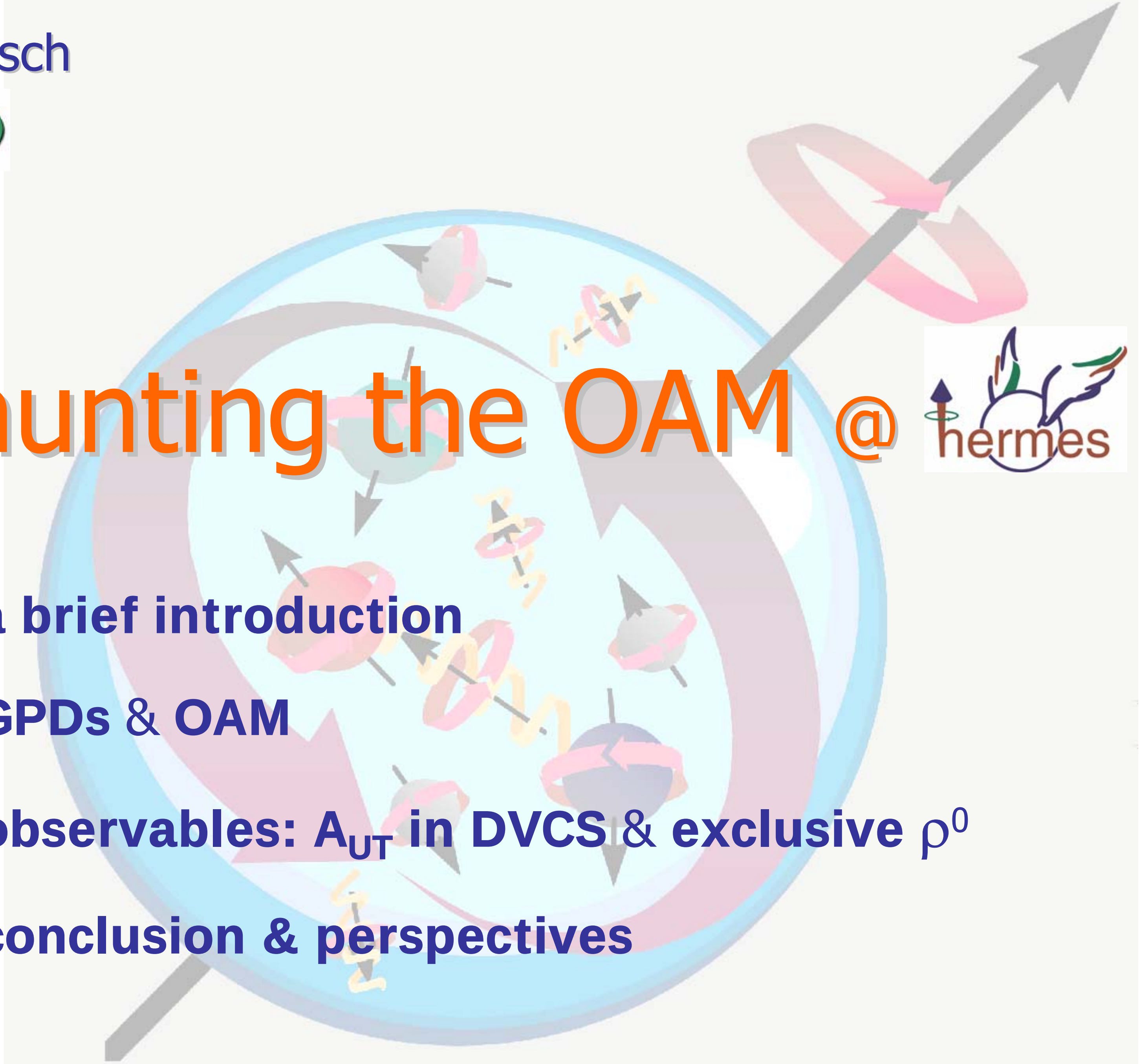
Delia Hasch

INFN Frascati

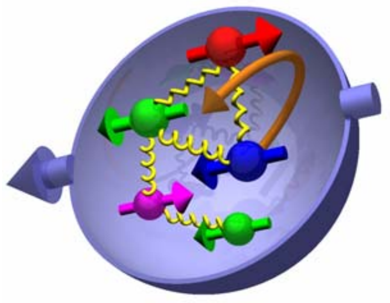


hunting the OAM @ hermes ...

- **a brief introduction**
- **GPDs & OAM**
- **observables: A_{UT} in DVCS & exclusive ρ^0**
- **conclusion & perspectives**

workshop on Partonic Transverse Momentum in Hadrons, DUKE-University, March 12/13, 2010

GPDs and the spin puzzle

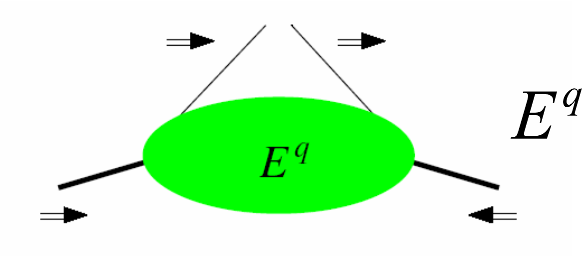


nucleon spin:

$$s_z^n = \frac{1}{2} = \frac{1}{2} \sum_q \underset{\substack{\uparrow \\ \approx 30\%}}{\Delta q} + L_z^q + \underset{\substack{\uparrow \\ \approx \text{zero}}}{\Delta G} + L_z^g = J_q + J_g$$

[X. Ji, 1997]

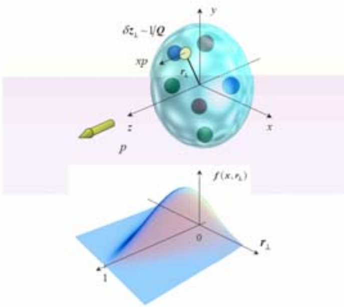
$$J_{q,g} = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} x dx \left[H^{q,g}(x,\xi,t) + E^{q,g}(x,\xi,t) \right]$$



$E^q \neq 0$ *requires* orbital angular momentum

proton helicity flipped but quark helicity conserved

GPDs: nucleon tomography



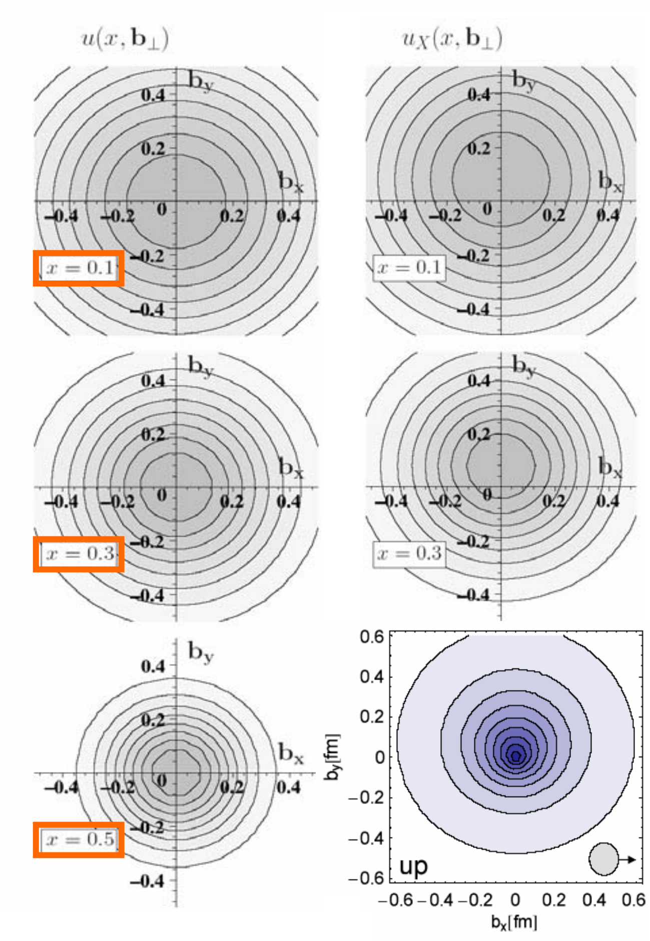
[M. Burkardt, M. Diehl 2002]

FT (GPD) : momentum space → impact parameter space:

