Quark transverse dynamics in hadrons from Lattice QCD

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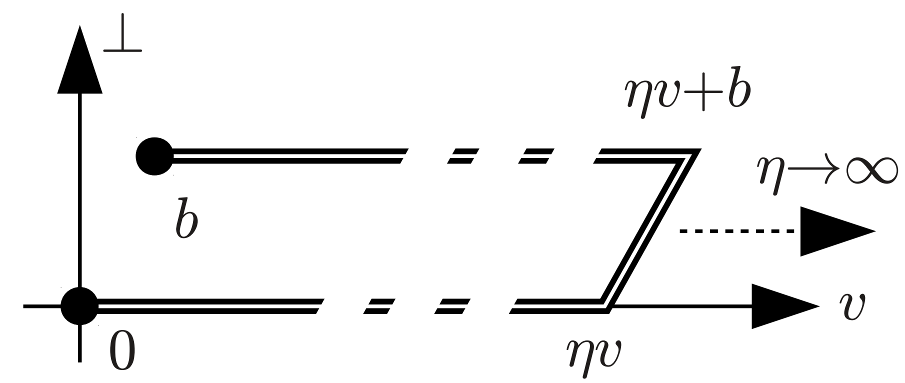
Fundamental TMD correlator

$$\widetilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}(b,P,S,\ldots) \equiv \frac{1}{2}\langle P,S|\ \bar{q}(0)\ \Gamma\ \mathcal{U}[0,\ldots,b]\ q(b)\ |P,S\rangle$$

$$\Phi^{[\Gamma]}(x,k_T,P,S,\ldots) \equiv \int \frac{d^2 b_T}{(2\pi)^2} \int \frac{d(b\cdot P)}{(2\pi)P^+} \exp\left(ix(b\cdot P) - ib_T\cdot k_T\right) \left.\frac{\widetilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}(b,P,S,\ldots)}{\widetilde{\mathcal{S}}(b^2,\ldots)}\right|_{b^+=0}$$

- "Soft factor" $\widetilde{\mathcal{S}}$ required to subtract divergences of Wilson line $\mathcal{U}$
- $\widetilde{\mathcal{S}}$ is typically a combination of vacuum expectation values of Wilson line structures
- Here, will consider only ratios in which soft factors cancel

Gauge link structure motivated by SIDIS



Beyond tree level: Rapidity divergences suggest taking staple direction slightly off the light cone. Approach of Aybat, Collins, Qiu, Rogers makes v space-like. Parametrize in terms of Collins-Soper parameter

$$\hat{\zeta} \equiv \frac{P \cdot v}{|P||v|}$$

Light-like staple for $\hat{\zeta} \to \infty$. Perturbative evolution equations for large $\hat{\zeta}$.

"Modified universality", $f^{\text{T-odd, SIDIS}} = -f^{\text{T-odd, DY}}$

Fundamental TMD correlator

$$\widetilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}(b,P,S,\ldots) \equiv \frac{1}{2}\langle P,S|\ \bar{q}(0)\ \Gamma\ \mathcal{U}[0,\eta v,\eta v+b,b]\ q(b)\ |P,S\rangle$$

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Decomposition of Φ into TMDs

All leading twist structures:

$$\Phi^{[\gamma^+]} = f_1 - \left[\frac{\epsilon_{ij} k_i S_j}{m_H} f_{1T}^{\perp}\right] \text{odd}$$

$$\Phi^{[\gamma^+\gamma^5]} = \Lambda g_1 + \frac{k_T \cdot S_T}{m_H} g_{1T}$$

$$\Phi^{[i\sigma^{i+}\gamma^5]} = S_i h_1 + \frac{(2k_i k_j - k_T^2 \delta_{ij}) S_j}{2m_H^2} h_{1T}^{\perp} + \frac{\Lambda k_i}{m_H} h_{1L}^{\perp} + \left[\frac{\epsilon_{ij} k_j}{m_H} h_1^{\perp}\right] \text{odd}$$

TMD Classification

All leading twist structures:

H $\downarrow$ \ $q \rightarrow$	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$\longleftarrow$ Boer-Mulders (T-odd)

$\uparrow$ Sivers (T-odd)

Decomposition of $\widetilde{\Phi}$ into amplitudes

$$\widetilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}(b, P, S, \hat{\zeta}, \mu) \equiv \frac{1}{2}\langle P, S|\ \bar{q}(0)\ \Gamma\ \mathcal{U}[0, \eta v, \eta v + b, b]\ q(b)\ |P, S\rangle$$

Decompose in terms of invariant amplitudes; at leading twist,

$$\begin{aligned}
\frac{1}{2P^+}\widetilde{\Phi}^{[\gamma^+]}_{\text{unsubtr.}} &= \widetilde{A}_{2B} + im_H\epsilon_{ij}b_iS_j\widetilde{A}_{12B} \\
\frac{1}{2P^+}\widetilde{\Phi}^{[\gamma^+\gamma^5]}_{\text{unsubtr.}} &= -\Lambda\widetilde{A}_{6B} + i[(b\cdot P)\Lambda - m_H(b_T\cdot S_T)]\widetilde{A}_{7B} \\
\frac{1}{2P^+}\widetilde{\Phi}^{[i\sigma^{i+}\gamma^5]}_{\text{unsubtr.}} &= im_H\epsilon_{ij}b_j\widetilde{A}_{4B} - S_i\widetilde{A}_{9B} \\
&\quad -im_H\Lambda b_i\widetilde{A}_{10B} + m_H[(b\cdot P)\Lambda - m_H(b_T\cdot S_T)]b_i\widetilde{A}_{11B}
\end{aligned}$$

(Decompositions analogous to work by Metz et al. in momentum space)

Relation between Fourier-transformed TMDs and invariant amplitudes $\widetilde{A}_i$

Invariant amplitudes directly give selected x-integrated TMDs in Fourier (b_T) space (showing just the ones relevant for Sivers, Boer-Mulders shifts), up to soft factors:

$$\tilde{f}_1^{[1](0)}(b_T^2, \hat{\zeta}, \ldots, \eta v \cdot P) = 2\widetilde{A}_{2B}(-b_T^2, 0, \hat{\zeta}, \eta v \cdot P)/\widetilde{S}(b^2, \ldots)$$

$$\tilde{f}_{1T}^{\perp[1](1)}(b_T^2, \hat{\zeta}, \ldots, \eta v \cdot P) = -2\widetilde{A}_{12B}(-b_T^2, 0, \hat{\zeta}, \eta v \cdot P)/\widetilde{S}(b^2, \ldots)$$

$$\tilde{h}_1^{\perp[1](1)}(b_T^2, \hat{\zeta}, \ldots, \eta v \cdot P) = 2\widetilde{A}_{4B}(-b_T^2, 0, \hat{\zeta}, \eta v \cdot P)/\widetilde{S}(b^2, \ldots)$$

Generalized shifts

Form ratios in which soft factors, (Γ-independent) multiplicative renormalization factors cancel

Boer-Mulders shift:

$$\langle k_y \rangle_{UT} \equiv m_H \frac{\tilde{h}_1^{\perp [1](1)}}{\tilde{f}_1^{[1](0)}} = \left. \frac{\int dx \int d^2 k_T \, k_y \Phi^{[\gamma^+ + s^j i\sigma^{j+}\gamma^5]}(x, k_T, P, \ldots)}{\int dx \int d^2 k_T \, \Phi^{[\gamma^+ + s^j i\sigma^{j+}\gamma^5]}(x, k_T, P, \ldots)} \right|_{s_T=(1,0)}$$

Average transverse momentum of quarks polarized in the orthogonal transverse ("T") direction in an unpolarized ("U") hadron; normalized to the number of valence quarks. "Dipole moment" in $b_T^2 = 0$ limit, "shift".

Issue: k_T-moments in this ratio singular; generalize to ratio of Fourier-transformed TMDs at *nonzero* b_T^2,

$$\langle k_y \rangle_{UT}(b_T^2, \ldots) \equiv m_H \frac{\tilde{h}_1^{\perp [1](1)}(b_T^2, \ldots)}{\tilde{f}_1^{[1](0)}(b_T^2, \ldots)}$$

(remember singular $b_T \to 0$ limit corresponds to taking k_T-moment). "Generalized shift".

