QCD, Spin, Nucleon Structure, and EIC Physics: A Theory Overview

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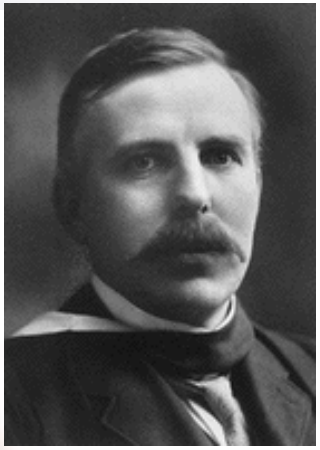
Exploring the nucleon: Of fundamental importance in science

- The nucleons (proton and neutron) are the most important building block of our universe
- Nucleon as important tool for discovery
  - New Physics beyond Standard Model: Tevatron, LHC, Jefferson Lab, …

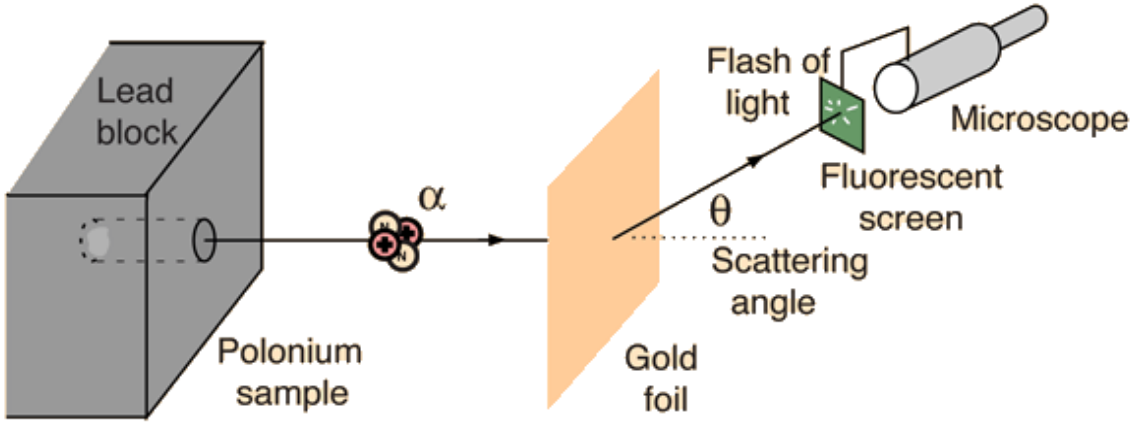
- Brief review of recent progresses
- Outstanding questions/challenges
- Future opportunities

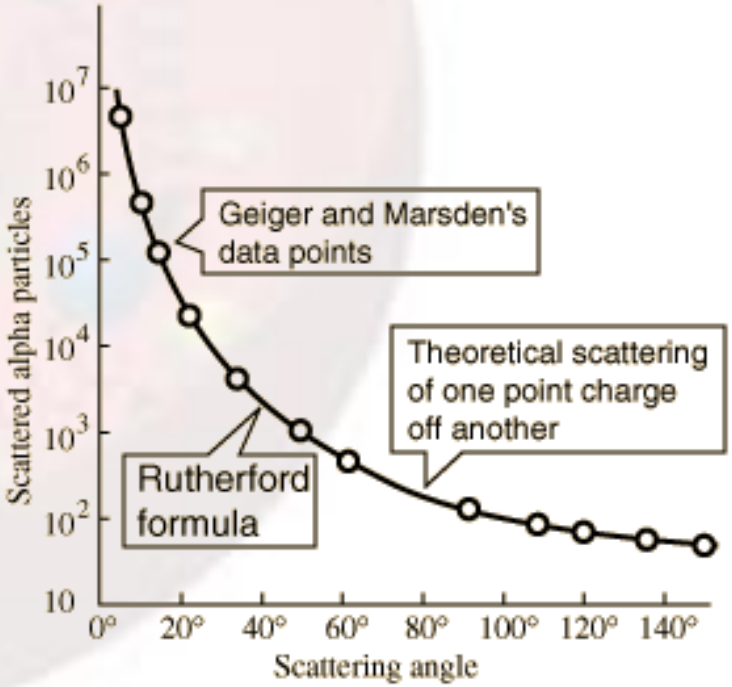
Rutherford scattering



The Scattering of α and β Particles by Matter and the Structure of the Atom

E. Rutherford, F.R.S.*
Philosophical Magazine
Series 6, vol. 21
May 1911, p. 669-688



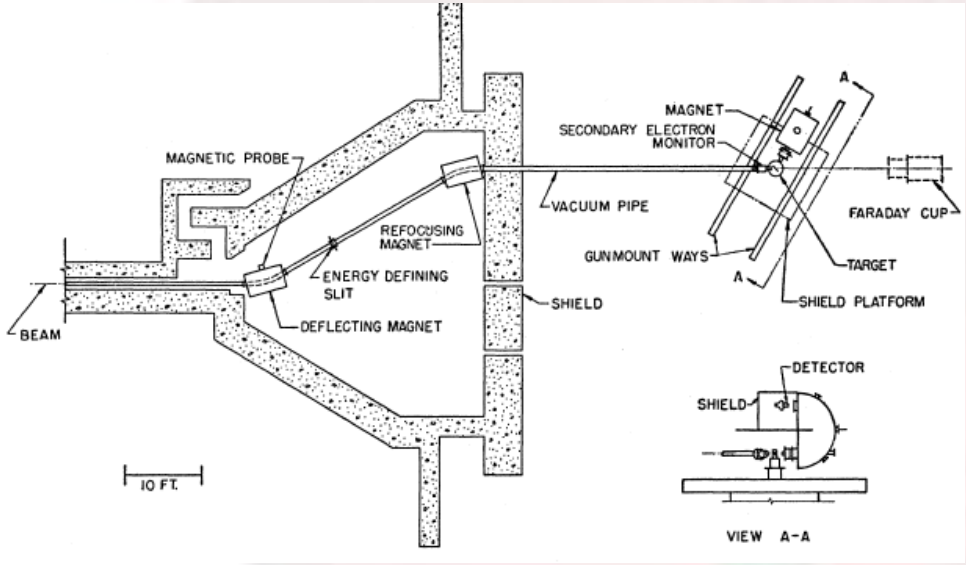


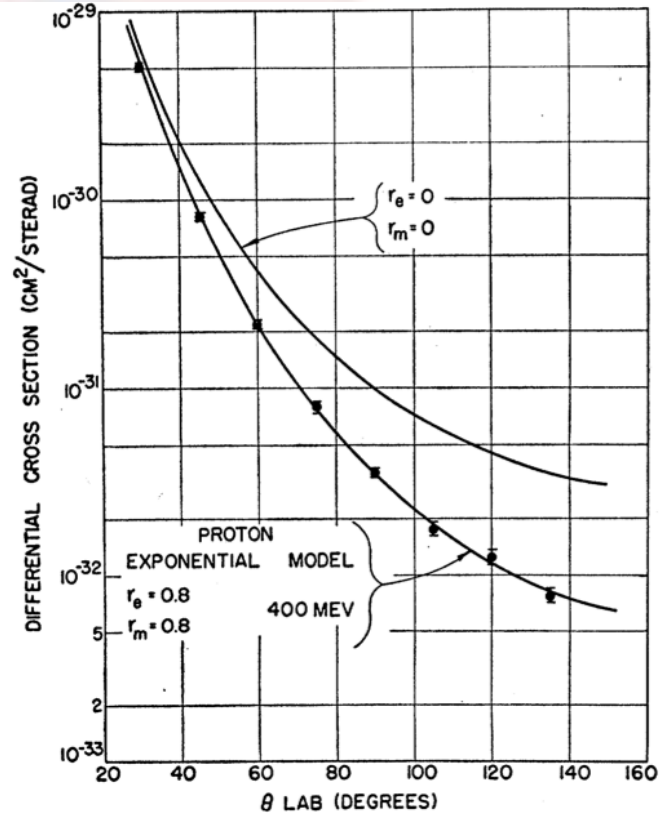
Discovery of Nuclei

Finite size of nucleon (charge radius)

Hofstadter

- Rutherford scattering with electron



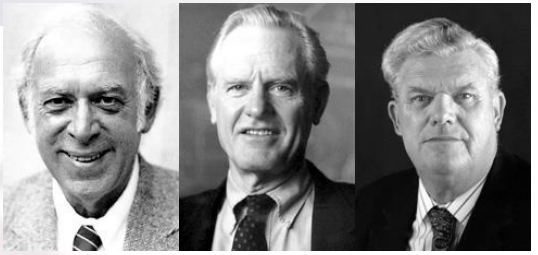


Renewed interest on proton radius:
μ-Atom vs e-Atom (EM-form factor)

