PRECISION JET PHYSICS IN ELECTRON-PROTON COLLISIONS

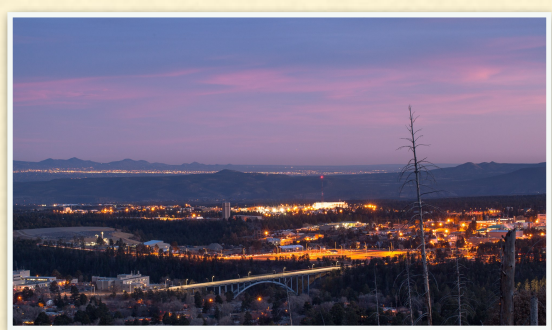
Christopher Lee

LANL

Based on work with Daekyoung Kang and Iain Stewart

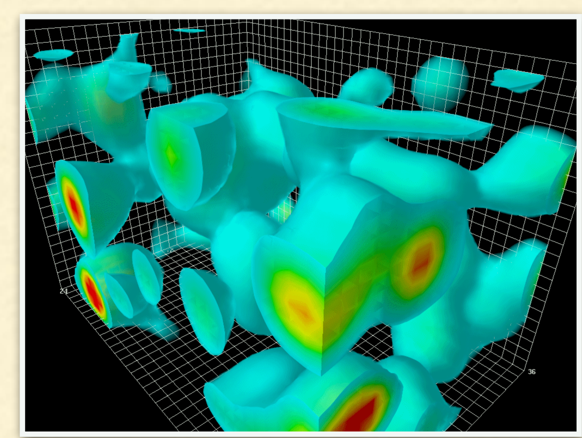
PRD **88**, 054004 (2013) [arXiv:1303.6952],

arXiv:1404.6706, and work in progress



Town Meeting on QCD

September 14, 2014



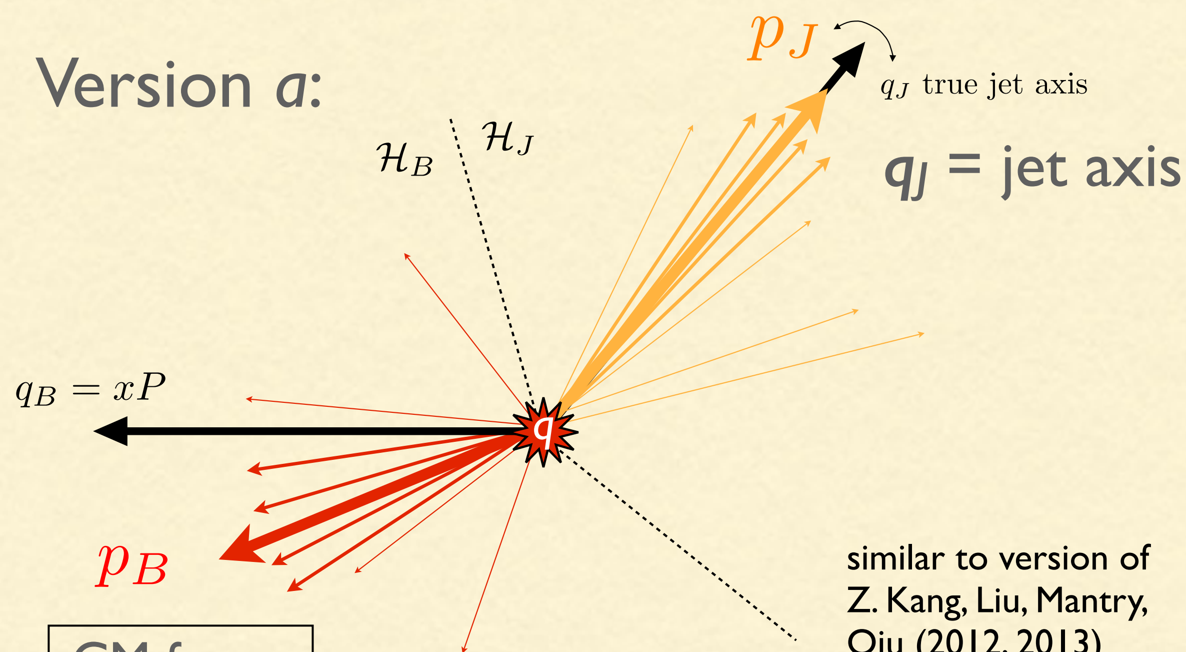
EVENT SHAPES IN DIS:

D. Kang, CL, Stewart (2013, 2014)

$$\tau_1 = \frac{2}{Q^2} \sum_{i \in X} \min\{q_B \cdot p_i, q_J \cdot p_i\}$$

- "1-jettiness" (or thrust) in DIS probes final states with beam radiation + one additional jet

Version *a*:



CM frame

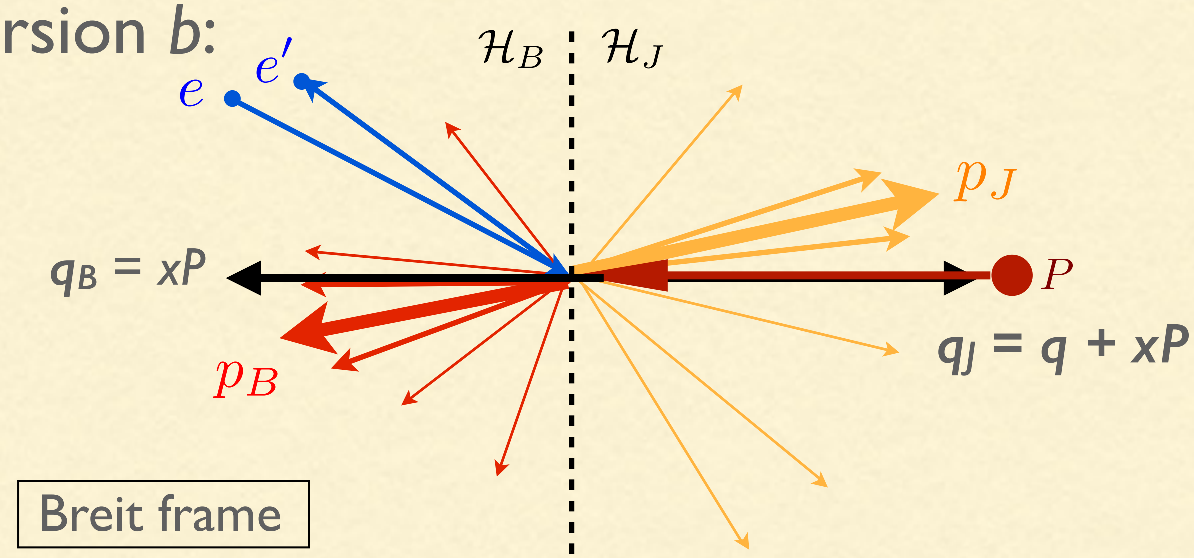
similar to version of Z. Kang, Liu, Mantry, Qiu (2012, 2013)

