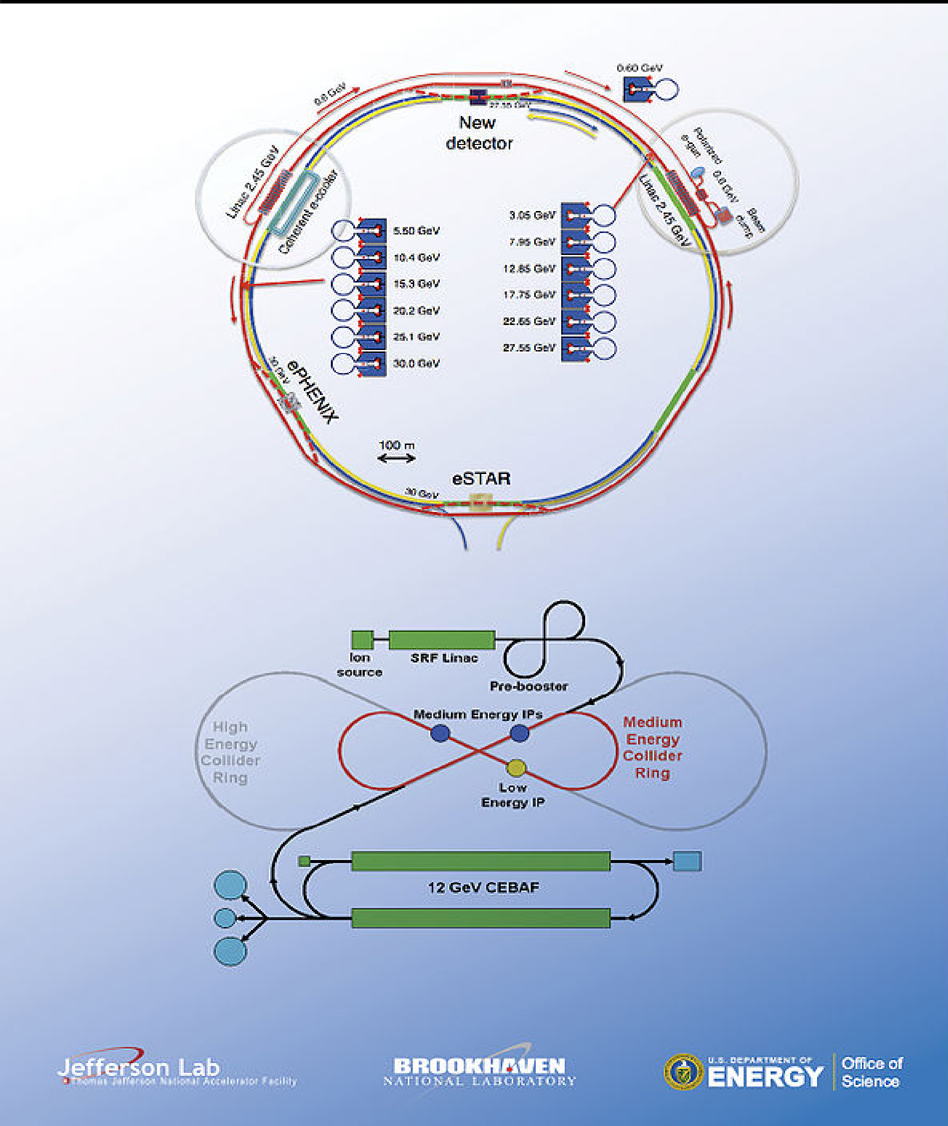
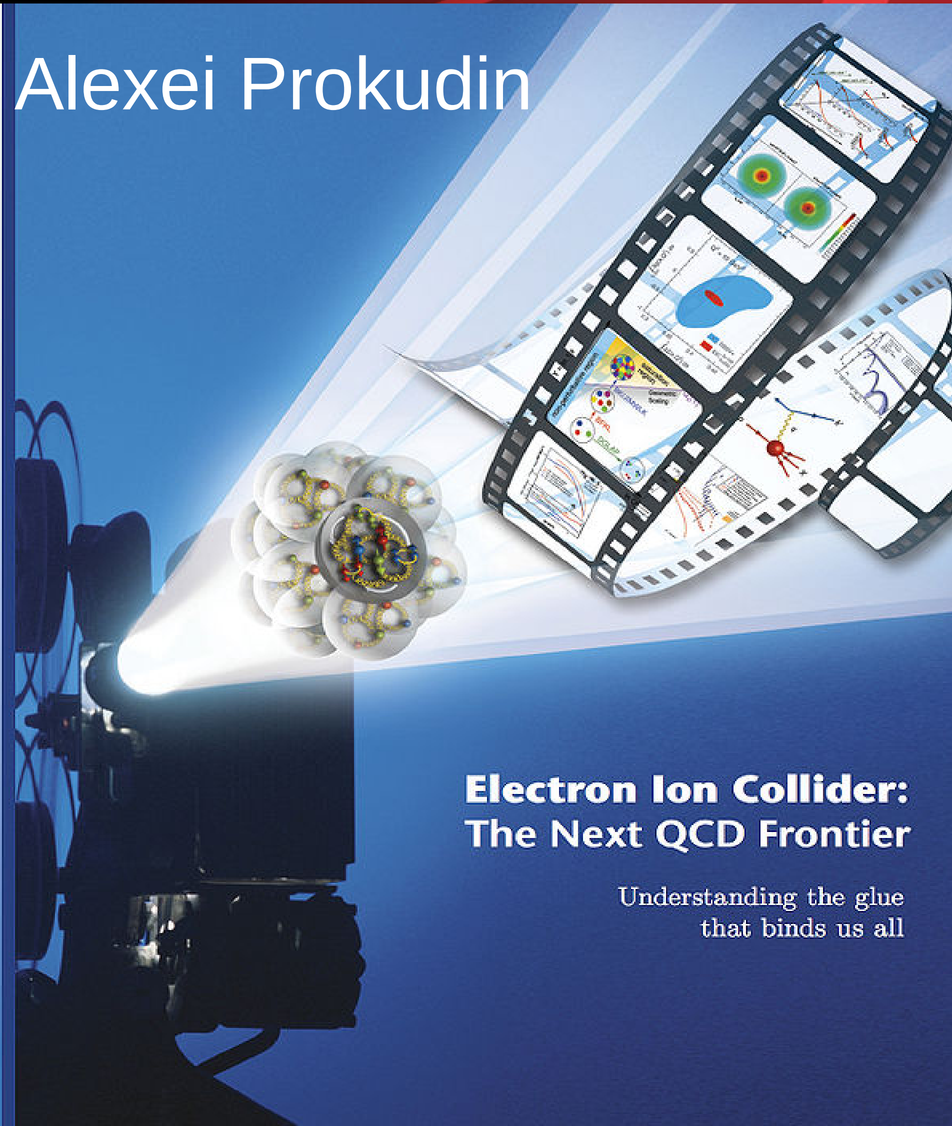
Electron Ion Collider

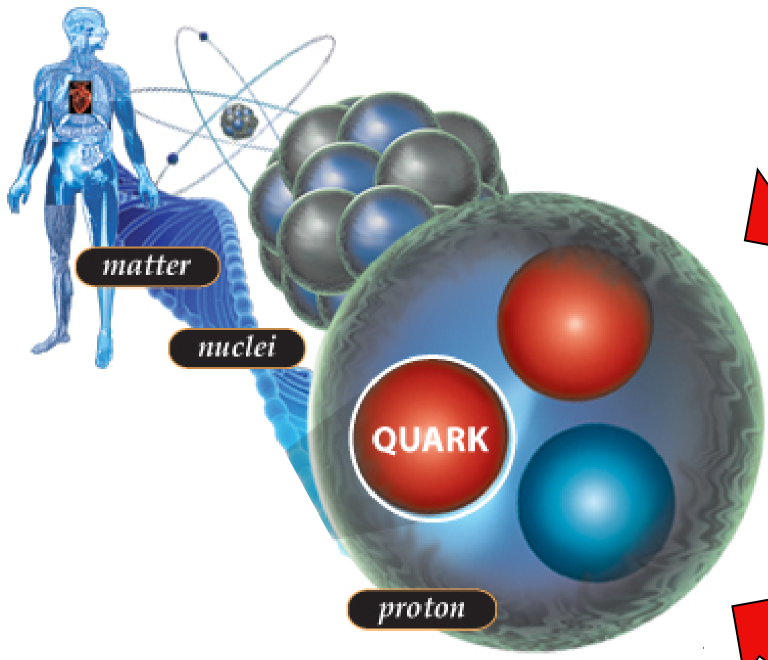


Alexei Prokudin



June 11 2015

Exploring the nucleon: a fundamental quest

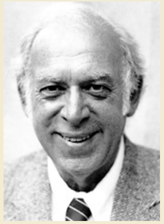
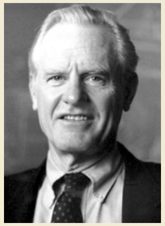


Know what we are made of !

Understand the strong force: "QCD"

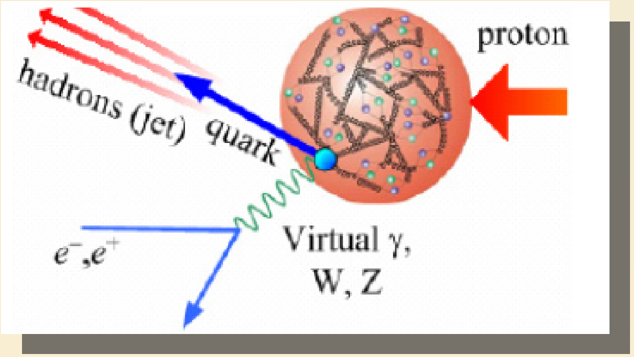
Use protons as tool for discovery (e.g. LHC)

Electron Scattering

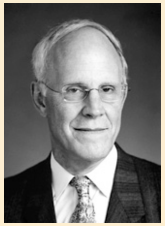




"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

Friedman, Kendal, Taylor, Nobel Prize 1990



"for the discovery of asymptotic freedom in the theory of the strong interaction"

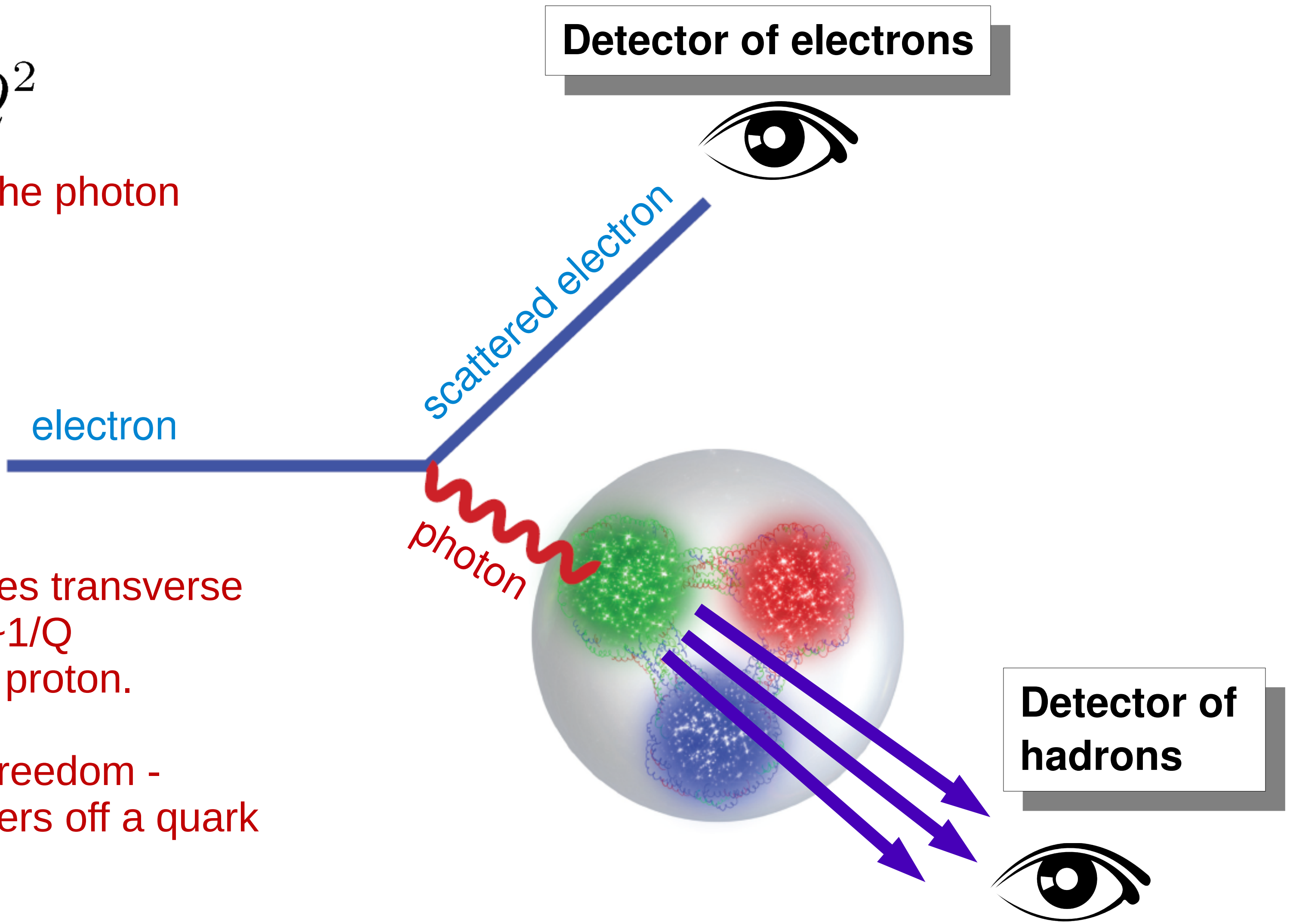


Gross, Politzer, Wilczek, Nobel Prize 2004

Electron Scattering

$$q^2 = -Q^2$$

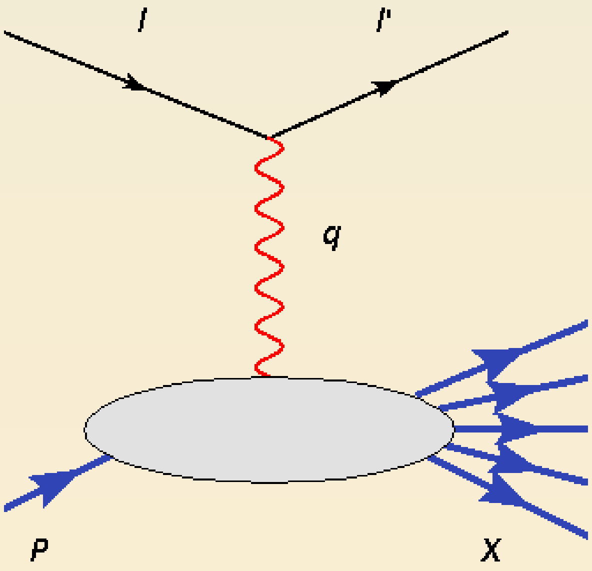
Virtuality of the photon



Photon probes transverse
distance of ~1/Q
inside of the proton.

