

Hard Photo- and Electroproduction of Mesons

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Outline:

- Handbag factorization for vector-meson electroproduction
- The failure of the leading-twist approach
- The subprocess in the modified pert. approach
- Remarks on wide-angle photoproduction
- Results for vector mesons
- Summary

Vector-meson electroproduction

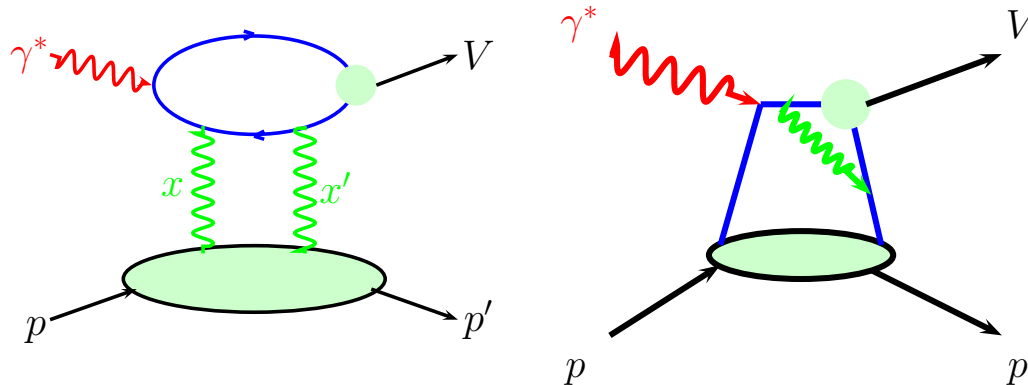
rigorous proof of collinear factorization for $Q^2 \rightarrow \infty$

(Radyushkin (96); Collins et al (97))

hard subprocesses

$$\gamma^* g \rightarrow V g, \quad \gamma^* q \rightarrow V q$$

and GPDs and meson w.f.
(encode the soft physics)



dominant transition $\gamma_L^* \rightarrow V_L$

other transitions power suppressed

As compared to DVCS:

disadvantage: two soft functions

advantages: diff. mesons ($\rho^0, \phi, \omega, \rho^+, K^{*0}, J/\Psi$) allow for flavor separation

wealth of good data for Q^2 up to 100 GeV^2 and W up to 180 GeV

The $\gamma^* p \rightarrow VB$ amplitudes

consider large Q^2 , W and small t ;

kinematics fixes skewness: $\xi \simeq \frac{x_{Bj}}{2-x_{Bj}} [1 + m_V^2/Q^2] \simeq x_{Bj}/2 + \text{m.m.c.}$

$$\mathcal{M}_{\mu+, \mu+}(V) = \frac{e_0}{2} \left\{ \sum_a e_a \mathcal{C}_V^{aa} \langle H_{\text{eff}}^g \rangle_{V\mu} + \sum_{ab} \mathcal{C}_V^{ab} \langle H_{\text{eff}}^{ab} \rangle_{V\mu} \right\},$$

$$\mathcal{M}_{\mu-, \mu+}(V) = -\frac{e_0}{2} \frac{\sqrt{-t}}{M+m} \left\{ \sum_a e_a \mathcal{C}_V^{aa} \langle E^g \rangle_{V\mu} + \sum_{ab} \mathcal{C}_V^{ab} \langle E^{ab} \rangle_{V\mu} \right\},$$

\mathcal{C}_V^{ab} flavor factors, $M(m)$ mass of $B(p)$, $H_{\text{eff}} = H - \xi^2/(1 - \xi^2)E$

contributions from \tilde{H} to T-T amplitude neglected

electroproduction with unpolarized protons at small ξ :

E not much larger than H (see below) $\implies H_{\text{eff}} \rightarrow H$ for small ξ

$|M_{\mu', \mu+}|^2 \propto t/m^2$ **neglected** \implies **probes H** (exception ρ^+)

trans. polarized target: probes $Im[\langle E \rangle^* \langle H \rangle]$ interference

The failure of the leading-twist approximation

for experimentally accessible Q^2

prediction for σ_L exceeds

data by a large factor (HERA)

power corr. and/or higher orders of pQCD?

