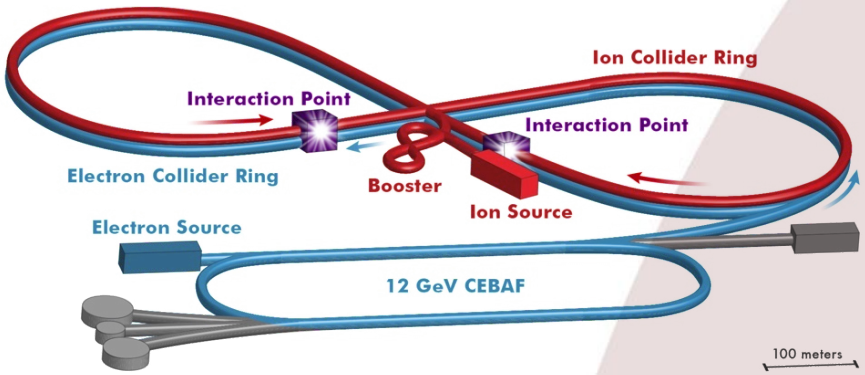
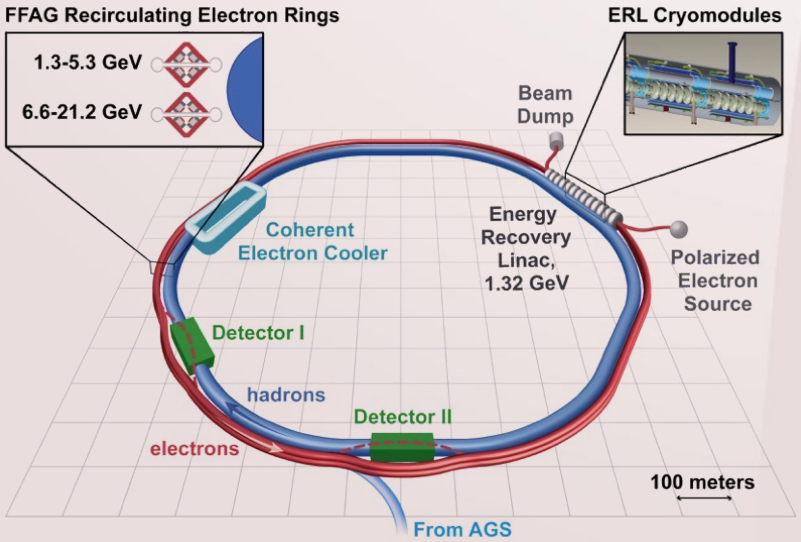
The Electron-Ion Collider:

Toward the next QCD frontier





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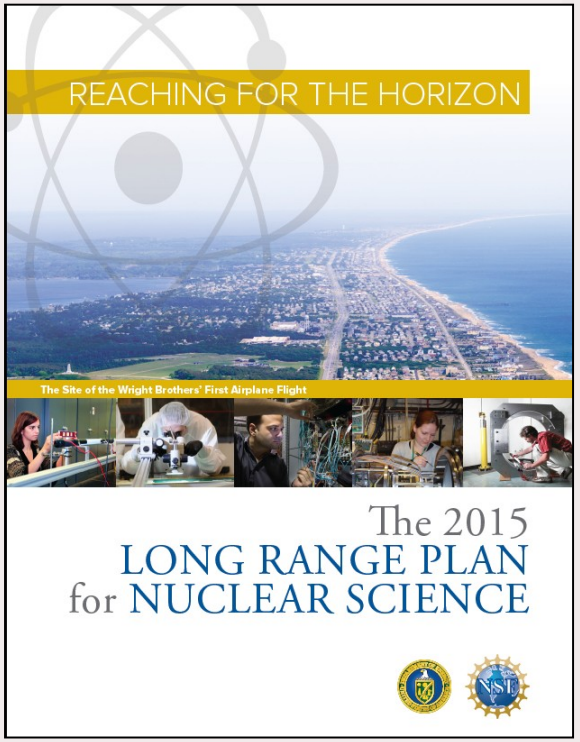
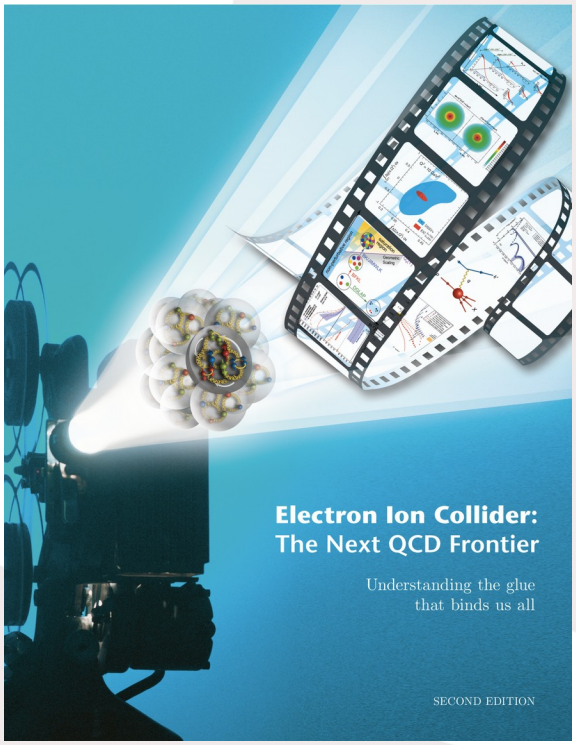
The EIC project

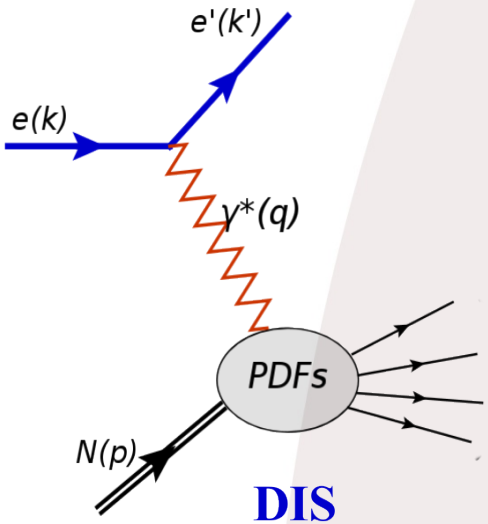
- **Project to build a multi-GeV electron-ion collider**
  - Polarized electrons ~10 GeV
  - Polarized protons and light nuclei ~100 GeV
  - Heavy ions up to lead ~100 GeV
- **Community formed for about a decade now**

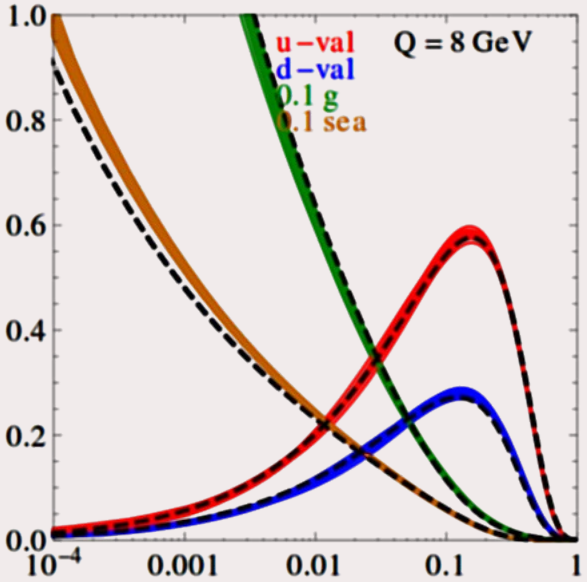


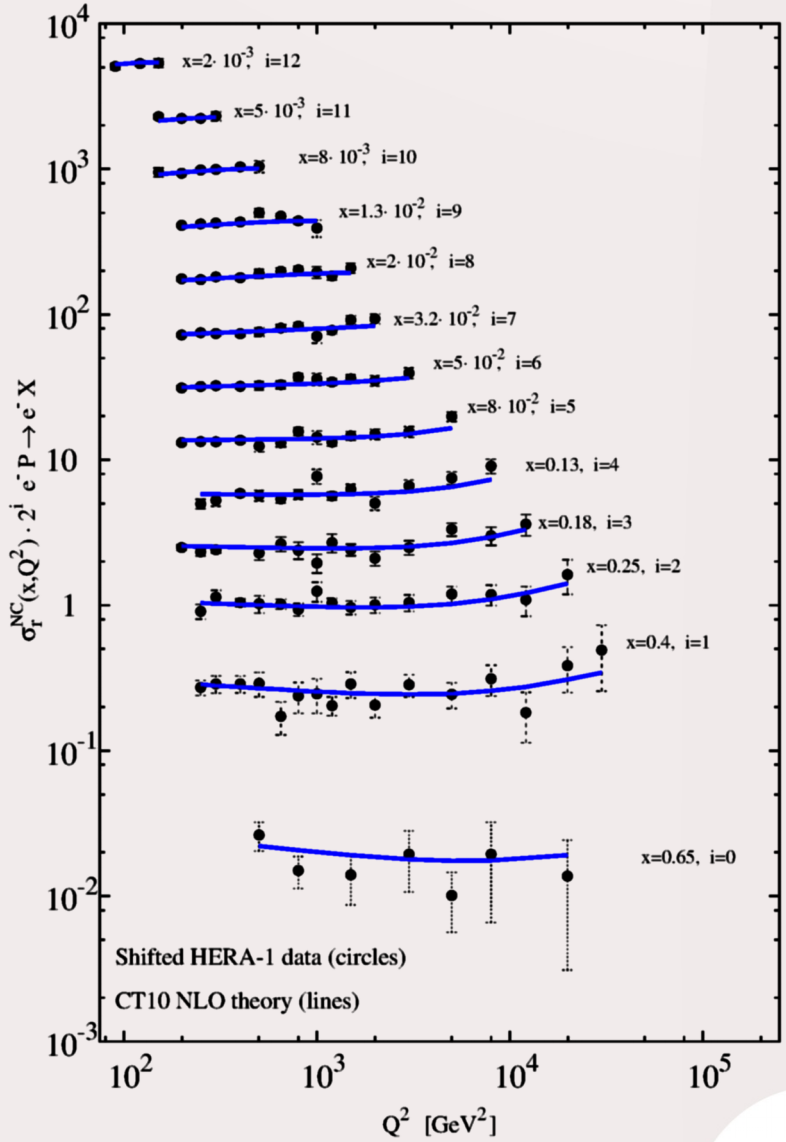


  - White paper published in 2012: arXiv:1212.1701.v3
- **American NSAC LRP recommendation**
  - "We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB."

