Center for Frontiers
in Nuclear Science

ICTS
INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

tifr

Introduction:
Science Case for the EIC
An experimental review…

Abhay Deshpande

Lecture 1 of 2

Complementary to Marco Radici's and Ravindran's talks on Day 1

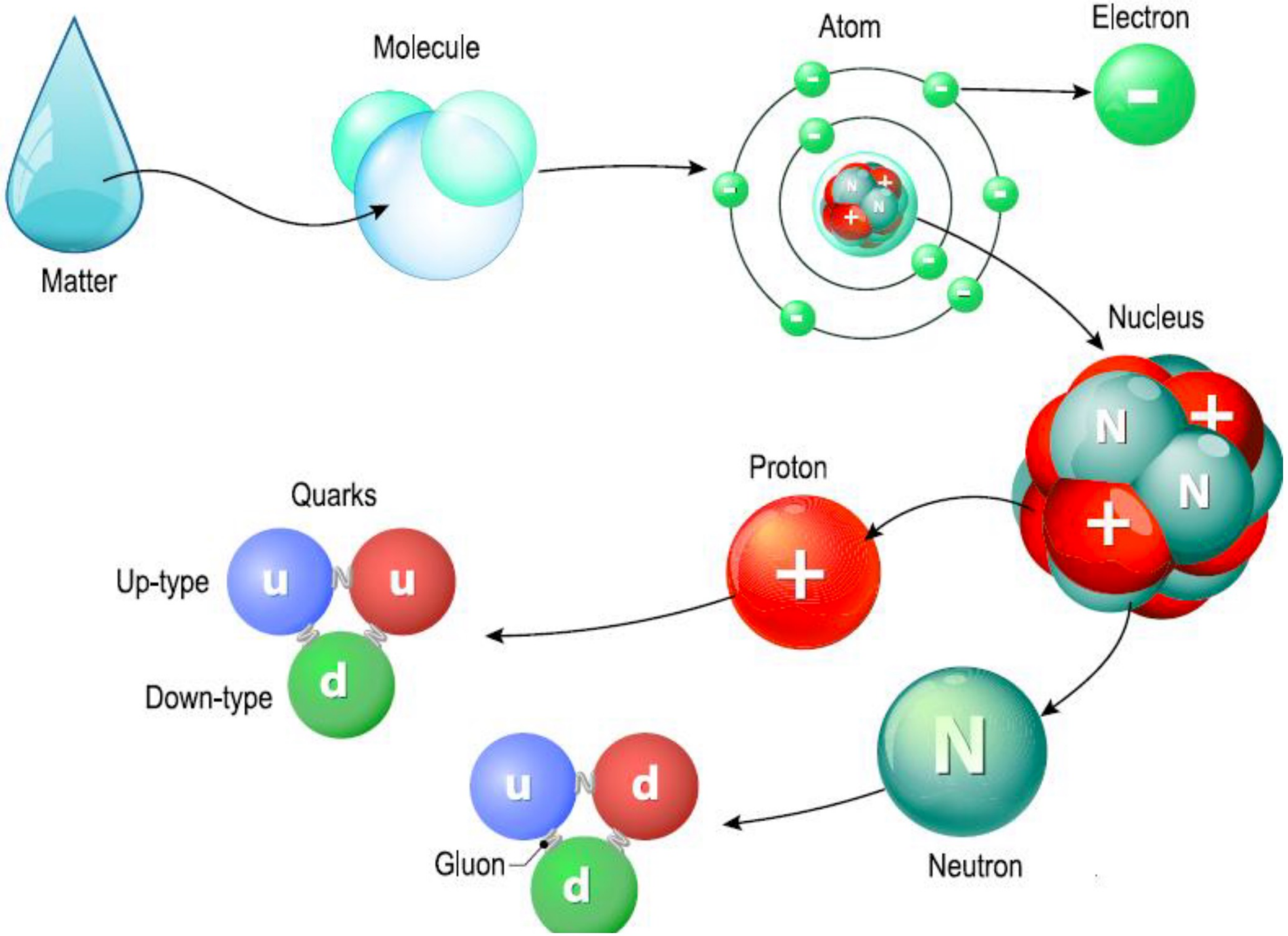
EIC Introduction @ International School and Workshop on Probing Hadron Structure ICTS Bengaluru, India

January 30, 2024

Stony Brook University

Brookhaven National Laboratory

Quest for the fundamental structure of matter



What’s in there?

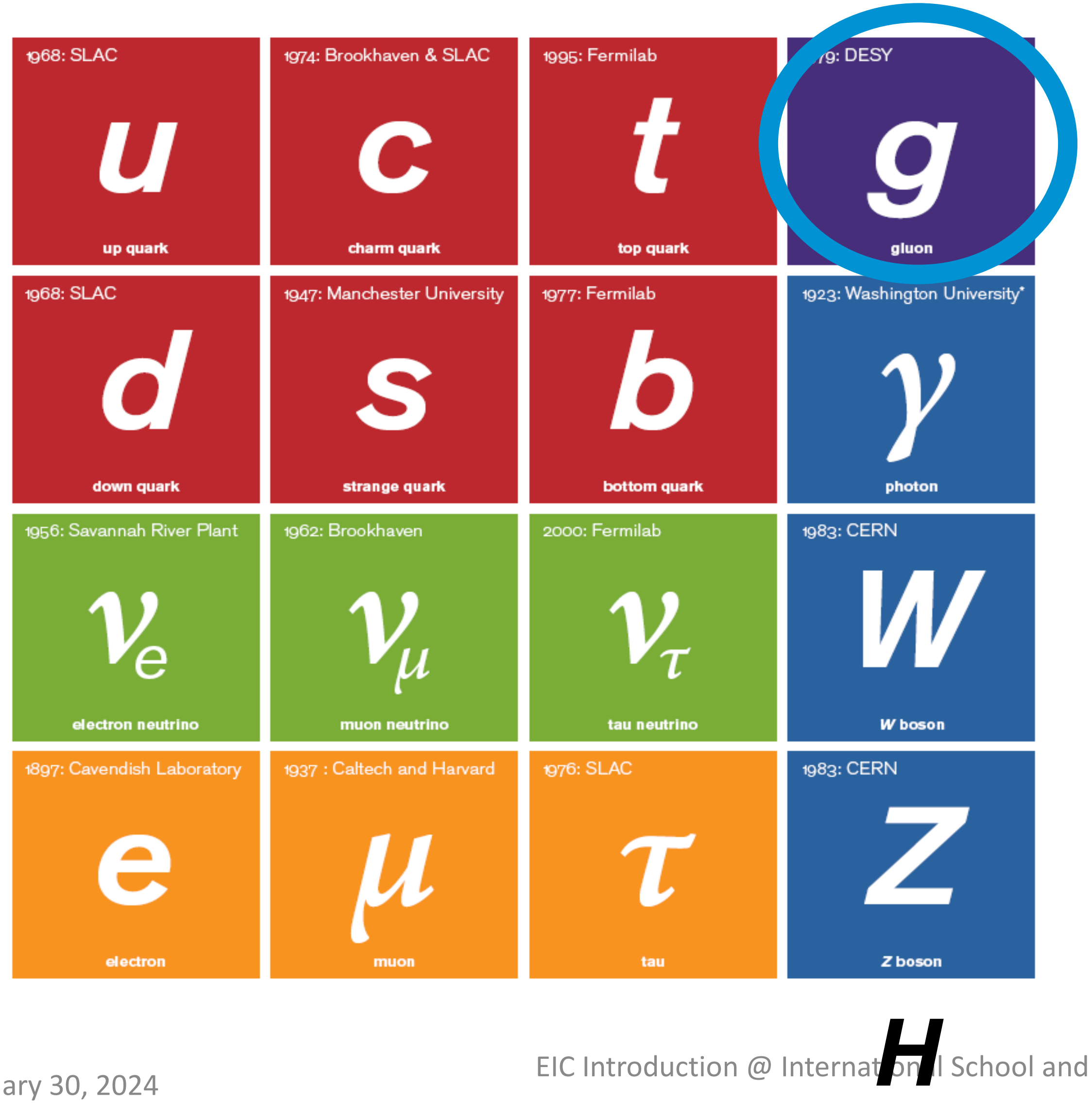
What are we made up of?

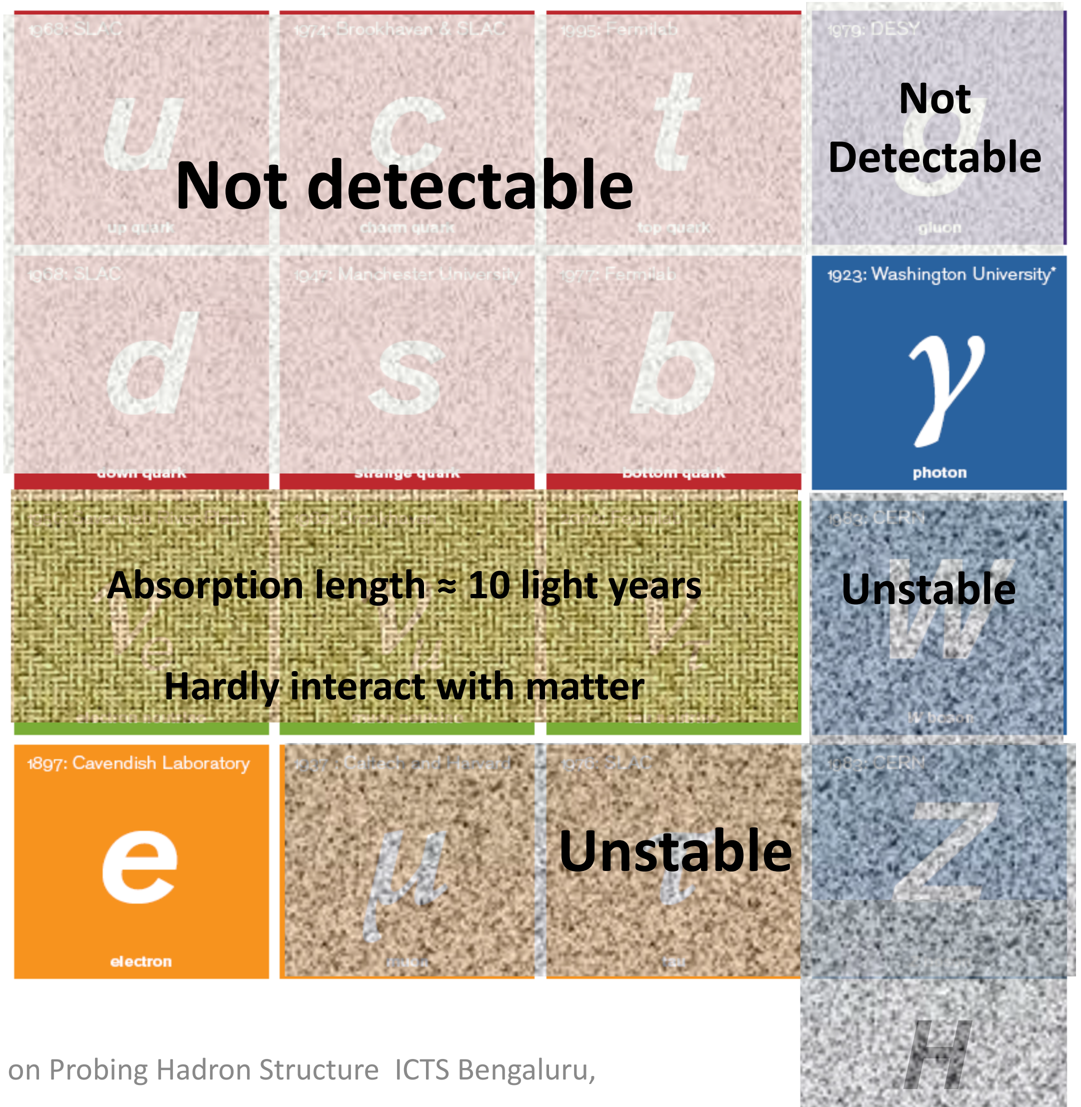
What is the ”smallest”?

What is “fundamental” that can’t be divided further?

National Academy of Sciences, Consensus Report on the US EIC

Many





Not detectable

Not Detectable

Absorption length ≈ 10 light years

Hardly interact with matter

Unstable

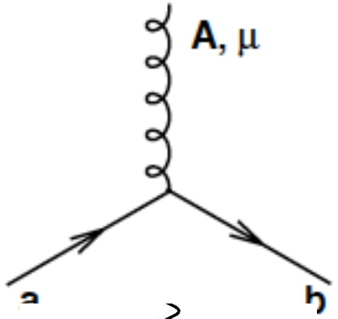
Unstable

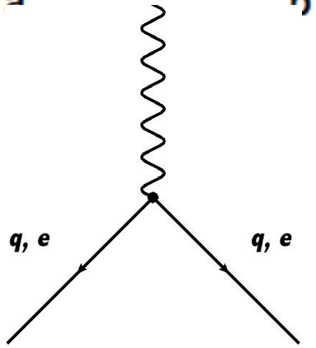
What distinguishes QCD from QED?

QED is mediated by photons (γ) which are charge-less (and couple to charged particles)

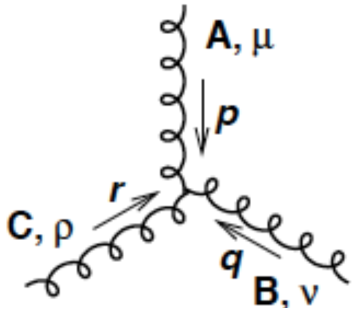
QCD is mediated by gluons (g), also charge-less but *are* colored! → can interact with themselves, and colored quarks

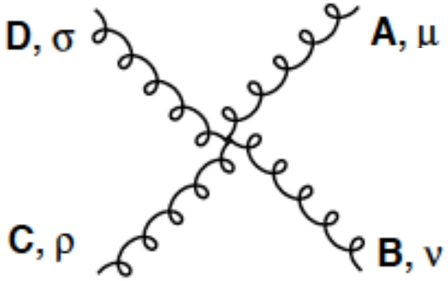
In QCD &
g → γ in QED





Only in QCD





Nonlinear growth in g-g interactions…
Bring richness and complexity to QCD
Experimental guidance always needed

Introduction to EIC – two lectures

- Hour 1: Why EIC? History
  - Science drivers
  - Past & current experiments: their limitations
- Hour 2: Why EIC? Today
  - What the EIC will deliver
  - When

Deep Inelastic Scattering (DIS)

Study of internal structure of a watermelon:

A-A (RHIC/LHC)

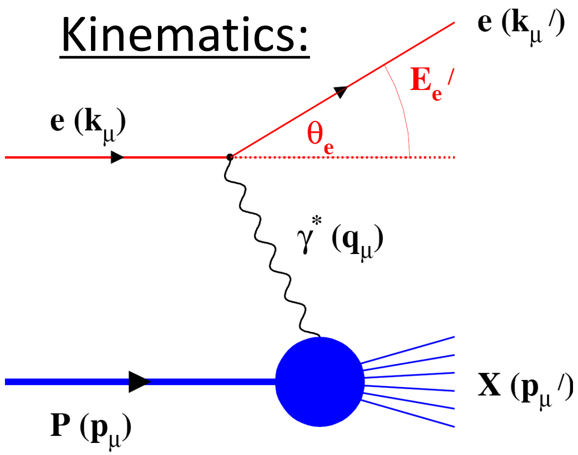
1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (Deep Inelastic Scattering -- DIS)

Deep Inelastic Scattering: Precision and control

Kinematics:



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

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

Measure of resolution power

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

Measure of inelasticity

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

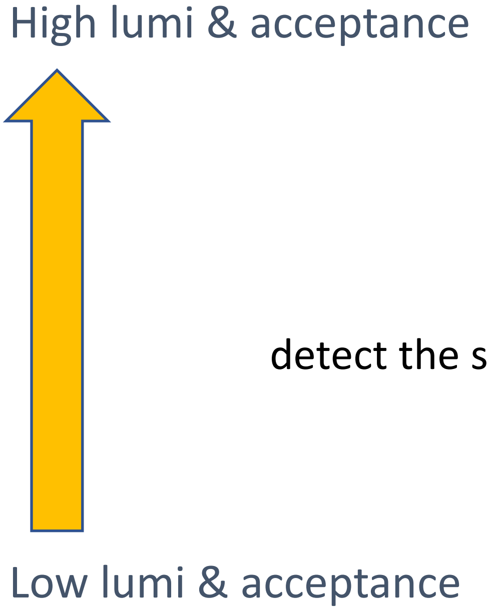
Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu};\ p_t$$

with respect to γ^*

$$s = 4\,E_h\,E_e$$



Exclusive DIS

detect & identify *everything* e+p/A → e'+h(π,K,p,jet)+…

Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets

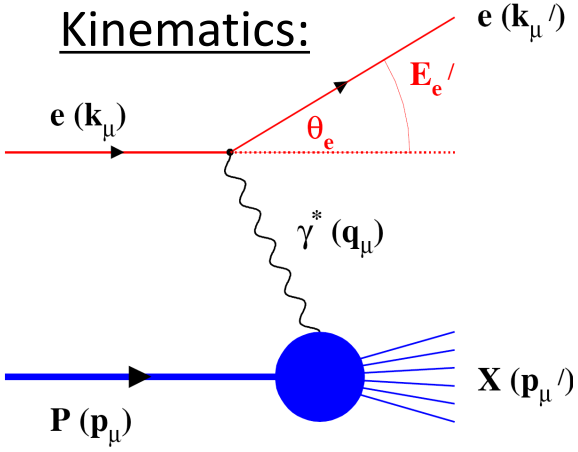
Inclusive events:

e+p/A → e'+X

detect *only the scattered lepton* in the detector

Deep Inelastic Scattering: Precision and control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k_\mu^{\prime})^2$$

$$Q^2 = 2E_e E_e^{\prime}(1-\cos\Theta_{e^{\prime}})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E_e^{\prime}}{E_e}\cos^2\left(\frac{\theta_e^{\prime}}{2}\right)$$

Measure of inelasticity

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

Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu};\ p_t$$ with respect to γ^*

$$s = 4\,E_h\,E_e$$

High lumi & acceptance

Exclusive DIS

detect & identify *everything* e+p/A → e'+h(π,K,p,jet)+…

Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets

Inclusive events:

e+p/A → e'+X

detect *only the scattered lepton* in the detector

Low lumi & acceptance

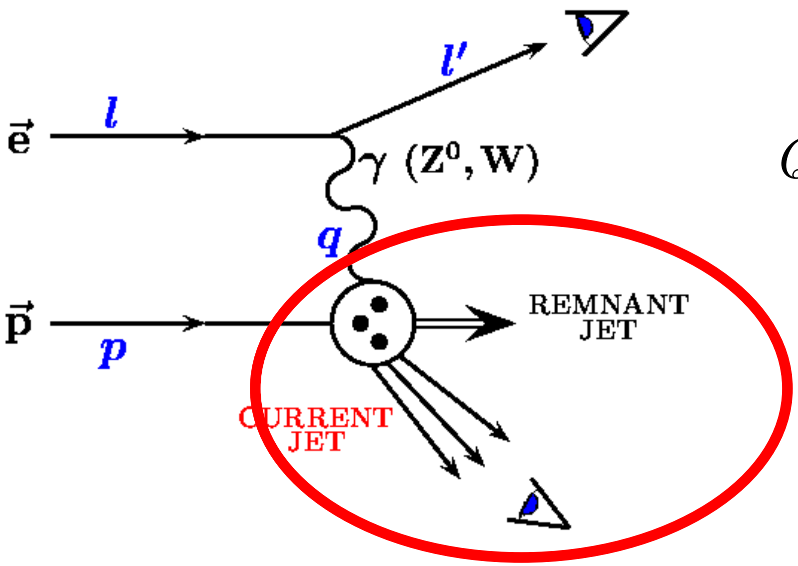
Some times scattered electron can’t be measured….

Reason:

1) Scattering angle so small that it is too close to the beam pipe

2) Radiative correction too large, i.e. electron lost its energy due to Initial State Radiation or Brehmstrahlung through material -- So the kinematic reconstruction unreliable.

What to do? Then see if we can reconstruct the hadronic final state?



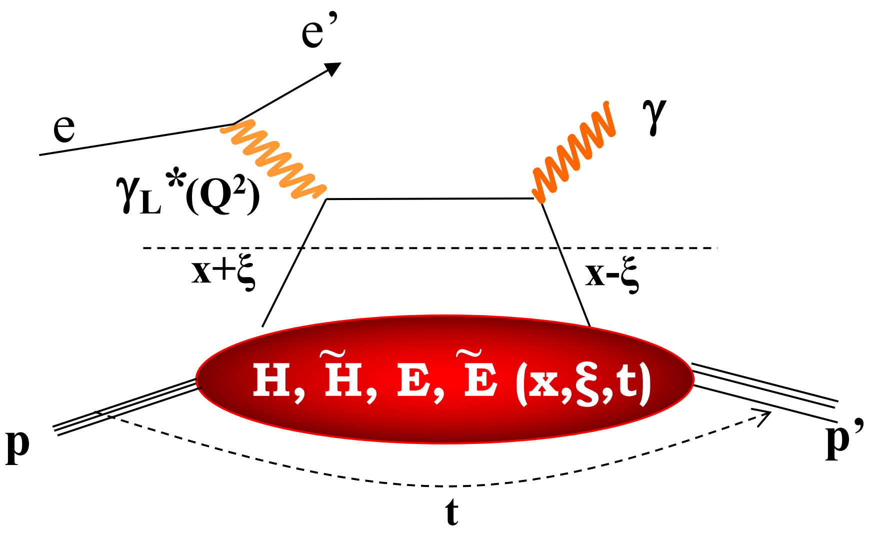
$$\begin{aligned} y &= \frac{E_j}{2E_e}(1 - cos\theta_j) \\ Q^2 &= E_j^2 sin^2\theta_j/(1 - y) \end{aligned}$$

$$\begin{aligned} x &= \frac{E_j}{2E_p}(1 + cos\theta_j)/(1 - y) \\ E_j &= yE_e + x(1 - y)E_p \\ cos\theta_j &= \frac{-yE_e + (1-y)xE_p}{y\,E_e + (1-y)xE_p} \\ E_j^2 sin^2\theta_j &= 4\,xy(1-y)E_eE_p = Q^2\,(1-y) \end{aligned}$$

$$\begin{aligned} y_{JB} &= \frac{1}{2E_e}\sum_h (E_h - p_{Zh}) \\ Q^2_{JB} &= \frac{(\sum_h p_{Xh})^2 + (\sum_h p_{Yh})^2}{1 - y_{JB}} \\ x_{JB} &= Q^2_{JB}/(y_{JB}s) \end{aligned}$$

Deep Inelastic Scattering: Deeply Virtual Compton Scattering

Kinematics:



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

Measure of resolution power

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

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

Measure of inelasticity

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

Measure of momentum fraction of struck quark

$$t = (p-p')^2, \xi = \frac{x_B}{2-x_B}$$

Exclusive measurement:

e + **(p/A)** → e'+ **(p'/A')**+ γ / J/Ψ / ρ / ϕ
detect **all** event products in the detector

Special sub-event category rapidity gap events
e + **(p/A)** → e' + γ / J/Ψ / ρ / ϕ / jet
Don't detect **(p'/A') in final state**

Complete set of variables for DIS e-p:

https://core.ac.uk/download/pdf/25211047.pdf

We will use some of these more often than others, you should know them all.

E_p	proton beam energy
E_e	electron beam energy
$p = (0, 0, E_p, E_p)$	four momentum of incoming proton with mass m_p
$e = (0, 0, -E_e, E_e)$	four momentum of incoming electron
$e' = (E'_e sin\theta'_e, 0, E'_e cos\theta'_e, E'_e)$	four momentum of scattered electron
$s = (e + p)^2 = 4E_pE_e$	square of total ep c.m. energy
$q^2 = (e - e')^2 = -Q^2$	mass squared of exchanged current J
	$=$ square of four momentum transfer
$\nu = q \cdot p/m_p$	energy transfer by J in p rest system
$\nu_{max} = s/(2m_p)$	maximum energy transfer
$y = (q \cdot p)/(e \cdot p) = \nu/\nu_{max}$	fraction of energy transfer
$x = Q^2/(2q \cdot p) = Q^2/(ys)$	Bjorken scaling variable
$q_c = x \cdot p + (e - e')$	four momentum of current quark
$M^2 = (e' + q_c)^2 = x \cdot s$	mass squared of electron - current quark system.

Unpolarized e-p/A DIS

DIS without Spin:

See Ravindran's talk
"Hadronic Cross section"
Factorized PDFs and cross
section (slides 7, 8)

Inclusive Cross-Section:

$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

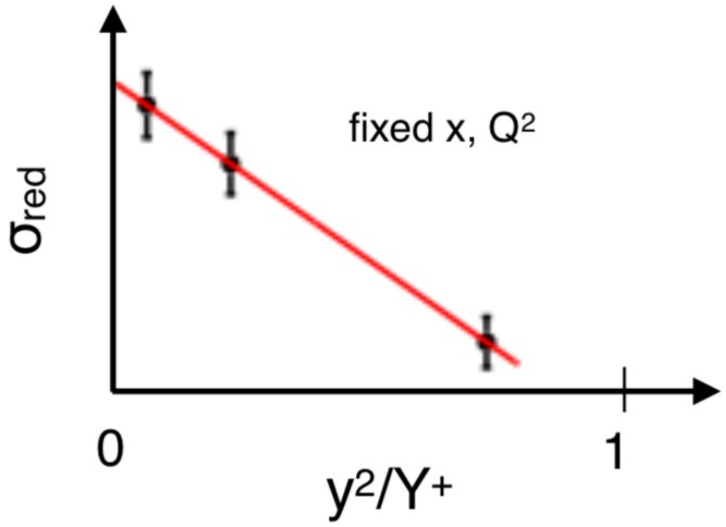
Reduced Cross-Section:

$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$

Rosenbluth Separation:

- Recall $Q^2 = x\ y\ s$
- Measure at different √s
- Plot σ_{red} versus $y2/Y^+$ for fixed x, Q^2
- F_2 is σ_{red} at $y2/Y^+ = 0$
- F_L = Slope of $y2/Y^+$



$$(\mathrm{CME})^2 = S = 4\, E_e\, E_p$$

Early experiments: fixed target

With electron (3-20 GeV) and muon (up to 240 GeV) beams

Range of Center of Mass Energies (CME)

HERA the first e-p **collider:**

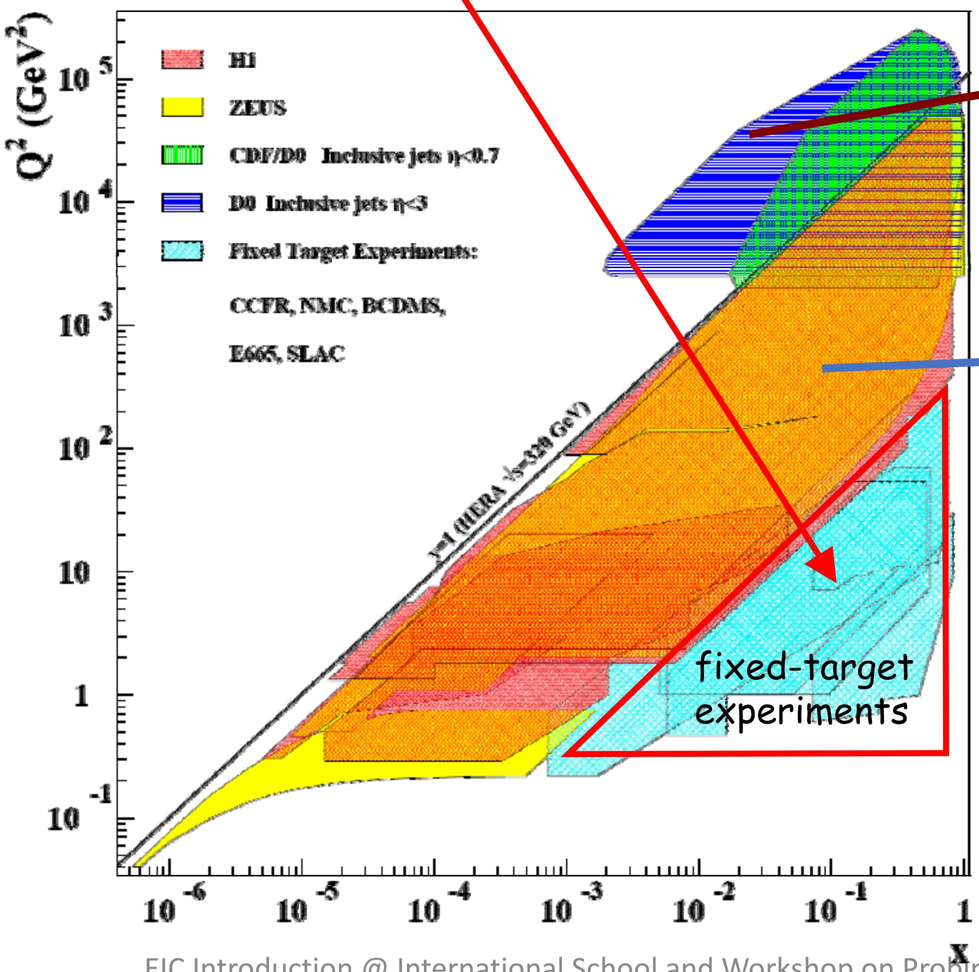
~300 GeV Center of Mass: 820 GeV p x 27 GeV e

HERA - Electron Proton Collider

HERA-I 1992-2000
HERA-II 2003-2007

Perspective on x,Q^2, Center of Mass

Fixed target e-N experiments
(center of mass < 30 GeV)



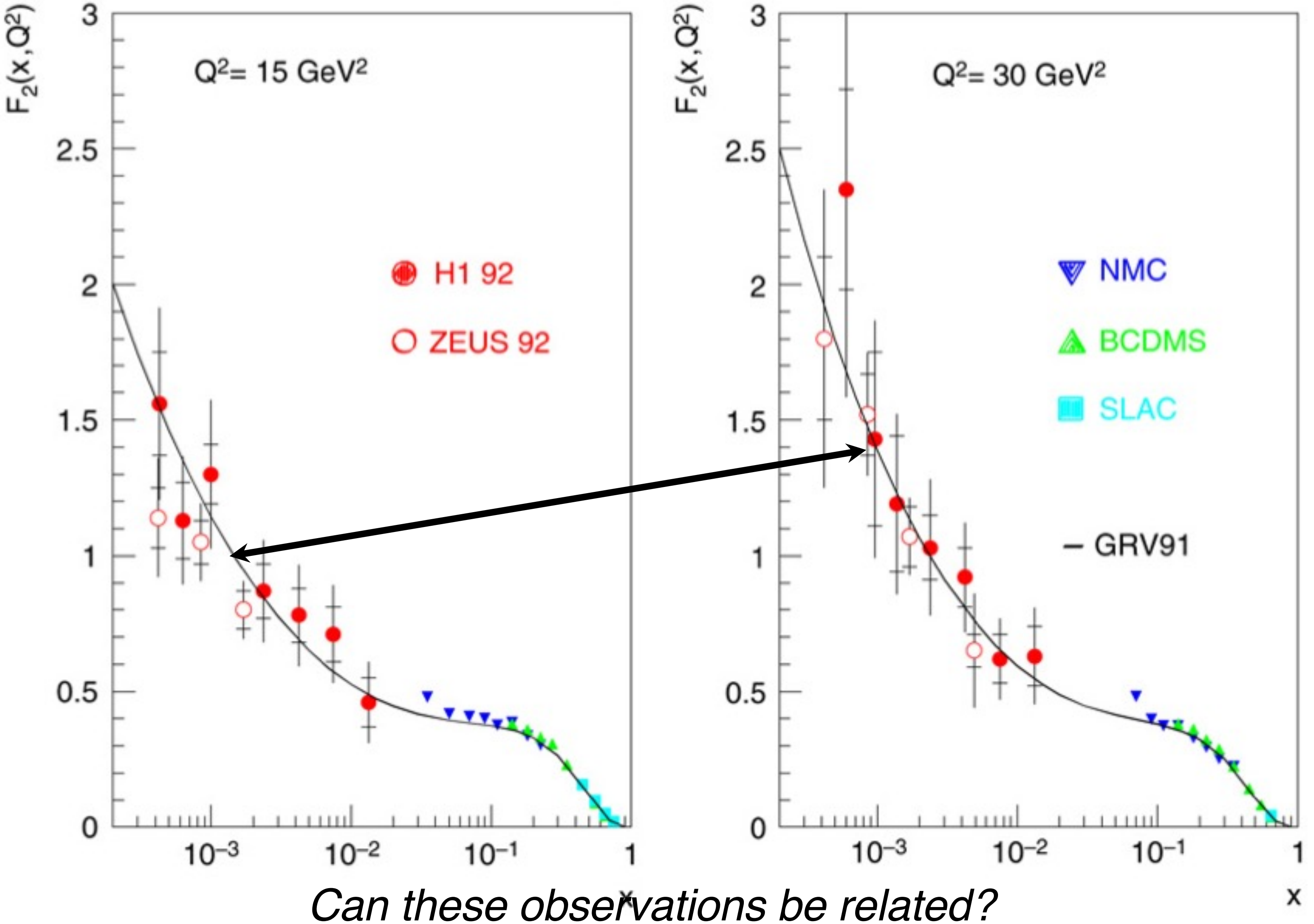
Hadron-Hadron
Collider: CM ~2 TeV

Typically accessible
By e-N collider experiments
CM ~ 300 GeV

$$Q^2 = S\ x\ y$$

Remember:
Meaning of x, Q^2, and y?

HERA - Early Measurements



Can these observations be related?

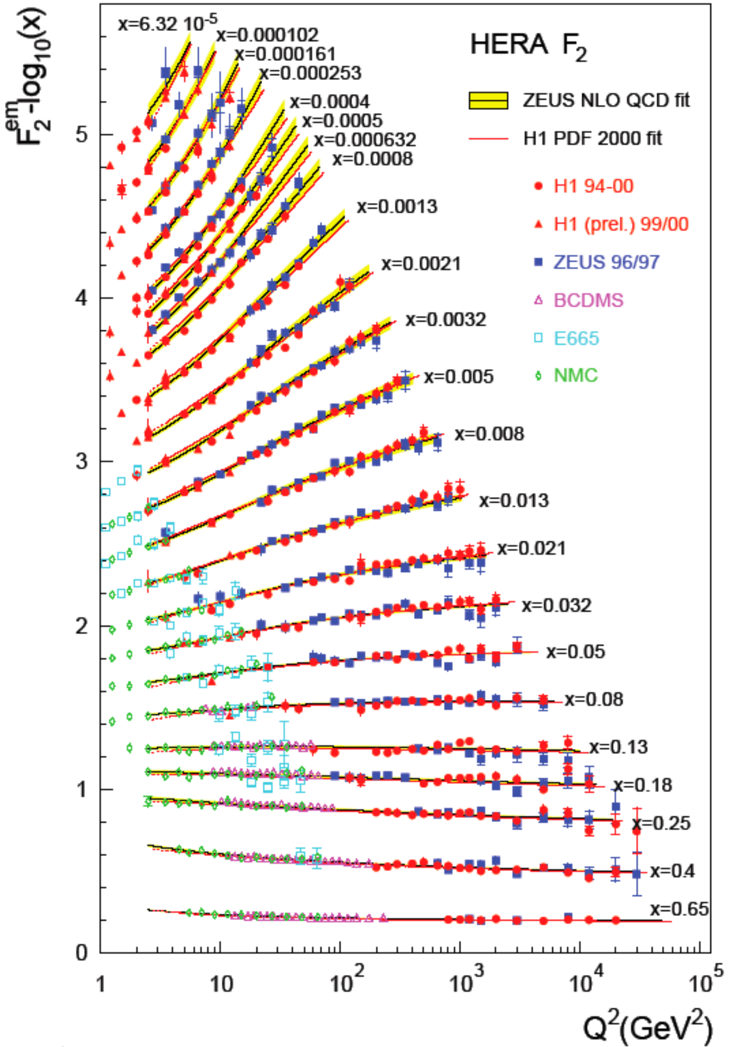
Yes! Through QCD evolution! At the heart of it are gluons

Measurement of unpolarized glue at HERA

F_2 Structure Function

Vs.

Q^2 mom. exchanged

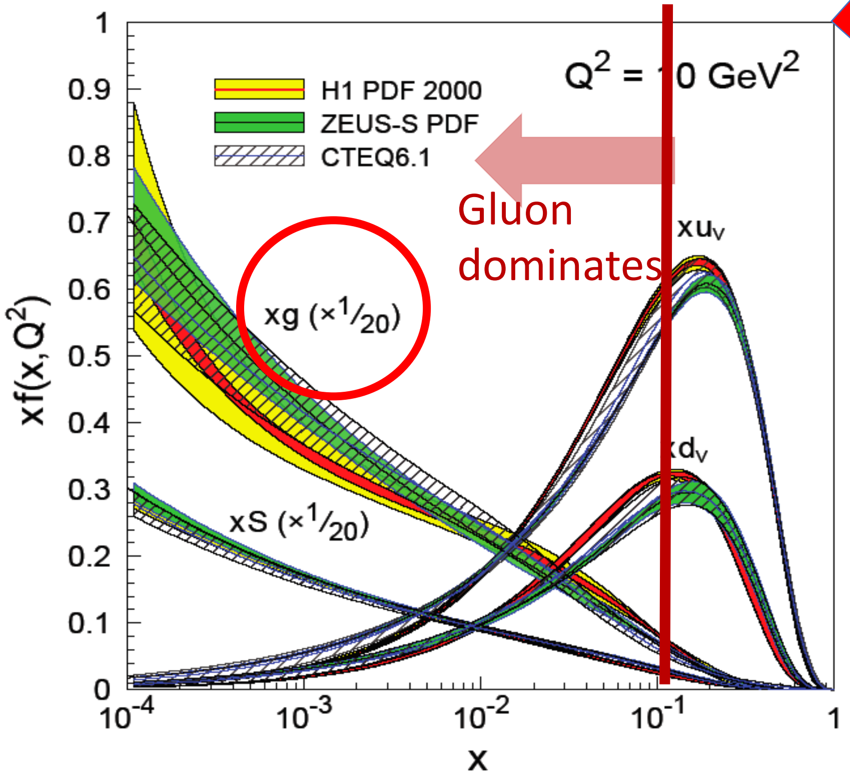


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

- Scaling violations of $F_2(x,Q^2)$

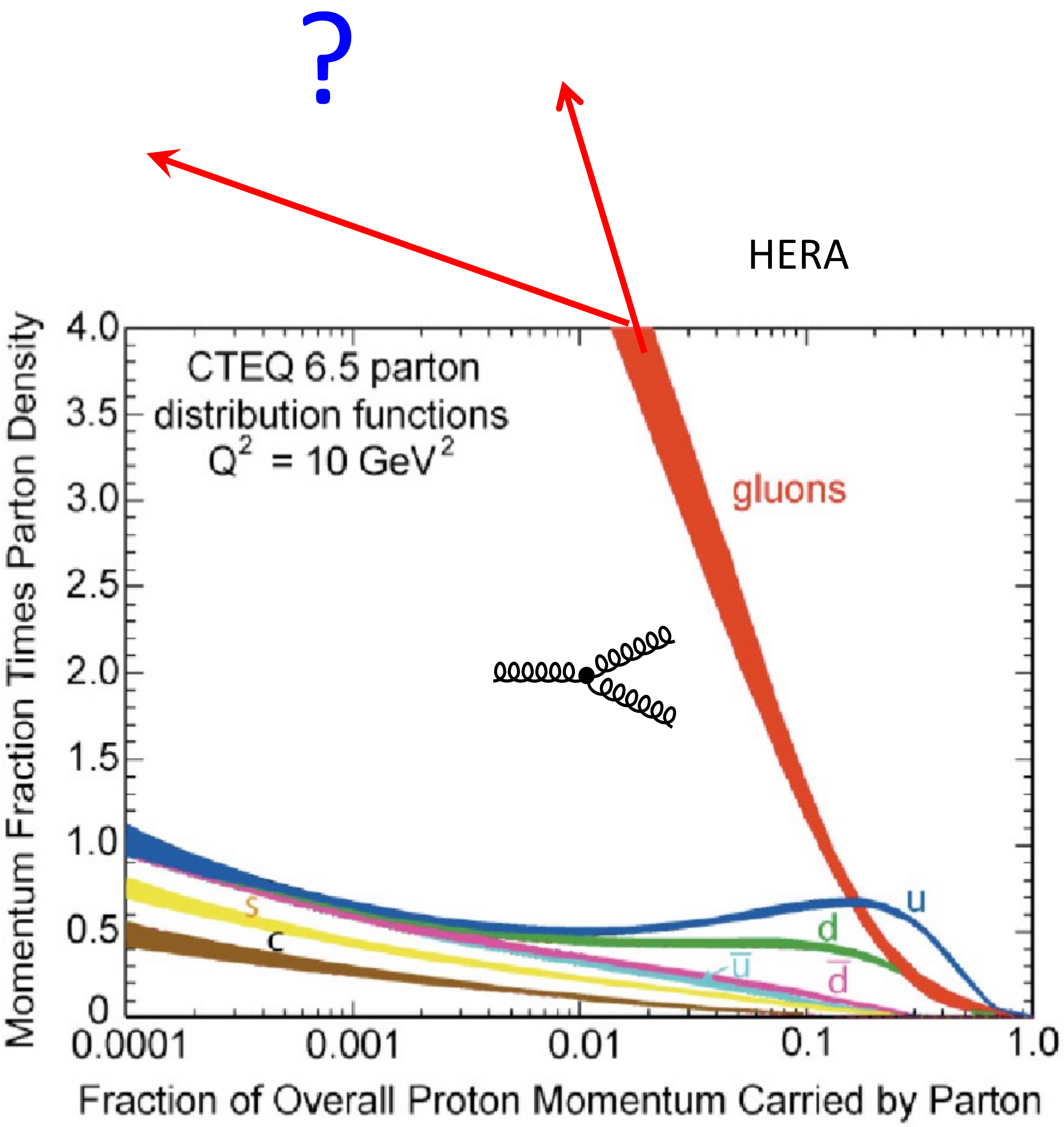
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

- NLO pQCD analyses: fits with **linear** DGLAP* equations



Gluon dominates

Low x rise of the gluon distribution



What could tame the low-x rise?