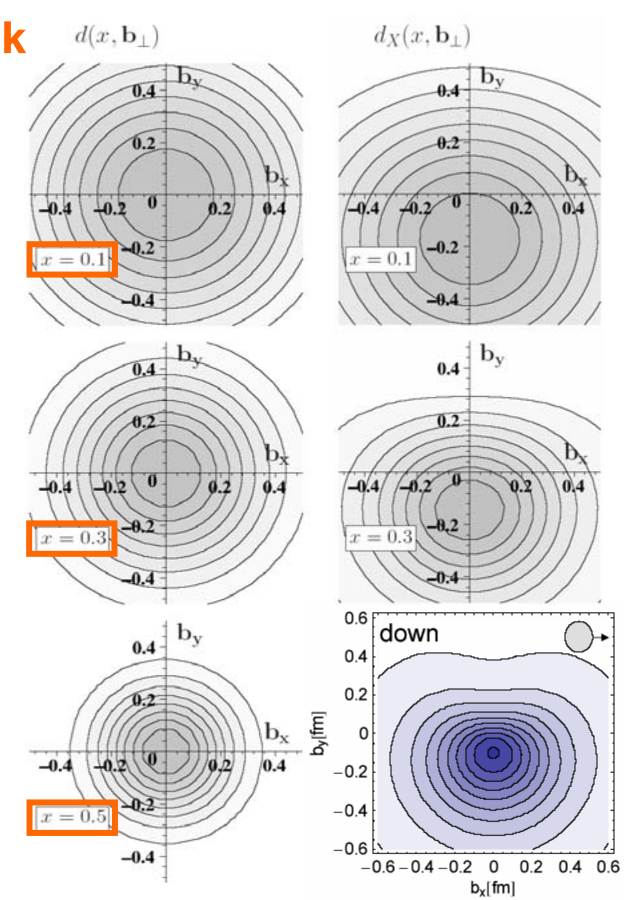
distribution of partons in plane transverse to longitudinal momentum x

polarised nucleon: *spin-orbit correlations* (TMDs)

u-quark



d-quark



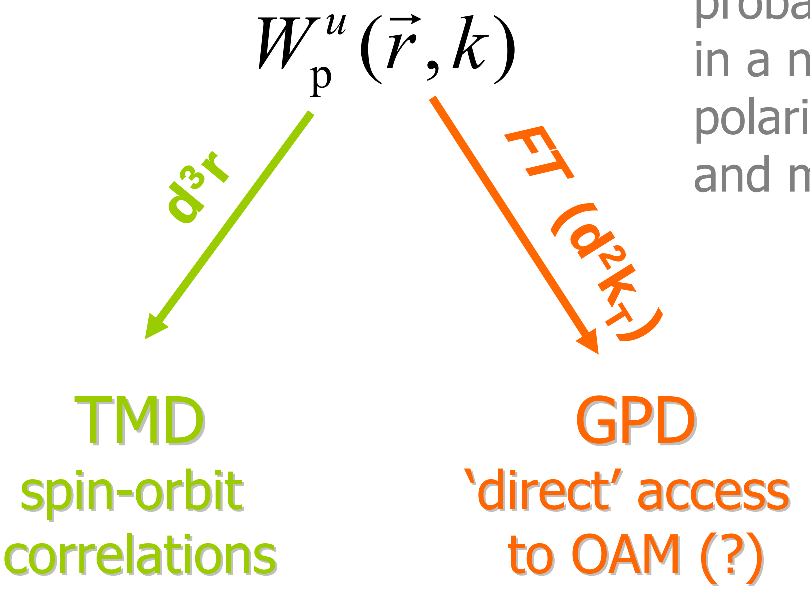
from lattice
[QCDSF]

TMDs ⟷ GPDs

3D structure of hadrons : nucleon tomography

→ **complementary:**

Wigner distribution: (“mother” function)



$$W_{\mathrm{p}}^{u}(\vec{r},k)$$

probability to find a quark **u** in a nucleon **P** with a certain polarisation in a position **r** and momentum **k**

TMD
spin-orbit
correlations

GPD
‘direct’ access
to OAM (?)

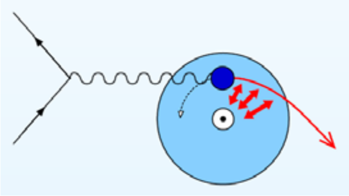
→ relations between TMDs and GPDs (?)

see talk by L.Gamberg

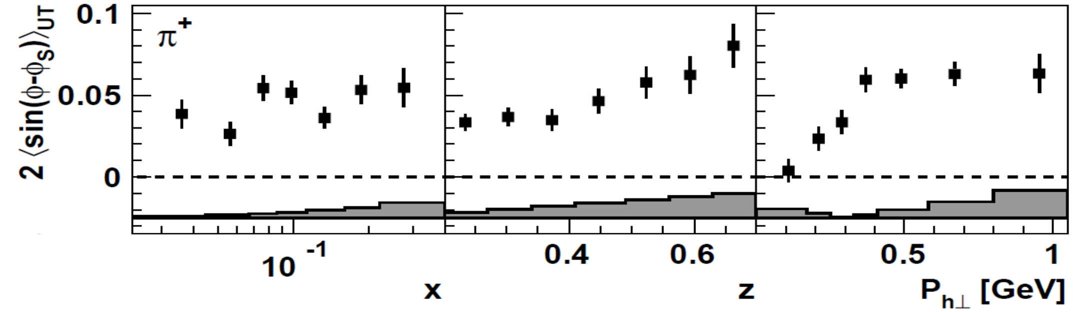
spin-orbit correlations @ hermes

Sivers fct., Boer-mulders fct., pretzelosity

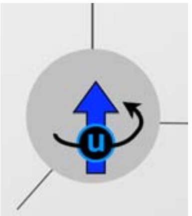
see talk by N. Makins



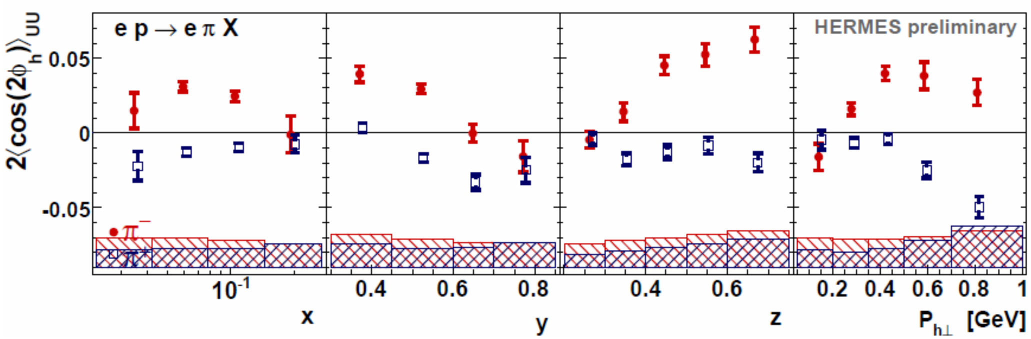
ΔL=1



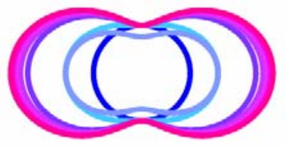
Sivers



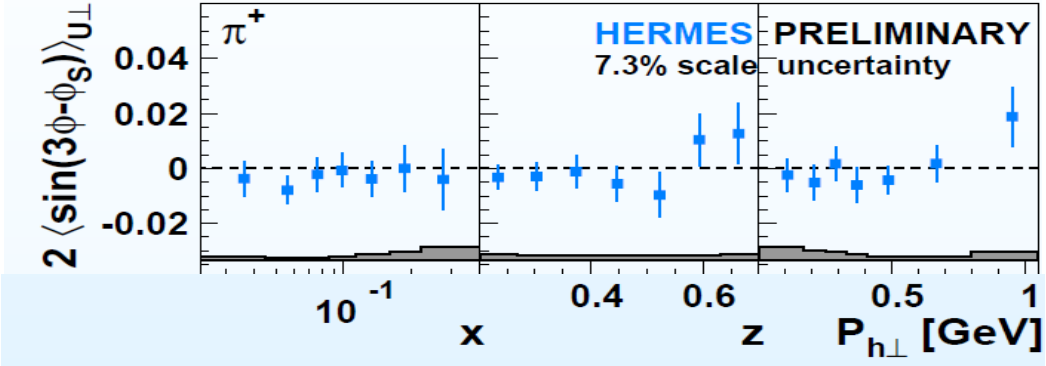
ΔL=1



Boer-Mulders

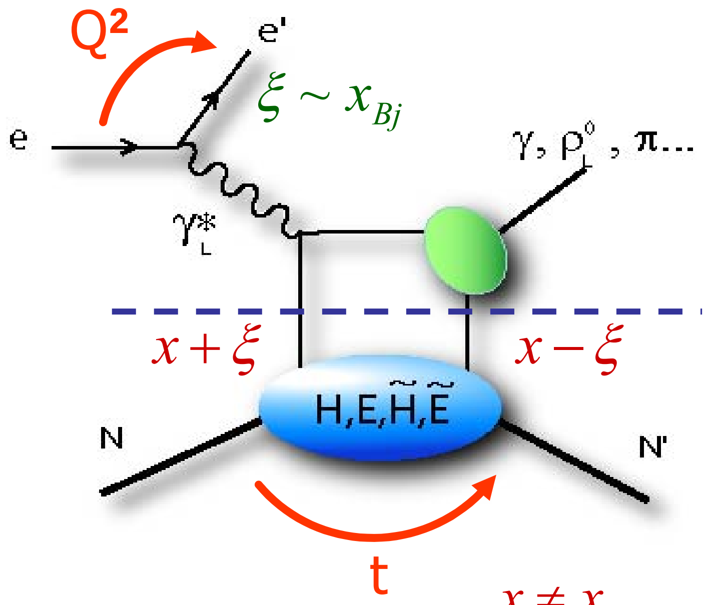


ΔL=2



pretzelosity

what do we know about GPDs ?



