

Generalized Parton Distributions from Lattice QCD

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Generalized parton distributions determine the angular momentum decomposition of the nucleon and the transverse distribution of partons within the nucleon. Additionally, in particular limits they reduce to form factors and ordinary parton distributions. I will review generalized parton distributions and present our lattice QCD calculations of moments of generalized parton distributions. In particular I will examine the transverse distribution of quarks within the nucleon and, time permitting, I will show an exploratory calculation of the nucleon axial coupling using chiral lattice fermions.

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Generalized Parton Distributions from Lattice QCD

What new physics do we learn?

- Spin Decomposition - decomposition of nucleon spin into quark helicity, quark orbital, and gluon contributions

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma_{u+d} + L_{u+d} + J_g$$

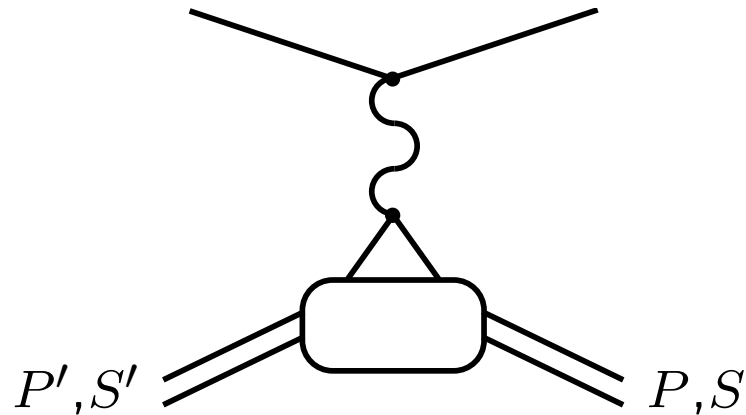
- Transverse Structure - 3D distribution of quarks in a mixed representation: 2 transverse coordinates \vec{b}_\perp and 1 longitudinal momentum x

$$q(x, \vec{b}_\perp) \quad \text{and} \quad \Delta q(x, \vec{b}_\perp)$$

What experiments probe the generalized parton distributions?

Form Factors

- lepton-nucleon scattering, $lN \rightarrow lN$, elastic



$$\Delta = P' - P$$

$$t = \Delta^2$$

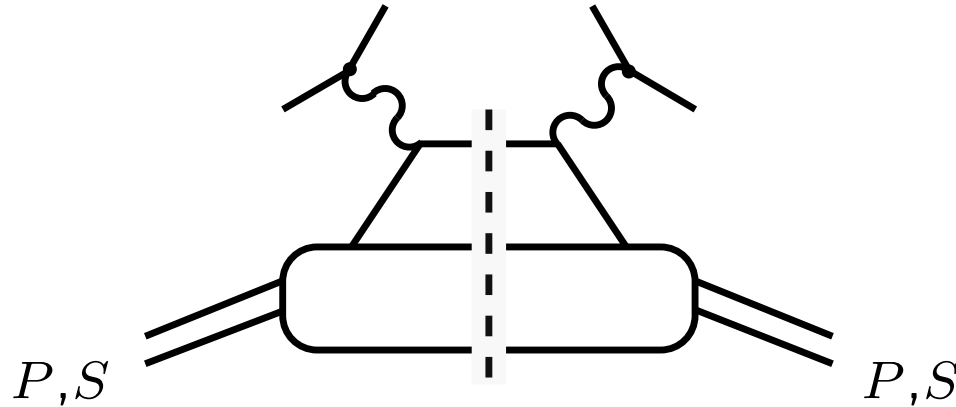
- off-forward matrix element of the electromagnetic current

$$\langle P', S' | J^\mu | P, S \rangle = \bar{U}(P', S') \left(\gamma^\mu F_1(t) + \frac{i\sigma^{\mu\nu} \Delta_\nu}{2m} F_2(t) \right) U(P, S)$$

- interpretation as Fourier transform of charge and current densities *in certain limits*
- magnetic moment, charge & current radii

Parton Distributions

- deep inelastic scattering, $lN \rightarrow lX$, inclusive



$$P^+ = \frac{1}{2} (P^t + P^z)$$

$$y^- = \frac{1}{2} (y^t - y^z)$$

- forward matrix element of light-cone quark correlator

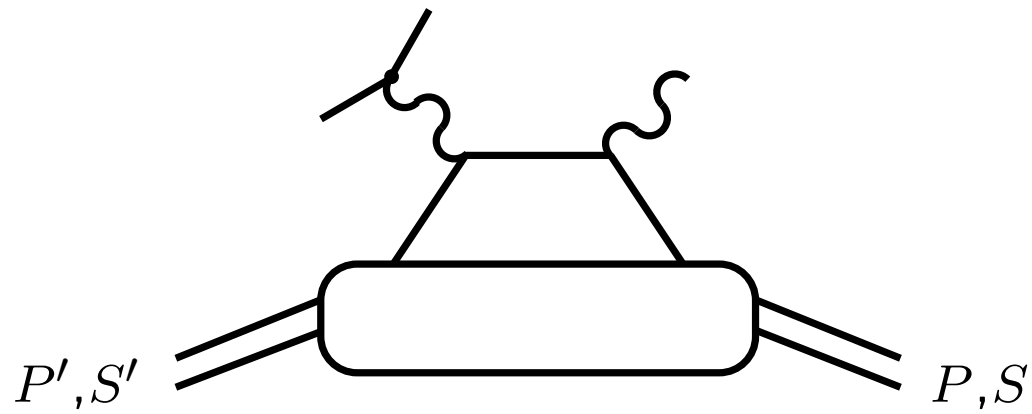
$$\mathcal{O}_q(x, \vec{b}_\perp) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \bar{q} \left(-\frac{y^-}{2}, \vec{b}_\perp \right) \gamma^+ q \left(\frac{y^-}{2}, \vec{b}_\perp \right)$$

$$\langle P, S | \mathcal{O}_q(x, \vec{0}_\perp) | P, S \rangle = q(x)$$

- longitudinal momentum distribution in the *infinite momentum frame*
- momentum fraction & spin fraction

Generalized Parton Distributions

- deeply virtual Compton scattering, $lN \rightarrow lN\gamma$, exclusive



$$\bar{P} = \frac{1}{2} (P' + P)$$

$$\xi = -\frac{\Delta^+}{2\bar{P}^+}$$

- off-forward matrix element of light-cone quark correlator

$$\langle P', S' | \mathcal{O}_q(x, \vec{0}_\perp) | P, S \rangle =$$

$$\frac{1}{2\bar{P}^+} \bar{U}(P', S') \left(\gamma^+ H(x, \xi, t) + i \frac{\sigma^{+\nu} \Delta_\nu}{2M} E(x, \xi, t) \right) U(P, S)$$

- meson production, Compton scattering

What matrix elements determine the quark angular momenta
and transverse quark distributions?

