The Angular Momentum Structure of the Nucleon

Perspectives in Hadronic Physics, May 12-16, 2008

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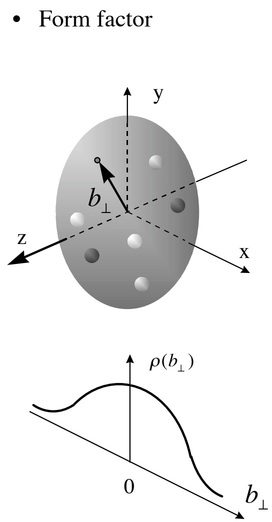
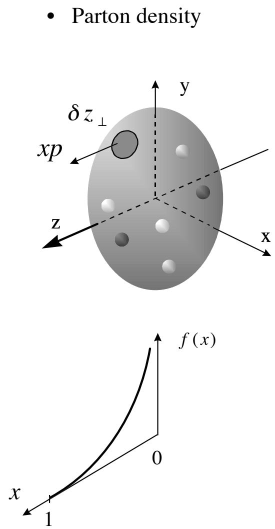
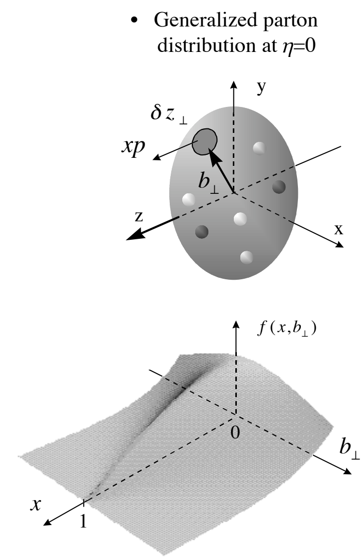
Table of Contents

3-dimensional Picture of the Proton

Nucleon momentum in Infinite Momentum Frame: $(p_{\gamma^*} + p_{nucl})_z \rightarrow \infty$







Nucleon's transv. charge distribution given by 2-dim. Fourier transform of **Form Factor**:
⇒ Parton's transverse localization $\mathbf{b}_\perp$

Probability density to find partons of given long. mom. fraction x at resol. scale $1/Q^2$ (no transv. inform.)
⇒ Parton's longitudinal momentum distribution function (**PDF**) f(x)

Generalized Parton Distrib.$^{\mathrm{s}}$ (GPDs) probe simultaneously transverse localization $\mathbf{b}_\perp$ for a given longitudinal momentum fraction x.
2nd moment by Ji relation:
$J_{q,g} = \frac{1}{2} \lim_{t\rightarrow 0} \int x \, dx \, [H_{q,g}(x,\xi,t) + E_{q,g}(x,\xi,t)]$

Proton Spin Budget in a Nutshell

NO unique and gauge-invariant decomposition of the nucleon spin:

(A) ‘GPD-based’: $\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + \widehat{\Delta g} + L_g$

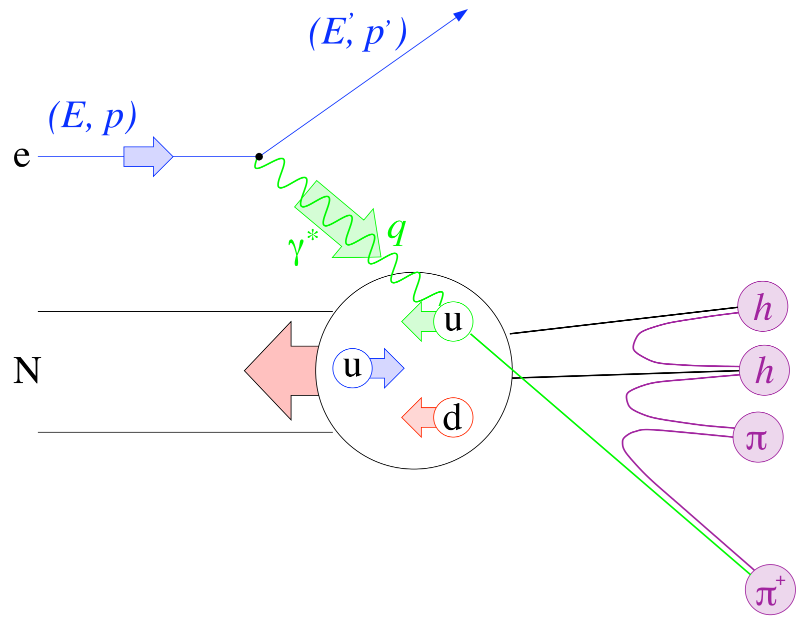
- **Total angular momenta** of quarks (J_q) and gluons (J_g) are gauge-invariant and calculable in lattice gauge theory
- **Intrinsic spin contribution** and **orbital angular momentum** are gauge inv. for quarks ($\frac{1}{2}\Delta\Sigma$ and L_q), but not for gluons ($\widehat{\Delta g}$ and L_g)
- Probabilistic interpretation only for $\frac{1}{2}\Delta\Sigma$ (well measured)
- J_q accessible through exclusive lepton nucleon scattering
- J_g very difficult to access experimentally

(B) Light-cone gauge: $\frac{1}{2} = \mathcal{J}_q + \mathcal{J}_g = \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta g + \mathcal{L}_g$

- All 4 terms have a probabilistic interpretation
- Δg is gauge invariant (being measured)

$\Rightarrow$ Results from both decompositions must not be mixed, as $\mathcal{L}_q \neq L_q, \Delta g \neq \widehat{\Delta g}, \mathcal{L}_g \neq L_g$, even $\mathcal{J}_g \neq J_g$!

DIS: Kinematics, Cross Sections, Asymmetry



Virtual-photon kinematics:

$$Q^2 = -q^2 \qquad \nu = E - E'$$

Fraction of nucleon momentum carried by struck quark: $x = \frac{Q^2}{2M\nu}$

fraction of virtual-photon energy carried by produced hadron h: $z = \frac{E_h}{\nu}$