Introduction to DIS







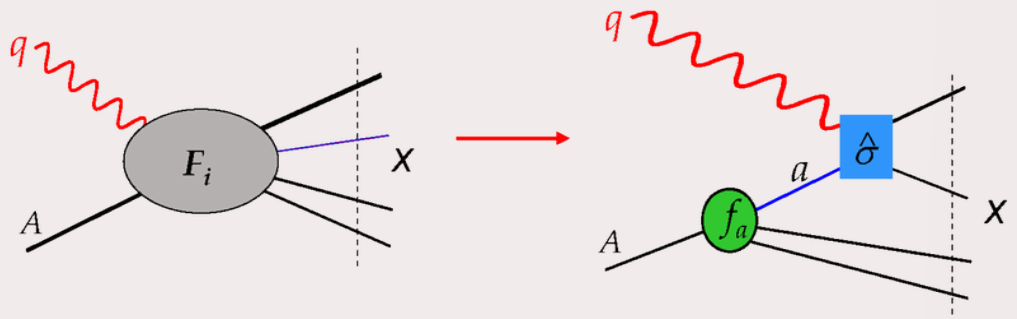
- **Deeply Inelastic Scattering**
  - Sums all inelastic scatterings in e-p
  - Probes quark's momentum in the form of parton distribution functions (PDFs)
- **Valence and sea quarks**
  - Valence ↔ constituent quarks
  - Gluon splitting is given by Q^2 evolution
  - Sea is not just evolution however!
    - Generated by non-perturbative effects

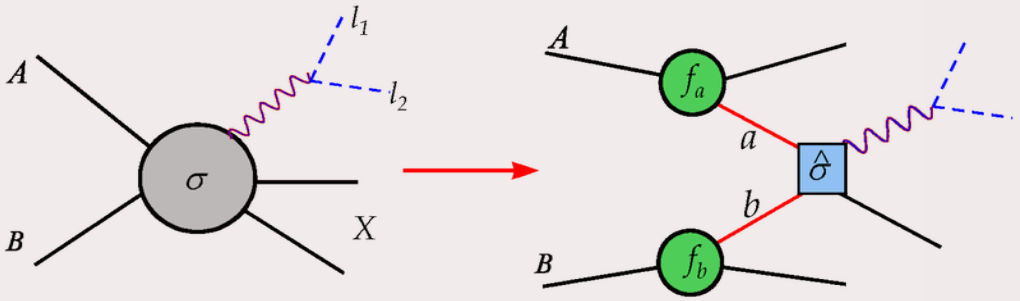
PDF CT10 NNLO J.Gao et al. Phys.Rev. D89 (2014) 3, 033009

Relation to other QCD processes

$$\lim_{Q^2 \to \text{large},\, x \text{fixed}} F_i(x,Q^2) = f_a \otimes \hat{\sigma}$$

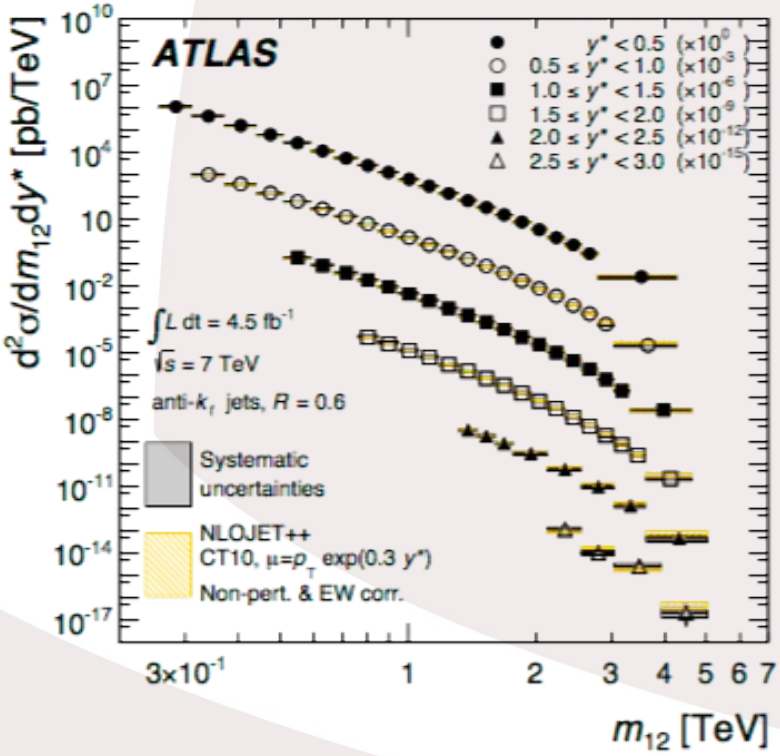
- **Collinear factorization**
  - Allows to separate structure and fragmentation functions
- **These objects are universal**
  - Can be related to all sorts of processes
  - pp, pA, AA, vA,…
- **Lepton scattering is the standard for their measurement**
  - The process is cleaner: one parton involved
  - Kinematic is driven by the lepton

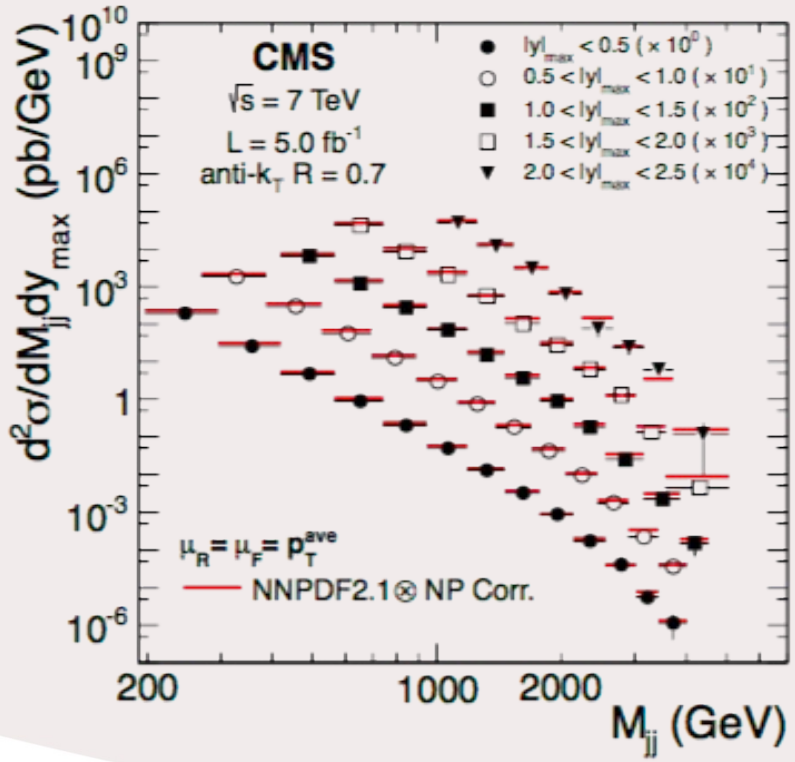




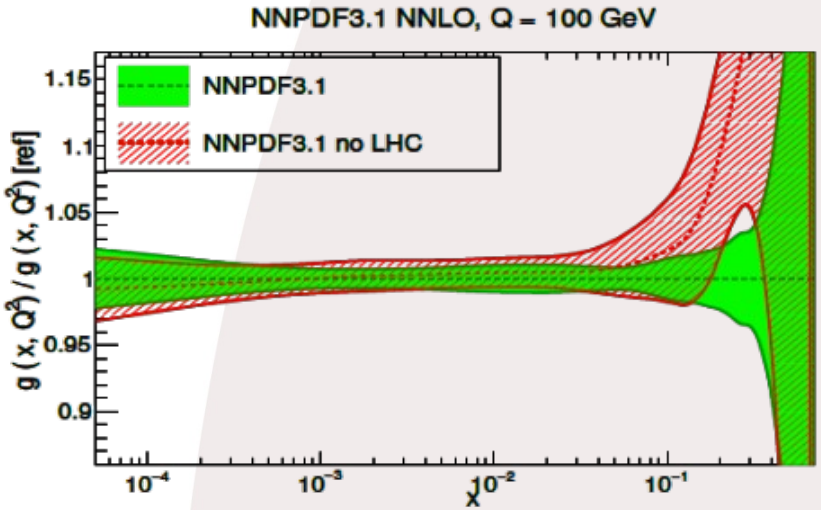
DIS applied to hadron collisions

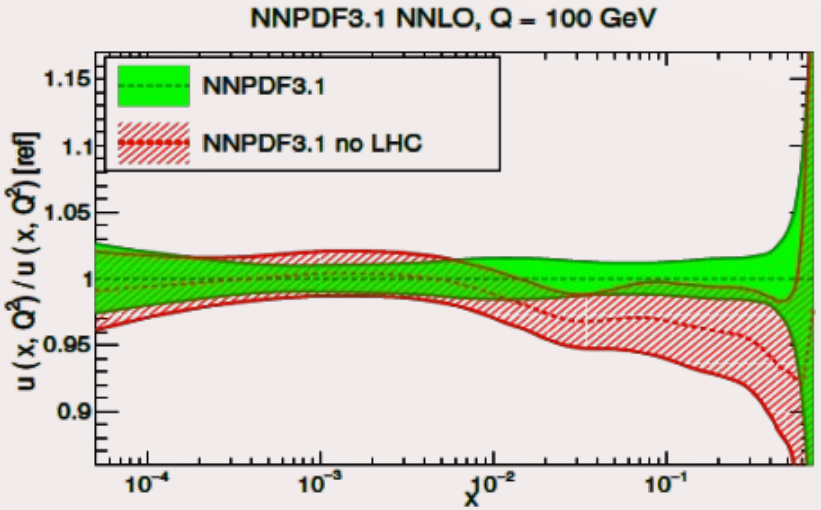
- **The description of LHC data based on past DIS measurements is very successful**
  - One of the great success of perturbative QCD has been to describe consistently experiments from the GeV to the TeV scale

