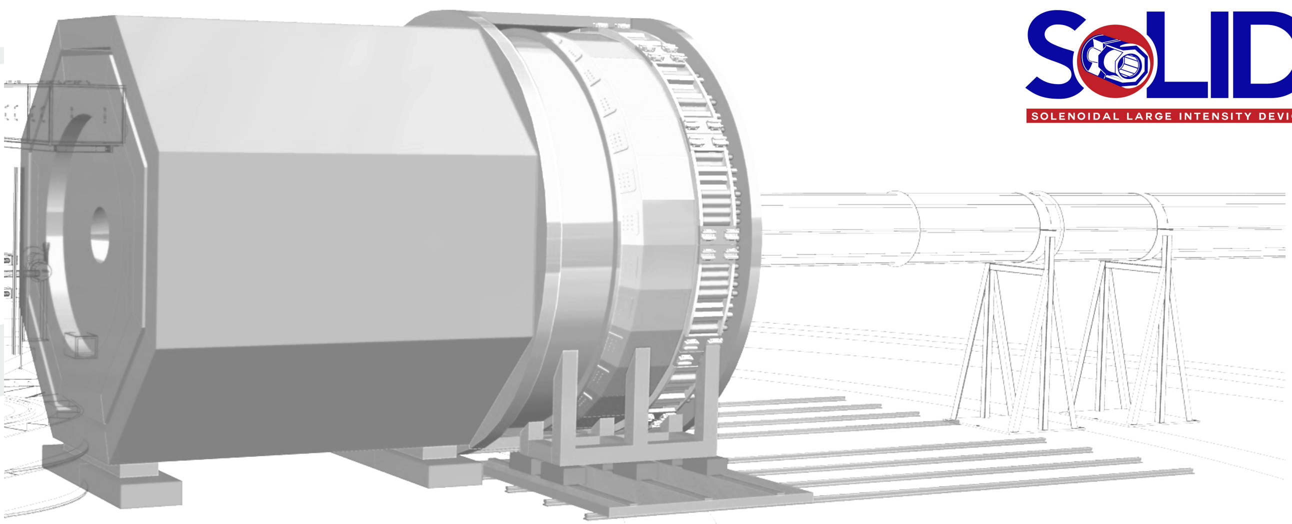
SoLID (Solenoidal Large Intensity Device)

Director's science review, Feb 9-10, 2021

Semi-Inclusive Deep Inelastic Scattering Theory



Jianwei Qiu
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Jefferson Lab

TMD Collaboration

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

U.S. based Electron-Ion Collider

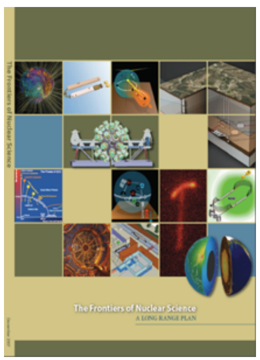
- **On January 9, 2020:**

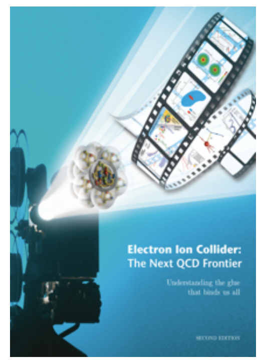
  The U.S. DOE announced the selection of BNL as the site for the Electron-Ion Collider

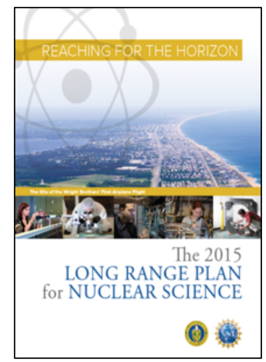
  → *A new era to explore the emergent phenomena of QCD!*

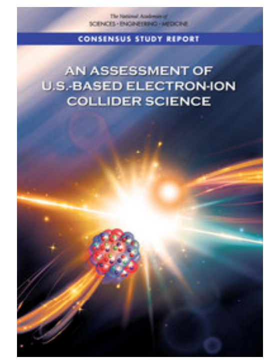
- **A long journey – a joint effort of the full community:**

…









…

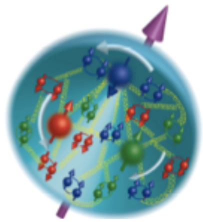
"… answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics."

… three profound questions:

How does the mass of the nucleon arise?
How does the spin of the nucleon arise?
What are the emergent properties of dense systems of gluons?

Scientific Questions – SoLID to address

- How does the mass of the nucleon arise?



Nucleon – a relativistic bound state of quarks and gluons

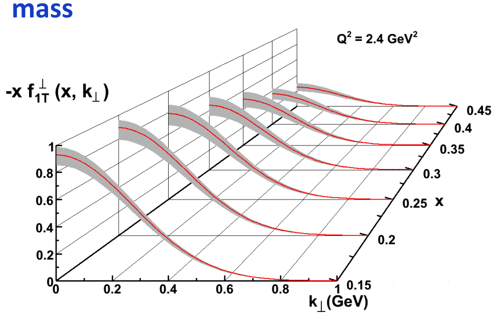
Mass is the Energy of the nucleon when it is at Rest!

Mass = Rest Mass of quarks and gluons + "Their Energy"

Quark mass
~ 1% of proton
mass

Higgs mechanism is far from enough!!!

It is the Energy of Confined Motion of quarks and gluons in nucleon's rest frame!!!



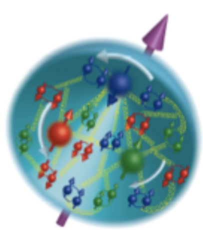
Transverse Motion of quarks and gluons inside a nucleon

$f(x, k_T)$ – the TMDs

Gives much needed information on the Confined Motion!

→ *Need probes to "see" 3D partonic motion!*

- How does the spin of the nucleon arise?



S_p = Q (~30%) + G (~40%) + Orbital (?)

Spin is the Angular Momentum of the nucleon when it is at Rest!

Spin = Spin of quarks and gluons + Orbital Angular Momentum

Helicity = Helicity of quarks and gluons
+ Their Transverse Motion!

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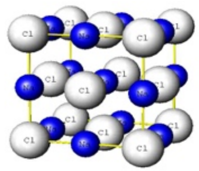
QCD and 3D hadron structure

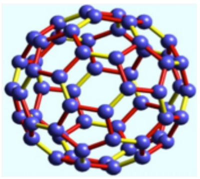
❑ Structure – "a still picture":

Crystal Structure:



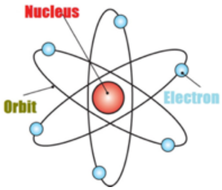
NaCl,
B1 type structure

Nano-material:



Fullerene, C60

Atomic structure

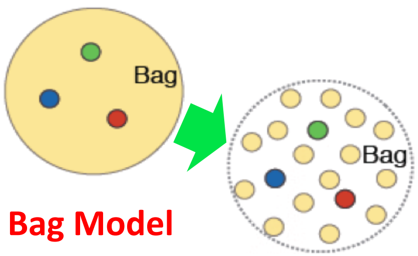


Quantum orbits

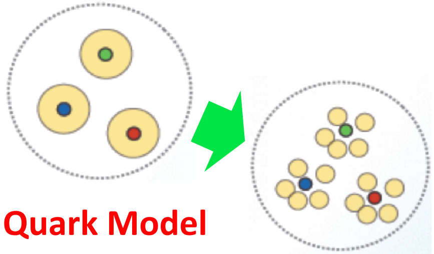
Motion of nuclei is so much slower than the speed of light, neutral photon!

❑ What does the proton look like?

