The Science Case for
An Electron-Ion Collider:
The Next QCD Frontier

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for both BNL and JLab EIC efforts, …

NSAC Subcommittee Meeting on Scientific Facilities
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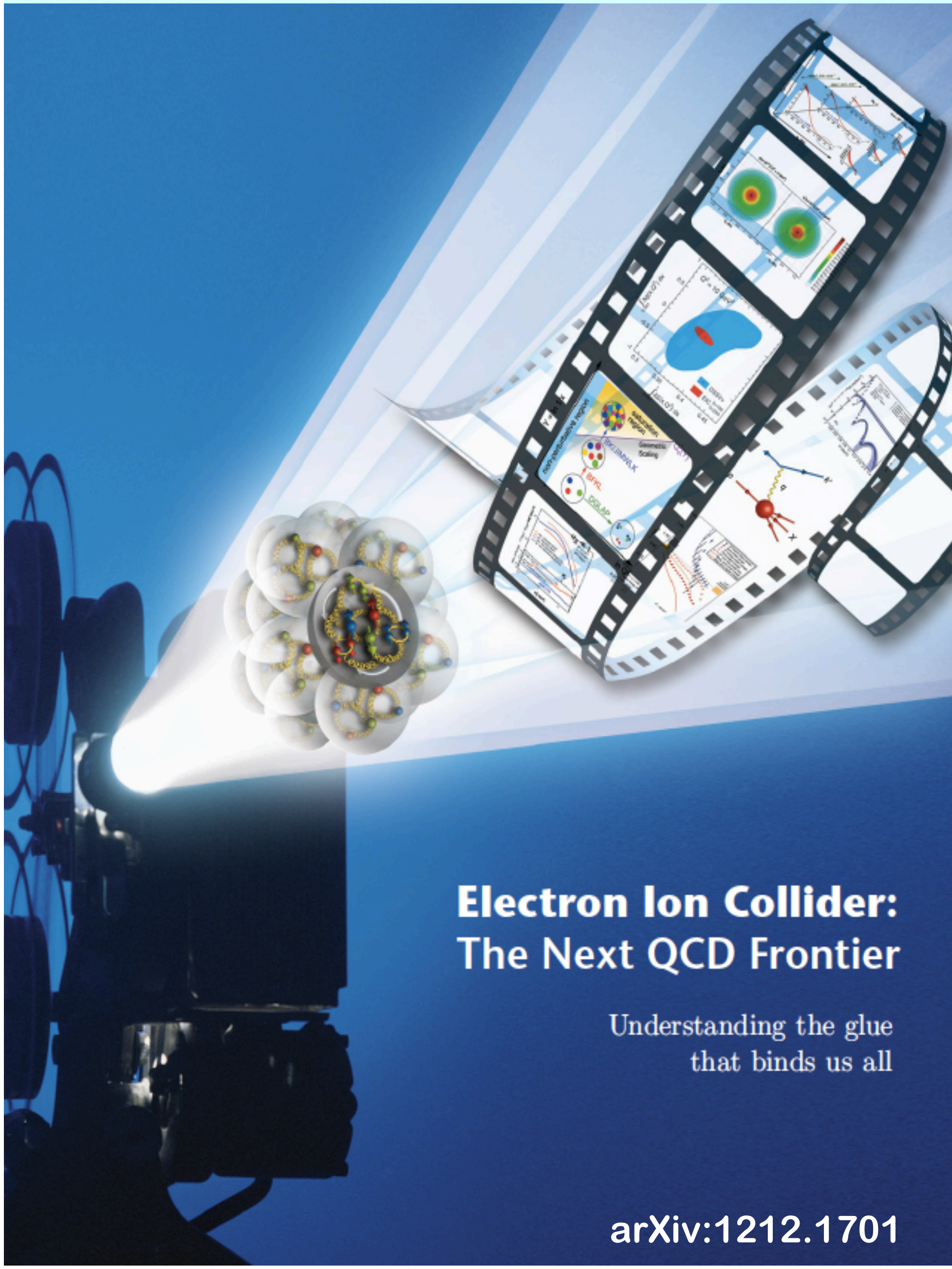
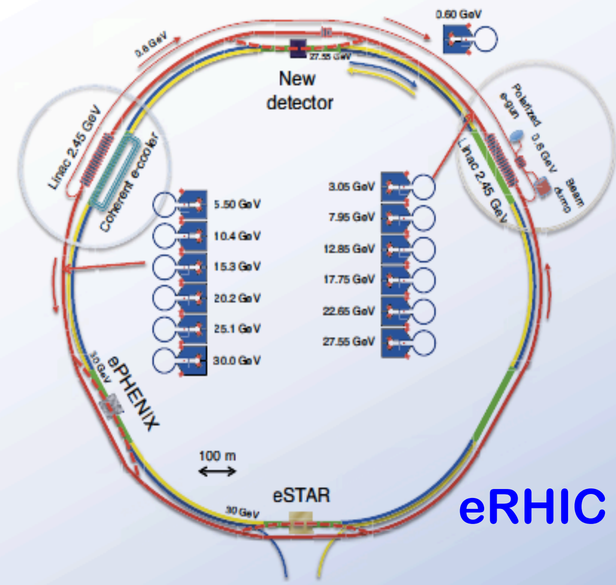
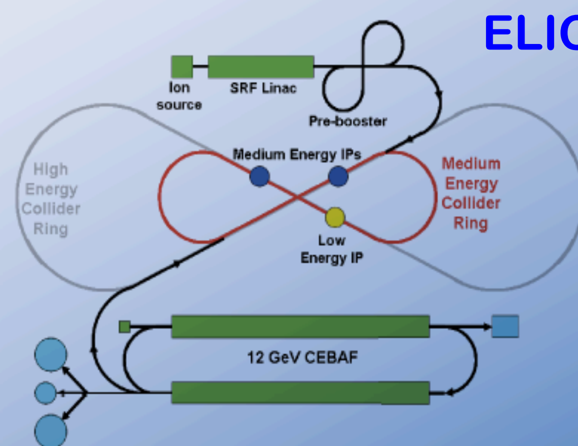
White Paper for the Electron-Ion Collider





eRHIC (BNL)

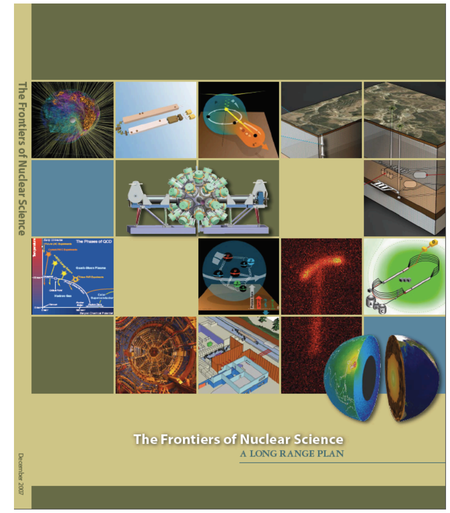
ELIC (JLab)



Community effort and commitment

❑ **2007 Nuclear Physics Long Range Plan**

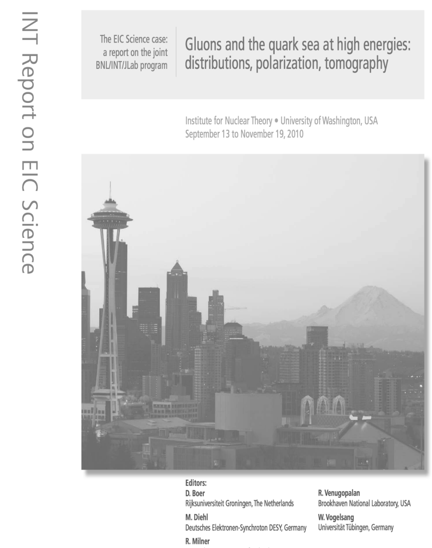
Designated Electron-Ion Collider (EIC) as "embodying the vision for reaching the next QCD frontier"



❑ **Many workshops on EIC physics:**

Ten-week program (9/13–11/19, 2010)
at Institute for Nuclear Theory

(INT Report: arXiv:1108.1713v2, 500+ pages)



❑ **Commitment from BNL and JLab:**

✧ **BNL EIC Task force**
(https://wiki.bnl.gov/eic/index.php/Main_Page)

✧ **EIC@JLab**
(https://eic.jlab.org/wiki/index.php/Main_Page)

✧ **Detector R&D** (https://wiki.bnl.gov/conferences/index.php/EIC_R%25D)

✧ **EICAC – jointly by BNL and JLab**

Outline

- ❑ **Why do we need an Electron-Ion Collider (EIC)?**

  In the big picture of Nuclear Science and QCD

- ❑ **What is the impact and discovery potential of the EIC?**

  In terms of the most intellectually pressing questions in QCD

- ❑ **What are the goals and deliverables of the EIC?**

  In the context of key measurements

- ❑ **Realization: the staged approach**

  the stage-I deliverables, and the stage-II opportunities

- ❑ **International context, a path to the full potential of an EIC**

  ENC@GSI, HIAF@CAS, LHeC@CERN, …

- ❑ **Summary and outlook**

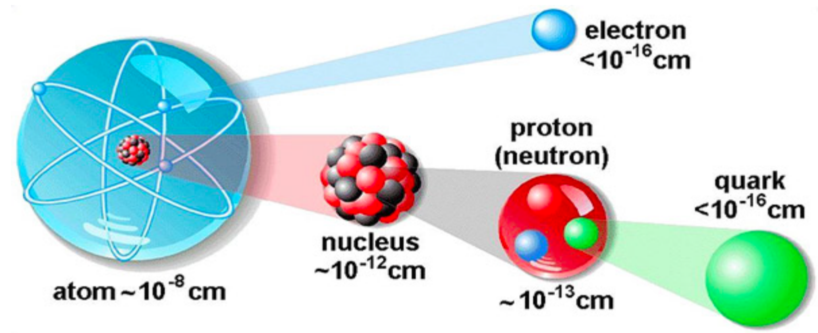
Nuclear Science and QCD

❑ **Nuclear Science:**

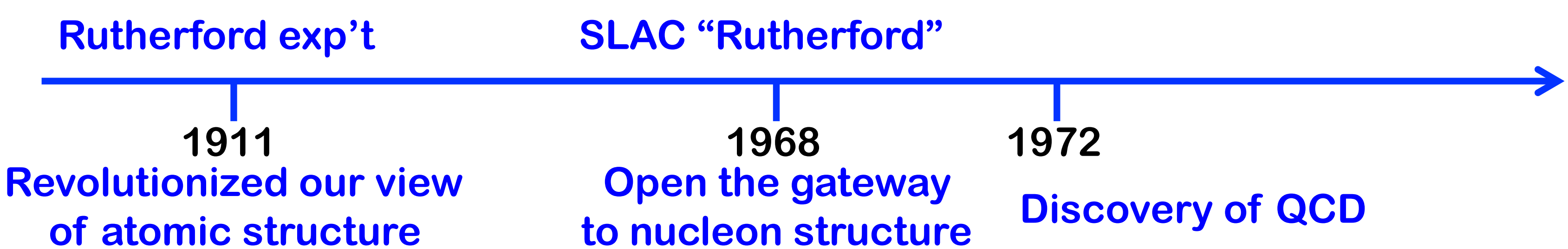
to discover, explore, and understand all forms of nuclear matter and its benefits to our society

❑ **Nuclear matter:**

- the nucleus
- the nucleons
- the quarks and gluons



Accounting for essentially all of the mass of the visible universe



❑ **Quantum Chromodynamics (QCD):**

✧ A fundamental theory for the dynamics of quarks and gluons

✧ It describes the formation of all forms of nuclear matter

Understanding QCD is a fundamental and compelling goal of Nuclear Science!

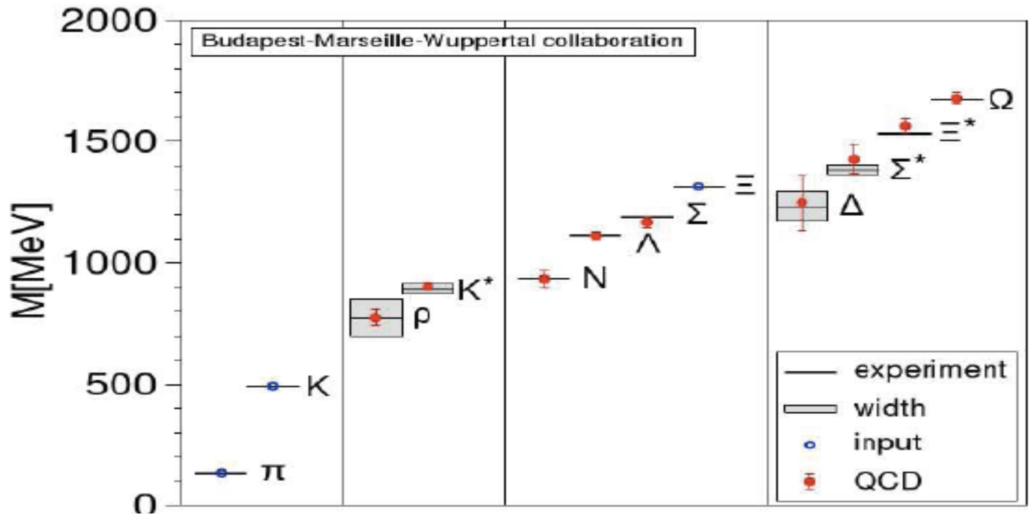
Successes of QCD

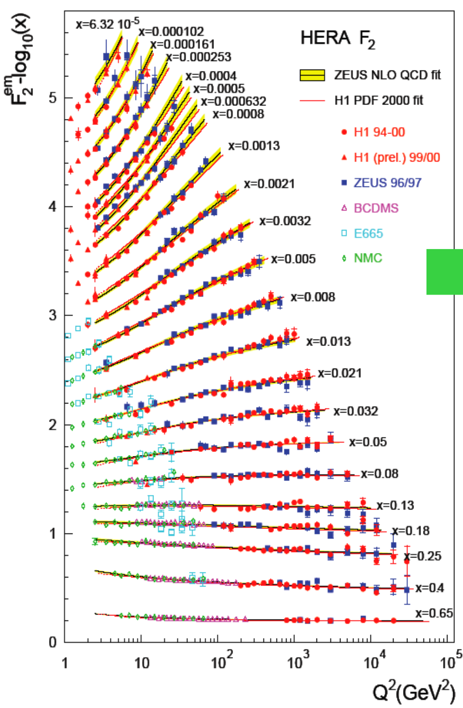
- @low energy:

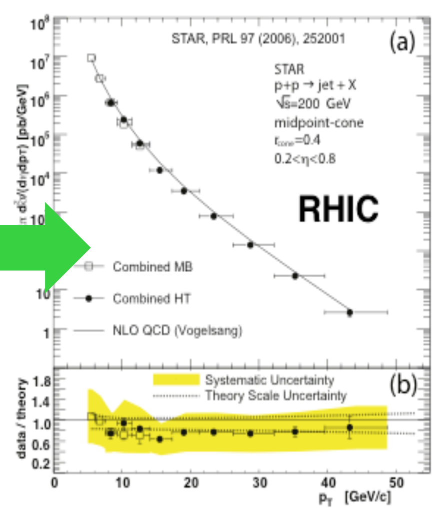
  Hadron mass spectrum from lattice QCD

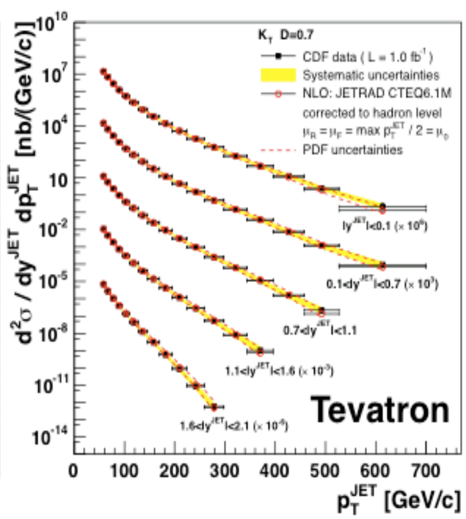
- @high energy:

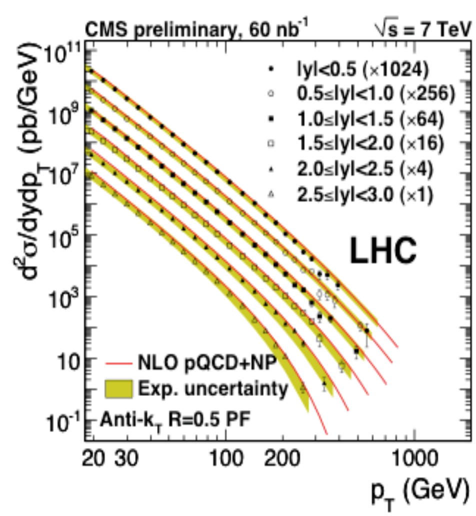
  Asymptotic freedom + perturbative QCD









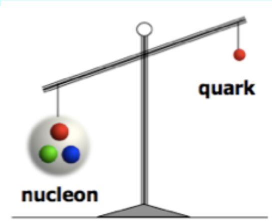


Measure e-p at 0.3 TeV (HERA)
Predict p-p and p-p̄ at 0.2, 1.96, and 7 TeV

Puzzles and challenges

- Proton mass "puzzles":

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

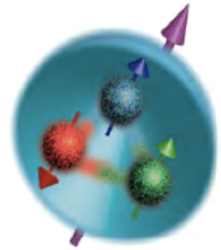


m_q ~ 10 MeV

m_N ~ 1000 MeV

  How does glue dynamics generate the energy for nucleon mass?

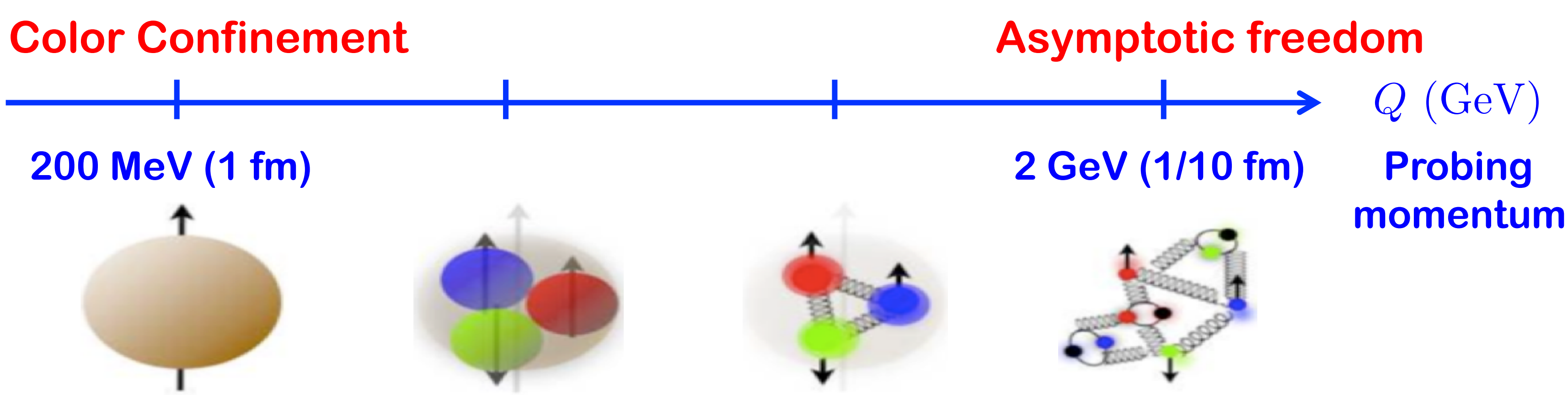
- Proton spin "puzzles":



  Quarks carry $\sim 30\%$ of proton's spin

  Why does quark spin contribute so little to proton's spin?

