The Electron Ion Collider

Abhay Deshpande

Lecture 1

Today on the menu…

- Overview of these lectures: plan

- Introduction to the Electron Ion Collider
- High level introduction to the Physics of the Electron Ion Collider

History:

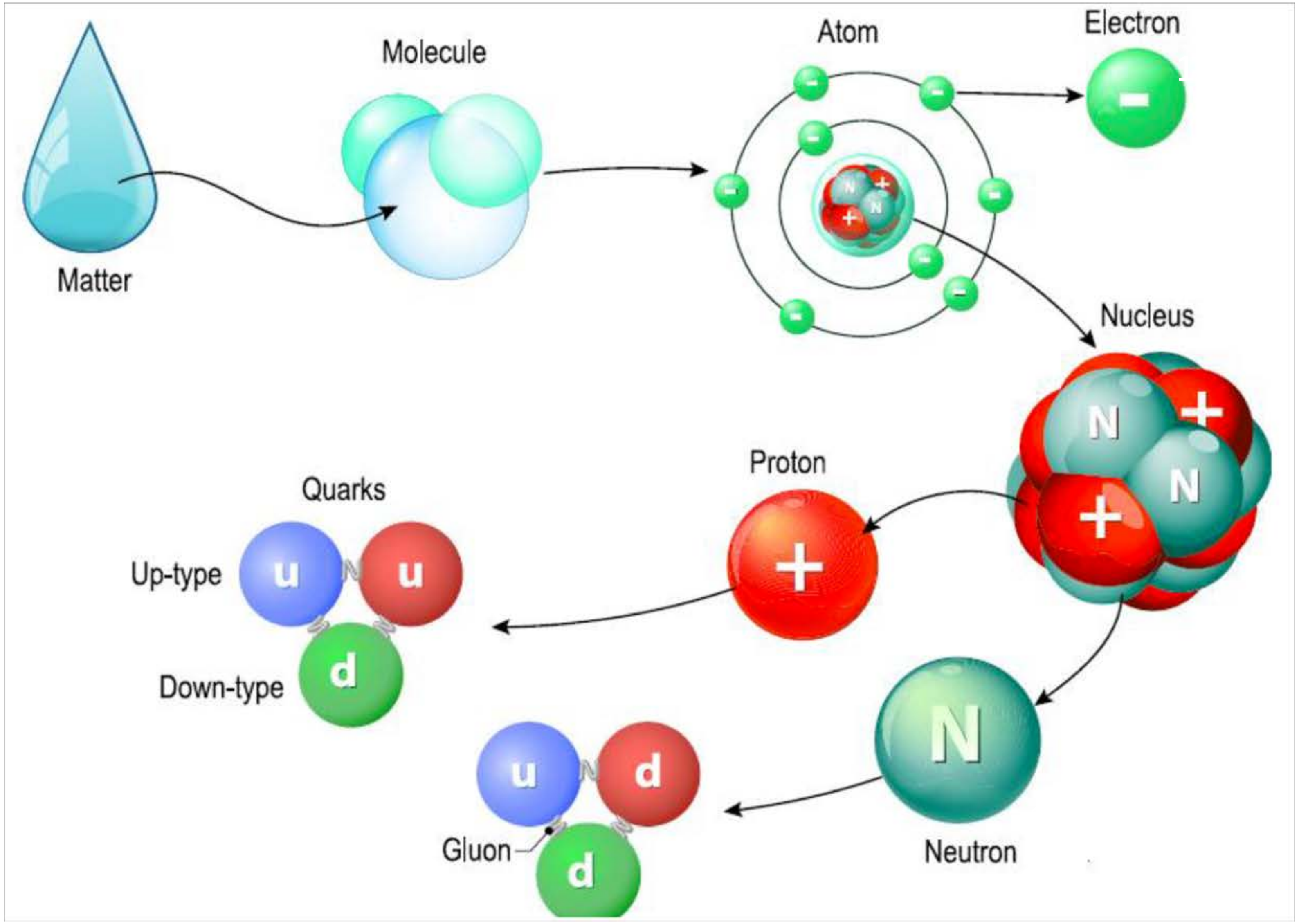
- Investigations in nuclear and particle physics over the last 100 years
- Experiments that changed the way we think about physics
- Discovery of atomic nuclei, protons, neutrons and quarks

Electron Proton Scattering Kinematics : and a home work

Overview of these lectures

- **Day 1:**
  - History: In search for fundamental particles, experimental methods, the Standard Model
  - Introduction to the Electron Ion Collider (EIC) and high level introduction to its physics
  - Deep Inelastic Scattering (DIS), fixed target and collider
- **Day 2:**
  - Spin: Polarized DIS, and the spin crisis: inclusive and semi-inclusive DIS
    - Limitations of the fixed target spin experiments
  - Relativistic Heavy Ion Collier: Gluon and anti-quark polarization
    - The transverse spin puzzle: *neglected clues*
  - DIS with nuclei another lesson from CERN….
- **Day 3:**
  - Polarized DIS with the EIC: Solving the spin puzzle: 3D imaging of the nucleon
  - Gluons in Nuclei: do they saturate?
  - Designing an EIC detector and integration in to the Interaction Region (IR)
  - EIC: Status and prospects

Quest for the fundamental structure of matter



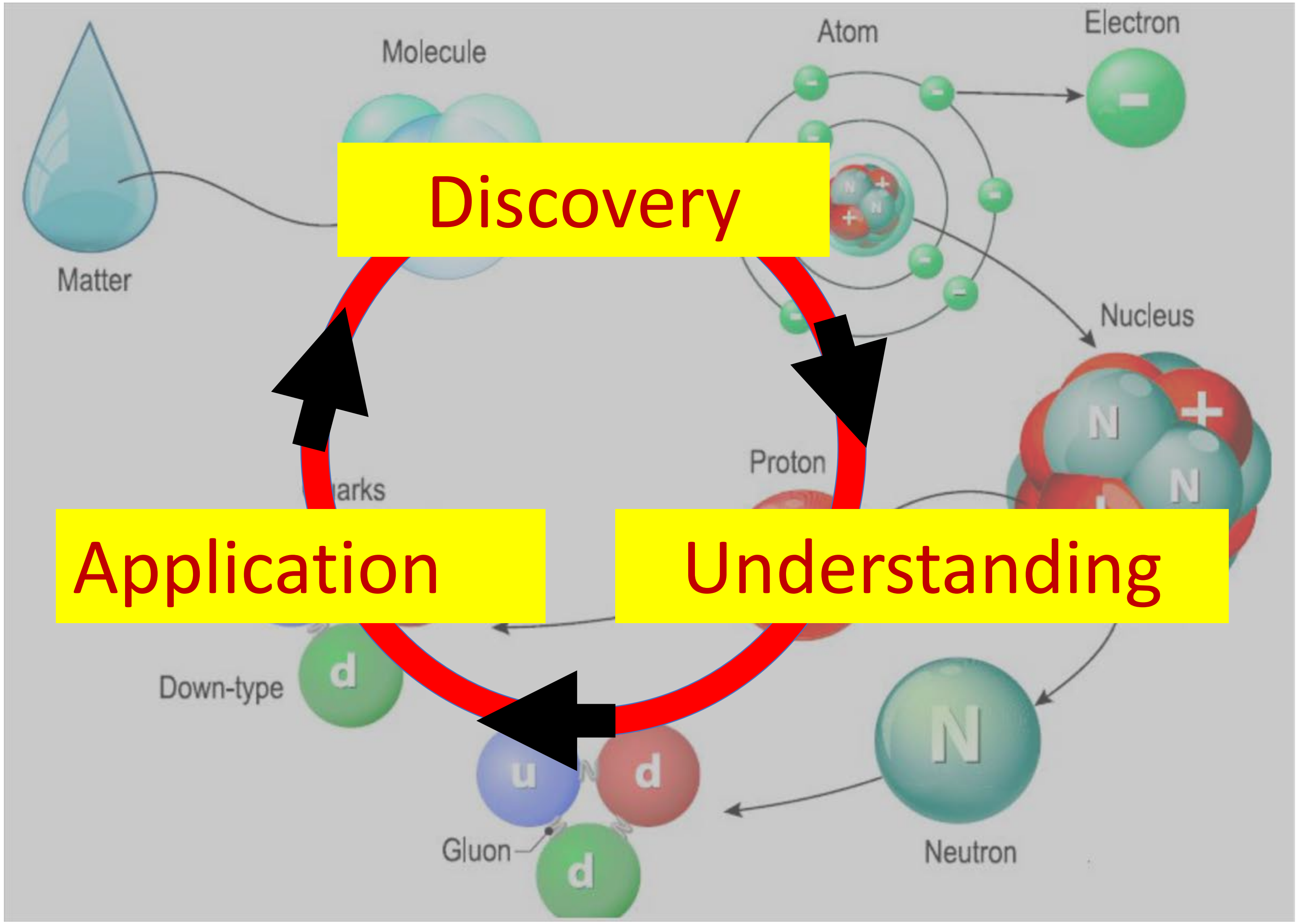
What's in there?

What are we made up of?

What is the "smallest"?

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

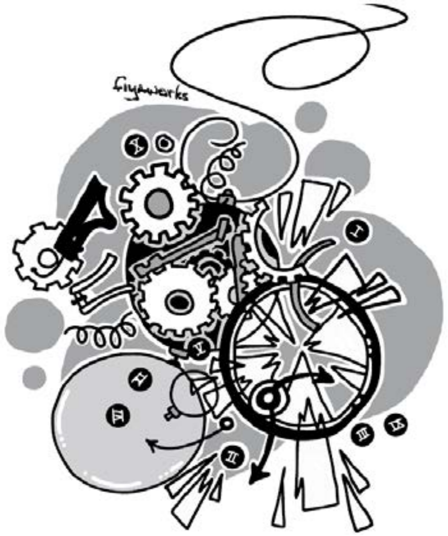
Science and society



History: Fundamental particles, experimental methods

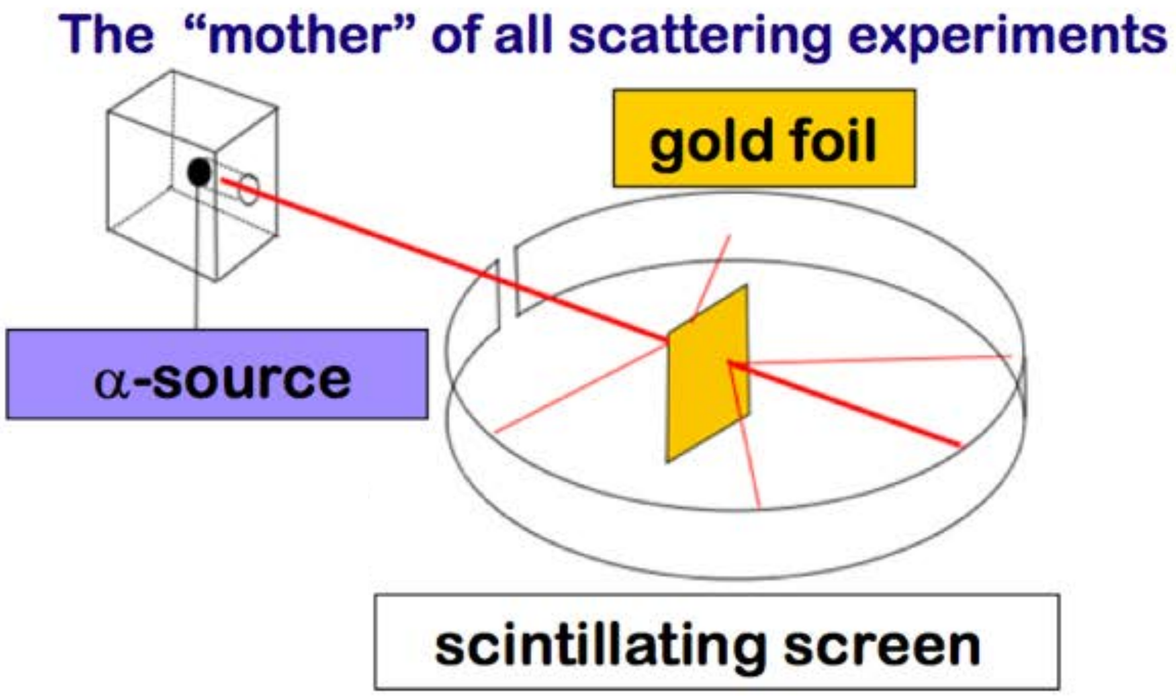
Day 1, Lecture 1

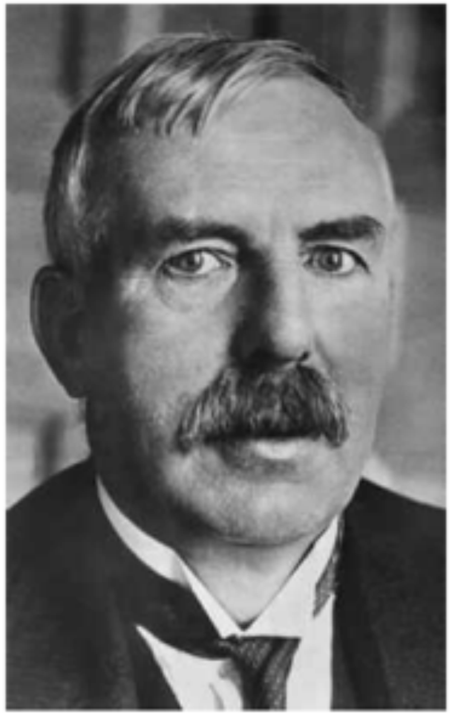
Scattering of protons on protons
is like colliding Swiss watches to find out
how they are build.



R. Feynman

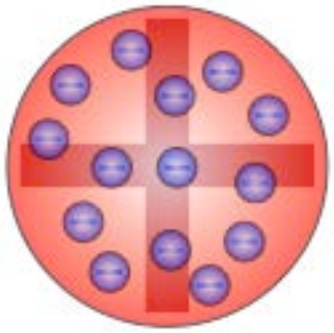
In the beginning we took whatever we had…





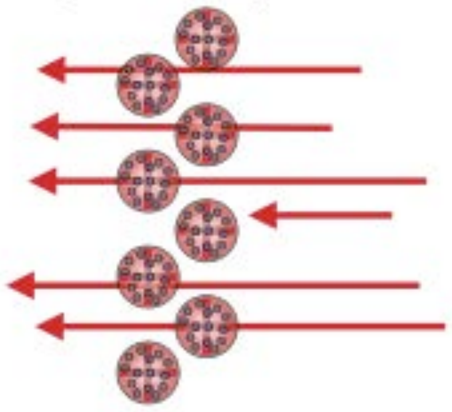
Rutherford

The expected….

