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The Angular Momentum Structure of the Nucleon

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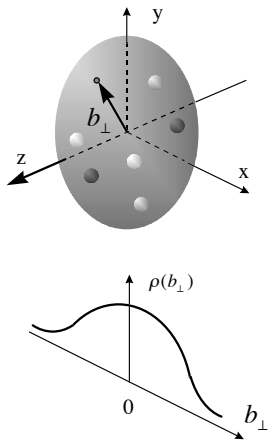
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3-dimensional Picture of the Proton

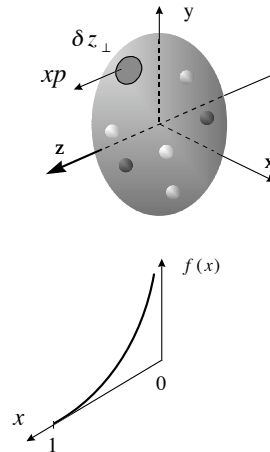
Nucleon momentum in Infinite Momentum Frame: $(p_{\gamma^*} + p_{nucl})_z \rightarrow \infty$

- Form factor



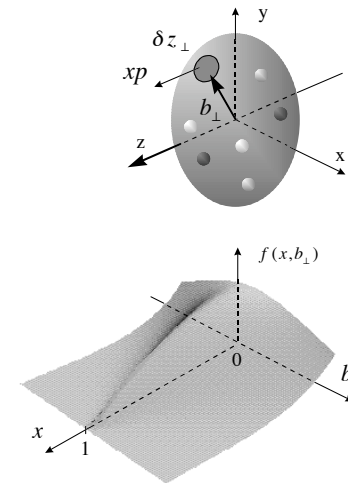
Nucleon's transv. charge distribution given by 2-dim. Fourier transform of **Form Factor**:
 \Rightarrow Parton's transverse localization b_{\perp}

- Parton density



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

- Generalized parton distribution at $\eta=0$



Generalized Parton Distrib.^S (GPDs) probe simultaneously transverse localization 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

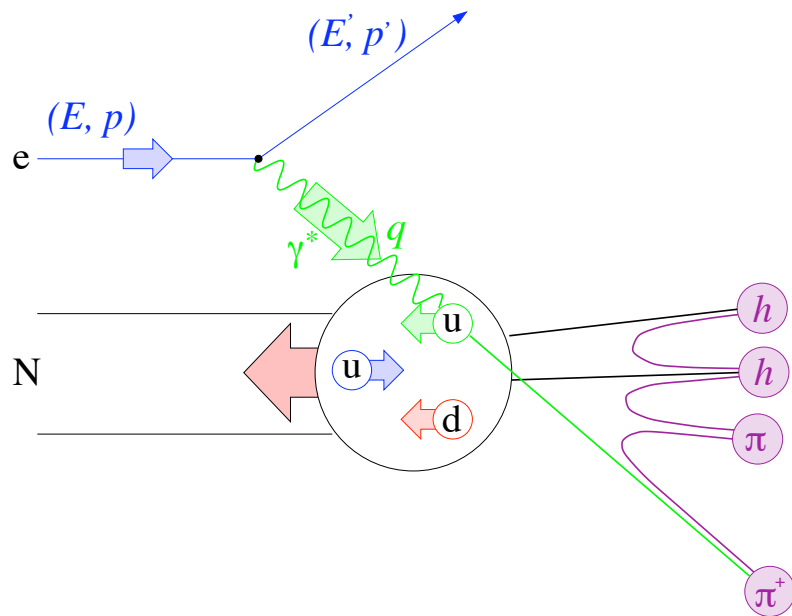
(B) Light-cone gauge: $\frac{1}{2} = \mathcal{J}_q + \mathcal{J}_g = \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta g + \mathcal{L}_g$

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

⇒ Results from both decompositions must not be mixed, as

$$\mathcal{L}_q \neq L_q, \Delta g \neq \widehat{\Delta}g, \mathcal{L}_g \neq L_g, \text{ even } \mathcal{J}_g \neq J_g !$$

DIS: Kinematics, Cross Sections, Asymmetry



Virtual-photon kinematics:

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

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: $P_{h\perp}$

$$\sigma_{UU} \equiv \frac{1}{2}(\sigma^{\leftarrow\leftarrow} + \sigma^{\rightarrow\rightarrow})$$

$$\sigma_{LL} \equiv \frac{1}{2}(\sigma^{\leftarrow\leftarrow} - \sigma^{\rightarrow\rightarrow})$$

● Unpolarized cross section:

● Cross section (helicity) difference:

