U.S. DEPARTMENT OF ENERGY | Office of Science

2017 JLab Users Group Workshop and Annual Meeting

June 19-21, 2017, Jefferson Lab

From JLab 12 to EIC: The Ultimate QCD Machine

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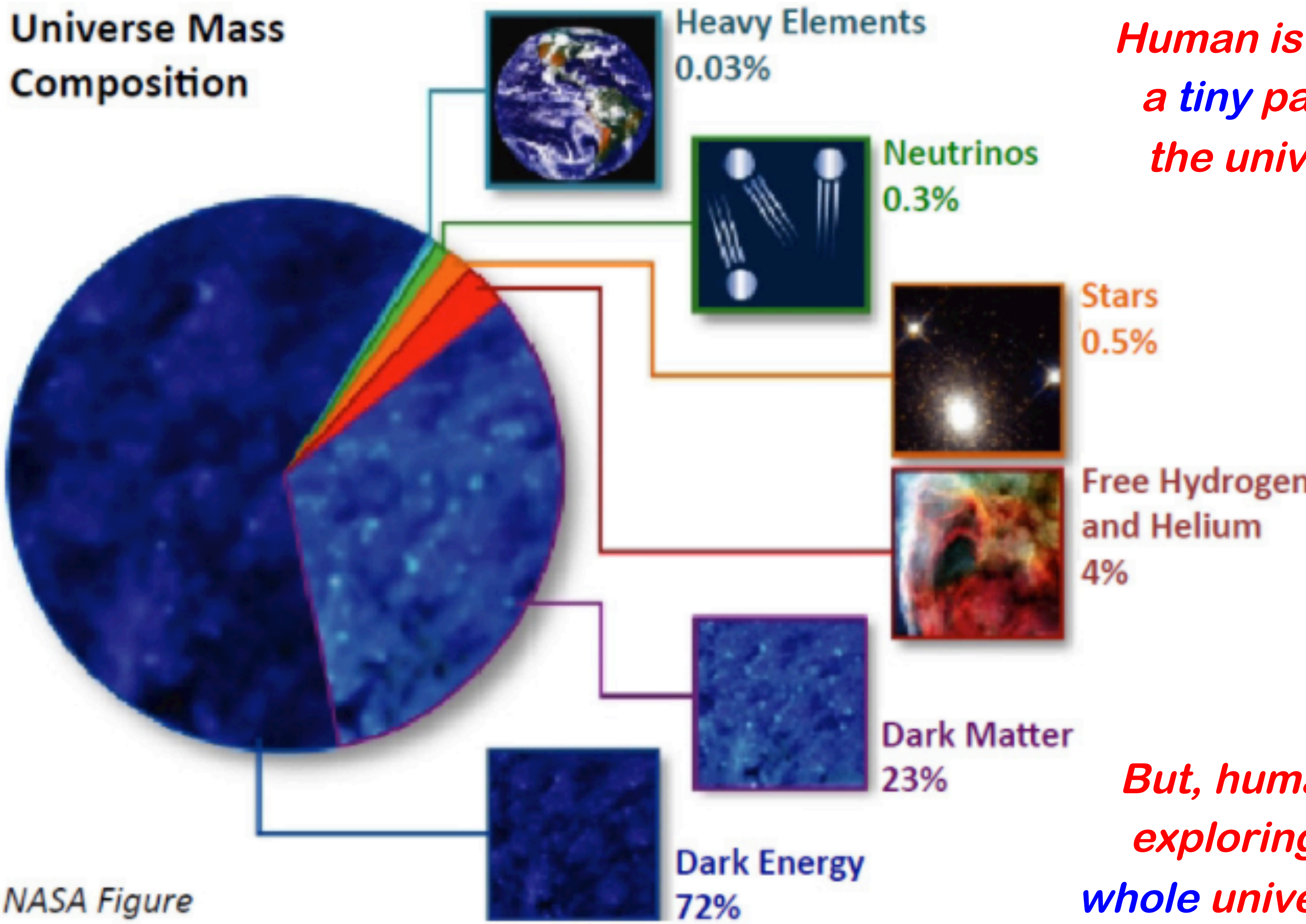
Theory Center, Jefferson Lab

What the world is made of?

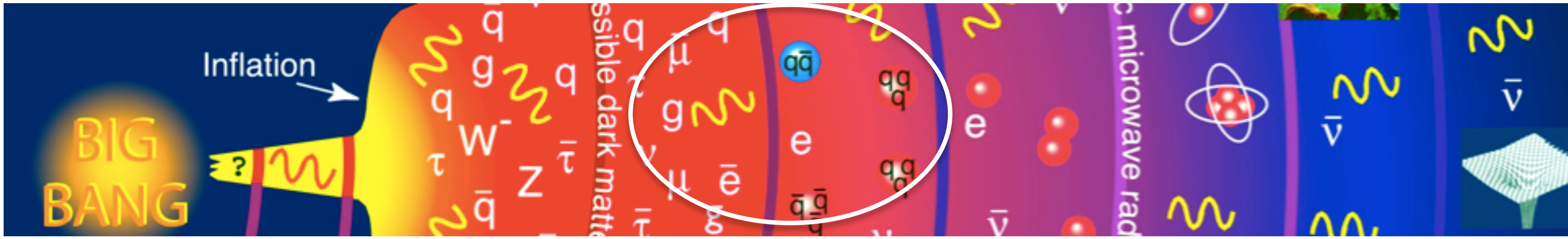


Human is only a tiny part of the universe

But, human is exploring the whole universe!

The next QCD frontier

- What is the role of QCD in the evolution of the universe?



- How hadrons are emerged from quarks and gluons?
- How does QCD make up the properties of hadrons?

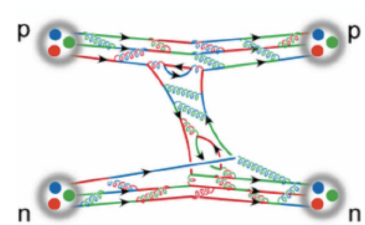
  Their mass, spin, magnetic moment, …

- What is the QCD landscape of nucleon and nuclei?

Color Confinement — Asymptotic freedom

Q (GeV)

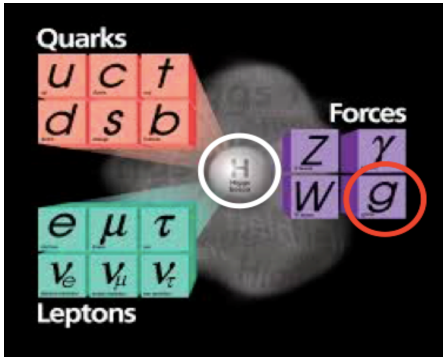
200 MeV (1 fm) — 2 GeV (1/10 fm) — Probing momentum

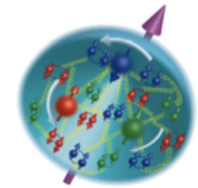


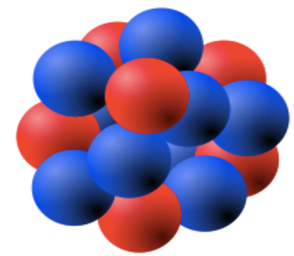
- How do the nuclear force arise from QCD?
- … ***Have to understand the role of glue!***

The next QCD frontier

- ❑ Understanding the glue that binds us all – the Next QCD Frontier!

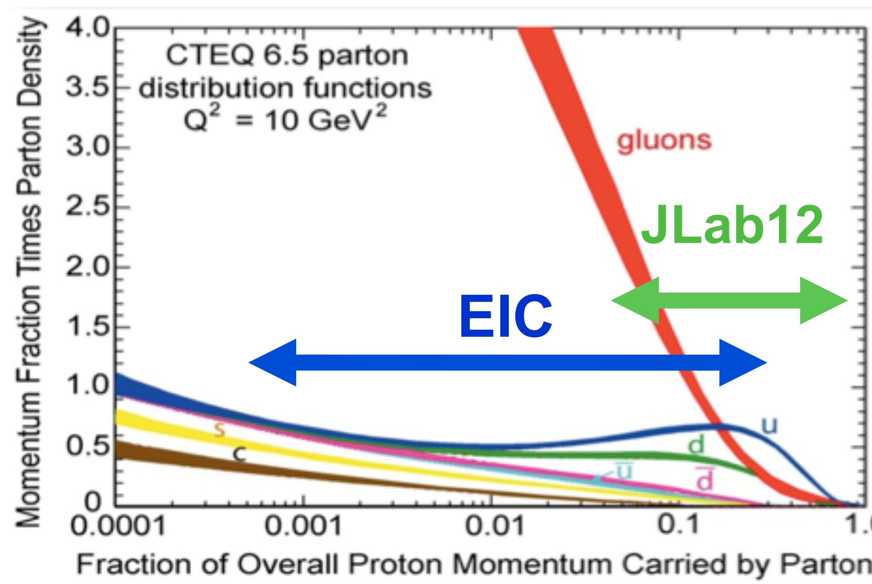






- ❑ Gluons are weird particles!
  - ✧ Massless, yet, responsible for nearly all visible mass
  - ✧ Carry color charge, unlike photon, responsible for color confinement but, also for asymptotic freedom, as well as the abundance of glue!

Without gluons, there would be NO nucleons, NO atomic nuclei… NO visible world!



Unprecedented Intellectual Challenge!

- **Facts:**

Gluons are dark!

No modern detector has been able to see quarks and gluons in isolation!

- **The challenge:**

How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, if we cannot see quarks and gluons?

- **Answer to the challenge:**

Theory advances:

QCD factorization – matching the quarks/gluons to hadrons with controllable approximations!

Experimental breakthroughs:

Jets – ***Footprints of energetic quarks and gluons***

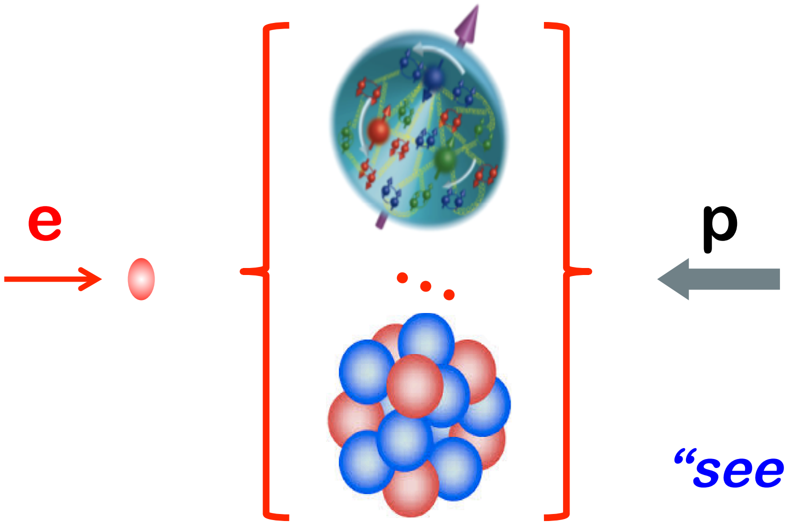
Quarks – ***Need an EM probe to "see" their existence, …***

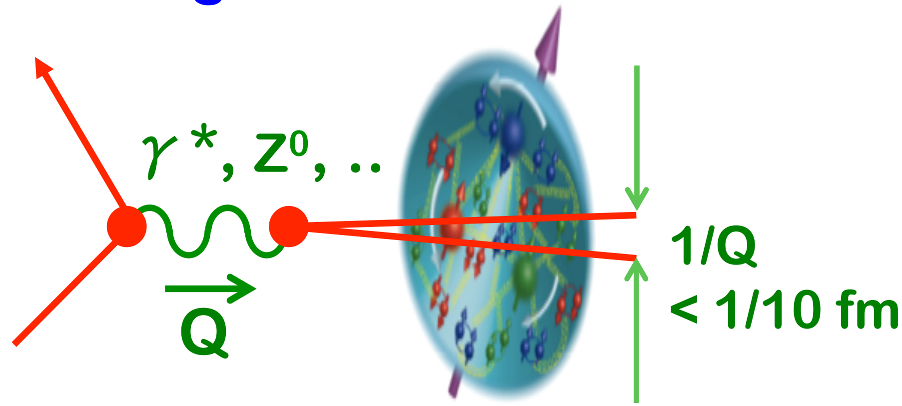
Gluons – ***Varying the probe's resolution to "see" their effect, …***

Energy, luminosity and measurement – Unprecedented resolution, event rates, and precision probes, especially EM probes, …

EM probes: lepton-hadron scattering

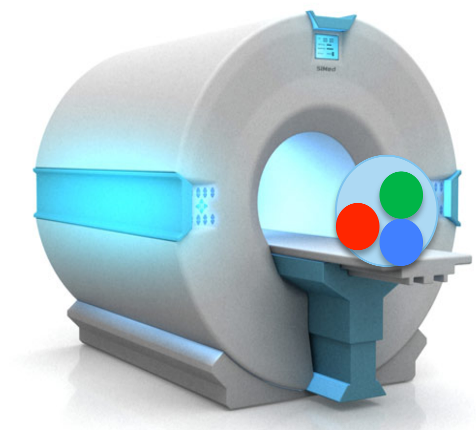
- "See" quarks and gluons by **breaking** the hadron/nuclei:





"see" the non-linear dynamics of QCD!

- "Imagine" quark/gluon **without breaking** the hadron/nuclei – A sharpest "CT"
  - "cat-scan" the nucleon and nuclei with better than 1/10 fm resolution
  - "see" the proton "radius" of quark/gluon density



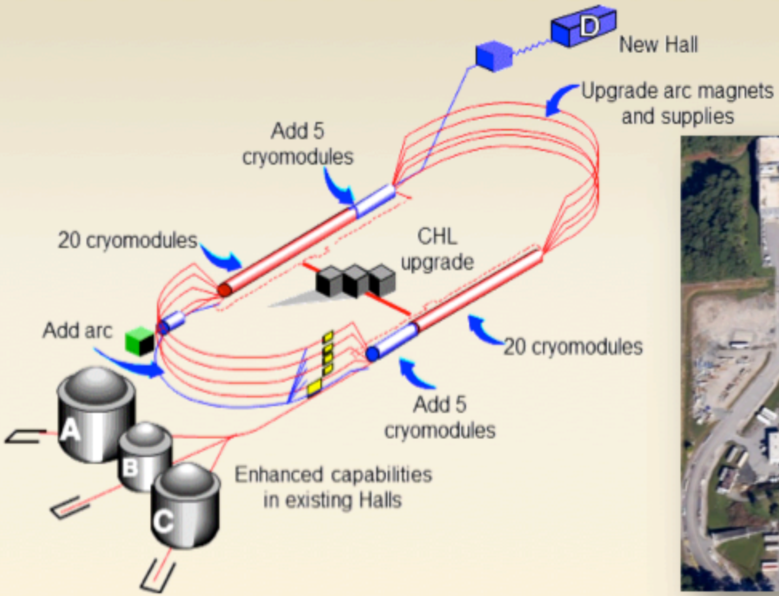
- From JLab12 to EIC:

JLab12: Spectroscopy, Hadron structure in valence regime, BSM, …

EIC: Sea structure, Many body glue dynamics, Color confining radius, …

12 GeV CEBAF upgrade

Completion of the 12 GeV CEBAF Upgrade was ranked the highest priority in the 2007 NSAC Long Range Plan.



Total Project Cost = $338M
Estimate to Complete = $1.2M

Project (99.7% complete):

- **Doubling the accelerator beam energy – DONE**
- **Civil construction including utilities – DONE**
- **New experimental Hall D and beam line – DONE**
- **Upgrade to Experimental Hall C – DONE**
- **Upgrade to Experimental Hall B – 99%**
  - **Solenoid magnet only remaining scope**

U.S. - based Electron-Ion Collider

❑ NSAC 2007 Long-Range Plan:

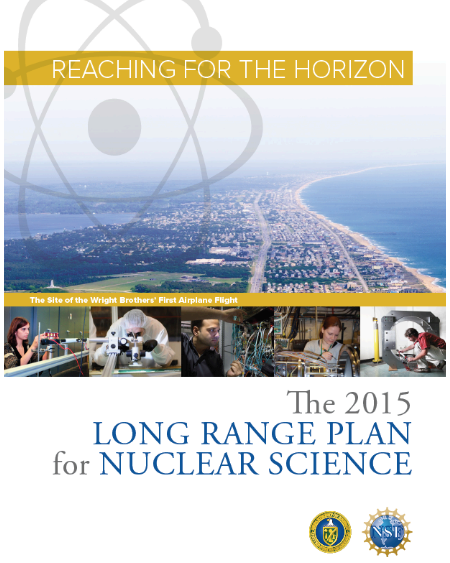
"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**."

❑ NSAC Facilities Subcommittee (2013):

"The Subcommittee ranks an EIC as **Absolutely Central** in its ability to contribute to world-leading science in the next decade."