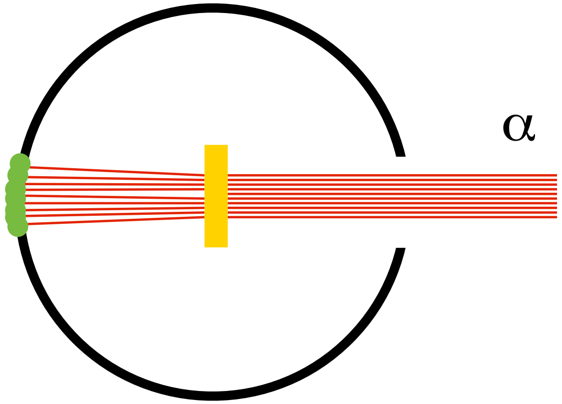


Thomson's
Plum Pudding Model

Detail of gold foil (Thomson):



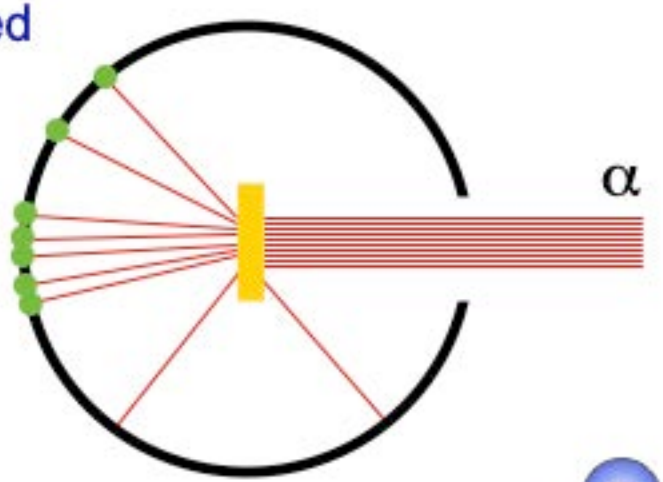
Predicted
result:



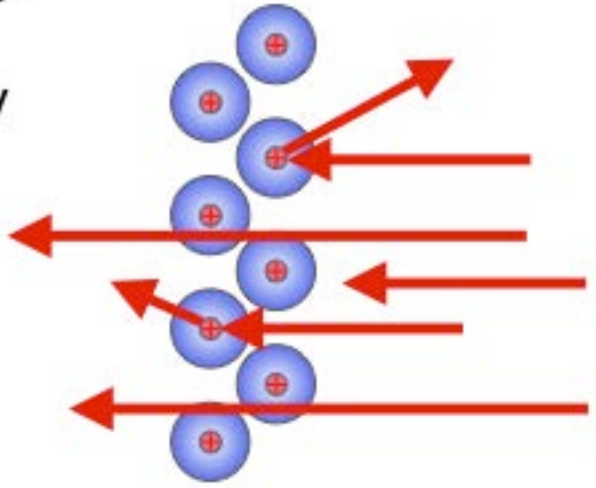
Expected
marks on screen

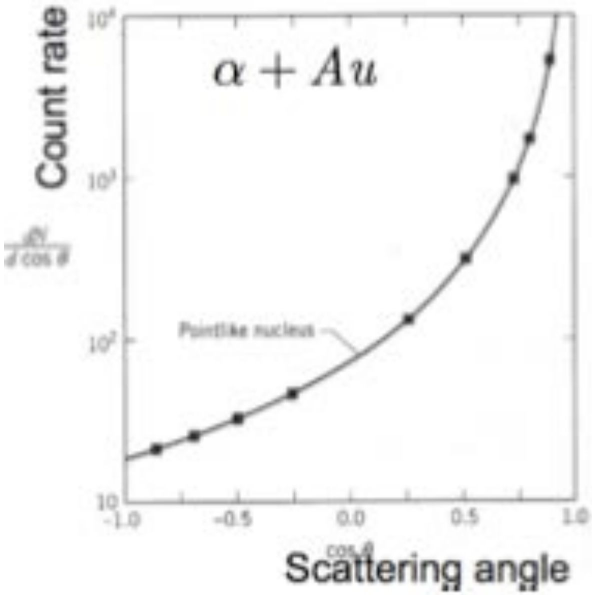
The observed… unexpected…

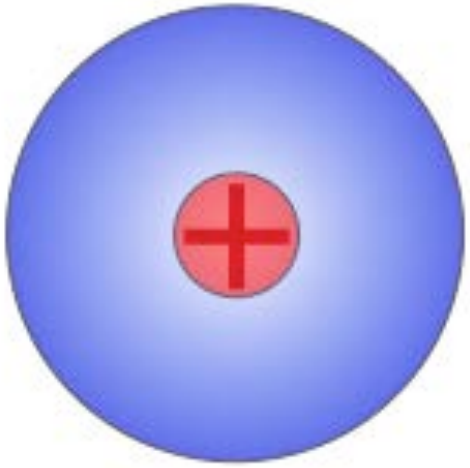
Observed result:



Positive Nucleus Theory explain α deflection:



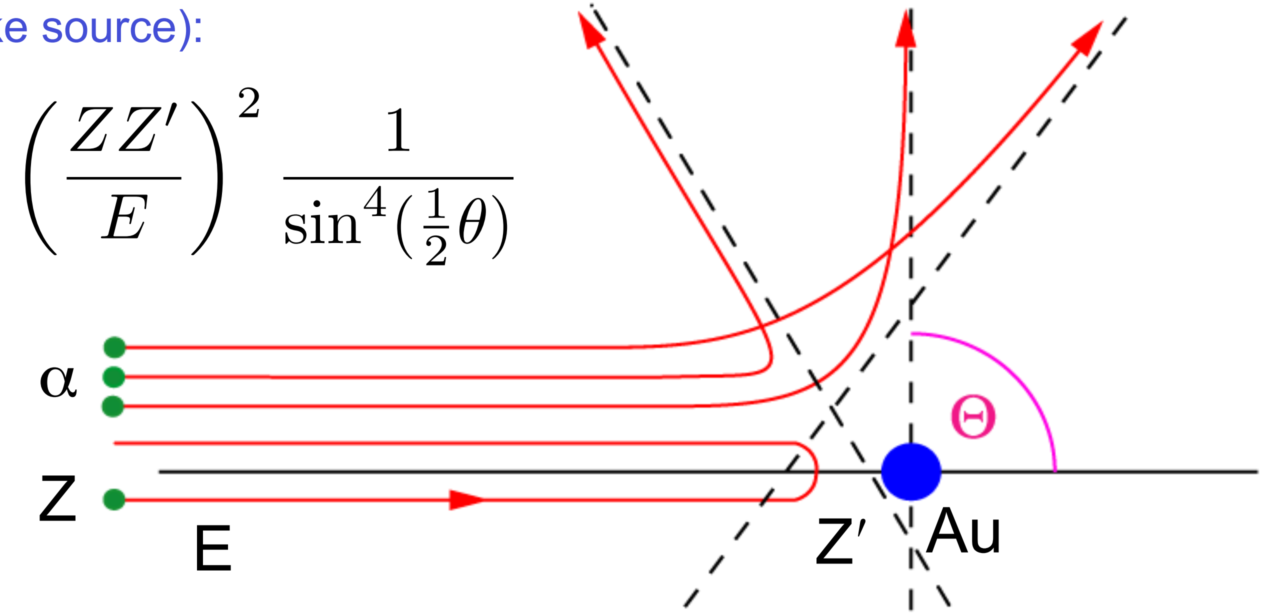




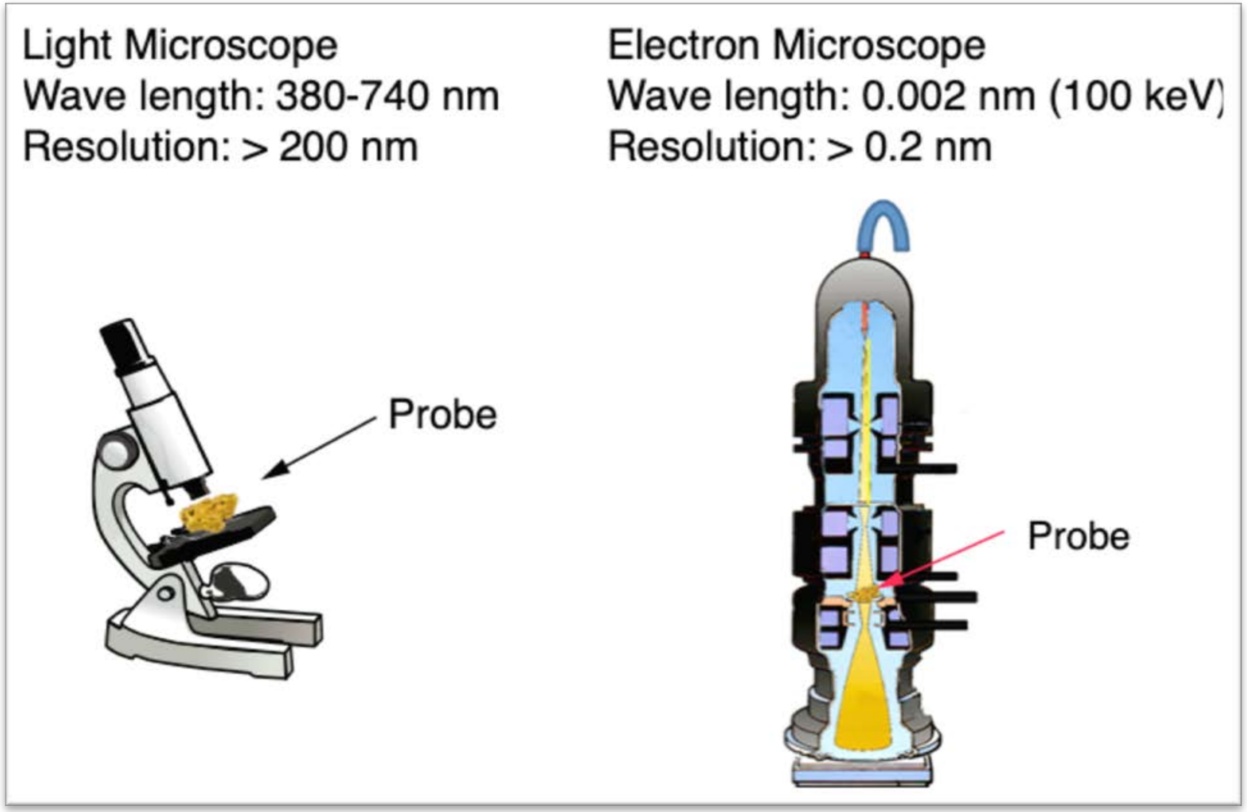
Rutherford Scattering

Elastic scattering of charged particles in Coulomb field (point-like source):

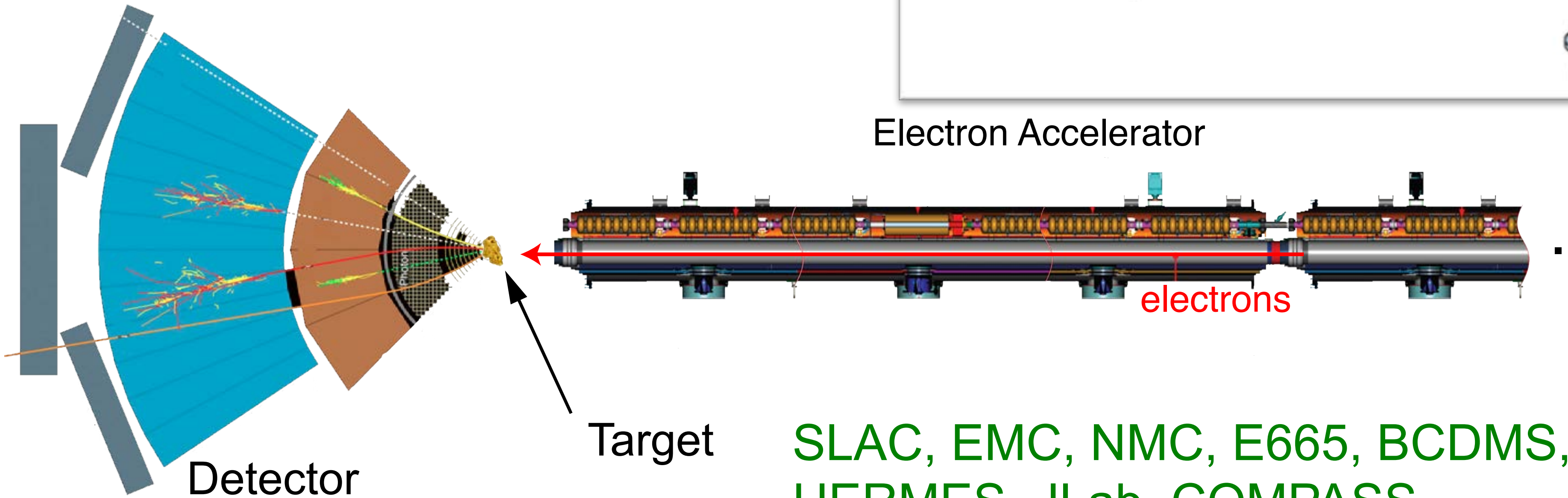
$$\frac{d\sigma}{d\Omega} = \left(\frac{ZZ'}{E}\right)^2 \frac{1}{\sin^4(\frac{1}{2}\theta)}$$



Studying smaller and smaller things…



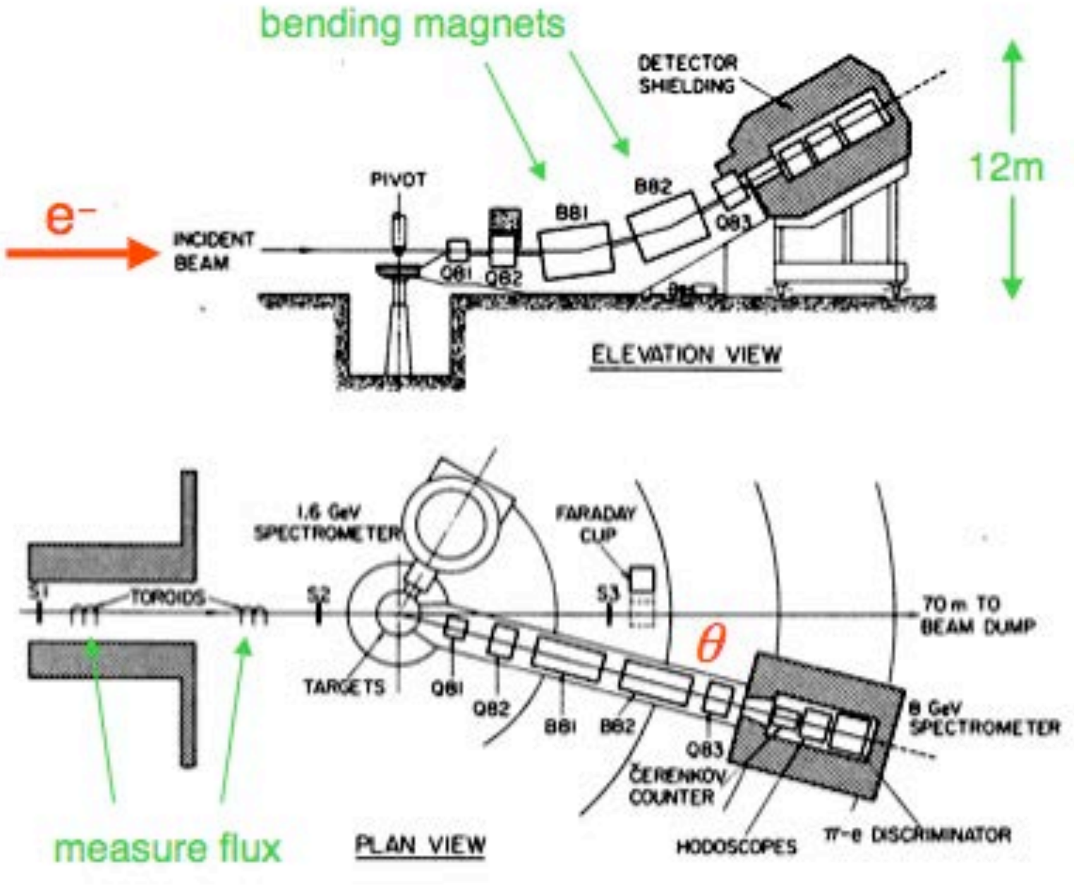
Fixed Target Particle
Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm



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

Probing matter with electrons…

- In the 1960s Experiments at Stanford Linear Accelerator Center (SLAC) established the quark model and our modern view of particle physics "the Standard Model"



Scattered electron is deflected by a known *B*-field and a fixed vertical angle:

determine *E'*

Spectrometer can rotate in the horizontal plane,

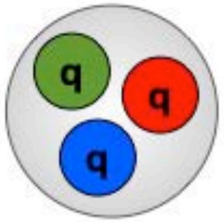
vary θ

The Static Quark Model

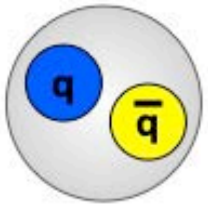
Quarks: spin 1/2 fermions, color charge

M. Gell-Mann,
K. Nishijima (> 1964)

Baryons:



Mesons:



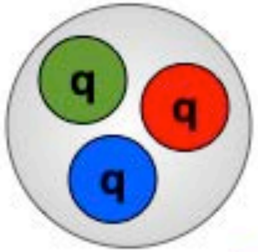
Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	$+1$

The Static (Constituent) Quark Model

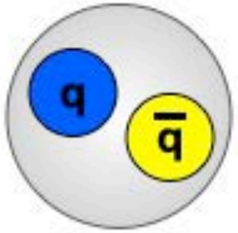
Quarks: spin 1/2 fermions, color charge

M. Gell-Mann,
K. Nishijima (> 1964)

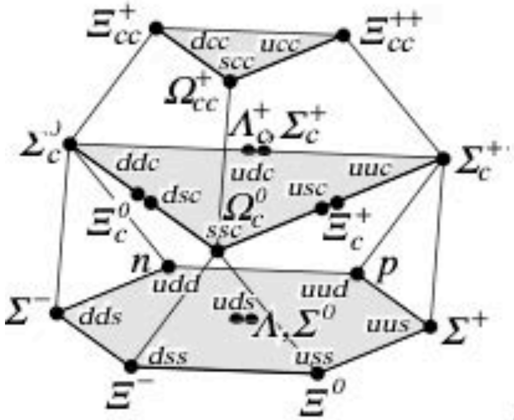
Baryons:

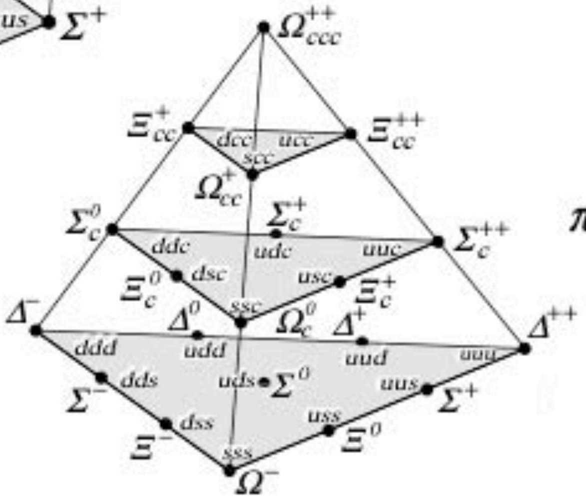


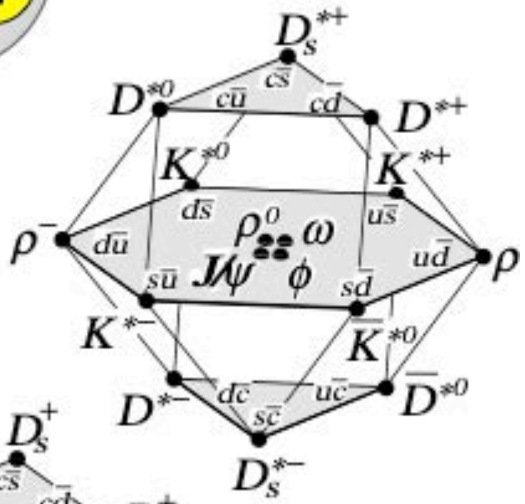
Mesons:

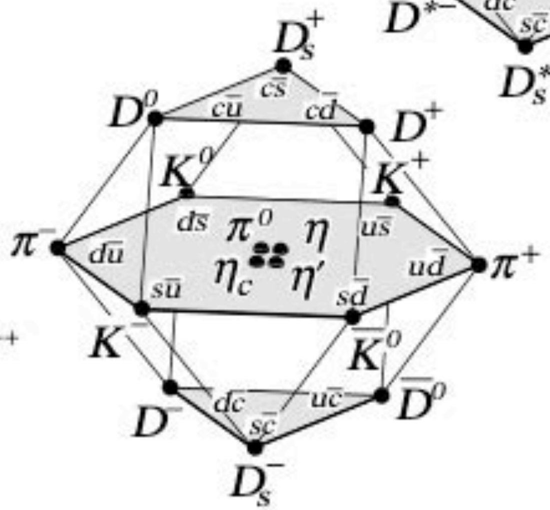


Eight-fold Way:
Account for every hadron we found so far









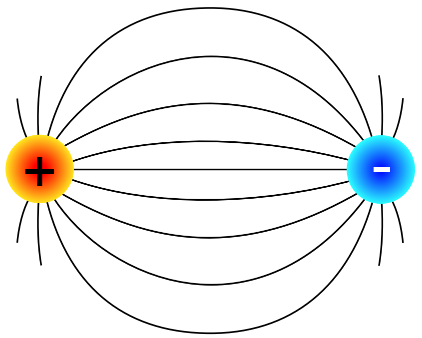
For detailed properties of the multiquark systems the model failed

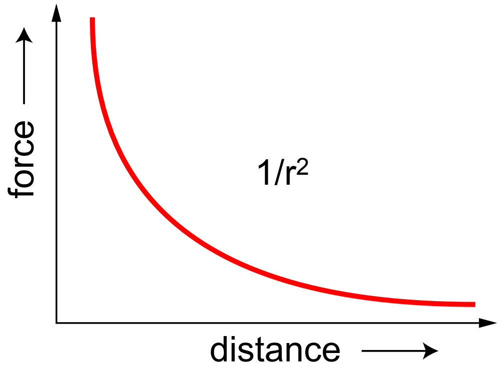
How come? What was missing?

Quantum Electrodynamics (QED)

Theory of electromagnetic interactions

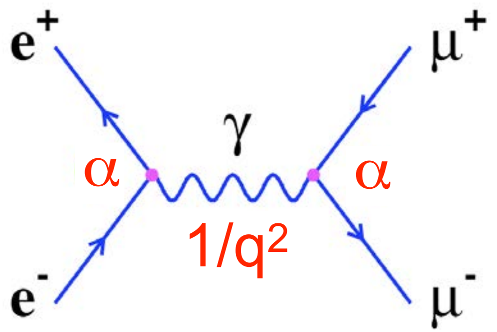
- Exchange particles (photons) do not carry electric charge
- Flux is not confined: $V(r) \sim 1/r$, $F(r) \sim 1/r^2$





$$V(r) = -\frac{q_1 \ q_2}{4\pi\varepsilon_0 \ r} = -\frac{\alpha_{em}}{r}$$

Example Feynman Diagram:
e^+e^- annihilation



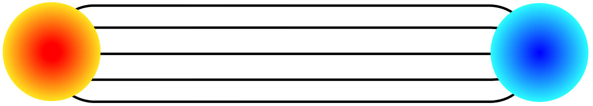
Coupling constant (α): Interaction Strength
In QED: $\alpha_{em} = 1/137$

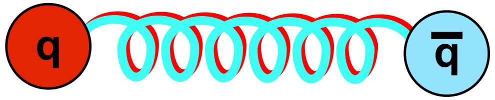
Quantum Chromodynamics (QCD)

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

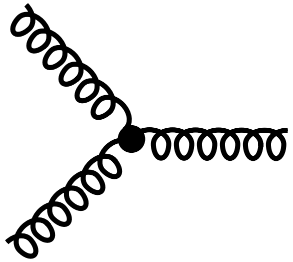
F. Wilczek, hep-ph/9907340

- 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

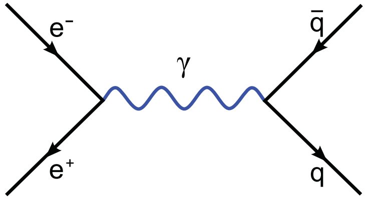
long range ~ r

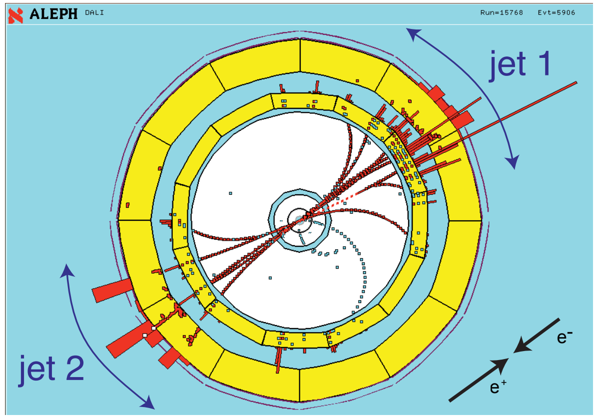
Long range aspect ⇒ quark confinement and existence of nucleons

Gluons!

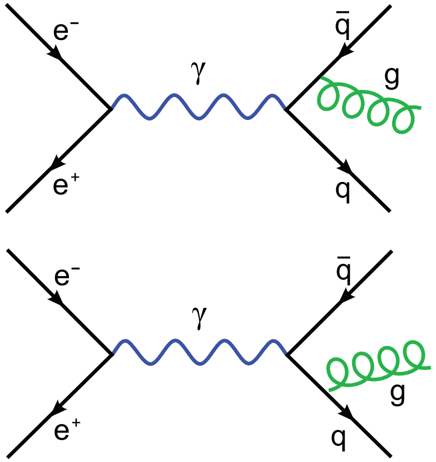
Discovery of gluons: Mark-J, Tasso, Pluto, Jade experiments at PETRA (e+e- collider) at DESY (CM energy 13-32 GeV)

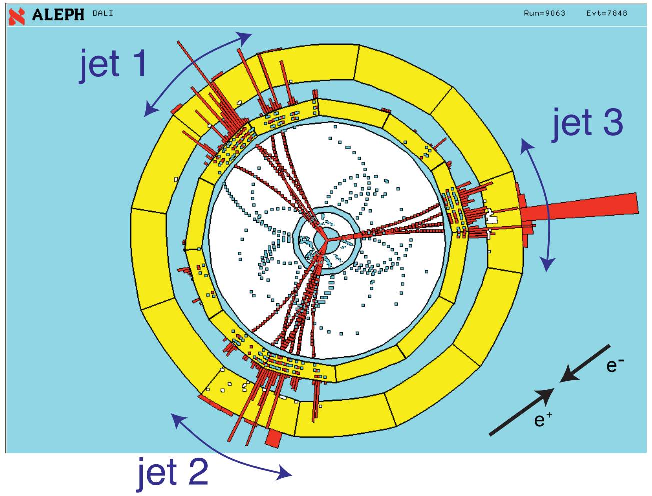
- $e^+ e^- \rightarrow q\ \bar{q} \rightarrow$ 2-jets





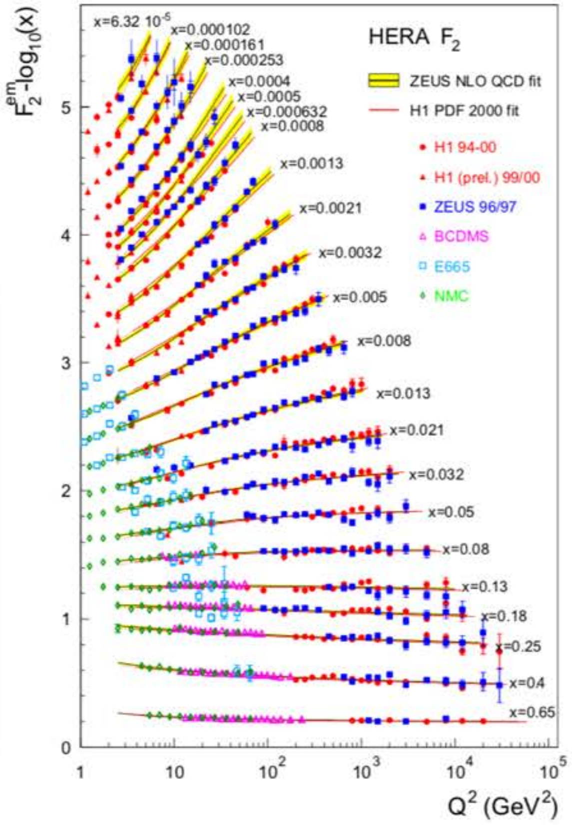
- $e^+ e^- \rightarrow q\ \bar{q}\ g \rightarrow$ 3-jets



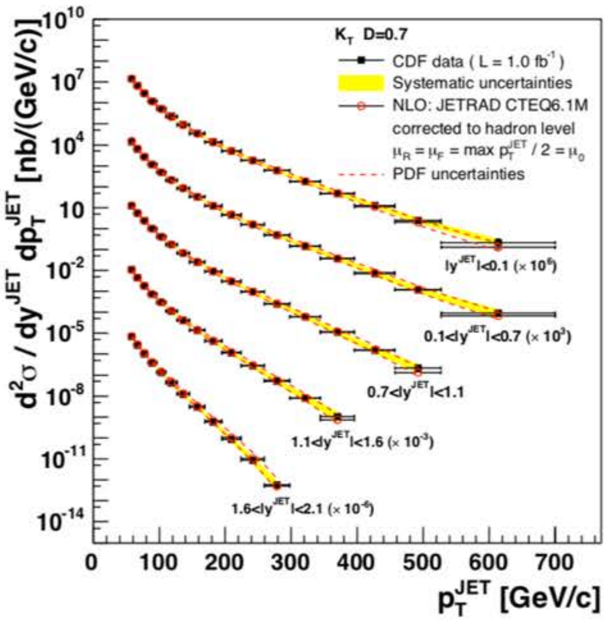


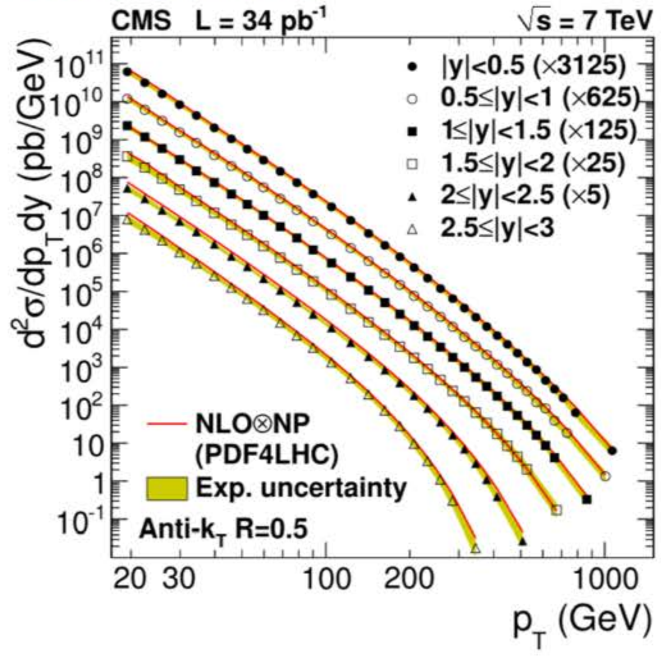
QCD works!

Structure functions measured at HERA ep collider

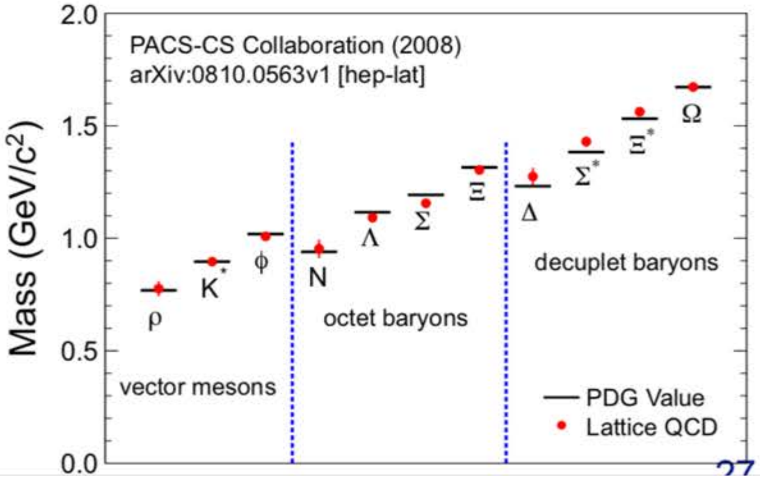


Jet cross-sections: pp collisions at LHC and $\bar{p}p$ collisions at Fermilab





Lattice QCD



Are we done?

