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Temple University, Philadelphia, PA, September 13-15, 2014

Theoretical Overview: Nucleon spin structure and orbital angular momentum

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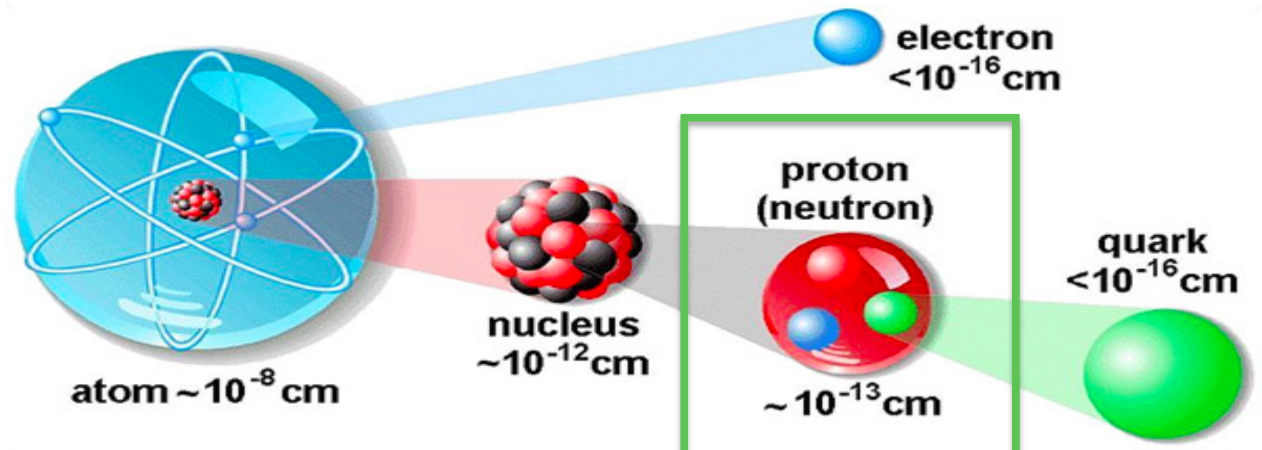
Acknowledgement: Thanks to those who have provided valuable inputs, …

Nucleon spin structure

- Nucleon: the key building block of the visible matter



$$\mathbf{M}_N \sim \mathrm{GeV}$$

$$s_N = \frac{1}{2}$$

$$\mu_N = \ldots$$

Emergent properties of QCD

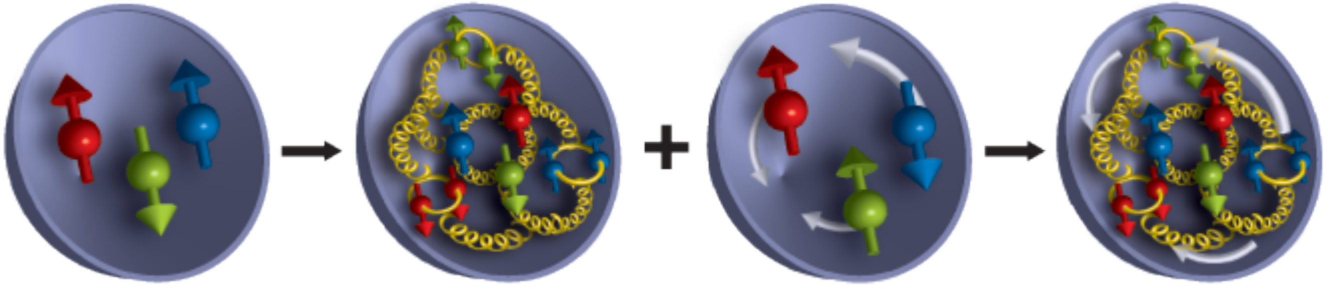
- 2007 Nuclear Physics Long Range Plan:

"… if we are to claim any understanding of QCD, we must be able to identify how this value (spin=1/2) arises from the nucleon's internal structure."

What has been done, what needs to be done, and future opportunities?

Nucleon's internal structure

- ❑ Our understanding of the nucleon evolves



1970s 1980s/2000s Now

Nucleon is a strongly interacting, relativistic bound state of quarks and gluons

- ❑ QCD bound states:
  - ✧ Neither quarks nor gluons appear in isolation!
  - ✧ Understanding such systems completely is still beyond the capability of the best minds in the world

- ❑ The great intellectual challenge:

  Nucleon (spin) structure without "seeing" quarks and gluons?

Nucleon spin structure

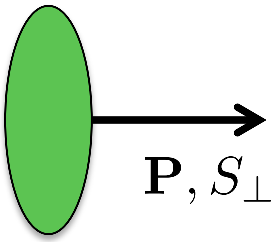
Jaffe-Manohar, 90
Ji, 96

- **QCD angular momentum operator:**

$$\mathbf{J}^i = \frac{1}{2}\epsilon^{ijk}\int d^3r\,\mathcal{M}^{0jk}(r)$$

Angular momentum density: $\mathcal{M}^{\mu\alpha\beta}(r)$

- **Transverse polarization:**



  - ✧ $J_\perp$ operator does not commute with P^+
  - ✧ Transversely polarized proton is in the eigenstate of transverse Pauli-Lubanski vector, $W_\perp$
  - ✧ Spin decomposition: $S_\perp = \frac{1}{2} = \sum_f \langle P,S|W_\perp|P,S\rangle \equiv J_q(\mu) + J_g(\mu)$

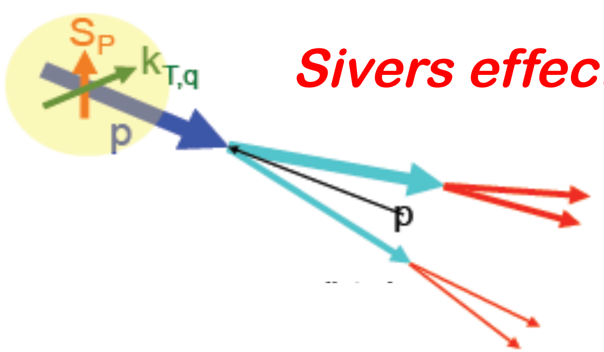
$$J_q = \frac{1}{2}\sum_q \int dx\, x[q(x) + E_q(x,0,0)]$$

Ratcliffe, 98; Burkardt, 2005

in terms of twist-2 quark momentum distribution and twist-2 GPD E

- **Transverse spin physics:**

Spin influences parton's motion (TMDs)
as well as its spatial distribution (GPDs)

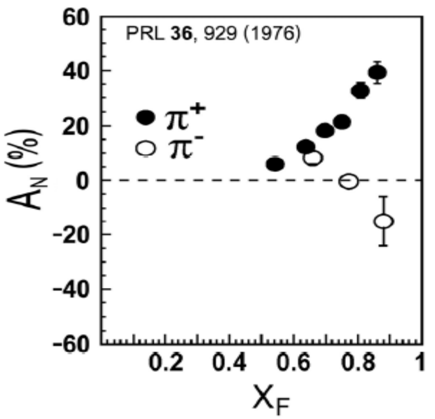


Sivers effect

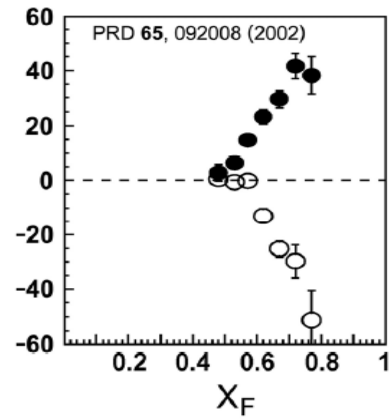
Single transverse-spin asymmetry

- A_N - consistently observed for over 35 years (~ 0 in parton model)!

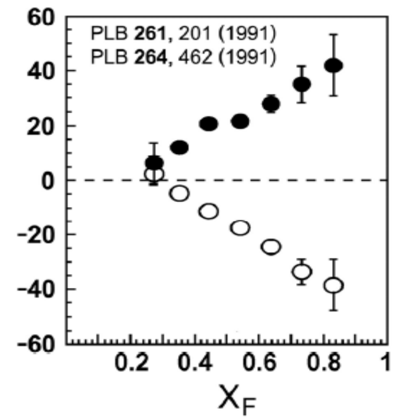
ANL – 4.9 GeV



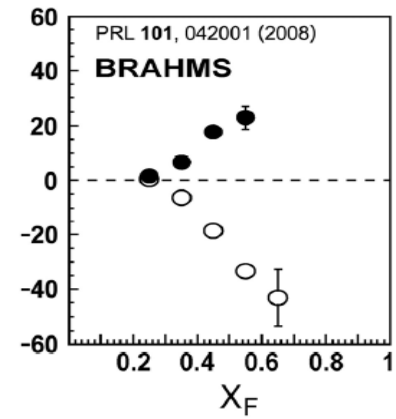
BNL – 6.6 GeV



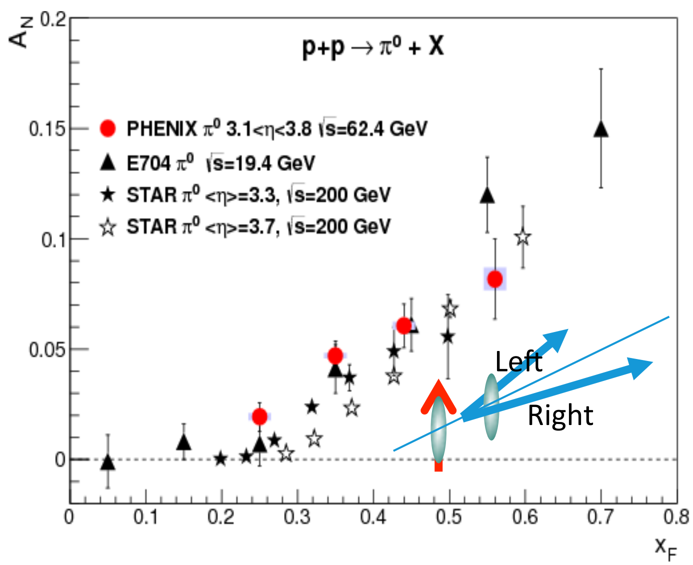
FNAL – 20 GeV

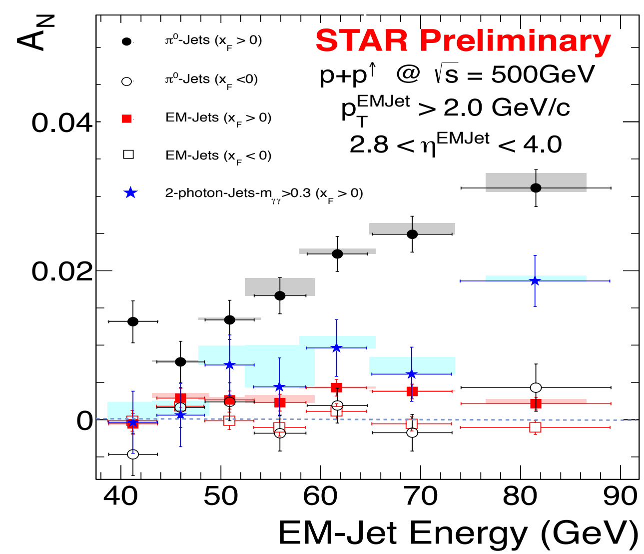


BNL – 62.4 GeV



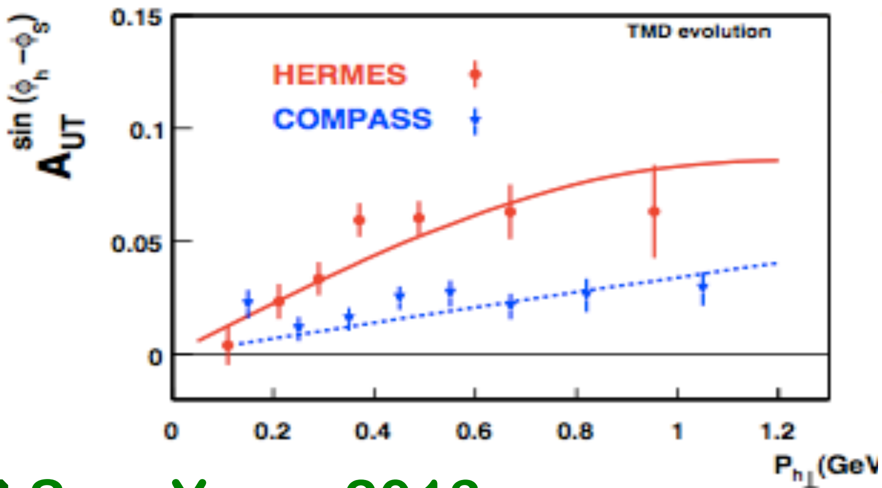
- Survived the highest RHIC energy:

