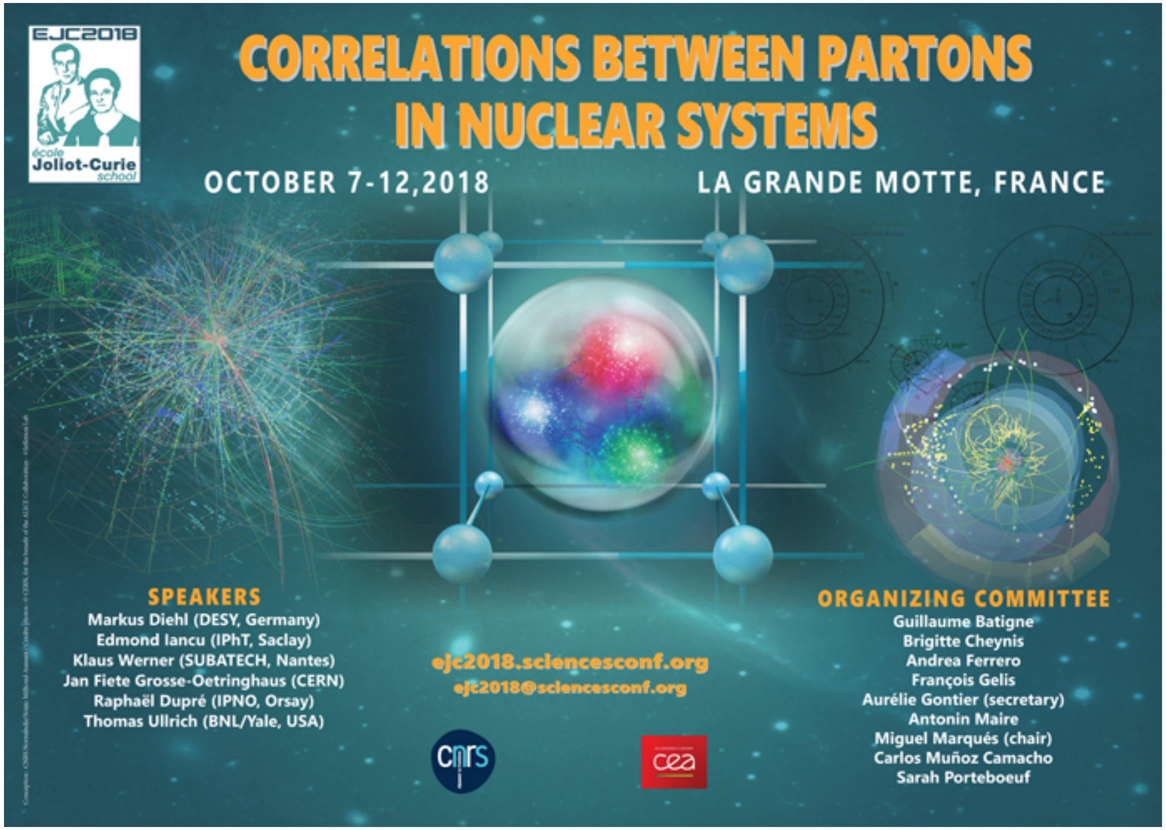
The Electron-Ion Collider

Lecture 1&2



EJC2018

école Joliot-Curie school

CORRELATIONS BETWEEN PARTONS IN NUCLEAR SYSTEMS

OCTOBER 7-12,2018

LA GRANDE MOTTE, FRANCE

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Edmond Iancu (IPhT, Saclay)
Klaus Werner (SUBATECH, Nantes)
Jan Fiete Grosse-Oetringhaus (CERN)
Raphaël Dupré (IPNO, Orsay)
Thomas Ullrich (BNL/Yale, USA)

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EJC2018, October 11-12, 2018

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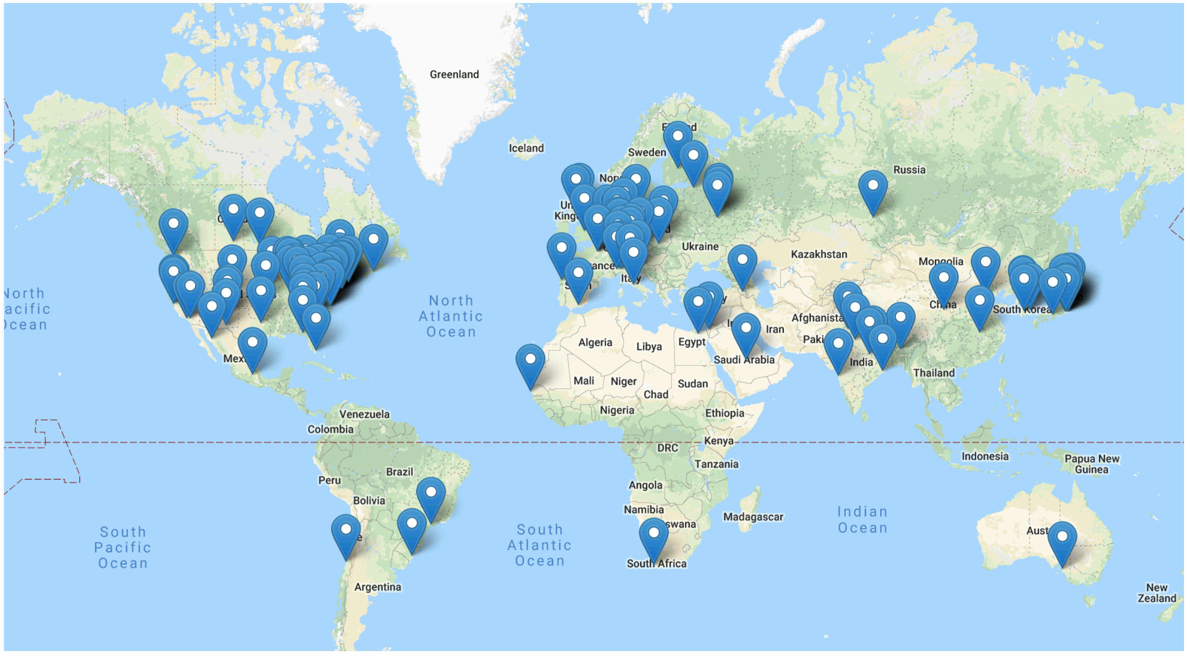
The Electron-Ion Collider

The Electron-Ion Collider does not exist

The Electron-Ion Collider does not exist

Yet!!



Over 800 people from 169 institutions and 29 countries are working hard to make it happen within the next decade.

I am one of them.

The Electron-Ion Collider on One Page

The Electron-Ion Collider will be a machine for learning about the secrets of gluons that binds the building blocks of visible matter in the universe.

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Tools:

- The world's first polarized electron-polarized proton collider
- The world's first electron-heavy ion collider
- Fine resolution inside proton down to 10^{-18} meters

The Electron-Ion Collider on One Page

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Tools:

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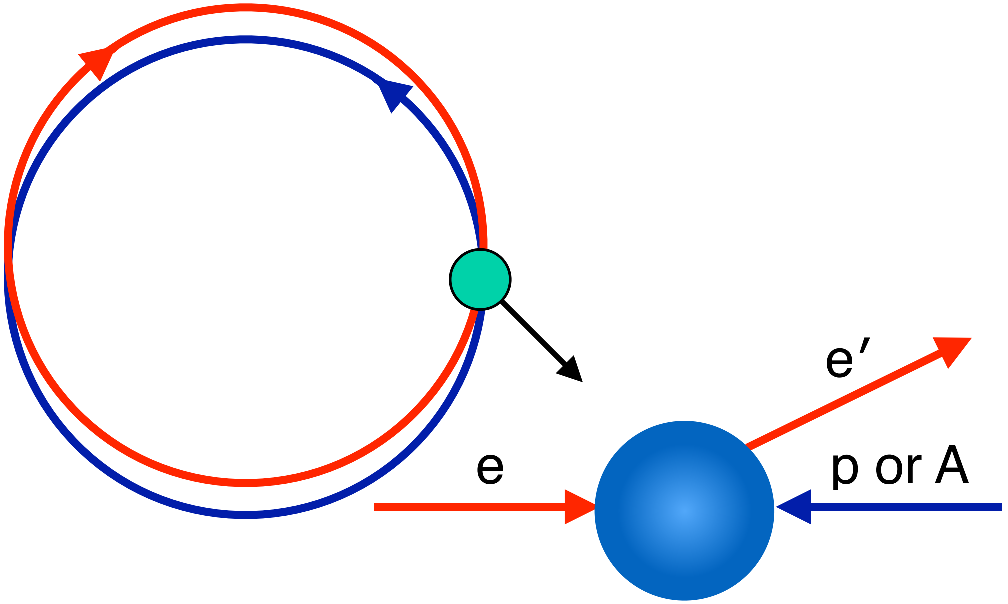
- Fine resolution inside proton down to 10^{-18} meters



- Counter rotating beams of electrons and protons/ions collide at an interaction point
- The probe (electron) is structure-less and scatters off a “target”. The process is called Deep Inelastic Scattering.

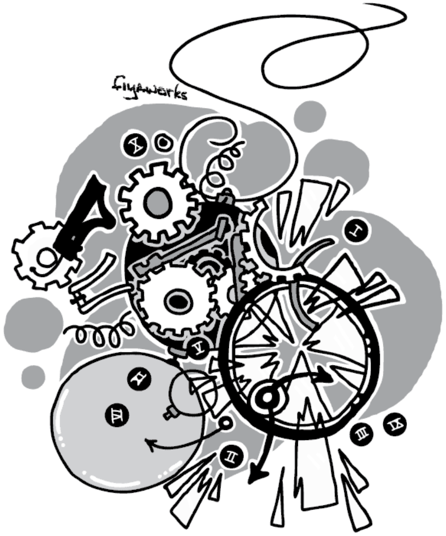
Syllabus

1. Probing Matter
    1.1. Scattering Experiments
    1.2. Electron Scattering
2. Quark Models and QCD
    2.1. Static Quark Model
    2.2. QCD
    2.3. Gluons
3. Studying Matter at the Smallest Scale
    3.1. DIS & Kinematics
    3.2. Structure Functions
    3.3. Parton Distribution Function
4. The Frontiers of Our Ignorance
    4.1. Mass
    4.2. Cross-Sections
    4.3. Saturation
    4.4. Spin Puzzle
    4.5. Imaging
    4.6. Fragmentation
5. Landscape of QCD
6. Big question and what we need to answer them
7. Realization of an EIC
8. Detectors
9. Examples of Key Measurements at an EIC
    9.1. Spin of the proton
    9.2. Imaging
    9.3. Structure Functions and Nuclear PDFs in eA Collisions
    9.4. Dihadron Correlations
    9.5. Diffractive physics in eA
10. Closing comments and further reading

1. Probing Matter

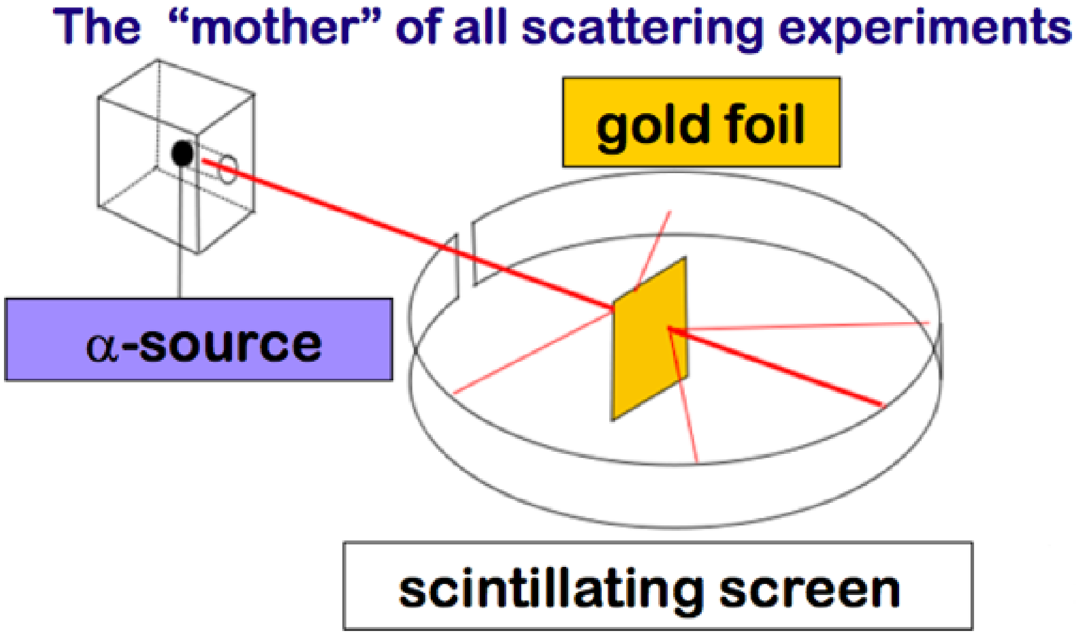
Scattering of protons on protons
is like colliding Swiss watches to find out
how they are build.

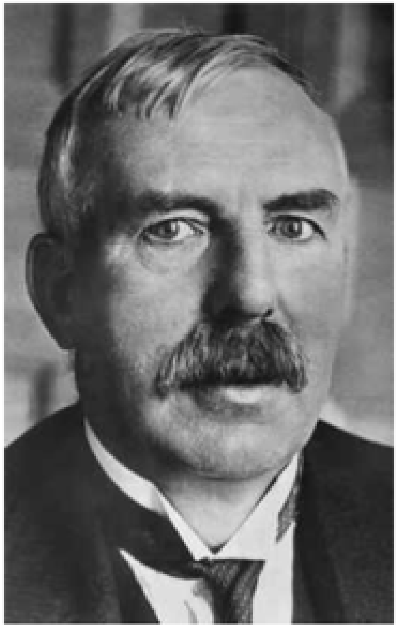
R. Feynman



Probing Matter (1909)

The first exploration of subatomic structure was undertaken by Rutherford at Manchester using Au atoms as targets and α particles as probes.





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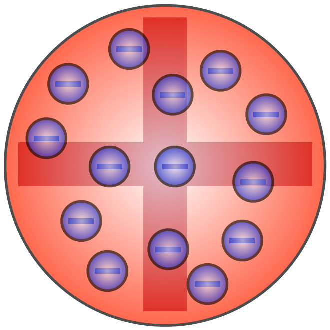
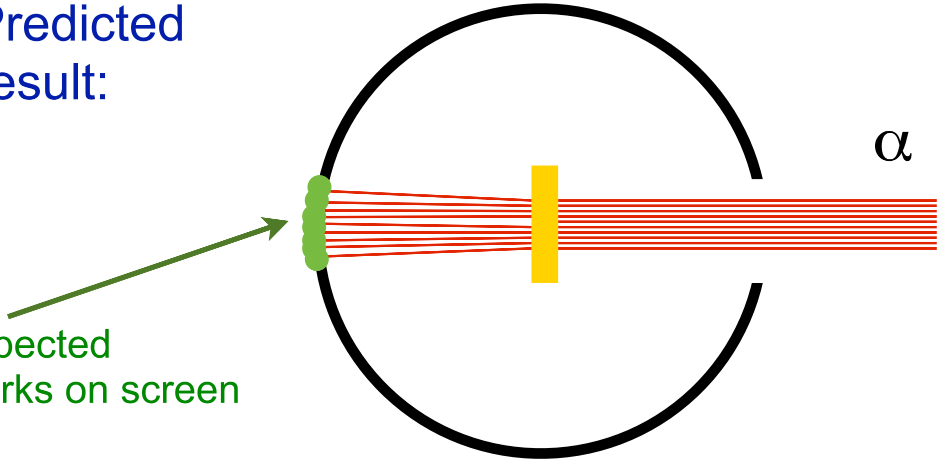


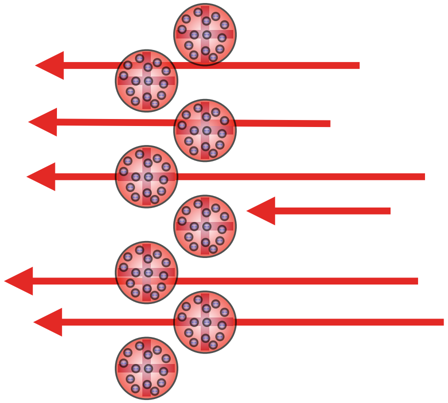
Thomson's
Plum Pudding Model

Predicted result:



Expected
marks on screen

Detail of gold foil (Thomson):



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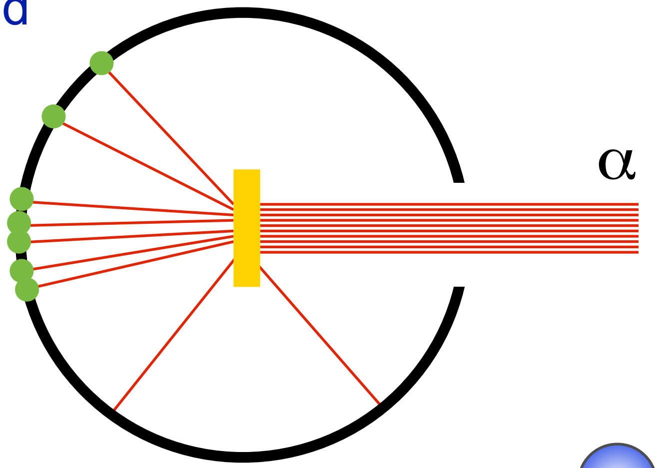
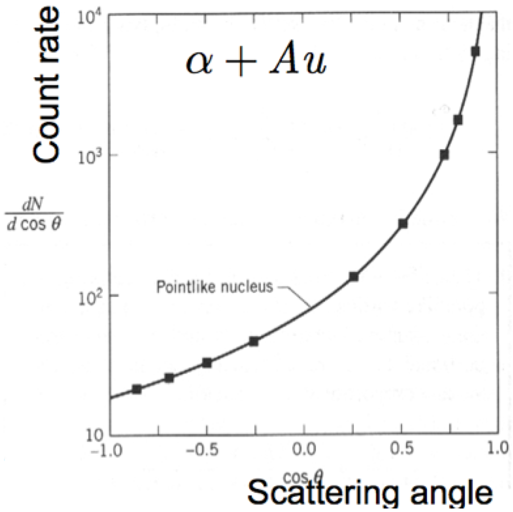
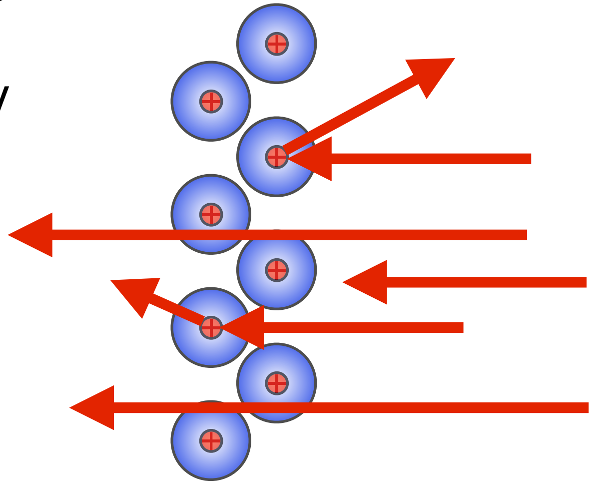
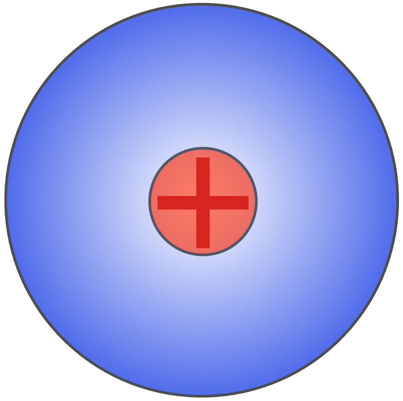
Observed result:





Positive Nucleus Theory explain α deflection:





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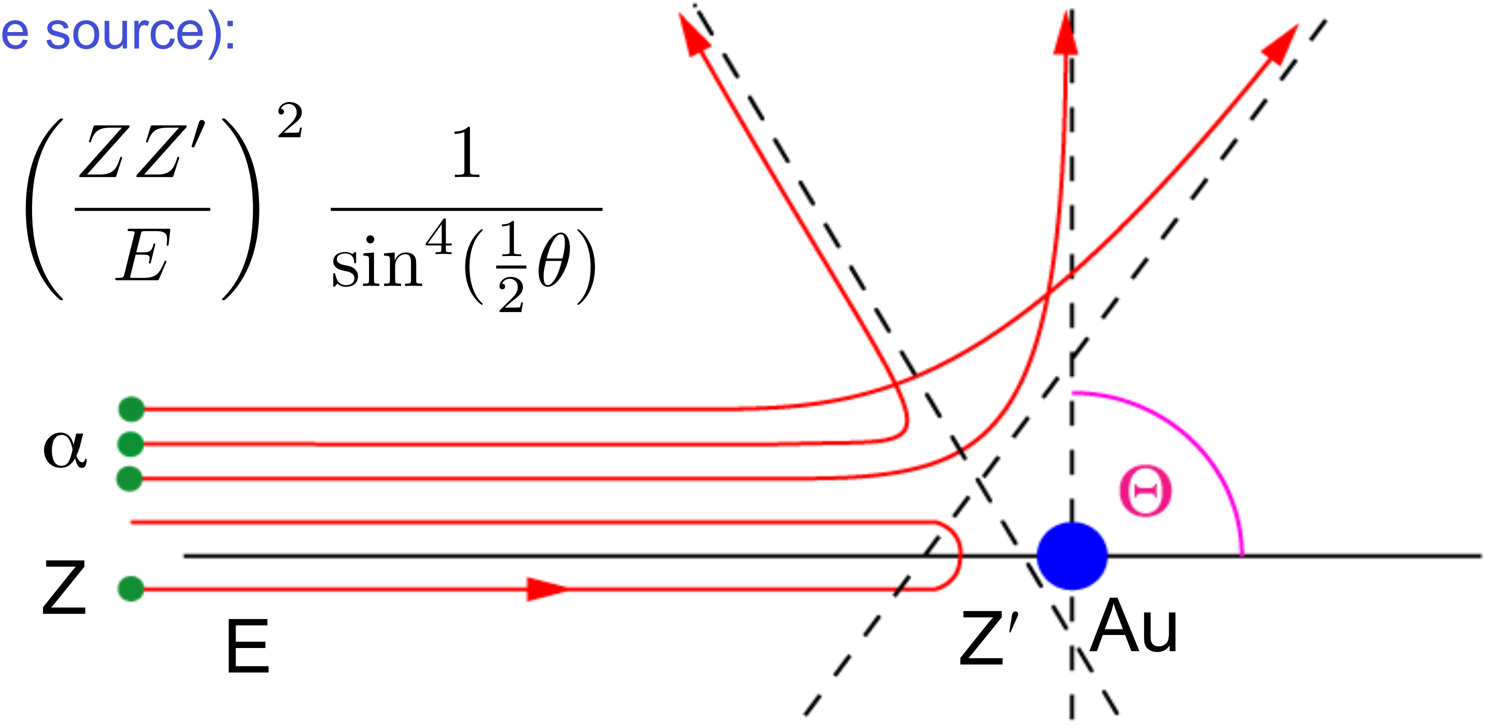
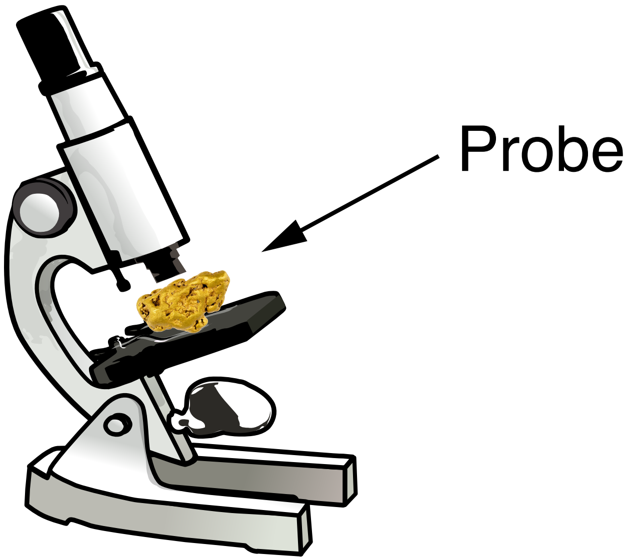
Elastic scattering of charged particles in Coulomb field (point-like source):

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



Studying Matter at Small Scales

Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm



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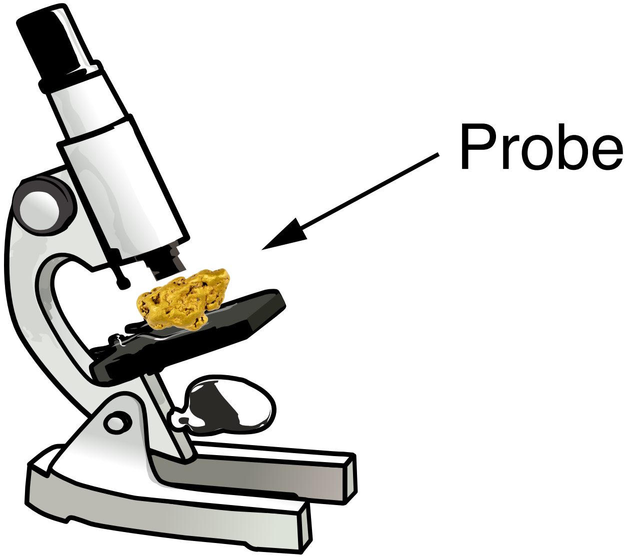
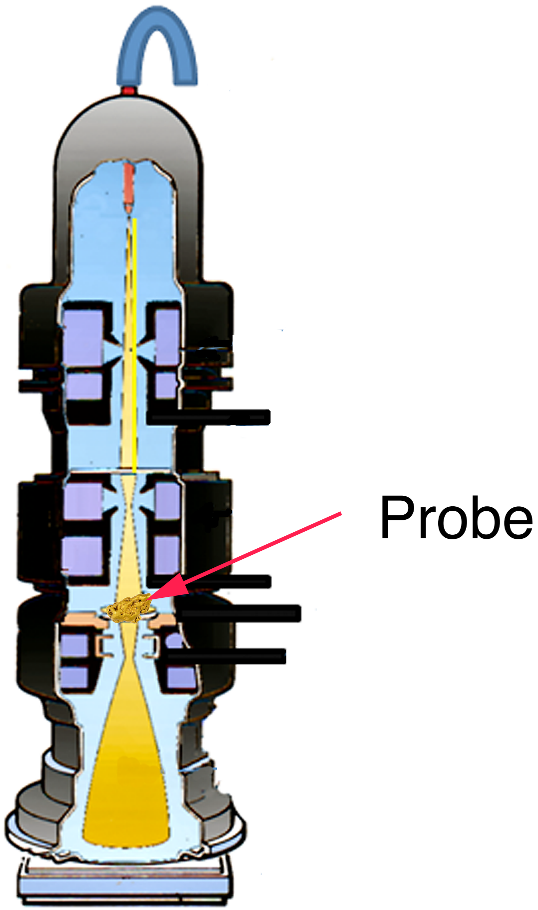


Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm



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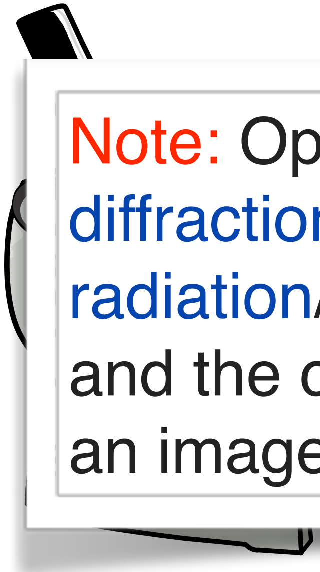
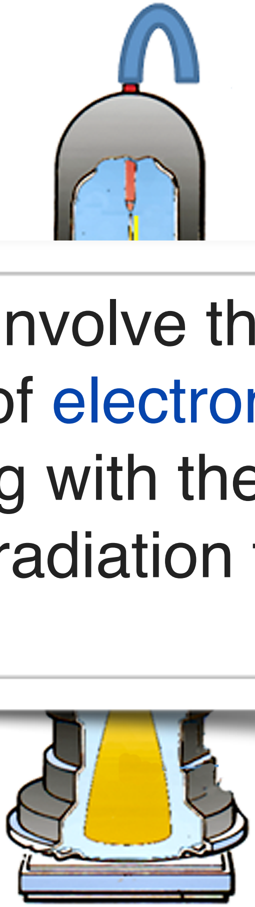




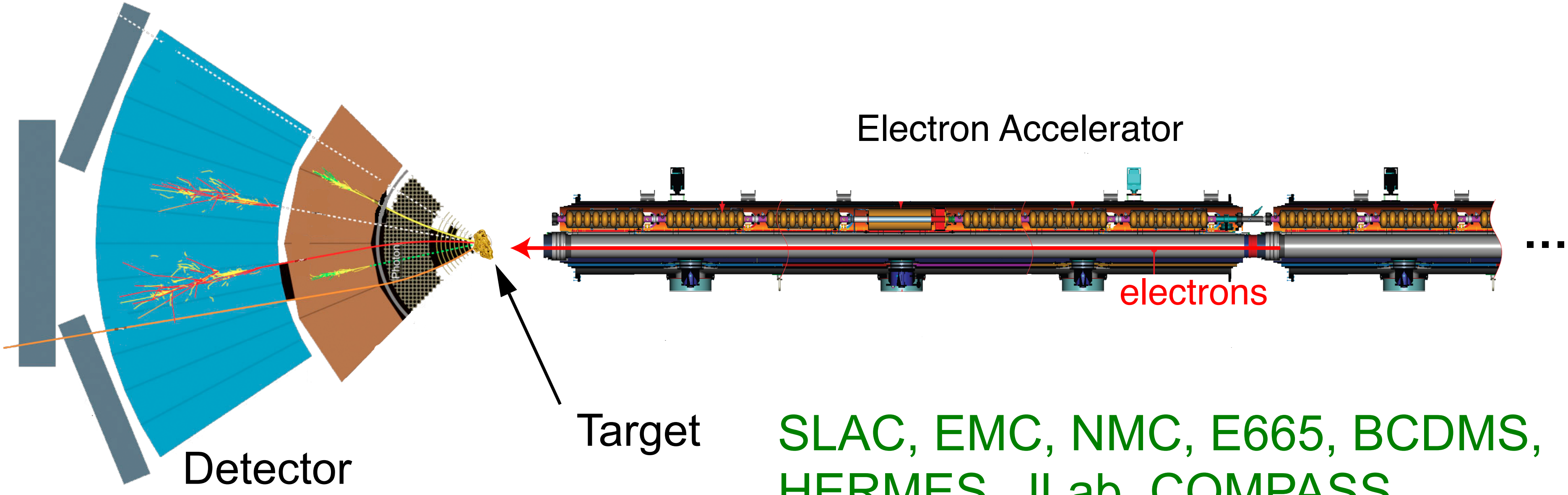
Note: Optical/electron microscopy involve the diffraction, reflection, or refraction of electromagnetic radiation/electron beams interacting with the target, and the collection of the scattered radiation to create an image. They don't go deep.

Studying Matter at Small Scales

Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm

Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm

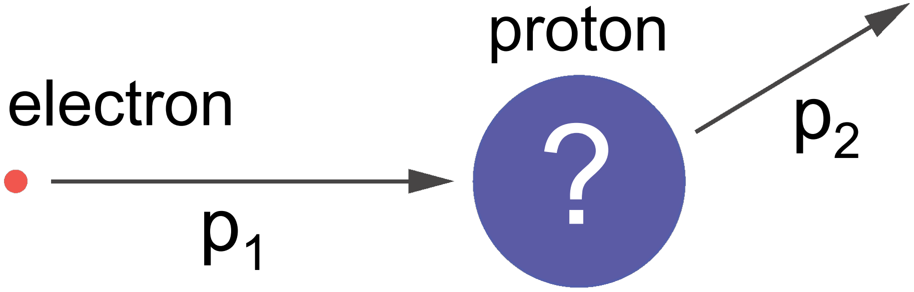
Fixed Target Particle Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm



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

Probing Matter with Electrons

The SLAC experiments in the 1960s established the quark model and our modern view of particle physics.



Mott = Rutherford + Spin

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} |F(q^2)|^2$$

$$q^2 = (\mathbf{p}_1 - \mathbf{p}_2)^2$$

Formfactor: *$F(q^2)$*
Fourier transform
of charge distributions

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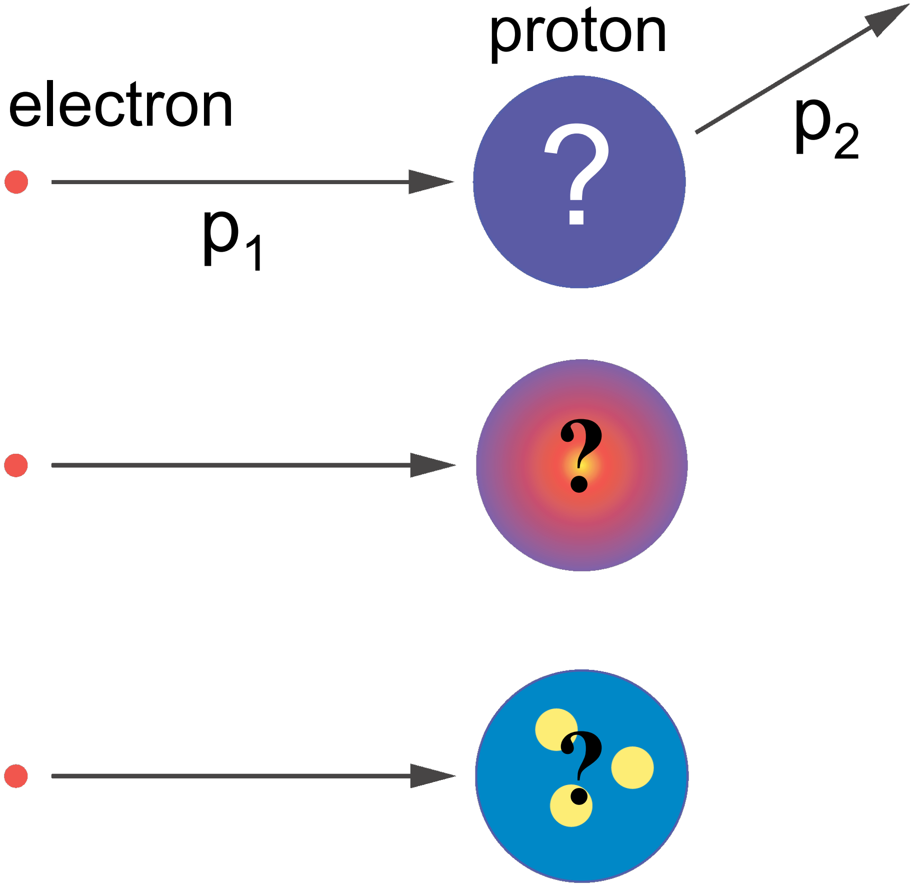

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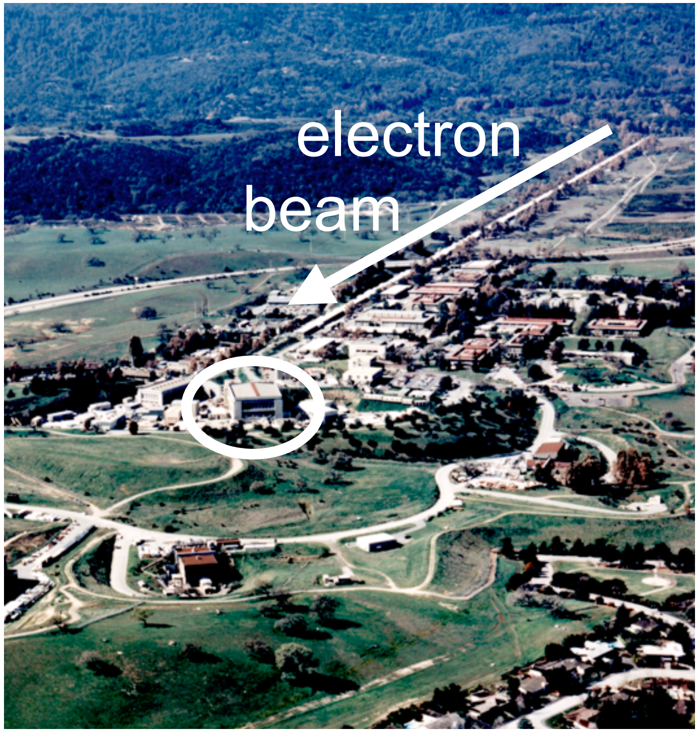

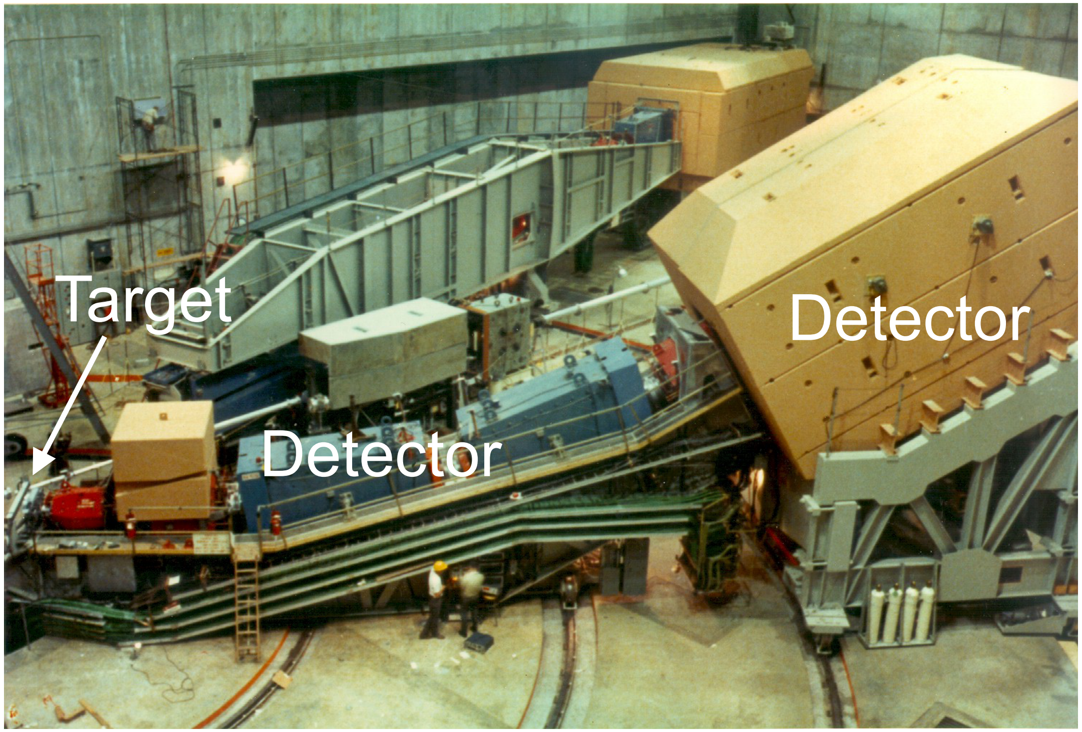

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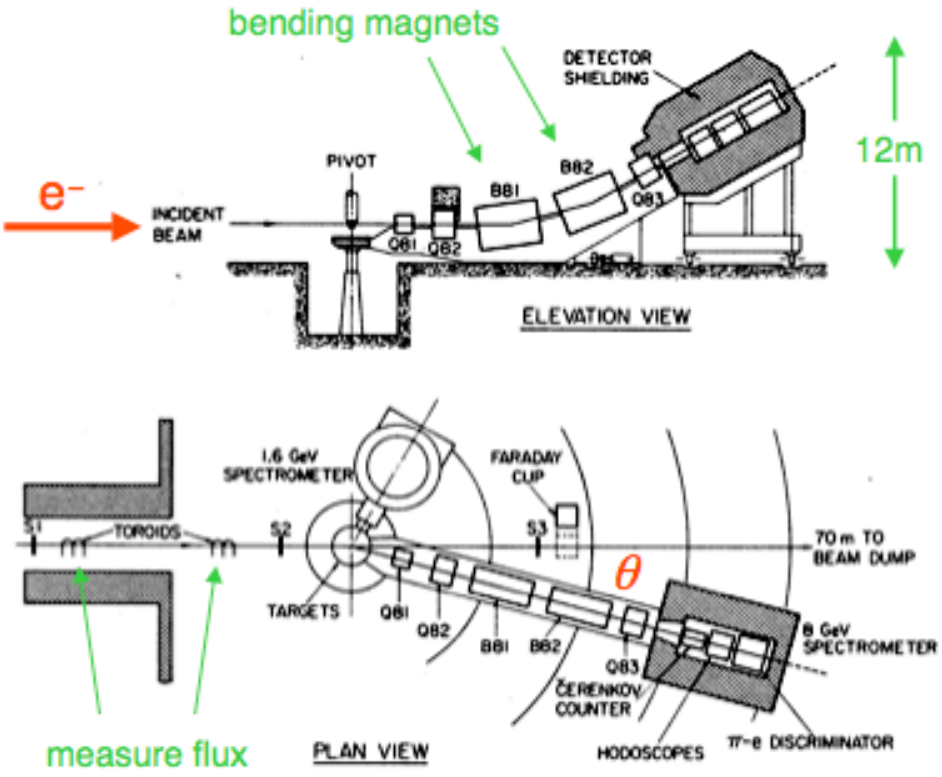

Scattered electron is deflected by a known B-field and a fixed vertical angle:

determine E'

