Informal Pre-Town Meeting at JLab

Thomas Jefferson National Accelerator Facility, Newport News, VA

August 13-15, 2014

EIC: current status — appropriate list of "so what questions"

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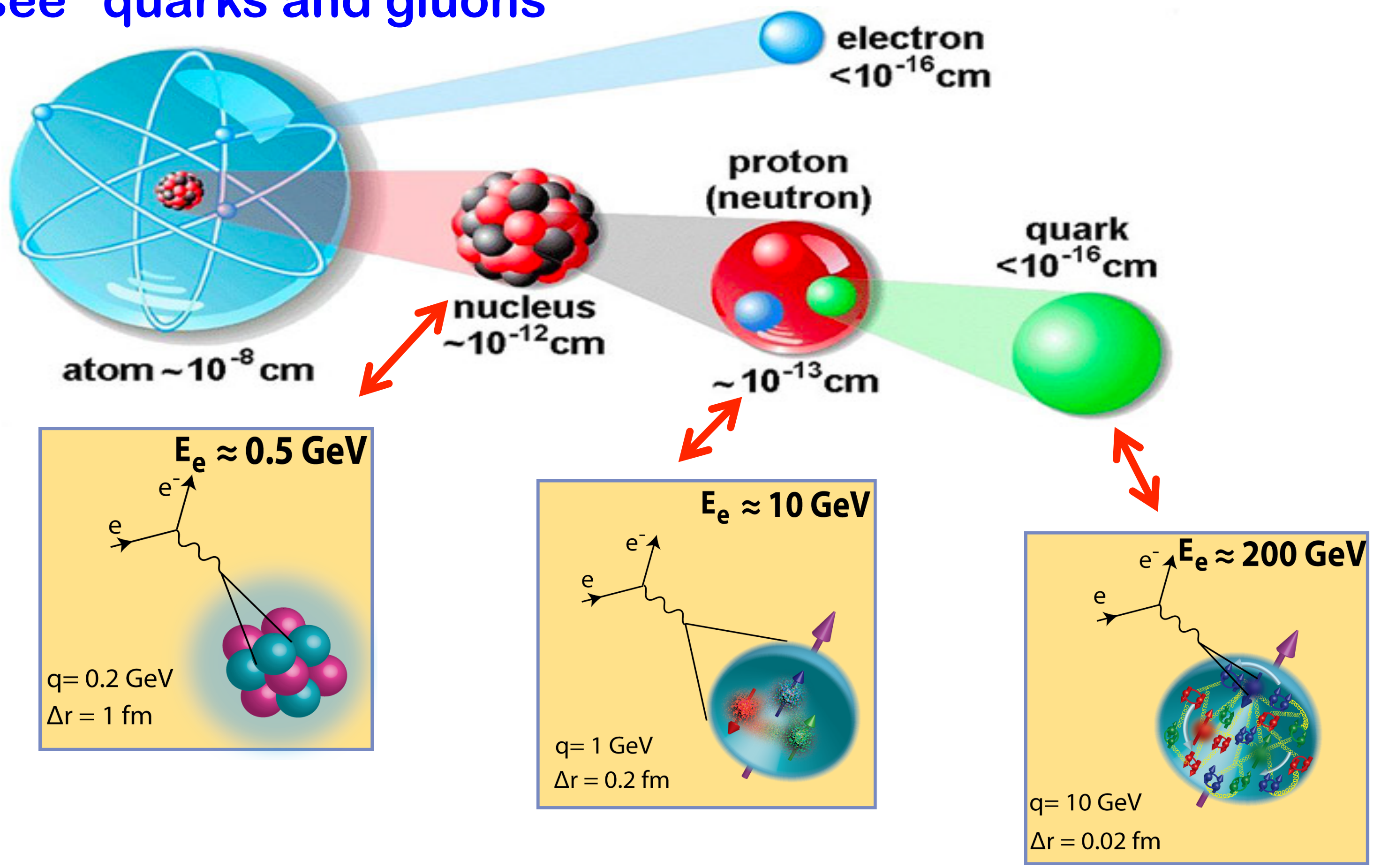
Acknowledgement: Much of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …

Electron-Ion Collider (EIC)

- A giant "Microscope"

  To "see" quarks and gluons

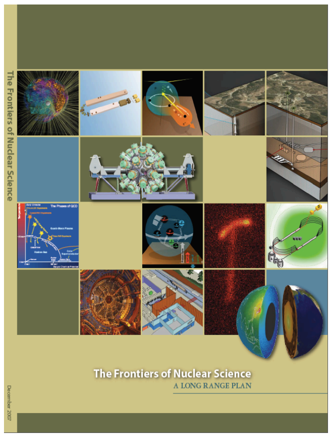


- A sharpest "CT" (computed tomography) machine:

  To "cat-scan" nucleons and nuclei (keep them intact!)

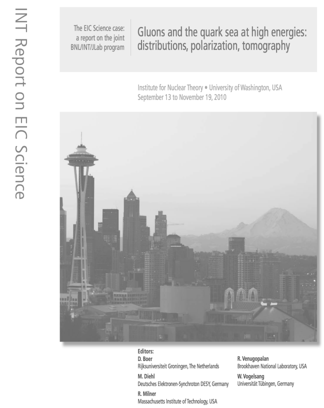
EIC: Community effort and status

2007 Long Range Plan Report:



Designated EIC as "embodying the vision for reaching the next QCD frontier"

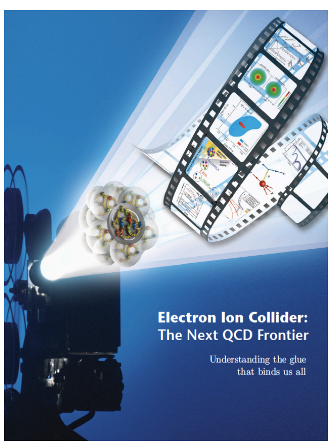
2011 INT Report:



Ten-week program at INT

arXiv:1108.1713
500+ pages

2012 EIC White Paper:



Organized effort by BNL and Jlab

Understanding the glue that binding us all

arXiv:1212.1701

2013 Facilities Subcommittee:

Major Nuclear Physics Facilities for the Next Decade

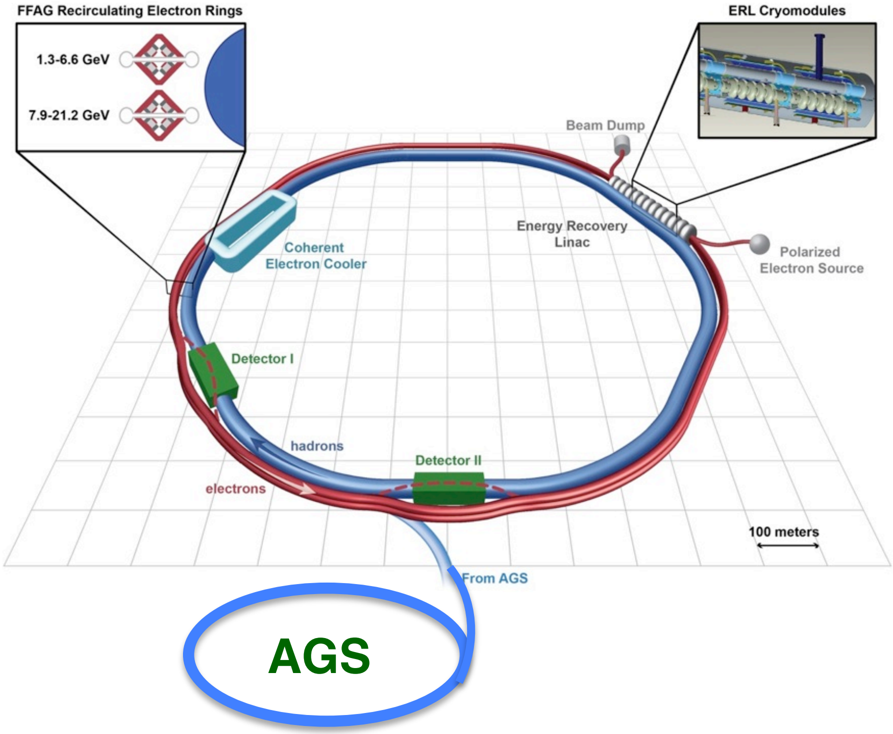
Report of the NSAC Subcommittee on Scientific Facilities

March 14, 2013

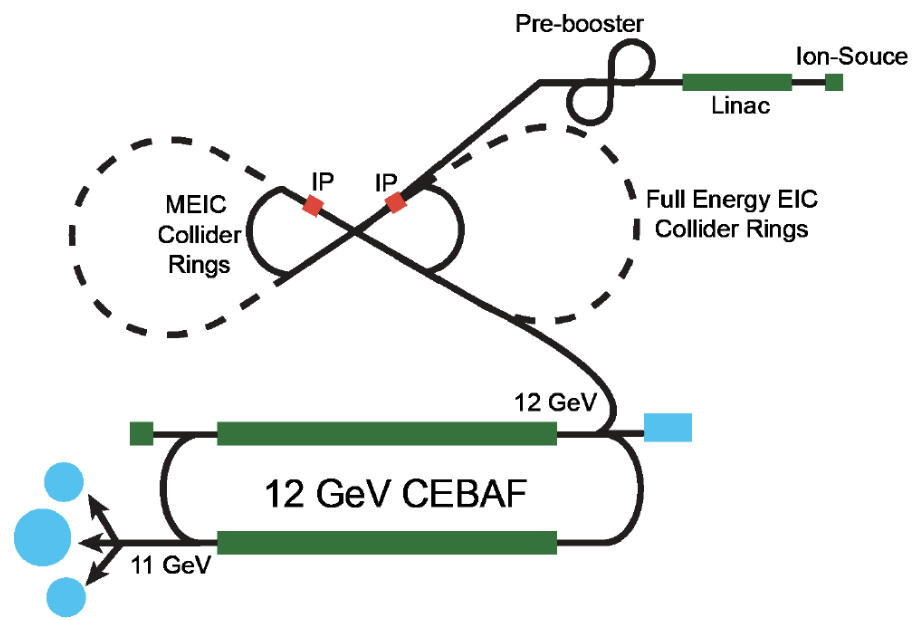
Ranks an EIC as "Absolutely Central" in its ability to contribute to world-leading science in the next decade

EIC: Machine designs

eRHIC (BNL)



MEIC (JLab)



eRHIC Task Force Wiki at BNL:

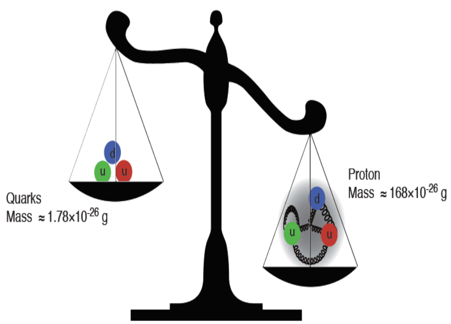
https://wiki.bnl.gov/eic/index.php/Main_Page

MEIC Working Group Wiki at JLab:

https://eic.jlab.org/wiki/index.php/Main_Page

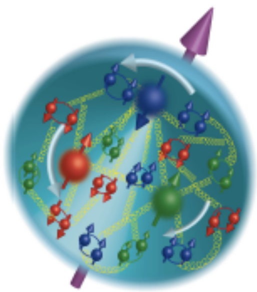
EIC: Science

Hadron properties



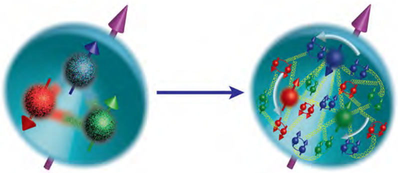
Mass

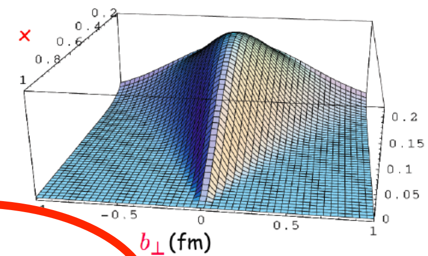
Spin



Hadron structures

"Two" pictures



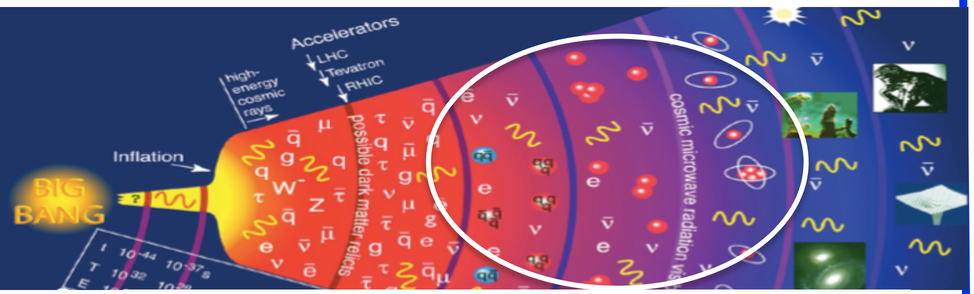


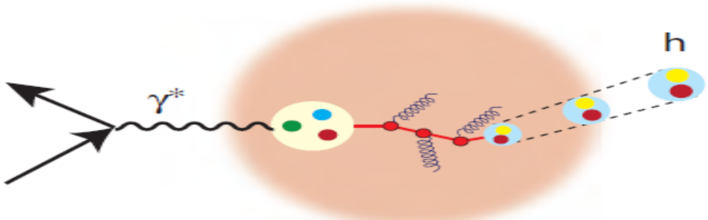
q/g distribution in space/momentum

Proton radiuses? e, q, g

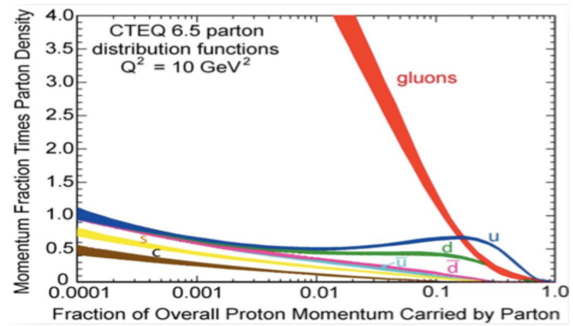
EIC

Emergence of hadrons





QCD dynamics



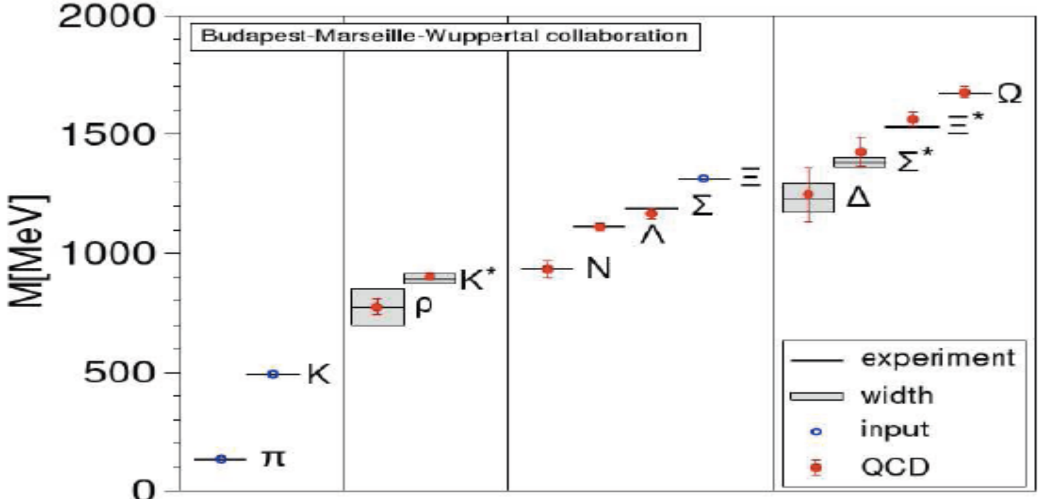
Too many gluons?

Manybody, nonlinear dynamics?
Liquid state?
Universal properties, dynamical mass scale?

We believe QCD

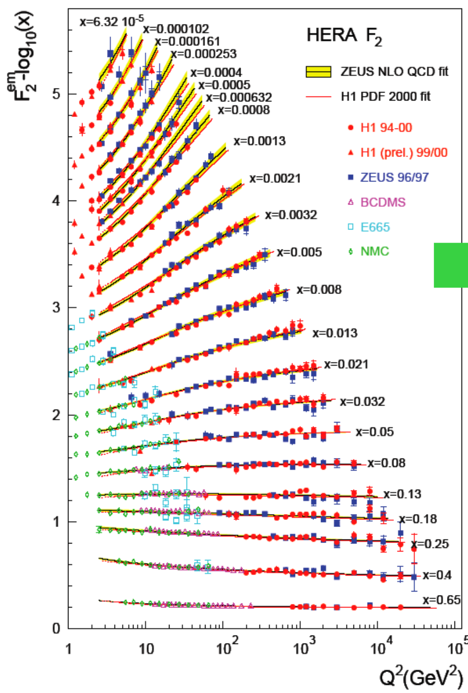
- **@low energy:**

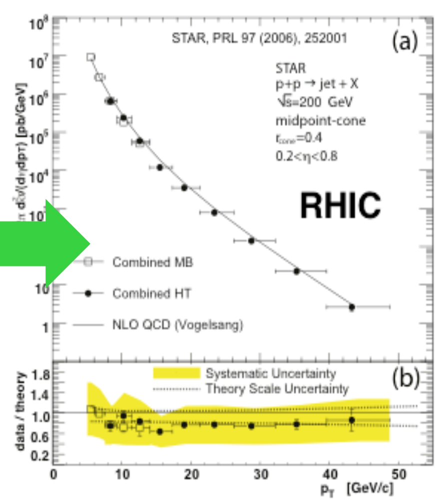
  Hadron mass spectrum from lattice QCD

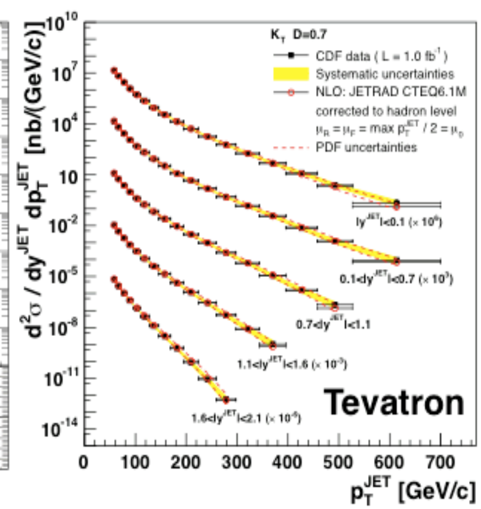


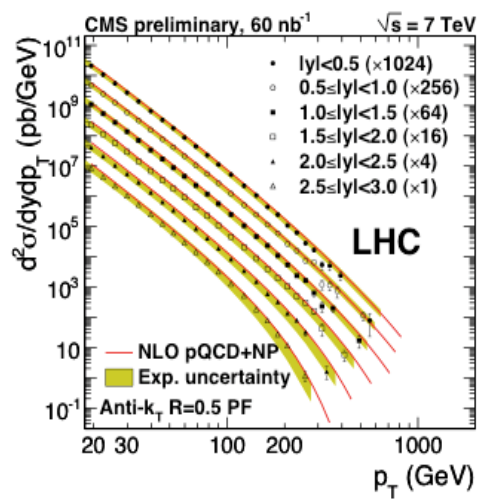
- **@high energy:**

  Asymptotic freedom + perturbative QCD





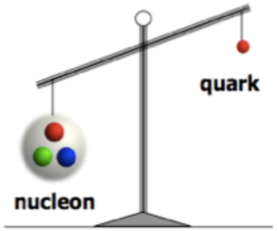




Measure e-p at 0.3 TeV (HERA)
Predict p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV

Hadron mass

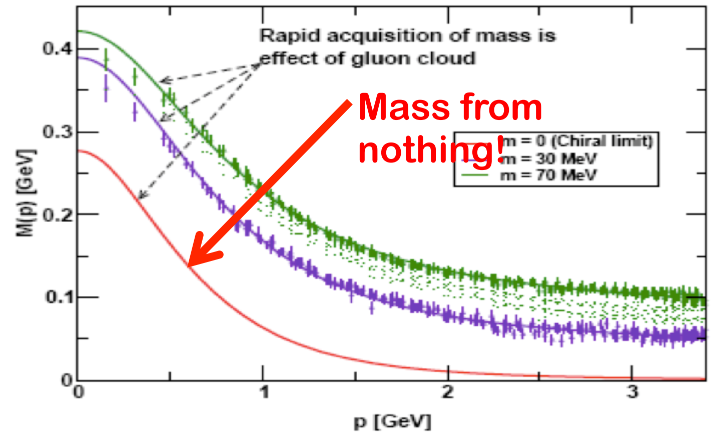
- ***Not from Higgs Mechanism!***



$m_q \sim 10$ MeV

$m_N \sim 1000$ MeV

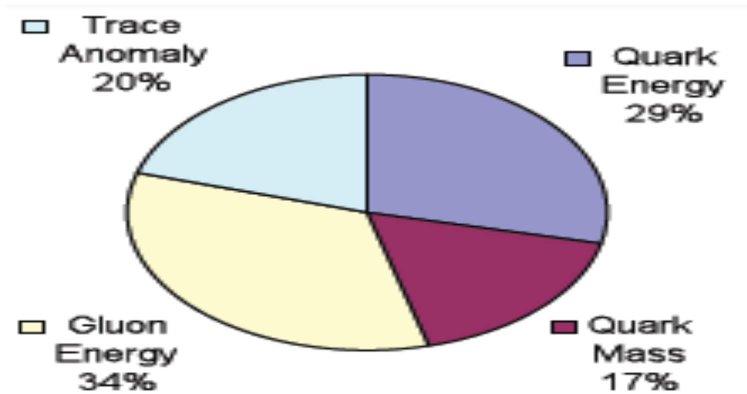
Quarks carry $\sim 1\%$ proton's mass



C.D. Roberts, Prog. Part. Nucl. Phys. 61 (2008) 50
M. Bhagwat & P.C. Tandy, AIP Conf.Proc. 842 (2006) 225-227

- **Dynamically generated:**

Light-quark mass comes from a cloud of soft gluons



- **QCD sum rule:** Ji, 1994

$$M = \frac{\langle P| \int d^3x\, T^{00}(0,\mathbf{x})|P\rangle}{\langle P|P\rangle} \equiv \langle T^{00}\rangle$$

Energy of hadron when it is at rest!

Mass type	H_i	M_i	$m_s \to 0$ (MeV)	$m_s \to \infty$ (MeV)
Quark energy	$\psi^\dagger(-i\mathbf{D}\cdot\boldsymbol{\alpha})\psi$	$3(a-b)/4$	270	300
Quark mass	$\bar{\psi}m\psi$	b	160	110
Gluon energy	$\frac{1}{2}(\mathbf{E}^2+\mathbf{B}^2)$	$3(1-a)/4$	320	320
Trace anomaly	$\frac{9\alpha_s}{16\pi}(\mathbf{E}^2-\mathbf{B}^2)$	$(1-b)/4$	190	210

Dark! → (Gluon energy)

Proton spin

Also see talks by Abhay, Ji & Matthias P.

- **QCD sum rule:**

$$S(\mu) = \sum_f \langle P, S|\hat{J}^z_f(\mu)|P, S\rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$
$$= \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + \Delta G(\mu) + [J_g(\mu) - \Delta G(\mu)]$$

By Local matrix elements – Lattice QCD

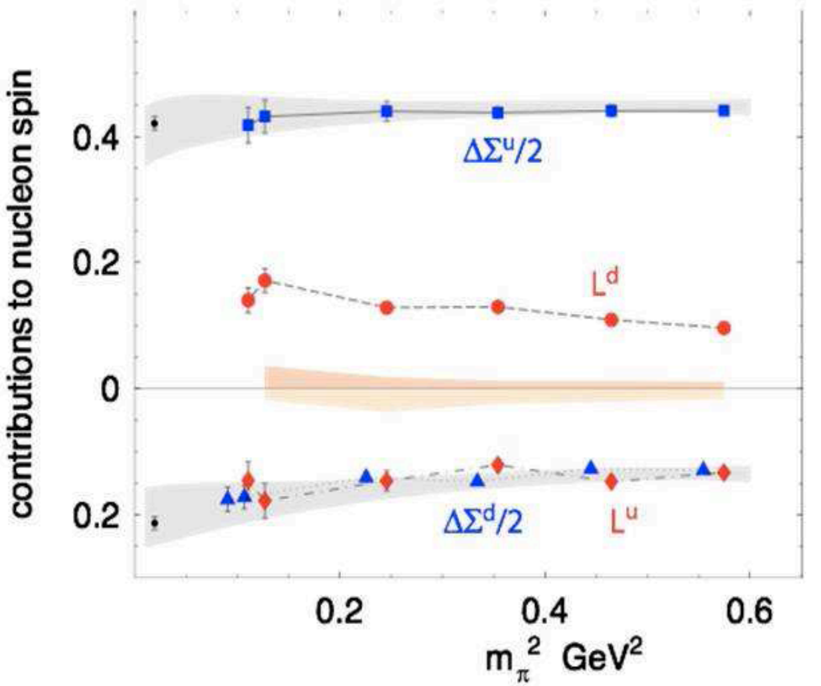
- **Early Lattice result:**

$$L^z_q = J^z_q - \tfrac{1}{2}\Delta q$$

Both L_u and L_d large, but, $L_u + L_d \sim 0$

Quark helicity: $\sim 30\%$

Gluon helicity: $\sim 20\%$ limited x range



- ***More interesting & important:***
  - X-dependence of the distribution
  - Connection to GPDs

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

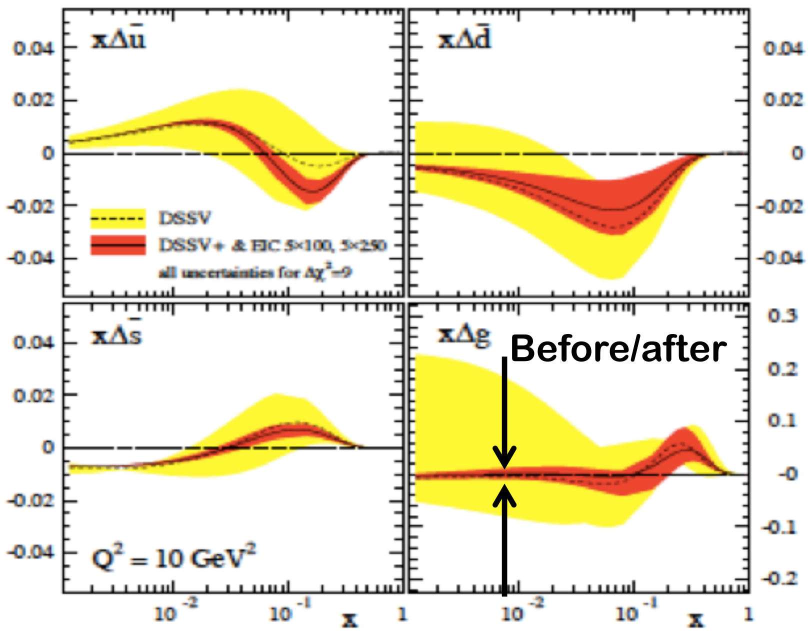
➡ More on dynamics/motion and structure!