- 3D structure of nucleon:

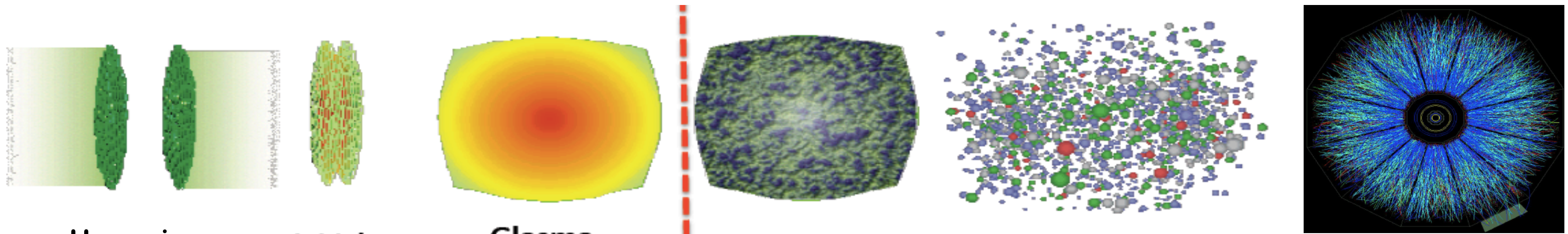


  How does glue bind quarks and itself into a proton and nuclei?

  Can we scan the nucleon to reveal its 3D structure?

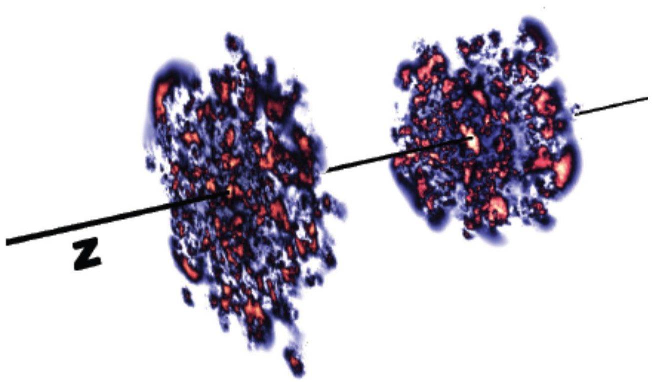
Puzzles and challenges

❑ QCD at high densities and temperatures:



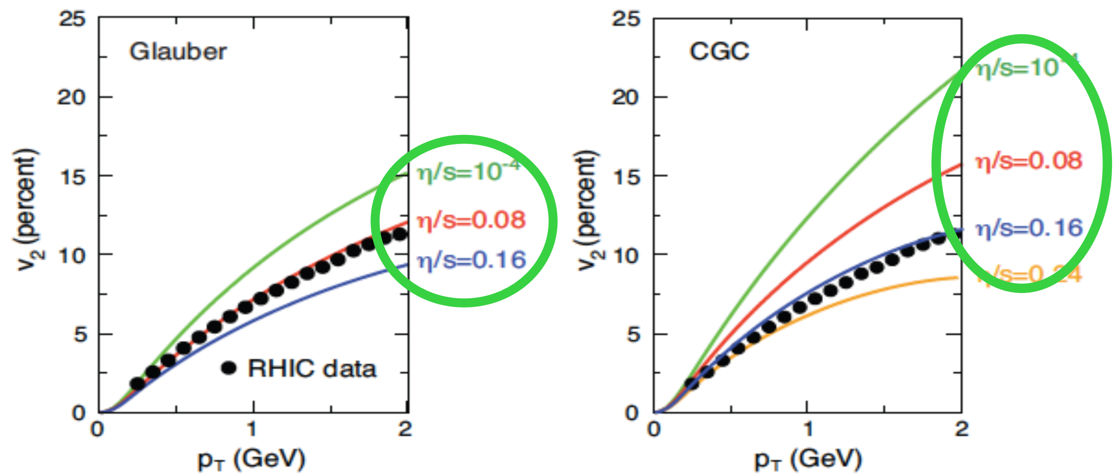
Heavy ions Relativistic | Initial Singularity | Glasma | τ_0 | sQGP - perfect fluid | Hadron Gas | In STAR detector

❑ Puzzles:



+ Viscous relativistic hydrodynamics

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n 2\, v_n\, \cos(n\tilde{\phi})\right)$$

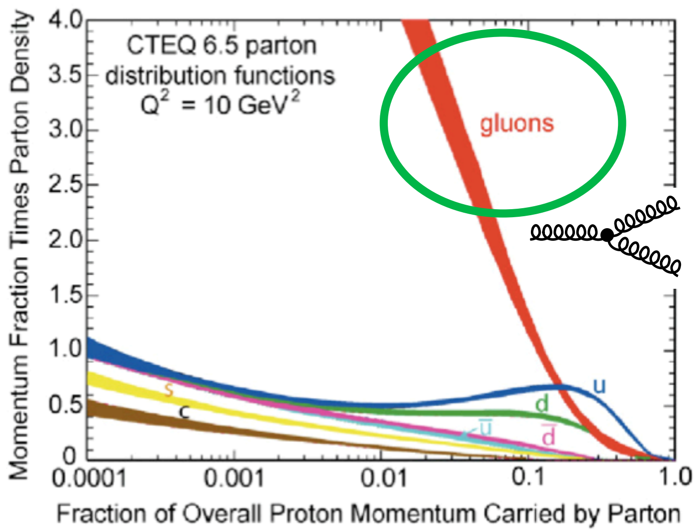


Initial condition - Fluctuation | **Flow and viscosity**

How can we measure such initial-state of gluons independently?

New regime of gluonic matter

❑ HERA's discovery: proliferation of soft gluons:

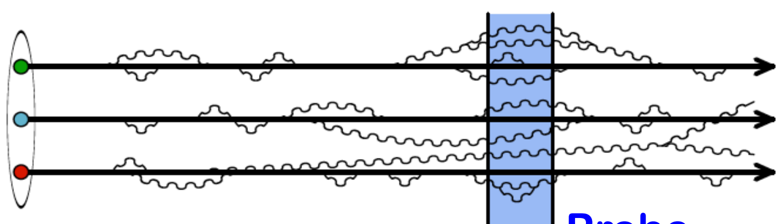


How does the unitarity bound of the hadronic cross section survive if soft gluons in a proton or nucleus continue to grow in numbers?

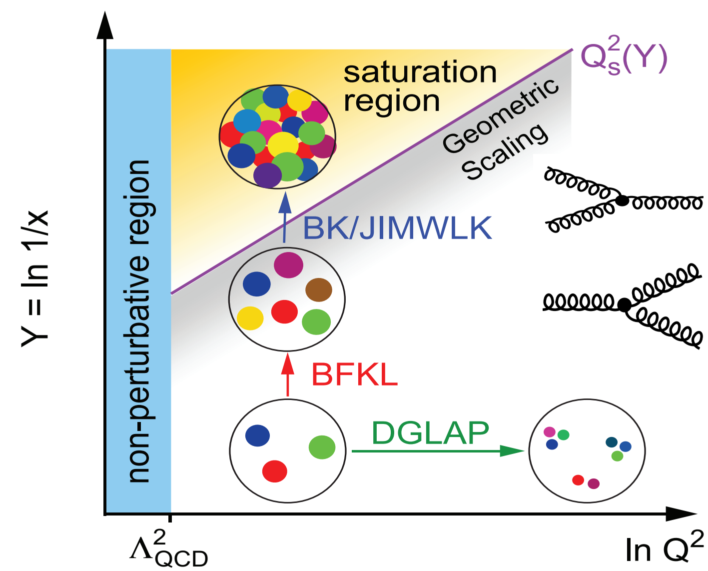
QCD: Dynamical balance between radiation and recombination

➡ Saturation of gluons?

❑ Gluon saturation has to be there!



➡



A new regime of QCD matter
– Color Glass Condensate (CGC)

Hints from HERA, RHIC and LHC

Can we find this regime for sure and study/understand its properties?

Fundamental QCD question - I

How do quarks and gluons confine themselves into a proton?

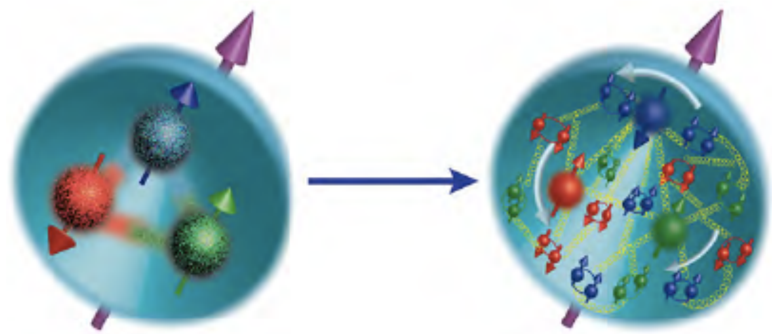
The color confinement

"Hints" from knowing hadron structure

❑ Hadron structure:

From the EIC White Paper

- **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?



❑ Proton spin:

If we do not understand proton spin from QCD, we do not understand QCD!

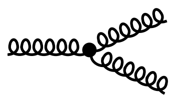
It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

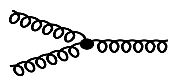
***Need a polarized proton beam*!**

Fundamental QCD question - II

How do gluons saturate themselves into a new form of matter?
Color Glass Condensate

❑ **Gluon $\neq$ photon:**

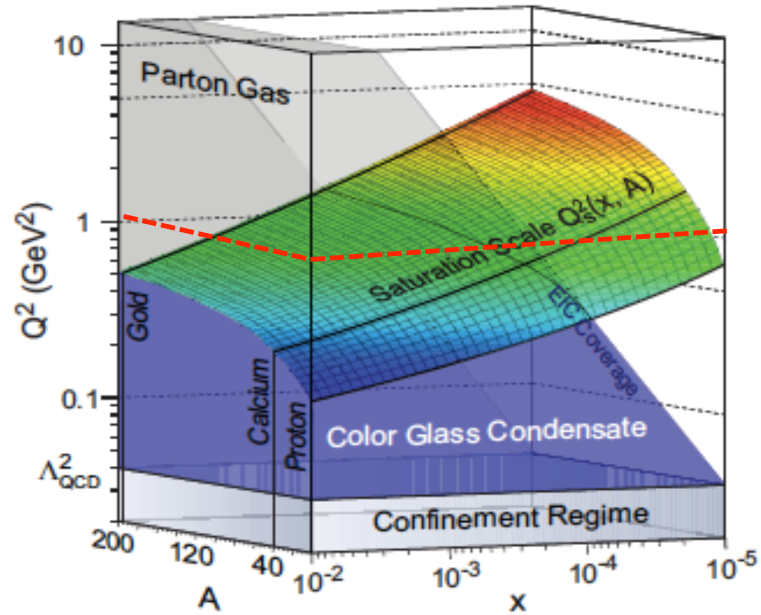
Radiate: 

Recombine: 

✧ Dynamical scale Q_s from the balance

✧ New mathematical framework

✧ Universal properties (CGC)



From the EIC White Paper

- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

Need a heavy ion beam!

Fundamental QCD question - III

How do hadrons emerge from a created quark or gluon?
Neutralization of color - hadronization

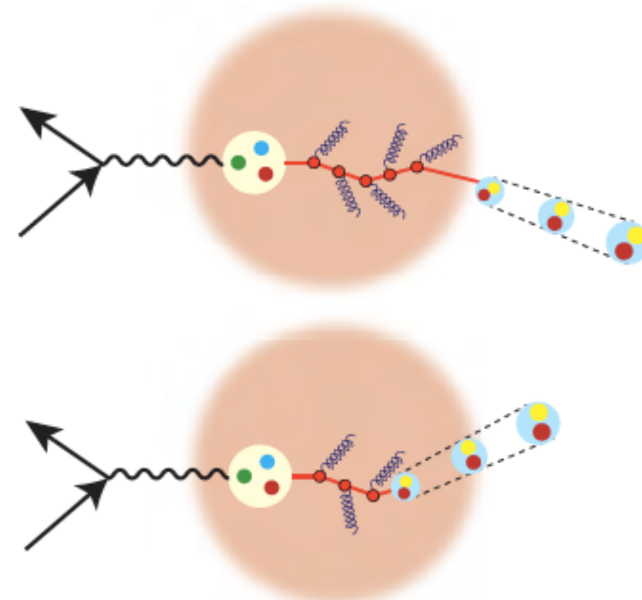
- **Femtometer detector/scope:**

  Nucleus, a laboratory for QCD

- **Quark/gluon properties:**

  Initial-condition for hadronization

  Semi-inclusive DIS



From the EIC White Paper

- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

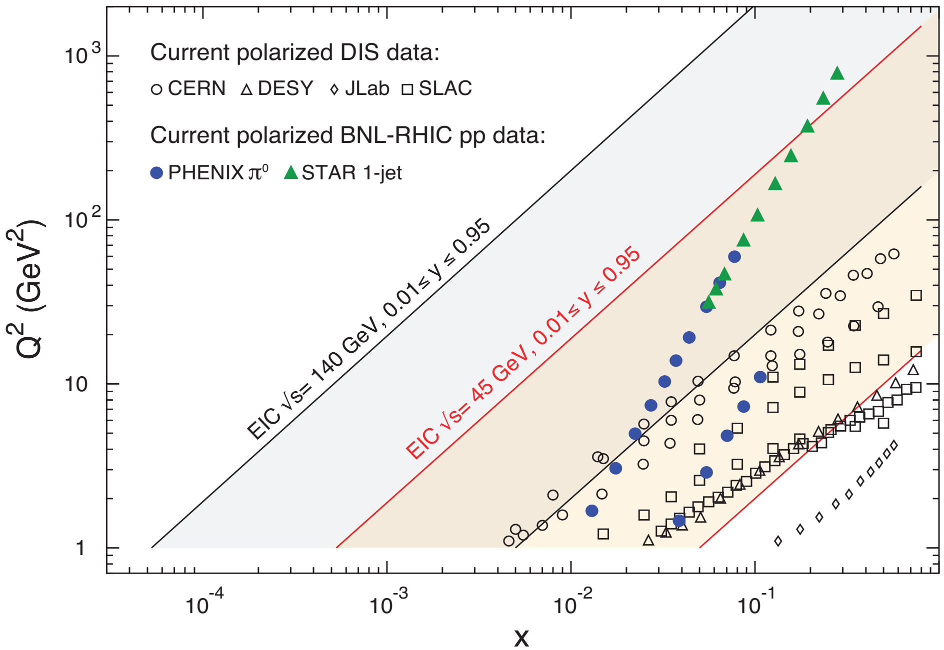
Need an EM probe to precisely control the initial-condition for hadronization!

Electron-Ion Collider

- **An ultimate machine to provide answers to these fundamental QCD questions:**
  - A collider to provide kinematic reach well into the gluon-dominated regime
  - An electron beam to bring to bear the unmatched precision of the EM interaction as a probe
  - Polarized nucleon beams to determine the correlations of sea quark and gluon distributions with the nucleon spin
  - Heavy ion beams to provide precocious access to the regime of saturated gluon densities, and to offer a precise dial in the study of propagation-length for color charges in nuclear matter
- **A machine at the frontier of polarized luminosity, combined with versatile kinematics and beam species**

Allow all these important QCD questions to be tackled at this facility

Kinematics and machine properties



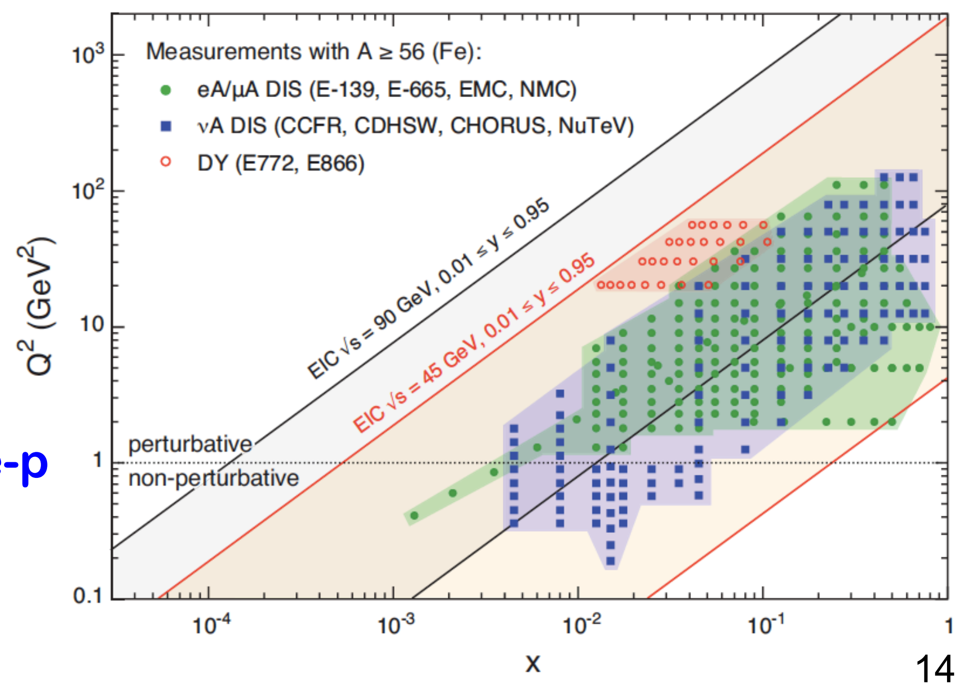
For e-N collisions at the EIC:

- ✓ First polarized e-p collider
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}s^{-1}

  HERA luminosity ~ 5×10^{31} cm^{-2} s^{-1}

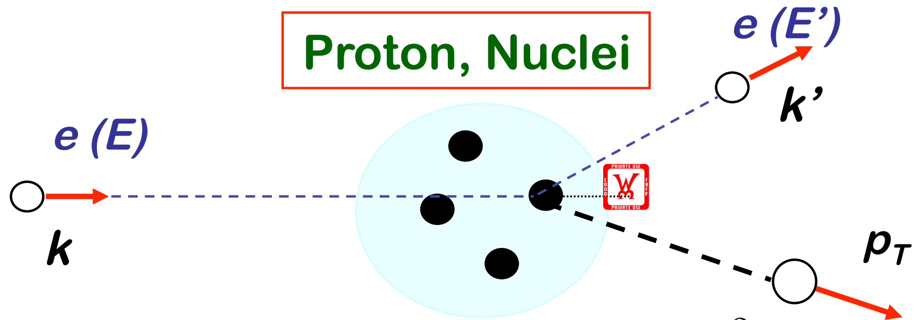
For e-A collisions at the EIC:

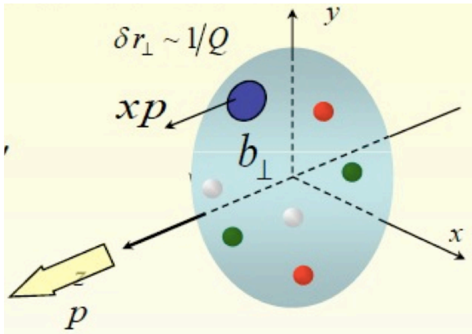
- ✓ First e-A collider
- ✓ Wide range in nuclei
- ✓ Variable center of mass energy
- ✓ Luminosity per nucleon same as e-p



EIC: A bright sub-femtometer scope

- New DIS "Rutherford" experiment:

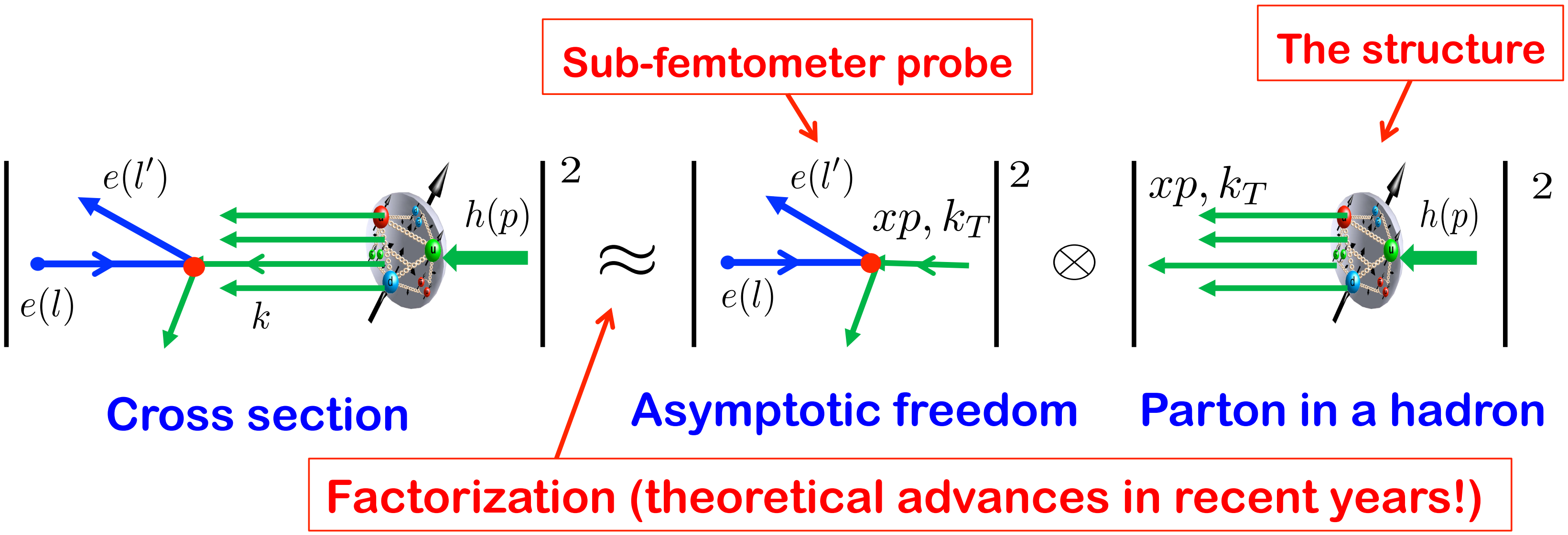




$$Q^2 = 4EE' \sin^2(\theta/2), \quad x_B = \frac{Q^2}{2m_N \nu}, \quad \nu = E - E'$$

$$Q > 2\ \text{GeV} \quad \Longleftrightarrow \quad \Delta r < 10^{-1}\ \text{fm}$$

- A sub-femtometer scope:



EIC: Goals and deliverables

The key measurements

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

Proton spin and hadron structure?

- **Proton – composite particle of quarks and gluons:**

  Spin = intrinsic (parton spin) + motion (orbital angular momentum)

- **Proton spin:**

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

$S(\mu) = \frac{1}{2}$

$\mu \Rightarrow \infty$

- **Over 20 years effort (following EMC discovery)**

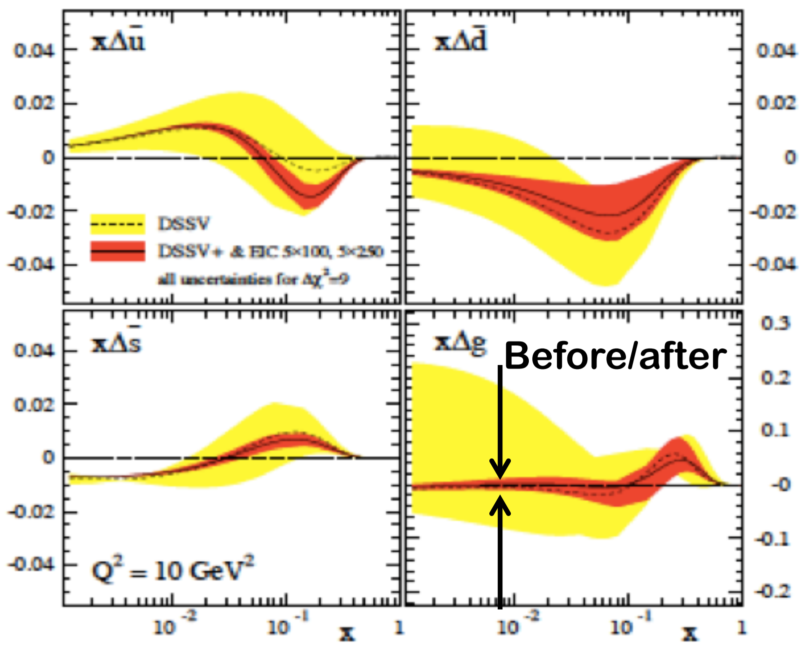
  - ✧ **Quark (valence + sea) helicity:** $\sim 30\%$ **of proton spin**
  - ✧ **Gluon helicity (latest RHIC data):** $\sim 20\%$ **from limited x range**

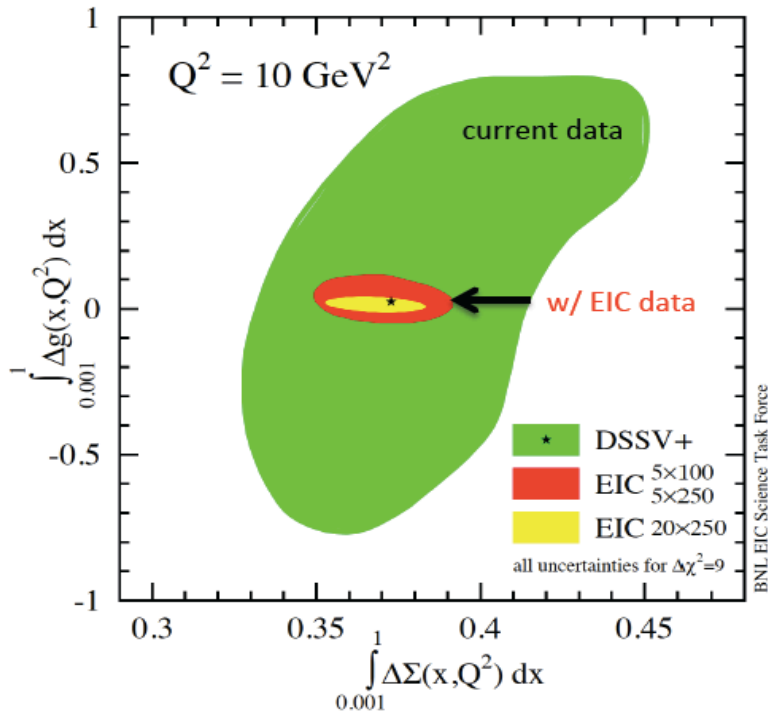
➡ **How to explore the “full” gluon and sea quark contribution?**
How to quantify the role of orbital motion?

Proton spin and hadron structure?

❑ The EIC – the decisive measurement (1st year of running):

(Low x and wide x range at EIC)





No other machine in the world can achieve this!

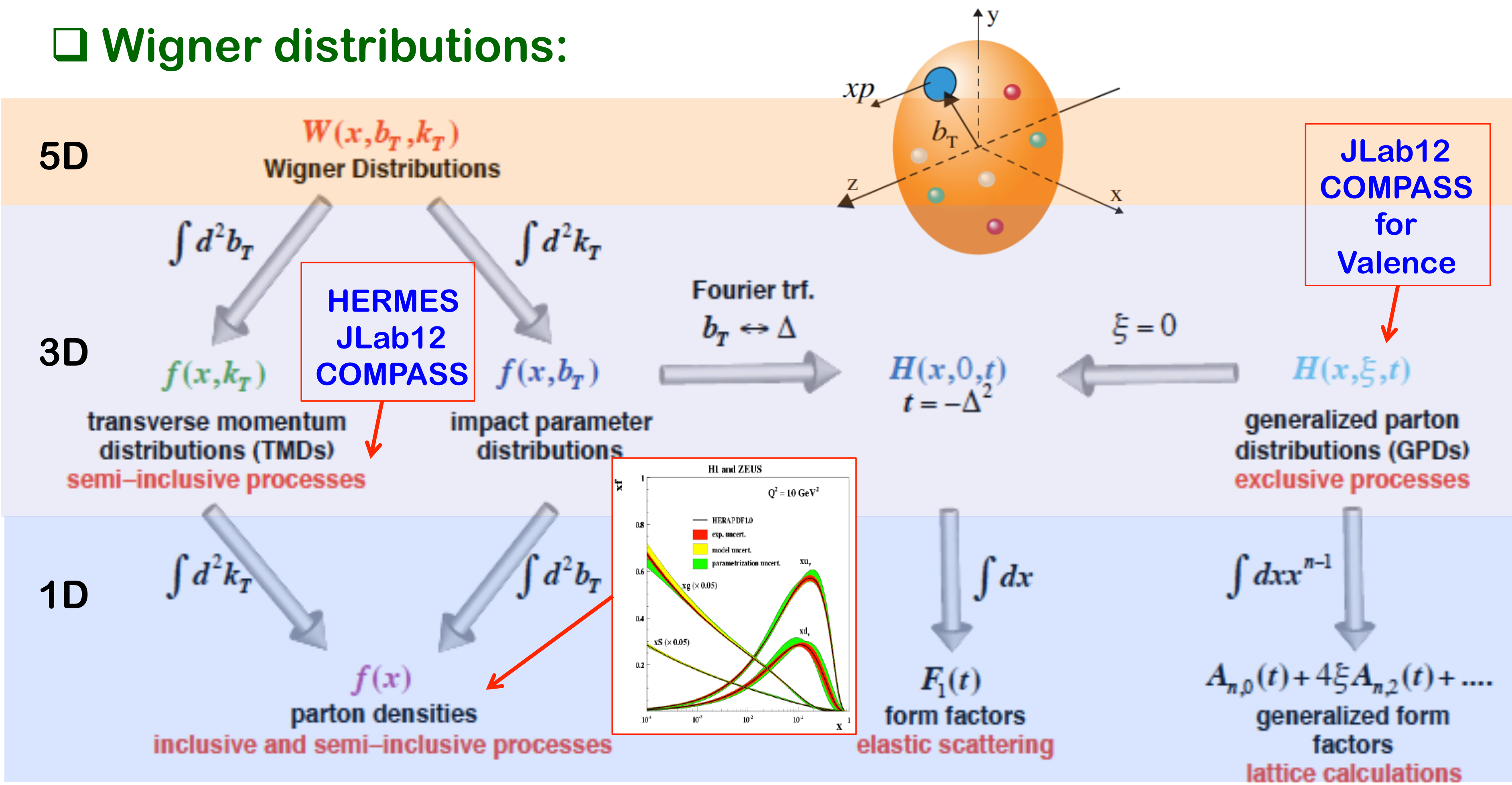
❑ Solution to the proton spin puzzle:

✧ *Precision measurement of Δg – extend to smaller x regime*

✧ *Orbital angular momentum – motion transverse to proton's momentum*

Unified view of nucleon structure

❑ Wigner distributions:



❑ EIC – 3D imaging of sea and gluons:

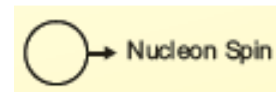
- ✧ TMDs – confined motion in a nucleon (semi-inclusive DIS)
- ✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS)

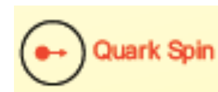
EIC is the best for probing TMDs

❑ **TMDs - rich quantum correlations:**

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1 =		$h_1^\perp$ = − Boer-Mulders
	L		g_{1L} = − Helicity	$h_{1L}^\perp$ = −
	T	$f_{1T}^\perp$ = − Sivers	$g_{1T}^\perp$ = −	h_1 = − Transversity $h_{1T}^\perp$ = −

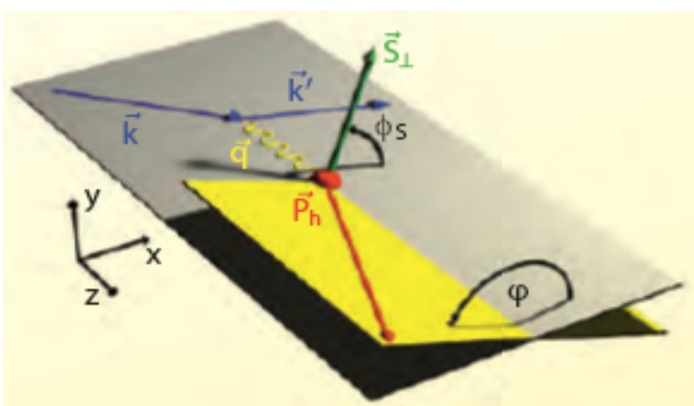
Leading twist TMDs





Similar for gluons

❑ **Naturally, two scales and two planes:**



✧ **Two scales:**

high Q - localized probe

Low p_T - sensitive to confining scale

✧ **Two planes:**

angular modulation to separate TMDs

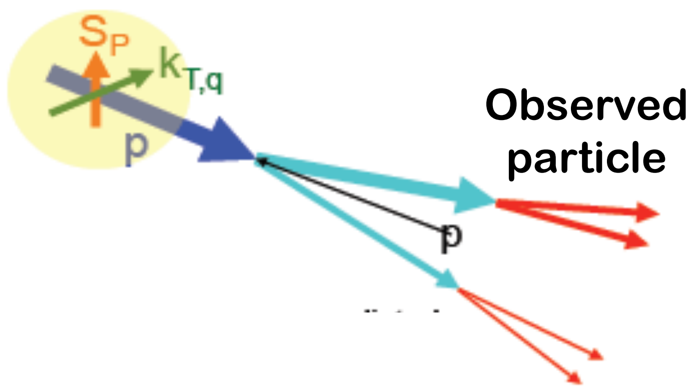
Hard to separate TMDs in hadronic collisions

Confined motion in a polarized nucleon

- Single-spin asymmetry: $$A(\ell,\vec{s}) \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s})-\sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s})+\sigma(\ell,-\vec{s})}$$

More sensitive to the role of quantum correlation!

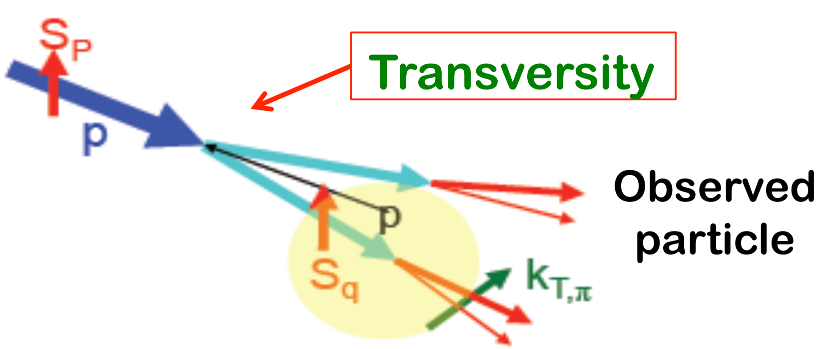
- Quantum correlation between hadron spin and parton motion:



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

- Quantum correlation between parton spin and hadronization:



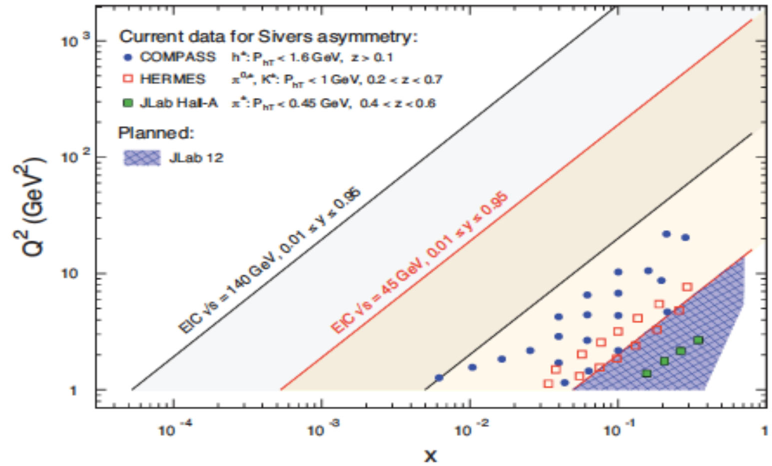
Collins effect – Collins function

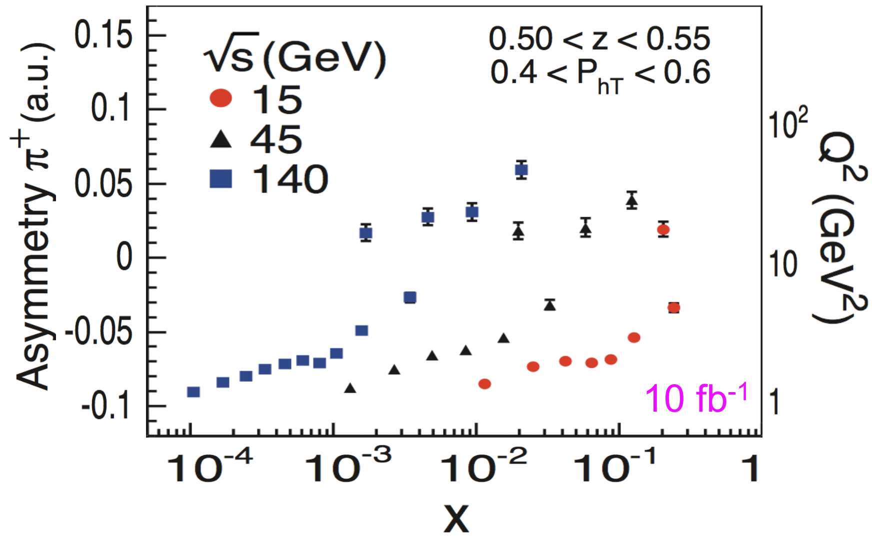
Parton's transverse spin influence its hadronization

JLab12 and COMPASS for valence, EIC covers the sea and gluon!

