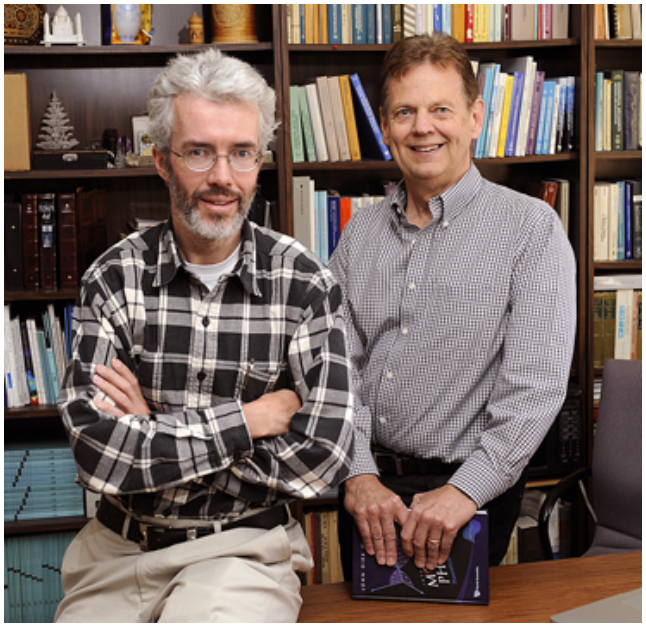
"SHOCKING REALITY"

James is 70!

Really? I do not believe it!

Everyone, older and younger,
whom I talked to in last a few months about this conference
in honor of James' 70th birthday,
cannot believe that James is 70 now



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Well,

Calendar rolls, James is 70!

LET'S CELEBRATE!

LET'S CELEBRATE

The Nucleus:
A Laboratory for QCD

Jianwei Qiu

Brookhaven National Laboratory

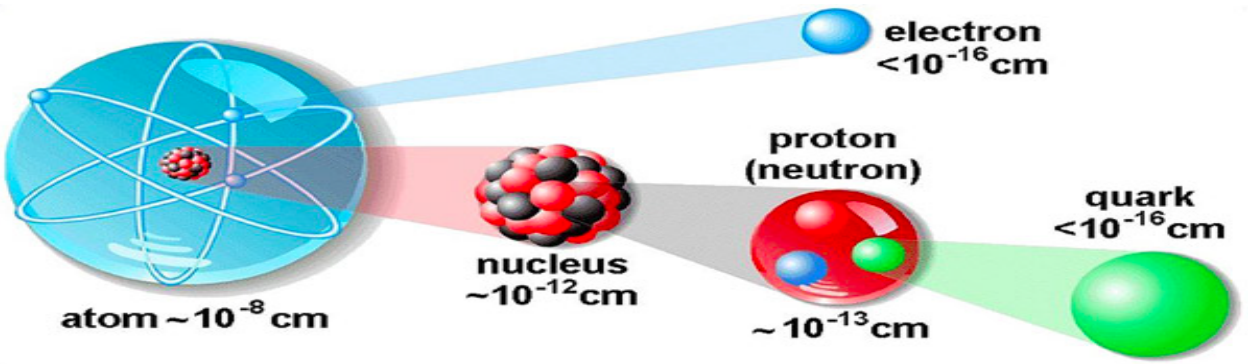
Much of the physics presented here and more can be found in EIC White Paper (arXiv:1212:1701)

International Conference on Nuclear Theory in the Supercomputing Era – 2013

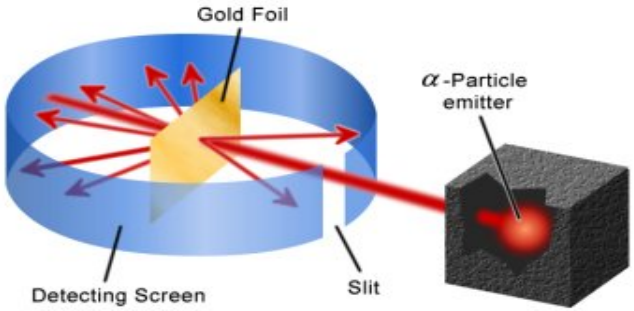
Iowa State University, Ames, Iowa, May 13 – 17, 2013

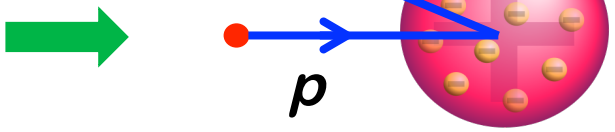
The Nucleus

- The core of all visible matter:

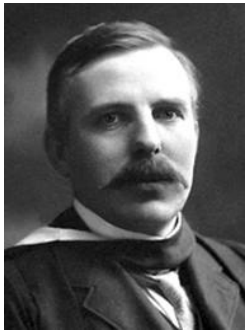


- Discovered over 100 years ago (1911):





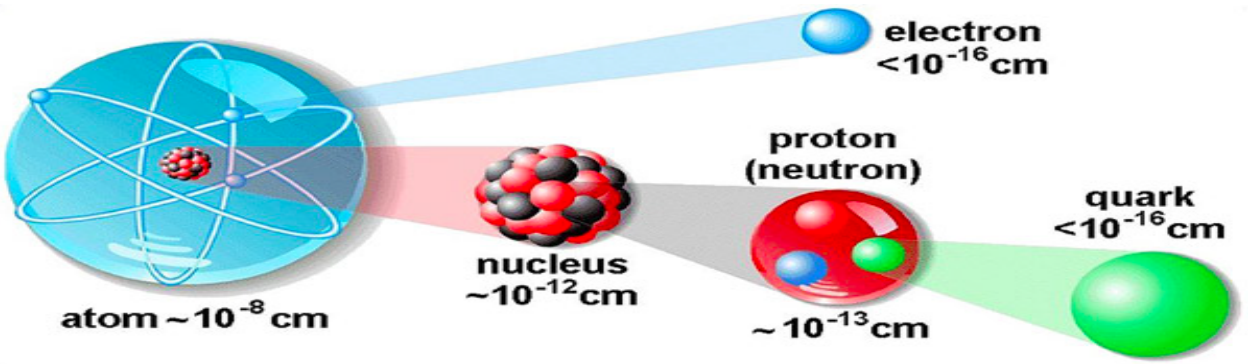
Large angle events!



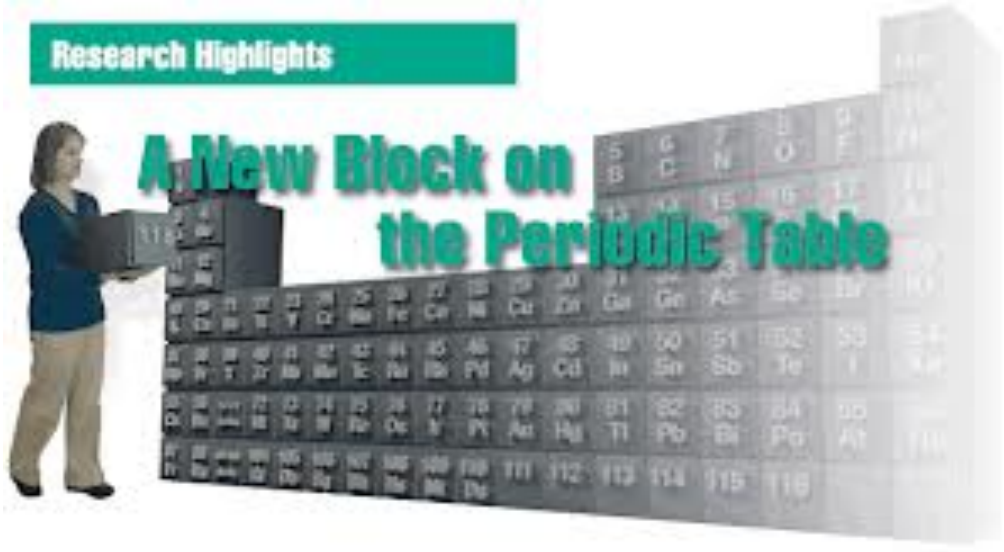
- ✧ Rutherford's experiment
- ✧ Momentum transfer square: $(p\text{-}p')^2 < 0$, large!
- ✧ Hadron-atom Deep Inelastic Scattering (DIS)

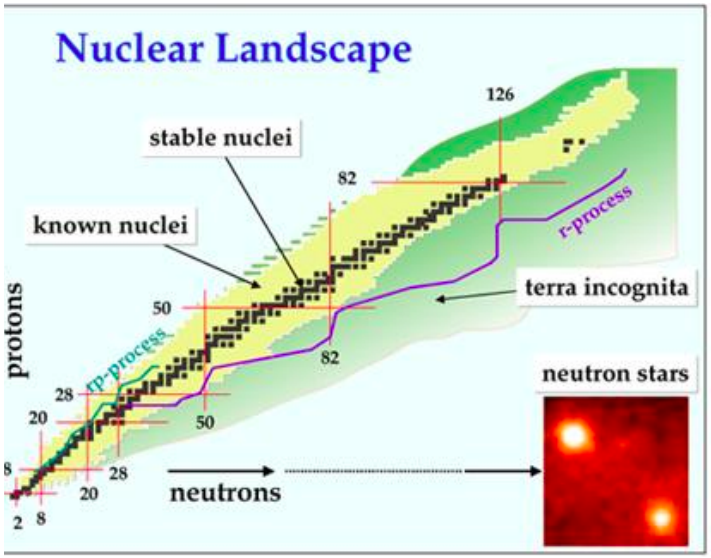
The Nucleus

- The core of all visible matter:



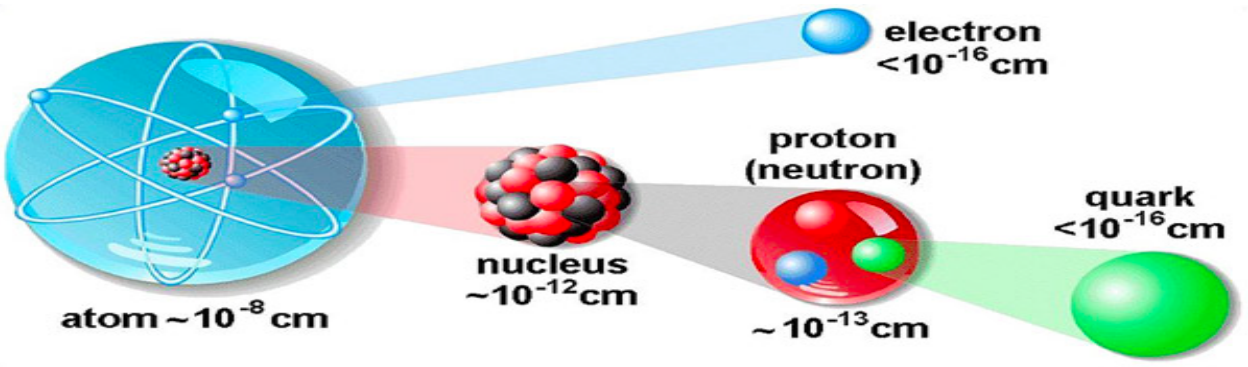
- Nucleus is a "molecule" of nucleons:



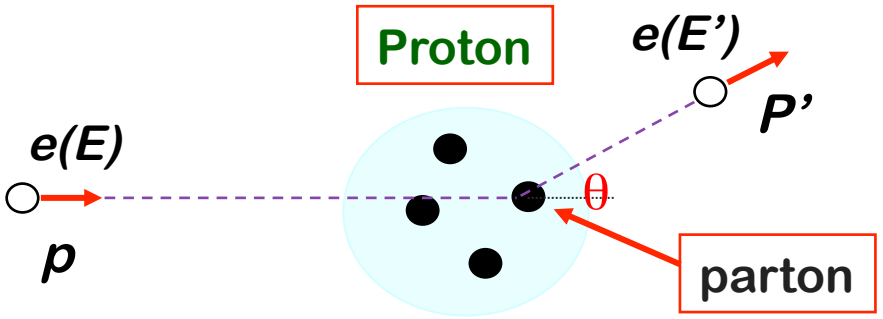


The Nucleus

❑ The core of all visible matter:



❑ Nucleon is not elementary – SLAC's "Rutherford" exp't (1968):



✧ Localized probe:

$$Q^2 = -(p - p')^2 \gg 1 \text{ fm}^{-2}$$

$$\Rightarrow \quad \frac{1}{Q} \ll 1 \text{ fm}$$

✧ Two variables:

$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$x_B = \frac{Q^2}{2m_N \nu}$$

$$\nu = E - E'$$

Electron-proton deep inelastic scattering (DIS)

The discovery of QCD (1972)

Quantum Chromodynamics (QCD)

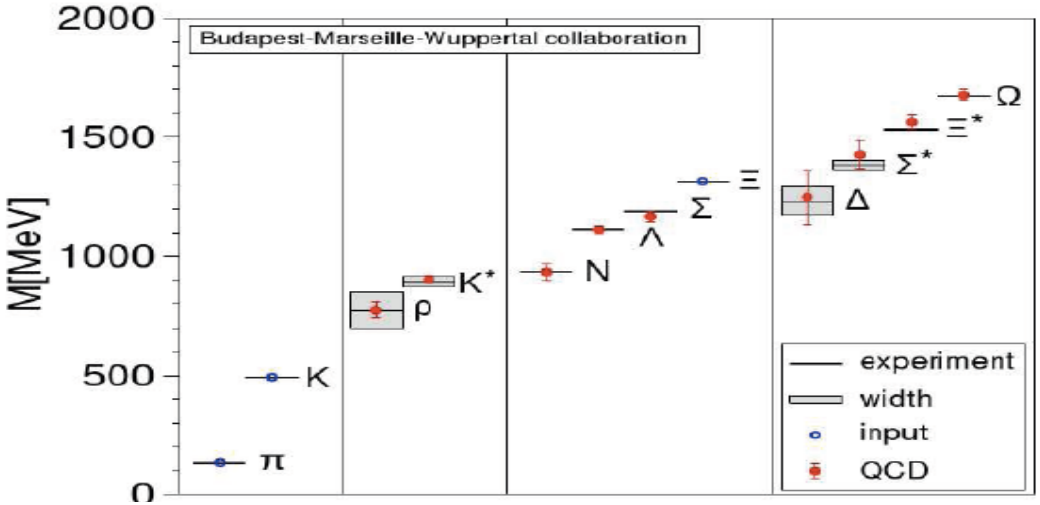
- **@low energy:**

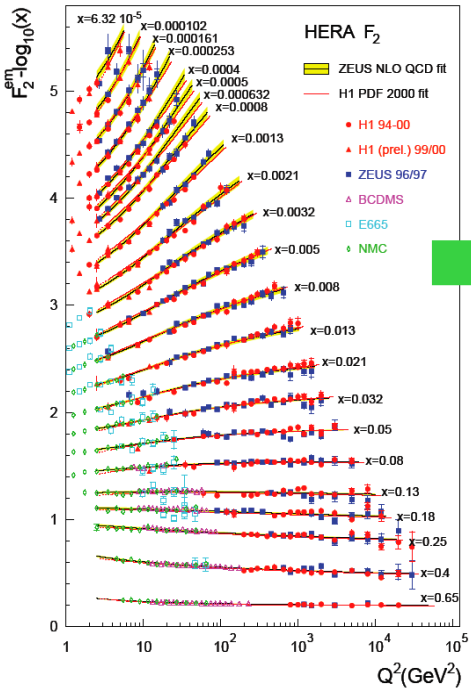
  Hadron mass spectrum from lattice QCD

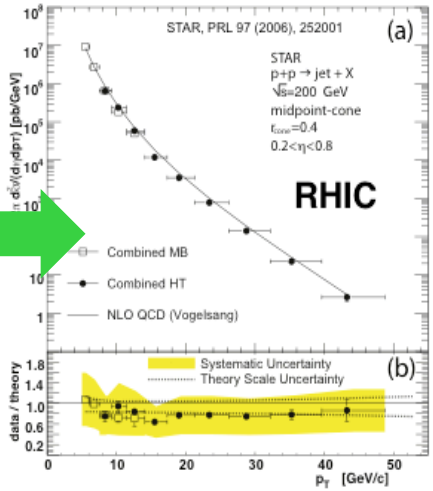
- **@high energy:**

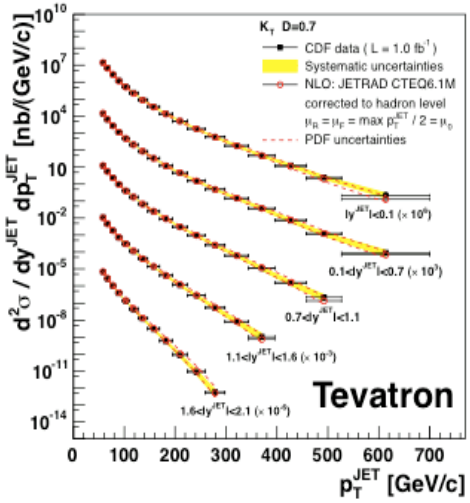
  Asymptotic freedom + perturbative QCD

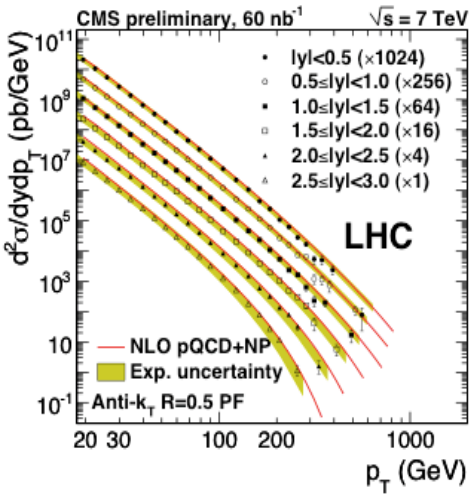
  Sharp probes (< 1/10 fm)









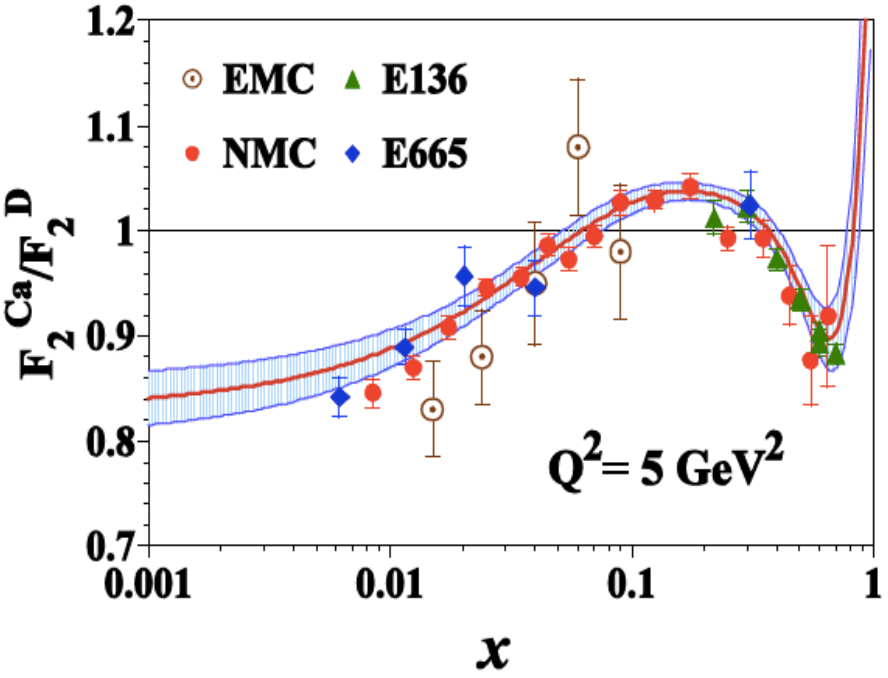


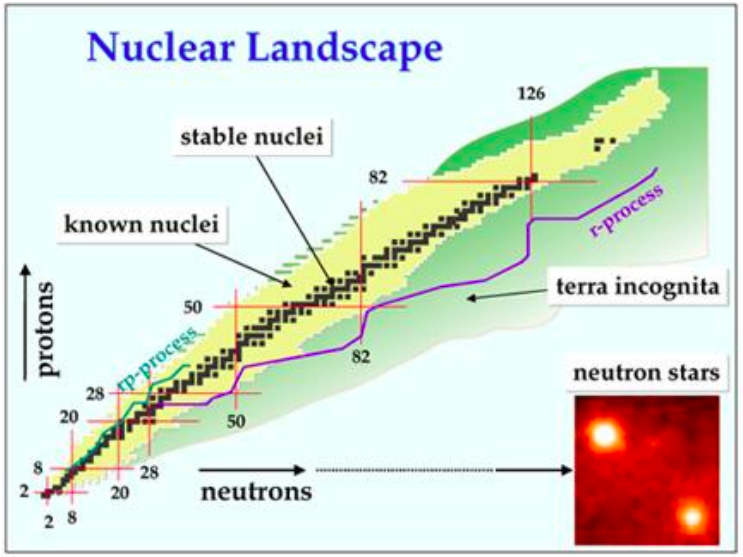
Measure e-p at 0.3 TeV (HERA)
Predict p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV

The Question

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

- **EMC's discovery – another "Rutherford" exp't (1983):**



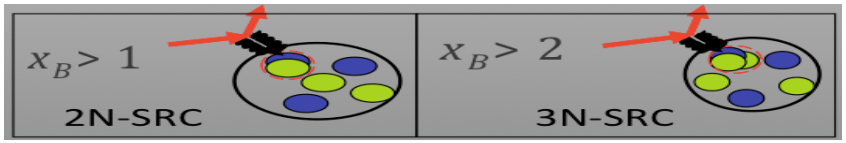


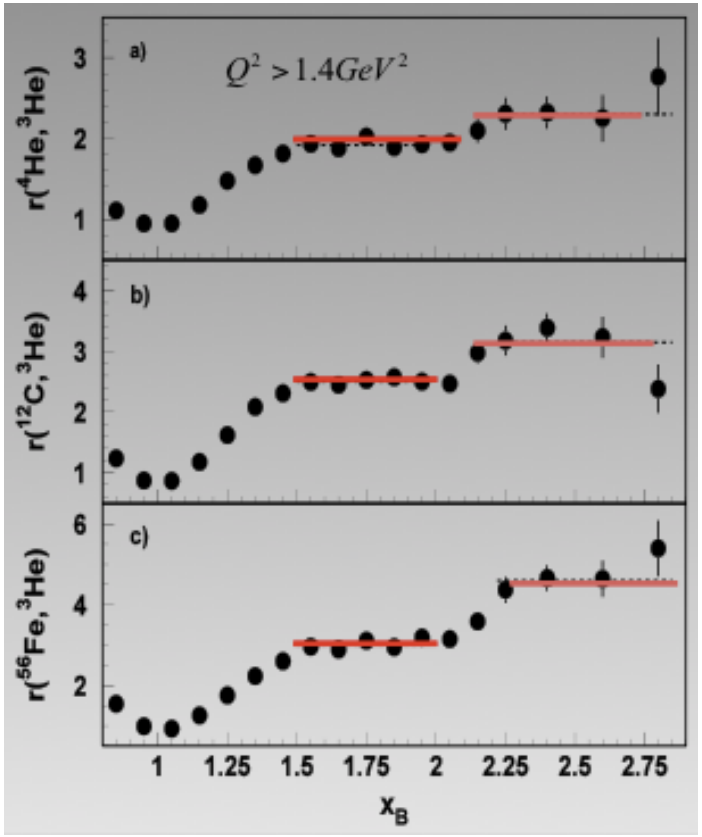
Nuclear landscape =\|= Superposition of nucleon landscape!

