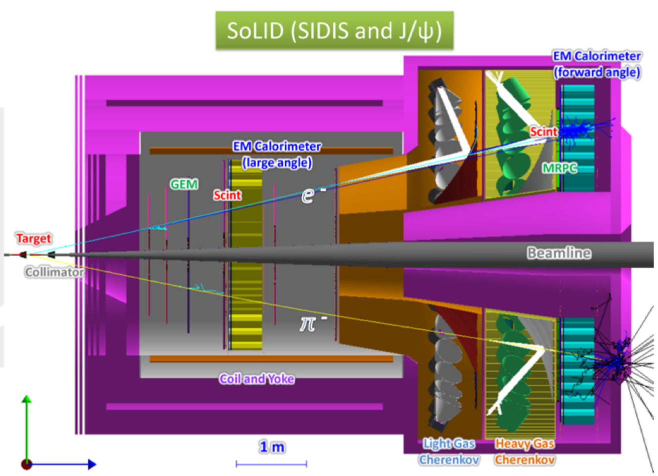
SoLID (Solenoidal Large Intensity Device)

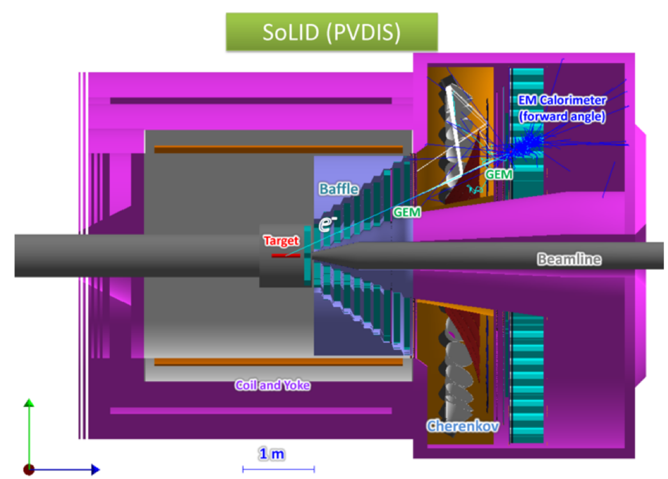
Collaboration meeting, October 8-9, 2020

Semi-Inclusive Deep Inelastic Scattering Theory

Jianwei Qiu

Theory Center, Jefferson Lab





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TMD Collaboration

U.S. DEPARTMENT OF ENERGY | Office of Science

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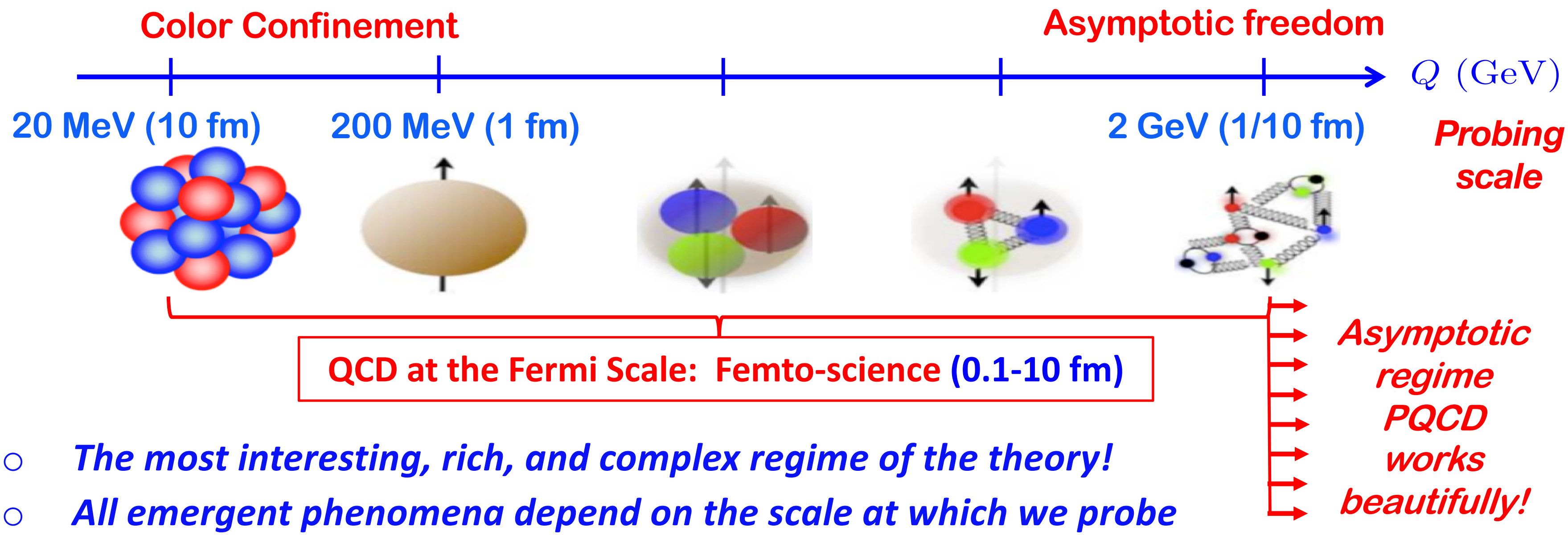
QCD at a Fermi Scale

❑ QCD – Color Confinement:

- *Do not see any quarks and gluons in isolation*
- *The structure of nucleons and nuclei – emergent properties of QCD*



- *The most interesting, rich, and complex regime of the theory!*
- *All emergent phenomena depend on the scale at which we probe them!*

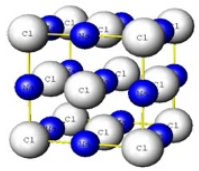
❑ QCD – Asymptotic Freedom:

- *Force becomes weaker at a shorter-distance – Controllable "Probes"*
- *Explore the structure of nucleons and nuclei indirectly by using "local", "sharp", and "controllable" probes, …*

How to "see" the structure of nucleon and nuclei

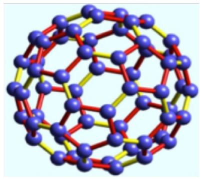
- **Structure – "a still picture":**

Crystal Structure:



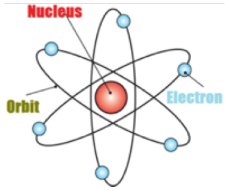
NaCl, B1 type structure

Nano-material:



Fullerene, C60

Atomic structure



Quantum orbits

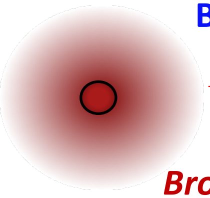
Motion of nuclei is so much slower than the speed of light, neutral photon!

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

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

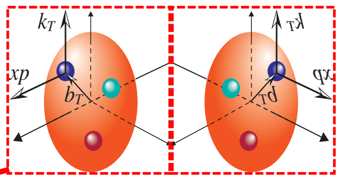
  Partonic structure = "Quantum Probabilities": $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^\mu)|P,S\rangle$