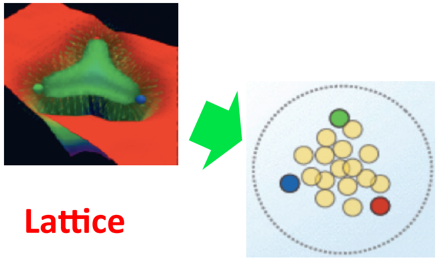
Proton radius of quark or gluon density



Bag Model



Quark Model



Lattice

❑ Hadron structure – emergent phenomena of QCD at a Fermi scale:

Color Confinement — Asymptotic freedom

Q (GeV)

20 MeV (10 fm) — 200 MeV (1 fm) — 2 GeV (1/10 fm)

Probing scale

PQCD works

Nuclear Femtography: Femto-science (0.1-10 fm)

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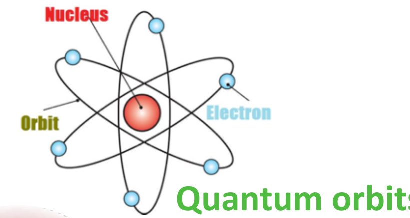
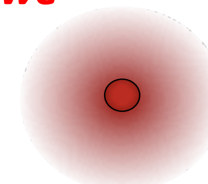
QCD and 3D hadron structure

- **The *challenge*:**
  - *How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, if we cannot see quarks and gluons?*
  - *Gluons are dark, but, carry color!*



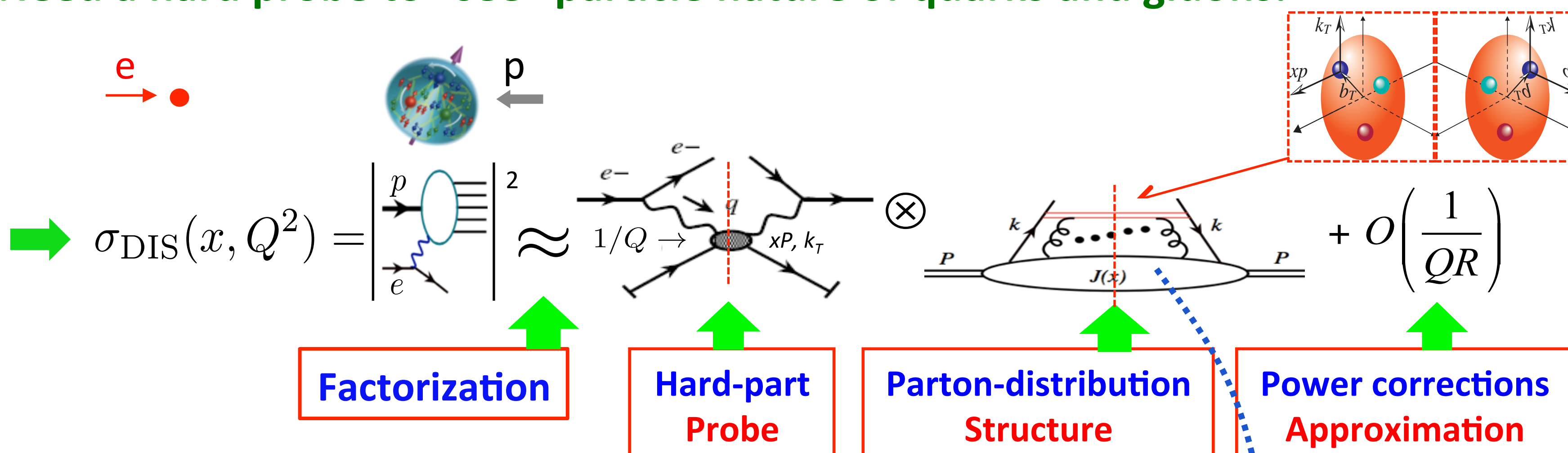


$B^+(u\bar{b})$

Brown-Muck

→ ***NO separation between color charges! Color is fully entangled!***

- **Need a hard probe to "see" particle nature of quarks and gluons:**



- **No "still picture" for hadron's partonic structure:**

Quarks and gluons are moving relativisticaly, color is fully entangled!

Partonic structure = "Quantum Probabilities": $\langle P, S | \mathcal{O}(\overline{\psi}, \psi, A^\mu) | P, S \rangle$

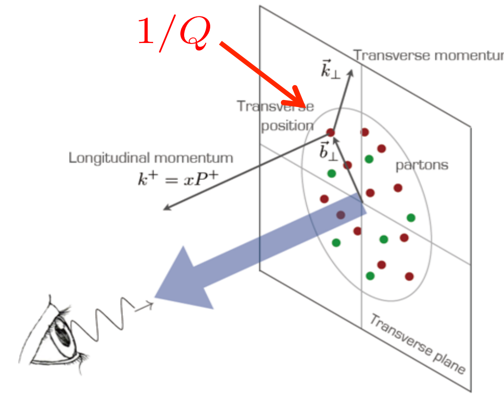
How to “see” 3D hadron structure?

- **Need new type of “Hard Probes” – Physical observables with TWO Scales:**

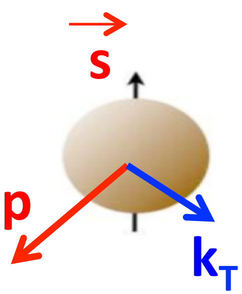
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

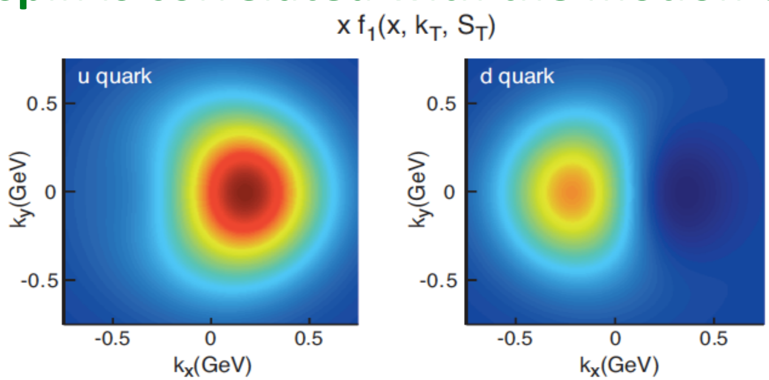
Hard scale: Q_1 **To localize the probe**
particle nature of quarks/gluons

“Soft” scale: Q_2 **could be more sensitive to the**
hadron structure ~ 1/fm



- **Proton’s spin is correlated with the motion of quarks/gluons:**

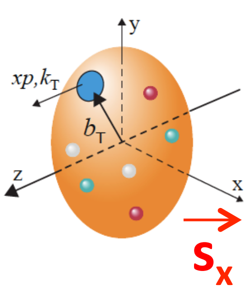


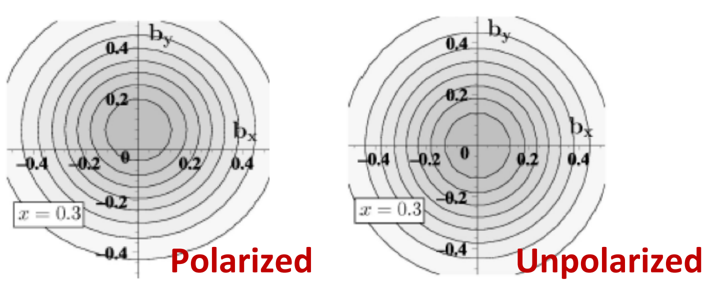


Deformation of parton’s *confined motion* when hadron is polarized

TMDs!

- **Proton’s spin is also correlated with the spatial distribution of quarks/gluons:**





Deformation of parton’s *spatial distribution* when hadron is polarized

GPDs!