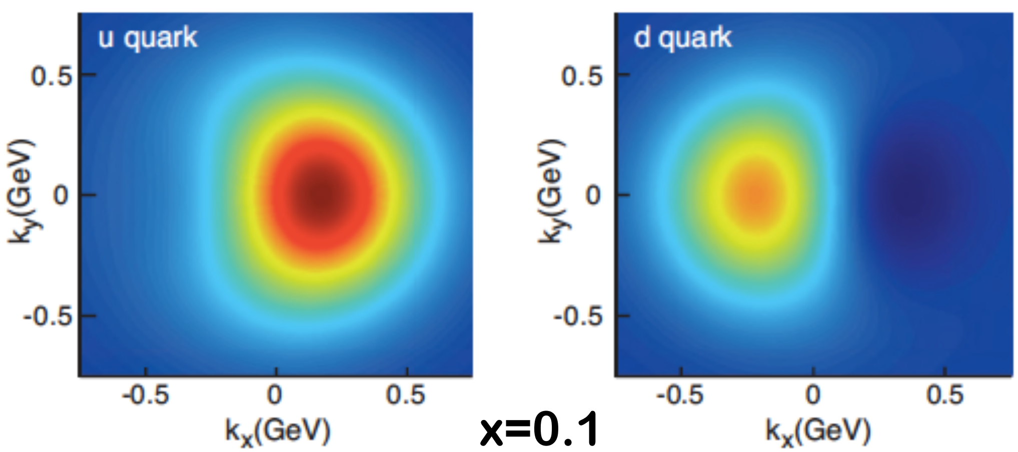
What can EIC do for Sivers function?

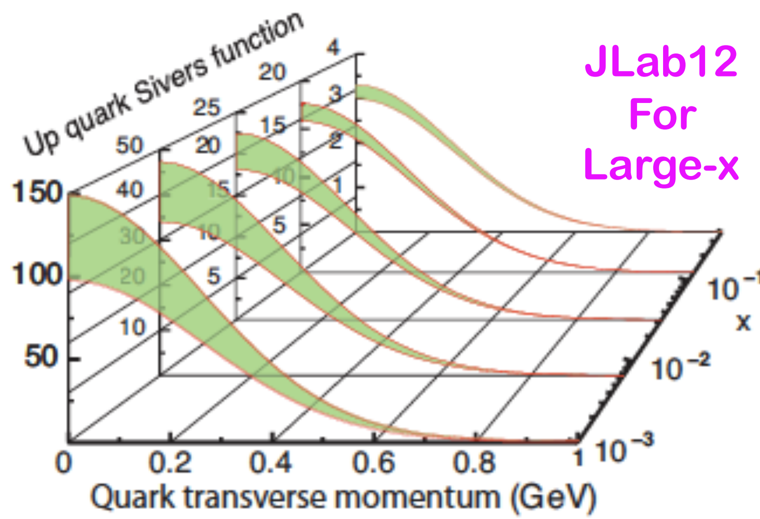
- Coverage and simulation:





- Unpolarized quark inside a transversely polarized proton:





JLab12
For
Large-x

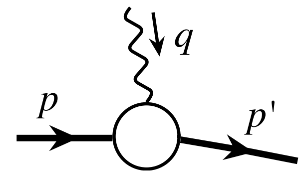
No other machine in world can do this!

How is color distributed inside the proton?

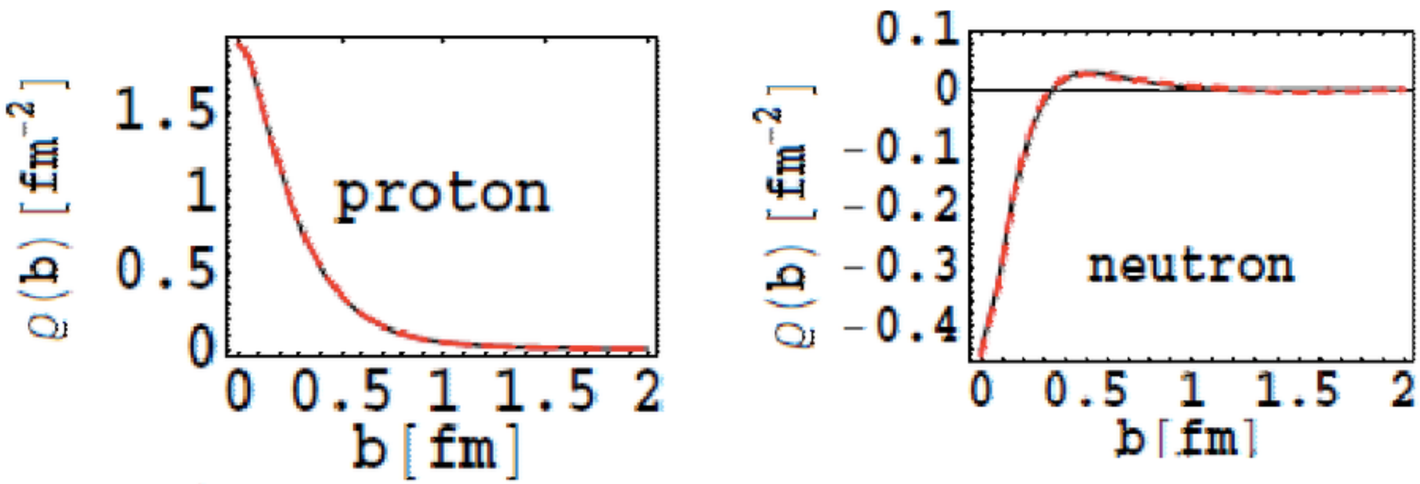
- The "big" question:

  How color is distributed inside a hadron? (clue for color confinement?)

- Electric charge distribution:

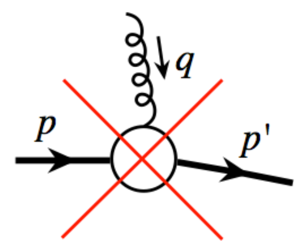


  Elastic electric form factor ➡ Charge distributions



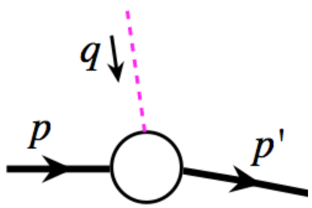
- But, NO color elastic nucleon form factor!

  Hadron is colorless and gluon carries color

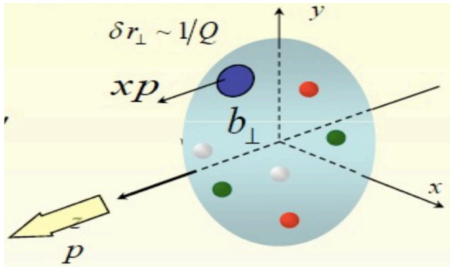


Spatial imaging of quarks and gluons

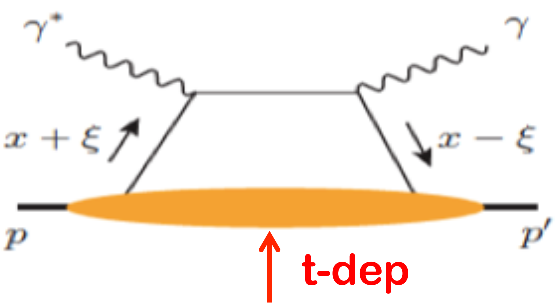
❑ Need Form Factor of density operator:



✧ Exchange of a colorless "object"
✧ "Localized" probe
✧ Control of exchanging momentum



❑ Exclusive processes - DVCS:



$$\frac{d\sigma}{dx_B dQ^2 dt}$$

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

$$\xi = (P' - P)\cdot n/2$$

GPDs

→ $H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$

F.T. of t-dep

→ Spatial distributions

❑ Quark GPDs and its orbital contribution to proton's spin:

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

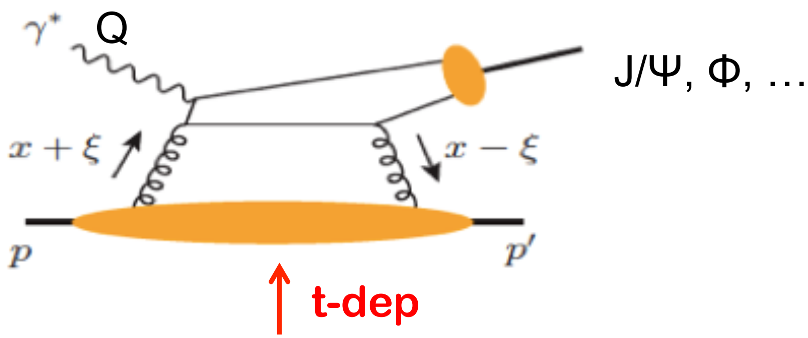
The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab 12

This could be checked by Lattice QCD?

Spatial imaging of gluon density

- ❑ **Exclusive vector meson production:**

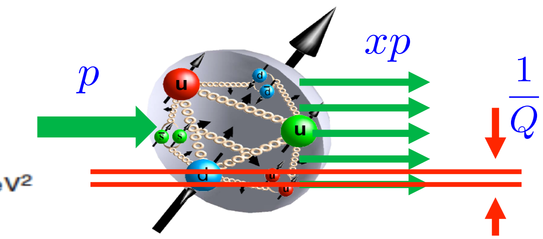
$$\frac{d\sigma}{dx_B dQ^2 dt}$$



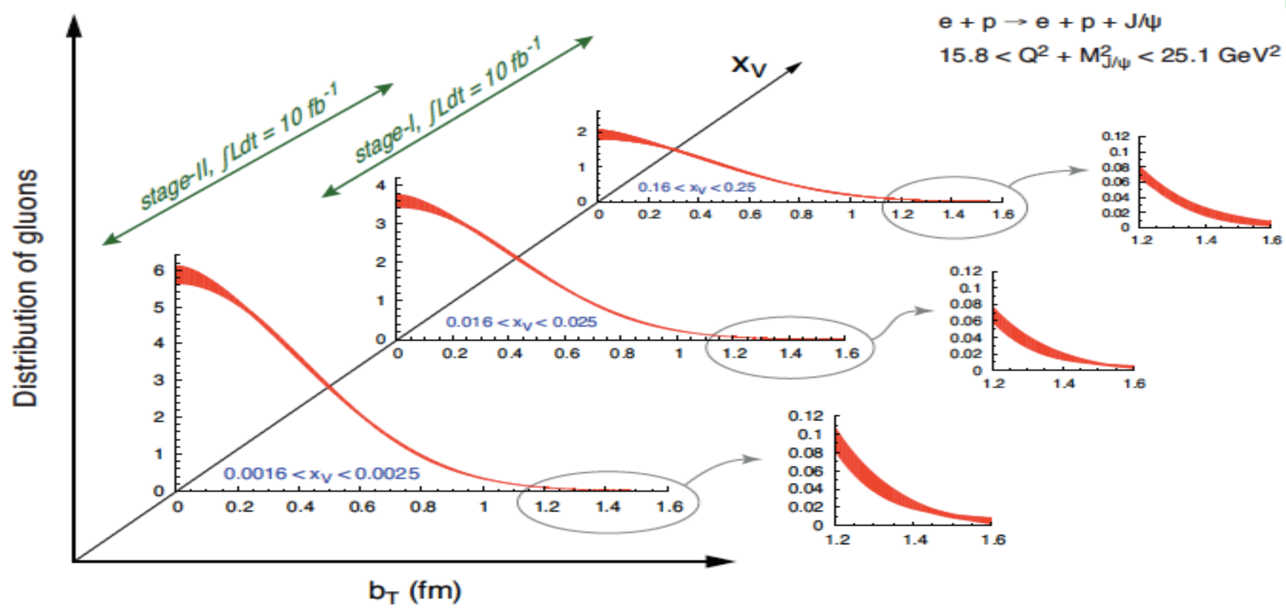
- ✧ **Fourier transform of the t-dep**

➡ **Spatial imaging of glue density**

- ✧ **Resolution ~ 1/Q or $1/M_Q$**



- ❑ **Gluon imaging from simulation:**



Images of gluons from exclusive J/ψ production

Only possible at the EIC

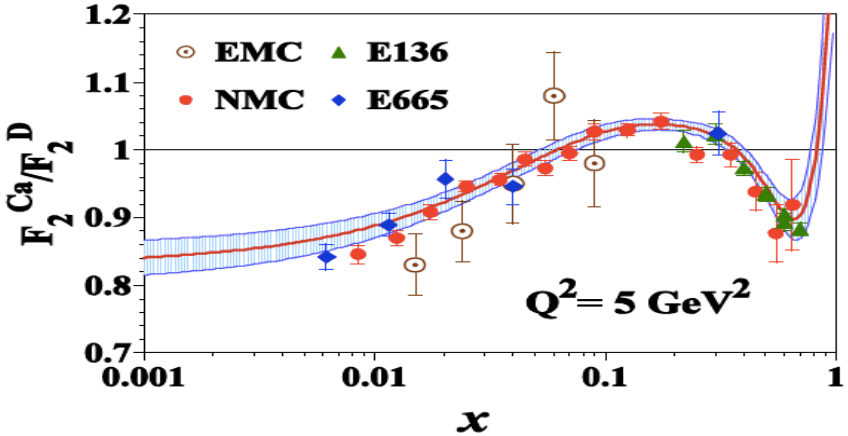
Nucleus, a QCD Laboratory

❑ **EMC discovery:**

Nuclear landscape

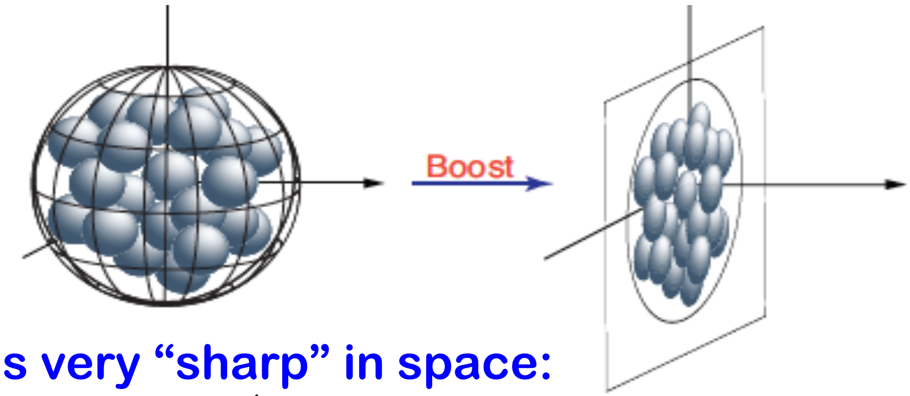
$\neq$ superposition

of nucleon landscape



How would/does a nucleus look if we only saw its quarks and gluons?

❑ **"Snapshot" does not have a "sharp" depth at small x_B**



✧ Hard probe is very "sharp" in space:

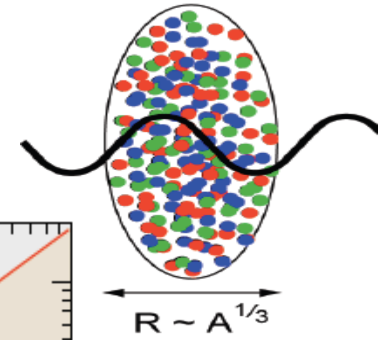
Transverse size - $\frac{1}{Q} \ll 1$ fm , longitudinal size - $\frac{1}{xp} \sim \frac{1}{Q} \ll 1$ fm

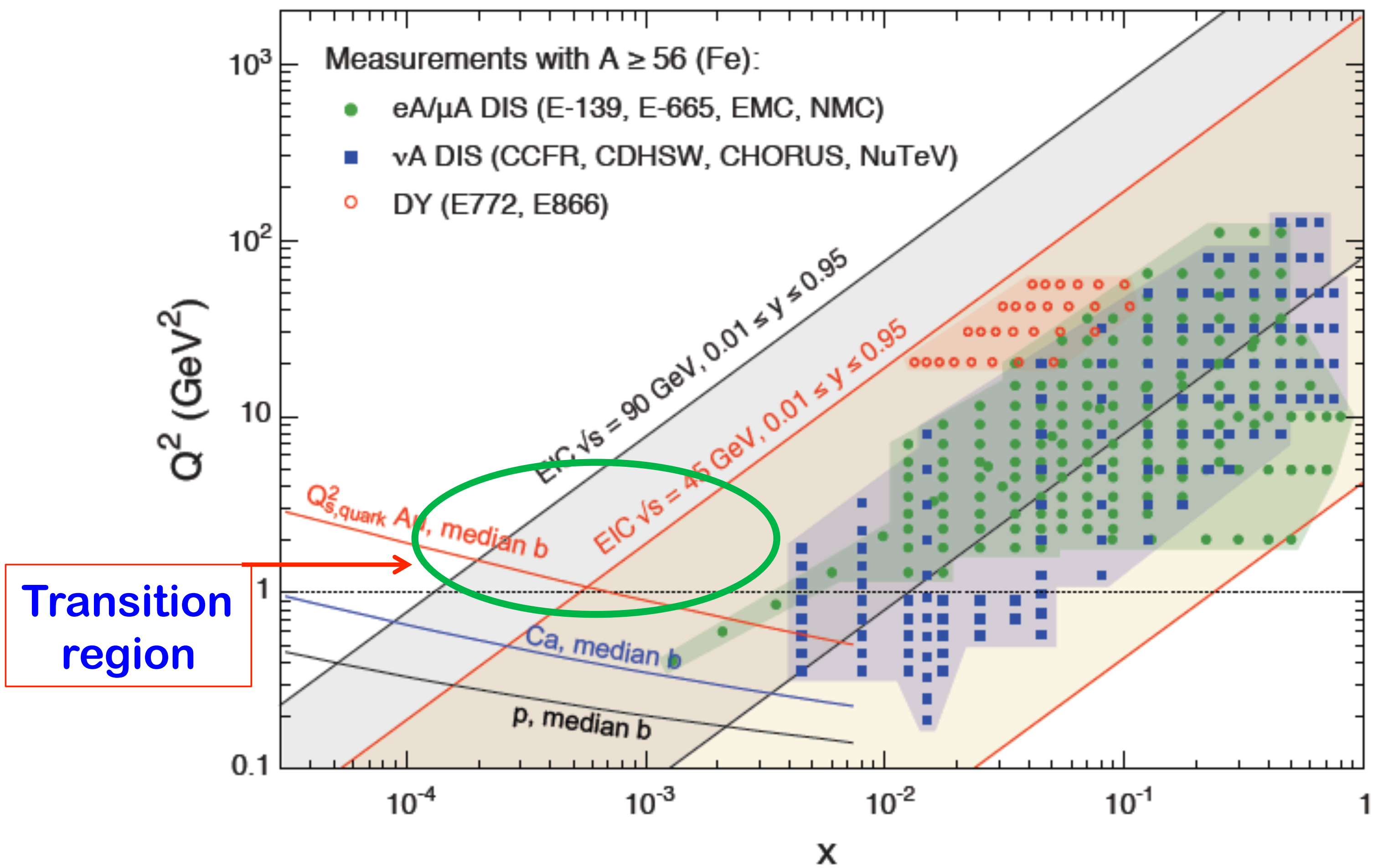
✧ Longitudinal size > Lorentz contracted nucleon:

$\frac{1}{xp} > 2R_A \frac{m}{p}$ or $x \lesssim 0.01$ *Hard probe can "see" gluons from all nucleons at the same impact parameter!*

Reaching the saturation with eA

- Many more soft gluons in nucleus at the same impact parameter: $Q_s^2(eA) \propto Q_s^2(ep)\, A^{1/3}$





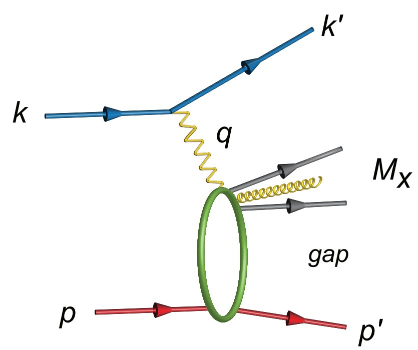
With a gold ion beam: EIC can reach the saturation regime at the stage-I

Saturation/CGC: What to measure?

