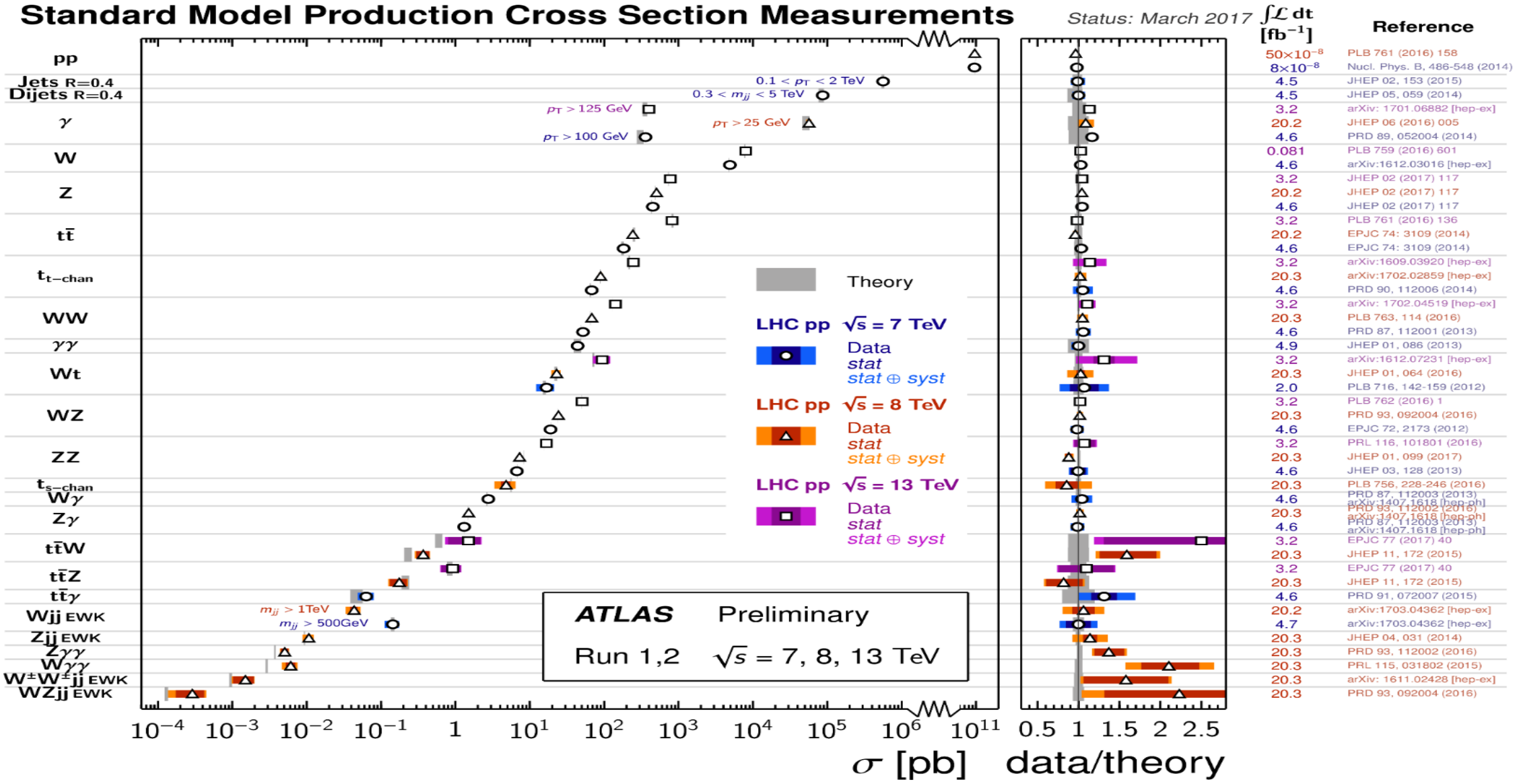
An Overview of the Physics Goals of the Electron-Ion Collider

- **Why do we need the Electron-Ion Collider (EIC)?**
  - Something is still missing in the great success story of the Standard Model (SM)
    - – QCD and strong force at the Fermi scale: questions and challenges
  - Why we need a lepton-hadron collider?
  - What the EIC can do, but, HERA could not do?
- **Some physics questions that the EIC could help address and corresponding opportunities:**
  - How are hadron properties (mass, spin, size(s), …) emerged from QCD?
  - How are quarks/gluons distributed/confined inside hadrons?
  - How do nuclei "look" like if we only "see" quarks and gluons (origin of nuclear force)?
  - How precise do we need to know QCD for discovering beyond SM (BSM), …?
- **Realization of the EIC:**
  - Schedule, challenges, …

Jian-Wei Qiu
Jefferson Lab, Theory Center

Unprecedented Success of the Standard Model (including QCD)!



FACT: Electroweak processes + QCD perturbation theory works!

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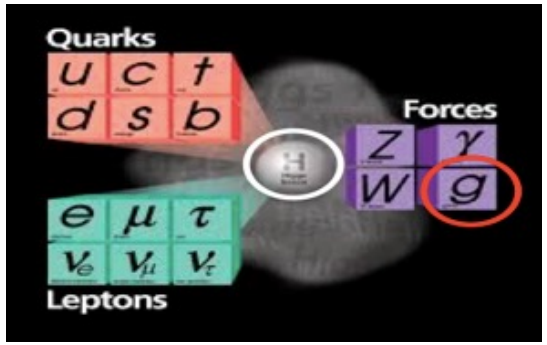
Frontiers of QCD and Strong Interaction

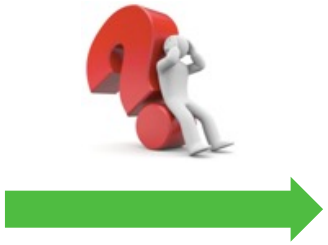
- QCD at high temperature, high density, phase transition, …

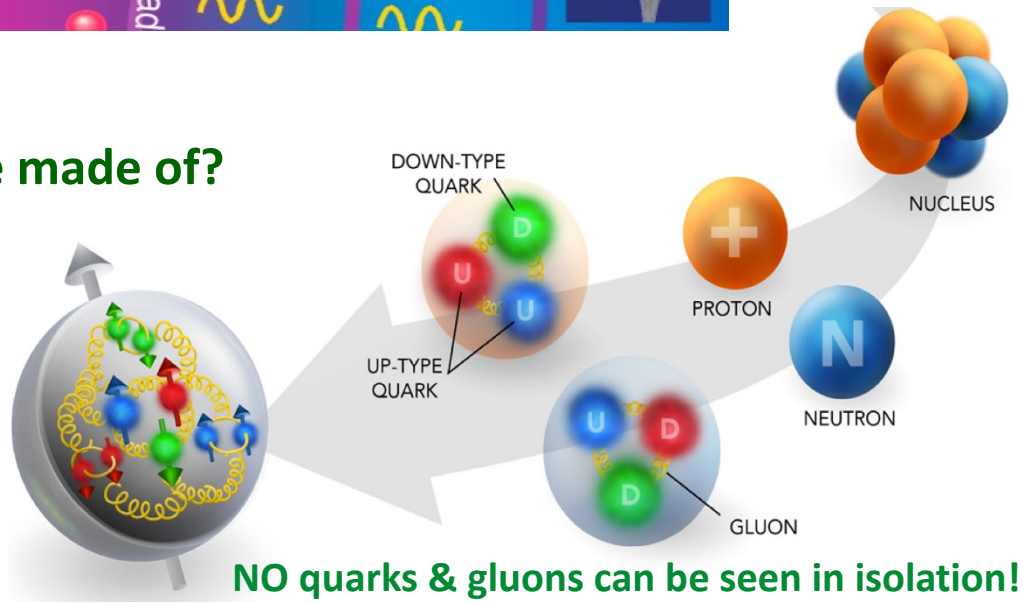
Global Time: ⟶

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

- Understanding QCD at about zero temperature – what we are made of?





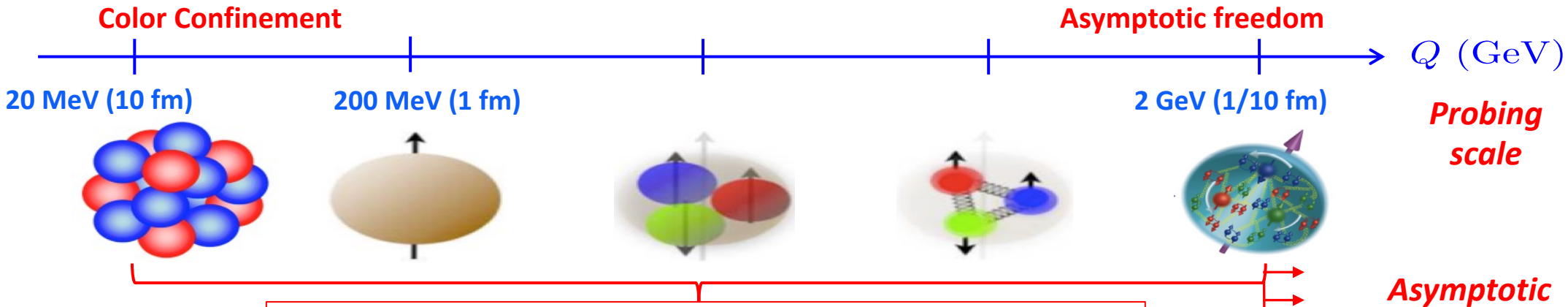


NO quarks & gluons can be seen in isolation!

- How are hadrons & their properties (mass, spin, size(s), …) emerged from quarks, gluons & their interactions?
- How are quarks and gluons confined and distributed inside hadrons (not seen in isolation)?
- How do nuclei "look" like if we only "see" quarks and gluons?
- How precise do we need to know QCD for discovering BSM?
- …

Need to explore QCD & strong interaction physics at a Fermi scale!
Facilities – CEBAF, EIC, EICC, LHeC, …

QCD Dynamics/Phenomena at the Fermi-Scale – Nuclear Femtography



QCD at the Fermi Scale: Femto-science (0.1-10 fm)

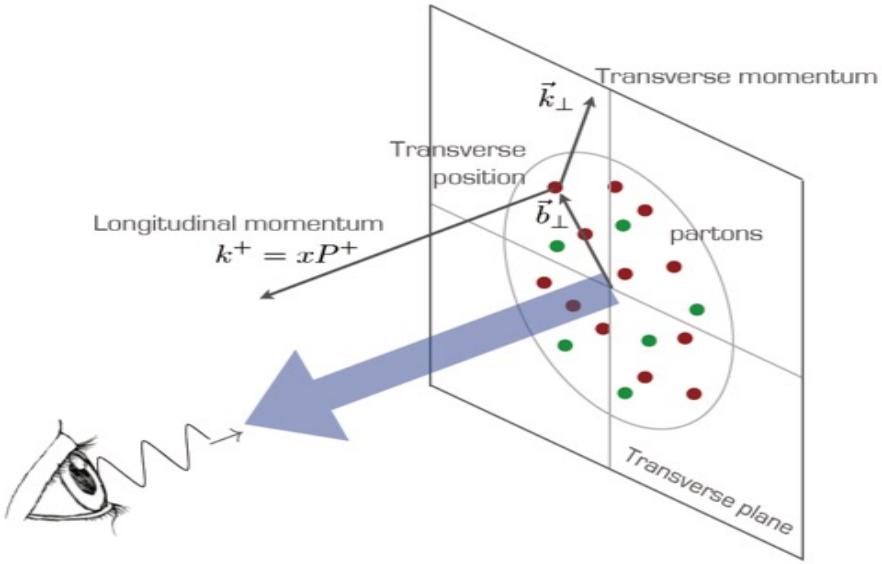
- ***The most interesting, rich, and complex regime of the theory!***
- ***All emergent phenomena depend on the scale at which we probe them!***

Asymptotic regime PQCD works beautifully!

❑ **Need new observables with two distinctive scales:**

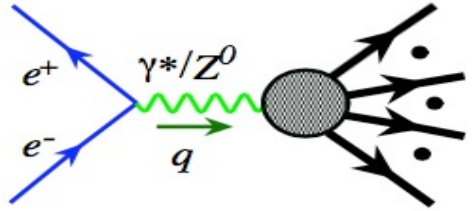
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

- **Hard scale:** Q_1 **to localize the probe to see the particle nature of quarks/gluons**
- **"Soft" scale:** Q_2 **could be more sensitive to the hadron structure ~ 1/fm**

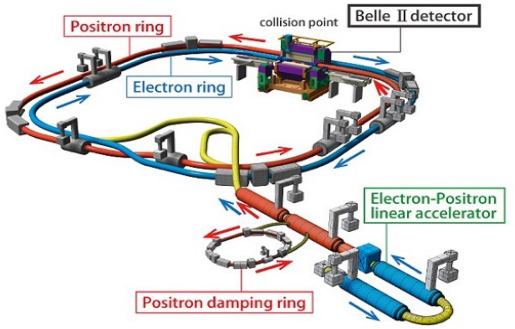


Exploring QCD & Hadron Structure Needs Lepton-Hadron Facilities

❑ Lepton-lepton colliders (e+e- collisions):

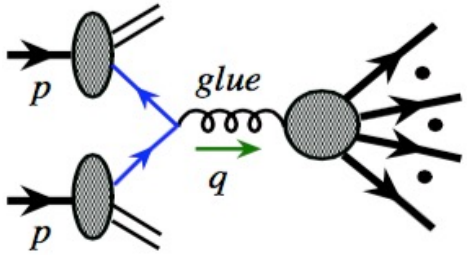


- *No hadron to start with*
- *Hadrons are produced in the collisions*
- *Emergence of hadrons*

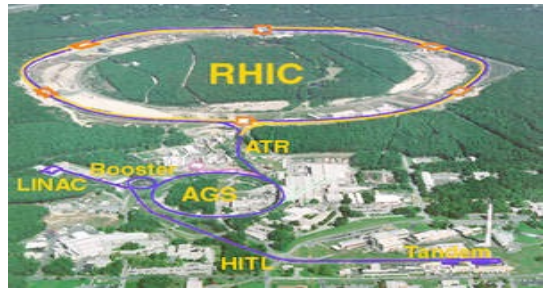


Also BES III

❑ Hadron-hadron facilities (hadrons are likely broken in the collisions):

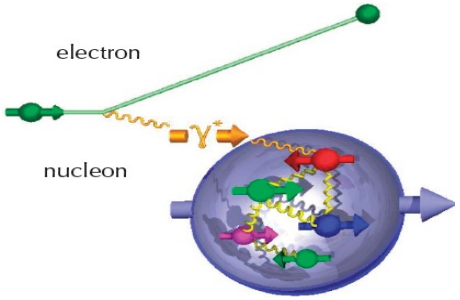


- *Partonic structure mixed with collision effects*
- *Emergence of hadrons*
- *Heavy ion beam(s) – dense medium, QGP*

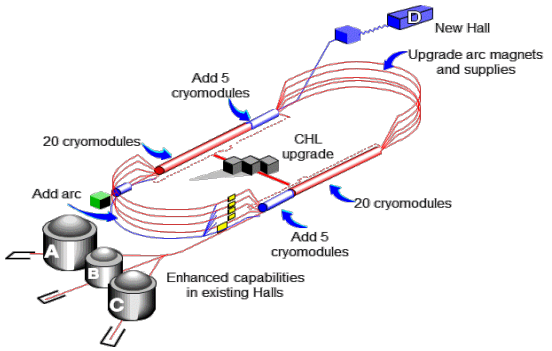


Also the LHC, J-PARC, …

❑ Lepton-hadron facilities (HERA discovery: hadron stays intact 10-15% time):



- *Two-scale observables are natural*
- *Imaging partonic structure without breaking it!*
- *Emergence of hadrons*
- *Heavy ion target or beam*



Also COMPASS/Amber & future EIC, …

Ideal facility for partonic structure of hadron/nuclei !

