Center for Frontiers in Nuclear Science

Introduction: EIC Science an experimental review…

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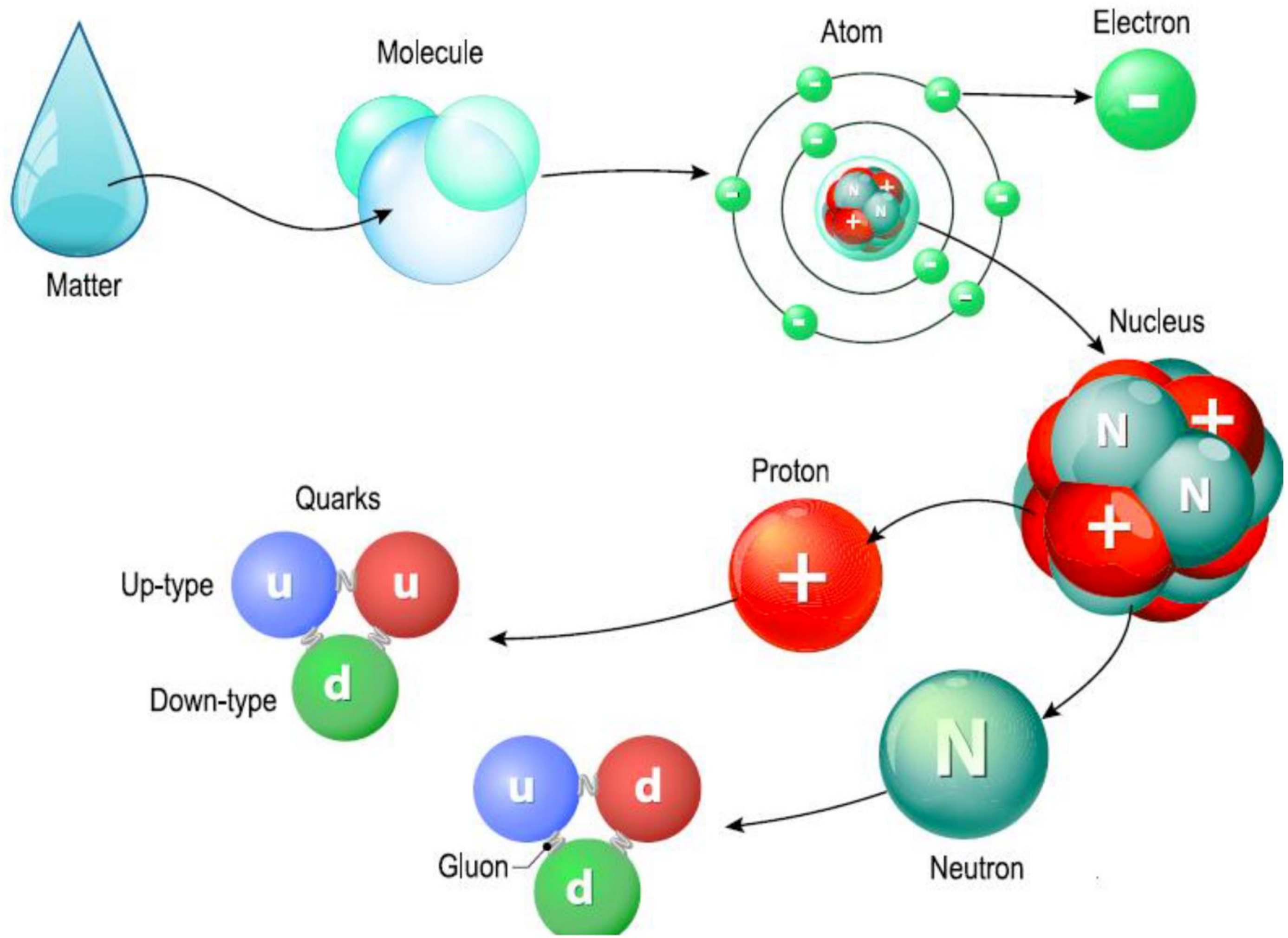
Quest for the fundamental structure of matter



What's in there?

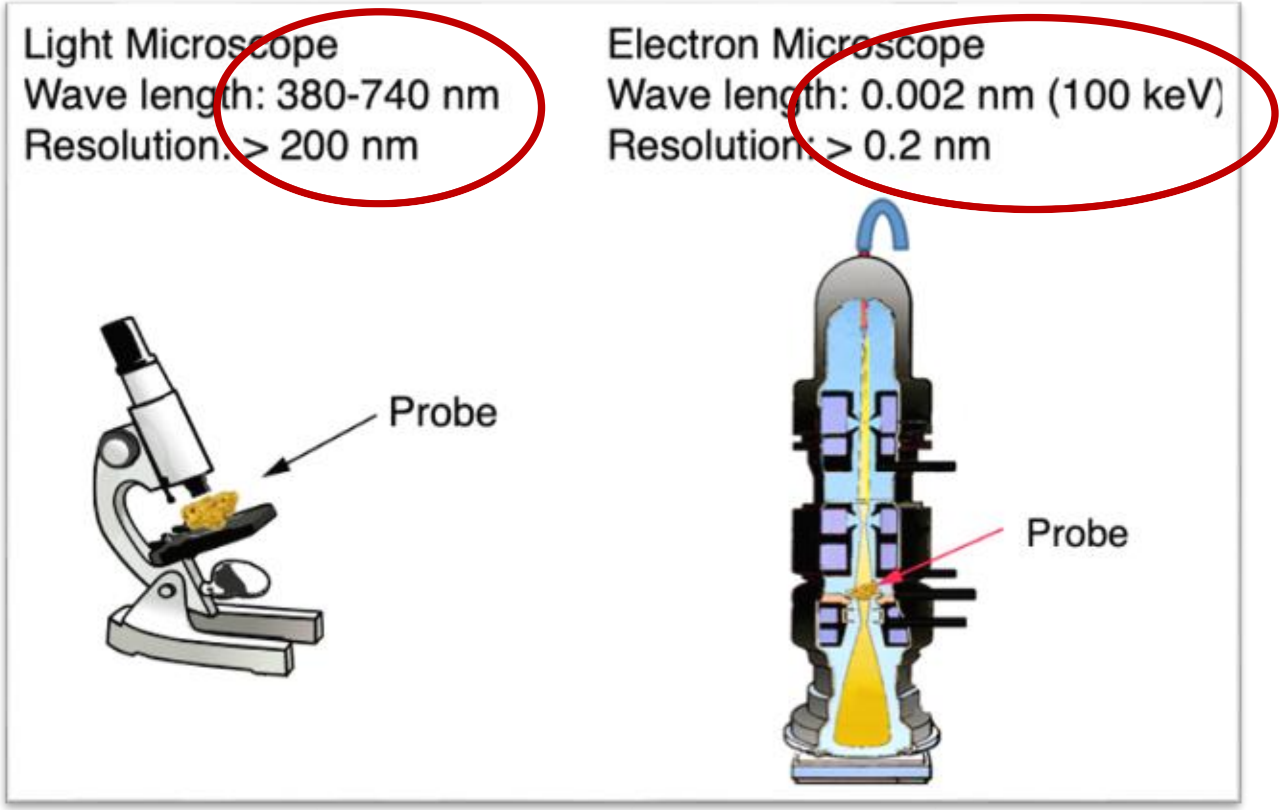
What are we made up of?

What is the "smallest"?

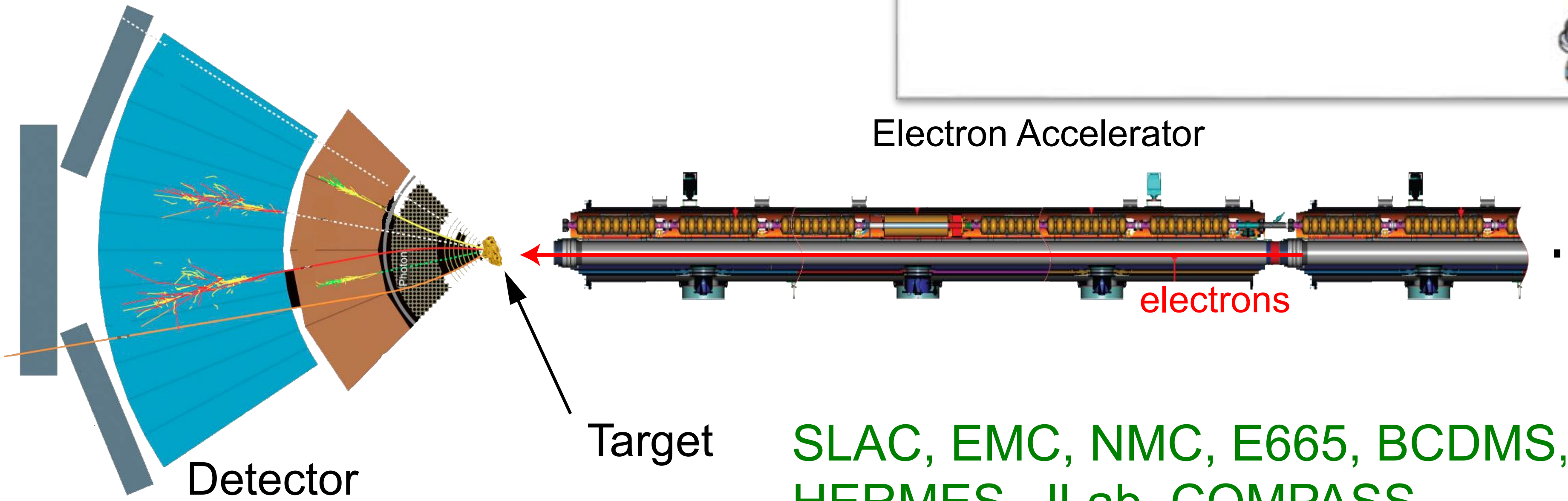
What is "fundamental" that can't be divided further?

National Academy of Sciences, Consensus Report on the US EIC

Studying smaller and smaller things…

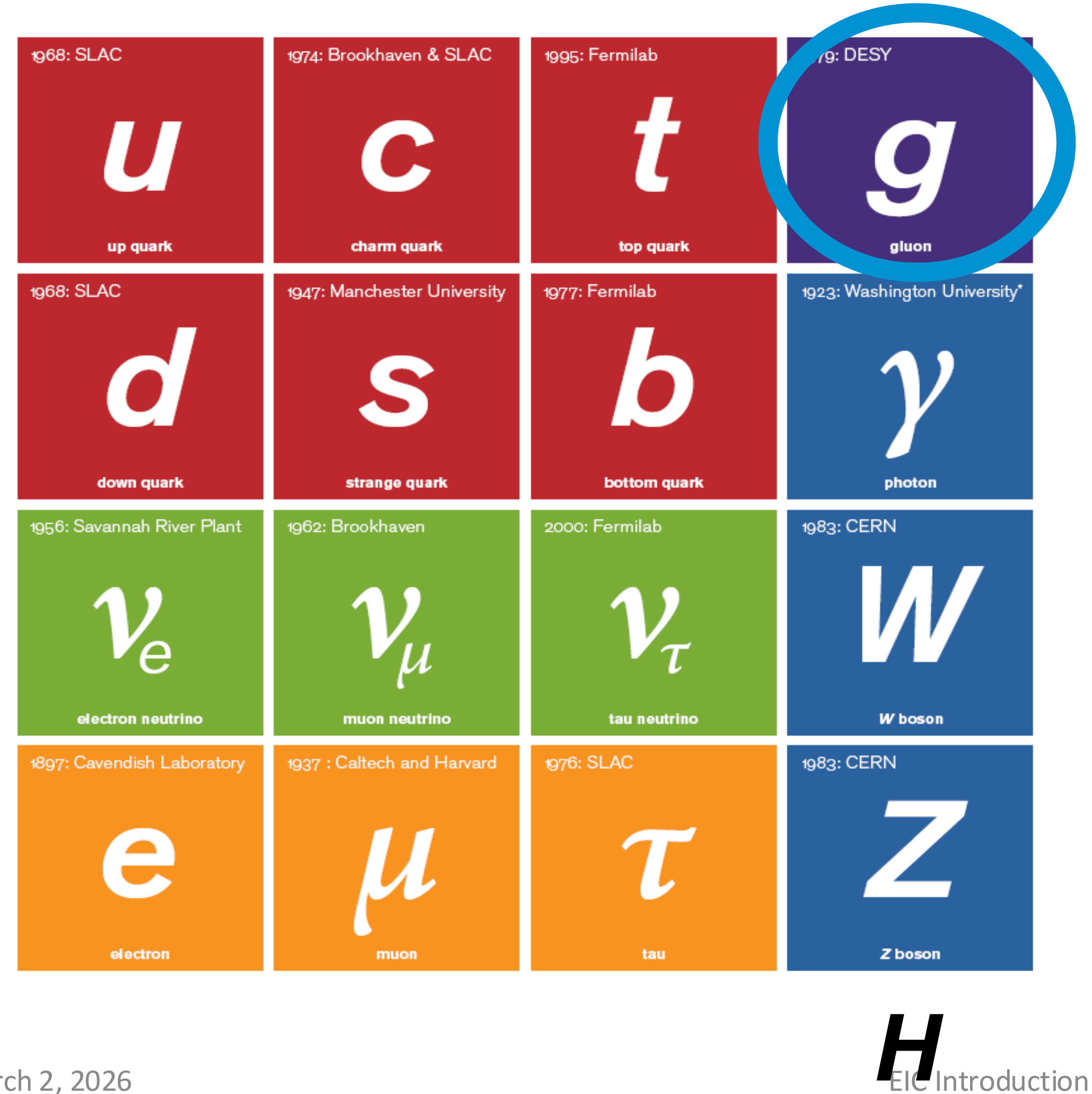


Fixed Target Particle Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm

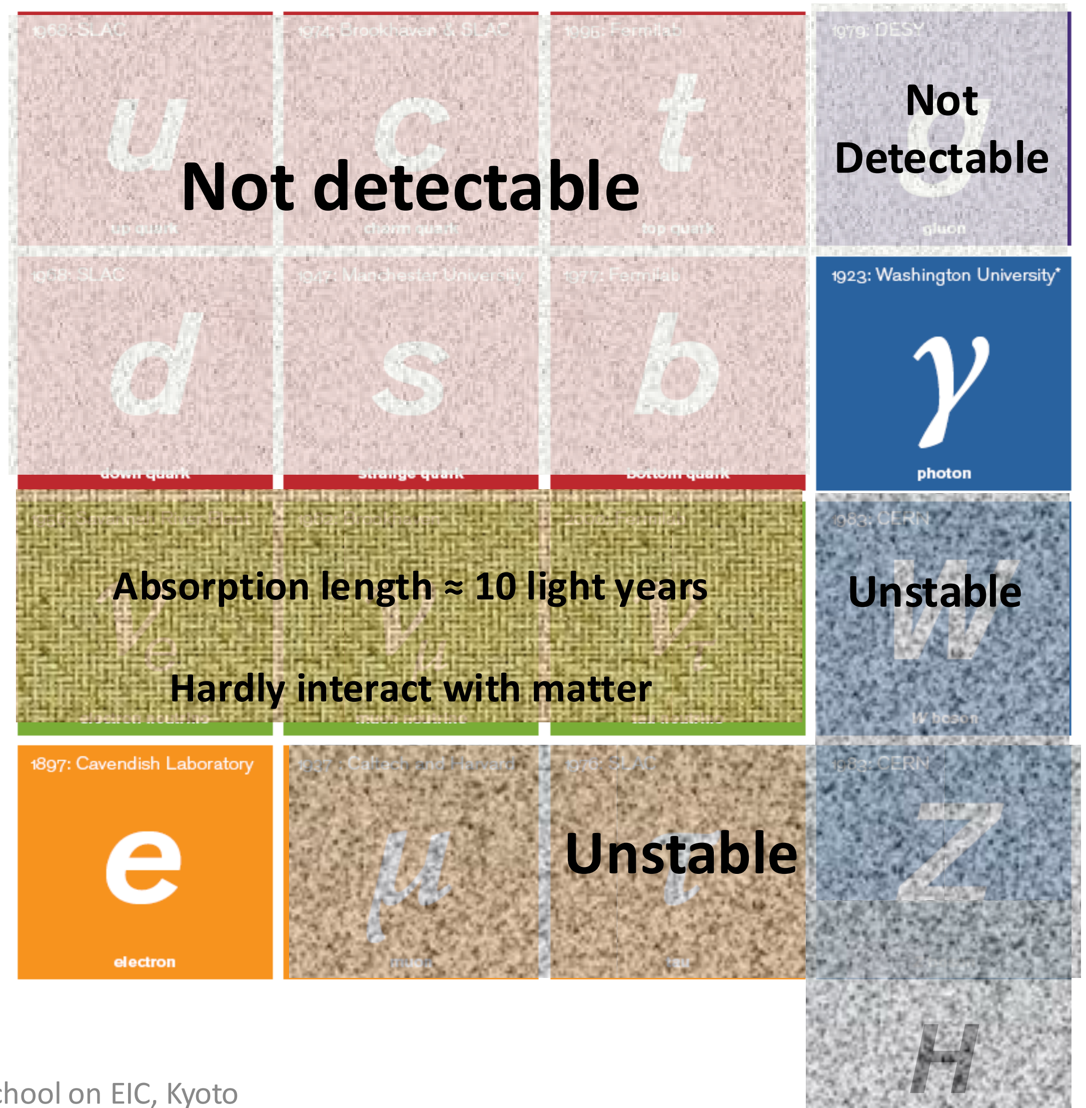


SLAC, EMC, NMC, E665, BCDMS, HERMES, JLab, COMPASS, …

Many 



1968: SLAC
u
up quark
1974: Brookhaven & SLAC
c
charm quark
1995: Fermilab
t
top quark
1979: DESY
g
gluon
1968: SLAC
d
down quark
1947: Manchester University
s
strange quark
1977: Fermilab
b
bottom quark
1923: Washington University*
γ
photon
1956: Savannah River Plant
ν_e
electron neutrino
1962: Brookhaven
ν_μ
muon neutrino
2000: Fermilab
ν_τ
tau neutrino
1983: CERN
W
W boson
1897: Cavendish Laboratory
e
electron
1937 : Caltech and Harvard
μ
muon
1976: SLAC
τ
tau
1983: CERN
Z
Z boson
H

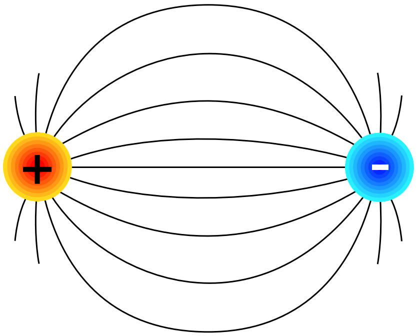


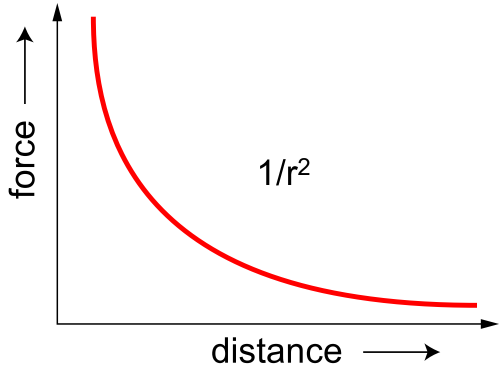
Not detectable
Not Detectable
1923: Washington University*
γ
photon
Absorption length ≈ 10 light years
Hardly interact with matter
Unstable
1897: Cavendish Laboratory
e
electron
Unstable

Quantum Electrodynamics (QED)

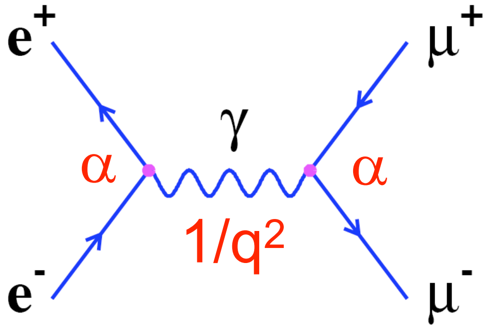
Theory of electromagnetic interactions

- Exchange particles (photons) do not carry electric charge
- Flux is not confined: $V(r) \sim 1/r$, $F(r) \sim 1/r^2$





Example Feynman Diagram:
e^+e^- annihilation



$$V(r) = -\frac{q_1 q_2}{4\pi\epsilon_0 r} = -\frac{\alpha_{em}}{r}$$

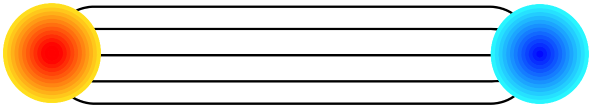
Coupling constant (α): Interaction Strength
In QED: $\alpha_{em} = 1/137$

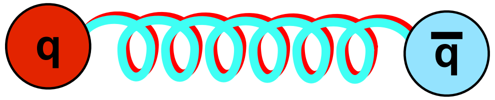
Quantum Chromodynamics (QCD)

Quantum Chromo Dynamics is the "nearly perfect" fundamental theory of the strong interactions

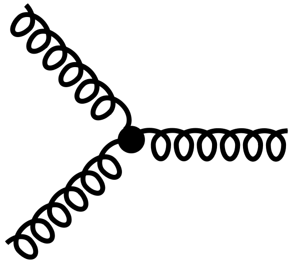
F. Wilczek, hep-ph/9907340

- Three color charges: red, green and blue





- Exchange particles (gluons) carry color charge and can self-interact



Self-interaction: QCD significantly harder to analyze than QED

- Flux is *confined*: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$

~1/r at short range

long range ~ r

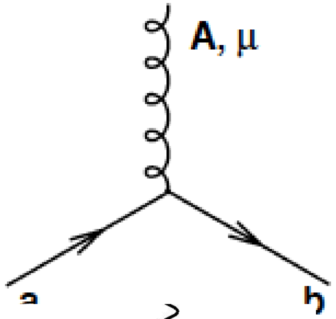
Long range aspect ⇒ quark confinement and existence of nucleons

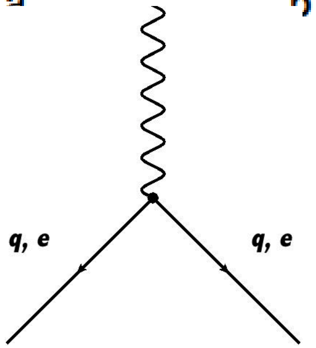
What distinguishes QCD from QED?

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

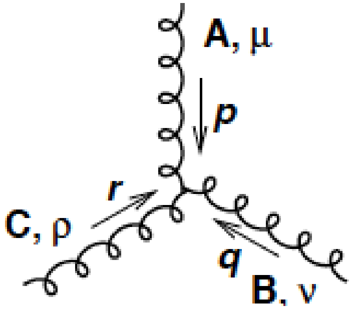
QCD is mediated by gluons (g), also charge-less but *are* colored! → can interact with themselves, and colored quarks

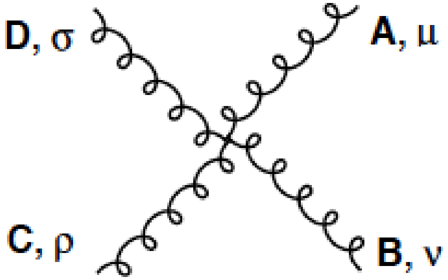
In QCD &
g → γ in QED





Only in QCD





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

Introduction to EIC – two sections

- History of "EIC Science"
  - ❖ Science drivers: Past & current experiments:
  - ❖ Their limitations
- EIC Science, status and realization
  - ❖ How EIC will overcome the limitation

Deep Inelastic Scattering (DIS)

Concept, kinematics and experimental measurements

Some puzzles : (science motivators for the EIC)

1) Low-x (high energy) behavior
2) The spin puzzle

Study of internal structure of a watermelon:

A-A (RHIC/LHC)

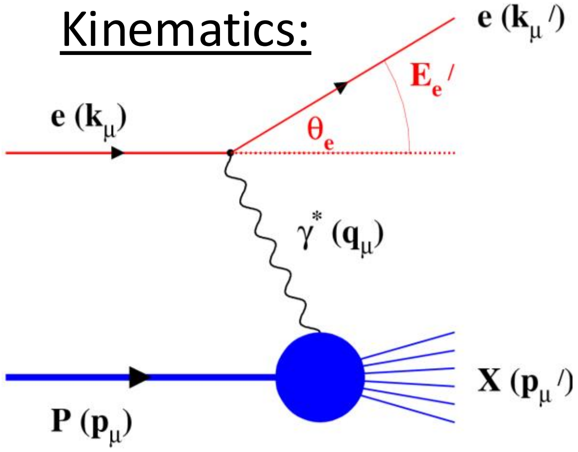
1) Violent collision of melons

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^*

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

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

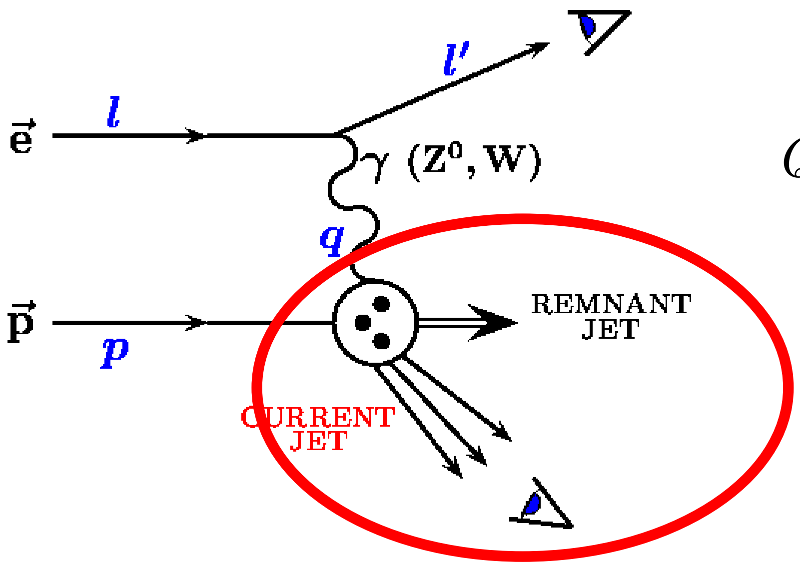
Sometimes scattered electron can't be measured….

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?



$$y = \frac{E_j}{2E_e}(1 - cos\theta_j)$$

$$Q^2 = E_j^2 sin^2\theta_j/(1 - y)$$

$$x = \frac{E_j}{2E_p}(1 + cos\theta_j)/(1 - y)$$

$$E_j = yE_e + x(1 - y)E_p$$

$$cos\theta_j = \frac{-yE_e + (1-y)xE_p}{y\,E_e + (1-y)xE_p}$$

$$E_j^2 sin^2\theta_j = 4\,xy(1-y)E_eE_p = Q^2\,(1-y)$$

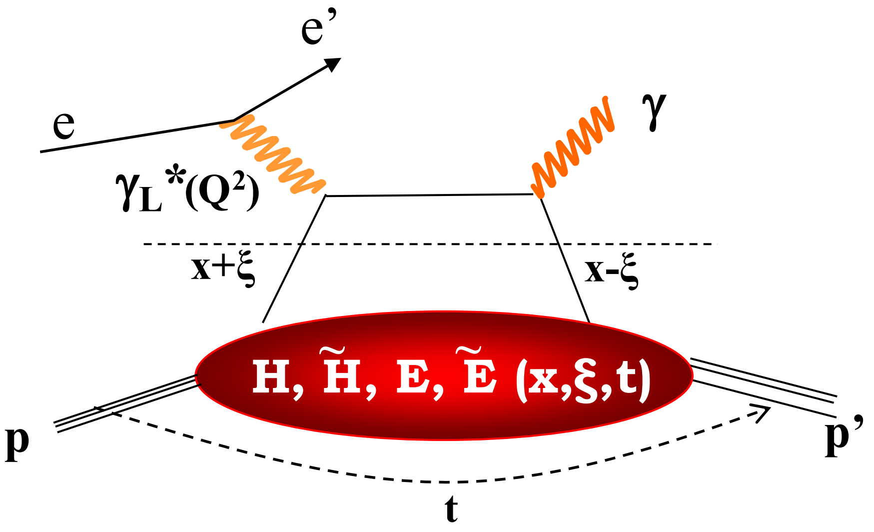
$$y_{JB} = \frac{1}{2E_e}\sum_h(E_h - p_{Zh})$$

$$Q^2_{JB} = \frac{(\sum_h p_{Xh})^2 + (\sum_h p_{Yh})^2}{1 - y_{JB}}$$

$$x_{JB} = Q^2_{JB}/(y_{JB}s)$$

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

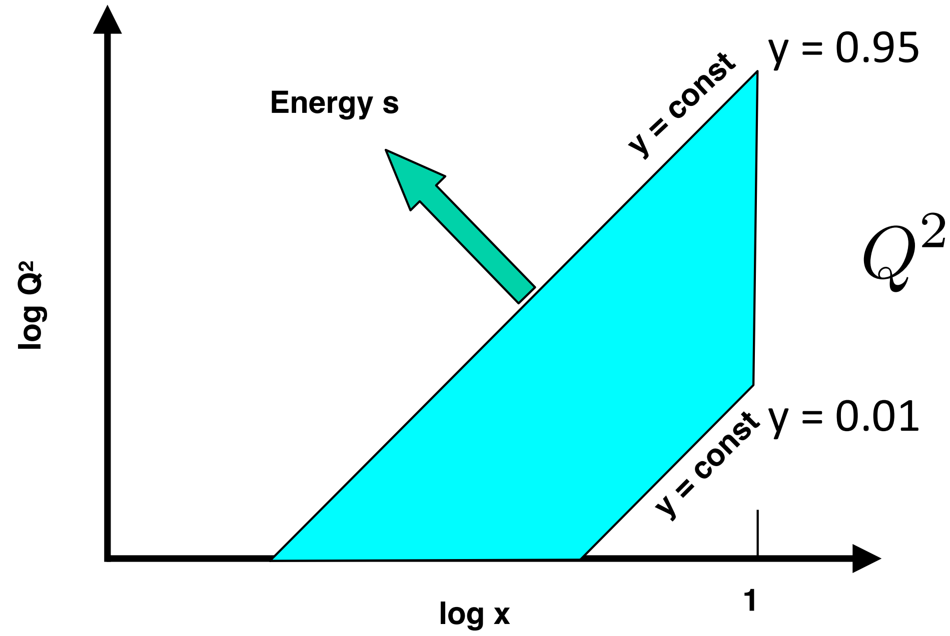
detect **all** event products in the detector

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**

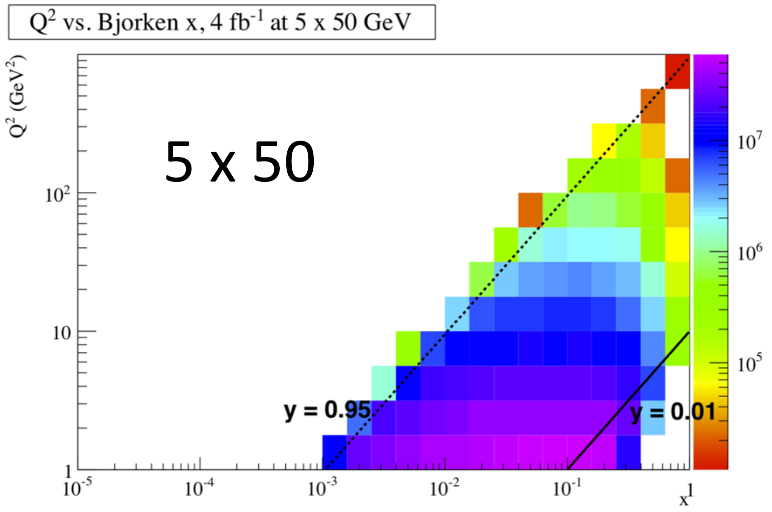
The x-Q^2 plane…

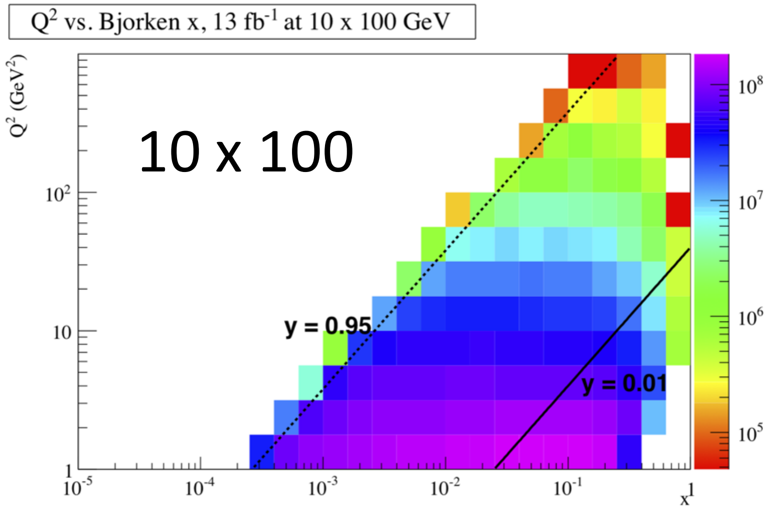


$$Q^2 \approx s \cdot x \cdot y$$

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

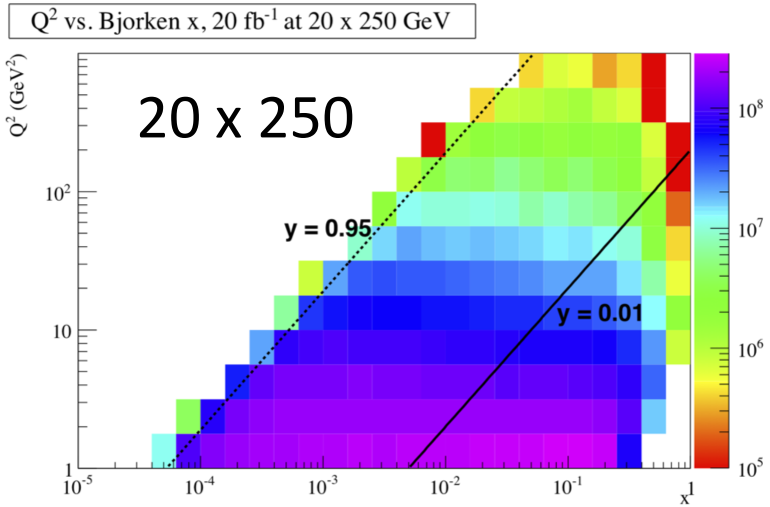
Kinematic coverage as a function of energy of collisions





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)



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 A. Cooper-Sarkar's set of lectures.

