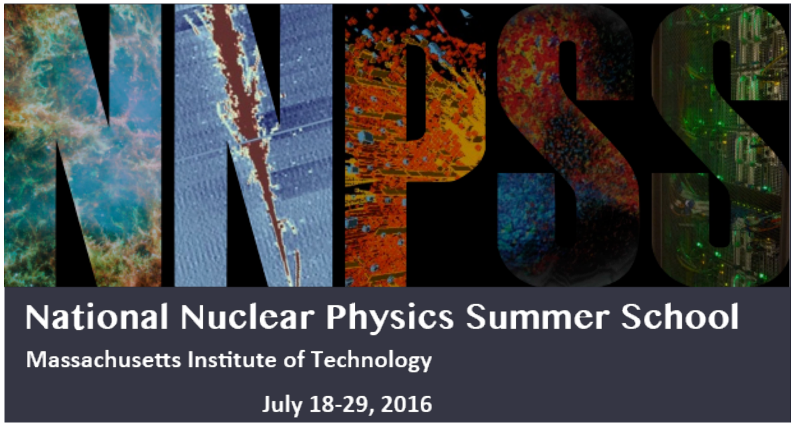


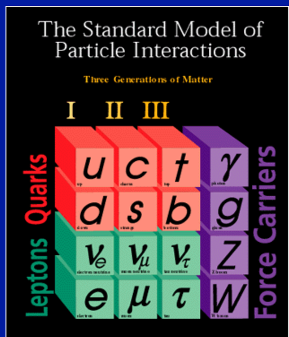
The Electron Ion Collider (EIC)

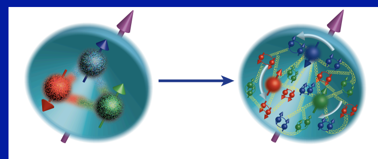
Abhay Deshpande

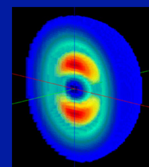
Lecture 1:
Introduction to the EIC & Overview of its Physics

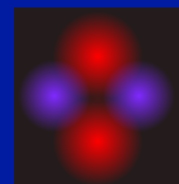
Stony Brook University

21st Century Nuclear Science: { Probing nuclear matter in all Its forms & exploring their potential for applications

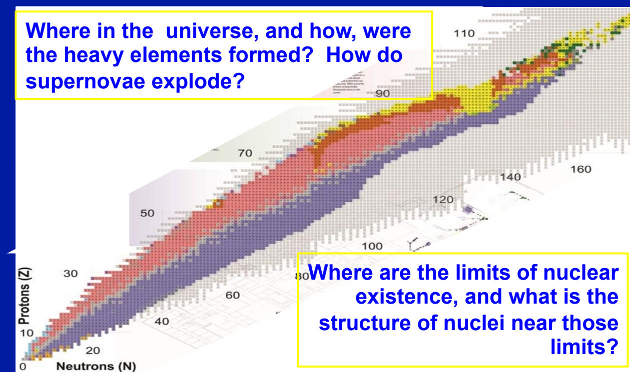






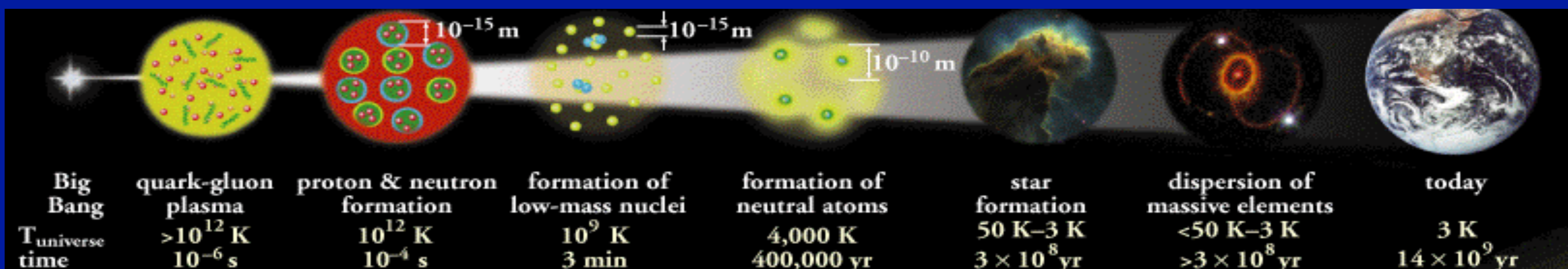


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?



Where in the universe, and how, were the heavy elements formed? How do supernovae explode?

Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?



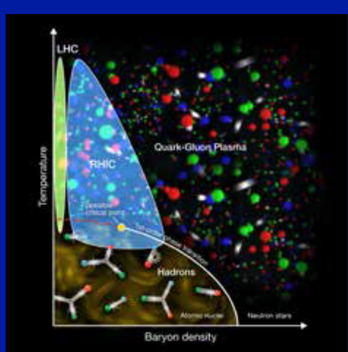
What is the nature of the different phases of nuclear matter through which the universe has evolved?

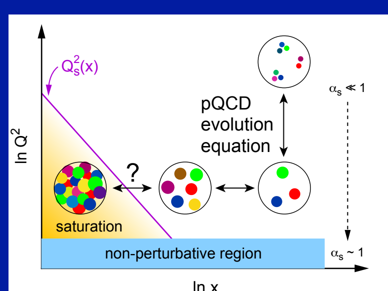
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?

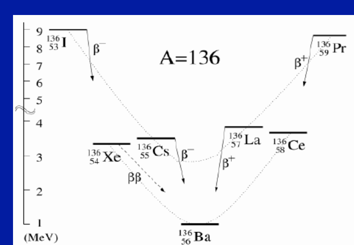
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?

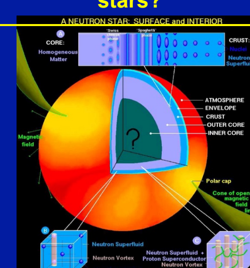
How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?

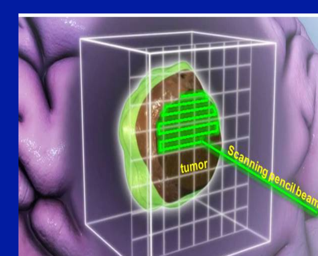
How can technologies developed for basic nuclear physics research be adapted to address society's needs?

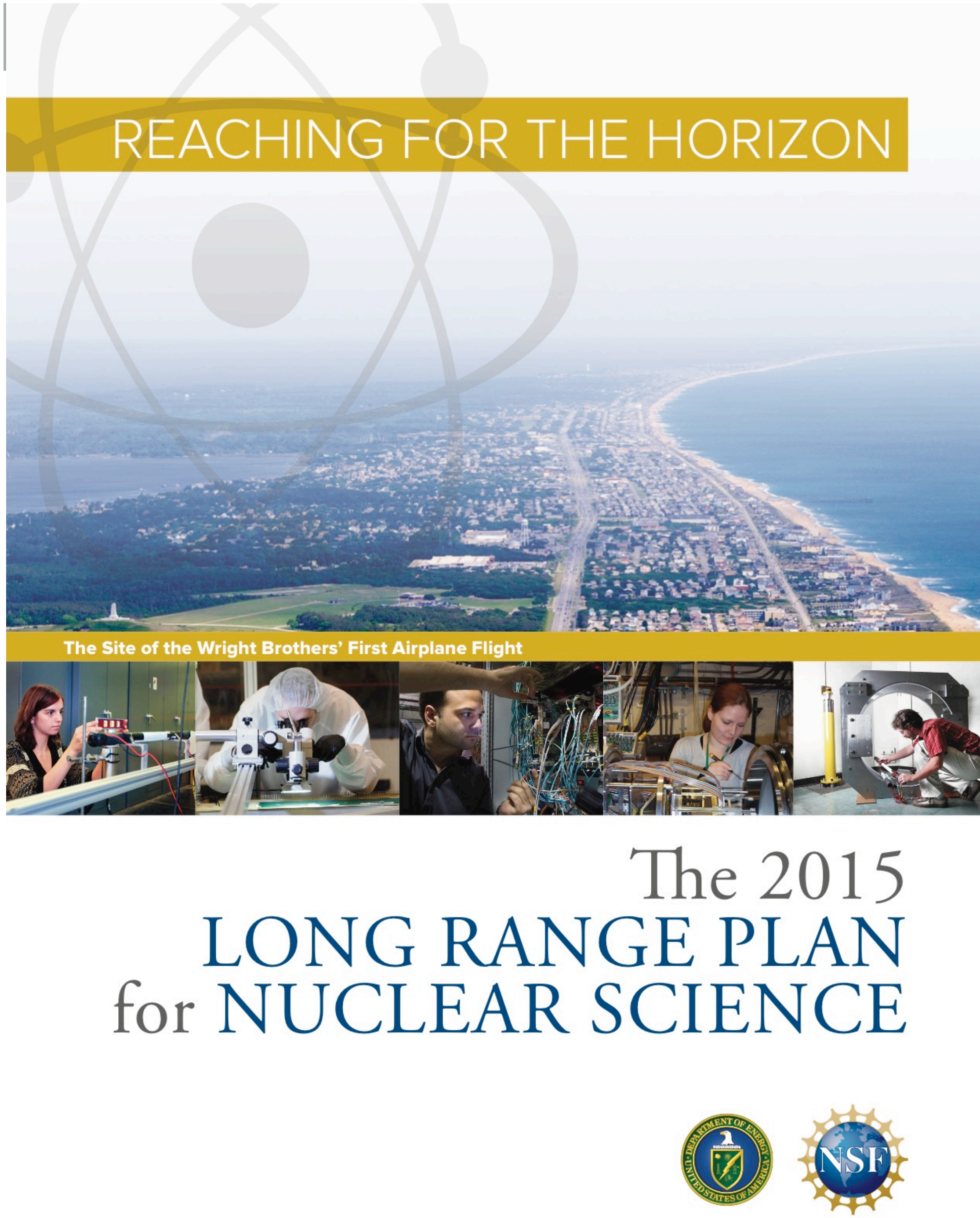












http://science.energy.gov/np/reports

RECOMMENDATION:

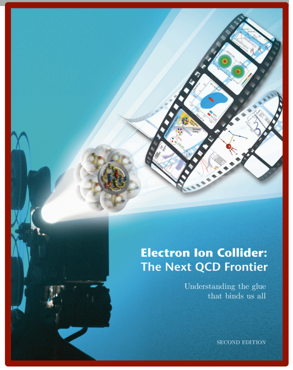
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

Theory

Detector & Accelerator R&D

About these lectures:



- These set of lectures are based on the “White Paper” written to make the case for this project to the broader US nuclear science community

- EIC White Paper (WP): https://arxiv.org/abs/1212.1701
  - It is also about to be published in European Physics Journal
- The WP was based on a far more technical document summarizing the INT Workshop:
  - http://www.int.washington.edu/PROGRAMS/10-3/
  - http://arxiv.org/abs/1108.1713 → (INT Report)

About these lectures

Introduce the EIC to you through these four lectures

Overview of the EIC : what is it?