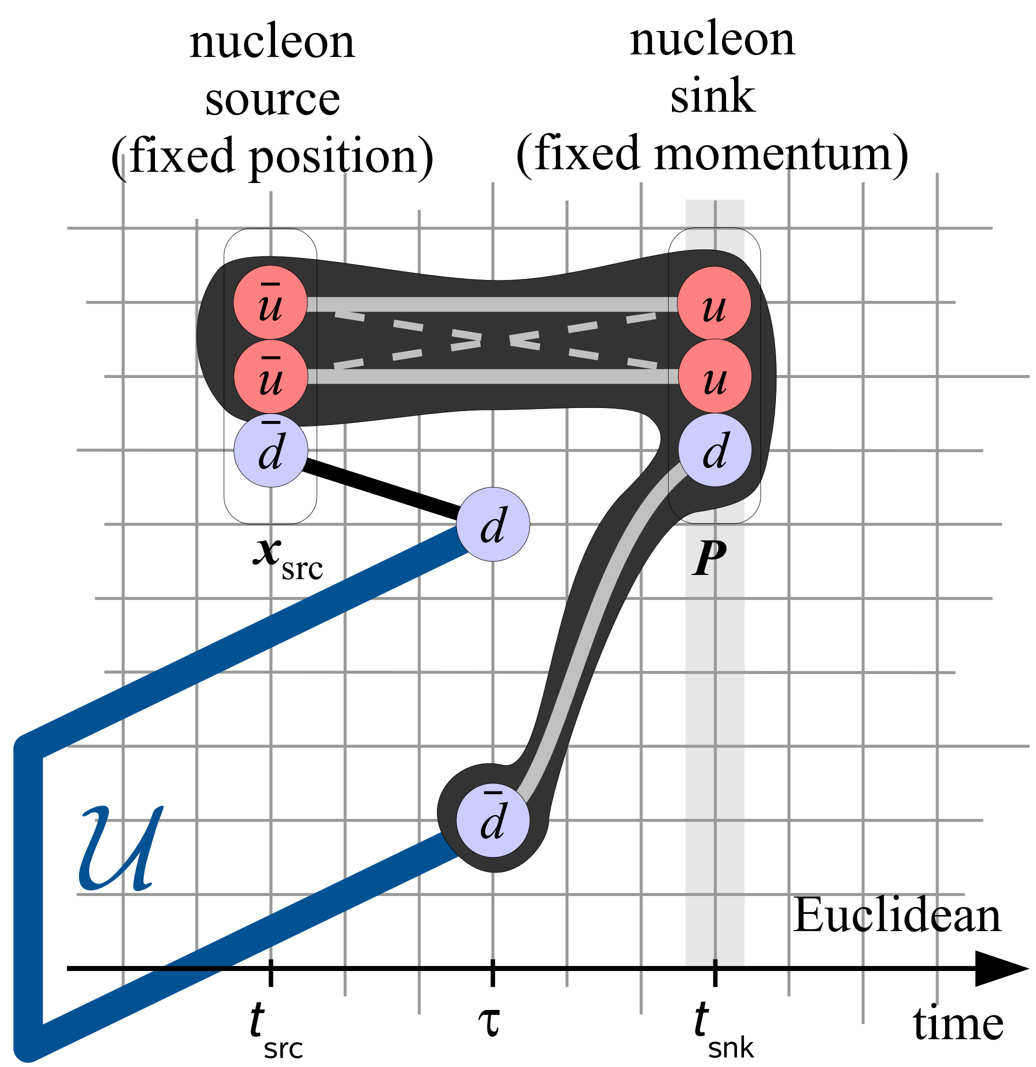
Generalized shifts from amplitudes

Now, can also express this in terms of invariant amplitudes:

$$\langle k_y \rangle_{UT}(b_T^2, \ldots) \equiv m_H \frac{\tilde{h}_1^{\perp[1](1)}(b_T^2, \ldots)}{\tilde{f}_1^{[1](0)}(b_T^2, \ldots)} = m_H \frac{\widetilde{A}_{4B}(-b_T^2, 0, \hat{\zeta}, \eta v \cdot P)}{\widetilde{A}_{2B}(-b_T^2, 0, \hat{\zeta}, \eta v \cdot P)}$$

Analogously, Sivers shift (in a polarized hadron):

$$\langle k_y \rangle_{TU}(b_T^2, \ldots) = -m_H \frac{\widetilde{A}_{12B}(-b_T^2, 0, \hat{\zeta}, \eta v \cdot P)}{\widetilde{A}_{2B}(-b_T^2, 0, \hat{\zeta}, \eta v \cdot P)}$$



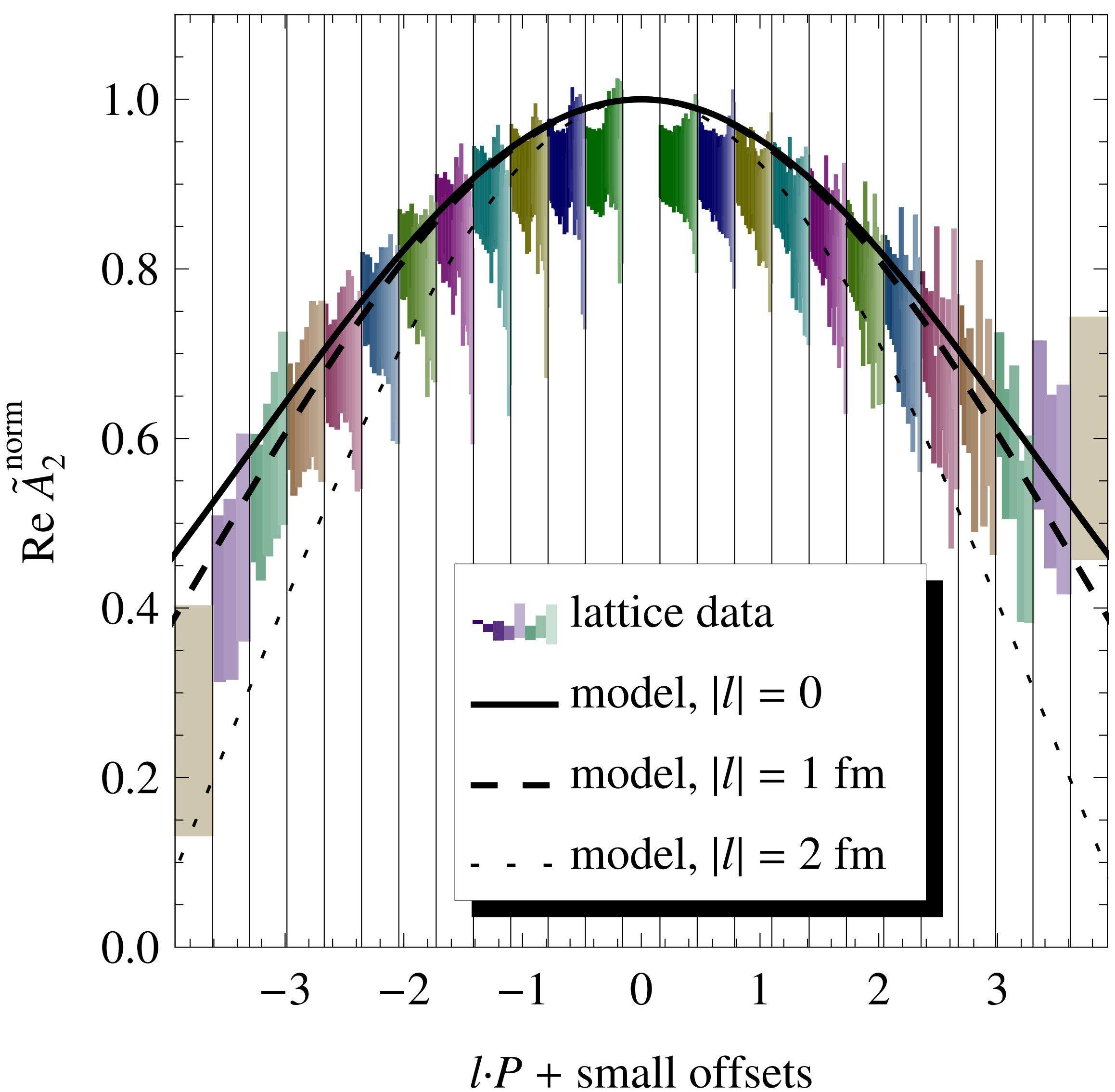
Lattice setup

- Evaluate directly $\widetilde{\Phi}^{[\Gamma]}_{\rm unsubtr.}(b, P, S, \hat{\zeta}, \mu)$

  $\equiv \frac{1}{2} \langle P, S|\ \bar{q}(0)\ \Gamma\ \mathcal{U}[0, \eta v, \eta v + b, b]\ q(b)\ |P, S\rangle$
- Euclidean time: Place entire operator at one time slice, i.e., b, ηv purely spatial
- Since generic b, v space-like, no obstacle to boosting system to such a frame!
- Parametrization of correlator in terms of $\widetilde{A}_i$ invariants permits direct translation of results back to original frame; form desired $\widetilde{A}_i$ ratios.
- Use variety of P, b, ηv; here $b \perp P$, $b \perp v$ (lowest x-moment, kinematical choices/constraints)
- Extrapolate $\eta \to \infty$, $\hat{\zeta} \to \infty$ numerically.

Memory lane: Accessing dependence on momentum fraction x

(Fourier transform of) unpolarized distribution, up quarks, normalized to unity at $l \cdot P = 0$



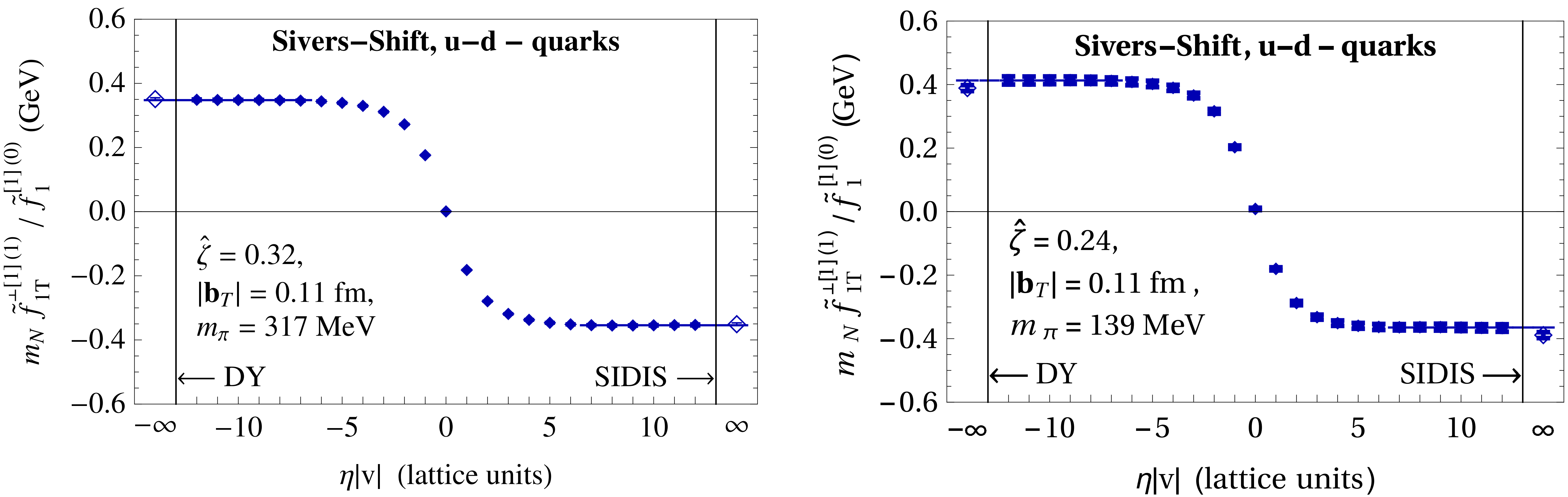
From: B. Musch, P. Hägler, J. Negele and A. Schäfer, Phys. Rev. **D 83** (2011) 094507.