Spectrometer can rotate in the horizontal plane,

vary θ

Probing Matter with Electrons

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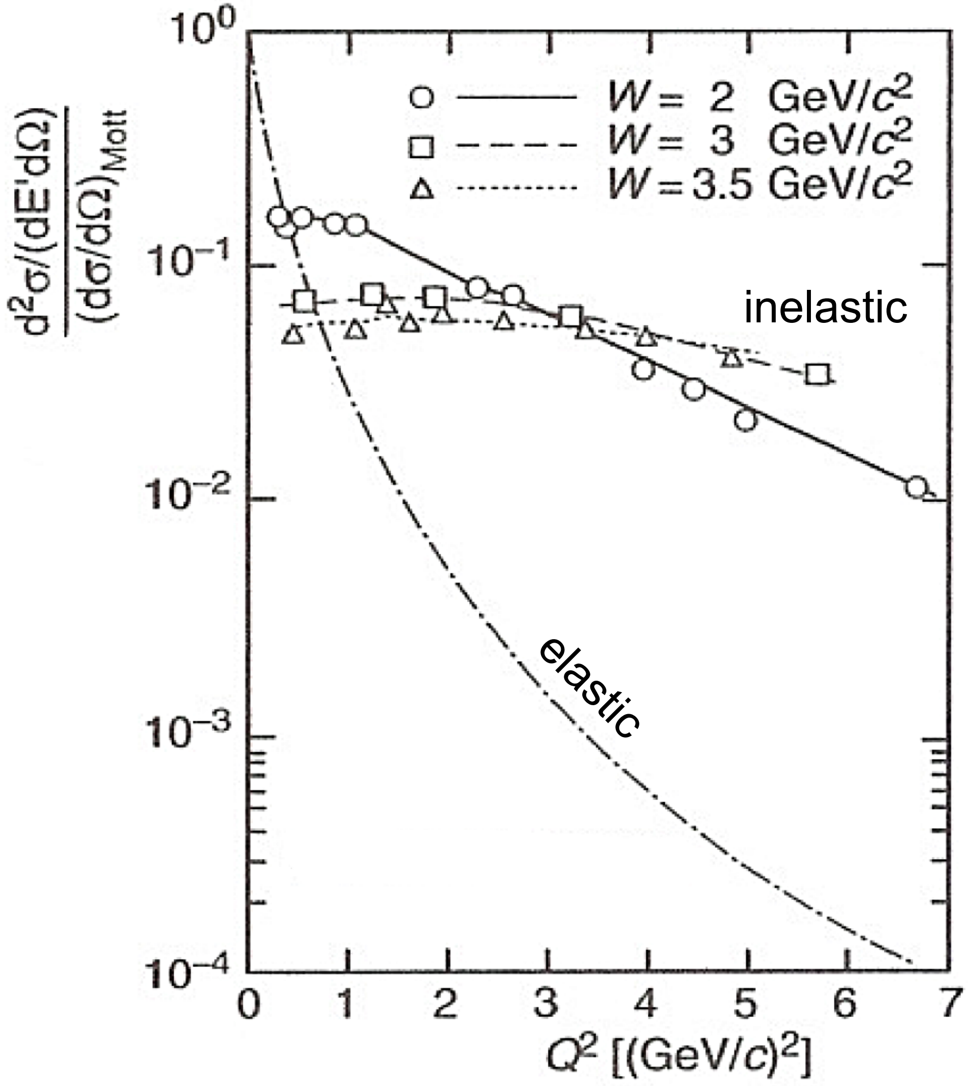
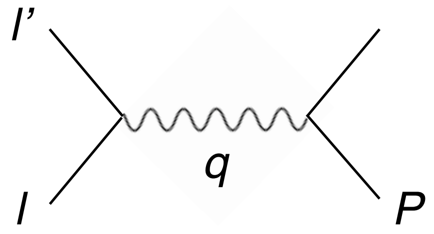
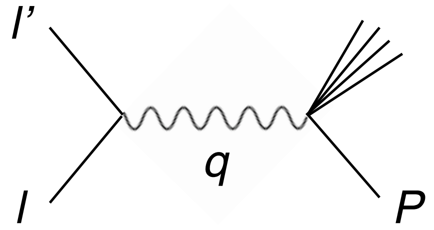


elastic:



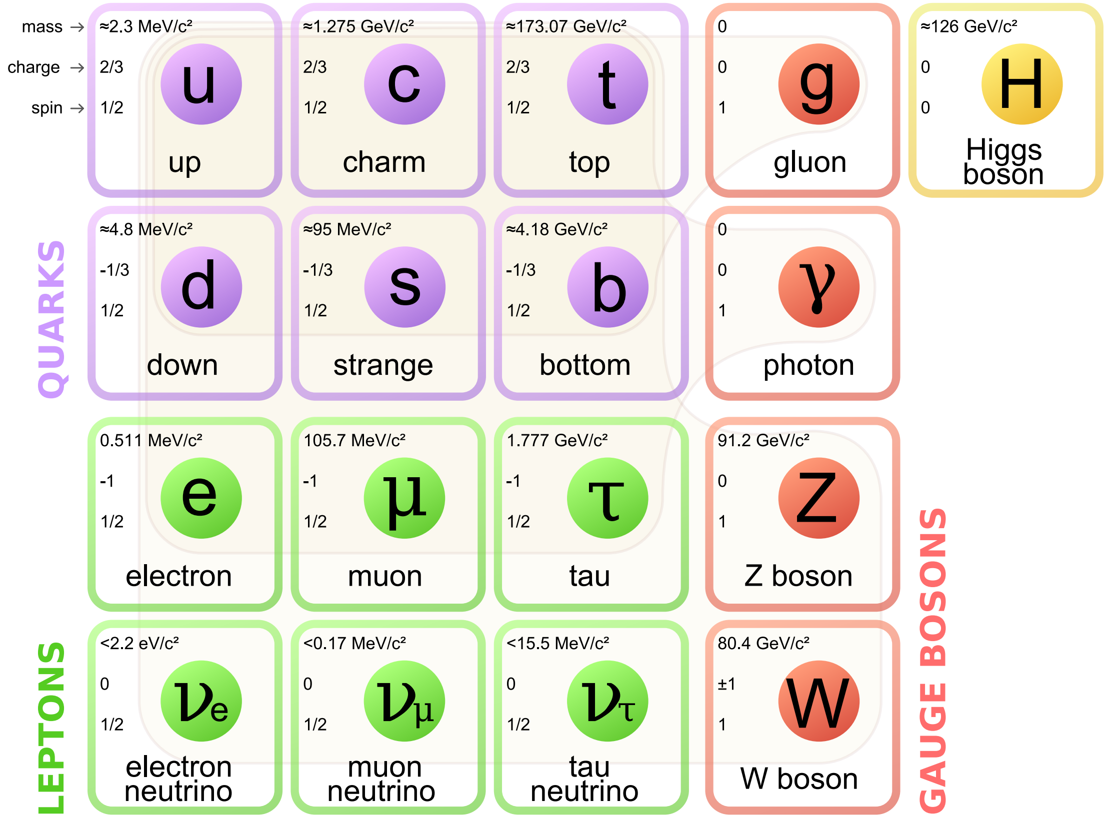
inelastic:



Constant $F(q^2)$:
$\Rightarrow$ scattering on point-like constituent of the nucleon

quarks

2. Quarks Gluons and QCD



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson	
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon		
LEPTONS	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson		**GAUGE BOSONS**
	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson		

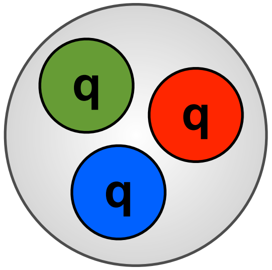
The proton is just 2 up quarks and 1 down quark, …

“Static” Quark Model

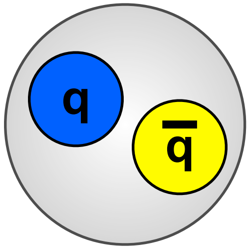
Quarks: spin 1/2 fermions, color charge

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

Baryons:



Mesons:



Quark Property	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	$+1$

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M. Gell-Mann,
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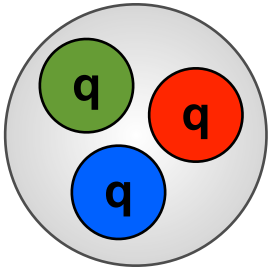

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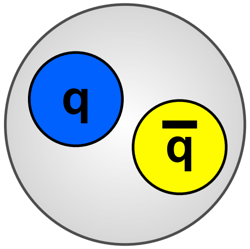
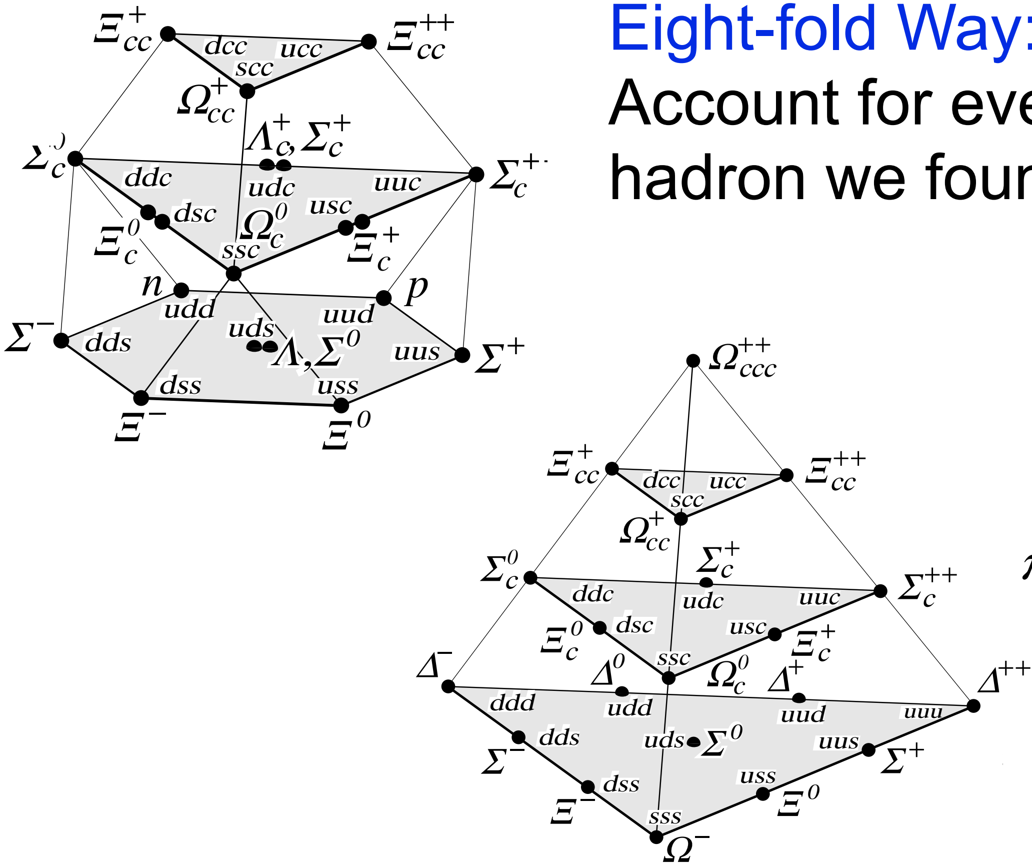
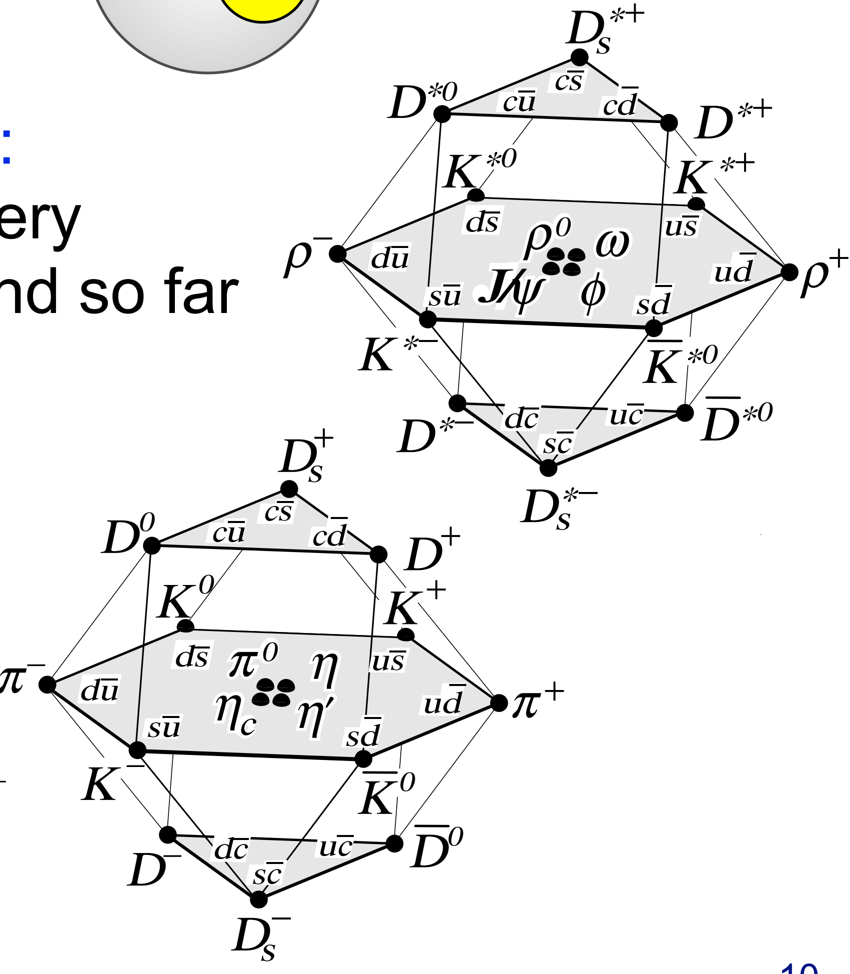


Eight-fold Way:
Account for every hadron we found so far





“Static” Quark Model

Quarks: spin 1/2 fermions, color charge

M. Gell-Mann,
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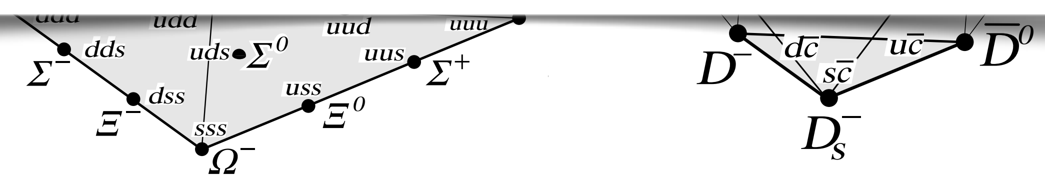
For detailed properties of multi-quark systems the static (constituent) model has failed almost completely and given no predictions which have been verified by experiment.

How can a model be so successful in the quark-antiquark and three quark systems and fail for almost everything else?

What’s missing?

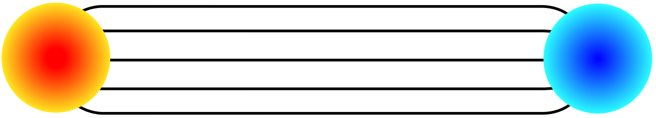


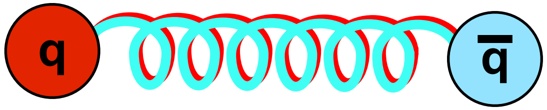
Quantum Chromodynamics (QCD)

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

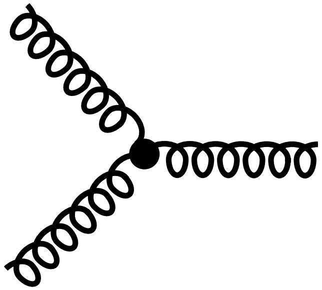
F. Wilczek, hep-ph/9907340

- 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

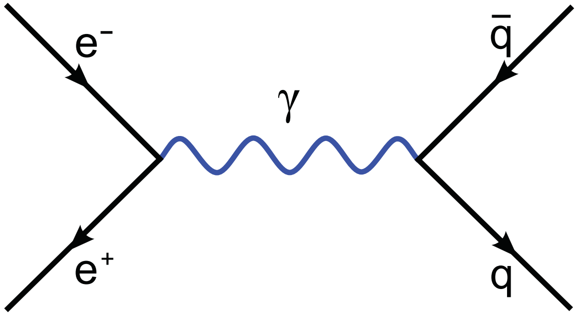
Gluons: They Exist!

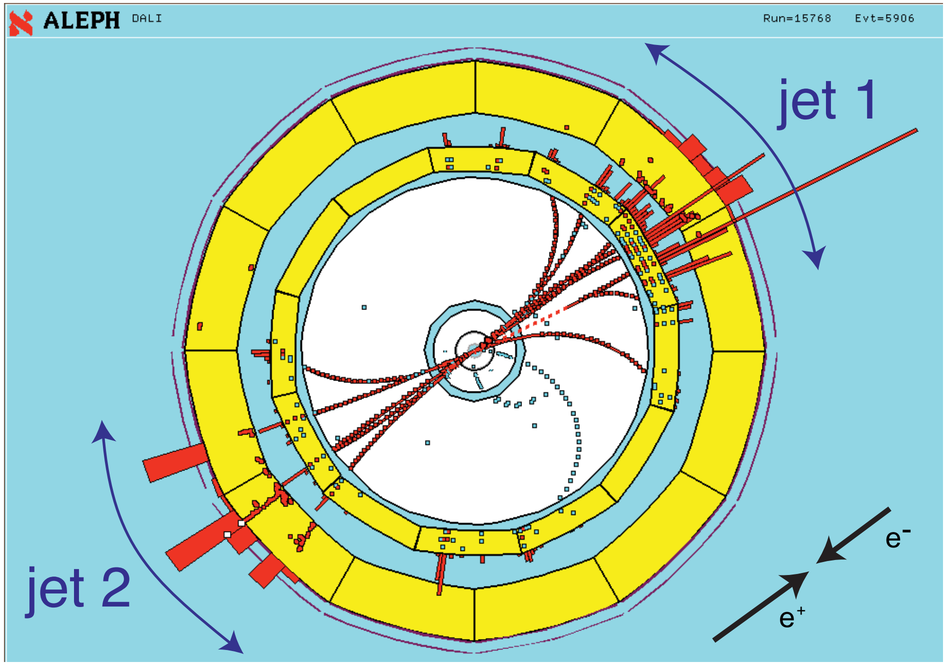
1979 Discovery of the Gluon

Physics Letters B, 15 December 1980

Mark-J, Tasso, Pluto, Jade experiment at PETRA (e^+e^- collider) at DESY ($\sqrt{s}$ = 13 - 32 GeV)

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





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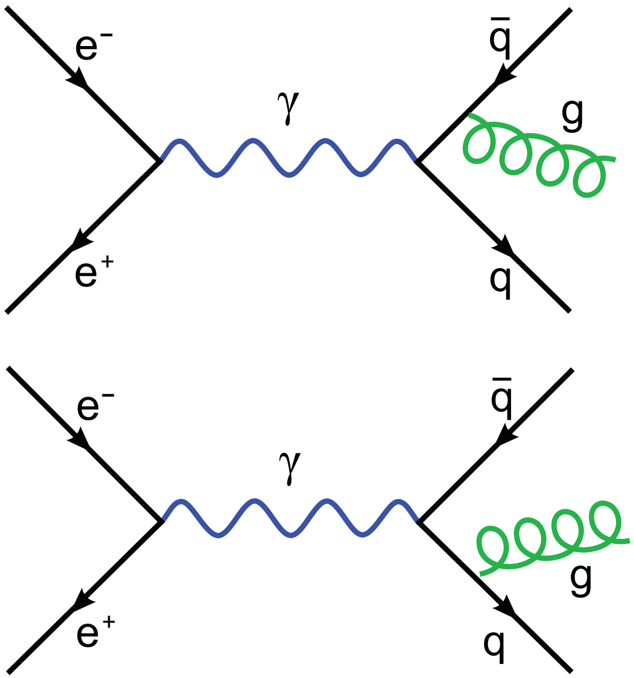

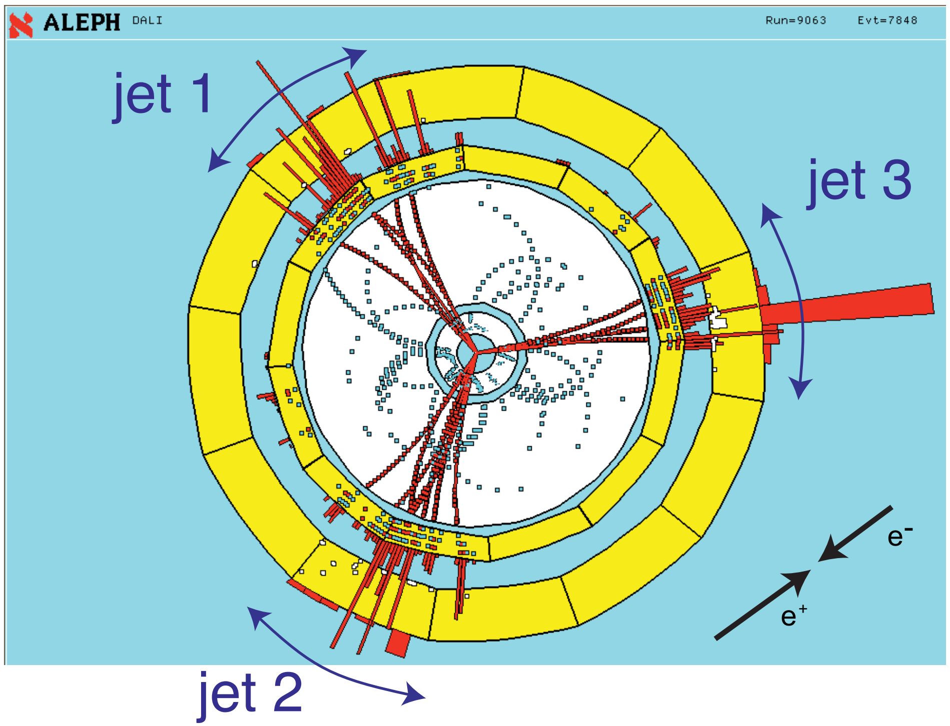

J. Ellis, arXiv:1409.4232

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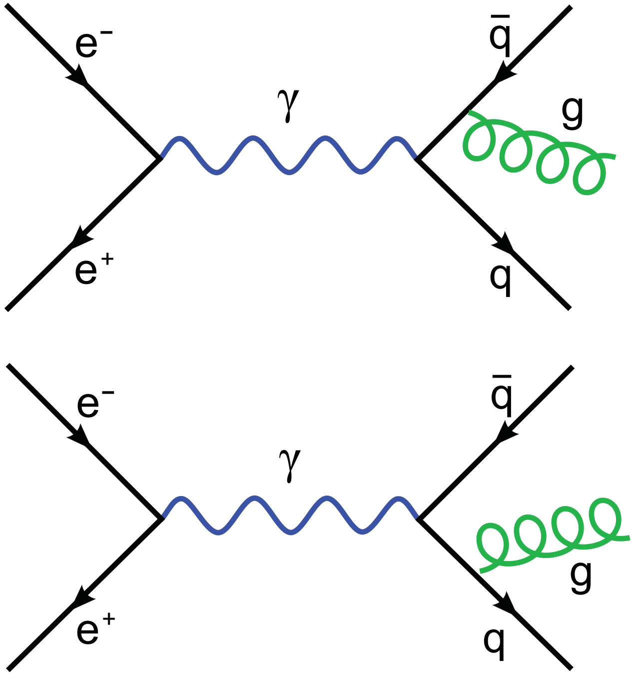
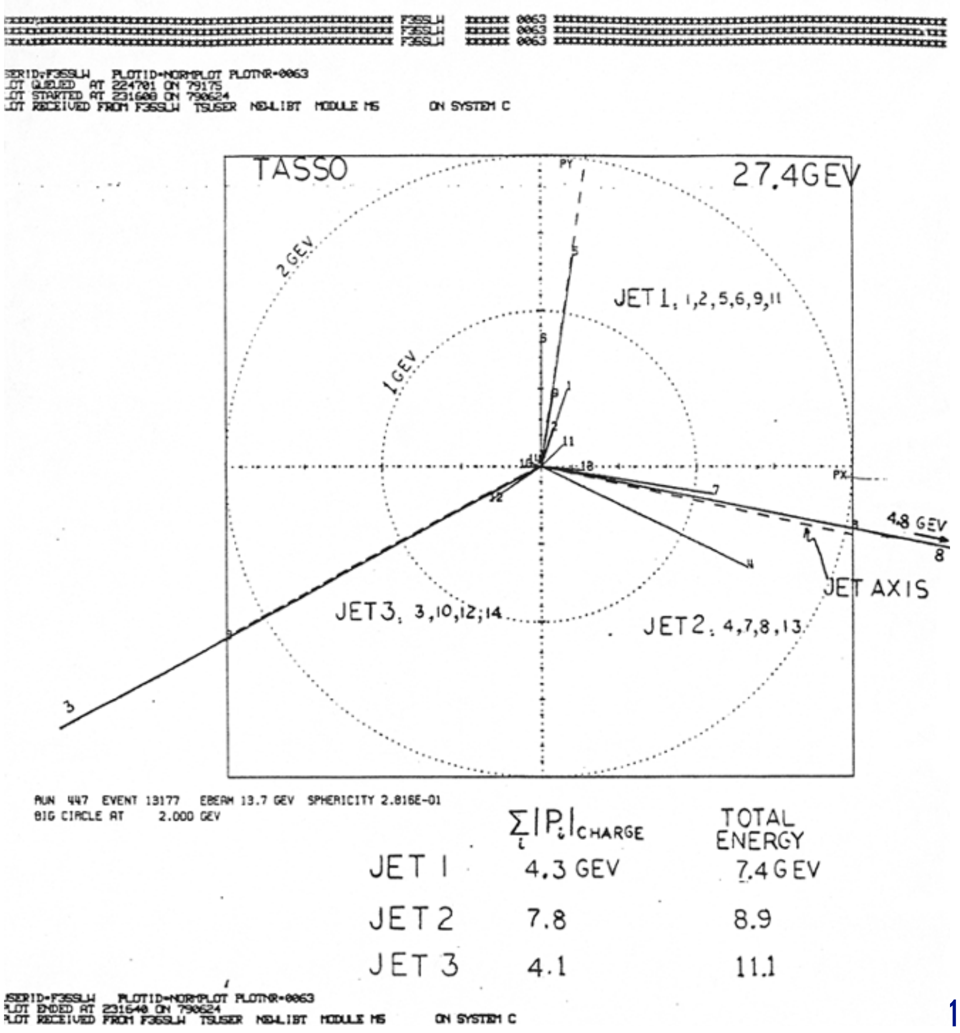




```
SERID=F36SLW    PLOTID=NORMPLOT PLOTNR=0063
LOT QUEUED  AT 224701 ON 79175
LOT STARTED AT 231608 ON 790624
LOT RECEIVED FROM F36SLW  TSUSER  NEWLIBT  MODULE MS       ON SYSTEM C
```

```
RUN  447  EVENT 13177   EBEAM 13.7 GEV  SPHERICITY 2.816E-01
BIG CIRCLE AT      2.000 GEV
```

	$\sum_i \lvert P_i \rvert_{\text{CHARGE}}$	TOTAL ENERGY
JET 1	4.3 GEV	7.4 GEV
JET 2	7.8	8.9
JET 3	4.1	11.1

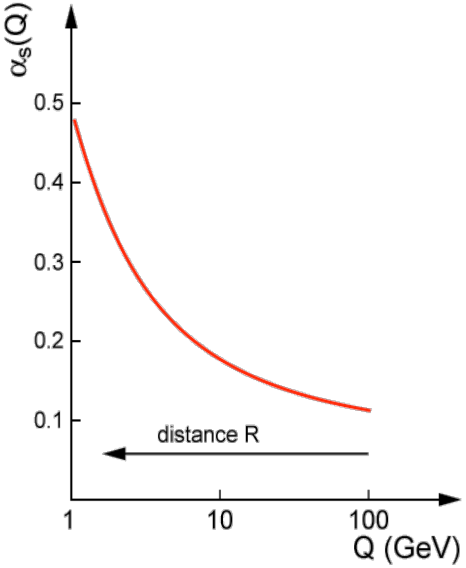
```
SERID=F36SLW    PLOTID=NORMPLOT PLOTNR=0063
LOT ENDED AT 231640 ON 790624
LOT RECEIVED FROM F36SLW  TSUSER  NEWLIBT  MODULE MS       ON SYSTEM C
```

J. Ellis, arXiv:1409.4232

Understanding QCD ?

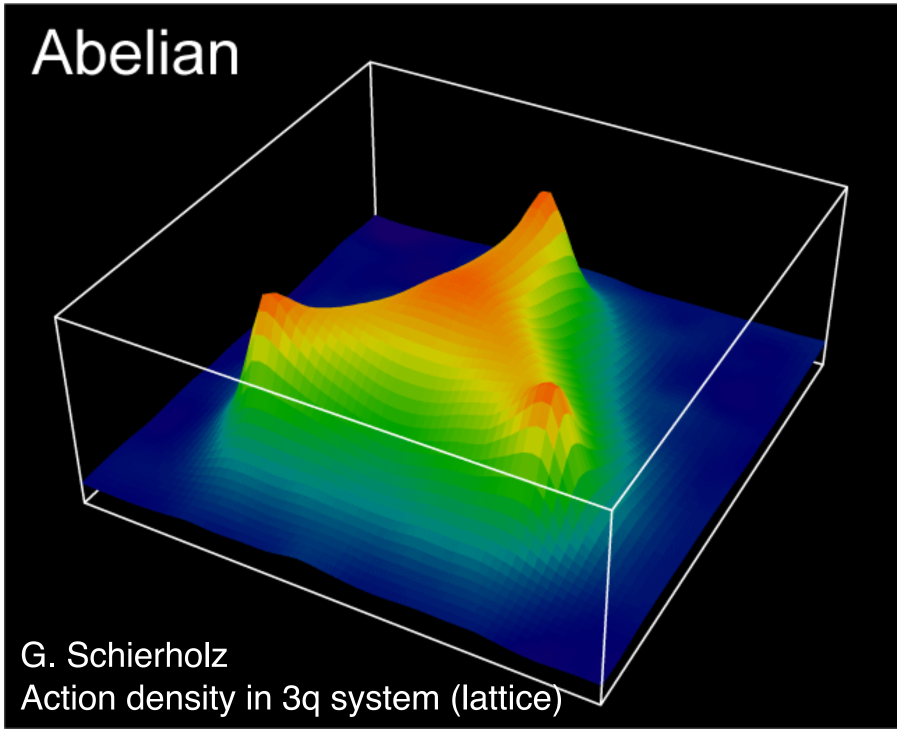
$$L_{QCD} = \bar{q}(i\gamma^{\mu}\partial_{\mu} - m)q - g(\bar{q}\gamma^{\mu}T_{a}q)A^{a}_{\mu} - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}$$

- "Emergent" Phenomena not evident from Lagrangian
- Asymptotic Freedom
  - $\alpha_s(Q^2) \sim 1 / \log(Q^2/\Lambda^2)$
  - in vacuum (Q ~ 1/R)
- Confinement
  - Free quarks not observed in nature
  - Quarks only in bound states

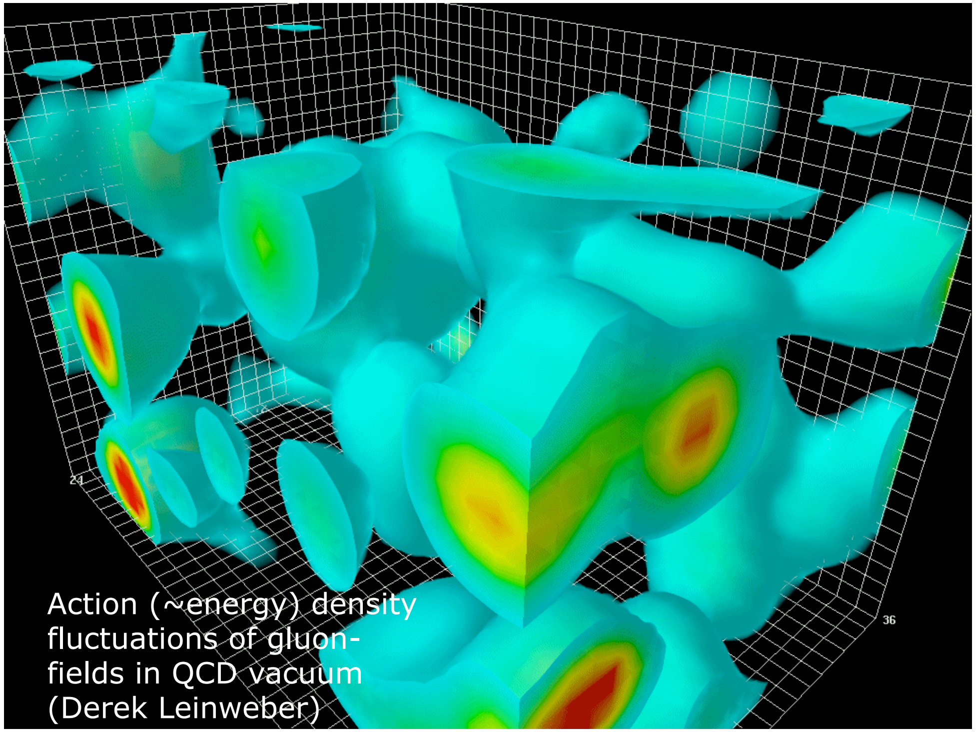


Understanding QCD ?

$$L_{QCD} = \bar{q}(i\gamma^\mu\partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$



G. Schierholz
Action density in 3q system (lattice)

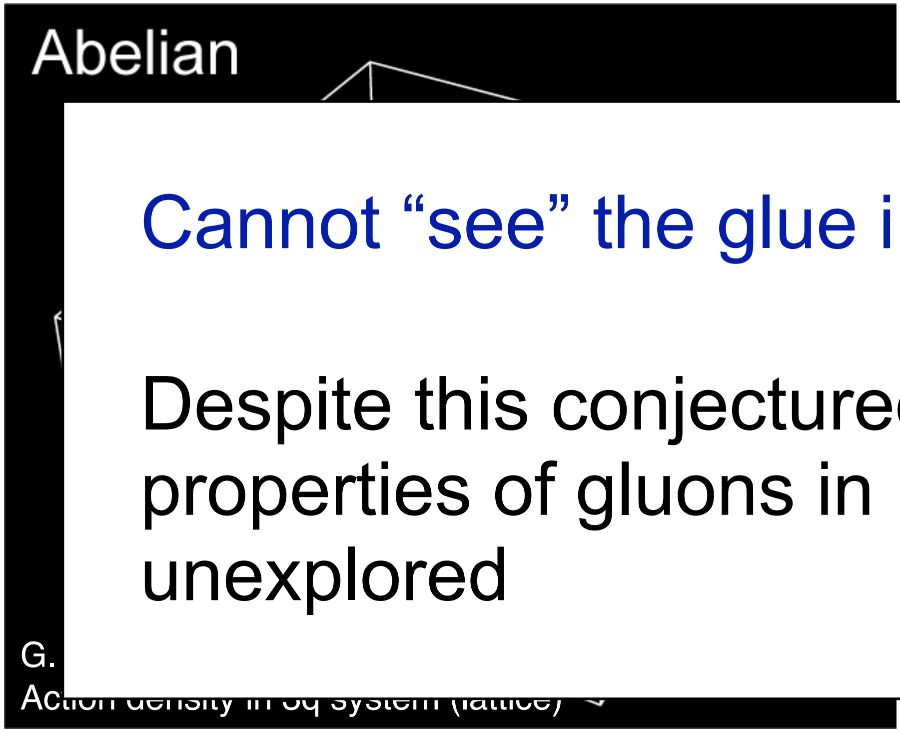


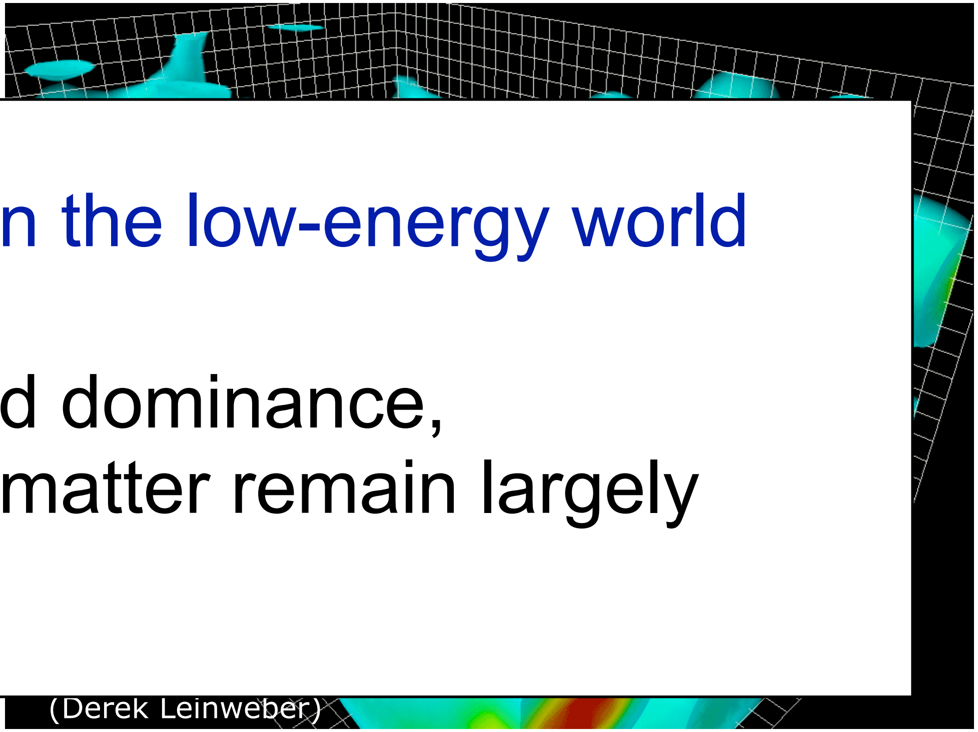
Action (~energy) density
fluctuations of gluon-
fields in QCD vacuum
(Derek Leinweber)

- Gluons & their self-interaction
  - Determine essential features of strong interactions
  - Dominate structure of QCD vacuum (fluctuations in gluon fields)
  - Responsible for > 98% of the visible mass in universe

Understanding QCD ?