Asymptotic freedom -
photon scatters off a quark

Electron Scattering: interpretation

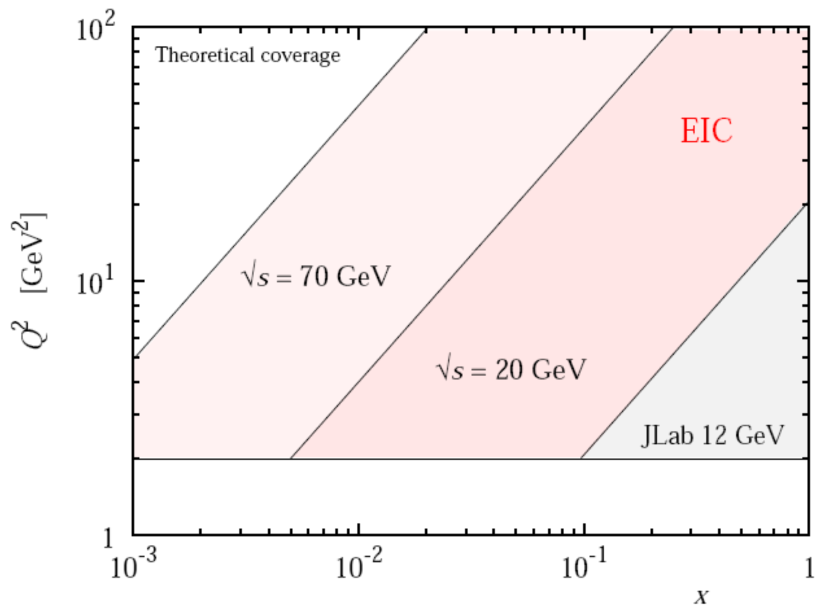


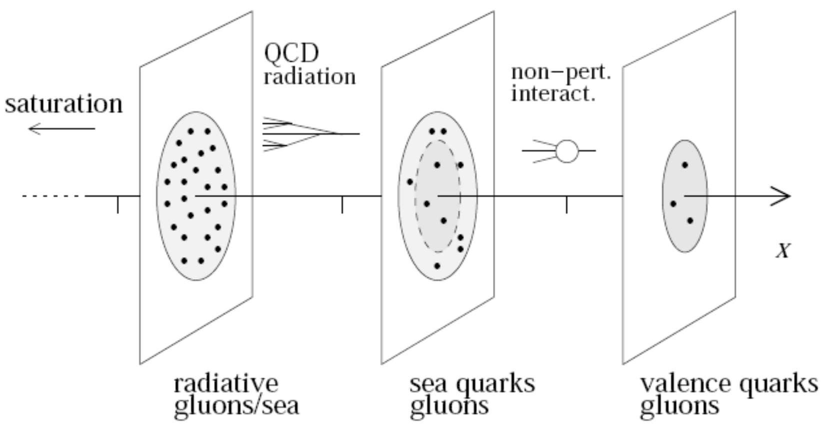
Electromagnetic probe resolves a quark or anti-quark with momentum **k = x P** inside of the proton of momentum **P**.

$$x_{Bj} = \frac{Q^2}{2P \cdot q}$$ Bjorken variable

Gives fraction of longitudinal momentum of the proton carried by the parton

Nucleon landscape





Nucleon is a many body dynamical system of quarks and gluons

Changing **x** we probe different aspects of nucleon wave function

How **partons move** and how they are distributed in **space** is one of the future directions of development of nuclear physics

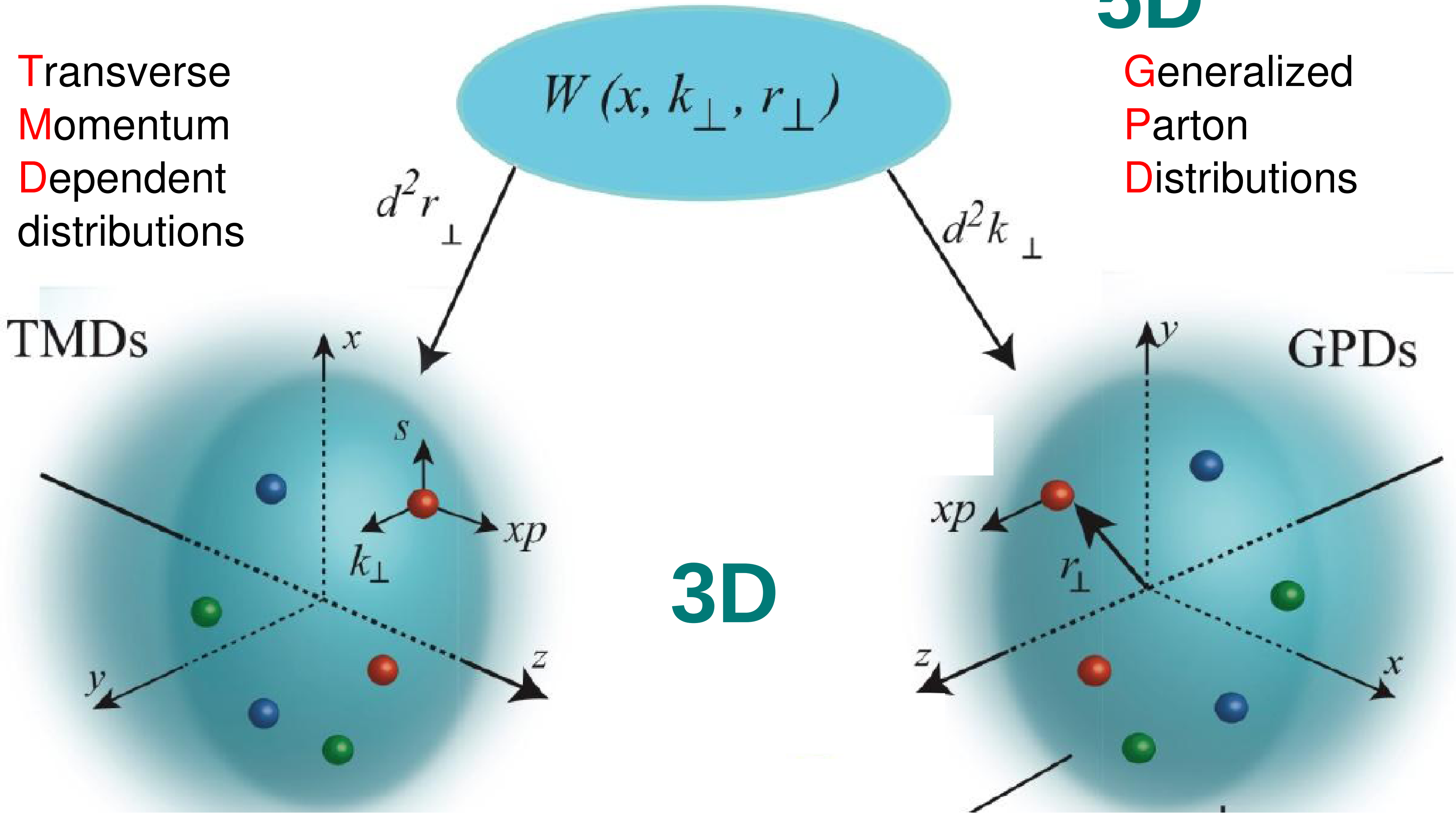
Technically such information is encoded into Generalised Parton Distributions and Transverse Momentum Dependent distributions

These distributions are also referred to as **3D (three-dimensional) distributions**

Unified View of Nucleon Structure

Wigner function

5D



Transverse
Momentum
Dependent
distributions

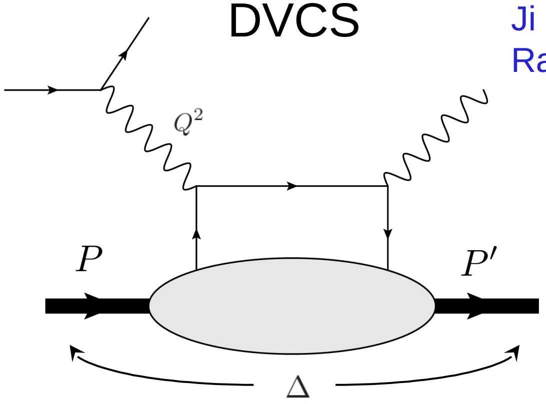
Generalized
Parton
Distributions

3D

GPDs   TMDs

DVCS

Ji (1997)
Radyushkin (1997)



Q^2 ensures hard scale, pointlike interaction

$\Delta = P' - P$ momentum transfer can be varied independently

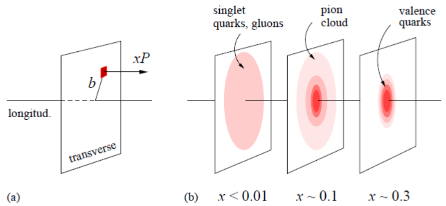
Connection to 3D structure

Burkardt (2000)
Burkardt (2003)

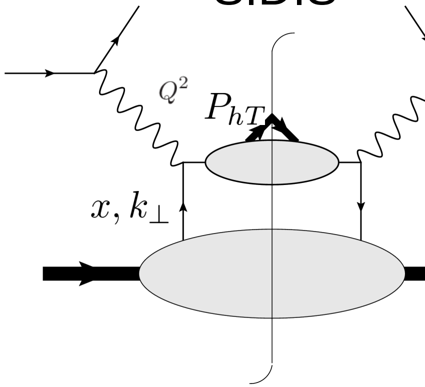
$$\rho(x, \vec{r}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\vec{\Delta}_\perp \cdot \vec{r}_\perp} H_q(x, \xi = 0, t = -\vec{\Delta}_\perp^2)$$

Drell-Yan frame $\Delta^+ = 0$

Weiss (2009)



SIDIS



Kotzinian (1995),
Mulders,
Tangerman (1995),
Boer, Mulders (1998)

Q^2 ensures hard scale, pointlike interaction

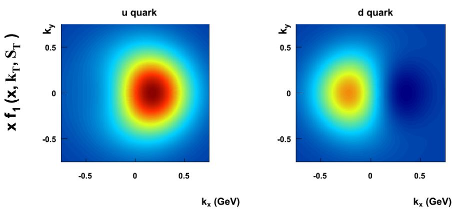
P_{hT} final hadron transverse momentum can be varied independently

Connection to 3D structure

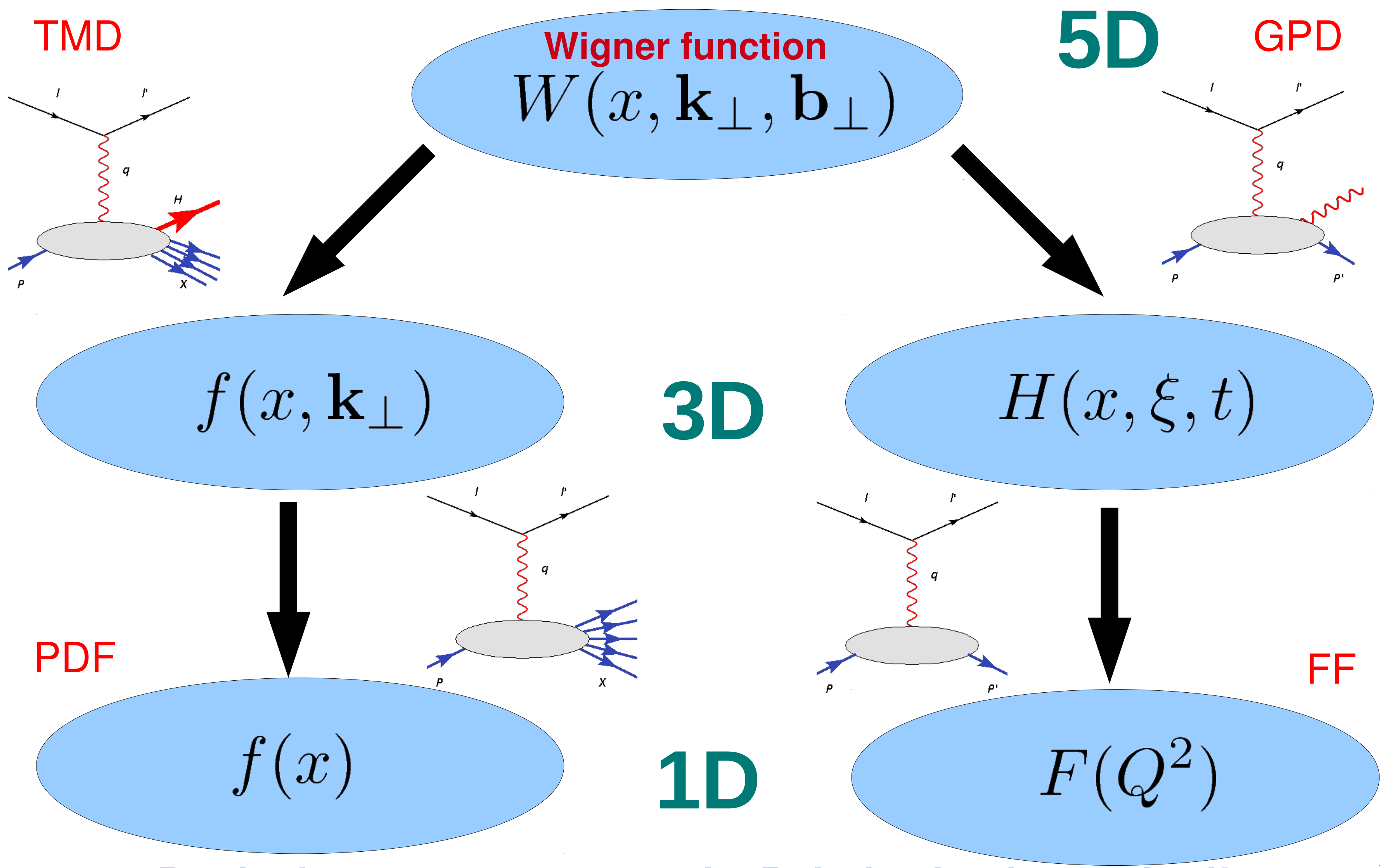
Ji, Ma, Yuan (2004)
Collins (2011)

$$\tilde{f}(x, \vec{b}_T) = \int d^2k_\perp e^{-i\vec{b}_T \cdot \vec{k}_\perp} f(x, \vec{k}_\perp)$$

AP (2012)

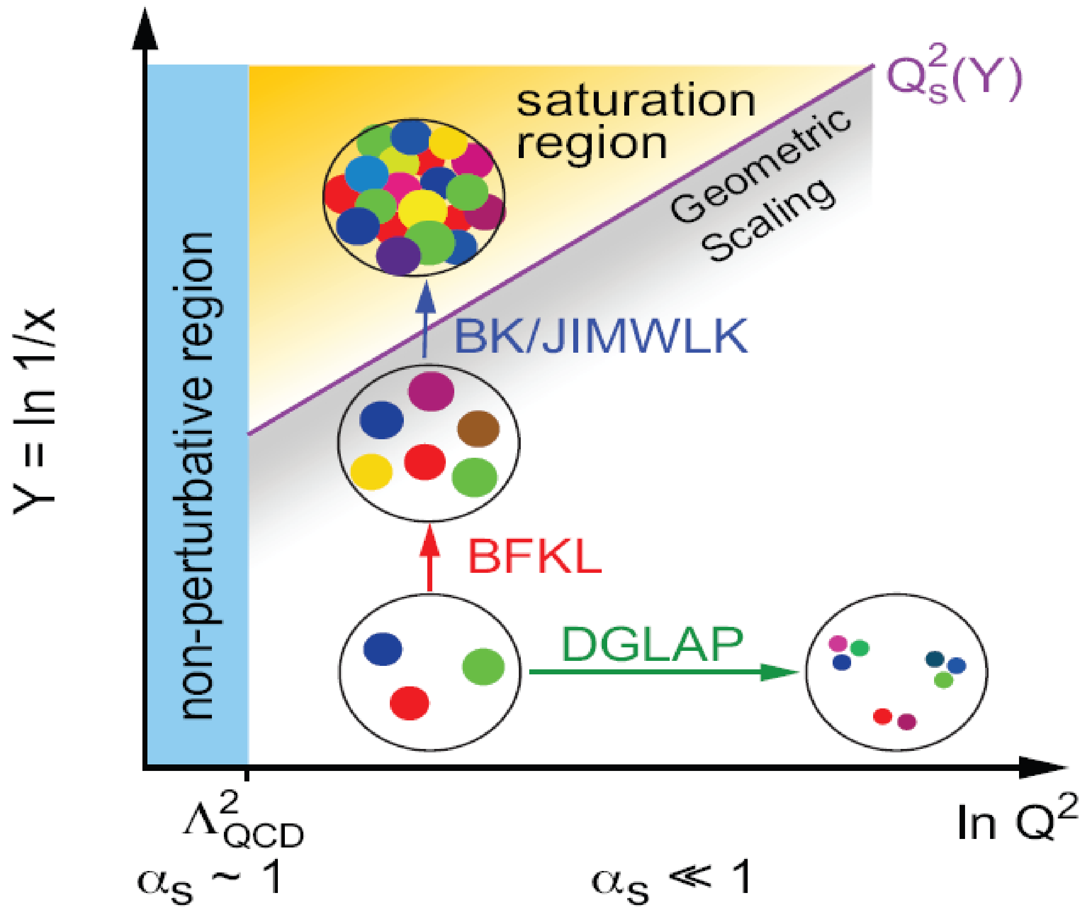


Unified View of Nucleon Structure



Particular processes to study. Polarization is required!

Nucleon landscape

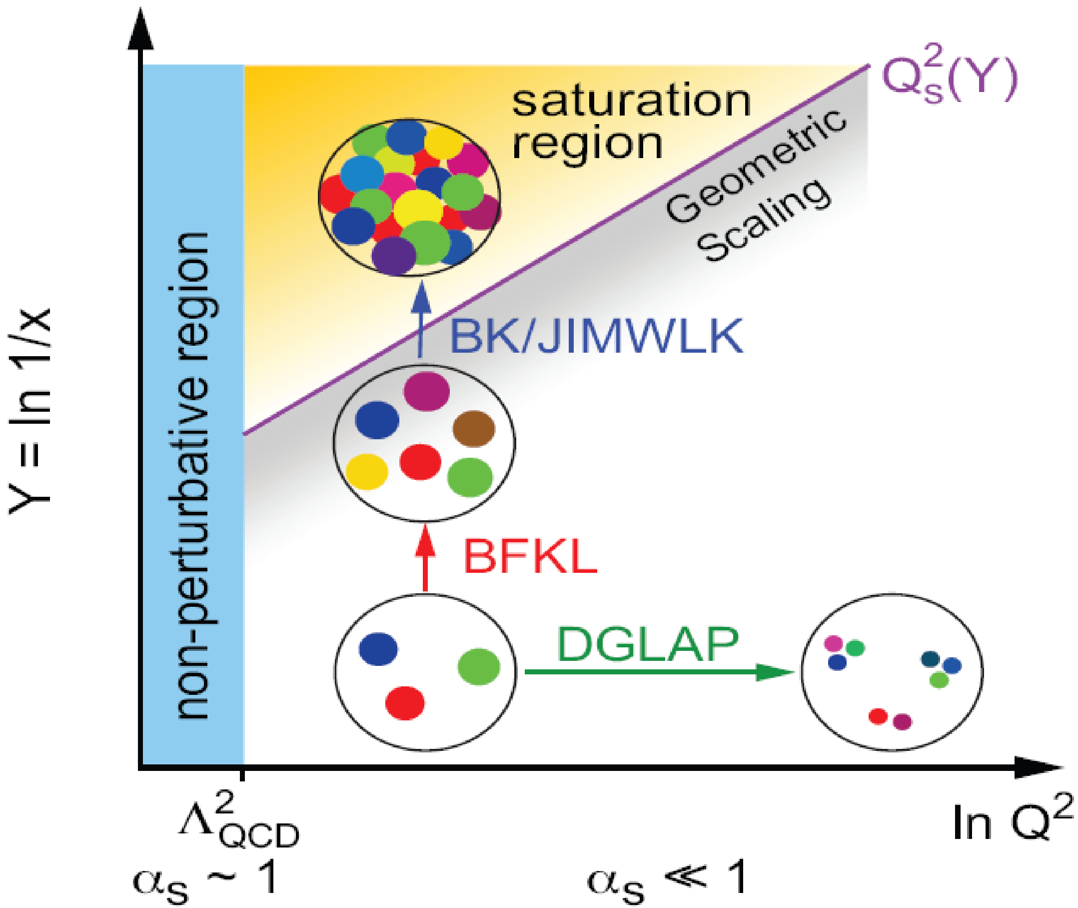


Virtual photon serves as a microscopic probe of the nucleon:

Larger Q^2 probe smaller distances – DGLAP evolution

Plot from EIC whitepaper

Nucleon landscape

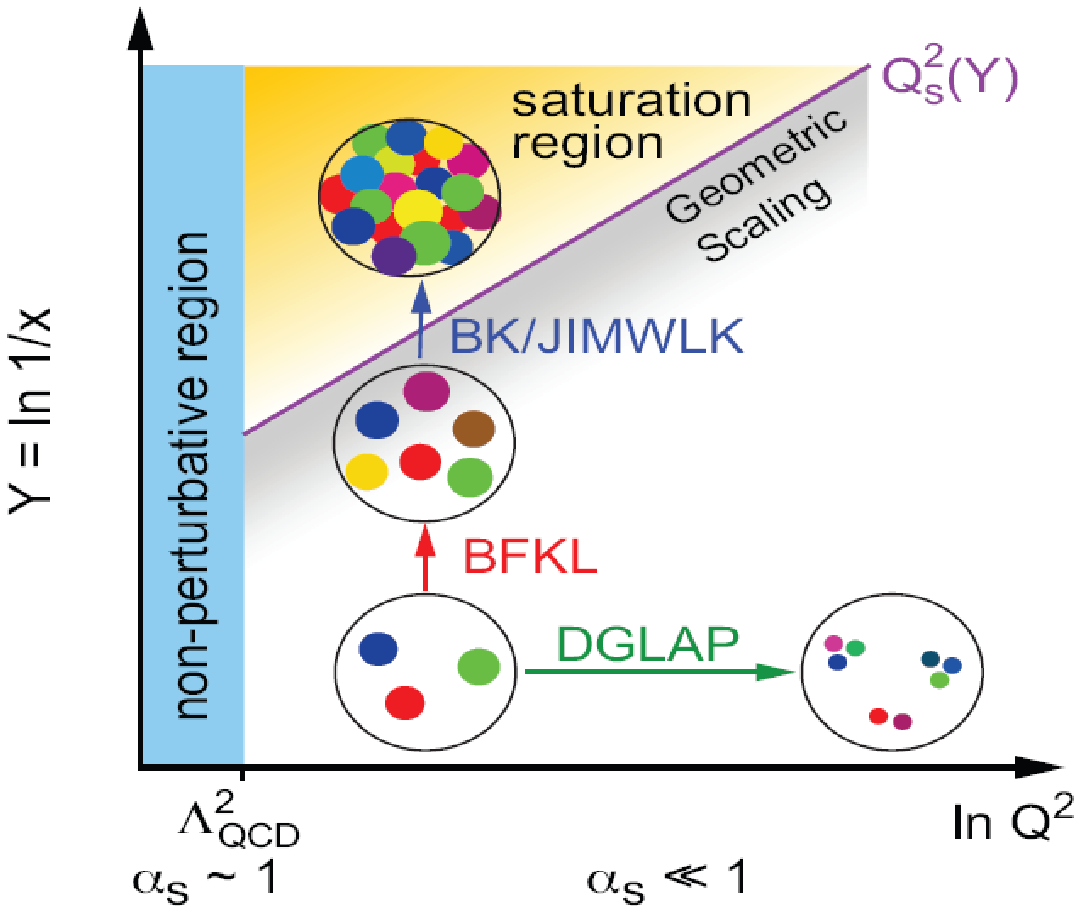


Virtual photon serves as a microscopic probe of the nucleon:

Fixing Q^2 and changing the energy we probe **BFKL** evolution

Plot from EIC whitepaper

Nucleon landscape



Plot from EIC whitepaper

Virtual photon serves as a microscopic probe of the nucleon:

Fixing Q^2 and changing the energy we probe **BFKL** evolution

The system undergoes transition from dilute to dense regime – saturation of gluon densities. **BK JIMWLK** evolution

Q_s^2 Dynamical scale, Enhanced in nuclei $\propto A^{1/3}$

QCD Fundamental Science Questions

- How do quarks and gluons confine themselves into a hadron?

- How do hadrons emerge from quarks or gluons?

- How do gluons saturate themselves into a new form of matter?

QCD Fundamental Science Questions

- How do quarks and gluons confine themselves into a hadron?
  Color confinement – the question for generations to answer
  Hints in quark-gluon structure?
  Need a facility to study how quark&gluon move inside of the hadron

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  Need a "vertex detector" at femtometer scale

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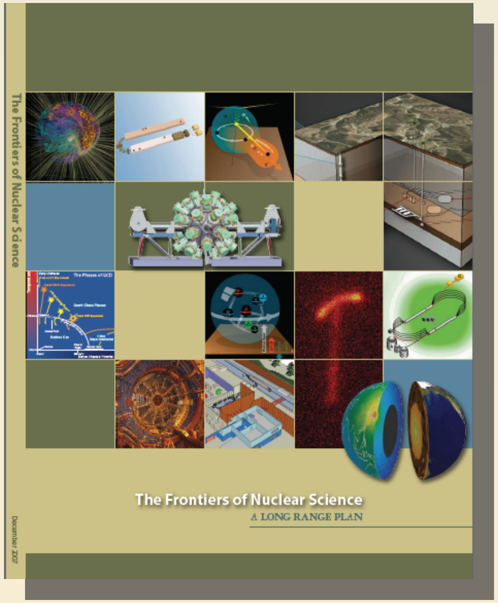
- How do gluons saturate themselves into a new form of matter?
  "Discover" the saturated gluonic matter and its universal properties?
  Need a "machine" capable of exploring
  QCD dynamics of dence gluon matter

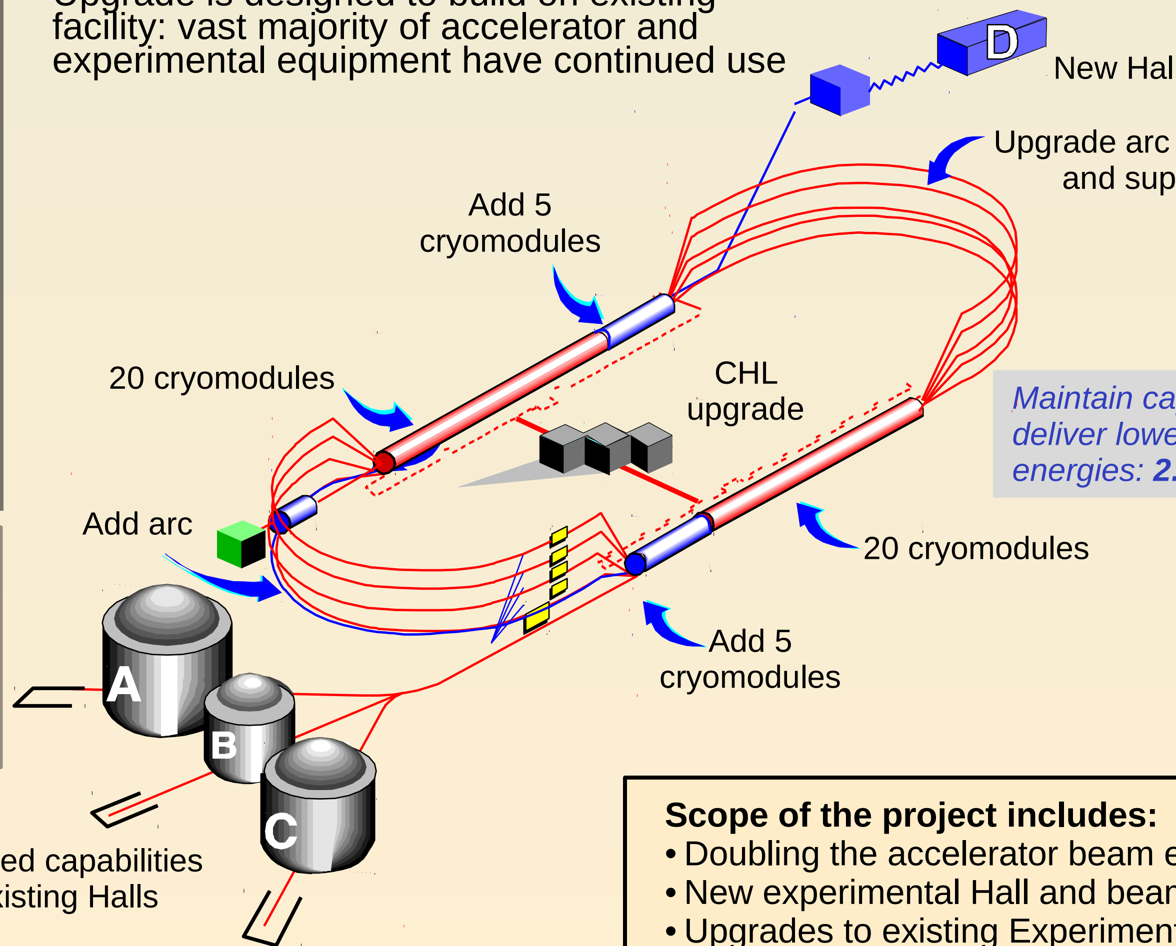
What are the plans of Jefferson Lab?

12 GeV Upgrade Project



The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



Maintain capability to deliver lower pass beam energies: ***2.2, 4.4, 6.6….***

Scope of the project includes:
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

12 GeV Science Program

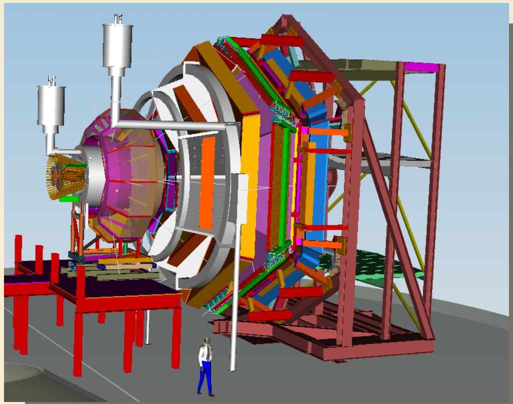
- The physical origins of quark confinement (GlueX, meson and baryon spectroscopy)
- The spin and flavor structure of the proton and neutron (PDF's, GPD's, TMD's…)
- The quark structure of nuclei
- Probe potential new physics through high precision tests of the Standard Model

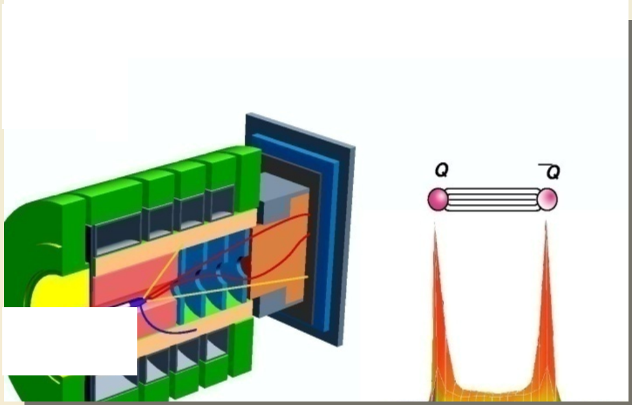
- Defining the Science Program:
  - Reviews: Program Advisory Committees (PAC) - 2006 through 2015
  - Results: *52 experiments approved; 15 conditionally approved*
  - White paper for NSAC subcommittee

Experiments for 4 Halls approved for
more than seven years of operation beginning in FY15.

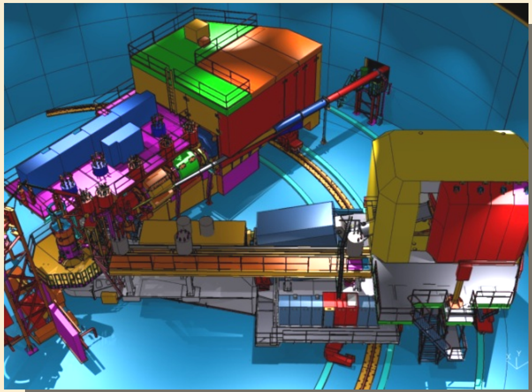
12 GeV Scientific Capabilities

Hall D – exploring origin of confinement by studying exotic mesons

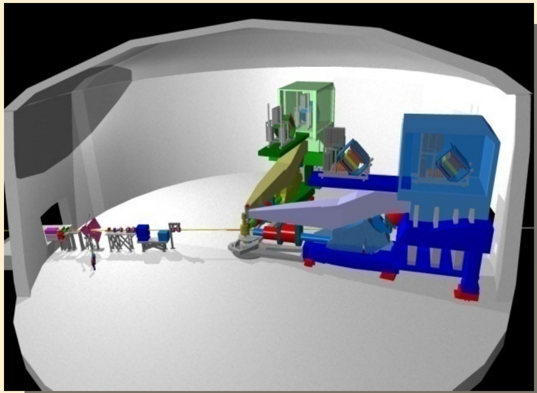




Hall B – understanding nucleon structure via 3D distributions: generalized parton distributions and transverse momentum dependent distributions



Hall C – precision determination of valence quark properties in nucleons and nuclei



Hall A –form factors, future new experiments (e.g., SoLID and MOLLER)

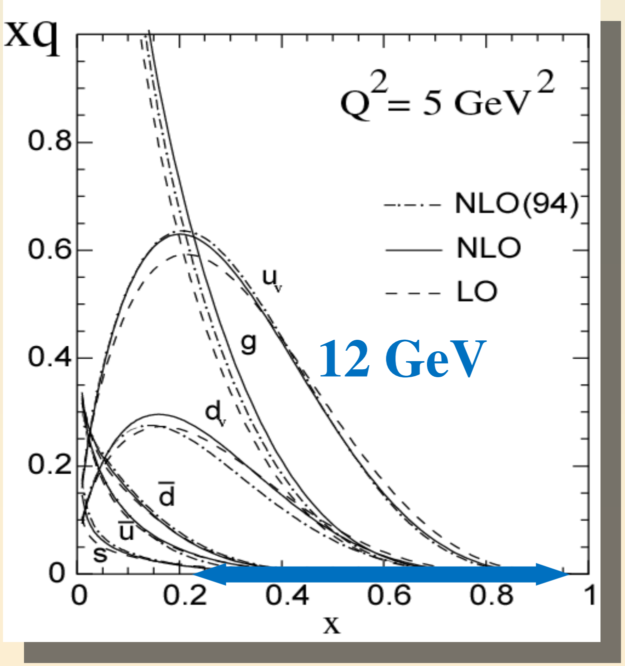
Now is the time to think of the future

Into the “sea”: Electron Ion Collider

With 12 GeV we study mostly the <u>valence quark component</u> of the proton wave function

$x \sim 0.3$

valence quarks



Jefferson Lab

Into the "sea": Electron Ion Collider

EIC aims to study the <u>sea quarks and gluons</u> of the polarised proton

$x \sim 0.3$

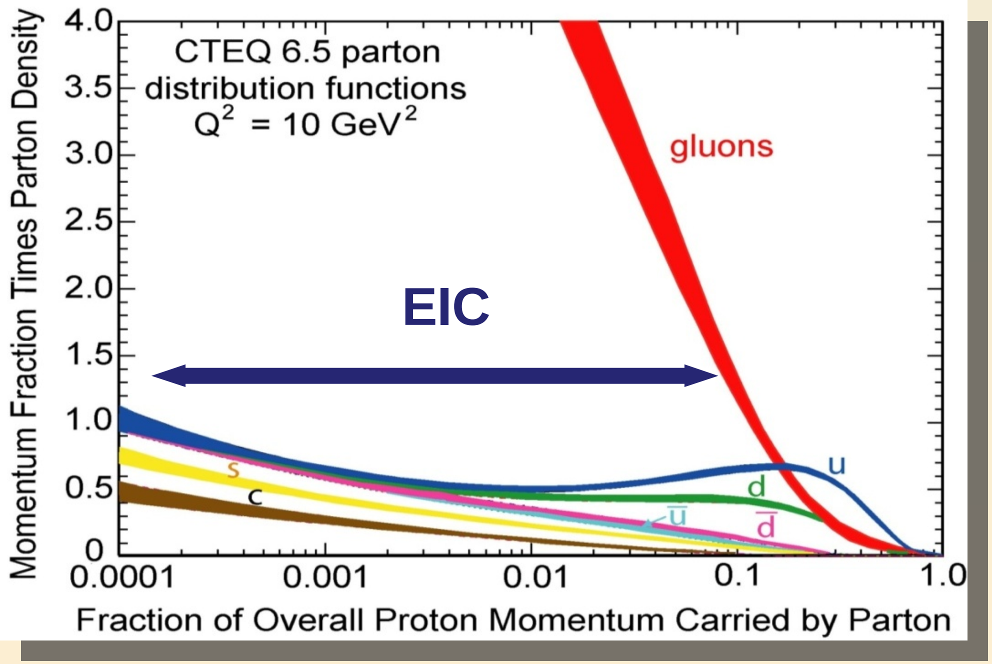
valence quarks

$x \sim 0.1$

sea quarks and gluons

$x \ll 0.01$

gluons dominant



Electron Ion Colliders in the world

	HERA@DESY	LHeC@CERN	eRHIC@BNL	MEIC@JLab
E_{CM} (GeV)	320	800-1300	45-175	12-140
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}
ion	p	p to Pb	p to U	p to Pb
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)
L [cm^{-2} s^{-1}]	2×10^{31}	10^{33}	10^{33-34}	10^{33-34}
IP	2	1	2+	2+
Year	1992-2007	2022 (?)	2022	Post-12 GeV

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FUTURE

Electron Ion Colliders in the world

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Year	1992-2007	2022 (?)	2022	Post-12 GeV

POLARISATION IS IMPORTANT

Electron Ion Colliders in the world

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IP	2	1	2+	2+
Year			2022	Post-12 GeV

$$\frac{N_{event}}{T} = L \times \sigma$$

Rate = Luminosity x cross section **LUMINOSITY IS IMPORTANT**

Why Collider?