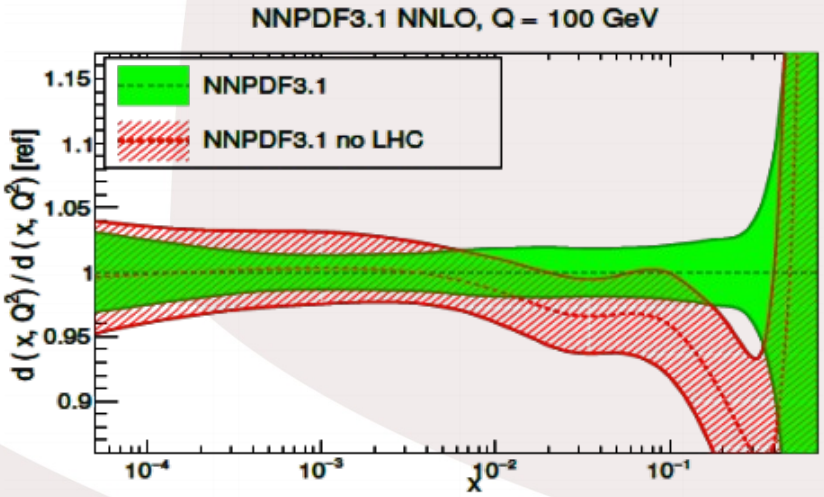




Universality works both ways



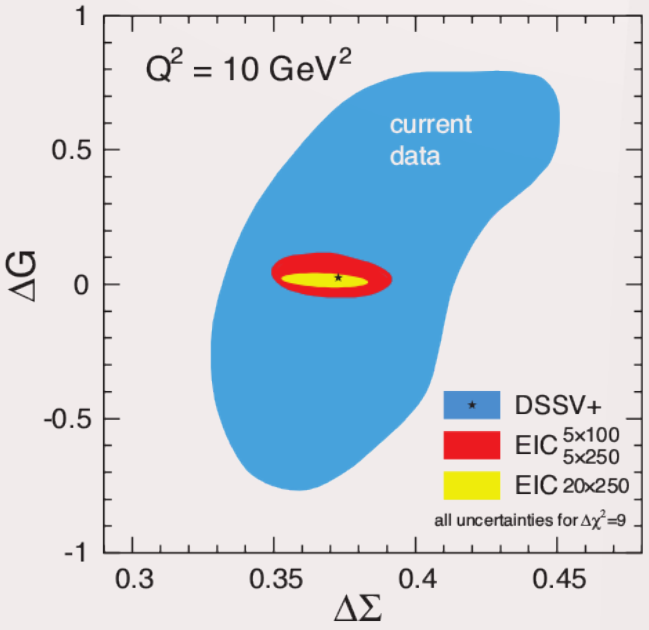




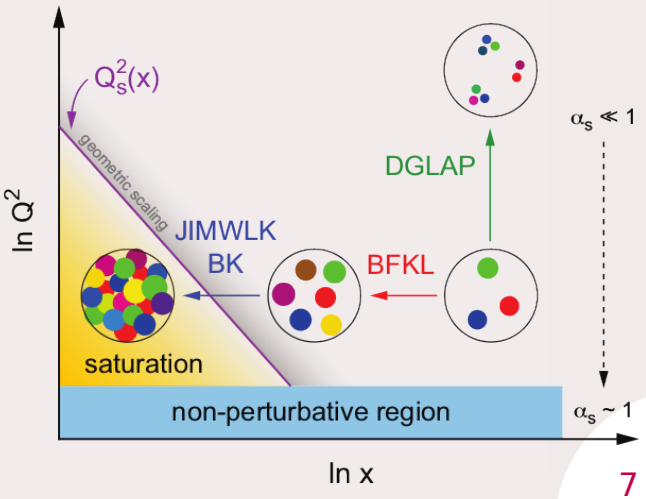
- **This works also the other way around**
  - LHC data constrains PDF extractions
  - In particular in high x (momentum fraction of the quark)

So what is missing? Why an EIC?

- **In the description of the nucleon**
  - The low and high x limits are still unknown
    - EIC will study the saturation effect at low x
  - The proton spin composition
    - EIC will help understand:
      - The orbital angular momentum of quarks
      - The contribution from gluons

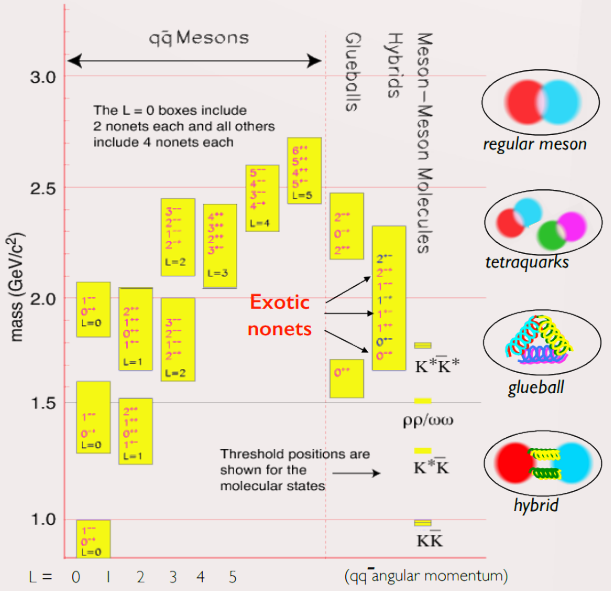


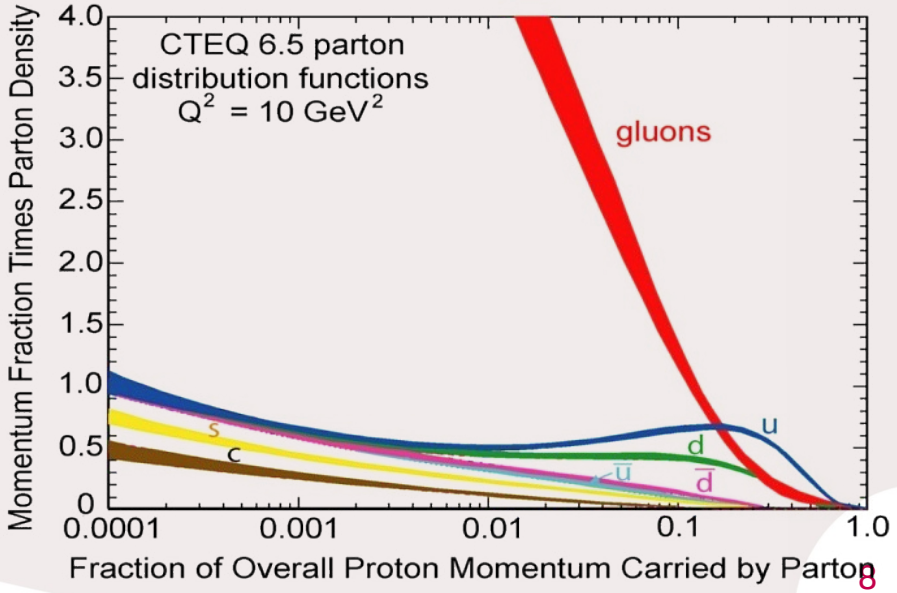
- **In the description of nuclei**
  - The nPDF and nFF are not so well known
    - EIC will scan nuclear PDFs on a wide x range
    - EIC will measure nuclear FF
  - N-N interaction
    - With EIC we will be able to correlate the nuclear and parton levels



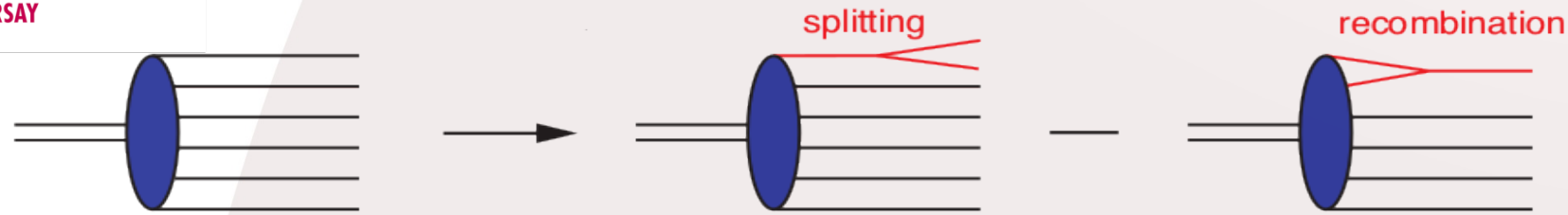
The Gluons in Hadrons

- **We know they are numerous**
  - But they are still mostly a mystery
- **It is an important focus today**
  - JLab 12 GeV upgrade main motivation is to find glueball and hybrid hadrons
- **At high energy they dominate**
  - The first detailed information are from pp (normal and polarized)
  - It is also possible to access them through DIS with high energy charm production
  - Or at very high energy by saturating their PDF