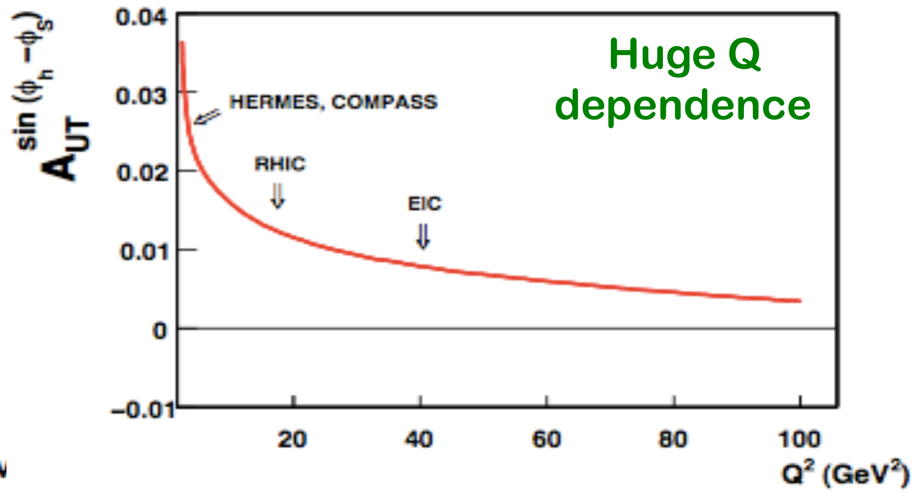




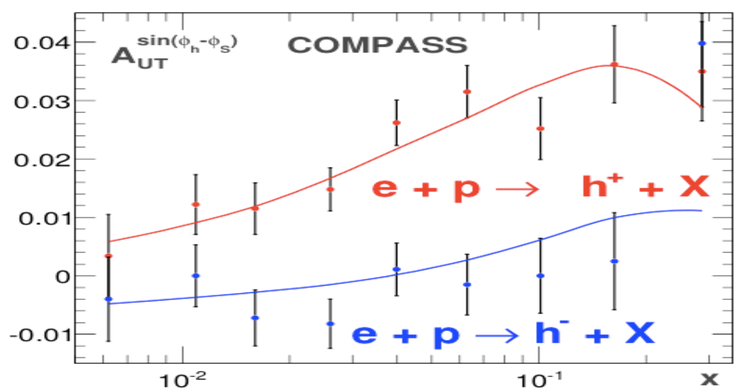
Opportunity: Q^2-dependence of TMDs

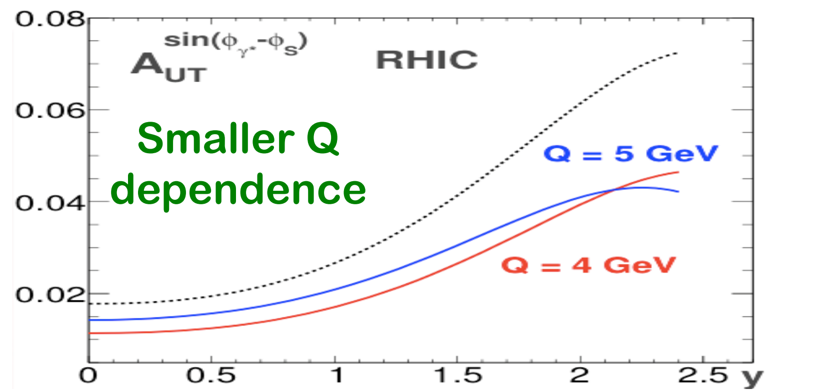
- Aybat, Prokudin, Rogers, 2012:





- Sun, Yuan, 2013:

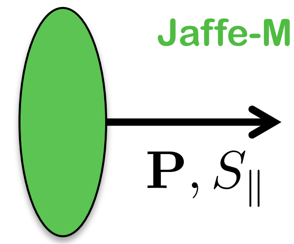




Puzzle: *Same evolution equation, but, predicted different Q-dependence?*

Evolution equation is in b-space, and sensitive to nucleon (spin) structure !

Nucleon spin structure



Jaffe-Manohar, 90
Ji, 96

❑ Longitudinal polarization:

$$S_{\|}(\mu) = \frac{1}{2} = \sum_f \langle P, S|\mathbf{J}_f^z|P.S\rangle \equiv J_q(\mu) + J_g(\mu)$$

✧ **Quark:** $\mathbf{J}_q = \int d^3r\ \psi^\dagger(r)[\vec{\gamma}\gamma_5 + (\vec{r} \times i\vec{D})]\psi(r)$

✧ **Gluon:** $\mathbf{J}_g = \int d^3r\ [\vec{r} \times (\vec{E}(r) \times \vec{B}(r))]$

Neither $J_q(\mu)$, $J_g(\mu)$,
nor $\Delta\Sigma, L_q, \Delta G, L_g$,
are directly observable
Infinite possibilities!

❑ Spin decomposition – subtlety:

$$S_{\|}(\mu) = \frac{1}{2} \equiv \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + \Delta G(\mu) + [J_g(\mu) - \Delta G(\mu)]$$

[Chen *et al.* (2008)]
[Wakamatsu (2010)]
[Hatta (2011)]
[Lorce (2013)]

$L_g(\mu)$

Quark helicity

Gluon helicity

Quark "orbital" angular momentum

Gluon "orbital" angular momentum

Many possible decompositions – what is the definition of "orbital"?
Mixture of twist-2 and twist-3 – complication in interpretation?

Spin decomposition

- The "big" question:

  If there are infinite possibilities, why bother and what do we learn?

- The "origin" of the difficulty/confusion:

  QCD is a gauge theory: a pure quark field in one gauge is a superposition of quarks and gluons in another gauge

- The fact:

  None of the items in all spin decompositions are direct physical observables, unlike cross sections, asymmetries, …

- Ambiguity in interpretation – two old examples:

  - Factorization scheme:

$$F_2(x, Q^2) = \sum_{q,\bar{q}} C_q^{\mathrm{DIS}}(x, Q^2/\mu^2) \otimes q^{\mathrm{DIS}}(x, \mu^2)$$

No glue contribution to F_2?

  - Anomaly contribution to longitudinal polarization:

$$g_1(x, Q^2) = \sum_{q,\bar{q}} \widetilde{C}_q^{\mathrm{ANO}} \otimes \Delta q^{\mathrm{ANO}} + \widetilde{C}_g^{\mathrm{ANO}} \otimes \Delta G^{\mathrm{ANO}}$$

$$\Rightarrow \quad \Delta\Sigma \longrightarrow \Delta\Sigma^{\mathrm{ANO}} - \frac{n_f \alpha_s}{2\pi} \Delta G^{\mathrm{ANO}}$$

Larger quark helicity?

Spin decomposition

- **Key for a good decomposition – sum rule:**

  - Every term can be related to a physical observable with controllable approximation – "independently measurable"

    DIS scheme is ok for F2, but, less effective for other observables

    Additional symmetry constraints, leading to "better" decomposition?

  - Natural physical interpretation for each term – "hadron structure"

  - Hopefully, calculable in lattice QCD – "numbers w/o distributions"

The most important task is,

Finding the connection to physical observables!

Quark and gluon helicity contribution

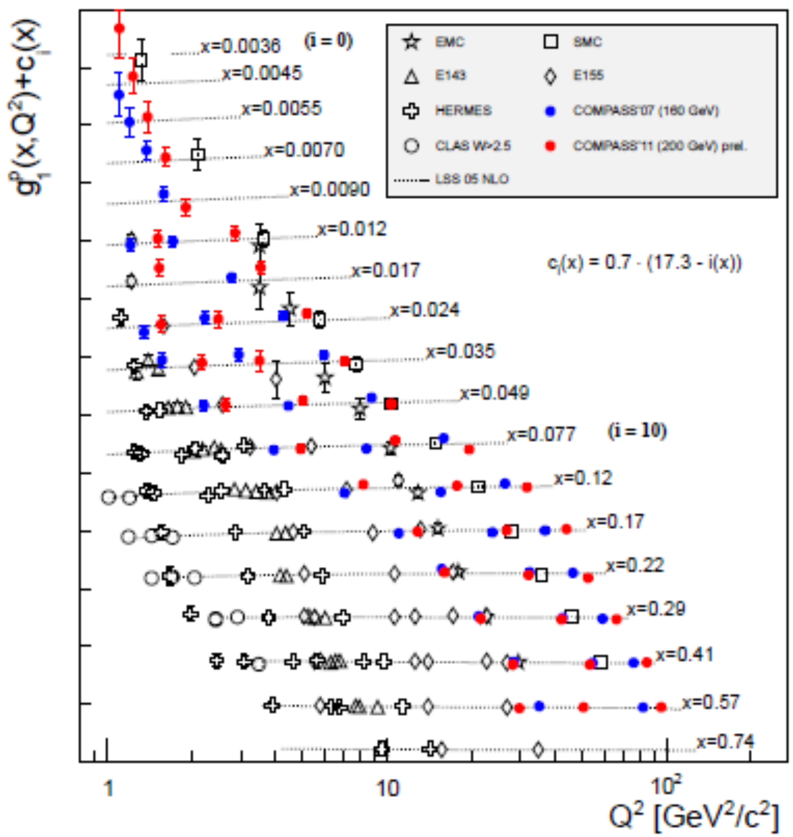
- QCD Factorization at the leading power:

  Link the helicity distributions to the longitudinal spin asymmetries

- Improved data since 2007:

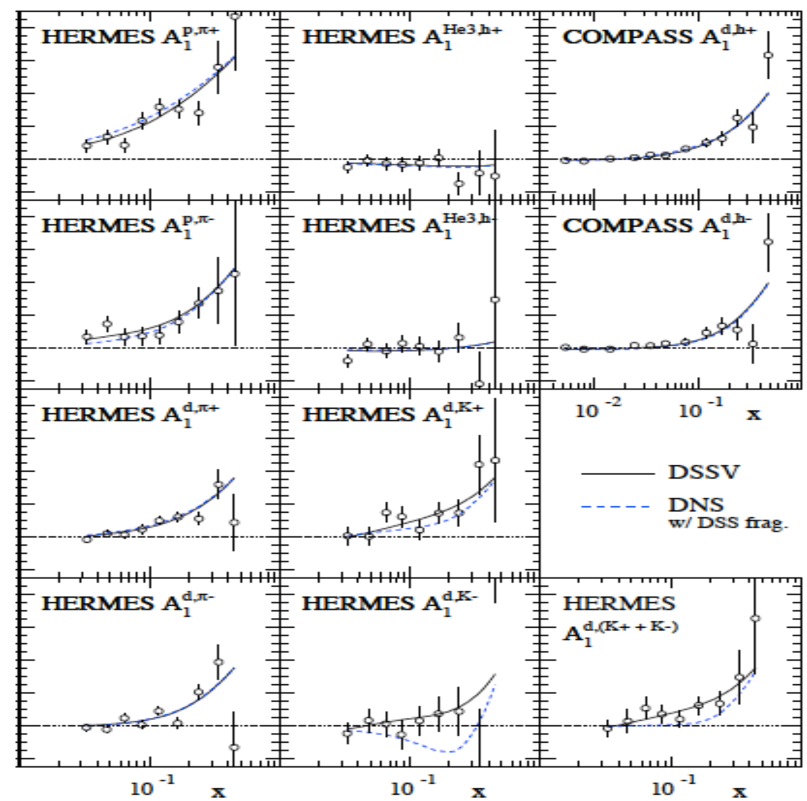
See Seidl's talk

Inclusive DIS



Jimenez-Delgado et al. arXiv:1310.3734

Semi-Inclusive DIS



de Florian et al. arXiv:0904.3821

Quark and gluon helicity contribution

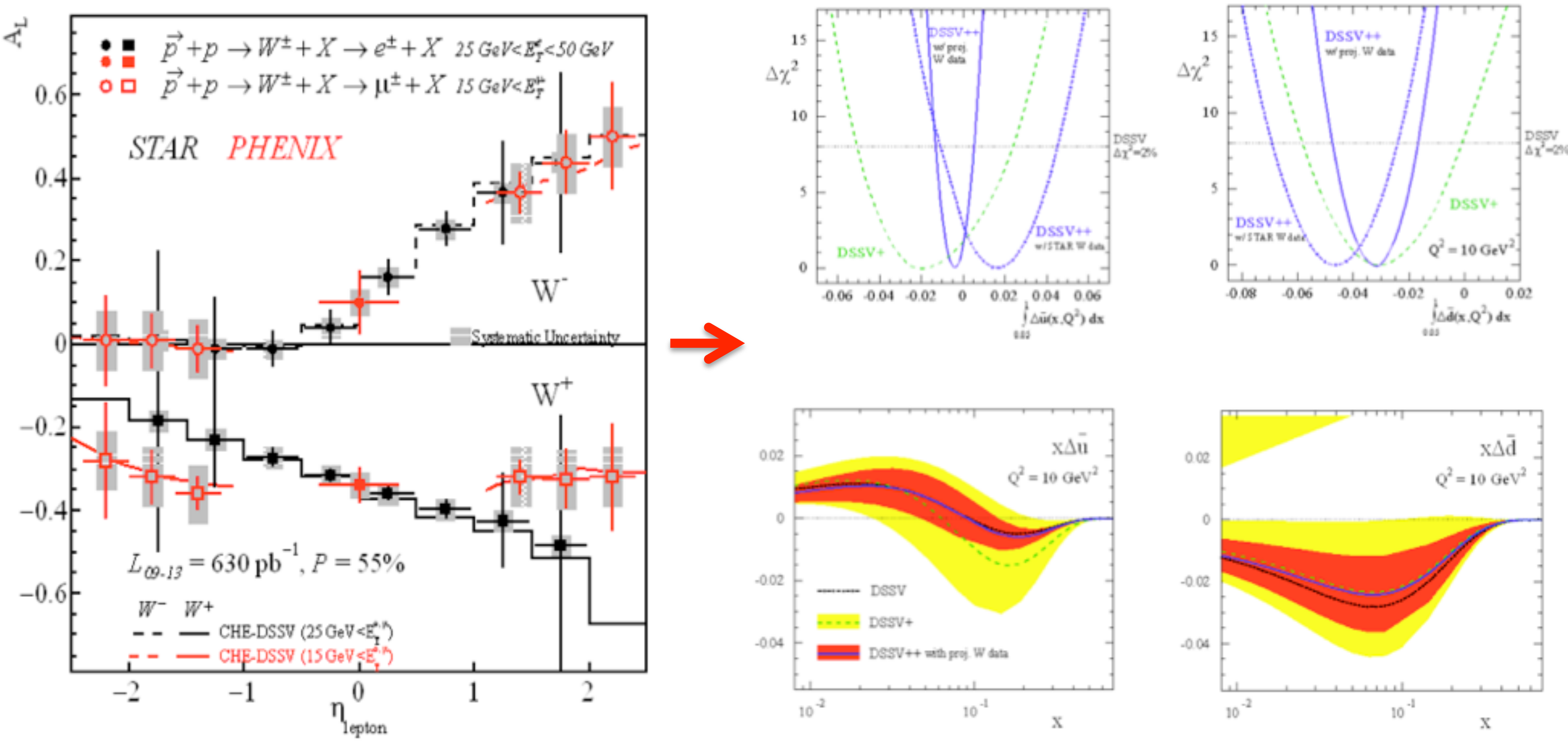
- QCD Factorization at the leading power:

  Link the helicity distributions to the longitudinal spin asymmetries

- Improved data since 2007:

  See Seidl's talk

  W-production at RHIC – sea flavor separation:



Quark and gluon helicity contribution

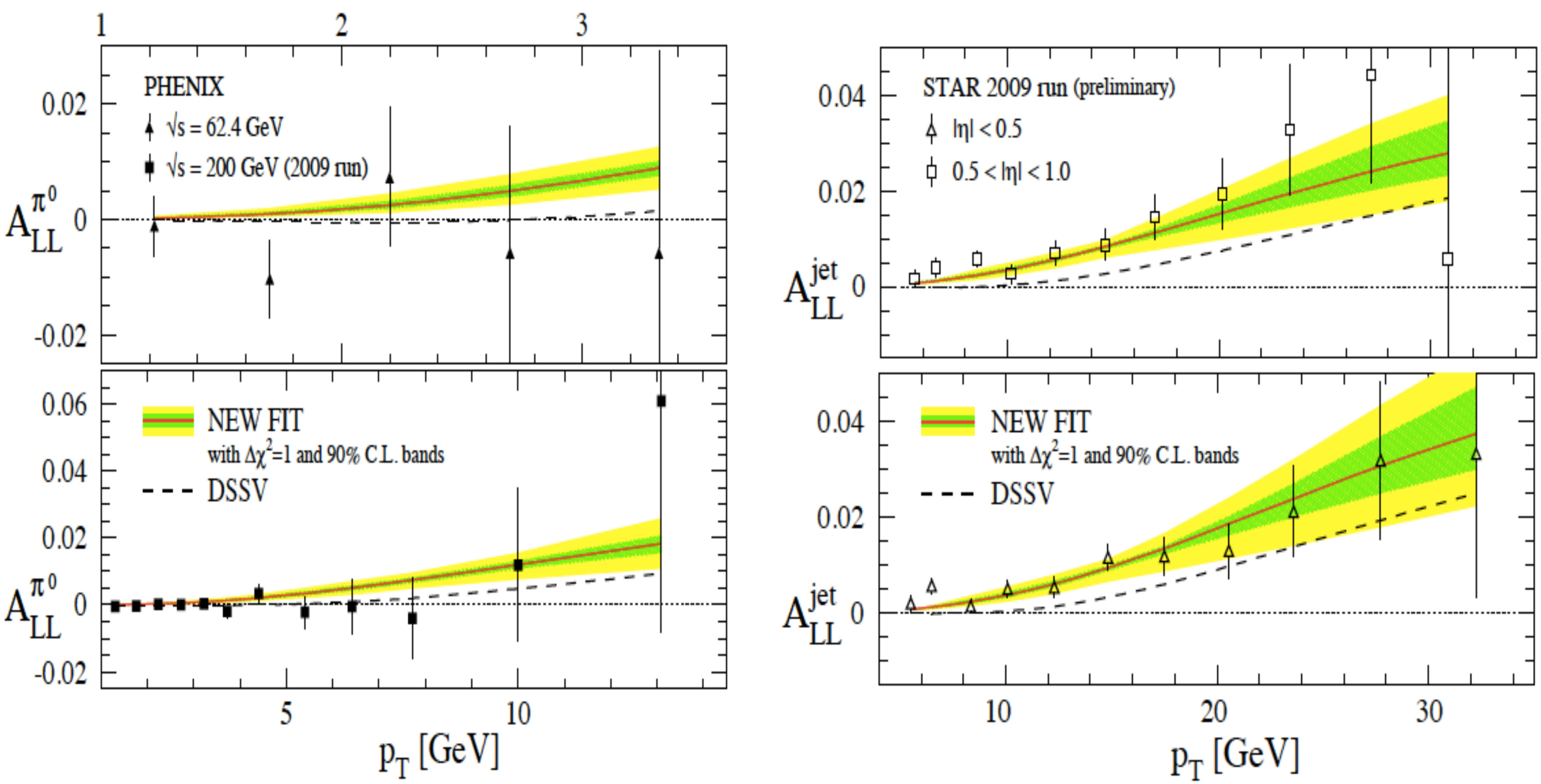
- QCD Factorization at the leading power:

  Link the helicity distributions to the longitudinal spin asymmetries

- Improved data since 2007:

  See Seidl's talk

  Jet/pion production at RHIC – gluon helicity:



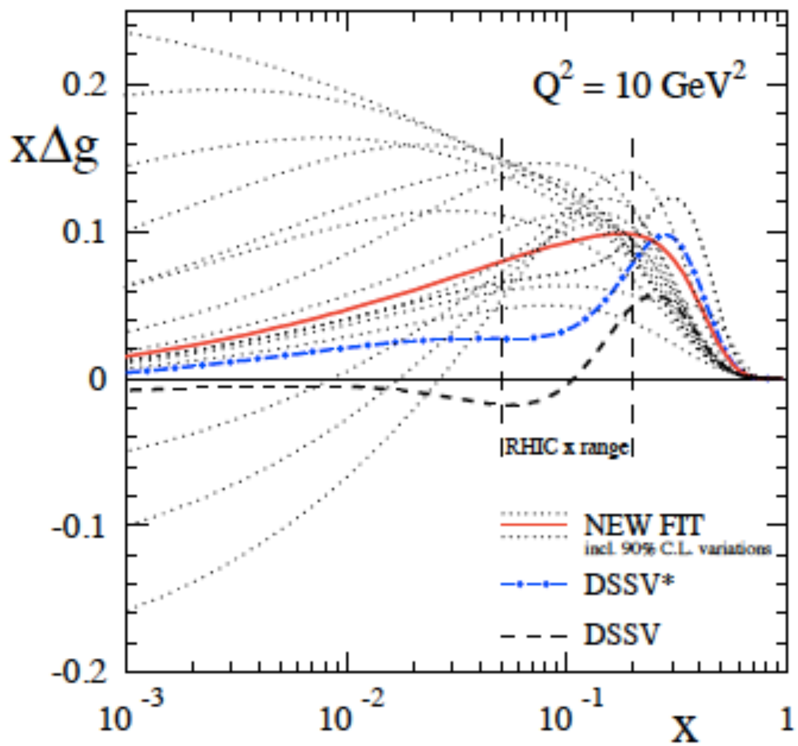
Quark and gluon helicity contribution

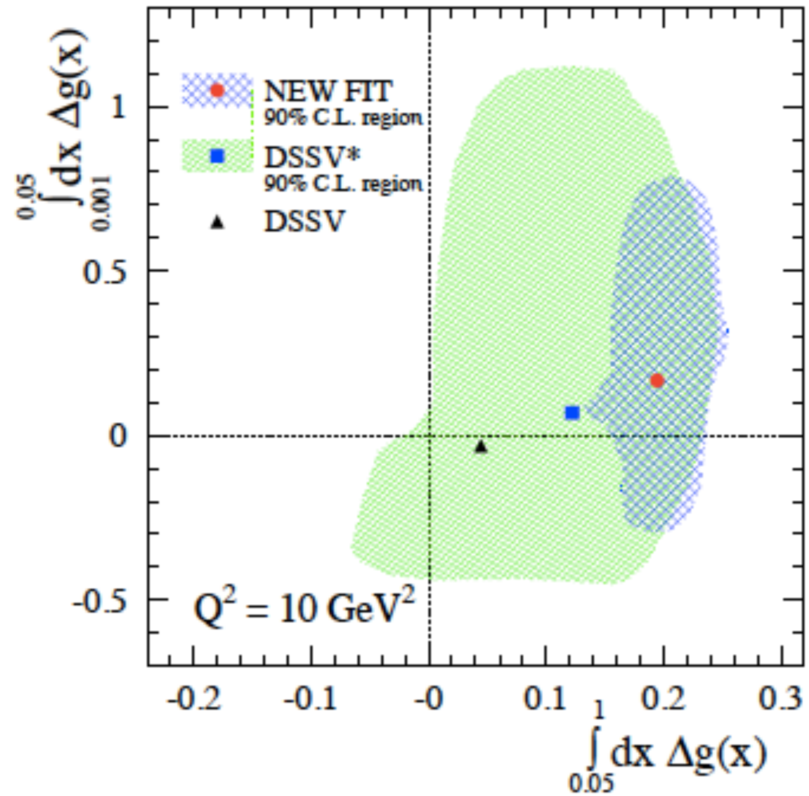
- ❑ QCD Factorization at the leading power:

  Link the helicity distributions to the longitudinal spin asymmetries

- ❑ Impact on gluon helicity:

de Florian, et al. 1404.4293





- ✧ Red line is the new fit
- ✧ Dotted lines = other fits with 90% C.L.

- ✧ 90% C.L. areas
- ✧ Leads ΔG to a positive #

Quark and gluon helicity contribution

- QCD Factorization at the leading power:

  Link the helicity distributions to the longitudinal spin asymmetries

- Quark helicity at x ~ 1:

Roberts et al, 2013
See also Peng's talk

	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	−0.11	0.65	−0.26	0.17	0.59
DSE-2	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
$0^+_{[ud]}$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

Extremely sensitive to the nucleon's partonic structure and internal spin correlation!

Big difference between two approximations of the DSE treatments

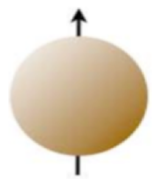
Quark and gluon helicity contribution

- **QCD Factorization at the leading power:**

  Link the helicity distributions to the longitudinal spin asymmetries

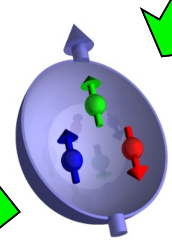
- **Improved knowledge since 2007:**

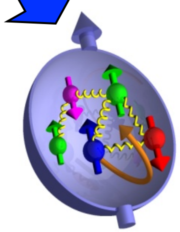
See Ji's talk



Proton Spin

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





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

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

$$\sim 20\% (\text{with RHIC data})$$

Orbital Angular Momentum
of quarks and gluons
Little known

OAM: Definitions, ambiguities, connection to observables, …

Orbital angular momentum contribution

- An obvious definition:

$$L = L_q + L_g = \frac{1}{2} - \left[\frac{1}{2}\Delta\Sigma + \Delta G\right]$$ Total helicity contribution

$\Delta\Sigma, \Delta G:$ Defined by QCD collinear factorization

- We need to know more than the number!
  - ✧ How is the number generated by the dynamics and the structure?
  - ✧ Relative role of quarks and gluons in generating the number?
  - ✧ ...

- Two recent workshops:
  - ✧ ECT* workshop on "Spin and Orbital Angular Momentum of Quarks and Gluons in the Nucleon" [http://www.ectstar.eu/node/787]
  - ✧ JLab workshop on "Informal Pre-Town Meeting" [http://www.jlab.org/conferences/pretownjlab2014/index.html]

Sea also talks by Ji, Metz, Meziani, Peng, and Seidl at this meeting

Orbital angular momentum contribution

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

❑ The definition in terms of Wigner function:

✧ **Gauge invariant:**

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

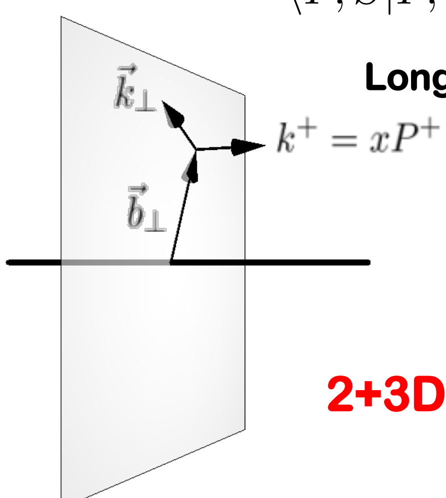
✧ **Canonical:**

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

✧ **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

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

❑ The Wigner function:

✧ **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

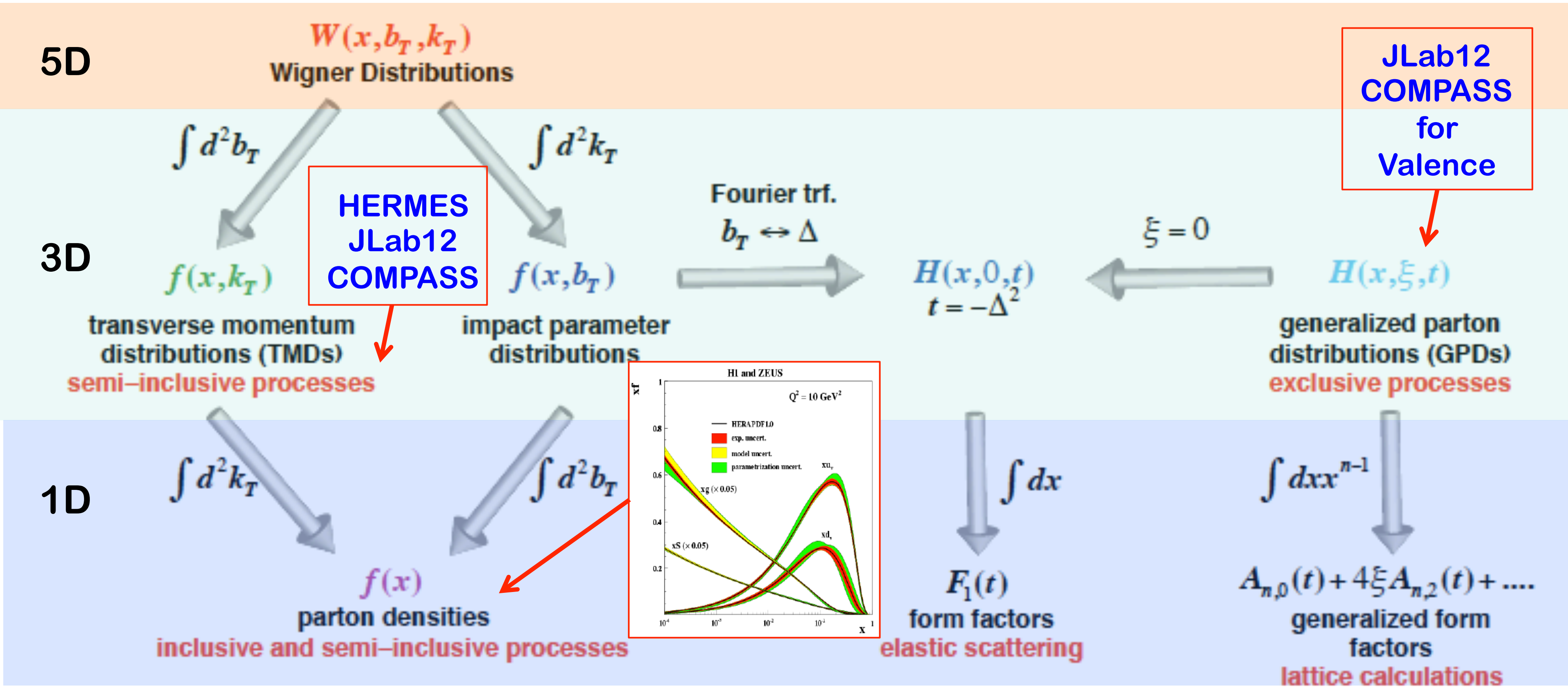
Fixed gauge local operators ⟺ gauge invariant non-local operators

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

Unified view of nucleon structure

❑ Wigner distributions:

Belitsky, Ji and Yuan, 2004
EIC White Paper, 2012



❑ Major advances since 2007:

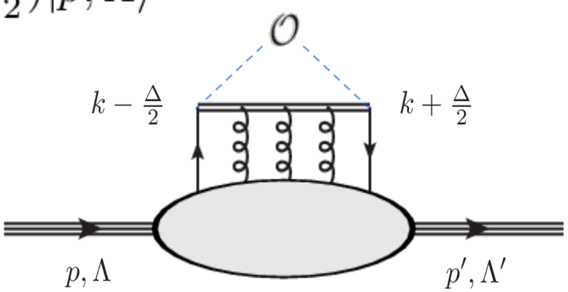
- ✧ TMDs – Correlation between hadron properties (spin) and parton motion
- ✧ GPDs – Hadron properties (spin) influence parton spatial distribution

Generalized TMDs (GTMDs)

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

❑ The definition:

$$W^{\mathcal{O}}_{\Lambda'\Lambda}(P,k,\Delta;\mathcal{W}) = \frac{1}{2}\int \frac{\mathrm{d}^4 z}{(2\pi)^4}\, e^{ik\cdot z}\, \langle p',\Lambda'|\overline{\psi}(-\tfrac{z}{2})\mathcal{W}\,\mathcal{O}\,\psi(\tfrac{1}{2})|p,\Lambda\rangle$$



❑ Connection to the Wigner distribution:

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

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

❑ Canonical OAM:

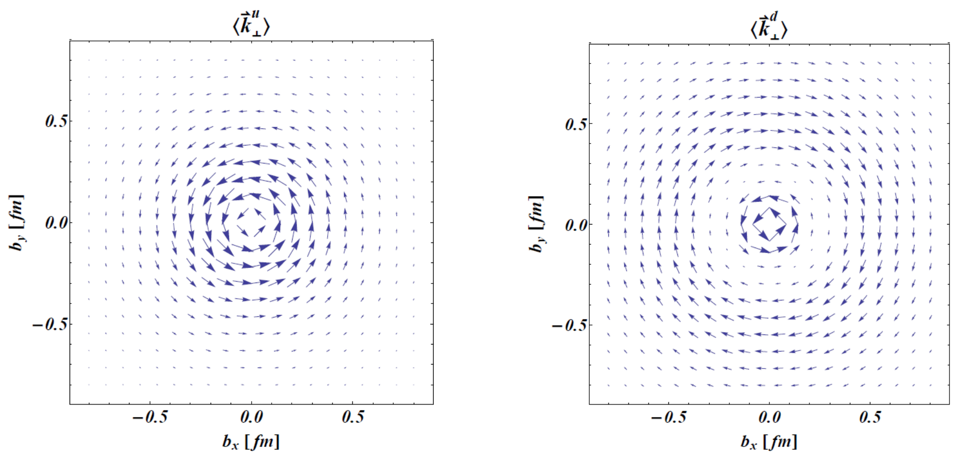
2+3D phase-space density

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

GTMD

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

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



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

Nucleon spin and OAM from lattice QCD

- QCD sum rule:

By Local matrix elements – Lattice QCD

$$S(\mu) = \sum_f \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$

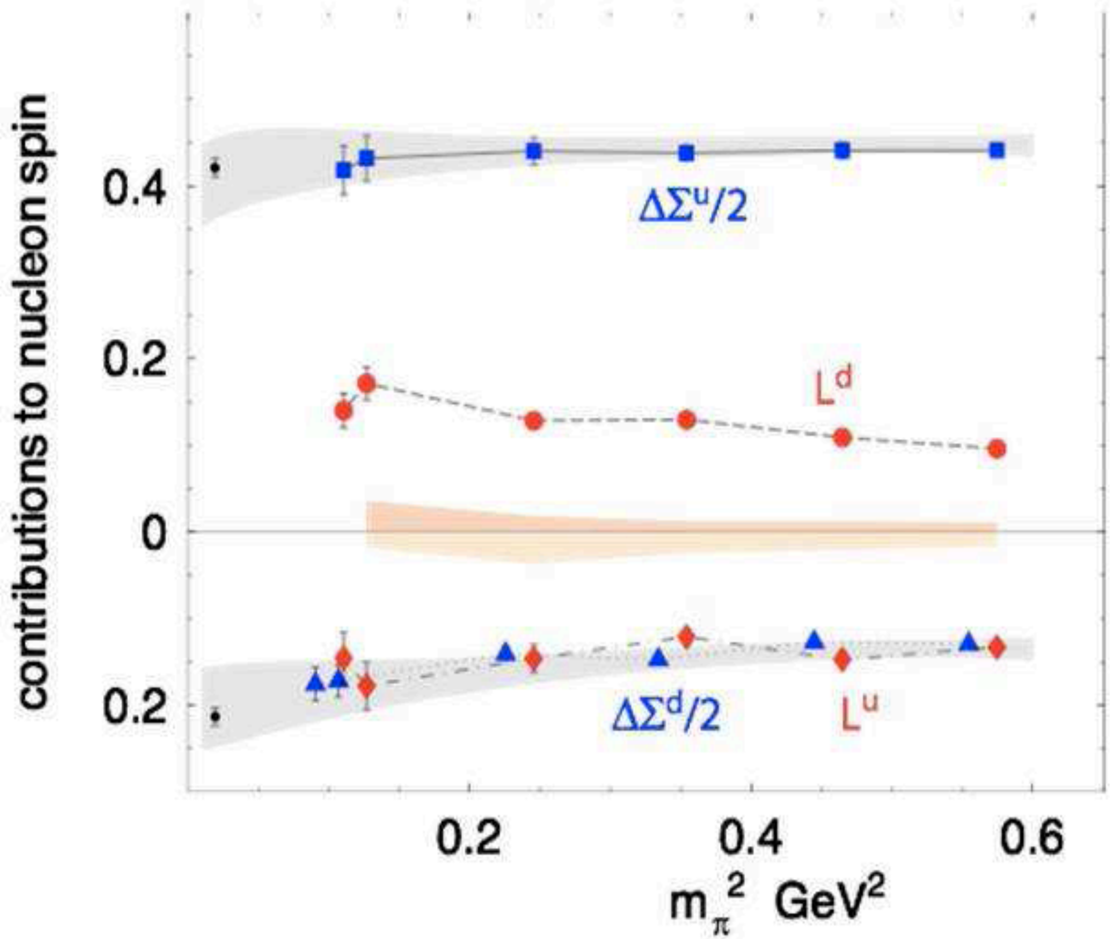
- Early Lattice result:

$$L_q^z = J_q^z - \tfrac{1}{2}\Delta q$$

Both L_u and L_d large,

but, $L_u + L_d \sim 0$

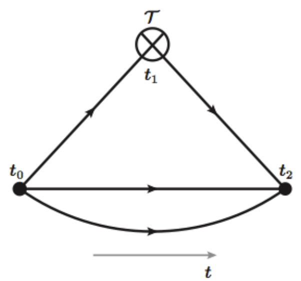
Note: no disconnected quark loops included (K.-F. Liu)



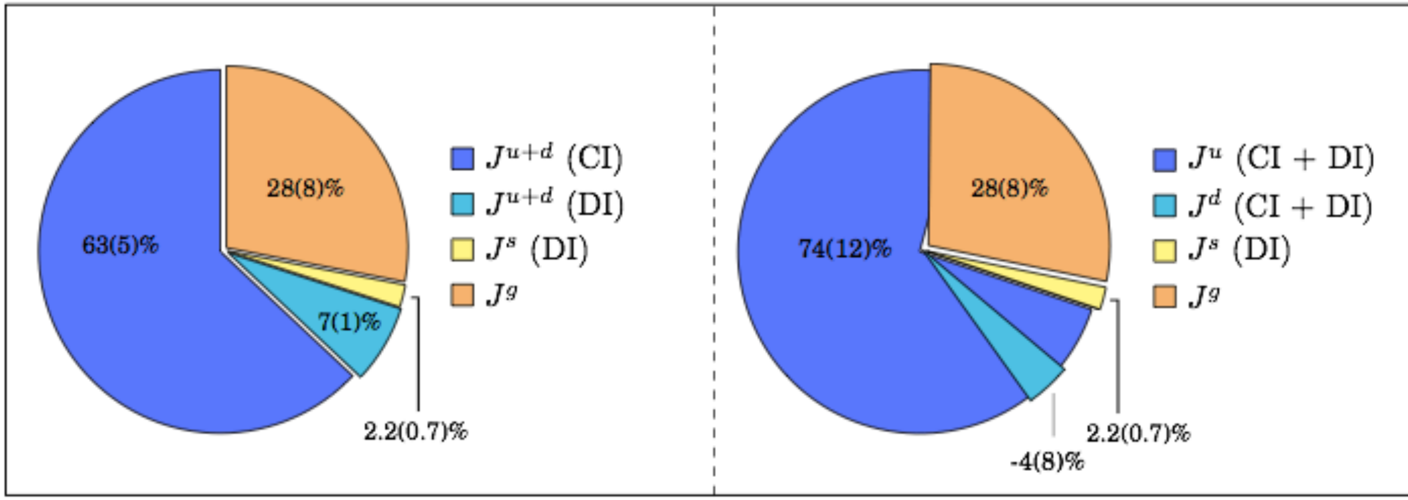
Nucleon spin and OAM from lattice QCD

❑ χQCD Collaboration:

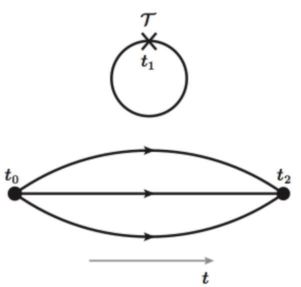
[Deka *et al.* arXiv:1312.4816]



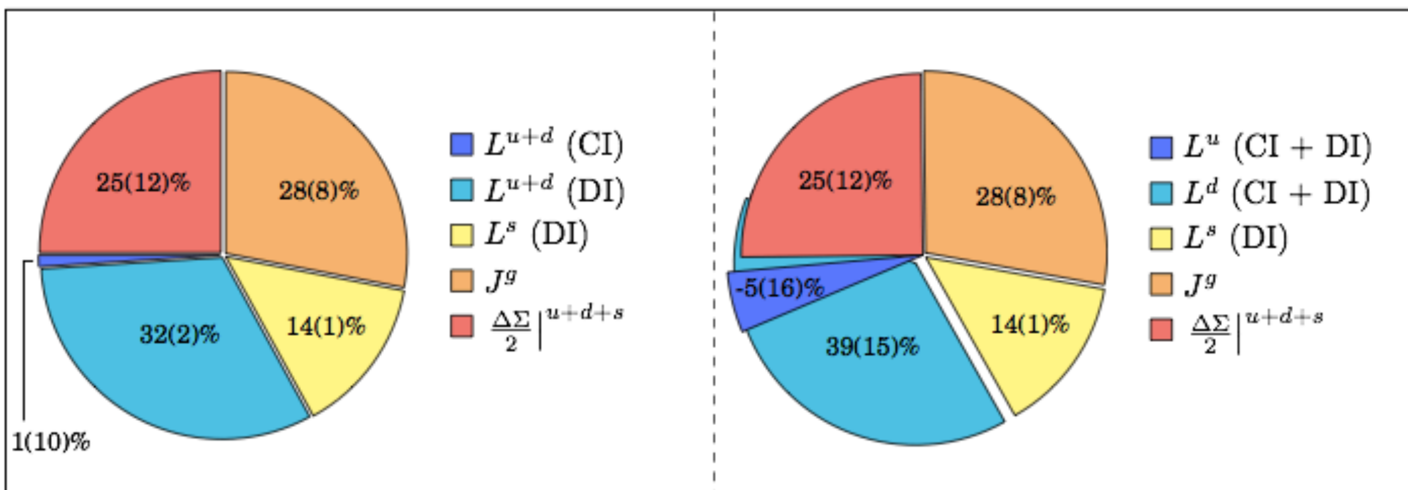
Connected Interaction (CI)



(b)



Disconnected Interaction (DI)



(c)

Connect OAM to observables

- **Difference between two OAM definitions:**

Burkardt, 2008

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

Caused by the work done by the torque along the trajectory of q

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

- **Connection to GPDs:**

Ji, 96
Burkardt, 2001, 2005

$$\langle J_q^i \rangle = S^i \int dx \left[H_q(x,0,0) + E_q(x,0,0)\right] x$$

- **Quark canonical OAM to TMDs, GTMDs – model dependent:**

$$\mathcal{L}_z = -\int dx\, d^2k_\perp \frac{\vec{k}_\perp^2}{2M^2} h_{1T}^\perp(x,\vec{k}_\perp)$$

$$\ell_z = -\int dx\, d^2k_\perp \frac{\vec{k}_\perp^2}{M^2} F_{14}(x,0,\vec{k}_\perp,\vec{0}_\perp)$$

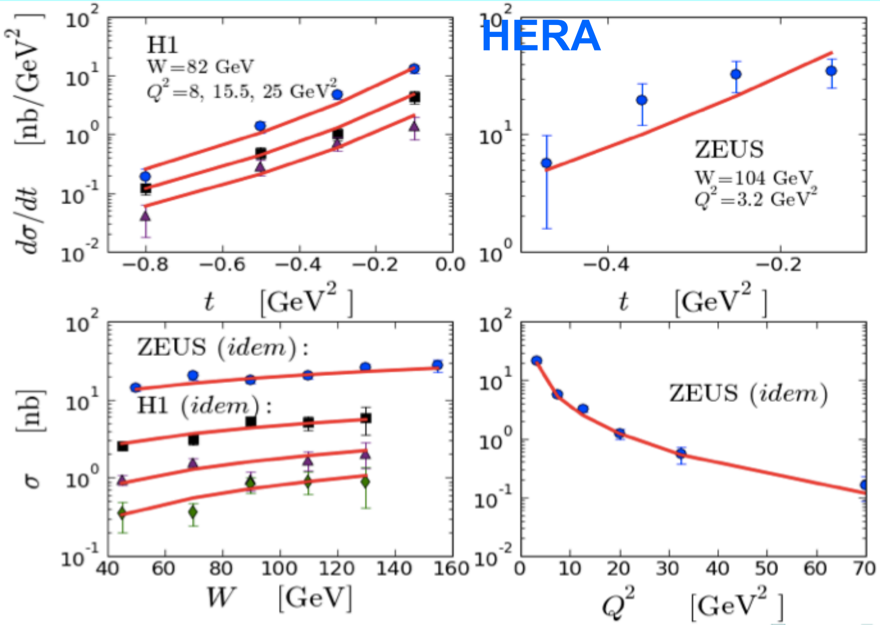
[Lorce, Pasquini (2012)]