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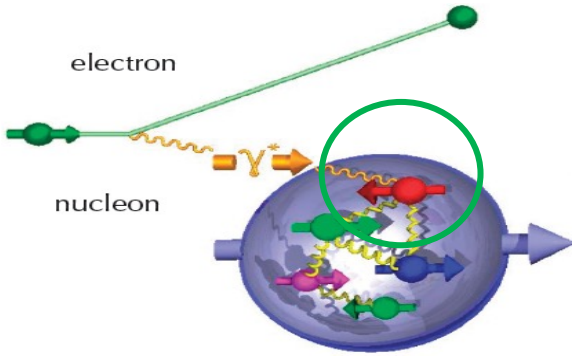
Lepton-Hadron Facility is Ideal for Exploring Hadron's 3D Partonic Structure

- **Two-scale observables are natural in lepton-hadron scattering**



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

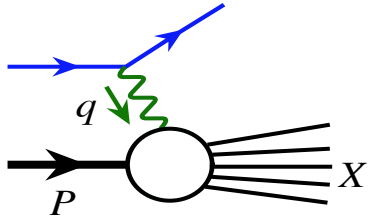
$$Q^2 = -q^2 \qquad x_B = Q^2/2P.q$$

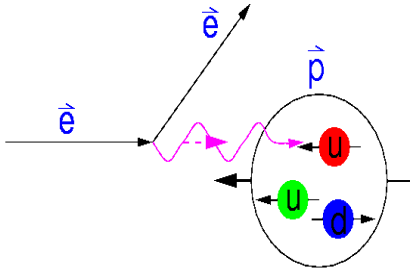
Sensitive to momentum fraction of colliding quark or gluon

- **Inclusive events: e+p/A → e'+X** (Single scale $Q \gg \Lambda_{\rm QCD}$)

  Detect only the scattered lepton in the detector

  (Modern Rutherford experiment!)

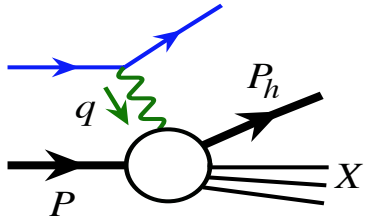


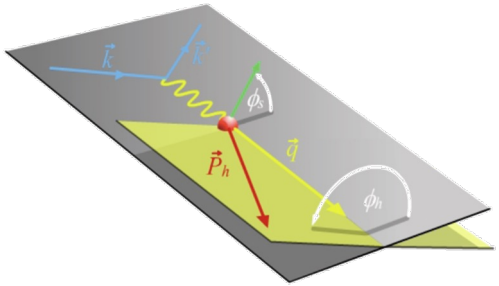


- **Semi-Inclusive events: e+p/A → e'+h(p,K,p,jet)+X** $Q \gg P_{hT}$

  Detect the scattered lepton along with identified hadrons/jets

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

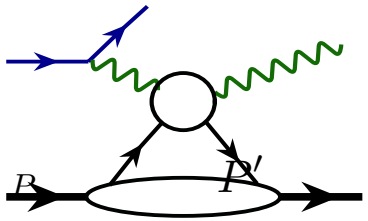


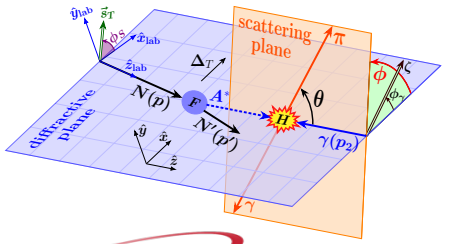


- **Exclusive events: e+p/A → e'+ p'/A'+ P**(γ,π,K,p,jet) $Q \gg \sqrt{-t}$

  Detect every things including scattered proton/nucleus $t = (P - P')^2$

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





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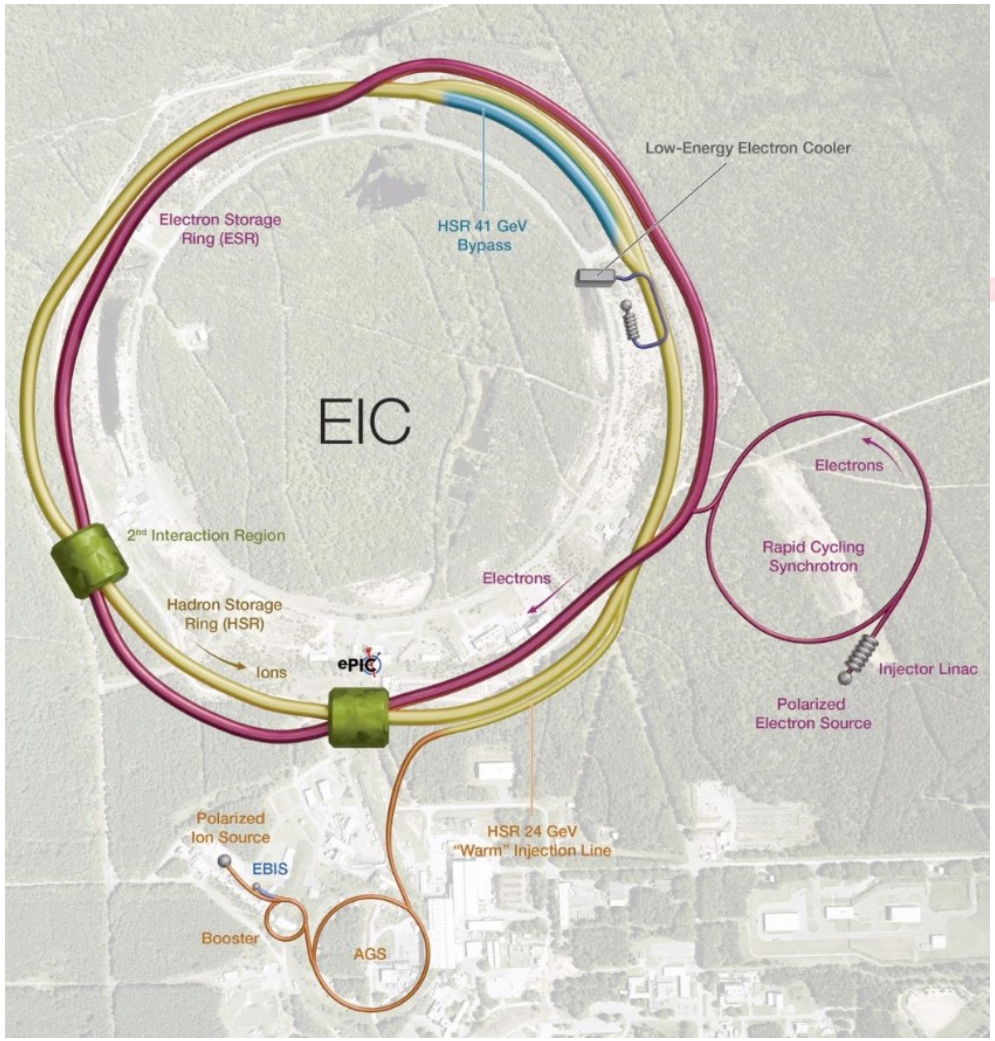
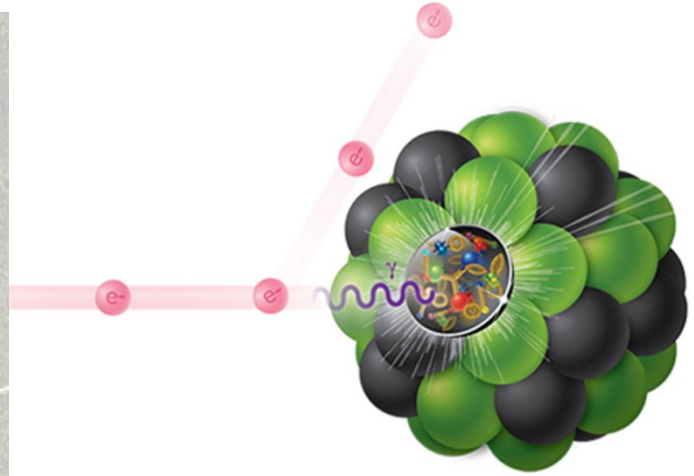
U.S. - based Electron-Ion Collider (EIC)

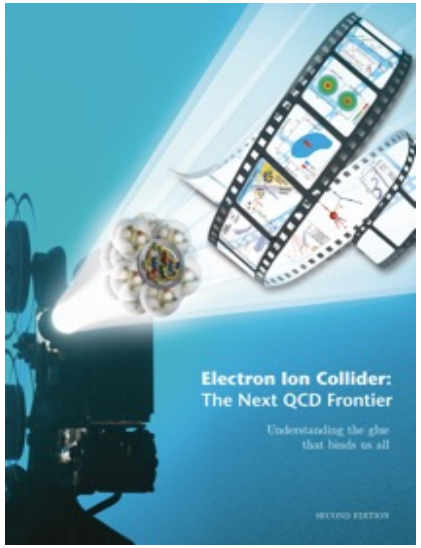
https://www.bnl.gov/eic/

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

Like a CT Scanner for Atoms







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

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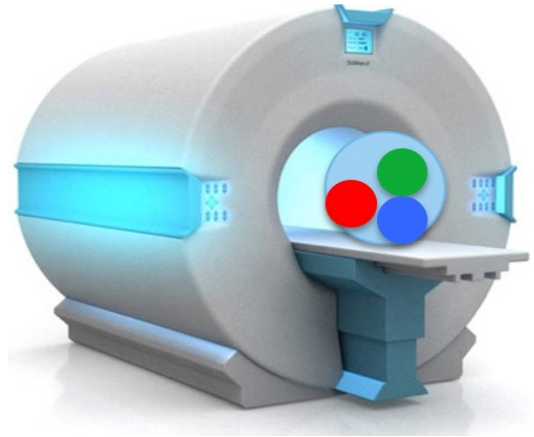
US-EIC – can do what HERA could not do

- **Quantum imaging:**
  - HERA discovered: 10-15% of e-p events is diffractive – Proton not broken!
  - US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!*

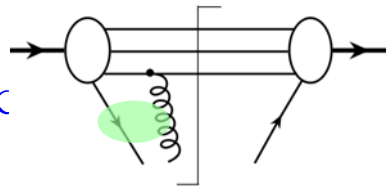
Large momentum transfer without breaking the proton
Need luminosity!



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

$$\sigma(Q,\vec{s}) \propto \left| \; + \; + \; + \cdots \right|^2$$

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



No probability interpretation!

- **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, color neutralization, …,
  - *– "Femtometer-detectors" with controllable size and properties – Atomic nuclei*

Wave nature of quark/gluon field

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U.S. - based Electron-Ion Collider (EIC)

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

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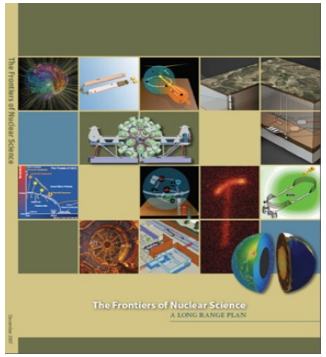

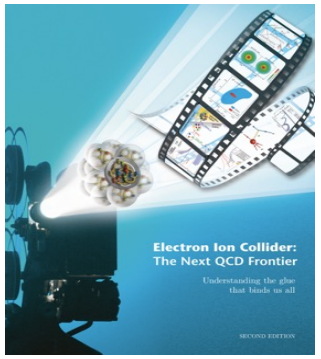

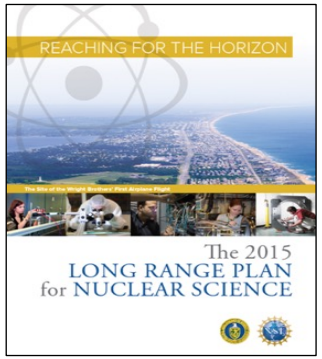

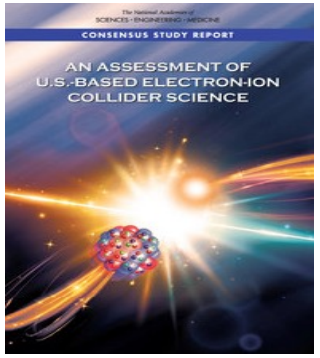

...

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?

- January 9, 2020: *The U.S. DOE announced the selection of BNL as the site for the Electron-Ion Collider*
- July 6, 2021: Achieved Critical Decision 1 (CD1) approval

DOE/NP approved 3A and 3B *Need CD2 for full baseline design and cost for the machine!*

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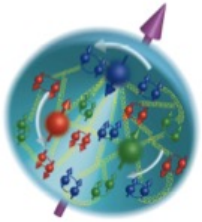
How does the Mass of the Nucleon arise?

❑ 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 + Energy of their motion

❑ Higgs mechanism is NOT enough – mass without mass!

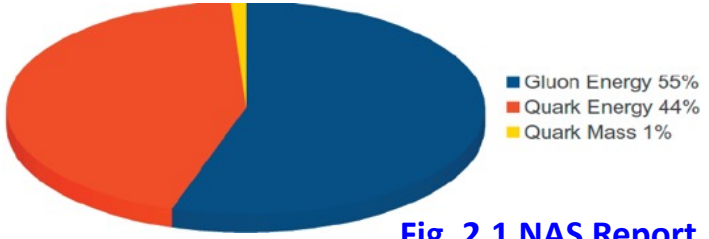


Fig. 2.1 NAS Report

Higgs mechanism is far from enough!!! ➡ Energy of Confined Motion of quarks and gluons

❑ Consistency check:

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 $K + T$:

$$M_p \sim \frac{4}{R} \sim \frac{4}{0.84\text{fm}} \sim 938\ \text{MeV}$$

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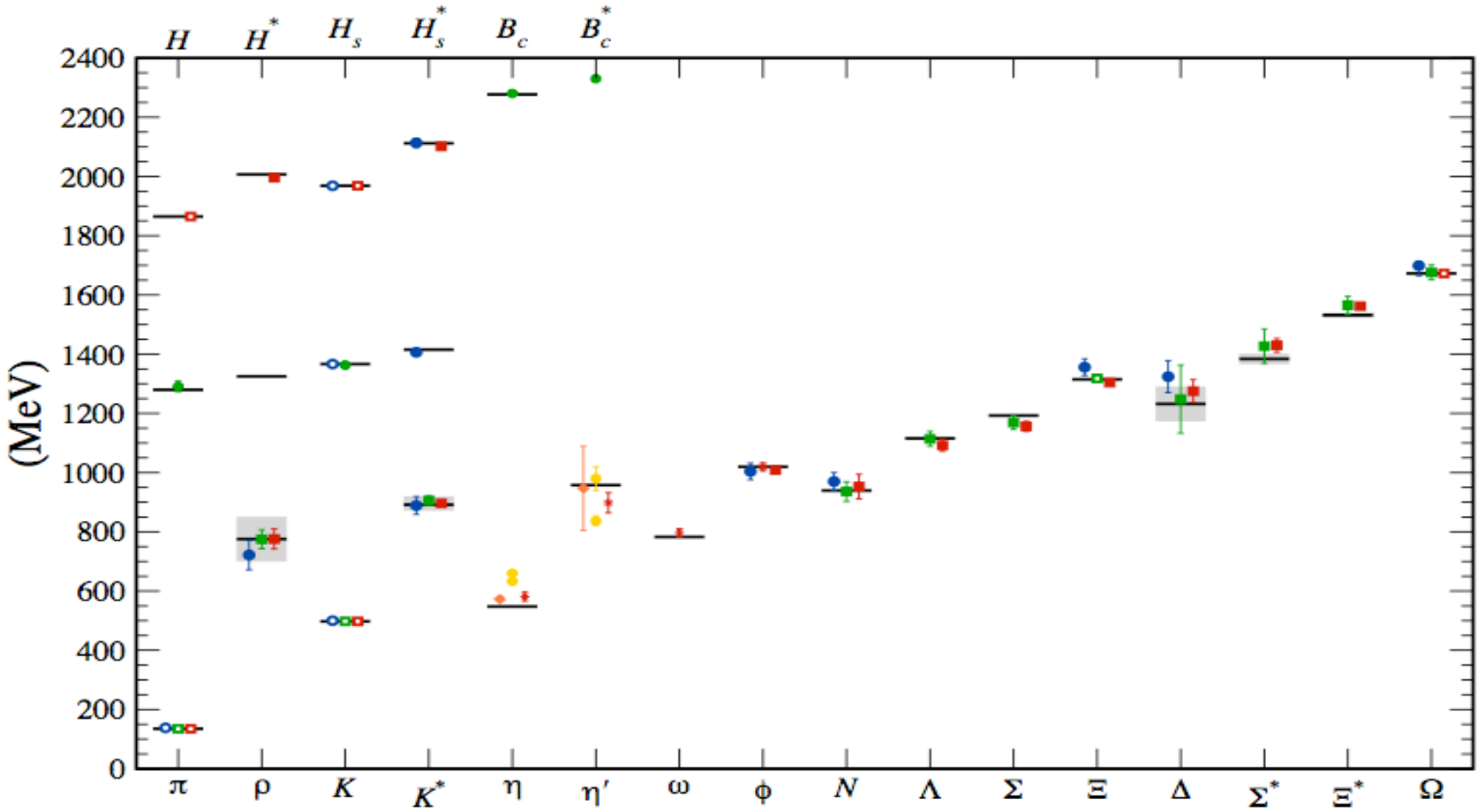
Who ordered the Hadron Mass Scale?

