The Institute for Particle Physics Phenomenology

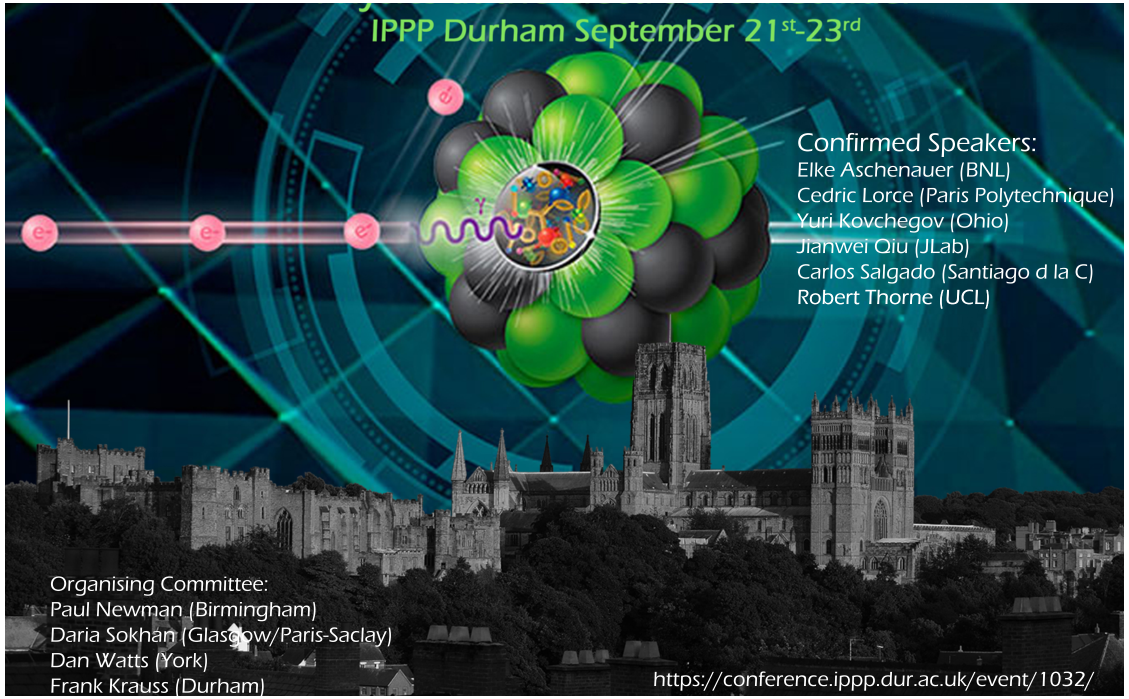
UK National Institute for Particle Physics Phenomenology

Nuclear Theory for Electron-Ion Collider

- Nuclear Theory
  = QCD + its Effective Theories
- Factorization
  = Controllable approximation
- Two-scale observables (Q_1 >> Q_2 ~ 1/fm)
  = Localized probe + sensitive to structure
- Wave nature of quarks and gluons
  = Hard probe at small-x is not localized

Jian-Wei Qiu

Jefferson Lab, Theory Center



Jefferson Lab

TMD Collaboration

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

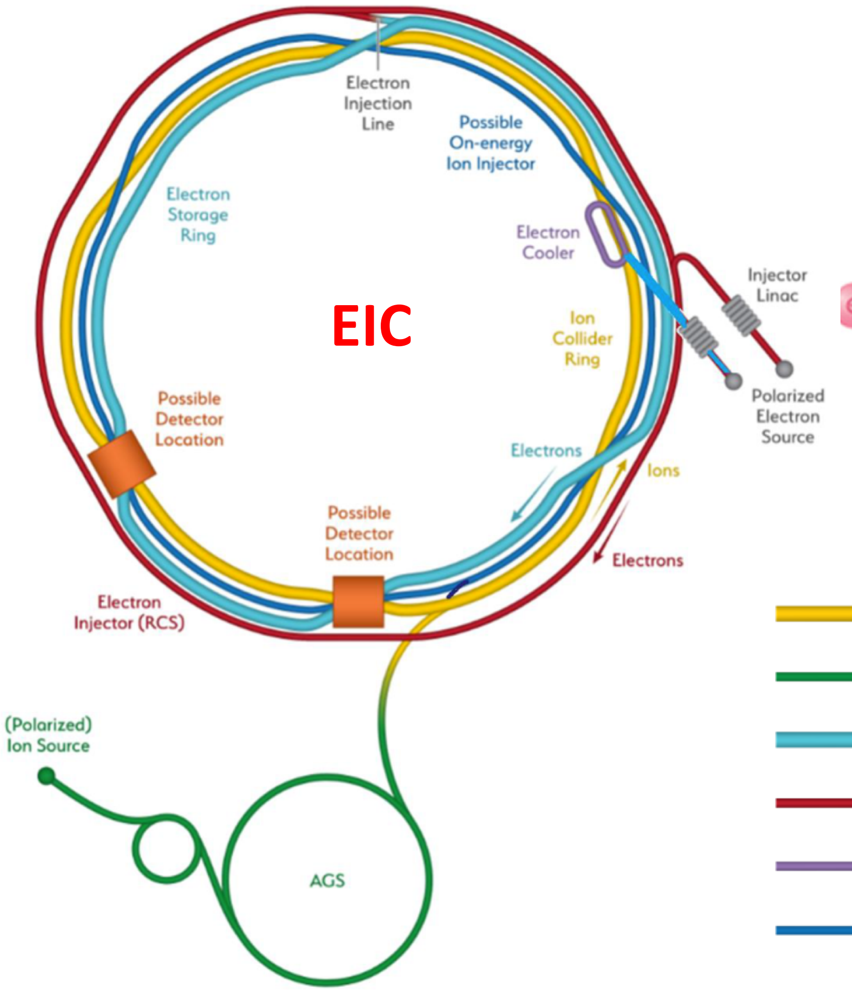
U.S. - based Electron-Ion Collider

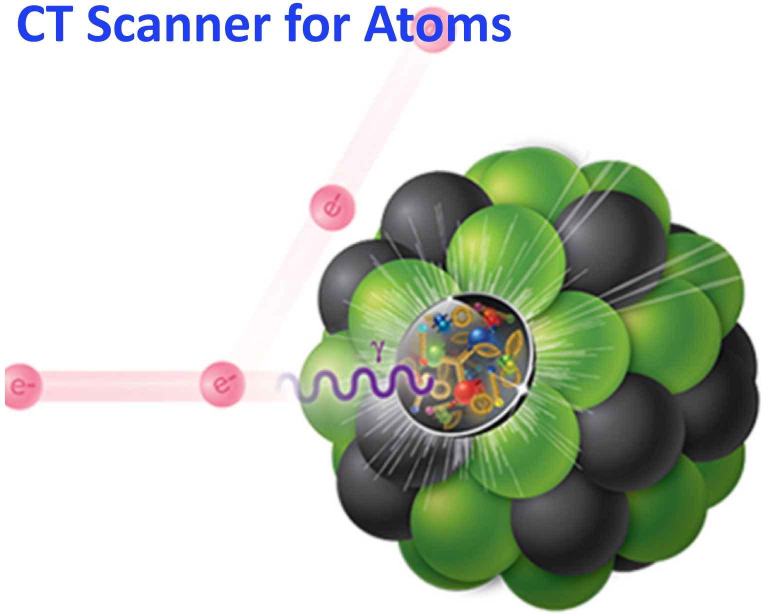
https://www.bnl.gov/eic/

See the talk by Elke

A machine that will unlock the secrets of the strongest force in Nature

Like a CT Scanner for Atoms





- Hadron Storage Ring
- Hadron Injector Complex
- Electron Storage Ring
- Electron Injector Synchrotron
- Electron Cooler
- Possible On-energy Hadron Injector Ring

Basic Tech Requirements

- **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*

U.S. - based Electron-Ion Collider

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

See the talk by Elke

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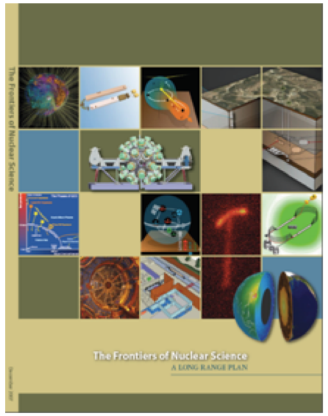
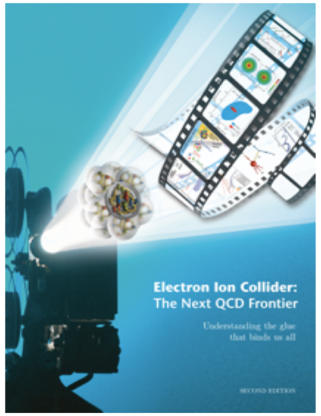
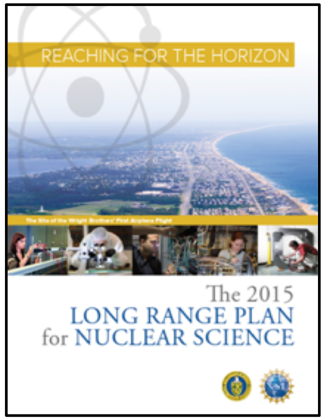
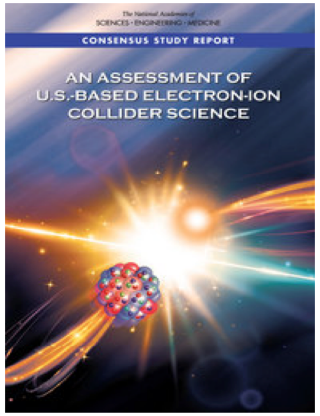








…

2018

"… 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?

- 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!

The project: passed CD-1, preparing for CD-2 (Preliminary design, baseline scope, cost and schedule)

QCD and Strong Interaction

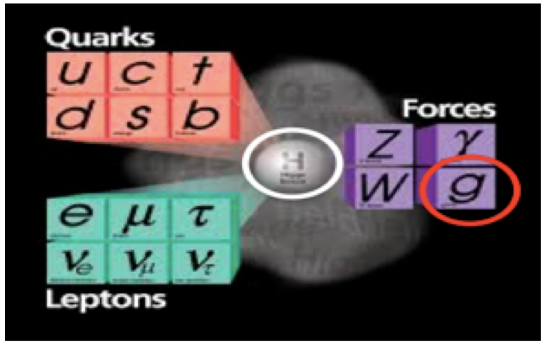
- ❑ **Understanding where did we come from?**

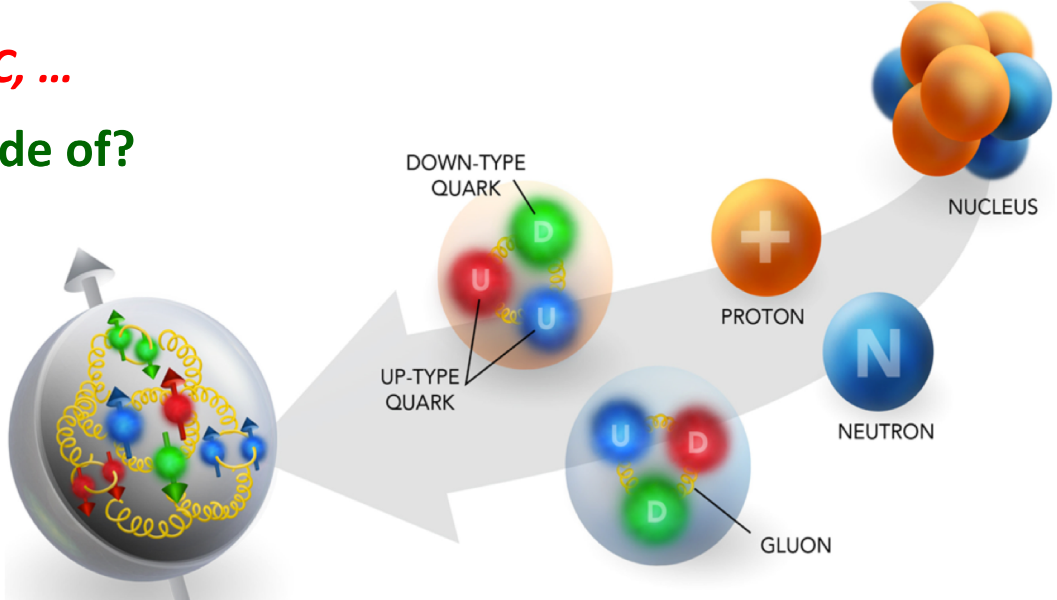
Global Time: →

QCD at high temperature, high densities, phase transition, …

Facilities – Relativistic heavy ion collisions: SPS, RHIC, the LHC, …

- ❑ **Understanding the visible world at 3°K – what are we made of?**





- How to understand the emergence and properties of nucleon and nuclei (elements of the periodic table) in terms of elements of the modern periodic table?
- How does the glue bind us all?

NO quarks and gluons can be seen in isolation!

- ❑ **Nuclear Femtography (0.1 – 10 fm)**

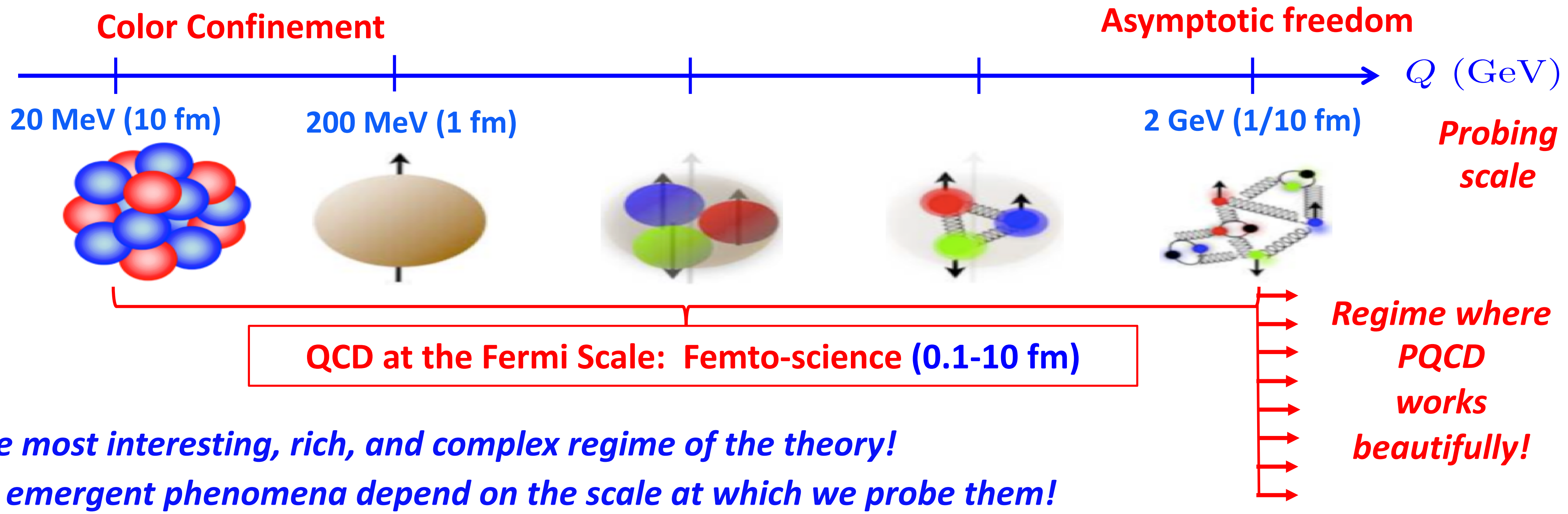
Search for answers to these questions at a Fermi scale!

