Exclusive meson production

recent experimental results

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Electromagnetic Interactions with Nucleons and Nuclei

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- Motivation
- Exclusive vector meson production at small x
  H1 and ZEUS
- Unpolarised cross sections for ρ^0 at large x
  CLAS
- Single transverse target spin asymmetries for ρ^0
  HERMES and COMPASS
- More results on spin dependence in VM production
  COMPASS and HERMES
- Exclusive π^+ and π^0 production
  HERMES, CLAS and JLAB Hall A
- Conclusions

Why hard exclusive meson production ?

- Nucleon structure ⟷ Hard exclusive processes (DVCS + DVMP)
  - constrain GPDs

    'Holy Grails' of GPDs:
    - distribution of partons in transverse plane vs. x 'nucleon tomography'
    - orbital angular momentum of quarks
  - VM production at small x sensitive to gluons

- Meson structure ⟷ Deep virtual meson production

  wave function / DA

- Mechanism of high energy diffraction (exclusive VM production)

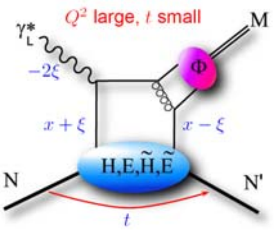
  BFKL vs. DGLAP, k_t-factorisation, …

- Space-time evolution of hadronic fluctuations of γ^*

  Color Transparency (also Color Opacity) – important predictions of pQCD

  → cf. talk by K. Hafidi

Hard exclusive meson production



- 4 Generalised Parton Distributions (GPDs)

  for each quark flavour and for gluons

  GPDs depend on 3 variables: $x,\ \xi,\ t$

- factorisation proven only for σ_L

  σ_T suppressed of by $1/Q^2$

  necessary to extract longitudinal contribution to observables (σ_L , …)

- allows separation (H,E) ↔ (H̃,Ẽ) and wrt quark flavours

  H, E → Vector mesons (ρ, ω, φ)

  H̃, Ẽ → Pseudoscalar mesons (π, η)

  H, H̃: conserve; E, Ẽ: flip nucleon helicity

Flavour sensitivity of DVMP on the proton

ρ^0	2u+d, 9g/4
ω	2u-d, 3g/4
φ	s, g
ρ^+	u-d
J/ψ	g

- quarks and gluons enter at the same order of α_S

- wave function of meson (DA Φ)

  additional information/complication

LT-LO observables in hard exclusive meson production relevant for GPDs

for vector mesons: ρ^0, ρ^+, f_2, …

unpolarised cross section ($\sigma_{00}^{++} \equiv \sigma_L$)

$$\frac{1}{\Gamma'}\frac{d\sigma_{00}^{++}}{dt} = (1-\xi^2)\,|\mathcal{H}_M|^2 - \left(\xi^2 + \frac{t}{4M_p^2}\right)|\mathcal{E}_M|^2 - 2\xi^2\,\mathrm{Re}\,(\mathcal{E}_M^*\mathcal{H}_M),$$

transverse target spin asymmetry

$$\frac{1}{\Gamma'}\,\mathrm{Im}\,\frac{d\sigma_{00}^{+-}}{dt} = -\sqrt{1-\xi^2}\,\frac{\sqrt{t_0-t}}{M_p}\,\mathrm{Im}\,(\mathcal{E}_M^*\mathcal{H}_M)$$

access to GPD E
related to orbital momentum

for pseudoscalar mesons: π^0, π^+, η, …

unpolarised cross section

$$\frac{1}{\Gamma'}\frac{d\sigma_{00}^{++}}{dt} = (1-\xi^2)\,|\tilde{\mathcal{H}}_M|^2 - \xi^2\frac{t}{4M_p^2}\,|\tilde{\mathcal{E}}_M|^2 - 2\xi^2\,\mathrm{Re}\,(\tilde{\mathcal{E}}_M^*\tilde{\mathcal{H}}_M),$$

transverse target spin asymmetry

$$\frac{1}{\Gamma'}\,\mathrm{Im}\,\frac{d\sigma_{00}^{+-}}{dt} = \sqrt{1-\xi^2}\,\frac{\sqrt{t_0-t}}{M_p}\,\xi\,\mathrm{Im}\,(\tilde{\mathcal{E}}_M^*\tilde{\mathcal{H}}_M)$$

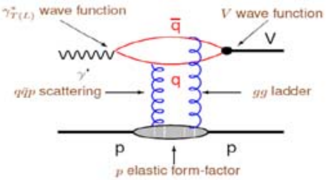
$$\Gamma' = \frac{\alpha_{em}}{Q^6}\,\frac{x_B^2}{1-x_B} \qquad \xi = \frac{x_B}{2-x_B}, \qquad -t_0 = \frac{4\xi^2 M_p^2}{1-\xi^2}$$

(large Q^2 approximation)

$\mathcal{H}_M, \tilde{\mathcal{H}}_M, \mathcal{E}_M, \tilde{\mathcal{E}}_M$ are integrals of GPDs $H, \tilde{H}, E, \tilde{E}$ appropriate for production of meson M

Models for exclusive VM production at small x

- at small x sensitivity mostly to gluons
- at very small x huge NLO corrections, large $\ln(1/x)$ terms (BFKL type logs)
- pQCD models to describe colour dipole-nucleon cross sections and meson WF



dipole transv. size	W-dep.	t-dep.
large	weak	steep
small	strong	shallow

- Frankfurt-Koepf-Strikman (FKS) Phys.Rev. D57 (1998) 512
- Martin-Ryskin-Teubner (MRT) Phys.Rev. D62 (2000) 014022

→ sensitivity to different gluon density distibutions

- Farshaw-Sandapen-Shaw (FSS) Phys.Rev. D69 (2004) 094013
- Kowalski-Motyka-Watt (KMW) Phys.Rev. D74 (2006) 074016
- Dosch-Fereira (DF) hep-ph/0610311 (2006)