Q^2>>, t<<

appear in factorisation theorem for *hard exclusive processes*

$H(x,\xi,t)$

$x \neq x_{Bj}$

$\xi \sim x_{Bj}$

form factors

$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1(t)$$

$\vdots$

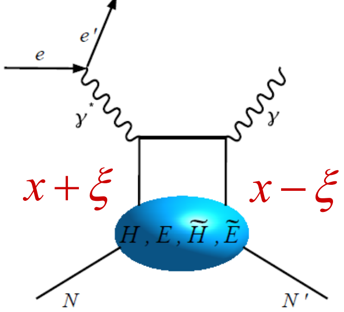
PDFs

$$H^{q,g}(x,0,0) = q(x)$$

$$\widetilde{H}^{q,g}(x,0,0) = \Delta q(x)$$

$E, \widetilde{E}$: *nucleon helicity flip* → don't appear in DIS
→ new information !

GPDs: caveats



$$T_{\mu\nu} = \left[\mathcal{H},\mathcal{E},\widetilde{\mathcal{H}},\widetilde{\mathcal{E}}\right](\xi,t,Q^2),$$

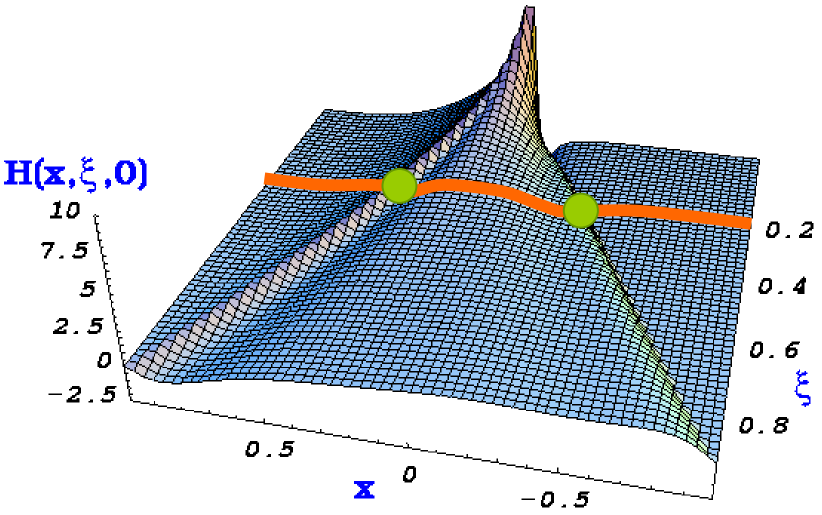
$$\boxed{\mathcal{F}(\xi,t,Q^2)} = \int_{-1}^{1} dx\, C^{-}(\xi,x)\,\boxed{F(x,\xi,t,Q^2)},$$

CFF hard scatt. part ***GPD***

- x is mute variable (integrated over):

  → apart from cross-over trajectory (ξ=x) GPDs not directly accessible

- extrapolation t → 0 is model dependent

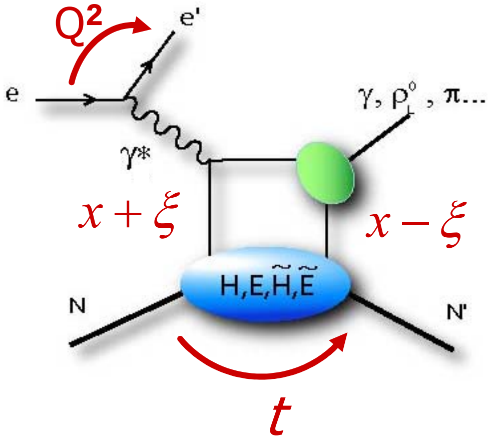


cross sections & beam-charge asymmetry ~ Re(T^{DVCS})

beam or target-spin asymmetries ~ Im(T^{DVCS})

→ **double DVCS:** $|x| < \xi$

attempts to constrain J_q



$$J_q = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} x dx \left[H^q(x, \xi, t) + E^q(x, \xi, t) \right]$$

GPD models: J_q free parameter in ansatz for *E*

observables sensitive to E:

- DVCS A_{UT} : HERMES
- **n**DVCS A_{LU} : Hall A
- excl. ρ^0 A_{UT} : HERMES, COMPASS

A_{UT}

beam — target

U, L — U, T

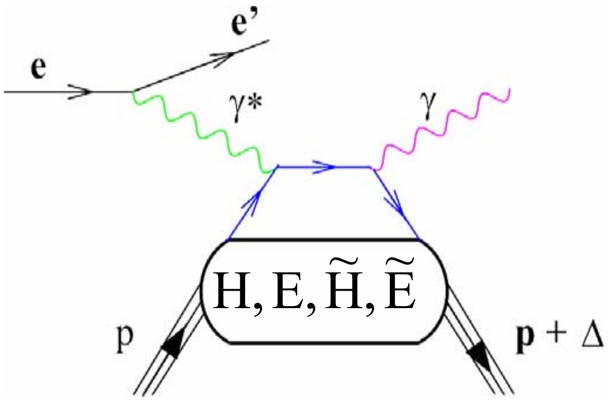
Unpolarised

Longitudinally

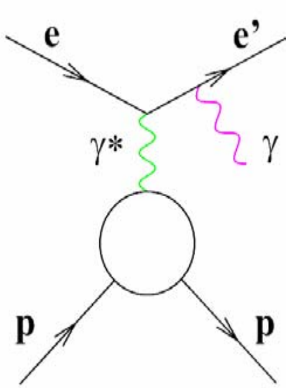
Transversely polarised

deeply virtual compton scattering

DVCS



Bethe-Heitler



@HERMES, JLab:

DVCS << Bethe-Heitler

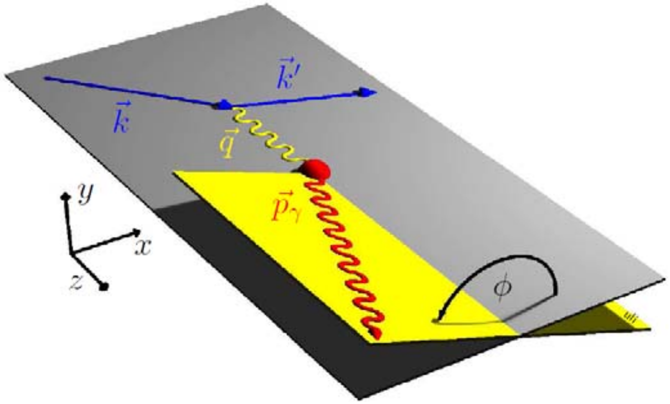
$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

DVCS interference term

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau_{BH}^{*}\tau_{DVCS} + \tau_{DVCS}^{*}\tau_{BH})$$

→ different charges: e^+ e^-

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



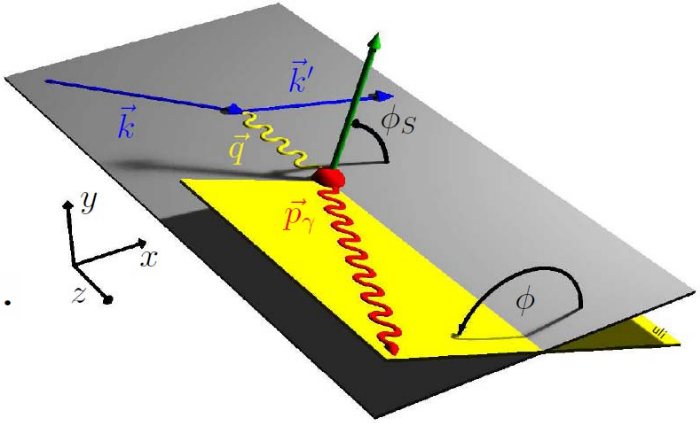
DVCS interference term

$$d\sigma \propto |\tau_{\mathrm{BH}}|^2 + |\tau_{\mathrm{DVCS}}|^2 + (\tau^*_{\mathrm{BH}}\tau_{\mathrm{DVCS}} + \tau^*_{\mathrm{DVCS}}\tau_{\mathrm{BH}})$$

→ different charges: e^+ e^-

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

→ polarisation observables:



- **beam spin asymmetry A_{LU}:**

$$d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi + \ldots$$

- **longitudinal target spin asymmetry A_{UL}:**

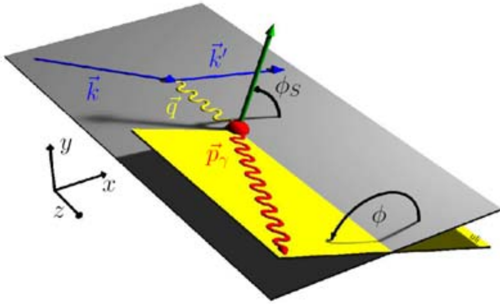
$$d\sigma(\overset{\Leftarrow}{P},\phi) - d\sigma(\overset{\Rightarrow}{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi + \ldots$$

- **transverse target spin asymmetry A_{UT}:**

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

[F_1, F_2: Pauli and Dirac *FF*, $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}$: Compton *FF*: moments of corresponding GPDs]