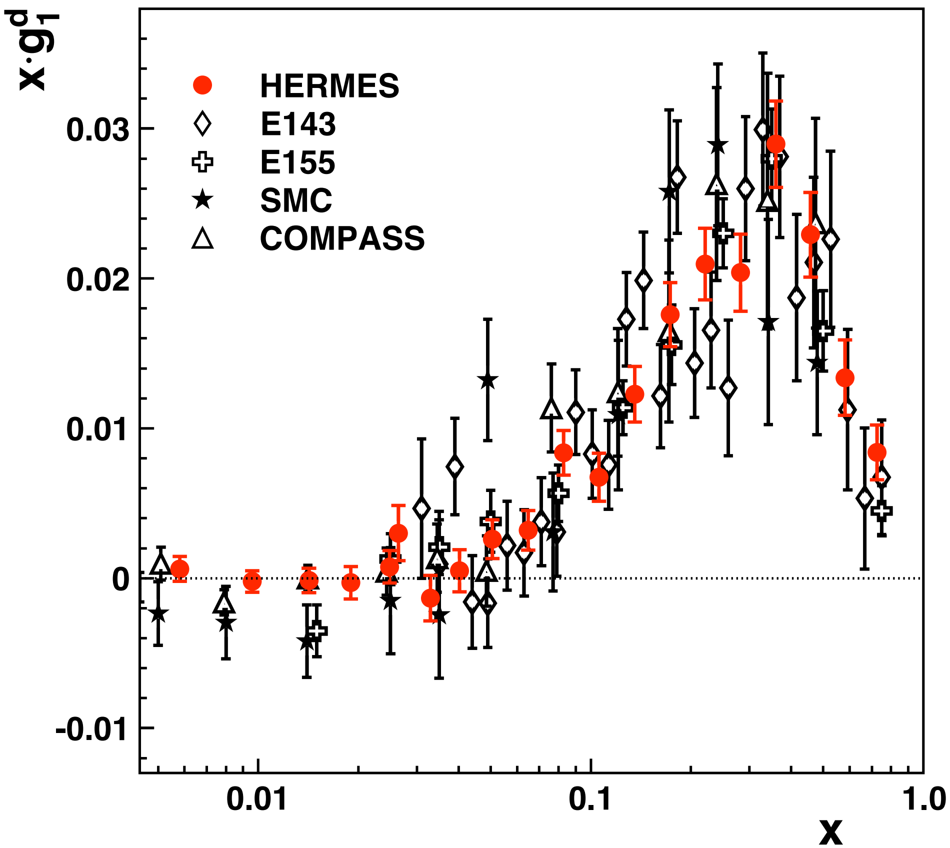
Hadron transverse momentum: $P_{h\perp}$

- Unpolarized cross section: $\sigma_{UU} \equiv \frac{1}{2}(\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}})$
- Cross section (helicity) difference: $\sigma_{LL} \equiv \frac{1}{2}(\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}})$
- Double-spin asymmetry: $A_{||} \equiv \frac{\sigma_{LL}}{\sigma_{UU}} \simeq \frac{g_1}{F_1}$ (neglecting small g_2 contribution)
- Measured asymmetry: $A_{||} = \frac{1}{\langle P_B \rangle \langle P_T \rangle} \frac{(\frac{N}{L})^{\overset{\rightarrow}{\Leftarrow}} - (\frac{N}{L})^{\overset{\rightarrow}{\Rightarrow}}}{(\frac{N}{L})^{\overset{\rightarrow}{\Leftarrow}} + (\frac{N}{L})^{\overset{\rightarrow}{\Rightarrow}}}$

with $P_B(P_T)$: longitudinal beam (target) polarization

Direct determination of quark spin contribution $\Delta\Sigma$

Most precise g_1^d result: Hermes inclusive data [PRD75(2007)012007,hep-ex/0609039]:



Method:

- NNLO leading twist analysis in $\overline{\mathrm{MS}}$ scheme
- assume SU_3 flavor symmetry in hyperon decay
- observe saturation of $\Gamma_1 = \int dx\, g_1^d(x)$ for $x < 0.04$
- assume no significant contribution of small-x region

Data for $Q^2 > 1$ GeV^2: evaluate $\Gamma_1^d(Q^2 = 5\ \mathrm{GeV}^2) = {}_{0.021}\int^{0.9} dx\, g_1^d(x)$

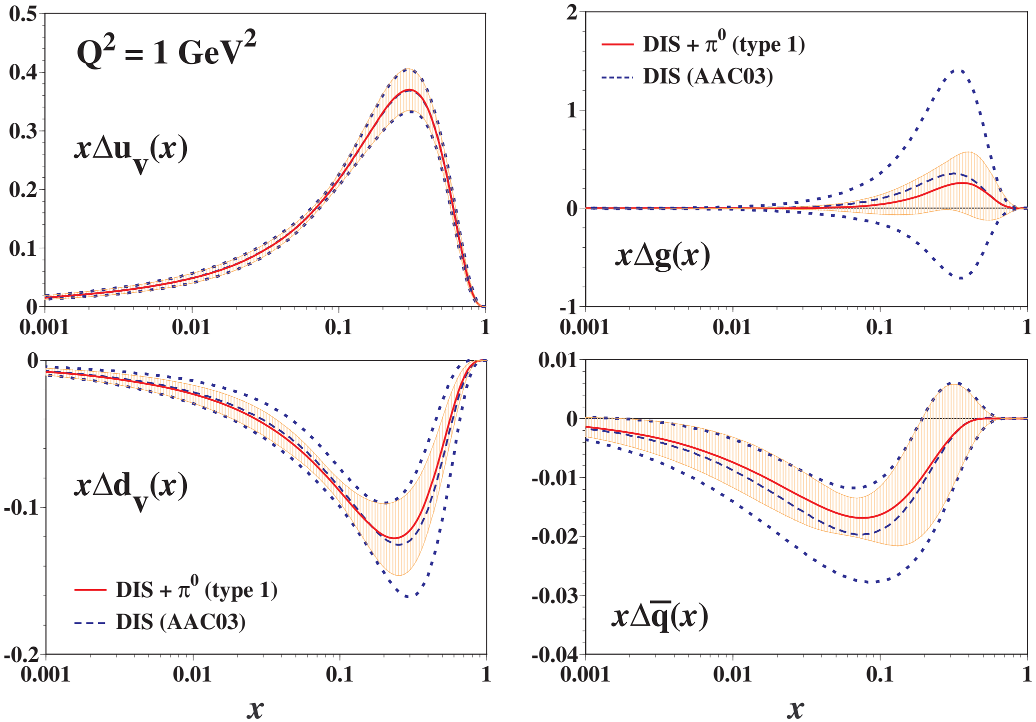
Result at $Q^2 = 5$ GeV^2 (all data points evolved):

$\Delta\Sigma = 0.330 \pm 0.011_{theor.} \pm 0.025_{exp.} \pm 0.028_{evol.}$

where 'exp.' includes stat., syst. and parameterization uncertainties

Next-to-leading Order QCD Fits

Results by AAC [PRD74(2006)014015,hep-ph/0603213]: NLO in α_s, $\overline{MS}$ scheme



Assumptions:

- Flavor-symmetric Δq_{sea}
- Integrals of Δq_u^{val} and Δq_d^{val} fixed by weak decay constants F and D

Input experimental data:

- $A_1^{p,d}$ from COMPASS,JLAB,HERMES
- $A_{LL}^{\pi^0}$ from PHENIX

Results at $Q^2 = 1$ GeV^2:

$\Delta\Sigma = 0.25 \pm 0.10$

$\Delta G = 0.47 \pm 1.08$ (DIS alone)

$\Delta G = 0.31 \pm 0.32$ (DIS+PHENIX)

Impact of recent CLAS and COMPASS data [PRD75(2007)074027,hep-ph/0612360]:

Fit with $\Delta g > 0 : \Delta G = 0.13 \pm 0.17$ Fit with $\Delta g < 0 : \Delta G = -0.20 \pm 0.41$

Impact of recent PHENIX and STAR data ($Q^2 = 10$ GeV^2) {DSSV, arXiv:0804.0422 [hep-ph]}:

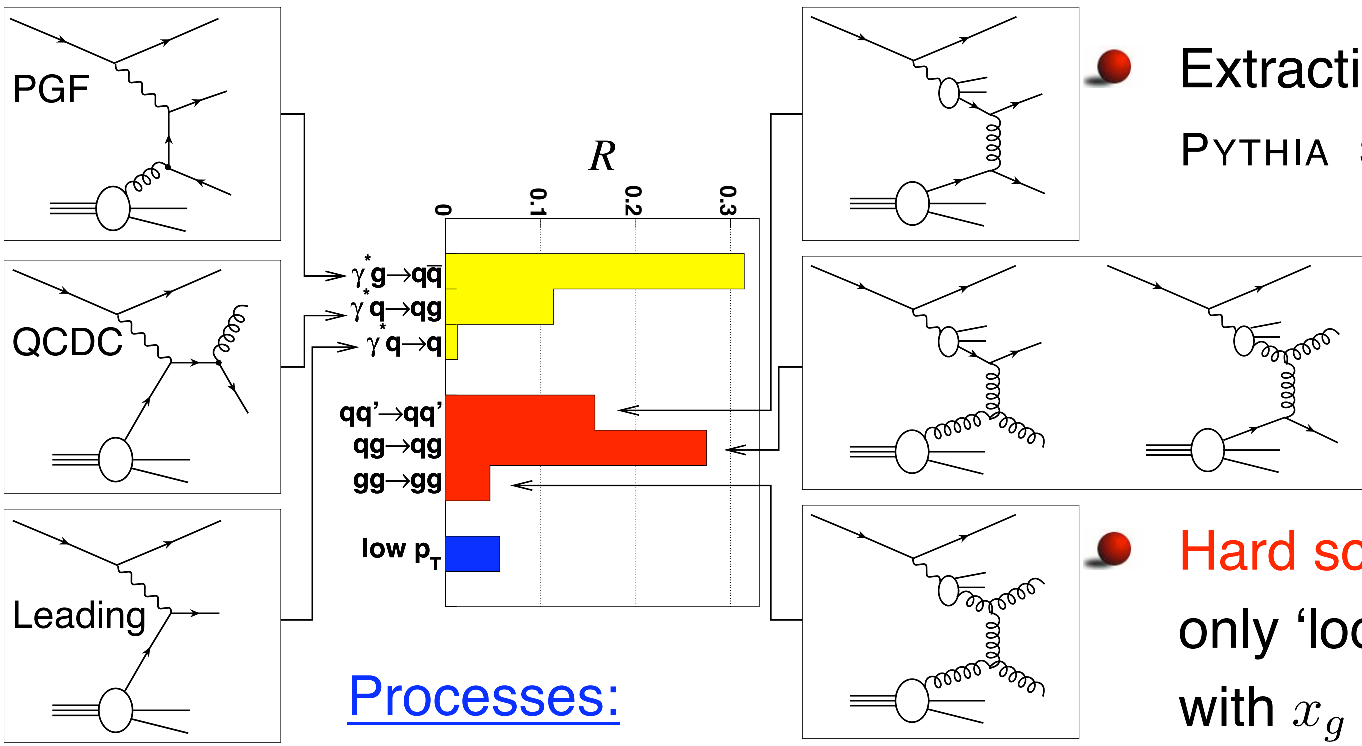
Clear indication for flavor-asymmetric sea. For $0 < x < 1 : \Delta G = -0.084$

For $0.001 < x < 1 : \Delta G = 0.013$ with $^{+0.106}_{-0.120}$ for $\Delta\chi^2 = 1$; $^{+0.702}_{-0.314}$ for $\Delta\chi^2/\chi^2 = 2\%$

Determination of Gluon Contribution to Nucleon Spin

- High-p_t hadron pairs or single hadrons quasi-real photoprod.: $\langle Q^2 \rangle \approx 0.1$ GeV^2
- Sensitivity through $\gamma^* g$ 'direct' hard scattering or 'resolved-photon' process

left graphs: direct processes; right graphs: resolved-photon processes [COMPASS analysis]

