Review on exclusive meson production

recent experimental results

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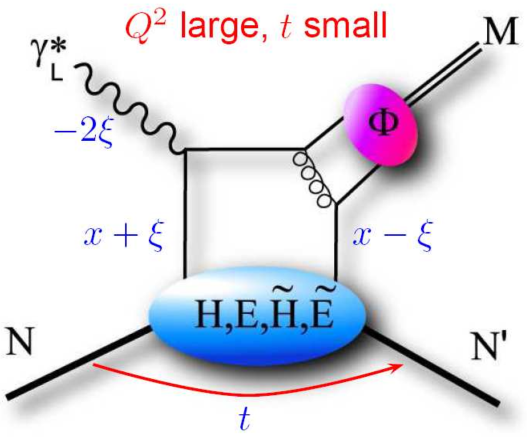
- Introduction
- Exclusive and proton-dissociative production of VM at small |t|
- Helicity amplitudes for VM production on unpolarised nucleons
- Production of pseudoscalar mesons
- Meson production on transversely polarised nucleons
- Conclusions

GPDs and Hard Exclusive Meson Production



- 4 Generalised Parton Distributions (GPDs)
  for each quark flavour and for gluons
- factorisation proven only for σ_L
  σ_T suppressed by $1/Q^2$
- applicable at DIS region, |t| << Q^2 and any x_B
- allows separation (H,E) ↔ ($\tilde{\text{H}}$,$\tilde{\text{E}}$) and wrt quark flavours

  $\left.\begin{matrix}\text{H}\\ \tilde{\text{H}}\end{matrix}\right\}$ conserve $\quad$ $\left.\begin{matrix}\text{E}\\ \tilde{\text{E}}\end{matrix}\right\}$ flip nucleon helicity

  Vector mesons (ρ, ω, φ)
  Pseudoscalar mesons (π, η)

Flavour sensitivity of HEMP on the proton

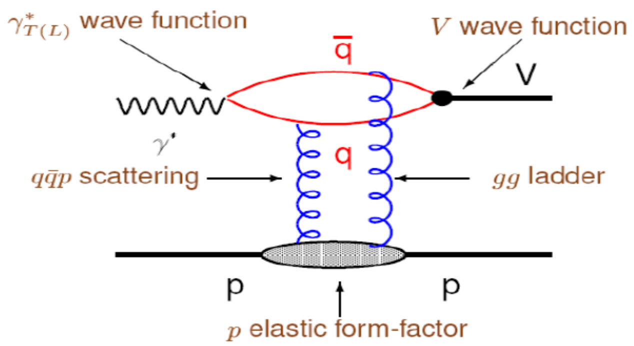
π^0	2Δu+Δd
η	2Δu−Δd
ρ^0	2u+d, 9g/4
ω	2u−d, 3g/4
ϕ	s, g
ρ^+	u−d
J/ψ	g

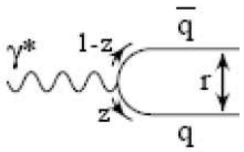
- quarks and gluons enter at the same order of α_S
- at Q^2 ≈ few GeV² power corrections/higher order pQCD terms are essential
- wave function of meson (DA Φ)
  additional nonperturbative component

Colour dipole models

an alternative description of VM production at small x

applicable at small x both for photoproduction and DIS region





$$< r > \approx k / \sqrt{\mu^2}$$

$$\Psi^{\gamma}(z,\vec{r}) \otimes \sigma^{q\bar{q}-p}(x_B,\vec{r};t) \otimes \Psi^{V}(z,\vec{r})$$

$$\mu^2 \approx z(1-z)(Q^2 + M_V^2)$$

for heavy mesons or γ^*_L $z \approx ½$

and $\mu^2 = (Q^2 + M_V^2)/4$

- at small x sensitivity mostly to gluons ⟹ universal dipole-nucleon cross section

  dipole-nucleon cross section related to inclusive photo- and DIS production

  the link exploited in certain colour dipole models

- cross section for VM production ~ $|g(x_B)|^2$ (at LO)

  hardening of the gluon distribution $g(x_B) \sim x_B^{-\lambda}$ at large Q^2 ⟹ strong W-dep.

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

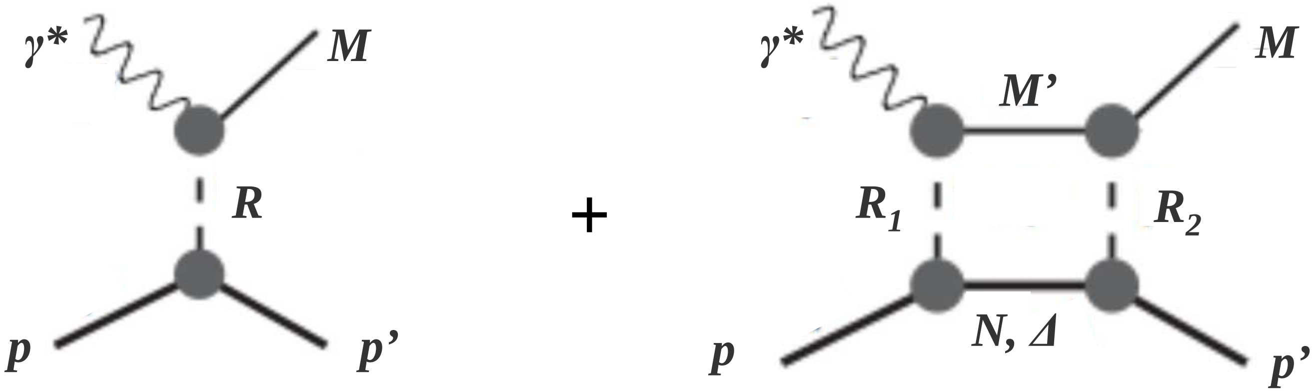
Regge models

another alternative description of meson photo- and electroproduction

based on general properties of amplitudes analiticity at $|t| \ll s$ (W)

applicable from photoproduction to moderate Q^2

t-channel exchange of Reggeon(s) R (R_1, R_2): $\mathcal{P}$, ρ, ω, σ, f_2, π, b_1…



Regge poles Regge cuts

M	R
ρ^0	$\mathcal{P}$, σ, f_2
ω	$\mathcal{P}$, π^0
ϕ	$\mathcal{P}$
ρ^+	π^+, ρ^+
π^0	ω, ρ^0, b_1

factorisation of vertices for a Regge pole exchange;
$g_{RNN}(t)$ at nucleon vtx. and meson form factor

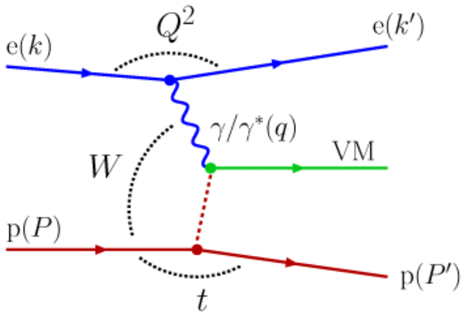
energy dependence determined by the Reggeon trajectory:

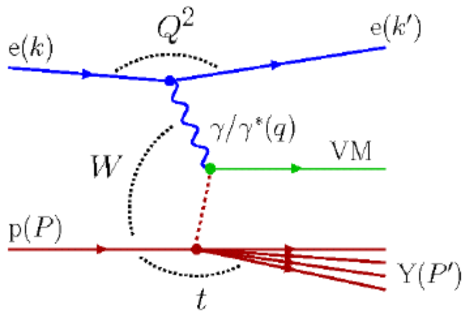
$$\frac{d\sigma}{dt}(W;R) = F(t)(W/W_0)^{2[2\alpha_R(t)-2]} \qquad \boxed{\alpha_R(t) \approx \alpha_R(0) + \alpha'_R t}$$

except $\mathcal{P}$, contributions of other Reggeons decrease with W

Elastic and proton-dissociative small |t| VM production at HERA

VM: ρ^0, ω, ϕ, J/ψ, $\psi(2s)$, Y





$10^{-4} \le x_B \le 10^{-2}$
$0 \le Q^2 < 160$ GeV^2
$30 < W < 180$ GeV
$|t| < 3$ GeV^2

VM measured in central detectors

no other activity, apart from forward detectors

elastic sample - scattered proton inside the beam pipe; 'no-tag events'

proton-dissociative sample - remnants of the proton hit forward detectors; 'tag events'

Main sources of background:

cross-contaminations between tag and no-tag samples ≈ 10%

diffractive ρ' production with not all decay particles being mesured - several %

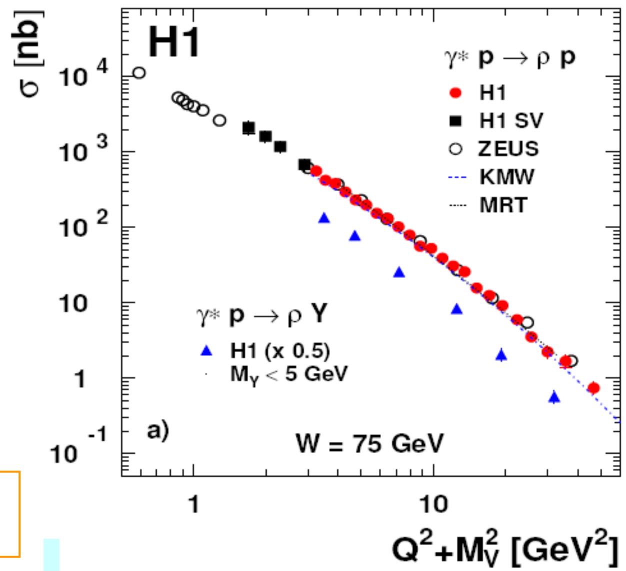
$\pi^+\pi^-$ background in ϕ samples ≈ 5%

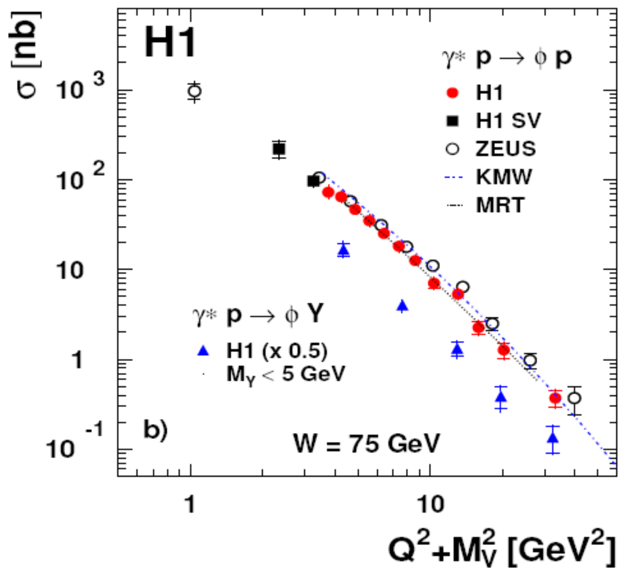
semi-inclusive events suppressed by large rapidity gap between VM and forward detectors

➢ Q^2 dependence

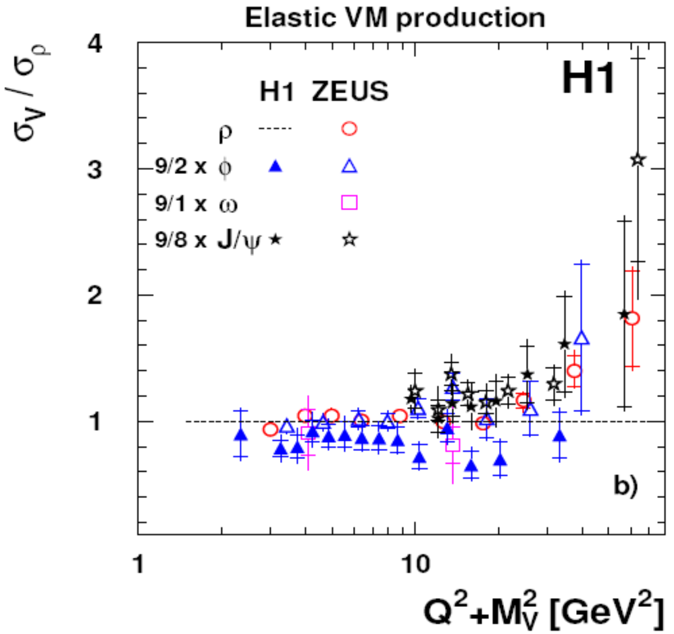
KMW (Kowalski, Motyka, Watt) dipole approach

MRT (Martin, Ryskin, Teubner) parton-hadron duality





➢ SU(4) universality (?)



for the ratios σ_V rescaled according to quark charge content

- shape similar for ρ & ϕ and for elastic & dissoc.

  power low fits $1/(Q^2+M_V{}^2)^n$ with $n \approx 2.4$

- shape reasonably well described by models

- normalization; some (< 20%) differences between exps

  similar level of agreement with models

- universality qualitative (within 20%)

  scaling factors from VM electronic decay widths

  expected to encompass wave function and soft effects

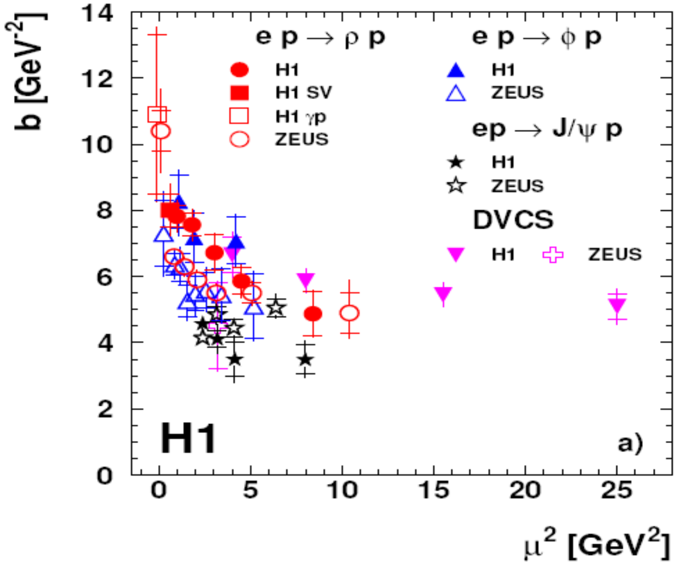
➢ *t* dependence

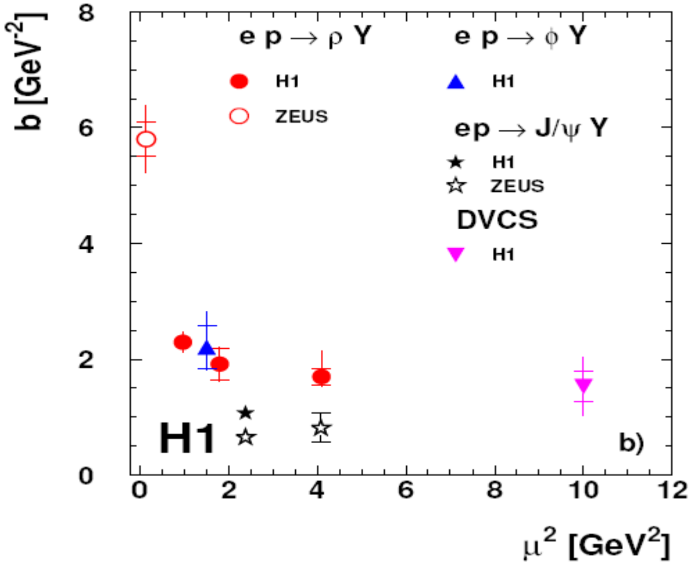
$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$ for elastic (| t | < 0.5(1.0) GeV²) and dissoc. (| t | < 3 GeV²)