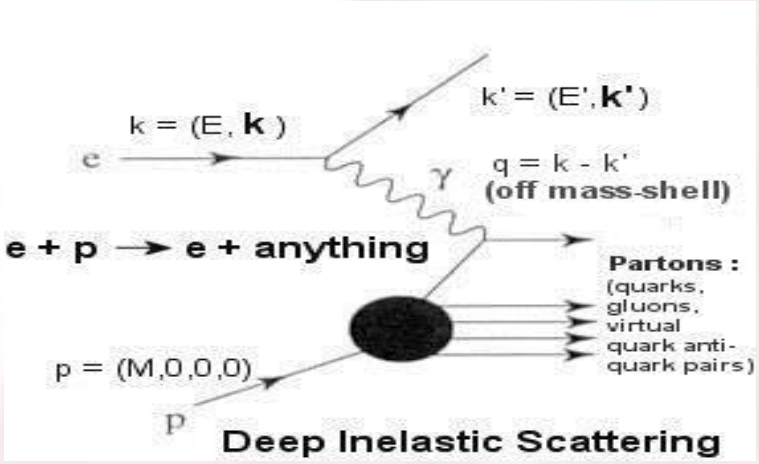
RevModPhys.28.214

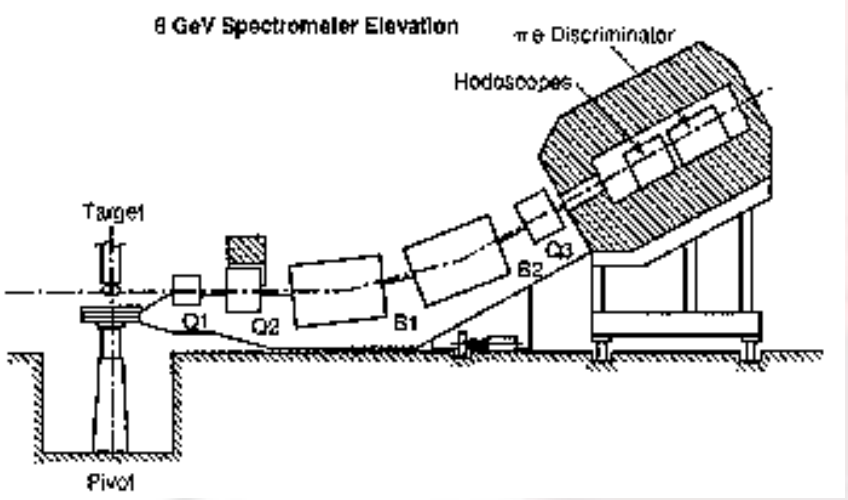
Deep Inelastic Scattering

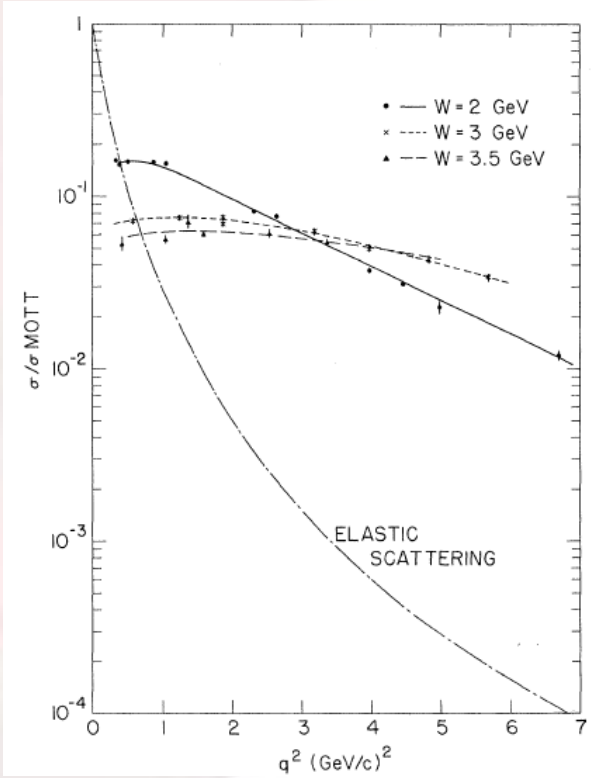
Discovery of Quarks



Friedman Kendall Taylor





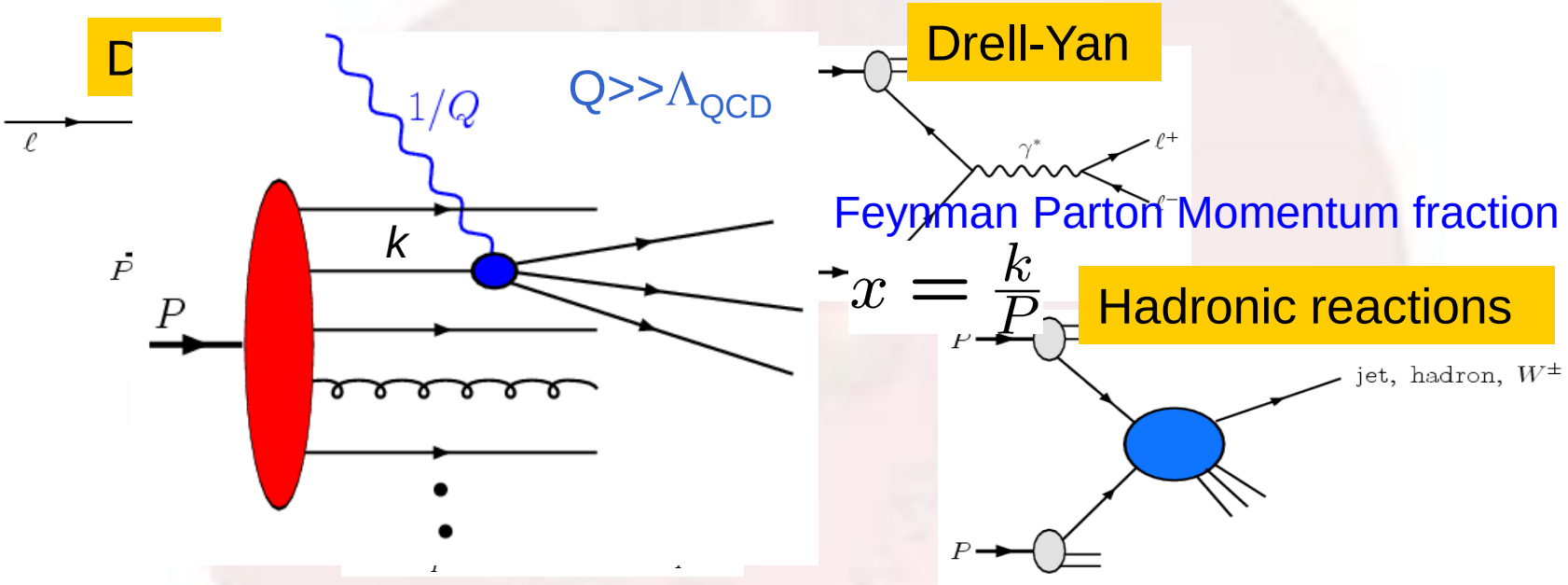


Bjorken Scaling: $Q^2 \rightarrow$ Infinity
Feynman Parton Model:
Point-like structure in Nucleon

Quantum Chromodynamics

- There is no doubt that QCD is the right theory for hadron physics
- However, many fundamental questions…
- How does the **nucleon mass** emerge from the light quarks dynamically?
- Why quarks and gluons are **confined** inside the nucleon?
- How do the fundamental **nuclear forces** arise from QCD?
- We don't have a **comprehensive picture** of the nucleon structure as we don't have an approximate QCD nucleon wave function

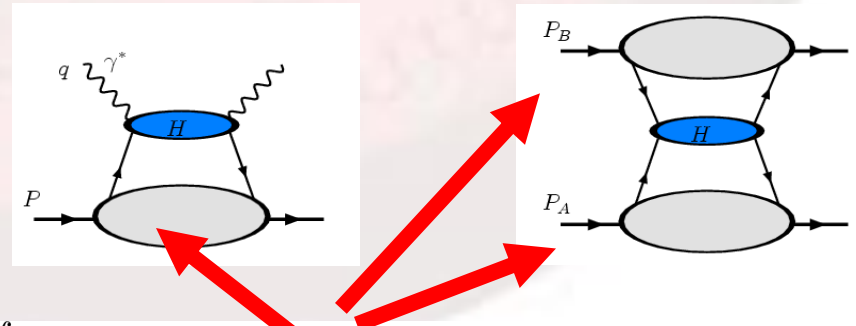
High energy scattering as a probe to the nucleon structure



- Many processes: Deep Inelastic Scattering, Deeply-virtual compton scattering, Drell-Yan lepton pair production, pp→jet+X
  - Momentum distribution: Parton Distribution
  - Spin density: polarized parton distribution
  - Wave function in infinite momentum frame: Generalized Parton Distributions