Facilities – CEBAF, EIC, …

Jefferson Lab

QCD at a Fermi Scale – Nuclear Femtography

- **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!*

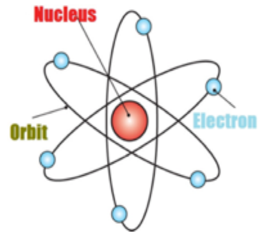
- **QCD – Asymptotic Freedom:**
  - *Force becomes weaker at a shorter-distance – chance to have perturbatively controllable "Probes"*
  - *Hadronic scales are non-perturbative – cross section with identified hadron is NOT perturbatively calculable*

Structure of Nucleons and Nuclei

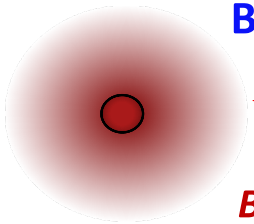
Hadron's partonic structure:

- Fundamentally different from atomic structure!
- Quarks and gluons are moving relativisticaly,
- No localized charge and mass centers & color is fully entangled!
- Partonic structure = "Quantum Probabilities": $\langle P, S | \mathcal{O}(\overline{\psi}, \psi, A^{\mu}) | P, S \rangle$

Atomic structure



Quantum orbits



B-meson

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

Brown-Muck

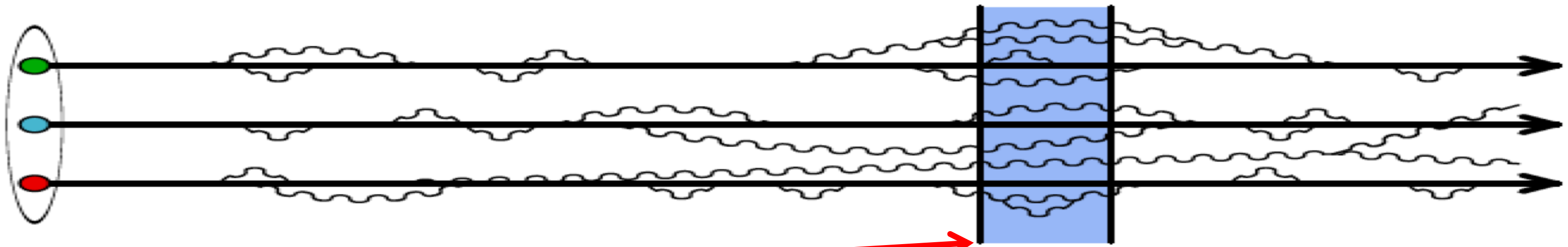
BUT, None of these matrix elements is a direct physical observable, No quark and gluon can be seen in isolation!

Need a probe to "see" quarks and gluons indirectly!

- High energy scattering with a large momentum transfer: $Q \gg 1/R \sim 1/\mathrm{fm} \sim 200\ \mathrm{MeV}$

Boost

p



Time-dilation

Hard probe: t ~ 1/Q to catch the fluctuation!

$$k^{\mu} = (k^{+}, k^{-}, k_T) \approx (k^{+}, 0^{-}, 0_T)$$
$$k^{+} = x p^{+} \sim Q \gg \langle k^{-} \rangle, \langle k_T \rangle$$

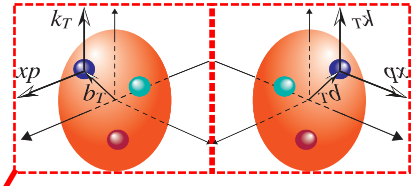
Momentum fraction $x = k^{+}/p^{+}$

BUT, Any cross sections with identified hadron(s) are non-perturbative!

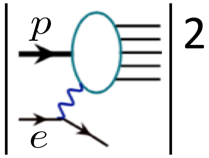
→ Need to separate the physics at different momentum scales!

Theoretical Approaches – “controllable” approximations

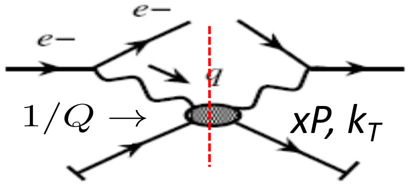
- **Perturbative QCD Factorization – *Approximation at Feynman diagram level*:**



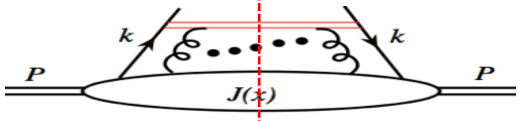
$\sigma_{\rm DIS}(x, Q^2) =$



$|\ \ |^2 \approx$



$\otimes$



$+\ O\left(\frac{1}{QR}\right)$

Factorization Theory	Hard-part Probe	Parton-distribution “Structure”	Power corrections Approximation

Leading power non-perturbative physics are universal and factorizable!

- **Effective field theory (EFT) – *Approximation at the Lagrangian level*:**

  Soft-collinear effective theory (SCET), Non-relativistic QCD (NRQCD), Heavy quark EFT, chiral EFT(s), …

- **Lattice QCD – *Approximation mainly due to computer power*:**

  Hadron spectroscopy, phase shift, nuclear structure, *hadron structure (with pQCD factorization)*, …

- **Other approaches:**

  Light-cone perturbation theory, Dyson-Schwinger Equations (DSE), Constituent quark models, AdS/CFT correspondence, …

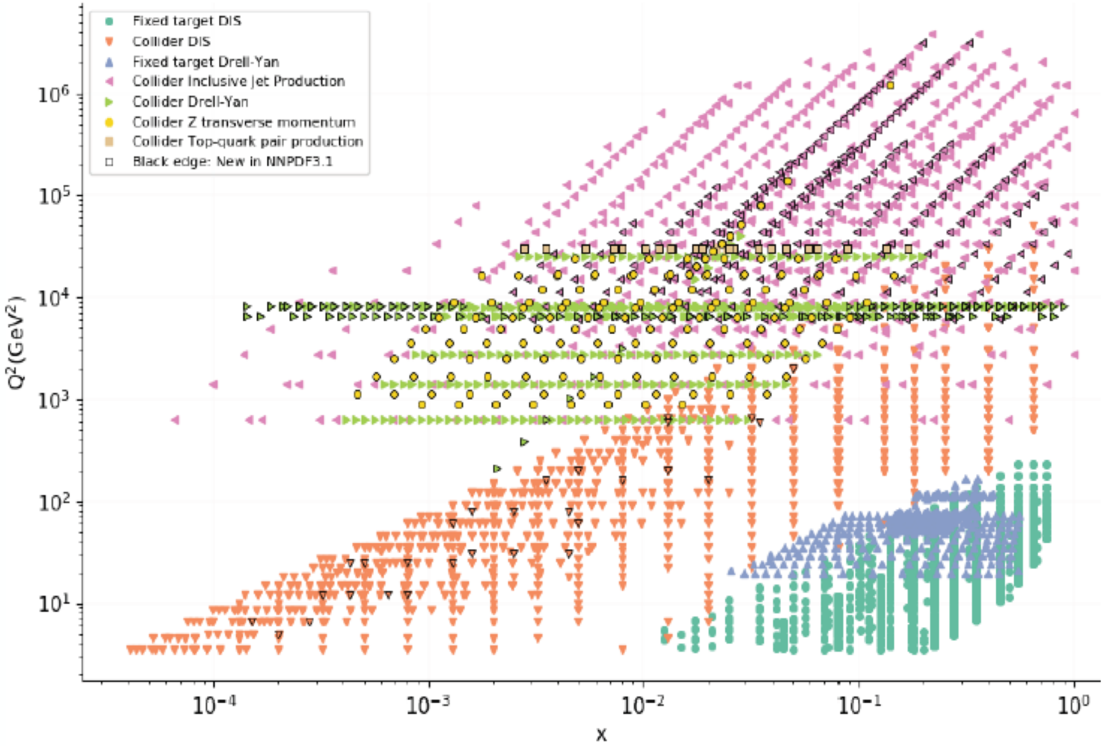
QCD Factorization Works to the Precision

❑ 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	$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	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

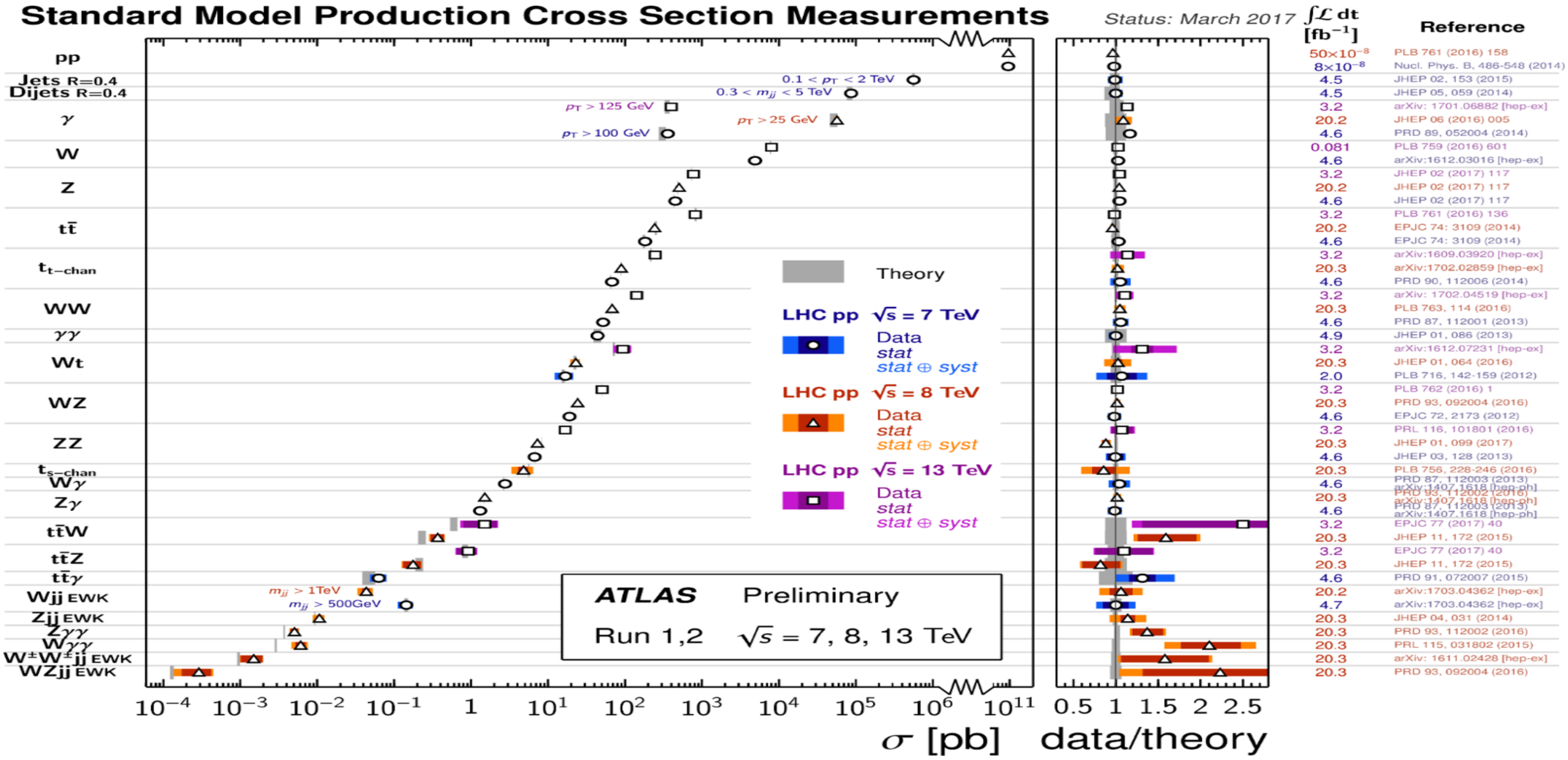


❑ Fit Quality:

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

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

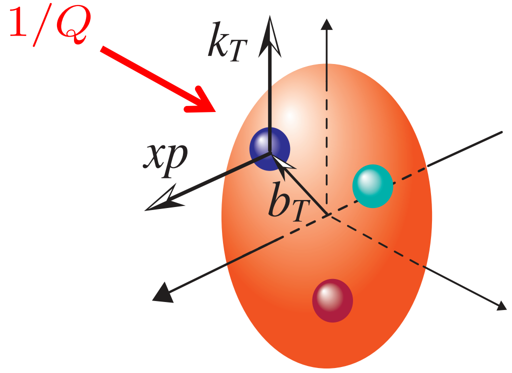
Unprecedent Success of QCD and Standard Model



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

3D Hadron Structure – Need probes with two scales

- **Single-scale hard probe is too "localized":**



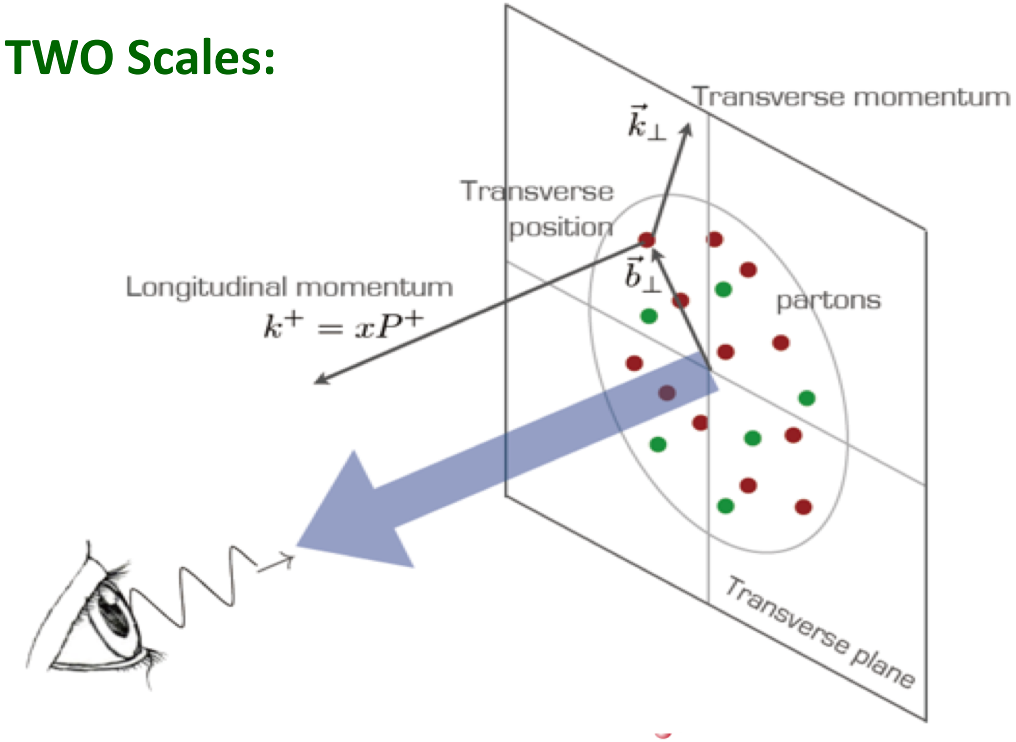
- It pins down the particle nature of quarks and gluons
- But, not very sensitive to the detailed structure of hadron ~ fm
- Confined transverse motion: k_T ~ 1/fm << Q
- Transverse spatial position: b_T ~ fm >> $1/Q$

- **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 – factorization particle nature of quarks/gluons

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

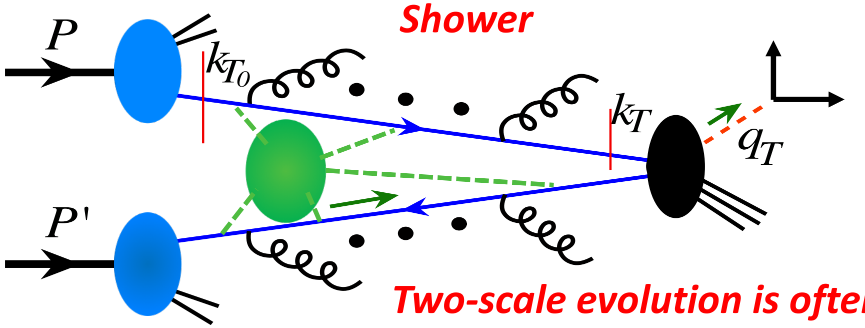


- **New challenge:**

QCD Factorization for observables with two scales!