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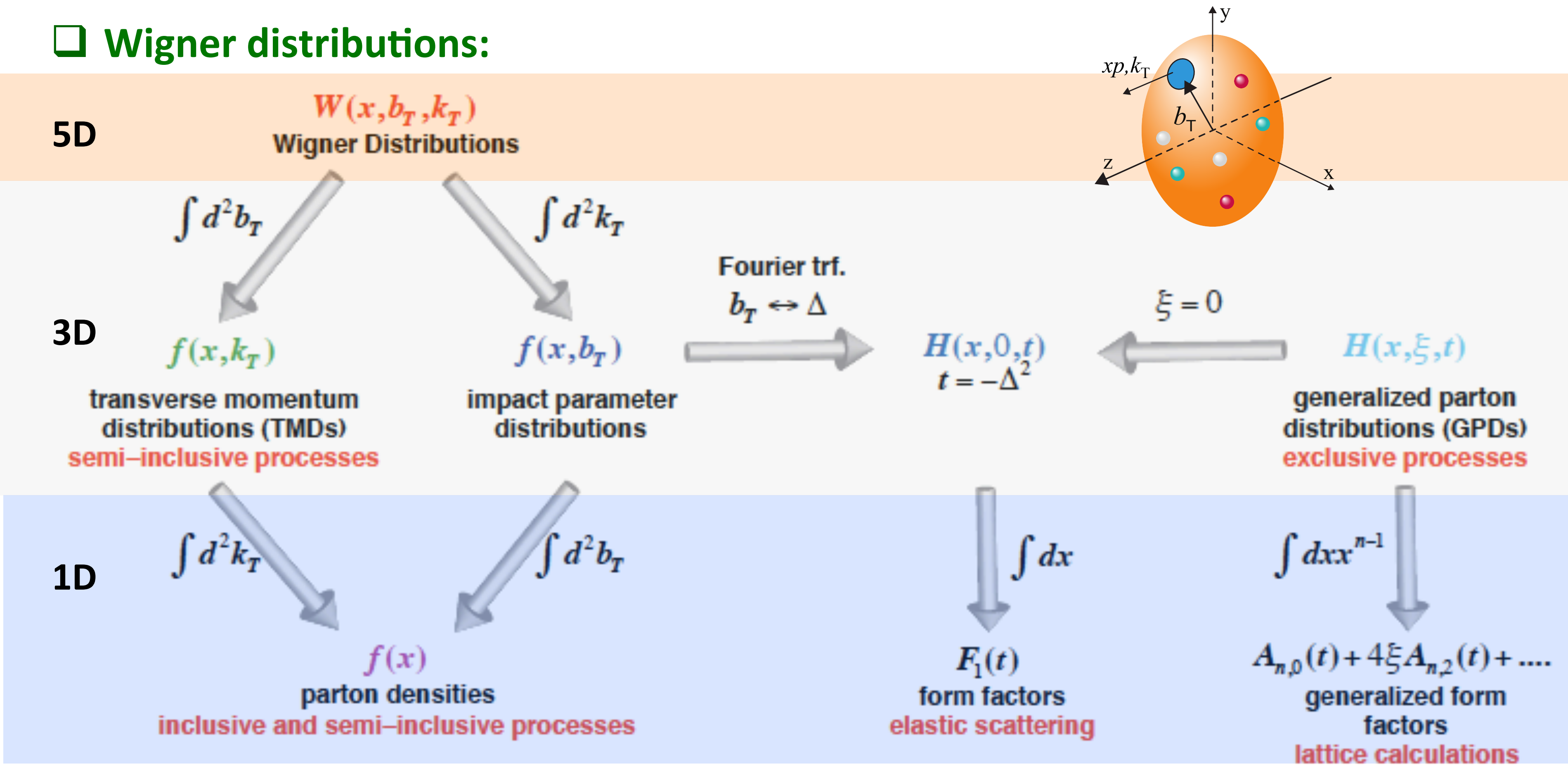
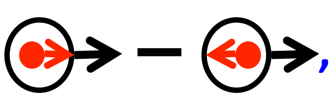
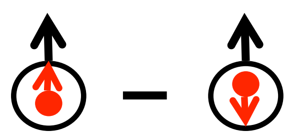
Unified view of hadron structure (EIC White Paper)

❑ Wigner distributions:



❑ Fundamental 1D hadron structure:

- ✧ quarks – $q(x,Q)$, $\Delta q(x,Q)$,  , $h_1(x,Q)$, 
- ✧ gluons – $g(x,Q)$, $\Delta g(x,Q)$

Transversity distribution

None of these are direct physical observables!

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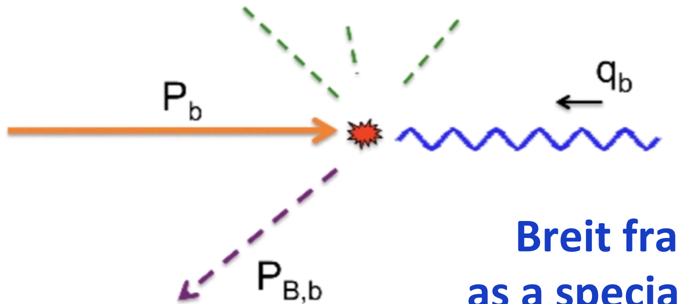
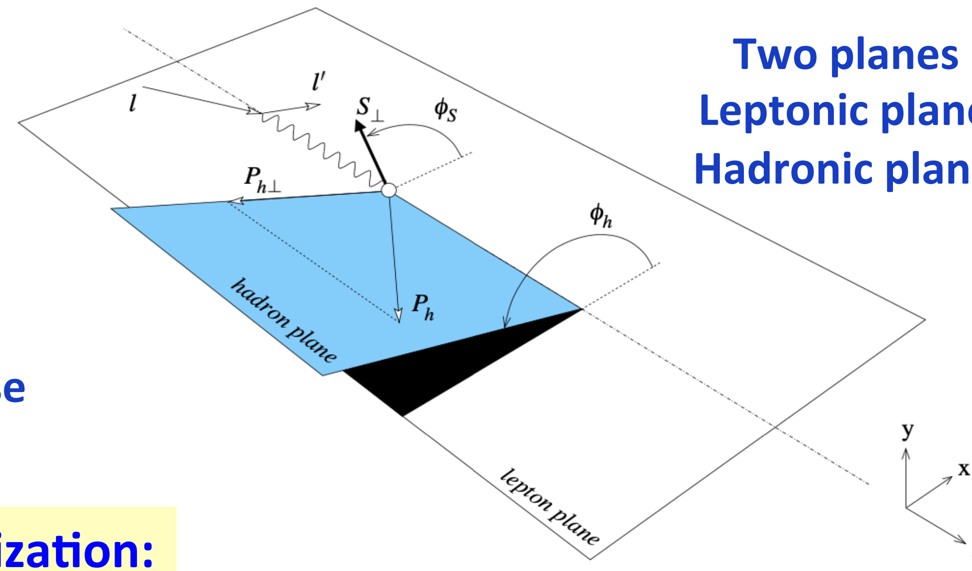
Semi-Inclusive Deep Inelastic Scattring (SIDIS)

- The photon-hadron frame:



Breit frame
as a special case



Two planes
Leptonic plane
Hadronic plane

- Theory is solid:

  ✧ **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:**

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

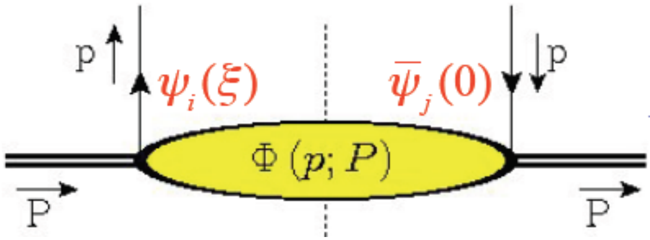
Matching between regions have been developed!

Transverse momentum dependent PDFs (TMDs)

❑ Non-perturbative definition:

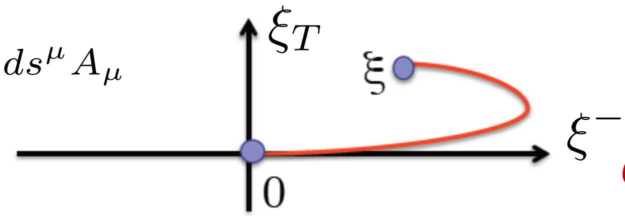
✧ **In terms of matrix elements of parton correlators:**

$$\Phi^{[U]}(x, p_T; n) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3}\, e^{i\,p\cdot\xi}\, \langle P, S|\overline{\psi}(0) U(0,\xi) \psi(\xi)|P, S\rangle_{\xi^+=0}$$



✧ **Depends on the choice of the gauge link:**

$$U(0,\xi) = e^{-ig\int_0^\xi ds^\mu A_\mu}$$



Choice is fixed by the factorization
Sign change of Sivers function

✧ **Decomposes into a list of TMDs:**

$$\Phi^{[U]}(x, p_T; n) = \Big\{ f_1^{[U]}(x, p_T^2) - f_{1T}^{\perp[U]}(x, p_T^2)\frac{\epsilon_T^{p_T S_T}}{M} + g_{1s}^{[U]}(x, p_T)\gamma_5 + h_{1T}^{[U]}(x, p_T^2)\,\gamma_5\, \not{S}_T + h_{1s}^{\perp[U]}(x, p_T)\frac{\gamma_5 \not{p}_T}{M} + i h_1^{\perp[U]}(x, p_T^2)\frac{\not{p}_T}{M}\Big\}\frac{\not{P}}{2},$$

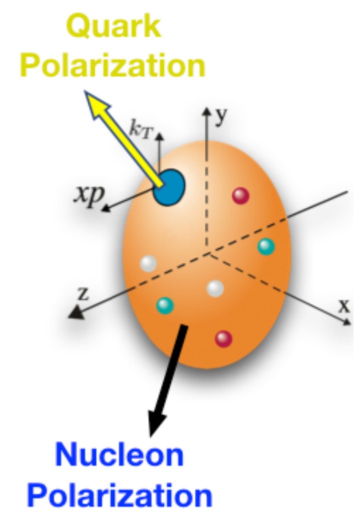
✧ **IF we knew proton wave function, this definition gives “unique” TMDs!**

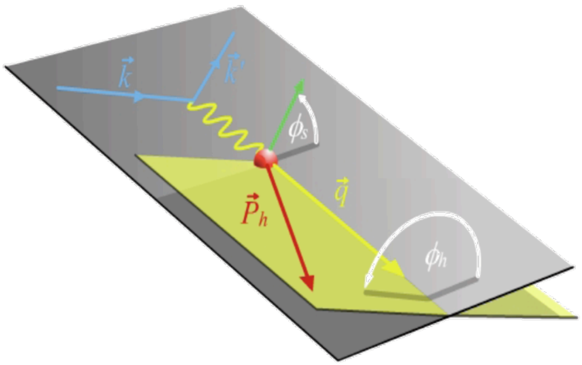
But, we do NOT know proton wave function!