❑ NSAC 2015 Long-Range Plan:

"We recommend a **high-energy high-luminosity polarized EIC** as **the highest priority for new facility construction following the completion of FRIB.**"

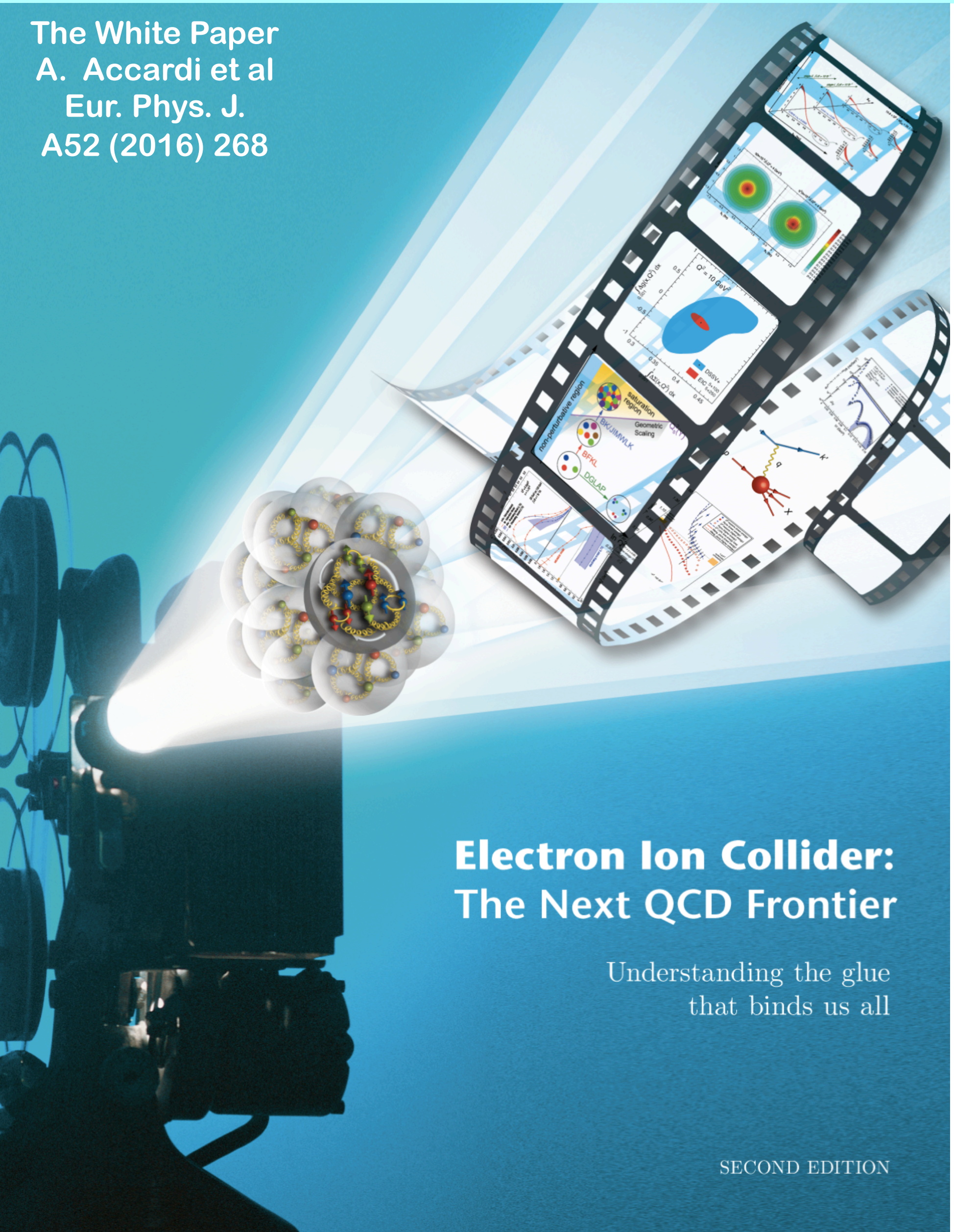


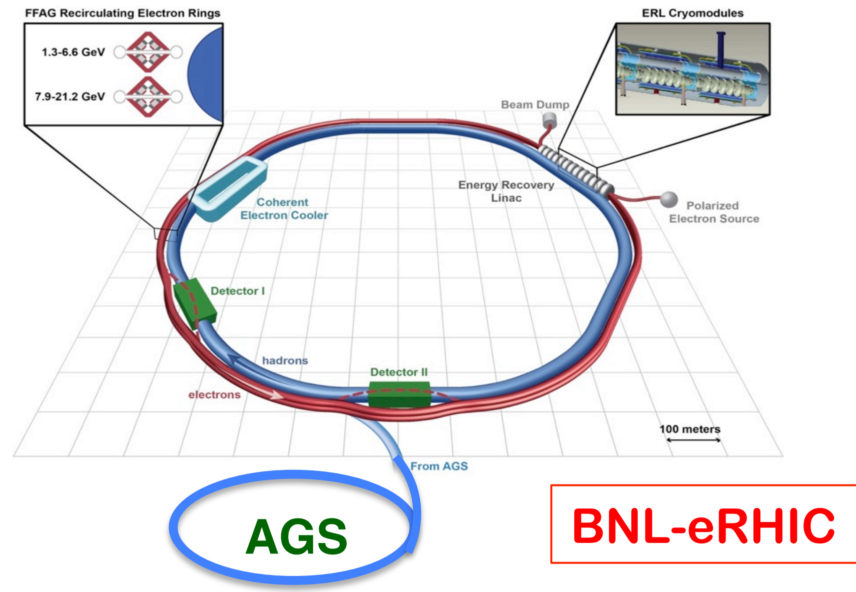
❑ Under review of National Academy of Science:

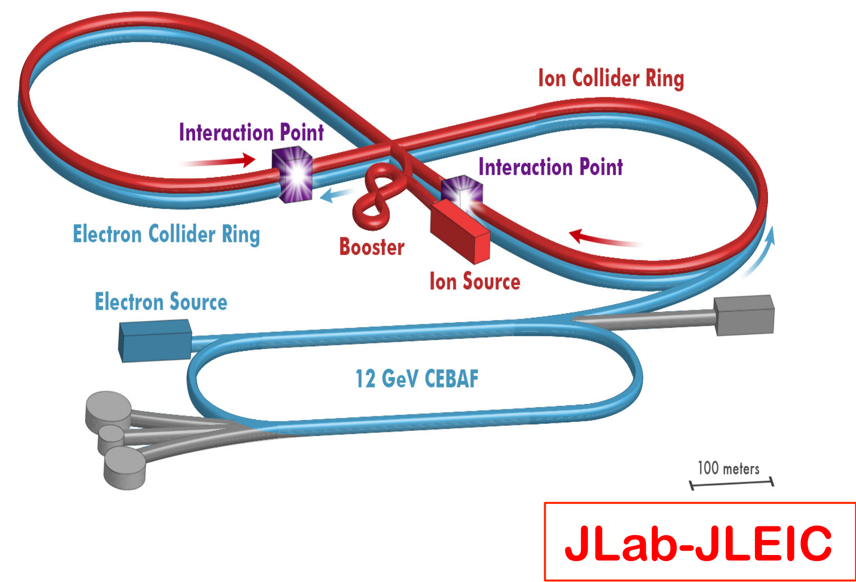
Last committee meeting: April 19-21
Expect to have the committee report late this year!

US EIC – two options of realization

The White Paper
A. Accardi et al
Eur. Phys. J.
A52 (2016) 268

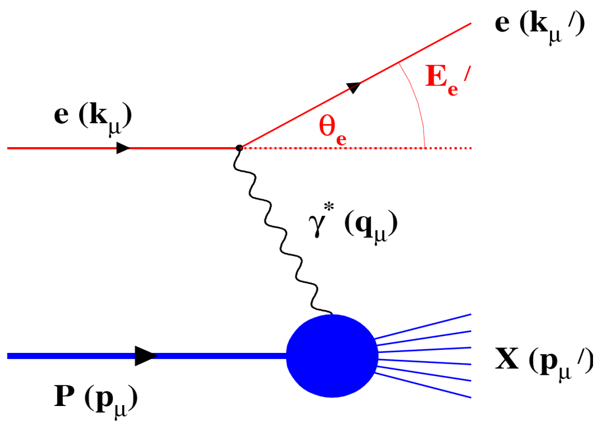






Many complementary probes at one facility

- High energy and luminosity Lepton-hadron facility:



Q^2 → Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$Q^2 = S\ x\ y$

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(π,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion!)

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

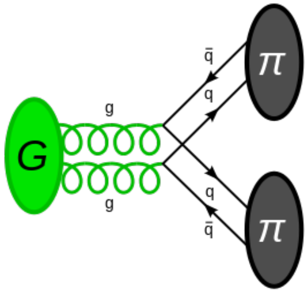
Detect every things including scattered proton/nucleus (or its fragments)

(Initial hadron is NOT broken – tomography!)

The "Big" Questions for JLab 12GeV Program

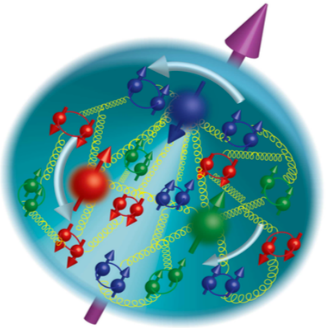
- What is the role of gluonic excitations in the spectroscopy of light mesons?

  Lattice QCD & Joint Physics Analysis Center (JPAC)



- Can we reveal a novel 5D landscape of nucleon substructure at the subfemtometer scale?

  Encoded in PDFs (1D), TMDs (3D), GPDs (3D),
  Wigner distributions (5D), …

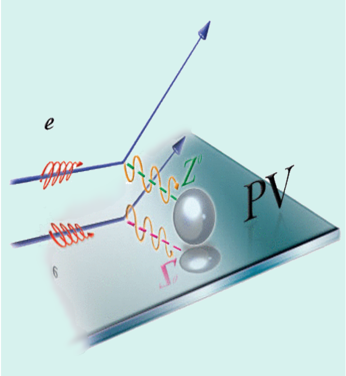


- Where is the missing spin in the nucleon?

  Role of orbital angular momentum?
  TMD Collaboration, …

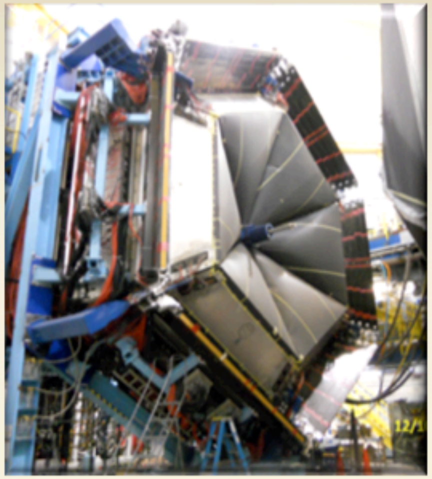
- Can we discover evidence for physics beyond the standard model of particle physics?

  Precision parity violating experiments, …
  $\mathrm{Sin}^2\theta_w$, dark photon – A', …



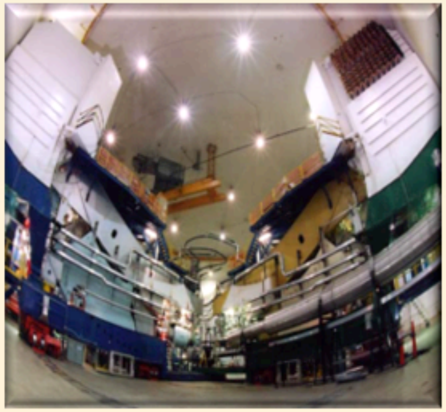
JLab 12 GeV Scientific Capabilities

Hall D – exploring origin of confinement by studying exotic mesons



Hall B – understanding nucleon structure via generalized parton distributions and transverse momentum distributions

Hall C – precision determination of valence quark properties in nucleons and nuclei



Hall A – short range correlations, form factors, hyper-nuclear physics, future new experiments (e.g., SoLID and MOLLER)

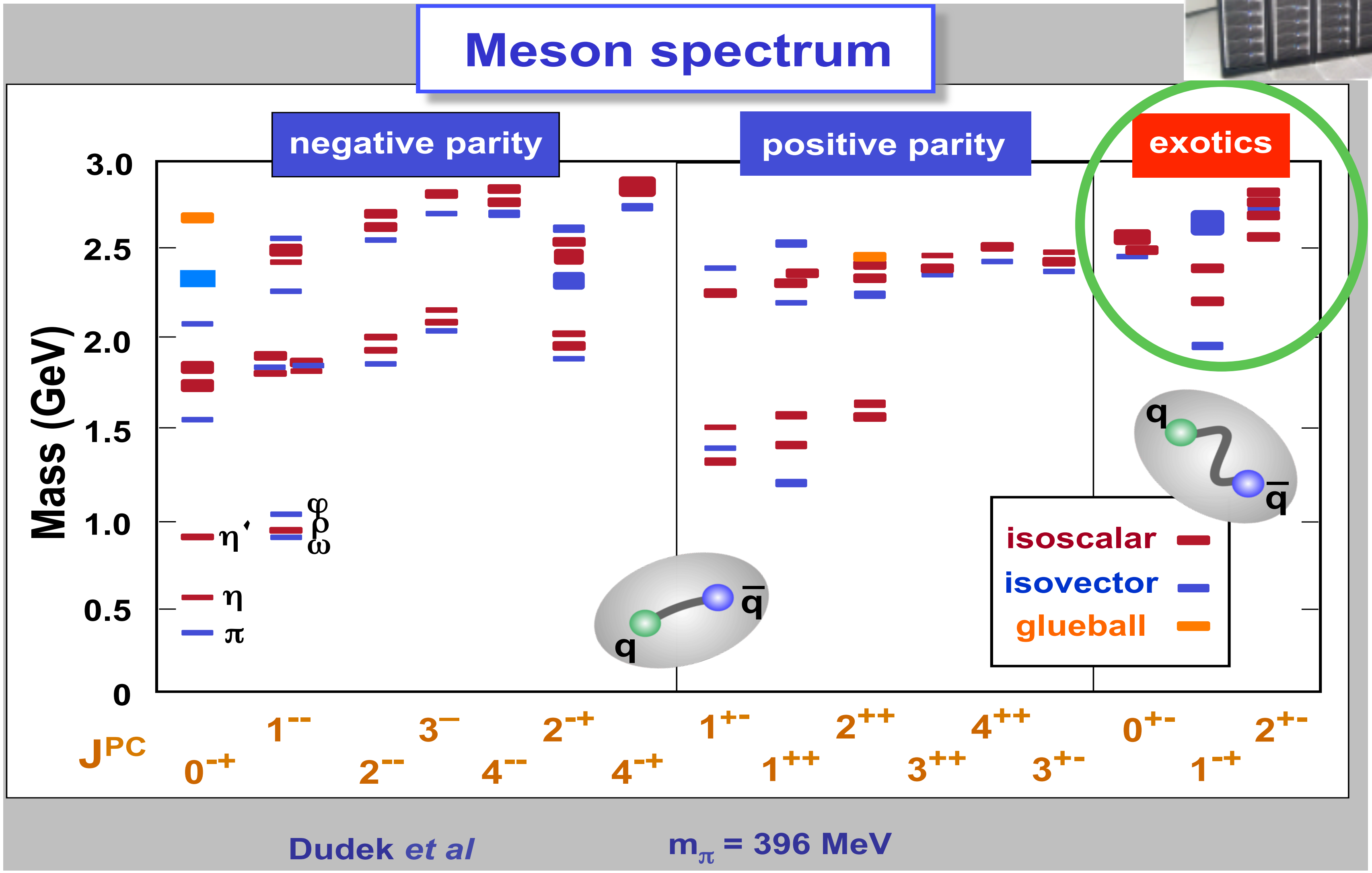
A decade of experiments at JLab 12

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	3	1	3	0	**7**
Transverse structure of the hadrons	5	4	3	1	0	**13**
Longitudinal structure of the hadrons	2	3	6	0	0	**11**
3D structure of the hadrons	5	9	7	0	0	**21**
Hadrons and cold nuclear matter	7	3	7	0	1	**18**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	1	**6**
Total	**22**	**23**	**24**	**5**	**2**	**76**
Total Experiments Completed	**2.5**	**1.1**	**0**	**0.4**	**0**	**4.0**
Total Experiments Remaining	**19.5**	**22**	**24**	**4.6**	**2**	**72.0**

Approved experiments by physics topics

Hadron spectroscopy

❑ **The role of the glue:**

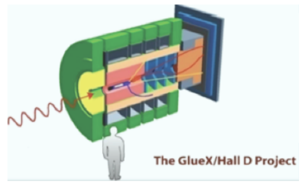


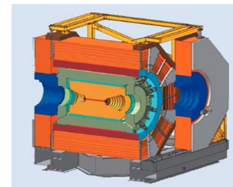
Need to know decay modes and rates to compare to experiments!