Inclusive Cross-Section:

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

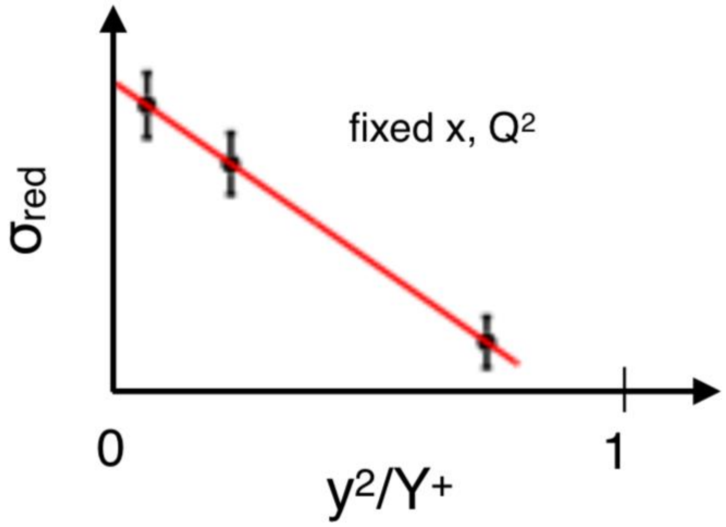
Reduced Cross-Section:

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

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

Rosenbluth Separation:

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



$$(CME)^2 = S = 4\ E_e\ E_p$$

Early experiments: fixed target

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

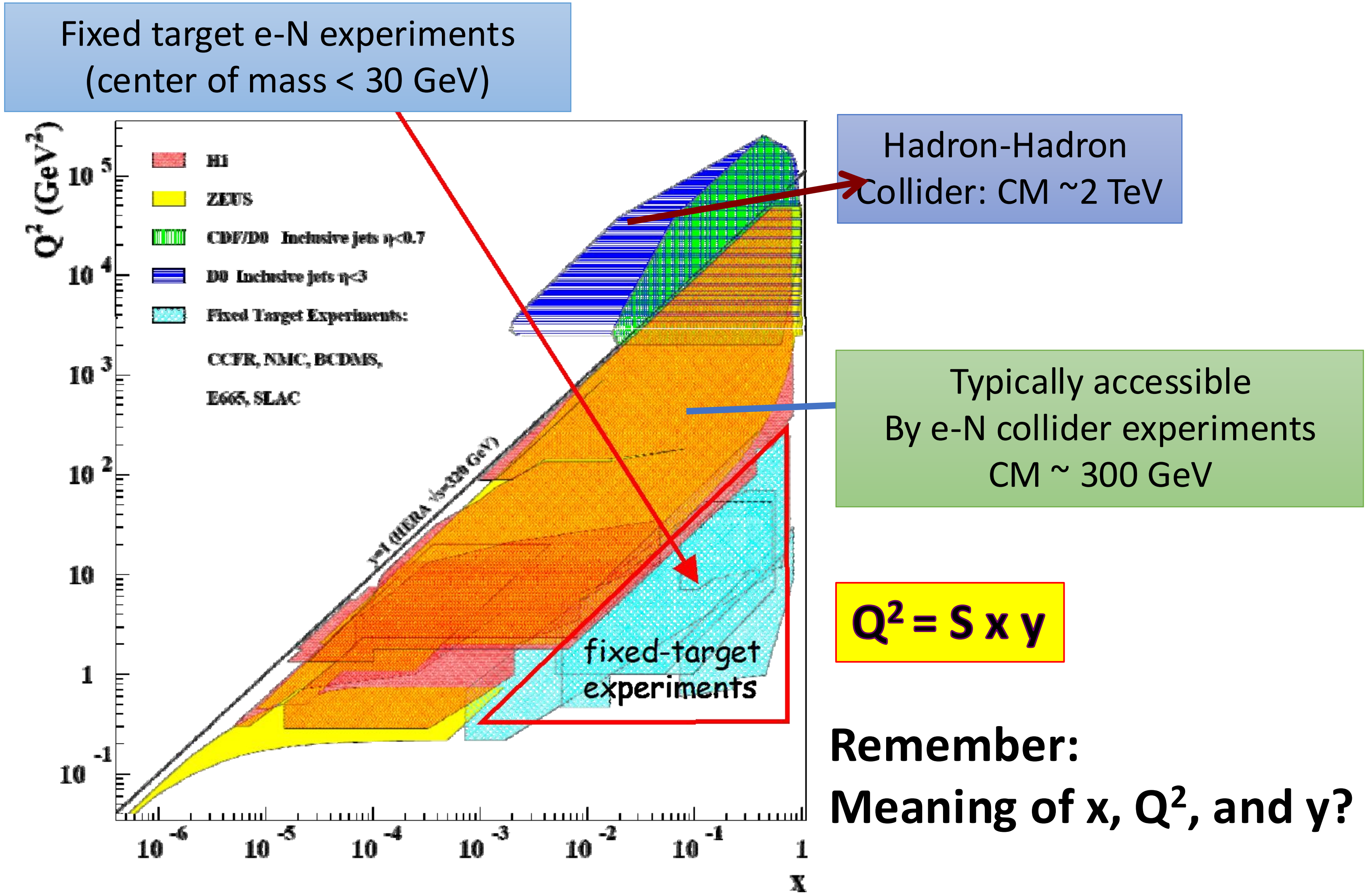
Range of Center of Mass Energies (CME)

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

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

HERA - Electron Proton Collider

Perspective on x,Q^2, Center of Mass



$Q^2 = S\ x\ y$

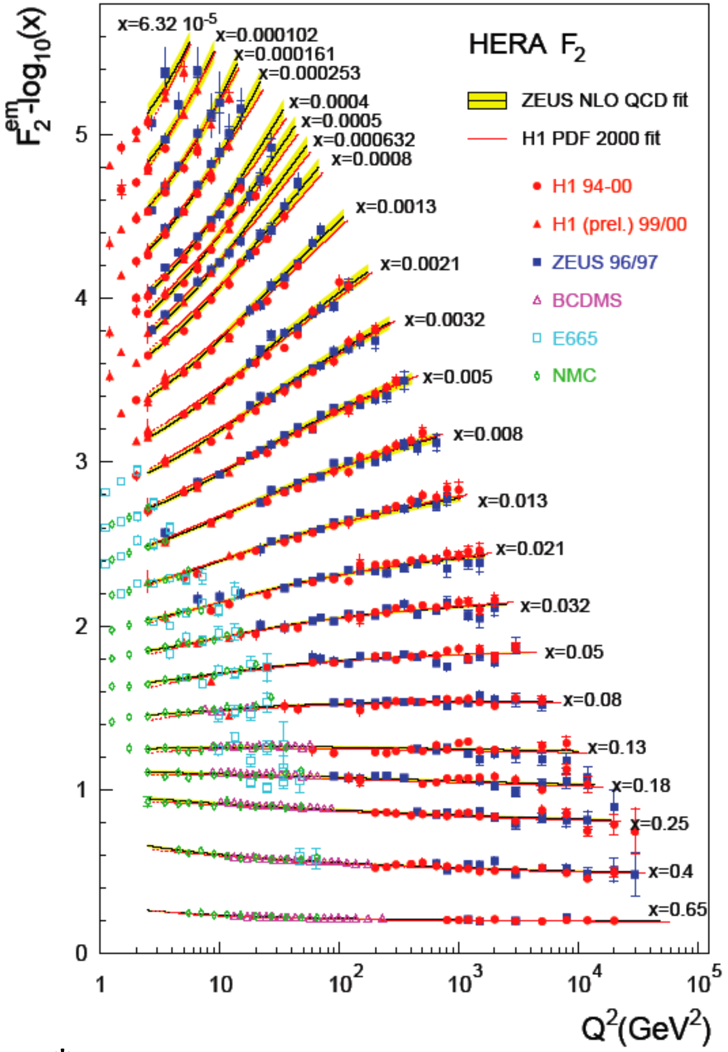
Remember:
Meaning of x, Q^2, and y?

Measurement of unpolarized glue at HERA

F$_2$ Structure Function

Vs.

Q^2 mom. exchanged

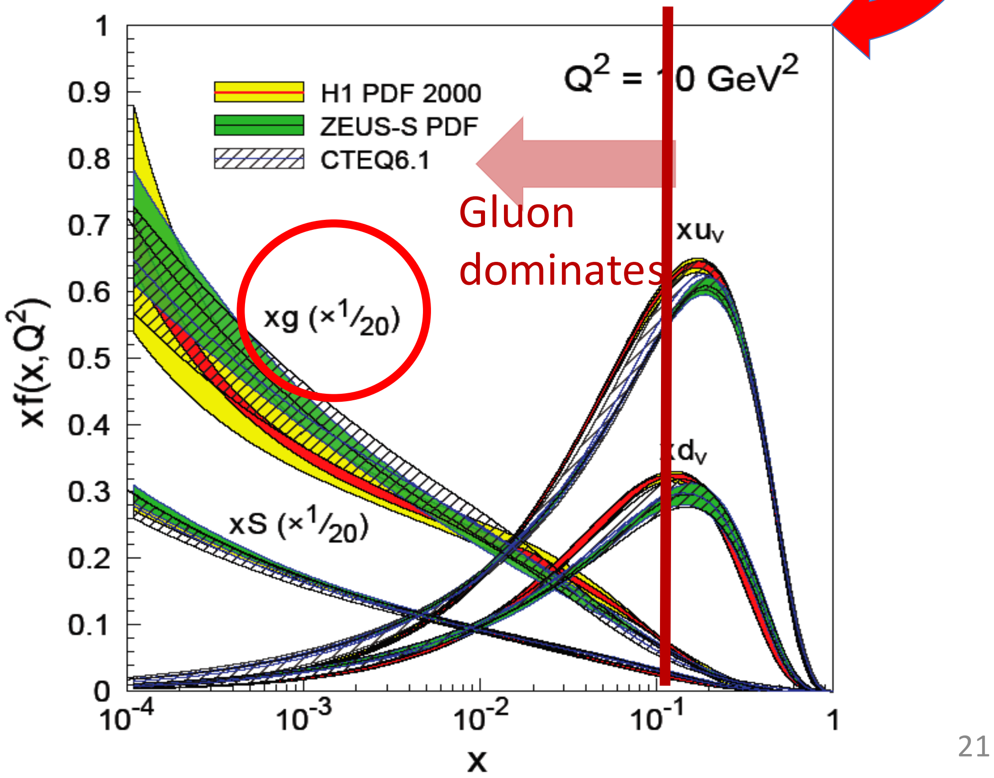


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

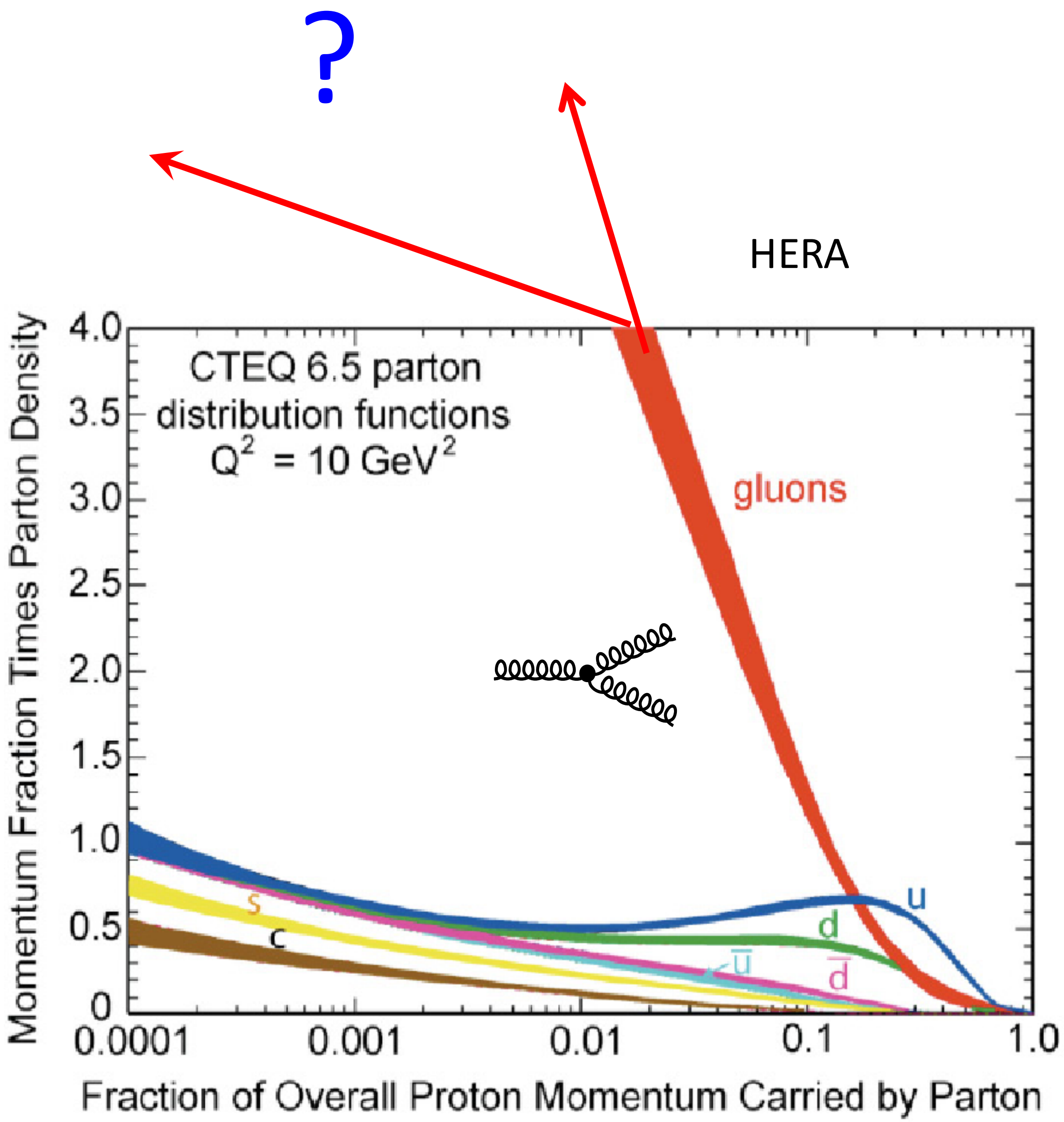
- Scaling violations of F$_2$(x,Q^2)

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

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



Low x rise of the gluon distribution



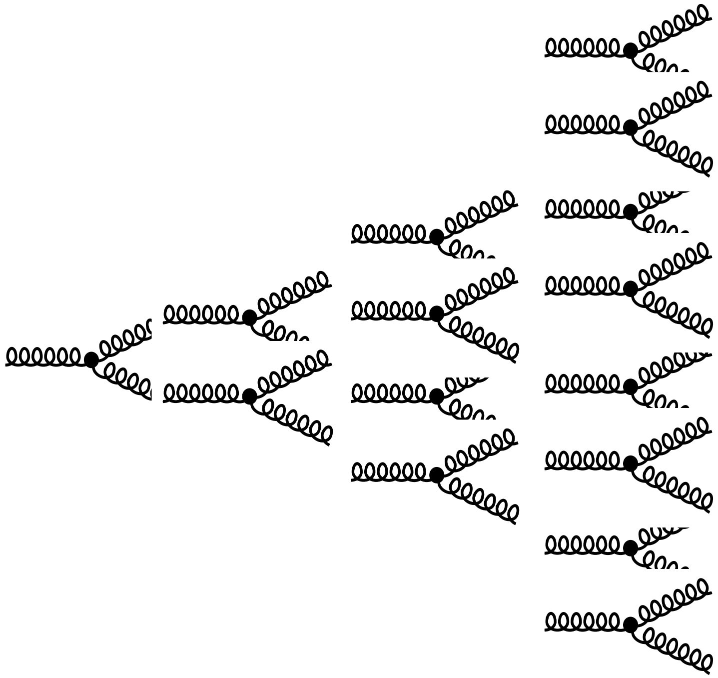
What could tame the low-x rise?

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!

Proton Spin Crisis

Unexpectedly, gluon emerges to be crucial…

Adeva et al, Phys. Rev. D 58, 112001 (1998) Spin asymmetry measurements

Adeva et al. Phys. Rev. D 58, 112002 (1998) NLO calculations and global fits

Aidala et al. Rev. Mod. Phys. 85, 655 (2013)

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

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

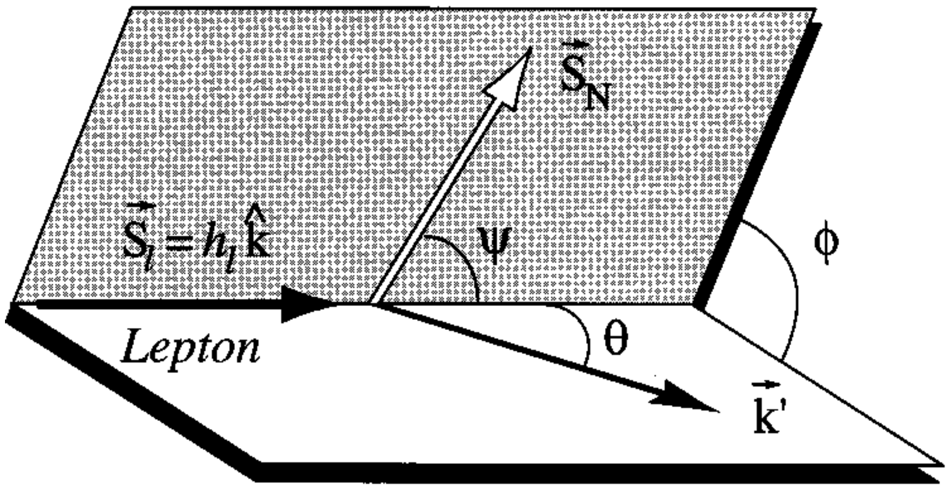
Proton Spin Crisis

Adeva et al, Phys. Rev. D **58**, 112001 (1998) Spin asymmetry measurements

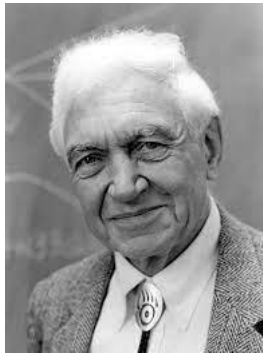
Adeva et al. Phys. Rev. D **58**, 112002 (1998) NLO calculations and global fits using the world Sample of data in 1998

Aidala et al. Rev. Mod. Phys. **85**, 655 (2013)

Lepton-nucleon cross section…*with spin*



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



V. W. Hughes
1922-2003

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

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:

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

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

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

Adeva et al, Phys. Rev. D **58**, 112001 (1998)

First Moments of SPIN Structure Functions

$$\Delta q = \int_0^1 \Delta q(x) dx$$

$$g_1(x) = \frac{1}{2}\Sigma_f e_f^2\{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

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

Neutron decay

(3F-D)/3
Hyperon Decay

$\Delta\Sigma$

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

Adeva et al, Phys. Rev. D **58**, 112001 (1998)

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 $SU(3)_f$ & **$\Delta s = 0$,**

J.Ellis and R.L.Jaffe, Phys.Rev.D9(1974), D10 (1974) 1669

$$\Gamma_1^p = 0.170 \pm 0.004$$

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!

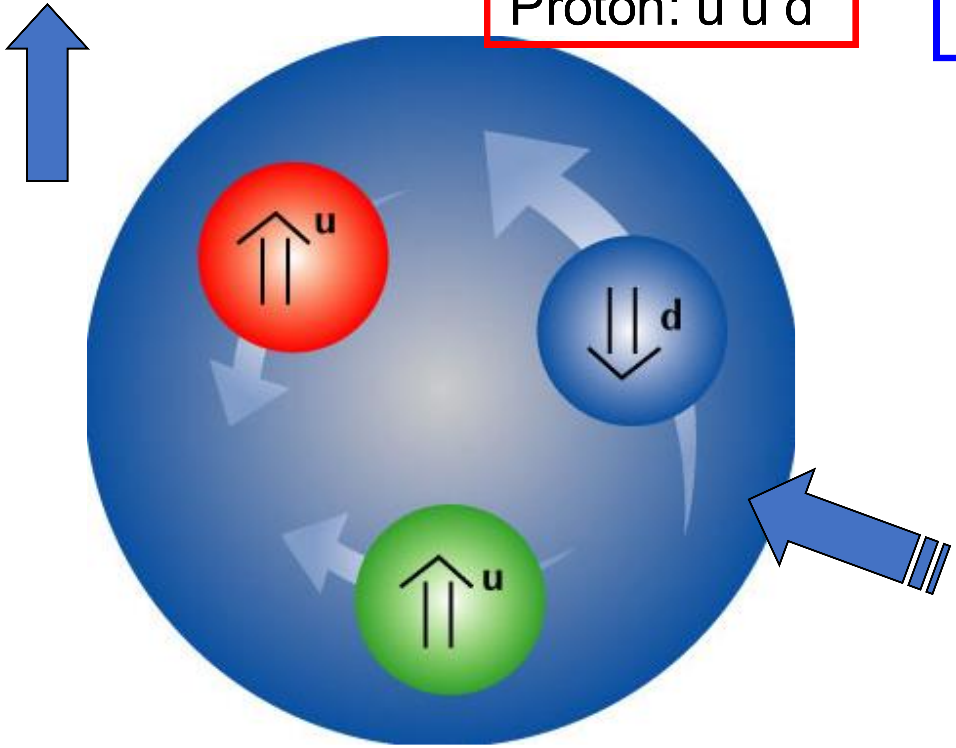
The measurement and surprises…

Nucleon's Spin: Naïve Quark Parton Model (ignoring relativistic effects… now, illustration only, but historically taken seriously)

- Protons and Neutrons are spin 1/2 particles
- Quarks that constitute them are also spin 1/2 particles
- And there are three of them in the

Proton: u u d

Neutron: u d d



S_{proton} = Sum of all quark spins!

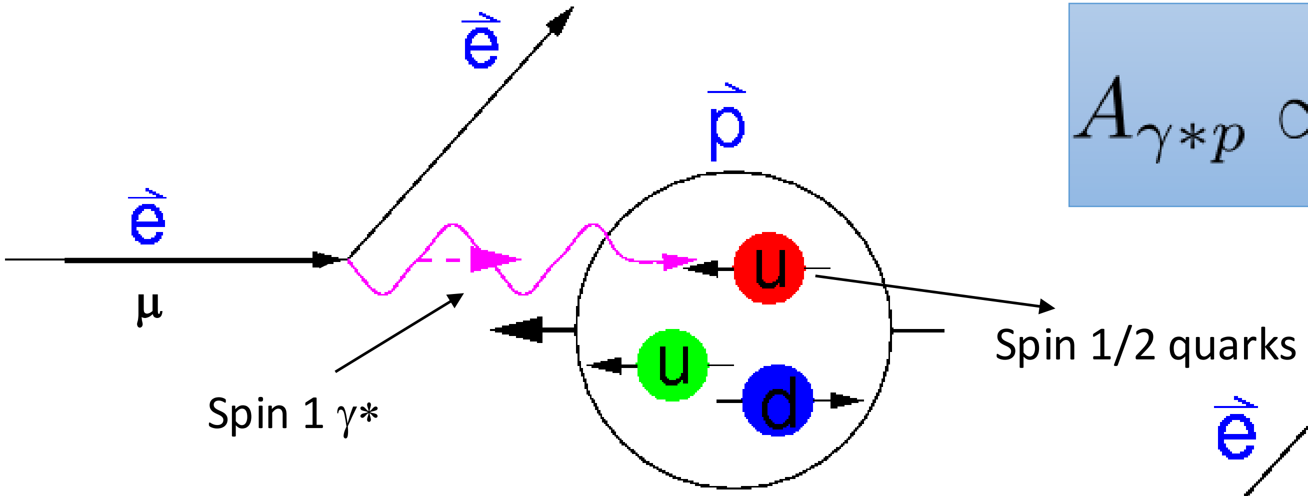
$$1/2 \overset{?}{=} 1/2 + 1/2 + 1/2$$

$$1/2 = 1/2 - 1/2 + 1/2$$

Adeva et al, Phys. Rev. D **58**, 112001 (1998)

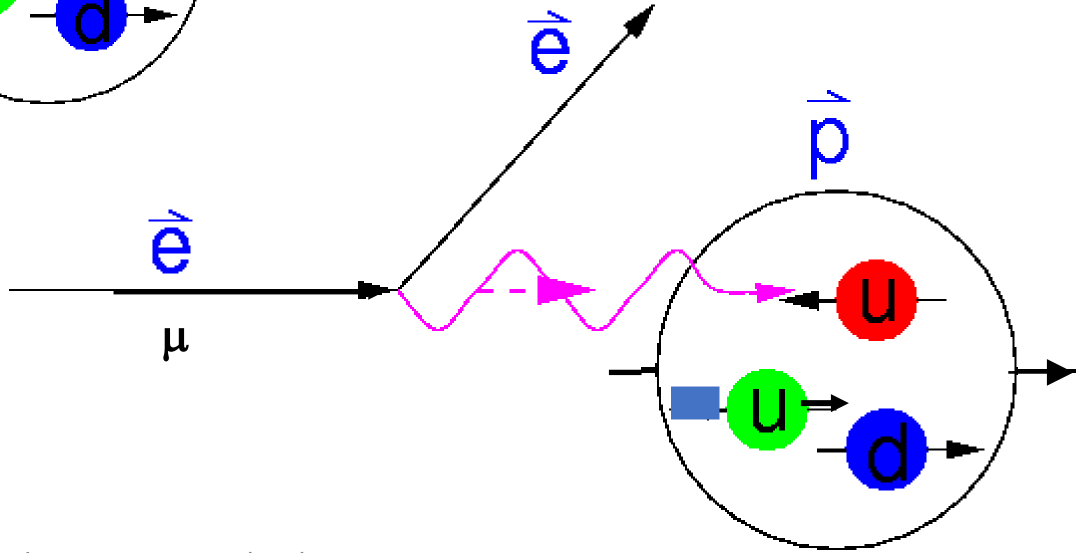
How was the Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering



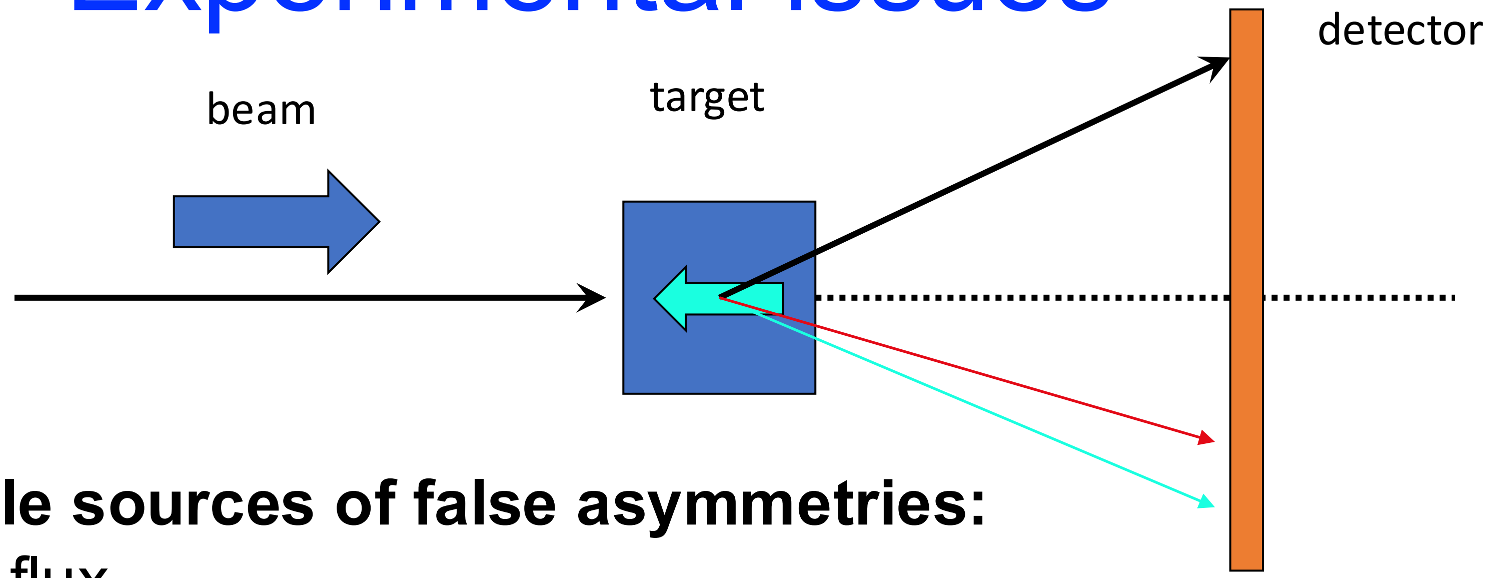
$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

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

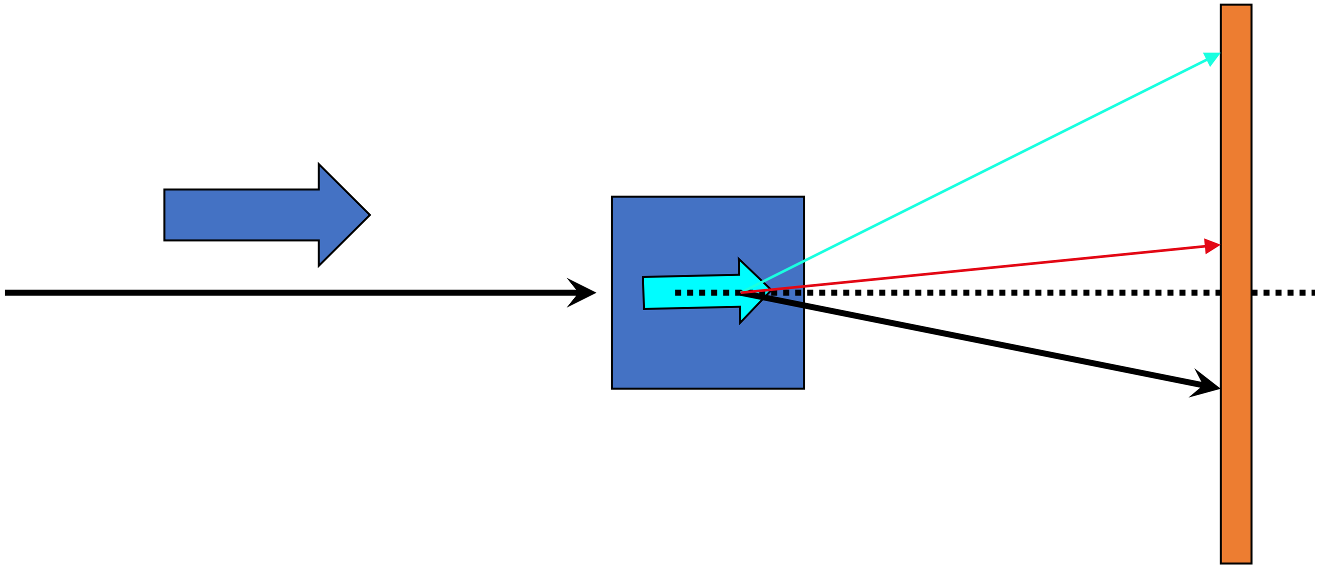


Adeva et al, Phys. Rev. D **58**, 112001 (1998)

Experimental issues



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



$A_{measured} = A_{LL}$
Double Longitudinal Spin asymmetry

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

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

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

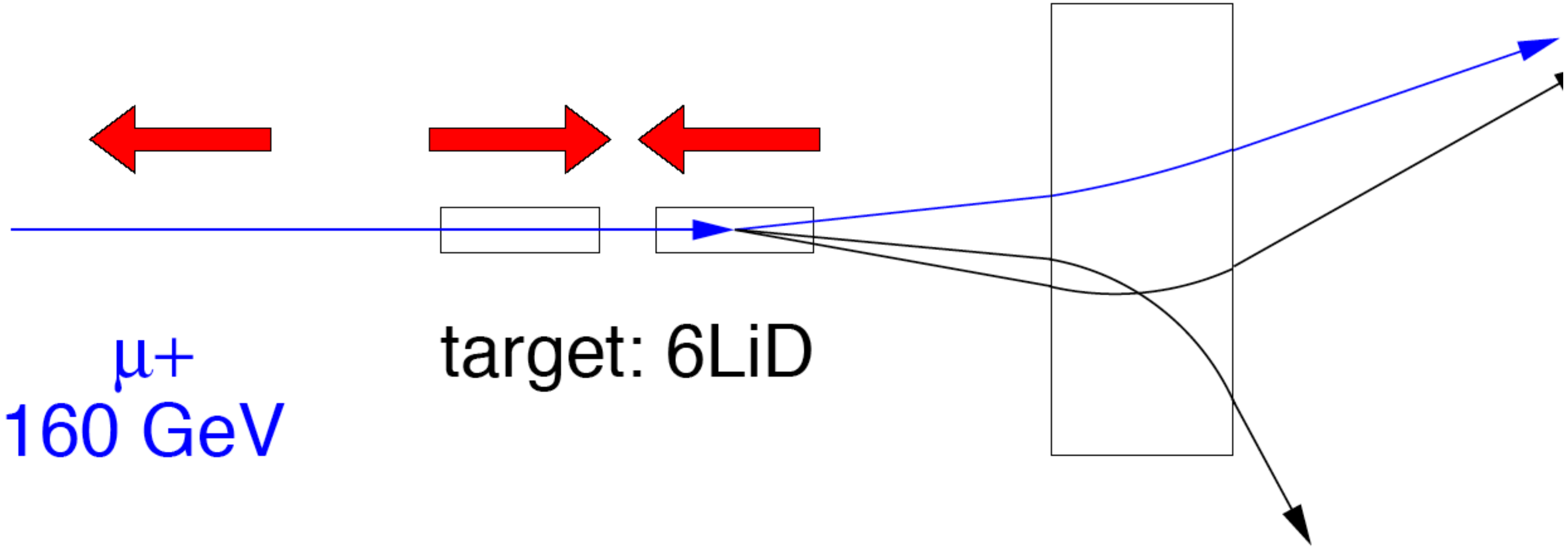
If all other things are equal,

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**

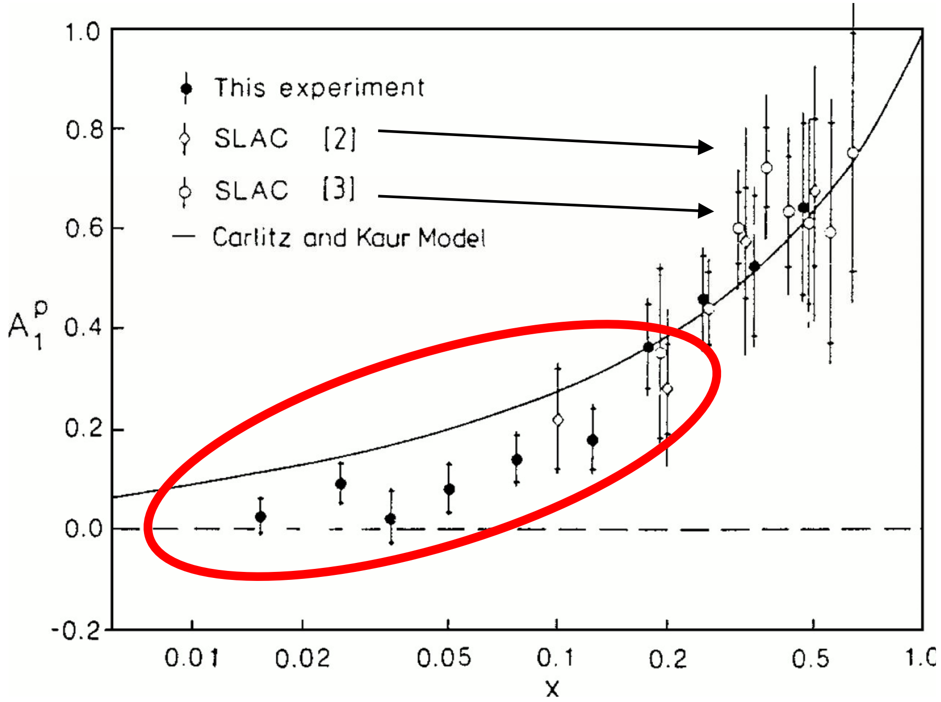
Control of false asymmetries:

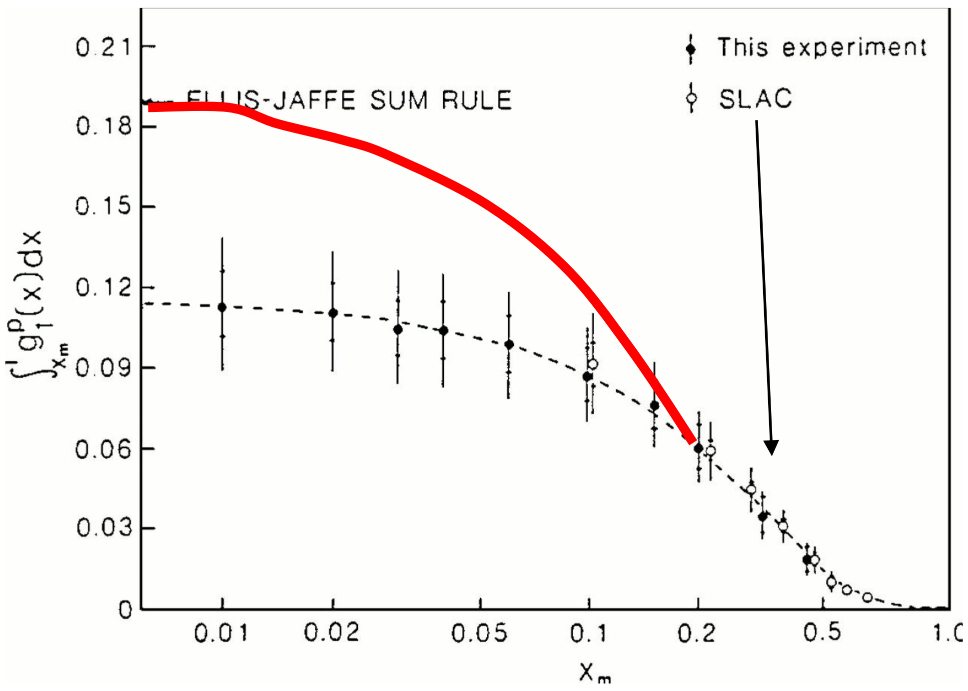
- Need excellent understanding and control of **false asymmetries** (time variation of the detector efficiency etc.)