DVCS A_{UT}



sensitivity to *E* (J_q) from both interference and DVCS^2 term:

$$\sigma(\phi, P_\ell, S_T) = \sigma_{UU}(\phi) \times \left[1 + S_T \mathcal{A}_{UT}^{\mathrm{DVCS}}(\phi, \phi_s) + S_T e_\ell \mathcal{A}_{UT}^{\mathrm{I}}(\phi, \phi_s) + e_\ell \mathcal{A}_C(\phi)\right]$$

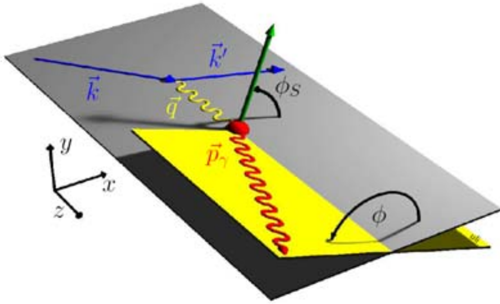
$$\begin{aligned} \mathcal{A}_{UT}^{\mathrm{I}}(\phi, \phi_S) \quad &= \quad \sum_{n=0}^{2} A_{UT,I}^{\sin(\phi-\phi_S)\cos(n\phi)} \sin(\phi - \phi_S)\cos(n\phi) \\ &+ \quad \sum_{n=1}^{2} A_{UT,I}^{\cos(\phi-\phi_S)\sin(n\phi)} \cos(\phi - \phi_S)\sin(n\phi) \end{aligned}$$

analogous modulations for DVCS^2 term

n = 0, 1 terms found to be most sensitive to values of J_u →

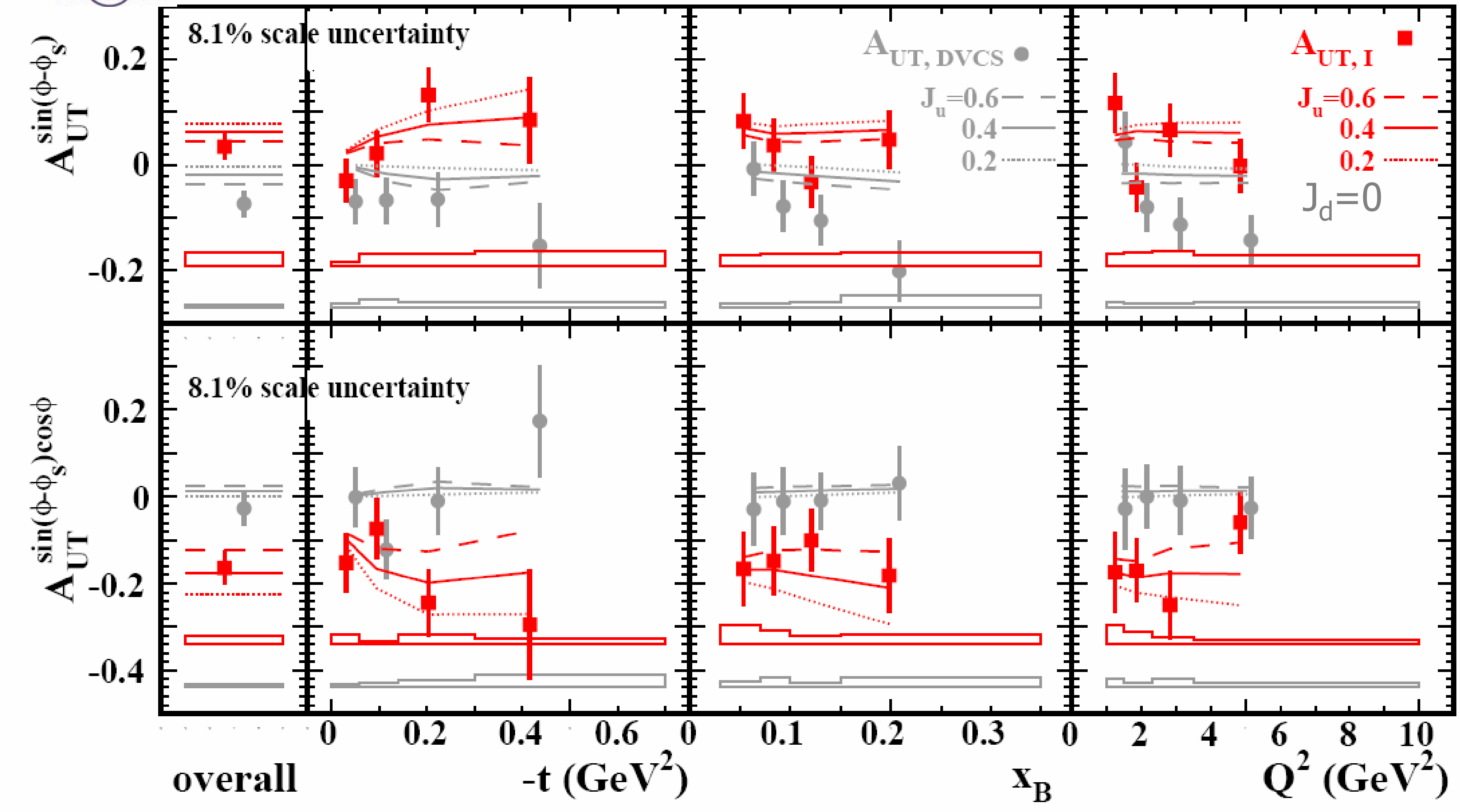
attempts to constrain J_q

J_q free parameter in ansatz for *E*



separate contributions from **DVCS²** and **interference** terms:

[JHEP06(2008)]



[VGG]

attempts to constrain J_q

Hall-A

J_q free parameter in ansatz for *E*

difference of polarised cross sections on LH_2 & LD_2 → **n**DVCS: [PRL99(2007)]

$$[\mathcal{C}_n^I] = F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

p target: $\mathcal{C}_n^I \sim \mathcal{H}$

n target: $\mathcal{C}_n^I \sim \mathcal{E}$ → F_1 small

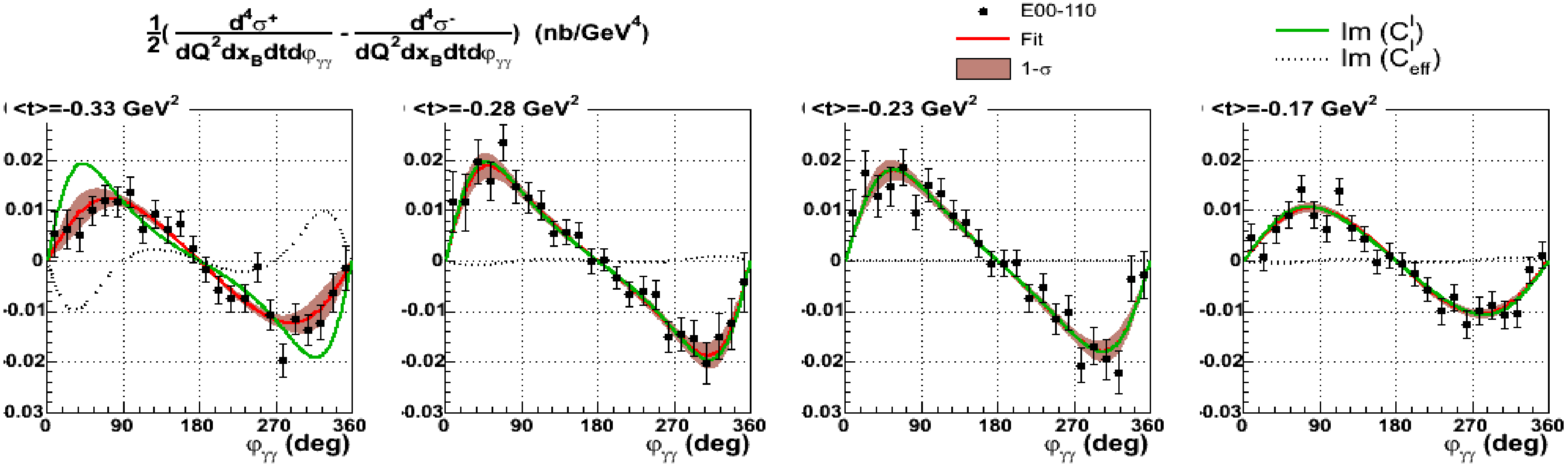
→ cancellation between u and d quark pol. pdfs in $\widetilde{\mathcal{H}}$

attempts to constrain J_q

Hall-A

J_q free parameter in ansatz for *E*

difference of polarised cross sections on LH_2 & LD_2 → **n**DVCS: [PRL99(2007)]