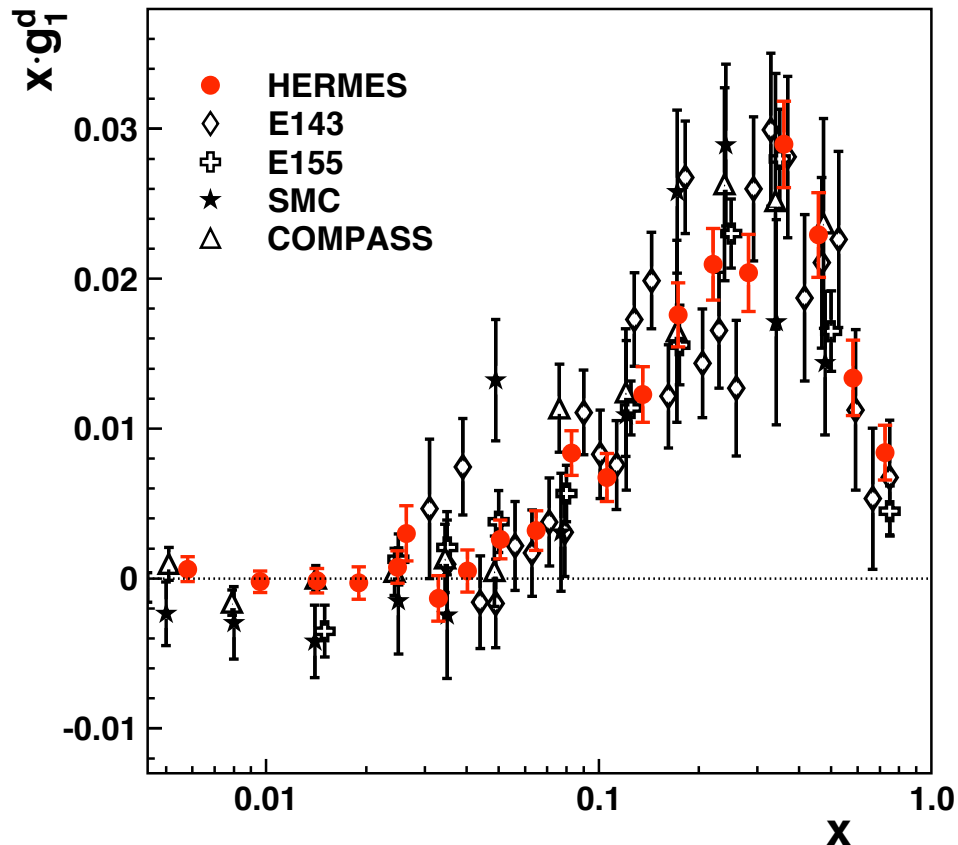
● Double-spin asymmetry: $A_{||} \equiv \frac{\sigma_{LL}}{\sigma_{UU}} \simeq \frac{g_1}{F_1}$ (neglecting small g_2 contribution)

● Measured asymmetry: $A_{||} = \frac{1}{\langle P_B \rangle \langle P_T \rangle} \frac{(\frac{N}{L})^{\leftarrow\leftarrow} - (\frac{N}{L})^{\rightarrow\rightarrow}}{(\frac{N}{L})^{\leftarrow\leftarrow} + (\frac{N}{L})^{\rightarrow\rightarrow}}$

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 $\overline{\text{MS}}$ 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 $Q^2 > 1 \text{ GeV}^2$: evaluate $\Gamma_1^d(Q^2 = 5 \text{ GeV}^2) = 0.021 \int^{0.9} dx g_1^d(x)$

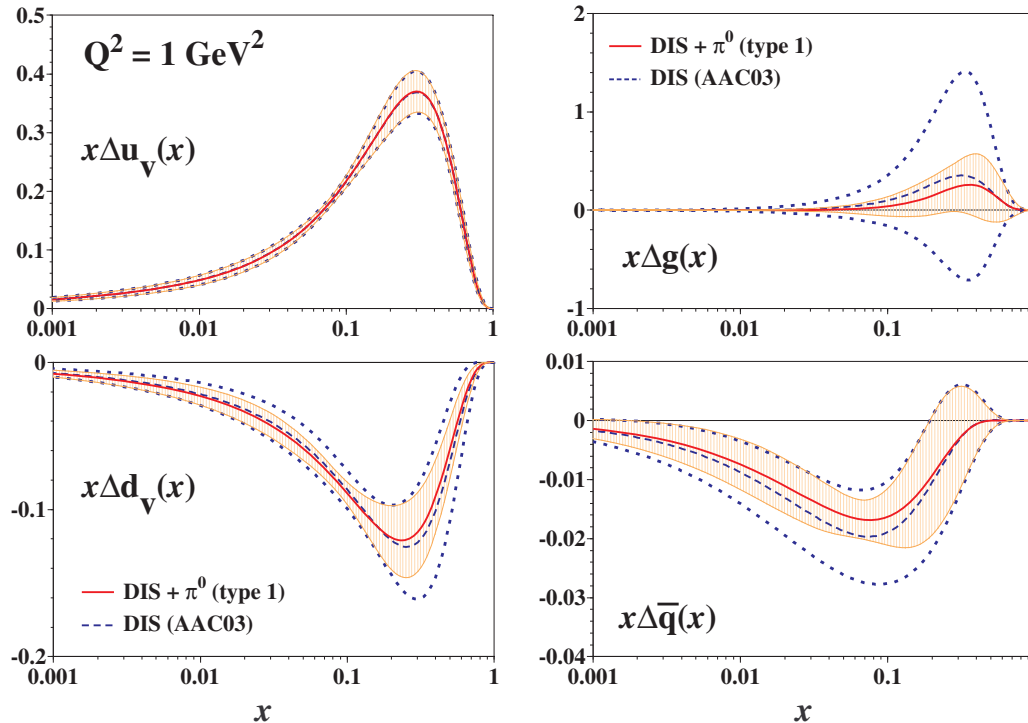
Result at $Q^2 = 5 \text{ GeV}^2$ (all data points evolved):