$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$



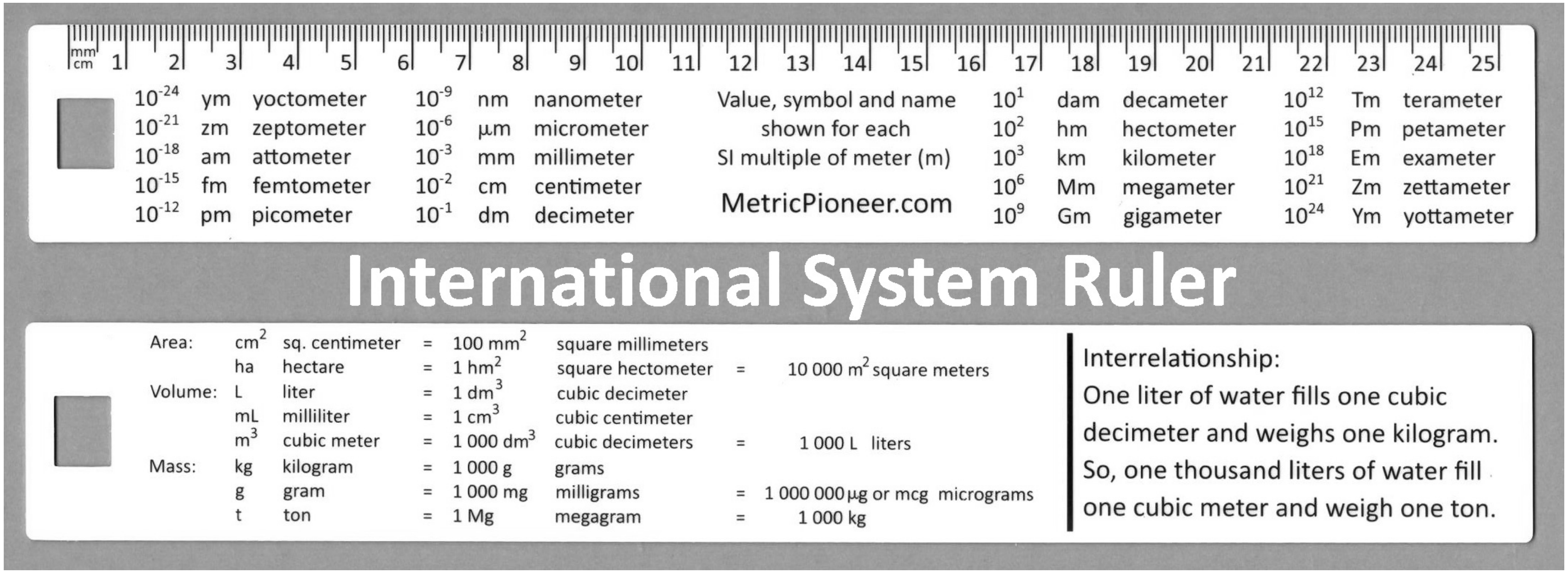


Cannot “see” the glue in the low-energy world

Despite this conjectured dominance, properties of gluons in matter remain largely unexplored

- Gluons & their self-interaction
  - Determine essential features of strong interactions
  - Dominate structure of QCD vacuum (fluctuations in gluon fields)
  - Responsible for > 98% of the visible mass in universe

3. Studying Matter at the Smallest Scale



10^{-24}	ym	yoctometer	10^{-9}	nm	nanometer	10^{1}	dam	decameter	10^{12}	Tm	terameter
10^{-21}	zm	zeptometer	10^{-6}	µm	micrometer	10^{2}	hm	hectometer	10^{15}	Pm	petameter
10^{-18}	am	attometer	10^{-3}	mm	millimeter	10^{3}	km	kilometer	10^{18}	Em	exameter
10^{-15}	fm	femtometer	10^{-2}	cm	centimeter	10^{6}	Mm	megameter	10^{21}	Zm	zettameter
10^{-12}	pm	picometer	10^{-1}	dm	decimeter	10^{9}	Gm	gigameter	10^{24}	Ym	yottameter

Value, symbol and name
shown for each
SI multiple of meter (m)

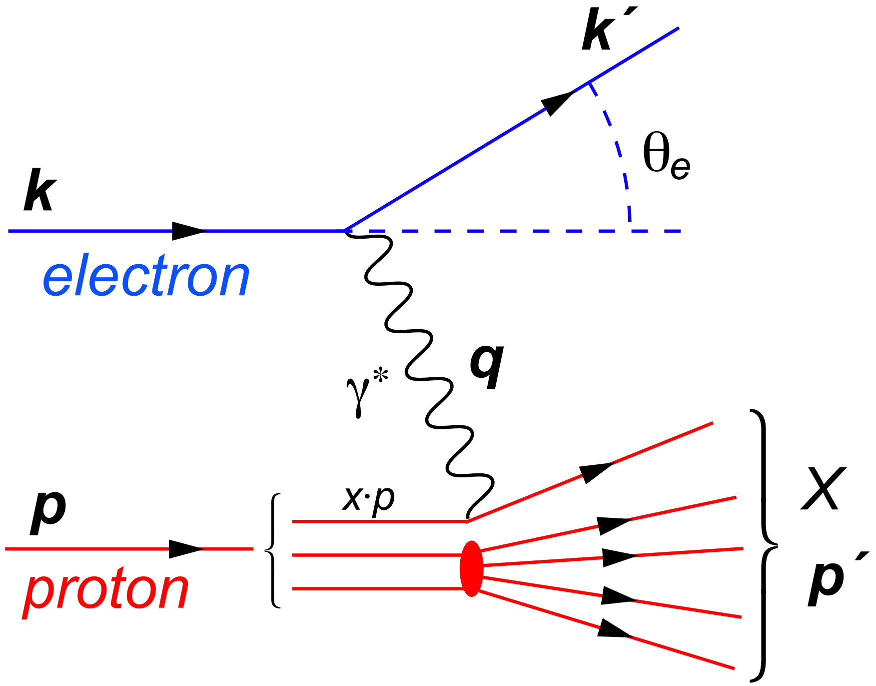
MetricPioneer.com

International System Ruler

Area:	cm^2	sq. centimeter	=	100 mm^2	square millimeters		
	ha	hectare	=	1 hm^2	square hectometer	=	10 000 m^2 square meters
Volume:	L	liter	=	1 dm^3	cubic decimeter		
	mL	milliliter	=	1 cm^3	cubic centimeter		
	m^3	cubic meter	=	1 000 dm^3	cubic decimeters	=	1 000 L liters
Mass:	kg	kilogram	=	1 000 g	grams		
	g	gram	=	1 000 mg	milligrams	=	1 000 000 µg or mcg micrograms
	t	ton	=	1 Mg	megagram	=	1 000 kg

Interrelationship:
One liter of water fills one cubic decimeter and weighs one kilogram. So, one thousand liters of water fill one cubic meter and weigh one ton.

Deep Inelastic Scattering (DIS)

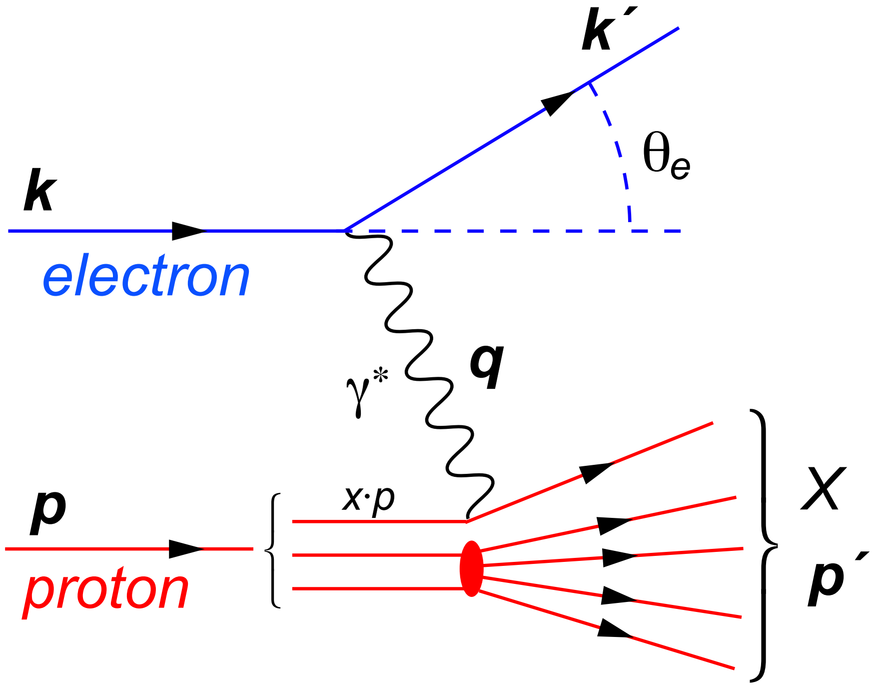


s:

$$s = (k+p)^2 \approx 4E_e E_p$$

- square of center-of-mass energy of electron-hadron system

Deep Inelastic Scattering (DIS)

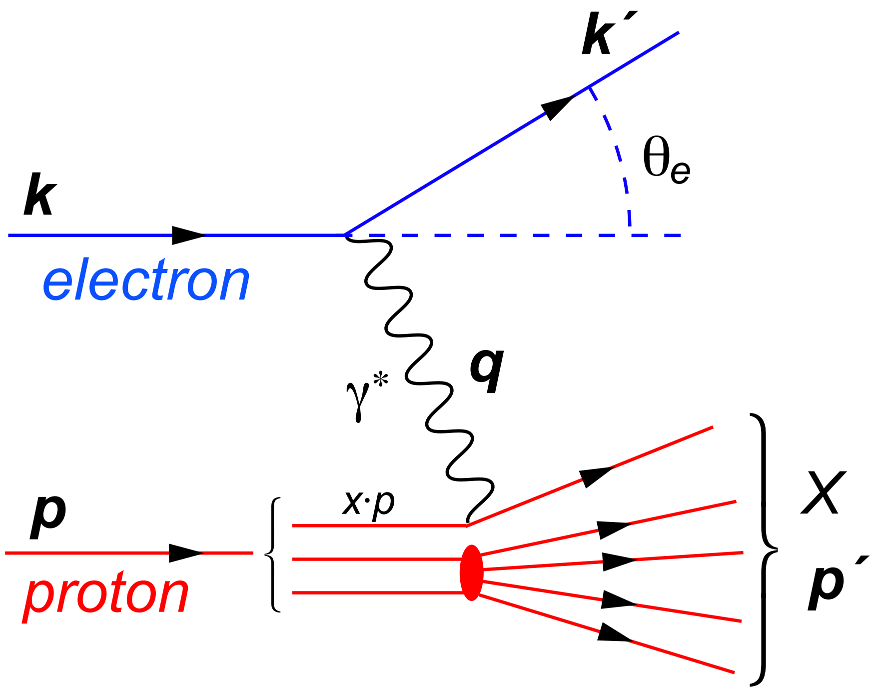


Q²:

$$\begin{aligned} Q^2 &= -q^2 = -(k-k')^2 \\ &\approx 4EE' \sin^2\left(\frac{\theta}{2}\right) \end{aligned}$$

- 4-momentum transfer from scattered electron
- invariant mass sq. of γ*
- “Resolution” power
- Virtuality
    - real photon Q = 0

Deep Inelastic Scattering (DIS)

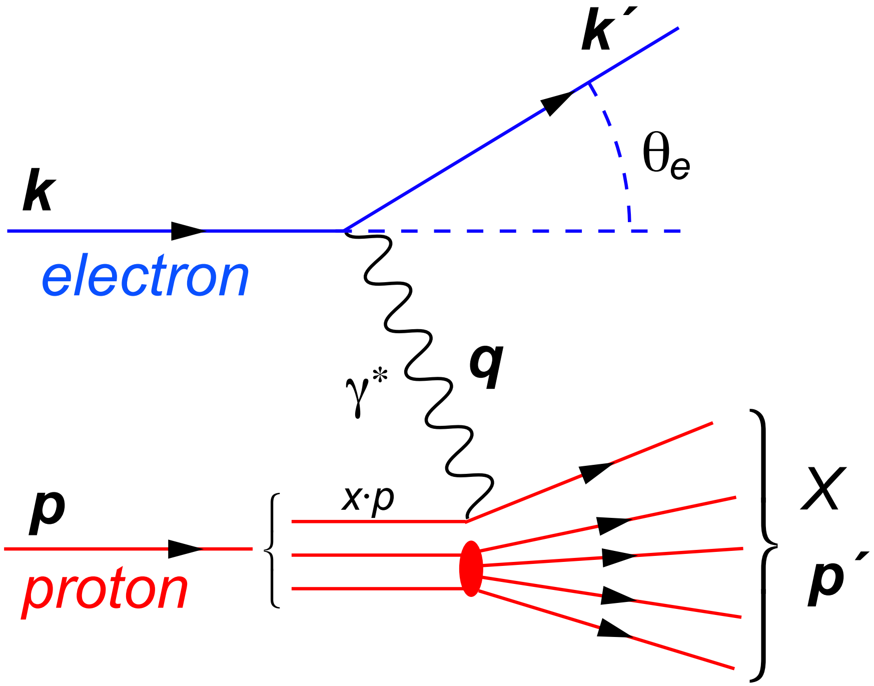


y:

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

- Inelasticity
- Fraction of electron’s energy lost in nucleon restframe
- 0 < y < 1

Deep Inelastic Scattering (DIS)

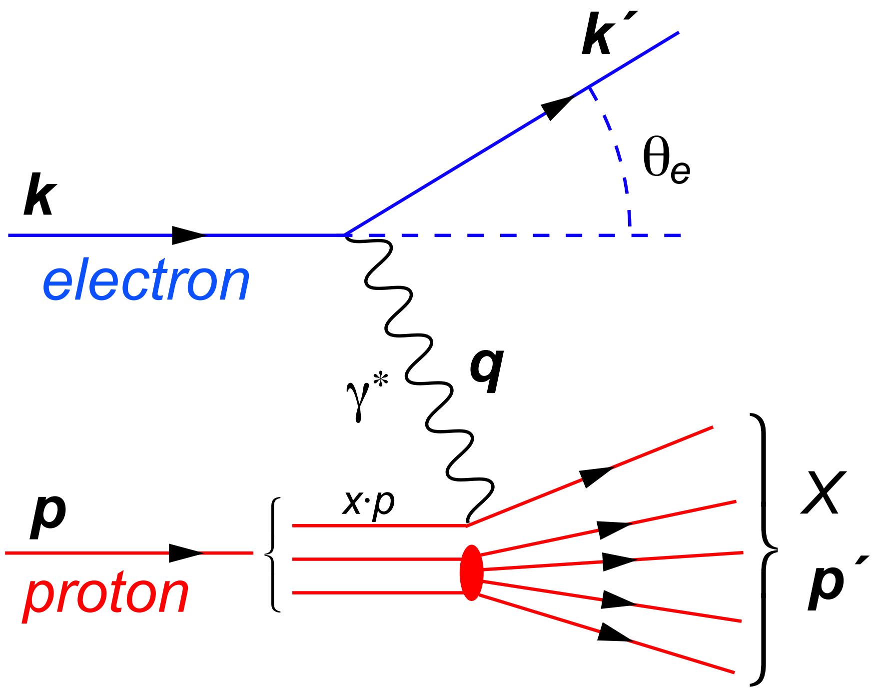


x:

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

- Bjorken-x
- x is fraction of the nucleon’s momentum carried by the struck quark

Deep Inelastic Scattering (DIS)



x: momentum fraction of parton

Q^2: resolution power

y: inelasticity

s: center-of-mass energy sq.

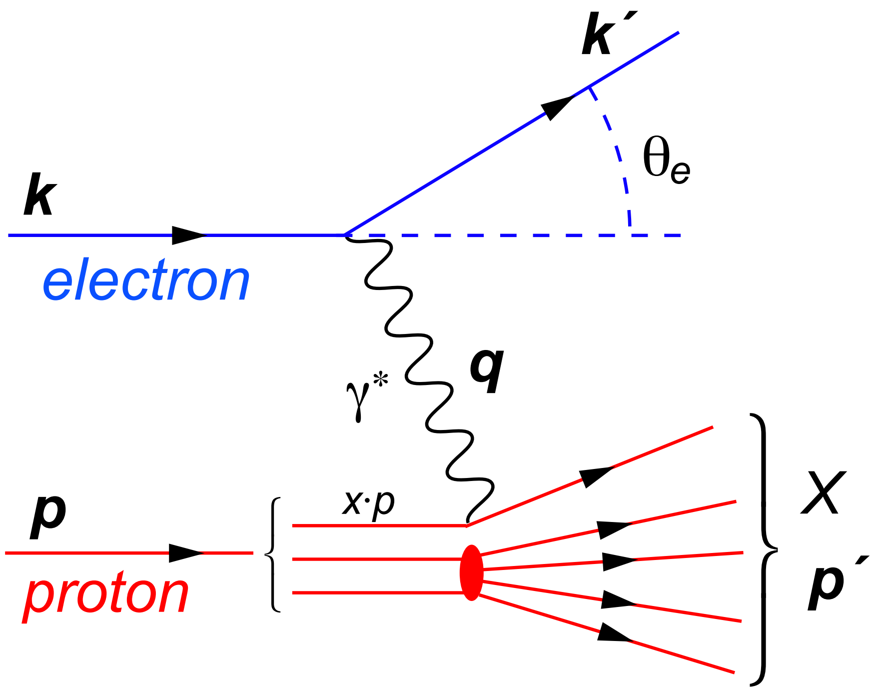
$$Q^2 \approx s \cdot x \cdot y$$

Deep ($Q^2 \gg m_p^2$)

Inelastic ($W^2 \gg m_p^2$)

Scattering = DIS

Deep Inelastic Scattering (DIS)



x: momentum fraction of parton

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y: inelasticity

s: center-of-mass energy sq.

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

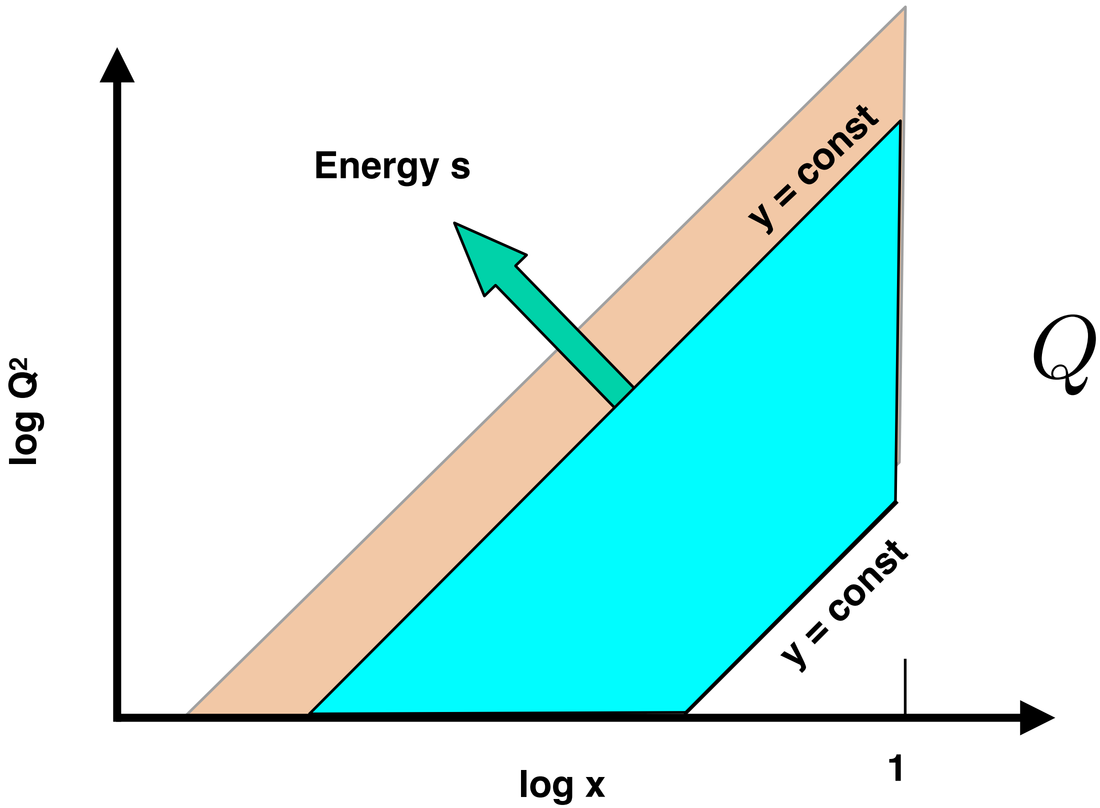
Deep ($Q^2 \gg m_p^2$)

Inelastic ($W^2 \gg m_p^2$)

Scattering = DIS

N.B.: This picture was developed in the “infinite momentum frame” (IMF). That works nicely when one assume massless quarks and gluons (partons). Despite all this it is also used for example for massive charm quarks. Some care has to be taken and x needs to be “adjusted”.

The x-Q^2 Plane



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

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

Structure Functions

Inclusive e+p collisions:
(only scattered electron is measured, rest ignored)

F_2 and F_L are key in understanding the structure of hadrons

N.B.: At very high energies a 3rd structure function comes into play: F_3
Ignored here and in the rest

Structure Functions

Inclusive e+p collisions:
(only scattered electron is measured, rest ignored)

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dx\,dQ^2}=\frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions

gluon momentum distribution

F_2 and F_L are key in understanding the structure of hadrons

N.B.: At very high energies a 3rd
structure function comes into play: F_3
Ignored here and in the rest

More Practical: Reduced Cross-Section

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:

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

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

More Practical: Reduced Cross-Section

Inclusive Cross-Section:

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

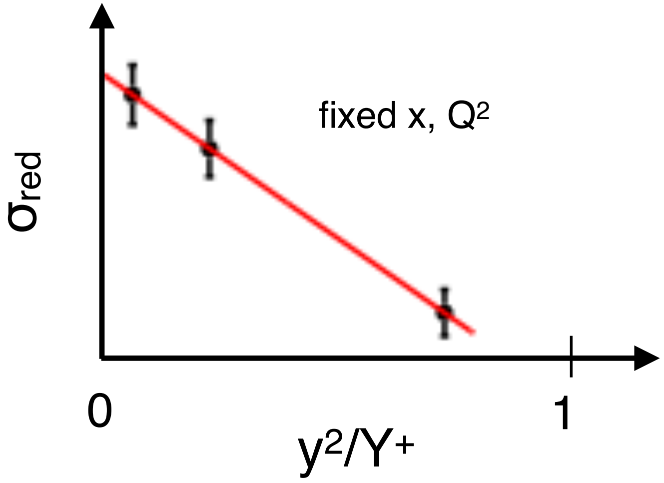
Reduced Cross-Section:

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

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

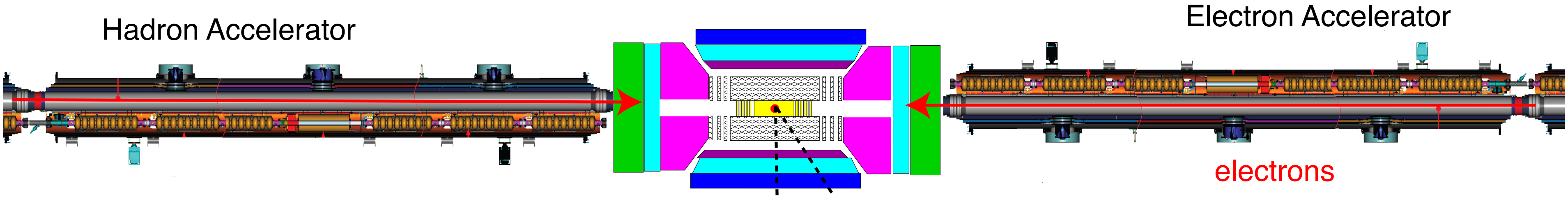
Rosenbluth Separation:

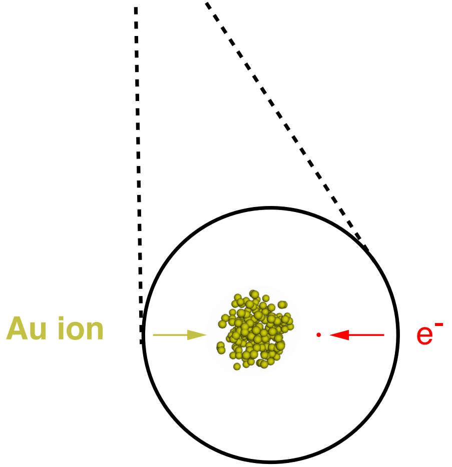
- Recall $Q^2 = x\ y\ s$
- Measure at different $\sqrt{s}$
- Plot σ_{red} versus $y2/Y^+$ for fixed x, Q^2
- F_2 is σ_{red} at $y2/Y^+ = 0$
- F_L = Slope of $y2/Y^+$

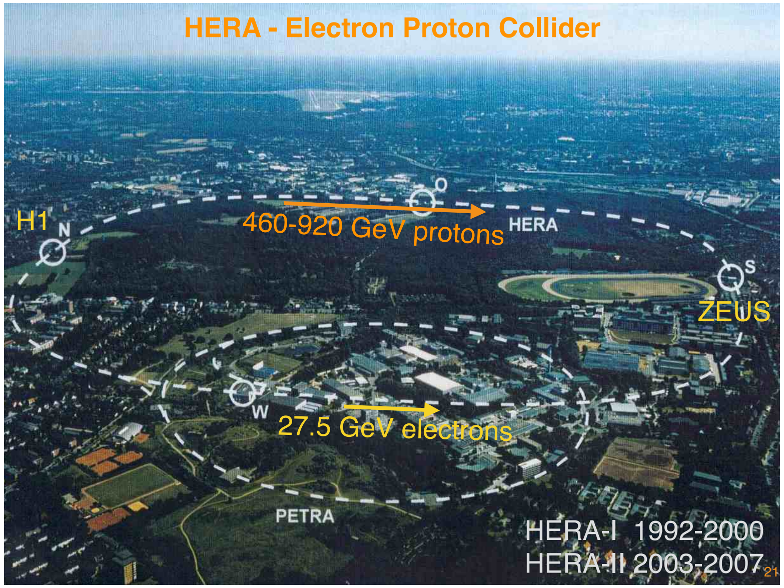


Studying Matter at the Smallest Scales

ep/eA Collider Experiments
Wave Length: 0.0001 fm (10 GeV + 100 GeV)
Resolution: ~ 0.01-0.001 fm

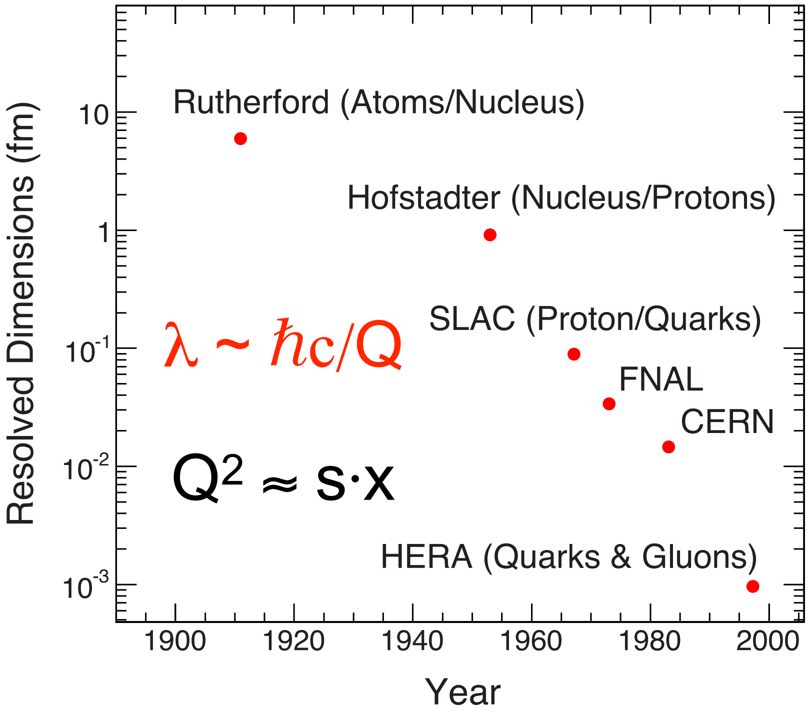






Past: HERA,
Future: EIC, LHeC, …

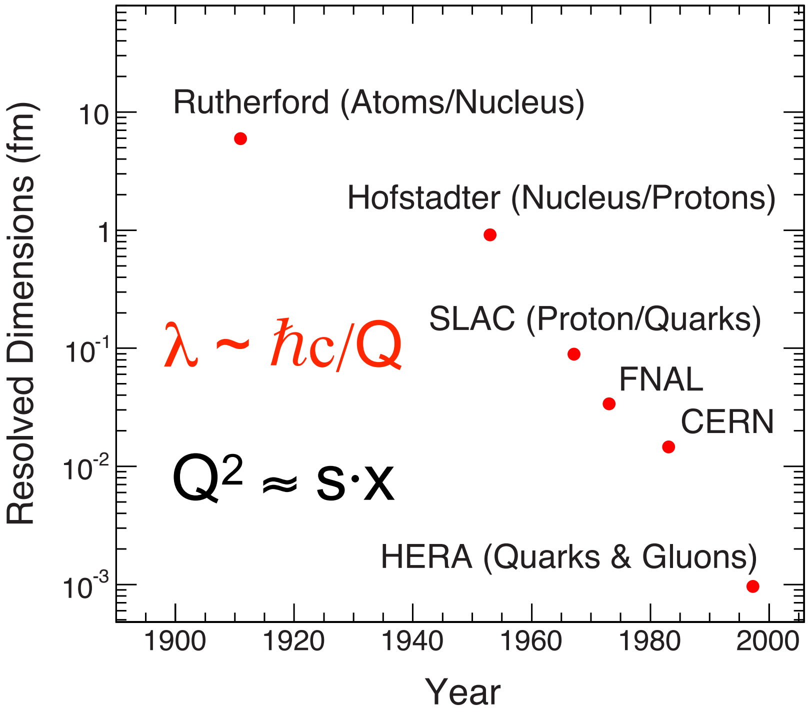
F_2: The Key Structure Function

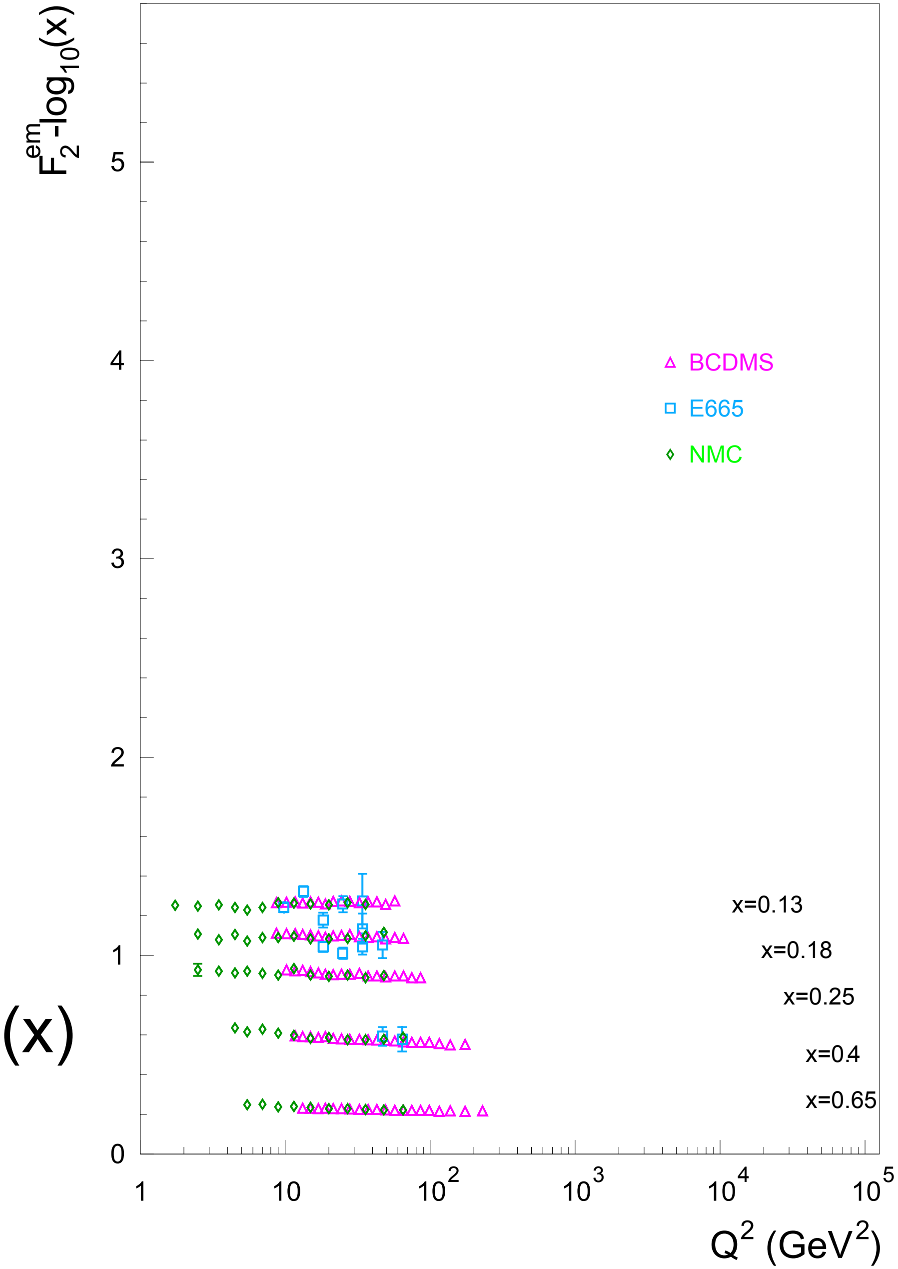


$$\lambda \sim \hbar c/Q$$

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

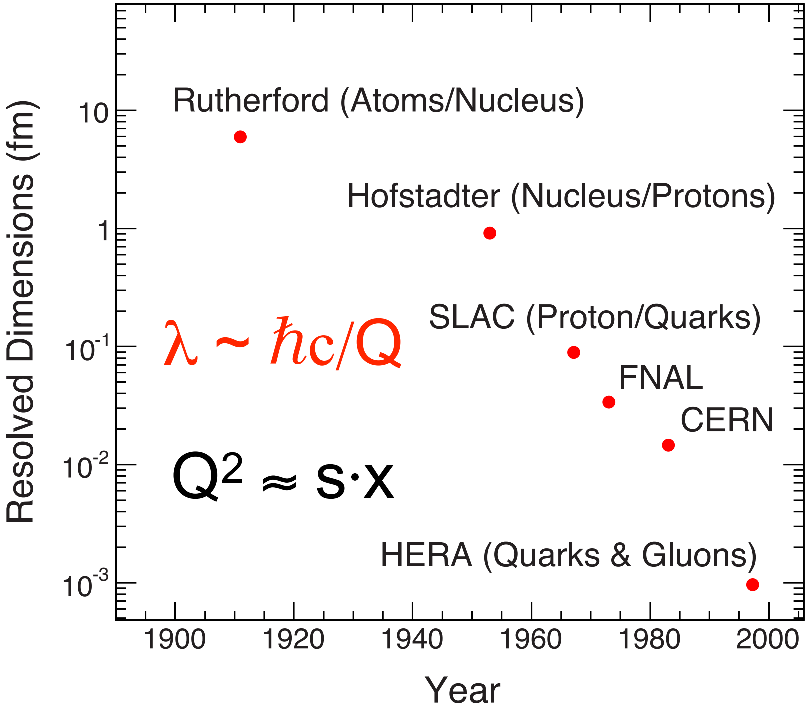
F_2: The Key Structure Function





Bjorken Scaling: $F_2(x, Q^2) \rightarrow F_2(x)$
virtual photon interacts with a single essentially **free quark**

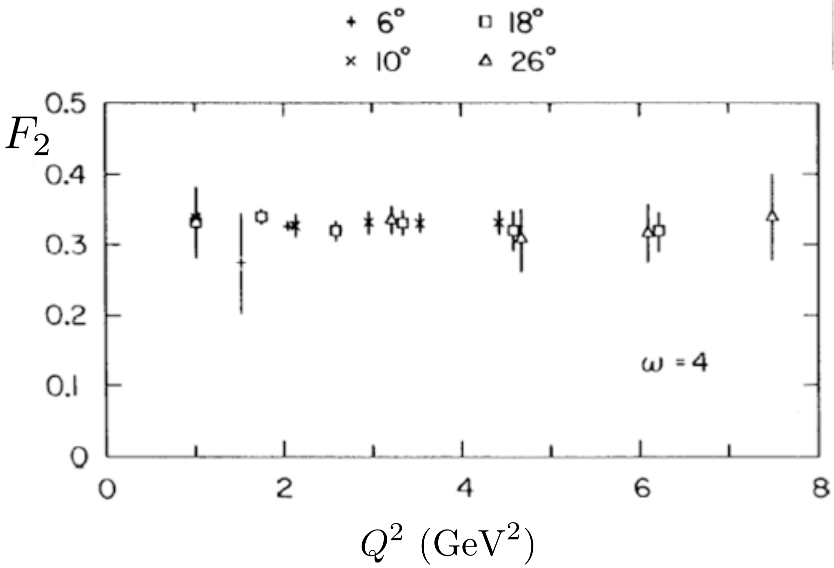
F_2: The Key Structure Function



$\lambda \sim \hbar c/Q$

$Q^2 \approx s \cdot x$

Bjorken scaling:

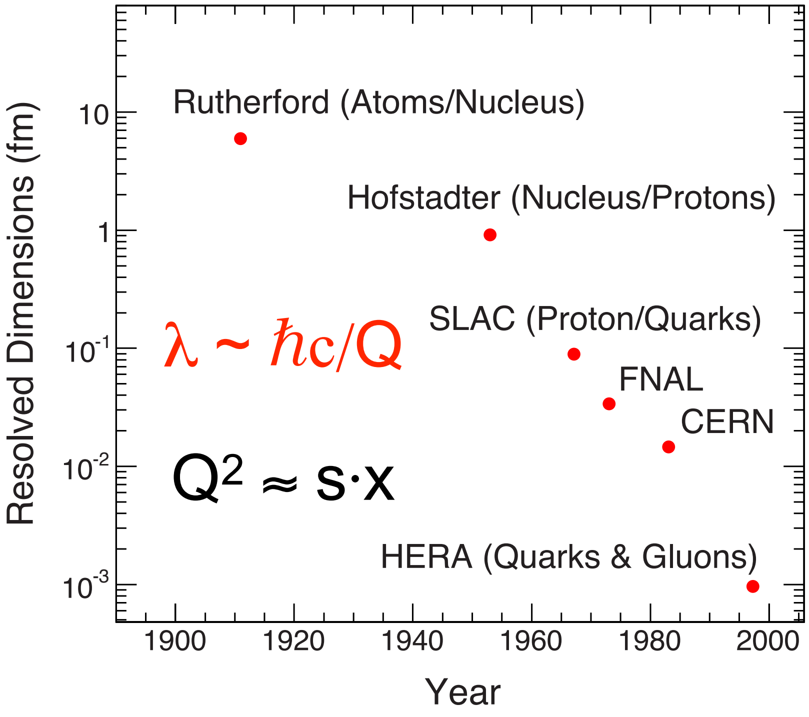


Point-like particles cannot be further resolved.

Their measurement does not depend on wavelength, hence Q^2 independence.

