QCD in Collisions with Polarized Beams

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Annual Hua-Da School on QCD: EIC physics
China Central Normal University (CCNU), Wuhan, China, May 23 – June 3, 2016

The plan for my eight lectures

- The Goal:

  To understand QCD and the strong interaction dynamics, and to explore hadron structure and its properties by studying high energy collisions with polarized beams

- The Plan (approximately):

See also talks by Yuan and Xiao

Electron-Ion Collider

Connecting QCD quarks and gluons to observed hadrons and leptons

Fundamentals of QCD factorization and evolution

Two lectures

Hard scattering processes with longitudinally polarized beams

Three lectures

Hard scattering processes with transversely polarized beams

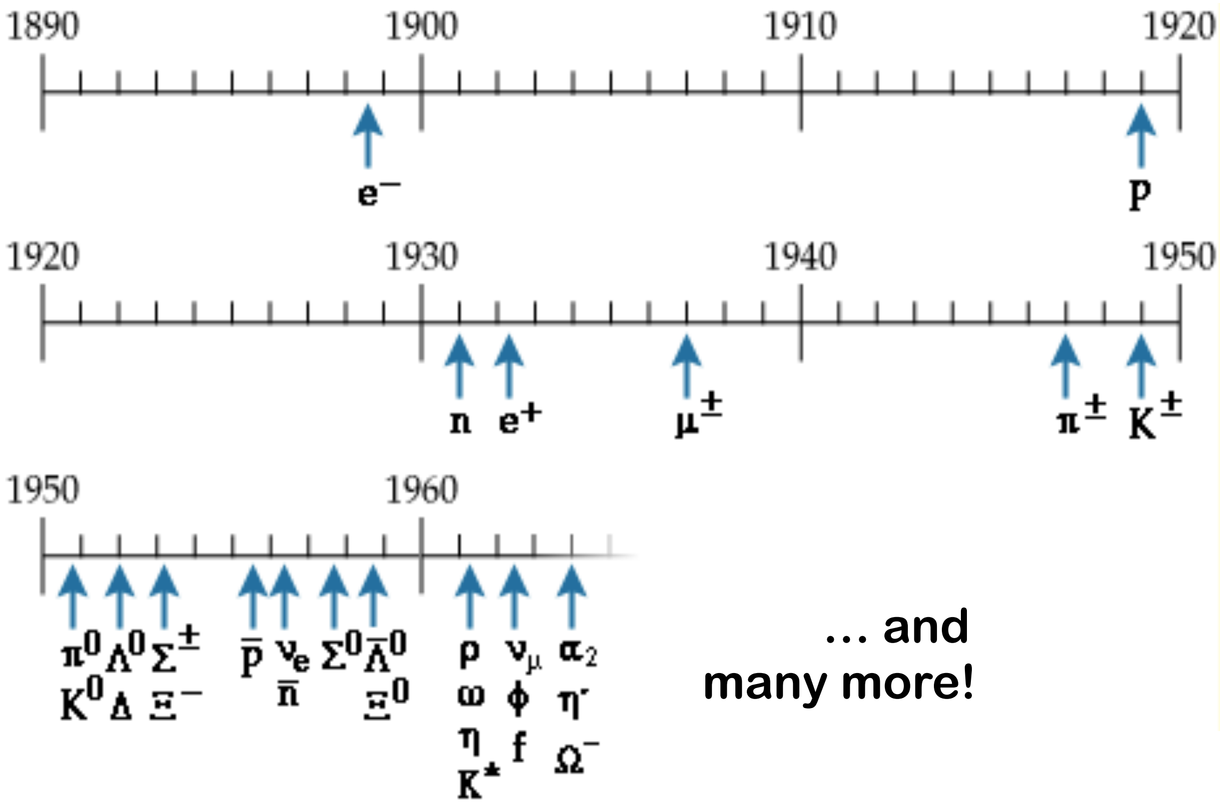
Three lectures

Why we need Electron-Ion Collider?

New particles, new ideas, and
new theories,
along with new facilities

New particles, new ideas, and new theories

- Early proliferation of new particles – “particle explosion”:

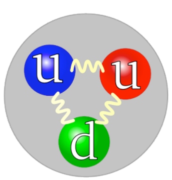


… and
many more!

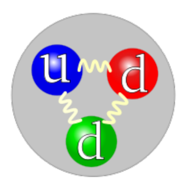
→ Quark Model

Nobel Prize, 1969

Proton



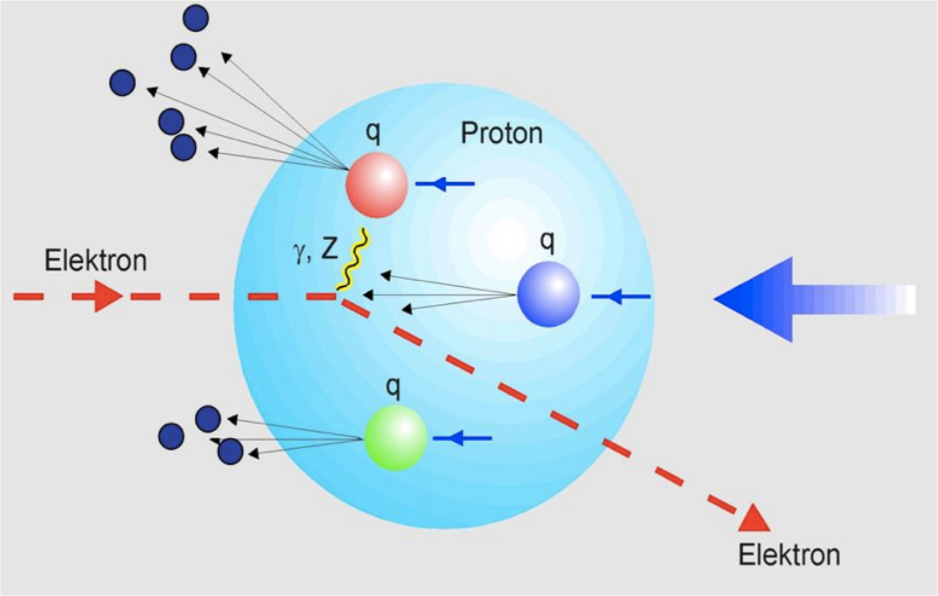
Neutron



Deep inelastic scattering (DIS)

❑ Modern Rutherford experiment – DIS (SLAC 1968)

$$e(p) + h(P) \to e'(p') + X$$



✧ **Localized probe:**

$$Q^2 = -(p - p')^2 \gg 1 \text{ fm}^{-2}$$

$$\Rightarrow \quad \frac{1}{Q} \ll 1 \text{ fm}$$

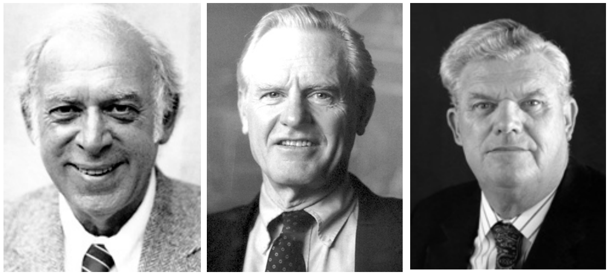
✧ **Two variables:**

$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$x_B = \frac{Q^2}{2m_N \nu}$$

$$\nu = E - E'$$

→ **Discovery of spin ½ quarks, and partonic structure!**



Nobel Prize, 1990

➡ **The birth of QCD (1973)**

– Quark Model + Yang-Mill gauge theory

Quantum Chromo-dynamics (QCD)

= A quantum field theory of quarks and gluons =

- **Fields:**

$\psi_i^f(x)$ **Quark fields: spin-½ Dirac fermion (like electron)**

Color triplet: $i = 1, 2, 3 = N_c$

Flavor: $f = u, d, s, c, b, t$

$A_{\mu,a}(x)$ **Gluon fields: spin-1 vector field (like photon)**

Color octet: $a = 1, 2, ..., 8 = N_c^2 - 1$

- **QCD Lagrangian density:**

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij}\right] \psi_j^f$$
$$-\frac{1}{4}\left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc}A_{\mu,b}A_{\nu,c}\right]^2$$
$$+ \text{ gauge fixing} + \text{ghost terms}$$

- **QED – force to hold atoms together:**

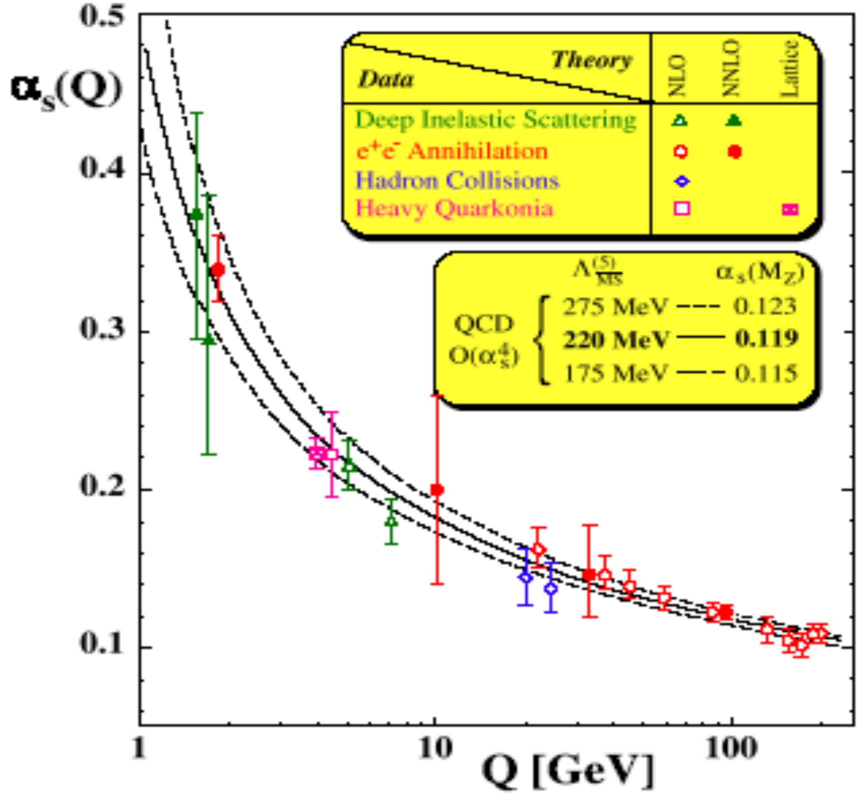
$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f\right] \psi^f - \frac{1}{4}\left[\partial_\mu A_\nu - \partial_\nu A_\mu\right]^2$$

- **QCD Color confinement:**

Gluons are dark, No free quarks or gluons ever been detected!

