QCD in hard exclusive processes

Selected results on generalized parton distributions

M. Diehl

Deutsches Elektronen-Synchroton DESY

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1. Introduction

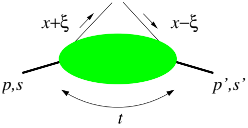
2. Quarks and gluons: some lessons from data

3. t dependence and impact parameter

4. Spin and the Pauli form factors

5. Conclusions

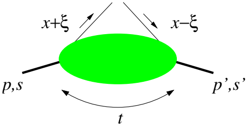
Generalized parton distributions in a nutshell



- GPDs $\leftrightarrow$ matrix elements $\langle p'|\mathcal{O}|p\rangle$
  $\mathcal{O}$ = non-local operator with
  quark/gluon fields
  - $p \neq p' \rightsquigarrow$ depend on two longitud. momentum fractions x, ξ
    and on $t = (p - p')^2$
  - for unpolarized quarks two dist's:
    - H^q conserves proton helicity
    - E^q responsible for proton helicity flip
  - if $p = p' \rightsquigarrow$ ordinary parton densities

$$H^q(x,0,0) = \begin{cases} q(x) & \text{for } x > 0 \\ -\bar{q}(x) & \text{for } x < 0 \end{cases}$$

Generalized parton distributions in a nutshell



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  - for unpolarized quarks two dist's:
    - H^q conserves proton helicity
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  - $\int dx\, x^n\, \text{GPD}(x,\xi,t) \to$ local operators $\to$ form factors

$$\sum_q e_q \int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1(t) \qquad \text{Dirac}$$

$$\sum_q e_q \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2(t) \qquad \text{Pauli}$$

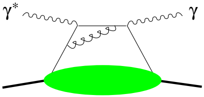
Processes

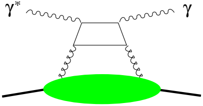
factorization theorems: GPDs appear in hard exclusive processes

calculated to NLO in α_s:

- DVCS $\gamma^* p \to \gamma p$ (including charm loop J. Noritzsch '03)
- light meson production $\gamma^* p \to \rho\, p$, $\pi\, p$, ...
  A. Belitsky and D. Müller '01, D. Ivanov et al. '04
- $\gamma p \to J/\Psi\, p$ D. Ivanov et al. '04

in meson production NLO corrections can be large
more detailed studies needed





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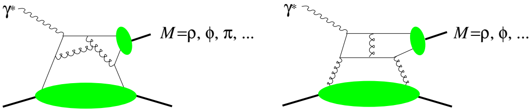

Evolution

- GPDs depend on resolution scale μ
  $\sim$ large momentum in hard process
- evolution interpolates between DGLAP eqs. (parton densities) and ERBL eqs. (meson distribution amplitudes)
- known to NLO A. Freund et al. '99

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- evolution interpolates between DGLAP eqs. (parton densities) and ERBL eqs. (meson distribution amplitudes)
- known to NLO A. Freund et al. '99
- new: explicit solution of LO evolution A. Manashov et al. '05
  - usual parton densities: invert Mellin transform

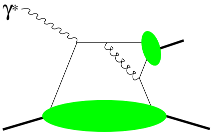
    $M^j(\mu) = \int dx\, x^{j-1}\, q(x,\mu)$ evolves multiplicatively

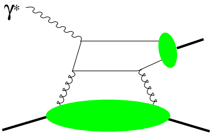
    $q(x,\mu) = -\frac{1}{2\pi i} \int_C dj\, x^{-j}\, M^j(\mu)$
  - GPDs: moments and inversion involve Legendre functions
  - $\longrightarrow$ fast numeric implementation
    analytic approximations

- vector meson production:
  quark and gluon GPDs at same $O(\alpha_s)$
- schematically:

$$\mathcal{A}_{\rho^0} \propto \frac{1}{\sqrt{2}}\left[\frac{2}{3}(u+\bar{u})+\frac{1}{3}(d+\bar{d})+\frac{3}{4}g\right]$$

$$\mathcal{A}_{\phi} \propto \frac{1}{3}(s+\bar{s})+\frac{1}{4}g$$





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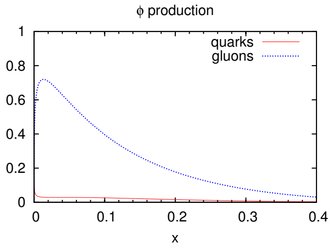

CTEQ6L at $\mu = 2$ GeV

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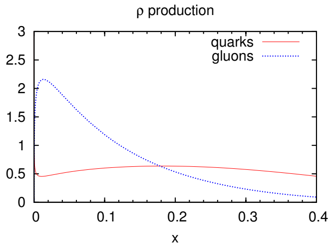

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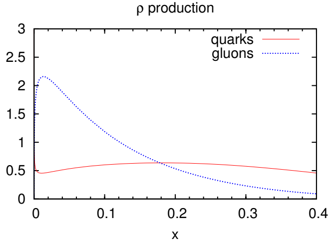