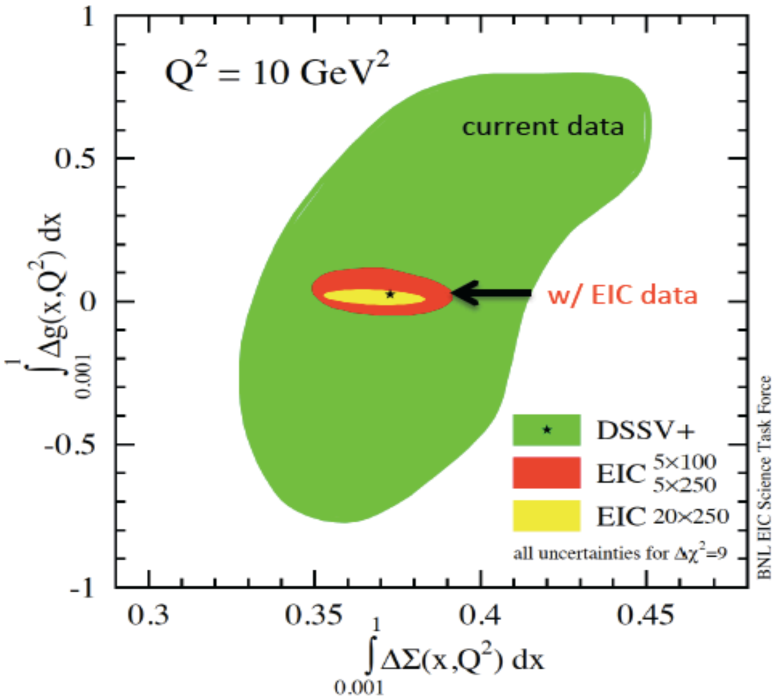
Need EIC!!!

Helicity contribution to proton spin

❑ **EIC@US – the decisive measurement (1st year of running):**

(Low x and wide x range at EIC)





No other machine in the world can achieve this!

❑ **Much more than the proton spin:**

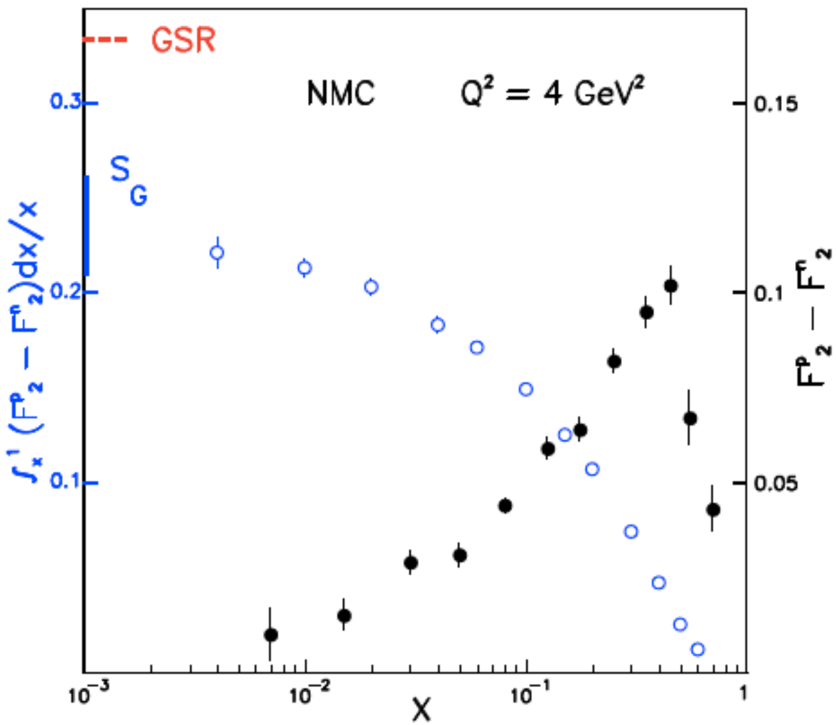
✧ *Precision measurement of $\Delta G(x)$ – extend to smaller x regime*

✧ *Physics beyond the parton picture – more important part of QCD*

Flavor structure of the proton sea

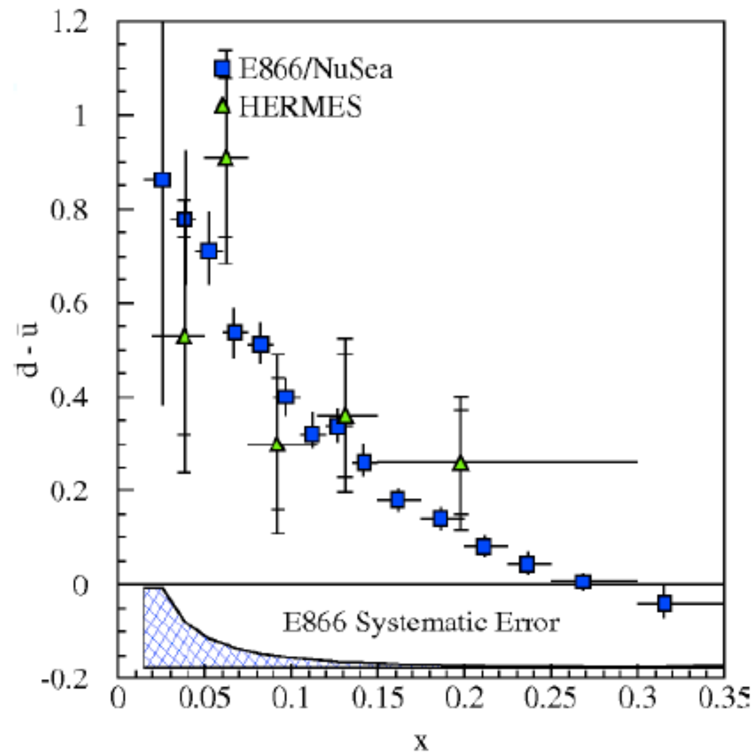
❑ **The proton sea is not SU(3) symmetric!**

Violation of Gottfried sum rule



$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$
$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\ dx$$
$$= \frac{1}{3} \quad (if\ \bar{u}_p = \bar{d}_p) \quad \text{NMC: } S_G = 0.235 \pm 0.026$$

Confirmed by Drell-Yan exp't

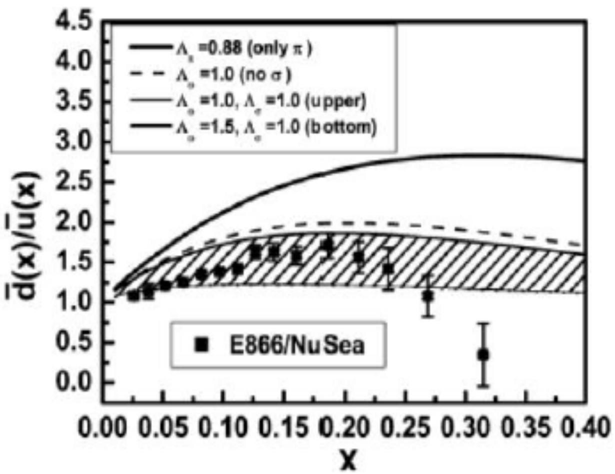


Why $\bar{d}(x) \neq \bar{u}(x)$?

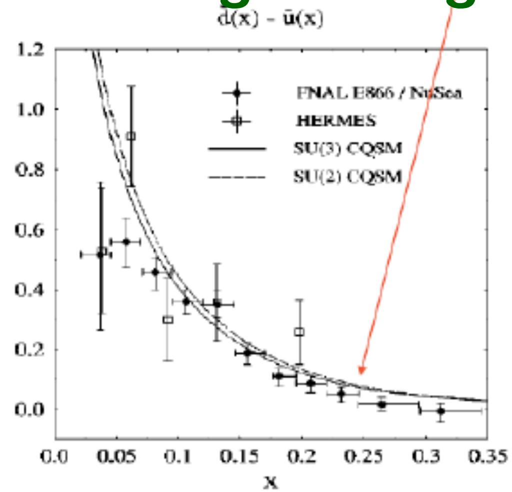
Why does $\bar{d}(x) - \bar{u}(x)$ change sign?

Challenges for $\bar{d}(x) - \bar{u}(x)$

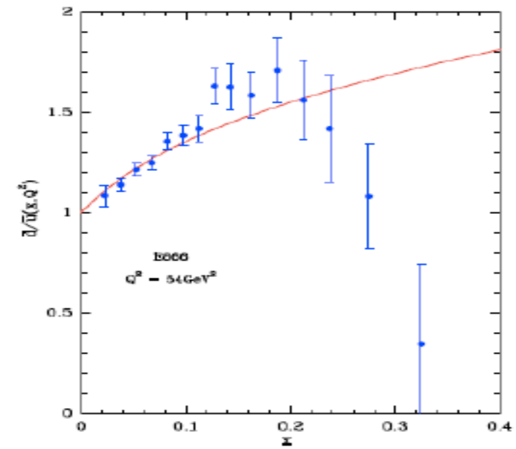
- All known models predict no sign change!



Meson cloud

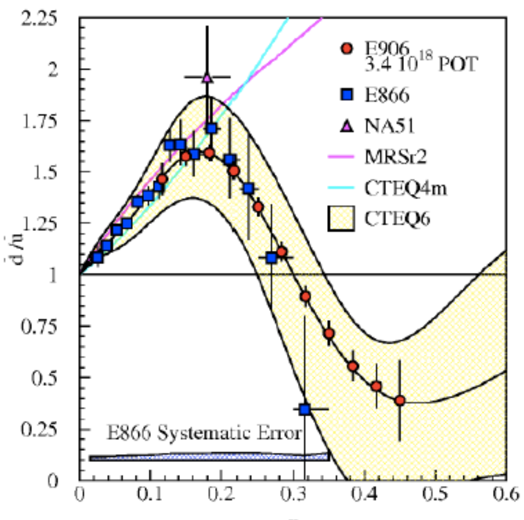


Chiral-quark soliton model

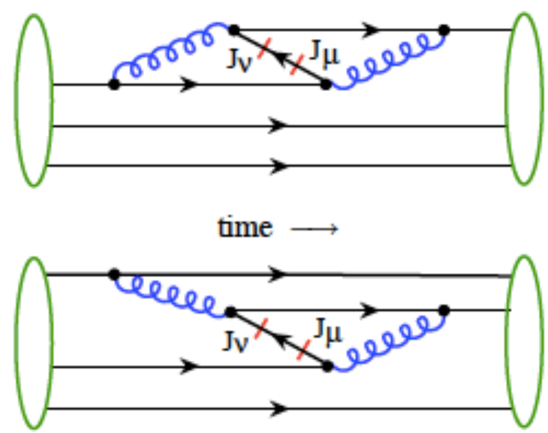


Statistic model

- Future experiments – E906, …



J.C. Peng et al. 2014



Recombination

$$\rightarrow \bar{u}(x) > \bar{d}(x)$$

due to more u(x) in proton

Confined motion in a hadron

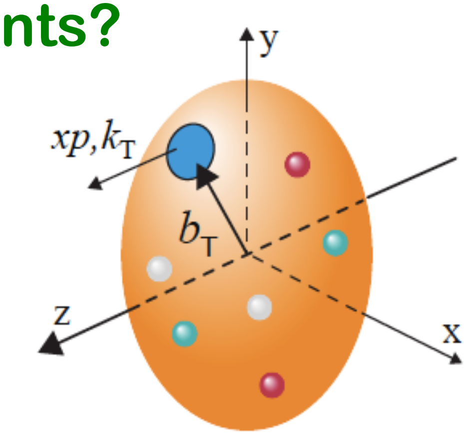
Also see talk by Feng & Ji

- ❑ **Too small to be seen in high energy experiments?**

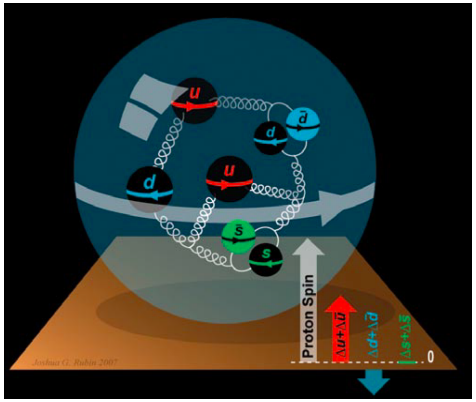
  ✧ Typical scattering with a large momentum transfer:

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

  ✧ Combined motion ~ 1/R is too week to be sensitive integrated into PDFs – averaged effect



- ❑ **Spin: its correlation with the "preference" of parton motion:**



The spin sum rule and beyond

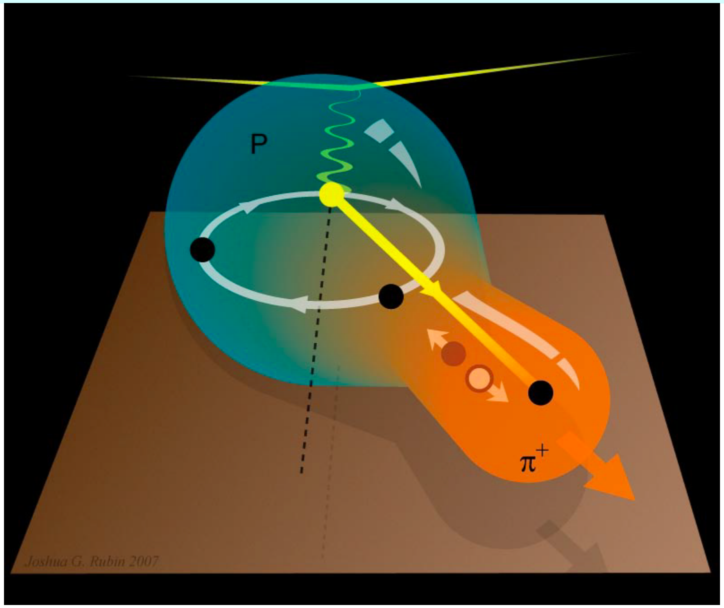
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

with the help of spin asymmtry

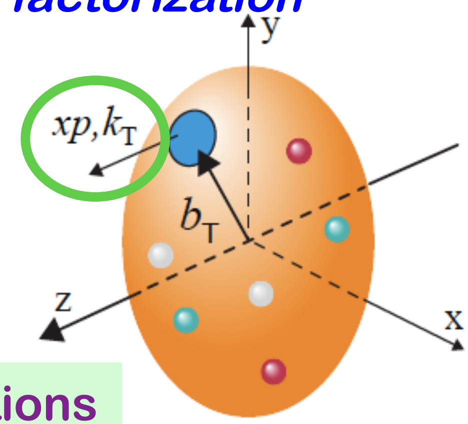
Orbital Angular Momentum of partons
Little known

Need observables having two different scales!

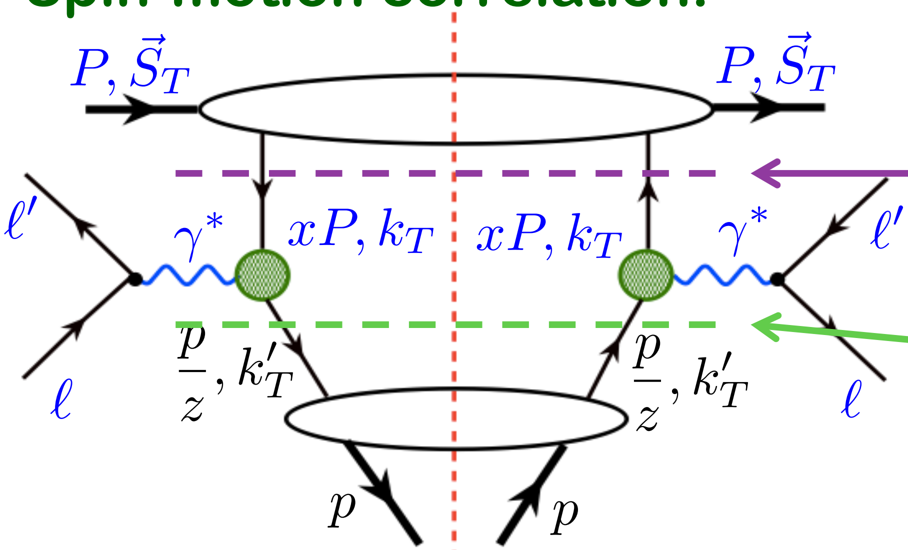
Semi-inclusive DIS @ EIC



- **Naturally, two scales:**
  - ✧ **high Q – localized probe**
    To "see" quarks and gluons
  - ✧ **Low p_T – sensitive to confining scale**
    To "see" their confined motion
  - ✧ ***Theory – QCD TMD factorization***



- **Spin-motion correlation:**

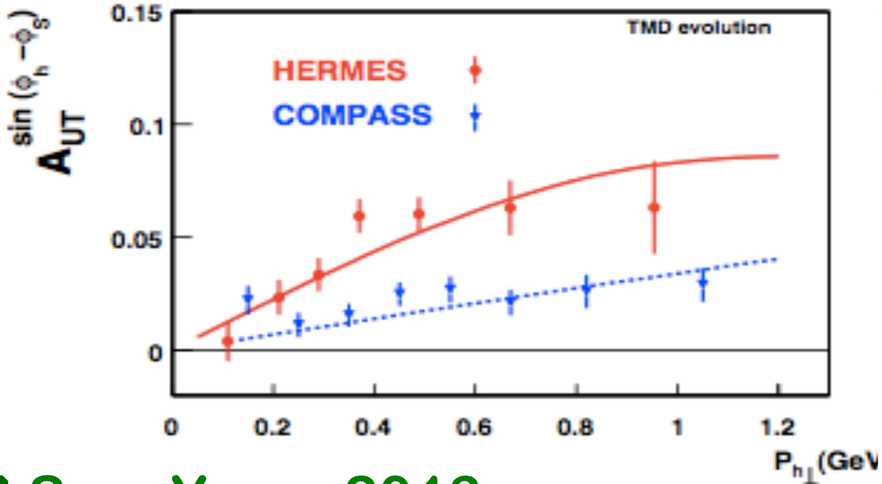


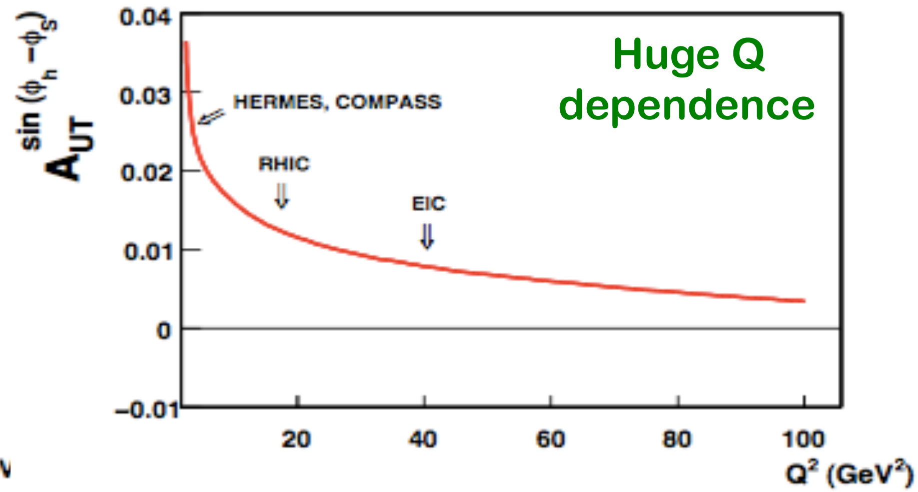
4 spin combinations
$\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma_\perp^\alpha$

4 spin combinations
$\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma_\perp^\alpha$

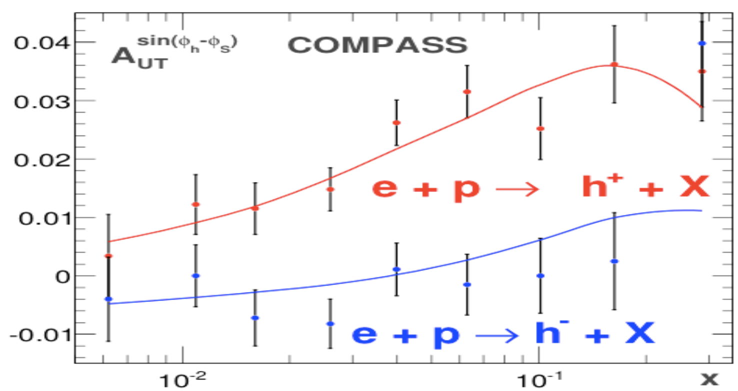
Importance/confusion of the evolution

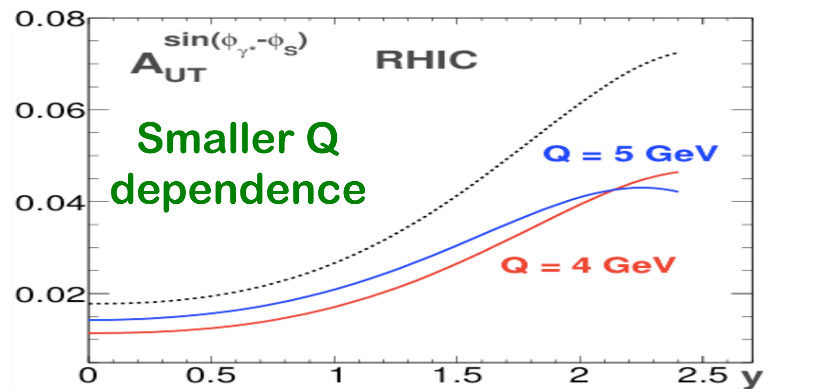
- Aybat, Prokudin, Rogers, 2012:





- Sun, Yuan, 2013:



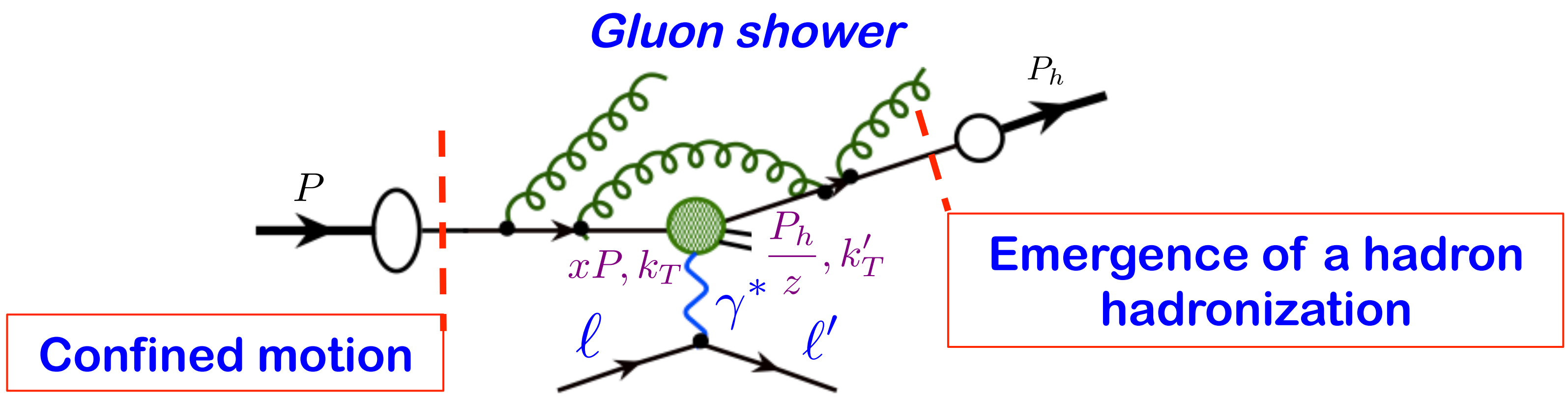


No disagreement on evolution equations!