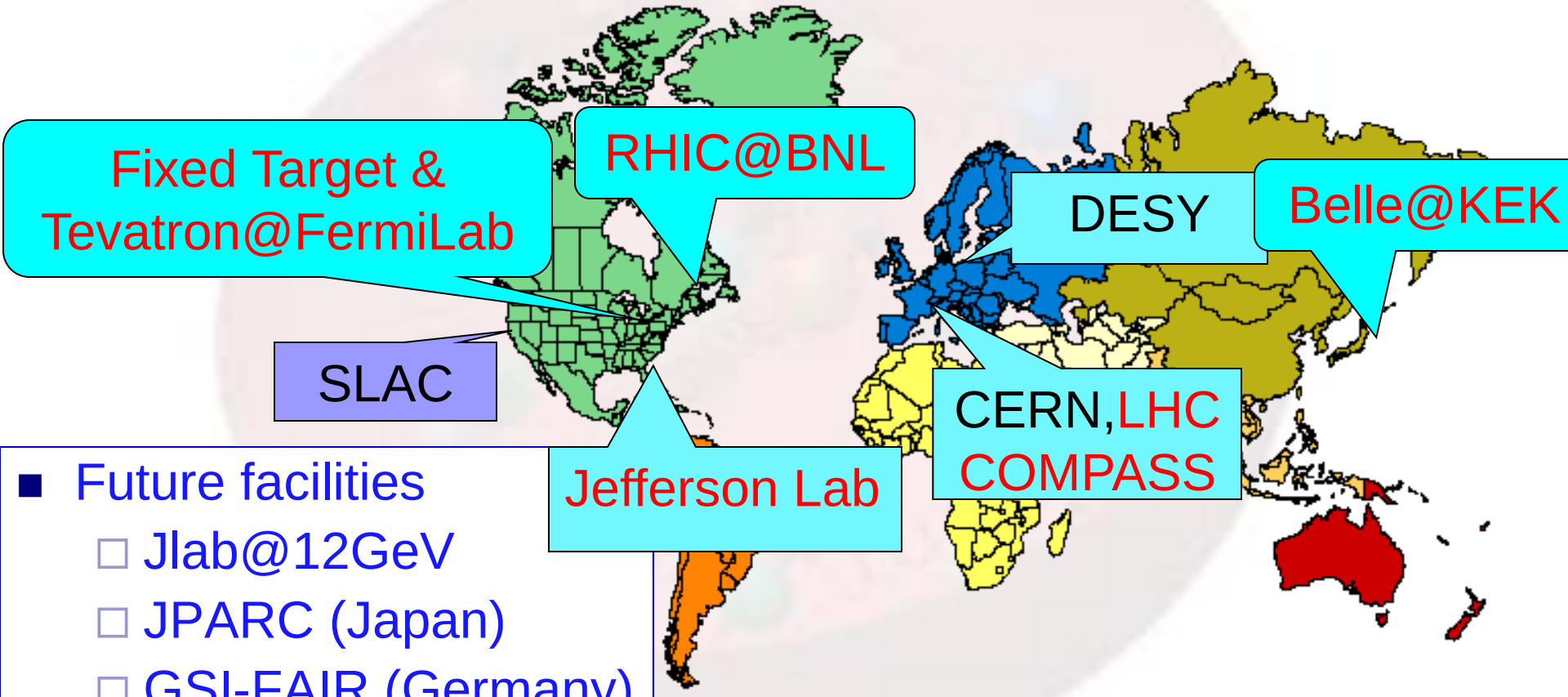
Feynman's parton language and QCD Factorization

- If a hadron is involved in high-energy scattering, the physics simplifies in the infinite momentum frame (Feynman's Parton Picture)
- The scattering can be decomposed into a convolution of parton scattering and parton density (distribution), or wave function or correlations
  - QCD Factorization!



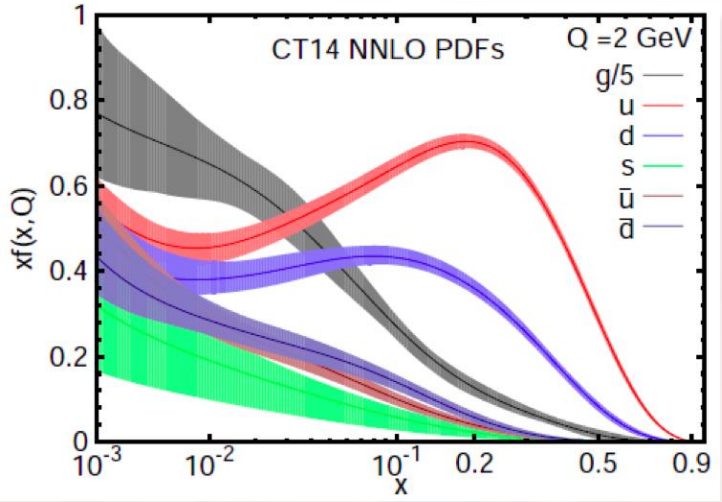
$$\sim \int \text{Parton Distributions} \otimes \text{Hard Partonic Cross Section}$$

Exploring the partonic structure of nucleon worldwide



- Future facilities
  - Jlab@12GeV
  - JPARC (Japan)
  - GSI-FAIR (Germany)
  - **EIC, LHeC, …**

Parton picture of the nucleon



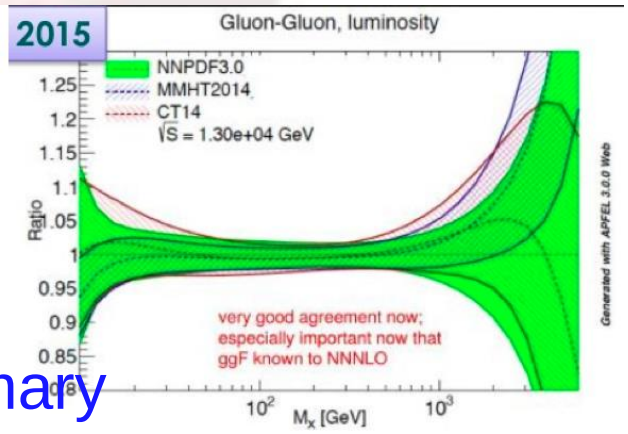
C.-P.Yuan@DIS15

- Beside valence quarks, there are sea and gluons
- Precisions on the PDFs are very much relevant for LHC physics: SM/New Physics

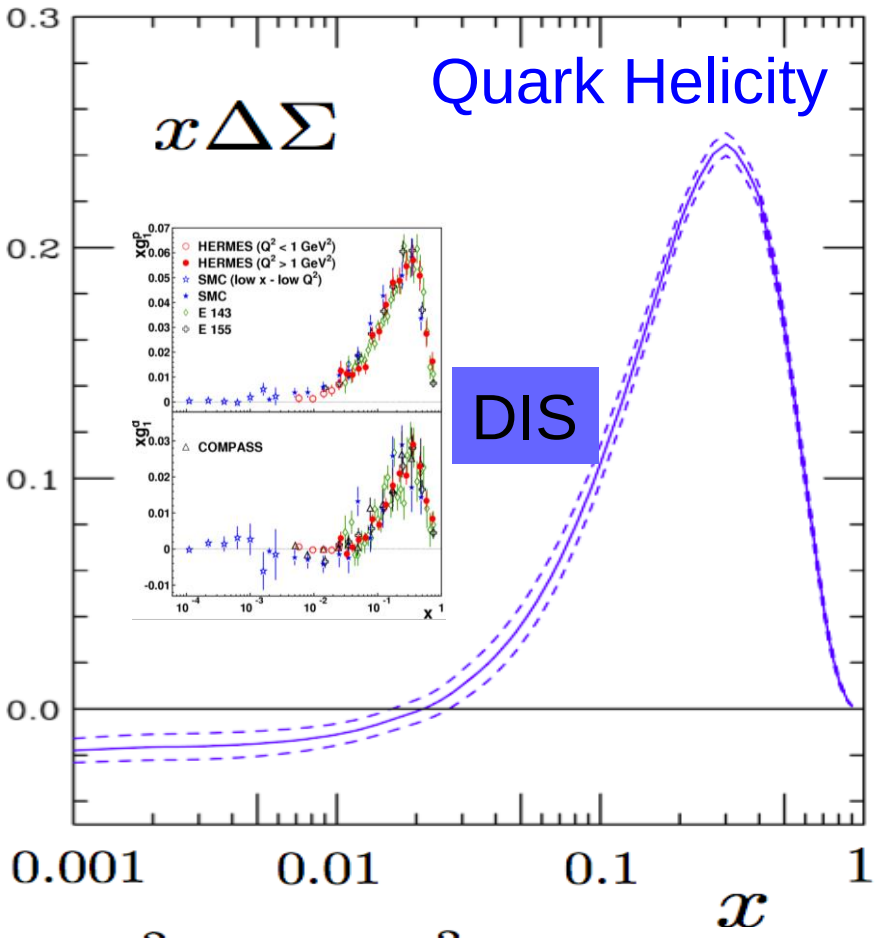
$$\sigma(gg \to H), \sqrt{(s)} = 13\text{TeV}$$