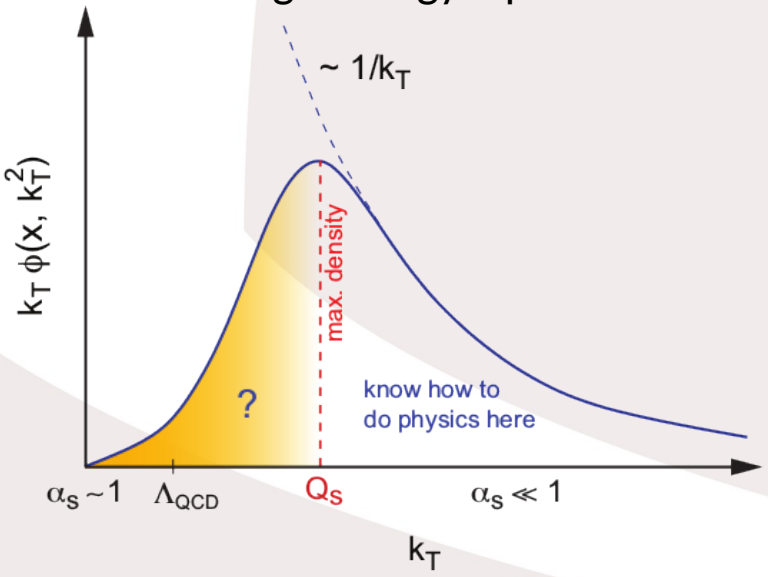


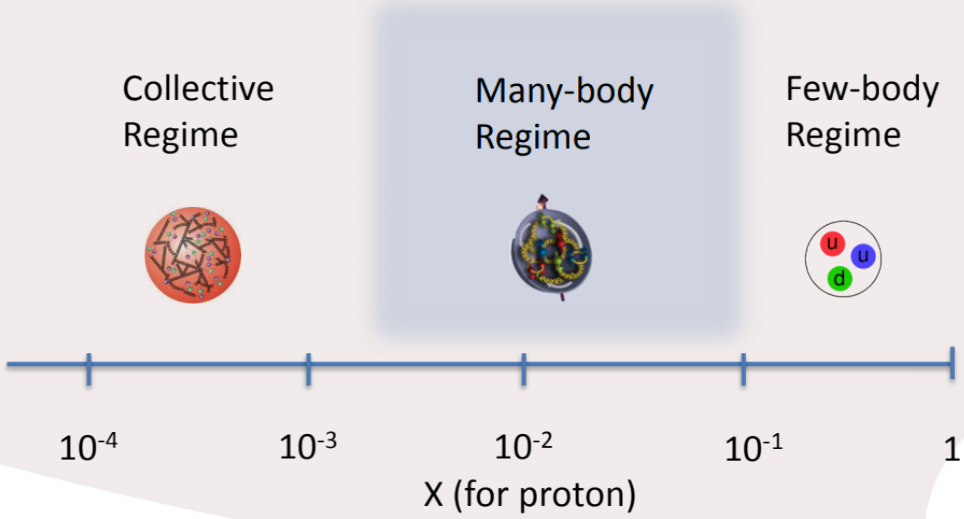


The Gluon Saturation



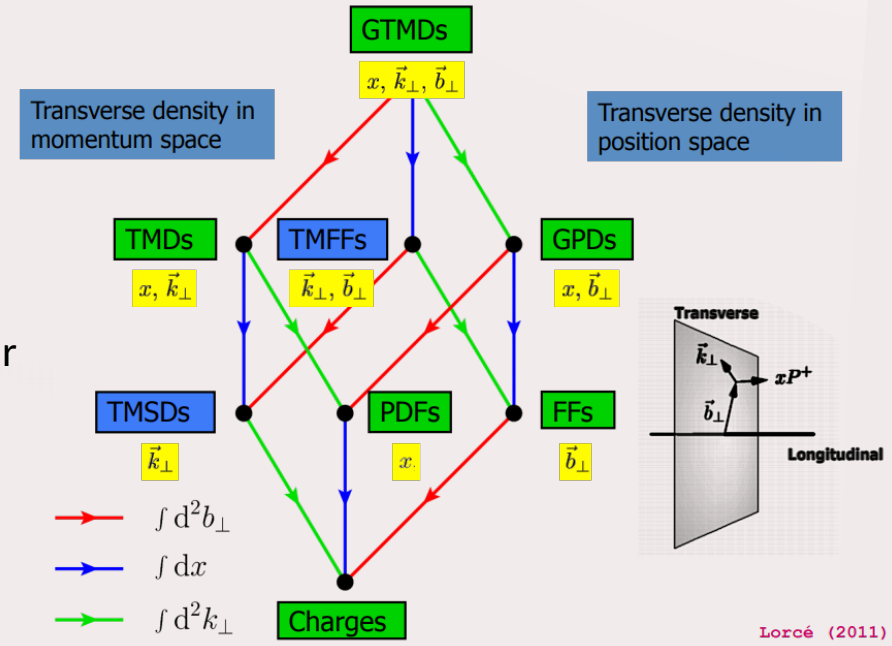
- **Saturation occurs when recombination diagrams become relevant**
  - It is the domain of collective effects and where QCD becomes non linear
  - It is probed only at very high energies, but can be enhanced in nuclei
  - Its presence has been hinted in many heavy ion experiments
  - EIC offers the best situation for discovery and study
    - High energy lepton scattering is much easier to theoretically describe

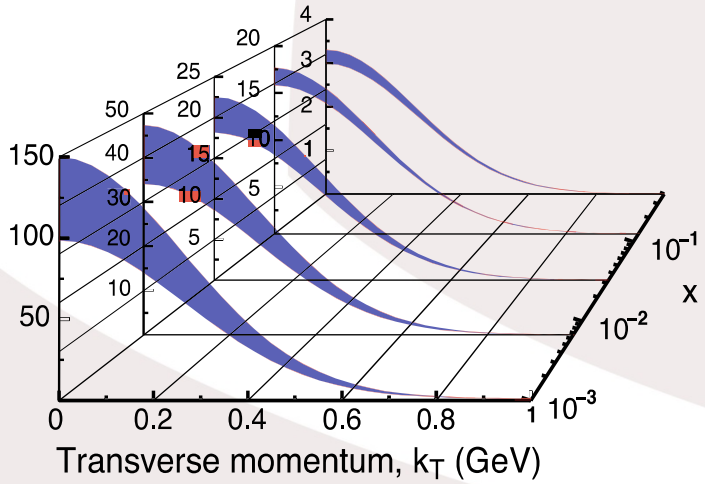


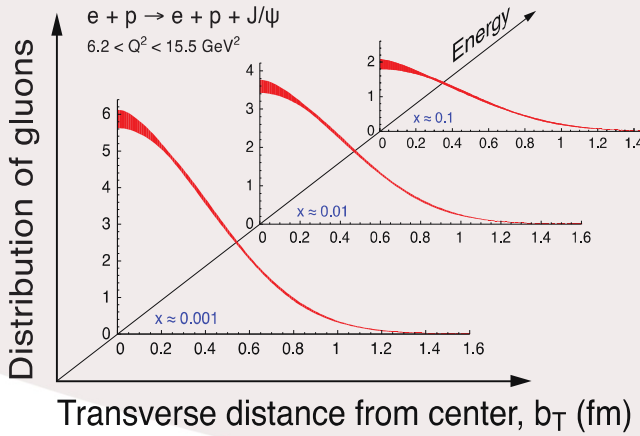


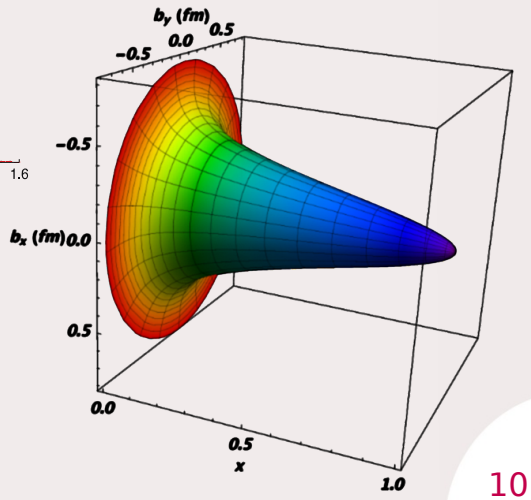
The nucleon structure

- **There are many more structure functions**
  - In the recent years, focus was on GPDs and TMDs
- **They allow to decompose the contributions to the spin of the proton**
  - Ji sum rule links the GPDs to the orbital angular momentum
  - Necessitate to integrate over x
- **Give access to the proton tomography**
  - Only intermediate x measured today
  - EIC will explore the low x region



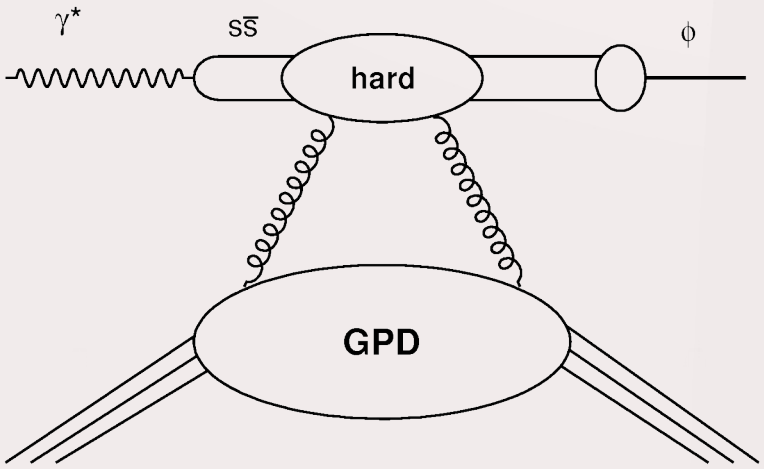




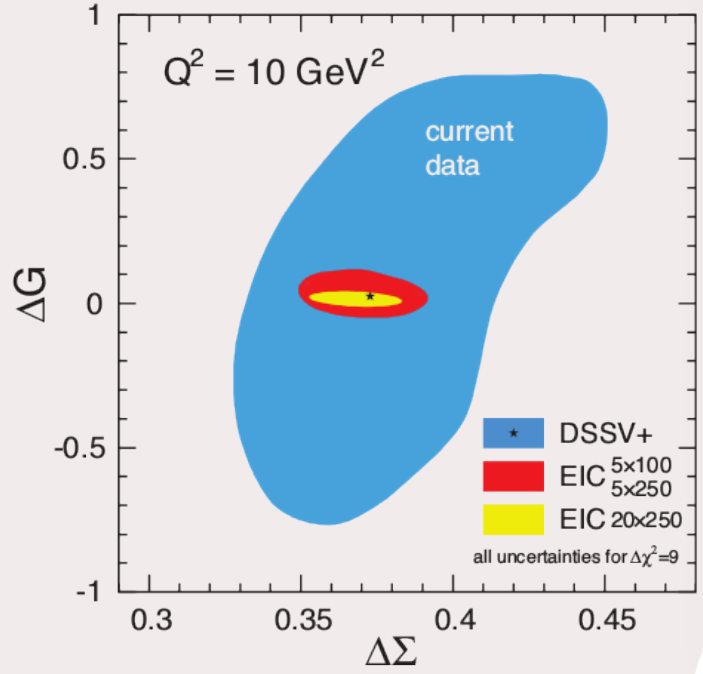


Gluons in the nucleon

- **Gluon GPDs can be accessed**
  - Using exclusive J/Psi production
  - Do the gluons spatially extend more than quarks at a given momentum?

