The Glue That Binds Us

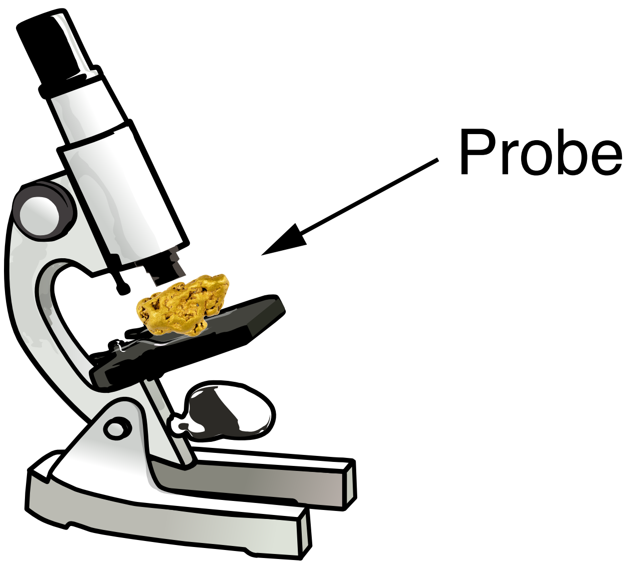
Imaging matter below 10^{-15} m with an Electron-Ion Collider

Thomas Ullrich (BNL/Yale)

Houston, March 24, 2015

Studying Matter at Small Scales

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



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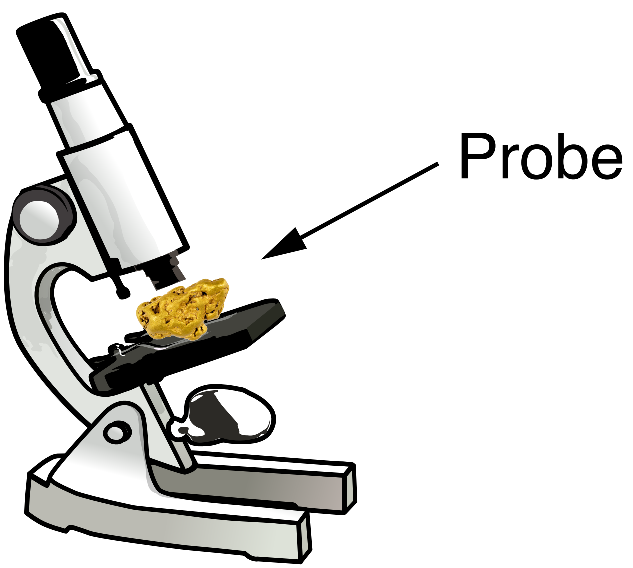
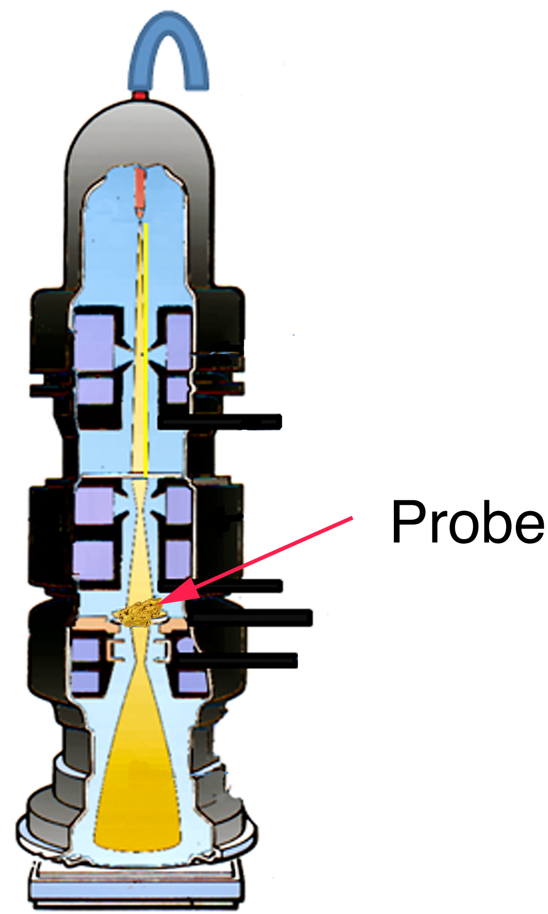


Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm

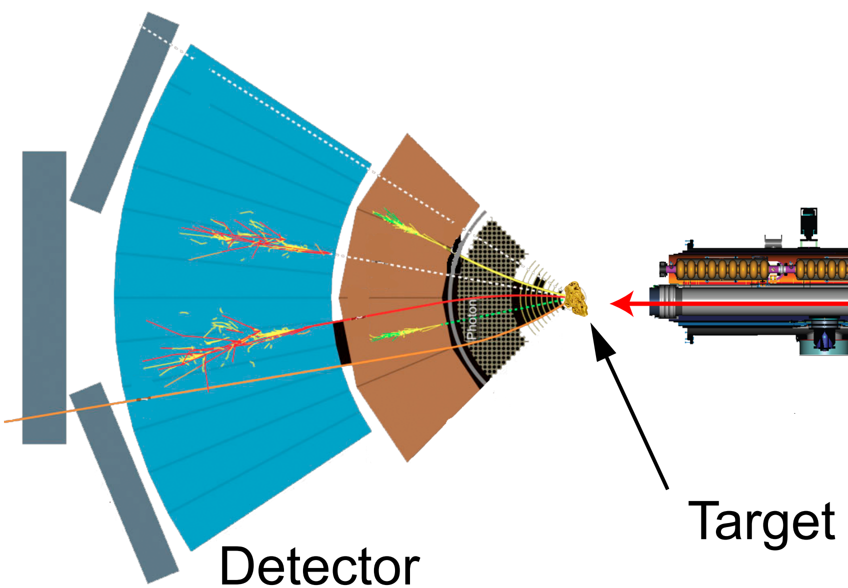


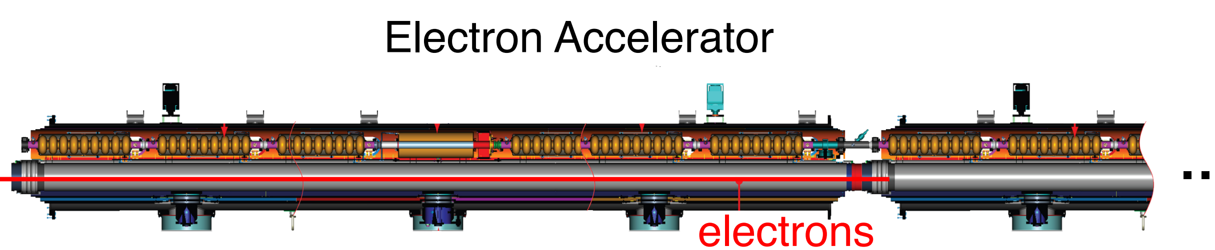
Studying Matter at Small Scales

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

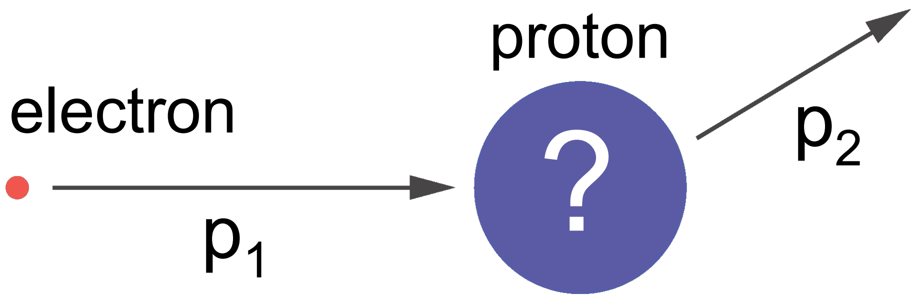




SLAC, EMC, NMC, E665, BCDMS,
HERMES, JLab, COMPASS, …

Probing Matter with Hard Probes

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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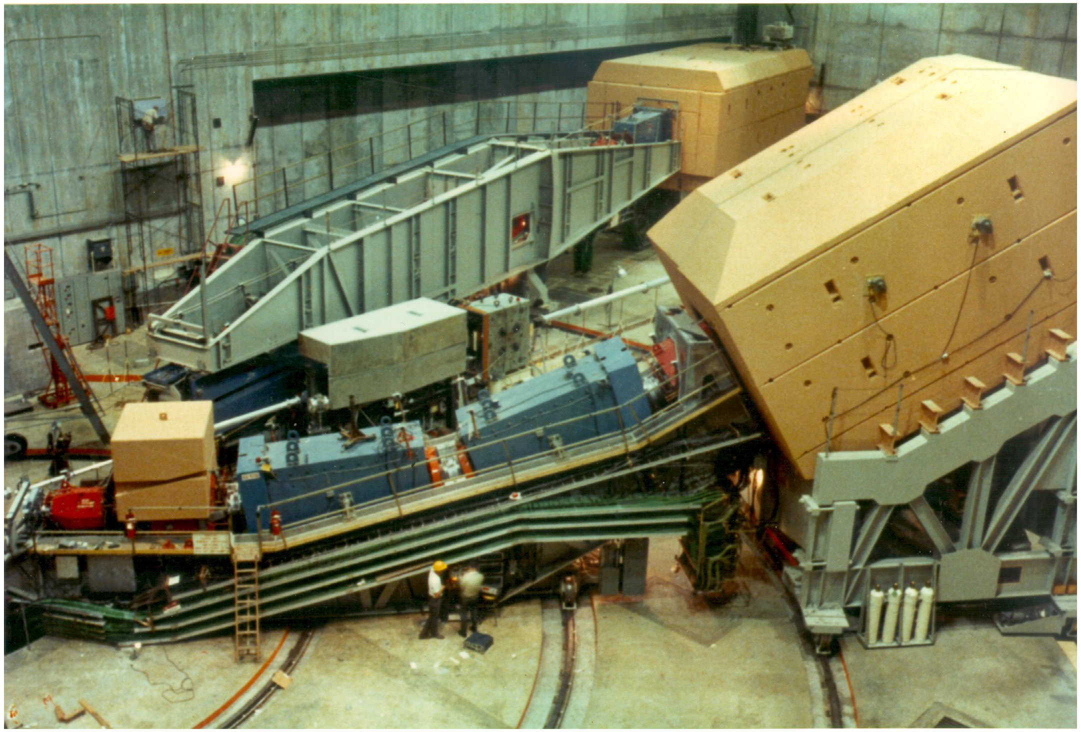