Generalized Form Factors

- light-cone expansion of $\mathcal{O}_q(x, \vec{b}_\perp)$ relates generalized parton distributions to generalized form factors
- unpolarized twist two operators

$$O_q^{\mu_1 \dots \mu_n} = \bar{q} i D^{(\mu_1} \dots i D^{\mu_{n-1}} \gamma^{\mu_n)} q$$

- off-forward matrix elements of the twist two operators [1]

$$\begin{aligned} \langle P', S' | O_q^{\mu_1 \dots \mu_n} | P, S \rangle = & \bar{U}(P', S') \left[\sum_{\substack{i=0 \\ \text{even}}}^{n-1} A_{ni}^q(t) K_{ni}^A(P', P) \right. \\ & \left. + \sum_{\substack{i=0 \\ \text{even}}}^{n-1} B_{ni}^q(t) K_{ni}^B(P', P) + \delta_{\text{even}}^n C_n^q(t) K_n^C(P', P) \right] U(P, S) \end{aligned}$$

- similar expression for the polarized observables: $\tilde{A}_{ni}^q(t)$ and $\tilde{B}_{ni}^q(t)$

Basic Properties of Generalized Form Factors

- moments of parton distributions - $\langle P|O_q^{\mu_1 \dots \mu_n}|P\rangle$ and $\langle P|\tilde{O}_q^{\mu_1 \dots \mu_n}|P\rangle$

$$A_{n0}^q(0) = \int_{-1}^1 dx x^{n-1} q(x) \quad \text{and} \quad \tilde{A}_{n0}^q(0) = \int_{-1}^1 dx x^{n-1} \Delta q(x)$$

- form factors - $O_q^\mu = \bar{q}\gamma^\mu q$ and $\tilde{O}_q^\mu = \bar{q}\gamma^\mu\gamma^5 q$

$$A_{10}^q(t) = F_1^q(t) \quad \text{and} \quad B_{10}^q(t) = F_2^q(t)$$

$$\tilde{A}_{10}^q(t) = G_A^q(t) \quad \text{and} \quad \tilde{B}_{10}^q(t) = G_P^q(t)$$

Quark Angular Momenta and Transverse Quark Distributions

- quark angular momenta [1]

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma^{u+d} + L^{u+d} + J^g$$

$$\Delta \Sigma^q = \tilde{A}_{10}^q(0) \quad J^q = \frac{1}{2} (A_{20}^q(0) + B_{20}^q(0)) \quad L^q = J^q - \frac{1}{2} \Delta \Sigma^q$$

- transverse quark distributions [2]

$$\int_{-1}^1 dx x^{n-1} q(x, \vec{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} A_{n0}^q(-\vec{\Delta}_\perp^2)$$

$$\int_{-1}^1 dx x^{n-1} \Delta q(x, \vec{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} \tilde{A}_{n0}^q(-\vec{\Delta}_\perp^2)$$

[1] X. D. Ji hep-ph/9603249

[2] M. Burkardt hep-ph/0005108

How do we calculate the matrix elements
of twist two operators in lattice QCD?

Lattice Fields and Correlation Functions

- Grassmann fermion fields $\psi_\alpha^a(x)$ and $\bar{\psi}_\alpha^a(x)$ at every lattice point x
- SU(3) gauge fields $U_\mu^{ab}(x)$ at every lattice link $x \rightarrow x + \mu$
- correlation function of $2N$ fermion fields and M gauge links

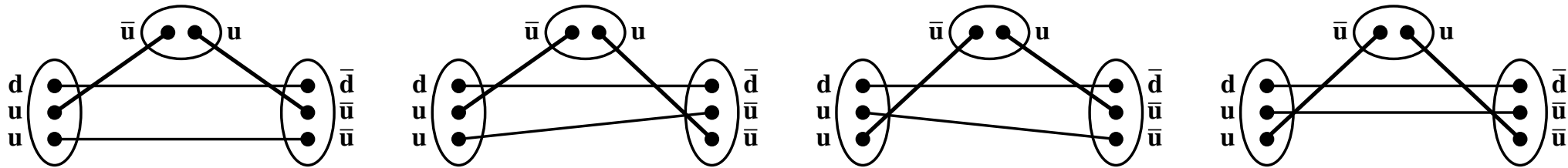
$$\begin{aligned} \langle \psi_1 \cdots \psi_N \bar{\psi}_N \cdots \bar{\psi}_1 U_1 \cdots U_M \rangle &= \\ &= \int DU \int D\psi D\bar{\psi} e^{-S_G[U]} e^{-\bar{\psi} M[U] \psi} \psi_1 \cdots \psi_N \bar{\psi}_N \cdots \bar{\psi}_1 U_1 \cdots U_M \\ &= \int DU e^{-S_G[U]} \det^{N_f}(M[U]) U_1 \cdots U_M \sum_{\pi} (-1)^\pi M[U]_{1\pi_1}^{-1} \cdots M[U]_{N\pi_N}^{-1} \end{aligned}$$

- numerical integration

$$\int DU e^{-S_G[U]} \det^{N_f}(M[U]) F[U] = \frac{1}{N} \sum_{i=1}^N F[U^i] \pm \frac{\sigma_F}{\sqrt{N}}$$

Quark Diagrams

- connected u quark diagrams



- disconnected u diagrams - not calculated - $(u + d)$ matrix elements only



- connected d quark diagrams



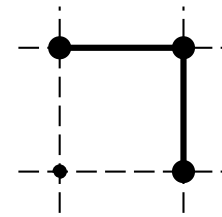
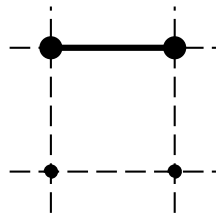
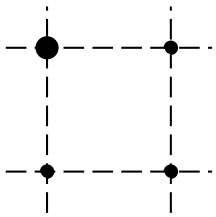
- disconnected d diagrams - not calculated - $(u + d)$ matrix elements only



Building Blocks

- twist two operators $\bar{q}\Gamma D^{\mu_1} \dots D^{\mu_n} q$ can be written in terms of a basic set of building blocks

$$\bar{q}(x) \Gamma_i q(x) \quad \bar{q}(x + \hat{\mu}) \Gamma_i U_{\mu}^{\dagger}(x) q(x) \quad \bar{q}(x + \hat{\nu} + \hat{\mu}) \Gamma_i U_{\nu}^{\dagger}(x + \hat{\mu}) U_{\mu}^{\dagger}(x) q(x)$$