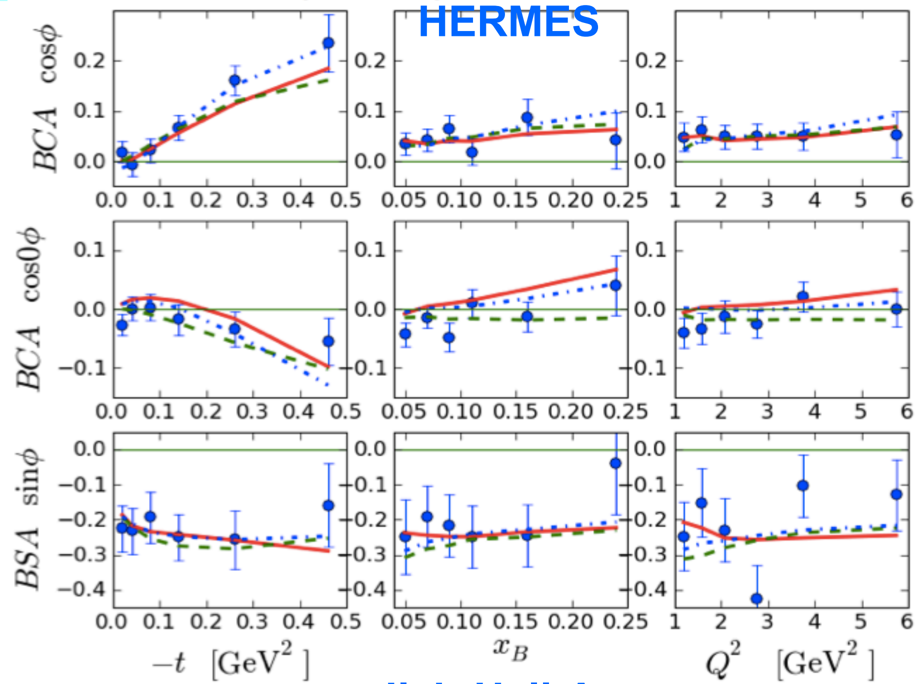
Model	LCCQM			χQSM		
q	u	d	Total	u	d	Total
ℓ_z^q	0.131	−0.005	0.126	0.073	−0.004	0.069
L_z^q	0.071	0.055	0.126	−0.008	0.077	0.069
$\mathcal{L}_z^q$	0.169	−0.042	0.126	0.093	−0.023	0.069

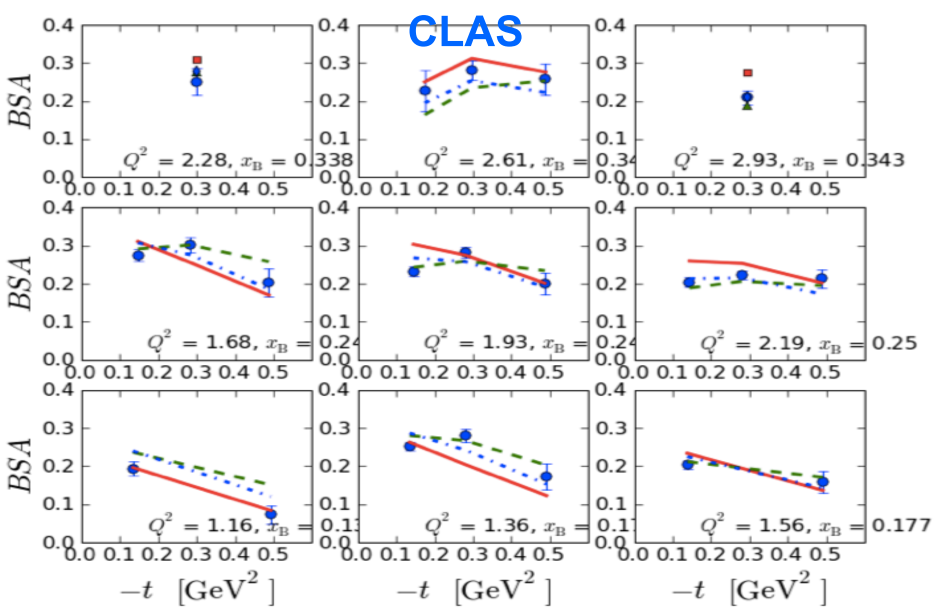
Note:
No gluons and not QCD EOM !

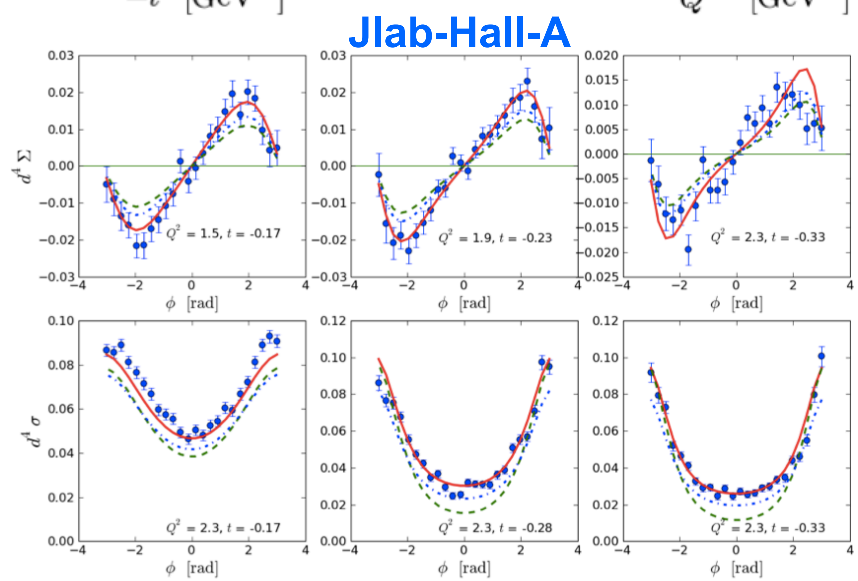
[Lorce, Pasquini (2011)]
[Lorce, et al (2012)]
[Kanazawa, et al (2014)]

GPDs: just the beginning





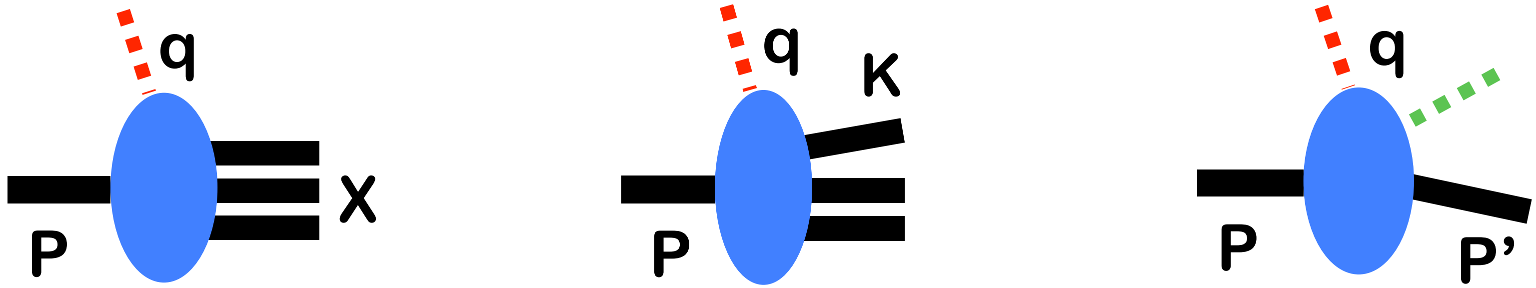




Structure vs collision dynamics

- **Probing nucleon structure (with/without breaking it):**

with a large momentum transfer ($-q^2 \gg 1/\mathrm{fm}^2$): "see" quarks and gluons

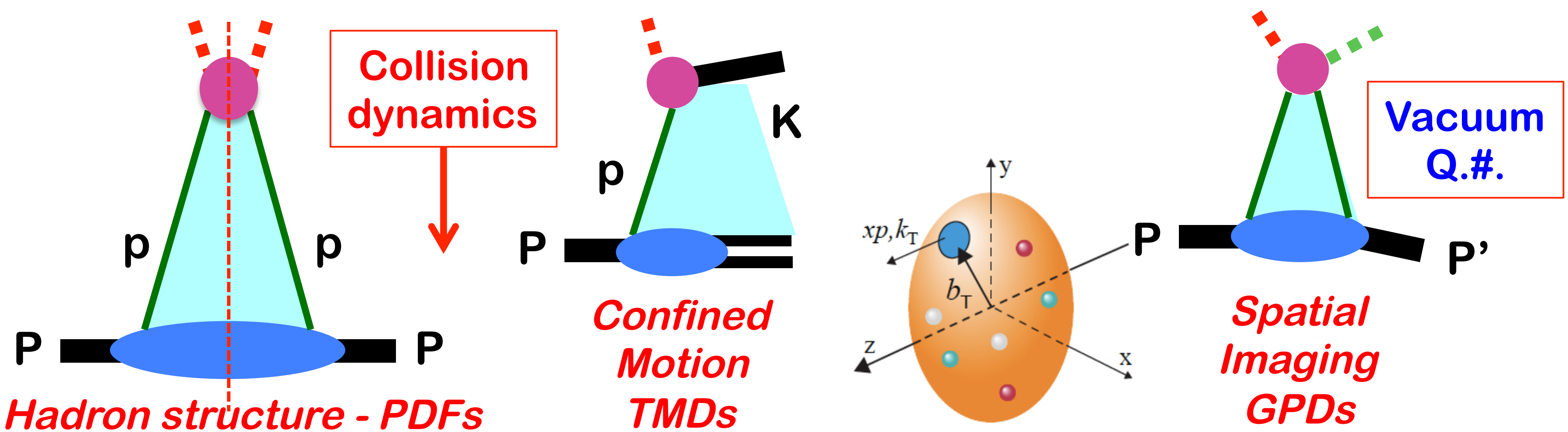


Without looking at the final-state

Measure the final-state

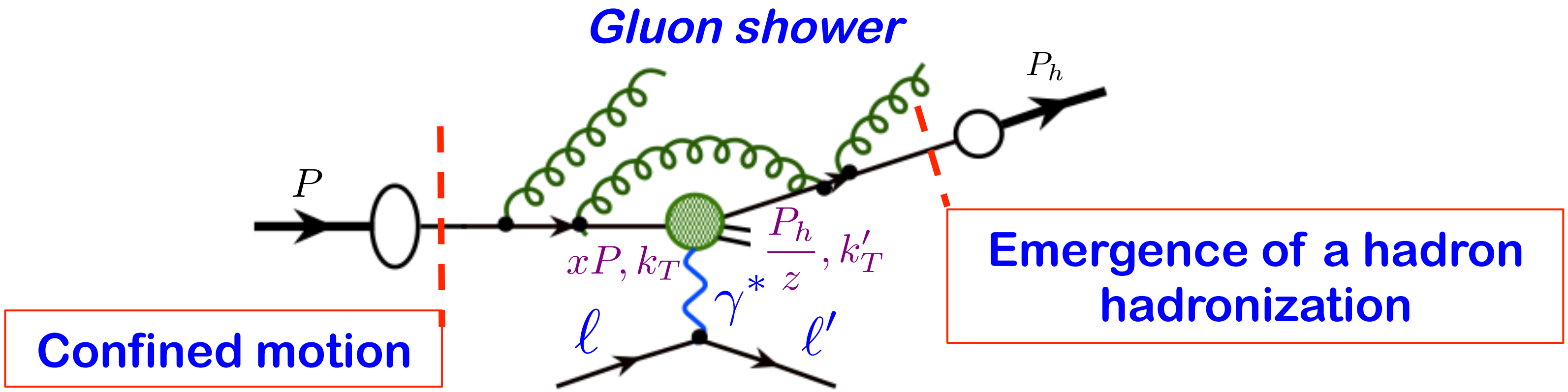
Keep the hadron intact

- **Separating structure from collision dynamics – *Factorization*:**



Example: measured parton k_T

- Sources of parton k_T at the hard collision:



- Large k_T generated by the shower caused by the collision:
  - ✧ Q^2-dependence – linear equation of TMDs in b-space
    perturbative at small b, but, not all b
  - ✧ Solution – TMDs proportional to "input distribution" – boundary condition
    Q^2-dependence of TMDs in k_T is sensitive to the "input"

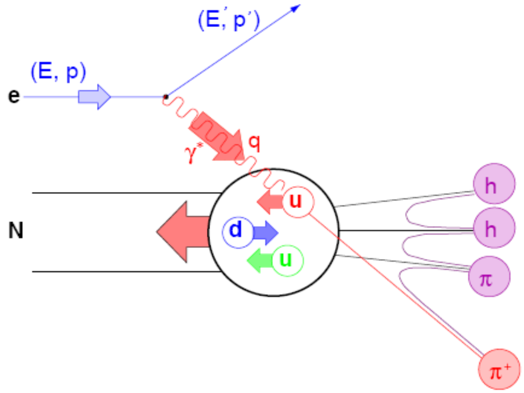
- "True" parton's confined motion – more theory work needed:
  - ✧ Separation of perturbative from nonperturbative – not as simple as PDFs
  - ✧ Ln(Q)-dependence of the "input" might get a large correction at low Q

TMDs are very interesting, SIDIS is the best place to measure!