We will come back to this a little later…

Levitating top

Despite understanding gravity, and rotational motion individually, when combined it produces unexpected, unusual and interesting results.

In nature, we observe such things and try to understand the physics behind it.

“*spin* has killed more theories in physics than any other single observables”
-- Elliot Leader

“If theorists had their way, they would ban all experiments with Spin”
-- James D. Bjorken (jokingly)

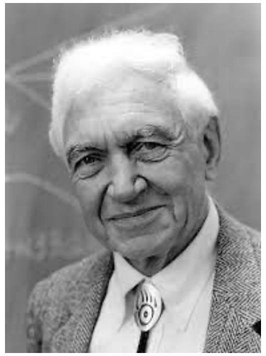
$$\frac{1}{2} = \left[\boxed{\frac{1}{2}\Delta\Sigma} + L_Q\right] + \left[\Delta g + L_G\right]$$

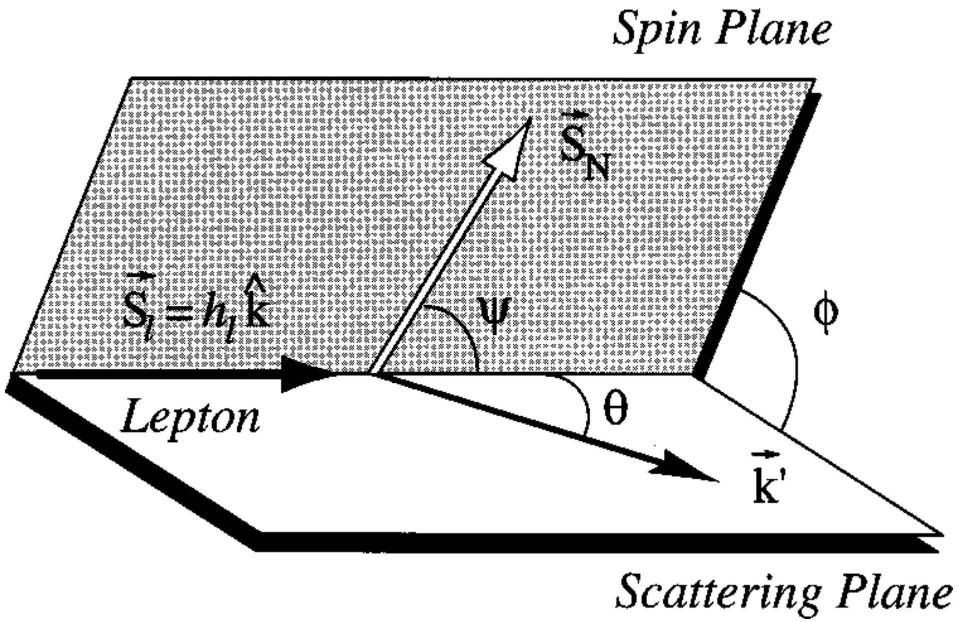
Quark Spin. Quark Ang. Mom. Gluon Spin. Gluon Ang. Mom

Proton Spin Crisis

In the following “quark spin” will generally mean “quark+anti-quark”’ spin orientation….

Lepton-nucleon cross section…*with spin*


V. W. Hughes
1922-2003



$$\Delta\sigma = \cos\psi\,\Delta\sigma_{\parallel} + \sin\psi\,\cos\phi\,\Delta\sigma_{\perp}$$

$$\gamma = \frac{2Mx}{\sqrt{Q^2}} = \frac{\sqrt{Q^2}}{\nu}.$$

For high energy scattering γ is small

$$\frac{d^2\Delta\sigma_{\parallel}}{dx\,dQ^2} = \frac{16\pi\alpha^2 y}{Q^4}\left[\left(1-\frac{y}{2}-\frac{\gamma^2 y^2}{4}\right)g_1 - \frac{\gamma^2 y}{2}\,g_2\right]$$

$$\frac{d^3\Delta\sigma_T}{dx\,dQ^2\,d\phi} = -\cos\phi\,\frac{8\alpha^2 y}{Q^4}\,\gamma\sqrt{1-y-\frac{\gamma^2 y^2}{4}}\left(\frac{y}{2}\,g_1 + g_2\right)$$

Cross section asymmetries….

- $\Delta\sigma_{||}$ = anti-parallel – parallel spin cross sections
- $\Delta\sigma_{perp}$= lepton-nucleon spins orthogonal
- Instead of measuring cross sections, it is prudent to measure the differences: Asymmetries in which many measurement imperfections might cancel:

$$A_{||} = \frac{\Delta\sigma_{||}}{2\bar{\sigma}}, \quad A_{\perp} = \frac{\Delta\sigma_{\perp}}{2\bar{\sigma}},$$

which are related to virtual photon-proton asymmetries A_1,A_2:

$$A_{||} = D(A_1 + \eta A_2), \quad A_{\perp} = d(A_2 - \xi A_1)$$

$$\boxed{A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1}}$$

$$A_2 = \frac{2\sigma^{TL}}{\sigma_{1/2} + \sigma_{3/2}} = \gamma \frac{g_1 + g_2}{F_1}$$

First Moments of SPIN Structure Functions

$$\Delta q = \int_0^1 \Delta q(x)\,dx \qquad g_1(x) = \frac{1}{2}\Sigma_f e_f^2\{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right] = \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3=g_a} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

Neutron decay

(3F-D)/3
Hyperon Decay

$\Delta\Sigma$

$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}}a_8\right] + \frac{1}{9}a_0$$

First moment of $g_1^p(x)$: Ellis-Jaffe Sum Rule

$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}} a_8\right] + \frac{1}{9} a_0$$

$$a_3 = \frac{g_A}{g_V} = F + D = 1.2601 \pm 0.0025 \qquad a_8 = 3F - D \Longrightarrow F/D = 0.575 \pm 0.016$$

Assuming $SU(3)_f$ & $\Delta s = 0$, Ellis & Jaffe:

$$\boxed{\Gamma_1^p = 0.170 \pm 0.004}$$

Measurements were done at SLAC (E80, E130) Experiments:

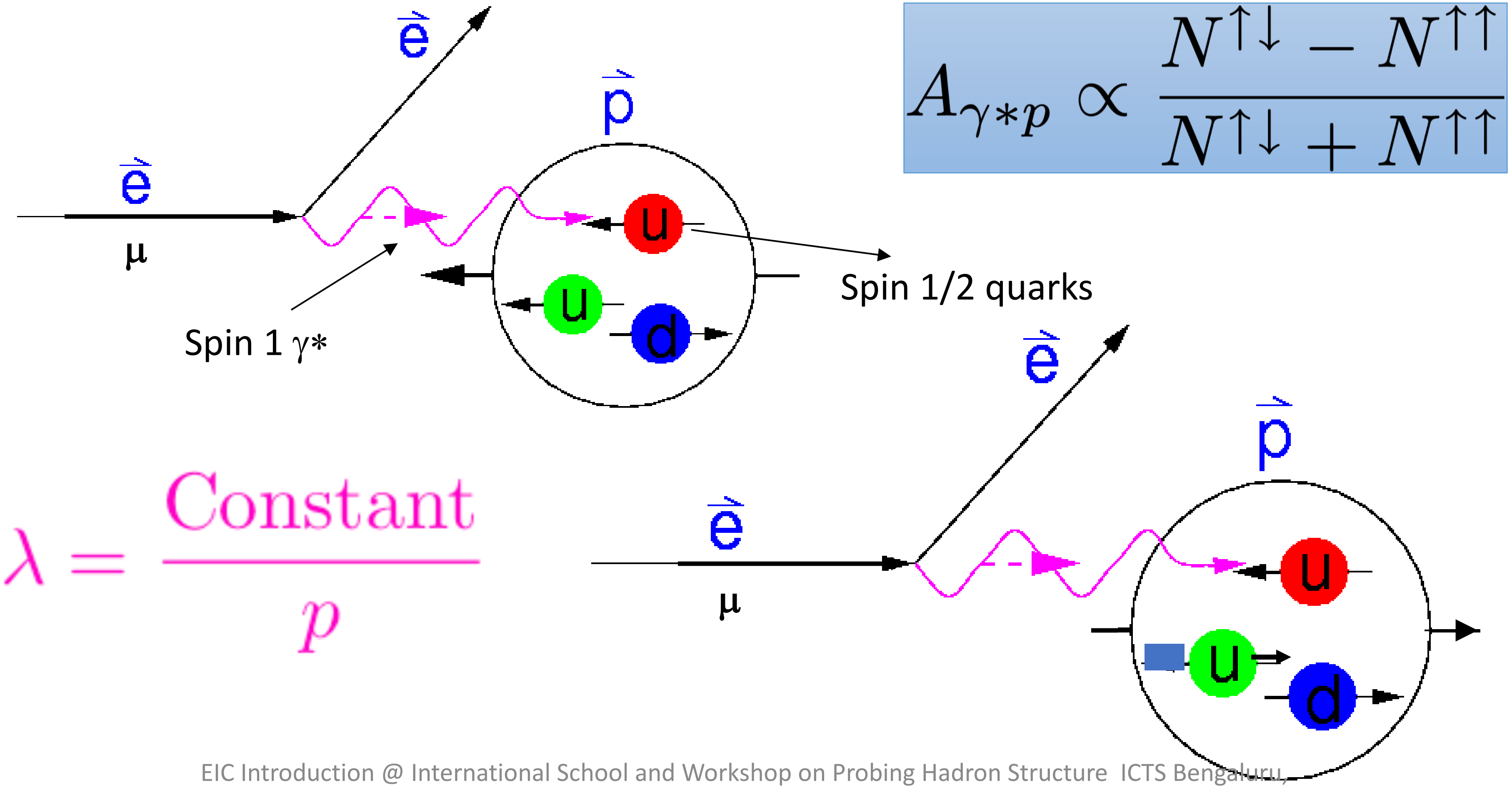
- Low 8-20 GeV electron beam on fixed target
- Did not reach low enough x → $x_{min} \sim 10^{-2}$
- Found consistency of data and E-J sum rule above

But higher energy muon beam exposed something important and unexpected!

The measurement and surprises…

How was the Quark Spin measured?

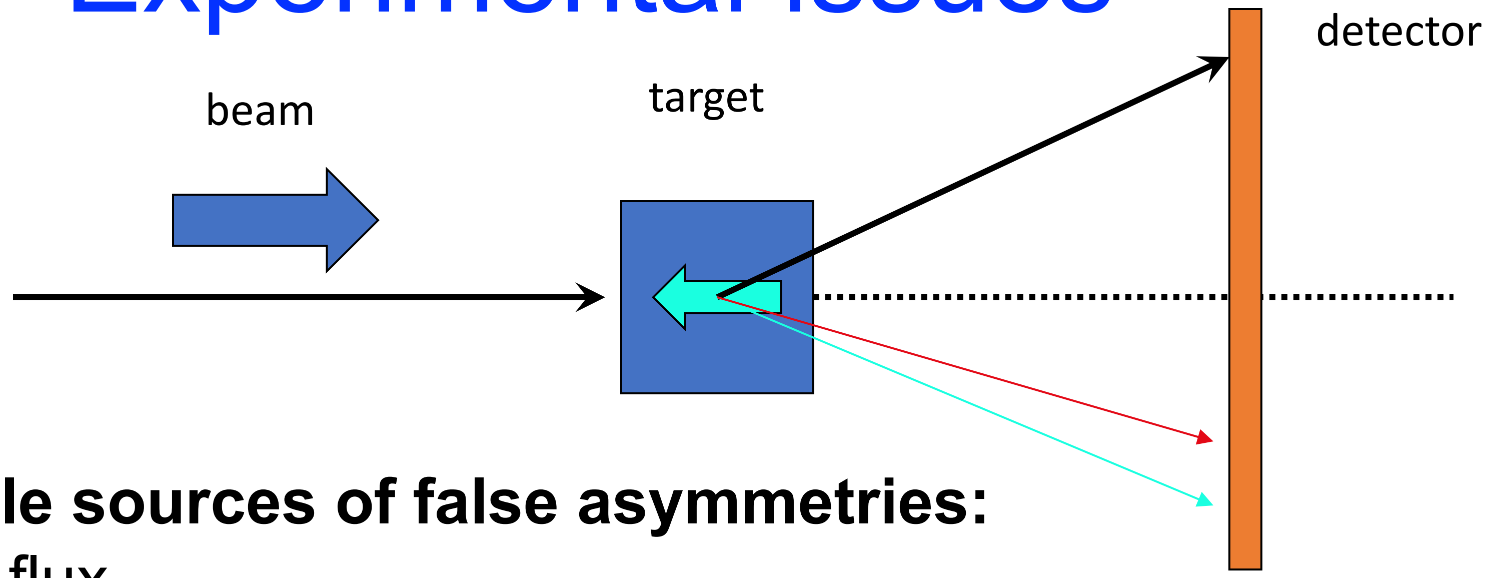
- Deep Inelastic polarized electron or muon scattering



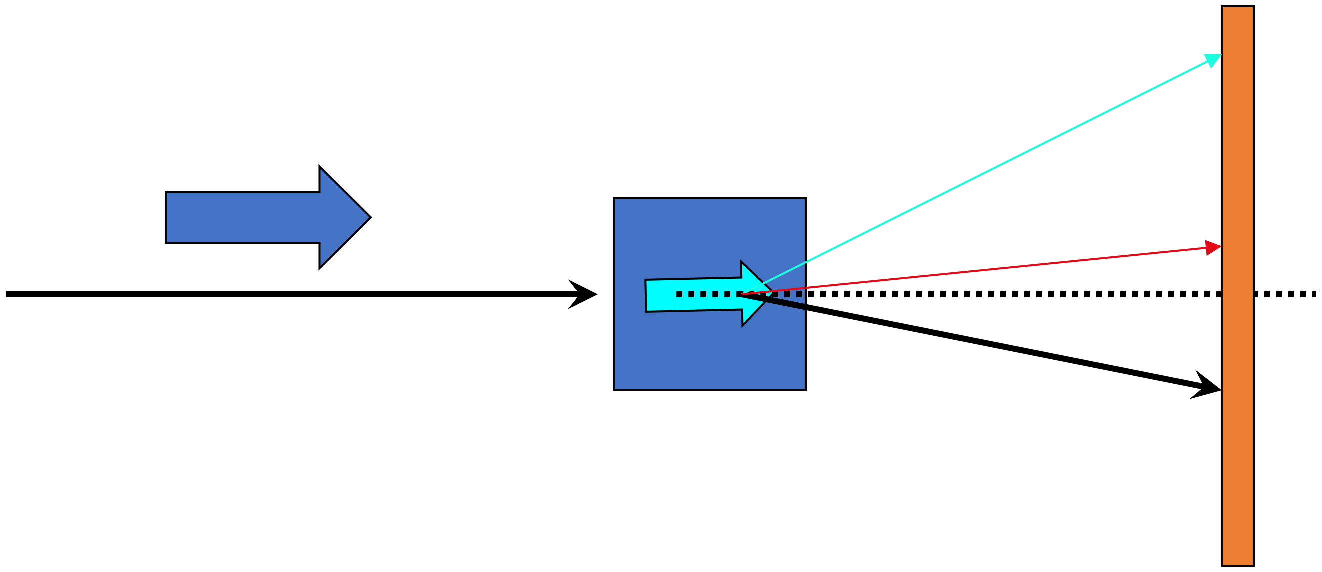
$$A_{\gamma*p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

$$\lambda = \frac{\text{Constant}}{p}$$

Experimental issues



Possible sources of false asymmetries:
- beam flux
- target size
- detector size
- detector efficiency



$A_{measured} = A_{LL}$

Double Longitudinal Spin asymmetry

$$A_{measured} = \frac{N^{\rightarrow\leftarrow} - N^{\rightarrow\rightarrow}}{N^{\rightarrow\leftarrow} + N^{\rightarrow\rightarrow}}$$

$$N^{\leftarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\leftarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

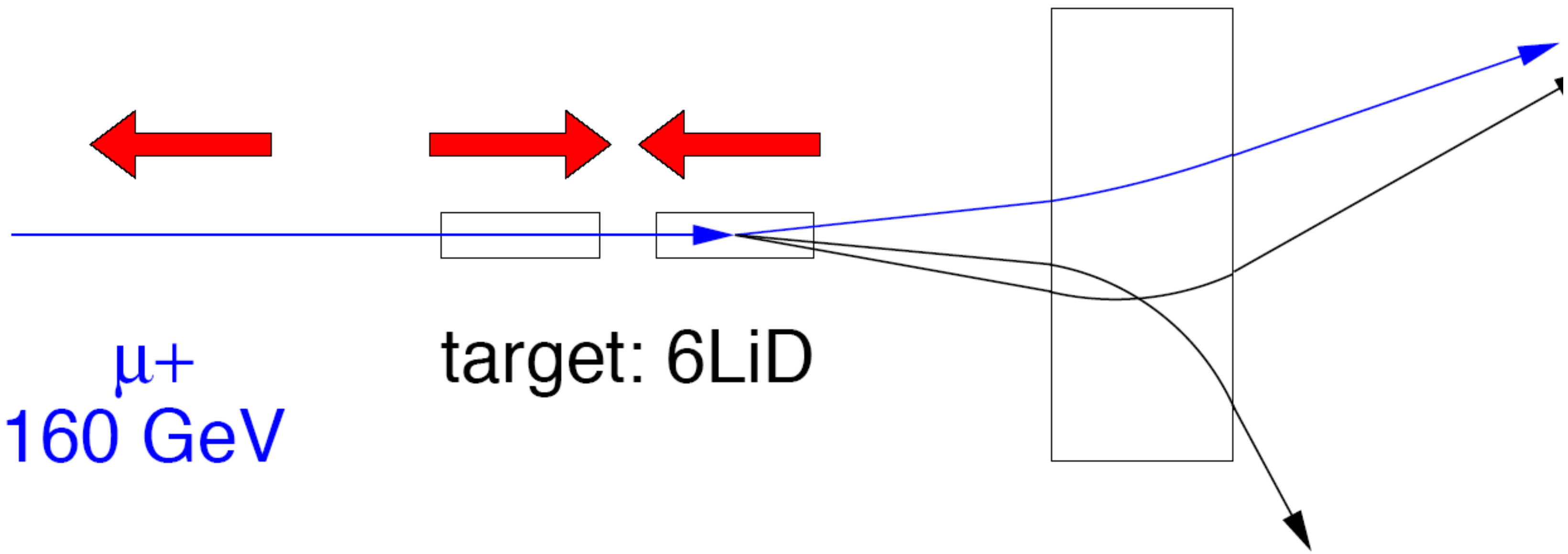
If all other things are equal,

they cancel in the ratio

$$A_{measured} = \frac{\sigma^{\rightarrow\leftarrow} - \sigma^{\rightarrow\rightarrow}}{\sigma^{\rightarrow\leftarrow} + \sigma^{\rightarrow\rightarrow}}$$

A Typical Setup

- Experiment setup (EMC, SMC, COMPASS@CERN)



- Target polarization direction reversed every 6-8 hrs
- Typically experiments try to limit false asymmetries to be about 10 times smaller than the physics asymmetry of interest

Experimental Needs in DIS

Polarized target, polarized beam

- Polarized targets: hydrogen (p), deuteron (pn), helium (^{3}He: 2p+n)
- Polarized beams: electron,muon used in DIS experiments

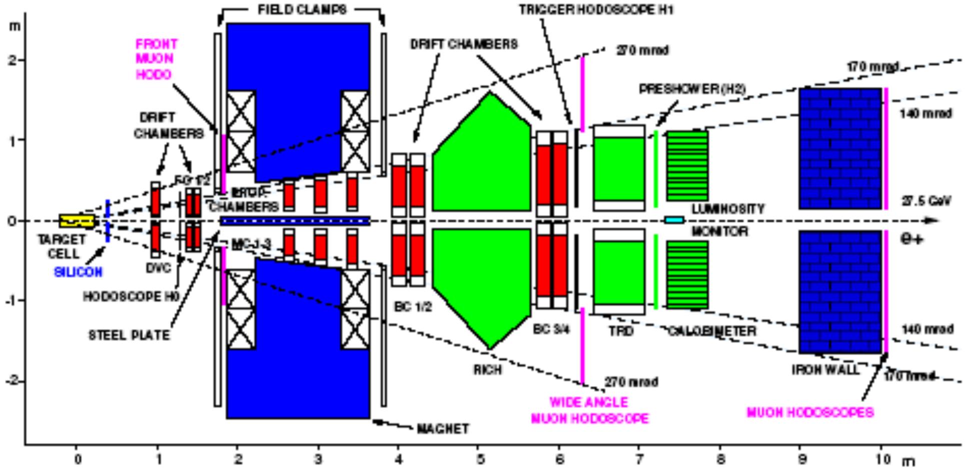
Determine the kinematics: measure with high accuracy:

- Energy of **incoming lepton**
- Energy, direction of **scattered lepton**: energy, direction
- Good identification of **scattered lepton**

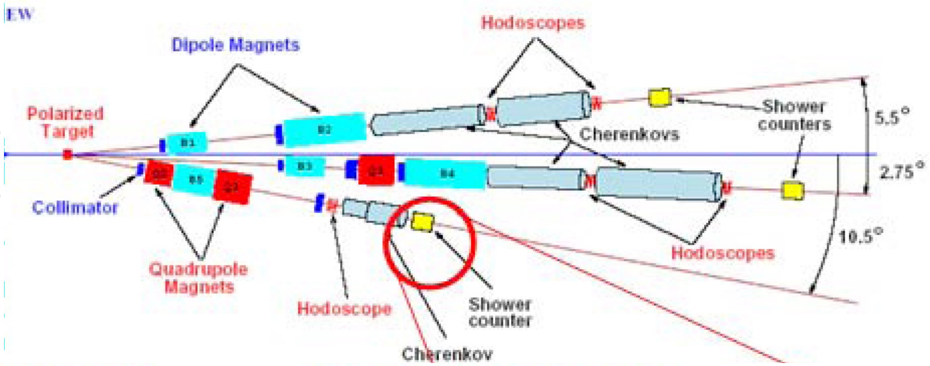
Control of false asymmetries:

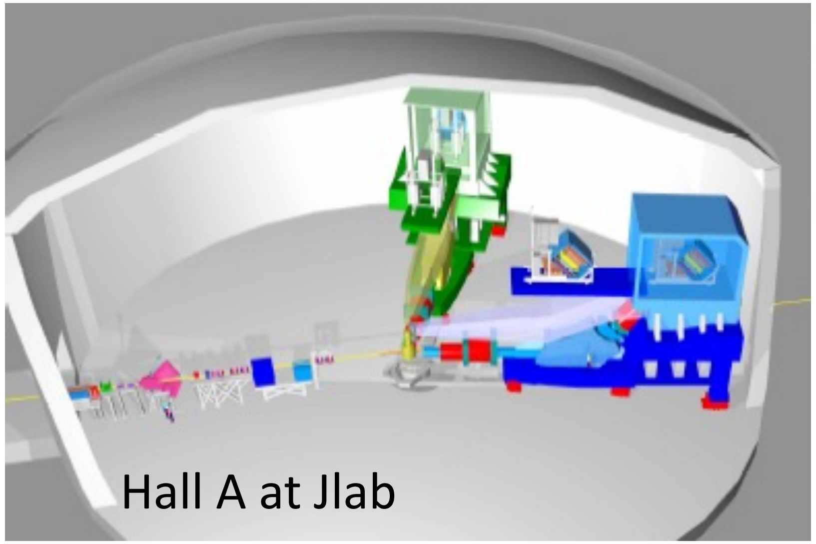
- Need excellent understanding and control of **false asymmetries** (time variation of the detector efficiency etc.)

Experiments



HERMES at DESY





Hall A at Jlab

- high energy beams
- large angular acceptance
- broad kinematical range

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

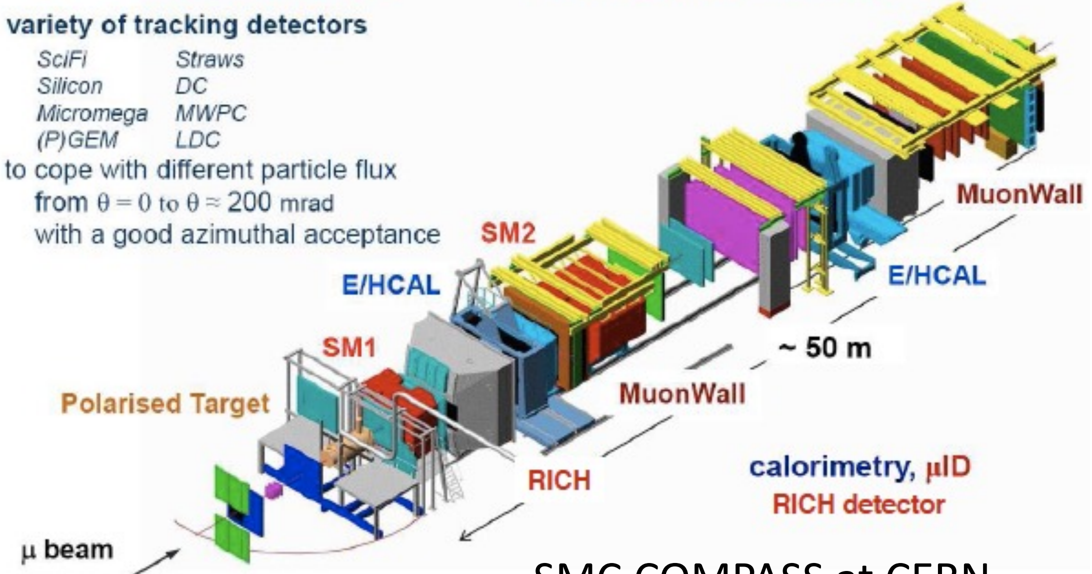
variety of tracking detectors

SciFi	*Straws*
Silicon	*DC*
Micromega	*MWPC*
(P)GEM	*LDC*

to cope with different particle flux

from $\theta = 0$ to $\theta \approx 200$ mrad

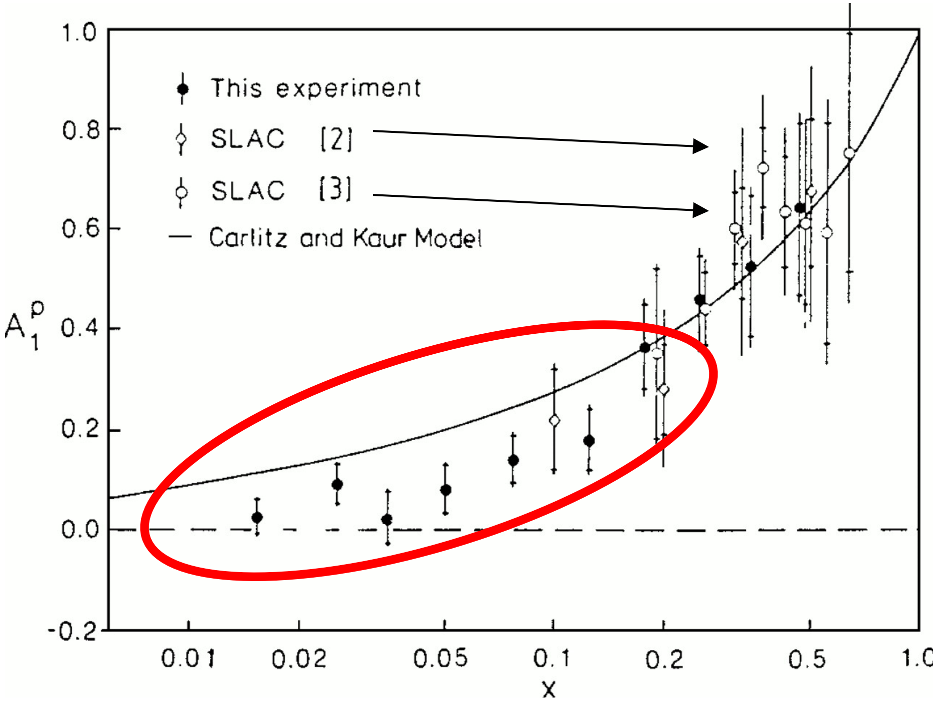
with a good azimuthal acceptance

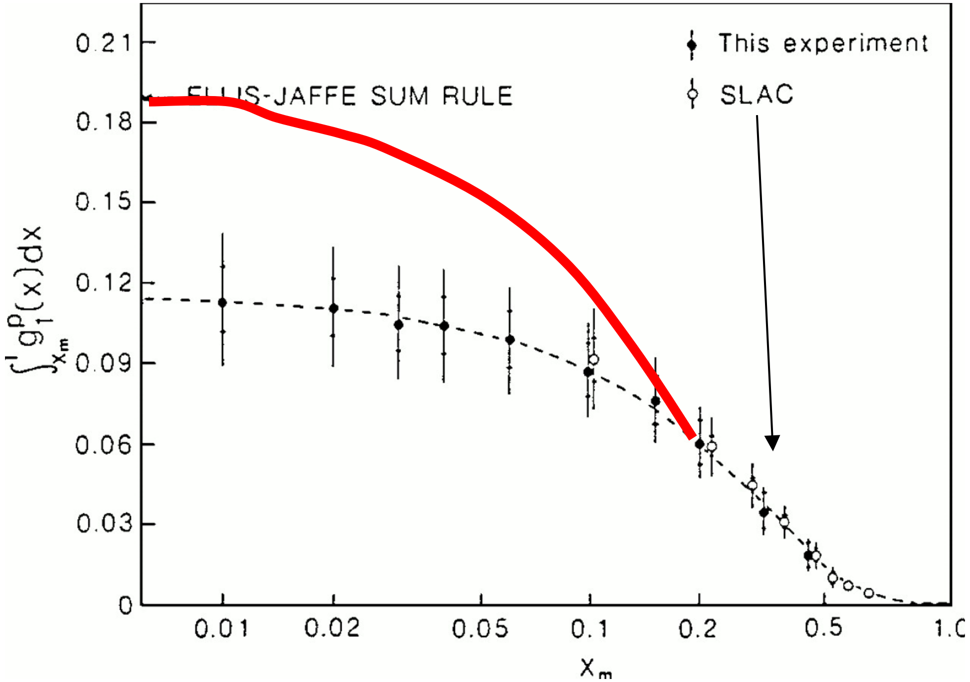


SMC,COMPASS at CERN

Proton Spin Crisis (1989)!

EMC experiment at CERN: high energy muon beam – reached lower x





$\Delta\Sigma/2 = (0.12)$ +/- (0.17) (EMC, 1989)

$\Delta\Sigma/2 = 0.58$ expected from E-J sum rule….

If the quarks did not carry the nucleon's spin, what did? → Gluons?

Consequence:

- Quark (+anti-quark) contribution to nucleon spin is small:

  $\rightarrow \frac{1}{2}\Delta\Sigma = 0.15 \pm 0.03$ instead of the expected 0.5
  - Is this smallness due to some cancellation between quark & anti-quark polarization?

- Or does glue makes a very large contribution? $\Delta G = 1 \pm 1.5$

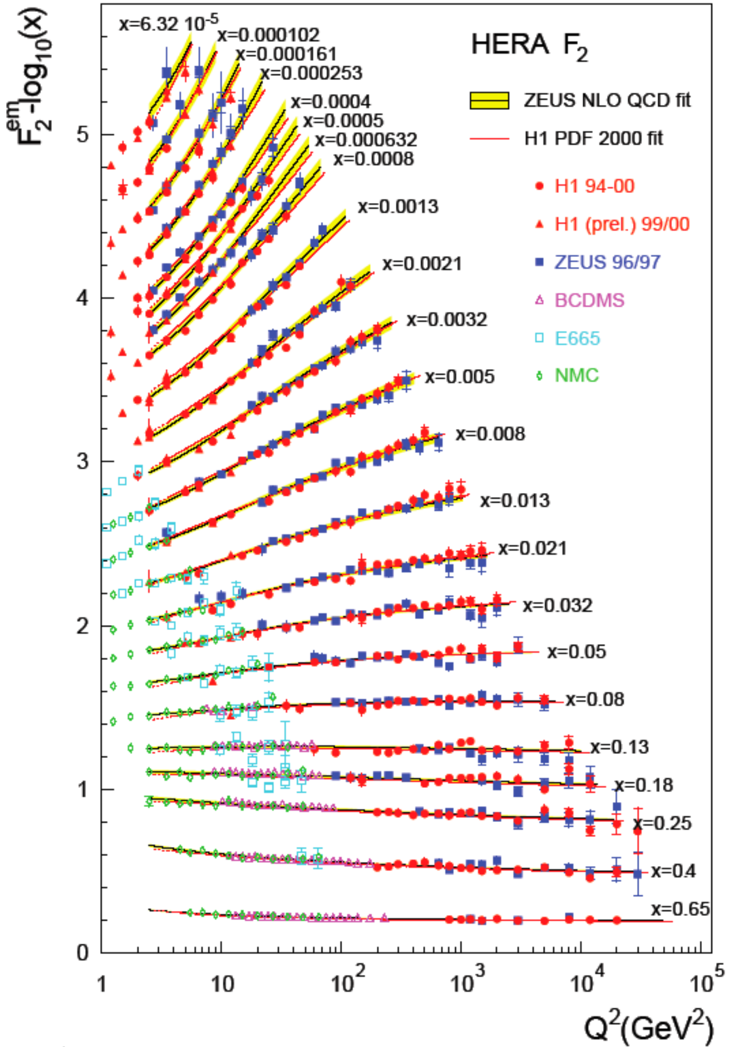
- Most NLO analyses by consistent with HIGH gluon contribution
  - Direct measurement of gluon spin with other probes warranted.
  - Seeded the RHIC Spin program

Measurement of unpolarized glue at HERA

F_2 Structure Function

Vs.

