SPIN 2018 SPIN 2018

9-14 September 2018 *University of Ferrara*
Europe/Rome timezone

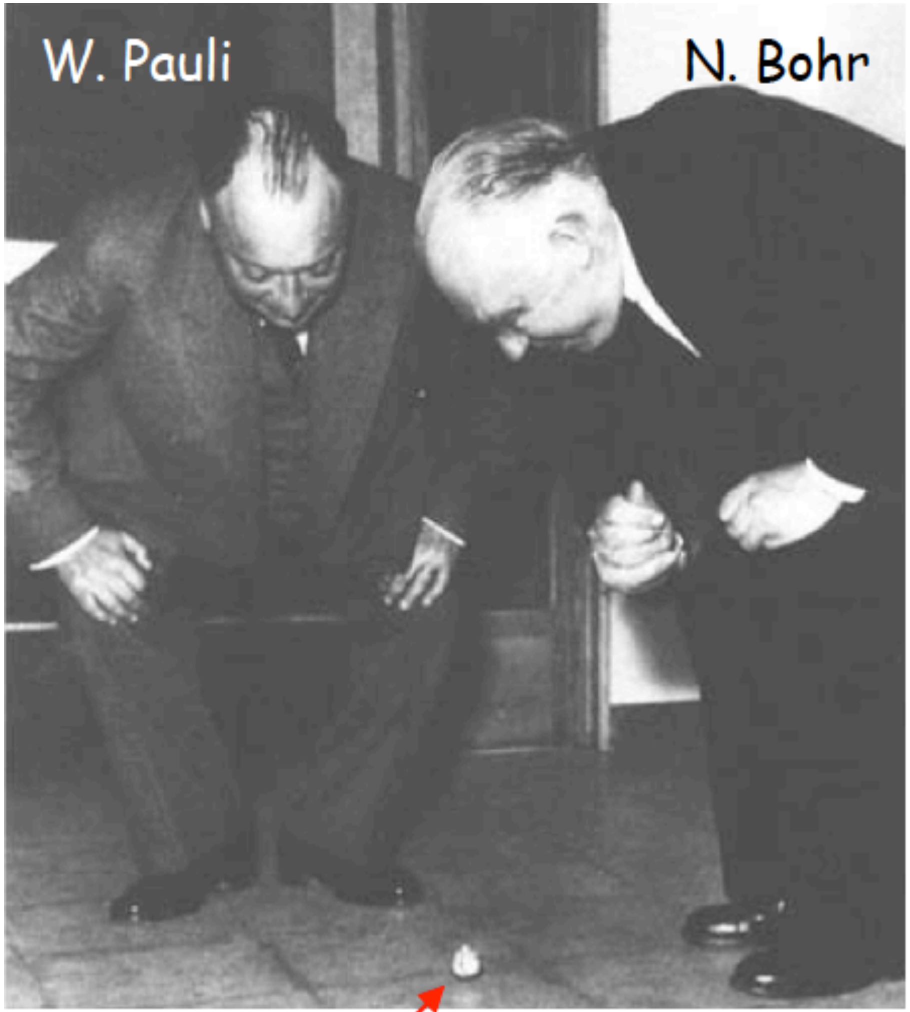
The Wonder of Spin Dynamics in Quantum Chromodynamics

Jianwei Qiu

Theory Center, Jefferson Lab



Curiosity and fascination of spin, …



a spinning tippy-top

Spin = an intrinsic and quantum property of all particles *regardless* if they are elementary or composite

Picture from M. Stratmann, RIKEN Spin Lectures, 2017

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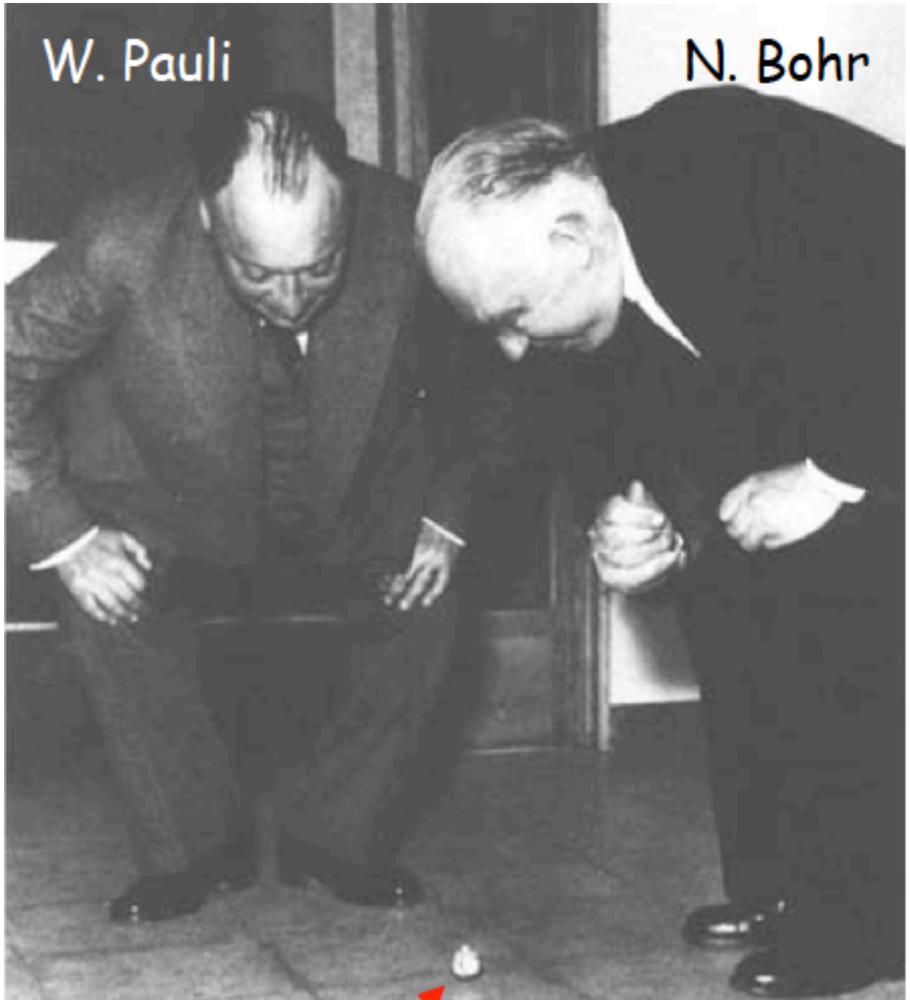

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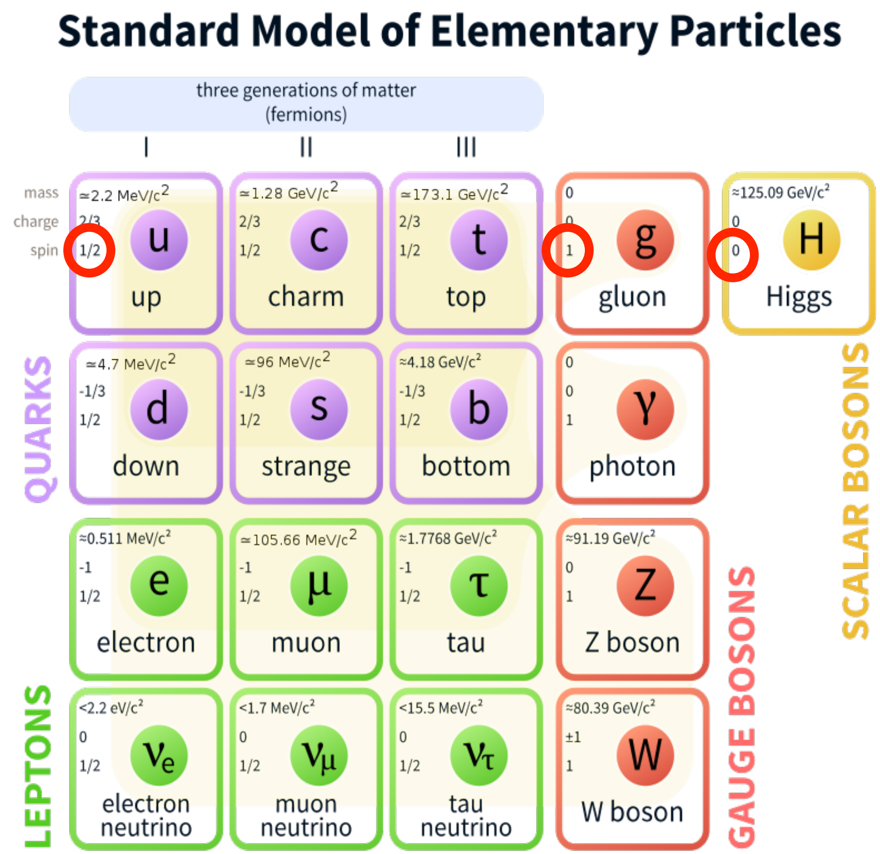

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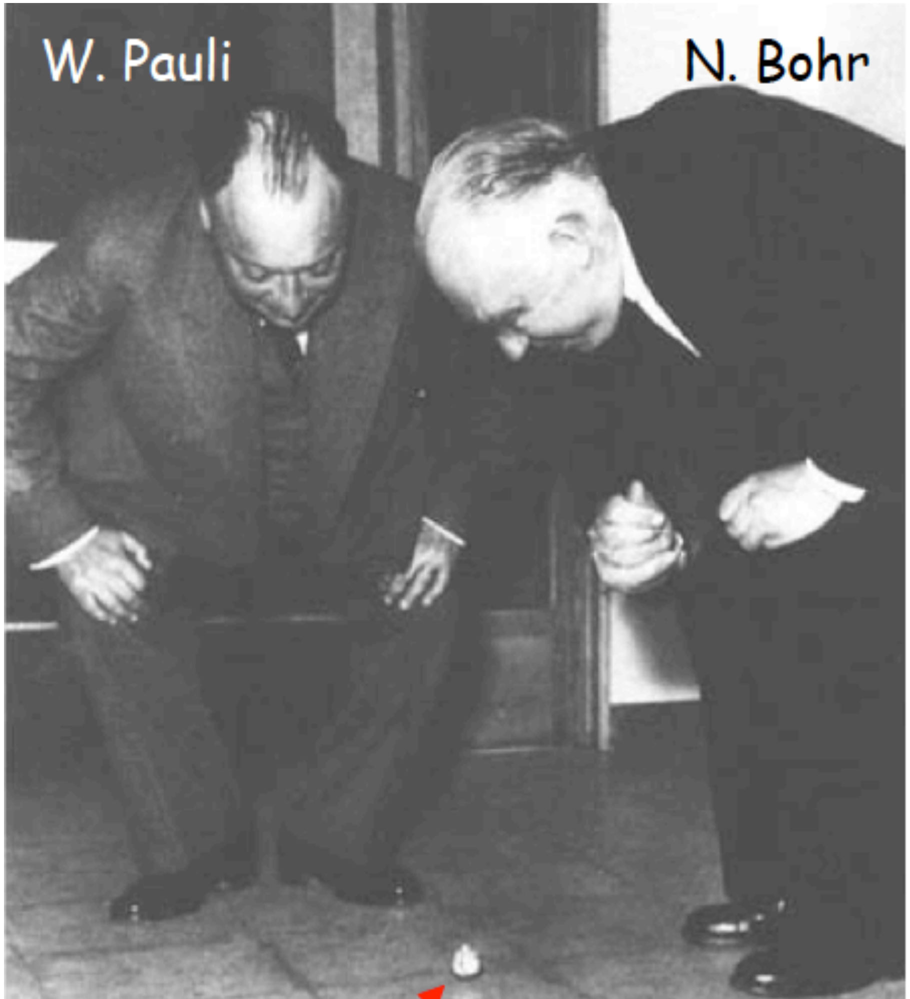

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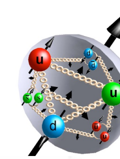
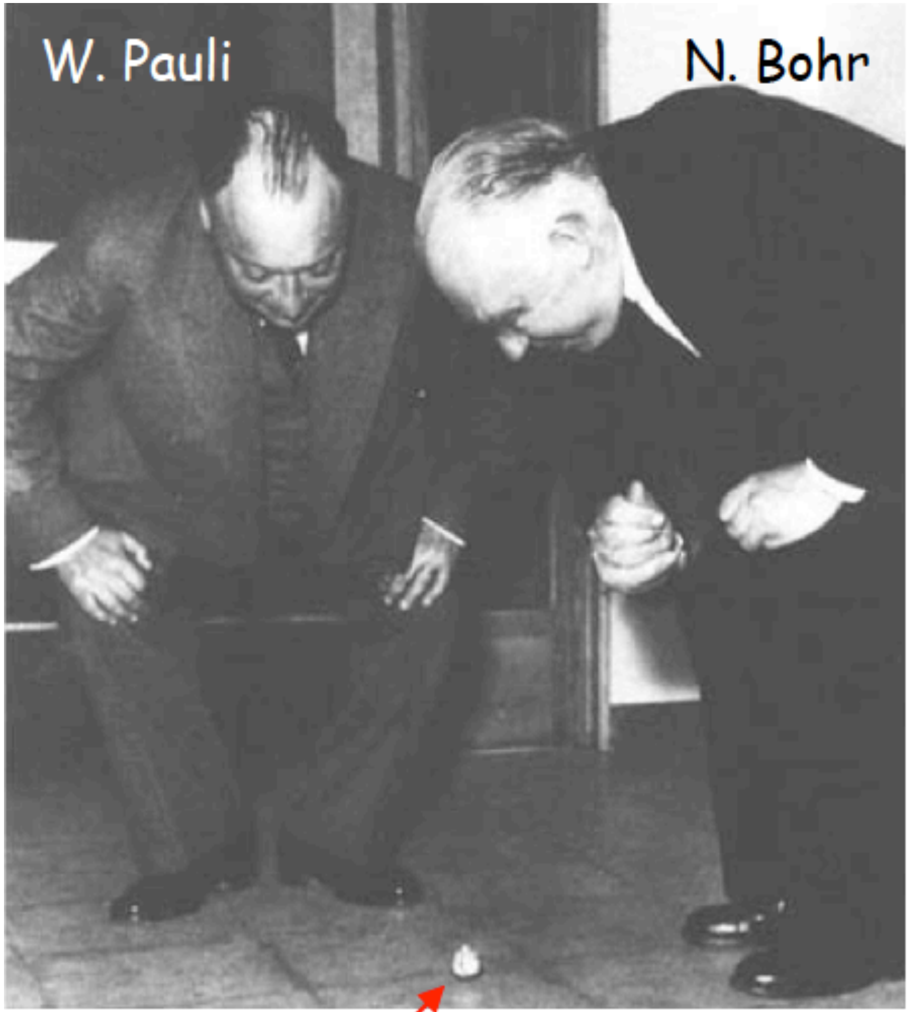


Nuclear Spin: I

Nucleus	p	n	*I*
^{1}H	1	0	½
^{2}H	1	1	1
^{3}H	1	2	½
^{3}He	2	1	½
^{11}B	5	6	3/2
^{12}C	6	6	0
^{13}C	6	7	½
^{15}N	7	8	½

Theory of NMR
slideplayer.com

Curiosity and fascination of spin, …



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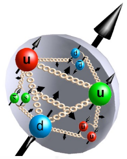

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^{13}C	6	7	½
^{15}N	7	8	½

The world would be very different without spin!

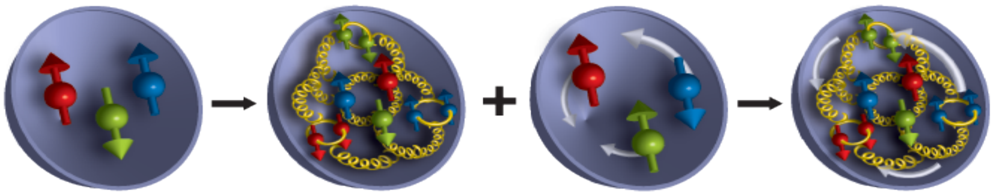
Outline of the rest of my talk

- ❑ **QCD and spin of nucleon**
- ❑ **Questions driving the spin physics**
- ❑ **Dual roles of the hadron spin**
- ❑ **The wonder of spin dynamics in QCD:**
  - ✧ **Surprises, crisis, and advances**
  - ✧ **Past, present, and future**
- ❑ **Summary and outlook**

If we do not understand proton spin, we do not know QCD!