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

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 $Q^2 = 1 \text{ GeV}^2$:

$$\Delta\Sigma = 0.25 \pm 0.10$$

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

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

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 ($Q^2 = 10 \text{ GeV}^2$) {DSSV, arXiv:0804.0422 [hep-ph]}:

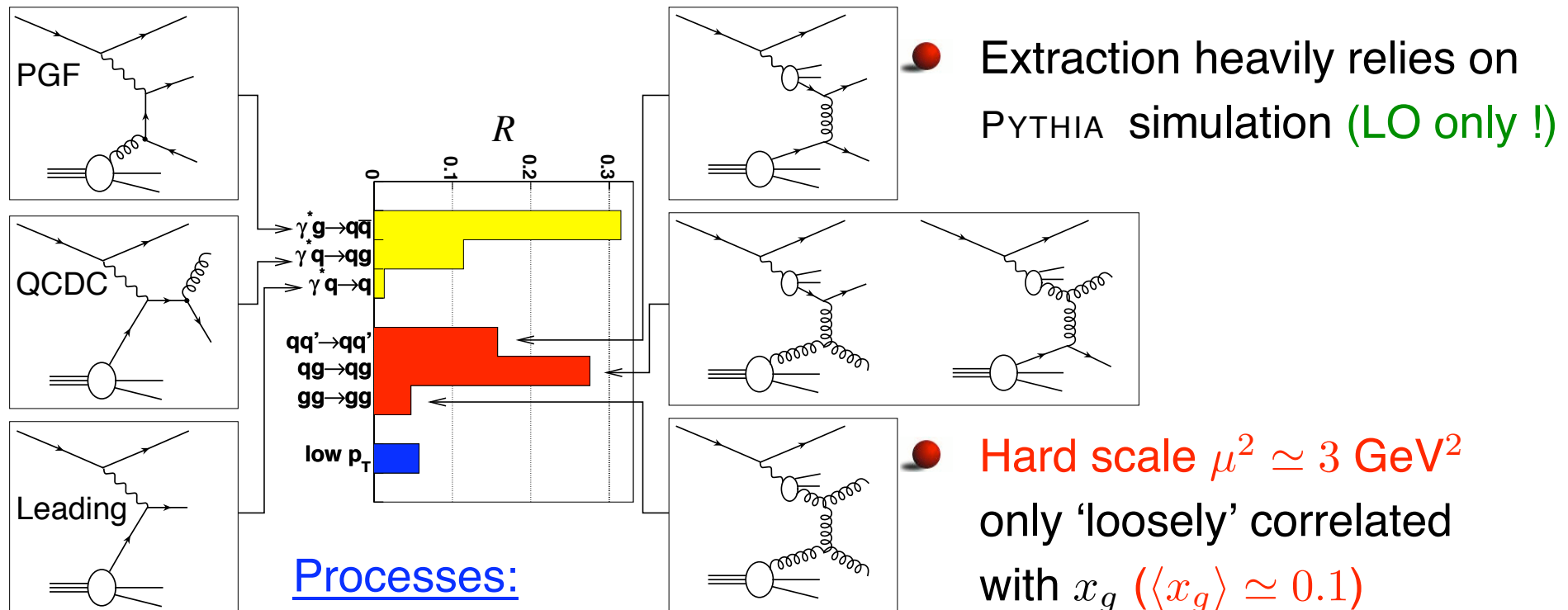
Clear indication for flavor-asymmetric sea. For $0 < x < 1$: $\Delta G = -0.084$

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

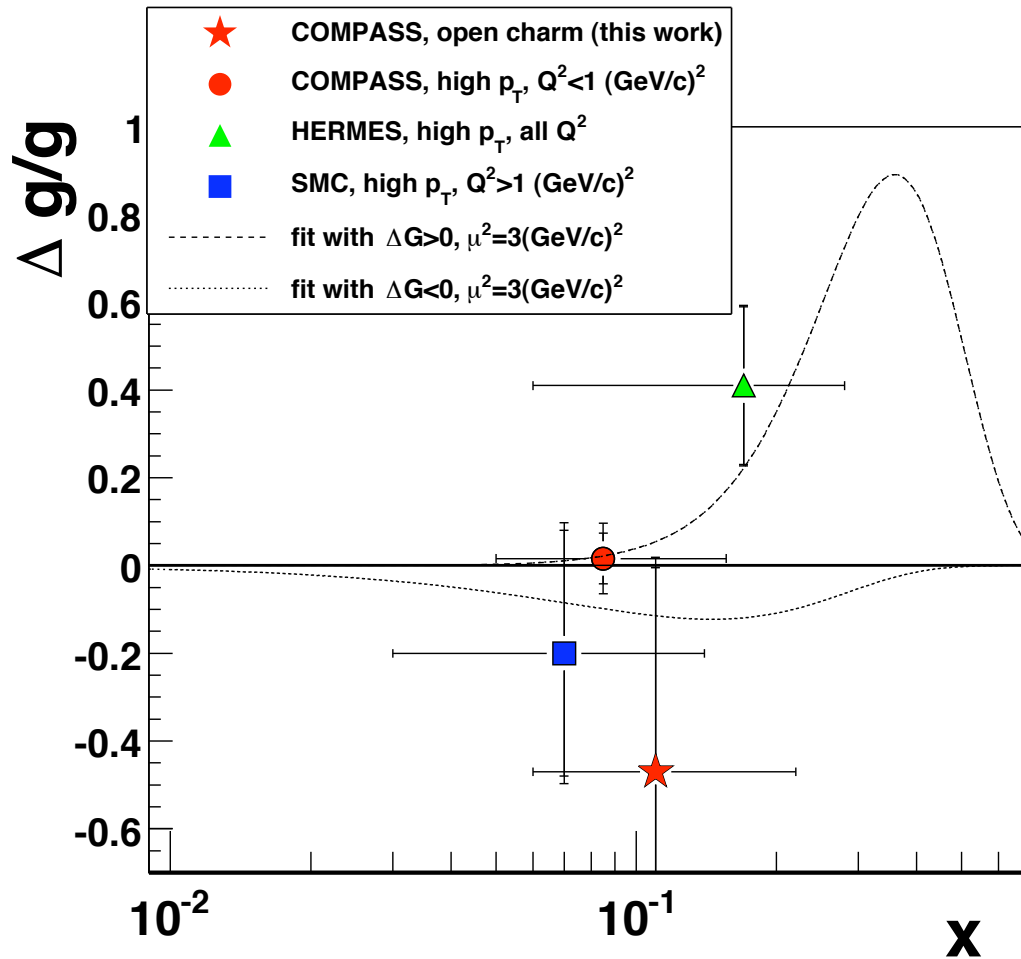
- High- p_t hadron pairs or single hadrons quasi-real photoprod.: $\langle Q^2 \rangle \approx 0.1 \text{ GeV}^2$
- Sensitivity through $\gamma^* g$ 'direct' hard scattering or 'resolved-photon' process