Q^2 mom. exchanged

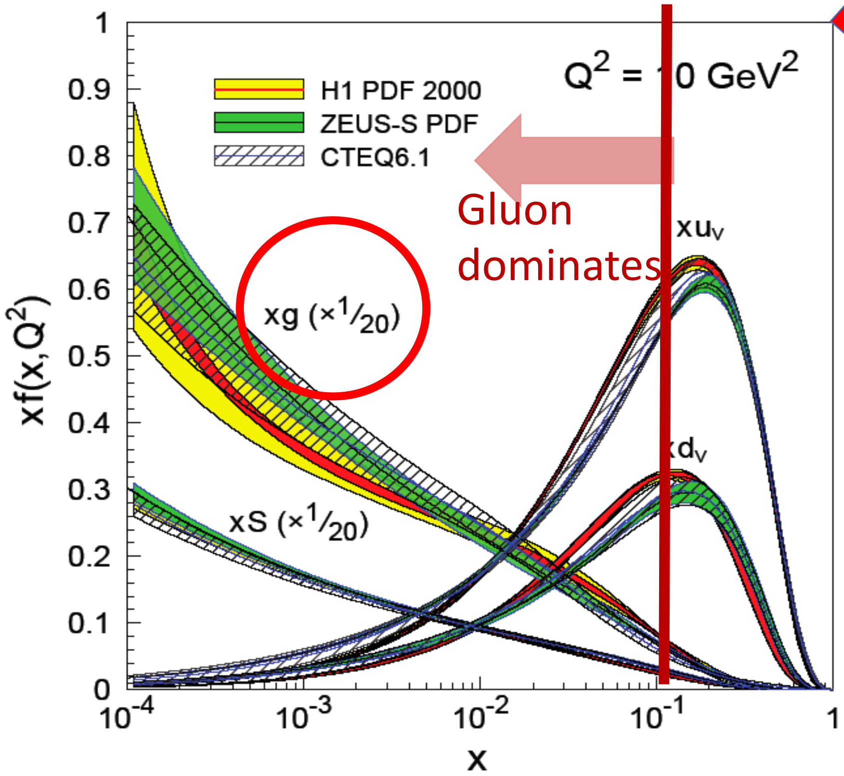


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

- Scaling violations of $F_2(x,Q^2)$

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

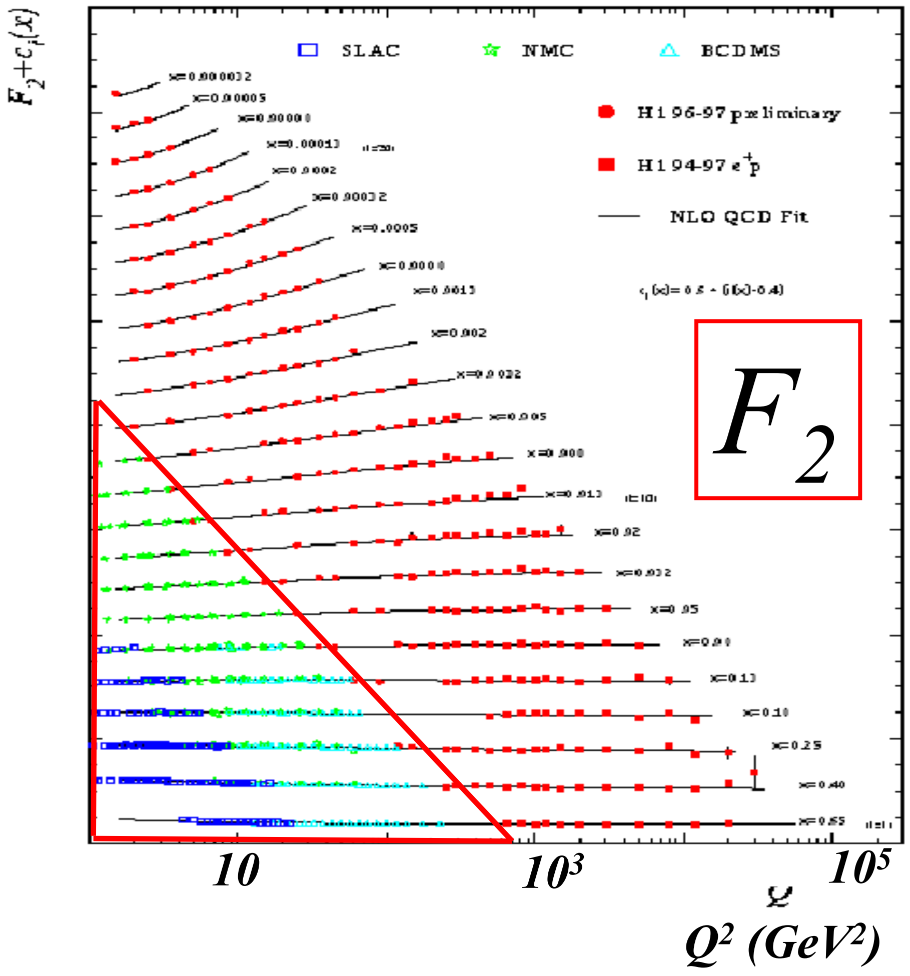
- NLO pQCD analyses: fits with **linear** DGLAP* equations



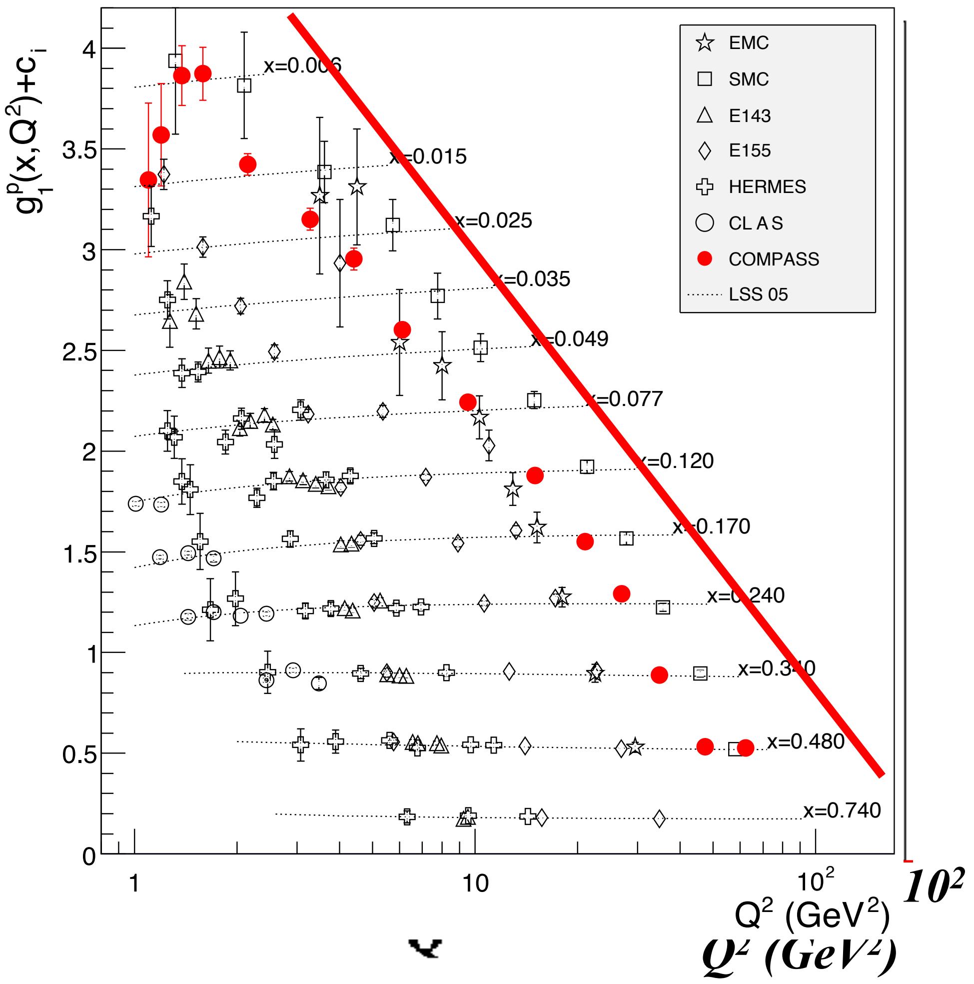
Can one do the same thing for spin structure function g_1?

Spin contribution of the gluon to the proton from scaling violation g_1 spin structure function?

F_2 vs. g_1 structure function measurements



Aidala et al.1209.2803v2

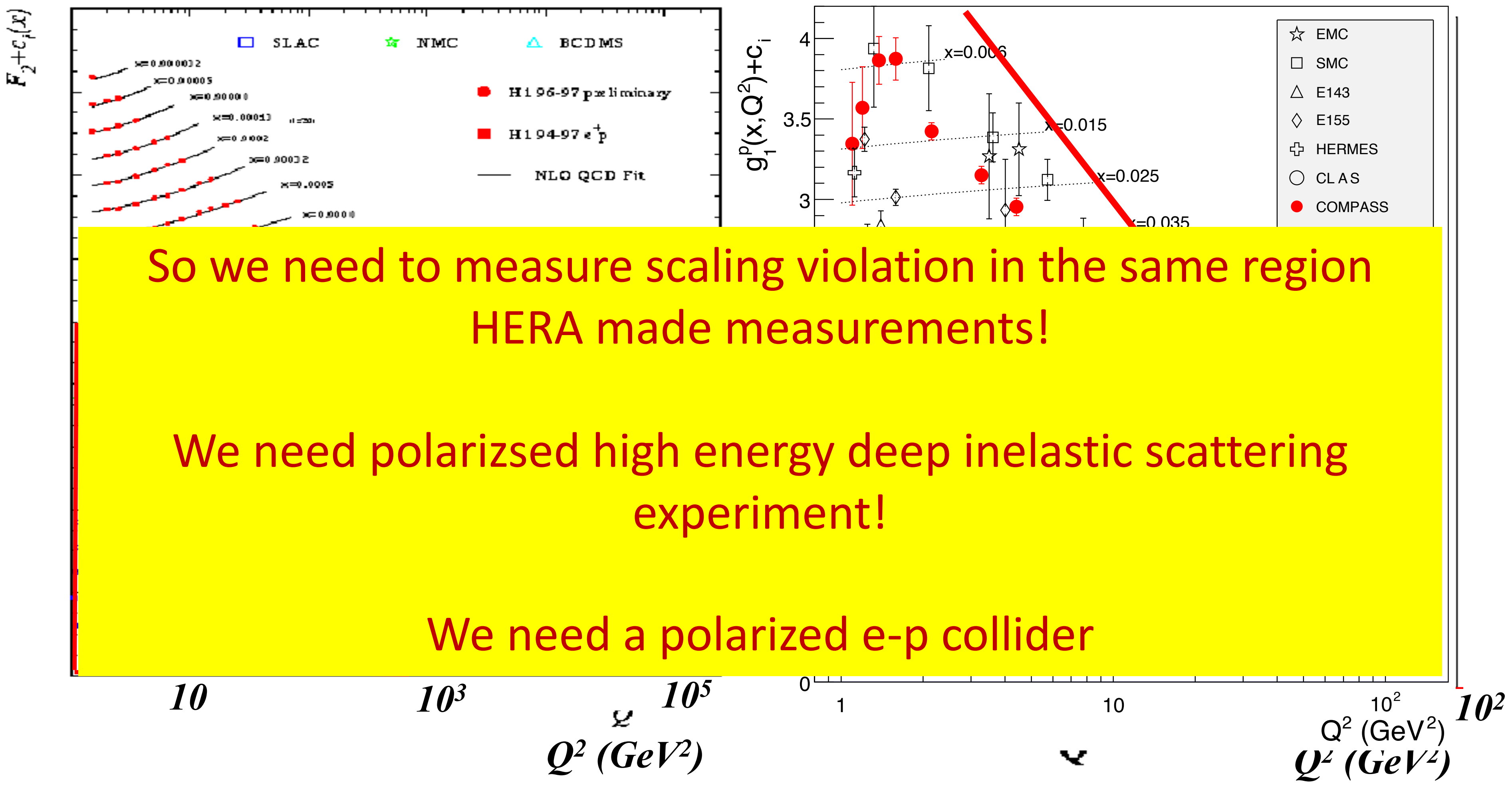


Large amount of polarized data since 1998… but not in NEW kinematic region!

Large uncertainty in gluon polarization (+/-1.5) results from lack of wide Q^2 arm

F_2 vs. g_1 structure function measurements

Aidala et al.1209.2803v2



So we need to measure scaling violation in the same region HERA made measurements!

We need polarizsed high energy deep inelastic scattering experiment!

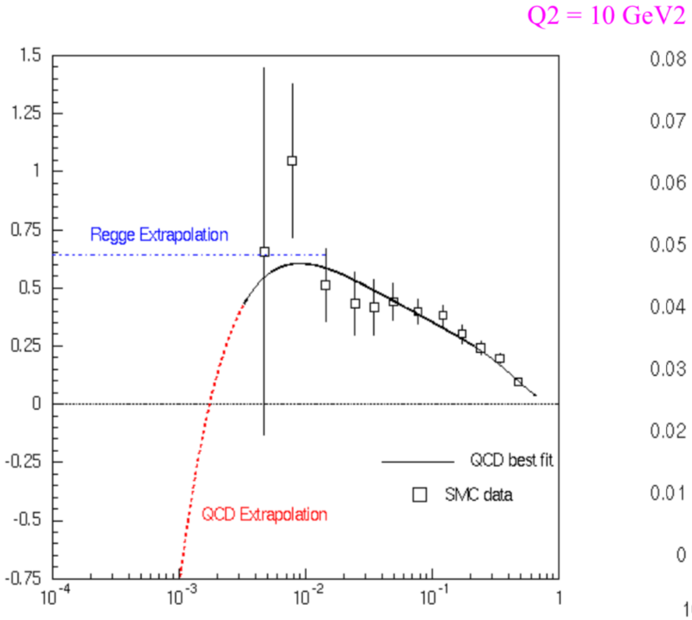
We need a polarized e-p collider

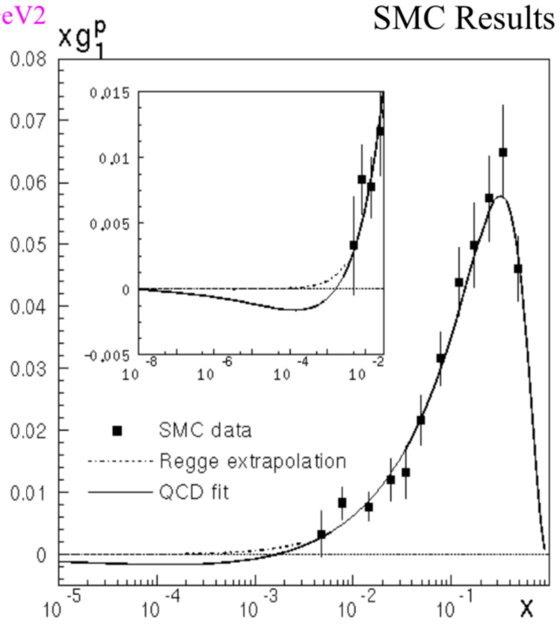
Large amount of polarized data since 1998… but not in NEW kinematic region!

Large uncertainty in gluon polarization (+/-1.5) results from lack of wide Q^2 arm

Recall from “EIC A Dream to Reality” on Day 1

Lack of low x data… consequences





- Regge extrapolation:

$$\int_0^{0.003} g_1^p(x,Q_0^2)dx = 0.002 \pm 0.002$$

- QCD fit extrapolation:

$$\int_0^{0.003} g_1^p(x,Q_0^2)dx = -0.011 \pm 0.011$$

$$g_1(x \to 0) \propto x^{\alpha} \quad \text{as } 0 < \alpha < 0.5$$

Regge/QCD

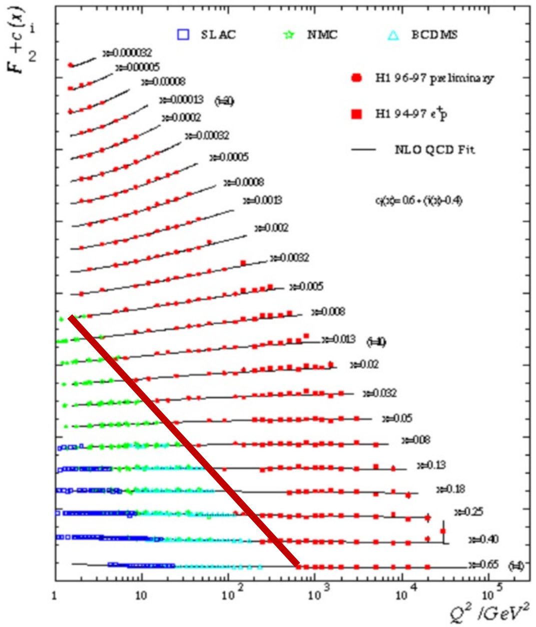
In these discussions, while many focused on the low-x Extrapolations.

SMC PRD98 (112002) 1998

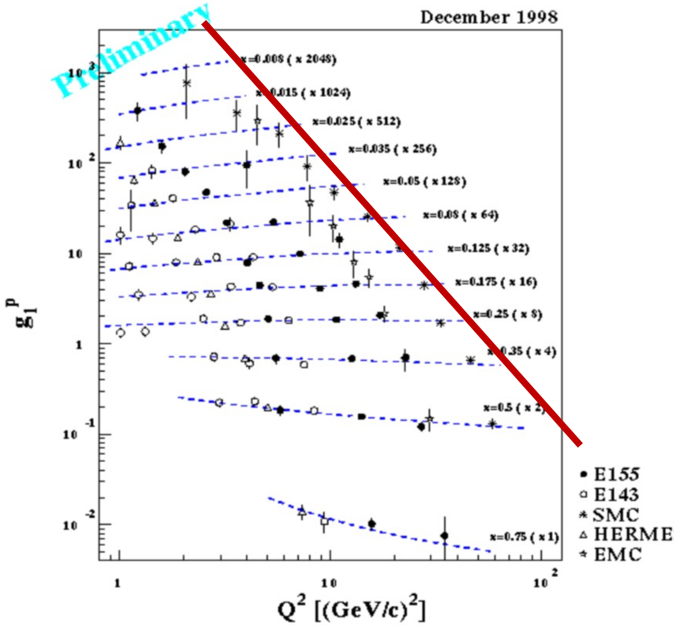
Seeds for a **polarized collider**

How far does polarized DIS have to go!

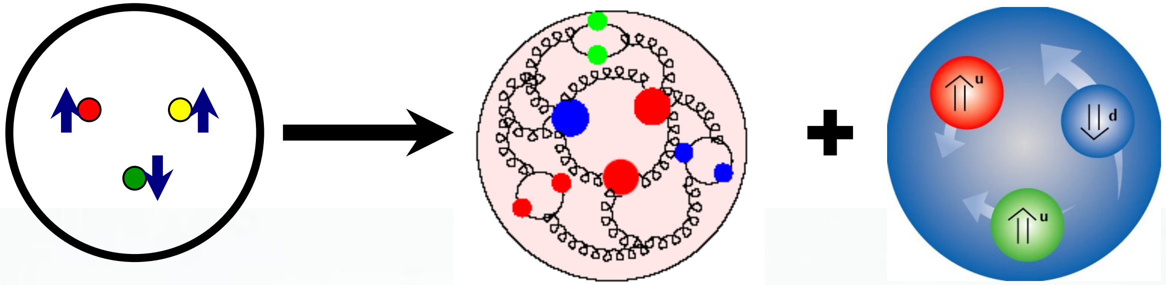
World data on F_2^p



World data on g_1^p



Our Understanding of Nucleon Spin Puzzle



1980s

1990/2000s

$\Delta\Sigma /2 = 0.12 +/- 0.17$

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

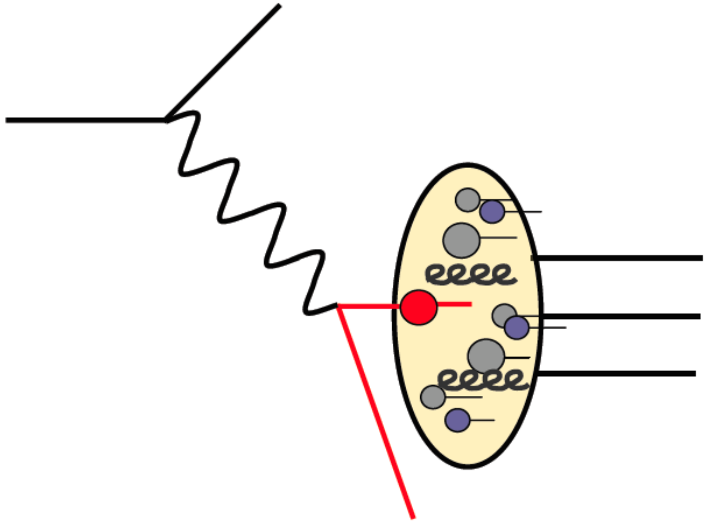
Need information about transverse dimensions of the proton

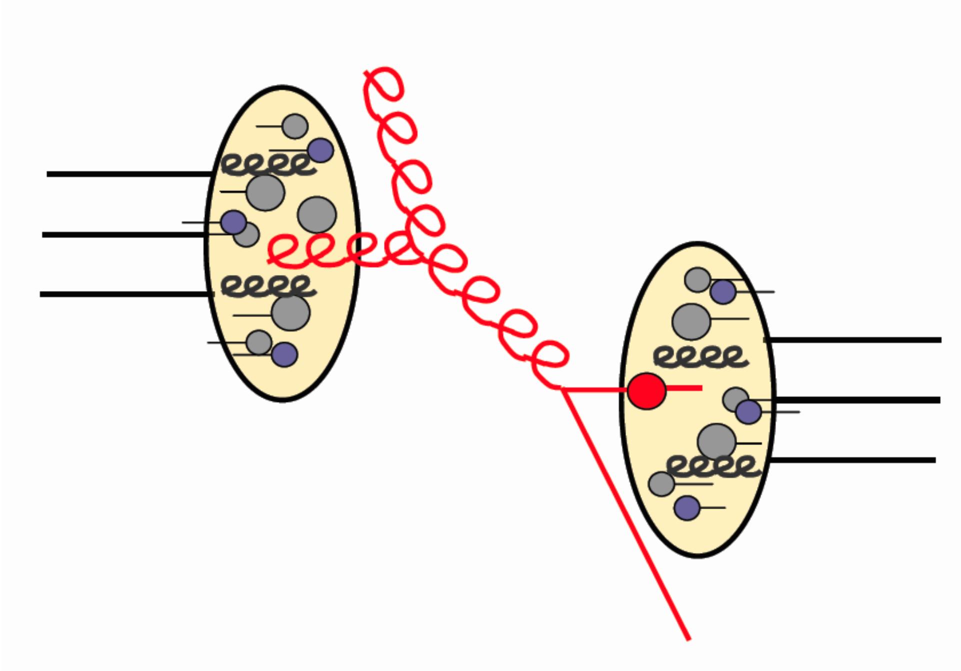
Spin discovered a problem…. What now? Need precision and investigations of gluons….

RHIC Spin program: a polarized collider

Pre-cursor to a polarized e-p --- Electron Ion Collider

Complementary techniques



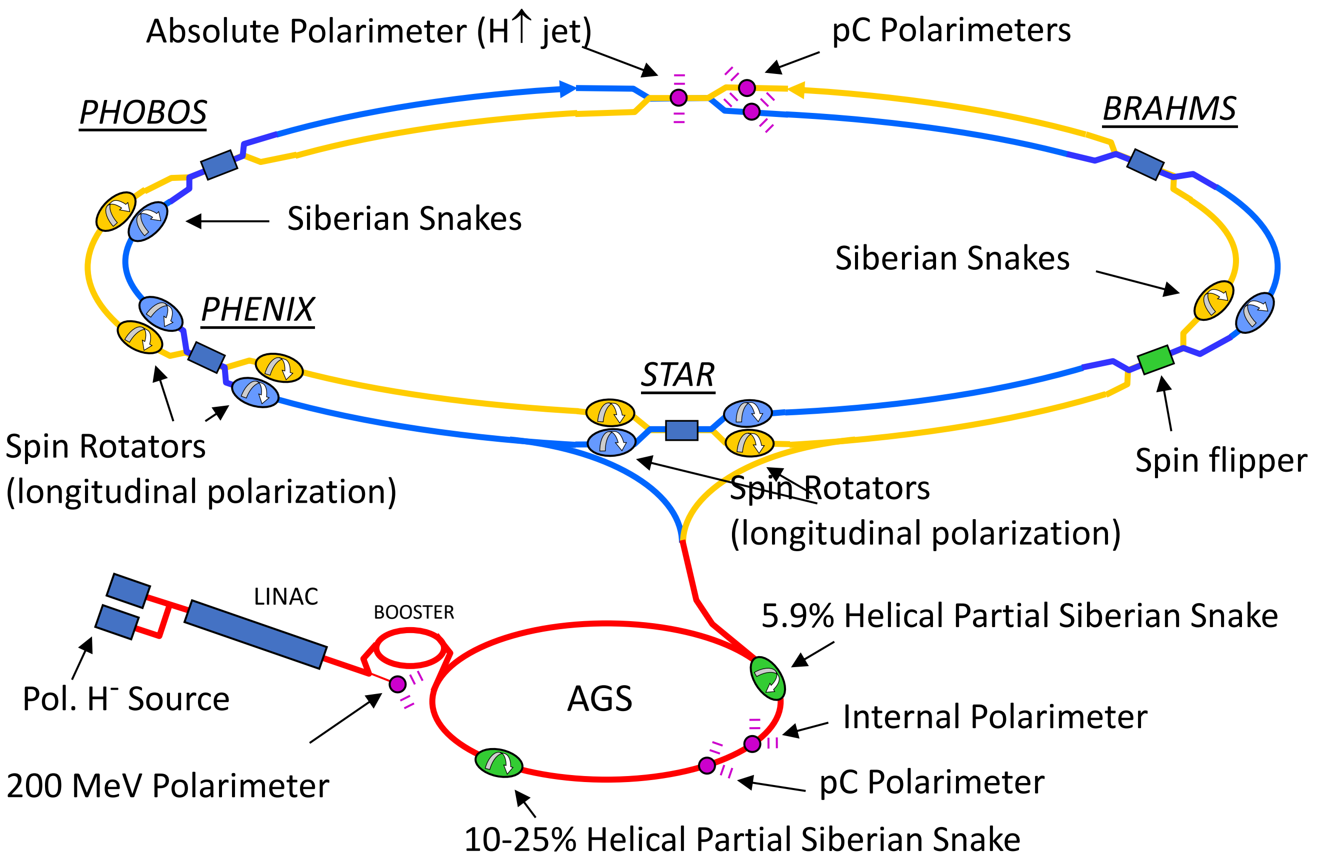


Photons colorless: forced to interact at NLO with gluons

Can't distinguish between quarks and anti-quarks either

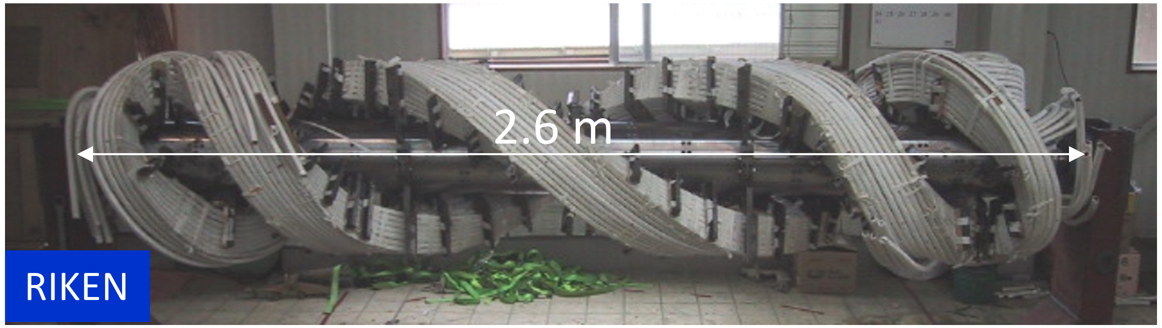
Why not use polarized quarks and gluons abundantly available in protons as probes ?

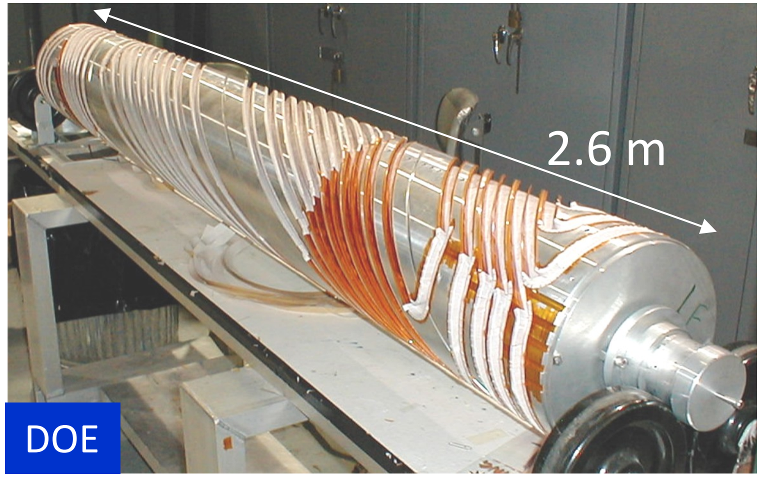
RHIC as a Polarized Proton Collider



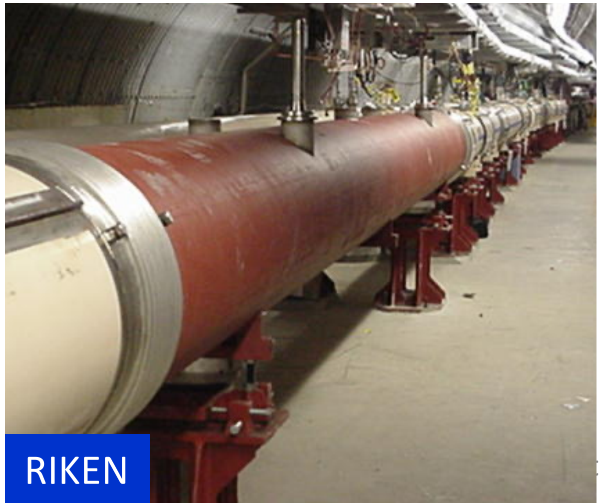
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

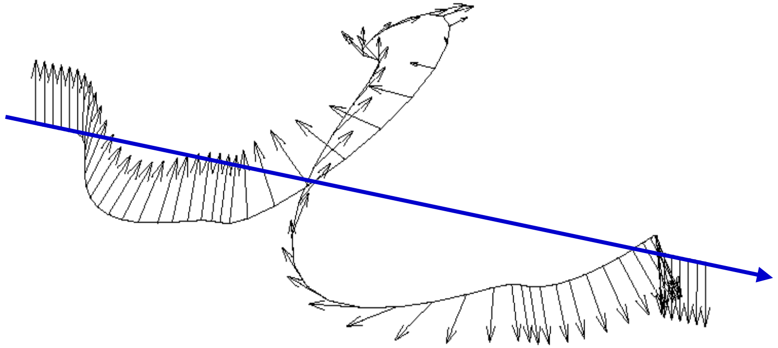
Siberian Snakes



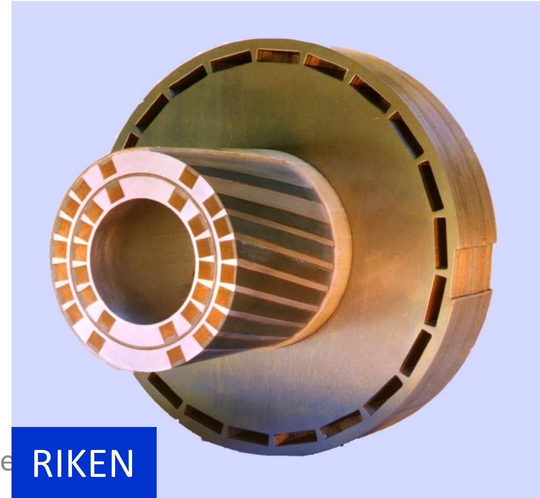


- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist





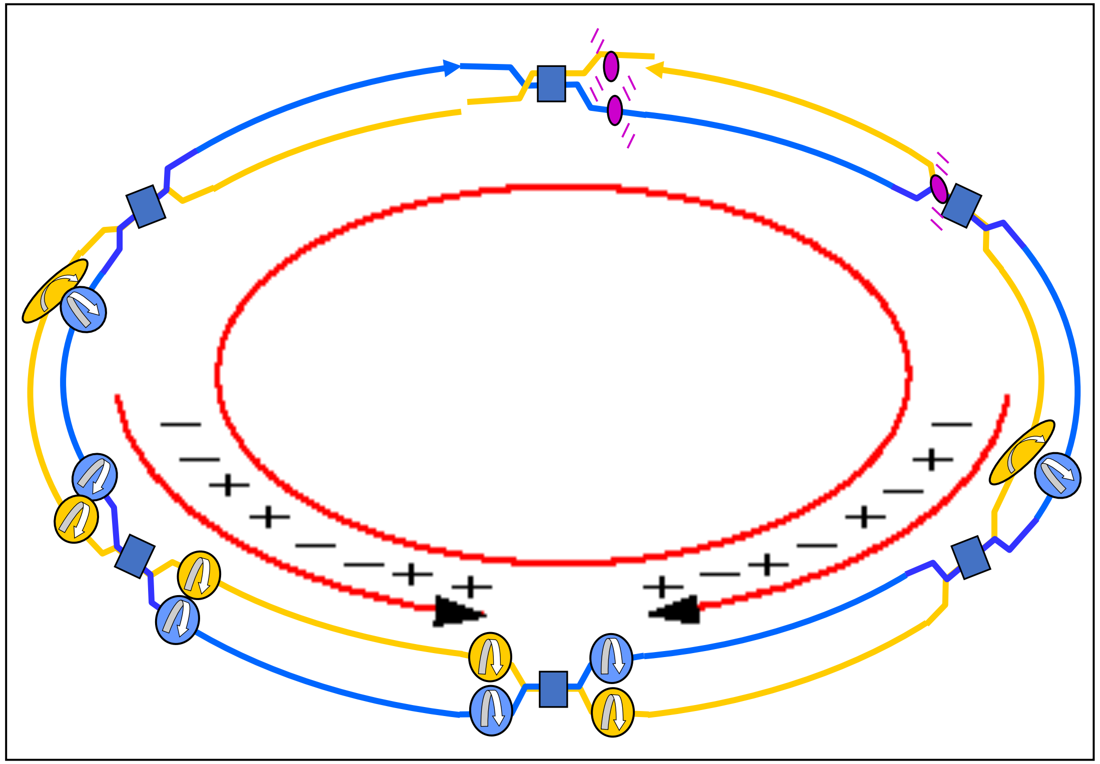
Courtesy of A. Luccio



Measuring A_{LL}

Longitudinal Spin Asymmetry using polarized proton bunches in the RHIC ring

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|}\frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$



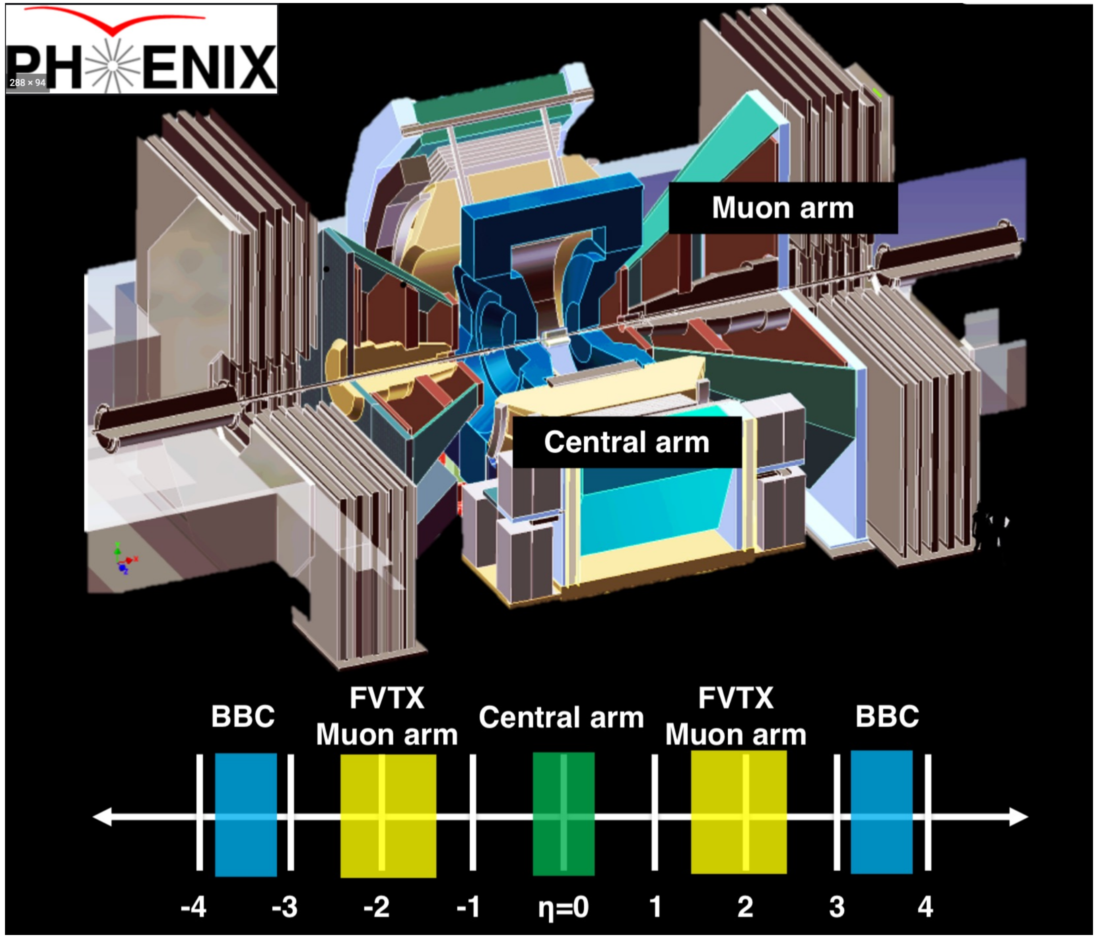
(N) Yield
(R) Relative Luminosity
(P) Polarization

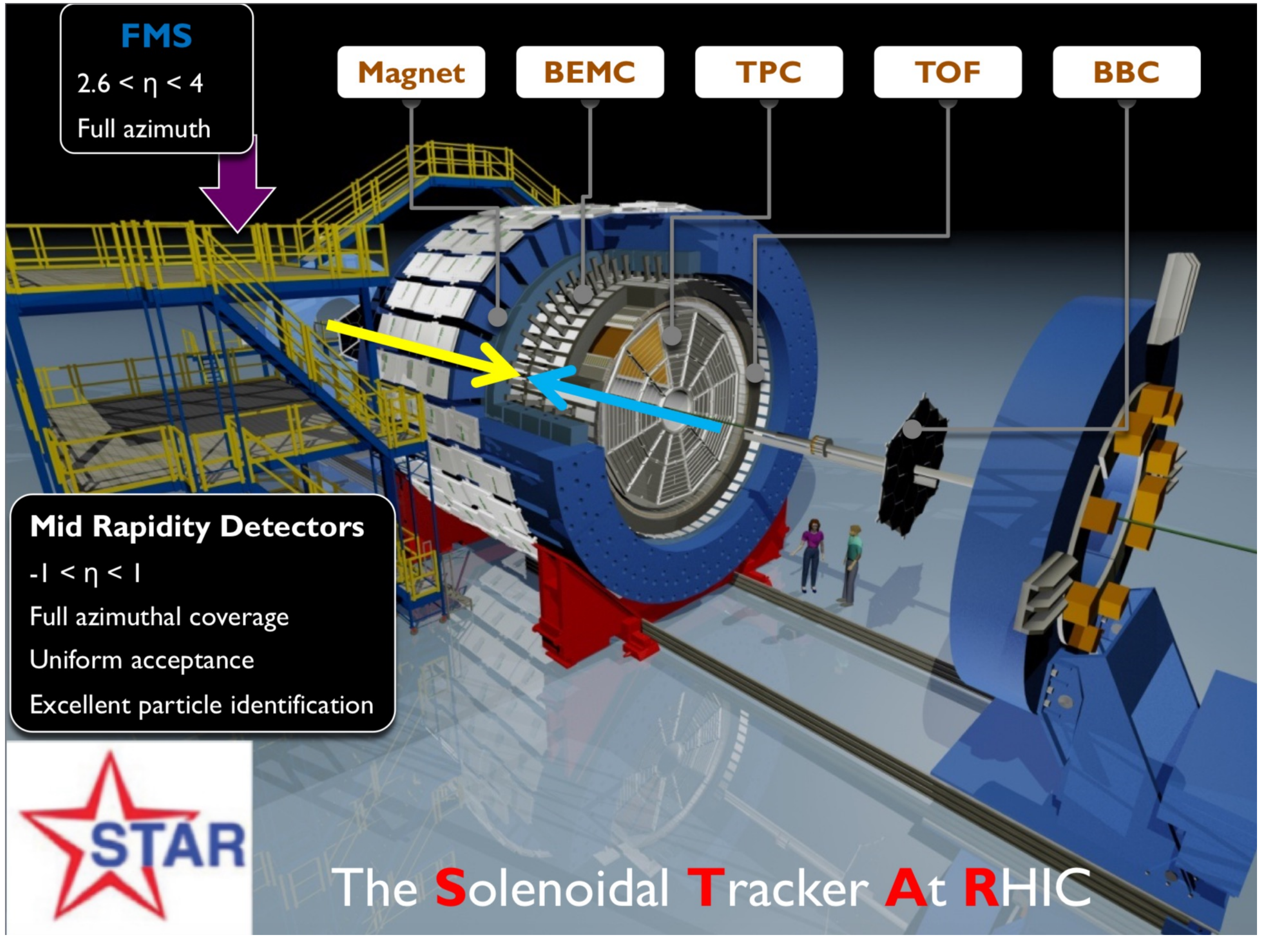
Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

- ✓ Bunch spin configuration alternates every 106 ns
- ✓ Data for all bunch spin configurations are collected at the same time

⇒ Possibility for false asymmetries are greatly reduced

Two main detectors for spin studies

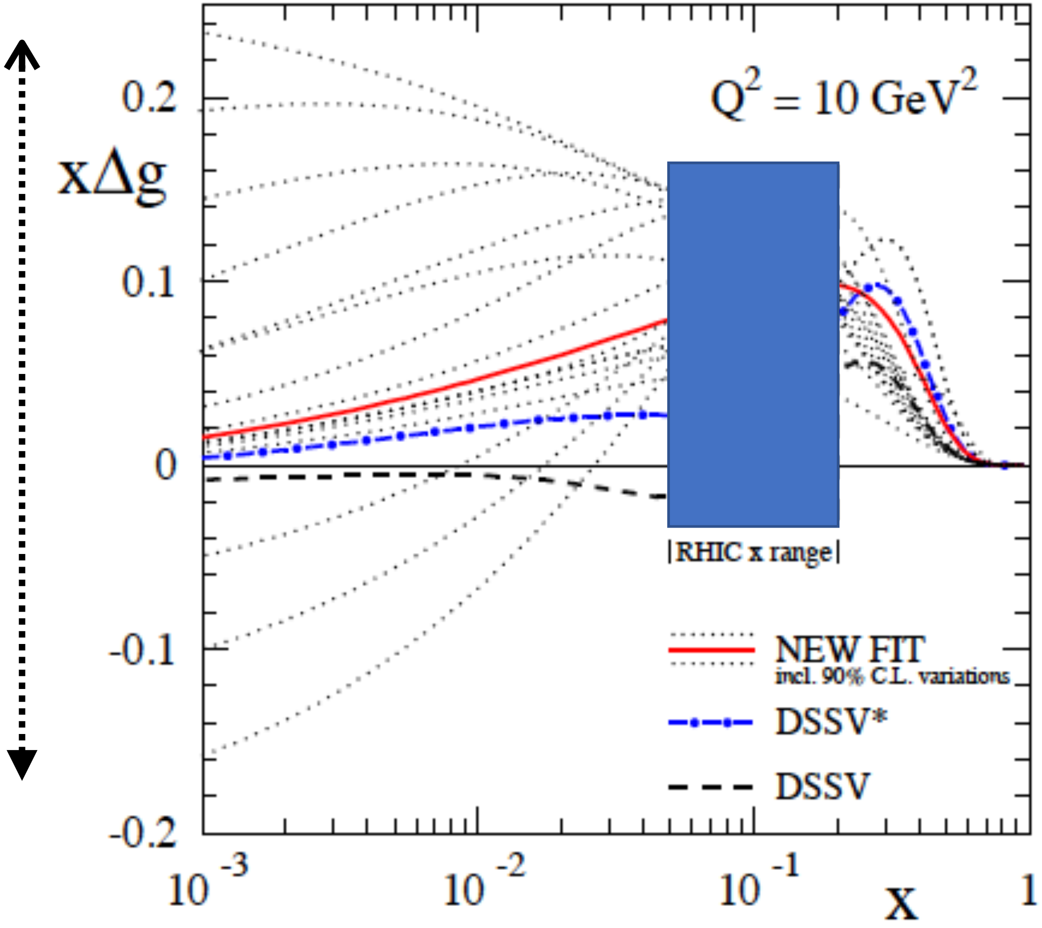




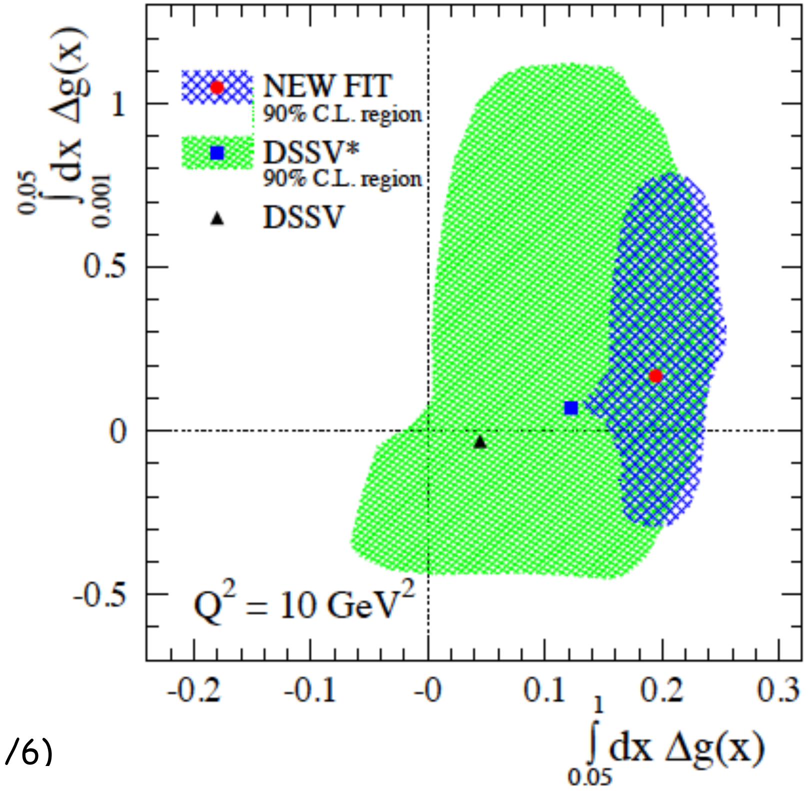
Recent global analysis: DSSV

D. deFlorian et al., arXiv:1404.4293

Wide spread at low x (x<0.05) of alternative fits consistent within 90% of C.L.