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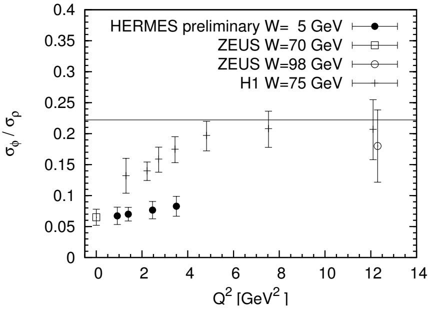
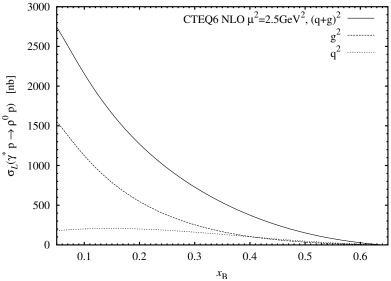
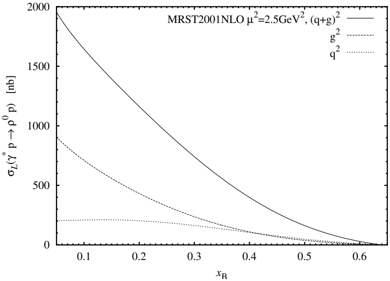


- prelim. HERMES data $\Rightarrow$
  substantial gluon contrib'n
  in ρ^0 production at $x_B \sim 0.1$
  M.D. and A. Vinnikov, '04

- leading twist LO calculation M.D. et al. '05
  ('conventional' double distribution model for GPDs)





- gluons may be non-negligible even in JLAB kinematics
- substantial uncertainties on conventional gluon densities
- warning: should do NLO evaluation

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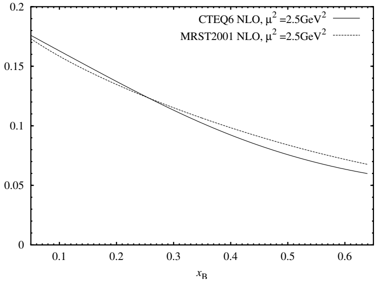

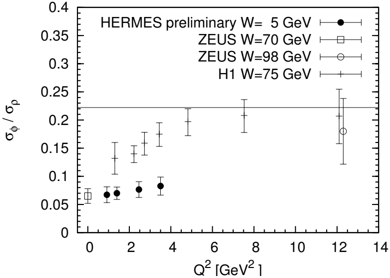

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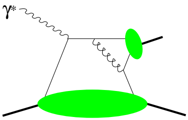
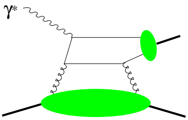
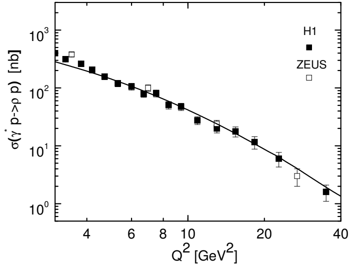
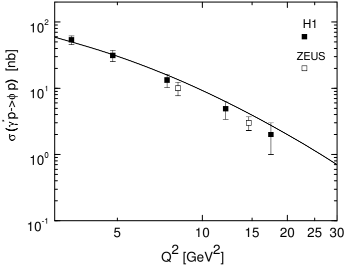
- substantial uncertainties on conventional gluon densities
- warning: should do NLO evaluation
- calculated $\sigma(\rho^0)/\sigma(\phi)$ too large
  but expect extra suppression for ϕ (strange quark mass)

- leading-twist calculations for vector meson production overshoot data
  factors of several at $Q^2 \lesssim 5$ GeV^2
- strong suppression from meson k_T in hard scattering
  L. Frankfurt et al. '95; M. Vanderhaeghen et al. '99
- new analysis for small x_B (gluons only)
  P. Kroll, S. Goloskokov '05









hep-ph/0501242, CTEQ5M gluon, double distribution model

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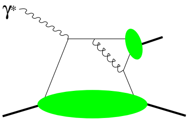
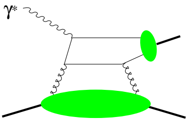
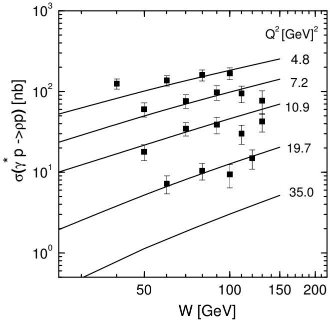
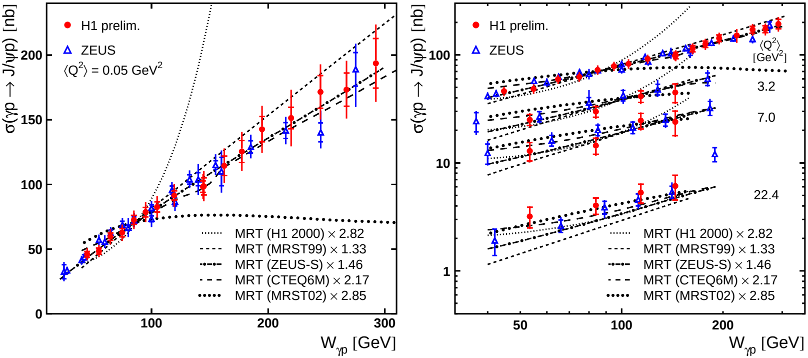






