Physics at the EIC: Tackling QCD from the inside out

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Hampton U. and Jefferson Lab

Giornata sulle opportunita' del progetto EIC
Genova, January 17, 2017

With many thanks to C.Aidala, M.Baker, W.Brooks, R.Ent, W.Melnitchouk, R.McKeown, V.Morozov, B.Muller, J.Owens, F.Pilat, J.Qiu, I.Vitev, R.Yoshida for ideas, discussions, (stolen) slides, and help preparing this talk

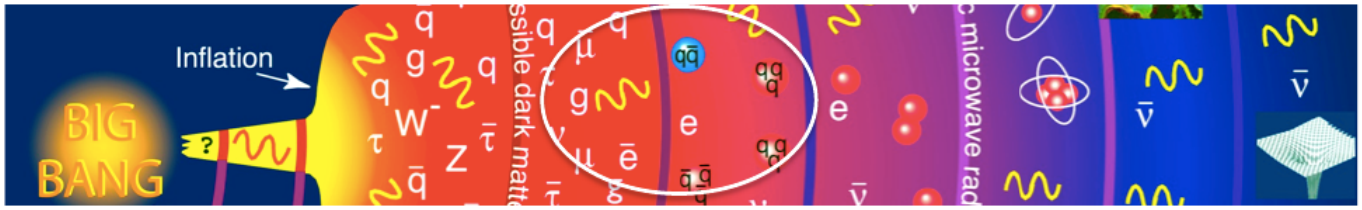
Outline

- A new era in quantitative QCD
- Physics opportunties at the EIC
- Big questions, observables
- Summary and Epilogue

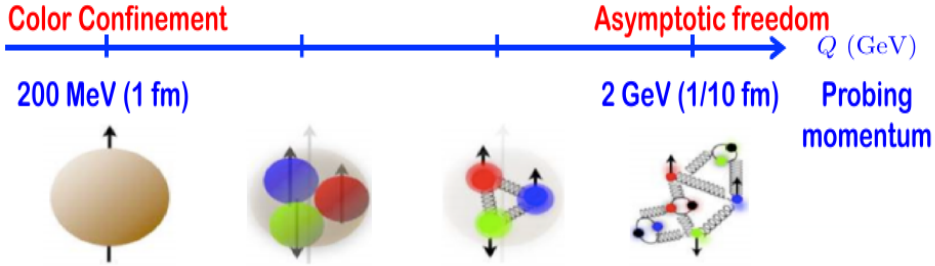
Intro:
A new era in quantitative QCD

21st century nuclear science

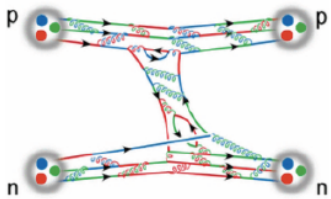
- What is the role of QCD in the evolution of the universe?



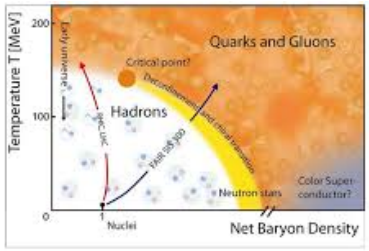
- What is the QCD landscape of nucleon and nuclei?
- How does QCD make up the properties of hadrons?
  - Their mass, spin, magnetic moment, …



- How do hadrons emerge from quarks and gluons?
  - Extended family of hadrons? XYZ? …

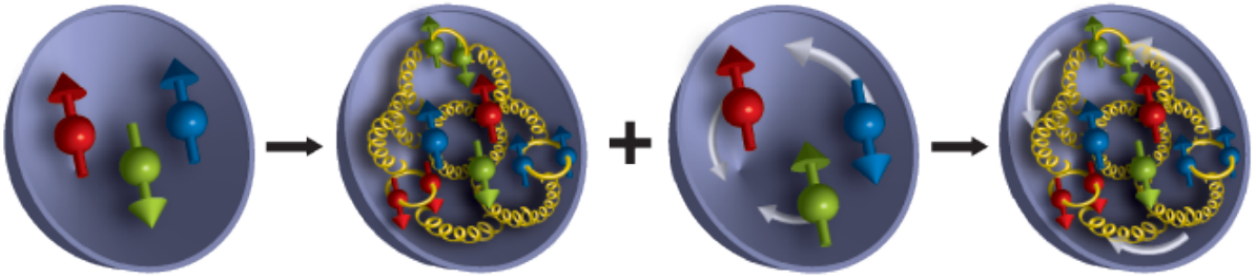


- How does the nuclear force arise from QCD?
- New states of nuclear matter
  - Deconfined: Quark Gluon Plasma
  - Universal: “wee” gluon saturation



How to “see” and quantify hadron structure?

- **Our understanding of hadrons evolves**



1970s 1980s/2000s Now

A strongly interacting, relativistic bound state of quarks and gluons

- **Challenge – color confinement:**

  No detector can see quarks and gluons in isolation!

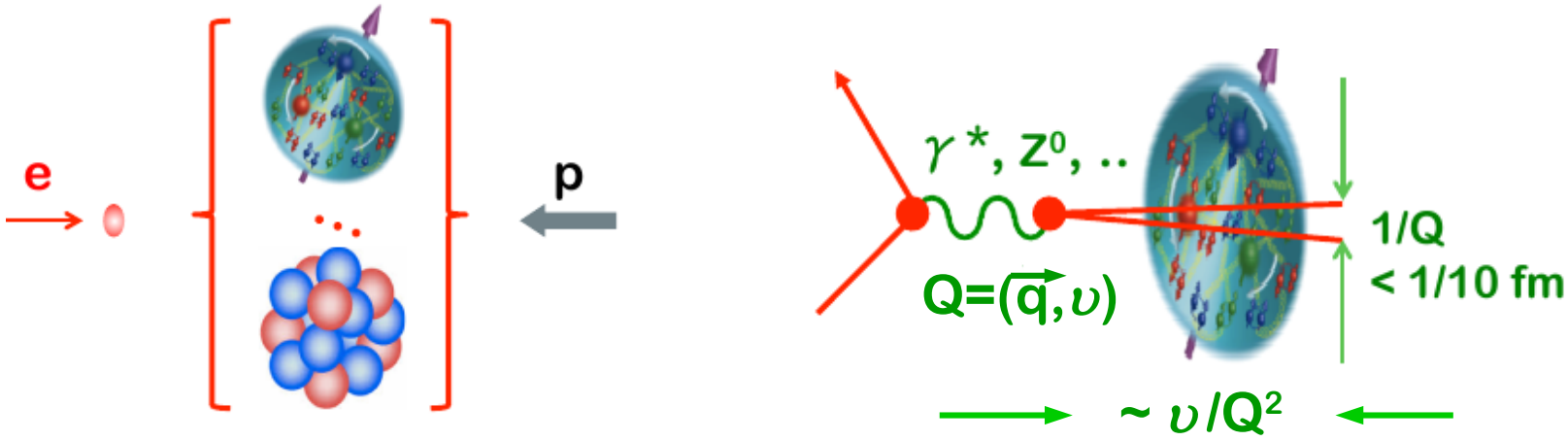
- **Question:**

  How then to quantify the hadron structure? We need a probe!

  - Leptons
  - Quarks and gluons in projectile hadrons
  - Final state hadrons

Electron-Ion collisions: a giant microscope

- "See" quarks and gluons and their dynamics **by breaking the hadron**



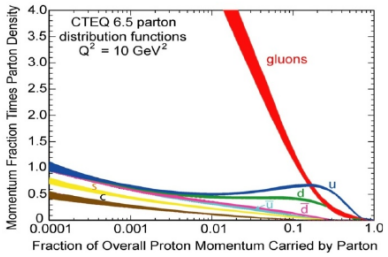
- "Image" quarks & gluons **without breaking the hadron**
  - "cat-scan" protons and nuclei
  - with better than 1/10 fm resolution

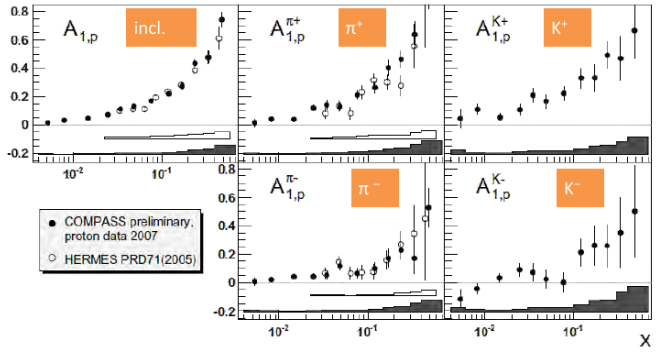
- **Control** the size and coherence length of the probe

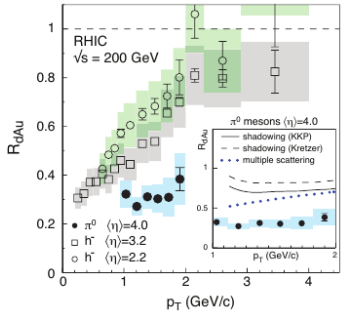
- **Need to connect observables to confined quarks and gluons:**
  - QCD factorization! Not exact, but, controllable approximation

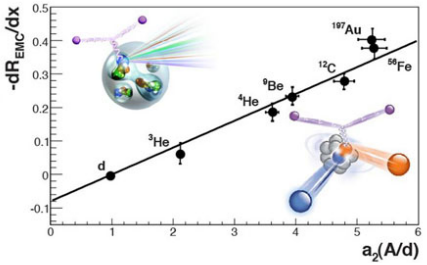
Why a new facility?

- **We have learned a lot** from HERA, HERMES/COMPASS, RHIC, JLab 6,









  - Limited kinematic coverage or precision
  - and **glimpses of more to come!**

- **New insights are coming / will come from COMPASS, RHIC, JLab 12, …**

- **Need new, more precise measurements** for
  - New physics at LHC
  - QGP tomography and interpretation
  - Discovering the unexpected

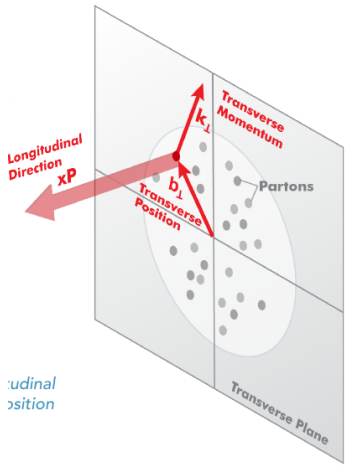
Why a new facility?

- **Recent experimental advances:** → *Pilat / Cisbani / Dalla Torre*
  - Luminosity, energy reach, detection capability, …

- **Recent theoretical advances:** → *J.Qiu, POETIC 2016*
  - Breakthroughs in factorization
  - Various resummation techniques
  - TMD evolution, NLO
  - GPD extraction frameworks

  } → from 1D to 3D parton imaging

  - Angular momentum in relativistic quantum fields
  - Lattice QCD
    - algortihms, more comp. power, novel approaches to observables
  - New global fitting techniques
    - Combine data across nuclear, hadronic, high-E measurements



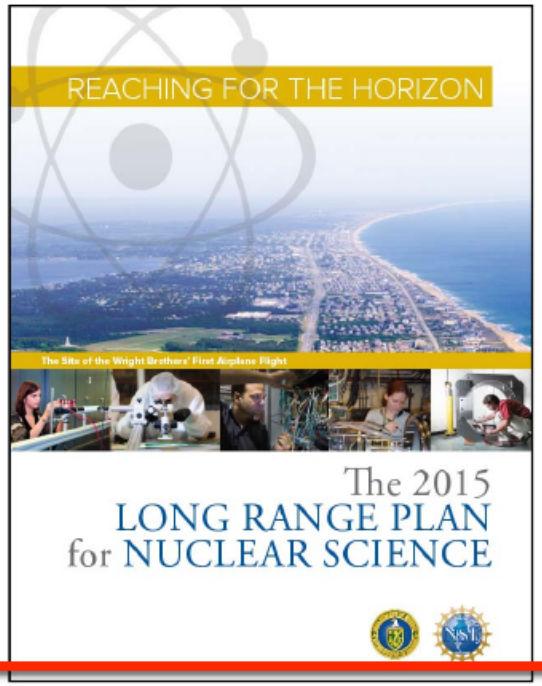
- **EIC will usher in a new era of quantitative QCD!**

The 2015 Long Range Plan for Nuclear Science

NSAC and APS DNP partnered to tap the full intellectual capital of the U.S. nuclear science community in identifying exciting, compelling, science opportunities

Recommendations:

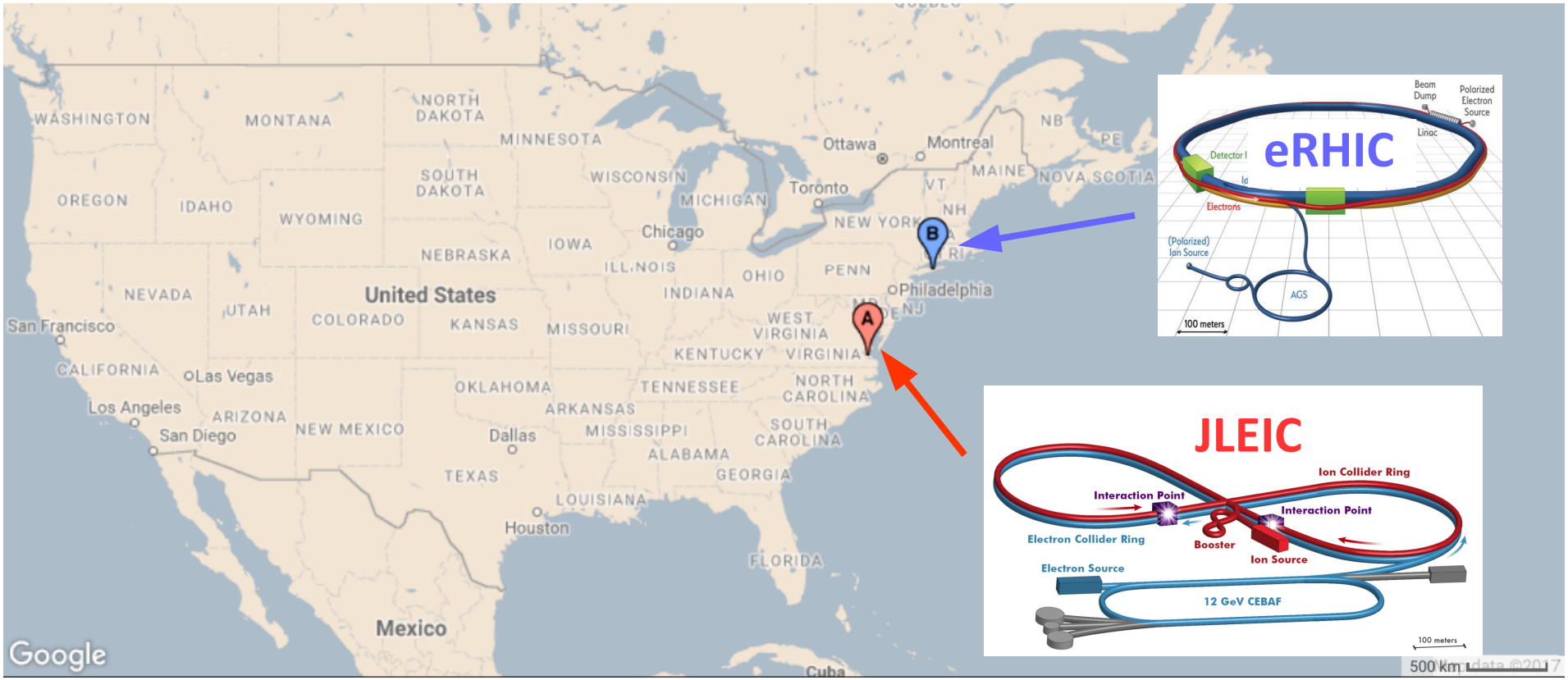
- The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. ***The highest priority in this 2015 Plan is to capitalize on the investments made.***
- The observation of neutrinoless double beta decay in nuclei would…have profound implications.. ***We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.***
- Gluons…generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain…. These can only be answered with a powerful new electron ion collider (EIC). ***We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.***
- ***We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.***