QCD and spin of nucleon

❑ **Our understanding of the nucleon and its spin evolves:**



1970s 1980s/2000s Now

✧ **A strongly interacting, relativistic bound state of quarks and gluons**

✧ **Understanding it fully is still beyond the best minds in the world**

❑ **From quantum mechanics to quantum field theory – QCD:**

✧ **Spin of a composite object in QM:** $\vec{S} = \sum_{i=1}^{N} \vec{s}_i$ ***N*** **is finite!**

✧ **Proton spin in QCD = Proton's angular momentum when it is at the rest**

- **QCD energy-momentum tensor & angular momentum density:**

$$M^{\alpha\mu\nu} = T^{\alpha\nu}x^{\mu} - T^{\alpha\mu}x^{\nu} \qquad J^i = \frac{1}{2}\epsilon^{ijk}\int d^3x M^{0jk}$$

- **Proton spin:** $S(\mu) = \sum_f \langle P, S|\hat{J}^z_f(\mu)|P, S\rangle = \frac{1}{2}$

As a quantum Probability!

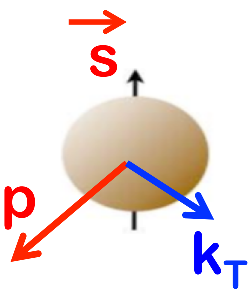
Questions driving the spin physics

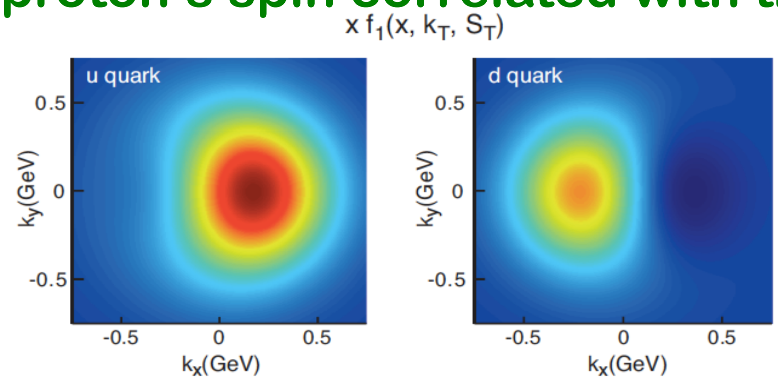
- ❑ **How do quarks/gluons + their dynamics make up the proton spin?**

$S(\mu) = \frac{1}{2}$  $\mu \Rightarrow \infty$

Helicity distributions + orbital contribution

- ❑ **How is proton's spin correlated with the motion of quarks/gluons?**

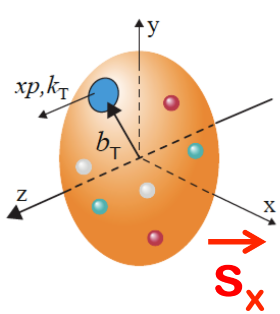


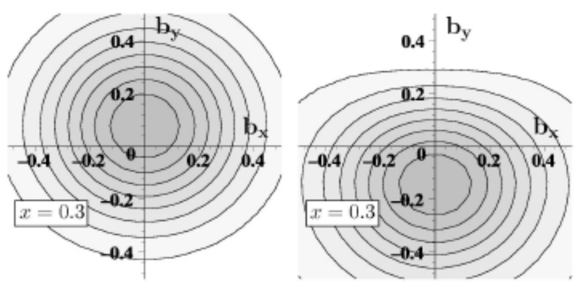


Deformation of parton's *confined motion* when hadron is polarized?

TMDs!

- ❑ **How does proton's spin influence the spatial distribution of partons?**



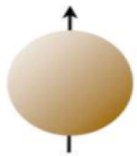


Deformation of parton's *spatial distribution* when hadron is polarized?

GPDs!

Dual roles of the hadron spin

- **Understand the hadron spin as its intrinsic quantum property:**



Proton Spin

$$= \sum_f \langle P, S | \hat{J}^z_f(\mu) | P, S \rangle$$

Role of the quark & gluon properties & their dynamics?

- **Use the spin orientation as a tool to help explore QCD dynamics:**

  ✧ **Asymmetry with both beams polarized:** A_{LL}, A_{TT}, A_{LT}

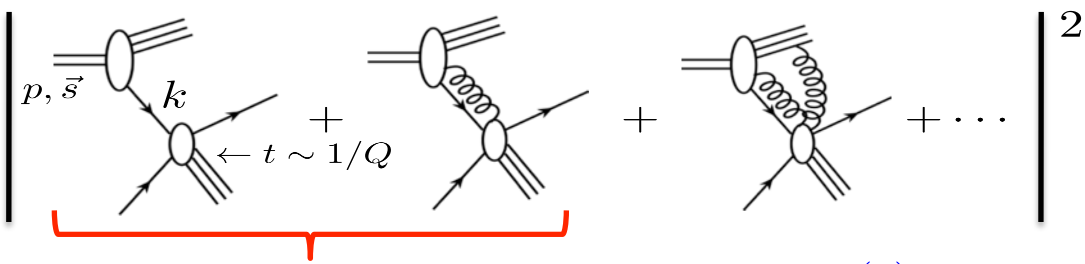
$$A_{LL} = \frac{[\sigma(+,+) - \sigma(+,-)] - [\sigma(-,+) - \sigma(-,-)]}{[\sigma(+,+) + \sigma(+,-)] + [\sigma(-,+) + \sigma(-,-)]} \quad \text{for } \sigma(s_1, s_2)$$

  ✧ **Asymmetry with one beam polarized:** A_L, A_N

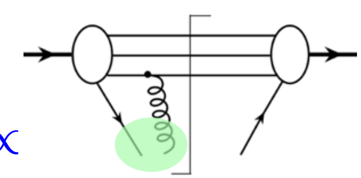
$$A_L = \frac{[\sigma(+) - \sigma(-)]}{[\sigma(+) + \sigma(-)]} \quad \text{for } \sigma(s) \qquad A_N = \frac{\sigma(Q, \vec{s}_T) - \sigma(Q, -\vec{s}_T)}{\sigma(Q, \vec{s}_T) + \sigma(Q, -\vec{s}_T)}$$

  ✧ **Access to quantum effect:**

$\sigma(Q, \vec{s}) \propto$



$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x, x) \propto$



The past: naïve quark model, …

- **Proton wave function – the state:**

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\,[uud(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow) + udu(\uparrow\uparrow\downarrow + \downarrow\uparrow\uparrow - 2\uparrow\downarrow\uparrow)$$
$$+duu(\uparrow\downarrow\uparrow + \uparrow\uparrow\downarrow - 2\downarrow\uparrow\uparrow)]$$

- **Normalization:**

$$\langle p\uparrow|p\uparrow\rangle = \frac{1}{18}[(1+1+(-2)^2)+(1+1+(-2)^2)+(1+1+(-2)^2)] = 1$$

- **Charge:** $\hat{Q} = \sum_{i=1}^{3} \hat{Q}_i$

$$\langle p\uparrow|\hat{Q}|p\uparrow\rangle = \frac{1}{18}[(\tfrac{2}{3}+\tfrac{2}{3}-\tfrac{1}{3})(1+1+(-2)^2)+(\tfrac{2}{3}-\tfrac{1}{3}+\tfrac{2}{3})(1+1+(-2)^2)$$
$$+(-\tfrac{1}{3}+\tfrac{2}{3}+\tfrac{2}{3})(1+1+(-2)^2)] = 1$$

- **Spin:** $\hat{S} = \sum_{i=1}^{3} \hat{s}_i$

$$\langle p\uparrow|\hat{S}|p\uparrow\rangle = \frac{1}{18}\{[(\tfrac{1}{2}-\tfrac{1}{2}+\tfrac{1}{2})+(-\tfrac{1}{2}+\tfrac{1}{2}+\tfrac{1}{2})+4(\tfrac{1}{2}+\tfrac{1}{2}-\tfrac{1}{2})]$$
$$+[\tfrac{1}{2}+\tfrac{1}{2}+4\tfrac{1}{2}]+[\tfrac{1}{2}+\tfrac{1}{2}+4\tfrac{1}{2}]\} = \frac{1}{2}$$

What a successful story!

- **Magnetic moment:**

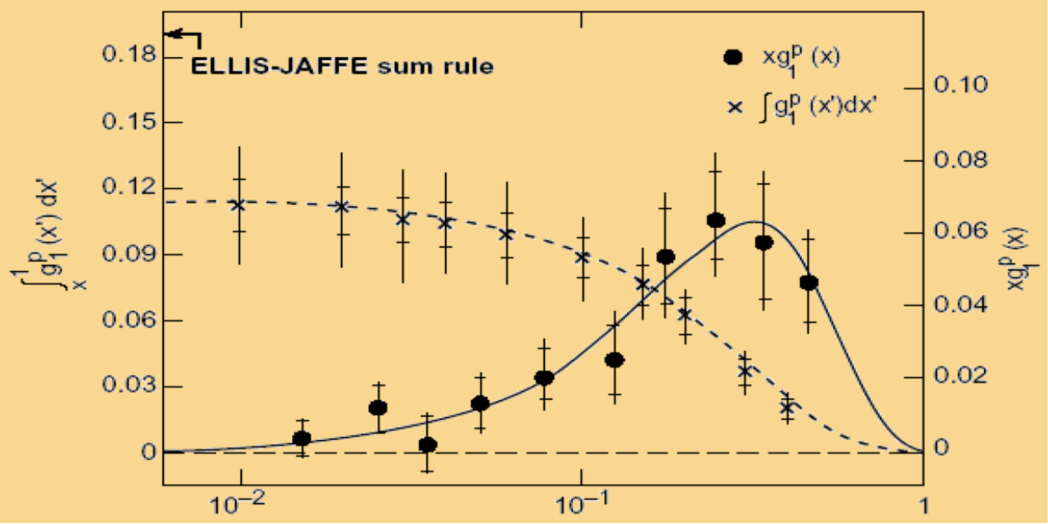
$$\mu_p = \langle p\uparrow|\sum_{i=1}^{3}\hat{\mu}_i(\hat{\sigma}_3)_i|p\uparrow\rangle = \frac{1}{3}[4\mu_u - \mu_d]$$

$$\mu_n = \frac{1}{3}[4\mu_d - \mu_u] \qquad \frac{\mu_u}{\mu_d} \approx \frac{2/3}{-1/3} = -2$$

$$\Rightarrow \left\{ \begin{array}{l} \left(\dfrac{\mu_n}{\mu_p}\right)_{\rm QM} = -\dfrac{2}{3} \\[2ex] \left(\dfrac{\mu_n}{\mu_p}\right)_{\rm Exp} = -0.68497945(58) \end{array} \right.$$

The surprise: “The Plot”, …

- ❑ **EMC (European Muon Collaboration ’87) – more than 30 years ago:**



$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x) + \Delta\bar{q}(x)\right] + \mathcal{O}(\alpha_s) + \mathcal{O}\left(1/Q\right)$$

- ✧ **Combined with earlier SLAC data:** $\int_0^1 g_1^p(x)dx = 0.126 \pm 0.018$
- ✧ **Combined with:** $g_A^3 = \Delta u - \Delta d$ **and** $g_A^8 = \Delta u + \Delta d - 2\Delta s$ **from low energy neutron & hyperon β decay**

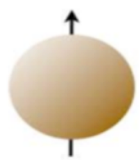
$$\Delta\Sigma = \sum_q\left[\Delta q + \Delta\bar{q}\right] = 0.12 \pm 0.17$$

- ❑ **“Spin crisis” or puzzle:**
  - ✧ **Strange sea polarization is sizable & negative**
  - ✧ **Very little of the proton spin is carried by quarks**

New era of spin physics

The present: Proton Spin, …

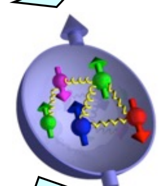
- **The sum rule:** $$S(\mu) = \sum_f \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$
  - Many possibilities of decompositions – connection to observables?
  - Intrinsic properties + dynamical motion and interactions
- **An incomplete story:**



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe-Manohar, 90
Ji, 96, …

Proton Spin



Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

$$\sim 40\% (\text{with RHIC data})$$

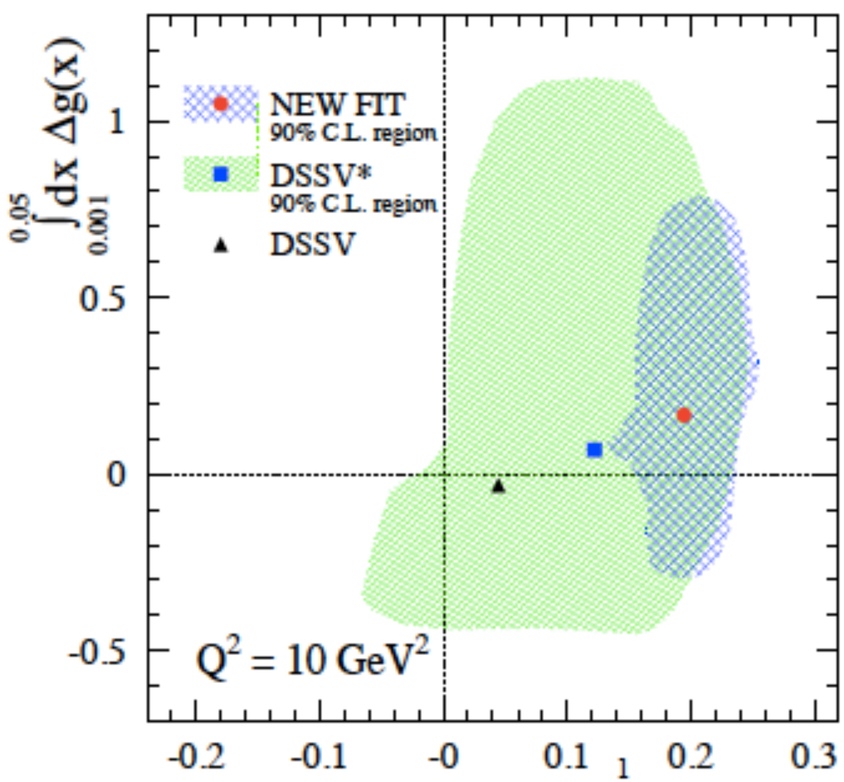
Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

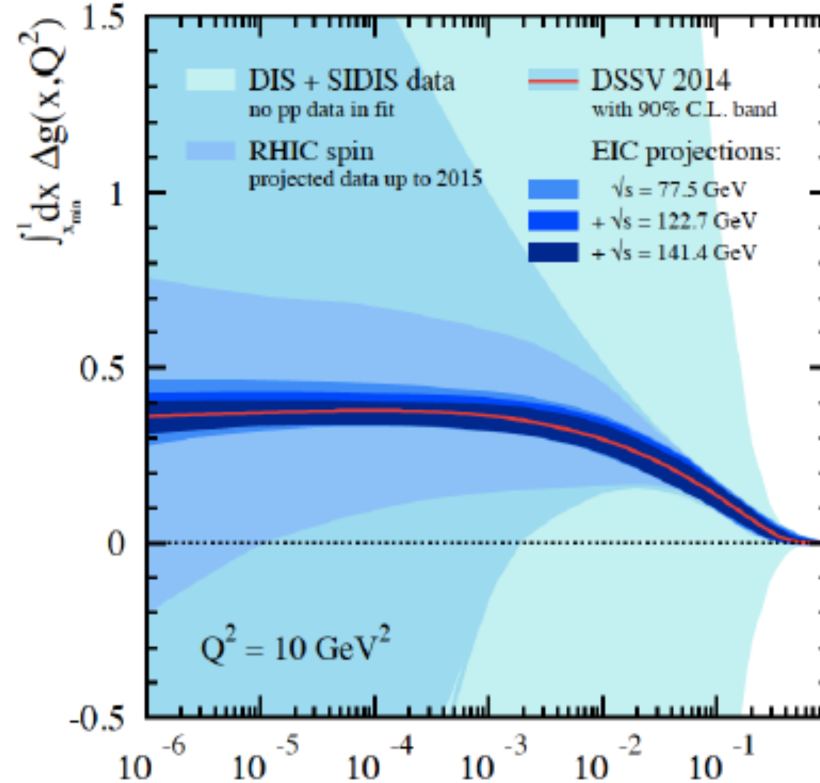
Dual roles of proton spin: property vs. tool!