Diehl-Kugler 07, Ivanov 07

$$R = \sigma_L / \sigma_T \quad (\text{HERA})$$

$\gamma_T^* \rightarrow V_T$ non-negligible

but in coll. factorization infrared singular

power corr. and/or higher twist needed

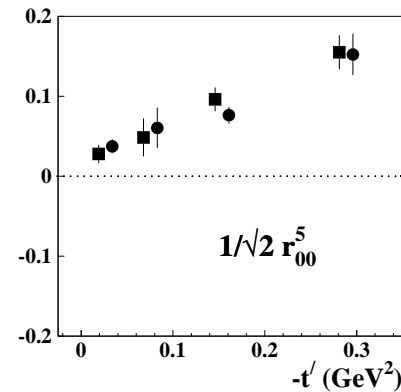
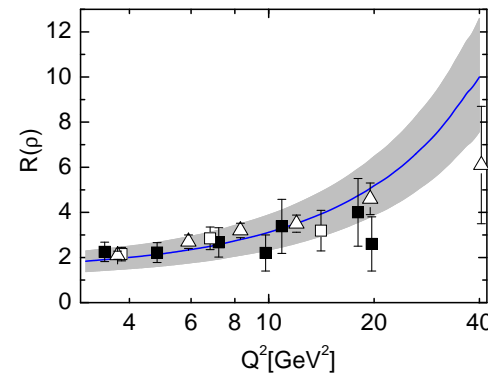
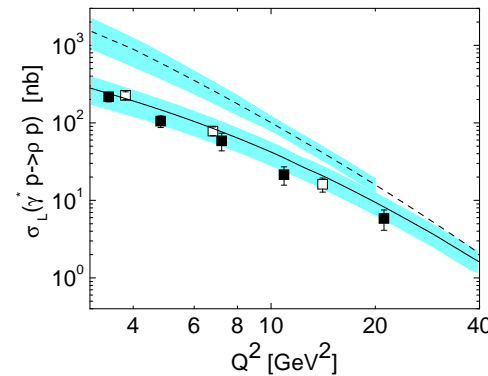
$T - L$ transition small but non-zero

seen in SDME r_{00}^5 (HERMES ρ^0)

twist-3 nf amplitude $\mathcal{M}_{0-,++}$?

$$r_{00}^5 \propto \text{Re} M_{0-,0+}^* M_{0-,++}$$

related to helicity-flip GPDs

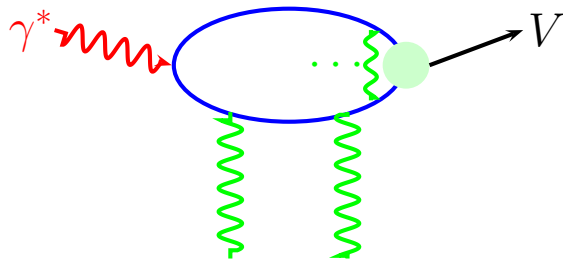


Subprocess amplitudes

$F = H, E$ λ parton helicities

$$\langle F \rangle_{V\mu}^{ab(g)} = \sum_{\lambda} \int d\bar{x} \mathcal{H}_{\mu\lambda, \mu\lambda}^{Vab(g)}(\bar{x}, \xi, Q^2, t=0) F^{ab(g)}(\bar{x}, \xi, t)$$

$$F^{aa} = F^a, \quad F^{ab} = F^a - F^b \quad (a \neq b) \text{ (with flavor symmetry)}$$



$$\mathcal{H}_{\mu\lambda, \mu\lambda}^{Vab} = \int d\tau d^2b \hat{\Psi}_{V\mu}(\tau, -\vec{b}) \exp[-S(\tau, \vec{b}, Q^2)] \times \hat{\mathcal{F}}_{\mu\lambda, \mu\lambda}^{ab}(\bar{x}, \xi, \tau, Q^2, \vec{b})$$

LO pQCD

+ quark trans. mom.