Standard Model (SM) of physics: Fundamental building blocks

+2/3

-1/3

0

-1

18 Nobel Prizes since 1950

2012: CERN

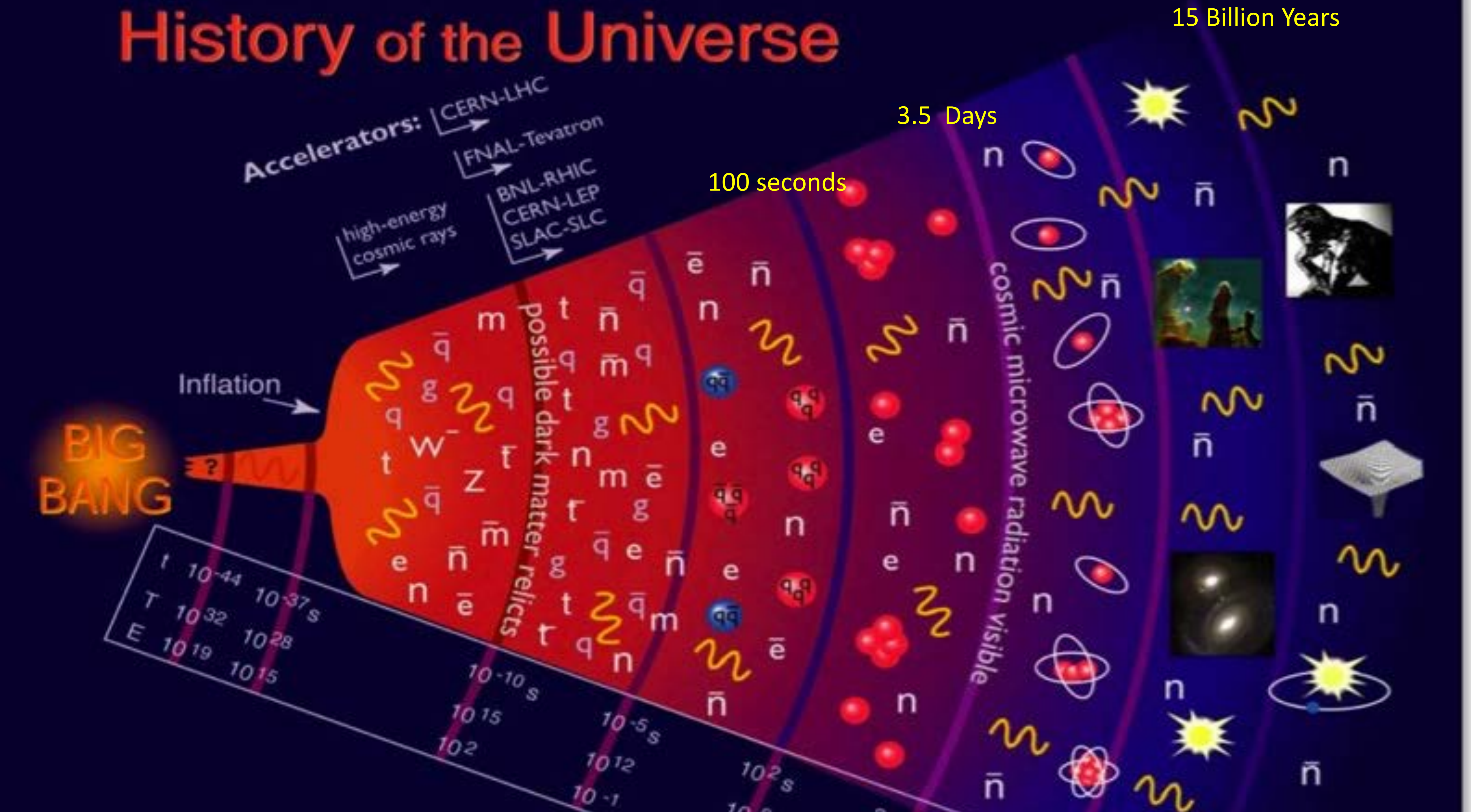
H

H BOSON

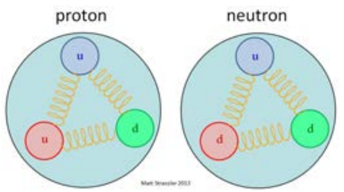
+

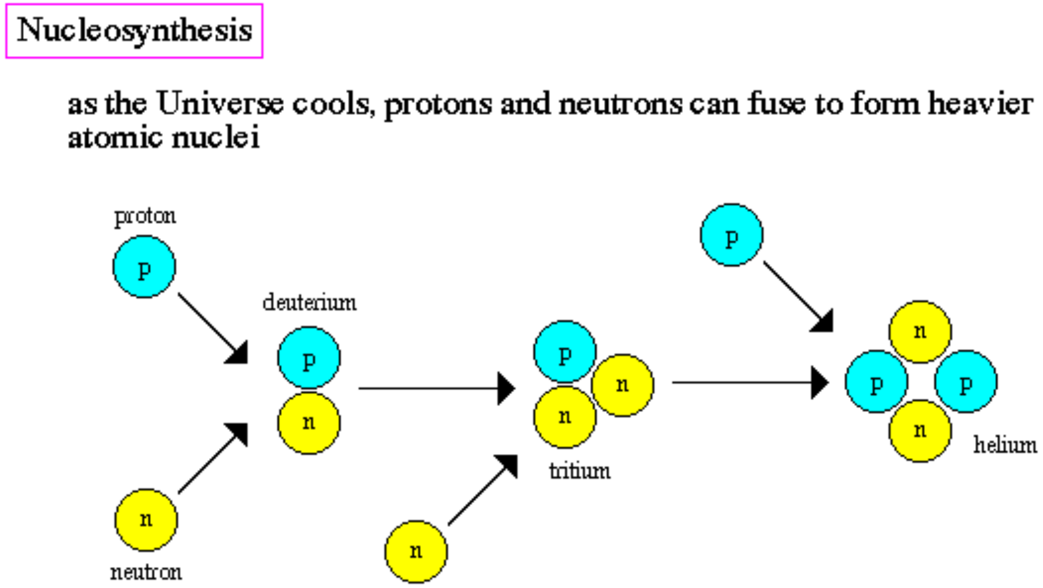
2015 Gravitational waves

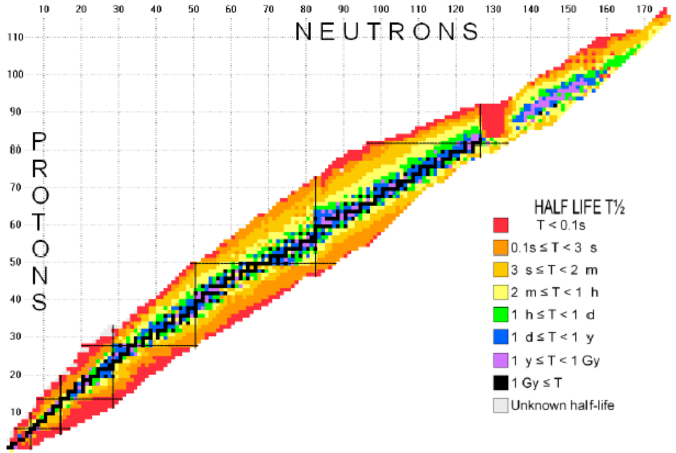
Einstein gravity

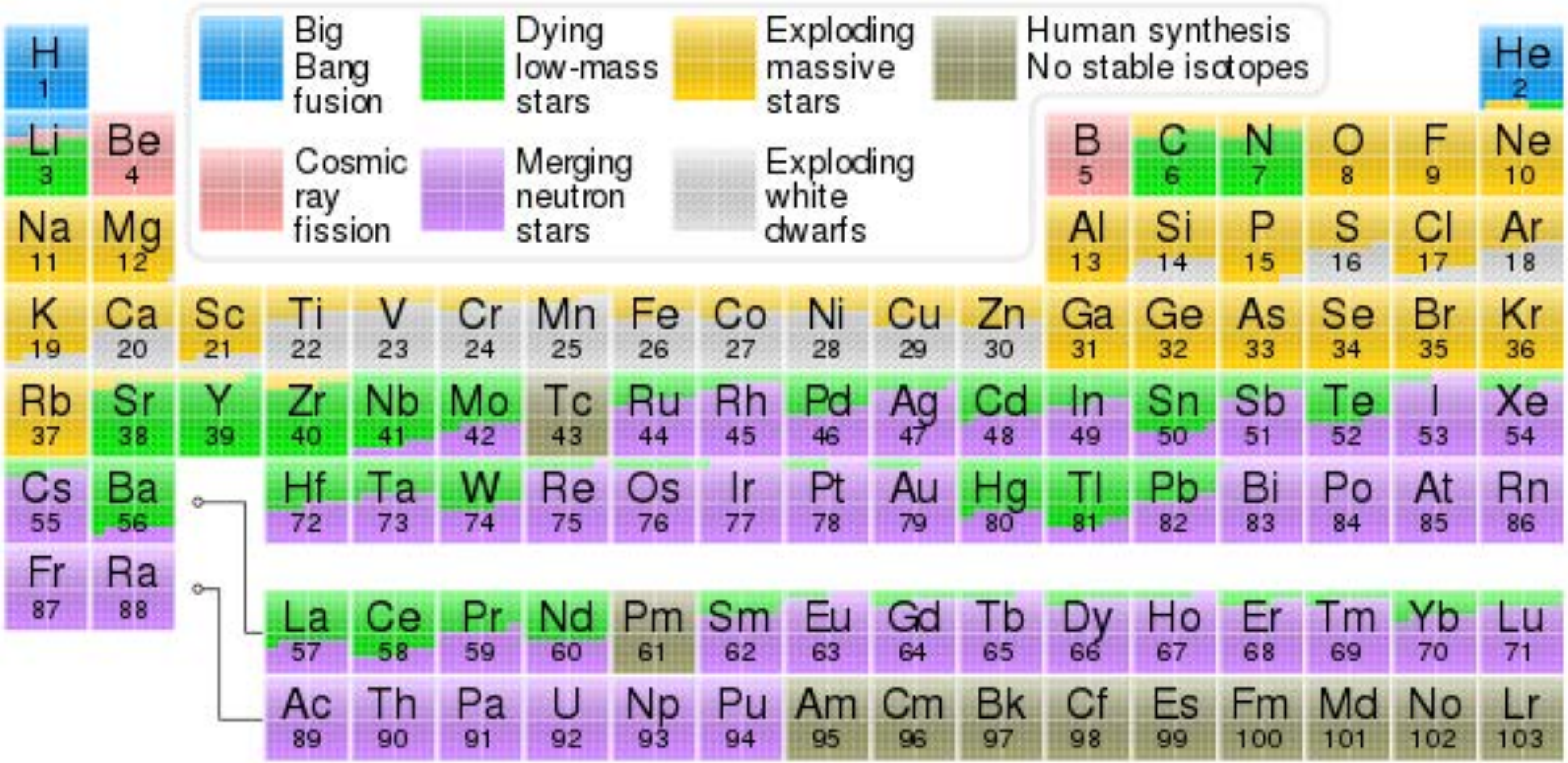

History of the Universe
15 Billion Years
3.5 Days
100 seconds
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
10 2 s

From protons/neutrons to visible nuclei We know what happened but don't fully understand why





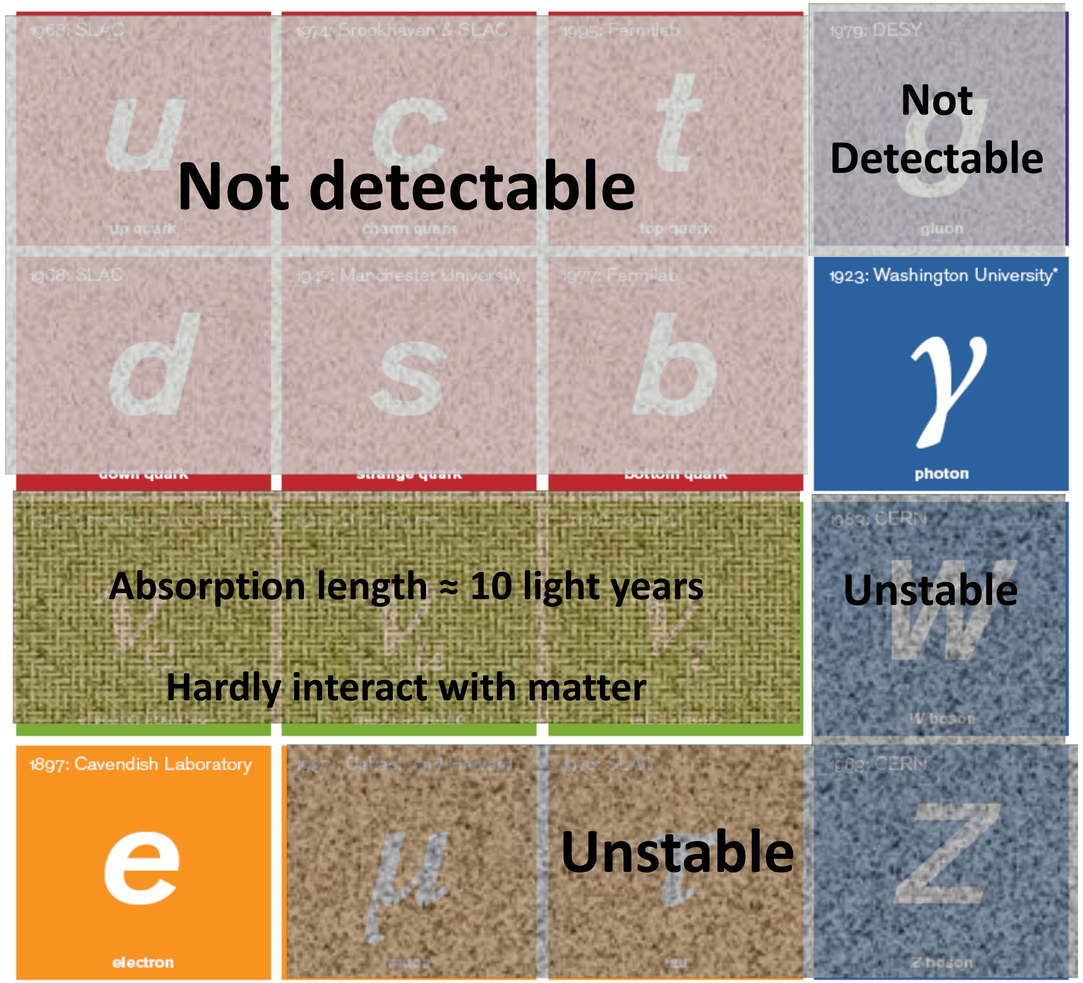




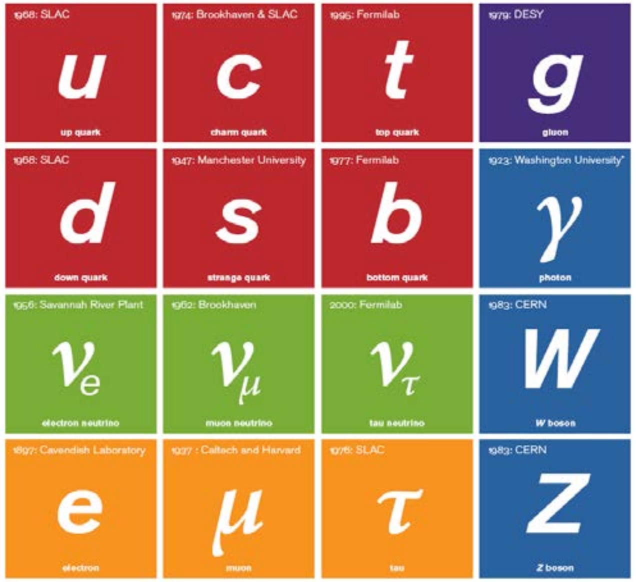
Dmitri Ivanovich Mendeleev

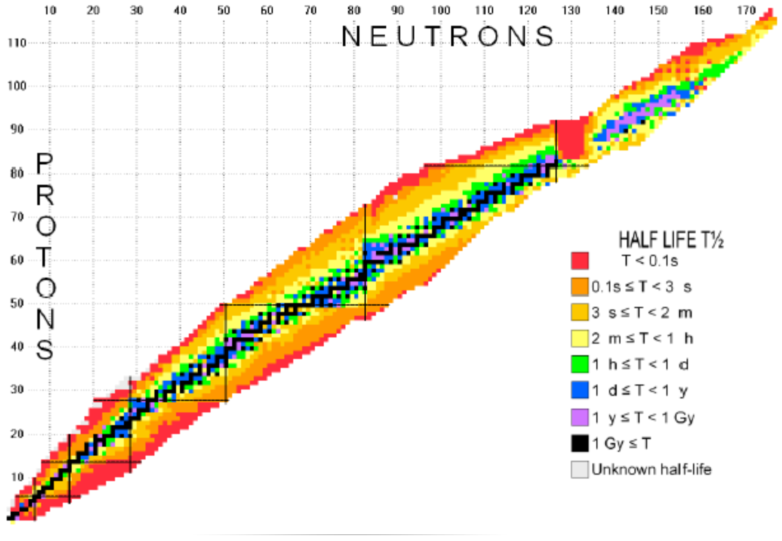
the periodic table of elements

Difficulties in understanding our universe



Bridge of understanding





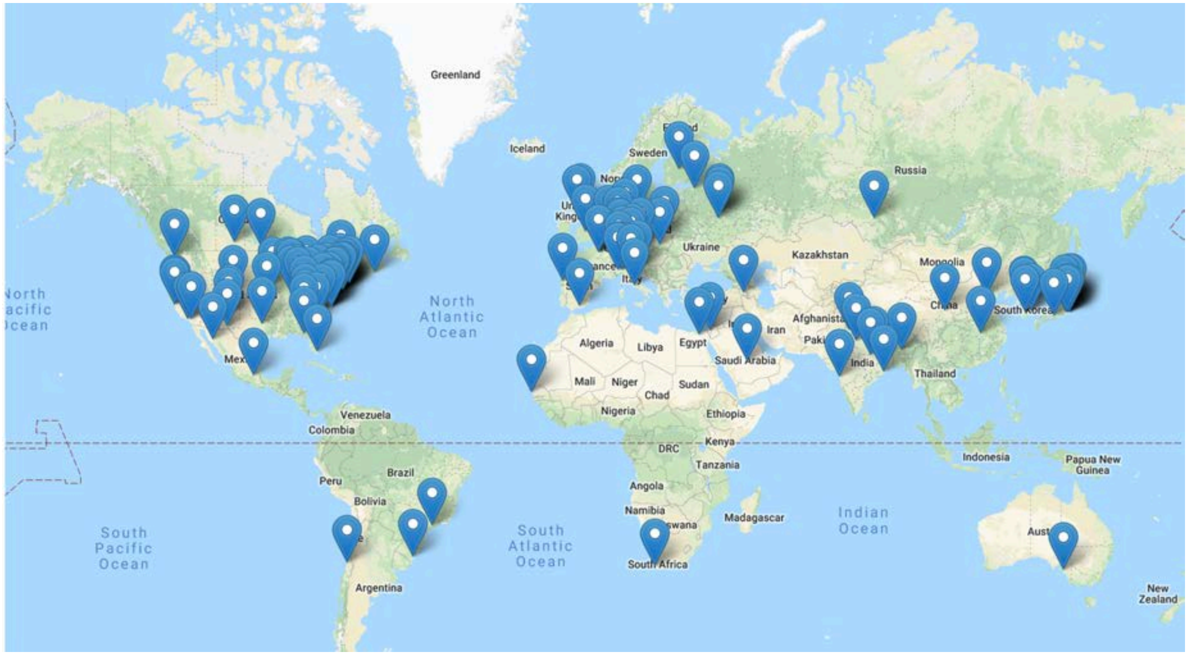
WE NEED A NEW 21^{ST} CENTURY TOOL

THE ELECTRON ION COLLIDER (EIC)