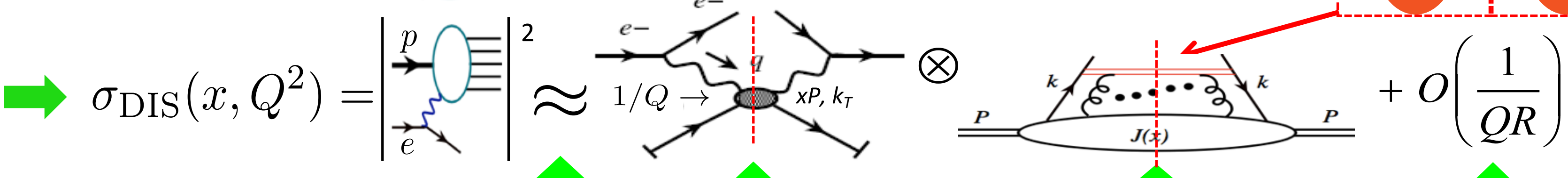
B-meson



Brown-Muck

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





Factorization

Hard-part Probe

Parton-distribution Structure

Power corrections Approximation

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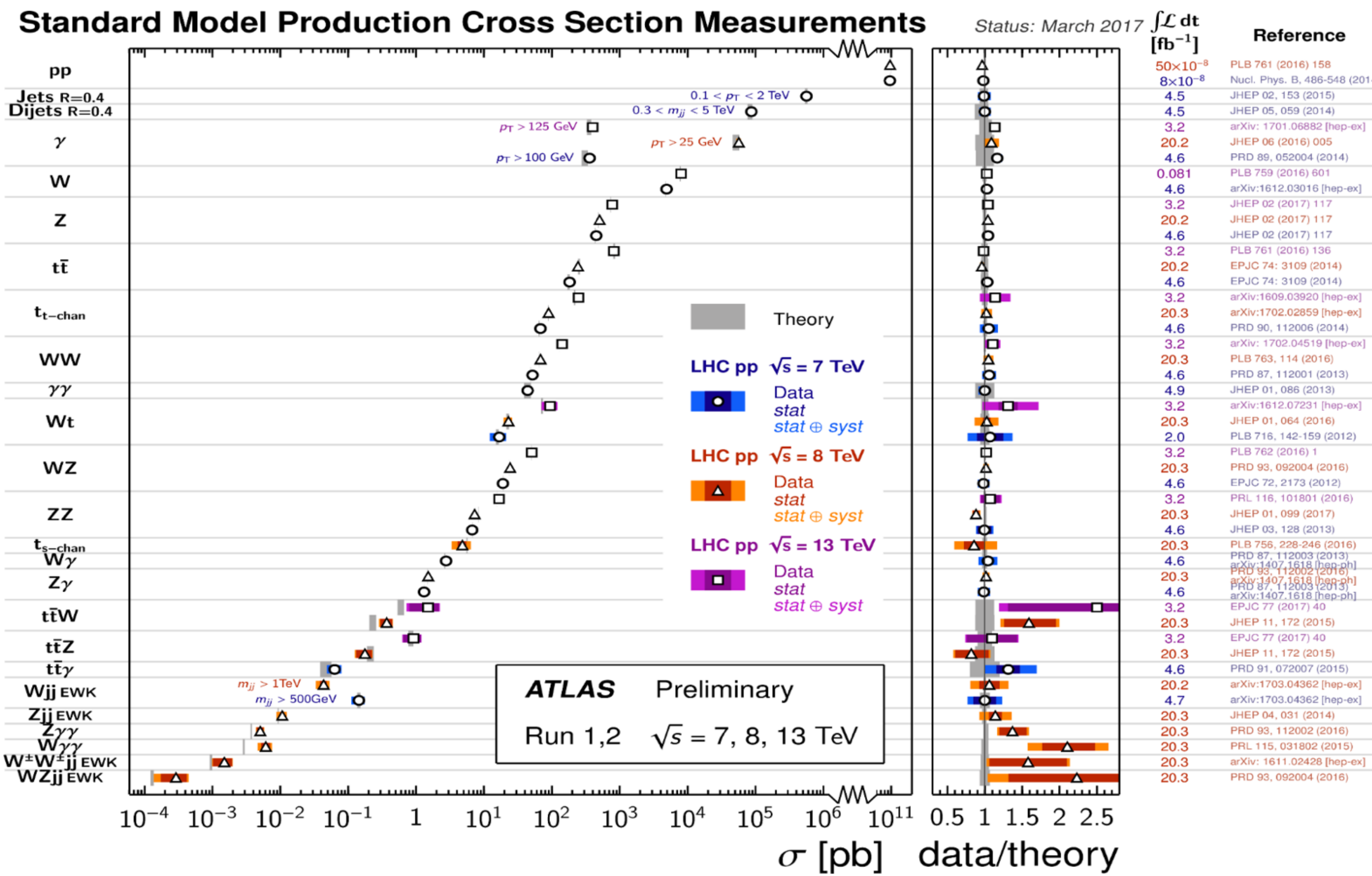
QCD factorization works to the precision



SM: Electroweak processes + QCD perturbation theory + PDFs works!

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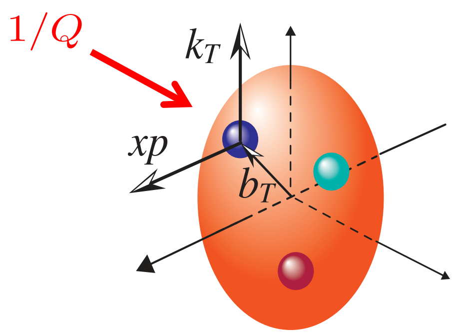
How to "see" 3D partonic structure of hadrons?

❑ Single scale hard probe is too "localized":



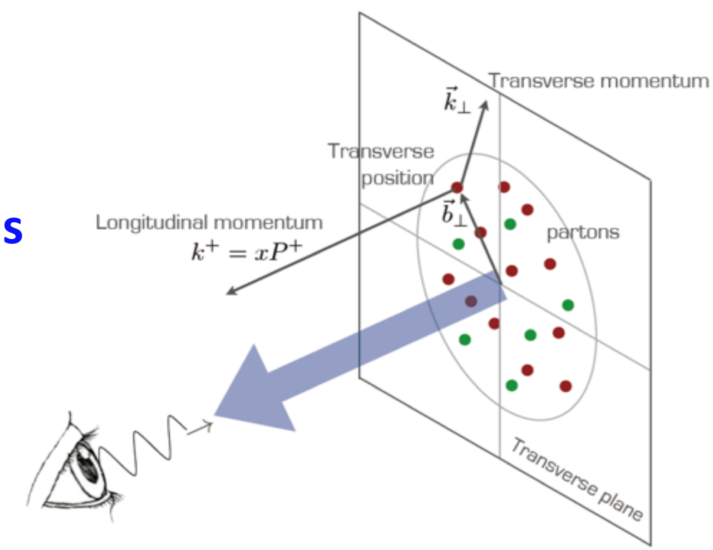
- It pins down the particle nature of quarks and gluons
- But, not very sensitive to the detailed structure of hadron ~ fm
- Transverse confined motion: $k_T \sim 1/\text{fm} \ll Q$
- Transverse spatial position: $b_T \sim \text{fm} \gg 1/Q$

❑ Need new type of "Hard Probes" – Physical observables with TWO Scales:

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

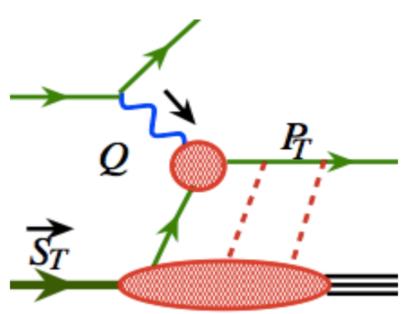
Hard scale: Q_1 To localize the probe
particle nature of quarks/gluons

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



SIDIS: $Q \gg P_T$

Break the hadron



TMDs – Confined motion

$$f(x) \Rightarrow f(x, k_T)$$

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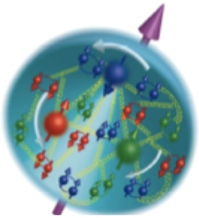
What do we learn from the 3D partonic structure?

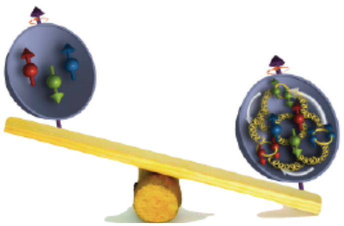
- ❑ **Nucleon Mass – dominates the Mass of visible world!**



Nucleon – a relativistic bound state of quarks and gluons

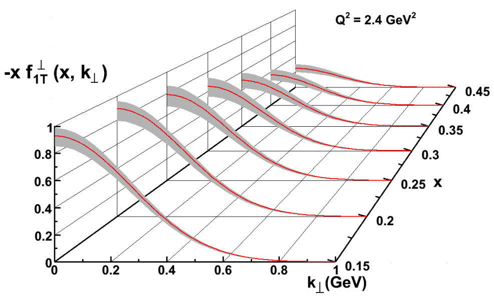
Mass is the Energy of the nucleon when it is at the Rest!

Mass = Rest Mass of quarks and gluons + Their Energy



Higgs mechanism is not far from enough!!!

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

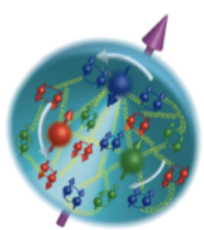


Transverse Motion of quarks and gluons inside a nucleon

$$f(x, k_T)$$ – the TMDs

Gives much needed information on the Confined Motion!

- ❑ **Nucleon Spin – without it, our world would not be the same!**



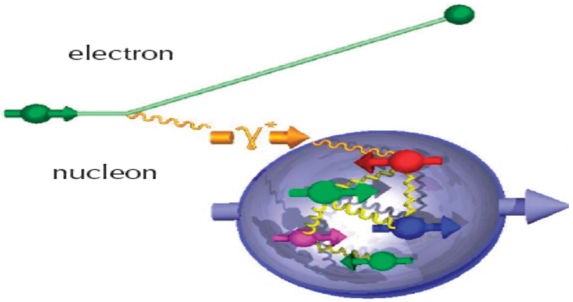
Spin is the Angular Momentum of the nucleon when it is at the Rest!

Spin = Spin of quarks and gluons + Orbital Angular Momentum

Helicity = Helicity of quarks and gluons
+ Their transverse motion

Lepton-hadron Deep Inelastic Scattring (DIS)

- The lepton-hadron scattering experiments:



- ✧ A controlled "probe" – virtual photon
- ✧ Can either break or not break the hadron

One facility covers all!

✧ Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

(Modern Rutherford experiment!)