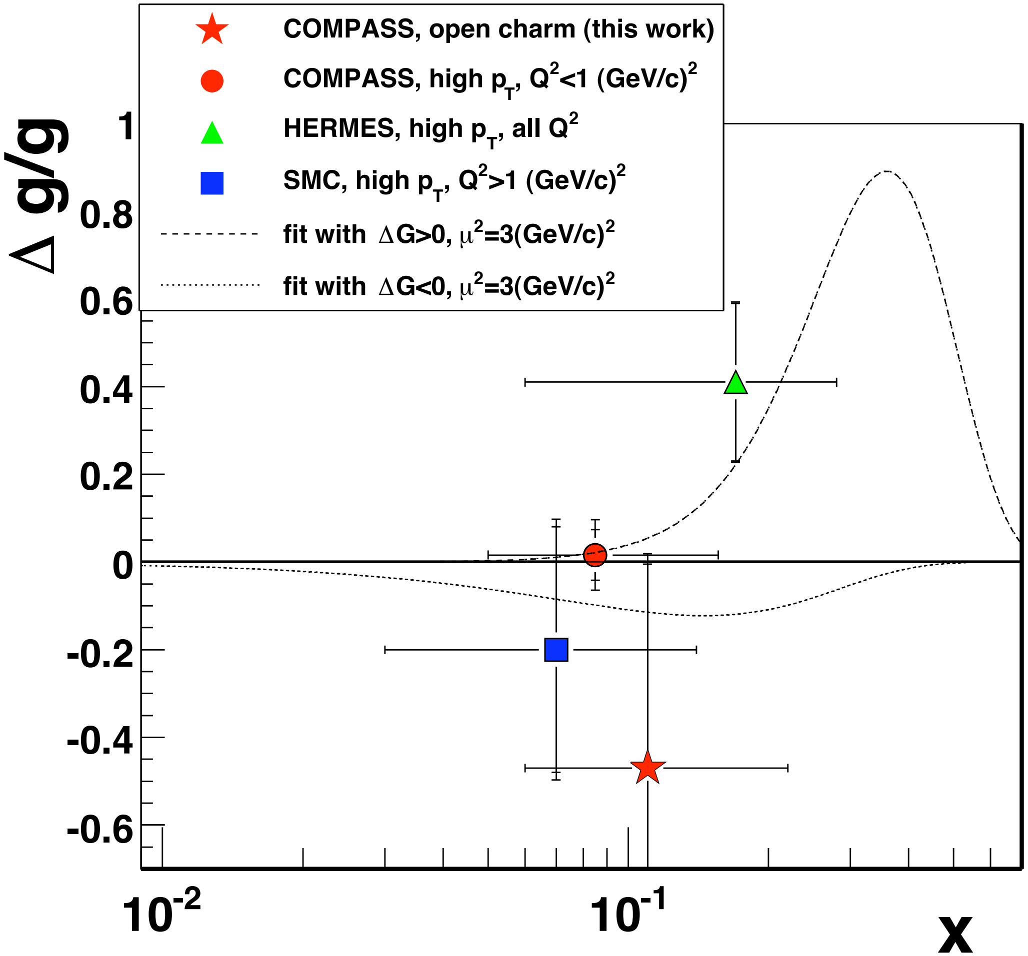


- Extraction heavily relies on PYTHIA simulation (LO only !)
- Hard scale $\mu^2 \simeq 3$ GeV^2 only 'loosely' correlated with x_g ($\langle x_g \rangle \simeq 0.1$)

- COMPASS: Open-charm production ($\gamma^* g \to c\bar{c}$) and hadron pairs
- HERMES: Single high-p_t hadrons. Pairs in old analysis (all Q^2, $\langle x_g \rangle \simeq 0.17$

  [PRL84 (2000) 2584] $\frac{\Delta g}{g} = 0.41 \pm 0.18_{stat} \pm 0.03_{sys-exp}$ ($\pm$unknown$_{sys-Model}$)
- RHIC: A_{LL} in inclusive direct γ & π^0 production, inclusive jet production

Results on Gluon Helicity Distribution $\frac{\Delta g}{g}(x)$



DIS results on $\frac{\Delta g}{g}(x)$:

COMPASS high-p_t hadron pairs:

$Q^2 < 1$ GeV^2 ($\langle x \rangle \simeq 0.085$):

$$\frac{\Delta g}{g} = 0.016 \pm 0.058_{stat} \pm 0.055_{syst}$$

{PLB 612,154 (2005)}

$Q^2 > 1$ GeV^2 ($\langle x_g \rangle \simeq 0.13$)

$$\frac{\Delta g}{g} = 0.06 \pm 0.31_{stat} \pm 0.06_{syst}$$

{prel.: K.Kurek,DIS06,hep-ex/0607061}

COMPASS open charm:

$$\frac{\Delta g}{g} = -0.47 \pm 0.44_{stat} \pm 0.15_{syst}$$

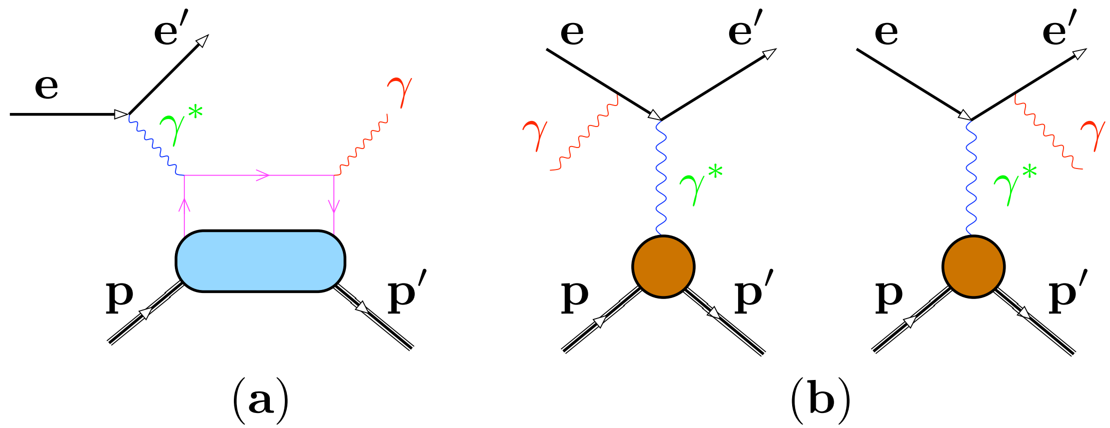
($\langle x_g \rangle \simeq 0.11$) {arXiv:0802.3023[hep-ex]}

HERMES high-p_t single hadrons [prel.]:

$$Q^2 \simeq 0; (\langle x_g \rangle \simeq 0.22): \frac{\Delta g}{g} = 0.071 \pm 0.034_{stat} \pm 0.010_{sys-exp} \pm^{0.127}_{0.105}\ {}_{sys-Models}$$

PHENIX: Confidence limits for fits with different $\frac{\Delta g}{g}$ assumptions

Deeply Virtual Compton Scattering



- Same final state in DVCS and Bethe-Heitler ⇒ Interference!

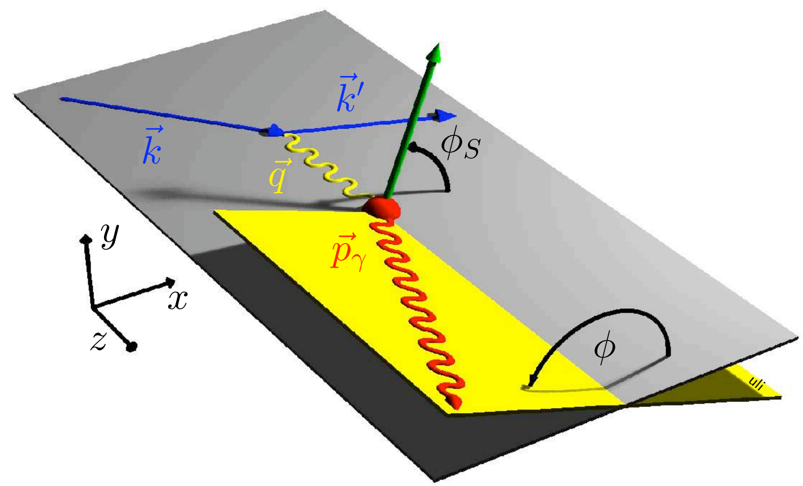
$$d\sigma(\mathrm{eN} \to \mathrm{eN}\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{I}$$

- $\mathcal{T}_{BH}$ is parameterized in terms of Dirac and Pauli Form Factors F_1, F_2, calculable in QED.
- $\mathcal{T}_{DVCS}$ is parameterized in terms of Compton form factors $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$ (which are convolutions of resp. GPDs $H, E, \widetilde{H}, \widetilde{E}$)
- (Certain Parts of) interference term I can be filtered out by forming certain cross section differences (or asymmetries)