- **Inclusive events – structure functions, F_2 and F_L:**
  - ✧ **High energy – smaller x, and larger range of Q^2**
  - ✧ **Search for deviation from DGLAP and BFKL**

- **Diffractive cross section:**

$$\sigma_{\rm diff} \propto [g(x,Q^2)]^2$$



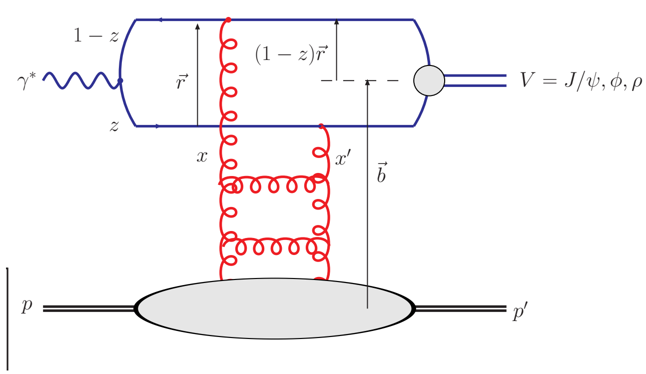
At HERA: ep observed 10-15% / total

If CGC/Saturation – multiple coherent gluons

→ **Diffraction eA expect ~25-30%/total**

Nucleus with 8 MeV/N binding can stay intact at 1 of 4 times when hit by a "TeV" beam!

- **Diffractive vector meson production:**

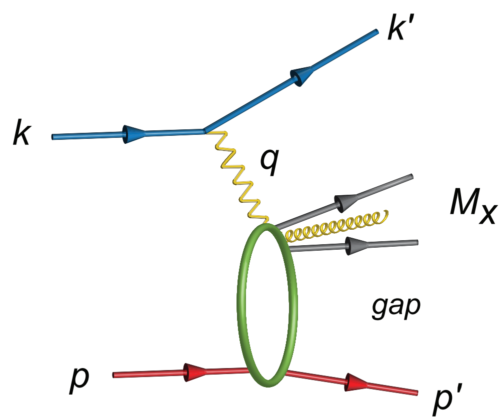


Cross section ratio for eA/ep: J/Y and f

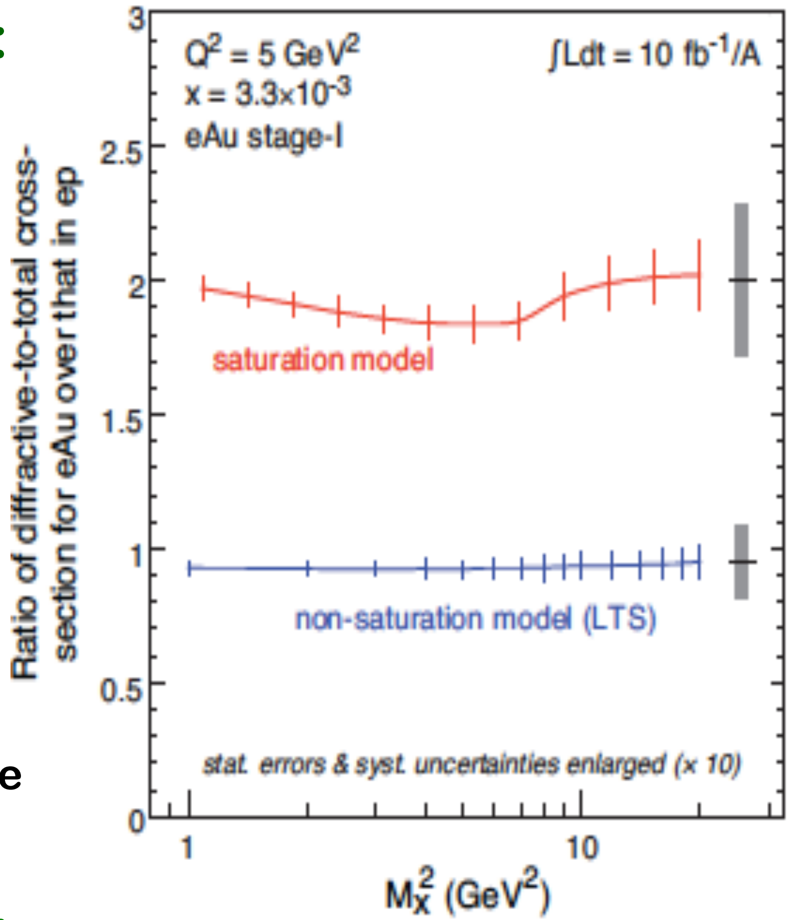
→ **Imaging of gluons in nuclei**

The best signature for gluon saturation

- Hard scattering with a rapidity gap:



Double ratios:
Diffractive over total cross section
eA over ep



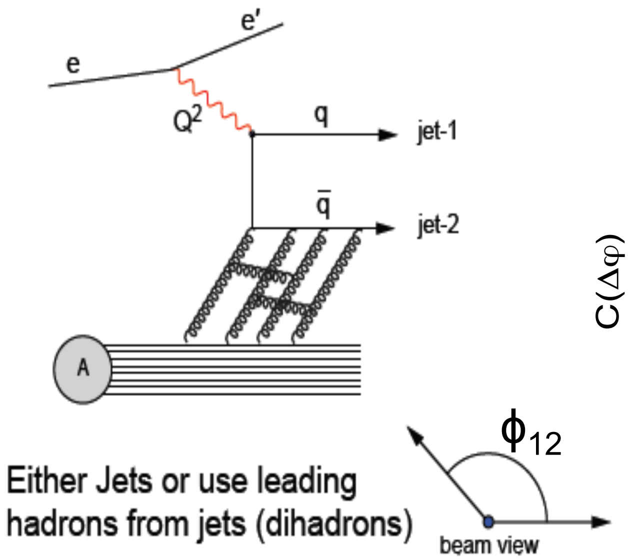
✧ Strong non-linear effect, color singlet exchange
✧ Factorization works in DIS, not in pp, pA, AA

The factor of 2 enhancement is only for eA
(no equivalent in pA!)

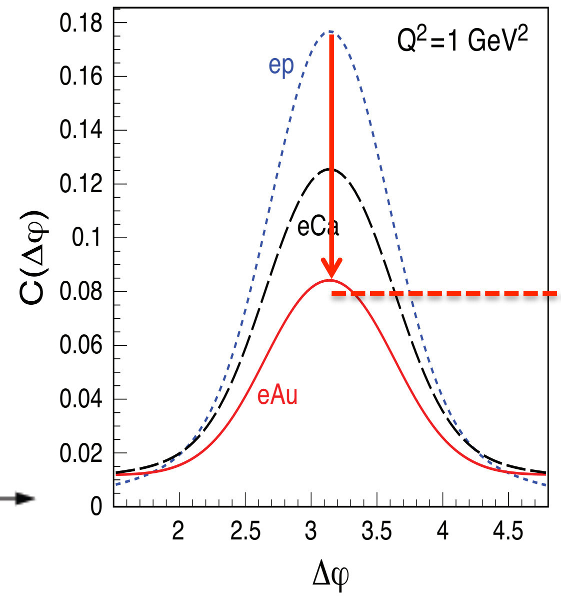
This is a clean and unambiguous signal of saturation physics
already at EIC stage-1

Another clean signature for gluon saturation

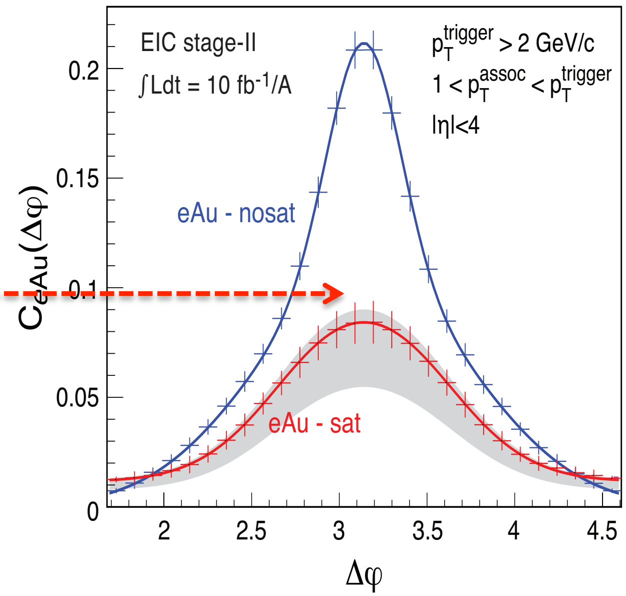
❑ Strong suppression of dihadron correlation in eA:



Theory



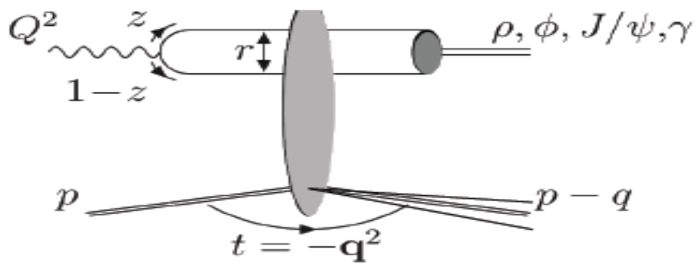
Simulation



- ✧ Never be measured!
- ✧ Directly probe Weizsacker-Williams (saturated) gluon distribution in a large nucleus
- ✧ A factor of 2 suppression of away-side hadron-correlation!
- ✧ No-sat: Pythia + nPDF (EPS09)

Spatial imaging of the glue in a nucleus

❑ Diffractive vector meson (Φ, J/ψ, ..) production:

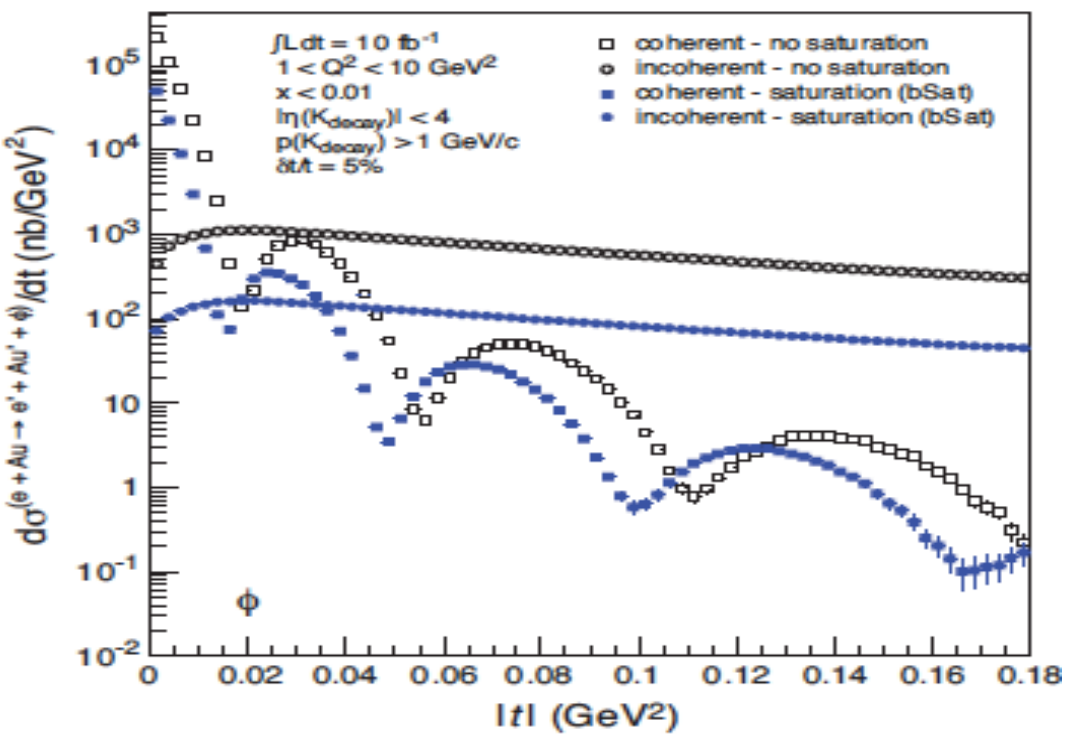


$$\frac{d\sigma}{dx_B dQ^2 dt}$$

✧ Coherent: Nucleus stays intact
✧ Incoherent: Nucleus breaks up

- as a function of t

❑ Φ–production – clean probe for spatial distributions:

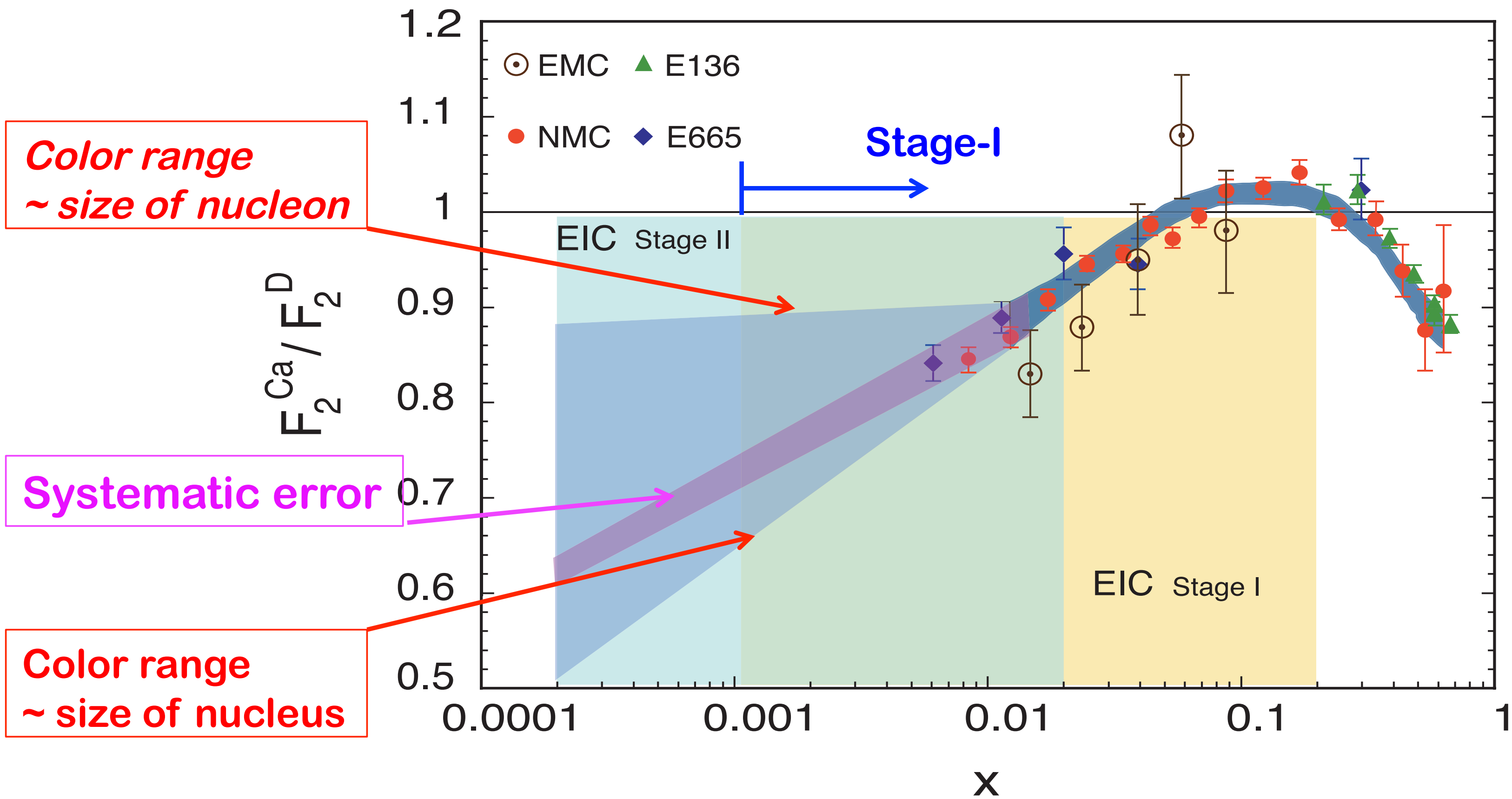


Fourier transform
of the t-dependence

Need EIC's
energy to do this!

Range of color correlation inside a nucleus?