EMC Collaboration, J. Ashman et al., Phys. Lett. B206 (1988) 364; Nucl. Phys. B328 (1989) 1

Proton Spin Crisis (1989)!

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





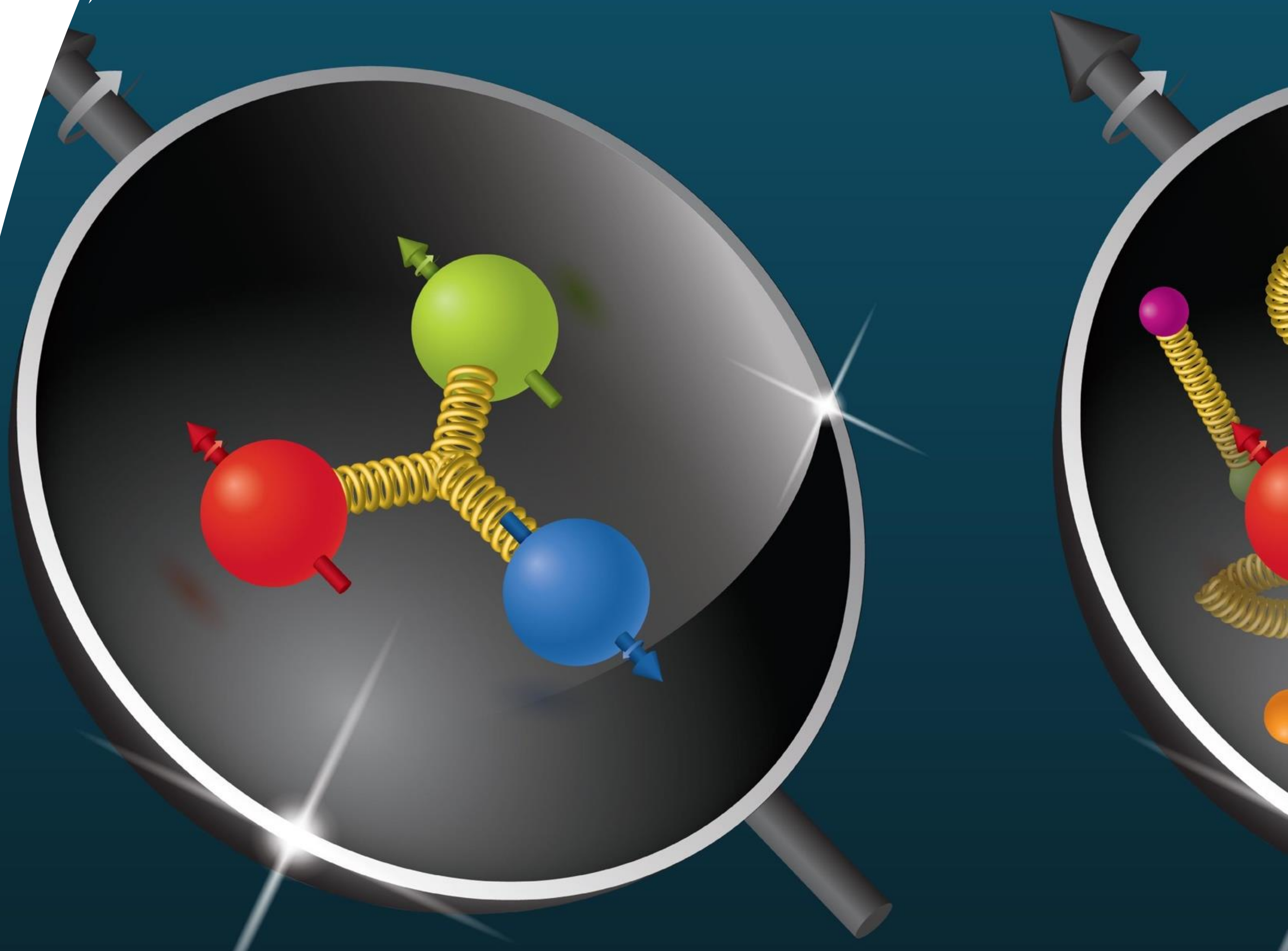
$\Delta\Sigma/2 = (0.12)$ +/- (0.17) (EMC, 1989)

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

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

Proton spin puzzle

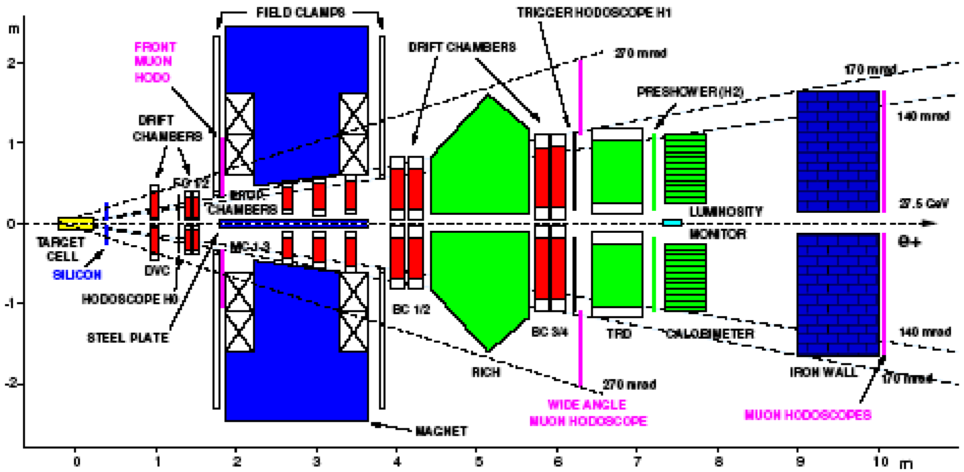
- EMC & SMC experiment at CERN along with experiments at SLAC established without any doubt that quarks do NOT explain the proton's spin quantum number.
- Ellis-Jaffe spin sum role is violated.
- $\Delta\Sigma = 0.25$ ➔ Quark's contribution is **½ (ΔΣ) = 0.12** out of proton's spin ½
- Where is the remaining SPIN? **GLUONS!**



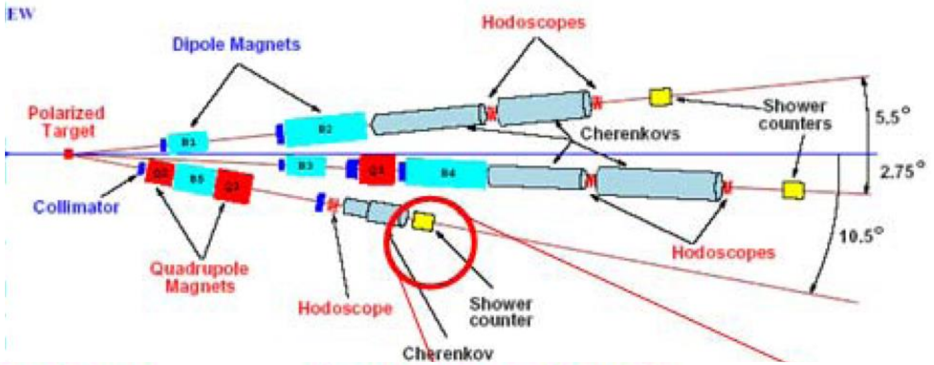
“*spin* has killed more theories in physics than any other single observables”
-- Elliot Leader

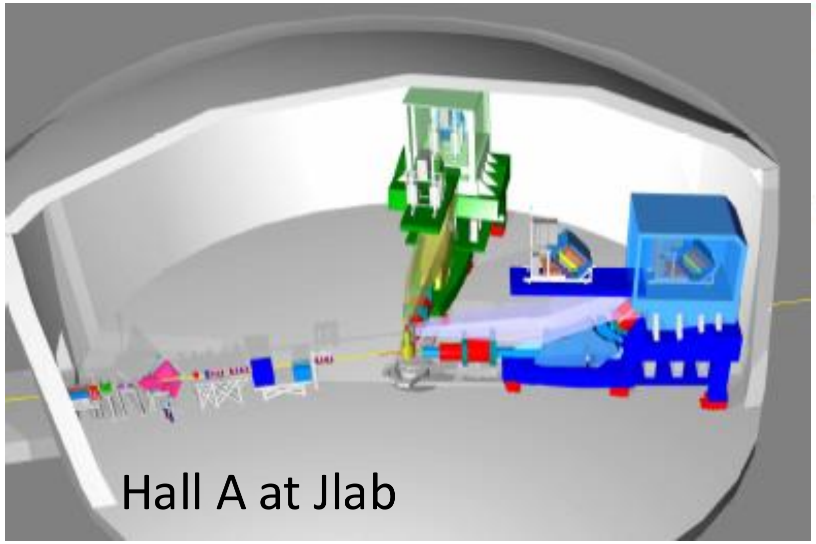
“If theorists had their way, they would ban all experiments with Spin”
-- James D. Bjorken (jokingly)

Experiments

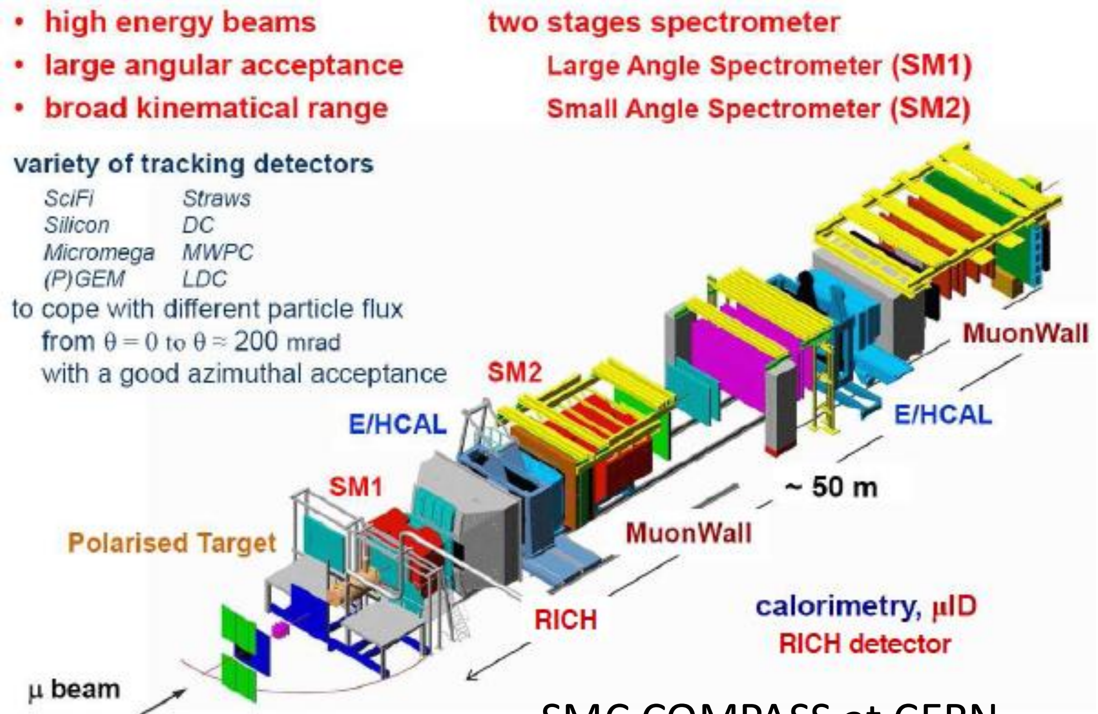


HERMES at DESY





Hall A at Jlab



SMC,COMPASS at CERN

Center for Frontiers in Nuclear Science

Part 2:
RHIC Spin:
polarized glue, transverse spin

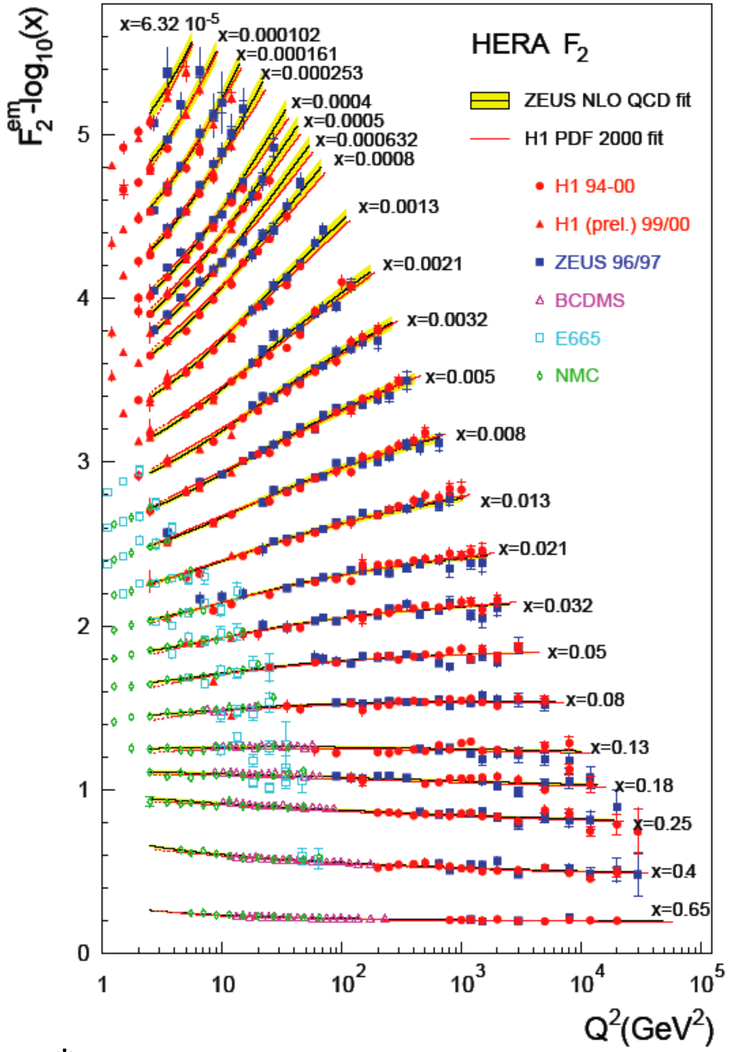
Abhay Deshpande

Measurement of unpolarized glue at HERA

F$_2$ Structure Function

Vs.

Q^2 mom. exchanged

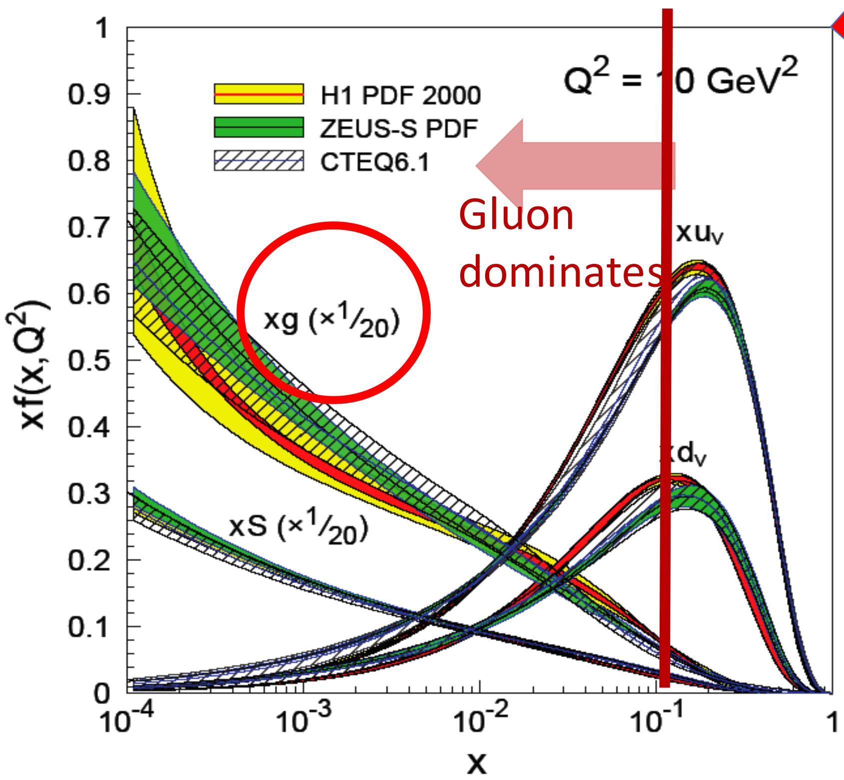


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

- 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

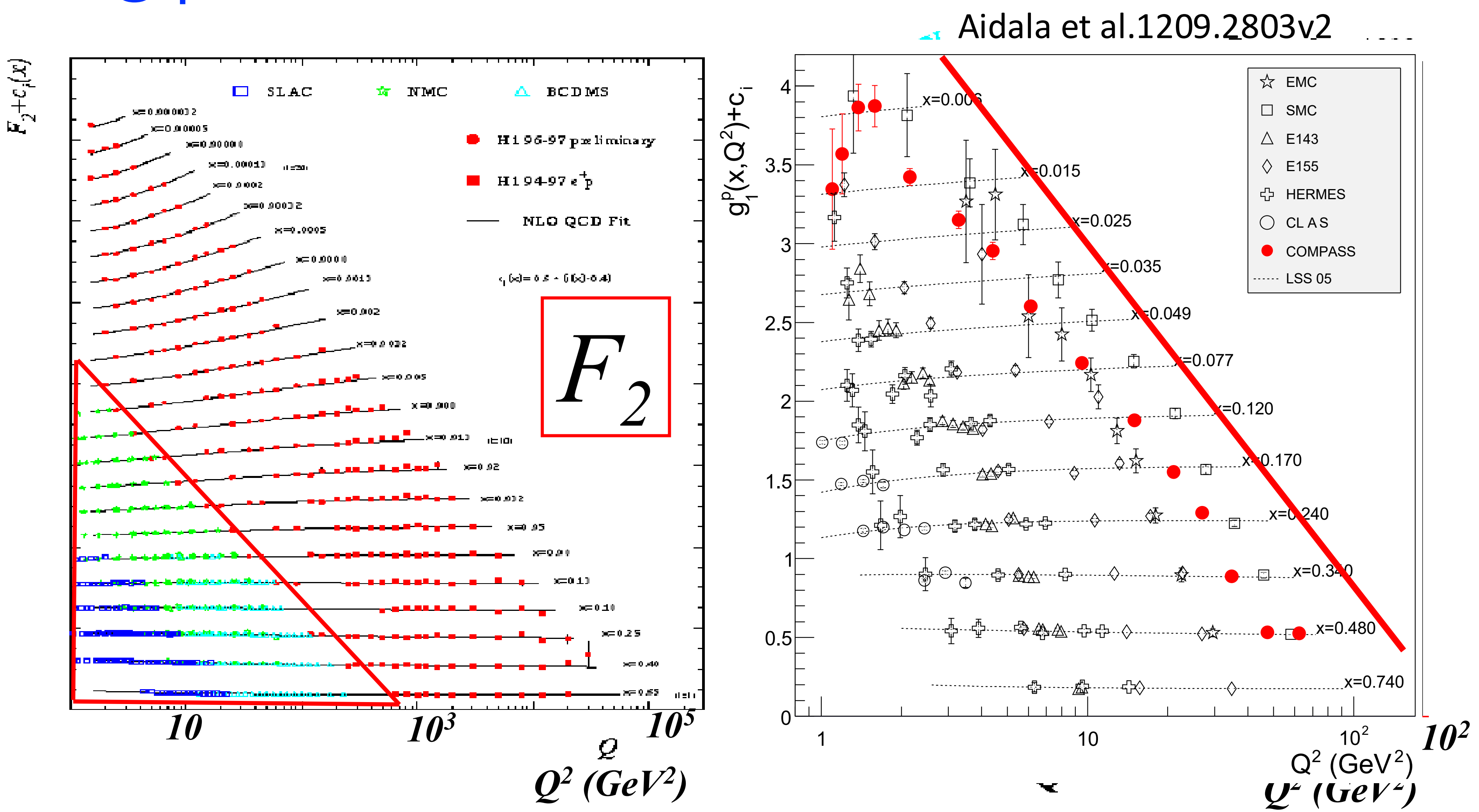


Can one do the same thing for spin structure function g_1?

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

F_2 vs. g_1 structure function measurements

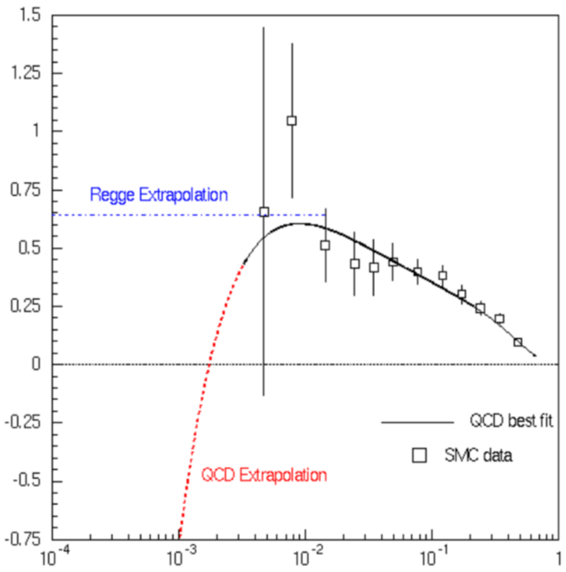
Aidala et al.1209.2803v2

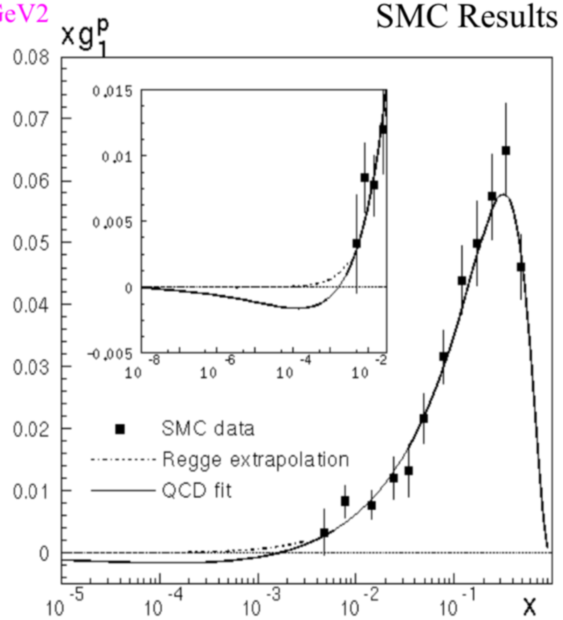


Large amount of polarized data since 1998… but not in NEW kinematic region!

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

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

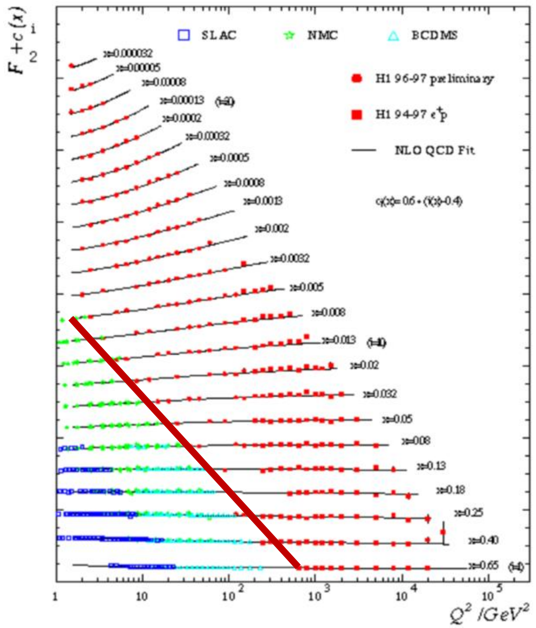
In these discussions, while many focused on the low-x Extrapolations.

SMC PRD98 (112002) 1998

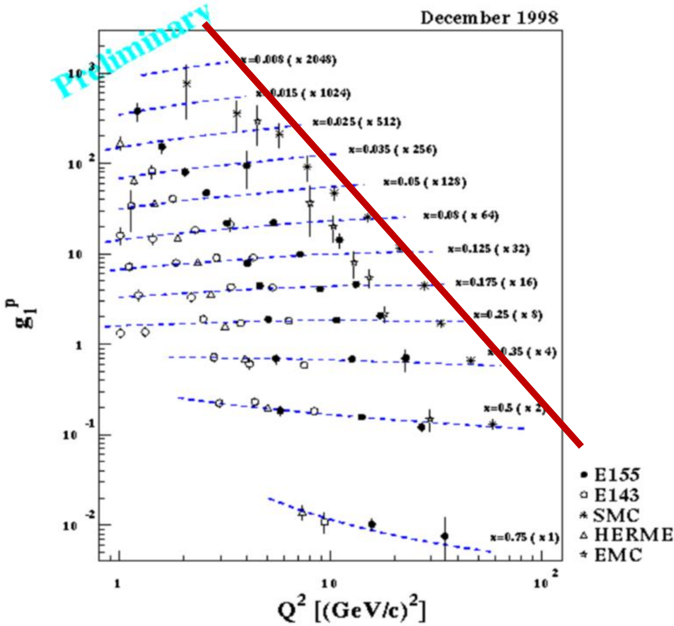
Seeds for a **polarized collider**

How far does polarized DIS have to go!

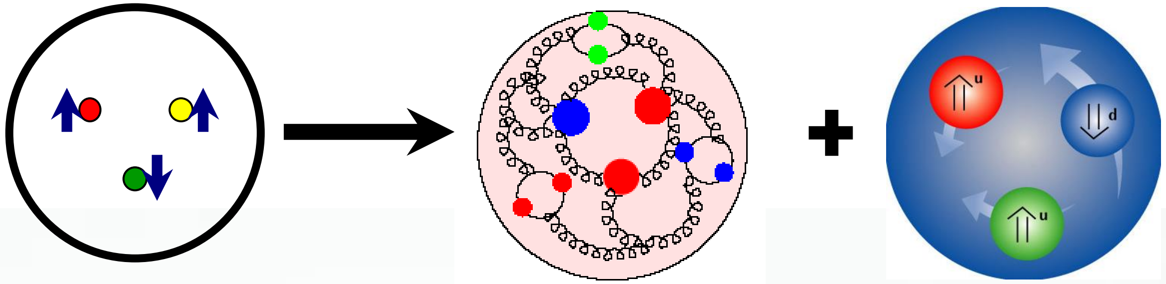
World data on F_1^p



World data on g_1^p



Our Understanding of Nucleon Spin Puzzle

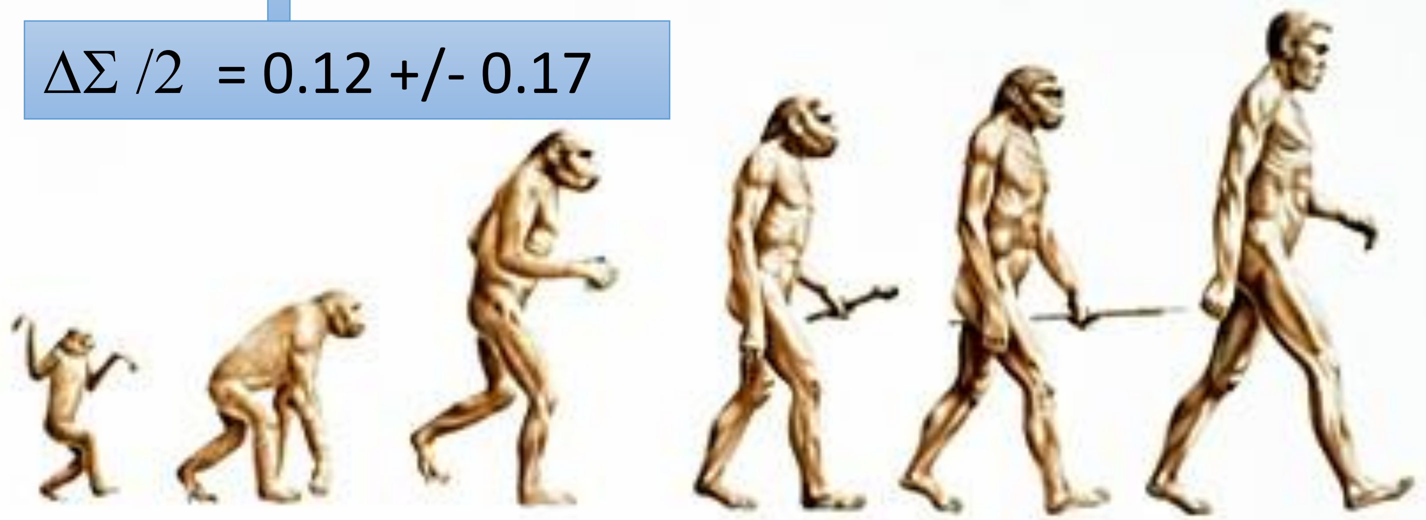


1980s

1990/2000s

$\Delta\Sigma/2 = 0.12 \pm 0.17$

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



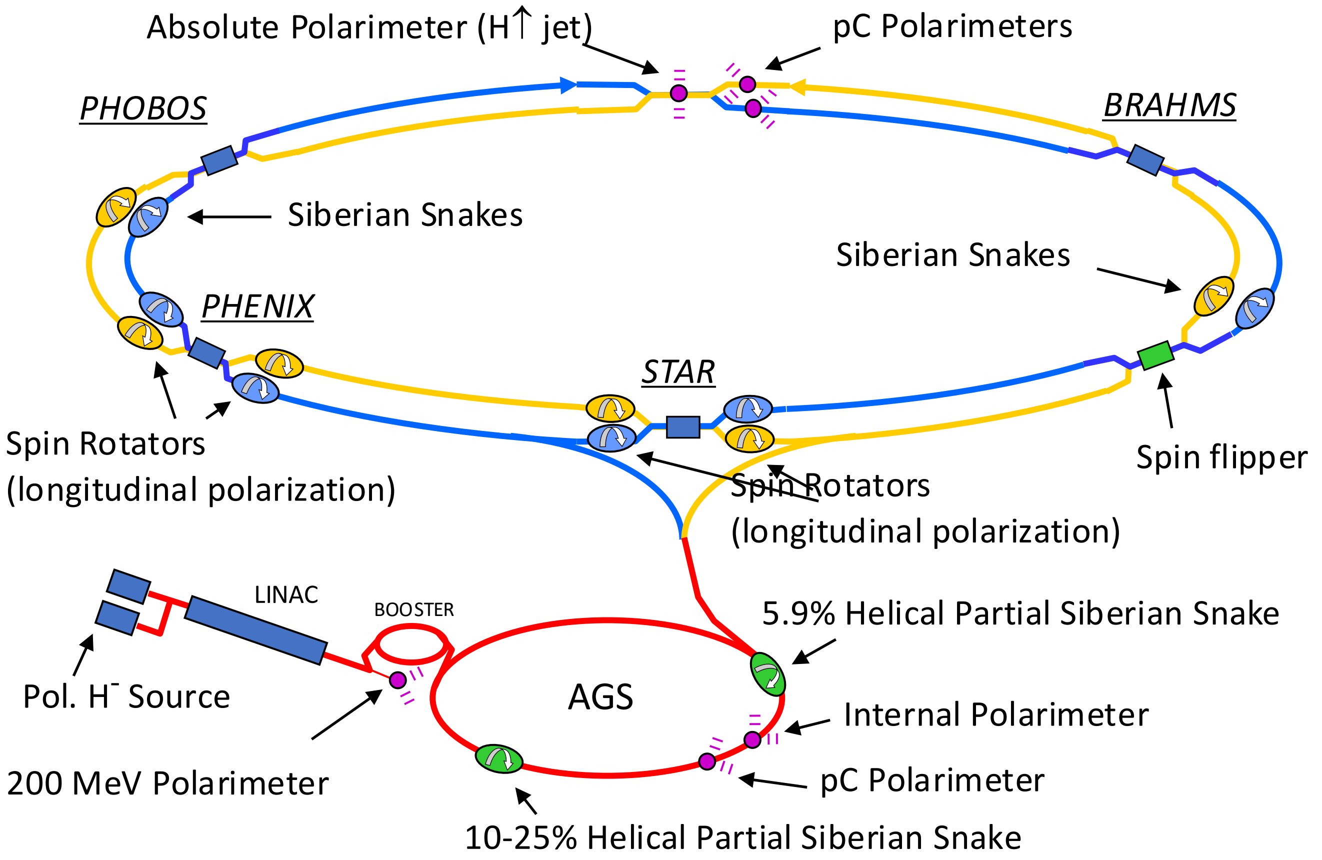
Need information about transverse dimensions of the proton