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



- COMPASS: Open-charm production ($\gamma^* g \rightarrow c\bar{c}$) 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:

$Q^2 < 1$ GeV² ($\langle x \rangle \simeq 0.085$):

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

{PLB 612,154 (2005)}

$Q^2 > 1$ GeV² ($\langle x_g \rangle \simeq 0.13$)

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

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

COMPASS open charm:

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

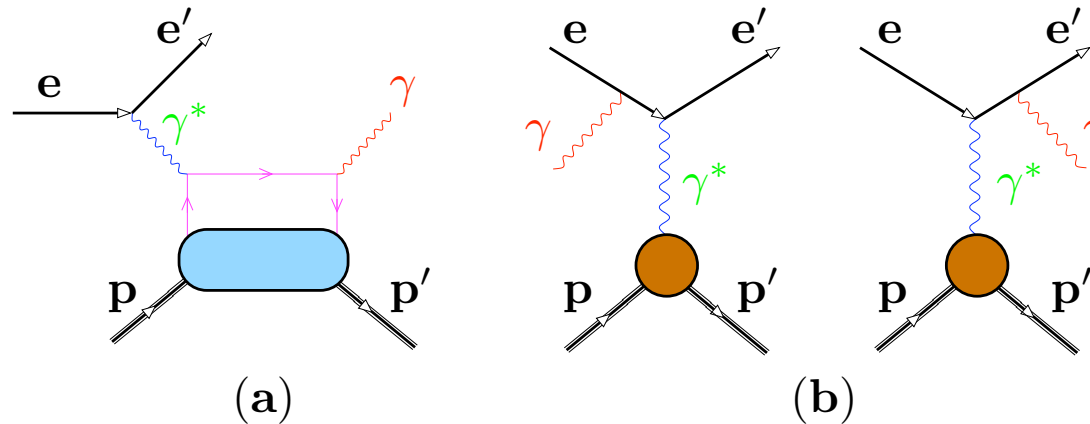
($\langle x_g \rangle \simeq 0.11$) {arXiv:0802.3023[hep-ex]}

HERMES high- p_T single hadrons [*prel.*]:

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

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

Deeply Virtual Compton Scattering



- Same final state in DVCS and Bethe-Heitler \Rightarrow Interference!

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

- \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 $\mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \tilde{\mathcal{E}}$ (which are convolutions of resp. GPDs $H, E, \tilde{H}, \tilde{E}$)
 - (Certain Parts of) interference term I can be filtered out by forming certain cross section differences (or asymmetries)
- \Rightarrow GPDs $H, E, \tilde{H}, \tilde{E}$ 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] :

$$d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \text{Re}[F_1 \mathcal{H}] \cdot \cos \phi$$

- Beam-spin asymmetry $\mathcal{A}_{LU}(\phi)$ [BSA] :

$$d\sigma(\vec{e}, \phi) - d\sigma(\overleftarrow{e}, \phi) \propto \text{Im}[F_1 \mathcal{H}] \cdot \sin \phi$$

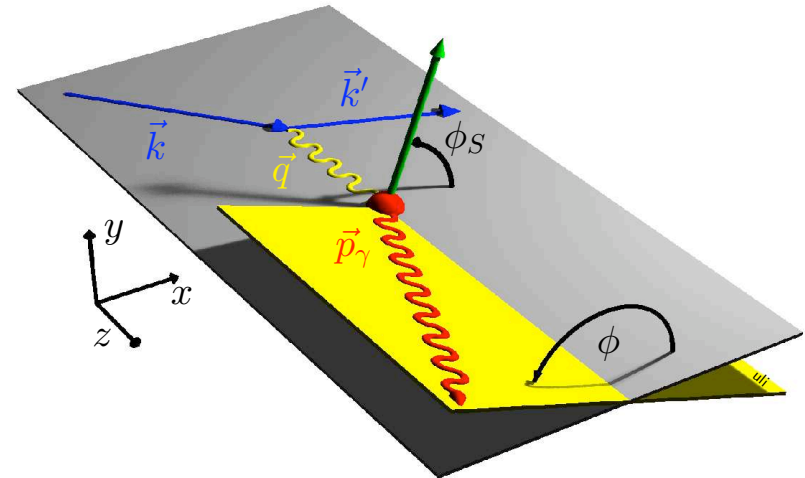
- Long. target-spin asymmetry $\mathcal{A}_{UL}(\phi)$:

$$d\sigma(\overleftarrow{P}, \phi) - d\sigma(\overrightarrow{P}, \phi) \propto \text{Im}[F_1 \tilde{\mathcal{H}}] \cdot \sin \phi \text{ [LTSA]}$$