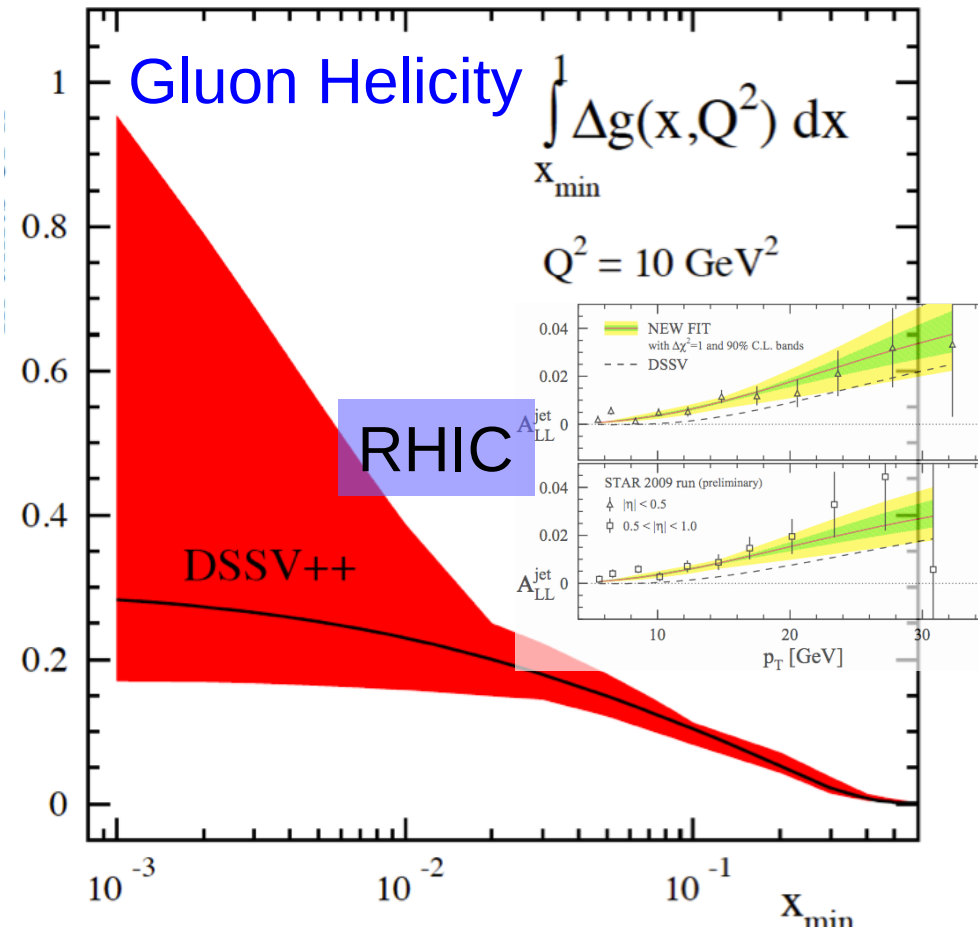
CT14	MMHT2014	NNPDF3.0
42.68 pb	42.70 pb	42.97 pb
+2.0% -2.4%	+1.3% -1.8%	+1.9% -1.9%

DIS summary



Parton distributions in a polarized nucleon





de Florian-Sassot-Stratmann-Vogelsang, 2014

Proton spin: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$

emerging phenomena?

- We know fairly well how much quark helicity contributions, $\Delta\Sigma = 0.3 \pm 0.05$
  - Start to constrain the sea polarization (SIDIS@HERMES/COMPASS and W@RHIC)
  - Large-x and small-x? (JLab12,EIC)
- With large errors we know gluon helicity contribution plays an important role
- No direct information on quark and gluon orbital angular momentum contributions

The orbital motion:

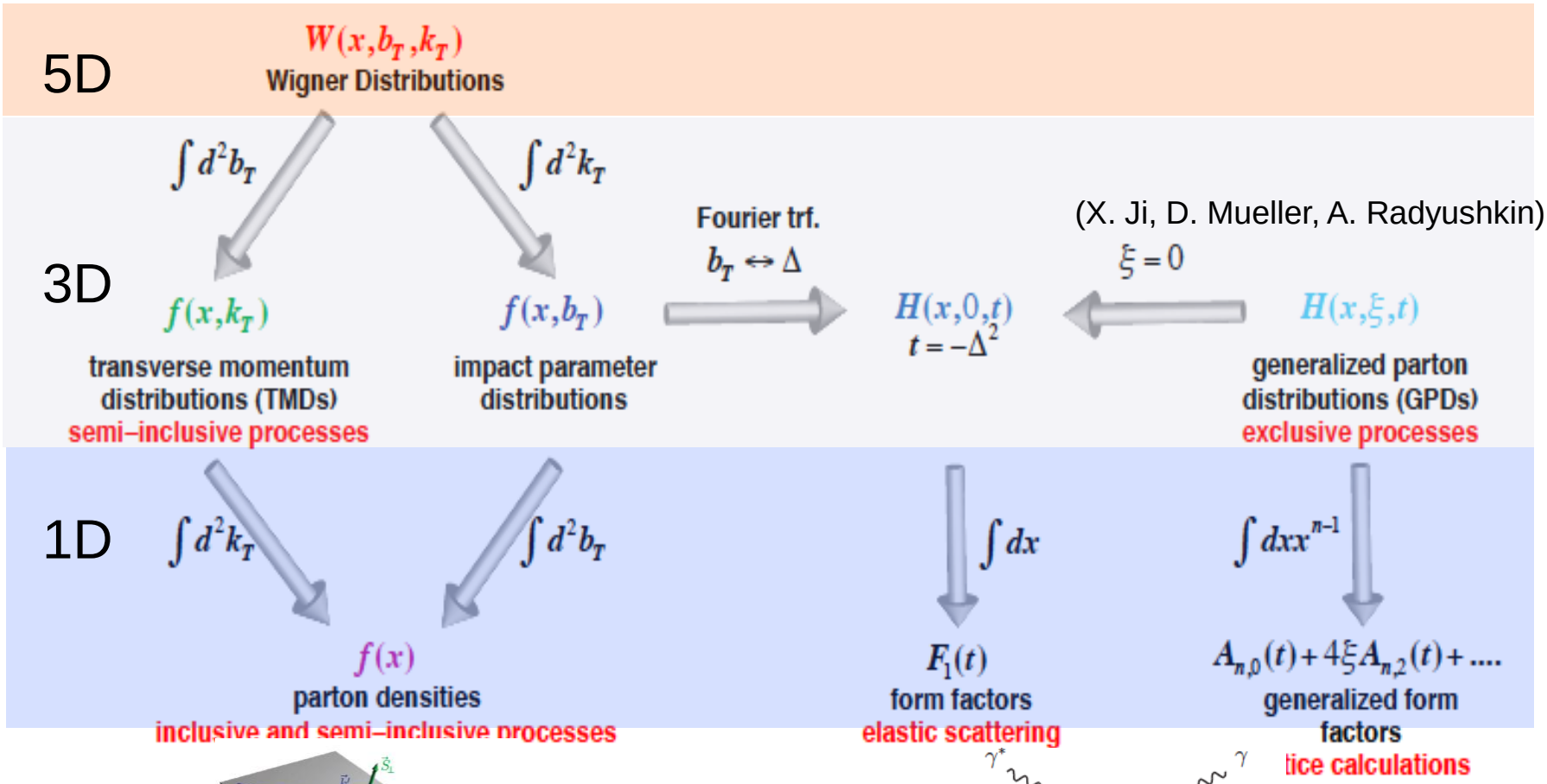
- Orbital motion of quarks and gluons must be significant inside the nucleons!
  - This is in contrast to the naive non-relativistic quark model, which was the motivation to introduce the color quantum number!
- Orbital motion shall generate direct orbital Angular Momentum which must contribute to the spin of the proton
- Orbital motion can also give rise to a range of interesting physical effects (Single Spin Asymmetries)

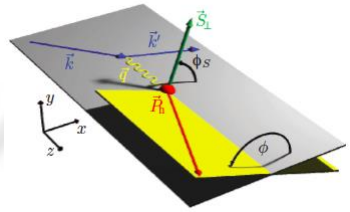
New ways to look at partons

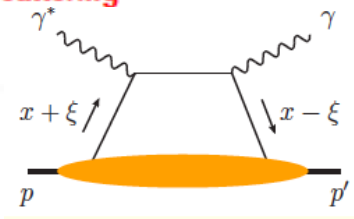
- We not only need to know that partons have long. momentum, but must have transverse degrees of freedom as well
- Partons in transverse coordinate space
  - Generalized parton distributions (GPDs)
- Partons in transverse momentum space
  - Transverse-momentum distributions (TMDs)
- Both? Wigner distributions!