- Γ_i ($i = 1, \dots, 16$) denote a complete basis of 4×4 Dirac spin matrices
- calculate upto 3 gauge link insertions: $U_{\mu_n}^{\dagger}(x + \hat{\mu}_{n-1} + \dots + \hat{\mu}_1) \dots U_{\mu_1}^{\dagger}(x)$
- calculate a broad range of momentum transfers \vec{q}
- more than 380,000 correlation functions

Overdetermined Set of Lattice Observables

- i labels all combinations of operator indices (μ_1, \dots, μ_n) and momenta P', P which give the same $t = (P' - P)^2$

$$\mathcal{O}_i^{\overline{\text{MS}}} = \langle P' | \mathcal{O}^{\mu_1 \dots \mu_n} | P \rangle$$

- expand $\mathcal{O}_i^{\overline{\text{MS}}}$ in terms of generalized form factors, $F_\alpha = A_{ni}, B_{ni}, \dots$

$$\mathcal{O}_i^{\overline{\text{MS}}} = \sum_{\alpha=1}^M K_{i\alpha} F_\alpha(t)$$

- match $\mathcal{O}_i^{\overline{\text{MS}}}$ to $\mathcal{O}_i^{\text{lat}}$ with one loop matching coefficients Z_{ij}

$$\mathcal{O}_i^{\overline{\text{MS}}} = \sum_{j=1}^N Z_{ij} \mathcal{O}_j^{\text{lat}}$$

- overdetermined set of observables, $N > M$

$$\mathcal{O}_i^{\text{lat}} = \sum_{\alpha} (Z^{-1}K)_{i\alpha} F_\alpha(t) \quad \chi^2 = \sum_{i=1}^N \left(\frac{\sum_{\alpha=1}^M (Z^{-1}K)_{i\alpha} F_\alpha(t) - \mathcal{O}_i^{\text{lat}}}{\sigma_i} \right)^2$$

What do we learn about the quark angular momentum
and transverse quark distributions?

Calculations with Heavy-*ish* Quarks

- Wilson quarks
- flavors: $N_F = 2$
- lattice spacing: $a = 0.095$ fm
- lattice size: $L = 1.52$ fm
- pion masses: $M_\pi = 753(10), 835(13), 895(15)$ MeV

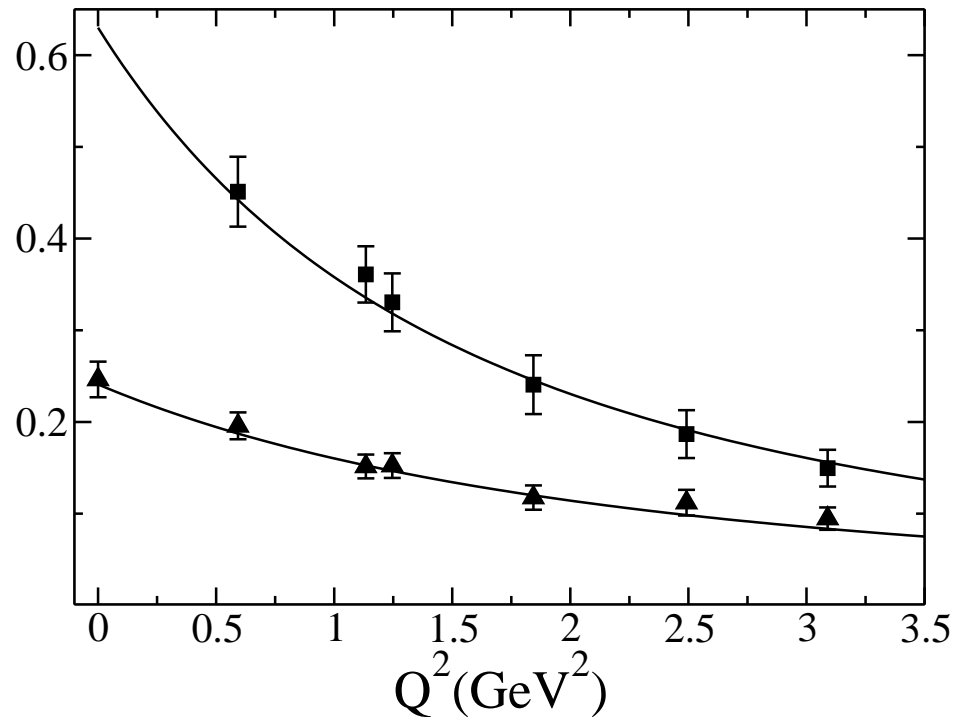
What do we learn about the nature of the nucleon spin?

Quark Angular Momenta

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma^{u+d} + L^{u+d} + Jg$$

$$\Delta\Sigma_q = \frac{1}{2}\tilde{A}_{10}^q(0) \qquad J_q = \frac{1}{2}\left(A_{20}^q(0) + B_{20}^q(0)\right)$$

$$L_q = J_q - \frac{1}{2}\Delta\Sigma_q \qquad J_g = \frac{1}{2} - J_{u+d}$$



Quark Angular Momenta: $m_\pi = 895$ MeV

- quark helicity, quark orbital, and gluon contributions (modulo disconnected diagrams)

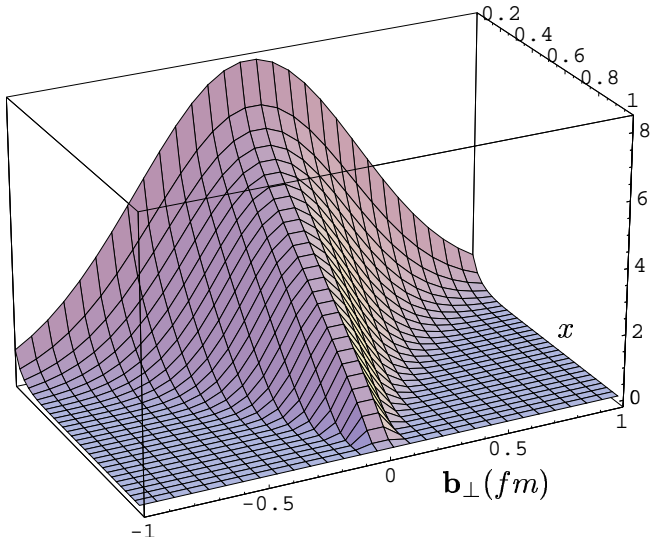
$$2 \cdot \frac{1}{2} = \begin{array}{ccc} \Delta\Sigma^{u+d} & + & 2L^{u+d} & + & 2J^g \\ +0.682(20) & & -0.002(3) & & + 0.320(16) \end{array}$$

- quark orbital motion, $L^{u-d} = -0.193(32)$

$$2L_{\min}^q = 2 \cdot \left(\frac{|L^u| + |L^d|}{2} \right) \geq |L^{u-d}| = 0.193(32)$$

What do we learn about the transverse quark structure of the nucleon?