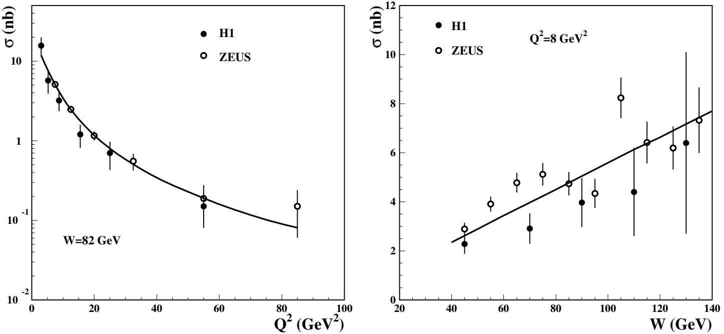
hep-ph/0501242, CTEQ5M gluon

- directly sensitive to gluon distribution at small x
  unlike inclusive struct. funct. $F_2(x, Q^2)$
- despite uncertainties in modelling $g(x) \rightsquigarrow$ GPD
  J/Ψ data cast doubt on some gluon distrib's



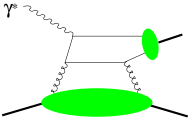
T. Teubner, DIS 2005, plots by P. Fleischmann (H1)

- alternative model for $g(x), q(x) \rightsquigarrow$ GPD
  (not based on double distrib's)
  V. Guzey and M. Polyakov '05, based on M. Polyakov and A. Shuvaev '02
- satisfies Lorentz invariance (polynomiality) relations
- good description of DVCS data from HERA (LO calculation)



hep-ph/0507183

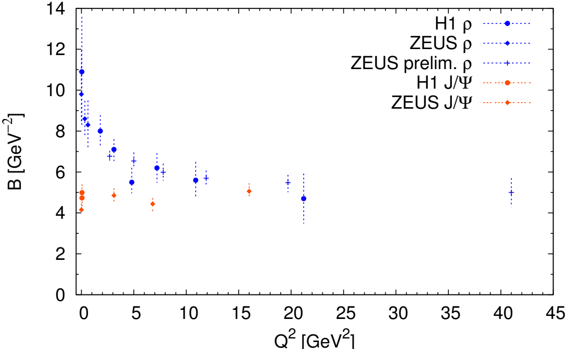
The t dependence



- at small x and small t parametrize

$$d\sigma/dt \propto e^{-B|t|}$$

- ρ and ϕ: "pointlike" $\gamma^* \to q\bar{q}$ for large Q^2
  J/Ψ: "pointlike" $\gamma \to c\bar{c}$ even for $Q^2 = 0$



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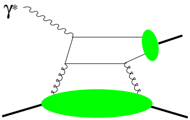

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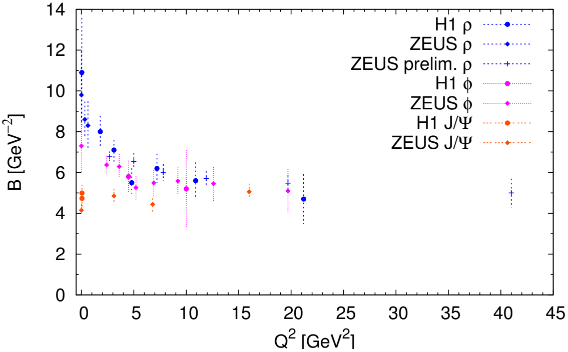

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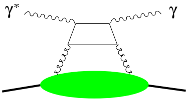

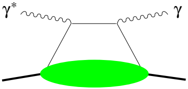

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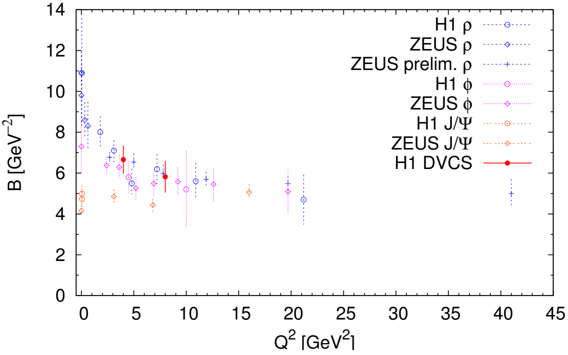

- first measurement for DVCS H1 Coll. '05
  sea quarks and gluons

Small x

neglect interplay of x and ξ

simple ansatz: $\text{GPD} \sim \left(\frac{1}{x}\right)^{\alpha+\alpha' t} = x^{-\alpha}\, e^{t\alpha' \log(1/x)}$

- exclusive J/Ψ production (gluons)
  - photoproduction H1 preliminary (DIS 05)

    $\alpha = 1.224 \pm 0.010 \pm 0.012$

    $\alpha' = 0.164 \pm 0.028 \pm 0.030$ GeV^{-2}
  - similar in electroproduction
- values very different in soft processes $\gamma p \to \rho p$, $pp \to pp$, ...
  for α is well-known from inclusive $\gamma^* p \to X$ vs. $\gamma p \to X$

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simple ansatz: $\text{GPD} \sim \left(\frac{1}{x}\right)^{\alpha+\alpha' t} = x^{-\alpha} \, e^{\, t\alpha' \log(1/x)}$

- in nonsinglet sector (quarks only, no gluons)
  $\alpha \sim 0.4 \ldots 0.5$ in parton distrib's at low scale
  similar to soft processes (meson trajectories)
- α' in partonic regime? ... wait a few slides