$b = b_Y + b_{qq} + b_{\mathbb{P}}$ (+ b_V ?)

related to 'transverse imaging' of the proton

$b_{\mathbb{P}}$ expected small and Q^2 independent





$\mu^2 = (Q^2+M_V^2)/4$

($= Q^2$ for DVCS)

- some discrepancy between experiments, due to subtraction of dissoc. background
- significant decrease from photoproduction already at $\mu^2 \approx 0.5$ GeV² and levelling at $\mu^2 \approx 5$ GeV²

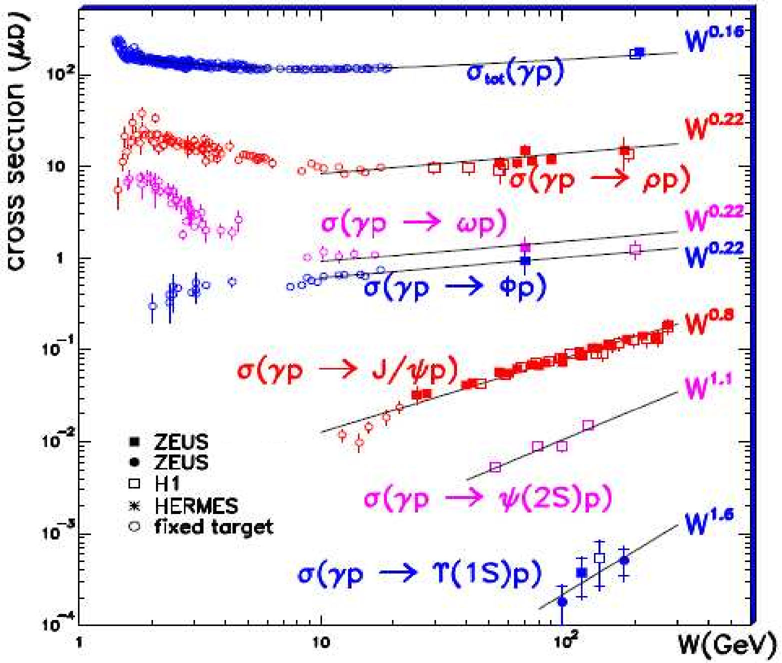
  decrease of dipole transverse size with increasing scale
- light mesons slightly above J/ψ (effect of VM form factors ?)
- slopes in diffractive dissociation significantly smaller

➤ *W* dependence

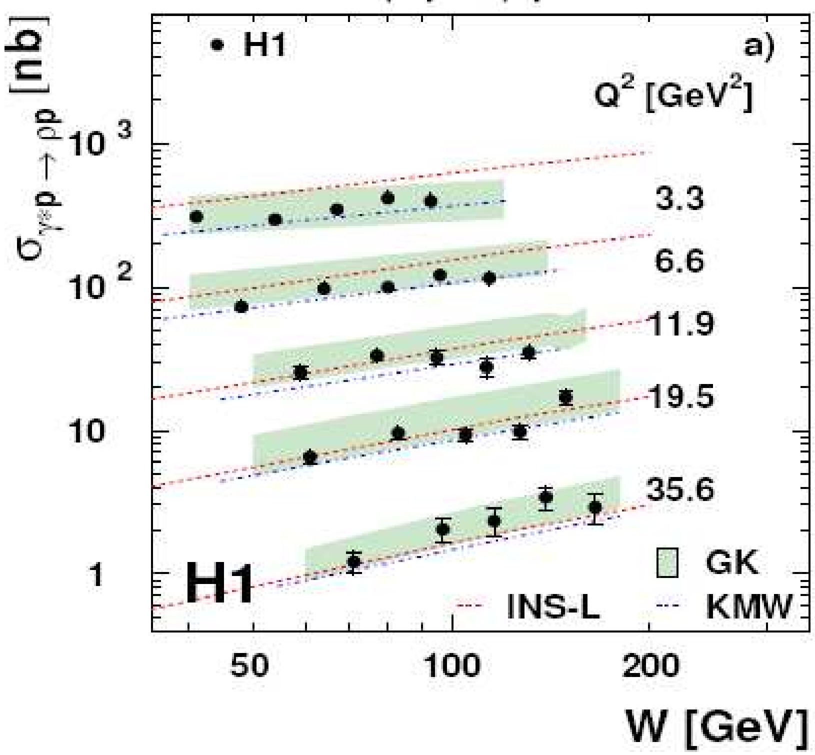
$\sigma \propto W^{\delta}$

GK - (Goloskokov, Kroll) GPD model
KMW
INS-L - (Ivanov, Nikolaev, Savin) dipole model with large meson wave function

photoproduction



DIS $\gamma^* p \to \rho p$



- faster growth at large mass or large Q^2

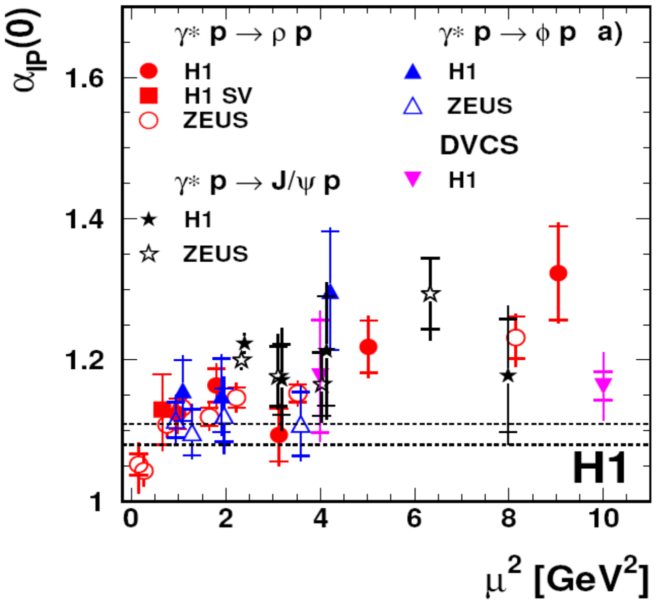
  hardening of the gluon distribution $g(x_B) \sim x_B^{-\lambda}$

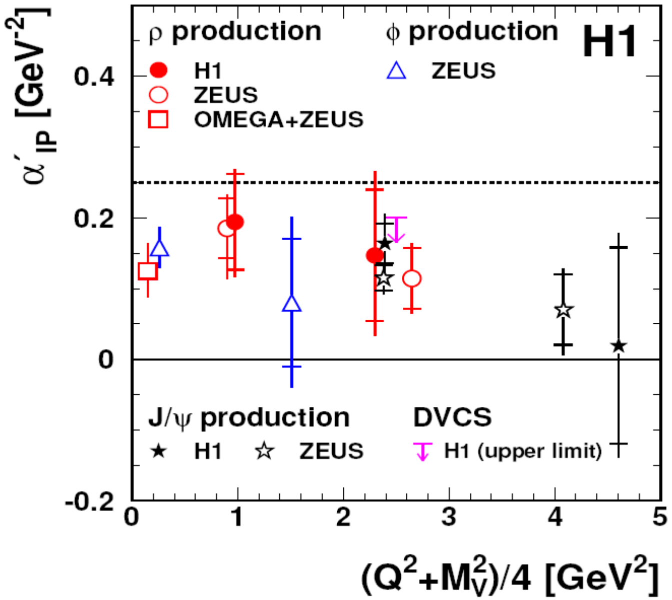
- pQCD models reproduce W dependence well, sensitivity to assumed gluon PDFs

➢ Interplay between W and t dependences

$$\frac{d\sigma}{dt}(W) = \frac{d\sigma}{dt}(W_0)\,(W/W_0)^{\delta(t)} \propto e^{b_0 t}(W/W_0)^{4(\alpha_P(0)+\alpha'_P t-1)} \quad \Longrightarrow \quad b = b_0 + 4\alpha'_P \ln\frac{W}{W_0}$$

effective Pomeron trajectory determined either by measuring W evolution of t-slope b or t evolution of W^{δ} (more accurate)





- increase of $\alpha_{\mathcal{P}}(0)$ with the scale due to hardening of gluon distribution
- at large μ^2 scales W dependence ($\alpha_{\mathcal{P}}(0)$) significantly stronger than in soft hadronic diffraction
- $\alpha'_{\mathcal{P}}$ smaller than for 'soft Pomeron', even at $Q^2 \approx 0$
- a hint that $\alpha'_{\mathcal{P}}$ may vanish at very large Q^2, as expected for BFKL dynamics

➡ L. Schoeffel

Exclusive VM production at CLAS

VM: ρ^0, ω, ϕ, ρ^+

preliminary, first results ever

S. Morrow et al. EPJ A39, 5 (2009)
L. Morand et al. EPJ A24, 445 (2005)
J.P. Santoro et al. PR C78, 025210 (2008)

ρ^0 : $e\,p \rightarrow e\,p\,\pi^+\pi^-$

ω : $e\,p \rightarrow e\,p\,\pi^+\pi^-\pi^0$ or $e\,p \rightarrow e\,p\,\pi^+\pi^-\pi^0$

ϕ : $e\,p \rightarrow e\,p\,K^+K^-$

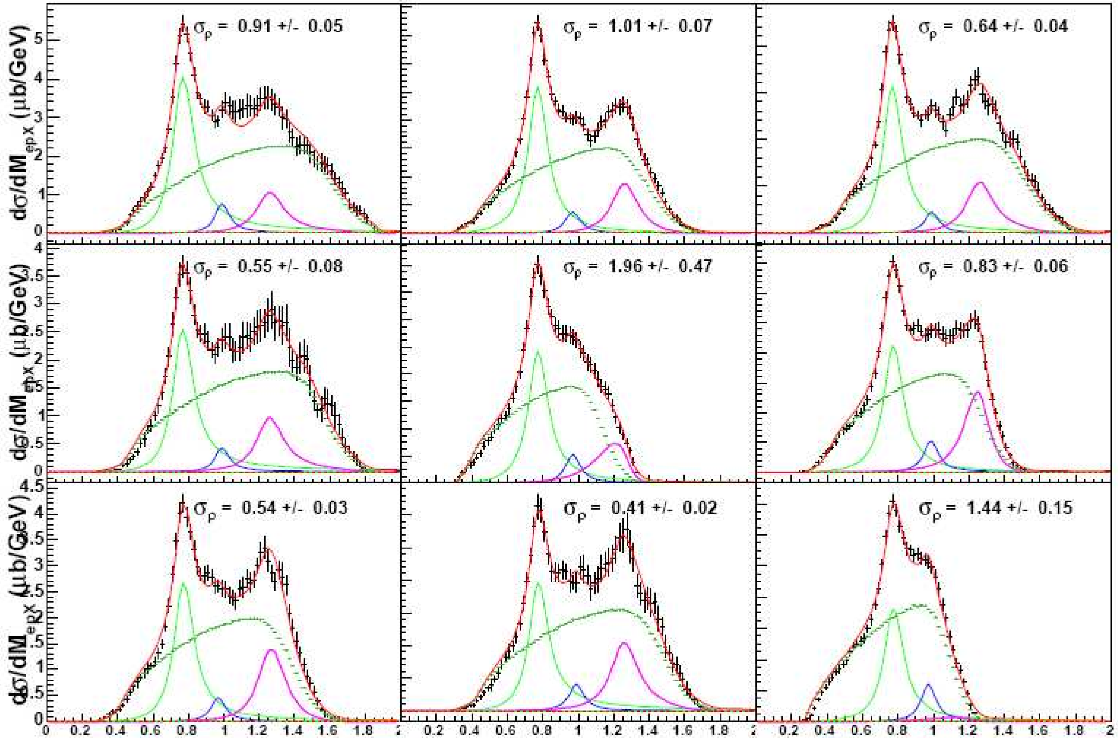
ρ^+ : $e\,p \rightarrow e\,n\,\pi^+\pi^0$

missing mass used to ensure exclusivity

'Typical' kinematic domain

$0.16 \leq x_B \leq 0.7$
$1.6 \leq Q^2 < 5.6$ GeV²
$1.8 < W < 2.8$ GeV
$0.1 < |t| < 4.3$ GeV²

ρ^0

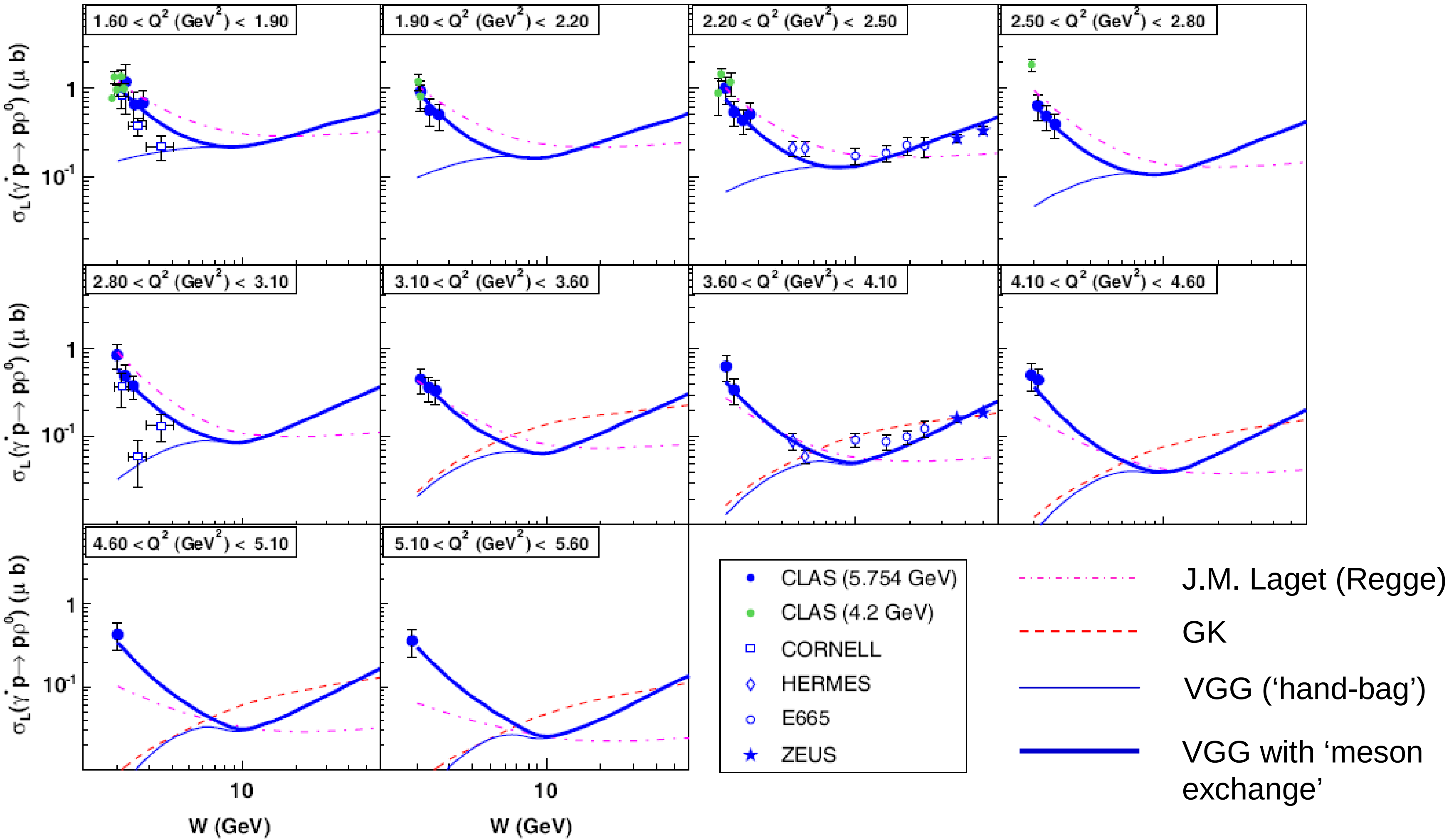


missing mass M_X[epX]

