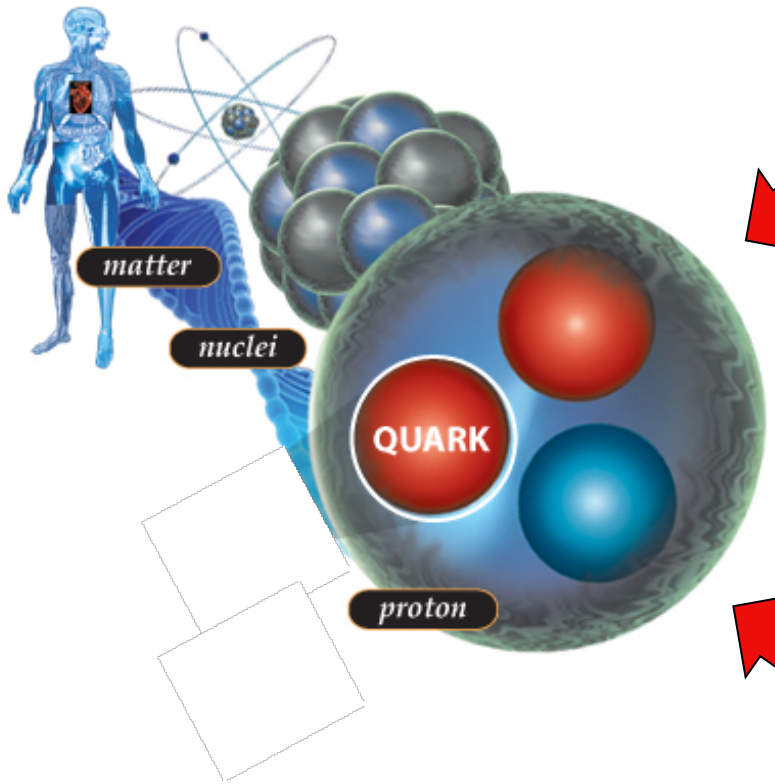
Hadron Structure: Jefferson Lab 12 and beyond

Alexei Prokudin

March 26, 2013

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Exploring the nucleon: a fundamental quest



Know what we are made of !

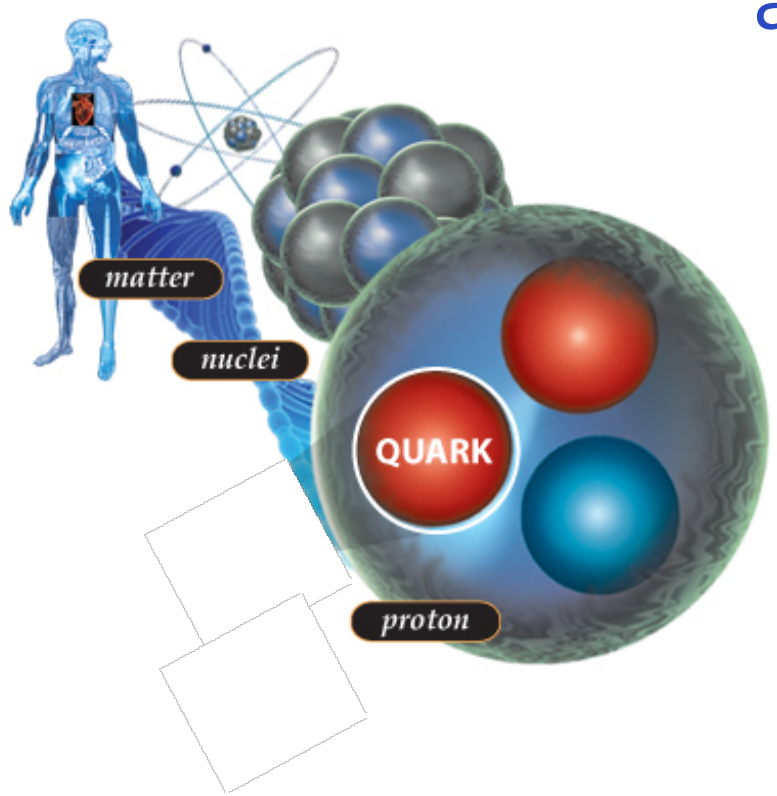
Understand the strong force: "QCD"

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

Exploring the nucleon: a fundamental quest

Know what we are made of !

1÷2 m



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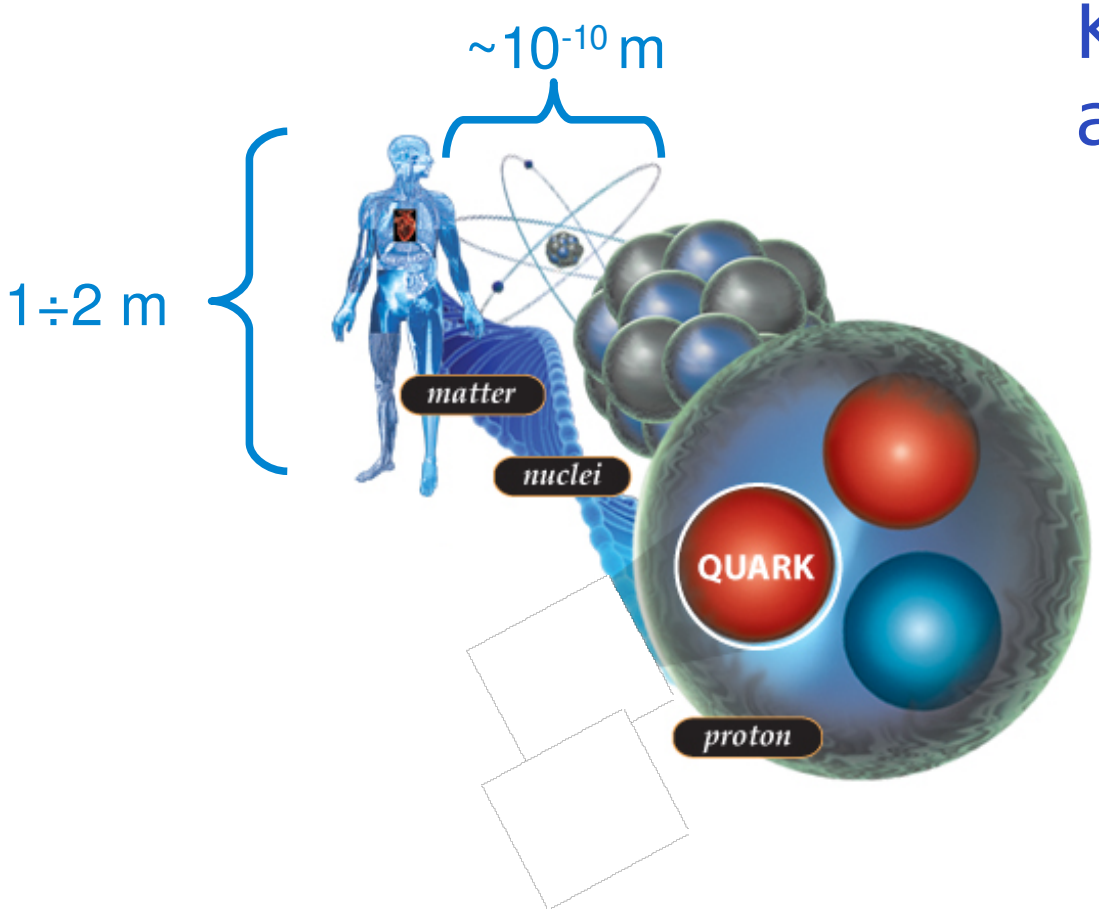

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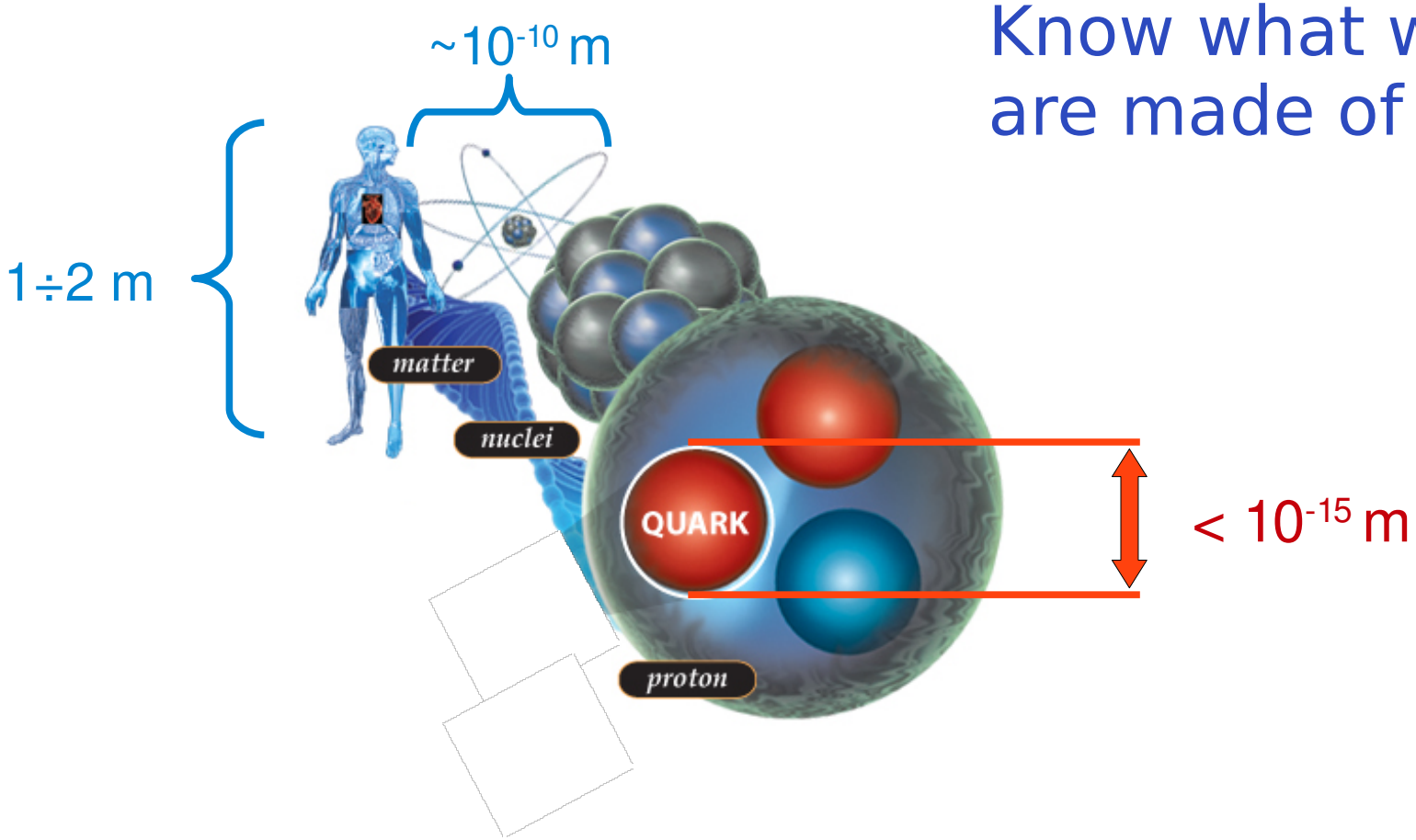

Exploring the nucleon: a fundamental quest

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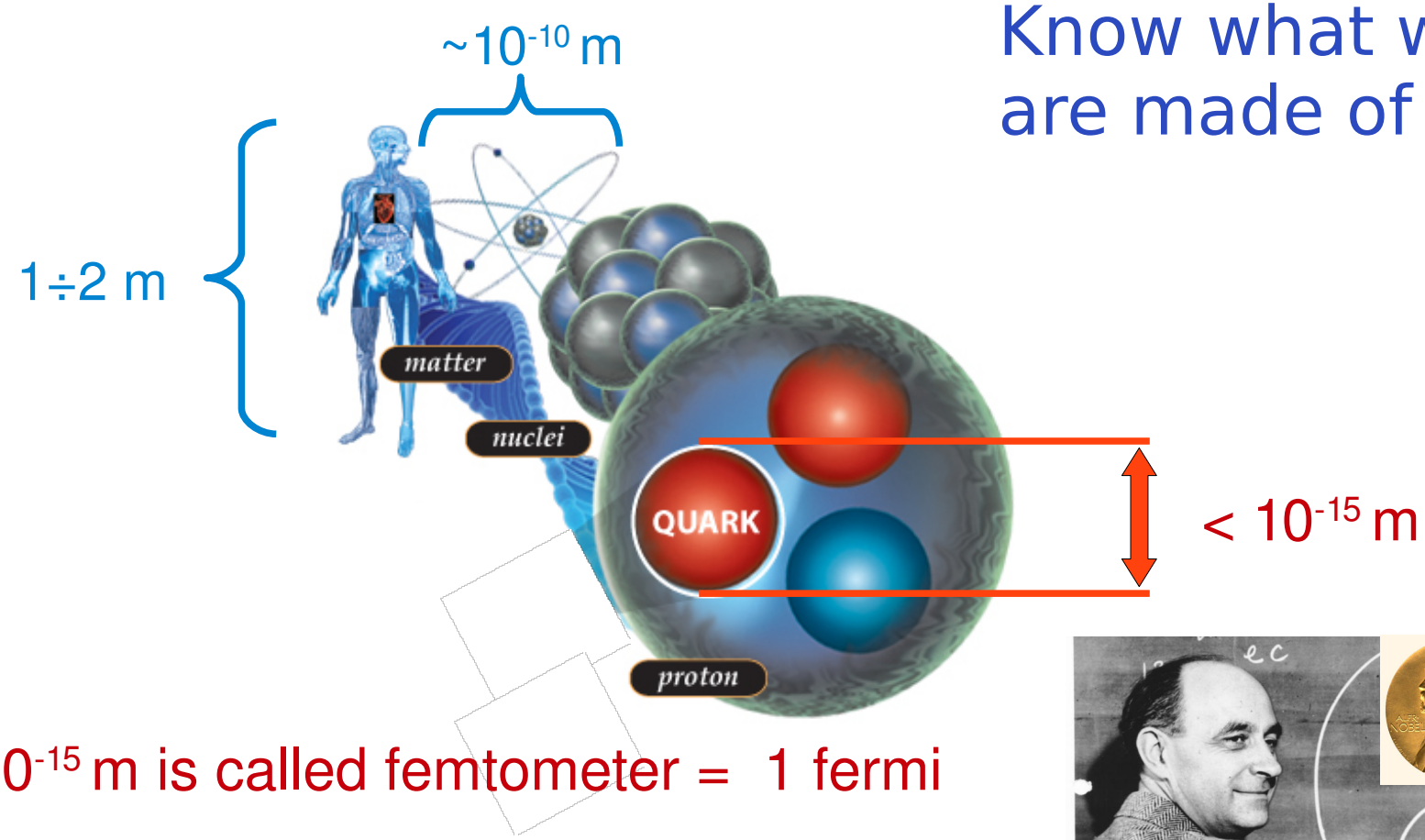
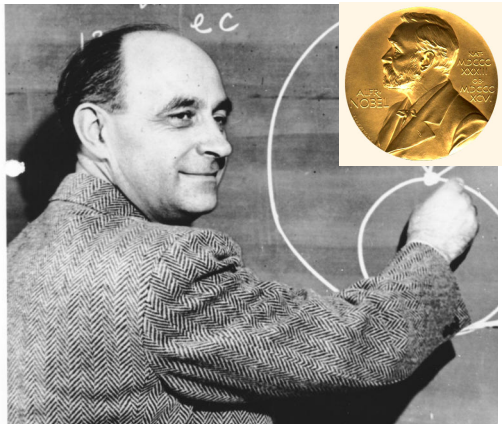


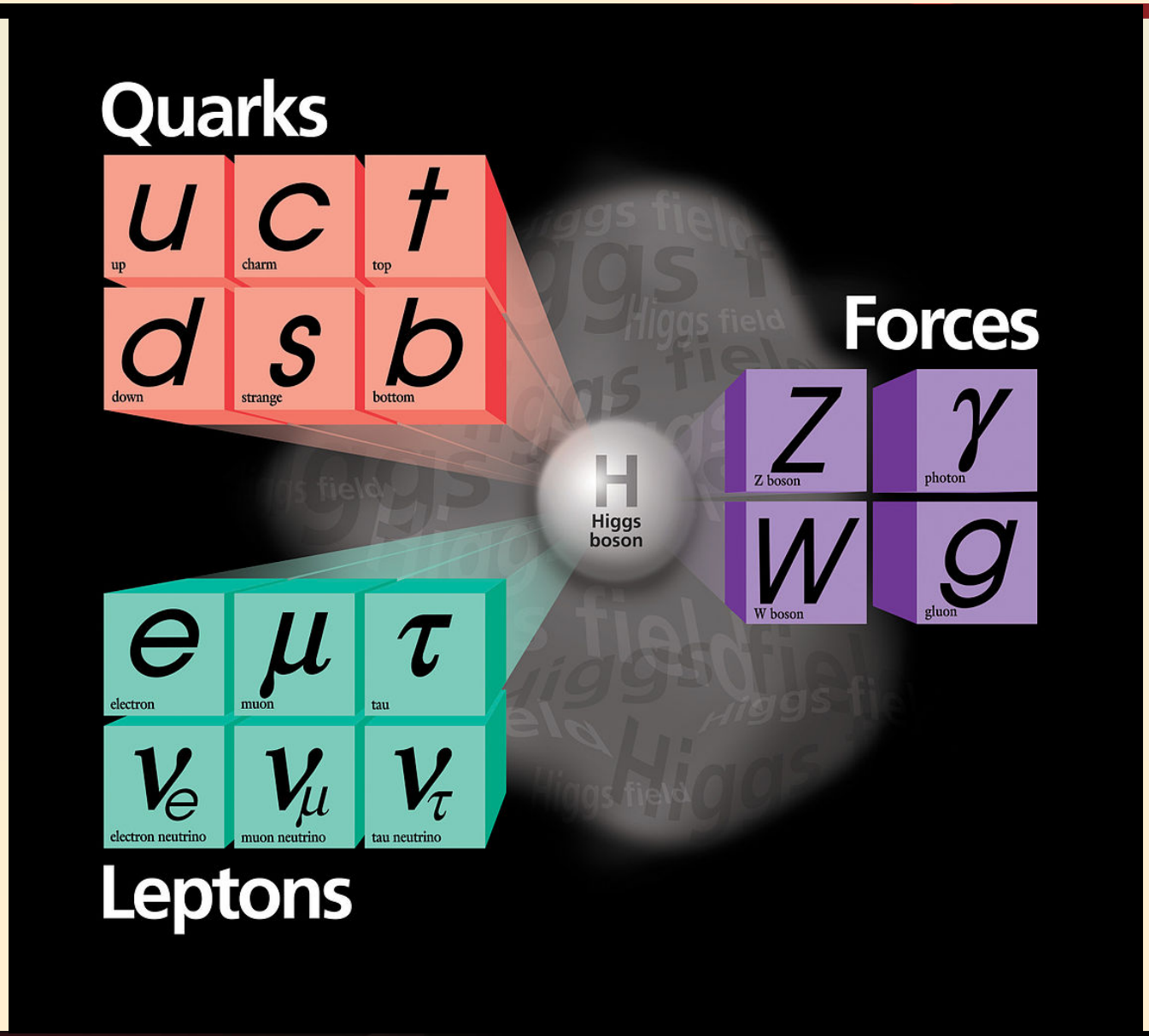
10^{-15} m is called femtometer = 1 fermi