- The collider concept & why is it unique?

Why is it needed? – Science of EIC

- Experimental investigations of hadron structure & parton dynamics:
  ➔ past & the future (EIC)
- Experimental investigations of cold QCD matter with nuclear DIS
  ➔ past & the future (EIC)
- What else could be possible at the highest machine properties
  ➔ introduce the technical challenges in machine & detector design
  ➔ when? How ? EIC?

Connections to others:

Direct & strong connections to these lectures:

- Hadron structure ➔ Prof. Jianwei Qiu's lectures
- Machine and detectors : ➔ Prof. Elke Aschenauer

Some what weaker connections to these lectures:

- Lattice QCD and hadron structure ➔ Prof. Sinead Ryan
- Fundamental Symmetries: ➔Prof. Vincenzo Cirigliano
- Nuclear structure: ➔ Prof. Andrew Steiner (?)

What is an Electron Ion Collider?

-- In the US context

Electron Ion Collider

- Counter rotating beams of electrons and ions collide at an interaction point (IP)
- Electron beams:
  - Are the “probe” in this case :
    - Structure-less : you can be assured that the resulting “hadronic debrie” comes entirely from the target under study…
    - A much cleaner probe than hadron-hadron scattering
- Ion beams: target
  - Could be protons, light nuclei or any heavy nuclei
  - Light nuclei can even be polarized (their spin oriented in particular direction) -- needed to study the “Spin” of the protons/neutrons
- Needs at least one detector located in the IP where the electron-hadron beams cross

The EIC Machine parameters:

For e-p/n collisions:

- Polarized e, p, deteron or ^{3}He beams
- Electron beam energy ~ 5-20 GeV
- Proton beam energy up to ~50 - 250 GeV (RHIC exists!)
- *Luminosity* L_{ep}~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$
- Center of mass energy ~ sqrt(4 x E_p x E_e) ~ 30 – 140 GeV

For e-A collisions: (use the same collider ring…)

- Wide range in Nuclei (proton-to-Uranium)
- Luminosity per nucleon (scaled) by the one for e-p
- Variable CM energy (scaled by A)

Two designs currently under considerations:

- Uses the existing RHIC and adds an electron beam facility
- Uses the recently upgraded 12 GeV electron beam of CEBAF and adds a hadron beam facility

Luminosity

- Number of events N_{exp} created in a two-beam collision experiment is the product of "cross section" of interest, σ_{exp}, and the time integral of "instantaneous luminosity":

$$N_{exp} = \sigma_{exp} \times \int L(t)dt$$

- In bunched EIC Collider, if n_e and n_p are the number of electrons and number of protons in each bunch (colliding head-on) with frequency f, then:

$$L = f\frac{n_e n_p}{4\pi\sigma_x\sigma_y}$$

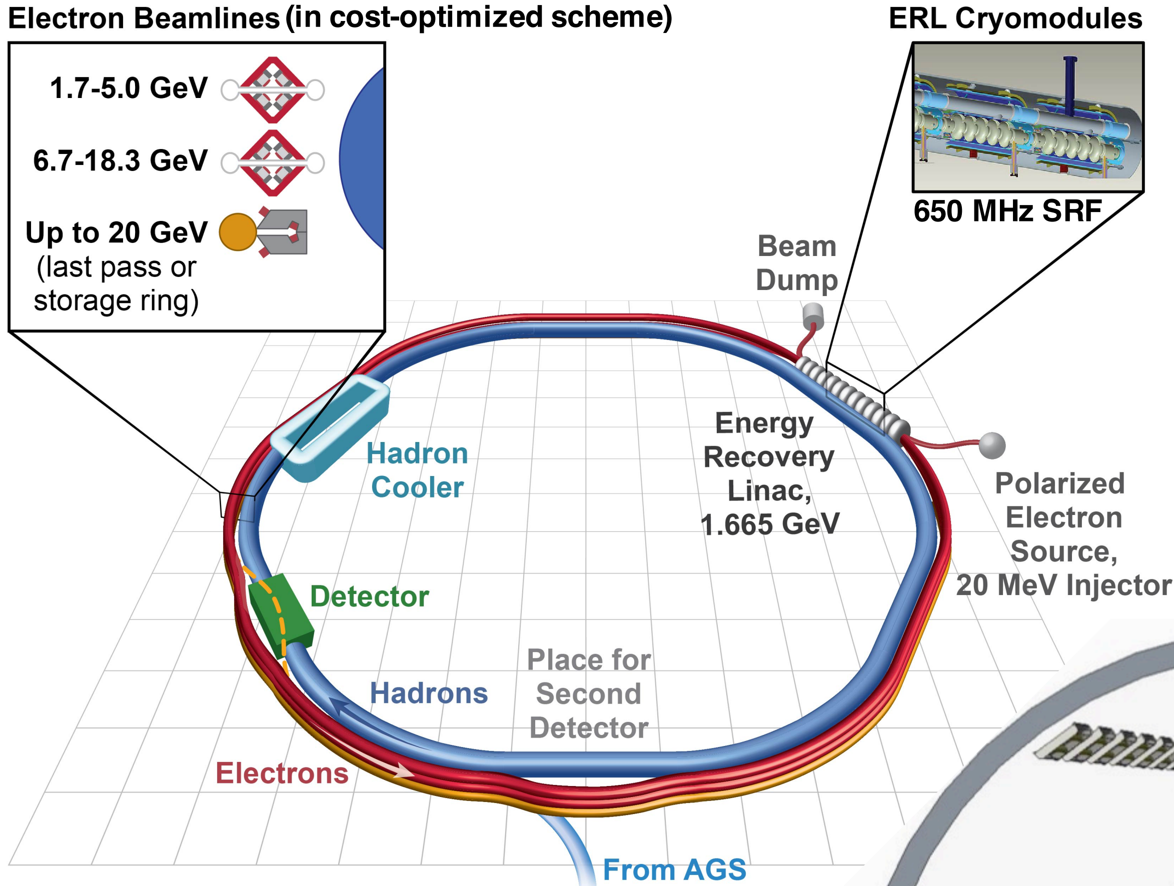
where s_x and s_y are the rms transverse beam sizes in horizontal (bend) and vertical directions.