Transverse momentum dependent PDFs (TMDs)

❑ Quark TMDs with polarization:

Nucleon Polarization		Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
	U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ Boer-Mulders
	L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^\perp(x,k_T^2)$ Long-Transversity
	T	$f_1^\perp(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity $h_{1T}^\perp(x,k_T^2)$ Pretzelosity





$$A_{UT} = \frac{1}{P}\frac{\sigma_{lN(\uparrow)} - \sigma_{lN(\downarrow)}}{\sigma_{lN(\uparrow)} + \sigma_{lN(\downarrow)}}$$

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Analogous tables for:

- **Gluons** $f_1 \rightarrow f_1^g$ etc
- **Fragmentation functions**
- **Nuclear targets** $S \neq \frac{1}{2}$

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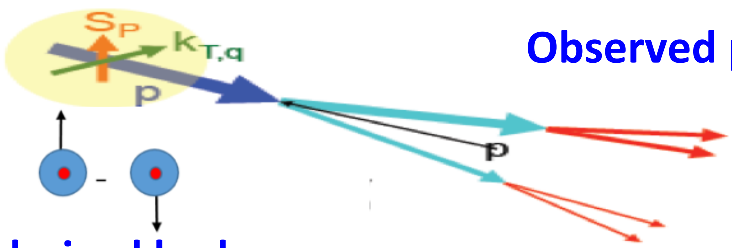
What can we learn from TMDs?

- **Quantum correlation between hadron spin and parton motion:**



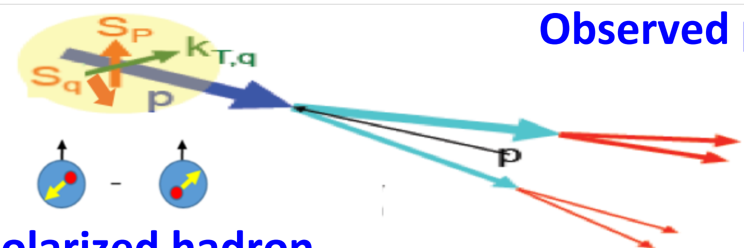
Observed particle

Polarized hadron

Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

- **Quantum correlation between hadron spin and parton spin:**



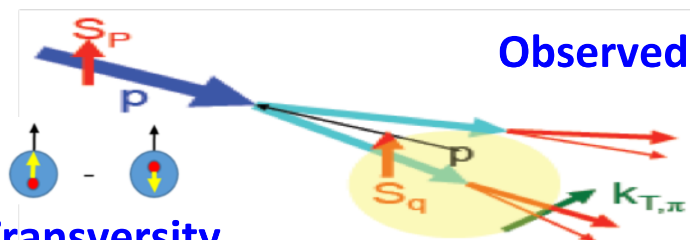
Observed particle

Polarized hadron

Pretzelosity – model OAM

Hadron spin and parton spin influence parton's transverse motion

- **Quantum correlation between parton's spin and its hadronization:**



Observed particle

Transversity

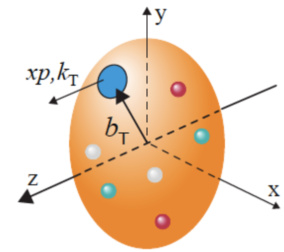
Polarized hadron

Collins effect – Collins function

Parton's transverse polarization influences its hadronization

Same reaction – different angular modulations !

Orbital angular momentum (OAM)



- **OAM:**

Classical: $\vec{L} = \vec{r} \times \vec{p} \;\rightarrow\; \vec{b}_T \times \vec{k}_T$

Quantum mechanic: $\vec{L} = \int d^3r \; \psi^\dagger(r)\, [\vec{r} \times (-i\vec{\partial})]\, \psi(r)$

Not unique in QCD: $\mathcal{L}_q^3 = \psi_q^\dagger [\vec{x} \times (-i\vec{\partial}\,)]^3 \psi_q$ **Jaffe-Manohar's quark OAM density**

$\mathcal{L}_q^3 = \psi_q^\dagger [\vec{x} \times (-i\vec{D}\,)]^3 \psi_q$ **Ji's quark OAM density:**

The difference is compensated by difference between gluon OAM density

- **Color Lorentz force/torque:**

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

"Chromodynamic torque"

Same color Lorentz force generates the single transverse-spin asymmetry (Qiu-Sterman function $\propto$ the 1st moment of Sivers function)
and is also responsible for the twist-3 part of DIS structure function g_2

- **Averaged OAM:** $\langle L^3 \rangle = \langle b_T \rangle \cdot \langle k_T \rangle$

Moment of GPDs → $\langle b_T \rangle$

Moment of TMDs → $\langle k_T \rangle$

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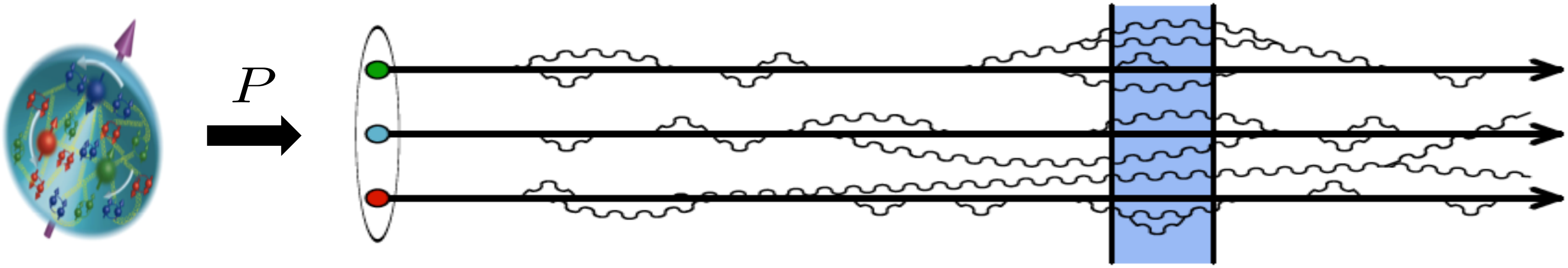
TMDs and the confined motion of partons

- **Hard "probe" – probability to "catch" the partons:**

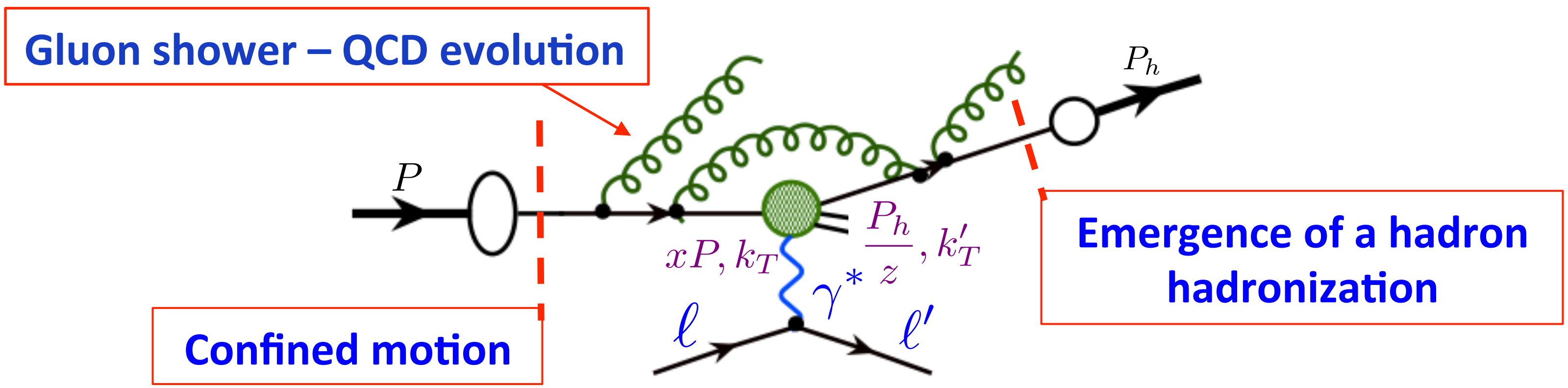
Boost = time dilation



Hard probe ($t \sim 1/Q$ << fm) → "catch" the quantum fluctuation

- **If the proton is broken, …**

Liberation of confined states → gluon shower → new particles produced



- *Measured k_T is NOT the same as k_T of the confined motion!*
- *Structure information vs. collision effects*