Transverse Distributions



$$A_{n0}^q(-\vec{\Delta}_\perp^2) = \int d^2b_\perp e^{i\vec{\Delta}_\perp \cdot \vec{b}_\perp} \int_{-1}^1 dx x^{n-1} q(x, \vec{b}_\perp)$$

$$\langle b_\perp^2 \rangle_{(n)}^q = -4 \frac{A_{n0}^{q'}(0)}{A_{n0}^q(0)}$$

- at $x = 1$ a single quark carries all the momentum

$$\lim_{x \rightarrow 1} q(x, \vec{b}_\perp) \propto \delta^2(\vec{b}_\perp)$$

- higher moments A_{n0}^q weight $x \sim 1$ more heavily

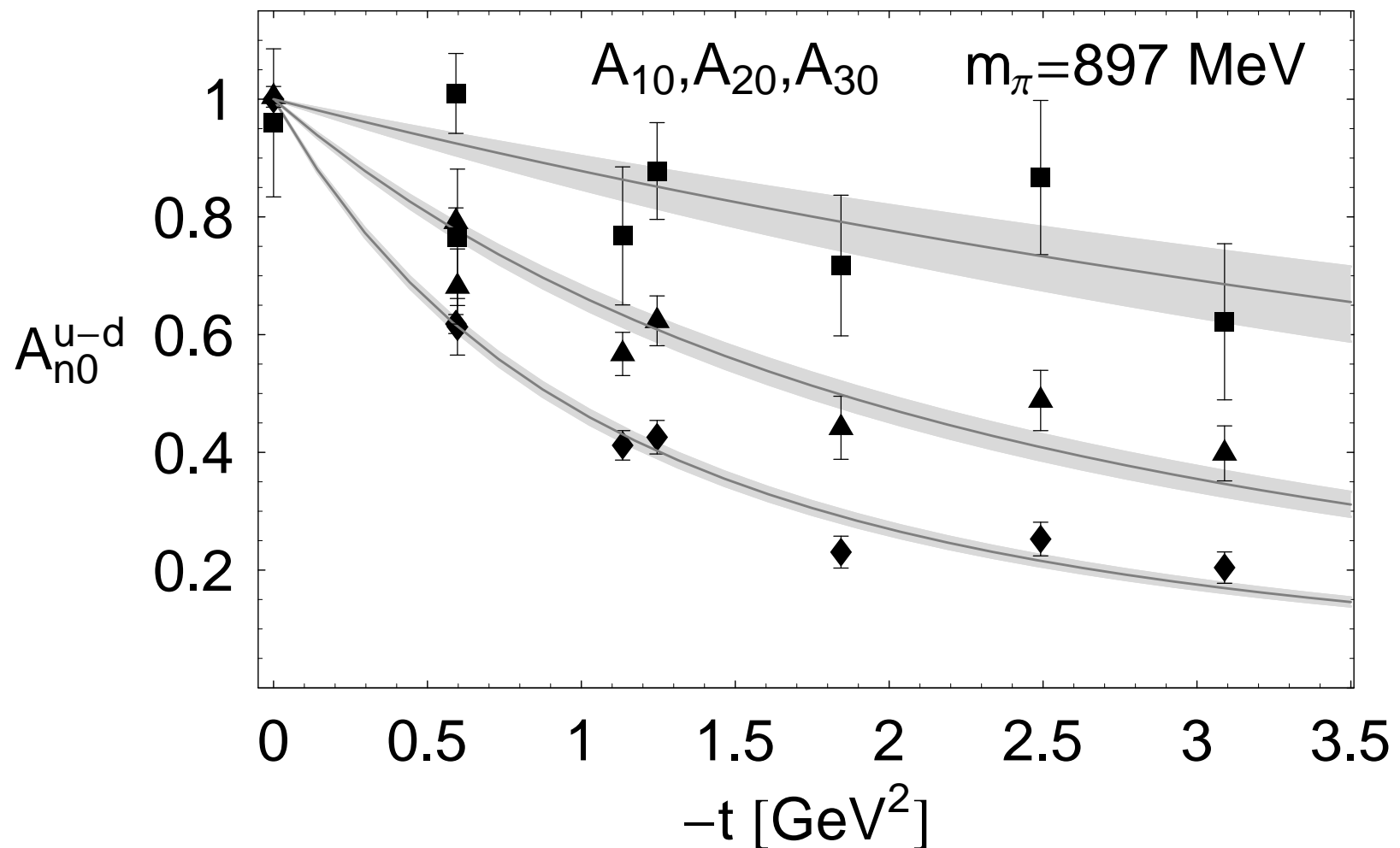
$$\lim_{n \rightarrow \infty} A_{n0}^q(t) \propto \int d^2b_\perp e^{i\vec{\Delta}_\perp \cdot \vec{b}_\perp} \delta^2(\vec{b}_\perp) = \text{constant}$$

- slopes of A_{n0}^q should decrease as n increases

- $A_{10}, A_{30}, \tilde{A}_{20}$ measure $q - \bar{q}$ & $\tilde{A}_{10}, \tilde{A}_{30}, A_{20}$ measure $q + \bar{q}$