How much proton spin is at small-x?

- Global fit and simulation:



de Florian, et al. PRL2014



Aschenauer, et al. PRD2015

- The wonder of QCD:

Kovchekov, et al. JHEP2017

Small-x evolution ➡

$$\Delta q(x,Q^2) \sim \left(\frac{1}{x}\right)^{\alpha_h^q} \quad \text{with} \quad \alpha_h^q = \frac{4}{\sqrt{3}}\sqrt{\frac{\alpha_s N_c}{2\pi}} \approx 2.31\sqrt{\frac{\alpha_s N_c}{2\pi}}$$

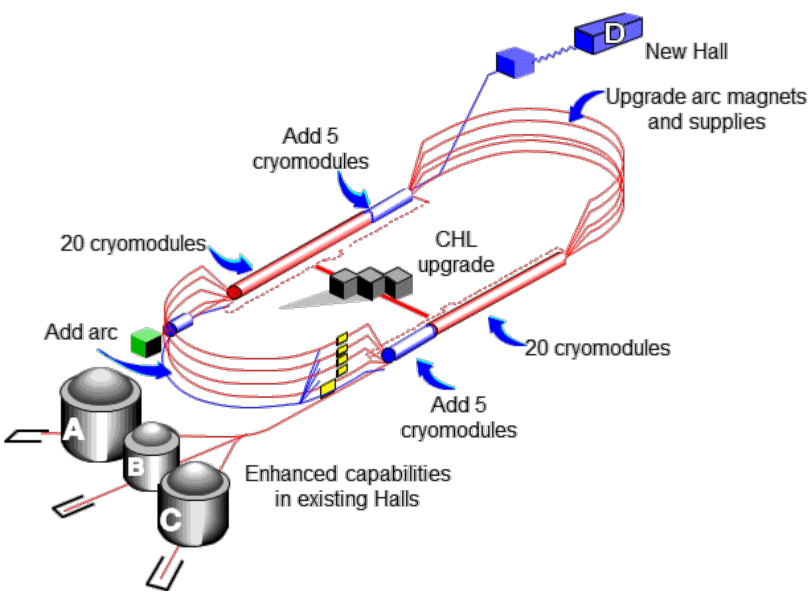
Integratable x-dependence

$$\Delta G(x,Q^2) \sim \left(\frac{1}{x}\right)^{\alpha_h^G} \quad \text{with} \quad \alpha_h^G = \frac{13}{4\sqrt{3}}\sqrt{\frac{\alpha_s N_c}{2\pi}} \approx 1.88\sqrt{\frac{\alpha_s N_c}{2\pi}}$$

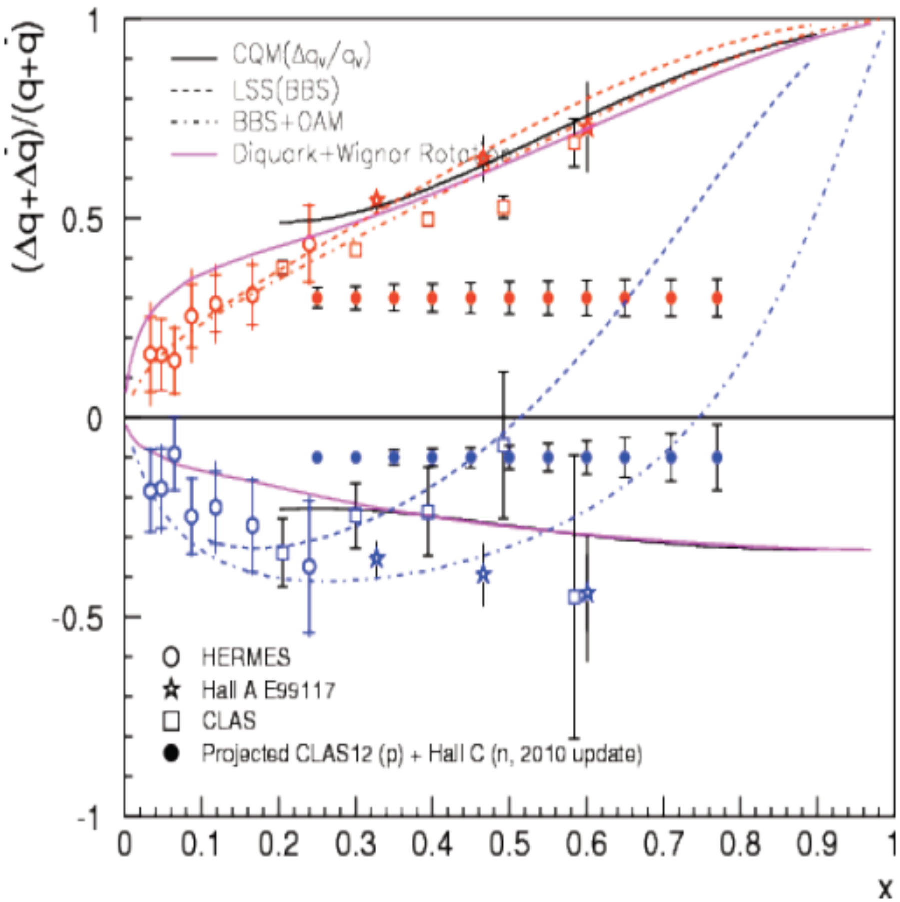
The future: JLab12, …

- **JLab 12GeV – upgrade project just completed:**

12 GeV CEBAF Upgrade Project is just complete, and all 4-Halls are taking data



CLAS12



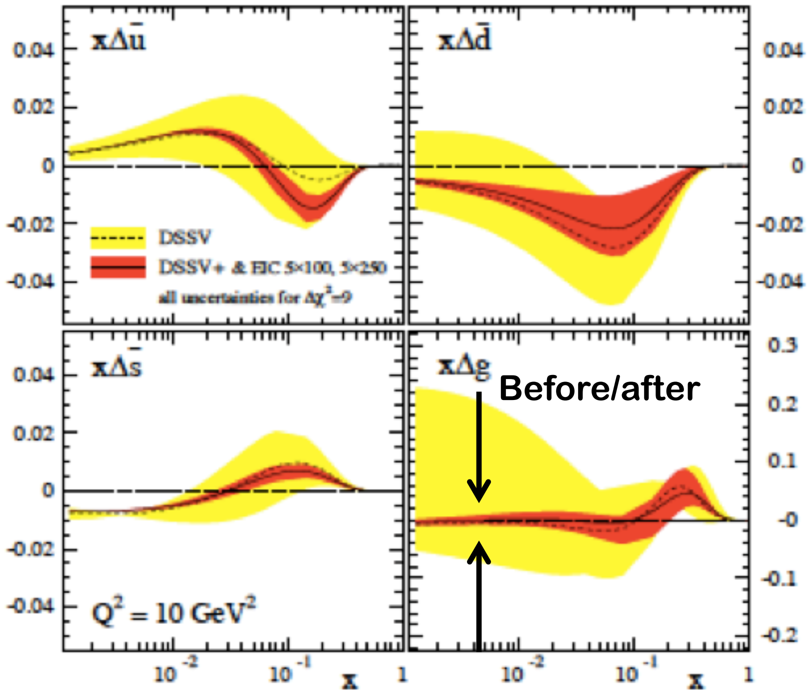
Plus many more JLab experiments, COMPASS, Fermilab-fixed target expts …

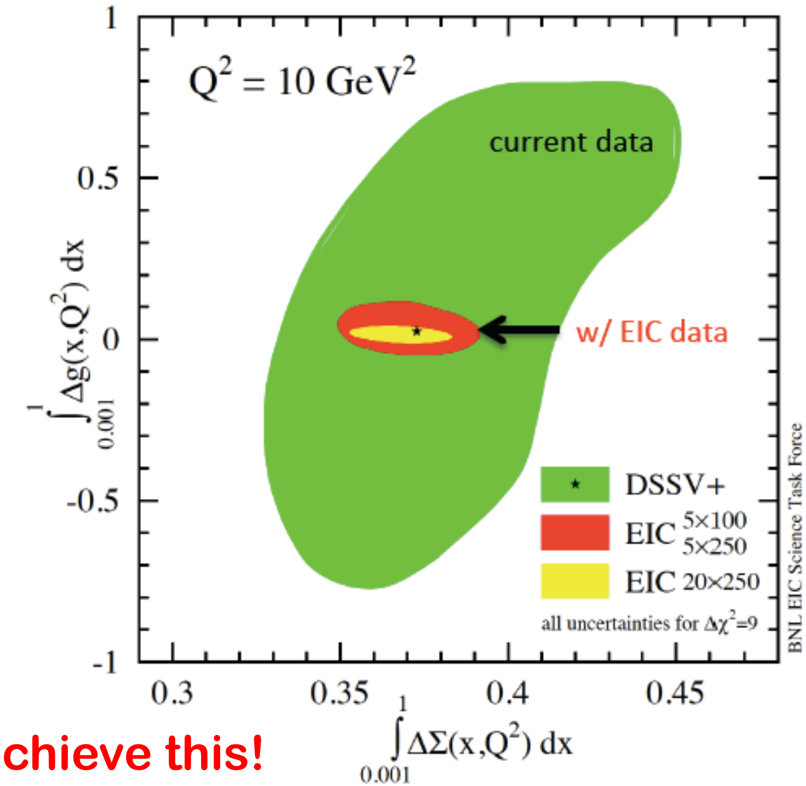
The future: EIC, …

The EIC White Paper

❑ One-year of running at EIC:

Wider Q^2 and x range including low x at EIC!





No other machine in the world can achieve this!

❑ Ultimate solution to the proton spin puzzle:

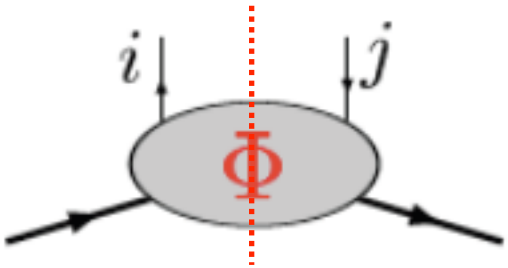
✧ *Precision measurement of Δg(x) – extend to smaller x regime*

✧ *Orbital angular momentum contribution – measurement of TMDs & GPDs!*

Transverse spin

- Two-quark correlator:

$$\Phi_{ij}(k,P,S) = \int d^4z\, e^{ik\cdot z} \langle PS|\bar{\psi}_j(0)\,\psi_i(z)|PS\rangle$$



- 4-independent collinear d.o.f. for spin-1/2 quarks:

→ 3 well-known leading power quark parton distributions:

$$q(x) = \frac{1}{4\pi}\int dz^- \, e^{iz^- xP^+} \langle P,S|\bar{\psi}(0)\,\gamma^+\,\psi\left(0,z^-,\mathbf{0}_\perp\right)|P,S\rangle$$

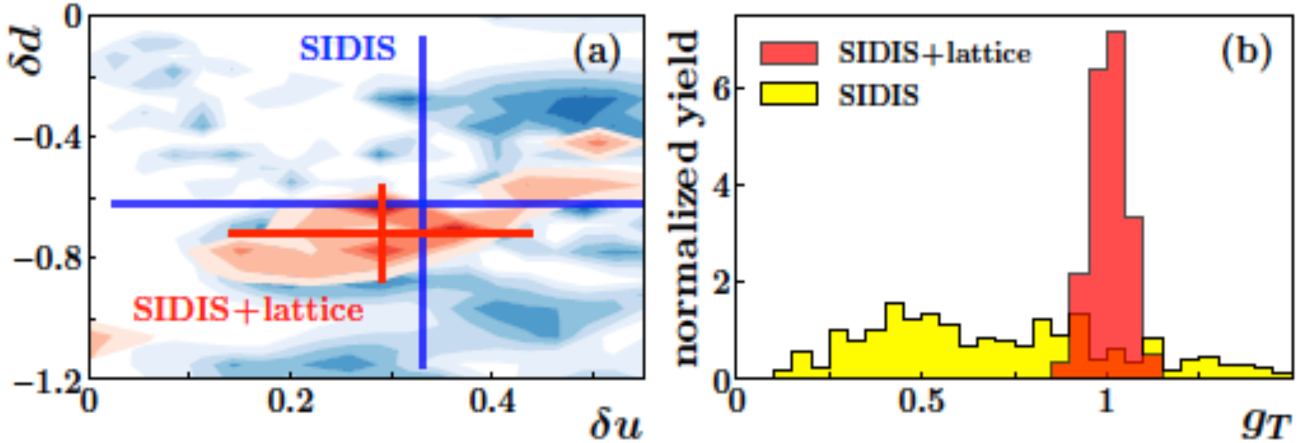
$$\Delta q(x) = \frac{1}{4\pi}\int dz^- \, e^{iz^- xP^+} \langle P,S|\bar{\psi}(0)\,\gamma^+\,\gamma_5\,\psi\left(0,z^-,\mathbf{0}_\perp\right)|P,S\rangle$$

$$\delta q(x) = \frac{1}{4\pi}\int dz^- \, e^{iz^- xP^+} \langle P,S|\bar{\psi}(0)\,\gamma^+\,\gamma_\perp\,\gamma_5\,\psi\left(0,z^-,\mathbf{0}_\perp\right)|P,S\rangle$$

"unpolarized" – "longitudinally polarized" – "transversity"

Global fit with the help of lattice QCD

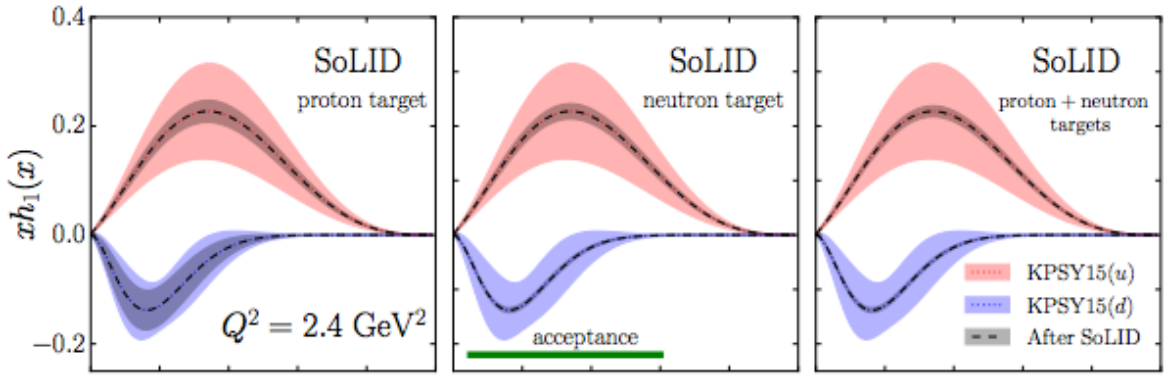
- First global QCD analysis of transversity distribution
  – using Monte Carlo methodology with lattice QCD constraints

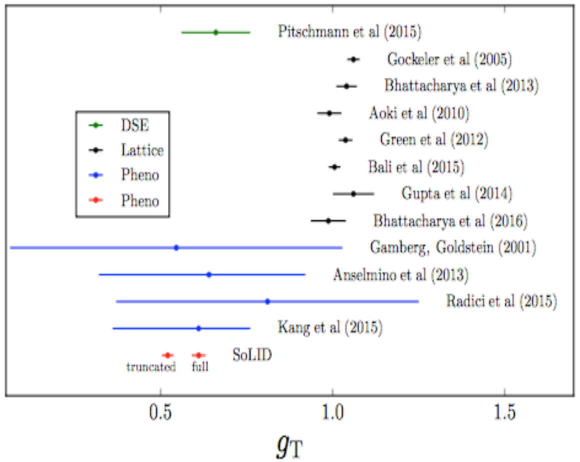


isovector tensor charge

H.W. Lin et al, PRL 120, 152502 (2018)

- Impact of a future SoLID, …



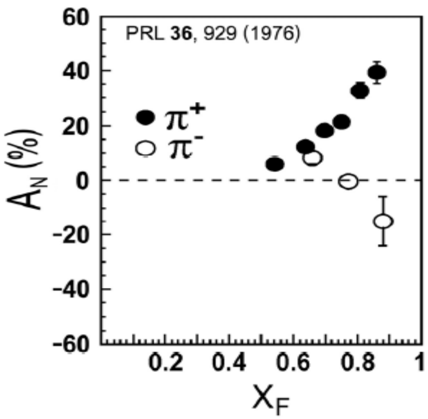


Hall A + Theory, Phys. Lett. B767, 91 (2017)

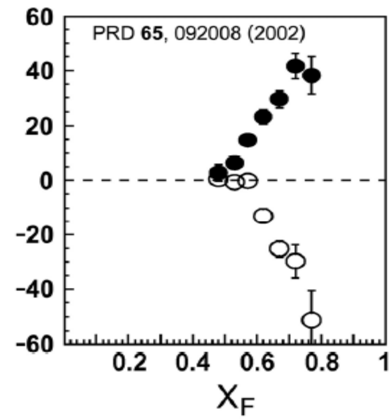
The challenge: Large A_N

- ❑ A_N - consistently observed for over 35 years!