for selected (Q^2, x_B) bins

fitted sum of ρ^0, f_0, f_2 and nonresonant $\pi^+\pi^-$

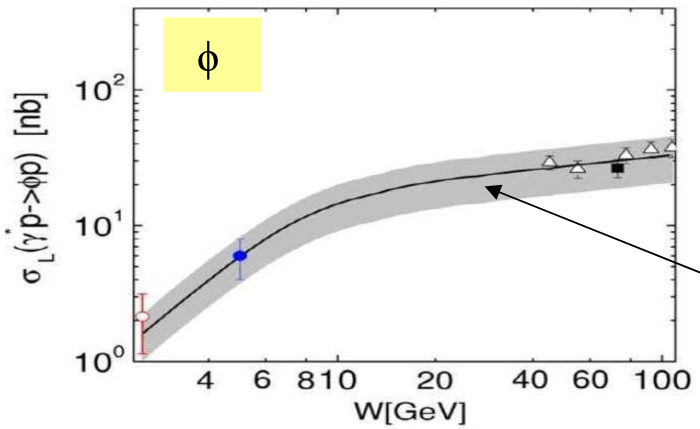
➢ W dependence of $\sigma(\gamma^* p \rightarrow \rho^0 p_L)$



- Laget (Regge) able to describe data up to $Q^2 \approx 4$ GeV^2
- GPD models using 'hand-bag' mechanism + power corrections OK at W ≥ 5 GeV fail by an order of magnitude at the lowest W
- at small W (large x_B) in the framework of GPDs important contrib. of $q\bar{q}$ exchange

➢ W dependence for ρ^+_L and ϕ_L

- for ρ^+ (not shown) qualitatively similar trends as for ρ^0

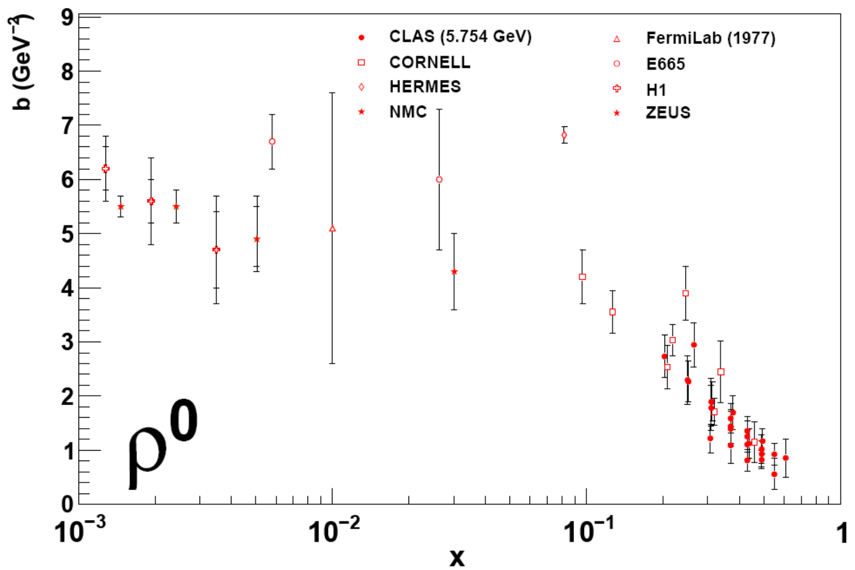


- for ϕ GPD model describes data well in all W range

  ϕ production through gluon and sea quark exchanges (Pomeron in Regge formalism)

  in contrast, for other mesons at small W also valence quark exchanges important (subleading Reggeons)

➢ b slope



courtesy of M. Guidal

- probing more compact object at large x_B

Spin Density Matrix Elements for VM production on unpolarised nucleons

VM angular distributions W(cosθ, φ, Φ) depend on the spin density matrix elements (SDME)

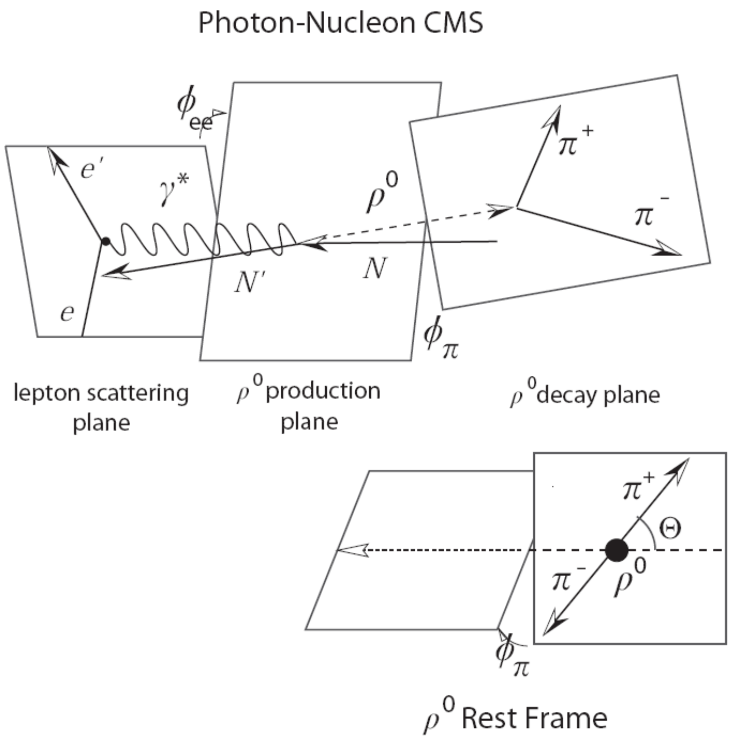
⇨ 23 (15) observables with polarized (unpolarized) beam

SDMEs are bilinear combinations of the helicity amplitudes

$$\boxed{F_{\lambda m\,\lambda N';\lambda\gamma\,\lambda N}(\gamma^{*}N \longrightarrow mN')}$$

$F = T + U$ (natural + unnatural PE)

convention $T_{\lambda m\,\lambda\gamma}$, $U_{\lambda m\,\lambda\gamma}$ implies $\lambda_{N'} = \lambda_N = +½$



- determine hierarchy of $T_{\lambda m\,\lambda\gamma}$, $U_{\lambda m\,\lambda\gamma}$ amplitudes
- check s-channel helicity conservation

  for SCHS the only non-vanishing are T_{00}, T_{11}, U_{11}
- describe parity of t-channel exchange

  NPE vs. UPE
- impact on GPD studies – determination of σ_L

  SDMEs $\longrightarrow R = \dfrac{\sigma_L}{\sigma_T}$

- in Regge formalism - NPE: Ƥ, ρ, ω, f_2, a_2 ; UPE: π, a_1, b_1 exchanges
- in GPD formalism - NPE: H, E ; UPE: $\tilde{H}$, $\tilde{E}$ GPDs

  at leading order only SCHC & NPE

➢ SDMEs from HERMES for ρ^0 production on protons and deuterons

comprehensive measurement and analysis of 15(8) unpolarised (polarised) SDMEs !

A. Airapetian et al. EPJ C 62, 659 (2009)

similar results (not shown here) also for ϕ

$1 < Q^2 < 7$ GeV²
$3.0 < W < 6.3$ GeV
$|t'| < 0.4$ GeV² (**)

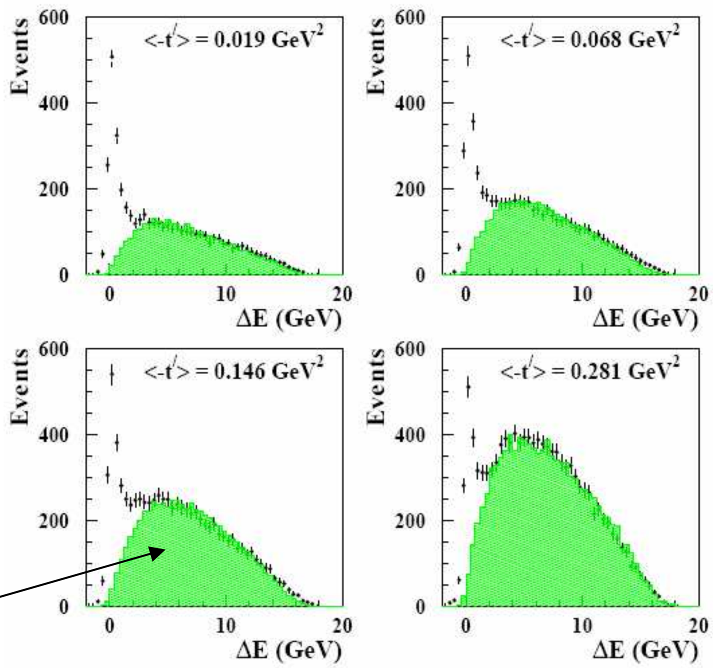
$\Delta E = (M_X^2 - M_p^2)/2 < M_p$
$t' = t - t_0$

selections and background

$0.6 < M_{\pi\pi} < 1.0$ GeV (*)
$-1.0 < \Delta E < 0.6$ GeV (**)

(*) non-resonant $\pi^+\pi^-$ background 4-8% (unsubtracted)

(**) SIDIS background 3-12% (subtracted bin-by-bin)
proton-dissociative background ≈4% (unsubtracted)



Main sources of systematic errors:

background subtraction
uncertainties of parameters in exclusive MC

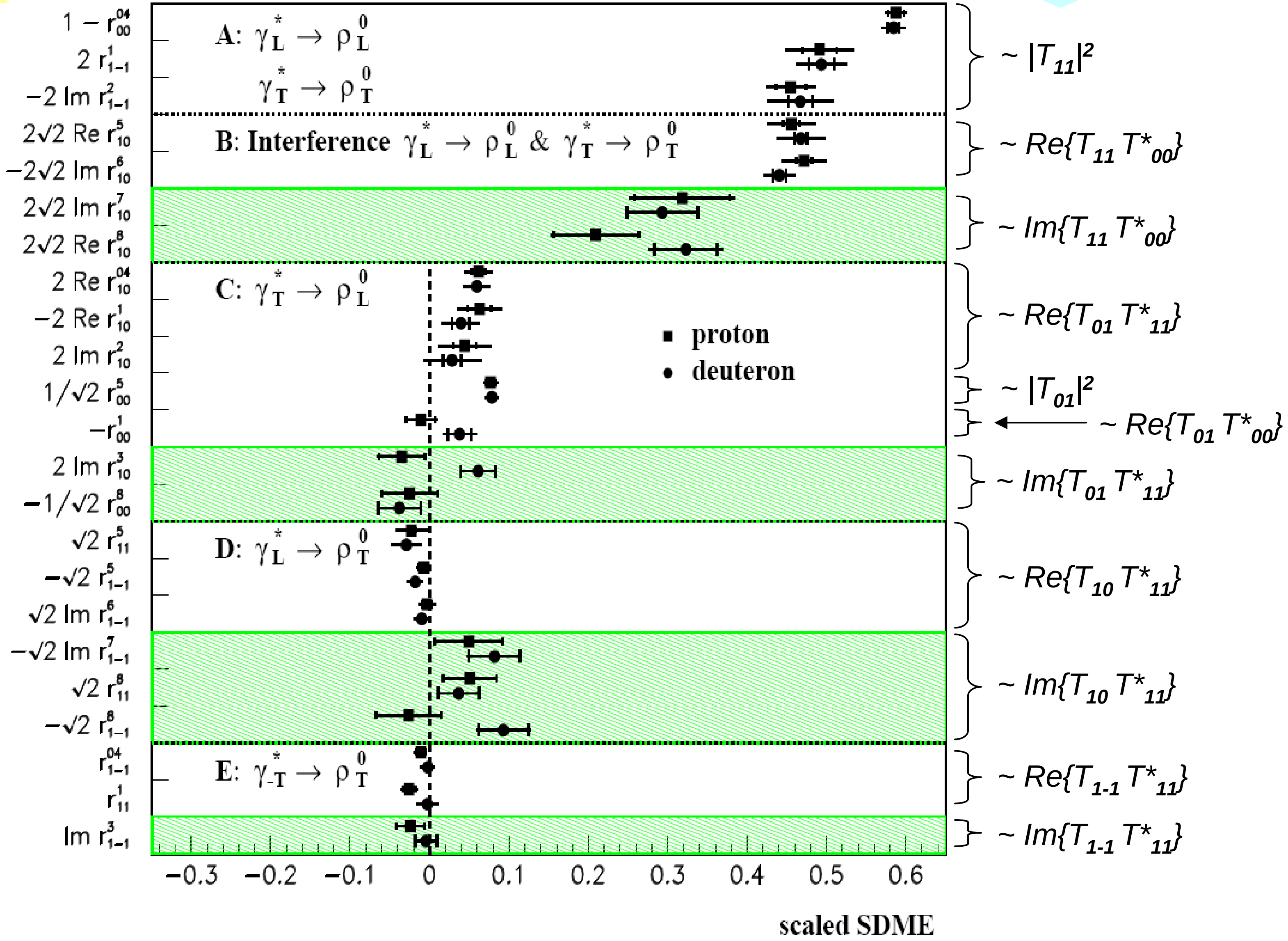
➤ SDMEs

combined 1996-2005 data over whole kinematic range EPJ C 62, 659 (2009)

ρ^0

$\langle x_B \rangle = 0.08$, $\langle Q^2 \rangle = 1.95$ GeV^2, $\langle -t' \rangle = 0.13$ GeV^2

leading contributions



observed hierarchy of NPE ampllitudes: $|T_{00}| \sim |T_{11}| >> |T_{01}| > |T_{10}| \approx |T_{1-1}|$