SCET factorization in small τ region:

$$\frac{1}{\sigma_0}\frac{d\sigma(x,Q^2)}{d\tau_1^a} = H(Q^2,\mu)\int dt_J dt_B dk_S \delta\left(\tau_1^a - \frac{t_J}{Q^2} - \frac{t_B}{Q^2} - \frac{k_S}{Q}\right) \times J_q(t_J,\mu) B_q(t_B,x,\mu) S(k_S,\mu)$$

- Averages over ISR transverse momentum
- Resummation to NNLL and N³LL
  Z. Kang, Liu, Mantry, Qiu (2013); D. Kang, CL, Stewart (2013, *2014*)
- Computed fixed-order $\mathcal{O}(\alpha_s)$ numerically
  Z. Kang, Liu, Mantry, Qiu (2013)

Version *b*:



Breit frame

same as "DIS thrust" Antonelli, Dasgupta, Salam (1999)

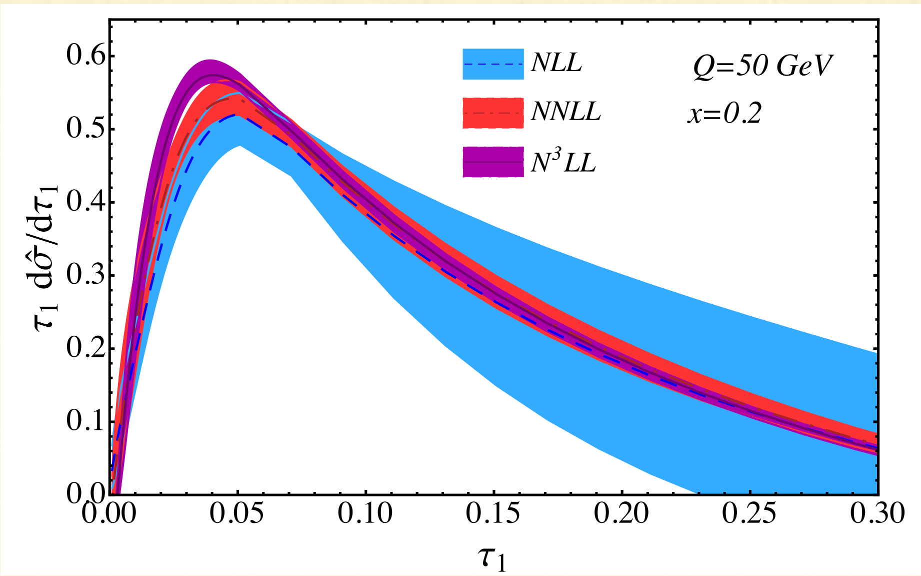
(can be measured solely from "current" hemisphere $\mathcal{H}_J$)

$$\frac{1}{\sigma_0}\frac{d\sigma(x,Q^2)}{d\tau_1^b} = H(Q^2,\mu)\int d^2p_\perp dt_J dt_B dk_S \delta\left(\tau_1^b - \frac{t_J}{Q^2} - \frac{t_B}{Q^2} - \frac{k_S}{Q}\right) \times J_q(t_J - \mathbf{p}_\perp^2,\mu) \mathcal{B}_q(t_B,x,\mathbf{p}_\perp^2,\mu) S(k_S,\mu)$$

- Sensitive to ISR transverse momentum
- Resummation to NNLL (& appx. N³LL)
  D. Kang, CL, Stewart (2013, *2014*)
- Computed fixed-order $\mathcal{O}(\alpha_s)$ analytically
  D. Kang, CL, Stewart (2014)

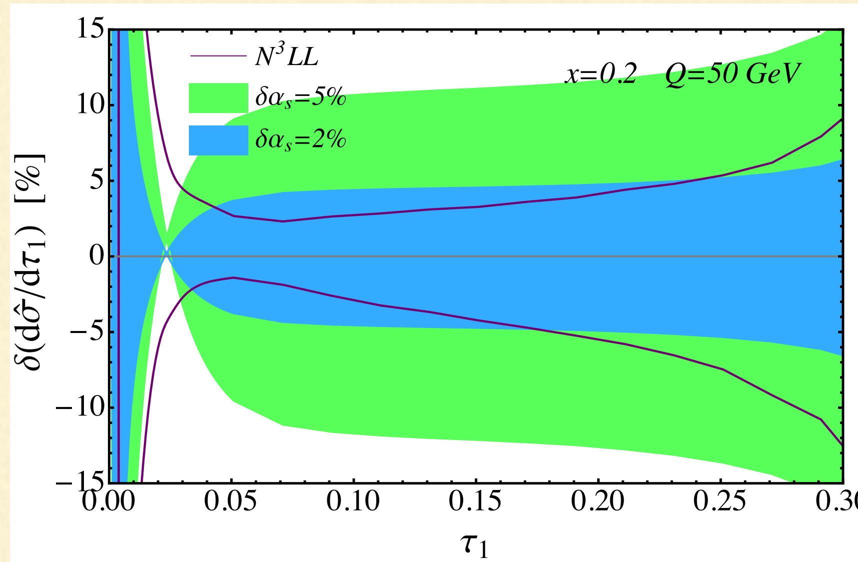
PERTURBATIVE AND NONPERTURBATIVE EFFECTS