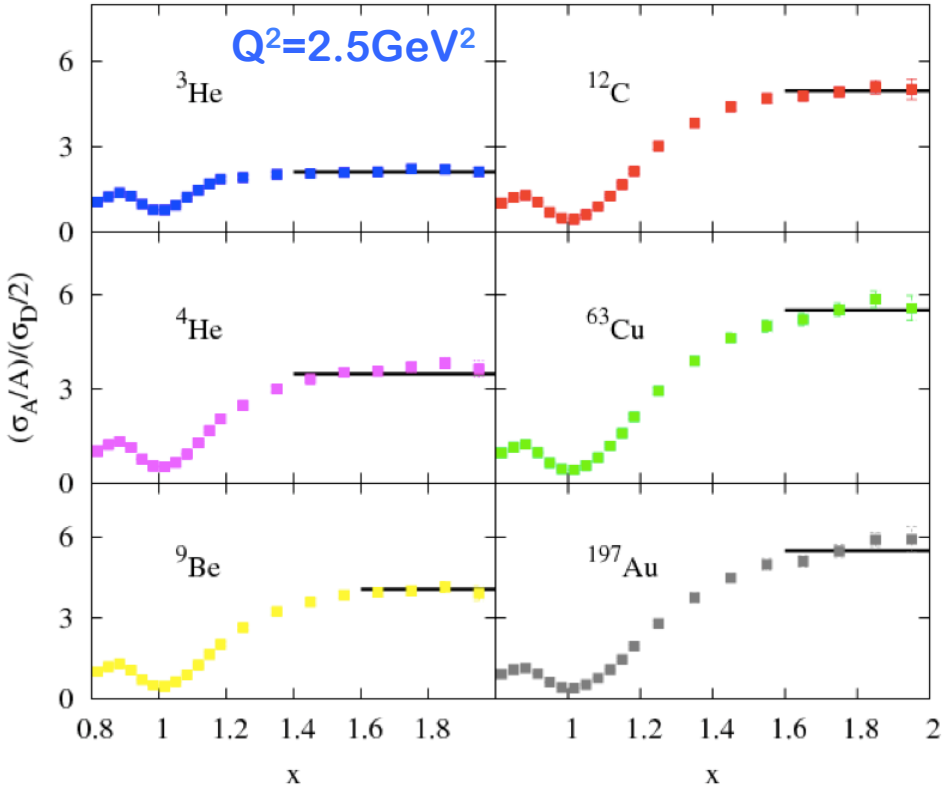
The Question

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

- **JLab data:**





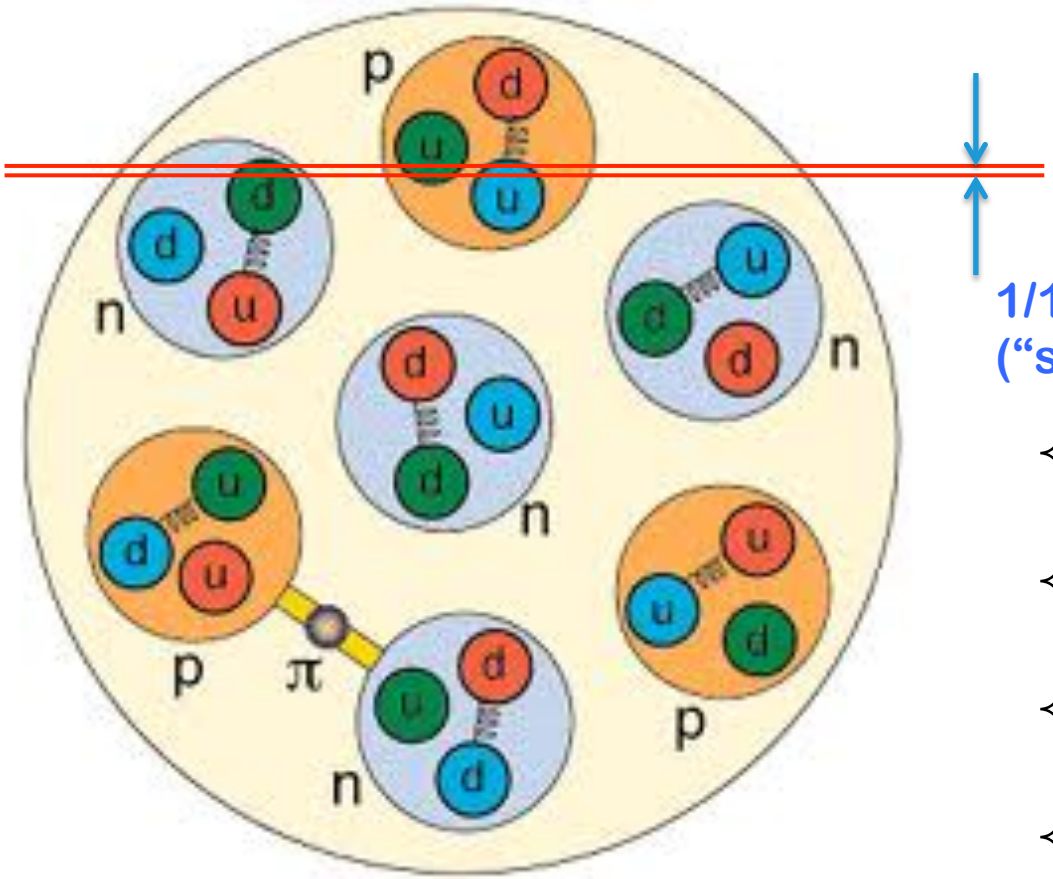


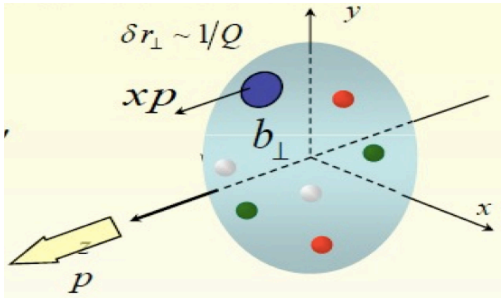
N. Fomin et al. Phys. Rev. Lett. 108:092502, 2012

The Question

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

- **Need a "machine" to cat-scan the nucleus (and nucleon)!**





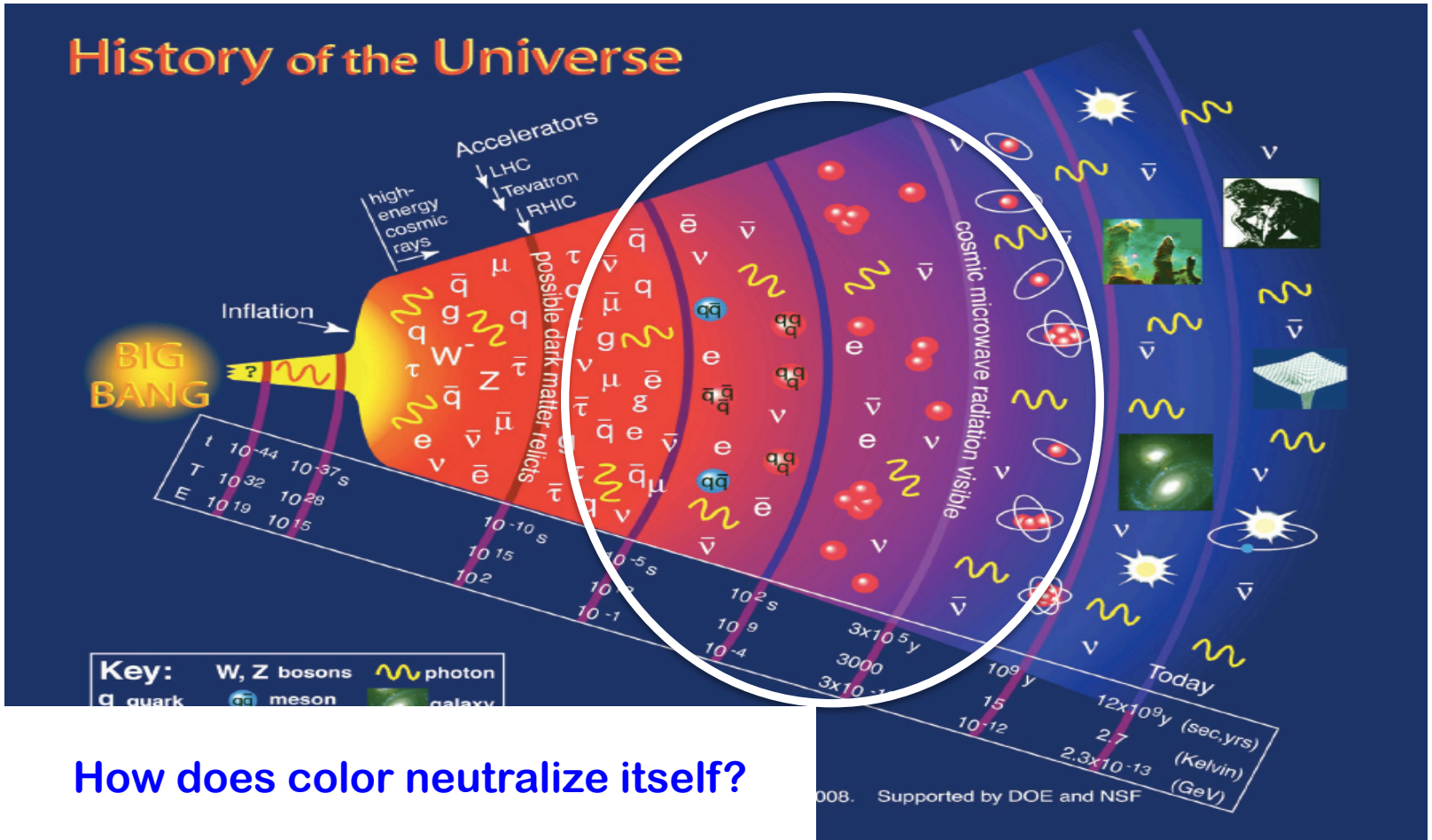
1/10 fm spatial resolution ("see" quarks and gluons)

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

More QCD Question

How do hadrons emerge from quarks and gluons?

- **Formation of nuclear matter:**

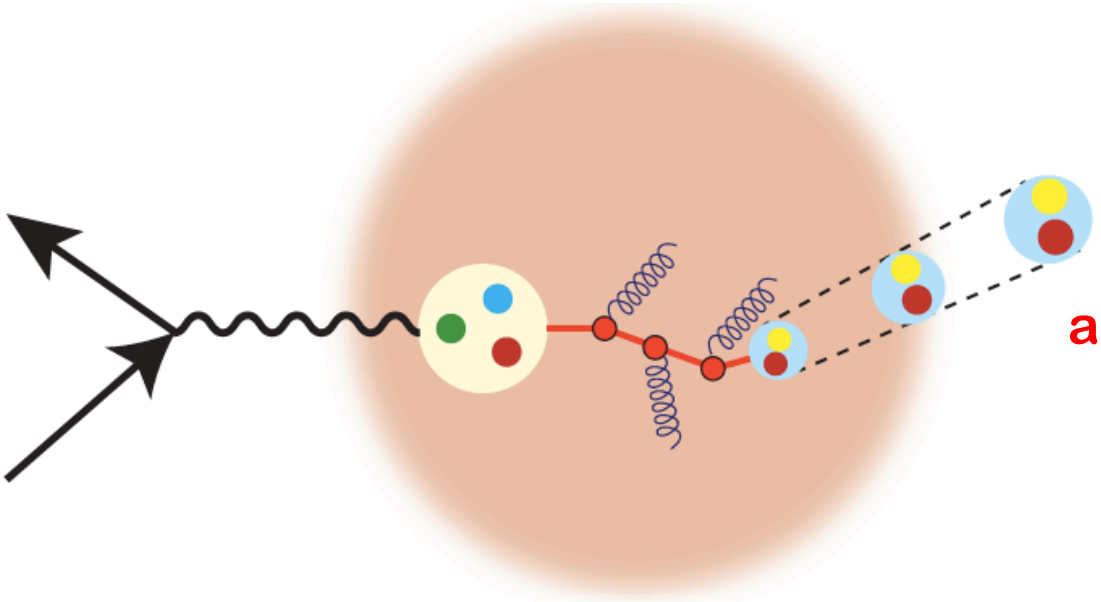


How does color neutralize itself?