Lattice: $m_\pi = 625\,\text{MeV}$
Model curves: Spectator diquark model

$l \cdot P$: Variable Fourier conjugate to momentum fraction x

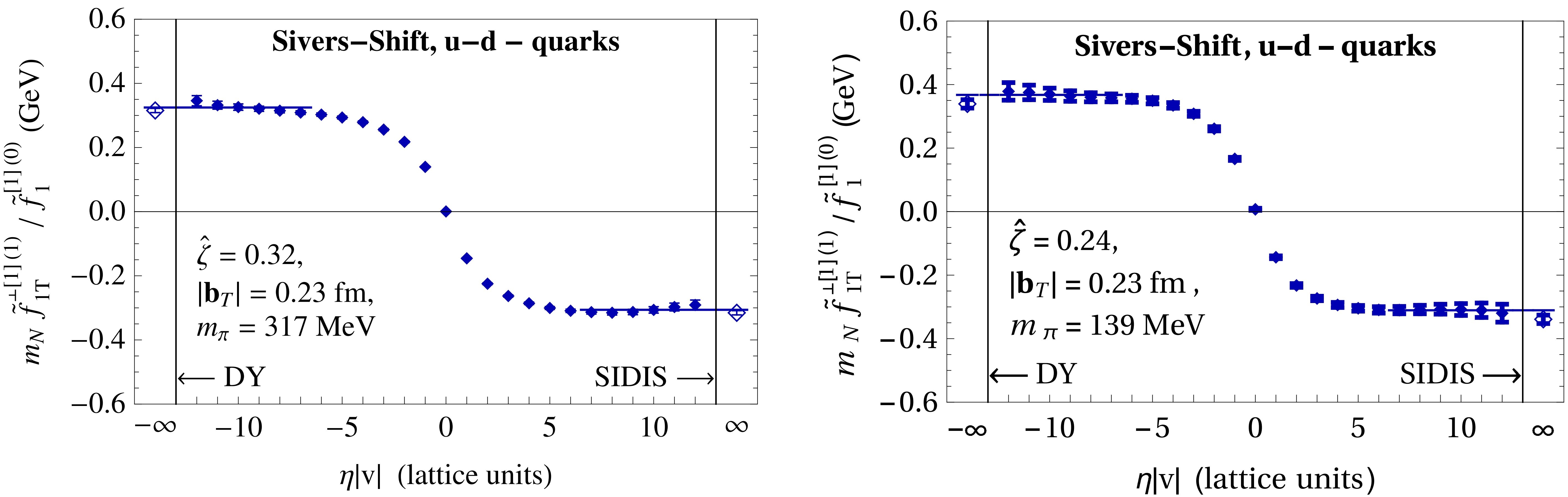
Results: Sivers shift

Dependence on staple extent; sequence of panels at different $|b_T|$



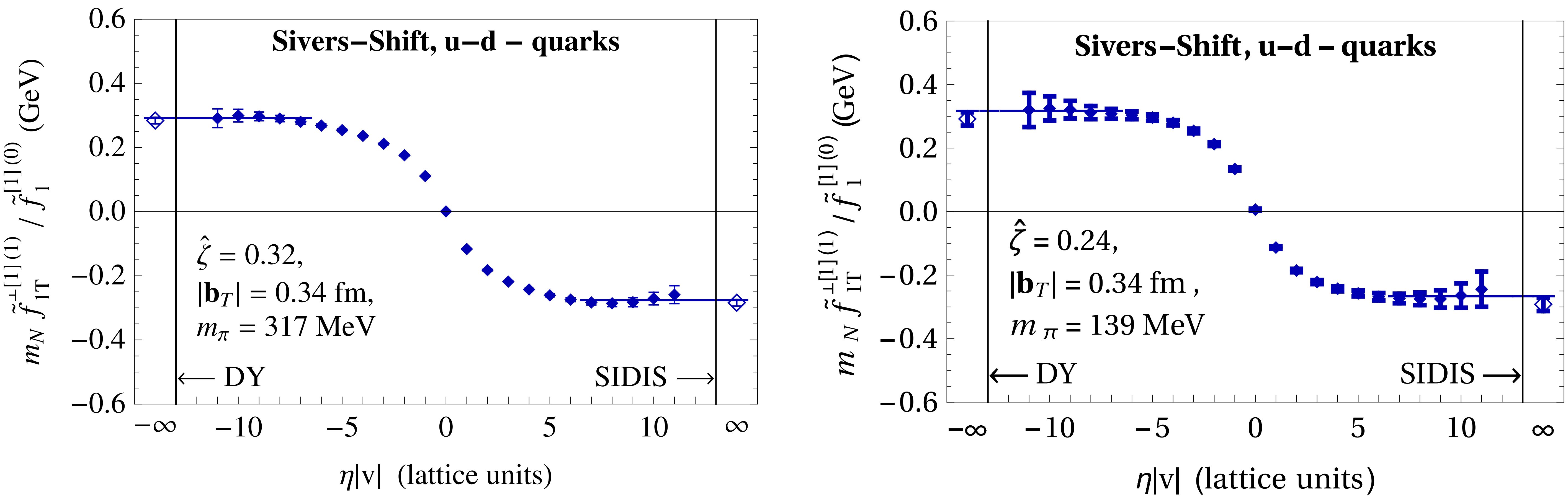
Results: Sivers shift