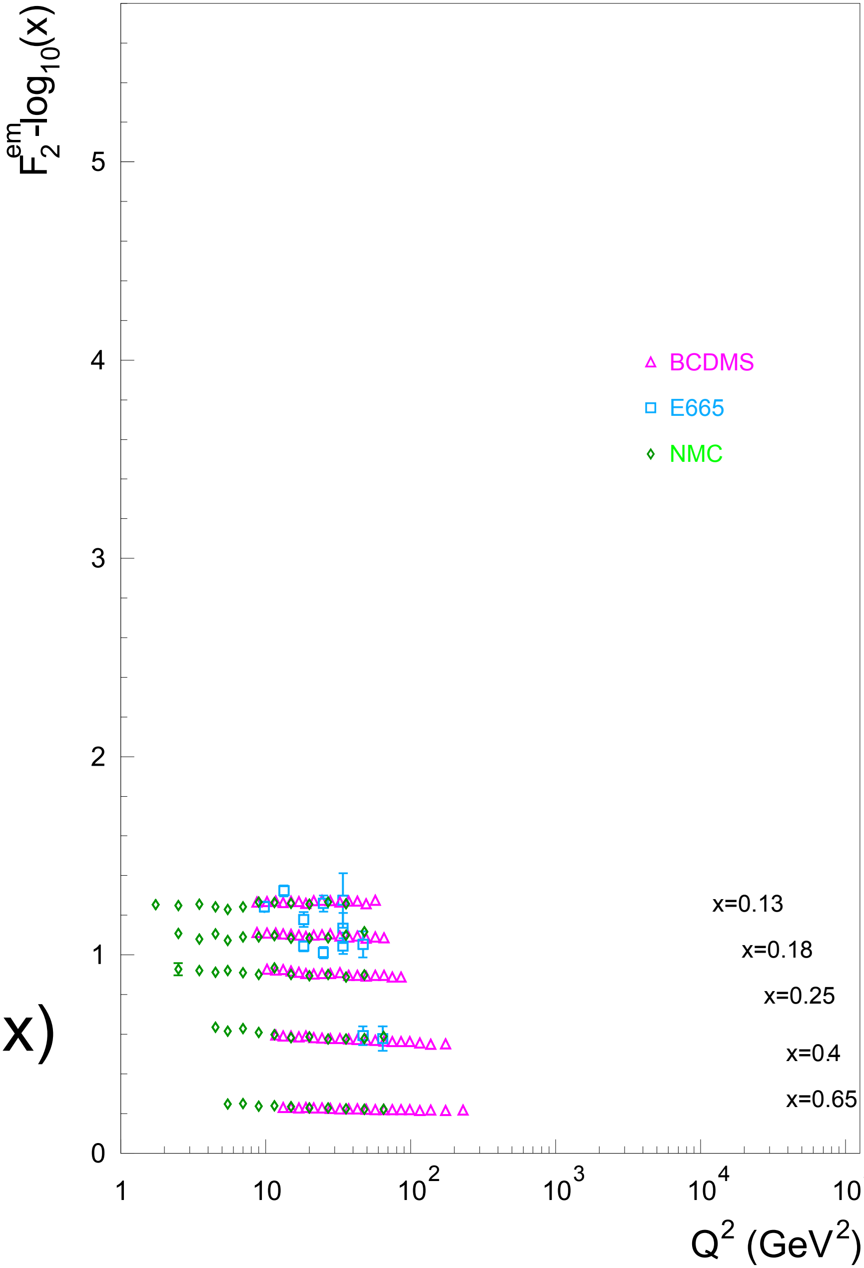
Bjorken Scaling: $F_2(x, Q^2) \rightarrow F_2(x)$ virtual photon interacts with a single essentially free quark

F_2: The Key Structure Function



$\lambda \sim \hbar c/Q$

$Q^2 \approx s \cdot x$



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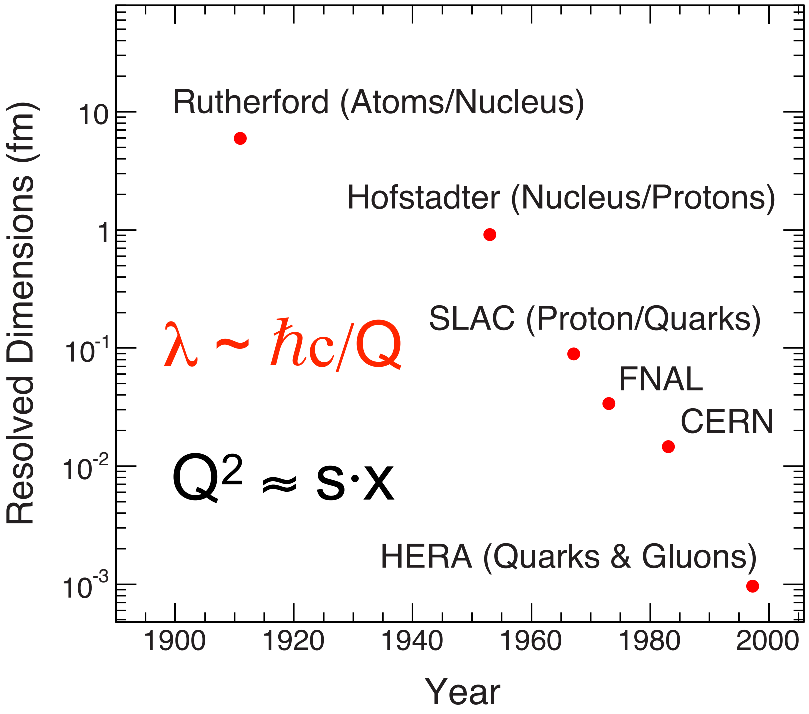
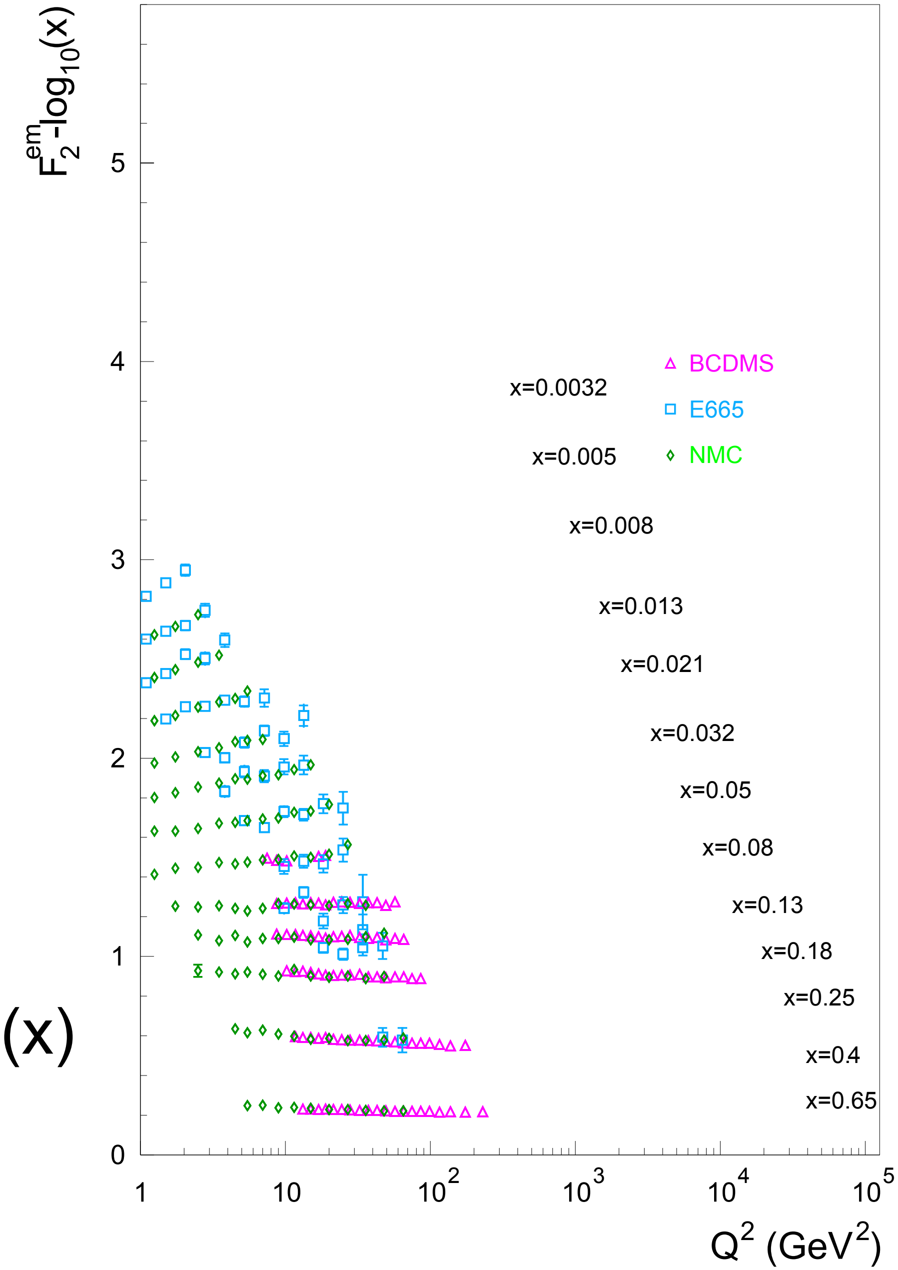
F_2: The Key Structure Function





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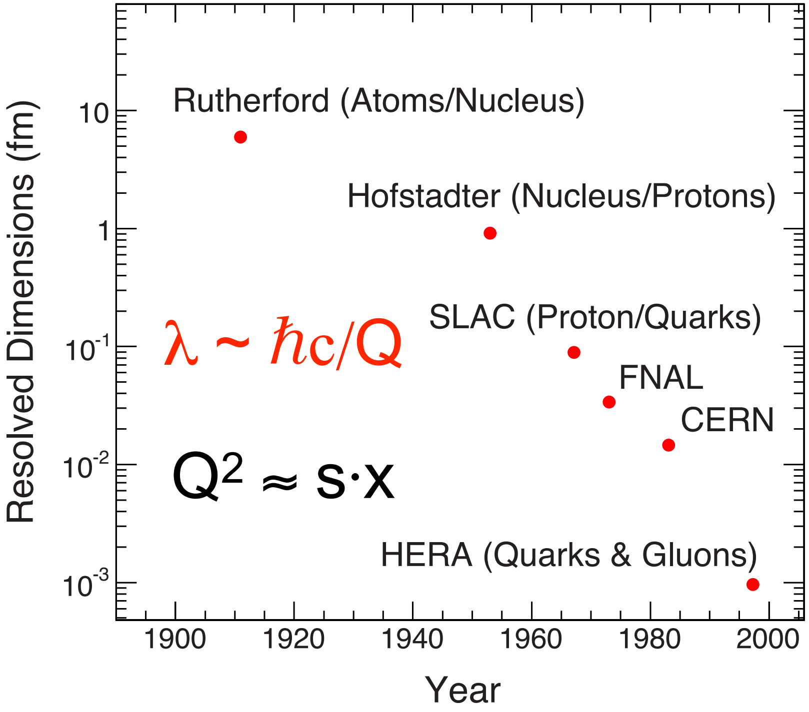
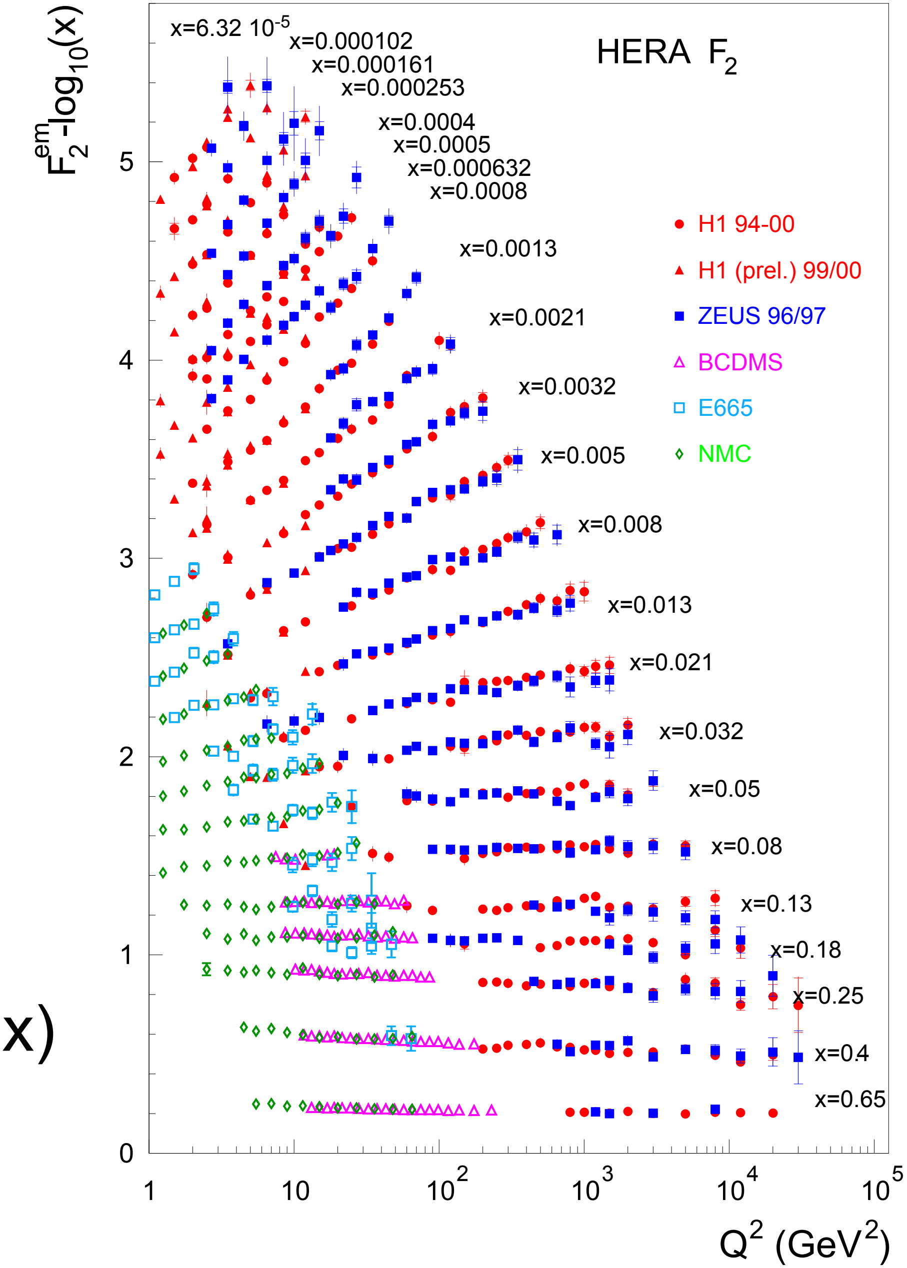


$\lambda \sim \hbar c/Q$

$Q^2 \approx s \cdot x$



Bjorken Scaling: $F_2(x, Q^2) \neq F_2(x)$

Broken - Big Time

It's the **Glue !!!**

Quark and Gluon Distributions

Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions (PDFs).

In LO: Probability to find parton with x, Q^2 in proton

PDF: Connecting experiment (e.g. pp) with theory

Jets, Drell-Yan, etc.: $\sigma_o = f_{i\to a} \otimes \hat{\sigma}_{a\to o}$

Observable

Parton Distribution Function (PDF)

Theoretical Calculations

Hadron Production: $\sigma_o = f_{i\to a} \otimes \hat{\sigma}_{a\to b} \otimes D_{b\to o}$

Fragmentation Functions

Quark and Gluon Distributions

Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions (PDFs).

In LO: Probability to find parton with x, Q^2 in proton

What is Needed:

- Good data
    - Best: F_2 (ep), jets, Drell-Yan (pp)
    - Bad: Hadrons
- pQCD Calculation of the processes
    - LO, NLO, NNLO
- QCD Evolution Equations
    - DGLAP: Evolution in Q^2 (small to large) at fixed x (integro-differential equations)
    - BFKL: Evolution in x at fixed Q^2

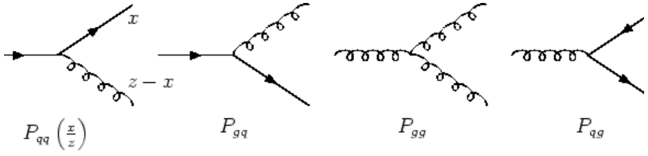
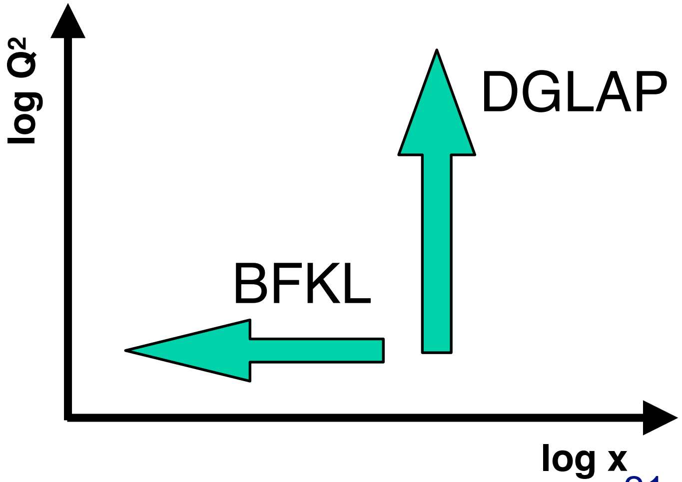
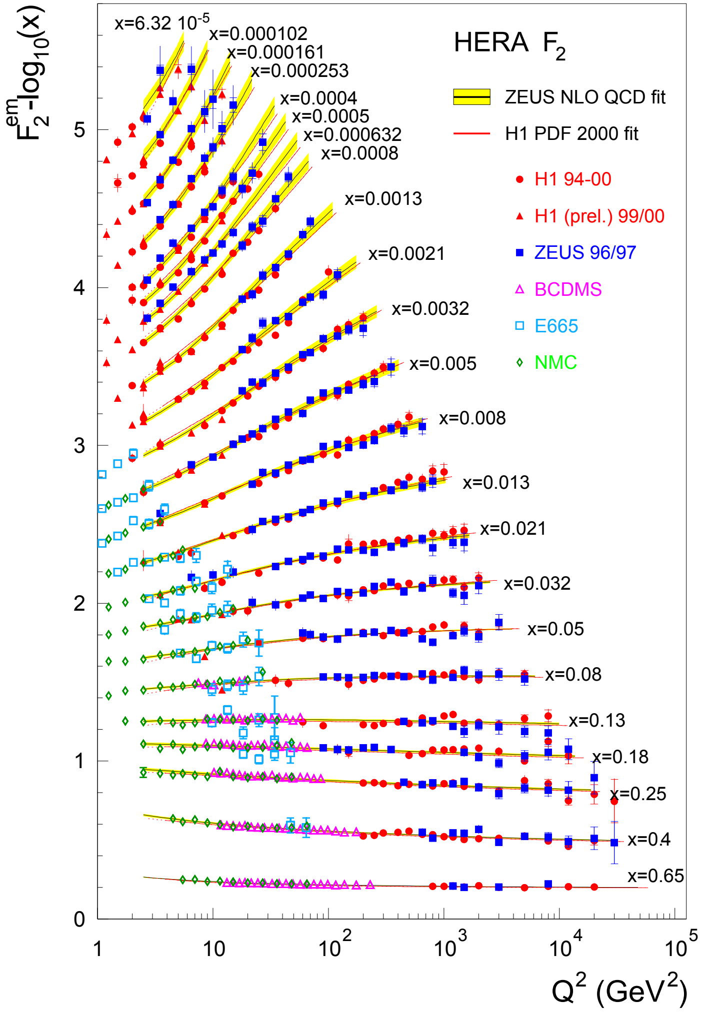


Figure 1.1: *The processes related to the lowest order QCD splitting functions. Each splitting function $P_{p'p}(x/z)$ gives the probability that a parton of type p converts into a parton of type p', carrying fraction x/z of the momentum of parton p*



Quark and Gluon Distributions

- Quarks: $q_i(x,Q^2)$ from F_2 (or reduced cross-section)
- Gluons: $g(x,Q^2)$ through scaling violation: $dF^2/d\ln Q^2$



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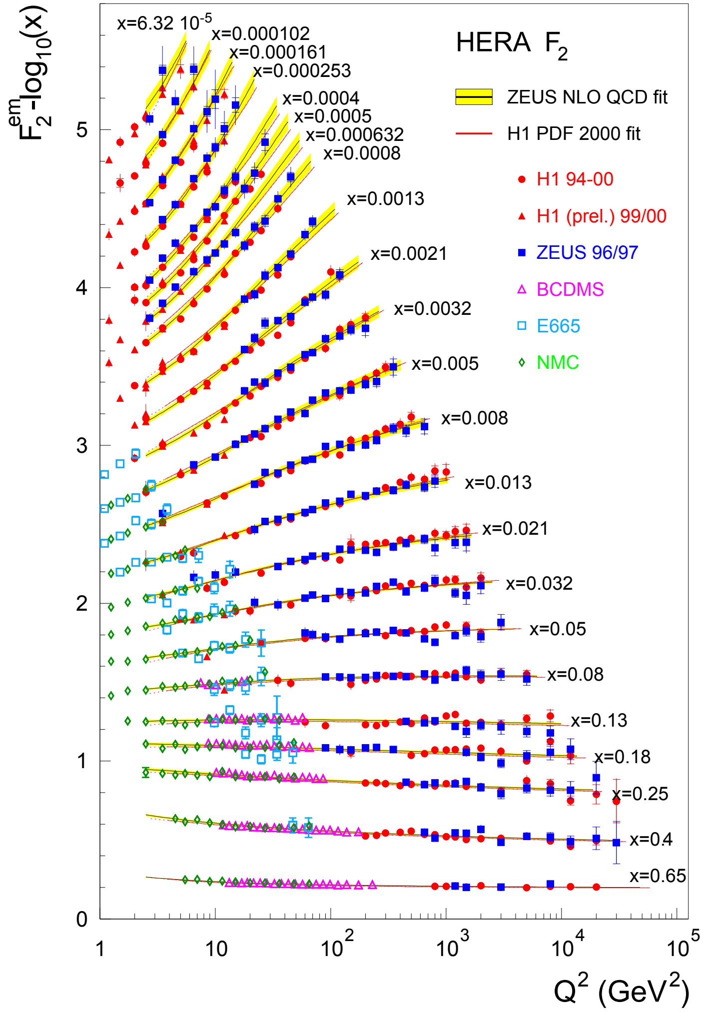

$\Rightarrow$

- F_2
- $dF_2/d\ln Q^2$

$+$ pQCD+ DGLAP Evolution

$$f(x, Q_1^2) \rightarrow f(x, Q_2^2)$$

Quark and Gluon Distributions

- Quarks: $q_i(x,Q^2)$ from F_2 (or reduced cross-section)
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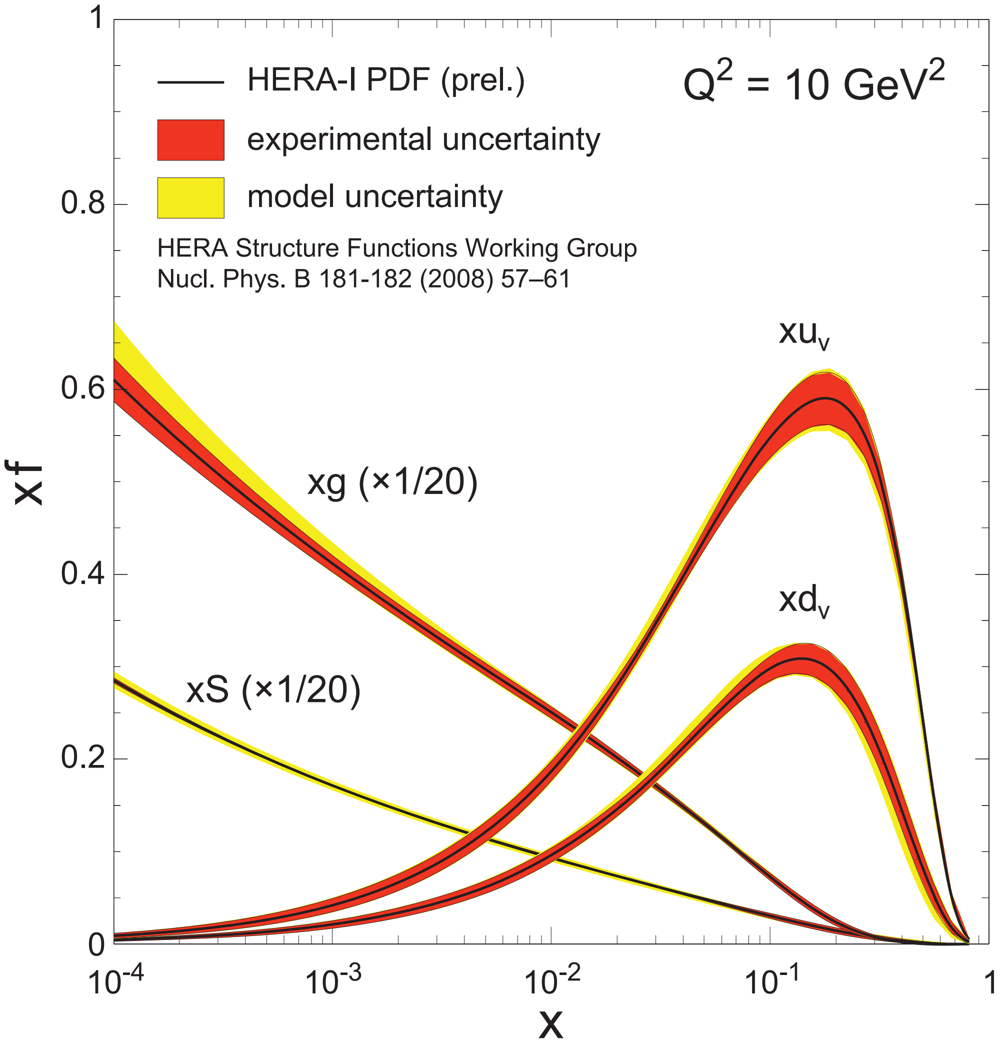

Quark and Gluon Distributions

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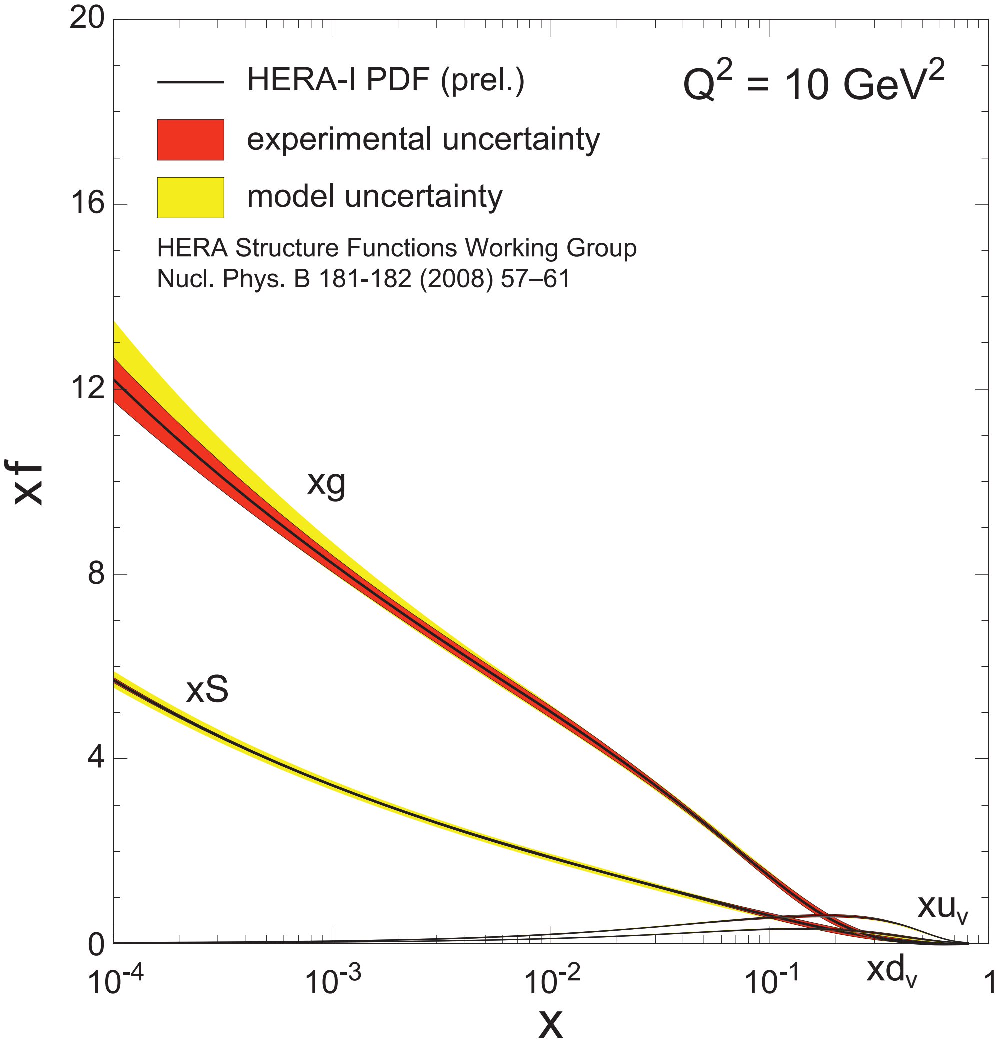


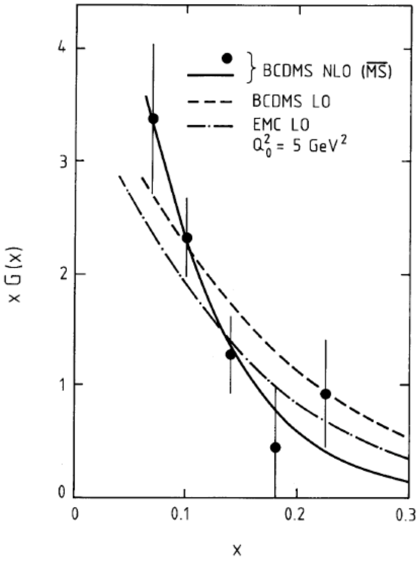
Proton is almost entirely glue for x<0.1

Here goes the naive picture that protons are made of 3 quarks (recall static quark model)

Hera’s Impact

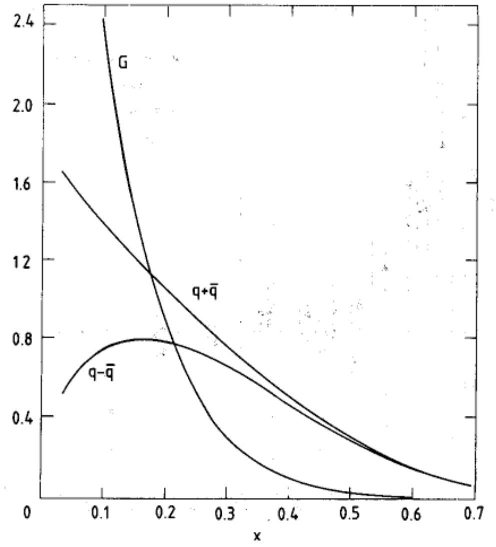
PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS



CERN-EP/89-07
January 17th, 1989

CDHS

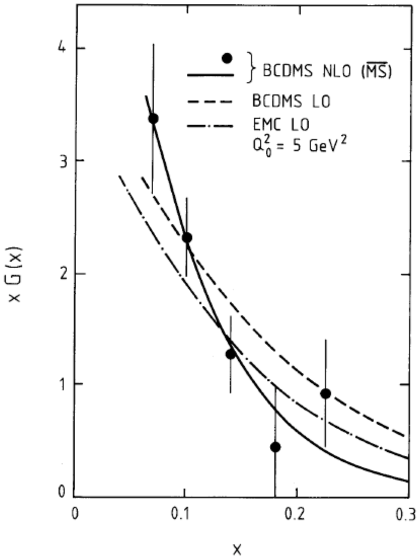


CERN-EP/89-103
15 August 1989

Hera's Impact

PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS



CERN-EP/89-07
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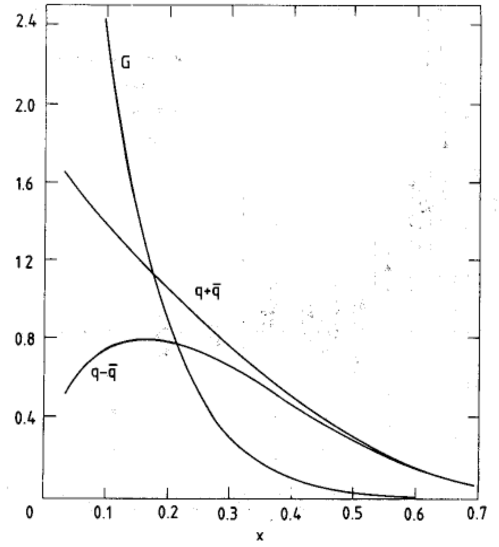
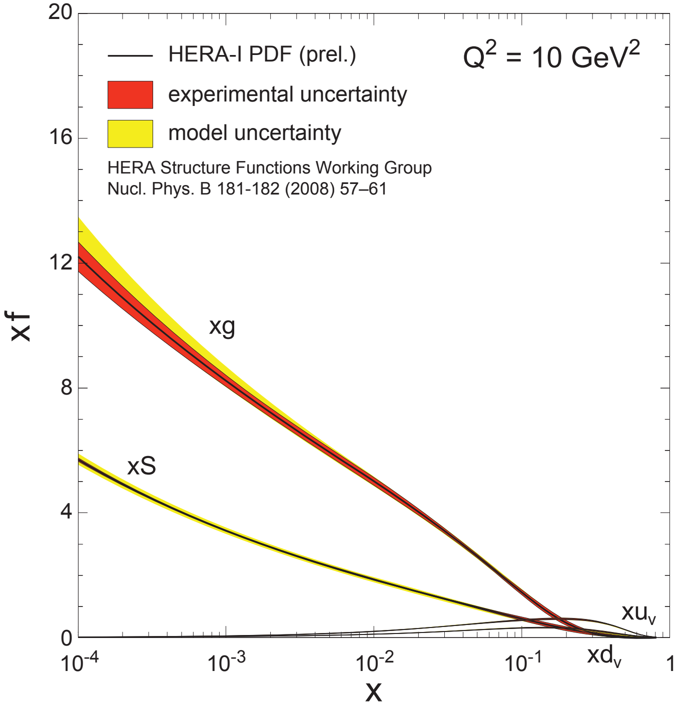
CDHS



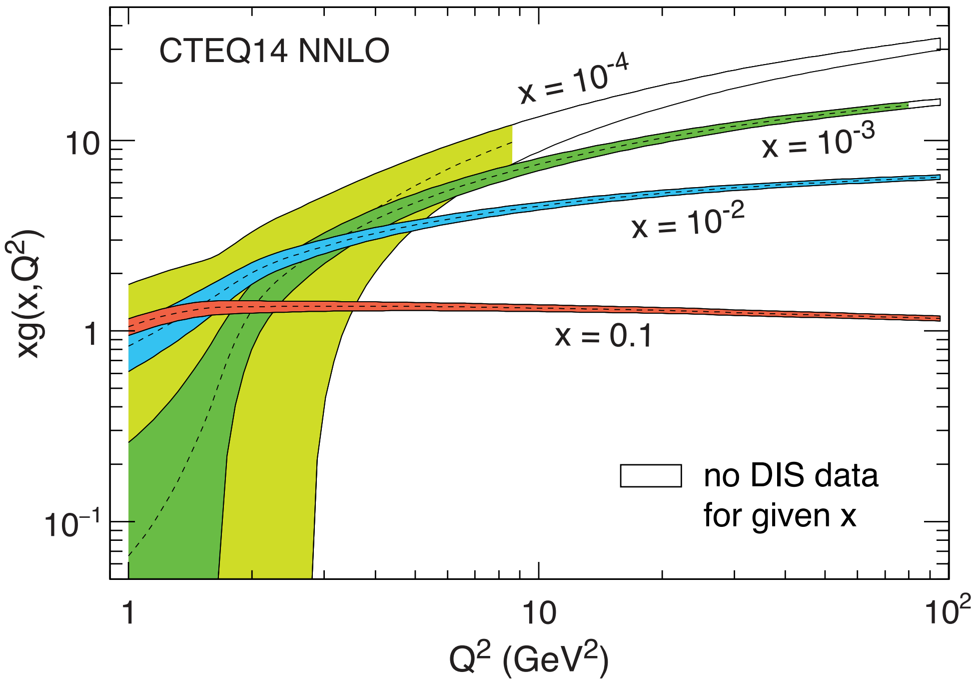
CERN-EP/89-103
15 August 1989



HERA Structure Functions Working Group
Nucl. Phys. B 181-182 (2008) 57–61

PDFs: Much Progress, Still Shortcomings

CTEQ14: a modern proton PDF

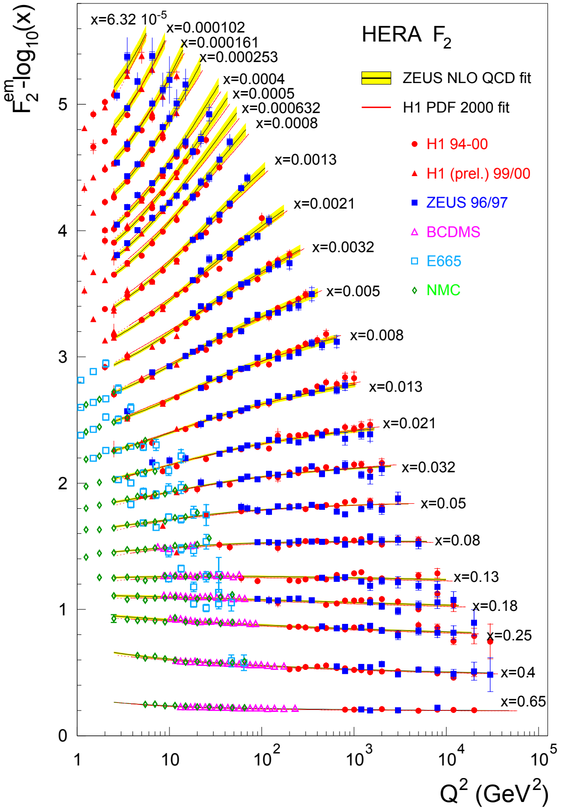


- Large uncertainties at $x=10^{-3}$ and 10^{-4} at the small Q^2 although high quality data exist.
- The precision of low Q^2 data is ineffectual due to the lack of data at the larger Q^2 (Evolution from low to high Q^2)

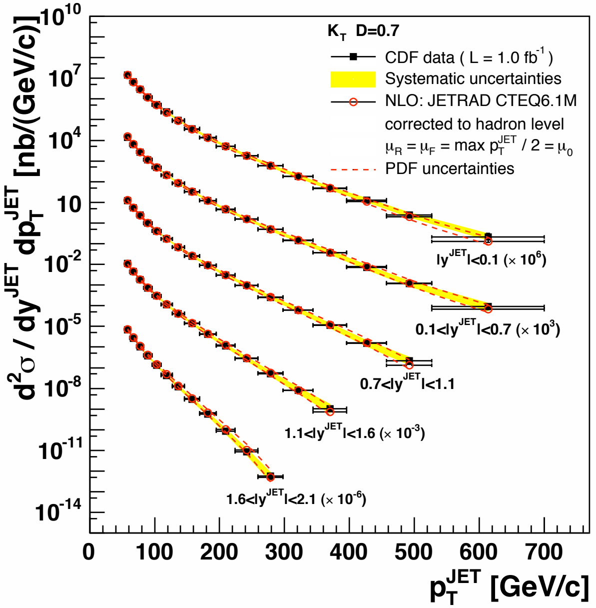
Uncertainties from PDF dominate many “BSM” searches

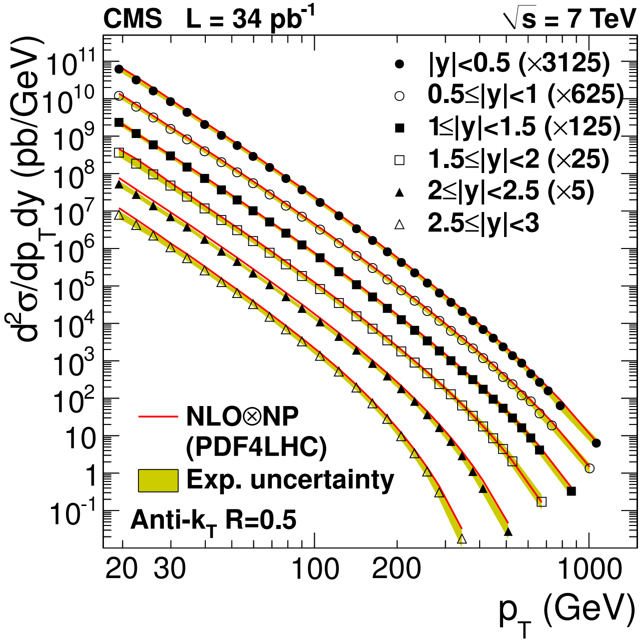
Strong Evidence that QCD is the Correct Theory

Structure functions measured at HERA ep collider

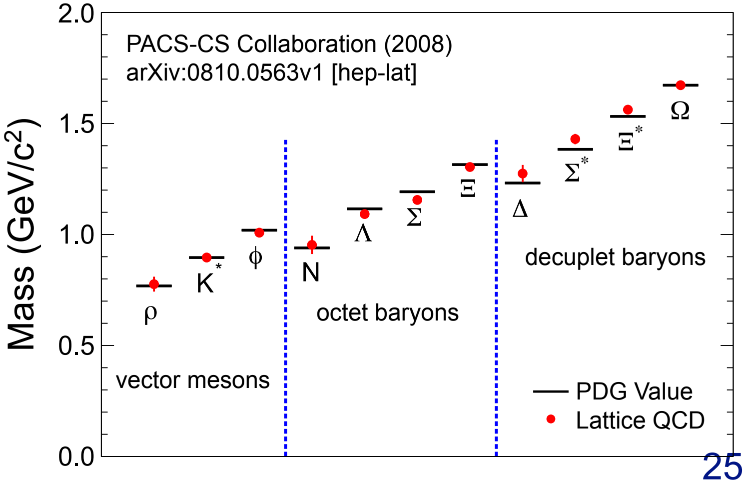


Jet cross-sections: pp collisions at LHC and $\bar{p}p$ collisions at Fermilab





Lattice QCD



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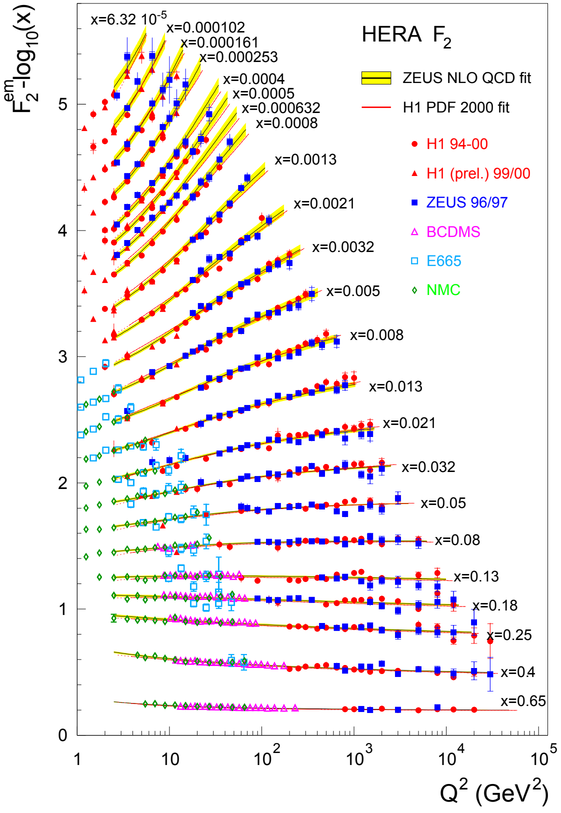

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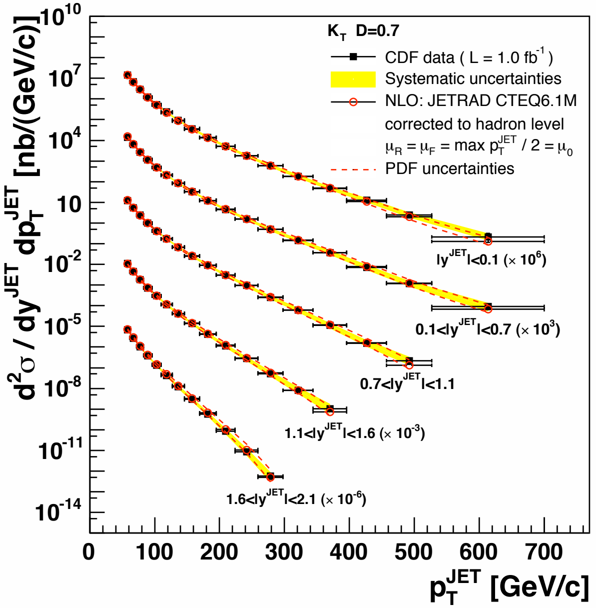

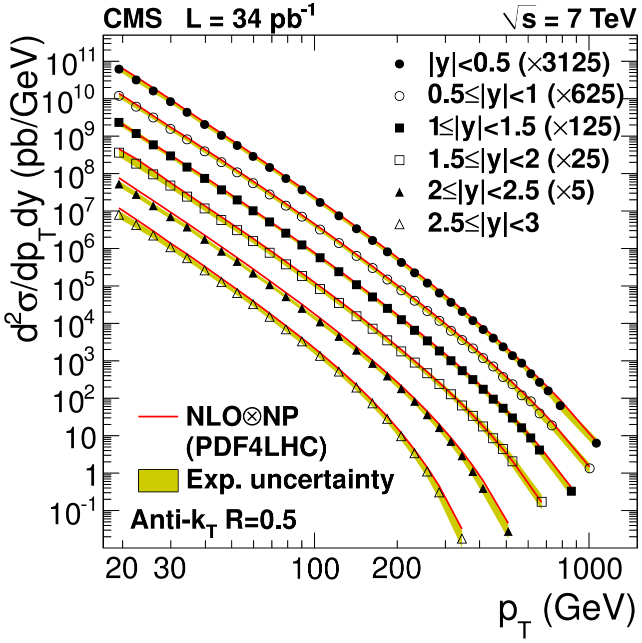

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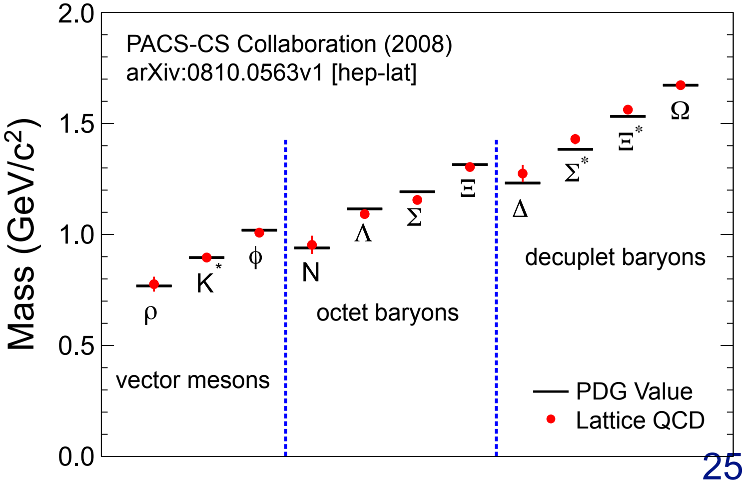
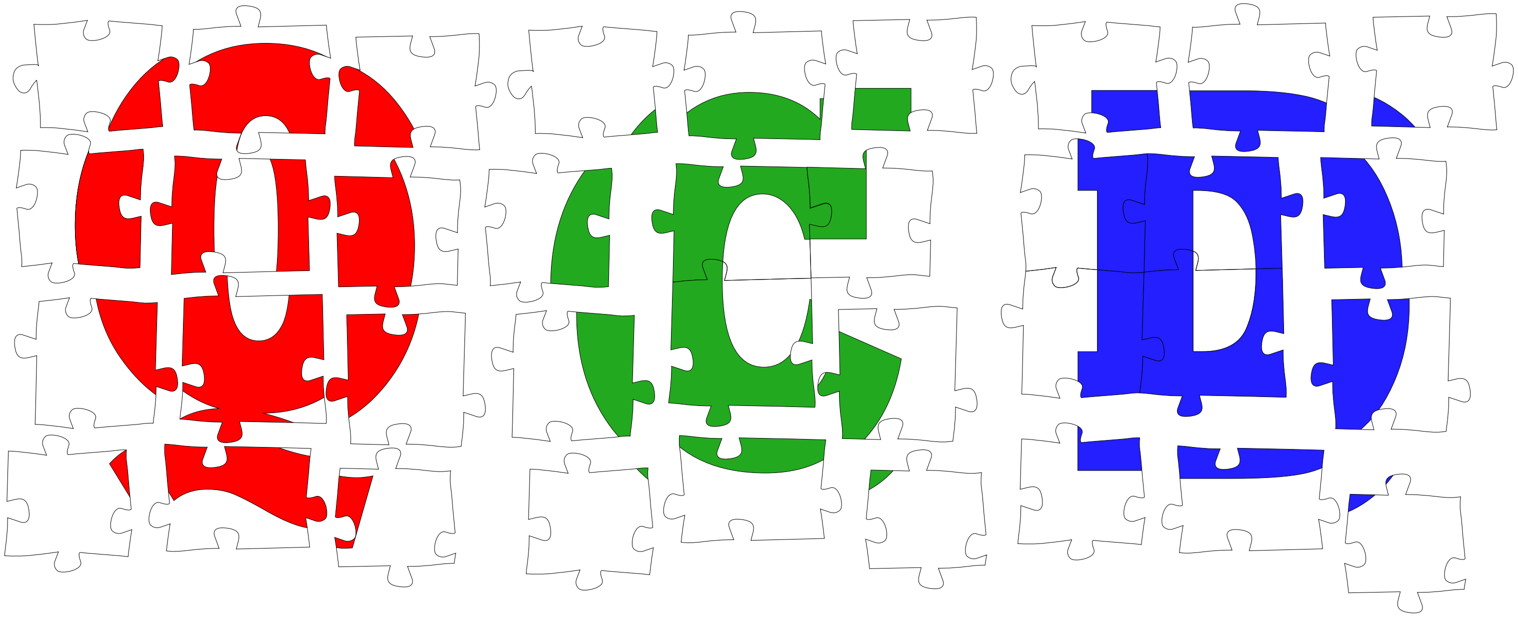


Are we done?