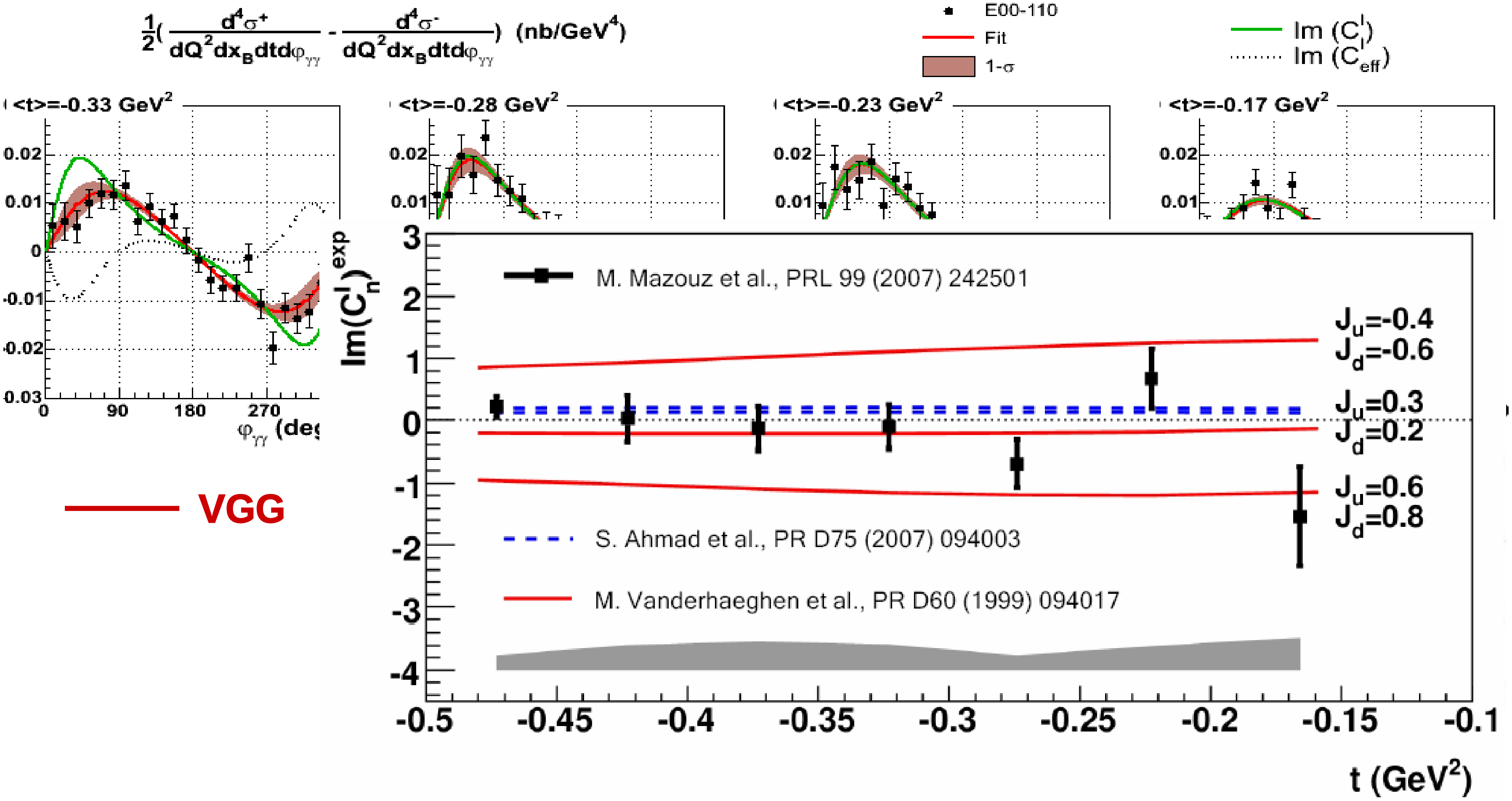
VGG : tw-2 CFF

attempts to constrain J_q

Hall-A

J_q free parameter in ansatz for *E*

difference of polarised cross sections on LH_2 & LD_2 → **n**DVCS: [PRL99(2007)]



a word about ‘user friendly’ GPD models

VGG: [Vanderhaegen, Guichon, Guidal 1999]

- double distributions [Radyshkin]; factorised or regge-inspired t-dependence
- D-term to restore full polynomiality
- skweness depending on free parameters b_{val} & b_{sea}
- includes tw-3 (WW approx)

Dual: [Guzey, Teckentrup 2006, 2009]

- GPDs based on infinite sum of t channel resonances (minimal: truncated k=[0,2])
- factorised or regge-inspired t-dependence
- tw-2 only

→ more models & new approaches [... an incomplete list]

- polynomials [Belitsky etal.(00), Liuti etal.(07), Moutarde(09)]
- analytical [Belitsky, Muller, Kirchner(01)]
- dispersion integral fits & flexible GPD modelling [Kumericki, Muller(08,09)]

a word about 'user friendly' GPD models

VGG: [Vanderhaegen, Guichon, Guidal 1999]

- double distributions [Radys
- D-term to restore full poly
- skweness depending on fr
- includes tw-3 (WW approx

→ describes well beam charge & target spin asymmetries

→ fails for beam spin asymm. & cross sections

→ charge asymm. favours 'no D-term' ← contradicts χQSM & lattice results

Dual: [Guzey, Teckentrup 2006, 2009]

- GPDs based on infinite su
- factorised or regge-inspire
- tw-2 only

→ describes well kinematic dependencies of beam charge & beam spin asymmetries

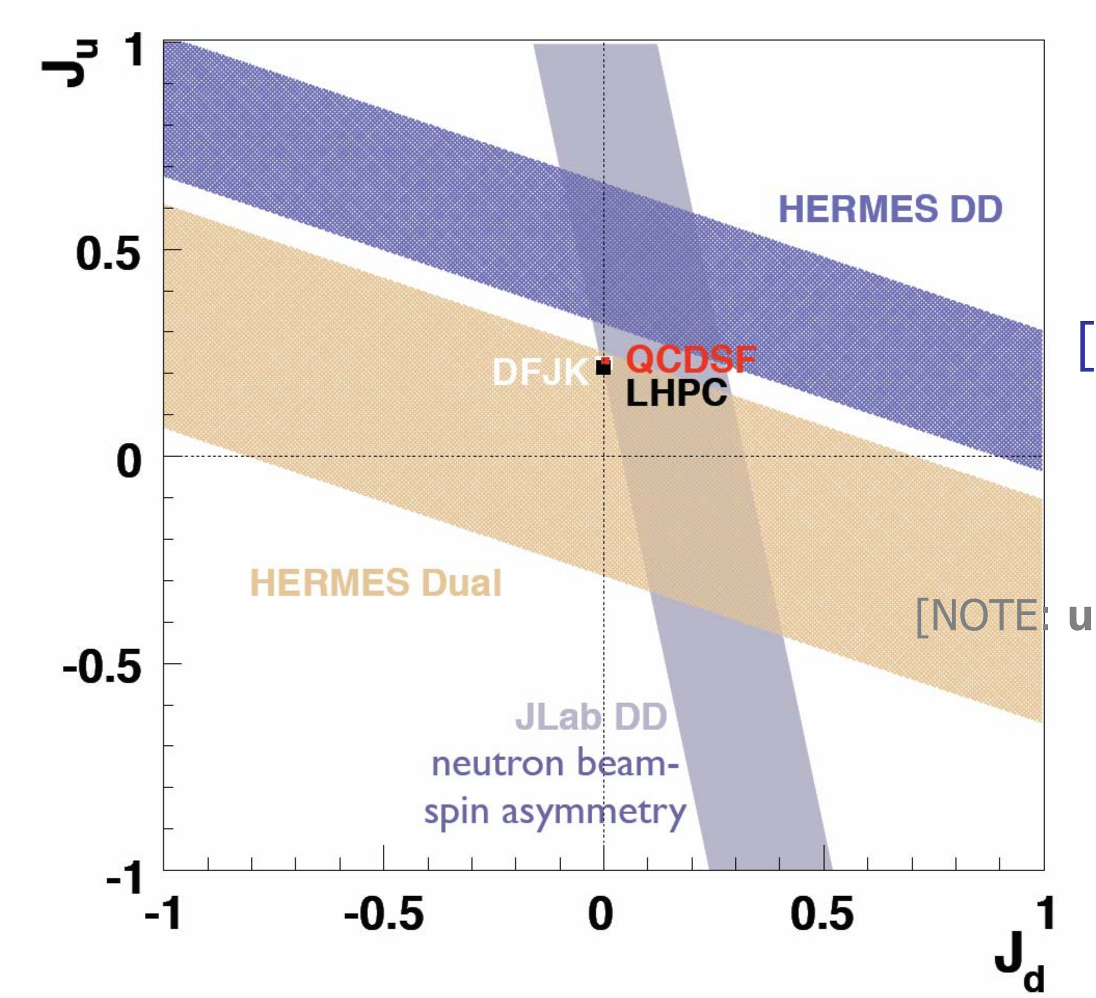
→ after correction in calculations: magnitude off by factor 2-4

→ more models & new ap

- polynomials [Belitsky etal.(00), Liuti etal.(07), Moutarde(09)]
- analytical [Belitsky, Muller, Kirchner(01)]
- dispersion integral fits & flexible GPD modelling [Kumericki, Muller(08,09)]

…nevertheless: constraining J_q

J_q free parameter in ansatz for *E*



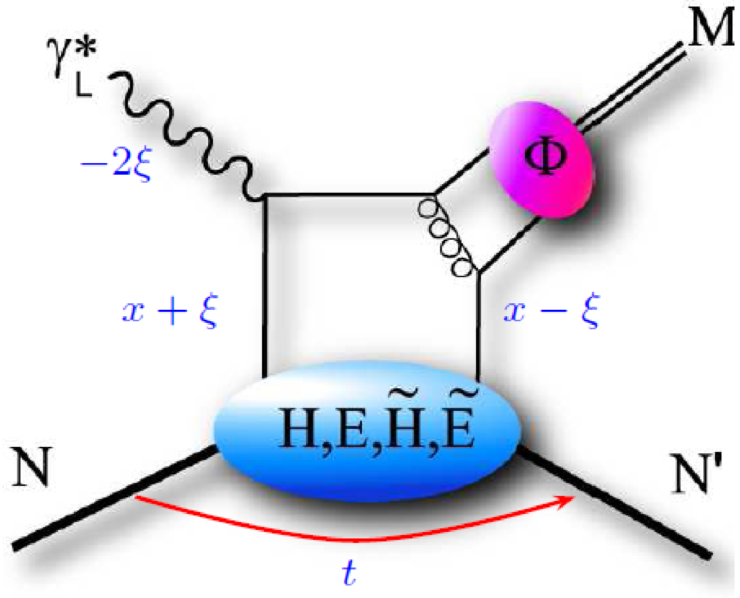
→ highly model dependent extraction !!!