- Transverse target-spin asymmetry $\mathcal{A}_{UT}(\phi, \phi_S)$ [TTSA]:

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

(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} :

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

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

BCA:
$$\mathcal{A}_C(\phi) = \frac{1}{\sigma_{UU}} c_1^I \cos \phi + \dots \quad c_1^I \propto \frac{\sqrt{-t}}{Q} F_1 \text{Re} \mathcal{H} + [\dots]$$

BSA (interference term):
$$\mathcal{A}_{LU}^I(\phi) = \frac{1}{\sigma_{UU}} s_1^I \sin \phi + \dots \quad s_1^I \propto \frac{\sqrt{-t}}{Q} F_1 \text{Im} \mathcal{H} + [\dots]$$

BSA (DVCS term):
$$\mathcal{A}_{LU}^{DVCS}(\phi) = \frac{1}{\sigma_{UU}} s_1^{DVCS} \sin \phi \quad (\text{small at HERMES energy})$$

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

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

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

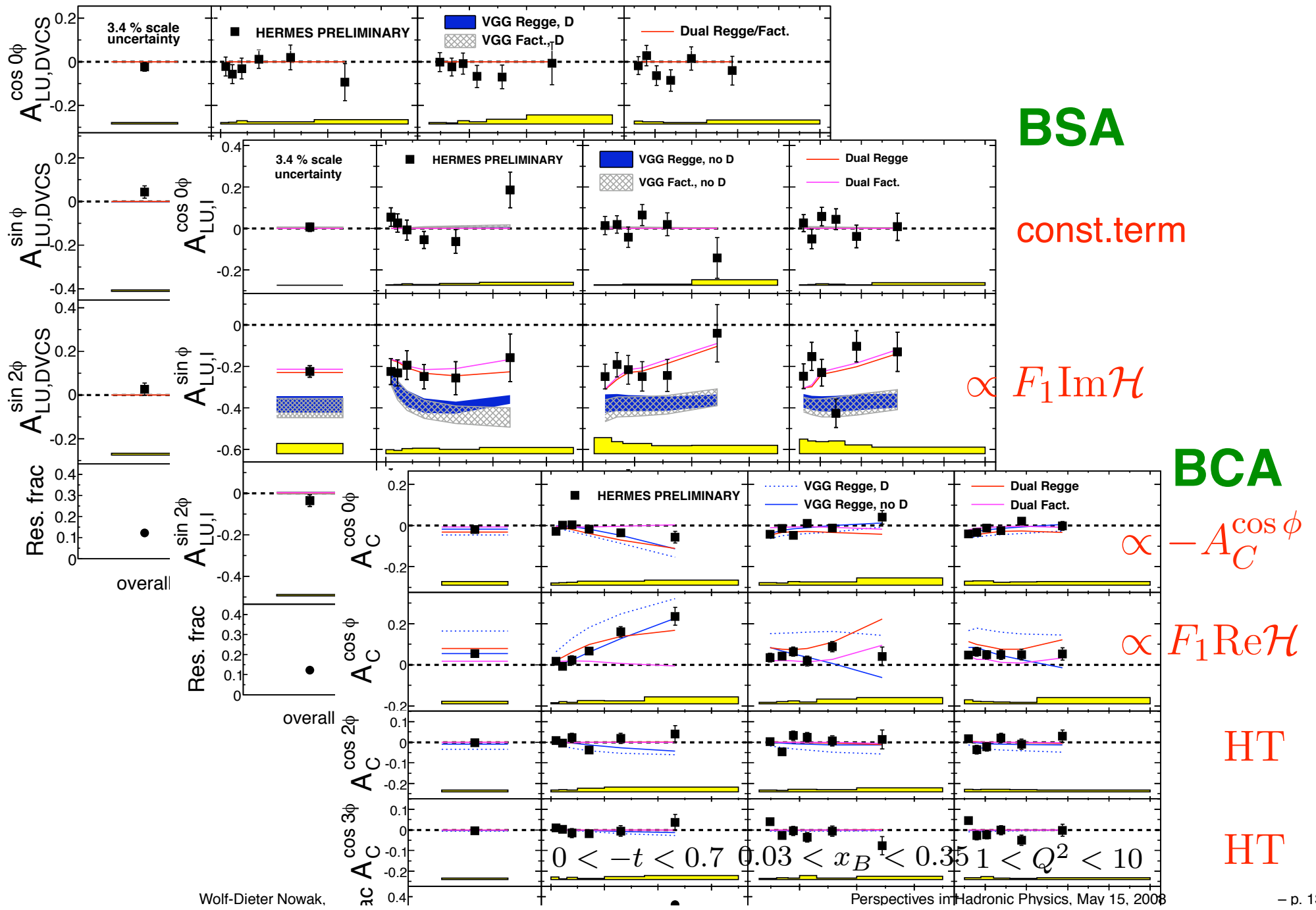
$$\mathcal{A}_{LU}^I(\phi) = \sum_{m=1}^2 A_{LU,I}^{\sin m\phi} \sin m\phi$$

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

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 !