D. Kang, CL, I. Stewart (2014)



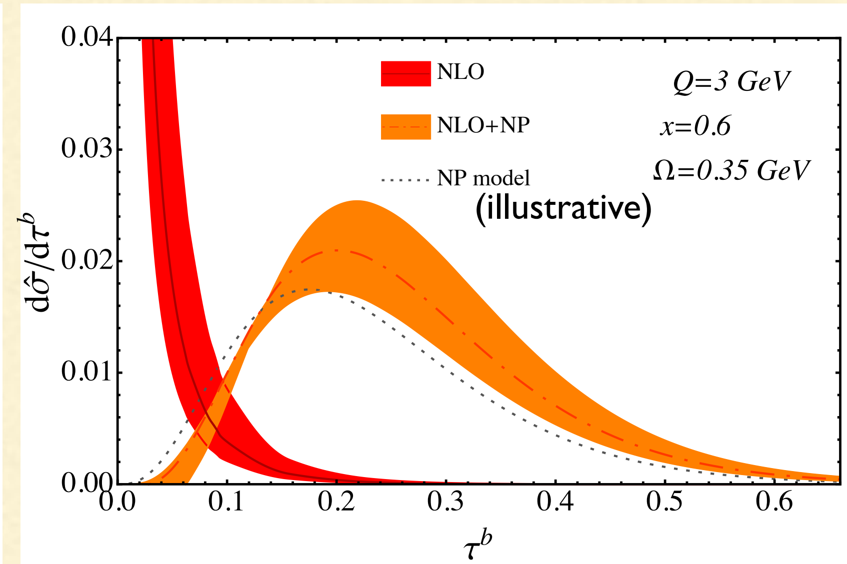
N³LL resummed PT prediction at EIC

highest resummed accuracy
for DIS event shapes, previously NLL



Sensitivity to strong coupling

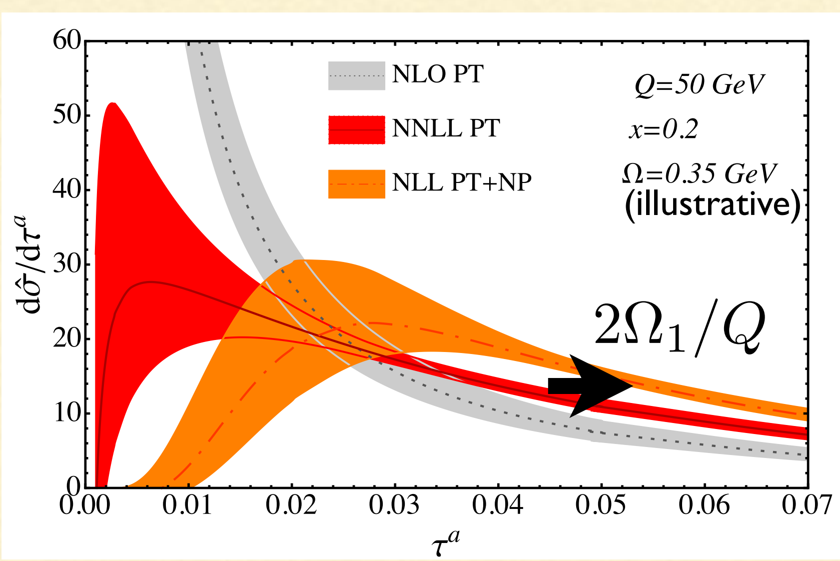
from one distribution at fixed x, Q;
expect improvement from multiple x, Q:
<1% level precision



NP shape function convolved with NLO PT at JLab12

Shape function should be independent of x, Q;
better measured at low Q

- For large enough Q, leading NP effect in the PT distribution tail is a **universal** shift



at EIC

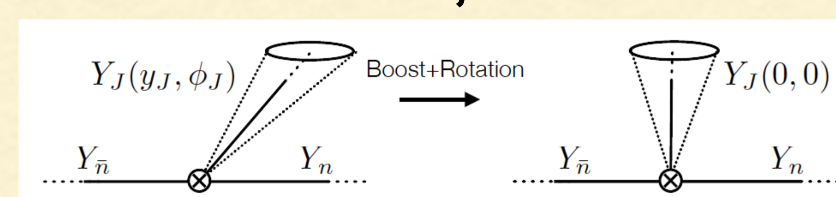
Using factorization theorems and boost invariance properties of soft Wilson lines, can prove that:

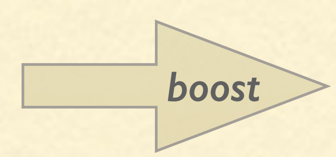
$$\boxed{\Omega_1^{\mathrm{a}} = \Omega_1^{\mathrm{b}} = \Omega_1^{\mathrm{c}}}$$

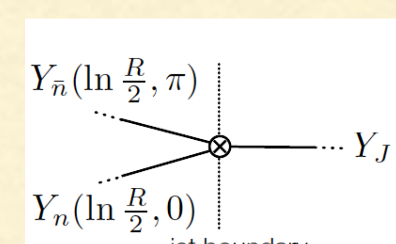
("c" = hemisphere thrust in CM frame)

D. Kang, CL, I. Stewart (2013)

Same Ω_1 even appears as leading soft NP correction to jet mass at *LHC!*



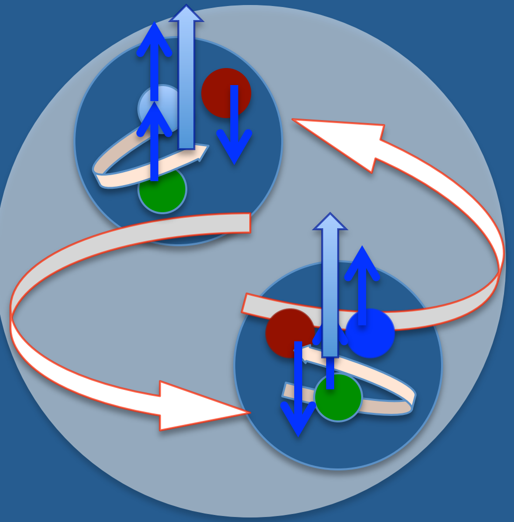




Stewart, Tackmann, Waalewijn (2014)

OAM and GTMDs

Simonetta Liuti
University of Virginia



APS DNP Town Meeting

Temple University

September 13th-15th, 2014

What is Orbital Angular Momentum?

THE PHENOMENOLOGIST'S TAKE

Defining observables

Measurements

Implications

What observables can be identified, what set of measurements will uniquely settle this question?

?