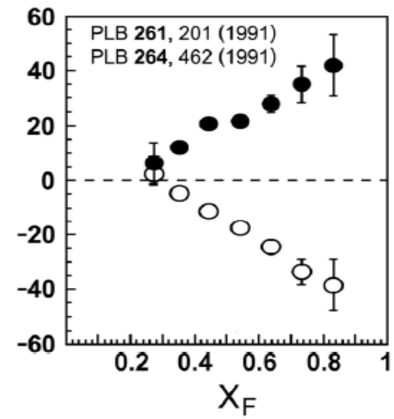
ANL – 4.9 GeV



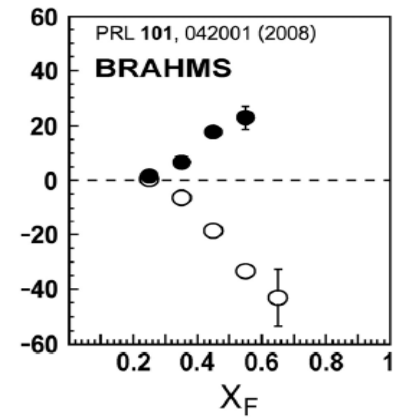
BNL – 6.6 GeV



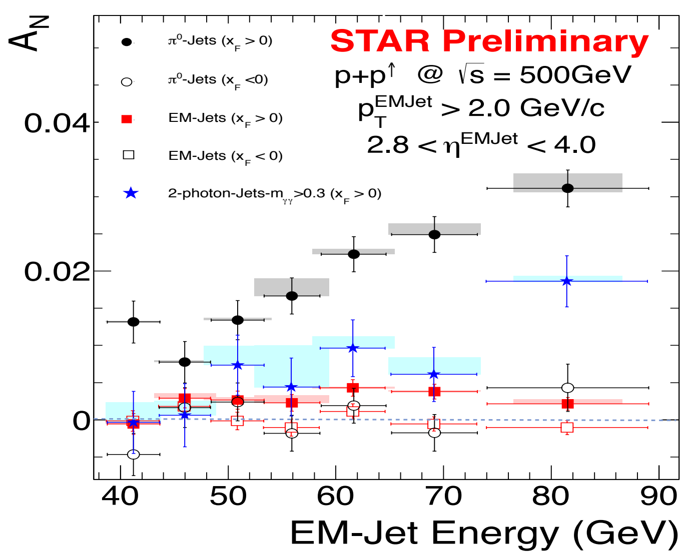
FNAL – 20 GeV

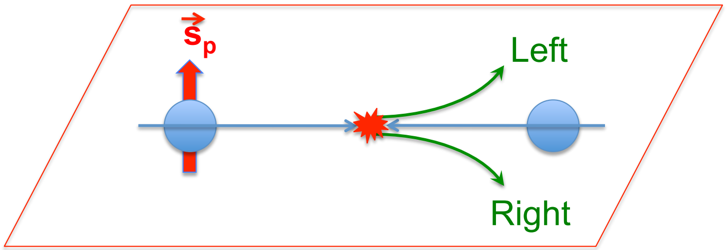


BNL – 62.4 GeV



- ❑ Survived the highest RHIC energy:





$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$

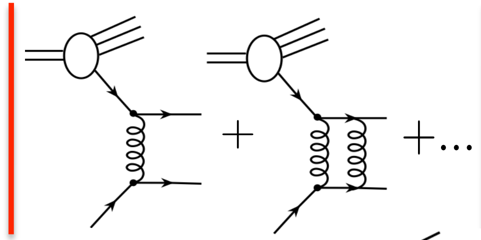
Do we understand this?

Do we understand this?

Kane, Pumplin, Repko, PRL, 1978

❑ Early attempt:

Cross section: $\sigma_{AB}(p_T, \vec{s}) \propto$



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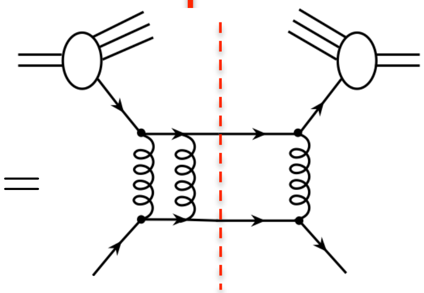
Asymmetry: $\sigma_{AB}(p_T, \vec{s}) - \sigma_{AB}(p_T, -\vec{s}) =$



$\propto \alpha_s \dfrac{m_q}{p_T}$

Too small to explain available data!

❑ What do we need?

$$A_N \;\propto\; i\vec{s}_p \cdot (\vec{p}_h \times \vec{p}_T) \;\Rightarrow\; i\epsilon^{\mu\nu\alpha\beta} p_{h\mu} s_\nu p_\alpha p'_{h\beta}$$

Need a phase, a spin flip, enough vectors

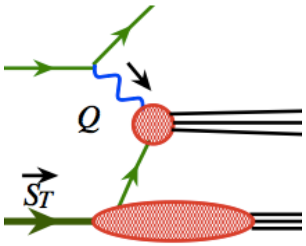
❑ Vanish without parton's transverse motion:

➡ **A direct probe for parton's transverse motion,**

Spin-orbital correlation, QCD quantum interference

Current understanding of TSSAs

❑ Symmetry plays important role:

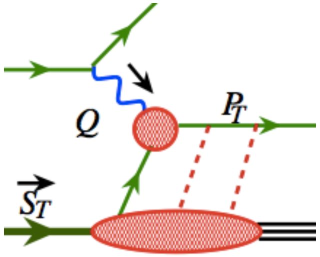


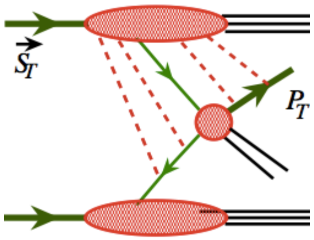
Inclusive DIS
Single scale
Q

Parity Time-reversal

➡ $A_N = 0$

❑ One scale observables – $Q \gg \Lambda_{QCD}$:





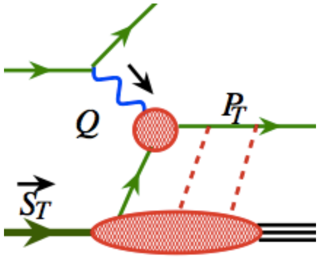
➡

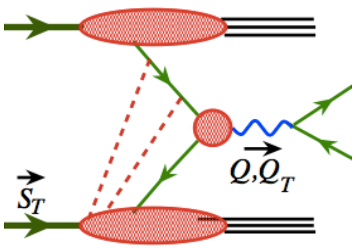
Collinear factorization Twist-3 distributions

~ Moment of TMDs

SIDIS: $Q \sim P_T$ DY: $Q \sim P_T$; Jet, Particle: P_T

❑ Two scales observables – $Q_1 \gg Q_2 \sim \Lambda_{QCD}$:





➡

TMD factorization TMD distributions

~ Direct k_T info.

SIDIS: $Q \gg P_T$ DY: $Q \gg P_T$ or $Q \ll P_T$

Twist-3 distributions relevant to A_N

- **Twist-2 distributions:**
  - **Unpolarized PDFs:**
  - **Polarized PDFs:**

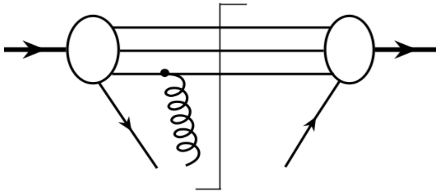
$$q(x) \propto \langle P|\overline{\psi}_q(0)\frac{\gamma^+}{2}\psi_q(y)|P\rangle$$

$$G(x) \propto \langle P|F^{+\mu}(0)F^{+\nu}(y)|P\rangle(-g_{\mu\nu})$$

$$\Delta q(x) \propto \langle P, S_\parallel|\overline{\psi}_q(0)\frac{\gamma^+\gamma^5}{2}\psi_q(y)|P, S_\parallel\rangle$$

$$\Delta G(x) \propto \langle P, S_\parallel|F^{+\mu}(0)F^{+\nu}(y)|P, S_\parallel\rangle(i\epsilon_{\perp\mu\nu})$$

- **Two-sets Twist-3 correlation functions:**



No probability interpretation!

$$\widetilde{T}_{q,F} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \langle P, s_T|\overline{\psi}_q(0)\frac{\gamma^+}{2}\left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)\right]\psi_q(y_1^-)|P, s_T\rangle$$

Kang, Qiu, 2009

$$\widetilde{T}_{G,F}^{(f,d)} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \frac{1}{P^+}\langle P, s_T|F^{+\rho}(0)\left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)\right]F^{+\lambda}(y_1^-)|P, s_T\rangle(-g_{\rho\lambda})$$

$$\widetilde{T}_{\Delta q,F} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \langle P, s_T|\overline{\psi}_q(0)\frac{\gamma^+\gamma^5}{2}\left[i\, s_T^\sigma\, F_\sigma{}^+(y_2^-)\right]\psi_q(y_1^-)|P, s_T\rangle$$

$$\widetilde{T}_{\Delta G,F}^{(f,d)} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \frac{1}{P^+}\langle P, s_T|F^{+\rho}(0)\left[i\, s_T^\sigma\, F_\sigma{}^+(y_2^-)\right]F^{+\lambda}(y_1^-)|P, s_T\rangle\,(i\epsilon_{\perp\rho\lambda})$$

Role of color magnetic force!

- **Twist-3 fragmentation functions:**

See Kang, Yuan, Zhou, 2010, Kang 2010

Collinear twist-3 contribution to A_N

$$d\Delta\sigma(s_T) \equiv d\sigma(s_T) - d\sigma(-s_T)$$

$$= H \otimes f_{a/A^\uparrow(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)}$$

$$\boxed{+ H' \otimes f_{a/A^\uparrow(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)}} \rightarrow$$

Negligible
Kanazawa & Koike (2000)

$$\boxed{+ H'' \otimes f_{a/A^\uparrow(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)}} \rightarrow$$

Important
Metz & Pitonyak (2013)

❑ Twist-3 fragmentation contribution:

$$\frac{P_h^0 d\sigma_{pol}}{d^3\vec{P}_h} = -\frac{2\alpha_s^2 M_h}{S}\epsilon_{\perp\mu\nu}\, S_\perp^\mu P_{h\perp}^\nu \sum_i \sum_{a,b,c}\int_{z_{min}}^1 \frac{dz}{z^3}\int_{x'_{min}}^1 \frac{dx'}{x'}\frac{1}{x'S+T/z}\frac{1}{-x\hat{u}-x'\hat{t}}$$

$$\times \frac{1}{x}h_1^a(x)\, f_1^b(x')\left\{\left(\hat{H}^{C/c}(z) - z\frac{d\hat{H}^{C/c}(z)}{dz}\right)S_{\hat{H}}^i + \frac{1}{z}H^{C/c}(z)\, S_H^i\right.$$

$$\left. + 2z^2\int \frac{dz_1}{z_1^2} PV\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\hat{H}_{FU}^{C/c,\Im}(z,z_1)\frac{1}{\xi}S_{\hat{H}_{FU}}^i\right\}$$

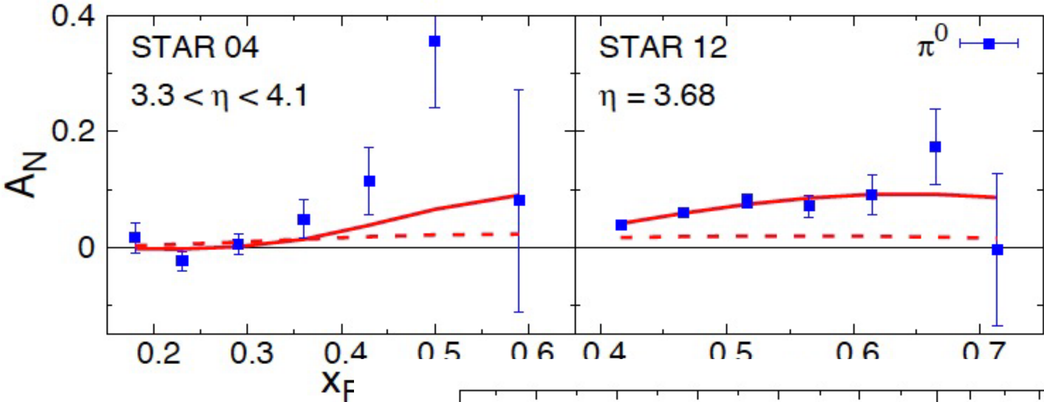
$$2z^3\int_z^\infty \frac{dz_1}{z_1^2}\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\hat{H}_{FU}^{\Im}(z,z_1) = H(z) + 2z\hat{H}(z) \quad \boxed{\text{3-parton correlator}}$$

$$\hat{H}(z) = H_1^{\perp(1)}(z) \quad \boxed{\text{Collins-type function}}$$

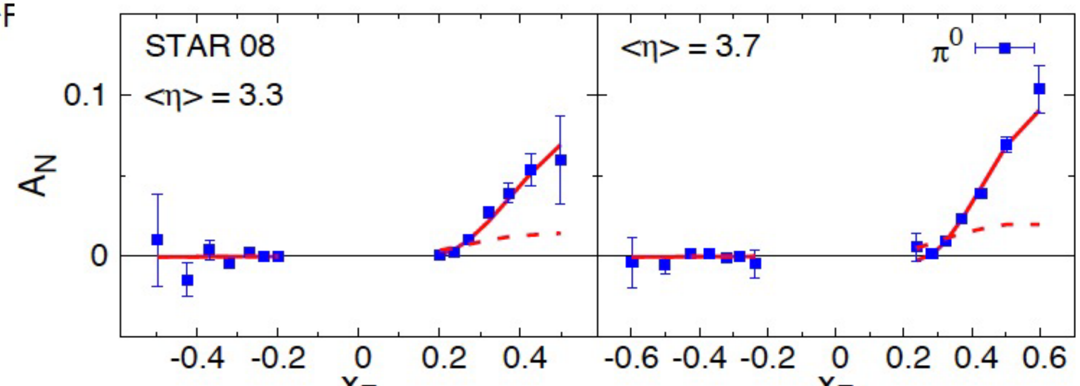
Collinear twist-3 contribution to A_N

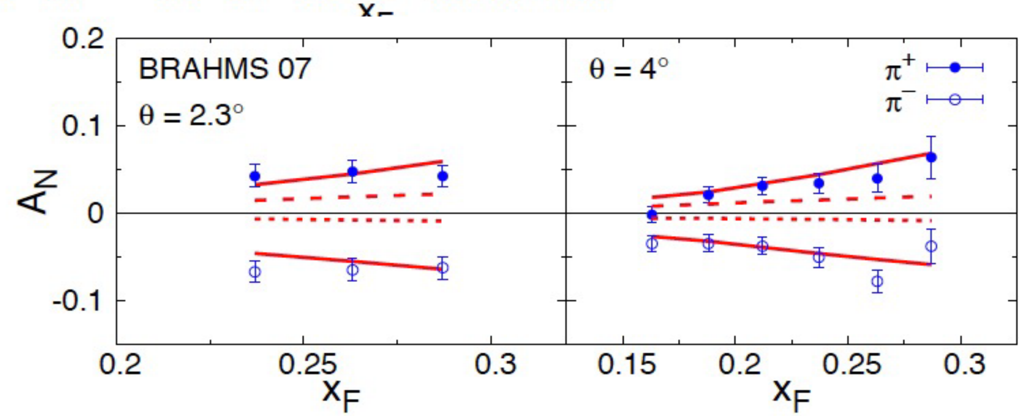
- ❑ **Fragmentation + QS (fix through Sivers function):**