More QCD Question

How do hadrons emerge from quarks and gluons?

❑ **Need a "vertex detector" at a femtometer scale:**



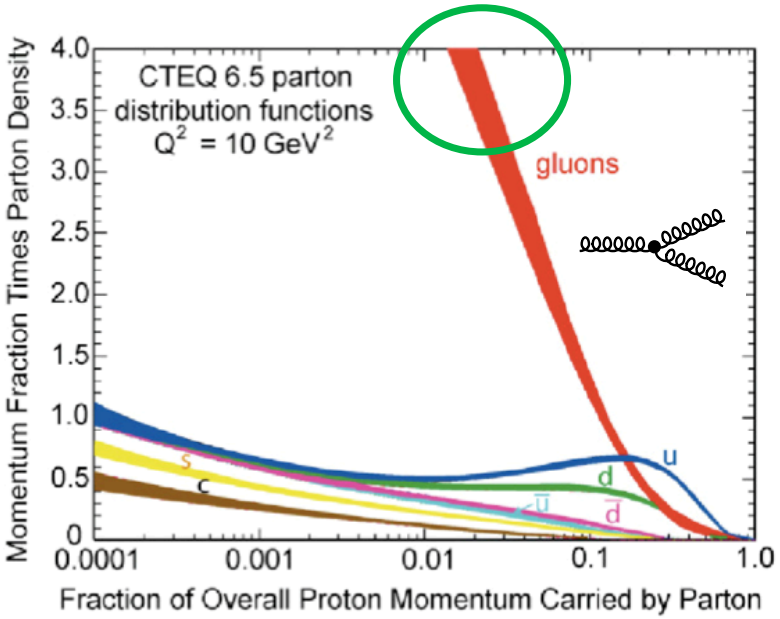
Nucleus in SIDIS is an ideal "vertex" detector

- ✧ Propagation of a "created" color
- ✧ Flavor and momentum of the "created" color particle
- ✧ Control of "Detector" properties and size

More Challenge to QCD

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

❑ **HERA's discovery: proliferation of soft gluons:**



✧ **Gluons interact among themselves when occupation number near 1**

✧ **Instead of reaching Bose-Einstein condensate, gluon density saturates – a dynamical balance of non-linear QCD interaction**

More Challenge to QCD

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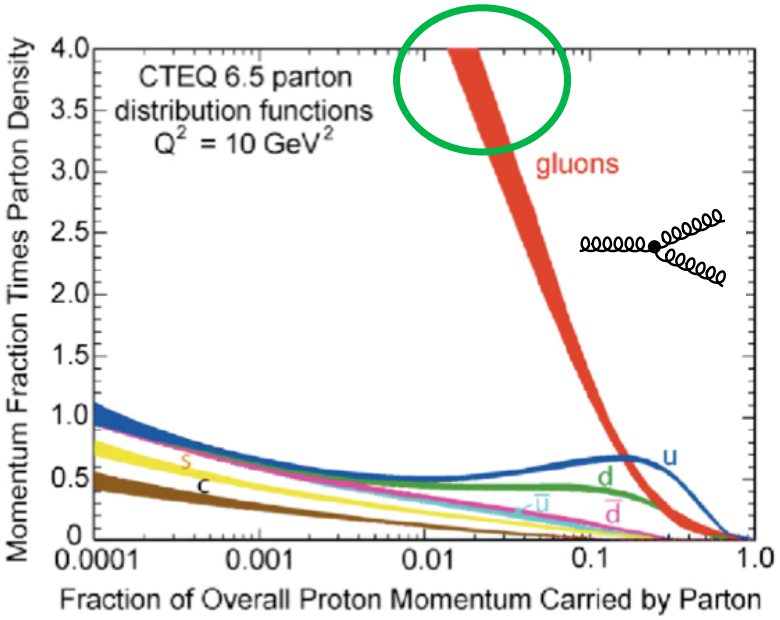
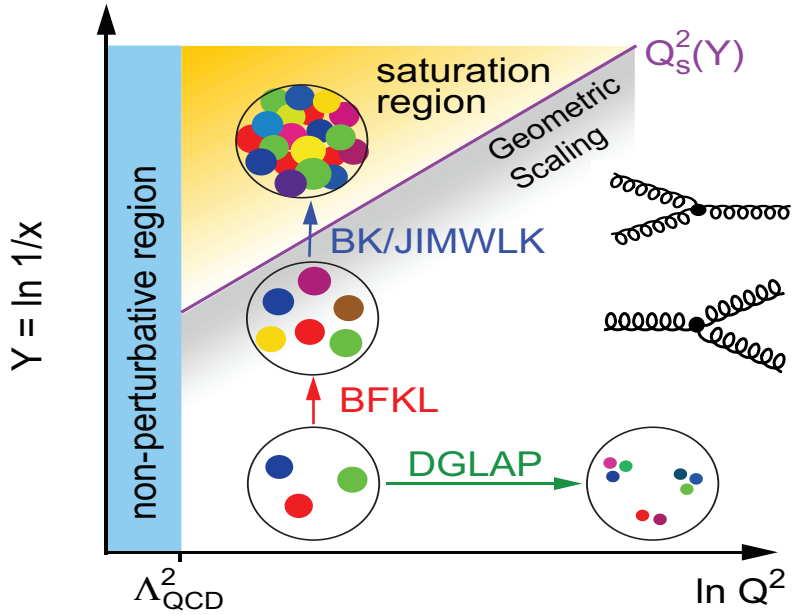




Dynamical scale: Q_s

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

Electron-Ion Collider

- **An ultimate machine(s) to answer the challenges:**
  - ✧ An electron beam to bring to bear the unmatched precision of the EM interaction as a probe
  - ✧ A collider to provide kinematic reach well into the gluon-dominated regime, and the phase space exploring hadron formation
  - ✧ Polarized nucleon beams to determine the correlations of quark and gluon structure with the nucleon spin
  - ✧ Heavy ion beams to offer femtometer "vertex detectors" for studying color propagation in nuclear matter, and to provide precocious access to the regime of saturated gluonic matter

    In a way that other types of machines cannot match!

- **A machine at the frontier of polarized luminosity, combined with versatile kinematics and beam species**

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^{33-34}	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]:

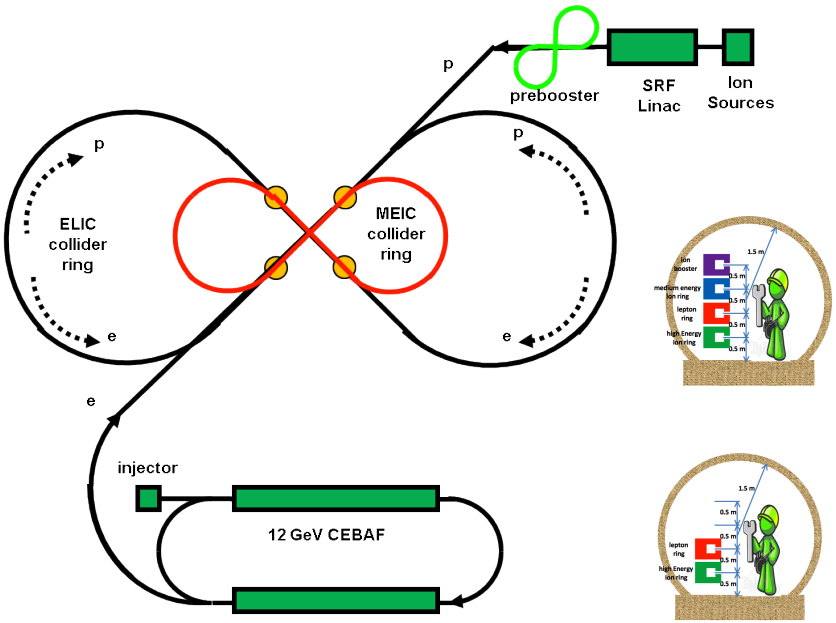
High energy polarized proton beam

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

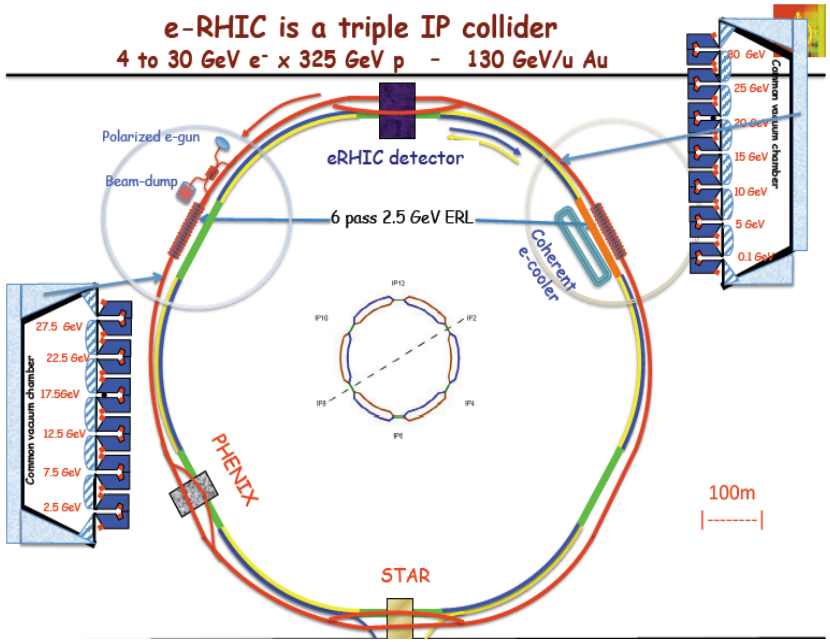
The US EIC proposals

❑ Two possible options:

ELIC (Jlab)



eRHIC (BNL)

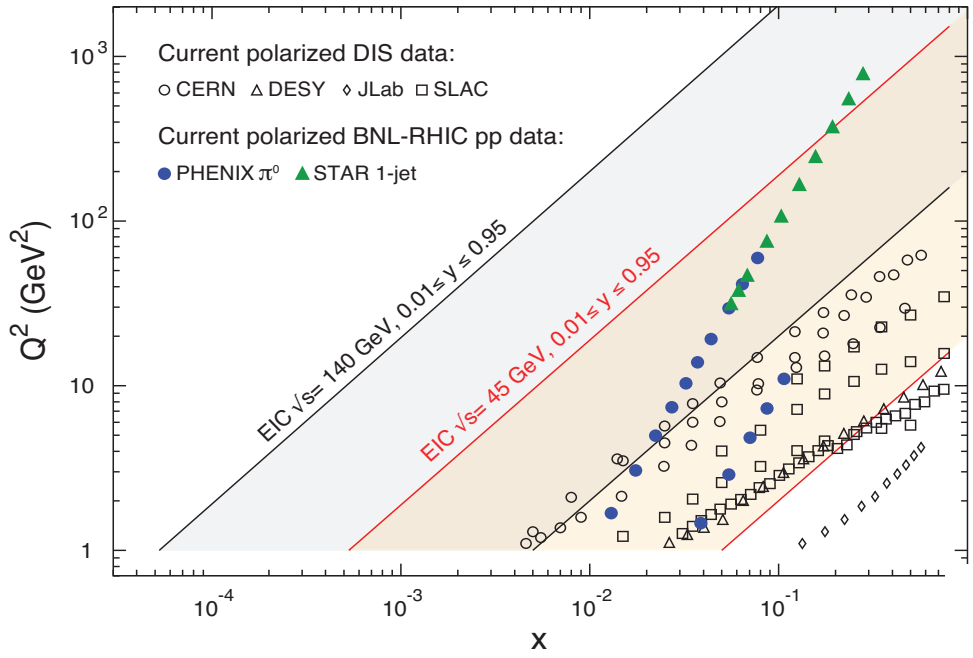


- ✧ First (might be the only) polarized electron-proton collider in the world
- ✧ First electron-nucleus (various species) collider in the world