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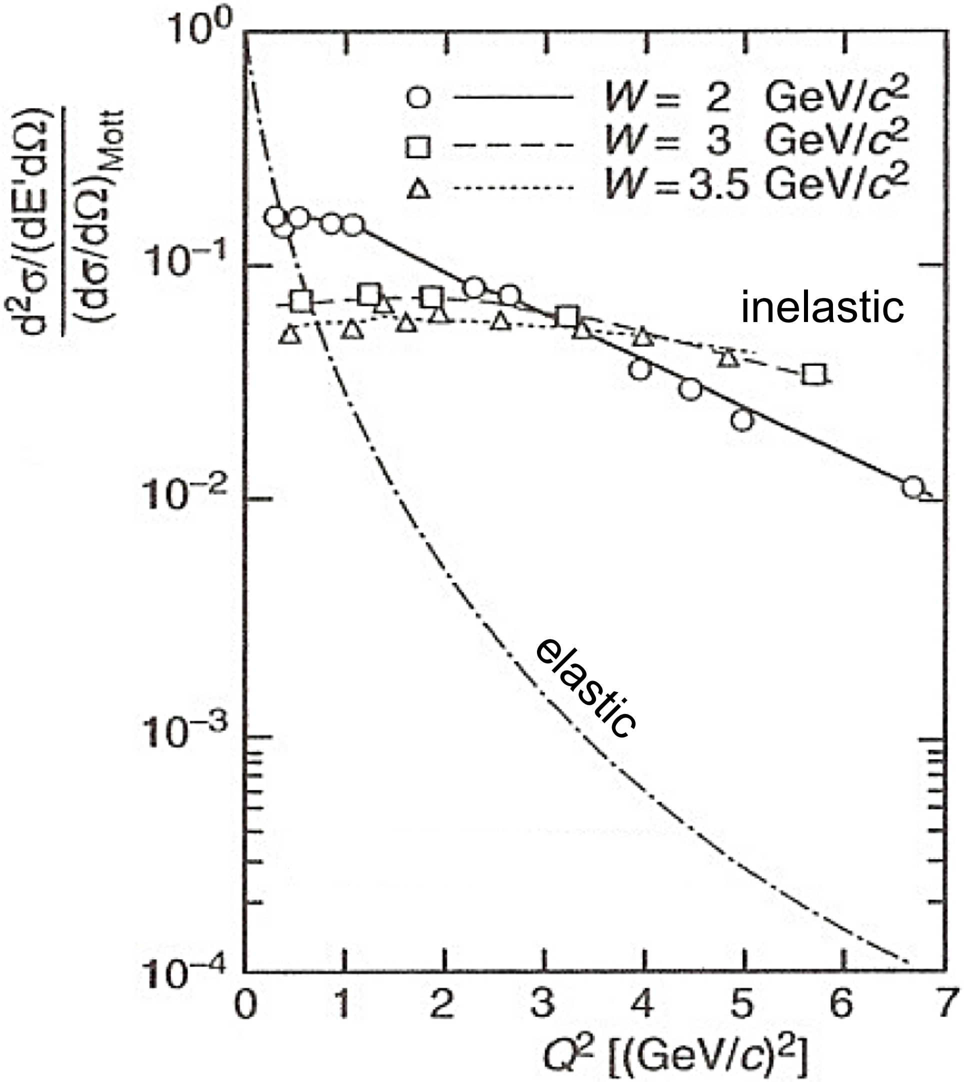

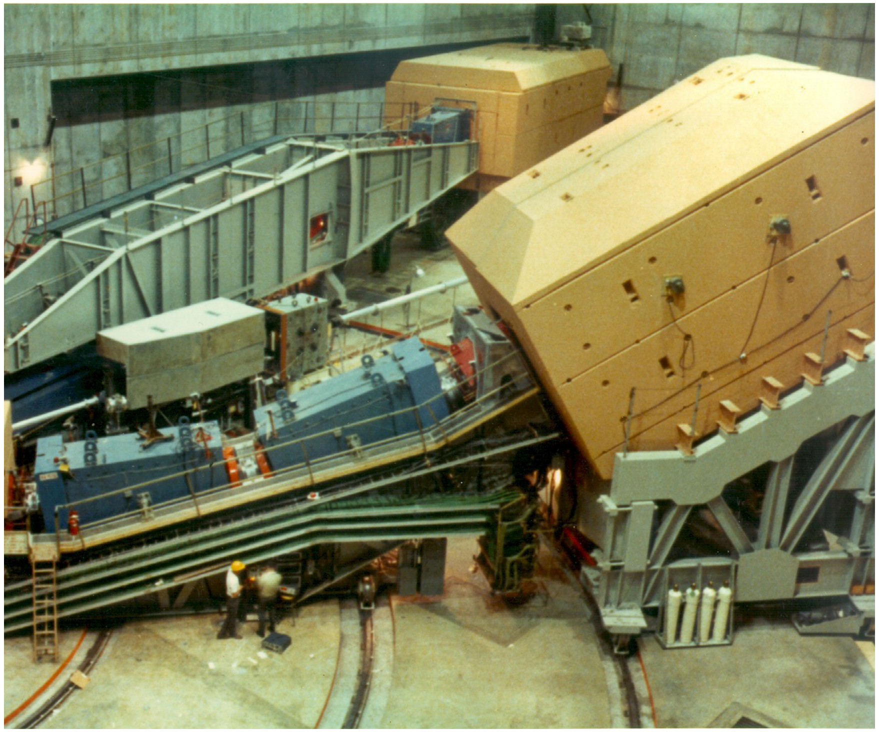

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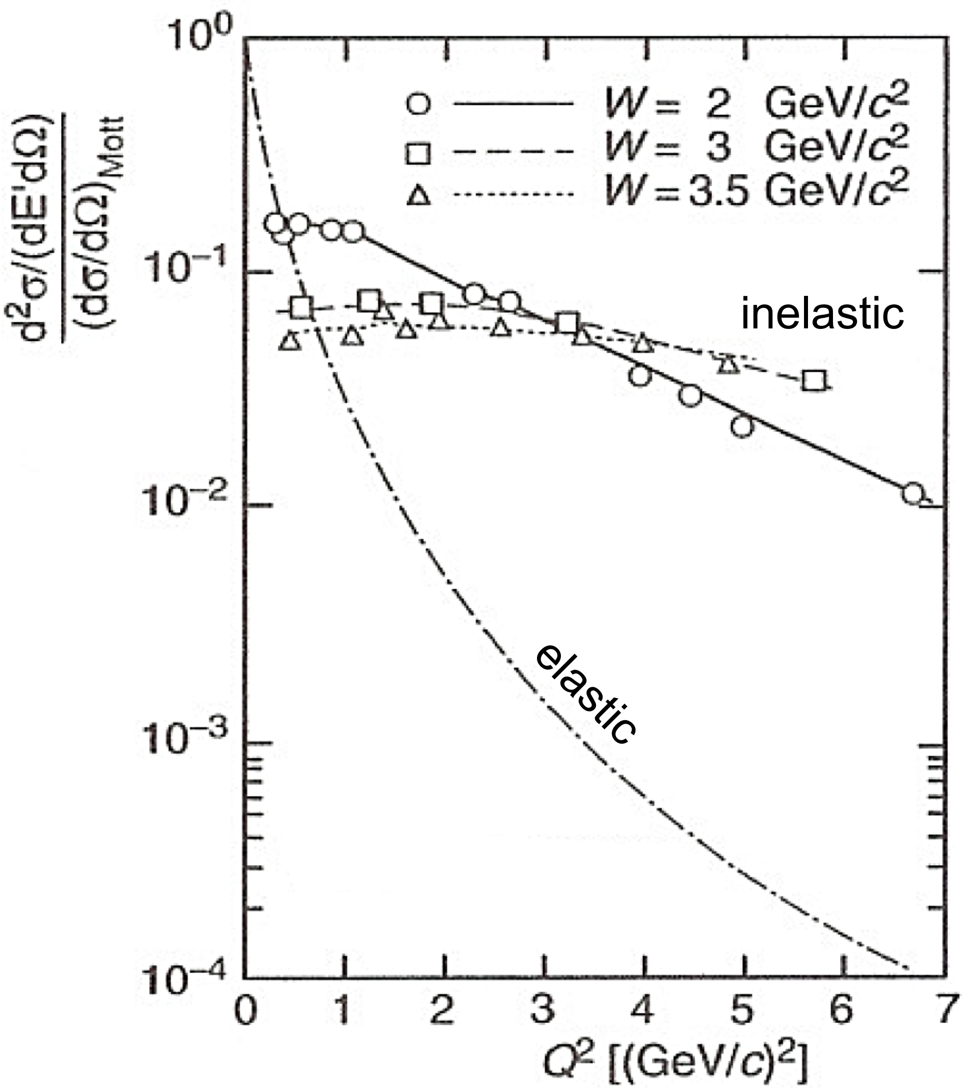