NP is implementing these recommendations which are supported in the President's FY 2017 request

From T.Hallman

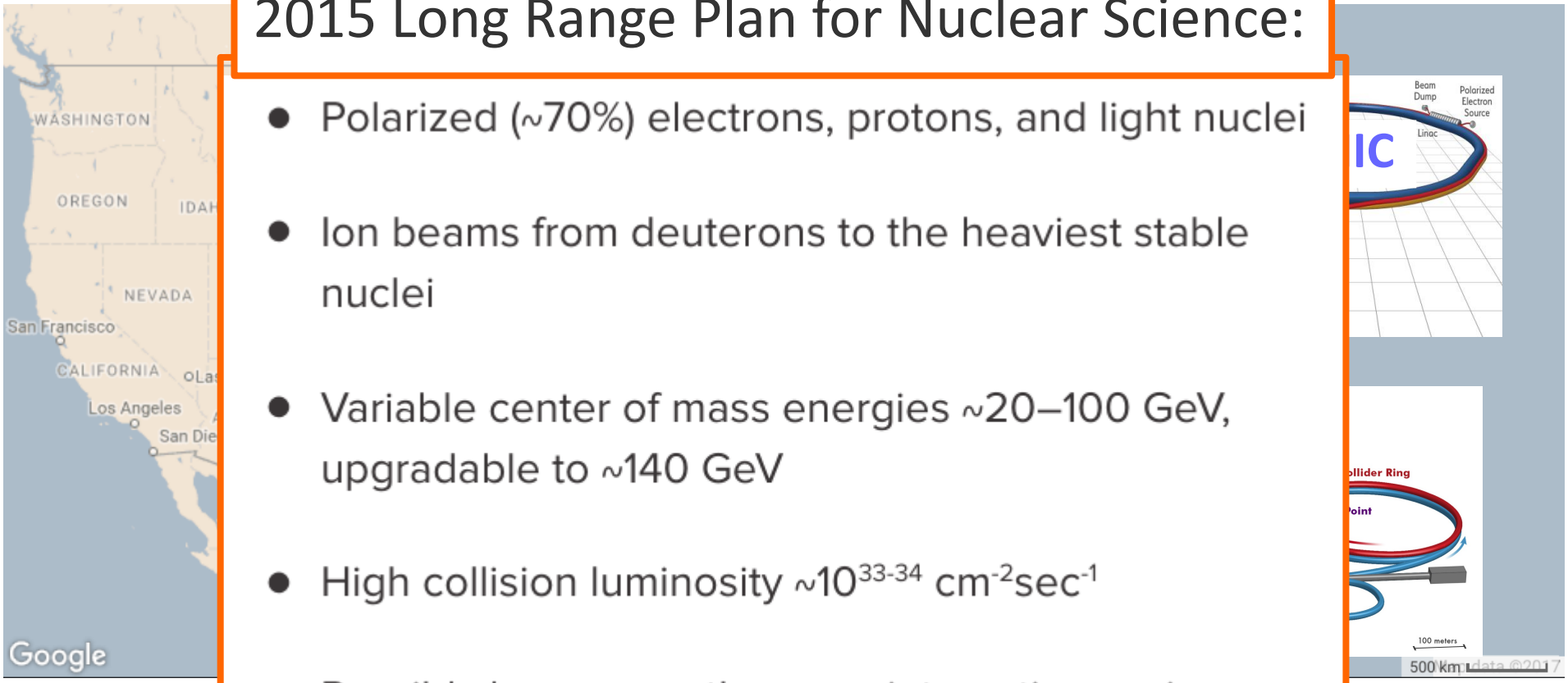
The Electron-Ion Collider



A very flexible machine

Machine parameters as identified in the 2015 Long Range Plan for Nuclear Science:

- Polarized (~70%) electrons, protons, and light nuclei
- Ion beams from deuterons to the heaviest stable nuclei
- Variable center of mass energies ~20–100 GeV, upgradable to ~140 GeV
- High collision luminosity ~$10^{33\text{-}34}$ $cm^{-2}sec^{-1}$
- Possibly have more than one interaction region

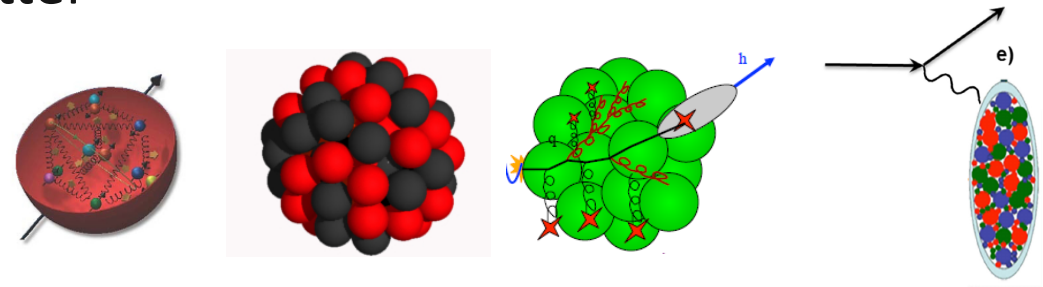


Physics opportunities at the EIC

The Electron-Ion Collider

- A facility to bring this new era of quantitative QCD to maturity!

- Study in detail
  - "Simple" QCD bound states: Nucleons
  - Collections of QCD bound states: Nuclei
  - Color propagation and neutralization in QCD matter
  - New states of QCD matter



Collider energies:
Focus on sea quarks and *gluons*

The 3 pillars of EIC science

- **What role do sea quarks and gluons play in nucleon structure?**
  - Spin, 3D imaging, angular momentum
- **What are the properties of fundamental QCD nuclear color fields?**
  - Shadowing, gluon saturation, universal "gluonic matter"
- **How does colored radiation:**
  - **interact with QCD matter?**
  - **materialize into colorless hadrons?**
  - Parton and hadron propagation in the nuclear medium
  - Using jets to characterize the nucleus color structure

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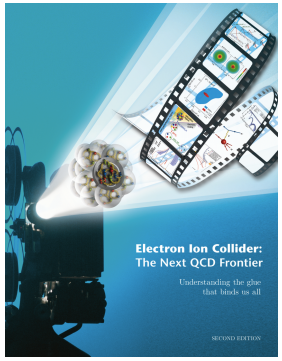
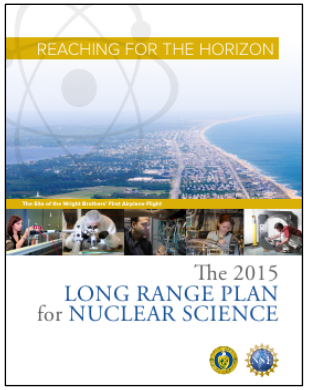
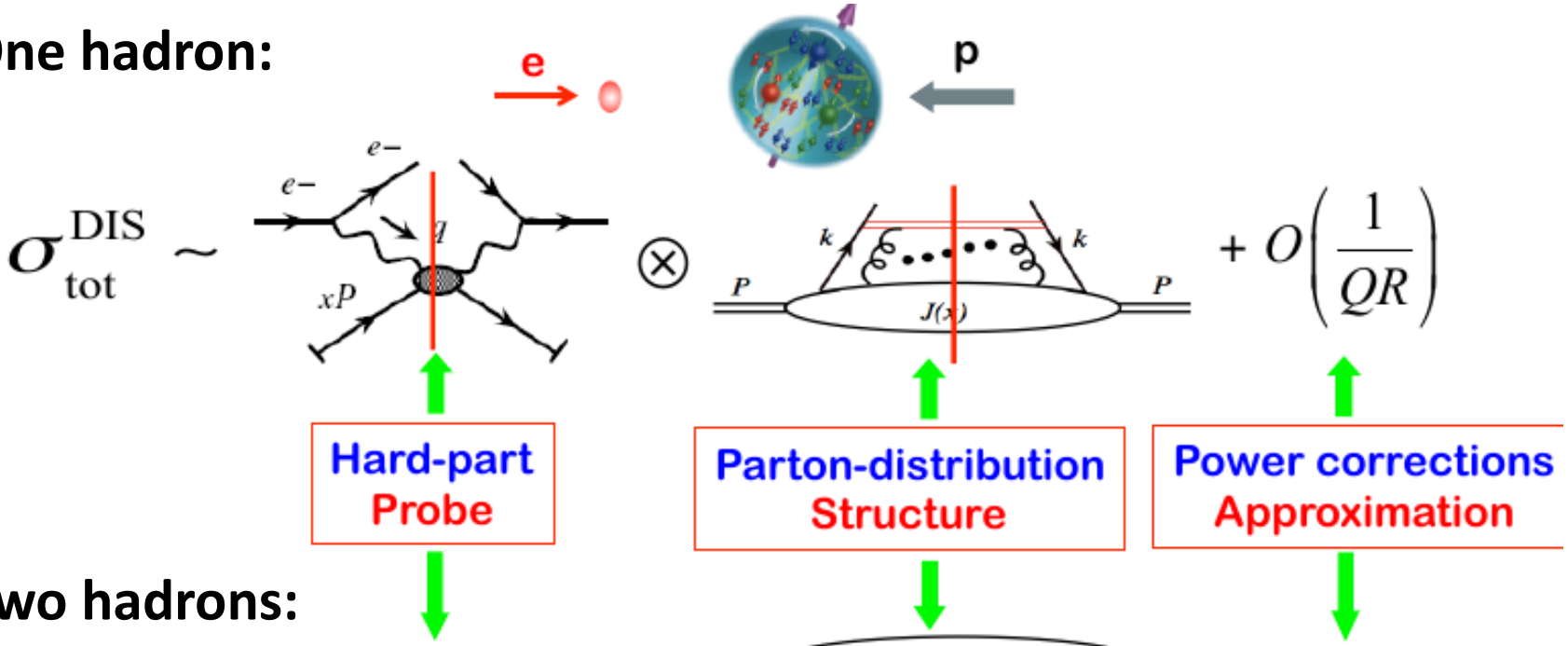