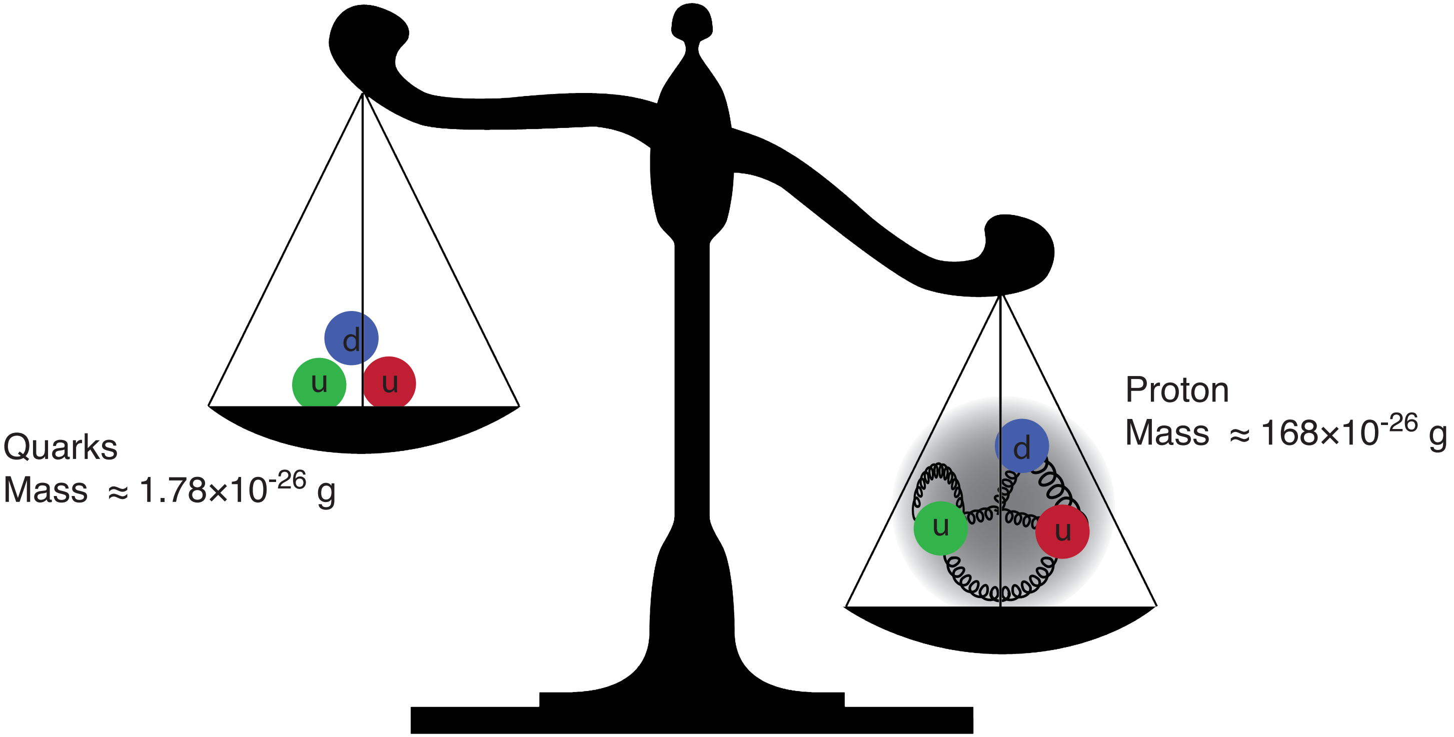
4. The Frontiers of Our Ignorance



... that motivate an Electron-Ion Collider

The Mass Puzzle

The Higgs is responsible for quark masses
~ 2% of the proton mass.



Gluons are massless…yet their dynamics are responsible for (nearly all) the mass of visible matter. We do not know how?

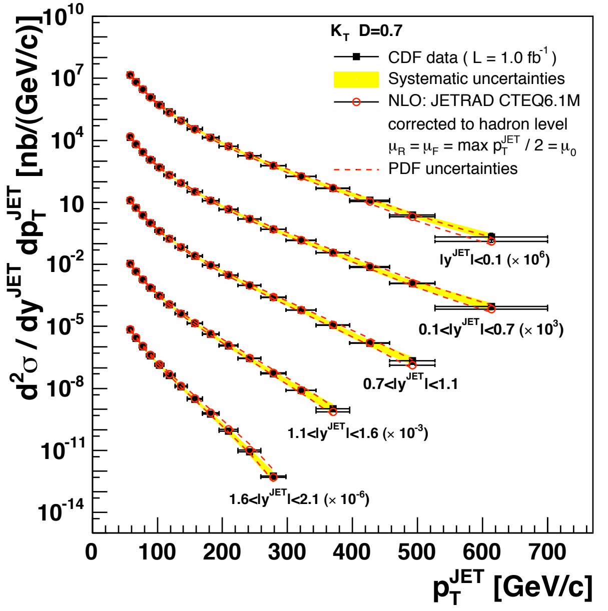
Scattering in the Strong Interactions

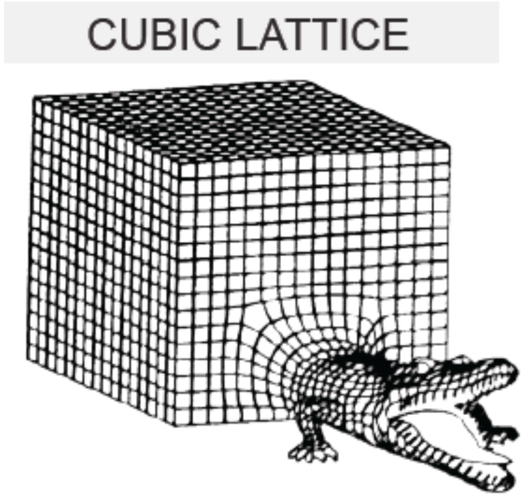
Perturbative QCD:

- Describes only a small part of the total cross-section

Lattice QCD:

- First principles treatment of static properties of QCD: masses, moments, thermodynamics
- Very challenging for dynamical processes and very limited utility in describing scattering





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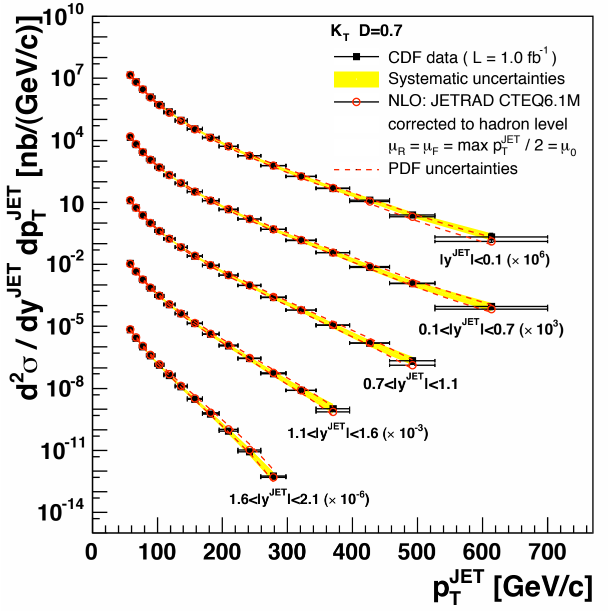
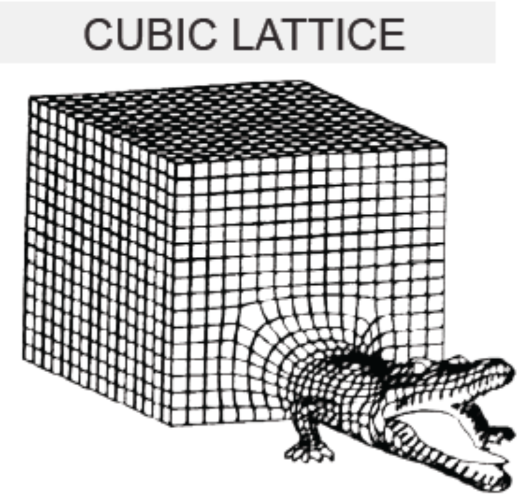
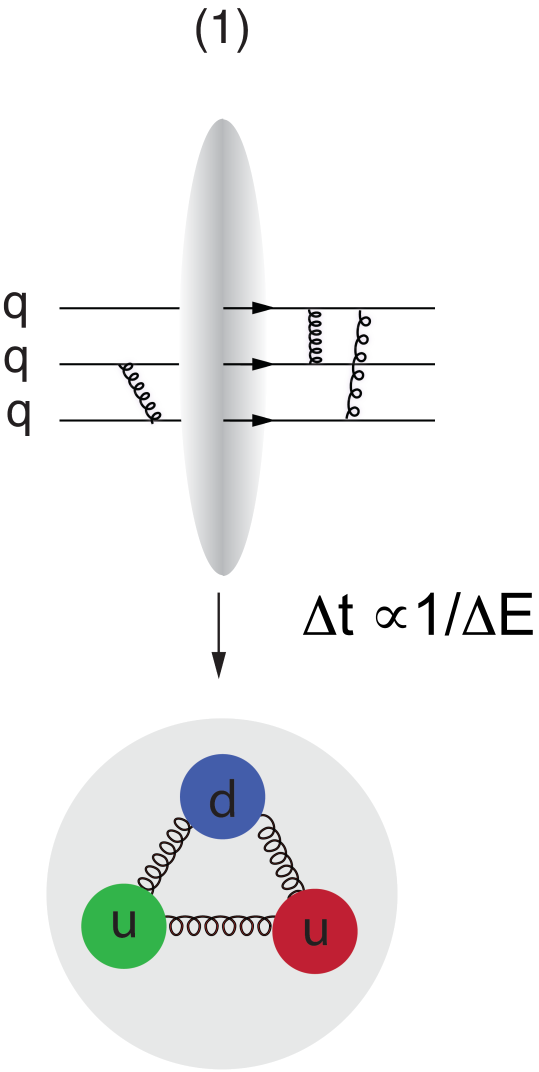




Instead ⇒ Effective theories:

- How do quark and gluon degrees organize themselves to describe the bulk of the cross-section?

A Look Inside the Boosted Proton



$\Delta t \propto 1/\Delta E$

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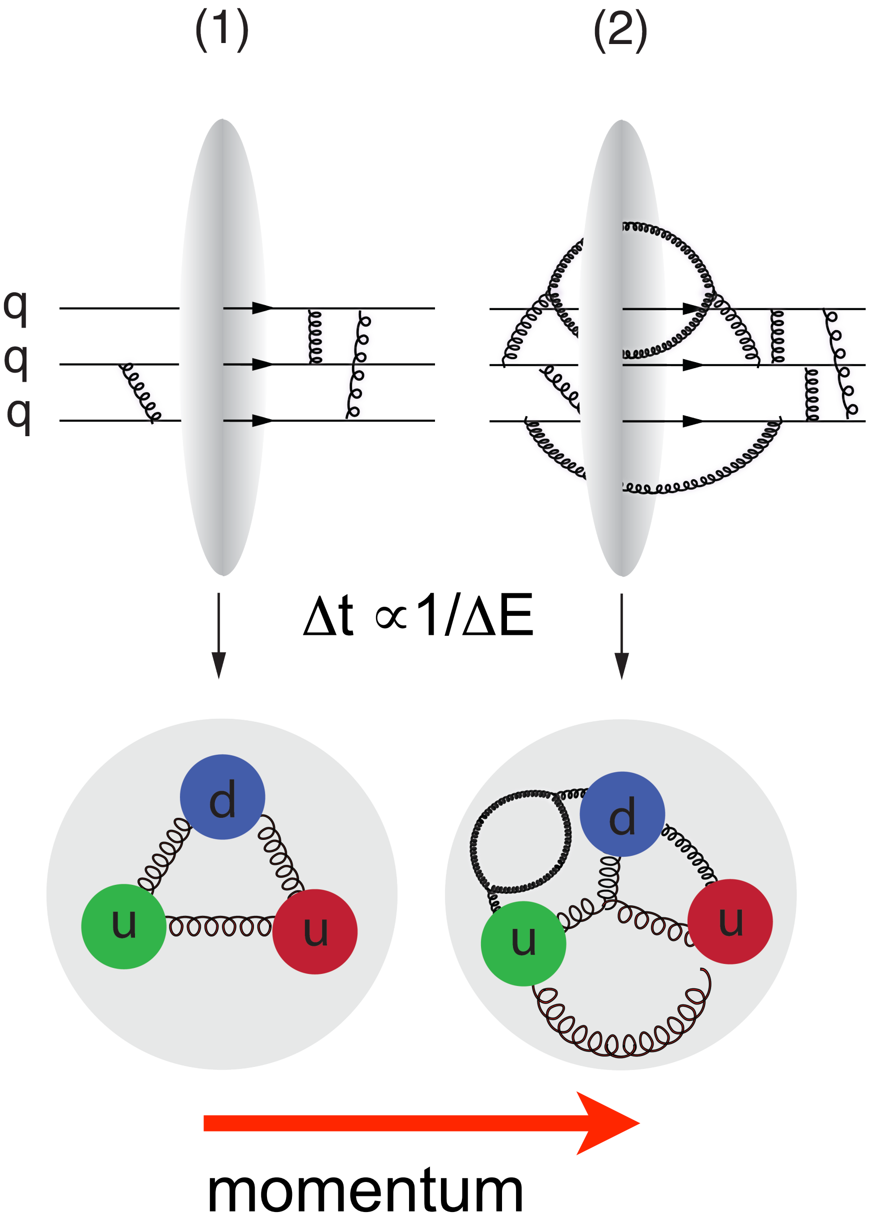

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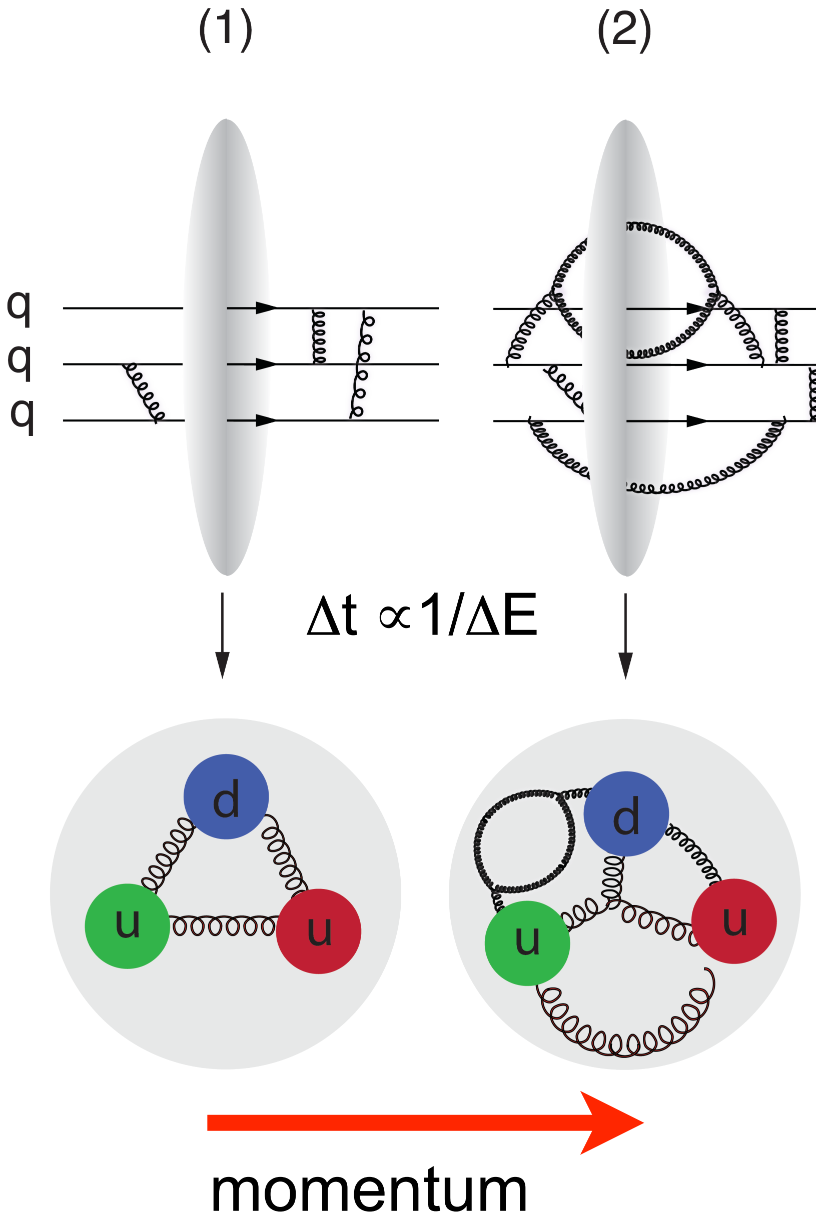
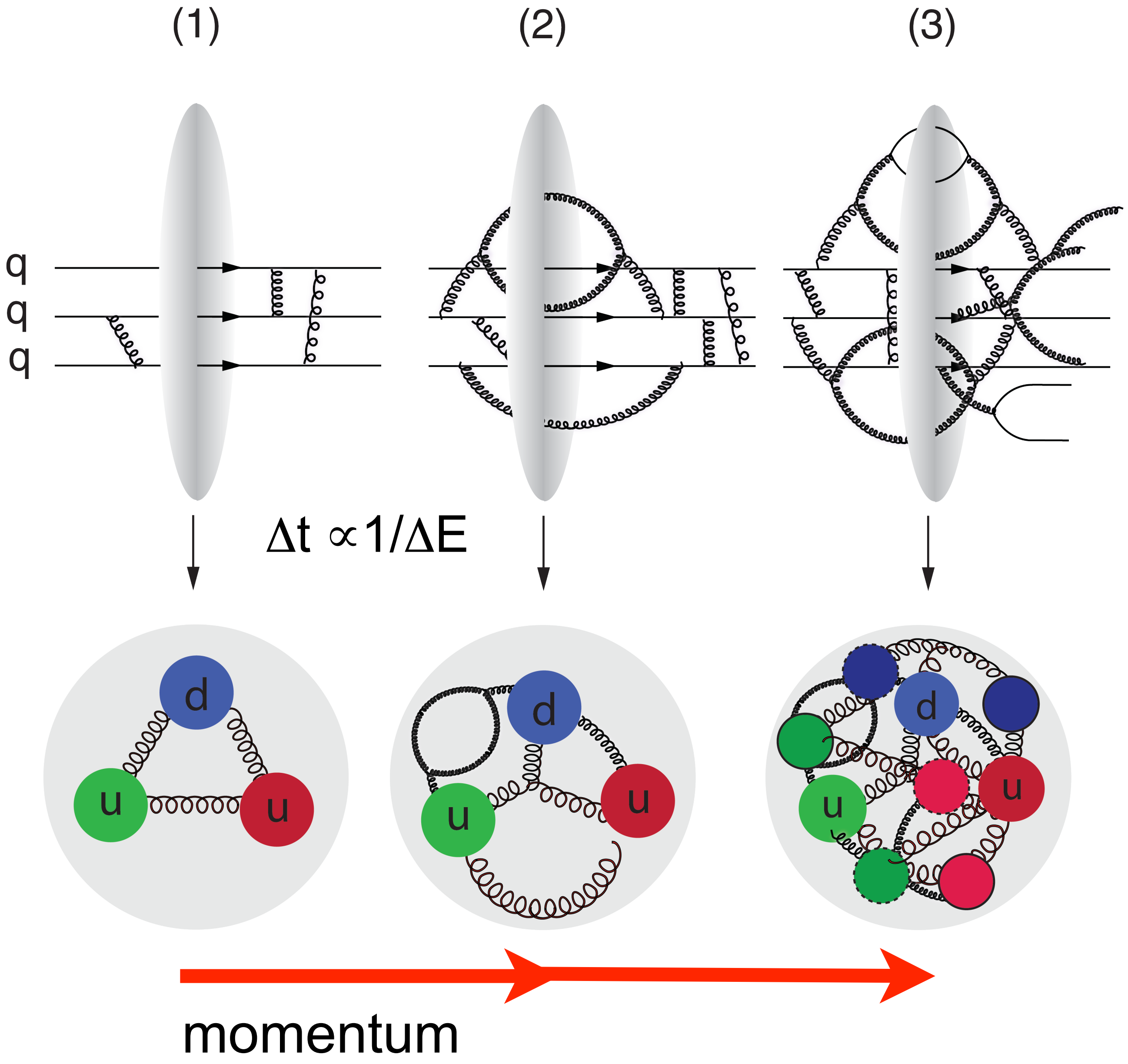


In QCD, the proton is made up of quanta that fluctuate in and out of existence

- Boosted proton:
  - Fluctuations time dilated on strong interaction time scales
  - Long lived gluons can radiate further small x gluons…
  - Explosion of gluon density

A Look Inside the Boosted Proton



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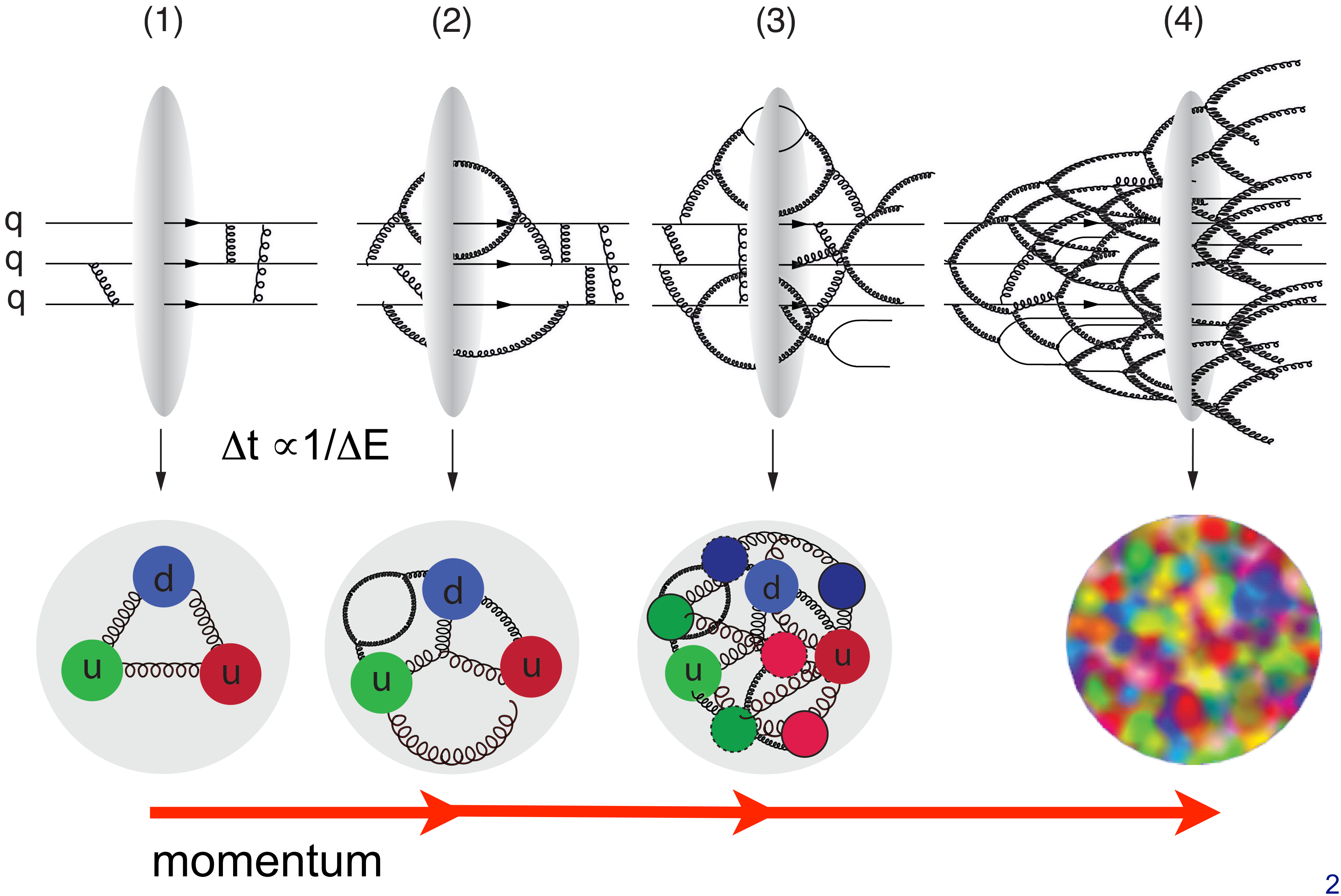

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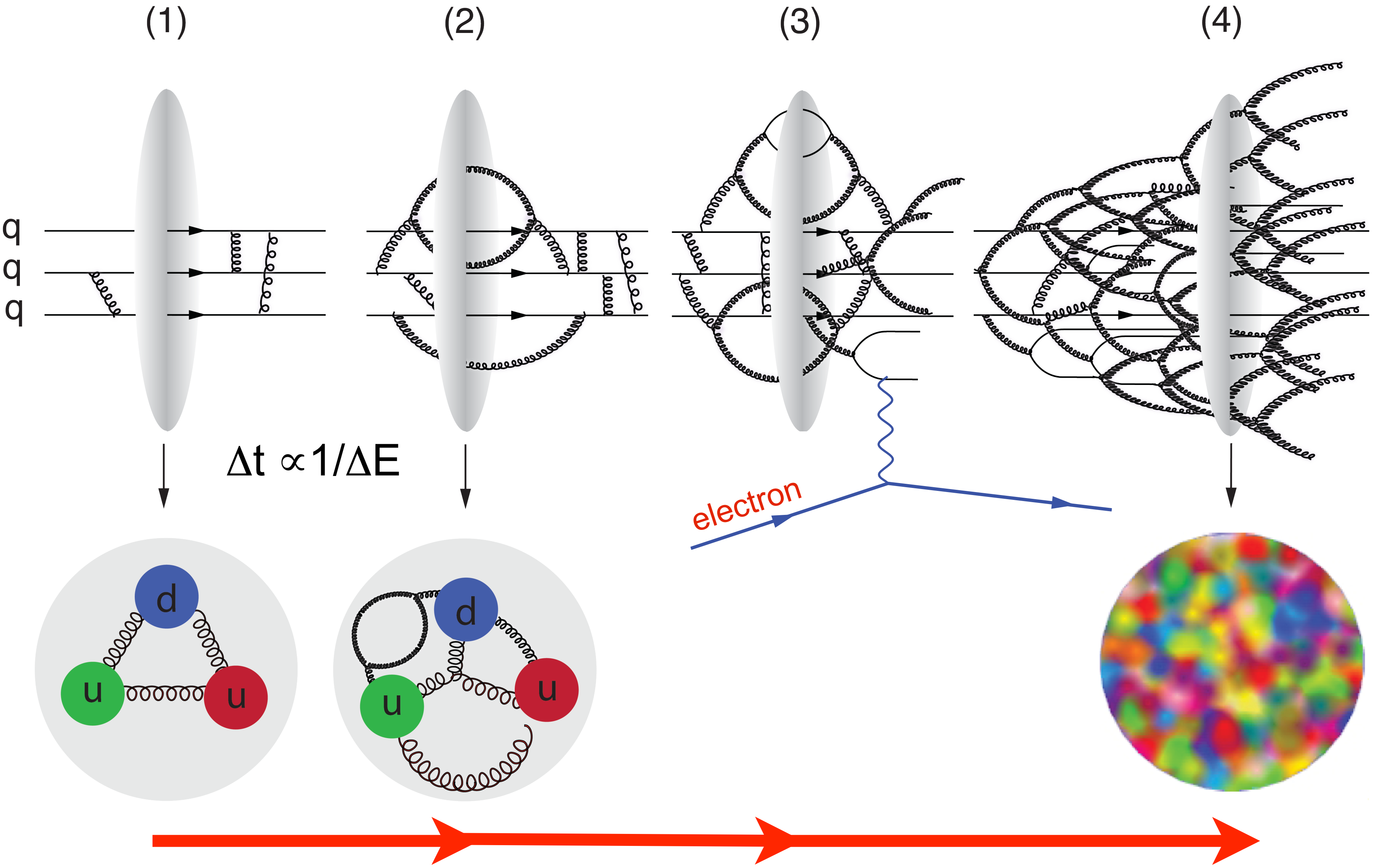


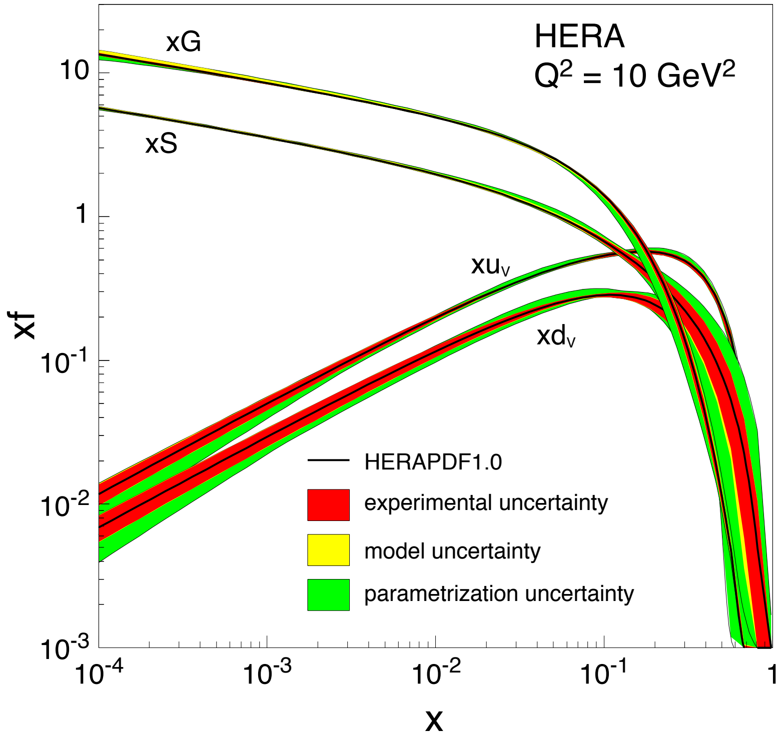
momentum

A Look Inside the Boosted Proton

Issues with our Current Understanding

Linear DGLAP Evolution Scheme

- built in high energy "catastrophe"
- G rapid rise violates unitary bound



Linear BFKL Evolution Scheme

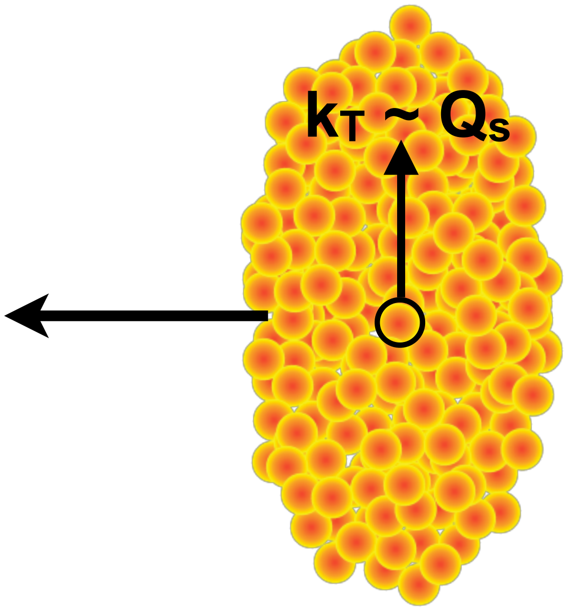
- Density along with σ grows as a power of energy
- Can densities & σ rise forever?
- Black disk limit: $\sigma_{total} \leq 2 \pi R^2$

Something's wrong:
Gluon density is growing too fast
⇒ Must saturate (gluons recombine)

What's the underlying dynamics? Need New Approach

Gluon Saturation

In transverse plane: nucleus/nucleon densely packed with gluons

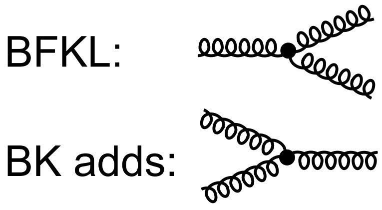


McLerran-Venugopalan Model:

- Weak coupling description of the wave function
- Gluon field $A_\mu \sim 1/g \Rightarrow$ gluon fields are strong classical fields!
- Most gluons $k_T \sim Q_S$

New Approach: Non-Linear Evolution:

- At very high energy: recombination compensates gluon splitting
- Cross sections reach unitarity limit ⇒ saturation
- Needs new evolution equations (JIMWLK/BK)
- Saturation regime characterized by $Q_s(x,A)$



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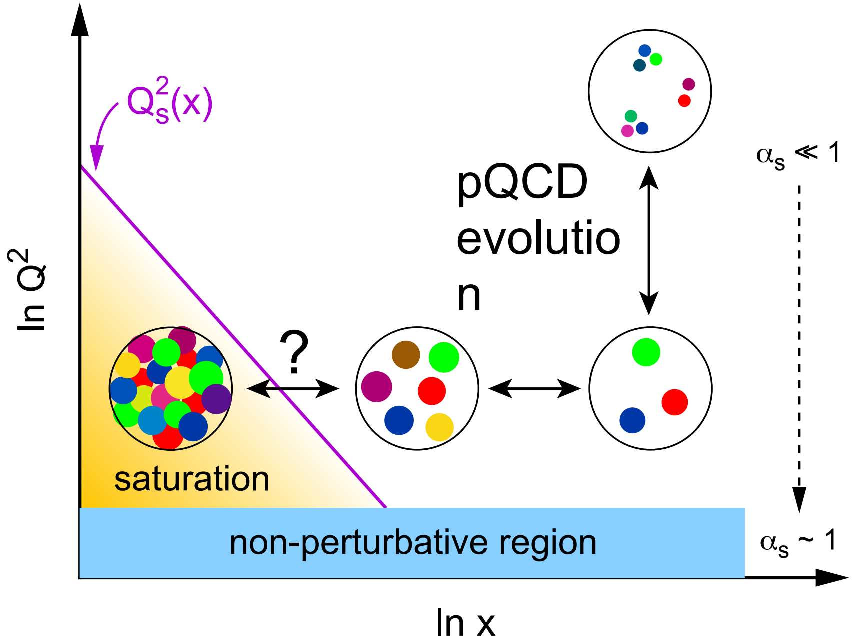

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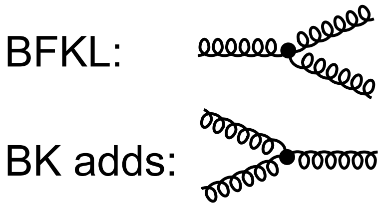
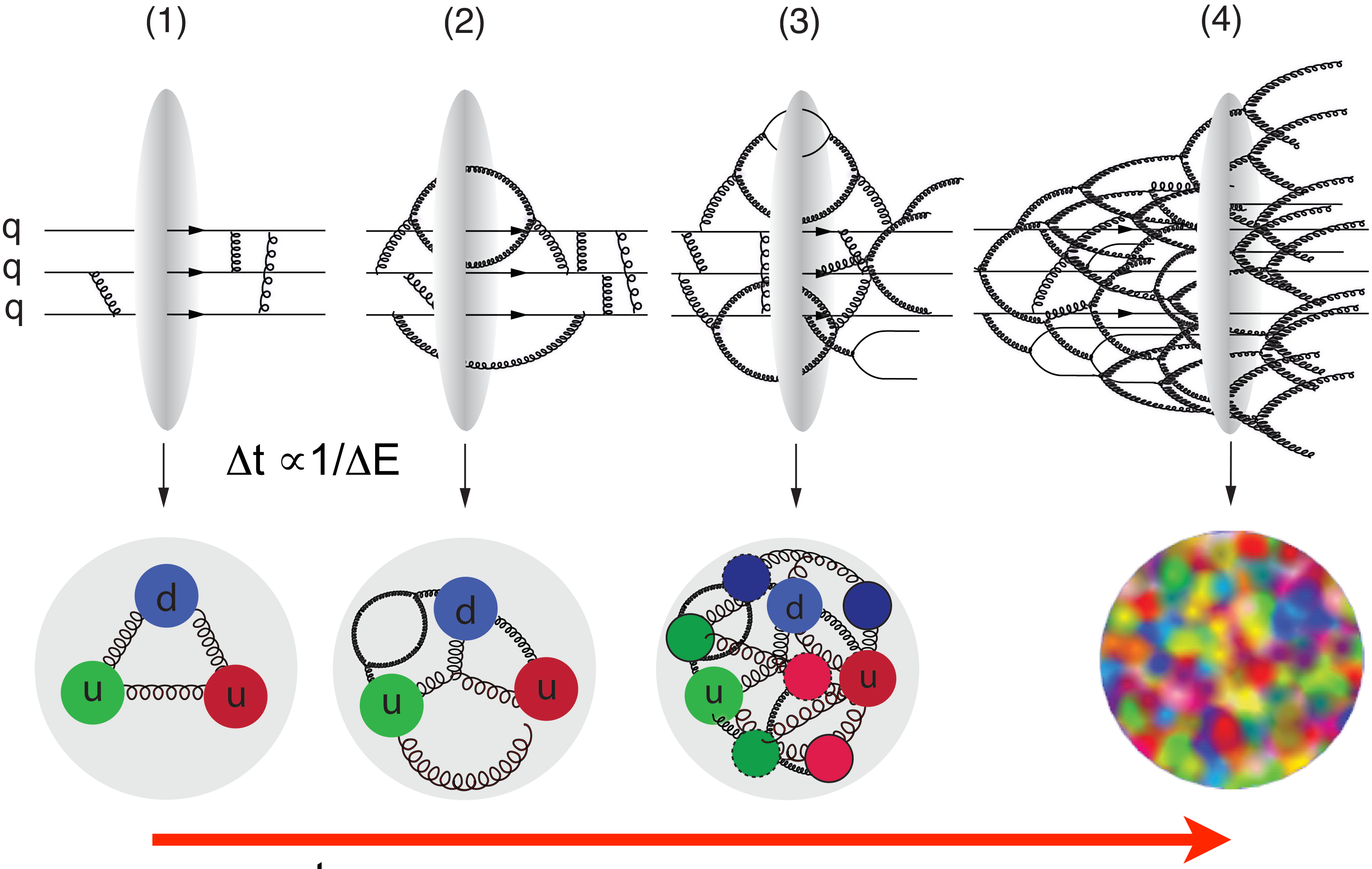