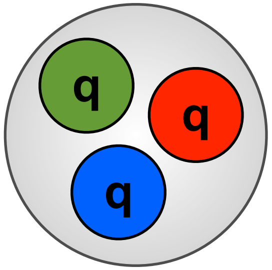
Constant $F(q^2)$:
$\Rightarrow$ scattering on point-like constituent of the nucleon

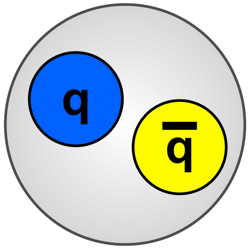
quarks

"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	$+1$

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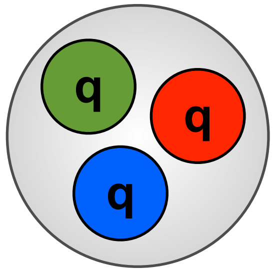

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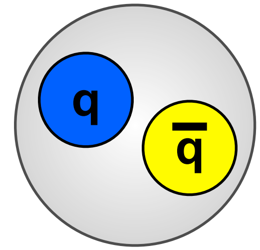
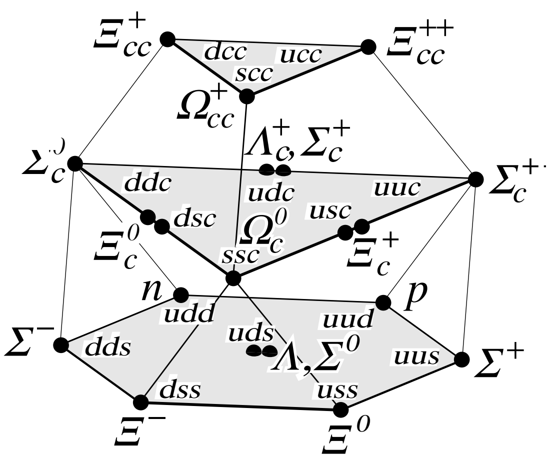
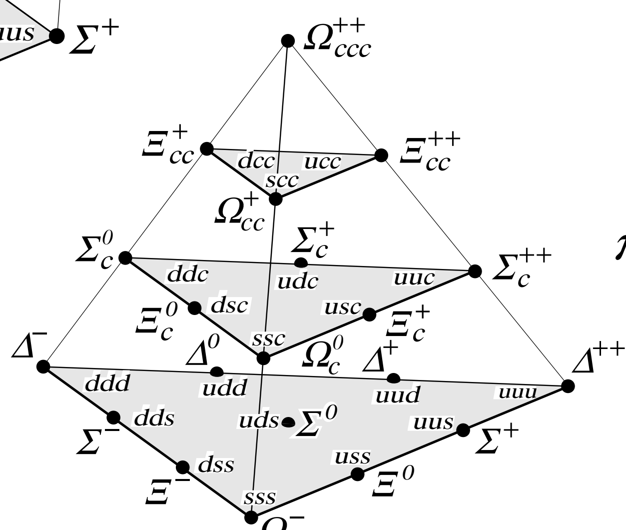
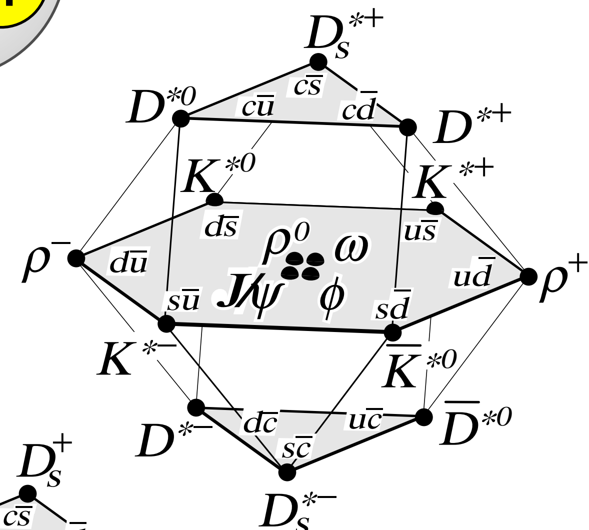
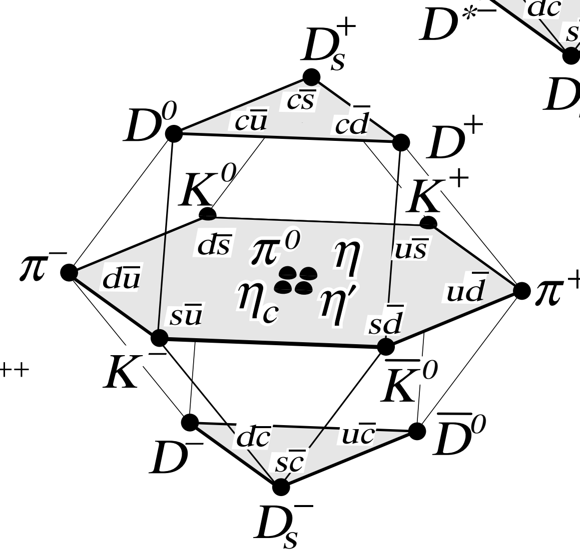




Eight-fold Way:
Account for every hadron we found so far







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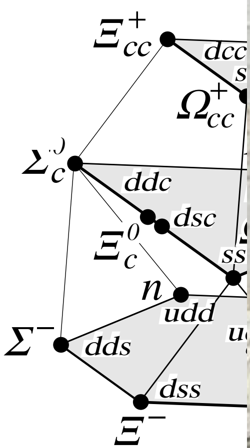
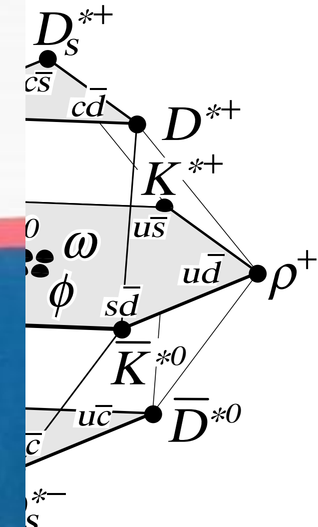
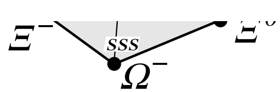






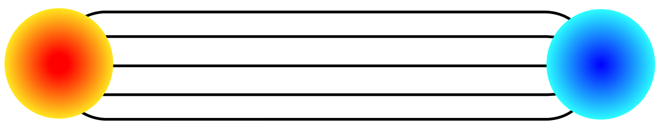
Where’s the Dynamics?

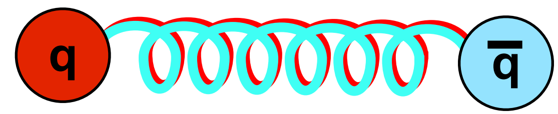
Quantum Chromodynamics (QCD)

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

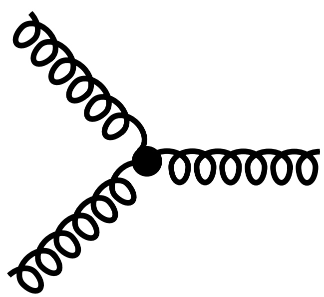
F. Wilczek, hep-ph/9907340

- 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

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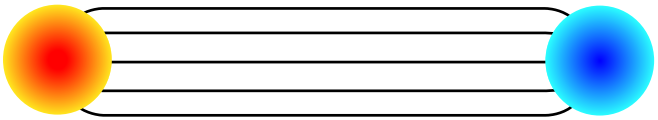

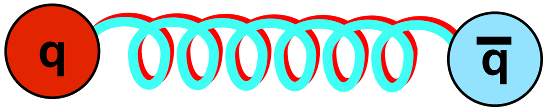

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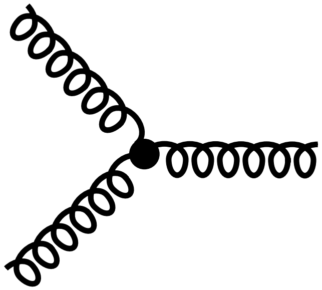


Self-interaction: QCD significantly harder to analyze than QED

- Rich in symmetries

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

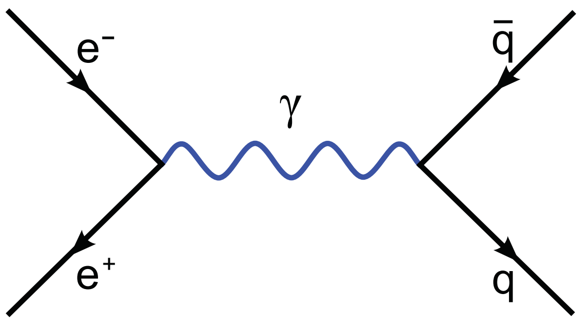
Gluons: They Exist!