- Hadron mass from lattice QCD calculation:



QCD is the right theory!

How to quantify and verify this, beyond LQCD simulation (black box)?

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The Proton Mass: Decomposition

- **Role of quarks and gluons?**
  - **Trace of the QCD energy-momentum tensor:**

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

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

  - **Hadron mass:** ***Gluon quantum effect + Chiral symmetry breaking!***

- **Decomposition or sum rules – could be frame dependent!**

$$M_p = \left. \frac{\langle P | \int d^3x\, T^{00} | P \rangle}{\langle P | P \rangle} \right|_{\text{at rest}} = E_q + E_g + \chi_{m_q} + T_g$$

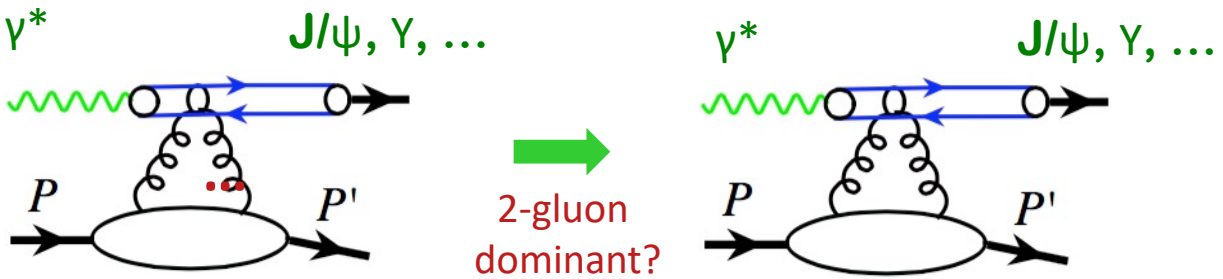
Relativistic motion → E_q; χ Symmetry Breaking → χ_{m_q}; Quantum fluctuation → T_g; Trace Anomaly → T_g; Quark Energy → E_q; Gluon Energy → E_g; Quark Mass → χ_{m_q}

Sum Rule is useful iff ALL individual terms can be measured independently!

- **Critical measurement:**

Probing Trace anomaly:

Probe parton's energy distribution inside the proton?



Extract the trace anomaly from exclusive J/ψ, Υ production at EIC

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The Proton Mass: Decomposition

- **Ji's decomposition/interpretation – NOT unique:**

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

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

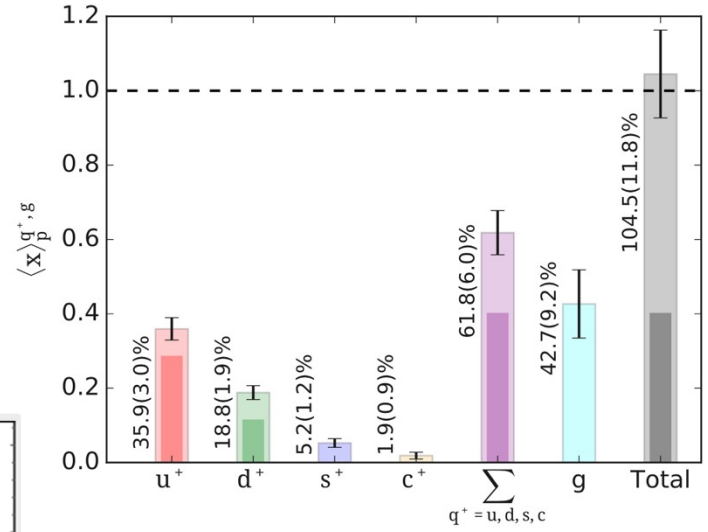
Quark Mass $\langle \widehat{T}_q^{00} \rangle$:
$$M_m = \sum_q \sigma_q$$

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:

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

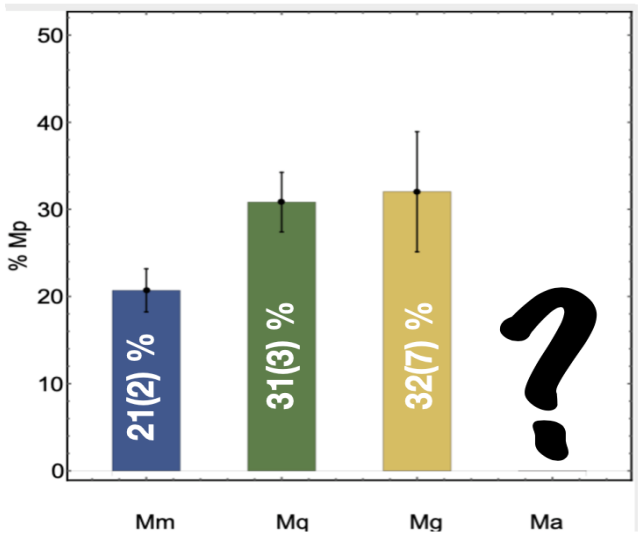


- **LQCD calculation:**

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?

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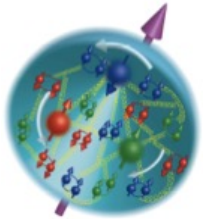
How does the Spin of the Nucleon arise?

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



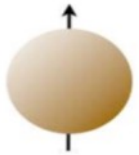
Spin is the Angular Momentum of the nucleon when it is at the Rest!

Spin = Spin of quarks and gluons + Angular Momentum from their orbital motion

Helicity = Angular momentum projected onto the direction of hadron's motion

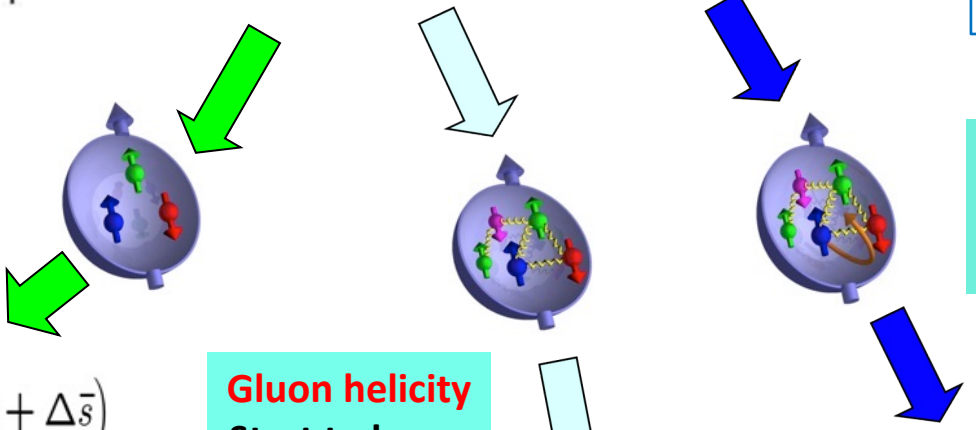
- **An incomplete story:**

Proton Spin



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

Numbers of quarks and gluons inside a proton depends on the scale at which the proton is probed!



Quark helicity
Best known

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

$$\sim 30\%$$

Gluon helicity
Start to know

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

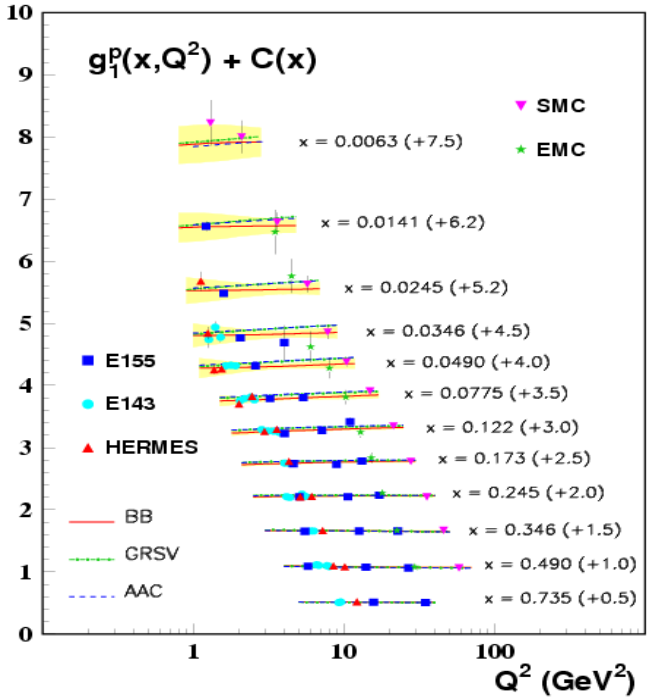
$$\sim 40\%(\text{with RHIC data})$$

Orbital Angular Momentum of quarks and gluons
Little known

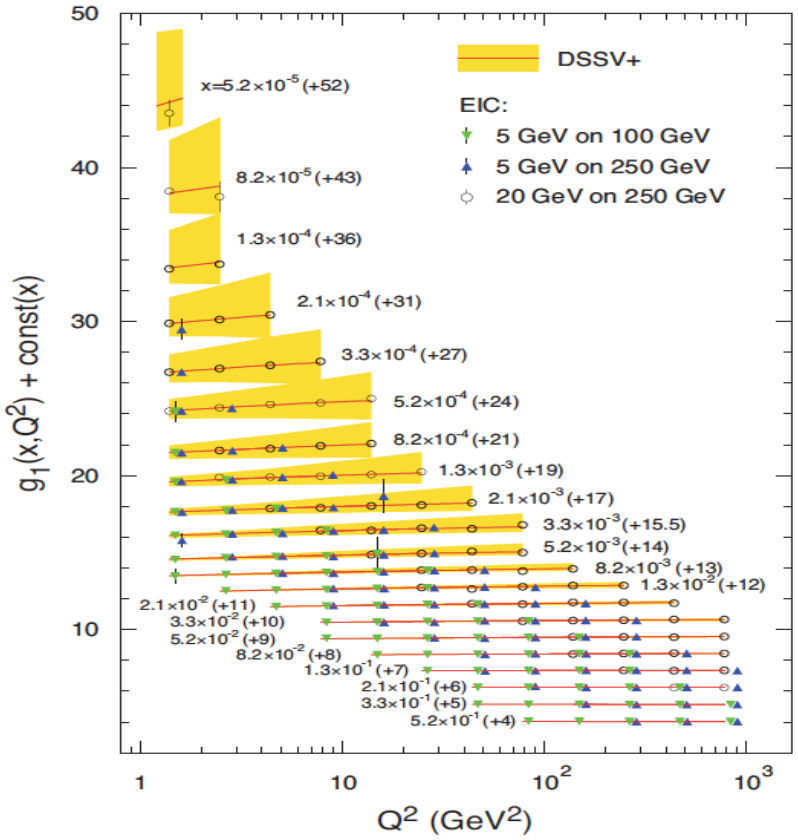
Net effect of partons' transverse motion?

The Proton Spin: from JLab12 to EIC

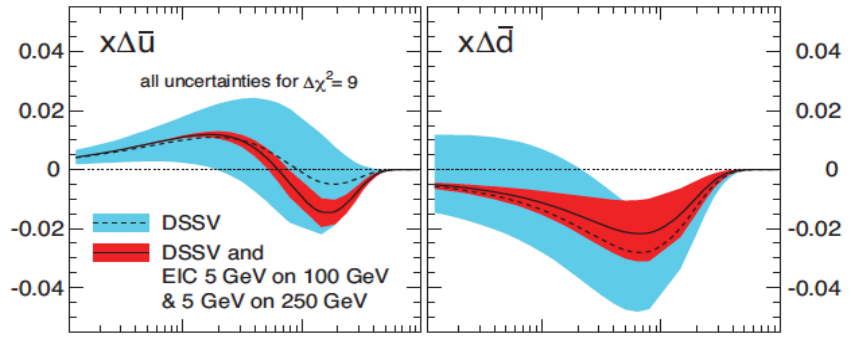
❑ The power & precision of EIC:

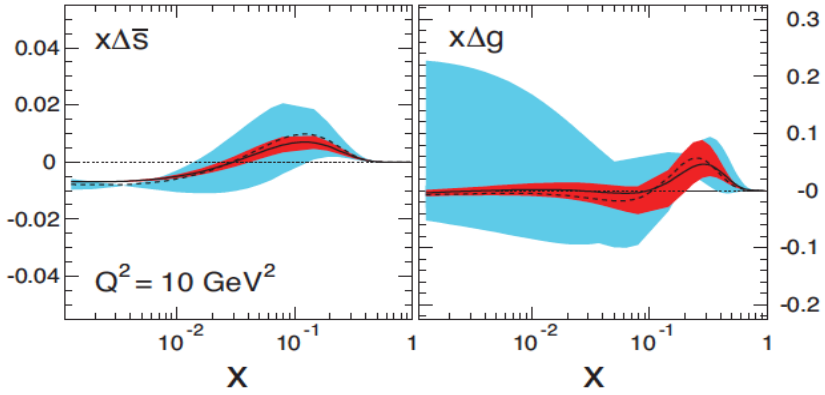


Polarized DIS at EIC



❑ What an EIC could help:





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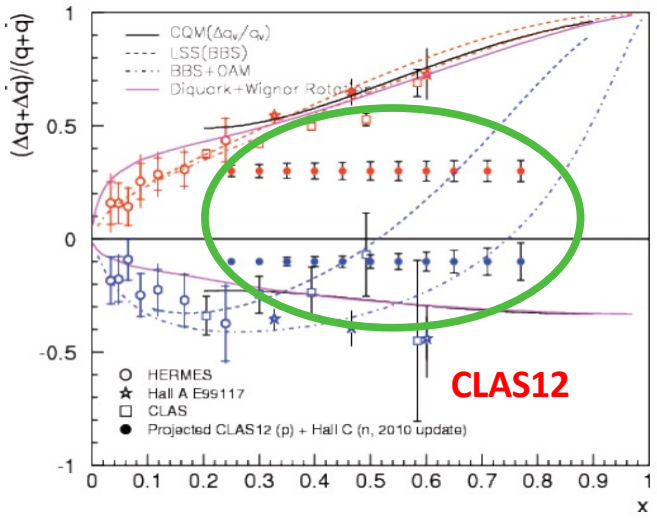
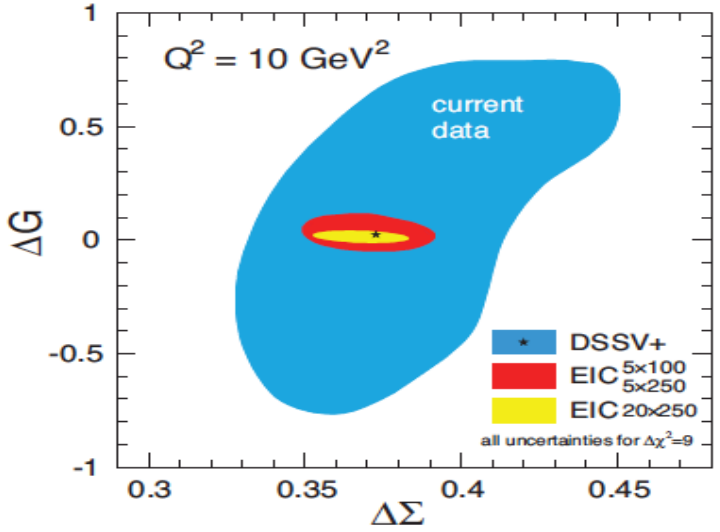
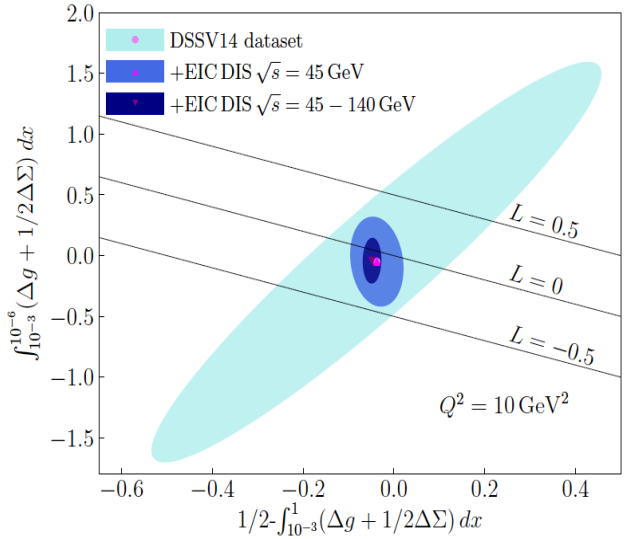
The Proton Spin: from JLab12 to EIC