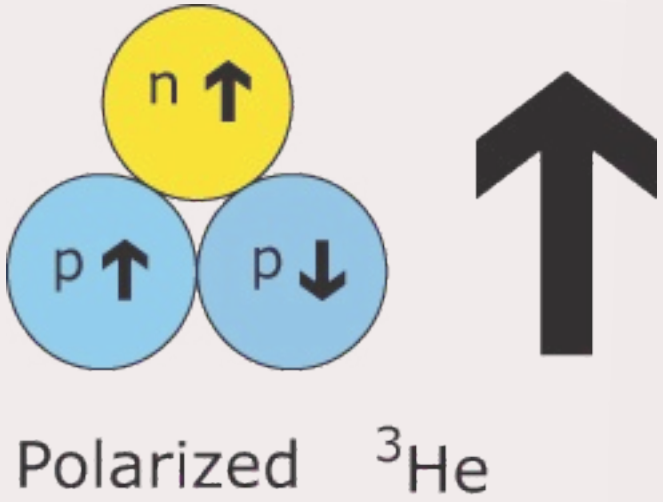


- **Gluons impact on the proton spin**
  - Completely unknown today
  - The gluon contribution to the proton spin could be very large
  - Accessed through polarized inclusive and semi-inclusive hadron production

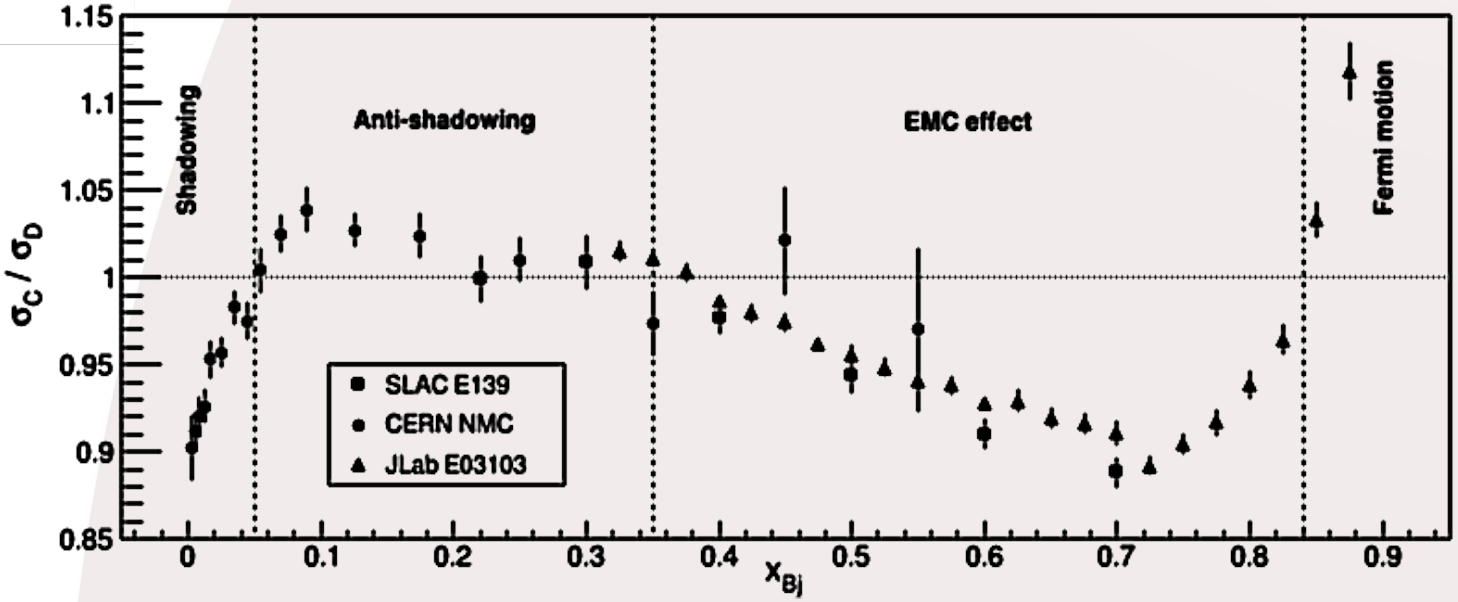


Looking into the neutron

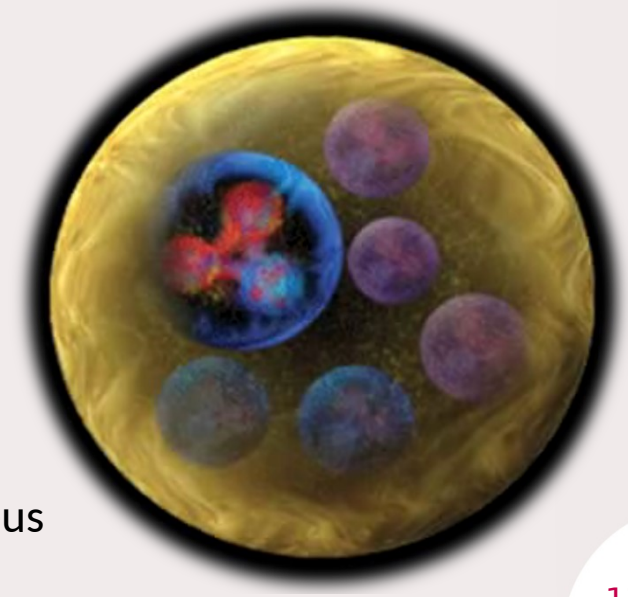
- **Why studying the neutron in detail?**
  - It gives access to the u/d flavor separation
    - To study charge symmetry breaking in QCD matter
    - It also impacts neutrino physics
- **Using deuteron and helium-3**
  - Both are going to be available in the EIC
  - (Deuterium – proton) is the best neutron target we have today
  - The same can be done with polarized helium-3 to obtain a polarized neutron beam
- **Allows to do all the same physics as for protons**



Nuclear physics at EIC

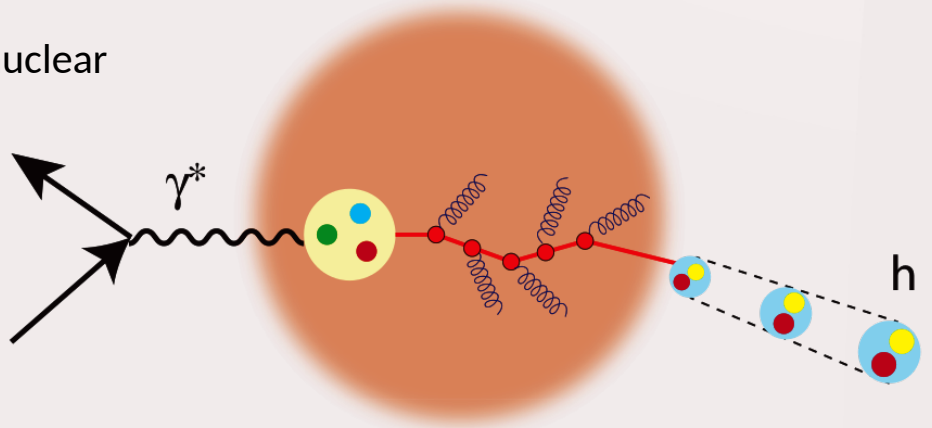


- **The nucleus is much more than a sum of nucleons**
  - Nuclear PDFs proved that a long time ago
  - We are unable to understand most of the nuclear quark structure
- **EIC will also be a machine for nuclear physics**
  - Precise measurement of nPDFs: shadowing, EIC …
  - Shadowing has never been formally observed!
  - These measurements are crucial to understand the nucleus
  - But also to interpret heavy ion collision data: pA & AA