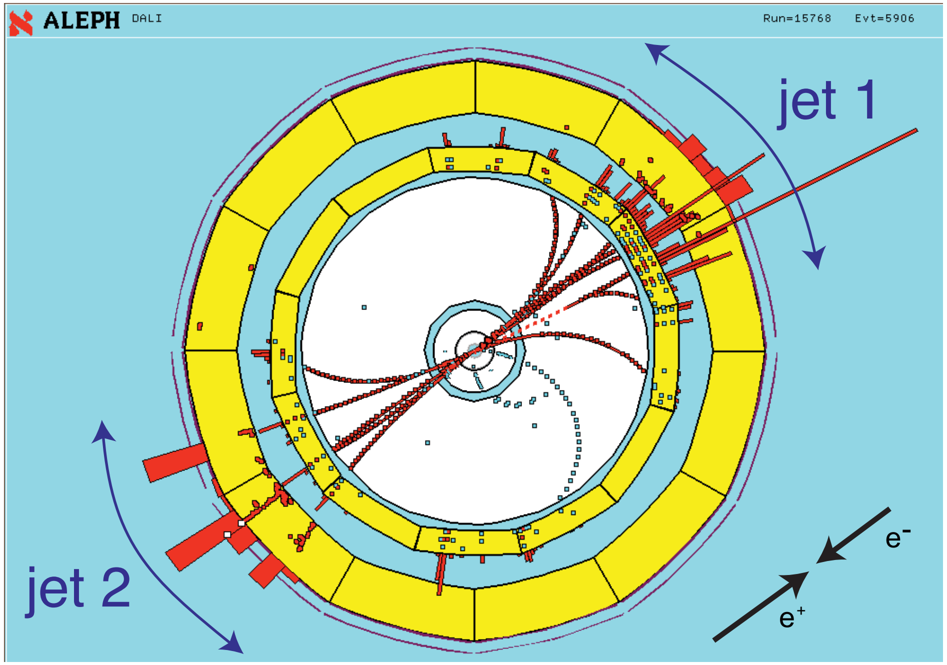
1979 Discovery of the Gluon

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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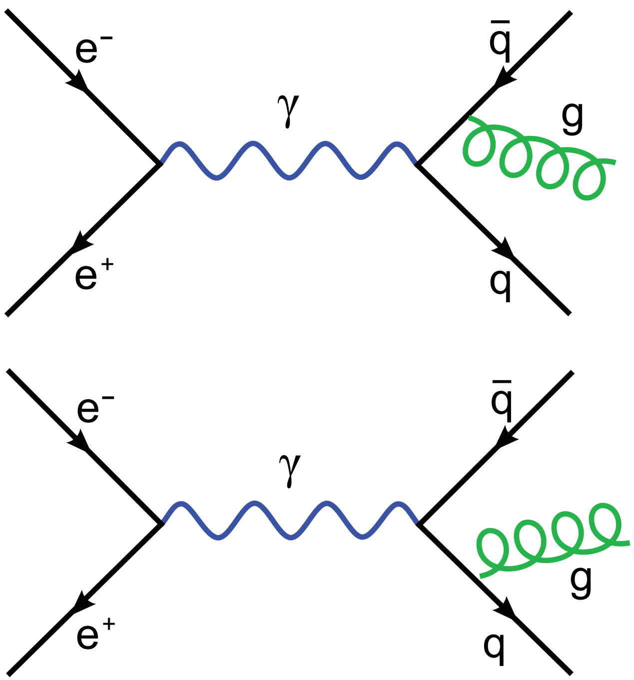

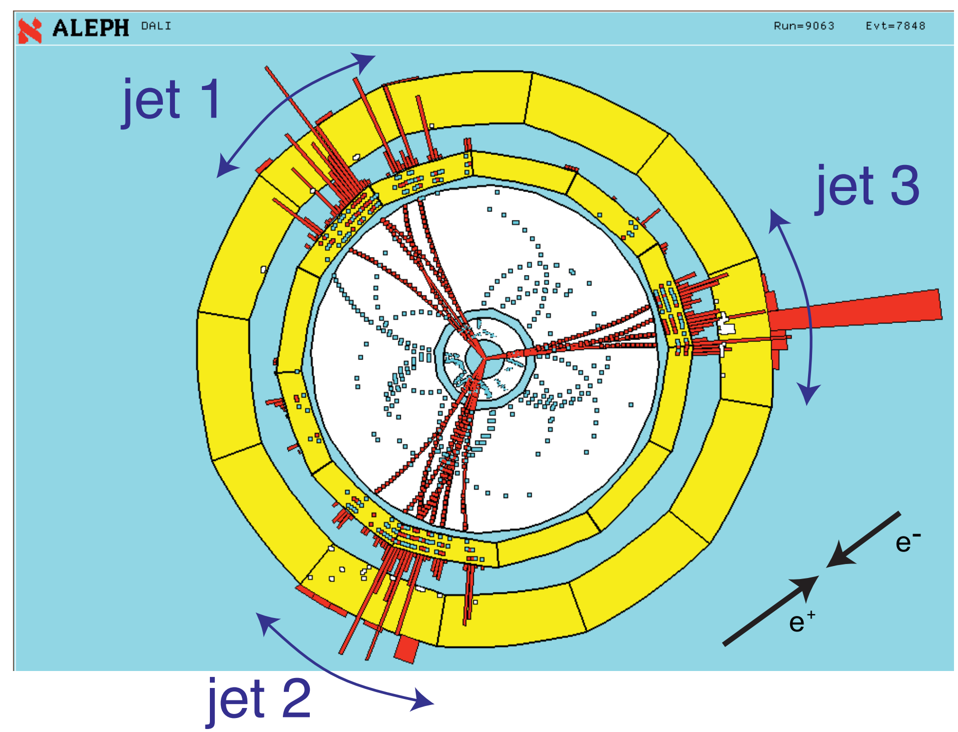

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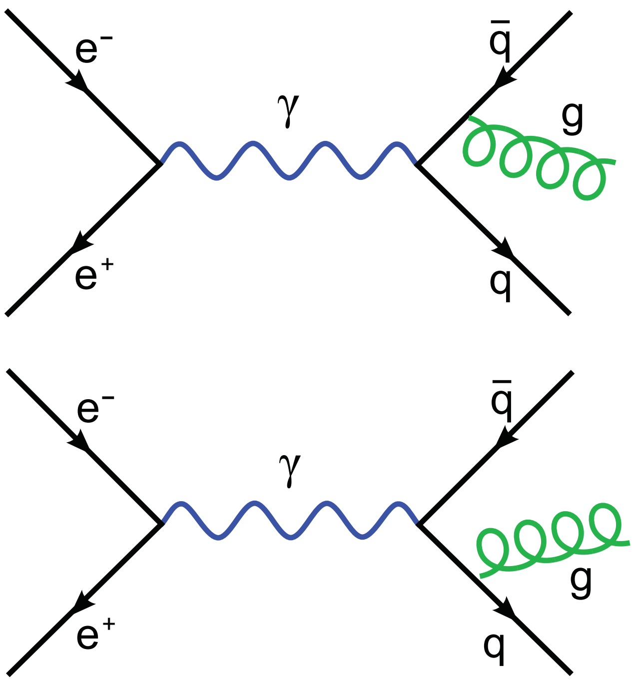
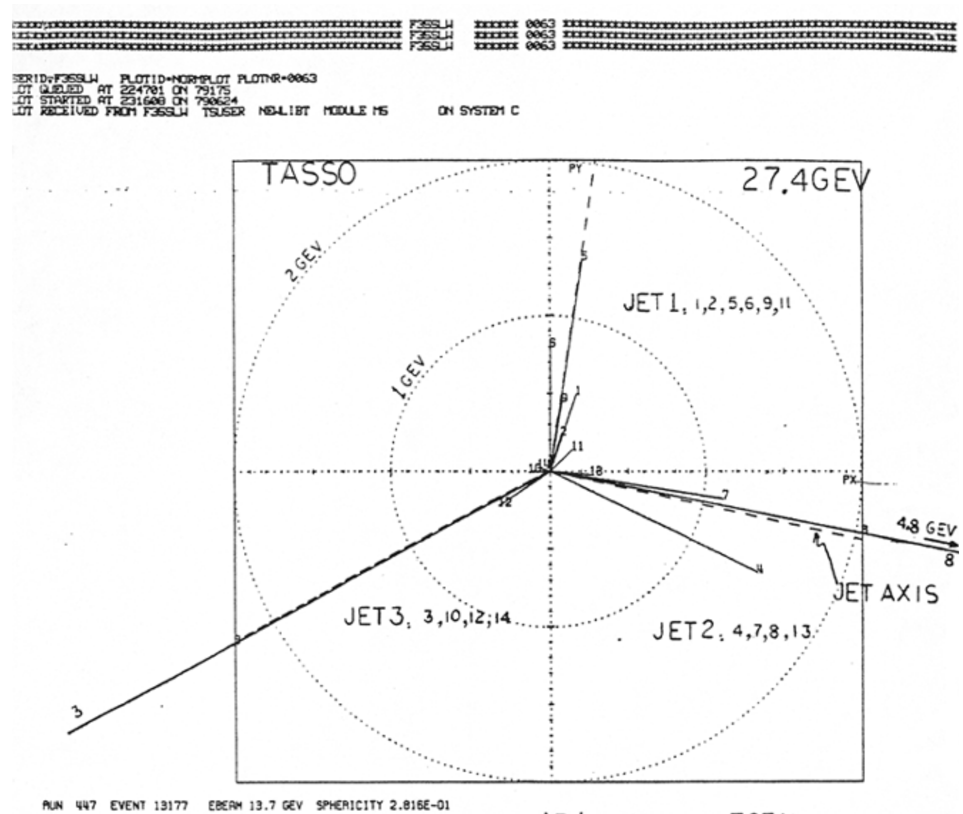
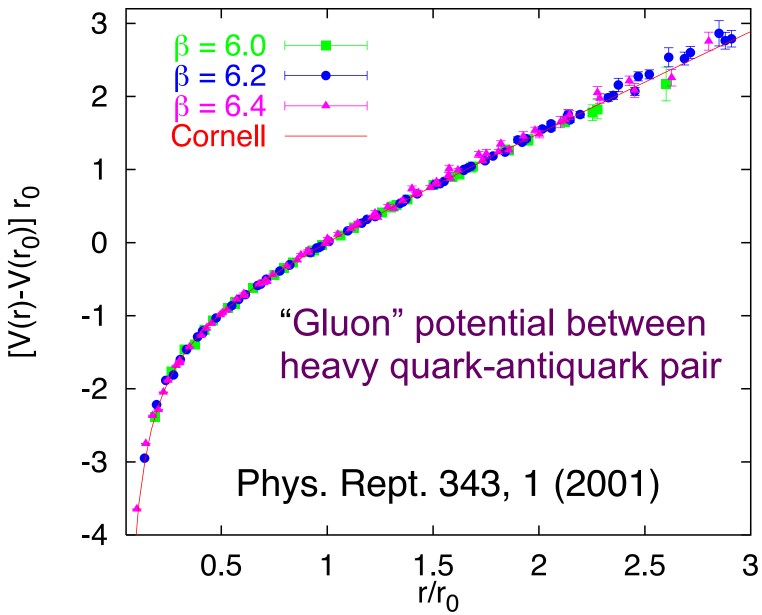