❑ Complementary between JLab12 and EIC – White Paper:

arXiv:2103.05419

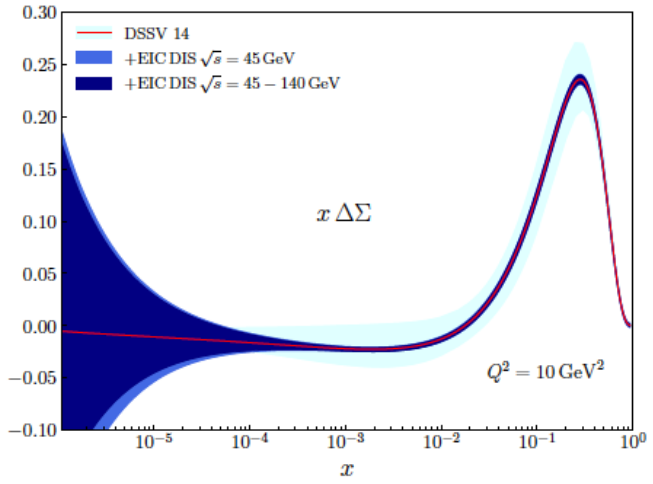


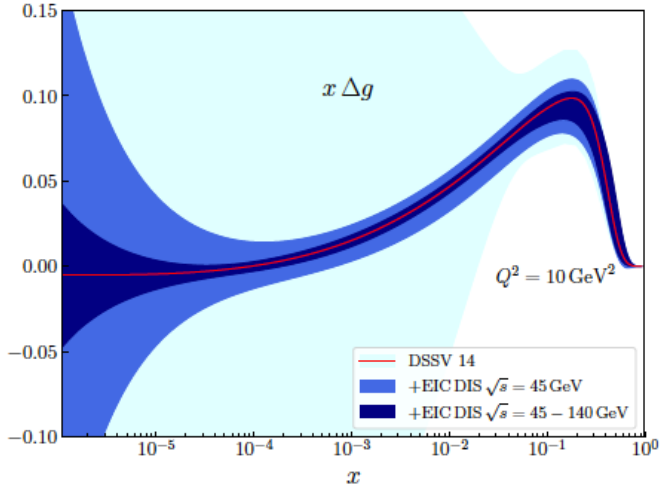


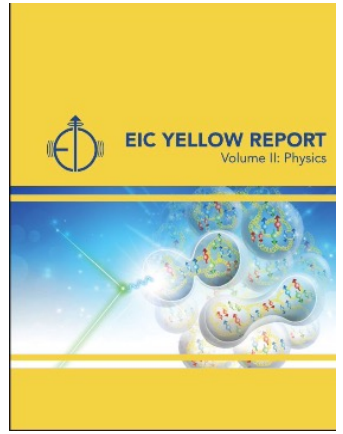


Room for orbital momentum

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







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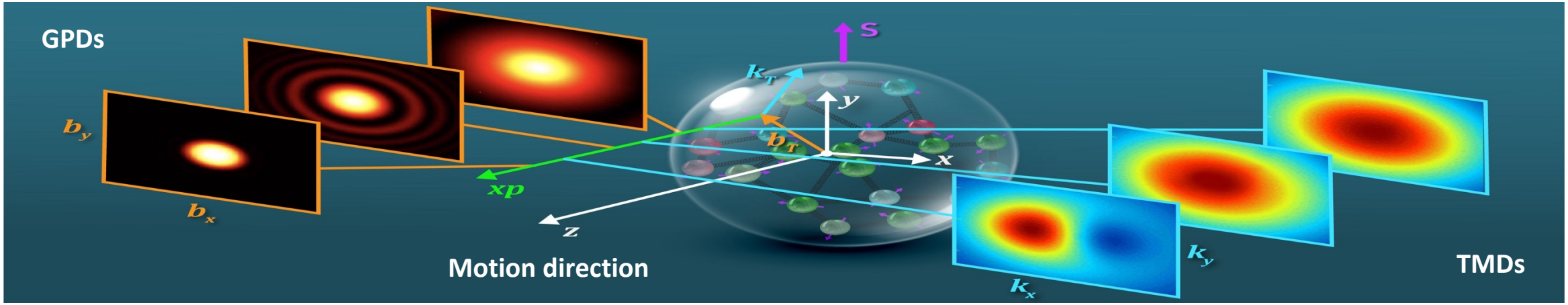
Exploring Hadron's 3D Partonic Structure

❑ **3D hadron's partonic structure:**

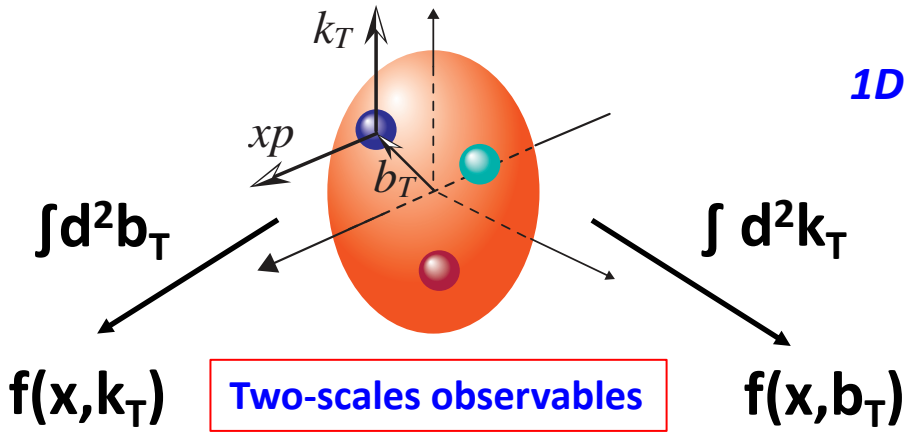


❑ **A unified description (Wigner distributions in 5D):**

3D Momentum Space

Transverse Momentum Dependent Parton Distributions (TMDs)

Parton's transverse motion



1D momentum + 2D Coordinate Space

Generalized Parton Distributions (GPDs)

Parton's transverse spatial distribution

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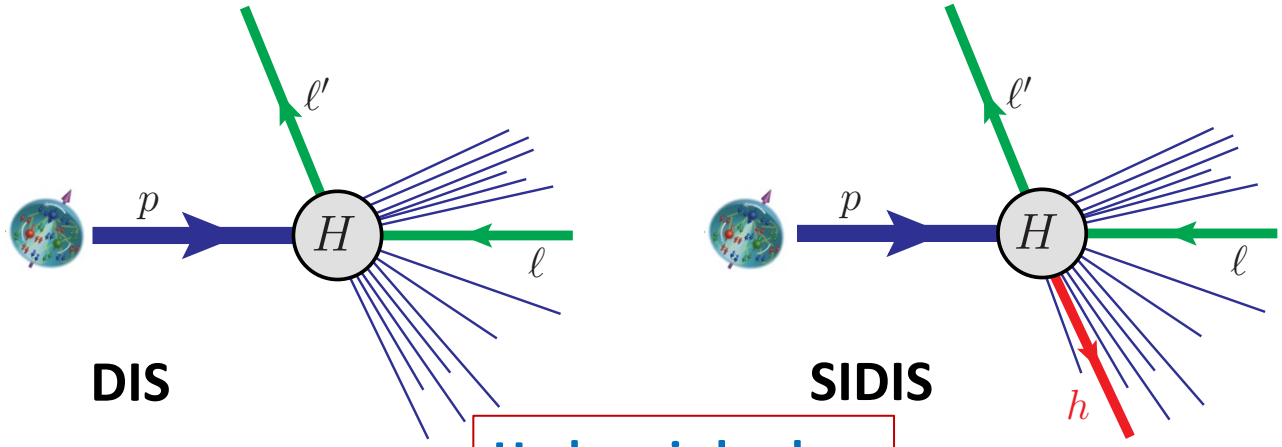
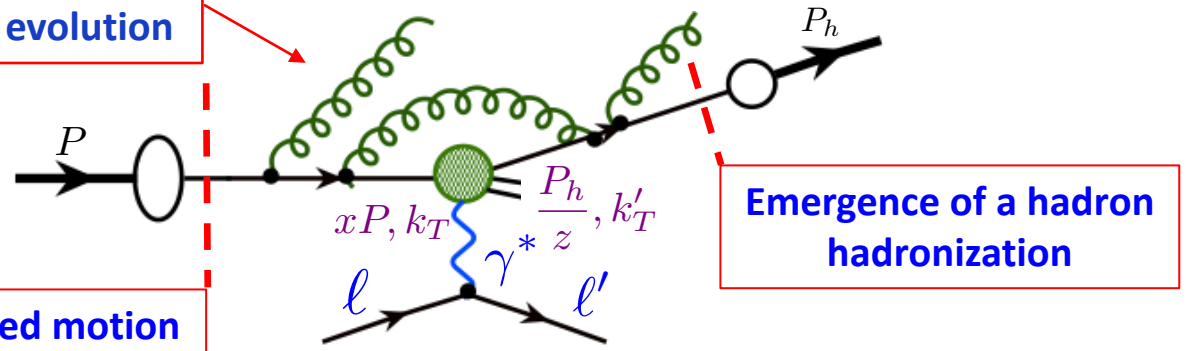
Partonic Structure with or without Breaking the Hadron

Inclusive scattering



Hadron is broken

Gluon shower – QCD evolution



Emergence of a hadron hadronization

Confined motion

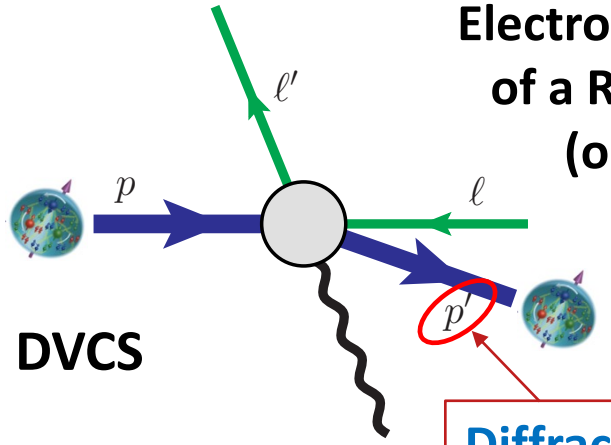
$$e + P \to e + h + X$$

Measured k_T of TMDs =\= the *confined* motion inside the hadron!

Challenge for interpretation!

Exclusive diffraction

Electroproduction of a Real Photon (or a hadron)

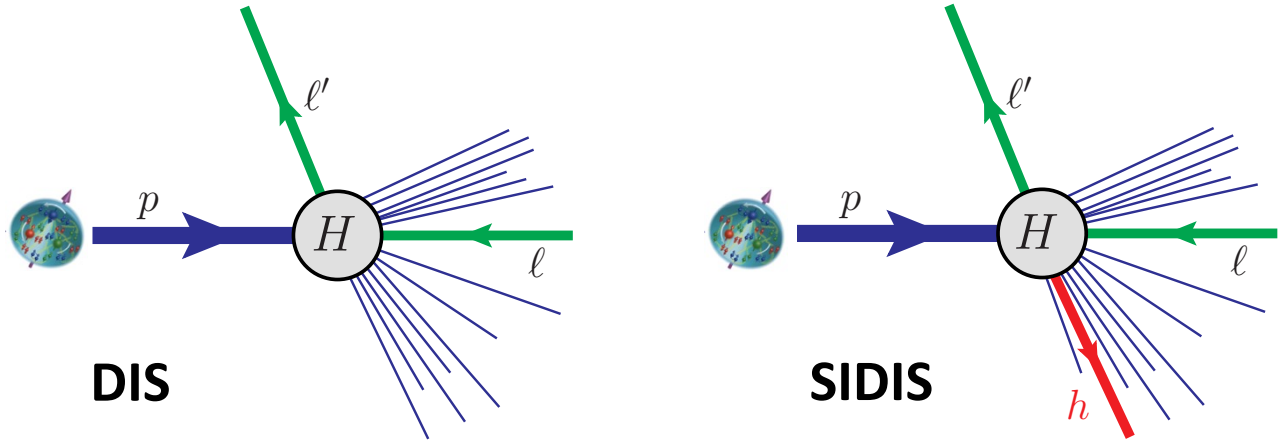


Diffraction

$$Q^2 = -(\ell - \ell')^2$$
$$\gg -(p - p')^2 = -t$$

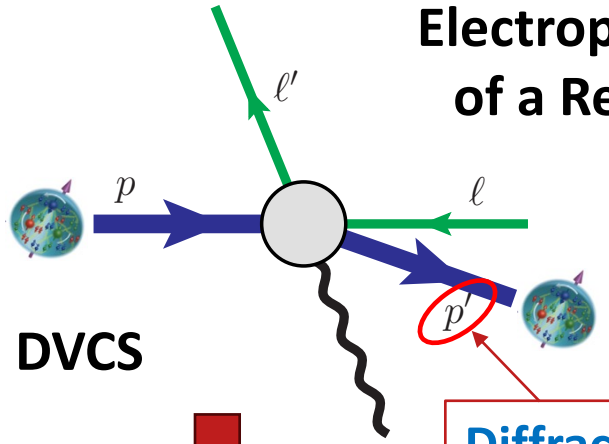
Partonic Structure with or without Breaking the Hadron

Inclusive scattering



Exclusive diffraction

Electroproduction of a Real Photon

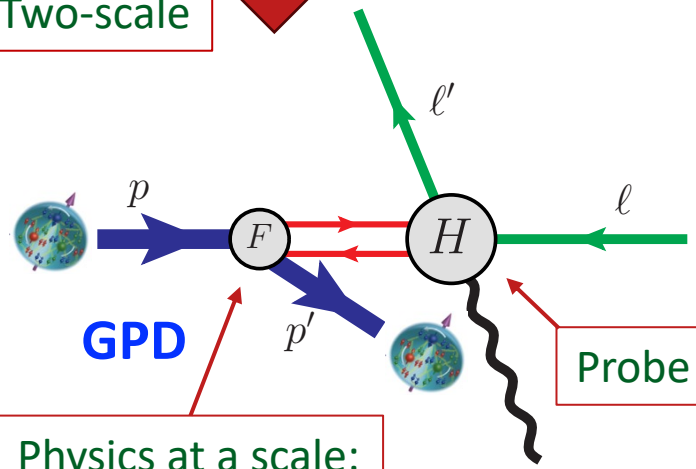


Diffraction

Two-scale

$(\ell - \ell')^2$

$(p - p')^2 = -t$



Probe at a time:

$\sim 1/Q$

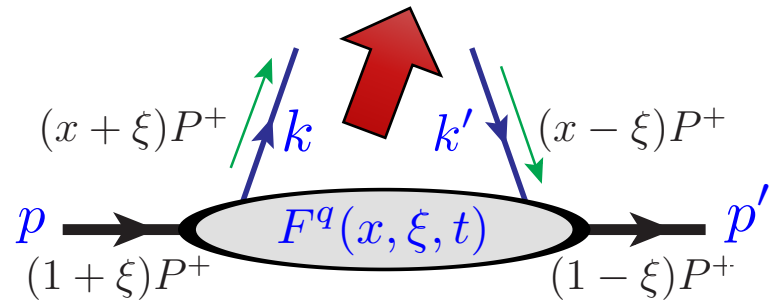
Physics at a scale:

$\sim (p - p')^2 = t$

FAC

GPDs

$\Delta^+ = 2\xi P^+$



$$F^q(x,\xi,t) = \int \frac{\mathrm{d}z^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+ q(-z^-/2)|p\rangle$$

$$\widetilde{F}^q(x,\xi,t) = \int \frac{\mathrm{d}z^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+\gamma_5 q(-z^-/2)|p\rangle$$

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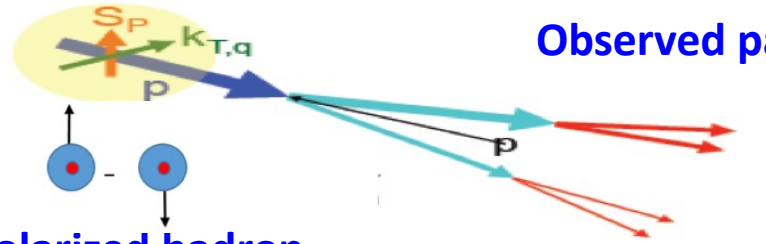
TMDs: Correlation between Hadron Property and Parton Flavor-Spin-Motion

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



Observed particle

Polarized hadron

Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

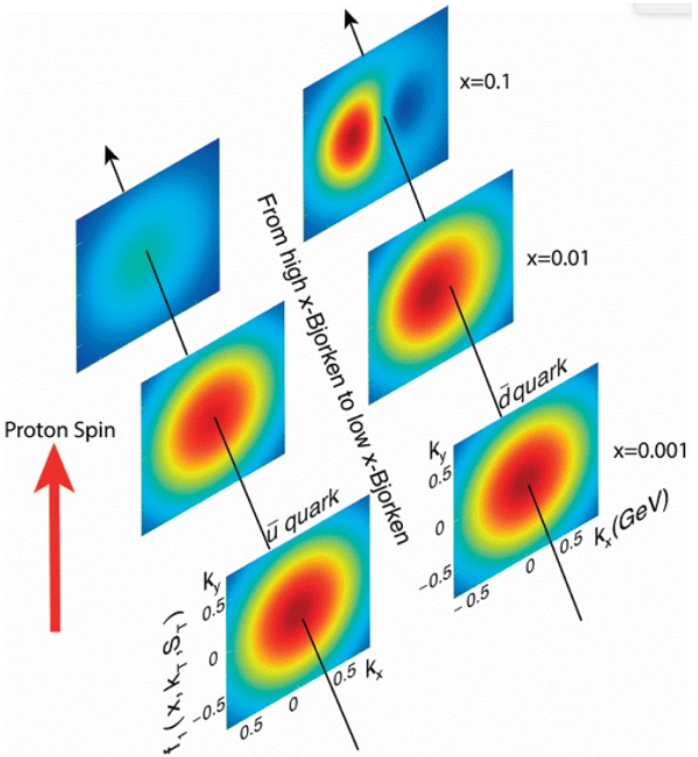
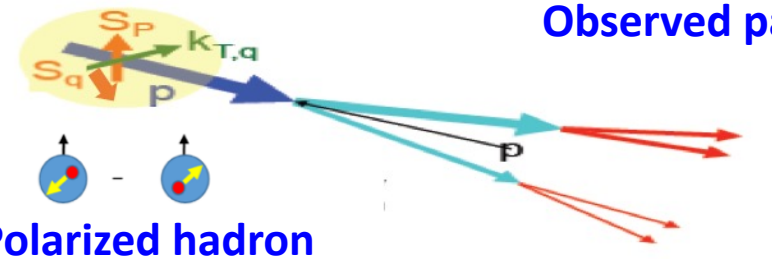


Fig. 2.7 NAS Report

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



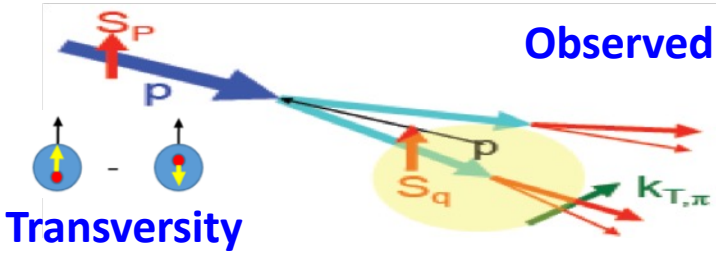
Observed particle

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

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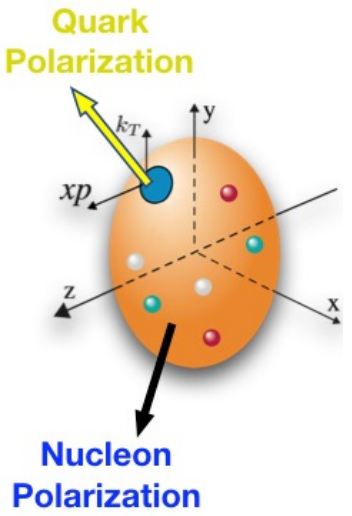
Transverse Momentum Dependent PDFs (TMDs) – Power of SIDIS

❑ 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

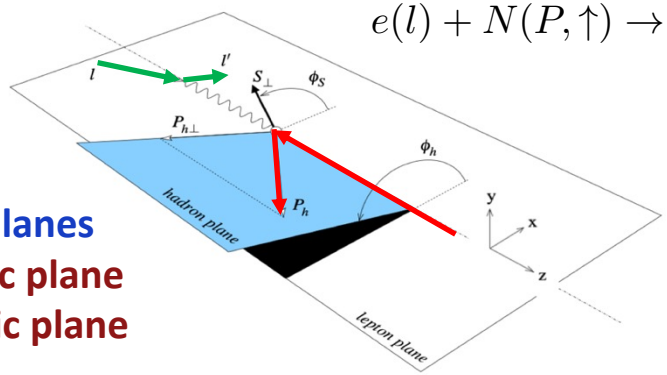
Analogous tables for:
- **Gluons** $f_1 \to f_1^g$ etc
- **Fragmentation functions**
- **Nuclear targets** $S \neq \frac{1}{2}$



See also TMD Handbook [2304.03302]

❑ Polarized lepton-hadron SIDIS:

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



Two planes
Leptonic plane
Hadronic plane

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

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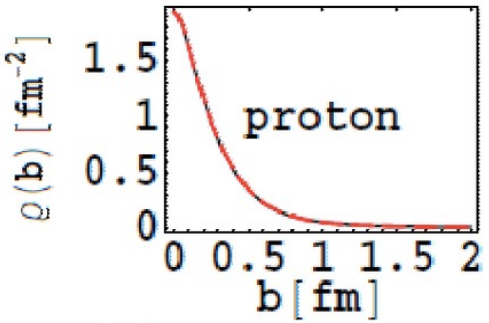
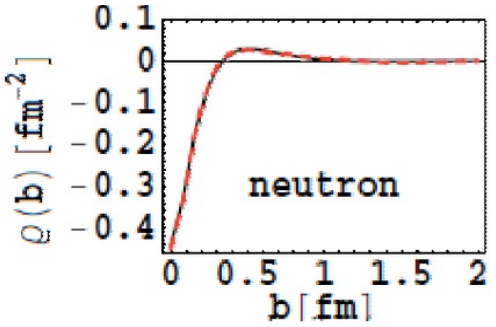
GPDs: Explore Internal Structure of Hadron without Breaking it?

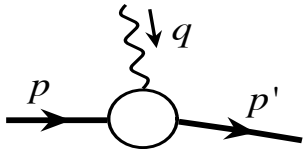
- **Form factors:**

  Elastic electric Form Factor ➡ **Charge distributions**





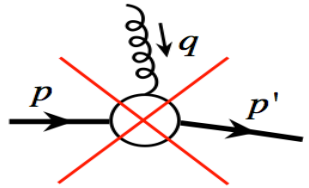
➡



Proton "Radius" in EM charge distribution

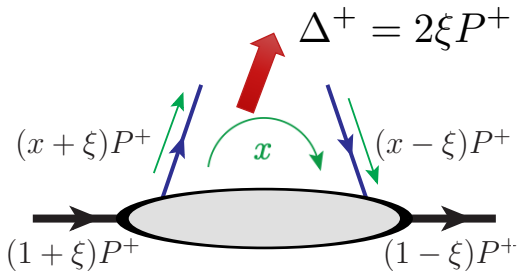
- **But, there is NO elastic "color" form factor in QCD!**

➡



No Proton "Radius" in color charge distribution!

- **Combine PDF and Form Factor – GPDs:**



$$\Delta = p - p'$$

$$t = \Delta^2$$

$$P^+ = \frac{p^+ + p'^+}{2}$$

Similar definition for gluon GPDs

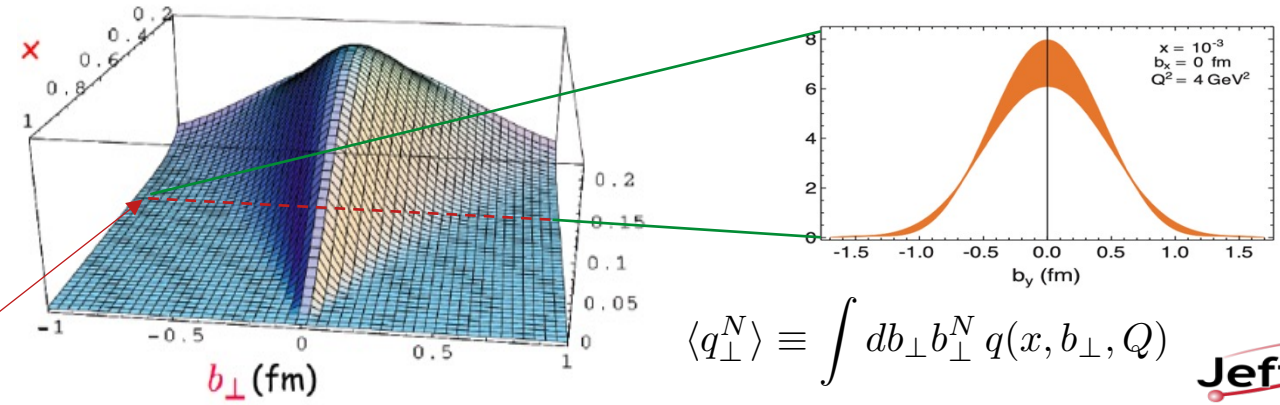
Q: $r_q(x) > r_g(x)$?
$r_q(x) < r_g(x)$?

- **Impact parameter dependent parton density distribution:**

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

➡ **Quark density in** $\mathrm{d}x\,\mathrm{d}^2\boldsymbol{b}_T$

- **Tomographic image of hadron in slice of x:**



Slice in (x,Q)

Modeled by M. Burkdart, PRD 2000

$$\langle q_\perp^N \rangle \equiv \int db_\perp b_\perp^N \, q(x, b_\perp, Q)$$

Proton radius?

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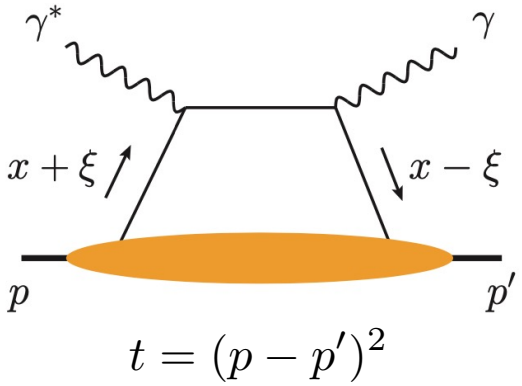
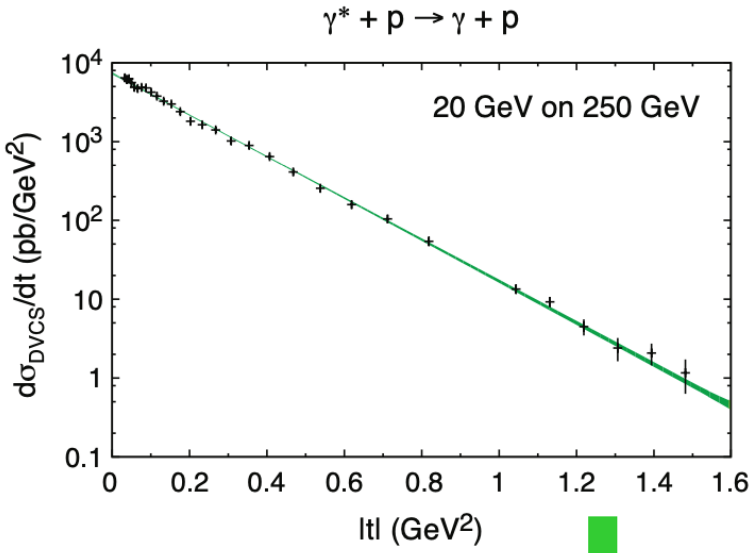
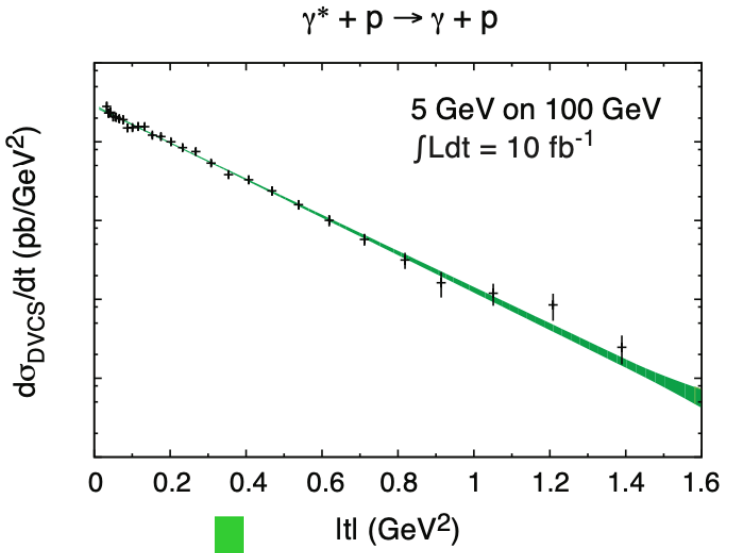
DVCS at a Future EIC (White Paper)

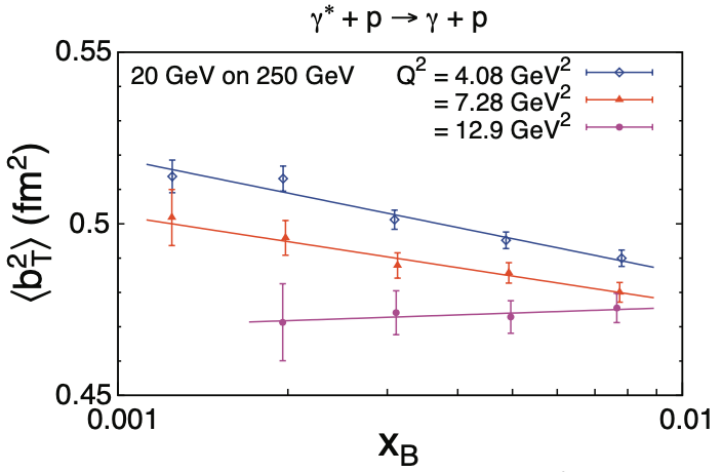
❑ Cross Sections:

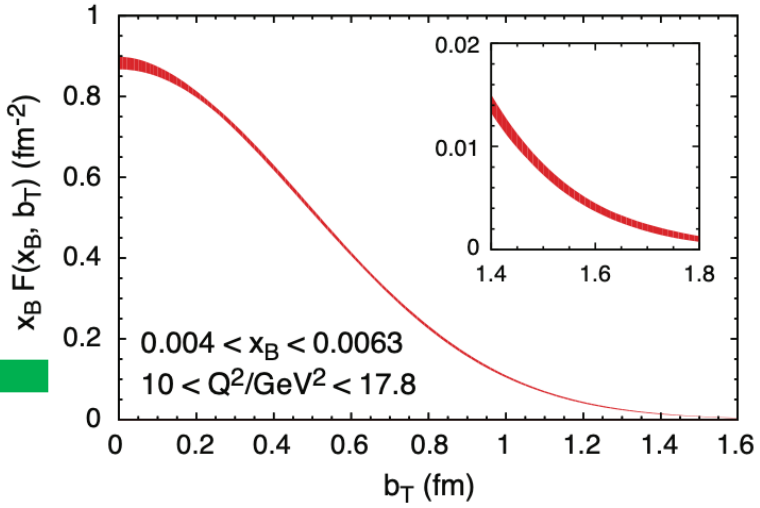


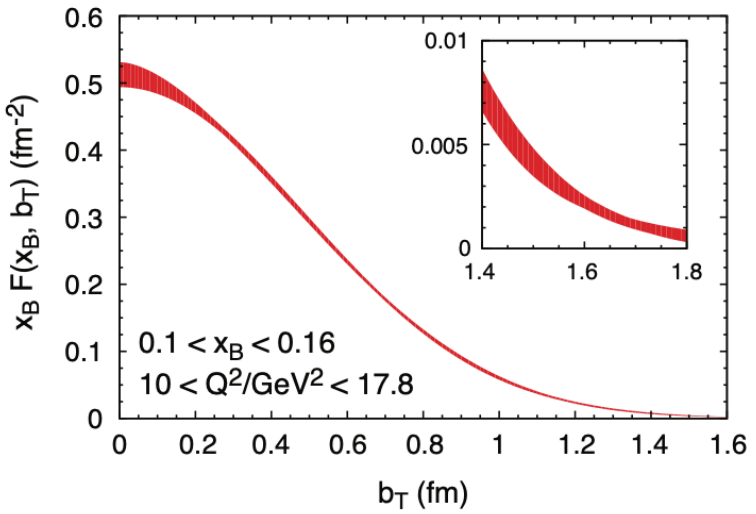




❑ Spatial distributions:







Effective "proton radius" in terms of quarks as a function of x_B

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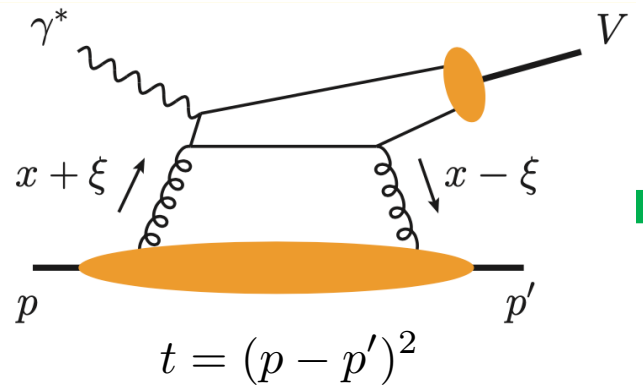
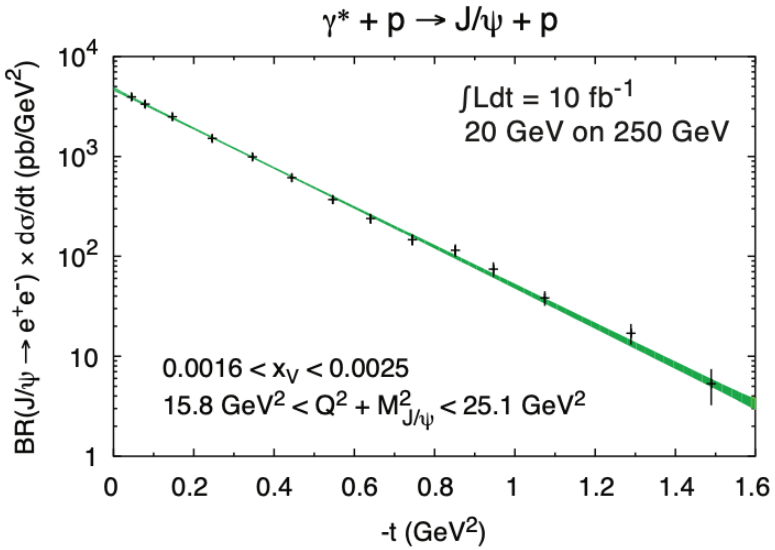
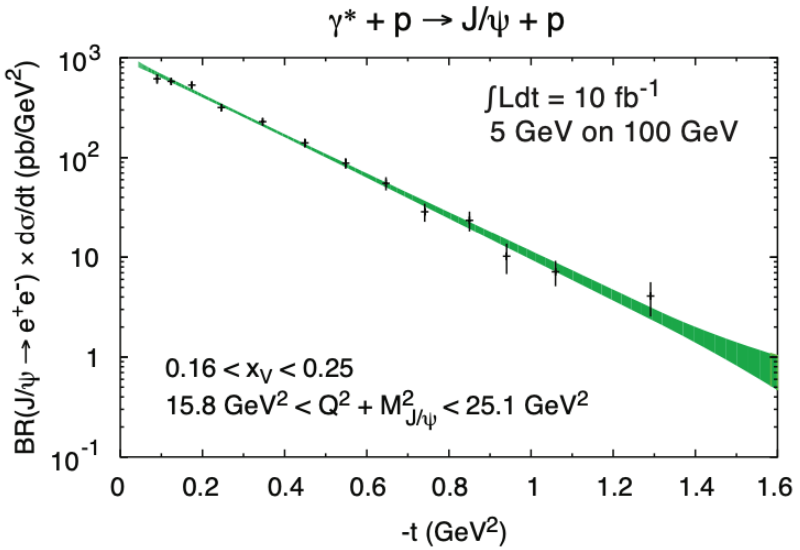
Imaging the Gluon at the EIC (White Paper)

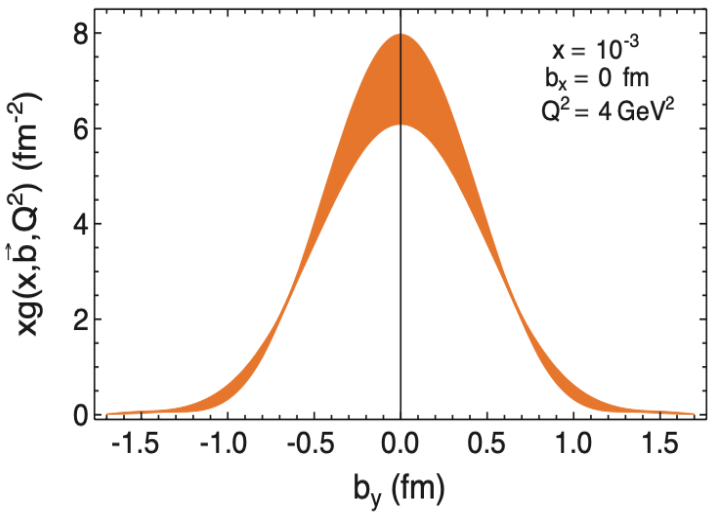
❑ Exclusive vector meson production:

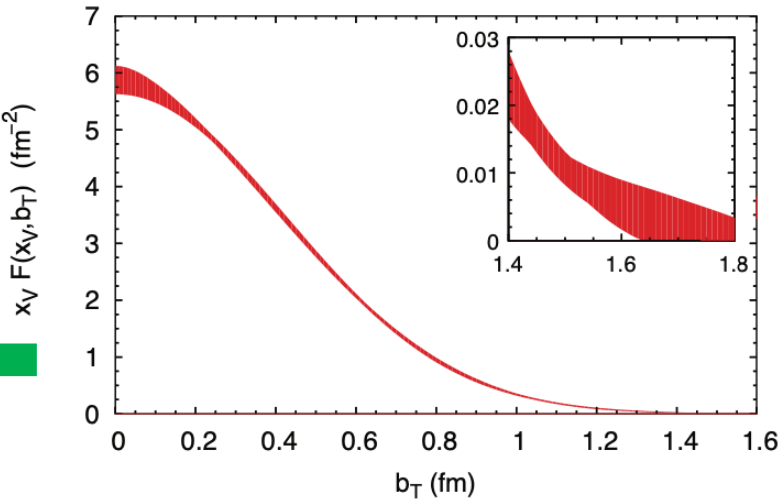


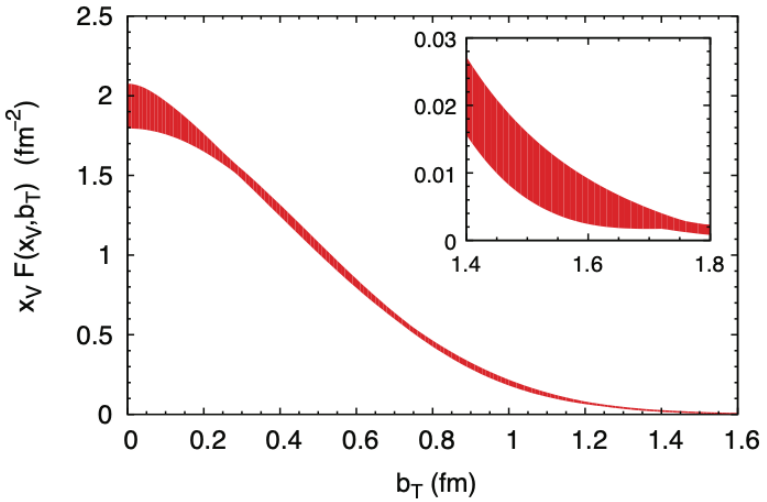




❑ Spatial distributions:







The b_T space density for gluons ➡ Effective "proton radius" in terms of gluons

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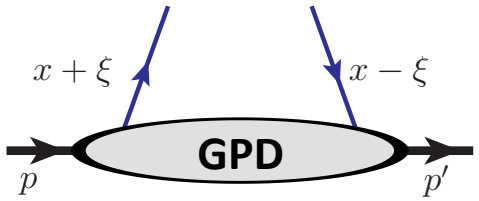
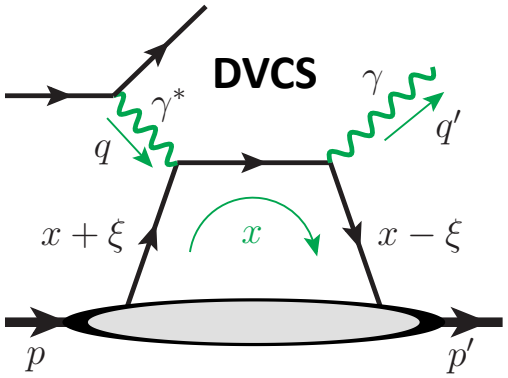
The x-dependence of GPDs is very *difficult* to measure!

❑ Amplitude nature: exclusive processes





$x \sim$ loop momentum

$$i\mathcal{M} \sim \int_{-1}^{1} \mathrm{d}x\, F(x,\xi,t)\cdot C(x,\xi;Q/\mu)$$

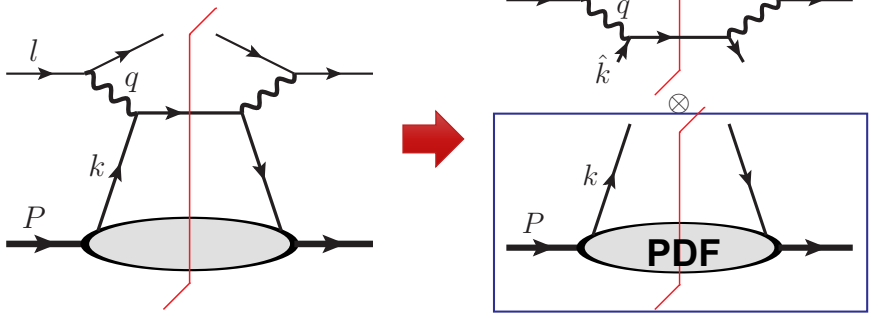
Full range of x, including $x=0;\quad x=\pm\xi$

❑ Sensitivity to x: comes from $C(x,\xi;Q/\mu)$

$$C(x,\xi;Q/\mu) = T(Q/\mu)\cdot G(x,\xi) \propto \frac{1}{x-\xi+i\epsilon}\cdots$$

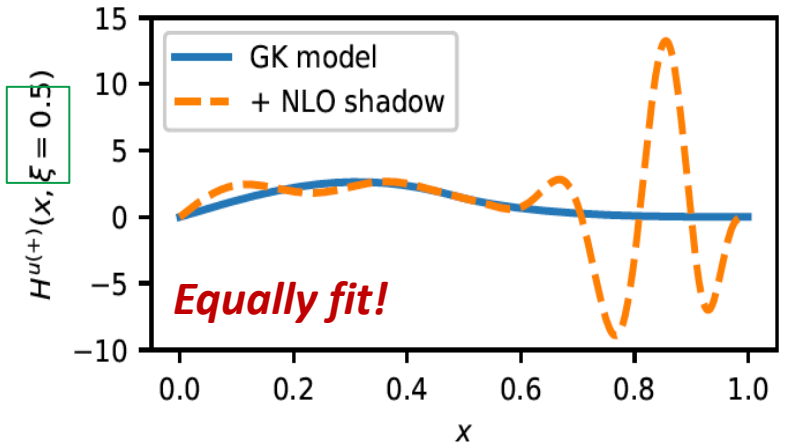
$$\Rightarrow\quad i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x\, \frac{F(x,\xi,t)}{x-\xi+i\varepsilon} \equiv \text{“}F_0(\xi,t)\text{”}$$ **“moment”**

Compare with DIS



cross section: **cut diagram**

$$\sigma_{\mathrm{DIS}} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\,\hat{\sigma}(x/x_B)$$



[Bertone et al. PRD `21]

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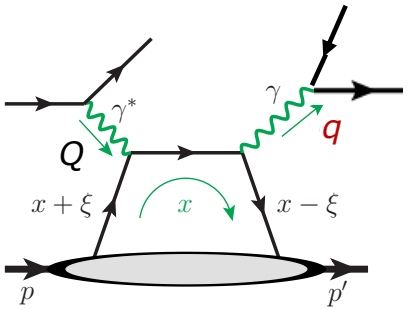
Processes sensitive to GPD's *x*-Dependence – New Development

- **Create an entanglement between the internal *x* and an externally measured variable?**

$$i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x \frac{F(x,\xi,t)}{x - x_p(\xi,q) + i\varepsilon}$$

Change external *q* to sample different part of x.