➢ selected results on helicity amplitudes from HERMES

- phase difference between T_{11} and T_{00} : δ = +26.4°± 2.3 ± 4.9 (p); +29.3°± 1.6 ± 3.6 (d)
  increases (20°→ 38°) with Q^2 (1 → 7 GeV^2)

- relative magnitude of SCHC non-conserving amplitudes $\tau_{ij} = \frac{|T_{ij}|}{\sqrt{\mathcal{N}}}$ $\mathcal{N} = \mathcal{N}_T + \epsilon \mathcal{N}_L$

HERMES	τ_{01}	τ_{10}	τ_{1-1}
proton	$0.114 \pm 0.007 \pm 0.010$	$0.075 \pm 0.030 \pm 0.003$	$0.051 \pm 0.029 \pm 0.010$
deuteron	$0.122 \pm 0.007 \pm 0.006$	$0.090 \pm 0.022 \pm 0.011$	$0.007 \pm 0.025 \pm 0.015$

- relative contributions to cross section, τ^2_T and τ^2_{UPE} , of NPE SCHC non-conserving and UPE amplitudes

τ^2_T = 0.025 ± 0.003 ± 0.003 (p); 0.028 ± 0.002 ± 0.002 (d)

τ^2_{UPE} = 0.063 ± 0.011 ± 0.025 (p); 0.046 ± 0.008 ± 0.023 (d)

➢ for ρ^0 small (≈ 10%) but statistically significant SCHS violating amplitudes T_{01} and T_{10}

➢ small contribution of unnatural-parity exchanges for ρ^0

➢ for φ no s-channel helicity violation and no UPE

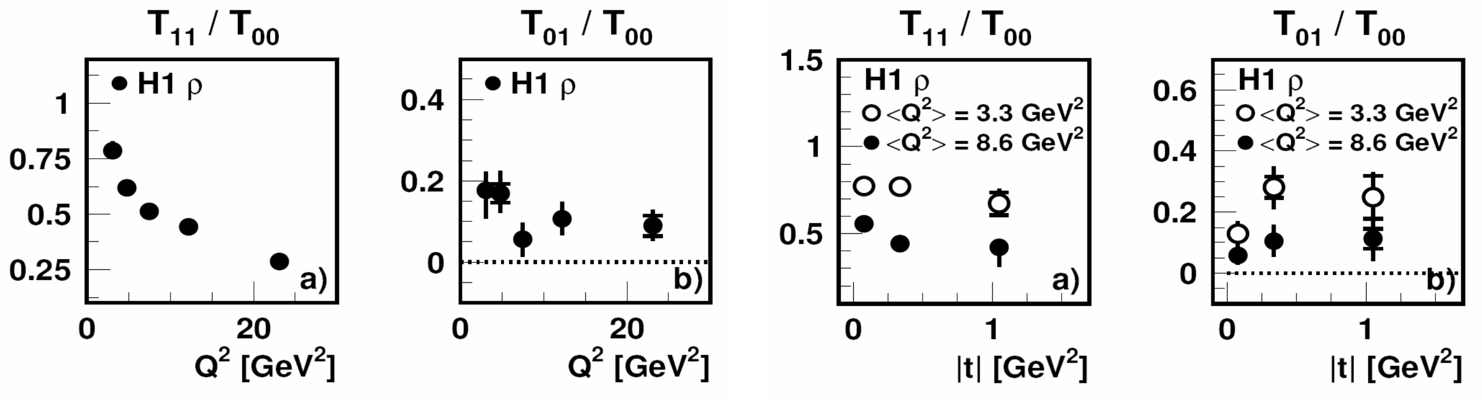
➢ for proton and deuteron SDMEs (mostly) the same

→ W.-D. Nowak

➢ selected results on helicity amplitudes from H1 and ZEUS

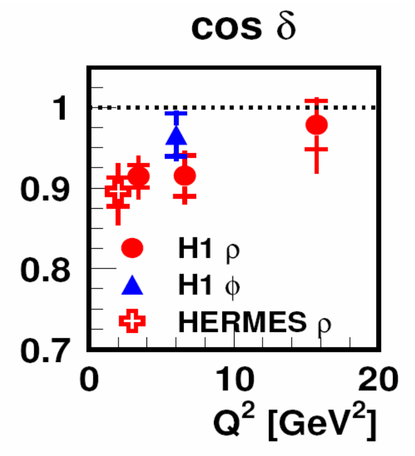
- among SCHS non-conserving SDMEs significantly ≠ 0 r^5_{00} ~ $Re(T_{01}\,T^*_{00})$
  smaller $Re\, r^{04}_{11}$, $Re\, r^1_{10}$, $Im\, r^2_{10}$ ~ $Re(T_{01}\,T^*_{11})$
- UPE consistent with 0 (checked for transverse photons)
- extracted ratios of helicity amplitudes T_{11}/T_{00}, T_{01}/T_{00}, T_{10}/T_{00}, T_{1-1}/T_{00} vs. Q^2 and t

example



observed hierarchy of amplitudes $|T_{00}| > |T_{11}| >> |T_{01}| > |T_{10}| \approx |T_{1-1}|$

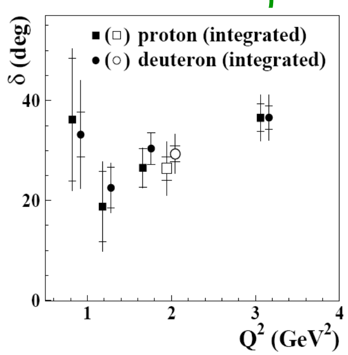
- phase difference δ between T_{11} and T_{00}



however opposite trend for HERMES only

?

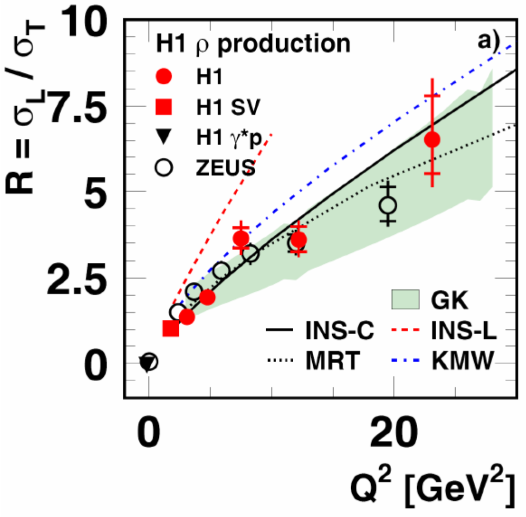
HERMES ρ^0

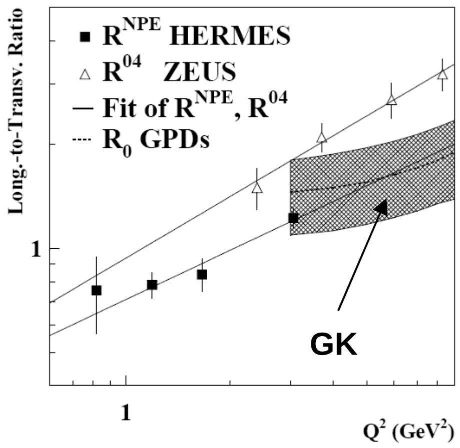


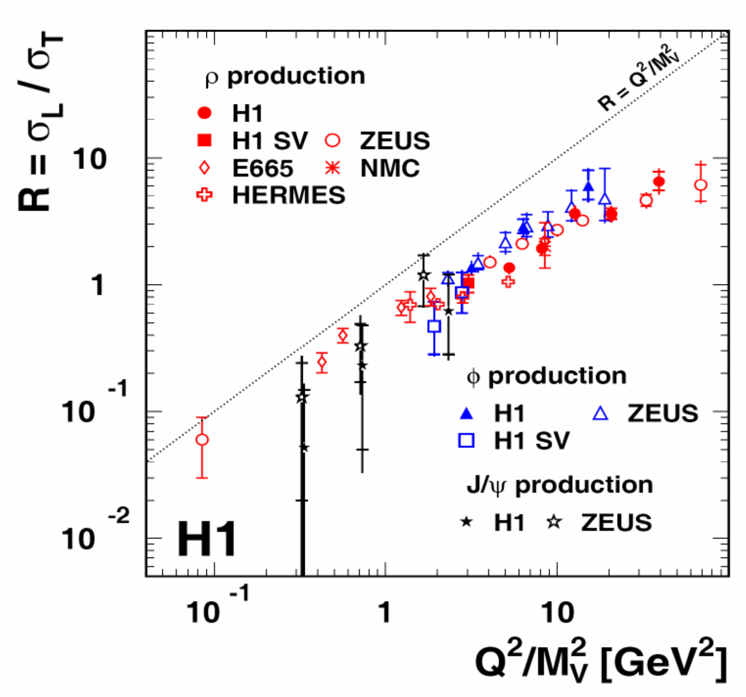
reflection of possible x_B dependence ?

(due to Q^2-x_B correlation in HERMES data)

➢ $R = \sigma_L/\sigma_T$







- several models able to desribe the data well
- qualitative universality of R vs. Q^2/M_V^2
- no significant W-dependence of R within single experiment

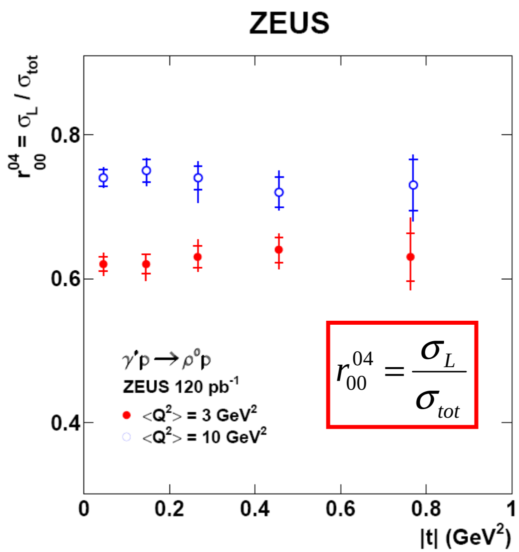
  an indication of moderate increase between low energies (HERMES) and HERA

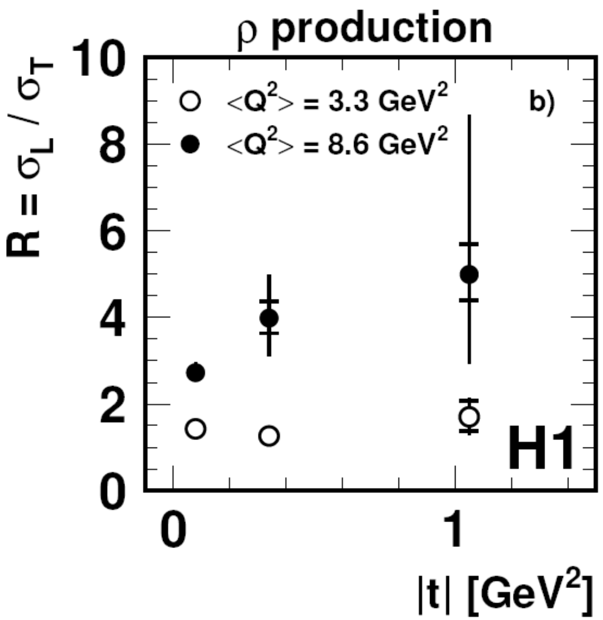
➡ S. Goloskokov, more comparison of GK model vs. data

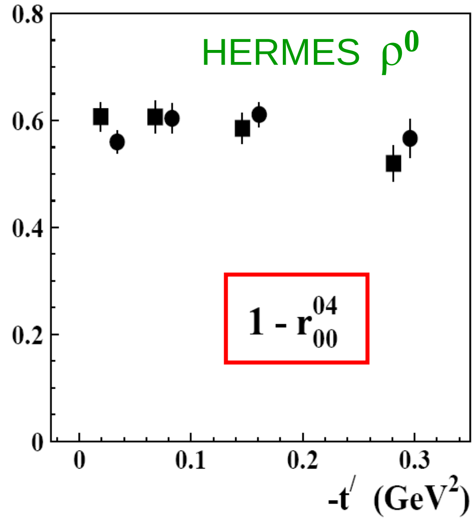
➤ t-dependence of R (or r^{04}_{00})

$$R(t) \propto e^{(b_L - b_T)\,t}$$

t-dependence of R would indicate different transverse sizes probed by γ^*_L and γ^*_T







- no significant t-dependence of R within total (statistical + systematic) errors

however from another H1 estimate of R using ratios of helicity amplitudes

$\langle Q^2 \rangle$ (GeV^2)	$b_L - b_T$ (GeV^{-2})
ρ production	
3.3	$-0.06 \pm 0.22\ ^{+0.24}_{-0.11}$
8.6	$-0.53 \pm 0.10\ ^{+0.14}_{-0.57}$
ϕ production	
5.3	$-0.70 \pm 0.23\ ^{+0.58}_{-0.63}$

3 σ from 0

Surprising !

needed to check by ZEUS and sensitivity to assumptions

Exclusive pseudoscalar meson production

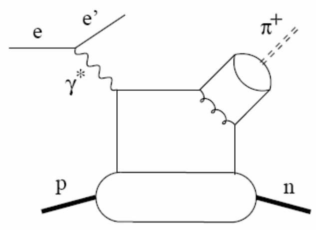
π^+ (HERMES, Hall C), π^0 (Hall A, CLAS), η (CLAS)

challenging at higher energies – small cross section

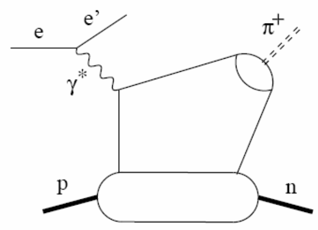
- for γ^*_L at leading order sensitivity to GPDs $\tilde{H}$, $\tilde{E}$
- flavour separation