} sensitivity to ρ^0 wave function

Recent ZEUS results on exclusive ρ^0 production

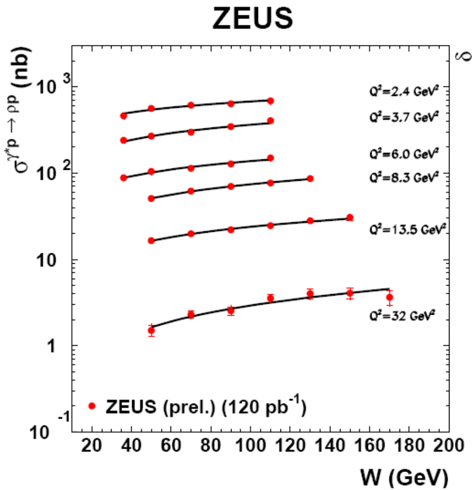
96-00 data: 120 pb^{-1}

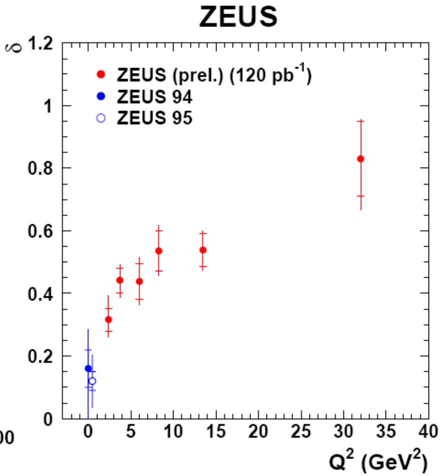
arXiv:0708.1478[hep-ex]

significant increase of precision
+ extended Q^2 range

$2 < Q^2 < 160$ GeV^2
$32 < W < 180$ GeV
$2 \cdot 10^{-4} < x_{Bj} < 10^{-2}$
$|t| < 1$ GeV^2

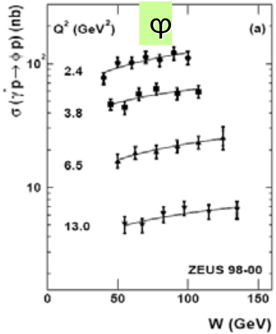
W-dependence $\sigma \propto W^{\delta}$

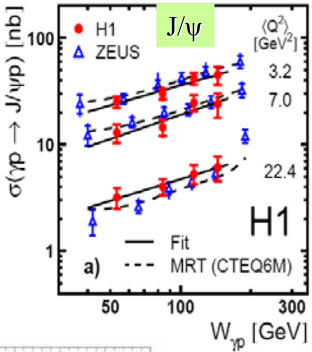


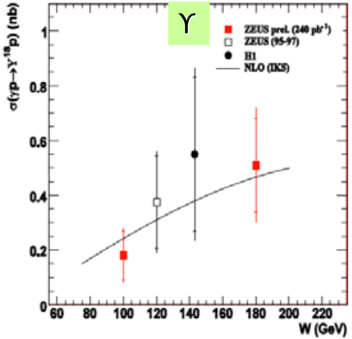


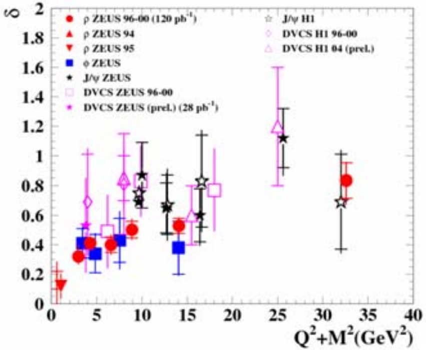
➢ steeper energy dependence with increasing Q^2

W-dependence for hard exclusive processes at small x







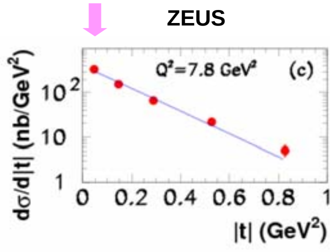


- steep energy dependence for all vector mesons in presence of hard scale Q^2 and/or M^2
- 'universality' of energy dependence at small x?

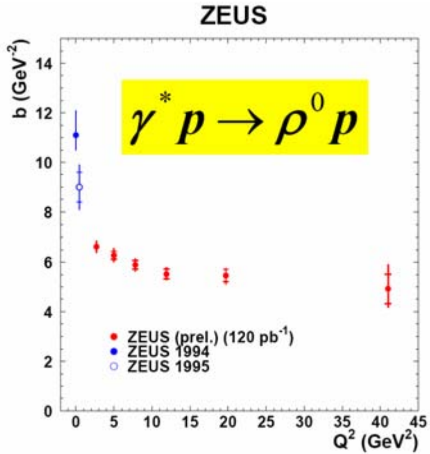
at $Q^2+M^2 \approx 10$ GeV² still significant difference between ρ and J/ψ

$d\sigma / dt$ - ρ^0

example (1 out of 6)

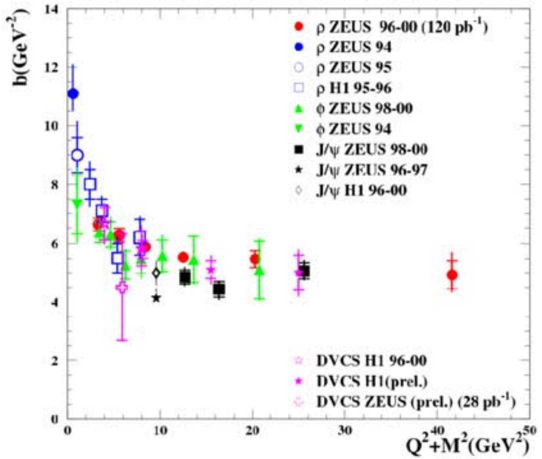


Fit $$\frac{d\sigma}{dt} \propto e^{-b|t|}$$



➢ shallower t-dependence with increasing Q^2

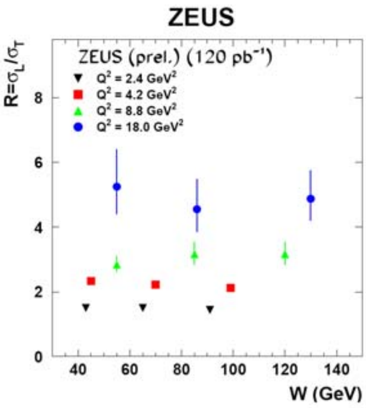
t-dependence for hard exclusive processes at small x

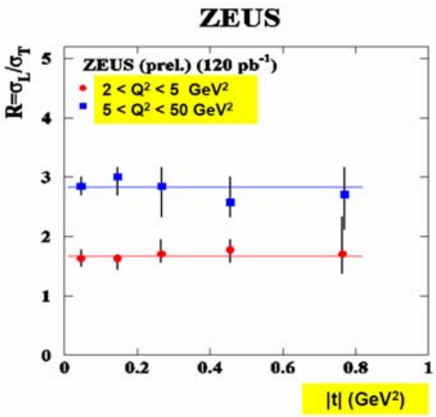


- b-slopes decrease with increasing scale Q^2 and/or M^2 approaching a limit ≈ 5 GeV^{-2} at large scales
- approximate 'universality' of slopes as a function of $(Q^2 + M^2)$

recent data suggestive of possible ≈ 15% difference between ρ and J/ψ

Selected results on $R = \sigma_L/\sigma_T$ for ρ^0 production





the same W- and t-dependence for σ_L and σ_T

$\delta_L \approx \delta_T$ $b_L \approx b_T$

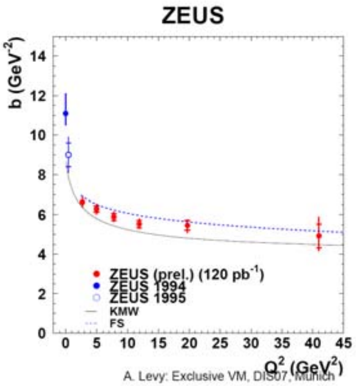
the same size of the longitudinal and transverse γ^* involved in hard ρ^0 production