Enrico Fermi (Nobel Prize 1938)

"for … nulear reactions … "



Standard model



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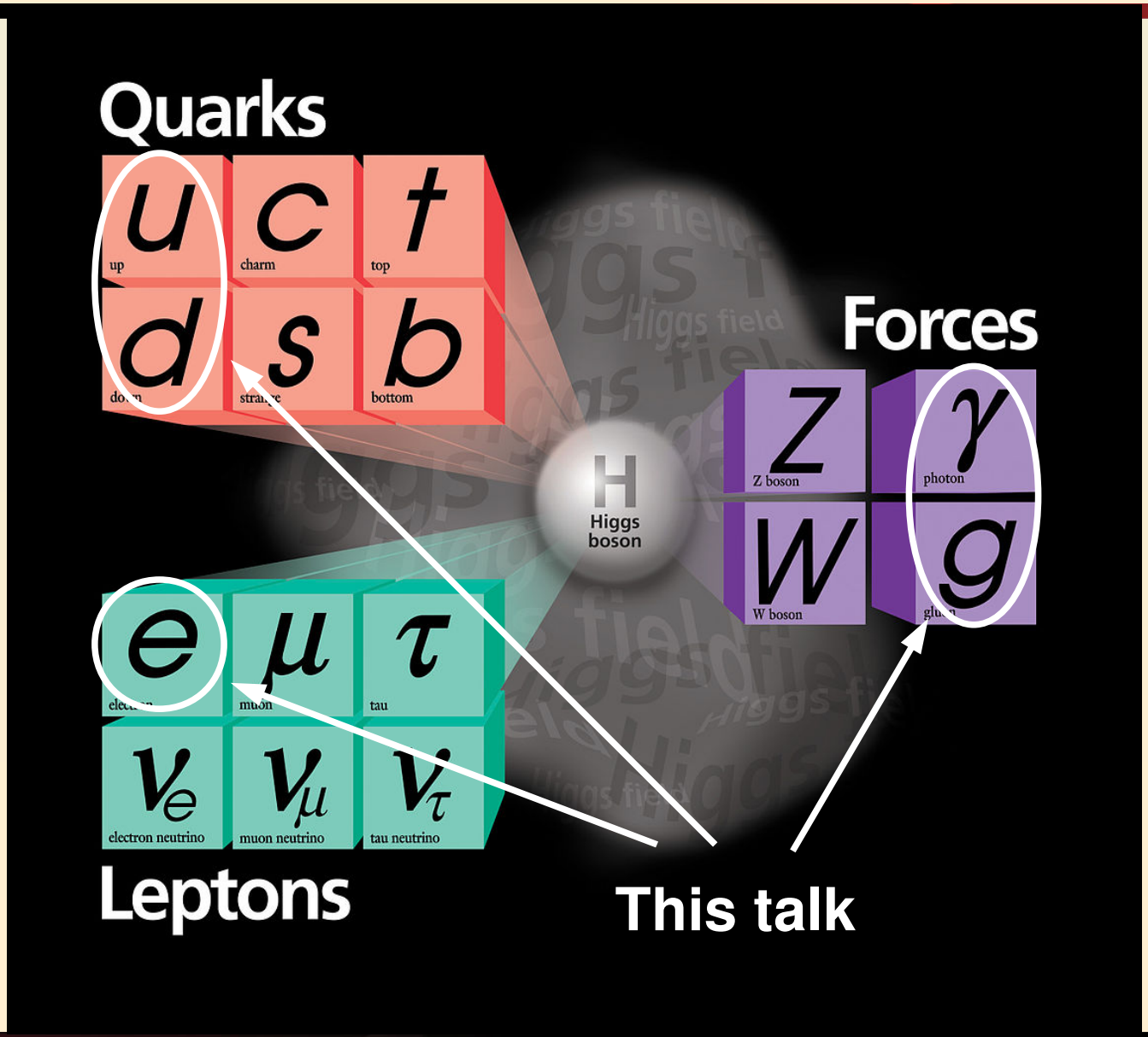
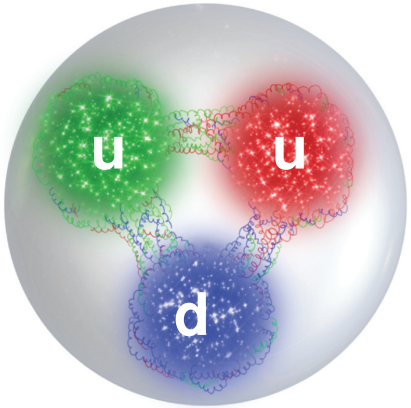


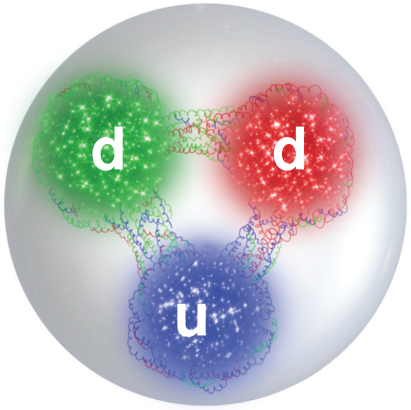
Quark model

Proton



Two “up”
one “down”

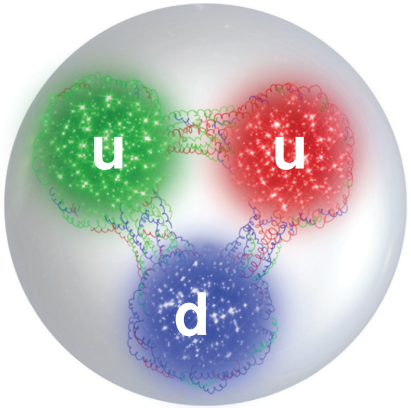
Neutron



Two “down”
one “up”

Quark model

Proton

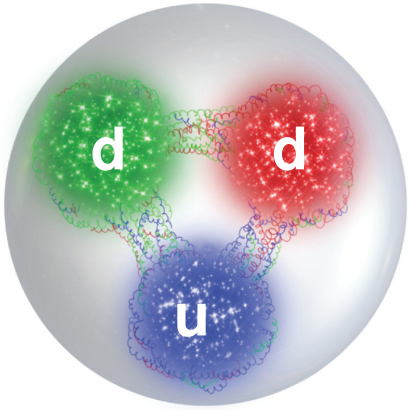


Charge

2/3 + 2/3 -1/3 = +1

Quark charges
are fractional

Neutron

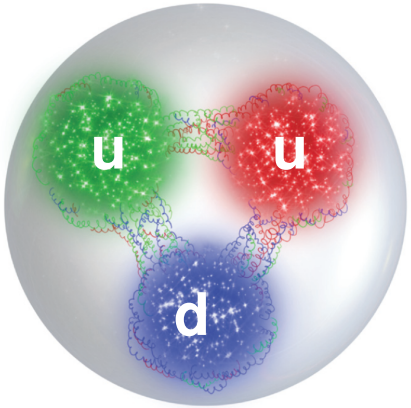


2/3 - 1/3 -1/3 = 0

Quarks are
bound (confined)
by strong interaction
(gluons)

Quark model

Proton



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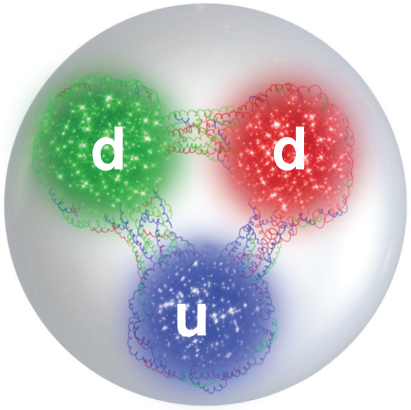


2/3 - 1/3 -1/3 = 0

Quarks are bound (confined) by strong interaction (gluons)

No evidence of free quarks observed directly in experiment

Long distance - quarks are confined in hadrons

Short distance - quarks behave as if they were free

Asymptotic freedom - later in this talk!

Quantum Electro Dynamics and Quantum Chromo Dynamics

QED

Gauge theory U(1)

Force carrier:

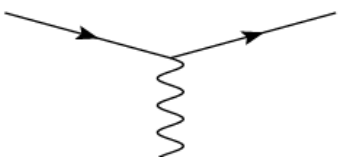
photon (electrically neutral)

electron

positron

Interaction

$$\alpha_{em} \simeq \frac{1}{137}$$



QCD

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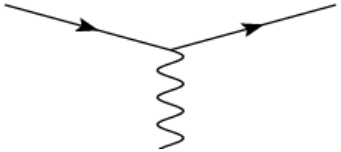

Richard Feynman, Nobel Prize 1965

"for ... fundamental work in quantum electrodynamics"

QCD

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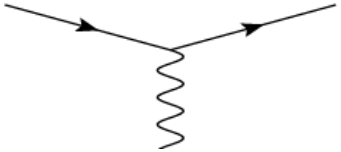

Richard Feynman, Nobel Prize 1965

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QCD

Gauge theory SU(3)

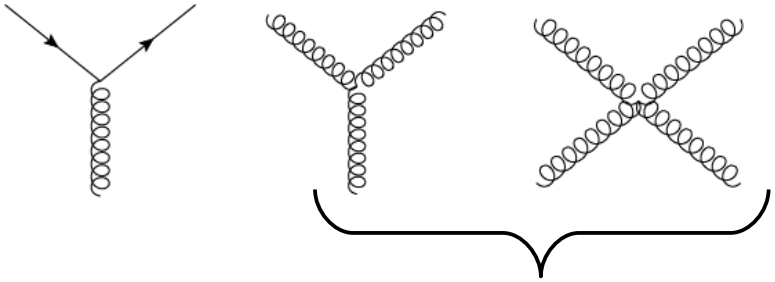
Force carriers:

gluons (carry color)

quark

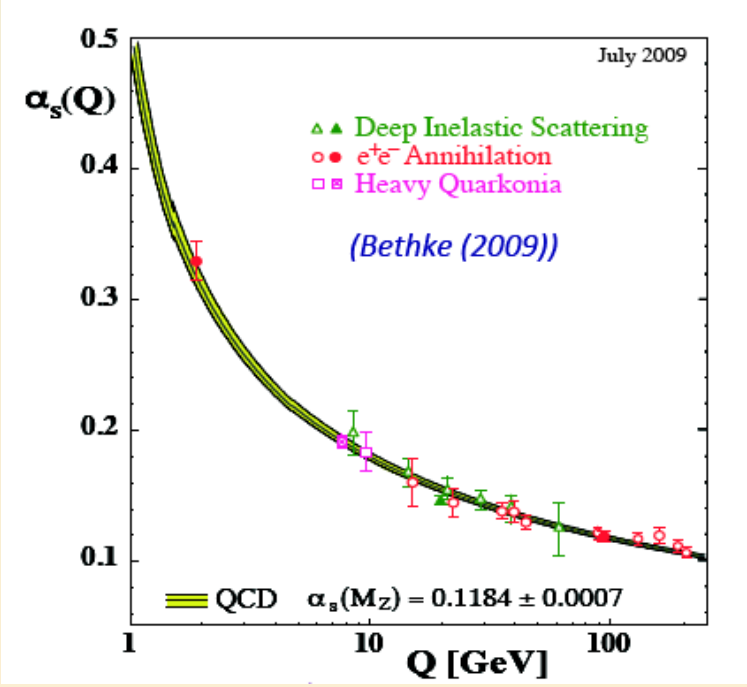
anti-quark

Interaction $\alpha_s \sim 0.1$ strong



Gluons interact with each other - non abelian theory

Asymptotic freedom



"Long" DISTANCE "short"

The coupling depends on the scale – consequence of renormalizability of the theory

At short distances quarks behave as if they were almost free particles!

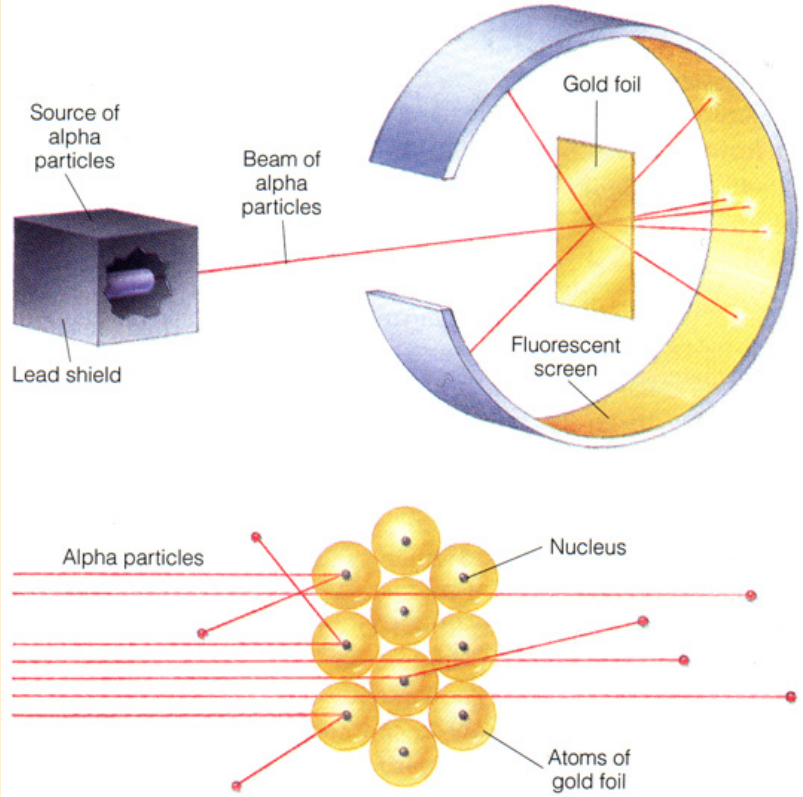
"for the discovery of asymptotic freedom in the theory of the strong interaction"

Gross, Politzer, Wilczek, Nobel Prize 2004

Scattering as the method of study

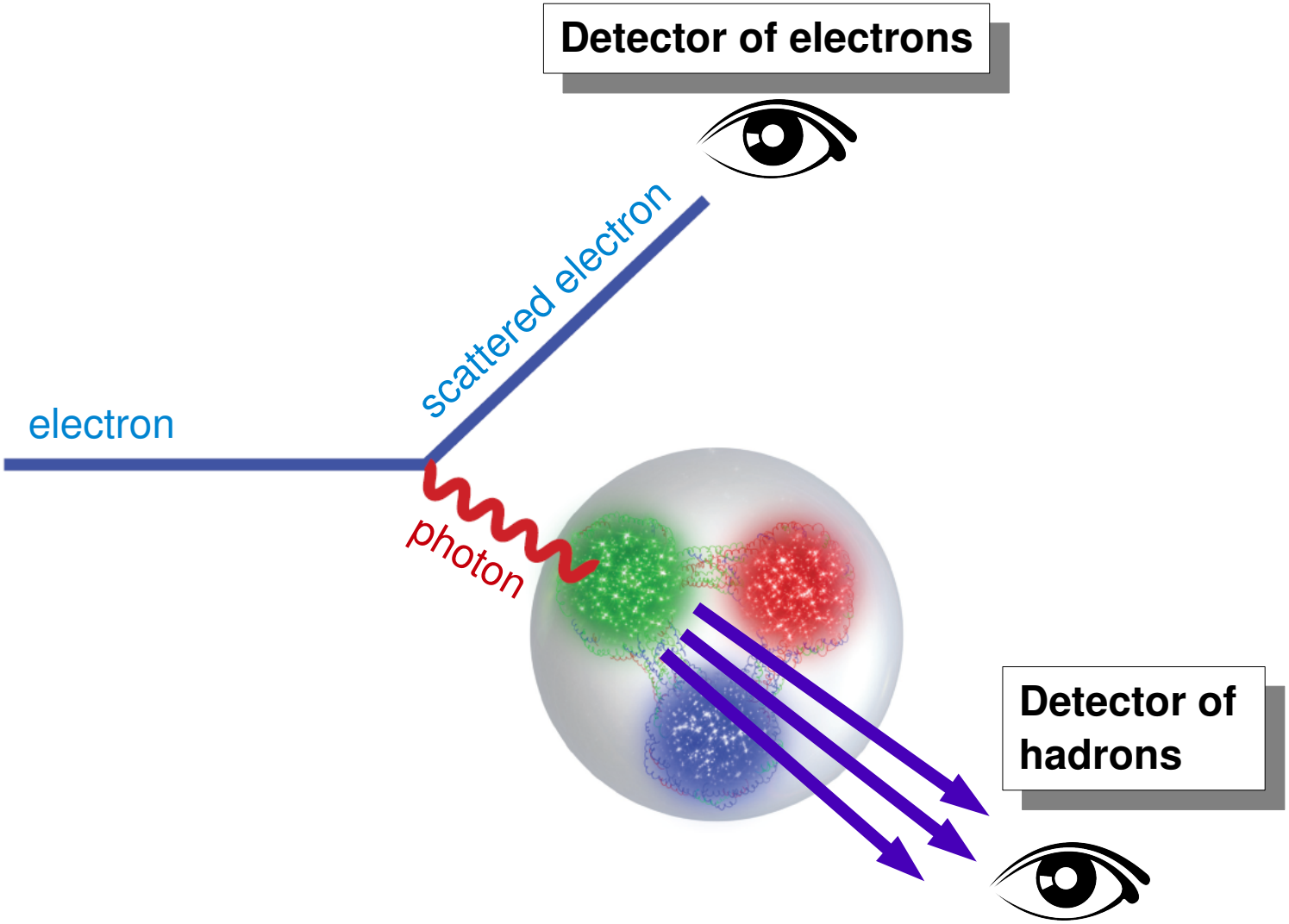
"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"