⇒ GPDs $H, E, \widetilde{H}, \widetilde{E}$ **indirectly** accessible via interference term I

Azimuthal Asymmetries in DVCS

DVCS–Bethe-Heitler Interference term I induces differences or azimuthal asymmetries $\mathcal{A}$ in the measured cross-section:



- Beam-charge asymmetry $\mathcal{A}_C(\phi)$ [BCA] :
  $$d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$$
- Beam-spin asymmetry $\mathcal{A}_{LU}(\phi)$ [BSA] :
  $$d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$$
- Long. target-spin asymmetry $\mathcal{A}_{UL}(\phi)$:
  $$d\sigma(\overset{\Leftarrow}{P},\phi) - d\sigma(\overset{\Rightarrow}{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$$ [LTSA]
- Transverse target-spin asymmetry $\mathcal{A}_{UT}(\phi,\phi_s)$ [TTSA]:

$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$$

(F_1, F_2 are the Dirac and Pauli elastic nucleon form factors)

HERMES Combined BSA & BCA Analysis

Various asymmetry amplitudes $\mathcal{A}$ contribute to polarized cross section σ_{LU}:

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi)[1 + e_l \mathcal{A}_C(\phi) + e_l P_l \mathcal{A}^I_{LU}(\phi) + P_l \mathcal{A}^{DVCS}_{LU}(\phi)]$$

L: longitudinally polarized lepton beam of charge e_l & polarization P_l; U: unpolarized proton target

BCA: $\mathcal{A}_C(\phi) = \frac{1}{\sigma_{UU}} c^I_1 \cos\phi + \cdots$ $\qquad c^I_1 \propto \frac{\sqrt{-t}}{Q} F_1 \mathrm{Re}\mathcal{H} + [\cdots]$

BSA (interference term): $\mathcal{A}^I_{LU}(\phi) = \frac{1}{\sigma_{UU}} s^I_1 \sin\phi + \cdots$ $\qquad s^I_1 \propto \frac{\sqrt{-t}}{Q} F_1 \mathrm{Im}\mathcal{H} + [\cdots]$

BSA (DVCS term): $\mathcal{A}^{DVCS}_{LU}(\phi) = \frac{1}{\sigma_{UU}} s^{DVCS}_1 \sin\phi$ (small at HERMES energy)

Unpolarized cross section: $\sigma_{UU} = \sigma_{BH} + \sigma_{DVCS} + \sigma_I$

F_1 : Dirac elastic nucleon form factor

$\mathcal{H}$: Compton Form Factor (CFF), embodies GPD H

$[\cdots]$: kinematically suppressed CFFs ($\tilde{\mathcal{H}}, \mathcal{E}$) embodying GPDs $\tilde{H}, E$

Fit to data: $\mathcal{A}_C(\phi) = \sum_{n=0}^{3} A_C^{\cos n\phi} \cos n\phi$

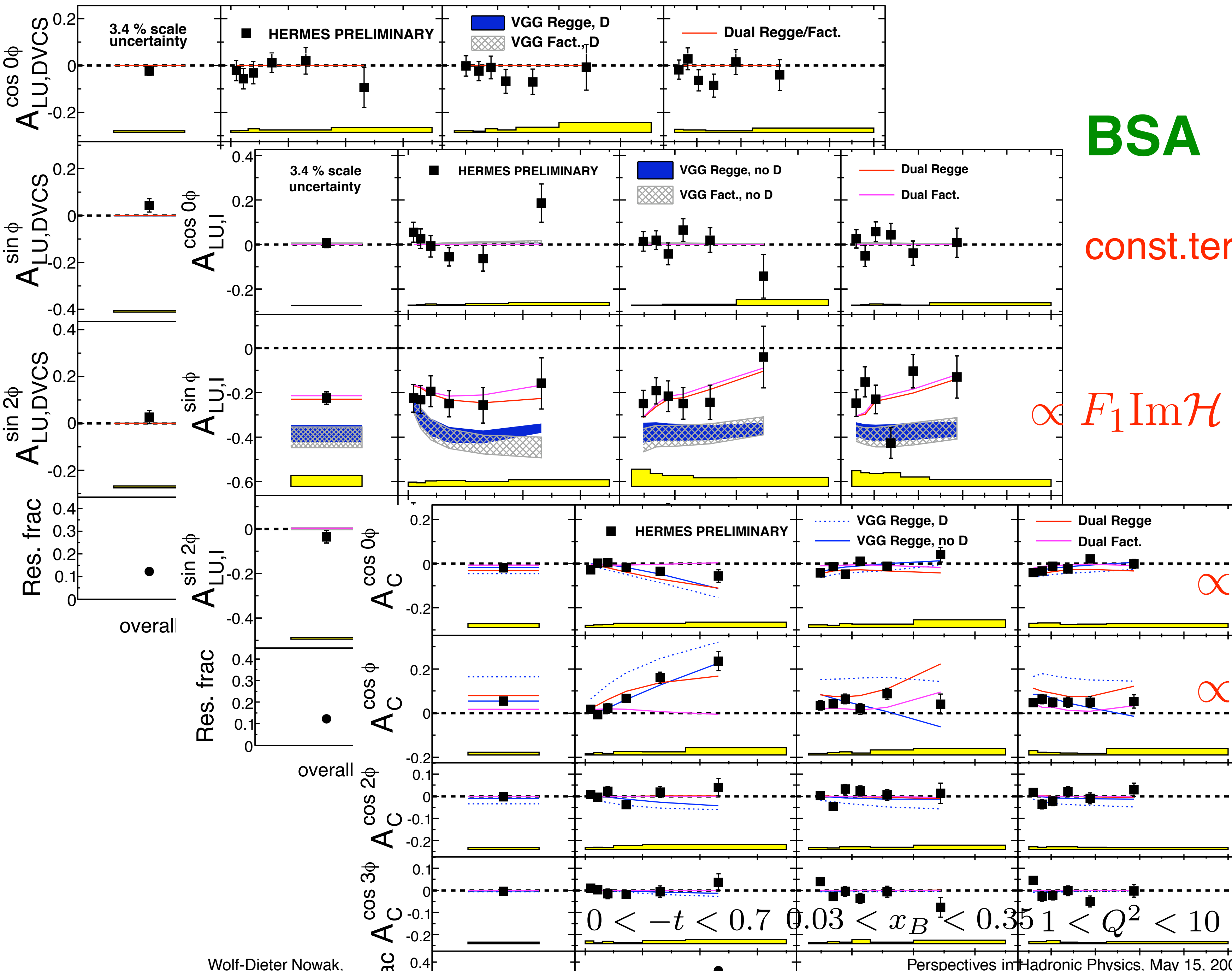
$$\mathcal{A}^I_{LU}(\phi) = \sum_{m=1}^{2} A_{LU,I}^{\sin m\phi} \sin m\phi$$

$$\mathcal{A}^{DVCS}_{LU}(\phi) = A_{LU,DVCS}^{\sin\phi} \sin\phi$$

Fit results: ‘effective’ asymmetry amplitudes: $A_C^{\cos n\phi}, A_{LU,I}^{\sin m\phi}, A_{LU,DVCS}^{\sin\phi}$

$\Rightarrow$ well defined in theory, can be compared to GPD models !