Defining the Observables: Two ways of getting at OAM

GTMD

$$L_q^{JM} = -\int dx\, d^2k_T \frac{k_T^2}{M^2} \boxed{F_{14}\left(x,0,0,k_T\right)}$$

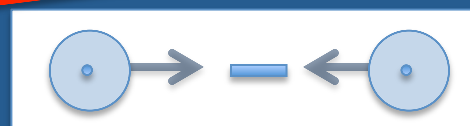
Hatta (2011)
Lorce', Pasquini (2011)
Burkardt (2012)

where the unintegrated in k_T structure is:

Meißner, Metz, Schlegel (2009)

$$W^{[\gamma^+]}_{\Lambda'\Lambda} = \frac{1}{2M}\,\overline{u}(p',\Lambda')\left[F_{11} + \frac{i\sigma^{k_\perp +}}{P^+}F_{12} + \frac{i\sigma^{\Delta_\perp +}}{P^+}F_{13} + \boxed{\frac{i\sigma^{k_\perp \Delta_\perp}}{M^2}F_{14}}\right]u(p,\Lambda)$$

$$\boxed{\sigma_{ij} k_T^i \Delta_T^j \Rightarrow \vec{S}_L \cdot \left(\vec{k}_T \times \vec{\Delta}_T\right)}$$



UL correlation

Polyakov Sum Rule

Twist 3 GPD

$$\underbrace{\int dx\, x \boxed{G_2}}_{-L_q} = -\frac{1}{2}\int dx\, x\underbrace{(H+E)}_{-J_q} + \frac{1}{2}\underbrace{\int dx\, \tilde{H}}_{S_q}$$

Polyakov et al., (2000)
Hatta, Yoshida (2012)

where the twist 3 integrated in k_T structure is:

$$W^{\gamma^i}_{\Lambda'\Lambda} = \frac{1}{2P^+}\overline{U}(p',\Lambda')\left[\frac{\Delta_T^i}{M}G_1 + \frac{i\sigma^{ji}\Delta_j}{M}\boxed{G_2} \frac{Mi\sigma^{i+}}{P^+}G_4 + \frac{\Delta_T^i}{P^+}\gamma^+ G_3\right]U(p,\Lambda),$$

UL correlation

… and the unintegrated in k_T structure is

$$-\frac{4}{P^+}\left[\underbrace{\frac{\mathbf{k}_T\cdot\mathbf{\Delta}_T}{\Delta_T}F_{27} + \Delta_T F_{28}}\left(\frac{\mathbf{k}_T\cdot\mathbf{\Delta}_T}{\Delta_T}G_{27} + \Delta_T G_{28}\right)\right] = A^{tw3}_{++,++} + A^{tw3}_{+-,+-} - A^{tw3}_{-+,-+} - A^{tw3}_{--,-}$$

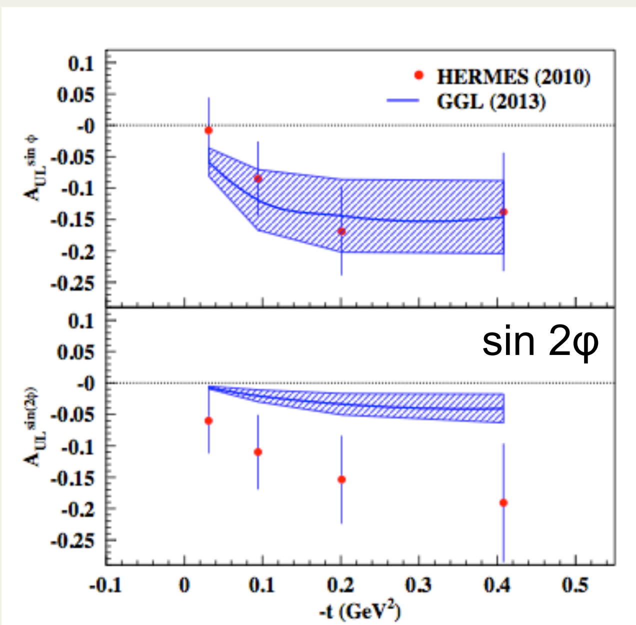
Calculable on lattice!! (M. Engelhardt)

Measurements

To measure OAM one has to be in a frame where the reaction cannot be described as a two-body quark-proton scattering (UL correlation does not exist because of Parity constraints).

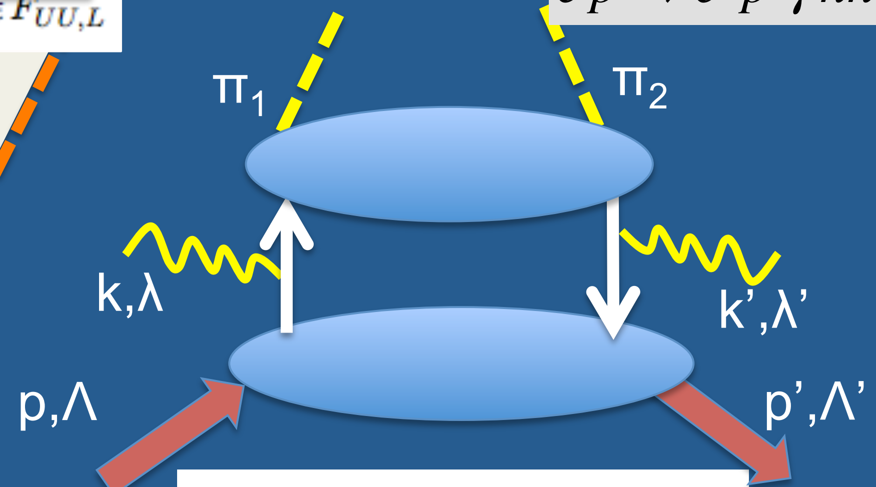
Twist three measurements

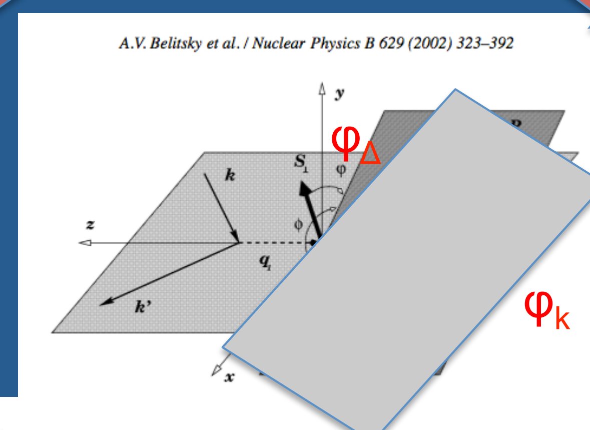
$$A_{UL,L} = \frac{N_{s_z=+} - N_{s_z=-}}{N_{s_z=+} + N_{s_z=-}} = \frac{\sqrt{2\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi}}{F_{UU,T} + \epsilon F_{UU,L}} + \frac{\epsilon \sin 2\phi \boxed{F_{UL}^{\sin 2\phi}}}{F_{UU,T} + \epsilon F_{UU,L}}$$