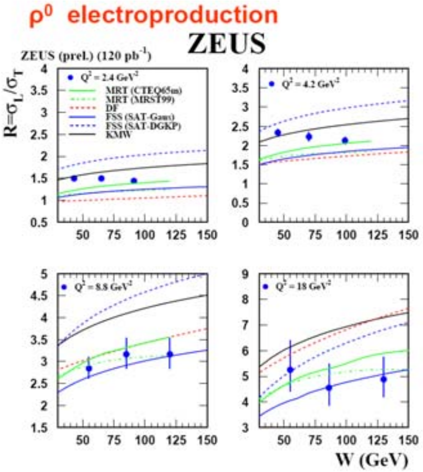
i.e. contribution of large qqbar fluctuations of transverse γ^* suppressed

Comparison to theory

extensive comparison of the models to recent ZEUS ρ^0 data in arXiv:0708.1478[hep-ex]

below just selected examples





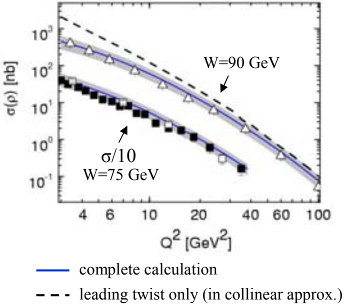
- considered models describe qualitatively all features of the data reasonably well
- recent ZEUS data are a challenge; none of the models gives at the moment satisfactory quantitative description of all features of the data

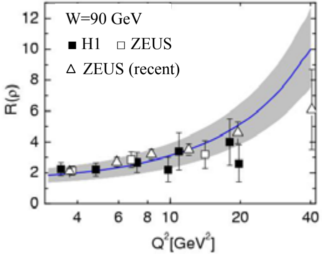
More comparison to theory

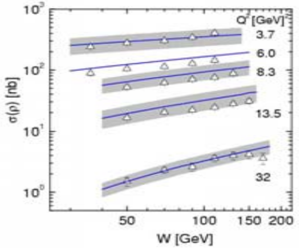
- Goloskokov-Kroll
  arXiv:0708,3569[hep-ph]

'Hand-bag model'; GPDs from DD using CTEQ6
power corrections due to k_t of quarks included

both contributions of γ^*_L and γ^*_T calculated







- leading twist prediction above full calculation, even at Q^2 = 100 GeV²
  ≈ 20%
- contribution of σ_T decreases with Q^2, but do not vanish even at Q^2 = 100 GeV²
  ≈ 10%
- sea quark contribution, including interference with gluons, non-negligible
  25% at Q^2 = 4 GeV²

Exclusive ρ^0 production at 5.75 GeV from CLAS

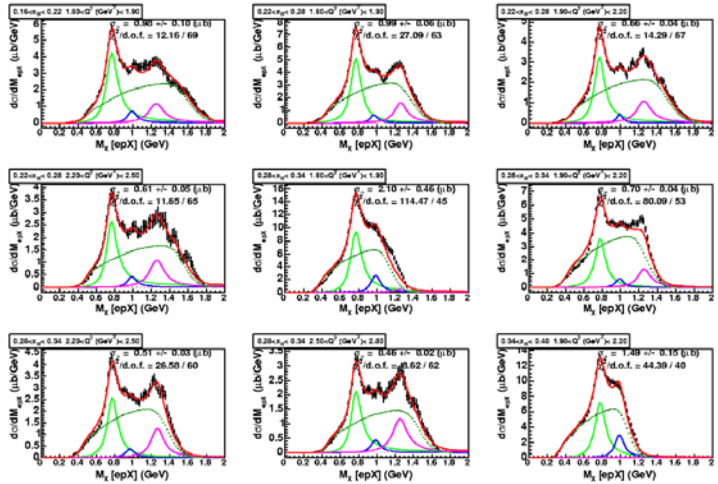
$e\,p \rightarrow e\,p\,\pi^+ (\pi^-)$

strong interference with $\Delta^{++}\pi^-$ production + $f_0(980)$ + $f_2(1270)$

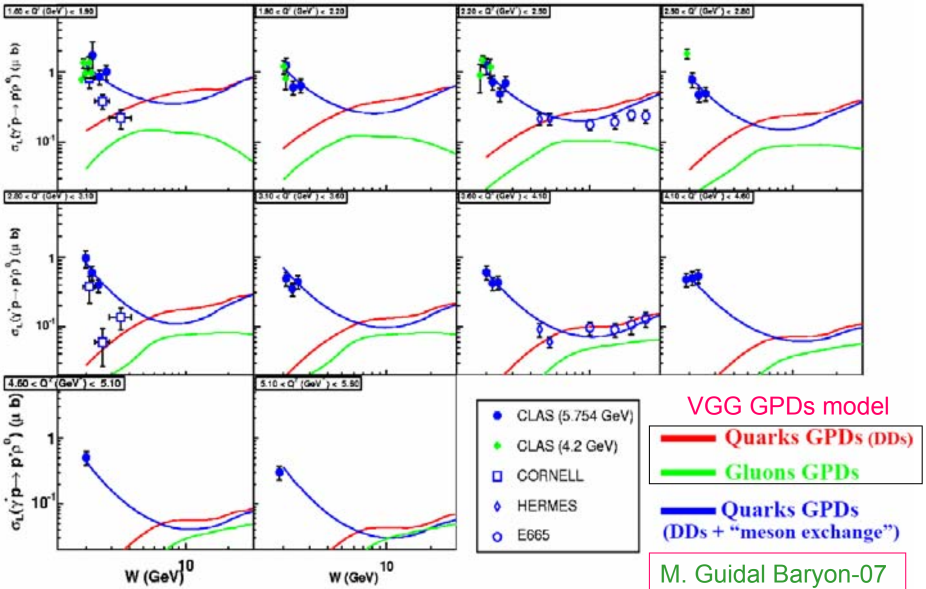
strong correlation between Q^2 and x

t_{min} increases with Q^2 and x (> 1.0 GeV^2 at x > 0.5)

$1.6 < Q^2 < 5.6\ GeV^2$
$1.8 < W < 2.5$ GeV
$0.16 < x_{Bj} < 0.7$
$|t_{min}| < |t| < 3\ GeV^2$



Longitudinal cross section $\sigma_L(\gamma^* p \to \rho^0_L\ p)$ and various GPD contributions



M. Guidal Baryon-07
preliminary

similar agreement for Regge approach of Laget
for the bins where data dominated by small t