Classical Two-Scale Observable – Drell-Yan P_T-distribution

- **Challenge to separate "true" hadron structure from "collision effects":**



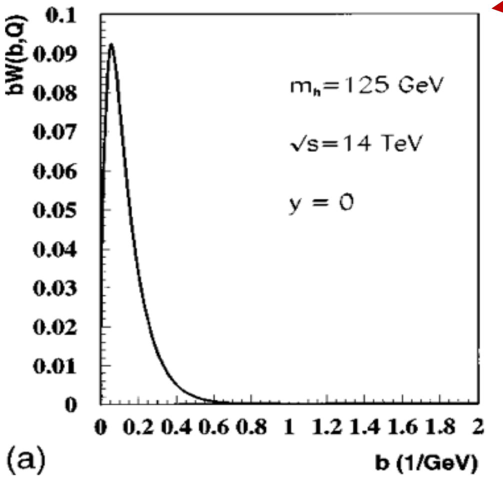
- Drell-Yan type (W/Z, H^0): $Q >> q_T$ (two scales)
- Parton *shower* develops when hadron is broken
- *Parton k_T probed at the hard collision is NOT the same as "confined motion" in a hadron*
- The difference is encoded in QCD evolution
- Two-scale evolution *is different* from DGLAP!

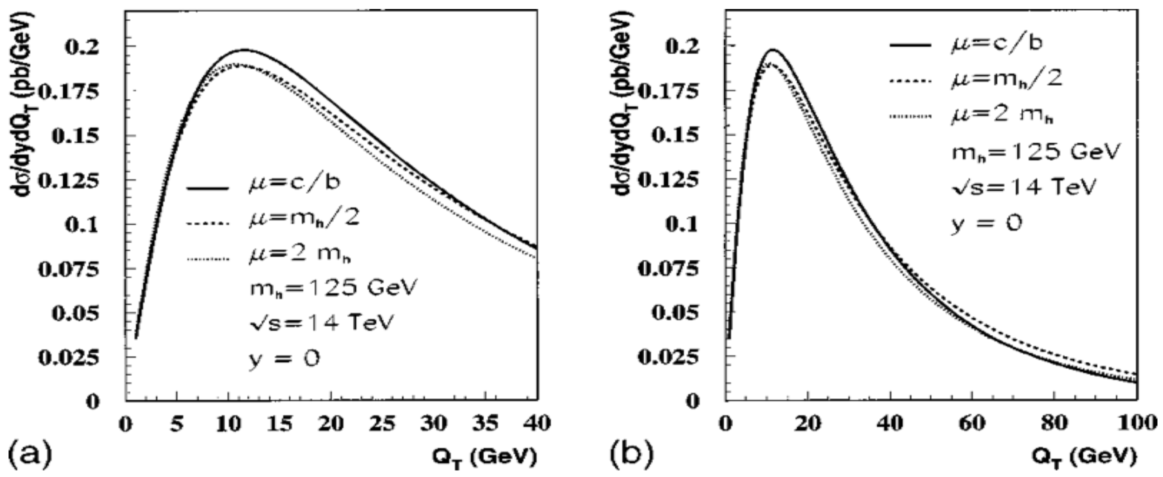
- **Structure information could be easily washed out in high energy collisions:** $f(x_b, k_T, \mu, \zeta_b)$

e.g., Higgs production at the LHC:

F.T.

$$\frac{d\sigma(Q,q_T)}{dy\,dq_T} = \int_0^\infty \frac{db_T}{2\pi} b_T J_0(q_T b_T) H(Q,\mu) f(x_a, b_T, \mu, \zeta_a) f(x_b, b_T, \mu, \zeta_b) + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$



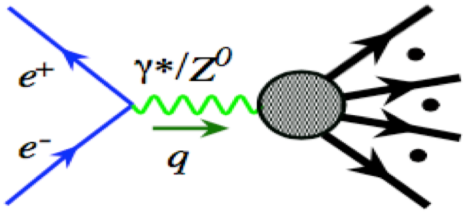


Berger, Qiu PRD67 (2003) 034026

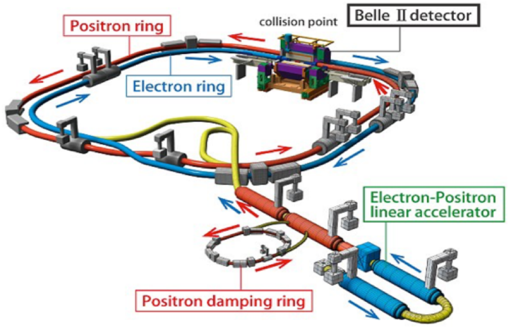
Not sensitive to the structure other than PDFs!

QCD & Hadron Structure needs Lepton-Hadron Collider

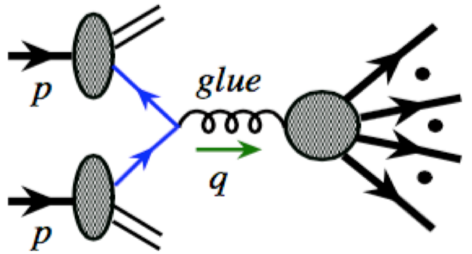
- **Hadrons are produced from the energy in e+e- collisions:**



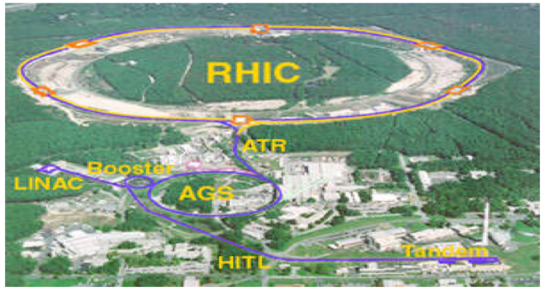
- *No hadron to start with*
- *Emergence of hadrons*



- **Hadrons are produced in hadron-hadron collisions:**

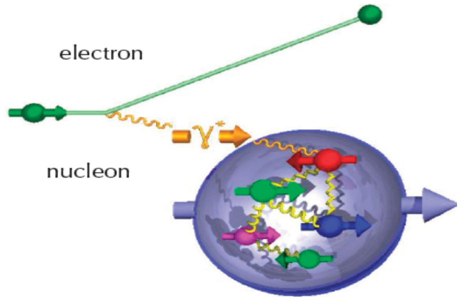


- *Partonic structure*
- *Emergence of hadrons*
- *Heavy ion target or beam(s)*

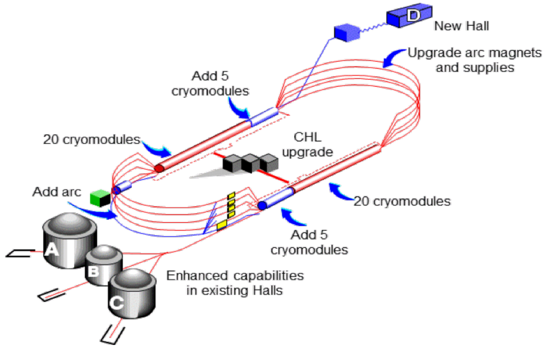


Also at the LHC

- **Hadrons are produced in lepton-hadron collisions:**



- *Colliding hadron can be broken or stay intact!*
- *Imaging partonic structure*
- *Emergence of hadrons*
- *Heavy ion target or beam*

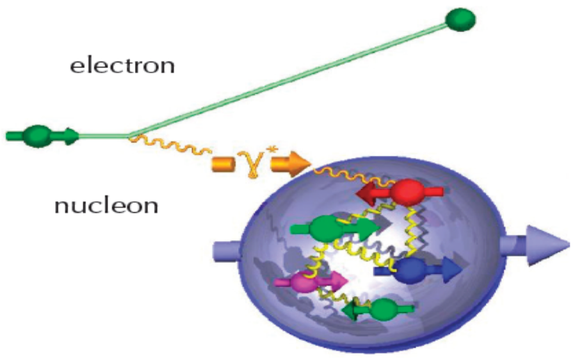


Also at COMPASS & future EIC

Ideal facility for hadron structure!

Many Complementary Probes at One Facility

- The new generation of "Rutherford" experiment:



✧ A controlled "probe" – virtual photon

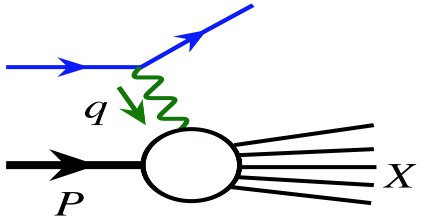
✧ Can either break or not break the hadron

Two-scale observables are natural at lepton-hadron facility!

✧ Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

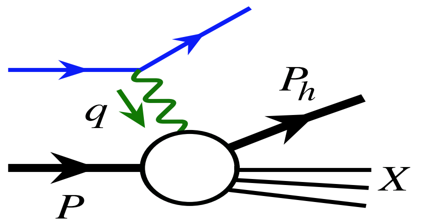
(Modern Rutherford experiment!)



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

Detect the scattered lepton in coincidence with identified hadrons/jets

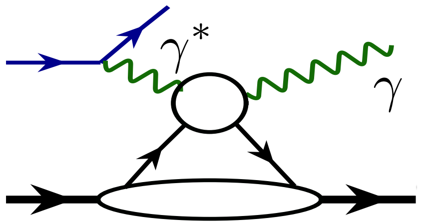
(Initial hadron is broken – confined motion! – cleaner than h-h collisions)



✧ 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)

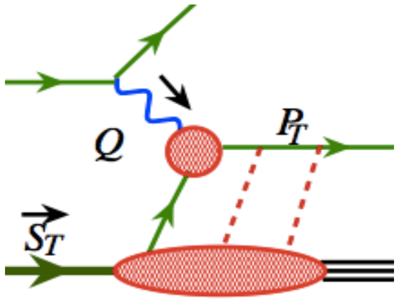


“See” 3D Hadron Structure at a Lepton-Hadron Facility

See also talk by Cédric

❑ **Two-scale observables are natural in lepton-hadron collisions:**

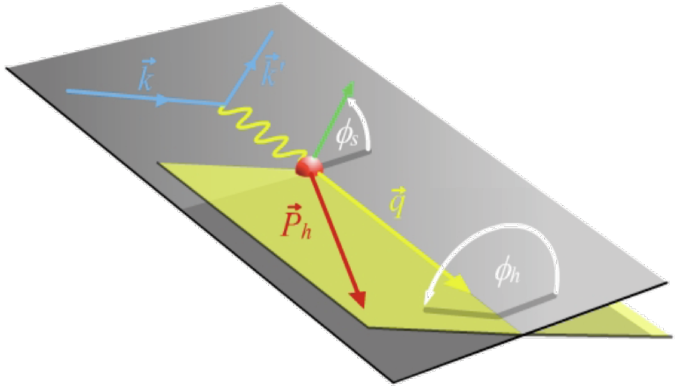
✧ **Semi-inclusive DIS:**



+ …

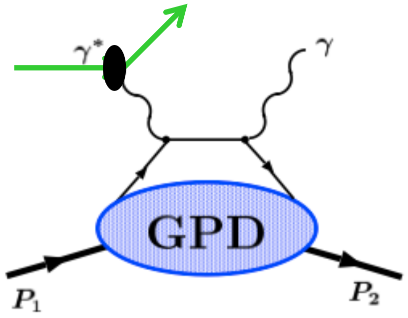
SIDIS: $Q \gg P_T$

Parton’s confined motion encoded into TMDs (too many of them?)



Two scales, two planes, Angular modulation, …

✧ **Exclusive DIS:**

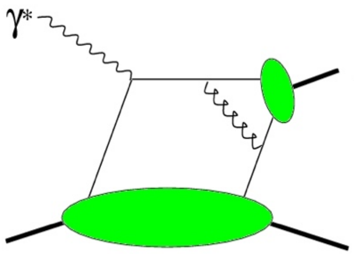


+ …

$t=(p_1-p_2)^2$

DVCS: $Q^2 \gg |t|$

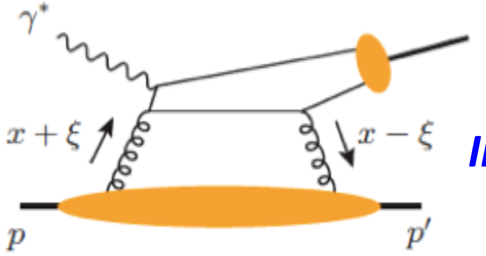
Parton’s spatial imaging from Fourier transform of GPDs’ t-dependence



+ …

DVEM: $Q^2 \gg |t|$

Imaging quarks



J/Ψ, Φ, …

Imaging gluons

Heavy quarkonium: $Q^2+M^2 \gg |t|$

Imaging the glue only at EIC

None of these processes is sensitive to x-dependence of GPDs!

Propose a new type of processes

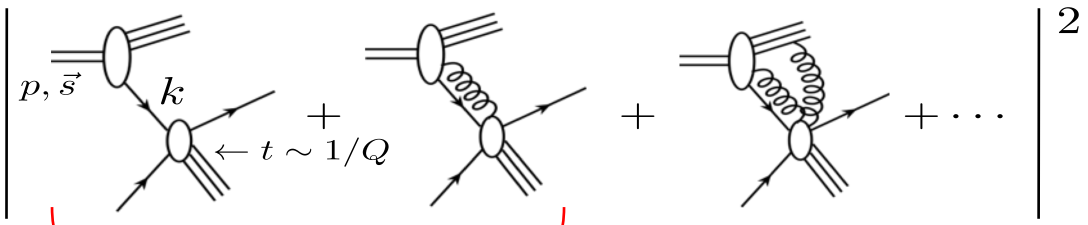
US-EIC – can do what HERA could not do

- **Quantum imaging:**
  - ✧ **HERA discovered: 15% of e-p events is diffractive – Proton not broken!**
  - ✧ **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

Large momentum transfer without breaking the proton Luminosity!

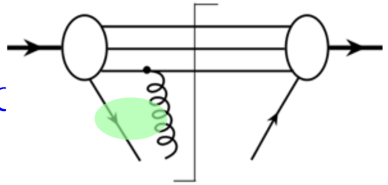
- **Quantum interference & entanglement:**
  - ✧ **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***
    Direct access to chromo-quantum interference!

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



No probability interpretation!

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



- **Nonlinear quantum dynamics:**
  - ✧ **US-EIC: Light-to-heavy nuclear beams – *Origin of nuclear force, …***
    Catch the transition from chromo-quantum fluctuation to chromo-condensate of gluons, …
    Emergence of hadrons (nuclei as femtometer size detectors!),
    – "a new controllable knob" – Atomic weight of nuclei

Wave nature of quark/gluon field

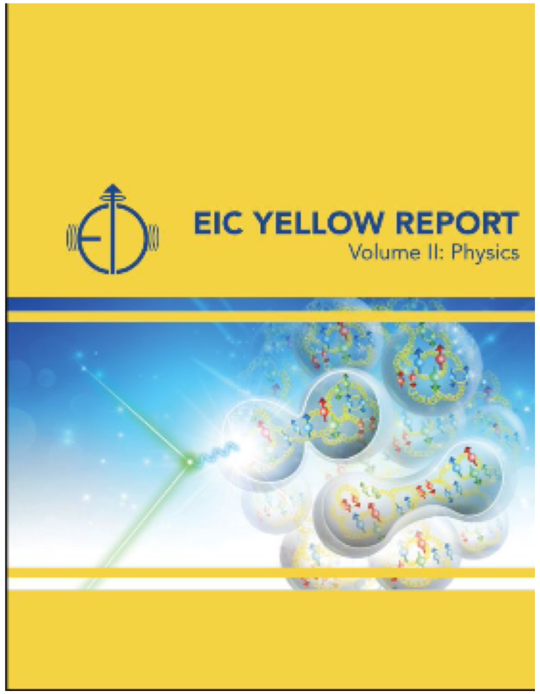
US EIC – Deliverables & Opportunities

Why existing facilities, even with upgrades, cannot do the same?