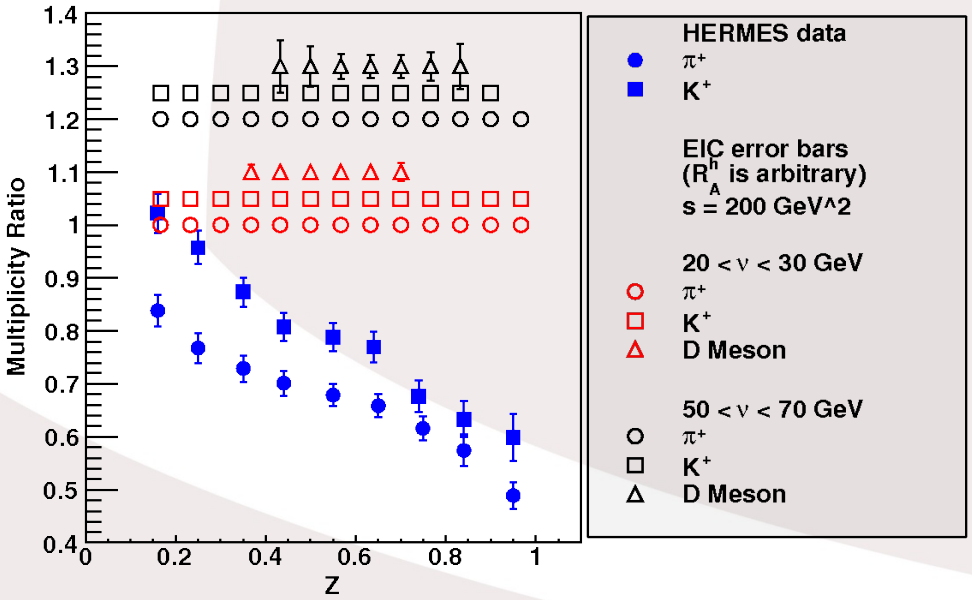


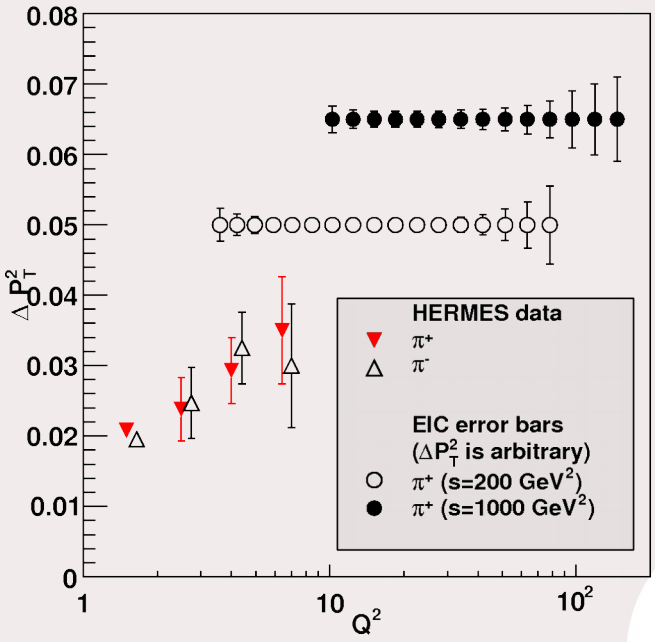
Parton Energy Loss in CNM

- **Parton Energy Loss**
  - Widely used to describe hadron suppression in nuclear material (Cold or hot like in QGP)
  - It gives access to the properties of the medium
    - In particular gluon density
  - Wide variety of calculations are available spreading over an order of magnitude



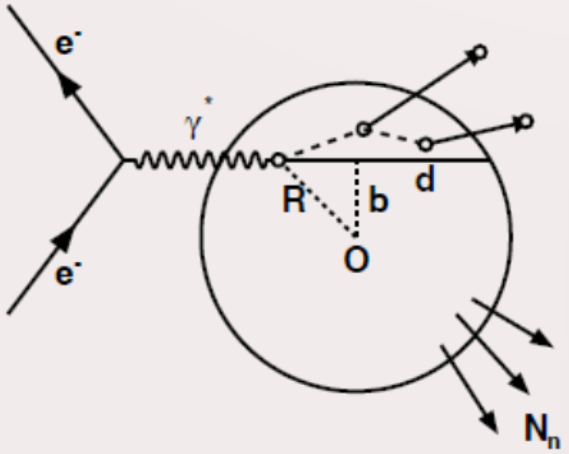
- **Cold nuclear matter is a perfect benchmark**
  - EIC will offer energies comparable to RHIC and LHC
  - In particular with access to heavy quarks

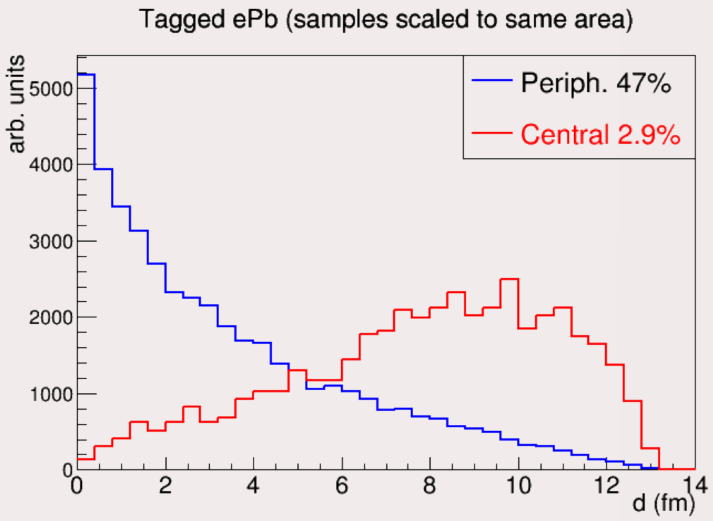




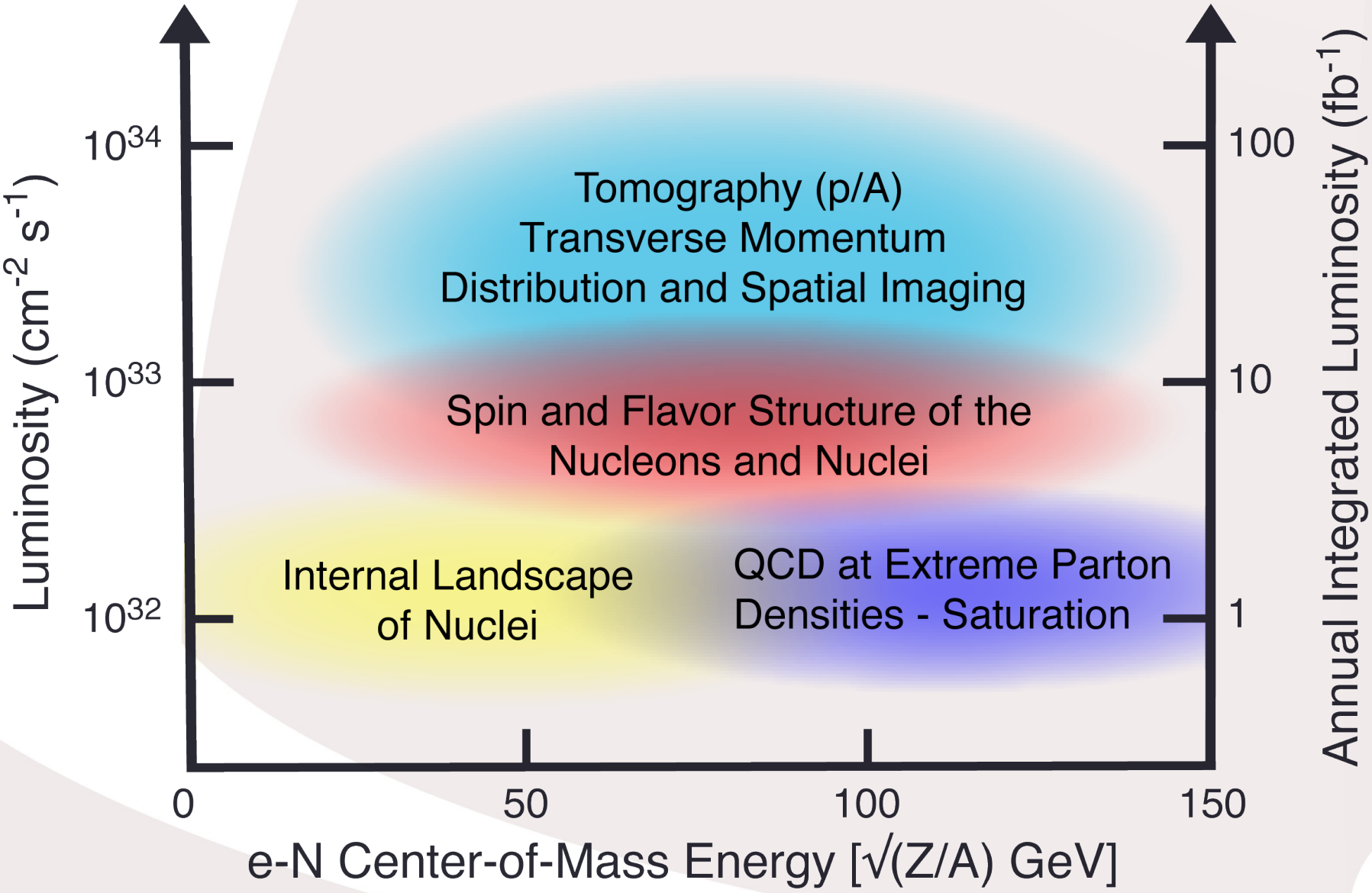
Centrality measurement

- **An example of one of many ongoing studies**
  - Lot of work to determine the physics channel of interest and drive the design of the machine
- **Centrality measurements are now standard in A-A**
  - They get more and more evolved
  - There are problems in p-A however
  - Hinting to similar issues with the unknown case of e-A
- **Monte-Carlo developments to inform detector design is starting now**
  - Use old data from Fermi lab to calibrate the simulation
  - Use the expertise from AA community