Transverse target spin asymmetry for exclusive ρ^0 production

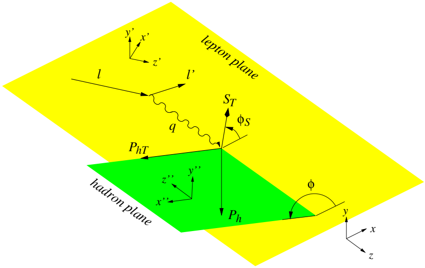
Give access to GPD E related to the orbital angular momentum of quarks

$$\frac{1}{2}\int_{-1}^{1} dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)] \overset{t\to 0}{=} J_q = \frac{1}{2}\Delta\Sigma + L_q$$

Ji's sum rule

So far GPD E poorly constrained by data (mostly by Pauli form factors)

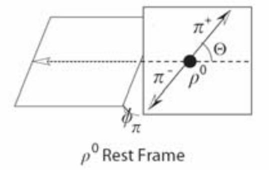
The asymmetry defined as $A_{UT}(\varphi,\varphi_s) = \frac{1}{S_T}\frac{d\sigma(\varphi,\varphi_s) - d\sigma(\varphi,\varphi_s+\pi)}{d\sigma(\varphi,\varphi_s) + d\sigma(\varphi,\varphi_s+\pi)}$



to disentangle contributions from γ_L and γ_T the distribution of ρ^0 decay polar angle needed in addition

Diehl and Sapeta

Eur. Phys. J.C 41, 515 (2005)



Method for L/T separation used by HERMES

A. Rostomyan and J. Dreschler arXiv:0707.2486

Angular distribution $W(\cos\theta, \varphi, \varphi_s)$ and Unbinned Maximum Likelihood fit

Assuming SCHC

$$W(\cos\theta,\varphi,\varphi_S) \propto \Big[\cos^2\theta\, r_{00}^{04}\, \{1 + A_{UU,\rho L}(\varphi) + S_T\, A_{UT,\rho L}(\varphi,\varphi_S)\} + \frac{1}{2}\sin^2\theta\,(1 - r_{00}^{04})\,\{1 + A_{UU,\rho T}(\varphi) + S_T\, A_{UT,\rho T}(\varphi,\varphi_S)\}\Big]$$

where $A_{UU,\rho L(\rho T)}(\varphi) = A_{UU,\rho L(\rho T)}^{\cos(\varphi)} \cos(\varphi) + A_{UU,\rho L(\rho T)}^{\cos(2\varphi)} \cos(2\varphi)$

$A_{UT,\rho L(\rho T)}(\varphi) = A_{UT,\rho L(\rho T)}^{\sin(\varphi-\varphi_S)} \sin(\varphi - \varphi_S) + \ldots$ (5 additional terms $A_{UT,\rho L(\rho T)}^{\sin(m\varphi\pm\varphi_S)} \sin(m\varphi \pm \varphi_S)$)

- $A_{UU,\rho L(\rho T)}^{\cos(\varphi)}$ and $A_{UU,\rho L(\rho T)}^{\cos(2\varphi)}$ obtained from SDMEs $r_{00}^5, r_{11}^5, r_{00}^1, r_{11}^1$
- 2 x 6 = 12 parameters $A_{UT,\rho L(\rho T)}^{\sin(m\varphi\pm\varphi_S)}$ from the fit

$$A_{UT,\rho L}^{\sin(\varphi-\varphi_S)} = -\frac{\mathrm{Im}\,\sigma_{00}^{+-}}{\sigma_L} \sim \mathrm{Im}\,(E^*_M H_M) / |H_M|^2$$

a prerequisite for the method: determination of acceptance correction

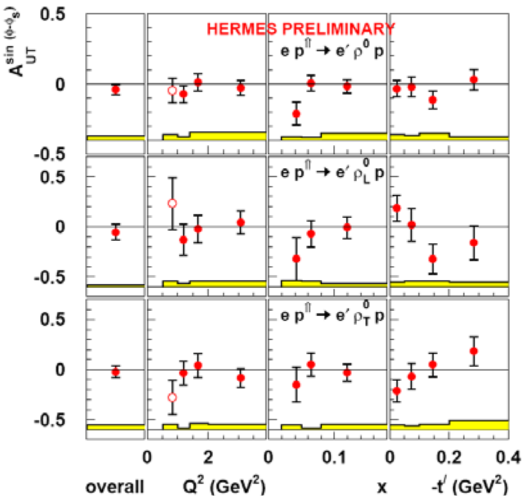
as a function of $\cos\theta$, φ and φ_s

ρ^0 transverse target spin asymmetry from HERMES

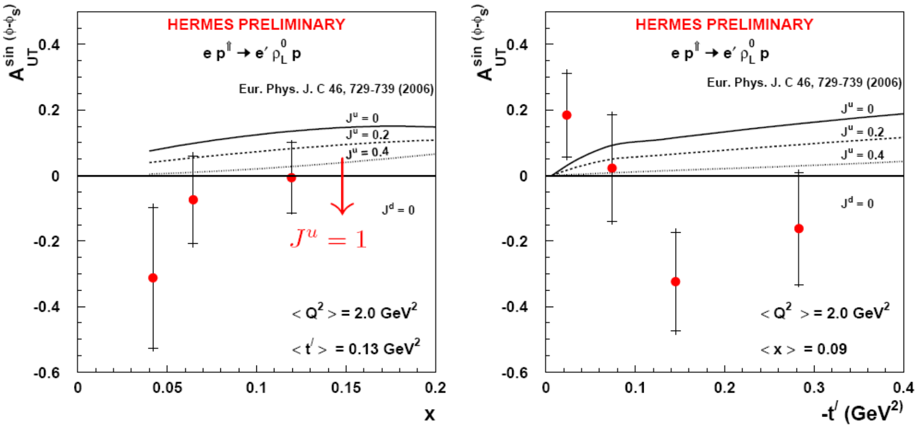
Transversely polarised proton target, $P_T \approx 75\%$
2002-2005 data, 171.6 pb^{-1}

$1 < Q^2 < 7$ GeV²
$W^2 > 4$ GeV²
$0.023 < x_{Bj} < 0.4$
$| t' | < 0.4$ GeV²

➤ for the first time ρ^0 TTSA extracted separately for γ^*_L and γ^*_T



ρ^0 transverse target spin asymmetry from HERMES



- in a model dependent analysis data favours positive J_u

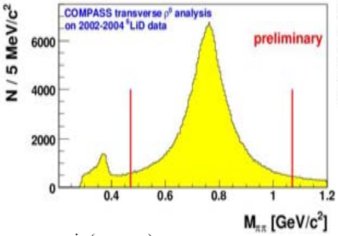
in agreement with DVCS results from HERMES