Ernest Rutherthord, Nobel Prize 1908



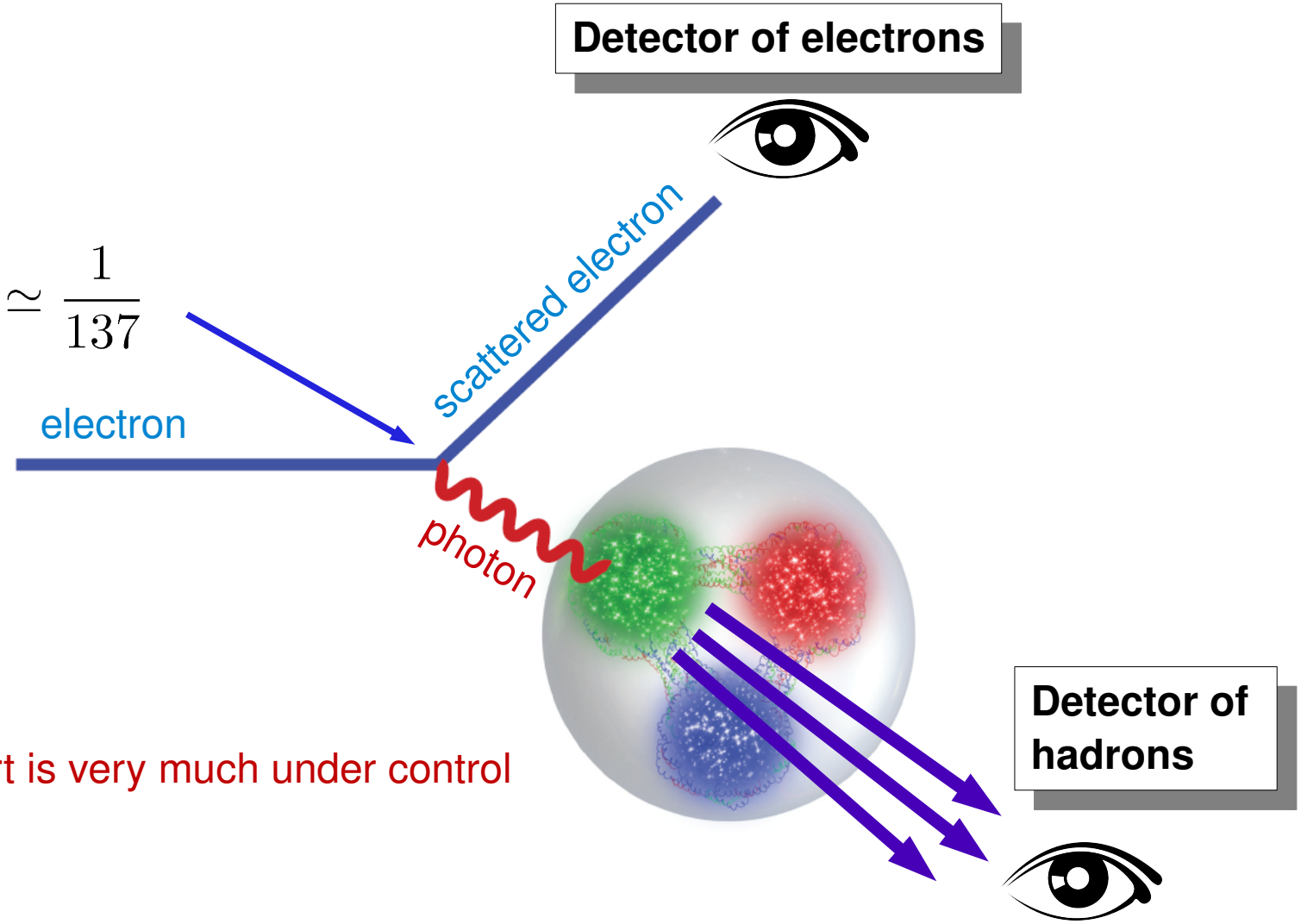
1911

Electron Scattering



Electron Scattering

$$\alpha_{em} \simeq \frac{1}{137}$$

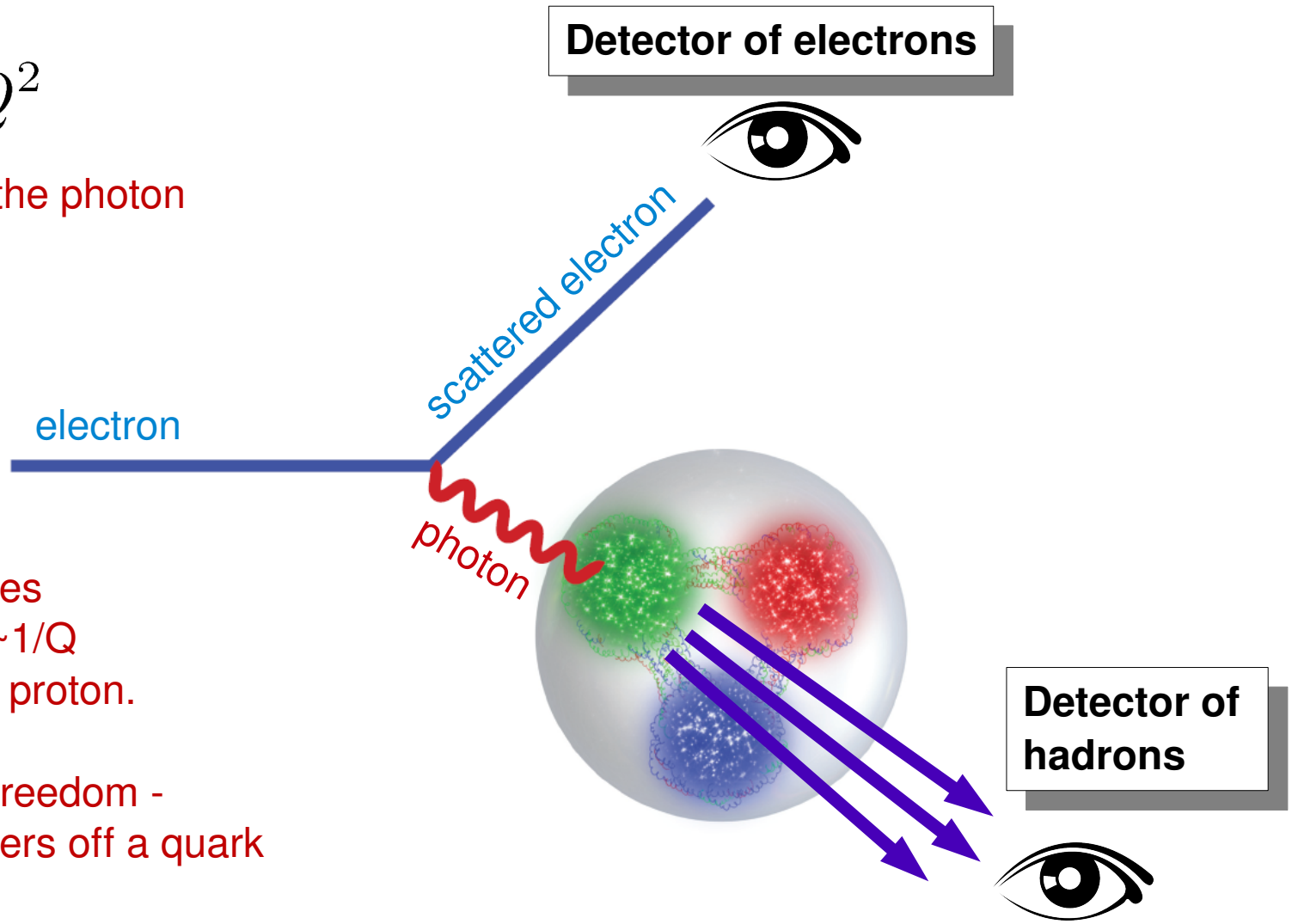


Electron part is very much under control

Electron Scattering

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

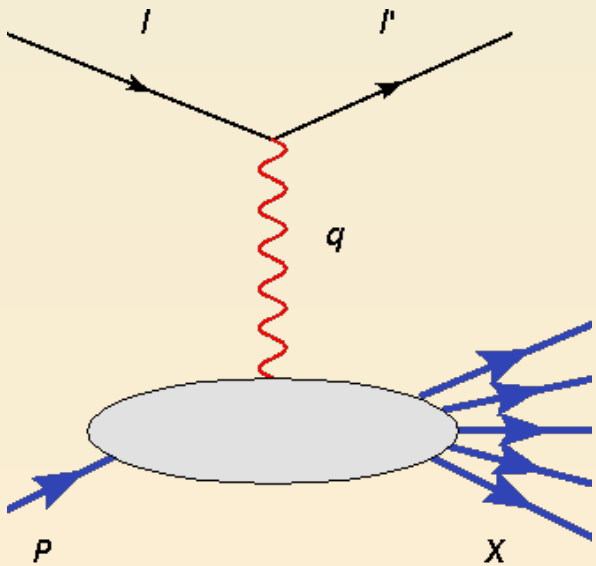
Virtuality of the photon



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

Asymptotic freedom - photon scatters off a quark

Electron Scattering: interpretation



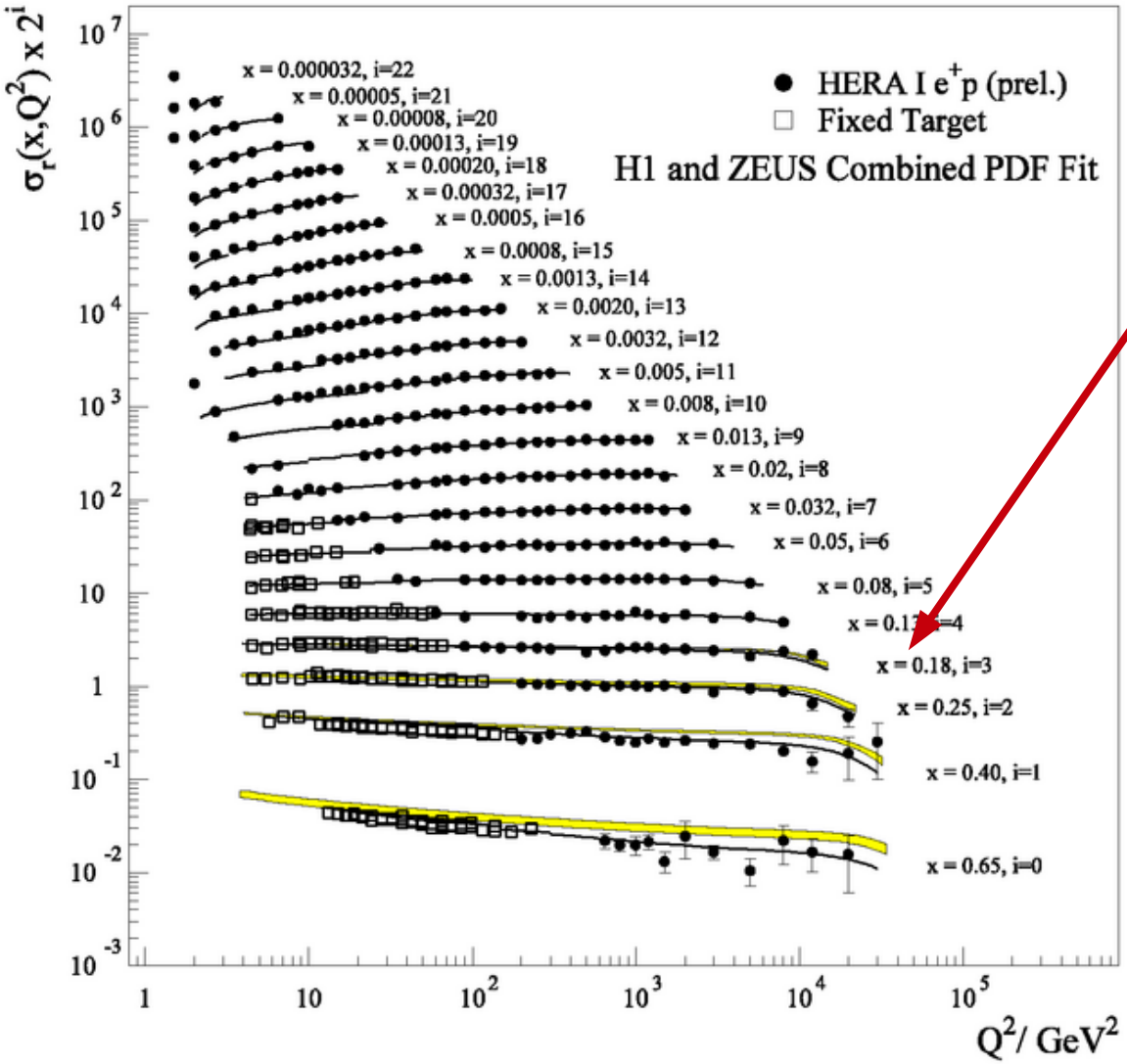
Electromagnetic probe resolves a quark or anti-quark with momentum **k** inside of the proton of momentum **P**.