Impact parameter

- states with definite light-cone momentum p^+ and transverse position (impact parameter):

$$|p^+, \boldsymbol{b}\rangle = \int d^2\boldsymbol{p}\, e^{-i\boldsymbol{b}\boldsymbol{p}}\, |p^+, \boldsymbol{p}\rangle$$

  formal: eigenstates of 2 dim. position operator

- can exactly localize proton in 2 dimensions
  no limitation by Compton wavelength
- and stay in frame where proton moves fast
  $\rightsquigarrow$ parton interpretation

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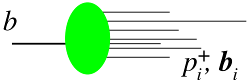
formal: eigenstates of 2 dim. position operator

- $\boldsymbol{b}$ is center of momentum of the partons in proton



$$\boldsymbol{b} = \frac{\sum_i p_i^+ \boldsymbol{b}_i}{\sum_i p_i^+} \qquad (i = q, \bar{q}, g)$$

consequence of Lorentz invariance
nonrelativistic analog: Galilei invariance $\Rightarrow$ center of mass

Impact parameter GPDs

in following specialize to $\xi = 0$

- impact parameter distribution

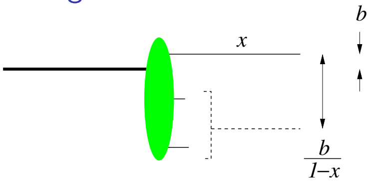
$$q(x, b^2) = (2\pi)^{-2} \int d^2\boldsymbol{\Delta}\, e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{b}}\, H^q(x, \xi = 0, t = -\boldsymbol{\Delta}^2)$$

gives distribution of quarks with
• longitudinal momentum fraction x
• transverse distance b from proton center M. Burkardt '00

- average impact parameter

$$\langle b^2 \rangle_x = \frac{\int d^2b\, b^2\, q(x, b^2)}{\int d^2b\, q(x, b^2)} = 4\, \frac{\partial}{\partial t} \log H^q(x, \xi, t)\Big|_{t=0}$$

Large x:



- for $x \to 1$ get $b \to 0$
  nonrel. analog:
  center of mass of atom
- $\Leftrightarrow$ t dependence becomes flat

- $d = b/(1-x)$
  $=$ distance of selected parton from spectator system
  gives lower bound on overall size of proton
- finite size of configurations with $x \to 1$ implies

$$\langle b^2 \rangle_x \sim (1-x)^2$$

M. Burkardt, '02, '04

Small x:

$$H(x,t) \sim e^{\,tB + \alpha' \log(1/x)} \quad \rightsquigarrow \quad \langle b^2 \rangle_x \sim B + \alpha' \log(1/x)$$

Evolution

- $q(x, b^2)$ fulfils usual DGLAP evolution equation for non-singlet (e.g. $q_{\mathrm{NS}} = q - \bar{q}$ or $q_{\mathrm{NS}} = u - d$):

$$\mu^2 \frac{d}{d\mu^2} q_{\mathrm{NS}}(x, b^2, \mu^2) = \int_x^1 \frac{dz}{z} \left[P\Big(\frac{x}{z}\Big) \right]_+ q_{\mathrm{NS}}(z, b^2, \mu^2)$$

evolution local in b (let $1/\mu \ll b$ to be safe)

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- average

$$\langle b^2 \rangle_x = \frac{\int d^2b\; b^2\, q_{\rm NS}(x, b^2)}{\int d^2b\; q_{\rm NS}(x, b^2)}$$

  evolves as

$$\mu^2 \frac{d}{d\mu^2} \langle b^2 \rangle_x = -\frac{1}{q_{\rm NS}(x)} \int_x^1 \frac{dz}{z}\, P\Big(\frac{x}{z}\Big)\, q_{\rm NS}(z) \Big[\langle b^2 \rangle_x - \langle b^2 \rangle_z \Big]$$

M.D. et al. '04

Information from electromagnetic form factors

- ff's constrain interplay of x and b dependence

  M.D. et al. '04, M. Guidal et al. '04

- e.m. current $\rightsquigarrow$ only $q - \bar{q}$

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

$$
\begin{aligned}
F_1^p(t) &= \int_0^1 dx \left[\tfrac{2}{3} H_v^u(x,t) - \tfrac{1}{3} H_v^d(x,t) \right] \\
F_1^n(t) &= \int_0^1 dx \left[\tfrac{2}{3} H_v^d(x,t) - \tfrac{1}{3} H_v^u(x,t) \right]
\end{aligned}
$$

- ansatz: $H_v^q(x,t) = q_v(x) \exp[\, t f_q(x) \,]$ $\quad \langle b^2 \rangle_x^q = 4 f_q(x)$
- ansatz for $f_q(x)$ interpolates between