Unified view of the Nucleon

- **Wigner distributions (Belitsky, Ji, Yuan)**

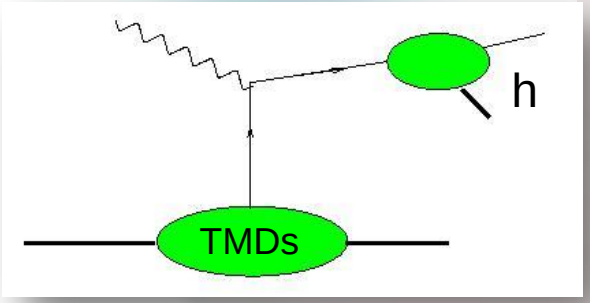




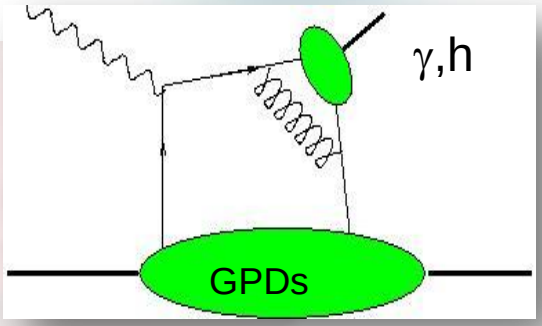


Zoo of TMDs & GPDs

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$



	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$

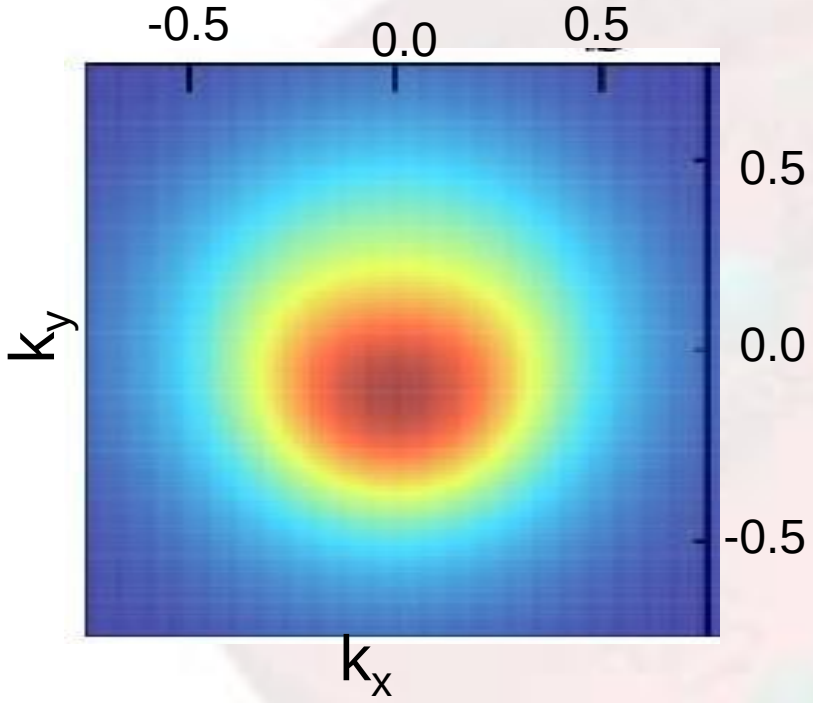


- NOT directly accessible
- Their extractions require measurements of x-sections and asymmetries in **a large kinematic domain of x_B, t, Q^2** (GPD) and **x_B, P_T, Q^2 , z** (TMD)

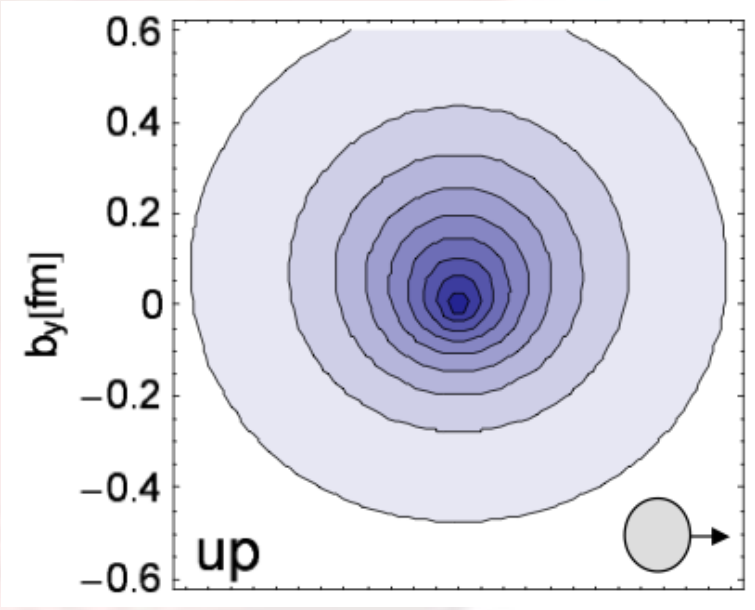
What can we learn

- 3D Imaging of partons inside the nucleon (non-trivial correlations)
  - Try to answer more detailed questions as Rutherford was doing 100 years ago
- QCD dynamics involved in these processes
  - Transverse momentum distributions: universality, factorization, evolutions,…
  - Small-x: BFKL vs Sudakov?

Deformation when nucleon is transversely polarized



Quark Sivers function fit to the SIDIS Data, Anselmino, et al. 2009



Lattice Calculation of the transvese density Of Up quark, QCDSF/UKQCD Coll., 2006

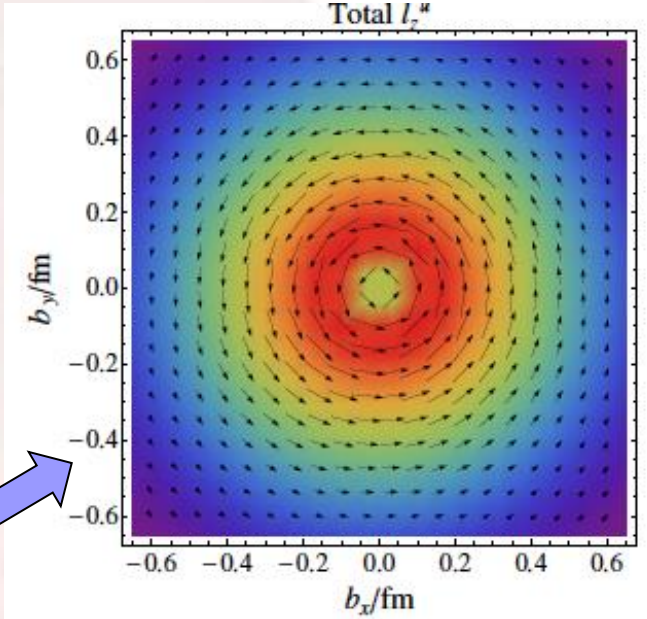
Parton's orbital motion through the Wigner Distributions

Phase space distribution:

Projection onto p (x) to get the momentum (probability) density

Quark orbital angular momentum

$$L(x) = \int (\vec{b}_\perp \times \vec{k}_\perp) W(x, \vec{b}_\perp, \vec{k}_\perp) d^2\vec{b}_\perp d^2\vec{k}_\perp$$

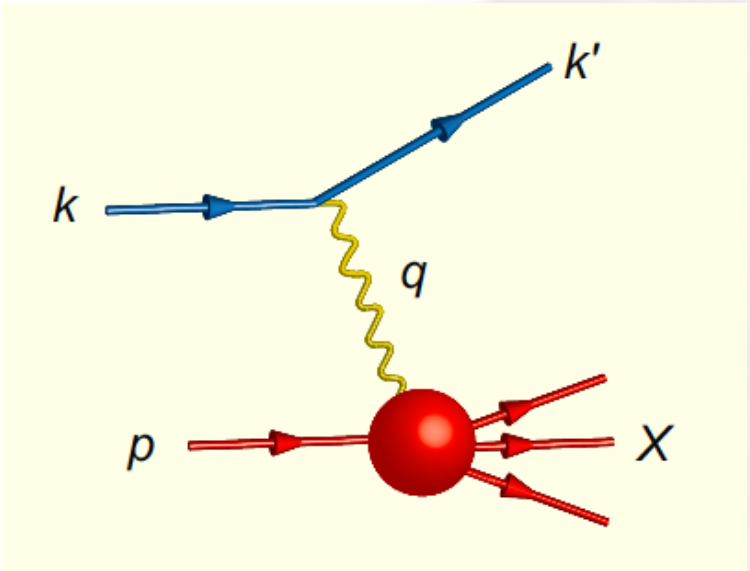


Well defined in QCD:

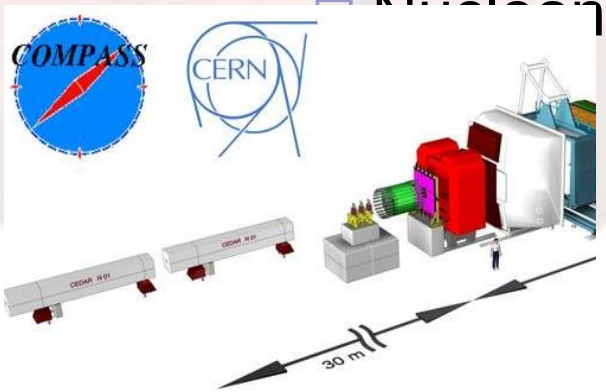
Ji, Xiong, Yuan, PRL, 2012; PRD, 2013

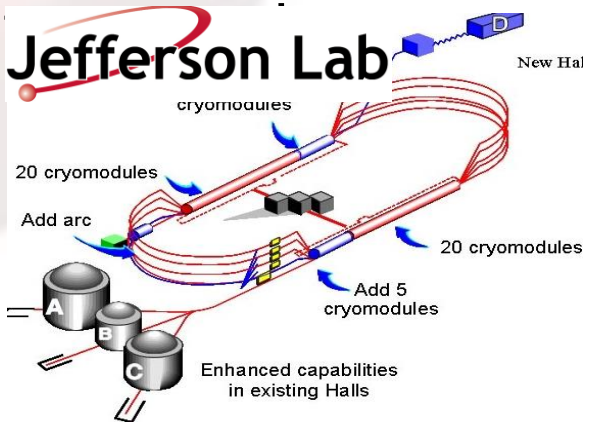
Lorce, Pasquini, Xiong, Yuan, PRD, 2012

Where can we study: Deep Inelastic Scattering



- Inclusive DIS
  - Parton distributions
- Semi-inclusive DIS, measure additional hadron in final state
  - Kt-dependence
- Exclusive Processes, measure recoiled nucleon
  - Nucleon