White Paper : 1212.1701/EPJA 2016

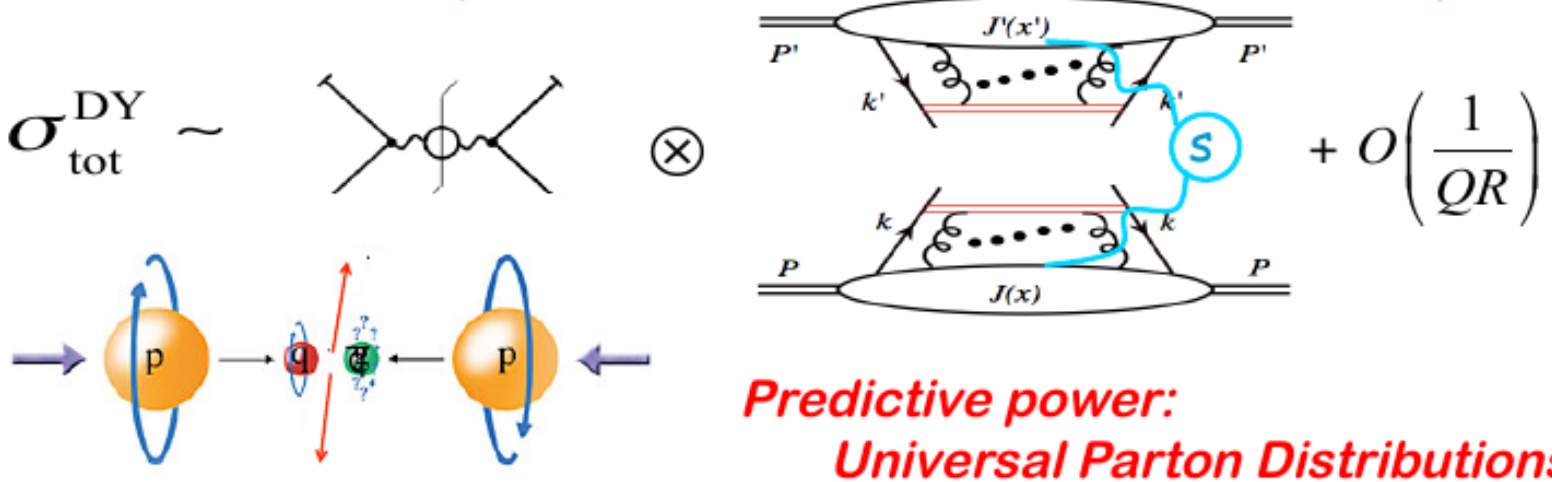


QCD factorization: connecting hadrons to partons

- **One hadron:**



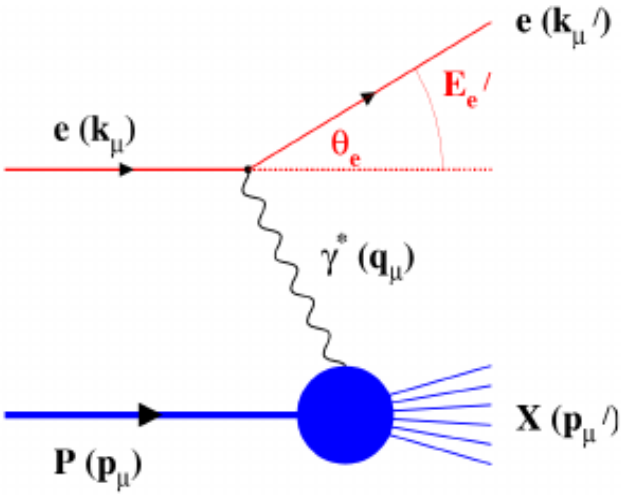
- **Two hadrons:**



Predictive power:
Universal Parton Distributions

Many complementary probes at one facility

- **Lepton-hadron collisions – many factorizable observables**



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

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

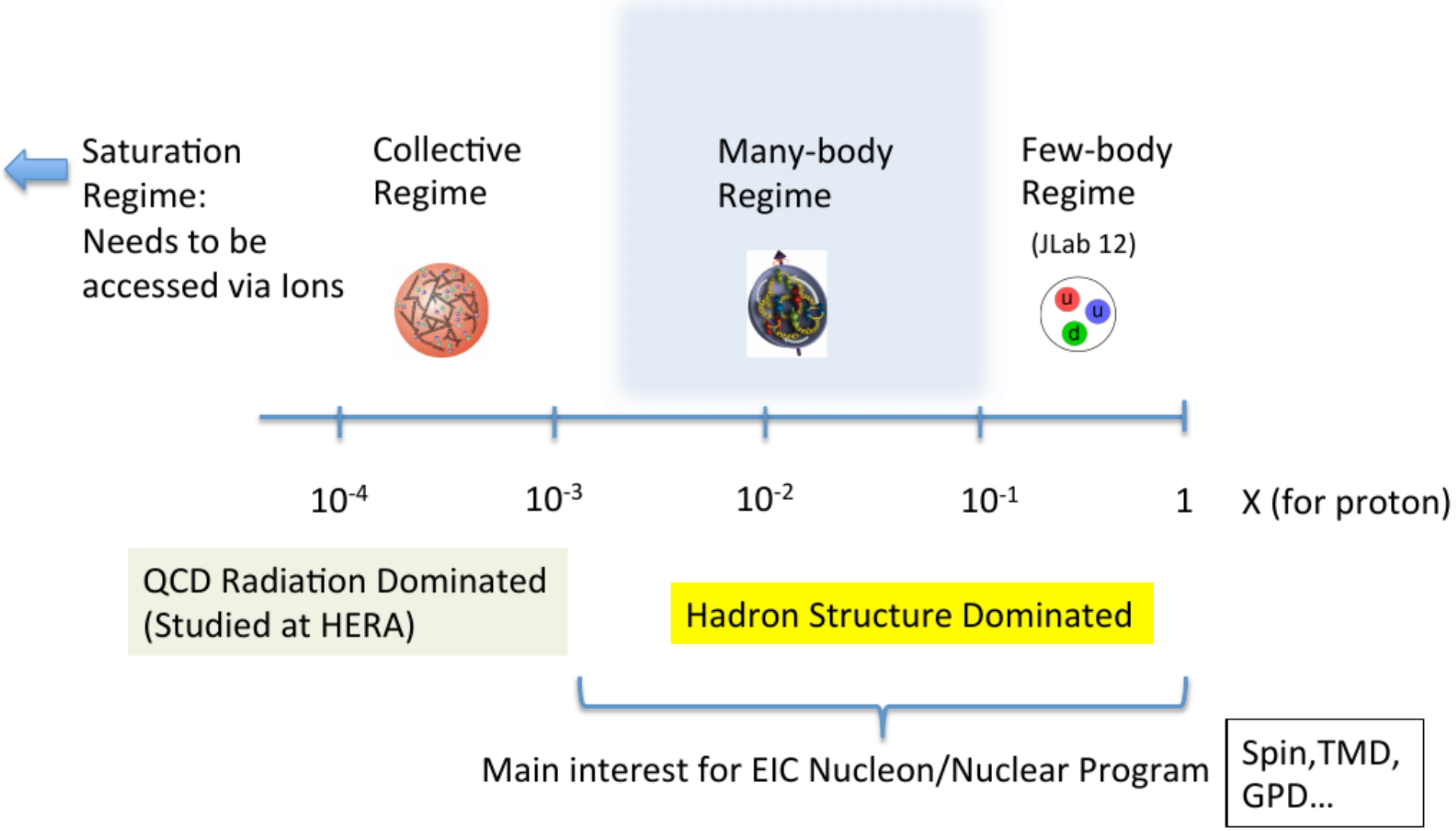
Detect the scattered lepton in coincidence with identified hadrons/jets

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

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

Where does EIC need to be in x ?

- *x* measures the fraction of proton momentum carried by partons



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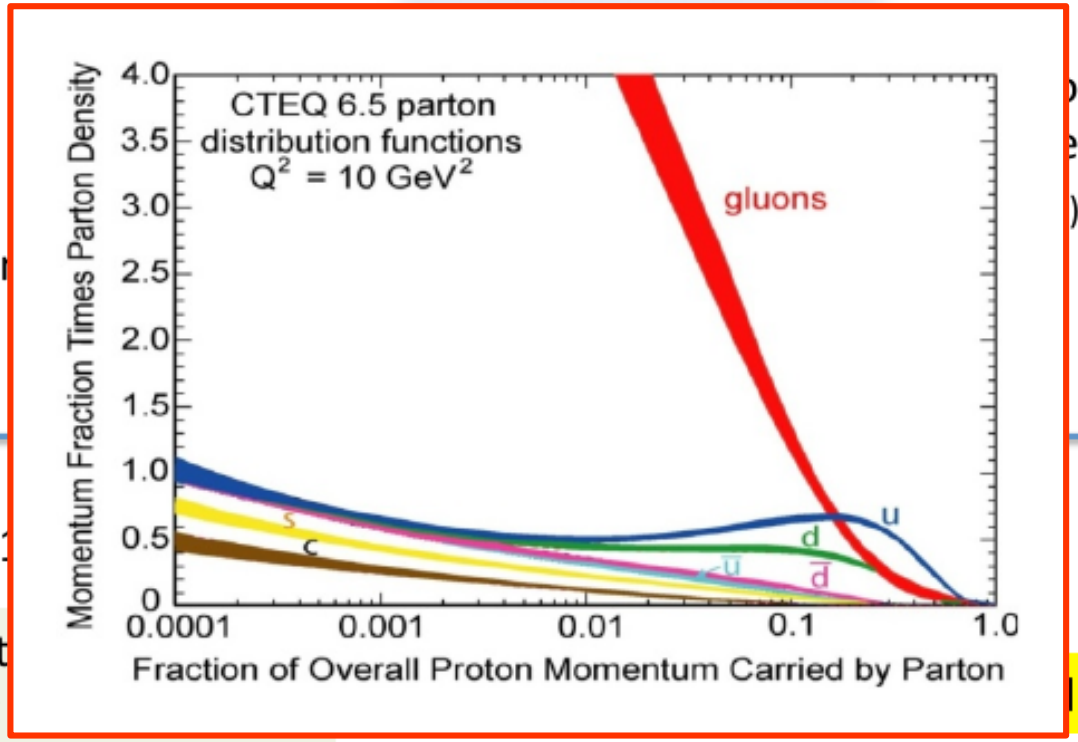
Saturation Regime: Needs to be accessed via lo



1 X (for proton)

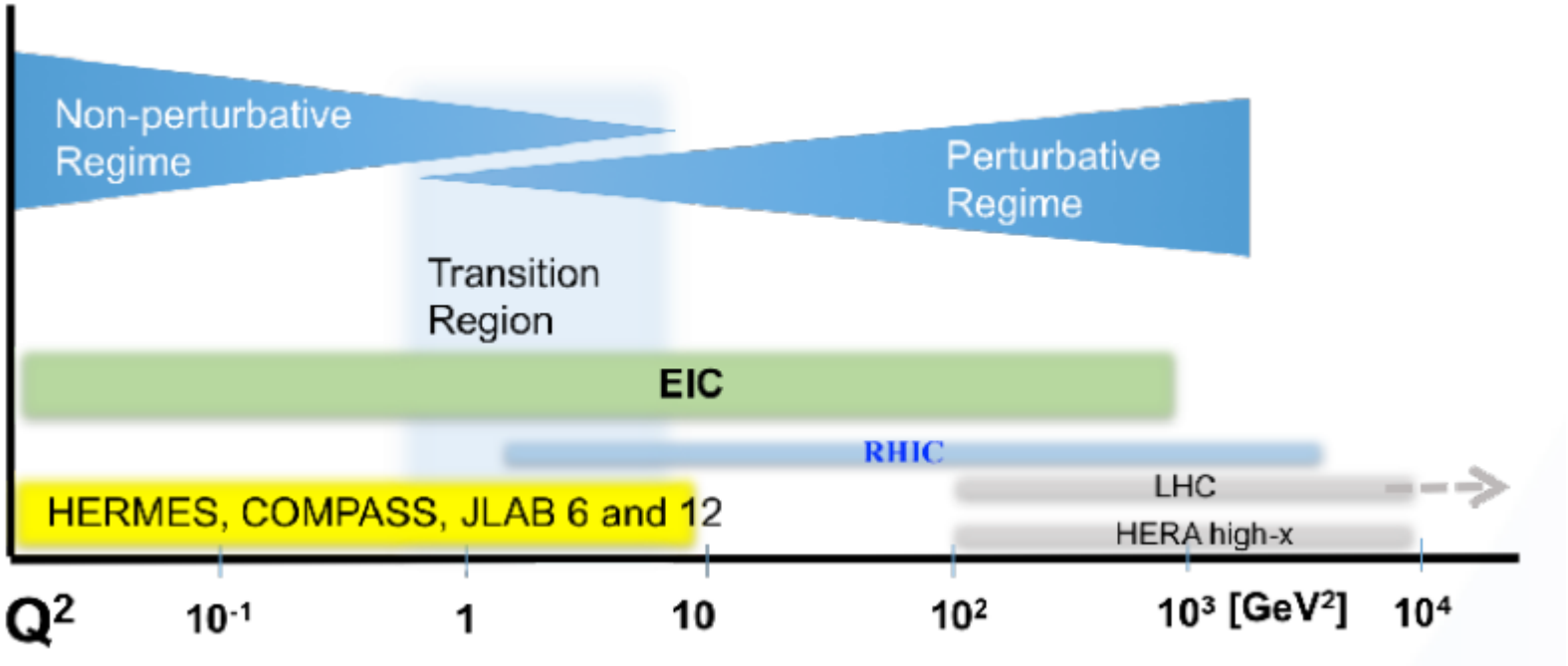
QCD Radiat
(Studied at

Main interest for EIC Nucleon/Nuclear Program

Spin,TMD, GPD…

Where does EIC need to be in Q^2 ?

- Q^2 provides factorization scale, transverse resolution



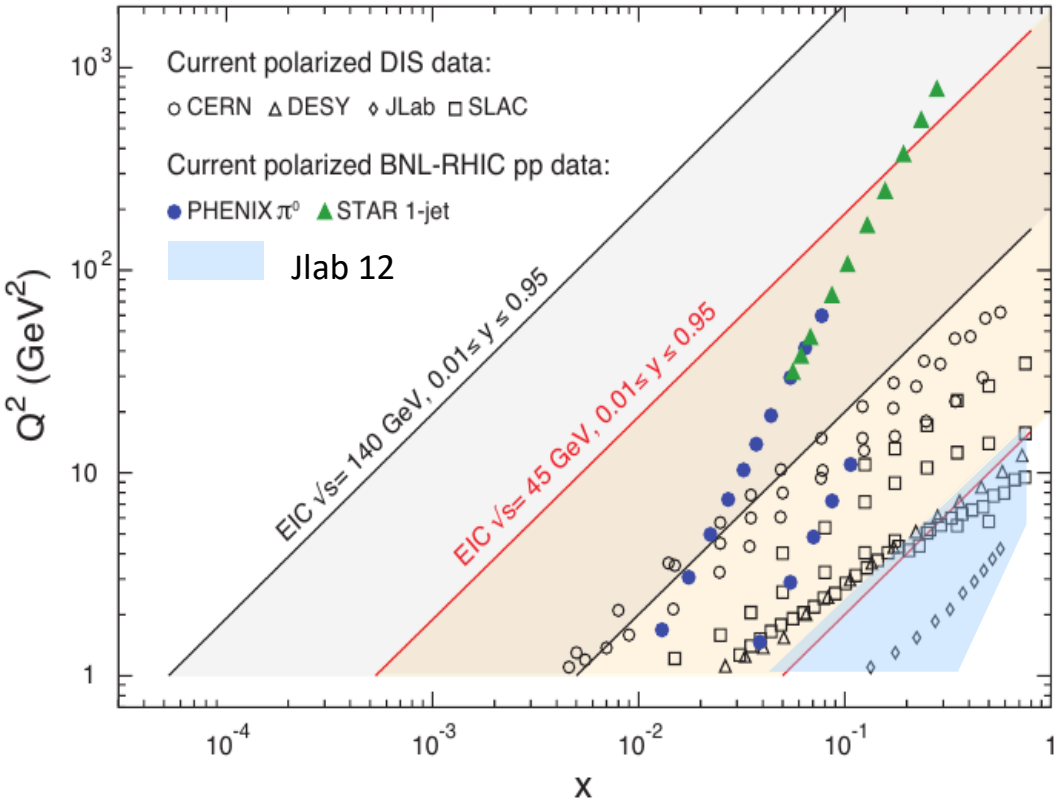
- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

Disentangle Pert./Non-pert., Leading Twist/Higher Twist

Where does EIC need to be in x and Q^2 ?

- The larger the energy, the larger the coverage ($Q^2 = s \times y$)
  - But cross section $\sigma \sim 1 / (x\, Q^4)$
  - Detector resolution limits $y > y_{min}$

→ need the (right) energy range



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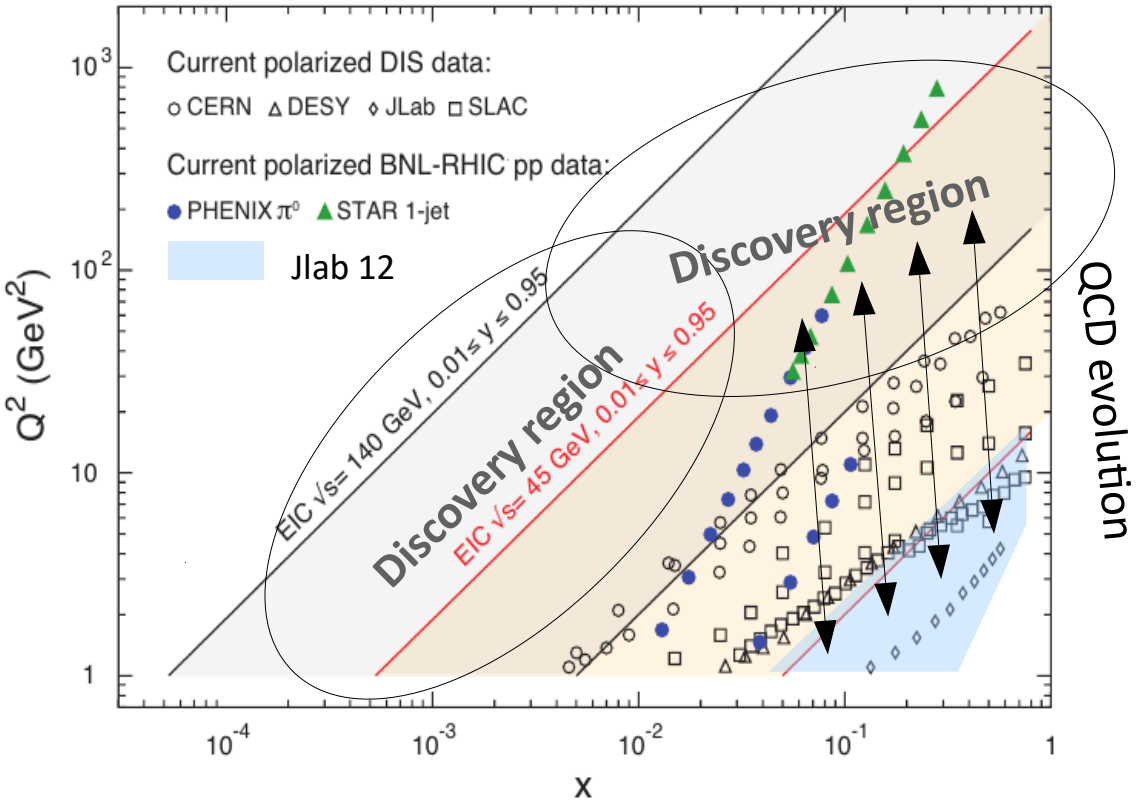
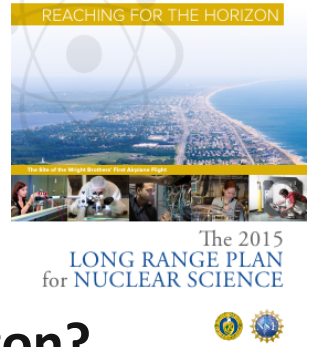