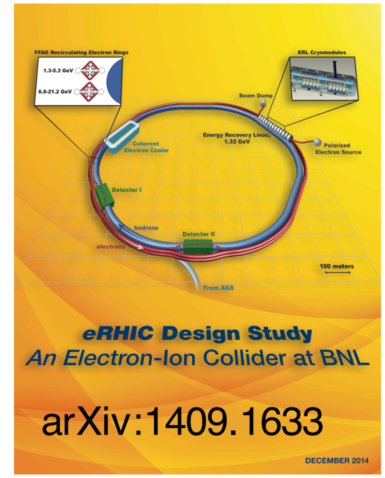
More in Aschenauer's Talk

Ultimate eRHIC design

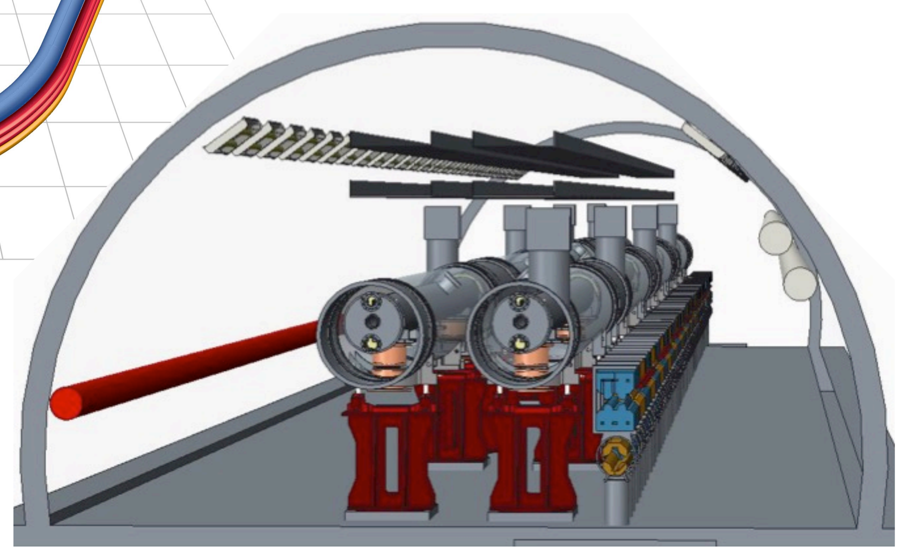
V. Ptitsyn, BNL

Highly advanced and energy efficient accelerator

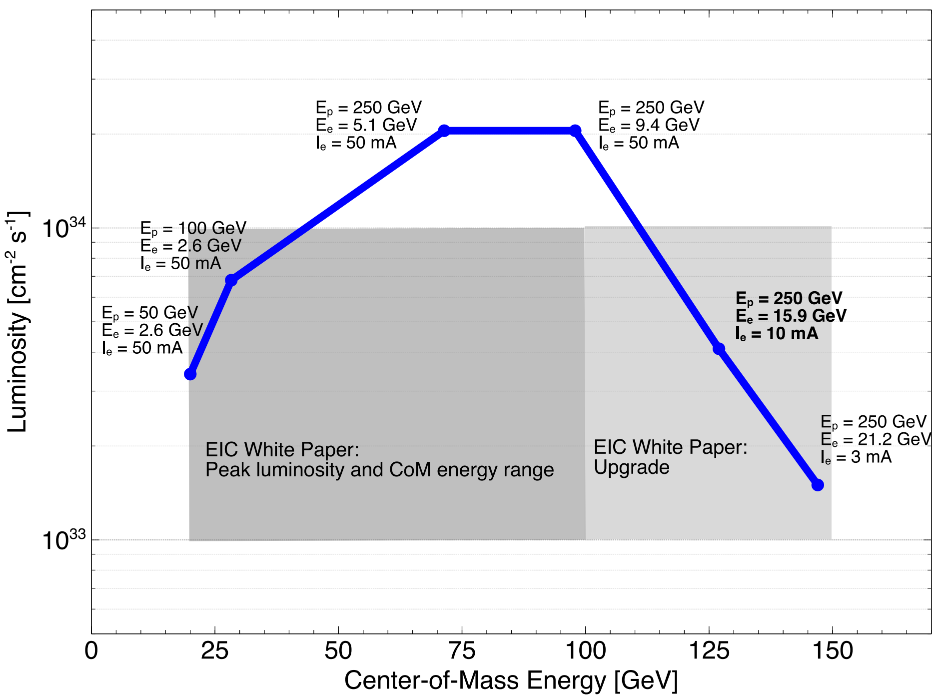


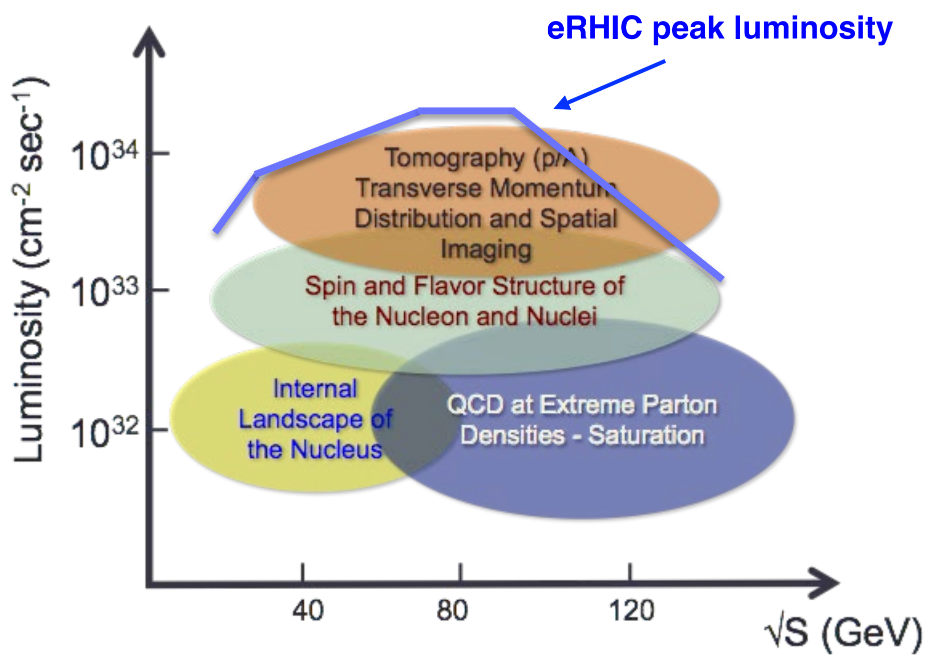


- Peak luminosity: 2×10^{34} cm^{-2} s^{-1}
- ERL, permanent magnet arcs and strong cooling of proton beam greatly reduce electric power consumption to about 15 MW!



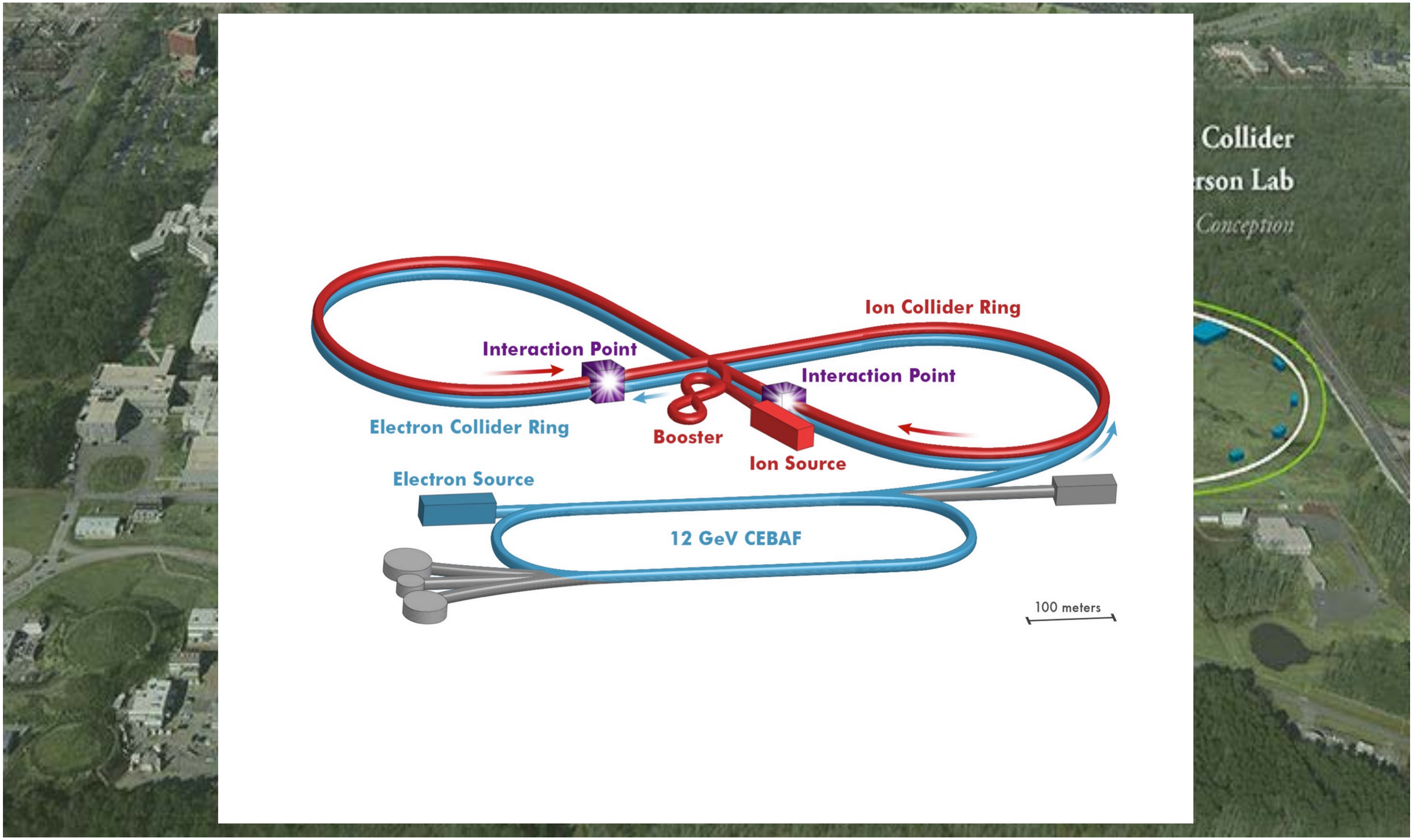
eRHIC performance



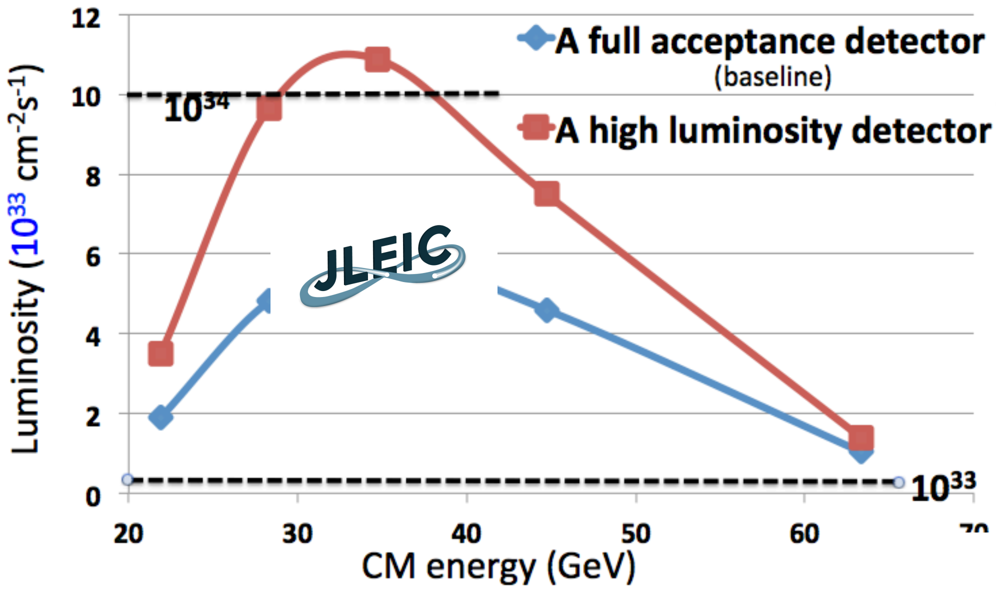


- eRHIC design covers whole Center-of-Mass energy range, including "EIC White Paper Upgrade" region
- Small beam emittances and IR design allows for full acceptance detector at full luminosity

EIC at JLab: JLEIC

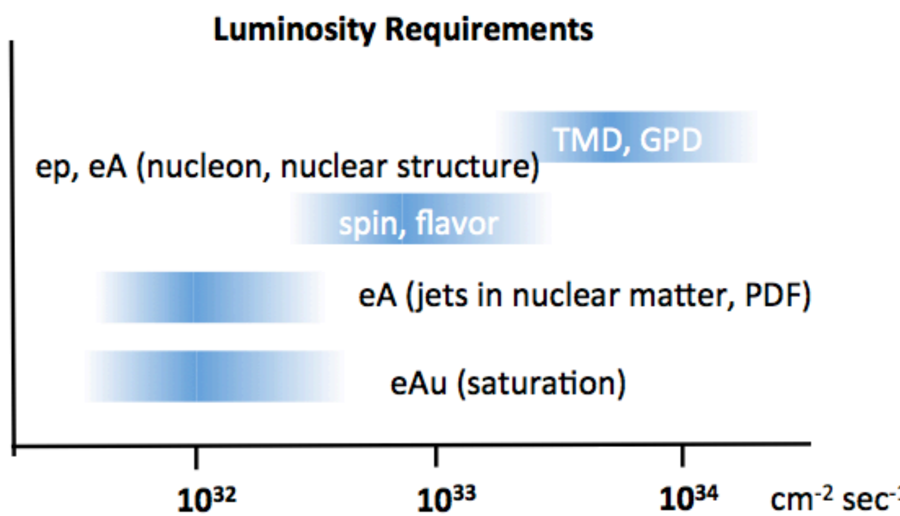


JLEIC Luminosity Reach



10^{34}

JLEIC baseline provides high luminosity needed to carry out the EIC physic program



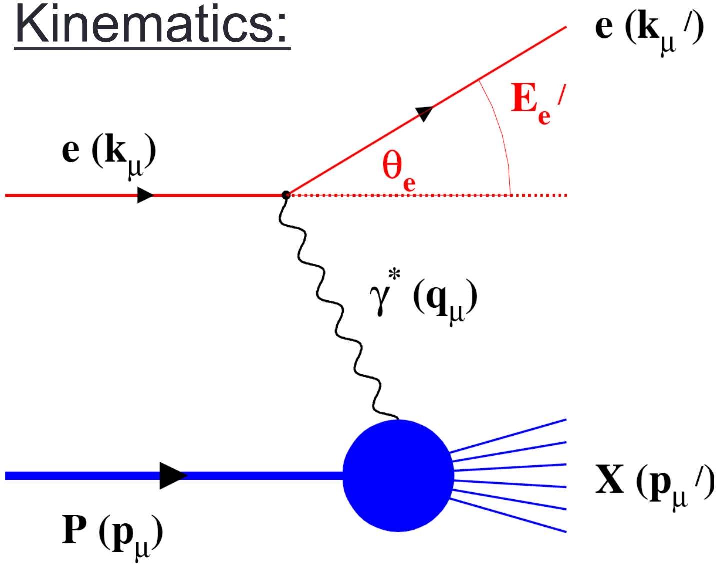
The Method & Kinematics

Deep Inelastic Scattering….