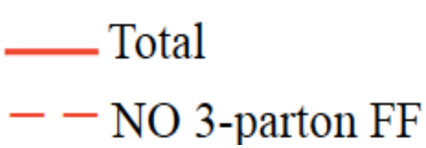
Kanazawa, Koike, Metz, Pitonyak
PRD 89(RC) (2014)



χ^2/d.o.f. = 1.03







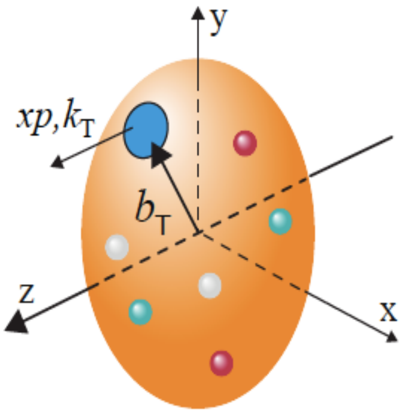
Paradigm shift: 3D structure of hadrons

❑ Cross sections with two-momentum scales observed:

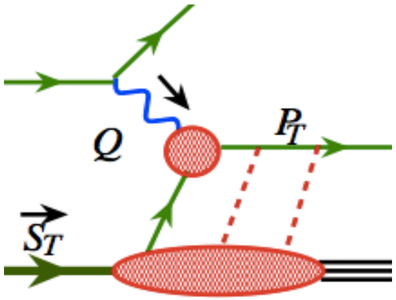
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

✧ Hard scale: Q_1 localizes the probe to see the quark or gluon d.o.f.

✧ "Soft" scale: Q_2 could be more sensitive to hadron structure, e.g., confined motion

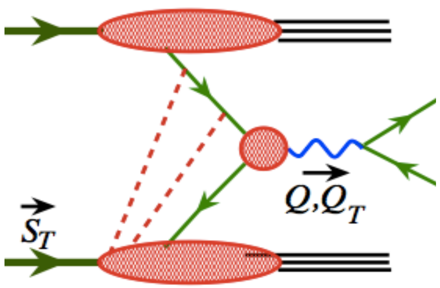


❑ Two-scale observables with the hadron broken:



SIDIS: $Q \gg P_T$

+



DY: $Q \gg P_T$

+ Two-jet momentum imbalance in SIDIS, …

➡

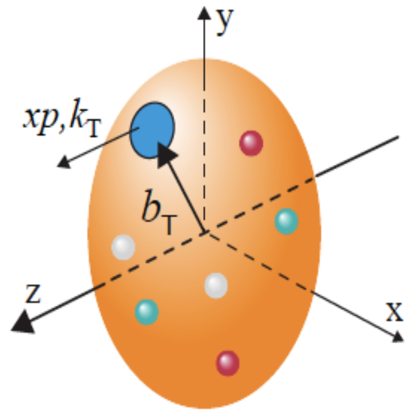
✧ Natural observables with TWO very different scales

✧ TMD factorization: partons' confined motion is encoded into TMDs

Paradigm shift: 3D structure of hadrons

❑ **Cross sections with two-momentum scales observed:**

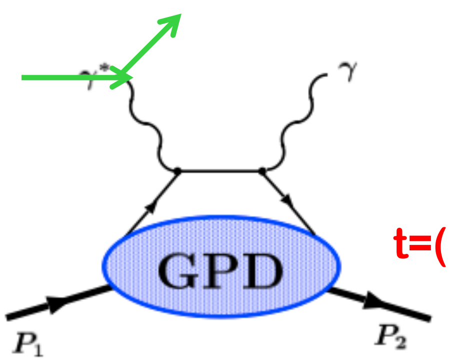
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



✧ **Hard scale:** Q_1 **localizes the probe to see the quark or gluon d.o.f.**

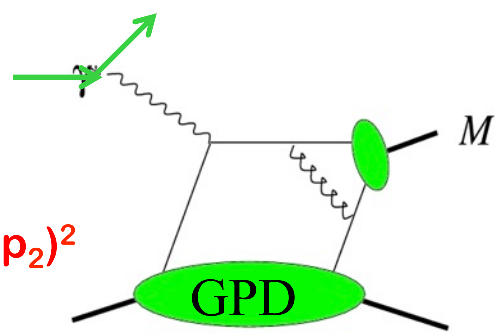
✧ **"Soft" scale:** Q_2 **could be more sensitive to hadron structure, e.g., confined motion**

❑ **Two-scale observables with the hadron unbroken:**

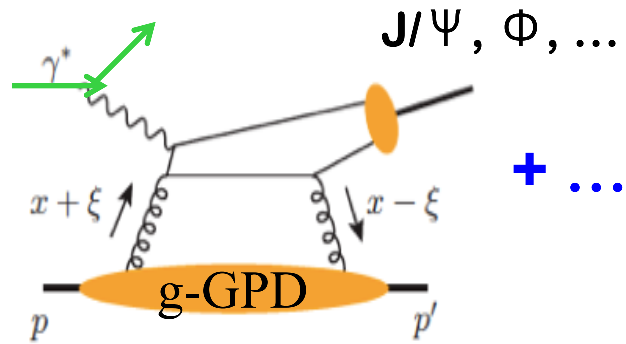


+

$t=(p_1-p_2)^2$



+



+ ...

DVCS: $Q^2 \gg |t|$ **DVEM: $Q^2 \gg |t|$** **EHMP: $Q^2 \gg |t|$**

✧ **Natural observables with TWO very different scales**

✧ **GPDs: Fourier Transform of t-dependence gives spatial b_T-dependence**

TMDs: confined motion & spin correlation

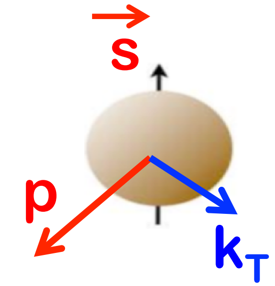
❑ Power of spin – many more correlations:

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	f_1 =		$h_1^{\perp}$ = − Boer-Mulders
L		g_{1L} = − Helicity	$h_{1L}^{\perp}$ = −
T	$f_{1T}^{\perp}$ = − Sivers	$g_{1T}^{\perp}$ = −	h_1 = − Transversity $h_{1T}^{\perp}$ = −

Nucleon Spin

Quark Spin

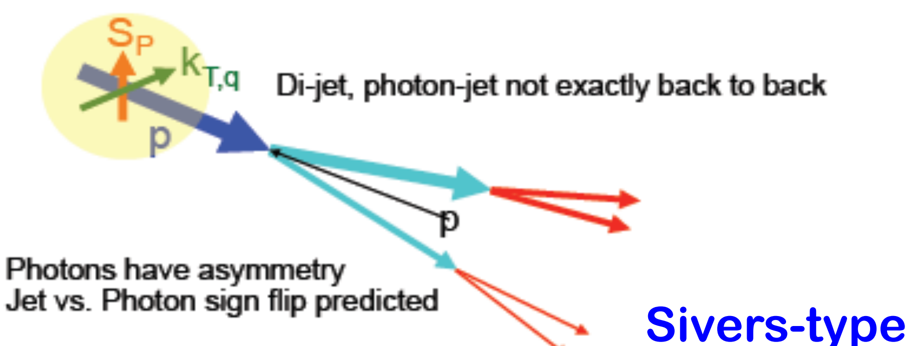
Similar for gluons

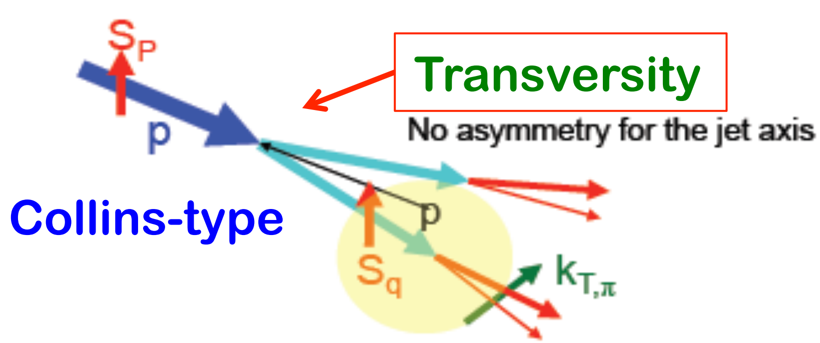


Require two Physical scales

More than one TMD contribute to the same observable!

❑ A_N – single hadron production:





The present: Theory is solid

- **TMDs & SIDIS as an example:**
  - **Low P_{hT} (P_{hT} << Q) – TMD factorization:**

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h) = \hat{H}(Q)\otimes\Phi_f(x,k_\perp)\otimes\mathcal{D}_{f\to h}(z,p_\perp)\otimes\mathcal{S}(k_{s\perp}) + \mathcal{O}\left[\frac{P_{h\perp}}{Q}\right]$$

  - **High P_{hT} (P_{hT} ~ Q) – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h) = \hat{H}(Q,P_{h\perp},\alpha_s)\otimes\phi_f\otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{P_{h\perp}},\frac{1}{Q}\right)$$

  - **P_{hT} Integrated - Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q,x_B,z_h) = \tilde{H}(Q,\alpha_s)\otimes\phi_f\otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{Q}\right)$$

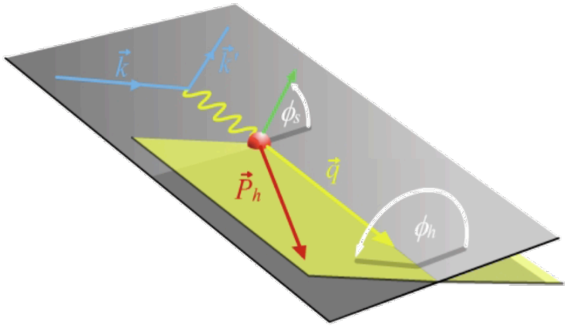
  - **Very high P_{hT} >> Q – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h) = \sum_{abc}\hat{H}_{ab\to c}\otimes\phi_{\gamma\to a}\otimes\phi_b\otimes D_{c\to h} + \mathcal{O}\left(\frac{1}{Q},\frac{Q}{P_{h\perp}}\right)$$

- **SIDIS is the best for probing TMDs:**

$$A_{UT}(\varphi_h^l,\varphi_S^l) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = A_{UT}^{Collins}\sin(\phi_h+\phi_S)$$

$$+A_{UT}^{Sivers}\sin(\phi_h-\phi_S) + A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S)$$



Modified universality for TMDs

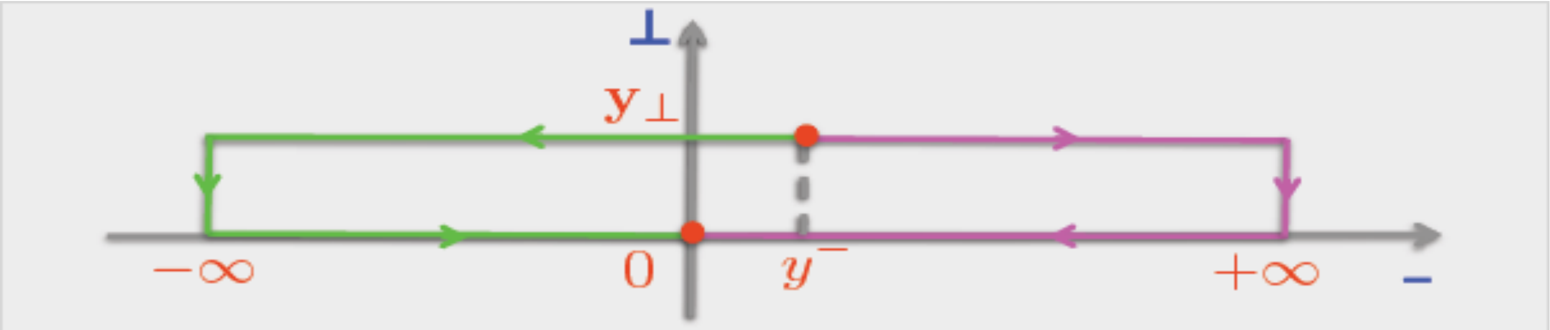
- **Definition:**

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp) \boxed{\text{Gauge link}} \frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

- **Gauge links:**

SIDIS:

DY:



- **Process dependence:**

$$f^{\text{SIDIS}}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \neq f^{\text{DY}}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S})$$

Collinear factorized PDFs are process independent

Critical test of TMD factorization

- **Parity – Time reversal invariance:**

$$f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x,\mathbf{k}_\perp,\vec{S}) = f_{q/h^\uparrow}^{\mathrm{DY}}(x,\mathbf{k}_\perp,-\vec{S})$$

- **Definition of Sivers function:**

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/h}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/h^\uparrow}(x,k_\perp)\,\vec{S}\cdot\hat{p}\times\hat{\mathbf{k}}_\perp$$

- **Modified universality:**

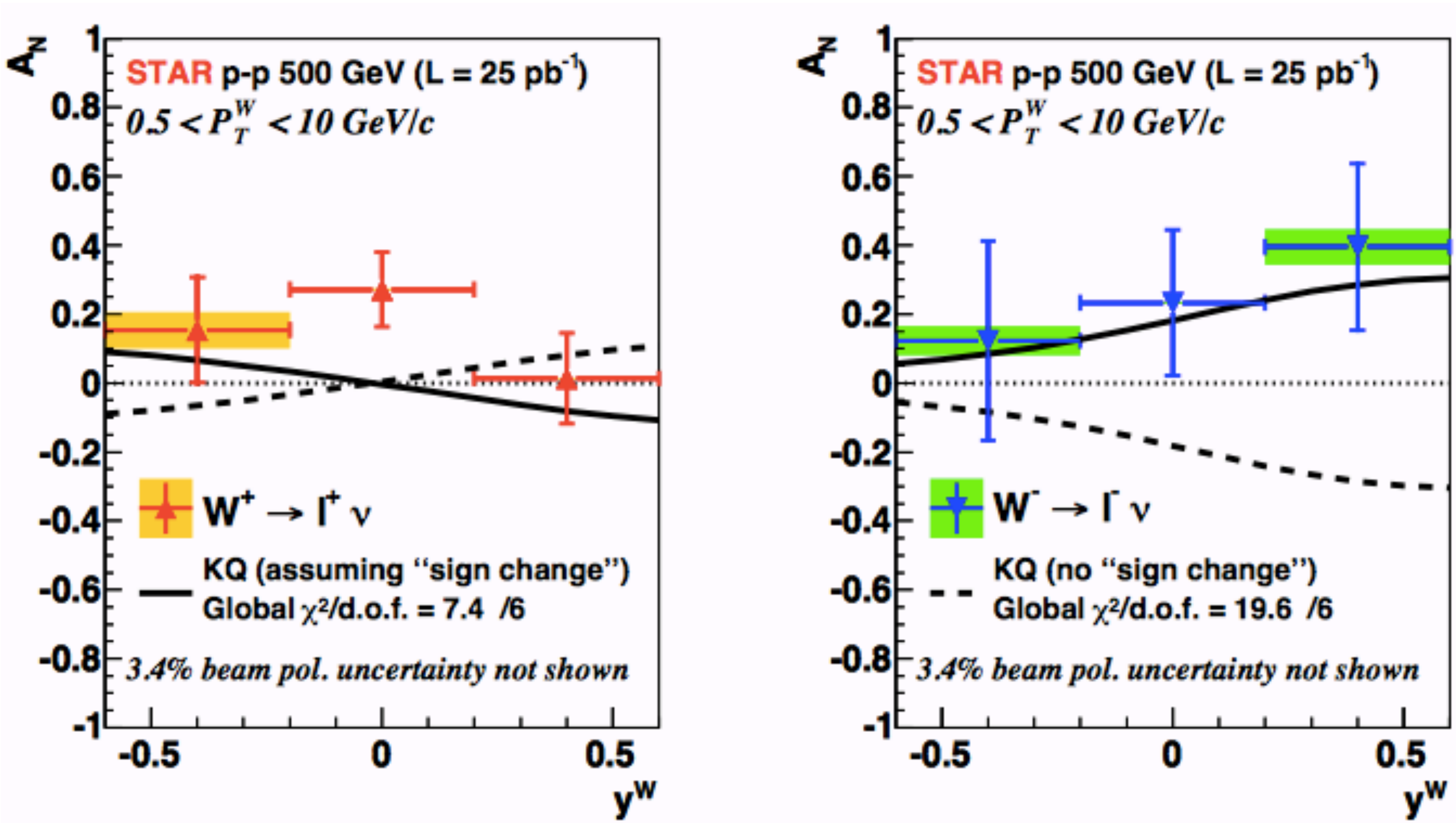
$$\Delta^N f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x,k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\mathrm{DY}}(x,k_\perp)$$

The spin-averaged part of this TMD is process independent,

but, spin-averaged Boer-Mulder's TMD requires the sign change!