HERMES Combined BSA & BCA Results



BSA

const.term

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

BCA

$\propto -A_C^{\cos\phi}$

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

HT

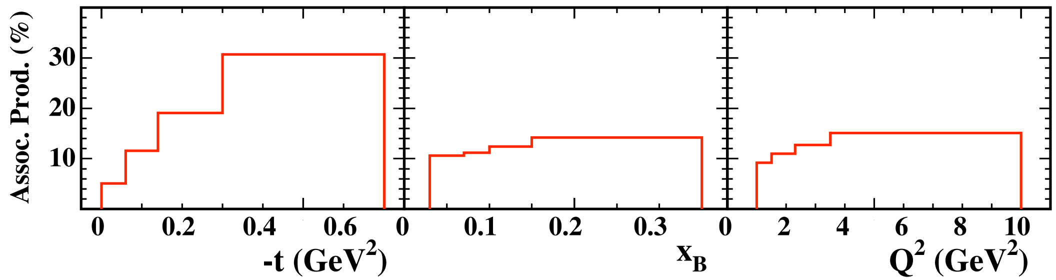
HT

Discussion of Combined BSA & BCA Analysis

!!! Asymmetries of 'associated (resonance) production' are unknown !!!

Kinematic dependence of fractions of associated production known from MC:

Average is 12%



⇒ In data associated production is part of the signal, while in models it is not included (still unknown)

- HERMES BSA agrees with Dual model Guzey,(Polyakov),Teckentrup 2006
- VGG model Vanderhaeghen, Guichon,Guidal 1999 clearly undershoots HERMES BSA

  (Improvement recently proposed Polyakov,Vanderhaeghen arXiv:0803.1271 [hep-ph])
- HERMES BCA disfavours factorized t dep., in both models and D-term in VGG
- Pure $|\mathrm{DVCS}|^2$ asymmetries found compatible with zero (as models assume)

⇒ HERMES data precise enough to discriminate between models or their variants

⇒ new models eagerly awaited !!! Müller,Kumericki

Why TTSA Data Expected to be Sensitive to J_q ?

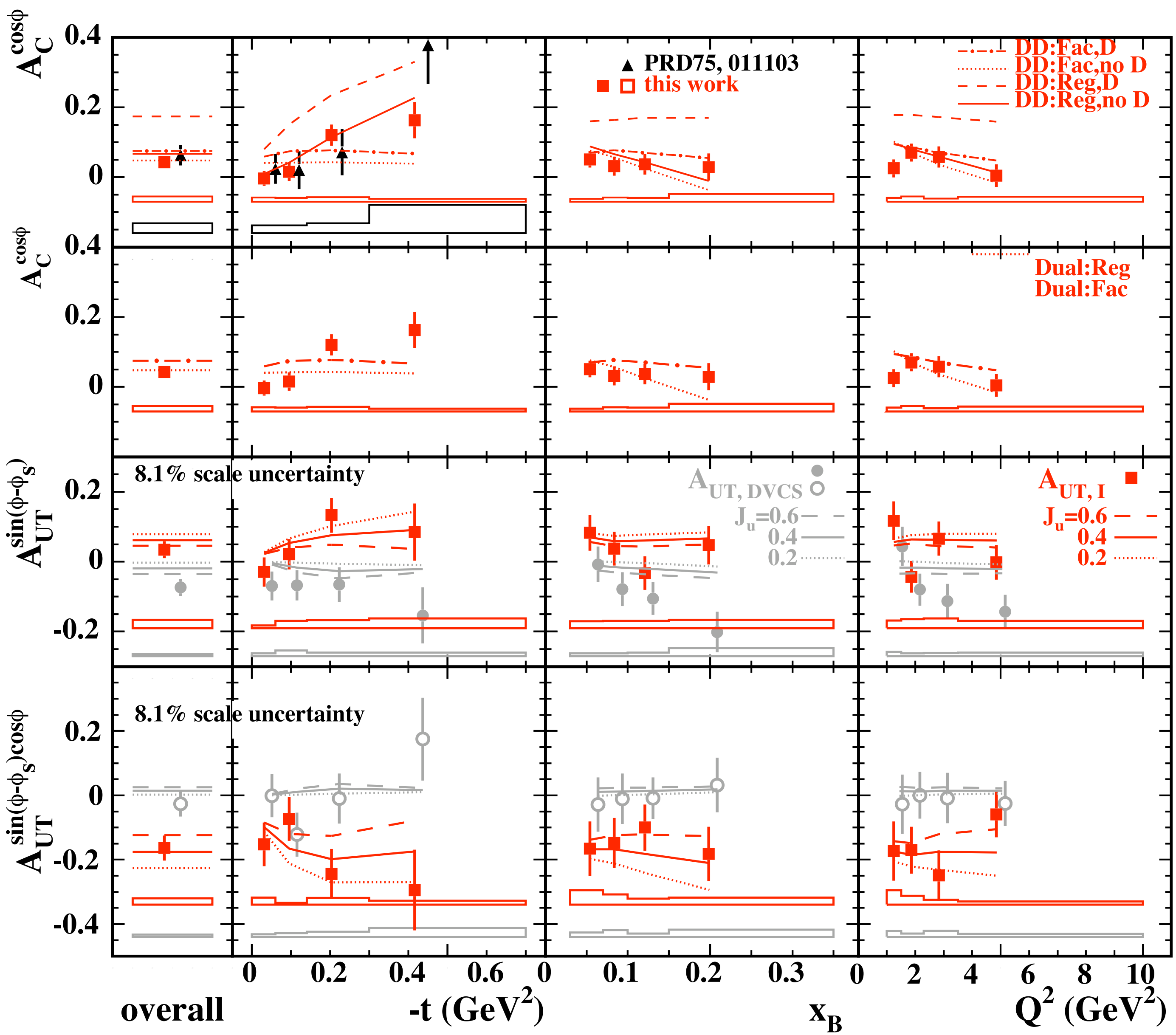
$$A_{UT}(\phi,\phi_S) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]\sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]\cos(\phi-\phi_S)\sin\phi$$