QCD Asymptotic Freedom

- **Interaction strength:** $\alpha_s(\mu_2) = \dfrac{\alpha_s(\mu_1)}{1 - \frac{\beta_1}{4\pi}\alpha_s(\mu_1)\ln\left(\frac{\mu_2^2}{\mu_1^2}\right)} \equiv \dfrac{4\pi}{-\beta_1 \ln\left(\frac{\mu_2^2}{\Lambda_{\rm QCD}^2}\right)}$



μ_2 and μ_1 not independent

Asymptotic Freedom ⇔ antiscreening

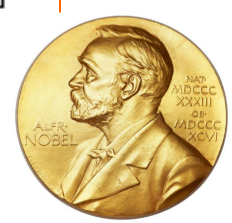
$$\text{QCD:}\ \frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0$$

Compare

$$\text{QED:}\ \frac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0$$

D.Gross, F.Willczek, Phys.Rev.Lett 30, (1973)
H.Politzer, Phys.Rev.Lett. 30, (1973)

→ **Discovery of QCD Asymptotic Freedom**

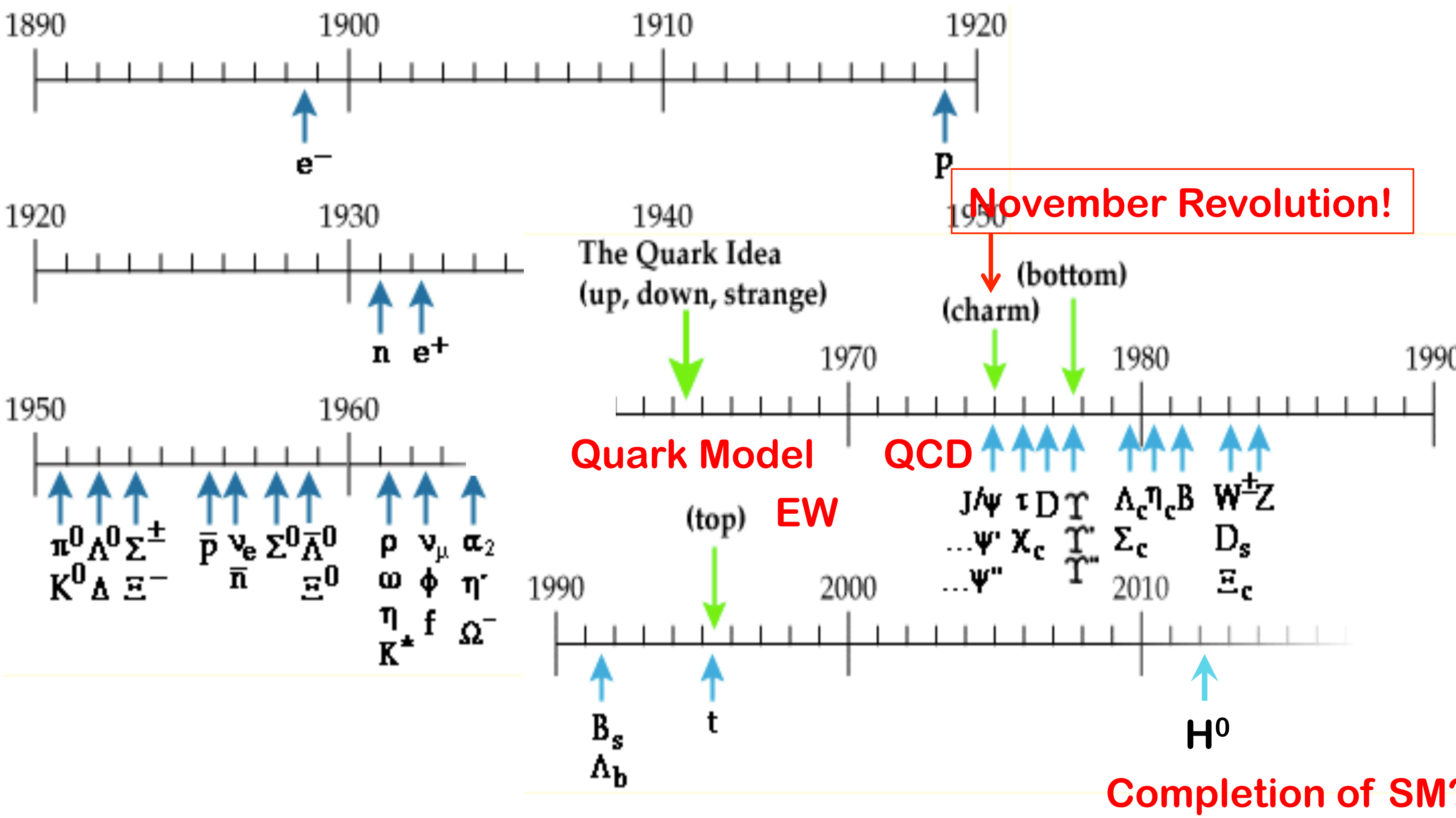


➡ **Collider phenomenology**
– *Controllable perturbative QCD calculations*

Nobel Prize, 2004

New particles, new ideas, and new theories

- Proliferation of new particles – “November Revolution”:



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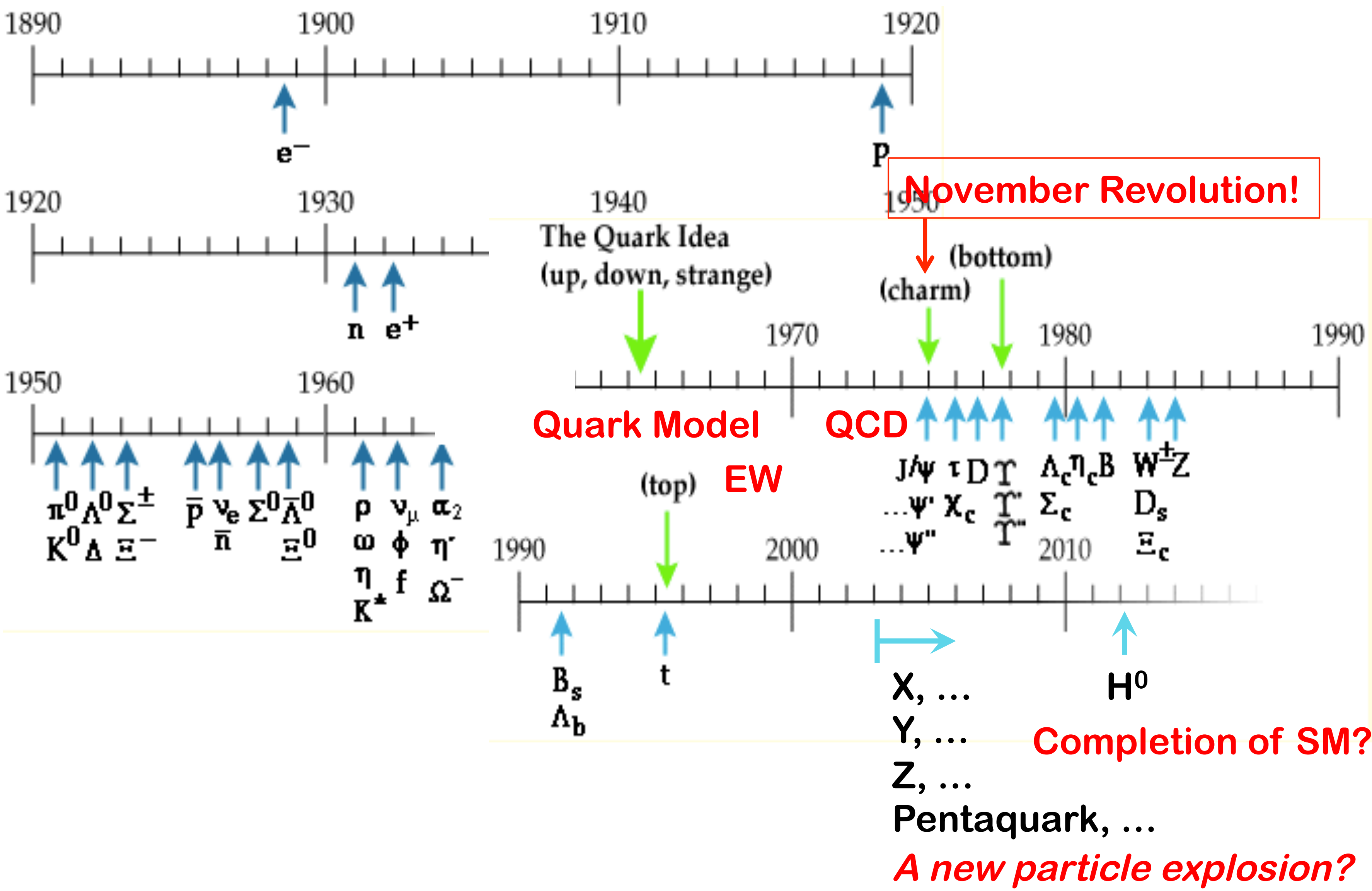
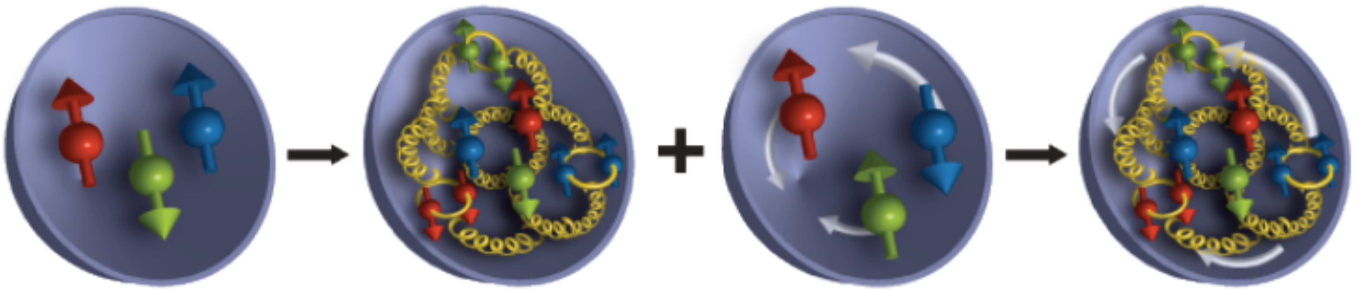


QCD and hadron internal structure

❑ Our understanding of the proton evolves



1970s　　1980s/2000s　　Now

Hadron is a strongly interacting, relativistic bound state of quarks and gluons

❑ QCD bound states:

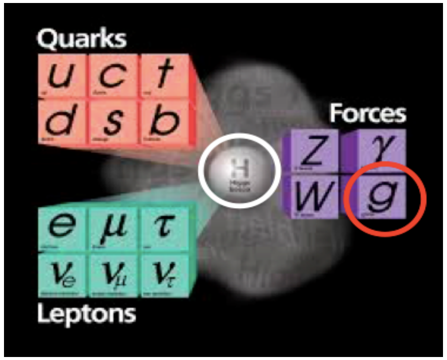
- ✧ Neither quarks nor gluons appear in isolation!
- ✧ Understanding such systems completely is still beyond the capability of the best minds in the world

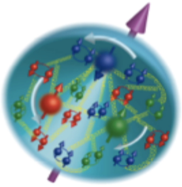
❑ The great intellectual challenge:

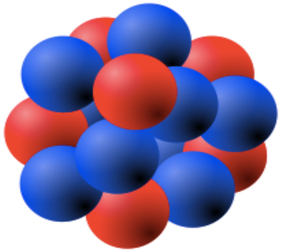
Probe nucleon structure without "seeing" quarks and gluons?

What holds hadron together – the glue?