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

RHIC as a Polarized Proton Collider

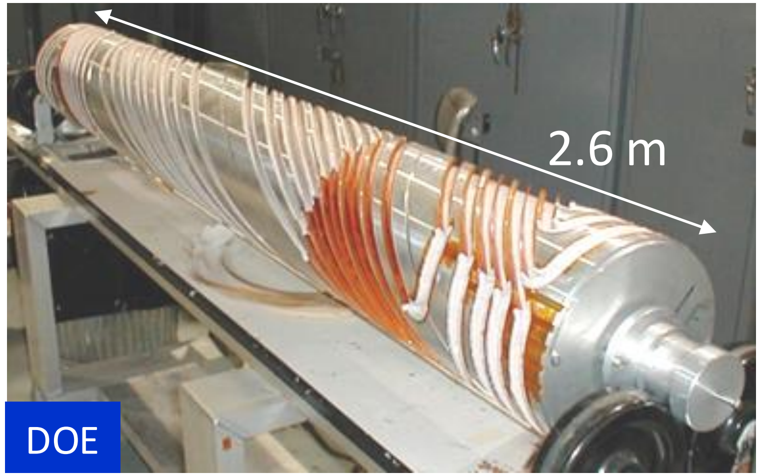


- RIKEN/Japan played a leading role in the RHIC Spin program

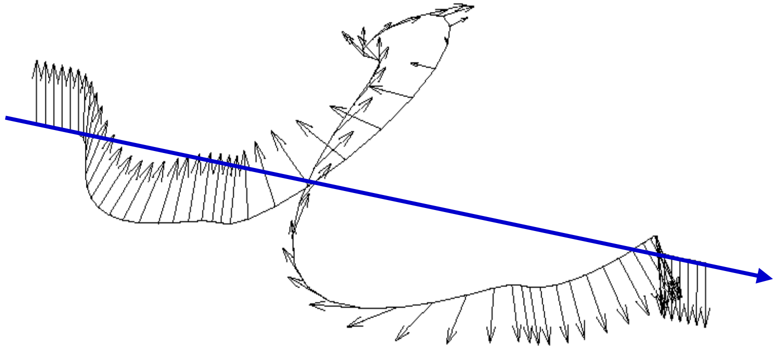
- Siberian Snake Magnets
- Spin Rotator Magnets
- PHENIX muon arm
- Many talented scientists
- 30 years of tremendous US-Japan Scientific Collaboration through RIKEN

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

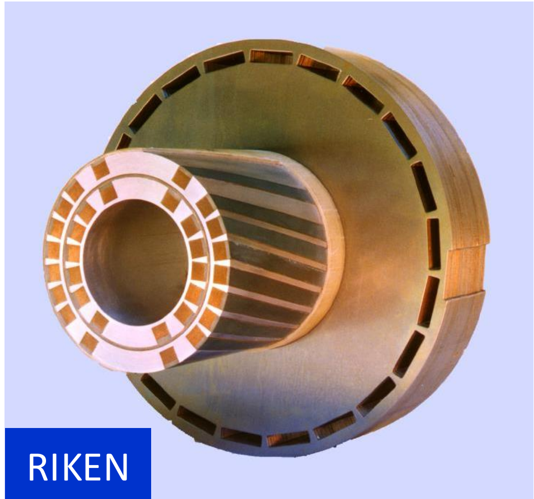
Siberian Snakes : RIKEN/Japan & DOE/BNL



- 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



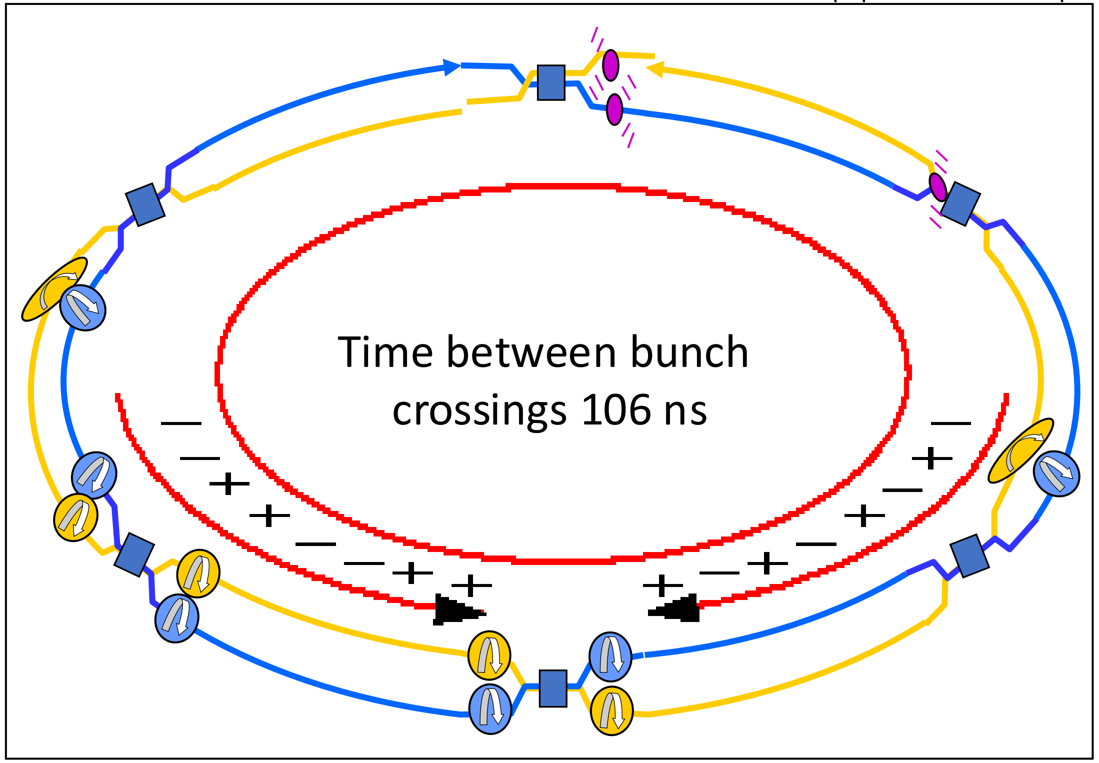
Courtesy of A. Luccio



Measuring A_{LL}

Longitudinal Spin Asymmetry using polarized proton bunches in the RHIC ring

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



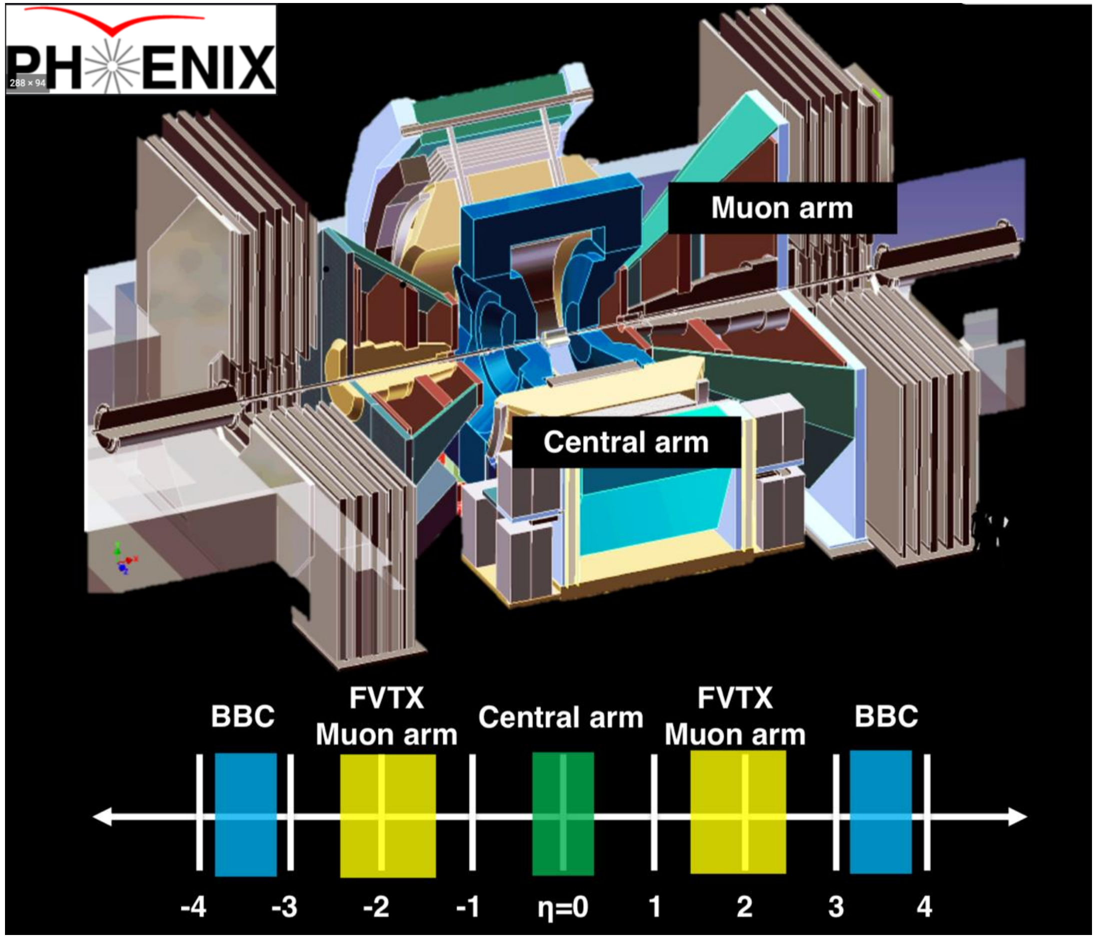
(N) Yield
(R) Relative Luminosity
(P) Polarization

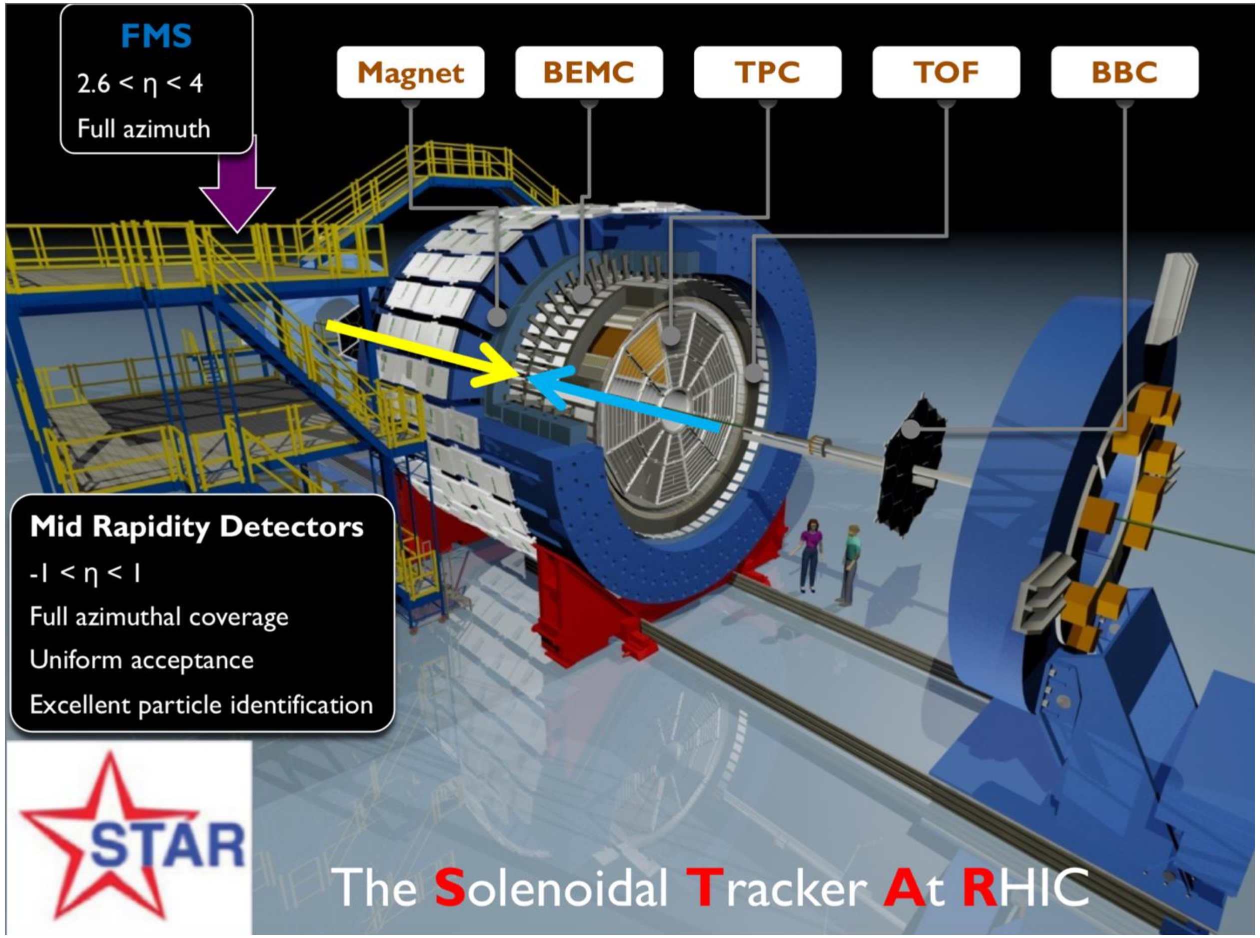
Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

- ✓ 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

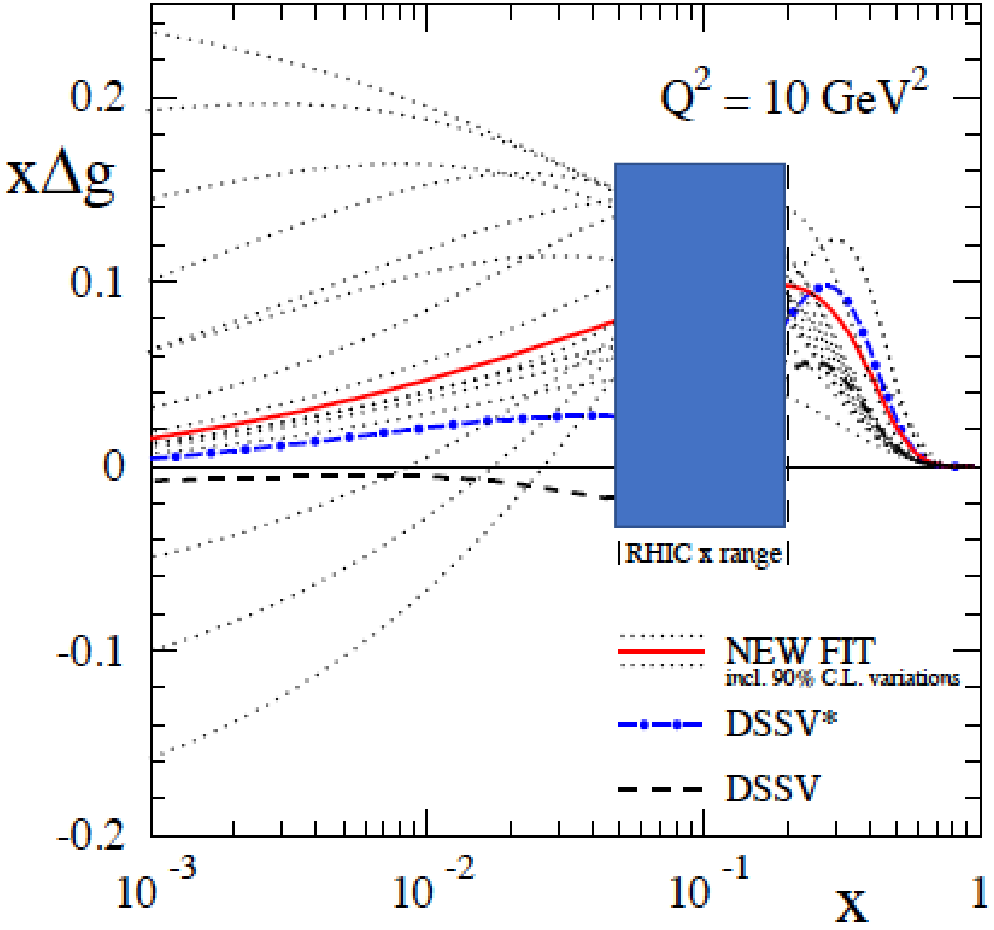




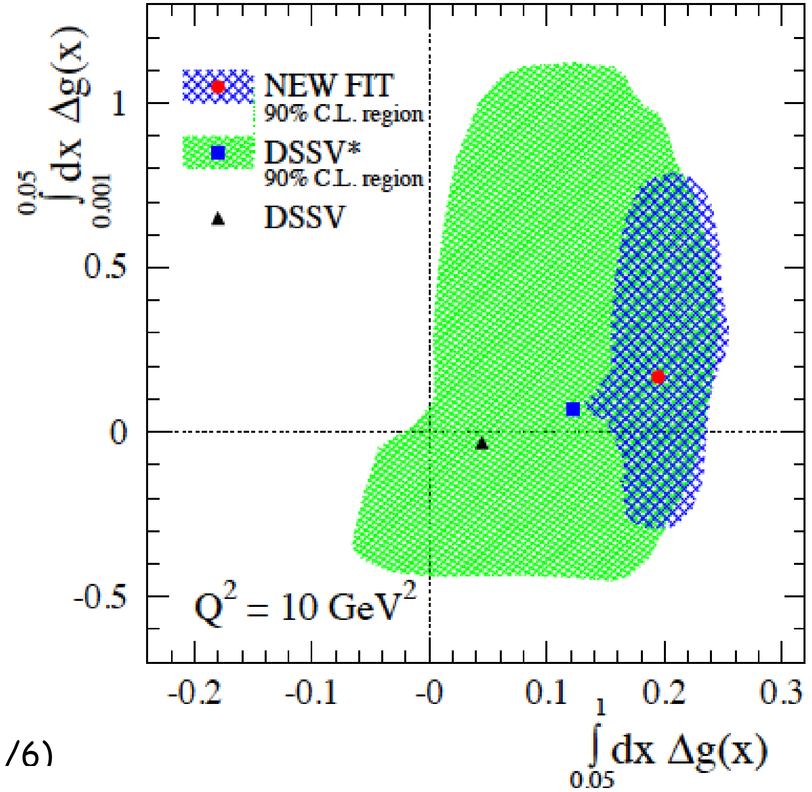
Recent global analysis: DSSV

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

D. deFlorian et al., arXiv:1404.4293



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



/6)

While RHIC made a huge impact on ΔG

large uncertainties remain in the low-x unmeasured region!

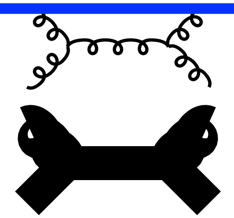
2009 RHIC data established non-zero ΔG

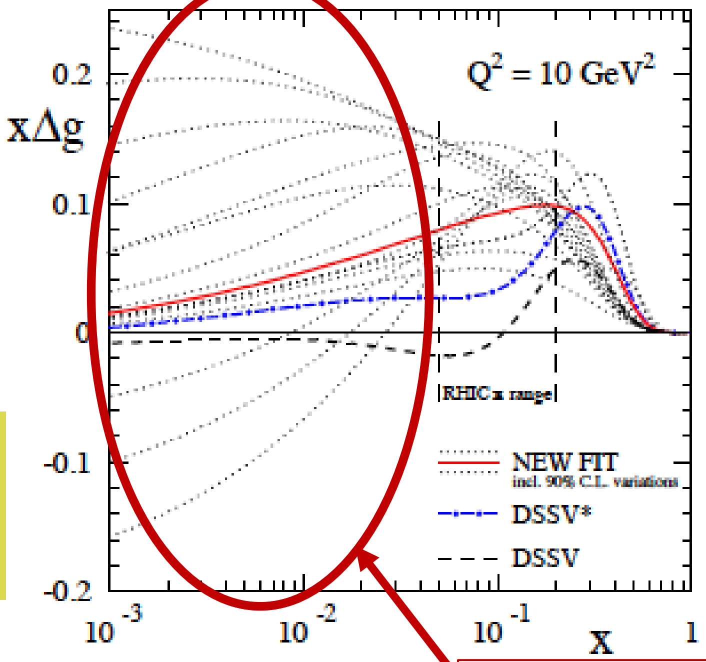
-- PHENIX 2005-9, PRD 90, 12007 (2014)

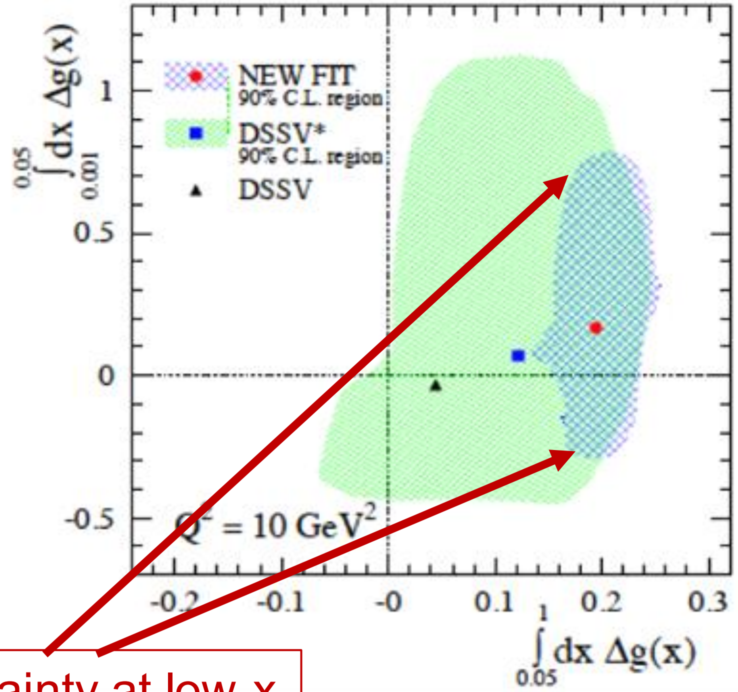
-- STAR 2009, PRL 115 (2015) 92002

-- DSSV PRL (113) 12001 (2014)

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

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	
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)

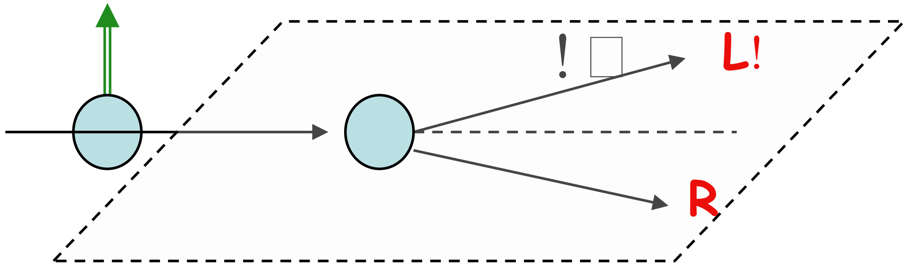




Large uncertainty at low-x

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

Transverse spin introduction



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

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

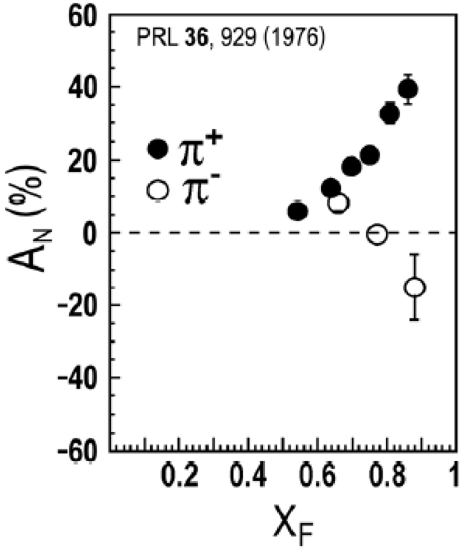
Kane, Pumplin and Repko
PRL 41 1689 (1978)

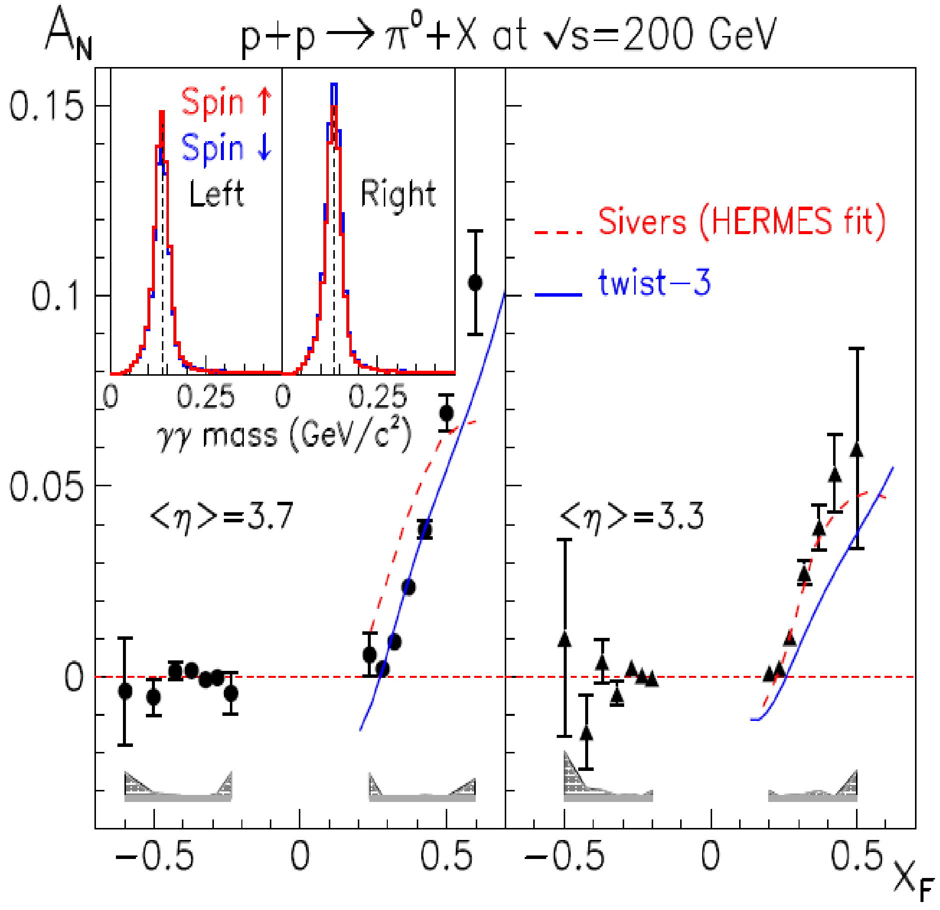
- Since people focused at high p_T to interpret them in pQCD frameworks, this (expected small effect) was “neglected However….

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

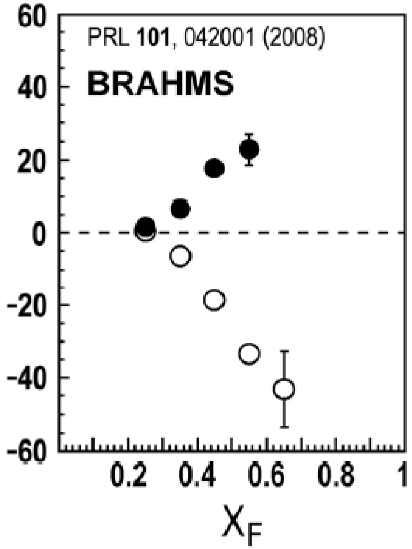
Pion asymmetries: at broad range in CM energies!

ZGS/ANL
√s=4.9 GeV





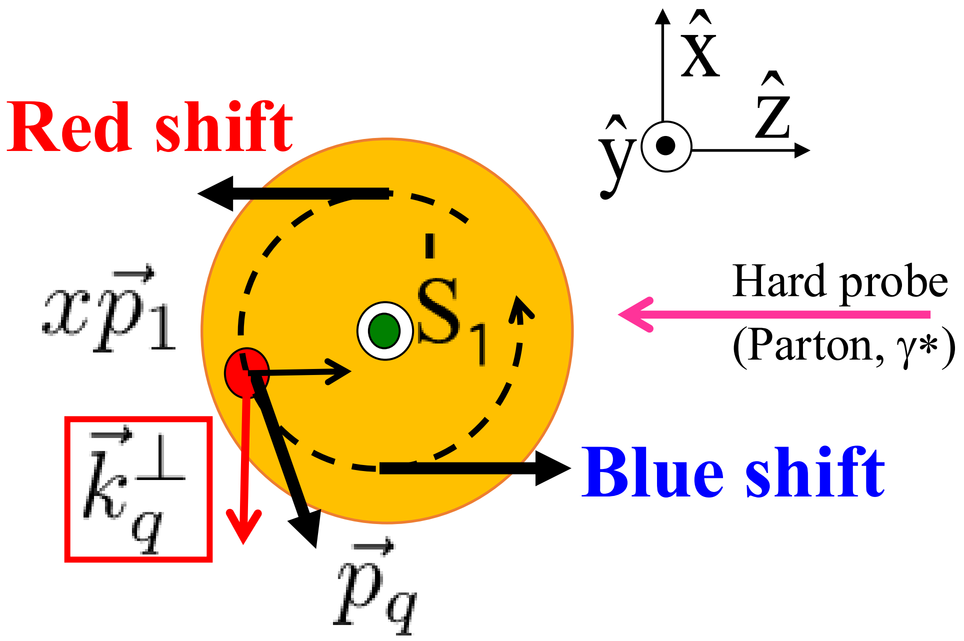
RHIC
√s=62.4 GeV



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**

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

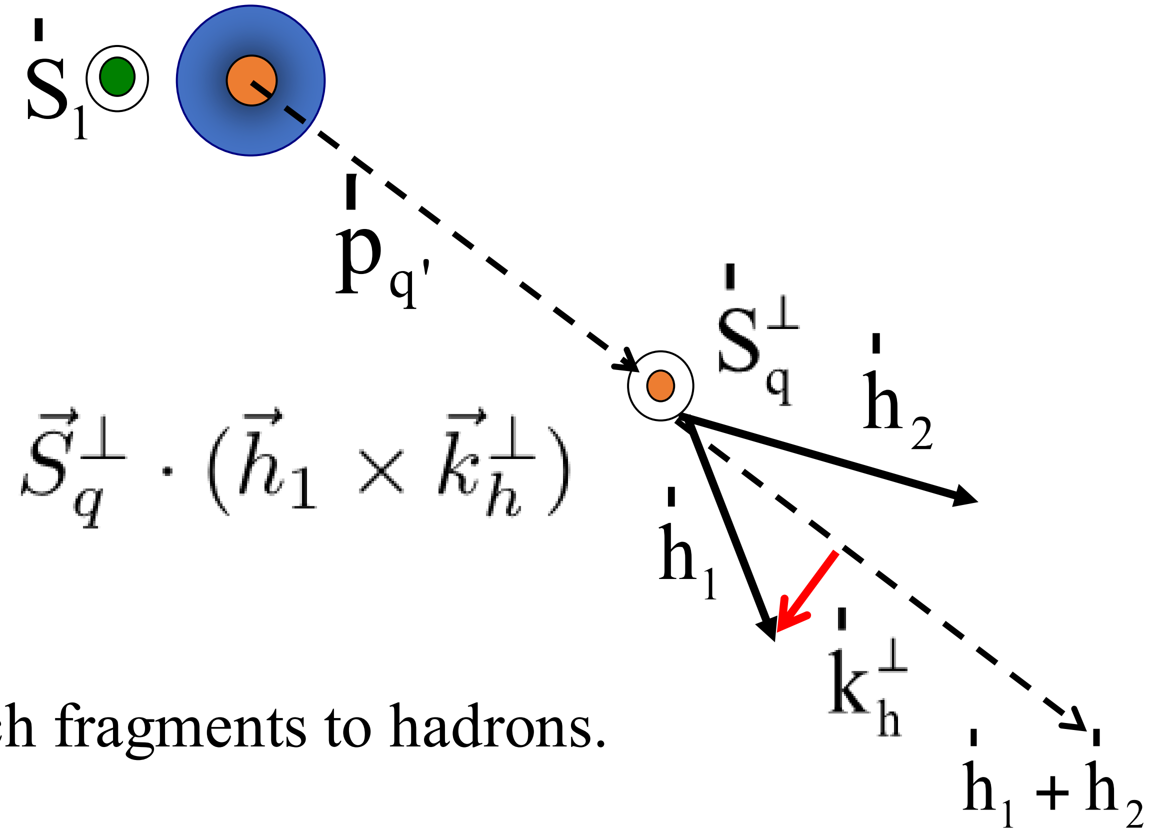
Generalized **P**arton **D**istribution Functions

PRD59 (1999) 014013

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



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

Polarization of struck quark which fragments to hadrons.

Proton Spin at the end of RHIC Spin @ BNL

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

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

0.12 ? 0.2 ?

But we definitely know of the transverse motion of quarks (and gluons) in the proton from the transverse spin asymmetries

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**

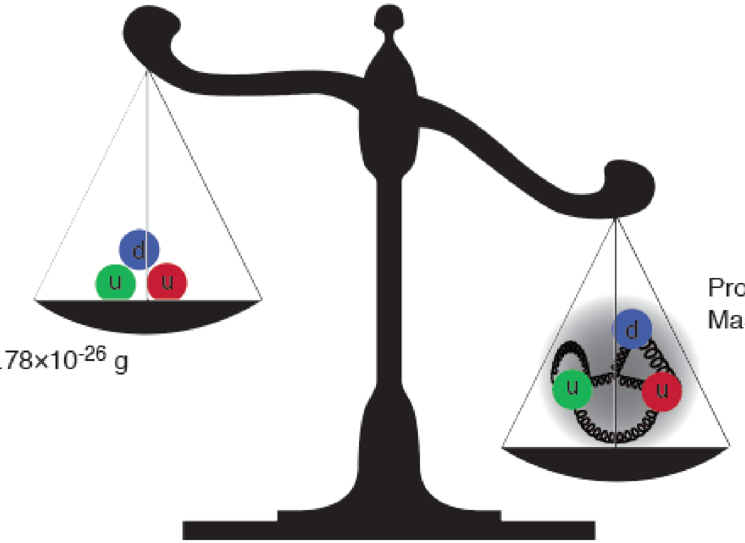
- To fully understand proton structure (including the above partonic dynamics)
  - one needs to explore over a **broader x-Q2 range** (not in fixed target but in collider experiment) Low-x behavior of gluons in proton also needed
  - Need *polarized* protons and electrons in colliders

- Low x behavior of partons in Nuclei essential to complete our understanding of structure of matter…

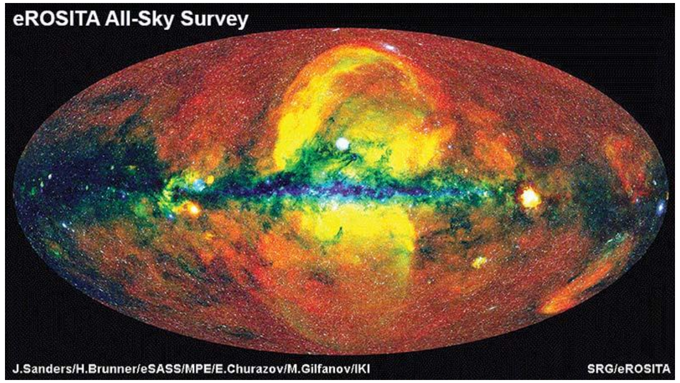
We need a new high-luminosity polarized **e-p/A** collider….

Proton mass puzzle

Nobel 2013 With
Francois Englert
"Higgs Boson" that gives mass to quarks, electrons,….



?



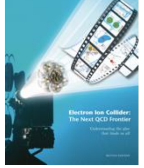
Add the masses of the quarks (HIGGS mechanism) together 1.78 x 10^{-26} grams

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

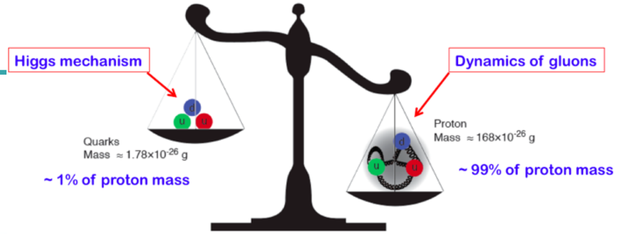
➔ **only 1% of the mass of the protons (neutrons)** ➔ Hence the Universe

➔Where does the rest of the mass come from?