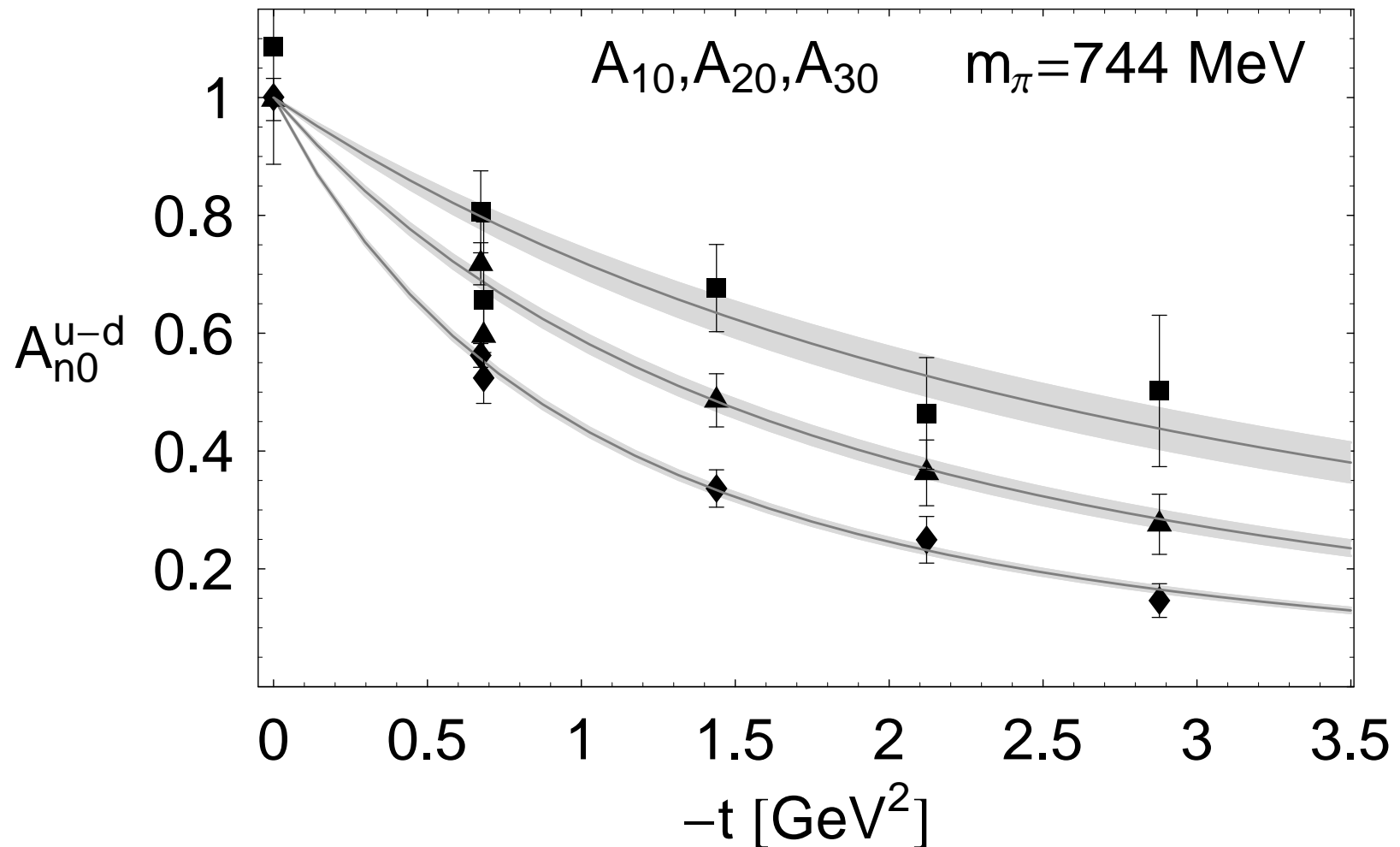
Transverse Distributions: $m_\pi = 897$ MeV

- slope of $A_{10}^{u-d} = -0.93 \pm 0.04$ (GeV) $^{-2}$
- slope of $A_{30}^{u-d} = -0.13 \pm 0.03$ (GeV) $^{-2}$ (factor of 7)



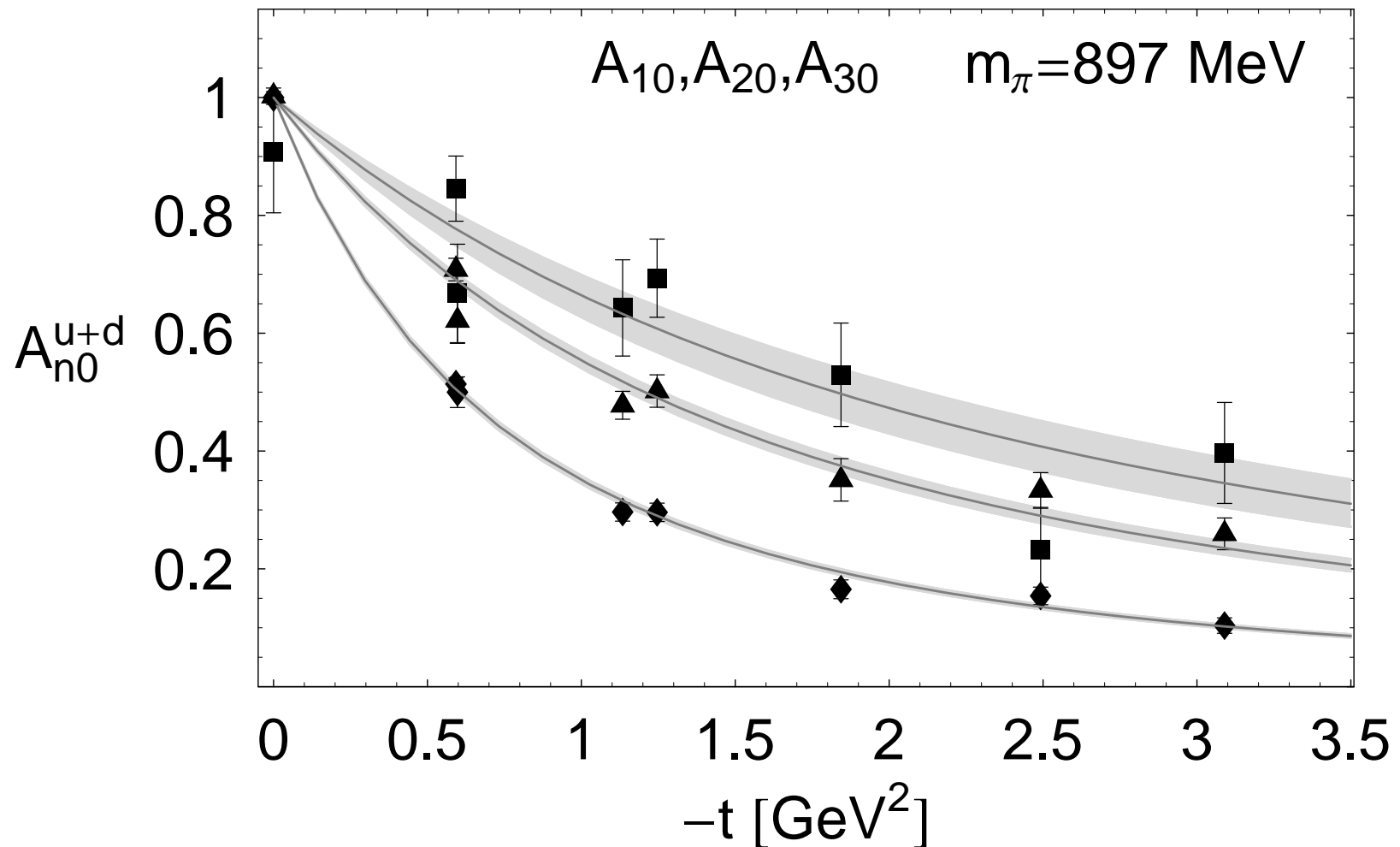
Transverse Distributions: Mass Dependence