Dependence on staple extent; sequence of panels at different $|b_T|$



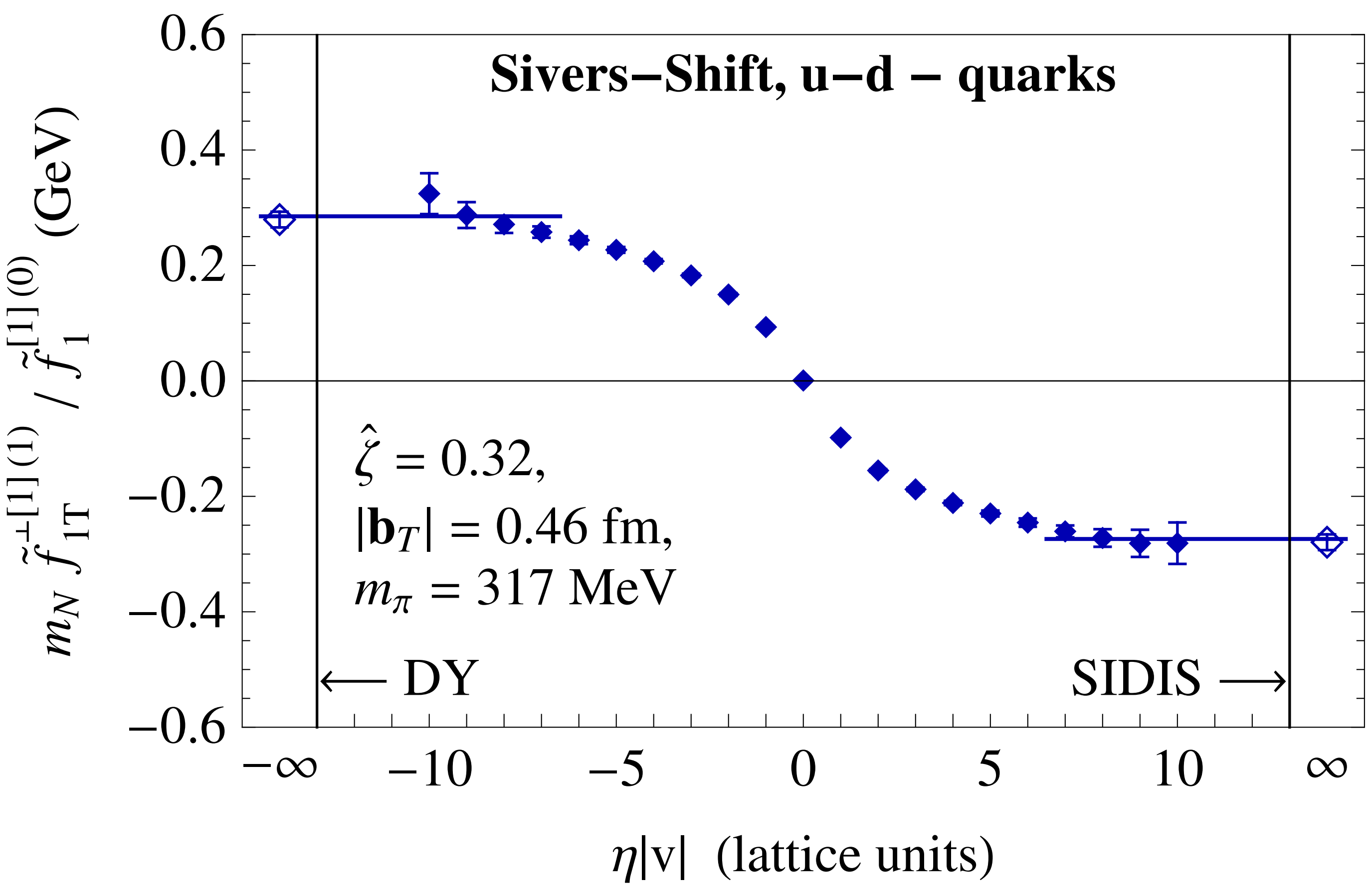
Results: Sivers shift

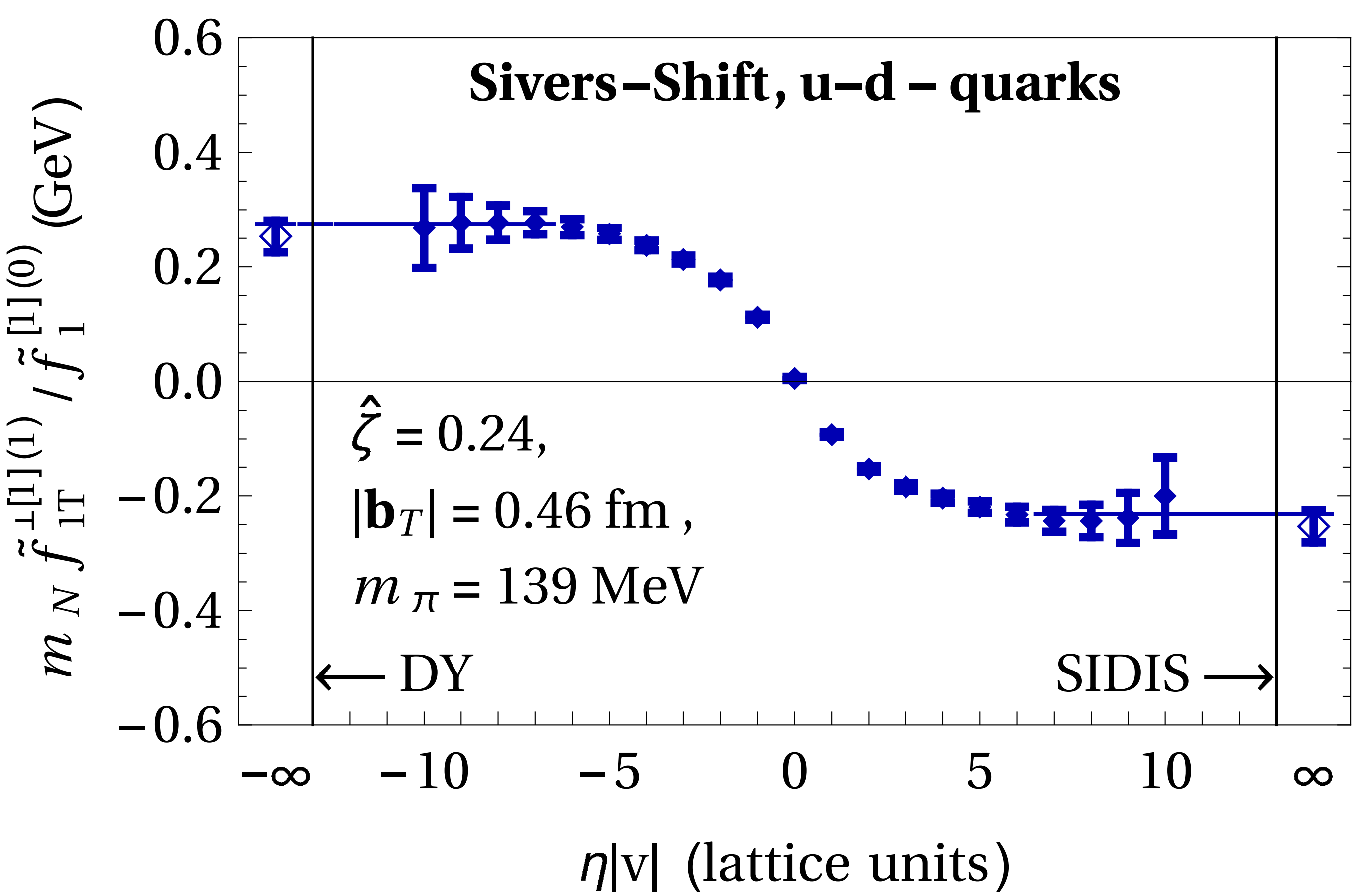
Dependence on staple extent; sequence of panels at different $|b_T|$



Results: Sivers shift

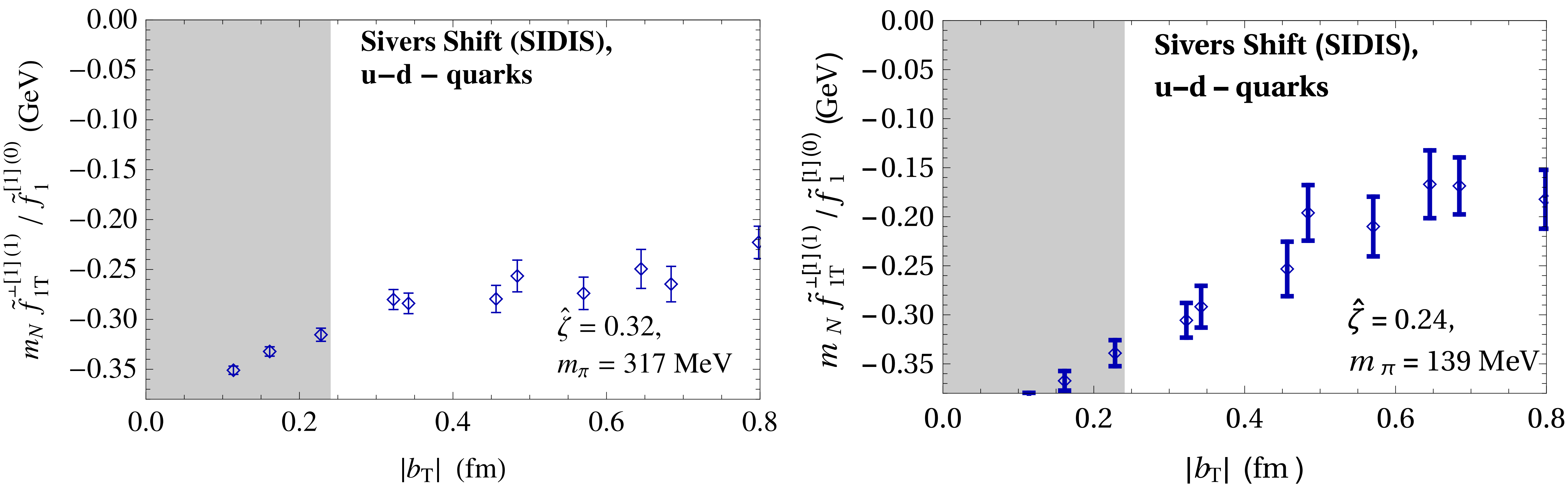
Dependence on staple extent; sequence of panels at different $|b_T|$