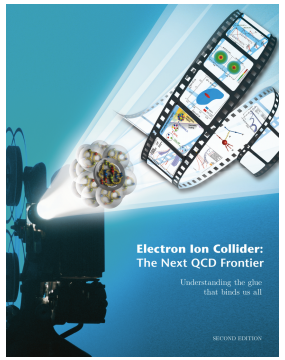
From large to small x, roughly:

- Intrinsic strange, charm ?
- Why EMC?
- Why EMC correlates with
- Why antishadowing ?
- "nuclear pions" ?
- Short Range nucl. Forces?
- Flavor structure of qk sea
- Glue @ very large, small x
- …

Big questions and measurements

Big questions and measurements

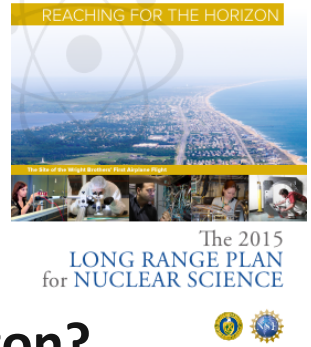


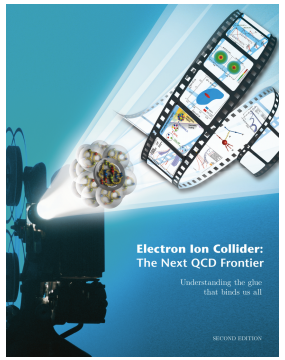


1212.1701/EPJA 2016

- **How does QCD generate the nucleon's spin?**
  - From 1D to 3D
- **How do quarks and gluons move inside a proton?**
  - SIDIS and Transverse Momentum Dependent parton distributions
- **What's the gluon radius of a proton?**
  - Exclusive processes, Generalized Parton Dist's, and proton "imaging"
- **How does nuclear binding affect quarks and gluons?**
  How do q&g contribute to nucleon-nucleon forces?
- **What happens to gluons and quarks in a high energy nucleus?**
  - Universal, saturated gluon matter? What about sea quarks?
- **How do color charges propagate, shower, hadronize?**
  - Nuclei as femto-detectors of hadron formation, parton showering
  - Jets as probes of nuclear matter

Big questions and measurements





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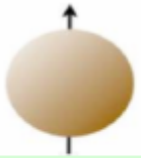
How does QCD generate the nucleon's spin?

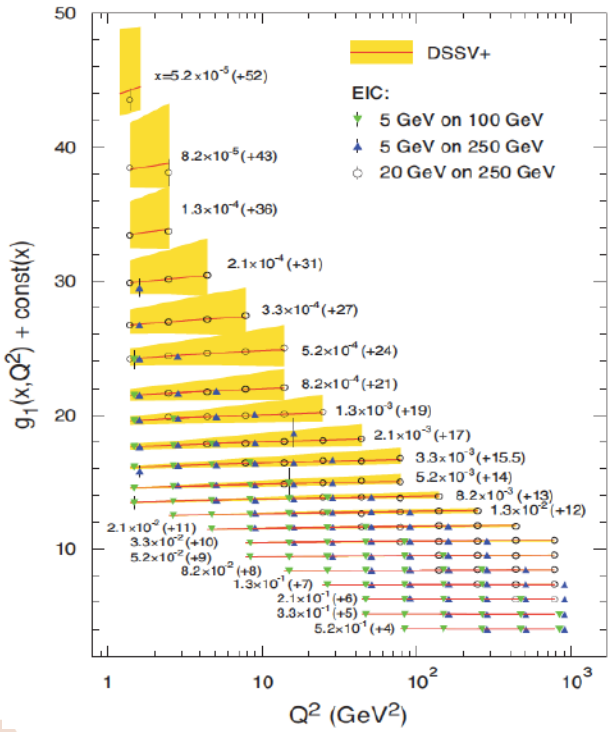
- Spin decomposition

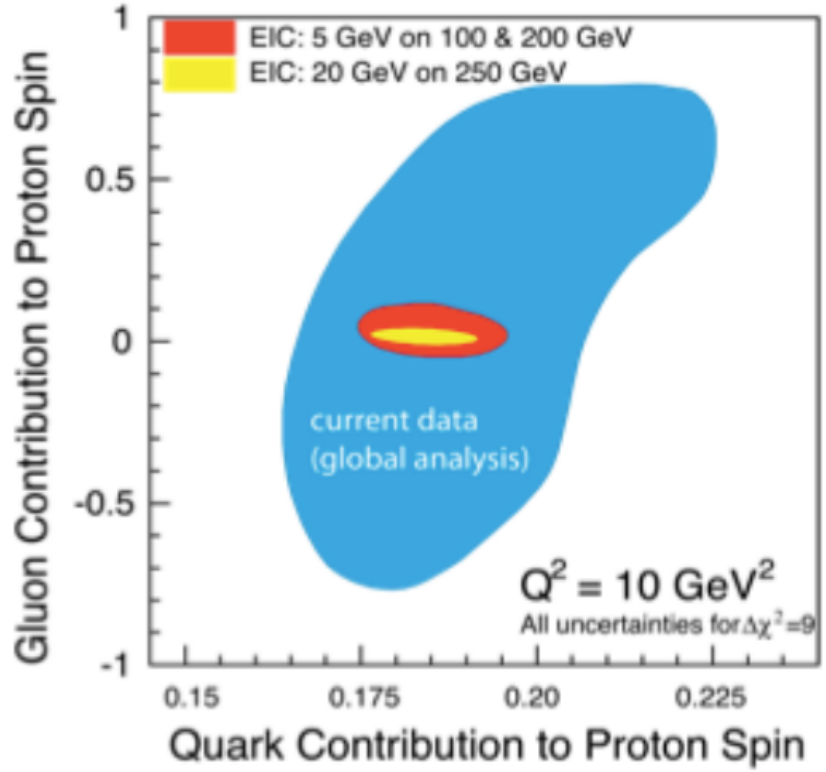


Proton Spin

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

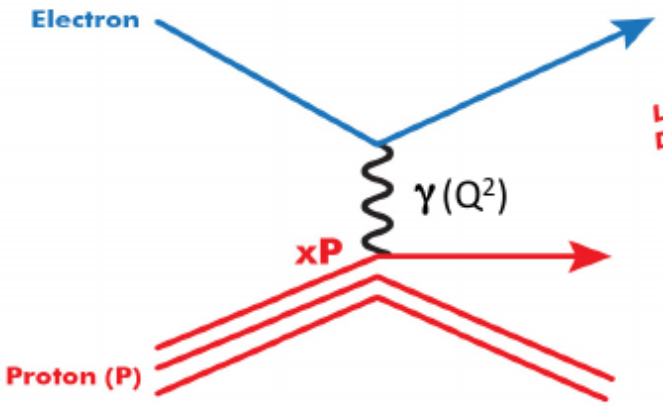
- What can EIC do?

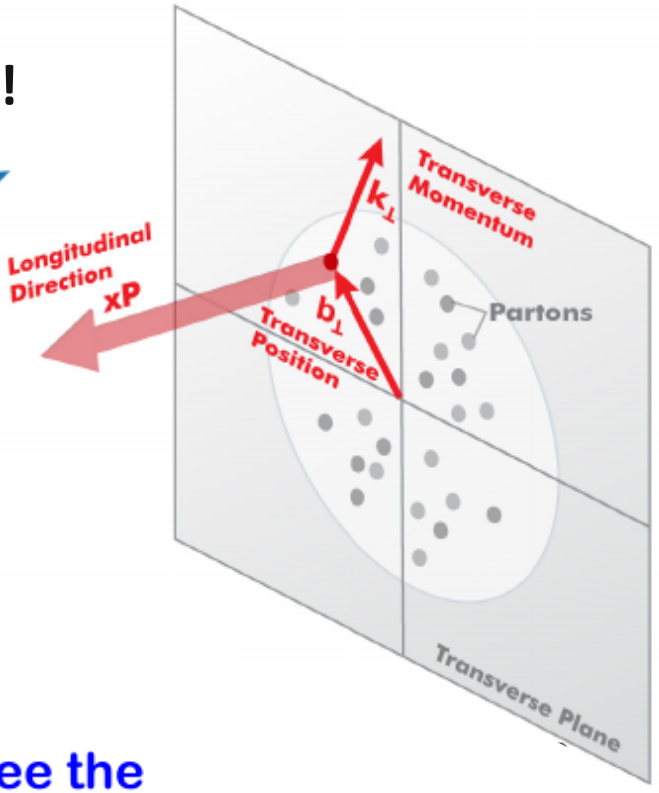




Two-scale observables

- Need to understand the confined motion of quarks and gluons in QCD
  - TMDs, GTMDs, …
- Need "probes" for **two-scale observables!**





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

✧ **Hard scale:** Q_1 **localizes the probe to see the particle nature of quarks/gluons**

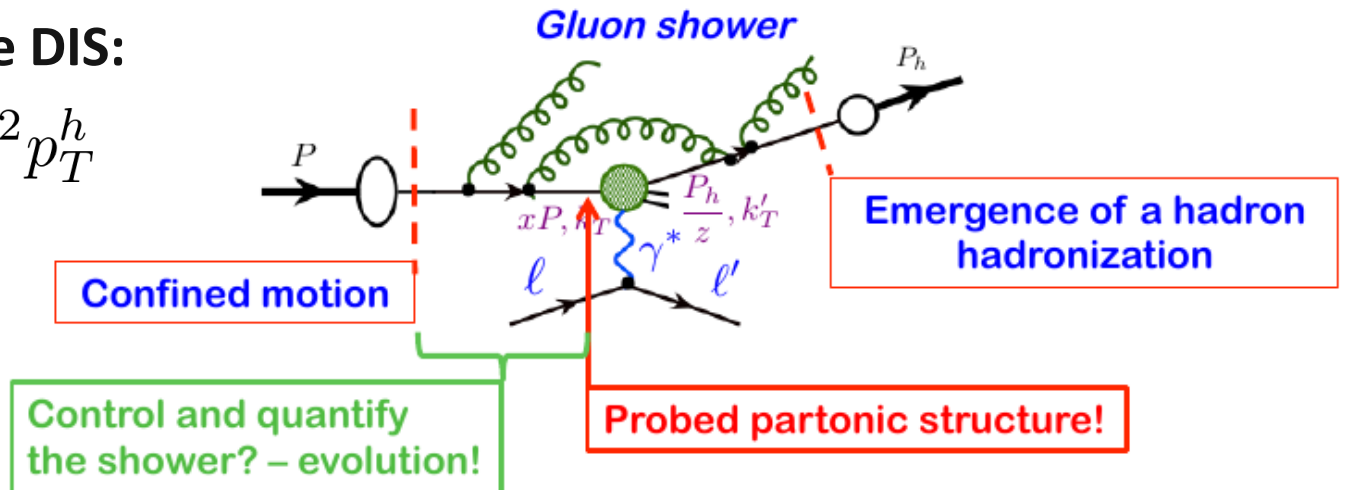
✧ **"Soft" scale:** Q_2 **could be more sensitive to the scale of confined motion**

High lumi needed!