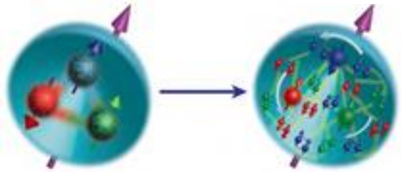
Electron Ion Collider: The solution to these and other QCD puzzles

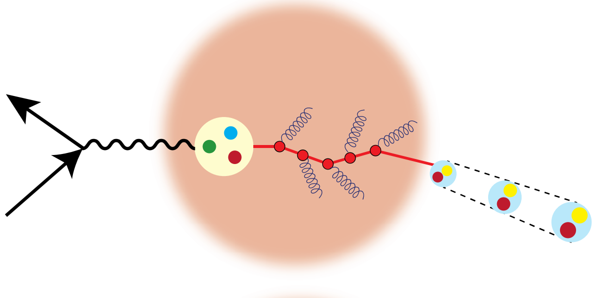


A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

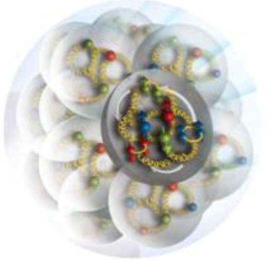


How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties (spin, mass) emerge from them and their interactions?



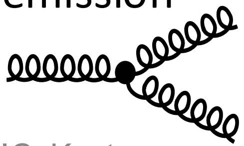


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?



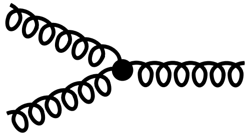
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission

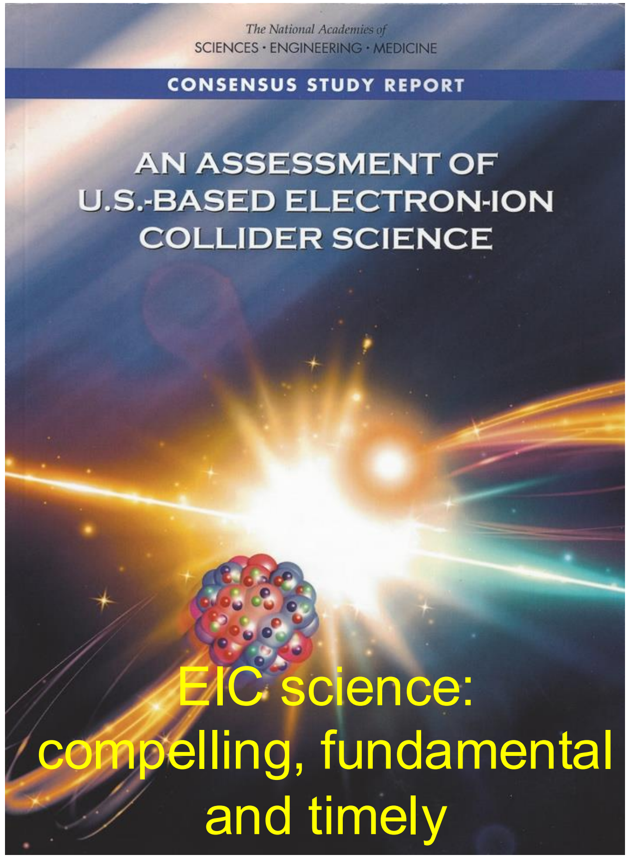


?=

gluon recombination

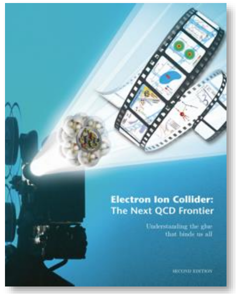


EIC proposal and the US National Academy's Assessment

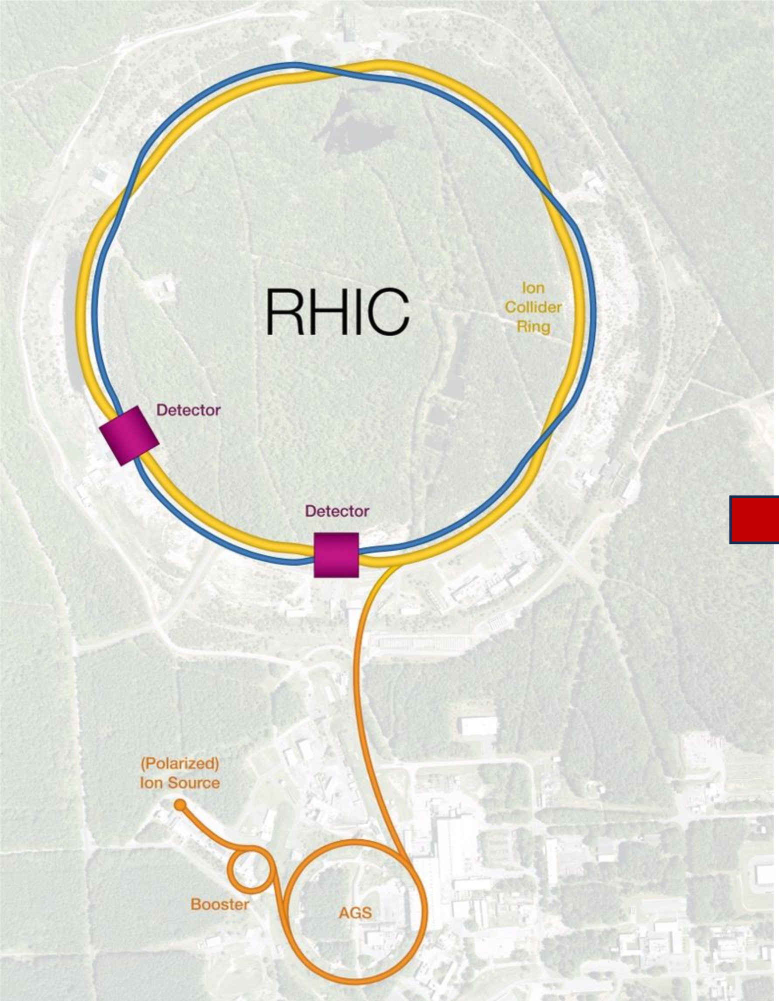


Machine Design Parameters:

- 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



Transition from RHIC to Electron Ion Collider (EIC) in 2026

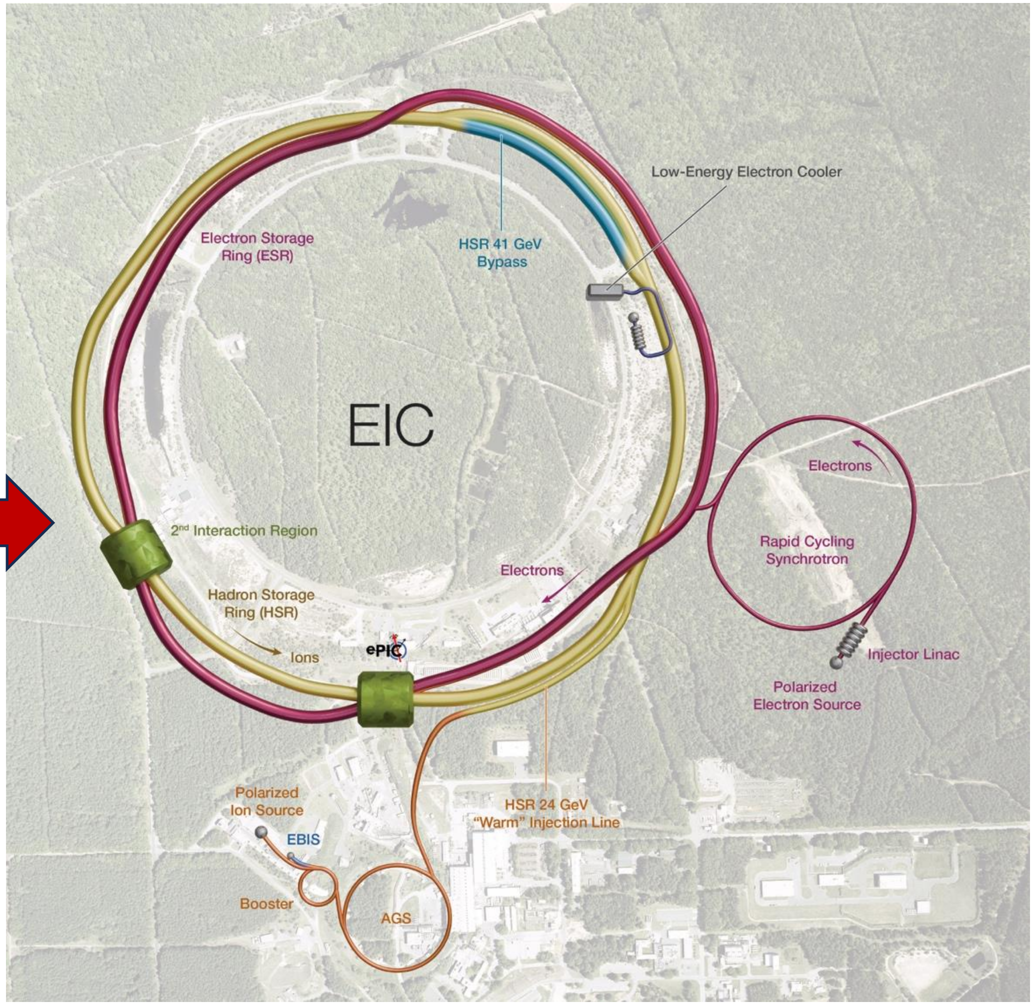


Re-Use the existing tunnel

Minimal modification to the hadron beam complex (yellow)

New electron beam facility

Build on the ~$2B+ investment



Present EIC Concept (2025)

•***Ultimate EIC Performance Parameters:***

- High Luminosity: L= $10^{33} – 10^{34} cm^{-2} sec^{-1}$
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: Ecm = 28 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Forward Acceptance and Low-Background Conditions
- Possibility to Implement a **Second Interaction Region (IR)**

Accelerator Status at a glance:

✓ Polarized ion/proton source

✓ Ion injection and initial acceleration systems – Linac (200 MeV), Booster (1.5 GeV), AGS (25 GeV)

UPGRADE Hadron Storage Ring (40-275 GeV) – HSR

NEW Electron Pre-Injector (750 MeV linac)

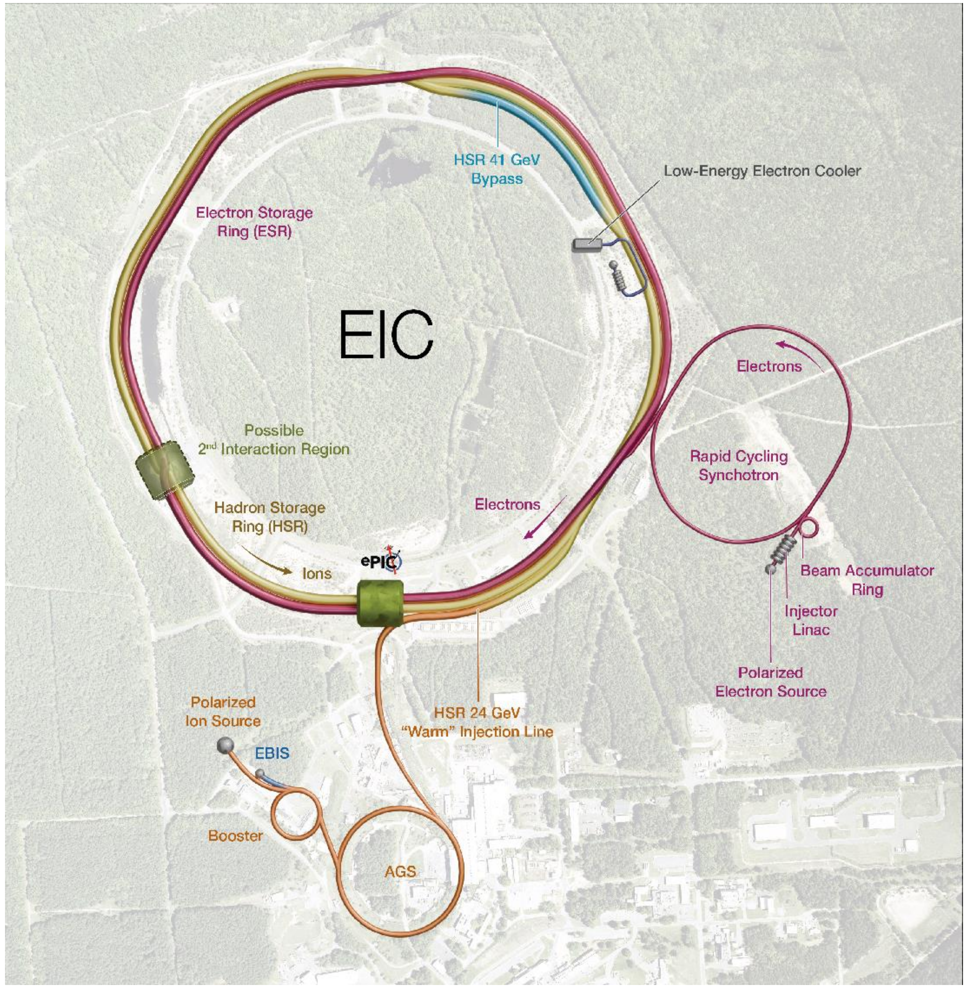
NEW Beam Accumulation Ring (750 MeV) – BAR

NEW Electron Rapid Cycling Synchrotron (0.75 GeV – top energy) – RCS

NEW Electron Storage Ring (5 GeV – 18 GeV) – ESR

NEW Interaction Region(s) – IR

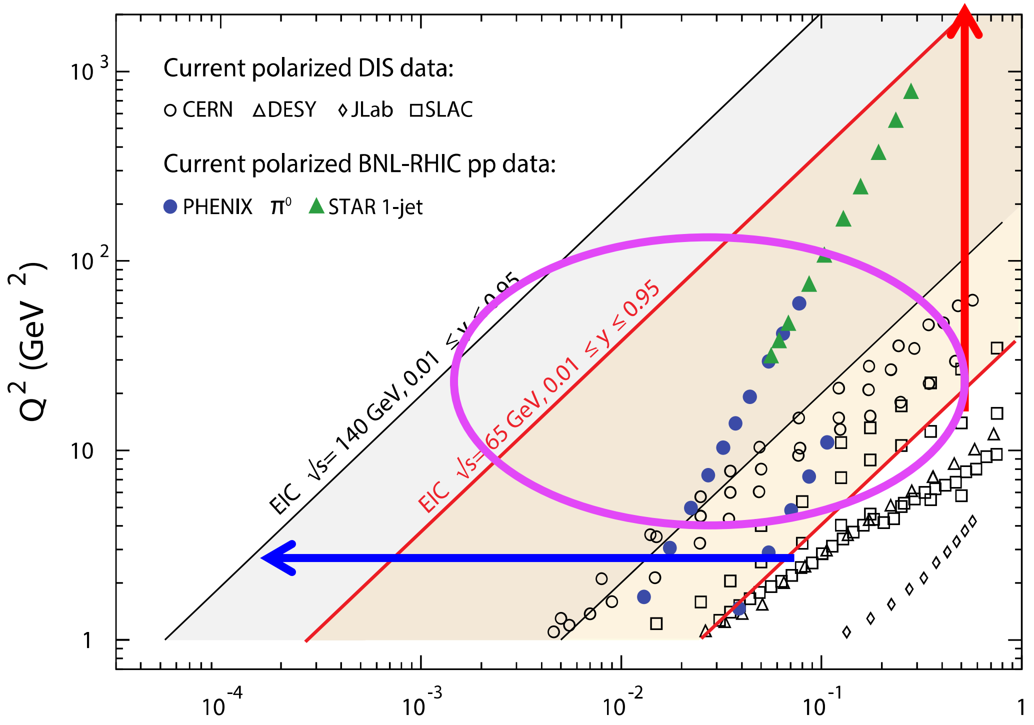
NEW Hadron Cooling System

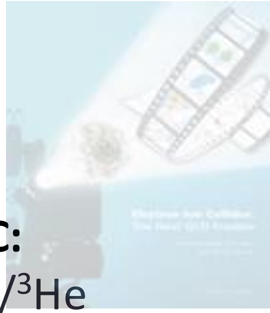


Protons: ~40 – 275 GeV
Electrons: 5 – 18 GeV

EIC Science → what it could provide

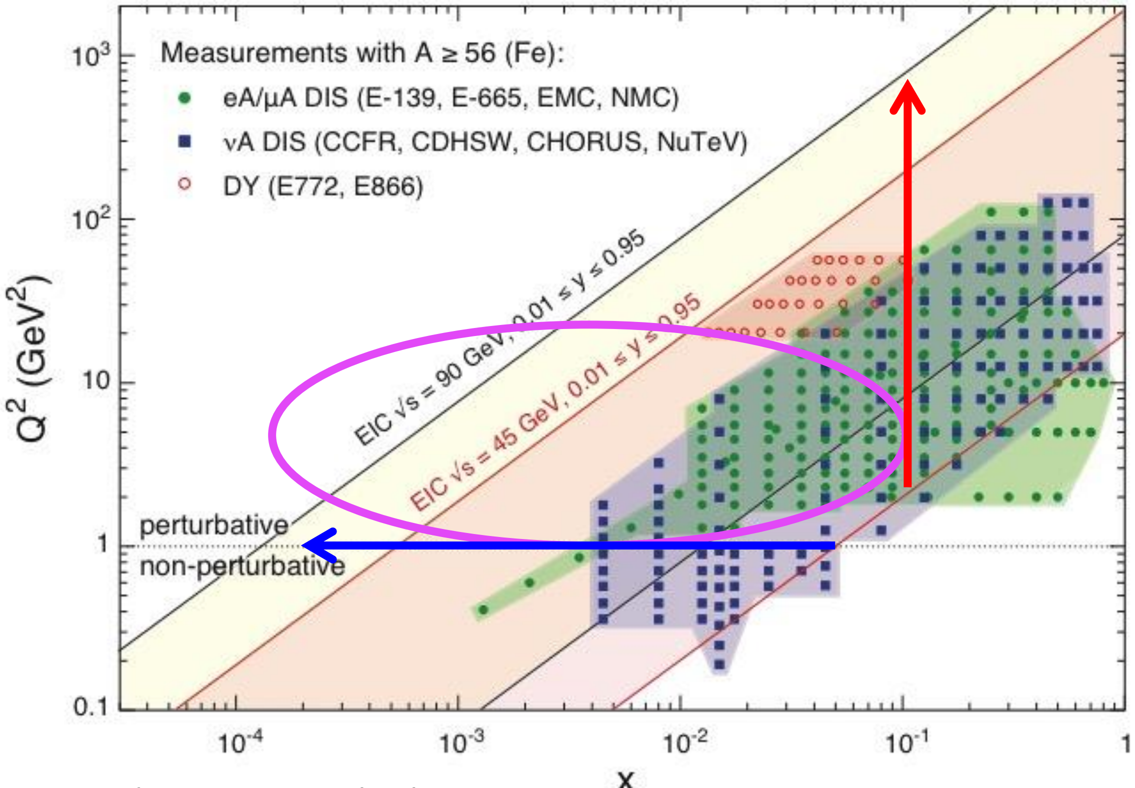
EIC: Kinematic reach & properties





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

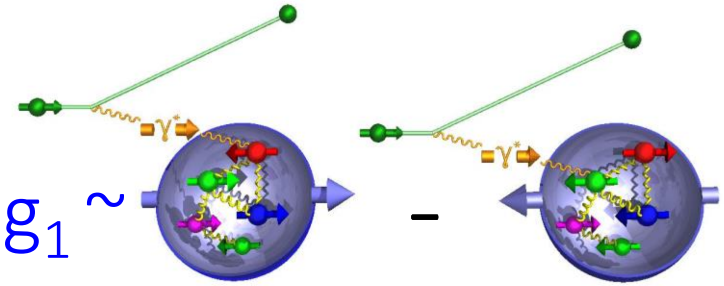
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

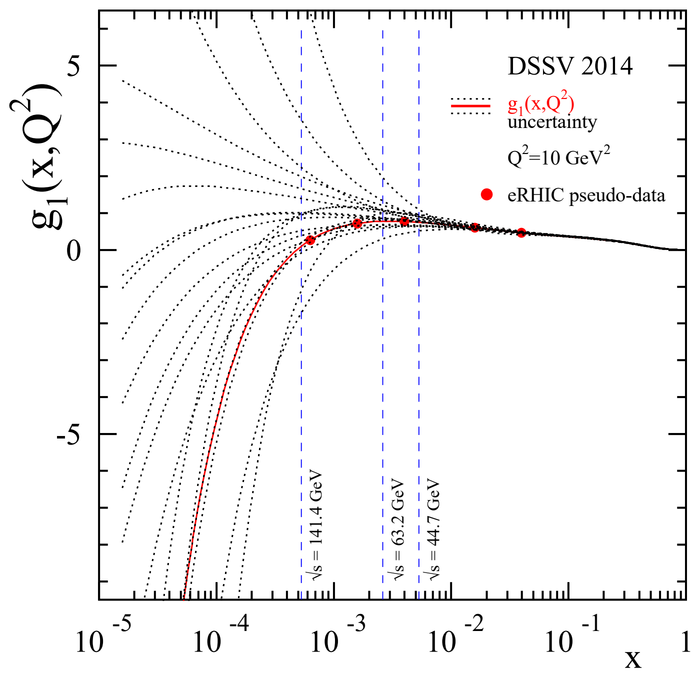
$\Delta\Sigma/2$ = Quark contribution to Proton Spin
Δg = Gluon contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
L_G = Gluon Orbital Ang. Mom

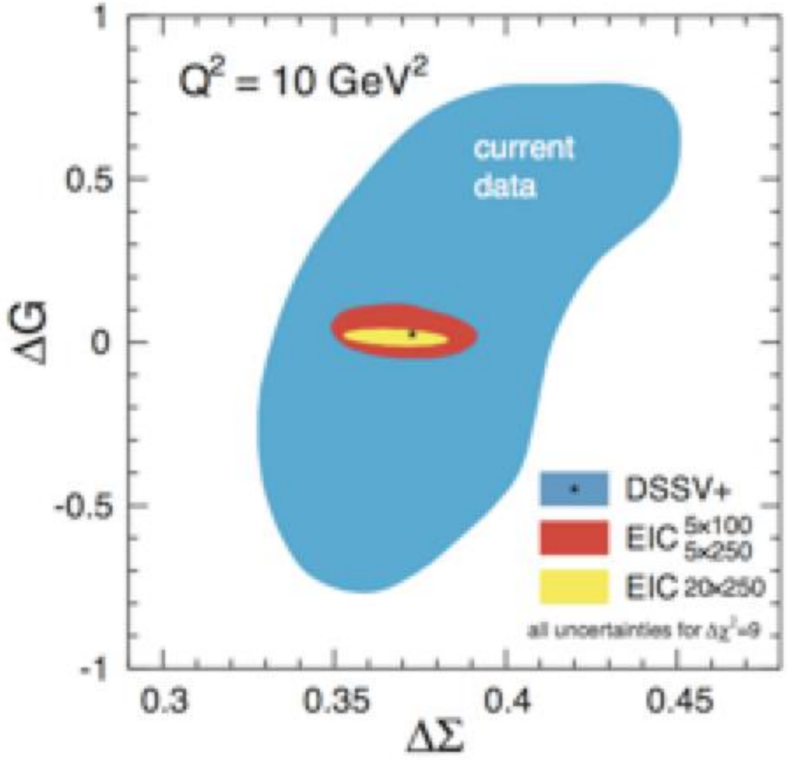
Spin structure function g_1 needs to be measured over a large range in x-Q^2

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

$g_1 \sim$ 

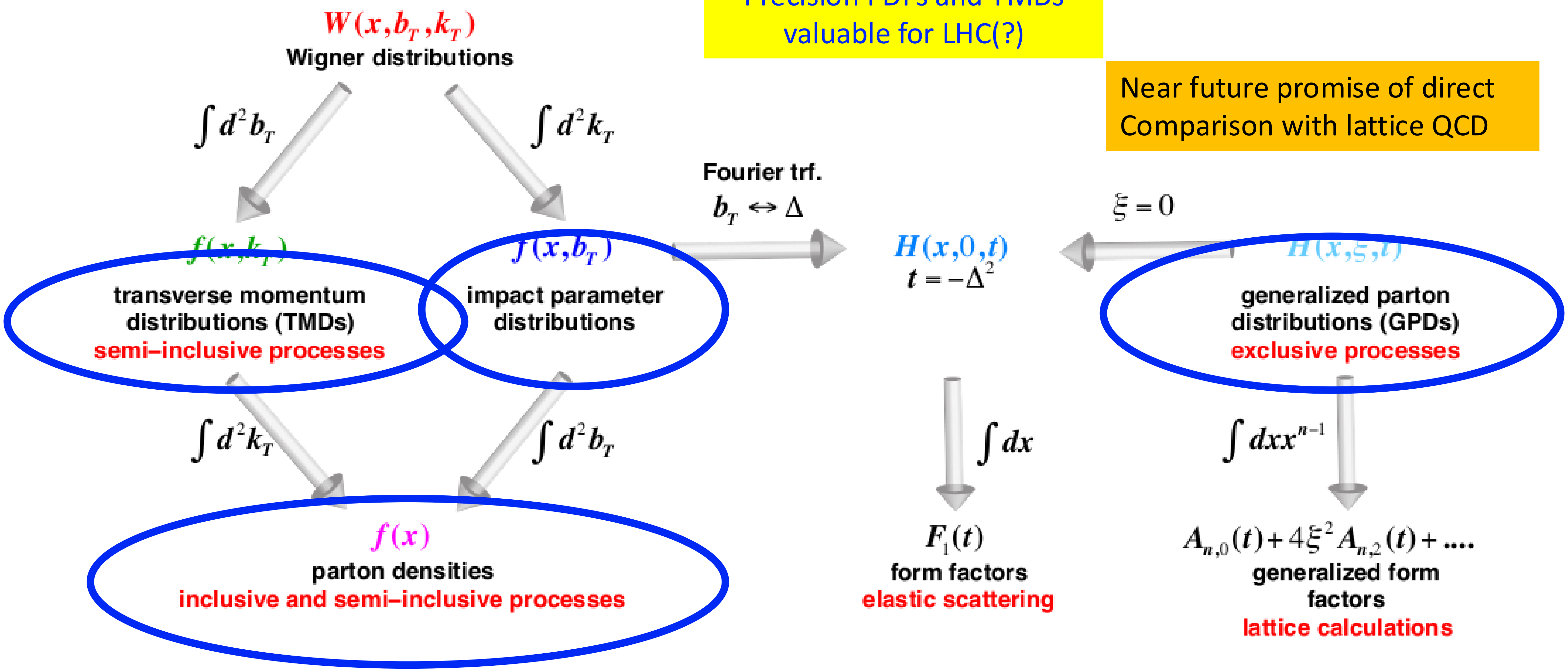




2+1D Imaging of hadrons: beyond precision PDFs

Precision PDFs and TMDs valuable for LHC(?)

Near future promise of direct Comparison with lattice QCD

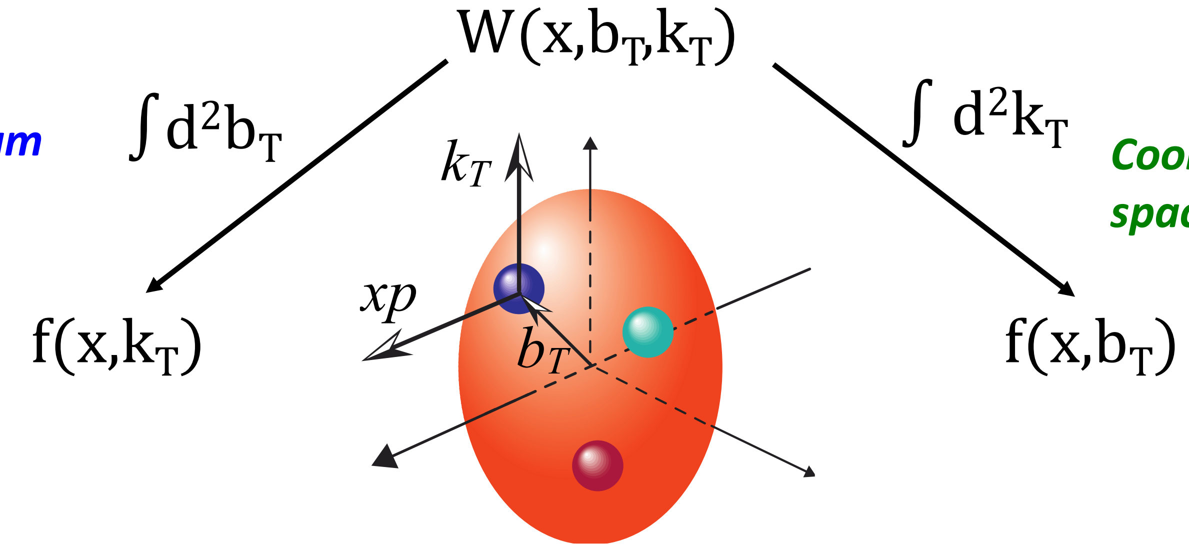


3-Dimensional Imaging Quarks and Gluons

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

offer unprecedented insight into confinement and chiral symmetry breaking.

Momentum space



Coordinate space

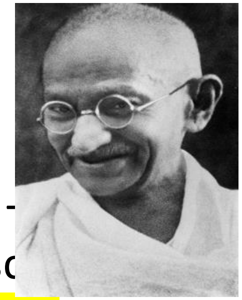
Spin-dependent 3D momentum space images from semi-inclusive scattering
→ **TMDs**

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

Position and momentum → Orbital motion of quarks and gluons

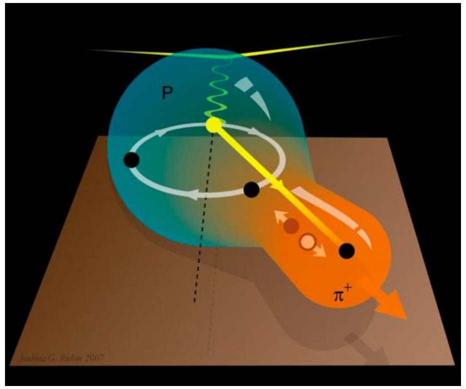
Possible direct access to gluon Wigner function through diffractive di-jet measurements at an EIC: Y. Hatta et al. PRL 16, 022301 (2016)

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

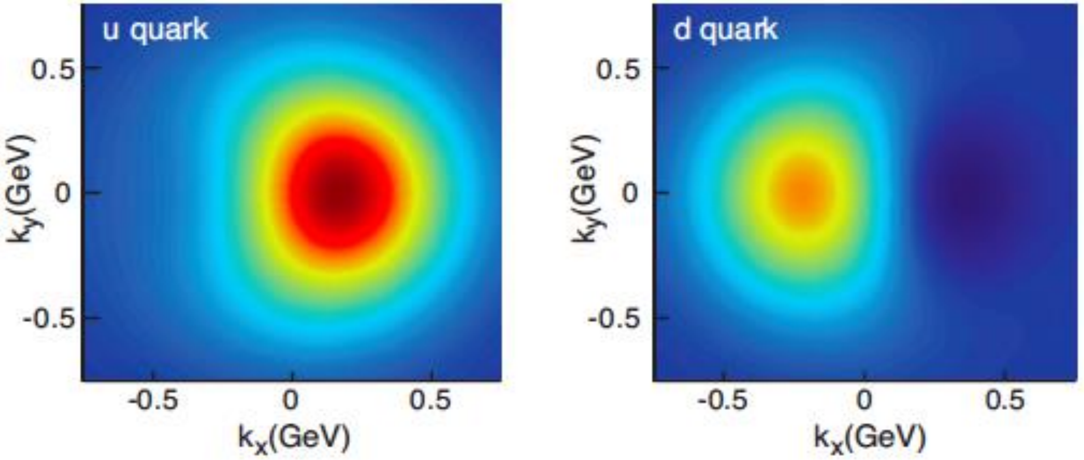


Spin-dependent 3D momentum space images from semi-inclusive scattering (SIDS)

Transverse Momentum Distributions



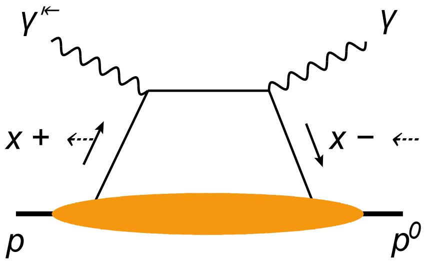
Possible measurements of K (s) and D (c)