- **Understanding the glue that binds us all – the Next QCD Frontier!**

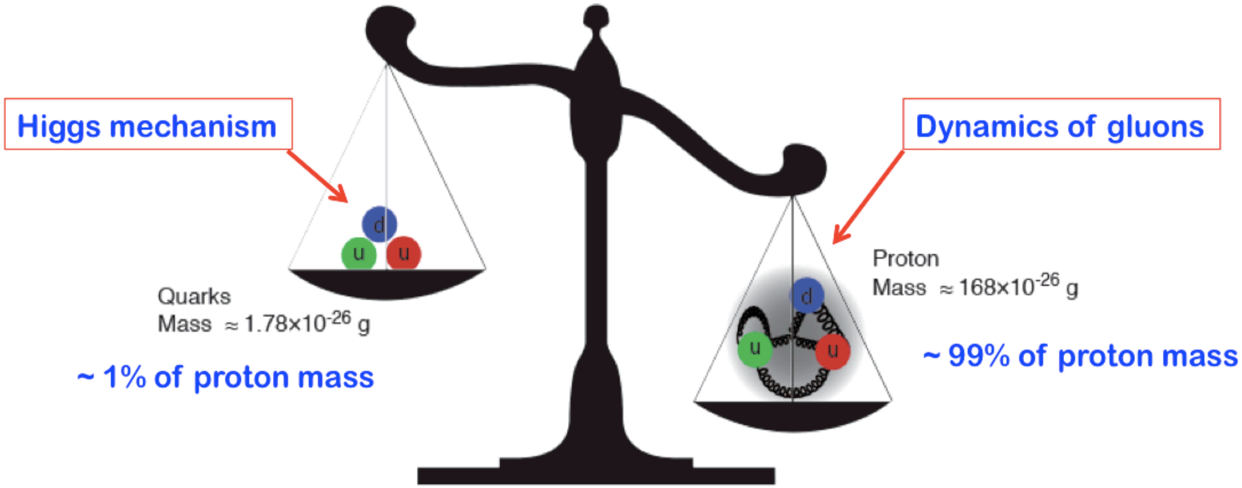


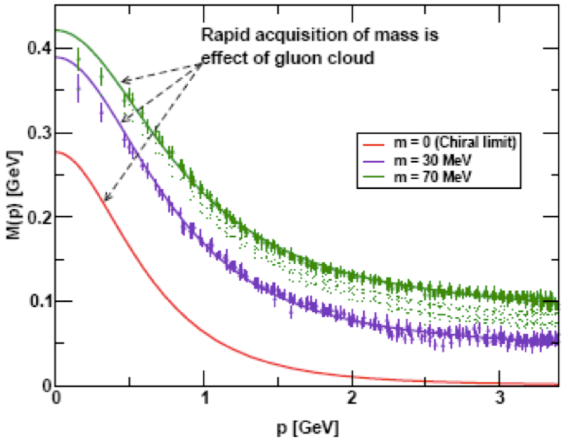




- **Gluons are wired particles!**
  - ✧ **Massless, yet, responsible for nearly all visible mass**

"Mass without mass!"

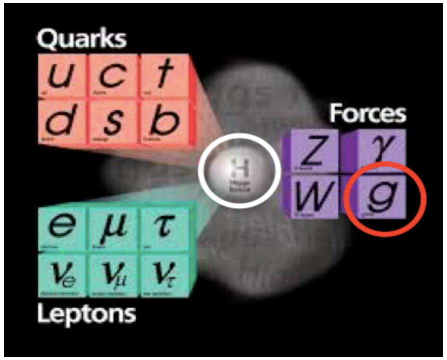


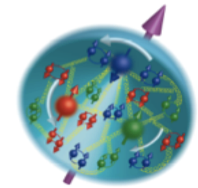


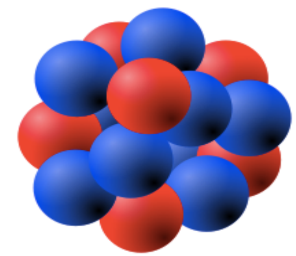
Bhagwat & Tandy/Roberts et al

What holds it together – the glue?

- ❑ Understanding the glue that binds us all – the Next QCD Frontier!







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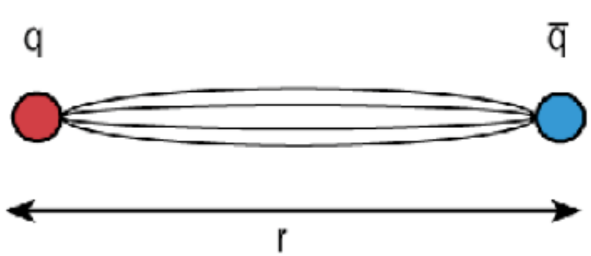
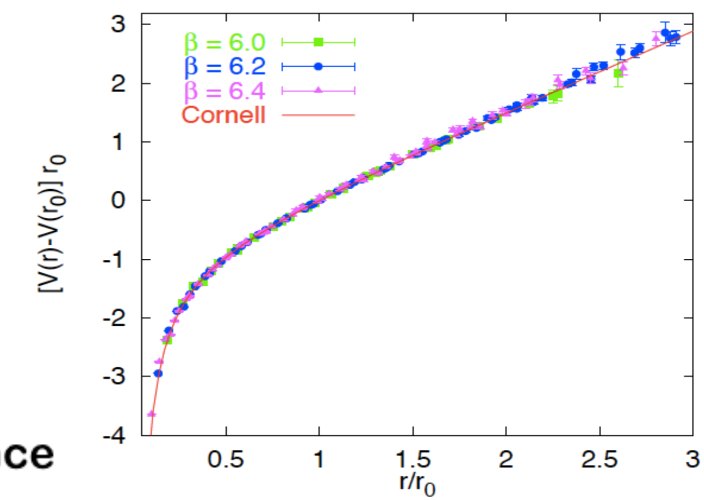
  - ✧ Carry color charge, responsible for color confinement and strong force

Force between a heavy quark pair



Heavy quarks experience a force of ~16 tons at ~1 Fermi (10^{-15} m) distance



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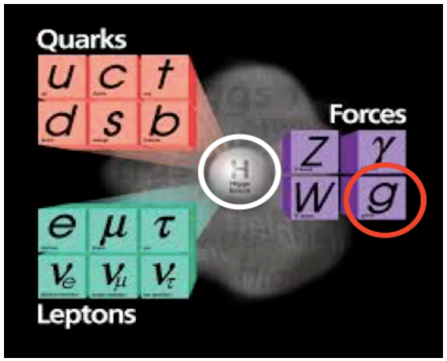

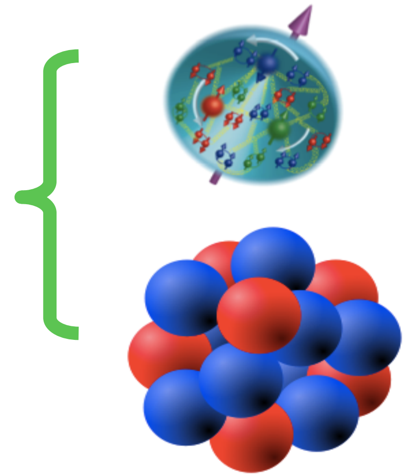

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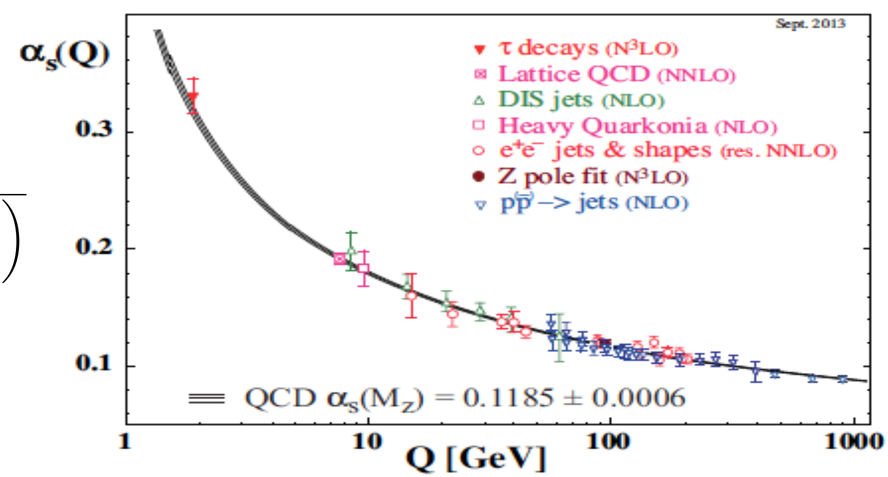
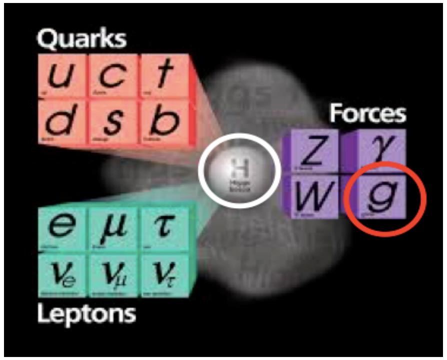
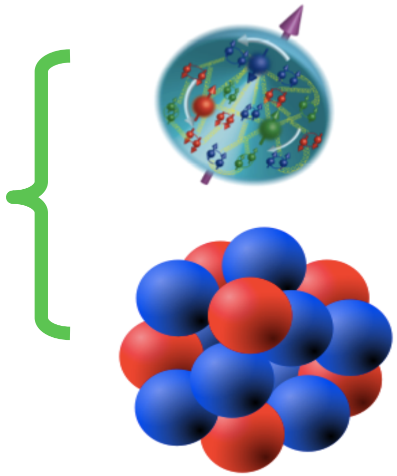


→ **QCD perturbation theory**

What holds it together – the glue?

- Understanding the glue that binds us all – the Next QCD Frontier!





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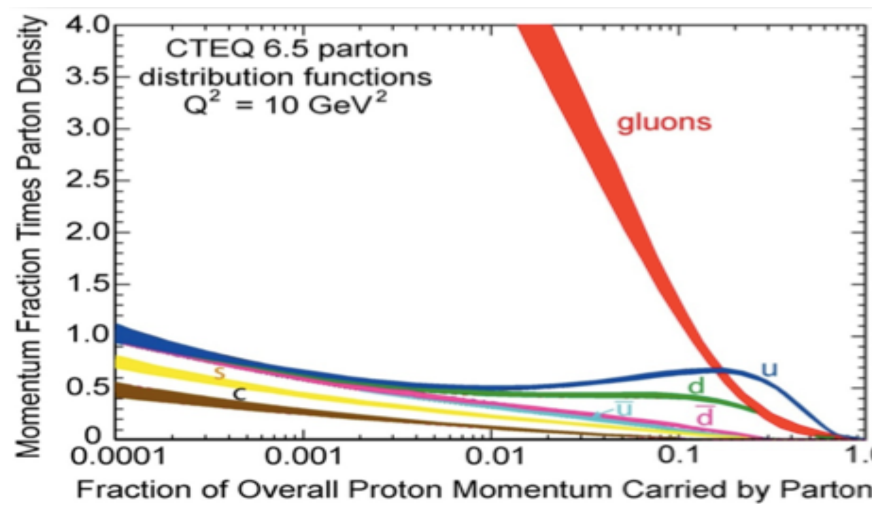
    but, also for asymptotic freedom,

    as well as the abundance of glue



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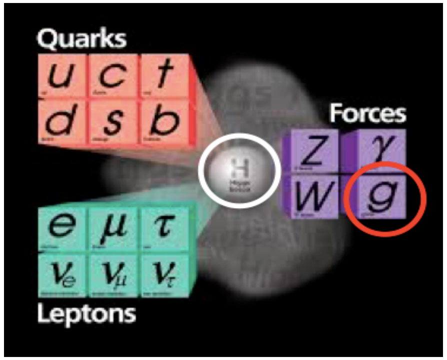
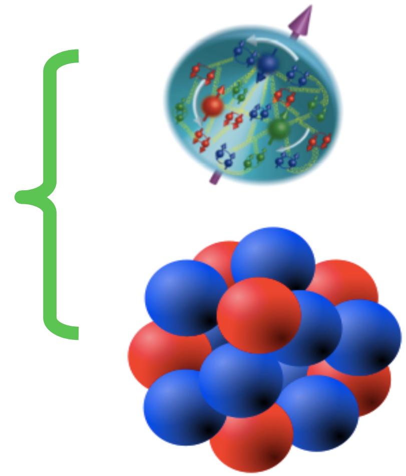
- Understanding the glue that binds us all – the Next QCD Frontier!