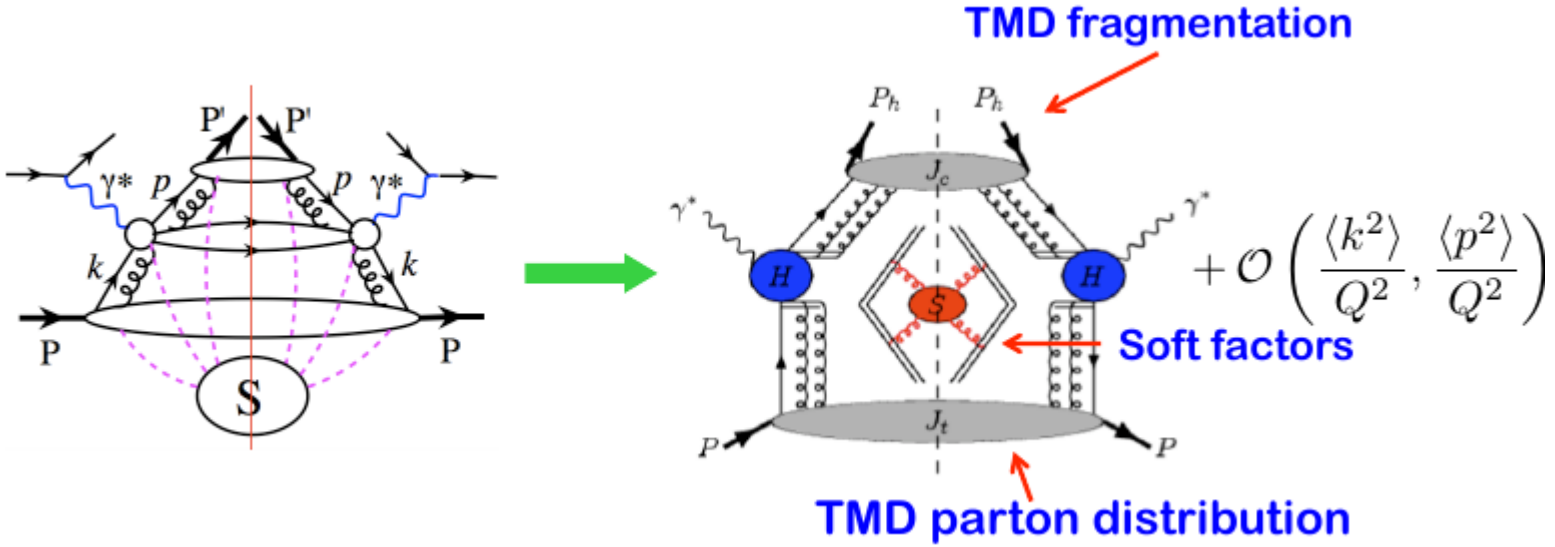
SIDIS and quark angular momentum

- **Semi-inclusive DIS:**

$$d\sigma / dx dQ^2 d^2 p_T^h$$

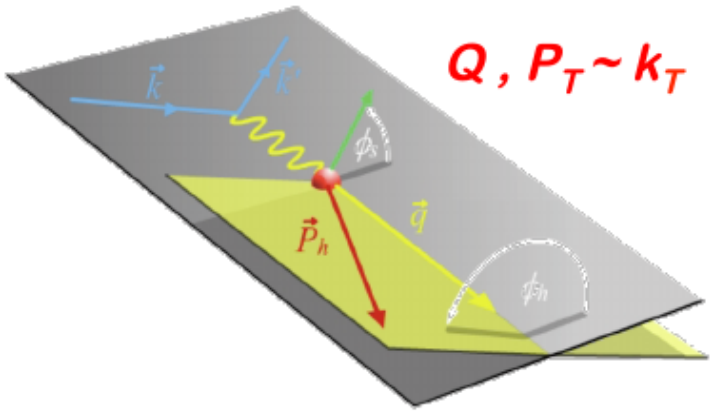


- Factorization of **"Transverse Momentum Dependent distributions"**



SIDIS and quark angular momentum

- Naturally, two planes, good control of the physics to probe, …



Q , $P_T \sim k_T$

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

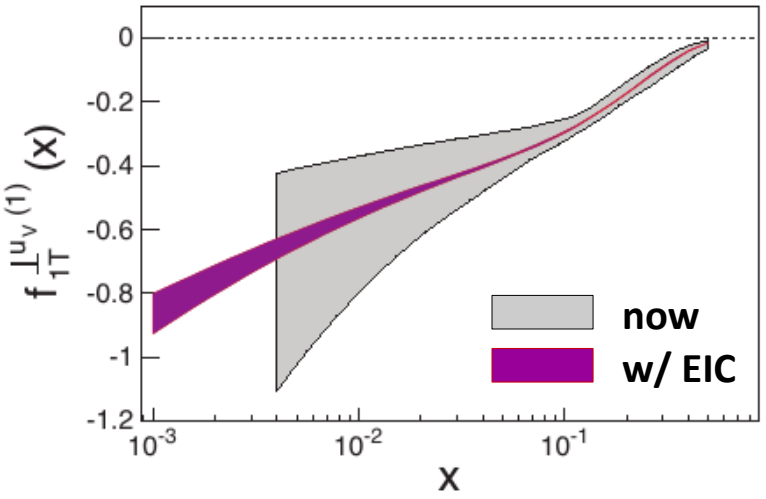
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

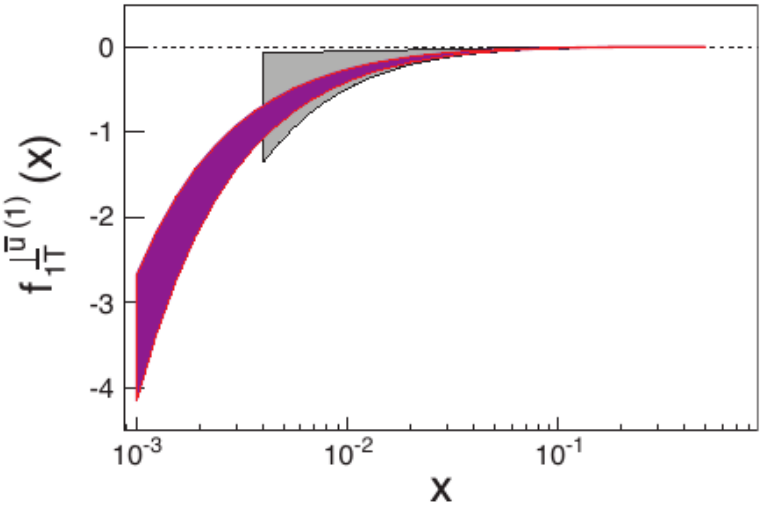
$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$

Semi-inclusive DIS

Separation of TMDs!

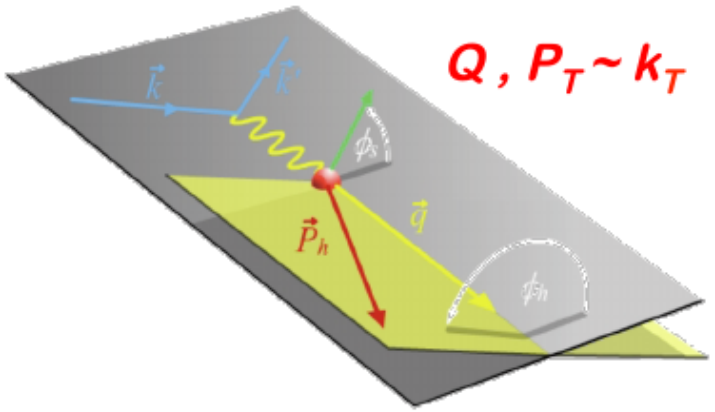
- Sivers function:





SIDIS and quark angular momentum

- Naturally, two planes, good control of the physics to probe, …



Q, $P_T \sim k_T$

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

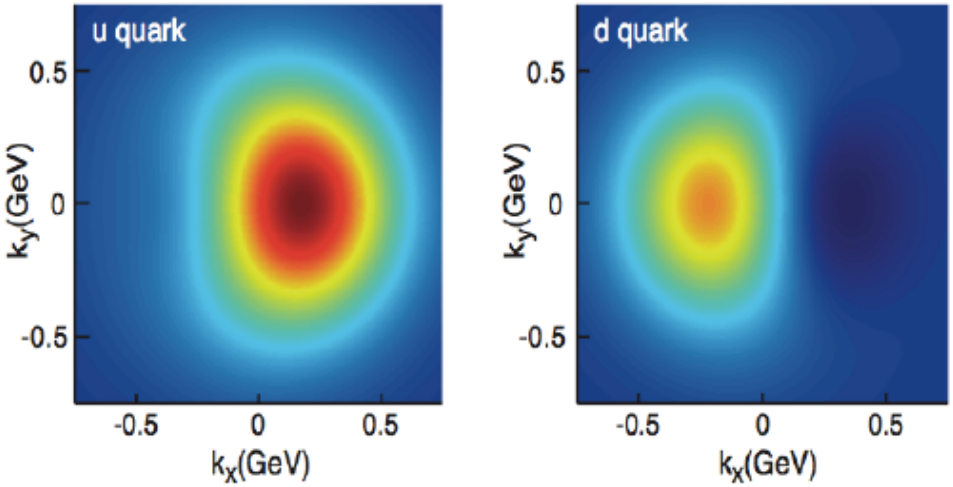
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$

Semi-inclusive DIS

Separation of TMDs!

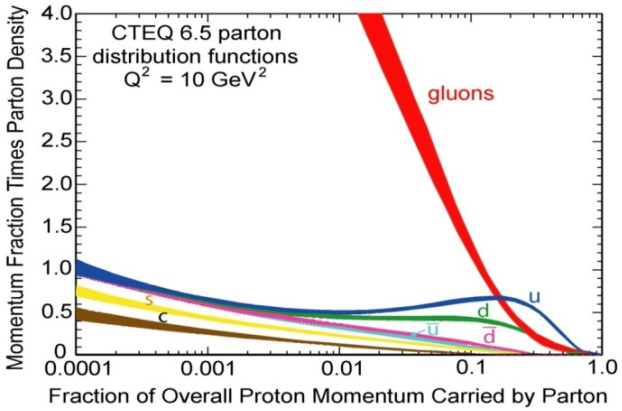
- Sivers function:



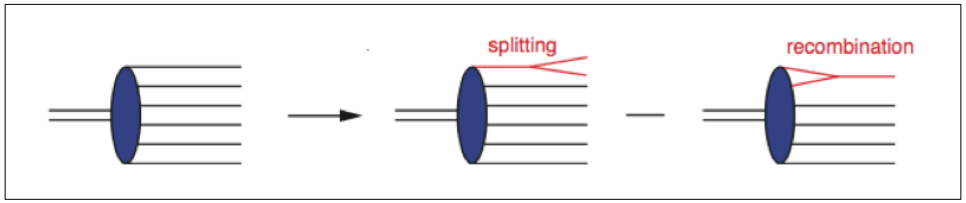
Density distribution of an unpolarized quark in a proton moving in z direction and polarized in y-direction

Correlation between hadronic property and partonic dynamics

QCD at extremes: gluon saturation



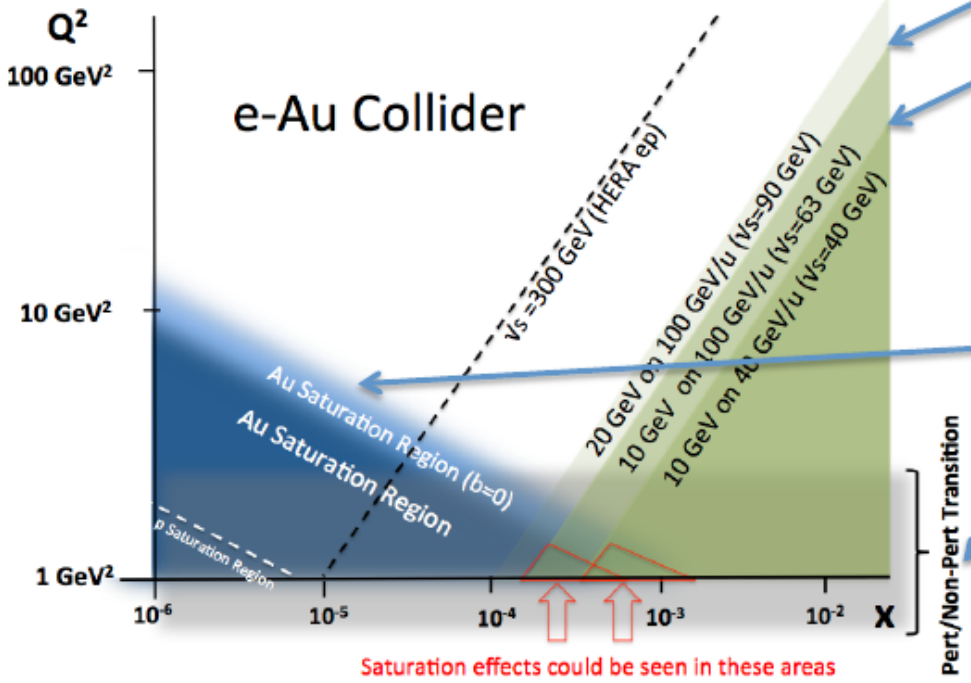
HERA discovered a dramatic rise in the number of gluons carrying a small fractional longitudinal momentum of the proton (i.e. small-x).



This cannot go on forever as x decrease: parton recombination must balance splitting (saturation).
→ new effective theory,
e.g., Color Glass Condensate?

- Protons (or ions) enter the saturation regime at $Q < Q_s$, where the **saturation scale** depends on gluon density:
  $Q_s = Q_s(x)$ for protons, $Q_s = Q_s(x,A)$ for nuclei
- We need measurements at $Q_s >\sim 1$ GeV for pQCD interpretation.
- Maximum accessible Q_s^{max} is a very weak function of *x*

Saturation regime with nuclei at EIC



eRHIC baseline (10x250 GeV ep)

JLEIC baseline (10x100 GeV ep)

Two competing scales

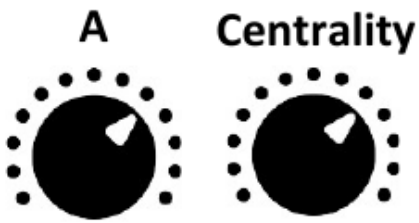
$Q_s(x)$: Saturation Scale

Q_0 : Perturtative when $Q > Q_0$

Ideally, x such that $Q_s >> Q_0$

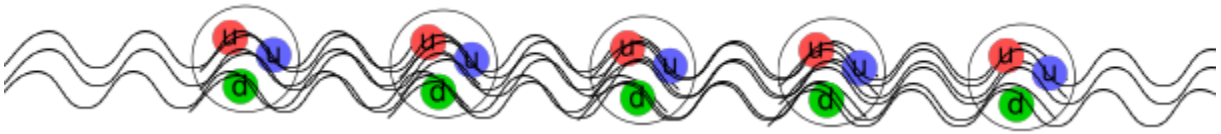
Difficult with EIC scenarios

EIC has two knobs to turn



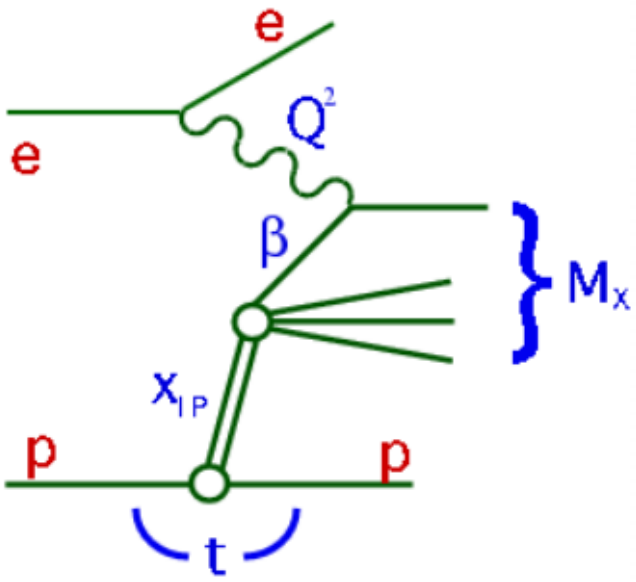
Investigate the on-set of saturation

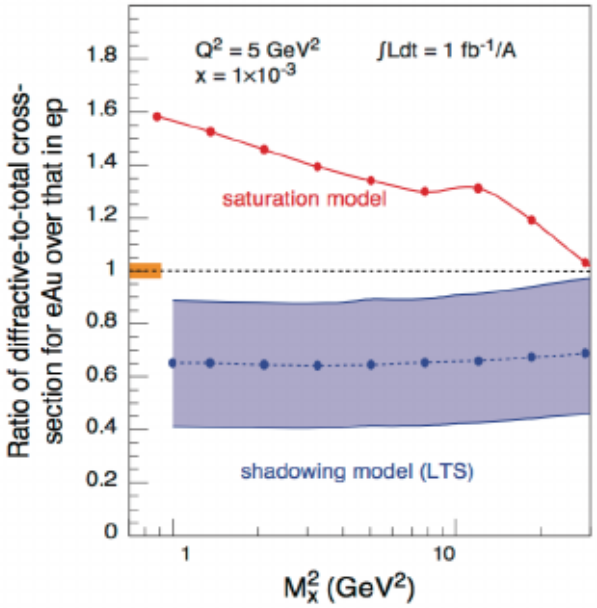
multi-nucleon coherence → saturation

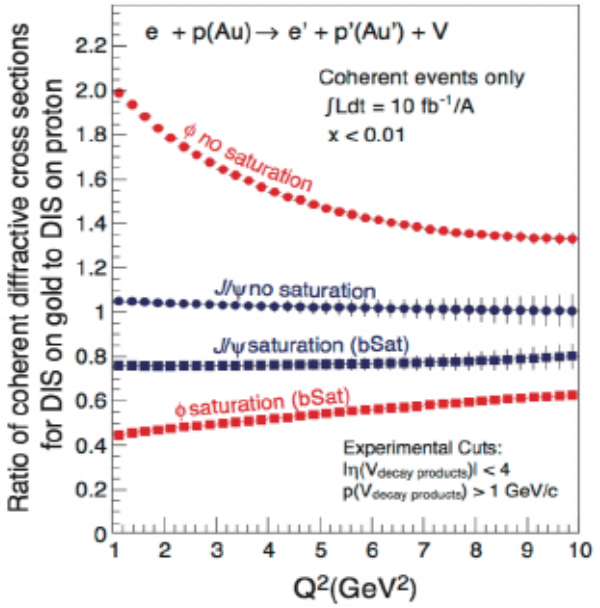


Saturation regime with nuclei at EIC

Signature for Saturation (among other things)