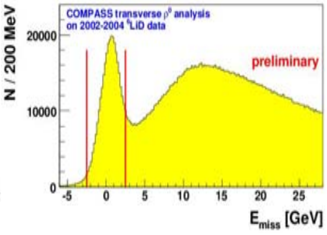
cf. talk by W.-D. Nowak

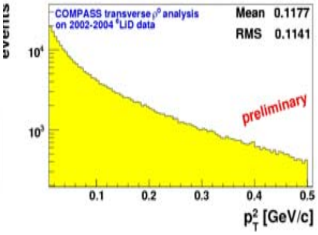
ρ^0 transverse target spin asymmetry from COMPASS

Transversely polarised deuteron target (^{6}LiD), $P_T \approx 50\%$
2002-2004 data

$Q^2 > 1$ GeV²
W > 5 GeV
$0.005 < x_{Bj} < 0.1$
$0.01 < p_t^2 < 0.5$ GeV²







$A_{UT}^{\sin(\varphi-\varphi_S)}$ obtained using Double Ratio Method

in bins of $\vartheta = \varphi - \varphi_S$:

$$DR(\eta) = \frac{N_u^{\uparrow}(\eta)\cdot N_d^{\uparrow}(\eta)}{N_u^{\downarrow}(\eta)\cdot N_d^{\downarrow}(\eta)} = \frac{a_u^{\uparrow}(\eta)\cdot a_d^{\uparrow}(\eta)}{a_u^{\downarrow}(\eta)\cdot a_d^{\downarrow}(\eta)}\frac{[1+\varepsilon\sin(\eta)]^2}{[1-\varepsilon\sin(\eta)]^2}$$
$$\cong C\cdot[1+4\varepsilon\sin(\eta)]$$

u (d) are for upstream (downstream) cell of polarised target
arrows indicate transverse polarisation of corresponding cells

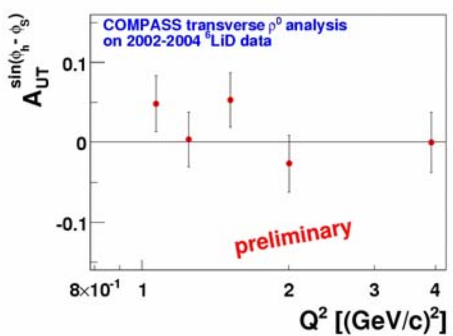
raw asymmetry ε
from the fit to $DR(\eta)$

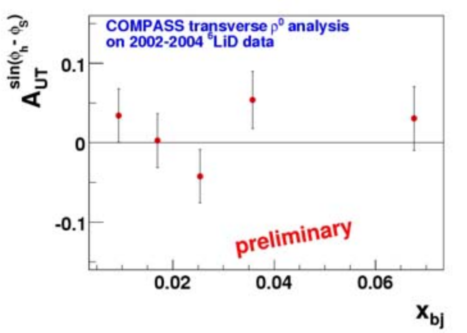
$$A_{UT}^{\sin(\varphi-\varphi_S)} = \frac{\varepsilon}{f\cdot\langle P_T\rangle}$$

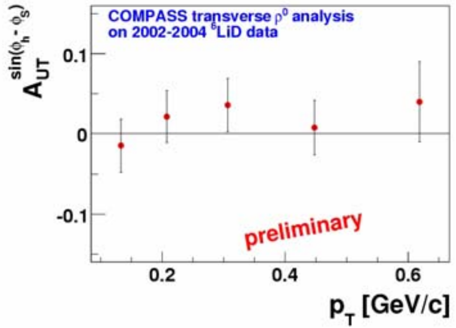
dilution factor $f \approx 0.38$

ρ^0 transverse target spin asymmetry from COMPASS

new







➢ asymmetry for deuteron target consistent with zero

ongoing work on:

- longitudinal/transverse separation
- separation of incoherent/coherent

in 2007 data taken with transversely polarised proton target (NH_3)

Longitudinal double-spin asymmetry for exclusive ρ^0 production (COMPASS)

arXiv:0704.1863[hep-ex]

longitudinally polarised deuteron target (^{6}LiD), $P_T \approx 50\%$

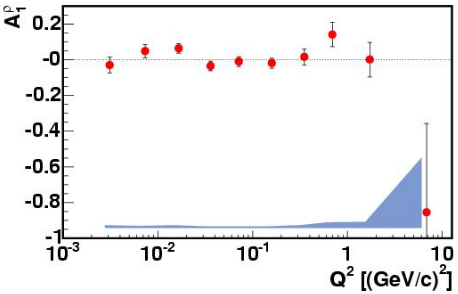
wide range of Q^2 and x , $W > 7.5$ GeV , $0.15 < p_t^2 < 0.5$ GeV²

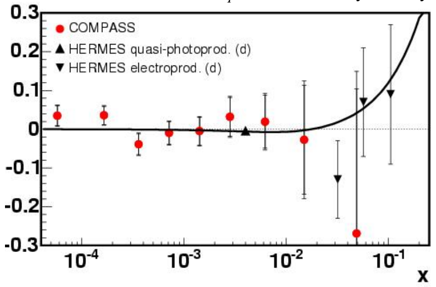
$$A_{LL}(\mu N \to \mu N \rho^0) = \frac{\sigma(\mu N)_{\uparrow\Downarrow} - \sigma(\mu N)_{\uparrow\Uparrow}}{\sigma(\mu N)_{\uparrow\Downarrow} + \sigma(\mu N)_{\uparrow\Uparrow}} = \frac{1}{f}\cdot\frac{1}{P_b}\cdot\frac{1}{P_t}\cdot A_{LL}^{raw}$$

$$A_1^\rho(\gamma^* N \to \rho^0 N) \approx \frac{1}{D} A_{LL}(\mu N \to \mu N \rho^0)$$

curve: $A_1^\rho = \frac{2\,A_1}{1 + (A_1)^2}$

where A_1 – inclusive asymmetry (d)





- A_1^ρ on polarised deuterons consistent with 0
- at small Q^2 and x precise constraint on contribution of exchanges with unnatural parity
- at large Q^2 A_1^ρ related to GPDs (higher-twist) $\propto k_T^2\, \widetilde{H}_g / (Q^2 H_g)$ Goloskokov, Kroll (2006)

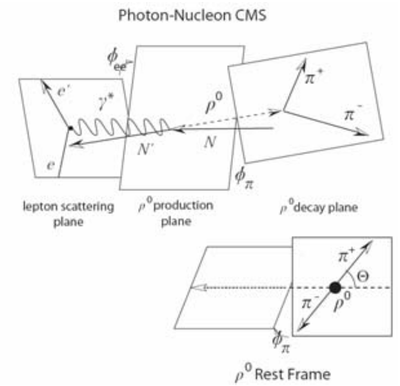
Spin Density Matrix Elements

VM angular distributions $W(\cos\theta, \varphi, \Phi)$ depend on the spin density matrix elements (SDME) ⇨ 23 (15) observables with polarized (unpolarized) beam