+ Sudakov supp.

\Rightarrow lead. twist for $Q^2 \rightarrow \infty$

Sudakov factor (Sterman et al)

$$S \propto \ln \frac{\ln(\tau Q / \sqrt{2} \Lambda_{\text{QCD}})}{-\ln(b \Lambda_{\text{QCD}})} + \text{NLL}$$

$\hat{\mathcal{F}}$ FT of hard scattering kernel

e.g. FT of $\propto e_a / [k_{\perp}^2 + \tau(\bar{x} + \xi)Q^2 / (2\xi)]$

regularizes also TT amplitude

in collinear appr:

$$\text{TT} : \int_0^1 d\tau \frac{\Phi_V(\tau)}{\tau} \frac{1}{(1-\tau)t + \tau Q^2}$$

IR singular for large Q^2

regular for large $-t$ (wide-angles)

Numerical results

Goloskokov-K. 06, 07, 08

GPDs constructed from CTEQ6 PDFs through the double distribution ansatz

Gaussian wave fcts for the mesons $\Psi_{Vj}(\tau, \mathbf{k}_\perp) \propto \exp[-a_{Vj}^2 \mathbf{k}_\perp^2 / (\tau \bar{\tau})]$

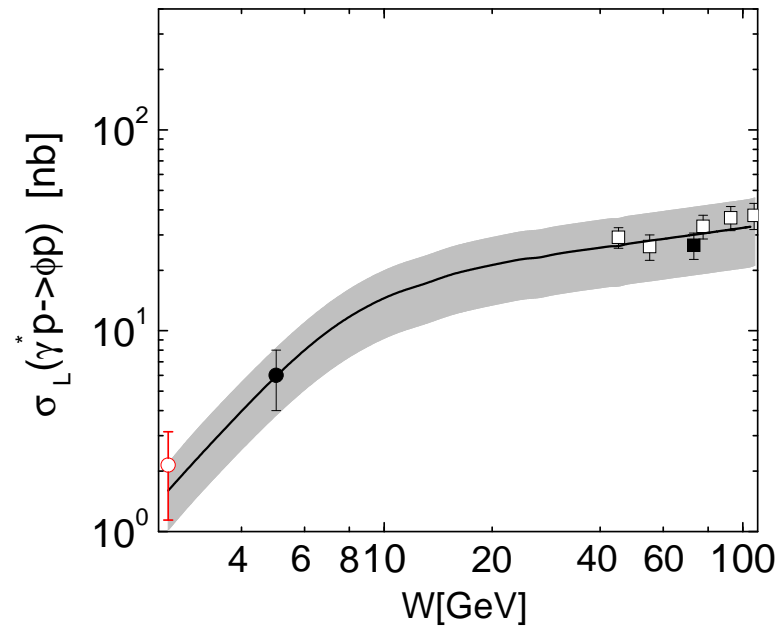
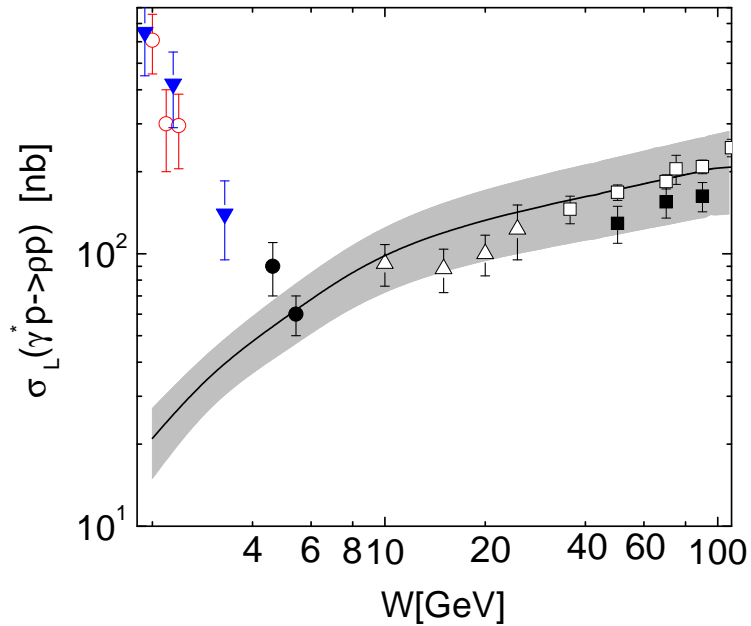
L and T different, free parameters - $a_{L,T}^V$ (transverse size $\langle k_\perp^2 \rangle^{1/2} \propto 1/a_{L,T}^V$)