ANSATZ: spin-flip Generalized Parton Distribution E is parameterized as follows:

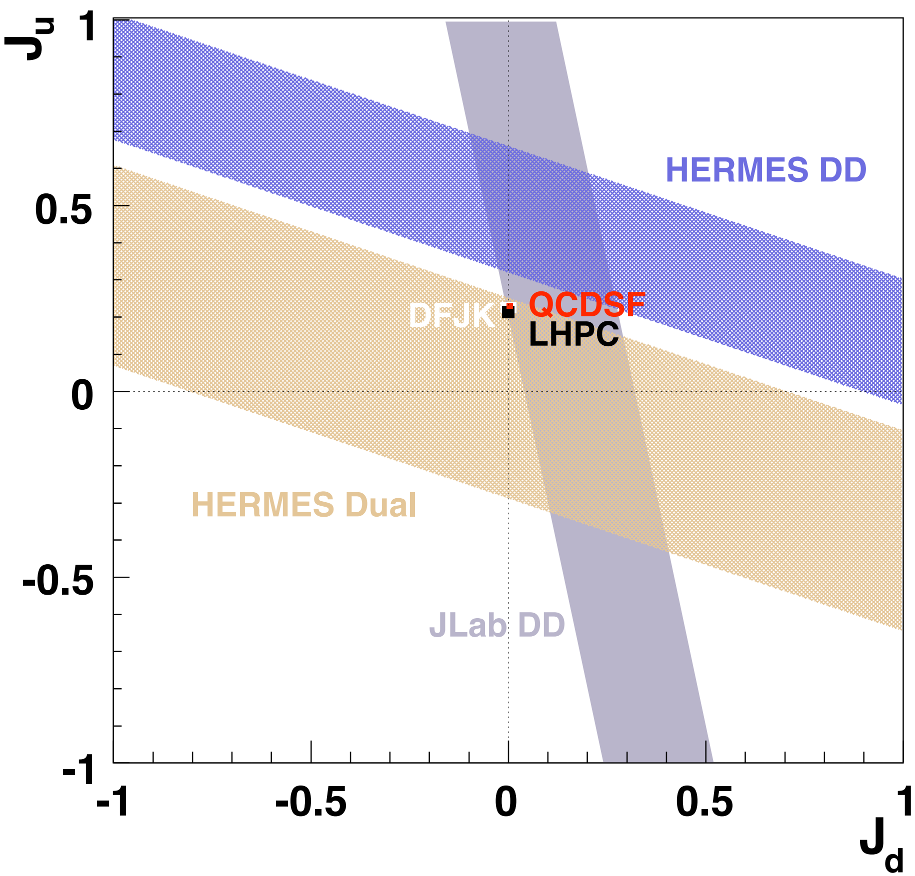
- Factorized ansatz for spin-flip quark GPDs: $E_q(x,\xi,t) = \frac{E_q(x,\xi)}{(1-t/0.71)^2}$
- t-indep. part via double distr. ansatz: $E_q(x,\xi) = E_q^{DD}(x,\xi) - \theta(\xi - |x|)D_q\left(\frac{x}{\xi}\right)$
- using double distr. K_q: $E_q^{DD}(x,\xi) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(x-\beta-\alpha\xi)\, K_q(\beta,\alpha)$
- with $K_q(\beta,\alpha) = h(\beta,\alpha)\, e_q(\beta)$ and $e_q(x) = A_q q_{val}(x) + B_q\delta(x)$ based on chiral QSM
- where coeff.s A, B constrained by Ji relation, and $\int_{-1}^{+1} dx\, e_q(x) = \kappa_q$
- A_u, A_d, B_u, B_d are functions of J_u, J_d
  $\Rightarrow J_u, J_d$ **are free parameters when calculating TTSA**
- Sensitivity to J_u (with $J_d = 0$) studied [EPJ C46, 729 (2006), hep-ph/0506264]

HERMES: First Measurement of TTSA

$$A_{UT}(\phi,\phi_S) = A_{UT}^{\sin(\phi-\phi_S)\cos\phi} \cdot \sin(\phi-\phi_S)\cos\phi + A_{UT}^{\cos(\phi-\phi_S)\sin\phi} \cdot \cos(\phi-\phi_S)\sin\phi + \ldots$$



Model-dependent constraints on J_u vs J_d



HERMES analysis method:

[arXiv:0802.2499, subm. to JHEP]

Unbinned maximum likelihood fit to all possible azimuthal asymmetry amplitudes at average kinematics:

$\Rightarrow$ 'combined fit' of HERMES BCA and TTSA data against various model calculations, leaving J_u and J_d as free parameters $\Rightarrow$ model-dep. 1-σ constraints on J_u vs. J_d:

- Double-distribution model: $J_u + J_d/2.8 = 0.49 \pm 0.17(\exp_{\rm tot})$
  [Vanderhaghen,Guichon,Guidal]
- Dual model [Guzey, Teckentrup]: $J_u + J_d/2.8 = -0.02 \pm 0.27(\exp_{\rm tot})$
- Lattice gauge theory: QCDSF [Göckeler et al.], LHPC [Hägler et al.]
- DFJK model: zero-skewness GPDs extracted from nuclear form factor data using valence-quark contributions only [Diehl et al.])