$\pi+$	$\Delta u - \Delta d$
π^0	$2\Delta u + \Delta d$
η	$2\Delta u - \Delta d$

- for π^+ important contribution to $\tilde{E}$ of pion-pole exchange in t-channel dominates σ_L at small t
- no pion-pole exchange for π^0; π^0 from the pion cloud cannot couple directly to γ^*
- expected sizeable higher twist corrections:
  - a) transverse momenta of partons
  - b) soft overlap diagrams



leading order



soft-overlap

➢ Exclusive π^+ production from HERMES

A. Airapetian et al. PL B 659, 486 (2008)

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

data collected in 1996-2005 from unpolarised and polarised proton target

$$0.02 \le x_B \le 0.55$$
$$1 < Q^2 < 11\ \text{GeV}^2$$
$$|t| \lesssim 2\ \text{GeV}^2$$

$$< W > = 4\ \text{GeV}$$

L - T separation not possible

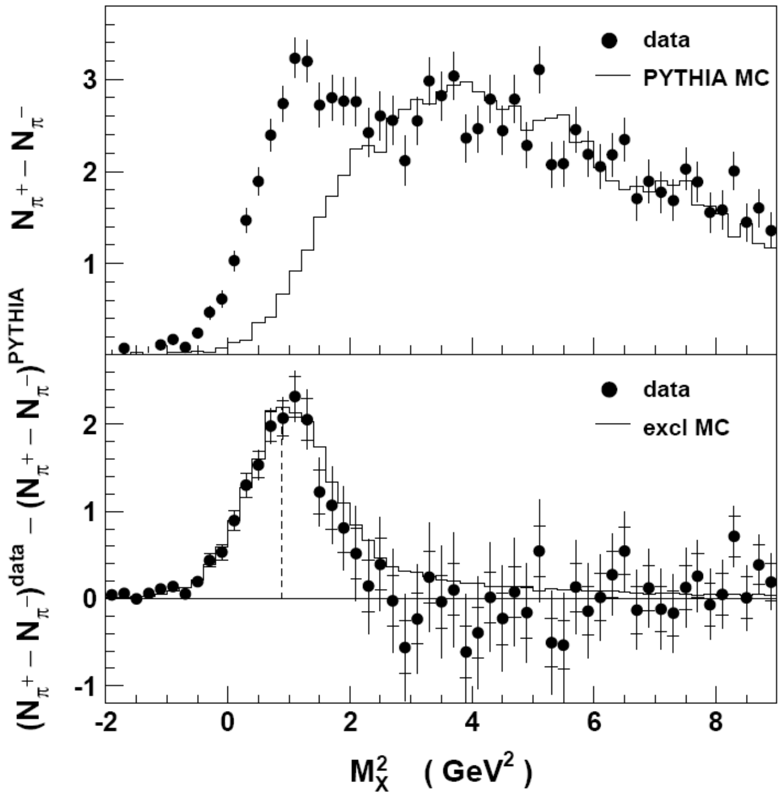
to ensure good efficiency and purity of pion identification

$$7 < p_\pi < 15\ \text{GeV}$$

selection of exclusive π^+ sample:

'double subtraction method'

cut: $M_X^2 < = 1.2\ \text{GeV}^2$

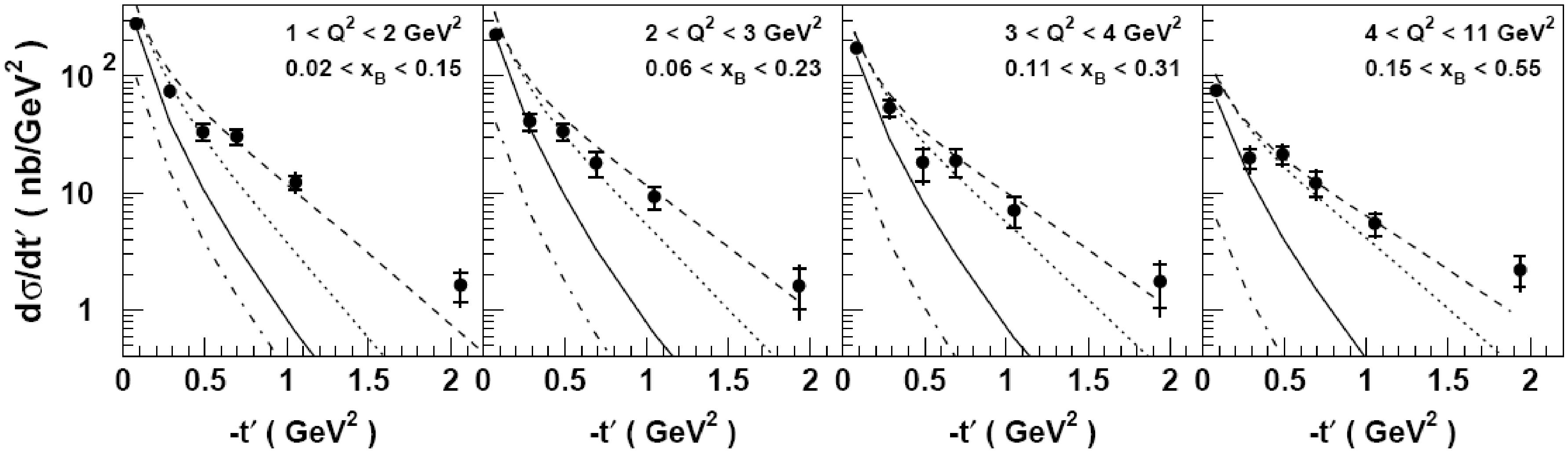


Main sources of systematic errors:

background subtraction

estimate of detection probability

HERMES π^+

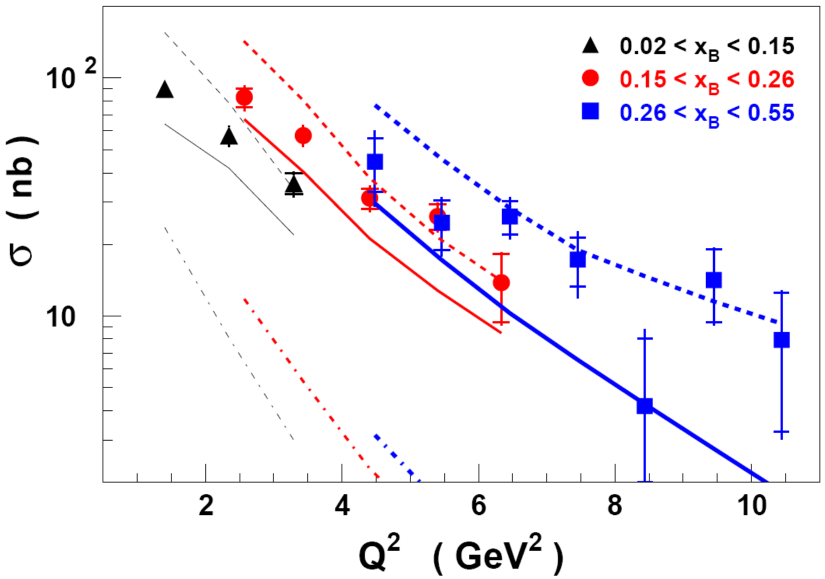


σ_L VGG LO

σ_L VGG LO+power corrections

σ_L Regge model (Laget)

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



- GPD LO calculations underestimate the data
- data support the order of the magnitude of the power corrections at low $-t'$ region
- Regge calculations for unseparated xsec. provides good description of magnitude and t' and Q^2 dependences

➤ Exclusive π^+ production at Hall C

experiments $F_\pi - 2$ [*] and π - CT [**]

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

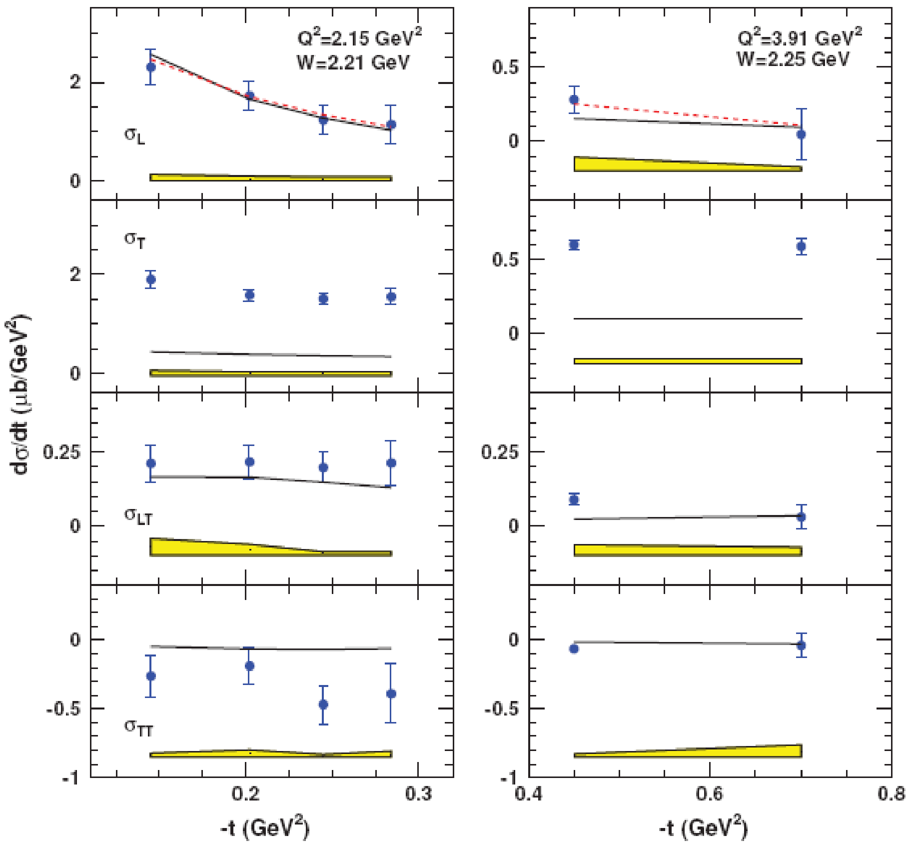
T. Horn et al. PRL 97, 192001 (2006)

T. Horn et al. PR C78, 058201 (2008)

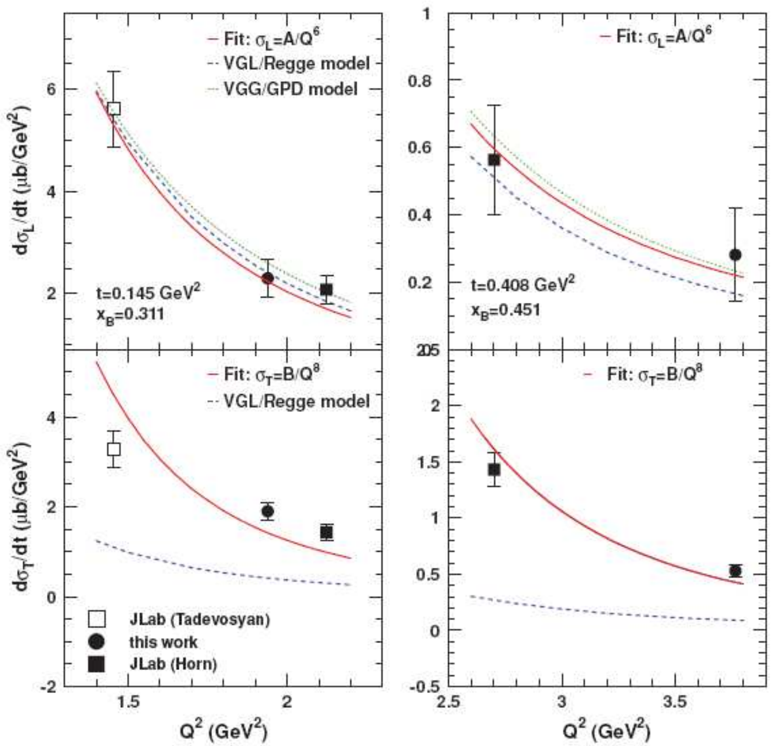
$< Q^2 >$ = 1.60, 2.45 GeV² [*]
= 2.15, 3.91 GeV² [**]
$< W > \approx$ 2.2 GeV

Rosenbluth separation of σ_L and σ_T

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



—— VGL(Regge)
- - - - VGG(GPD with power corrections)



- GPD model describes σ_L well
- Regge calculations also reproduce σ_L well
  σ_T underestimated by factor ~ 3 - 6
- Q² dependence of σ_T significantly softer than ~Q^{-8}

Hall C π^+

A model for solving longstanding problem of observed large σ_T

M.M. Kaskulov, K. Gallmeister, U. Mosel PR D78, 114022 (2008)

combined description of longitudinal and transverse components:

σ_L dominated by hadronic exchanges (Regge) and pion form factor

σ_T at moderate and large Q^2 mostly hard scattering process (DIS) $\gamma^* q \to q$

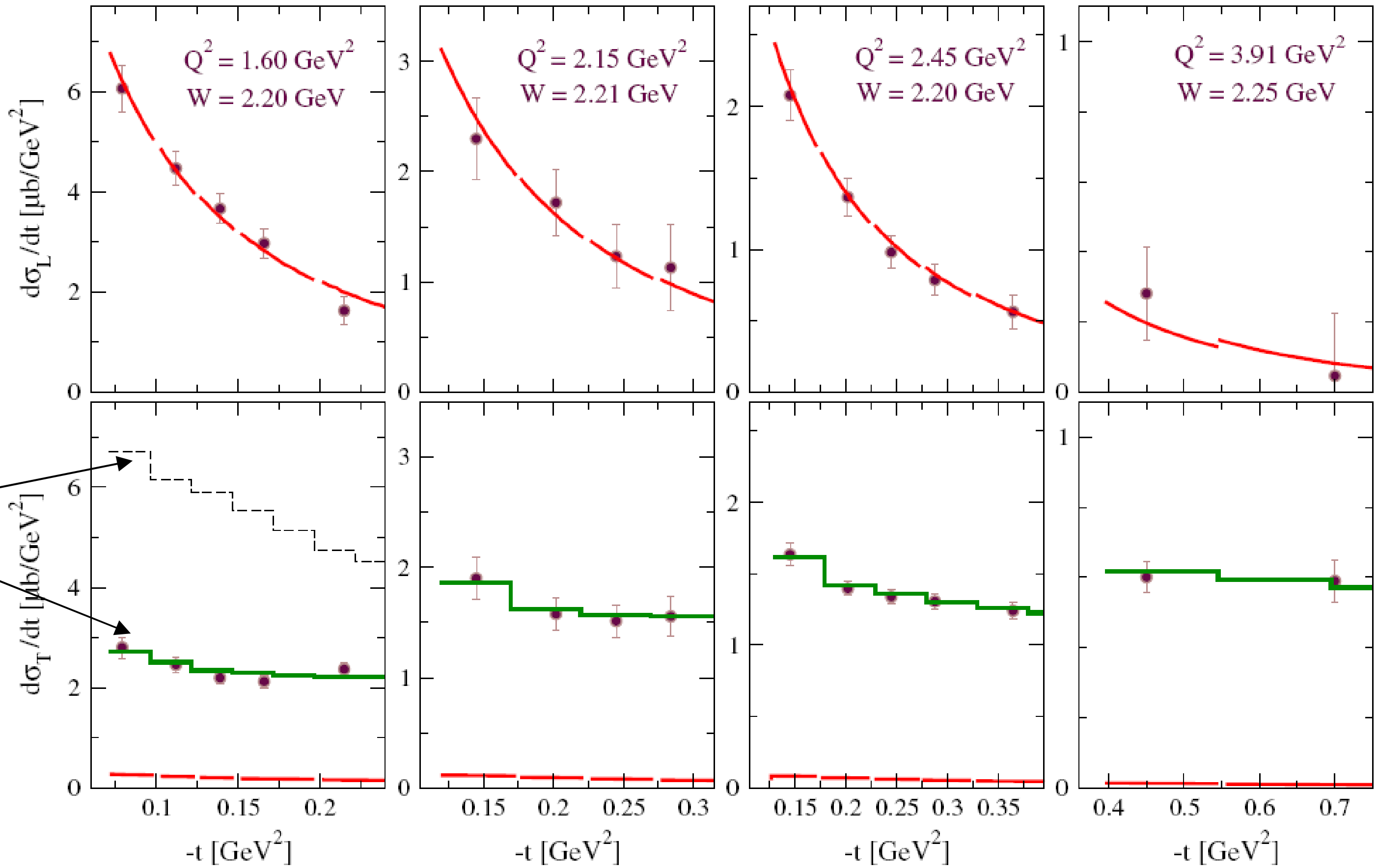
followed by fragmentation into $\pi^+ n$