  $f_q(x) \to \alpha' \log(1/x)$ for $x \to 0$

  $f_q(x) \sim (1-x)^2$ for $x \to 1$

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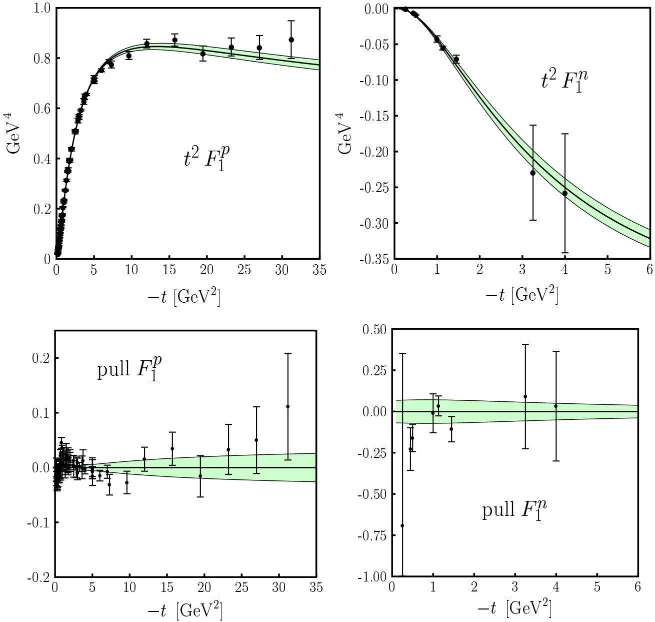
  $$H_v^q(x,t) = H^q(x,t) - H^{\bar{q}}(x,t)$$

  $$\begin{aligned} F_1^p(t) &= \int_0^1 dx \left[\tfrac{2}{3} H_v^u(x,t) - \tfrac{1}{3} H_v^d(x,t) \right] \\ F_1^n(t) &= \int_0^1 dx \left[\tfrac{2}{3} H_v^d(x,t) - \tfrac{1}{3} H_v^u(x,t) \right] \end{aligned}$$

- ansatz: $H_v^q(x,t) = q_v(x) \exp[\, t f_q(x) \,]$ $\quad \langle b^2 \rangle_x^q = 4 f_q(x)$
- ansatz for $f_q(x)$ interpolates between

  $f_q(x) \to \alpha' \log(1/x)$ for $x \to 0$

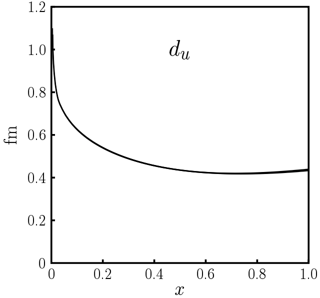
  $f_q(x) \sim (1-x)^2$ for $x \to 1$
- good description of data with $\alpha' = 0.9$ to 1 GeV^{-2}

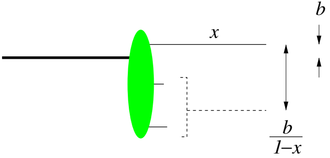


χ^2/d.o.f. $= 1.93$

pull = data/fit -1

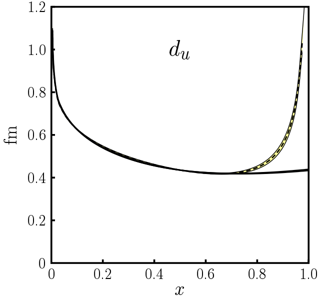
Lessons from the fit

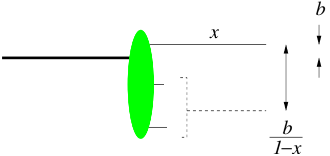




- clear drop with x of average distance $d = b/(1-x)$
  $\leftrightarrow$ strong correlation of x and t dependence

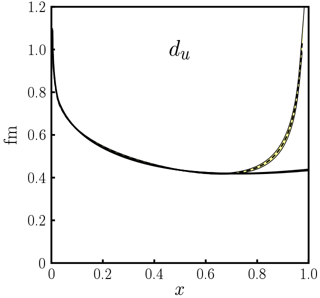
Lessons from the fit

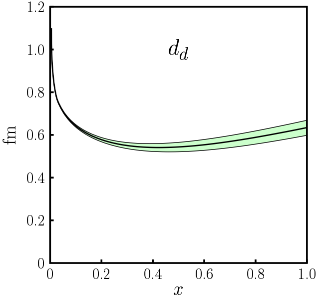




- clear drop with x of average distance $d = b/(1-x)$
  $\leftrightarrow$ strong correlation of x and t dependence
- region $x \gtrsim 0.8$ contributes less than 5% to form factors
  $\rightarrow$ data cannot fix asymptotic behavior of $d_q(x)$ for $x \rightarrow 1$

Lessons from the fit

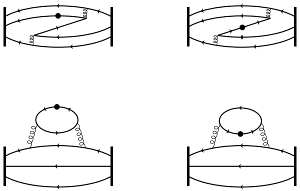




- d quark distribution less well determined
  improvement with better data for F_1^n
- to describe both F_1^p and F_1^n well
  fit wants $d_d(x) > d_u(x)$ for moderate to large x
  $\leftrightarrow$ d quarks more "spread out" than u quarks

Compare with lattice results

matrix elements of local operators $\leftrightarrow$ form factors
calculate in lattice QCD