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

Transverse Position Distributions

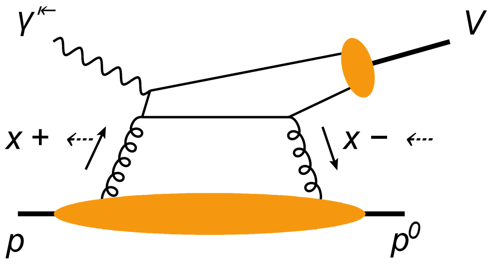
Quarks Motion



Deeply Virtual Compton Scattering

Measure all three final states

e + **p** → e' + **p'** + γ

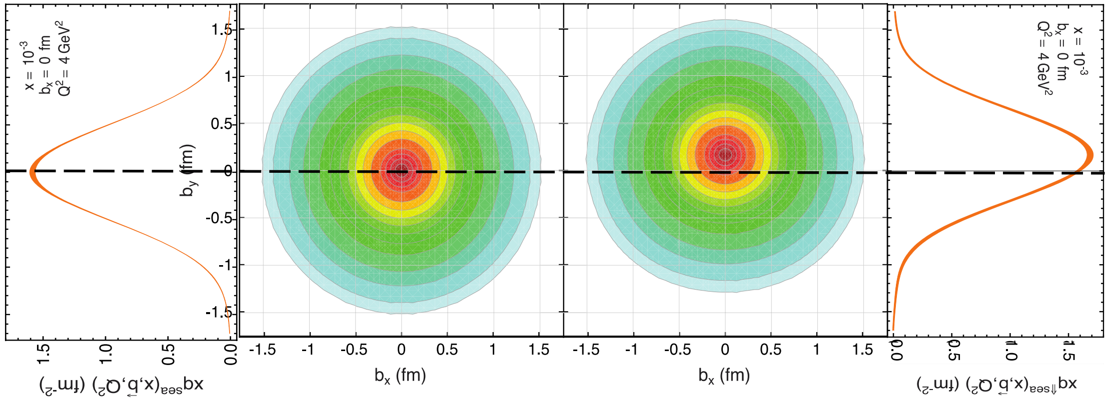


Gluons: Only @ Collider

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

2D position distribution for sea-quarks

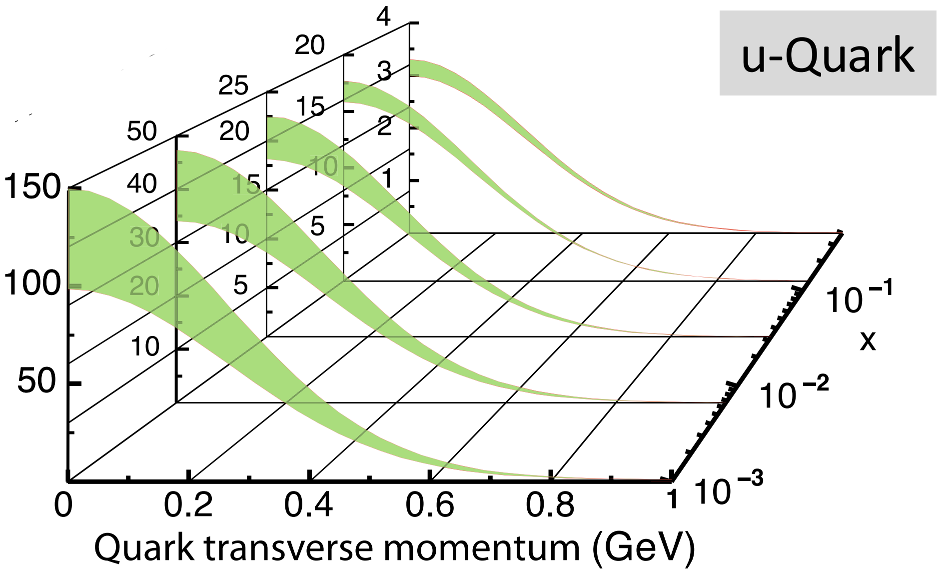
unpolarized polarized



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

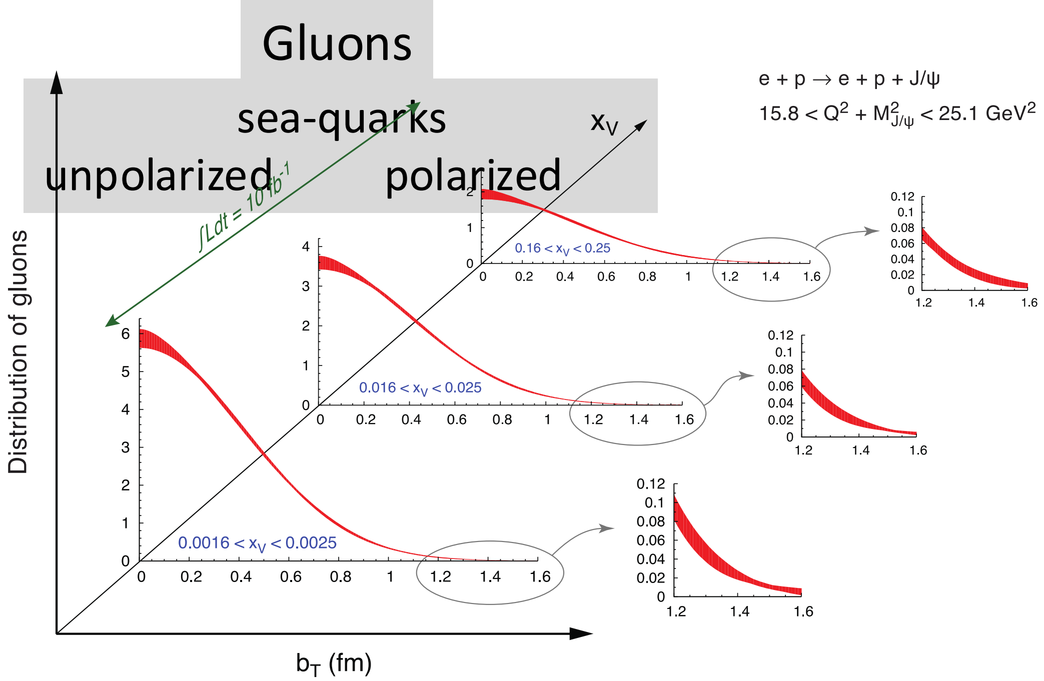
Spin-dependent 3D momentum space images from semi-inclusive scattering

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)

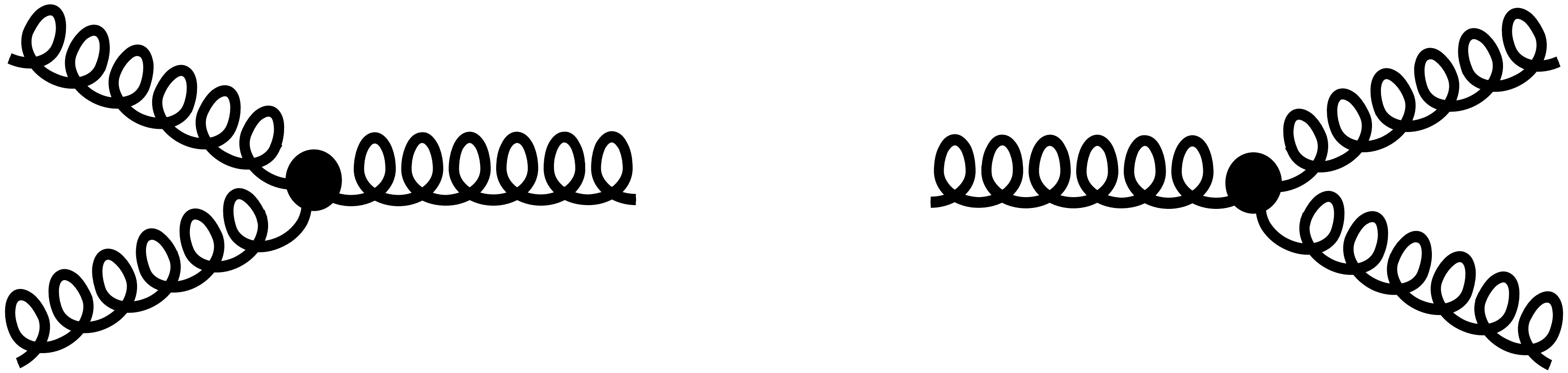
1) Violent collision of melons

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… ?

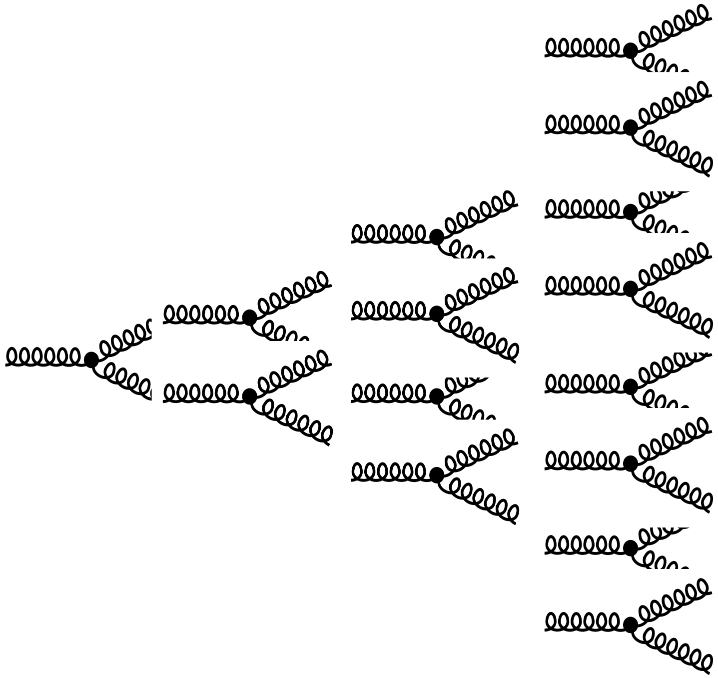
Particularly at high energy ➔ low-x

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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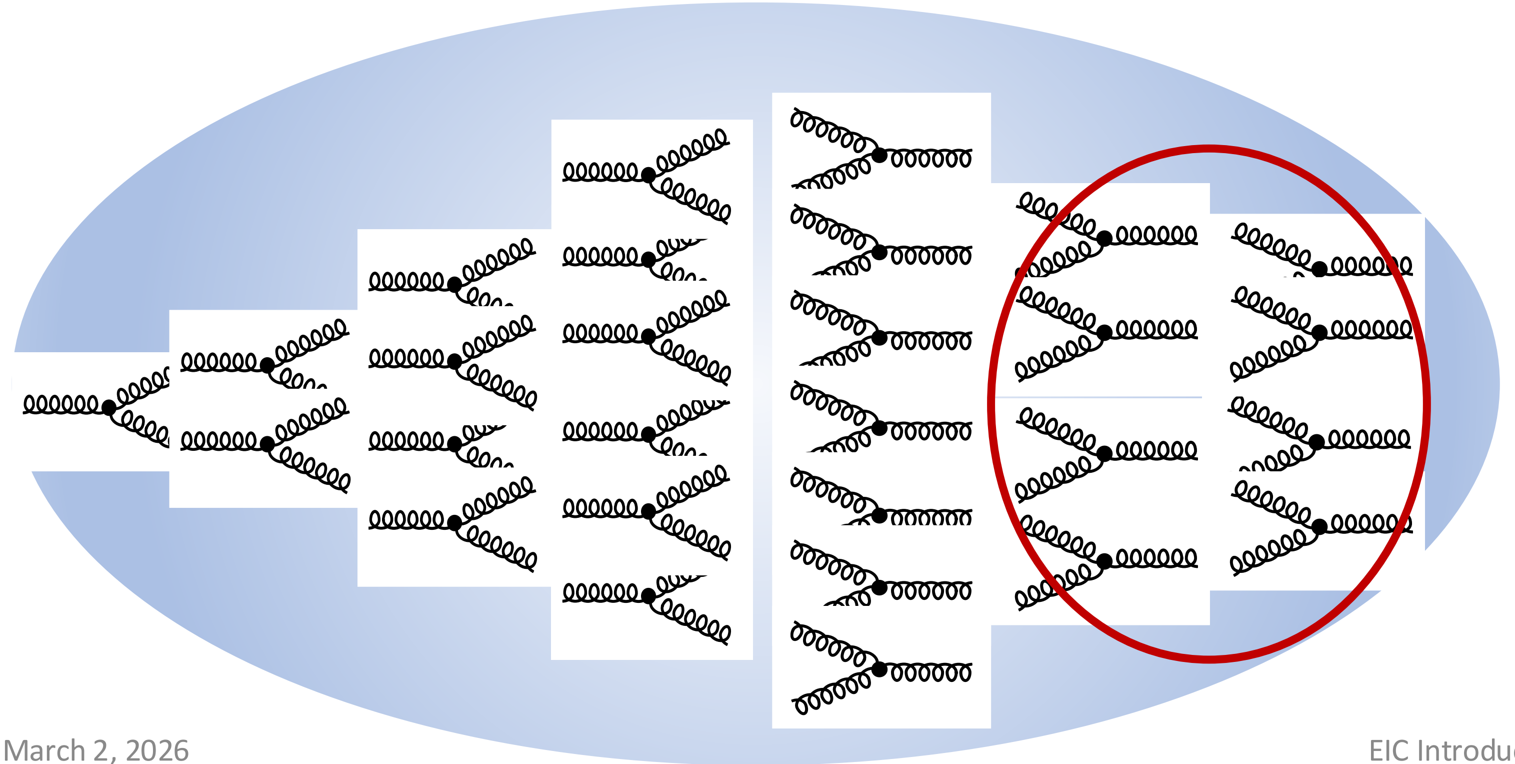
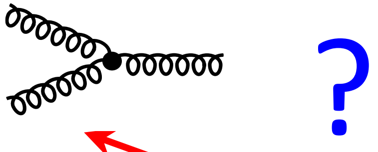
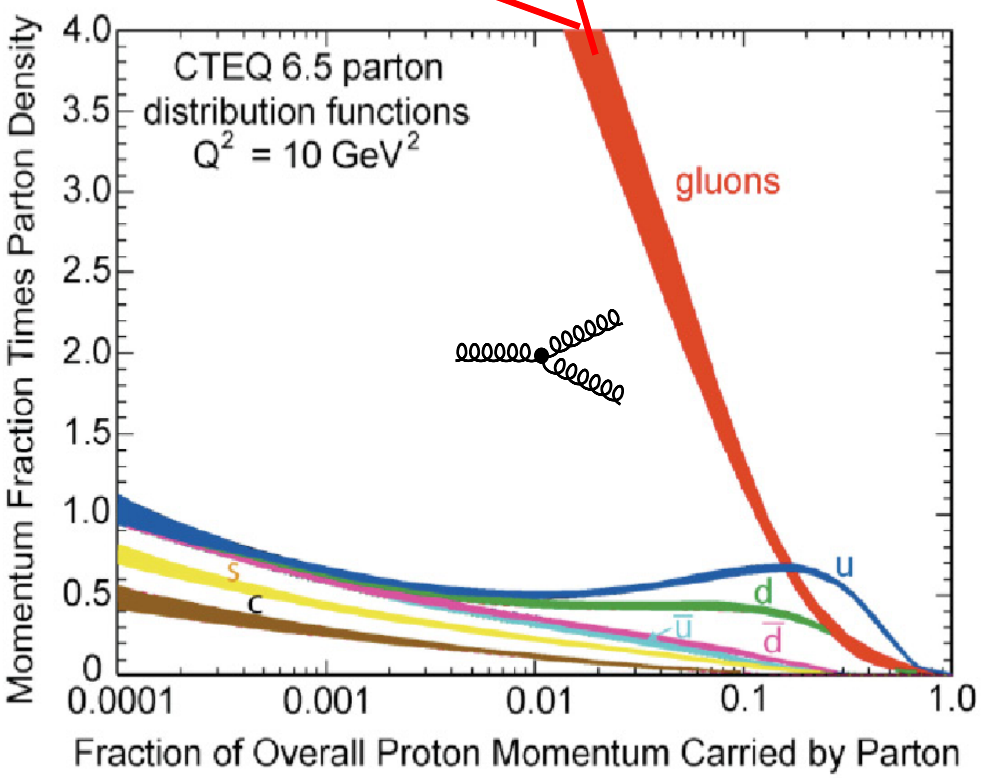


In search of a new state of matter!





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.

gluon emission = gluon recombination At Q_S

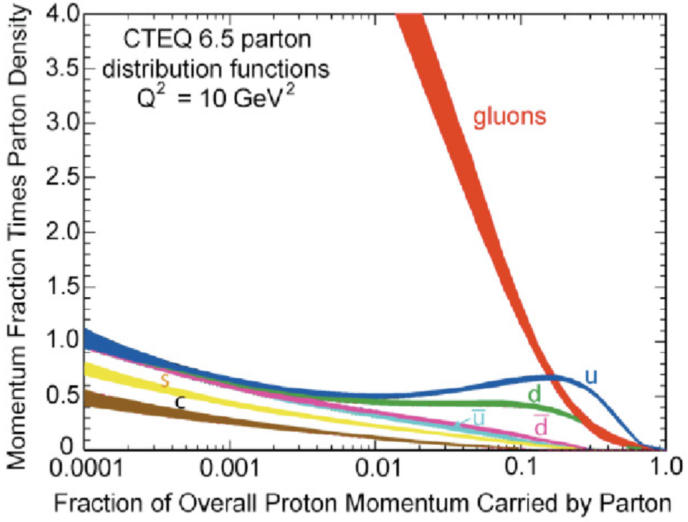
Observation of gluon recombination effects

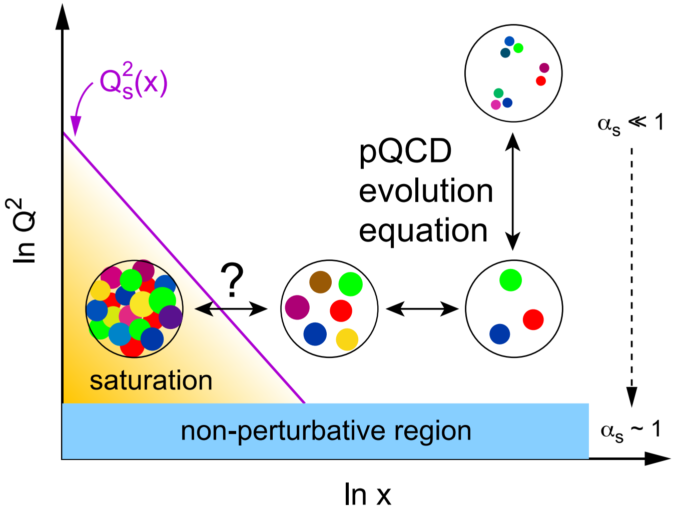
➔Is there such new state of matter?

→ "Color Glass Condensate"

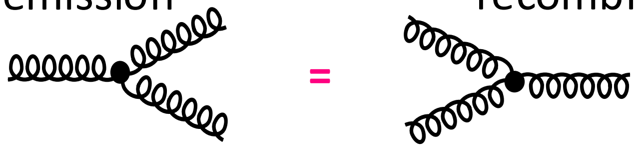
→ 50-100 times higher energy density than the core of the neutron star

Low x physics with nuclei

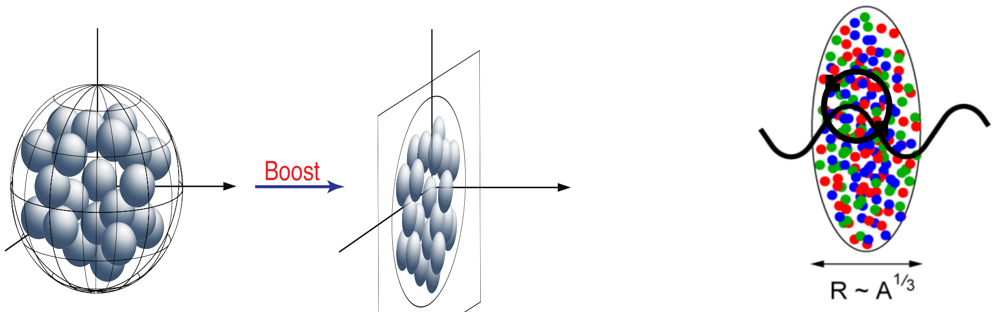




gluon emission = gluon recombination



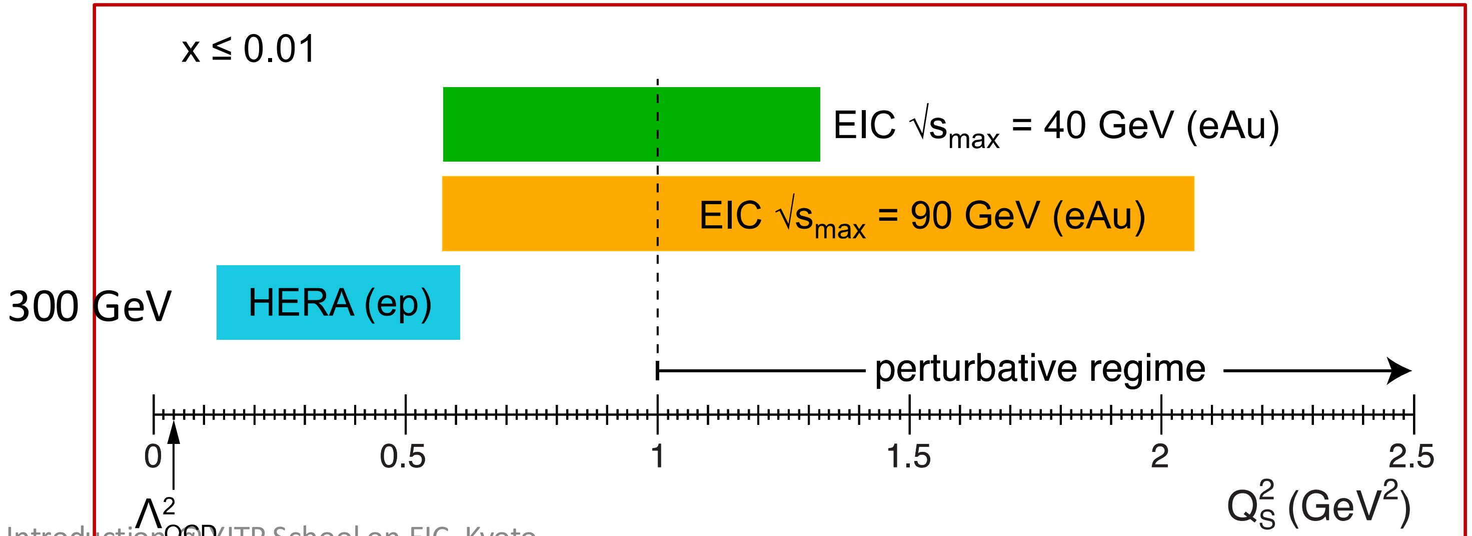
At Q_S



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

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

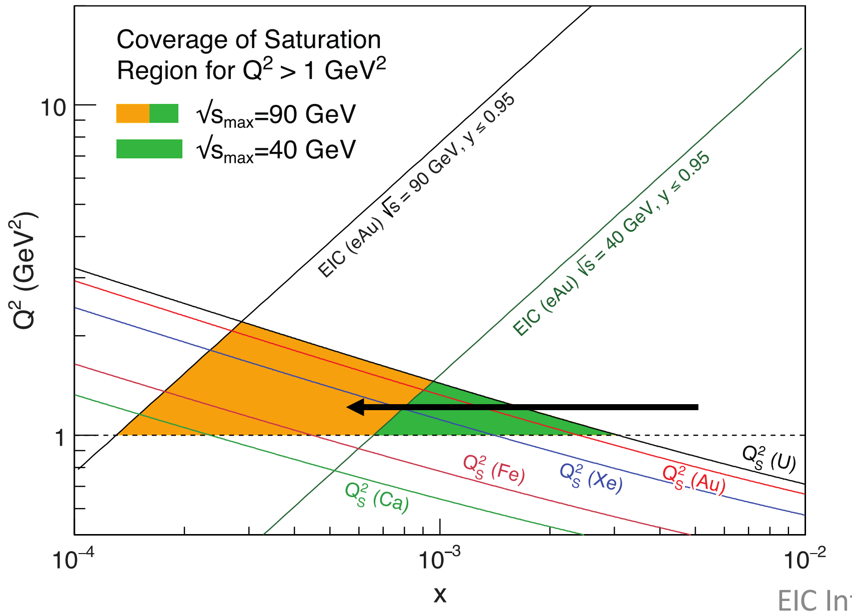
Accessible range of saturation scale Q_s^2 at the EIC with e+A collisions.
arXiv:1708.01527



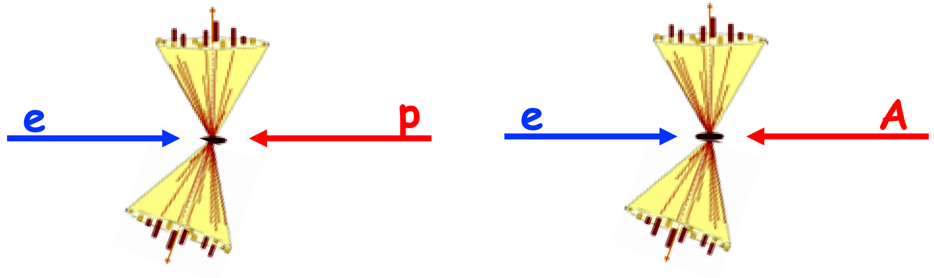
Can EIC discover a new state of matter?

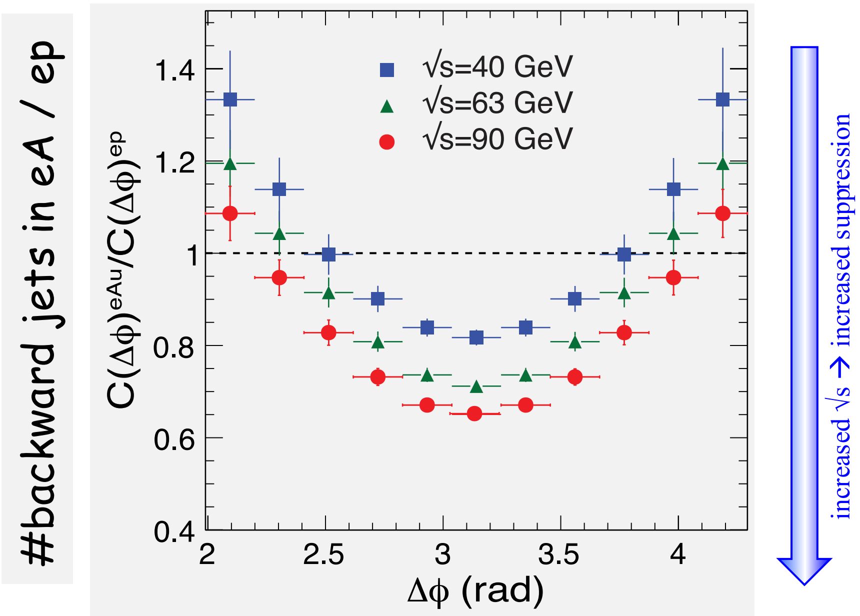
EIC provides an absolutely unique opportunity
to have very high gluon densities
→ electron – lead collisions
combined with an unambiguous observable

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



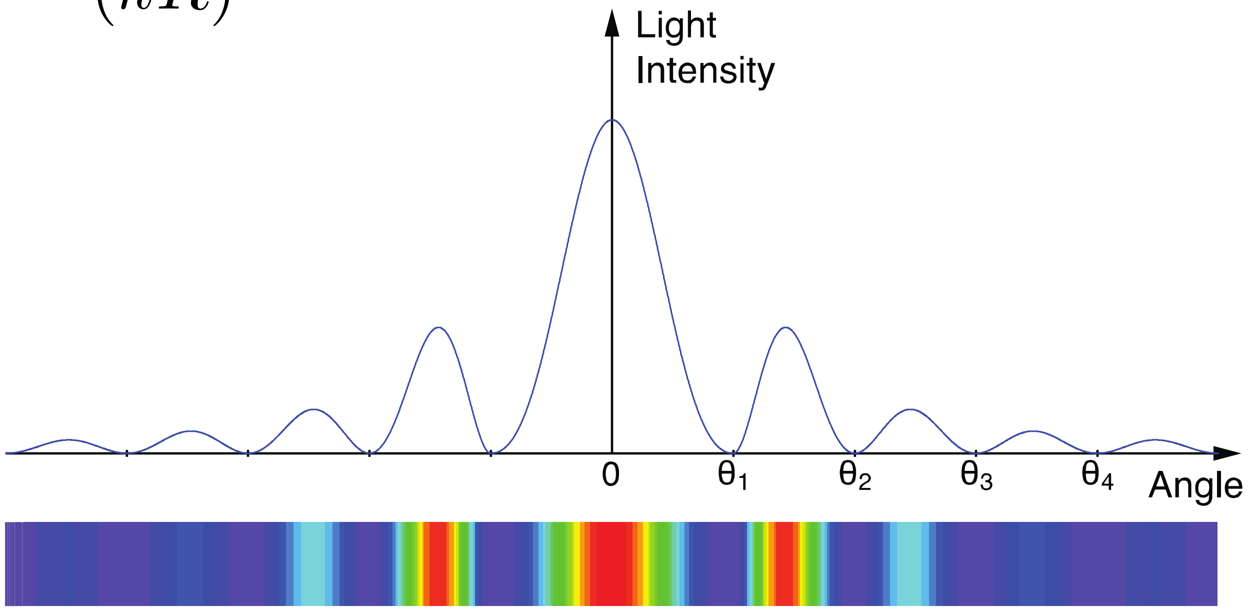


Diffraction in Optics and high energy scattering

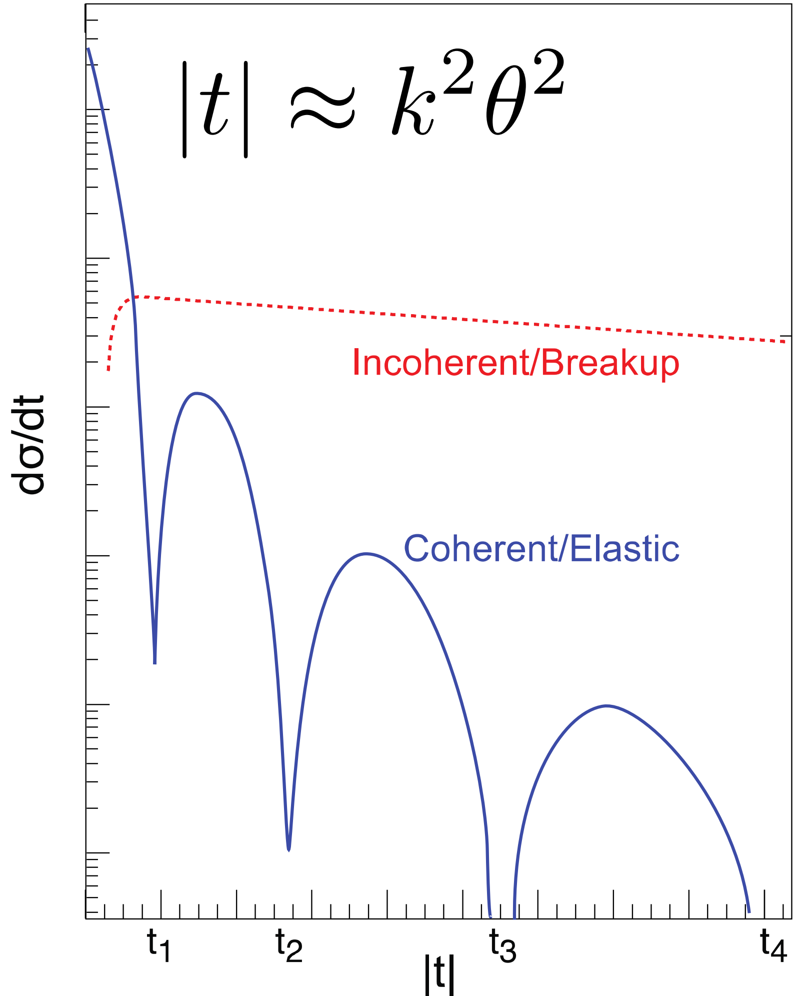
Light with wavelength λ obstructed by an opaque disk of radius R suffers diffraction:

k → wave number

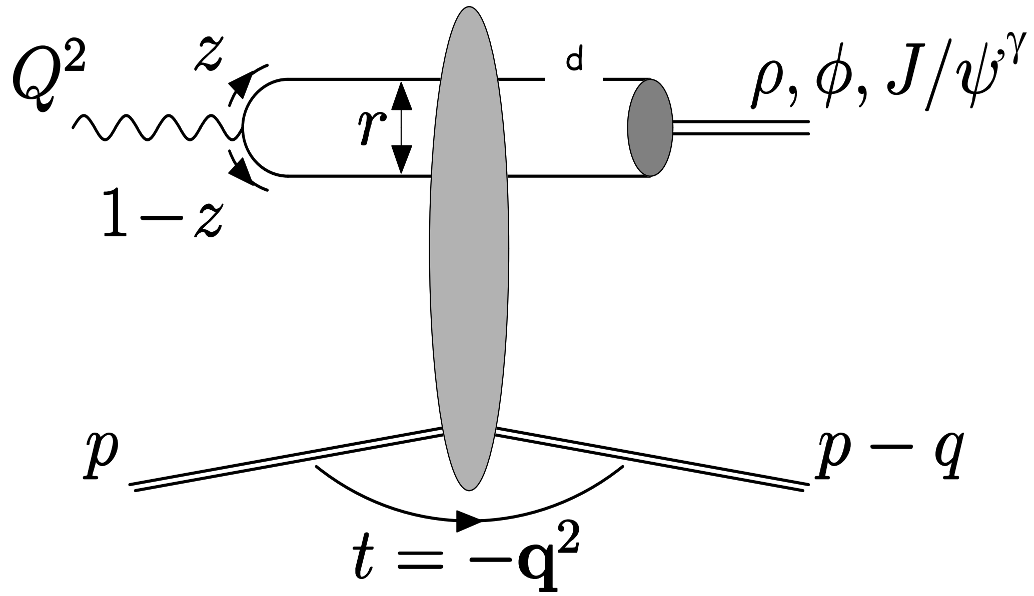
$$\theta_i \sim \frac{1}{(kR)}$$



Calculation of e-A diffraction

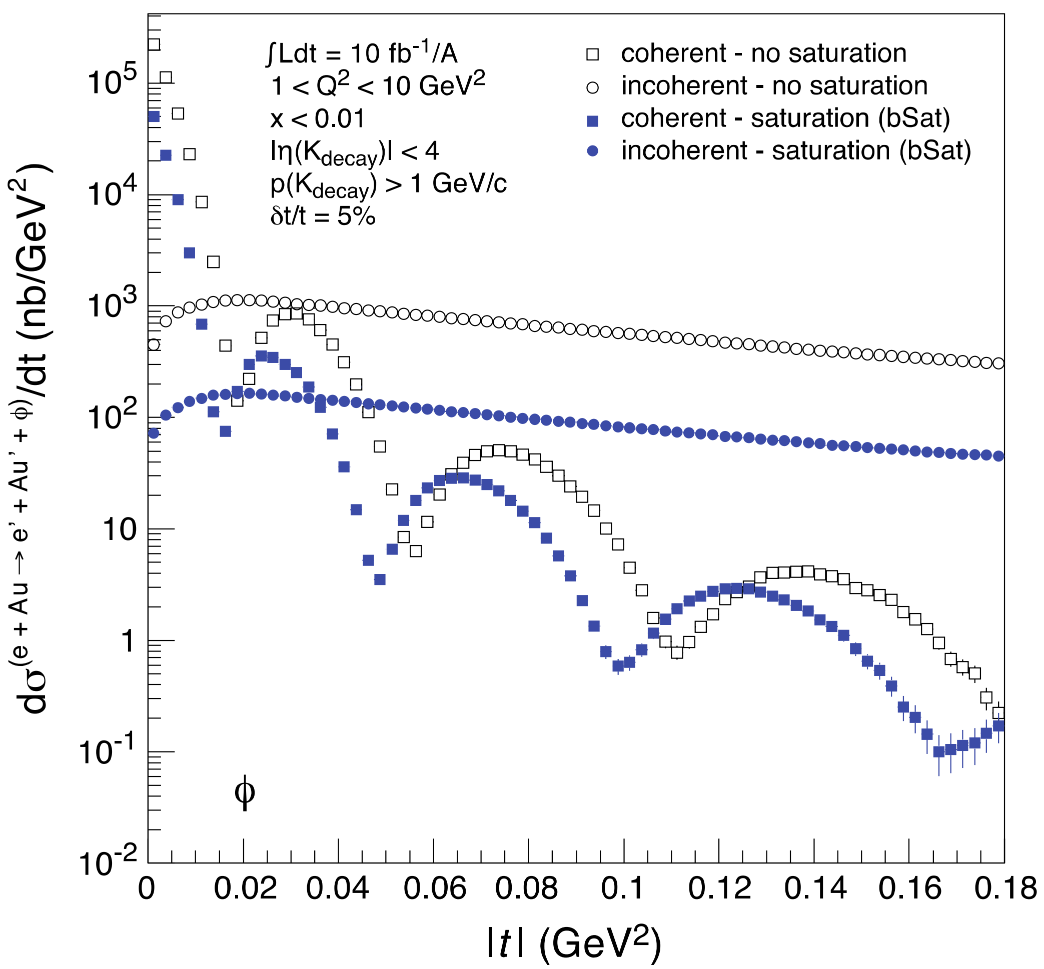


Transverse imaging of the gluons nuclei



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

Diff. MC: "Sartre"

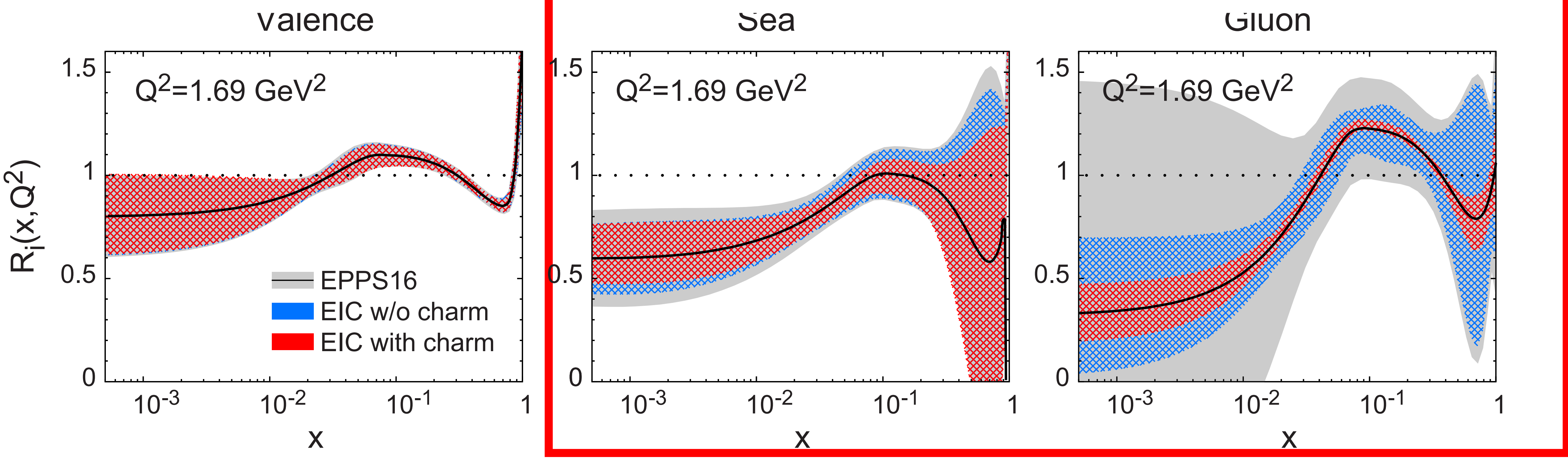


➔Does low x dynamics (Saturation) modify the transverse gluon distribution?