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

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

JSA
Jefferson Lab

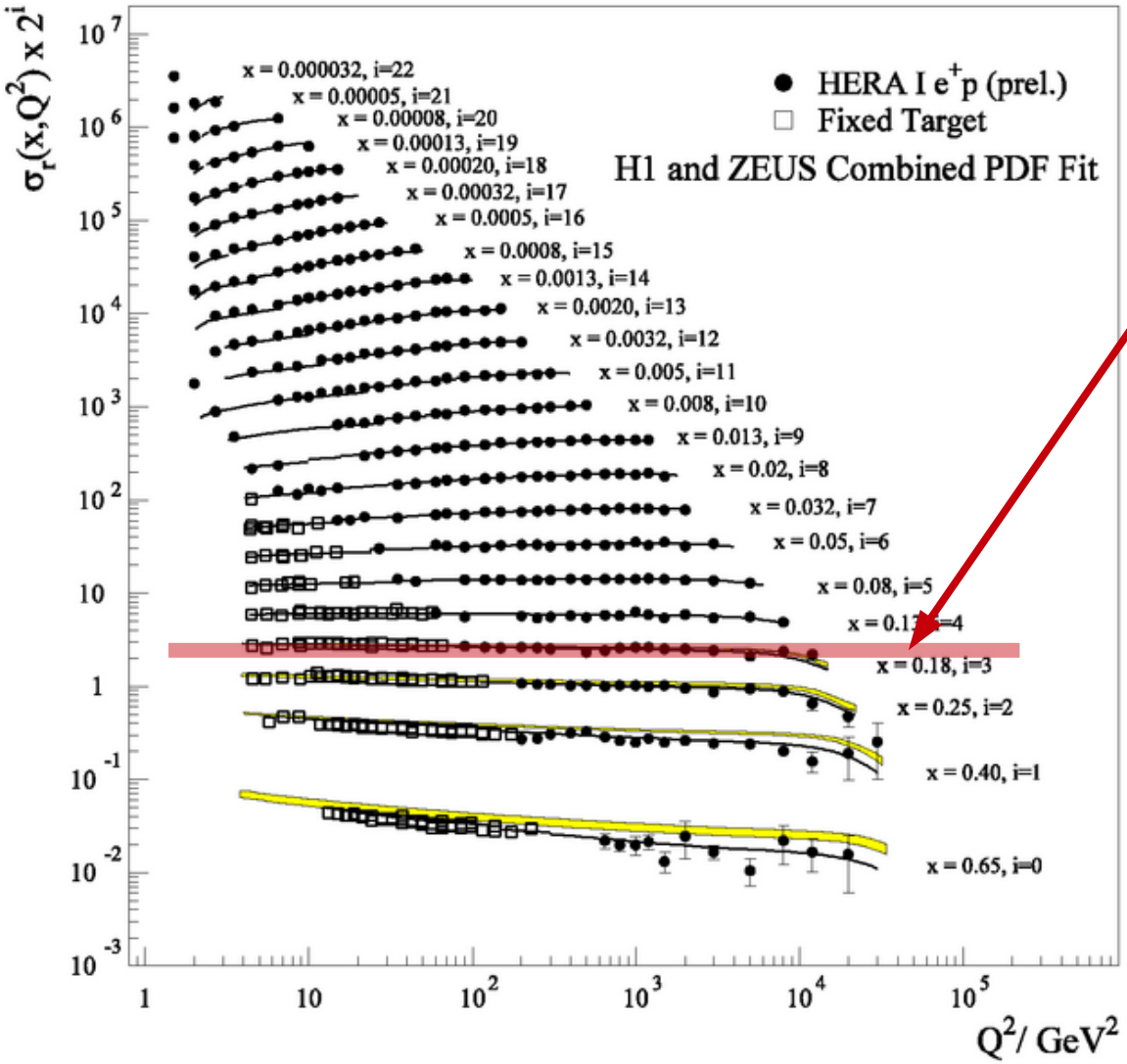
Electron Scattering: interpretation



Experimental data

$$x_{Bj} = 0.18$$

Electron Scattering: interpretation

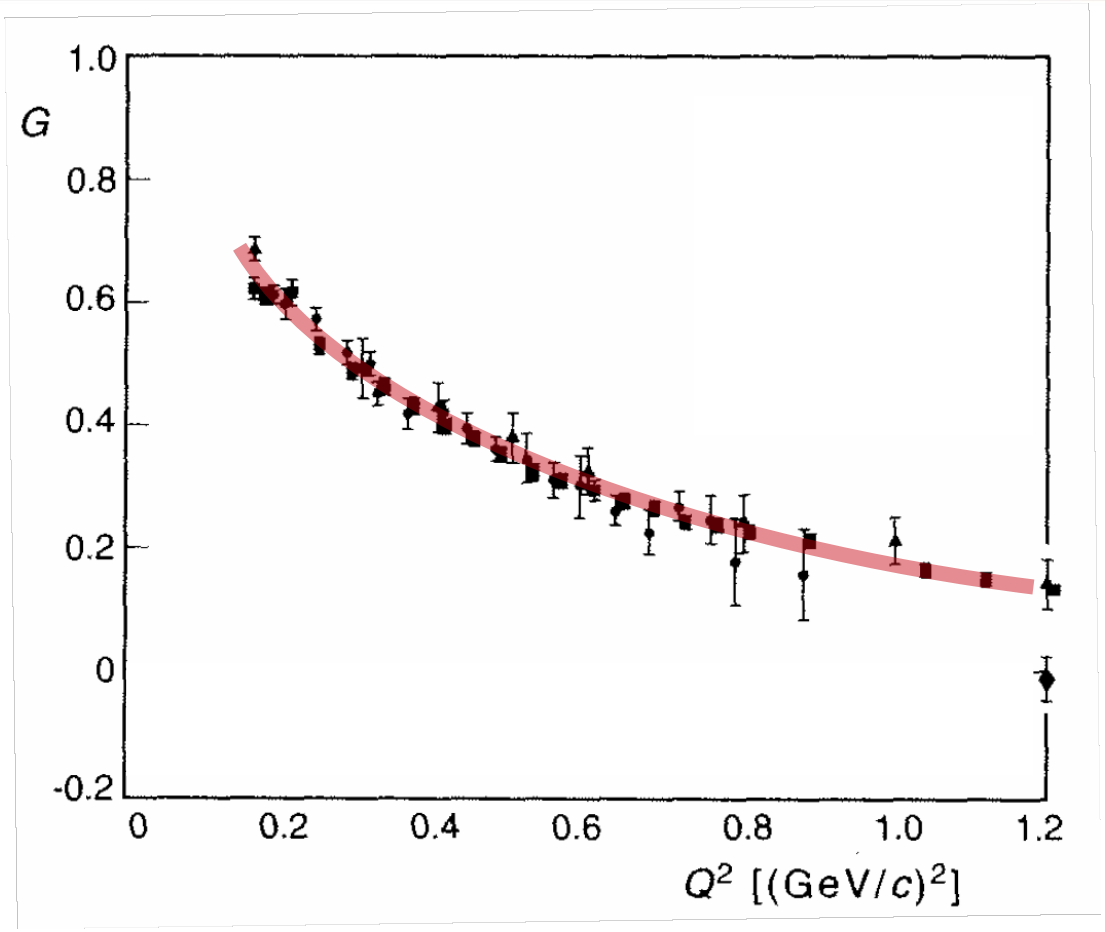


Experimental data

$$x_{Bj} = 0.18$$

Behaviour is almost flat
– **quarks are pointlike**

Electron Scattering: interpretation

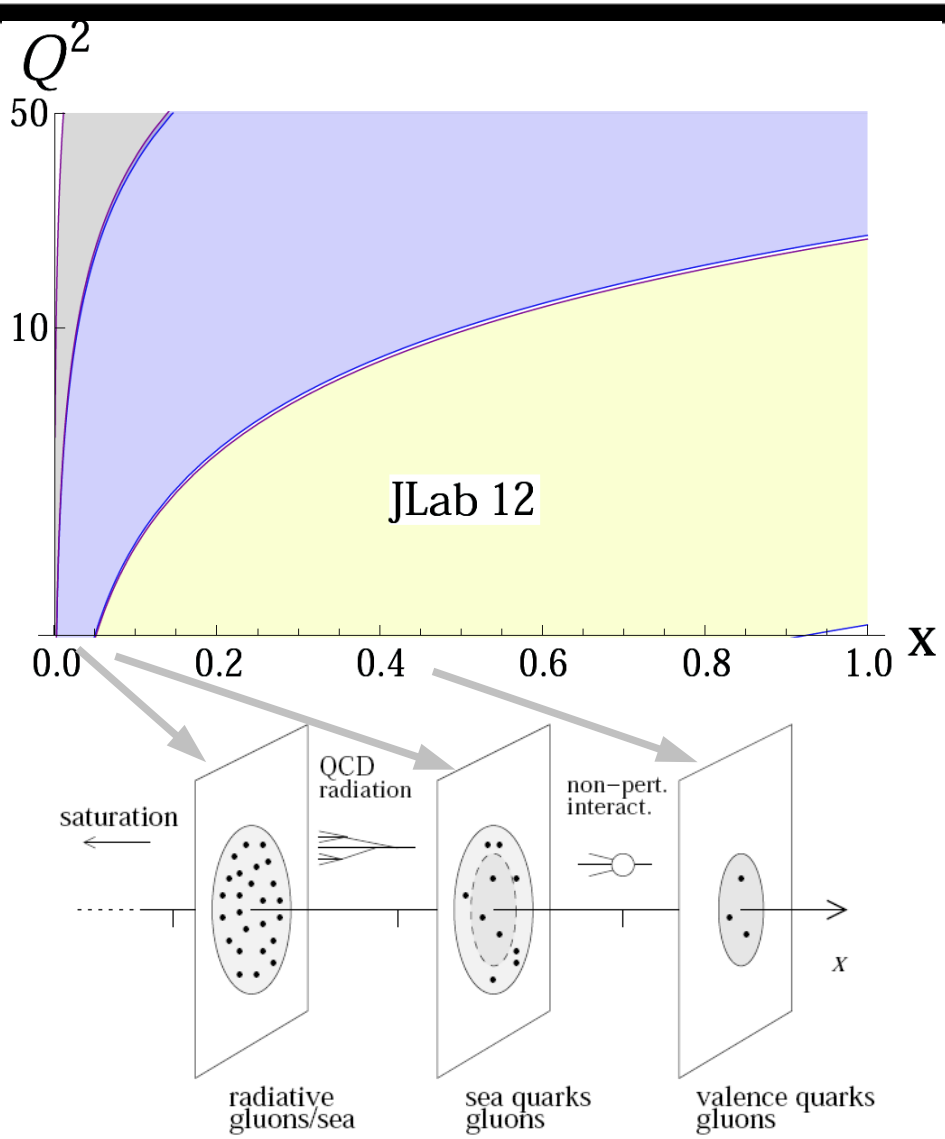


Unlike the proton itself:

Proton size ~ **1 fm**

What do we want to learn about hadron structure
in the new millenium?

Nucleon landscape



Nucleon is a many body dynamical system of quarks and gluons

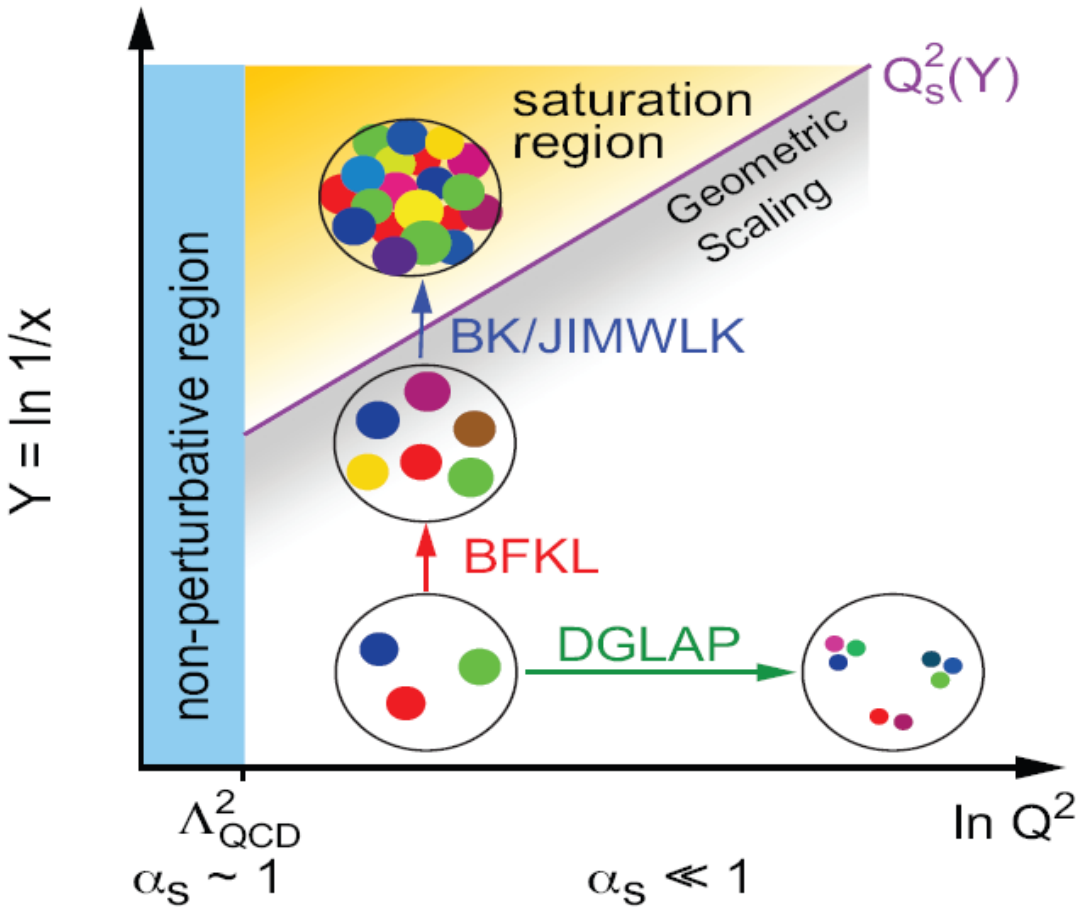
Changing x we probe different aspects of nucleon wave function

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**

Nucleon landscape

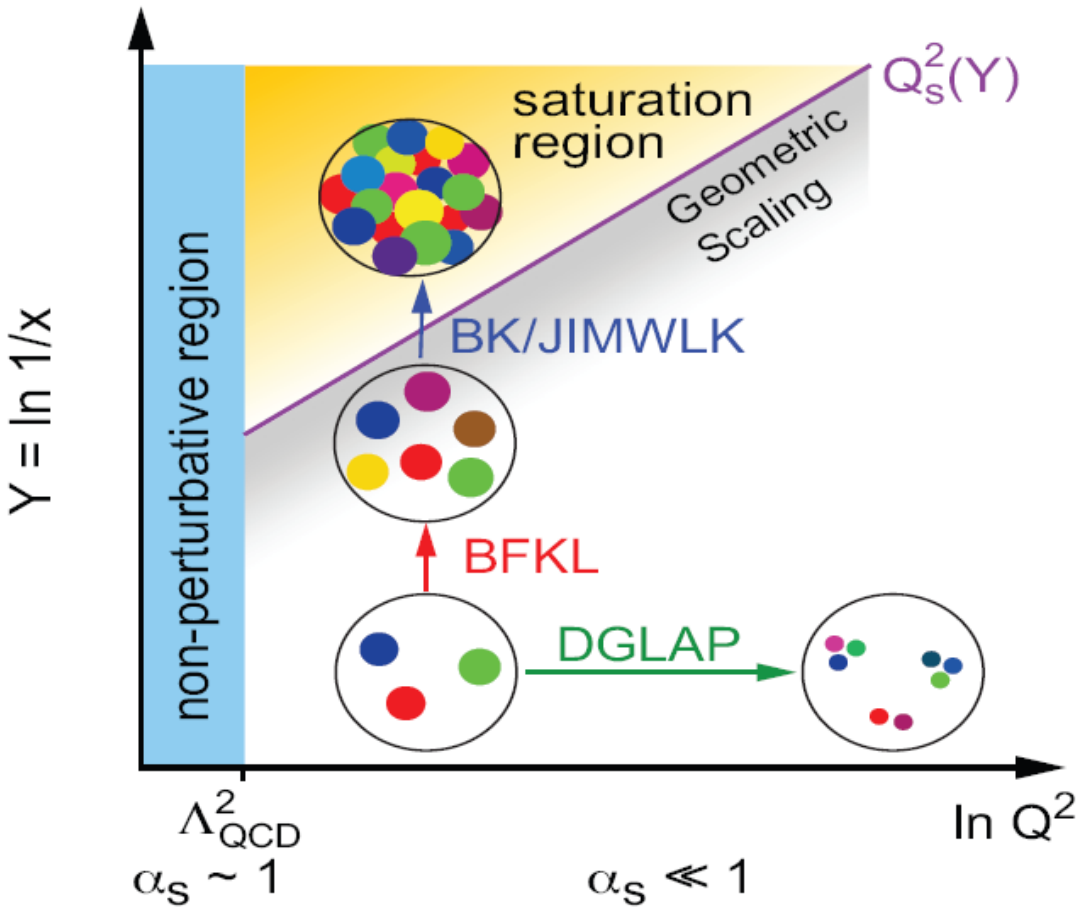


Virtual photon serves as a microscopic probe of the nucleon:

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

Ian Balitsky

Plot from EIC whitepaper

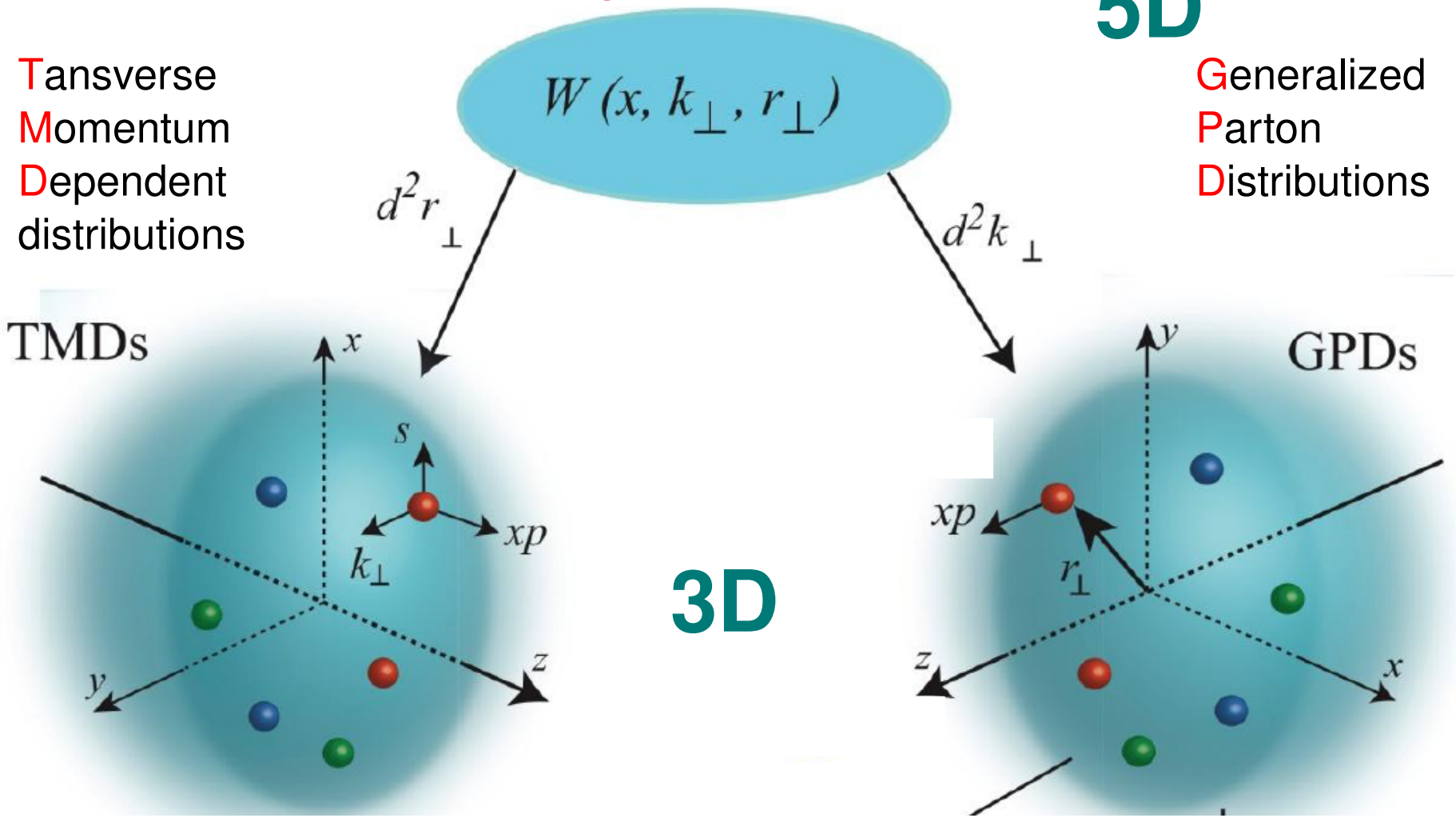
Unified View of Nucleon Structure

Wigner function

5D

Tansverse
Momentum
Dependent
distributions

Generalized
Parton
Distributions



Unified View of Nucleon Structure

Wigner function

$$W(x, k_\perp, r_\perp)$$

$d^2 r_\perp$

$d^2 k_\perp$

5D

Generalized
Parton
Distributions

Tansverse
Momentum
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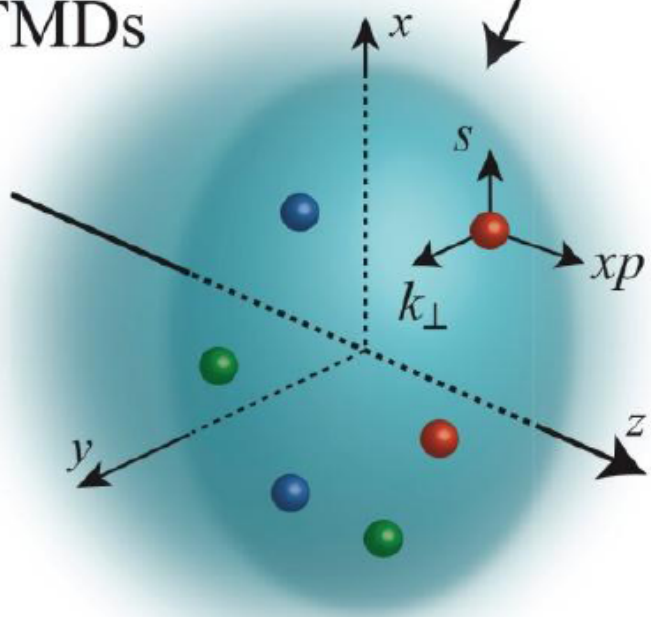
TMDs

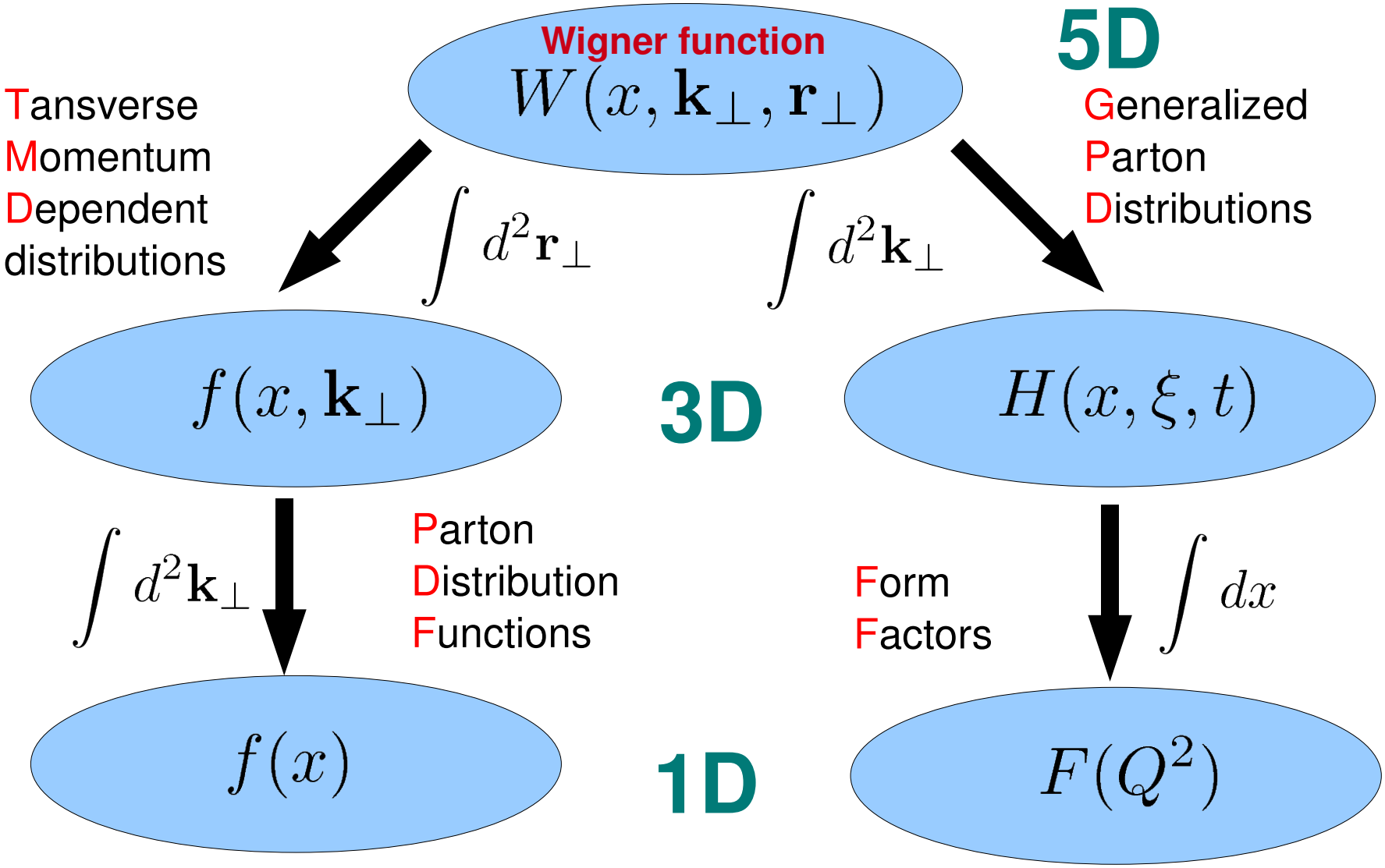


3D

Anatoly Radyushkin

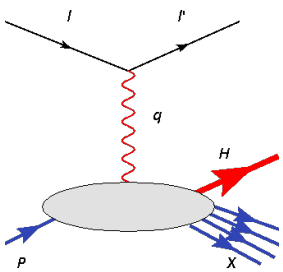
GPDs

Unified View of Nucleon Structure



Unified View of Nucleon Structure

TMD

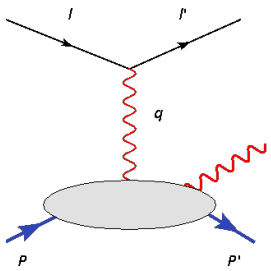


Wigner function

$$W(x, \mathbf{k}_\perp, \mathbf{b}_\perp)$$

5D

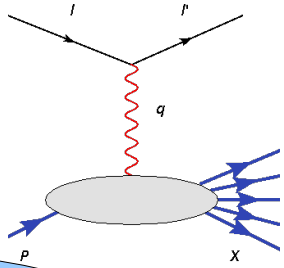
GPD

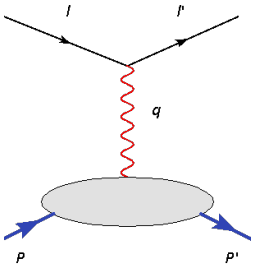


$$f(x, \mathbf{k}_\perp)$$

3D

$$H(x, \xi, t)$$





PDF

FF

$$f(x)$$

1D

$$F(Q^2)$$

Particular processes to study. Polarization is required!