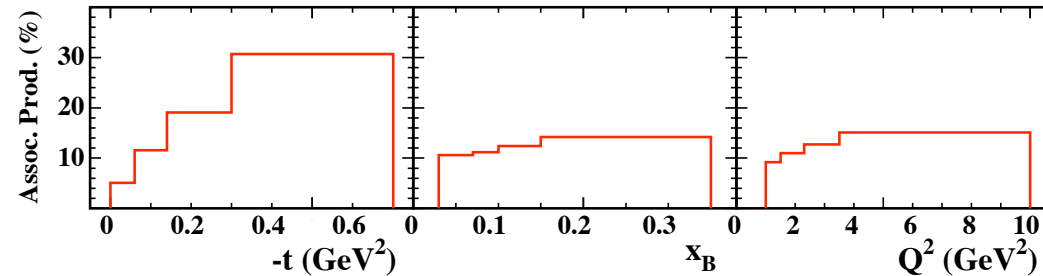
HERMES Combined BSA & BCA Results



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 $|DVCS|^2$ 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 ?

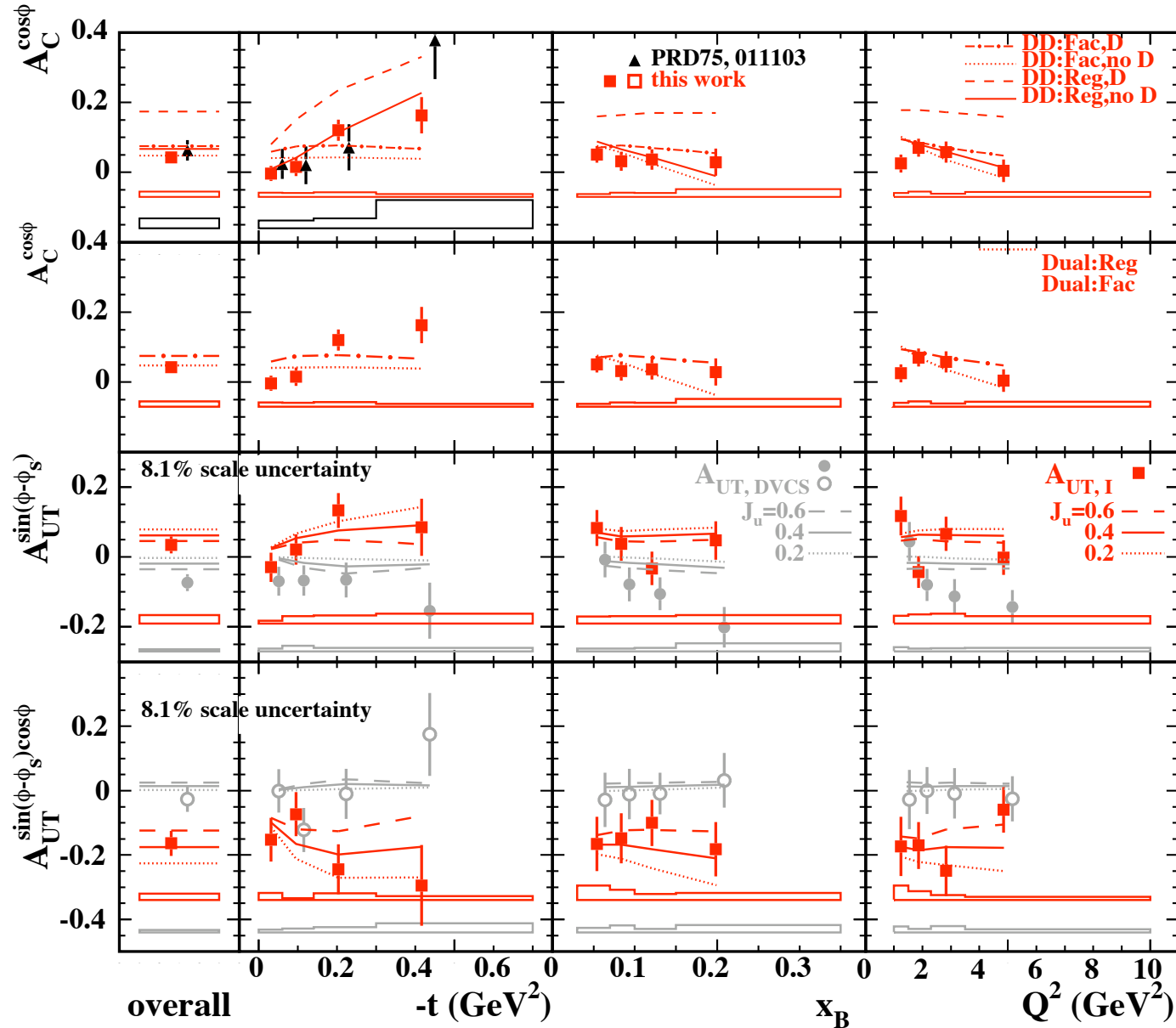
$$A_{UT}(\phi, \phi_S) \propto \text{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \sin(\phi - \phi_S) \cos \phi + \text{Im}[F_2\tilde{\mathcal{H}} - F_1\xi\tilde{\mathcal{E}}] \cos(\phi - \phi_S) \sin \phi$$