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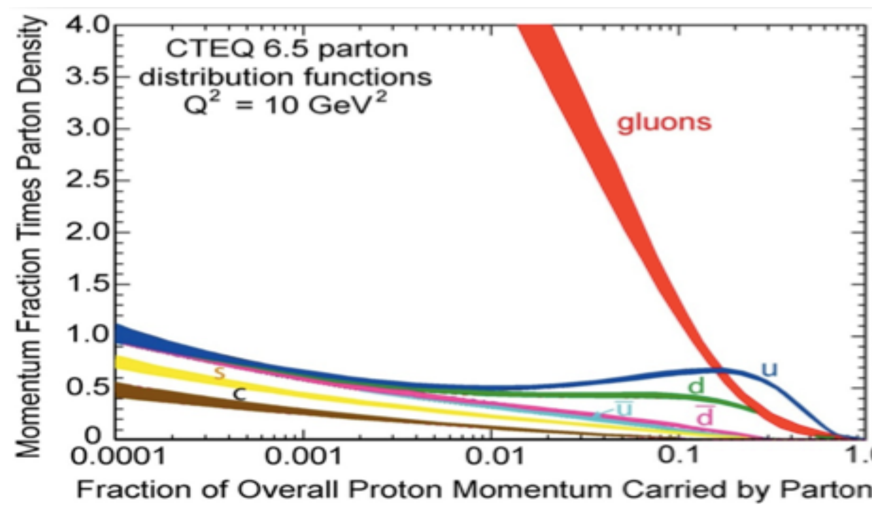


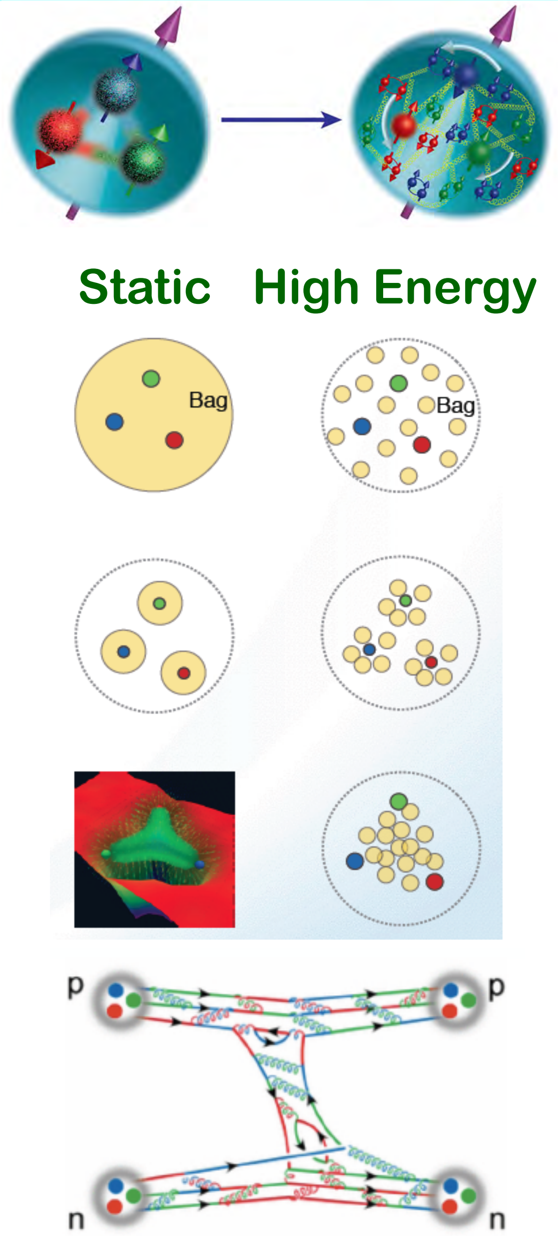
Without gluons, there would be no nucleons, no atomic nuclei… no visible world!

“Big” questions/puzzles about QCD, glue, …

- ❑ **How quarks and gluons are confined inside the hadrons – 3D structure?**
  - ✧ **Can we develop analytical tools to connect hadron structure and properties at low energy to their parton descriptions at high energy?!**

    Hadron mass, spin, confined parton motion, …
    Proton radius: EM charge, quarks, gluons, …
    Nuclear force from QCD, …

  - ✧ **Can lattice QCD and EFT help?**



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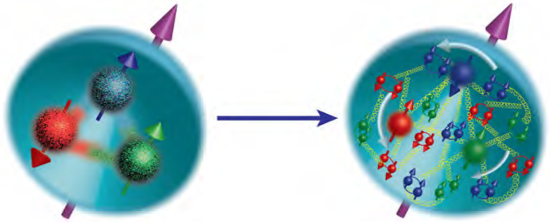
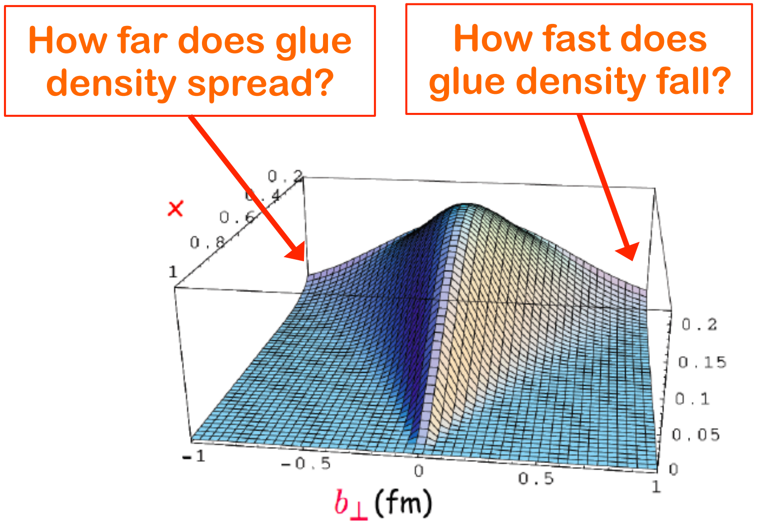
    Hadron mass, spin, confined parton motion, ...
    Proton radius: EM charge, quarks, gluons, ...
    Nuclear force from QCD, ...
  - ✧ Can lattice QCD and EFT help?
- How does the glue fill out hadron's inner space – 3D glue distribution?
  - ✧ Can we develop better probes to go beyond the current accuracy?!

    Glue distribution in proton, and in ions,
    Color confinement radius, ...
    Initial condition for HI collision,
    The physics and role of the momentum "x", ...



Glue tomography toward small-x

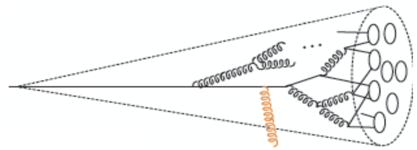


Only possible at EIC

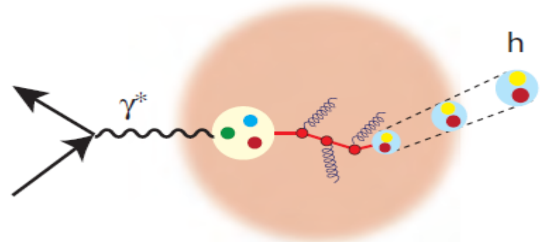
"Big" questions/puzzles about QCD, glue, …

- ❑ **How hadrons are emerged from the color charge(s)?**
  - ✧ Can we develop analytical tools to "see" the evolution of the color/jet and to predict the jet structure and the emergence of hadrons?!

    Control of the partonic kinematics?
    Hadronization mechanism?



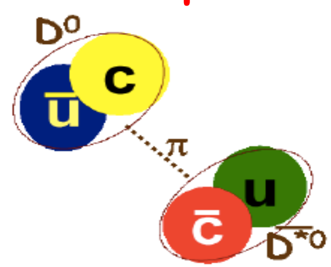
Jet structure



Nucleus as a "vertex detector" at a femtometer scale

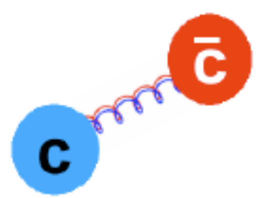
- ❑ **How to understand the family of hadrons?**
  - ✧ Can we see gluonic excitations in hadron spectrum?
  - ✧ Can we understand the newly observed hadronic particles, XYZ, …?
  - ✧ XYZ particles at future ep + eA, …

A new particle explosion?



$D^0 - \overline{D}^{*0}$ "molecule"