meson wf. provides effects of order $\langle k_\perp^2 \rangle / Q^2$ separation of both
GPDs mainly influence the $\xi(x_{Bj})$ dependence effects possible

fit to all data from HERMES, COMPASS, E665, H1, ZEUS

cover large range of kinematics $Q^2 \simeq 3 - 100 \text{ GeV}^2$ $W \simeq 5 - 180 \text{ GeV}$

ρ^0 and ϕ cross sections

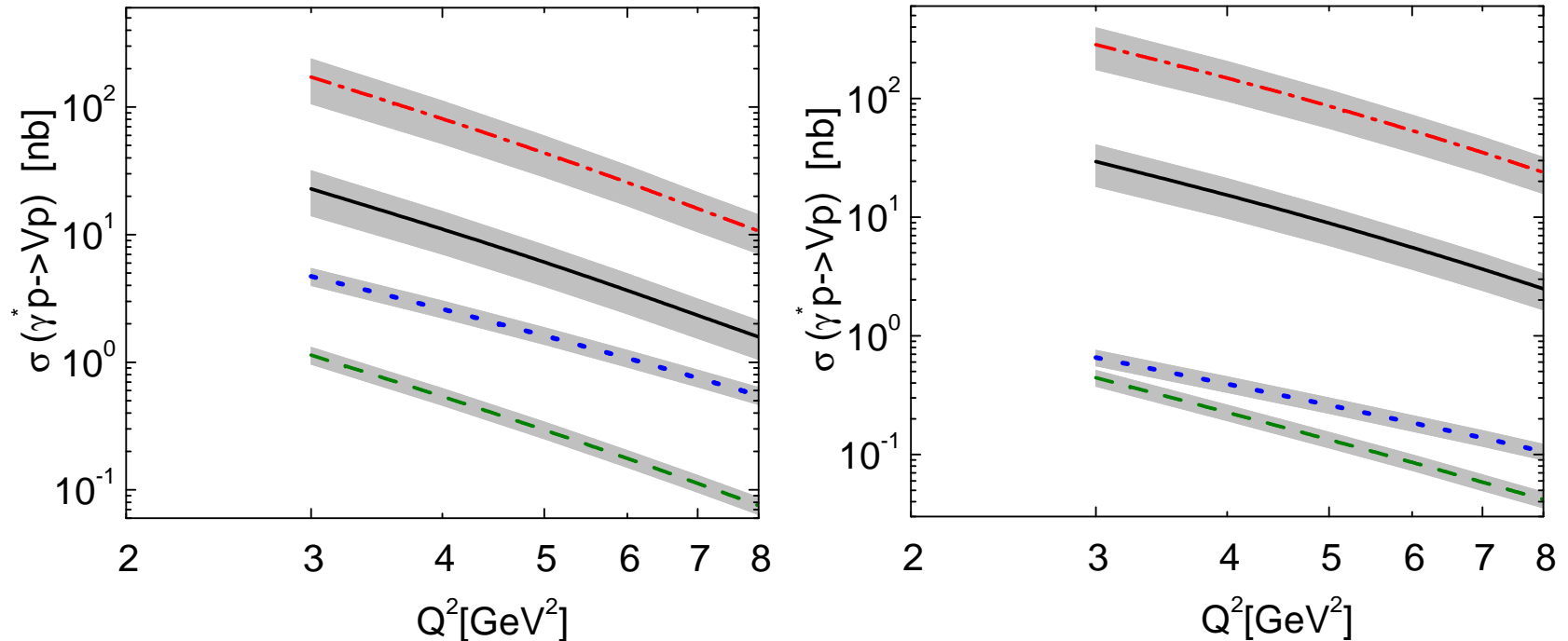


at $Q^2 = 4(3.8) \text{ GeV}^2$ E665 (Δ), HERMES (\bullet), CORNELL (\blacktriangle)
 ZEUS (\square), H1 (\blacksquare), CLAS (\circ)

double distribution model too simple for valence quarks for large ξ ?
 breakdown of handbag physics? Lacking nucleon resonances?

JLAB12 may explore region close to minimum

Cross sections for ω, ρ^+ and K^{*0}



results for HERMES and COMPASS ($W = 5, 10 \text{ GeV}$) $\rho^0, \omega, \rho^+, K^{*0}$

W dependence controlled by Regge behaviour $\sigma \propto W^{4(\alpha(0)-1)}$ at fixed Q^2

ρ^0, ω : $\alpha - 1 = \delta \simeq 0.1$ diffractive (gluon + sea)

ρ^+ : $\alpha - 1 \simeq -0.5$ K^{*0} intermediate

valence quark contributions die out quickly with increasing W at small ξ

What do we know about E ?

analysis of Pauli FF for proton and neutron at $\xi = 0$ Diehl et al (04):

$$F_2^{p(n)} = \int_0^1 dx \left[e_{u(d)} E_v^u(x, \xi = 0, t) + e_{d(u)} E_v^d(x, \xi = 0, t) \right]$$

ansatz for small $-t$: $E_v^a = e_v^a(x) \exp \left\{ t(\alpha' \ln(1/x) + B_a) \right\}$