Regge (KGM)

DIS + LM

with fitted $\sqrt{< k_t^2 >}$

$\sqrt{< k_t^2 >} = \begin{cases} 0.4 \text{ GeV} \\ 1.2 \text{ GeV} \end{cases}$



fit to SIDIS by Anselmino et al. (2005) results in $\sqrt{< k_t^2 >}$ = 0.5 GeV

➢ Exclusive π^0 production at Hall A

preliminary

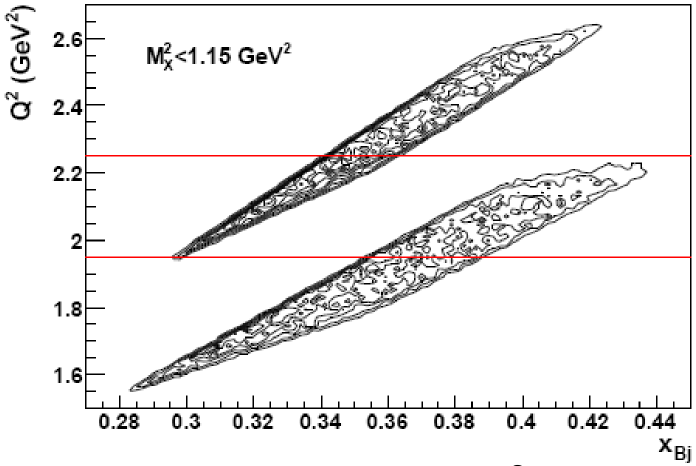
$$e\,p \rightarrow e\,p\,\pi^0 \rightarrow e\,p\,\gamma\,\gamma$$

at 5.75 GeV electron energy

high resolution spectrometer + PbF_2 calorimeter

$E_\gamma > 1$ GeV

kinematic domain



$|t'| < 0.22$ GeV^2

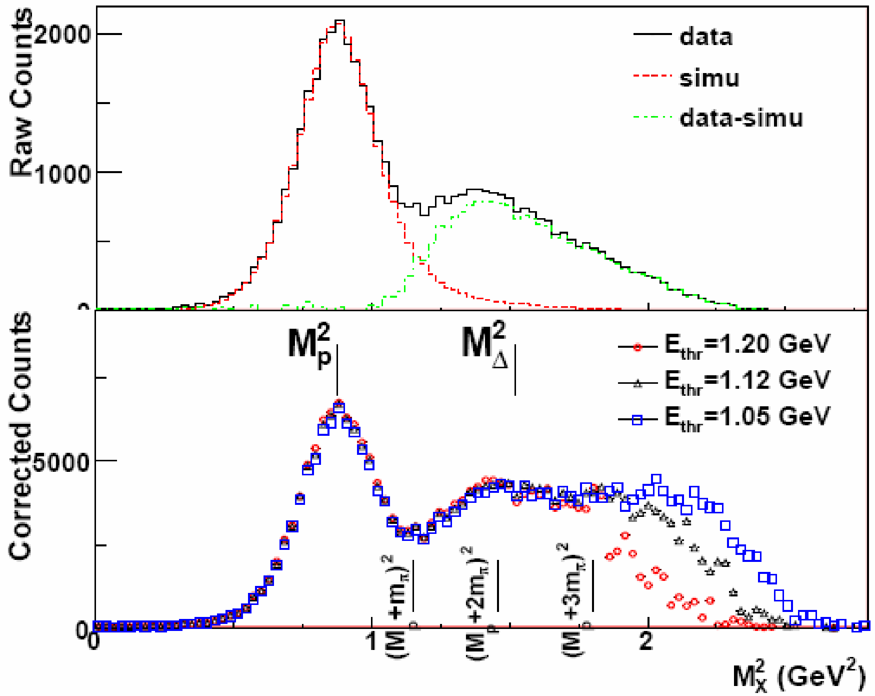
results given for:

two values of Q^2 (= 1.9, 2.3 GeV^2) at fixed $x_B = 0.36$

two values of x_B (= 0.40, 0.33) at fixed $Q^2 = 2.1$ GeV^2

missing mass $M_X[e\pi^0X]$ resolution

exclusivity cut $M_X^2 < 1.0$ GeV^2



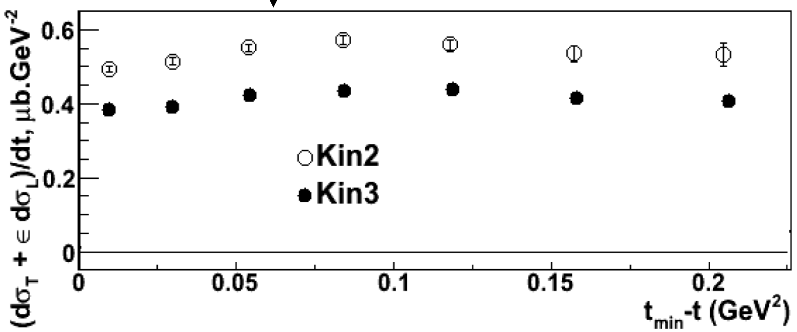
Main sources of systematic errors (≈ 3.4%):

- HRS acceptance
- beam polarisation
- radiative corrections

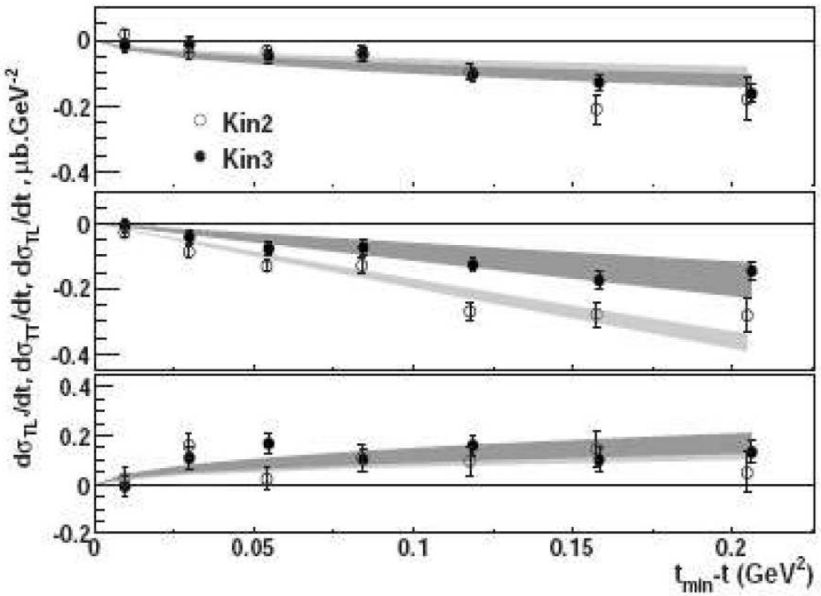
Hall A π^0

$$\frac{d\sigma}{dt} = \underbrace{\frac{d\sigma_T}{dt} + \epsilon_L \frac{d\sigma_L}{dt}} + \sqrt{2\epsilon_L(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos\phi_\pi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi_\pi + h\sqrt{2\epsilon_L(1-\epsilon)}\frac{d\sigma_{TL'}}{dt} sin\phi_\pi$$

ε (ε_L) degree of linear (longitudinal) polarisation of γ^*



Kin2: $Q^2 = 1.9$ GeV^2, $x_B = 0.36$
Kin3: $Q^2 = 2.3$ GeV^2, $x_B = 0.36$



bands show fits ~ $\sin\theta_\pi^{CM}$, $\sin^2\theta_\pi^{CM}$, $\sin\theta_\pi^{CM}$
for components σ_{TL}, σ_{TT}, $\sigma_{TL'}$ respectively

- no depletion at t'=0
  and no significant t-dependence of $\sigma_T + \varepsilon\,\sigma_L$
- slow Q^2-dependence of $\sigma_T + \varepsilon\,\sigma_L \sim (Q^2)^{-1.35\pm0.10}$
  far from the QCD leading twist prediction
  for $\sigma_L \sim (Q^2)^{-3}$
- reasonable agreement (within ≈ 15%) between
  Regge model (Laget) and $\sigma_T + \varepsilon\,\sigma_L$
  no agreement for interference terms
- need σ_L - σ_T separation
  E07-007 taking data now

➢ Exclusive π^0 and η production at CLAS

preliminary

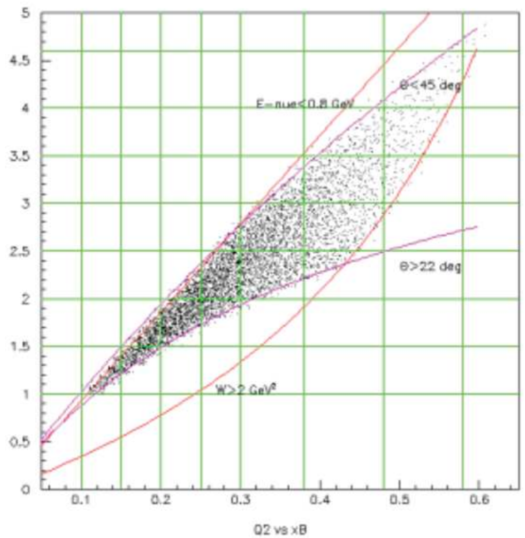
$$e\,p \rightarrow e\,p\,\pi^0 \rightarrow e\,p\,\gamma\,\gamma$$
$$e\,p \rightarrow e\,p\,\eta \rightarrow e\,p\,\gamma\,\gamma$$

at 5.78 GeV electron energy

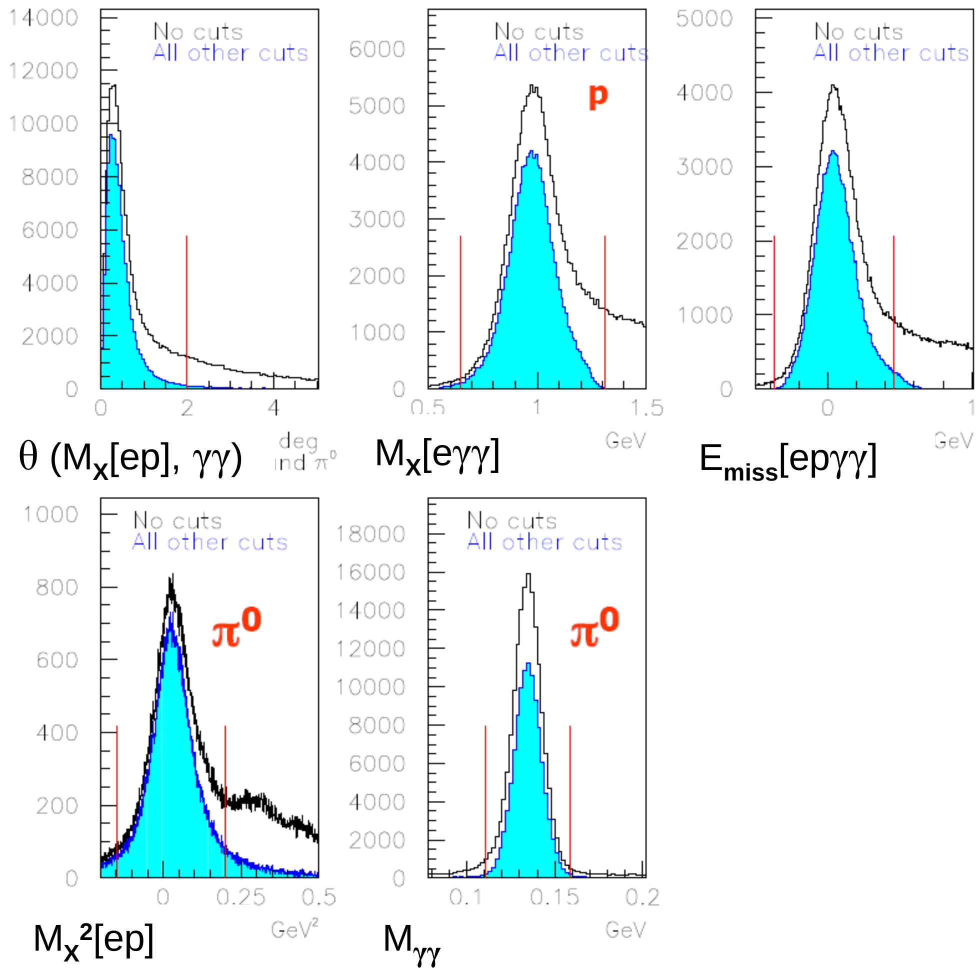
$1 \leq Q^2 < 4.5\ \mathrm{GeV}^2$

$0.1 < x_B < 0.58$

$0.09 < |t| < 2.0\ \mathrm{GeV}^2$



various cuts to ensure exclusivity ☺



CLAS π^0

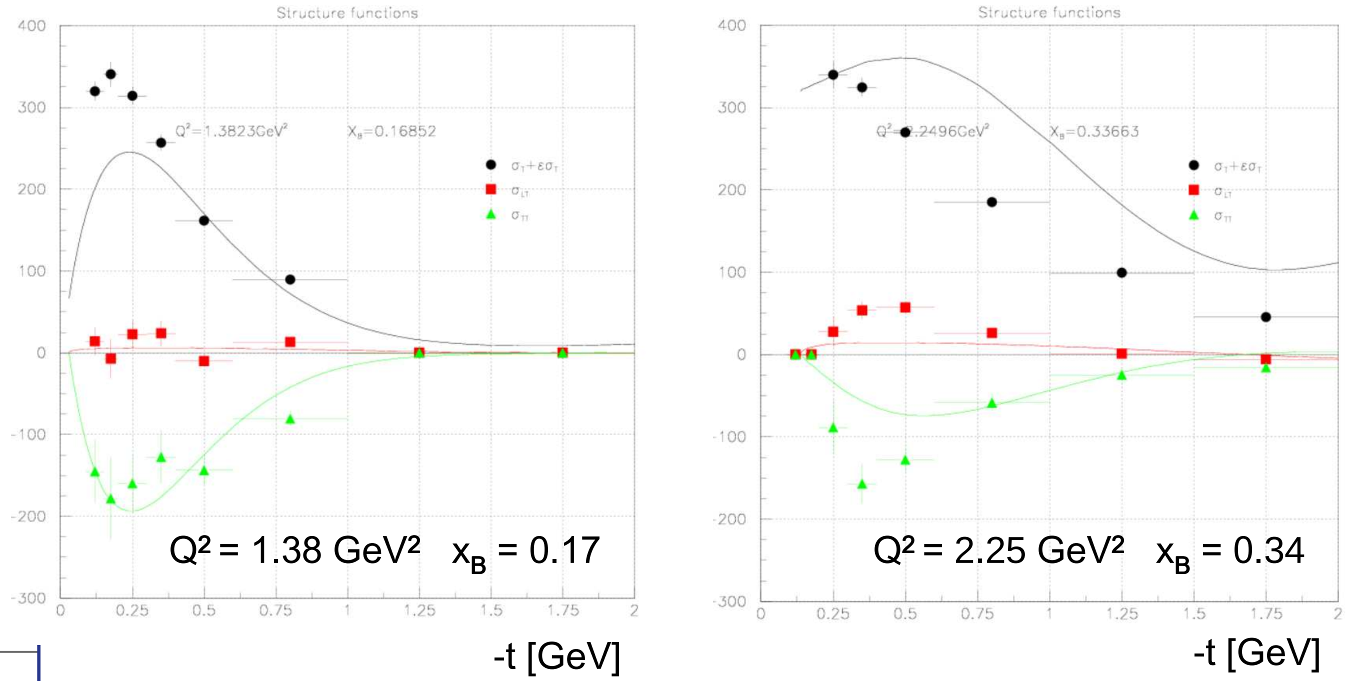
$$\frac{d^2\sigma_{\gamma^* p\to p\pi^0}}{dt\,d\varphi}=\frac{1}{2\pi}\left(\underbrace{\frac{d\sigma_T}{dt}+\varepsilon\frac{d\sigma_L}{dt}}+\varepsilon\cos 2\varphi\underbrace{\frac{d\sigma_{TT}}{dt}}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\varphi\underbrace{\frac{d\sigma_{LT}}{dt}}\right)$$