Introduce two hadronic planes: Off forward SIDIS

$e\,p \to e'\,p'\,\gamma\,h\,\bar{h}$



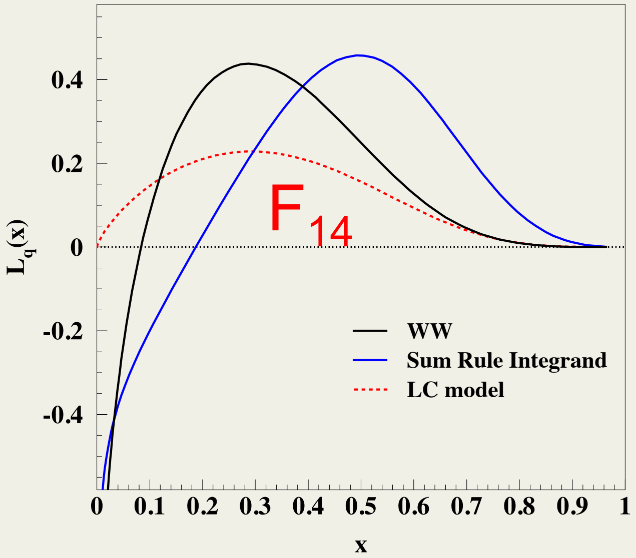


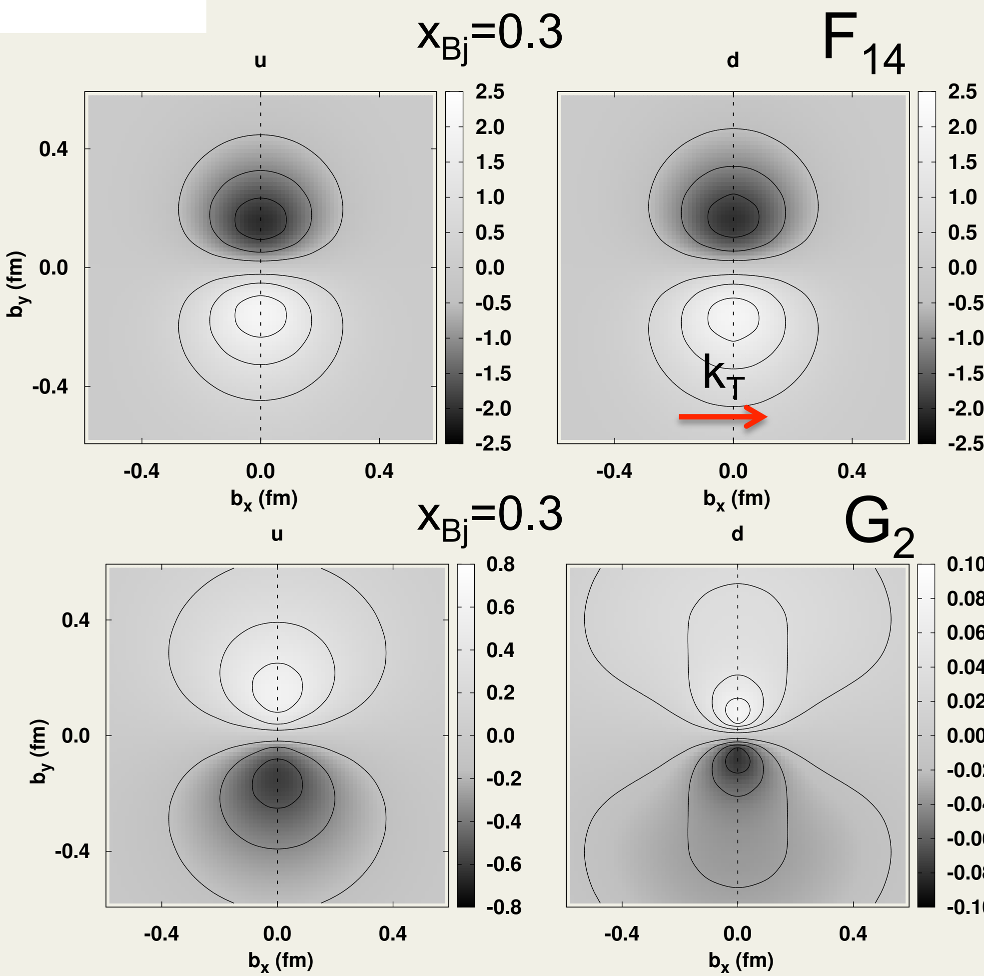
$$g_{\Lambda'_\gamma,\Lambda'_N,0;\Lambda_\gamma,\Lambda_N,0} = \sum_{\lambda,\lambda'} \tilde{g}^{\lambda'\lambda}_{\Lambda'_\gamma\Lambda_\gamma} \otimes A_{\Lambda'_N,\lambda',\Lambda_N,\lambda}(x,\xi,t) \otimes F^{\pi_1}_{\lambda 0}(z) F^{\pi_2}_{\lambda' 0}(v)$$

Implications: knowing the helicities configurations allows us to interpret OAM in the proton

Comparison of different OAM density distributions for Jaffe Manohar and Ji

$$L_q(x,0,0) = x\int_x^1 \frac{dy}{y}(H_q(y,0,0)+E_q(y,0,0)) - x\int_x^1 \frac{dy}{y^2}\widetilde{H}_q(y,0,0),$$





I am indebted to

Harut Avakian
Aurore Courtoy
Michael Engelhardt
Gary Goldstein
Osvaldo Gonzalez Hernandez
Silvia Pisano
Abha Rajan

Details can be found in:

- ✓ Courtoy et el., Phys. Lett.B 2014, arXiv:1310.5157
- ✓ ECT* talks by A. Courtoy, G. Goldstein, S.L.

https://indico.in2p3.fr/conferenceTimeTable.py?confId=10071#20140826

The prospects for 2γ physics with lattice QCD

Brian Tiburzi

14 September, 2014

A few 2γ observables to compute

Electric & Magnetic polarizabilities of pion

- *ChPT* vs. Experiment:

One Loop ChPT $\alpha_{\pi^+} = 2.7\,[10^{-4}\,\mathtt{fm}^3]$

COMPASS $\alpha_{\pi^+} = 1.9(0.7)_{st.}(0.8)_{sy.}\,[10^{-4}\,\mathtt{fm}^3]$

- Contribution to hadronic light-by-light (ingredient in dispersive treatment)

[Engel, *et al*. PRD (2012), Colangelo, *et al*. 1402.7081]

- JLAB Hall D: PR-13-008

Magnetic polarizability of nucleon

- Experiment: 50% - 100% uncertainty for neutron?
- *ChPT* in single and few nucleon systems

[Talks by **Philips** & **Grieβhammer**]

- Dominant error in determining nucleon EM splitting

[Walker-Loud, Carlson, Miller PRL (2012)]

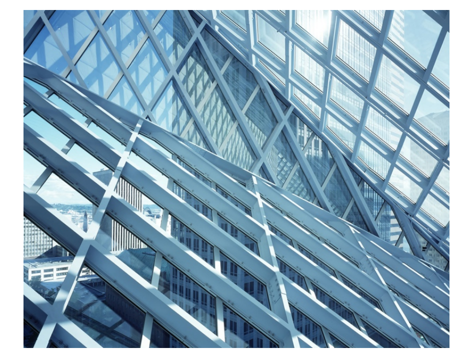
- Help constrain proton structure corrections to *μ-H*

[Hill, Paz PRL (2011)]

HIγS @ TUNL

[Talks by **Howell** & **Ahmed**]

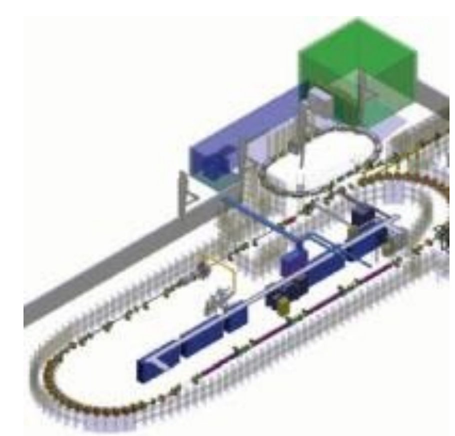
Spin polarizabilities, …



QCD

$n \to \pi^- + p \to n$

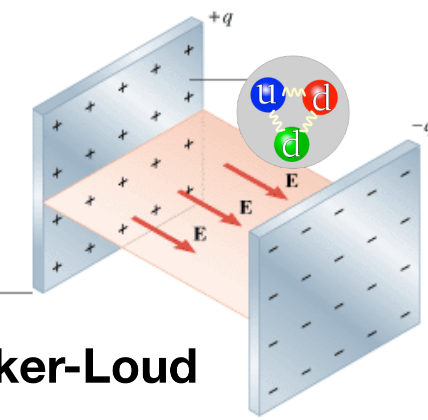
EFT



EXP

Lattice QCD Methods for Hadronic Polarizabilities

$\alpha_E \quad \beta_M$



$$U_\mu^{\text{e.m.}}(x) = e^{iqA_\mu(x)} \in U(1)$$

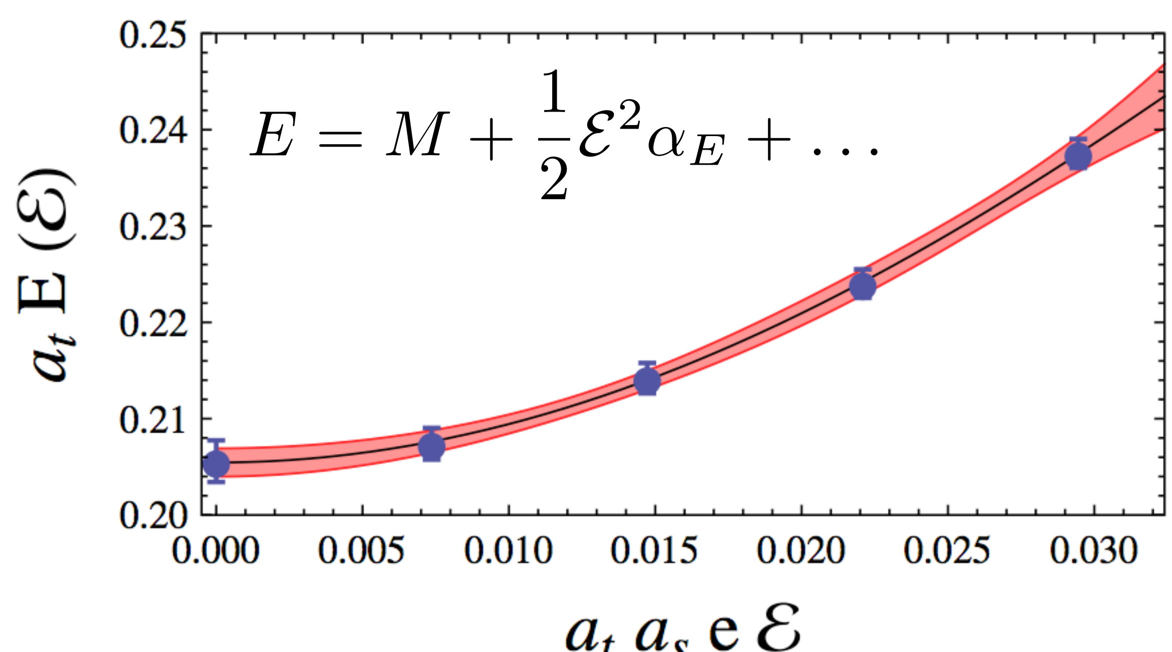
W. Detmold, B. Tiburzi, A. Walker-Loud

PRD 2006, 2009, 2010

- Determine E&M polarizabilities from QCD by: turning on external fields + study external field dependence of hadronic correlation functions

E.g. neutron in electric field

$$E_{\text{eff}} = M + \frac{1}{2}\mathcal{E}^2\left(\alpha_E - \frac{\mu^2}{4M^3}\right) + \ldots$$



Simultaneous fit to boost projected correlators

$$\text{Tr}[\mathcal{P}_\pm G(\tau)] = Z\left(1 \pm \frac{\mu\mathcal{E}}{2M_N^2}\right)\exp(-\tau E_{\text{eff}})$$

Anisotropic clover lattices (**HadSpec**)