diquark-diantiquark



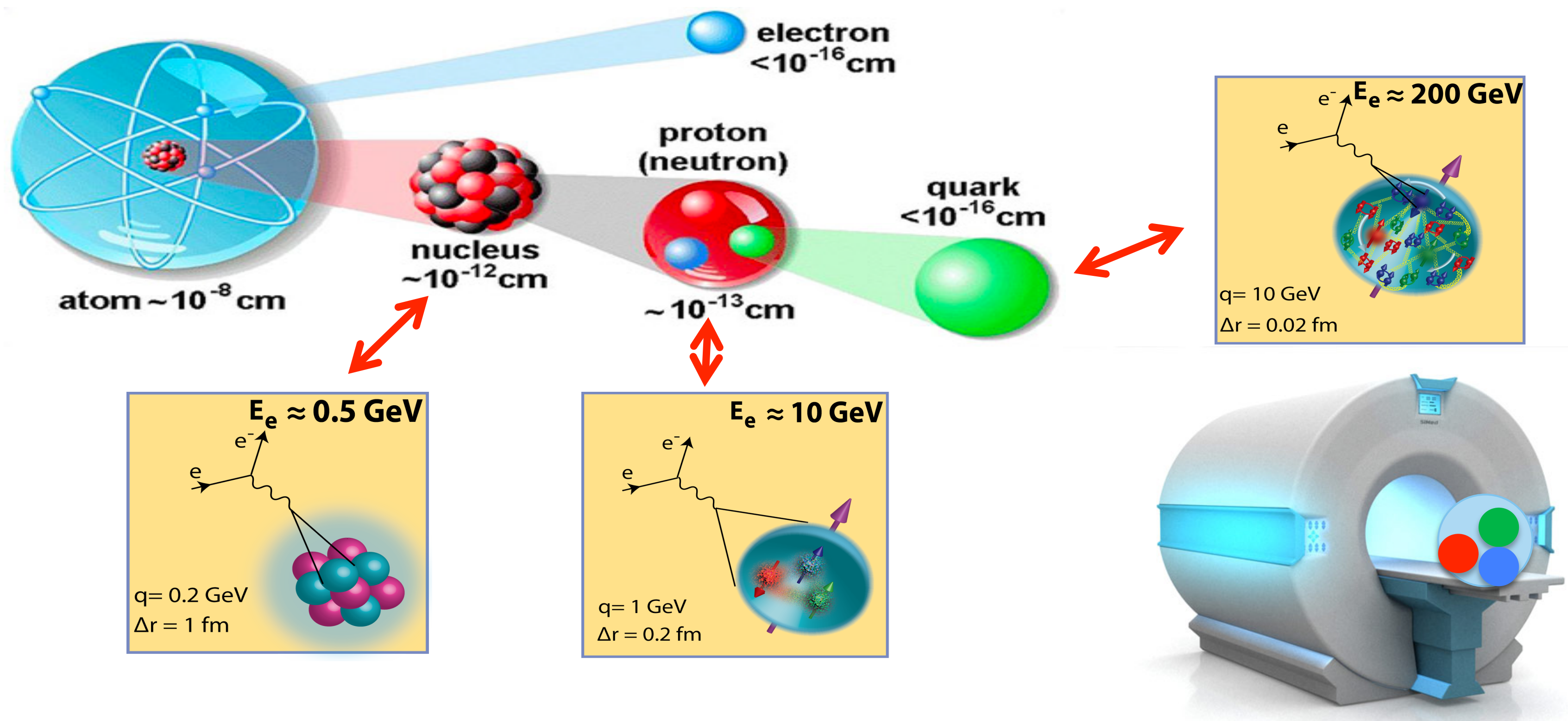
$q\bar{q}$-gluon"hybrid"

Pentaquarks?

We need EIC to answer these questions!

Electron-Ion Collider (EIC)

- A giant "Microscope" – "see" quarks and gluons by breaking the hadron



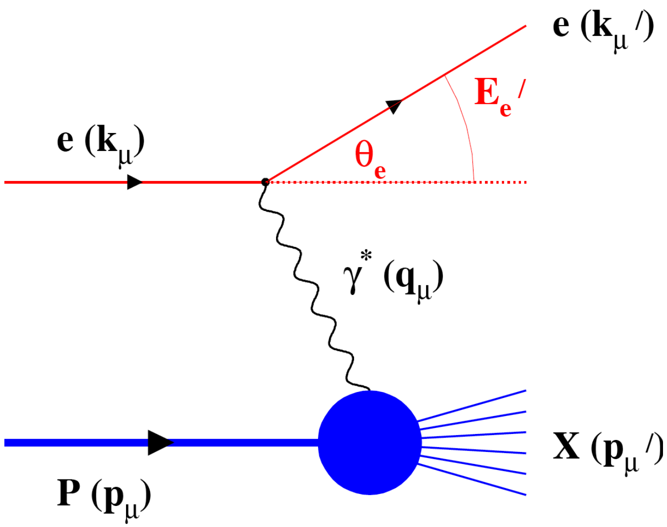
- A sharpest "CT" – "imagine" quark/gluon without breaking the hadron
  – "cat-scan" the nucleon and nuclei with better than 1/10 fm resolution
- Why now?

  Exp – advances in luminosity, energy reach, detection capability, …

  Thy – breakthrough in factorization – "see" confined quarks and gluons, …

Many complementary probes at one facility

- Lepton-hadron facility:



Q^2 → Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

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

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

Detect every things including scattered proton/nucleus (or its fragments)

EIC: the World Wide Interest

	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [cm^{-2} s^{-1}]	2×10^{31}	10^{33}	10^{33-34}	10^{33-34}	$10^{32-33} \rightarrow 10^{35}$	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2022	Post-12 GeV	2019 → 2030	upgrade to FAIR

The past (HERA@DESY) — **Possible future** (LHeC@CERN, eRHIC@BNL, JLEIC@JLab, HIAF@CAS, ENC@GSI)

EIC: the World Wide Interest

	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
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ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
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High Energy (LHeC@CERN) — Medium Energy (eRHIC@BNL, JLEIC@JLab) — Low Energy (HIAF@CAS, ENC@GSI)

U.S. - based Electron-Ion Collider

- ❑ **NSAC 2007 Long-Range Plan:**

  "An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**."

- ❑ **NSAC Facilities Subcommittee (2013):**

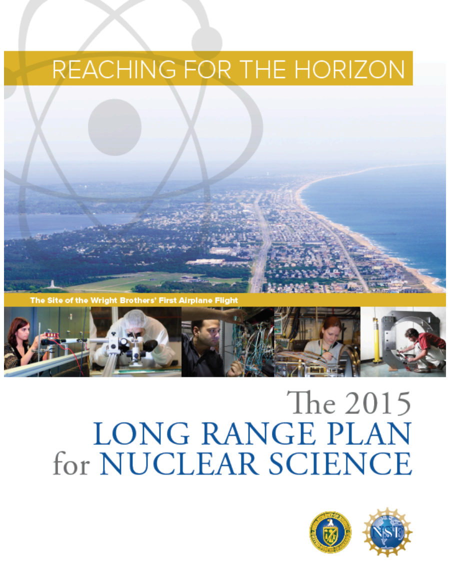
  "The Subcommittee ranks an EIC as **Absolutely Central** in its ability to contribute to world-leading science in the next decade."

- ❑ **NSAC 2015 Long-Range Plan:**

  "We recommend **a high-energy high-luminosity polarized EIC** as **the highest priority for new facility construction following the completion of FRIB.**"

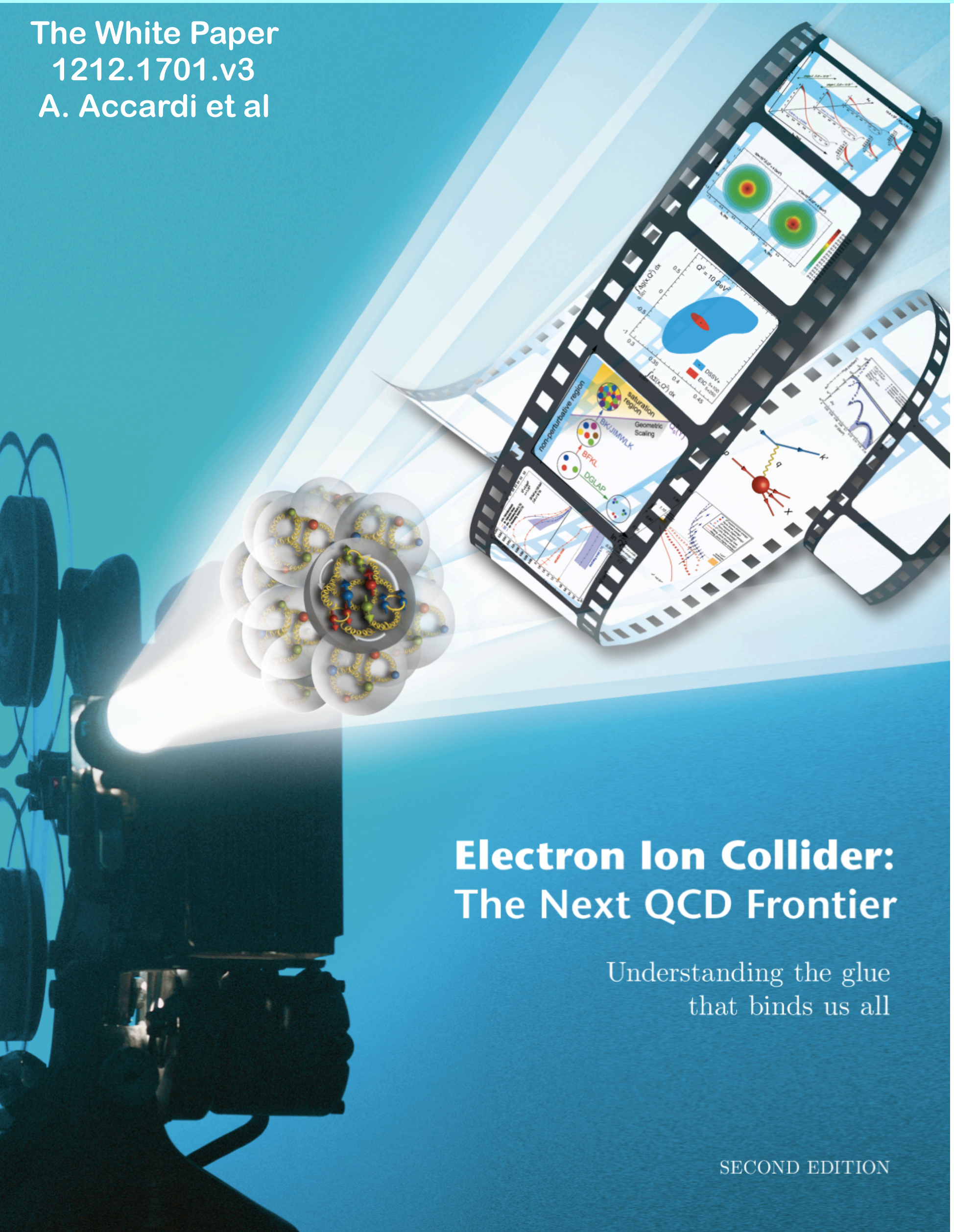
- ❑ **EIC User Group Meetings:**

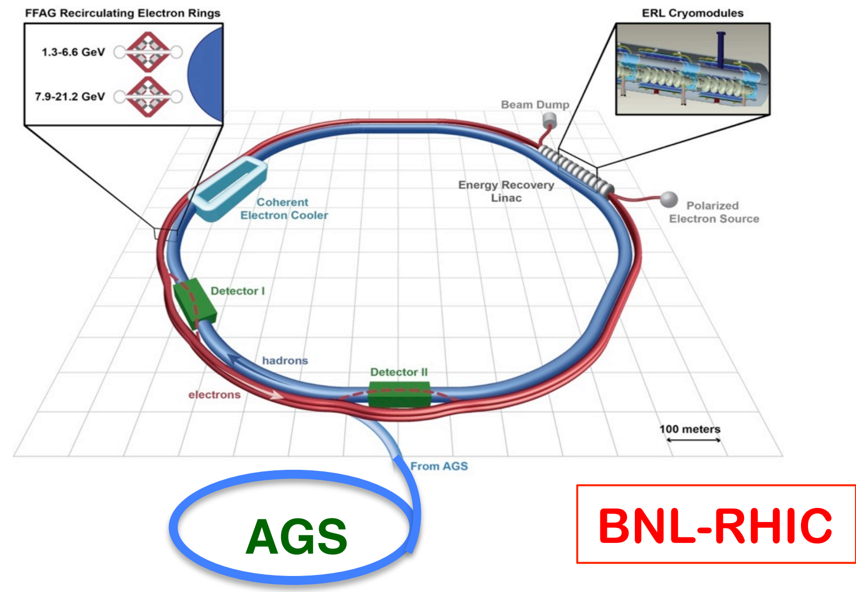
  Stony Brook University, NY – June 24-27, 2014
  UC at Berkeley, CA – January 6-9, 2016
  Argonne National Lab, IL – July 7-10, 2016