forward limit: $e_v^a = N_a x^{-\alpha_v(0)} (1-x)^{\beta_v^a}$ (analogously to PDFs)

N_a fixed from $\kappa_a = \int_0^1 dx E_v^a(x, \xi = 0, t = 0)$ ($\kappa_u \simeq 1.67$, $\kappa_d \simeq -2.03$)

fitting FF data provides: $\beta_v^u = 4$, $\beta_v^d = 5.6$ (other powers not excluded)

($G_{E,M}^n$ at large Q^2 required) (upgraded JLab?)

sum rule (Ji's s.r. and momentum s.r. of DIS) at $t = \xi = 0$

$$\int_0^1 dx x e_g(x) = e_{20}^g = -\sum e_{20}^{av} - 2 \sum e_{20}^{\bar{a}}$$

valence term very small, in particular if $\beta_v^u \leq \beta_v^d$

\Rightarrow gluon and sea quark moments cancel each other almost completely

positivity bound forbids large sea \Rightarrow gluon small too

parameterization: $e^i = N_i x^{-\alpha_g(0)} (1-x)^{\beta^i}$ (flavor symm. sea for E assumed)

input to double distribution model for E (E_v^a is d.d. model at $\xi = 0$)

Solutions for E and Ji's sum rule

$$\langle J^a \rangle = \frac{1}{2} [q_{20}^a + e_{20}^a] \quad \langle J^g \rangle = \frac{1}{2} [g_{20} + e_{20}^g]$$

($\xi = 0$) $\langle J \rangle$ means average value of three component of J

var.	β_{val}^u	β_{val}^d	β^g	β^s	N_g	N_s	J^u	J^d	J^s	J^g
1	4	5.6	-	-	0.000	0.000	0.250	0.020	0.015	0.214
2	4	5.6	6	7	-0.873	0.155	0.276	0.046	0.041	0.132
3	4	5.6	6	7	0.776	-0.155	0.225	-0.005	-0.011	0.286
4	10	5	7	-	0.523	0.000	0.209	0.013	0.015	0.257