- slope of $A_{10}^{u-d} = -1.02 \pm 0.03 \text{ (GeV)}^{-2}$
- slope of $A_{30}^{u-d} = -0.36 \pm 0.04 \text{ (GeV)}^{-2}$ (factor of 3)



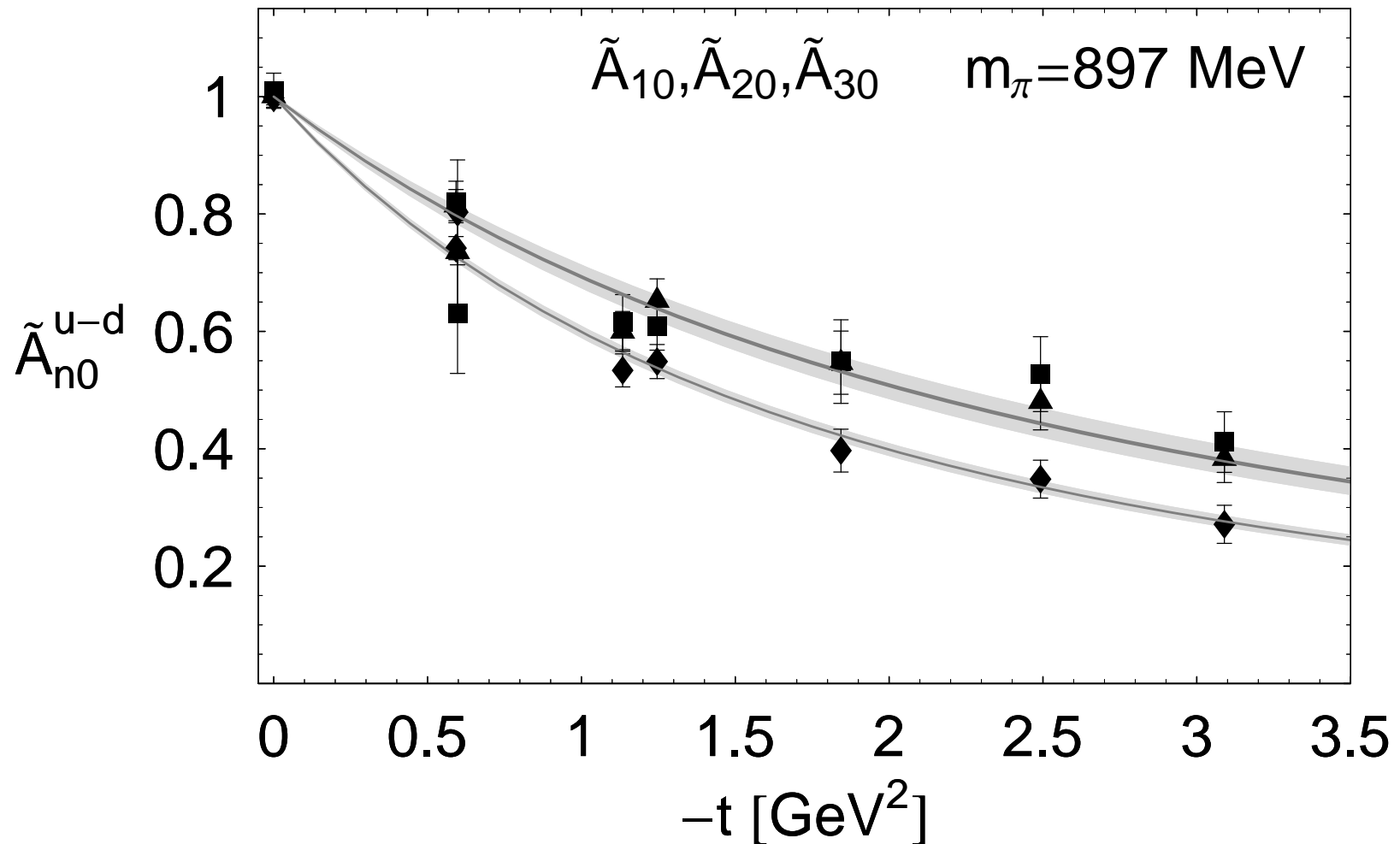
Transverse Distributions: Flavor Dependence

- slope of $A_{10}^{u+d} = -1.38 \pm 0.03 \text{ (GeV)}^{-2}$
- slope of $A_{30}^{u+d} = -0.45 \pm 0.07 \text{ (GeV)}^{-2}$ (factor of 3)



Transverse Distributions: Spin Dependence

- slope of $\tilde{A}_{10}^{u-d} = -0.58 \pm 0.02 \text{ (GeV)}^{-2}$
- slope of $\tilde{A}_{30}^{u-d} = -0.40 \pm 0.03 \text{ (GeV)}^{-2}$ (factor of 1.5)



Transverse Distributions: x Dependence

- transverse rms radius

$$\langle b_{\perp}^2 \rangle_x = \frac{\int d^2 b_{\perp} b_{\perp}^2 q(x, \vec{b}_{\perp})}{\int d^2 b_{\perp} q(x, \vec{b}_{\perp})}$$