Deep Inelastic Scattering

$$s = 4E_pE_e$$

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_eE'_e(1-\cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$\boxed{\lambda = \frac{h}{p} = \frac{h}{\sqrt{Q^2}}}$$

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu};\ p_t \quad \text{with respect to } \gamma$$

Inclusive measurements:

e+p/A → e'+X

Detect only the scattered lepton in the detector

Semi-inclusive measurements:

e+p/A → e'+h(π,K,p,jet)+X

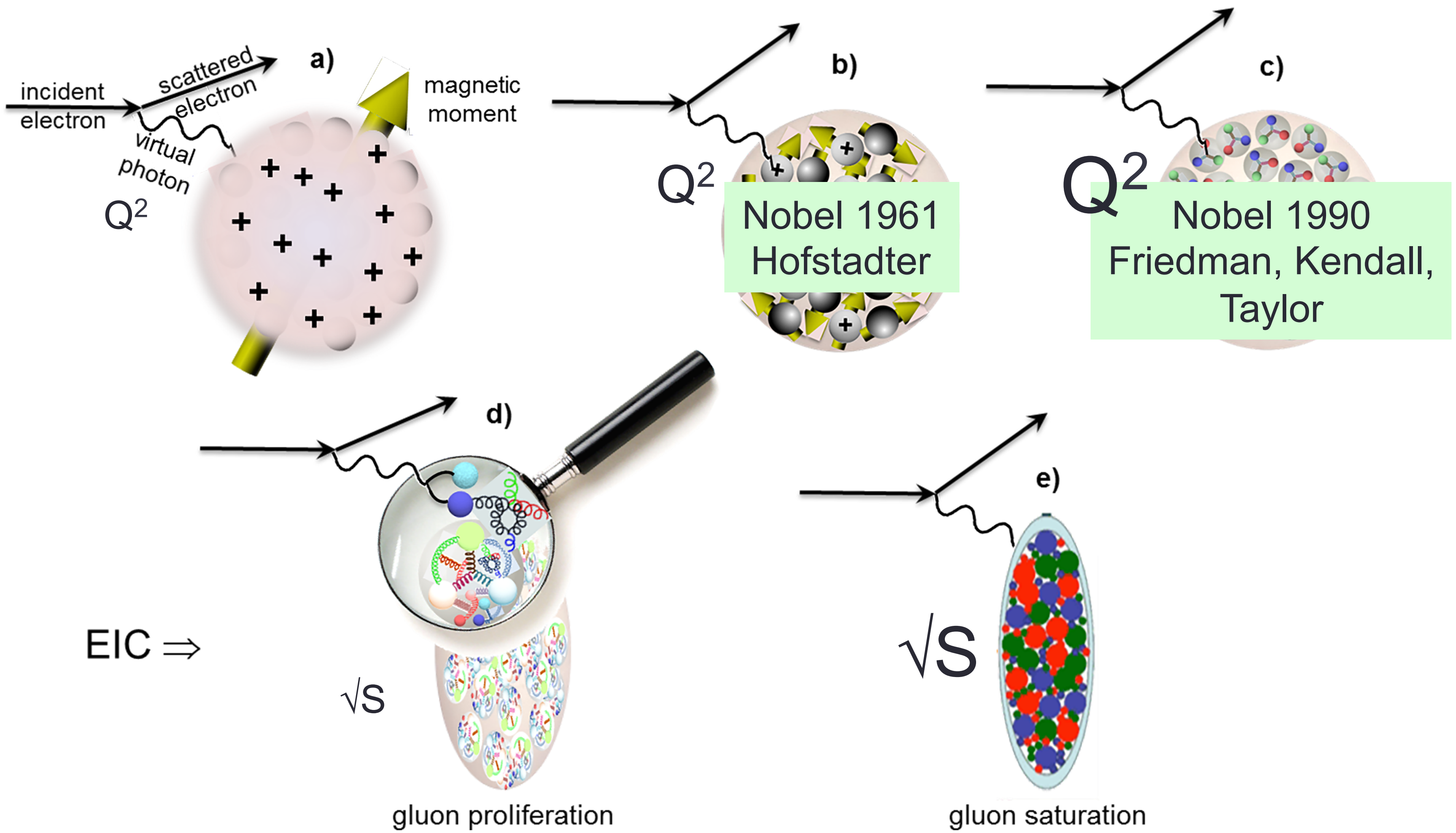
Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive measurements:

e+p/A → e'+h(π,K,p,jet)+p'/A'

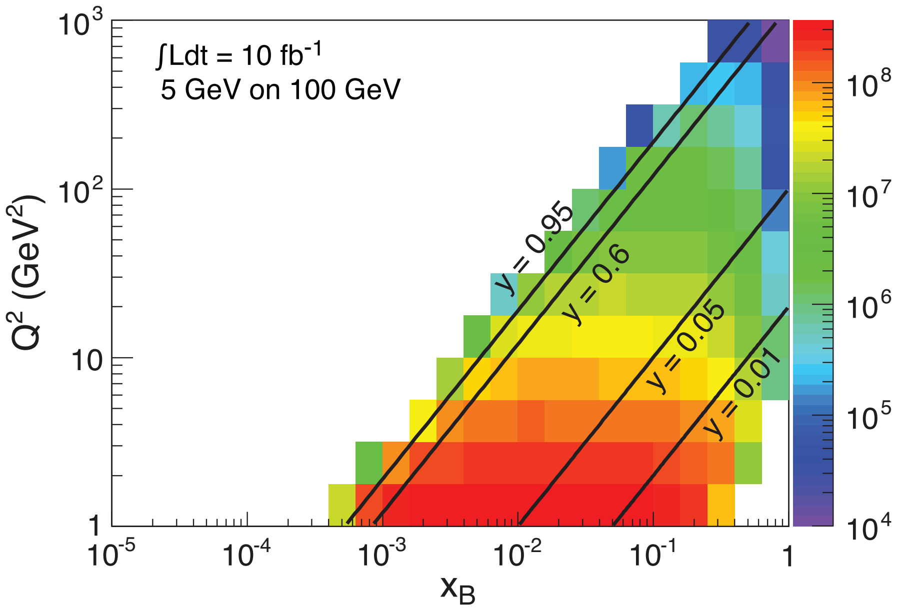
Detect scattered lepton, identify produced hadrons/jets and measure target remnants

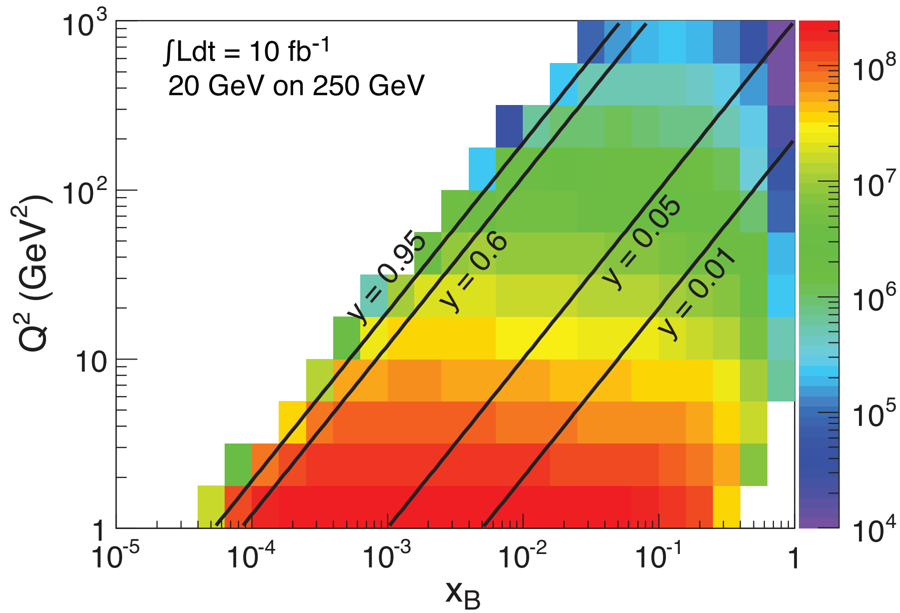
Deep Inelastic Scattering allows the Ultimate Experimental Control



Kinematics and event distribution

$$s = 4E_pE_e$$



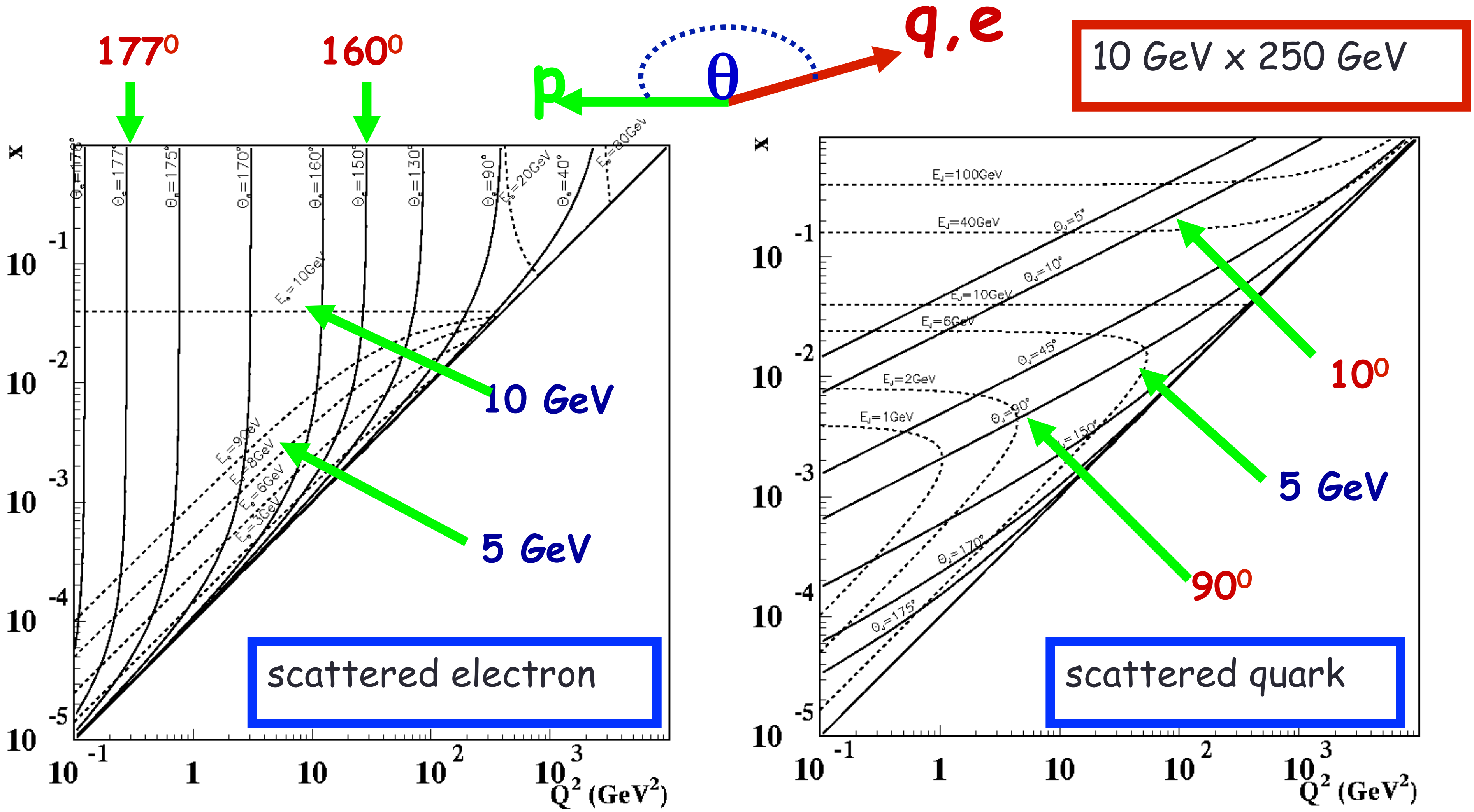


In designing detectors : their location, they types (tracking, particle ID, energy) requires one to ask other questions:

- Where do the electrons go after collision?
- Where do the quarks (jets) fly after collision?