Introduction to EIC and its science, and kinematics

Lecture 1, Day 2

EIC does not exist yet



- Over 800 people from 170 institutions and 30 countries are working hard to realize the Electron Ion Collider.
- It is expected to be ready to take data in about 10 years…. About the time you will be ready to launch your independent scientific careers

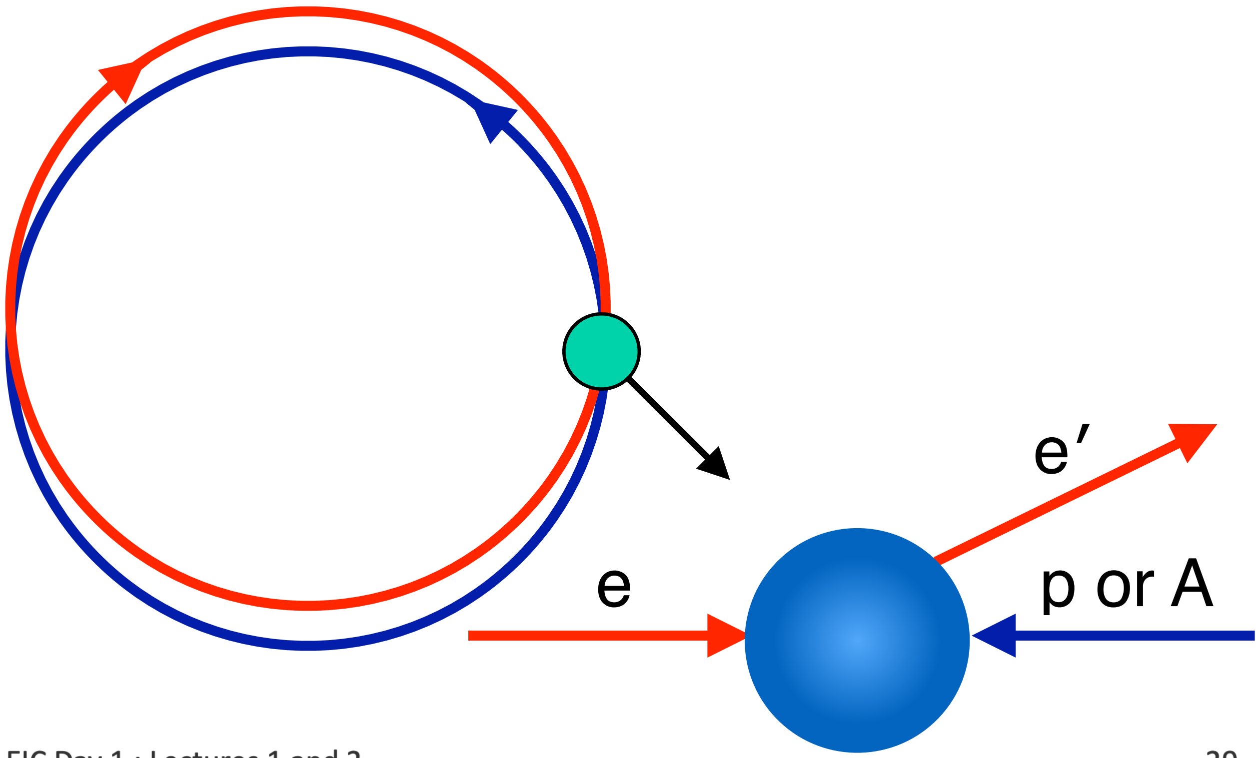
Why the excitement?

Electron Ion Collider : introduction

- First polarized electron-polarized proton collider
- First electron-nucleus collider
- Resolution reaching resolution of 10^{-18}m

Counter rotating beams of electrons, protons and nuclei collide at an interaction point.

- Electron is structureless
- Protons or nuclei are target ← with structure
- Deep Inelastic Scattering (DIS)



Scattering of protons on protons
is like colliding Swiss watches to find out
how they are build.

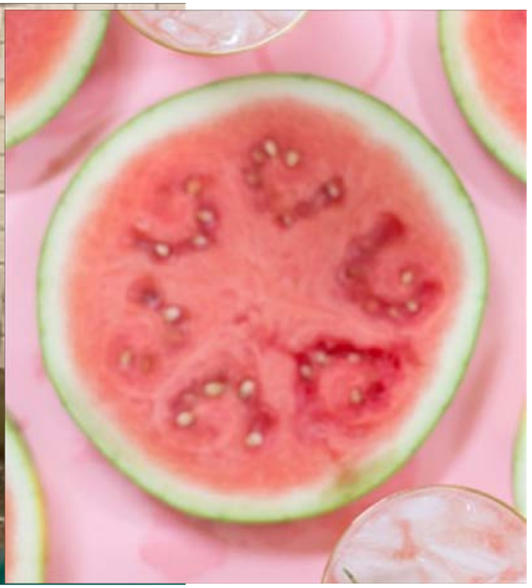
R. Feynman

We can ask : What is in there, but not how they are built or how they work!

Study of internal structure of a watermelon:

A-A (RHIC/LHC)

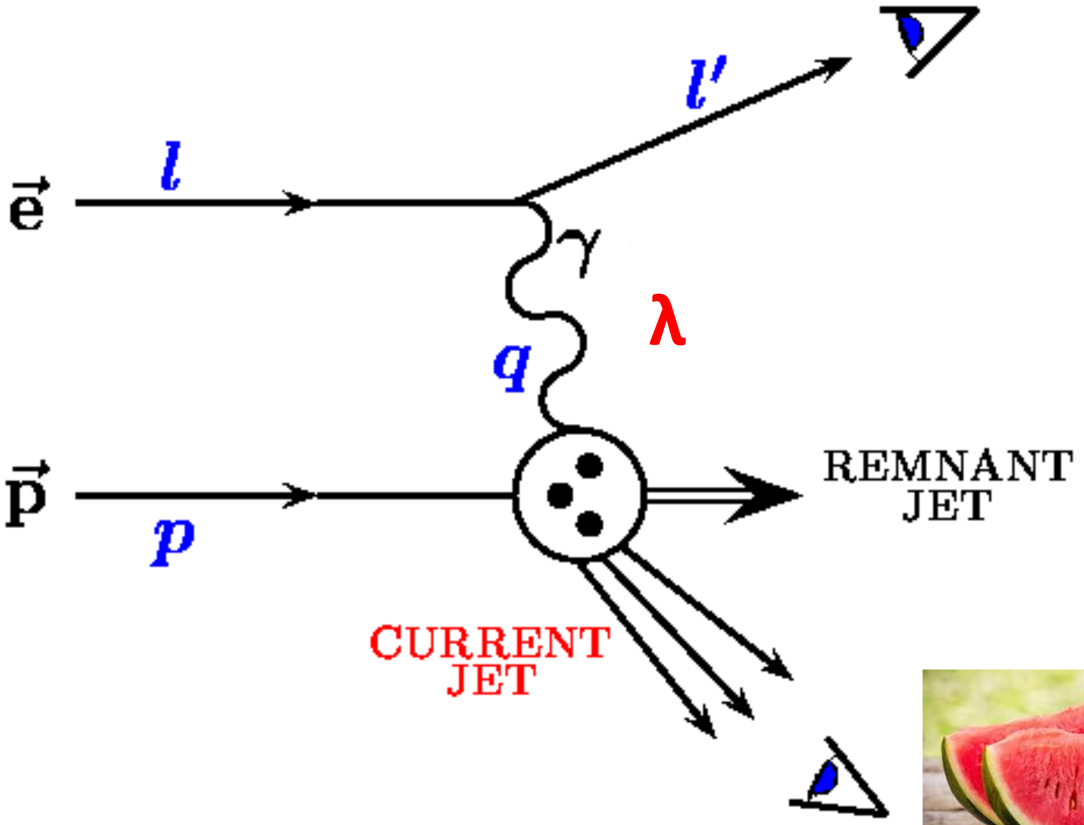
1) Violent collision of melons



2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

Deep Inelastic Scattering



q = h/λ

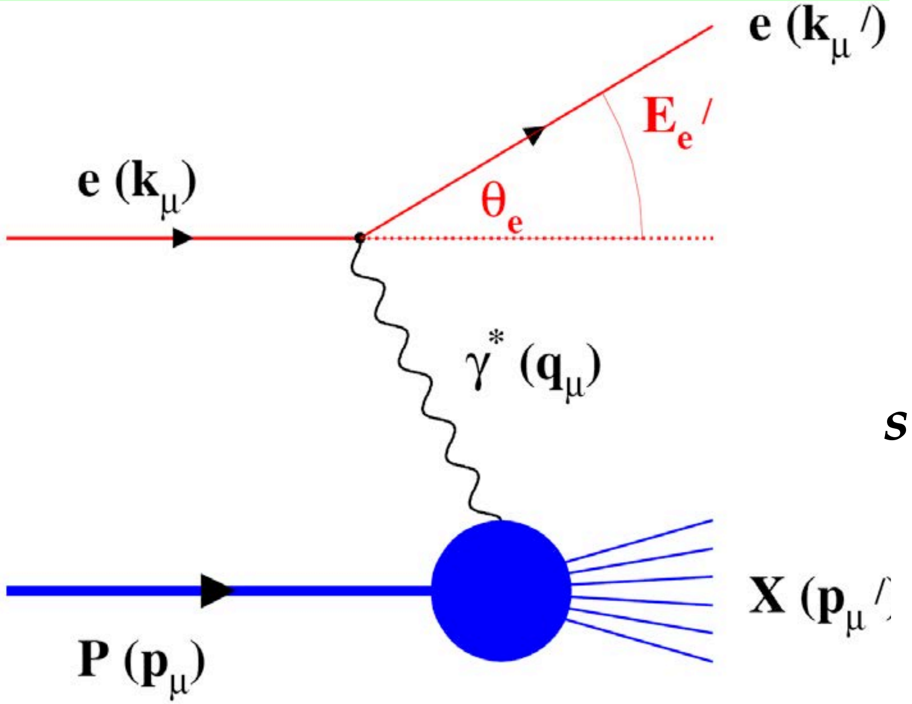
h = constant

λ = wavelength

q = momentum transferred

Deep Inelastic: (λ << Proton Size)

Deep Inelastic Scattering: Precision & Control



Kinematics:

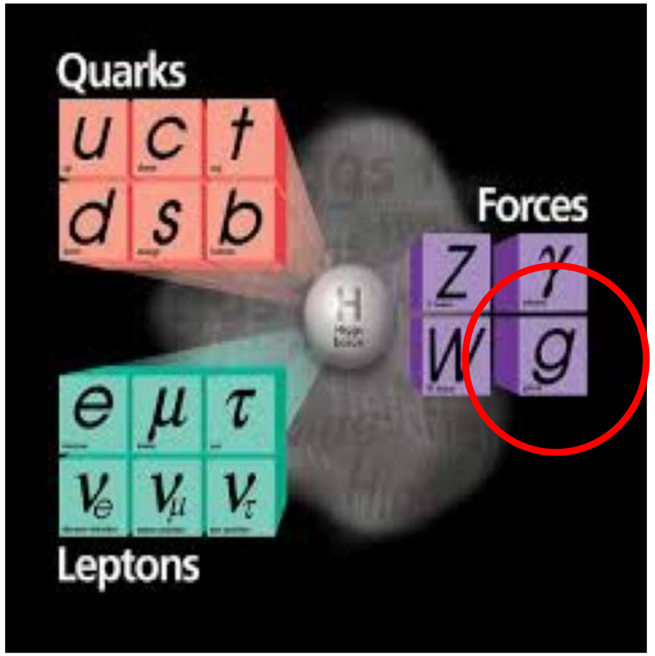
$$s = 4\,E_e\,E_p$$

Inclusive events: e+p/A → e'+X

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

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

Gluon in the Standard Model of Physics



Gluon: carrier of strong force (QCD)
Charg-eless, massless, but carries color-charge
Binds the quarks and gluons inside the hadrons with tremendous force!
At the heart of many un/(ill)-understood phenomena:

Color Confinement, composition of nucleon spin, quark-gluon plasma at RHIC & LHC…

All hadrons and mesons are made up of quarks & anti-quarks bound together by gluons…

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$ Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Mass and spin are fundamental properties of atomic particles…

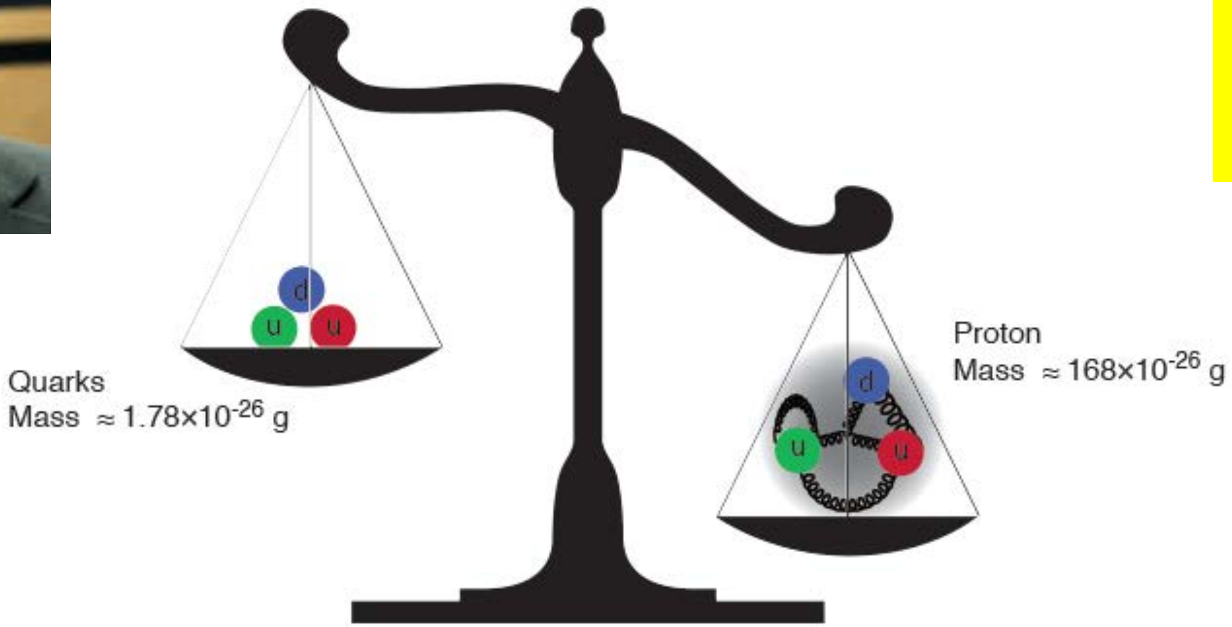
If a particle is composed of other smaller ones, they should contribute to those properties of the composite particles…

Sum of masses of quarks and gluons should add up to the mass of the proton

Sum of the spins of quarks and gluons should add p to the spin of the proton…

Proton mass puzzle

Peter Higgs



It is like saying:

1 + 1 + 1 = 300

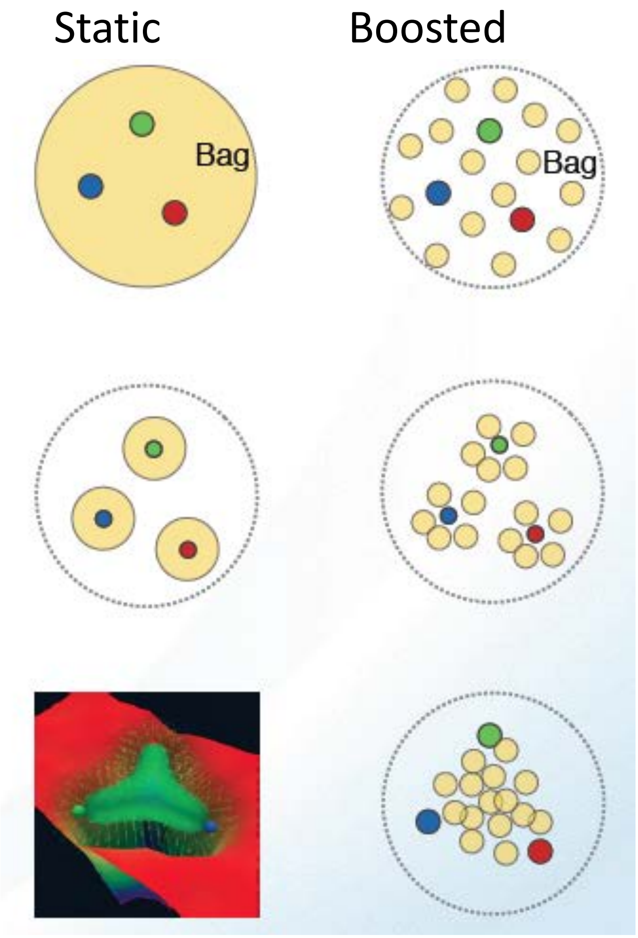
Add the masses of the quarks together 1.78 x 10^{-26} grams ← This mass comes from HIGGS mechanism

But the proton's mass (which is made of 3 dominant quarks and massless gluons) is 168 x 10^{-26} grams

→ only 1% of the mass of the protons (neutrons) and hence the visible universe comes from Higgs

→ Where does the rest of the mass come from?