TMDs and the confined motion of partons

❑ Gluon shower - Q^2 evolution:

- is a part of cross section once the proton is broken
- is not necessarily "controllable perturbatively"
- mixes the structure information with the collision effect
- mixes the role of quarks and gluons
- dilutes the quantum correlation between hadron spin and parton properties

Ex: Sivers effect from single transverse-spin asymmetry:

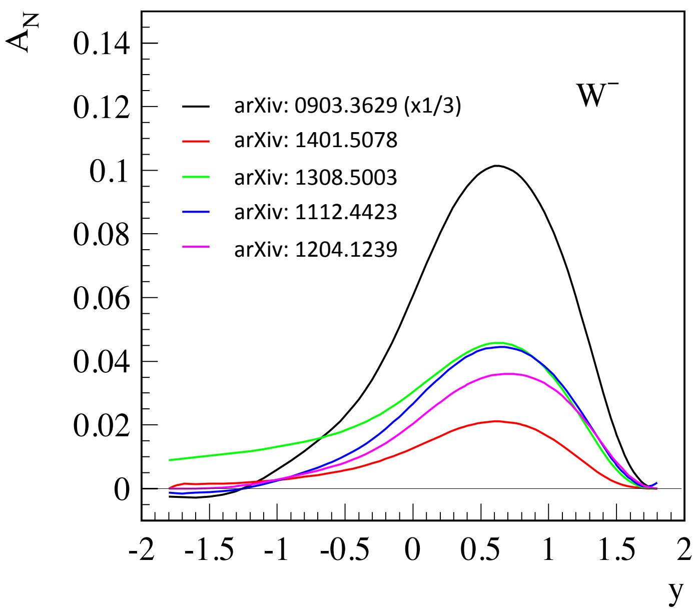
- *W-production at RHIC with polarized proton:*

$$p(\vec{s}_T) + p' \to W^{\pm}(q) + X$$

- *Single transverse-spin asymmetry:*

$$A_N \equiv \frac{\sigma(s_T) - \sigma(-s_T)}{\sigma(s_T) + \sigma(-s_T)} \propto \frac{f_1^{\perp}(x, k_T^2)}{f_1(x)}$$

- *no fragmentation, clean, …*



Challenge:

Structure information vs. collision effects, …

- *Stronger radiation at larger Q^2*
- *More radiation at small-x (larger phase space)*

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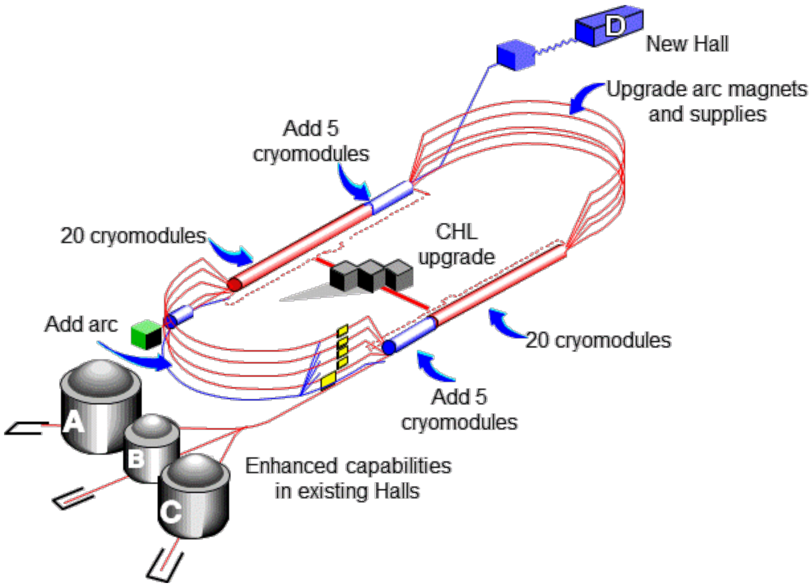
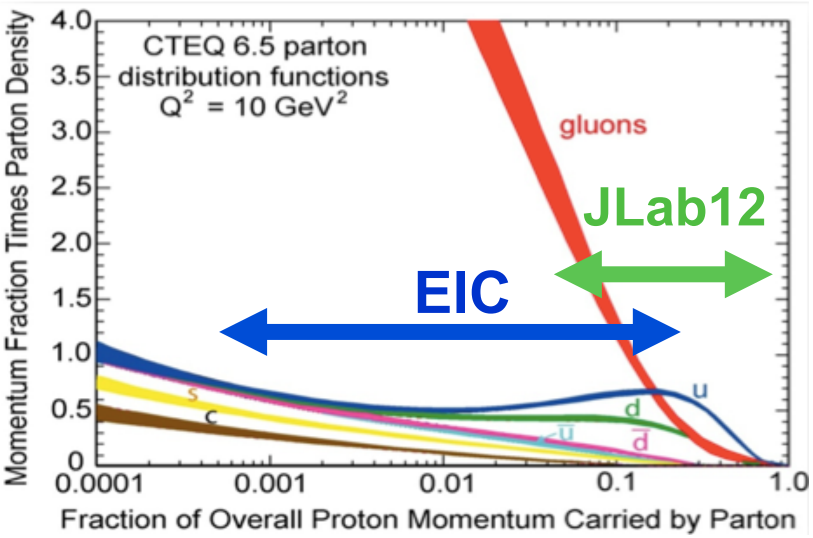
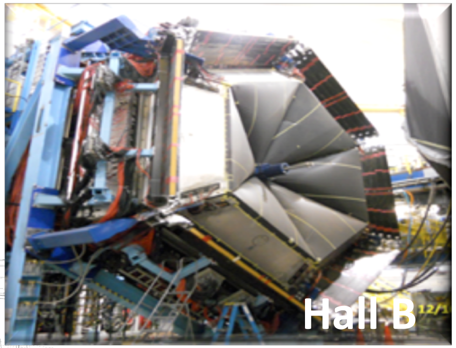
Jefferson Lab @ 12 GeV and SoLID's impact

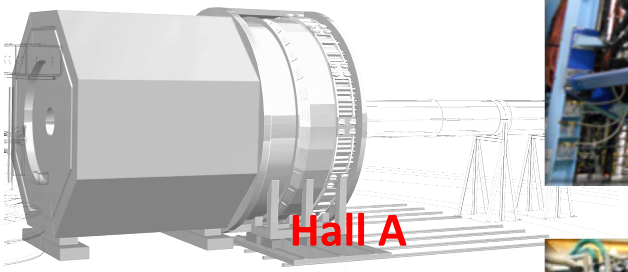
- **CEBAF – Lepton-hadron facility:**







SoLID
SOLENOIDAL LARGE INTENSITY DEVICE



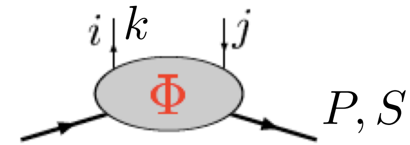
SoLID covers the phase space not be covered by EIC

See Haiyan's talk

Transversity distribution – Tensor charge

- **Probability to "see" a quark in a proton:**

$$\Phi_\Gamma(x) = \int d^4z\, e^{ik\cdot z} \langle PS|\,\overline{\psi}_j(0)\,\Gamma_{ji}\,\psi_i(z)\,|PS\rangle$$



Γ_{ji} **Picks up 4-spin combinations of** $\overline{\psi}_j$ **and** ψ_i

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

Unpolarized

"No spin flip"

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

Longitudinally polarized

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

Transversity

Also as $h_1(x)$

- **Transversity distribution – Direct evidence of relativistic quarks inside a proton:**

In non-relativistic QM: $\Delta q^{\rm NR}(x) = \delta q^{\rm NR}(x)$

With the relativity: $\Delta q(x) \neq \delta q(x)$

Transverse spin is not boost invariant along $\vec{P}$

Two invariants of a Lorentz invariant relativistic system $|PS\rangle$ **:**

Mass: $\mathcal{P}_\mu \mathcal{P}^\mu = P^2 = m^2$ **Spin:** $\mathcal{W}_\mu \mathcal{W}^\mu = \mathcal{S}^2 = m^2 S(S+1)$

Pauli-Lubanski vector: $\mathcal{W}_\mu = -\frac{1}{2}\epsilon_{\mu\nu\rho\sigma}\mathcal{M}^{\nu\rho}\mathcal{P}^\sigma$ $\mathcal{S}_i \equiv \frac{1}{m}\mathcal{W}^i$

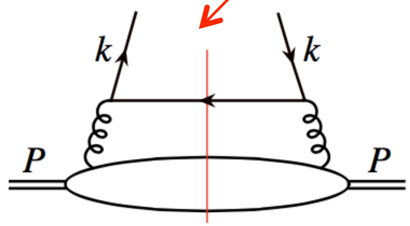
$\left[\mathcal{W}^i, \mathcal{W}^j\right] = i\, m\, \epsilon_{ijk}\, \mathcal{W}^k$ *if acting on states at the rest*

Transversity distribution – Tensor charge

- **Transversity distribution – Disconnected from gluons:**

$\gamma \cdot n \gamma_\perp \gamma_5$ ← **Even # of γ's**

No mixing with gluons!