Same PT symmetry examination needs for TMD gluon distributions!

Hint of the sign change: A_N of W production



Data from STAR collaboration on A_N for W-production are consistent with a sign change between SIDIS and DY

Consistent with COMPASS data

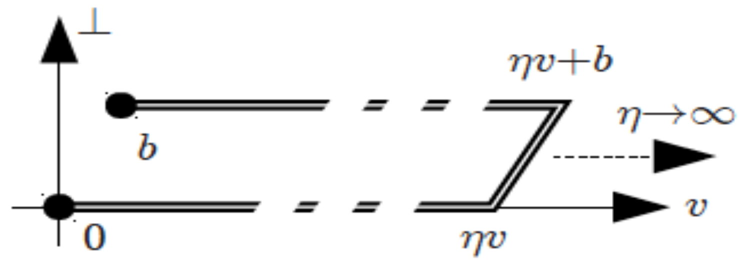
STAR Collab. Phys. Rev. Lett. 116, 132301 (2016)

Hint of the TMD sign change from lattice QCD

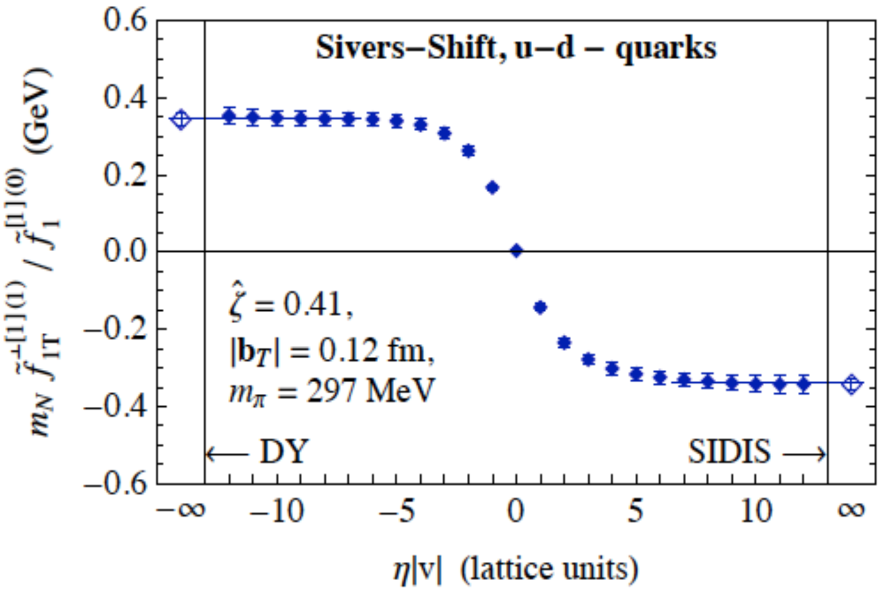
M. Engelhardt

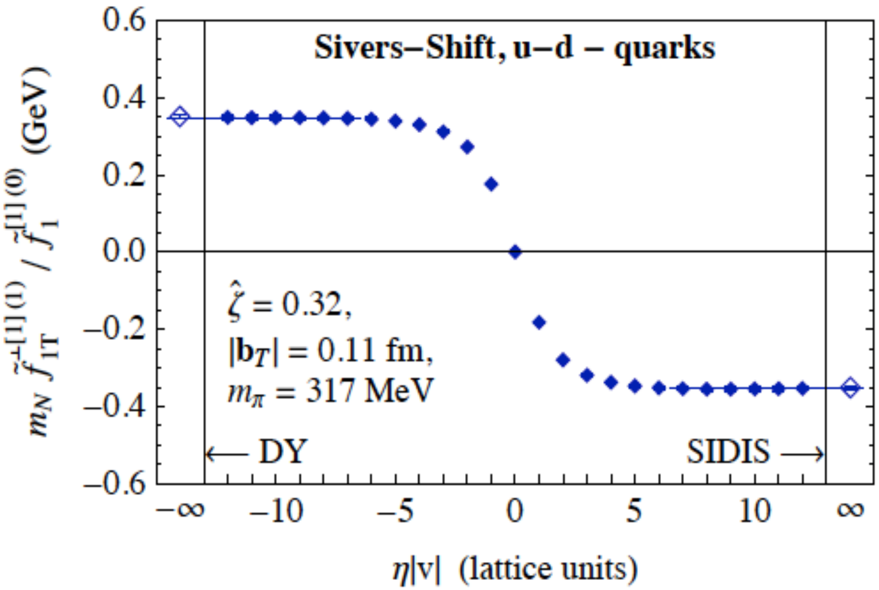
- Gauge link for lattice calculation:

Staple-shaped gauge link $\mathcal{U}[0, \eta v, \eta v + b, b]$



- Normalized moment of Sivers function – at given b_T:



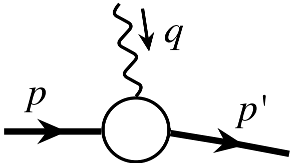


Confining radius in color distribution?

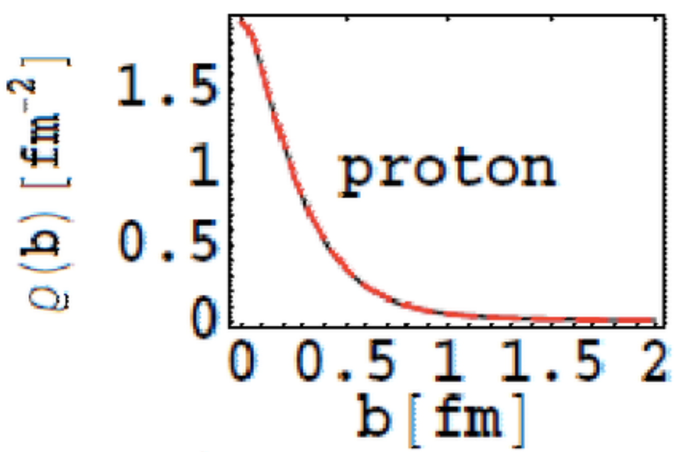
- **The "big" question:**

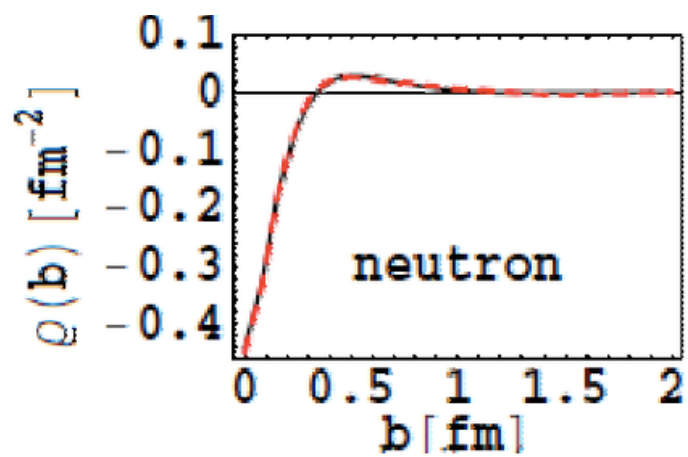
  How color is distributed inside a hadron? (clue for color confinement?)

- **Electric charge distribution:**



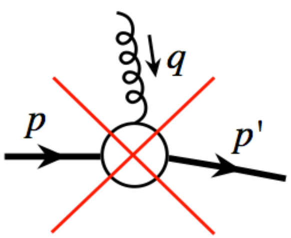
  Elastic electric form factor ➡ Charge distributions





- **But, NO color elastic nucleon form factor!**

  Hadron is colorless and gluon carries color



➡ ***Parton density's spatial distributions – a function of x as well (more "proton"-like than "neutron"-like?) – GPDs***

GPDs: Density distributions & spin correlation

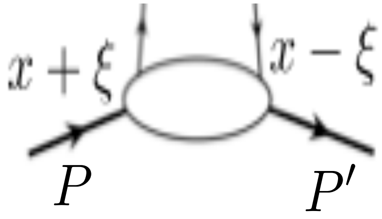
❑ **Quark "form factor":**

Exchanging vacuum Q.#.
"Density current"

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{\psi}_q(\lambda/2) \frac{\gamma\cdot n}{2P\cdot n} \psi_q(-\lambda/2) | P\rangle$$

$$\equiv \; H_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P')\gamma^\mu \mathcal{U}(P)\right] \frac{n_\mu}{2P\cdot n}$$

$$+ \; E_q(x,\xi,t,\mu^2) \left[\bar{\mathcal{U}}(P') \frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M} \mathcal{U}(P)\right] \frac{n_\mu}{2P\cdot n}$$



with $\xi = (P'-P)\cdot n/2 \;$ and $\; t = (P'-P)^2 \;\Rightarrow\; -\Delta_\perp^2 \;$ if $\; \xi \to 0$

$\tilde{H}_q(x,\xi,t,Q), \quad \tilde{E}_q(x,\xi,t,Q)$ **Different quark spin projection**

$H_q(x,0,0,\mu^2) = q(x,\mu^2)$ **The limit when** $\xi \to 0$

❑ **Total quark's orbital contribution to proton's spin:**

Ji, PRL78, 1997

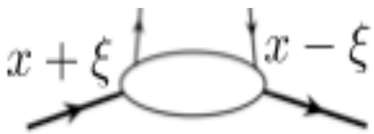
$$J_q = \frac{1}{2} \lim_{t\to 0} \int dx\, x \left[H_q(x,\xi,t) + E_q(x,\xi,t)\right]$$

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

JLab12 – valence quarks, EIC – sea quarks and gluons

GPDs: Density distributions & spin correlation

- **GPDs of quarks and gluons:**

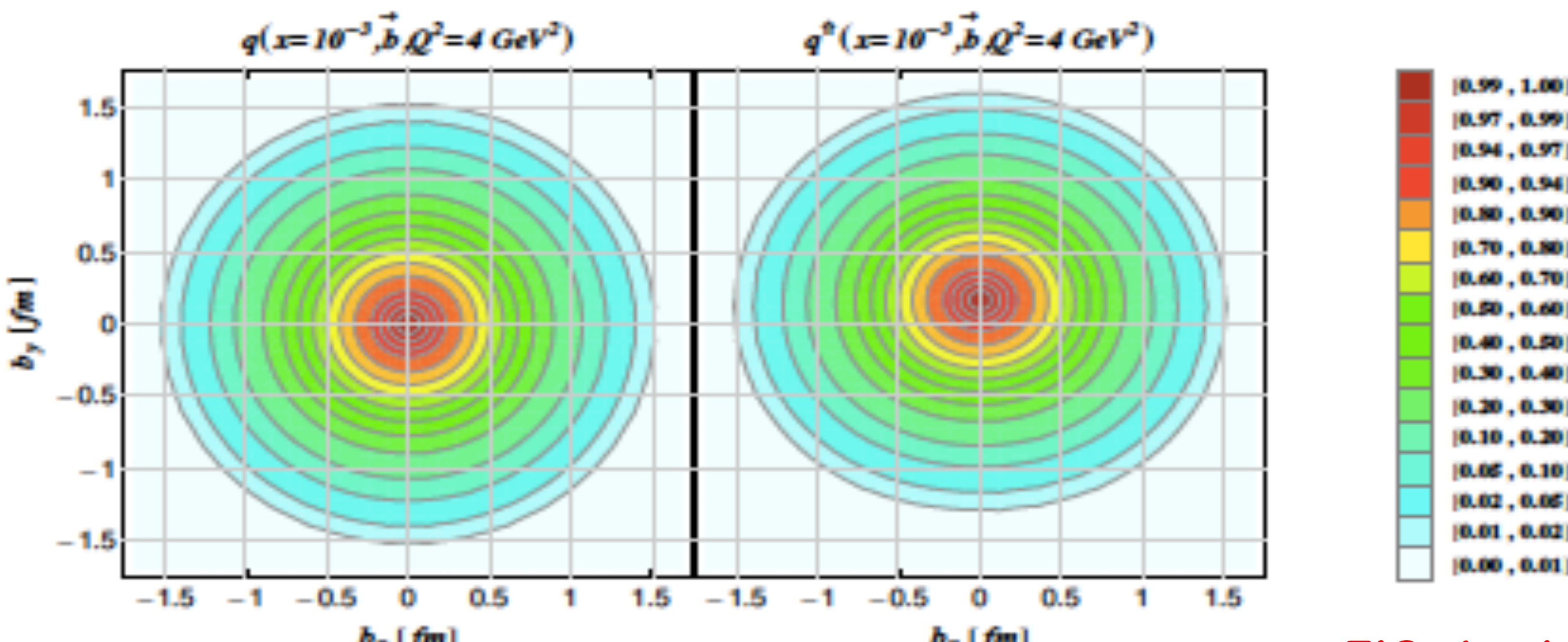


$$H_q(x,\xi,t,Q), \quad E_q(x,\xi,t,Q),$$
$$\tilde{H}_q(x,\xi,t,Q), \quad \tilde{E}_q(x,\xi,t,Q)$$

Evolution in Q – gluon GPDs

- **Imaging (** $\xi \to 0$ **):** $$q(x,b_\perp,Q) = \int d^2\Delta_\perp e^{-i\Delta_\perp\cdot b_\perp} H_q(x,\xi=0,t=-\Delta_\perp^2,Q)$$

- **Influence of transverse polarization – shift in density:**



EIC simulation

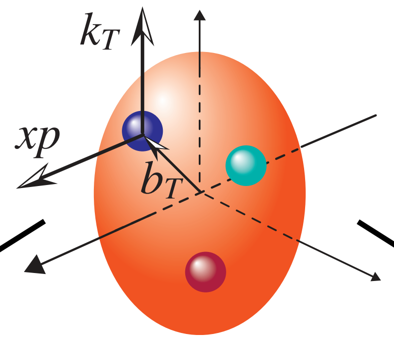
Orbital angular momentum

OAM: Correlation between parton's position and its motion – in an averaged (or probability) sense

- **Wigner distribution:**

Momentum Space | *Coordinate Space*

TMDs | *GPDs*



$\int d^2b_T$ $\int d^2k_T$

Confined motion | Spatial distribution

$f(x,k_T)$ Two-scales observables $f(x,b_T)$

- **Note:**

  ✧ Partons' confined motion and their spatial distribution are unique – the consequence of QCD

  ✧ But, the TMDs and GPDs that represent them are not unique!