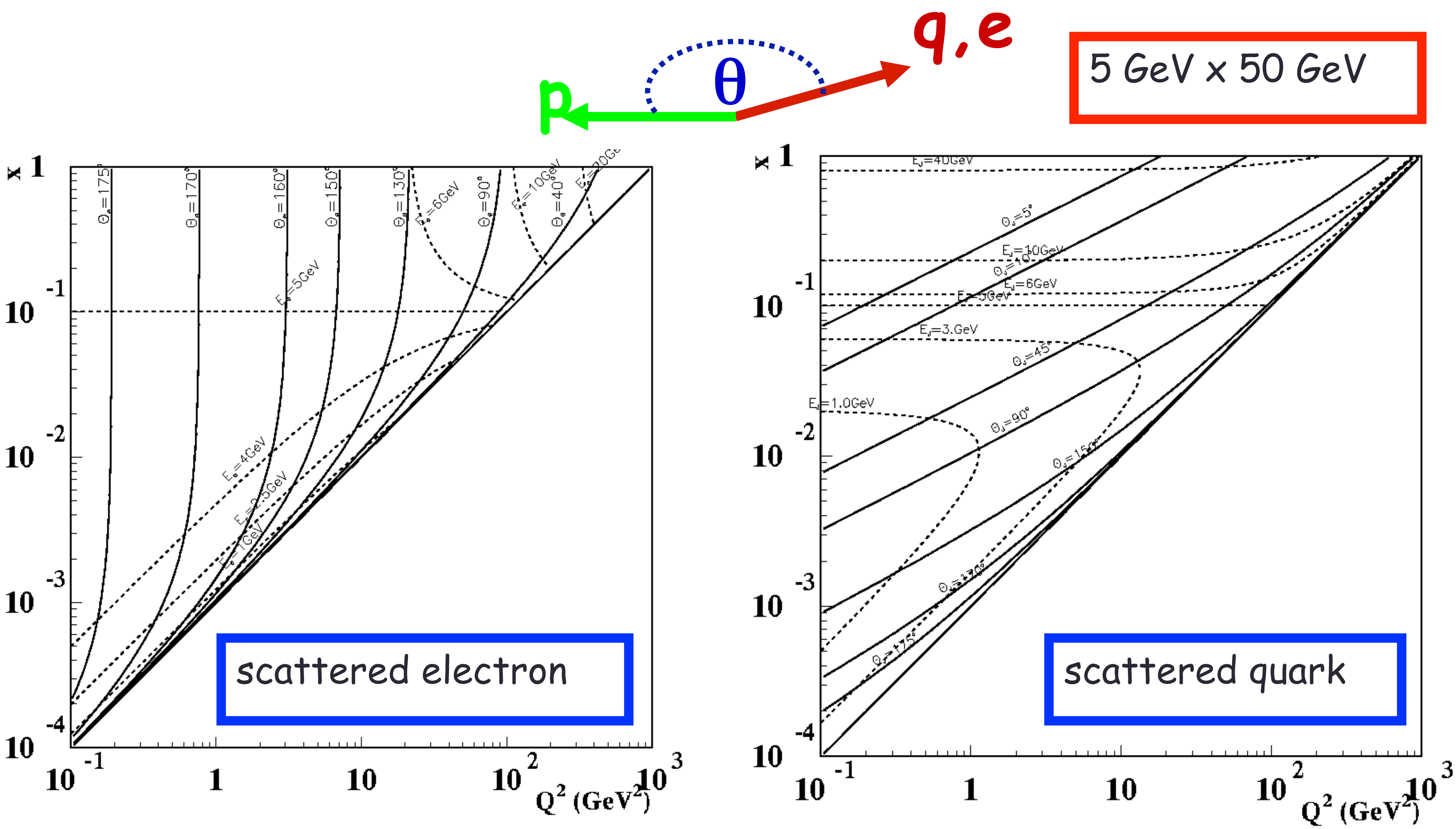
Where do electrons and quarks go?

Angles measured w.r.t. proton direction



HOMEWORK: CALCULATE TONIGHT

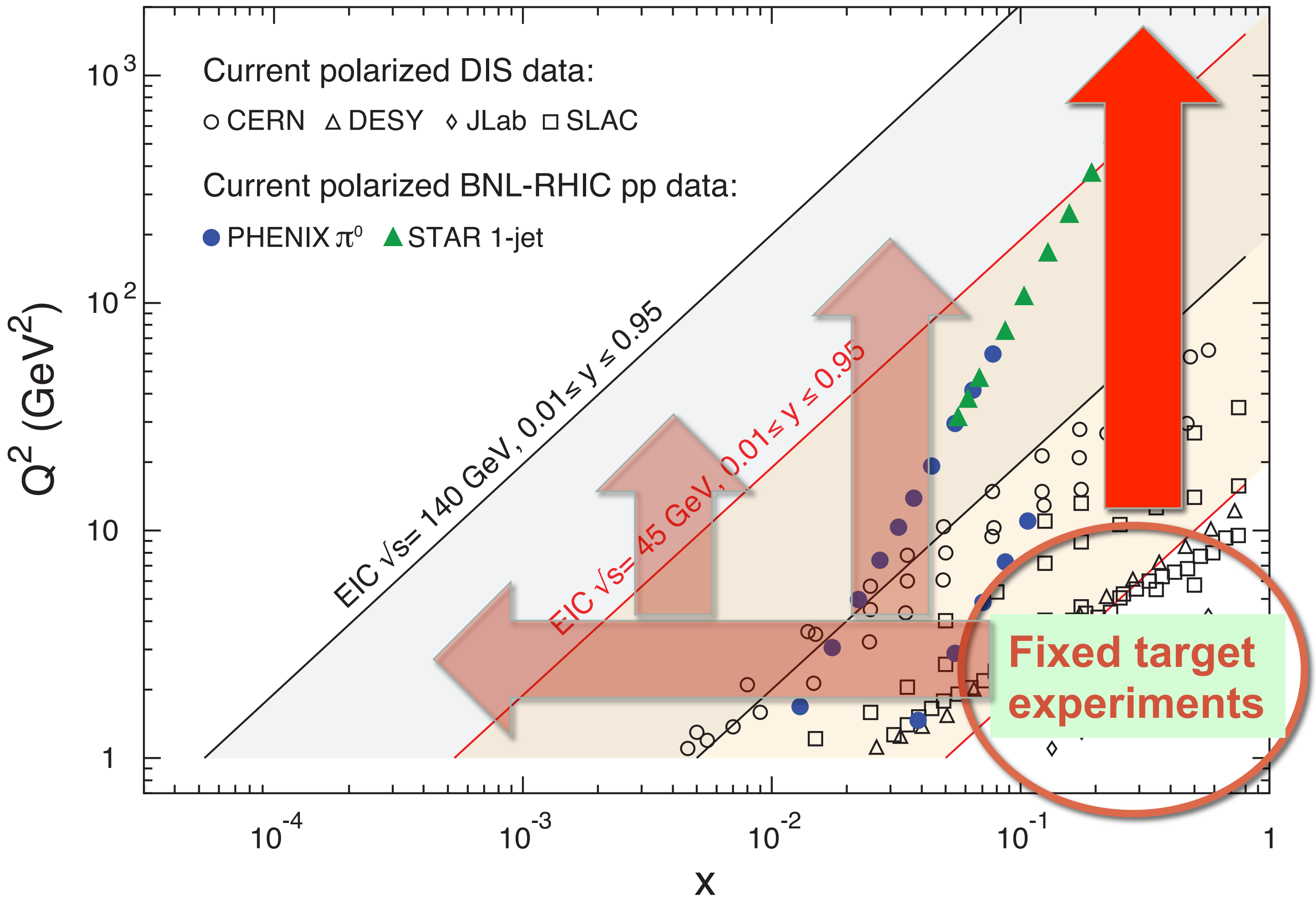
Electron, Quark Kinematics



HOMEWORK: CALCULATE TONIGHT

EIC: Enormous increase in x-Q^2 reach

Significance of this will be clear later in the lectures…



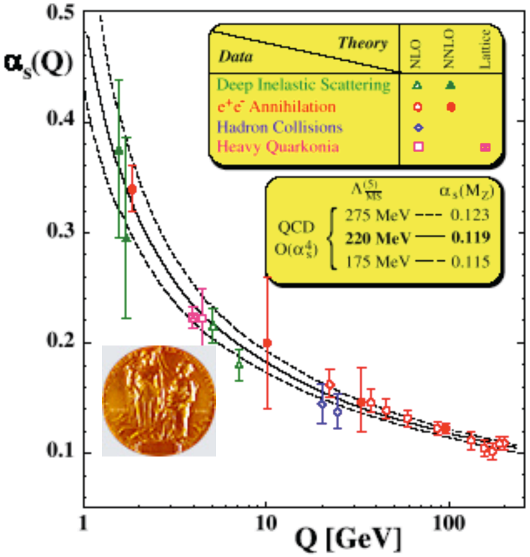
What Physics?

Motivation, overview & introduction…. Details in later lectures as needed...