What does a proton look like in transverse dimension?



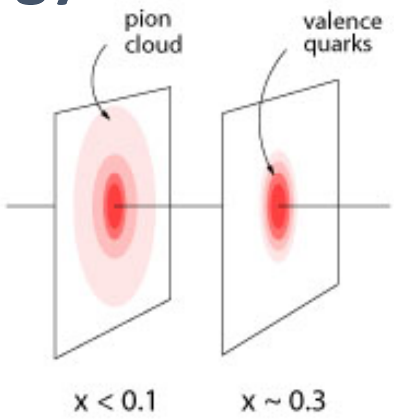
Bag Model: Gluon field distribution is wider than the fast moving quarks. Color (Gluon) radius > Charge (quark) Radius

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

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

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

What does a proton look like with increasing energy?

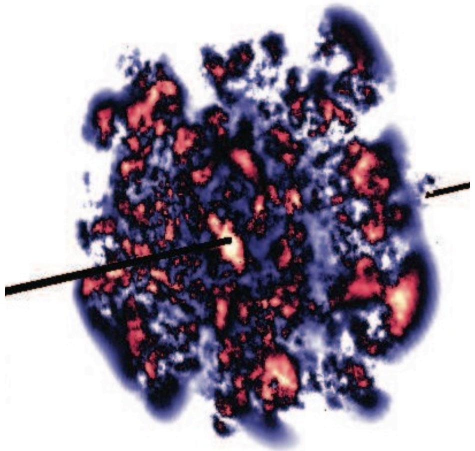


One of several possible scenarios: a pion cloud model

A parton core in the proton gets increasingly surrounded by a meson cloud with decreasing x
→ large impact on gluon and sea-quark observables

What do we expect to see:
- ❑ $q\bar{q}$ pairs (sea quarks) generated at small(ish)-x are predicted to be unpolarized
- ❑ gluons generated from sea quarks are unpolarized

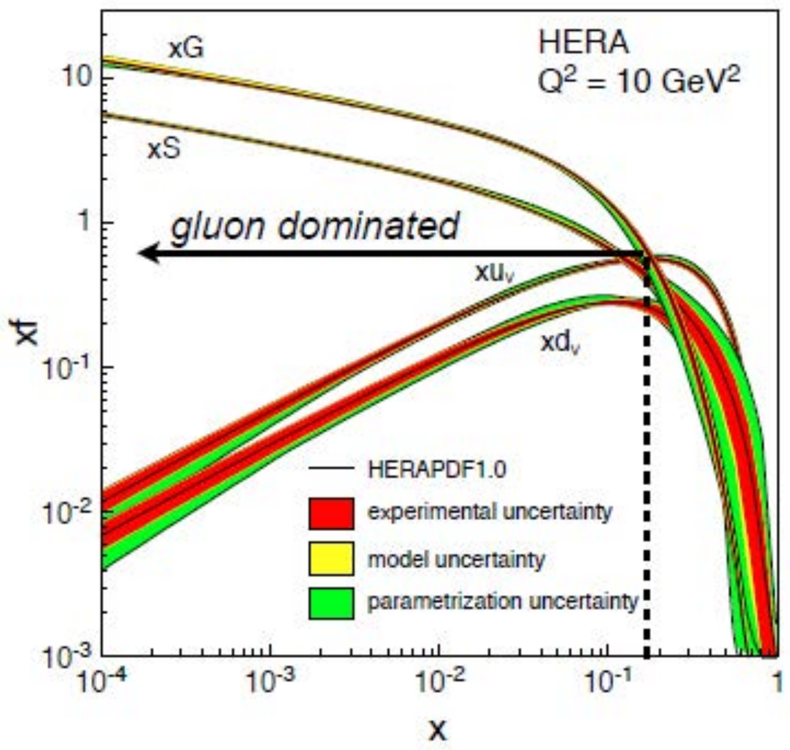
→ needed:
- ➢ high precision measurement of flavor separated polarized quark and gluon distributions as functions of x
- ➢ high precision spatial imaging: Gluon radius ~ sea-quark radius ?



What happens in the gluon dominated small-x regime?
- ➢ possible scenario: lumpy glue

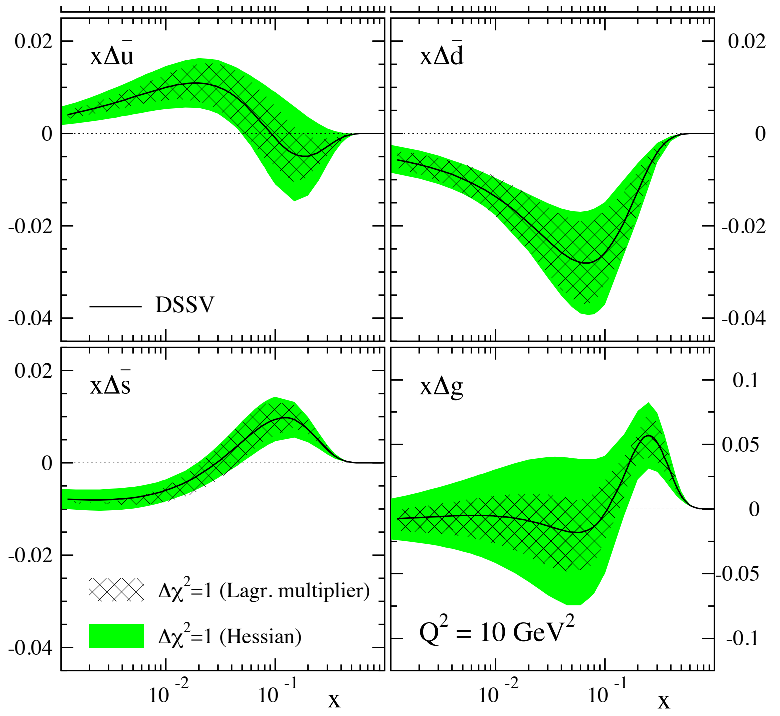
EIC needs to and will explore the dynamical spatial structure of hadrons

What do ***gluons*** in protons look like?
Unpolarized & polarized parton distribution functions



QCD
Terra-incognita!

High Potential for Discovery



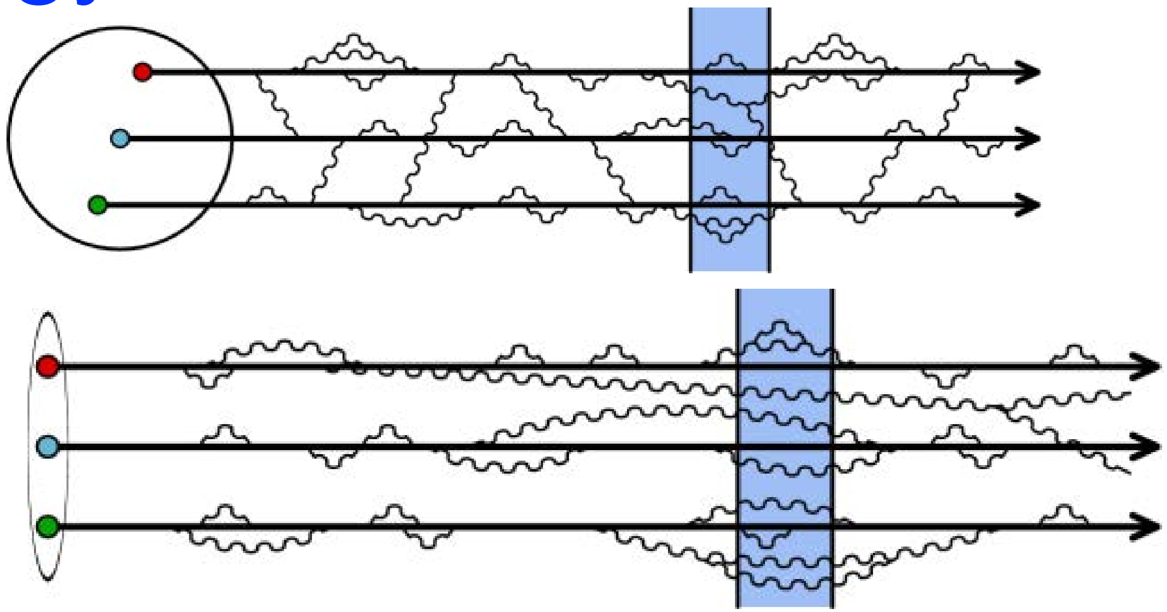
Need to go beyond 1-dimension!

Need (2+1)D image of gluons in a nucleon in position & momentum space

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

Low energy: High x
Regime of fixed target exp.

High energy: Low- x
Regime of a Collider



Cartoon of boosted proton

At high energy:

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

Gluon and the consequences of its interesting properties:

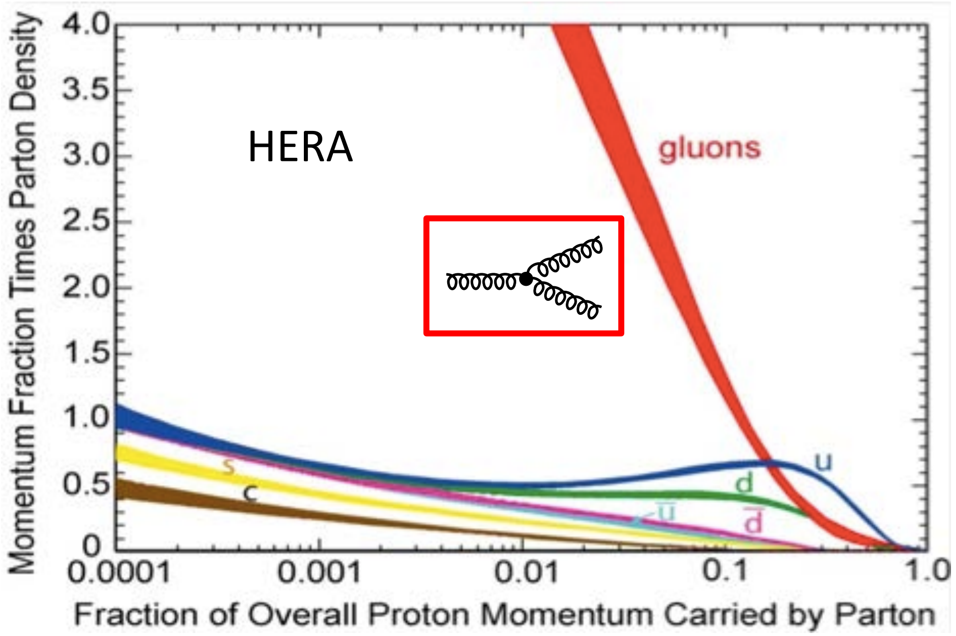
Gluons carry color charge ➔ Can interact with other gluons!

"…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

Gluon and the consequences of its interesting properties:

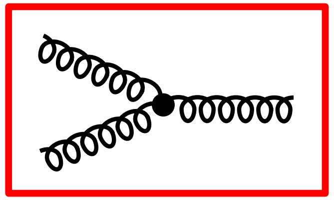
Gluons carry color charge ➔ Can interact with other gluons!



Apparent "indefinite rise" in gluon distribution in proton!

What could **limit this indefinite rise?** → saturation of soft gluon densities via gg→g recombination must be responsible.

recombination



Where? No one has unambiguously seen this before!

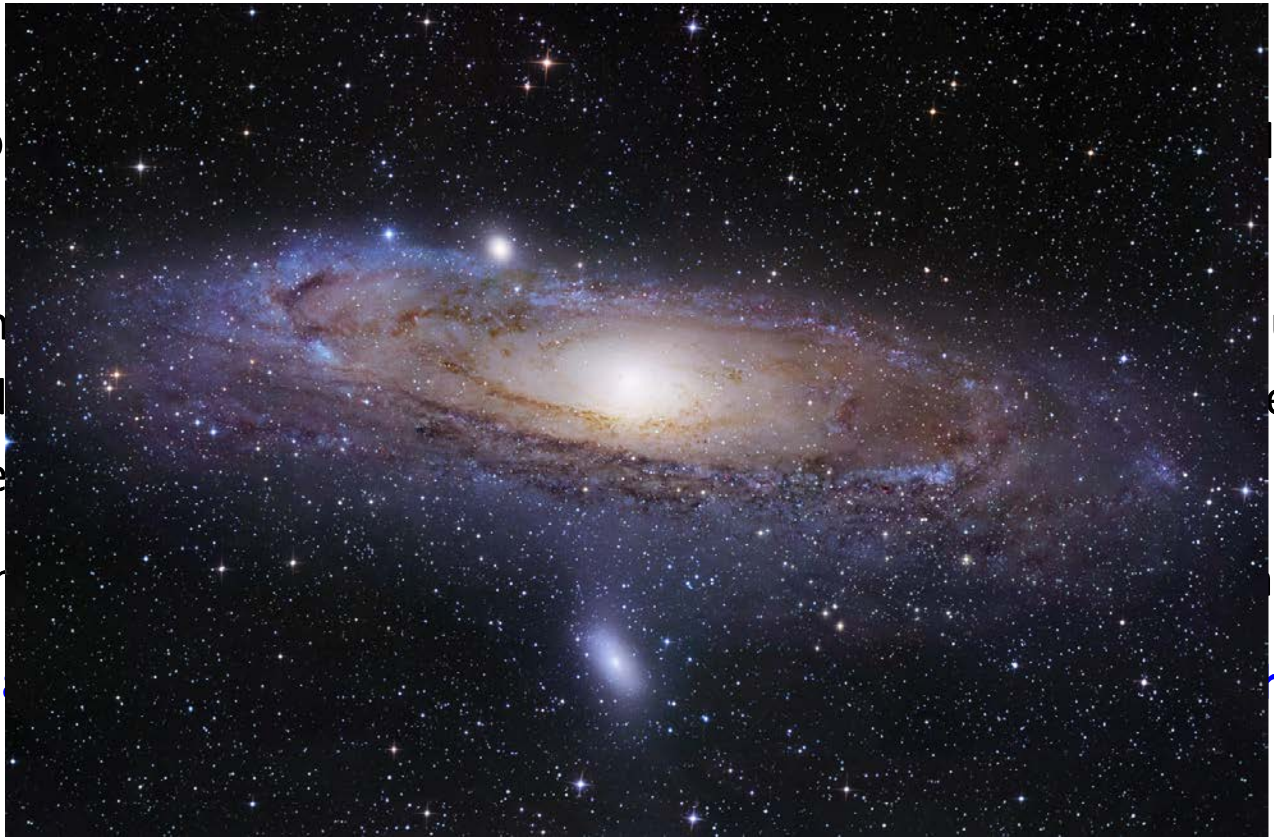
If true, effective theory of this →"Color Glass Condensate"

Emergent Dynamics in QCD

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

- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% o **leon's spin**, and are essential for the dyn
- Properties of hadron uation of motion but are also inextricably tied esides confinement are spontaneous symme
- The nucleon-nucleor ppens remains a mystery

Experimental insight adrons & nuclei emerge



QCD: The Holy Grail of Quantum Field Theories

- QCD : "nearly perfect" theory that explains nature's strong interactions, is a fundamental quantum theory of quarks and gluon fields
- QCD is rich with symmetries:

$$SU(3)_C \times SU(3)_L \times SU(3)_R \times U(1)_A \times U(1)_B$$

(1) (2) (3)

(1) Gauge "color" symmetry : unbroken but confined
(2) Global "chiral" flavor symmetry: exact for massless quarks
(3) Baryon number and axial charge (massless quarks) conservation
(4) Scale invariance for massless quarks and gluon fields
(5) Discrete C, P & T symmetries

- Chiral, Axial, Scale & P&T symmetries broken by quantum effects: Most of the visible matter in the Universe emerges as a result
- Inherent in QCD are the deepest aspects of relativistic quantum field theories: (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry) ➔ all depend on non-linear dynamics in QCD