JLab: 21st Century Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation between short-range N-N correlations and the partonic structure of nuclei?
- Can we discover evidence for physics beyond the standard model of particle physics?

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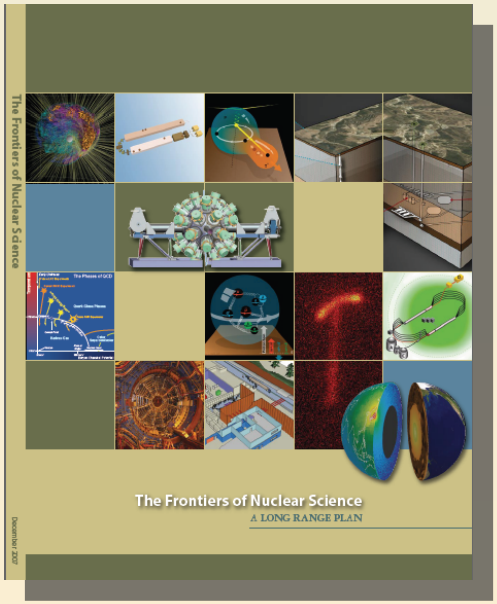
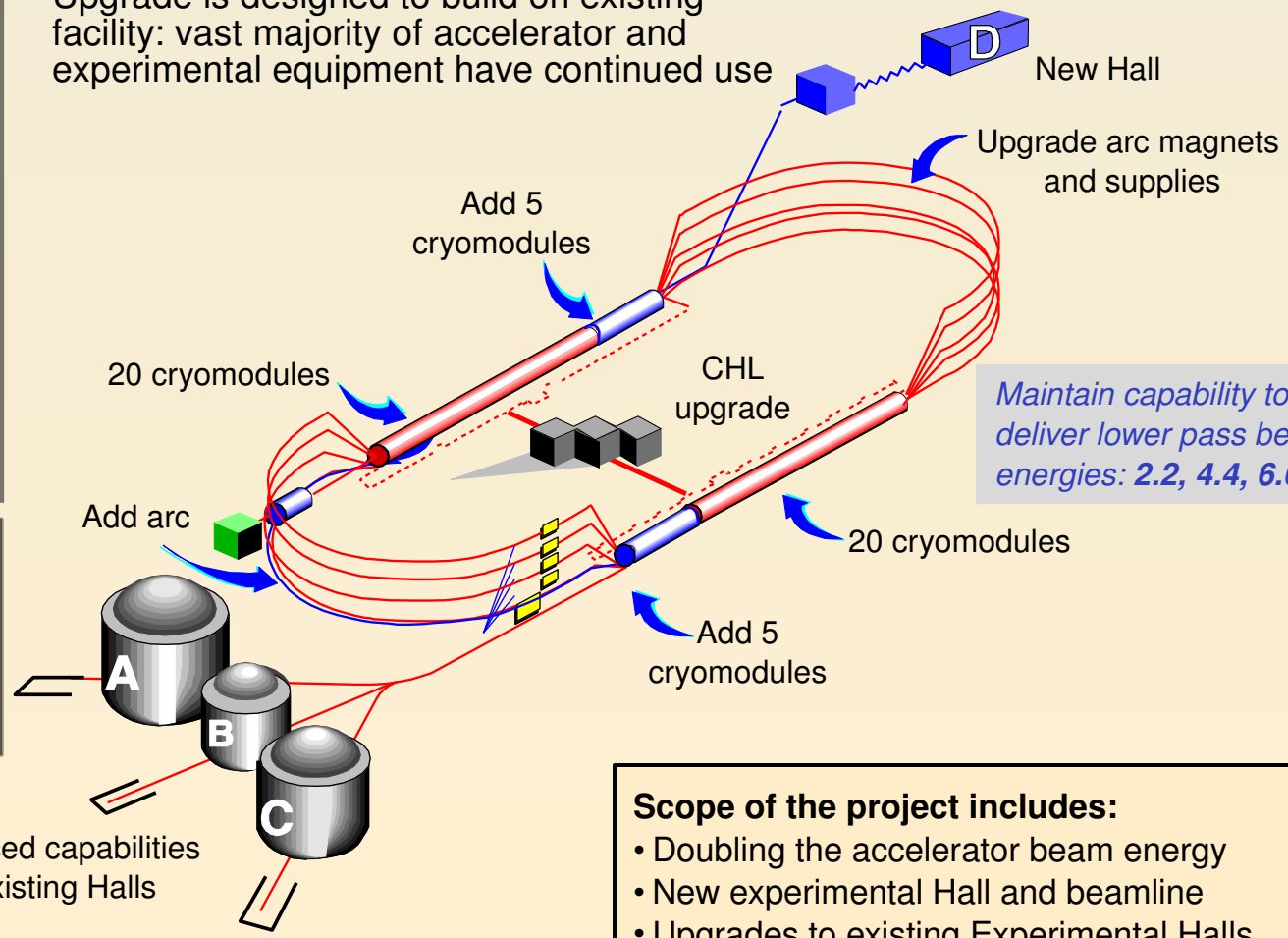
12 GeV Upgrade Project



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 Approved Experiments by Physics Topics

	Hall A	Hall B	Hall C	Hall D	Total
The Hadron Spectra as Probes of QCD (GluEx & heavy baryon and meson spectroscopy)		1		1	2
The Transverse Structure of the Hadrons (elastic and transition form factors)	4	3	2		9
The Longitudinal Structure of the Hadrons (Unpolarized and polarized parton distributions)	2	2	5		9
The 3D Structure of the Hadrons (GPDs and TMDs)	5	10	3		18
Hadrons and Cold Nuclear Matter	3	2	6		11
Low-Energy Tests of the Standard Model and Fundamental Symmetries	2			1	3
Total	**16**	**18**	**16**	**2**	**52**

Program Advisory Committee in the period 2006 – 2011 approved 52 experiments

12 GeV Approved Experiments by Physics Topics

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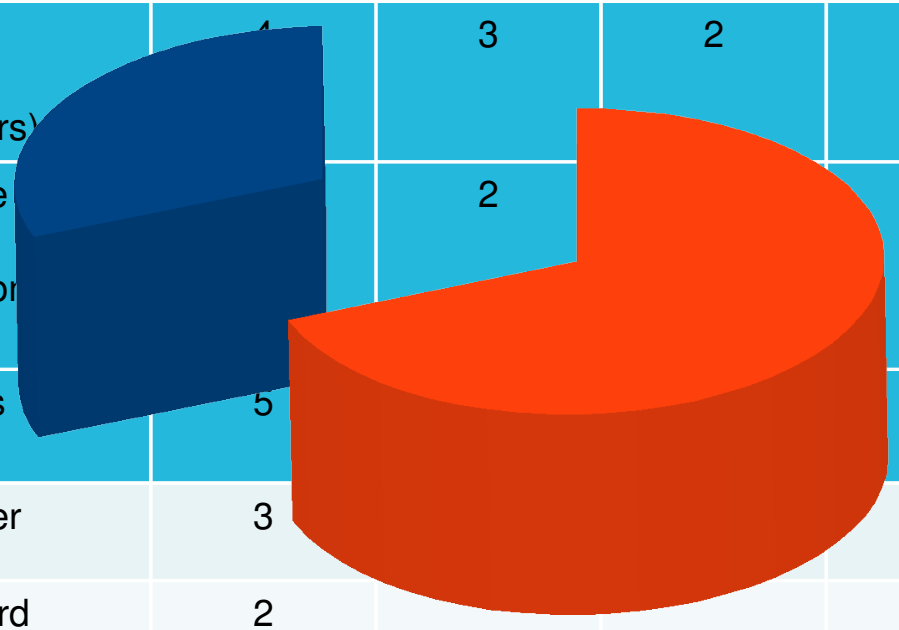
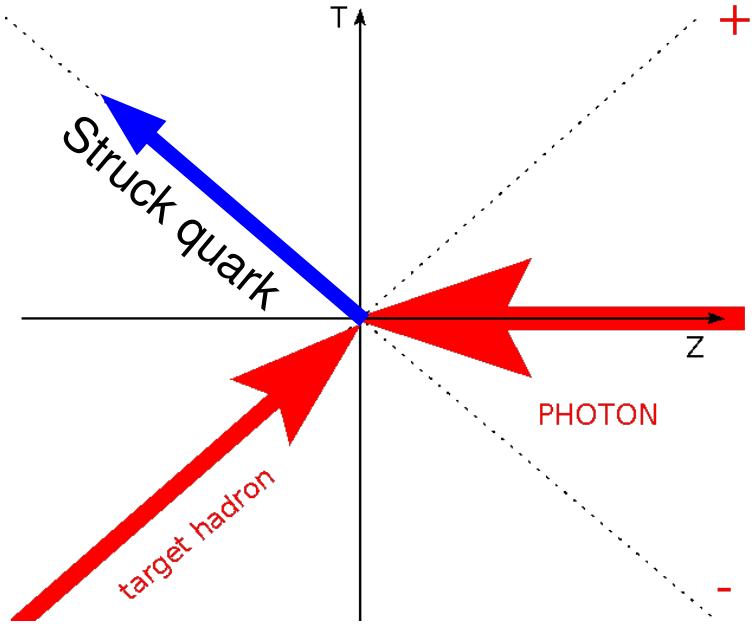


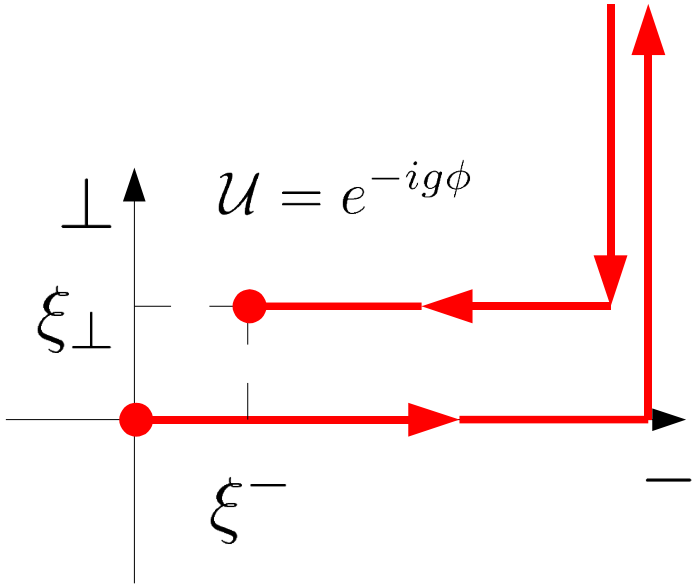
>50% is dedicated to hadron structure!

Transverse Momentum Dependent distributions

Electron Scattering in Infinite Momentum Frame:



Quark passing through the gauge field of the hadron aquires a phase called gauge link

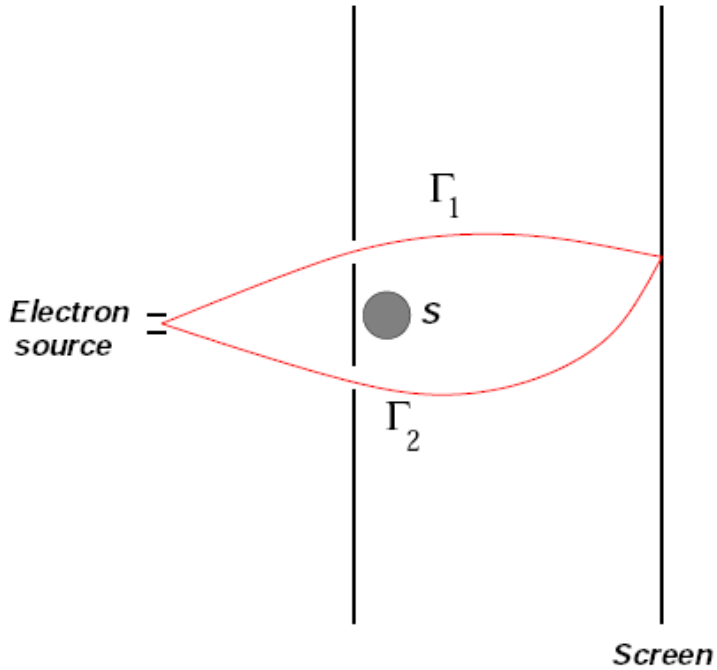


TMDs are sensitive to gauge field!

Ensures gauge invariance of the distribution

Quantum mechanics: Aharonov-Bohm effect

S – solenoid with magnetic field confined inside.
Electrons pass through vector potential
and aquire a phase



$$\mathcal{U} = e^{-ig\phi}$$

Interference pattern is observed on the screen

News about the structure

Both proton and quarks are so called spin-½ particles

Quarks are confined inside an extended proton and move – the motion creates Orbital Angular Momentum

Can this motion be correlated with the spin of the proton?

Yes, it can!

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

Correlation of the spin and motion of the quarks

Yes, it can!

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

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.

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: $S_T = (0, 1)$

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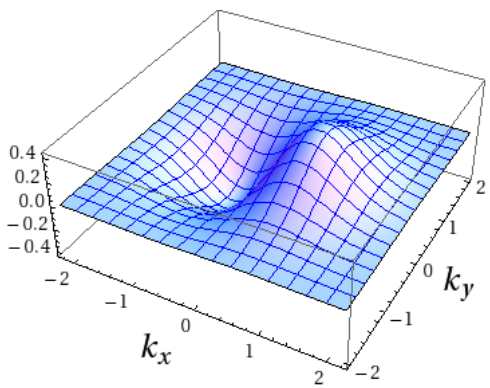
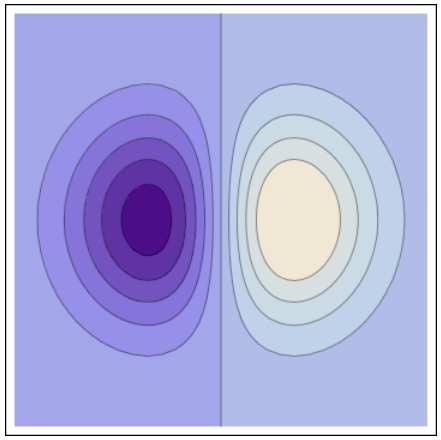
This is called “dipole” deformation.





Yes, it can!

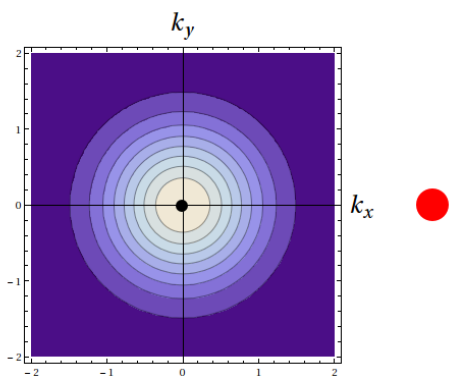
$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_x}}{M}$$

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

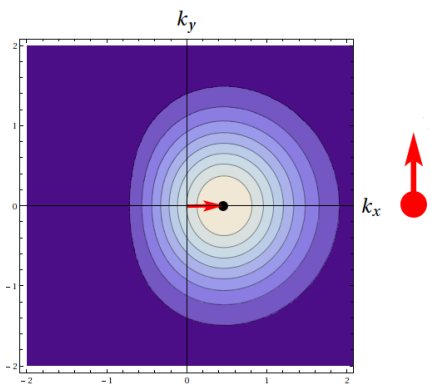
Deformation in momentum space is: $x \cdot f(x^2 + y^2)$

This is called “dipole” deformation.

No correlation:



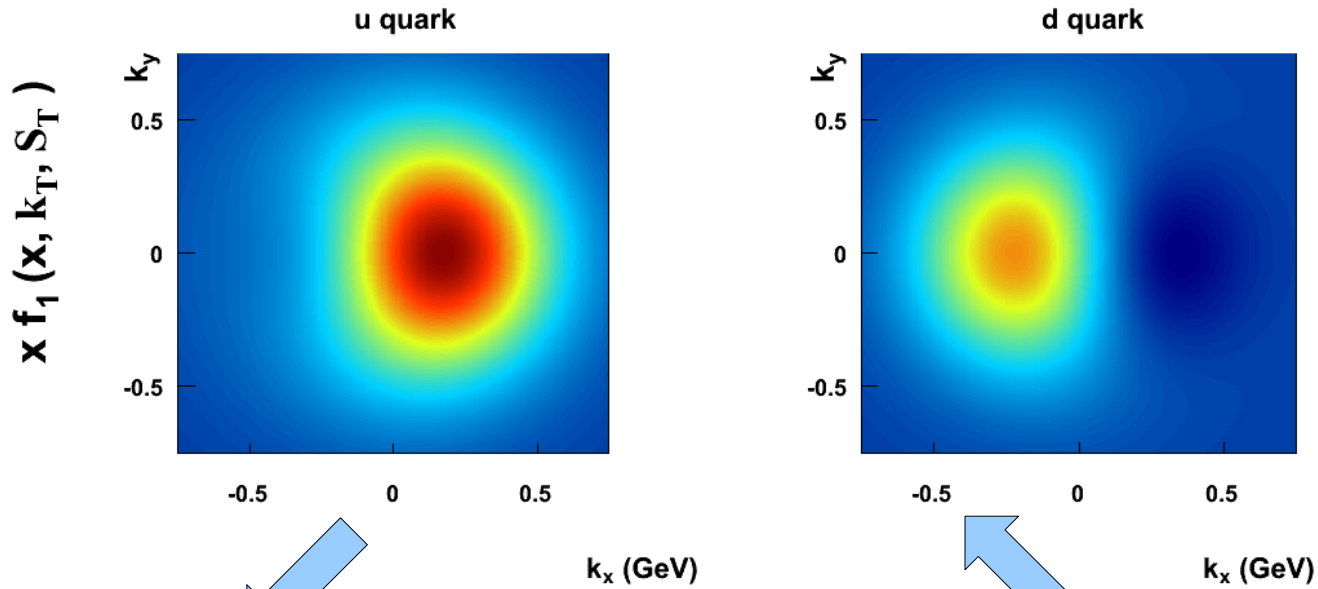
Correlation:



How do we extract/measure all this?