Fixed target

$$s = 2M_N P_{lab}$$

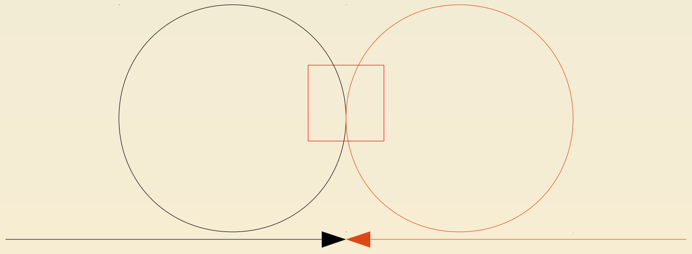
M ~ 1 GeV

High rates from density of particles in target

Collider

$$s = 4E_l E_N$$

Product of beam energies!



Energy–efficient:
- Beams collide multiple times

Clean:
- No scattering from atomic electrons

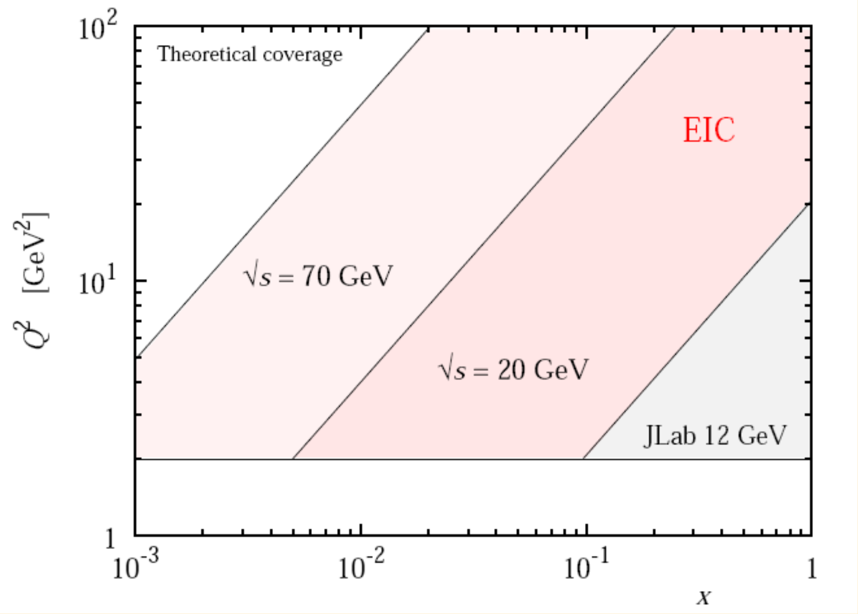
Detection:
- Recoil proton/nucleus, variable angles

Demands much higher beam quality:
Focusing, cooling, time structure
Integration of detectors and accelerator elements at interaction point

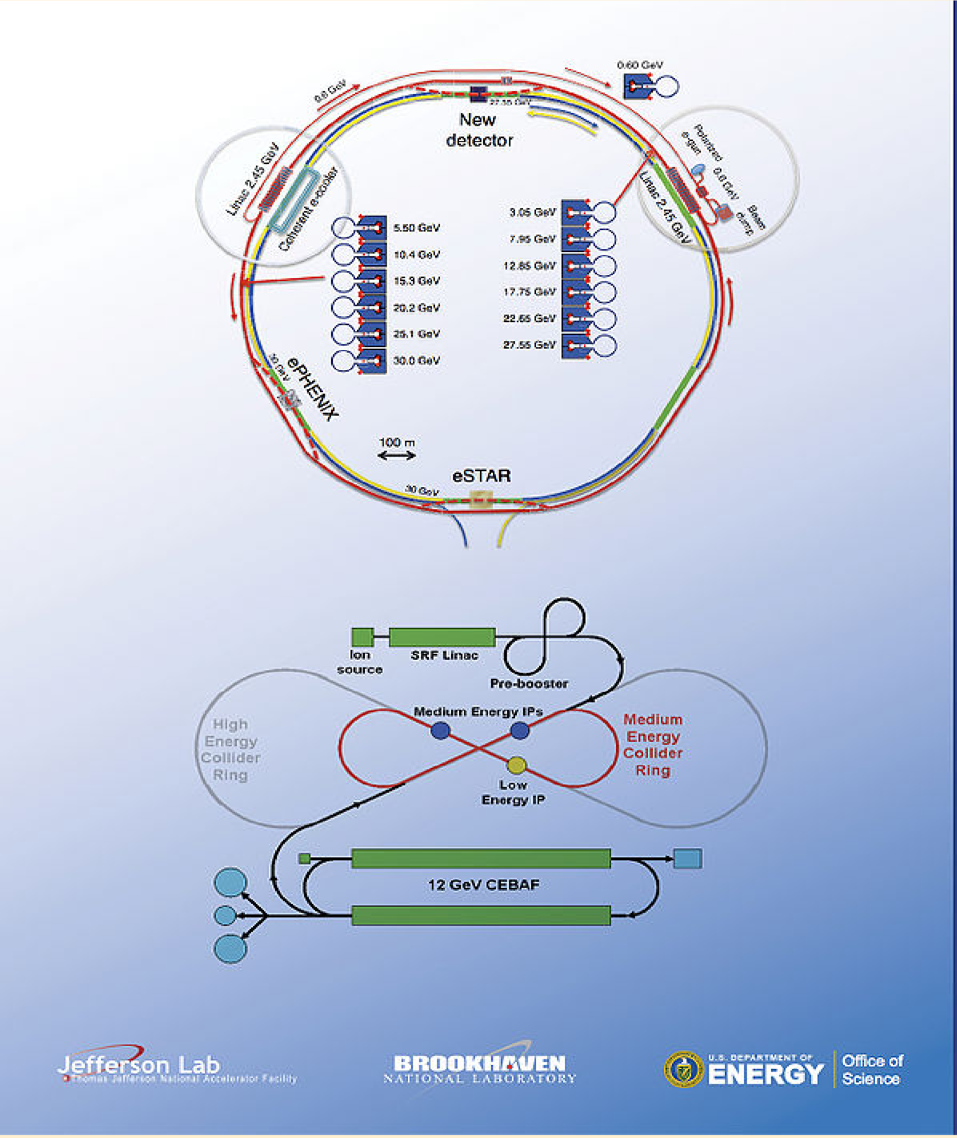
Why Collider?

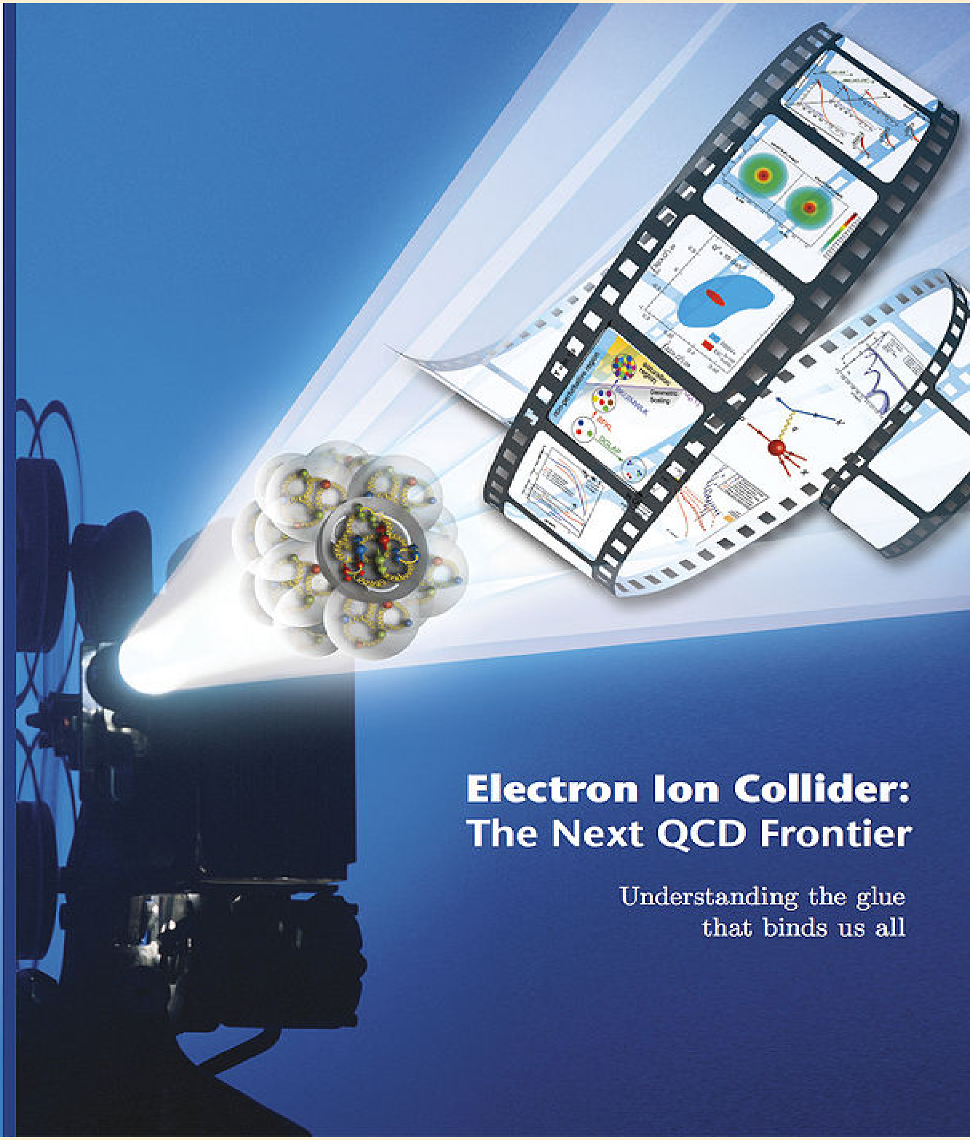
$$Q^2 < s x_B$$ kinematical limit

Large Q^2 or small-x region require high energy



Electron Ion Colliders in the USA





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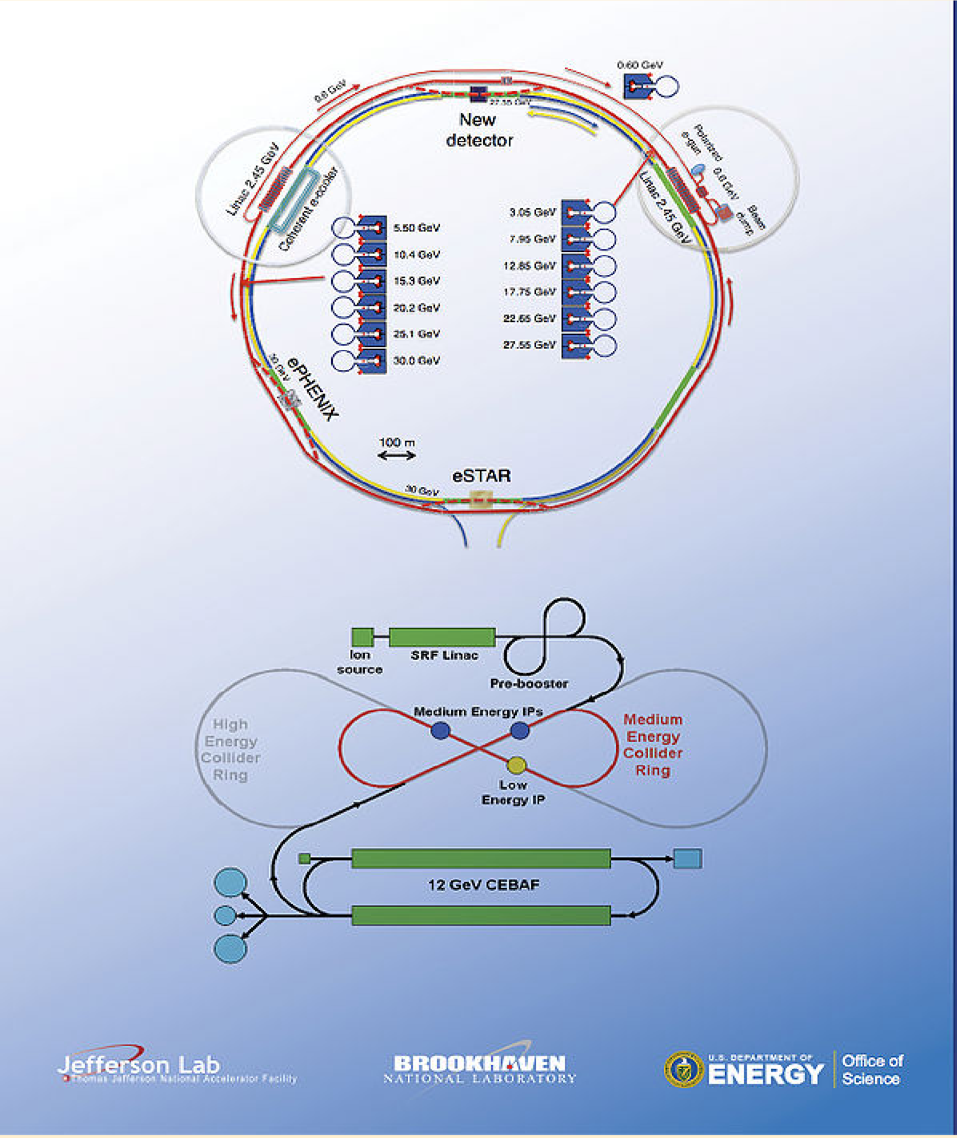
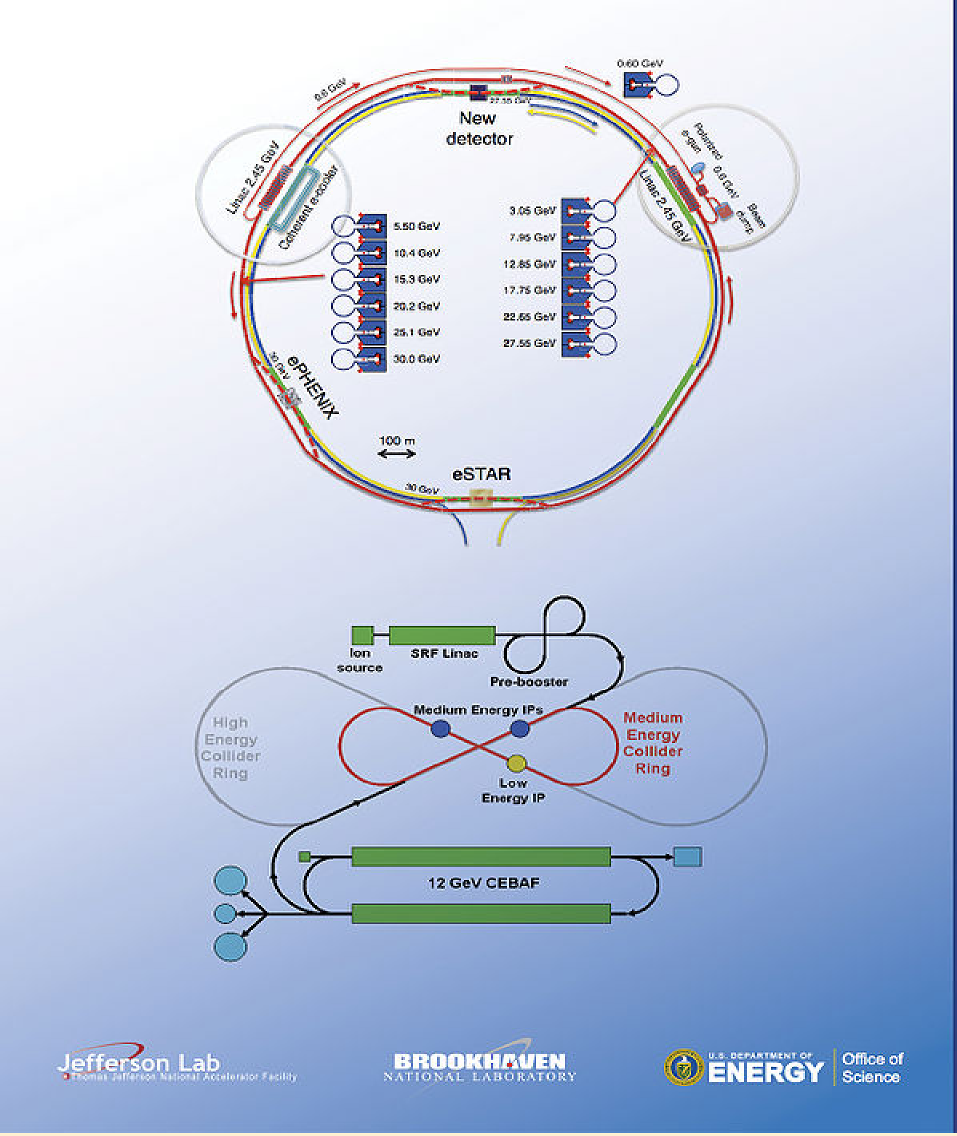
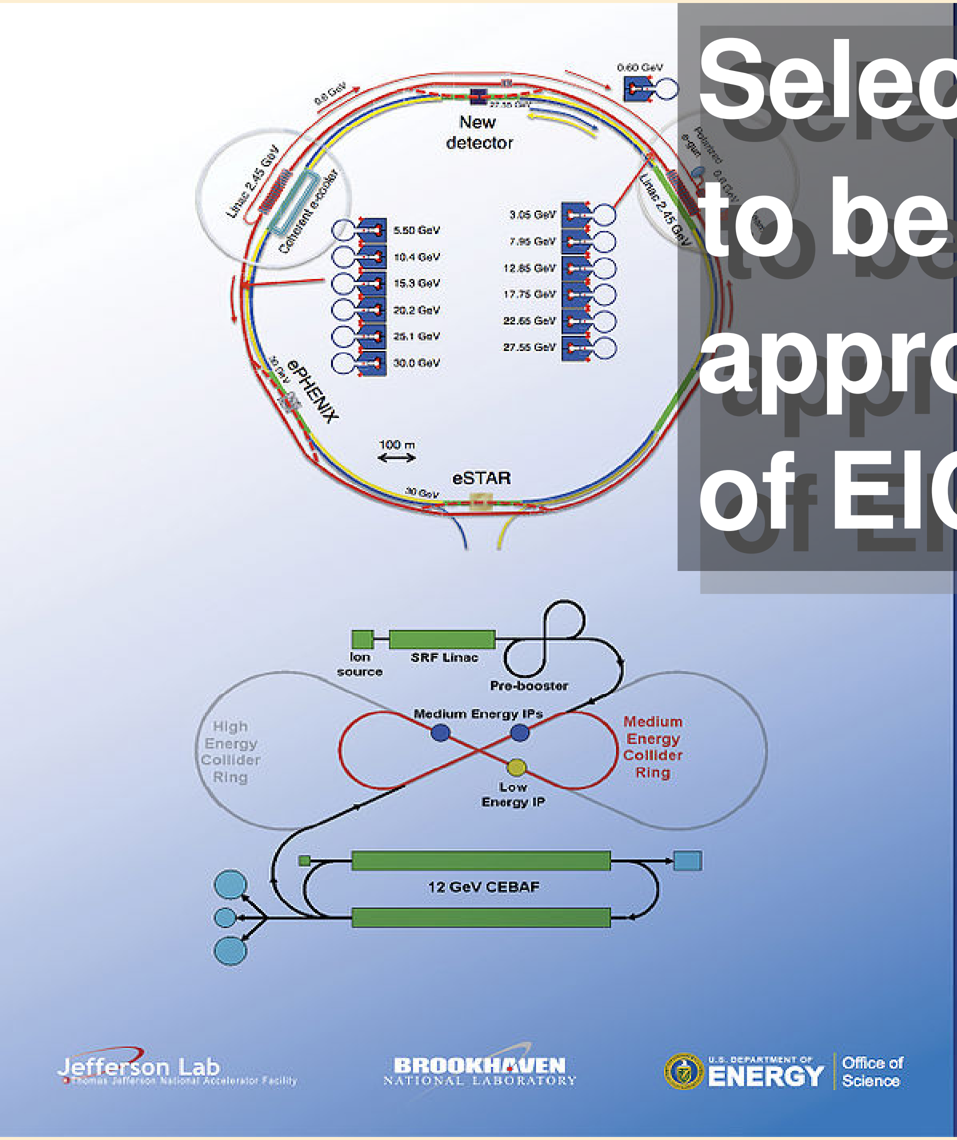
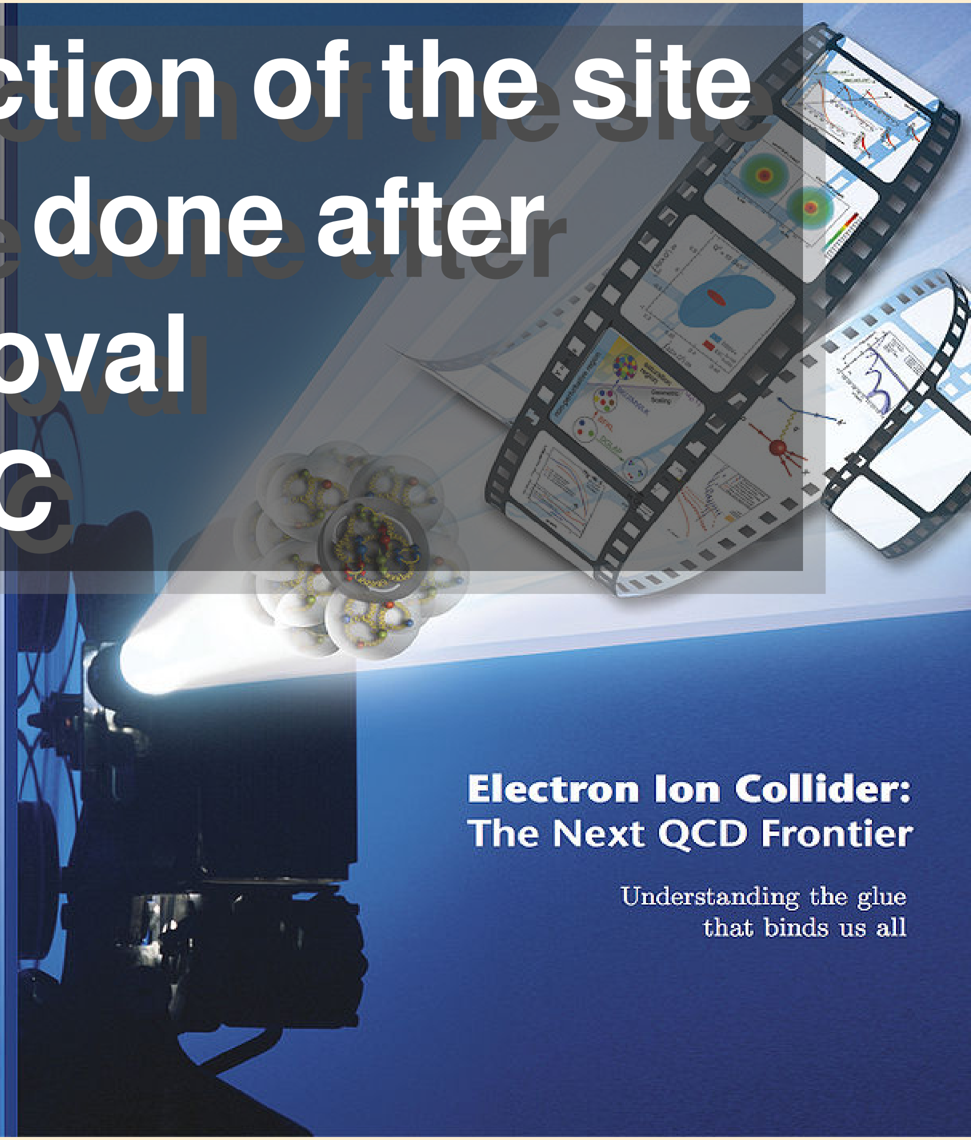