✧ Semi-Inclusive events: e+p/A → e'+h(p,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

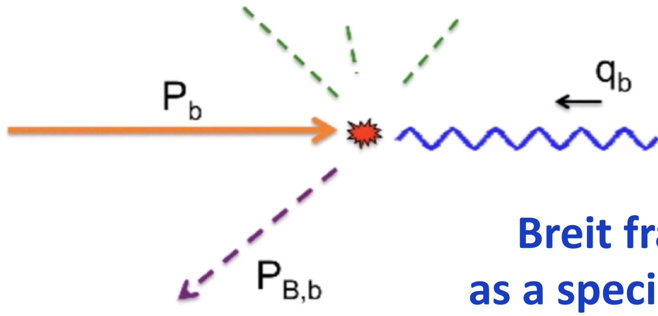
✧ Exclusive events: e+p/A → e'+ p'/A'+ h(p,K,p,jet)

Detect every things including scattered proton/nucleus (or its fragments)

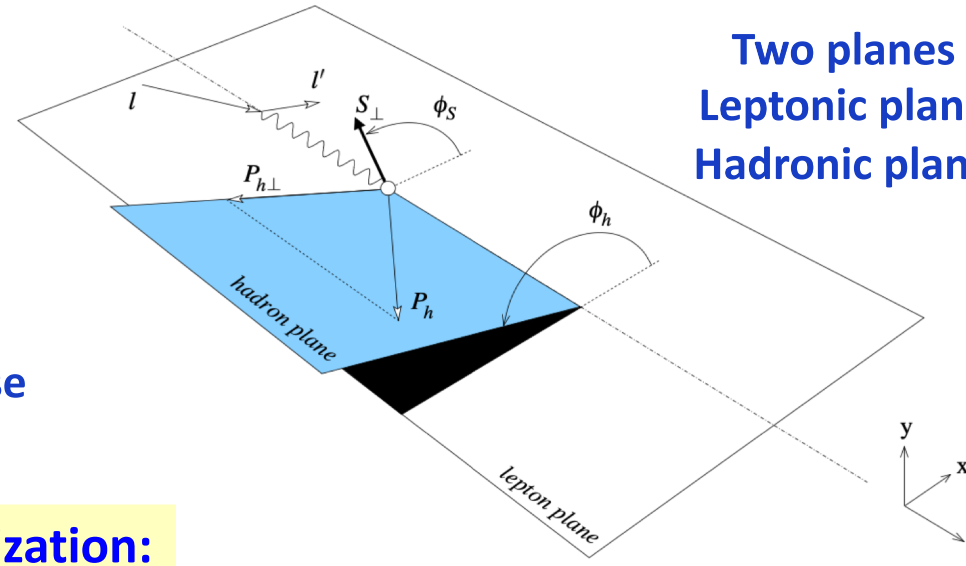
(Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)

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:**

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

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

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

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

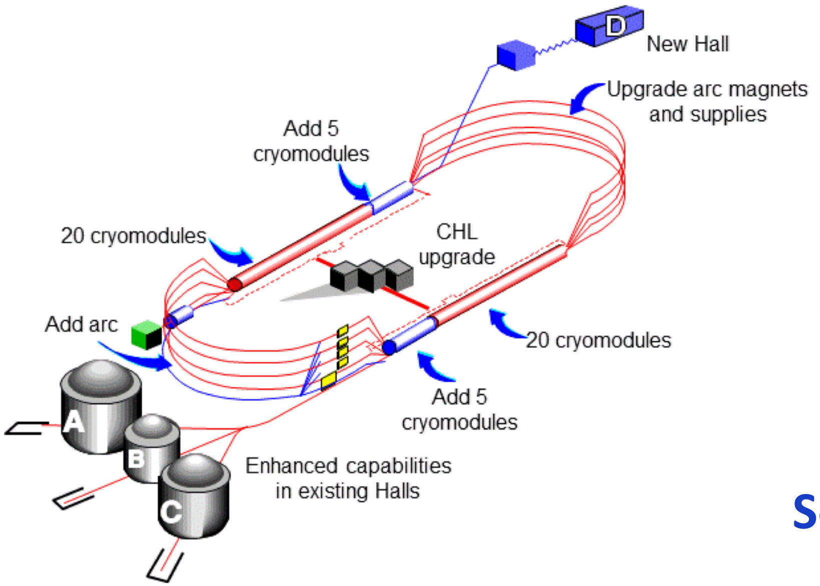
$$\sigma_{\mathrm{SIDIS}}(Q, x_B, z_h) = \tilde{H}(Q, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{Q}\right)$$

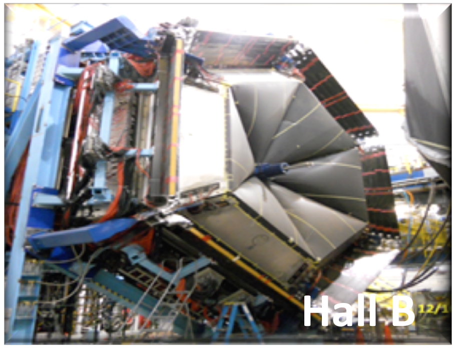
  - ✧ **Very high P_{hT} >> Q – Collinear factorization:**

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

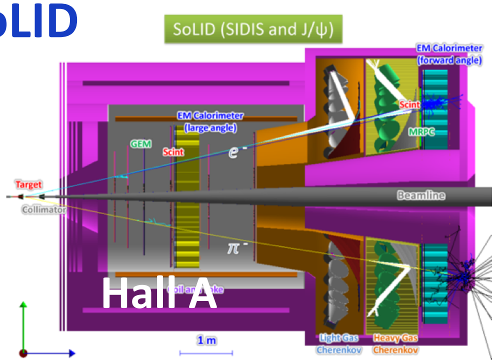
Jefferson Lab @ 12 GeV

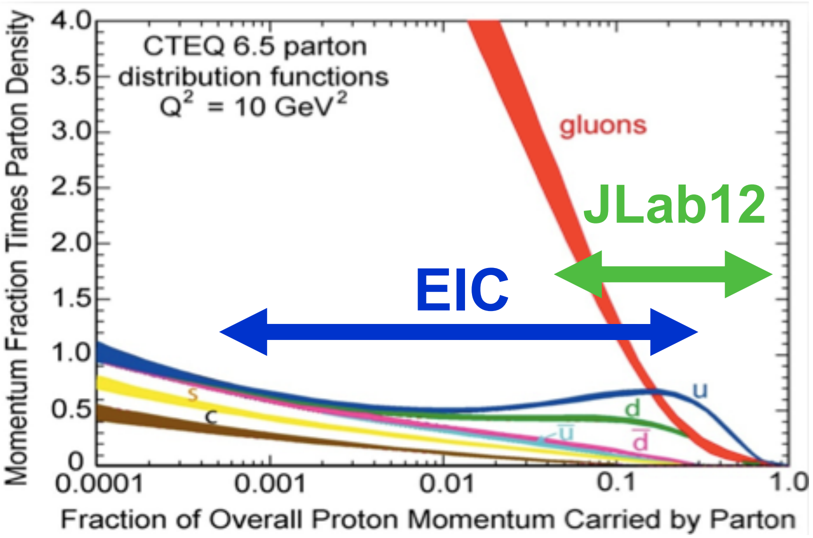
❑ CEBAF – Lepton-hadron facility:





SoLID





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U.S. based Electron-Ion Collider

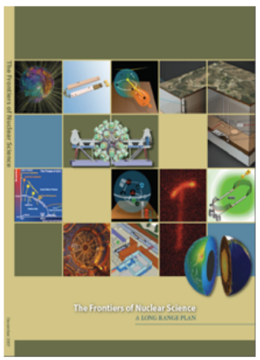
- **On January 9, 2020:**

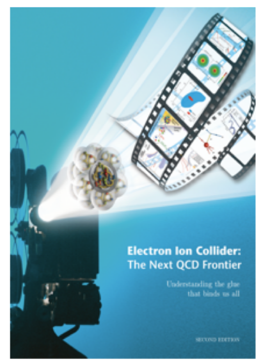
  The U.S. DOE announced the selection of BNL as the site for the Electron-Ion Collider

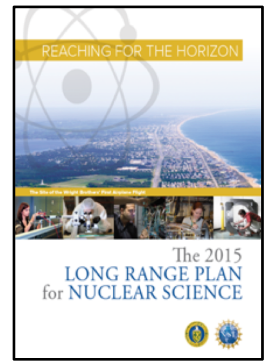
  → *A new era to explore the emergent phenomena of QCD!*

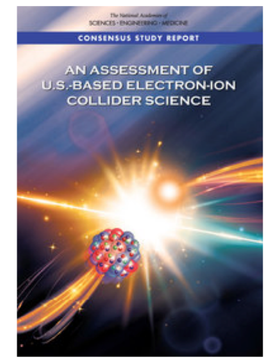
- **A long journey – a joint effort of the full community:**

…









…

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

… three profound questions:

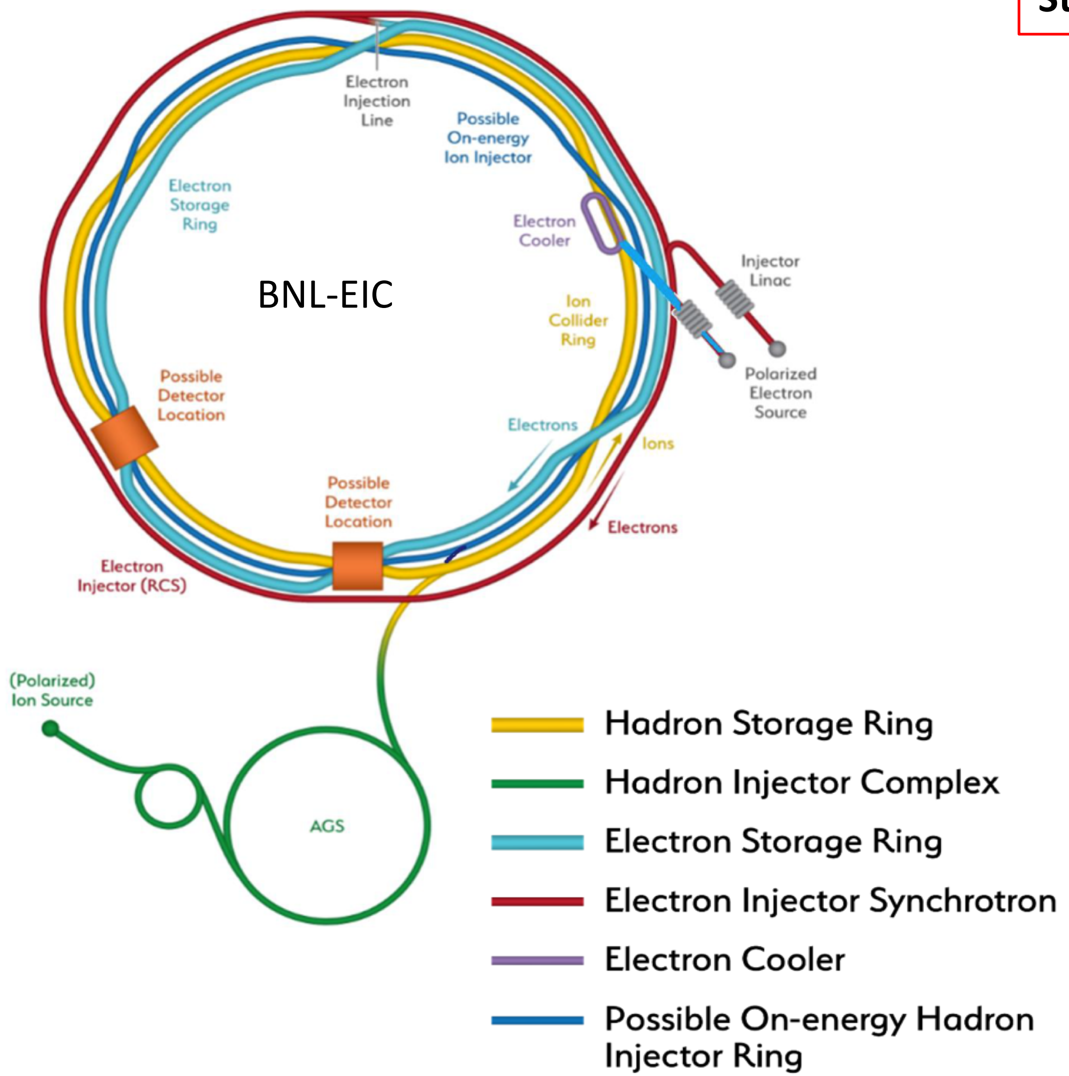
How does the mass of the nucleon arise?

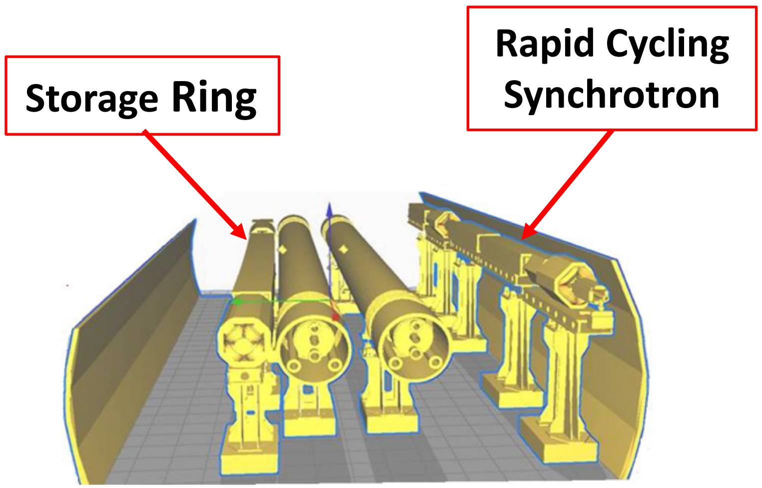
How does the spin of the nucleon arise?

What are the emergent properties of dense systems of gluons?

U.S. based Electron-Ion Collider

❑ The winning design - BNL:

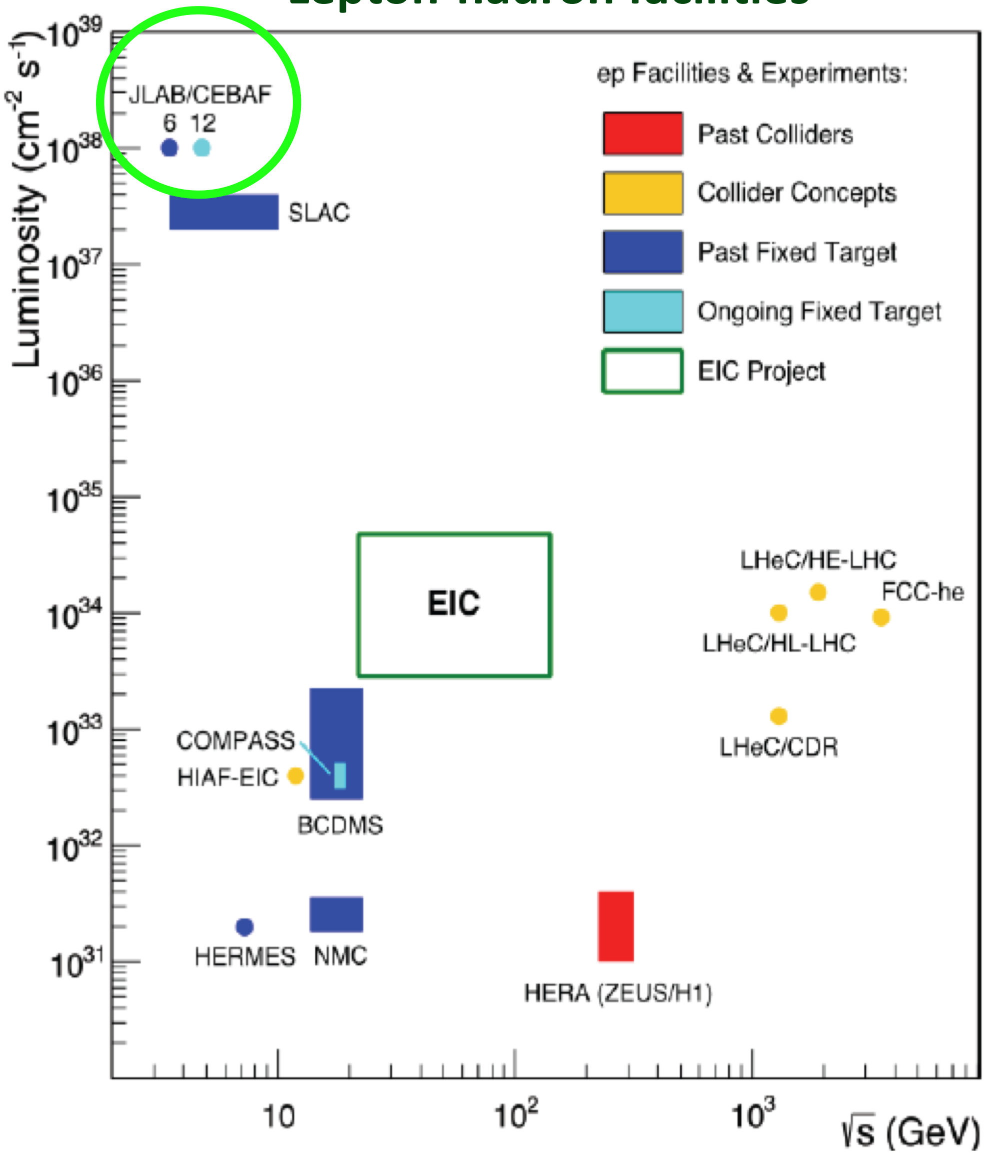


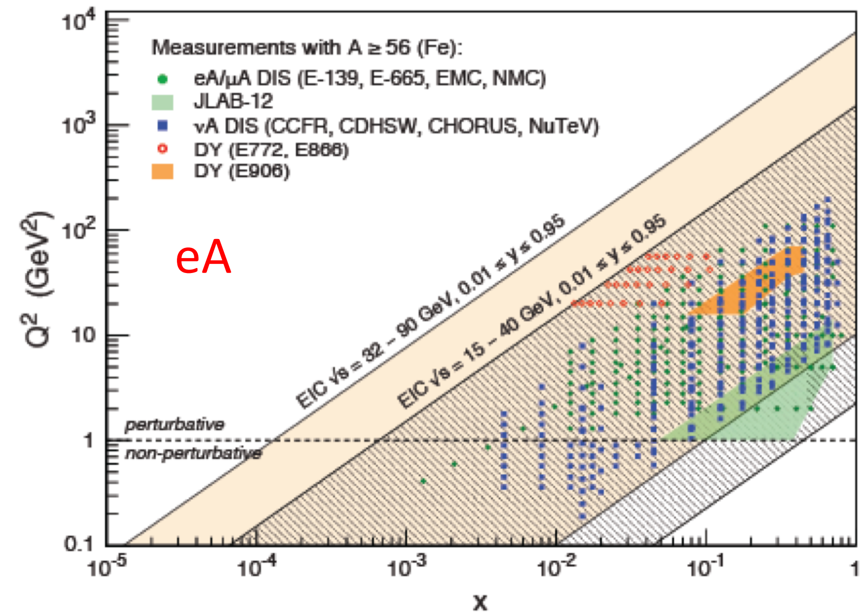


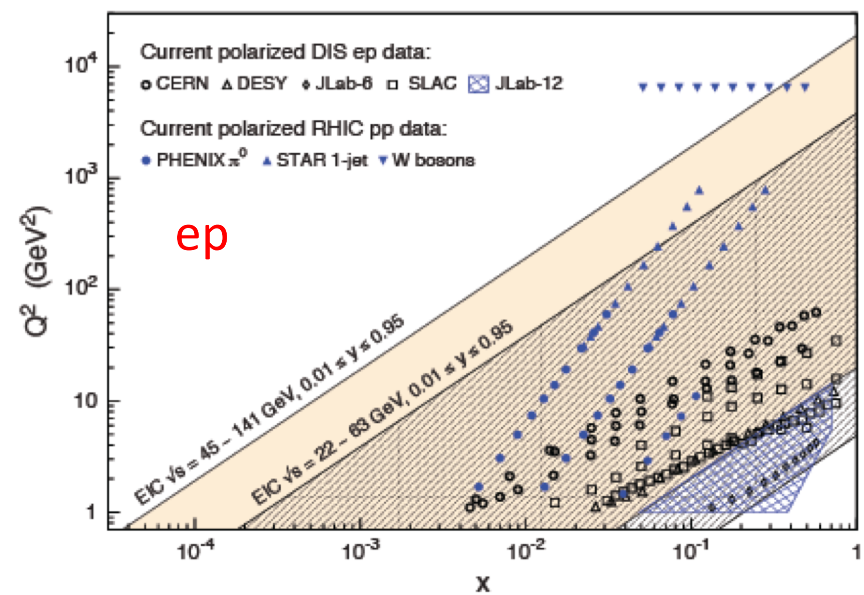
- **Center of Mass Energies:**
  20 GeV – 141 GeV
- **Required Luminosity:**
  10^{33} - 10^{34} $cm^{-2}s^{-1}$
- **Hadron Beam Polarization:**
  80%
- **Electron Beam Polarization:**
  80%
- **Ion Species Range:**
  p to Uranium
- **Number of interaction regions:**
  up to two

Luminosity and kinematic coverage

Lepton-hadron facilities





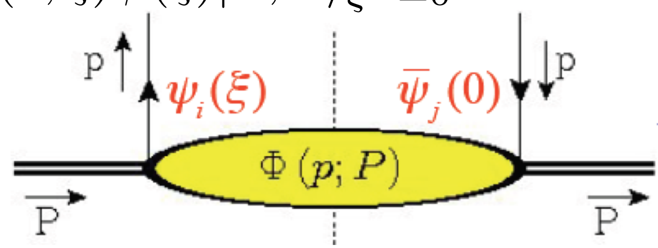


Transverse momentum dependent PDFs (TMDs)

❑ Non-perturbative definition:

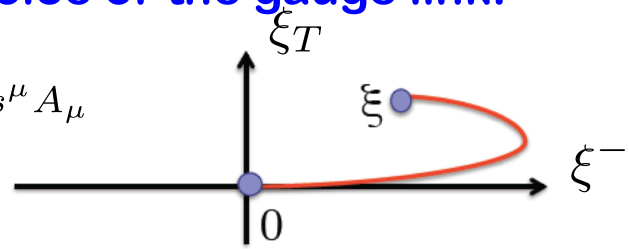
✧ **In terms of matrix elements of parton correlators:**

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



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

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



✧ **Decomposes into a list of TMDs:**

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

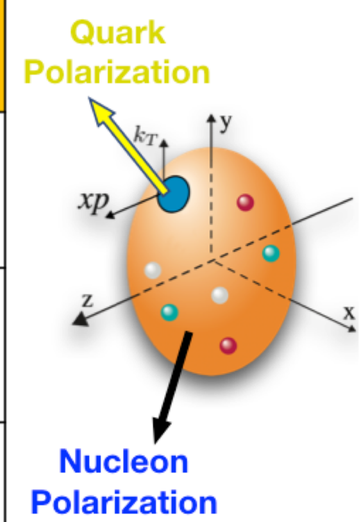
✧ **IF we knew proton wave function, this definition gives "unique" TMDs!**

But, we do NOT know proton wave function!

Transverse momentum dependent PDFs (TMDs)

❑ Quark TMDs with polarization:

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	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*

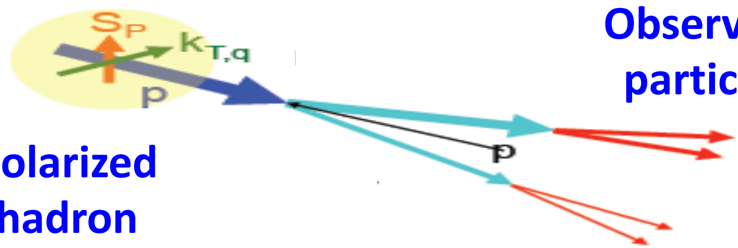


Analogous tables for:

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

What can we learn from TMDs?

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



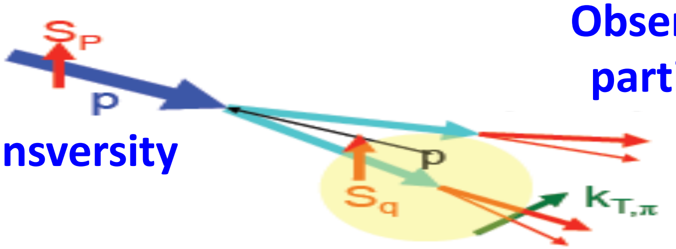
Observed particle

Polarized hadron

Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

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



Observed particle

Transversity

Collins effect – Collins function

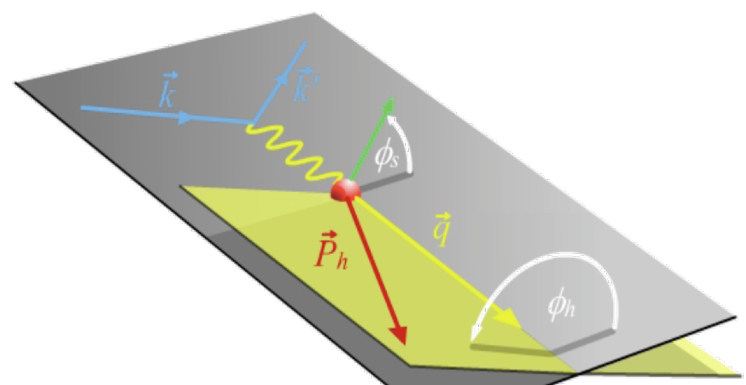
Parton's transverse polarization influences its hadronization

- **SIDIS is ideal for probing TMDs:**

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

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

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

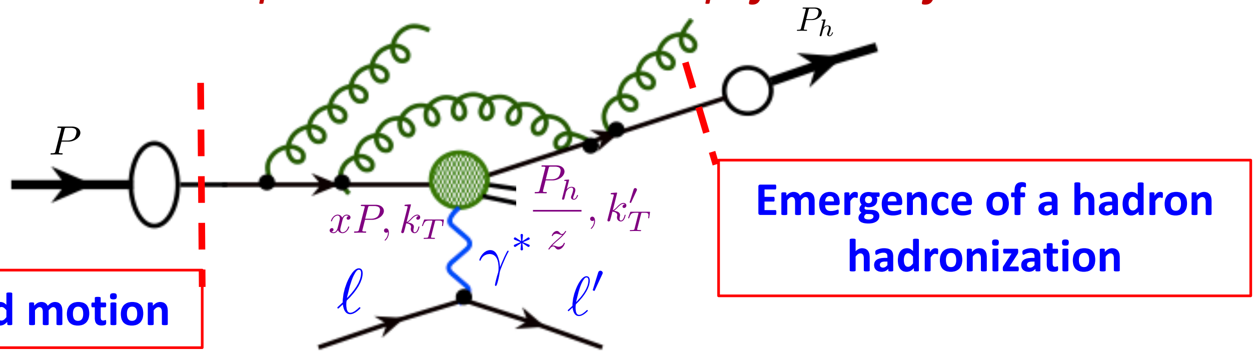


TMD factorization

- **Structure vs collision effect:**

  Gluon shower – liberation of confined states

  – measured k_T is NOT the same as k_T of the confined motion!