$20^3 \times 128 \qquad m_\pi = 390\,\texttt{MeV}$

$\mu_n = -1.6(1)\,[\mu_N]$

$\alpha_E^n = 3(1) \times 10^{-4}\,\texttt{fm}^3$

m_π

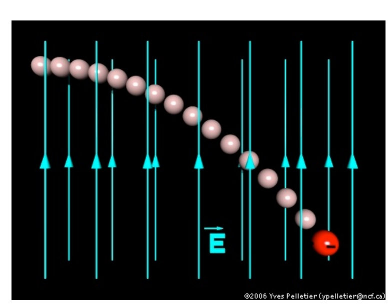
a

L

q_{sea}

Hadrons considered

π^0, K^0, n **and** π^+, K^+, p

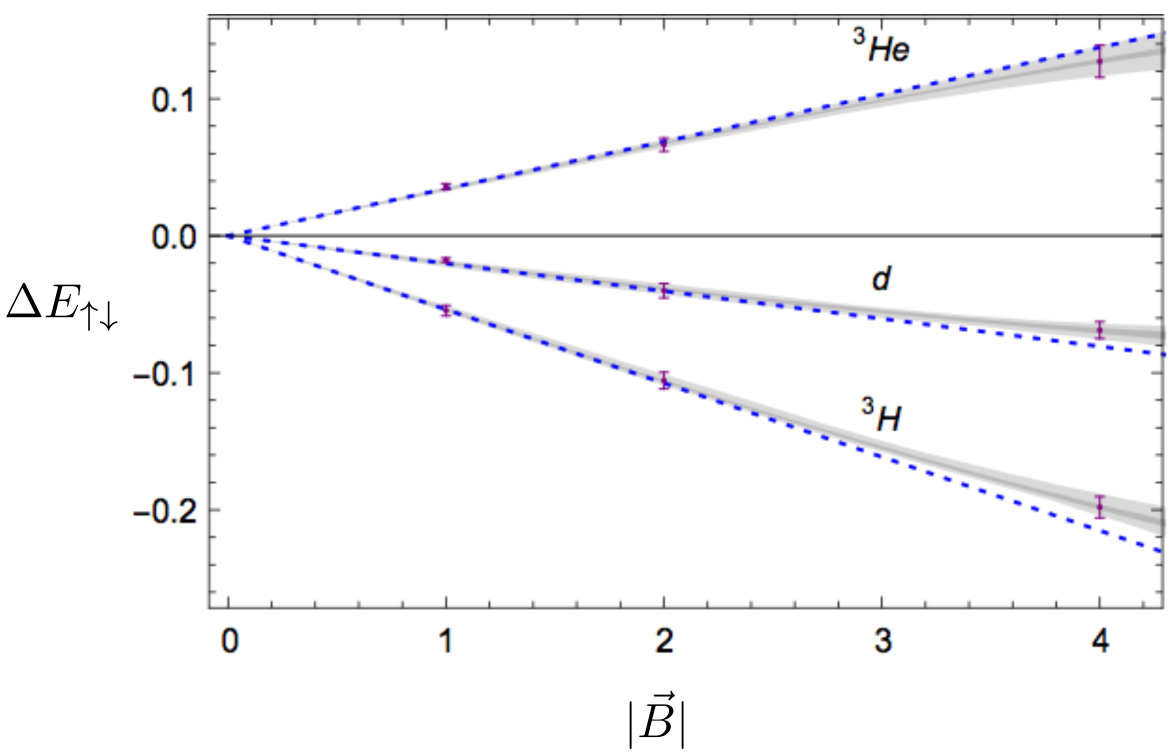


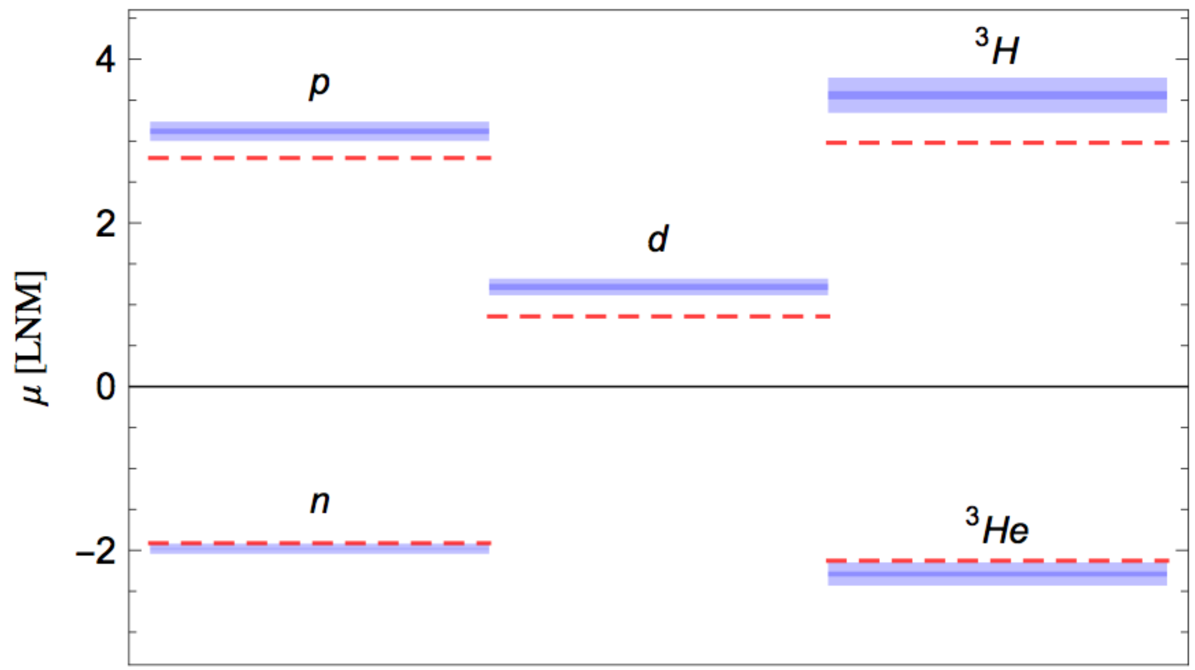
STATISTICAL UNCERTAINTIES ONLY
NOT FOR USE WITH EXPERIMENT

Magnetic Moments of Light Nuclei

[Beane, *et al*. 1409.3556]