Staged realization:
Using existing facility

Stage I: $\sqrt{s}$ ~ 60-100 GeV
Stage II: $\sqrt{s}$ > 100 GeV

US EIC: Kinematics and properties

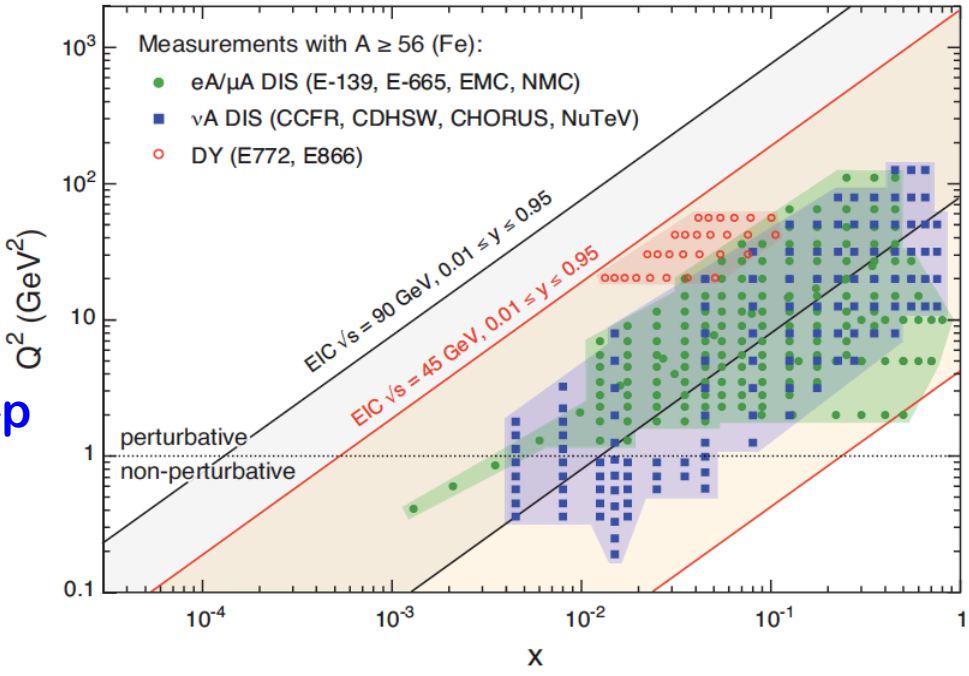


For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ Variable center of mass energy

For e-A collisions at the EIC:

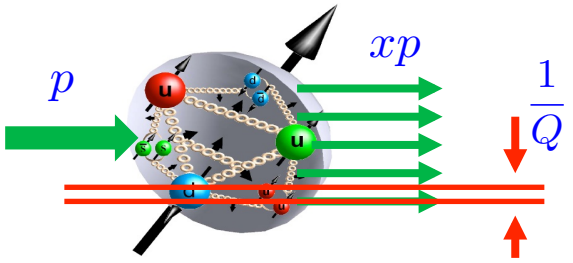
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy



What and why EIC can do and do better?

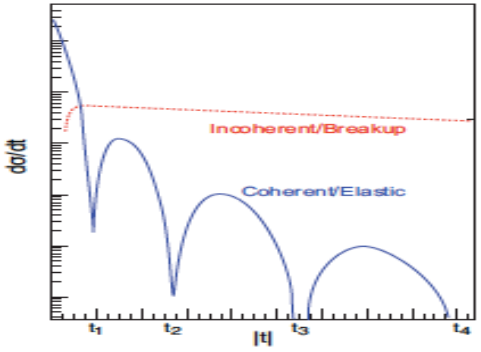
❑ High energy collider:

Sharper probe and better "snapshot" in probing the confined motion of quarks and gluons
– 3D momentum distributions



❑ High 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

❑ Major theoretical advances in last decade!

- ✧ QCD factorization connects partons to observed hadrons/leptons
- ✧ QCD factorization for two scales (1 hard + 1 soft) cross sections, necessary for extracting TMDs, and GPDs
- ✧ QCD factorization for many new spin dependent observables

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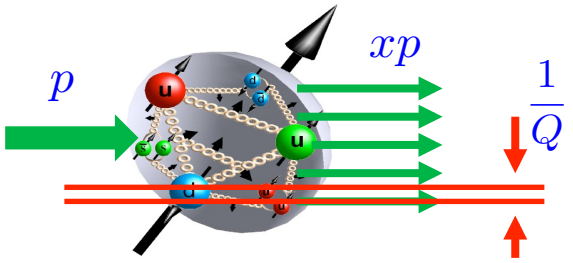

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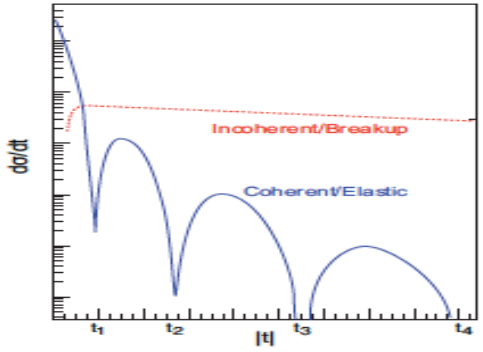


❑ Polarization:

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

Suppress probability – enhance quantum interference

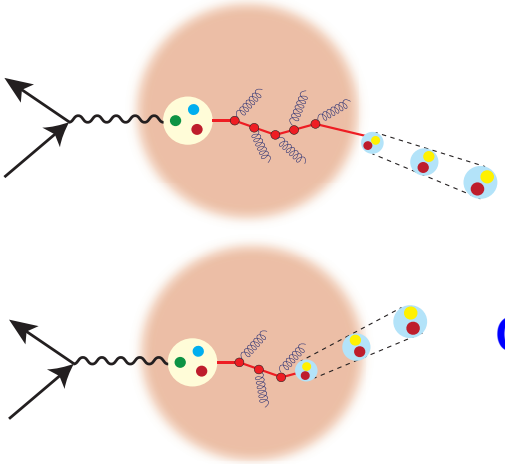
❑ Nucleus, a QCD Laboratory:

- ✧ More soft gluons – Lab for exploring non-linear gluon dynamics
- ✧ Condensed color matter – Lab for QCD tomography
- ✧ Nuclear landscape – color confinement and quantum fluctuation
- ✧ "Vertex detector" for color propagation and neutralization

THE “VERTEX” DETECTOR

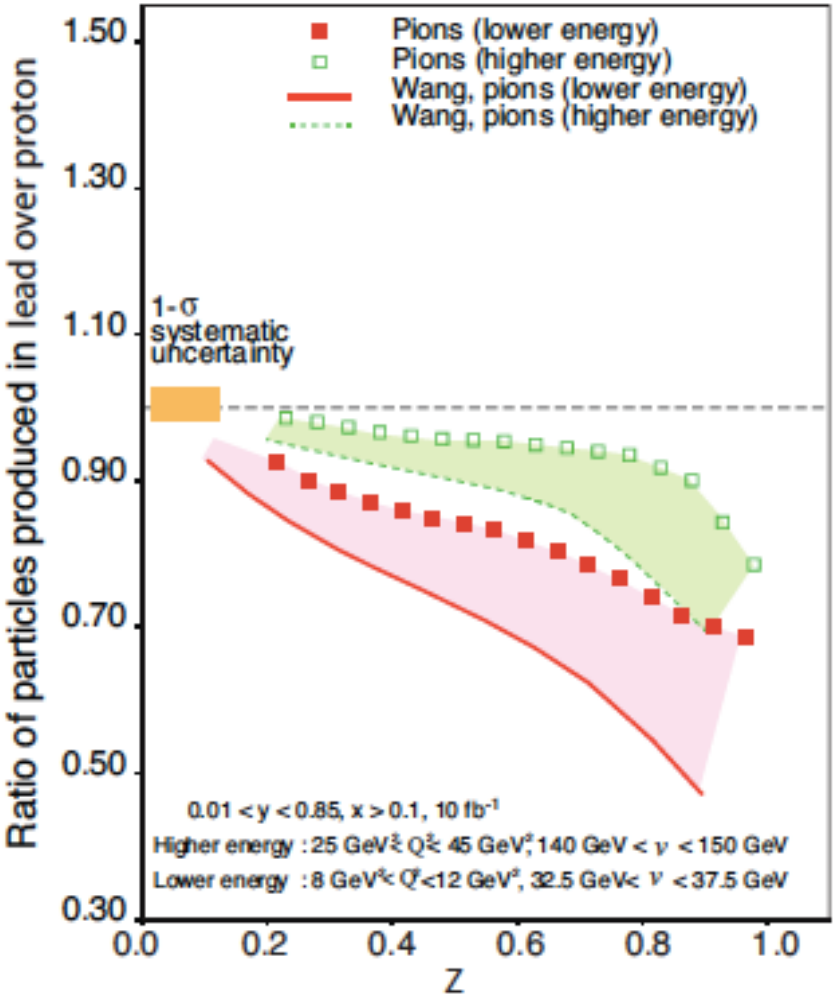
Color neutralization – energy loss

- **Unprecedented ν range at EIC:**



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

Control of ν and medium length!