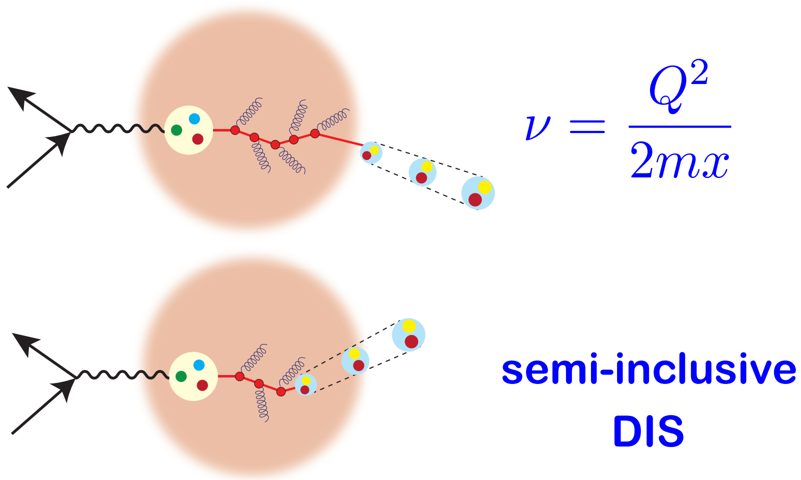
❑ Ratio of DIS F_2 structure functions:



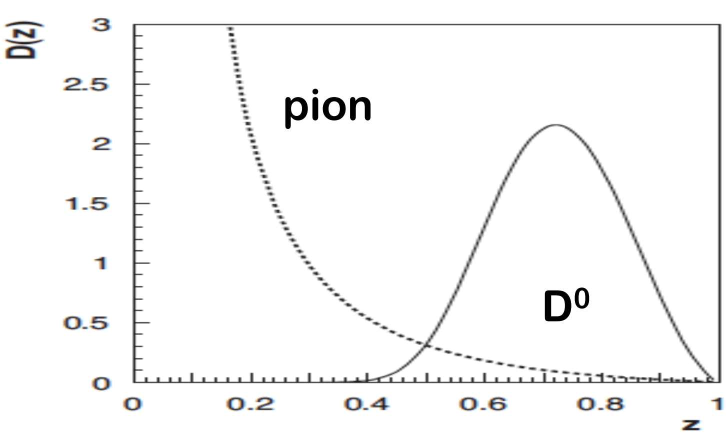
A clean stage-I measurement at EIC (statistical error < systematic error)

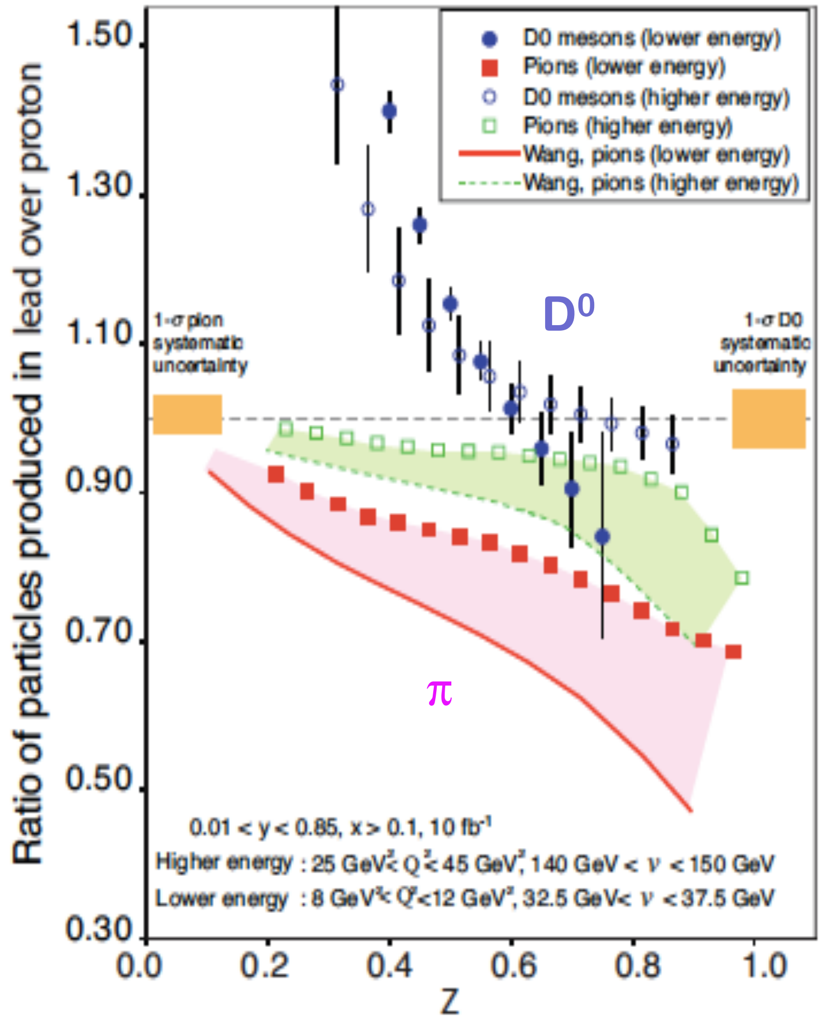
Hadronization – energy loss

- ❑ Unprecedented ν range at EIC:



- ❑ Heavy quark energy loss:
  - Mass dependence of fragmentation

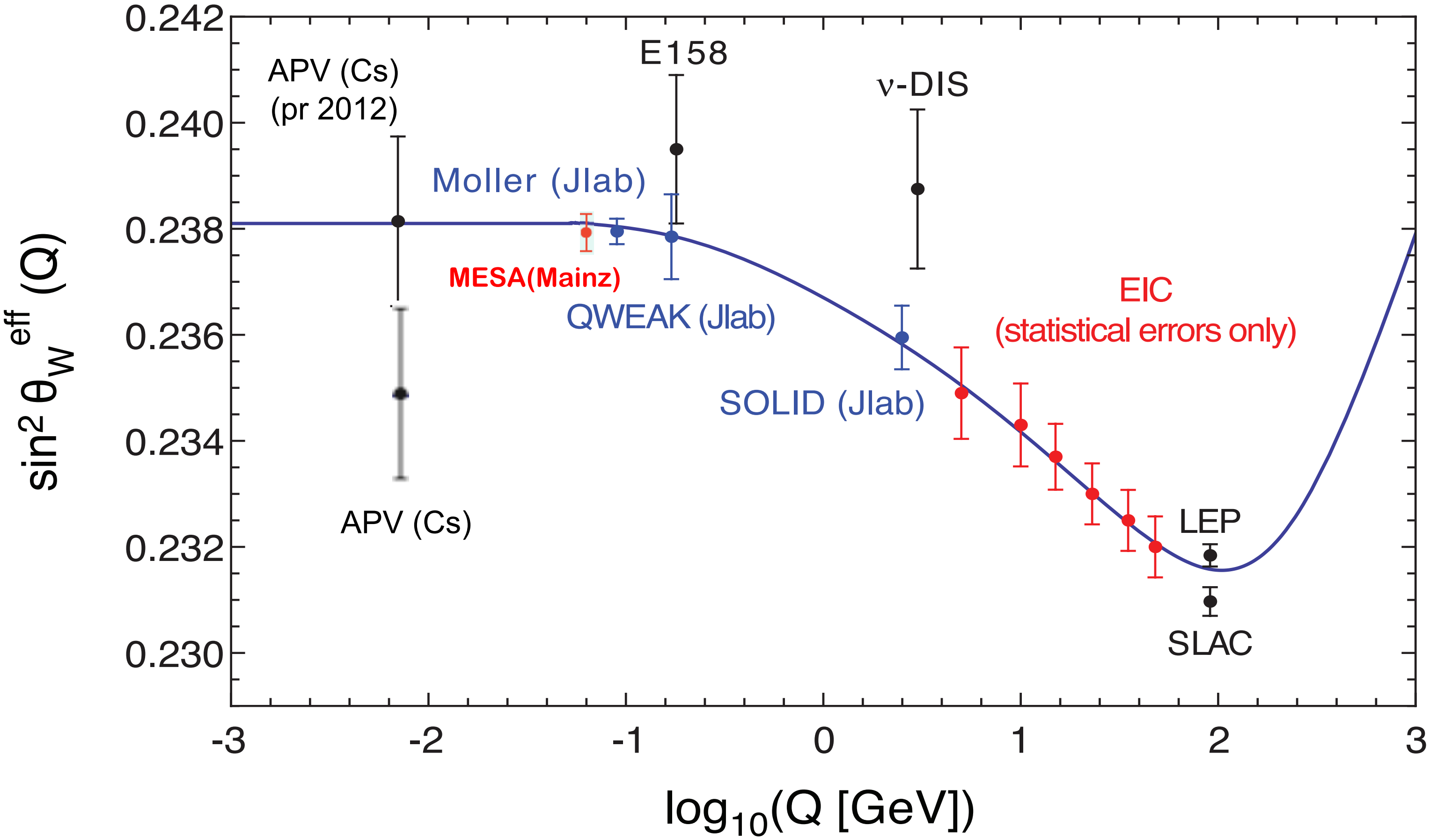




Need the collider energy of EIC and its control on parton kinematics

Electroweak physics at EIC

❑ Running of weak interaction – high luminosity:



- ✧ **Fills in the region that has never been measured**
- ✧ ***Has a real impact on testing the running of weak interaction***

Physics deliverables of the stage-I EIC

- **EIC at the stage-I:**
  - ✧ **Collision energy:** $\sqrt{s} \sim 20\text{–} \sim 100\ \text{GeV}$
  - ✧ **Luminosity:** $10^{33\text{-}34}\ cm^{-2}\ s^{-1}$ (HERA luminosity ~ $5\text{x}10^{31}\ cm^{-2}\ s^{-1}$)
  - ✧ **Polarized proton and various nuclei**
- **Deliverables at the stage-I:**

Processes	What we learn
Inclusive polarized e-p	Sea and gluon helicity contribution to proton spin
Inclusive e-A	Nuclear PDFs: x_B, Q^2, A-dep Range of color correlation
Semi-inclusive e-p	TMDs, Quark-gluon correlation functions Fragmentation functions
Semi-inclusive e-A	Hadronization and color neutralization TMDs of nuclei, Energy loss mechanism
Diffractive e-p	Quark GPDs, and its evolution Spatial imaging of quarks
Diffractive e-A	Unambiguous signal of gluon saturation

Physics opportunities at the stage-II EIC

- The stage-II machine – as a upgrade:
  - ✧ Collision energy: $\sqrt{s} \sim 90 - 170\ \mathrm{GeV}$
  - ✧ Luminosity: $10^{33-34}\ cm^{-2}\ s^{-1}$ (HERA luminosity ~ $5 \times 10^{31}\ cm^{-2}\ s^{-1}$)
  - ✧ Polarized proton and various nuclei
- Key measurements:

Deliverables	Observables	What we learn
Sea/gluon at x ~10^{-4} EW spin S.F.	Inclusive DIS at low-x at high Q^2	Sea/gluon to proton spin flavor separation
Polarized and unpolarized TMDs	Dihadron and heavy flavors	3D momentum images of quarks and gluons
Sea quarks and gluon GPDs	DVCS, Exclusive J/Ψ, ρ, ϕ production	Spatial images of sea and gluon, angular mom. J_q , J_g
Nuclear gluon density in 3D momentum	Dihadron correlation, diffractive x-section	Non-linear QCD evolution Gluon saturation
Color transport coefficient in medium	Semi-inclusive DIS for light/heavy flavors	Color propagation, energy loss, hadronization, color fluctuation
Weak mixing angle	PV asymmetries in DIS	EW symmetry breaking, BSM

International Context

❑ Electron-Ion Colliders in the world:

	HERA@DESY	LHeC@CERN	eRHIC@BNL	MEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	7×10^{-3} → 3×10^{-4}	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [cm^{-2} s^{-1}]	2×10^{31}	10^{33}	10^{33-34}	10^{34-35}	10^{32-33} → 10^{35}	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2022	Post-12 GeV	2019 → 2030	upgrade to FAIR

Possible future

❑ EIC@US [arXiv:1212:1701]:

High energy polarized proton beam

Sits near the "sweet spot" for the transition into the saturation regime

Summary

- EIC is a machine to understand the glue that bind us all

- Is THE brightest sub-femtometer scope to ANSWER fundamental questions in QCD in ways that no other facilities in the world can

- Extends the QCD programs developed at BNL and Jlab in dramatic and fundamentally important ways

- EIC@US would extend (and maintain) US leadership in nuclear science and accelerator/detector technology

- Facilities and experiments:

Rutherford exp't — 1911 — Revolutionized our view of atomic structure

SLAC "Rutherford" — 1968 — Open the gateway to nucleon structure

EIC - future "Rutherford" — 2020? — Revolutionize our view of nucleon structure and the glue!

Thanks!

Acknowledgment

Received inputs from both BNL and JLab communities

Backup slices

EICAC

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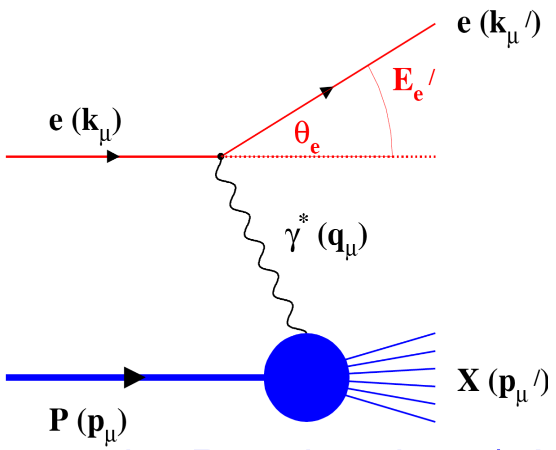
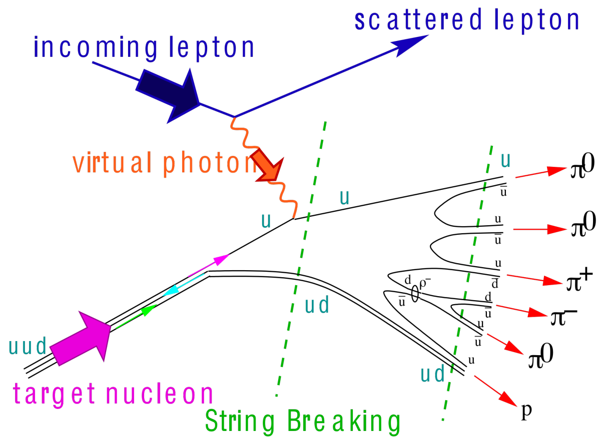
Vladimir Shiltsev (FNAL) shiltsev@fnal.gov

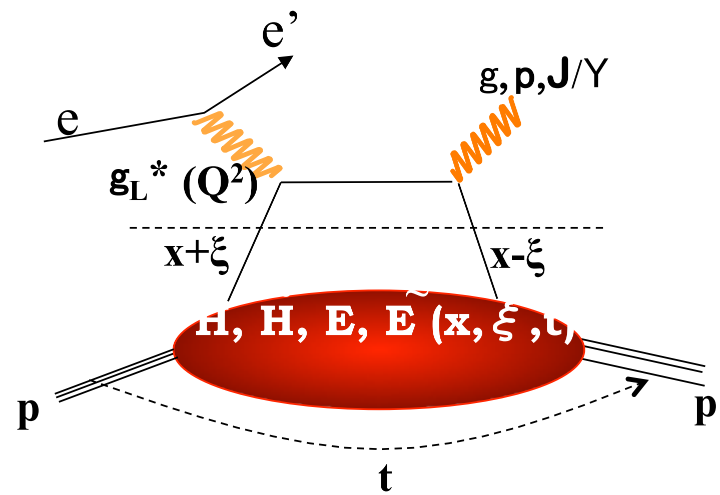
❑ Last meeting:

April 9, 2011 at JLab

What needs to be covered BY THE DETECTOR







Inclusive Reactions in ep/eA:

- Physics: Structure Fcts.: F_2, F_L
- Very good electron id → find scattered lepton
- Momentum/energy and angular resolution of e' critical
- scattered lepton → kinematics

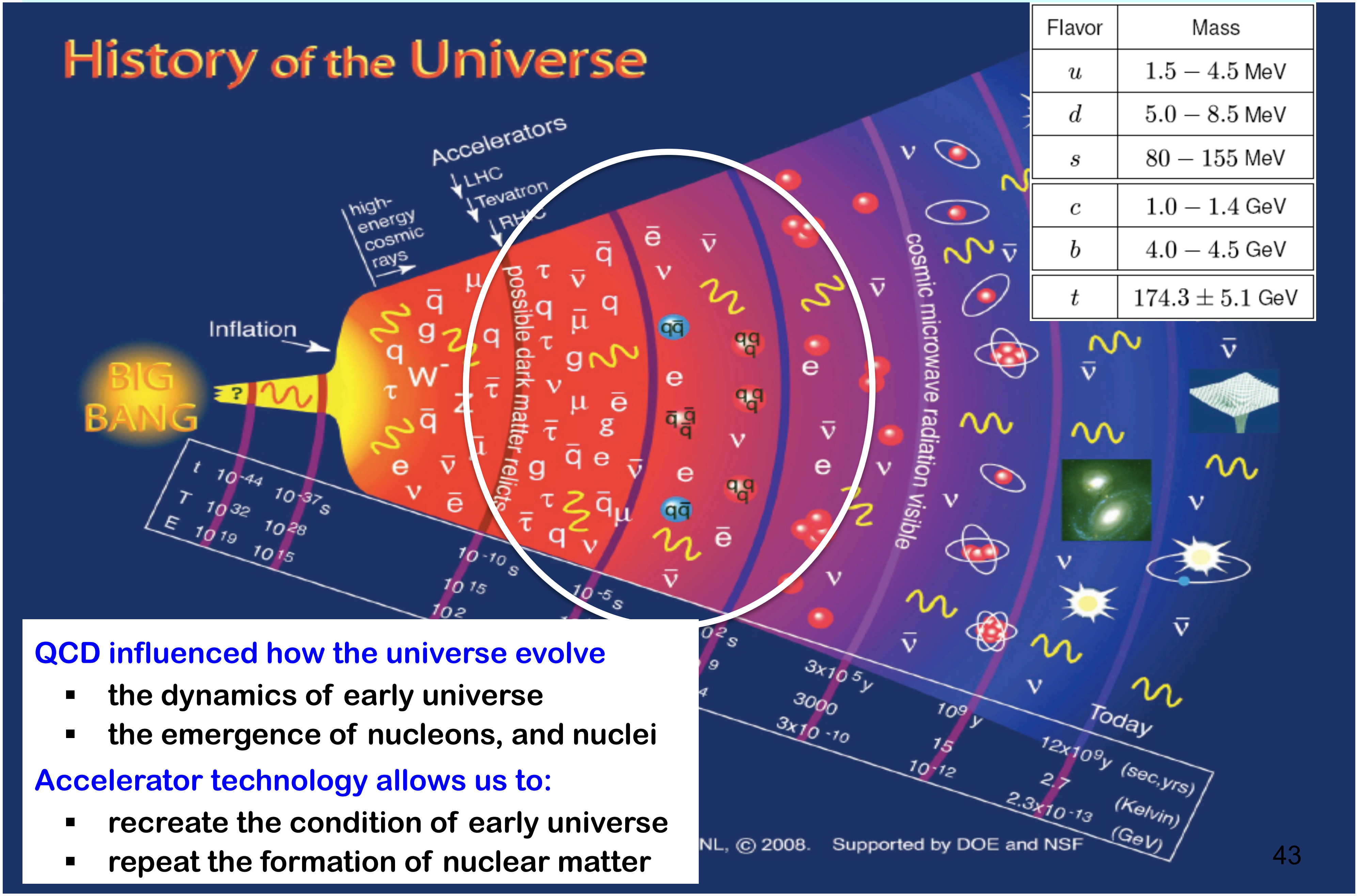
Semi-inclusive Reactions in ep/eA:

- **Physics: TMDs, Helicity PDFs → flavor separation,** dihadron-corr.,…
  → **Kaon asymmetries, cross sections**
- **Excellent particle ID**: p±,K±,p± separation over a wide range in h
- full F-coverage around g*
- **Excellent vertex resolution → Charm, Bottom identification**

Exclusive Reactions in ep/eA:

- Physics: GPDs, proton/nucleus imaging, DVCS, excl. VM/PS prod.
- Exclusivity → large rapidity coverage → rapidity gap events
- ↘ reconstruction of all particles in event
- high resolution in t → Roman pots

Formation of nuclear matter



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

QCD influenced how the universe evolve

- the dynamics of early universe
- the emergence of nucleons, and nuclei

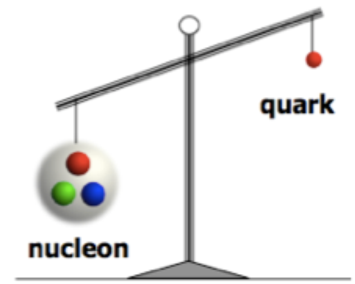
Accelerator technology allows us to:

- recreate the condition of early universe
- repeat the formation of nuclear matter

We tested QCD - low energy

❑ **Hadron mass:**

Higgs mechanism generates
too little quark mass to be relevant!