Experimental challenges being studied.

Simulation study by Toll & Ullrich

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.

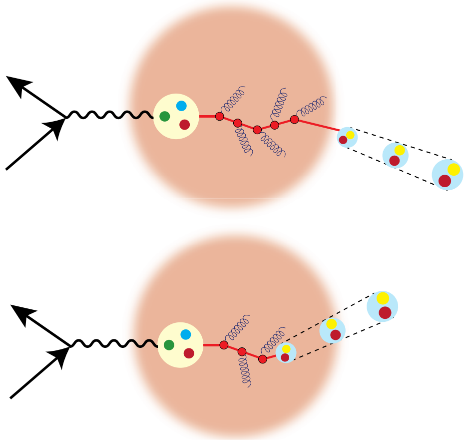
❖ Does the nucleus behave like a proton at low-x? ➔ such color correlations relevant to the understanding of astronomical objects

Emergence of Hadrons from Partons

Nucleus as a Femtometer sized filter

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

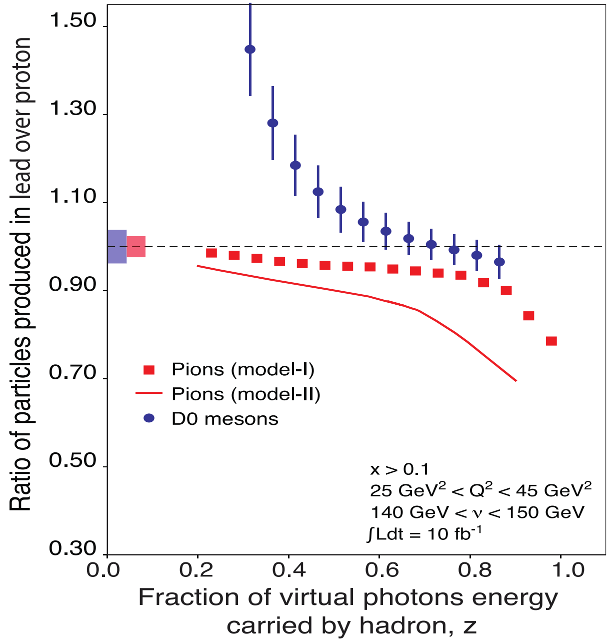
$$\nu = \frac{Q^2}{2mx}$$



Study in light quarks
vs.
heavy quarks

Control of ν by selecting kinematics;
Also under control the nuclear size.

Energy loss by light vs. heavy quarks:



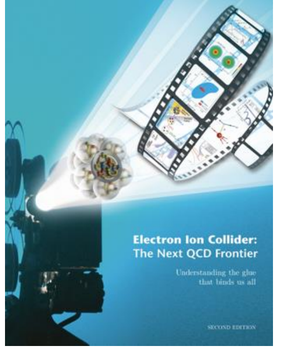
Identify π vs. D^0 (charm) mesons in e-A collisions:

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

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?)

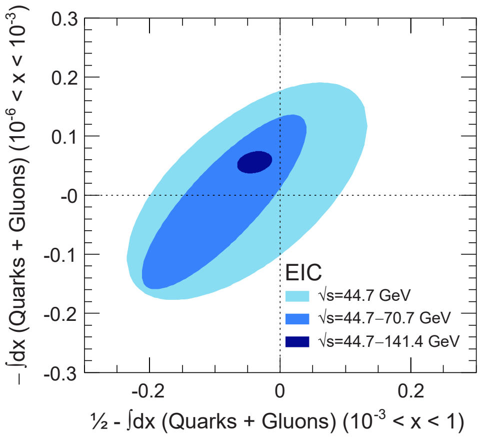
Physics with nucleons and nuclear targets:

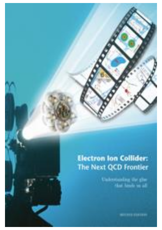
- Quark Exotica: 4,5,6 quark systems…? Much interest after recent LHCb led results.
- Physic of and with jets with EIC as a precision QCD machine:
  - Internal structure of jets : novel new observables, energy variability, polarization, beam species
  - Entanglement, entropy, connections to fragmentation, 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

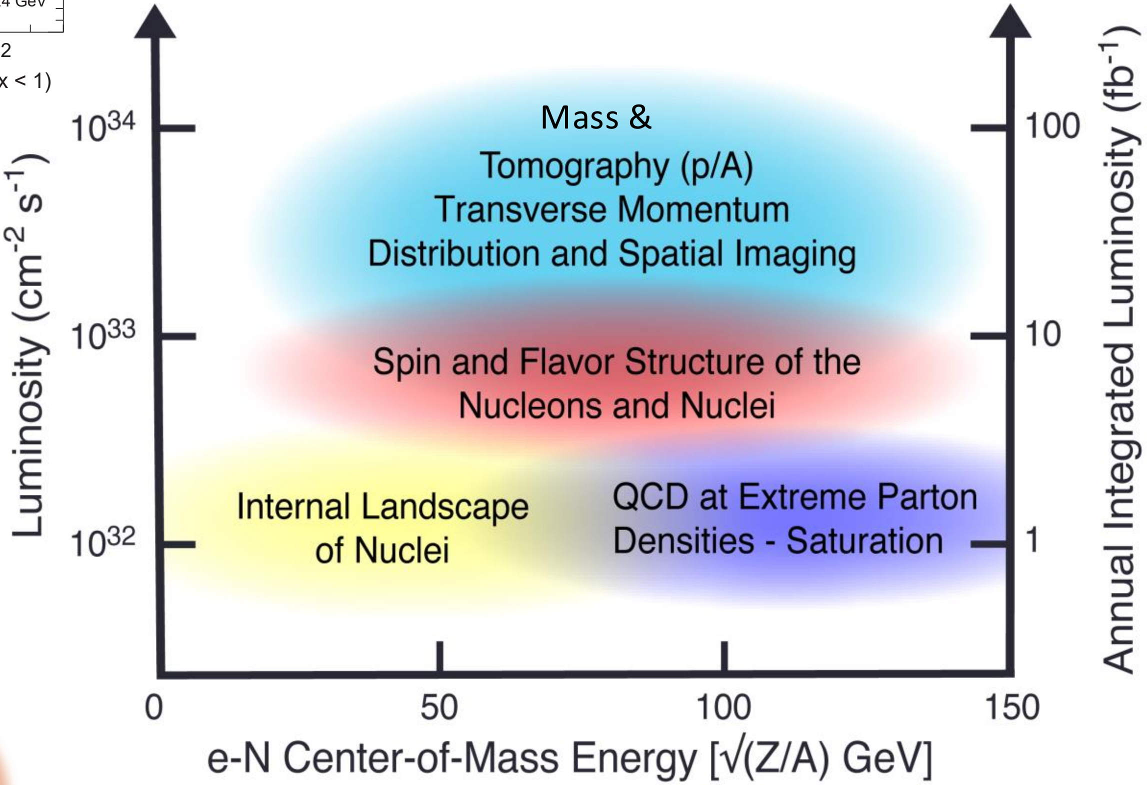
Precision electroweak and BSM physics:

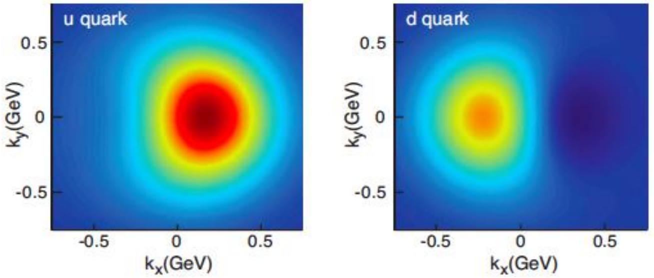
- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation

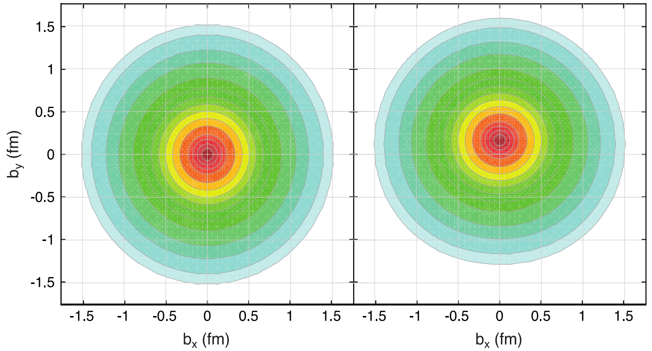
EIC science highlights

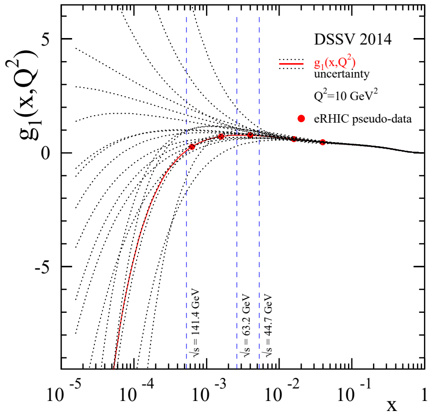


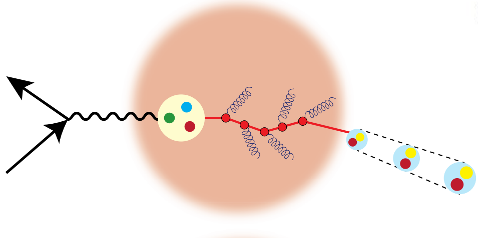


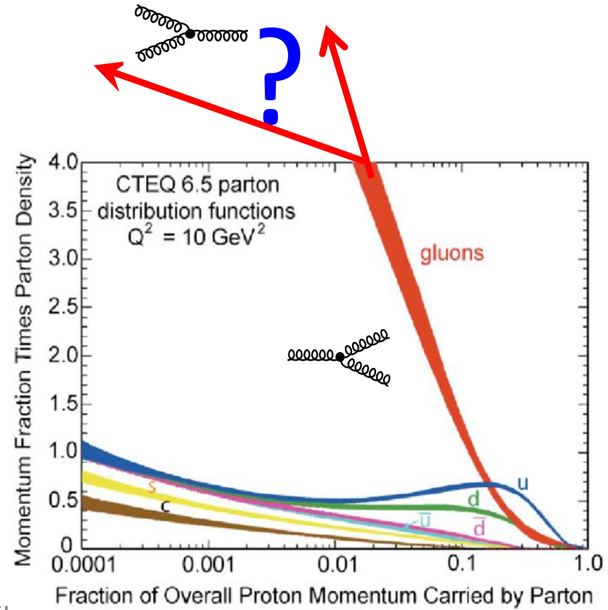




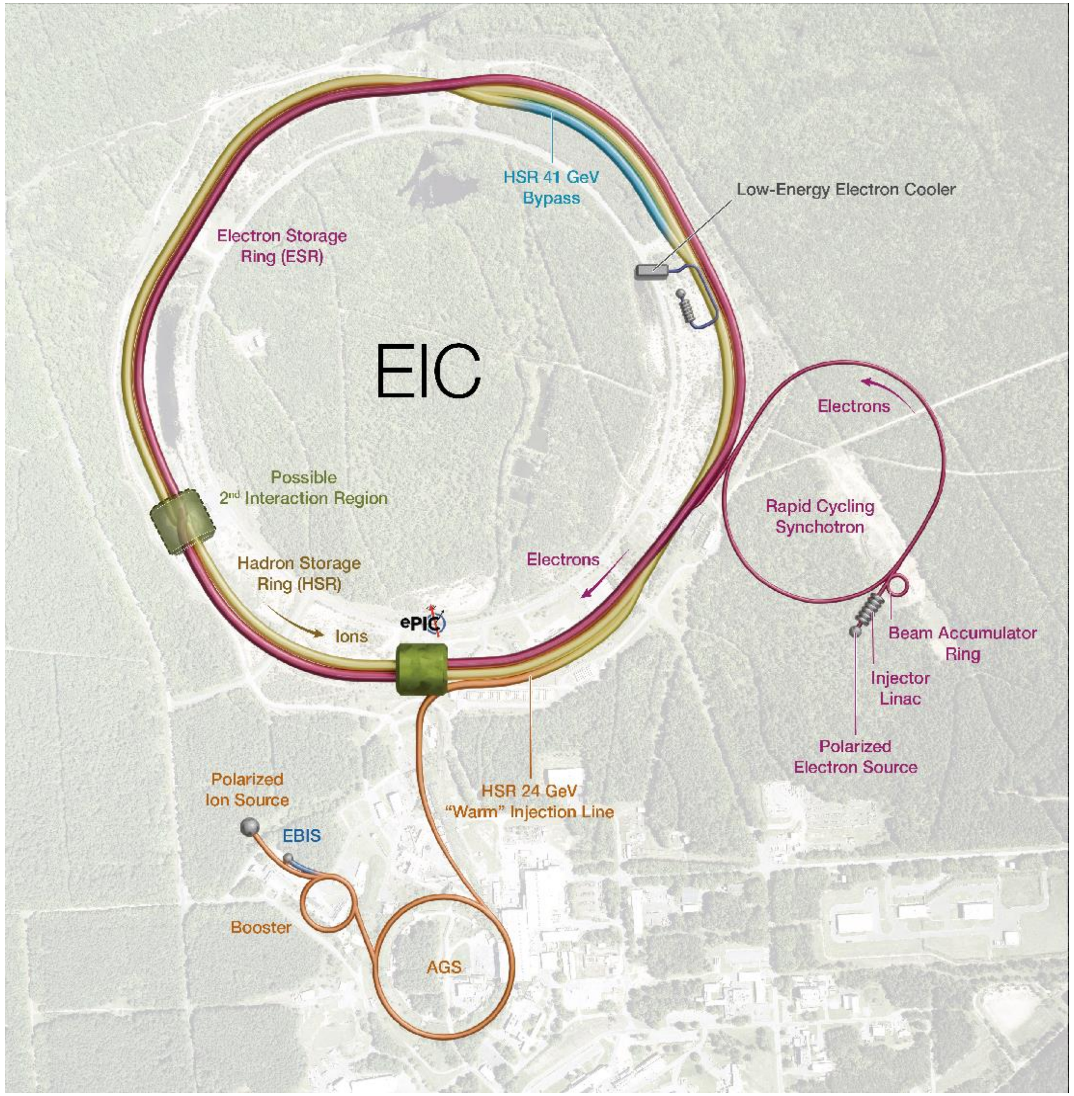




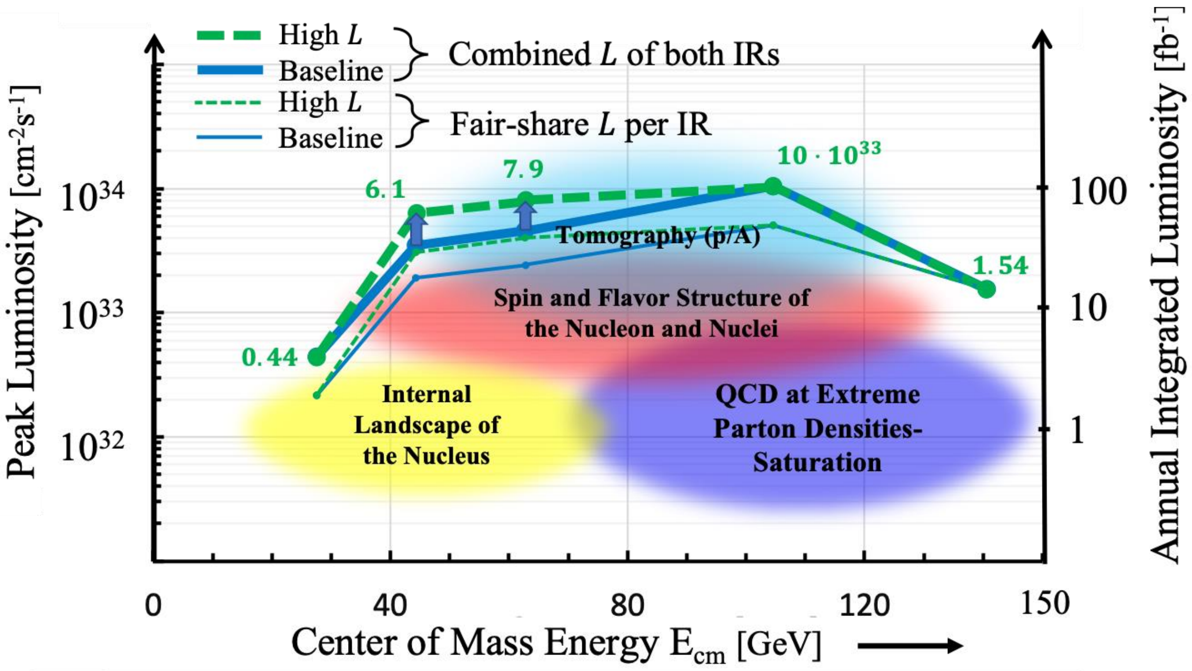




EIC Accelerator Design

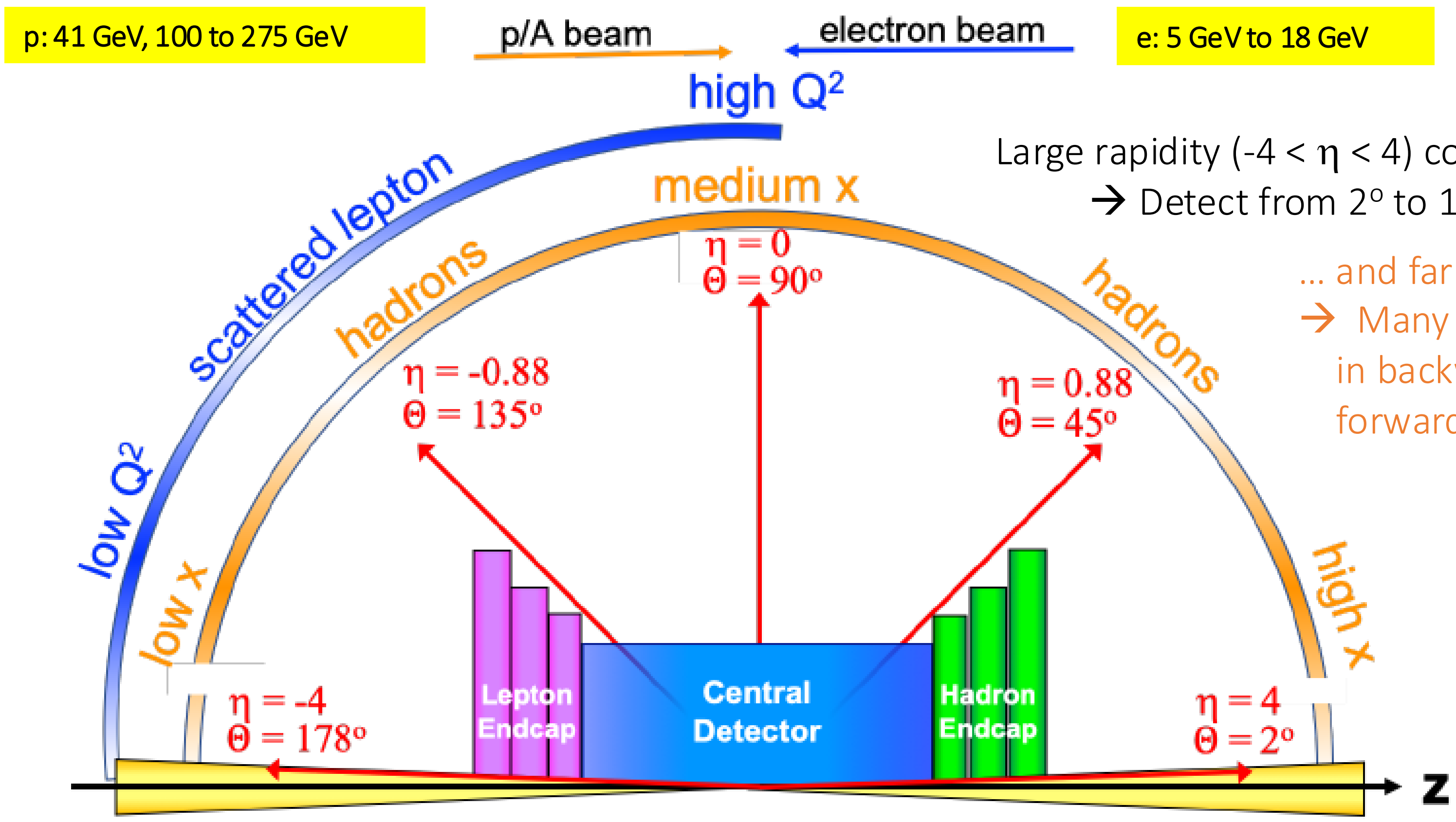


Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



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

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



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

Backward

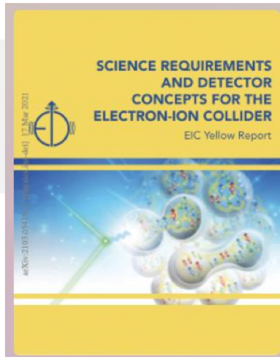
Main detector =
Barrel +
Lepton Endcap +
Hadron Endcap

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.

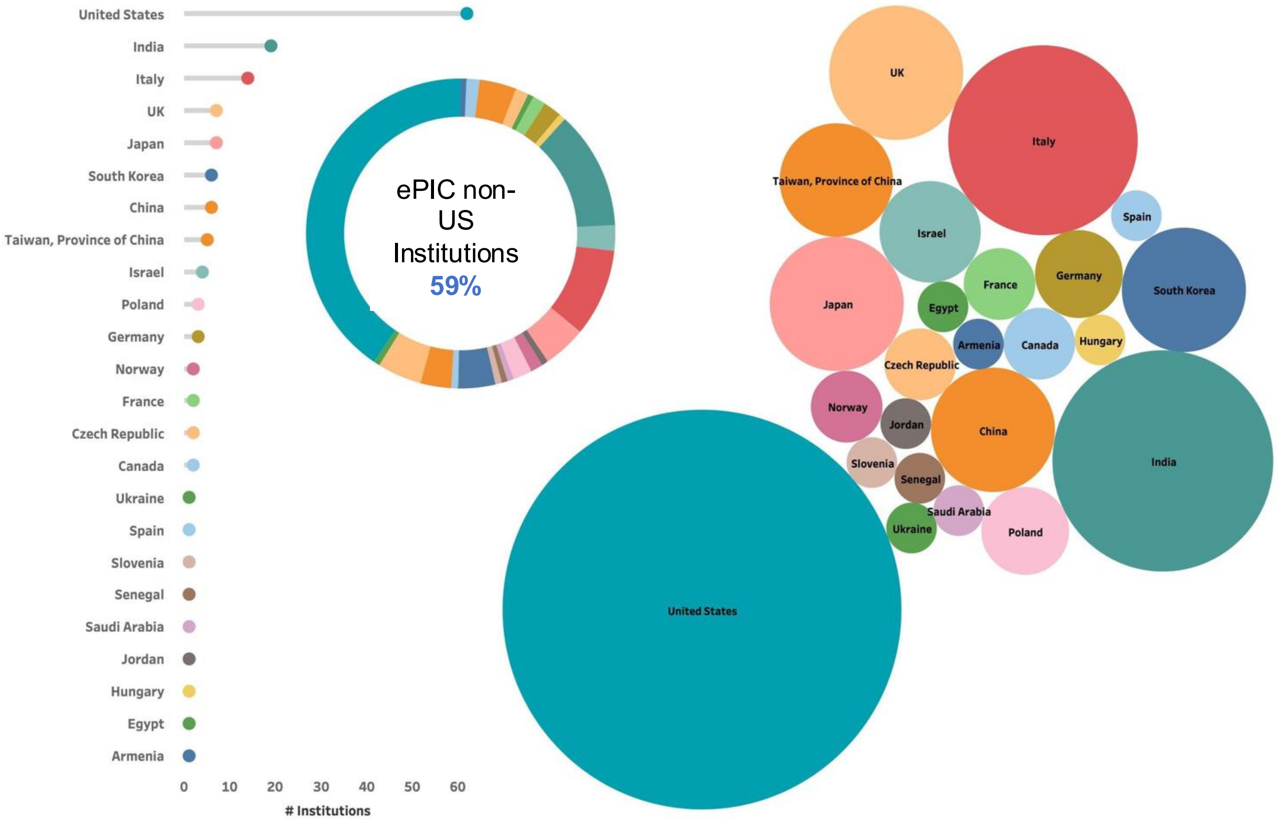
Resulting Experimental Requirements



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**

The ePIC Collaboration



ePIC formed in 2022

ePIC is now 176 institutions.

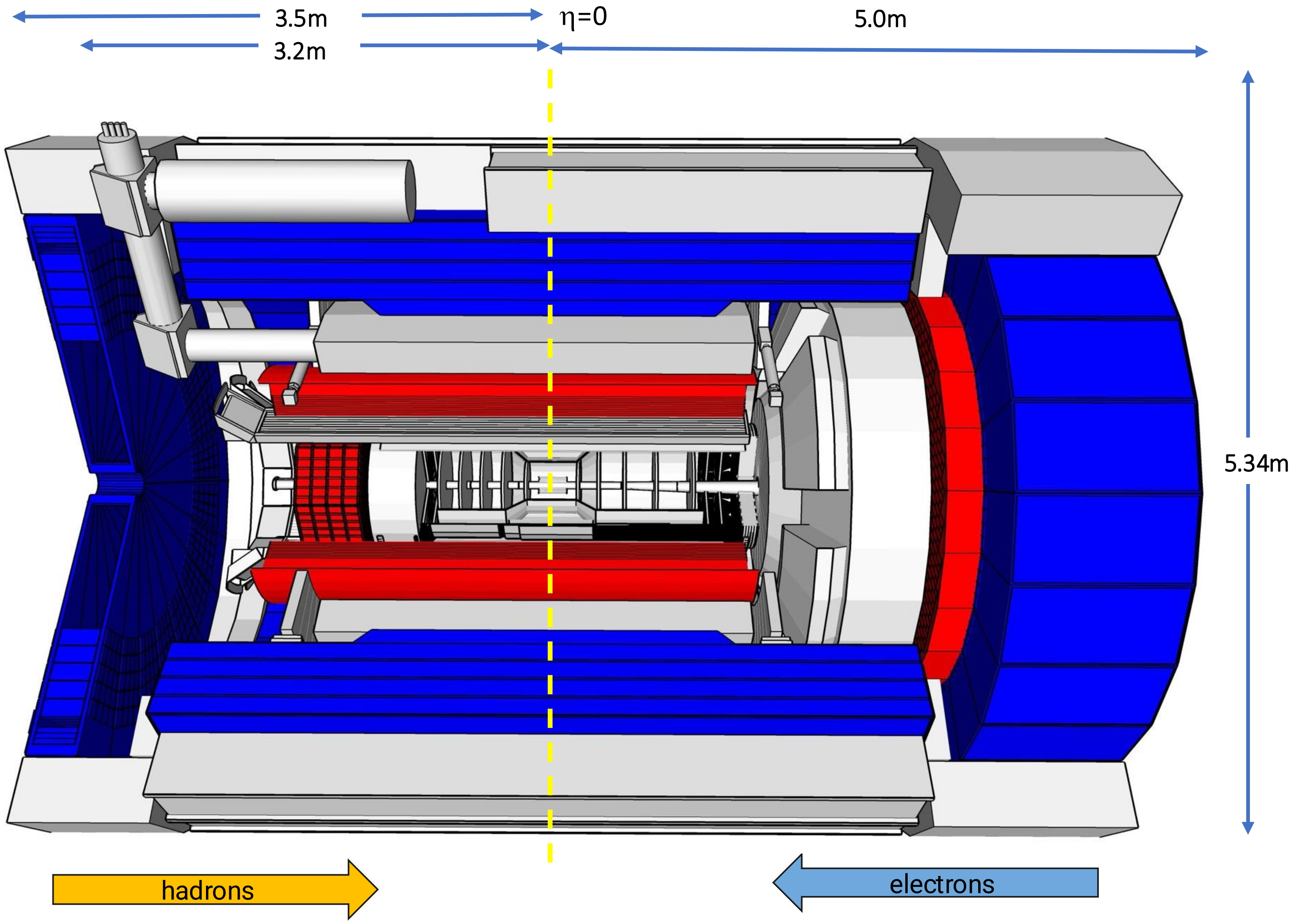
Representing 40+ countries

1000+ participants

A global pursuit for a new experiment at the EIC!

ePIC Spokesperson:
John Lajoie (ORNL)
ePIC Deputy Spokesperson & Interim Technical Director
Silvia Dalla Torre (INFN Trieste)

ePIC Detector Design



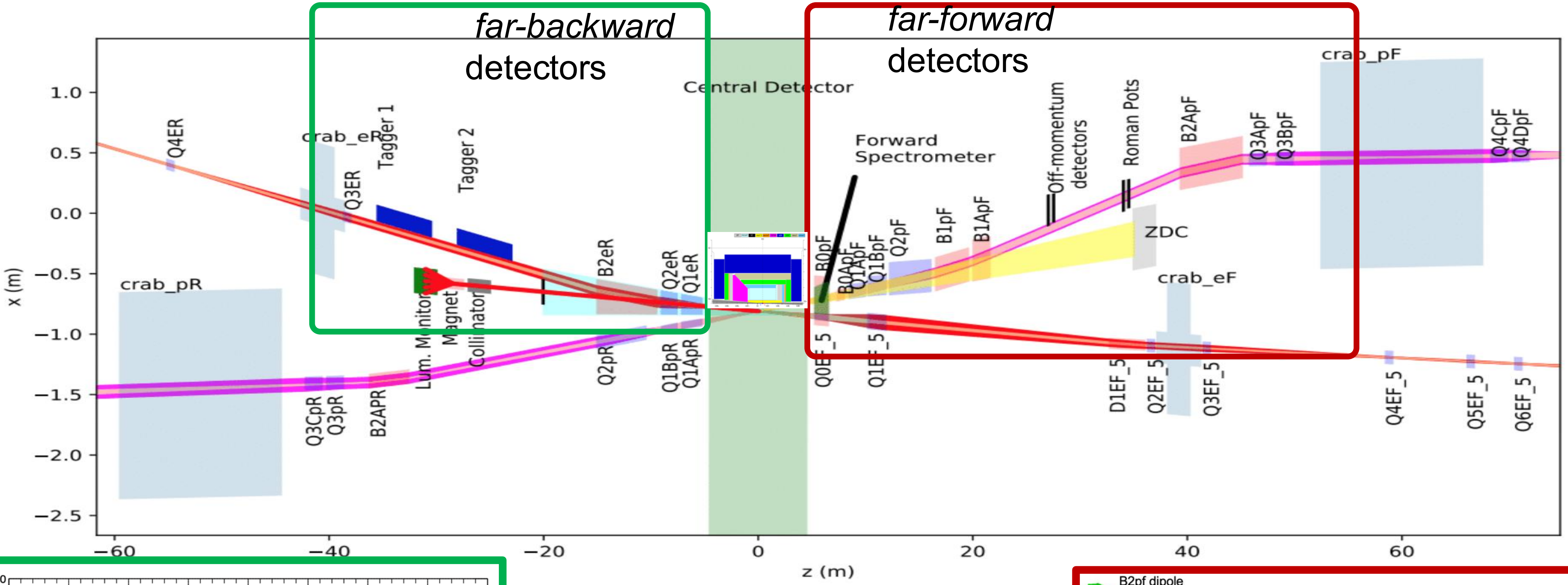
Tracking:
- New 1.7T solenoid
- Very thin Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

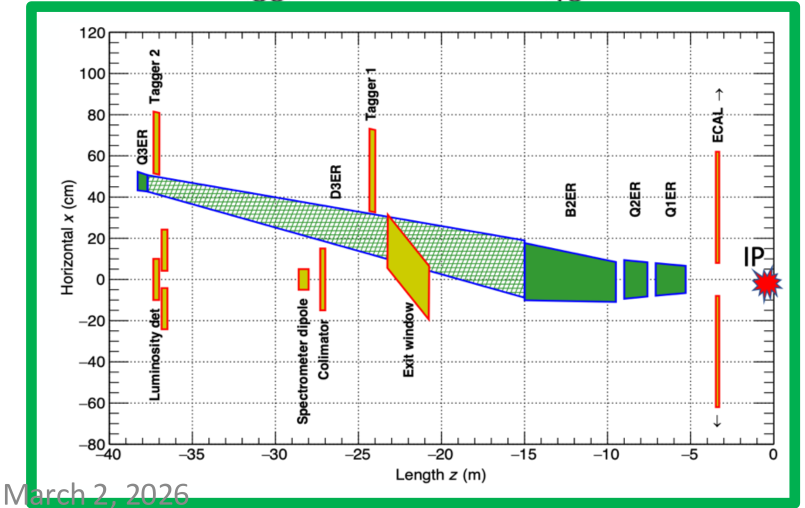
PID:
- hpDIRC
- pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:
- **Imaging** Si+PbW Barrel EMCal
- PbWO4 EMCal in backward cal
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

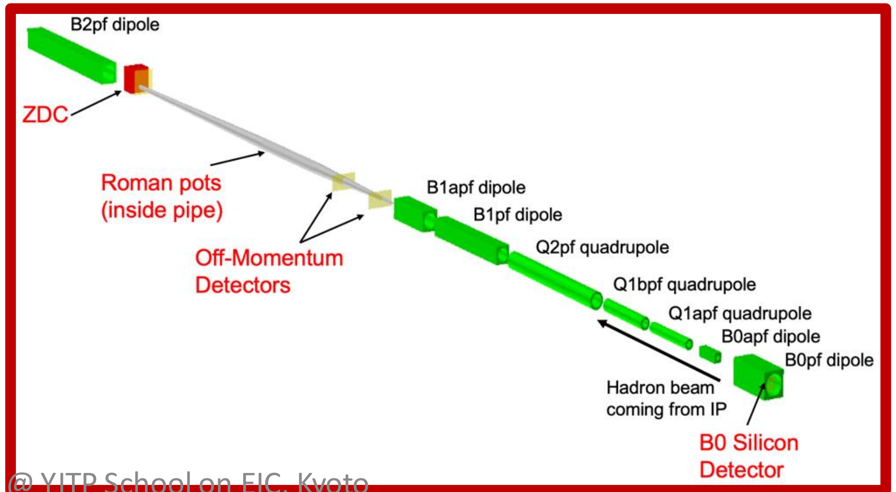
Overlap in technology R&D with LHC-future detectors