SDMEs are bilinear combinations of the helicity amplitudes $T_{\lambda m\, \lambda \gamma}(\gamma^* N \longrightarrow mN)$

$\lambda_\gamma = \pm 1, 0 \quad \lambda_m = \pm 1, 0$

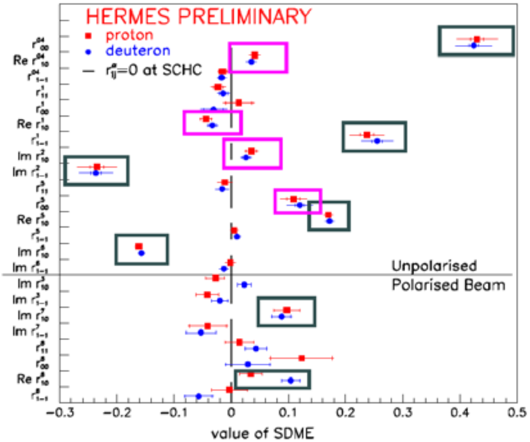
(averaged over nucleon spins)



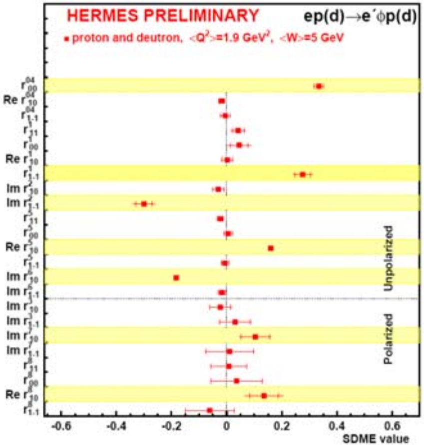
- describe helicity transfer from γ^* to VM
  s-channel helicity conservation (SCHC)
- describe parity of t-channel exchange
  (NPE vs. UPE)
- impact on GPD studies – determination of σ_L
  SDME $r^{04}_{00} \xrightarrow{SCHC} R = \frac{\sigma_L}{\sigma_T}$

Spin Density Matrix Elements from HERMES

ρ^0



φ



- for ρ^0 s-channel helicity violation in $\mathrm{Re}\, r^{04}_{10}, \mathrm{Re}\, r^{1}_{10}, \mathrm{Im}\, r^{2}_{10}$ (mild) and r^{5}_{00} (~ 10%)
- for ρ^0 a (small) contribution of unnatural-parity exchanges seen
- for φ no s-channel helicity violation
- for proton and deuteron targets SDMEs (mostly) the same

more in talk of S. Manayenkov

Exclusive π^+ production from HERMES

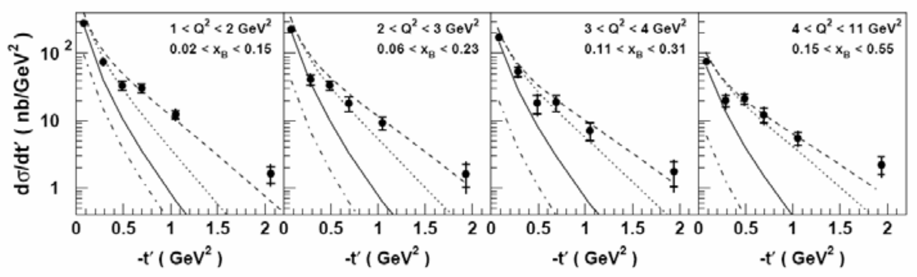
accepted for Phys Lett B

$e\,p \rightarrow e\,n\,\pi^+$

1996-2005 data with proton target (unpolarised and polarised)

$1 < Q^2 < 11$ GeV²
$W^2 > 11$ GeV²
$0.02 < x_{Bj} < 0.55$
$|t'| < 2$ GeV²

- L/T separation at HERMES not possible
- σ_T expected to be supressed as $1/Q^2$
  dominance of σ_L at large Q^2 supported by Regge model (Laget 2005)
- at leading twist σ_L sensitive to GPDs $\tilde{H}$ and $\tilde{E}$
- at small $|t'|$ $\tilde{E}$ dominates as it contains t-channel pion-pole



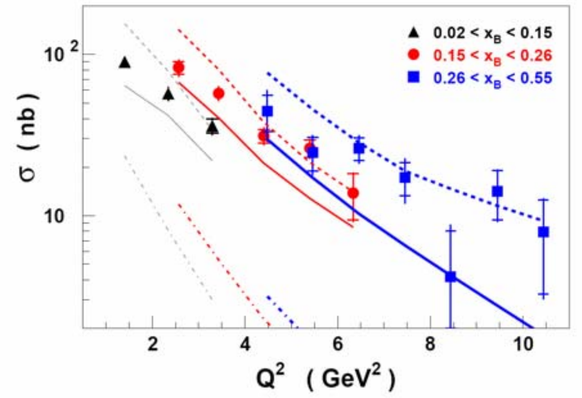
-·-·- σ_L VGG LO

—— σ_L VGG LO+power corrections

········ σ_L Regge model (Laget)

- - - - $\sigma_T + \varepsilon\, \sigma_L$ Regge model (Laget)

Exclusive π^+ production from HERMES



σ_L VGG LO

σ_L VGG LO+power corrections

$\sigma_T + \varepsilon\, \sigma_L$ Regge model (Laget)

- LO calculations underestimate the data
- data support magnitude of the power corrections (k_t and soft overlap)
- Regge calculations provides good description of the magnitude of σ_{tot} and of t' and Q^2 dependences

Beam spin asymmetry in exclusive π^0 production from CLAS

$e\,p \rightarrow e\,p\,\pi^0$

2005 data, E_e = 5.77 GeV, all final state particles measured

Extended acceptance for γ's due to installation of Inner Calorimeter

$1 < Q^2 < 4.5$ GeV^2
$W > 2$ GeV
$0.1 < x_{Bj} < 0.55$
$0.09 < |t| < 1.8$ GeV^2

- essentially no experimental data for neutral pseudoscalar mesons in this range
- at leading twist σ_L sensitive to GPDs $\tilde{H}$
- no t-channel pion-pole (in contrast to exclusive π^+ production)
- magnitude of σ_T contribution unknown

$$\frac{d^2\sigma_{\gamma^* p \to p\pi^0}}{dt\,d\varphi} = \frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\cos 2\varphi\frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\varphi\frac{d\sigma_{TL}}{dt} + h\sqrt{2\varepsilon(1-\varepsilon)}\sin\varphi\frac{d\sigma_{TL'}}{dt}\right)$$