$\Delta G = 0.2$ +/- 0.02 +/- 0.5



/6)

While RHIC made a huge impact on ΔG

large uncertainties to remain in the low-x unmeasured region!

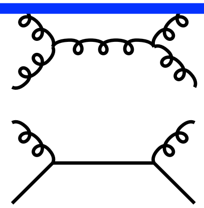
2009 RHIC data established non-zero ΔG

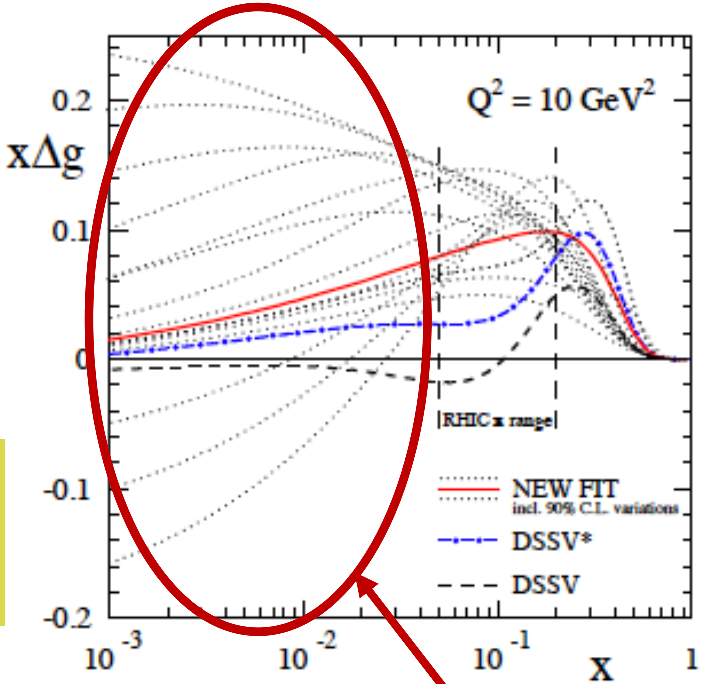
-- PHENIX 2005-9, PRD 90, 12007 (2014)

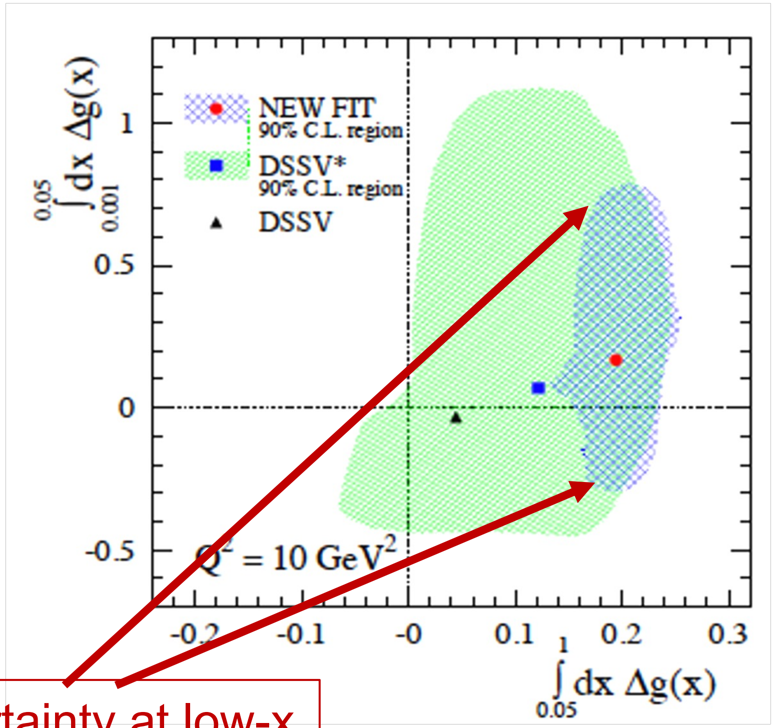
-- STAR 2009, PRL 115 (2015) 92002

-- DSSV PRL (113) 12001 (2014)

$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ \mathrm{GeV}^2$$

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)



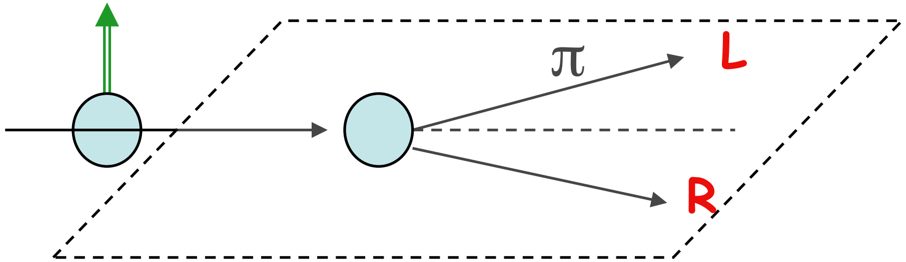


Large uncertainty at low-x

Transverse Spin effects in p-p observed but ignored for 40+ years

Recent developments and state of the art in Alessandro Bacchetta’s and Silvia Dalla Torre’s lectures

Transverse spin introduction



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

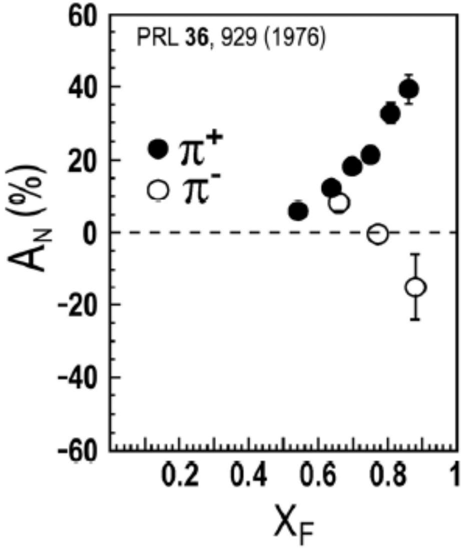
Kane, Pumplin and Repko
PRL 41 1689 (1978)

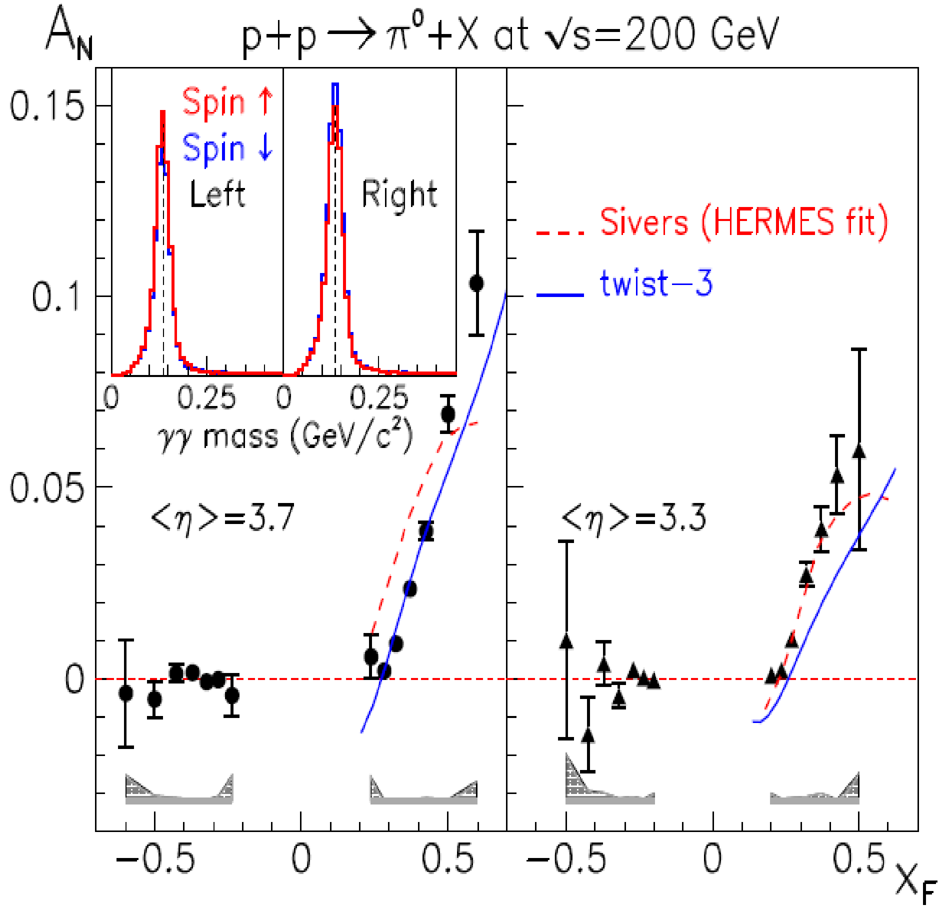
- Since people focused at high p_T to interpret them in pQCD frameworks, this (expected small effect) was "neglected However….

- Pion production in single transverse spin collisions showed us something different….

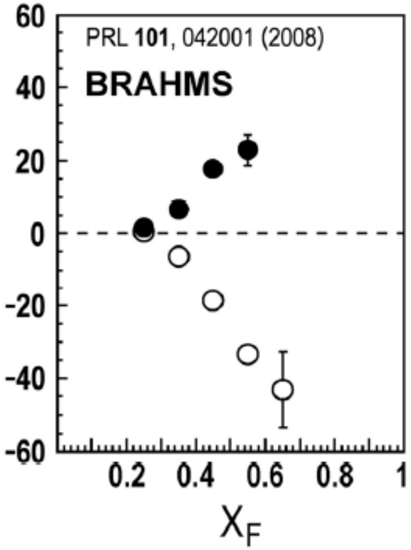
Pion asymmetries: at broad range in CM energies!

ZGS/ANL
√s=4.9 GeV





RHIC
√s=62.4 GeV

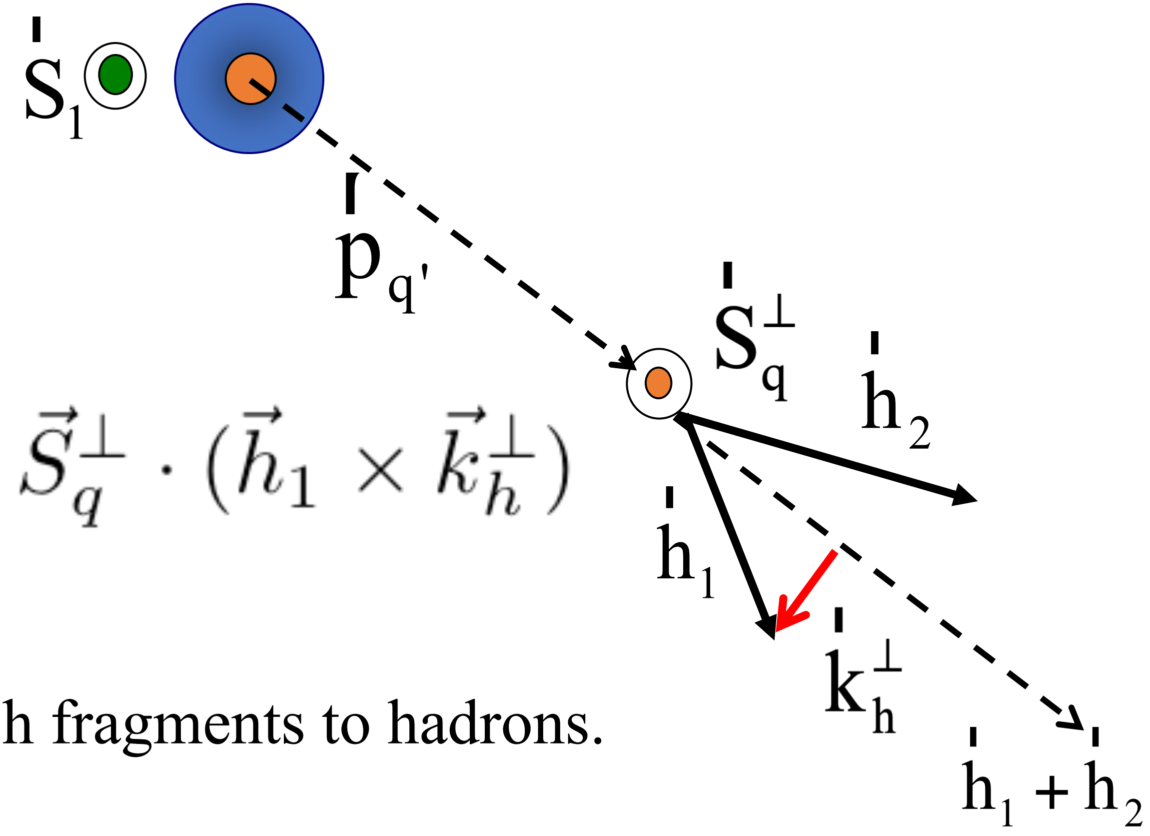


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well ➔ **0.001 expected 0.2-0.6 observed at all Center of Mass Energies**

What could be the origin of such effect?
Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

Nucl Phys B396 (1993) 161,
Nucl Phys B420 (1994) 565

Example: $\boxed{p^{\uparrow} + p \rightarrow h_1 + h_2 + X}$

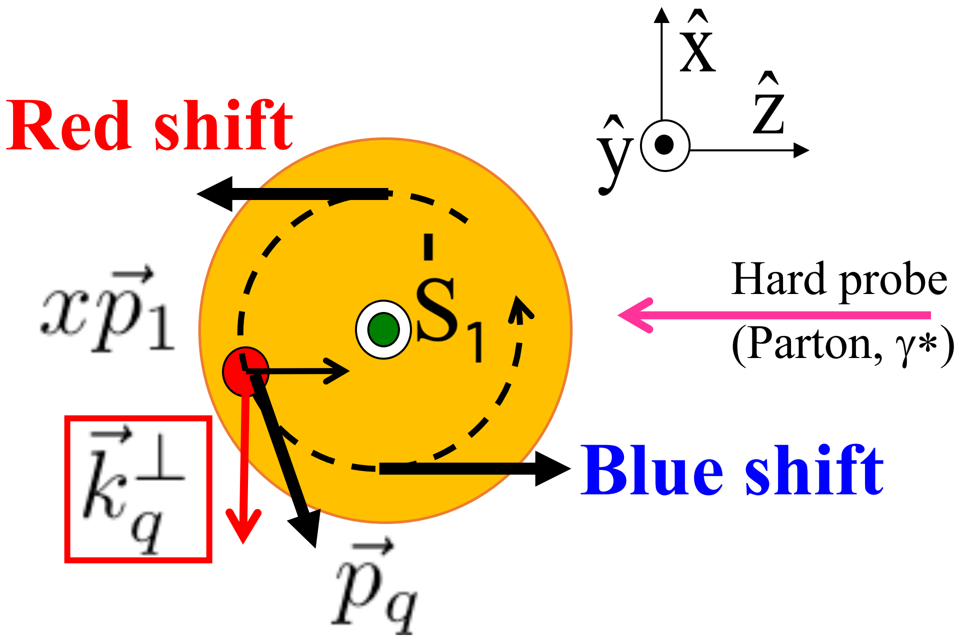


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

Polarization of struck quark which fragments to hadrons.

Other possibility: What does "Sivers effect" probe?

Top view, Breit frame



Quarks orbital motion adds/ subtracts longitudinal momentum for negative/positive $\hat{x}$.

PRD66 (2002) 114005

Parton **D**istribution **F**unctions rapidly fall in longitudinal momentum fraction x.

Final **S**tate **I**nteraction between outgoing quark and target spectator.

Sivers function

$f_{1T}^{\perp}(x, \vec{k}_q^{\perp})$

hep-ph/ 0703176

Quark Orbital angular momentum

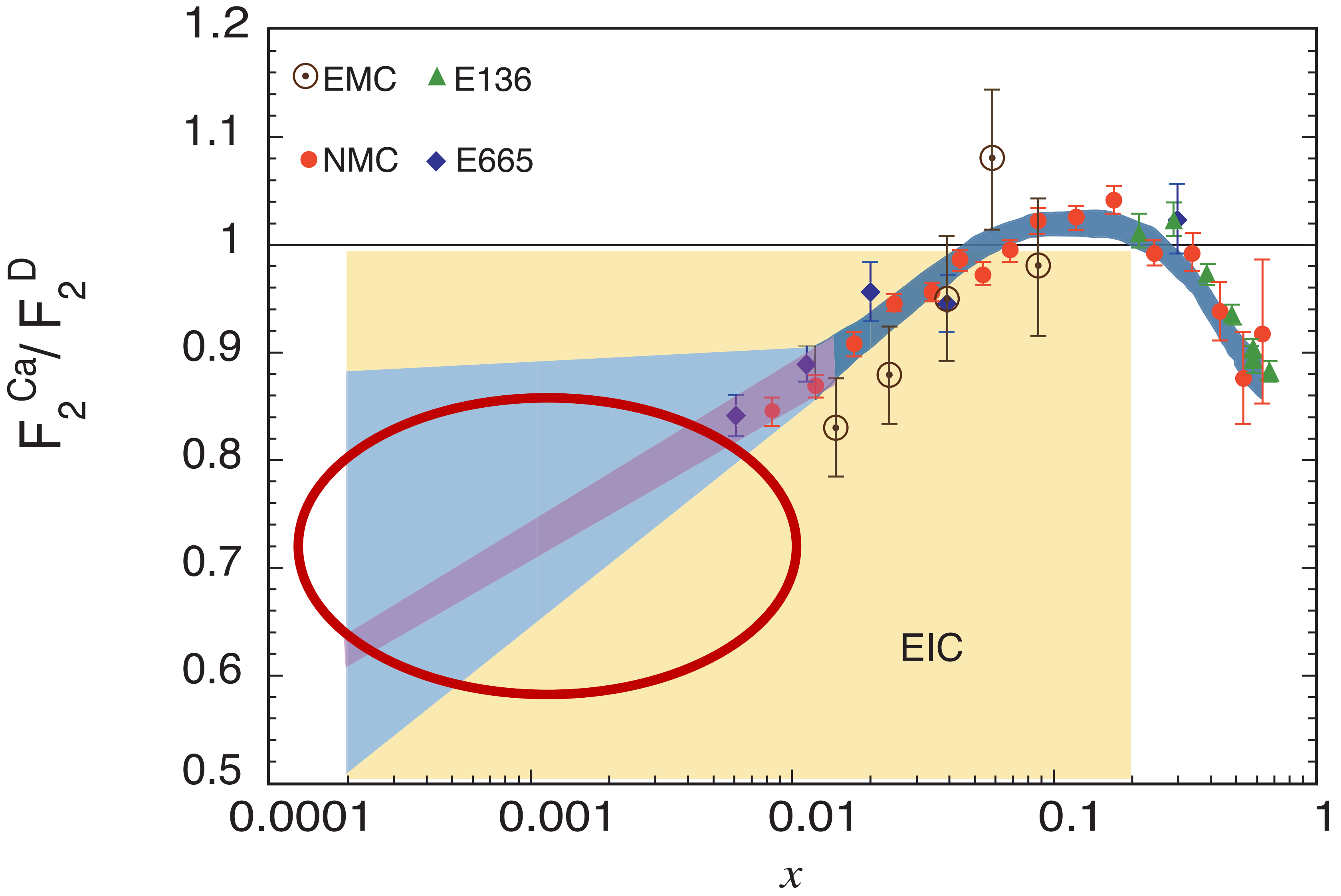
Generalized **P**arton **D**istribution **F**unctions

PRD59 (1999) 014013

Lepton nucleus scattering for understanding the nuclear structure and dynamics:

Nuclear structure a known unknown….

PDFs in nuclei are different than in protons!



Since 1980's we know the ratio of F_2's of nuclei to that of Deuteron (or proton) are different.

Nuclear medium modifies the PDF's.

Fair understanding of what goes on, in the x > 0.01.

However, what happens at low x?

Does this ratio saturate? Or keep on going? – Physics would be very different depending on what is observed.

Data needed at low-x

Lessons learned:

- Proton and neutrons spin *not just* alignment of quarks and gluons….
  - Proton's spin is complex: alignment of quarks + **gluons and orbital motion**
- To fully understand proton structure (including the above partonic dynamics)
  - one needs to explore over a **broader x-Q2 range** (not in fixed target but in collider experiment) Low-x behavior of gluons in proton also needed
  - Need *polarized* protons and electrons in colliders

- Low x behavior of partons in Nuclei essential to complete our understanding of structure of matter…
- To understand the nuclear fragments – target fragment – one needs to measure e-A in a collider geometry

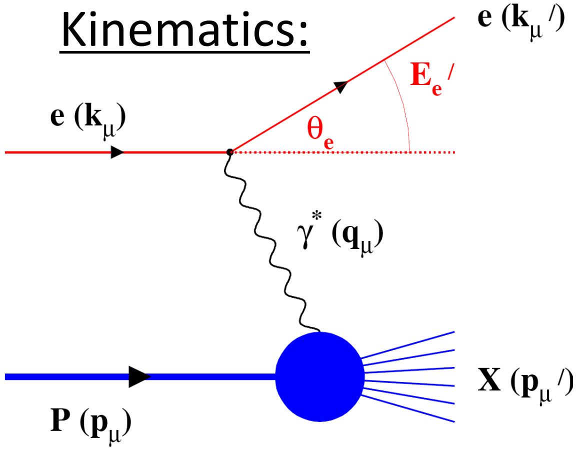
We need a new high-luminosity polarized **e-p/A** collider….

Lecture 2:
Physics and Status of EIC

Abhay Deshpande

Deep Inelastic Scattering: Precision and control

Kinematics:



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

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

Measure of resolution power

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

Measure of inelasticity

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

Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu}; p_t$$ with respect to γ^*

$$s = 4\,E_h\,E_e$$

High lumi & acceptance

Exclusive DIS

detect & identify *everything* e+p/A → e'+h(π,K,p,jet)+…

Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets

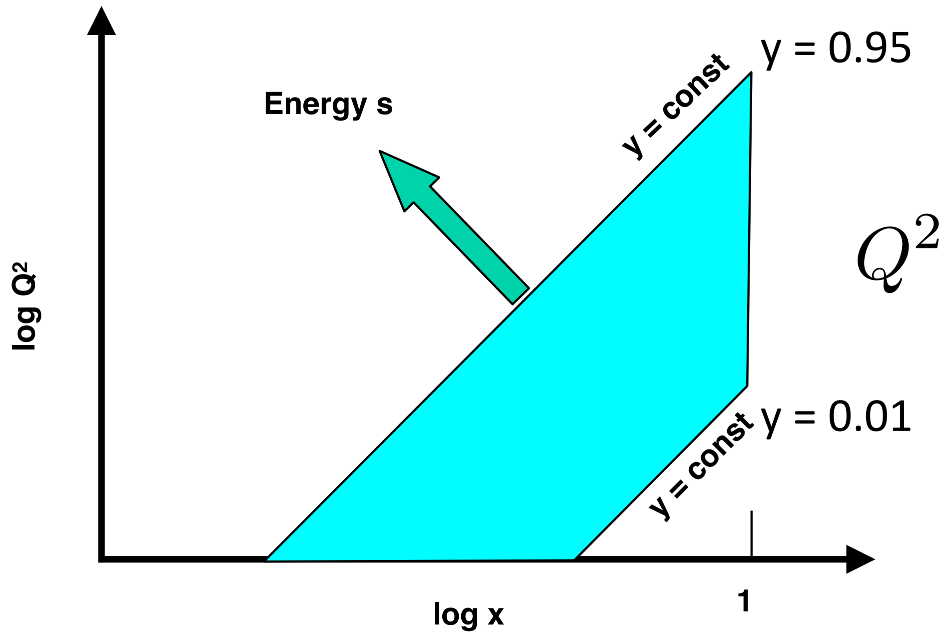
Inclusive events:

e+p/A → e'+X

detect *only the scattered lepton* in the detector

Low lumi & acceptance

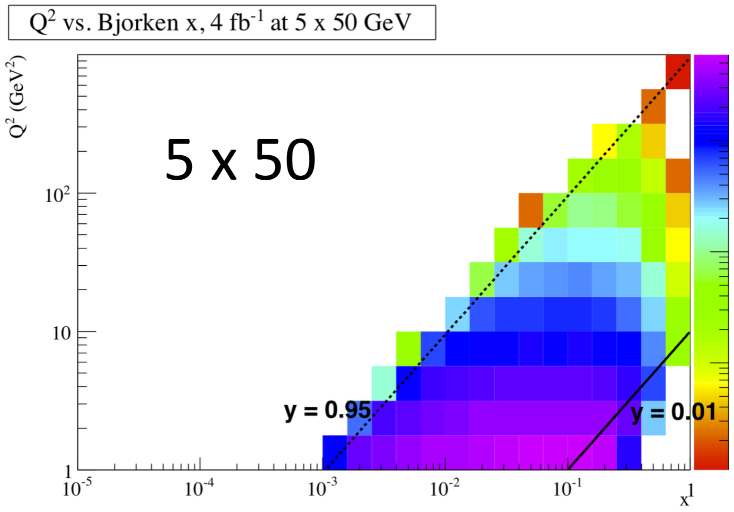
The x-Q^2 plane…

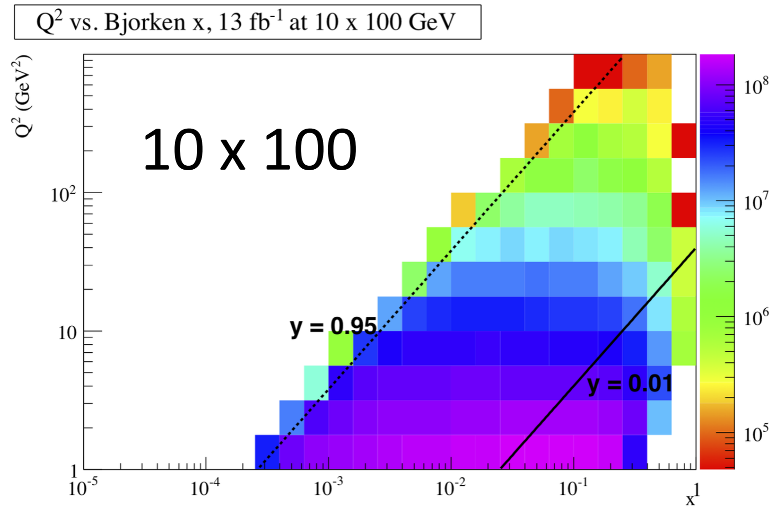


$$Q^2 \approx s \cdot x \cdot y$$

- Low-x reach requires large √*s*
- Large-Q^2 reach requires large √*s*
- *y* at colliders typically limited to $0.95 < y < 0.01$

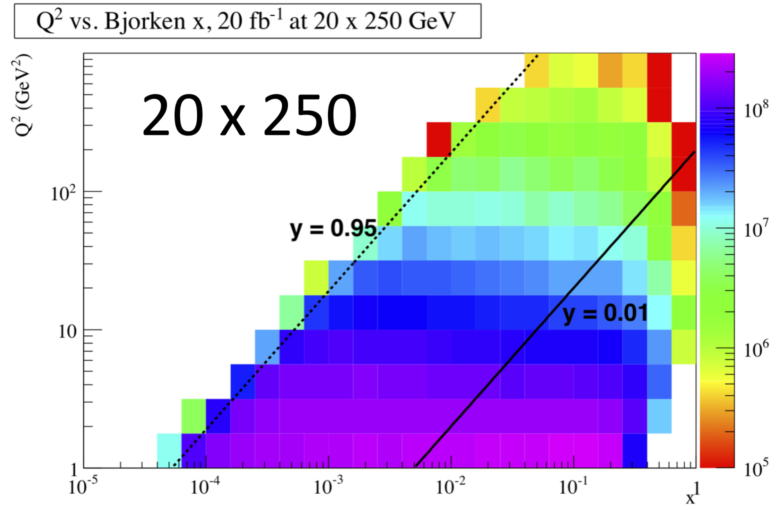
Kinematic coverage as a function of energy of collisions





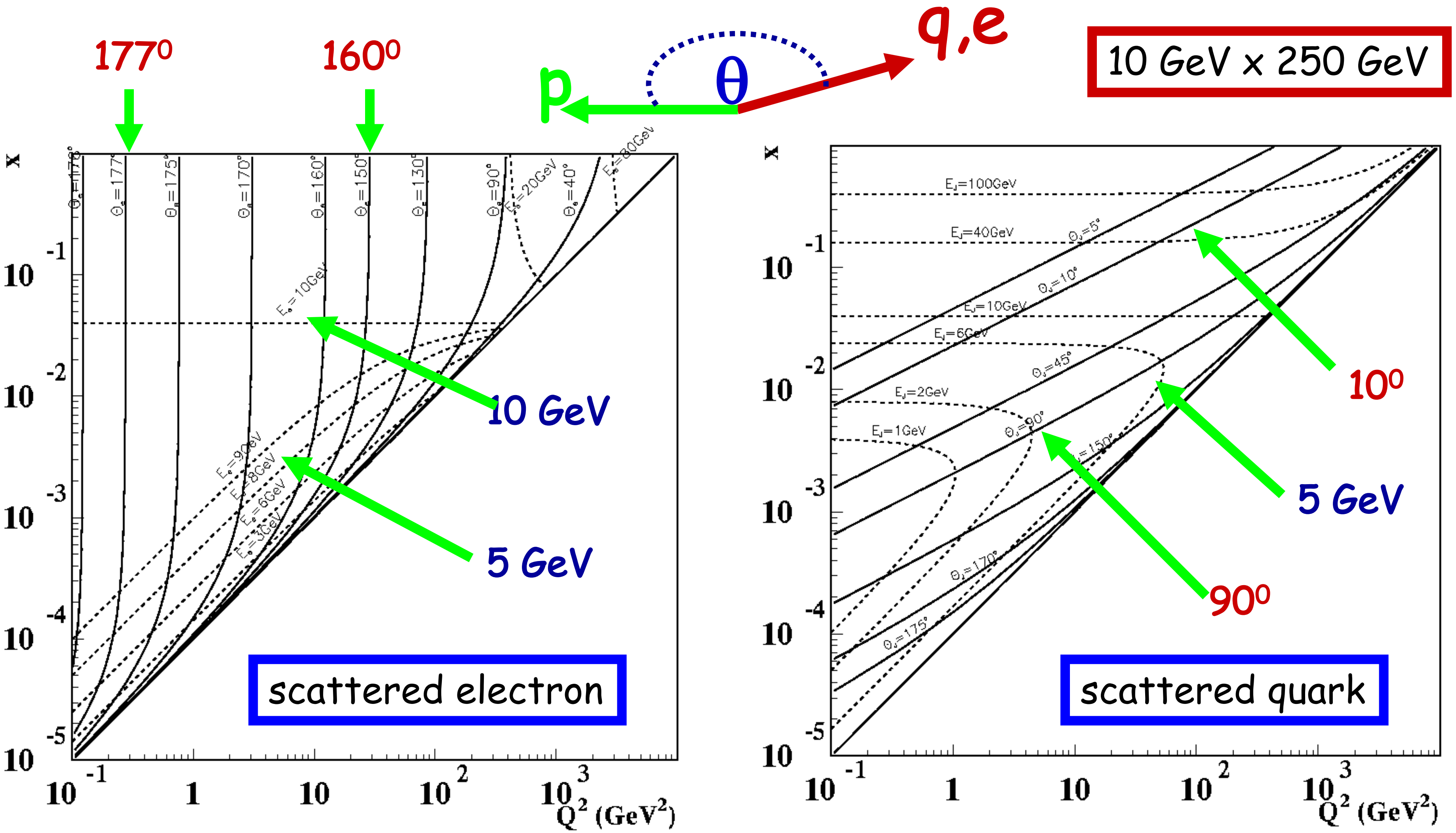
As beam energies increase, so does the x, Q^2 coverage of the collider: 5, 10 and 20 GeV electrons colliding with 50, 100 and 250 GeV protons

y = 0.95 and 0.01 are shown on all plots (they too shift as function of energy of collisions)

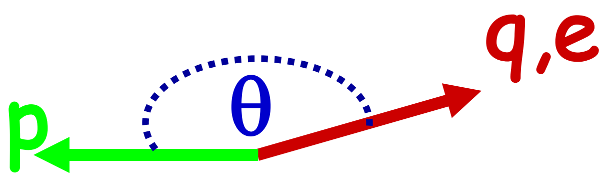


Home Work: Where do electrons and quarks go?