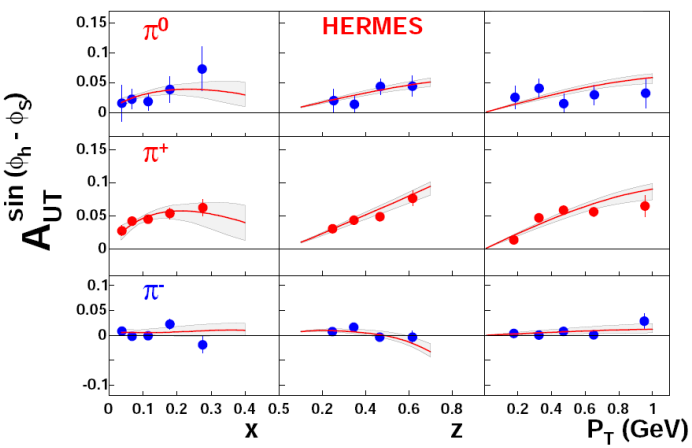
Tomographic scan of the nucleon

Theory



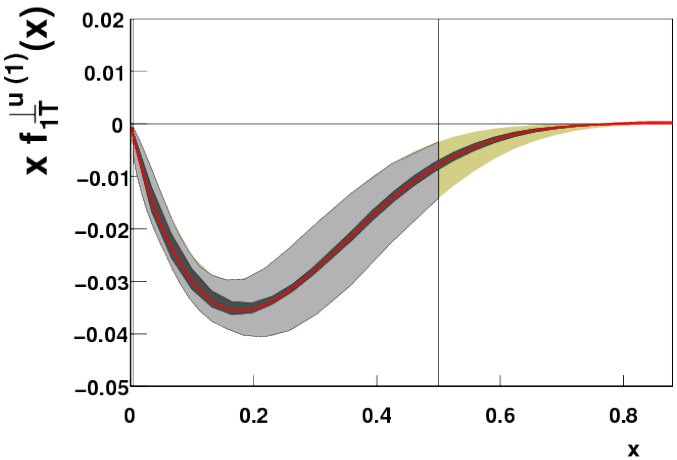
AP 2012

Measurement

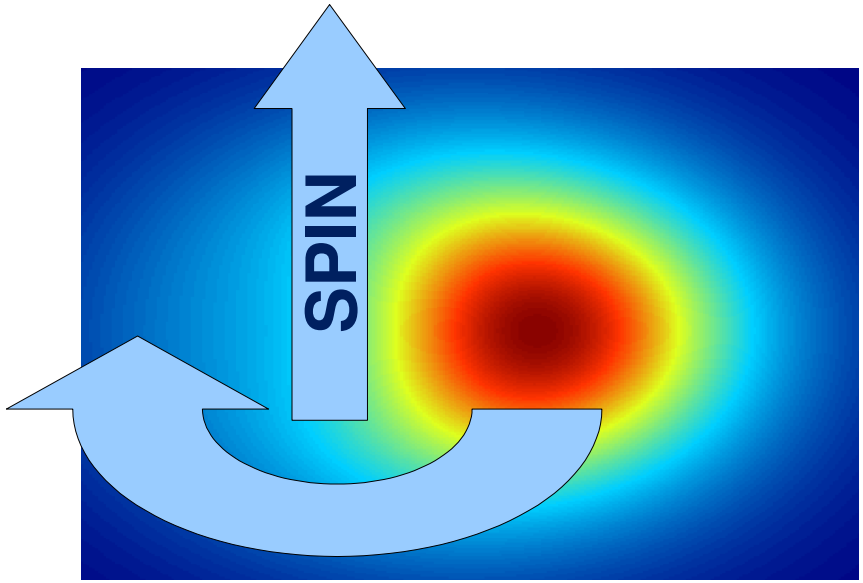


Global analysis of the data

Results



Tomographic scan of the nucleon



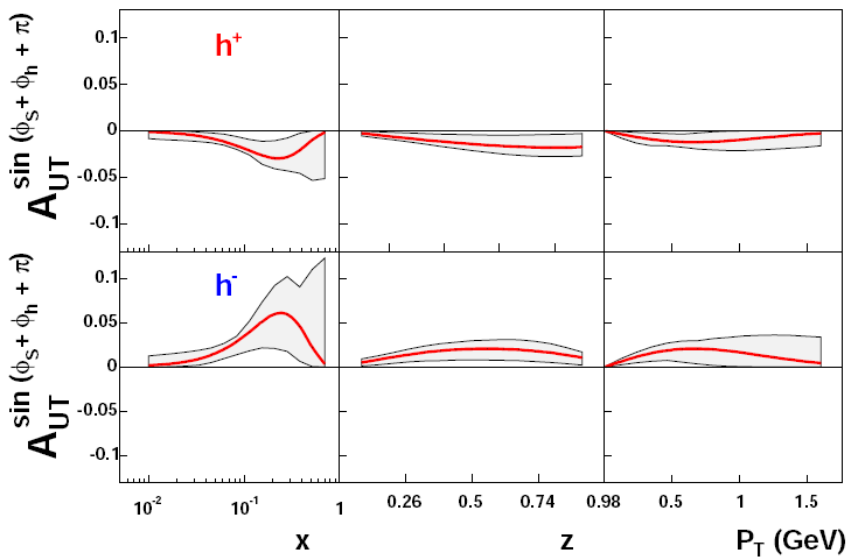
Internal motion of quarks is correlated with the spin of the proton!

Phenomenology

It is extremely important to test our knowledge by **predicting** results of future measurements

Phenomenology

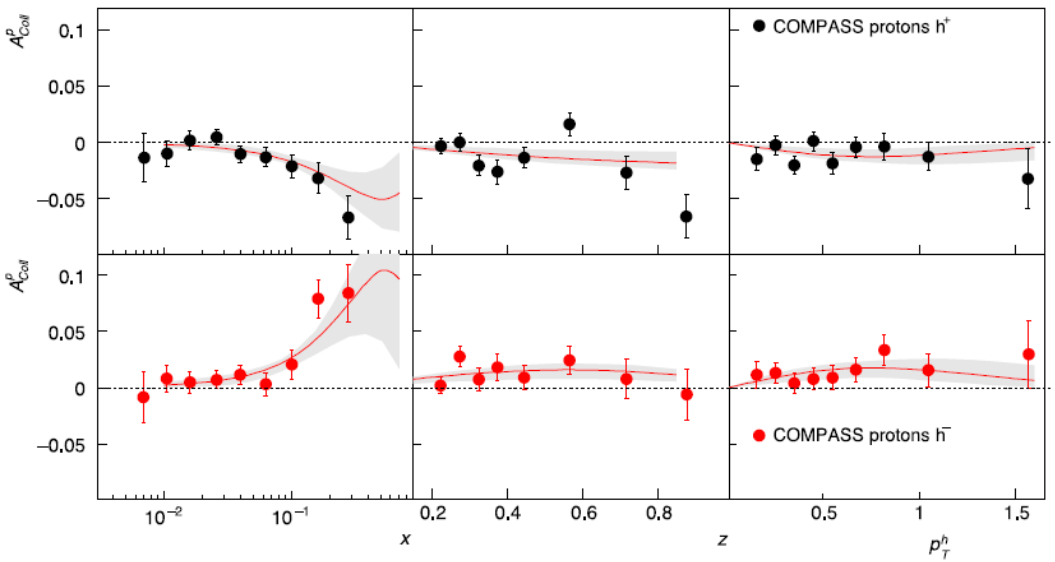
It is extremely important to test our knowledge by **predicting** results of future measurements



Prediction
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, **AP**, Turk
PRD75 (**2007**) 054032

Phenomenology

It is extremely important to test our knowledge by **predicting** results of future measurements

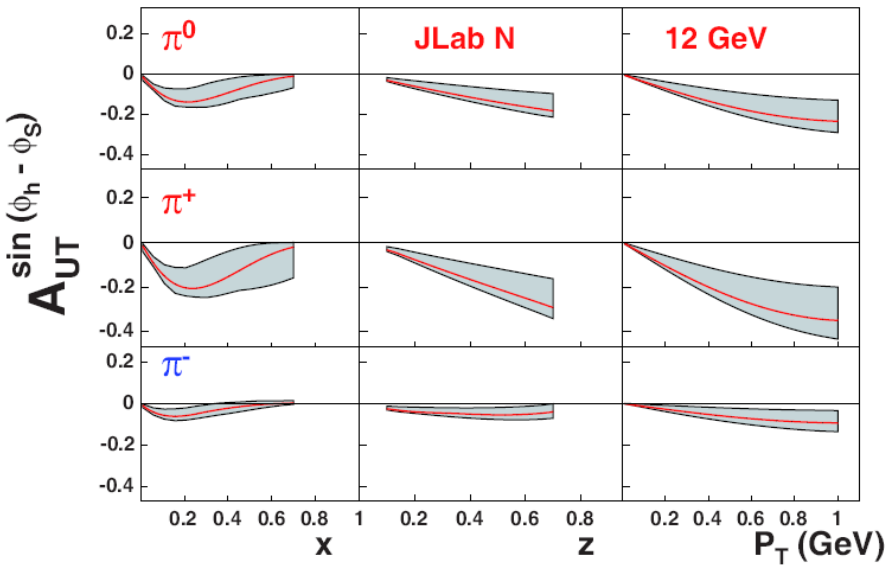


Prediction
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, **AP**, Turk
PRD75 (**2007**) 054032

Measurement
COMPASS Collaboration CERN
PLB717 (**2012**) 376-382

Phenomenology

It is extremely important to test our knowledge by **predicting** results of future measurements

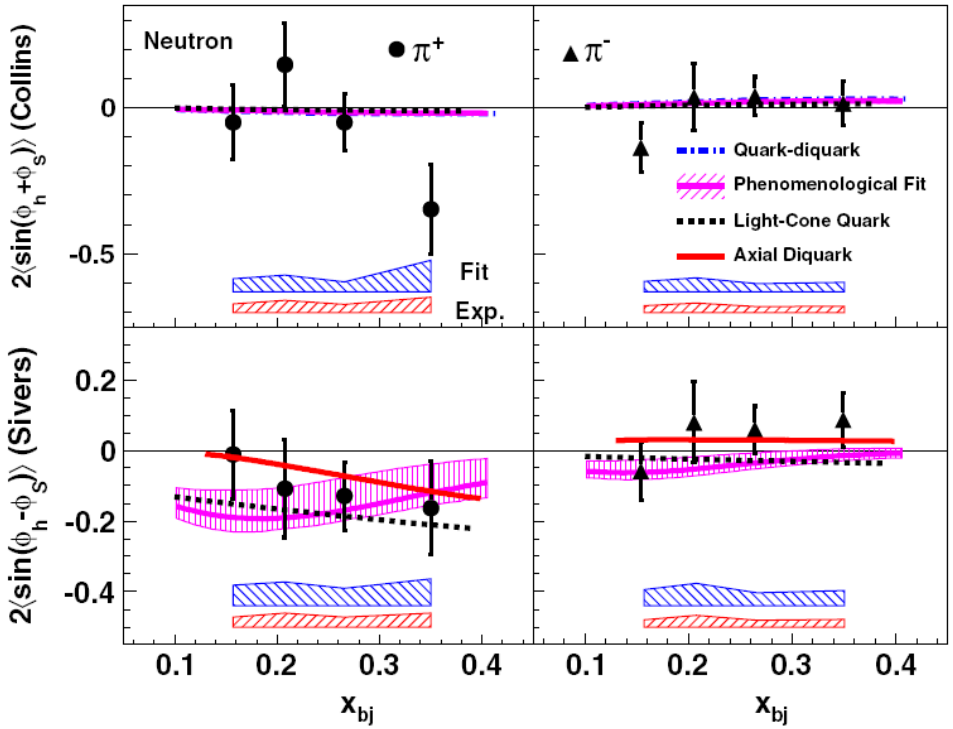


Prediction
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Melis, **AP**, Turk
EPJA 39 (**2009**) 89-100

Jefferson Lab

Phenomenology

It is extremely important to test our knowledge by **predicting** results of future measurements



Prediction

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Melis, **AP**, Turk

EPJA 39 (**2009**) 89-100

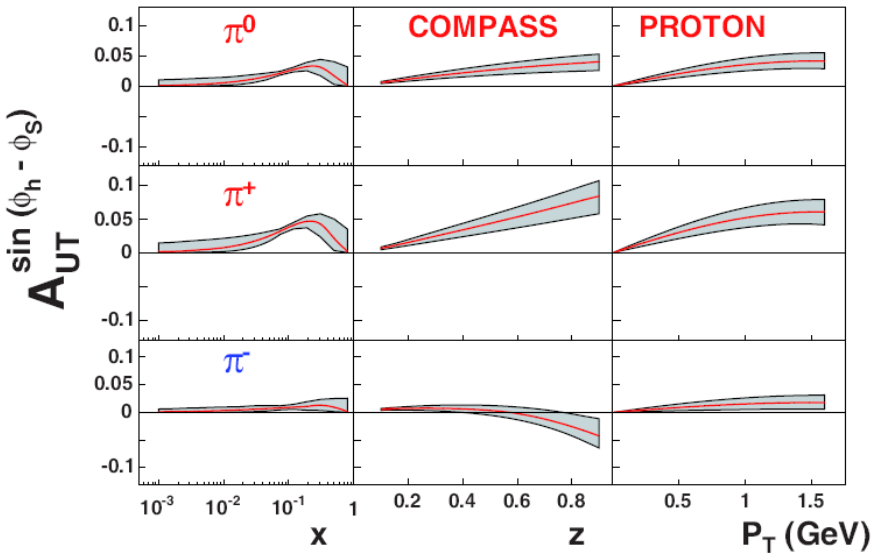
Measurement

X. Qian et all (JLab HALL A Coll)

PRL 107 (**2011**) 072003

Phenomenology

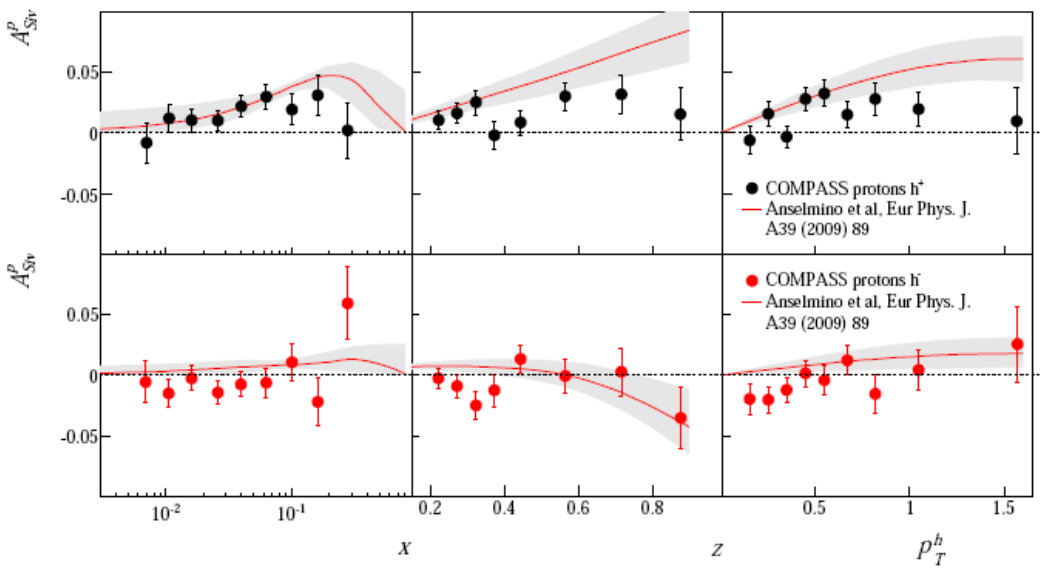
It is extremely important to test our knowledge by **predicting** results of future measurements



Prediction
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Melis, **AP**, Turk
EPJA 39 (**2009**) 89-100

Phenomenology

It is extremely important to test our knowledge by **predicting** results of future measurements

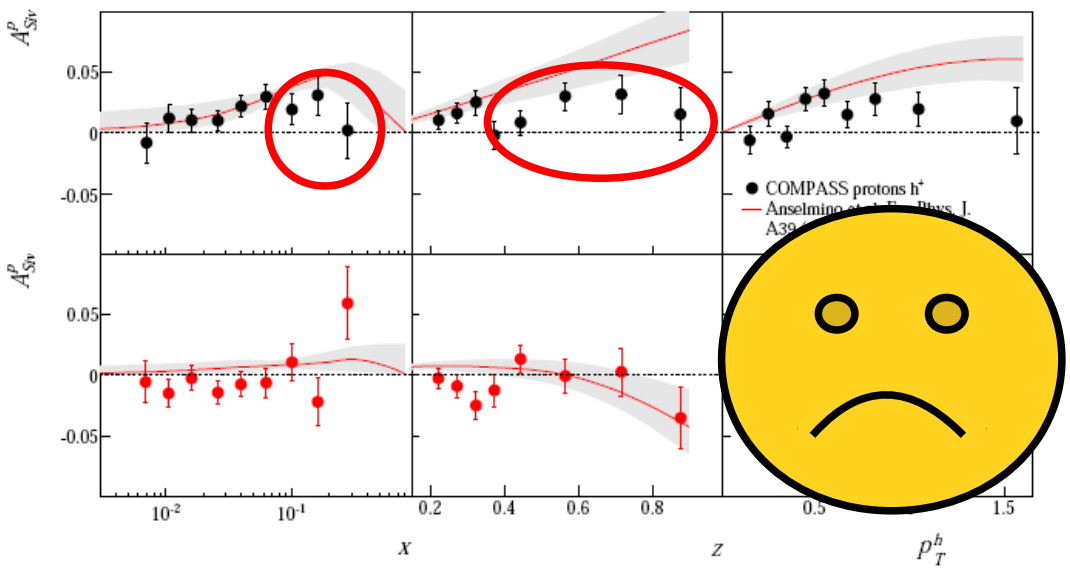


Prediction
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Melis, **AP**, Turk
EPJA 39 (**2009**) 89-100

Measurement
Compass Collaboration
Fizika B20 (**2011**) 93-106

Phenomenology

It is extremely important to test our knowledge by **predicting** results of future measurements

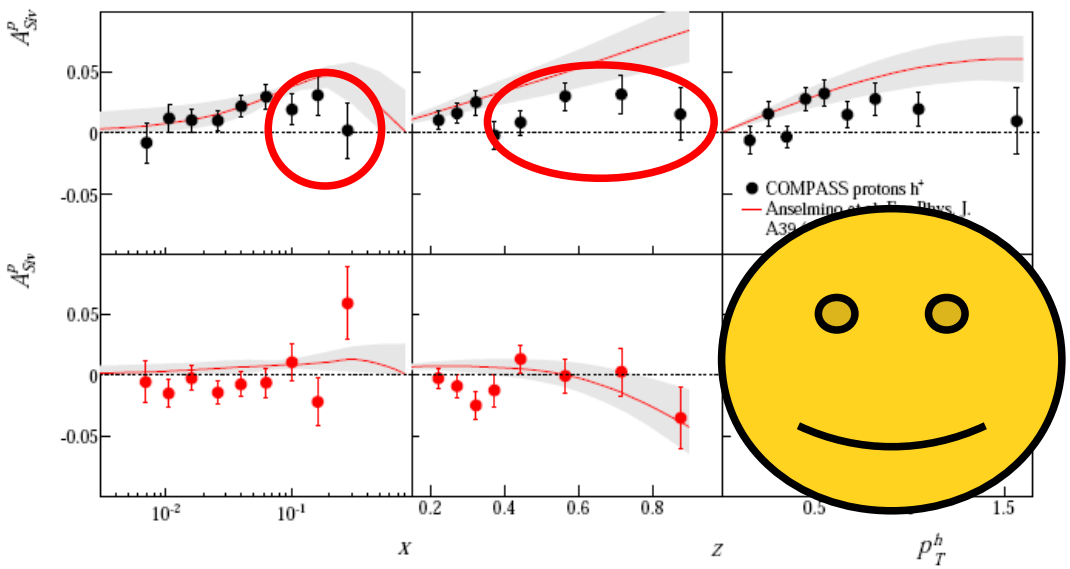


Prediction
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Melis, **AP**, Turk
EPJA 39 (**2009**) 89-100