Issue: extrapolation to non-perturbative large b-region
choice of the Q-dependent "form factor"

Measured parton k_T

- Sources of parton k_T at the hard collision:



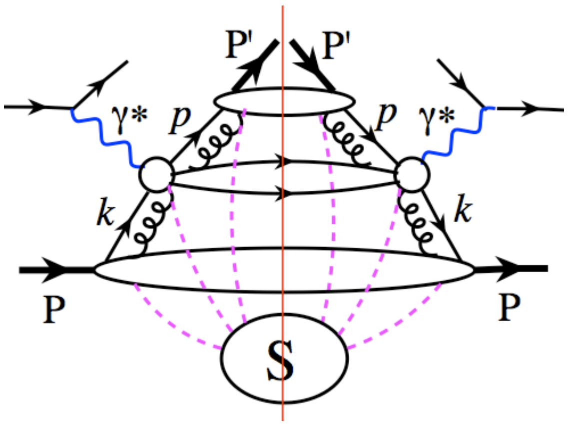
- Large k_T generated by the shower caused by the collision:
  - ✧ Q^2-dependence – linear equation of TMDs in b-space
    perturbative at small b, but, not all b
  - ✧ Solution – TMDs proportional to "input distribution" – boundary condition
    Q^2-dependence of TMDs in k_T is sensitive to the "input"

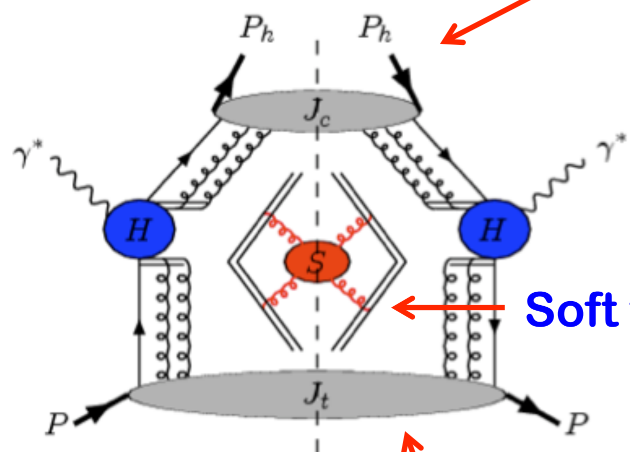
- "True" parton's confined motion – more theory work needed:
  - ✧ Separation of perturbative from nonperturbative – not as simple as PDFs
  - ✧ Ln(Q)-dependence of the "input" might get large correction at low Q

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

Factorization for SIDIS

- Leading power contribution:





- 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:

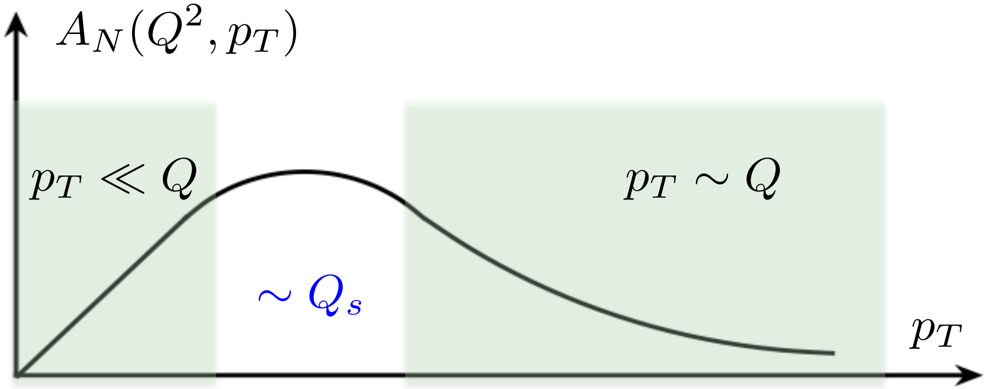
$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q, P_{h\perp}, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{P_{h\perp}}, \frac{1}{Q}\right)$$

- P_{hT} Integrated - Collinear factorization:

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

Transition from low p_T to high p_T @ EIC

❑ TMD factorization to collinear factorization:



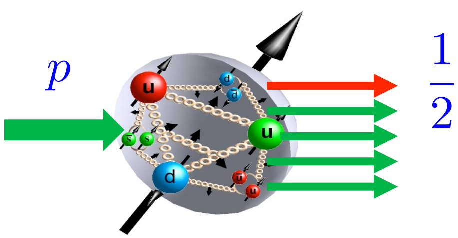
TMD   Collinear Factorization

Two factorization are consistent in the overlap region where

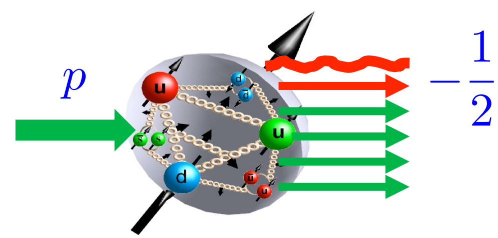
$$\Lambda_{\rm QCD} \ll p_T \ll Q$$

❑ Quantum interference – high p_T region (integrate over all k_T):

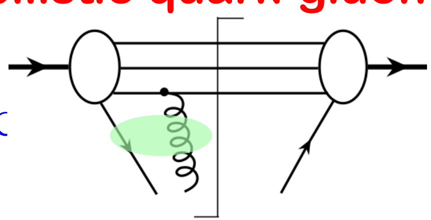
Single quark state   quark-gluon composite state

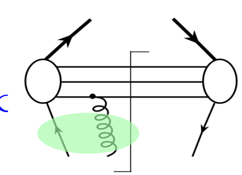


interfere with (Spin flip)



➡ Non-probabilistic quark-gluon quantum correlation

$T^{(3)}(x,x) \propto$ 

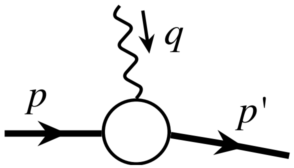
$D^{(3)}(z,z) \propto$ 

Kang, Yuan, Zhou, 2010

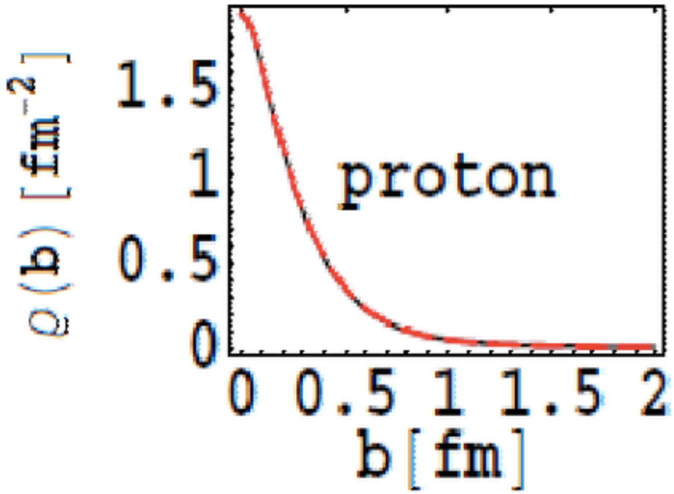
Confined spatial distribution in a hadron

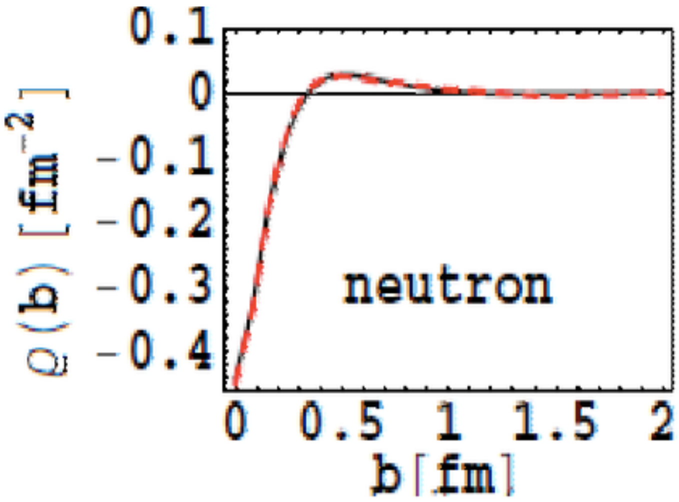
Also see talk by Matthias B.

- ❑ "See" partons without breaking the proton!
- ❑ Proton radius – EM charge distribution:

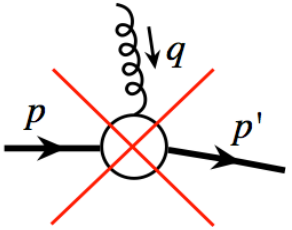


Elastic electric form factor ➡ Charge distributions





- ❑ But, NO color elastic nucleon form factor!



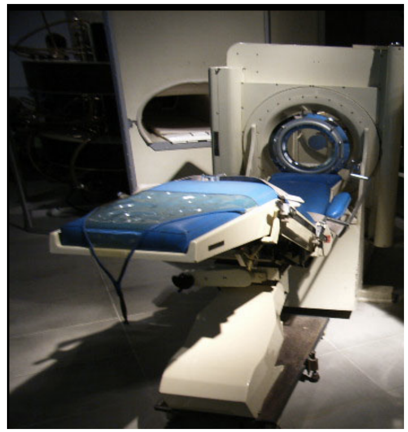
Hadron is colorless and gluon carries color

No direct measurement of color distribution - confinement

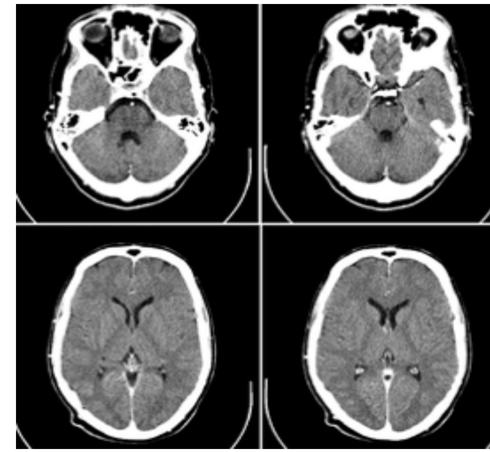
Exclusive DIS @ EIC

- A giant "computed" tomography machine of hadron:

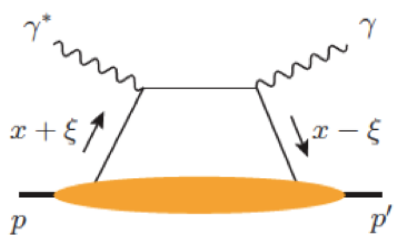
X-ray Computed Tomography (CT) in hospital

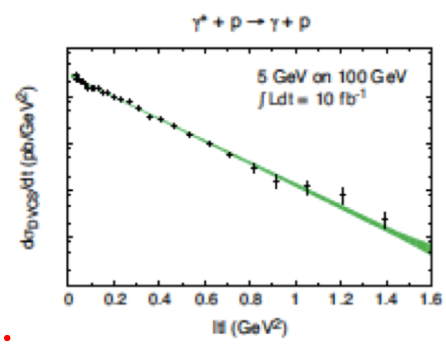


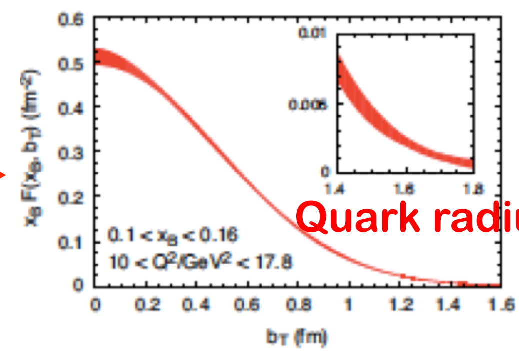
Computer software



- Exclusive processes:



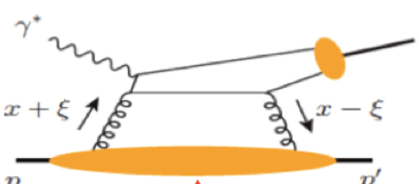




Quark radius

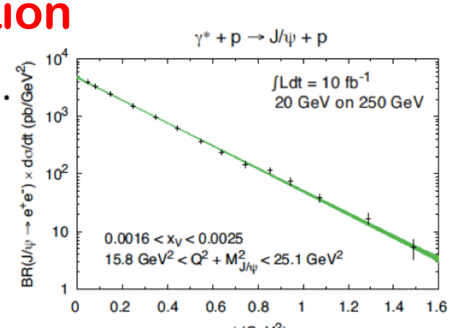
Factorization

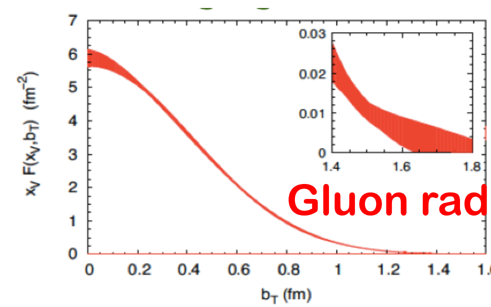
F.T.



t-dep

J/Ψ, Φ, ..