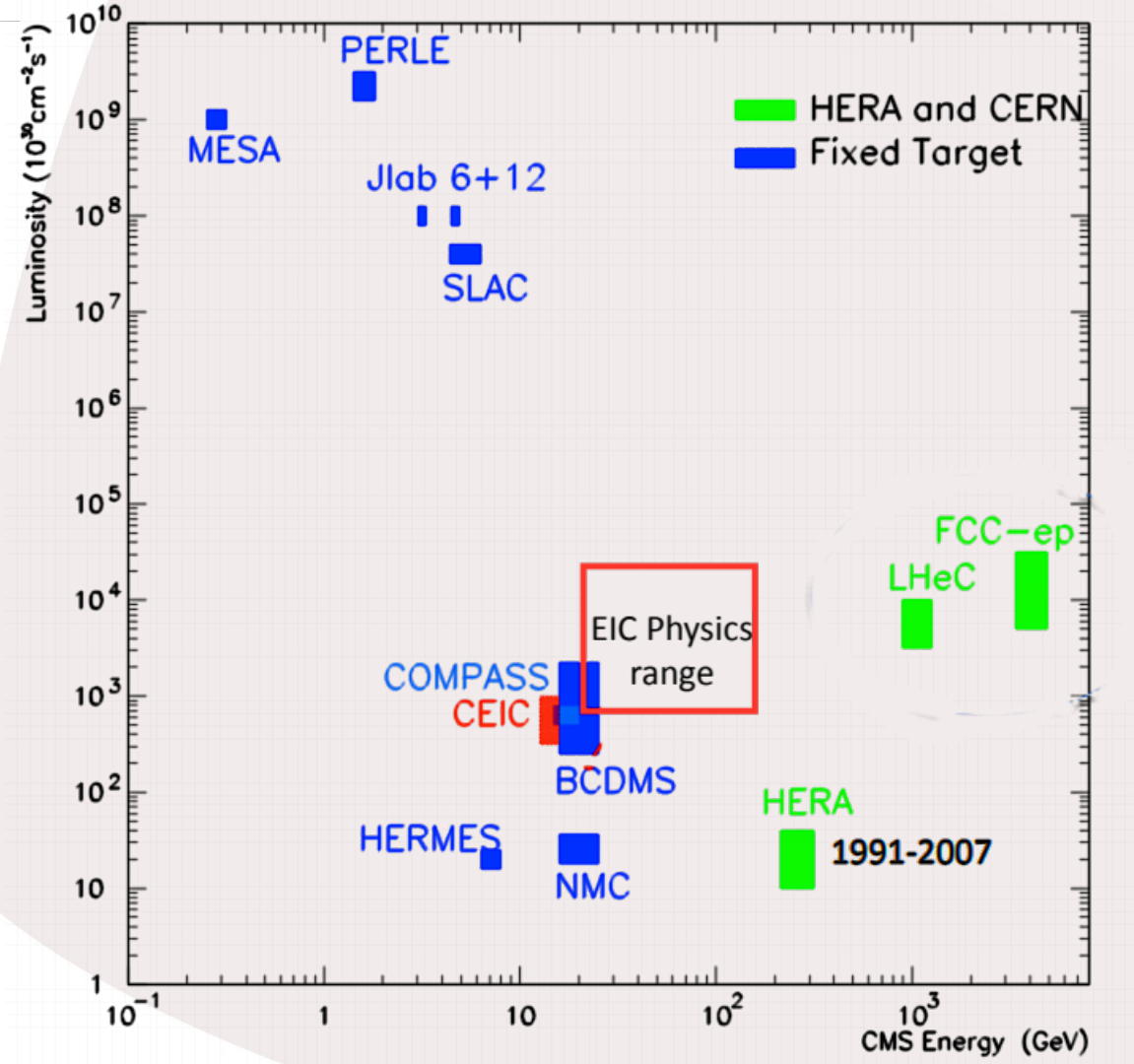




What EIC do we need?

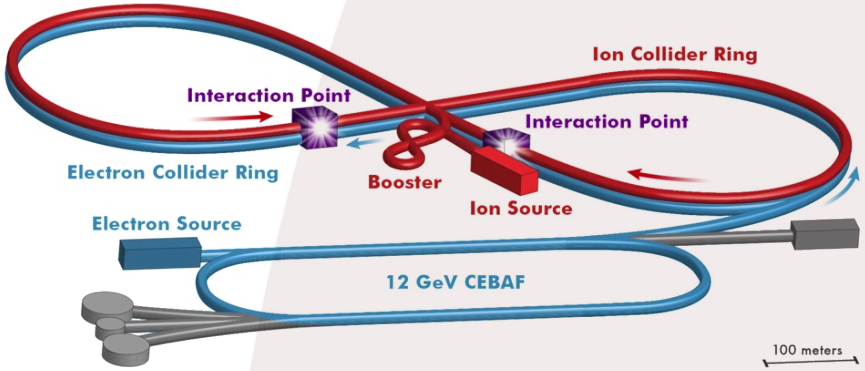


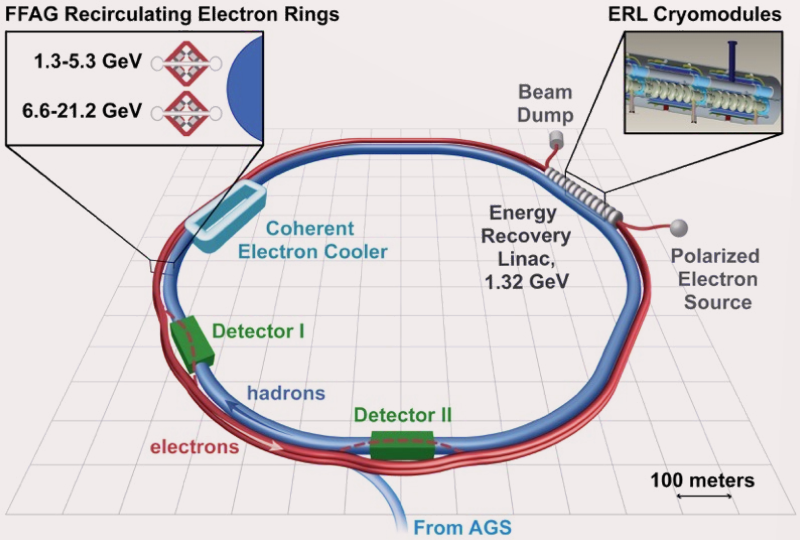
EIC in the International Landscape



- Improves on previous machines by an order of magnitude in energy and luminosity
- Adds nuclear targets, together with polarized electrons and nucleons capabilities

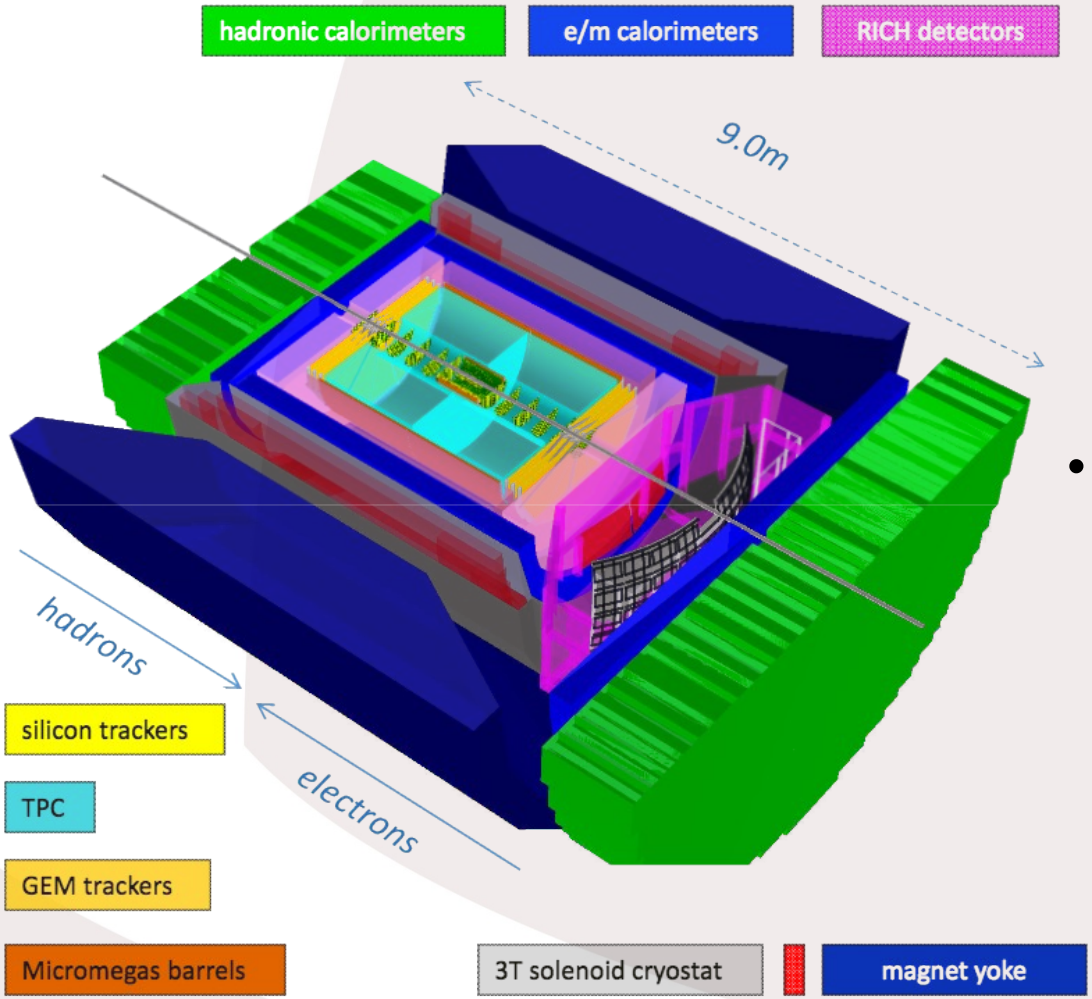
The BNL and the JLab projects





- **Today, there are two competing designs**
  - Jefferson Lab electron machine reused with a new heavy ion accelerator
  - BNL heavy ion machine reused with a new electron machine
- **Both are very similar with small variations**
  - The JLab 8 shaped designs helps with polarization
    - Good for proton spin studies
  - The BNL facility offers slightly more energy
    - More suitable for saturation studies
- **Development of the physics case will help settle the matter**