See also talks by Elke, Robert, Cédric Yuri, and Carlos

- Emergence of hadrons
- Hadron properties:
  mass, spin, …
- Hadron's 3D partonic structure:
  confined motion, spatial distribution,
  color correlation, fluctuation,
  saturation, …
- Quantum correlation between
  hadron properties and parton dynamics, …
- Hadron spectroscopy, XYZ, …

…

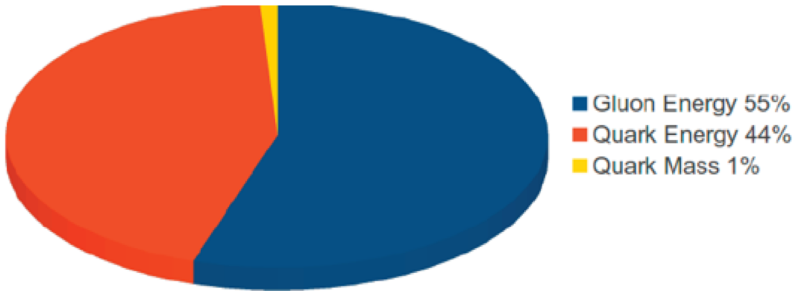


arXiv:2103.05419

Minimize the overlap, go beyond the Yellow Report!

Who ordered the hadron mass scale?

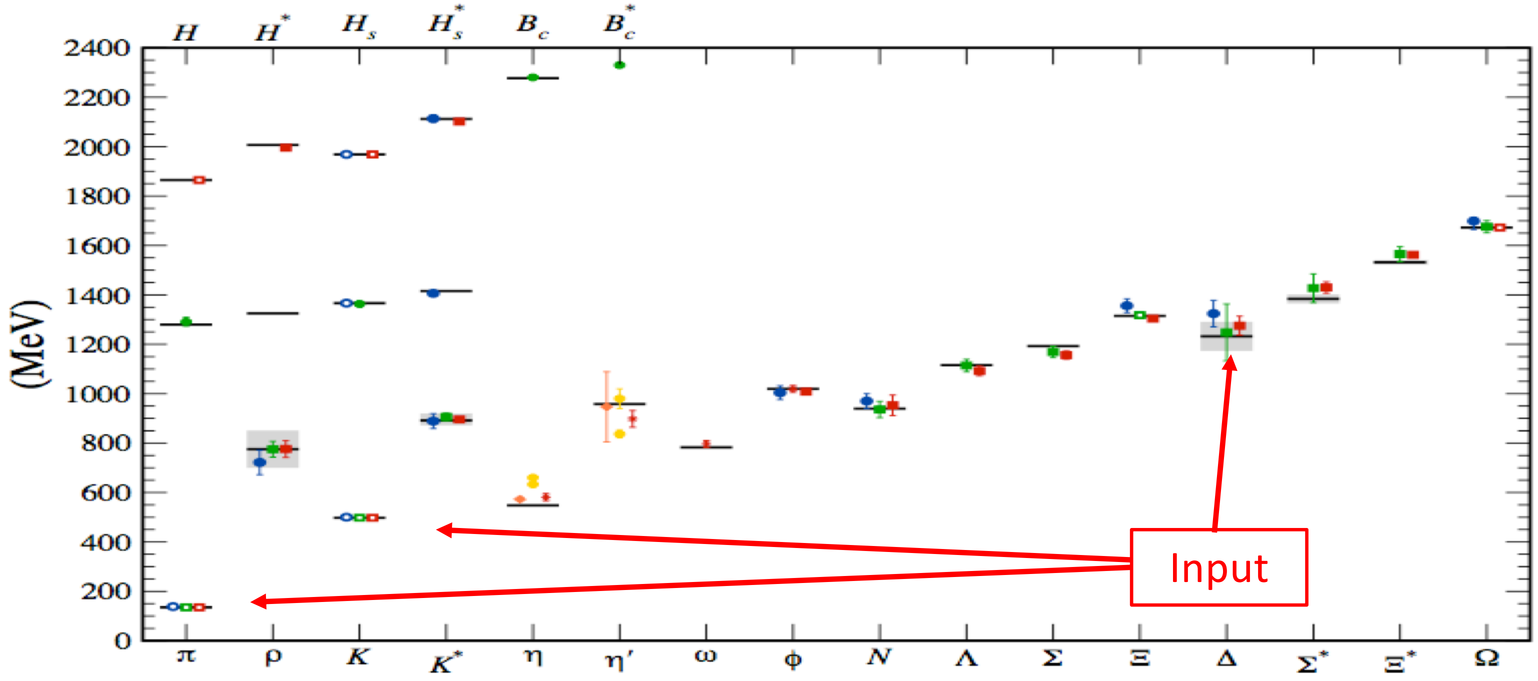
- ❑ **Nucleon mass – dominates the mass of visible world:**



Higgs mechanism is far from enough!!!

Fig. 2.1 NAS Report

- ❑ **Hadron mass from lattice QCD calculation:**



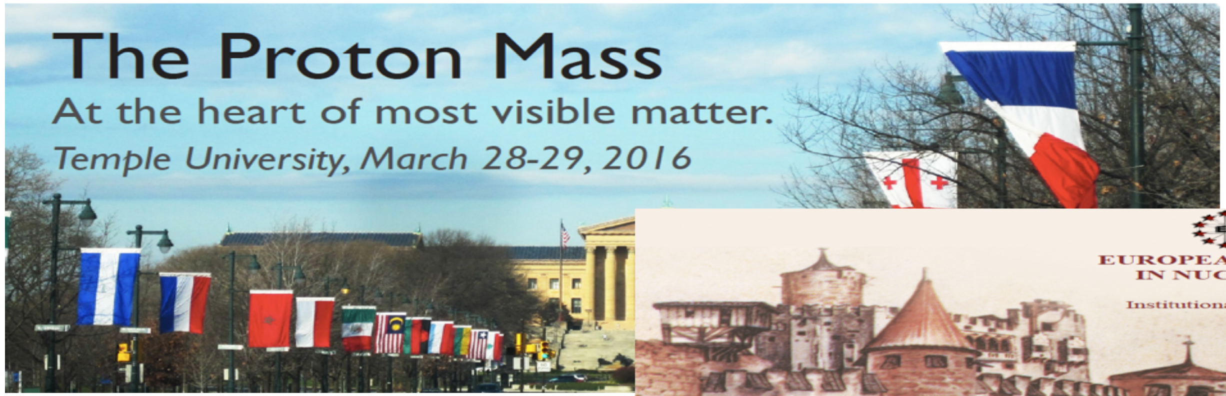
How to "see" the role of quarks and gluons, and their dynamics in generating these?

The Origin of Proton Mass – An Open Question

- Three-pronged approach to explore the origin of hadron mass
  - ✧ Lattice QCD
  - ✧ Mass decomposition – roles of the constituents
  - ✧ Model calculation – approximated analytical approach

Bag model:

- Kinetic energy of three quarks: $K_q \sim 3/R$
- Bag energy (bag constant B): $T_b = \frac{4}{3}\pi R^3\, B$
- Minimize $K_q + T_b$: $M_p \sim \frac{4}{R} \sim \frac{4}{0.88 fm} \sim 912\text{MeV}$



(> 200 participants!)

A true international effort!

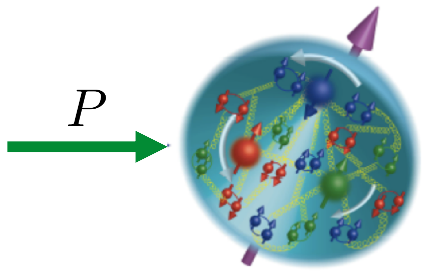
A focused INT workshop has been planned

https://indico.phy.anl.gov/event/2/

Mass of Nucleon in QCD

❑ Decomposition of the trace of EMT:

Trace of the QCD energy-momentum tensor:



$$T^{\alpha}_{\ \alpha} = \underbrace{\frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu}}_{\text{QCD trace anomaly}} + \sum_{q=u,d,s} \underbrace{m_q(1+\gamma_m)\overline{\psi}_q \psi_q}_{\text{Chiral symmetry breaking}}$$

$$\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$$

$$\langle P|T^{\alpha}_{\ \alpha}(0)|P\rangle = 2P^2 = 2M_n^2$$

$$\Rightarrow \quad \langle T^{\alpha}_{\ \alpha}\rangle = \frac{\langle P|T^{\alpha}_{\ \alpha}(0)|P\rangle}{2P^0} = \frac{M_n^2}{P^0}$$

$$\Rightarrow \quad M_n = \langle T^{\alpha}_{\ \alpha}\rangle|_{\text{at reest}}$$

Without separate the quark from gluon contribution to EMT

In the nucleon's rest frame, $\underbrace{\langle \int d^3r\, T^{\mu}_{\ \mu}\rangle}_{=M} = \underbrace{\langle \int d^3r\, T^{00}\rangle}_{=M} - \sum_i \underbrace{\langle \int d^3r\, T^{ii}\rangle}_{=0}$

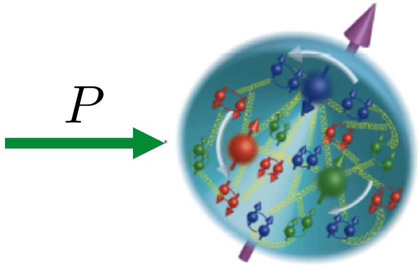
Nucleon mass: ***Gluon quantum effect + Chiral symmetry breaking!***

The sigma-term can be calculated in LQCD, Need the trace anomaly to test the sum rule!

Mass of Nucleon in QCD

❑ Decomposition of "energy"-operator of EMT:

$$M_n = \sum_{f=q,g} \frac{\langle P|T_f^{00}(0)|P\rangle}{2P^0}\Bigg|_{\rm cm}$$



- Decompose the RHS into a sum of several gauge invariant terms
- Decomposition is not unique, since only the sum is a physical observable
- Usefulness – Each term can be related to physical observables with controllable approximations
- Individual contribution to the nucleon mass – physical interpretation of each term (?)

❑ Ji's decomposition:

Let $T^{\mu\nu} = \overline{T^{\mu\nu}} + \widehat{T^{\mu\nu}}$ **With** $\overline{T^{\mu\nu}} = T^{\mu\nu} - \frac{1}{4}g^{\mu\nu}T^\alpha_{\ \alpha}$ **and** $\widehat{T^{\mu\nu}} = \frac{1}{4}g^{\mu\nu}T^\alpha_{\ \alpha}$

$\overline{T^{\mu\nu}}, \widehat{T^{\mu\nu}}$ **Renormalized separately, in different Lorentz representations**

$$\Rightarrow \quad M_n = \sum_{f=q,g} \frac{\langle P|T_f^{00}(0)|P\rangle}{2P^0}\Bigg|_{\rm cm} = \overbrace{M_q + M_g}^{\text{Relativistic motion}} + \underbrace{M_m}_{\chi\text{ Symmetry Breaking}} + \underbrace{M_a}_{\text{Quantum fluctuation}}$$

Trace Anomaly $\langle \widehat{T}_g^{00}\rangle$

Quark Energy $\langle \overline{T}_q^{00}\rangle$ Gluon Energy $\langle \overline{T}_g^{00}\rangle$ Quark Mass $\langle \widehat{T}_q^{00}\rangle$

Mass of Nucleon in QCD

❑ Physics interpretation:

Quark Energy $\langle T_q^{00} \rangle$: $$M_q = \frac{3}{4}\left(M\sum_q \langle x\rangle_q - \sum_q \sigma_q\right)$$

Gluon Energy $\langle T_g^{00} \rangle$: $$M_g = \frac{3}{4} M \langle x\rangle_g$$

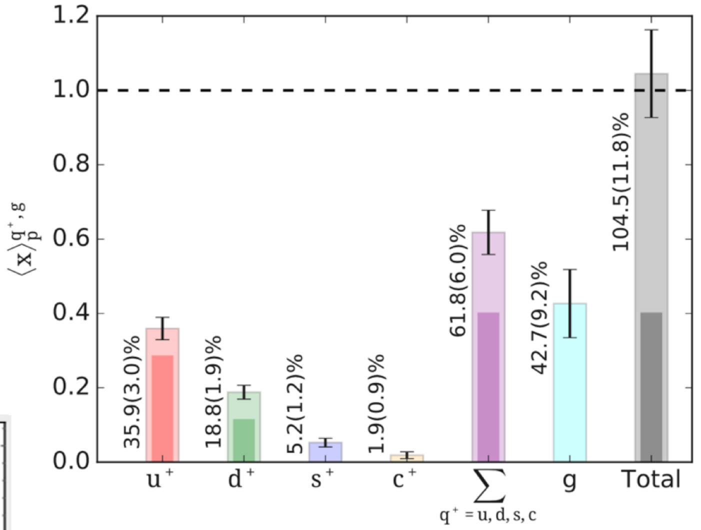
Quark Mass $\langle \widehat{T}_q^{00} \rangle$: $$M_m = \sum_q \sigma_q$$

Trace Anomaly $\langle \widehat{T}_g^{00} \rangle$: $$M_a = \frac{\gamma_m}{4}\sum_q \sigma_q - \frac{\beta(g)}{4g}(E^2 + B^2)$$

Note: $\langle x\rangle_f$ and σ_q are calculable in lattice QCD

Parton momentum fraction:

$$\langle x\rangle_f = \int_0^1 dx\, x f(x,\mu^2)$$

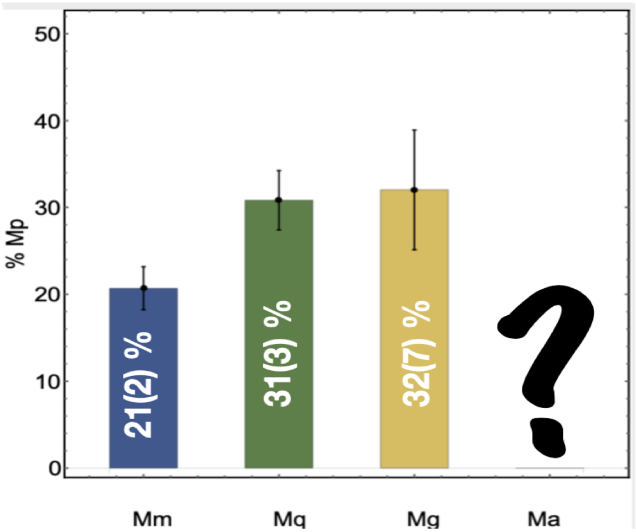


❑ LQCD calculation:

Quark sigma-term:

$$\sigma_q = \frac{\langle P|\overline{\psi}_q(0) m_q \psi_q(0)|P\rangle}{2P^0}$$

	$u+d$	s	c
σ [MeV]	41.6(3.8)	45.6(6.2)	107(22)



Access the trace anomaly Indirectly?

$$M_a = \frac{M}{4} - \sum_q \frac{\sigma_q}{4}$$

Or by experiment?