Measurement
Compass Collaboration
Fizika B20 (**2011**) 93-106

Phenomenology

It is extremely important to test our knowledge by **predicting** results of future measurements



Prediction
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Melis, **AP**, Turk
EPJA 39 (**2009**) 89-100

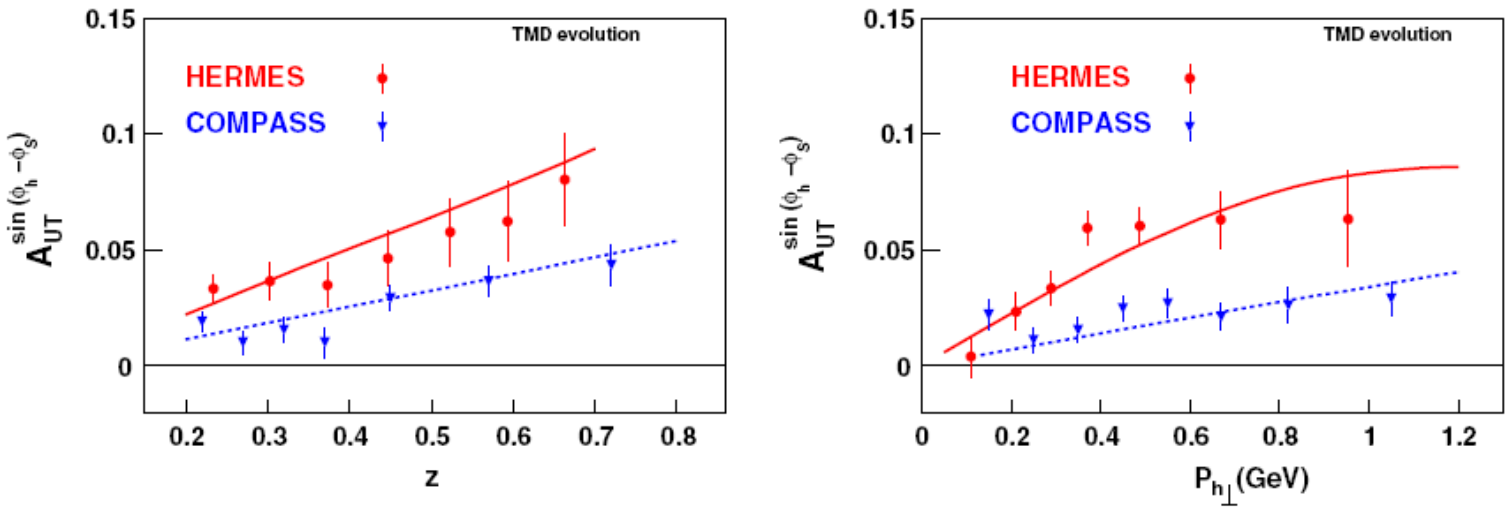
Measurement
Compass Collaboration
Fizika B20 (**2011**) 93-106

This is a chance to learn something new!

Phenomenology

It is extremely important to test our knowledge by **explaining** results of future measurements

TMD evolution taken into account:

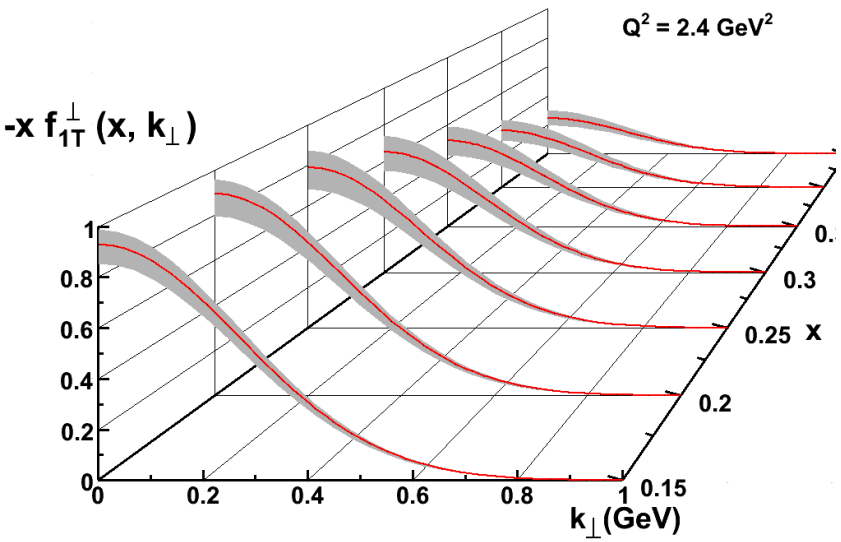


Aybat, **AP**, Rogers, PRL 108 (**2012**) 242003

This is a chance to learn something new!

What will be achieved? Example:

Expected result for tensor charge extraction:



Expected accuracy of TMD profile

1 - JLab 12
2 - Anselmino et al., Nucl.Phys.Proc.Suppl. (2009)
3 - Cloet, Bentz and Thomas, Phys.Lett.B (2008)
4 - Wakamatsu, Phys.Lett.B (2007)
5 - Gockeler et al., Phys.Lett.B (2005)
6 - He and Ji, Phys. Rev. D (1995)
7 - Pasquini et al, Phys. Rev. D (2007)
8 - Gamberg and Goldstein, Phys. Rev. Lett. (2001)
9 - Hecht, Roberts and Schmidt Phys. Rev. C (2001)

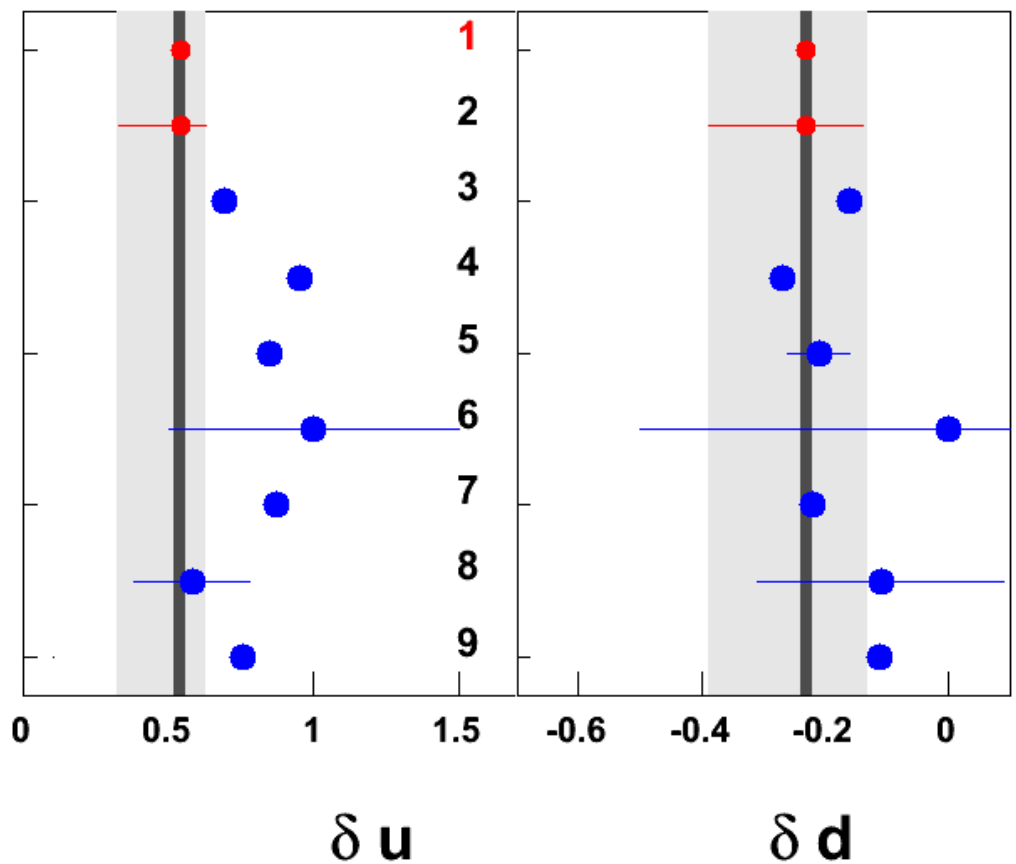
$$\delta q = \int dx\, (h^{q}(x) - h_1^{\bar{q}}(x))$$

$\delta u = 0.54^{+0.09}_{-0.22}$, $\delta d = -0.23^{+0.09}_{-0.16}$

JLab 12 Proton and He^3 targets

$\delta u = 0.54^{+0.02}_{-0.02}$, $\delta d = -0.23^{+0.01}_{-0.01}$

Statistical errors only



A. Prokudin (2012) contribution
To JLab12 white paper

What will be achieved? Example:

Expected result for tensor charge extraction:

1 - JLab 12
2 - Anselmino et al., Nucl.Phys.Proc.Suppl. (2009)
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5 - Gockeler et al., Phys.Lett.B (2005)
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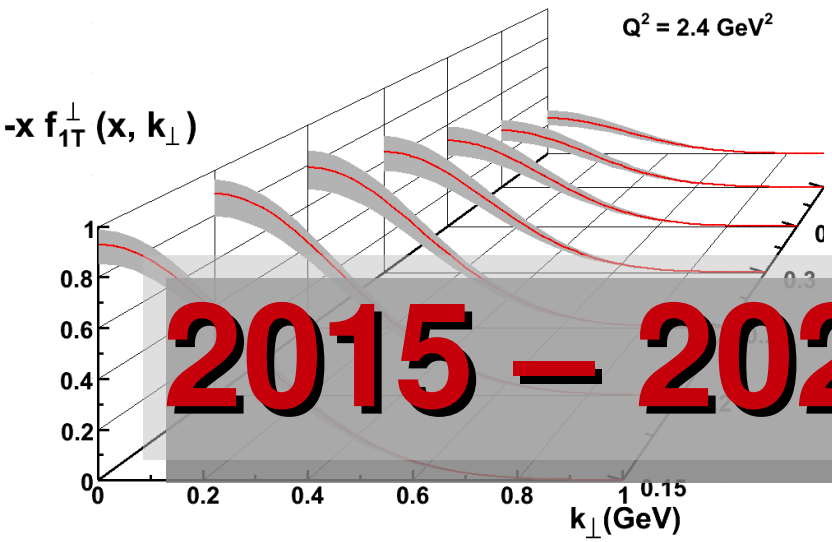
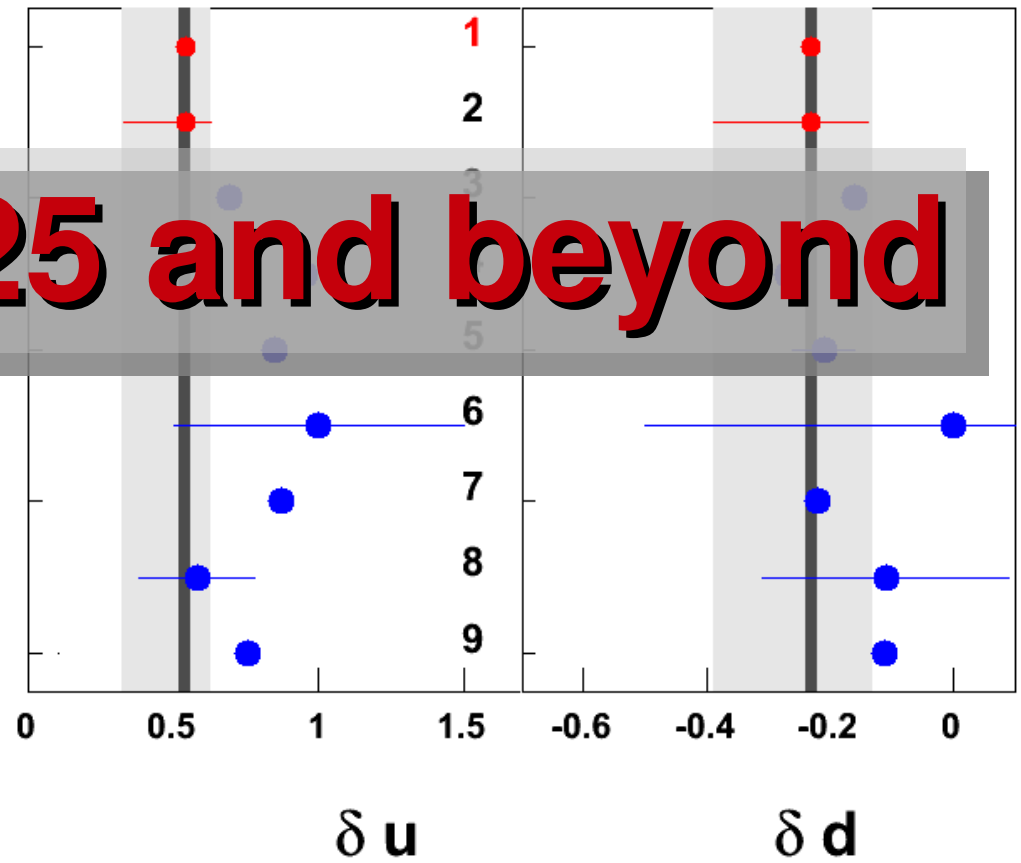


Expected accuracy of TMD profile



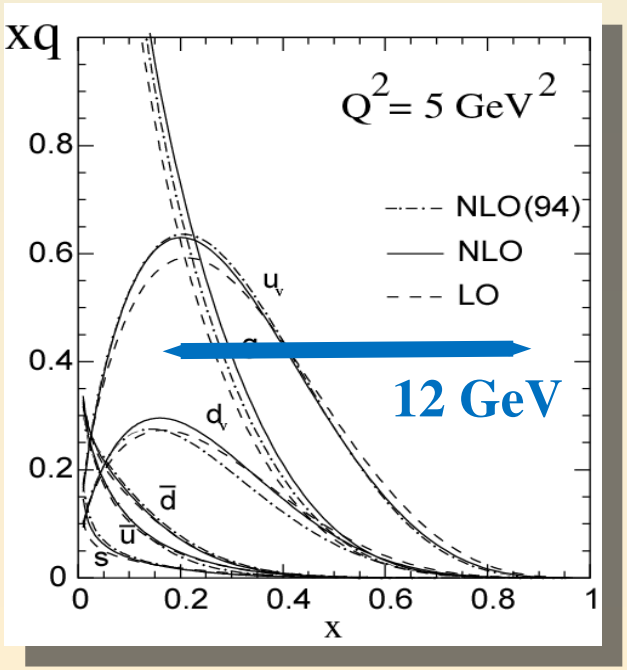
2015 – 2025 and beyond

A. Prokudin (2012) contribution
To JLab12 white paper

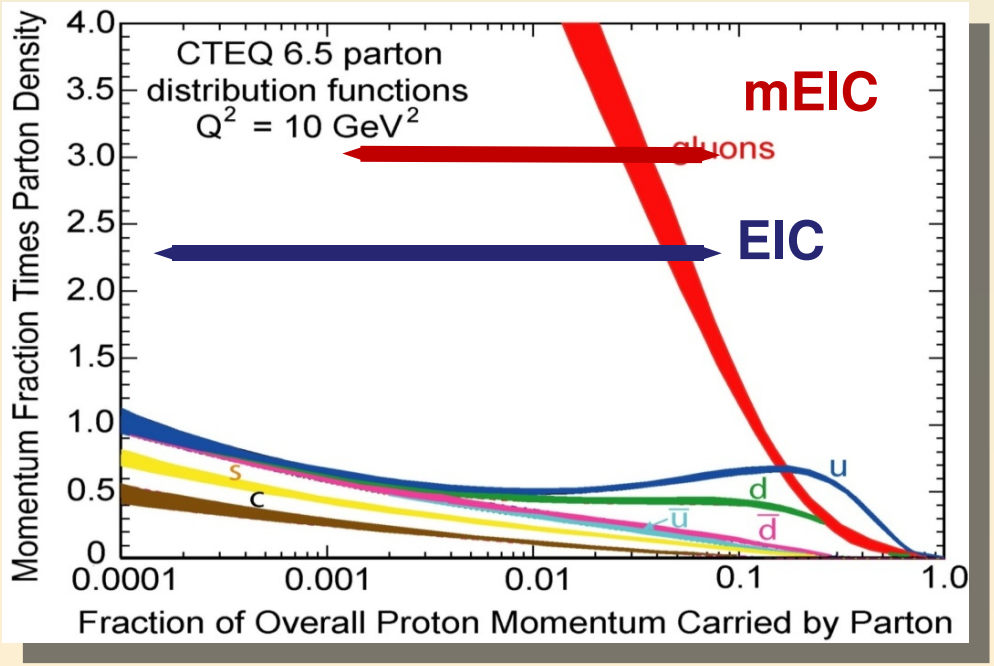
What will happen after Jefferson Lab 12?

Into the "sea": Electron Ion Collider

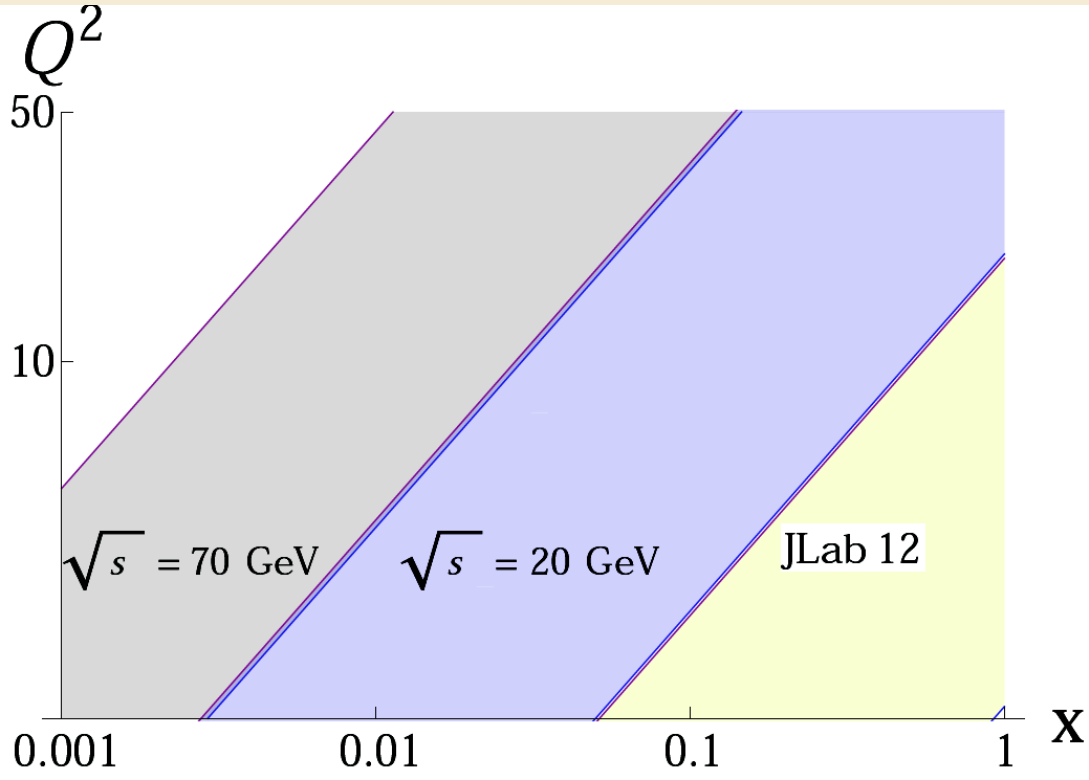
- With 12 GeV we study mostly the valence quark component



An EIC aims to study the sea quarks, gluons, and scale dependence.