The Future: Helicity distributions

- ❑ Quark polarization – better determined:
  - ✧ Quark polarization at $x \rightarrow 1$ – challenges – JLab12
- ❑ Sea quark polarization – not well-determined:
  - ✧ Polarized RHIC + SIDIS @ EIC

    A sizable contribution to the proton spin
    (~ 6%, current global fittings)



- ❑ Gluon polarization – need small-x region:
  - ✧ Inclusive DIS + SIDIS @ EIC

    Current small-x technique for unpolarized gluon
    Need to develop new technique to treat polarized small-x glue
- ❑ Lattice QCD to calculate PDFs, not the moments:
  - ✧ Quasi-PDFs ~ two-parton correlators along z-axis $\neq$ PDFs

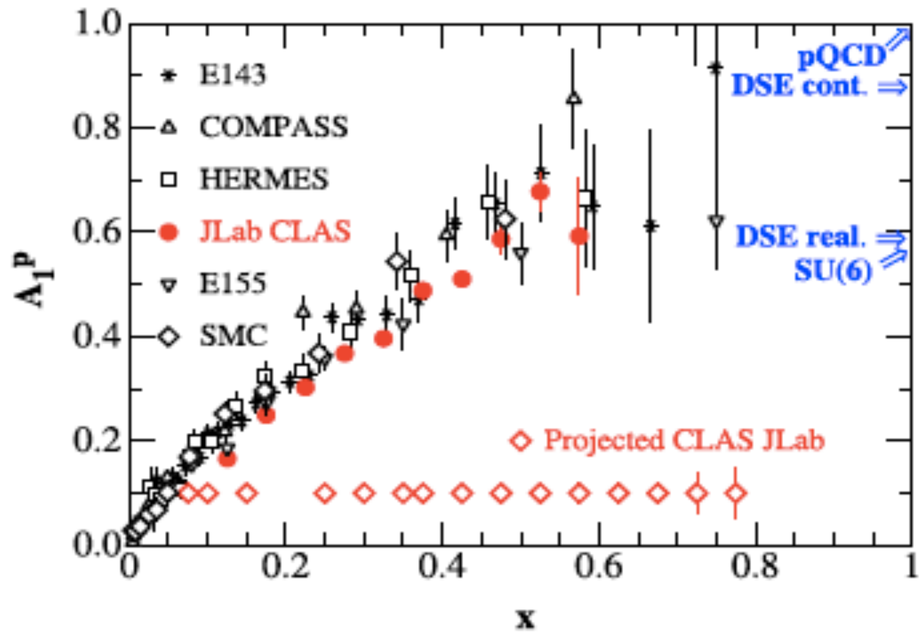
    ⟶ Normal PDFs as $P_z \rightarrow \infty$ — Ji, Lin, et al. 2013

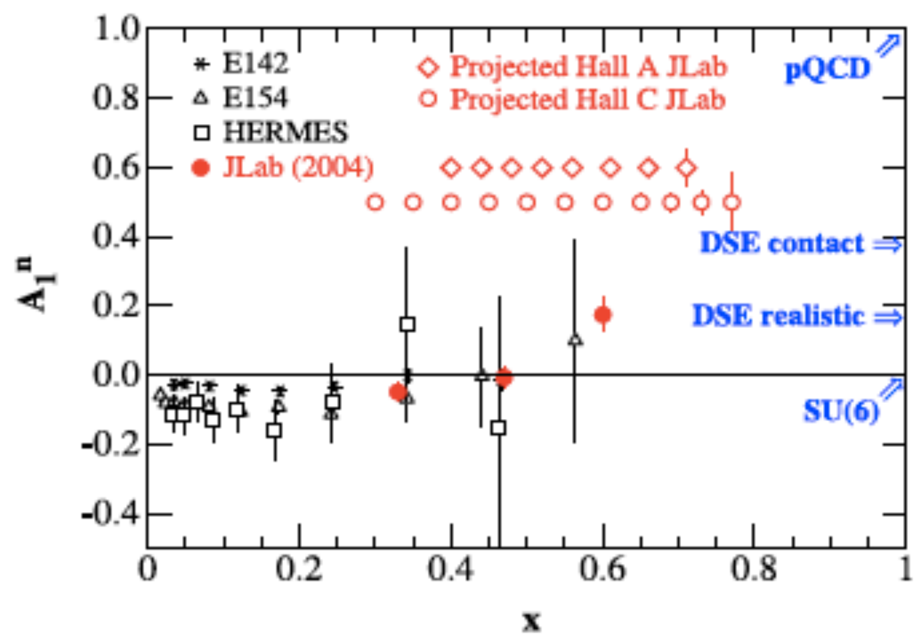
    ⟶ Factorized to Normal PDFs at a finite P_z — Ma, Qiu, 2014

    Global analysis of lattice "data" for PDFs

Valence quark helicity at large x

❑ JLab program:





	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	−0.11	0.65	−0.26	0.17	0.59
DSE-2	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
$0^+_{[ud]}$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

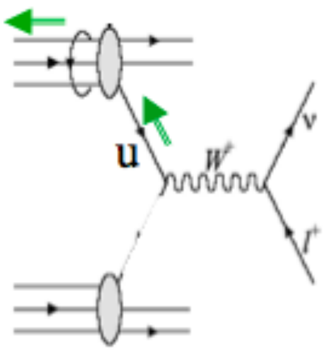
Sea quark helicity – RHIC program

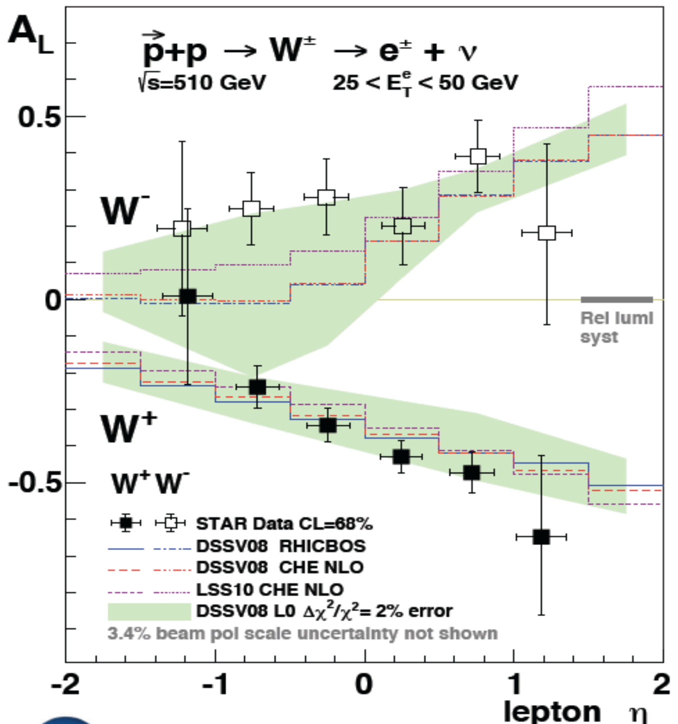
Talks by Seidl, …

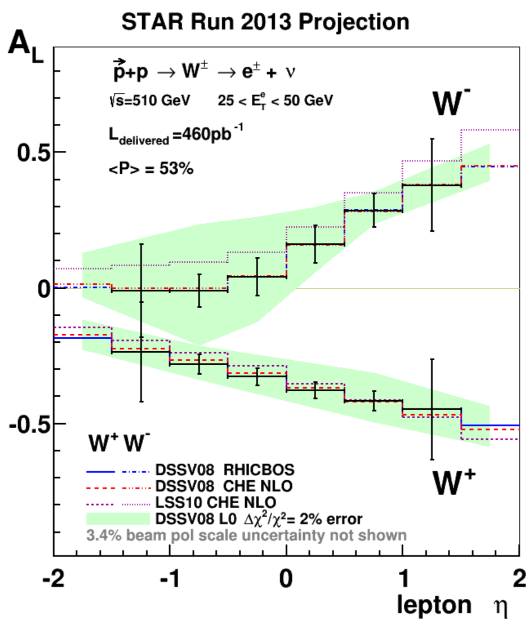
❑ Single longitudinal spin asymmetries:

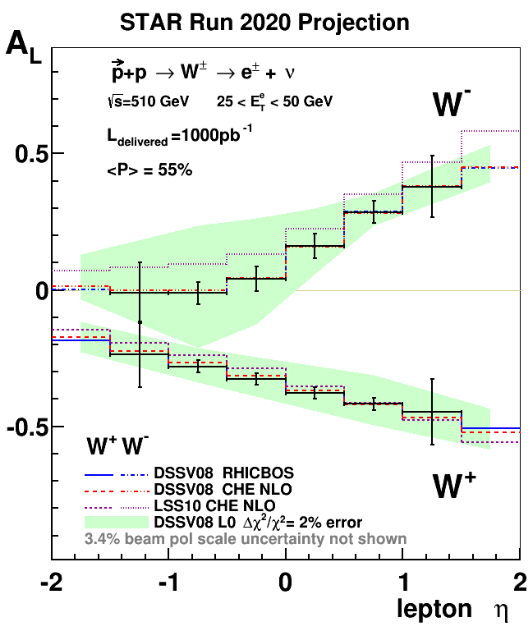
$$A_L = \frac{[\sigma(+) - \sigma(-)]}{[\sigma(+) + \sigma(-)]} \quad \text{for } \sigma(s)$$

Parity violating weak interaction









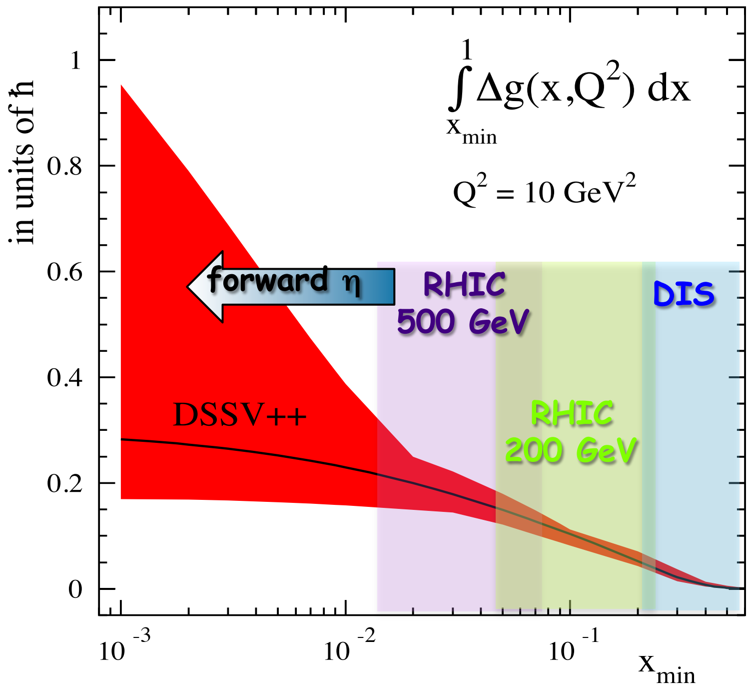
NEW arXiv:1404.6880

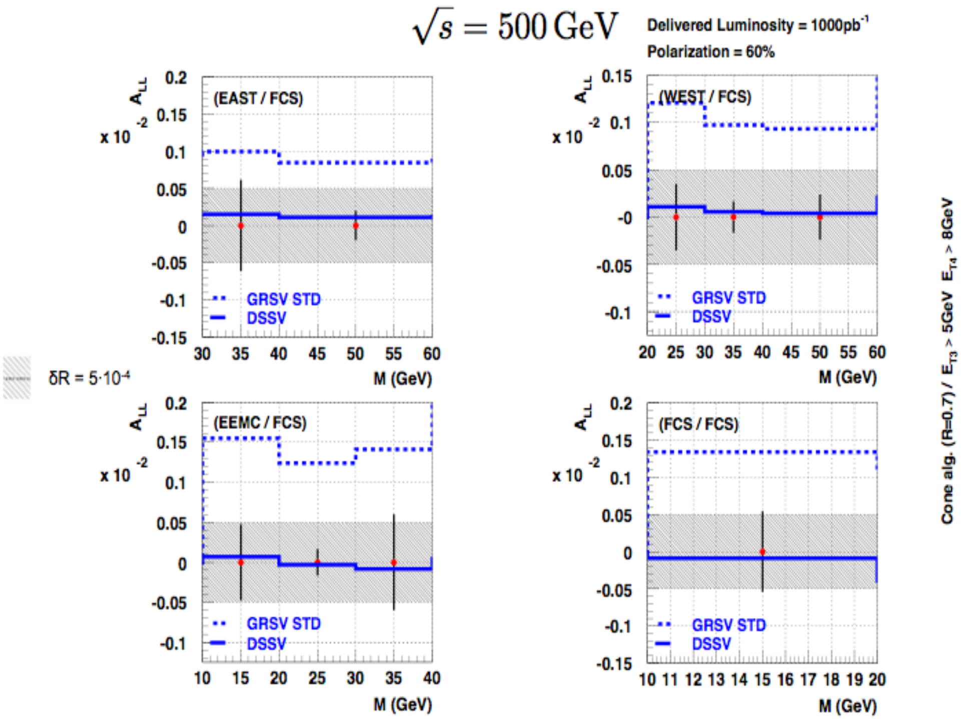
Sea quarks at medium/high x without target mass, HT, and FFs corrections!

Gluon helicity – RHIC program

Talks by Seidl, …

❑ Go to the forward region:





$x: \quad 0.01 \to 0.001$

❑ Theory:

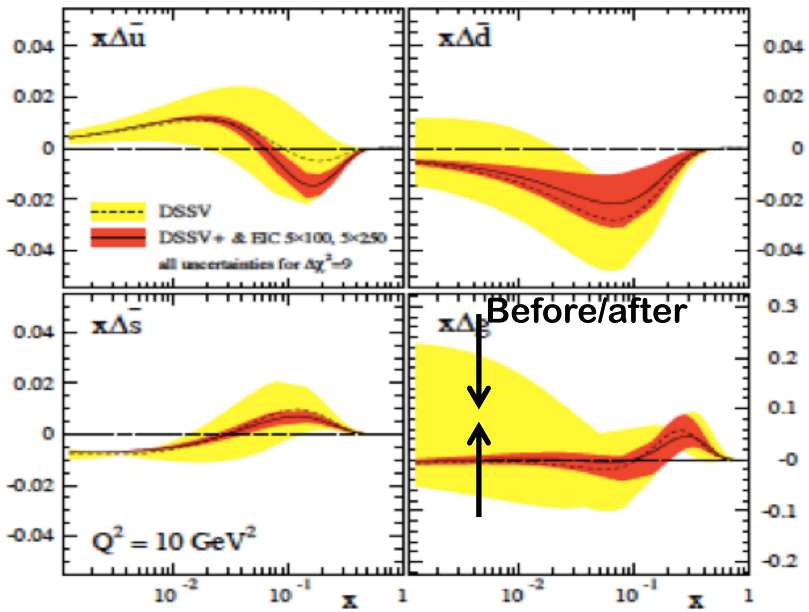
✧ How to handle the small-x physics with polarized partons?