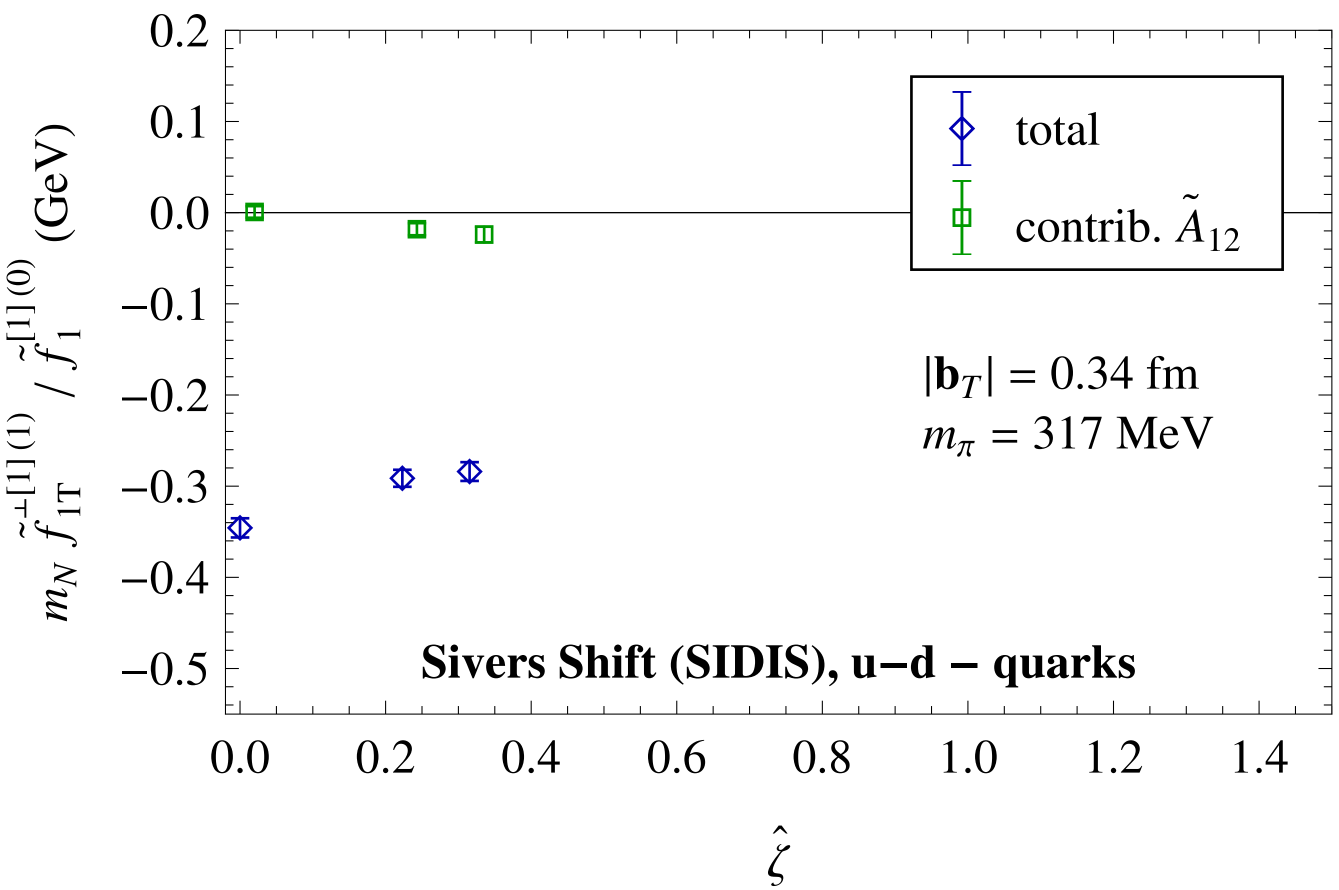
Results: Sivers shift

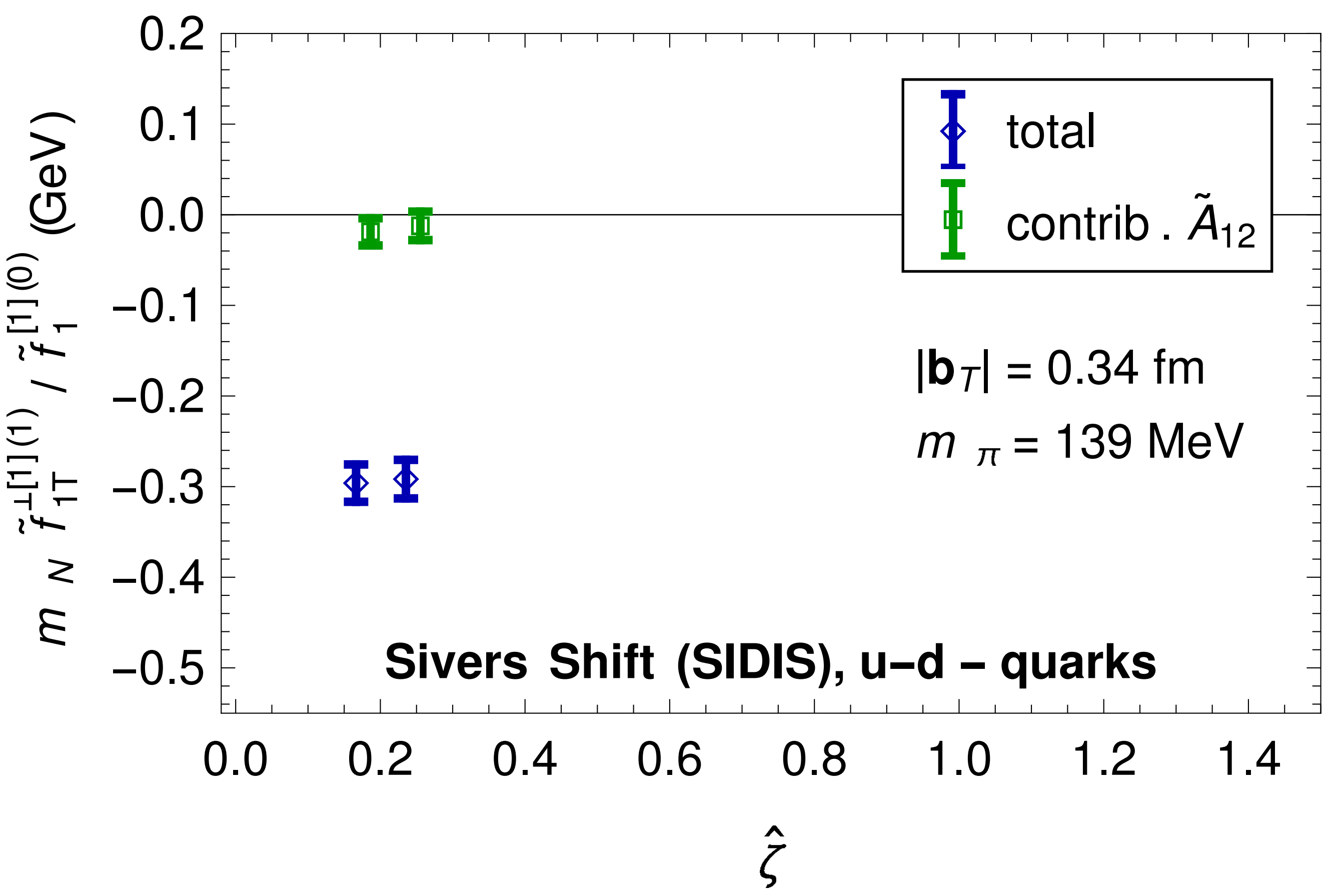
Dependence of SIDIS limit on $|b_T|$



Results: Sivers shift

Dependence of SIDIS limit on $\hat{\zeta}$

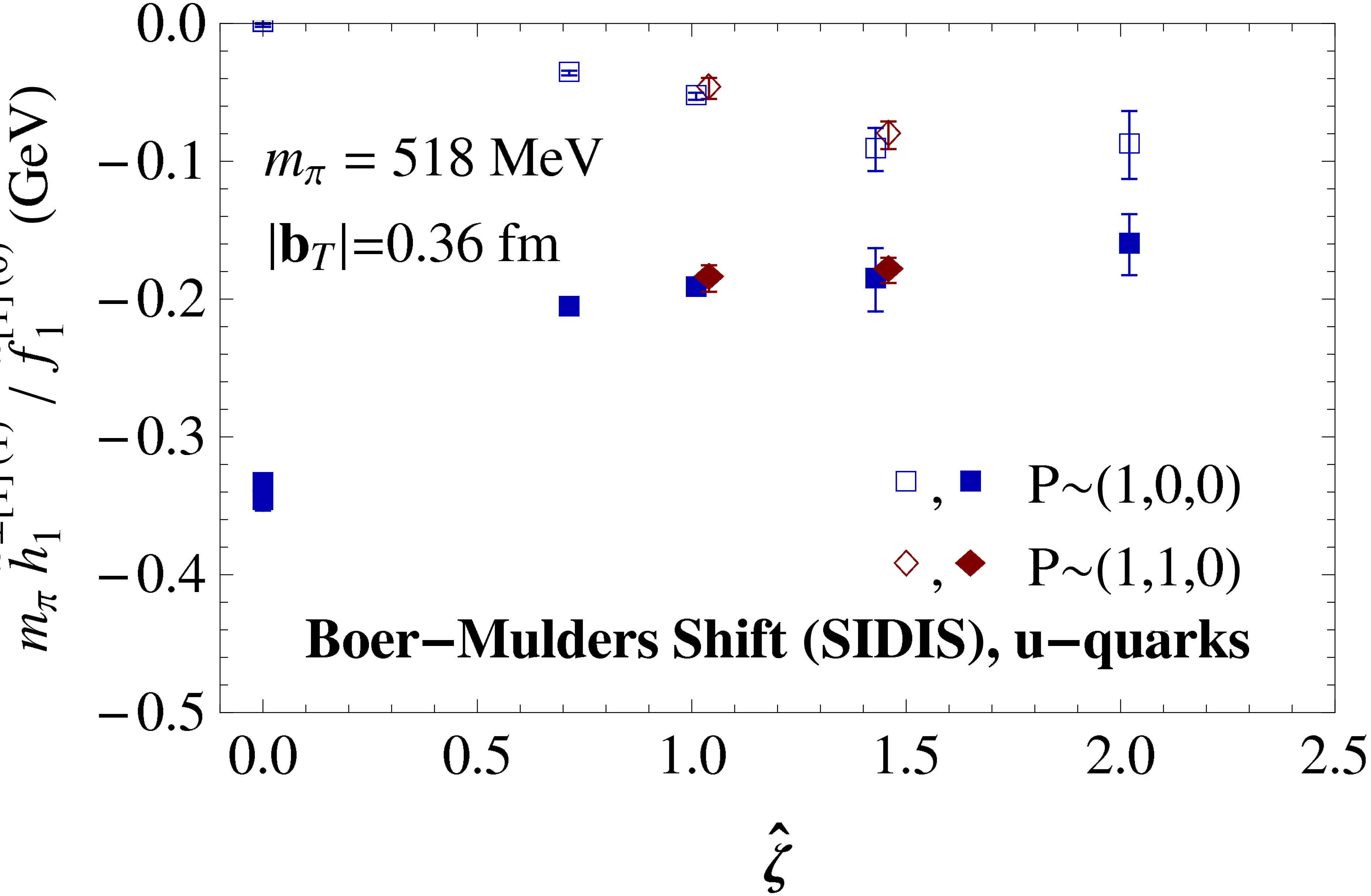




Approaching the light cone

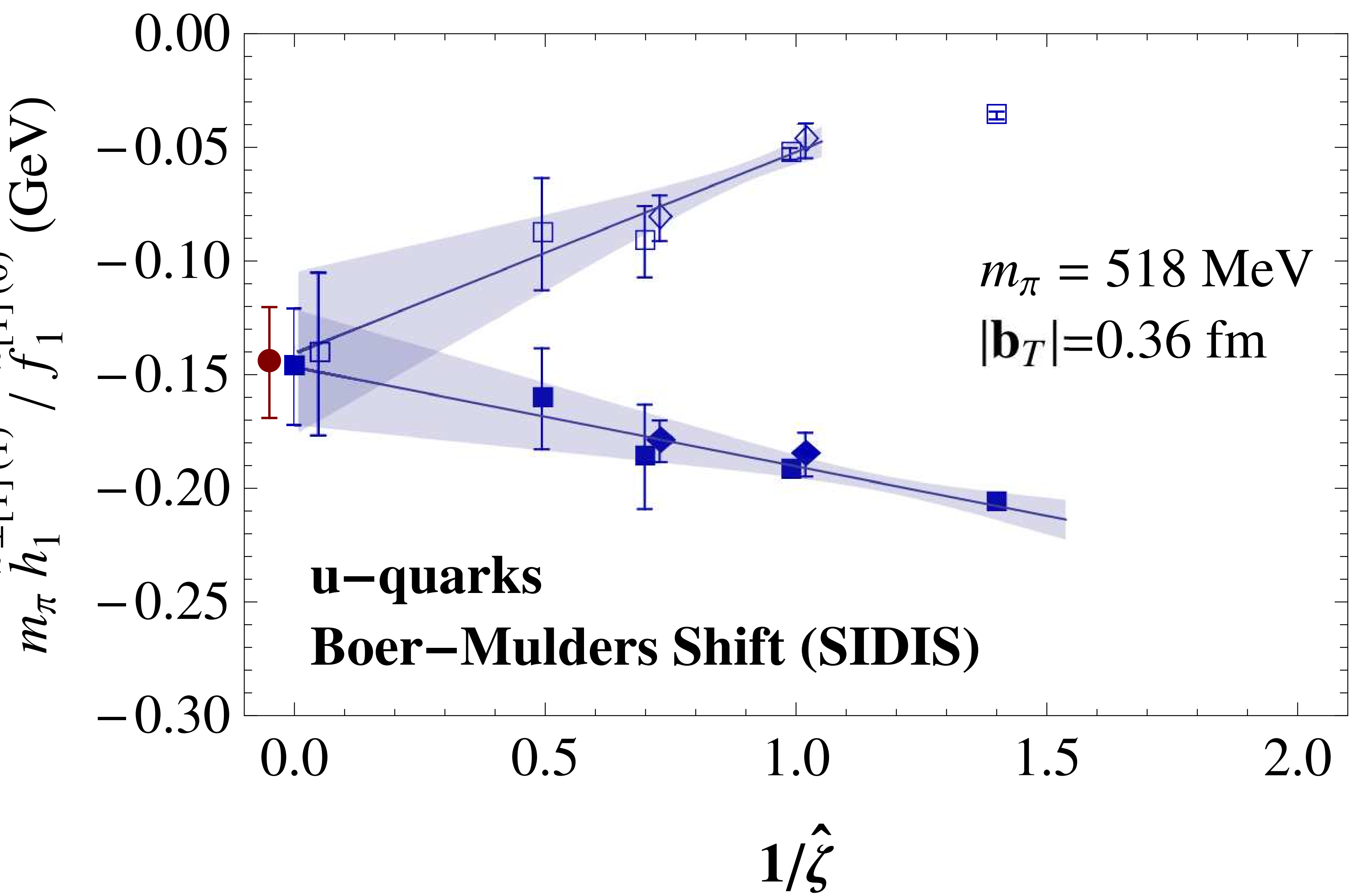
Results: Boer-Mulders shift (pion)