- **Q^2 evolution and non-perturbative structure information:**

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

$$k_T \sim b_T^{-1} \gg \Lambda_{\text{QCD}} \quad f_q(x, \vec{k}_T, \mu, \zeta) = \sum_i \int \frac{dy}{y} C_{qi}\left(\frac{x}{y}, \vec{k}_T, \mu, \zeta\right) f_i(x, \mu)$$

PDF

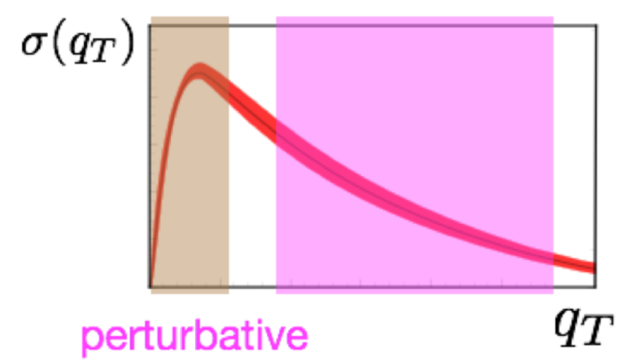
$$k_T \sim b_T^{-1} \sim \Lambda_{\text{QCD}} \quad f_q(x, \vec{k}_T)$$

nonperturbative

$$\mu \frac{d}{d\mu} \ln f_q(x, \vec{b}_T, \mu, \zeta) = \gamma_\mu^q(\mu, \zeta)$$

$$\zeta \frac{d}{d\zeta} \ln f_q(x, \vec{b}_T, \mu, \zeta) = \gamma_\zeta^q(\mu, b_T)$$

Collins-Soper Equation



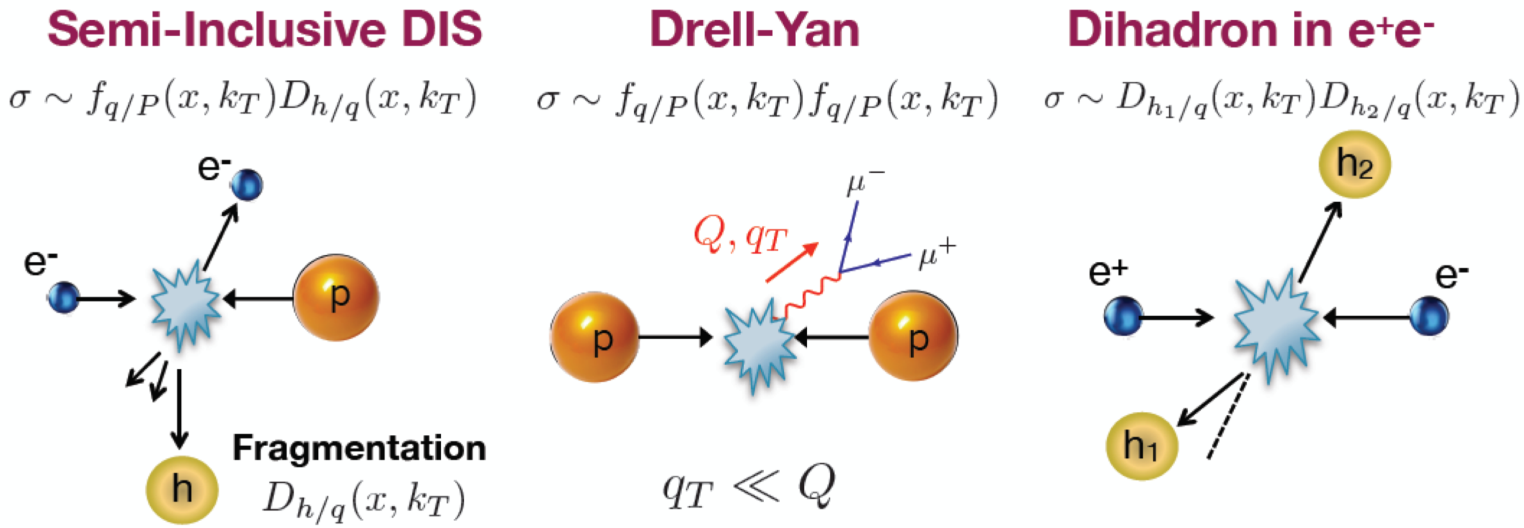
Shower dilutes the structure information!

Extract TMDs from QCD global analyses

- 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 QCD global analyses of TMDs

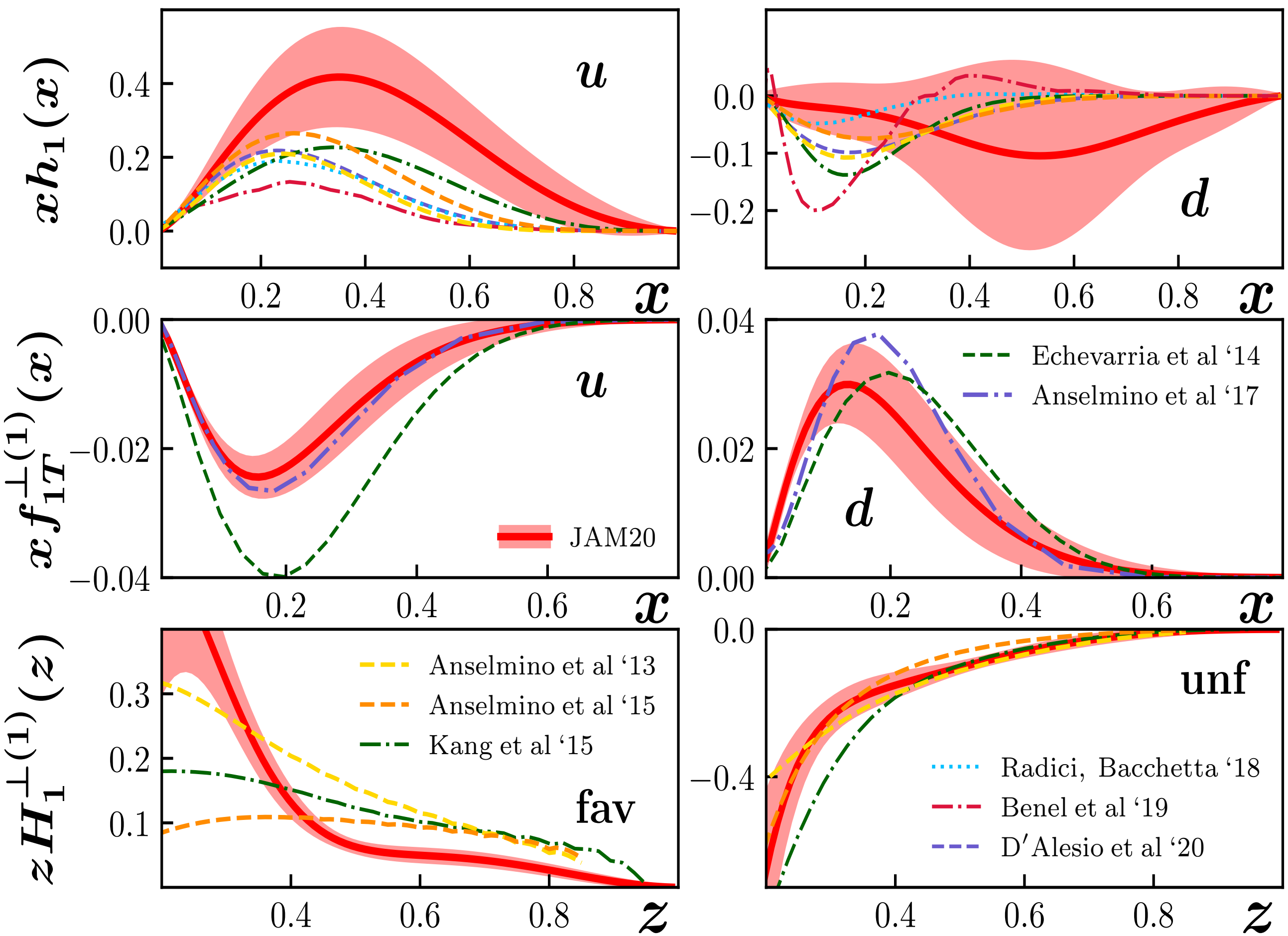
Cammarota et al., arXiv:2002.08384

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

Extract TMDs from QCD global analyses

❑ JAM – Global fit of TMD PDFs (or TMDs):

Cammarota et al., arXiv:2002.08384



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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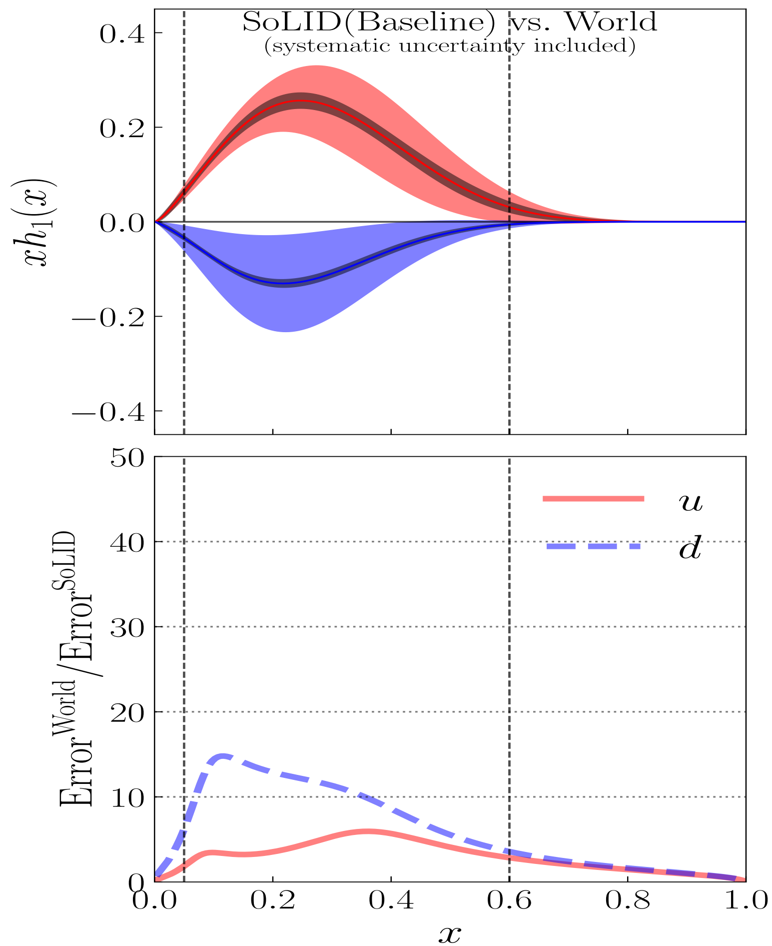
What can we learn from SoLID?