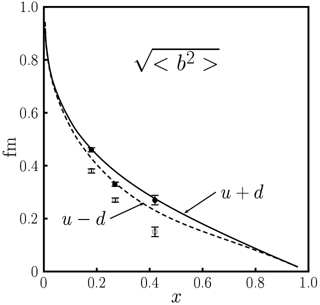


- main systematic uncertainties from
  - omission of “disconnected” diagrams
    but: cancel in difference of u and d
  - extrapolation to physical pion mass

figure: J. Negele, hep-lat/0211022

Compare with lattice results

matrix elements of local operators ↔ form factors
calculate in lattice QCD

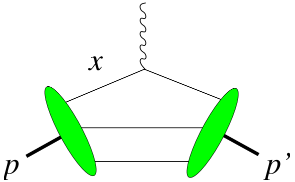


J. Negele et al., hep-lat/0404005

- Wilson fermions
- $m_\pi = 870$ MeV
- typical x in $\int dx\, x^n q(x,b)$ estimated as

$$\langle x \rangle = \frac{\int dx\, x^{n+1} q(x)}{\int dx\, x^n q(x)}$$

Large t and the Feynman mechanism



- if impose that spectators have virtualities $\sim \Lambda^2$ then

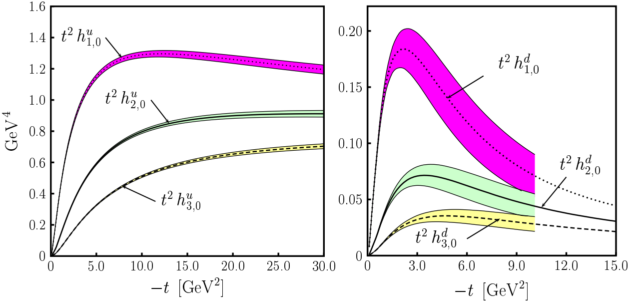
$$1 - x \sim \Lambda/\sqrt{-t}$$

- large-t asymptotics with our ansatz: $\langle 1-x \rangle_t \sim 1/\sqrt{-t}$ numerically seen for $-t \gtrsim 5$ GeV^2
- get Drell-Yan relation $F_1^q(t) \sim |t|^{-(1+\beta_q)}$ if $q(x) \sim (1-x)^{\beta_q}$ at large x

  CTEQ6M distributions at $\mu = 2$ GeV:

  $\beta_u \sim 3.4$ and $\beta_d \sim 5.0$ (for $0.5 < x < 0.9$)

- very different $u(x)$ and $d(x)$ for large x
  $\leftrightarrow$ very different u and d moments at large t
- hope to test with experimental data on $F_1^n(t)$ and $F_1^p(t)$ and lattice calculations of higher moments



$$h^q_{n,0}(t) = \int_0^1 dx\, x^{n-1}\, H^q_v(x,t)$$

Spin and the Pauli form factors

- $E \leftrightarrow$ nucleon helicity flip $\langle\downarrow|\mathcal{O}|\uparrow\rangle$

  $\leftrightarrow$ transverse pol. difference $|X\pm\rangle = \frac{1}{\sqrt{2}}(\,|\uparrow\rangle \pm |\downarrow\rangle\,)$

  $\langle X{+}|\mathcal{O}|X{+}\rangle - \langle X{-}|\mathcal{O}|X{-}\rangle = \langle\uparrow|\mathcal{O}|\downarrow\rangle + \langle\downarrow|\mathcal{O}|\uparrow\rangle$

- quark density in proton state $|X{+}\rangle$

$$q_v^X(x,\mathbf{b}) = q_v(x,b) - \frac{b^y}{m}\frac{\partial}{\partial b^2}\, e_v^q(x,b)$$

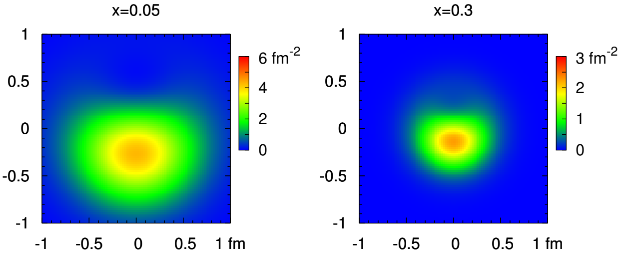
shifted in y direction M. Burkardt '02

$e_v^q(x,b)$ is Fourier transform of $E_v^q(x,t)$

quark density in proton state $|X+\rangle$

$$q_v^X(x,\mathbf{b}) = q_v(x,b) - \frac{b^y}{m}\frac{\partial}{\partial b^2}\, e_v^q(x,b)$$

is shifted



$(d-\bar{d})$ density in transverse plane M.D. et al. '04

- $\int dx\, E^u(x,0) = \kappa^u \approx 1.67$ and $\int dx\, E^d(x,0) = \kappa^d \approx -2.03$
  $\rightarrow$ large spin-orbit correlations
- relation with transverse momentum dependent densities
  $\rightarrow$ Sivers function M. Burkardt et al. '04
- similar for generalized transversity distributions
  M.D. and P. Hägler '05, M. Burkardt '05

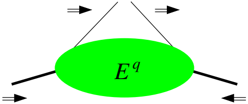
- density representation

$$q_v^X(x, \mathbf{b}) = q_v(x, b) - \frac{b^y}{m} \frac{\partial}{\partial b^2} e_v^q(x, b)$$

gives positivity bound M. Burkardt '03

$$\Big[E^q(x, t=0)\Big]^2 \quad \leq \quad m^2 \Big[q(x) + \Delta q(x)\Big] \Big[q(x) - \Delta q(x)\Big] \\ \times 4 \frac{\partial}{\partial t} \ln \Big[H^q(x,t) \pm \tilde{H}^q(x,t)\Big]_{t=0}$$