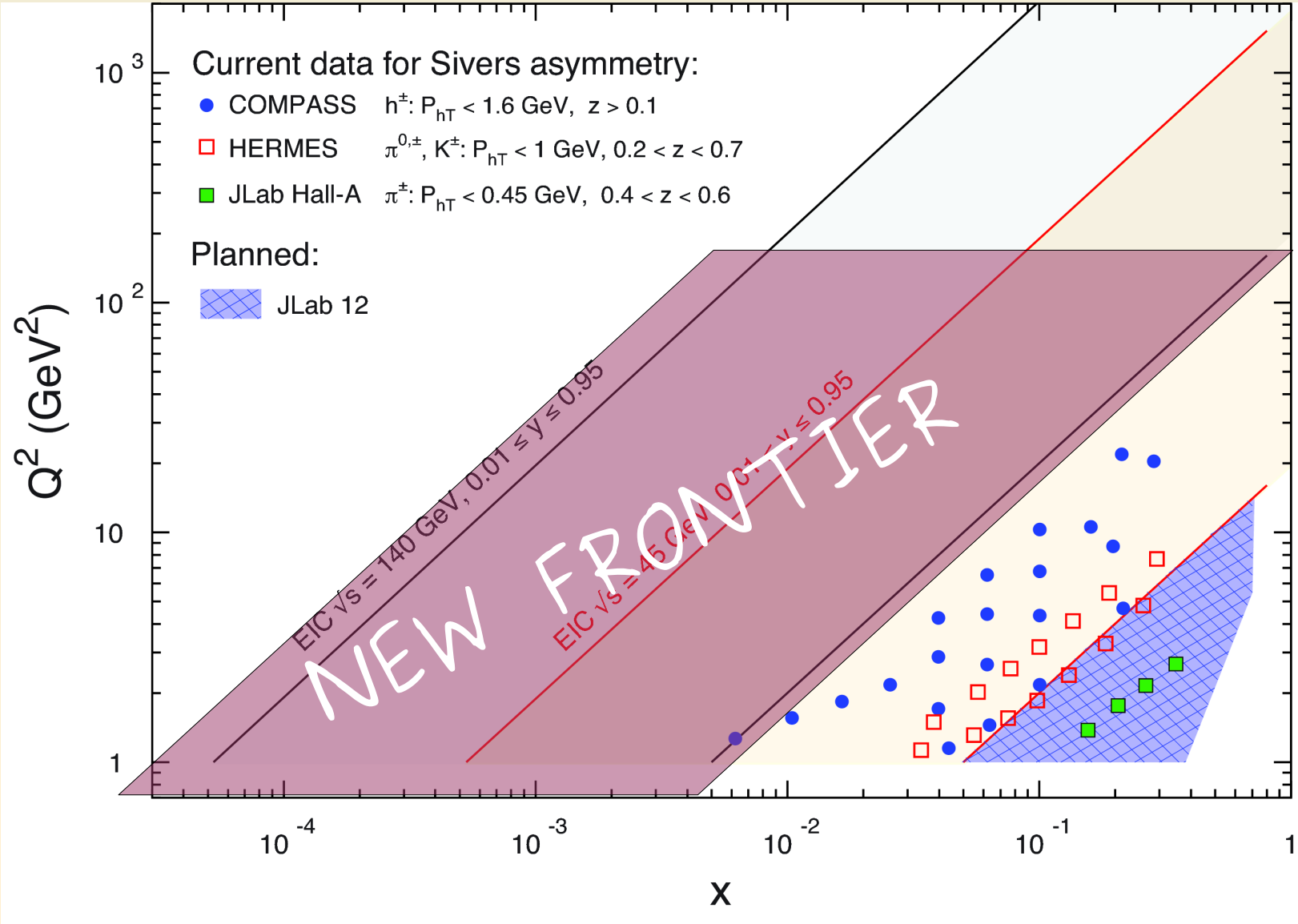


Into the "sea": Electron Ion Collider



JLab 12 and future Electron Ion Collider are complimentary

Into the "sea": Electron Ion Collider



Medium Energy EIC@JLab

Physics driven design

Spin and 3D quark/gluon structute of the hadron

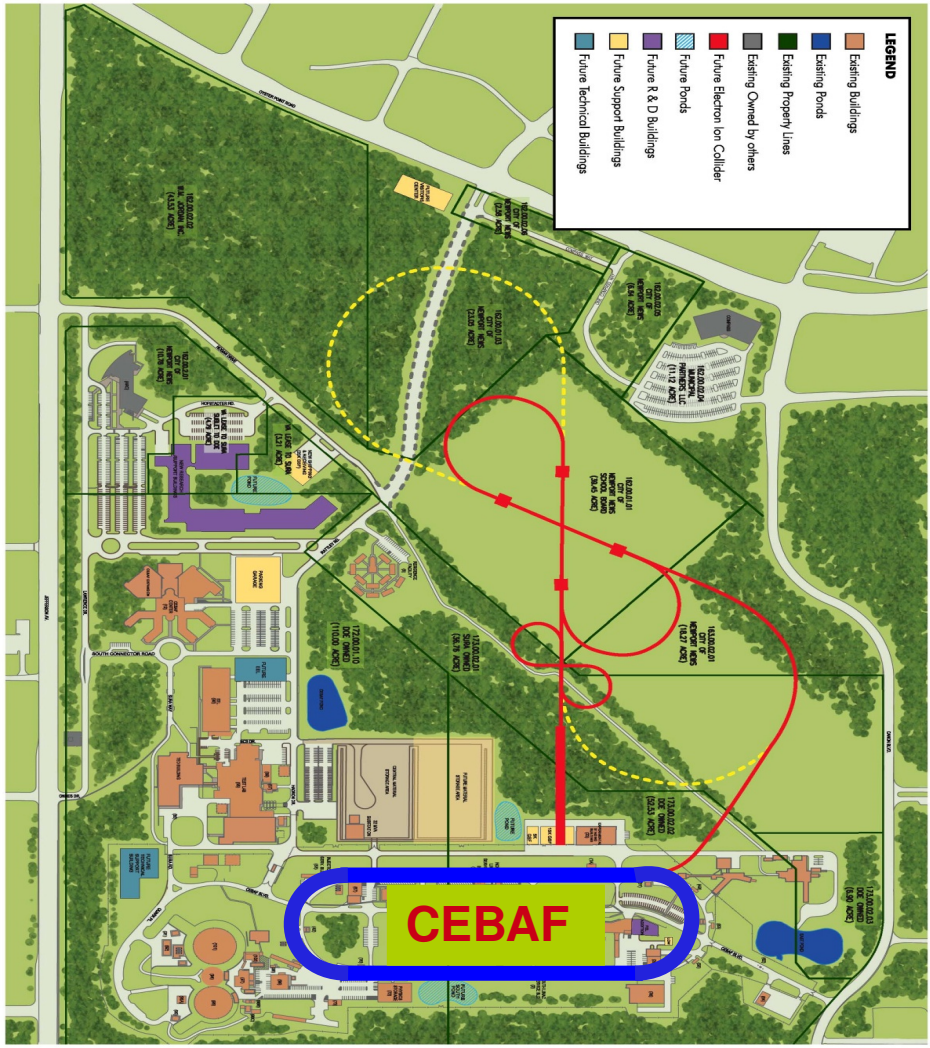
Dynamics of color fields in nuclei

Emergence of hadrons from color charge

JLab Concept

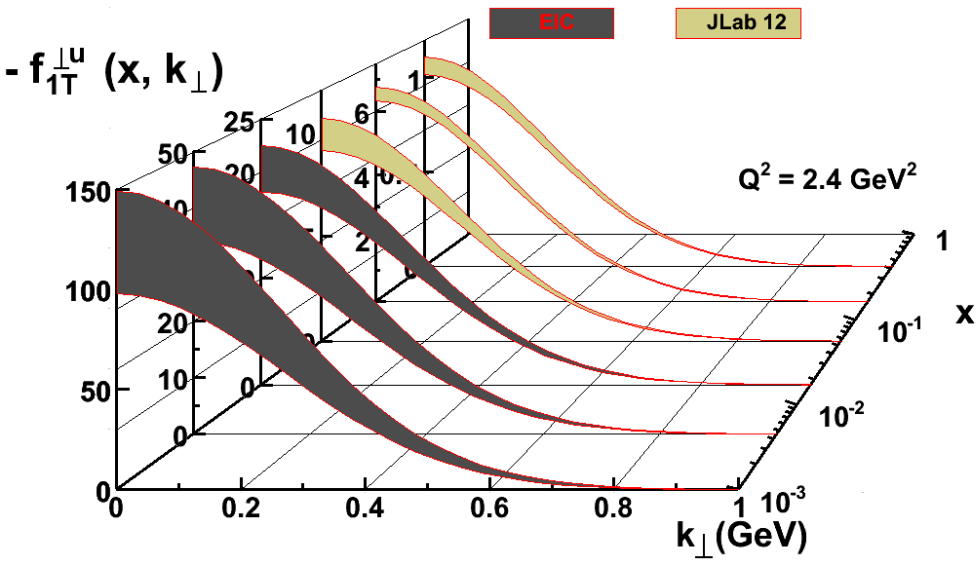
Initial configuration (MEIC):
3-12 GeV on 20-100 GeV ep/eA collider
fully-polarized, longitudinal and transverse
luminosity: few x 10^{34} e-nucleons cm^{-2} s^{-1}

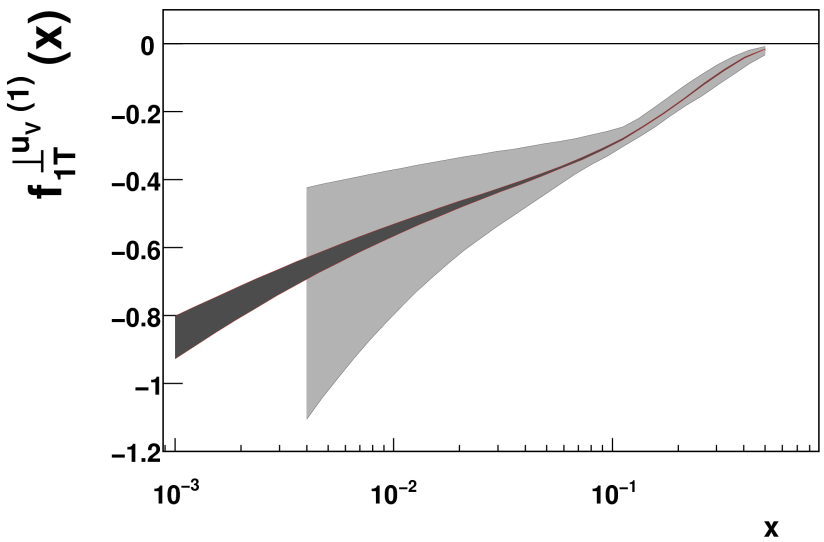
Upgradable to higher energies (250 GeV)



What will be achieved? Example:

Expected result for an individual function:

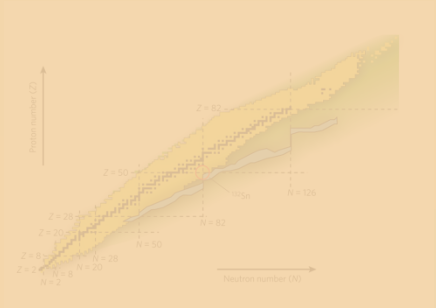


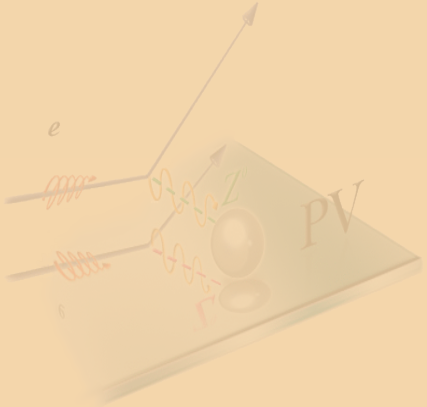


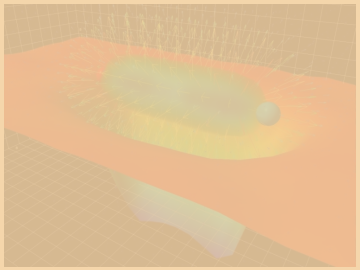
Expected accuracy of TMD profile

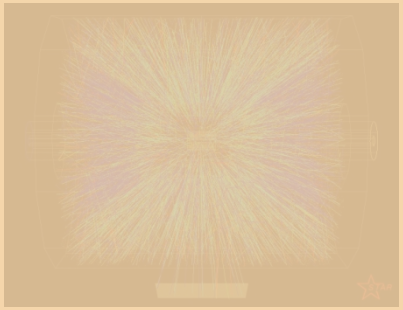
A. Prokudin (2012) contribution to EIC white paper

Conclusions

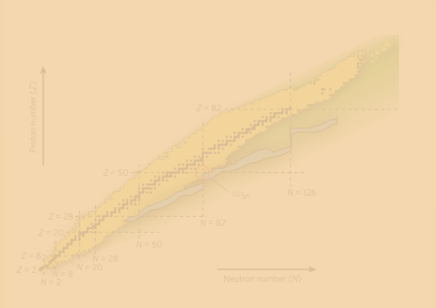


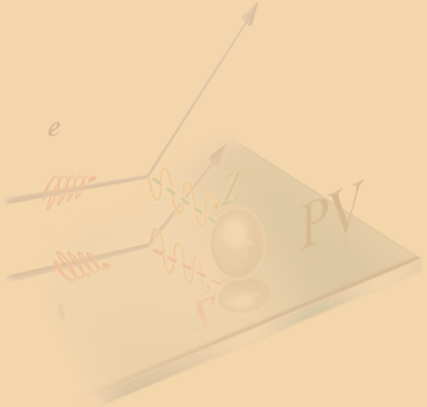




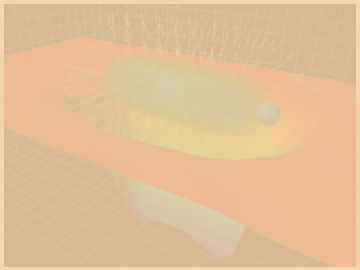


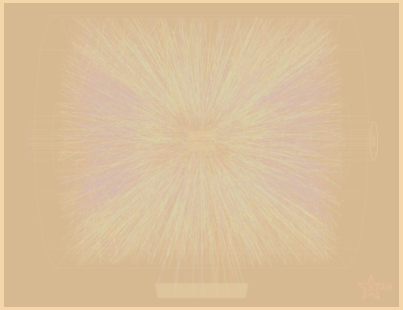
~~Conclusions~~





FUTURE





Collaborations are important

PDFs

GPDs

TMDs

Experiment

Part of my collaborators is listed

LANL
Znongbo Kang
Xin Qiang

BNL
Jianwei Qiu
Elke Aeschenauer

PENN STATE
Leonard Gamberg

Jefferson Lab
Anatoly Radyushkin
Christian Weiss
Alberto Accardi
Harut Avakian
etc

UCONN
Peter Schweitzer

Stony Brook
Ted Rogers

China
Bo-Qiang Ma

NETHERLANDS
Daniel Boer

GERMANY
Werner Vogelsang
Marc Schlegel

ITALY
University of Torino
Mauro Anselmino
Stefano Melis
Elena Boglione
Vincenzo Barone
University of Cagliari
Umberto D'Alesio
Franceso Murgia
University of Pavia
Alessandro Bacchetta

Workshops

Quarks and Gluons
All the visible matter in the universe is made of quarks and gluons. They form the particles studied at Jefferson Lab.
CALIF
QCD Evolution Workshop
May 14-17, 2012 Jefferson Lab

Workshops

http://www.jlab.org/conferences/qcd2013/

QCD Evolution Workshop

May 6-10, 2013, Jefferson Lab

Workshops

http://www.jlab.org/conferences/qcd2013/

QCD Evolution Workshop

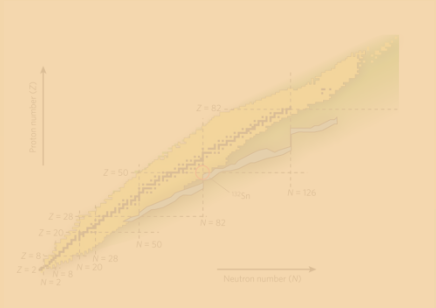
May 6-10, 2013, Jefferson Lab

Schools

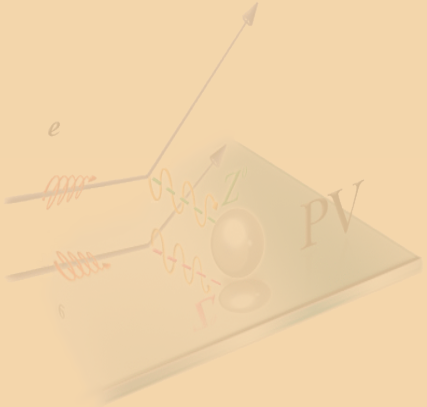
HUGS2012
27th Annual Hampton University Graduate Studies Program

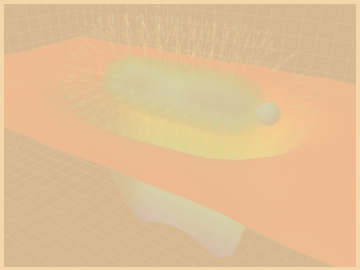
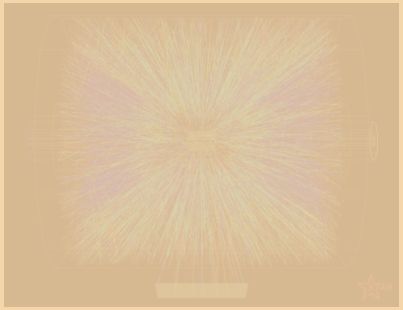
Schools

Coordinator,lecturer
http://www.jlab.org/hugs/
HUGS2013
May 28-June14, 2013, Jefferson Lab


Proton number (Z)
Neutron number (N)
Z = 82
Z = 50
Z = 28
Z = 20
Z = 8
Z = 2
N = 126
N = 82
N = 50
N = 28
N = 20
N = 8
N = 2

Proton Spin
Quark Spin


e
PV

D
A
B
C

THANK YOU!