Hadron spectroscopy

❑ Joint Physics Analysis Center (JPAC):

✧ Working closely with the GlueX and CLAS12 Collaborations





BESIII

❑ (Exotic) Resonance production at JLab12:

✧ Development of (quasi) 2-to-2 reactions, establish factorization (and corrections to) of beam-target fragmentation

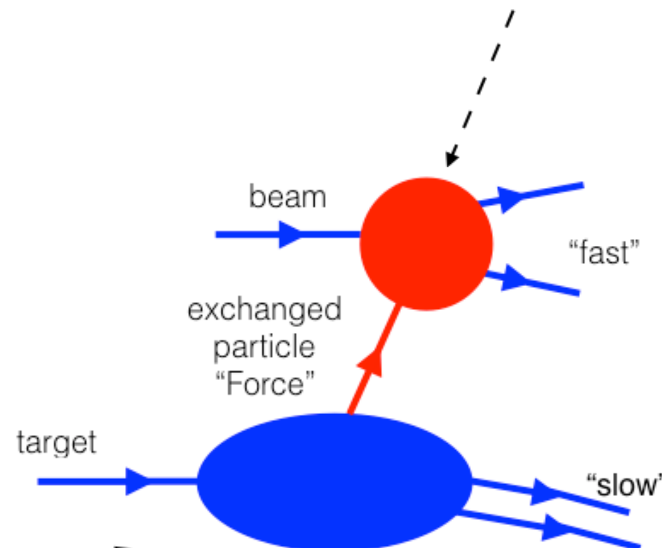
✧ Development of analytical constraints to relate direct resonance production with high energy (cross channel Regge) dynamics

✧ Baryon spectroscopy

Experiment (CLAS *et al.*)
$\gamma p \to \pi N,\ \eta p,\ K\Lambda$
$\pi N \to \pi N,\ \eta n,\ K\Lambda,\ K\Sigma$

Doering, Ronchen, Workman with CLAS

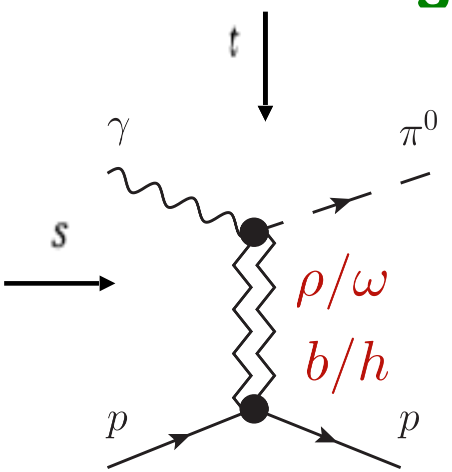
"upper vertex" : Meson spectroscopy



"lower vertex" : Baryon spectroscopy

(Exotic) Resonance production at JLab12

❑ Establishing factorization:

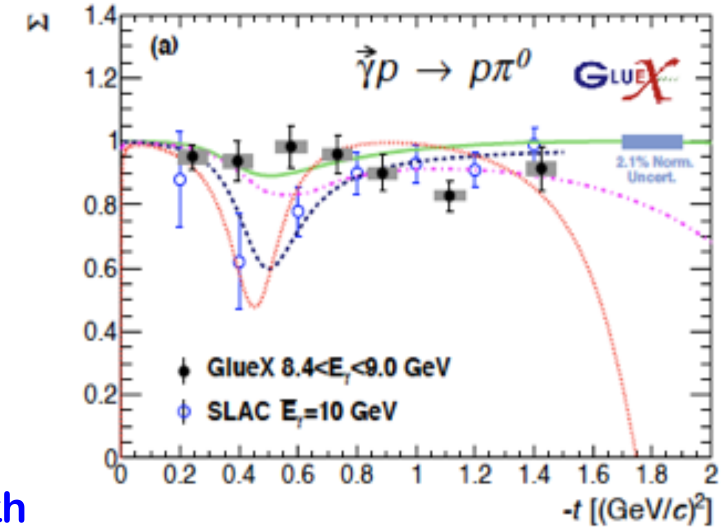


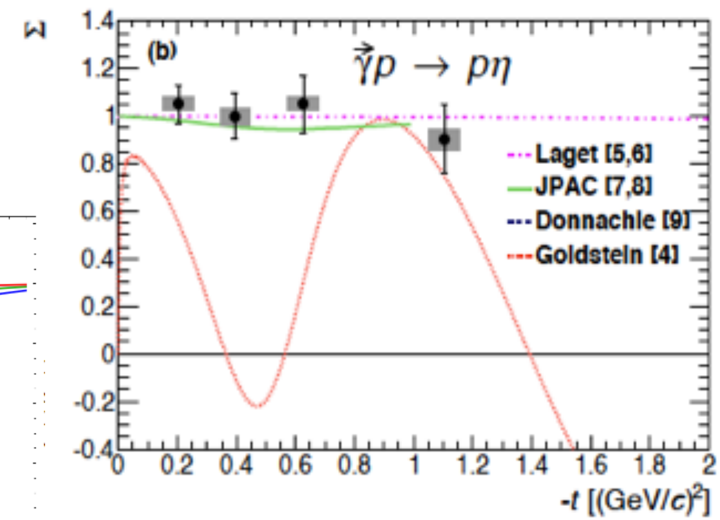
Key to determine separation meson from baryon resonance production

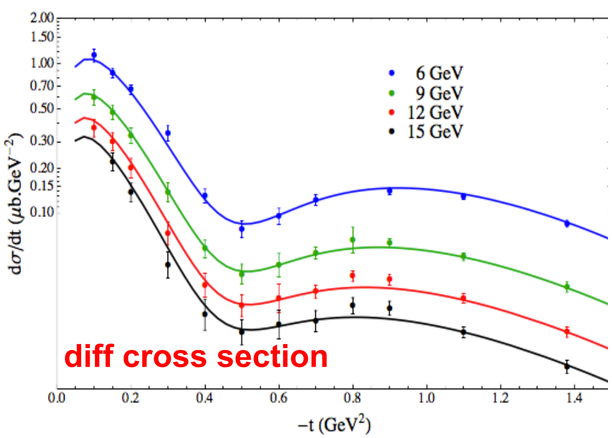
$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

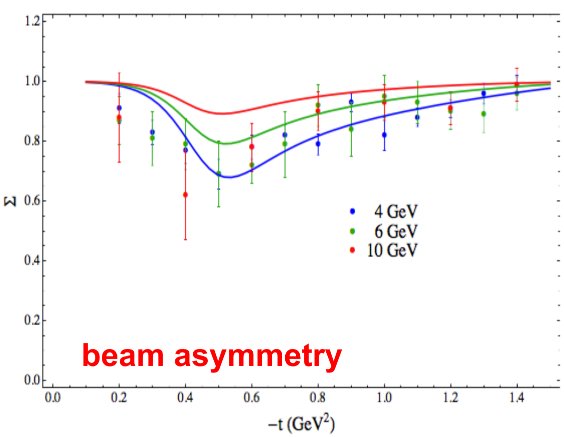
Axial-vector exchange strength decreases with energy

$$A_{\mu_i}(s,t) = \beta_{13}(t)\beta_{24}(t)\frac{1-e^{-i\pi\alpha(t)}}{2\sin\pi\alpha(t)}s^{\alpha(t)}$$





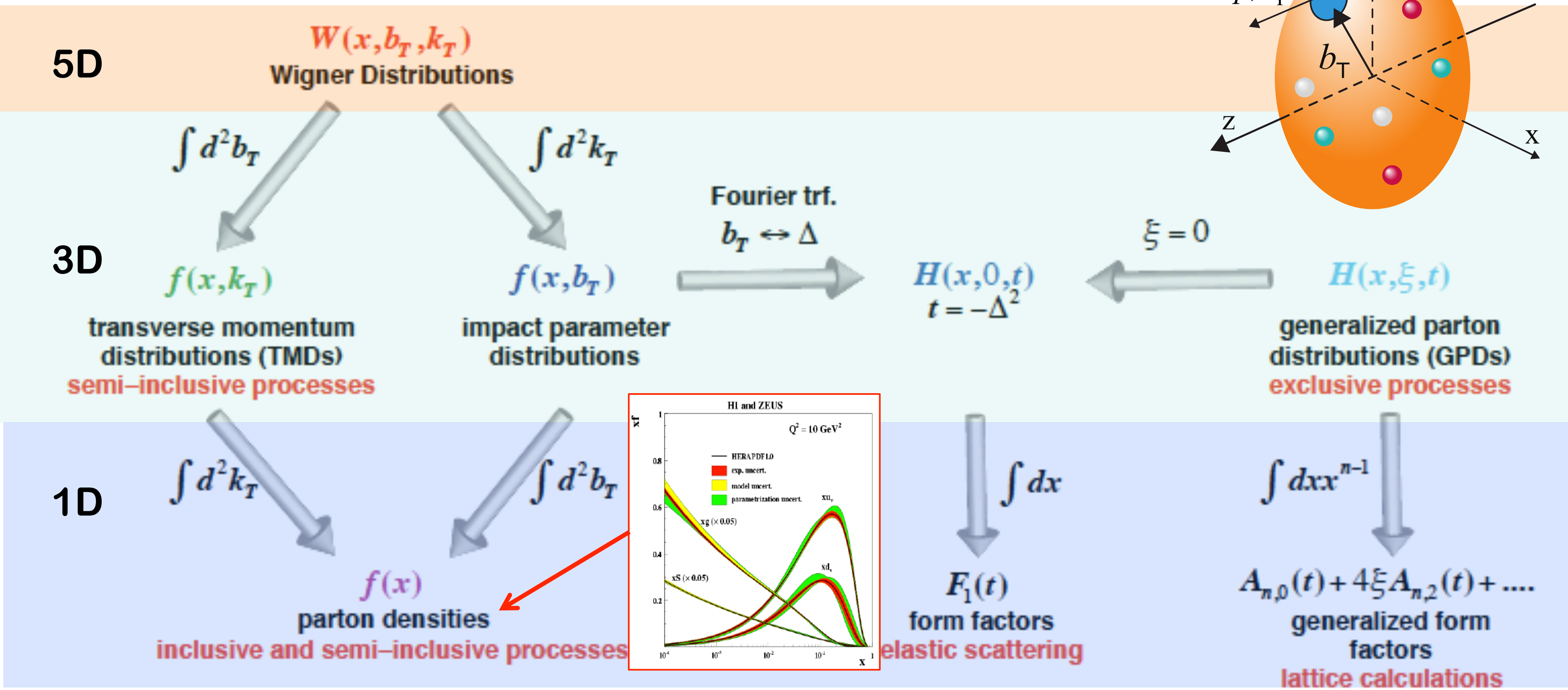




V. Mathieu et al., PRD92 (2015) 074013
J. Nys et al., PRD95 (2017) 034014

Hadron structure at sub-fermi scales

❑ **Wigner distributions (or GTMDs ($\Delta p_T \leftrightarrow b_T$)):**



❑ **JLab12 + EIC – 3D imaging of quarks and gluons:**

✧ **TMDs – Confined motion in a nucleon (semi-inclusive DIS)**

✧ **GPDs – Spatial imaging of quarks and gluons (exclusive DIS)**

PDFs at large x – Testing ground of QCD

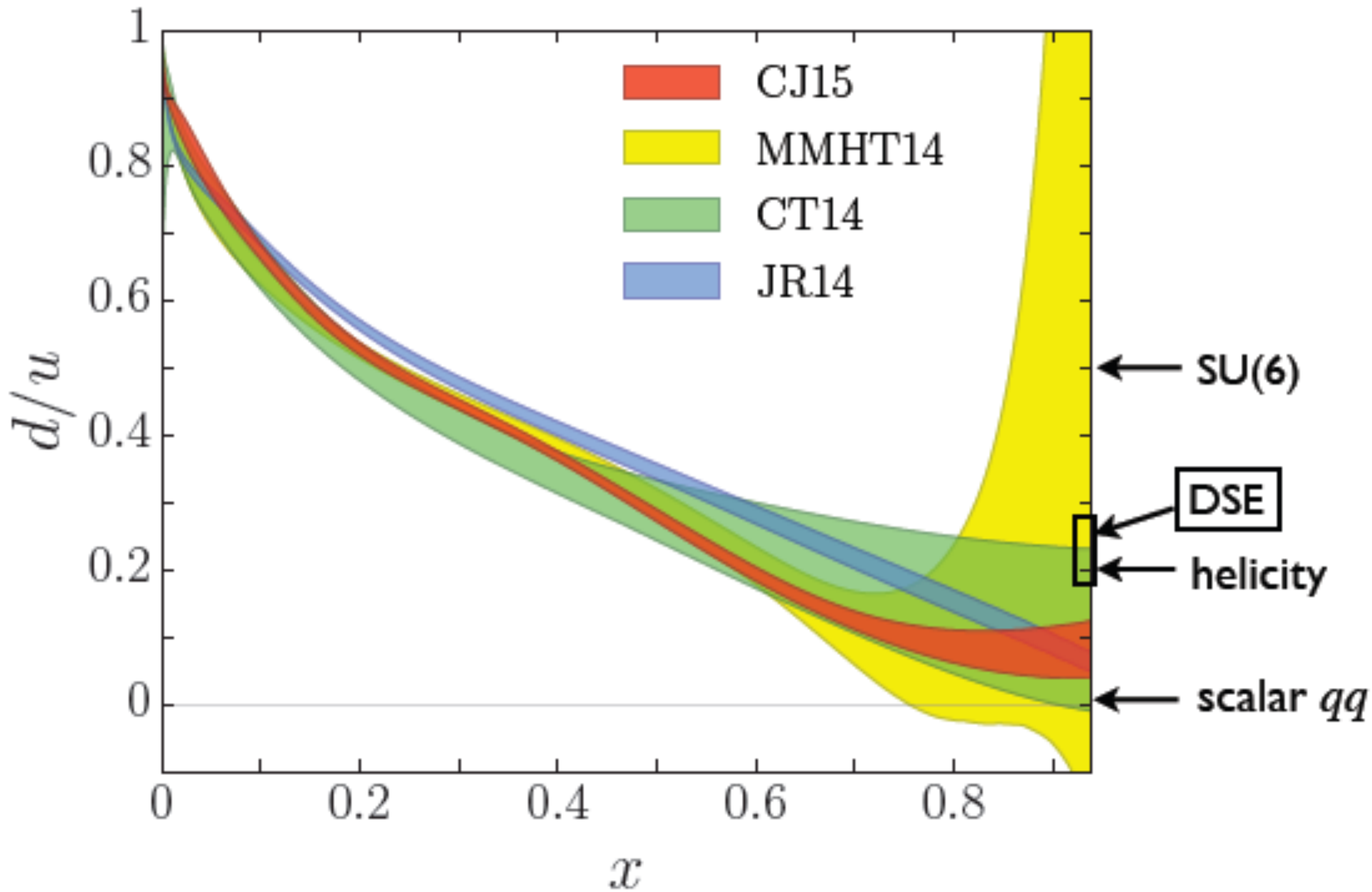
❑ **"Model" predictions for x → 1:**

✧ $d/u \to 1/2$	**SU(6) Spin-flavor symmetry**	✧ $\Delta u/u \to 2/3$ $\Delta d/d \to -1/3$
✧ $d/u \to 0$	**Scalar diquark dominance**	✧ $\Delta u/u \to 1$ $\Delta d/d \to -1/3$
✧ $d/u \to 1/5$	**pQCD power counting**	✧ $\Delta u/u \to 1$ $\Delta d/d \to 1$
✧ $d/u \to \dfrac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$	**Local quark-hadron duality**	✧ $\Delta u/u \to 1$ $\Delta d/d \to 1$

PDFs at large x – Unique JLab strength: Exp + Thy + Lattice

JLab theory effort – QCD global fits

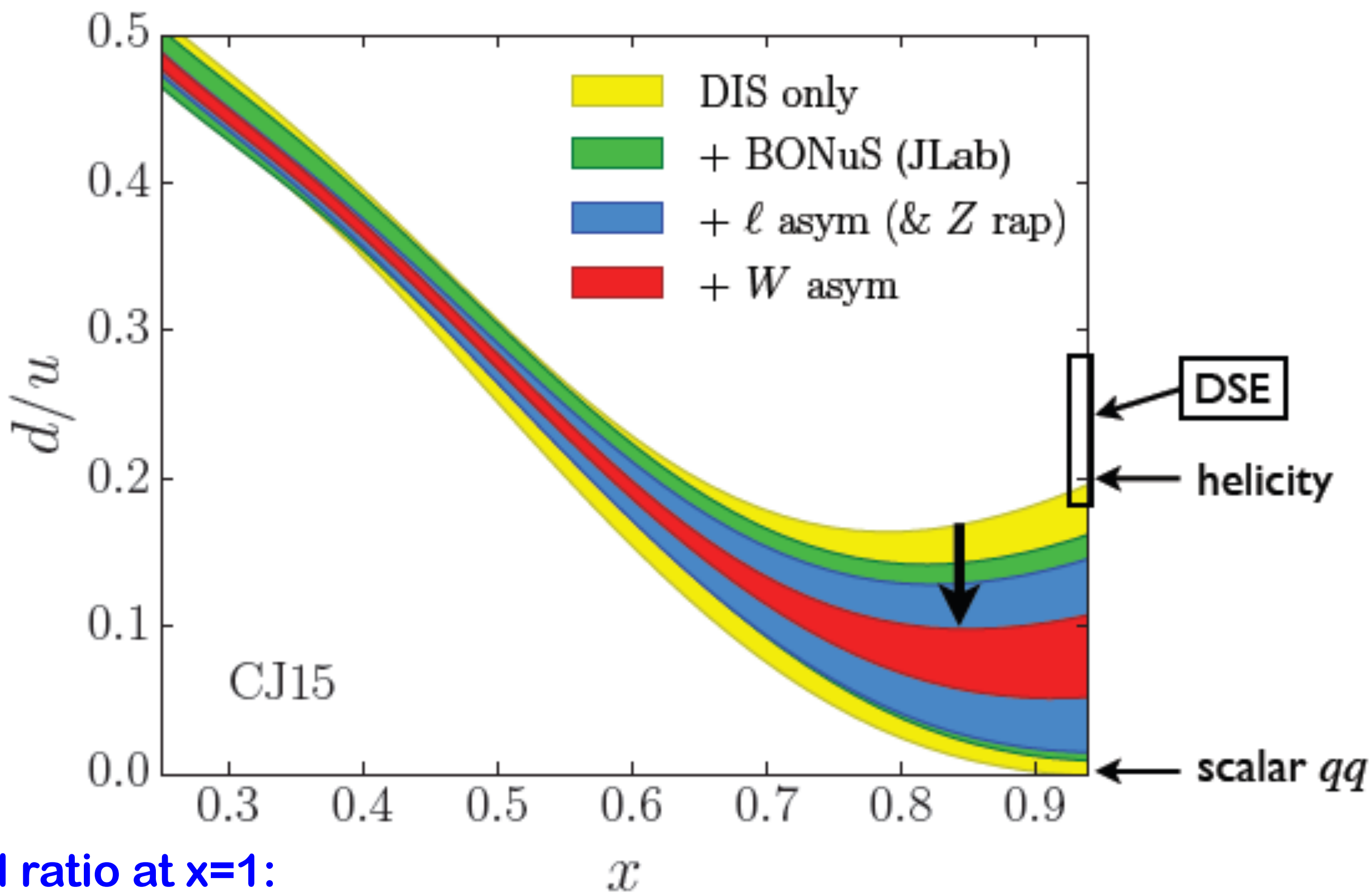
- Various global fits for $x \to 1$:



CTEQ-Jefferson Lab collaboration
http://www.jlab.org/CJ

JLab theory effort – QCD global fits

❑ **Adding additional constraints:**



Extracted ratio at x=1:

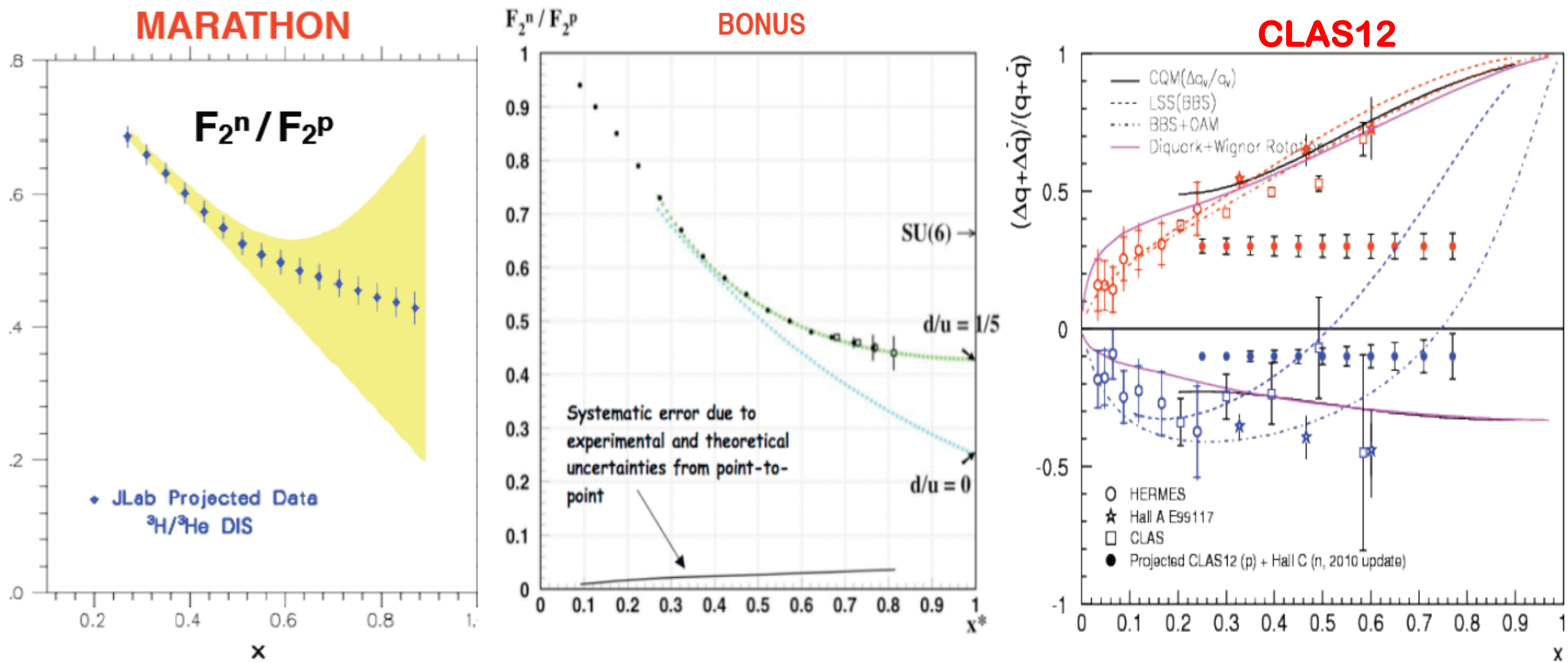
$$d/u \rightarrow 0.09 \pm 0.03$$

Does not match any models!

CTEQ-Jefferson Lab collaboration
http://www.jlab.org/CJ

JLab experiments – unique strength!

❑ NSAC milestone HP14 (2018):



Plus many more JLab experiments:

E12-06-110 (Hall C on ^3He), E12-06-122 (Hall A on ^3He),

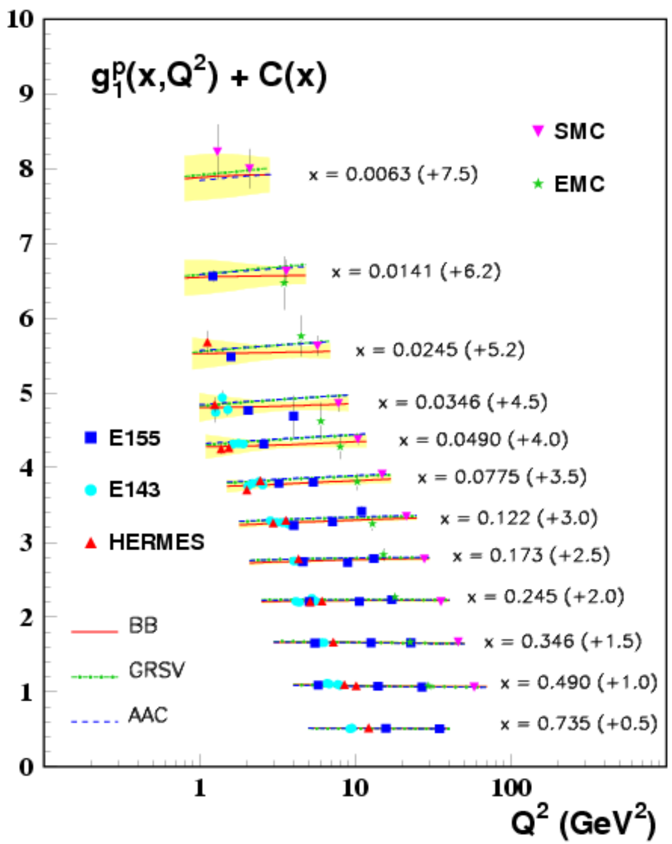
E12-06-109 (CLAS on NH_3, ND_3), … ➡ Data sensitive to x=0.85

JLab Solid, and Fermilab E906, …

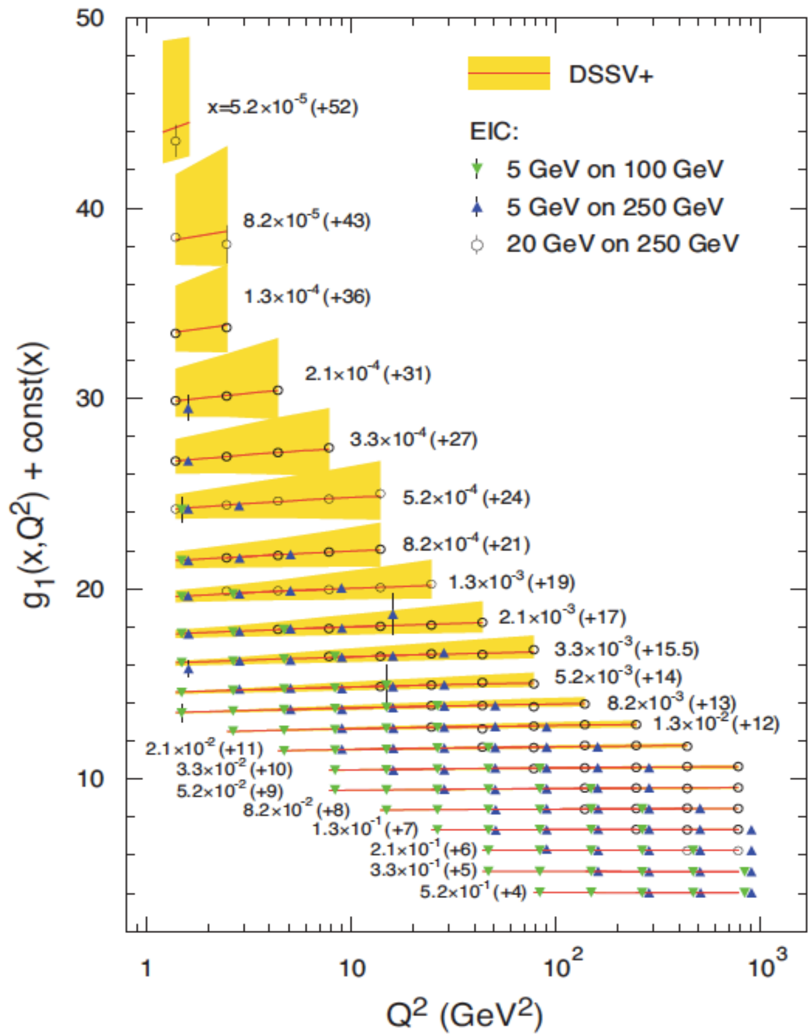
Additional help from Lattice?

PDFs and Helicity distributions at small x

- ❑ **The power & precision of EIC:**



at EIC

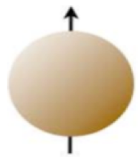


- ❑ **Reach out the glue:**

$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

Ultimate solution to the proton spin puzzle?

Proton Spin



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

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 $\Delta G = \int dx \Delta g(x) \sim 20\% (\text{with RHIC data})$

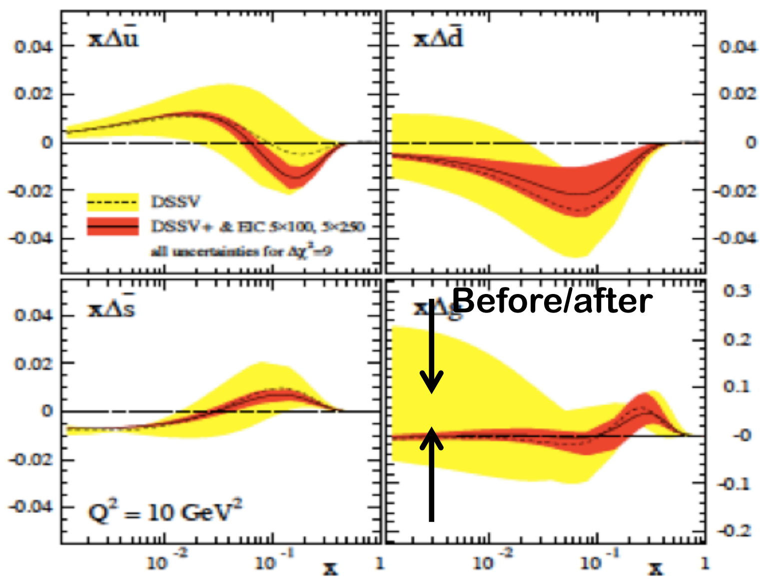
Orbital Angular Momentum of quarks and gluons - Little known

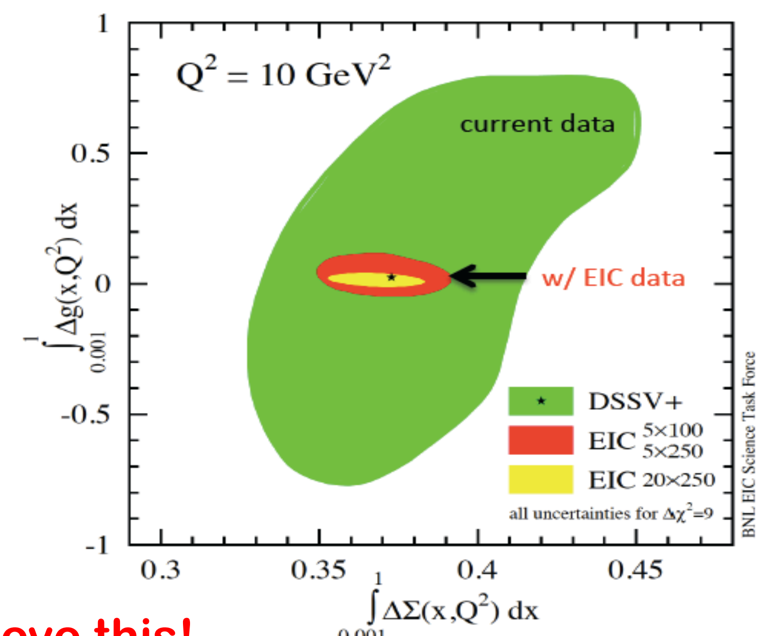
Spin "puzzle"

EIC!

Transverse motion!

- **One-year of running at EIC:**





No other machine in the world can achieve this!

Paradigm shift: 3D imaging of hadrons

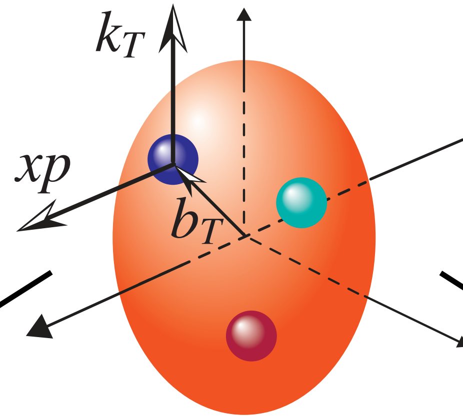
- 3D boosted partonic structure:

Momentum Space

TMDs (3D)

Confined motion

$\int d^2 b_T$



$\int d^2 k_T$

Coordinate Space

GPDs (3D)

Spatial distribution

$f(x,k_T)$

Two-scales observables

$f(x,b_T)$

Paradigm shift: 3D imaging of hadrons

❑ 3D boosted partonic structure:

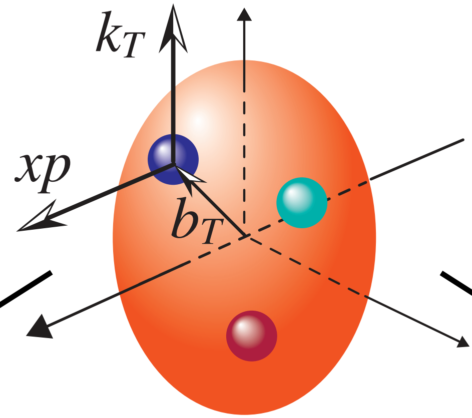
Momentum Space

TMDs (3D)

Confined motion

$\int d^2 b_T$

$f(x,k_T)$



Two-scales observables

$\int d^2 k_T$

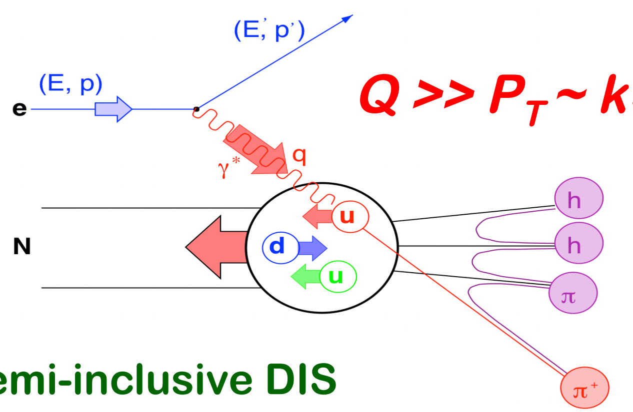
$f(x,b_T)$

Coordinate Space

GPDs (3D)

Spatial distribution

3D momentum space images

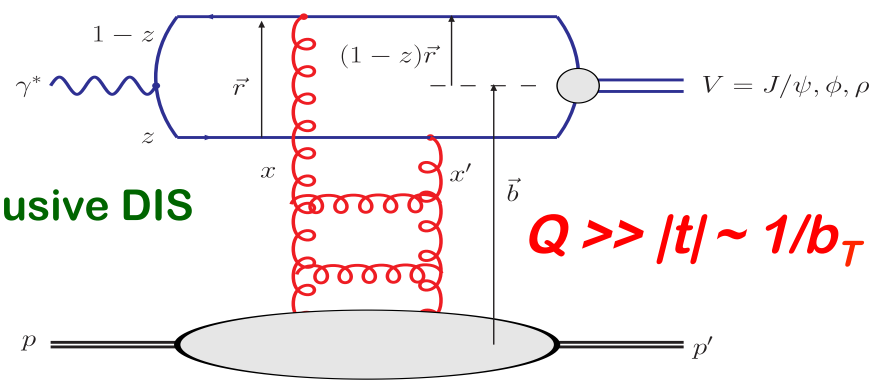


Q >> P_T ~ k_T

Semi-inclusive DIS

2+1D coordinate space images

Exclusive DIS



Q >> |t| ~ $1/b_T$

JLab12 – valence quarks, EIC – sea quarks and gluons

Paradigm shift: 3D imaging of hadrons

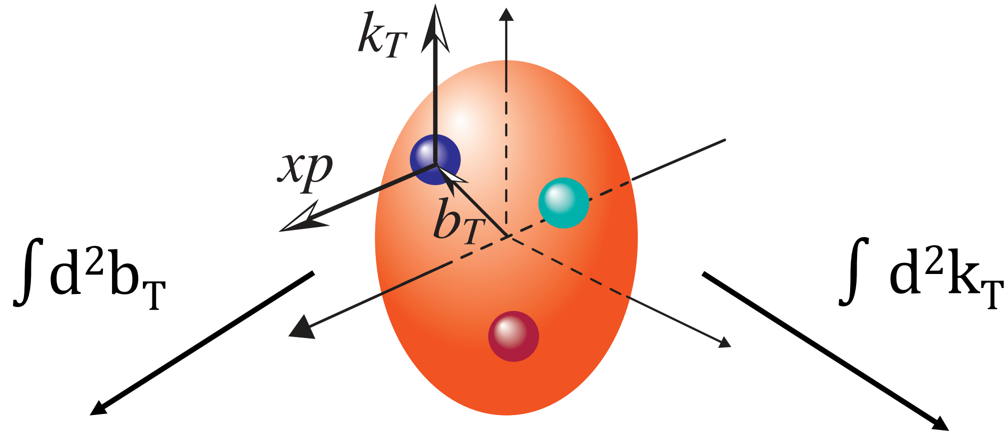
- 3D boosted partonic structure:

Momentum Space

TMDs

Coordinate Space

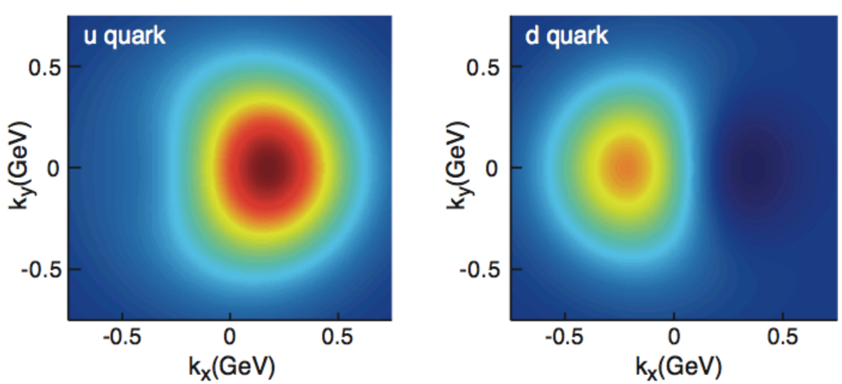
GPDs

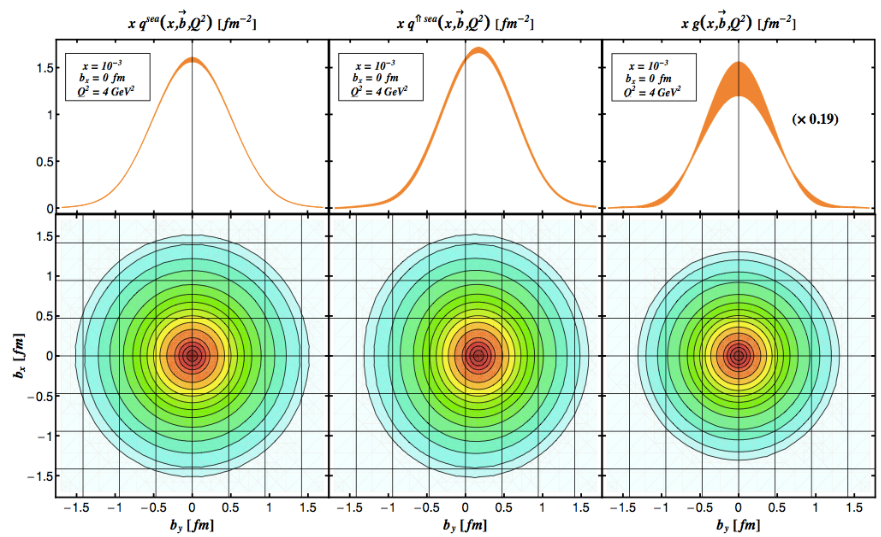


$f(x,k_T)$ EIC white paper: arXiv:1212.1701 $f(x,b_T)$

Sivers Function

Imaging





Density distribution of an unpolarized quark in a proton moving in z direction and polarized in y-direction

Spatial density distributions – "radius"

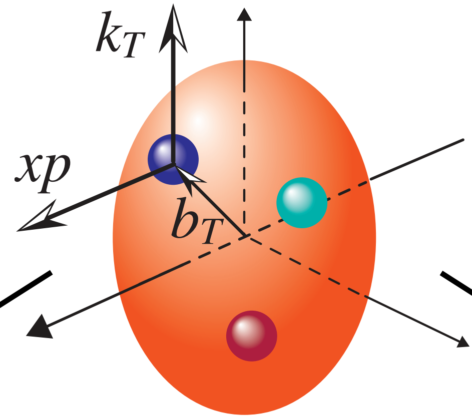
Paradigm shift: 3D imaging of hadrons

❑ **3D boosted partonic structure:**

Momentum Space

TMDs

$\int d^2b_T$



$\int d^2k_T$

Coordinate Space

GPDs

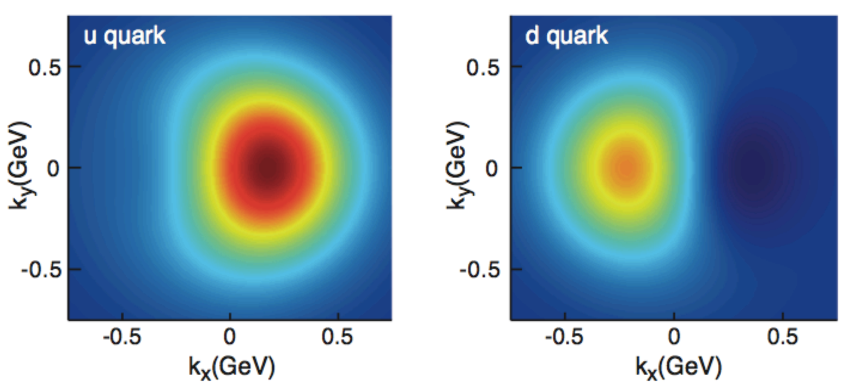
$f(x,k_T)$

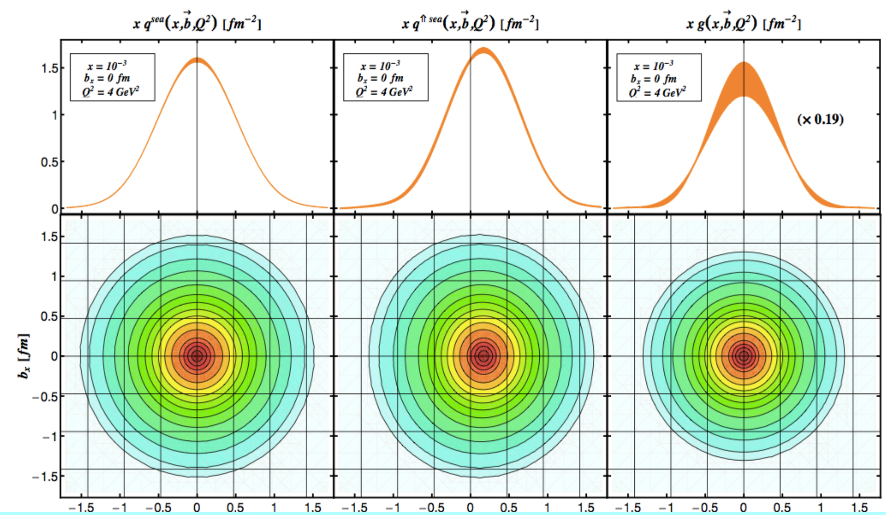
EIC white paper: arXiv:1212.1701

$f(x,b_T)$

Sivers Function

Imaging





Position *r* x Momentum *p* → Orbital Motion of Partons

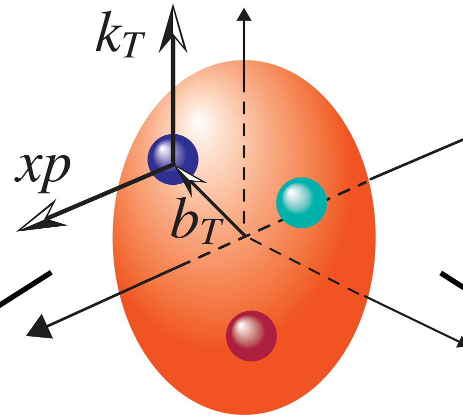
Paradigm shift: 3D imaging of hadrons

❑ 3D boosted partonic structure:

Momentum Space

TMDs

$\int d^2 b_T$



Coordinate Space

GPDs

$\int d^2 k_T$

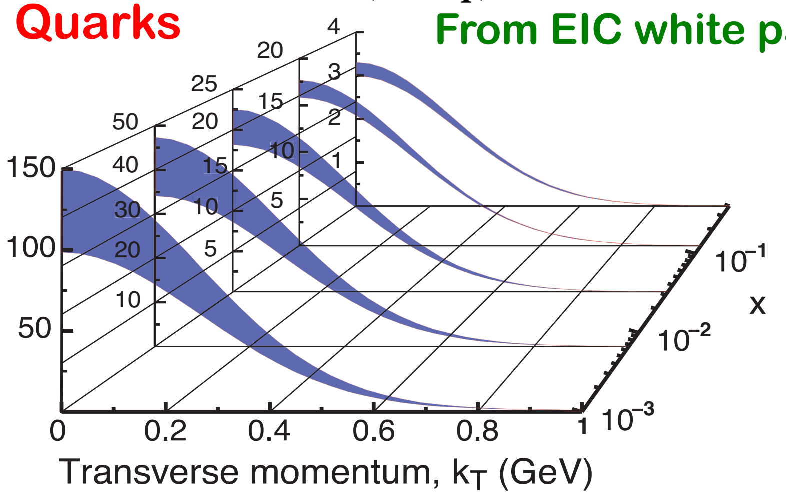
$f(x, k_T)$

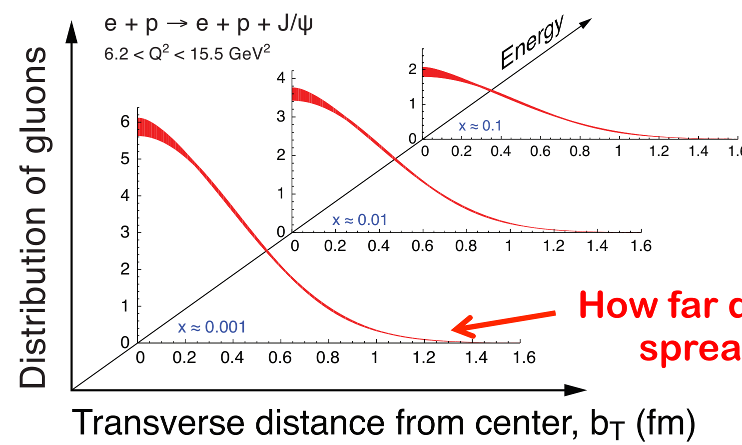
$f(x, b_T)$

Quarks

From EIC white paper: arXiv:1212.1701

Gluons



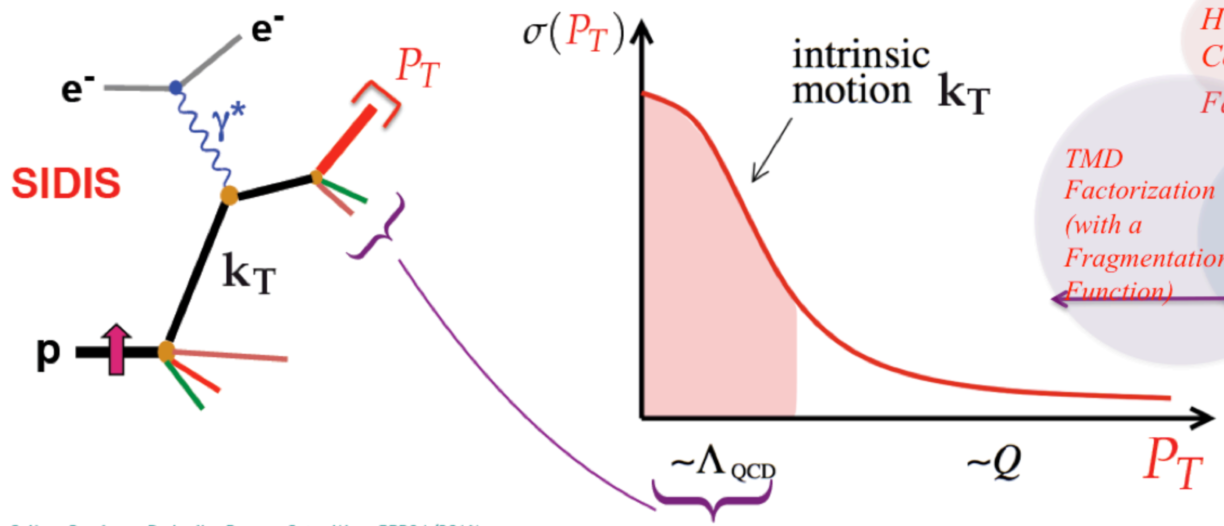


How far does it spread?

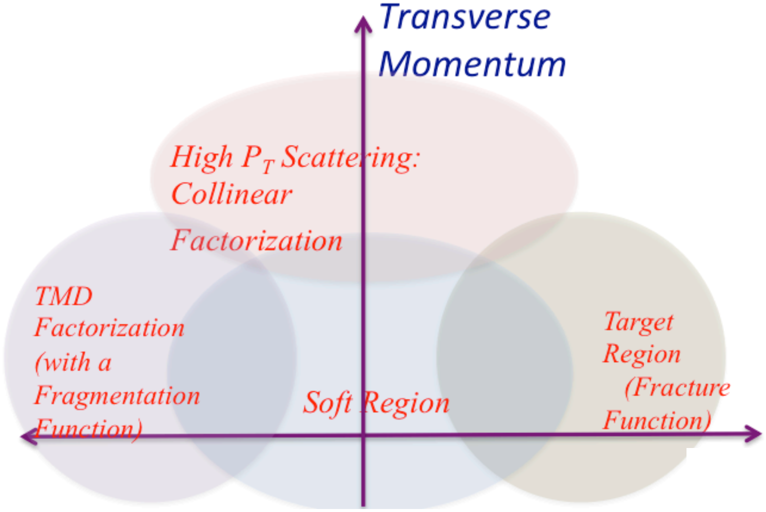
Role of momentum fraction -"x", and nature of pion cloud?

Why 3D motion of quarks and gluons?

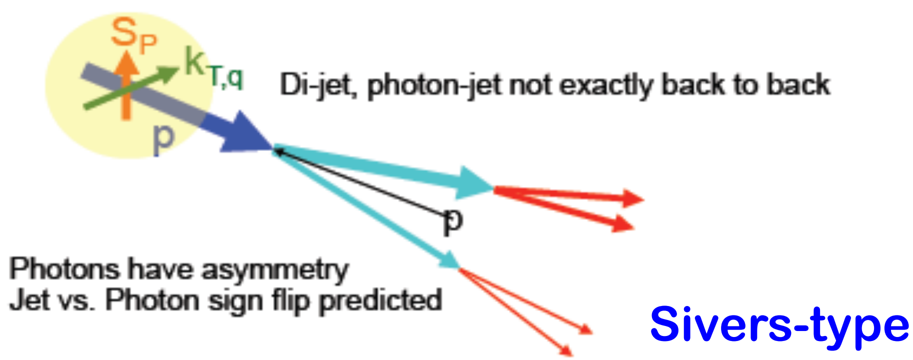
❑ TMDs – Confined Motion:

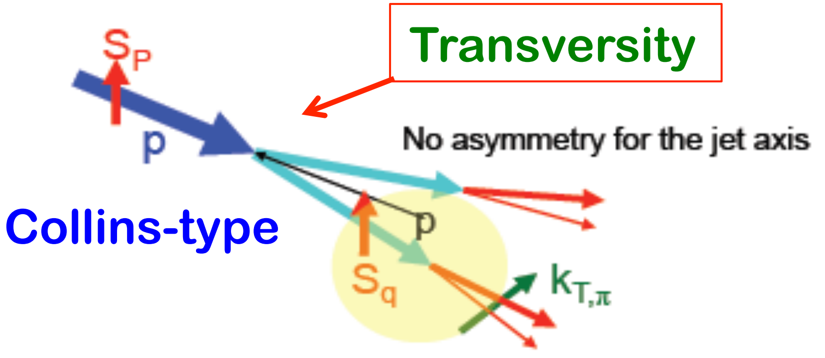


Colins, Gamberg, Prokudin, Rogers, Sato, Wang PRD94 (2016)



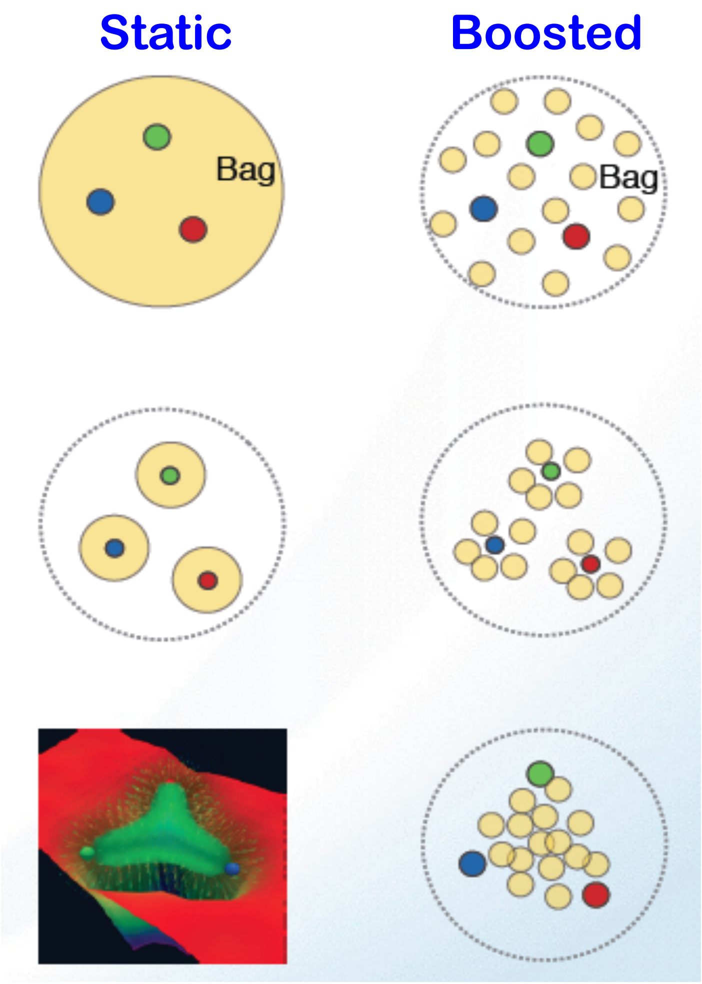
❑ Correlation of hadron properties and parton dynamics:





Why 3D nucleon spatial structure?