Non-linear Structure of QCD has Fundamental Consequences

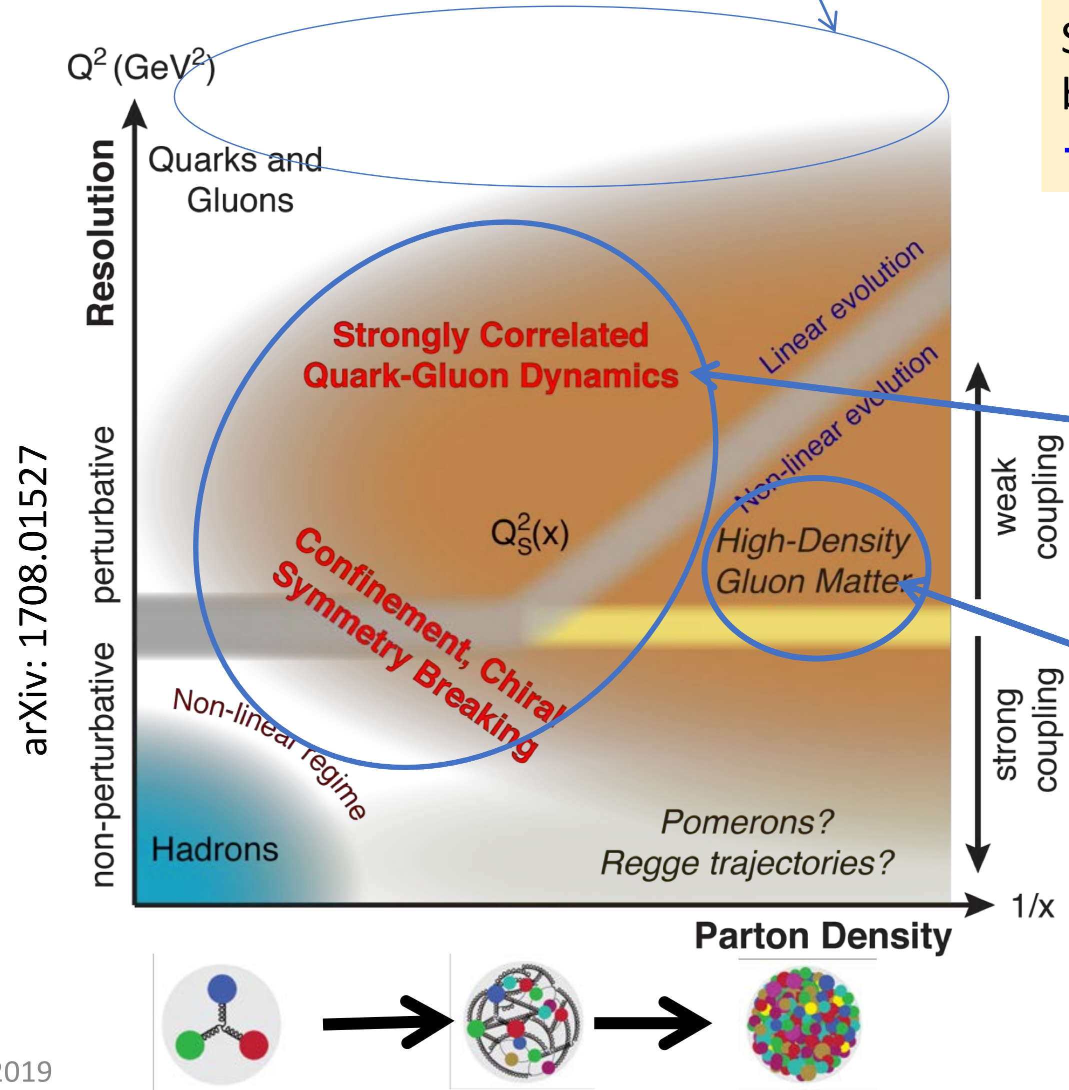
Emergence of spin, mass & confinement, gluon fields

- Quark (Color) confinement:
  - Unique property of the strong interaction
  - Consequence of nonlinear gluon self-interactions
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs):
  - Confined spatial correlations of quark and gluon distributions – Generalized Parton Distributions (GPDs):
- Ultra-dense color (gluon) fields:
  - Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?

QCD Landscape to be explored by EIC

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

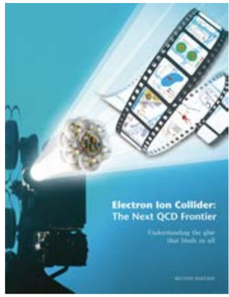
Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges



EIC will systematically explore correlations in this region.

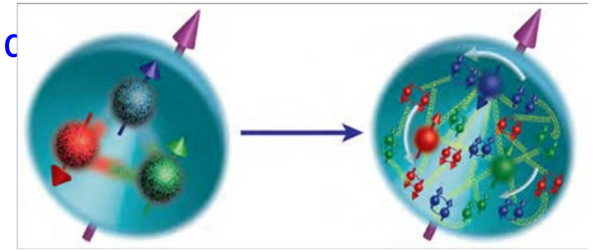
An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter

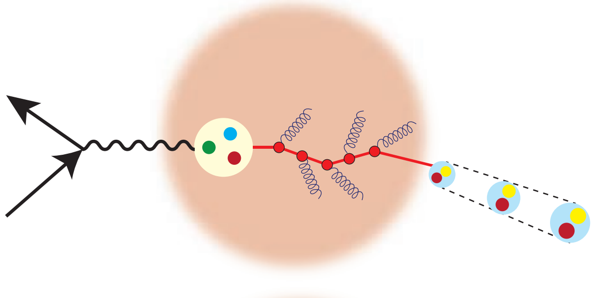
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter



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

How do the nucleon properties emerge from them and their interactions?

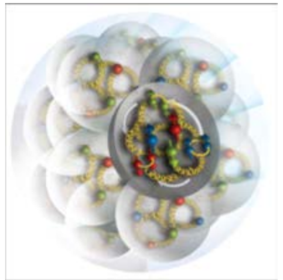




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

How do the quark-gluon interactions create nuclear binding?

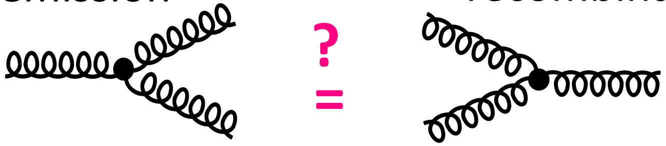


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

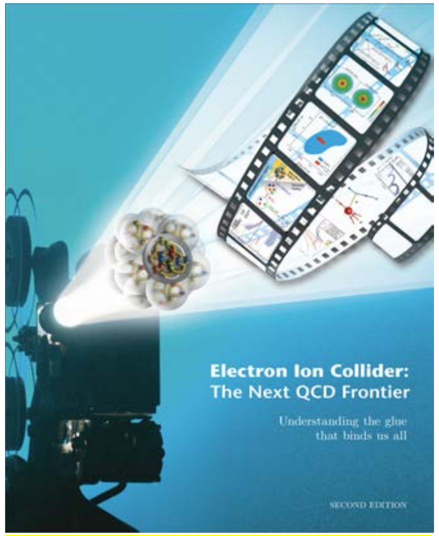
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission

gluon recombination



The Electron Ion Collider



1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

For e-N collisions at the EIC:

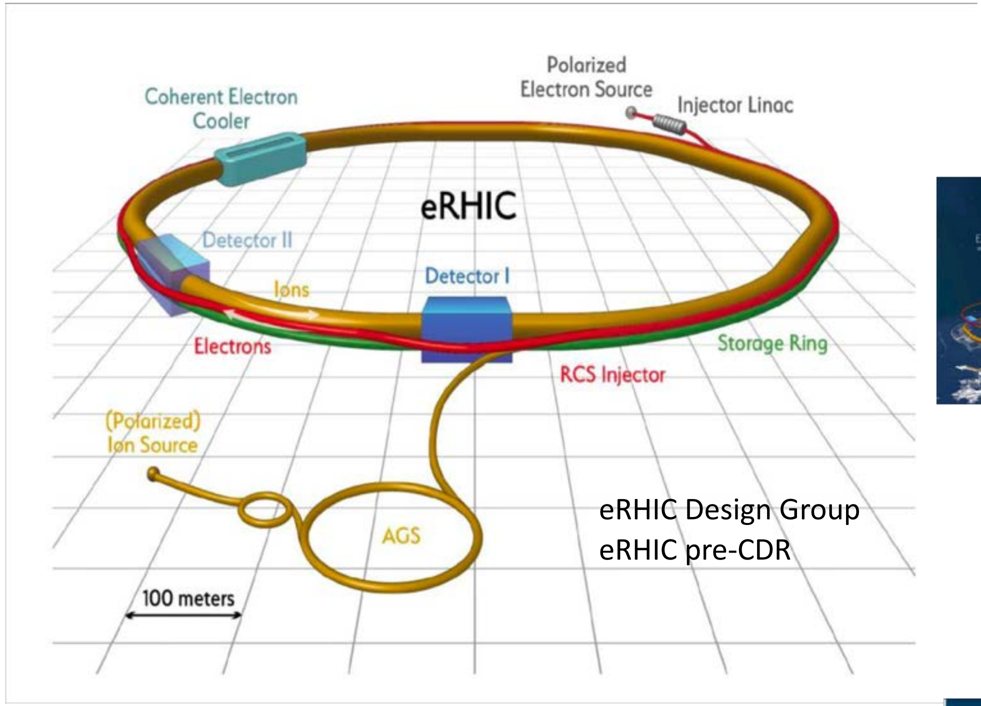
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
  - ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

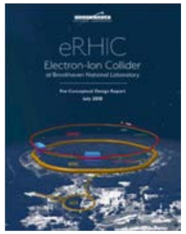
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

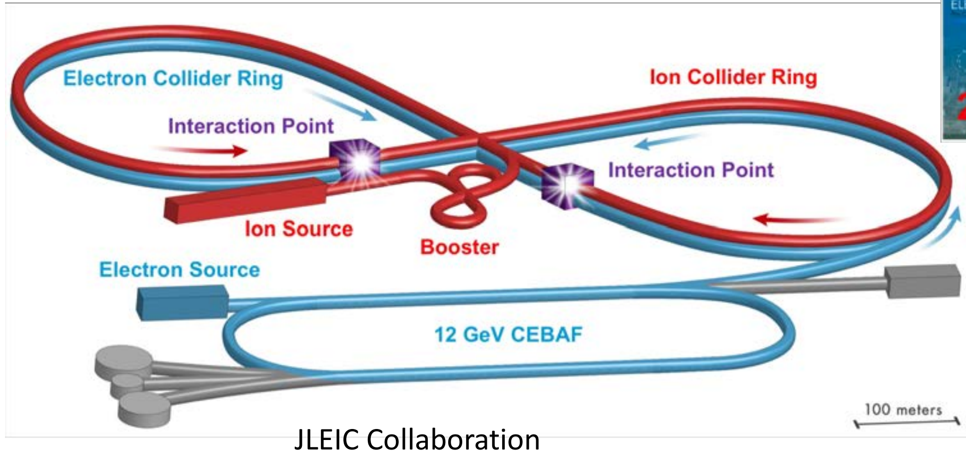
Both designs use DOE's significant investments in infrastructure

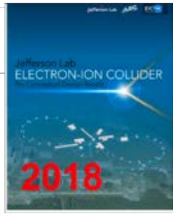


eRHIC Design Group
eRHIC pre-CDR



2018





JLEIC Collaboration
JLEIC Pre-CDR about to be finalized

Deep Inelastic Scattering

A most impressive investigative method in particle physics

If you wanted to look inside the hadrons….

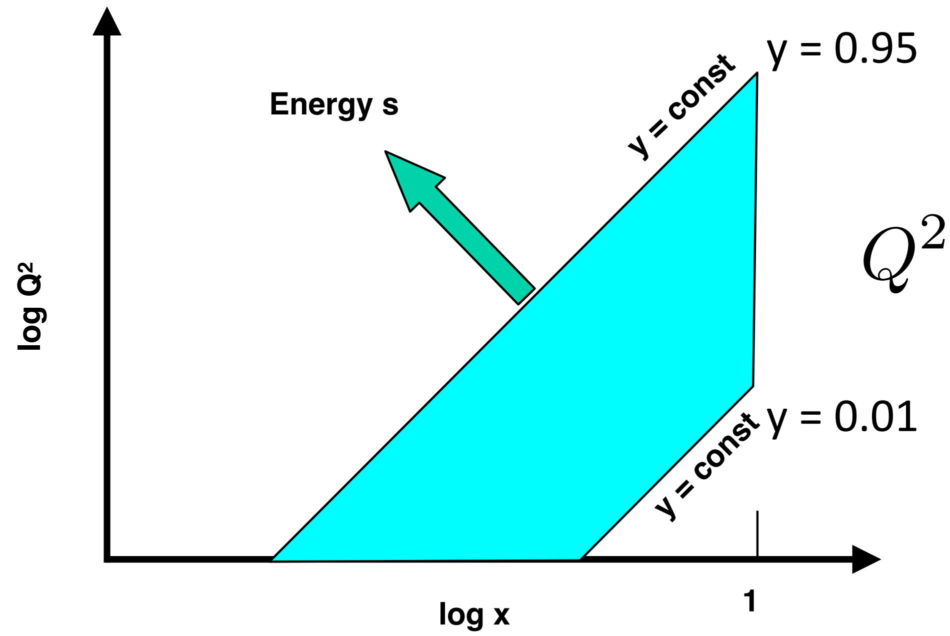
Understanding the proton structure

How would you do it?

Deep Inelastic Scattering (DIS)

- Discovered quarks inside the nucleons → birth of QCD → Nobel Prizes in 1990 and 2004, respectively…
- Discovered Nucleon Spin Crisis
- Discovered the quarks inside a proton in nucleus behave differently

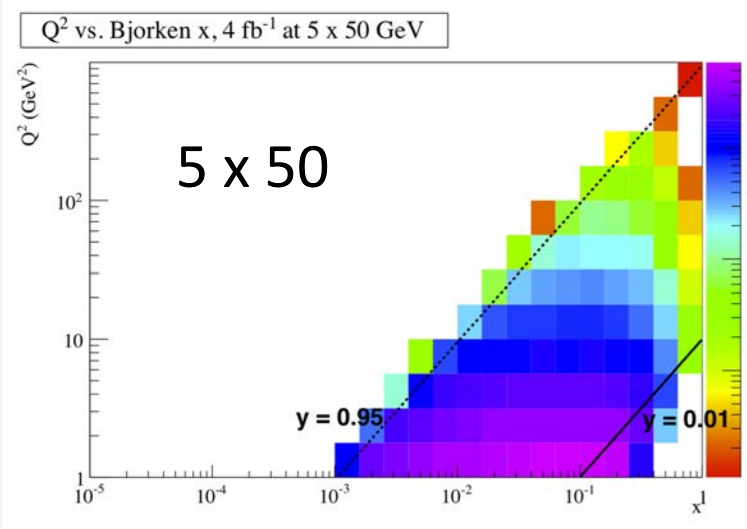
The x-Q^2 plane…

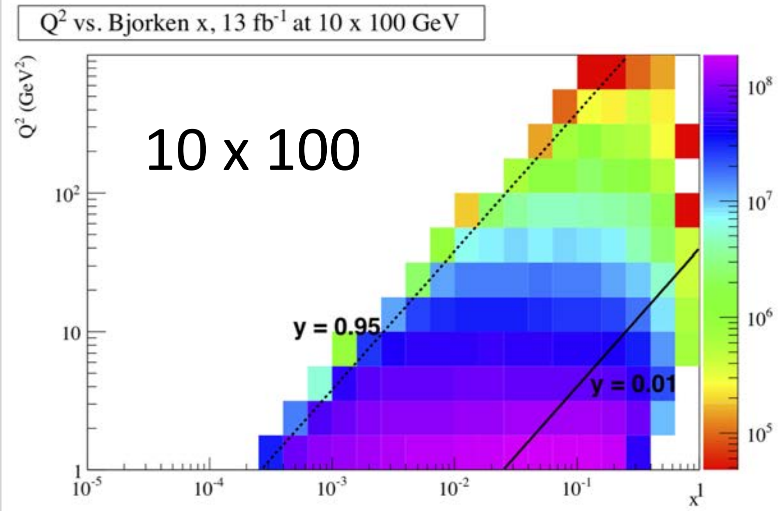


$$Q^2 \approx s \cdot x \cdot y$$

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

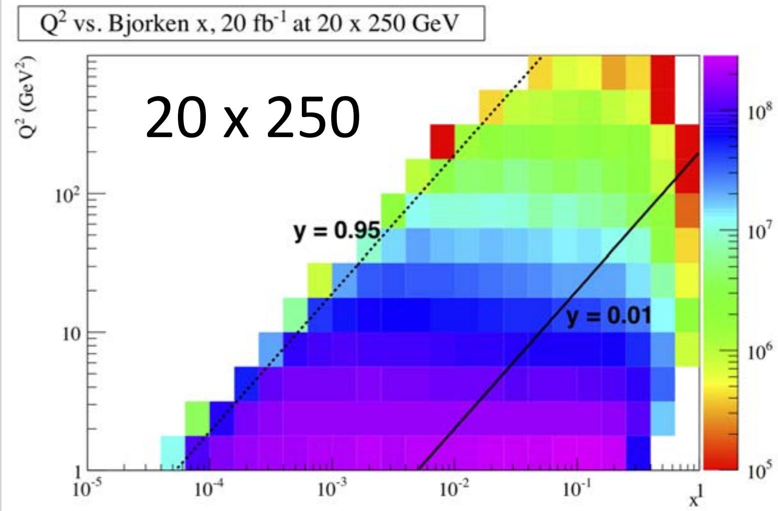
Kinematic coverage as a function of energy of collisions





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:

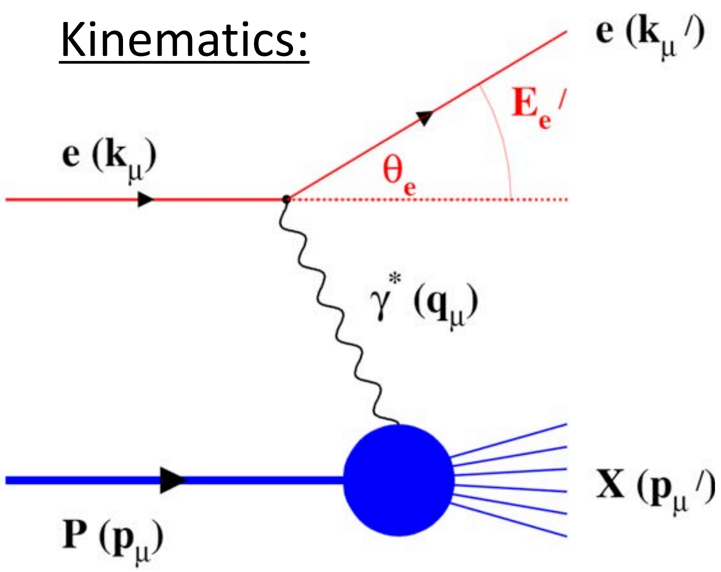
https://core.ac.uk/download/pdf/25211047.pdf

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.