	$\sum_i \lvert P_i \rvert_{CHARGE}$	TOTAL ENERGY
JET 1	4.3 GEV	7.4 GEV
JET 2	7.8	8.9
JET 3	4.1	11.1

The Role of Gluons

Confinement:



$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

~1/r at short range

long range ~ r

Quarks experience force of 16 tons at distances of ~ 1 Fermi (10^{-15} m)

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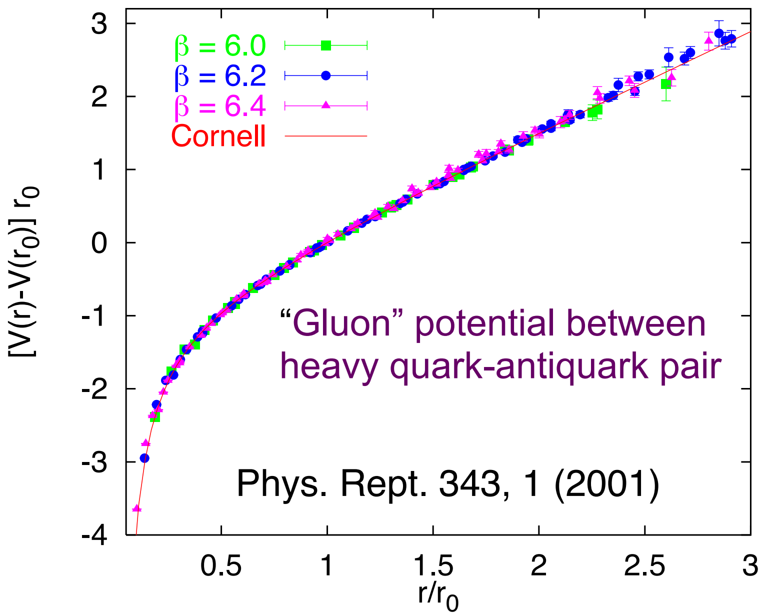

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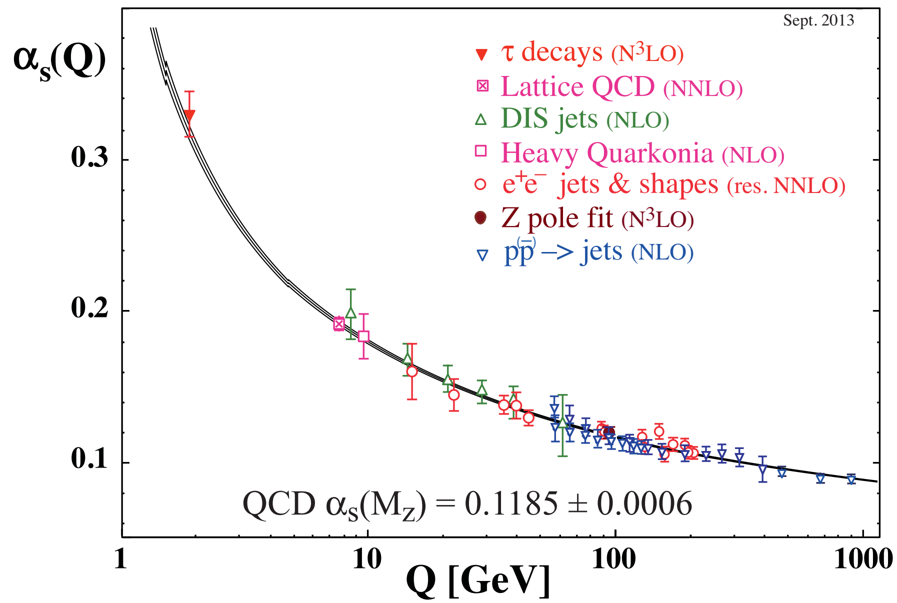
Asymptotic freedom:



The self-interaction of gluons is fundamentally responsible for the asymptotic freedom of quarks and gluons in QCD

2004, Gross, Politzer, Wilczek

The Essential Mystery

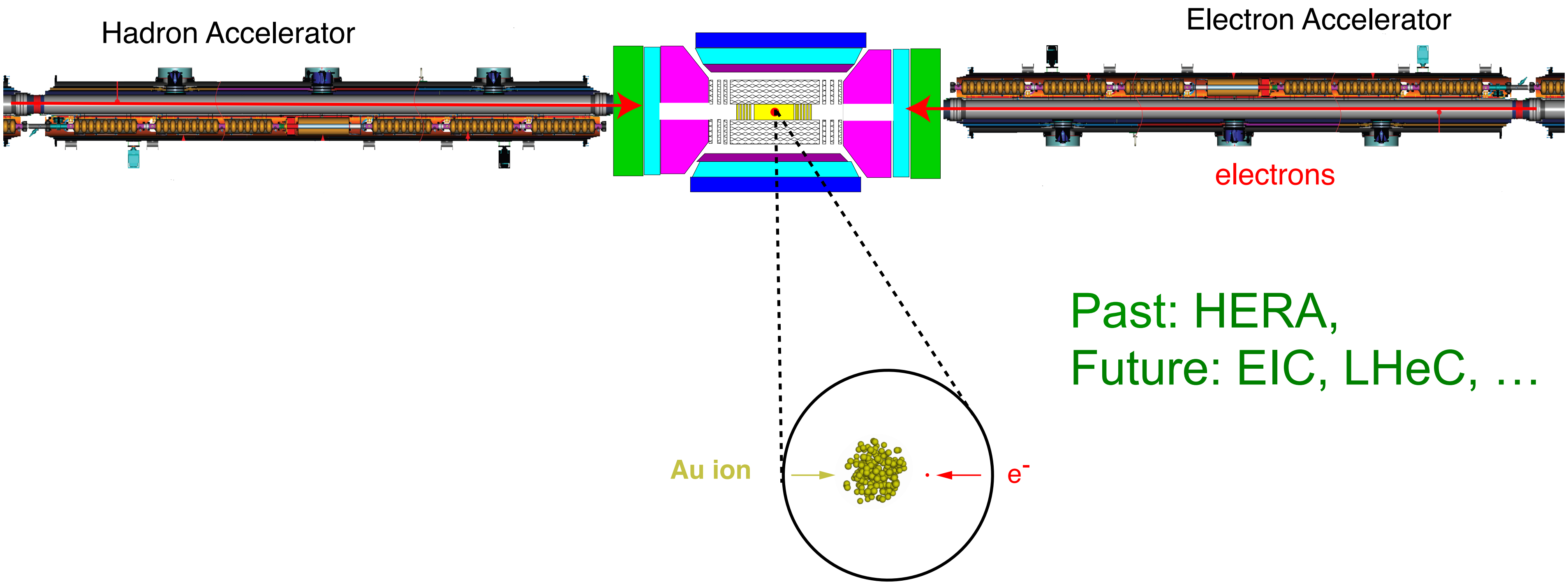
There is an elegance and simplicity to nature's strongest force we do not understand