J^i quoted at scale 4 GeV^2 (spread indicates uncertainties of present knowledge)

$\sum J^i = 1/2$, the spin of the proton

characteristic, stable pattern: for all variants J^u and J^g are large, others small

The first moments at $t = 0$

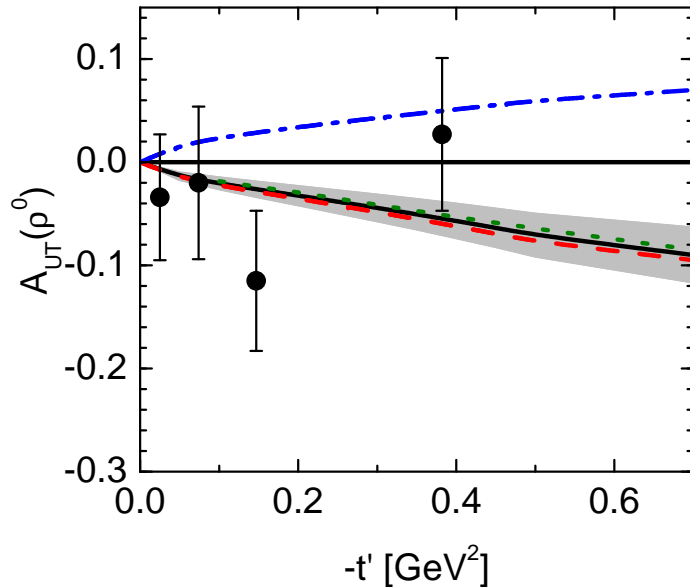
for orientation

(assuming that the GPDs have no nodes and similar t dependence)

	H	E
u_v	2	$\kappa_u = 1.67$
d_v	1	$\kappa_d = -2.03$

Results for $A_{UT}(V)$

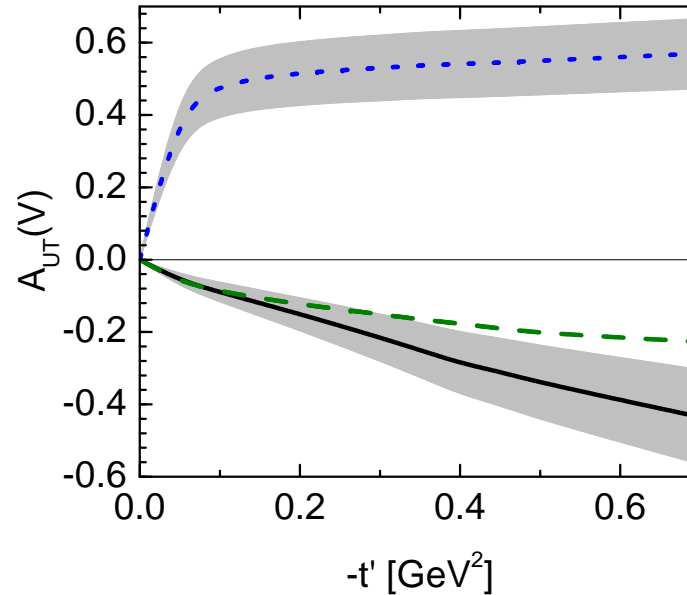
Goloskokov-K (08)



$W = 5 \text{ GeV}$ $Q^2 = 3 \text{ GeV}^2$

variant 1, 2, 3, 4

preliminary data: HERMES (07)



variant 1 for ω , ρ^+ , K^{*0}

t dependence controlled by trivial factor $\sqrt{-t'}$

except for ρ^+ : since $H(E)_v^u - H(E)_v^d$

E non-negligible in cross section, contribution from helicity flip ampl. $\propto t'$