Electron Ion Colliders in the USA



Electron Ion Colliders in the USA





Selection of the site to be done after approval of EIC

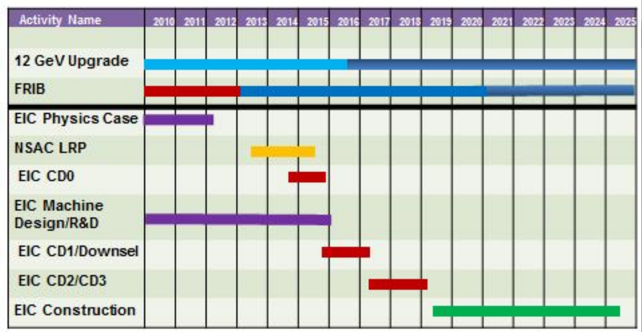
Jefferson Lab Future: MEIC

JLab MEIC Figure 8 Concept

- **Initial configuration**:
  - 3-10 GeV on 20-100 GeV ep/eA collider
  - Optimized for high ion beam polarization:
    - polarized deuterons
  - Luminosity:
    - up to few x 10^{34} e-nucleons cm^{-2} s^{-1}
- **Low technical risk**
- **Upgradable to higher energies**

  250 GeV protons + 20 GeV electrons
- **Flexible timeframe for construction**

  consistent w/running 12 GeV CEBAF

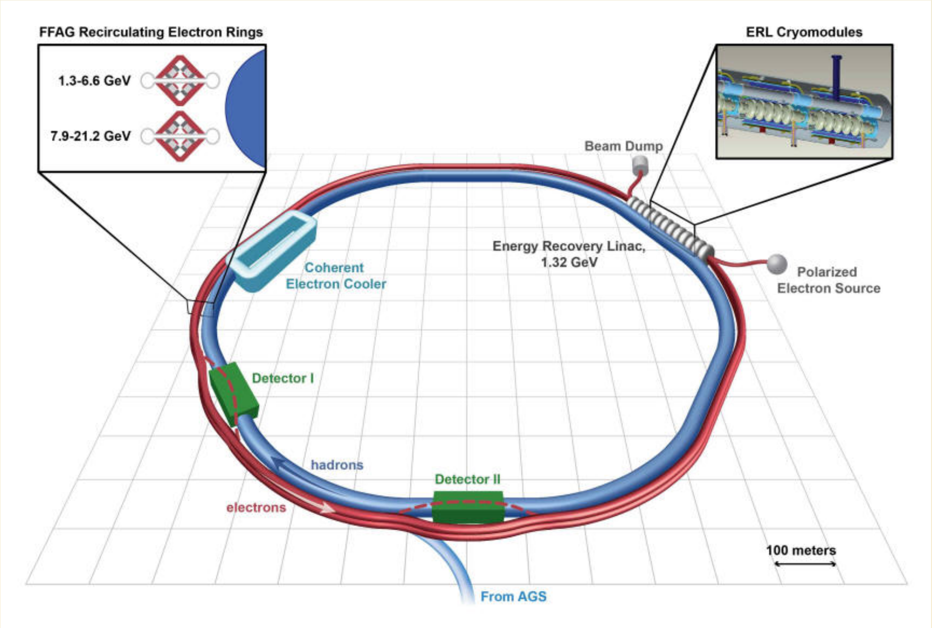


Assumes endorsement for an EIC at the next NSAC Long Range Plan
Assumes relevant accelerator R&D for down-select process done around 2016

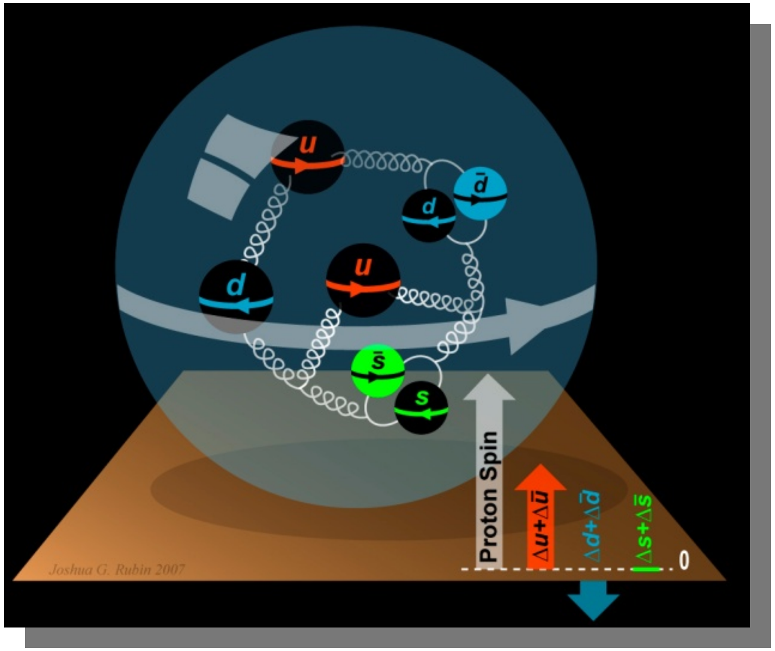
BNL Future: eRHIC

<u>**eRHIC Concept**</u>

- **Initial configuration**:
  - 5-21 GeV on 50-250 GeV ep/eA collider
  - Polarized protons or up to 100 GeV/u gold ions
- **Heavy ions up to Au**
- **High polarization of electron, proton and 3He beams.**
  - Luminosity:
    - up to few x 10^{34} e-nucleons cm^{-2} s^{-1}
- **Reuse of existing RHIC detectors: ePHENIX and eSTAR**



The Incomplete Nucleon: Spin Puzzle

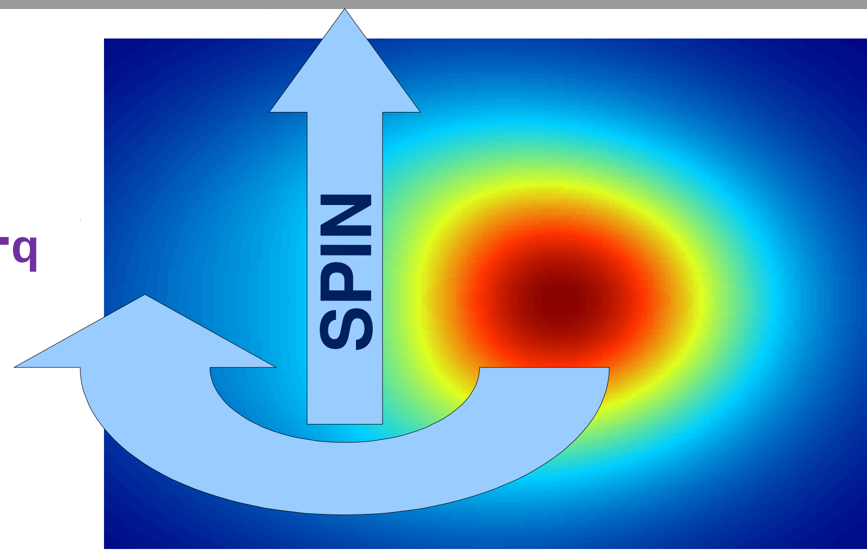


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

[Xiandong Ji, 1997]

Relation to GPDs

$$J^q = \frac{1}{2}\int_{-1}^{+1} dx\, x\left[H^q(x,\xi,t) + E^q(x,\xi,t)\right] = \Delta\Sigma^q/2 + L^q$$



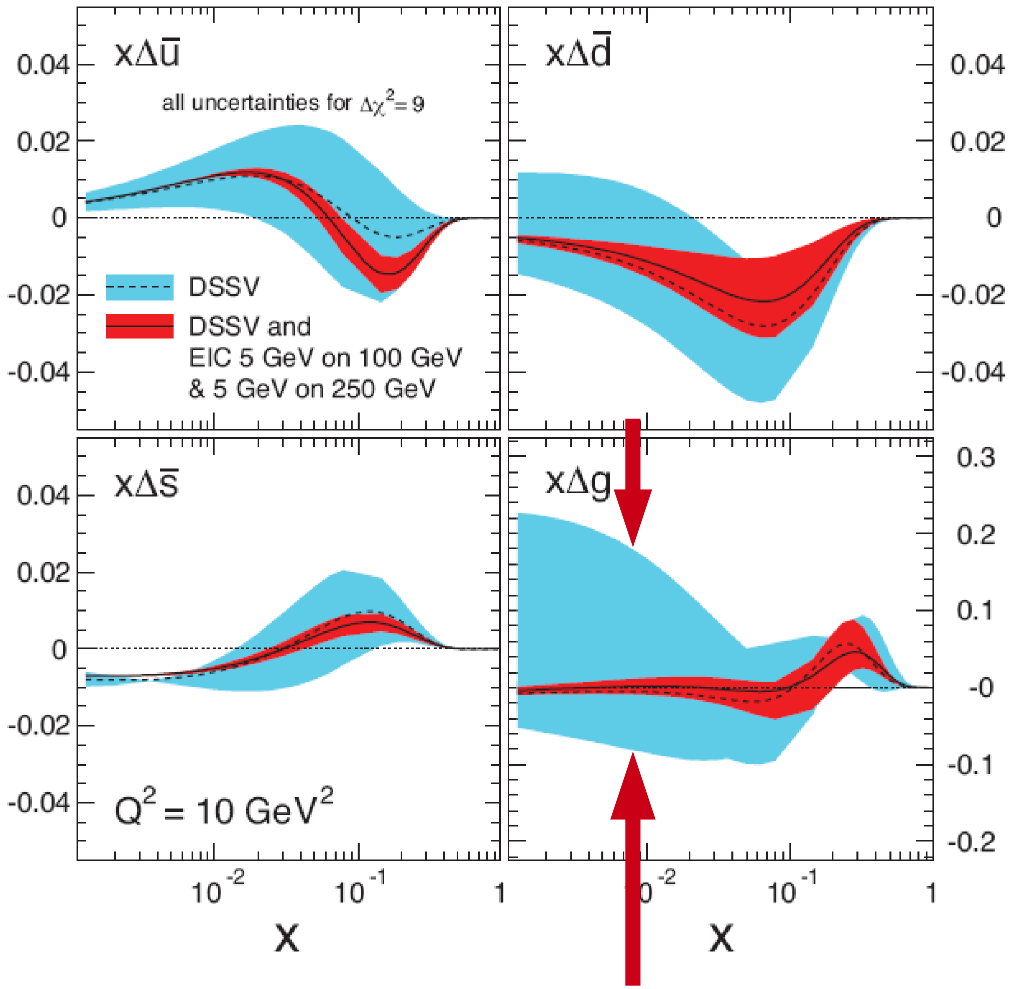
- **DIS → $\Delta\Sigma \cong 0.25$ → L_q**
- **RHIC + DIS → $\Delta G \ll 1$**
- **Clear indication that OAM is important**