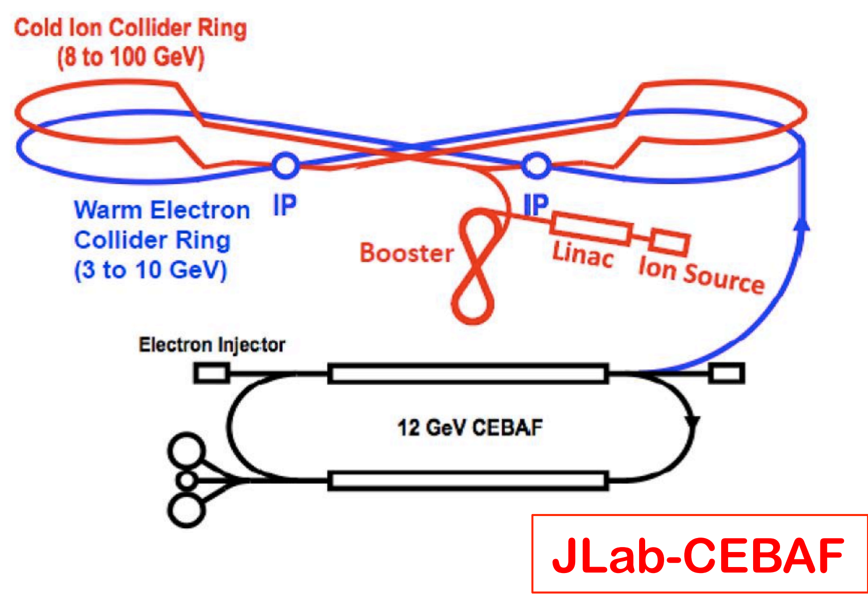


US EIC – two options of realization

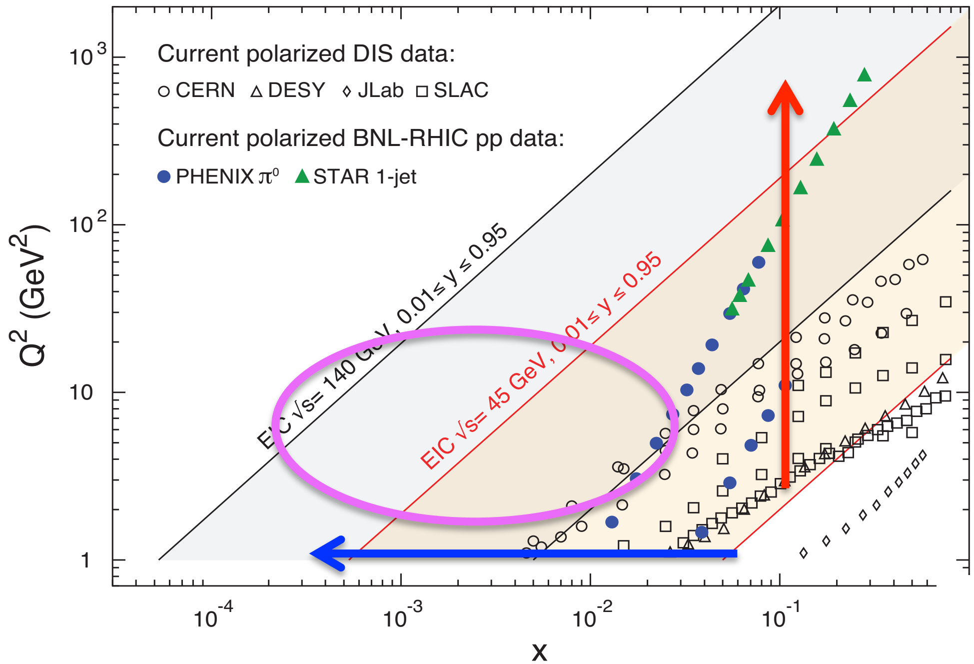
The White Paper
1212.1701.v3
A. Accardi et al







US EIC – Kinematic reach & properties

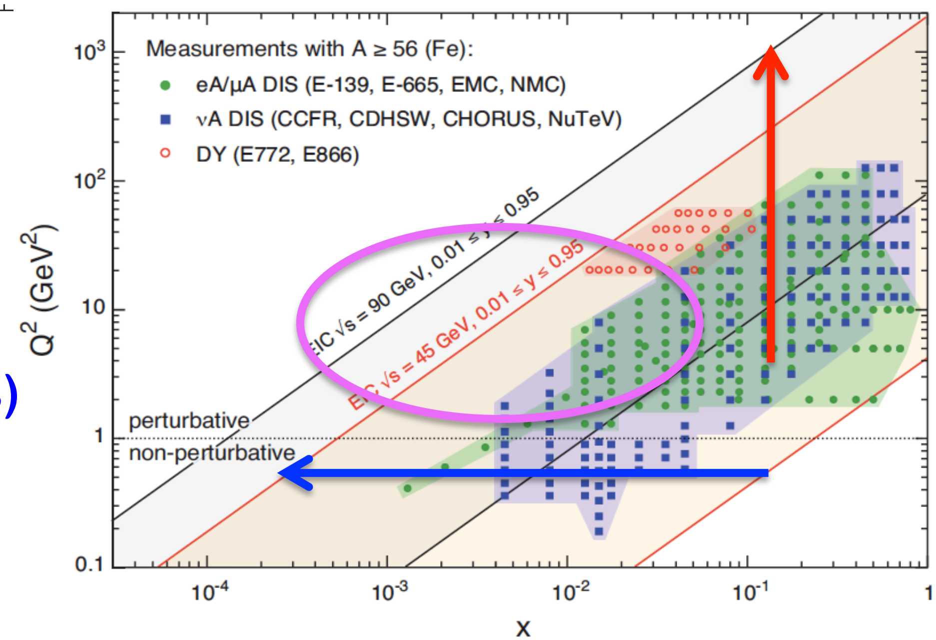


For e-N collisions at the EIC:

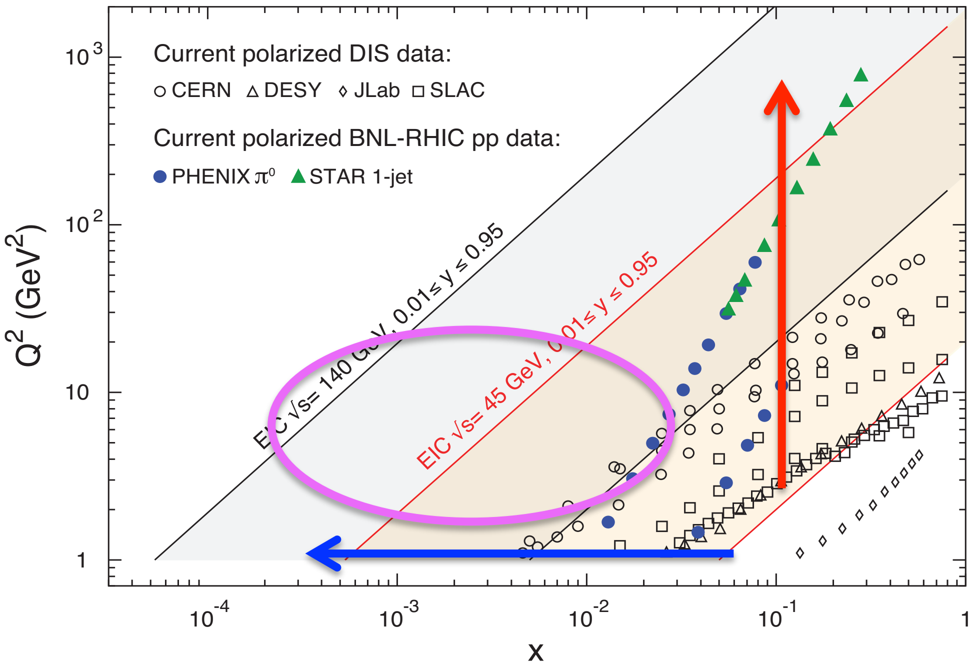
- ✓ Polarized beams: e, p, d/³He
- ✓ Variable center of mass energy
- ✓ Wide Q² range → evolution
- ✓ Wide x range → spanning from valence to low-x physics
- ✓ 100-1K times of HERA Luminosity

For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Variable center of mass energy
- ✓ Wide Q² range (evolution)
- ✓ Wide x region (high gluon densities)



US EIC – Kinematic reach & properties



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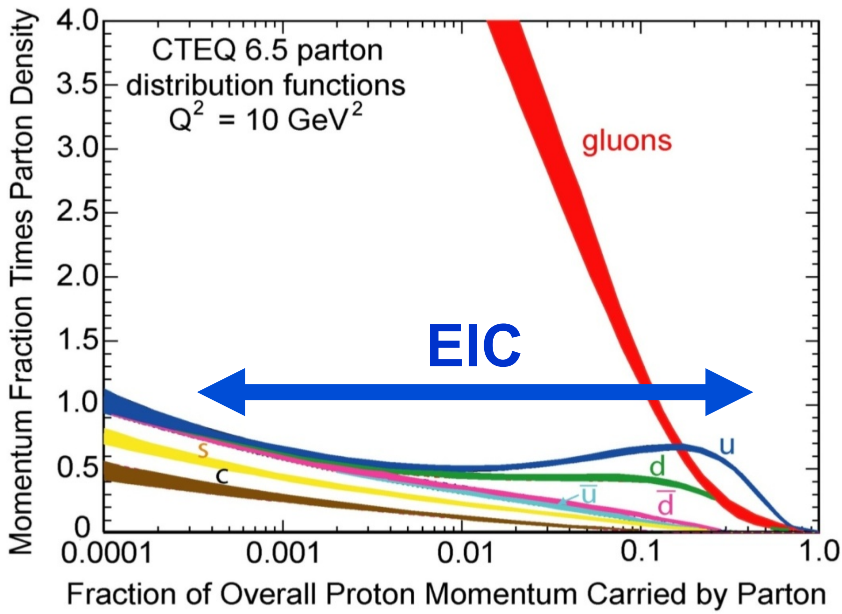
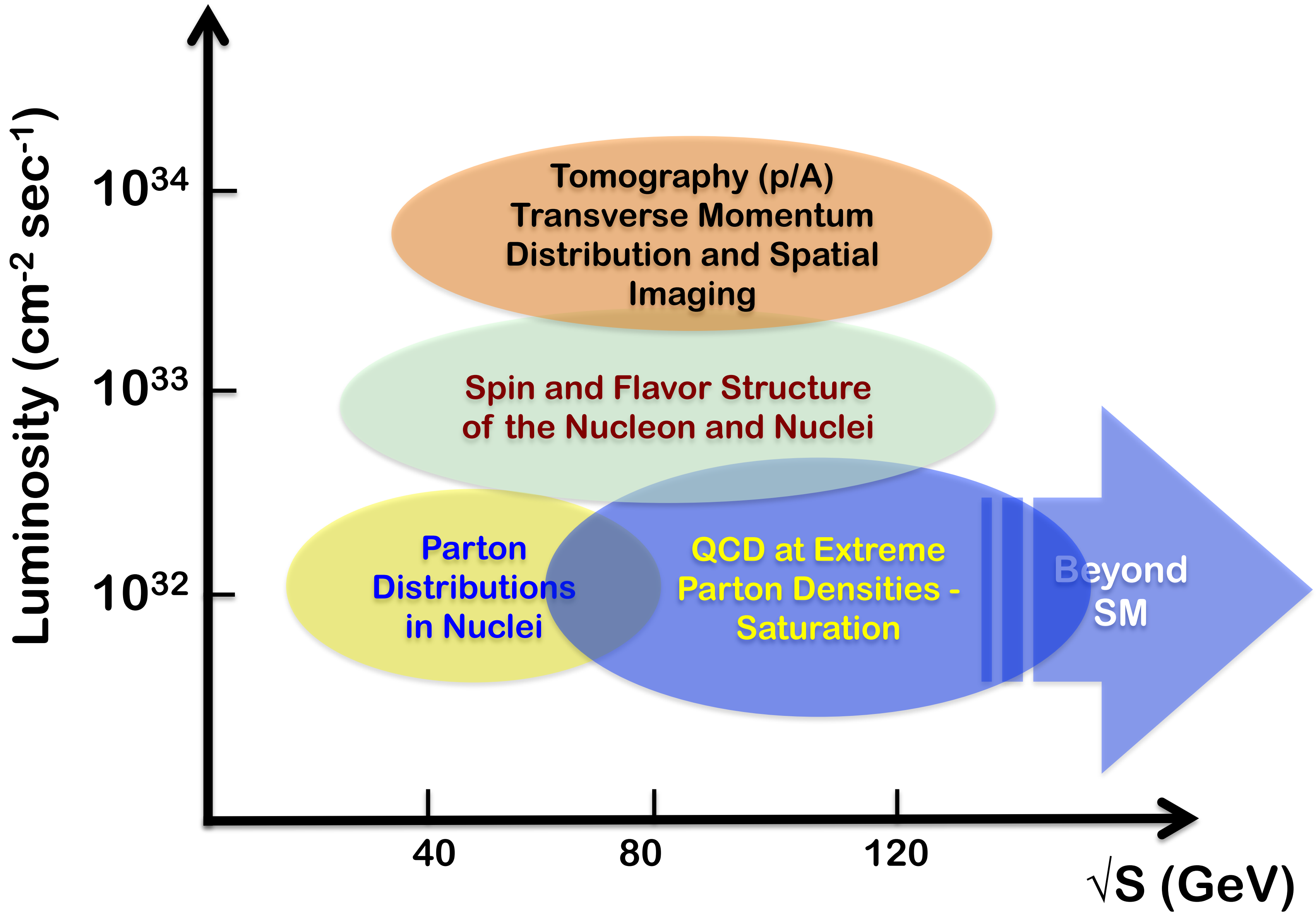
For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range (evolution)
- ✓ Wide x region (high gluon densities)