Remarks on wide-angle photoproduction

kinematical requirement $s, -t, -u \gg m^2$ Q^2 small

factorization obtained with assumption of restricted parton virtualities and transverse momenta [Huang-K\(02\)](#), [Huang-Jakob-K-Passek\(04\)](#)

work in a symmetric frame (c.m.s. with $p_3 = p'_3 \Rightarrow \xi = 0$)

amplitude follows from electroproduction amplitude putting $\xi = 0$

factorization in hard subprocess amplitudes and $1/x$ moments of GPDs, i.e. generalized form factors

$$R_i^a(t) = \int_0^1 \frac{dx}{x} F_i^a(x, \xi = 0, t), \quad F_i = H, \tilde{H}, E$$

Phenomenology of wide-angle photoproduction:

leading-twist, lowest order of pQCD: cross sections too small

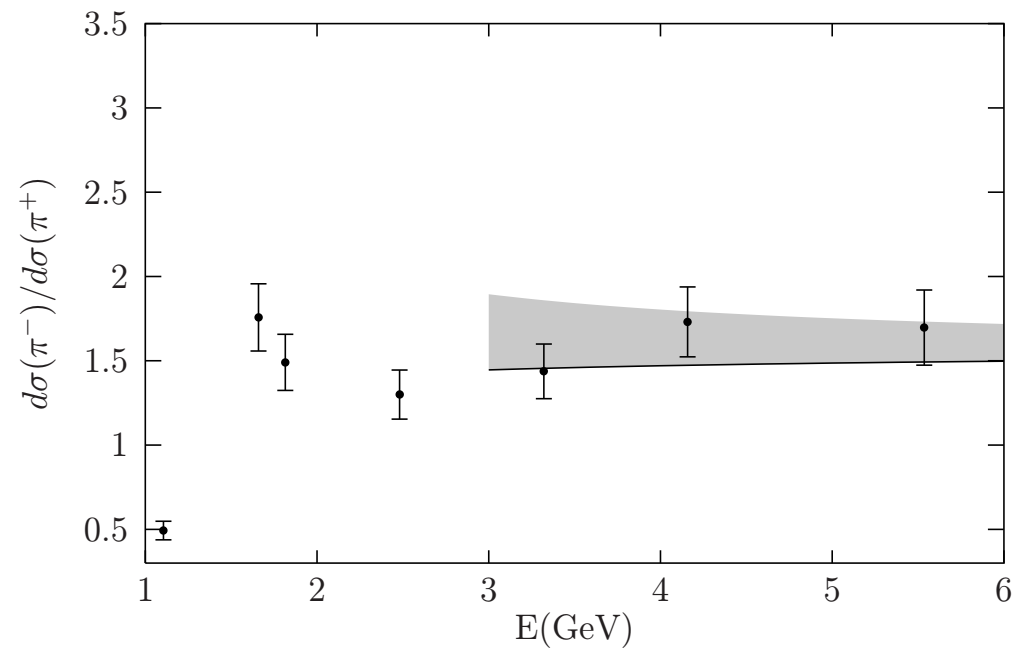
by order of magnitude in comparison with SLAC data (**larger $s, -t, -u$ needed?**)

ratios like spin correlations (e.g. A_{LL}, K_{LL}) may work better

π^-/π^+ ratio OK

π^-/π^+ ratio

$$\frac{d\sigma(\gamma n \rightarrow \pi^- p)}{d\sigma(\gamma p \rightarrow \pi^+ n)} = \left(\frac{e_u s + e_d u}{e_u u + e_d s} \right)^2$$



Hall A (02)

Summary

- phenomenology of DVME within the handbag approach is complicated, still a lot of work to be done
- cross section at small x_{Bj} provides information on the GPD H
- GPDs modeled through reggeized double distributions and subprocess calculated within mod. pert. approach
few free parameters (a_V), essentially for $T \rightarrow T$ amplitude
fair agreement with experiment for
 $Q^2 \simeq 3 \dots 100 \text{ GeV}^2$, $W \simeq 5 \dots 180 \text{ GeV}$
- E constructed with the help of Pauli FF, sum rules and positivity bounds
- data on A_{UT} will fix E better and hence details on parton angular momenta