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

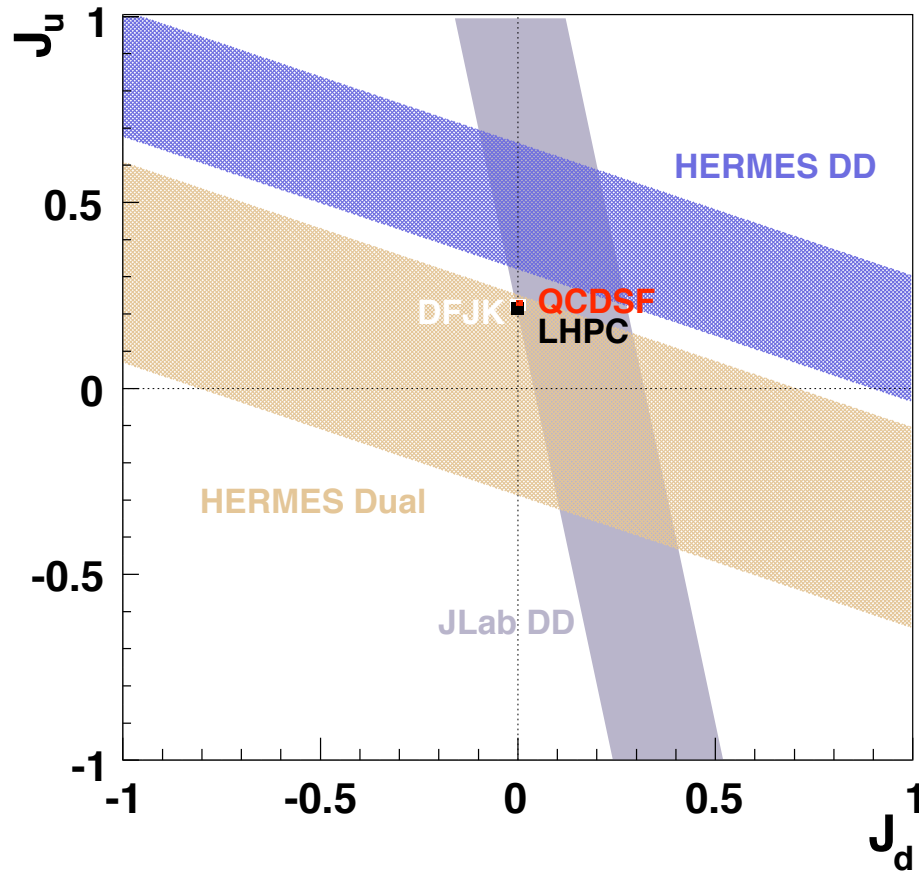
- Factorized ansatz for spin-flip quark GPDs: $E_q(x, \xi, t) = \frac{E_q(x, \xi)}{(1-t/0.71)^2}$
- t -indep. part via double distr. ansatz: $E_q(x, \xi) = E_q^{DD}(x, \xi) - \theta(\xi - |x|)D_q\left(\frac{x}{\xi}\right)$
- using double distr. K_q : $E_q^{DD}(x, \xi) = \int_{-1}^1 d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(x - \beta - \alpha\xi) K_q(\beta, \alpha)$
- 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

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



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:

⇒ ‘combined fit’ of HERMES BCA
and TTSA data against various model
calculations, leaving J_u and J_d
as free parameters ⇒ model-dep.

1- σ constraints on J_u vs. J_d :

- Double-distribution model: $J_u + J_d/2.8 = 0.49 \pm 0.17(\text{exp}_{\text{tot}})$
[Vanderhaghen, Guichon, Guidal]
- Dual model [Guzey, Teckentrup]: $J_u + J_d/2.8 = -0.02 \pm 0.27(\text{exp}_{\text{tot}})$
- 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. LH₂ 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:
 $Q^2 = 1.5, 1.9, 2.3 \text{ GeV}^2$. For each: $-t = 0.17, 0.23, 0.28, 0.33 \text{ GeV}$
- **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 $\frac{d^4\sigma}{d^4\Phi} = \frac{1}{2} \left[\frac{d^4\sigma^+}{d^4\Phi} + \frac{d^4\sigma^-}{d^4\Phi} \right]$

⇒ **distinct information on GPDs:**

$\frac{d^4\Sigma}{d^4\Phi} \propto \text{Im } I$: as in BSA numer.