Reference Detector – Backward/Forward Detectors

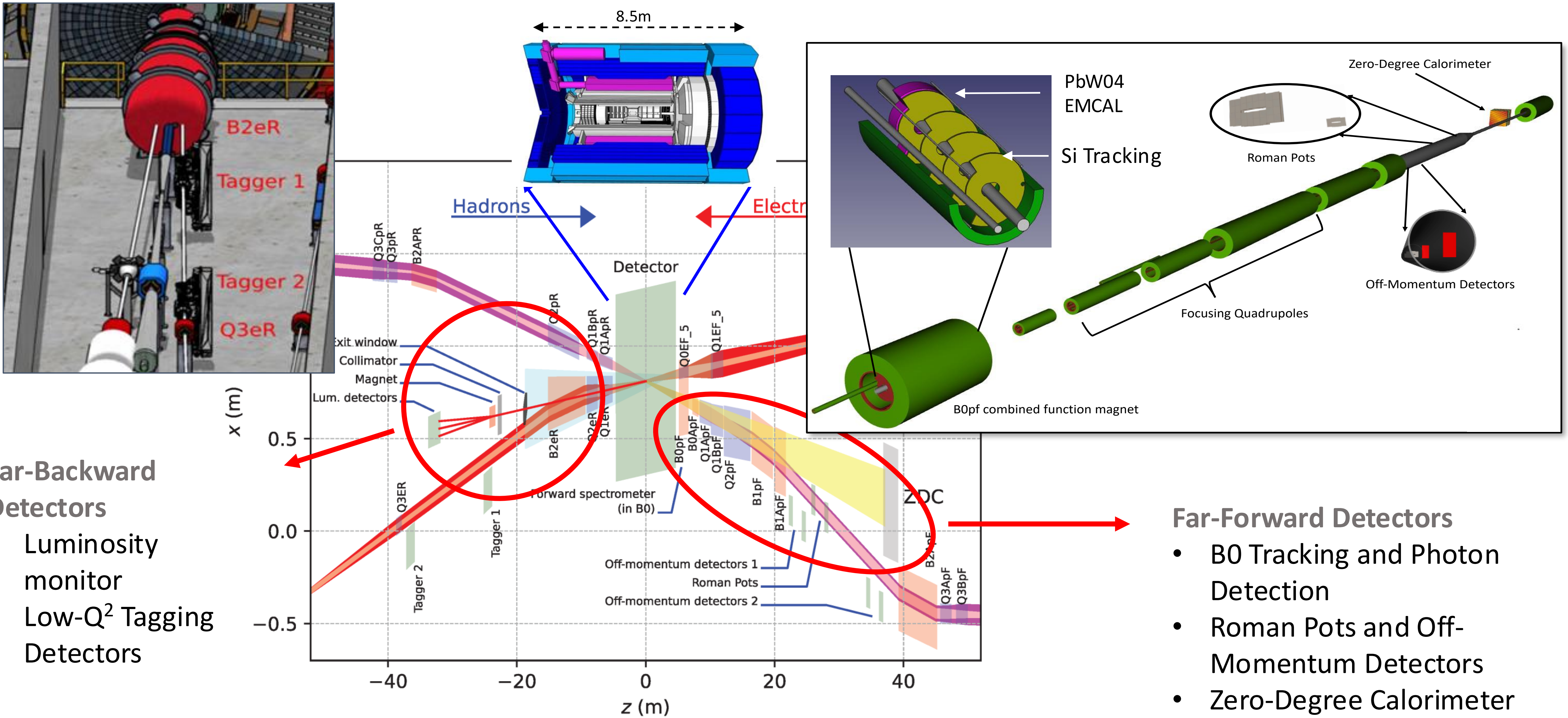




Extensive integration of forward and backward detector elements into the accelerator lattice



Far-Forward and Far-Backward Detectors



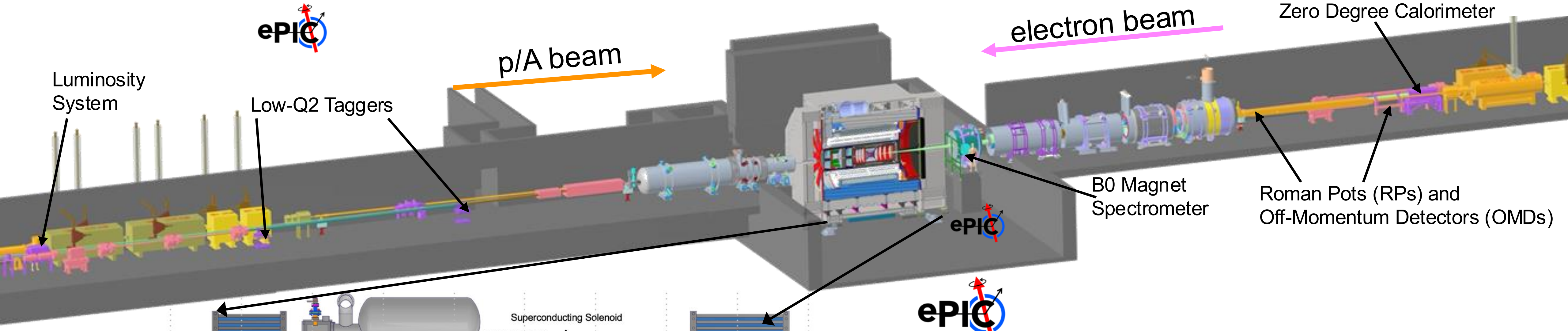
Far-Backward Detectors

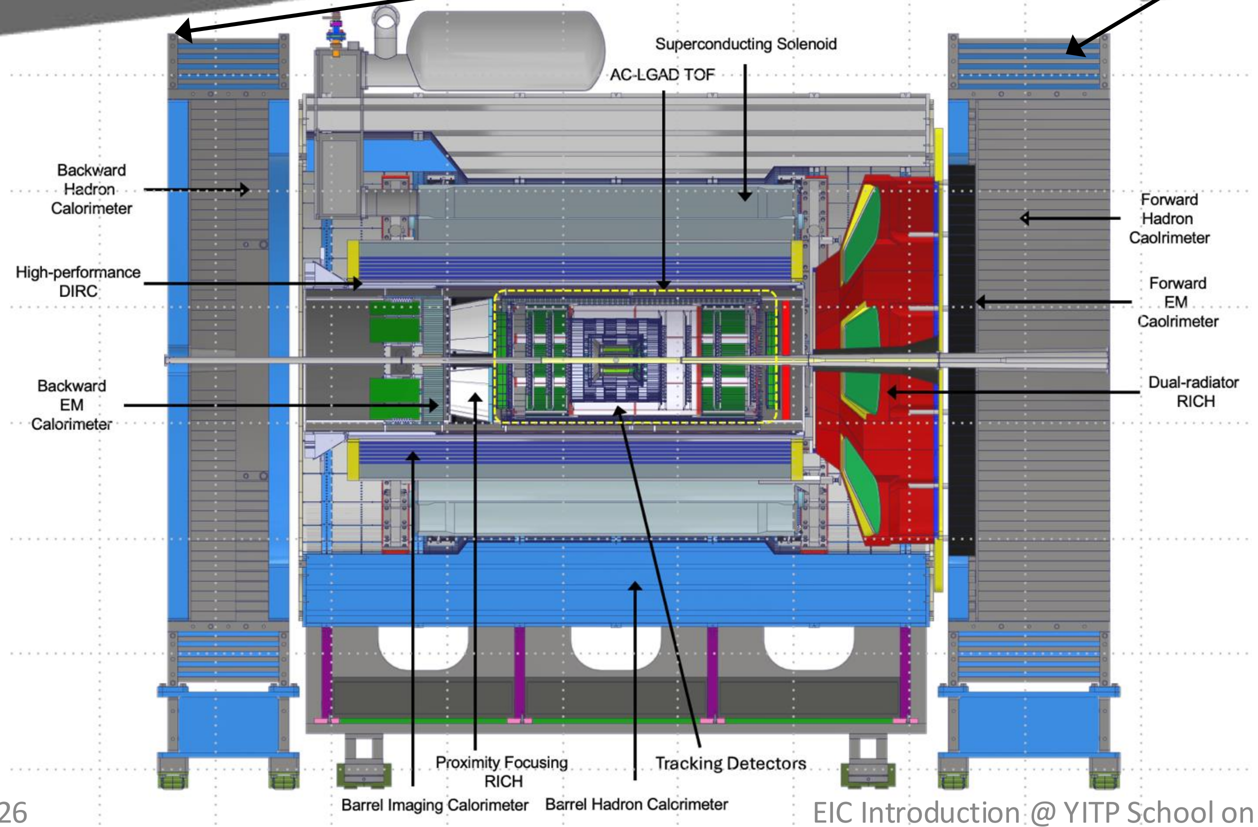
- Luminosity monitor
- Low-Q^2 Tagging Detectors

Far-Forward Detectors

- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors
- Zero-Degree Calorimeter

ePIC – The EIC State-of-the-Art General-Purpose Detector





ePIC

26 subsystems over ± 40 m

to measure particle momenta, energy and particle type

- 3 electromagnetic calorimeters
- 3 hadronic calorimeters
- Silicon and Multi-pattern gas detectors
- 3 RICH detector + time-of-flight
- 7 Auxiliary detectors (Si + HCal + ECals)
- electron and hadron polarimetry

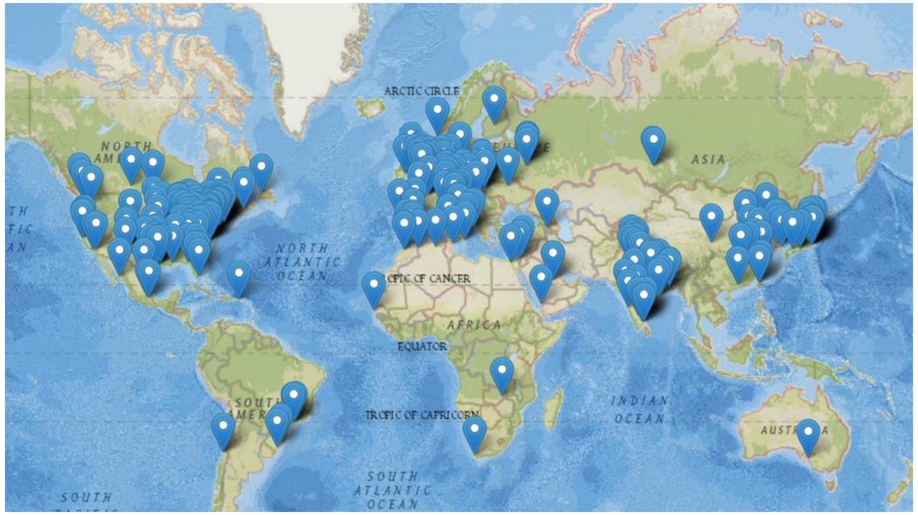
Integration, Installation and Infrastructure

Non-Beam Commissioning

Highest scientific flexibility

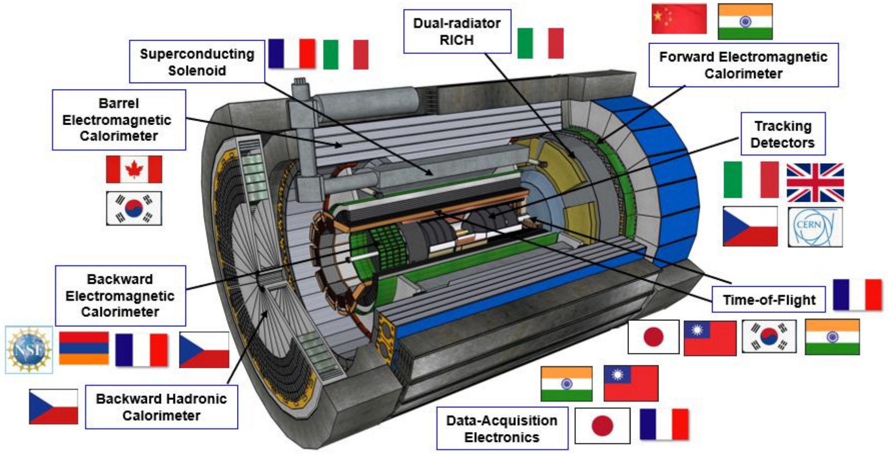
→ fully streaming readout electronics and data acquisition
→ integration AI/ML capabilities from the start

Attracting Worldwide Attention, Collaborators



The EIC design and construction has many scientific and technical challenges, creating opportunities for worldwide collaborators to become part of this exciting endeavor.

- **EIC U.S. Partners** (performing work and/or providing materials)
  - Brookhaven and Jefferson Lab among eight, total, national laboratories
  - 22 universities
- **EIC Collaborators** (developing experiments, contributing expertise)
  - EIC User Group: 1,558 members and increasing
  - 907 institutions worldwide representing 41 countries
  - 80+ U.S. universities



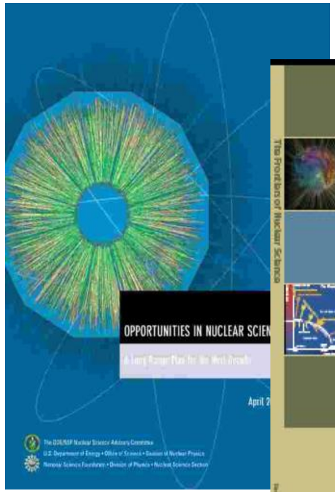
Department of Energy Lab Partners

Brookhaven National Laboratory | Jefferson Lab | Argonne National Laboratory | Berkeley Lab Lawrence Berkeley National Laboratory

Fermilab | Oak Ridge National Laboratory | Los Alamos National Laboratory Est. 1943 | SLAC National Accelerator Laboratory

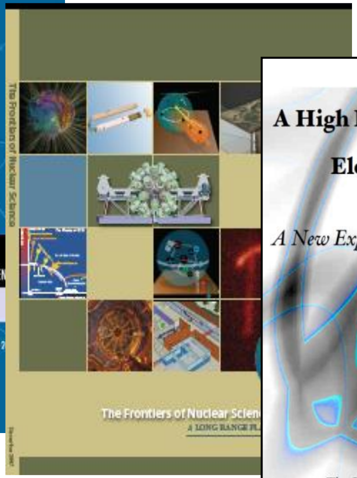
The Scientific Foundation for an EIC was Built Over Two Decades

2002



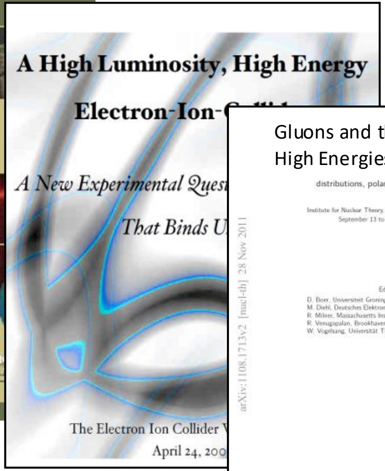
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007



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

2009

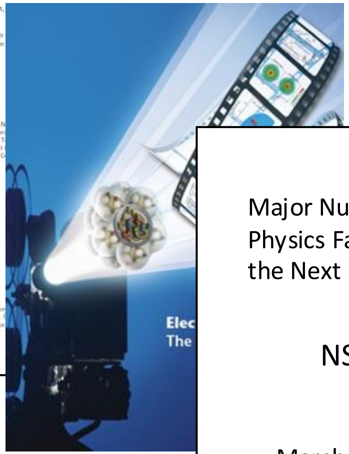


"..a new dedicated facility will be essential for answering some of the most central questions."

2010

Gluons and the Quark Sea at High Energies

2012



"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.

2013

Major Nuclear Physics Facilities for the Next Decade

NSAC

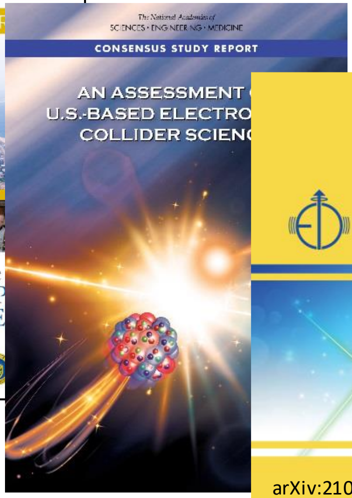
March 14, 20

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

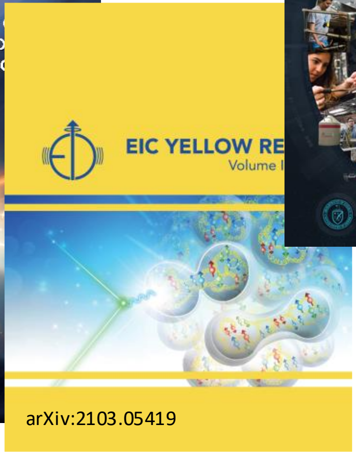
2015

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."

2018

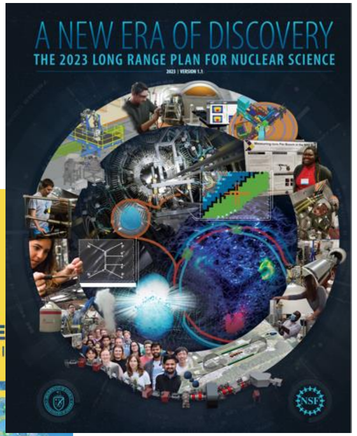


2021



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

2023



Build expeditiously

Summary & Outlook

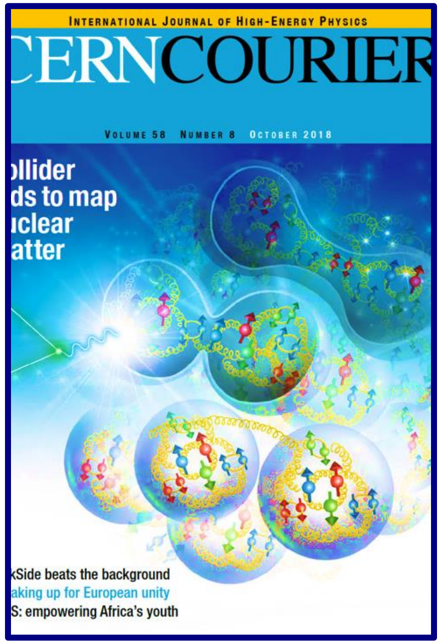
- Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, funded by the DOE will be built in this decade and operate in 2030's.
  - Will address some of the most profound question yet unanswered in the Standard Model of Strong Interactions (and beyond)
- Up to two hermetic 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 : early collisions around 2034/5**
  - **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!

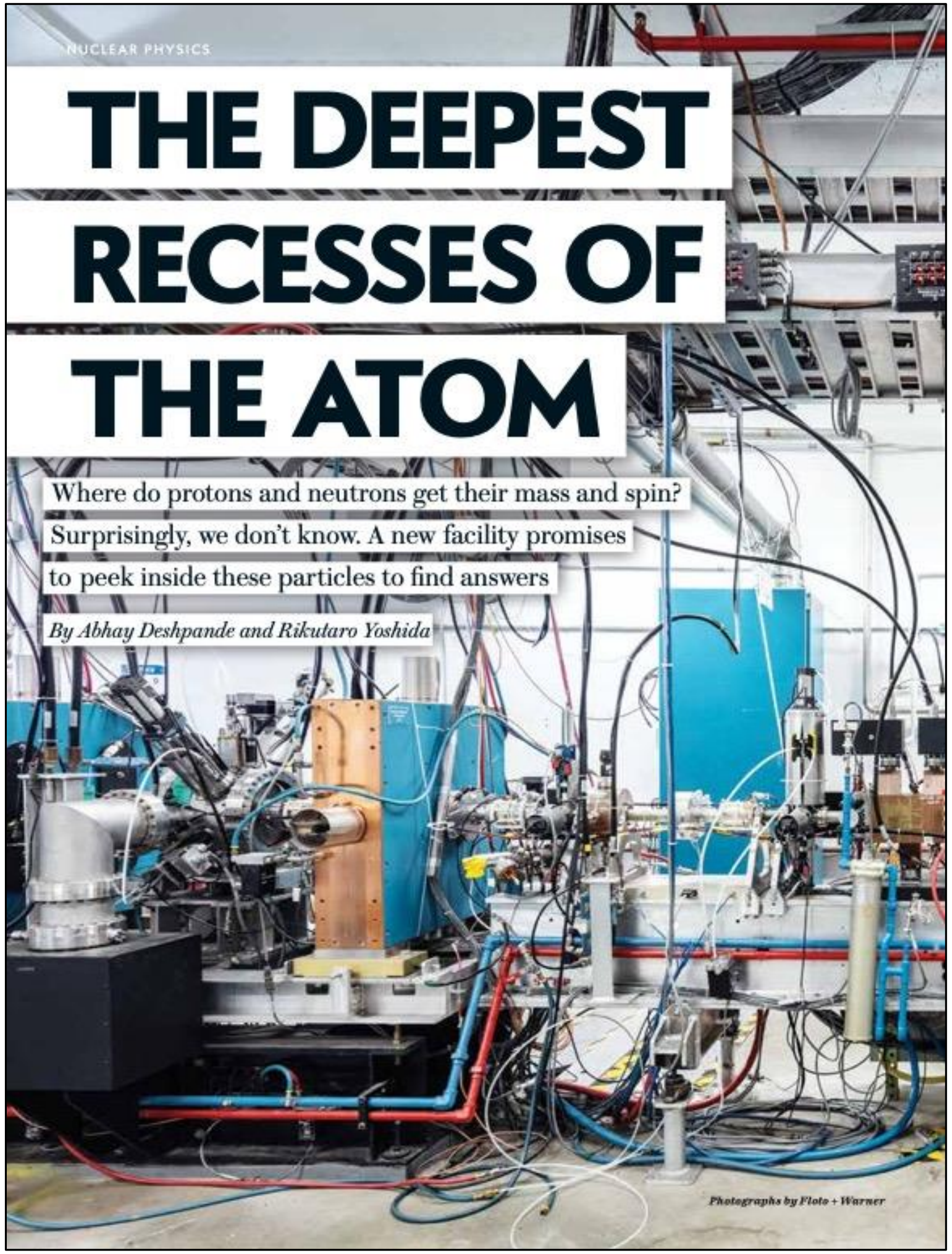

"New directions in science are launched by new tools much more often than by new concepts."
Freeman Dyson

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



E. Aschenauer
R. Ent
October 2018

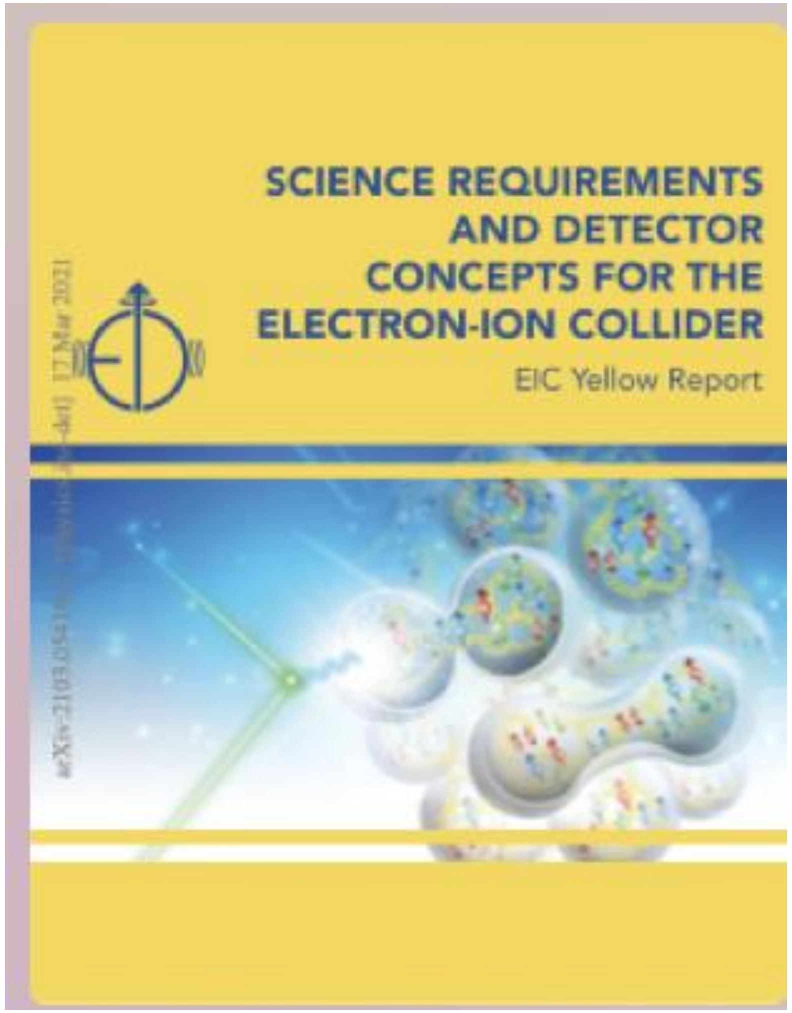
A. Deshpande
& R. Yoshida
June 2019
Translated in to multiple languages



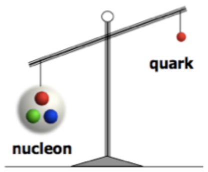
December 2019 – March 2021
EICUG Yellow Report

- Led by EICUG Steering Committee, with R. Ent & T. Ullrich as point people for the effort, initiated a UG-wide effort towards a detailed detector design effort with a detailed document.

- Kick off meeting at MIT in December 2019 followed by 4 more meetings in 2020 all remote: Philadelphia, Pavia, Miami, Washington DC, Berkeley



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

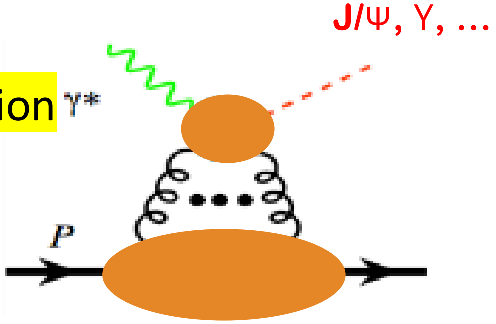
- Criticisms: not scale-invariant, decompositions: Lorentz invariant vs. rest frame
- Recent interest (workshops planned) to clarify how to determine the different contributions
- **Lattice QCD providing estimates**

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

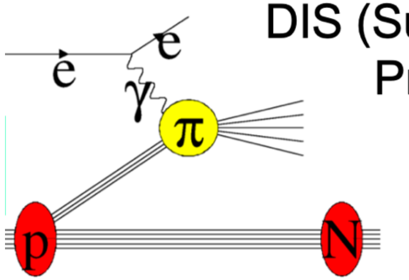
arXiv: 1710.09011

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

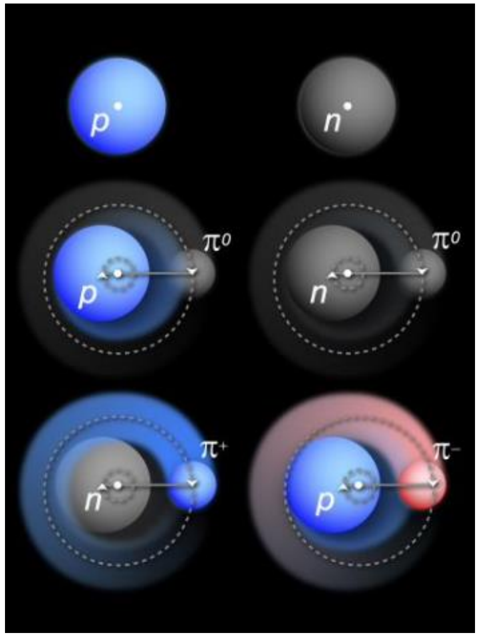
SoLID@JLab & EIC



DIS (Sullivan Process)



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

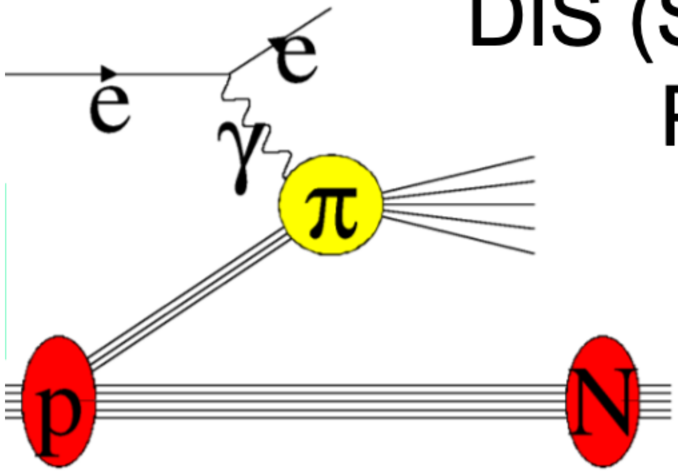


Pion/Kaon mass & PDFs

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**

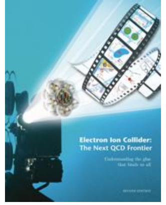


DIS (Sullivan Process)

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?

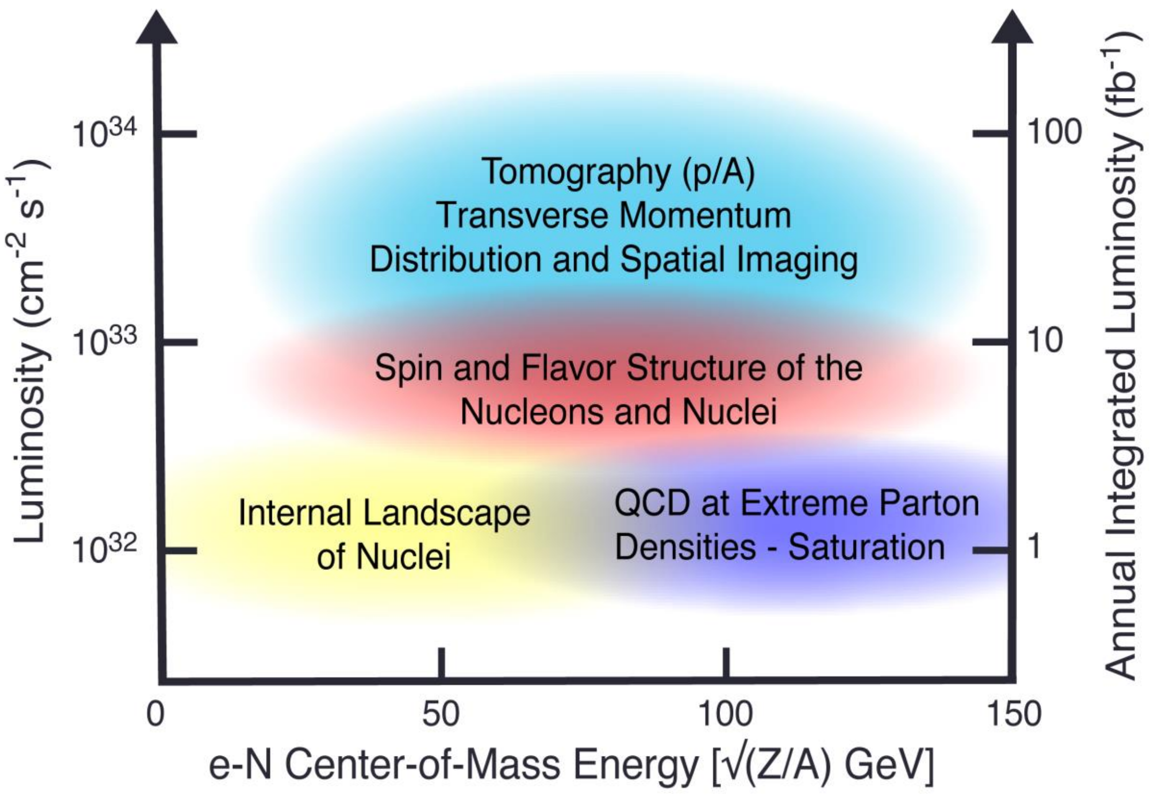
PDFs @ EIC : J> Arrington et al. J. of Physics G. 48 (2021) 075106
PDFs: P. C. Barry et al. PRL 127, 232001 (2021)

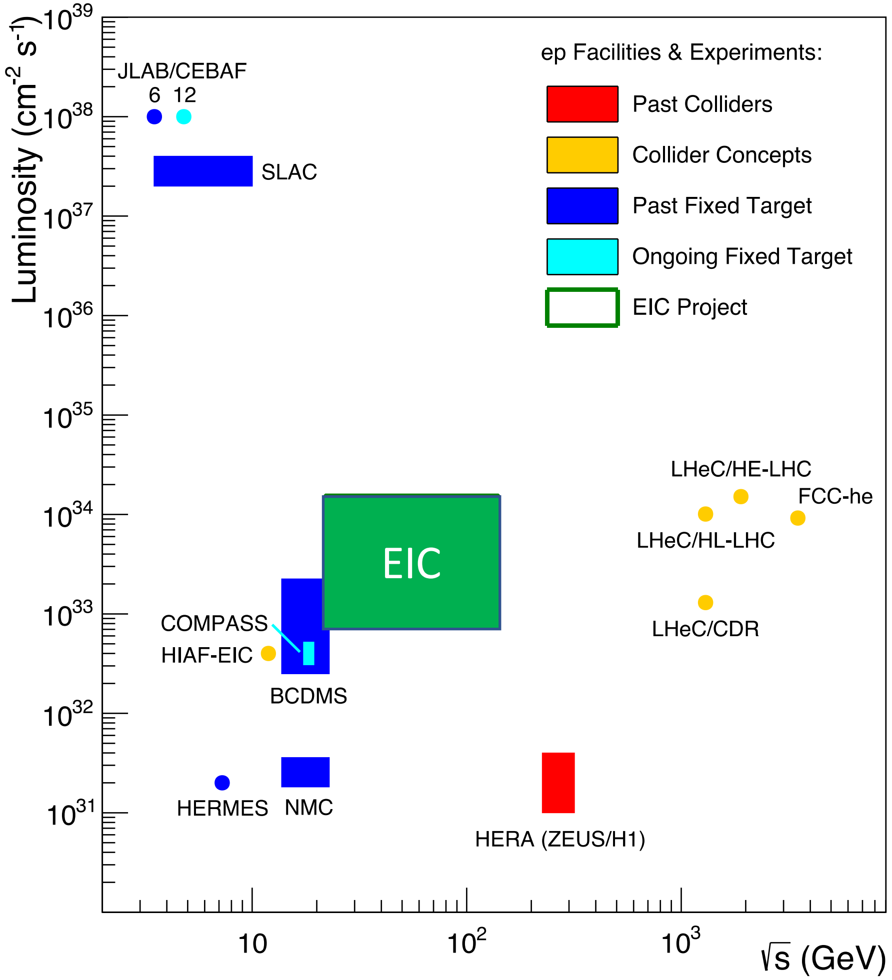


Make the Science Diagram more prominent?

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.