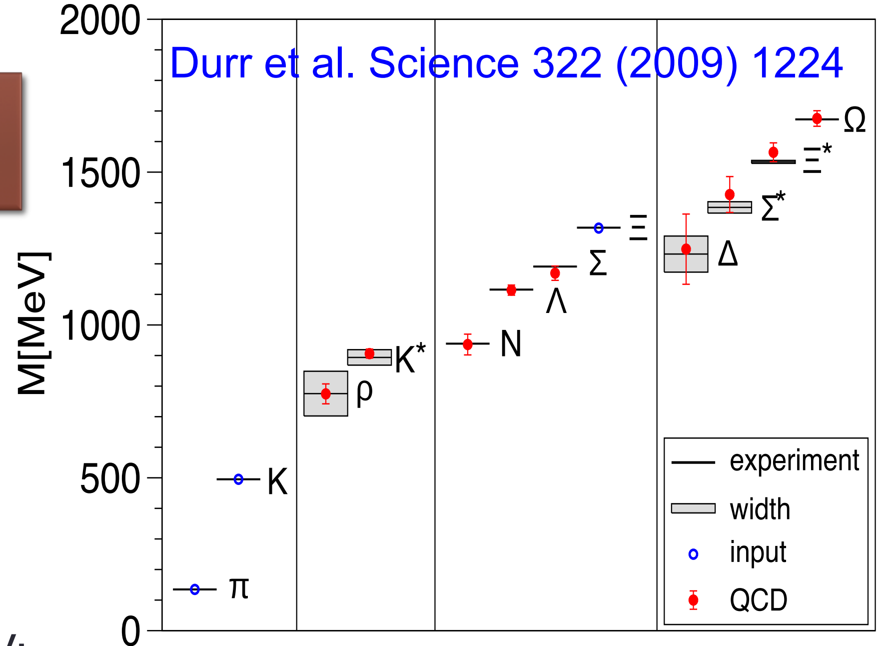
"Folks, we should stop testing QCD, and start understanding it." Yuri Dokshitzer (ICHEP'98, Vancouver)

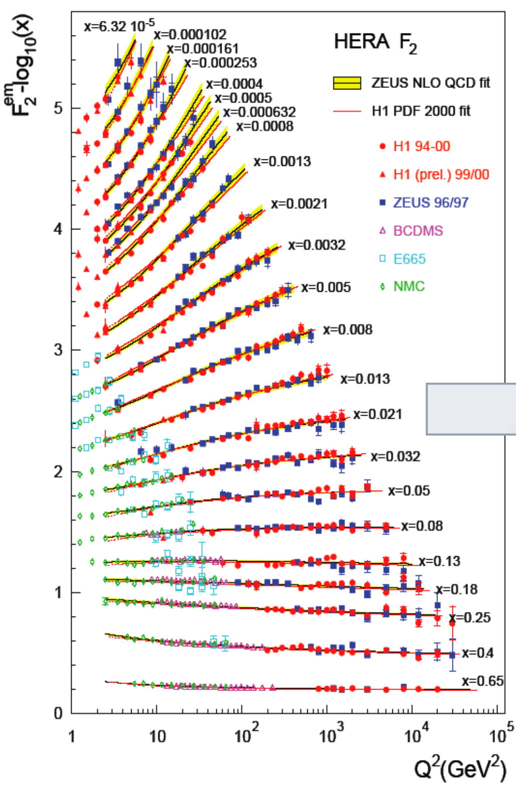
QCD is the correct theory of strong interactions, but do we understand it?

Do we understand the role of gluons & sea quarks in QCD?



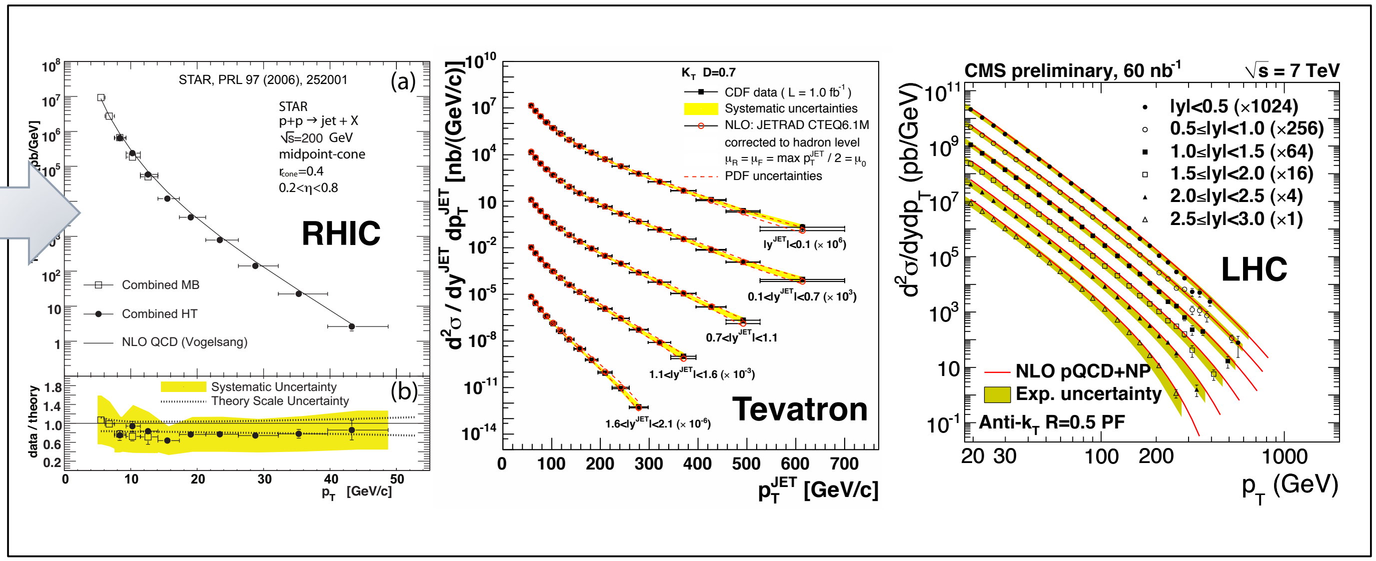
Successes of QCD



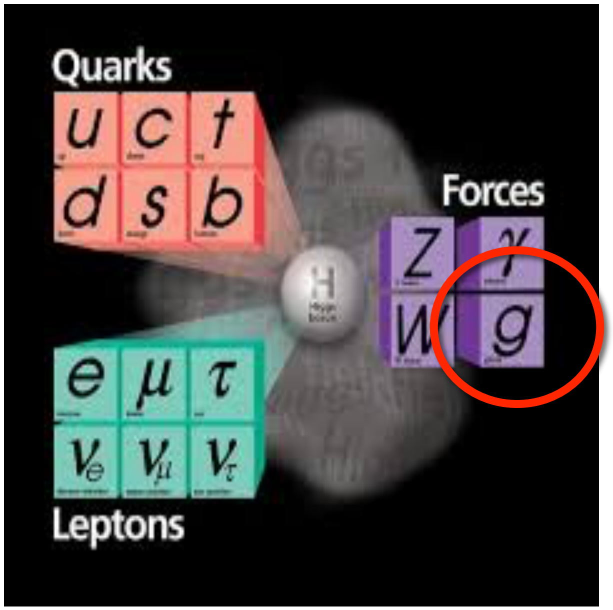


Measure **e-p** 0.3 TeV:

➔ Use pQCD Calculate **p-p, p-pbar Jet x-sctn** at 0.2, 2, 7 TeV



Gluon in the Standard Model of Physics



Gluon: carrier of strong force (QCD)

Chargeless, massless, but carries color-charge

Binds the quarks and gluons inside the hadrons with tremendous force! (Strong force)

At the heart of many un/(ill)-understood phenomena:

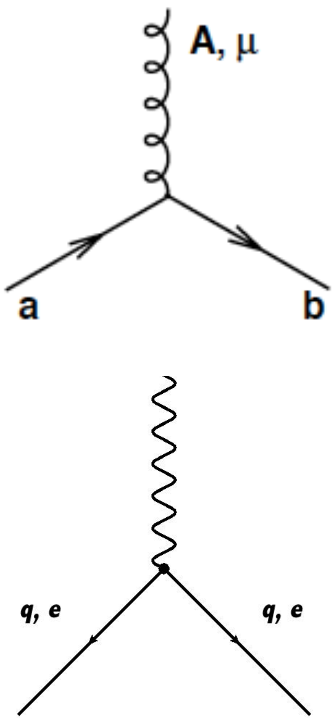
Color Confinement, composition of nucleon spin, quark-gluon plasma at RHIC & LHC…

What distinguishes QCD from QED?

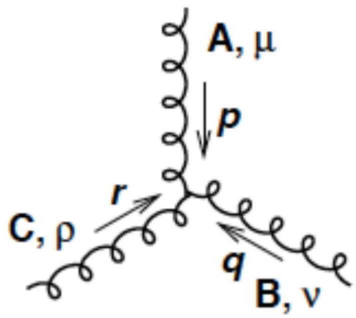
QED is mediated by photons (γ) which are charge-less

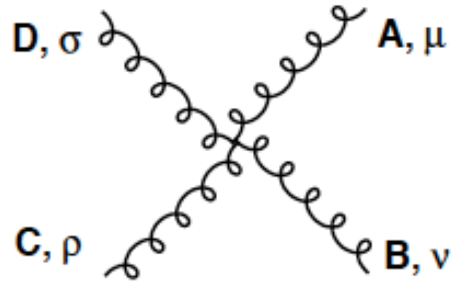
QCD is mediated by gluons (g), also charge-less but *are* colored!

In QCD &
g → γ in QED

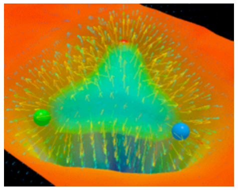


Only in QCD





Role of gluons in hadron & nuclear structure



Dynamical generation of hadron masses & nuclear binding

- Massless gluons & almost massless quarks, *through their interactions,* generate more than 95% of the mass of the nucleons:

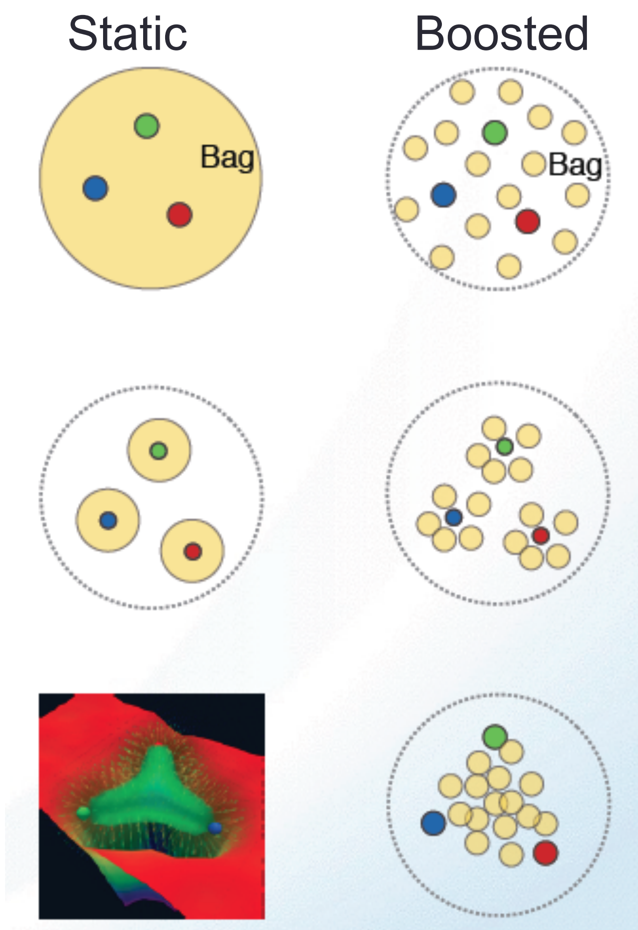
Without gluons, there would be no nucleons, no atomic nuclei… no visible world!