Color Glass Condensate (CGC)

- The saturated regime is called a Color Glass Condensate
  - "Color" in the name refers to the color charge of quarks and gluons
  - “Glass” is borrowed from the term for silica and other materials that are disordered and act like solids on short time scales but liquids on long time scales. In the CGC the gluons themselves are disordered and do not change their positions rapidly because of time dilation.
  - "Condensate" means that the gluons have a very high density (there is some speculation if the CGC is a BEC)
- The effective theory that describes the CGC is also called the CGC (just to confuse you)
- The CGC evolution equation is called JIMWLK and it’s mean field equivalent BK (replacing BFKL)

A Look Inside the “Saturated” Proton



$\Delta t \propto 1/\Delta E$

momentum

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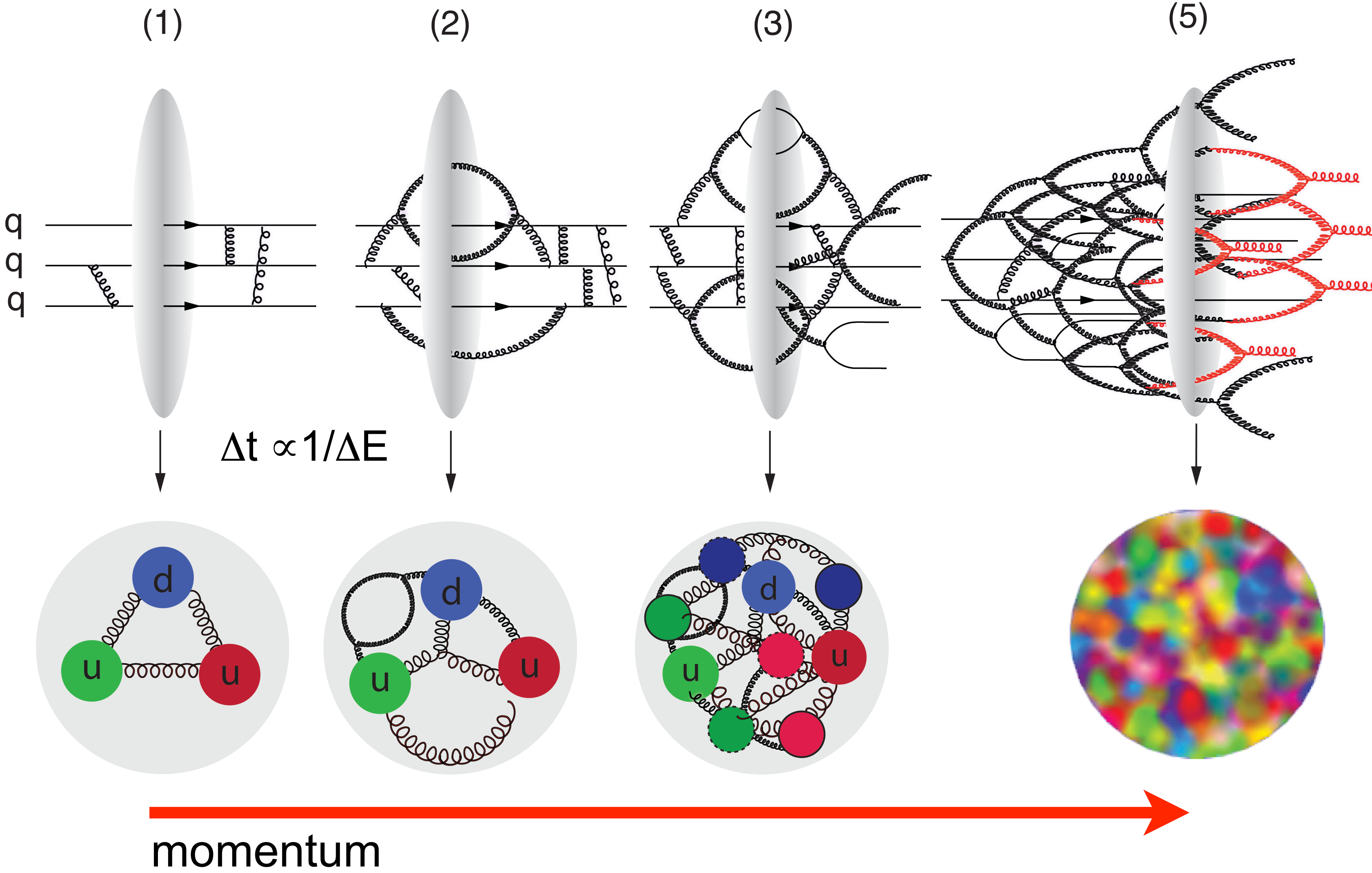

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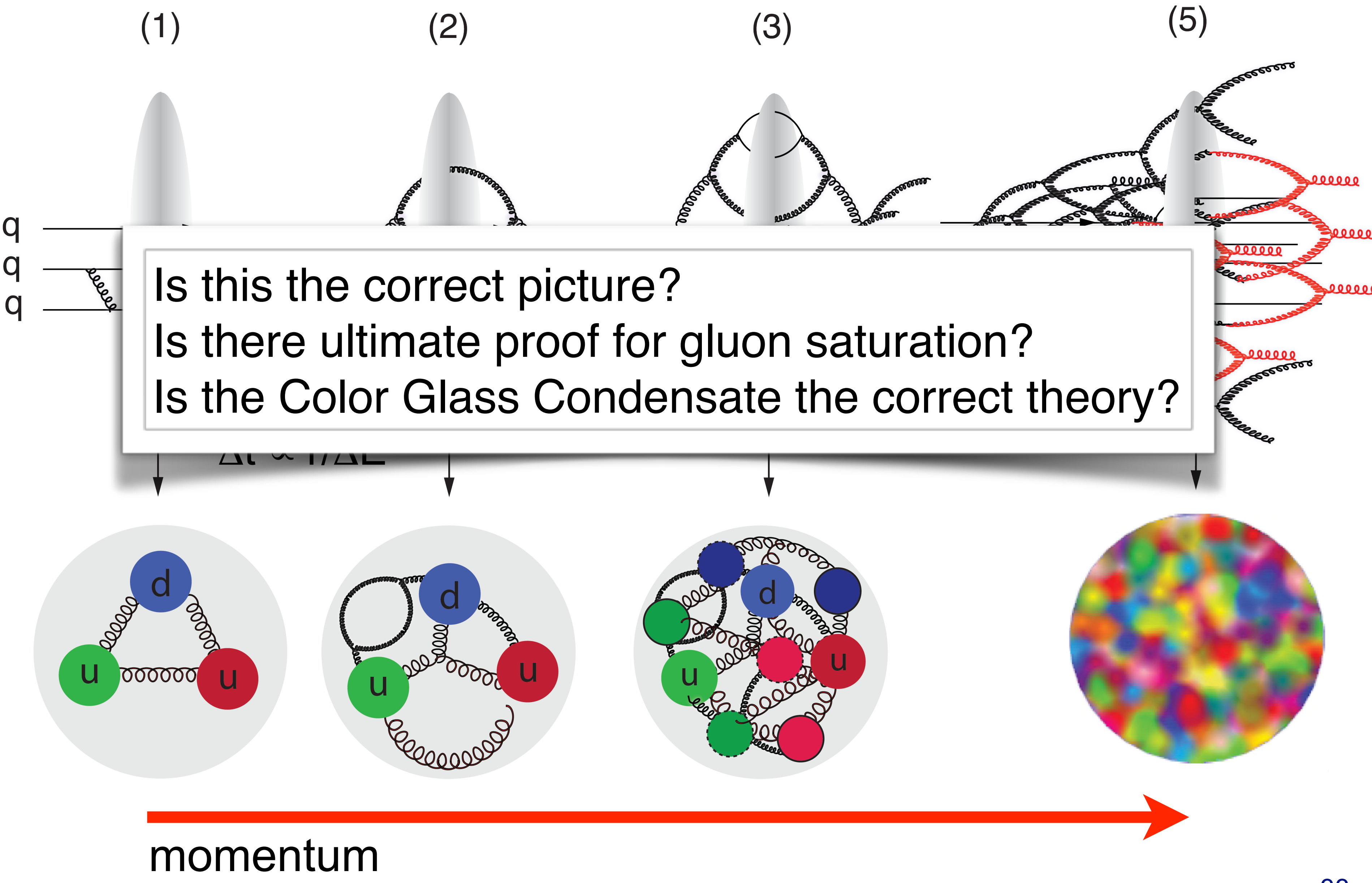
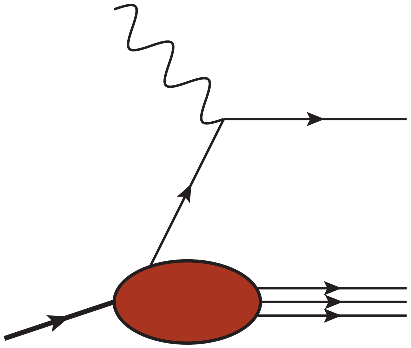
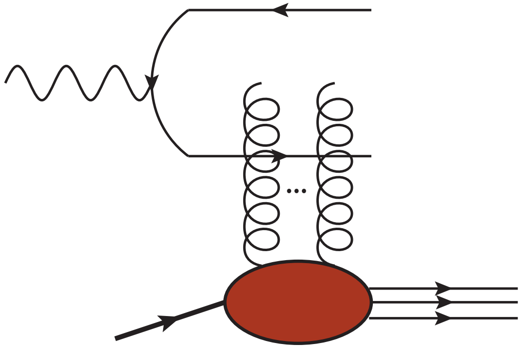


Is this the correct picture?
Is there ultimate proof for gluon saturation?
Is the Color Glass Condensate the correct theory?

N.B.: Important Dual Description of DIS



Bjorken frame



Dipole frame

- Bjorken frame: Partonic picture of a hadron is manifest. Saturation shows up as a limit on the occupation number of quarks and gluons.

- Dipole frame: Partonic picture is no longer manifest. Saturation appears as the unitarity limit (black disk) for scattering. Convenient to resum the multiple gluon interactions.

Dipole frame commonly used to describe diffractive processes
[A. Mueller, 01; Parton Saturation-An Overview]

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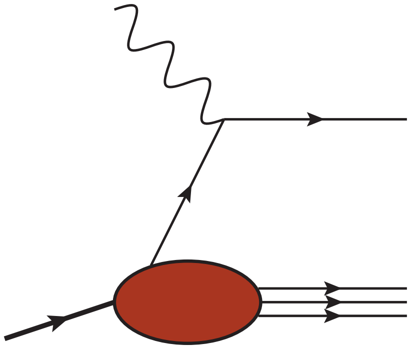

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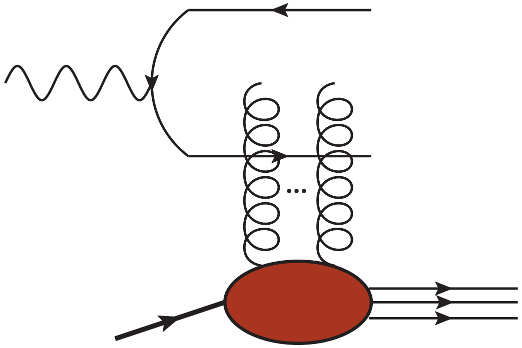
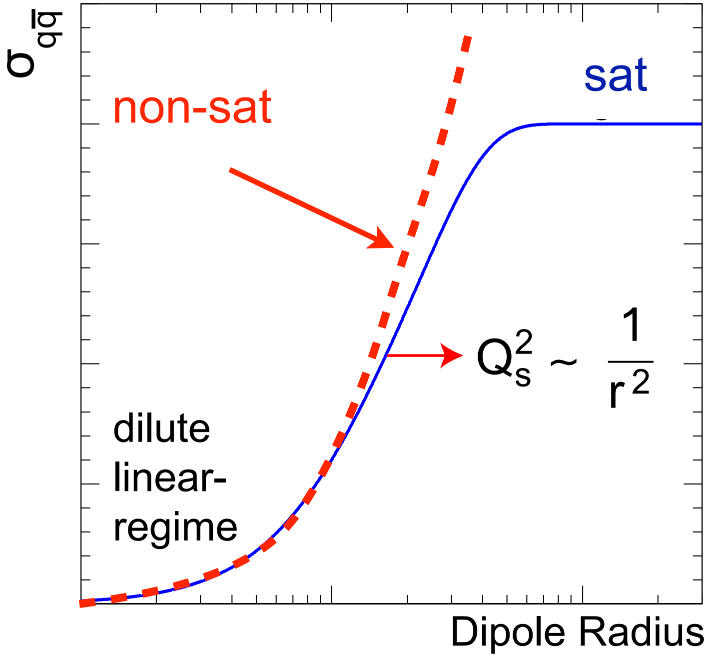


Dipole frame

Dipole Cross-Section:



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Dipole frame commonly used to describe diffractive processes

[A. Mueller, 01; Parton Saturation-An Overview]

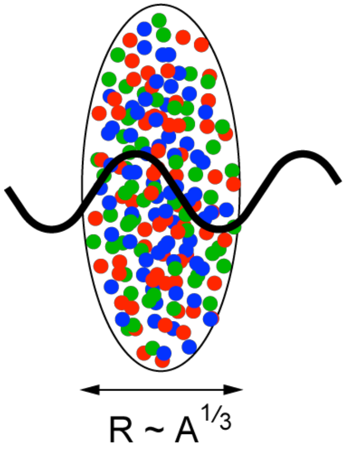
Nuclear Oomph

Scattering of electrons off nuclei:

Probes interact over distances $L \sim (2m_N x)^{-1}$

For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon

Probe interacts ***coherently*** with all nucleons

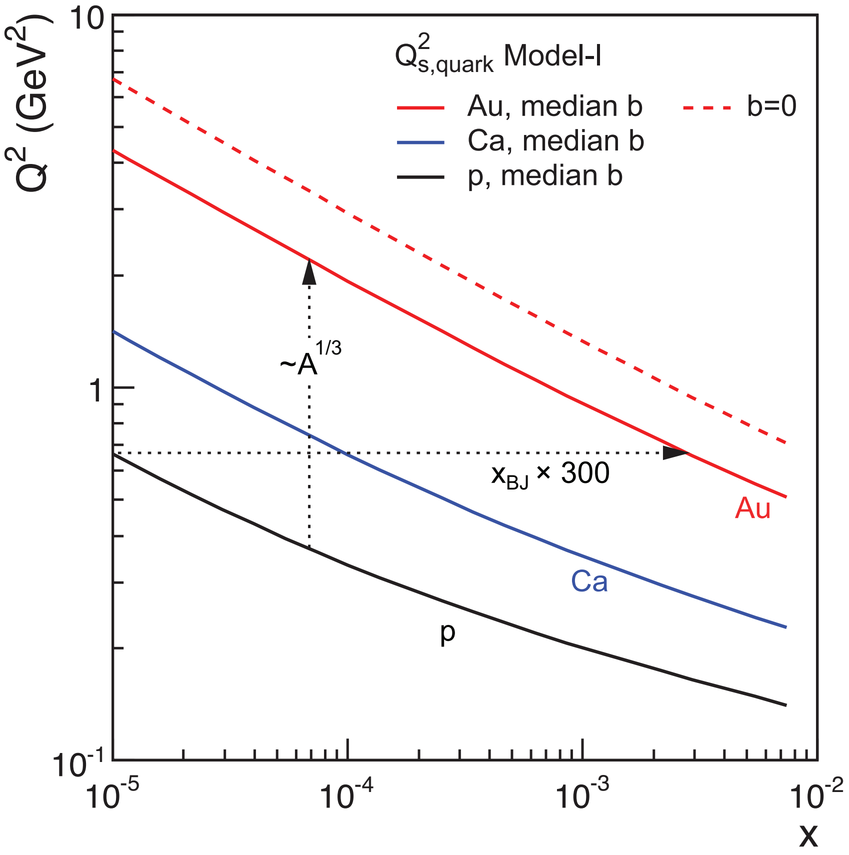


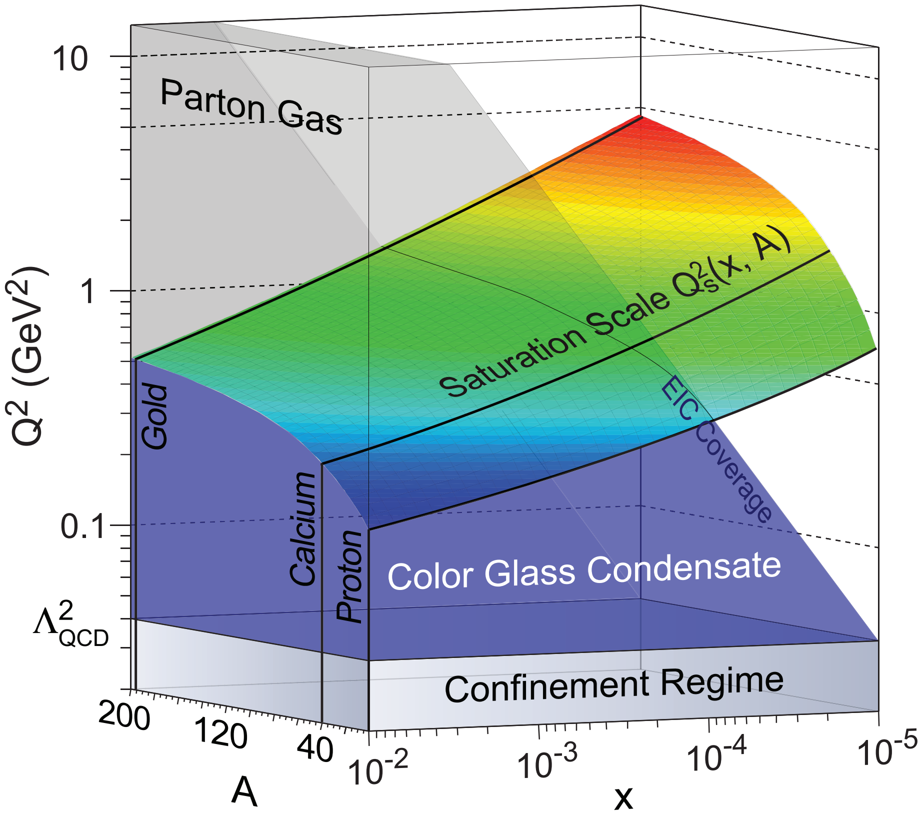
$$Q_s^2 \sim \frac{\alpha_s\, xG(x,Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \;\; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \;\; xG_A \sim A$$

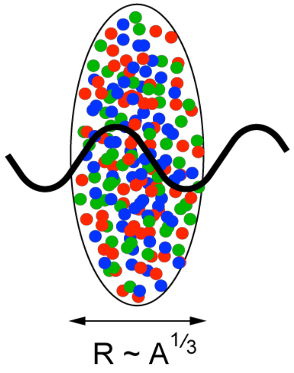
“Expected”
Nuclear Enhancement Factor
(Pocket Formula):

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

Enhancement of Saturation Scale







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

Enhancement of Q_S with A:

saturation regime reached at significantly lower energy in nuclei (and lower cost)

Some Interesting Ideas

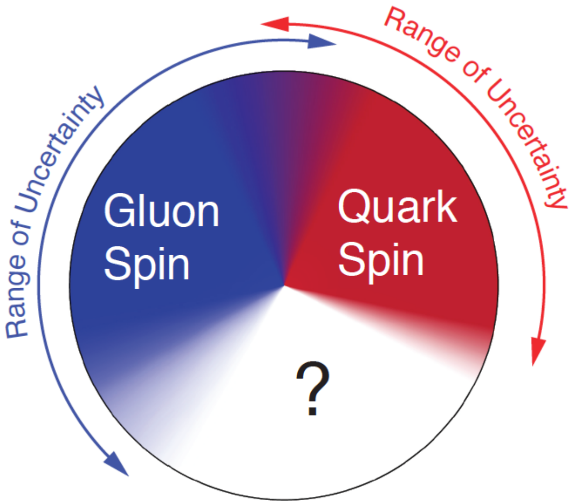
- Conjecture I:
  - at very low-x all hadrons $Q_S(x)$ becomes equal for nucleons, nuclei, mesons, baryons …
  - maybe even for photons (more later)
  - truly **universal** regime
- Conjecture II:
  - as $Q_s(x)$ grows towards small-x, Q_s becomes the largest scale, hence $\alpha_s(Q^2) \rightarrow \alpha_s(Q_s^2)$
  - end of the line for α_s (as long as $Q < Q_s$) ?

Physics at extreme low-x appears to be a wonderland.
Experimentally we might not get there in our life time.

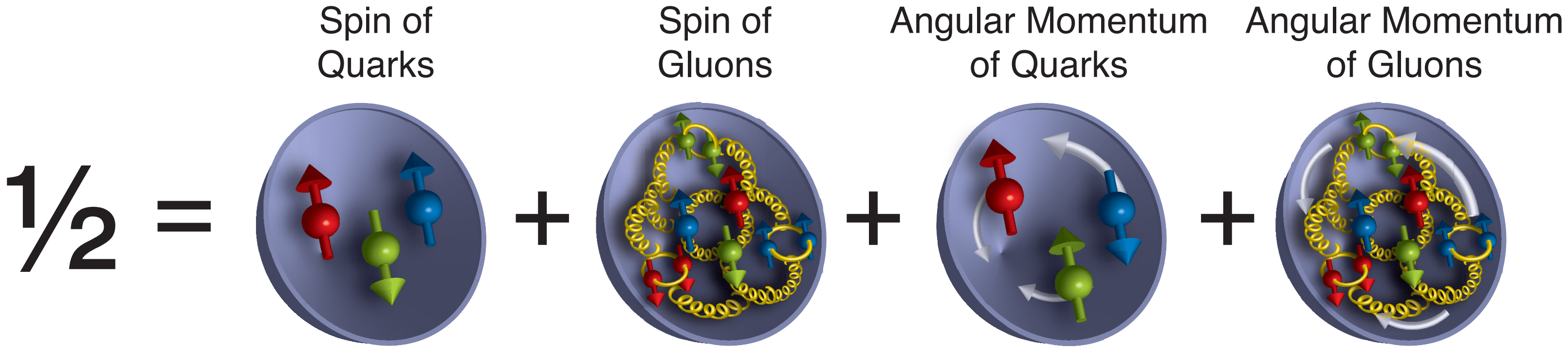
Key Topic in ep: Proton Spin Puzzle

What are the appropriate degrees of freedom in QCD that would explain "spin" of a proton?

- After 20 years effort
  - Quarks (valence and sea): ~30% of proton spin in limited range
  - Gluons (latest RHIC data): ~20% of proton spin in limited range
  - Where is the rest?



It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons



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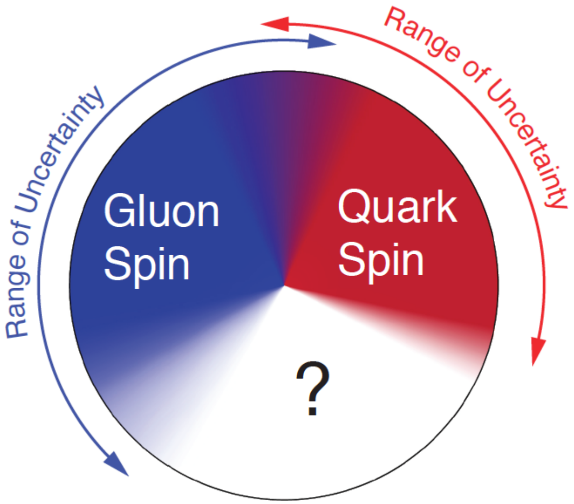

It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

Jaffe-Manohar sum rule:

$$\frac{1}{2} = \frac{1}{2}\int_0^1 \mathrm{d}x \Delta\Sigma(x, Q^2) + \int_0^1 \mathrm{d}x \Delta g(x, Q^2) + \sum_q L_q + L_g$$

What Does a Proton Look Like?

- In transverse momentum?
- In transverse space?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

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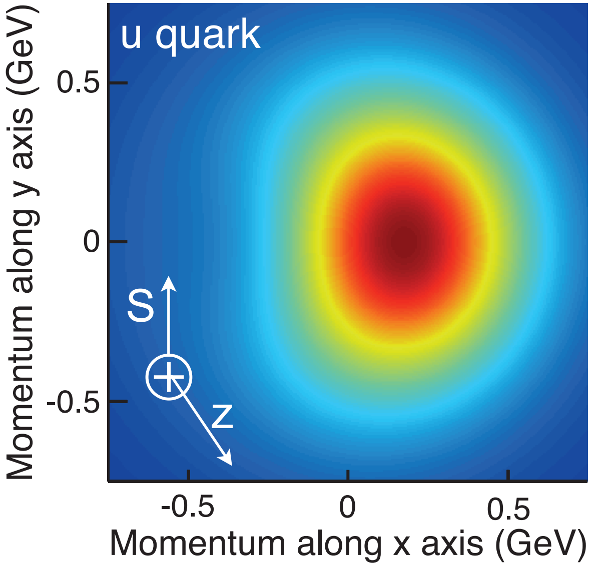
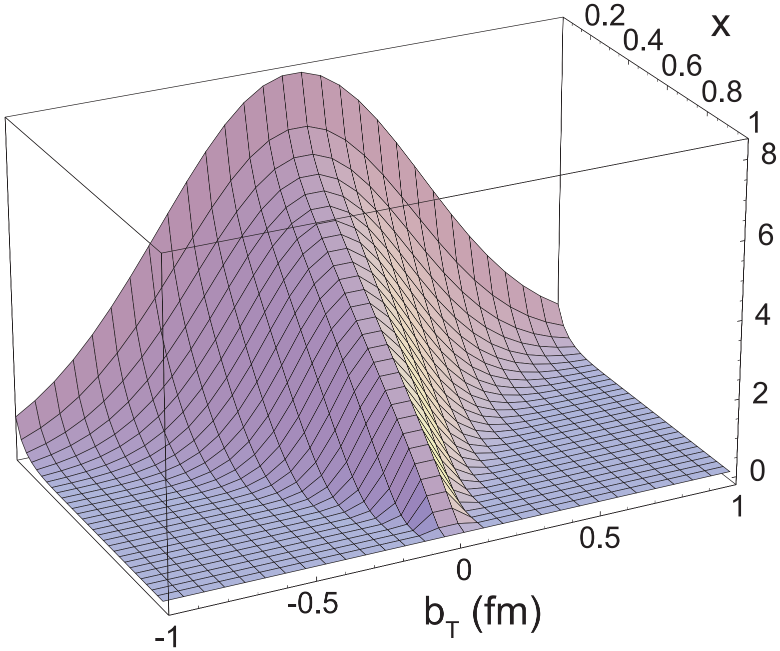
3D Imaging with EIC

What Does a Proton Look Like?

- **Transverse Momentum Distributions (TMDs):**
  - 2D+1 picture in momentum space (k_T)



- **Generalized Parton Distributions (GPDs):**
  - 2D+1 picture in coordinate space (b_T)

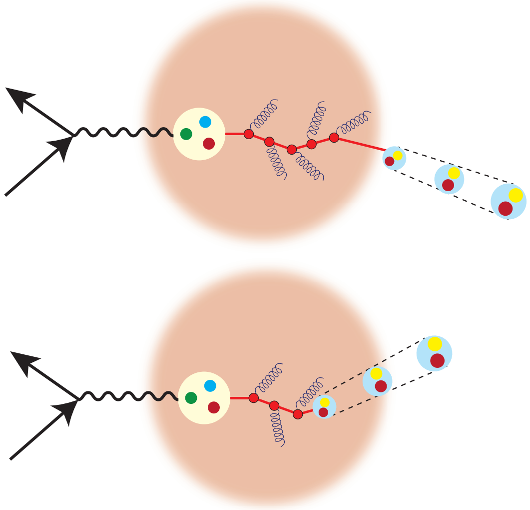


Fragmentation

Color propagation and neutralization

- Fundamental QCD Processes:
  - Partonic elastic scattering
  - In Nucleus: Gluon bremsstrahlung in vacuum and in medium (E-loss)
  - Color neutralization
  - Hadron formation

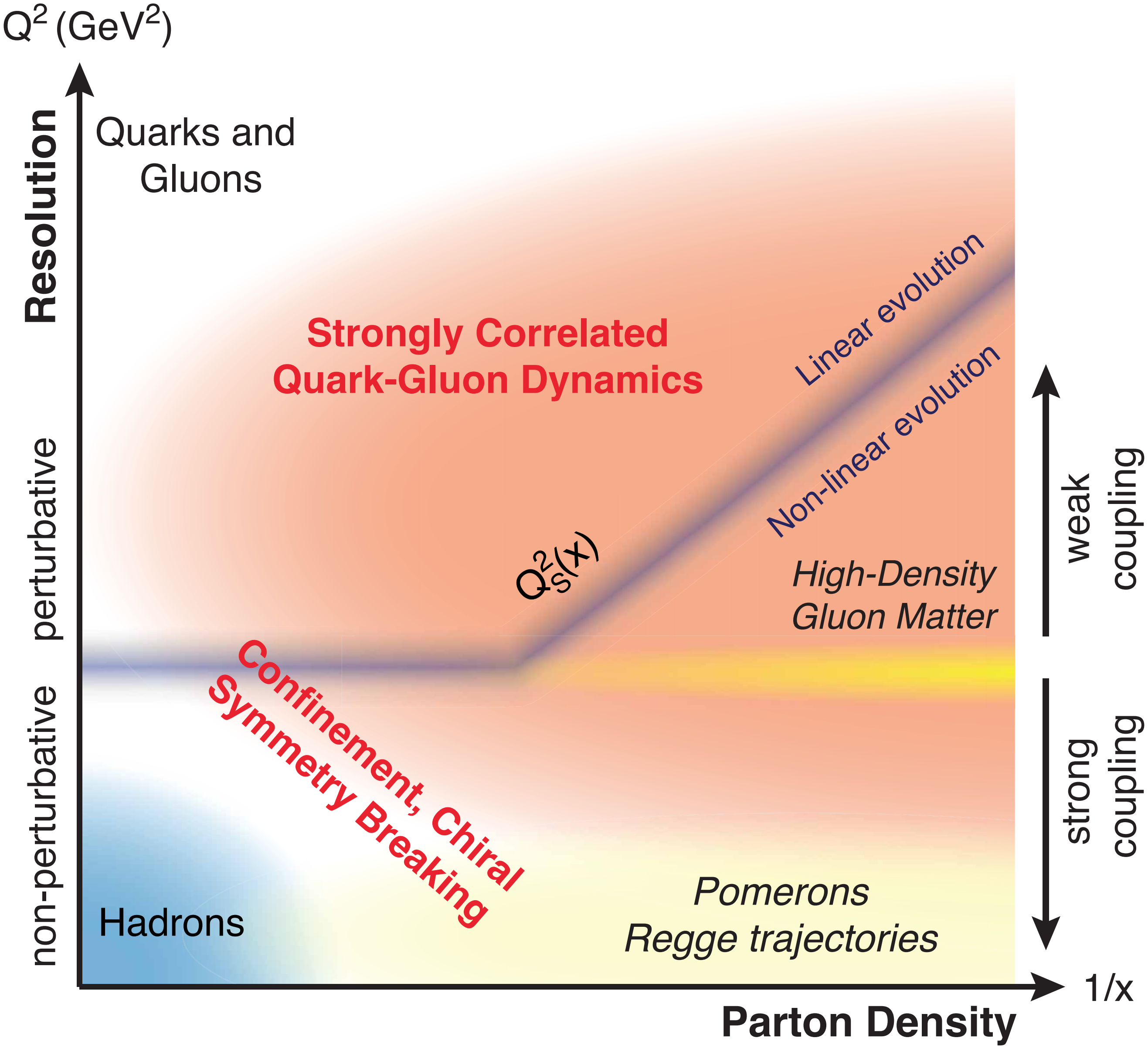
} dynamic confinement



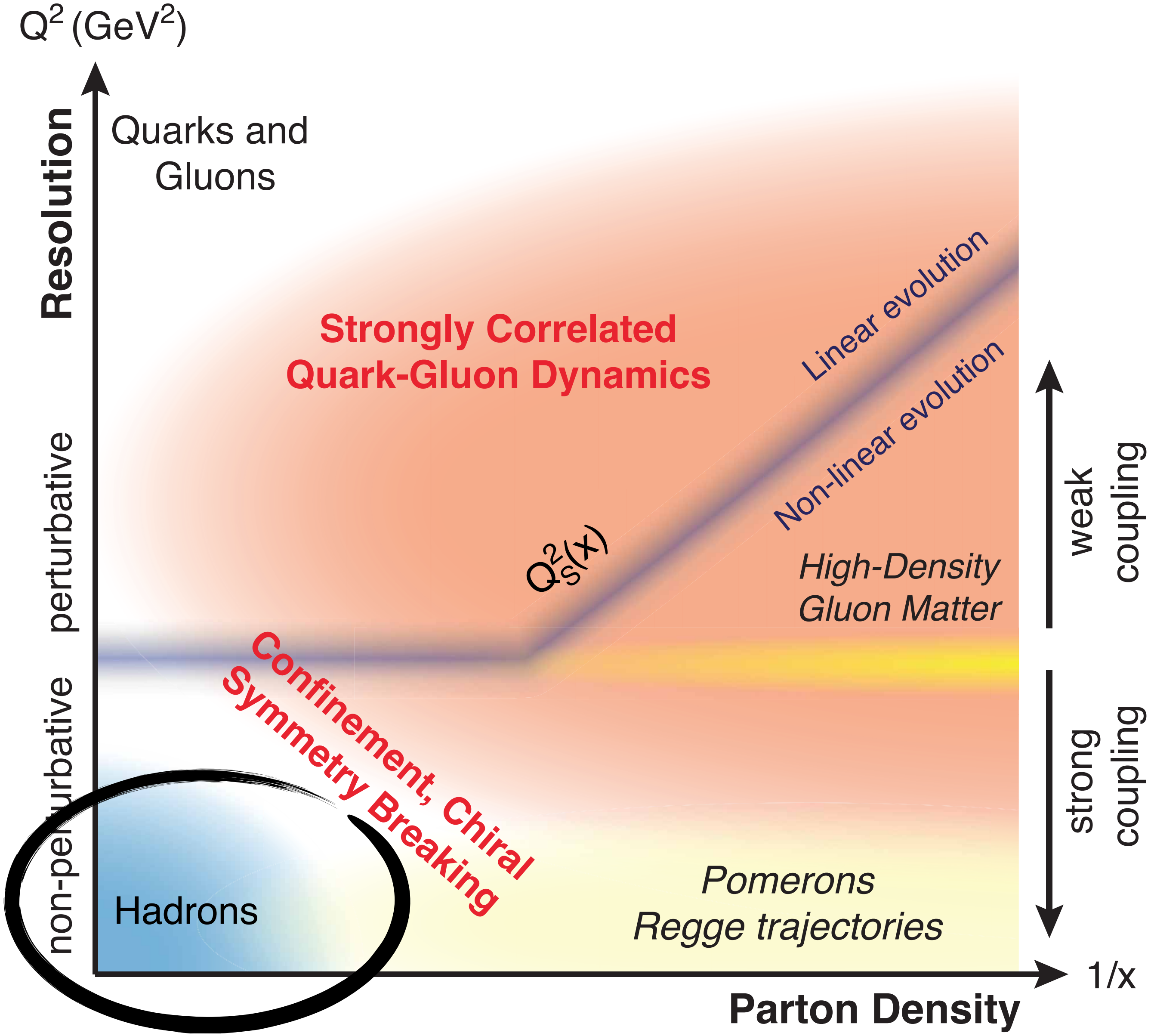
- Process not understood from first principles (QCD)
- Parametrization: Fragmentation Functions
- Nuclei as space-time analyzer allows to dissect process

5. Landscape of QCD

Landscape of QCD

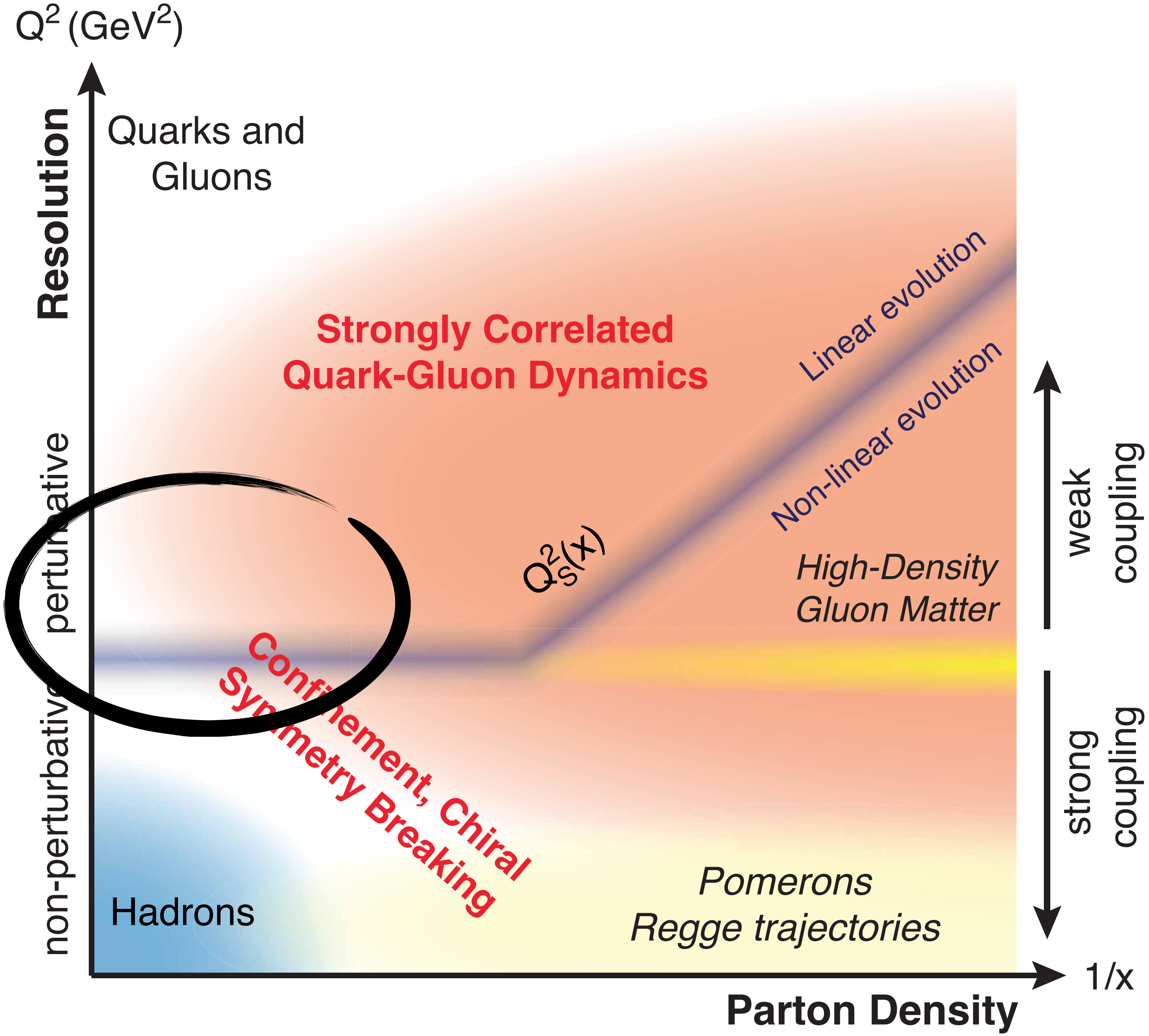


Landscape of QCD



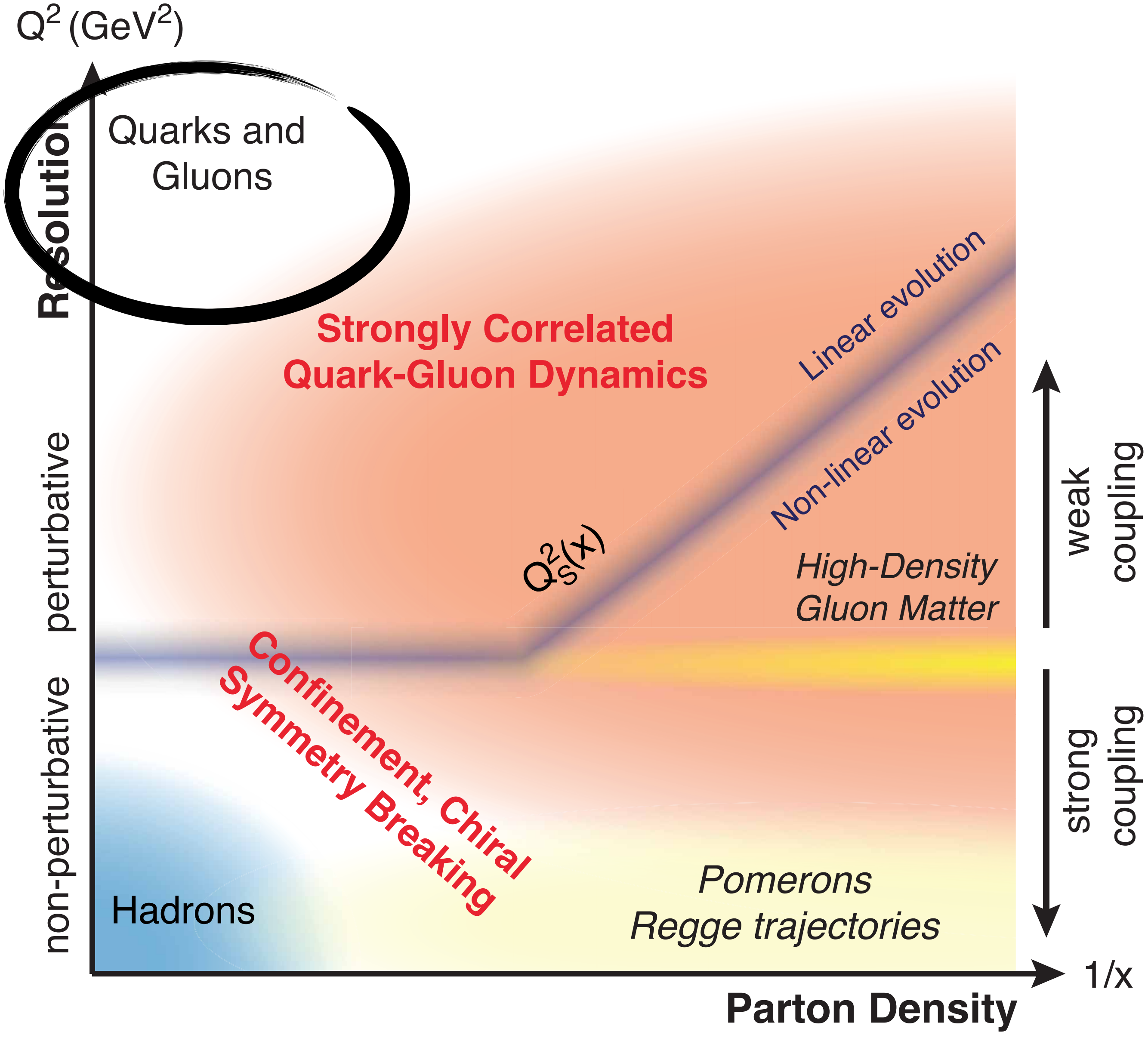
QCD coupling is large, the fields are nonlinear, and the physics is nonperturbative.