EIC explores the "sea" and the "glue", the "valence" with a huge level arm



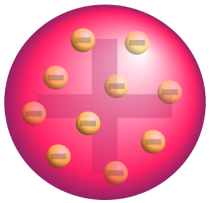
US EIC – Physics vs. Luminosity & Energies



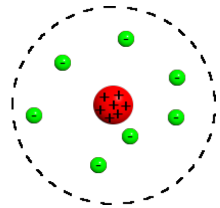
Why 3D hadron structure?

- ❑ Rutherford's experiment – atomic structure (100 years ago):

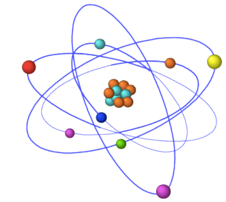
Atom:



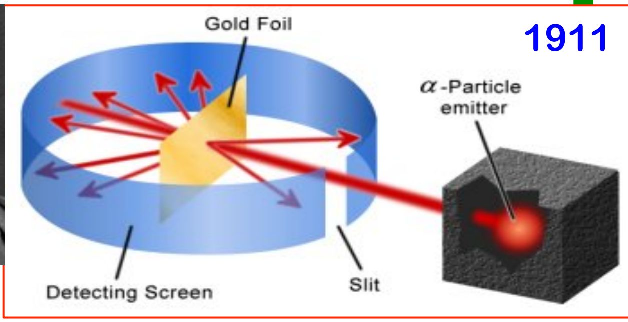
J.J. Thomson's
plum-pudding model



Rutherford's
planetary model



Modern model
Quantum orbitals



Discovery of nucleus
A localized
charge/force center
A vast
"open" space

Discovery of
Quantum Mechanics,
and
the Quantum World!

- ❑ Completely changed our "view" of the visible world:
  - ✧ Mass by "tiny" nuclei – *less than 1 trillionth in volume of an atom*
  - ✧ Motion by quantum probability – *the quantum world!*
- ❑ Provided infinite opportunities to improve things around us:
  - ✧ Gas, Liquid, Solid, Nano materials, Quantum computing, …

How to connect QCD quarks and gluons to observed hadrons and leptons?

Fundamentals of QCD factorization and evolution

Quantum Chromo-dynamics (QCD)

= A quantum field theory of quarks and gluons =

- **Fields:**

$\psi_i^f(x)$ — **Quark fields: spin-½ Dirac fermion (like electron)**

Color triplet: $i = 1, 2, 3 = N_c$

Flavor: $f = u, d, s, c, b, t$

$A_{\mu,a}(x)$ — **Gluon fields: spin-1 vector field (like photon)**

Color octet: $a = 1, 2, ..., 8 = N_c^2 - 1$

- **QCD Lagrangian density:**

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij}\right] \psi_j^f$$
$$- \frac{1}{4}\left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc}A_{\mu,b}A_{\nu,c}\right]^2$$
$$+ \text{ gauge fixing} + \text{ghost terms}$$

- **QED – force to hold atoms together:**

$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f\right] \psi^f - \frac{1}{4}\left[\partial_\mu A_\nu - \partial_\nu A_\mu\right]^2$$

- **QCD Color confinement:**

Gluons are dark, No free quarks or gluons ever been detected!

Effective quark mass

- **Running quark mass:**

$$m(\mu_2) = m(\mu_1)\exp\left[-\int_{\mu_1}^{\mu_2}\frac{d\lambda}{\lambda}[1+\gamma_m(g(\lambda))]\right]$$

Quark mass depend on the renormalization scale!

- **QCD running quark mass:**

$$m(\mu_2) \Rightarrow 0 \qquad \text{as } \mu_2 \to \infty \qquad \text{since } \gamma_m(g(\lambda)) > 0$$

- **Choice of renormalization scale:**

$\mu \sim Q$ **for small logarithms in the perturbative coefficients**

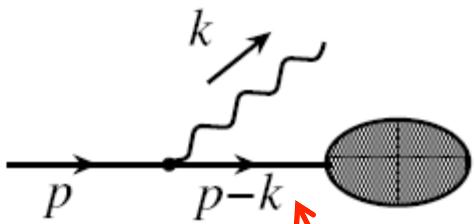
- **Light quark mass:** $m_f(\mu) \ll \Lambda_{\rm QCD}$ for $f = u, d,$ even s

QCD perturbation theory ($Q \gg \Lambda_{QCD}$) is effectively a massless theory

Infrared and collinear divergences

❑ Consider a general diagram with a *"unobserved gluon"*:

$$p^2 = 0, \quad k^2 = 0$$ for a massless theory



Singularity

✧ $$k^\mu \to 0 \;\Rightarrow\; (p-k)^2 \to p^2 = 0$$

⟹ Infrared (IR) divergence

✧ $$k^\mu \,||\, p^\mu \;\Rightarrow\; k^\mu = \lambda p^\mu \quad \text{with} \;\; 0 < \lambda < 1$$

$$\Rightarrow\; (p-k)^2 \to (1-\lambda)^2 p^2 = 0$$

⟹ Collinear (CO) divergence

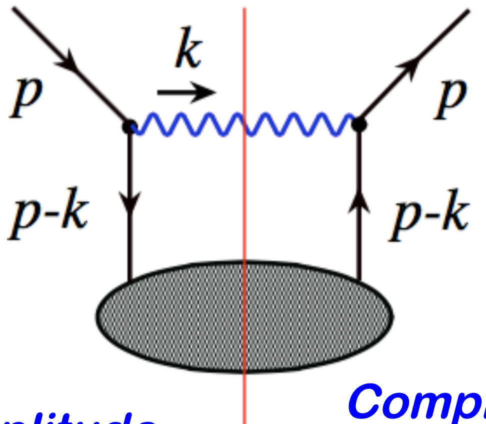
IR and CO divergences are generic problems of a massless perturbation theory

Pinch singularity and pinch surface

- "Square" of the diagram **with a *"unobserved gluon"*:**

"Cut-line" – final-state

– in a "cut-diagram" notation



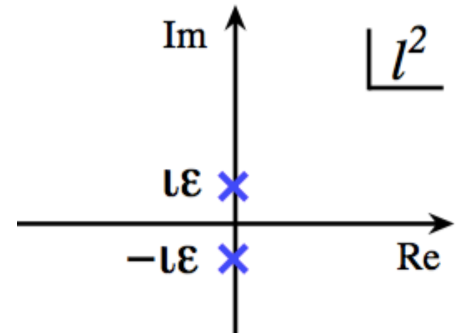
Amplitude

Complex conjugate of the Amplitude

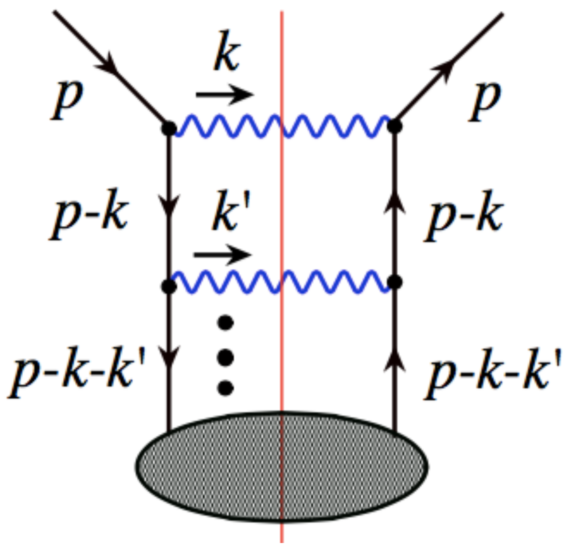
$$\propto \int \mathcal{T}(p-k,Q)\,\frac{1}{(p-k)^2+i\epsilon}\,\frac{1}{(p-k)^2-i\epsilon}\,d^4k\,\delta(k^2)_+$$

$$\propto \int \mathcal{T}(l,Q)\,\frac{1}{l^2+i\epsilon}\,\frac{1}{l^2-i\epsilon}\,dl^2$$

$$\Rightarrow \infty$$



Pinch singularities "perturbatively"



Pinch surfaces

= "surfaces" in k, k', …

determined by $(p-k)^2=0$, $(p-k-k')^2=0$, …

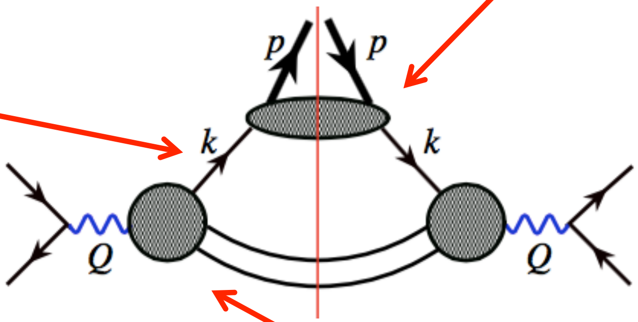
"perturbatively"

Hard collisions with identified hadron(s)

- ❑ Creation of identified hadron(s):

Non-perturbative!