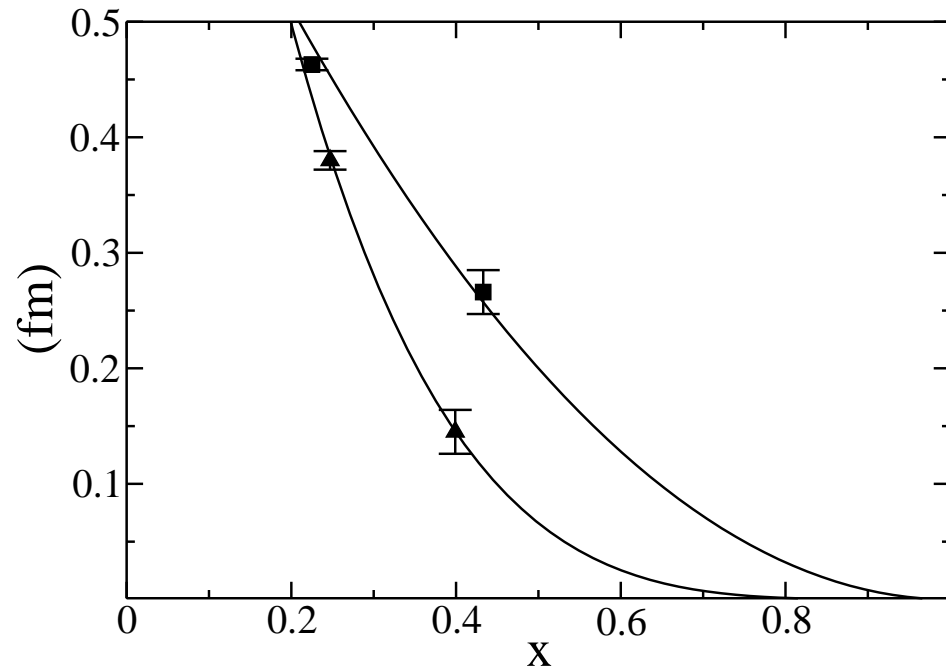
- transverse rms *moment* radius

$$\frac{A'_{n0}(0)}{A_{n0}(0)} = -\frac{1}{4} \langle b_{\perp}^2 \rangle_{(n)} \quad \langle b_{\perp}^2 \rangle_{(n)} = \frac{\int d^2 b_{\perp} b_{\perp}^2 \int_{-1}^1 dx x^{n-1} q(x, \vec{b}_{\perp})}{\int d^2 b_{\perp} \int_{-1}^1 dx x^{n-1} q(x, \vec{b}_{\perp})}$$

- the average x in $\langle b_{\perp}^2 \rangle_{(n)}$

$$x_{\text{av}}^{(n)} = \frac{\int d^2 b_{\perp} \int_{-1}^1 dx |x| \cdot x^{n-1} q(x, \vec{b}_{\perp})}{\int d^2 b_{\perp} \int_{-1}^1 dx x^{n-1} q(x, \vec{b}_{\perp})} \approx \frac{\langle x^n \rangle}{\langle x^{n-1} \rangle}$$

Transverse Distributions: x Dependence

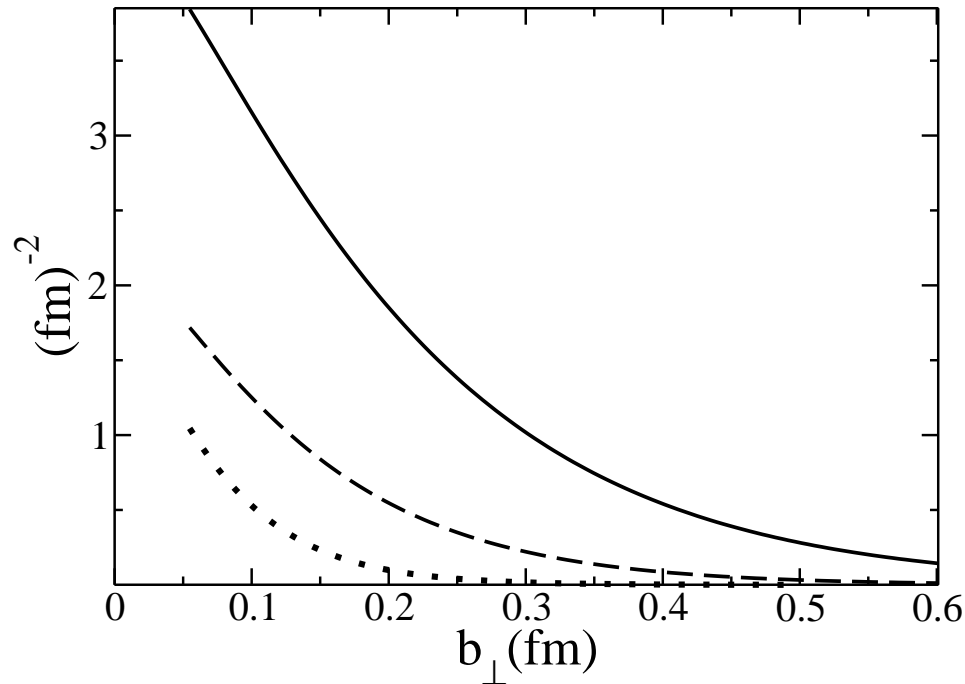


- non-singlet radius: $\sqrt{\langle b_{\perp}^2 \rangle_{u-d}^{(1)}} = 0.38 \text{ fm}$ & $\sqrt{\langle b_{\perp}^2 \rangle_{u-d}^{(3)}} = 0.15 \text{ fm}$,
61% decrease
- singlet radius: $\sqrt{\langle b_{\perp}^2 \rangle_{u+d}^{(1)}} = 0.46 \text{ fm}$ & $\sqrt{\langle b_{\perp}^2 \rangle_{u+d}^{(3)}} = 0.27 \text{ fm}$,
41% decrease

Transverse Distributions: \vec{b}_\perp Dependence

$$q_1(\vec{b}_\perp) = \int_{-1}^1 dx q(x, \vec{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} A_{10}^q(-\vec{\Delta}_\perp^2)$$

$$q_2(\vec{b}_\perp) = \int_{-1}^1 dx x q(x, \vec{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} A_{20}^q(-\vec{\Delta}_\perp^2)$$