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

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

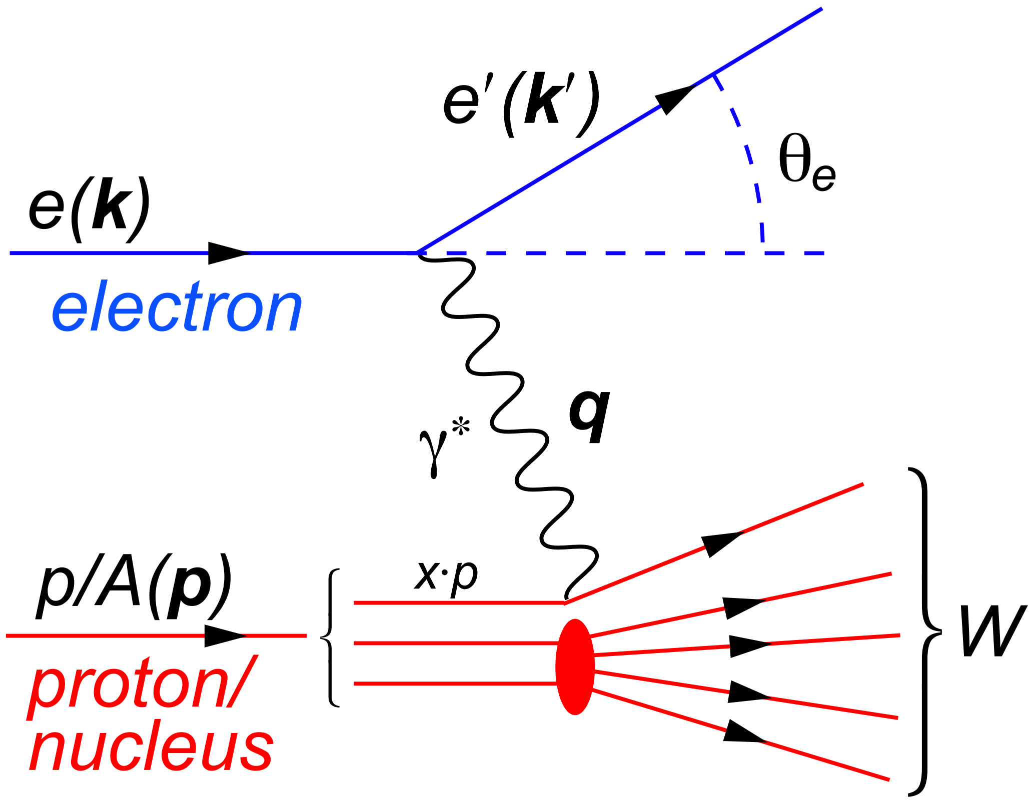
Studying Matter at the Smallest Scales

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



Past: HERA,
Future: EIC, LHeC, …

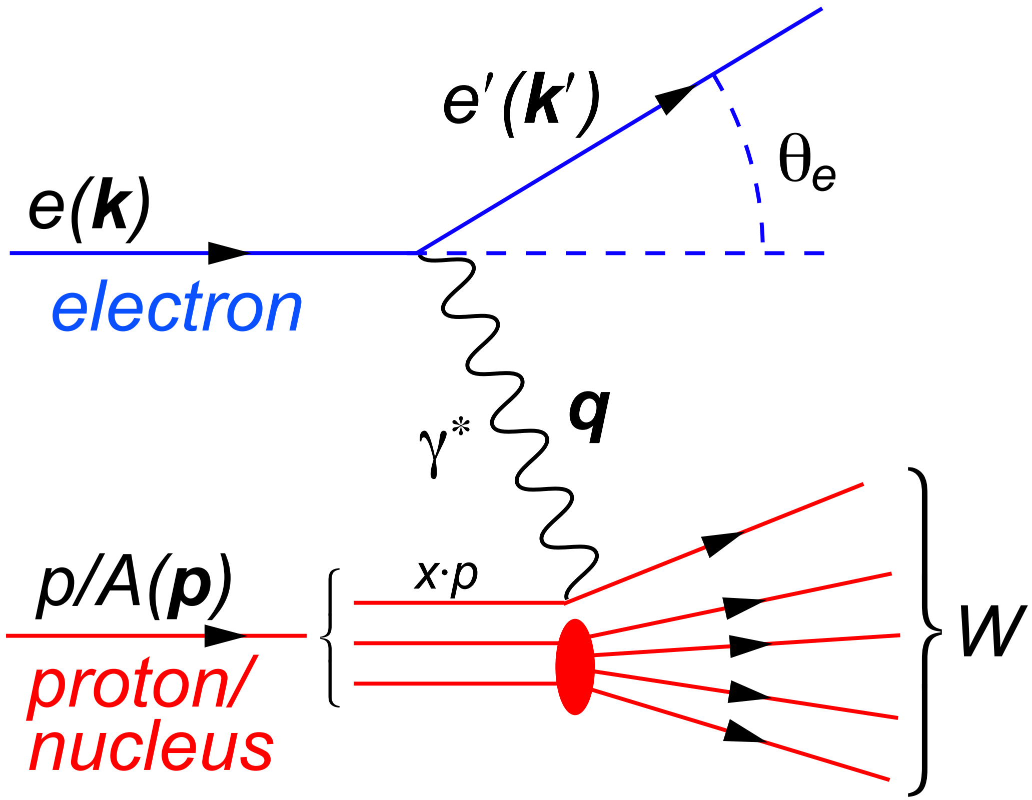
Deep Inelastic Scattering (DIS)



DIS:

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent, determination of kinematics of physics processes

Deep Inelastic Scattering (DIS)



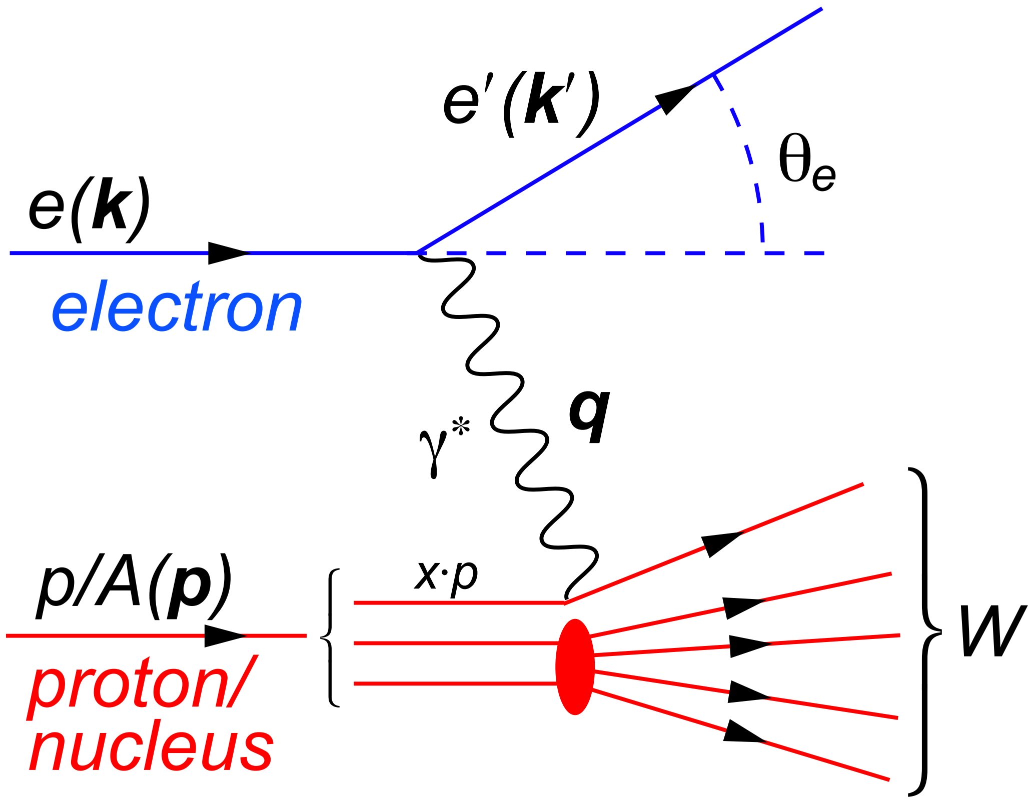
s:

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

$$\sqrt{s} \simeq 2\sqrt{E_e E_p}$$

s: center-of-mass energy squared

Deep Inelastic Scattering (DIS)



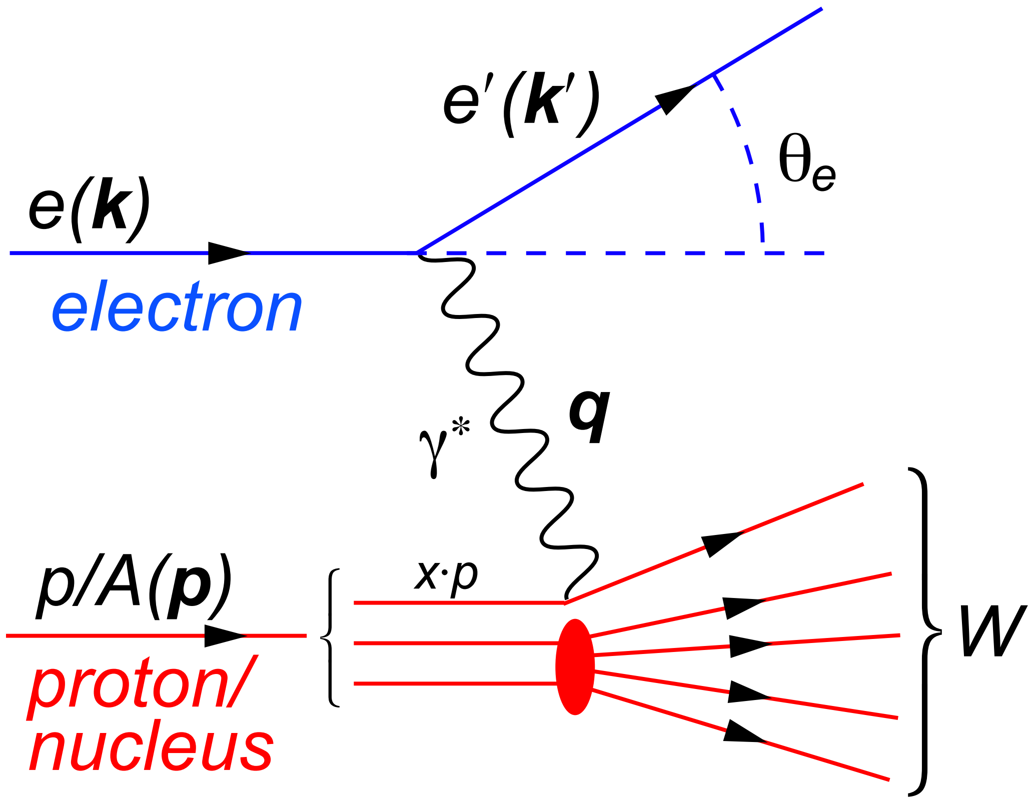
Q²:

- squared momentum transfer from scattered electron
- Virtuality
- “Resolution” power

s: center-of-mass energy squared

Q²: resolution power

Deep Inelastic Scattering (DIS)



x:

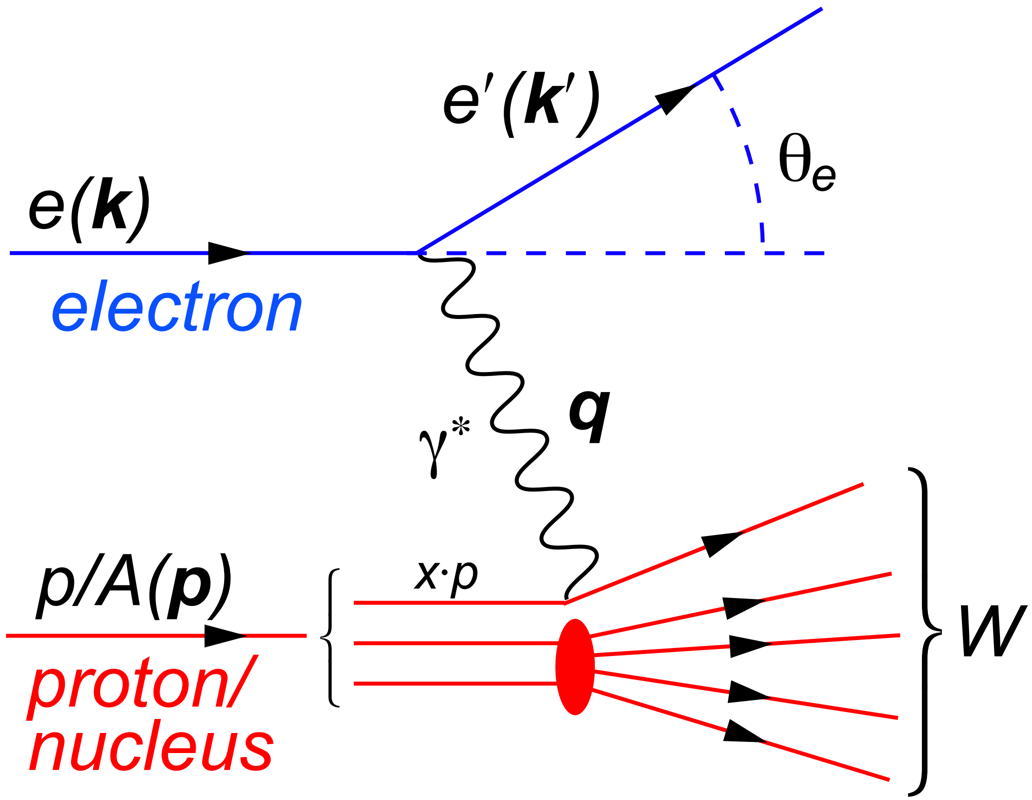
- Bjorken-x
- x is fraction of the nucleon's momentum carried by the struck quark
- $0 < x < 1$

s: center-of-mass energy squared

$\mathbf{Q^2}$: resolution power

x: momentum fraction of parton

Deep Inelastic Scattering (DIS)



y:

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

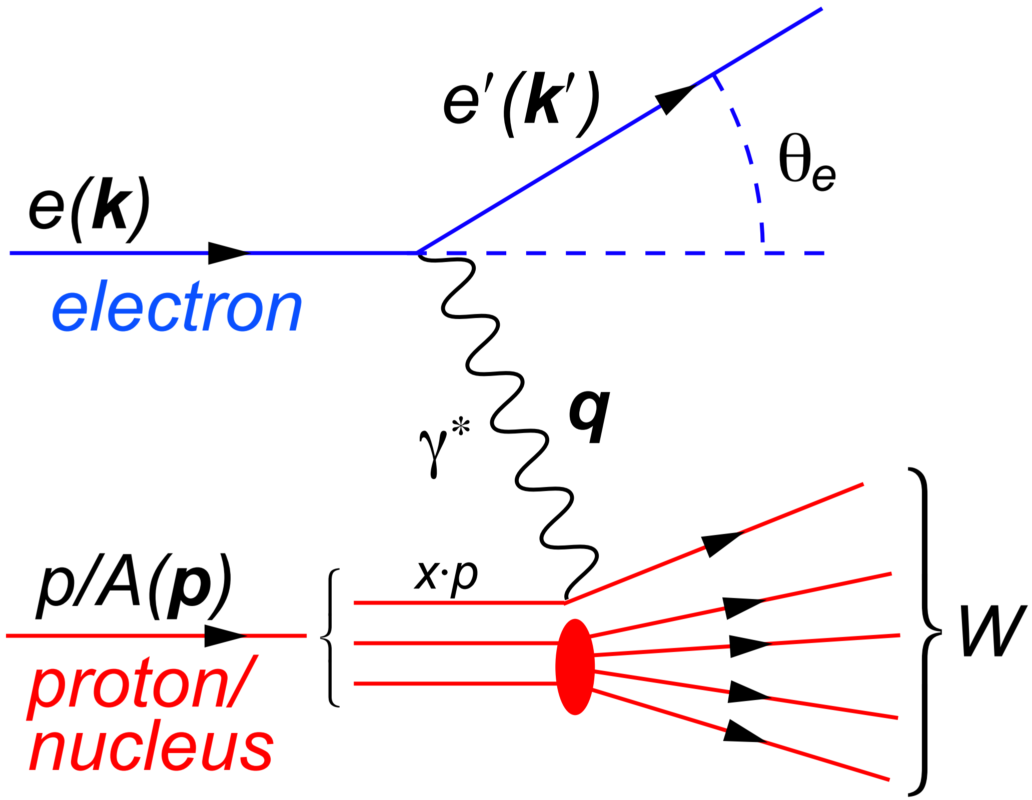
s: center-of-mass energy squared

Q²: resolution power

x: momentum fraction of parton

y: inelasticity

Deep Inelastic Scattering (DIS)



s: center-of-mass energy squared

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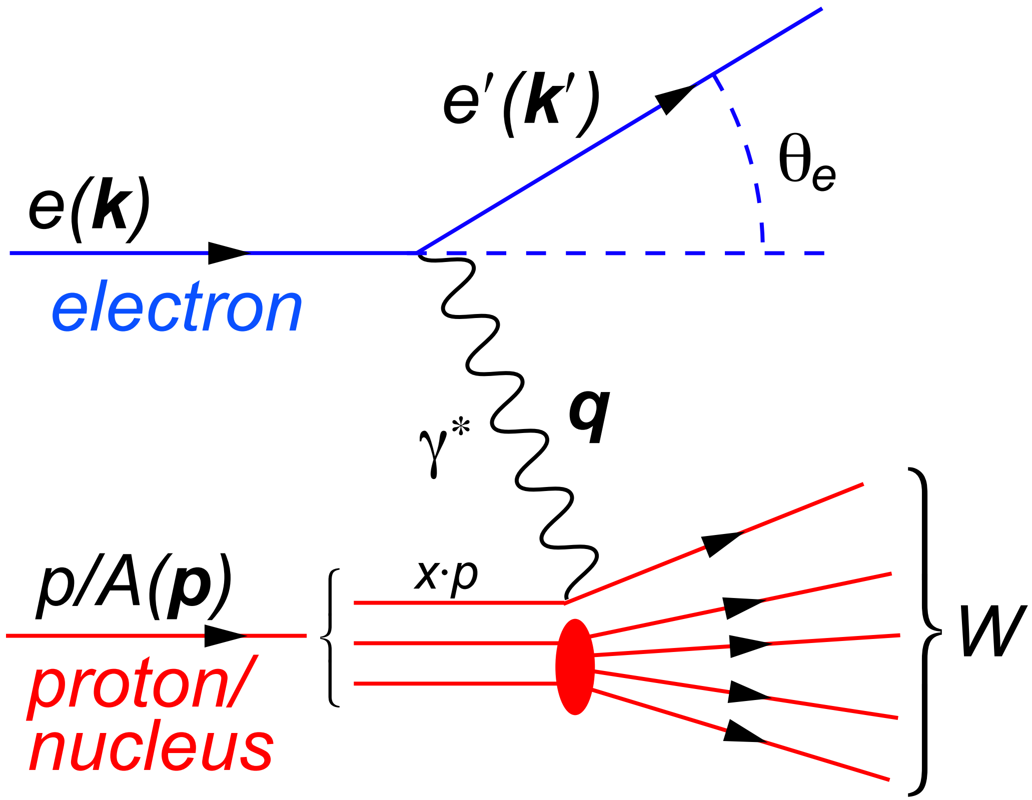
$$Q^2 \approx s \cdot x \cdot y$$

Deep Inelastic Scattering (DIS)