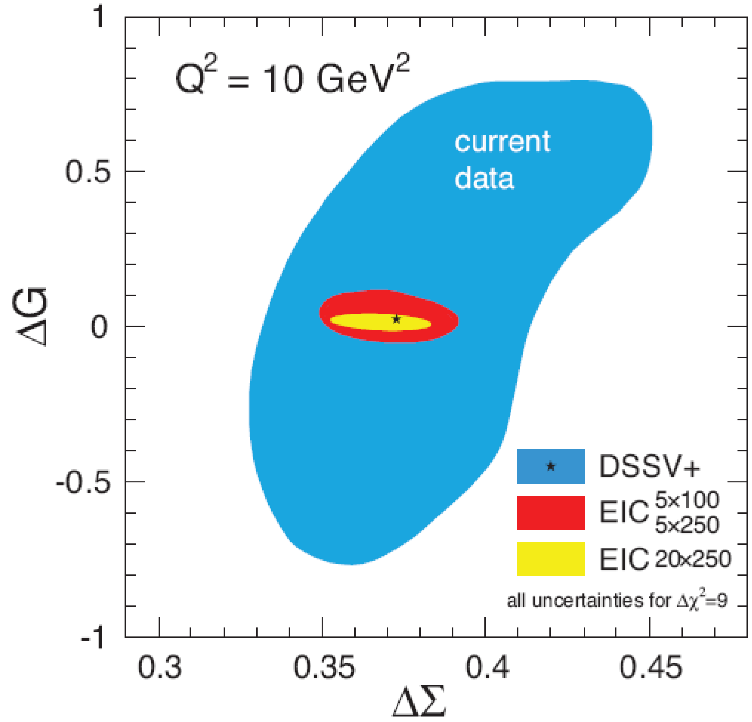
Solution of Spin Crisis

Measure ΔG at low x

Quantify the role of orbital angular momentum

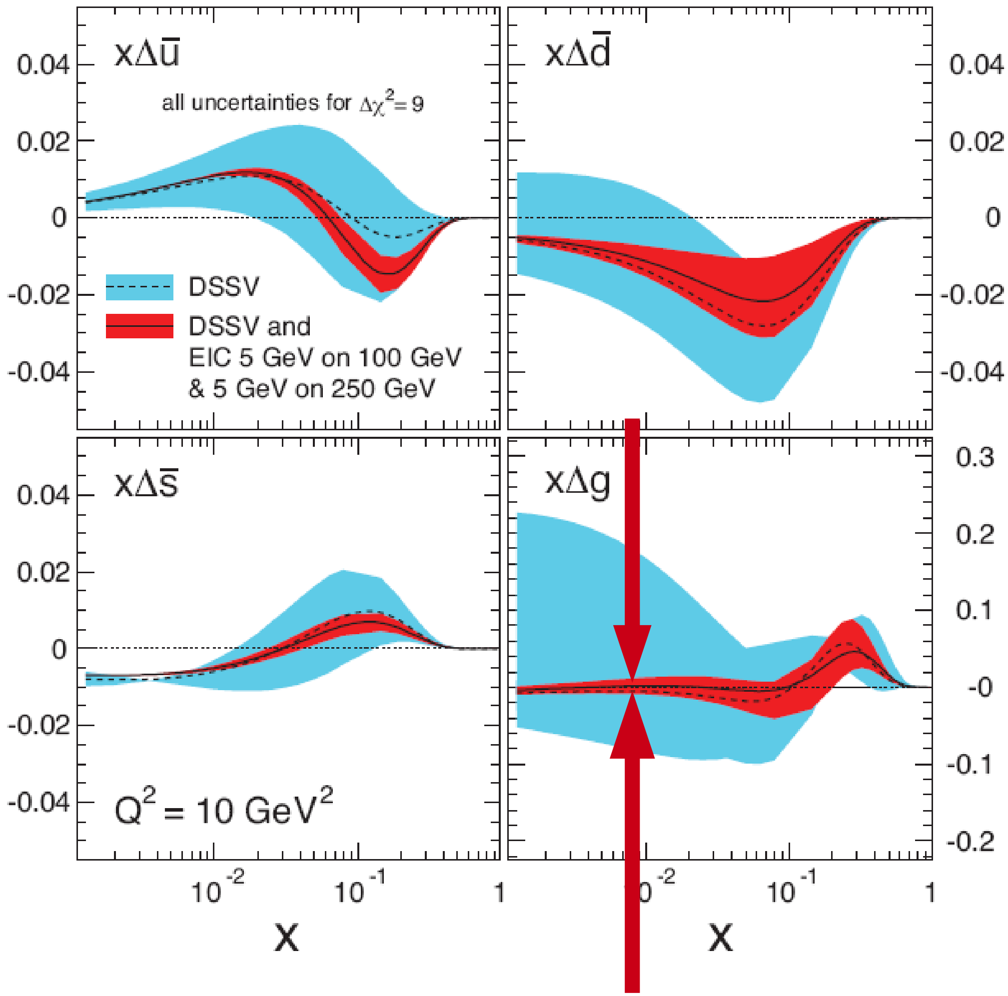
Gluon and quark spin contribution

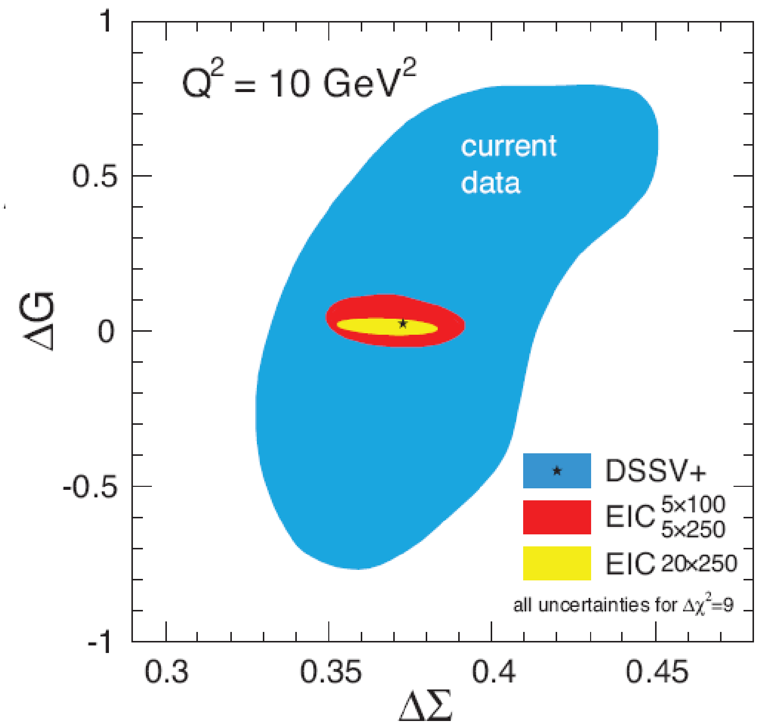




Modern knowledge

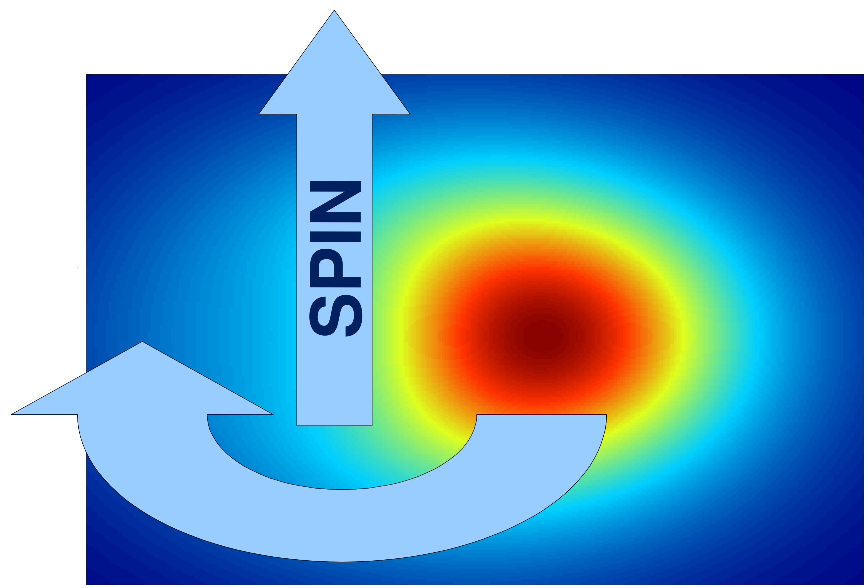
Gluon and quark spin contribution





After 1 year of EIC

Orbital Angular Momentum



Can motion of quarks and spin of the proton be correlated?

Yes, it can!

$$f(x,\mathbf{k_T},\mathbf{S_T}) = f_1(x,\mathbf{k_T^2}) - f_{1T}^{\perp}(x,\mathbf{k_T^2})\frac{\epsilon_T^{ij}\mathbf{k_{Ti}}\mathbf{S_{Tj}}}{M}$$

Sivers function

Yes, it can!

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_x}}{M}$$

Suppose the spin is along Y direction: $S_T = (0, 1)$

Deformation in momentum space is: $x \cdot f(x^2 + y^2)$

This is called “dipole” deformation.

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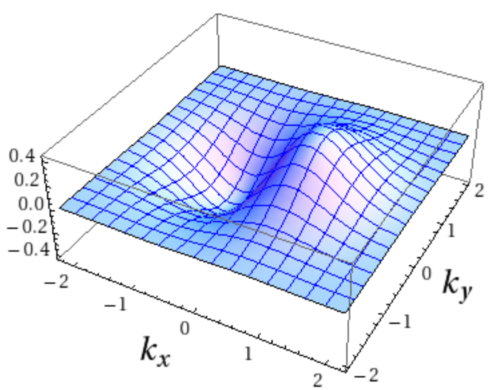

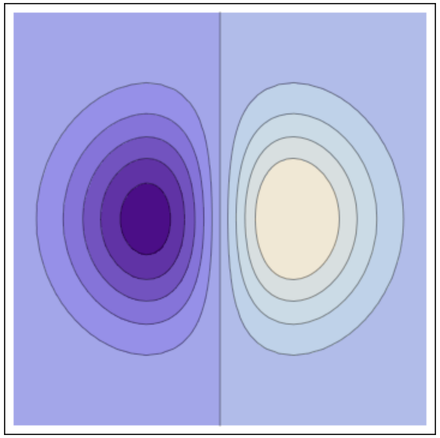

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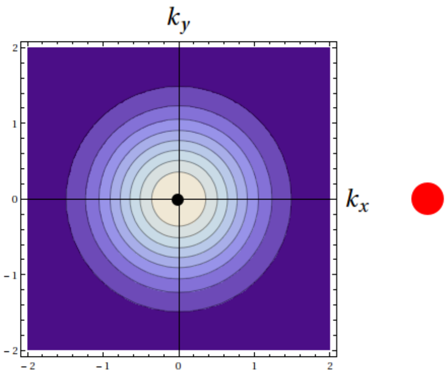
$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_x}}{M}$$

Suppose the spin is along Y direction: $S_T = (0, 1)$

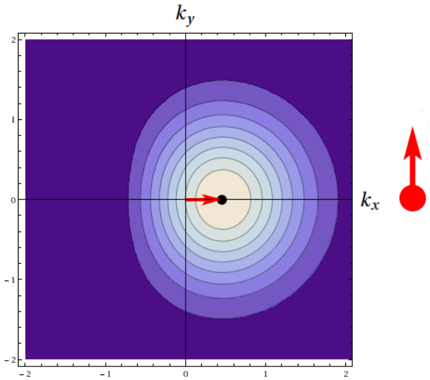
Deformation in momentum space is: $x \cdot f(x^2 + y^2)$

This is called "dipole" deformation.

No correlation:

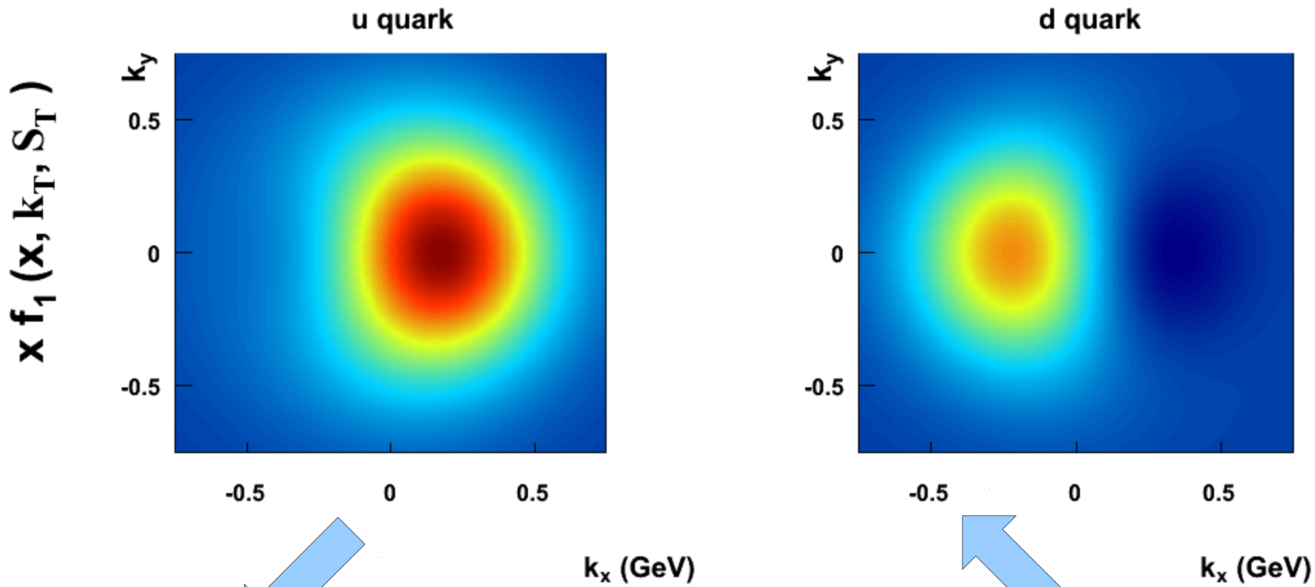


Correlation:

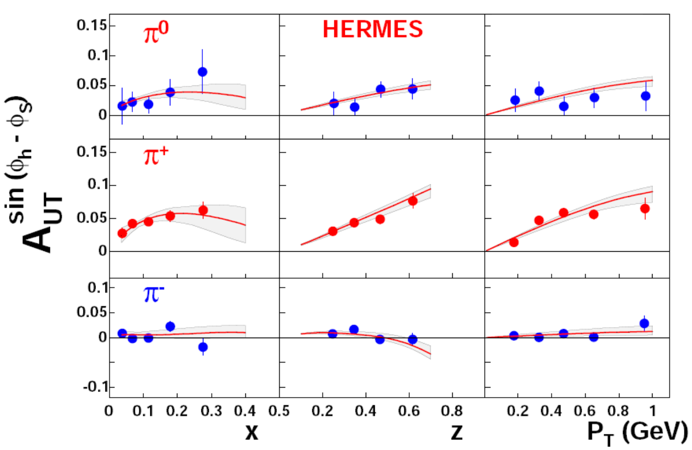


Tomographic scan of the nucleon

Theory
Theory

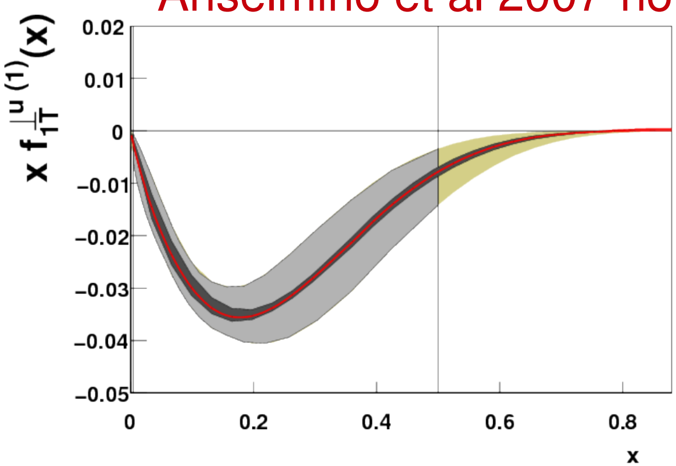


Measurement
Measurement



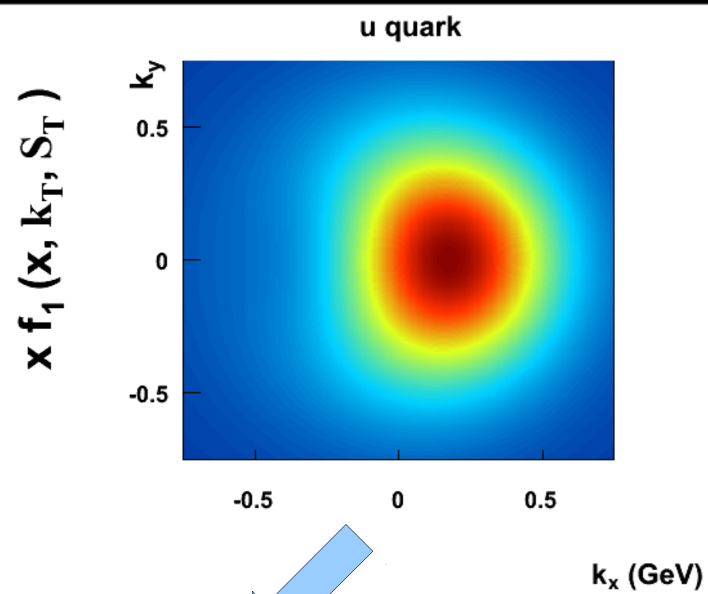
Global analysis of the data

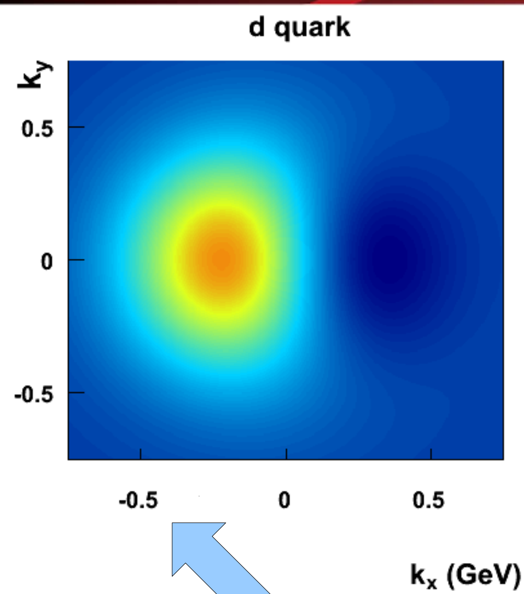
Results
Anselmino et al 2007-now



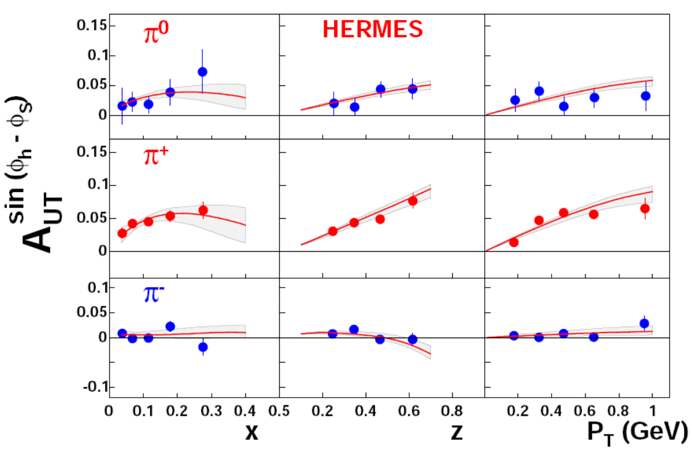
Tomographic scan of the nucleon

Theory
Theory





Measurement
Measurement



Global analysis of the data

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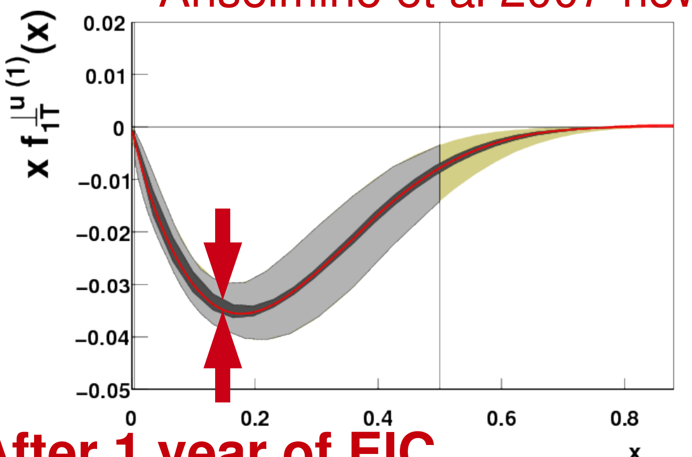
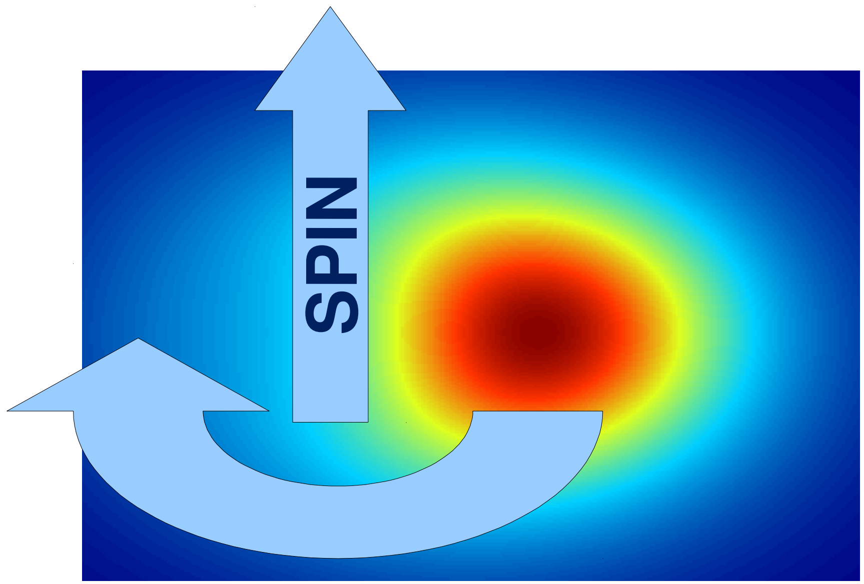
Anselmino et al 2007-now



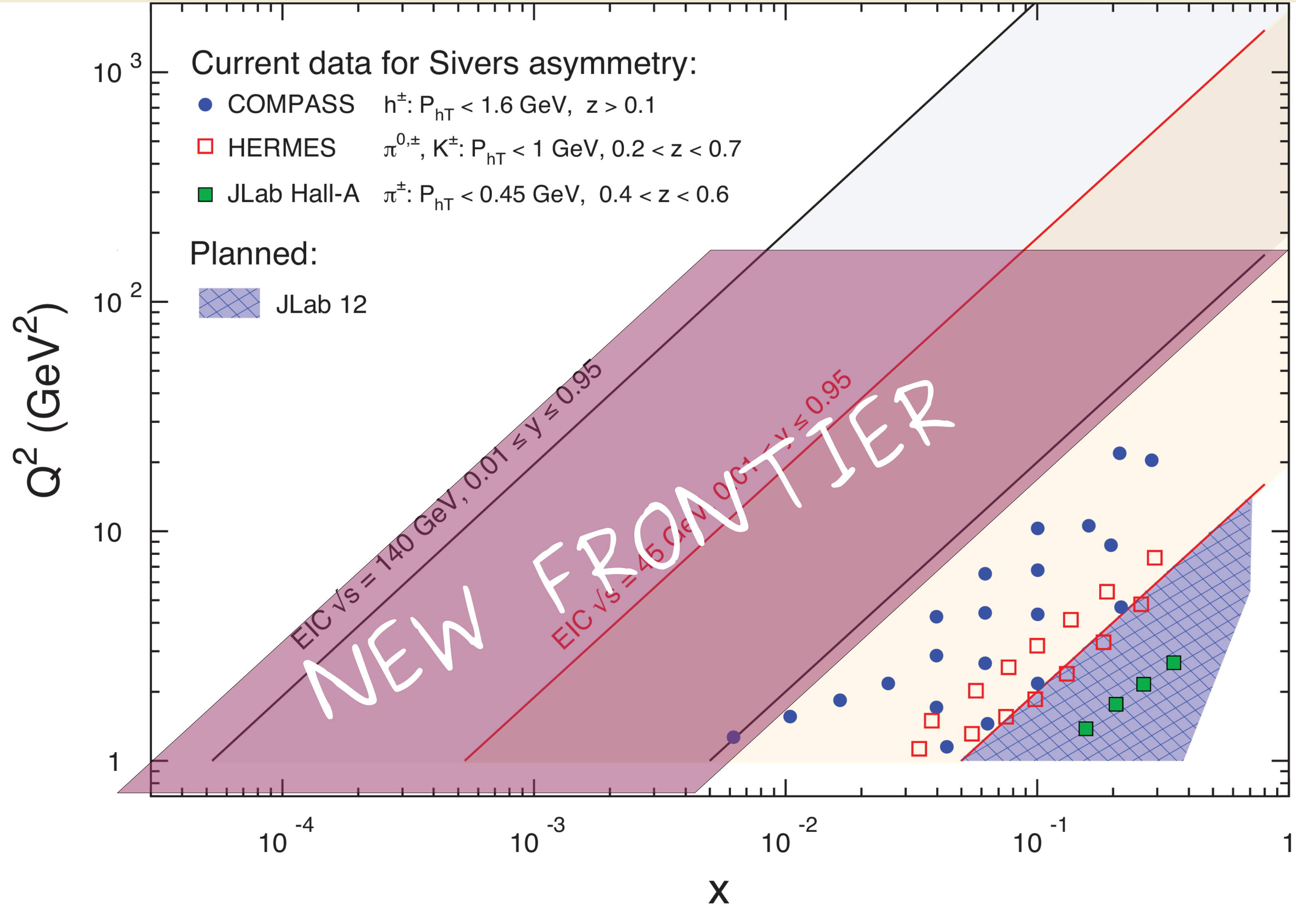
After 1 year of EIC

Tomographic scan of the nucleon



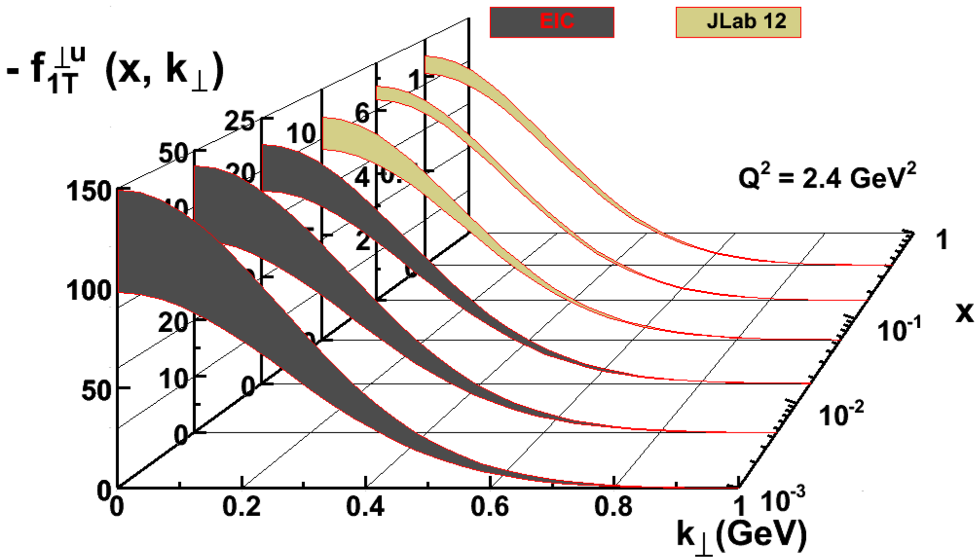
Internal motion of quarks is correlated with the spin of the proton!

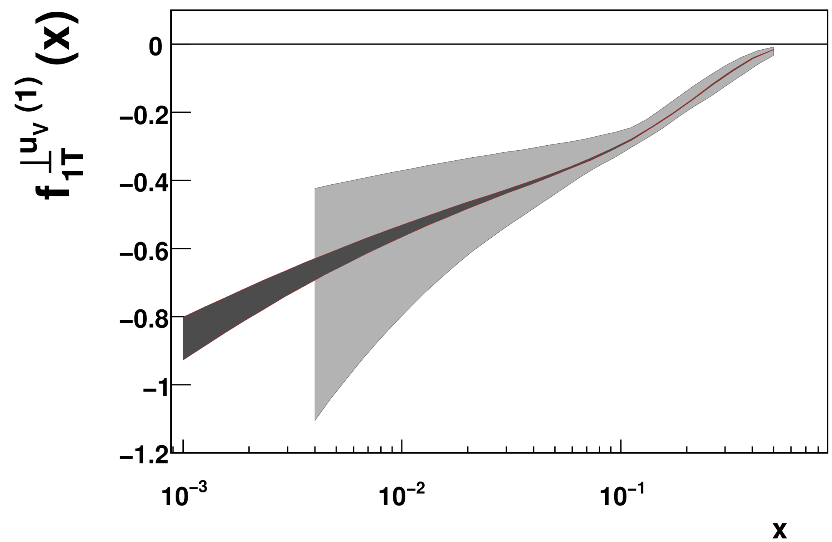
Into the "sea": Electron Ion Collider



What will be achieved? Example:

Expected result for an individual function:



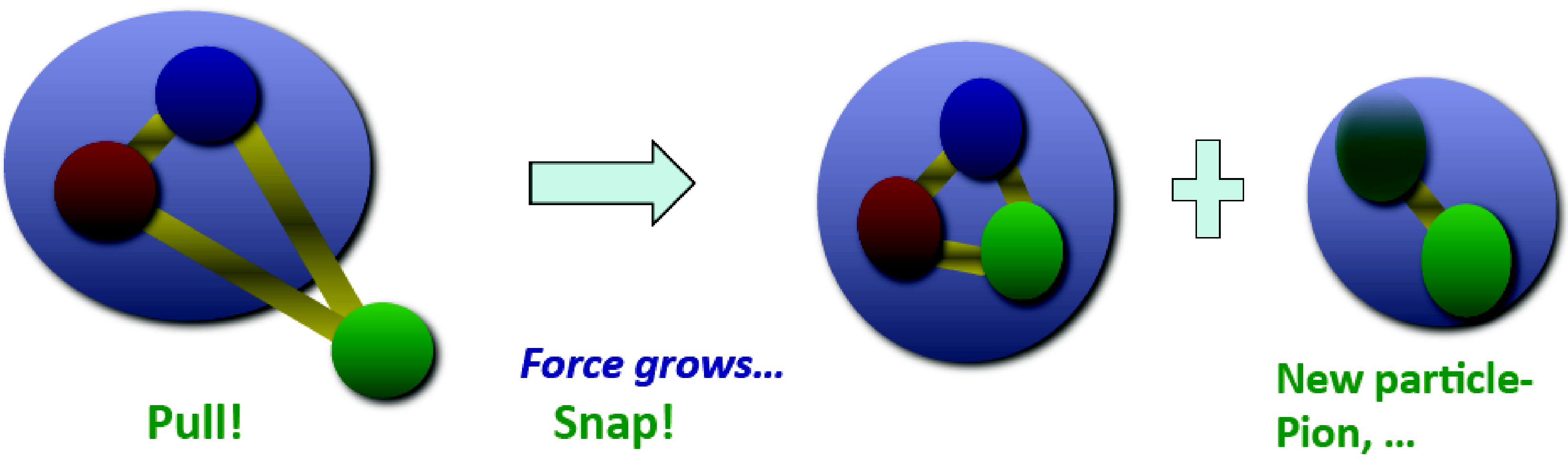


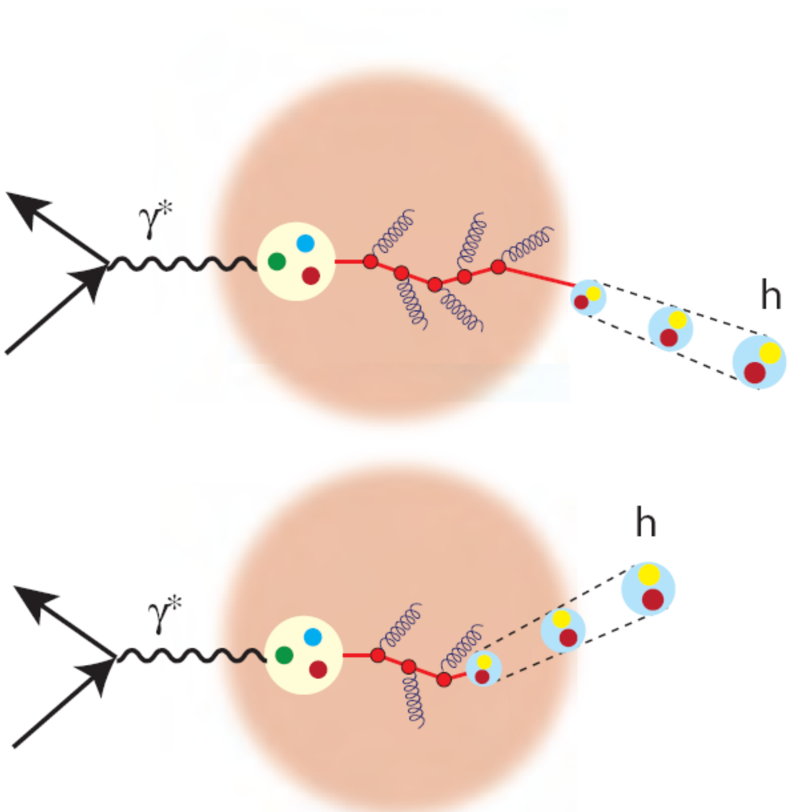
Expected accuracy of TMD profile

A. Prokudin (2012) contribution to EIC white paper

Hadronization

What is the mechanism of hadronisation?