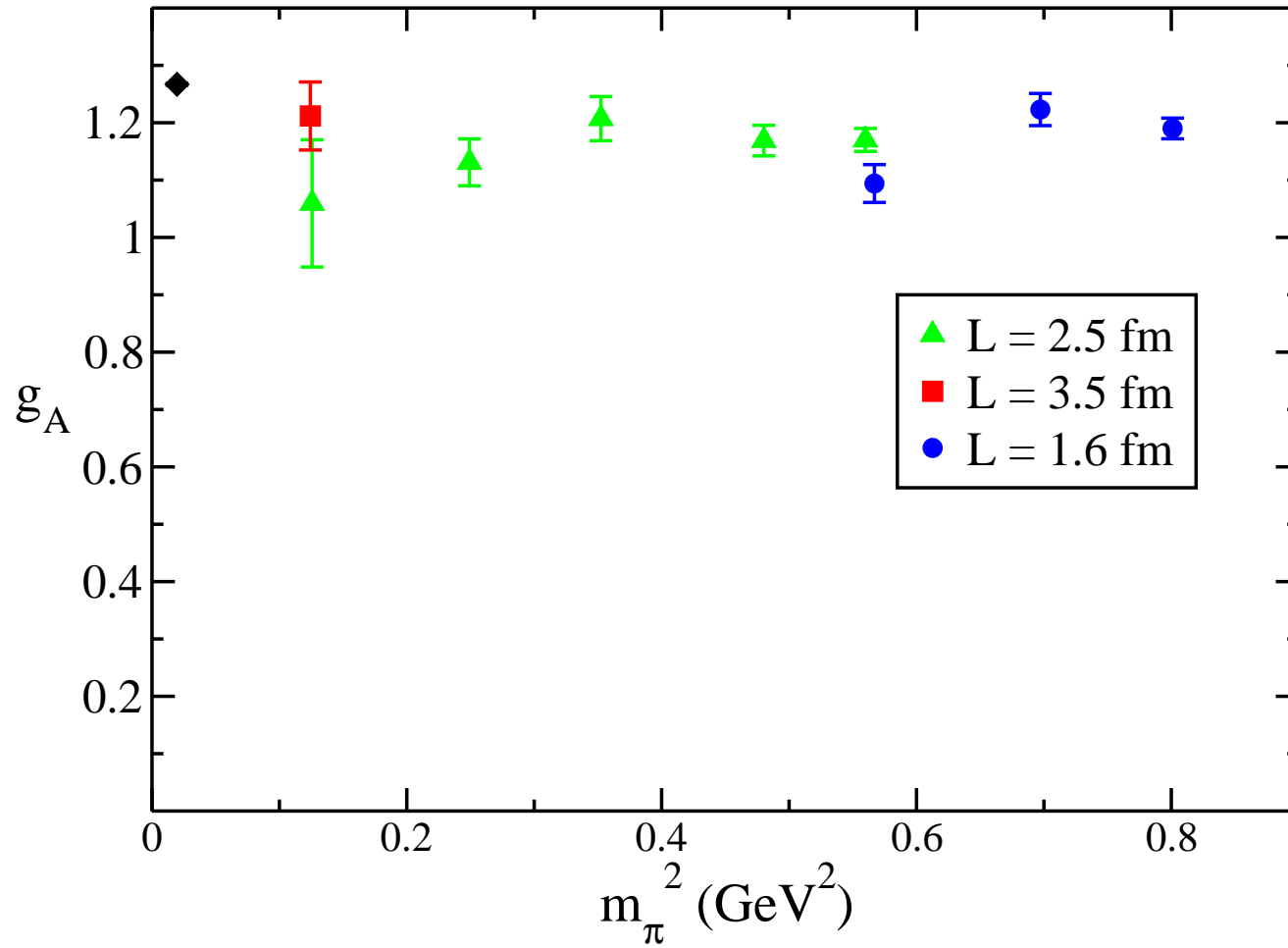


What about the chiral limit?

Calculations with Light-*ish* Quarks

- Kogut-Susskind sea quarks and domain wall valence quarks
- flavors: $N_F = 2 + 1$
- lattice spacing: $a = 0.13$ fm
- lattice sizes: $L = 2.6$ fm and $L = 3.6$ fm
- pion masses: $M_\pi = 329(15), 354(3), 564(2), 693(3), 730(3)$ MeV

Axial Charge g_A



Conclusions

- unambiguous observation of quark orbital motion, $L^{u-d} = -0.193(32)$, for even heavy pion masses
- the transverse size of the nucleon, $\sqrt{\langle r_{\perp}^2 \rangle}$, in the heavy pion world, shows a significant dependence on the longitudinal momentum fraction $\langle x \rangle$
- current and ongoing calculations are exploring the chiral limit of these and other observables, for example g_A

Extra Slides

Moments of Generalized Parton Distributions

- moments of generalized parton distributions

$$\int_{-1}^1 dx x^{n-1} H_q(x, \xi, t) = \sum_{\substack{i=0 \\ \text{even}}}^{n-1} A_{ni}^q(t) (-2\xi)^i + \delta_{\text{even}}^n C_n^q(t) (-2\xi)^n$$

$$\int_{-1}^1 dx x^{n-1} E_q(x, \xi, t) = \sum_{\substack{i=0 \\ \text{even}}}^{n-1} B_{ni}^q(t) (-2\xi)^i - \delta_{\text{even}}^n C_n^q(t) (-2\xi)^n$$

- transverse momentum transfer, $\xi \rightarrow 0$

$$\int_{-1}^1 dx x^{n-1} H_q(x, 0, t) = A_{n0}^q(t)$$

$$\int_{-1}^1 dx x^{n-1} E_q(x, 0, t) = B_{n0}^q(t)$$

- similar results relating the polarized GPDs, $\tilde{H}_q(x, 0, t)$ and $\tilde{E}_q(x, 0, t)$, to the polarized GFFs, $\tilde{A}_{n0}^q(t)$ and $\tilde{B}_{n0}^q(t)$

Quark Angular Momentum

- angular momentum operator

$$J_q^i = \frac{1}{2} \epsilon^{ijk} \int d^3x \left(T_q^{0k} x^j - T_q^{0j} x^k \right)$$

- energy momentum tensor

$$T_q^{\mu\nu} = \bar{q} \gamma^{\{\mu} i D^{\nu\}} q = O_q^{\mu\nu}$$

- angular momentum

$$J_q = \langle P, 1/2 | J_q^z | P, 1/2 \rangle \text{ involves } \langle P, 1/2 | O_q^{\mu\nu} | P, 1/2 \rangle$$

- matrix elements of $n = 2$ twist 2 operator $O_q^{\mu\nu}$: $A_{20}(t)$, $B_{20}(t)$, $C_2(t)$

$$J_q = \frac{1}{2} \left(A_{20}^q(0) + B_{20}^q(0) \right)$$

Transverse Quark Distribution

- wave packet in transverse coordinates

$$|\psi\rangle = \int \frac{d^2 p_\perp}{(2\pi)} \frac{\psi(\vec{p}_\perp)}{\sqrt{2E_{\vec{p}}}} |\vec{p}_\perp, P_z\rangle \quad \vec{p} = (\vec{p}_\perp, P_z)$$

- transverse quark distribution

$$q_\psi(x, \vec{b}_\perp) = \langle \psi | O_q(x, \vec{b}_\perp) | \psi \rangle \quad \text{involves} \quad \langle \vec{k}_\perp, P_z | O_q(x, \vec{b}_\perp) | \vec{p}_\perp, P_z \rangle$$

- infinite momentum limit & transverse localization

$$M \ll P_z \quad \psi(\vec{k}_\perp) \approx \psi(\vec{p}_\perp)$$

- matrix elements of $O_q(x, \vec{b}_\perp)$: $H_q(x, \xi, t)$, $E_q(x, \xi, t)$

$$q(x, \vec{b}_\perp) = \int d^2 \Delta_\perp e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} H_q(x, 0, -\vec{\Delta}_\perp^2)$$

- relativistic corrections controlled by

$$\frac{1}{\sqrt{M^2 + P_z^2}} \quad \text{not} \quad \frac{1}{M}$$