$\Rightarrow$ E^q must fall faster than H^q at large x



- E $\leftrightarrow$ orbital angular momentum
  $\Rightarrow$ carried by partons with smaller x

M.D. et al. '04, M. Guidal et al. '04

- sum rules: Pauli ff's $\leftrightarrow$ $E_v^q(x,t) = E^q(x,t) - E^{\bar{q}}(x,t)$
- ansatz $E_v^q(x,t) = e_v(x) \exp[\, t\, g_q(x)\,]$
  $g_q(x)$ same form as $f_q(x)$ in ansatz for H_v^q
- shape of forward limit $e_v^q(x)$ not known $\longrightarrow$ ansatz

$$e_v^q = \mathcal{N}_q\, x^{-\alpha}(1-x)^{\beta_q}$$

$\mathcal{N}_q$ determined by p and n magnetic moments

M.D. et al. '04, M. Guidal et al. '04

- sum rules: Pauli ff's $\leftrightarrow$ $E_v^q(x,t) = E^q(x,t) - E^{\bar{q}}(x,t)$
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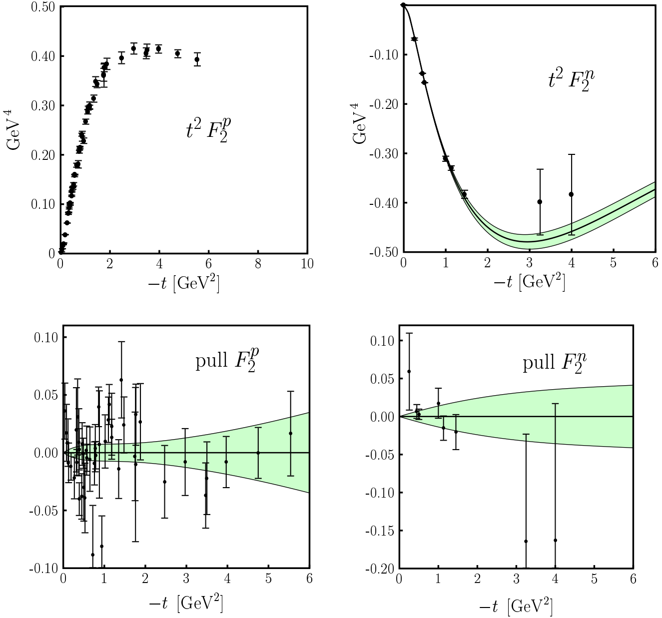
$$e_v^q = \mathcal{N}_q \, x^{-\alpha} (1-x)^{\beta_q}$$

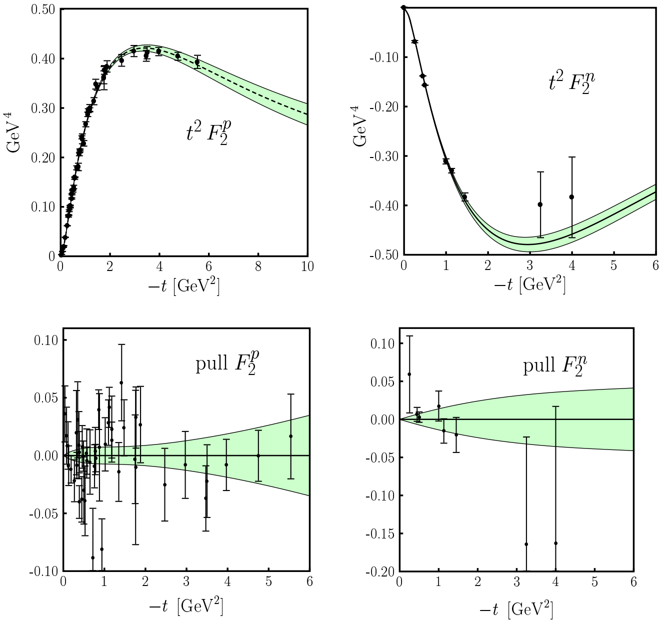
$\mathcal{N}_q$ determined by p and n magnetic moments

- obtain good fit of $F_2^p(t)$ and $F_2^n(t)$
  - $\alpha' = 0.9$ GeV^{-2} and $\alpha = 0.55$
    ok with Regge phenomenology
- large allowed regions of β_q and parameters in $g_q(x)$
  but positivity constraints seriously limit parameter space
  in particular $\beta_d \geq 5$ and $\beta_u \geq 3.5$



χ^2/d.o.f.
$= 1.31$

pull =
data/fit -1

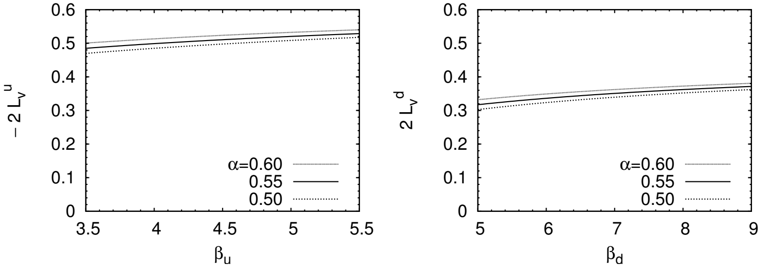


χ^2/d.o.f.
$= 1.31$

pull $=$
data/fit -1

orbital angular momentum carried by valence quarks

$$\langle L_v^q \rangle = \frac{1}{2} \int dx \left[x e_v^q(x) + x q_v(x) - \Delta q_v(x) \right]$$