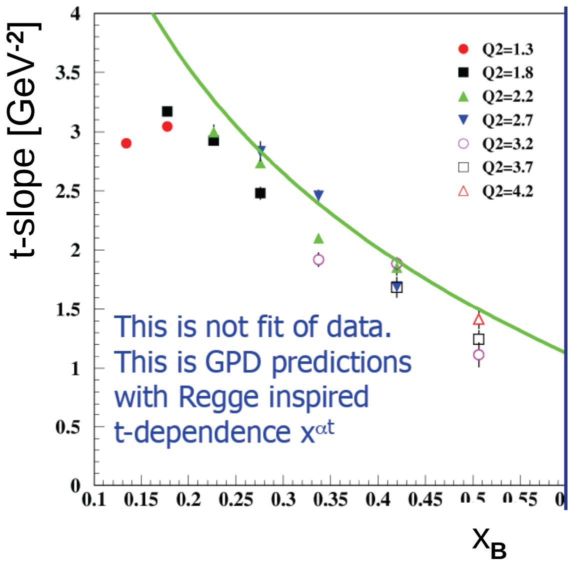
example:

2 out of 25 (Q^2,x_B) bins

compared to

Regge model (Laget)





- Regge model exhibits similar trends as the data
  but quantitative differences, in paricular at |t| (< 0.5 GeV^2)
- t-slope almost independent of Q^2, decreases with x_B
- ratio σ_η/σ_π = 0.2 -0.4, very weak dependence on Q^2 and x_B
  increases with | t |

V. Kubarovsky

Exclusive meson production on transversely polarised targets

at leading twist cross section sensitive to GPD E and $\tilde{E}$

transverse target spin dependent cross section

$$\frac{1}{2}\left(\frac{d\sigma_{00}^{\uparrow\uparrow}}{dt} - \frac{d\sigma_{00}^{\downarrow\downarrow}}{dt}\right) = -\mathrm{Im}\frac{d\sigma_{00}^{+-}}{dt} = \Gamma'\sqrt{1-\xi^2}\,\frac{\sqrt{t_0-t}}{M_p}\,\mathrm{Im}(\underline{E_M^*}H_M)$$

for vector mesons

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

for pseudoscalar mesons

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

H_M, E_M $(\tilde{H}_M, \tilde{E}_M)$ are weighted sums of convolutions of hard scattering kernels , corresponding GPDs of quarks and gluons, and meson DAs

weights depend on contributions of various quark flavours and of gluons to the production of meson M

access to ‘elusive’ GPD E and the orbital angular momentum of quarks

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

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

Ji’s sum rule

➢ exclusive ρ^0 production on $p^{\uparrow}$ at HERMES

A. Airapetian et al. PL B 679, 100 (2009)

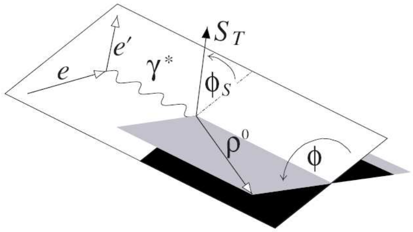
Transversely polarised
proton target, $P_T \approx 73\%$
2002-2005 data

$Q^2 > 1$ GeV^2
W > 2 GeV^2
| t' | < 0.4 GeV^2

30 new SDMEs determined for the first time !

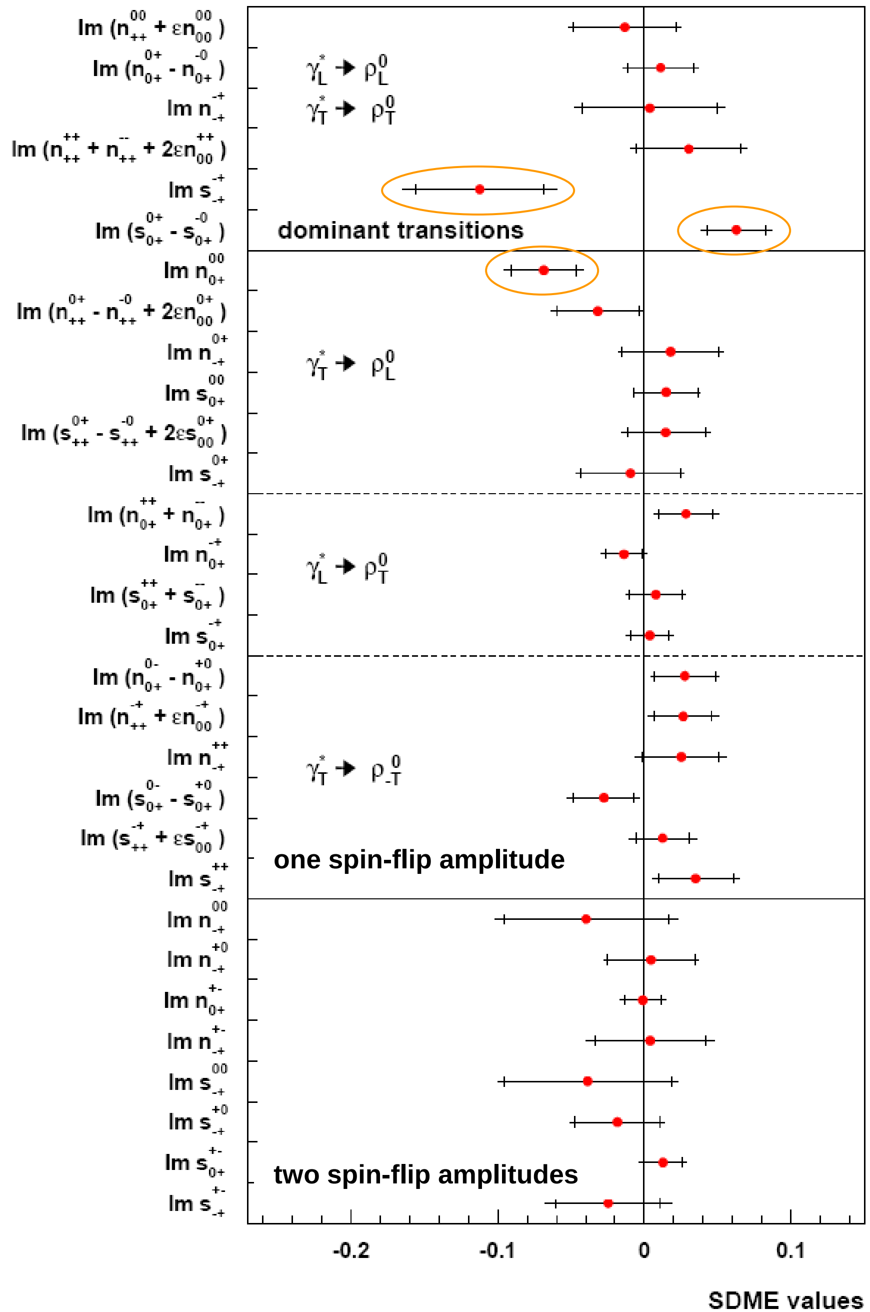
$n^{\nu\nu'}_{\mu\mu'}$ and $s^{\nu\nu'}_{\mu\mu'}$ from $W_{UT}(\phi, \phi_s, \varphi, \vartheta)$
(similarly $u^{\nu\nu'}_{\mu\mu'}$ from $W_{UU}(\phi, \varphi, \vartheta)$)

Diehl's convention:
$\mu, \mu'(\nu, \nu')$ helicities of $\gamma^*(\rho^0)$.
For amplitudes $T(U)_{\mu\ \alpha}^{\ \nu\ \beta}$
α (β) correspond to helicity
of initial (final) proton



- $\mathrm{Im}\, s^{-+}_{-+}$, $\mathrm{Im}(s^{0+}_{0+} - s^{-0}_{0+})$ > 2.5σ from 0
  $\mathrm{Im}\, s^{-+}_{-+} \sim T^{-+}_{-+}(U^{++}_{+-})^*$ $\qquad$ $\mathrm{Im}\, s^{0+}_{0+} \sim T^{0+}_{0+}(U^{++}_{+-})^*$
  signal of UPE; related to $\tilde{H}$, $\tilde{E}$
- $\mathrm{Im}\, n^{00}_{0+}$ > 2.5σ from 0
  another indication of SCHC violation
  in $\gamma_T^* \to \rho_L$

$\langle x_B \rangle = 0.08$, $\langle Q^2 \rangle = 1.95$ GeV^2, $\langle -t' \rangle = 0.13$ GeV^2



HERMES ρ^0 off $p^\uparrow$

for ρ^0_L

$$A_{UT}^{LL,\sin(\phi-\phi_S)} = \frac{\mathrm{Im}\left(n^{0\,0}_{++} + \varepsilon n^{0\,0}_{0\,0}\right)}{u^{0\,0}_{++} + \varepsilon u^{0\,0}_{0\,0}}$$

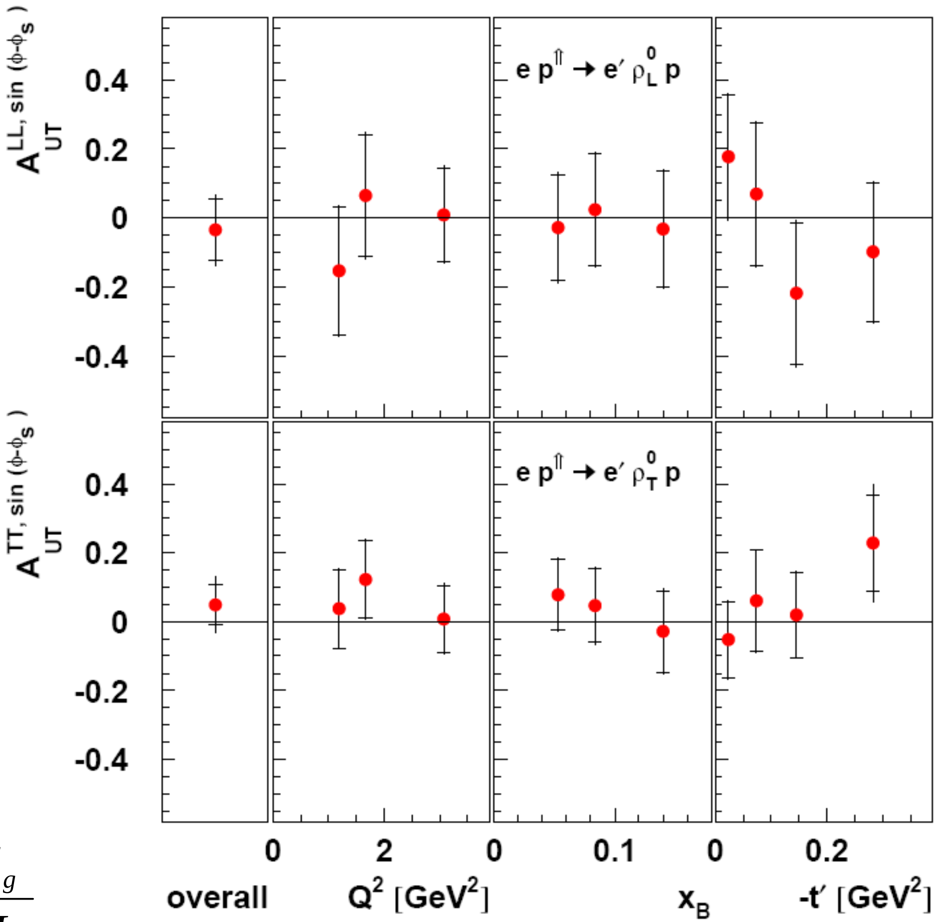
$$u^{00}_{++} + \varepsilon u^{00}_{00} = \frac{\sigma(\rho^0_L)}{\sigma(\rho^0_T) + \varepsilon\,\sigma(\rho^0_L)} \quad (\equiv r^{04}_{00})$$

(in Schilling-Wolf notation)

for ρ^0_T

$$A_{UT}^{TT,\sin(\phi-\phi_S)} = \frac{\mathrm{Im}\left(n^{++}_{++} + n^{--}_{++} + 2\varepsilon n^{++}_{0\,0}\right)}{1 - \left(u^{0\,0}_{++} + \varepsilon u^{0\,0}_{0\,0}\right)}$$

if SCHC $\quad A_{UT}^{LL,\sin(\phi-\phi_s)} \cong \frac{\mathrm{Im}\, n^{00}_{00}}{u^{00}_{00}} \propto \frac{E_M}{H_M} \propto \frac{E_q + E_g}{H_q + H_g}$



$A_{UT}^{LL,\sin(\phi-\phi s)} = -\,0.035 \pm 0.103$

a few GPD model calculations for $A_{UT}^{\sin(\phi-\phi s)}$ for ρ^0

Goeke, Polyakov, Vanderhaegen (2001)

Ellinghaus, Nowak, Vinnikov, Ye (2006)

E_q parameterised in terms of J^u and J^d

ENVY includes also E_g

- J^u in the range 0.2 - 0.4 and $J^d = 0$ consistent with ρ^0 data, although within large errors

W.-D. Nowak

➢ exclusive ρ^0 production on $p^\uparrow$ and $d^\uparrow$ at COMPASS

preliminary

Transversely polarised deuteron target (^{6}LiD), $P_T \approx 50\%$, 2002-2004 data
Transversely polarised proton target (NH_3), $P_T \approx 90\%$, 2007 data