$h = \pm 1$ is the beam helicity

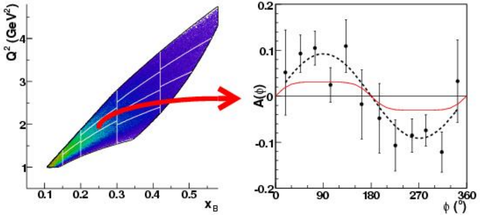
Beam Spin Asymmetry has the following φ dependence

$$A_{LU} = \frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{d^4\vec{\sigma} + d^4\overleftarrow{\sigma}} = \frac{\alpha\sin\varphi}{1| + \beta\cos\varphi + \gamma\cos 2\varphi}$$

- any non-zero BSA would indicate L-T interference

  i.e. contribution not described in terms of GPD's

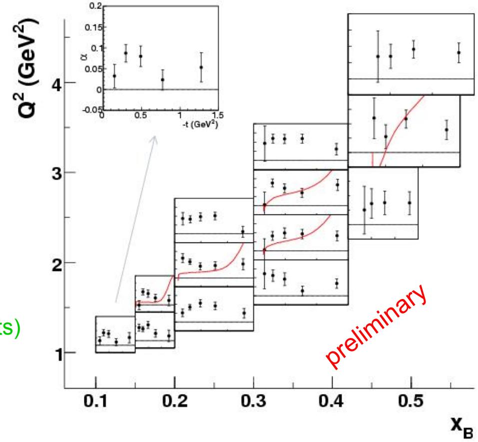
Beam spin asymmetry in exclusive π^0 production from CLAS



- - - -   a fit $\alpha \sin\varphi$

——   Regge model (Laget)

pole terms (ω, ρ, b_1) + box diagrams (cuts)



- first measurement of BSA for exclusive π^0 production above resonance region
- sizeable BSA (0.04 – 0.11) indicate that both transverse and longitudinal amplitudes participate
- necessity for L/T separation and measurements at higher Q^2

Cross sections for exclusive π^0 production from JLAB HALL A DVCS Collab.

E00-110

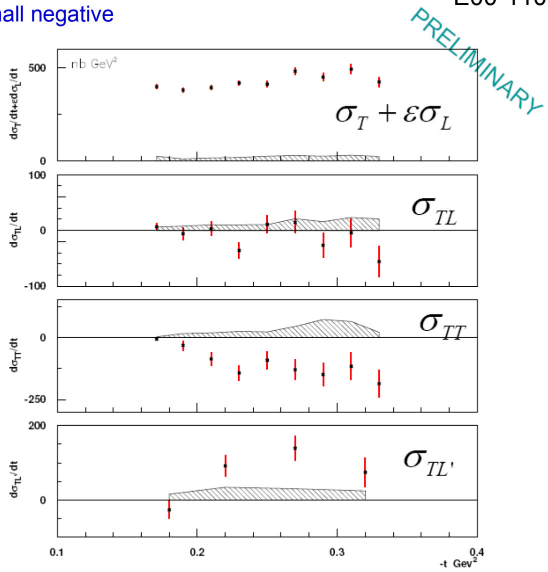
t-slope close to 0, maybe even small negative

Q^2=2.3 GeV^2

x_{Bj}=0.36

ε=0.64

χ^2=1.11



from P. Bertin, Baryon-07

more in talk of A. Camsonne

Corrected for real+virtual RC
Corrected for efficiency
Corrected for acceptance
Corrected for resolution effects

Regge model (Laget) underestimates cross sections ≈ 5x

Prospects for more results on exclusive meson production

➢ Other ongoing analyses of the data already taken

- ZEUS + H1 data from HERA II : ρ^0, φ, J/ψ, Υ cross sections + SDMEs
- HERMES : ρ^0, φ SDMEs + unpolarised cross sections for full set of data including 2006-2007, expected factor of 2 gain in accuracy, hopefully with RD
  π^+ transverse target spin asymmetry (protons)
- COMPASS : ρ^0 TSA for polarised deuterons with γ^*_L-γ^*_T separation
- CLAS : ρ^+, φ, π^+, π^0 and η cross sections

➢ Data being taken or expected soon

- COMPASS : ρ^0 from transversely polarised proton target (2007)
  mesons from longitudinally polarised proton target (2007 (?))
- Hall A DVCS Coll.: π^0 Rosenbluth separation (2009)
- CLAS : π^0 and η cross sections and BSA (2008), LTA (2009)

➢ Future projects with impact on GPDs

- COMPASS : DVCS and DVMP with Recoil Detector, large LH (LD) target and extended EM calorimetry , ρ up to 20 GeV^2, γ, ω, φ, π and η up to 7 GeV^2 (2010)
- JLAB 12 GeV Upgrade (2014) cf. talk by B. Wojtsekhowski
- PANDA at FAIR (2014) cf. next-to-last talk on Saturday
- EIC (> 2014) cf. talk by H. Kowalski

Conclusions

- New precise data on cross sections and SDME's result in significantly more stringent constraints on the models for DVMP

- To describe present data on DVMP, both at large and small x, including power corrections (or higher order pQCD terms) is essential

- First experimental efforts in DVMP to constrain GPD E and quark orbital momentum

- A rich program of future experiments and projects with impact on studies of DVMP and GPDs

Backup slides

GPDs properties, link to DIS and elastic form factors

Generalized Parton distributions

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Link to form factors (sum rules)

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t) \;,\; \int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = g_A^q(t) \;,\; \int_{-1}^{1} dx \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

Link to DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x) = -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x) = -\Delta\bar{q}(-x)$$

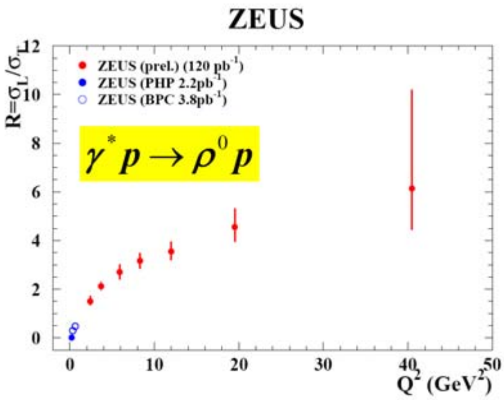
No similar relations for E^q and $\tilde{E}^q$

Access to quark angular momentum (Ji's sum rule)