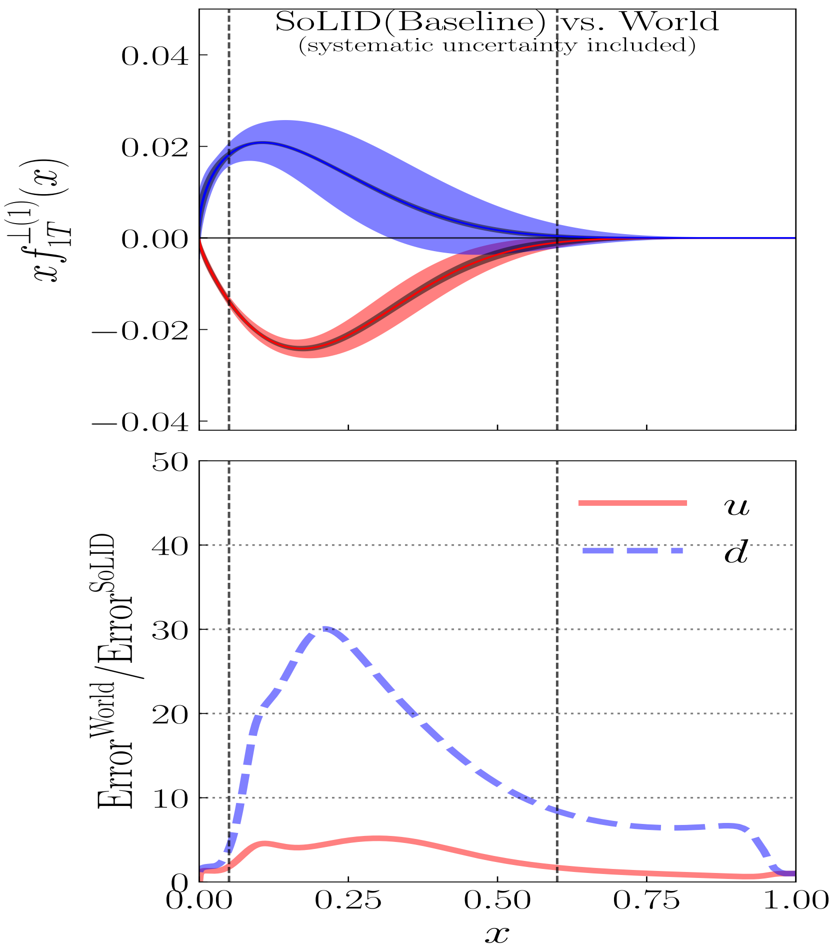
❑ Compare SoLID projection with world data:

Z. Ye *et al*, Phys. Lett. B 767, 91 (2017)

Transversity



Sivers Functions



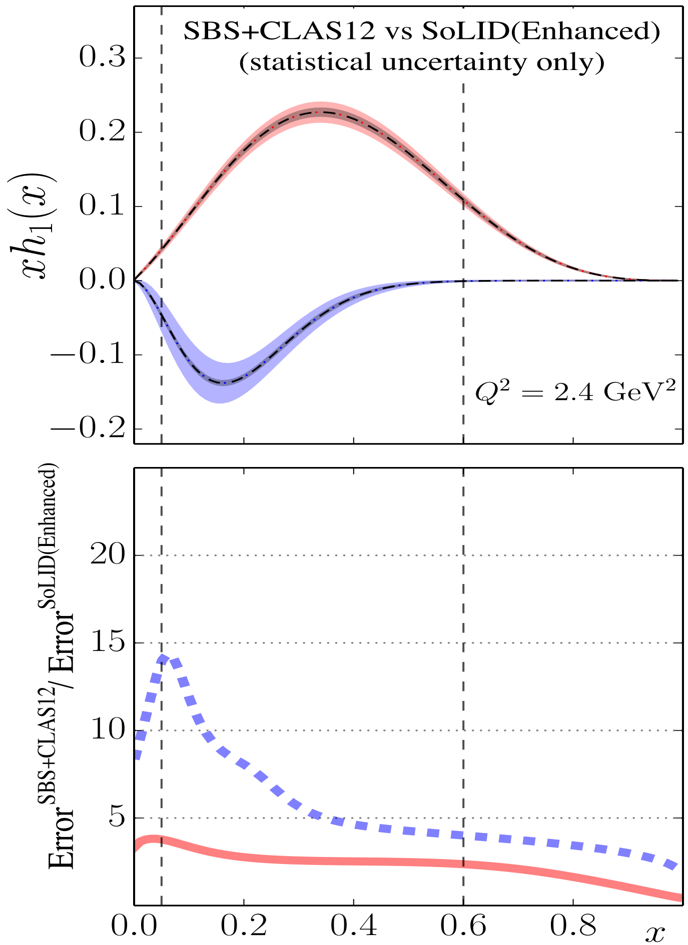
- Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation
- World data: HERMES, COMPASS, JLab6, BELLE, and BARBAR

What can we learn from SoLID?

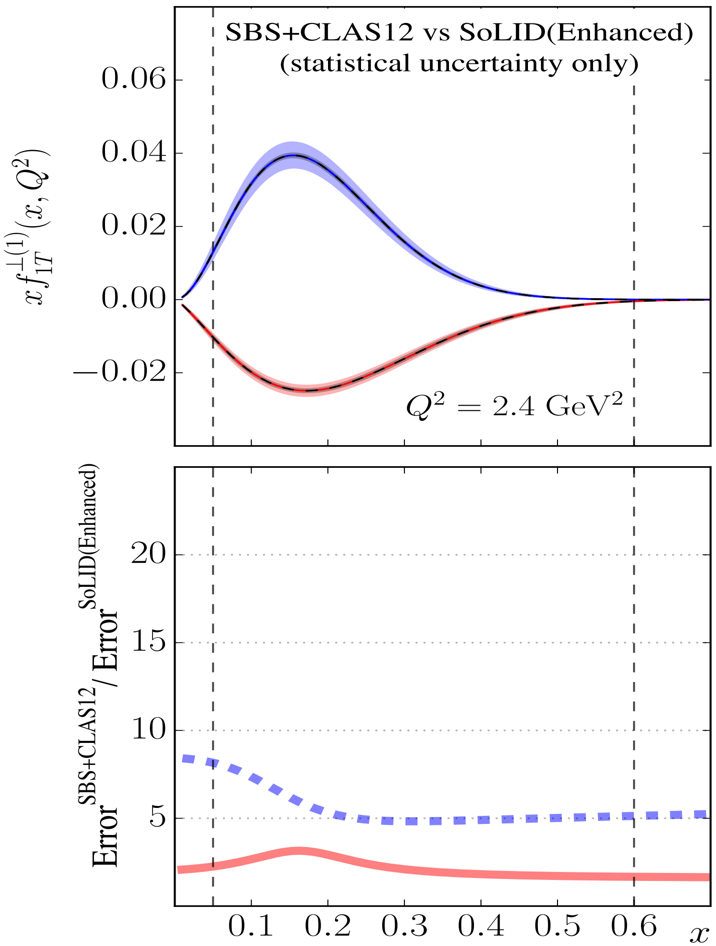
Z. Ye *et al*, Phys. Lett. B 767, 91 (2017)

❑ SoLID vs JLab SBS + CLAS12:

Transversity



Sivers Functions



- Needs to investigat the potential impact from a polarized ^{3}He target in CLAS12
- See Haiyan's talk on comparison with EIC

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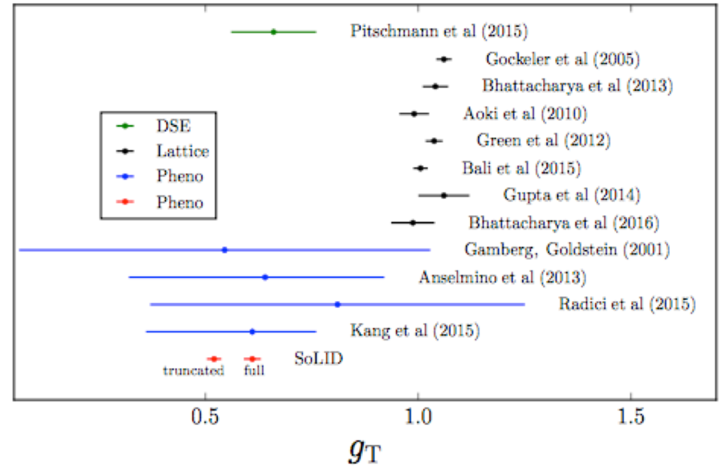
What can we learn from SoLID?