What we have learned

- Unpolarized transverse momentum (coordinate space) distributions from, mainly, DIS, Drell-Yan, W/Z boson productions, (HERA exp.)
- Indications of polarized quark distributions from low energy DIS experiments (HERMES, COMPASS, JLab)

What we are missing

- Precise, detailed, mapping of polarized quark/gluon distribution
  - Universality/evolution more evident
- Spin correlation in momentum and coordinate space/tomography
  - Crucial for orbital motion
- Small-x: links to other hot fields (Color-Glass-Condensate)

Perspectives

- HERA (ep collider) limited by the statistics, and not polarized in both beams
- Existing fixed target experiments are limited by statistics and kinematics
- JLab 12 will provide un-precedent data with high luminosity
- Ultimate machine will be the Electron-Ion-Collider (EIC): kinematic coverage with high luminosity

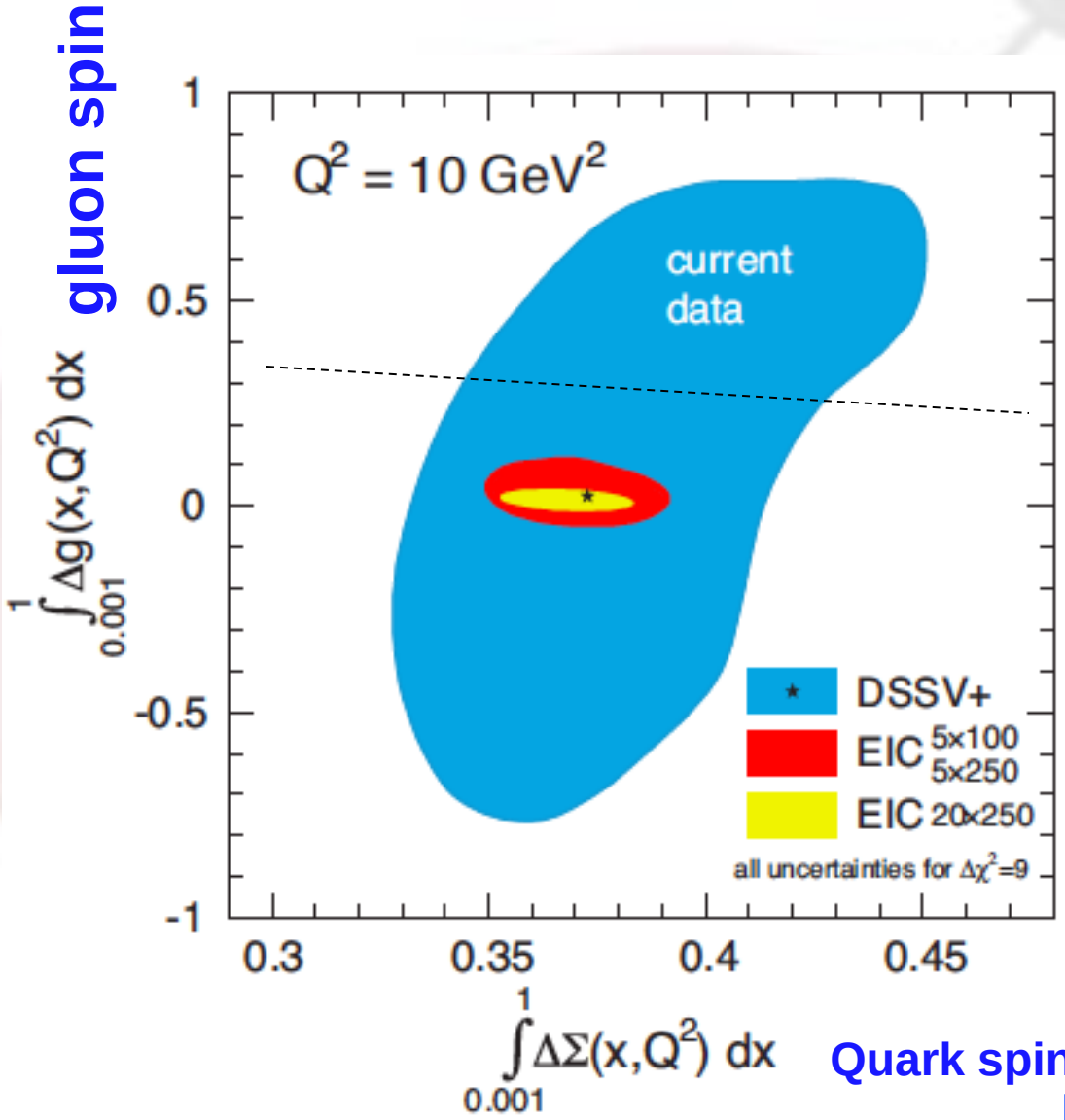
What an EIC can do?

talk this afternoon

- Studying partonic content of a QCD bound state (nucleon and nucleus)
- The probe is hard and relativistic, the nucleon is measured in the infinite momentum frame (light-cone correlations)
- Wide kinematics to study QCD factorization, evolution, and strong interaction dynamics

EIC: Understanding the glue that bind us all

- Gluon plays an important role in the momentum of the nucleon
- It also has the key role in the nucleon mass
- Nucleon spin structure through helicity ΔG
- Gluon orbital motion
  - Nucleon tomography (orbital-spin correlations)
- Small x: gluon saturation (CGC)-> a saturated transverse-momentum distribution