Jefferson Lab

Mass of Nucleon in QCD

❑ Other decompositions:

EPJC78 (2018),JHEP09 (2020) PRD102 (2020)

$$M = \underbrace{\left[\langle \int d^3r\, \bar{\psi}\gamma^0 iD^0\psi\rangle - \langle \int d^3r\, \bar{\psi}m\psi\rangle\right]}_{\substack{\text{Quark}\\ \text{kinetic and potential energy}}} + \underbrace{\langle \int d^3r\, \bar{\psi}m\psi\rangle}_{\substack{\text{Quark}\\ \text{rest mass energy}}} + \underbrace{\langle \int d^3r\, \tfrac{1}{2}(\vec{E}^2 + \vec{B}^2)\rangle}_{\substack{\text{Gluon}\\ \text{total energy}}}$$

Without separate EMT into traceless piece – mixing of terms via renormalizations

❑ Compare to Ji's decomposition:

C.L., EPJC78 (2018)

$$T_a^{00} = \underbrace{\bar{T}_a^{00}}_{=\frac{3}{4}T_a^{00} + \frac{1}{4}\sum_i T_a^{ii}} + \underbrace{\hat{T}_a^{00}}_{=\frac{1}{4}T_a^{00} - \frac{1}{4}\sum_i T_a^{ii}} \qquad a = q, g$$

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) M \quad \neq \langle \int d^3r\, \psi^\dagger i\vec{D}\cdot\vec{\alpha}\psi\rangle \qquad M_m = \frac{4+\gamma_m}{4(1+\gamma_m)}\, b\, M \quad = \langle \int d^3r\, \left(1 + \tfrac{1}{4}\gamma_m\right)\bar{\psi}m\psi\rangle$$

$$M_g = \frac{3}{4}(1-a)\, M \quad \neq \langle \int d^3r\, \tfrac{1}{2}(\vec{E}^2 + \vec{B}^2)\rangle \qquad M_a = \frac{1}{4}(1-b)\, M \quad = \langle \int d^3r\, \tfrac{1}{4}\, \tfrac{\beta(g)}{2g}\, G^2\rangle$$

Matter of interpretations! Key is how can we measure each term with controllable approximations!

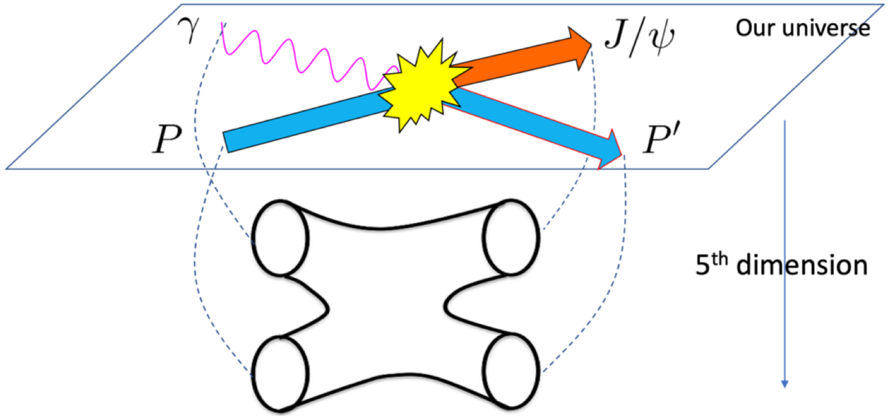
Extract the Trace Anomaly from Experiments

❑ Holographic approach:

Boussarie & Hatta et al, Phys.Rev.D 101 (2020) 11, 114004)

$$\frac{d\sigma}{dt} = \frac{\alpha_{em}}{4(W^2 - M_p^2)^2}\overline{\Sigma}_{pol}\overline{\Sigma}_{spin}\left|\langle P|\vec{\epsilon}\cdot\vec{J}(0)|P'p\rangle\right|^2$$

$$\sigma_{tot} = \int_{t_{min}}^{t_{max}} \frac{d\sigma}{dt}\, dt$$



How to calculate the scattering amplitude?

$$\langle P|\vec{\epsilon}\cdot\vec{J}(q)|P'p\rangle = (2\pi)^4\delta^4(P + q - P' - p)\langle P|\vec{\epsilon}\cdot\vec{J}(0)|P'p\rangle$$

Y. Hatta, D.L. Yang (1801.02163) – gauge/string duality:

$$\langle P|\epsilon\cdot J(0)|P'k\rangle = -\frac{2\kappa^2}{f_\psi R^3}\int_0^{z_m} dz \frac{\delta S_{D7}(q,k,z)}{\delta g_{\mu\nu}}\frac{z^2R^2}{4}\langle P|T^{gTT}_{\mu\nu}|P'\rangle + \frac{2\kappa^2}{f_\psi R^3}\frac{3}{8}\int_0^{z_m} dz \frac{\delta S_{D7}(q,k,z)}{\delta\phi}\frac{z^4}{4}\langle P|\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu}|P'\rangle$$

Gluon from Traceless $T^{\mu\nu}$

Trace Anomaly

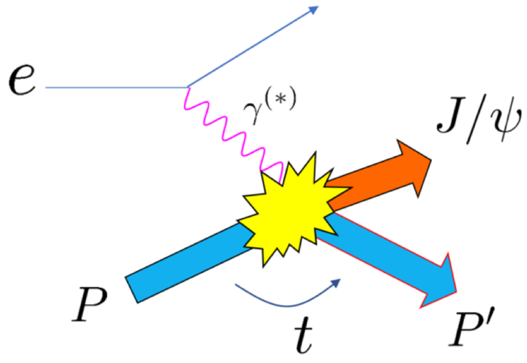
Dilaton field

$2\kappa^2 = \frac{8\pi^2}{N_c^2}R^3$ – 5D gravitational constant

Extract the Trace Anomaly from Experiments

- **Lepton production at high Q^2 – Need EIC:**

Boussarie & Hatta et al,
Phys.Rev.D 101 (2020) 11, 114004)



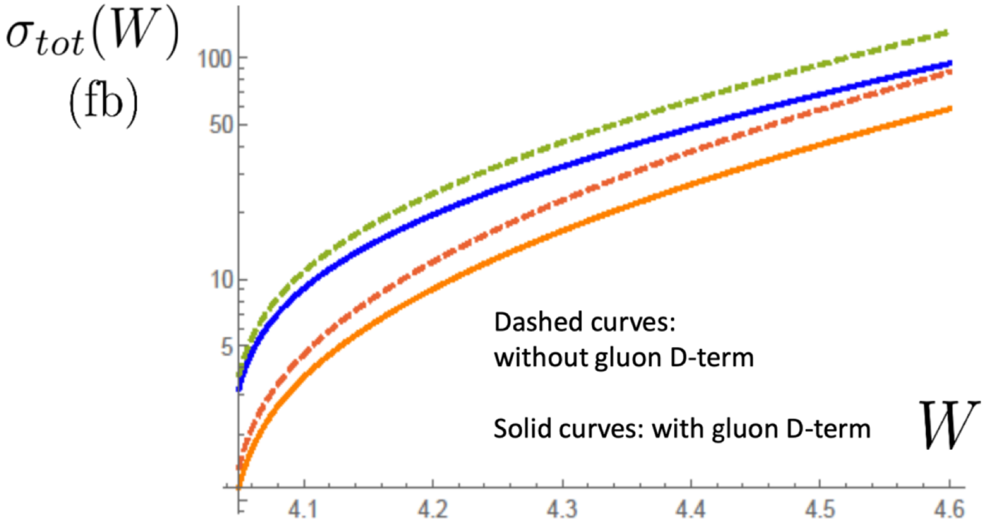
High Q2 allows to use OPE

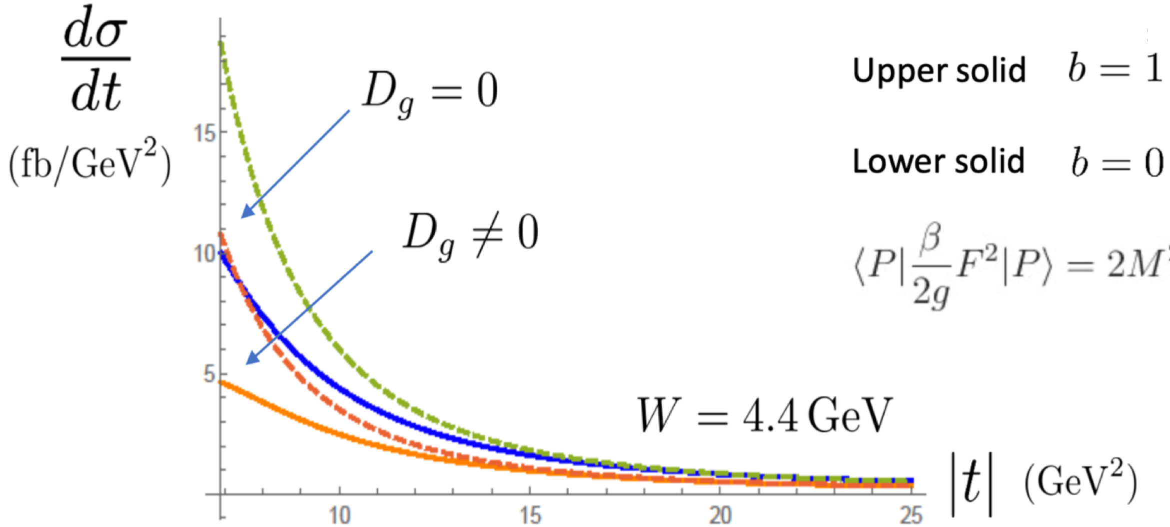
Large $S_{l\text{-}p}$ can still be near threshold:

$$W^2 = y(S_{ep} - m_N^2) + m_N^2 - Q^2$$

$$Q^2 \gg M_V^2 \gg m_N^2 \qquad Q^2 \gg |t|$$

$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \bar{u}(P')\left[A_{q,g}\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D_{q,g}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \bar{C}_{q,g}Mg^{\mu\nu}\right]u(P)$$





Upper solid $b = 1$

Lower solid $b = 0$

$$\langle P|\frac{\beta}{2g}F^2|P\rangle = 2M^2(1-b)$$

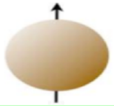
$J/\psi \quad Q^2 = 64\,\mathrm{GeV}^2 \quad \sqrt{S_{ep}} = 20\,\mathrm{GeV}$ (plots revised from 2004.12715)

Jefferson Lab

How does the Spin of the Nucleon Arise?

❑ An incomplete story:

See the talk by Elke



Proton Spin

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

Jaffe-Manohar, 90, Ji, 96, …

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

$\sim 30\%$

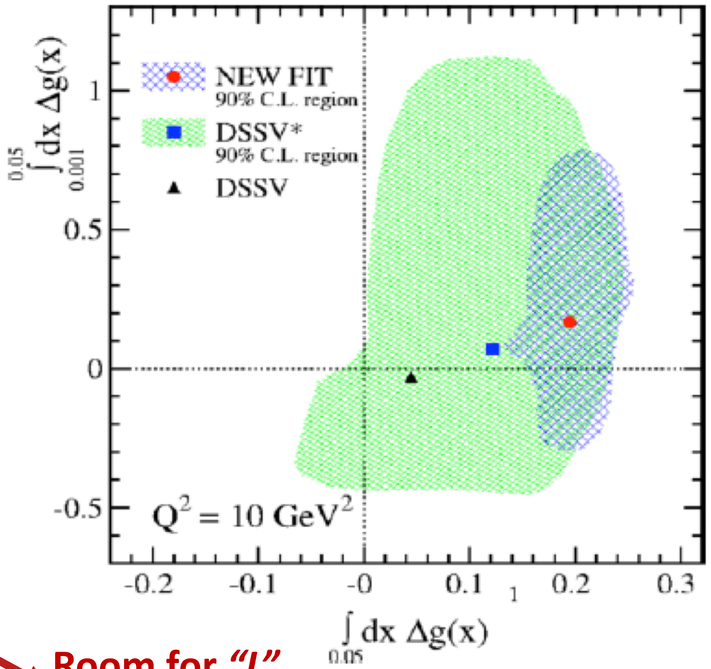
Quark helicity
Best known

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

$\sim 40\%$(with RHIC data)

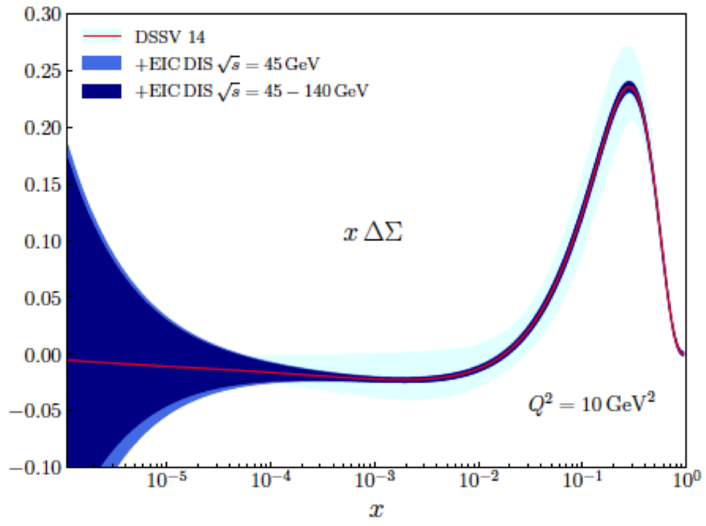
Gluon helicity
Start to know

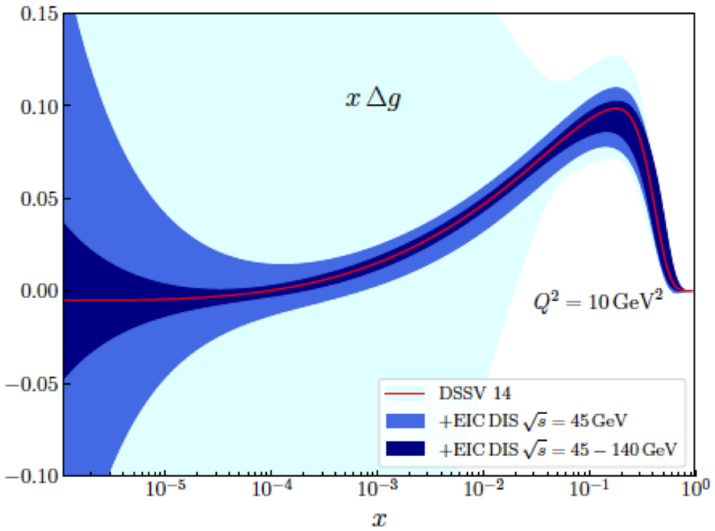
Orbital Angular Momentum of quarks and gluons
Little known

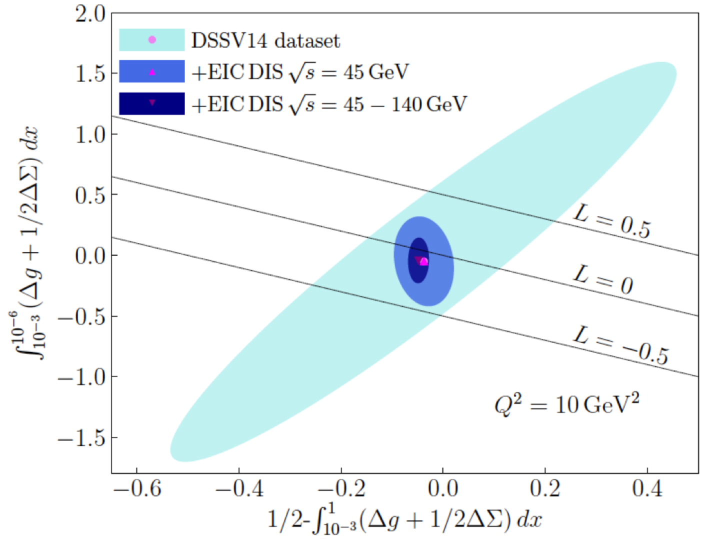


Room for *"L"*

❑ What the EIC could do/help – EIC Yellow Report:





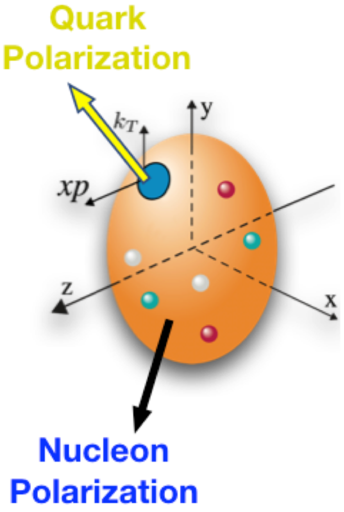


Semi-Inclusive DIS (SIDIS)

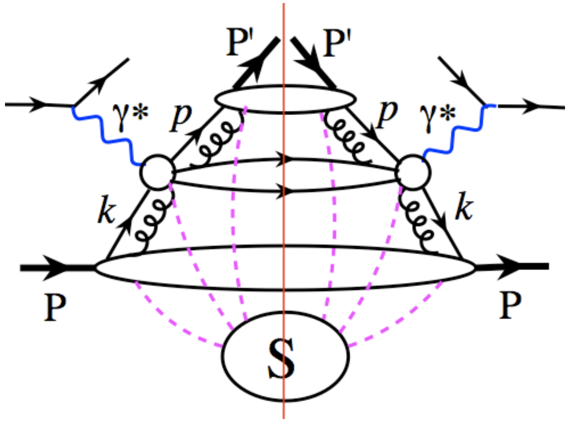
- **Process:** $e(k) + N(p) \longrightarrow e'(k') + h(P_h) + X$

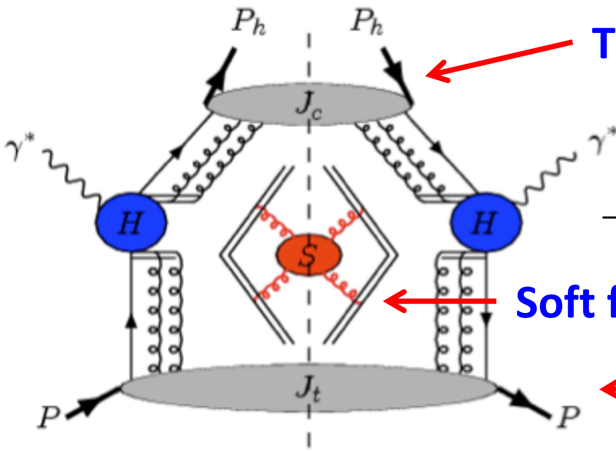
  In the photon-hadron frame (one-photon approximation): $P_{h_T} \approx 0$

  $Q \gg P_{h_T} \gtrsim \Lambda_{\rm QCD}$ **Localized probe sensitive to parton's transverse motion**



- **QCD Factorization:**





$$+\,\mathcal{O}\left(\frac{\langle k^2\rangle}{Q^2}, \frac{\langle p^2\rangle}{Q^2}\right)$$

- **Low P_{hT} – 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} – Collinear factorization:**

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

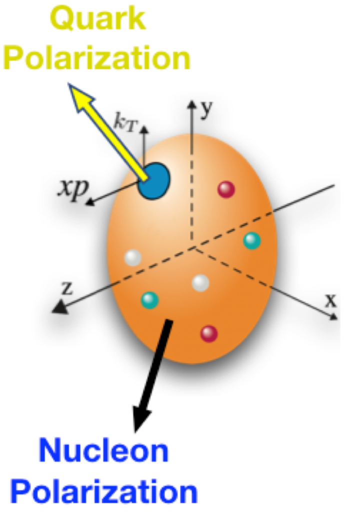
- **P_{hT} Integrated - Collinear factorization:**

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

Transverse momentum dependent PDFs (TMDs)

❑ Quark TMDs with polarization:

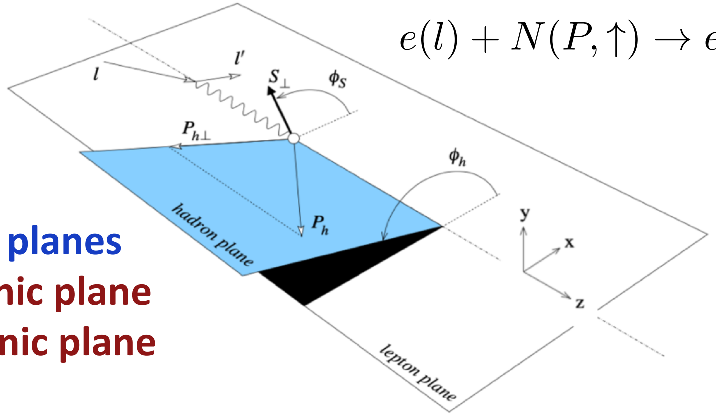
Nucleon Polarization \ Quark Polarization	Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1(x,k_T^2)$		$h_1^{\perp}(x,k_T^2)$ – Boer-Mulders
L		$g_1(x,k_T^2)$ – Helicity	$h_{1L}^{\perp}(x,k_T^2)$ – Long-Transversity
T	$f_1^{\perp}(x,k_T^2)$ – Sivers	$g_{1T}(x,k_T^2)$ – Trans-Helicity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



Analogous tables for:

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

❑ Polarized SIDIS:



Two planes
Leptonic plane
Hadronic plane

$$e(l) + N(P,\uparrow) \to e(l') + h(P_h) + X$$

Single Transverse-Spin Asymmetry

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

In photon-hadron frame:

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

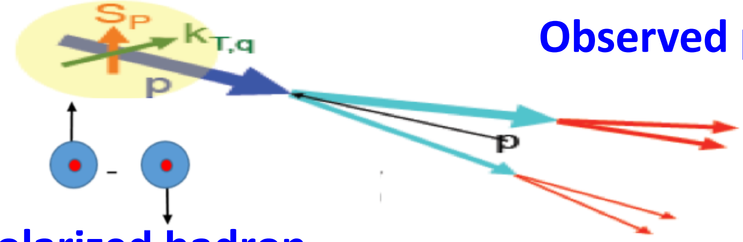
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

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

Angular modulation provides the best way to separate TMDs

TMDs: Explore the Flavor-Spin-Motion Correlation

- Quantum correlation between hadron spin and parton motion:



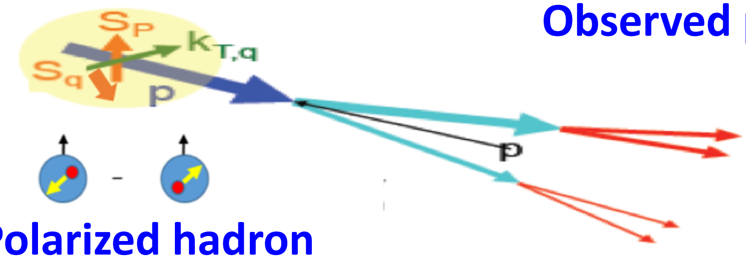
Observed particle

Polarized hadron

Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

- Quantum correlation between hadron spin and parton spin:



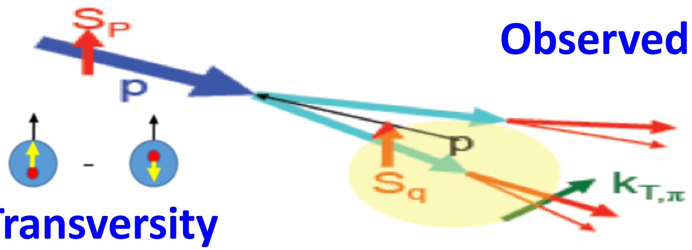
Observed particle

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

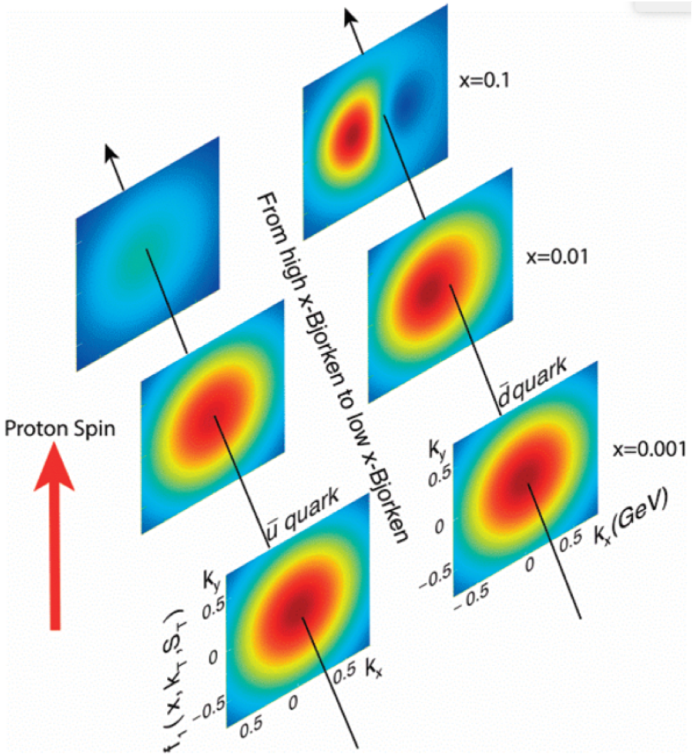
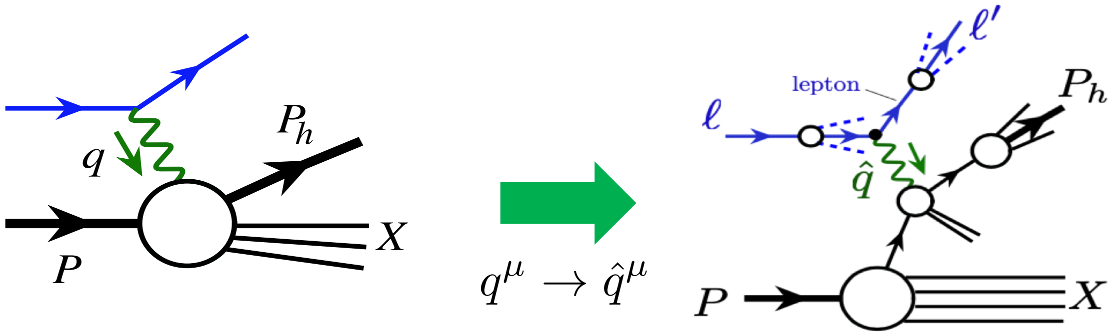


Fig. 2.7 NAS Report

QED Contribution to SIDIS

Collision induced QED radiation:

Liu, Melnitchouk, Qiu, Sato
2008.02895, 2108.13371

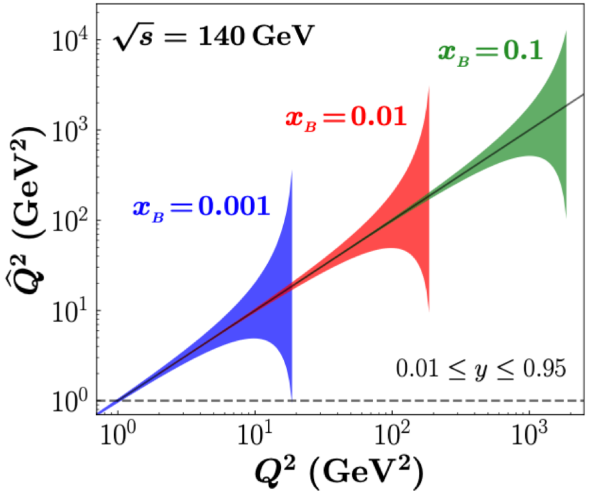


$$(x_B, Q^2) \to (\hat{x}_B, \widehat{Q}^2)$$

$$x_B \to \hat{x}_B \in [x_B, 1]$$

$$\widehat{Q}^2_{\rm min} = Q^2 \frac{(1-y)}{(1-x_B\, y)} \le Q^2$$

$$\widehat{Q}^2_{\rm max} = Q^2 \frac{1}{(1-y+x_B\, y)}$$



- Prevents a well-defined "photon-hadron" frame
- Radiation is IR sensitive as $m_e/Q \to 0$
- Create uncertainty to the angular modulations, needed to separate TMDs
- …

QED factorization of collision induced radiation:

$$E_{\ell'} E_{P_h} \frac{d^6\sigma_{\ell(\lambda_\ell)P(S)\to\ell' P_h X}}{d^3\ell'\, d^3P_h} \approx \sum_{ij\lambda_k} \int_{\zeta_{\rm min}}^1 \frac{d\zeta}{\zeta^2} D_{e/j}(\zeta) \int_{\xi_{\rm min}}^1 d\xi\, f_{i(\lambda_k)/e(\lambda_\ell)}(\xi) \left[E_{k'} E_{P_h} \frac{d^6\hat{\sigma}_{k(\lambda_k)P(S)\to k' P_h X}}{d^3k'\, d^3P_h} \right]_{k=\xi\ell,\, k'=\ell'/\zeta} + \mathcal{O}\left(\frac{m_e^n}{Q^n}\right)$$

- Leading power IR sensitive contribution is universal, as $m_e/Q \to 0$, factorized into LDFs and LFFs
- IR safe contributions are calculated order-by-order in powers of α
- Neglect m_e/Q power suppressed contributions
- Collinear QED factorization for both inclusive DIS and SIDIS, or e^+e^-, … [global fits of LDFs, LFFs]

QED Contribution to SIDIS

- **Two-step approach to SIDIS:**

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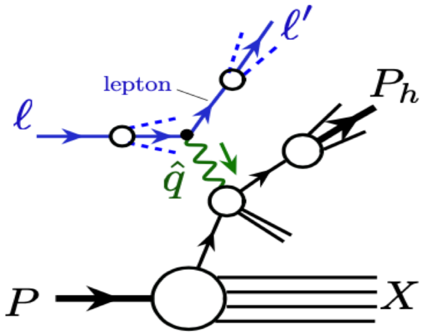


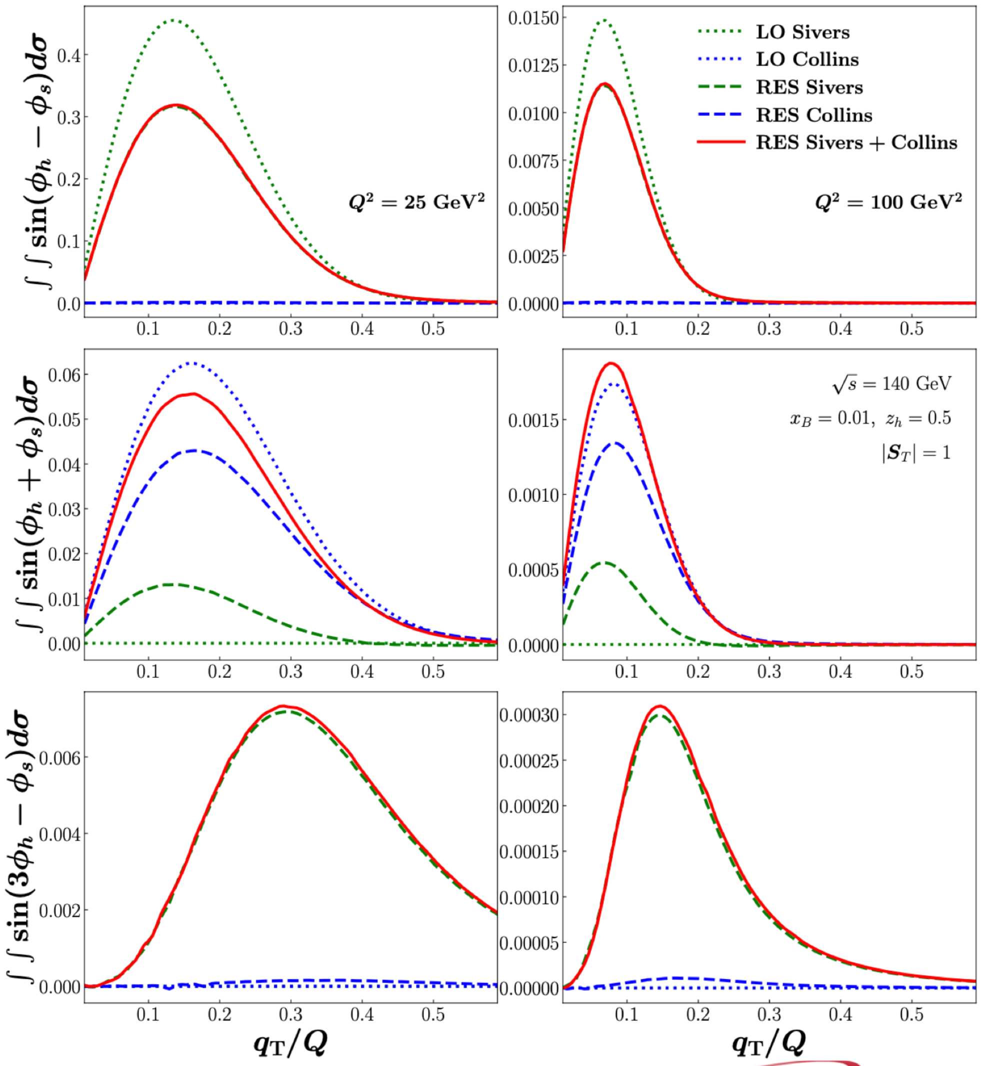
One-photon approximation

1) In "virtual-photon" frame, defined by $\hat{q}(\xi,\zeta) - p$

- TMD factorization when $\widehat{P}_T^2 \ll \widehat{Q}^2$
- CO factorization when $\widehat{P}_T^2 \sim \widehat{Q}^2$
- Matching to get the $\widehat{P}_T$-distribution

2) Lorentz transformation from the "virtual-photon" frame to any experimentally defined frame
– lepton-hadron Lab frame, Breit frame (x_B,Q^2), …

QED contribution (not correction) can be systematically improved order-by-order in power α!