- **Double DVCS (two scales):**

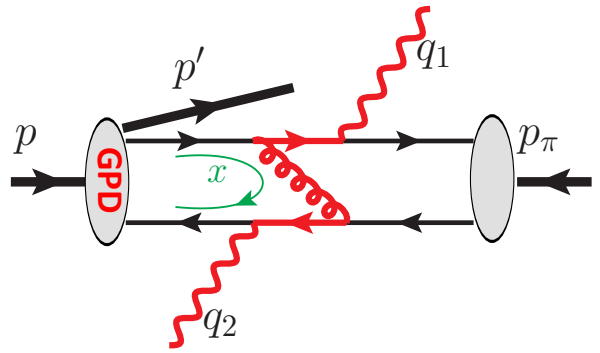
$$x_p(\xi,q) = \xi\left(\frac{1-q^2/Q^2}{1+q^2/Q^2}\right) \to \xi \quad \text{same as} \quad \text{DVCS} \quad \text{if } q \to 0$$

- **Production of two back-to-back high pT particles (say, two photons):**

$$\pi^-(p_\pi) + P(p) \to \gamma(q_1) + \gamma(q_2) + N(p')$$

Hard scale: $q_T \gg \Lambda_{\mathrm{QCD}}$ Soft scale: $t \sim \Lambda^2_{\mathrm{QCD}}$

Qiu & Yu
JHEP 08 (2022) 103



- **Factorization:**

$$\mathcal{M}(t,\xi,q_T) = \int_{-1}^{1} \mathrm{d}x\, F(x,\xi,t;\mu)\cdot C(x,\xi;q_T/\mu) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/q_T)$$

[suppressing pion DA factor]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\ \mathrm{d}\xi\ \mathrm{d}q_T} \sim |\mathcal{M}(t,\xi,q_T)|^2$$

q_T distribution is "conjugate" to x distribution

$x \leftrightarrow q_T$

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The "Origin" of Hadron Properties – the x-Moments of GPDs

❑ **Form Factors of QCD energy-momentum tensor:**

Ji, PRL78, 1997

$$\langle N'|\hat{T}^{a}_{\mu\nu}|N\rangle = \bar{u}(p')\Big[\, A^a(t,\mu^2)\,\frac{P_\mu P_\nu}{M} + J^a(t,\mu^2)\,\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + \overline{C}^a(t,\mu^2)\,M\,g_{\mu\nu} + D^a(t,\mu^2)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4M}\,\Big]u(p)$$

- **Conserved current:**

$$\partial_\mu \hat{T}^{\mu\nu} = 0, \quad \hat{T}_{\mu\nu} = \sum_a \hat{T}^a_{\mu\nu} \quad (a = q, g)$$

- **Sum over flavor:**

$$A(t) = \sum_a A^a(t,\mu^2), \text{ etc, } \sum_a \overline{C}^a(t,\mu^2) = 0$$

- **Constraints:**

mass $\Leftrightarrow$ $A(0) = 1$

q/g carry total hadron momentum

spin $\Leftrightarrow$ $J(0) = \frac{1}{2}$

q/g carry total hadron spin

D-term $\Leftrightarrow$ $D(0) \equiv D$

Unconstrained/largely unknown

❑ **Connection to GPD moments:**

$$\int_{-1}^{1} dx\, x\, F_i(x,\xi,t) \propto \langle p'|T_i^{++}|p\rangle$$

➡ **Angular momentum sum rule:**

$$J_i = \lim_{t\to 0}\int_{-1}^{1} dx\, x\,[H_i(x,\xi,t) + E_i(x,\xi,t)]$$

$$i = q, g$$

➡ **3D tomography**
Relation to "GFF"

➡ ***x*-moments of GPDs!**

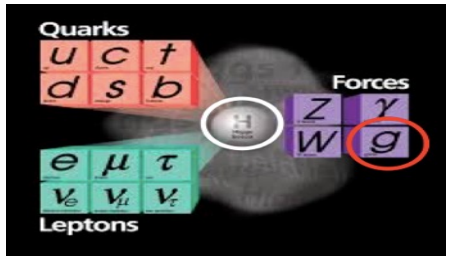
Related to pressure & stress force inside hadron

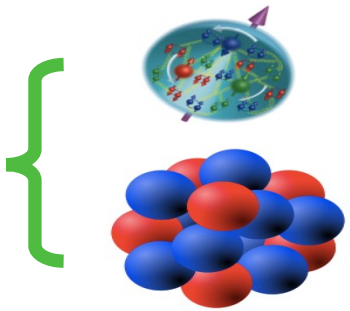
Polyakov, schweitzer, Inntt. J. Mod. Phys. A33, 1830025 (2018)
Burkert, Elouadrhiri , Girod Nature 557, 396 (2018)

Need to know the x-dependence of GPDs to construct the proper moments and the "origin" of hadron properties – New observables for the EIC!

Properties of Dense Systems of Gluons – Nonlinear Dynamics of QCD?

❑ Understanding the Glue that binds us all:



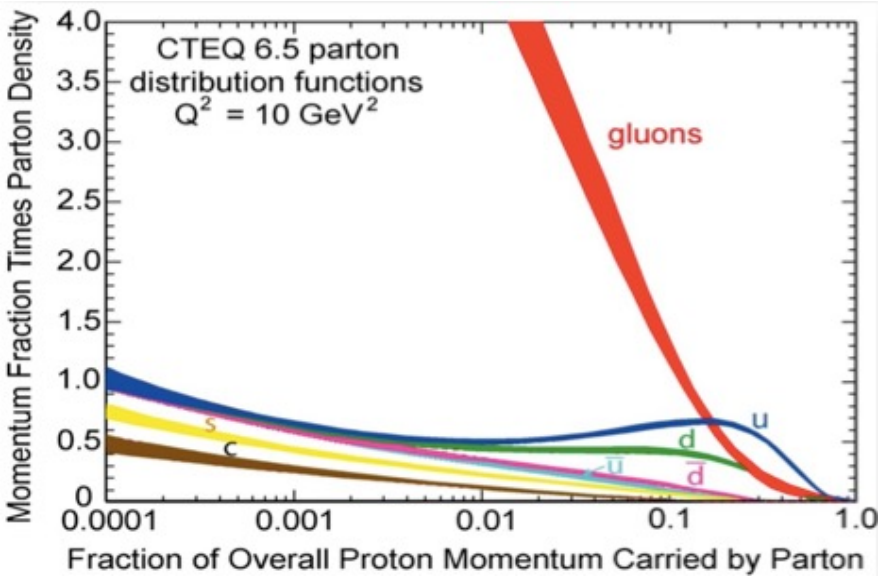


❑ Gluons are weird particles!

- Massless, yet, responsible for a lot of visible mass
- Carry color charge, unlike photon, responsible for color confinement, but, also for asymptotic freedom, as well as the abundance of glue!

Without gluons, there would be

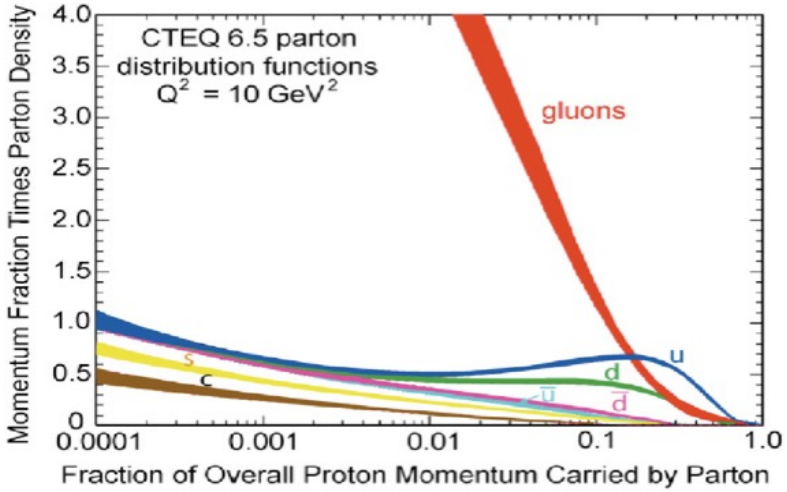
NO nucleons, NO atomic nuclei, … NO visible world!



- *What are the emergent properties of dense systems of gluons?*
- *What does a nucleus look like if we only see quarks and gluons?*
- *What is the coherent length of color force? …*

Gluon Saturation – Color Glass Condensate

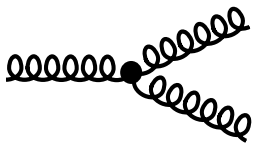
❑ Run away gluon density at small-x?



What causes the low-x rise?

gluon radiation

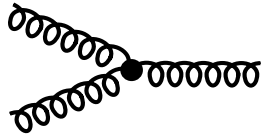
– non-linear gluon interaction



What could tame the low-x rise?

gluon recombination

– non-linear gluon interaction



❑ QCD vs. QED:

QCD – gluon in a proton:

$$Q^2\frac{d}{dQ^2}xG(x,Q^2) \approx \frac{\alpha_s N_c}{\pi}\int_x^1 \frac{dx'}{x'}x'G(x',Q^2)$$

QED – photon in a positronium:

$$Q^2\frac{d}{dQ^2}x\phi_\gamma(x,Q^2) \approx \frac{\alpha_{em}}{\pi}\left[-\frac{2}{3}x\phi_\gamma(x,Q^2) + \int_x^1 \frac{dx'}{x'}x'[\phi_{e^+}(x',Q^2)+\phi_{e^-}(x',Q^2)]\right]$$

In the dipole model:

$$\frac{\partial N(x,k^2)}{\partial \ln(1/x)} = \alpha_s\,\mathcal{K}_{\mathrm{BFKL}}\otimes N(x,k^2) - \alpha_s\left[N(x,k^2)\right]^2$$

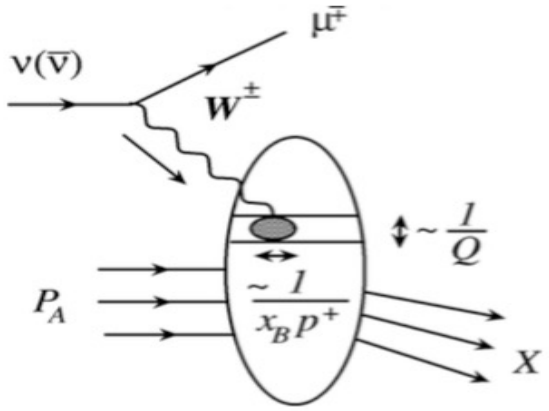
BK Equation

✧ At very small-x, proton is "black", positronium is still transparent!

✧ Recombination of large numbers of glue could lead to saturation phenomena

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

- **Need hard probes to "see" quarks and gluons at small-x!**
  But, a hard probe at small-x is NOT necessarily "localized":



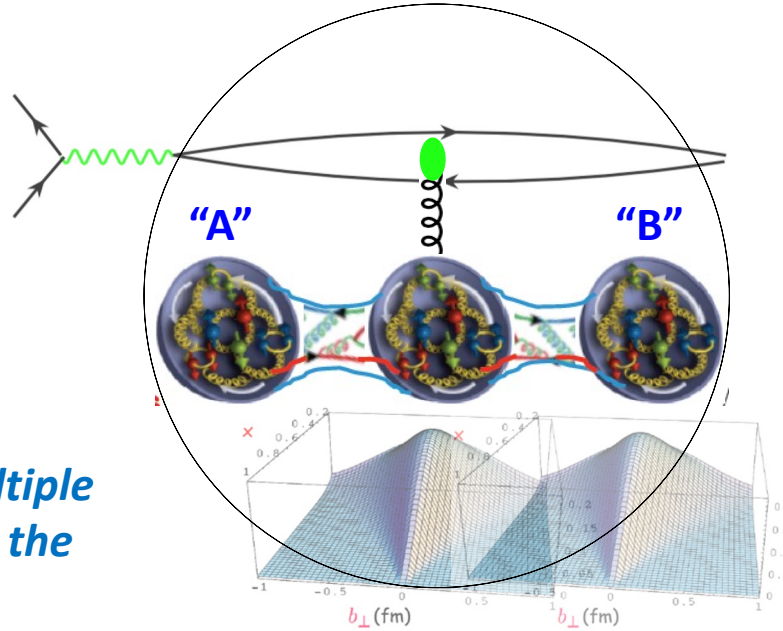
In c.m. frame

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



- **A 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

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

EIC can tell !

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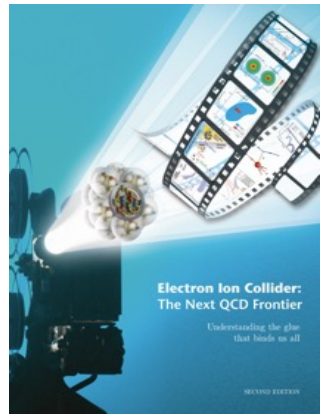
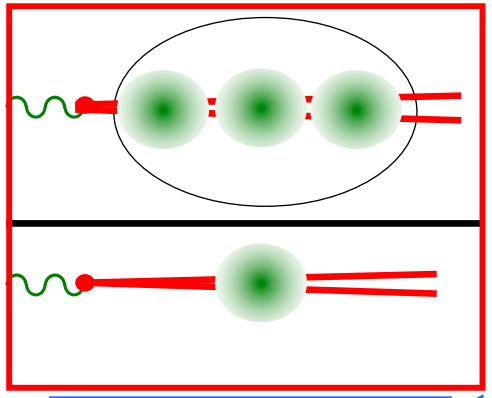
Coherent Length of the Color

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

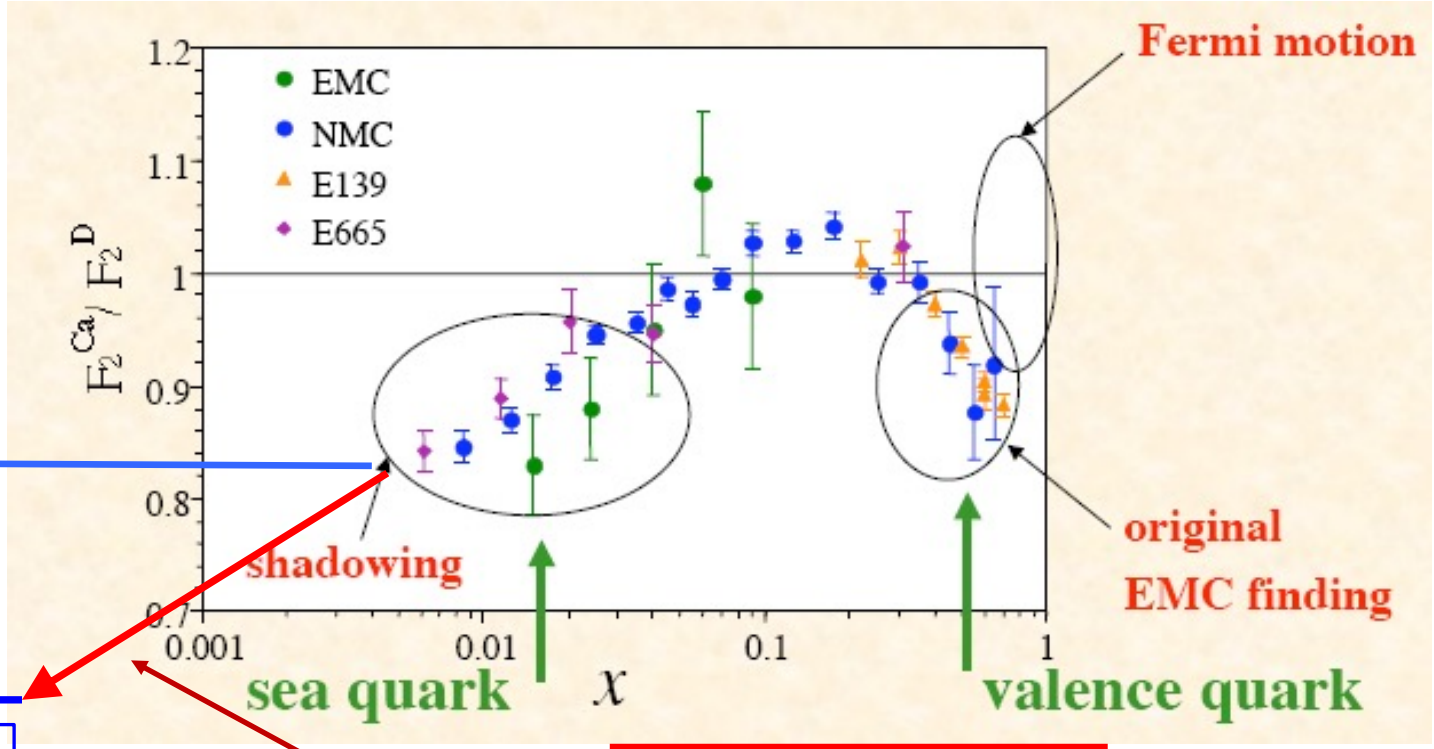
  Will the nuclear shadowing continue to fall as x decreases?

EIC White Paper

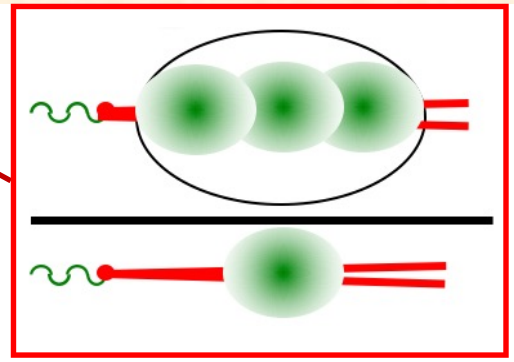




Color localized Inside nucleons



Nucleus as a bigger proton



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

EIC can tell !