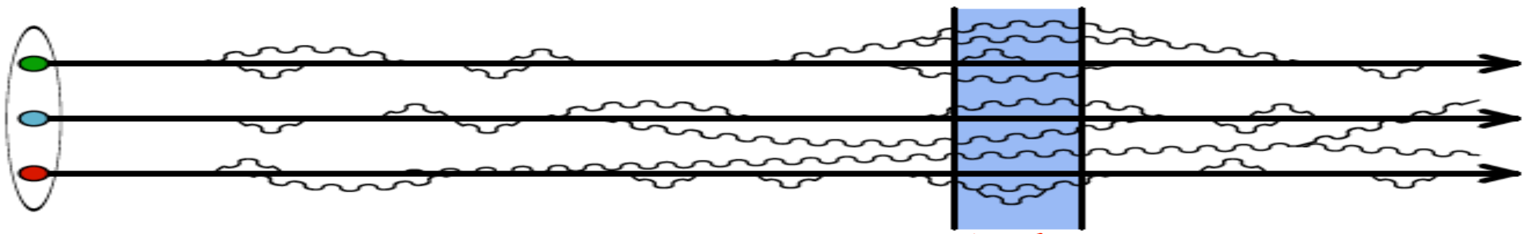




Gluon radius

More than the radiuses

- **High energy scattering:** Boost – time dilation

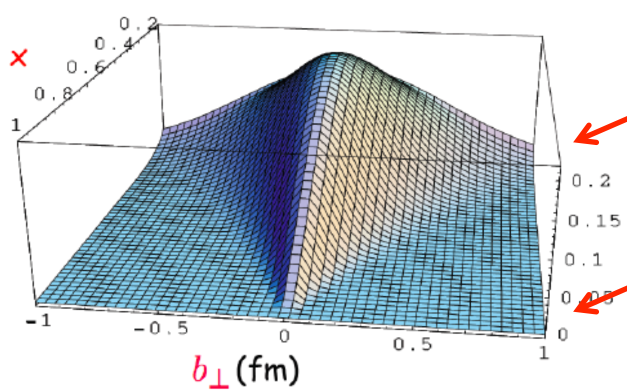


Hard probe: $t \sim 1/Q < 1/10$ fm

Momentum fraction x

Need TWO-scale observables! $Q_1 >> Q_2 \sim 1/fm$ *EIC can deliver!*

- **"Clues" for answers to the fundamental questions:**



How spread at small-x?

Range of color confinement?

Hadron is very small at large-x?

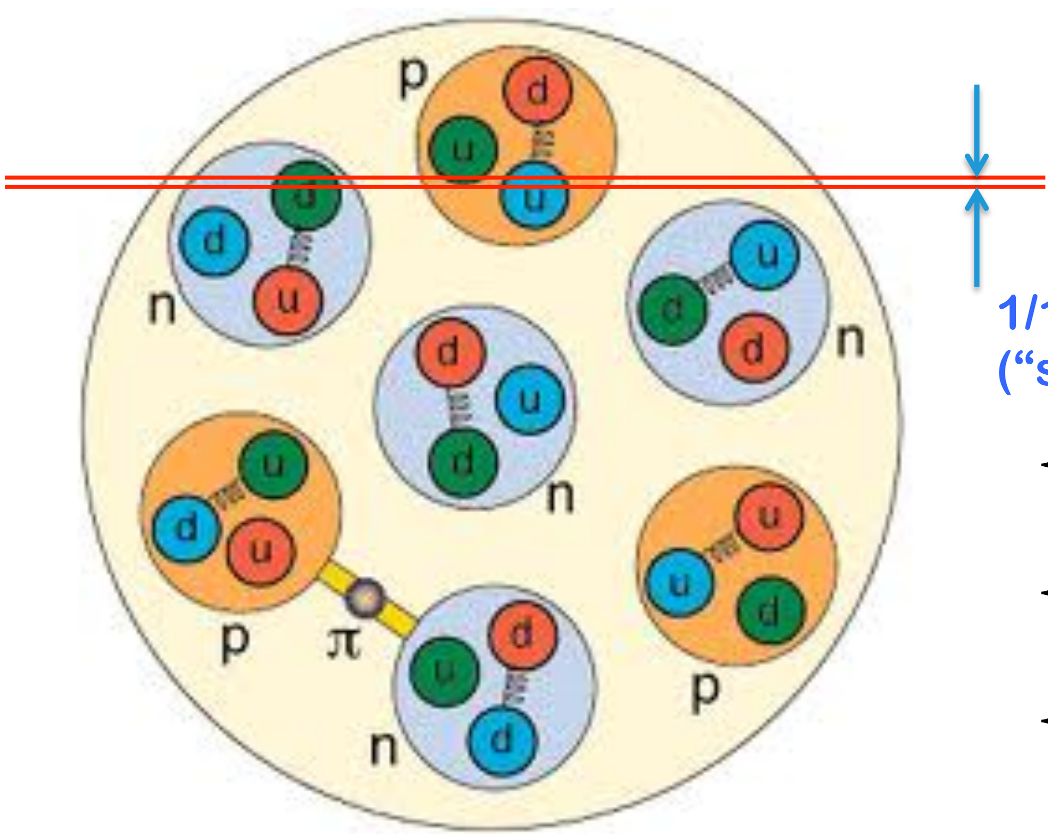
Nucleus = a molecule of "small" nucleons, deuterons, …

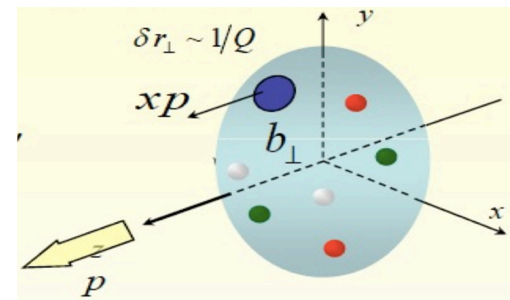
- **Nucleon structure determines the properties of nuclei!**

Quark-gluon nuclear physics/structure

How would/does a nucleus look (the landscape)
if we only "saw" its quarks and gluons?

❑ **EIC could be a "machine" to cat-scan the nucleus!**





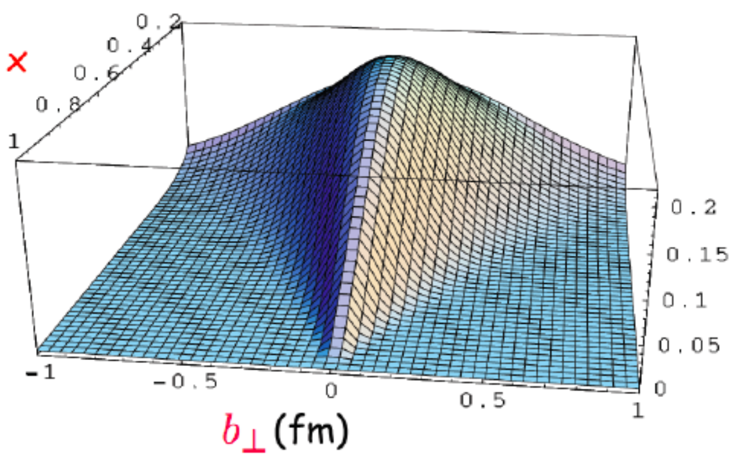
1/10 fm spatial resolution
("see" quarks and gluons)

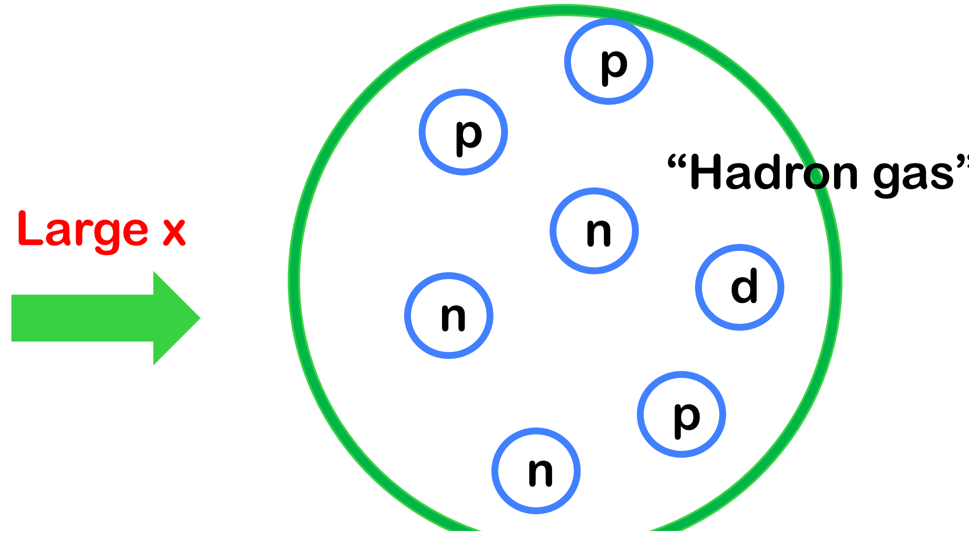
✧ Spatial distribution?
  GPDs, diffractive, …
✧ Confined motion?
  TMDs, semi-inclusive, …
✧ Color coherence?
  Attenuation, …
✧ Nuclear forces?

A natural program at EIC!

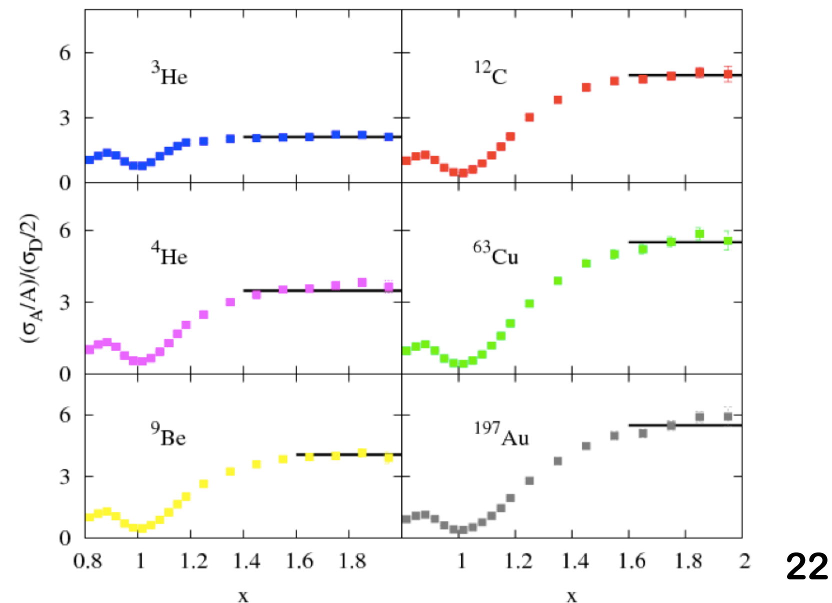
The opportunities – role of “x”

- ❑ What is the nuclear structure at a large “x”?





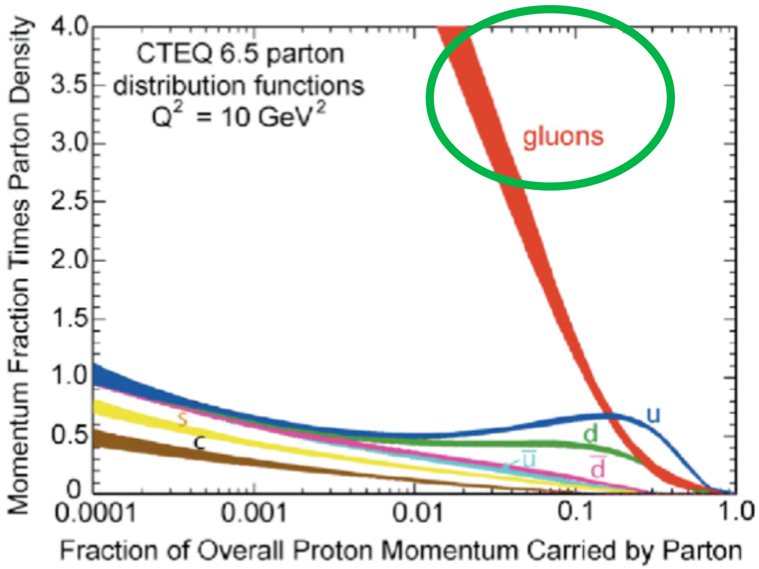
- ❑ What is a nucleus looks like at smaller “x”, when “hadrons” are overlapped in space?



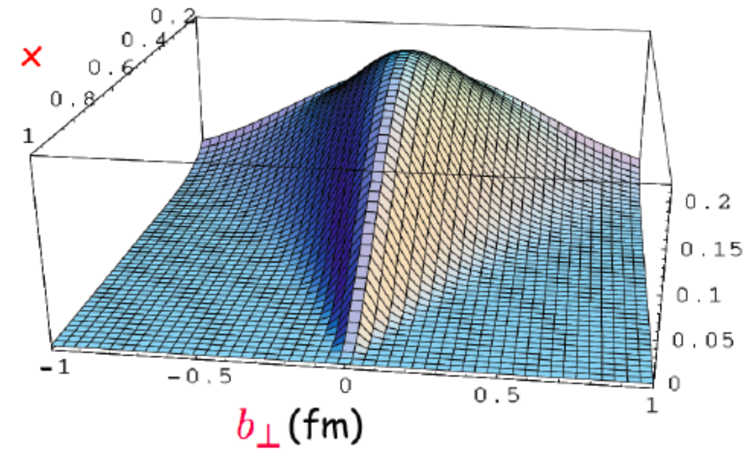
- ❑ How color is correlated?
- ❑ Can nucleus be a larger proton?