- Spatial distributions of quarks and gluons:



Bag Model:
Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

Constituent Quark Model:
Gluons and sea quarks hide inside massive quarks.
Gluon radius ~ Charge Radius

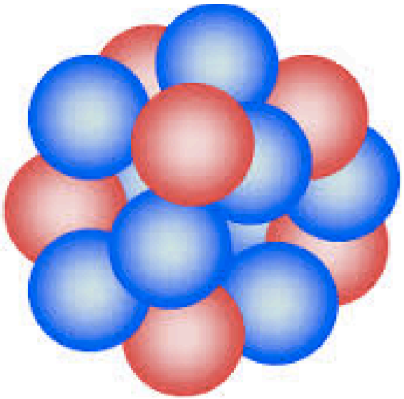
Lattice Gauge theory (with slow moving quarks):
Gluons more concentrated inside the quarks
Gluon radius < Charge Radius

3D Confined Motion (TMDs) + Spatial Distribution (GPDs)

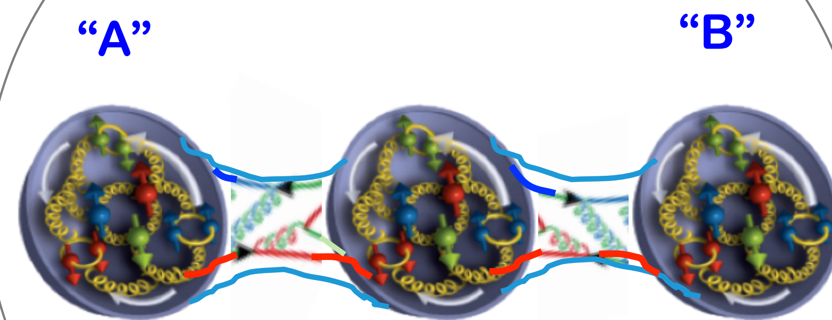
Relation between charge radius, quark radius (x), and gluon radius (x)?

Why 3D nucleon structure?

- **Nature of nuclear force:**



If we only see
quarks and gluons, …



What does the nucleus look like?

- **Range of color force:**

Does the color of nucleon “A” correlated with the color of nucleon “B”?

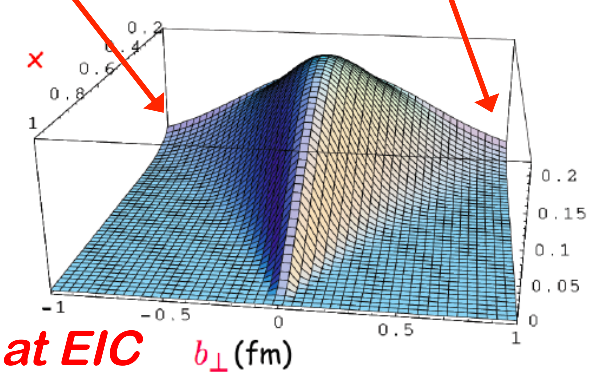
If it does, what is the strength of such correlation?

Can a large nucleus look like a big proton at small-x? the range of color correlation?

How far does glue density spread?

How fast does glue density fall?

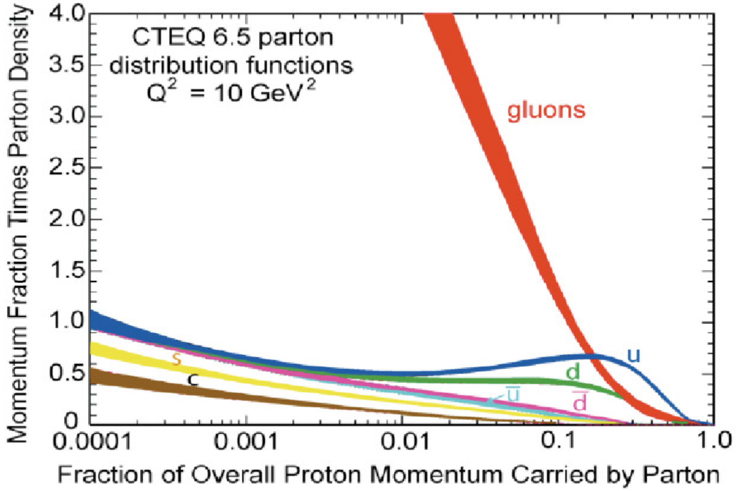
Imagine of gluon density



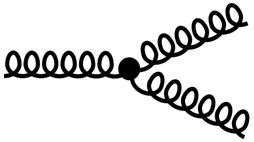
Only possible at EIC

Non-linear interaction – dynamical mass scale?

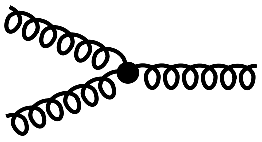
❑ Run away gluon density at small x?



What causes the low-x rise?
gluon radiation
– non-linear gluon interaction



What tames 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:

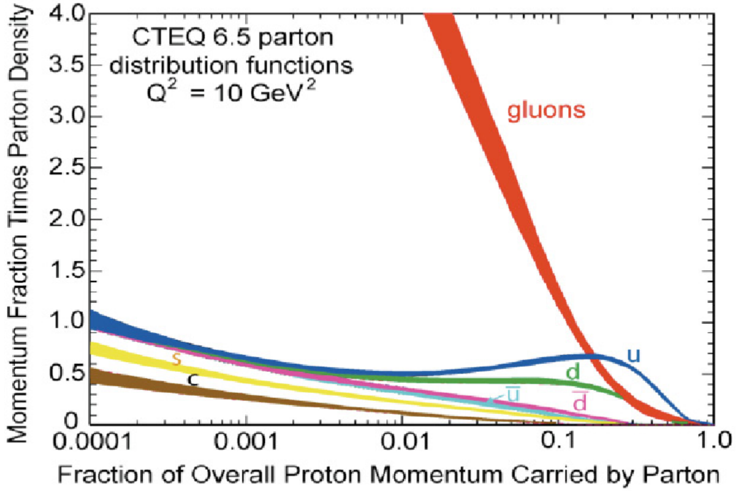
$$Q^2\frac{d}{dQ^2}x\phi_\gamma(x,Q^2)\approx\frac{\alpha_{em}}{\pi}\left[-\frac{2}{3}x\phi_\gamma(x,Q^2)+\int_x^1\frac{dx'}{x'}x'[\phi_{e^+}(x',Q^2)+\phi_{e^-}(x',Q^2)]\right]$$

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

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

How to answer the "big" questions?

❑ Run away gluon density at small x?



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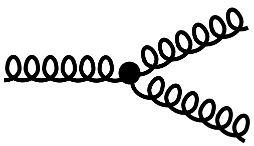

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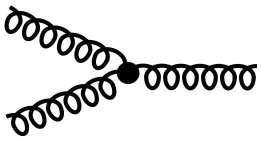
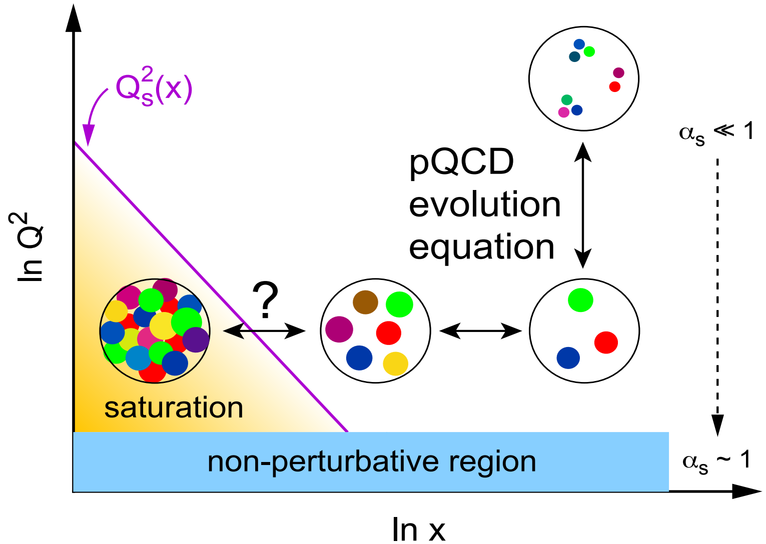
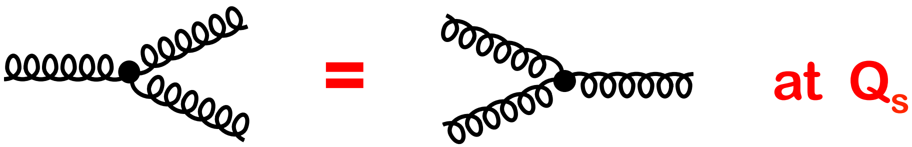


❑ Particle vs. wave feature:



Gluon saturation – Color Glass Condensate
Radiation = Recombination



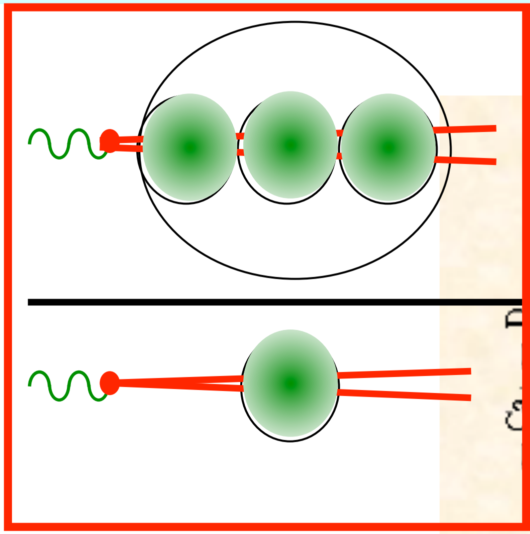
Leading to a collective gluonic system?

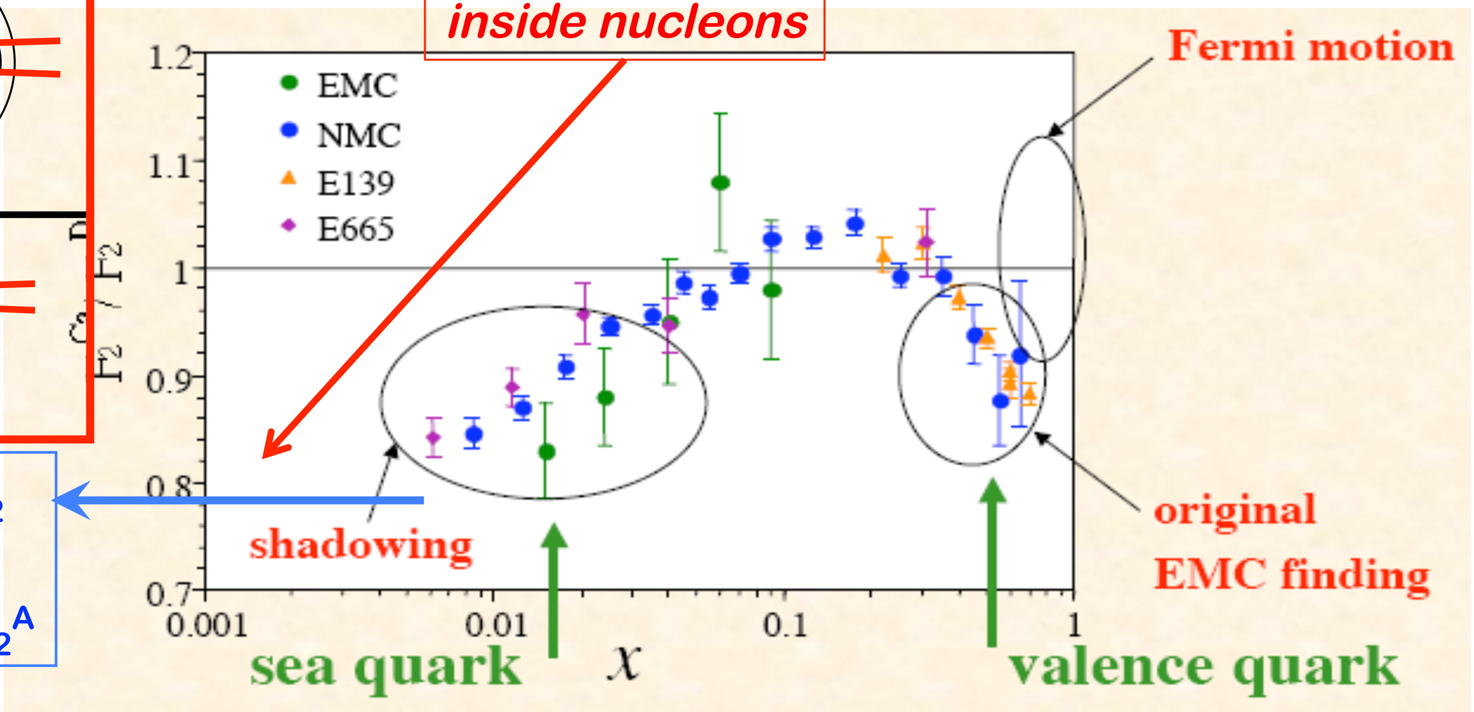
with a universal property of QCD?

new effective theory QCD – CGC?

Expectation: $x=10^{-5}$ in a proton at $Q^2=5$ GeV^2

True structure – separation of collision effect?





Saturation in RF_2
=
No saturation in F_2^A

Collision effects

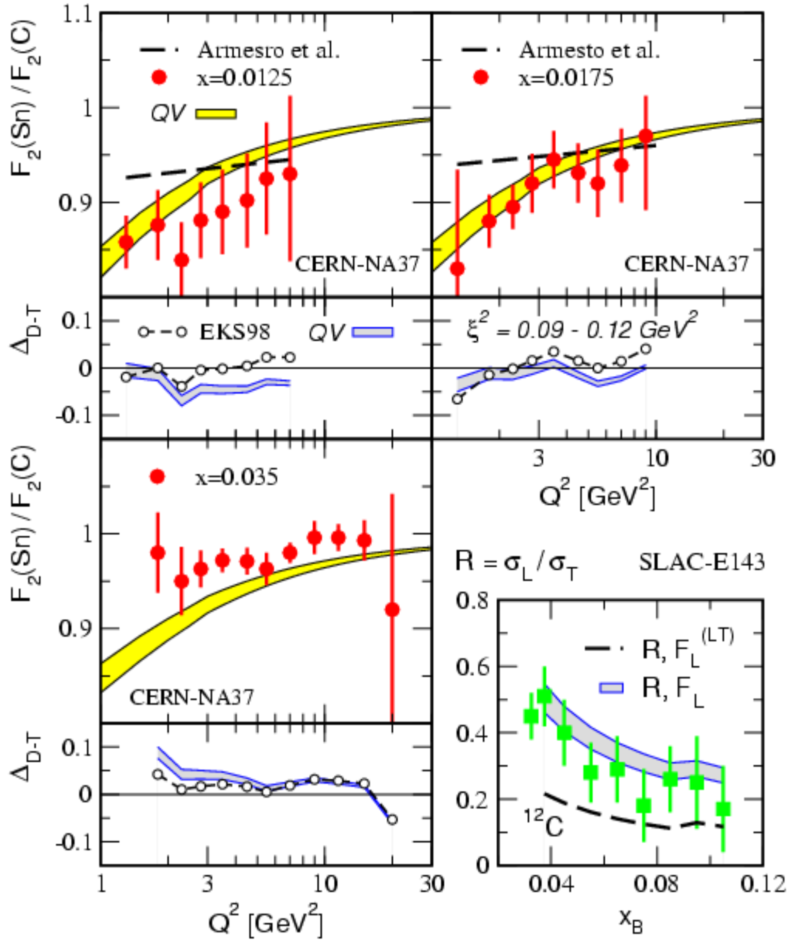
- ❑ A simple question:

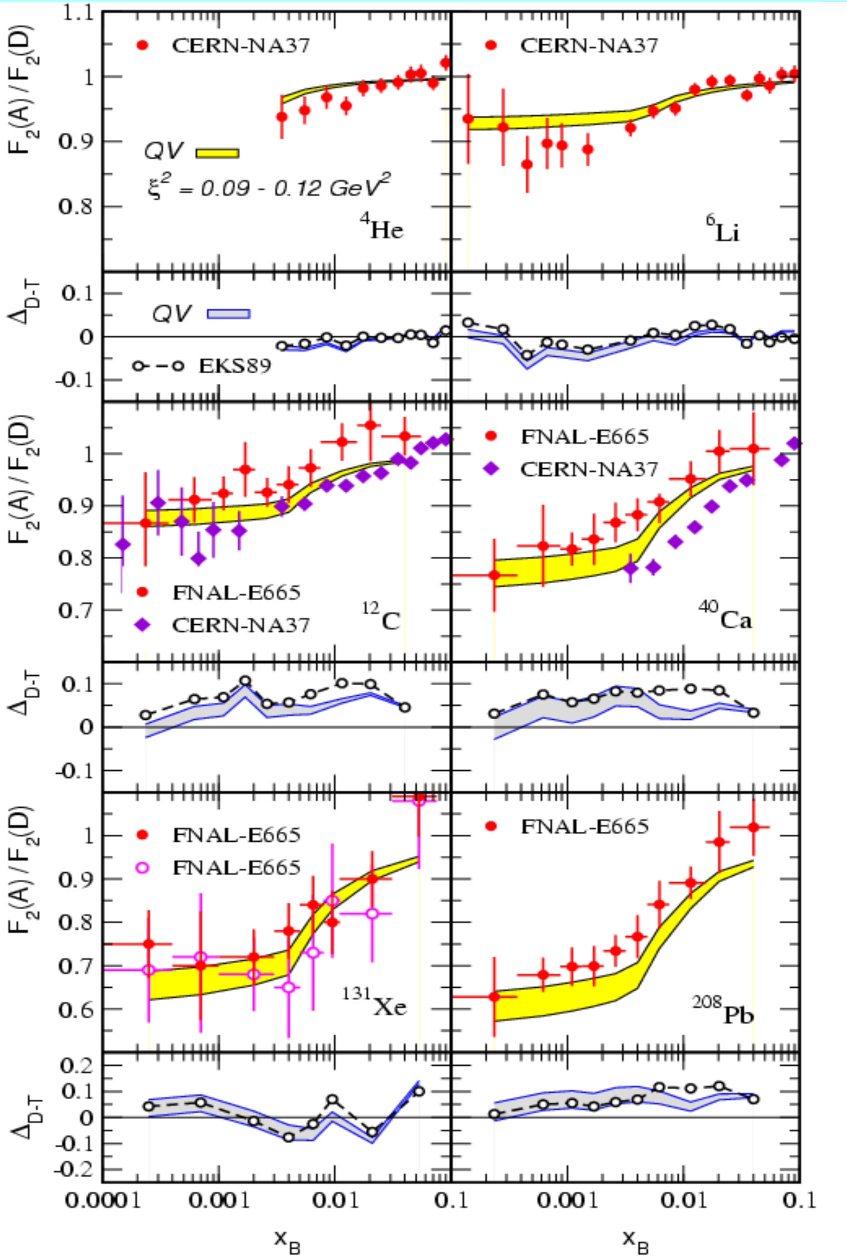
  Will the suppression/shadowing continue to fall as x decreases?

DIS on a large nucleus

- If the color is localized inside nucleon, … Qiu, Vitev, PRL2004

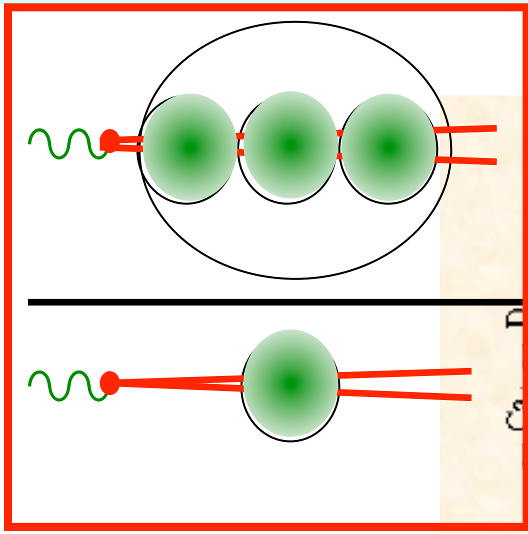
$\xi^2 = 0.09 - 0.12\ \text{GeV}^2$



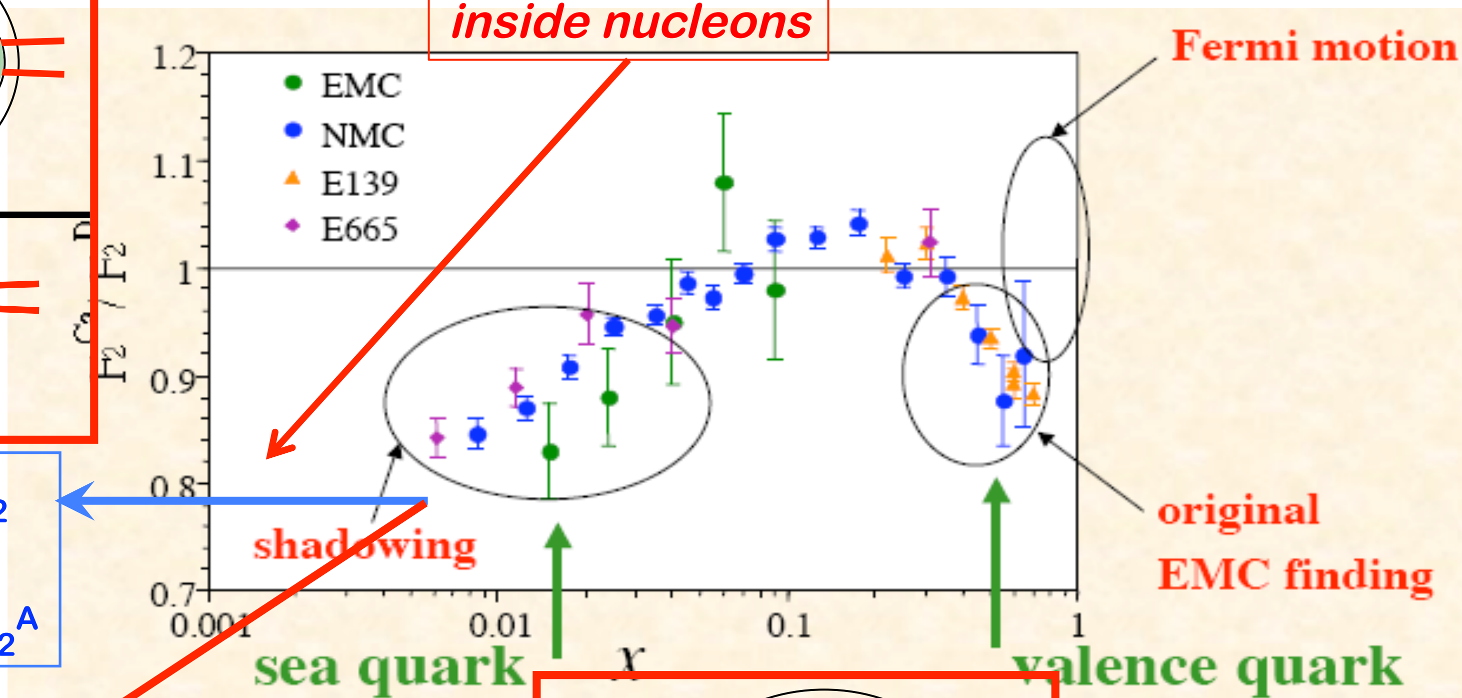


One number for all x_B, Q, and A dependence !

Color confining radius?



Color localized inside nucleons



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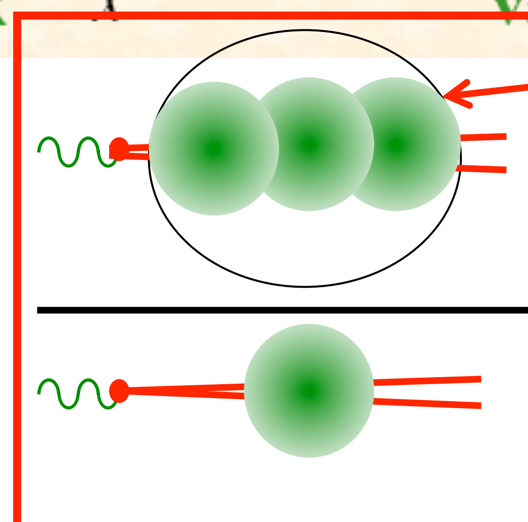
Collision effects

Saturation in nucleon



Color leaks outside nucleons Soft gluon radius is larger

❑ A simple question:

Will the suppression/shadowing continue to fall as x decreases?

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

- JLab12 is a prerequisite of the full EIC program, plus more

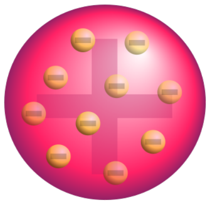
- EIC@US is sitting at a sweet spot for rich QCD dynamics – capable of taking us to the next QCD frontier

Thanks!

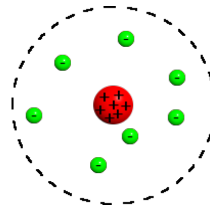
Why 3D nucleon structure?

❑ Rutherford's experiment – atomic structure (100 years ago):

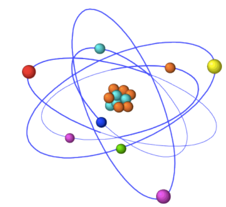
Atom:



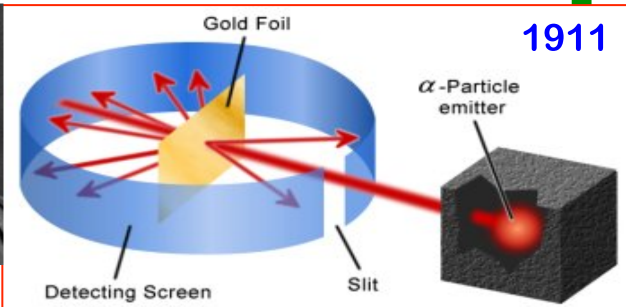
J.J. Thomson's
plum-pudding model



Rutherford's
planetary model



Modern model
Quantum orbitals



Discovery of nucleus
A localized
charge/force center
A vast
"open" space

Discovery of
Quantum Mechanics,
and
the Quantum World!

❑ Completely changed our "view" of the visible world:

✧ Mass by "tiny" nuclei – *less than 1 trillionth in volume of an atom*

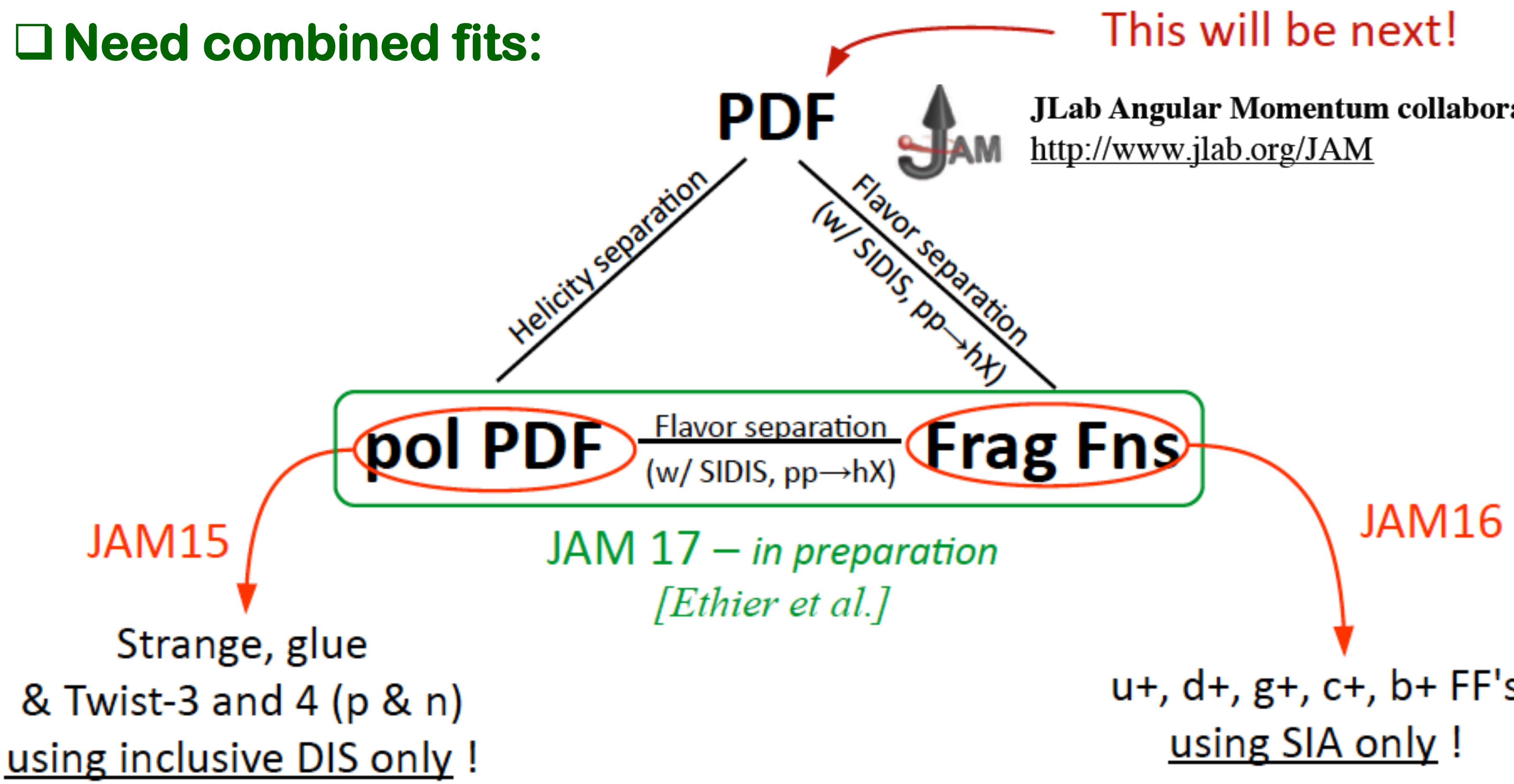
✧ Motion by quantum probability – *the quantum world!*

❑ 3D nucleon/nuclear structure:

✧ Distribution and motion of quarks and gluons – confining mechanism?

JLab Theory Effort

- **Need combined fits:**



JLab Angular Momentum collaboration
http://www.jlab.org/JAM

Iterative Monte Carlo: the JAM approach

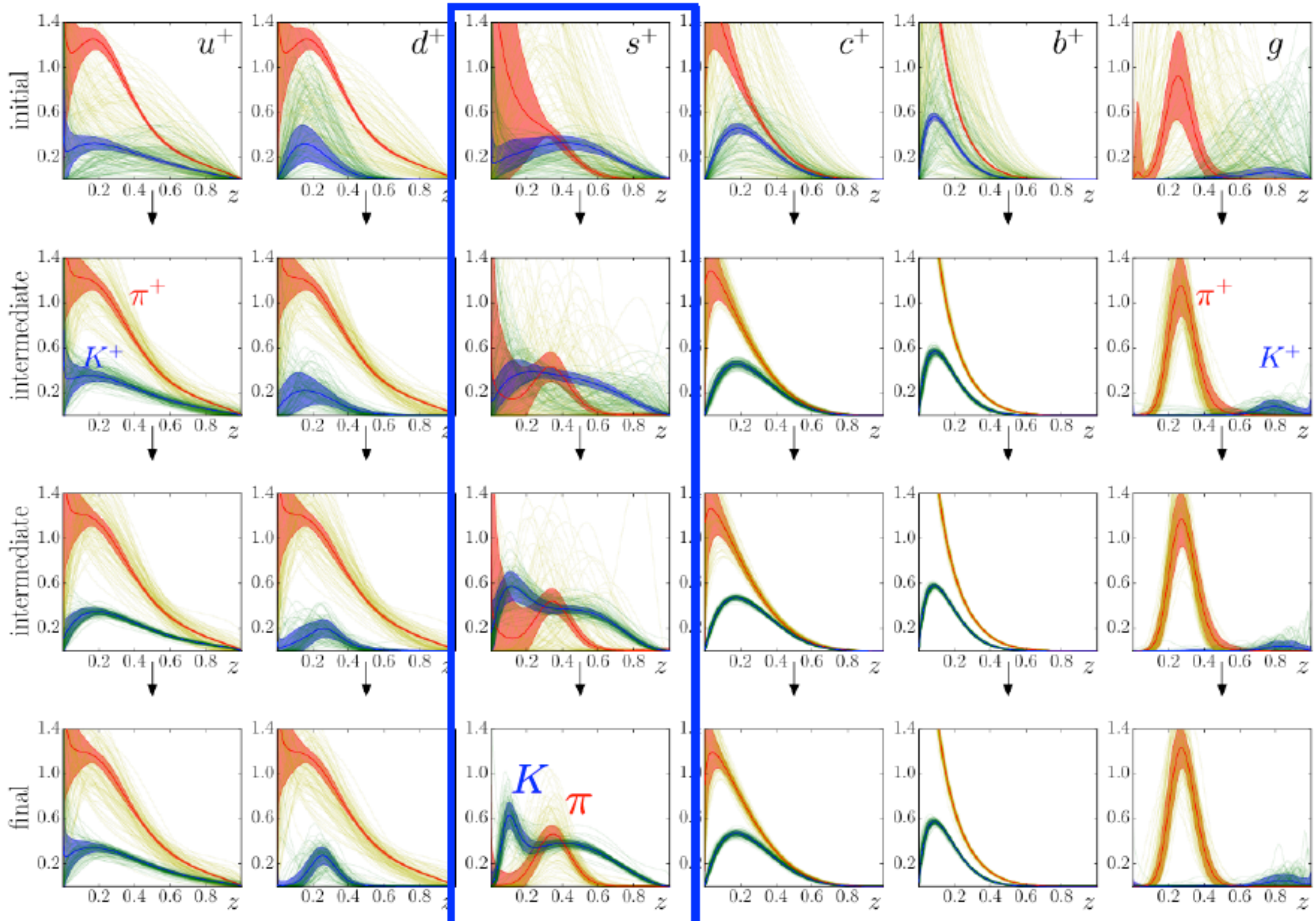
Sato, Ethier, Melnitchouk, Kuhn, Accardi, Hirai, Kumano