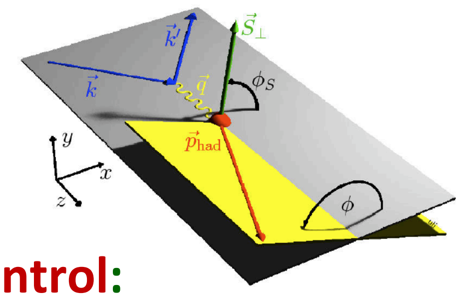


= 0

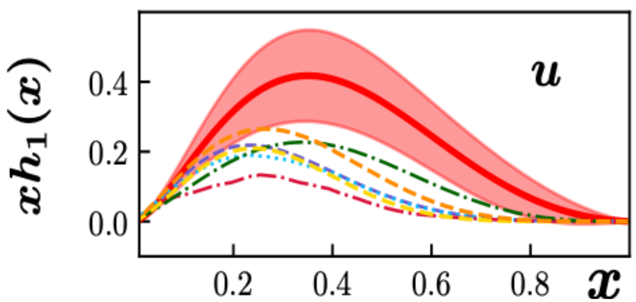
No mixing with PDFs, helicity distributions

Not contribute to inclusive DIS!

Drell-Yan (low rate), or SIDIS $\sim A_T^{\sin(\phi+\phi_s)}$
$\sim h_1(x) \otimes D_{\text{Collins}}(z)$



- **Valence quark like distribution – QCD evolution is under control:**



Need reliable large-x information,
Not much small-x contribution!
Unique for SoLID

- **Tensor charge:**

$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

As fundamental as the vector and axial-vector charge
More about transverse spin

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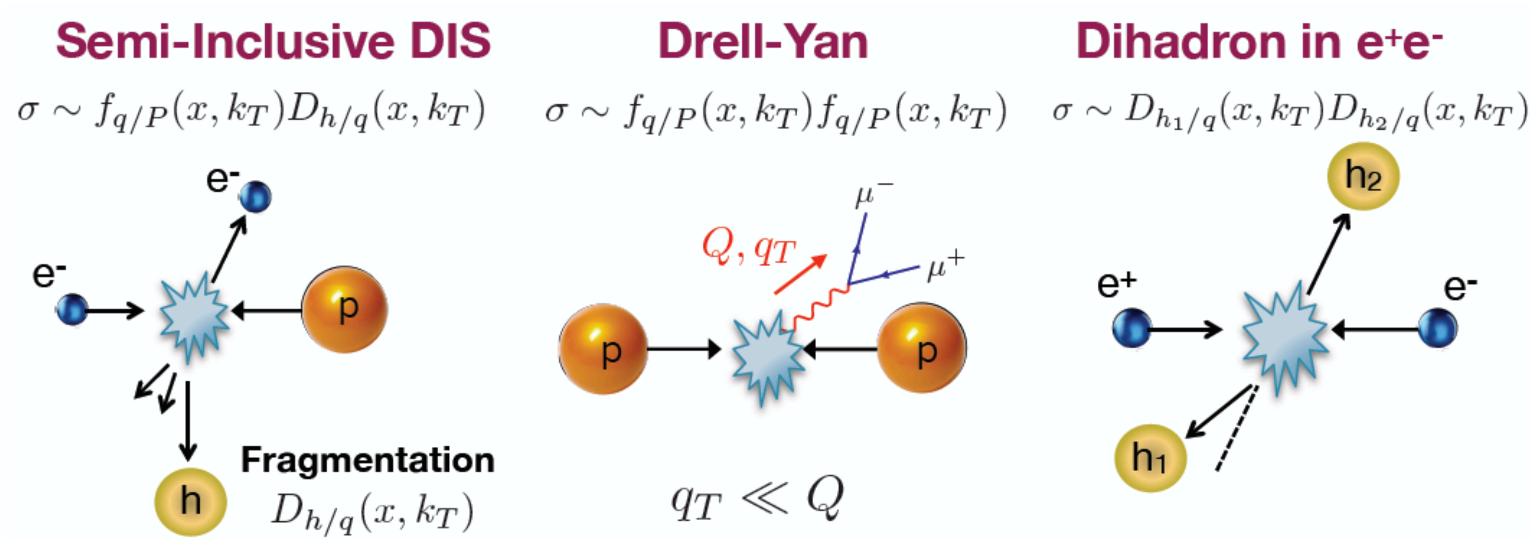
Extract TMDs from two-scale cross sections

- **Single observable cannot fix TMDs – the inverse problem!**

$$\sigma_{\rm SIDIS}(Q,q_T) = H(Q)\int d^2\vec{b}_T e^{i\vec{q}_T\cdot\vec{b}_T} f_{q/h}(x,\vec{b}_T,Q) D_{h/q}(z,\vec{b}_T,Q) + \mathcal{O}\left(\frac{q_T}{Q}\right)$$

- **Classical two-scale observables:**



- **Predictive power of QCD – Universality and global analyses:**

JLab JAM Collaboration + TMD Collaboration:
QCD global analyses of TMDs

Cammarota et al., Phys. Rev. D102 (2020) 054002

- First extraction of transversity, Sivers and Collins functions, simultaneously

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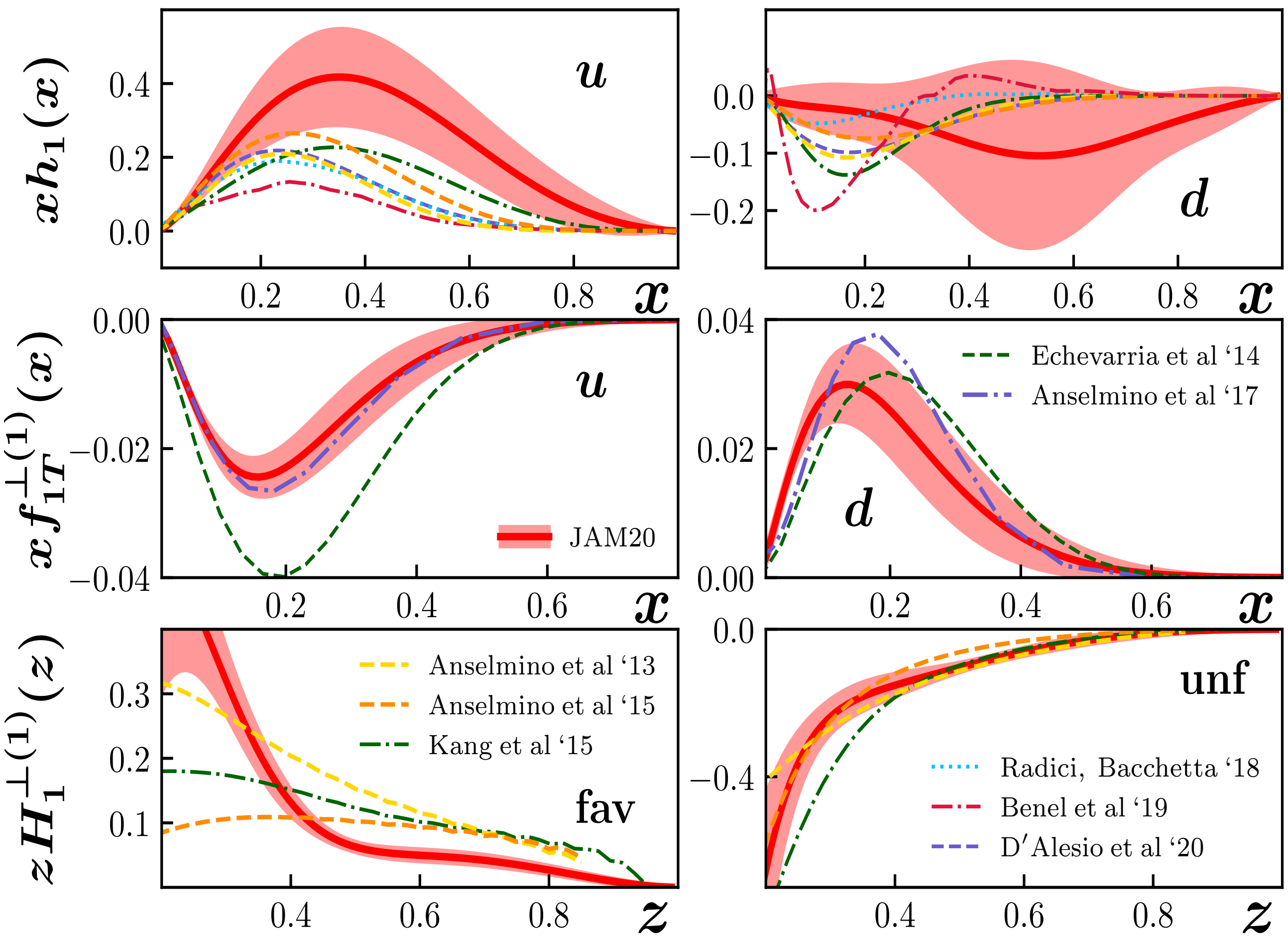
Extract TMDs from QCD global analyses