Stratmann, et al.
EIC-White Paper

EIC-White paper
arXiv:1212.1701

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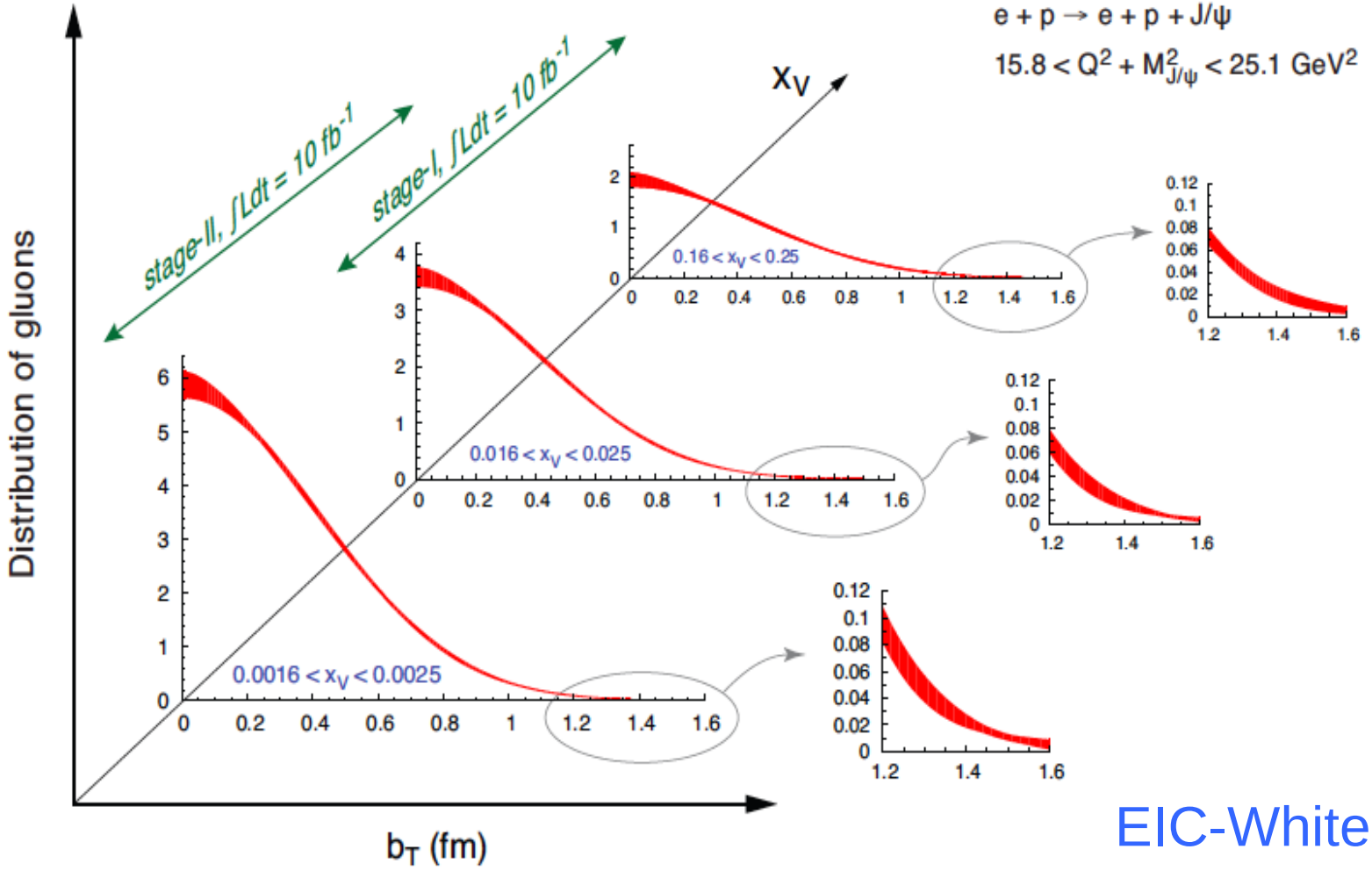
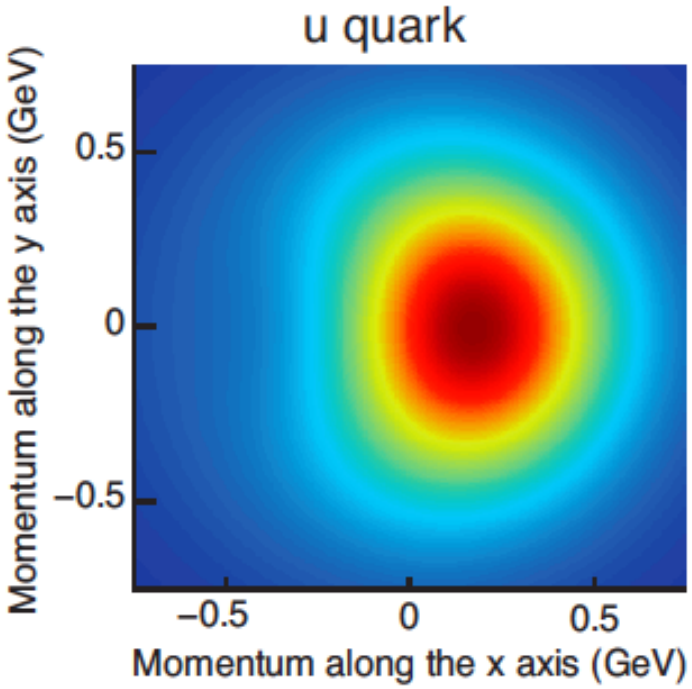
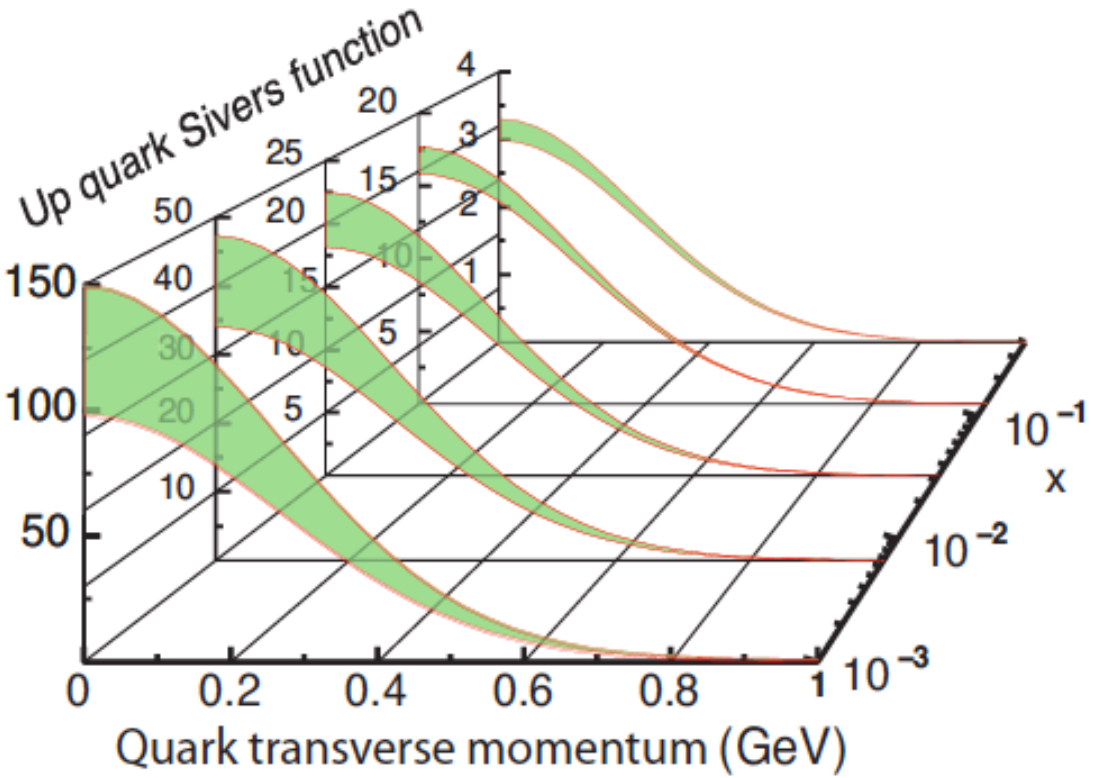
Gluon tomography at small x (GPDs)