Landscape of QCD



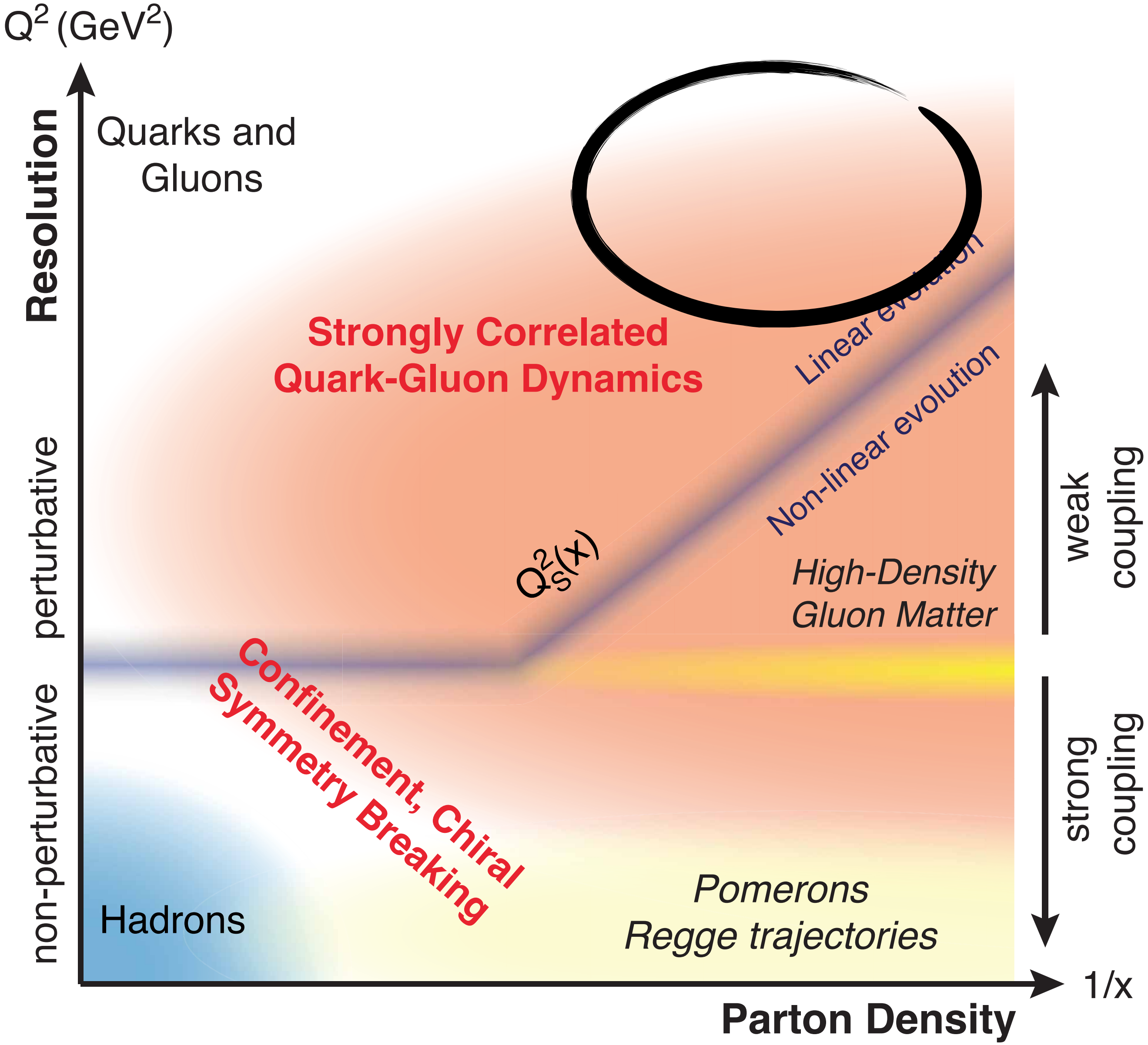
What the degrees of freedom describing this transition region are, is not understood

Landscape of QCD



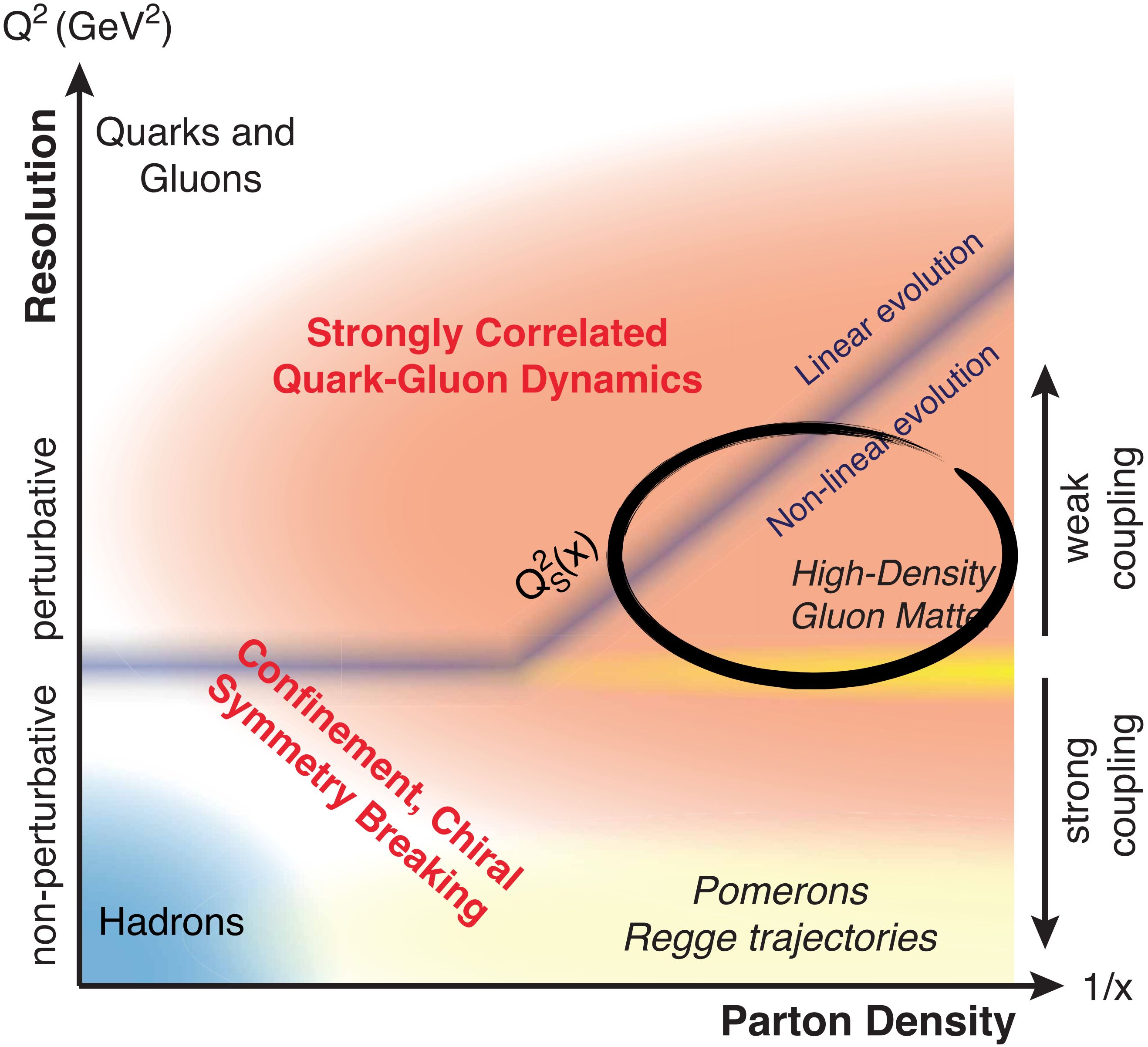
The coupling becomes weak due to asymptotic freedom, and perturbative QCD describes well the interactions of quarks and gluons.

Landscape of QCD



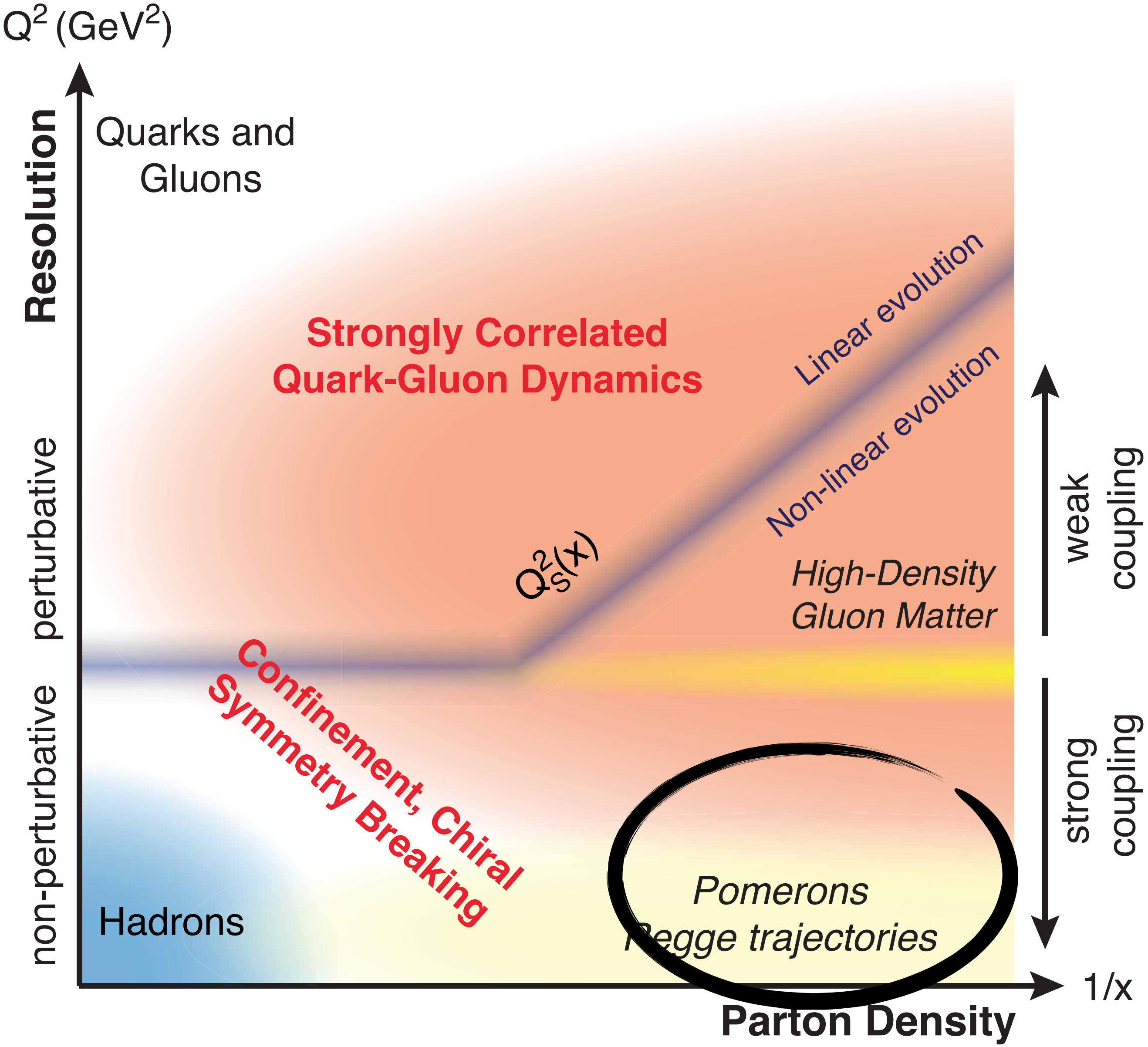
At large Q², as one moves towards higher parton density, many-body correlations between quarks and gluons become increasingly important.

Landscape of QCD



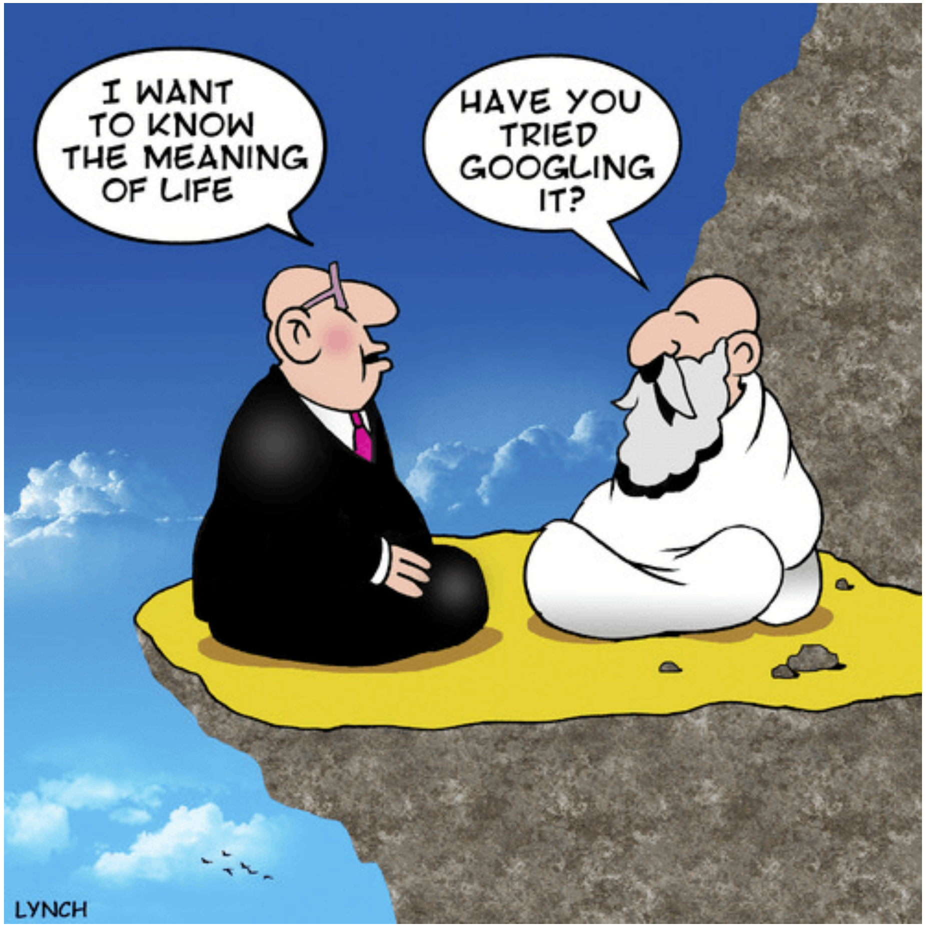
The feature of weak coupling is key because it allows, for the first time, systematic computations of the manybody dynamics of quarks and gluons in an intrinsically nonlinear regime of QCD.

Landscape of QCD



Total cross-sections in high energy scattering are dominated by the physics of small x and low Q^2. The least understood region

6. Big Question and what we need to answer them



The Essential Mystery

There is an elegance and simplicity to nature's strongest force we do not understand

- (Nearly) all visible matter is made up of quarks and gluons
- But quarks and gluons are not visible
- All strongly interacting matter, their properties and dynamics are an *emergent* consequence of many-body quark-gluon dynamics.

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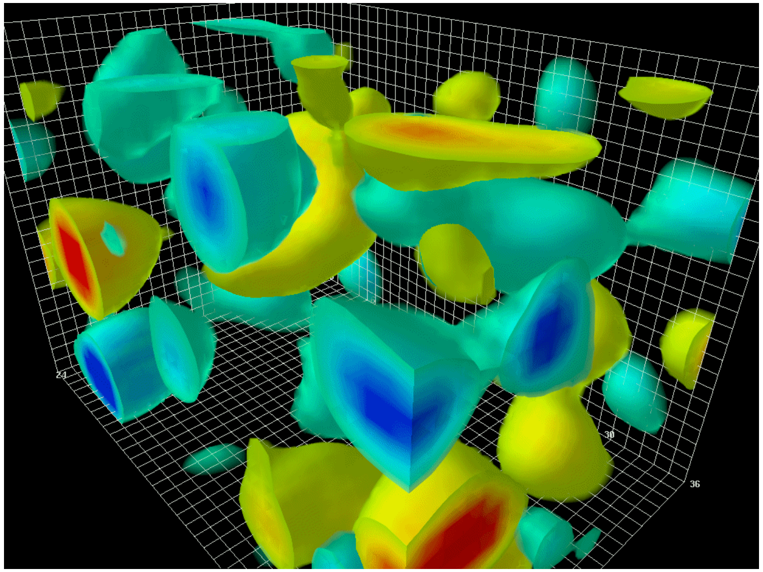
Understanding the origins of matter demands we develop a deep and varied knowledge of this emergent dynamics



Driving Fundamental Questions in e+p

Proton serves as:

- How do quark and gluon dynamics generate the proton spin?
- What is the role of the orbital motion of sea quarks and gluons in building up the nucleon spin?
- How are the sea quarks and gluons distributed in space and transverse momentum inside the nucleon?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

Object of Interest

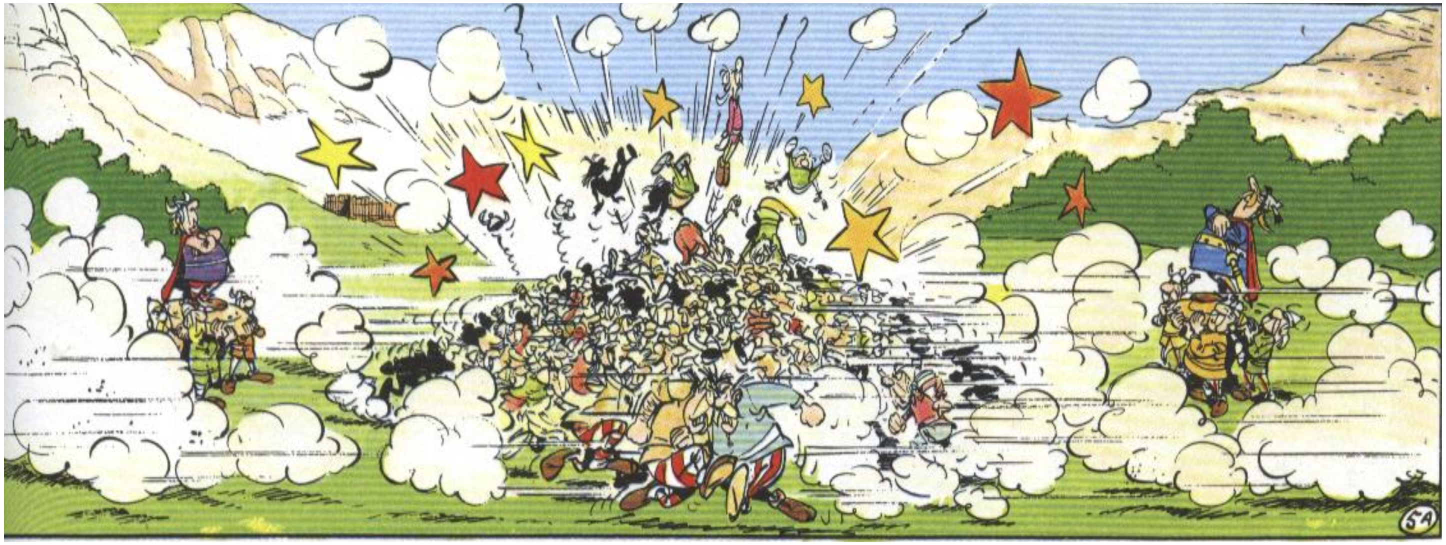
Driving Fundamental Questions in e+A

	Nucleus serves as:
• What is the fundamental quark-gluon structure of atomic nuclei?	**Object of Interest**
• Can we experimentally find and explore a novel universal regime of strongly correlated QCD dynamics? • What is the role of saturated strong gluon fields, and what are the degrees of freedom in this strongly interacting regime?	**Amplifier**
• Can the nuclear color filter provide novel insight into propagation, attenuation and hadronization of colored probes?	**Analyzer**

Requirements: What is Needed?

- Access to wide range in x and Q^2
  - ➡ Large center-of-mass energy ($\sqrt{s}$) range
- Access to spin structure of nucleons and nuclei
- Access to 3D spatial and momentum structure of nucleon
  - ➡ Polarized electron and hadron beams
- Accessing the highest gluon densities ($Q_S^2 \sim A^{1/3}$)
  - ➡ Nuclear beams, the heavier the better (up to U)
- Essential for mapping 3D structure of nucleons and nuclei access to rare probes
- Studying observables as a fat of x, Q^2, A, etc.
  - ➡ High luminosity (100x HERA)

7. Realization of an EIC



Reality Check

Designing a dream machine is easy but

- It has to be fundable
- The technology has to be available

Find the parameters that do the job (here EIC White Paper):

- Highly polarized (70%) e- and p beams
- Ion beams from D to U
- Variable center-of-mass energies from $\sqrt{s}=20\text{-}140$ GeV
- High collision luminosity $10^{33\text{-}34}$ $cm^{-2}s^{-1}$ (HERA ~ 10^{31})
- Possibilities of having more than one interaction region

Electron-Ion Collider Initiatives

Past

Future

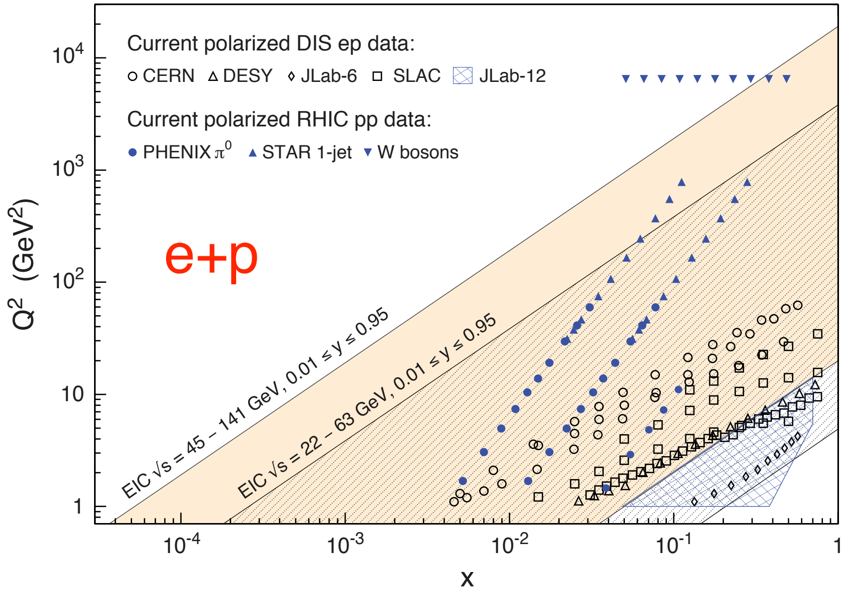
	HERA@DESY	LHeC@CERN	HIAF@CAS	ENC@GSI	JLEIC@JLab	eRHIC@BNL
$\sqrt{s}$ (GeV)	320	800-1300	12-65	14	20-64	32-140
Proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-4}	5×10^{-3}	3×10^{-4}	5×10^{-5}
Ions	p	p … Pb	p … U	p … Ca	p … Pb	p … U
L ($cm^{-2}s^{-1}$)	2×10^{31}	$\sim10^{34}$	$\sim10^{32-35}$	$\sim10^{32}$	$\sim10^{33-35}$	$\sim10^{33-34}$
IRs	2	1	1	1	2+	2+
Year	1992-2007	post ALICE	> 2020	Fair Upgrade	post 12 GeV	post RHIC

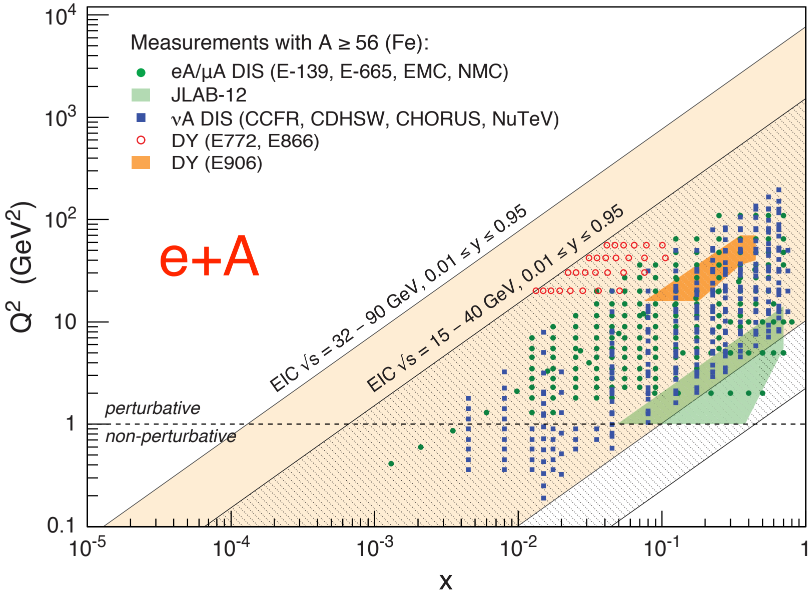
High-Energy Physics

Nuclear Physics

- World-wide interest in EIC
- All future collider include e+A in their planning

EIC: Kinematic Range

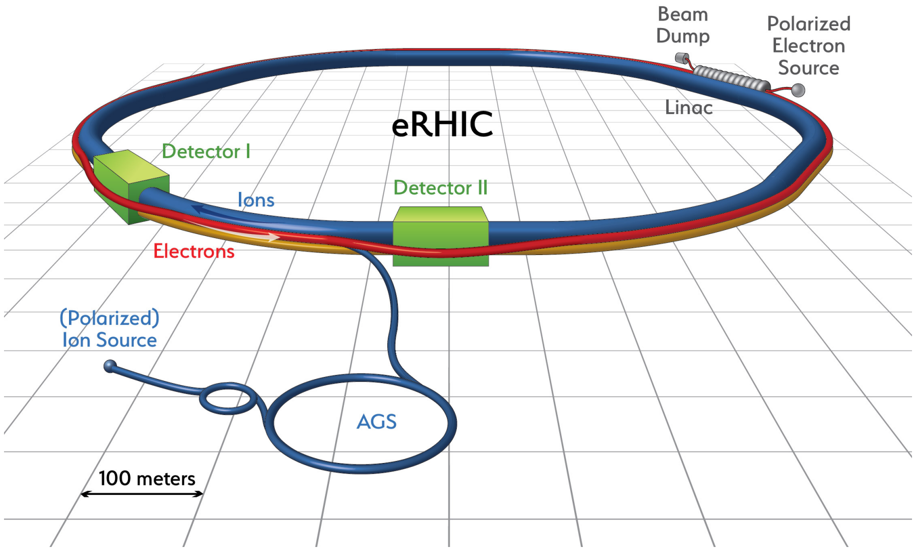


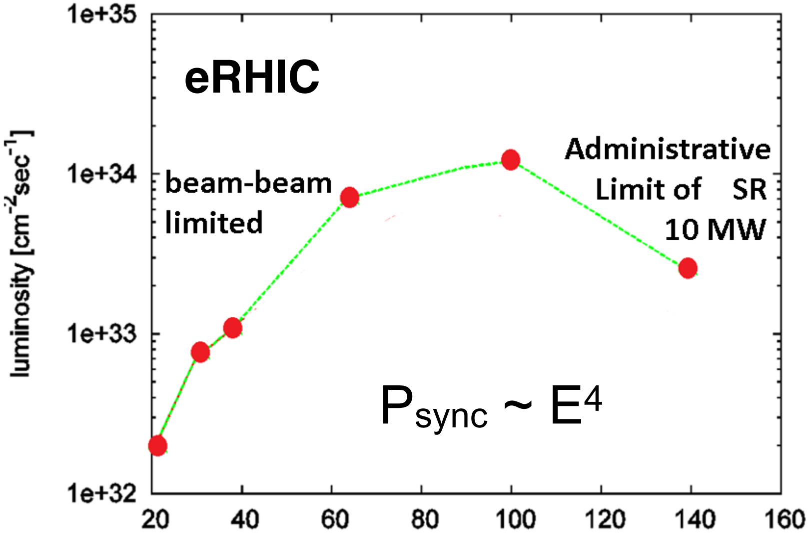


- EIC cannot compete with e+p at HERA (√s = 318 GeV)
- EIC's strength is polarized e↑+p↑ and e+A collisions
- Here the kinematic reach extends substantially compared to past (fixed target) coverage
    - Q^2×20, *x*/20 for e+A
    - Q^2×20, *x*/100 for polarized e↑+p↑

US Electron Collider: eRHIC Options

- **eRHIC (BNL)**
  - Add e Rings to RHIC facility: Ring-Ring (alt. recirculating Linac-Ring)
  - Electrons up to 18 GeV
  - Protons up to 275 GeV
  - √s=30-140 √(Z/A) GeV
  - L ≈ 1×10^{34} cm^{-2}s^{-1} at √s=105 GeV
  - 2 IRs

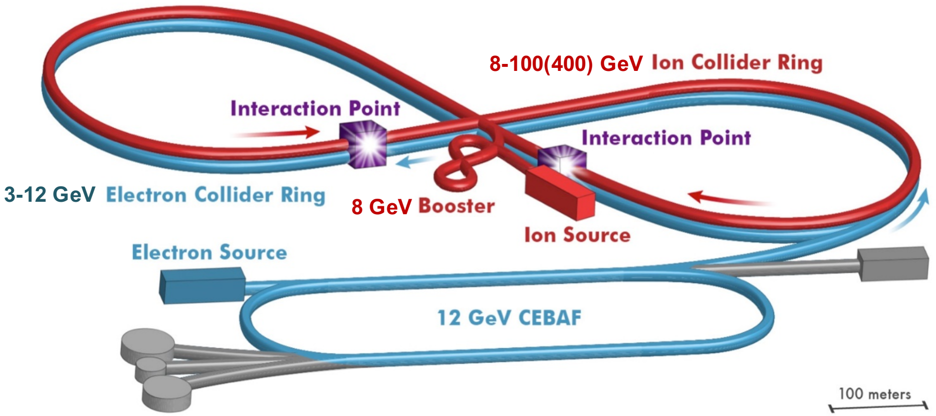


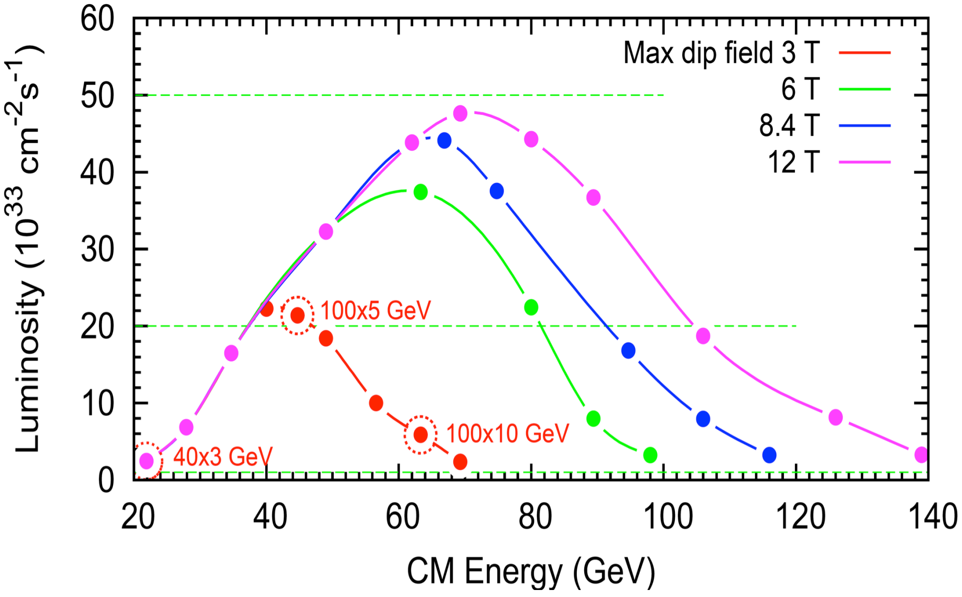


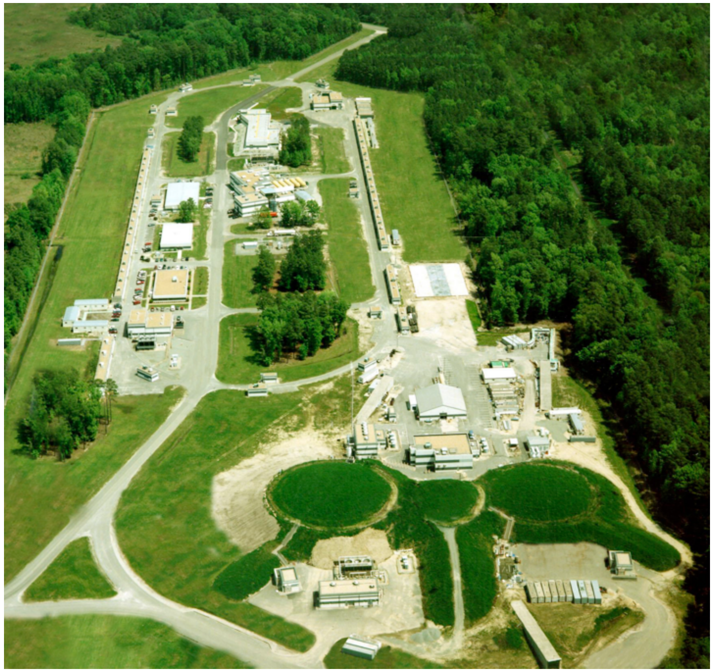
eRHIC: pre-CDR in preparation

US Electron Collider: JLEIC Option

- **JLEIC (JLab)**
  - Figure-8 Ring-Ring Collider, use of CEBAF as injector
  - Electrons 3-10 GeV
  - Protons 20-100 GeV
  - e+A up to $\sqrt{s}=40$ GeV/u
  - e+p up to $\sqrt{s}=64$ GeV
  - $L \approx 2\times10^{34}$ cm^{-2} s^{-1} at $\sqrt{s}=45$ GeV

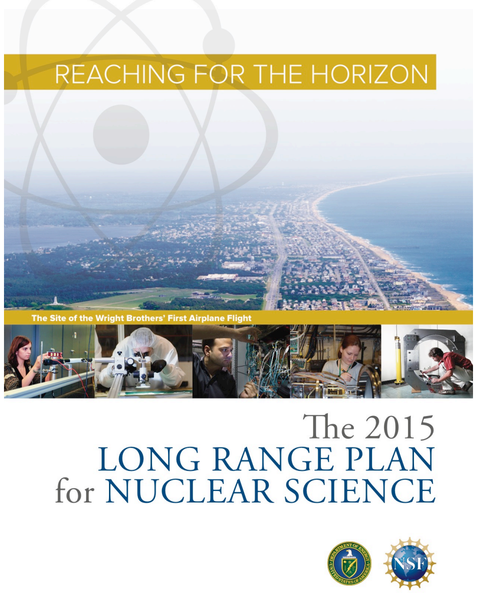






arXiv:1504.07961

Status of US Based EIC?



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

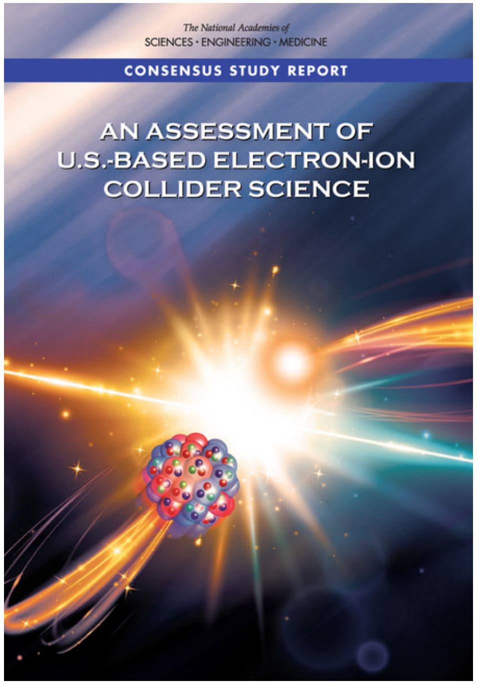
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

2015:
US Nuclear Physics 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."

2018: National Academy EIC Review

"An EIC—with its exceptionally powerful probing capability—would uniquely address profound, fundamental questions about nucleons (neutrons and protons) and their assembly into nuclei of atoms …"



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

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

https://www.nap.edu/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science

Department of Energy Process

DOE's Order 413.3B outlines a series of staged project approvals, referred to as a "Critical Decision (CD)"

- CD-0 – Approve Mission Need
- CD-1 – Approve Alternative Selection and Cost Range
- CD-2 – Approve Performance Baseline
- CD-3 – Approve Start of Construction
- CD-4 – Approve Start of Operations or Project Completion

Where is the EIC in this Process?

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At the very beginning!