Dependence of SIDIS limit on $\hat{\zeta}$; open symbols: contribution $\widetilde{A}_4$ only



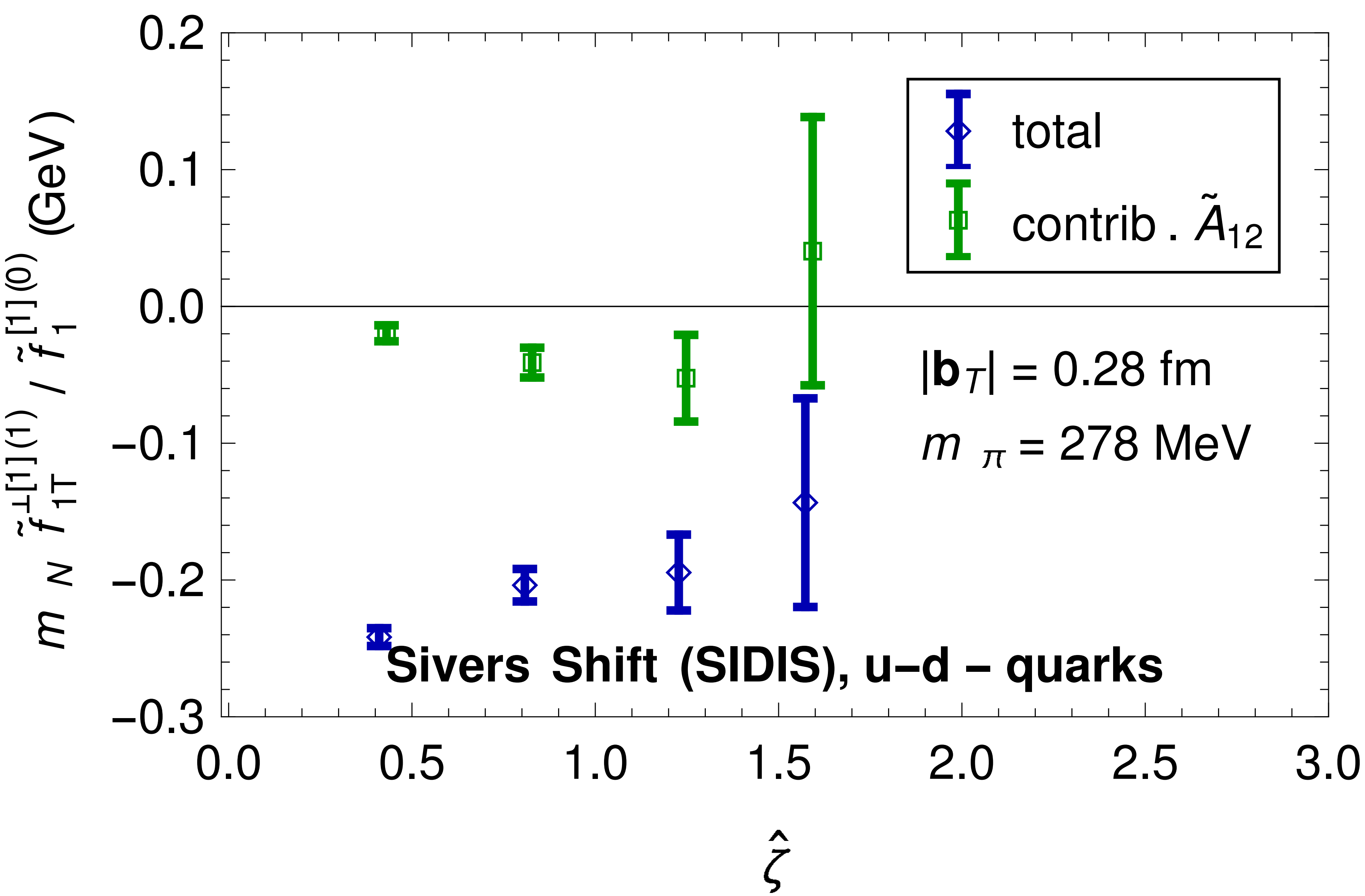
Results: Boer-Mulders shift (pion)

Dependence of SIDIS limit on $\hat{\zeta}$; fit function $a + b/\hat{\zeta}$



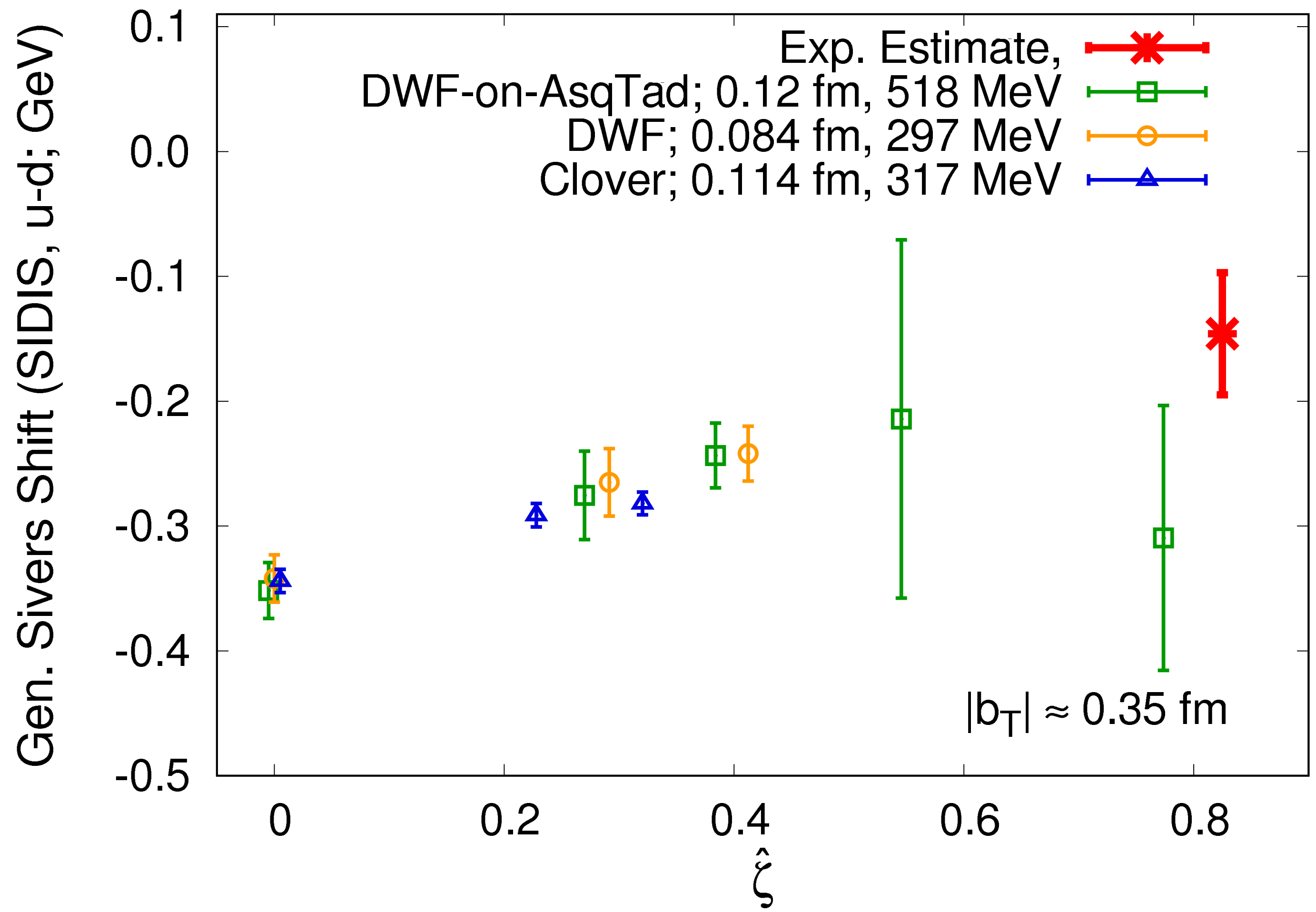
Momentum smearing - preliminary results in a nucleon

Dependence of SIDIS limit on $\hat{\zeta}$



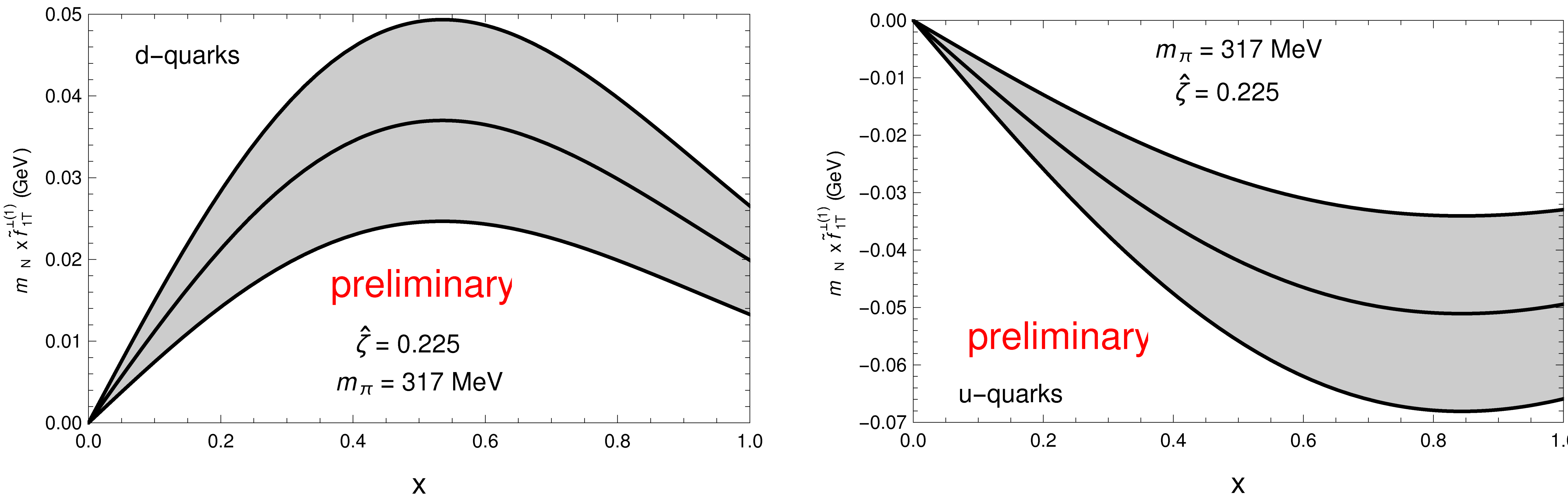
Results: Sivers shift summary

Dependence of SIDIS limit on $\hat{\zeta}$



Experimental value from global fit to HERMES, COMPASS and JLab data,
M. Echevarria, A. Idilbi, Z.-B. Kang and I. Vitev, Phys. Rev. D 89 (2014) 074013