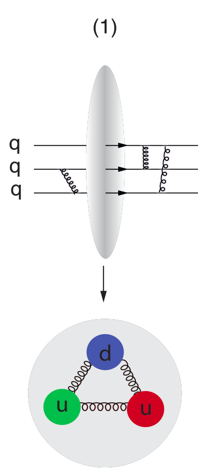
Skyrocketing gluon density

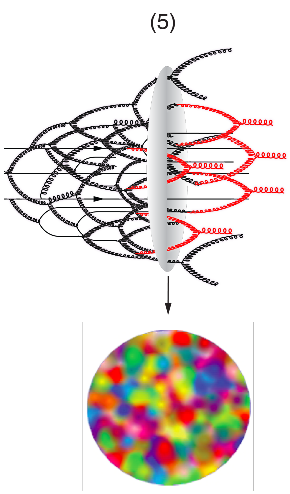
- HERA's discovery: proliferation of soft gluons:

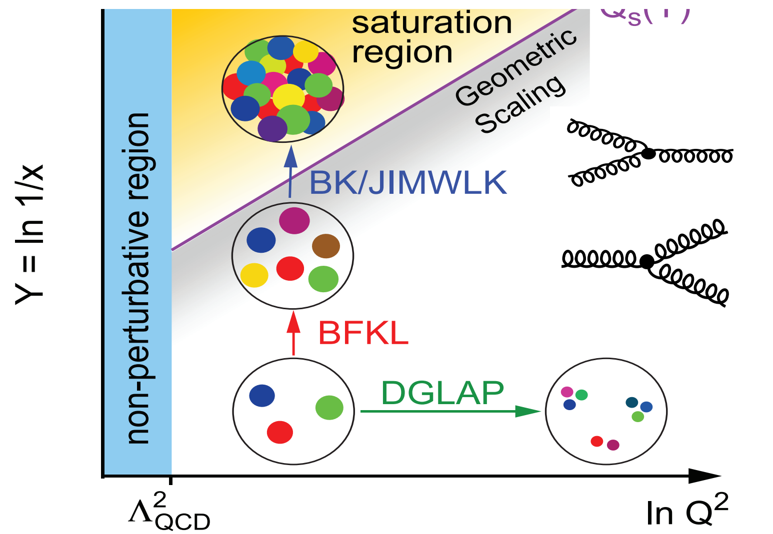


Need GPD of gluon at small x!!!





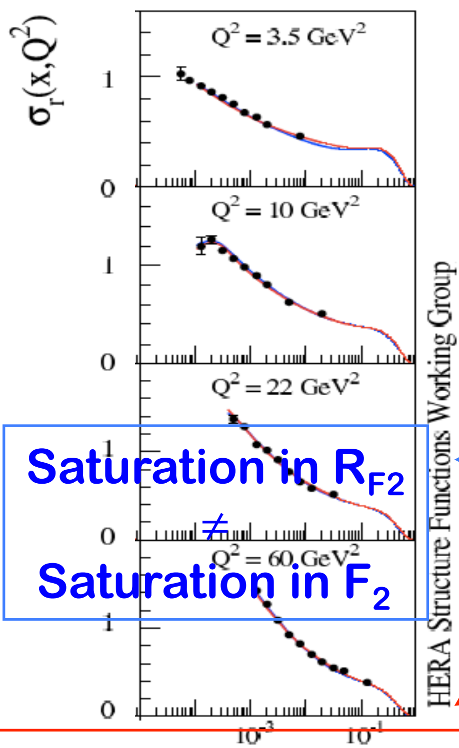




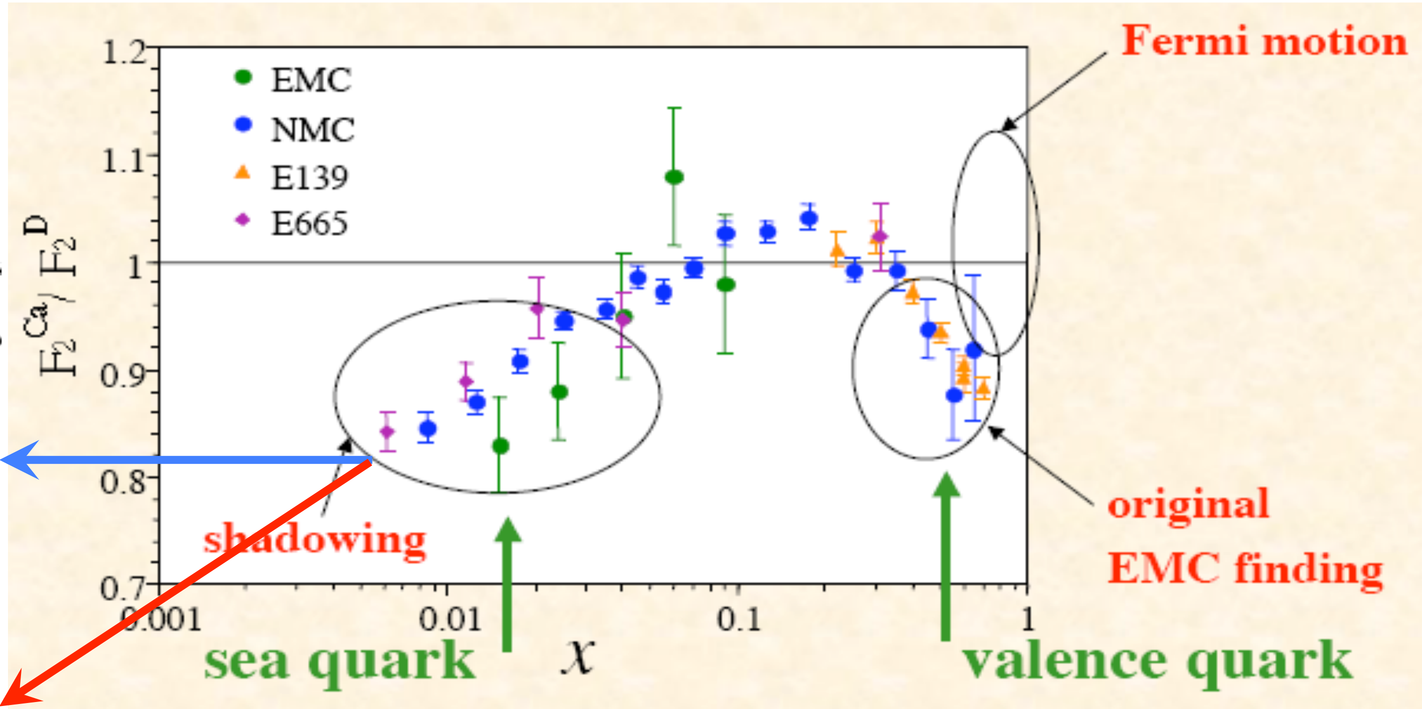
Highly fluctuated liquid?

An “easiest” measurement

❑ EMC effect, Shadowing and Saturation:



Saturation in R_{F2} $\neq$ Saturation in F_2



Saturation in $F_2(A) = R_{F2}$ decreases until saturation in $F_2(D)$

❑ Questions:

Why nuclear structure function suppressed at small x?

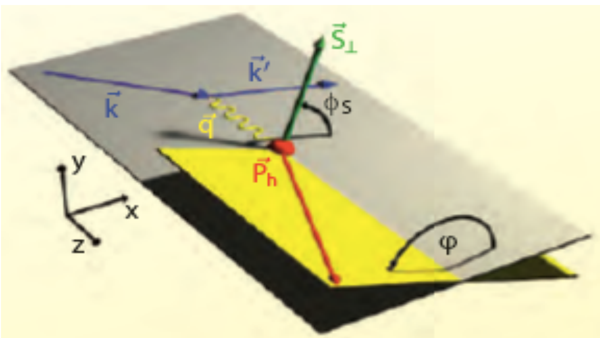
Will the suppression/shadowing continue fall as x decreases?

Range of color correlation – could impact the center of neutron

Color fluctuation – azimuthal asymmetry

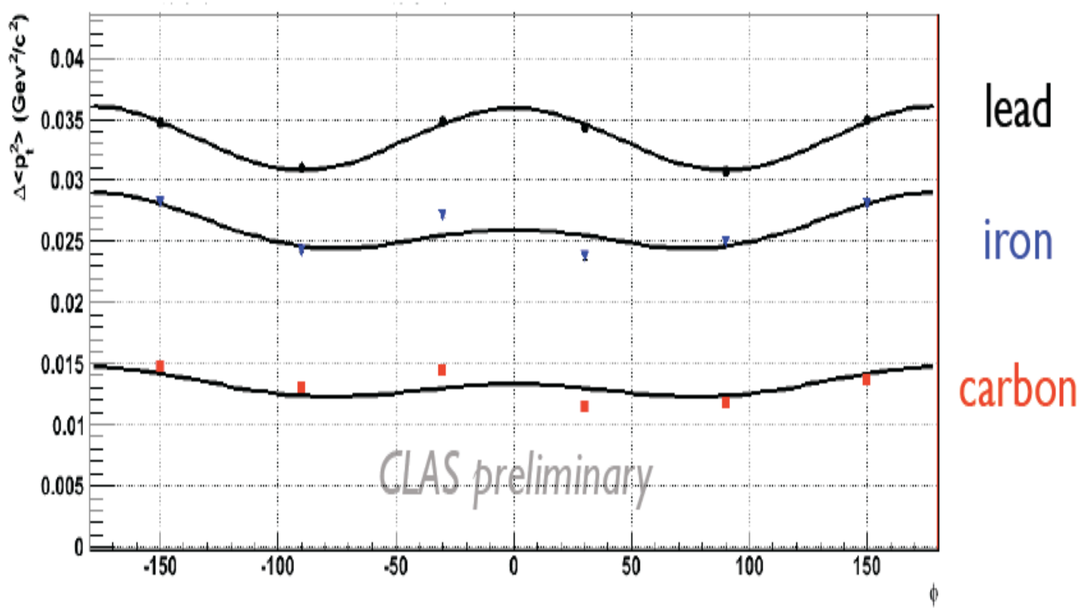
Hicks, KEK-JPAC2013

❑ Preliminary low energy data:



$$\langle p_T^2(\phi_{pq})\rangle_A = \int dp_T^2\, p_T^2 \frac{d\sigma_{eA}}{dx_B dQ^2 dp_T^2 d\phi} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}$$

$$\langle \Delta p_T^2(\phi)\rangle_{AN} \equiv \langle p_T^2(\phi)\rangle_A - \langle p_T^2(\phi)\rangle_N$$



Contain terms in cos(ϕ_{pq}) and cos($2\phi_{pq}$)
only statistical uncertainties shown

❑ Classical expectation:

Any distribution seen in Carbon should be washed out in heavier nuclei

❑ Surprise:

Azimuthal asymmetry in transverse momentum broadening

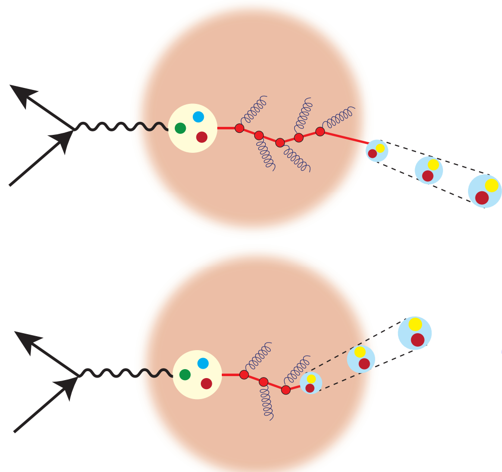
➡ ***Fluctuation and v_n at EIC too!***

See Brooks talk at EICAC

Emergence of hadrons

How hadrons emerge from quarks and gluons?