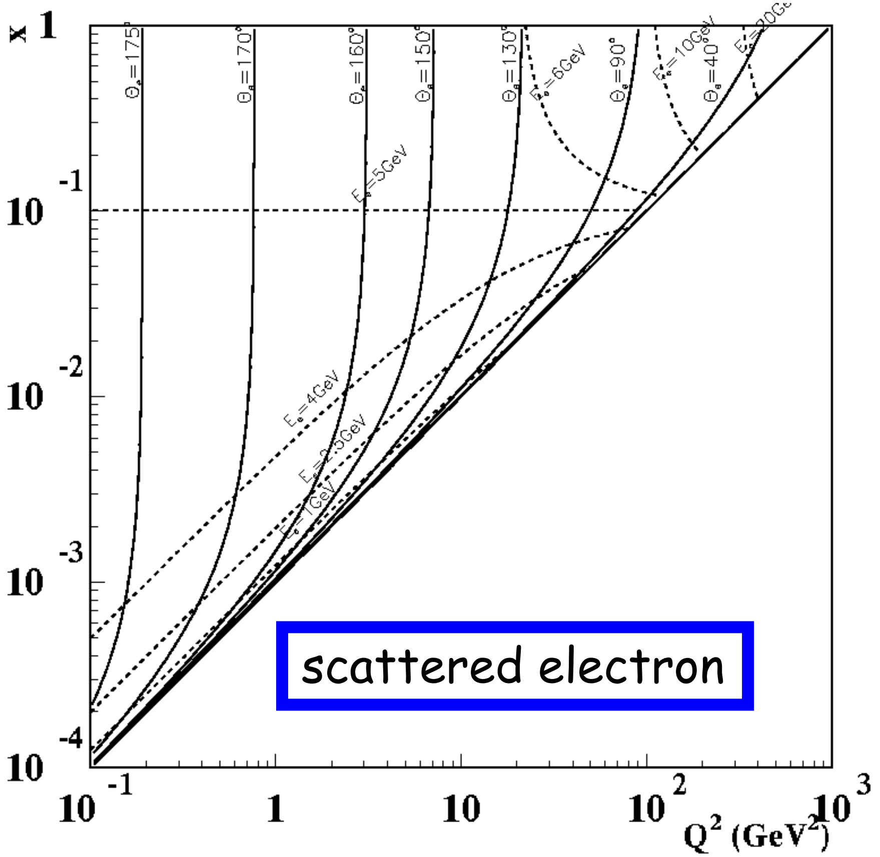
Angles measured w.r.t. proton direction



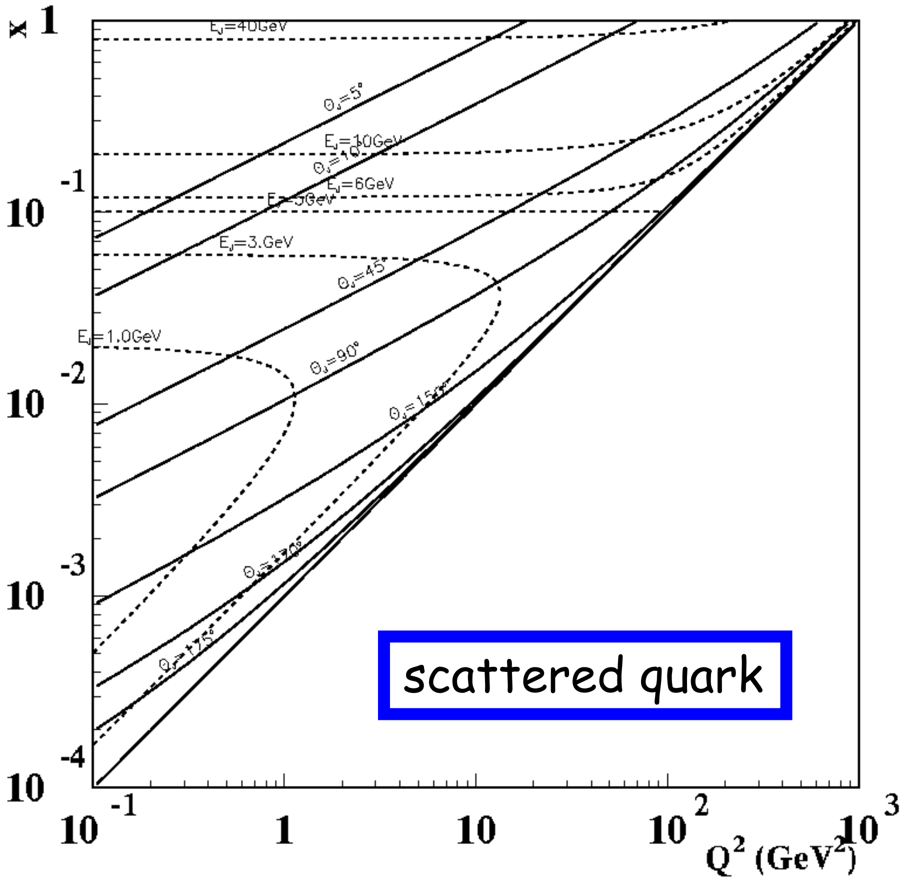
Electron, Quark Kinematics



5 GeV x 50 GeV



scattered electron

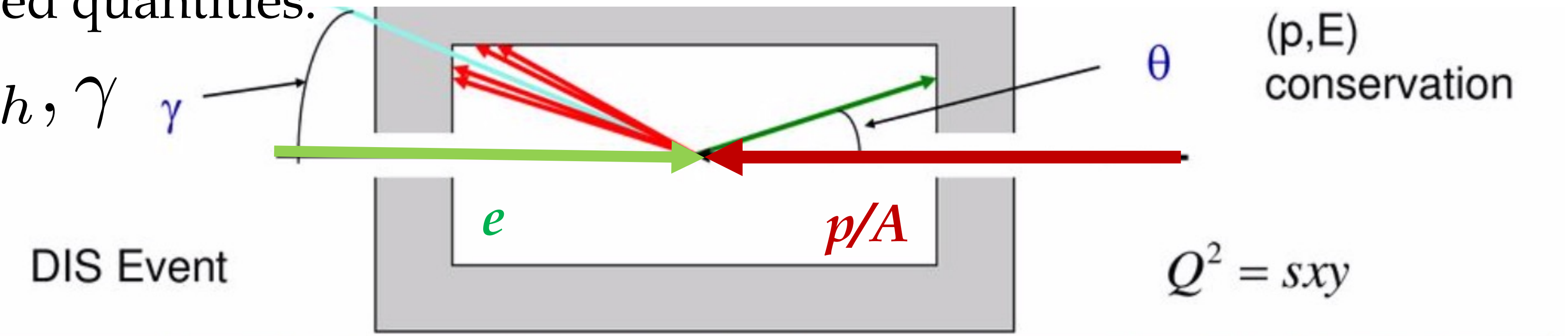


scattered quark

There are multiple ways to reconstruct events:

Four measured quantities:

$$E'_e, \theta, E_h, \gamma$$

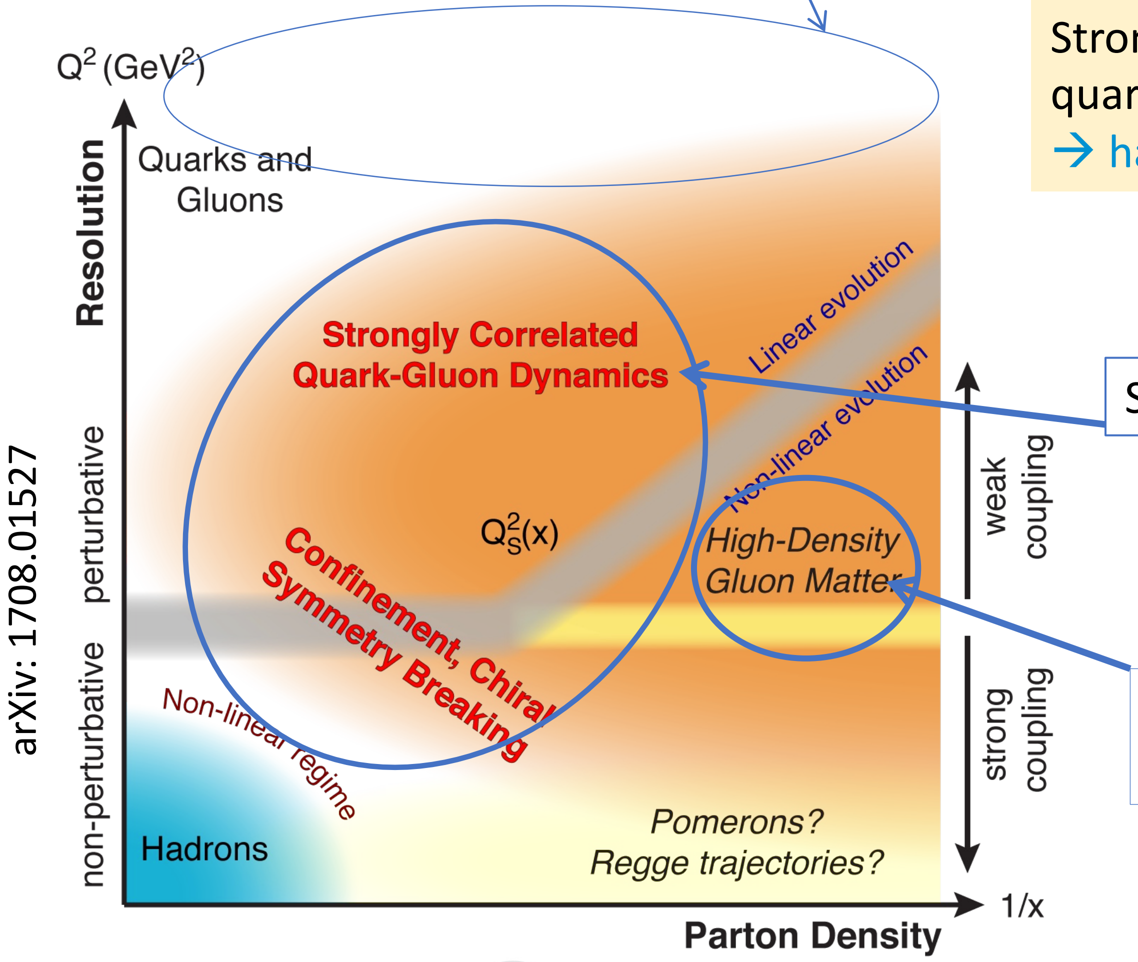


QCD Landscape to be explored by a future facility

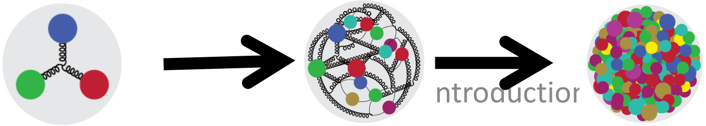
QCD at high resolution (Q^2) — weakly correlated quarks and gluons are well-described

Strong QCD dynamics creates many-body correlations between quarks and gluons

→ hadron structure emerges



arXiv: 1708.01527



Systematically explore correlations in this region.

An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter

Need Precision and Control

Proton mass puzzle

© Nobel Media AB. Photo: A. Mahmoud

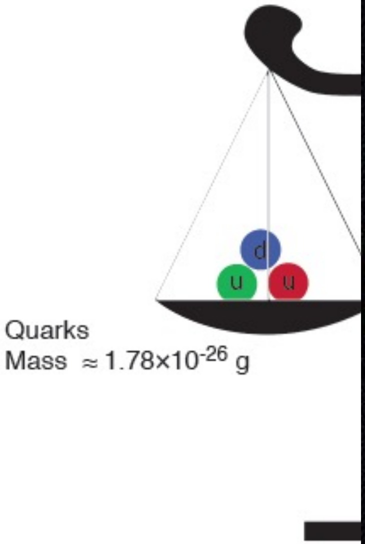
François Englert

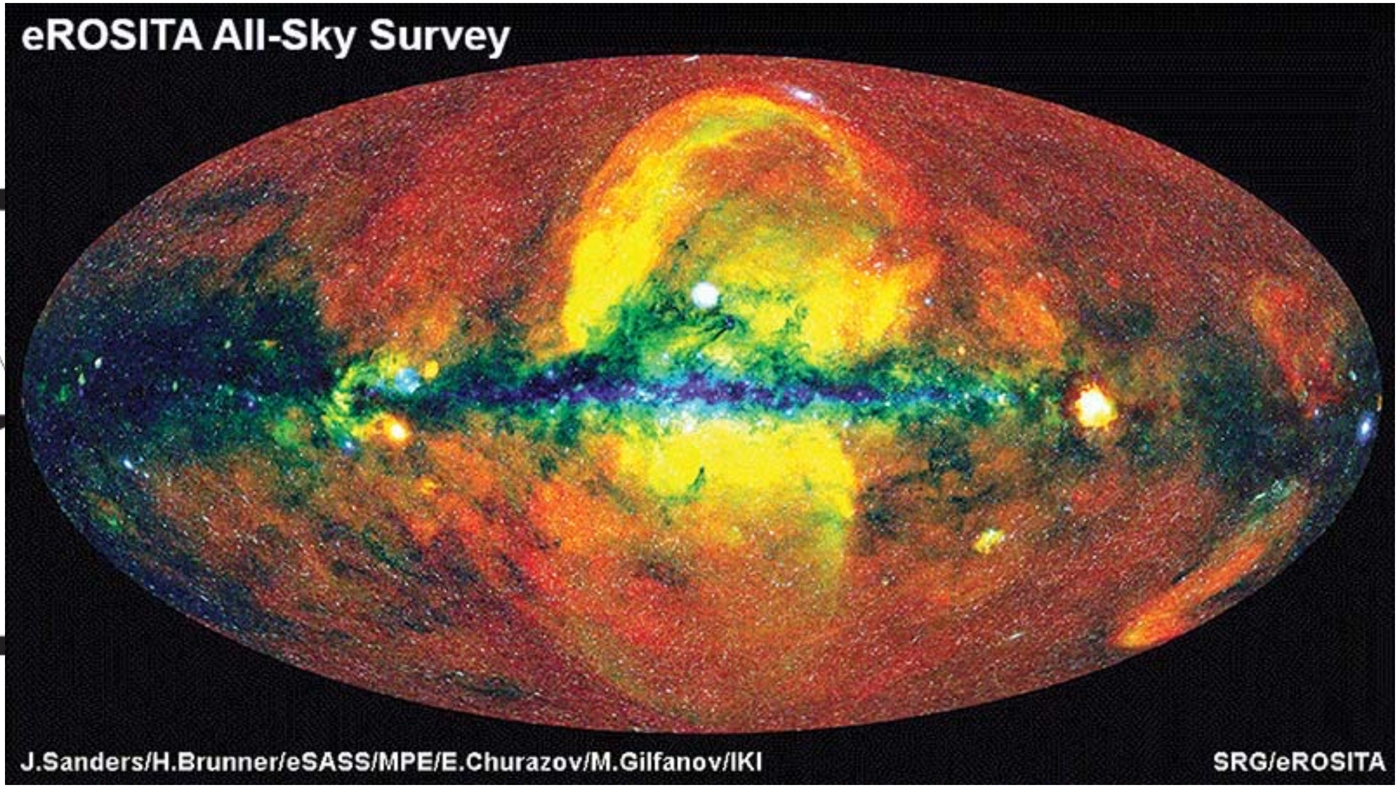
© Nobel Media AB. Photo: A. Mahmoud

Peter W. Higgs

Nobel 2013 With Francois Englert

“Higgs Boson” that gives mass to quarks, electrons,….





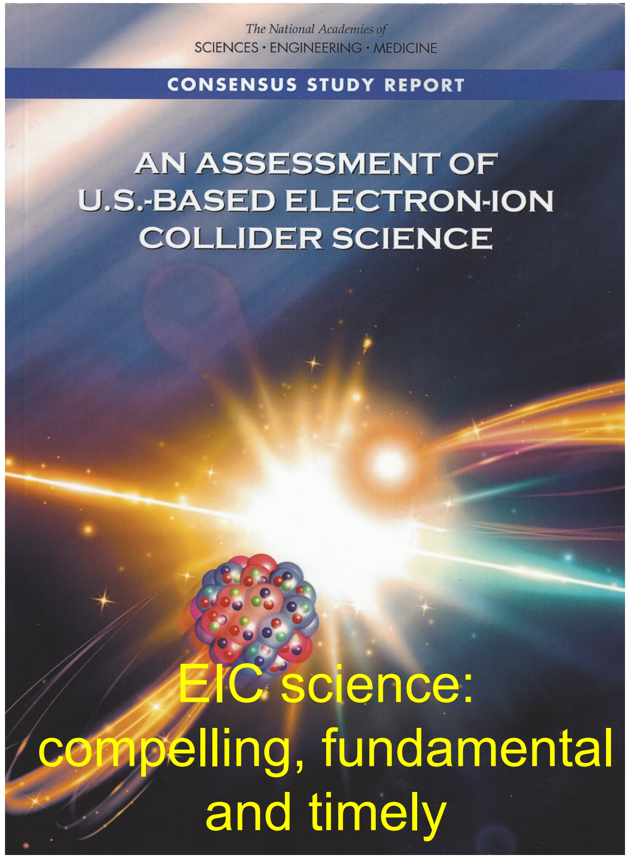
Add the masses of the quarks (HIGGS mechanism) together 1.78 x 10^{-26} grams

But the proton’s mass is 168 x 10^{-26} grams

→ **only 1% of the mass of the protons (neutrons)** → Hence the Universe

→ Where does the rest of the mass come from?

National Academy’s Assessment



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

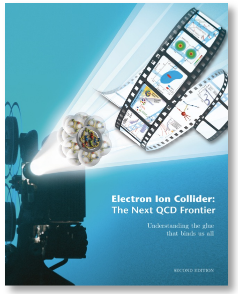
CONSENSUS STUDY REPORT

AN ASSESSMENT OF
U.S.-BASED ELECTRON-ION
COLLIDER SCIENCE

EIC science:
compelling, fundamental
and timely

Machine Design Parameters:

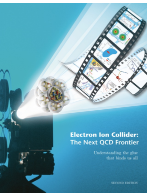
- High luminosity: up to 10^{33}-10^{34} $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-100 GeV upgradable to 140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice



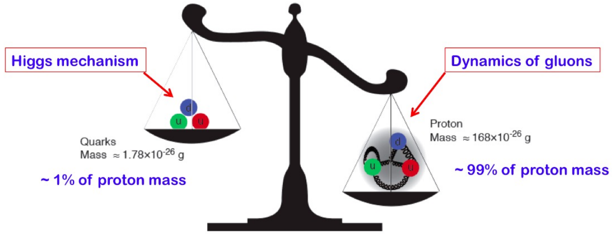
Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

SECOND EDITION

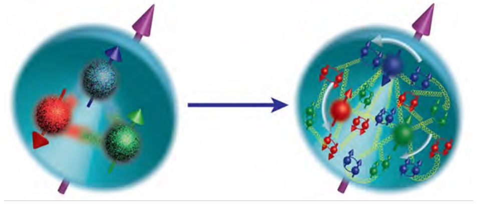


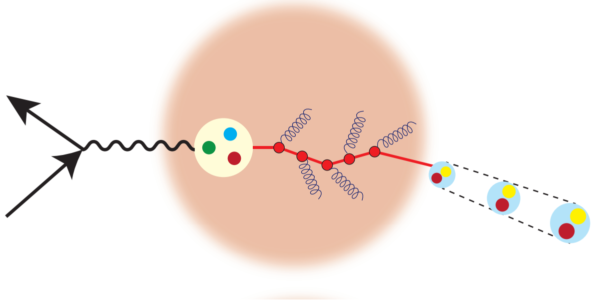
EIC Physics at-a-Glance



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

How do the nucleon properties (mass & spin) emerge from their interactions?





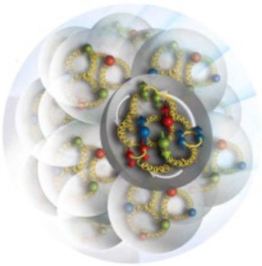
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

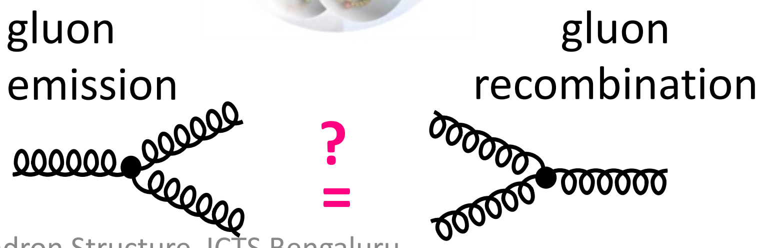
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

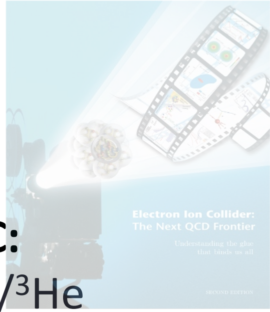
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

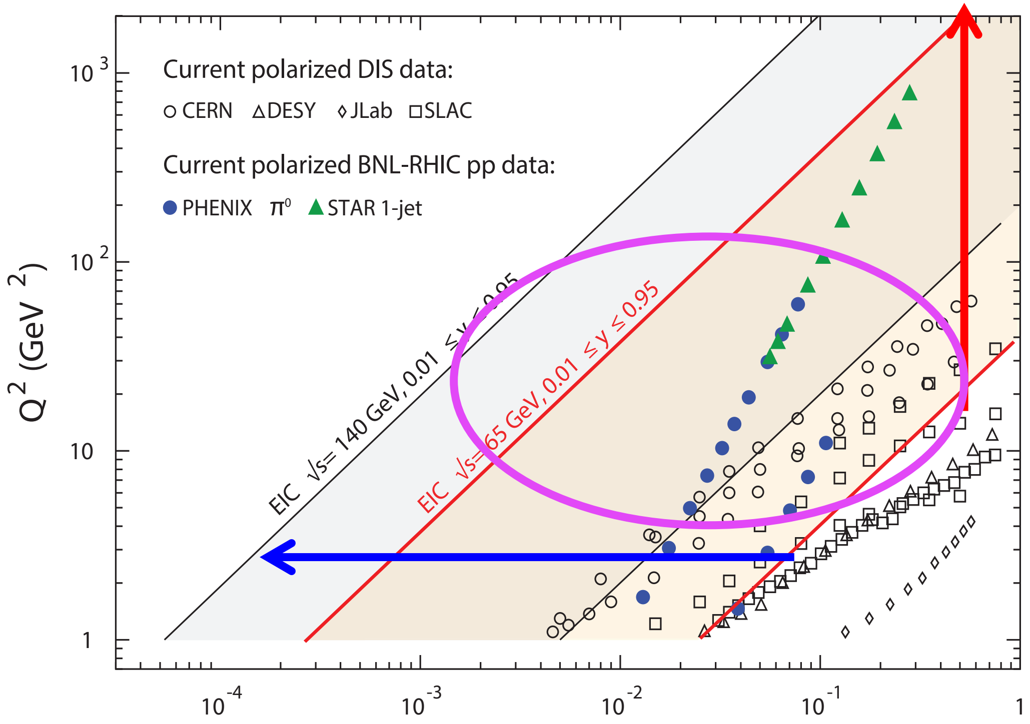




EIC Science ➔ what it could provide

EIC: Kinematic reach & properties



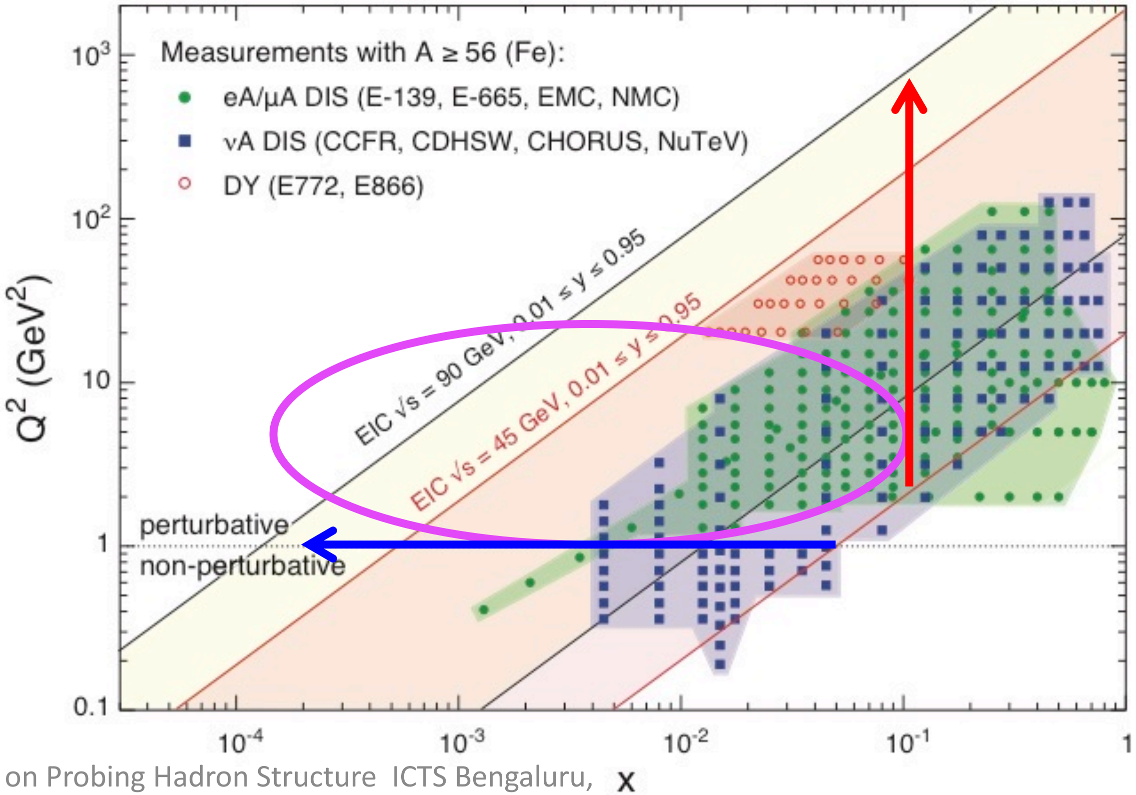


For e-N collisions at the EIC:

- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

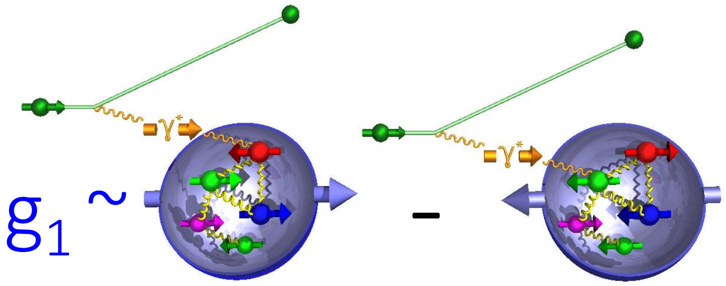
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)



Nucleon Spin: Precision with EIC

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

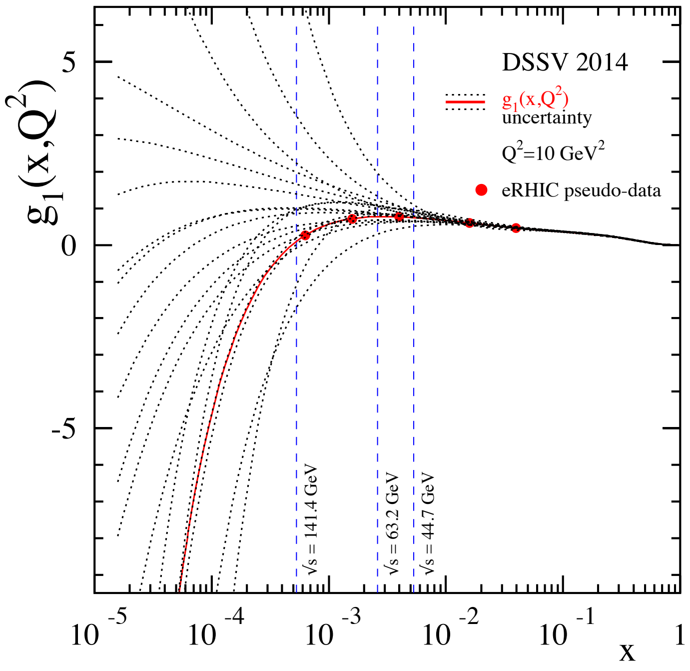


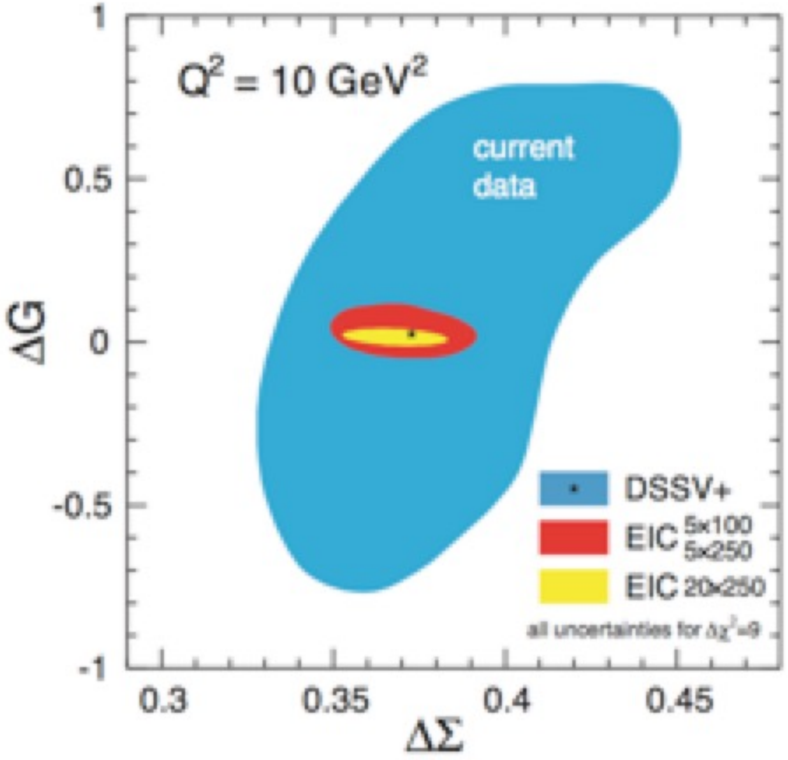
$\Delta\Sigma/2$ = Quark contribution to Proton Spin
Δg = Gluon contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
L_G = Gluon Orbital Ang. Mom

Spin structure function g_1 needs to be measured over a large range in x-Q^2

Precision in $\Delta\Sigma$ and Δg ➔ A clear idea Of the magnitude of L_Q+L_G = L

SIDIS: strange and charm quark spin contributions

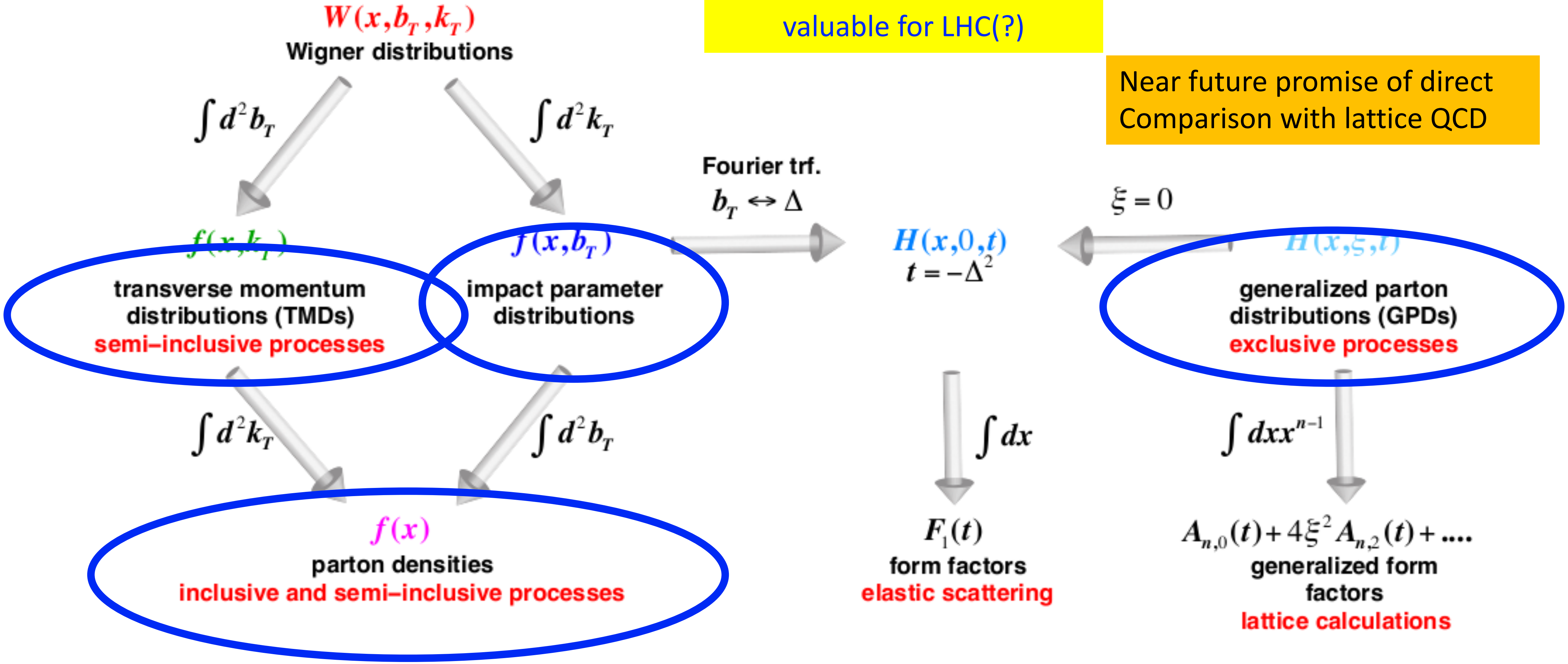




2+1D Imaging of hadrons: beyond precision PDFs

Precision PDFs and TMDs valuable for LHC(?)

Near future promise of direct Comparison with lattice QCD



$W(x,b_T,k_T)$
Wigner distributions

$\int d^2b_T$

$\int d^2k_T$

$f(x,k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x,b_T)$
impact parameter distributions

Fourier trf.
$b_T \leftrightarrow \Delta$

$H(x,0,t)$
$t=-\Delta^2$

$\xi = 0$

$H(x,\xi,t)$
generalized parton distributions (GPDs)
exclusive processes

$\int d^2k_T$

$\int d^2b_T$

$f(x)$
parton densities
inclusive and semi–inclusive processes

$\int dx$

$F_1(t)$
form factors
elastic scattering

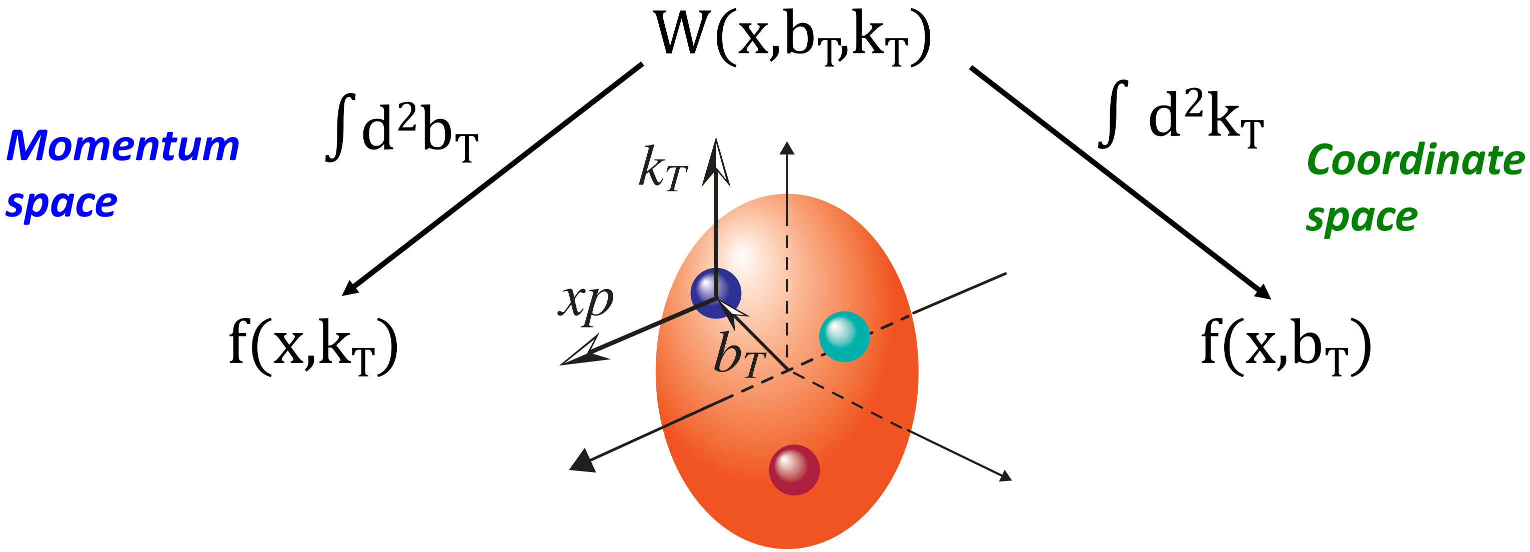
$\int dx x^{n-1}$

$A_{n,0}(t)+4\xi^2A_{n,2}(t)+....$
generalized form factors
lattice calculations

3-Dimensional Imaging Quarks and Gluons

Wigner functions $W(x,b_T,k_T)$

offer unprecedented insight into confinement and chiral symmetry breaking.