Advertisement: Dependence of Sivers shift on momentum fraction x



Quark Orbital Angular Momentum

$$L_3^{\mathcal{U}} = \int dx \int d^2k_T \int d^2r_T \,(r_T \times k_T)_3 \, \mathcal{W}^{\mathcal{U}}(x, k_T, r_T)$$

Wigner distribution

$$= -\int dx \int d^2k_T \, \frac{k_T^2}{m^2} \, F_{14}(x, k_T^2, k_T \cdot \Delta_T, \Delta_T^2) \Big|_{\Delta_T = 0}$$

Generalized transverse momentum-dependent parton distribution (GTMD)

$$= \epsilon_{ij} \frac{\partial}{\partial z_{T,i}} \frac{\partial}{\partial \Delta_{T,j}} \langle p', S \mid \overline{\psi}(-z/2)\gamma^+ \mathcal{U}[-z/2, z/2]\psi(z/2) \mid p, S\rangle \Big|_{z^+=z^-=0\,,\ \Delta_T=0\,,\ z_T \to 0}$$

Y. Hatta, X. Ji, M. Burkardt:
Staple-shaped $\mathcal{U}[-z/2, z/2] \longrightarrow$ Jaffe-Manohar OAM
Straight $\mathcal{U}[-z/2, z/2] \longrightarrow$ Ji OAM

Connection to GTMDs – A. Metz, M. Schlegel, C. Lorcé, B. Pasquini, A. Rajan, S. Liuti, . . .

Direct evaluation of quark orbital angular momentum

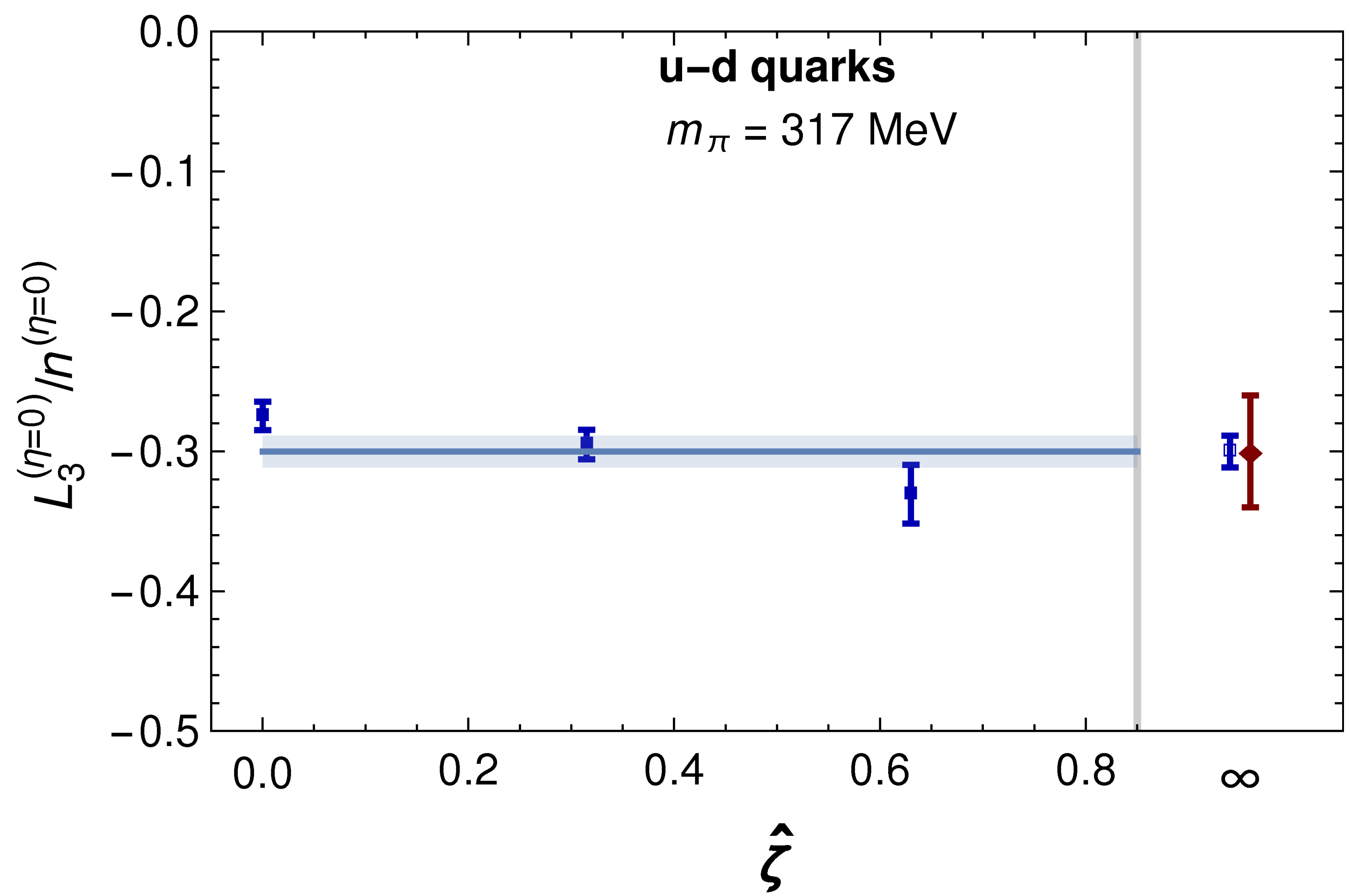
$$L_3^{\mathcal{U}} = \int dx \int d^2k_T \int d^2r_T \, (r_T \times k_T)_3 \, \mathcal{W}^{\mathcal{U}}(x, k_T, r_T) \qquad \text{Wigner distribution}$$

$$\frac{L_3^{\mathcal{U}}}{n} = \frac{\epsilon_{ij} \frac{\partial}{\partial z_{T,i}} \frac{\partial}{\partial \Delta_{T,j}} \left. \langle p', S \mid \overline{\psi}(-z/2) \gamma^+ \mathcal{U}[-z/2, z/2] \psi(z/2) \mid p, S \rangle \right|_{z^+=z^-=0\,,\ \Delta_T=0\,,\ z_T \to 0}}{\left. \langle p', S \mid \overline{\psi}(-z/2) \gamma^+ \mathcal{U}[-z/2, z/2] \psi(z/2) \mid p, S \rangle \right|_{z^+=z^-=0\,,\ \Delta_T=0\,,\ z_T \to 0}}$$

n : Number of valence quarks

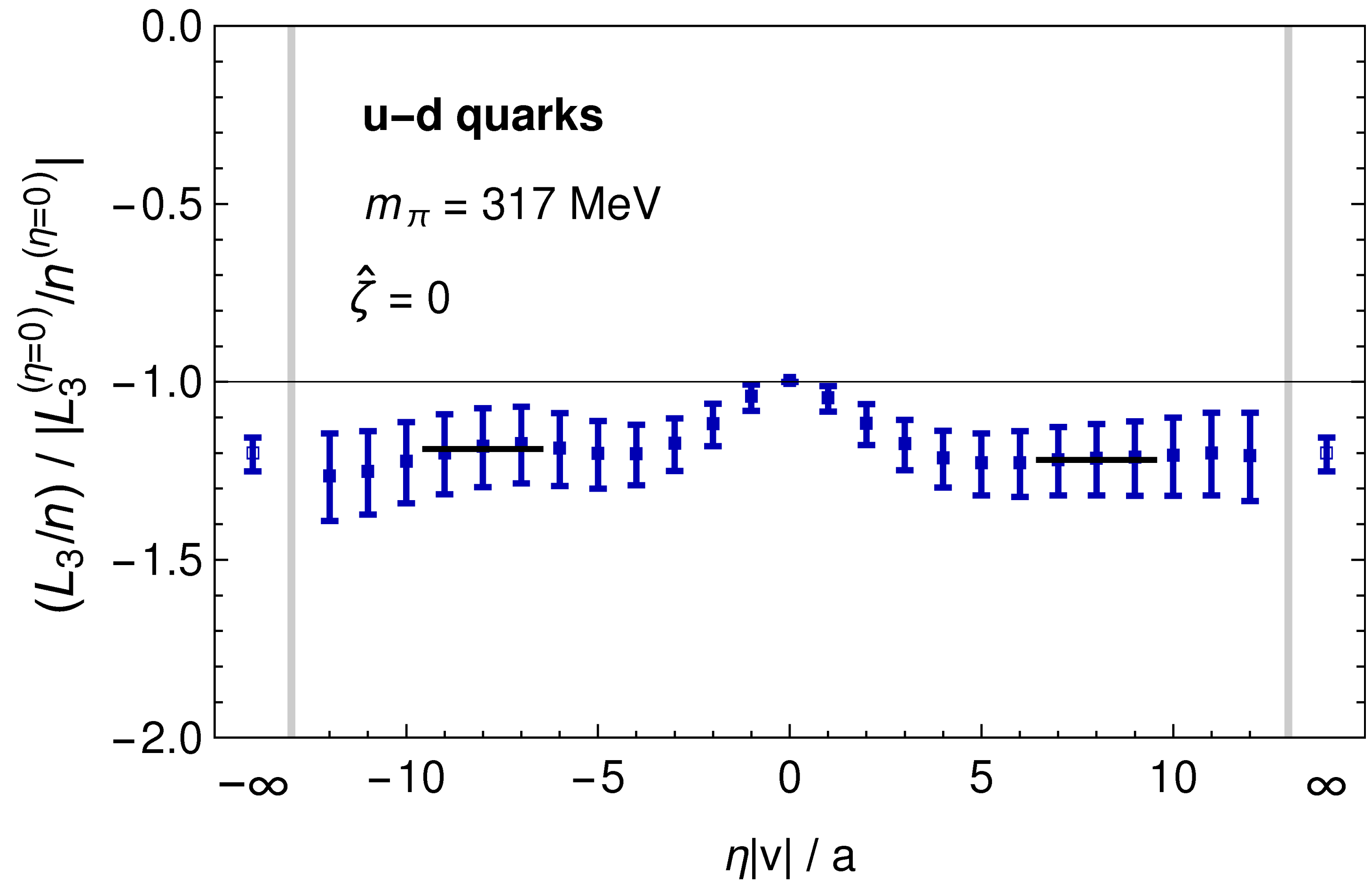
$p' = P + \Delta_T/2$, $p = P - \Delta_T/2$, P, S in 3-direction, $P \to \infty$