❑ Unprecedented ν range at EIC:

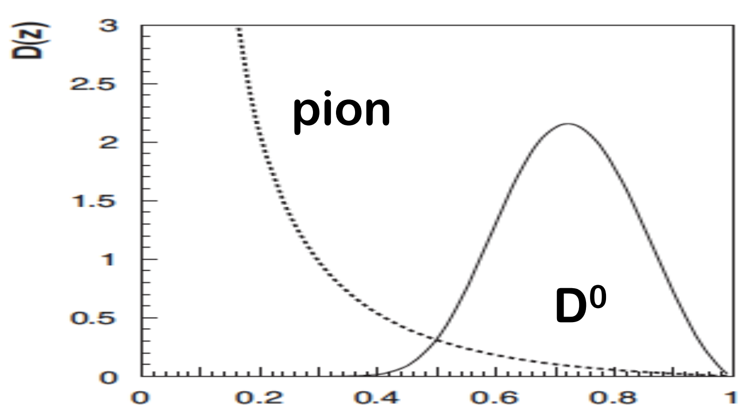


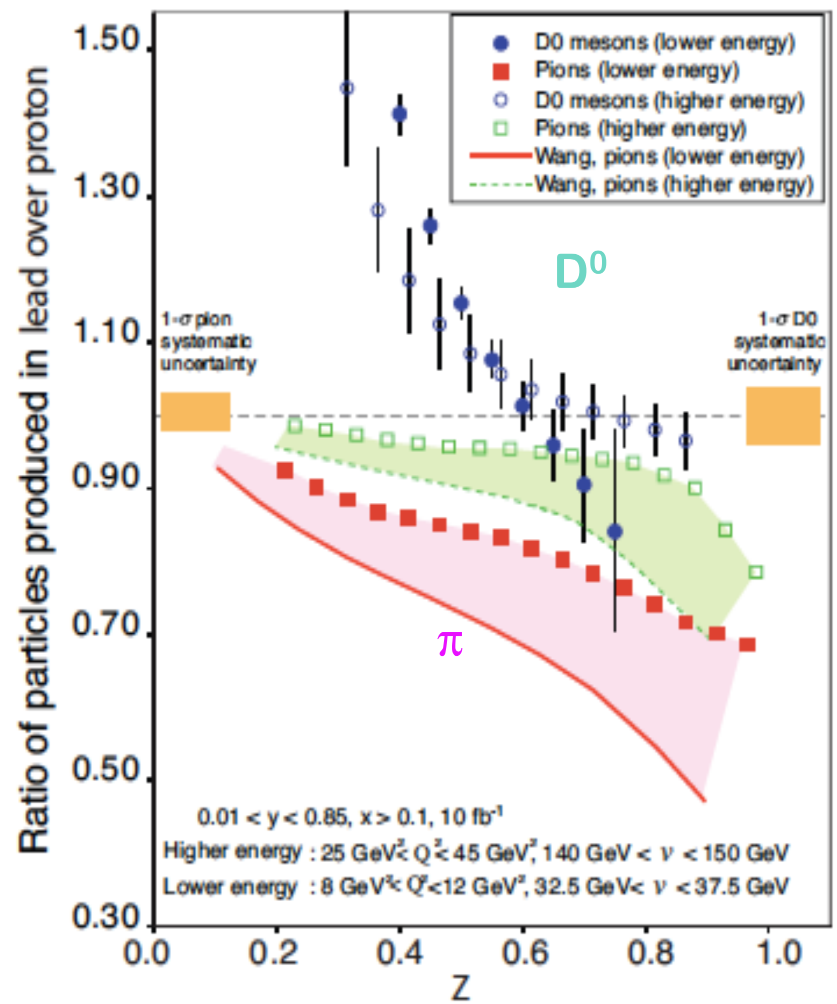
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

❑ Femtometer “detector”:

Mass dependence of fragmentation





Need the collider energy of EIC and its control on parton kinematics

Summary

- EIC is a ultimate QCD machine:
  1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
  2) to search for hints and clues of color confinement, and
  3) to measure the color fluctuation and color neutralization

- EIC is a tomographic machine for nucleons and nuclei with a resolution better than 1/10 fm

- EIC designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology

- EIC and Lattice QCD are complementary to each other

- Complementary designs of EIC around the world have been proposed to cover different kinematic regimes of QCD – EIC@US is sitting at a sweet spot for rich QCD dynamics

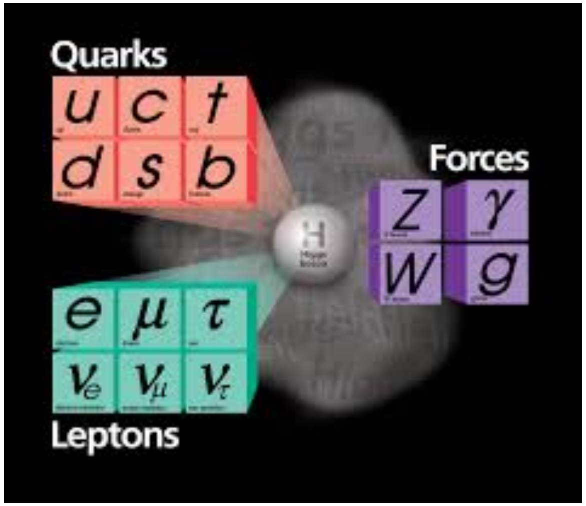
Thanks!

Backup Slides

The "most" successful story to tell

The Standard Model (SM)

Found every elementary particles in the table but, not even one extra!



All of them behave in the way that they are supposed to behave

We found the "lonely" Higgs too!

What is *beyond* the Higgs and the SM?

The true nature of the effective theory?

What we have not been able to address *within* the SM?

The magic of glue that binds us all

Color confinement, mass generation, QCD and beyond, …

Experimental studies at an EIC

Inclusive DIS

Generalized Parton Distributions

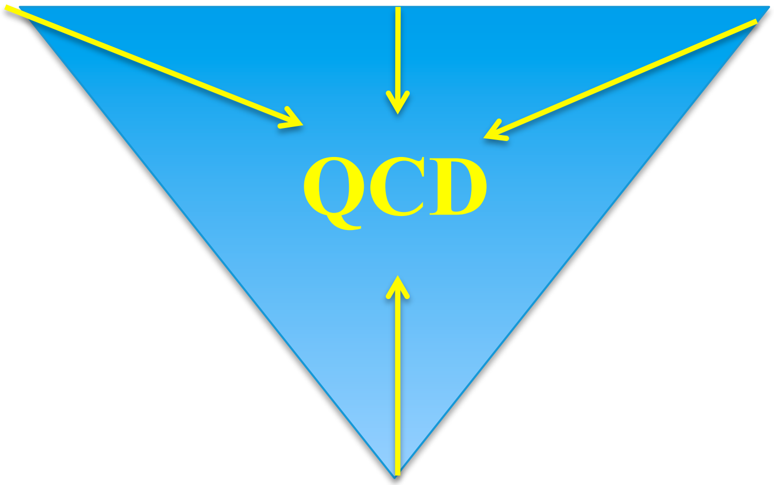
Since 1998

Exclusive reactions In nucleons and nuclei

Elastic form factors
Deep Virtual Compton Scattering
Deep Virtual Meson Production

Parton distributions

Sum rules and polarizabilities



Transverse Momentum Distributions

Since 2002

Semi-Inclusive DIS In nucleons and nuclei

Distributions and Fragmentation functions

Saturation in Nucleon and Nuclei

Inclusive, Semi-Inclusive and Exclusive reactions in Nucleon and Nuclei

Structure functions, hadron correlations and diffractive scattering

Electroweak probe to hadronic systems

Precision electroweak/Beyond the standard Model

QCD and hadrons

Gell-Mann, Zweig, 1964
Gell-Mann, Nobel Prize 1969

❑ "Quark atoms" – Quark Model (1964):

Meson:

$q\bar{q} \quad \Rightarrow \quad \mathbf{3} \otimes \bar{\mathbf{3}}$

Baryon:

$qqq \quad \Rightarrow \quad \mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3}$

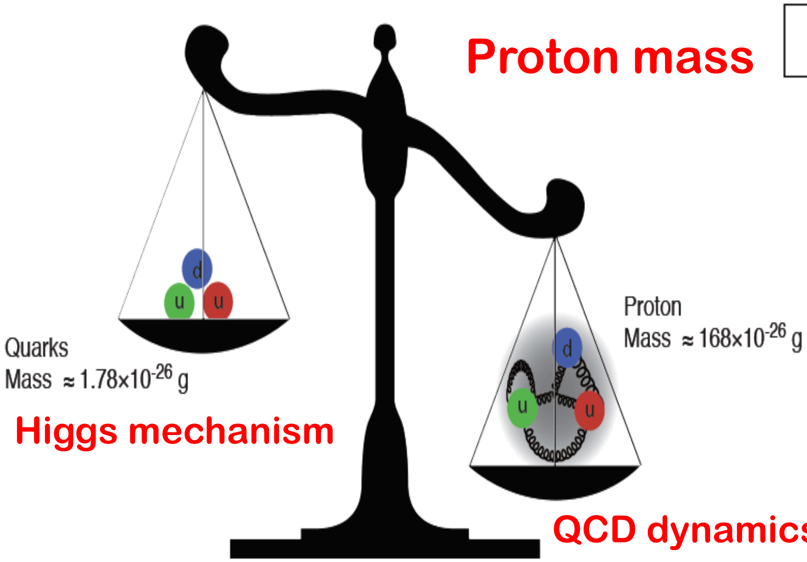
Flavor	Mass
u	1.5 – 4.5 MeV
d	5.0 – 8.5 MeV
s	80 – 155 MeV
c	1.0 – 1.4 GeV
b	4.0 – 4.5 GeV
t	174.3 ± 5.1 GeV

Light quarks (u, d, s)

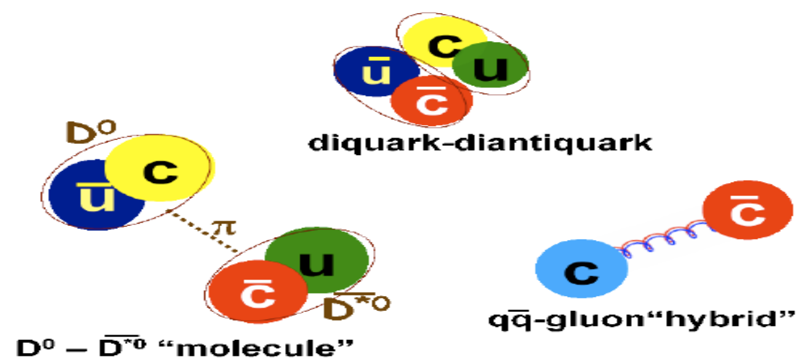
$\Lambda_{\rm QCD} \sim 1/{\rm fm}$

Heavy quarks (c, b, t)

❑ Light, heavy hadrons:



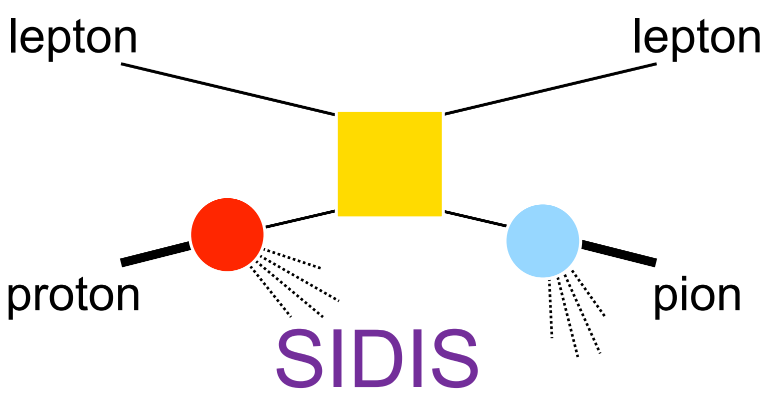
❑ New X, Y, Z hadrons:

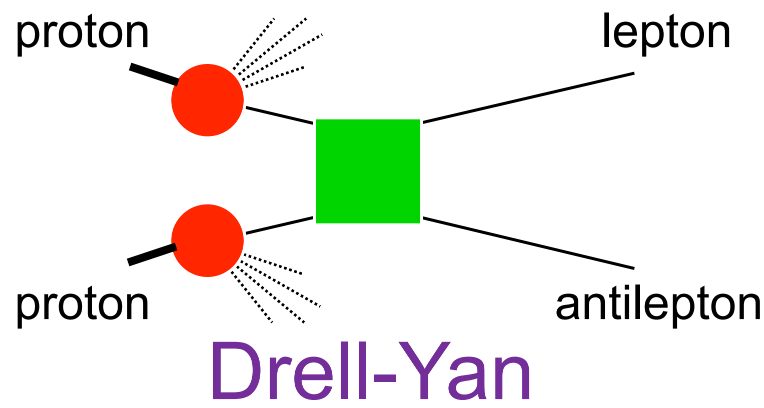


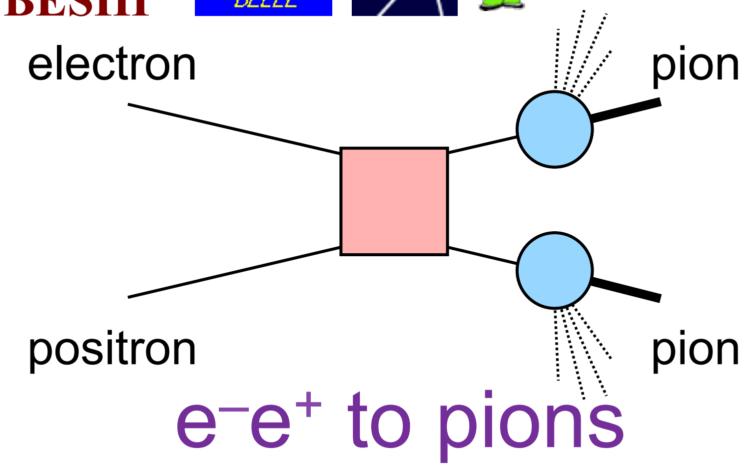
❑ Questions:

Color confinement, 3D hadron structure?

World effort on TMDs







- **Partonic scattering amplitude** (yellow square)
- **Fragmentation amplitude** (light blue circle)
- **Distribution amplitude** (red circle)

Test of the sign change!

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

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

Polarized DVCS @ EIC