$\frac{d^4\sigma}{d^4\Phi} \propto \text{Re } I$: same as in BCA

- **Fit following terms separately:**

$|BH^2|$ (dot-dot-dashed),

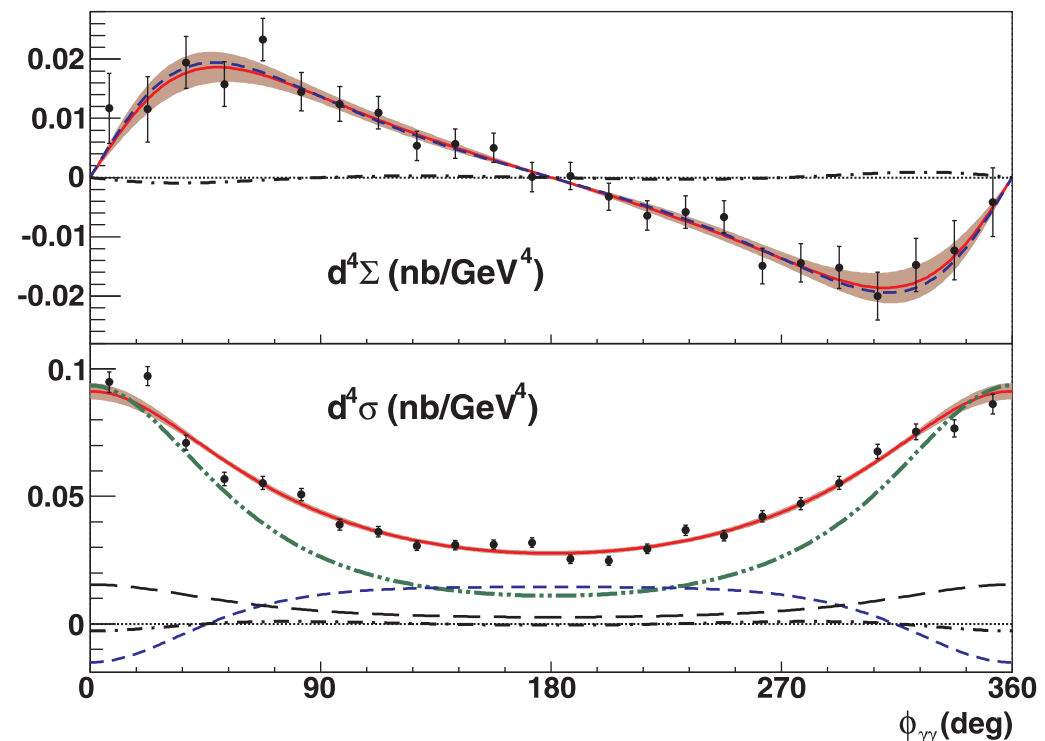
twist-2 int. term (dashed),

twist-3 int. term (dot-dashed)

($|DVCS|^2$ found below few %)

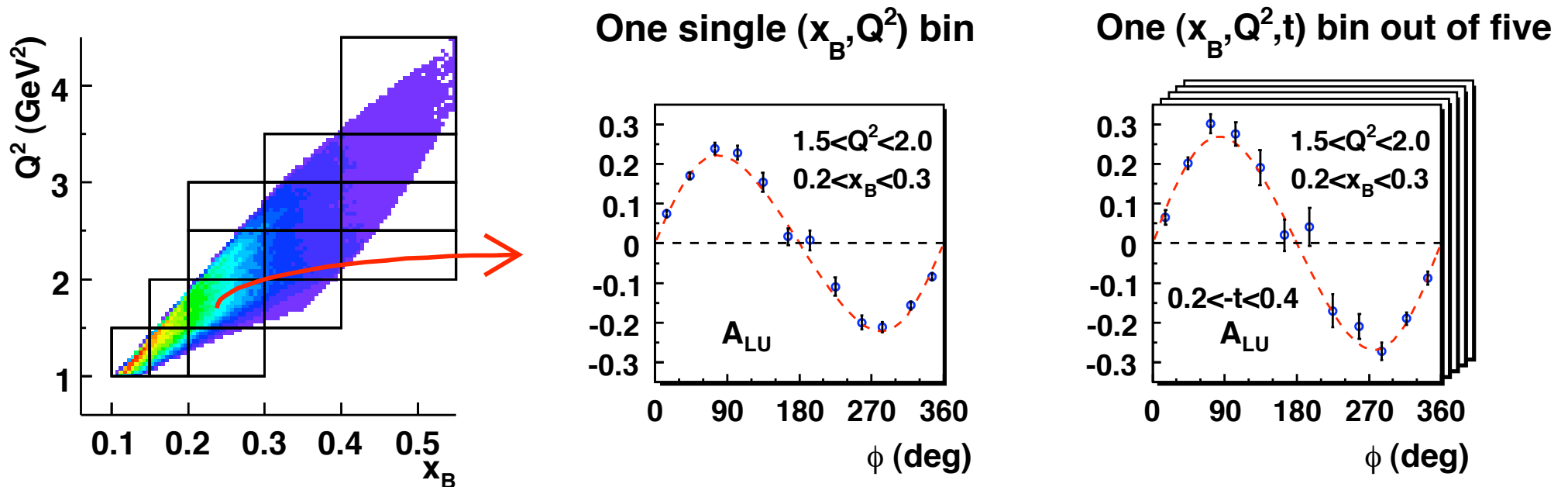
- **Twist-3 terms small**

- $\frac{d^4\sigma}{d^4\Phi} > |BH^2| \rightarrow \text{BSA and } \text{Im } I/|BH^2| \text{ are not exactly the same over } \Phi$



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

- 1st dedicated Hall-B DVCS exp't: 5.76 GeV e^- beam, pol. 76-82%; unpol. LH₂
- CLAS spectrometer upgraded by inner calorimeter to detect γ 's at small angles
→ all 3 final state particles ($e' N \gamma$) detected !
- Broad kinematic coverage at medium x (0.1...0.5), combined with high lumi
→ 3-dim. binning possible. Unpublished (White Paper) preview:



⇒ Very promising first glimpse into statistical power of JLab DVCS measurements