Cammarota et al., Phys. Rev. D102 (2020) 054002

❑ Global fit of TMD PDFs (or TMDs):



Momentum distributions of Transversity, Sivers functions, and Collins functions

- First extraction of transversity, Sivers and Collins functions, simultaneously
- Data from SIDIS, DY, e+e- and pp (RHIC)

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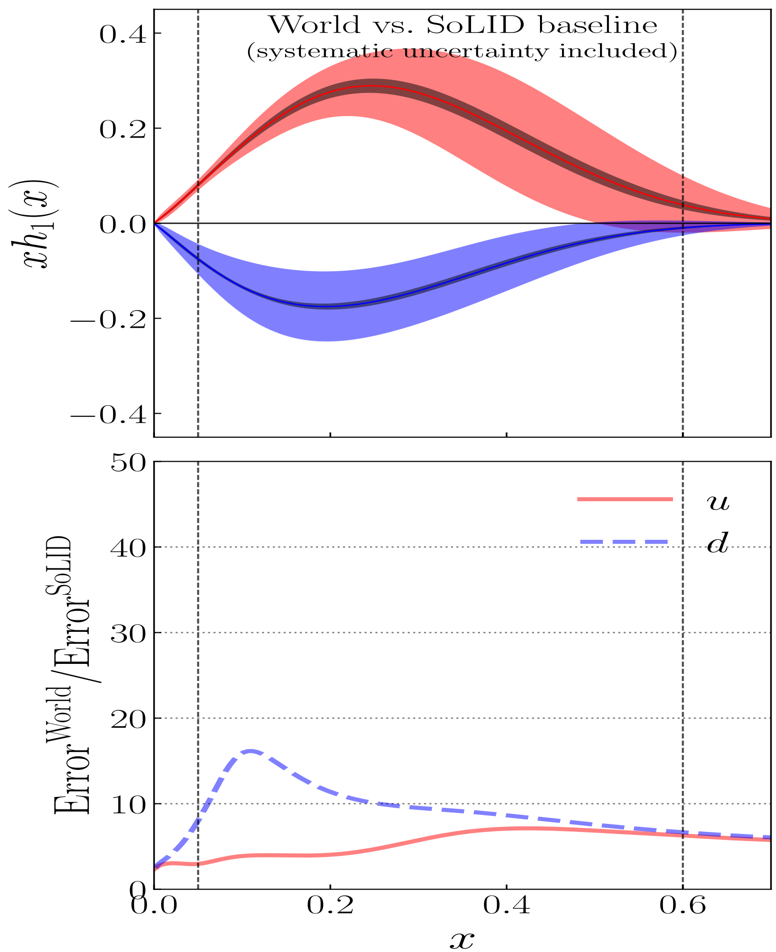
What can we learn from SoLID?

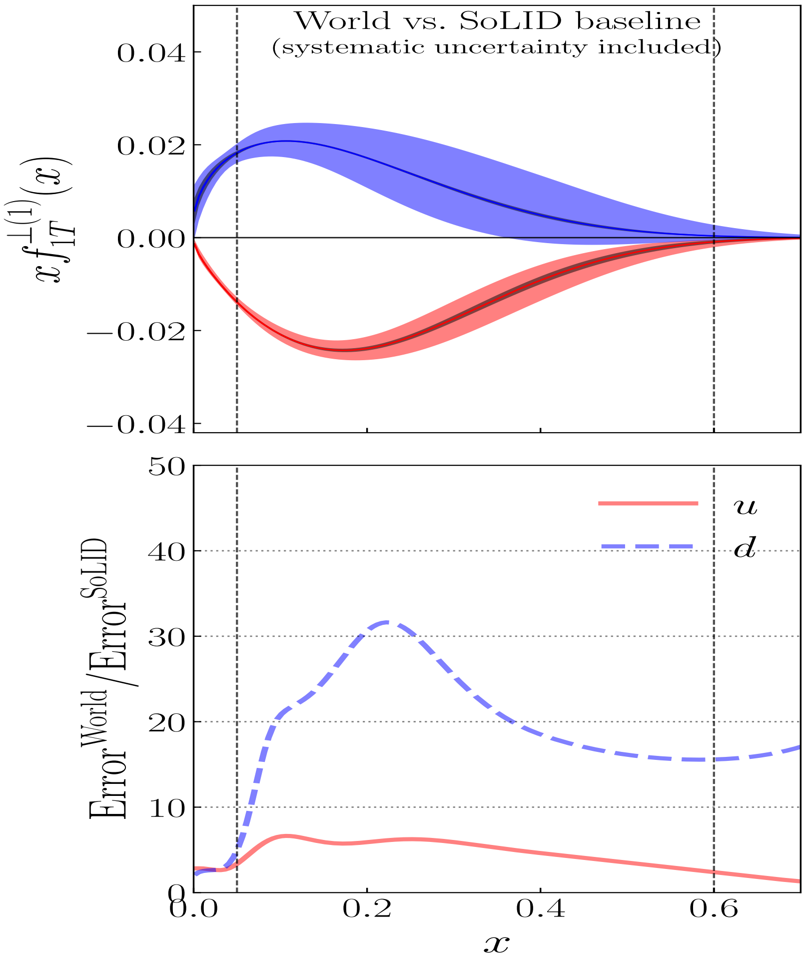
D'Alesio et al., Phys. Lett. B 803 (2020)135347
Anselmino et al., JHEP 04 (2017) 046

❑ Compare SoLID projection with world data:

Transversity



Sivers Functions



- Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation
- World data: HERMES, COMPASS, JLab6, BELLE, and BARBAR