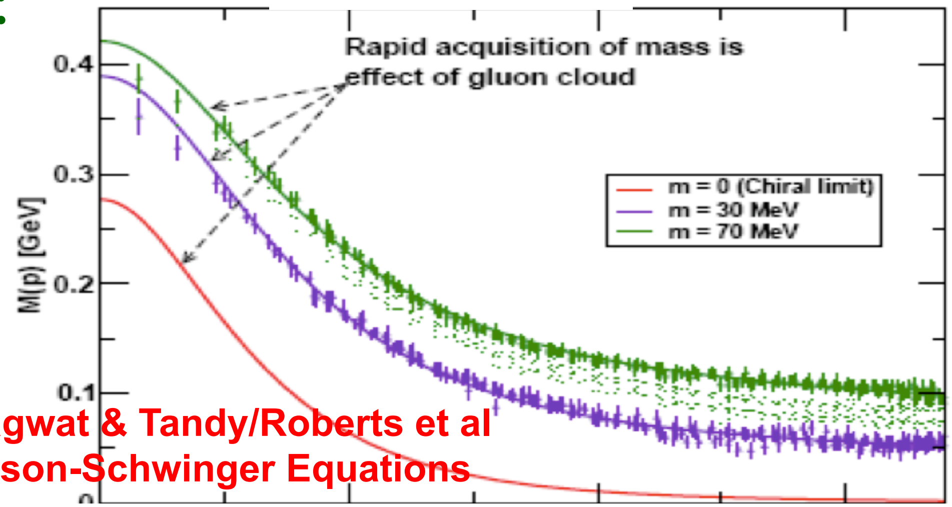
$m_q \sim 10$ MeV

$m_N \sim 1000$ MeV

❑ **QCD and the "dark" gluons:**

✧ "Quark" Mass function:

$$S_F(p) = \frac{\mathcal{F}(p)}{\not{p} - \mathcal{M}(p)}$$



✧ Mystery:

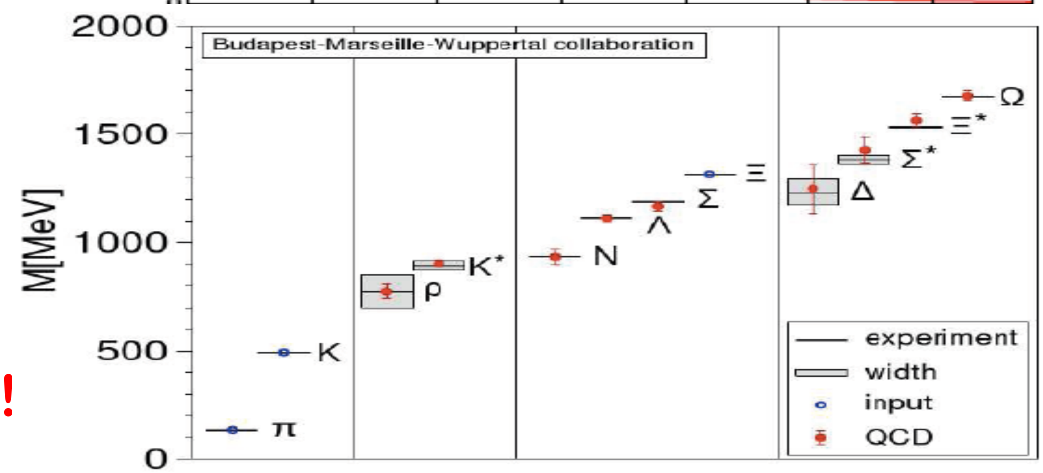
"Mass without mass!"

Bhagwat & Tandy/Roberts et al
Dyson-Schwinger Equations

✧ Hadron mass spectrum:

Lattice QCD calculation

With limited input,
predicted the rest!



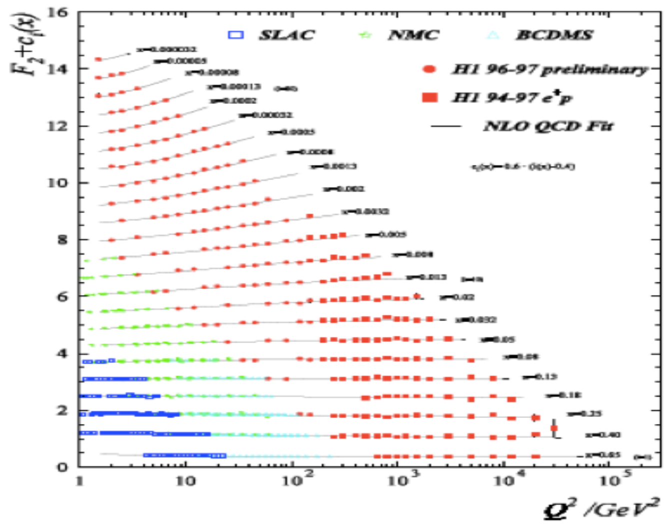
Success of lattice QCD!

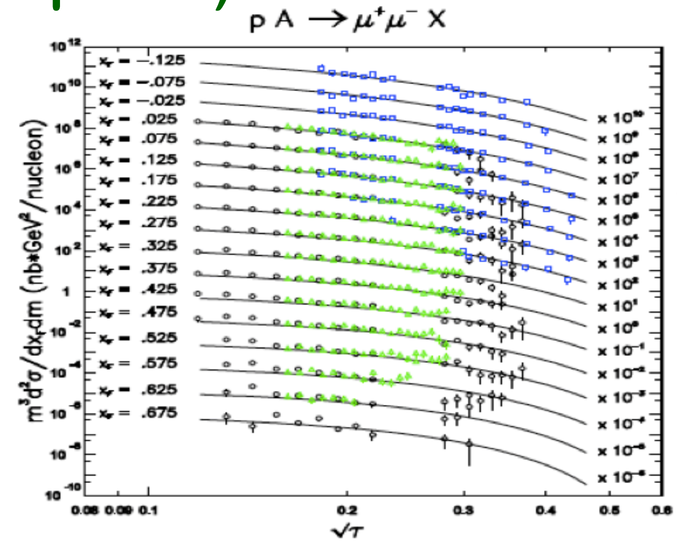
We tested QCD - high energy

❑ From inclusive DIS to Drell-Yan (EM probe):

Probe size

< 1/10 fm

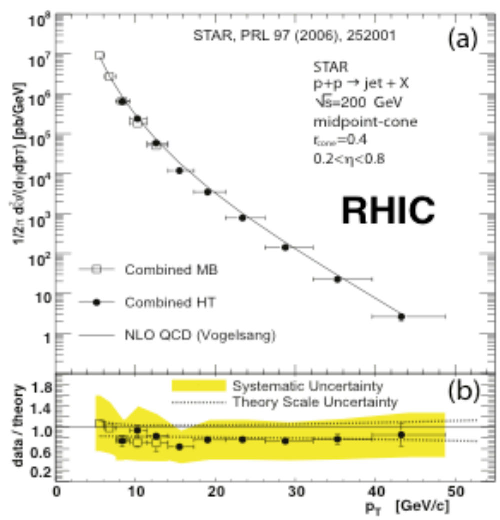


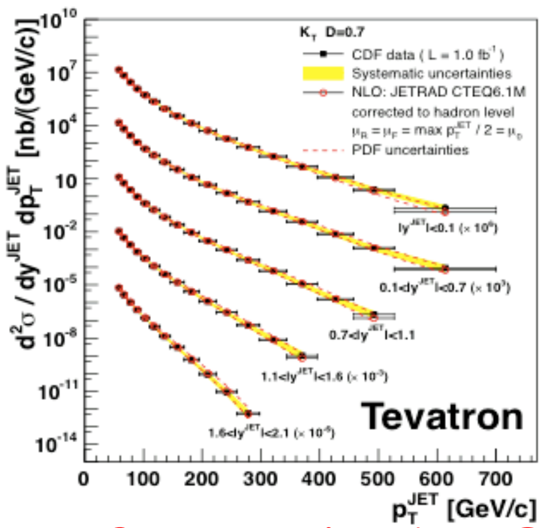


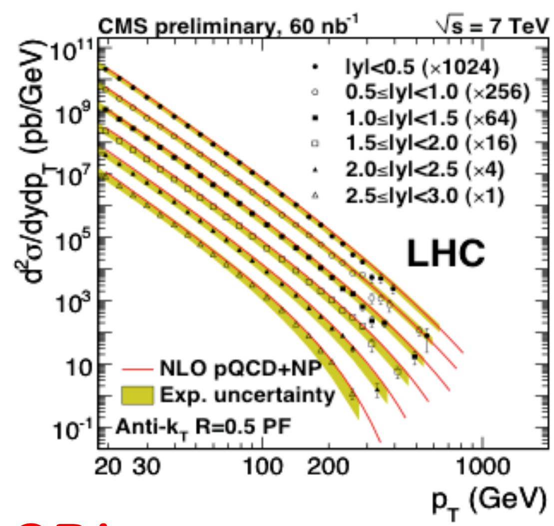
❑ From RHIC to LHC (dominated by gluon fusion):

Probe
as small as

~ 10^{-3} fm



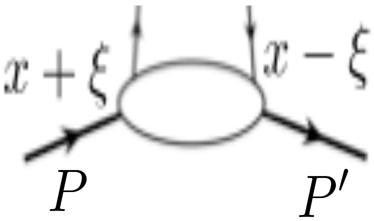




Success of perturbative QCD!

Generalized parton distributions (GPDs)

❑ **Quark:**



$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P'|\bar{\psi}_q(\lambda/2)\frac{\gamma\cdot n}{2P\cdot n}\psi_q(-\lambda/2)|P\rangle$$

$$\equiv H_q(x,\xi,t,\mu^2)\,[\bar{\mathcal{U}}(P')\gamma^\mu\mathcal{U}(P)]\,\frac{n_\mu}{2P\cdot n}$$

$$+\; E_q(x,\xi,t,\mu^2)\left[\bar{\mathcal{U}}(P')\frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M}\mathcal{U}(P)\right]\frac{n_\mu}{2P\cdot n}$$

with $\xi = (P'-P)\cdot n/2 \;\text{ and }\; t = (P'-P)^2 \;\Rightarrow\; -\Delta_\perp^2 \;\text{ if }\; \xi\to 0$

$\tilde{H}_q(x,\xi,t,Q)$, $\tilde{E}_q(x,\xi,t,Q)$ **Different quark spin projection**

❑ **Total quark's orbital contribution to proton's spin:** Ji, PRL78, 1997

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)]$$

$$= \frac{1}{2}\Delta q + L_q$$

❑ **Connection to normal quark distribution:**

$H_q(x,0,0,\mu^2) = q(x,\mu^2)$ **The limit when** $\xi\to 0$

Lattice calculation on parton orbital motion

Negele et al

- Moments of GPDs on lattice:

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

- Ji's relation:

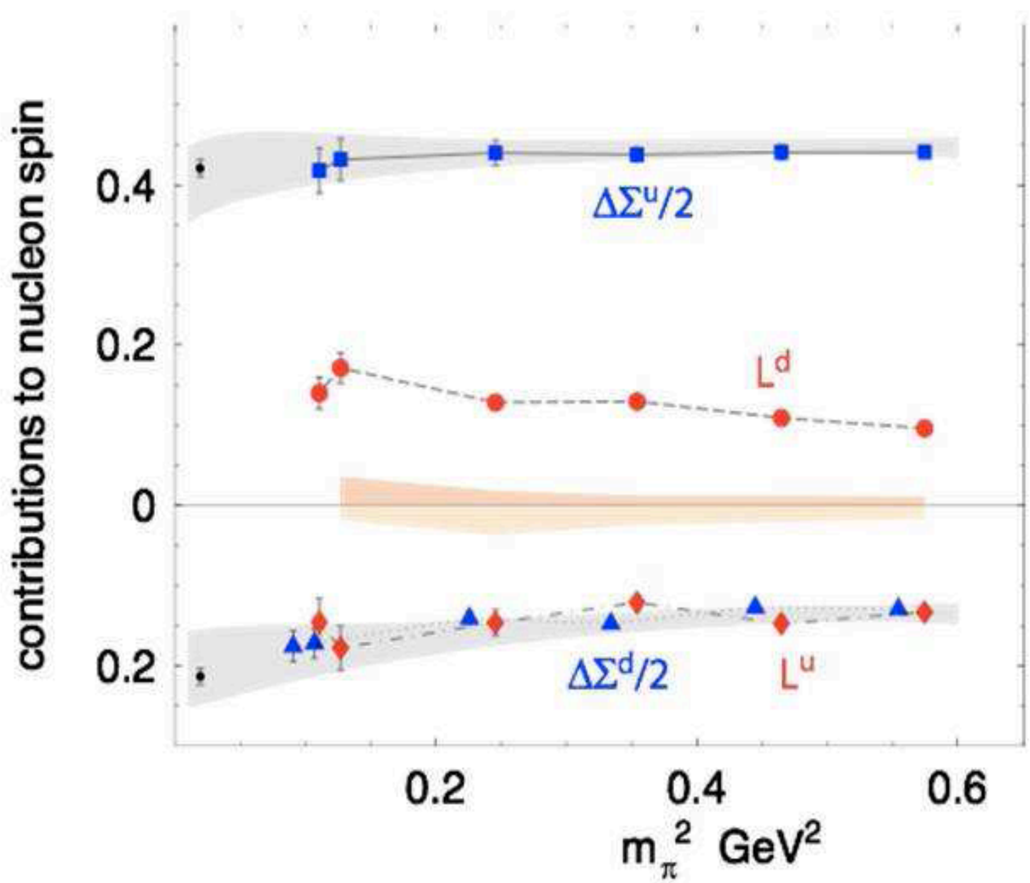
$$L_q^z = J_q^z - \frac{1}{2}\Delta q$$

- Both L_u and L_d large:

But, $L_u + L_d \sim 0$

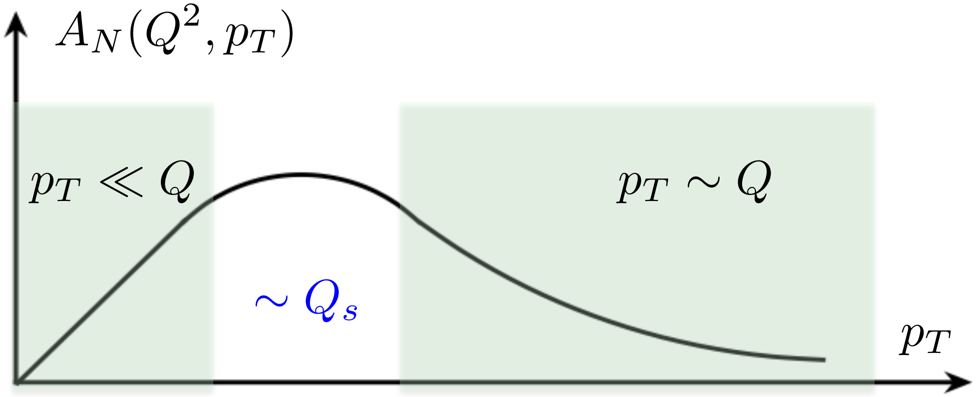
- Spin from the gluon?

EIC is an ideal place
to measure gluon GPDs
From QCD evolution and
diffractive J/ψ



Transition from low p_T to high p_T

❑ **TMD factorization to collinear factorization:**



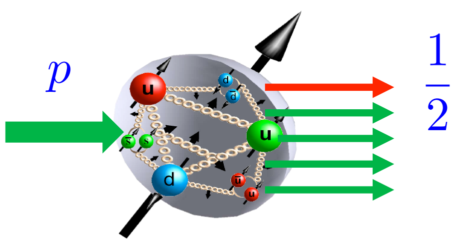
TMD **Collinear Factorization**

Two factorization are consistent in the overlap region where

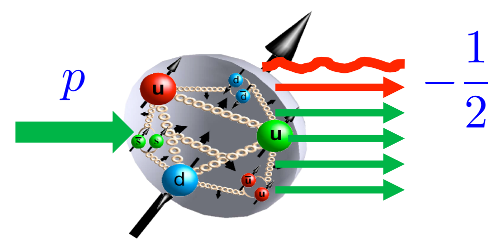
$$\Lambda_{\rm QCD} \ll p_T \ll Q$$

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

Single quark state **quark-gluon composite state**

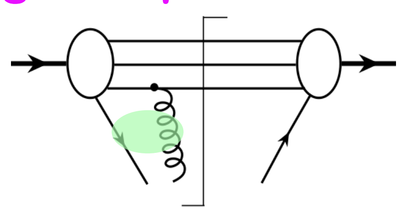


interference with (Spin flip)



➡ **Non-probabilistic quark-gluon quantum correlation – color Lorentz force:**

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

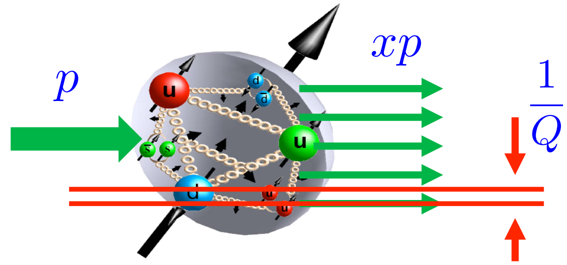


Complication with hadronic machine!

What and why EIC can do and do better?