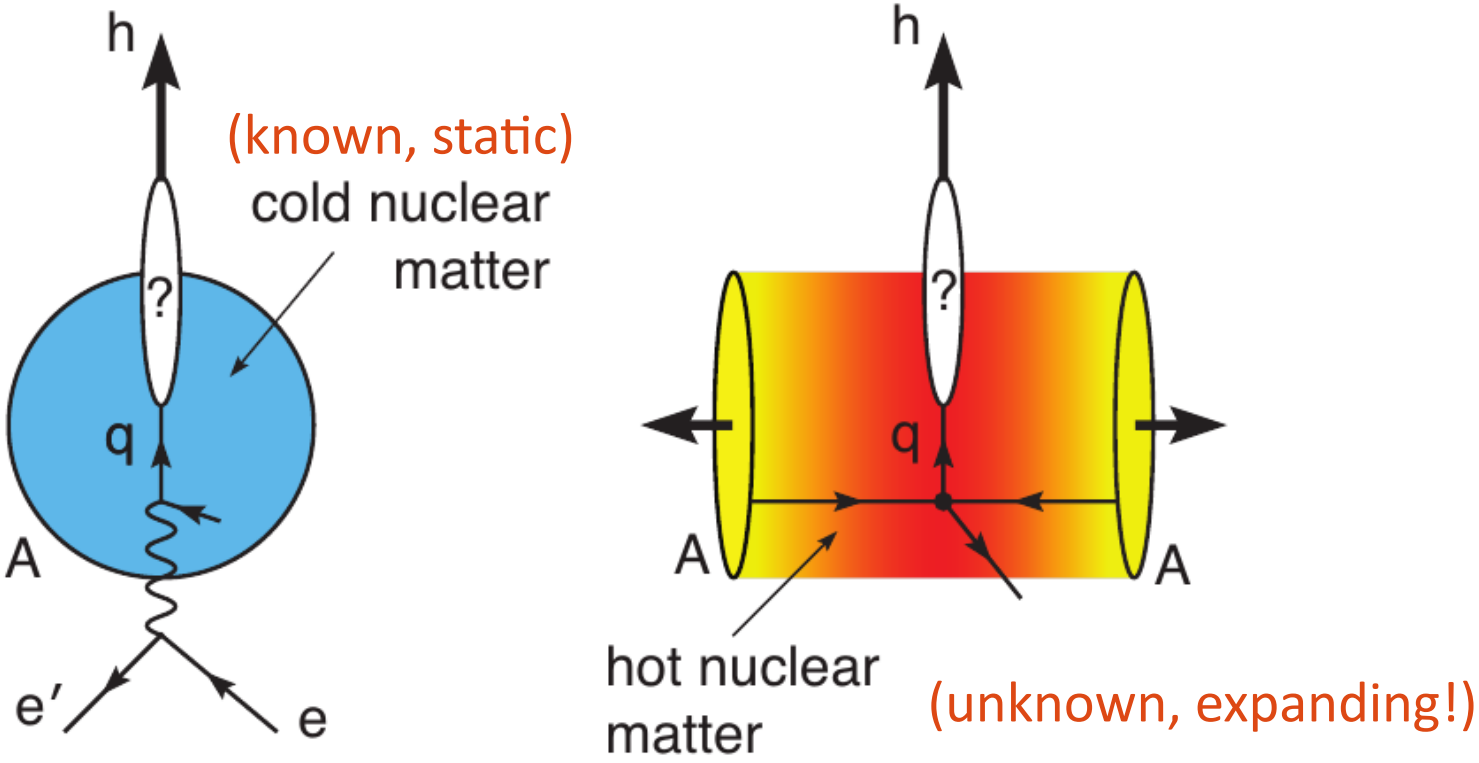
Vacuum quantum no. exchange

→ perturbatively like 2 gluons → **more sensitive to saturation than inclusive DIS**

Identify the scattered proton: distinguish from proton dissociation
Measure $\mathbf{X_L = E_p'/E_p}$, and $\mathbf{P_t}$ (or **t**) (equiv. to measuring M_x)

Color propagation in cold and hot nuclear matter

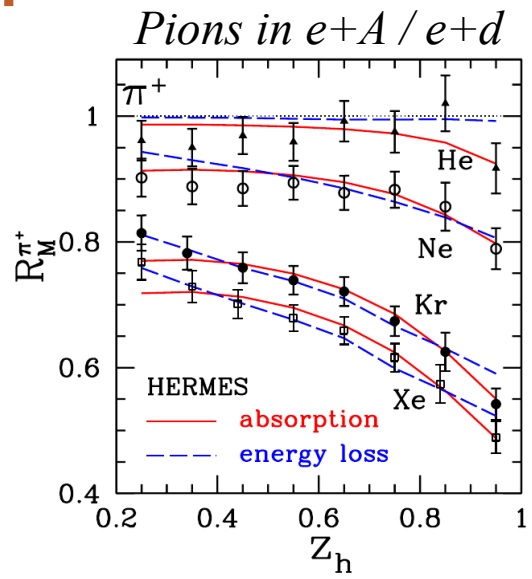
Review: Riv. Nuovo Cim. 032,2010

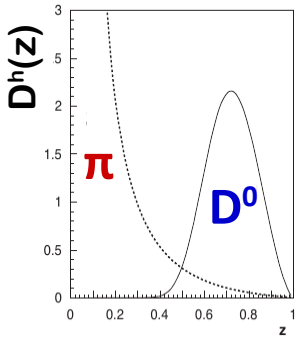


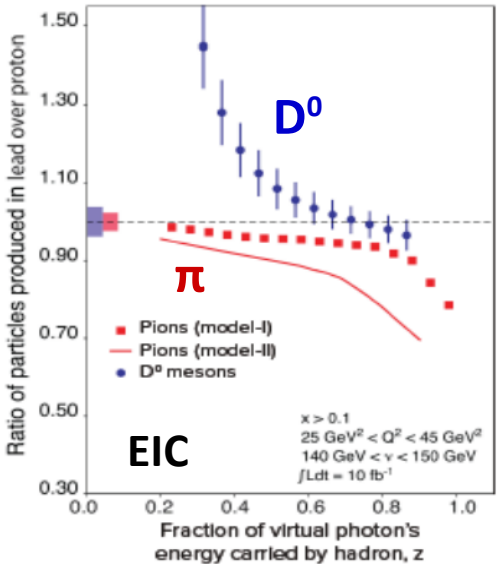
Need to calibrate the probe in e+A collisions !

The future: the Electron-Ion Collider

- **High luminosity → precision studies**
- **Larger energy → unique opportunities**
  - **Very large ν, Q^2 leverage**
    - Hadrons in and out of medium
    - Deep perturbative regime
  - **Heavy quarks**
    - B and D, J/Ψ
    - Dramatic difference in energy loss effects
    - Can detect D^0 formation time by progressively lowering *ν*

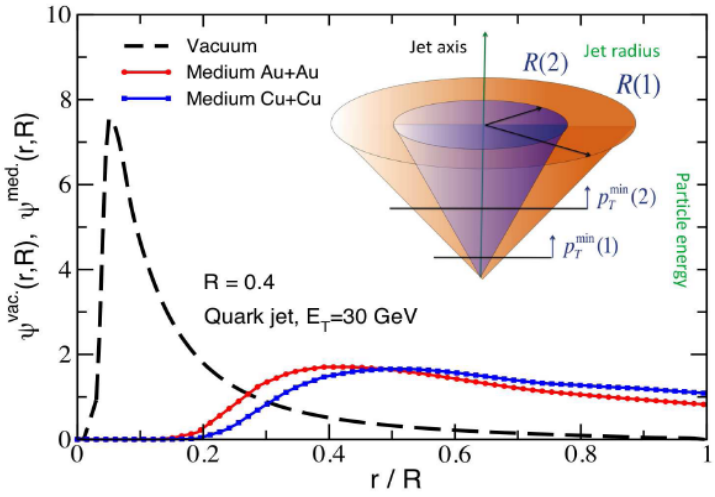


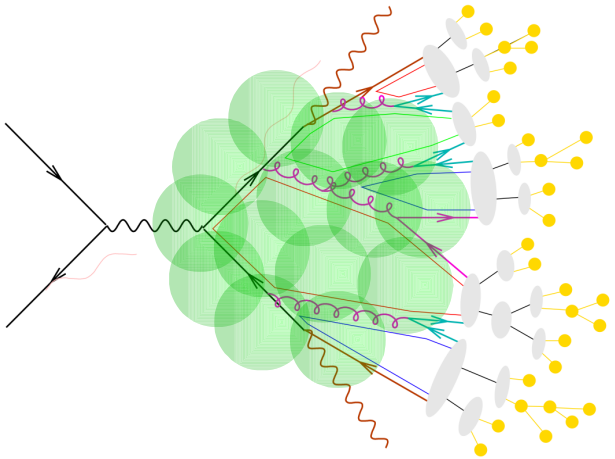




Jets: a unique EIC opportunity

- **More handles on energy loss**
  - *e.g.*, jet rates vs. cone:
    (gluon radiation broadens the jets)
- **Femto-detection of parton showering**
- **20 years of theory to be harvested**
  - Precise definitions of jets
  - Large choice of "jet shapes"
  - Soft Collinear Effective Theory (SCET)
- **In-medium color transport:**
  theory & pheno in A+A at RHIC, LHC





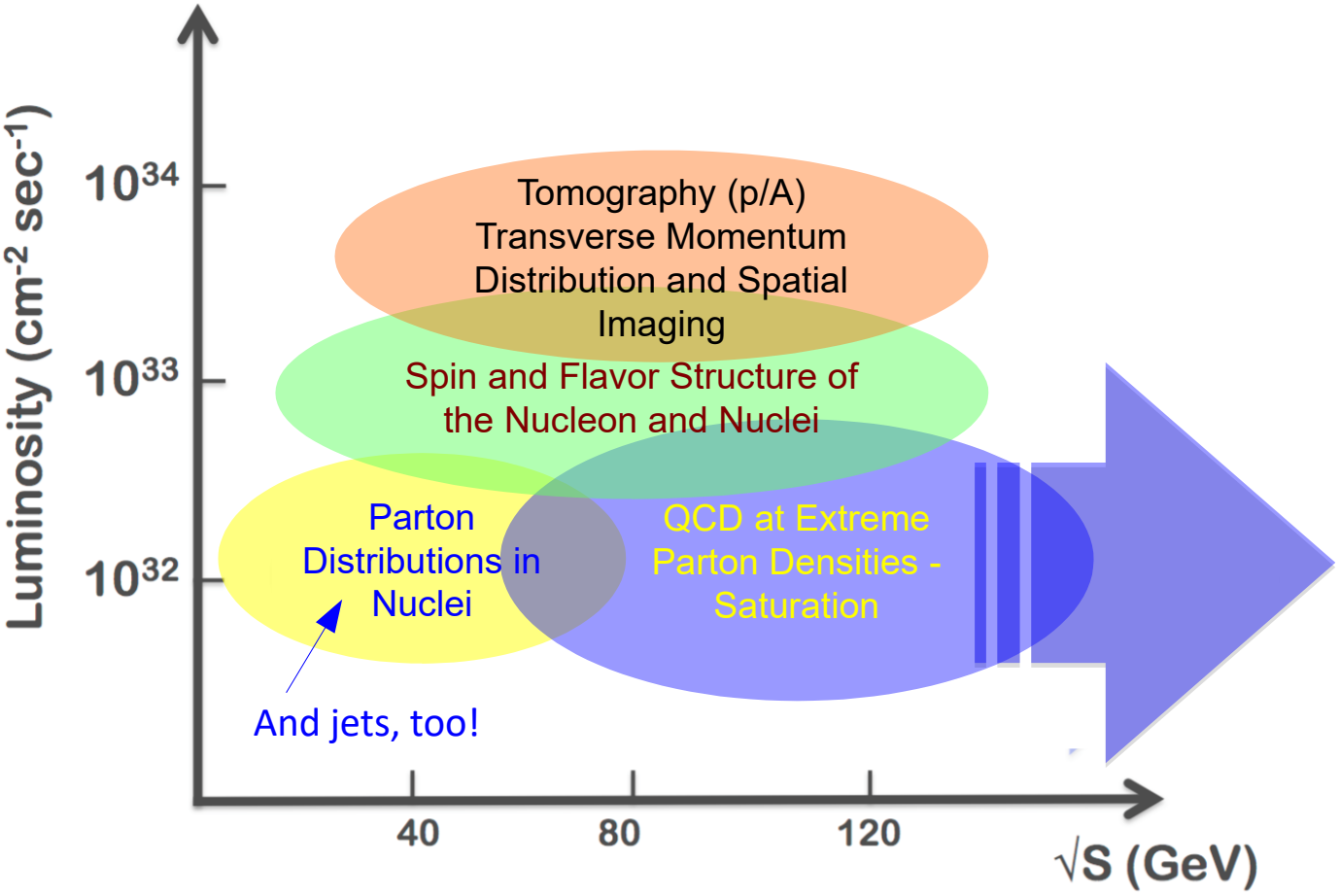
$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0) \right\rangle$$

$$\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle i U^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0) \right\rangle$$