Color neutralization – energy loss

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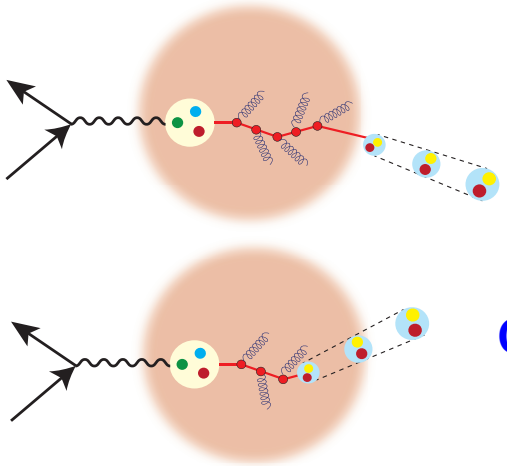
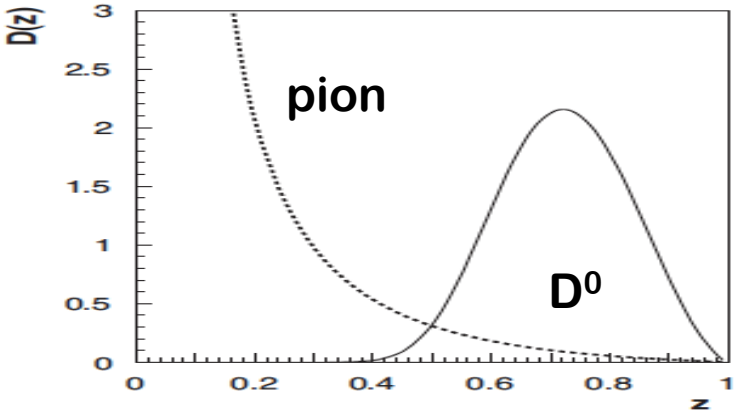
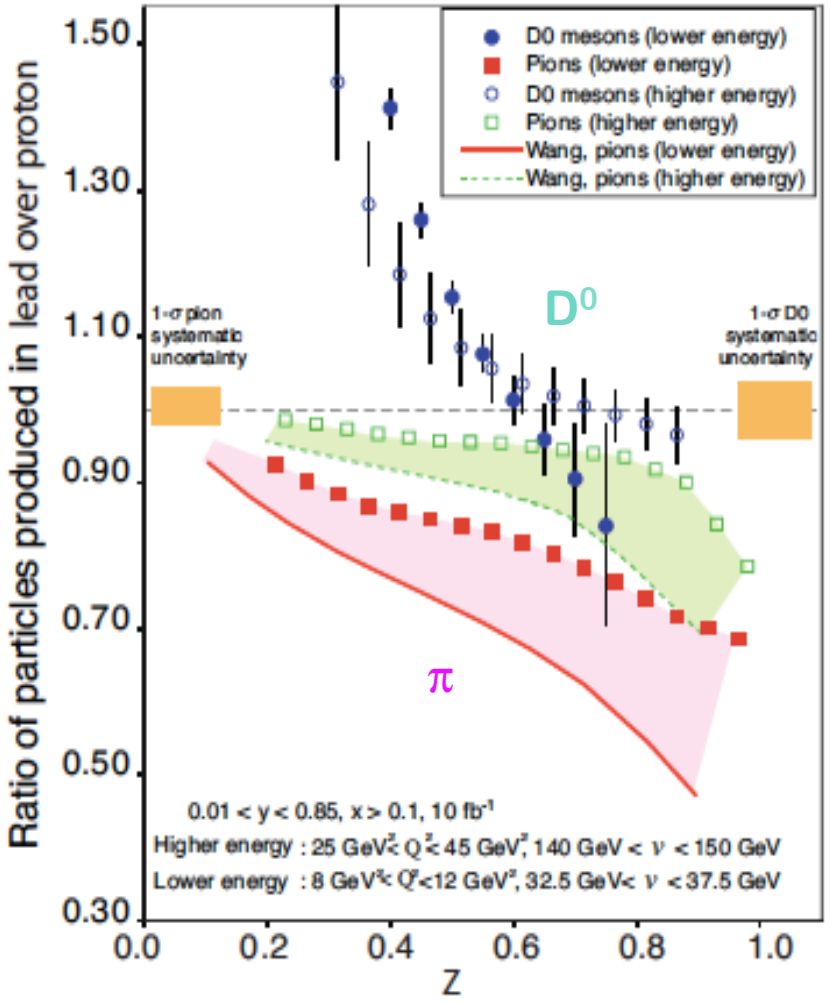


$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

- Heavy quark energy loss:
  - Mass dependence of fragmentation



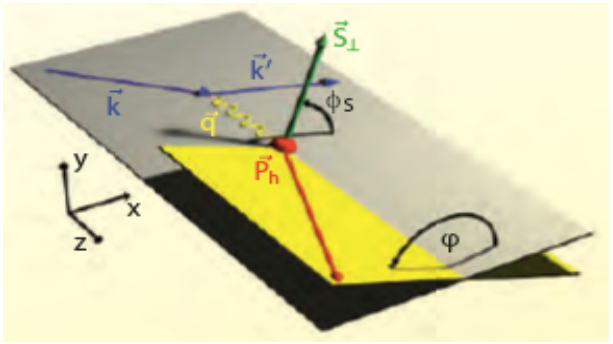


Need the collider energy of EIC and its control on parton kinematics

Color fluctuation – azimuthal asymmetry

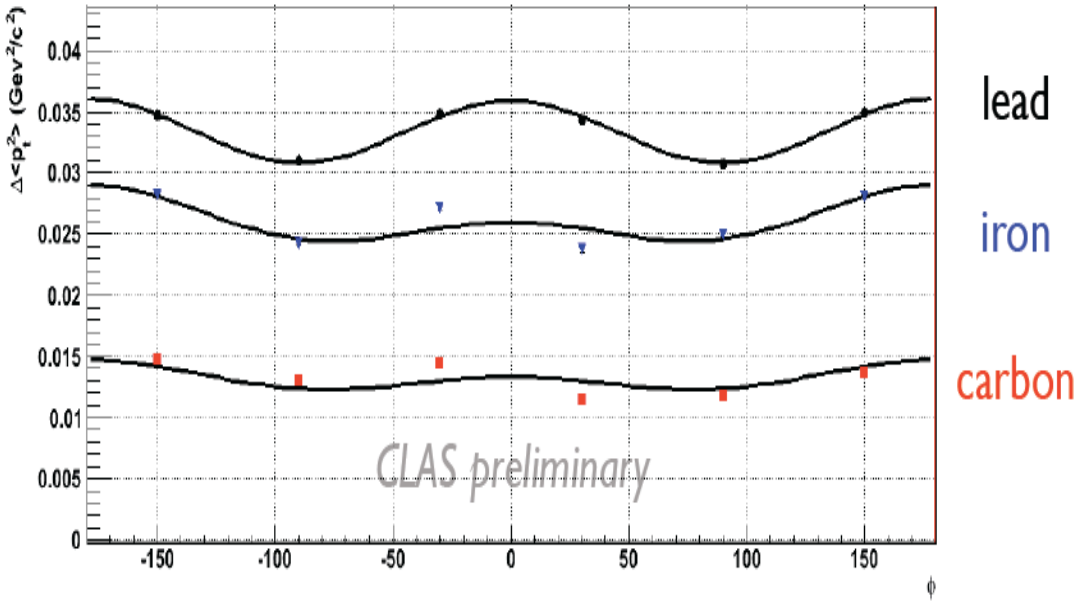
❑ Preliminary low energy data:

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:

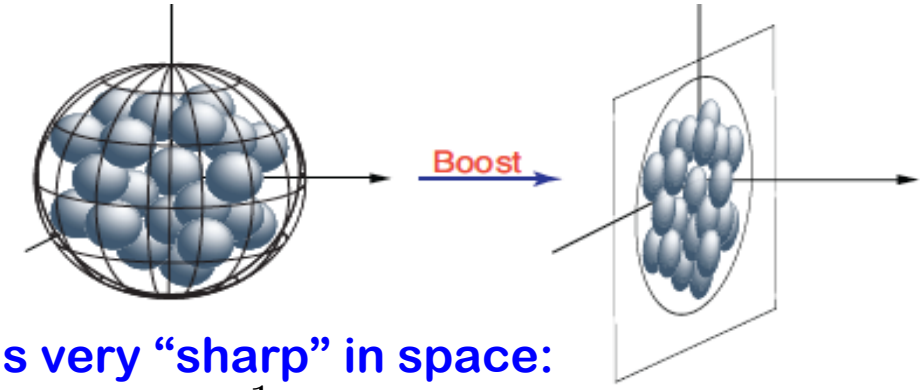
Azimuthal asymmetry in transverse momentum broadening

➡ ***Density fluctuation and v_n!***

DISCOVER THE NATURE OF SOFT GLUONS

Color coherence

- "Snapshot" does not have a "sharp" depth at small x_B



  - Hard probe is very "sharp" in space:

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

  - Longitudinal size > Lorentz contracted nucleon:

$$\frac{1}{xp} > 2R_A \frac{m}{p} \quad \text{or} \quad x \lesssim 0.01$$

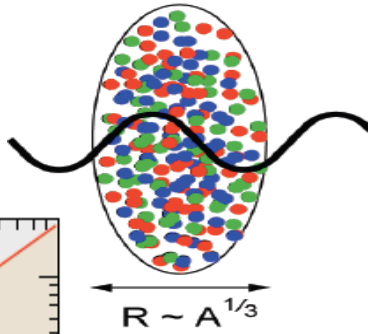
Hard probe can "see" gluons from all nucleons at the same impact parameter!

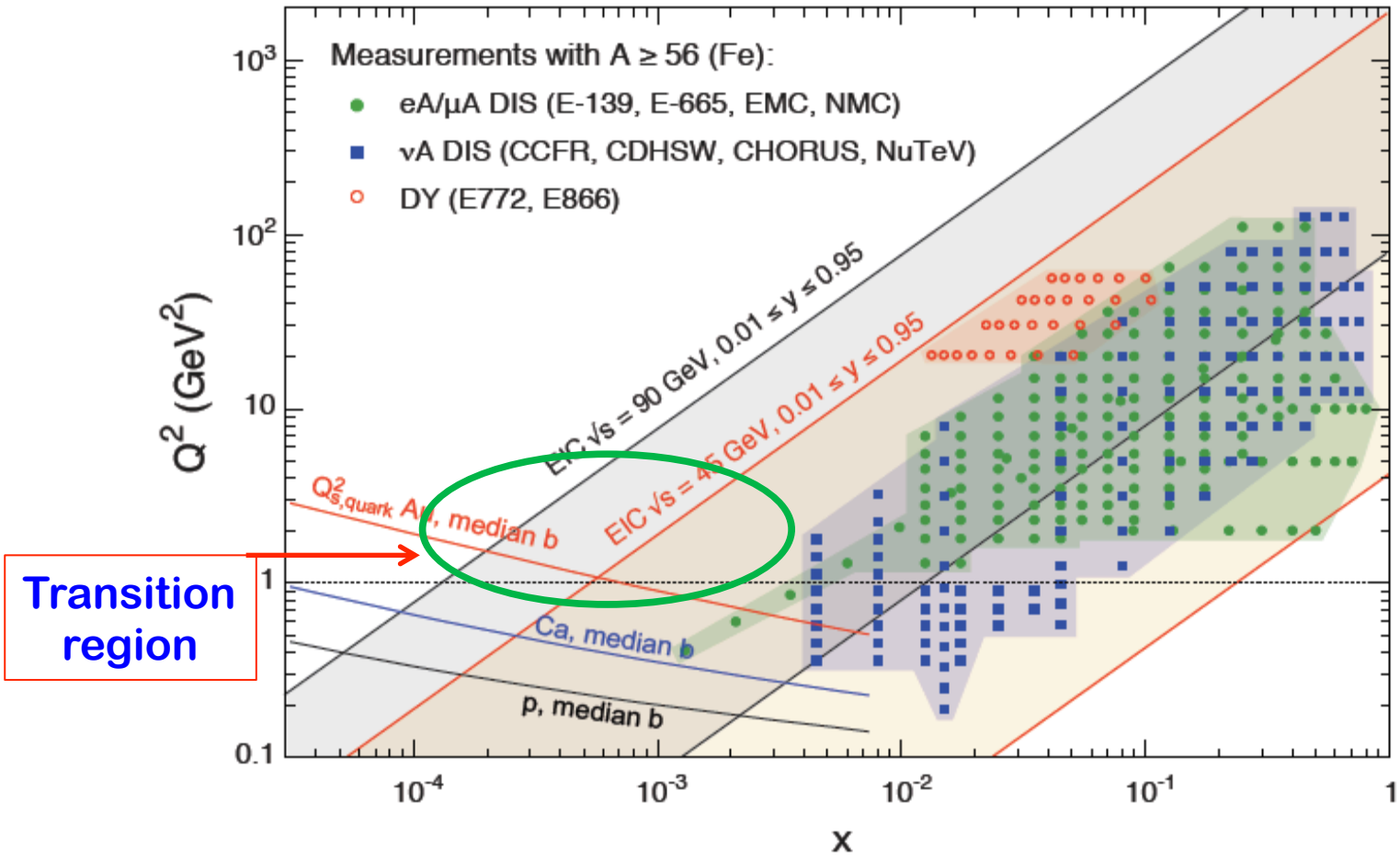
- Could the nucleus act like a "bigger" nucleon at small x_B?