EIC-White paper
arXiv:1212.1701

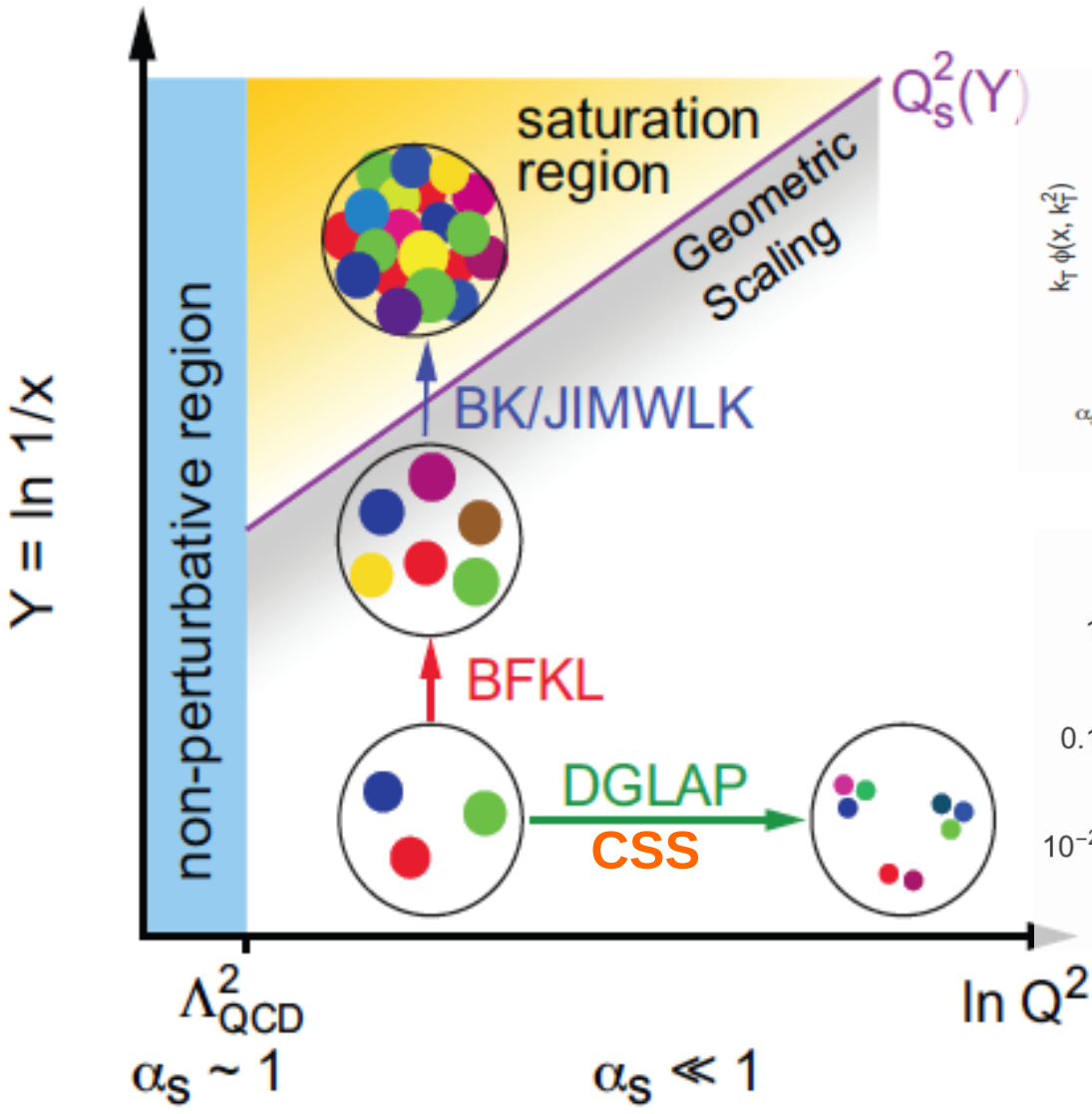
Transverse momentum distributions

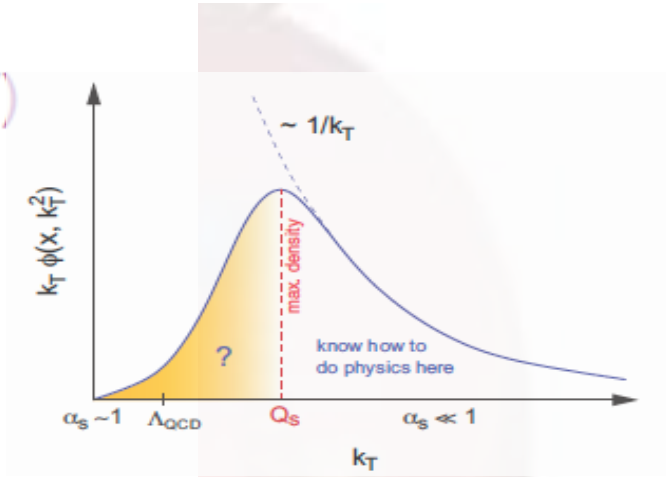


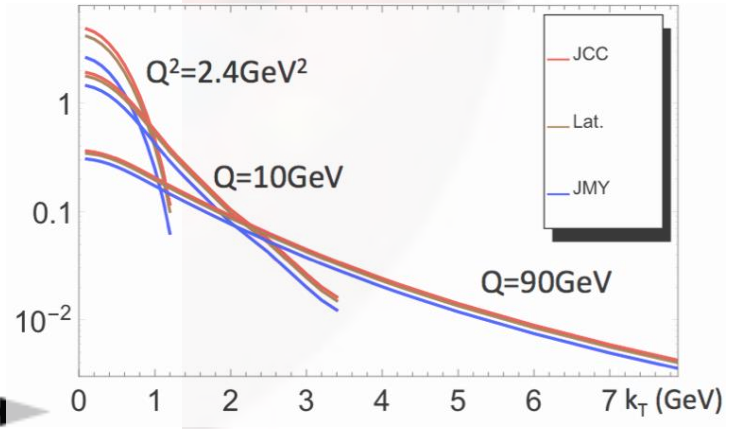


EIC-White paper
arXiv:1212.1701

Transverse momentum distributions: A unified picture







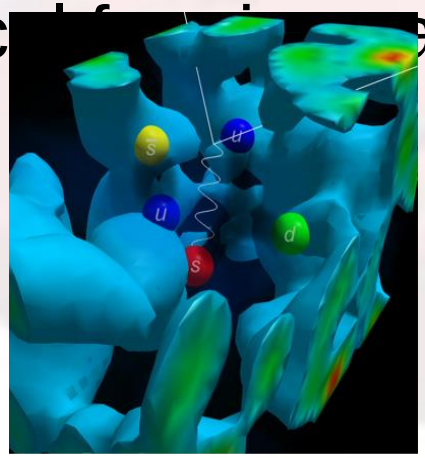
Prokudin-Sun-Yuan 15

Theoretical Issues

- New structure, new dynamics and new phenomena!
  - Structure and probe physics separation or factorization
  - New processes to measure novel observables
  - Study partons directly on lattice

Future: Lattice QCD

- The only known rigorous framework for *ab-initio* calculation of the structure of protons and neutrons with controllable errors.
- After decades of effort, one can finally calculate nucleon properties with dynamic [illegible] at p[illegible] mass!



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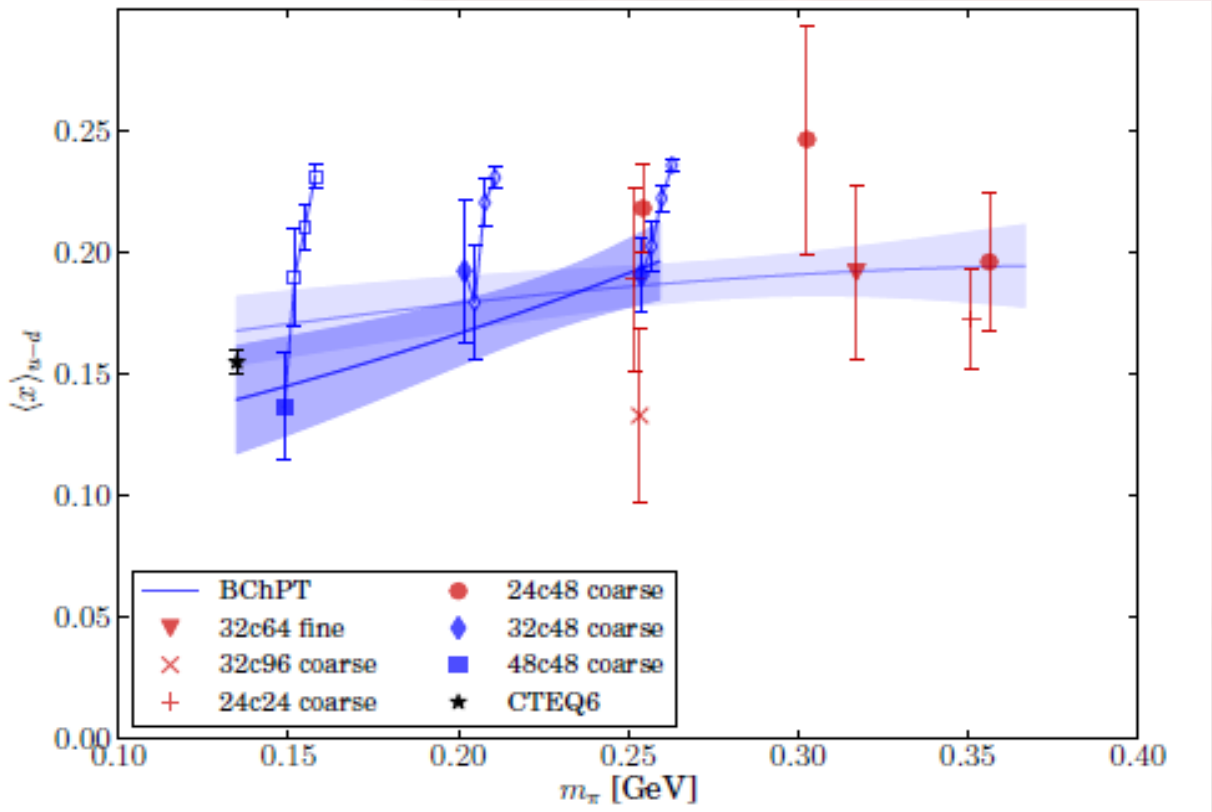
Nucleon Structure from Lattice QCD

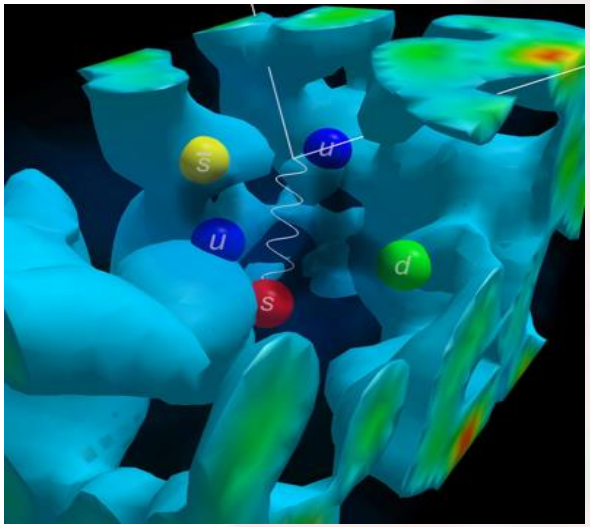
J.R. Green et al, 2012 & 2014



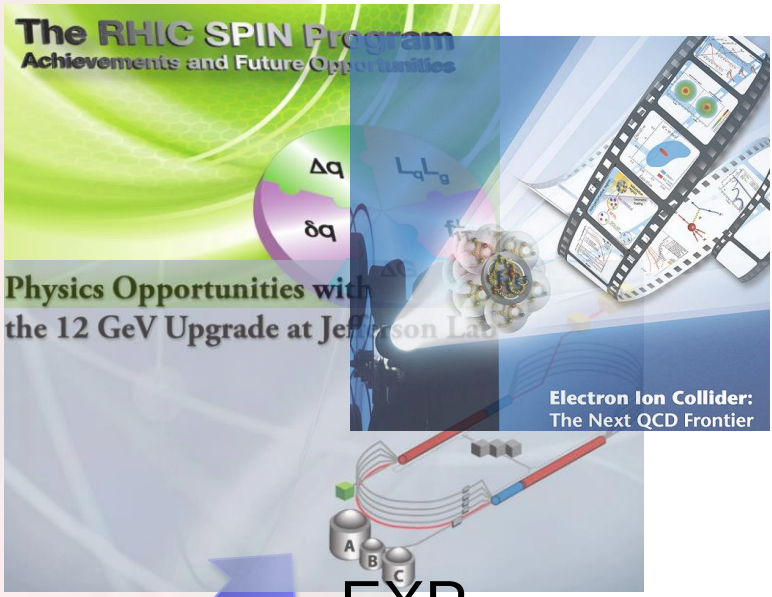
Nearly physical pion mass m_π=149MeV

Quark momentum fraction $\langle x \rangle_{u-d} = \int dx\, x\, (u + \bar{u} - d - \bar{d})$

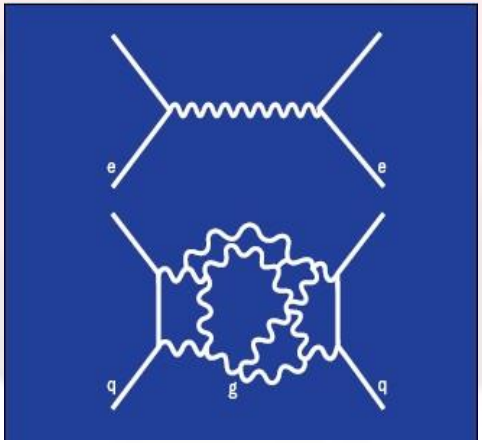
Fundamental Understanding of the Nucleon Structure in QCD



Lattice QCD



EXP. Measurements



Theory/ Phenomenology