Summary and Outlook

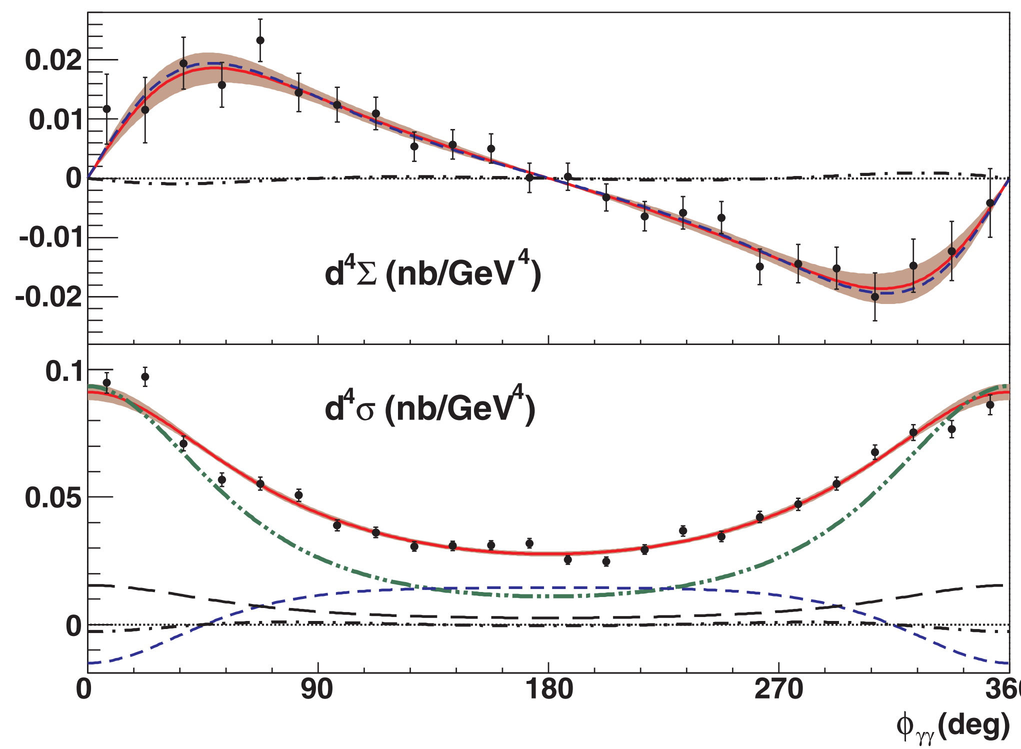
- ▷ No unique and gauge-invariant decomposition of the nucleon spin
- ▷ HERMES and COMPASS results on Deep Inelastic Scattering yield intrinsic quark and gluon contribution to the nucleon spin (in light-cone gauge)
- ▷ Total angular momenta of quarks and gluons accessible in context of Generalized Parton Distributions
- ▷ Deeply Virtual Compton Scattering is prime candidate to constrain total quark angular momenta (no feasible approach known for gluons)
- ▷ Pioneering HERMES results on azimuthal asymmetries, and first promising JLAB results on cross section differences in DVCS, allow us to severely constrain GPD models
- ▷ Increasing theoretical activities on improved and new GPD models
- ▷ Short-term future: for DVCS and other exclusive reactions final HERMES results and many more very precise JLAB 6 GeV data expected
- ▷ Medium-term future: hopefully unique COMPASS BCA data, presumably many very precise JLAB 12 GeV data

Back-up Slides

JLab E00-110 Scaling Test of DVCS Cross Section

- 5.75 GeV e^- beam (76% pol.), unpol. LH_2 target, [PRL 97 (2006) 262002]
- Detect e' by HRS, γ by EM calorimeter, recoil p by scintillator array
- 3 different kinematic settings with $x_{Bj} = 0.36$ fixed: $Q^2 = 1.5, 1.9, 2.3$ GeV^2. For each: $-t = 0.17, 0.23, 0.28, 0.33$ GeV
- **Measured separately:** $\frac{d^4\Sigma}{d^4\Phi} = \frac{1}{2}\left[\frac{d^4\sigma^+}{d^4\Phi} - \frac{d^4\sigma^-}{d^4\Phi}\right]$ and $\frac{d^4\sigma}{d^4\Phi} = \frac{1}{2}\left[\frac{d^4\sigma^+}{d^4\Phi} + \frac{d^4\sigma^-}{d^4\Phi}\right]$

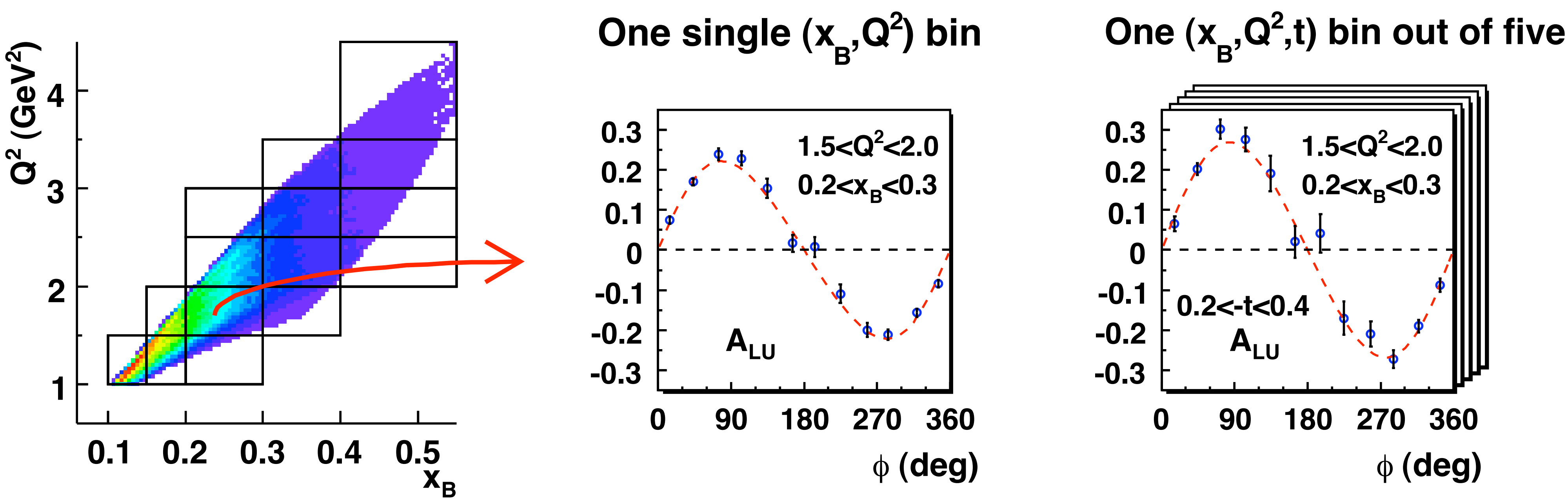
$\Rightarrow$ distinct information on GPDs:
$\frac{d^4\Sigma}{d^4\Phi} \propto \mathrm{Im}\, I$: as in BSA numer.
$\frac{d^4\sigma}{d^4\Phi} \propto \mathrm{Re}\, I$: same as in BCA



- Fit following terms separately: $|BH^2|$ (dot-dot-dashed), twist-2 int. term (dashed), twist-3 int. term (dot-dashed) ($|DVCS|^2$ found below few %)
- Twist-3 terms small
- $\frac{d^4\sigma}{d^4\Phi} > |BH^2| \rightarrow$ BSA and $\mathrm{Im}\, I/|BH^2|$ are not exactly the same over Φ

CLAS E01-113: High-stat. Beam-spin Asymmetry

- 1st dedicated Hall-B DVCS exp't: 5.76 GeV e^- beam, pol. 76-82%; unpol. LH_2
- CLAS spectrometer upgraded by inner calorimeter to detect γ's at small angles
  $\rightarrow$ all 3 final state particles (e' N γ) detected !
- Broad kinematic coverage at medium x (0.1...0.5), combined with high lumi
  $\rightarrow$ 3-dim. binning possible. Unpublished (White Paper) preview:



$\Rightarrow$ Very promising first glimpse into statistical power of JLab DVCS measurements