- Gluons carry ~50% the proton's momentum, **?%** of the nucleon's spin, and are responsible for the transverse momentum of quarks
- The quark-gluon origin of the nucleon-nucleon forces in nuclei not quite known
- Lattice QCD can't presently address dynamical properties on the light cone

Experimental insight and guidance crucial for complete understanding of *how* hadron & nuclei emerge from quarks and gluons

CONFINEMENT!

What does a proton look like?



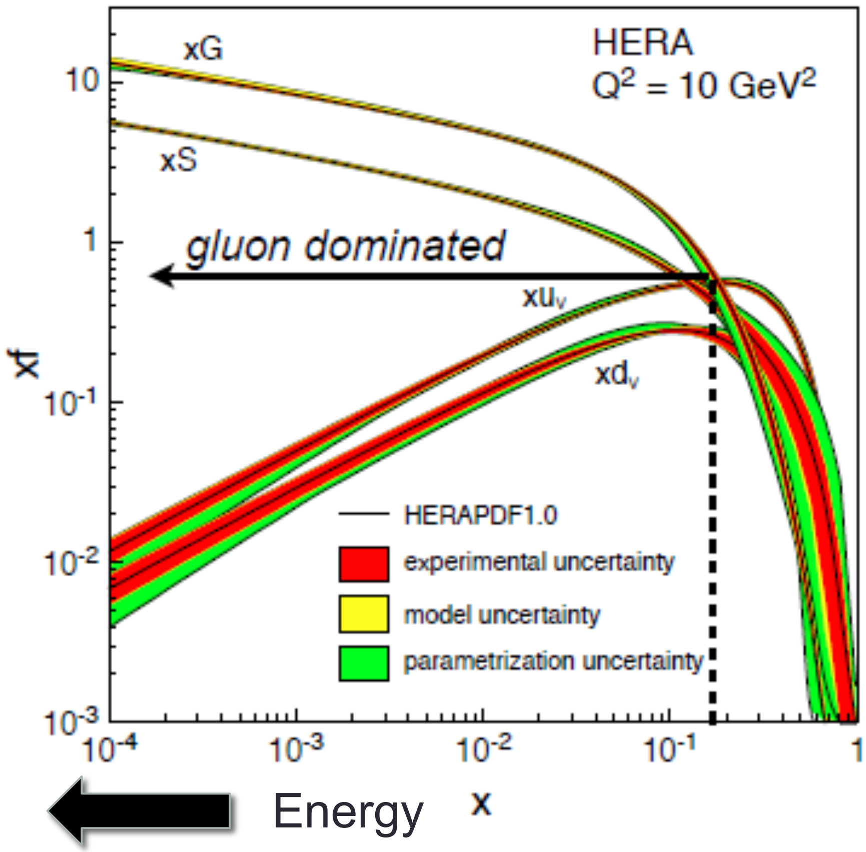
Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

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

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

Need transverse images of the quarks *and gluons* in protons

What does a proton look like?
Unpolarized & polarized



QCD
Terra-
incognita!

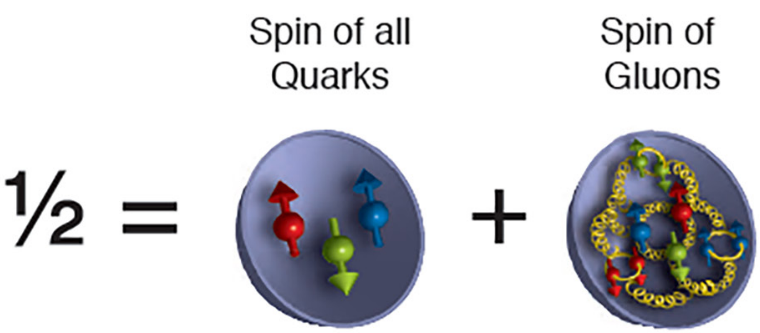
High Potential for Discovery

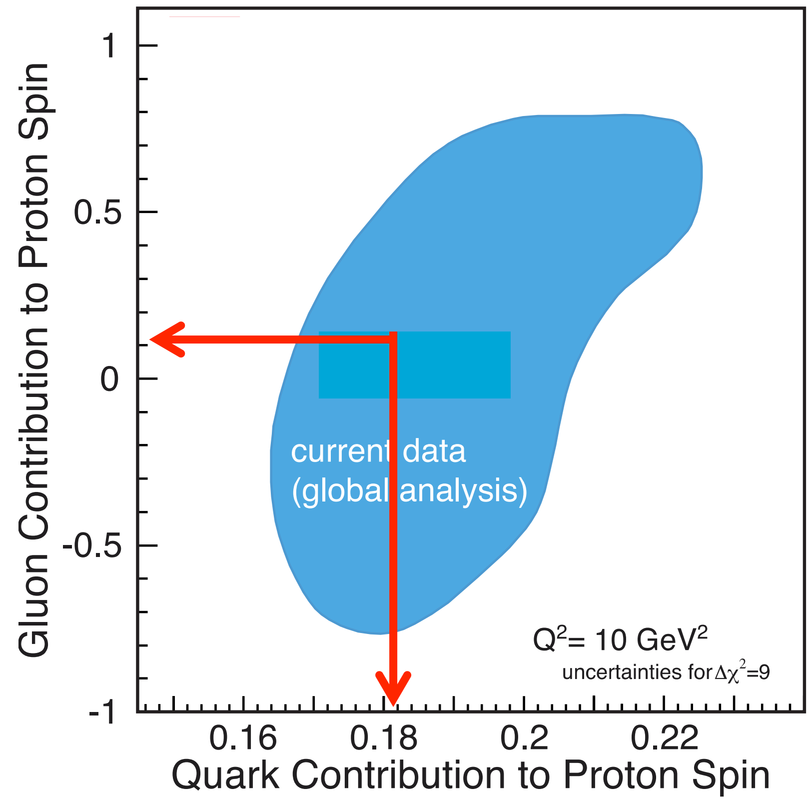
We only have a 1-dimensional picture!

Need to go beyond 1-dimension!

Need 3D Images of nucleons in Momentum & Position space

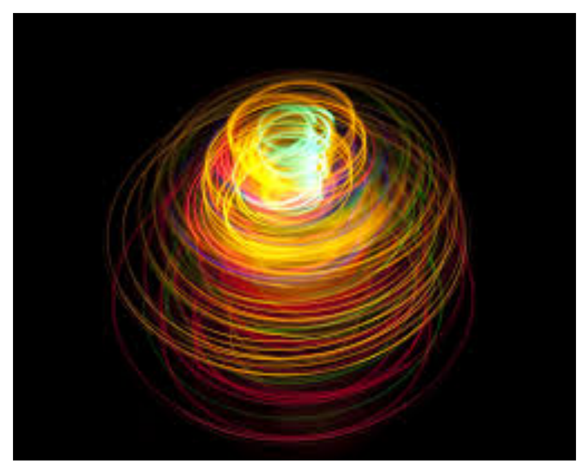
The nucleon spin puzzle…. Since 1988..





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G$$

0.18 0.12 ? ?



A thought experiment:

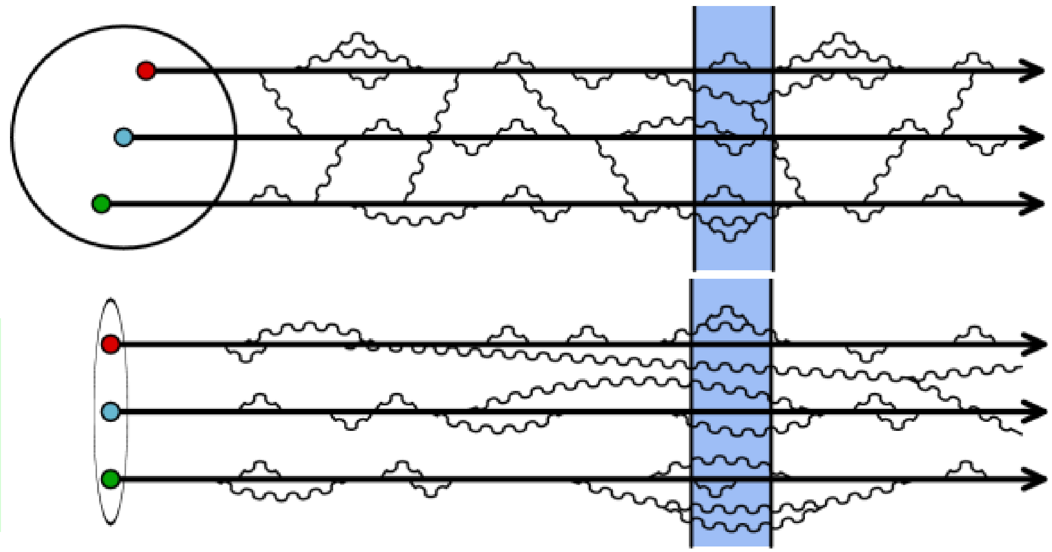
A color charge (quark) walks in to a bar!

Of course there are no free quarks….
So lets take a more realistic case....

How does a Proton look at low and high energy?

Low energy
High x
Regime of fixed target exp.

High energy
Low- x
Regime of a Collider



At high energy:

- Wee partons fluctuations are time dilated in strong interaction time scales
- Long lived gluons radiate further smaller x gluons ➔ which intern radiate more……. Leading to a **runaway growth?**

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

"…The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud…."

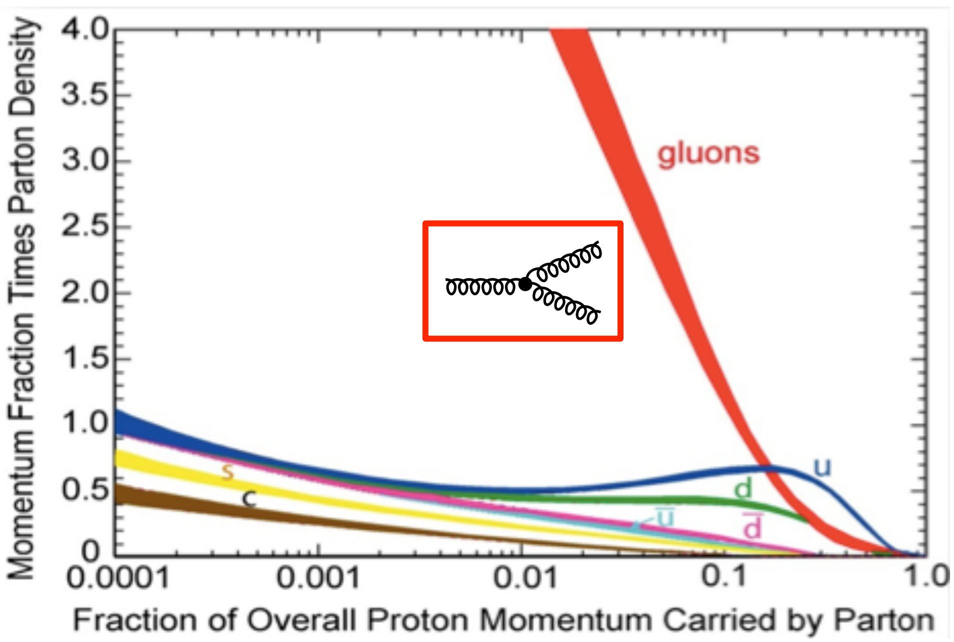
F. Wilczek, in "Origin of Mass"
Nobel Prize, 2004

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with oth

QCD
Terra-
incognita!