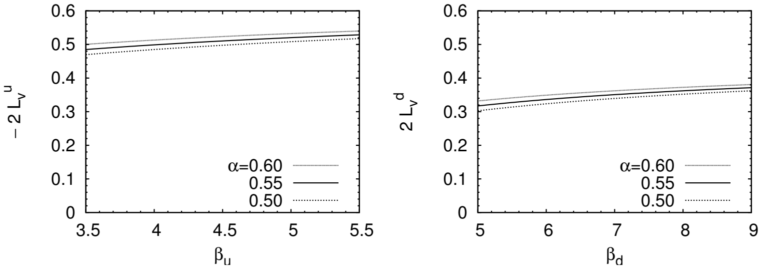


- individual u and d quite well determined
- $2\langle J_v^u \rangle = 2\langle L_v^u \rangle + 0.93$ and $2\langle J_v^d \rangle = 2\langle L_v^d \rangle - 0.34$
- $2\langle L_v^u - L_v^d \rangle = -(0.77 \div 0.92)$ at $\mu = 2$ GeV

  strong cancellations in $2\langle L_v^u + L_v^d \rangle = -(0.11 \div 0.22)$

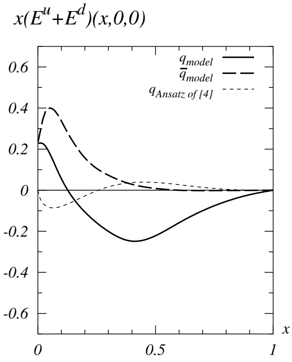
orbital angular momentum carried by valence quarks

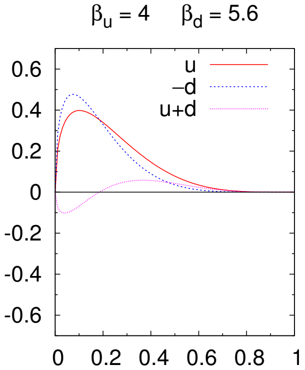
$$\langle L_v^q \rangle = \frac{1}{2} \int dx \Big[x e_v^q(x) + x q_v(x) - \Delta q_v(x) \Big]$$



- $2\langle L_v^u - L_v^d \rangle = -(0.77 \div 0.92)$ at $\mu = 2$ GeV
- lattice results:
  QCDSF: $2\langle L_v^u - L_v^d \rangle = -0.9 \pm 0.12$ G. Schierholz, LC 2005
  LHPC: $2\langle L_v^u - L_v^d \rangle = -0.25 \pm 0.05$ for $m_\pi = 897$ MeV
  from hep-lat/0410017

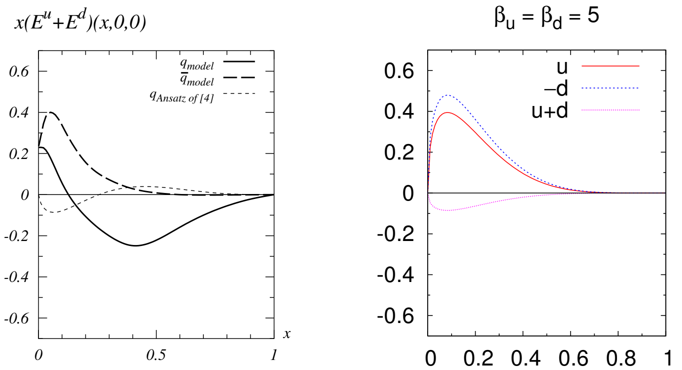
calculation of $E^u + E^d$ in chiral soliton model J. Ossmann et al. '05





hep-ph/0411172, $\mu^2 = 5$ GeV^2 $E^q - E^{\bar{q}}$, $\mu^2 = 4$ GeV^2

- shape differs from our fit (with central values of par's) calculation of $E^u + E^d$ in chiral soliton model J. Ossmann et al. '05



hep-ph/0411172, $\mu^2 = 5$ GeV^2 $E^q - E^{\bar{q}}$, $\mu^2 = 4$ GeV^2

- shape differs from our fit (with central values of par's)
- but fit has large parameter uncertainties for $E^u + E^d$
- normalization: chiral soliton model: $\kappa_u + \kappa_d = 0.35$
  experiment: $\kappa_u + \kappa_d = 0.12$

Conclusions

- vector meson prodution:
  very sensitive to gluon distrib'n even in fixed-target kinematics
  higher twist corrections essential for realistic cross sections
- impact parameter picture:
  naturally implemented at a rigorous level
- $F_1(t)$ data and lattice $\rightsquigarrow$ strong decrease of $\langle \boldsymbol{b}^2 \rangle$ with x
- $F_1(t)$ data consistent with Feynman mechanism
  $\rightsquigarrow$ Drell-Yan relation
  $\rightsquigarrow$ striking effects for d quark part of form factors
- $E \quad \rightarrow$ physics of transverse spin
  and $\rightarrow$ orbital angular momentum
- attempts for quantitative understanding of E
  "valence" contributions: L^{u-d} big and L^{u+d} small
  need direct measurements to learn more