More from Haiyan's talk

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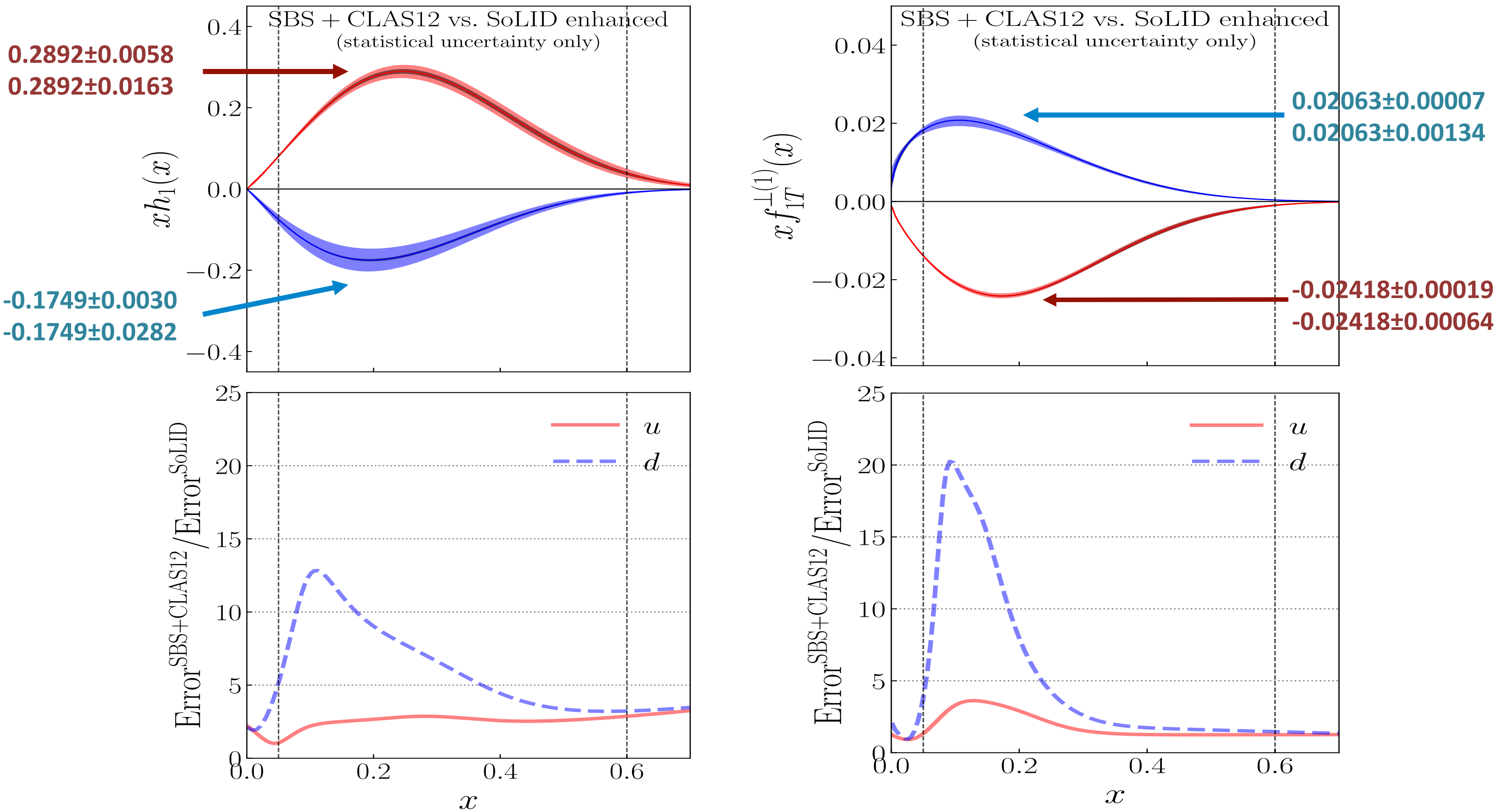
What can we learn from SoLID?

❑ SoLID vs JLab SBS + CLAS12:

D'Alesio et al., Phys. Lett. B 803 (2020)135347
Anselmino et al., JHEP 04 (2017) 046

Transversity | **Sivers Functions**



- See Haiyan's talk on comparison with CLAS12-^{3}He and EIC

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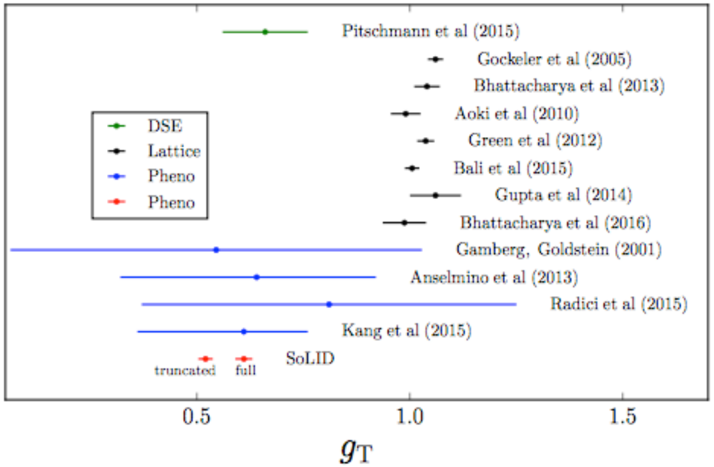
What can we learn from SoLID?

- **Tensor Charges:**

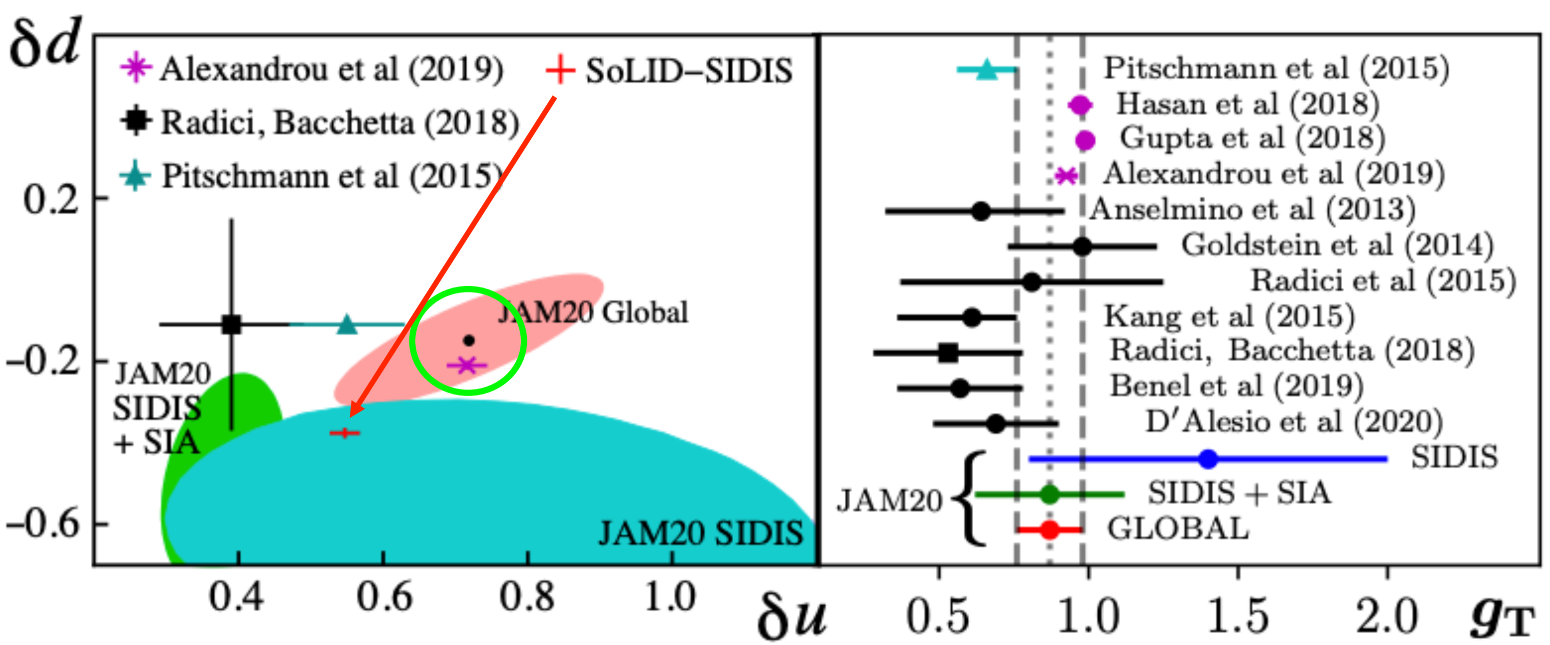
$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

Cammarota et al. Phys. Rev. D102 (2020) 054002

Lattice QCD calculated values consistently *differ* from those extracted from phenomenological fits?



- **Immediate impact of global fits:**



Global fitted results are now consistent with LQCD calculations!

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The JLab Director's Review Charge

- (**C1**) The significance of scientific questions identified by the SoLID Collaboration and Thomas Jefferson National Accelerator Facility;

- (**C2**) The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities, including whether the scientific reach of the proposed detector could be realized with modest upgrades to existing detectors at Thomas Jefferson National Accelerator Facility;

- (**C3**) The new experimental and theoretical research efforts and technical capabilities needed to accomplish the proposed scientific program; and,

- (**C4**) The feasibility of the approach or method presented to carry out the proposed scientific program and the likelihood that significant results can be obtained in the first three years of detector operations.

Summary

- SoLID addresses two of the three profound questions for the EIC,
  the origin of the nucleon mass and spin,
  from the phase space that cannot be covered by the EIC
- SoLID's science program on the TMDs and 3D structure is unique, due to its large acceptance and luminosity, and can not be achieved by existing facilities, even with modest upgrades
- QCD factorization to match TMDs to SIDIS and other classical two-scale observables are well-established – allow QCD global analyses
- Parton shower in SIDIS dilutes the information on the hadron structure, and mix the collision effect with structure information
- SoLID is more sensitive to the nonperturbative 3D hadron structure, complementary to what the EIC can and cannot do

Thank you!