Range of color correlation inside a nucleus – "nature of nuclear force"?

Reaching saturation with eA

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



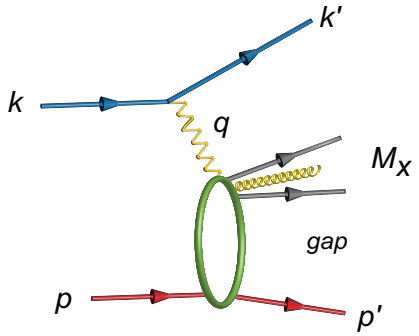


With a gold ion beam: EIC@US can reach the saturation regime at the stage-I

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:**



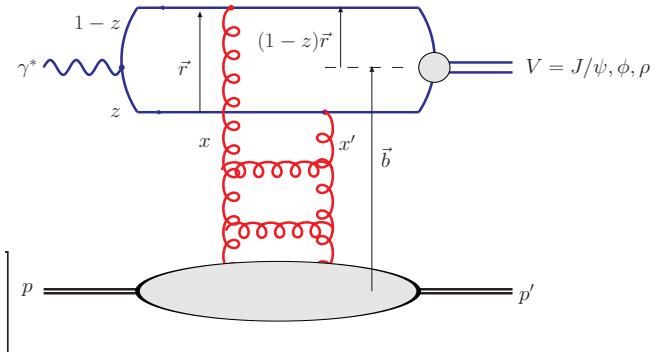
$$\sigma_{\mathrm{diff}} \propto [g(x, Q^2)]^2$$

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 in 4 times when hit by a "TeV" beam!

- **Diffractive vector meson production:**

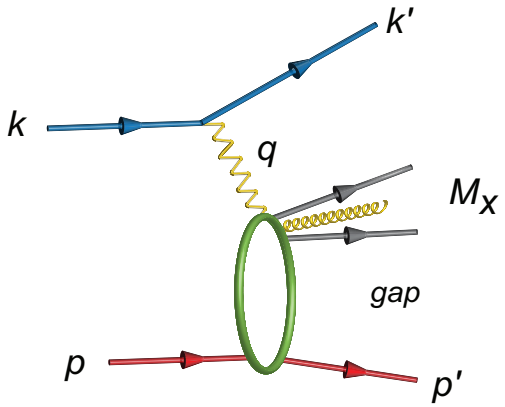


Cross section ratio for eA/ep: J/Ψ and ϕ

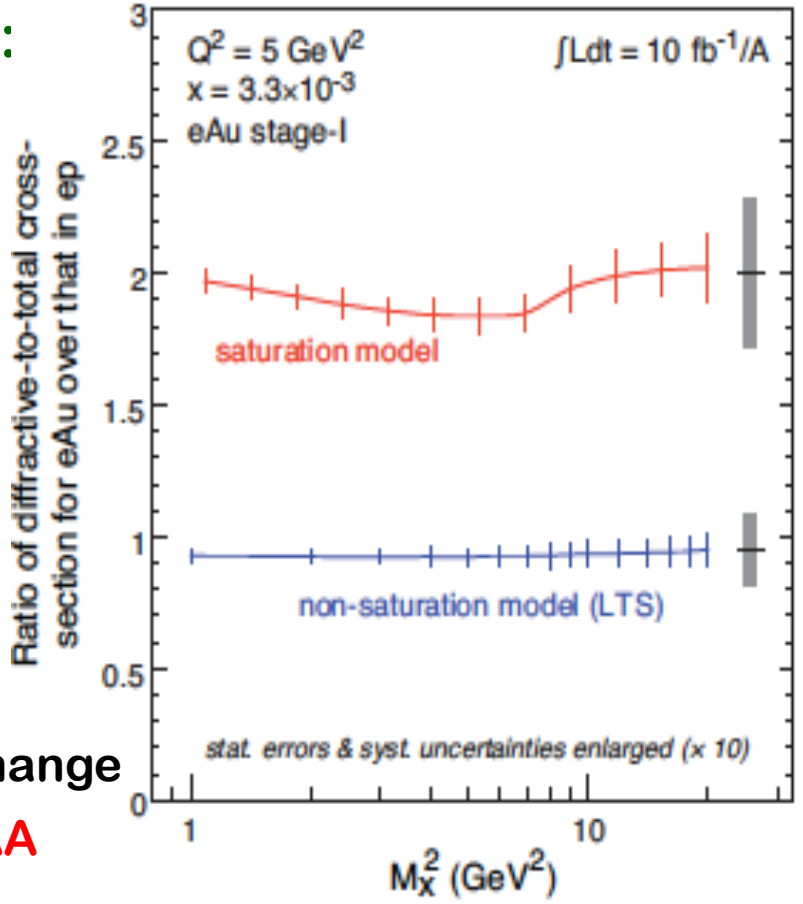
→ Imaging of gluons in nuclei

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**

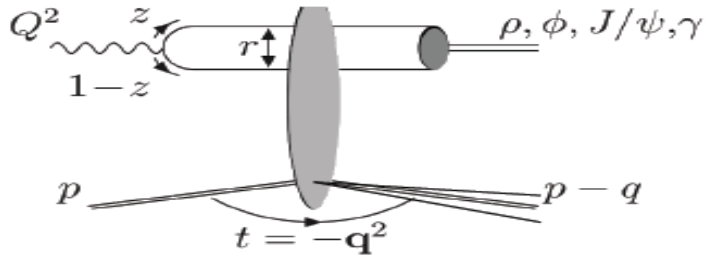
The factor of 2 enhancement is only for eA
(no equivalent in pA!)

This is a clean and unambiguous signal of saturation physics

already at EIC stage-1

Spatial imaging of the glue in a nucleus

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

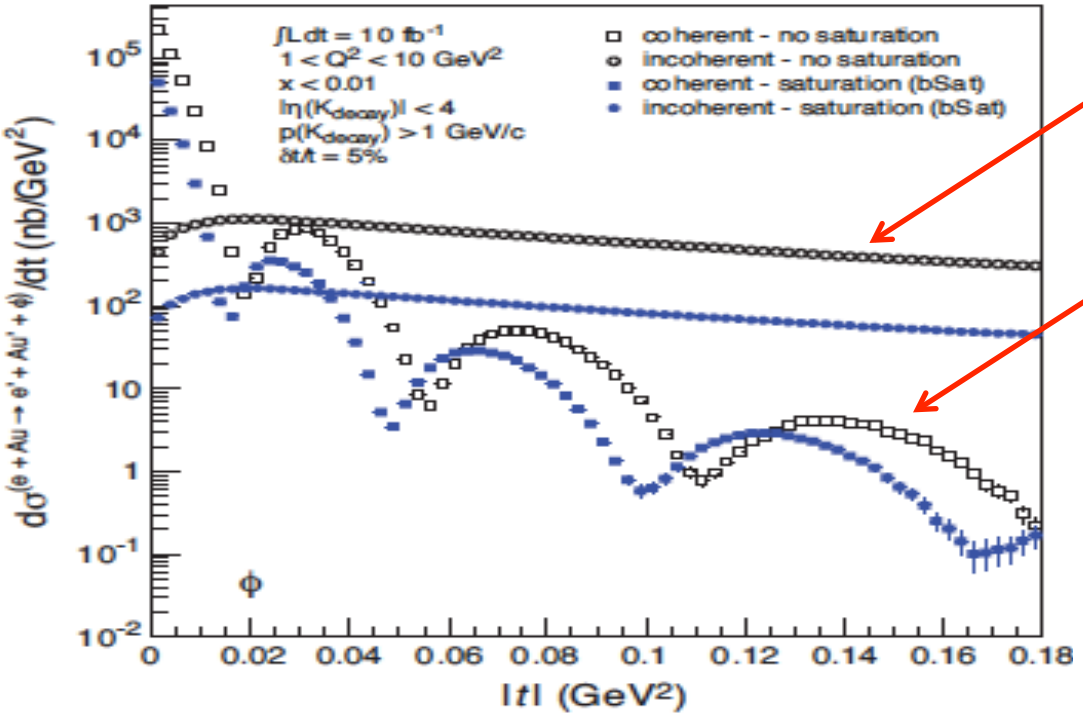


$$\frac{d\sigma}{dx_B dQ^2 dt}$$

Fourier transform of the t-dependence

- as a function of **t**

- **Φ–production – clean probe for spatial distributions:**



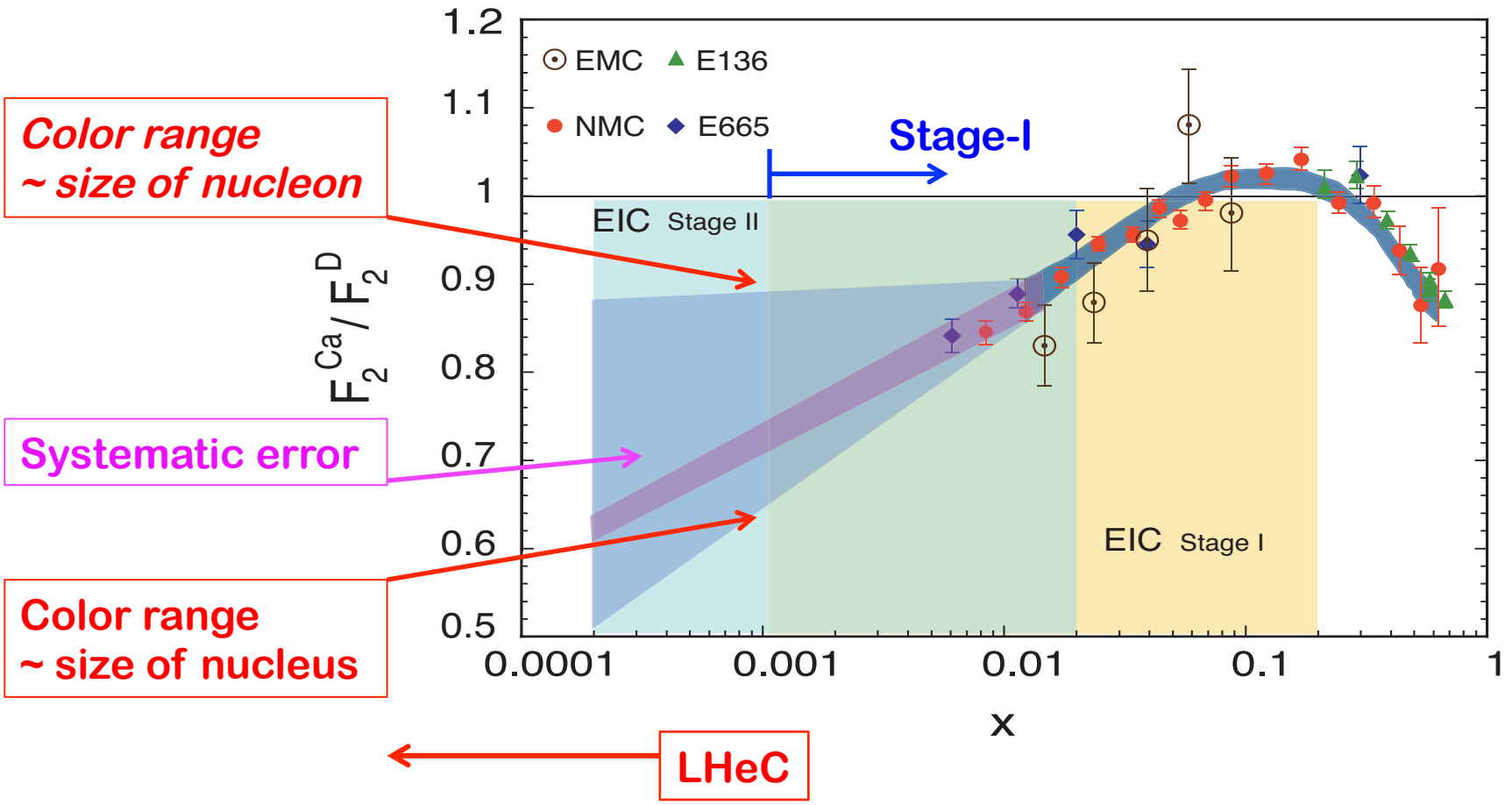
✧ **Incoherent:**
Nucleus breaks up

✧ **Coherent:**
Nucleus stays intact

Need EIC's energy to do this!