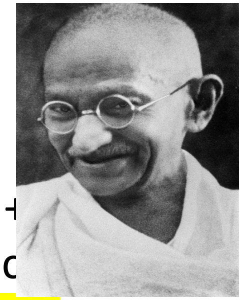
Spin-dependent 3D momentum space images from semi-inclusive scattering → **TMDs**

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering → **GPDs**

Position and momentum → Orbital motion of quarks and gluons

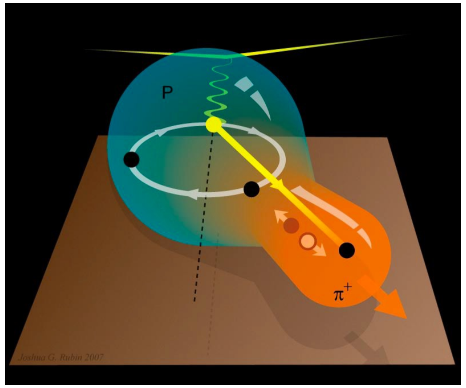
Possible direct access to gluon Wigner function through diffractive di-jet measurements at an EIC: Y. Hatta et al. PRL 16, 022301 (2016

2+1 D partonic image of the proton with the EIC

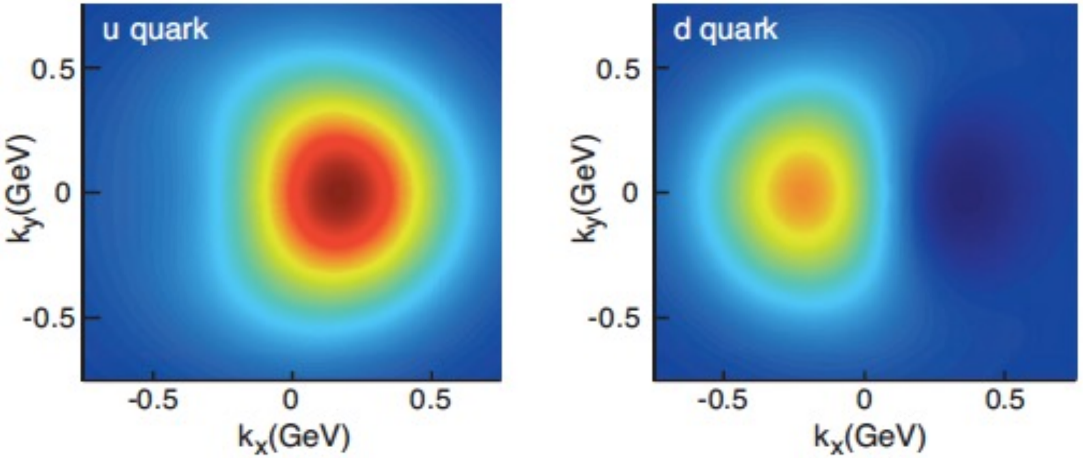


Spin-dependent 3D momentum space images from semi-inclusive scattering (SIDS)

Transverse Momentum Distributions



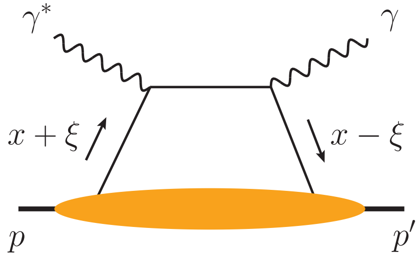
Possible measurements of K (s) and D (c)

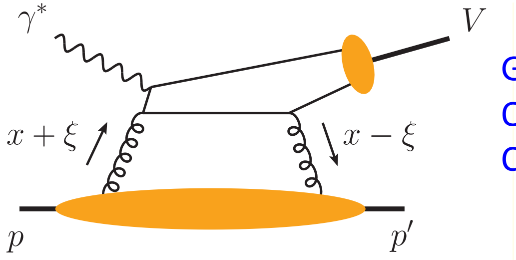


Spin-dependent 2D coordinate space (transverse) +
(longitudinal momentum) images from exclusive sc

Transverse Position Distributions

Quarks Motion





Gluons: Only @ Collider

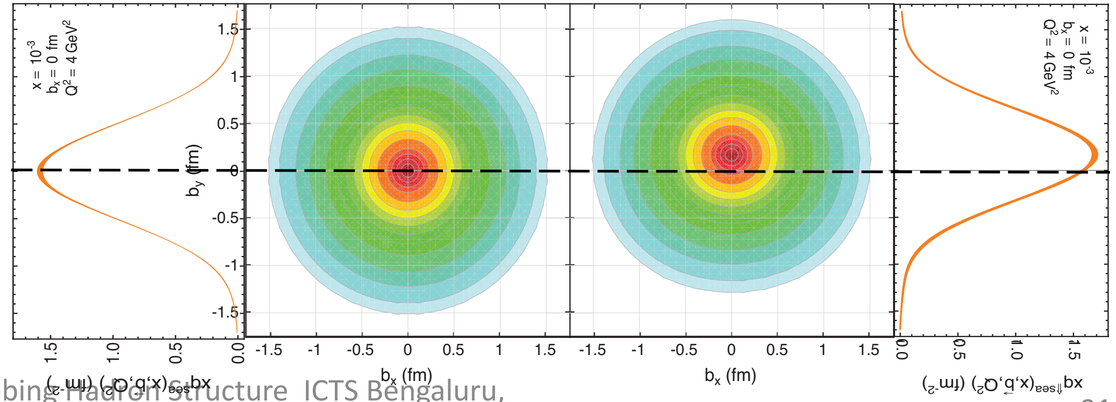
Deeply Virtual Compton Scattering

Measure all three final states

e + **p** → e’+ **p’**+ γ

Fourier transform of momentum transferred=(p-p’) → Spatial distribution

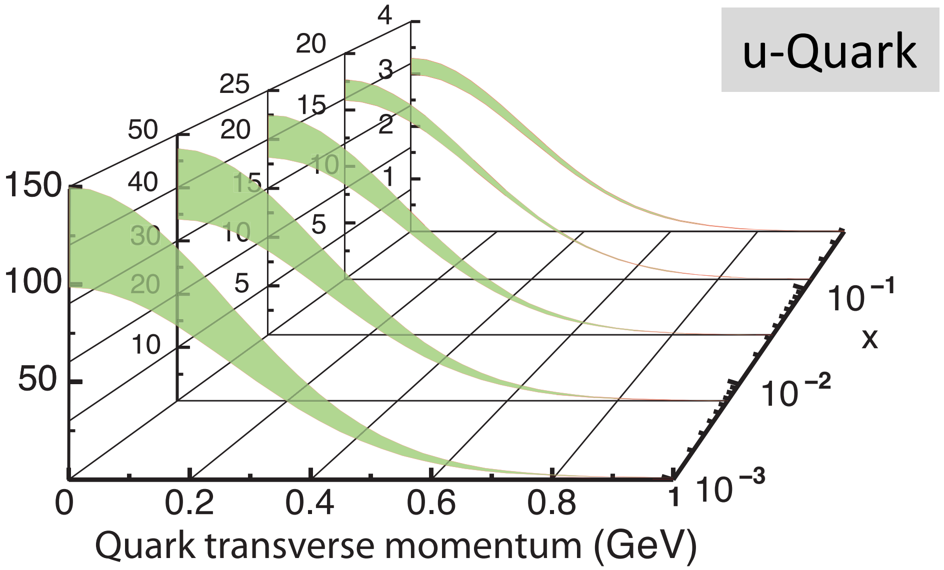
2D position distribution for sea-quarks
unpolarized polarized



2+1 D partonic image of the proton with the EIC

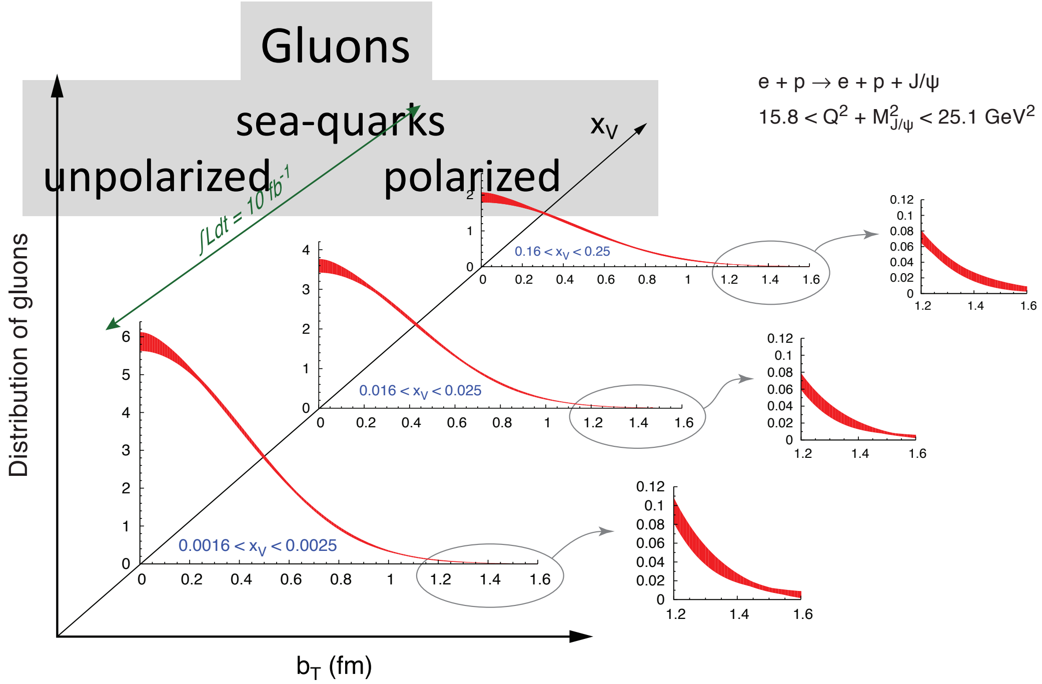
Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions



Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions



“Color form factor” of proton…

Study of internal structure of a watermelon:

A-A (RHIC)

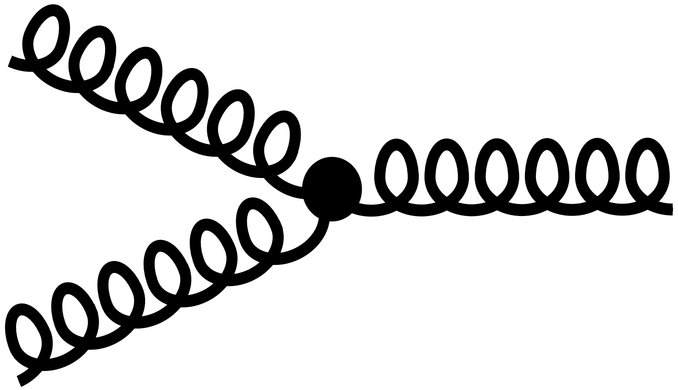
1) Violent collision of melons

2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

3) MRI of a watermelon

Non-Violent e-A (EIC)



Consequence of gluon self interactions ➔ non-linear GDLAP evolution… ?

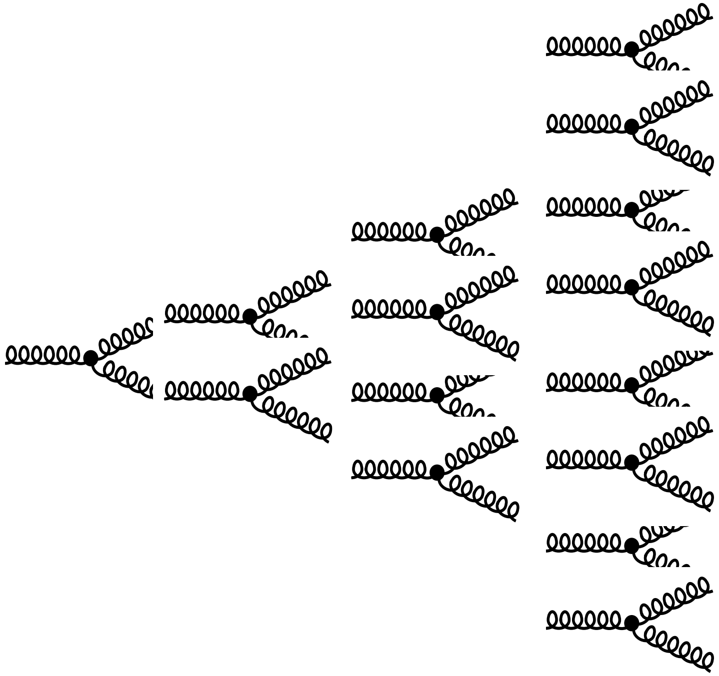
Particularly at high energy ➔ low-x

Gluon and the consequences of its interesting properties:

Gluons carry color charge ➔ Can interact with other gluons!

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

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



? Infinity?

No!

Gluon and the consequences of its interesting properties:

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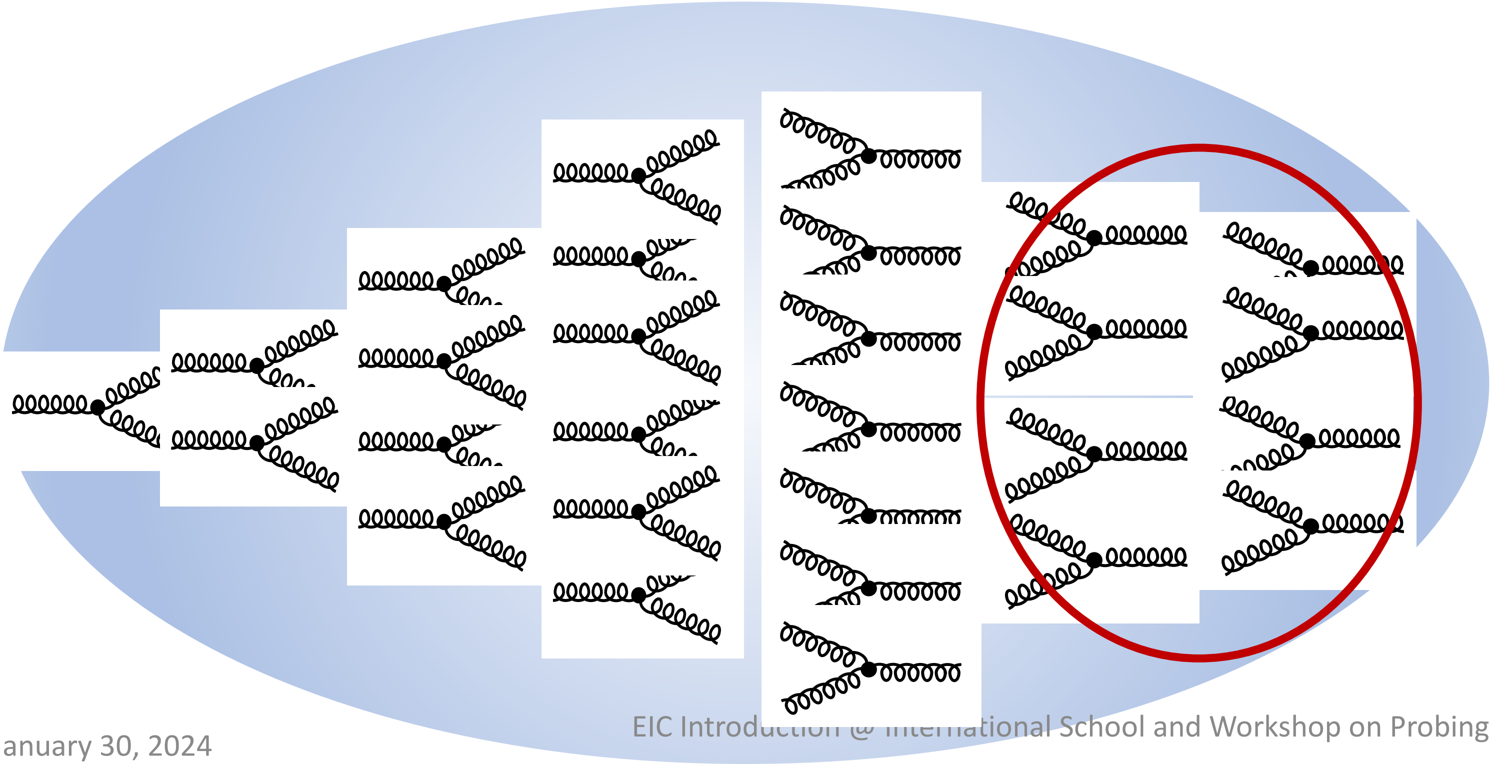
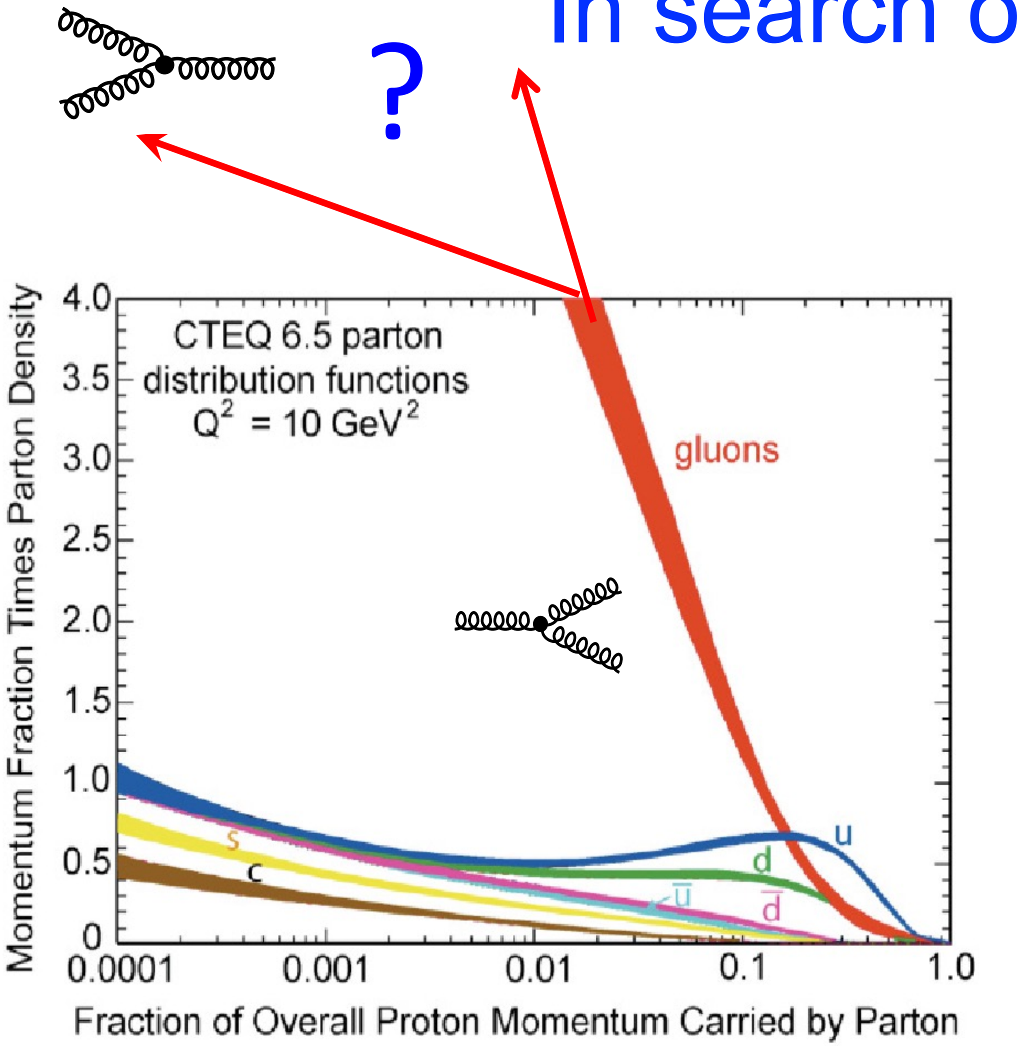


Saturation State of Gluons reached

In search of a new state of matter!

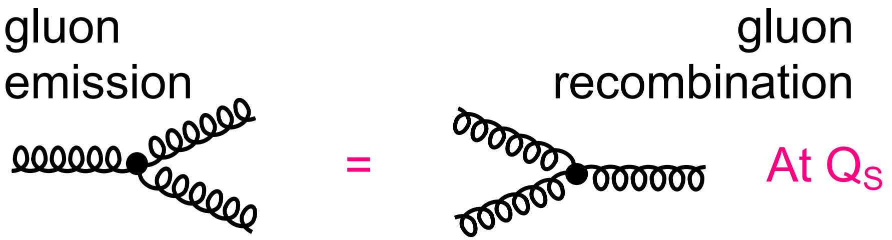


Experimental evidence needed

What could tame the low-x rise?

Can EIC access this region?

QCD inherently has the needed mechanism for this taming but we don't know when it gets triggered.



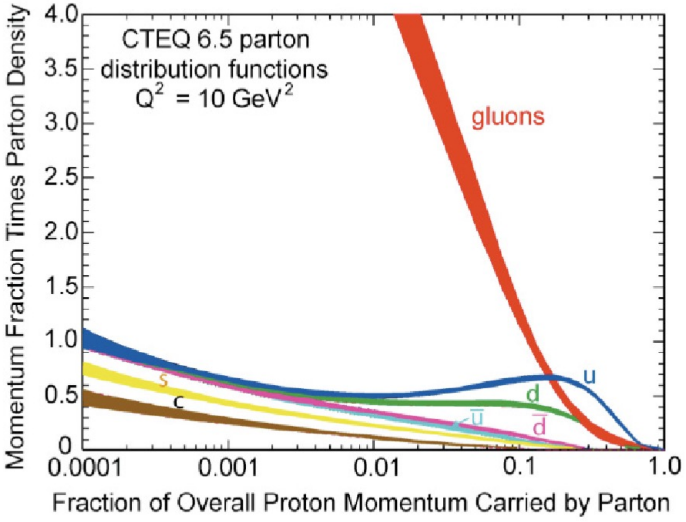
Observation of gluon recombination effects

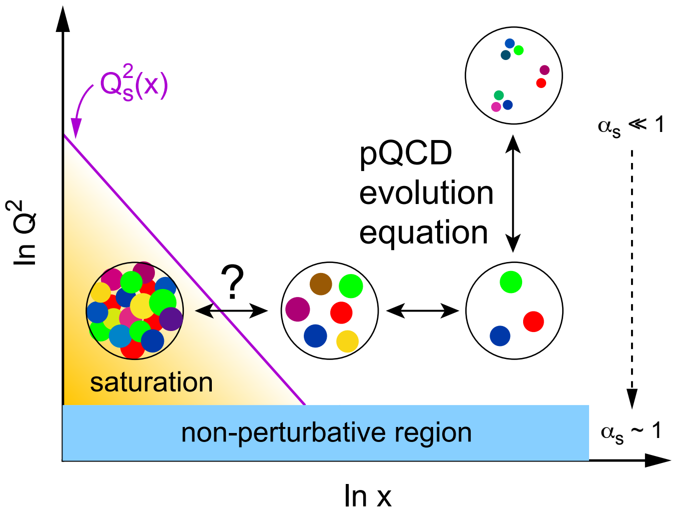
➔Is there such new state of matter?

→ "Color Glass Condensate"

→ 50-100 times higher energy density than the core of the neutron star

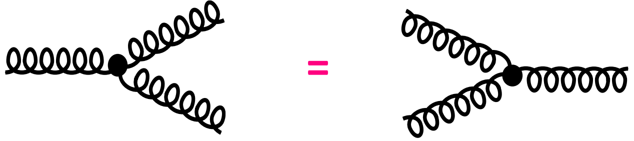
Low x physics with nuclei



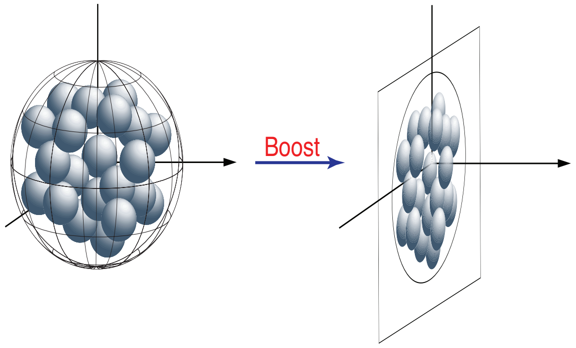


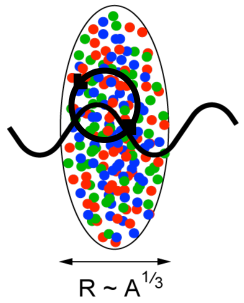
gluon emission

gluon recombination



= At Q_S

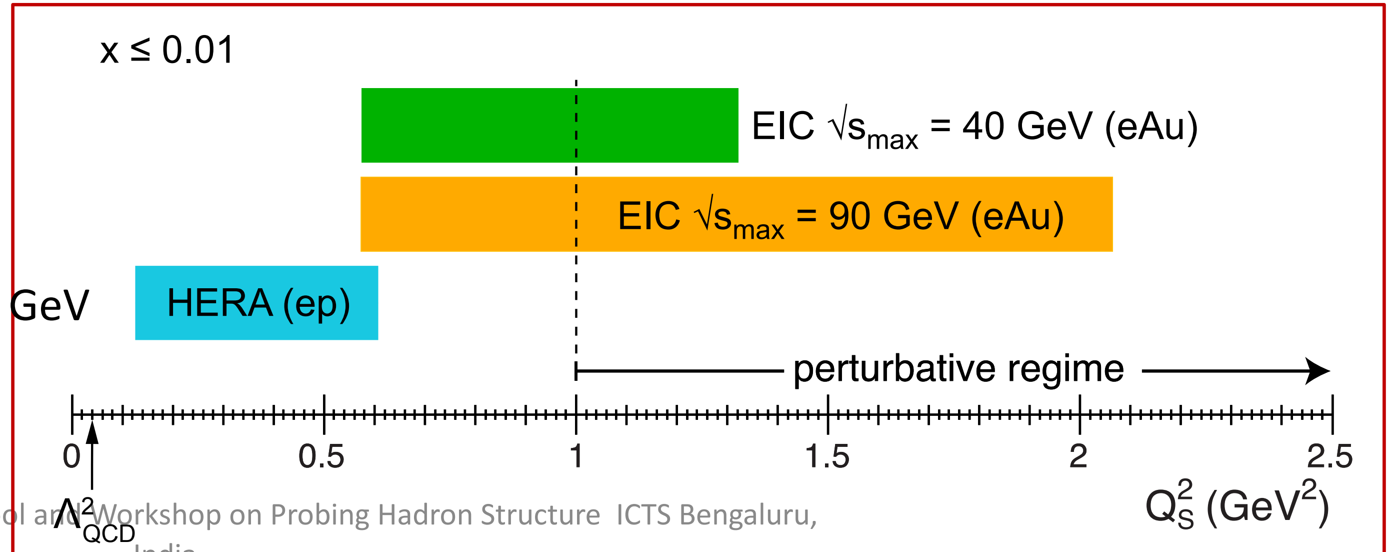




$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$

$L \sim (2m_N x)^{-1} > 2 R_A \sim A^{1/3}$

Accessible range of saturation scale Q_s^2 at the EIC with e+A collisions.
arXiv:1708.01527

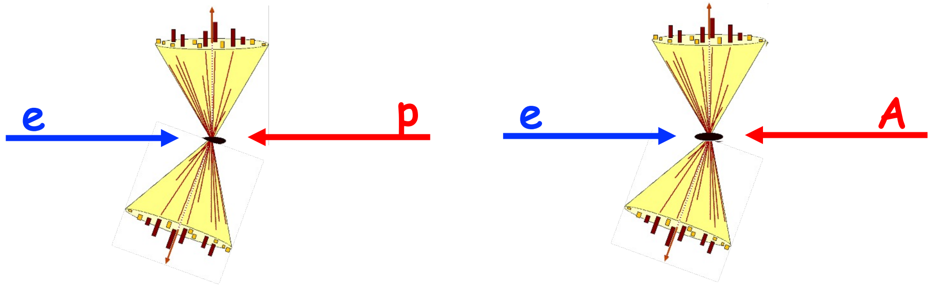


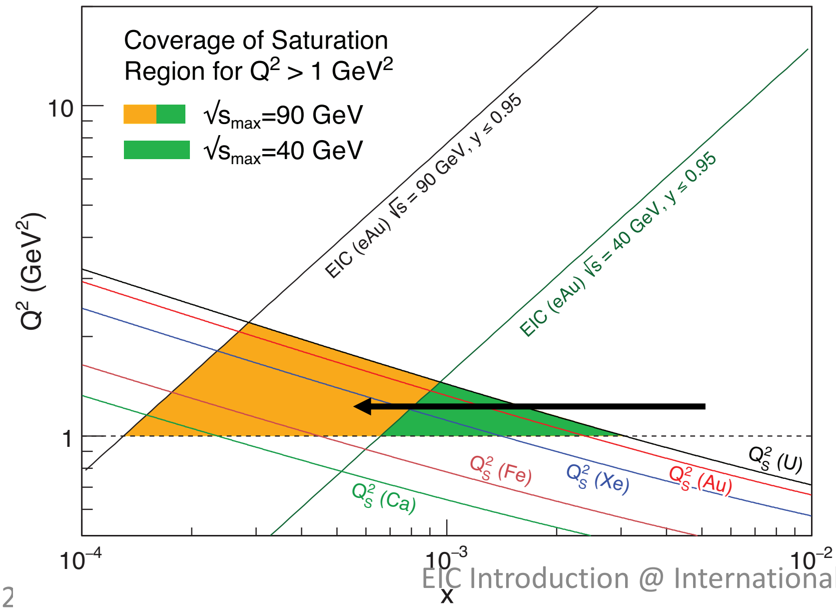
Can EIC discover a new state of matter?

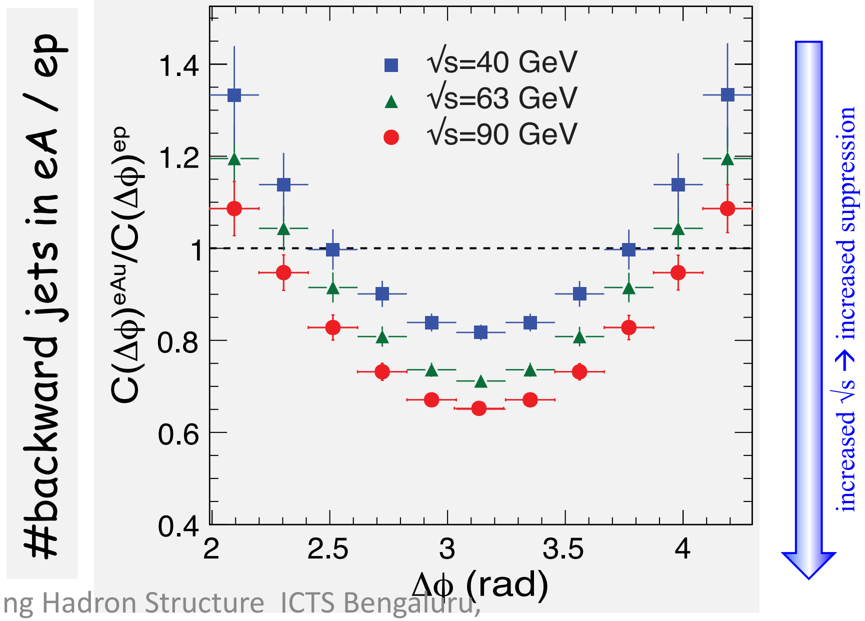
EIC provides an absolutely unique opportunity
to have very high gluon densities
→ electron – lead collisions
combined with an unambiguous observable

EIC will allow to unambiguously
map the transition from a non-saturated to
saturated regime

counting experiment of
Di-jets in ep and eA
Saturation:
Disappearance of backward jet in eA





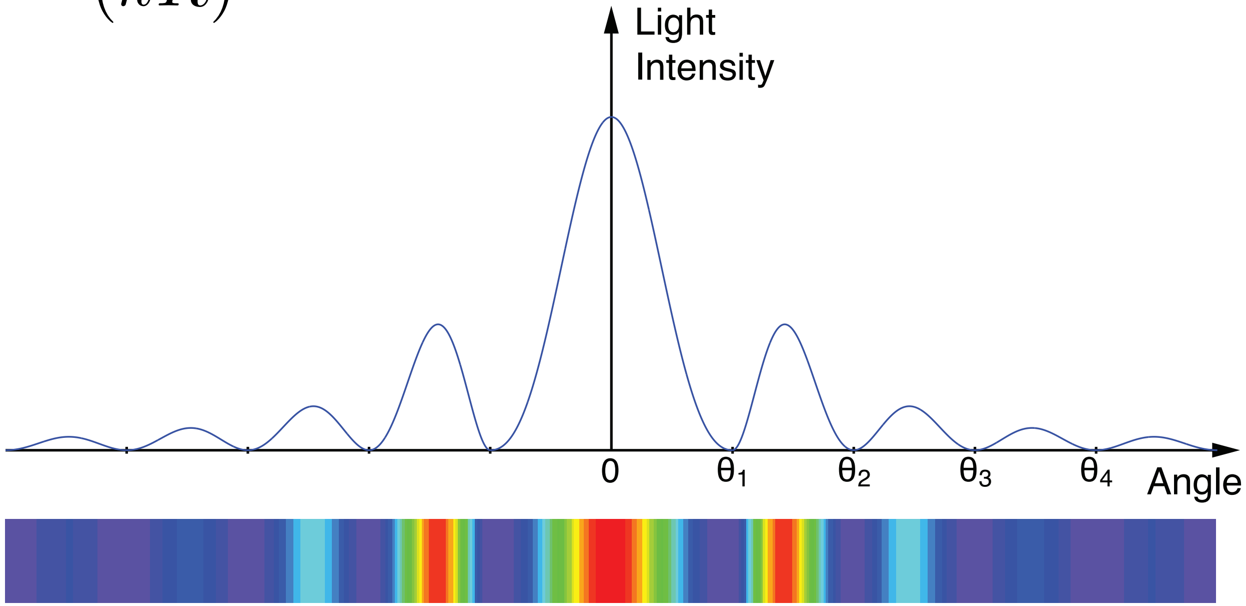


Diffraction in Optics and high energy scattering

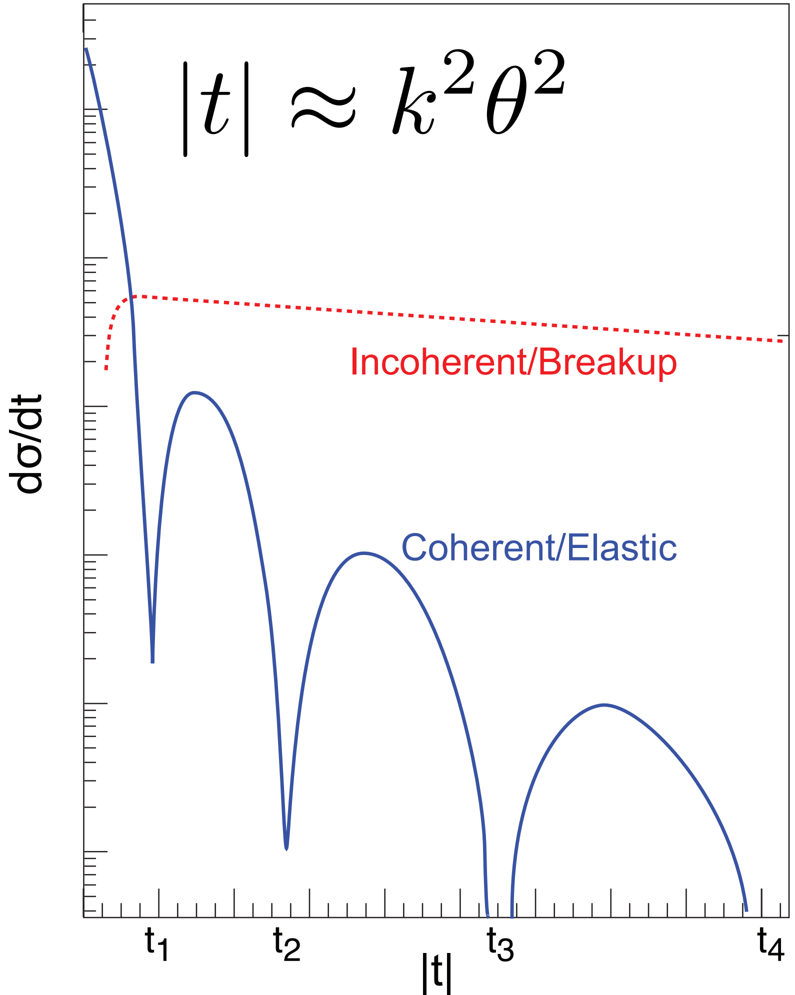
Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction:

k → wave number

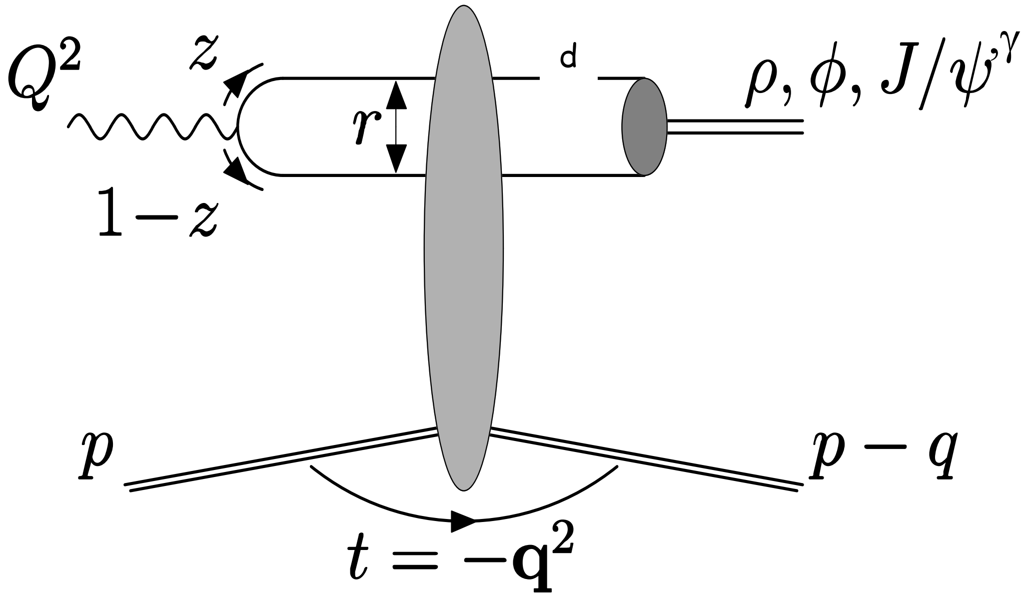
$$\theta_i \sim \frac{1}{(kR)}$$



Calculation of e-A diffraction

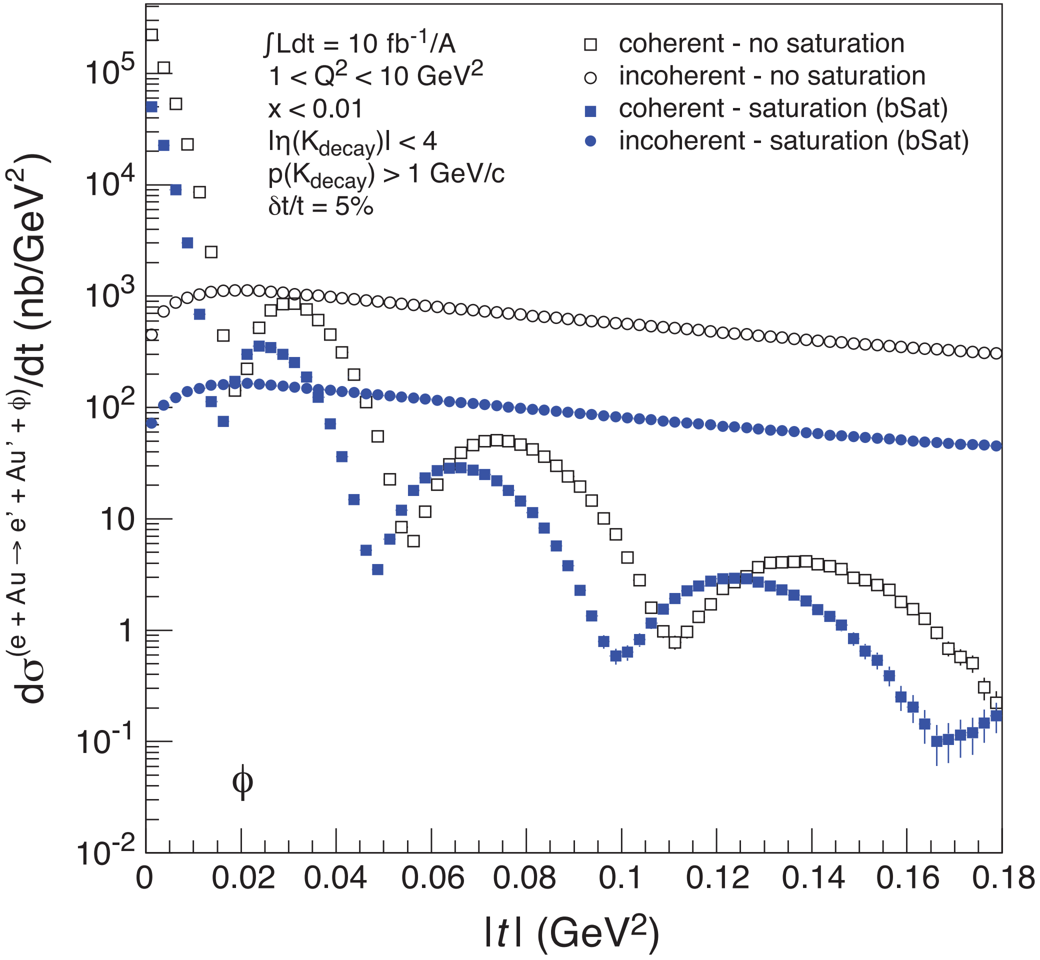


Transverse imaging of the gluons nuclei



Diffractive vector meson production in **e-Au**

Diff. MC: “Sartre”

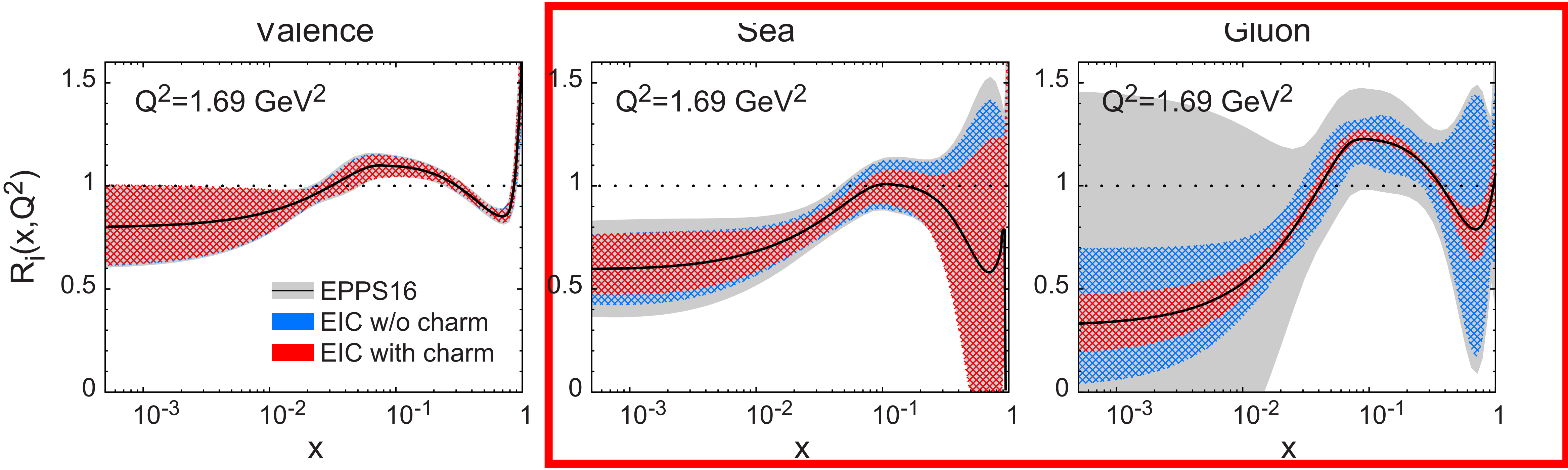


Simulation study by Toll & Ullrich

➔Does low x dynamics (Saturation) modify the transverse gluon distribution?

Experimental challenges being studied.