Ji quark orbital angular momentum: $\eta = 0$

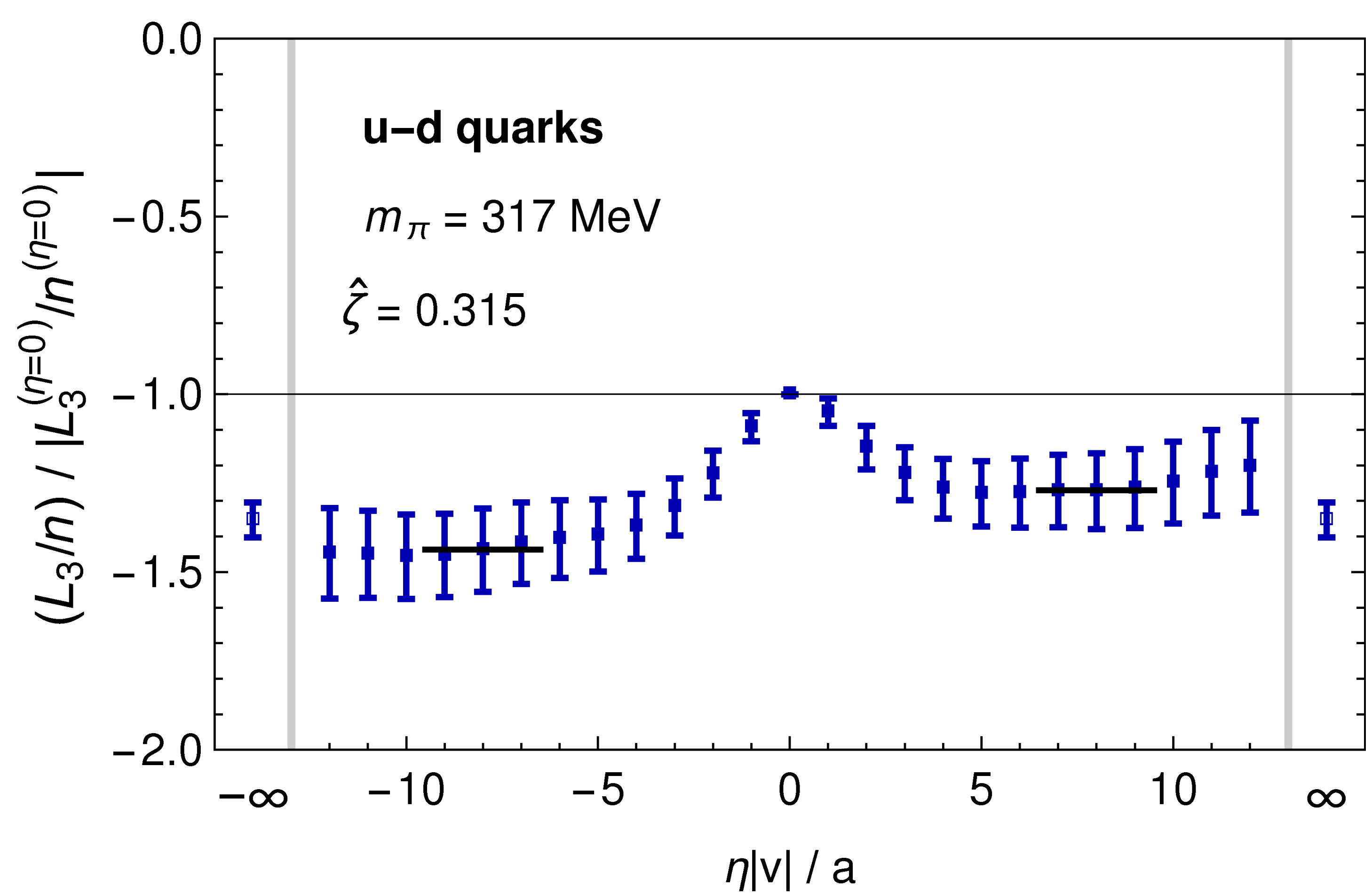


$\longrightarrow$ Careful evaluation of $\partial f/\partial \Delta_T$ using direct derivative method

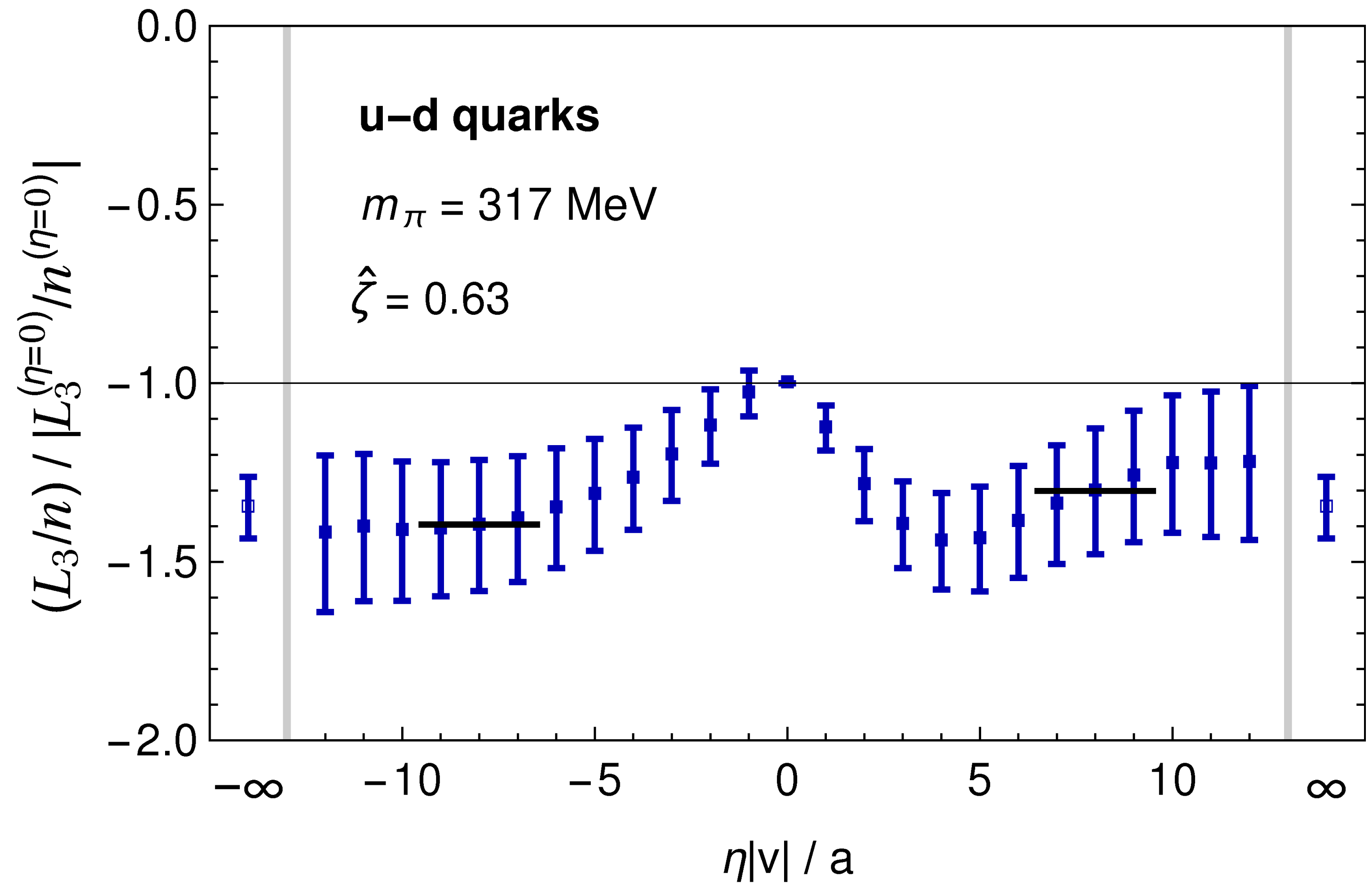
From Ji to Jaffe-Manohar quark orbital angular momentum



From Ji to Jaffe-Manohar quark orbital angular momentum



From Ji to Jaffe-Manohar quark orbital angular momentum



Conclusions and Outlook

- Continued exploration of transverse quark dynamics using bilocal quark operators with staple-shaped gauge link structures. Soft factors, multiplicative renormalizations are canceled by constructing appropriate ratios of Fourier-transformed TMDs / GTMDs.
- Progress on challenges posed by physical pion mass limit, $\hat{\zeta} \to \infty$ limit, discretization effects.
- A first comparison with experiment (Sivers shift) is encouraging.
- Currently analyzing initial data on the dependence of the Sivers shift on momentum fraction x.
- Alternative "Quasi-TMD" scheme in development (M. Ebert, I. Stewart, Y. Zhao), for which lattice data are being recorded in parallel; also, extraction of Collins-Soper kernel (P. Shanahan, M. Wagman).
- Generalization to mixed transverse momentum / transverse position observables (Wigner functions / GTMDs) gives direct access to quark orbital angular momentum.
- Plan to explore further new TMD/GTMD observables (longitudinal polarization, twist-3 TMDs, spin-orbit coupling).