Range of color correlation inside a nucleus?

❑ Ratio of DIS F_2 structure functions:

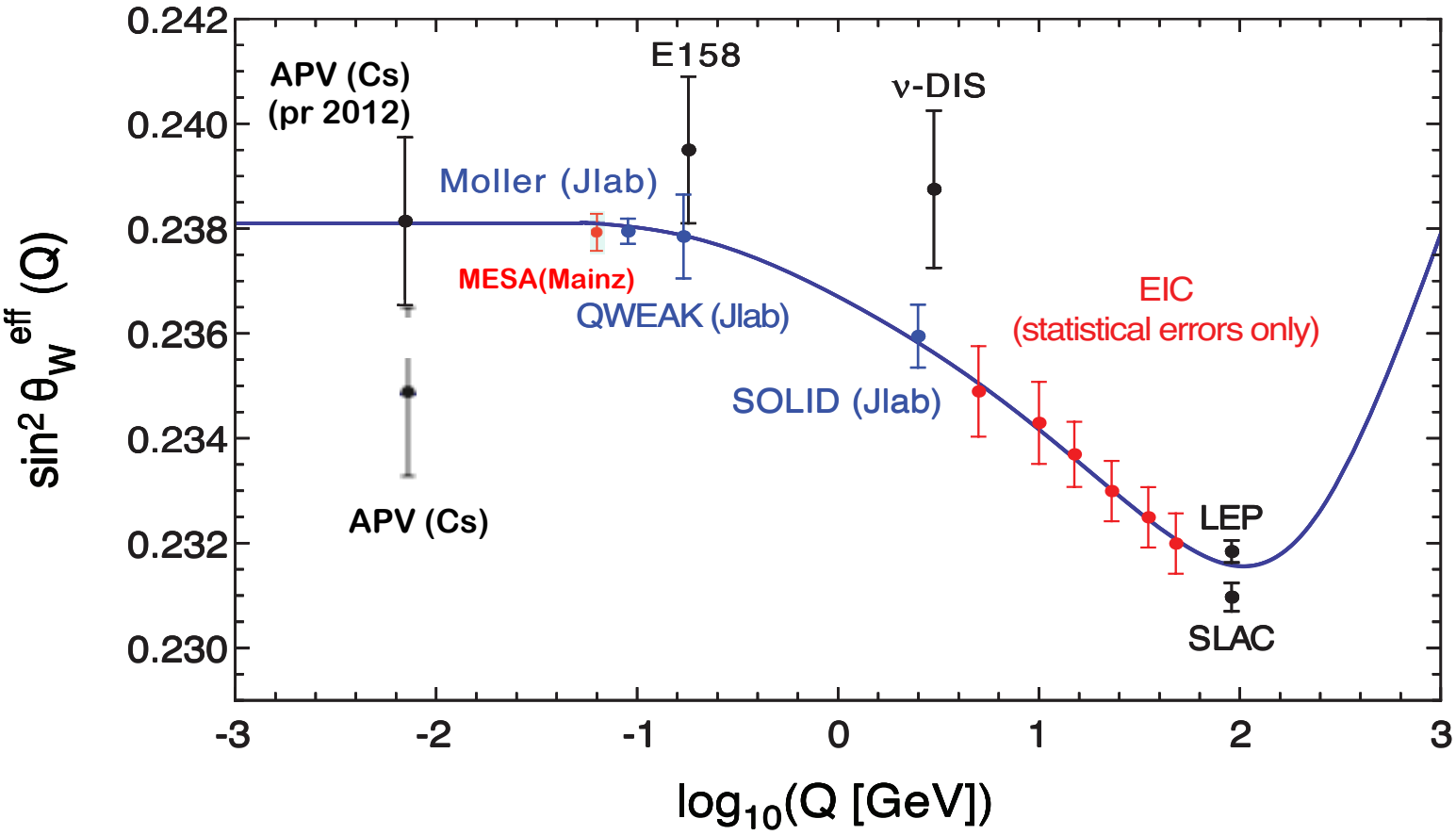


A clean stage-I measurement at EIC@US (systematic error only)

BEYOND THE STANDARD MODEL?

Electroweak physics at EIC

- Running of weak interaction – high luminosity:



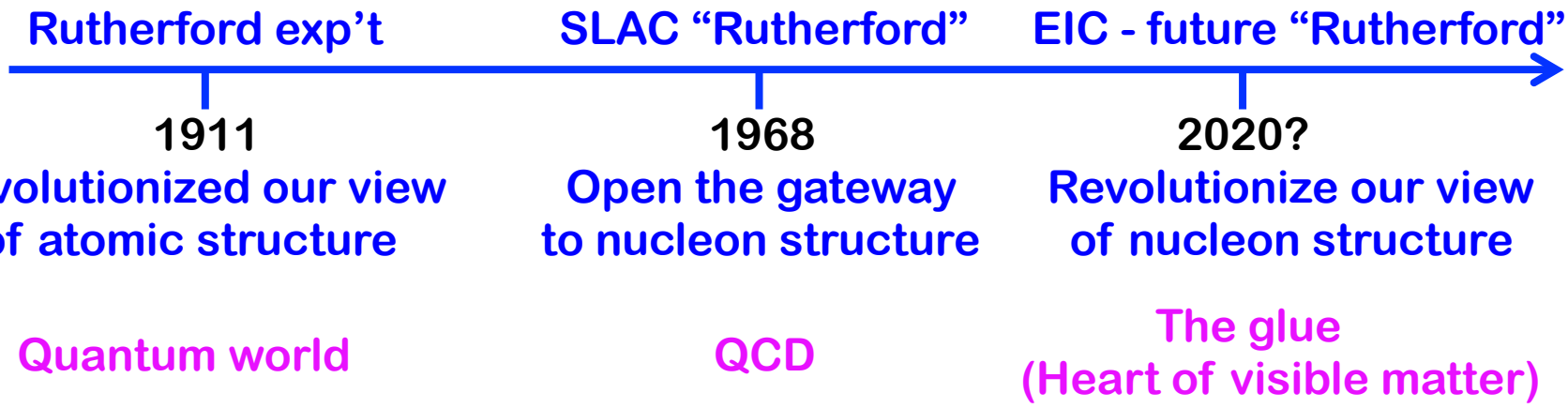
- ✧ Fills in the region that has never been measured
- ✧ *have a real impact on testing the running of weak interaction*

Summary

- QCD is very successful in the asymptotic regime (< 1/10 fm):

  But, we have learned very little about hadron structure and formation

- EIC – an ideal machine to explore hadron/nuclei structure:



We have learned a lot, but, much much more need to be learnt!

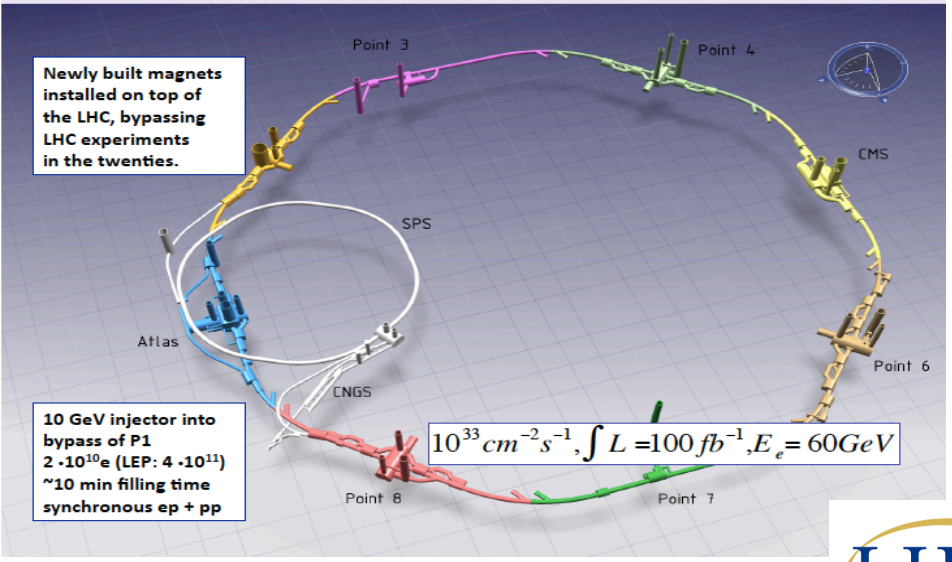
- EIC – an ideal machine to study the glue, binding us all, and discover the saturated gluonic matter – must be existed, but, where for sure?

Thanks!

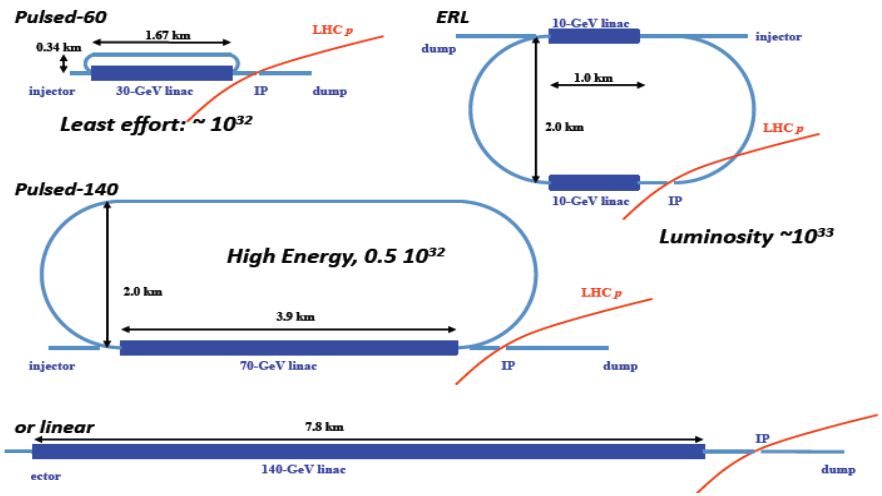
LET'S CELEBRATE

European proposal: LHeC

Ring-Ring configuration



Linac-Ring Configurations



LHeC

LHeC Physics:

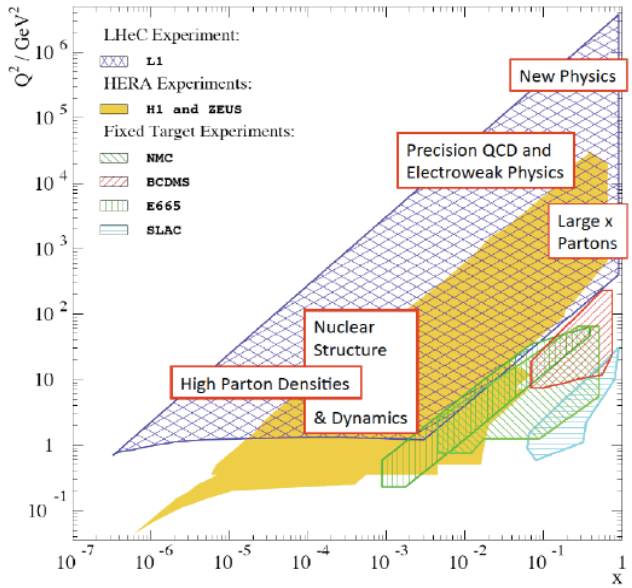
Proton structure & QCD

Small x physics eP & eA

Electron-Quark systems

BSM: at 1 TeV scale

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



eA → eX