- CD-0 expected this calendar year (2018)
  - Important step since the EIC is becoming a “project” and not just a cool idea

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We hope it will be more like this

rather than this

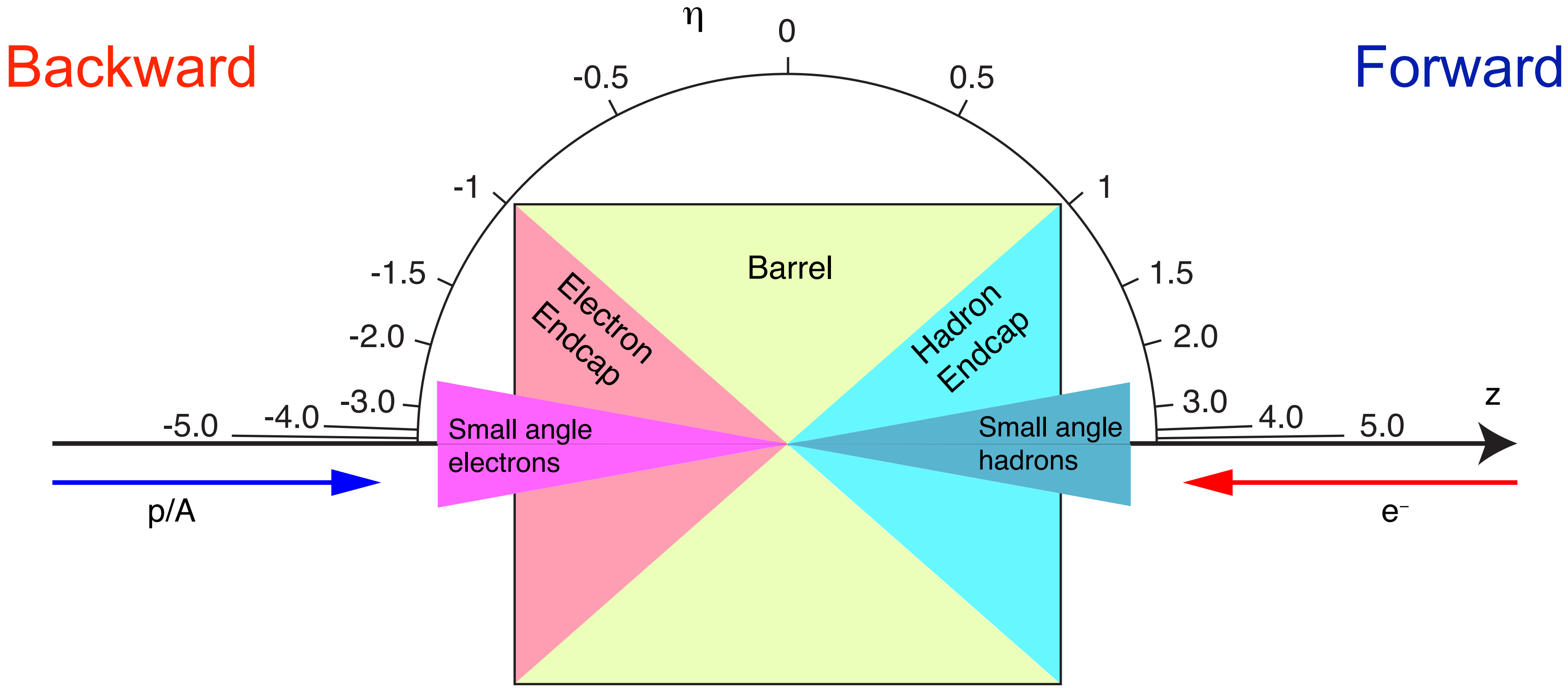
8. Detectors

© Forschungszentrum Karlsruhe/KIT Katrin

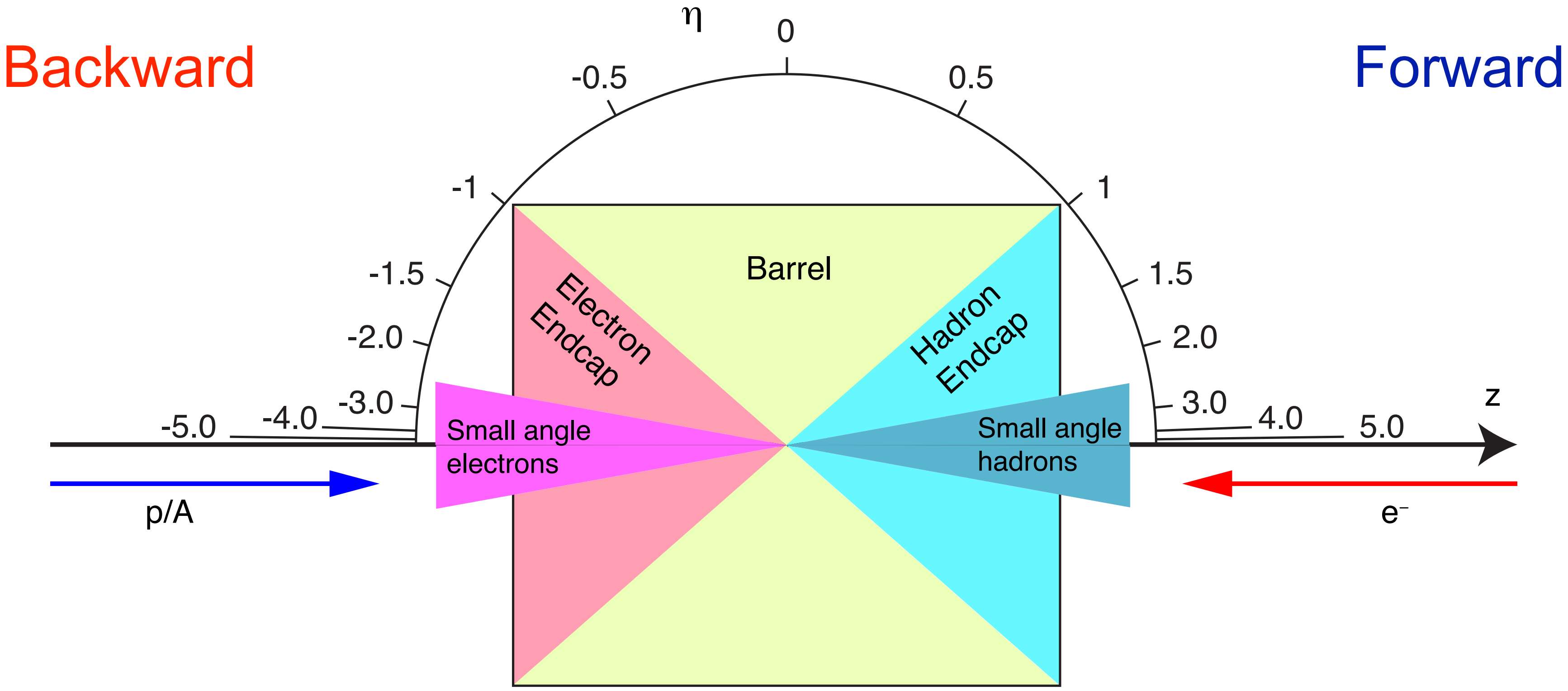
Setting the Stage: EIC Detector(s)

- Consensus within the EIC community:
  - A least 1 general purpose detector
  - Needs for a second detector - majority favors a second general purpose detector instead of more specialized detector
  - Arguments for 2 detectors similar as for every collider
  - The 2 detectors should be complementary (different strengths) - success of combined HERA data is good example
- Both machine designs include at least 2 IRs

General Purpose EIC Detectors



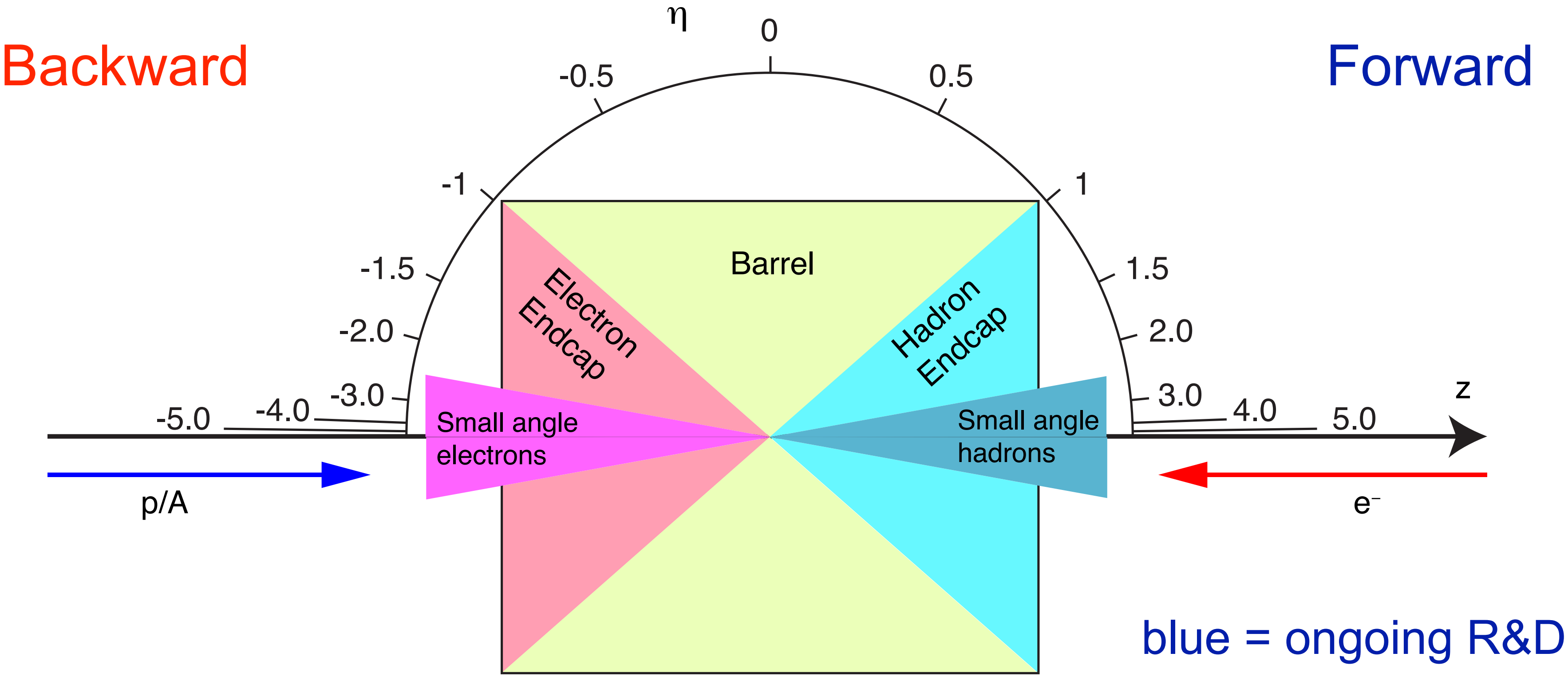
General Purpose EIC Detectors



Magnet

- Originally many solutions discussed (Dipole, Toroid, …)
- Focus now on Solenoidal Magnet
- Compact EIC detector requires large fields: B ~ 3T
- Available magnet: BaBar B = 1.5 T
- No ongoing R&D

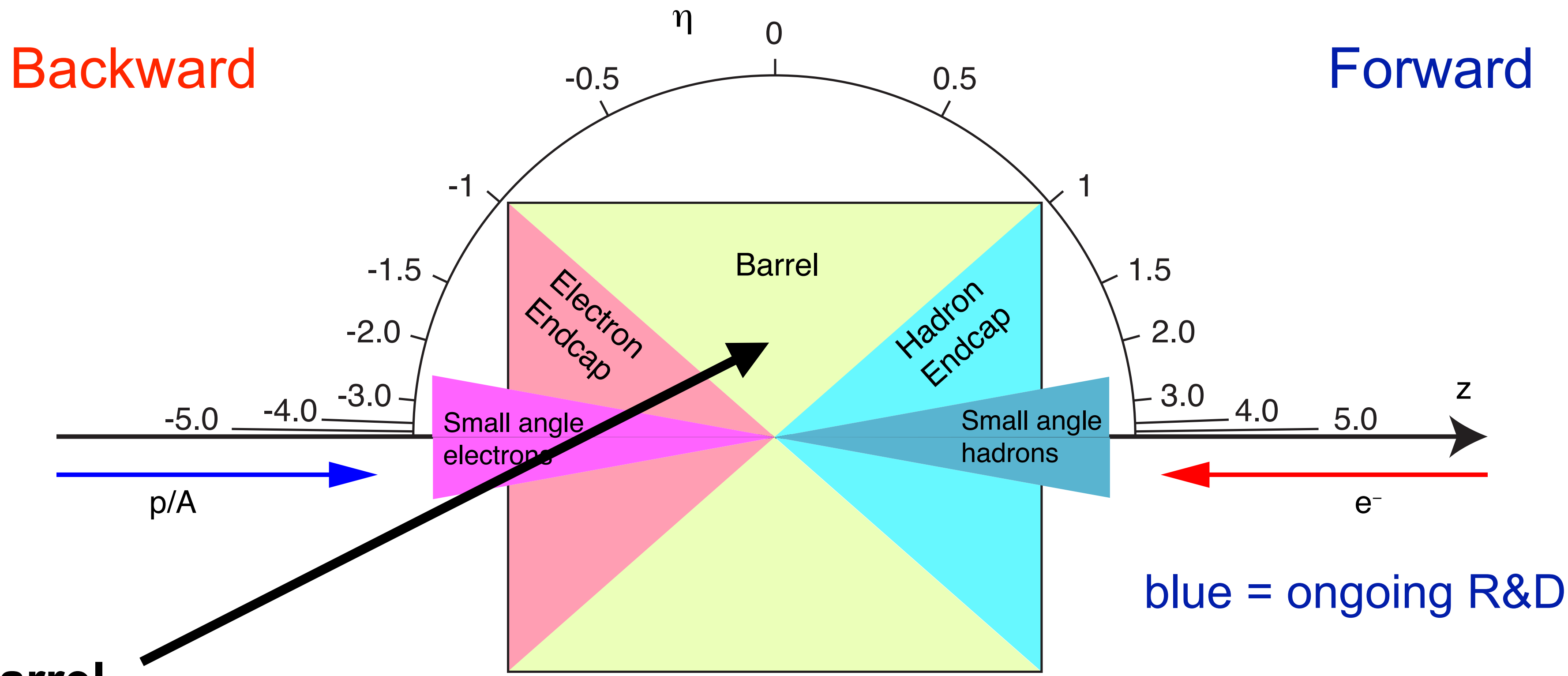
General Purpose EIC Detectors



Polarization/Luminosity

- Electron Polarization: Compton Process (need 1% or better)
- Proton/Light Ion Polarization: experience from RHIC but tighter requirements at EIC
- Luminosity Measurements

General Purpose EIC Detectors

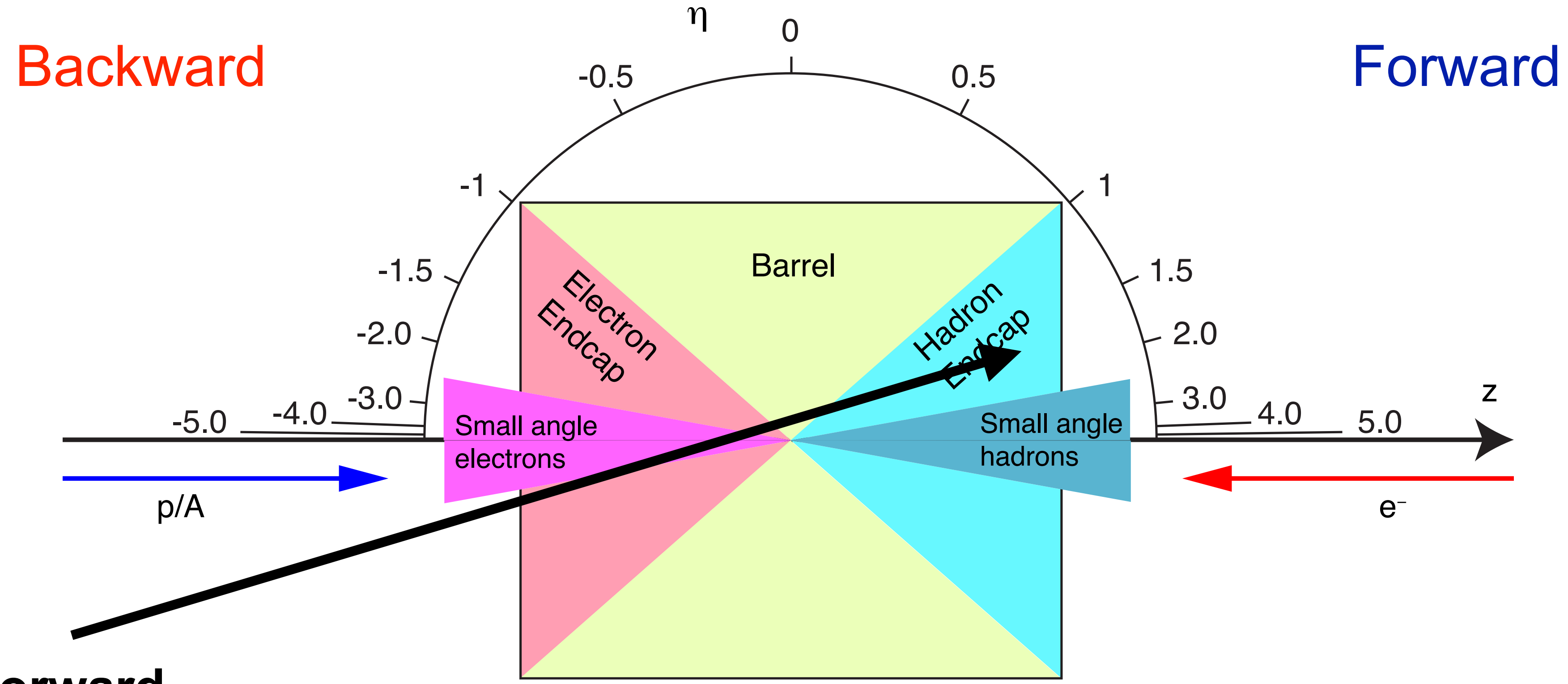


blue = ongoing R&D

Barrel

- Si-Vertex tracker: low X/X_0, resolve charm vertices ⇒ MAPS, ….
- Main tracker: p, dE/dx ⇒ TPC, Si-Tracker, GEM, MMG, μRWELL, …
- Particle ID (PID): p < 10 GeV ⇒ DIRC, EMCal, …
- EM Calorimetry: e/h, γ, π^0, …
- Hadron Calorimetry: jets (neutral component) ⇒ optional
- Muon Detector: vector mesons ⇒ optional

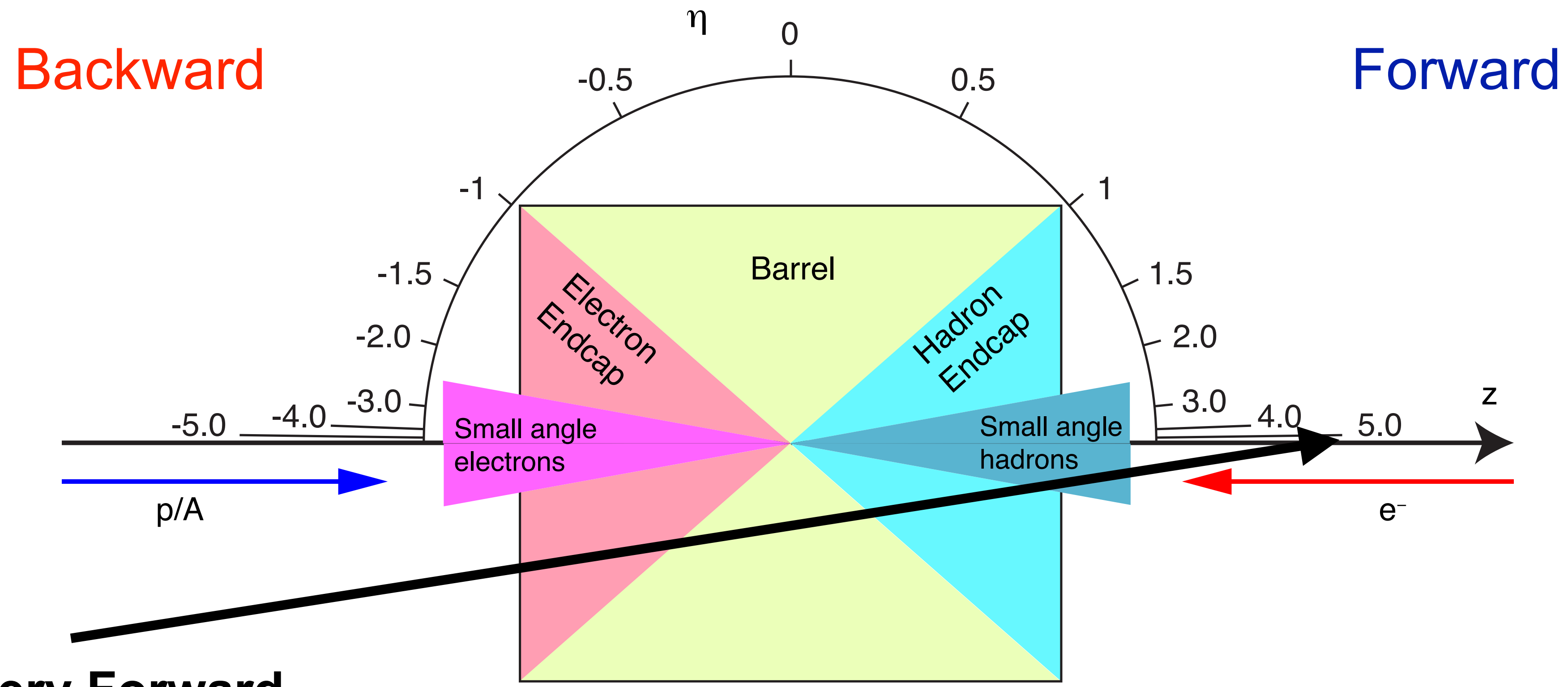
General Purpose EIC Detectors



Forward

- Si-Vertex tracker: resolve charm vertices ⇒ MAPS, ….
- Tracker: p ⇒ GEM, MMG, μRwell, …
- Particle ID (PID): $p < 50$ GeV ⇒ RICH, TRD, …
- EM Calorimetry: E, e/h, γ, $\pi 0$, …
- Hadron Calorimetry: E, e/h, jets ⇒ high resolution needed

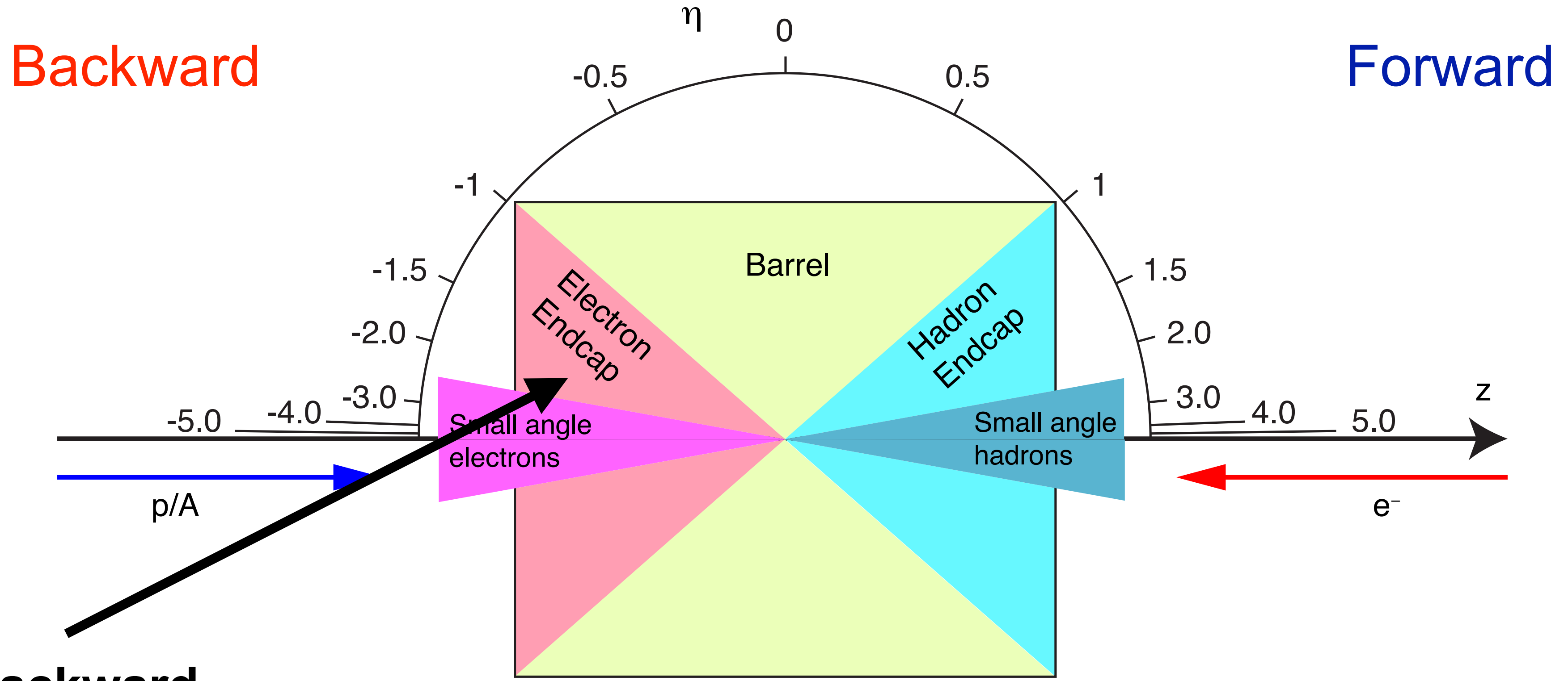
General Purpose EIC Detectors



Very Forward

- Nuclear Breakup/Fragments: ZDC, Roman Pots, Forward proton detector
- Proton p_T, t measurement: Roman Pots

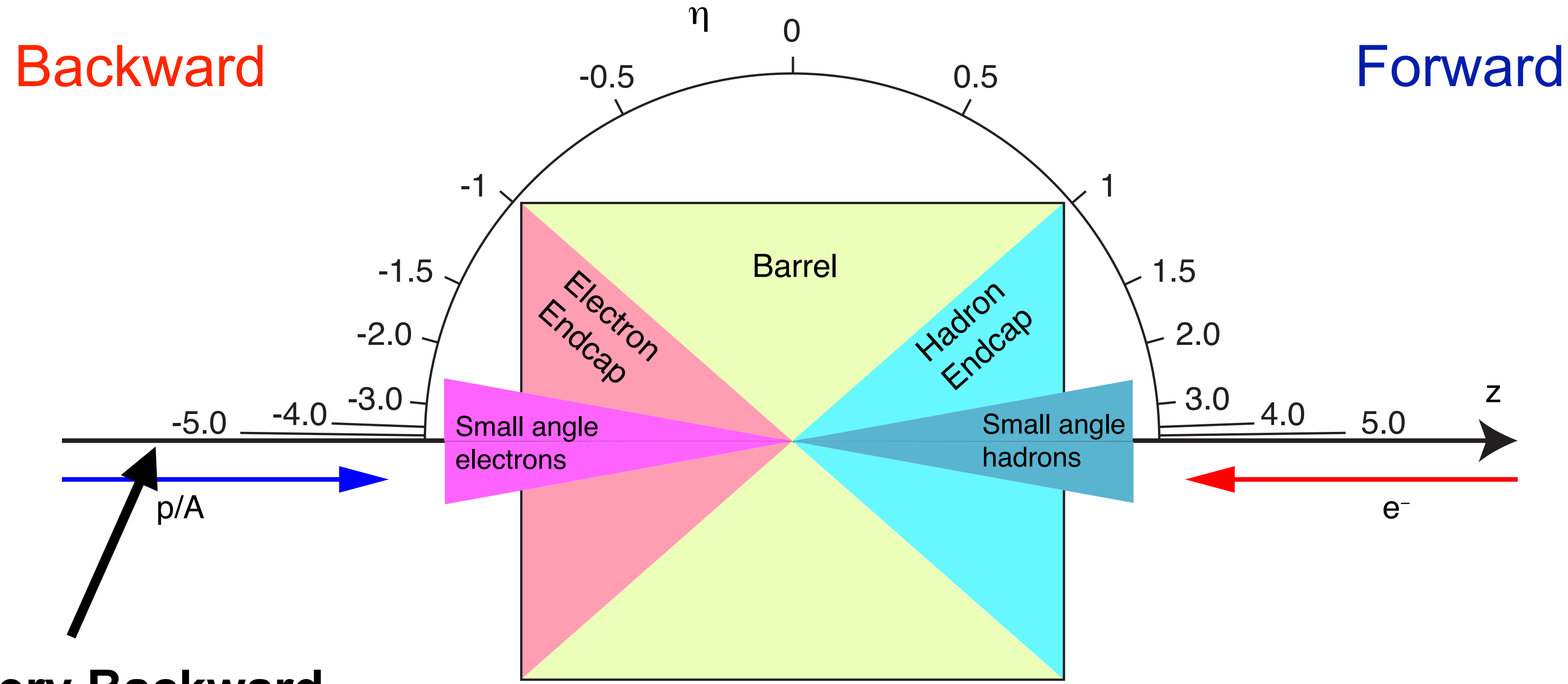
General Purpose EIC Detectors



Backward

- Si-Vertex tracker
- Tracker: p ⇒ GEM, MMG, μRwell, …
- Particle ID (PID): ⇒ RICH, EMCal
- EM Calorimetry: E, e/h ⇒ high resolution needed

General Purpose EIC Detectors

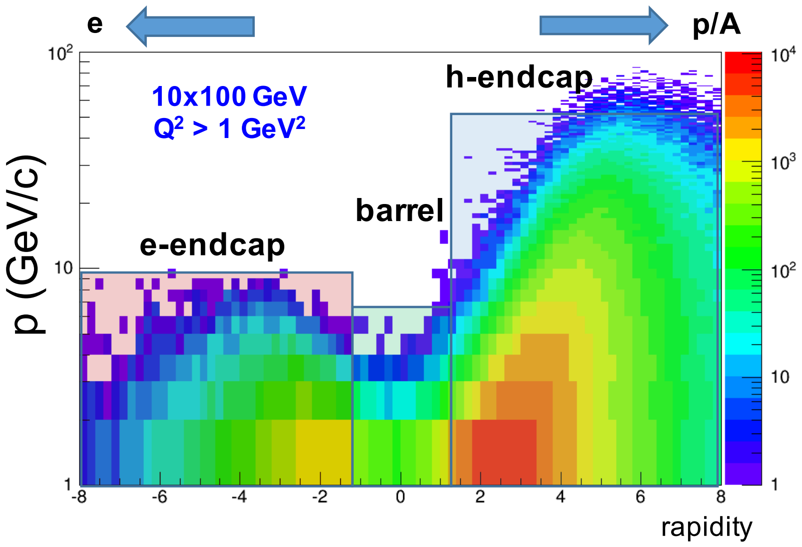


Very Backward

- Access to low Q^2 region: Low Q2 tracker

Challenges

- **Big View:**
  - Hermetic detector, low mass inner tracking
  - good PID (e and π/K/p)
    - extreme requirements in forward region
  - Good calorimetry
    - HCAL: extreme req. in forward region
    - EMCAL: extreme req. backwards region
  - Moderate radiation hardness requirements, low pile-up, low multiplicity
- **Challenges:**
  - PID
  - EMCal at $2\%/\sqrt{E}$



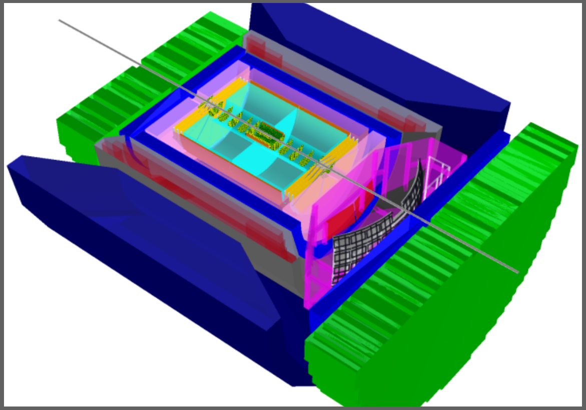
R&D Driver: Requirements

η	Nomenclature			Tracking			Electrons		π/K/p PID		HCAL	Muons
				Resolution	Allowed X/X_0	Si-Vertex	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q^2 tagger	$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV^2								
…												
-4.5 — -4.0			Instrumentation to separate charged particles from photons				2%/√E					
-4.0 — -3.5												
-3.5 — -3.0		Central Detector	Backwards Detectors	$\sigma_p/p \sim 0.1\% \times p + 2.0\%$	~5% or less	TBD		π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3σ	~50%/√E	
-3.0 — -2.5												
-2.5 — -2.0				$\sigma_p/p \sim 0.05\% \times p + 1.0\%$								
-2.0 — -1.5							7%/√E					
-1.5 — -1.0												
-1.0 — -0.5			Barrel	$\sigma_p/p \sim 0.05\% \times p + 0.5\%$		$\sigma_{xyz} \sim 20$ µm, $d_0(z) \sim d_0(r\phi) \sim 20/p_T$ GeV µm + 5 µm	(10-12)%/√E		≤ 5 GeV/c		TBD	TBD
-0.5 — 0.0												
0.0 — 0.5												
0.5 — 1.0												
1.0 — 1.5			Forward Detectors	$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		TBD			≤ 8 GeV/c		~50%/√E	
1.5 — 2.0												
2.0 — 2.5									≤ 20 GeV/c			
2.5 — 3.0				$\sigma_p/p \sim 0.1\% \times p + 2.0\%$								
3.0 — 3.5									≤ 45 GeV/c			
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from photons									
4.0 — 4.5												
…												
> 6.2			Proton Spectrometer	$\sigma_{intrinsic}(\lvert t\rvert)/\lvert t\rvert < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c								

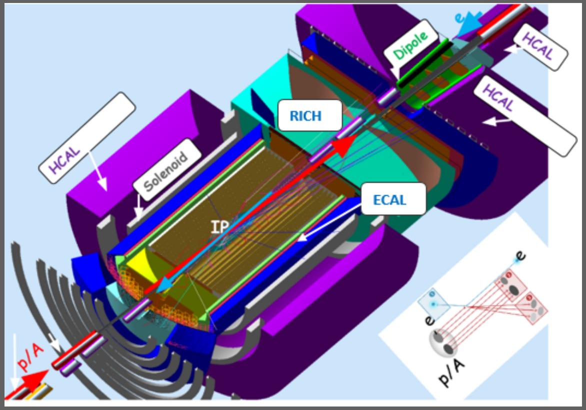
From R&D Handbook (later more)

Generic EIC Detector Concepts

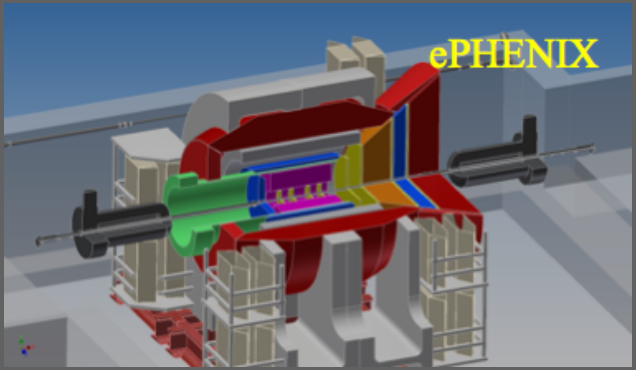
Brookhaven concept: BEAST



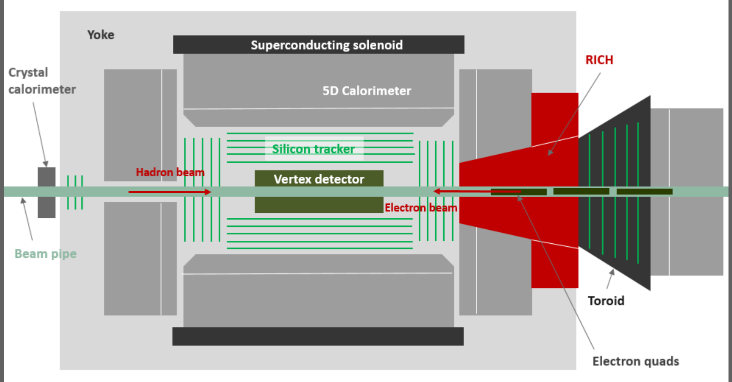
Jefferson lab concept: JLEIC



sPhenix → ePhenix

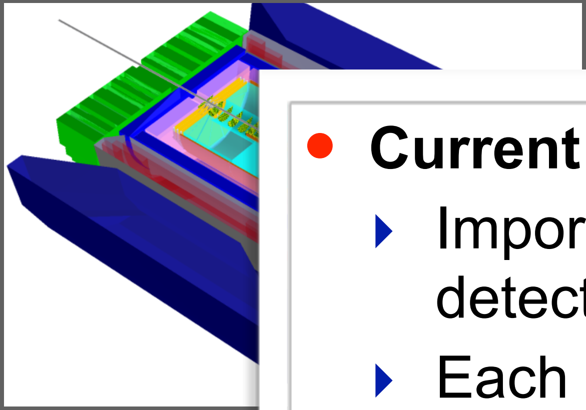


Argonne concept: TOPSiDE



Generic EIC Detector Concepts

Brookhaven concept: BEAST



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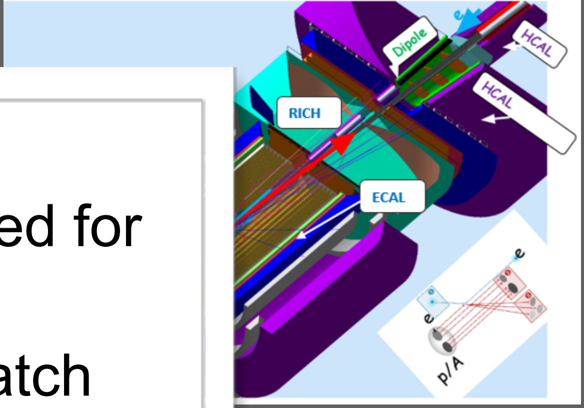
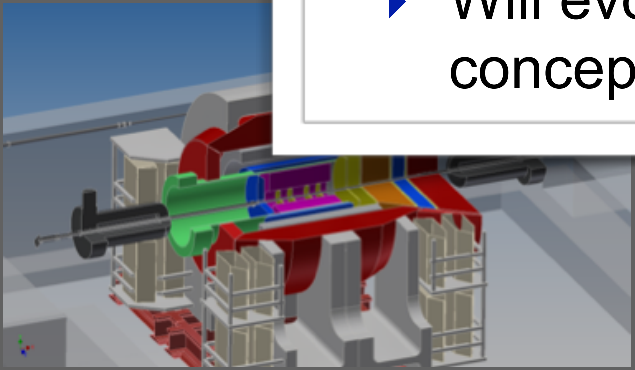
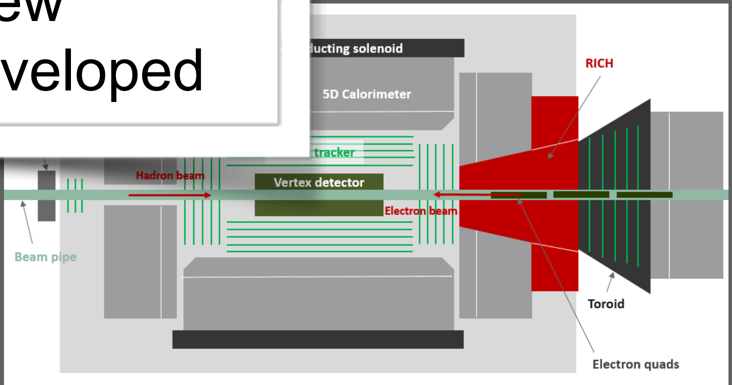


- **Current Concepts**
  - Important as test bed for detector R&D
  - Each attempt to match requirements
  - Nothing is cast in stone
  - Will evolve as new concepts are developed

sPhenix –



ncept: TOPSiDE



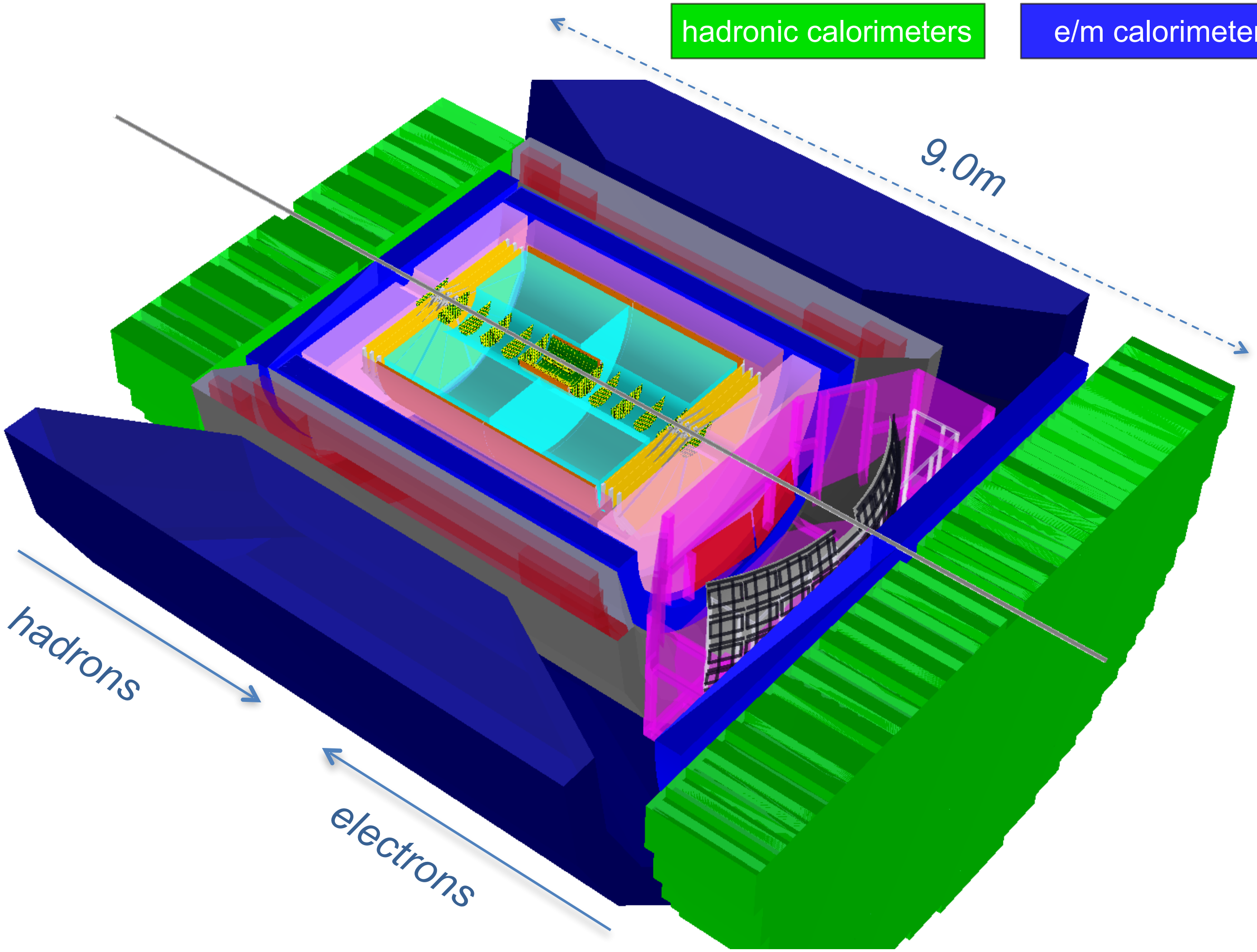
BEAST (Brookhaven eA Solenoidal Tracker)

-3.5 < η < 3.5: Tracking & e/m Calorimetry (hermetic coverage)

hadronic calorimeters

e/m calorimeters

RICH detectors



silicon trackers

TPC

GEM trackers

Micromegas barrels

3T solenoid cryostat

🟥

magnet yoke

JLEIC Concept Detector

- Similar concept to BEAST
  - Vertex detector
  - Central tracker (all options – TPC considered)
  - Forward tracking
  - Cerenkov detectors
  - Electromagnetic calorimeters
  - Hadron calorimeter in the forward and barrel region (new), possible in rear direction
  - Muon chambers considered