[VGG]

[NOTE: **uncorrected** Dual !]

→ data are free to be re-used at any time with new models ☺

exclusive ρ^0 production



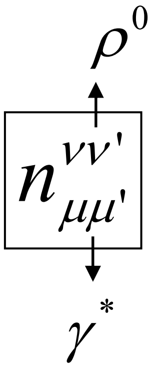
$$A_{UT}^{\gamma_L^*}(\phi,\phi_s) \propto \frac{\mathrm{Im}(\mathcal{E}_\rho^* \mathcal{H}_\rho)}{|\mathcal{H}_\rho|^2} \propto \left| \frac{\mathcal{E}_\rho}{\mathcal{H}_\rho} \right|$$

exclusive ρ^0 production

after the full glory of transverse SDME extraction [formalism: M. Diehl (2007)] :

$$(\gamma^*_{\mathrm{L}} \to \rho^0_{\mathrm{L}}):$$

$$A^{\gamma^*}_{UT}(\phi, \phi_s) = \frac{\mathrm{Im}\, n^{00}_{00}}{u^{00}_{00}}$$

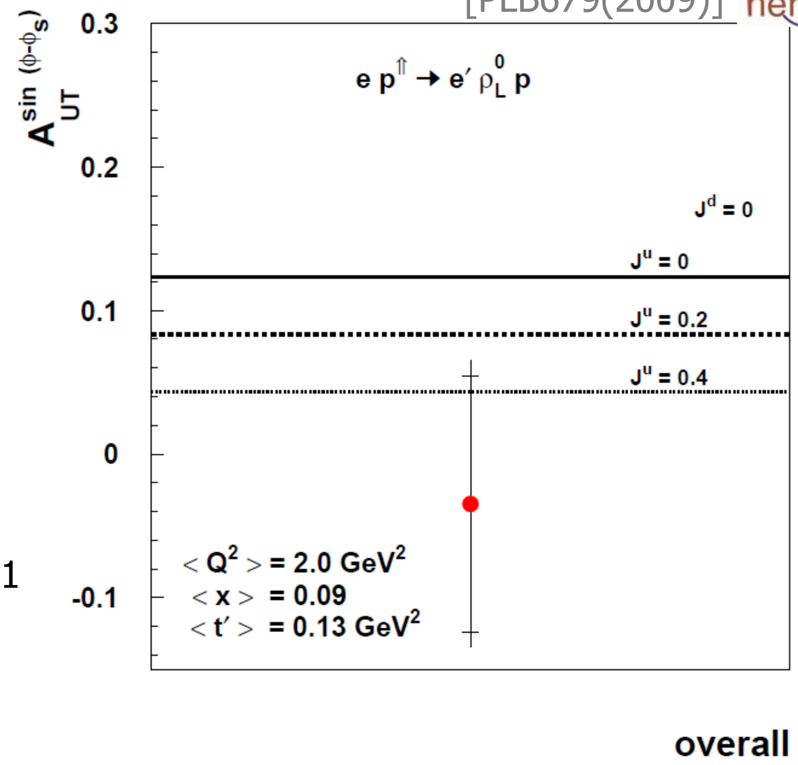


$\mu, \nu = 0, \pm 1$

long.pol: 0

transv.pol: ±1

[PLB679(2009)]



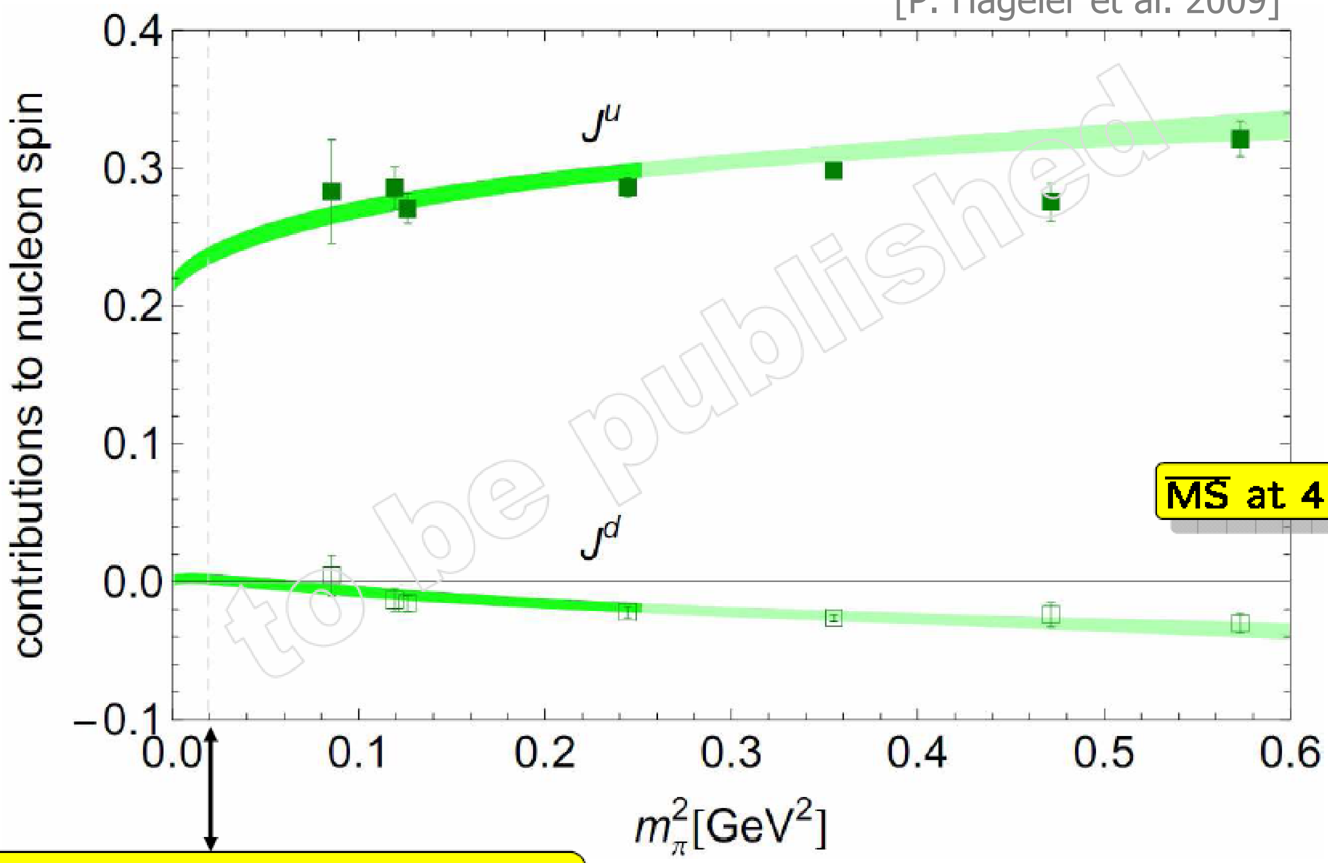
[GPD model:
Ellighaus et al. (2004)]

→ more data coming: COMPASS , CLAS12 with transverse target

→ more models: Goloskokov, Kroll (09)

lattice's opinion about J^q

[P. Hägeler et al. 2009]