  – Depending on the definition of the Wigner distribution and QCD factorization to link them to physical observables

Position r x Momentum p → Orbital Motion of Partons

Orbital angular momentum

OAM: Its definition is not unique in gauge field theory!

- **Jaffe-Manohar's quark OAM density:**

$$\mathcal{L}_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{\partial})\right]^3 \psi_q$$

- **Ji's quark OAM density:**

$$L_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{D})\right]^3 \psi_q$$

- **Difference between them:**

Hatta, Lorce, Pasquini, …

✧ compensated by difference between gluon OAM density

✧ represented by different choice of gauge link for OAM Wagner distribution

$$\mathcal{L}_q^3 \left\{L_q^3\right\} = \int dx\, d^2b\, d^2k_T \left[\vec{b} \times \vec{k}_T\right]^3 \mathcal{W}_q(x,\vec{b},\vec{k}_T) \left\{W_q(x,\vec{b},\vec{k}_T)\right\}$$

with

$$\mathcal{W}_q \left\{W_q\right\}(x,\vec{b},\vec{k}_T) = \int \frac{d^2\Delta_T}{(2\pi)^2} e^{i\vec{\Delta}_T\cdot\vec{b}} \int \frac{dy^- d^2y_T}{(2\pi)^3} e^{i(xP^+y^- - \vec{k}_T\cdot\vec{y}_T)}$$

$$\times \langle P'|\, \overline{\psi}_q(0)\, \frac{\gamma^+}{2}\, \underbrace{\Phi^{\mathrm{JM}\{\mathrm{Ji}\}}(0,y)}_{\text{Gauge link}}\, \psi(y)\, |P\rangle_{y^+=0}$$

JM: "staple" gauge link

Ji: straight gauge link

between 0 and $y=(y^+=0, y^-, y_T)$

Orbital angular momentum

OAM: Its definition is not unique in gauge field theory!

- **Jaffe-Manohar's quark OAM density:**

$$\mathcal{L}_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{\partial})\right]^3 \psi_q$$

- **Ji's quark OAM density:**

$$L_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{D})\right]^3 \psi_q$$

- **Difference between them:**

  ✧ generated by a "torque" of color Lorentz force

Hatta, Yoshida, Burkardt, Meissner, Metz, Schlegel, …

$$\mathcal{L}_q^3 - L_q^3 \propto \int \frac{dy^- d^2 y_T}{(2\pi)^3} \langle P' | \overline{\psi}_q(0) \frac{\gamma^+}{2} \int_{y^-}^{\infty} dz^- \Phi(0, z^-)$$
$$\times \underbrace{\sum_{i,j=1,2} \left[\epsilon^{3ij} y_T^i F^{+j}(z^-)\right]}_{\text{“Chromodynamic torque”}} \Phi(z^-, y) \psi(y) | P \rangle_{y^+=0}$$

Similar color Lorentz force generates the single transverse-spin asymmetry (Qiu-Sterman function), and is also responsible for the twist-3 part of g_2

Unified view of nucleon structure & spin

- **Wigner distributions:**

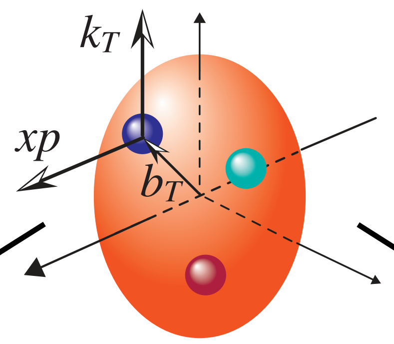
Momentum Space

TMDs

Confined motion

$\int d^2 b_T$

$f(x, k_T)$



Two-scales observables

$\int d^2 k_T$

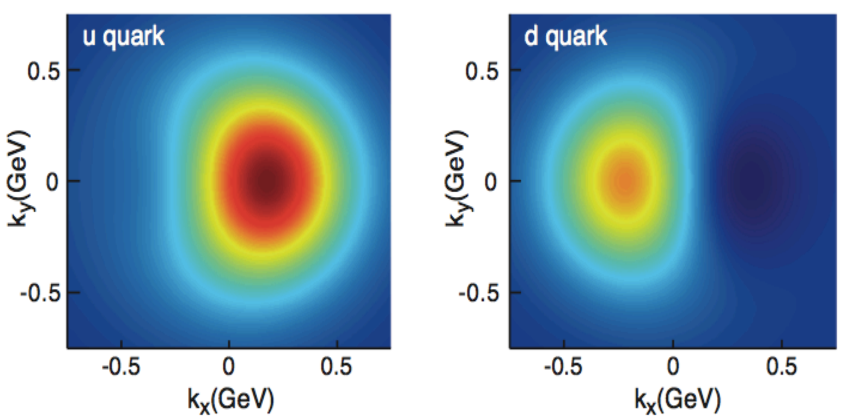
$f(x, b_T)$

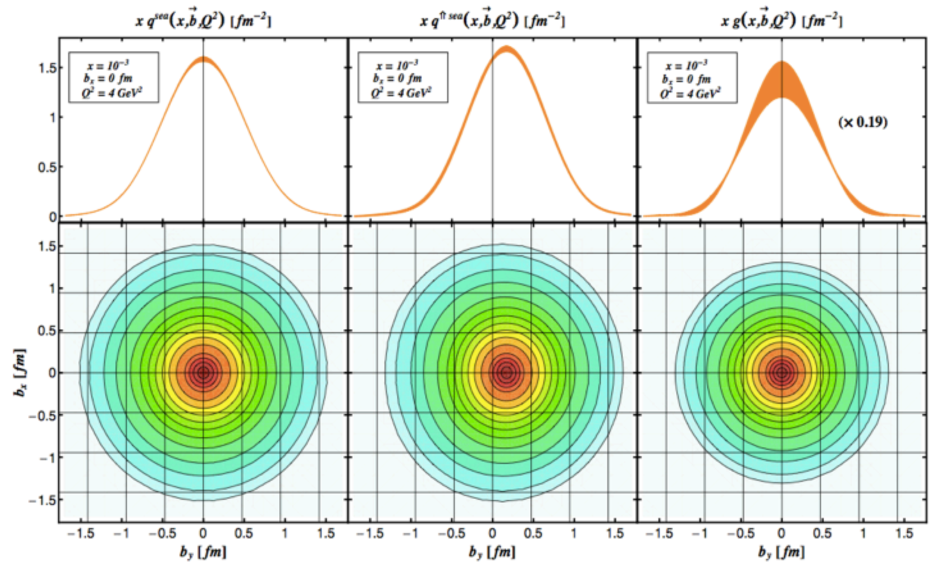
Coordinate Space

GPDs

Spatial distribution

Sivers Functions



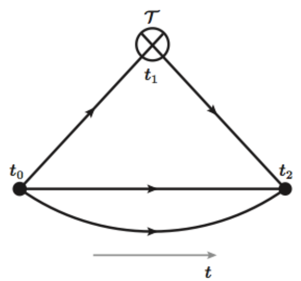


Position r x Momentum p → Orbital Motion of Partons

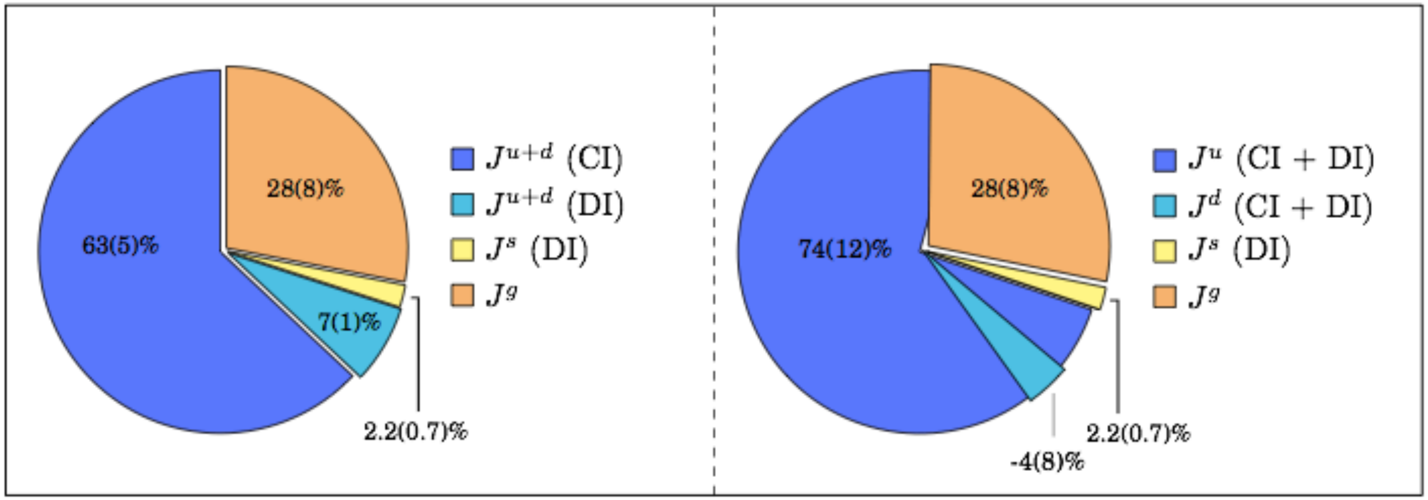
Nucleon spin and OAM from lattice QCD

❑ χQCD Collaboration:

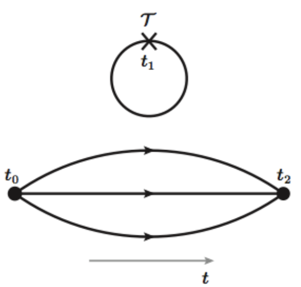
[Deka *et al.* arXiv:1312.4816]



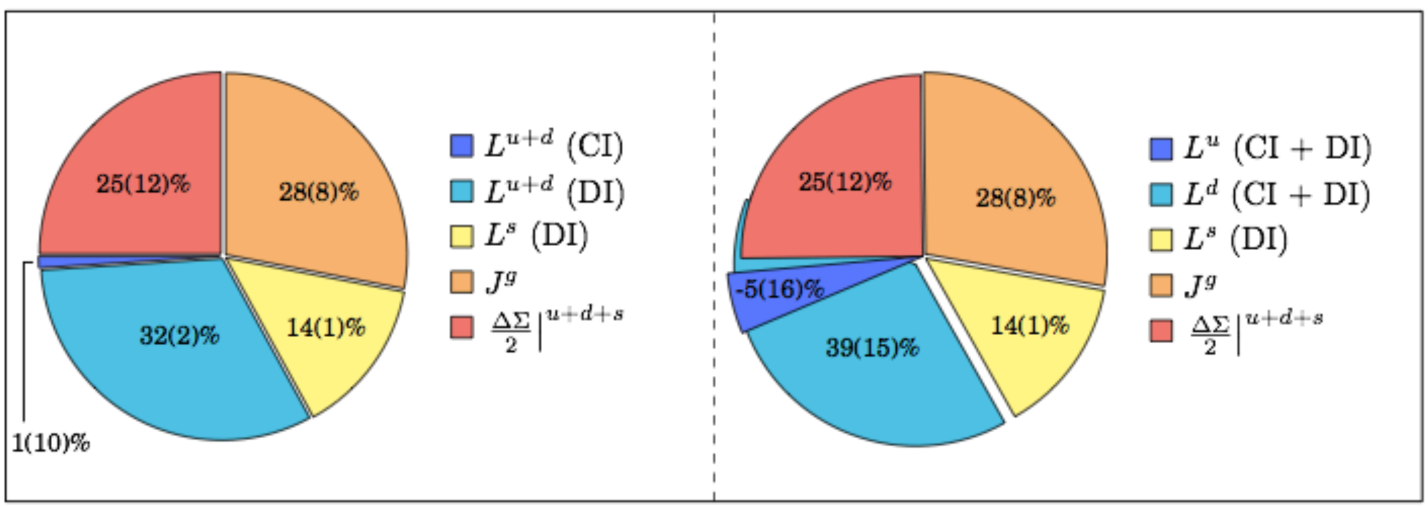
Connected Interaction (CI)



(b)



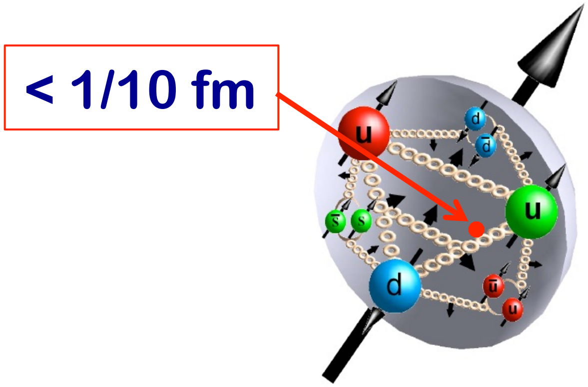
Disconnected Interaction (DI)



(c)

Summary

- QCD has been extremely successful in interpreting and predicting high energy experimental data!



- But, we still do not know much about hadron structure and its spin correlation!

- Since the "spin crisis" in the 80th, we have learned a lot about proton spin – but, still a long way to go!

- TMDs and GPDs, accessible by high energy scattering with polarized beams at JLab12 & EIC, carry important information on hadron's 3D structure, and its correlation with hadron's spin!

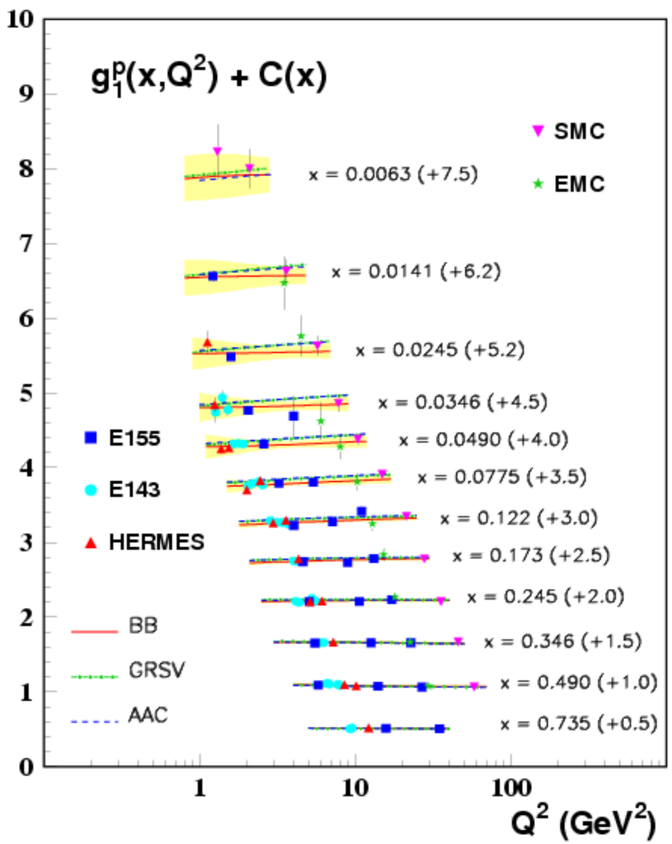
No "still pictures", but quantum distributions, for hadron structure!

Thank you!