EIC: impact on the knowledge of 1D Nuclear PDFs



Ratio of Parton Distribution Functions of Pb over Proton:

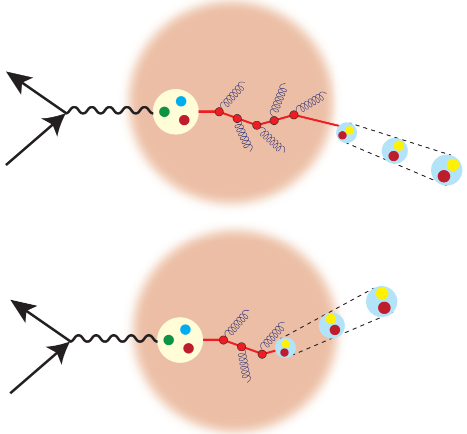
- Without EIC, large uncertainties in **nuclear sea quarks and gluons** ➔With EIC significantly reduced uncertainties
- Complementary to RHIC and LHC pA data. Provides information on initial state for heavy ion collisions.
- Does the nucleus behave like a proton at low-x? ➔ such color correlations relevant to the understanding of astronomical objects

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

Unprecedented ν, the virtual photon energy range
@ EIC : *precision & control*

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



Study in light quarks
vs.
heavy quarks

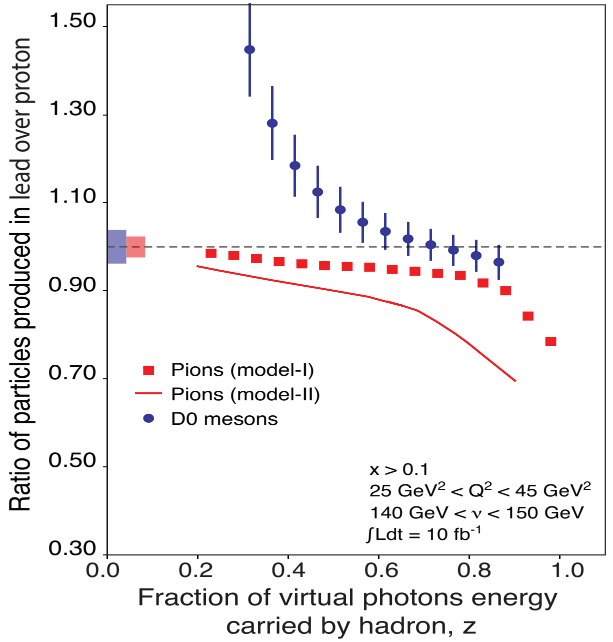
Control of ν by selecting kinematics;

Also under control the nuclear size.

(colored) Quark passing through cold QCD matter emerges as color-neutral hadron ➔

Clues to color-confinement?

Energy loss by light vs. heavy quarks:

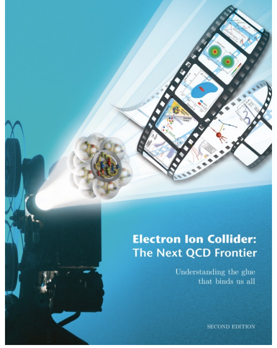


Identify π vs. D^0 **(charm)** mesons in e-A collisions:

Understand energy loss of light vs. heavy quarks
traversing the cold nuclear matter:
Connect to energy loss in Hot QCD

Need the collider energy of EIC and its control on parton kinematics

Physics @ the US EIC beyond the EIC's core science



New Studies with proton or neutron target:

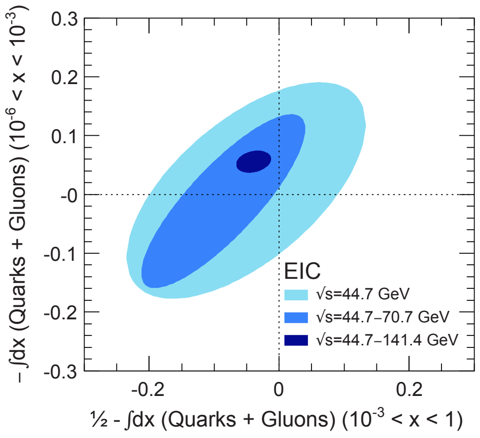
- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Upgrade results(?)
- What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs at low-x!
- Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
- Does polarization of play a role (in all or many of these?)

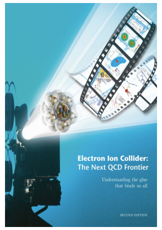
Physics with nucleons and nuclear targets:

- Quark Exotica: 4,5,6 quark systems…? Much interest after recent LHCb led results.
- Physic of and with jets with EIC as a precision QCD machine:
  - Internal structure of jets : novel new observables, energy variability, polarization, beam species
  - Entanglement, entropy, connections to fragmentation, hadronization and confinement
  - Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium
- Connection to p-A, d-A, A-A at RHIC and LHC
- Polarized light nuclei in the EIC

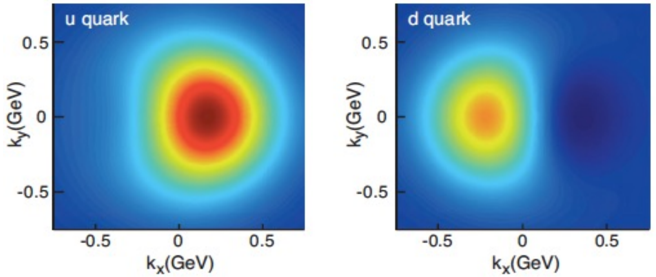
Precision electroweak and BSM physics:

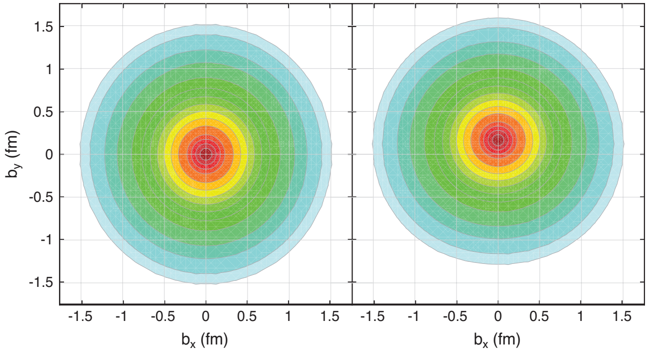
- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation

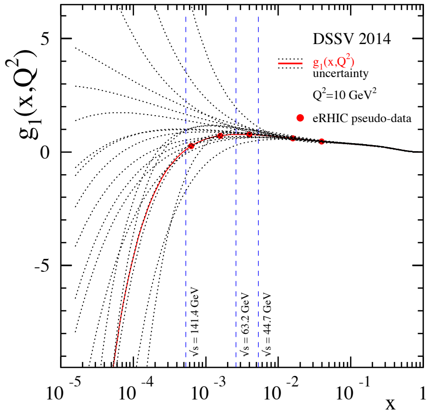


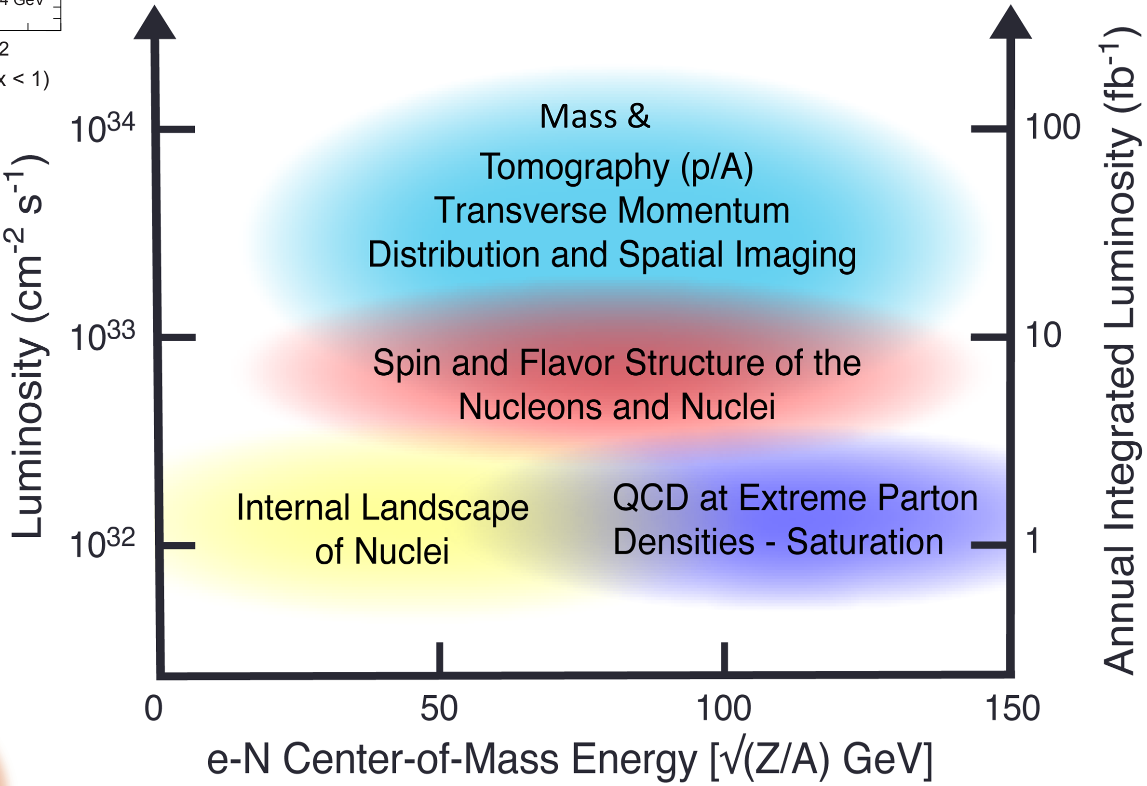


EIC science highlights







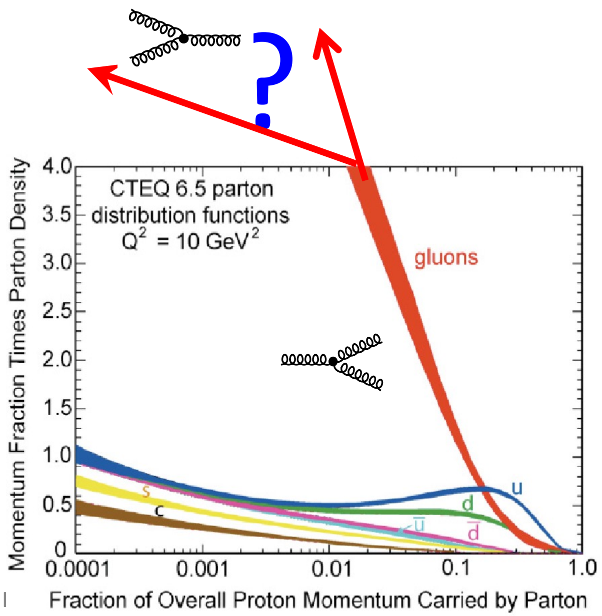


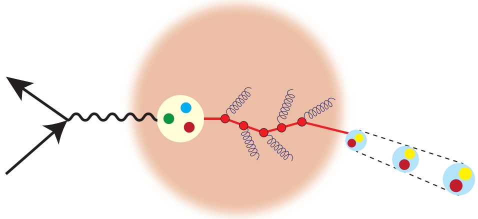
Mass &
Tomography (p/A)
Transverse Momentum
Distribution and Spatial Imaging

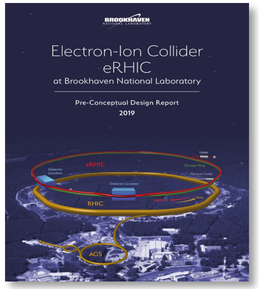
Spin and Flavor Structure of the
Nucleons and Nuclei

Internal Landscape
of Nuclei

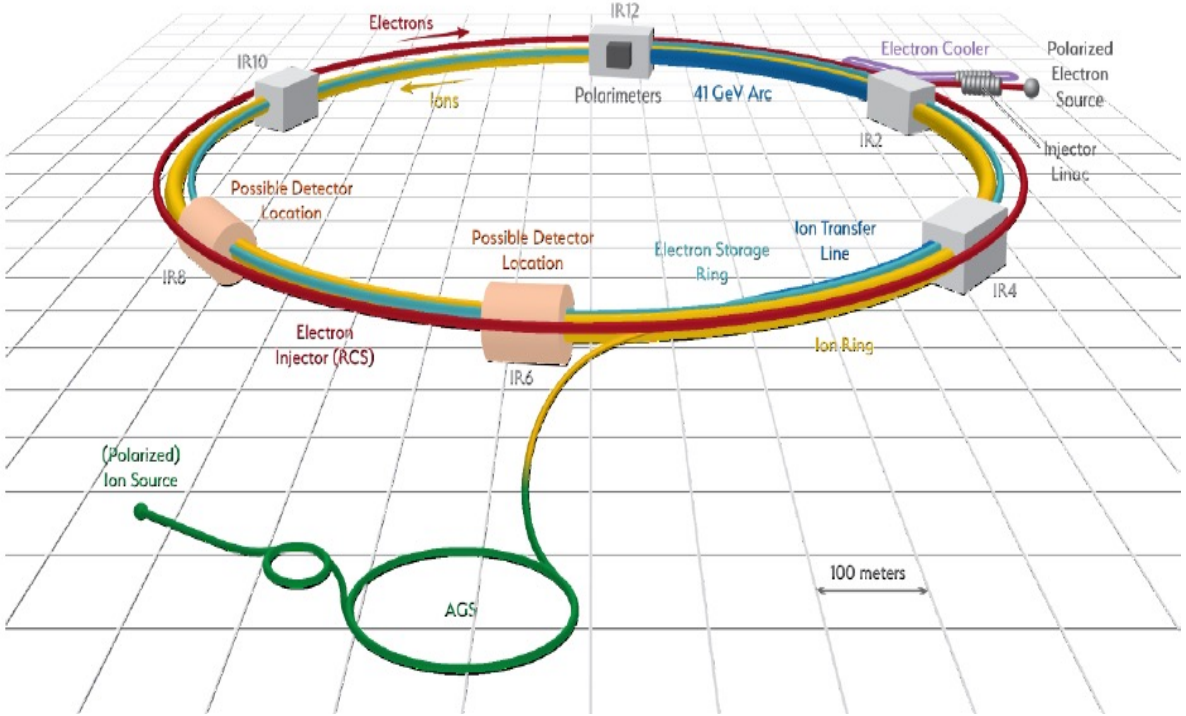
QCD at Extreme Parton
Densities - Saturation






Electron-Ion Collider
eRHIC
at Brookhaven National Laboratory
Pre-Conceptual Design Report
2019

The US Electron Ion Collider



- ❖ Electron storage ring with frequent injection of fresh polarized electron bunches
- ❖ Hadron storage ring with strong cooling or frequent injection of hadron bunches

Hadrons up to 275 GeV

- ➢ Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- ➢ Need few modifications
- ➢ RHIC beam parameters fairly close to those required for EIC@BNL

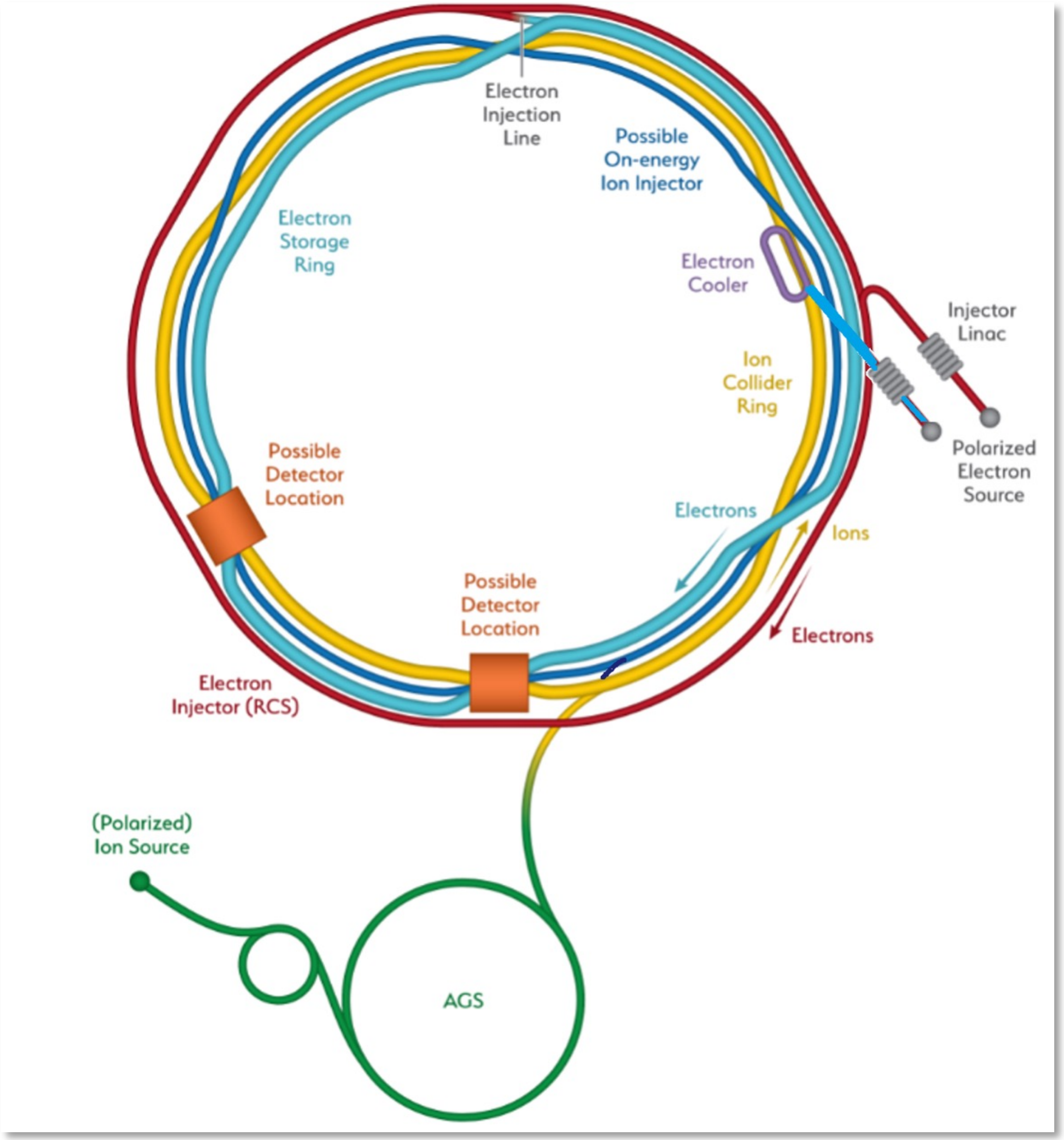
Electrons up to 18 GeV

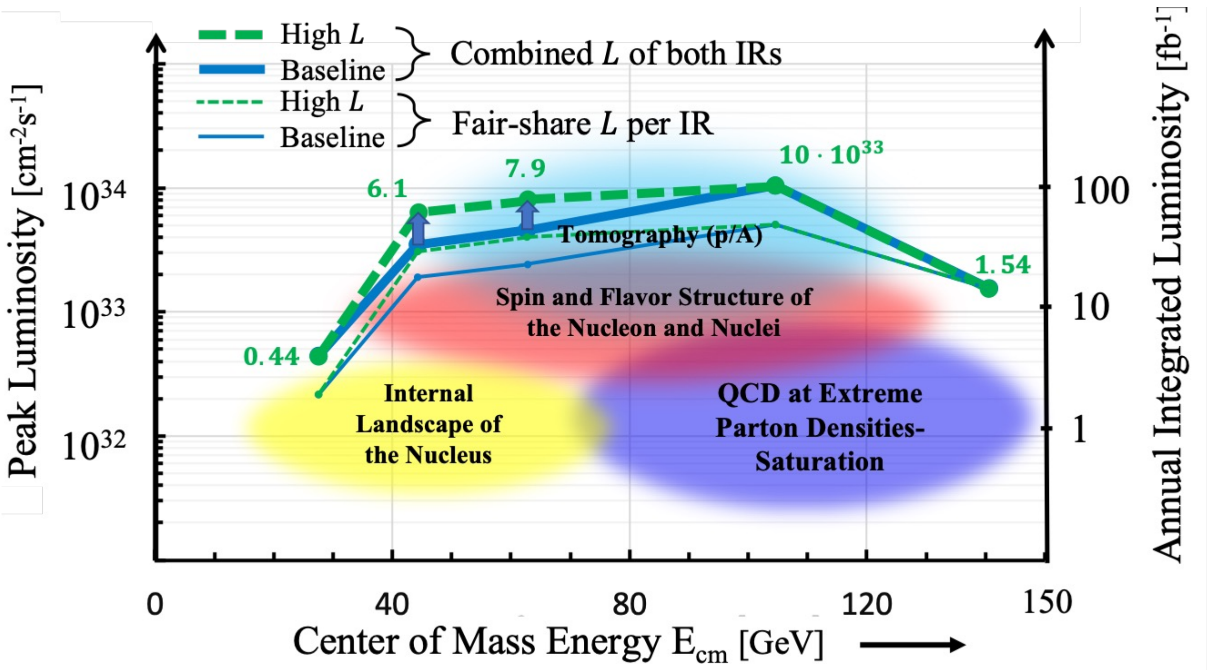
- ➢ Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- ➢ Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- ➢ Polarized e-source and a 400 MeV s-band injector LINAC in the existing tunnel

Design optimized to reach 10^{34} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

EIC Accelerator Design

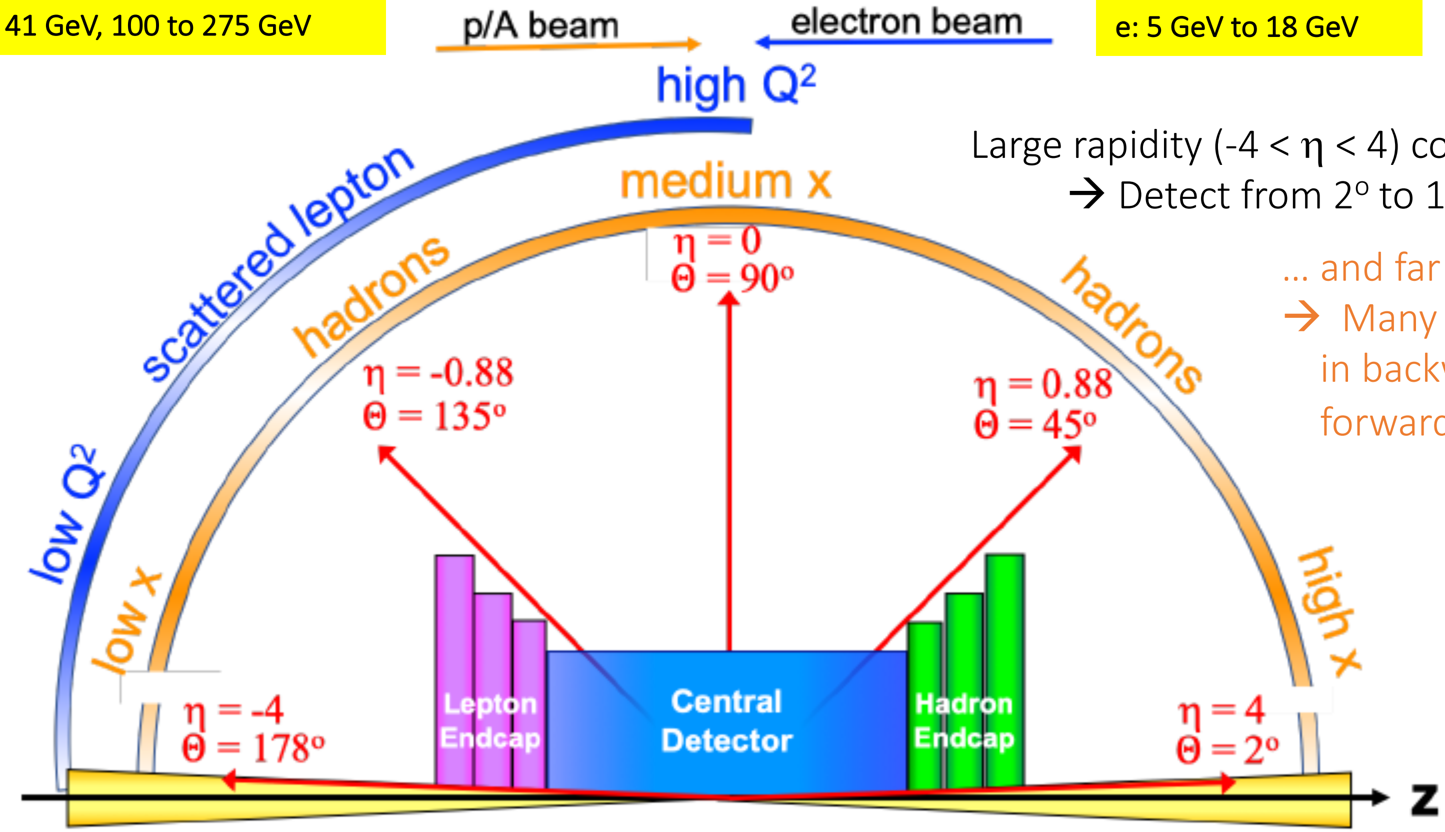
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} cm^{-2}s^{-1} / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!





p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV



Large rapidity ($-4 < \eta < 4$) coverage
→ Detect from 2^o to 178^o…

… and far beyond
→ Many detectors in backward + forward region

low Q^2 scattered electrons
Bethe-Heitler photons
for luminosity

Backward

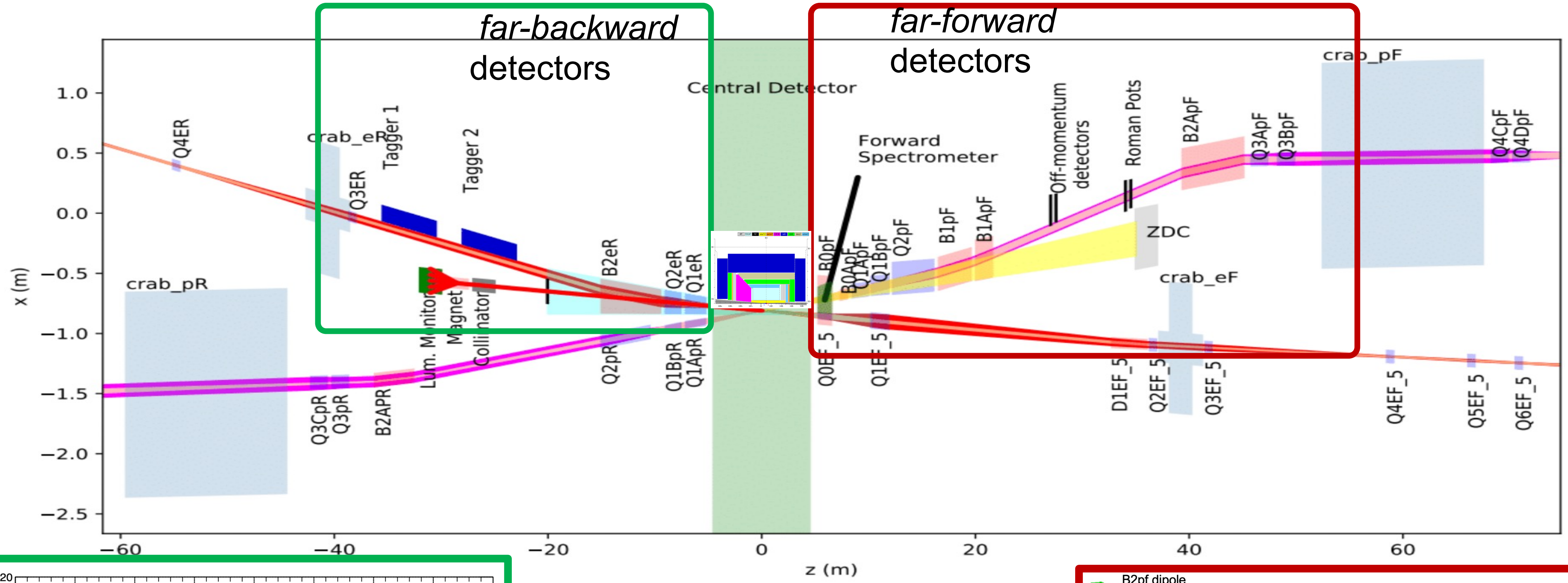
Main detector =
Barrel +
Lepton Endcap +
Hadron Endcap

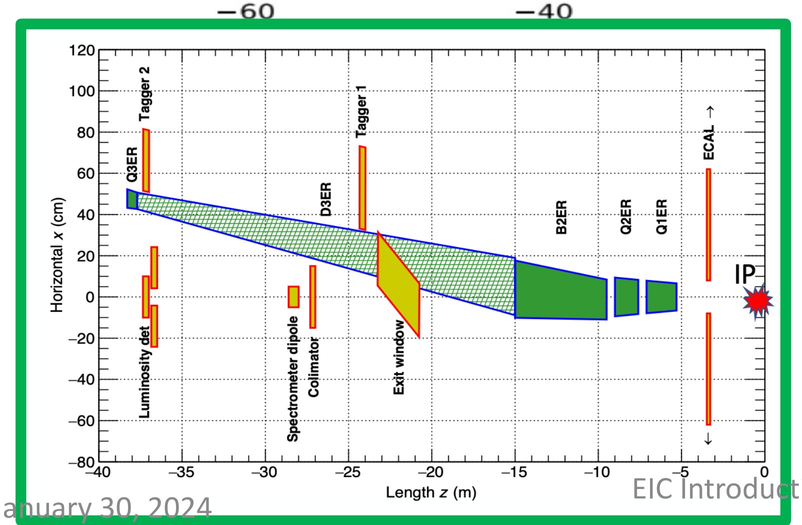
particles from nuclear breakup, i.e. neutrons, scattered protons, and ions from diffractive reactions

Forward

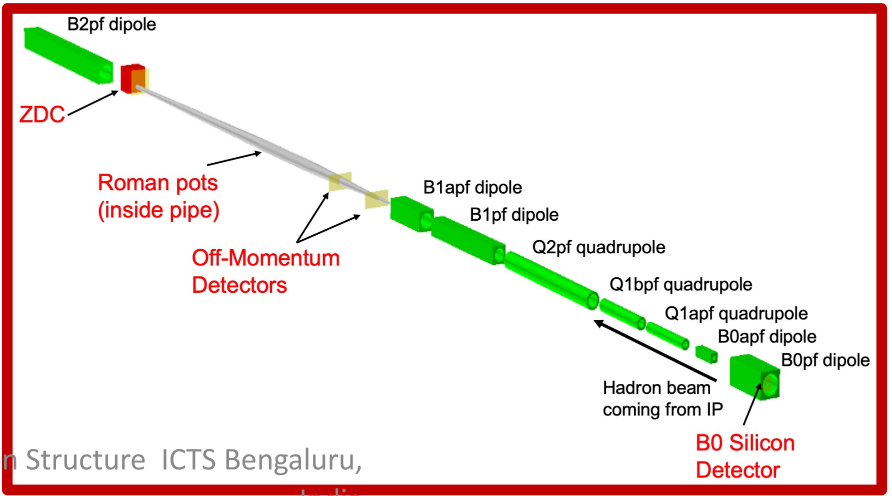
Endcaps critical because of largely asymmetric beam energies (with different beams).
Similar large impact on IR/accelerator.

Reference Detector – Backward/Forward Detectors

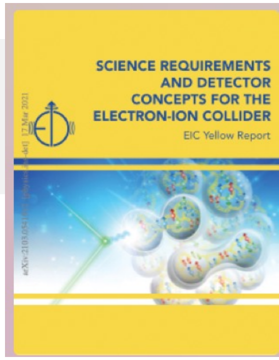




Extensive integration of forward and backward detector elements into the accelerator lattice



Resulting Experimental Requirements


SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER
EIC Yellow Report

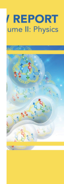
More and more demanding moving from inclusive to fully exclusive scattering

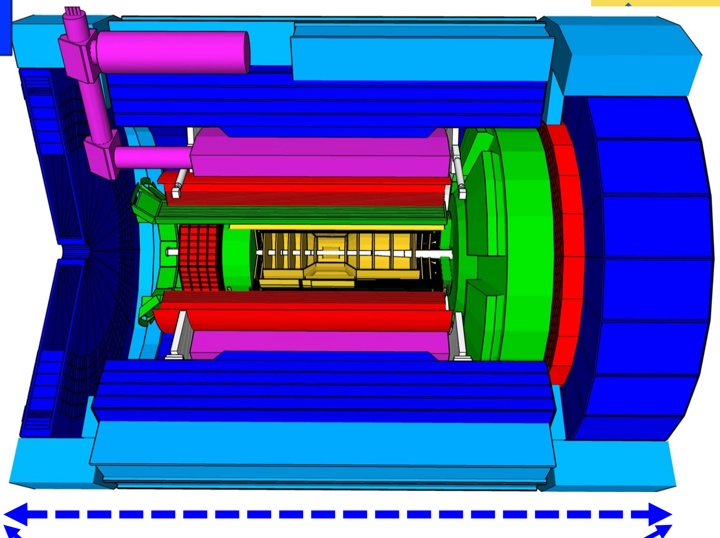
- **Inclusive measurements (DIS), required:**
  - Precise scattered electron identification (e.m. calorimetry, e/h PID) and extremely fine resolution in the measurement of its angle (tracking) and energy (calorimetry)
- **Semi-inclusive measurements (SI-DIS), also required:**
  - excellent hadron identification over a wide momentum and rapidity range (h-PID)
  - full 2π acceptance for tracking (tracking) and momentum analysis (central magnet)
  - excellent vertex resolution (low-mass vertex detector)
- **Exclusive measurements also required:**
  - Tracker with excellent space-point resolution (high resolution vertex) and momentum measurement (tracking),
  - Jet energy measurements (h calorimetry)
  - very forward detectors also to detect n and neutral decay products (Roman pots, large acceptance zero-degree calorimetry)
- **And luminosity control, e and A polarimeters, r-o electronics, DAQ, data handing**

EIC Detector Advisory Committee (DAC) Meeting, 28-29 September 2020 S. Dalla Torre (INFN) & T. Horn (CUA)

The ePIC Detector

- ❑ Asymmetric beam energies
  - ➢ requires an asymmetric detector with electron and hadron endcap
  - ➢ tracking, particle identification, EM calorimetry and hadronic calorimetry functionality in all directions
  - ➢ very compact Detector, **Integration** will be key
- ❑ Imaging science program with protons and nuclei
  - ➢ requires specialized detectors integrated in the IR over 80 m
- ❑ Momentum resolution for EIC science requires a large bore 2T magnet
- ❑ Highest scientific flexibility
  - ➢ requires Streaming Readout electronics model





hadronic calorimeters (HCAL)

Solenoidal Magnet

e/m calorimeters (ECal)

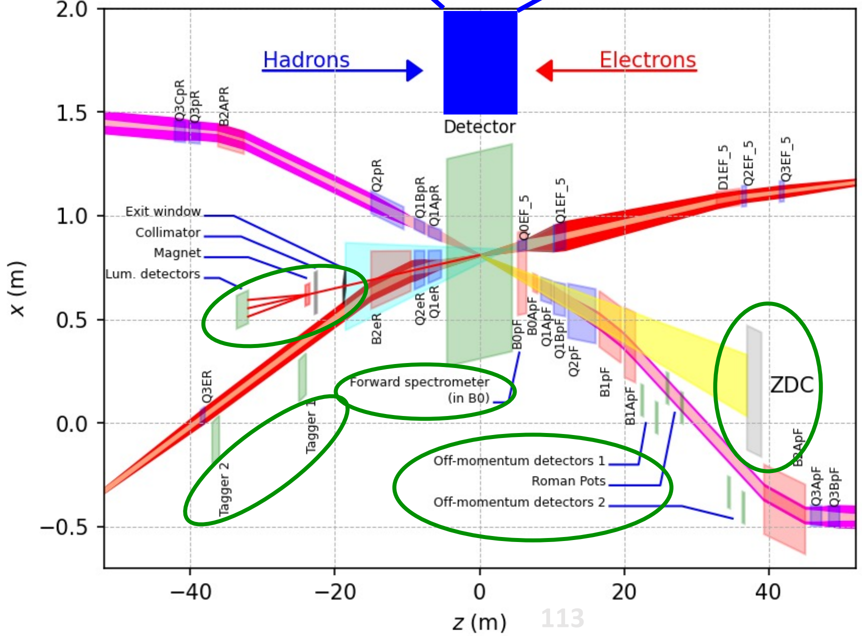
Time.of.Flight (ToF), DIRC, RICH detectors

MPGD trackers

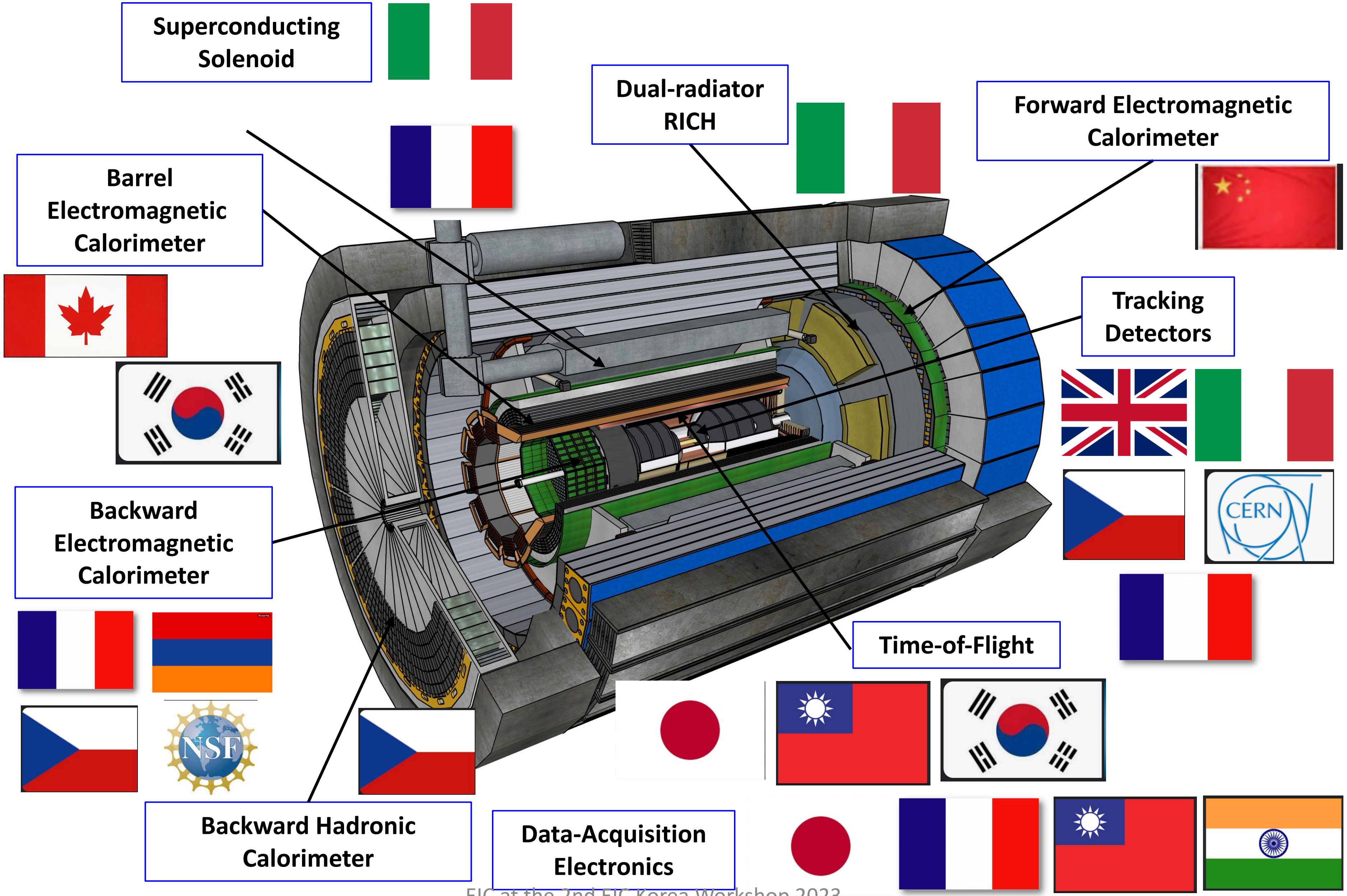
MAPS tracker

23 Subdetectors incl. Polarimeters + Data Acquisition

9.5 m



Central Detector Non-DOE Interest & In-Kind



Superconducting Solenoid

Dual-radiator RICH

Forward Electromagnetic Calorimeter

Barrel Electromagnetic Calorimeter

Tracking Detectors

Backward Electromagnetic Calorimeter

Time-of-Flight

Backward Hadronic Calorimeter

Data-Acquisition Electronics

Worldwide Interest in EIC

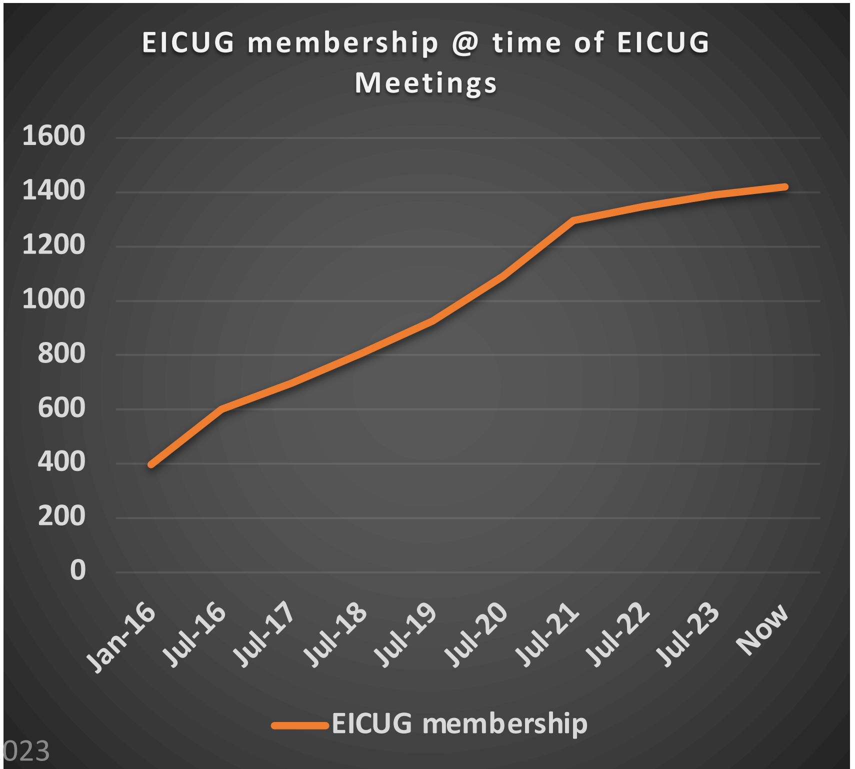

Map of institution's locations

The EIC User Group:
https://eicug.github.io/

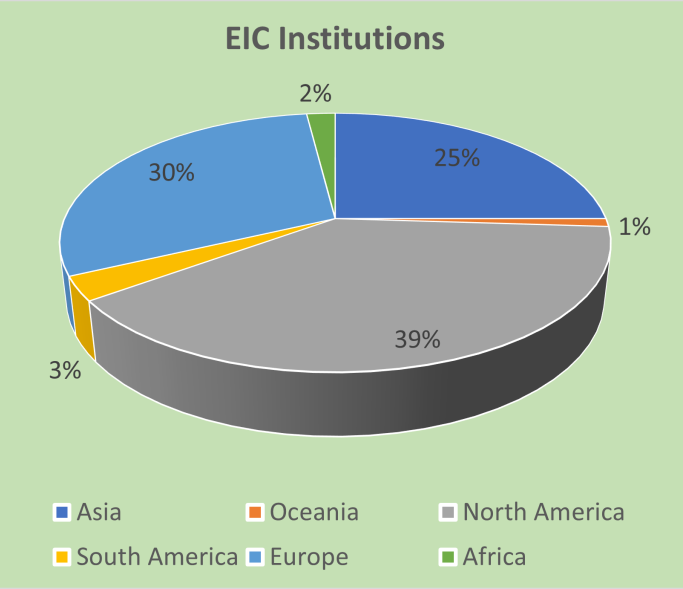
Formed 2016 –
- **1417 collaborators,**
- **37 countries,**
- **285 institutions**

as of October 02, 2023.