Proof of principle: lattice QCD computation of Zeeman splittings $m_\pi^{\text{latt}} = 800\,\texttt{MeV}$ $M_N^{\text{latt}} = 1600\,\texttt{MeV}$





Remarkable surprise! $[\text{LNM}] = \dfrac{e}{2M_N^{\text{latt}}}$

QCD

EFT

EXP

Lattice presents tremendous opportunity:

- Understand interplay between single and few nucleon dynamics from QCD
- Lower pion mass to expose chiral dynamics
- Ultimately confront experiment

Transverse Force on Quarks in DIS

Matthias Burkardt

New Mexico State University

September 13, 2014

$d_2 \leftrightarrow$ average $\perp$ force on quark in DIS from $\perp$ pol target

polarized DIS:

- $\sigma_{LL} \propto g_1 - \frac{2Mx}{\nu} g_2$
- $\sigma_{LT} \propto g_T \equiv g_1 + g_2$

$\hookrightarrow$ 'clean' separation between g_2 and $\frac{1}{Q^2}$ corrections to g_1

- $g_2 = g_2^{WW} + \bar{g}_2$ with $g_2^{WW}(x) \equiv -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y)$

$$d_2 \equiv 3 \int dx\, x^2 \bar{g}_2(x) = \frac{1}{2MP^{+2}S^x} \left\langle P,S \left| \bar{q}(0)\gamma^+ gF^{+y}(0)q(0) \right| P,S \right\rangle$$

color Lorentz Force on ejected quark (MB, PRD 88 (2013) 114502)

$$\sqrt{2}F^{+y} = F^{0y} + F^{zy} = -E^y + B^x = -\left(\vec{E} + \vec{v} \times \vec{B}\right)^y \text{ for } \vec{v} = (0,0,-1)$$

matrix element defining d_2 $\leftrightarrow$ 1^{st} integration point in QS-integral
$\hookrightarrow$ Sivers

$\int x^2 e(x)$ (scalar twist-3 PDF) $\leftrightarrow$ 'Boer-Mulders force':
$\perp$ pol. quarks; unpol. target

OAM from Wigner Functions

Wigner Functions (Belitsky, Ji, Yuan; Metz et al.)

$$W(x,\vec{b}_\perp,\vec{k}_\perp) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} \int \frac{d^2\xi_\perp d\xi^-}{(2\pi)^3} e^{ik\cdot\xi} e^{-i\vec{q}_\perp\cdot\vec{b}_\perp} \langle P'S'|\bar{q}(0)\gamma^+ q(\xi)|PS\rangle.$$

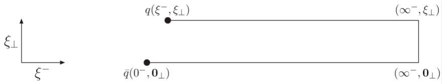
- TMDs: $f(x,\mathbf{k}_\perp) = \int d^2\mathbf{b}_\perp W(x,\vec{b}_\perp,\vec{k}_\perp)$
- GPDs: $q(x,\mathbf{b}_\perp) = \int d^2\mathbf{k}_\perp W(x,\vec{b}_\perp,\vec{k}_\perp)$
- $L_z = \int dx \int d^2\mathbf{b}_\perp \int d^2\mathbf{k}_\perp W(x,\vec{b}_\perp,\vec{k}_\perp)(b_x k_y - b_y k_x)$
- need to include Wilson-line gauge link $\mathcal{U}_{0\xi}$ to connect 0 and ξ (Ji, Yuan; Hatta; Lorcé;...)

straight line (Ji et al.)

straigth Wilson line from 0 to ξ yields Ji-OAM:

$$L^q = \int d^3x \langle P,S|q^\dagger(\vec{x})\left(\vec{x}\times i\vec{D}\right)^z q(\vec{x})|P,S\rangle$$

Light-Cone Staple for $\mathcal{U}^{\pm LC}_{0\xi}$ (Hatta)



'light-cone staple' yields $\mathcal{L}_{Jaffe-Manohar}$

Quark OAM from Wigner Distributions

straight line (→Ji)

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + L_q + J_g$$

$$L_q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x} \times i\vec{D}\right)^z q(\vec{x})|P,S\rangle$$

- $i\vec{D} = i\vec{\partial} - g\vec{A}$

light-cone staple (→ Jaffe-Manohar)

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

$$\mathcal{L}^q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x} \times i\vec{\mathcal{D}}\right)^z q(\vec{x})|P,S\rangle$$

$$i\mathcal{D}^j = i\partial^j - gA^j(x^-, \mathbf{x}_\perp) - g\int_{x^-}^{\infty} dr^- F^{+j}$$

difference $\mathcal{L}^q - L^q$

$$\mathcal{L}^q - L^q = -g\int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left[\vec{x} \times \int_{x^-}^{\infty} dr^- F^{+\perp}(r^-, \mathbf{x}_\perp)\right]^z q(\vec{x})|P,S\rangle$$

color Lorentz Force on ejected quark (MB, PRD 88 (2013) 014014)

$$\sqrt{2}F^{+y} = F^{0y} + F^{zy} = -E^y + B^x = -\left(\vec{E} + \vec{v} \times \vec{B}\right)^y \text{ for } \vec{v} = (0,0,-1)$$

Torque along the trajectory of q

$$T^z = \left[\vec{x} \times \left(\vec{E} - \hat{\vec{z}} \times \vec{B}\right)\right]^z$$

Change in OAM

$$\Delta L^z = \int_{x^-}^{\infty} dr^- \left[\vec{x} \times \left(\vec{E} - \hat{\vec{z}} \times \vec{B}\right)\right]^z$$

straight line ($\rightarrow$Ji)

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + L_q + J_g$$

$$L_q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x}\times i\vec{D}\right)^z q(\vec{x})|P,S\rangle$$

- $i\vec{D} = i\vec{\partial} - g\vec{A}(\vec{x})$

light-cone staple ($\rightarrow$ Jaffe-Manohar)

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

$$\mathcal{L}^q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x}\times i\vec{\mathcal{D}}\right)^z q(\vec{x})|P,S\rangle$$

- $i\vec{\mathcal{D}} = i\vec{\partial} - g\vec{A}(x^- = \infty, \mathbf{x}_\perp)$

difference $\mathcal{L}^q - L^q$ (MB, PRD 88 (2013) 014014)

$\mathcal{L}^q - L^q = \Delta L^q_{FSI}$ = change in OAM as quark leaves nucleon

example: torque in magnetic dipole field