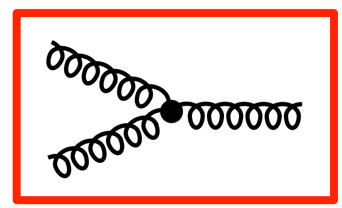
High Potential for Discovery



Apparer ” in gluon distribut

What **ndefinite rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

recombination



Where? No one has unambiguously seen this before!

If true, effective theory of this →“Color Glass Condensate”

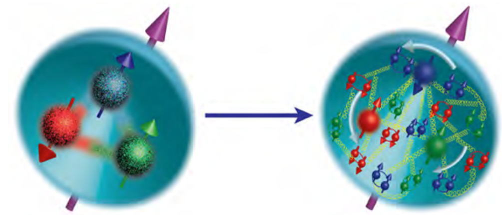
McLerran & Venugopalan et al

Puzzles and challenges in understanding these QCD many body emergent dynamics

How are the gluons and sea quarks, and their intrinsic spins distributed in space & momentum inside the nucleon?

Role of Orbital angular momentum?

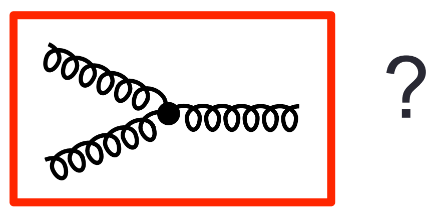
How do they constitute the nucleon Spin?



(This talk)

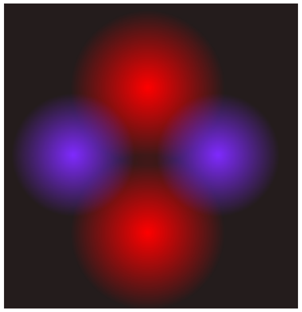
What happens to the gluon density in nuclei at high energy? Does it saturate in to a gluonic form of matter of universal properties?

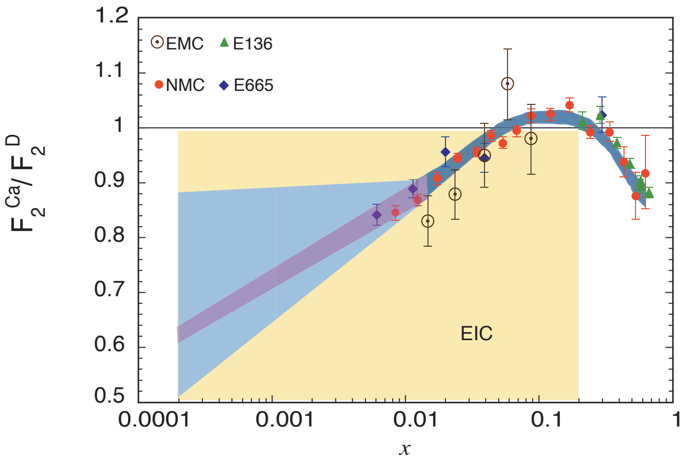
(Eyser's talk)



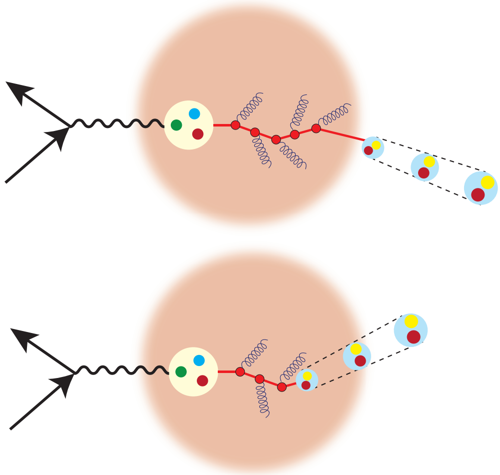
Puzzles and challenges….

How do gluons and sea quarks contribute to the nucleon-nucleon force?
(Related to Nicolescu's talk)





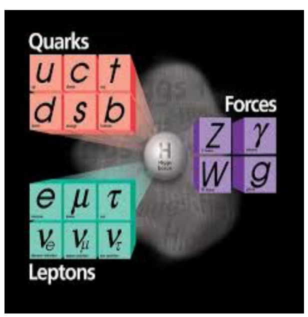
How does the nuclear environment affect the distributions of quarks and gluons and their interactions inside nuclei?
(Eyser)

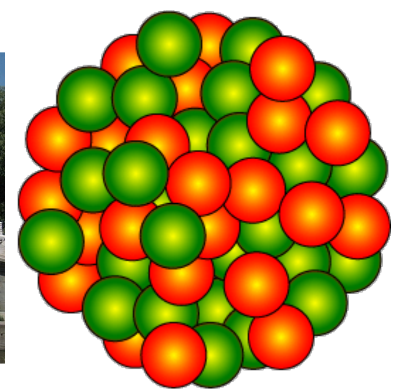


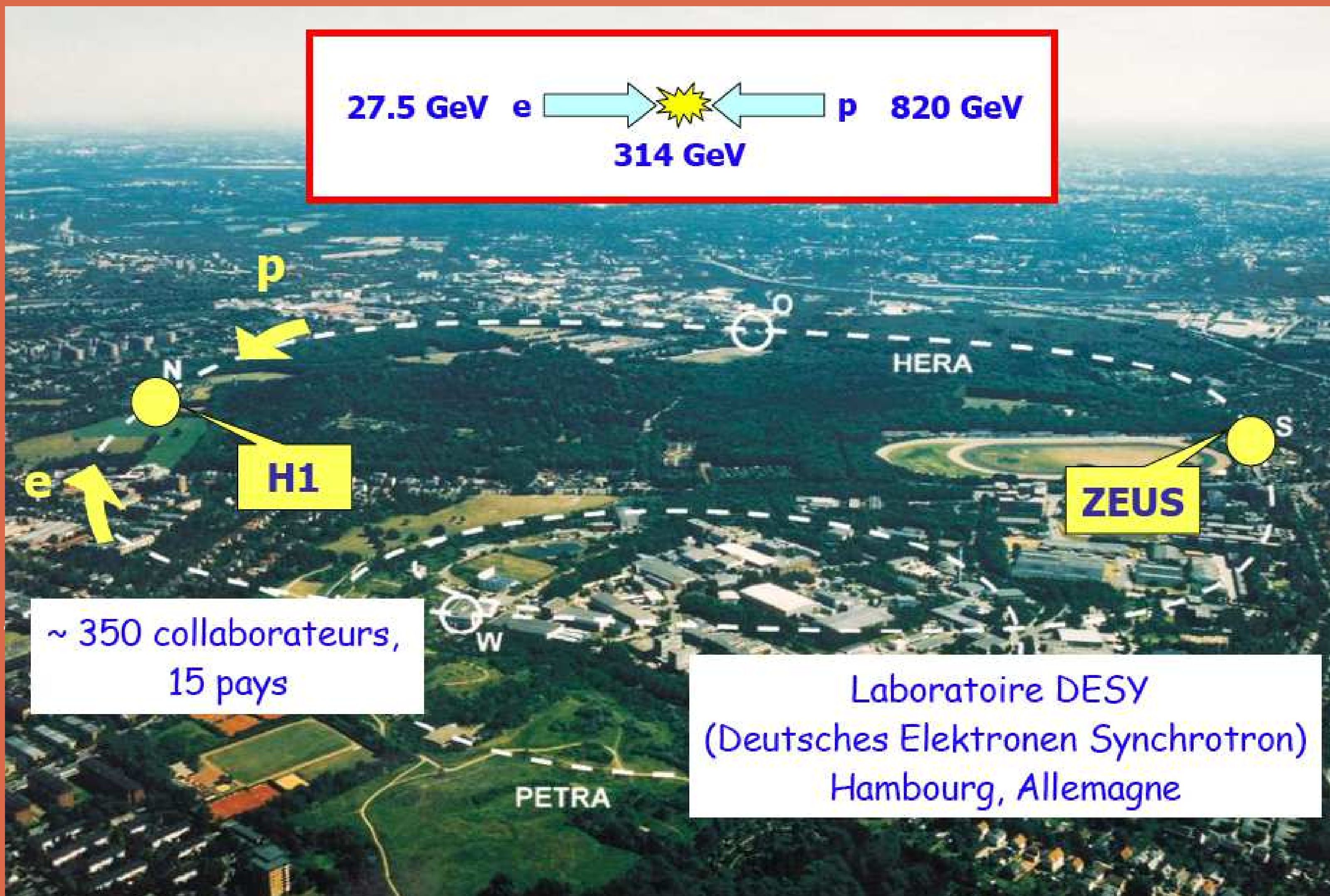
How does nuclear matter respond to fast moving color charge passing through it? (hadronization…. confinement?) (Eyser)

Why we need an EIC?

A new facility, EIC, with a versatile range of kinematics, beam polarizations, high luminosity and beam species, is required to ***precisely image*** *the sea quarks and gluons in nucleons and nuclei,* to explore the new QCD frontier of strong color fields in nuclei, and to resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD






27.5 GeV e
p 820 GeV
314 GeV
p
e
N
H1
HERA
S
ZEUS
W
PETRA
~ 350 collaborateurs,
15 pays
Laboratoire DESY
(Deutsches Elektronen Synchrotron)
Hambourg, Allemagne

EIC Distinct from HERA

- Luminosity 100-1000 times that of HERA
  - Enable 3D tomography of gluons and sea quarks in protons
- Polarized protons and light nuclear beams
  - Critical to all spin physics related studies, including precise knowledge of gluon's & angular momentum contributions from partons to the nucleon's spin
- Nuclear beams of all A (p→U)
  - To study gluon density at saturation scale and to search for coherent effects like the color glass condensate and test its universality
- Center mass variability with minimal loss of luminosity
  - Critical to study onset of interesting QCD phenomena
- Detector & IR designs mindful of "Lessons learned from HERA"
  - No bends in e-beam, maximal forward acceptance….