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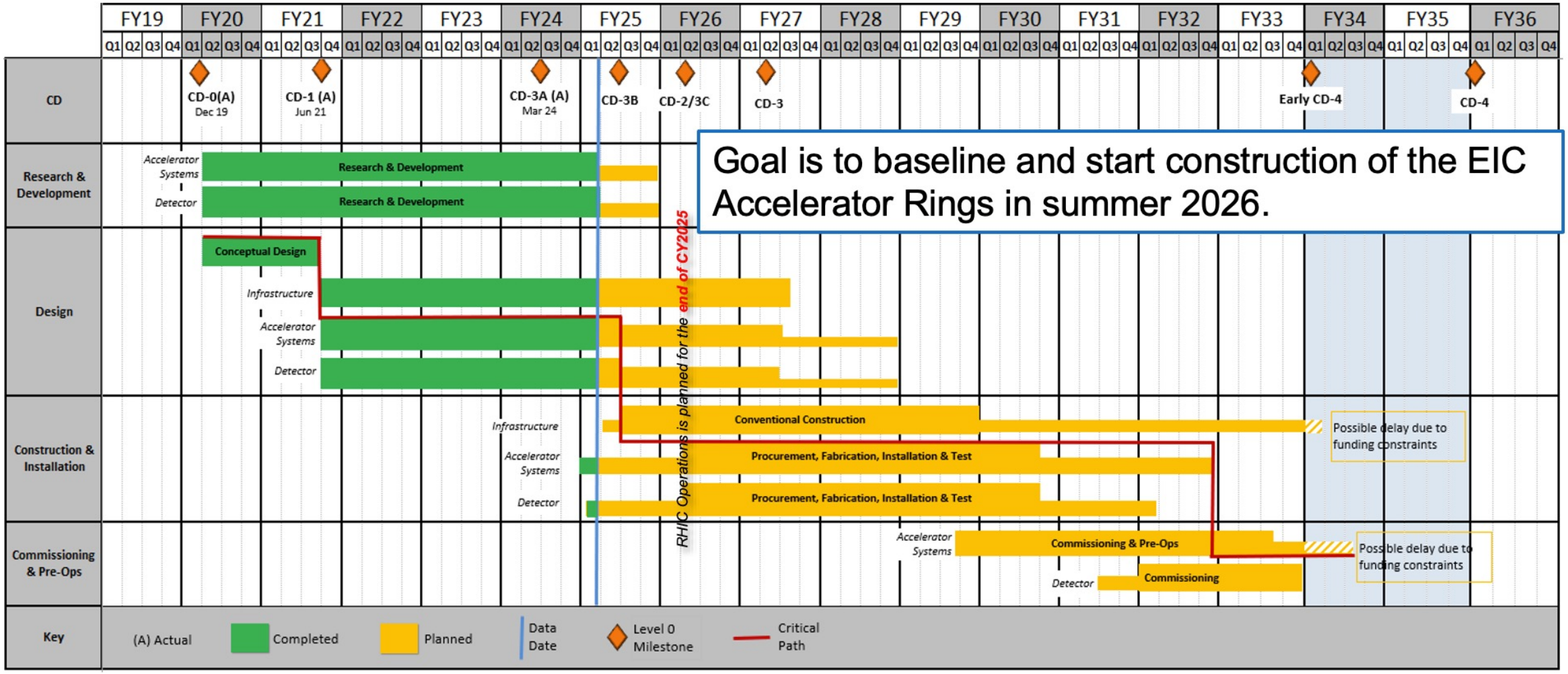
Realization of the Electron-Ion Collider:

- EIC project is moving from R&D and design into the construction phase in 2026 (CD3A, CD3B):



Note: Fermilab DUNE at LBNF still does not have CD2 approval – more than 10 years after CD1, many CD3#, …

Summary and Outlook

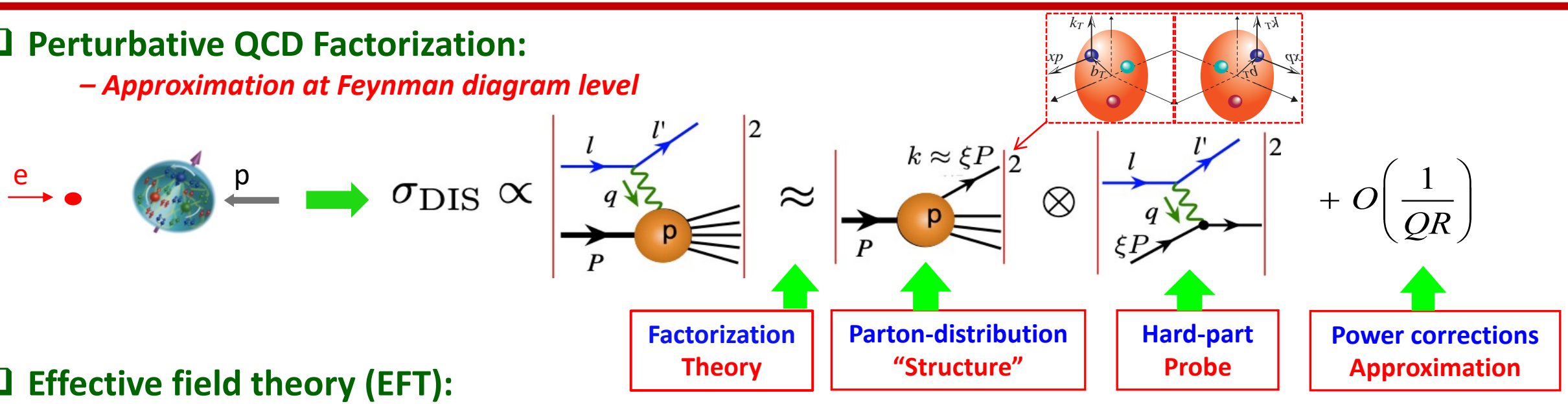
- **We have a right theory for the String Force – QCD, but, unprecedented challenges**
  - QCD has been very successful in describing the short-distance dynamics, in particular, phenomena at the LHC
  - Challenges to understand the emergent phenomena of QCD:
    - Hadron properties, such as the mass, spin, …, in the most fundamental way
    - Internal structure and landscape of hadrons, such as confined motion, spatial tomography of nuclei, …
    - Emergence of hadrons from quarks and gluons, neutralization of the color, femto-meter sized detectors, …
    - Particle and wave nature of quarks and gluons, …
    - Role in BSM searches, …
- **CEBAF (luminosity) & EIC are two complementary QCD machines, capable of discovering and exploring the emergent phenomena of QCD, and the role of color and glue, …**
- **US-EIC, to be constructed at BNL, is sitting at a sweet spot for rich QCD dynamics, capable of taking us to the next frontier of QCD and the Standard Model!**

Thanks!

Theoretical Approaches – Approximations:

❑ Perturbative QCD Factorization:

– *Approximation at Feynman diagram level*



❑ 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 for finite lattice spacing, finite box, lightest quark masses, … with Euclidean time formulation (removable with increased computational cost)*

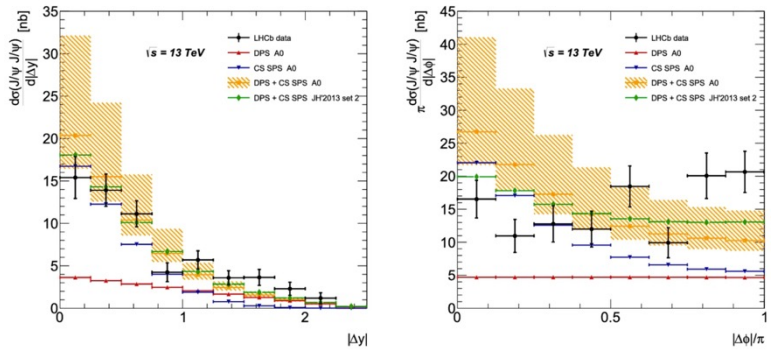
Hadron structure, hadron spectroscopy, nuclear structure, phase shift, …

❑ Other approaches:

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

From Cross Sections to Quantum Correlation Functions (PDFs, TMDs, GPDs, …)

❑ Event-based analysis – replacing the histogram approach?

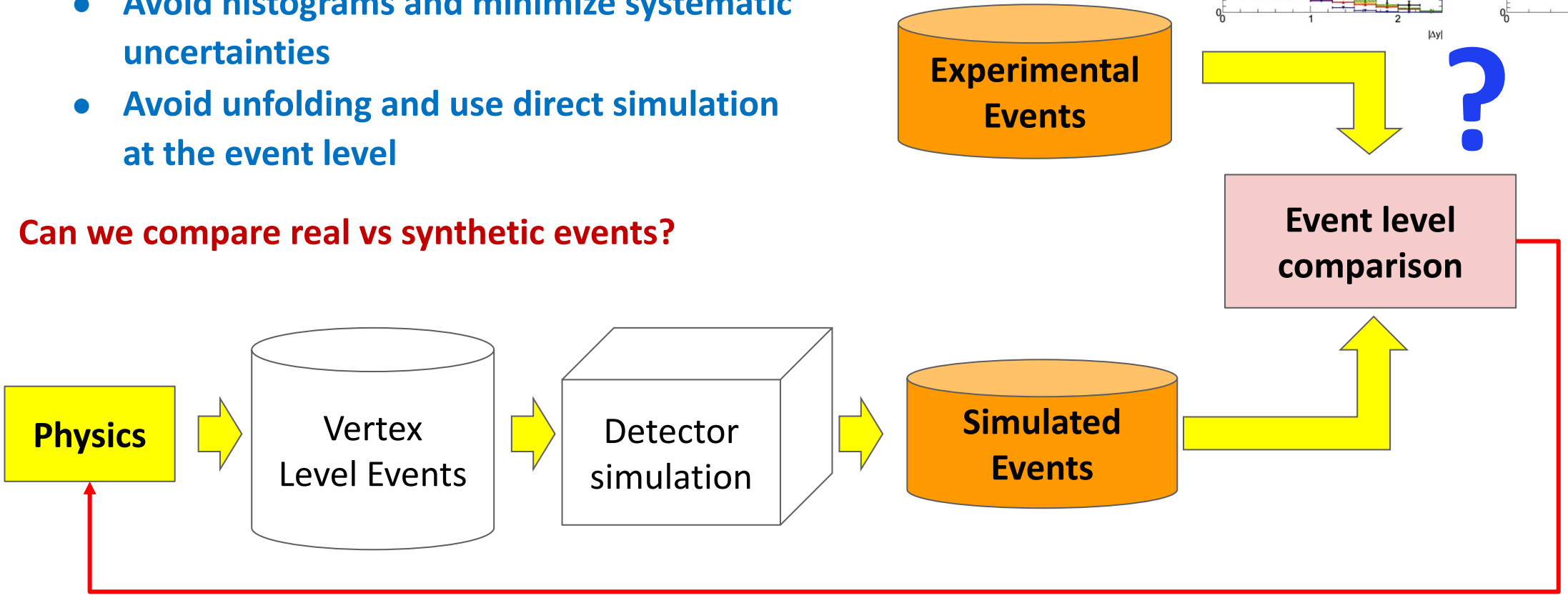


Eur. Phys. J. C (2020) 80:1046

Why?

- Avoid histograms and minimize systematic uncertainties
- Avoid unfolding and use direct simulation at the event level

Can we compare real vs synthetic events?



Optimize physics parameters ⟷ extraction of QCFs

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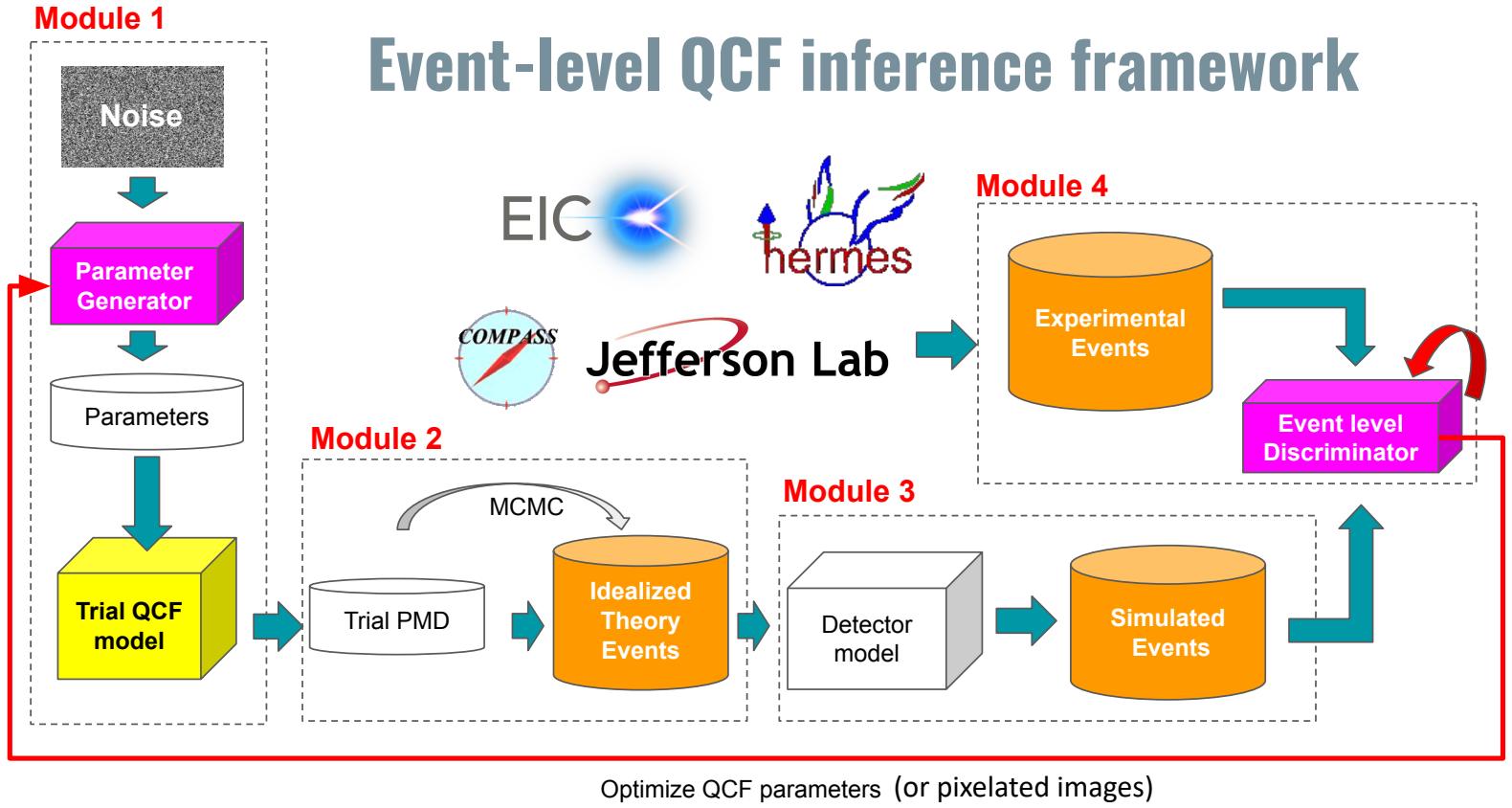
From Cross Sections to Quantum Correlation Functions (PDFs, TMDs, GPDs, …)

❑ Femtoscale Imaging of Nuclei using Exascale Platforms:

Pixelating hadron in terms of probabilities to find quarks and gluons in slices of the momentum fraction x



PMD: Particle Momentum Distribution - Observables

QCF: Quantum Correlation Functions: PDFs, TMDs, GPDs, …

QuantOm Collaboration

NP: ANL, JLab, ODU, VT

ASCR: FASTMath, RAPIDs

Exp Events (PMD):

- **DIS:**
  1 particle inclusive
- **SIDIS:**
  2 particle inclusive
- **SDHEP:**
  3 particle exclusive

Generated Events:

Many templates from trial QCFs & trusted theory

Inference:

Optimized QCFs or pixelated images in trusted phase space

New regimes:

Go beyond the trusted phase space

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