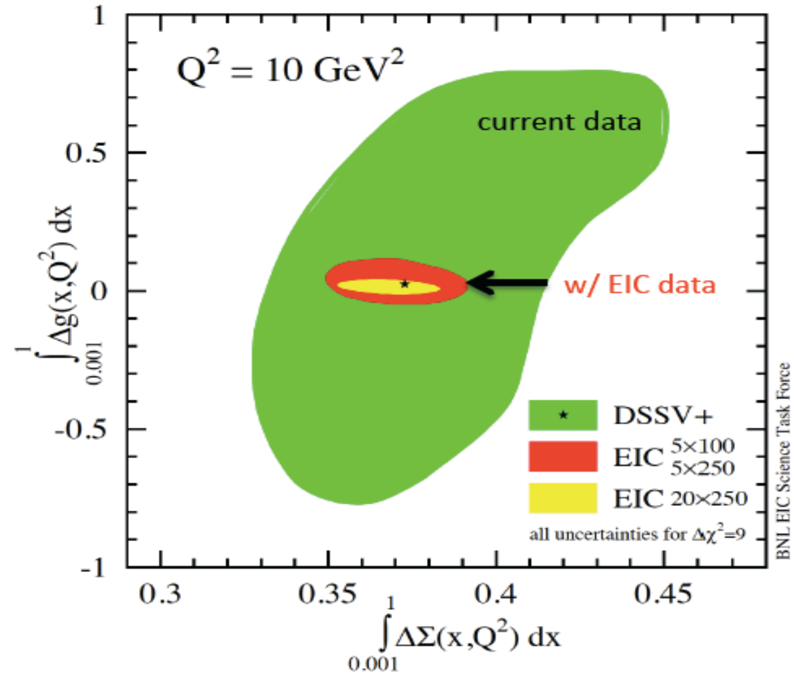
✧ How should the resummation of ln(1/x)) powers be handled?

Helicity contribution to nucleon spin

❑ **One-year of running at EIC – the decisive measurement:** See talk by Meziani

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





No other machine in the world can achieve this!

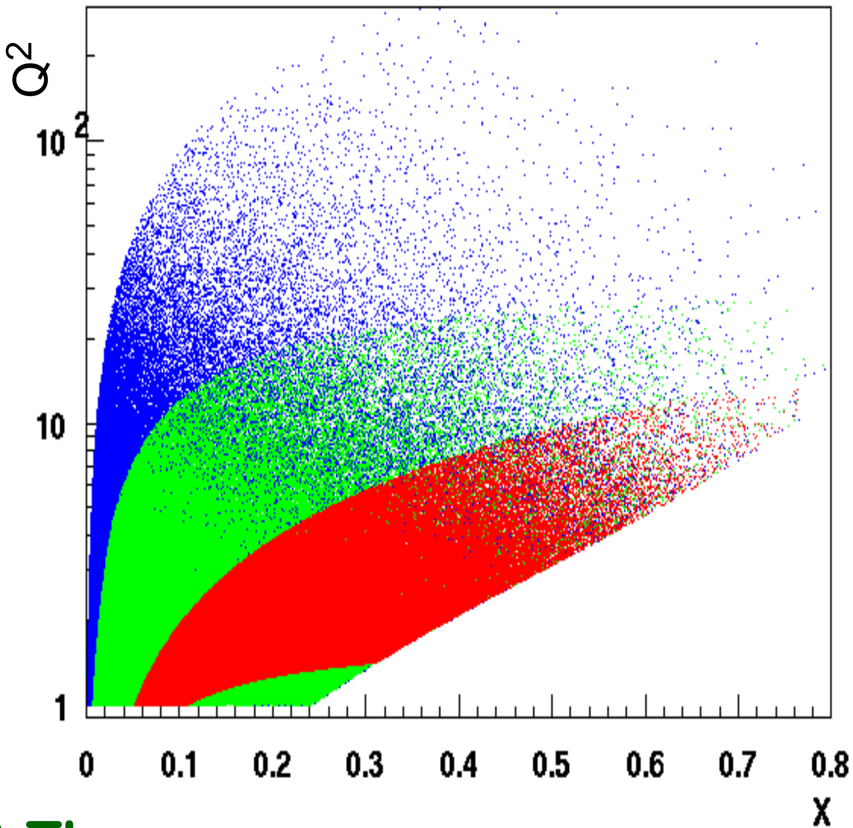
❑ **Ultimate solution to the proton spin puzzle:**

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

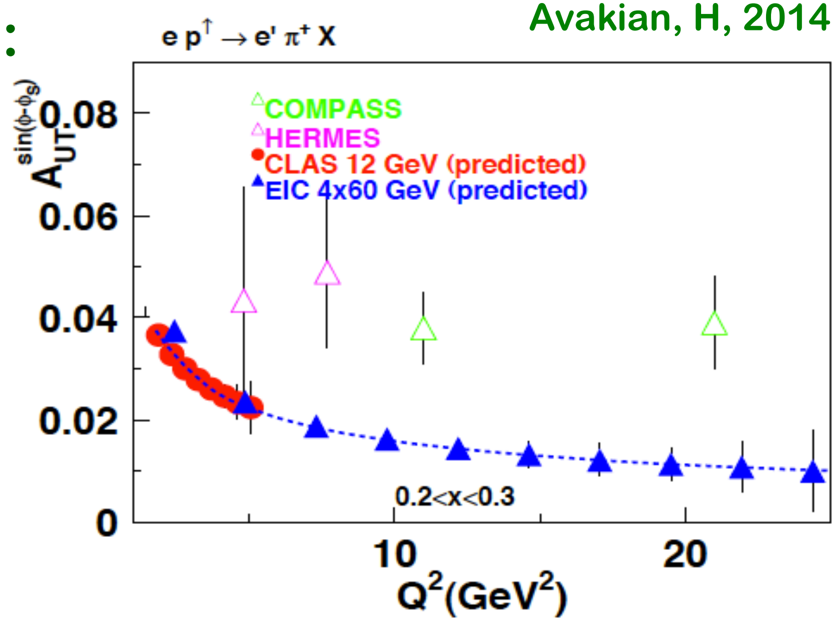
✧ ***Orbital angular momentum contribution – measurement of GPDs!***

The Future: TMDs, GPDs, and OAM

- Sivers TMD – from JLab12 to EIC:



Avakian, H, 2014



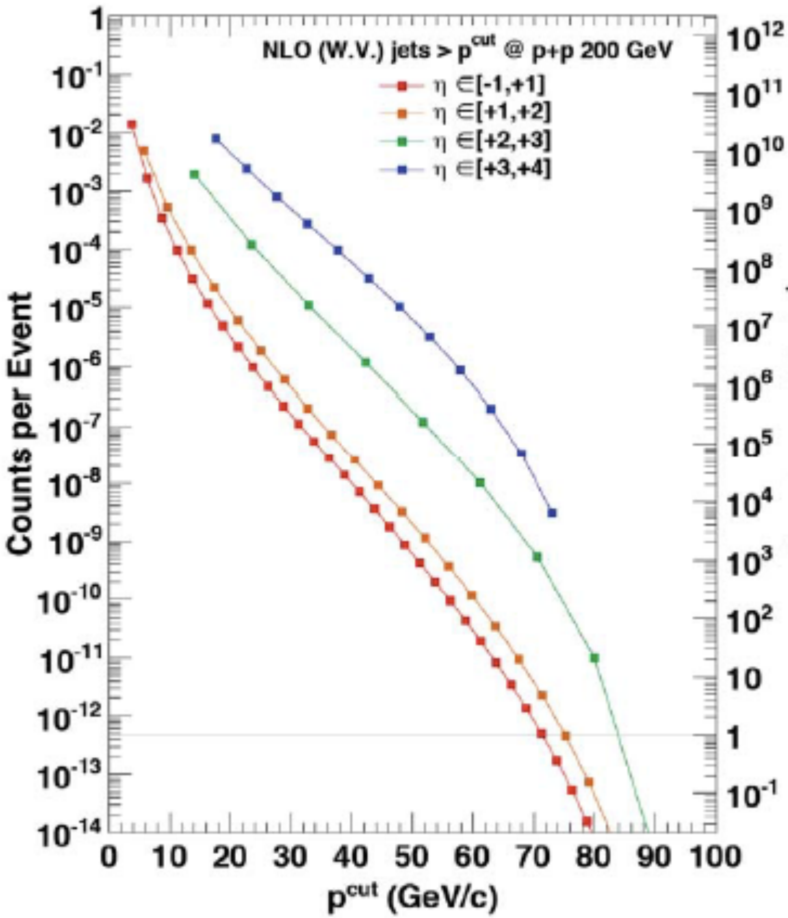
JLab@12GeV (25/50/75)
→ $0.1<x_B<0.7$: valence quarks
EIC $\sqrt{s}$ = 140, 50, 15 GeV
→ $10^{-4}<x_B<0.3$: gluons and quarks, higher P_T and Q^2.

- Theory:
  - Theoretical control of Q2-evolution of TMDs, and its sensitivity on Non-perturbative input TMDs – confined parton motion in hadrons
  - Any connection to orbital angular momentum?

The Future: TMDs, GPDs, and OAM

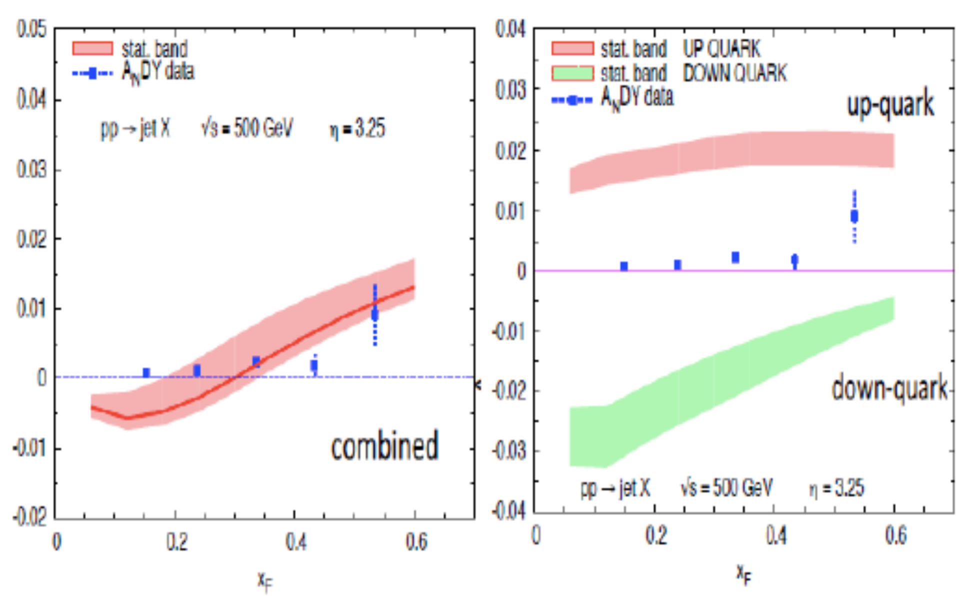
Lajoie, 2014

❑ Sivers Effect – from fsPHENIX:



fsPHENIX Jet acceptance $1.7 < \eta < 3.3$ with anti-k_T R=0.7

Directly use Sivers function from SIDIS fit



❑ Theory:

✧ **TMD approach vs high twist collinear approach, and parton correlation!**

The Future: TMDs, GPDs, and OAM

- ❑ **SoLId at JLab:**
  - ✧ **Transversity:**

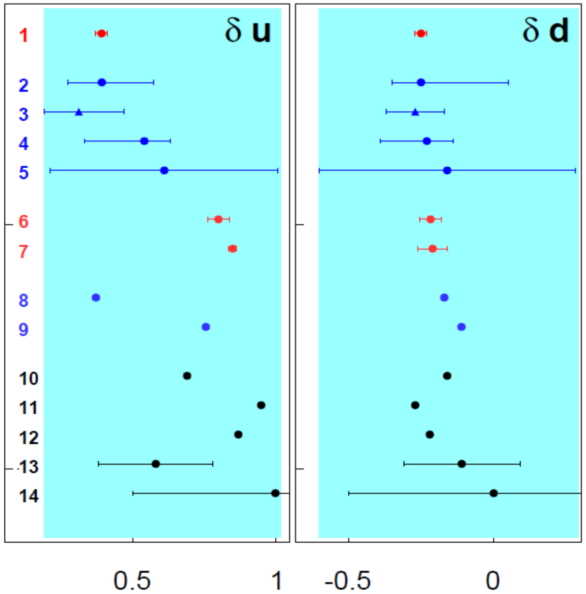
    Chiral-odd,
    no coupling to gluon,
    Transverse spin flip,
    Least known PDFs…