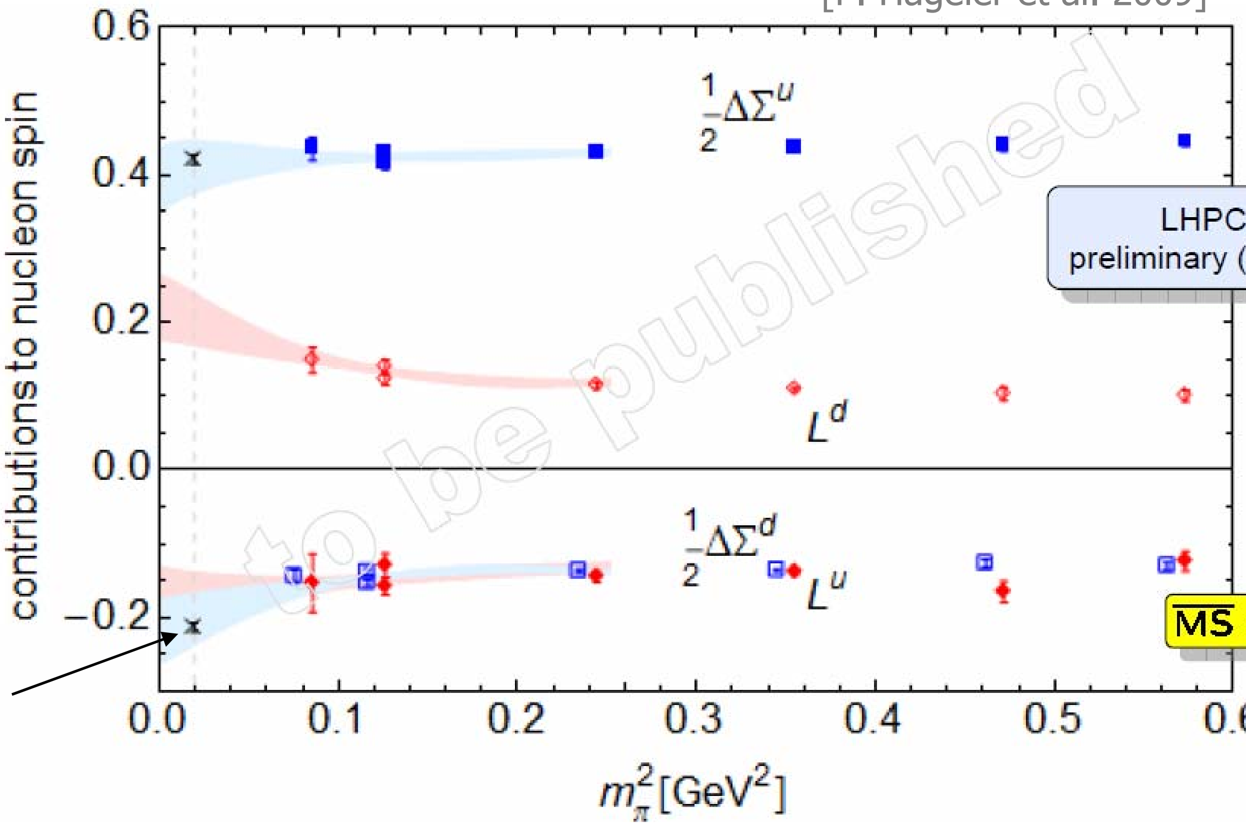
$\overline{\text{MS}}$ at 4 GeV^2

$J^u = 0.236(6) \approx 47\%$ of 1/2
$J^d = 0.0018(37) \approx 1\%$ of 1/2

$J^{u+d} \approx 0.238 \pm 0.008 \approx 48\%$ of 1/

lattice's opinion about $J^q \rightarrow L^q$

[P. Hägeler et al. 2009]



LHPC n_f=2+1 mixed
preliminary (updating PRD 2008)

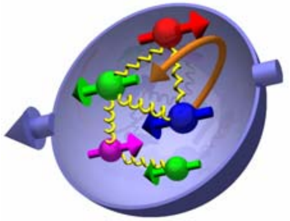
$\overline{\text{MS}}$ at 4 GeV^2

[HERMES]

$L^d \approx -L^u \approx 0.185 \pm 0.06 \approx 36\%$ of 1/2

$L^{u+d} \approx 0.030 \pm 0.012 \approx 6\%$ of 1/2

conclusion



presence of OAM w/o debate → how to measure it ?

- GPDs: only known frame work to *quantify* OAM [Ji - SR]

  we got an idea how to measure it but still a long way to go:

  → more data needed over a much wider kinematic range

  → call for more sophisticated GPD models & new approaches

- prior to any interpretation of data: what is OAM ? [M. Burkardt, …]

- complementary information from TMDs :

  role of transverse momenta & *spin-orbit correlations*

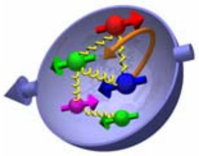
GPDs – a much wider concept: nucleon *tomography*

→ correlated information on longitudinal momentum fraction of quarks and their spatial distribution in the transverse plane → multi-D picture

relations GPDs ←→ TMDs ?

perspectives

hunting the OAM



contribution to nucleon spin:

- determination of $\Delta\Sigma$ and ΔG → missing piece attributed to OAM

quest for ΔG:

- from scaling violation of g_1
- charm production & high pT hadrons

over wide x_B range

EIC @highest possible energies

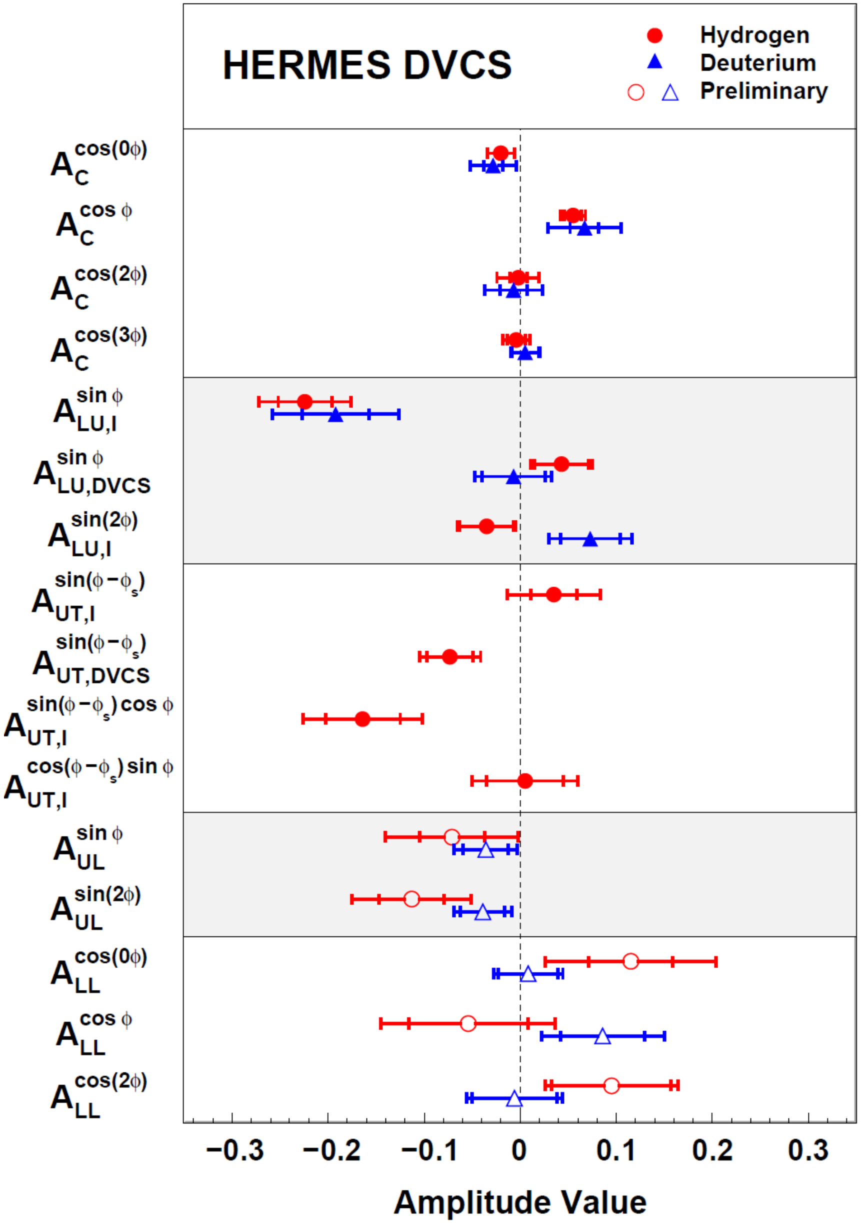
- 'direct' measurement via Ji-SR (GPDs)
- spin-orbit correlations from TMDs

EIC @modest energies, high lumi (symmetric beams)

JLab12

backup

DVCS @ hermes



→ beam charge asymmetry

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

→ beam spin asymmetry

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

→ transverse target spin asymm.