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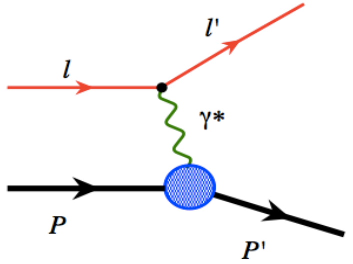
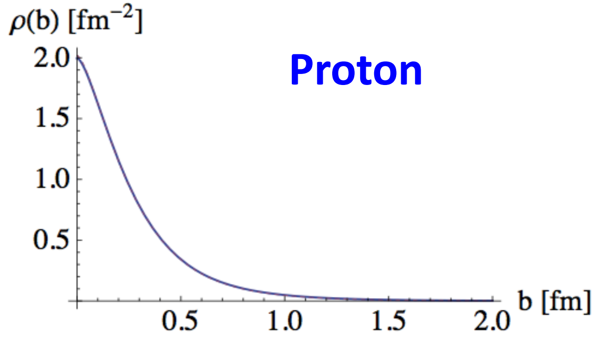
Exclusive lepton-hadron – Spatial Imaging

- Elastic e-p scattering – Electric charge distribution:

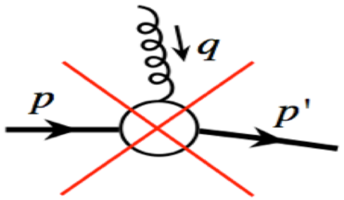


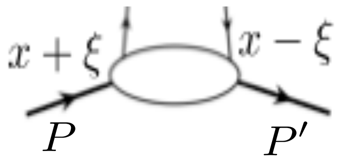


Proton
EM Charge
radius!

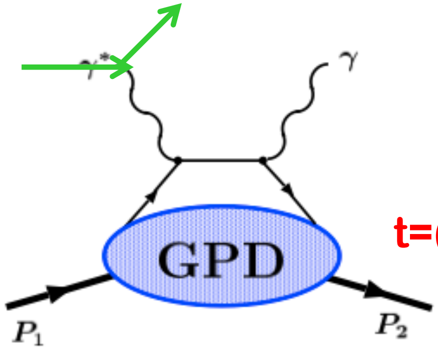
- No color nucleon elastic form factor!

No proton color charge radius!



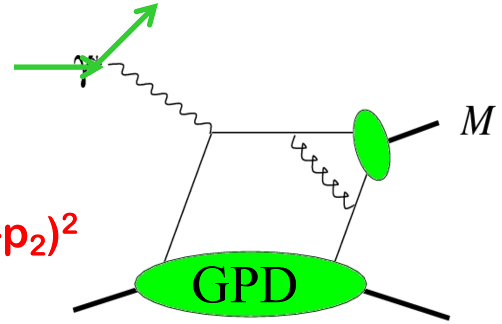


- Spatial quark/gluon density distributions – imaging:



+

$t=(p_1-p_2)^2$



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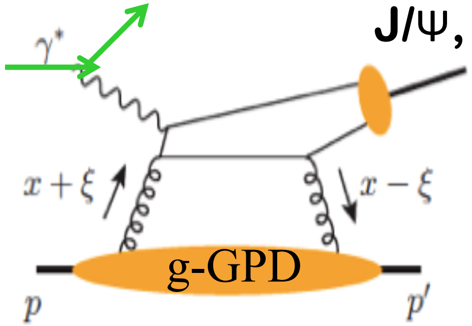


+ …

DVCS: $Q^2 >> |t|$

DVEM: $Q^2 >> |t|$

EHMP: $Q^2 >> |t|$

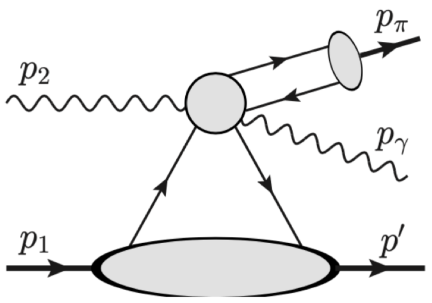
Sensitive to total momentum of the exchanged pair
Not
the relative momentum – x-dependence!

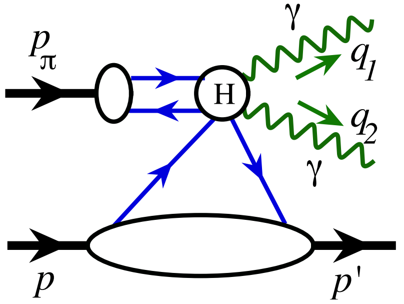
Exclusive lepton-hadron – Spatial Imaging

Qiu & Yu at QCD Evolution
arXiv:2109.xxxxx

❑ New-type of exclusive processes:

- Hard scale is not given by a point like virtual photon
- Hard scale is given by invariant mass of a final-state pair
- Both the invariant mass and PT (or angle) are sensitive to x-dependence of GPDs





QCD Factorization:

$$Q^2 = (p_\pi + p_\gamma)^2 \gg |t| = |(p_1 - p')^2|$$

$$|p_{\pi_T}| = |p_{\gamma_T}| \gg \Lambda_{\rm QCD}$$

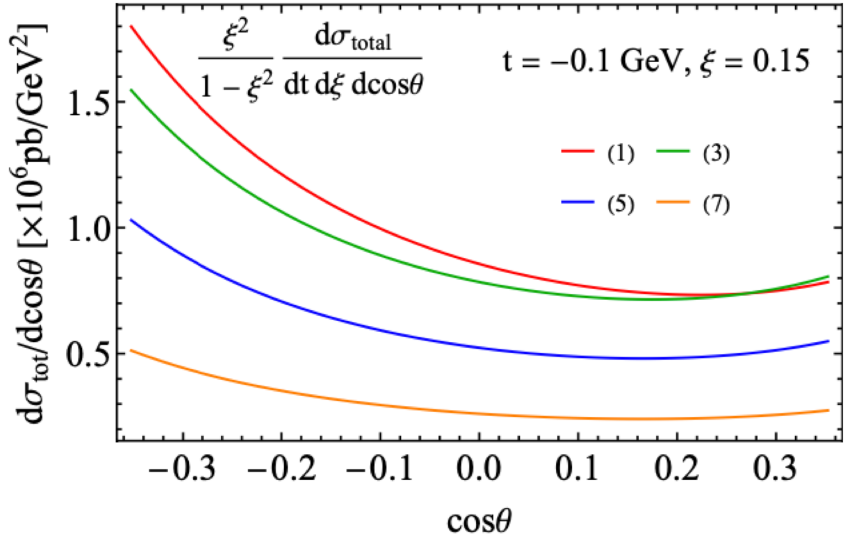
$$\mathcal{M} \propto \sum C(x, \xi, Q^2, p_{\pi_T}) \otimes \phi_\pi(z) \otimes \mathcal{H}(x, \xi, t)$$

❑ Numerical estimates:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|t|\,\mathrm{d}\xi\,\mathrm{d}\cos\theta_\pi\,\mathrm{d}\phi_\pi} = \frac{|\mathcal{A}|^2}{32\,s\,(2\pi)^4\,(1+\xi)^2}$$

$$\frac{1}{2}\overline{|\mathcal{A}|^2} = \left(\frac{2\pi\alpha_s}{s} f_\pi\right)^2 \left(\frac{C_F}{N_c}\right)^2 \left(\frac{1+\xi}{\xi}\right)^2 (1-\xi^2)$$

$$\times \left[|\mathcal{M}^{[\tilde{H}]}_{++}|^2 + |\mathcal{M}^{[\tilde{H}]}_{+-}|^2 + |\mathcal{M}^{[H]}_{++}|^2 + |\mathcal{M}^{[H]}_{+-}|^2\right]$$



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Exclusive lepton-hadron – Spatial Imaging

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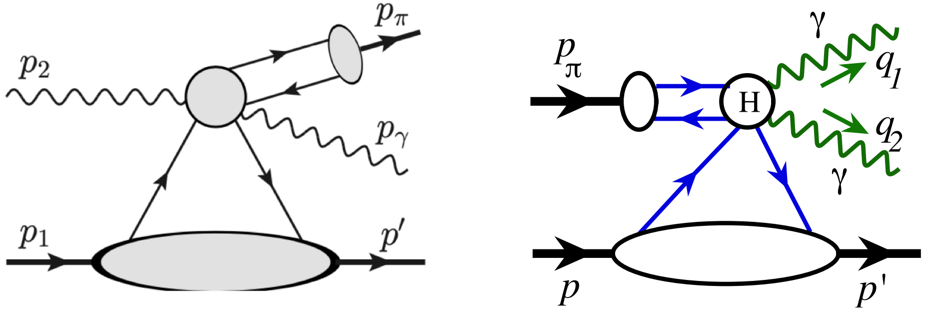

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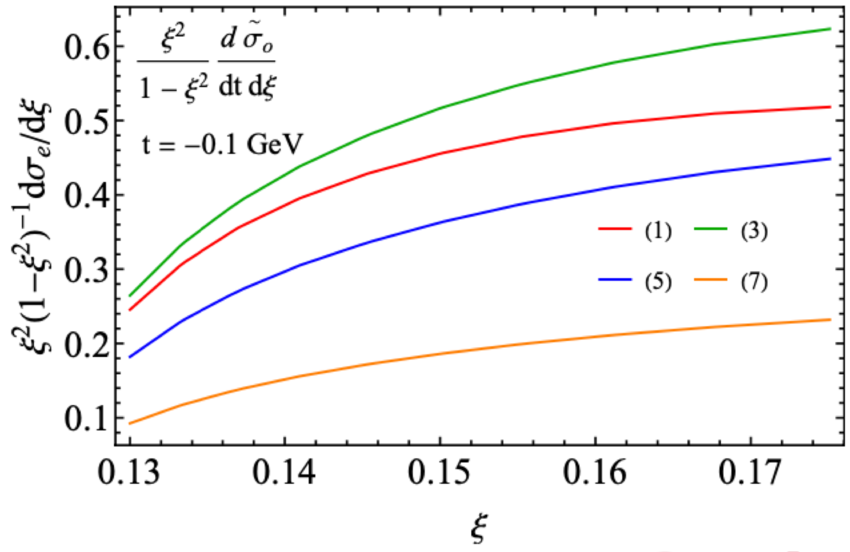

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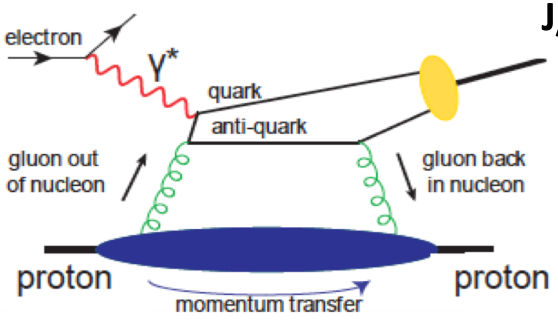
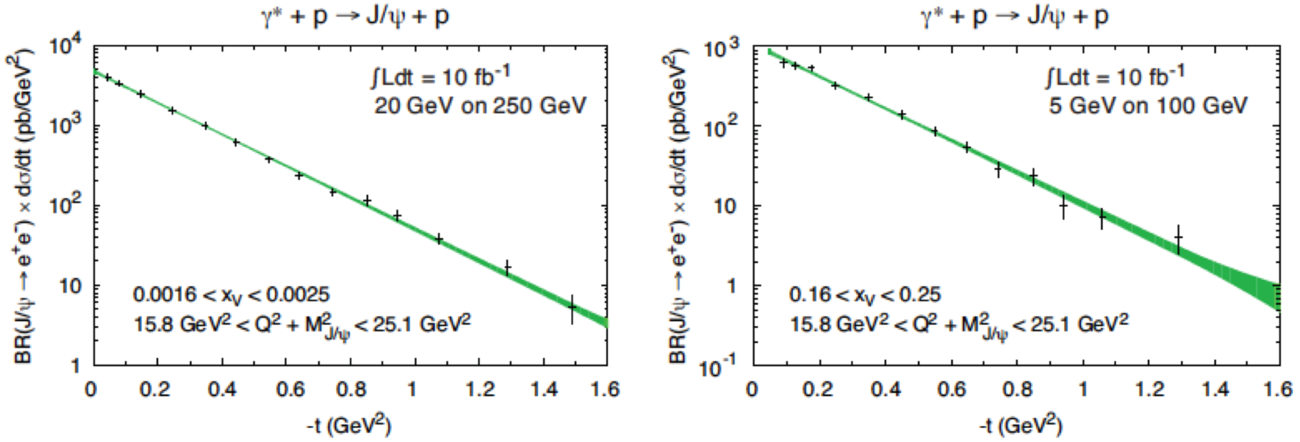
Spatial Imaging of Gluon Density

- "Seeing" the glue at EIC:



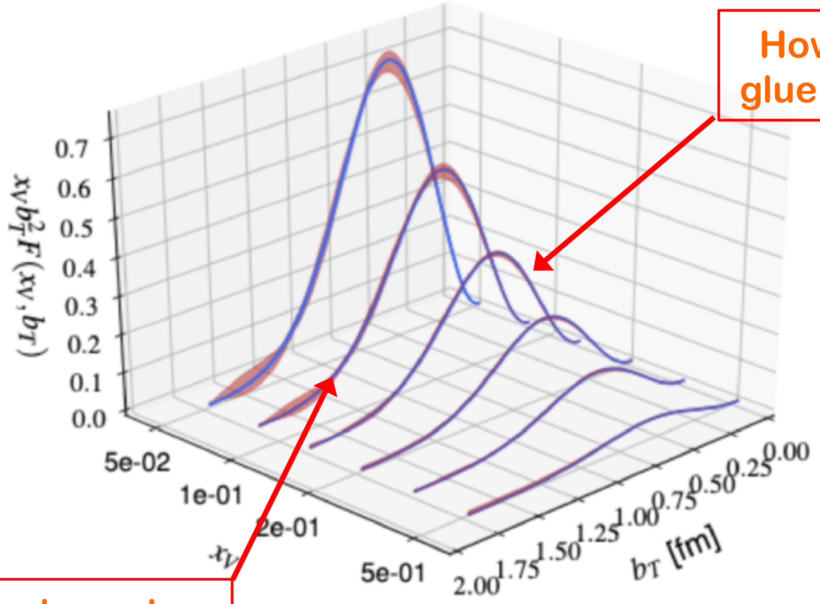
J/Ψ, Φ, …

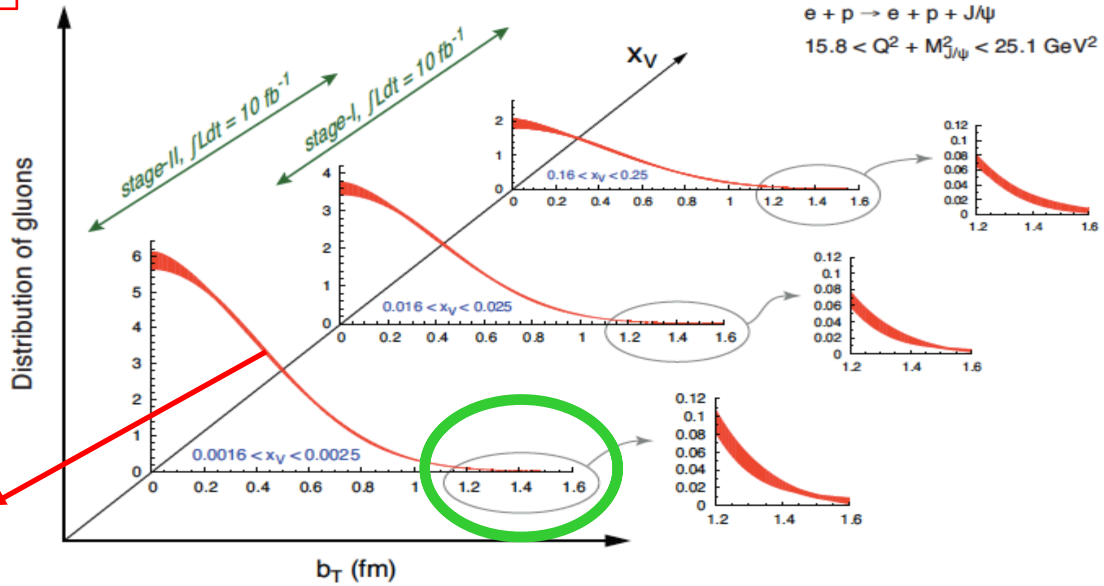
t-dep



F.T.

How fast does glue density fall?





How far does glue density spread?

Proton radius of gluons (x)!

Only possible at EIC!

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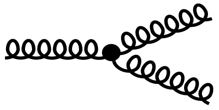
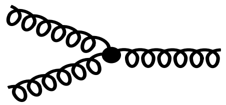
Emergent Properties of Dense Gluons

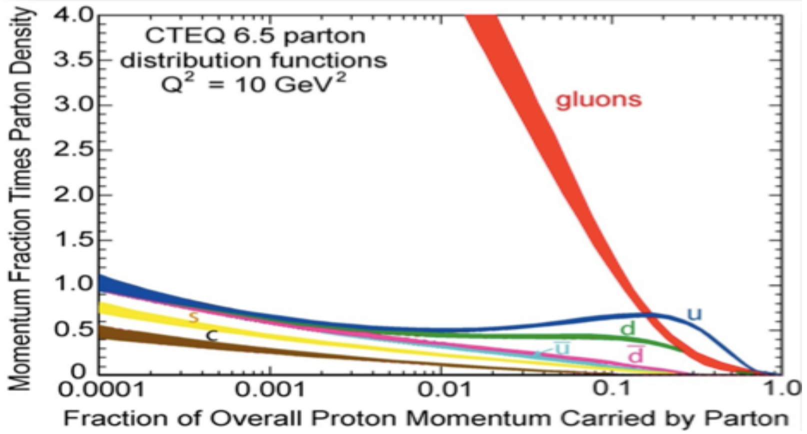
- **Another HERA discovery:**
  - **What are the emergent properties of dense systems of gluons, when the occupation number is ~ O(1)?**



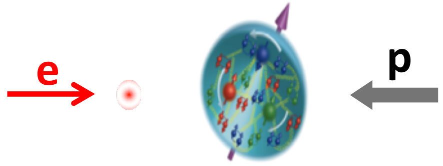
vs.



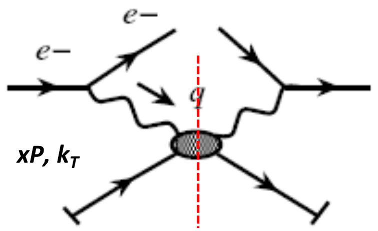
Part of QCD



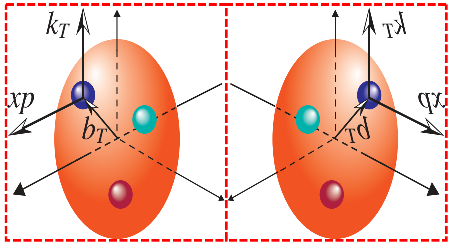
- **Impact of color entanglement enhanced at small-x:**



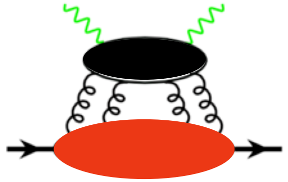
$\sigma^{\rm DIS}_{\rm tot} \sim$



$\otimes$



$+$



$+ \ldots$

$\mathcal{O}(Q_s^n/Q^n)$

$$= \sum_f \hat{C}_f \otimes \Phi_f + \mathcal{O}\left(Q_s^2/Q^2\right) + \mathcal{O}\left(Q_s^4/Q^4\right) + \ldots$$

$Q_s^2 \propto$ parton density

Color entangled or correlated between two active partons

- **Saturation:**

When $Q_s \sim Q$, every term is equally important, and counting single parton is meaningless

➡ ***Need new and coherent degree of freedom More of the wave nature of the glue!***

➡ ***Saturation of gluons = Color Glass Condensate (CGC)***

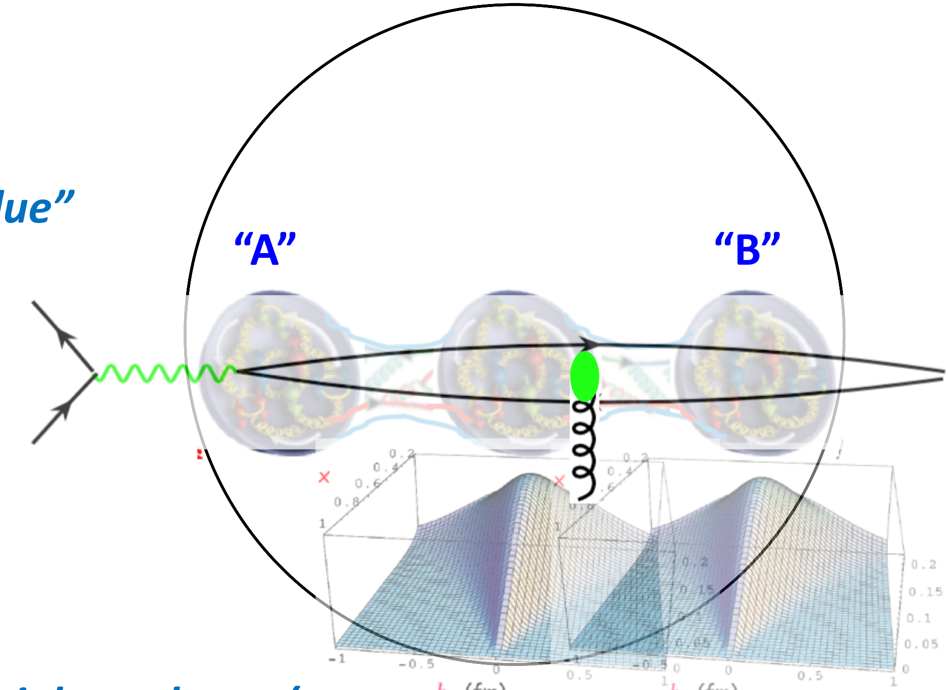
Saturation is a part of QCD, where to find it?

Internal Nuclear Landscape

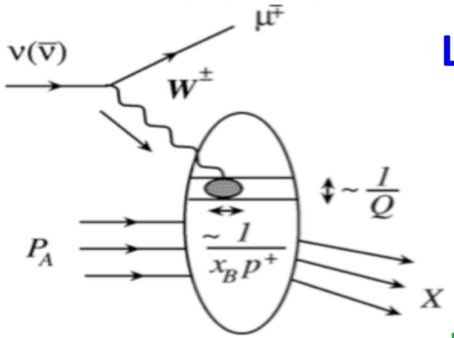
- A simple, but fundamental, question:

  What does a nucleus look like *if we only see quarks and gluons ?*

  Need localized hard probes – "see" more particle nature of the "glue"



- But, a hard probe at small-x is NOT necessarily localized:



In c.m. frame

Longitudinal probing size

> Lorentz contracted nucleon

if $\frac{1}{xp} > 2R\frac{m}{p}$ or $x < 0.1$

➡ ***A hard probe at small-x can interact with multiple nucleons (partons from multiple nucleons) at the same impact parameter coherently***

- Another simple, and fundamental, question:

  Does the color of a parton in nucleon "A" know the color of a parton in nucleon "B"?

  IF YES, Nucleus could act like a bigger proton at small-x (long range of color correlation), and could reaching the saturation much sooner!

  IF NOT, only short-range color correlation, and observed nuclear effect in cross-section at small-x is dominated by coherent collision effect

EIC can tell !

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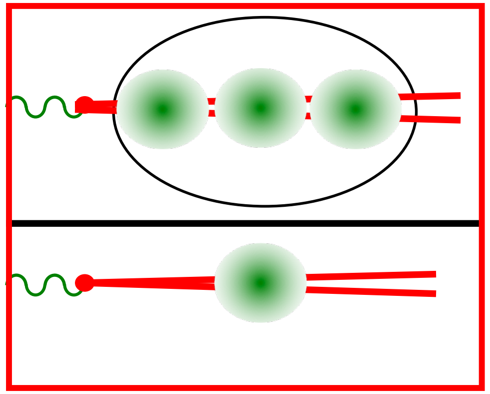
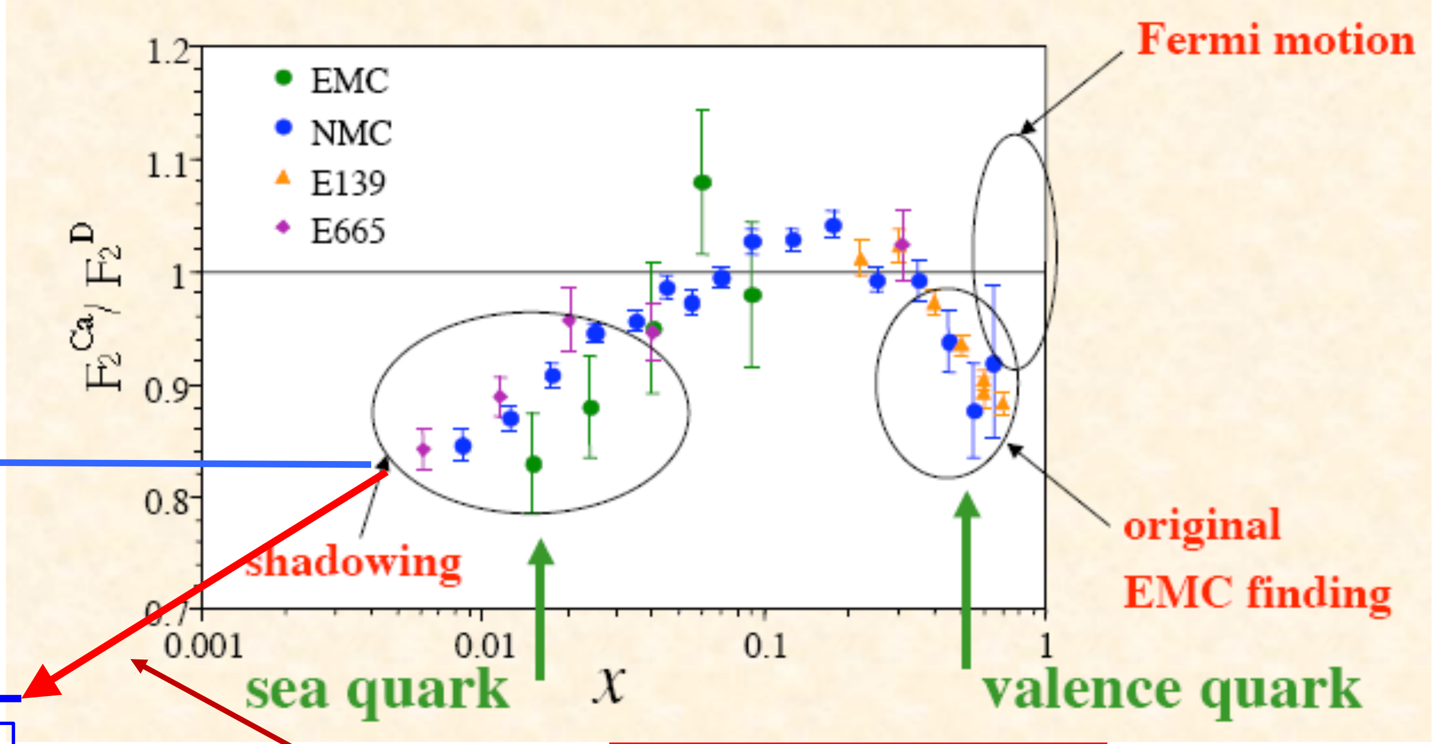
Coherent Length of the Color

- A simple experiment to address a "simple" question:

Will the nuclear shadowing continue to fall as x decreases?

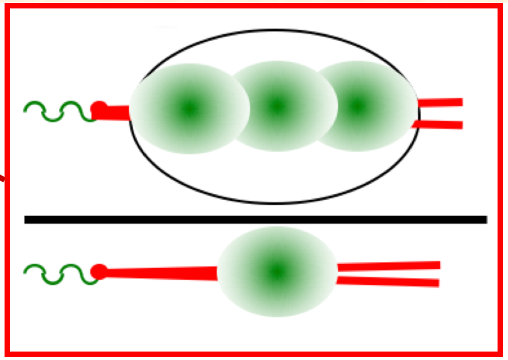




Color localized
Inside nucleons

Nucleus as a
bigger proton

Color leaks outside nucleons
Proton radius of soft gluon is larger !



EIC can tell !

Summary and Outlook

- QCD has been very successful in describing the short-distance dynamics owing to its “Asymptotic Freedom”, a defining property of QCD
- QCD’s another defining property, “Confinement”, makes the QCD and its emergent phenomena extremely rich, opening up a new femto-science
- EIC is a ultimate QCD machine and a facility, capable of discovering and exploring the emergent phenomena of QCD, and the role of color and glue
- US-EIC is sitting at a sweet spot for rich QCD dynamics, capable of taking us to the next frontier of the Standard Model!

September 18 2020

Thanks!