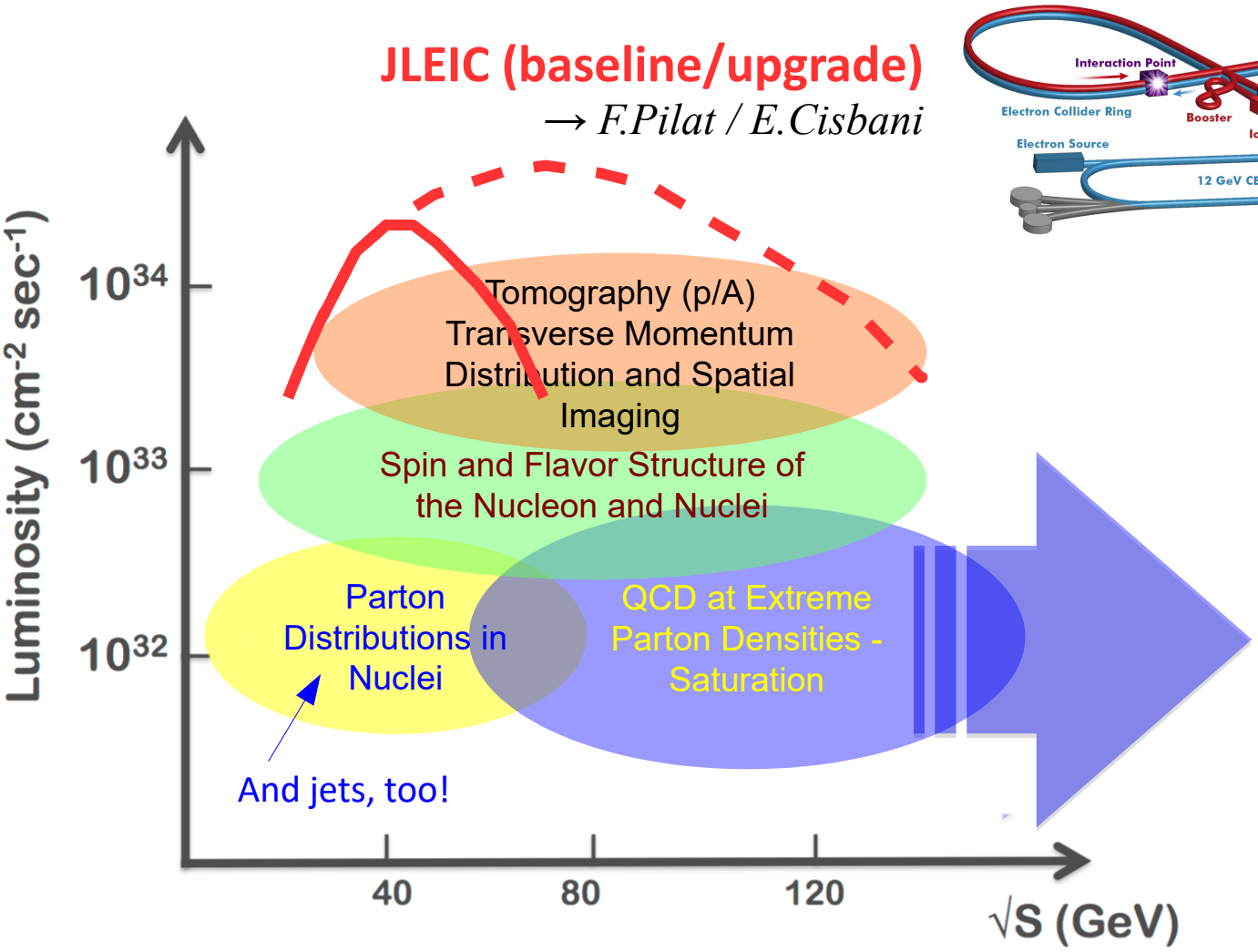
$$\kappa = \frac{4\pi\alpha_s}{3N_c} \int d\tau \left\langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b \right\rangle$$

Summary and Epilogue

The EIC science matrix



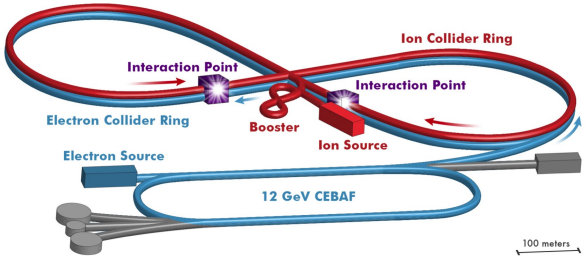
The EIC science matrix

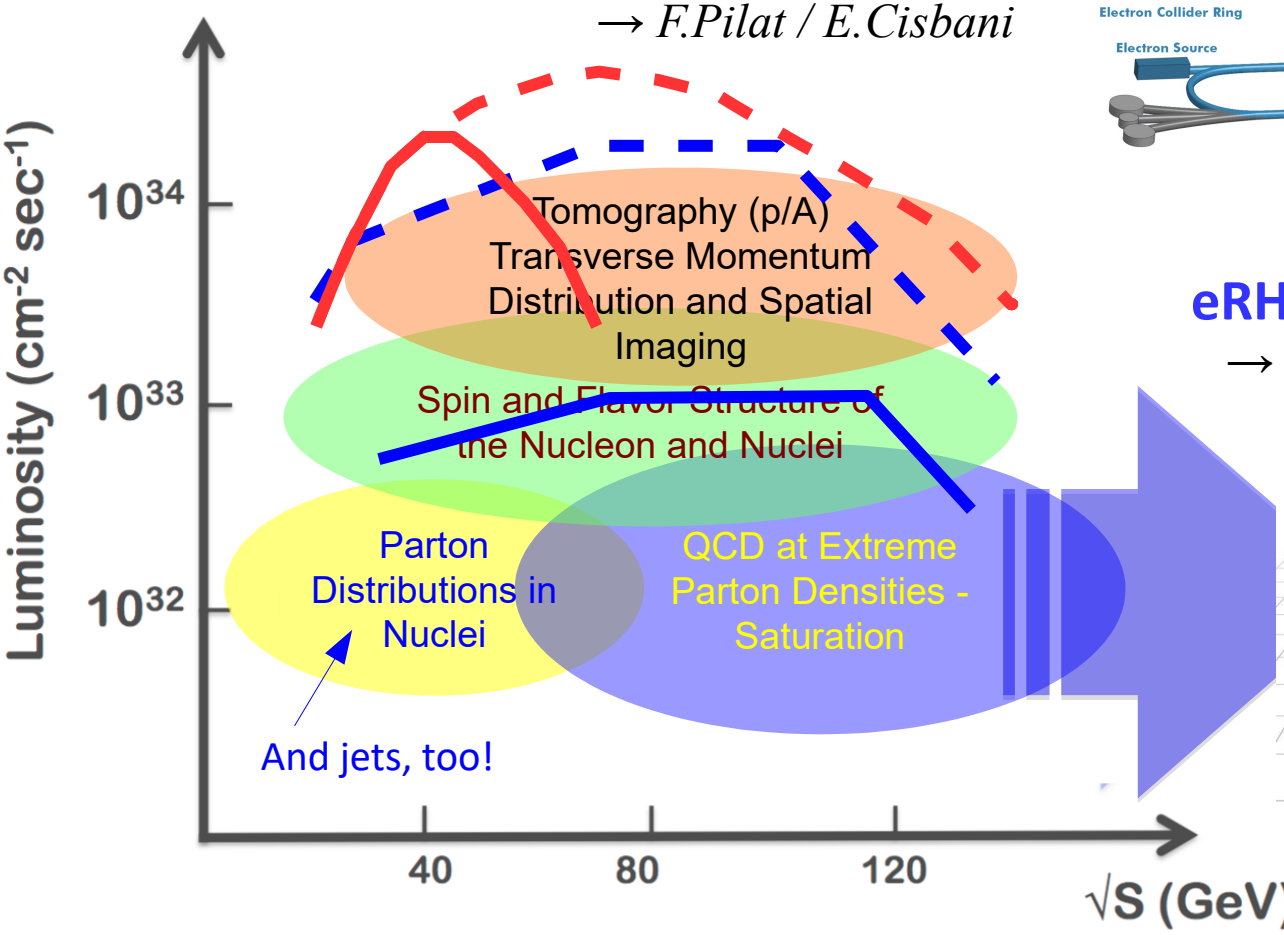


The EIC science matrix

JLEIC (baseline/upgrade)

→ *F.Pilat / E.Cisbani*

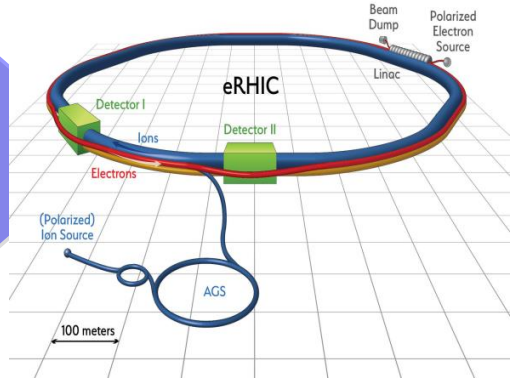




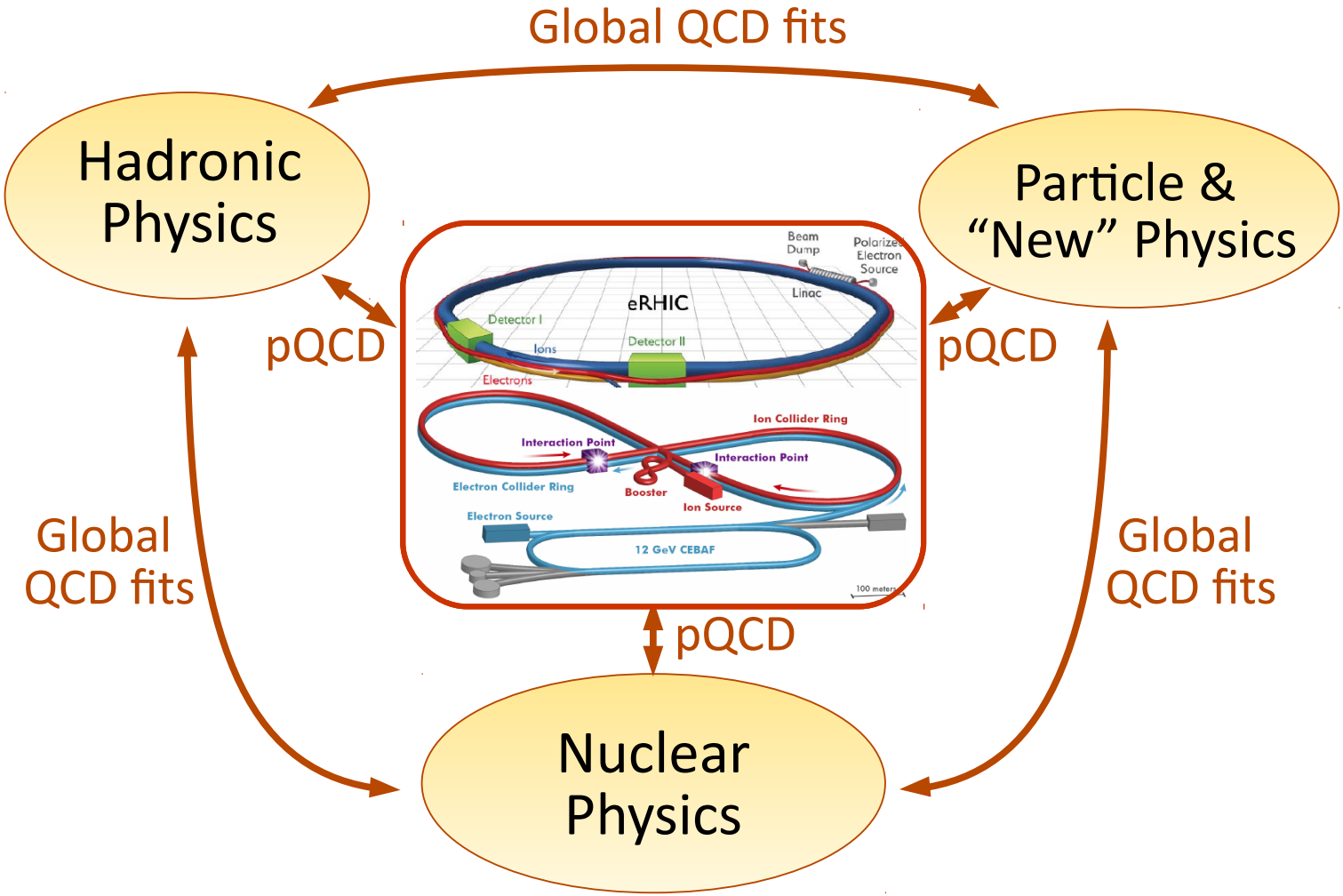
eRHIC (initial/ultimate)

→ *B.Muller, POETIC 2016*

→ *S. Dalla Torre*

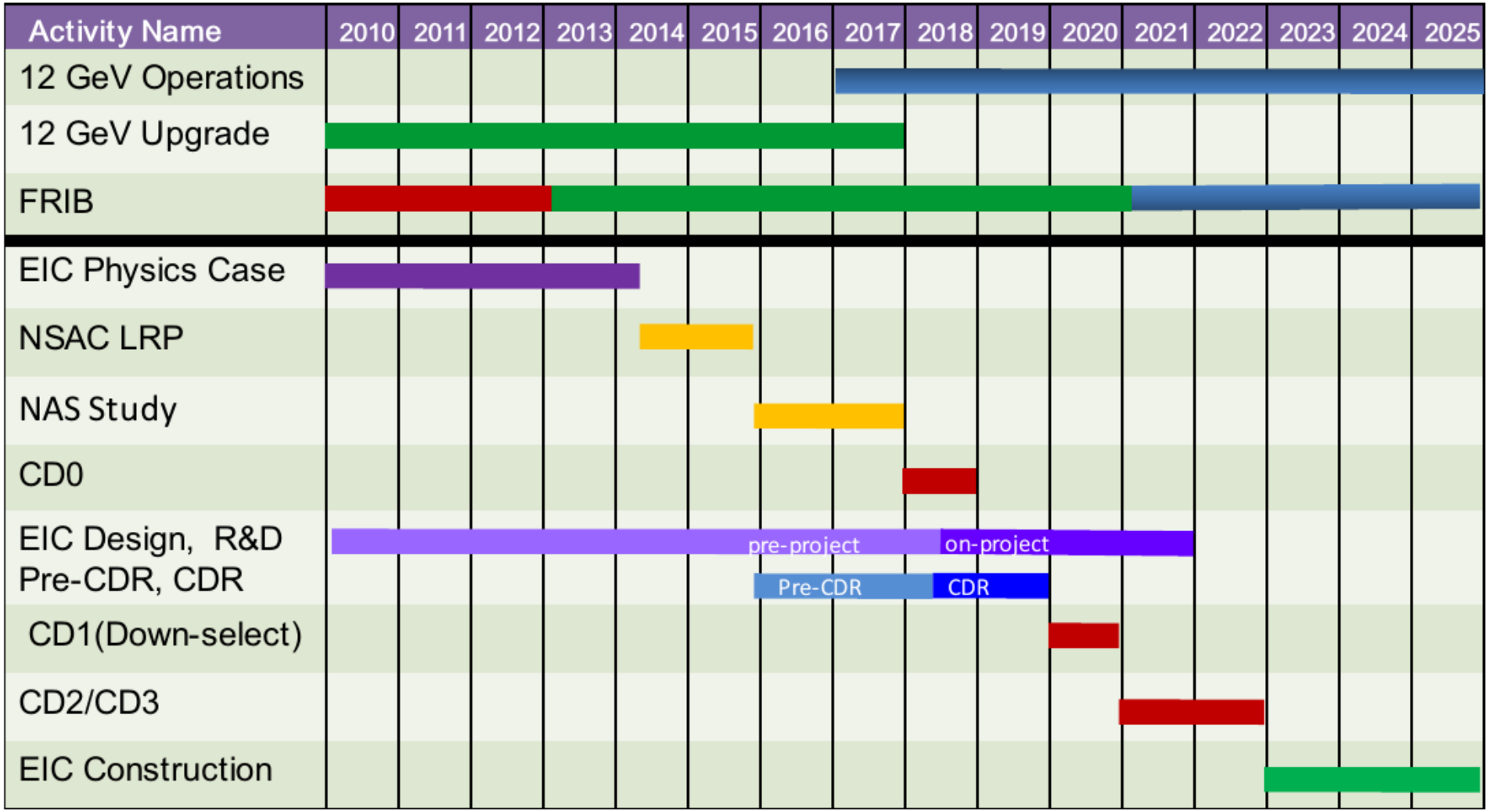


An EIC to bind them all!