$\mathrm{Im}(\mathcal{H}\,\mathcal{E})$

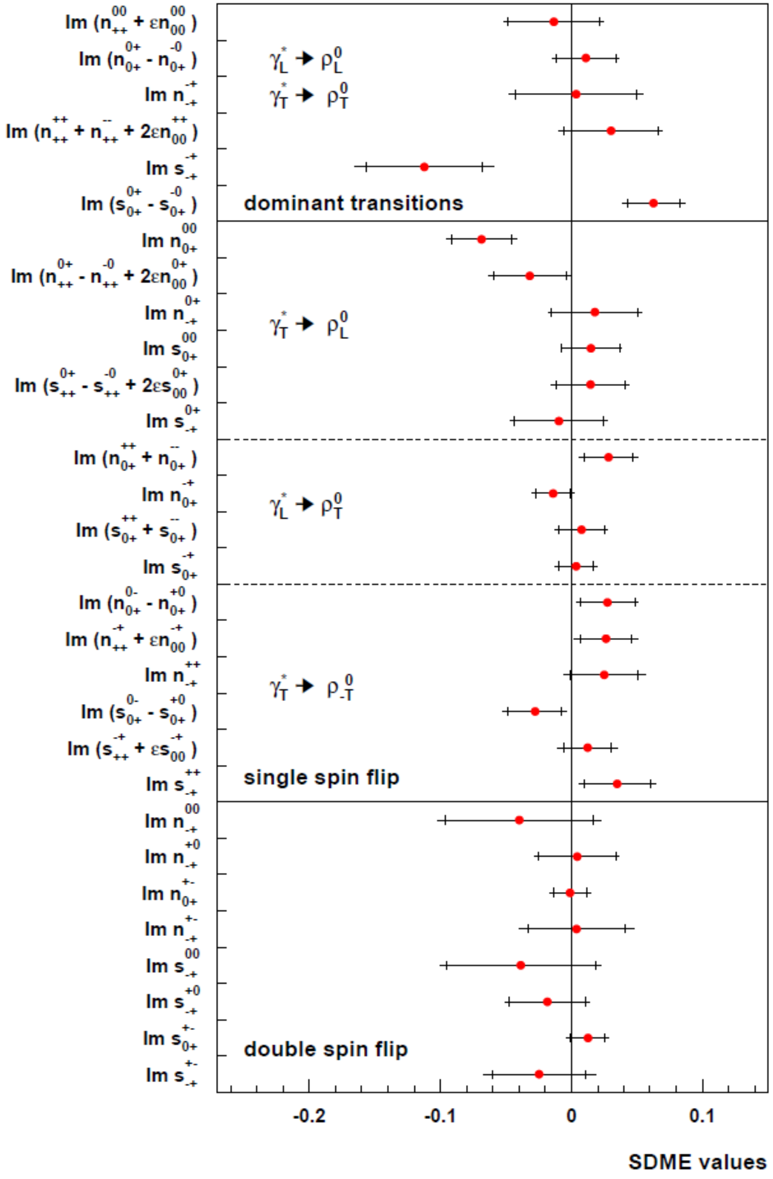
→ longitudinal target spin asymm.

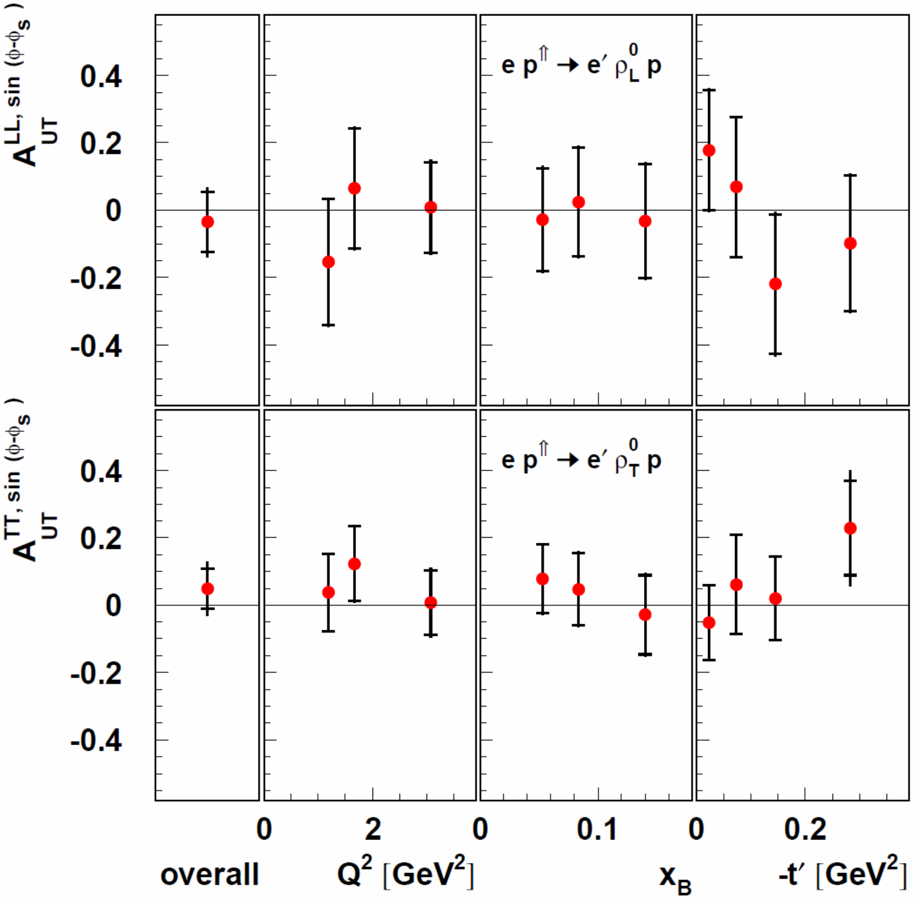
$\mathrm{Im}\widetilde{\mathcal{H}}$

→ double spin asymmetry

$\mathrm{Re}\widetilde{\mathcal{H}}$

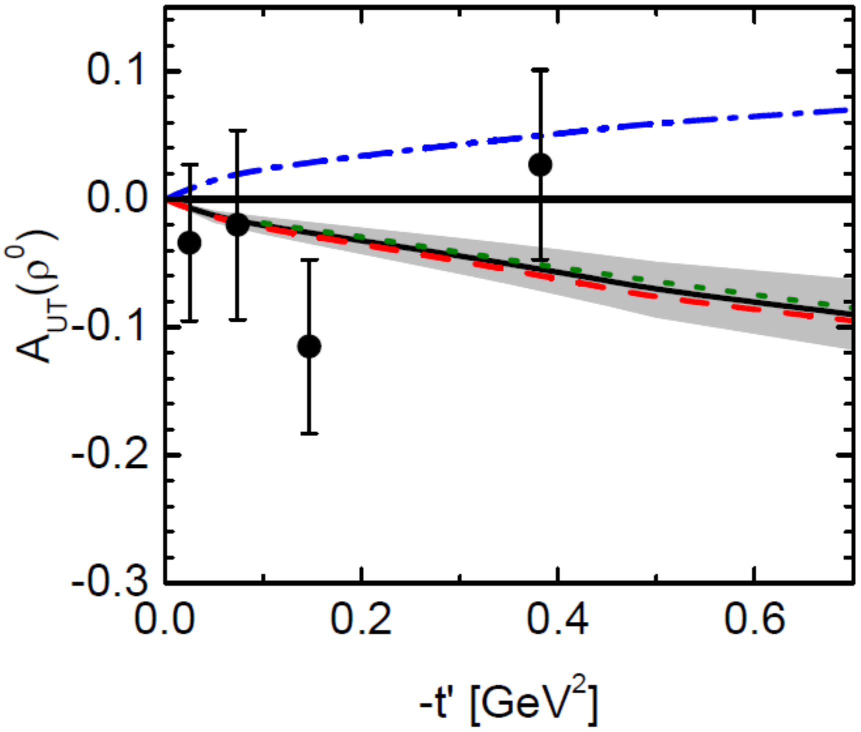
exclusive ρ^0 production

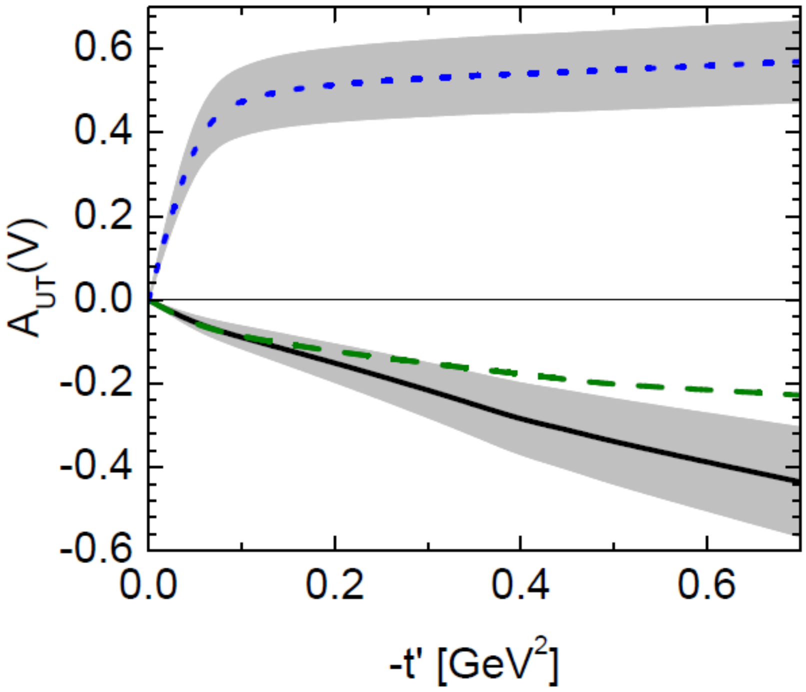




exclusive meson production

GPD model: Goloskokov, Kroll





$W = 5\,\mathrm{GeV} \quad Q^2 = 3\,\mathrm{GeV}^2$

variant 1, 2, 3, 4

variant 1 for ω, ρ^+, K^{*0}