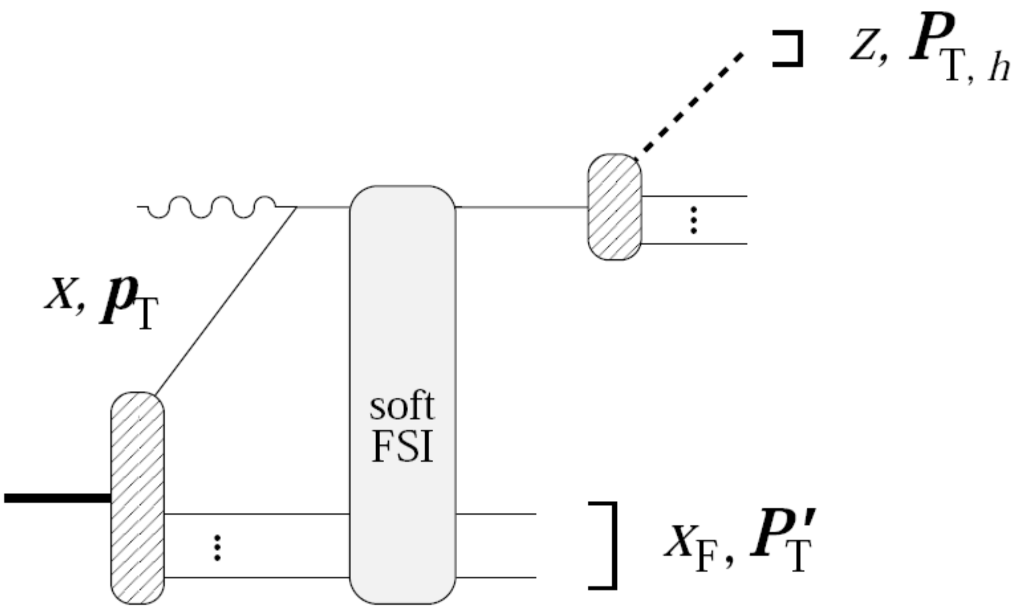


Parton propagates in strong matter and radiate – energy loss

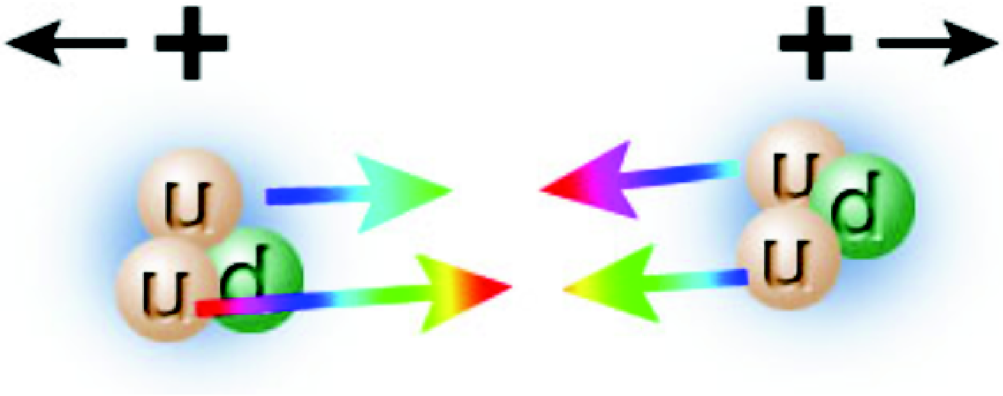
We can control the length of the propagation using

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

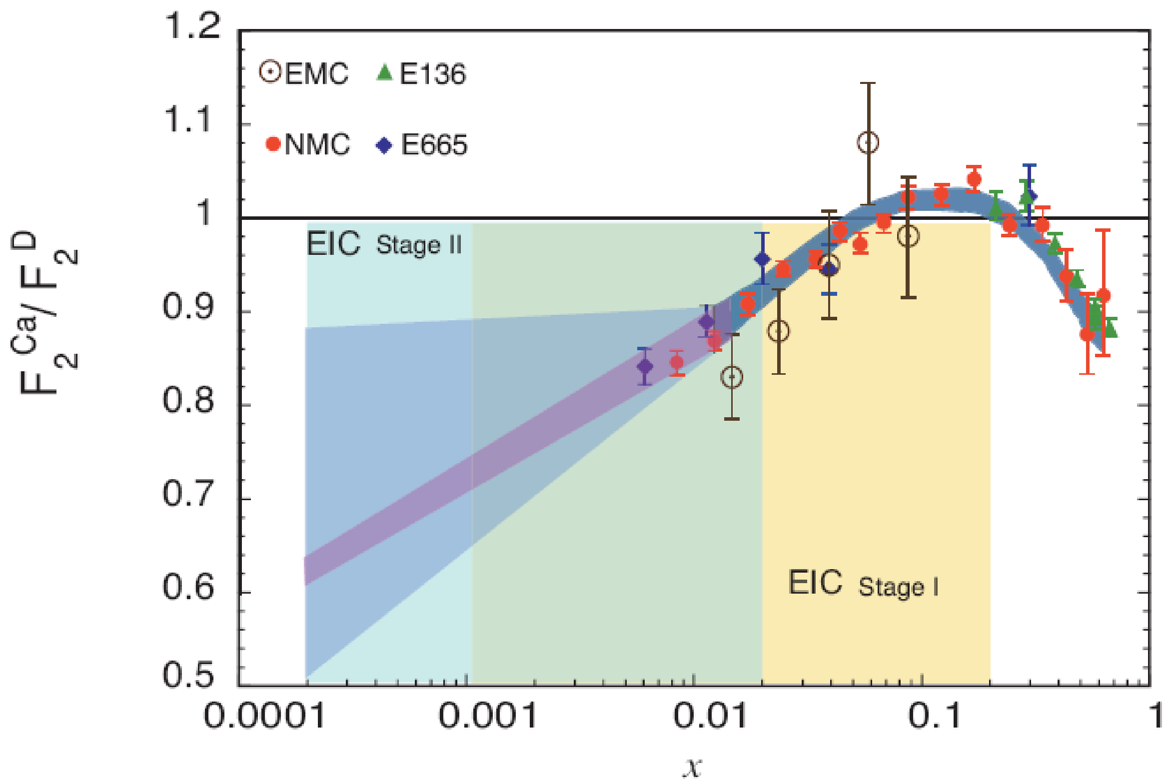
We can study also target fragmentation region at a collider!



Nuclei

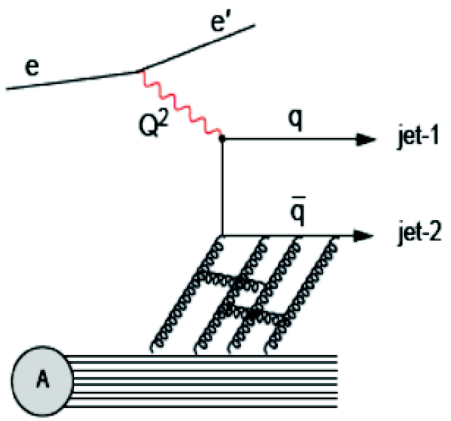


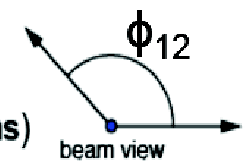
The residual strong force holding protons (and neutrons) together to form a stable nuclei overcomes electromagnetic repulsion!



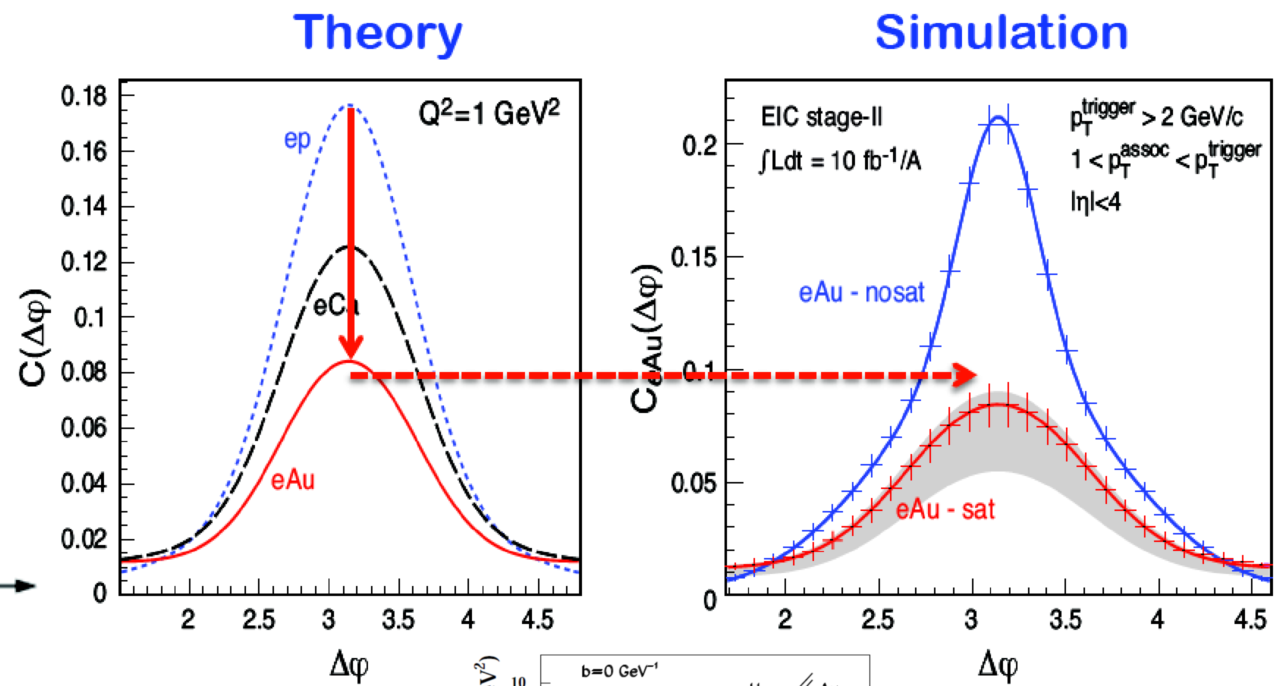
Paton densities are modified – EMC effect

Theory   Simulation

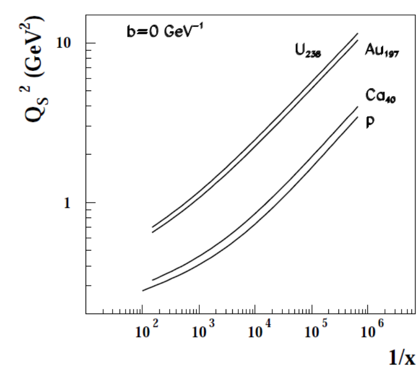




Either Jets or use leading hadrons from jets (dihadrons)

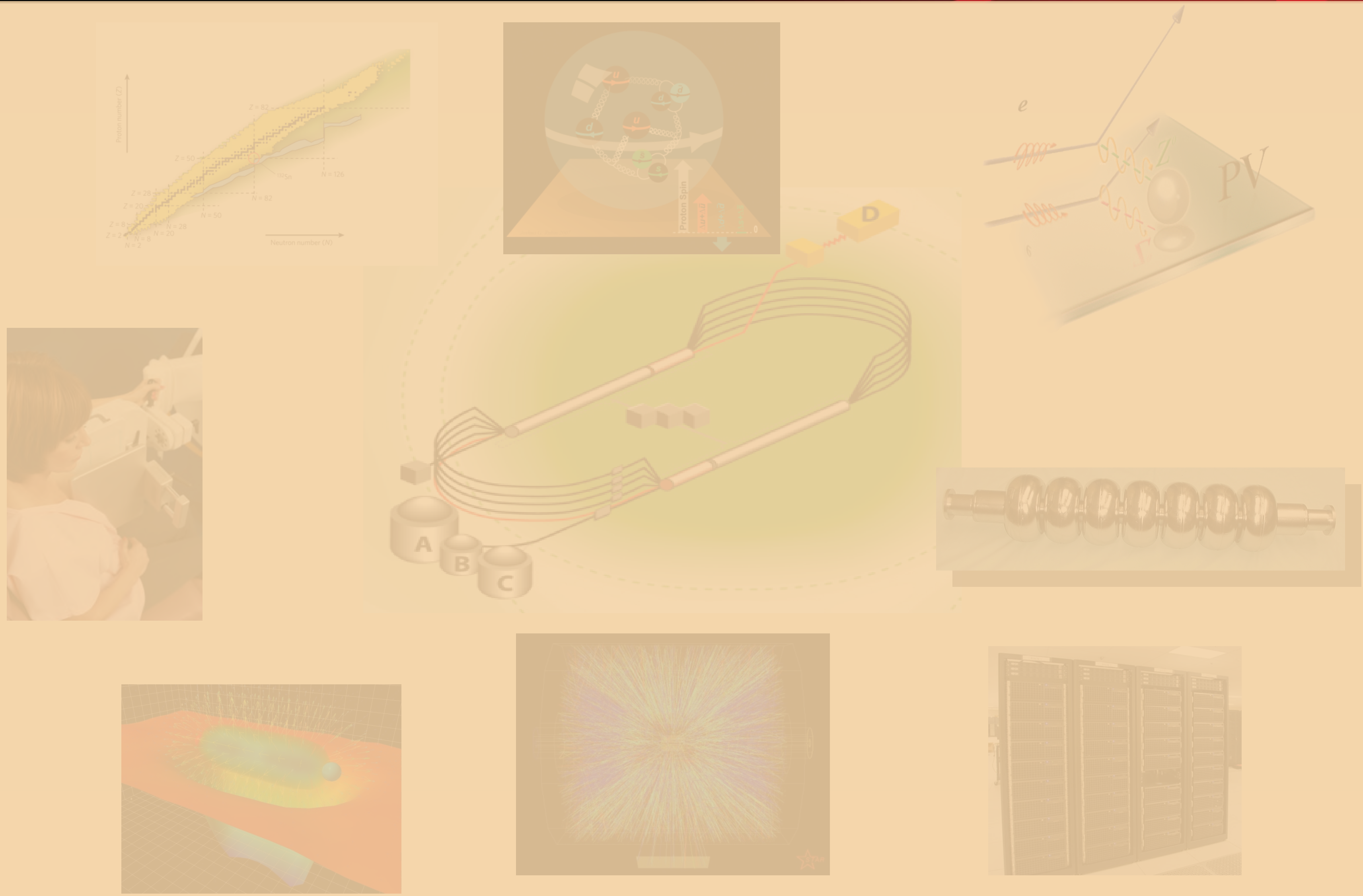


Saturation, one example



Kowalski, Teaney 03

References



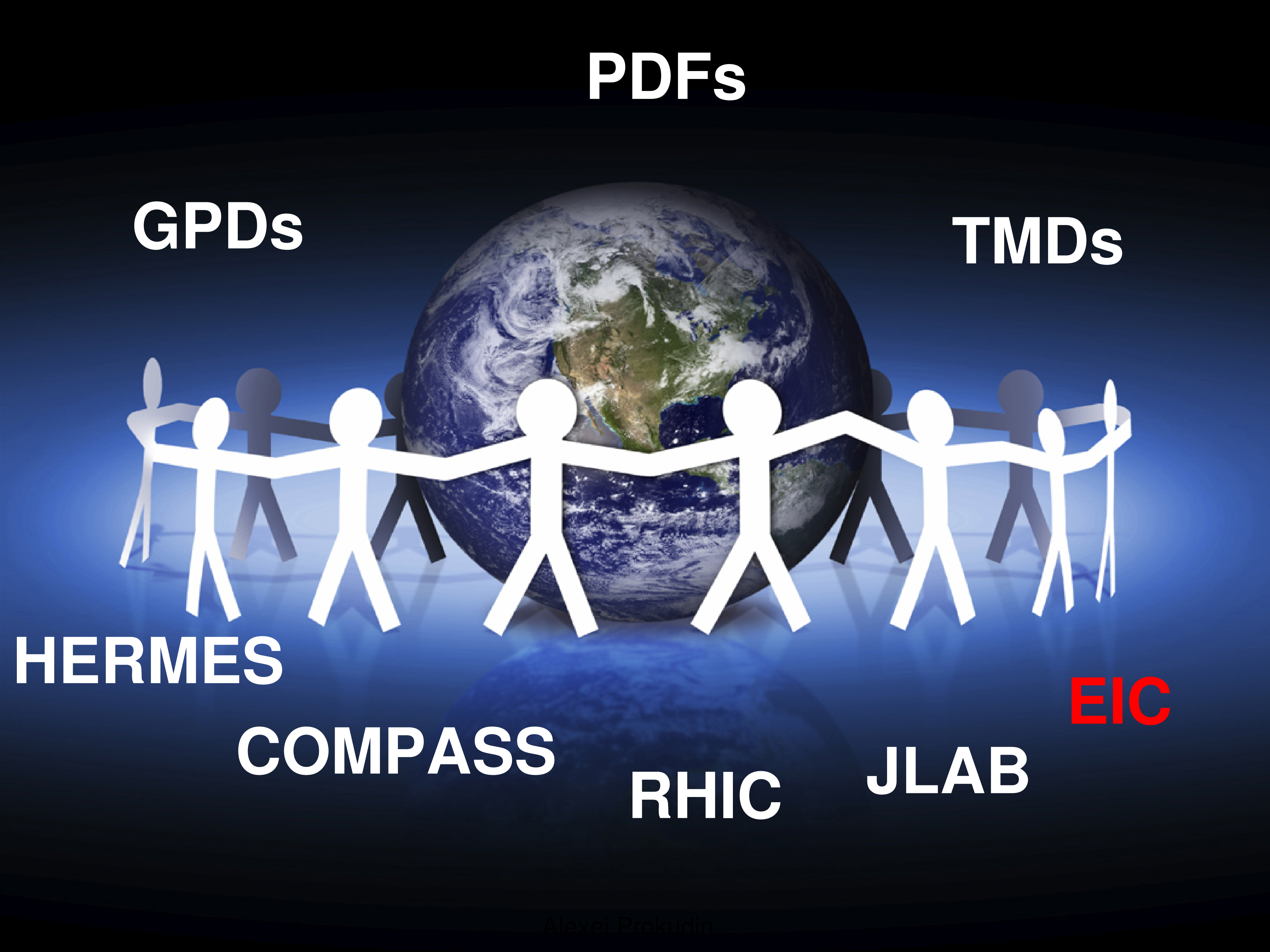
References

- EIC White Paper: "Electron Ion Collider: The Next QCD Frontier – Understanding the glue that binds us all," A. Accardi et al., http://arxiv.org/abs/arXiv:1212.1701

- Introductory overview: "Nuclear physics with a medium-energy Electron-Ion Collider," A. Accardi, V. Guzey, A. Prokudin, C. Weiss Eur. Phys. J. A48 (2012) 92, http://arxiv.org/abs/arXiv:1110.1031

- Detailed summary report: "Gluons and the quark sea at high energies: Distributions, polarization, tomography," D. Boer et al. http://arxiv.org/abs/arXiv:1108.1713

- Web resources:
  https://eic.jlab.org/wiki/index.php/Main_Page (JLab)
  https://wiki.bnl.gov/eic/ (BNL)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GPDs
TMDs
HERMES
COMPASS
RHIC
JLAB
EIC