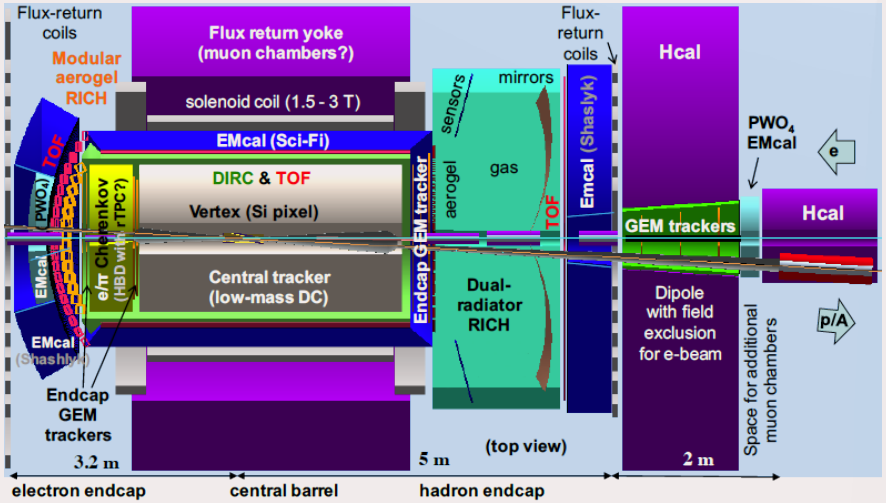
Detector concepts BNL

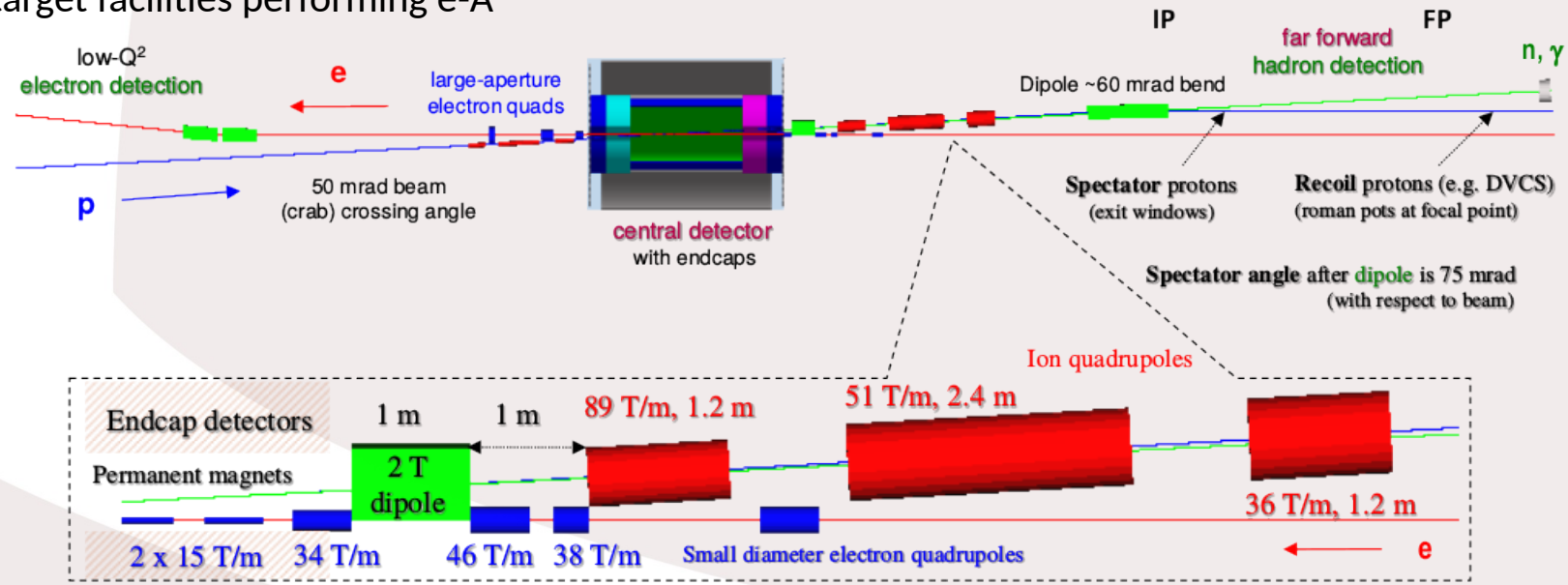


- **Use all the modern detector technologies**
  - Silicon vertex in the center, trackers around
  - Then Cerenkov detectors
  - Followed by EM and hadronic calorimeters
  - Surrounded by a solenoid
- **Detectors are standard collider designs**
  - Very similar to RHIC or LHC detectors
    - With strong effort on individual PID capabilities
  - There is also an asymmetry between the hadron and electron sides
    - Which need rather different PID capabilities

Detector concepts: JLab

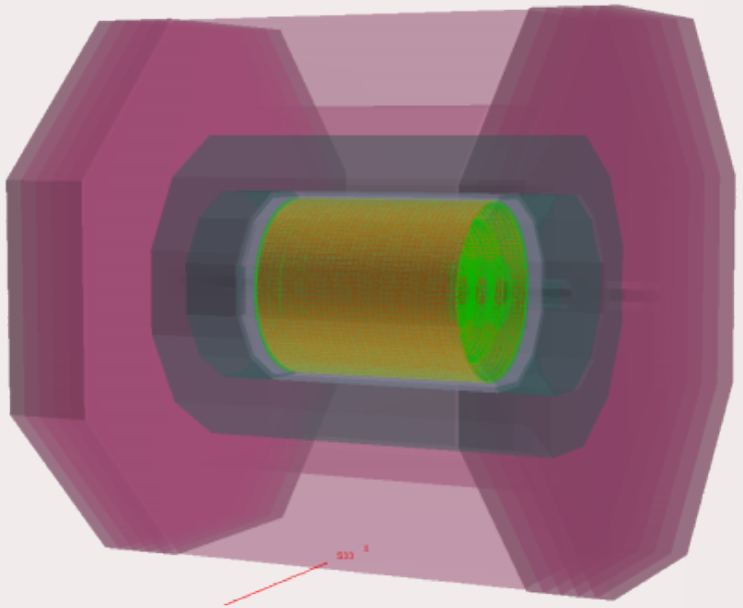
- **JLab has a similar concept**
  - With lots of room devoted to RICH detectors
  - The low multiplicity expected in e-A allows for better Particle ID
- **Low angle capabilities**
  - Critical for many processes
    - Coherent scatterings
    - Centrality measurements
  - Unique in comparison to the many fixed target facilities performing e-A

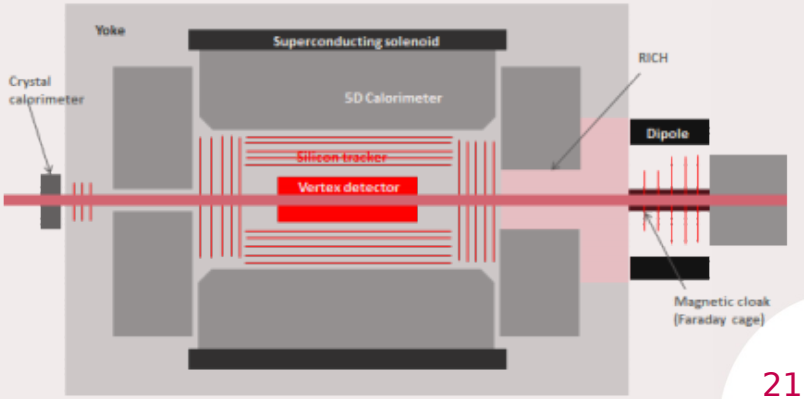




Detector R&D Opportunities

- **Many other activities**
  - A new accelerator is the occasion to start completely new detector R&D programs
  - Funding was made available by the American DOE (through BNL)
- **Argonne National Lab detector as an example**
  - A third detector project
  - All in on silicon R&D
  - Perform all particle ID with TOF
    - 10 ps resolution goal
- **Calorimetry R&D in IPN Orsay**
  - Active PbWO crystal recovery
  - Using UV light to recover radiation damage *during* data tacking
- **And much more…**





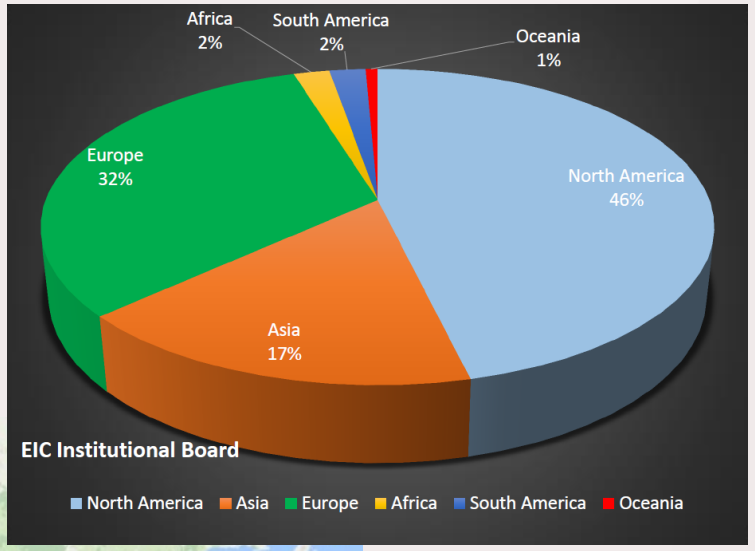
Time Line of the Project

- 2009 – INT 8 weeks program to define the physics goal
- 2012 – White paper summarizing the key measurements
- 2015 – Recommendation by DOE NSAC in their Long Range Plan
- 2017 – (American) National Science Academy review

- 2018 – Expected “CD0”: official administrative start of project
- ~2019-2020 Decision on the site (JLab or BNL)
- ~2022-2023 Start of construction
- ~2027 First beam for physics!

EIC User Group

- **With beam expected in about 10 years**
  - It is now time to organize! We created a user group
  - Physics and detector groups are starting to form
- **Strong European involvement**
  - General UG meeting in Trieste past Summer
  - France involvement however remains low



http://www.eicug.org

Already

700 physicists

100 institutions

Summary

- **The next big machine for QCD will be the Electron-Ion Collider**
  - Two accelerator designs are being developed in JLab and BNL
- **Many physics topics will be explored**
  - Measure in detail the partonic structure of the nuclei
  - Access to the low x tomography of the nucleon
    - Necessary to access precisely quark orbital angular momentum
  - EIC will be a machine to measure the gluons in the nucleon
    - Polarized PDFs and overall contribution to the nucleon spin
  - Access gluon saturation in nuclei at low x
  - Parton energy loss and fragmentation in cold nuclear matter
- **The physics community is starting to organize**
  - Detector projects are starting to be proposed
  - Detector R&D programs are also starting in many institutions
- **These activities regroup the heavy ion and lepton scattering communities worldwide**
  - Hopefully, it will trigger a similar effect in France!