JLEIC possible timeline (eRHIC similar)

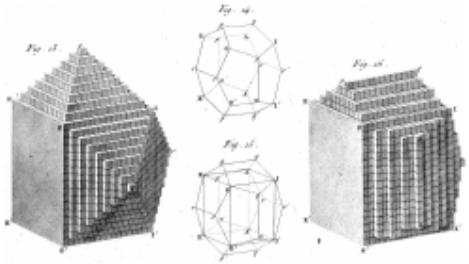
Updated: 1/13/17



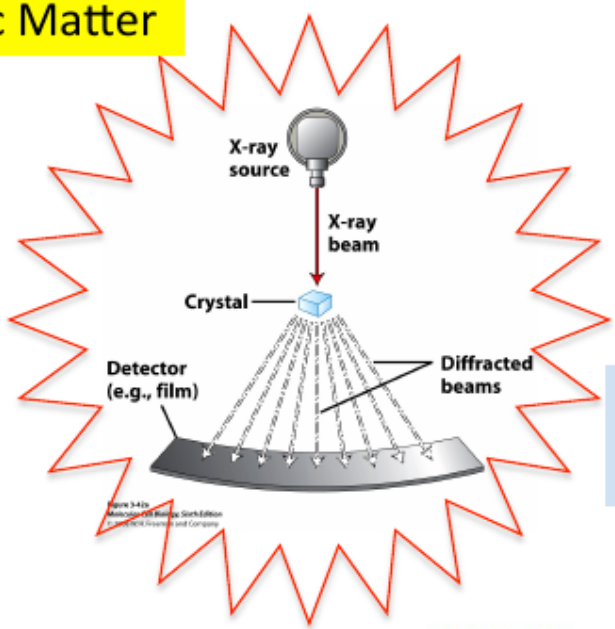
CD0 = DOE "Mission Need" statement; **CD1** = design choice and site selection
CD2/CD3 = establish project baseline cost and schedule

New probes, new science

Example: Structure of Atomic Matter

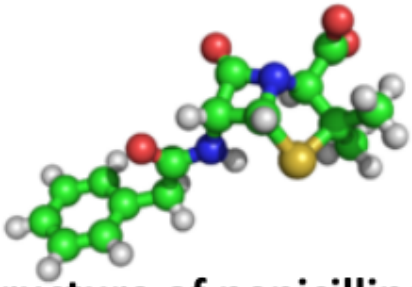


Crystal Structure: 1801

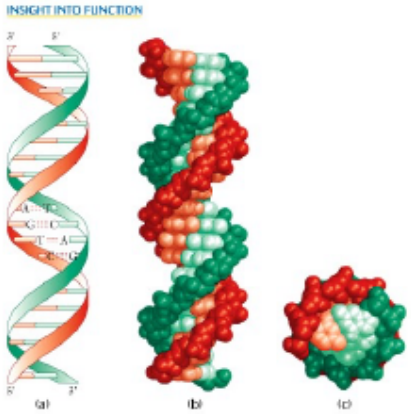


Advent of X-ray Diff. 1912

Probe with the right scale!



3D structure of penicillin: 1945

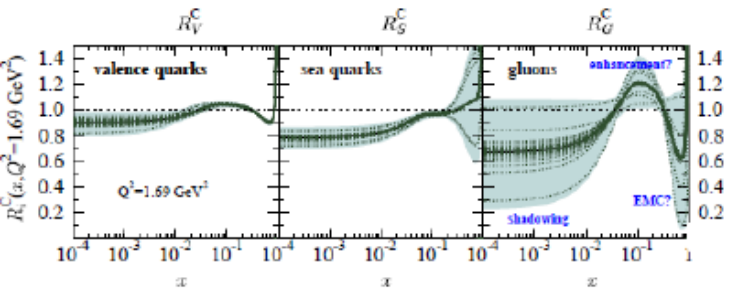


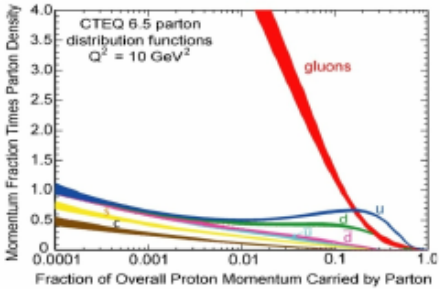
Double Helix: 1953

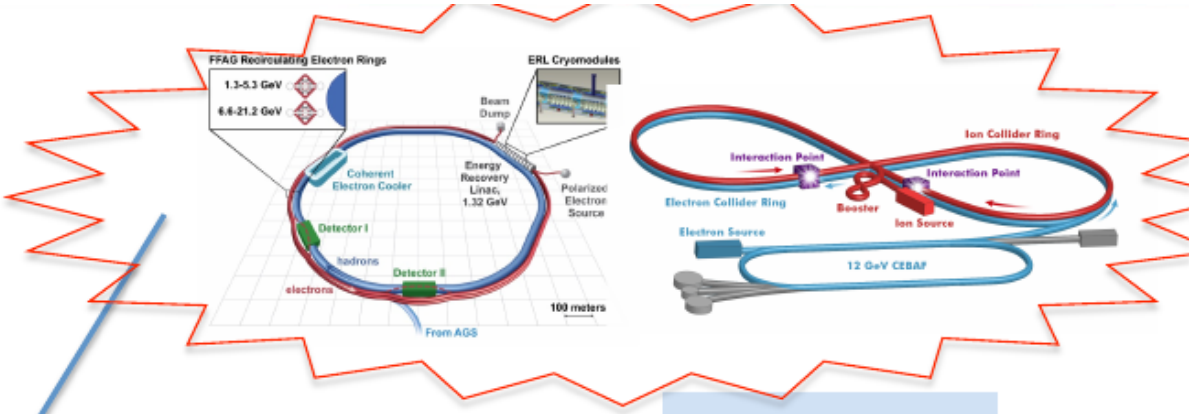
Precise understanding of structure leads to rich new sciences

New probes, new science

2016

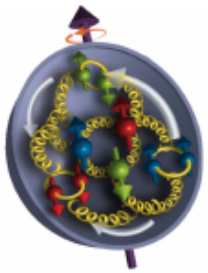


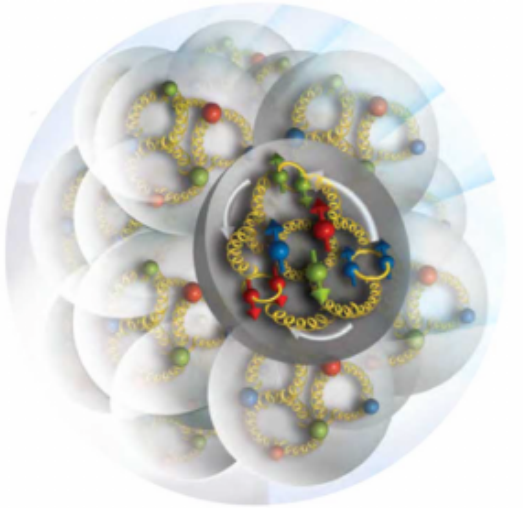




Advent of EIC: ~2027

Probe with the right scale!



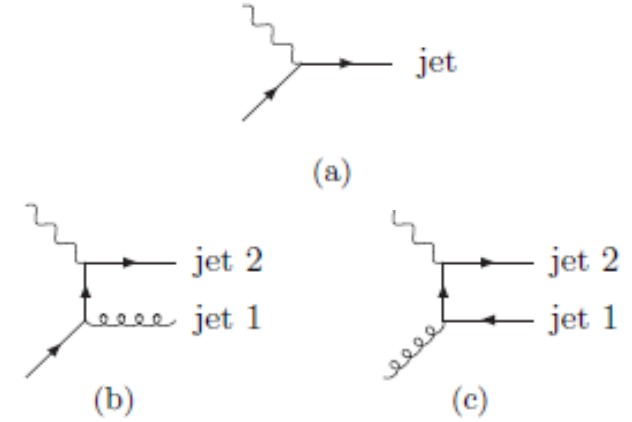


Precise understanding of structure and dynamics: dawn of new science

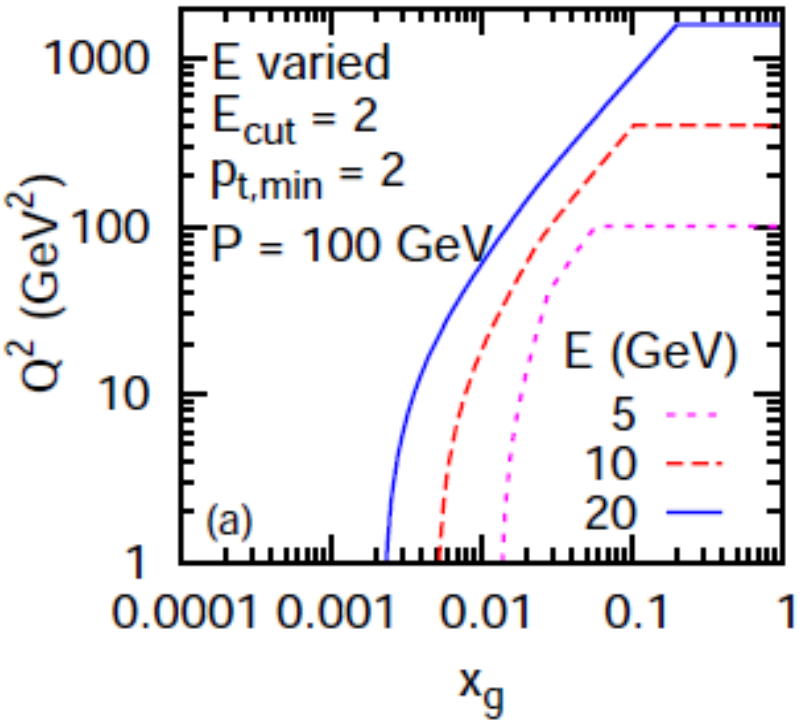
Backup slides

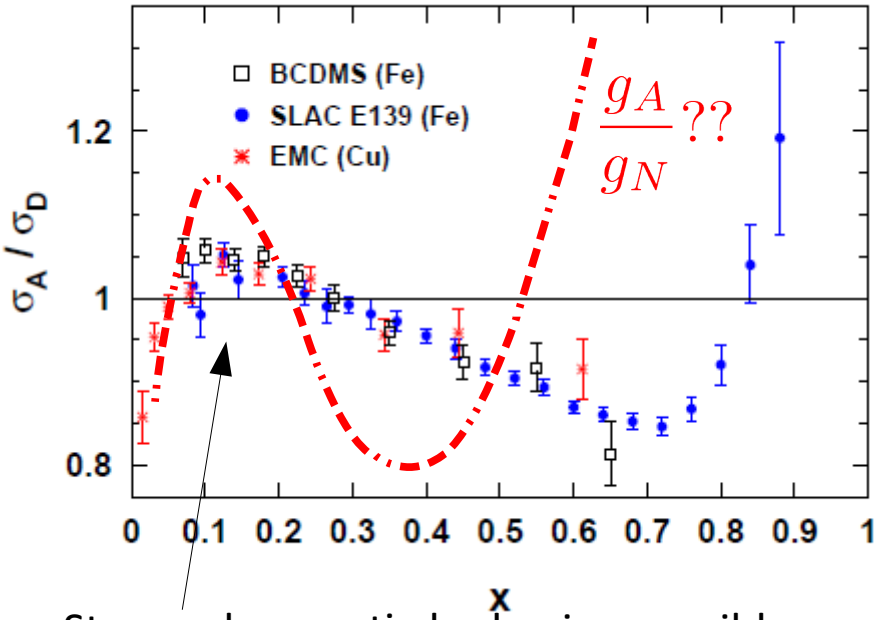
Jets: a unique EIC opportunity

- **Dijets: alternative access to nuclear gluons**
  - Pre-saturation region
  - Gluon antishadowing / EMC effect?



[G.Soyez]

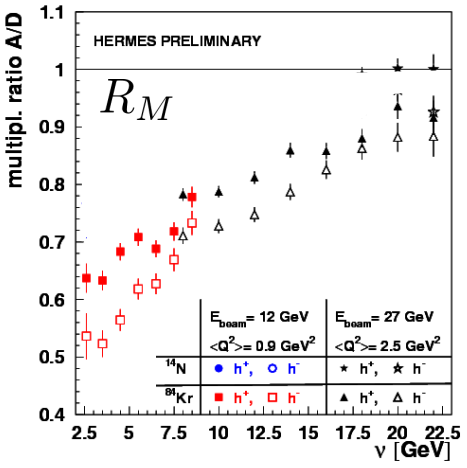


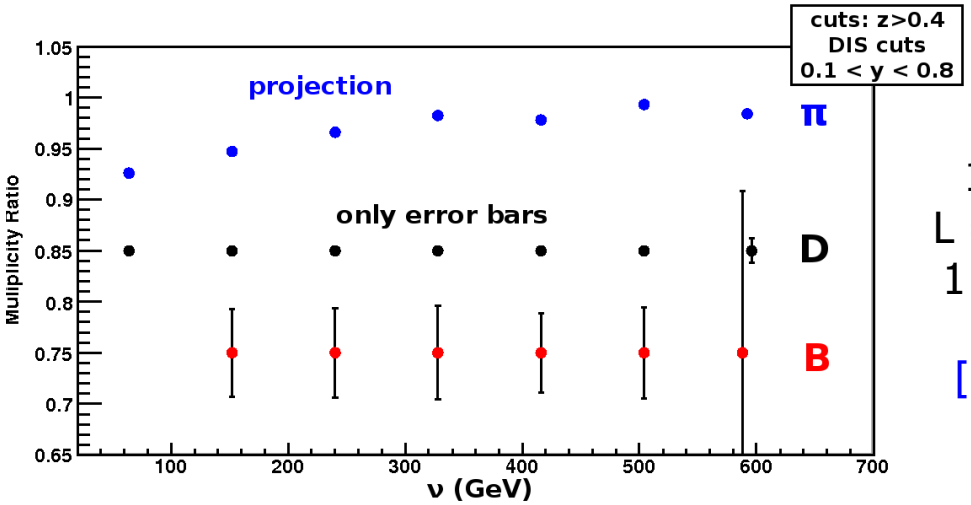


Strong gluon anti-shadowing possible

Guzey et al., PRC 2012

Isolate, study energy loss





11+30 GeV/A Fe
$L = 0.4 \times 10^{33}$ cm^{-2}s^{-1}
1 month, 100% eff.

[Dupré, Accardi]

mixed phase

pure energy loss (?)