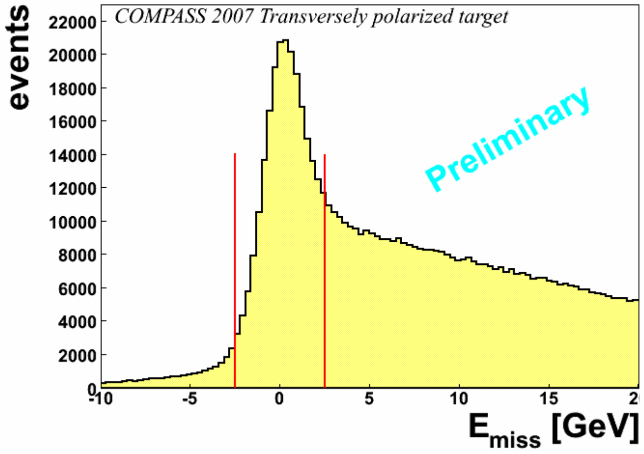
Target segmented in 2 (3 in 2007) cells with opposite polarisations   Spins reversed regularly by DNP

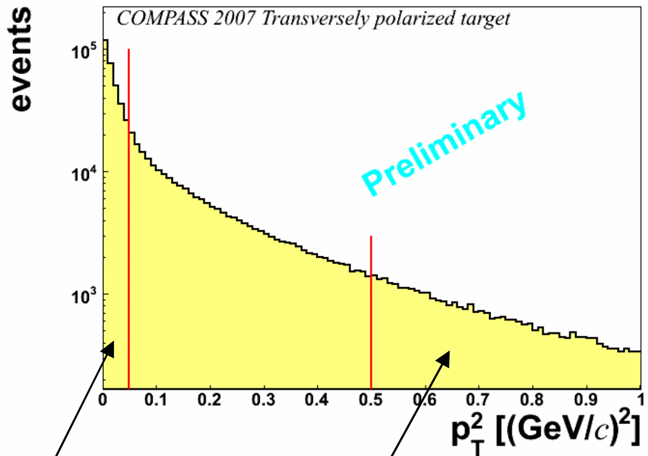
Kinematic domain

$Q^2 > 1$ GeV^2
$W > 5$ GeV
$0.005 < x_{Bj} < 0.1$
$0.05 < p_t^2 < 0.5$ GeV^2 [NH_3]
$0.01 < p_t^2 < 0.5$ GeV^2 [^{6}LiD]

$-0.3 < M_{\pi\pi} - M_{\rho(\mathrm{PDG})} < 0.3$ GeV/c^2

$$E_{miss} = \frac{M_X^2 - M_{proton}^2}{2M_{proton}} \in [-2.5, 2.5]\, GeV$$





dominant coherent on N
dominant non-exclusive bkg.

A_{UT} extracted with the double ratio (DR) method;

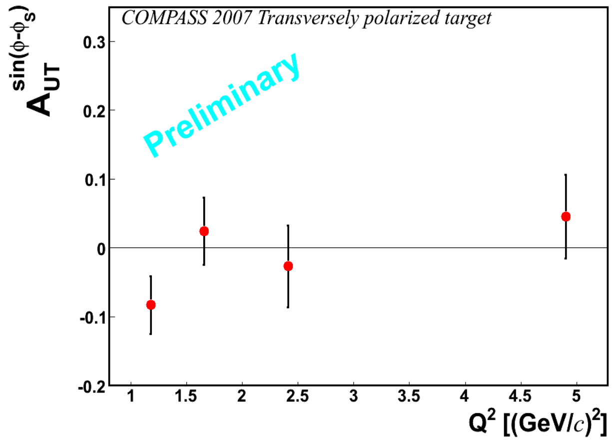
in DR(ϕ-ϕ_s) counts from different cells for the data before and after spin reversal combined such that in the ratio muon flux, numbers of target nucleons and unpolarised cross section σ_0 cancel
also acceptance cancels provided no changes between spin reversals

fit to DR(ϕ-ϕ_s) ➡ $$A_{UT}^{\sin(\phi-\phi_s)} = -\frac{\mathrm{Im}(\sigma_{++}^{+-} + \varepsilon\sigma_{00}^{+-})}{\sigma_0} \qquad \sigma_0 = \frac{1}{2}(\sigma_{++}^{++} + \sigma_{++}^{--}) + \varepsilon\sigma_{00}^{++} \equiv \sigma_T + \varepsilon\sigma_L$$

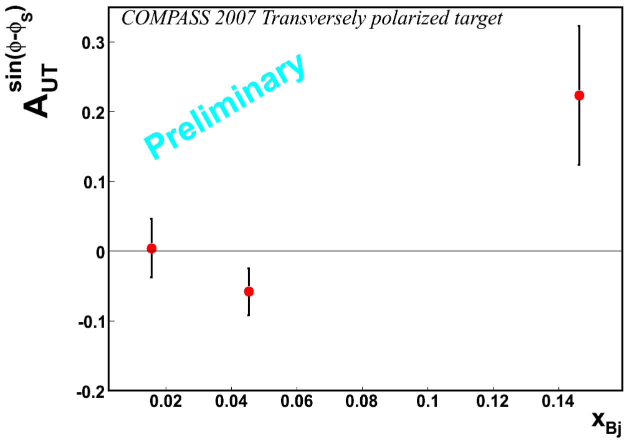
COMPASS ρ^0 off $p\uparrow$ and $d\uparrow$

$p\uparrow$

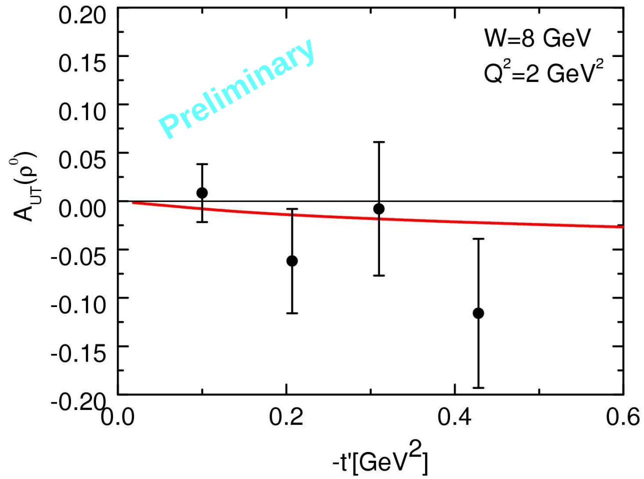
$< Q^2 > \approx 2.2\ (\mathrm{GeV}/c)^2$



$< x_{Bj} > \approx 0.04$



$< p_t^2 > \approx 0.18\ (\mathrm{GeV}/c)^2$



- $A_{UT}^{\sin(\phi-\phi s)}$ for transversely polarised protons compatible with 0
- compatible with predictions of the GPD model of GK for protons
- for the proton target errors ≈ 2x smaller than for HERMES
- for transversely polarised deuterons $A_{UT}^{\sin(\phi-\phi s)}$ also compatible with 0

in progress: L/T ρ^0 separation
coherent/incoherent separation for deuteron data
estimate effects of the non-exclusive background

in 2010 data with transverse polarisation with NH_3 target → 3-fold increase of statistics

➤ exclusive π^+ production on $p^\uparrow$ at HERMES

determined for the first time !

A. Airapetian et al. PL B 682, 345 (2010)

Transversely polarised proton target

$P_T \approx$ 73%, 2002-2005 data

$0.03 \leq x_B \leq 0.35$

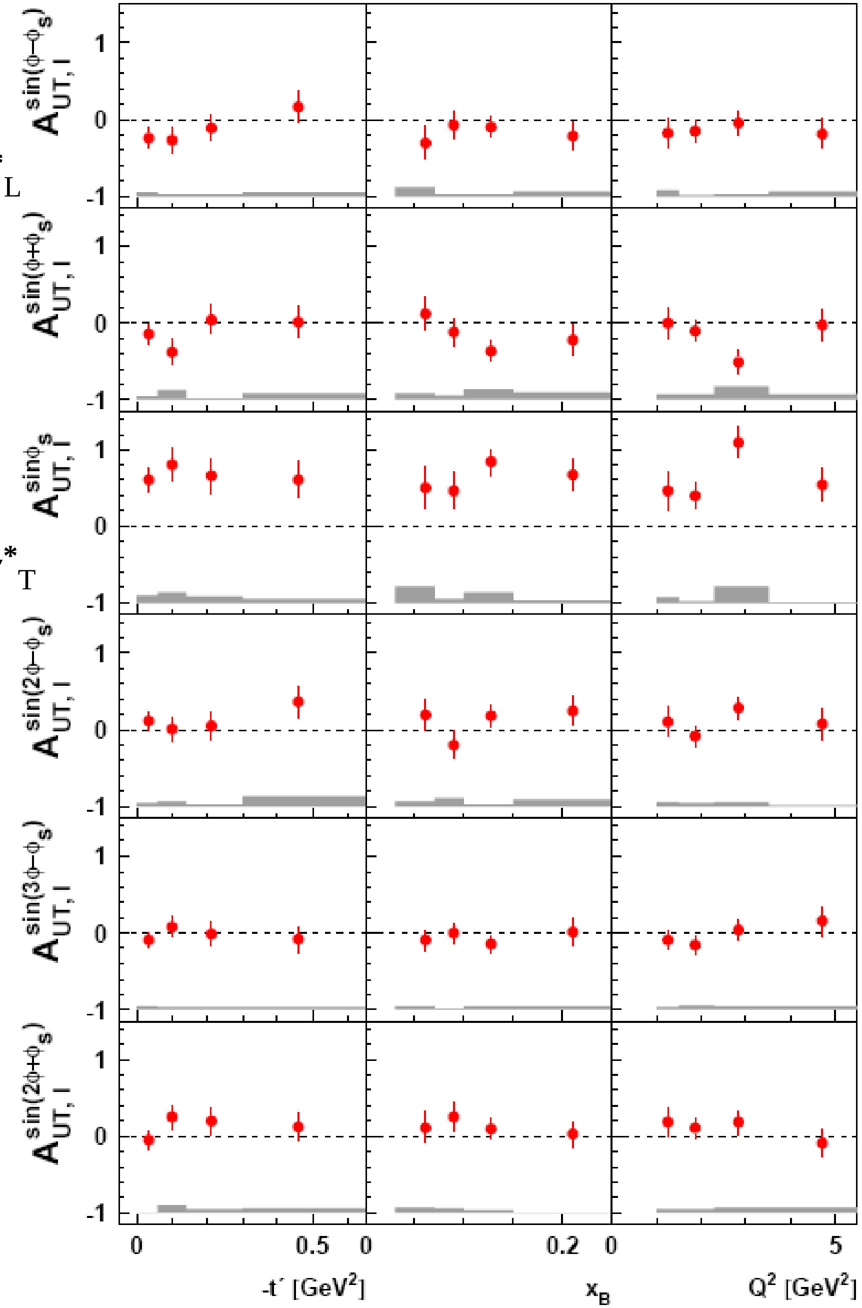
$1 < Q^2 < 10$ GeV^2

$|\, t \,| \lesssim 0.7$ GeV^2

$< W >$ = 4 GeV

LT contrib from γ^*_L

HT contrib from γ^*_T



selection of exclusive π^+ sample:

$7 < p_\pi < 15$ GeV

'double subtraction method'

$-1.2 < M_X^2 < = 1.2$ GeV^2

Main systematic errors

background subtraction

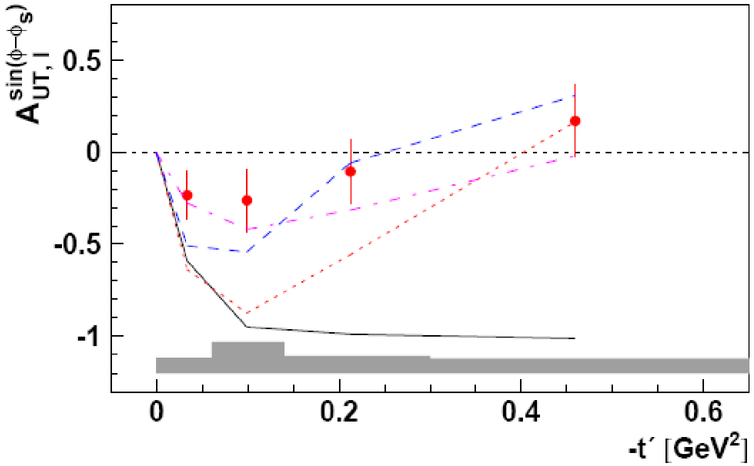
estimate of detection probability

determination of target polarisation

➡ W.-D. Nowak

HERMES π^+ off $p^\uparrow$

$$A_{UT,\ell}^{\sin(\phi-\phi_S)} = -\frac{\sqrt{-t'}}{M_p} \times \frac{\xi\sqrt{1-\xi^2}\,\mathrm{Im}(\widetilde{\mathcal{E}}^*\widetilde{\mathcal{H}})}{(1-\xi^2)\widetilde{\mathcal{H}}^2 - \frac{t\xi^2}{4M_p^2}\widetilde{\mathcal{E}}^2 - 2\xi^2\,\mathrm{Re}(\widetilde{\mathcal{E}}^*\widetilde{\mathcal{H}})}$$



C. Bechler, D. Müller — pion pole dominates $\widetilde{E}$; more t-channel exchanges

K. Kumericki, D. Müller

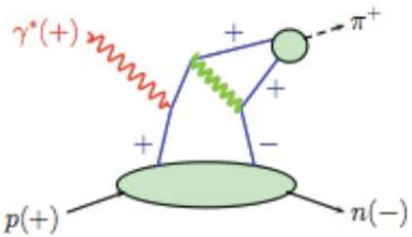
S. Goloskokov, P. Kroll

$$A_{UT,\ell}^{\sin\phi_S} \propto \mathcal{M}^*_{0+++}\mathcal{M}_{0+0-} + \mathcal{M}^*_{0-++}\mathcal{M}_{0-0-}$$

π n γ* p

in LT $\mathcal{M}^*_{0-++} \sim \sqrt{-t'}$

higher twist contributions involving H_T and $\widetilde{H}_T$ doesn't have to vanish



$H_T(x,0,0) = h_1(x)$

- $A_{UT,l}^{\sin(\phi-\phi_S)}$ consistent with zero within errors
  excluding pure pion-pole contribution to GPD $\widetilde{E}$
- $A_{UT,l}^{\sin(\phi_S)}$ signal of $\gamma^*_T \to \pi^+$ transitions
  interesting link to transversity and chiral odd GPDs

→ S. Goloskokov

Conclusions

- Significant progress on meas. of cross sections, SDME's and spin asymmetries provide more stringent constraints on the models for DVMP

- Description of the present data on DVMP in terms of GPDs more complex than LT handbag approach:
  power corrections, higher order pQCD terms,
  quark-antiquark exchanges, semiinclusive-like contribution etc.

- For DVMP program at future facilities: JLAB12, COMPASS-II, EIC
  essential experimental requirements for further progress:
  high luminosity, hermetic detector (or recoil detector), $\gamma^*_L - \gamma^*_T$ separation