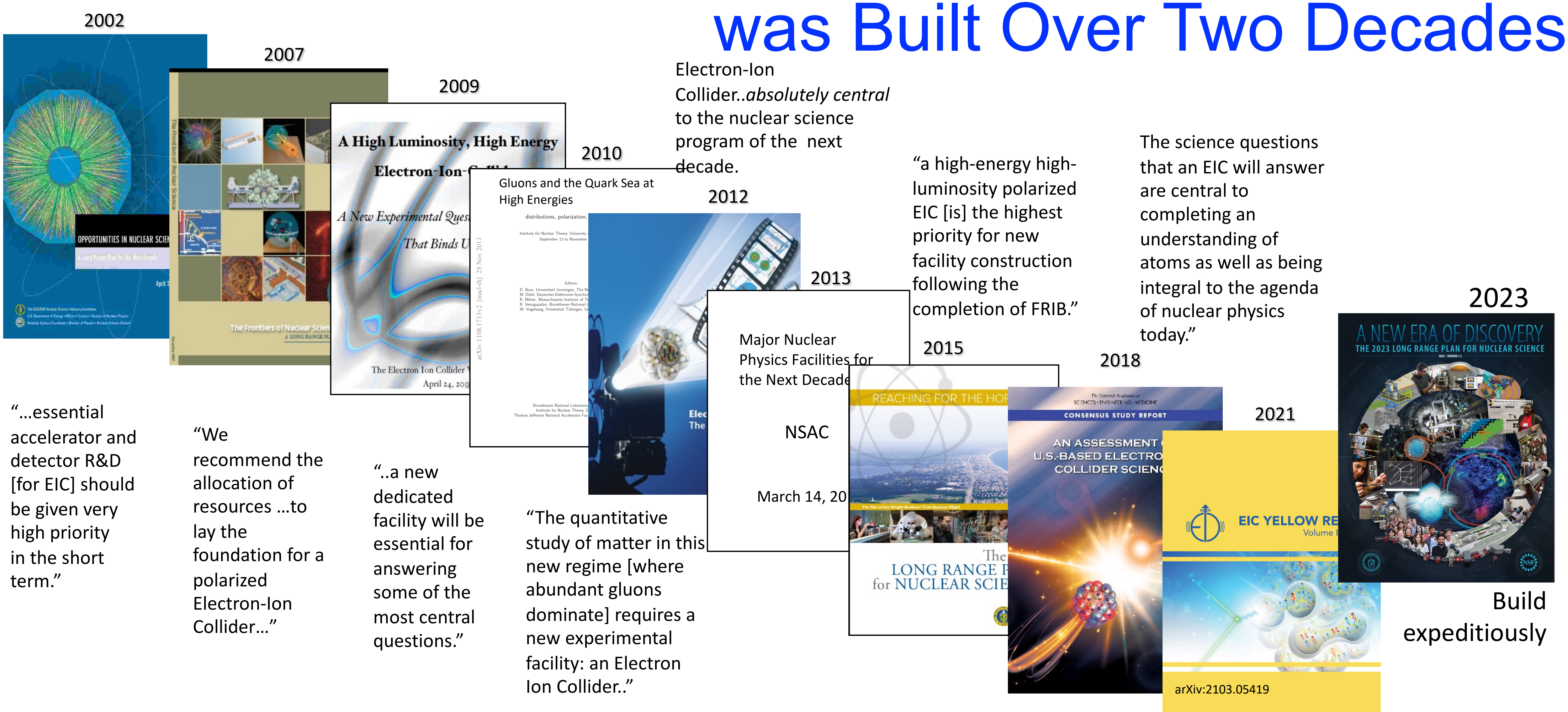
Strong International Participation.



Annual EICUG meeting
2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 CUA, Washington, DC
2019 Paris, France
2020 FIU, Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland
2024 Lehigh U, PA



The Scientific Foundation for an EIC was Built Over Two Decades



"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

"..a new dedicated facility will be essential for answering some of the most central questions."

"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

Electron-Ion Collider..*absolutely central* to the nuclear science program of the next decade.

"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors

Build expeditiously

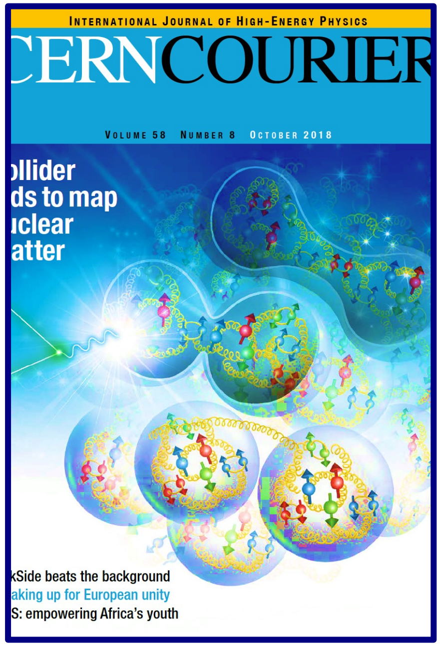
Summary & Outlook

- Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, funded by the DOE will be built in this decade and operate in 2030's.
  - Will address some of the most profound question yet unanswered in the Standard Model of Strong Interactions (and beyond)
- Up to two hermetic full acceptance detectors under consideration, currently **EIC project has funds for 1 detector**, cost of a second detector from non-DOE sources
  - Experimental collaboration formed: ePIC)
  - EIC project assumes **an aggressive timeline : engineering collisions around 2031/2, physics collisions within 2-years of that.**
- **High interest in having international partners both on detector and accelerator**

- *For all early career scientists, graduate and undergraduate students: This machine is for you! Ample opportunity to contribute to machine, detector & physics of a new project.*

Welcome to the EIC family….

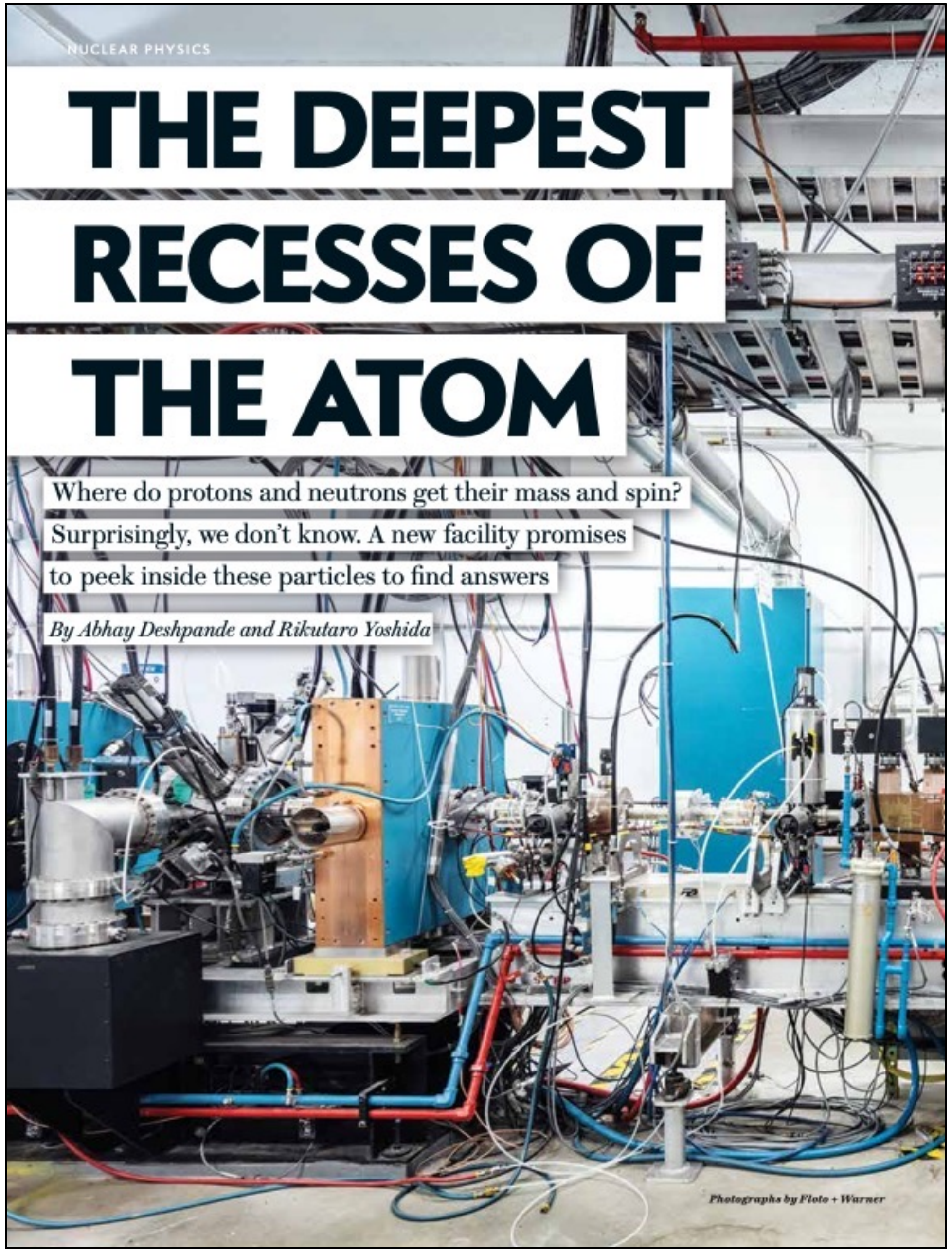
R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)
Translated into multiple languages



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERNCOURIER
VOLUME 58 NUMBER 8 OCTOBER 2018
llider
ds to map
clear
atter
kSide beats the background
aking up for European unity
S: empowering Africa's youth

E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019
Translated in to multiple languages



NUCLEAR PHYSICS

THE DEEPEST RECESSES OF THE ATOM

Where do protons and neutrons get their mass and spin? Surprisingly, we don't know. A new facility promises to peek inside these particles to find answers

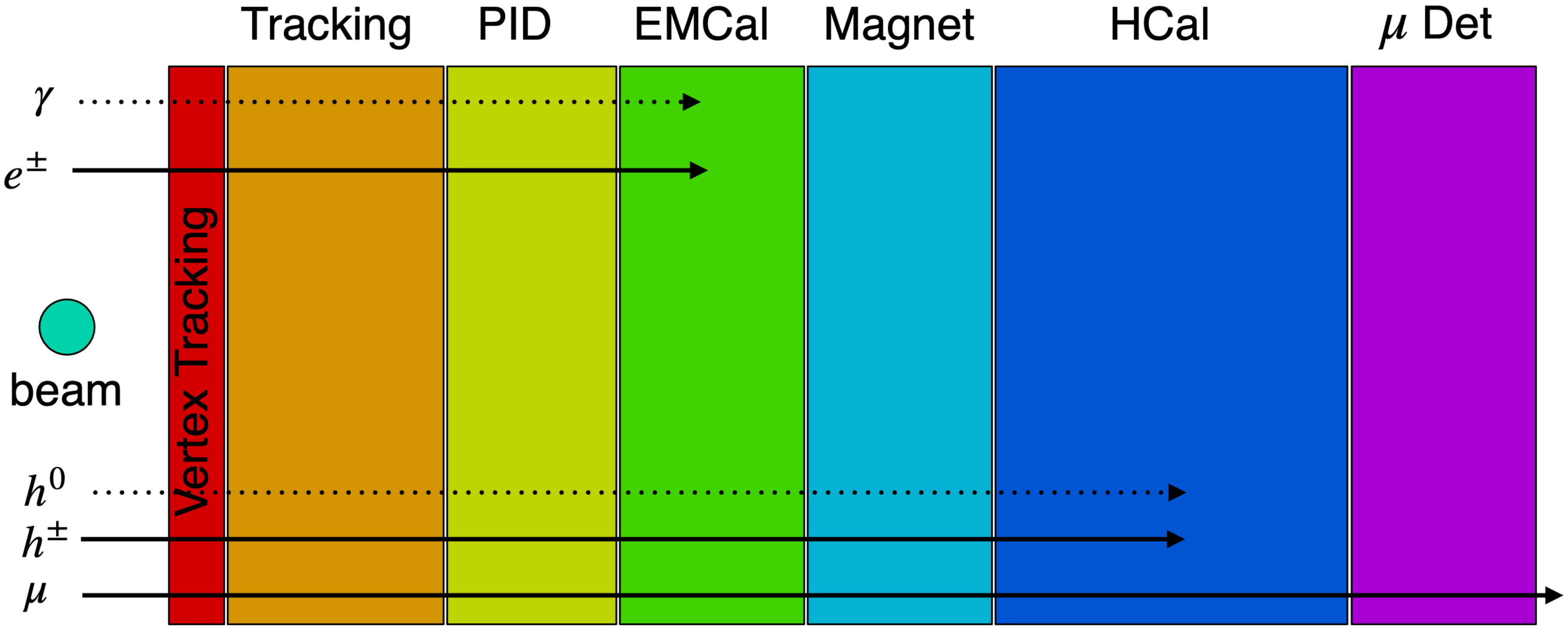
By Abhay Deshpande and Rikutaro Yoshida

Photographs by Floto + Warner

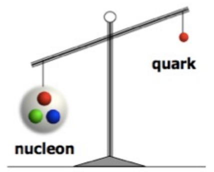
"New directions in science are launched by new tools much more often than by new concepts."

Freeman Dyson

Bringing it All Together



Mass of the Nucleon (Pion & Kaon)



"The mass is the result of the equilibrium reached through dynamical processes." **X. Ji**

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"
-- The 2015 Long Range Plan for Nuclear Science

Relativistic Motion ***Chiral Symmetry Breaking*** ***Quantum Fluctuations***

X. Ji, PRL 74 1071 (1995)

$$M = E_q + E_g + \chi_{m_q} + T_g$$

Quark Energy **Gluon Energy** **Quark Mass** **Trace Anomaly**

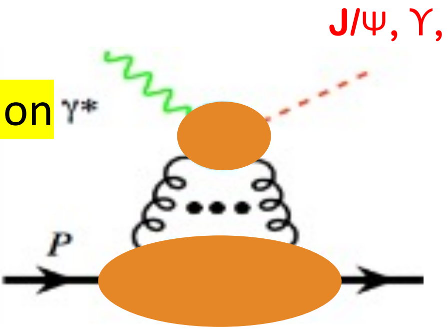
- Criticisms: not scale-invariant, decompositions: Lorentz invariant vs. rest frame
- Recent interest (workshops planned) to clarify how to determine the different contributions
- **Lattice QCD providing estimates**

E_q ~30% E_g ~40% χ_{m_q} ~10% T_g ~ 25%

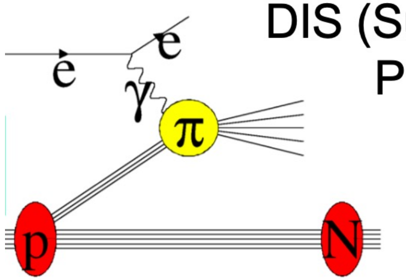
arXiv: 1710.09011

Trace anomaly:
J/Psi & Upsilon production near threshold:

SoLID@JLab & EIC

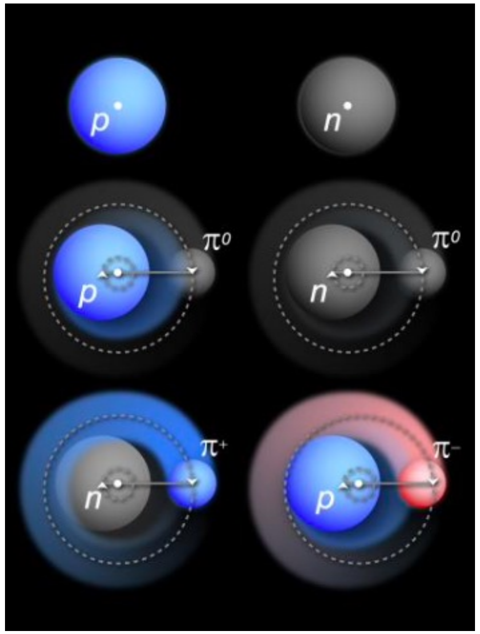


DIS (Sullivan Process)



(pion/Kaon) PDFs: P. C. Barry et al. PRL 127, 232001 (2021)

Pion/Kaon mass & PDFs



Relativistic Motion

Chiral Symmetry Breaking

Quantum Fluctuations

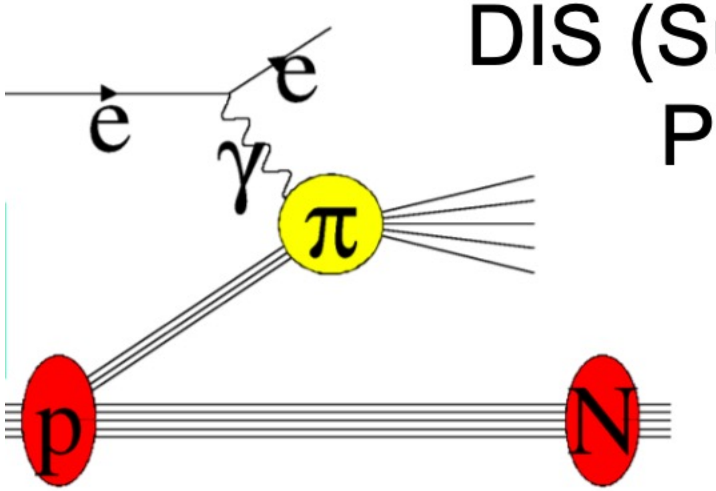
$$M = E_q + E_g + \chi_{m_q} + T_g$$

Quark Energy

Gluon Energy

Quark Mass

Trace Anomaly



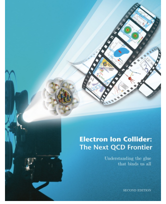
DIS (Sullivan Process)

For PDF studies

- How different are these terms in 2-quark systems? Light vs. heavy quarks?
- What can we learn from Sullivan Process about their structure?
- Hints for learning about origin of emergent mass?

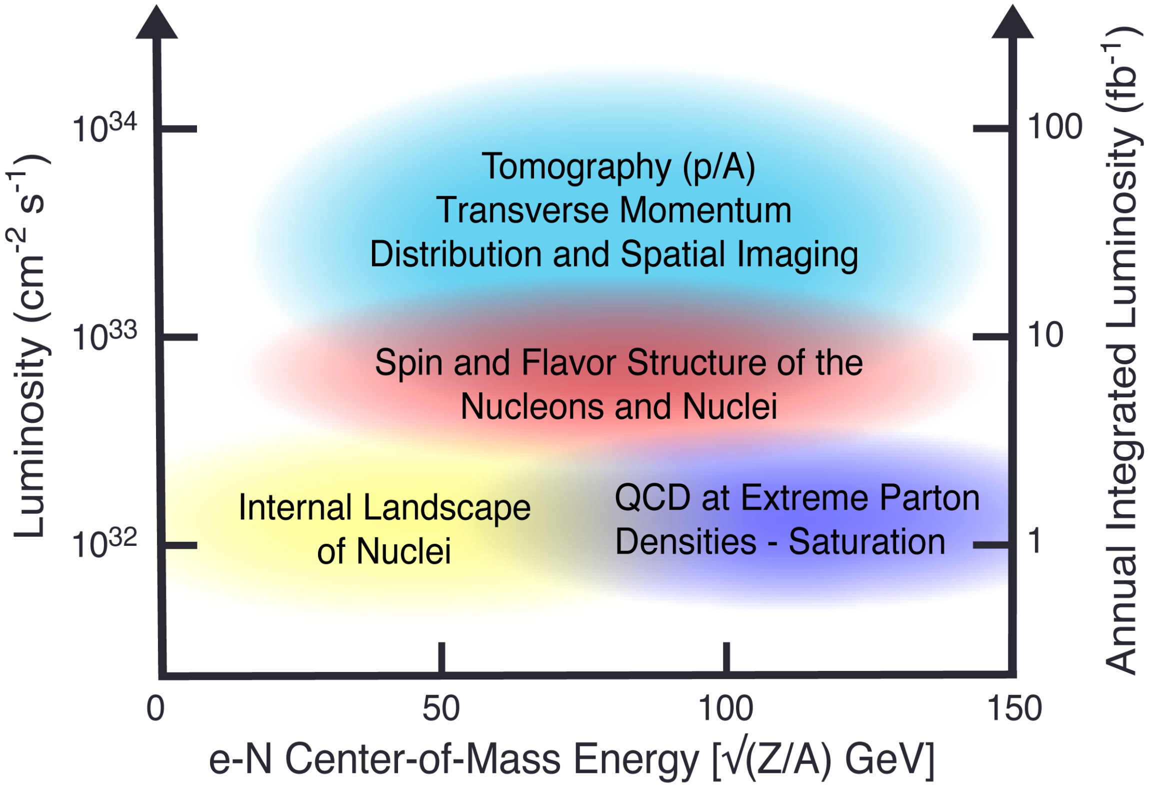
PDFs @ EIC : J> Arrington et al. J. of Physics G. 48 (2021) 075106

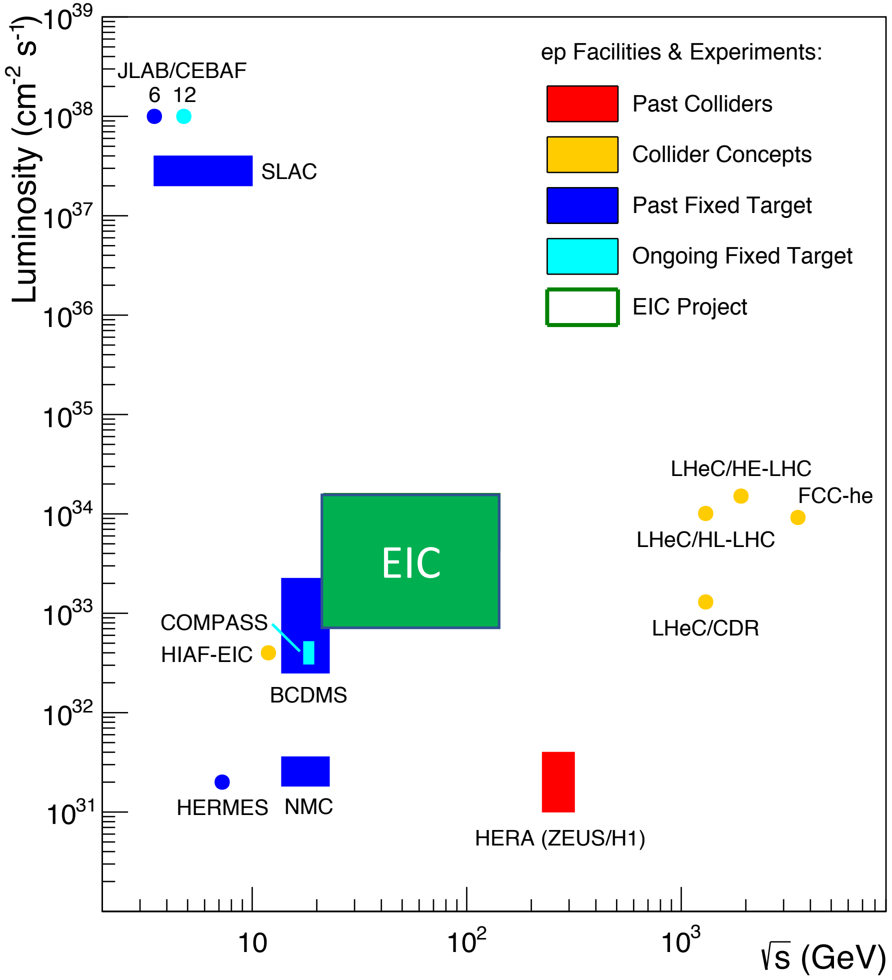
PDFs: P. C. Barry et al. PRL 127, 232001 (2021)



EIC Physics and the machine parameters

CM vs. Luminosity vs. Integrated luminosity



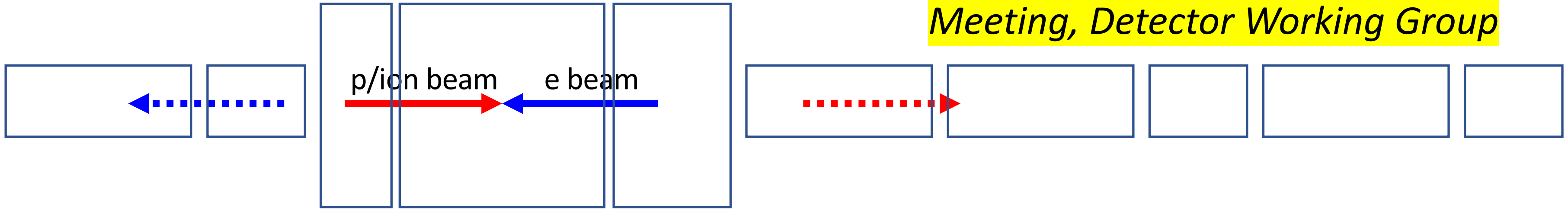


The US EIC with a wide range in $\sqrt{s}$, polarized electron, proton and light nuclear beams and luminosity makes it a unique machine in the world.

Cartoon/Model of the Extended Detector and IR

- ❑ EIC physics covers the entire region (backward, central, forward)
- ❑ Many EIC science processes rely on excellent and fully integrated forward detection scheme

Adapted from 2nd Yellow Report Meeting, Detector Working Group



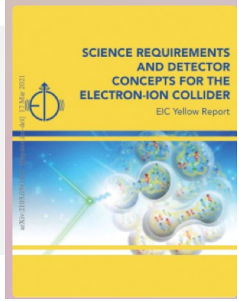
far-backward e-detection	e final-focus quads	"Central detector", includes e-endcap, central, and p/ion endcap detectors	forward dipole incl. h detection	Ion final-focus quads	forward dipole	far-forward h-detection	far-forward h-detection
Low-Q^2 spectroscopy		Inclusive Structure Functions, TMDs, heavy flavors and jets, electrons for GPDs	GPDs/DVCS, tagging, diffraction, high-medium t			Baryon decay π/K structure evaporated n	GPDs, tagging, diffraction, lowest-t
GEMs Diamond detectors?		Vertex and Tracking detectors, particle identification detectors, calorimetry detectors, muon detectors, etc.	Si/GEMs Roman pots, e/γ calorim.			GEMs Roman pots e/γ calorim.	Roman pots ZDCs

🟩 physics examples

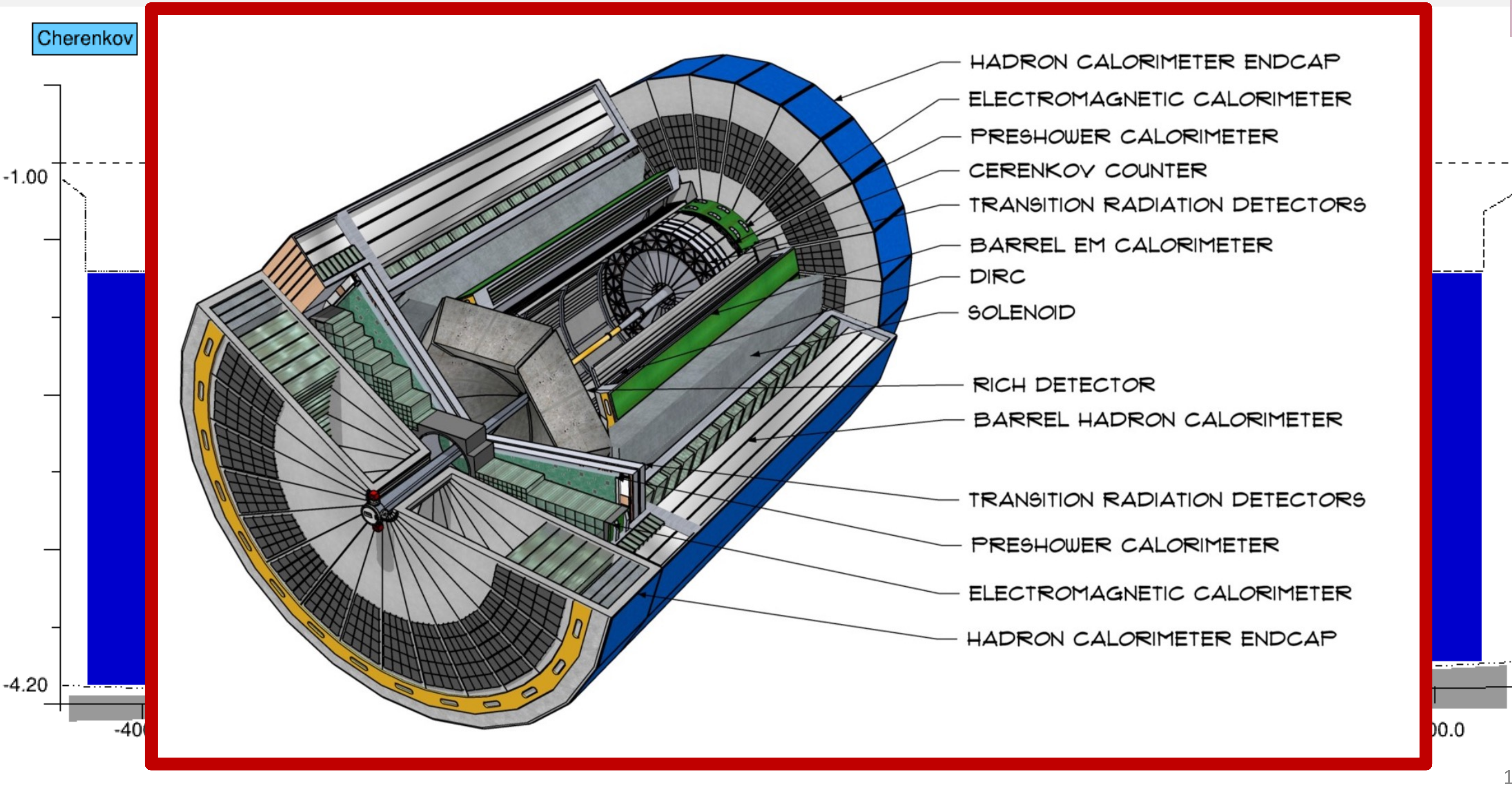
🟨 detector examples

Concept DETECTOR

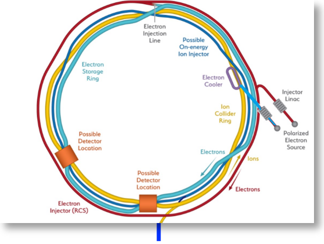
This detector concept was included in the EIC CDR prepared for the CD1 Review



SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER
EIC Yellow Report

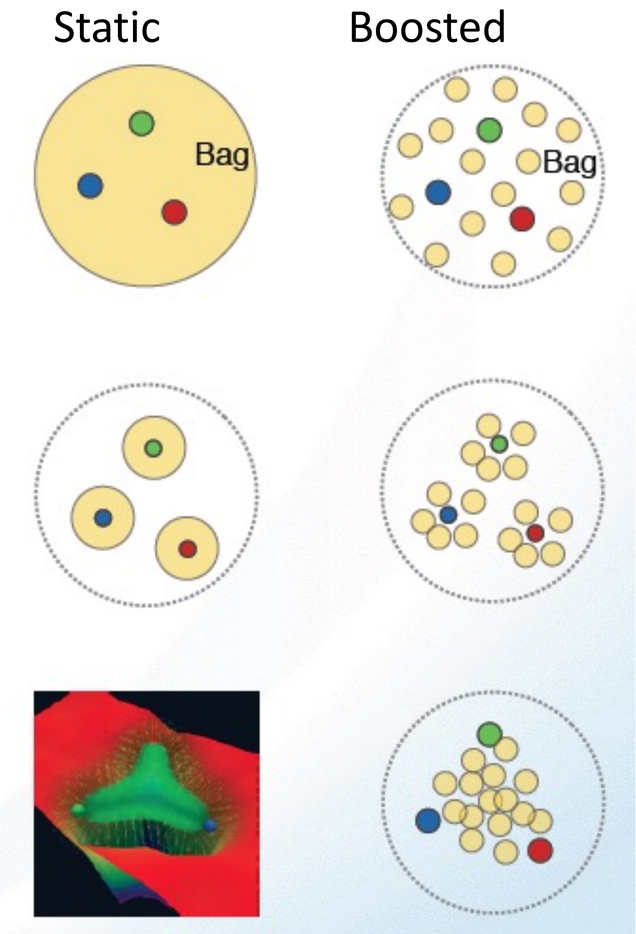


Complementarity for 1^{st}-IR & 2^{nd}-IR



	1^{st} IR (IP-6)	**2^{nd} IR (IP-8)**
Geometry:	ring inside to outside	ring outside to inside
	tunnel and assembly hall are larger Tunnel: ⦸ 7m +/- 140m	tunnel and assembly hall are smaller Tunnel: ⦸ 6.3m to 60m then 5.3m
Crossing Angle:	25 mrad	35 mrad secondary focus
	different blind spots different forward detectors and acceptances different acceptance of central detector	
Luminosity:	more luminosity at lower E_{CM} optimize Doublet focusing FDD vs. FDF → impact of far forward p_T acceptance	
Experiment:	1.5 Tesla or 3 Tesla different subdetector technologies	

What does a proton look like in transverse dimension?



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

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

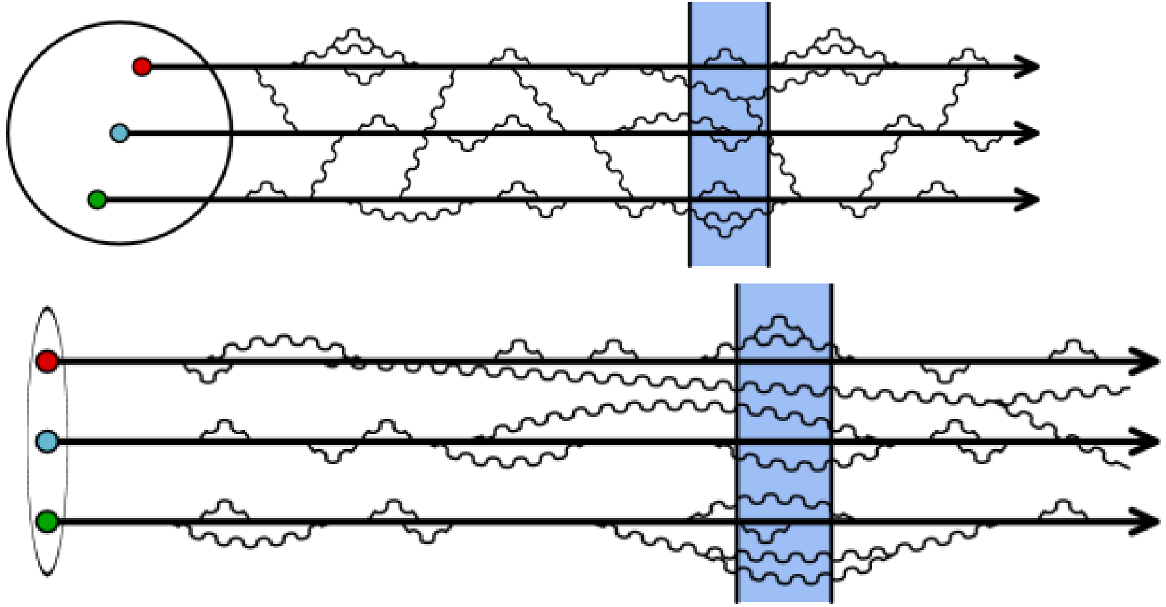
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks: Color (Gluon) radius < Charge (quark) Radius

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

How does a Proton look at low and very high energy?

Low energy: High x
Regime of fixed target exp.

High energy: Low- x
Regime of a Collider



Cartoon of boosted proton

At high energy:

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

Recall Marco Radici’s comment