- ❑ **JAM – Tensor Charges:**

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

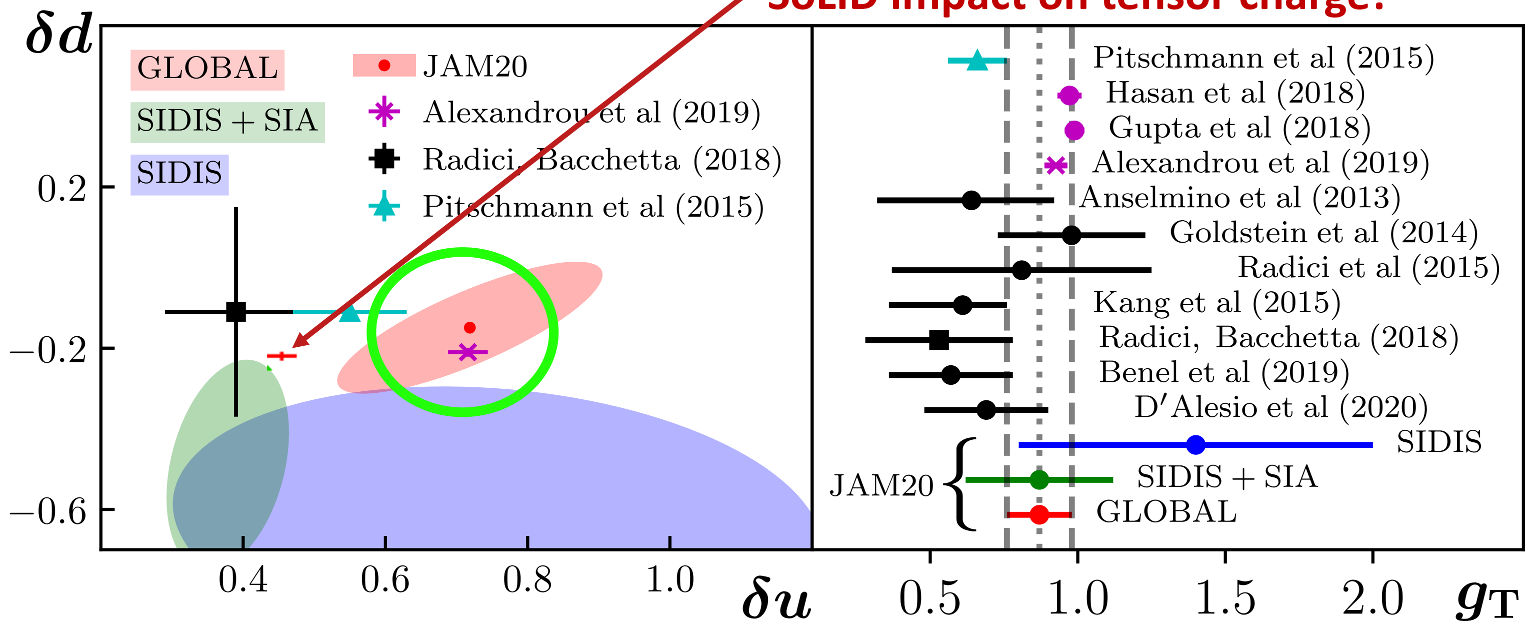
Cammarota et al. arXiv:2002.08384

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



- ❑ **Immediate impact of global fits:**

SoLID impact on tensor charge!



Global fitted results are now consistent with LQCD calculations!

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Summary

- TMDs, like PDFs, are NOT direct physical observables, but they are universal and give the fundamental information on the 3D motion of combined quarks and gluons
- 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
- High luminosity and good coverage will make SoLID an advantageous detector for extracting TMDs and confined motion, as well as correlation between hadron spin and parton motion, the rich emergent phenomena of QCD, complementary to EIC

Thank you!

Backup slides

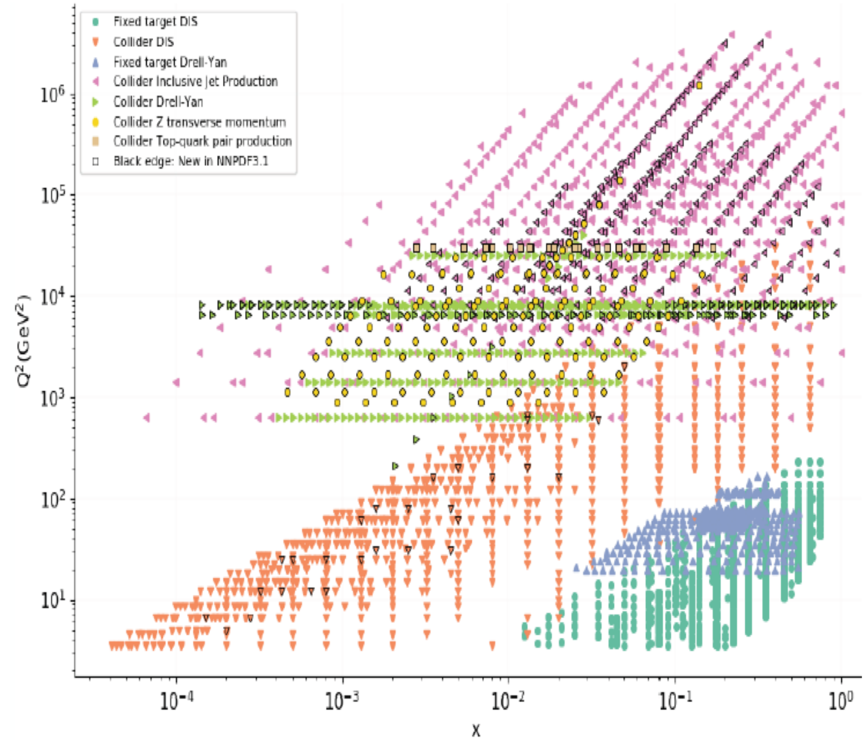
QCD factorization works to the precision

❑ Data sets for Global Fits:

	Process	Subprocess	Partons	x range
Fixed Target	$\ell^\pm\{p,n\} \to \ell^\pm + X$	$\gamma^* q \to q$	$q,\bar{q},g$	$x \gtrsim 0.01$
	$\ell^\pm n/p \to \ell^\pm + X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$pp \to \mu^+\mu^- + X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- + X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$\nu(\bar{\nu})N \to \mu^-(\mu^+) + X$	$W^* q \to q'$	$q,\bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^-\mu^+ + X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu} N \to \mu^+\mu^- + X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
Collider DIS	$e^\pm p \to e^\pm + X$	$\gamma^* q \to q$	$g,q,\bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} + X$	$W^+\{d,s\} \to \{u,c\}$	d,s	$x \gtrsim 0.01$
	$e^\pm p \to e^\pm c\bar{c} + X$	$\gamma^* c \to c, \gamma^* g \to c\bar{c}$	c, g	$10^{-4} \lesssim x \lesssim 0.01$
	$e^\pm p \to e^\pm b\bar{b} + X$	$\gamma^* b \to b, \gamma^* g \to b\bar{b}$	b, g	$10^{-4} \lesssim x \lesssim 0.01$
	$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
Tevatron	$p\bar{p} \to \text{jet} + X$	$gg, qg, q\bar{q} \to 2j$	g,q	$0.01 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm\nu) + X$	$ud \to W^+, \bar{u}\bar{d} \to W^-$	$u,d,\bar{u},\bar{d}$	$x \gtrsim 0.05$
	$p\bar{p} \to (Z \to \ell^+\ell^-) + X$	$uu, dd \to Z$	u,d	$x \gtrsim 0.05$
	$p\bar{p} \to t\bar{t} + X$	$qq \to t\bar{t}$	q	$x \gtrsim 0.1$
LHC	$pp \to \text{jet} + X$	$gg, qg, q\bar{q} \to 2j$	g,q	$0.001 \lesssim x \lesssim 0.5$
	$pp \to (W^\pm \to \ell^\pm\nu) + X$	$u\bar{d} \to W^+, d\bar{u} \to W^-$	$u,d,\bar{u},\bar{d},g$	$x \gtrsim 10^{-3}$
	$pp \to (Z \to \ell^+\ell^-) + X$	$q\bar{q} \to Z$	$q,\bar{q},g$	$x \gtrsim 10^{-3}$
	$pp \to (Z \to \ell^+\ell^-) + X, p_\perp$	$gq(\bar{q}) \to Zq(\bar{q})$	$g,q,\bar{q}$	$x \gtrsim 0.01$
	$pp \to (\gamma^* \to \ell^+\ell^-) + X$, Low mass	$q\bar{q} \to \gamma^*$	$q,\bar{q},g$	$x \gtrsim 10^{-4}$
	$pp \to (\gamma^* \to \ell^+\ell^-) + X$, High mass	$q\bar{q} \to \gamma^*$	$\bar{q}$	$x \gtrsim 0.1$
	$pp \to W^+\bar{c}, W^-c$	$sg \to W^+c, \bar{s}g \to W^-\bar{c}$	$s,\bar{s}$	$x \sim 0.01$
	$pp \to t\bar{t} + X$	$gg \to t\bar{t}$	g	$x \gtrsim 0.01$
	$pp \to D, B + X$	$gg \to c\bar{c}, b\bar{b}$	g	$x \gtrsim 10^{-6}, 10^{-5}$
	$pp \to J/\psi, \Upsilon + pp$	$\gamma^*(gg) \to c\bar{c}, b\bar{b}$	g	$x \gtrsim 10^{-6}, 10^{-5}$
	$pp \to \gamma + X$	$gq(\bar{q}) \to \gamma q(\bar{q})$	g	$x \gtrsim 0.005$

❑ Kinematic Coverage:

NNPDF3.1



❑ Fit Quality:

$\chi^2/\text{dof} \sim 1 \;\Rightarrow$ Non-trivial check of QCD

All data sets	3706 / 2763	3267 / 2996	2717 / 2663
	LO	NLO	NNLO

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