  - ✧ **Tensor charges:**

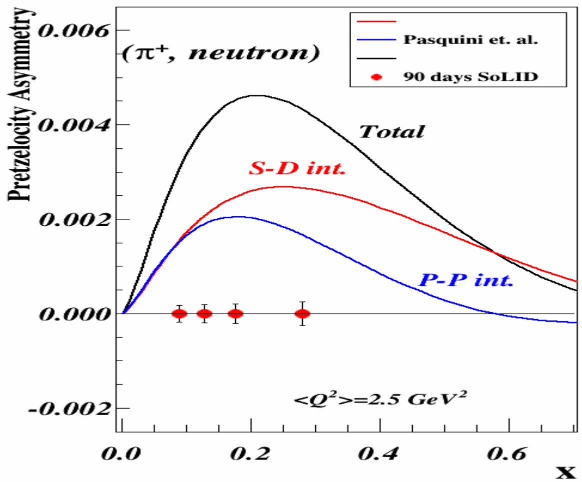
    Fundamental, many predictions

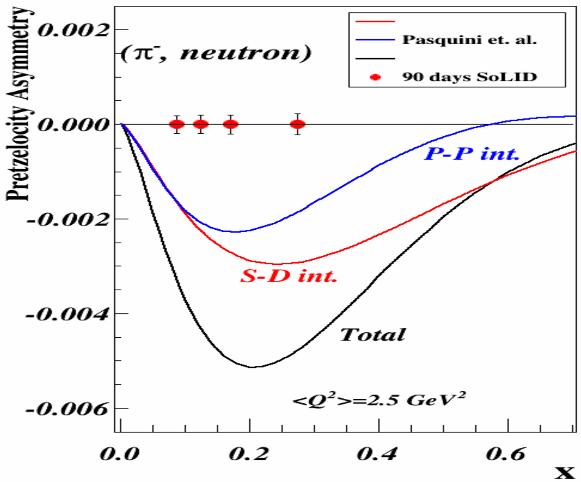
Tensor Charges

J.P. Chen, 2014



  - ✧ **Pretzelosity: TMD with ΔL=2 (L=0 an L=2 interference)**

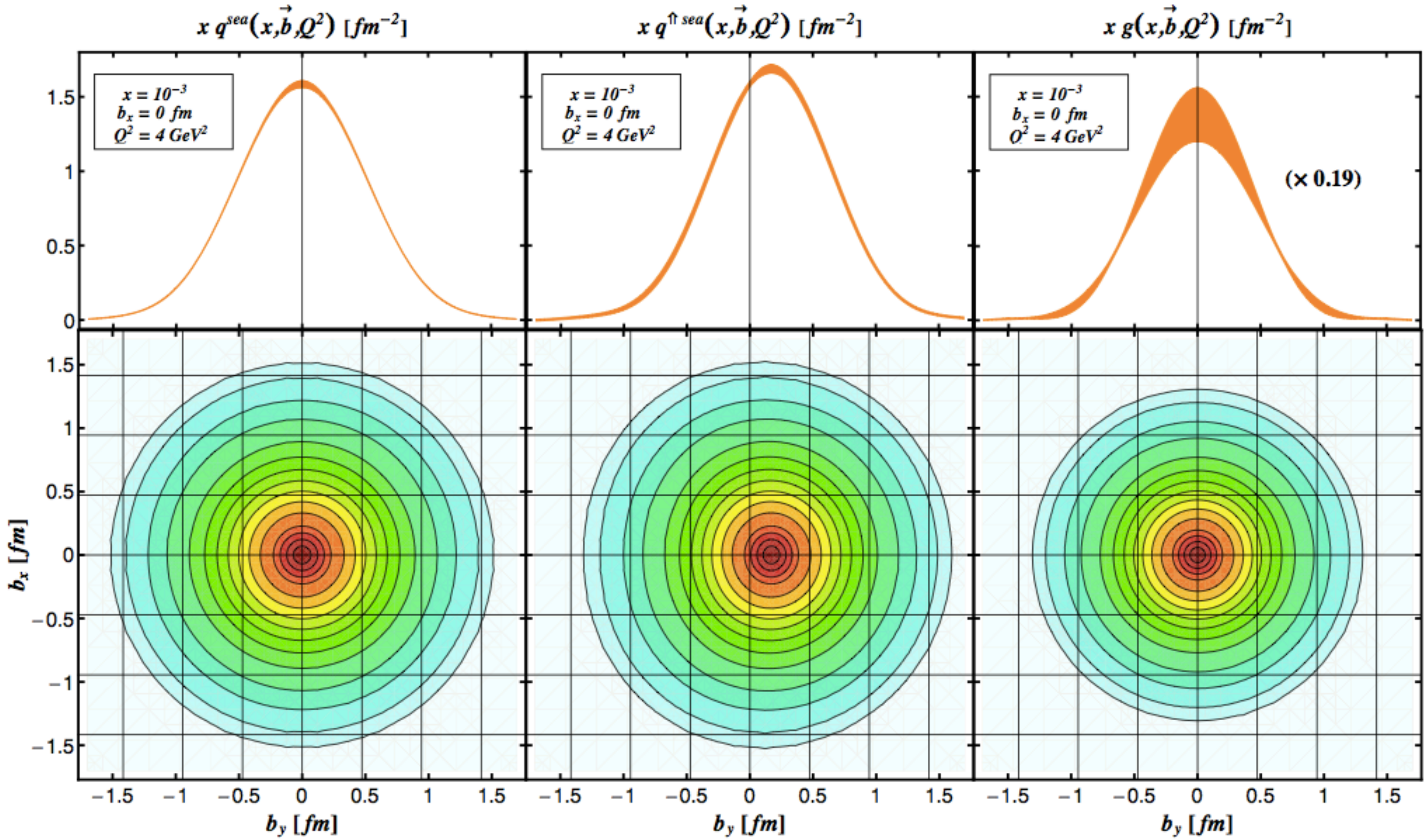




Model relates it to OAM

The Future: TMDs, GPDs, and OAM

- GPDs: Spatial imaging:



$$q(x, |\vec{b}|, Q^2) = \frac{1}{4\pi}\int_0^\infty d|t|\; J_0(|\vec{b}|\sqrt{|t|})\; H(x, \xi = 0, t, Q^2)$$

Quark radius?
Sea radius?
Gluon radius?

Summary

- After 40 years, we have learned a lot of QCD dynamics, but, only at very short-distance - less than 0.1 fm, and limited information on non-perturbative parton structure
- Understanding nucleon spin structure could provide the first complete example to describe the emerging hadron property from QCD dynamics
- Orbital angular momentum in QCD does not have a simple classical correspondence, since motion in QCD is always associated with phases and additional particles
- GPDs and TMDs are fundamental, and measurable with controlled approximation. They are necessary for getting a comprehensive 3D ``view'' of hadron's internal structure

Thank you!

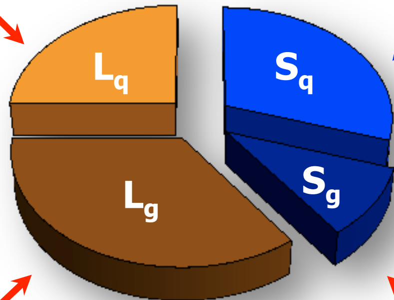
Backup Slides

Spin decomposition – Longitudinal polarization

$$\vec{\mathcal{L}}_q = \int d^3r\, \psi^\dagger [\vec{r} \times (-i\vec{\nabla})]\psi \qquad \vec{\mathcal{S}}_q = \frac{1}{2}\int d^3r\, \psi^\dagger \vec{\Sigma}\psi$$

$n \cdot A = 0$

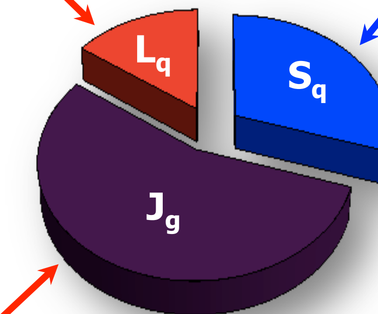
gauge



[Jaffe, Manohar (1990)]

$$\vec{\mathcal{L}}_g = \int d^3r\, E^{ai}[\vec{r} \times (-i\vec{\nabla})]A^{ai} \qquad \vec{\mathcal{S}}_g = \int d^3r\, [\vec{E}^a \times \vec{A}^a]$$

$$\vec{\mathcal{L}}_q = \int d^3r\, \psi^\dagger [\vec{r} \times (i\vec{D})]\psi \qquad \vec{\mathcal{S}}_q = \frac{1}{2}\int d^3r\, \psi^\dagger \vec{\Sigma}\psi$$



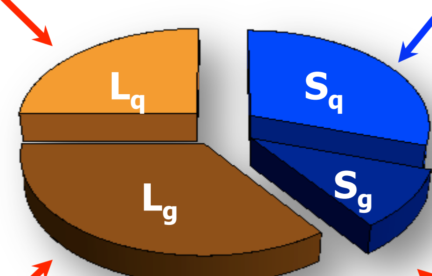
Gauge invariance

[Ji (1997)]

$$\vec{\mathcal{J}}_g = \int d^3r\, [\vec{r} \times (\vec{E}^a \times \vec{B}^a)]$$

$$\vec{\mathrm{L}}_q = \int \mathrm{d}^3r\, \psi^\dagger \vec{r} \times (i\vec{D}_{\mathrm{pure}})\psi \qquad \vec{\mathcal{S}}_q = \frac{1}{2}\int d^3r\, \psi^\dagger \vec{\Sigma}\psi$$

Gauge Invariant Extension (GIE)

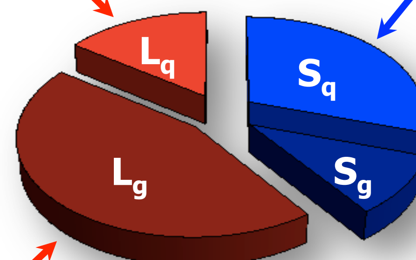


$$\boxed{A = A_{\mathrm{pure}} + A_{\mathrm{phys}}}$$

[Chen *et al.* (2008)]

$$\vec{\mathrm{L}}_q = \int \mathrm{d}^3r\, E^{ai}\vec{r} \times \vec{\mathcal{D}}_{\mathrm{pure}} A^{ai}_{\mathrm{phys}} \qquad \vec{\mathrm{S}}_g = \int \mathrm{d}^3r\, \vec{E}^a \times \vec{A}^a_{\mathrm{phys}}$$

$$\vec{\mathcal{L}}_q = \int d^3r\, \psi^\dagger [\vec{r} \times (i\vec{D})]\psi \qquad \vec{\mathcal{S}}_q = \frac{1}{2}\int d^3r\, \psi^\dagger \vec{\Sigma}\psi$$



Gauge Invariant extension

[Wakamatsu (2010)]

$$\vec{L}_g = \int \mathrm{d}^3r\, \vec{r} \times (\vec{E}^a \times \vec{B}^a) - \int \mathrm{d}^3r\, \vec{E}^a \times \vec{A}^a_{\mathrm{phys}} \qquad \vec{S}_g = \int \mathrm{d}^3r\, \vec{E}^a \times \vec{A}^a_{\mathrm{phys}}$$

Spin decomposition – Longitudinal polarization

[Stoilov (2010)]
[Lorce (2013)]

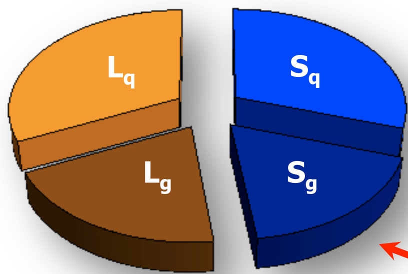
- Not unique: $A = A_{\text{pure}} + A_{\text{phys}} = \underbrace{\bar{A}_{\text{pure}}}_{A_{\text{pure}}+C} + \underbrace{\bar{A}_{\text{phys}}}_{A_{\text{phys}}-C}$

Stueckelberg symmetry

Infinitely possibilities!

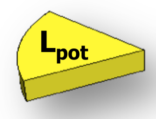
Light-cone GIE

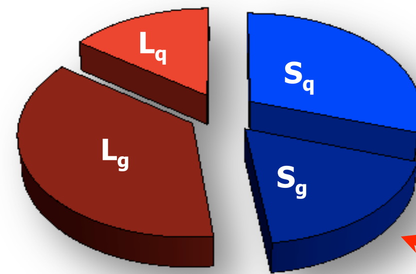
$$A^+_{\text{phys}} = 0$$



ΔG

[Hatta (2011), Lorce (2013)]



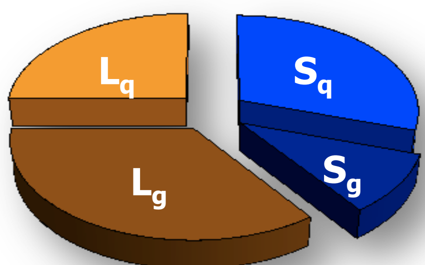


ΔG

[Ji (2013)]

Coulomb GIE

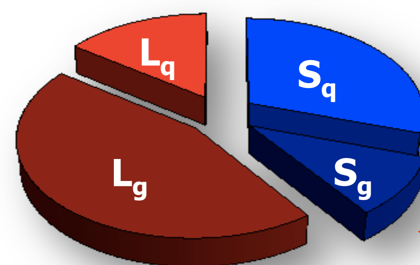
$$\vec{\mathcal{D}}_{\text{pure}} \cdot \vec{A}_{\text{phys}} = 0$$



[Chen *et al.* (2008)]

$$\vec{L}_{\text{pot}} = \int d^3r\, \rho^a \vec{r} \times \vec{A}_{\text{phys}}$$

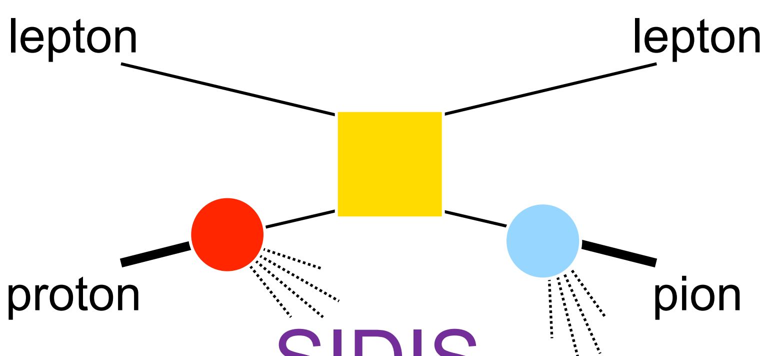
$$\rho^a = g\psi^\dagger t^a \psi = (\vec{\mathcal{D}} \cdot \vec{E})^a$$



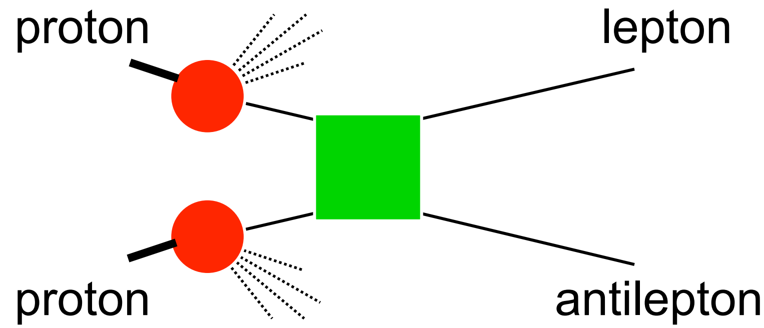
$\Delta\widetilde{G}$

[Wakamatsu (2010)]

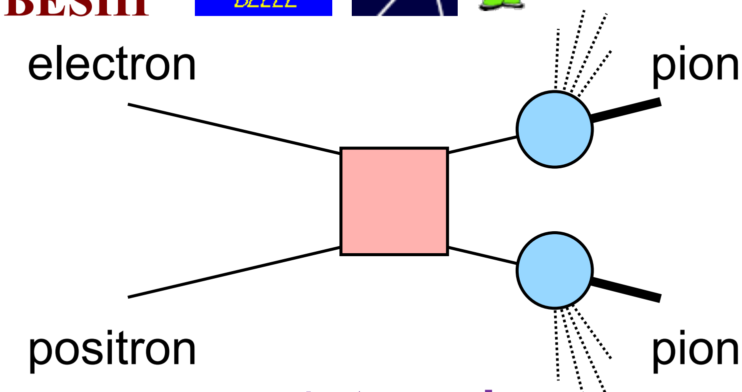
World effort on TMDs



SIDIS



Drell-Yan



$e^{-}e^{+}$ to pions

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

Test of the sign change!

$$f_{1T}^{\perp q}(\mathrm{SIDIS}) = -f_{1T}^{\perp q}(\mathrm{DY})$$

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$