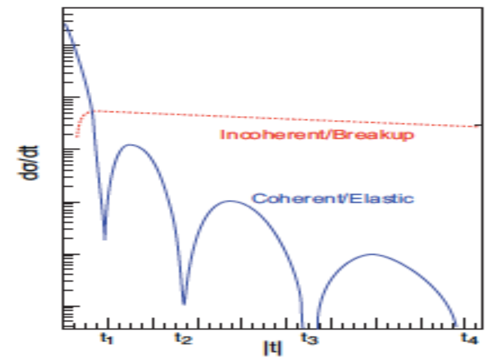
❑ Higher energy + collider:

Semi-inclusive scattering - probing
the confined motion of quarks and gluons
– 3D momentum distributions/images



❑ Higher luminosity:

Diffractive scattering - CAT scan the proton/nucleus
– 1+2D spatial imaging



❑ Polarization:

$$\frac{\sigma(s) - \sigma(-s)}{\sigma(s) + \sigma(-s)}$$

Suppress probability – enhance quantum interference

❑ Nucleus, a QCD Laboratory:

✧ More soft gluons – Lab for exploring non-linear gluon dynamics

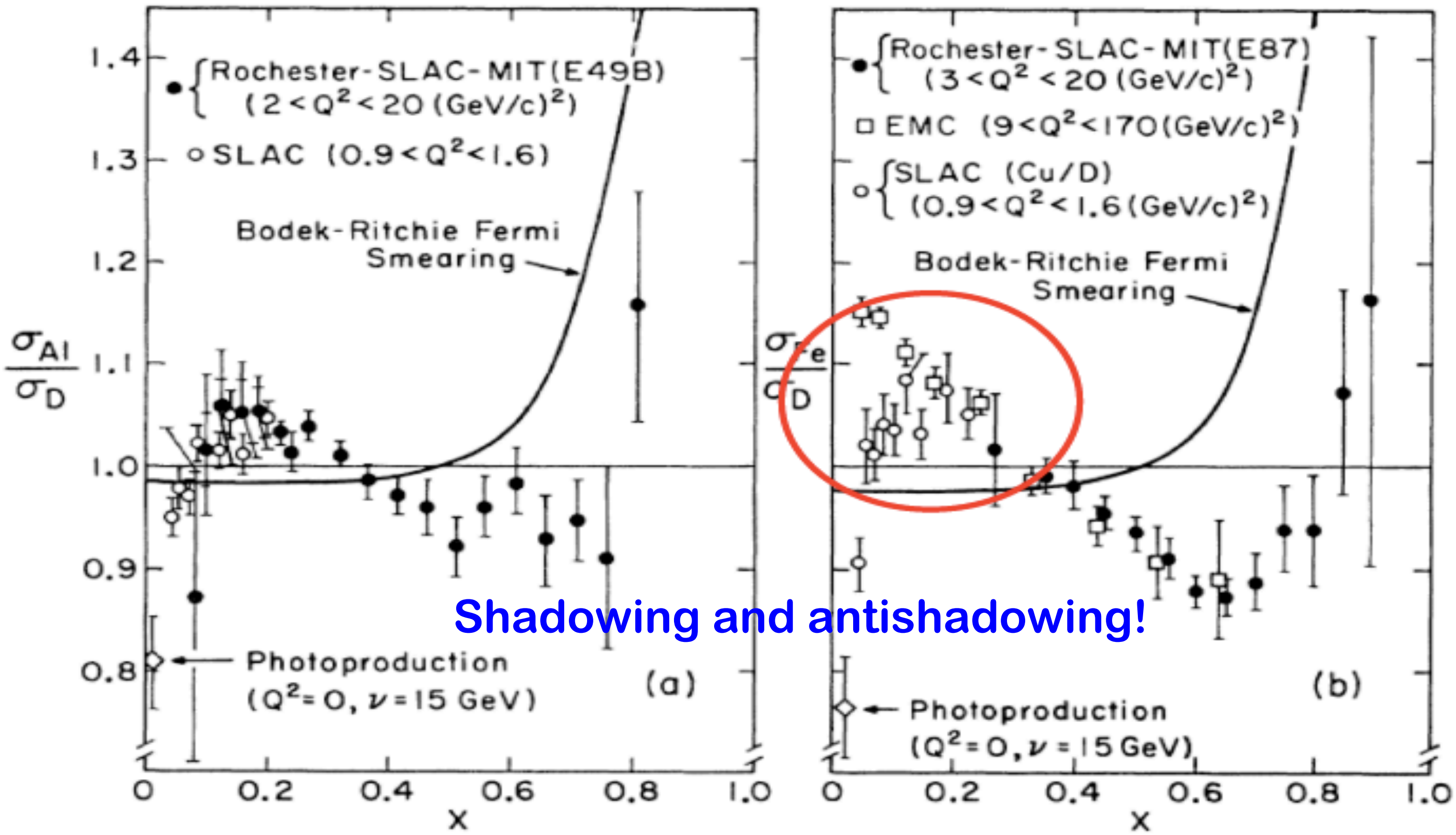
✧ Condensed color matter – Lab for QCD tomography

✧ Nuclear landscape – color confinement and quantum fluctuation

How would/does a nucleus look if we only saw its quarks and gluons?

Nucleus in terms of quarks and gluons?

- ❑ Ratio of F_2 structure functions – large momentum transfer:



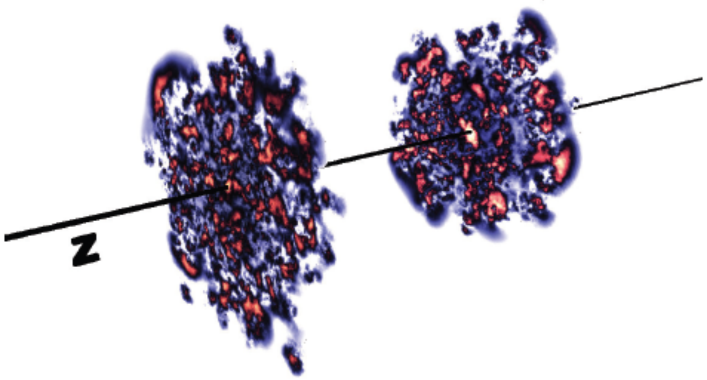
Nucleus $\neq$ a simple sum of nucleons with Fermi motion?

How would/does a nucleus look if we only saw its quarks and gluons?

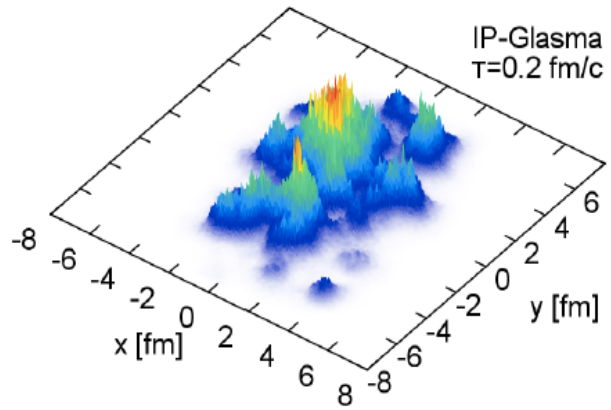
(Crystal(s) of nuclei and electrons)

Color fluctuation and QGP properties?

- ❑ Initial-state color fluctuation:



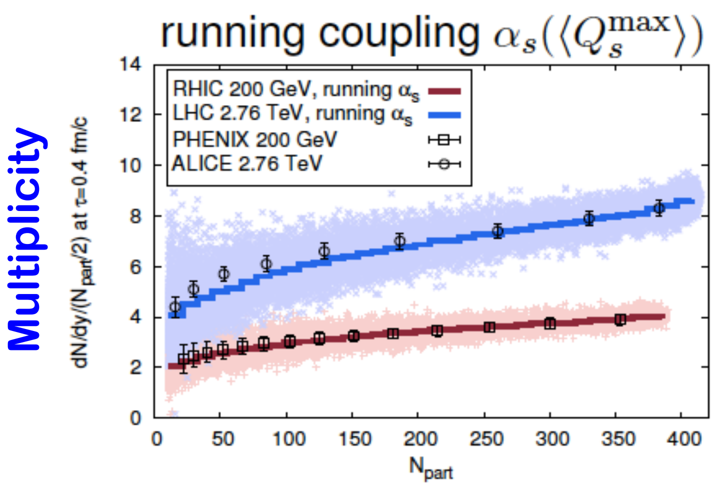
Gluon fields before collision at the LHC

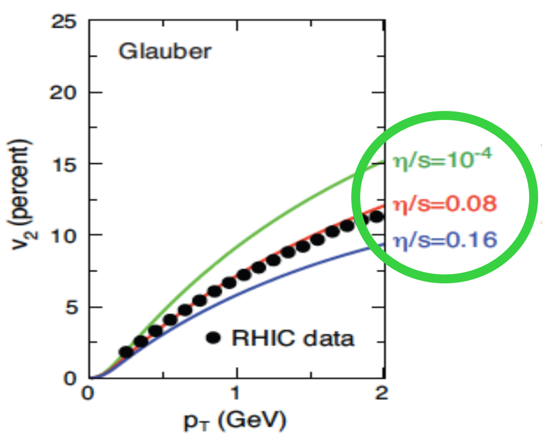


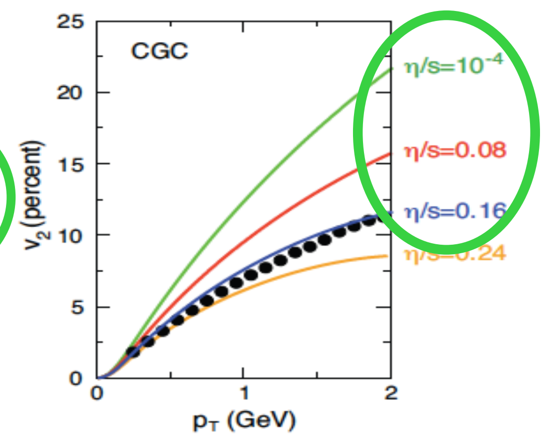
Energy density - CGC

- ❑ "Plus" viscous relativistic hydro:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n 2\, v_n\, \cos(n\tilde{\phi})\right)$$



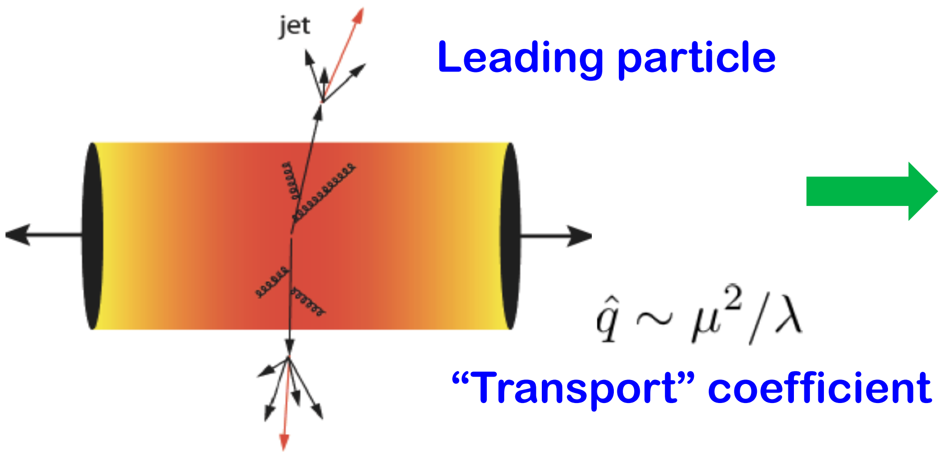


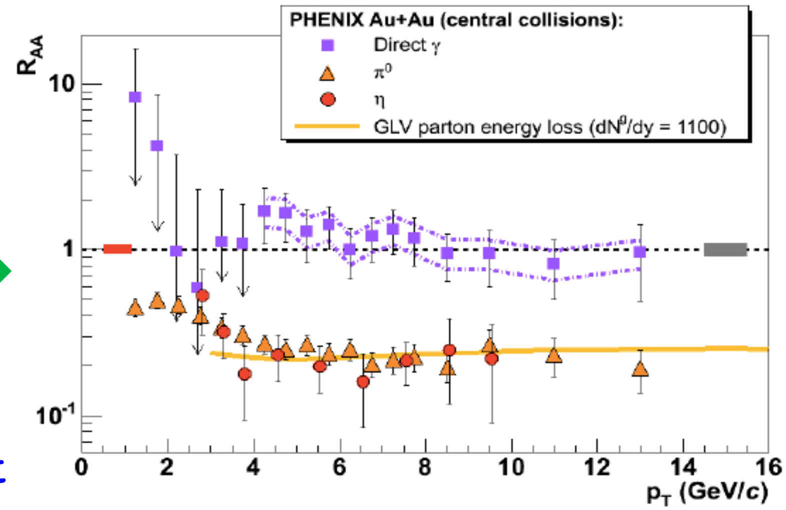


How can we measure such initial-condition independently?

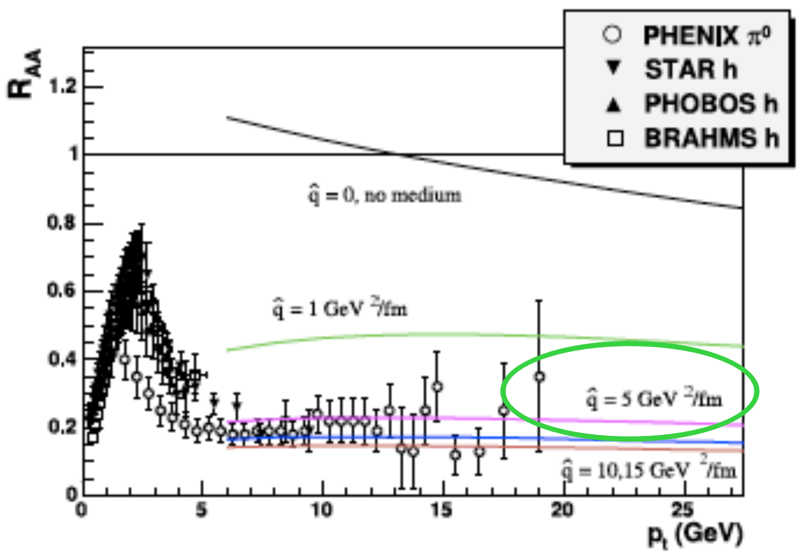
Color propagation and tomography?

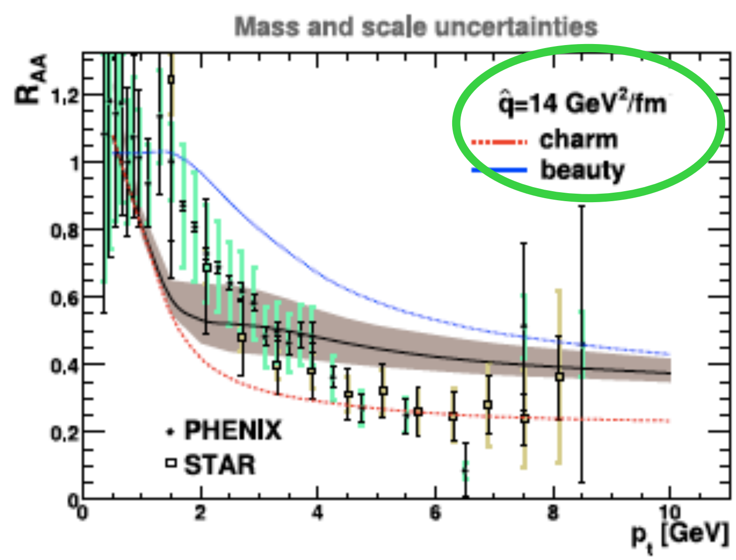
❑ Jet quenching – QGP property:





❑ Why do heavy quarks lose as much energy as the light quarks?



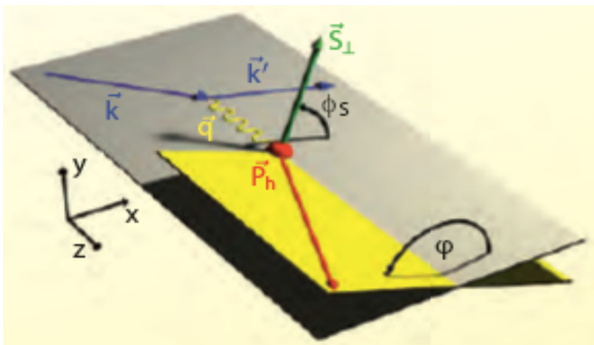


Independent test of energy loss mechanism, formation of hadrons?

Azimuthal asymmetry - fluctuation

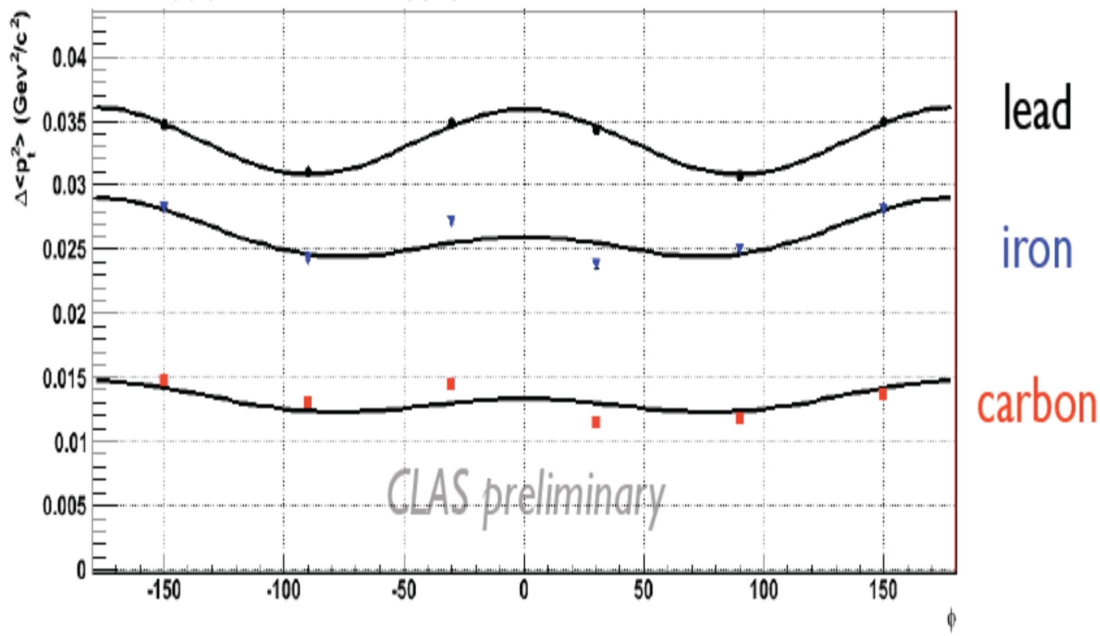
- **Preliminary low energy data:**

Hicks, KEK-JPAC2013



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

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



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

- **Classical expectation:**

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

- **Surprise:**

Quantum effect in transverse momentum broadening – fluctuation!

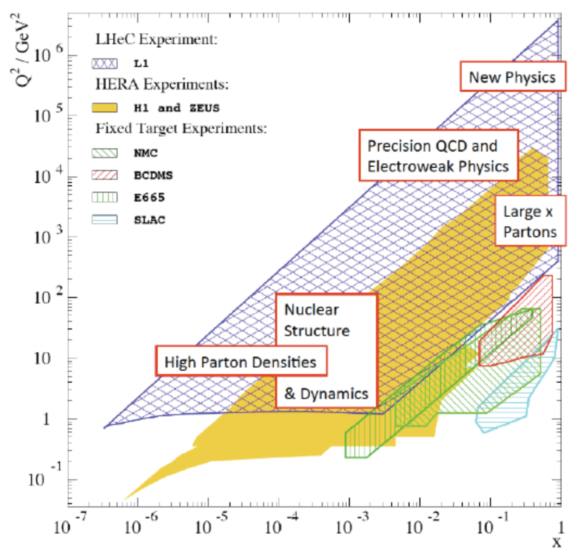
Competitions?

❑ **EIC@China** [http://qcd2013.csp.escience.cn/dct/page/65560]:

Energy: **3 GeV electron + 12 GeV proton**
Luminosity: **10^{32-33} cm^{-2} s^{-1}**

Sit between JLab12 and COMPASS
Physics goals are complementary to US-EIC

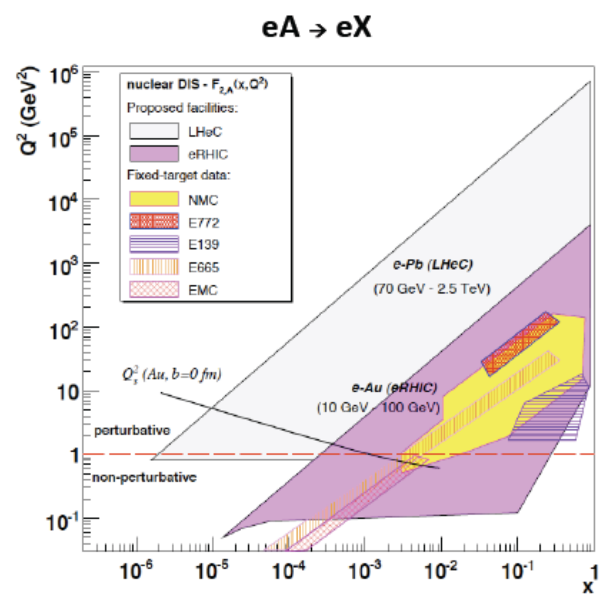
❑ **LHeC@CERN** [arXiv:1211:4831]:



Proton structure & QCD
Small x physics
eP & eA

Electron-Quark Systems BSM: at 1 TeV scale

Search for new EW physics: RH-W's, Contact Interactions



Did not make the recent European's priority list