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

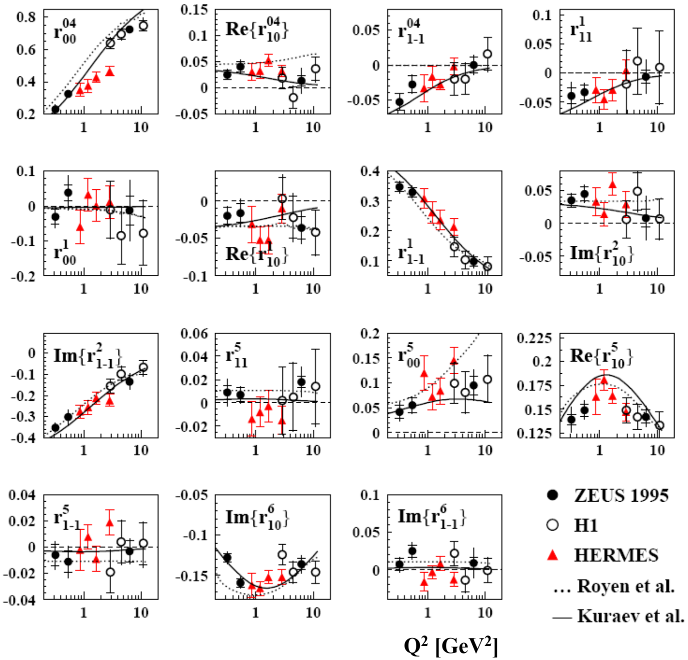
from Z.-E. Mezziani

$R = \sigma_L/\sigma_T\ (Q^2)$ - ρ^0



- σ_L dominant at large Q^2
- suppresion of σ_T at large Q^2 weaker than $1/Q^2$

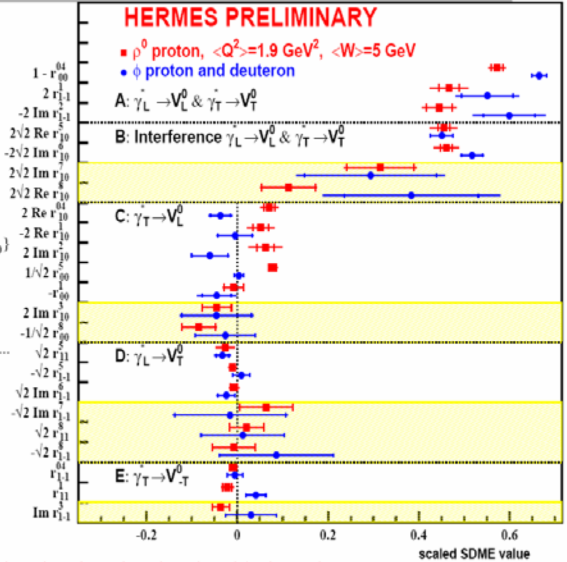
Q^2-dependence of SDMEs



Spin Density Matrix Elements from HERMES

SDMEs According to Hierarchy of Amplitudes without&with Helicity Flip: ρ^0, ϕ

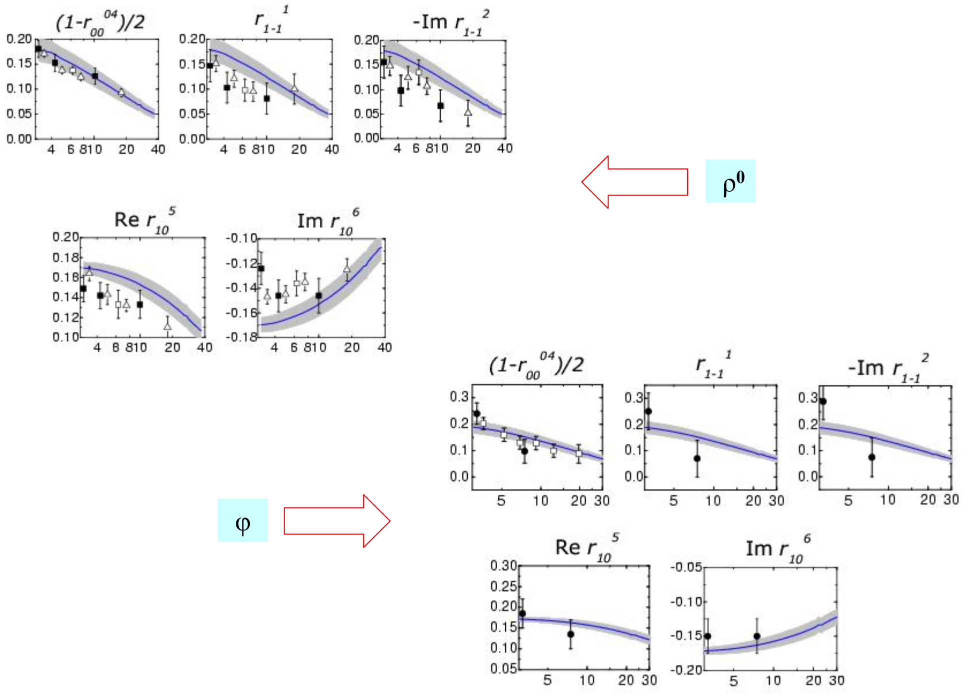
- A, $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$
  $|T_{11}|^2 \propto 1 - r^{04}_{00} \propto r^1_{1-1} \propto -Im\{r^2_{1-1}\}$
- B, Interference: γ^*_L, ρ^0_T
  $Re\{T_{00}T^*_{11}\} \propto Re\,\{r^5_{10}\} \propto -Im\{r^6_{10}\}$
  $Im\{T_{11}T^*_{00}\} \propto Im\{r^7_{10}\} \propto Re\{r^8_{10}\}$
- C, Spin Flip: $\gamma^*_T \to \rho^0_L$
  $Re\{T_{11}T^*_{01}\} \propto Re\{r^{04}_{10}\} \propto Re\{r^1_{10}\} \propto Im\{r^2_{10}\}$
  $Re\{T_{01}T^*_{00}\} \propto r^5_{00}$
  $|T_{01}|^2 \propto r^1_{00}$
  $Im\{T_{01}T^*_{11}\} \propto Im\{r^3_{10}\}$
  $Im\{T_{01}T^*_{00}\} \propto r^8_{00}$
- D, Spin Flip: $\gamma^*_L \to \rho^0_T$
  $Re\{T_{10}T^*_{11}\} \propto r^5_{11} \propto r^5_{1-1} \propto Im\{r^6_{1-1}\}$
  $Im\{T_{10}T^*_{11}\} \propto Im\{r^7_{1-1}\} \propto r^8_{11} \propto r^8_{1-1}$
- E, Spin Flip: $\gamma^*_T \to \rho^0_{-T}$
  $Re\{T_{1-1}T^*_{11}\} \propto r^{04}_{1-1} \propto r^1_{11}$
  $Im\{T_{1-1}T^*_{11}\} \propto Im\{r^3_{1-1}\}$



$\Longrightarrow$ Hierarchy of ρ^0 amplitudes: $|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \gtrsim |T_{1-1}|$, $(0 \to L, 1 \to T)$

$\Longrightarrow$ ϕ meson SDMEs are consistent with SCHC, $|T_{00}| \sim |T_{11}|$

A. Borissov, Baryon-07



(1-r 00 04)/2
r 1-1 1
-Im r 1-1 2
Re r 10 5
Im r 10 6
ρ0
φ