Deep Inelastic Scattering: Precision and control

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

$$s = 4\, E_t\, E_e \qquad x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Hadron **:**

$$z = \frac{E_h}{\nu}; \; p_t \text{ with respect to } \gamma$$

Inclusive events:

e+p/A → e'+X

detect only the scattered lepton in the detector

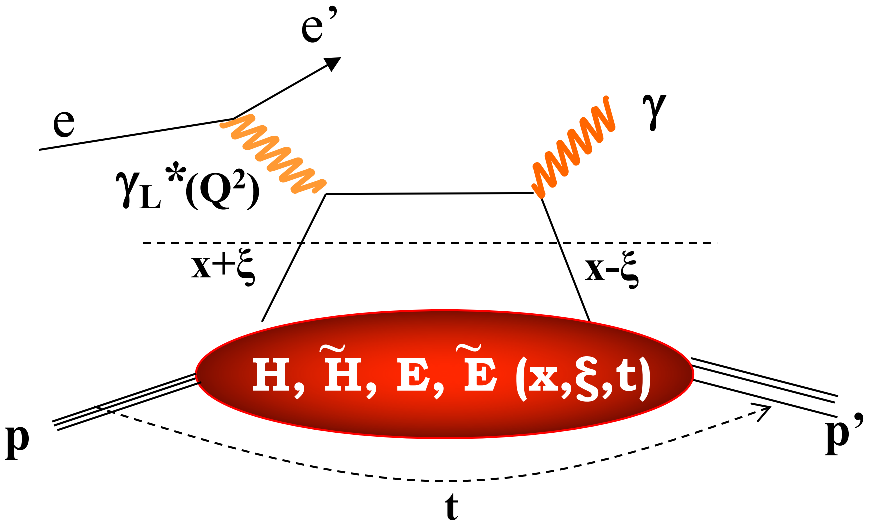
Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets in the detector

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

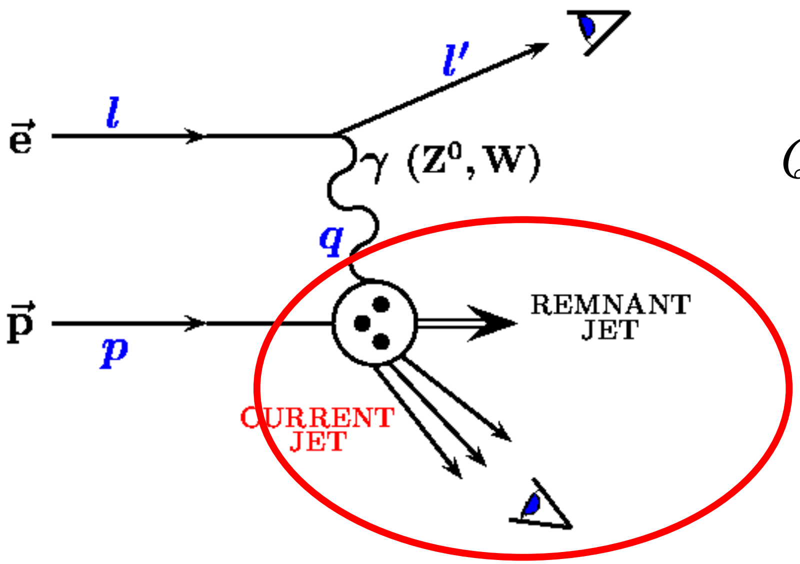
Special sub-event category rapidity gap events
e + **(p/A)** → e' + γ / J/ψ / ρ / ϕ / jet
Don't detect **(p'/A') in final state**

Some times scattered electron can't be measured….

Reason:

1) Scattering angle so small that it is too close to the beam pipe
2) Radiative correction too large, i.e. electron lost its energy due to Initial State Radiation or Brehmstrahlung through material -- So the kinematic reconstruction unreliable.

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



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

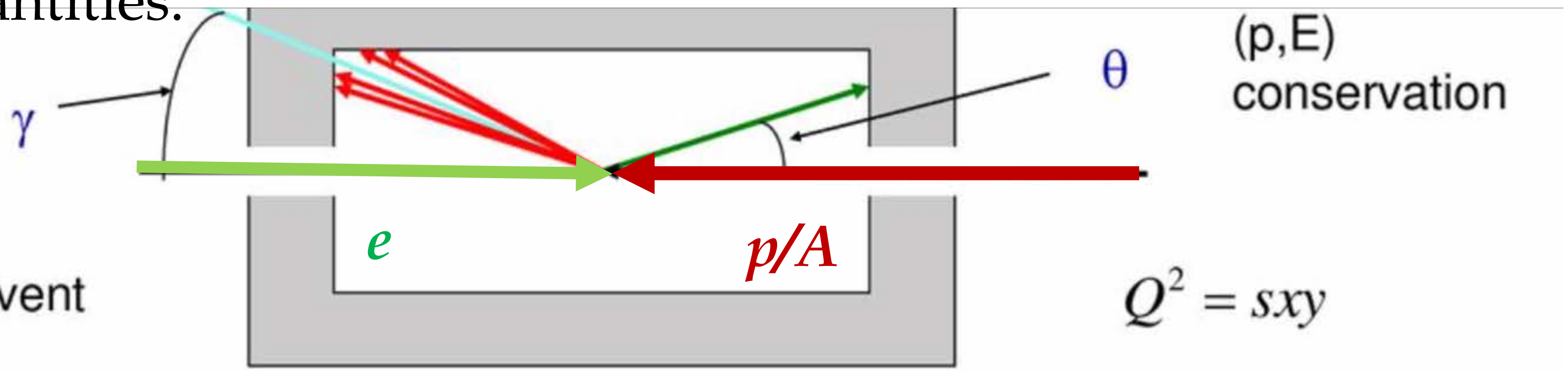
$$x = \frac{E_j}{2E_p}(1 + cos\theta_j)/(1 - y)$$
$$E_j = yE_e + x(1 - y)E_p$$
$$cos\theta_j = \frac{-yE_e + (1-y)xE_p}{y\,E_e + (1-y)xE_p}$$
$$E_j^2 sin^2\theta_j = 4\,xy(1-y)E_eE_p = Q^2\,(1-y)$$

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

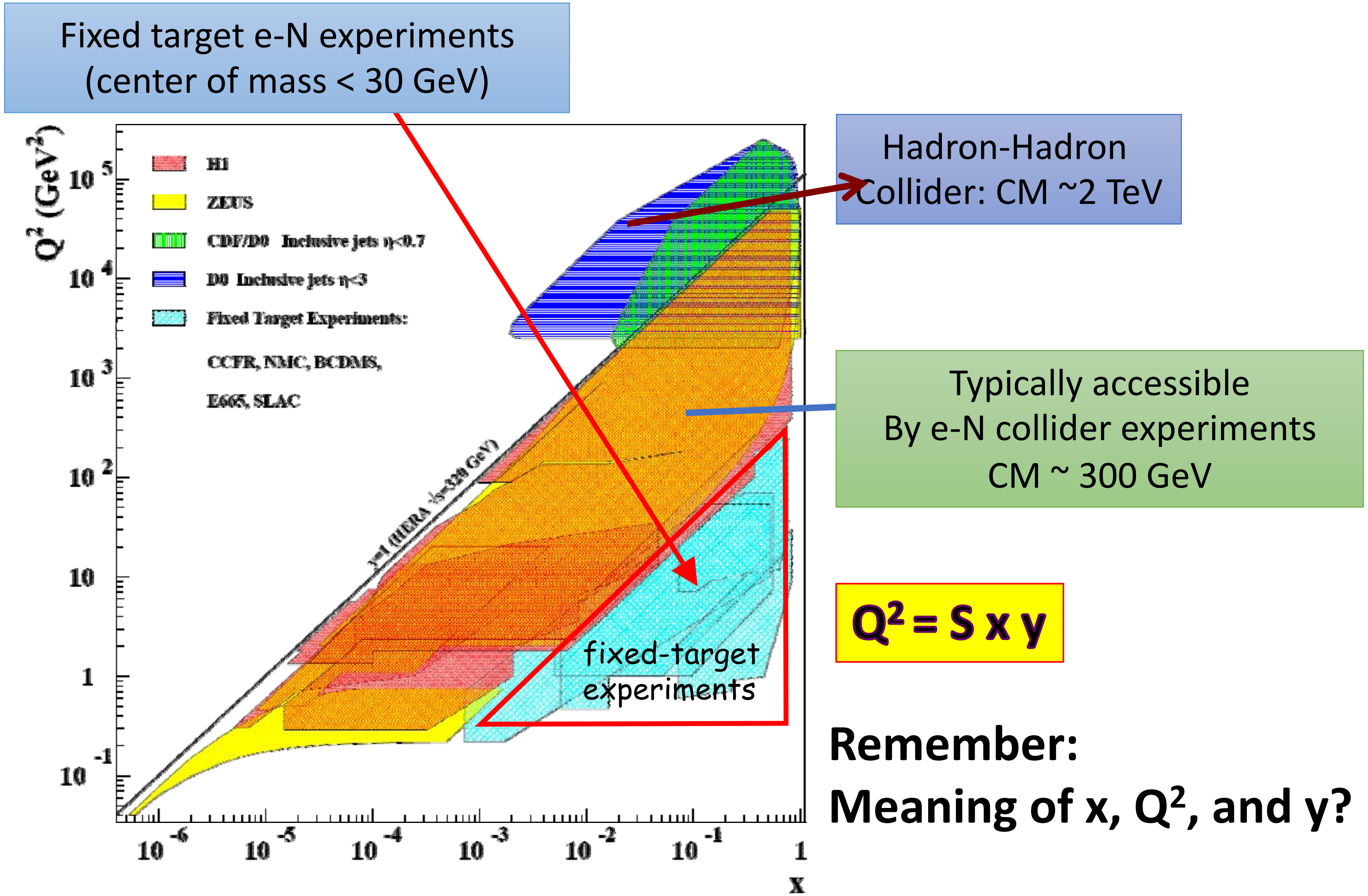
There are multiple ways to reconstruct events:

Four measured quantities:

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



Perspective on x,Q^2, Center of Mass



$\boxed{Q^2 = S\ x\ y}$

Remember:

Meaning of x, Q^2, and y?

Home work

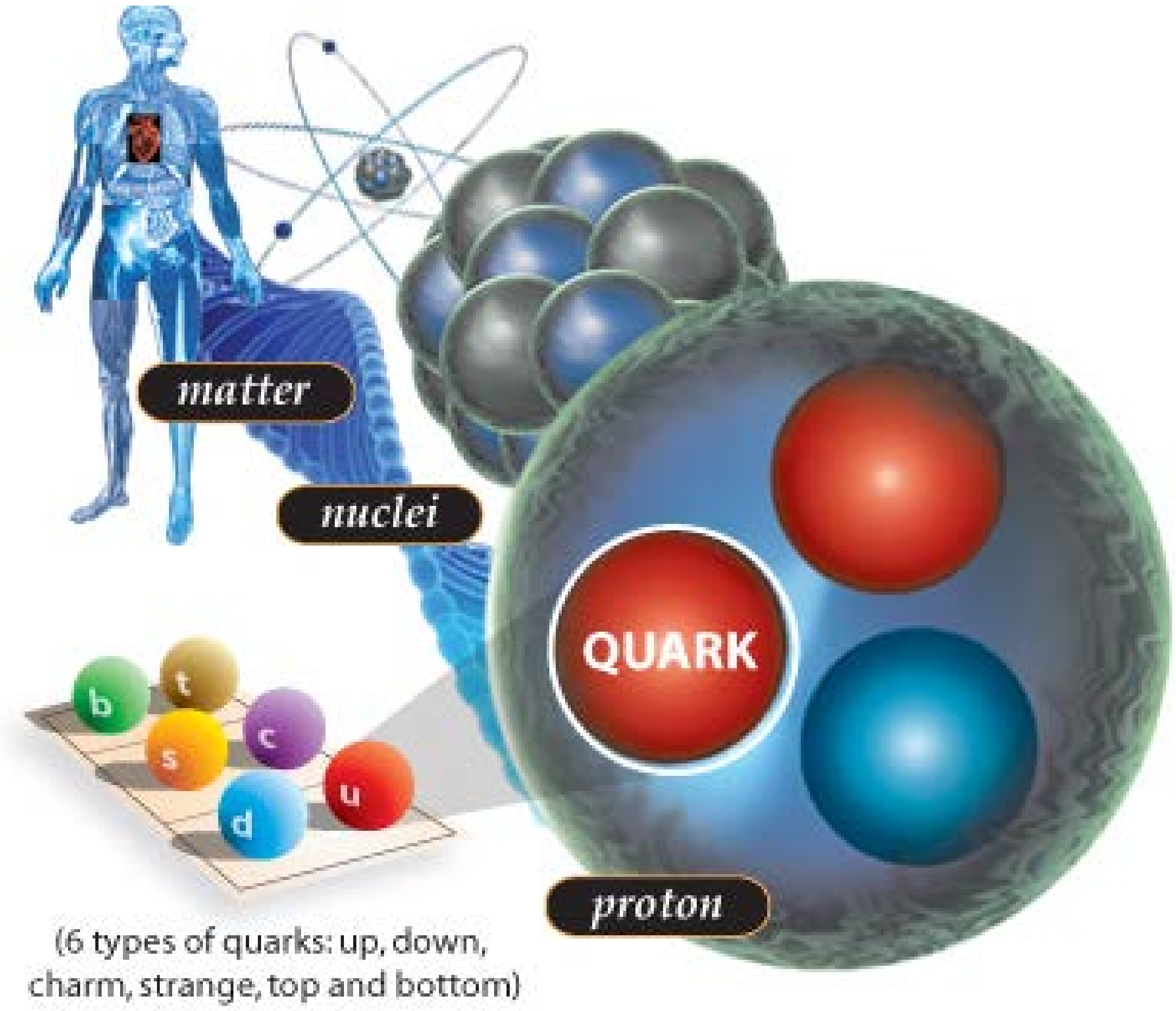
- Assume a 10 GeV electron hits a 250 GeV proton
- Using xls or any other computing tool you may have at the center or on your laptop, calculate the x-Q2 range in which DIS events will fall (like on slide 60).
  - Limit the events to 0.1 < y < 0.9 in kinematic variable for inelasticity
  - On the same x-Q2 plane, calculate the locus of constant angle scatter of electron: 5, 100 and 170 degrees. Remember: the proton going direction is considered forward (positive) rapidity direction.
  - Sanity check: can final electron energy in DIS/Collider be more than the initial energy? No? – Why not? ; Yes? Why?
  - On the x-Q2 plane: calculate the locus of the constant energy of the scattered electron: 5 GeV, 10 GeV and 15 GeV.

Thanks, we will stop here today…

How are quarks related to us?

- Quarks and the electrons are the smallest indivisible particles found in nature…

- we are all made up of them, and quarks are bound by **gluons**
- electrons interact with protons by the exchange of **photons**
- Quarks are never free, they are confined inside 3 or 2 quark systems



QED vs. QCD

- Quantum Electro-Dynamics (QED) ➔ force mediated by photons (light)
  - Electric charges : 2 types + & -
  - Electrons, protons carry electric charge
  - Interactions mediated by massless "photons"
  - Photons are electrically neutral

- INSIDE a proton: Quantum Chromo-Dynamics (QCD)
  - Color charges : 3 types → red, blue, green ➔ Never seen separately
  - Quarks carry electric AND color charge
  - Interactions between quarks mediated by massless "gluons" → "g"
  - Gluons are electrically neutral but **carry color charge!**

?