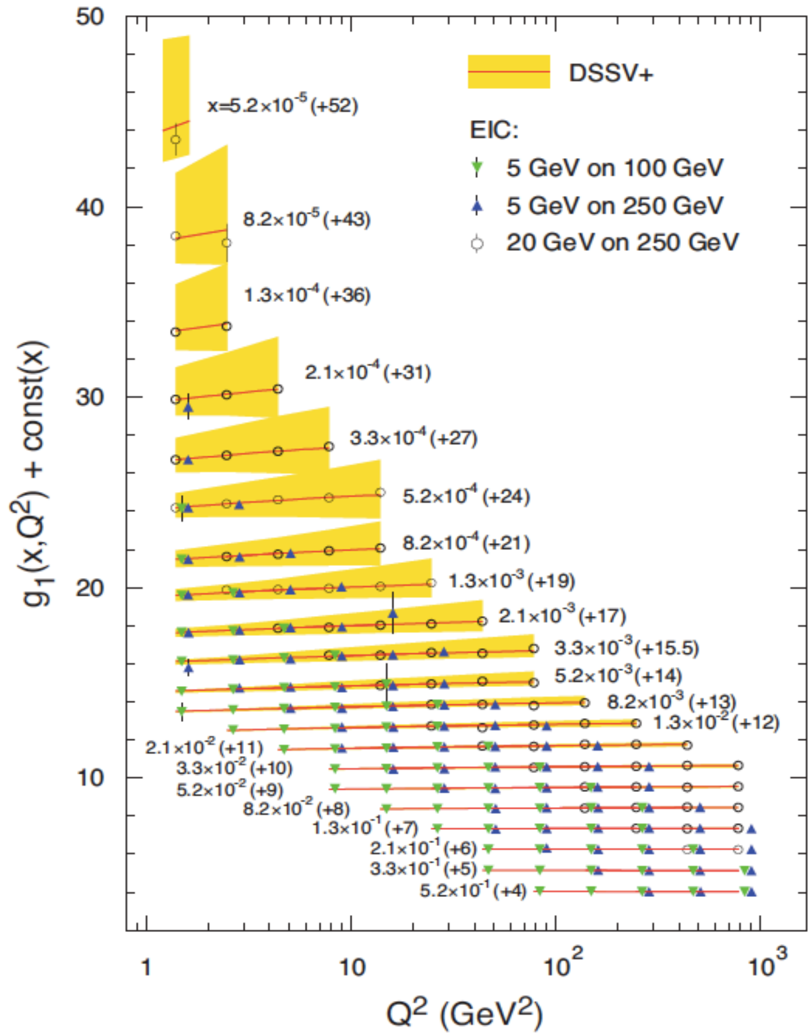
Backup slides

The future: EIC, …

- The power & precision of EIC:



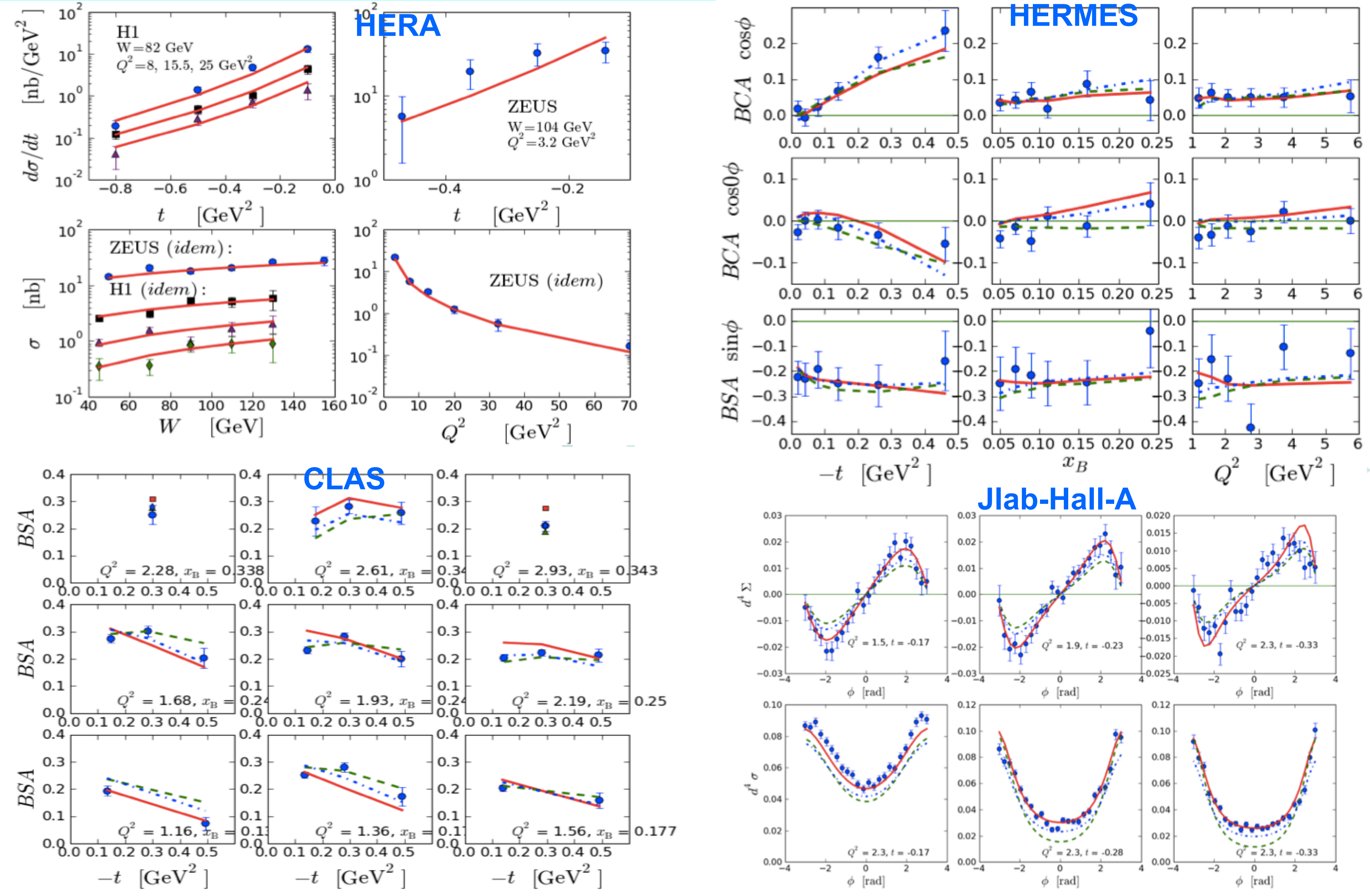
at EIC



- Reach out the glue:

$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

GPDs: just the beginning



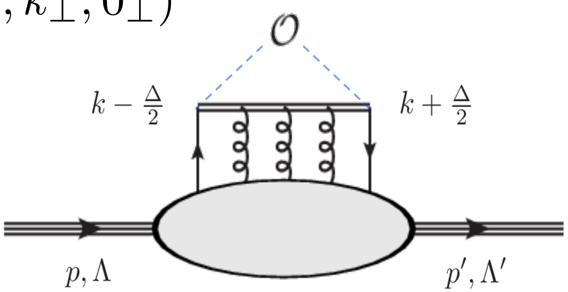
OAM from Generalized TMDs?

- **Canonical OAM:**

GTMD

Meissner, et al. 2008
See talk by Metz
Also, Lorce at ECT*

$$l_q^3 = \int d^2 b_\perp \, [\vec{b}_\perp \times \langle \vec{k}_\perp \rangle (\vec{b}_\perp)] = -\int dx \, d^2 k_\perp \frac{\vec{k}_\perp^2}{M^2} F_{14}(x, 0, \vec{k}_\perp, \vec{0}_\perp)$$



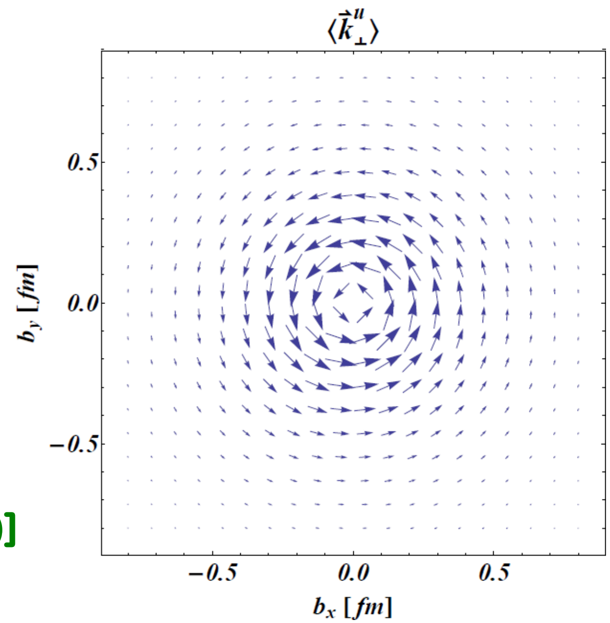
- **Connection to the Wigner distribution:**

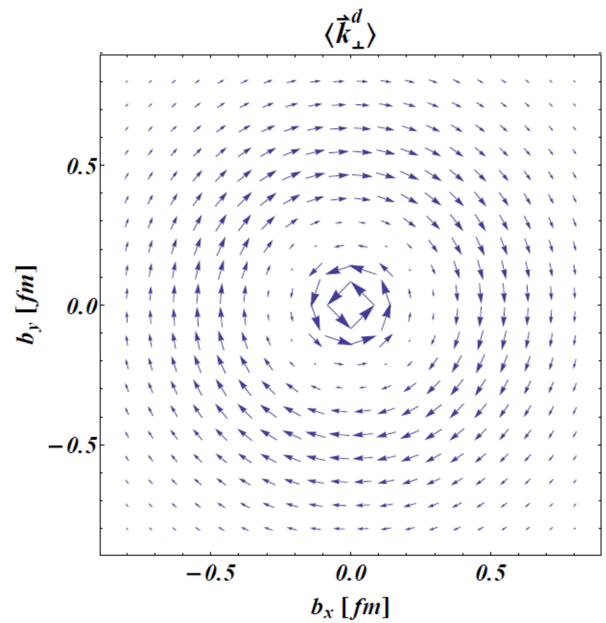
2D FT of GTMDs ($\Delta_\perp \to b_\perp$)

$$\rho^{\mathcal{O}}_{\Lambda'\Lambda}(P, k, \vec{b}_\perp; \mathcal{W}) = \int \frac{\mathrm{d}^2 \Delta_\perp}{(2\pi)^2} \, e^{-i \vec{\Delta}_\perp \cdot \vec{b}_\perp} \, W^{\mathcal{O}}_{\Lambda'\Lambda}(P, k, \Delta; \mathcal{W}) \big|_{\Delta^+ = 0}$$

- **Spatial distribution of $\langle \vec{k}_\perp \rangle$:**

$$\langle \vec{k}_\perp \rangle (\vec{b}_\perp) = \int \mathrm{d}^4 k \, \vec{k}_\perp \, \rho^{\gamma^+}_{\Lambda'\Lambda}(P, k, \vec{b}_\perp; \mathcal{W})$$





[C.L., Pasquini (2011)]
[C.L., Pasquini, Xiong, Yuan (2012)]
[Hatta (2012)]
[Kanazawa, et al. (2014)]

Orbital angular momentum contribution

❑ **The definition in terms of Wigner function:**

Ji, Xiong, Yuan, PRL, 2012
Lorce, Pasquini, PRD, 2011
Lorce, et al, PRD, 2012

✧ **Gauge invariant:**

$$L_q \equiv \frac{\langle P,S|\int d^3r\,\overline{\psi}(\vec{r})\gamma^+(\vec{r}_\perp \times i\vec{D}_\perp)\psi(\vec{r})|P.S\rangle}{\langle P,S|P,S\rangle} = \int (\vec{b}_\perp \times \vec{k}_\perp) W_{FS}(x,\vec{b}_\perp,\vec{k}_\perp)\,dx\,d^2\vec{b}_\perp d^2\vec{k}_\perp$$

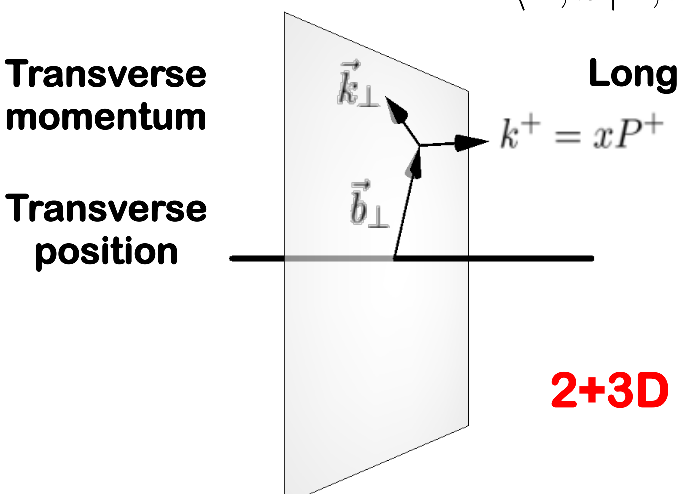
✧ **Canonical:**

$$l_q \equiv \frac{\langle P,S|\int d^3r\,\overline{\psi}(\vec{r})\gamma^+(\vec{r}_\perp \times i\vec{\partial}_\perp)\psi(\vec{r})|P.S\rangle}{\langle P,S|P,S\rangle} = \int (\vec{b}_\perp \times \vec{k}_\perp) W_{LC}(x,\vec{b}_\perp,\vec{k}_\perp)\,dx\,d^2\vec{b}_\perp d^2\vec{k}_\perp$$

✧ **Gauge-dependent potential angular momentum – the difference:**

$$l_{q,pot} \equiv \frac{\langle P,S|\int d^3r\,\overline{\psi}(\vec{r})\gamma^+(\vec{r}_\perp \times (-g\vec{A}_\perp))\psi(\vec{r})|P.S\rangle}{\langle P,S|P,S\rangle} = L_q - l_q$$

Quark-gluon correlation



2+3D

$$\langle \mathcal{O} \rangle = \int \mathcal{O}(\vec{b}_\perp,\vec{k}_\perp)\,W_{GL}(x,\vec{b}_\perp,\vec{k}_\perp)\,dx\,d^2\vec{b}_\perp d^2\vec{k}_\perp$$

Gauge-link dependent Wigner function

Same for gluon OAM

Orbital angular momentum contribution

❑ The Wigner function:

Ji, Xiong, Yuan, PRL, 2012
Lorce, Pasquini, PRD, 2011
Lorce, et al, PRD, 2012

✧ **Quark:**

$$W^q_{GL}(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp} \int \frac{dz^- d\vec{z}_\perp}{(2\pi)^3} e^{ik\cdot z} \left\langle P+\frac{\vec{\Delta}_\perp}{2}\right| \overline{\Psi}_{GL}\left(-\frac{z}{2}\right)\gamma^+\Psi_{GL}\left(\frac{z}{2}\right)\left| P-\frac{\vec{\Delta}_\perp}{2}\right\rangle$$

GL: gauge link dependence — Gauge to remove "GL"

$$\Psi_{FS}(z) = \mathcal{P}\left[\exp\left(-ig\int_0^\infty d\lambda\, z\cdot A(\lambda z)\right)\right]\psi(z)$$ Fock-Schwinger

$$\Psi_{LC}(z) = \mathcal{P}\left[\exp\left(-ig\int_0^\infty d\lambda\, n\cdot A(\lambda n + z)\right)\right]\psi(z)$$ Light-cone

✧ **Gluon:**

$$W^g_{GL}(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp} \int \frac{dz^- d\vec{z}_\perp}{(2\pi)^3} e^{ik\cdot z} \left\langle P+\frac{\vec{\Delta}_\perp}{2}\right| \mathbf{F}^{i+}_{GL}\left(-\frac{z}{2}\right)\mathbf{F}^{+i}_{GL}\left(\frac{z}{2}\right)\left| P-\frac{\vec{\Delta}_\perp}{2}\right\rangle$$

❑ Gauge-invariant extension (GIE):

$$i\vec{\partial}^\alpha_\perp = i\vec{D}^\alpha_\perp(\xi) + \int^{\xi^-} d\eta^-\, L_{[\xi^-,\eta^-]}\, gF^{+\alpha}(\eta^-,\xi_\perp)\, L_{[\eta^-,\xi^-]}$$ Twist-3 correlators

Fixed gauge local operators ⟺ gauge invariant non-local operators

Note: the 2+3D Wigner distributions are not "physical"
But, their reduced distributions could be connected to observables