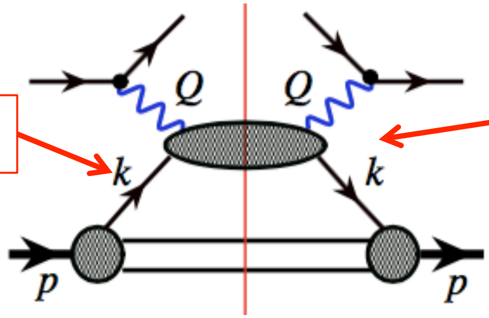
Pinch in k^2



Perturbative!

- ❑ Initial identified hadron(s):

Pinch in k^2

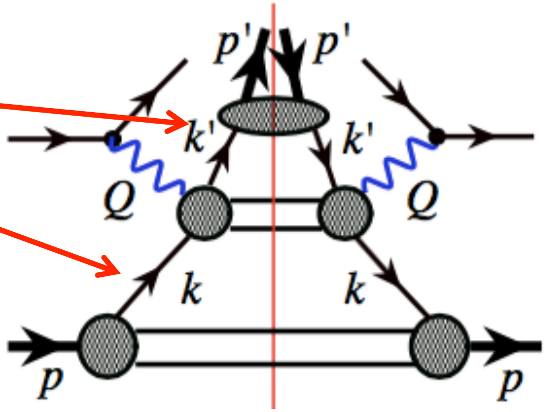


Perturbative!

Non-perturbative!

- ❑ Initial + created identified hadron(s):

Pinch in both k^2 and k'^2



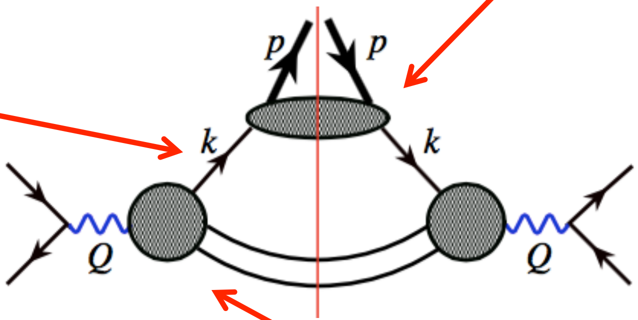
Cross section with identified hadron(s) is NOT perturbatively calculable

Hard collisions with identified hadron(s)

- Creation of identified hadron(s):

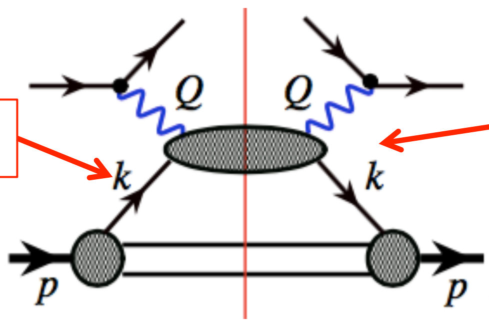
Non-perturbative!

Pinch in k^2



Perturbative!

- Initial identified hadron(s):



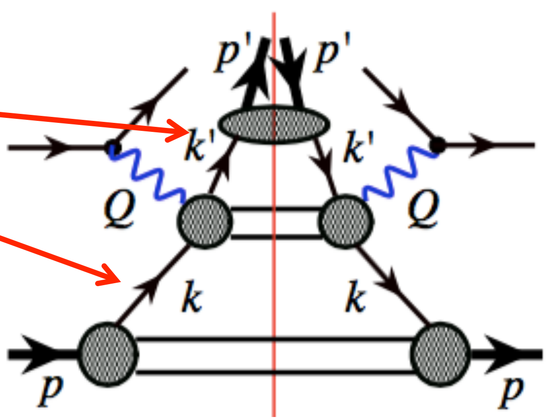
Pinch in k^2

Perturbative!

Non-perturbative!

- Initial + created identified hadron(s):

Pinch in both k^2 and k'^2



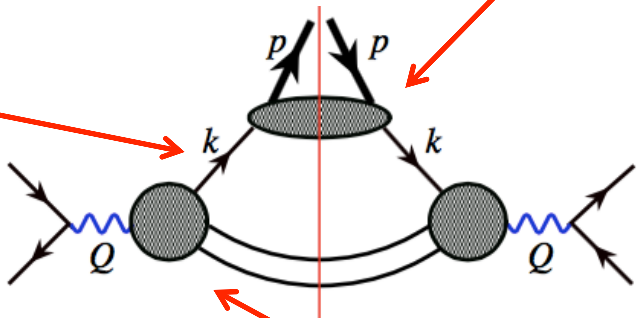
Dynamics at a HARD scale is linked by partons almost on Mass-Shell

Hard collisions with identified hadron(s)

- ❑ Creation of identified hadron(s):

Non-perturbative!

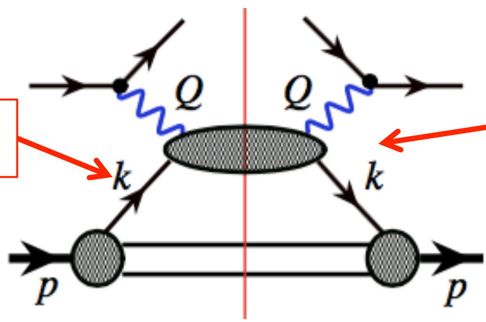
Pinch in k^2



Perturbative!

- ❑ Initial identified hadron(s):

Pinch in k^2

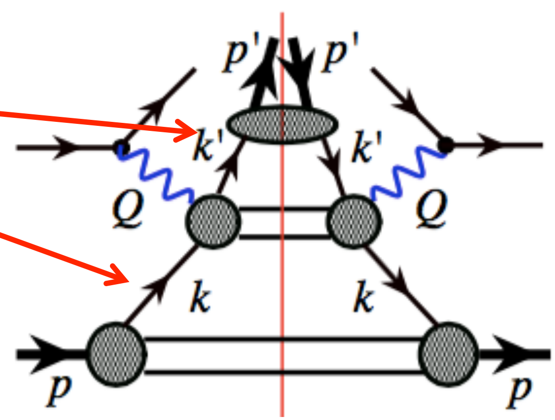


Perturbative!

Non-perturbative!

- ❑ Initial + created identified hadron(s):

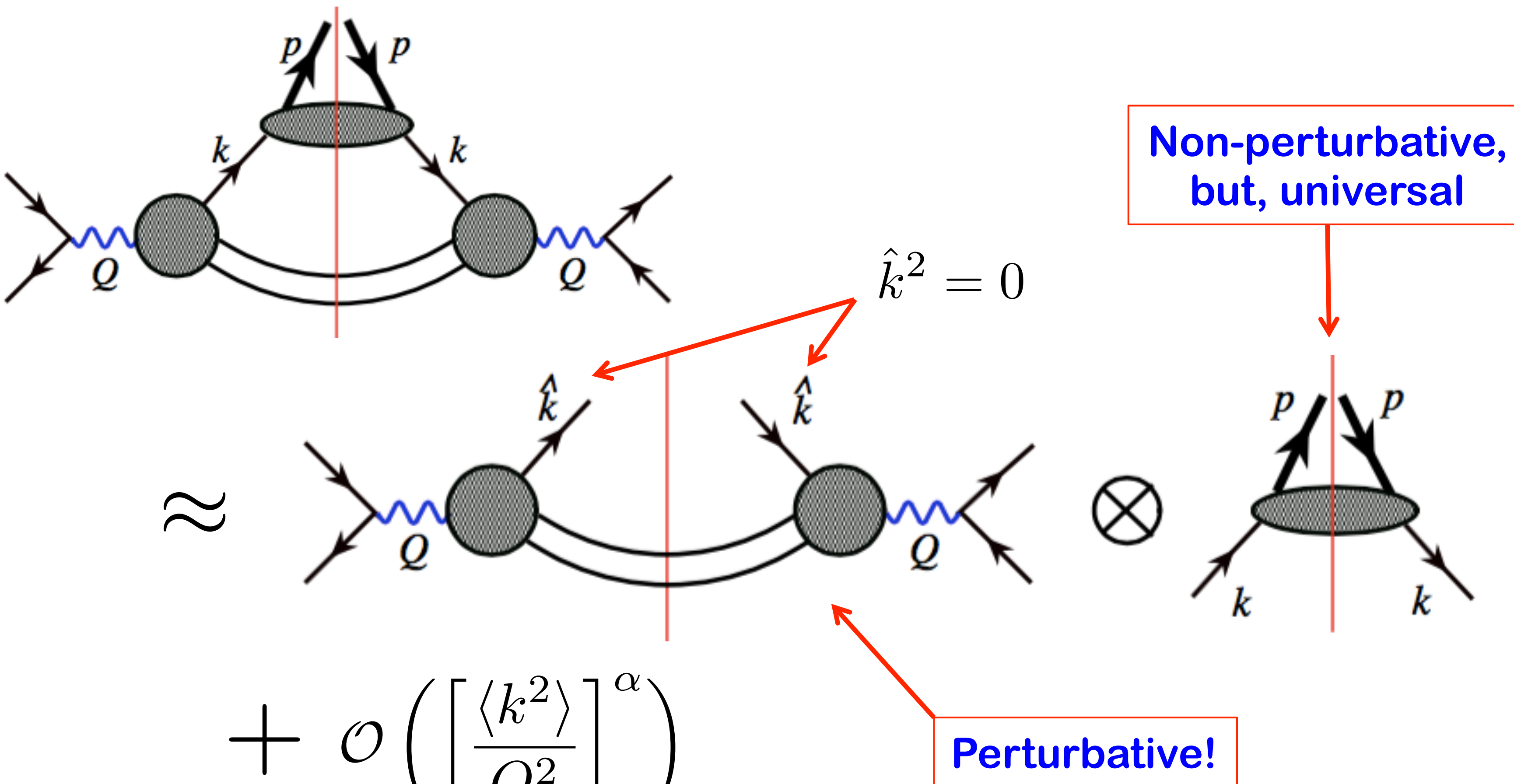
Pinch in both k^2 and k'^2



Quantum interference between dynamics at the HARD and hadronic scales is powerly suppressed!

QCD factorization – approximation

- **Creation of identified hadron(s):**



$$+ \; \mathcal{O}\left(\left[\frac{\langle k^2 \rangle}{Q^2}\right]^{\alpha}\right)$$

Factorization: factorized into a product of "probabilities" !

Summary of lecture one

- EIC is a ultimate QCD machine:
  1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
  2) to search for hints and clues of color confinement, and
  3) to measure the color fluctuation and color neutralization
- EIC is a tomographic machine for nucleons and nuclei with a resolution better than 1/10 fm
- Cross section with identified hadron(s) is NOT completely calculable in QCD perturbation theory
- QCD Factorization – neglecting quantum interference between dynamics at hard partonic scattering and those at hadronic scales – approximation
- Predictive power of QCD factorization relies on the universality of PDFs (or TMDs, GPDs, …), the calculations of perturbative coefficient functions – hard parts

Backup slides