PRD93 (2016) 074005 and PRD94 (2016) 114004

JLab Theory Effort

Accardi @ PDFLattice2017

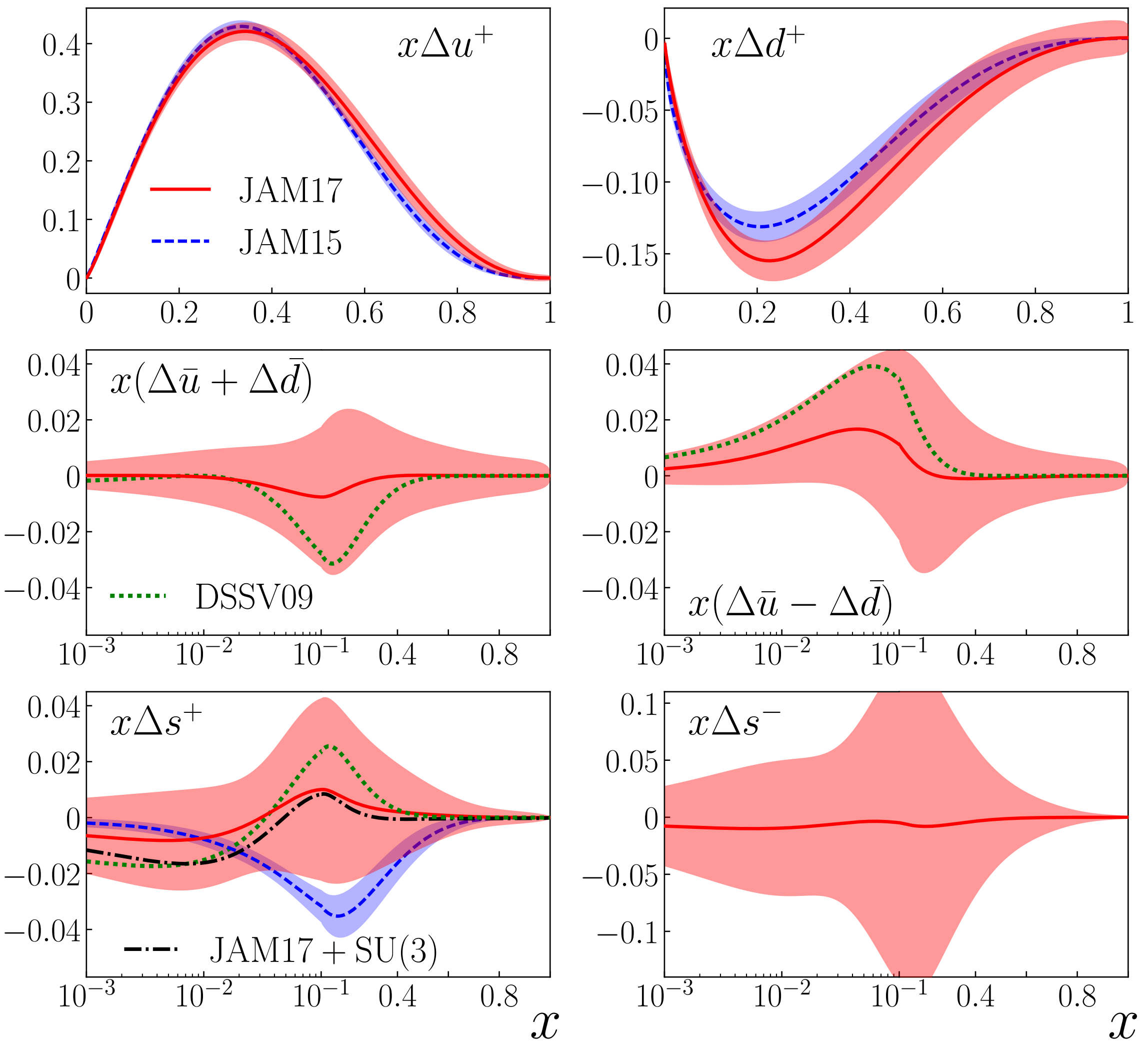
IMC method in action



JLab Theory Effort

Ethier et al, 1705.05889
Submitted to PRL

❑ Impact on polarized PDFs:



no assumption of SU(3) symmetry

strange quark polarization slightly positive at large x, but consistent with zero

previous analyses (e.g. JAM15) had negative Δs, induced by SU(3) assumption and parametrization bias

strange-antistrange asymmetry, and light antiquark polarization, consistent with zero

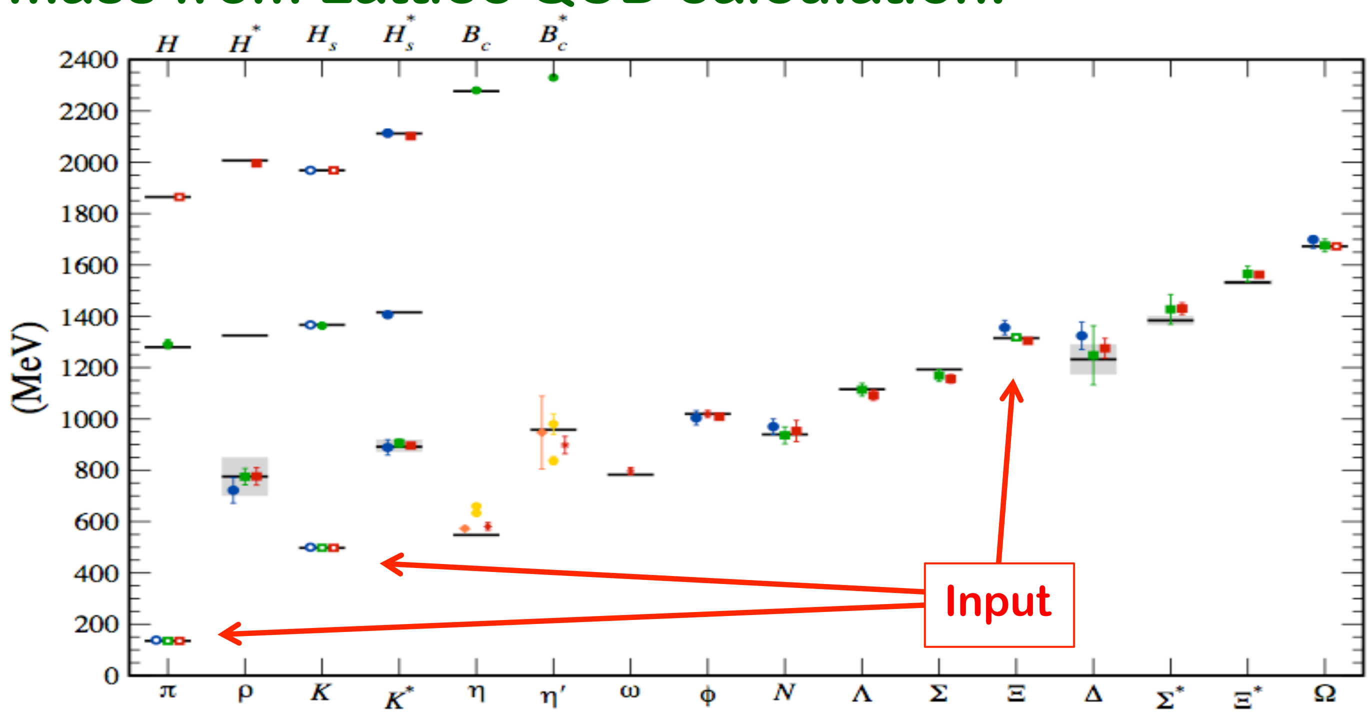
How EIC could answer the "big" questions?

- **How does QCD generate the nucleon mass?**

  "… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

  REACHING FOR THE HORIZON
  The 2015 Long Range Plan for Nuclear Science

- **Hadron mass from Lattice QCD calculation:**



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  REACHING FOR THE HORIZON
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- **Role of quarks and gluons?**

  - QCD energy-momentum tensor:

  $$T^{\mu\nu} = \frac{1}{2}\,\overline{\psi} i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}\,g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}{}_{\alpha}$$

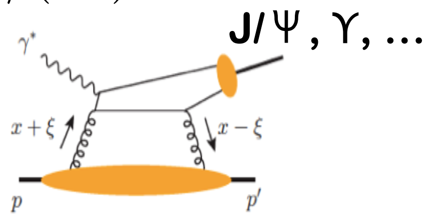
  - Trace of the QCD energy-momentum tensor:

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

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

  - Mass, trace anomaly, chiral symmetry break, and …

  $$m^2 \propto \langle p|T^{\alpha}{}_{\alpha}|p\rangle \quad \Rightarrow \quad \frac{\beta(g)}{2g}\langle p|F^2|p\rangle$$



➡ Heavy quarkonium production near the threshold, from JLab12 to EIC

How EIC could answer the “big” questions?

Three-pronged approach to explore the origin of hadron mass:

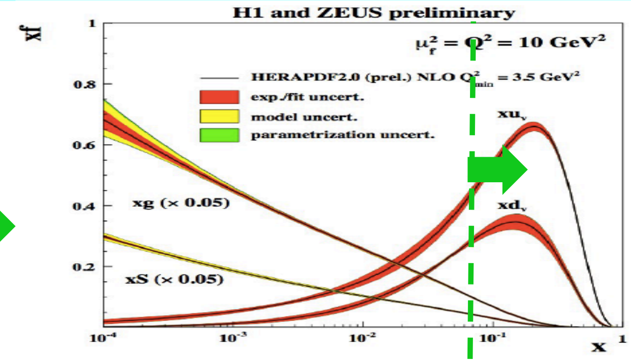
- ✧ lattice QCD
- ✧ mass decomposition – roles of the constituents
- ✧ model calculation – approximated analytical approach

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

The Proton Mass: At the Heart of Most Visible Matter
April 3-7, 2017
Z.-E. Meziani, B. Pasquini, J.-W. Qiu, M. Vanderhaeghen

Lattice calculations of hadron structure

Lattice QCD



X-dep distributions

❑ New ideas – from quasi-PDFs (lattice calculable) to PDFs:

✧ High P_z effective field theory approach:

$$\tilde{q}(x,\mu^2,P_z) = \int_x^1 \frac{dy}{y} Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) q(y,\mu^2) + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2},\frac{M^2}{P_z^2}\right)$$

Ji, et al., arXiv:1305.1539
1404.6680

✧ QCD collinear factorization approach:

$$\tilde{q}(x,\mu^2,P_z) = \sum_f \int_0^1 \frac{dy}{y} \mathcal{C}_f\left(\frac{x}{y},\frac{\mu^2}{\bar{\mu}^2},P_z\right) f(y,\bar{\mu}^2) + \mathcal{O}\left(\frac{1}{\mu^2}\right)$$

Non-perturbative lattice UV renormalization:
Effective mass renormalization, Gradient flow, …

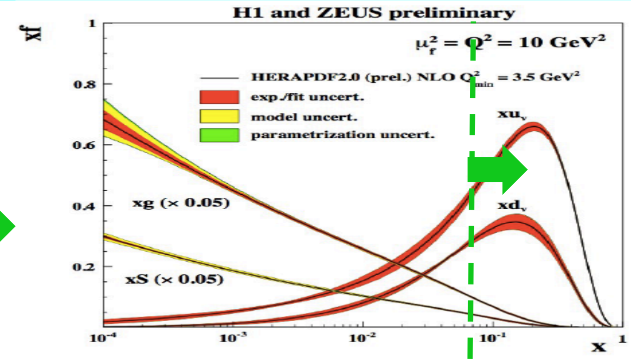
Ma and Qiu, arXiv:1404.6860
1412.2688
Ishikawa, Ma, Qiu, Yoshida, 1609.02018
Monohan, Orginos, 1612.01584
…

❑ The TMD Collaboration + on-going effort around the world!

Plus the intense local JLab theory effort!

Lattice calculations of hadron structure

Lattice QCD



X-dep distributions

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Ji, et al., arXiv:1305.1539, 1404.6680

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Ma and Qiu, arXiv:1404.6860, 1412.2688
Ishikawa, Ma, Qiu, Yoshida, 1609.02018
Monohan, Orginos, 1612.01584
…

Non-perturbative lattice UV renormalization:
Effective mass renormalization, Gradient flow, …

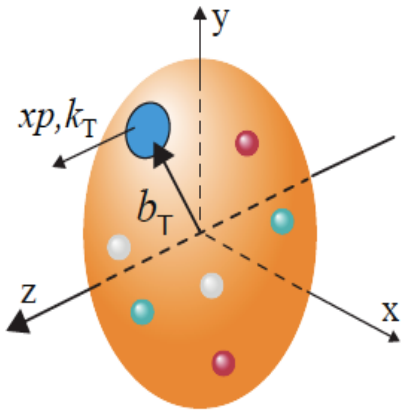
- **Tremendous potentials!**

PDFs of proton, neutron, pion, …; TMDs, GPDs, …; JLab12 expts

Two-momentum-scale observables

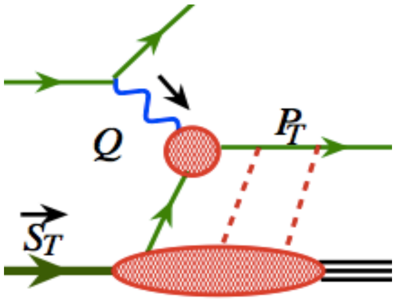
- **Cross sections with two-momentum scales observed:**

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



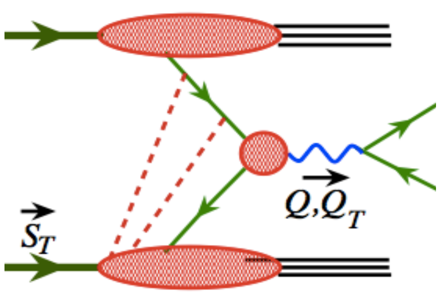
- ✧ Hard scale: Q_1 localizes the probe to see the quark or gluon d.o.f.
- ✧ "Soft" scale: Q_2 could be more sensitive to hadron structure, e.g., confined motion

- **Two-scale observables with the hadron broken:**



SIDIS: Q>>P_T

\+



DY: Q>>P_T

\+ Two-jet momentum imbalance in SIDIS, …

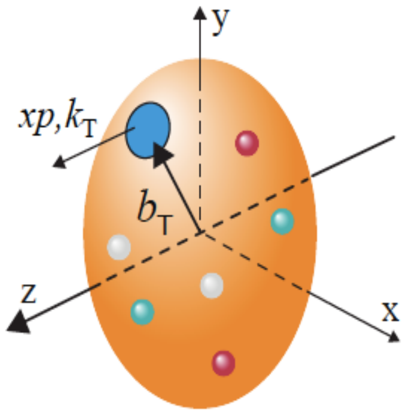
⇒

- ✧ Natural observables with TWO very different scales
- ✧ TMD factorization: partons' confined motion is encoded into TMDs

Two-momentum-scale observables

❑ Cross sections with two-momentum scales observed:

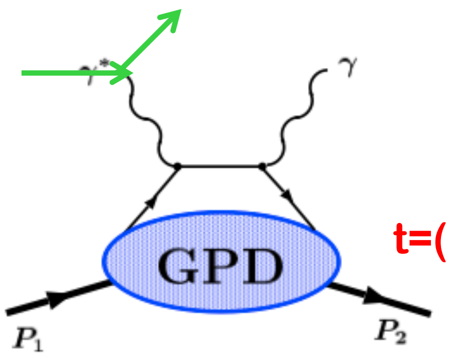
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



✧ Hard scale: Q_1 localizes the probe to see the quark or gluon d.o.f.

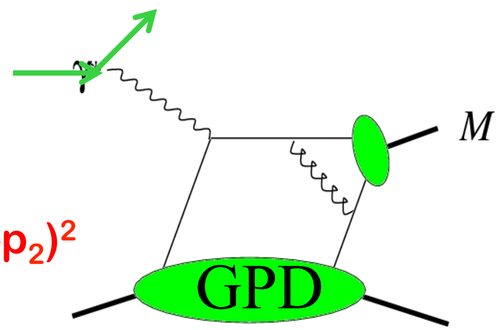
✧ "Soft" scale: Q_2 could be more sensitive to hadron structure, e.g., confined motion

❑ Two-scale observables with the hadron unbroken:



+

$t=(p_1-p_2)^2$



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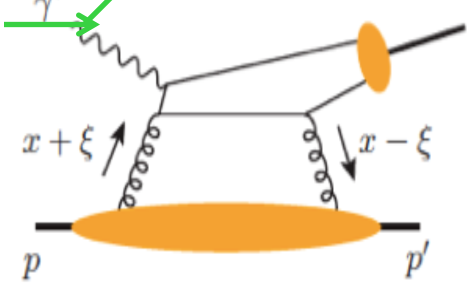

+ …

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

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

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

✧ Natural observables with TWO very different scales

✧ GPDs: Fourier Transform of t-dependence gives spatial b_T-dependence