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

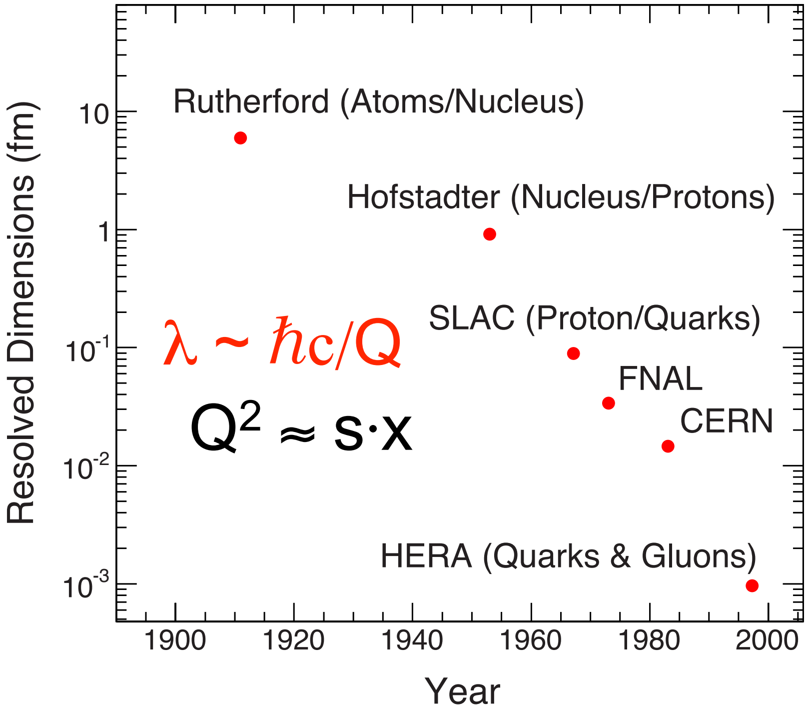
$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions

gluon momentum distribution

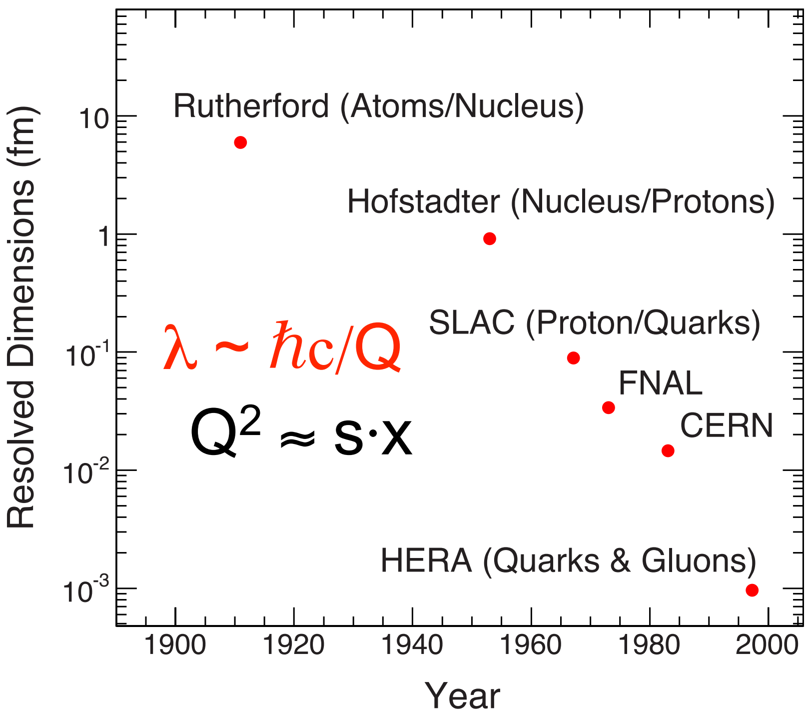
F_2: The Key Structure Function

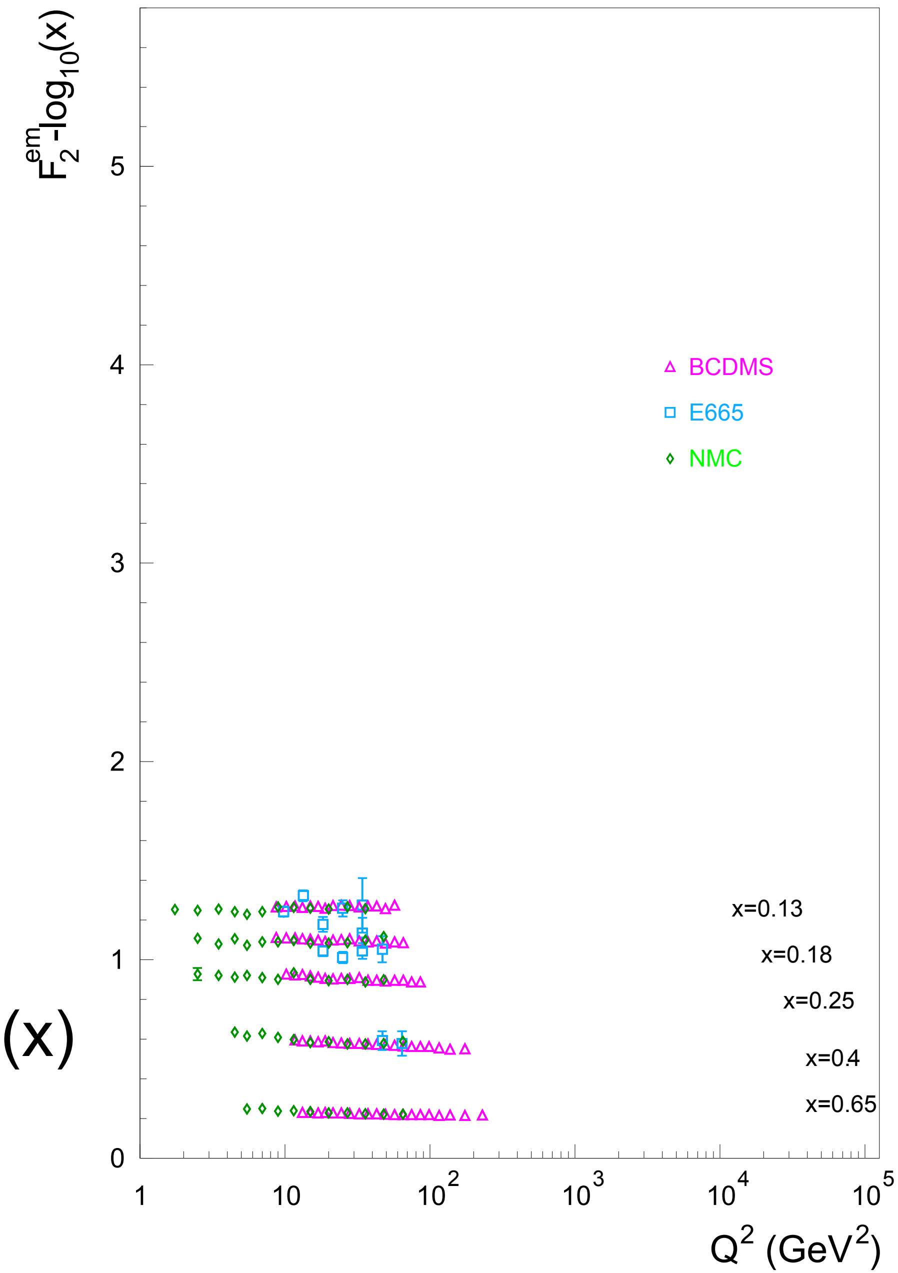
$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2)$$



F_2: The Key Structure Function

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2)$$





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

virtual photon interacts with a single essentially free quark

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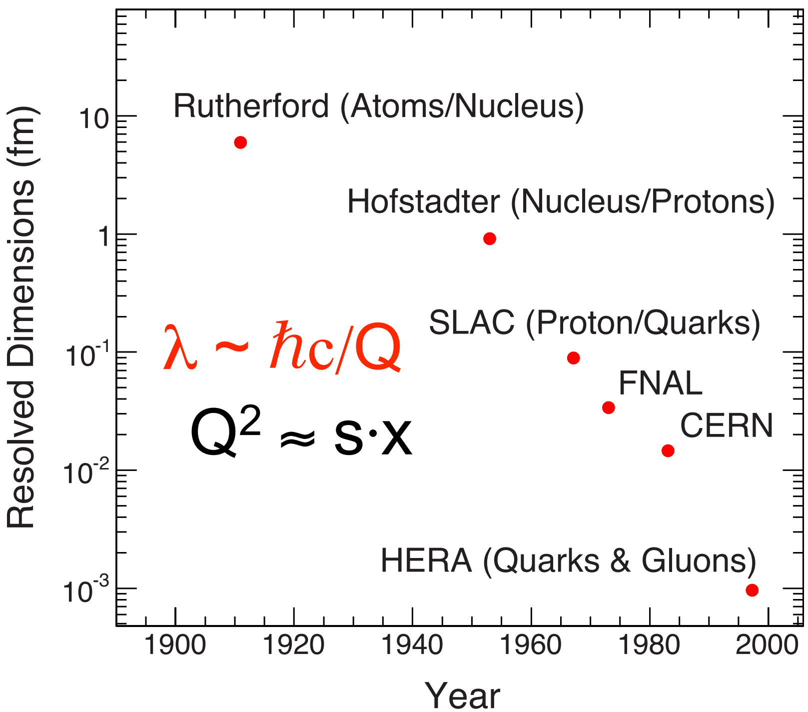

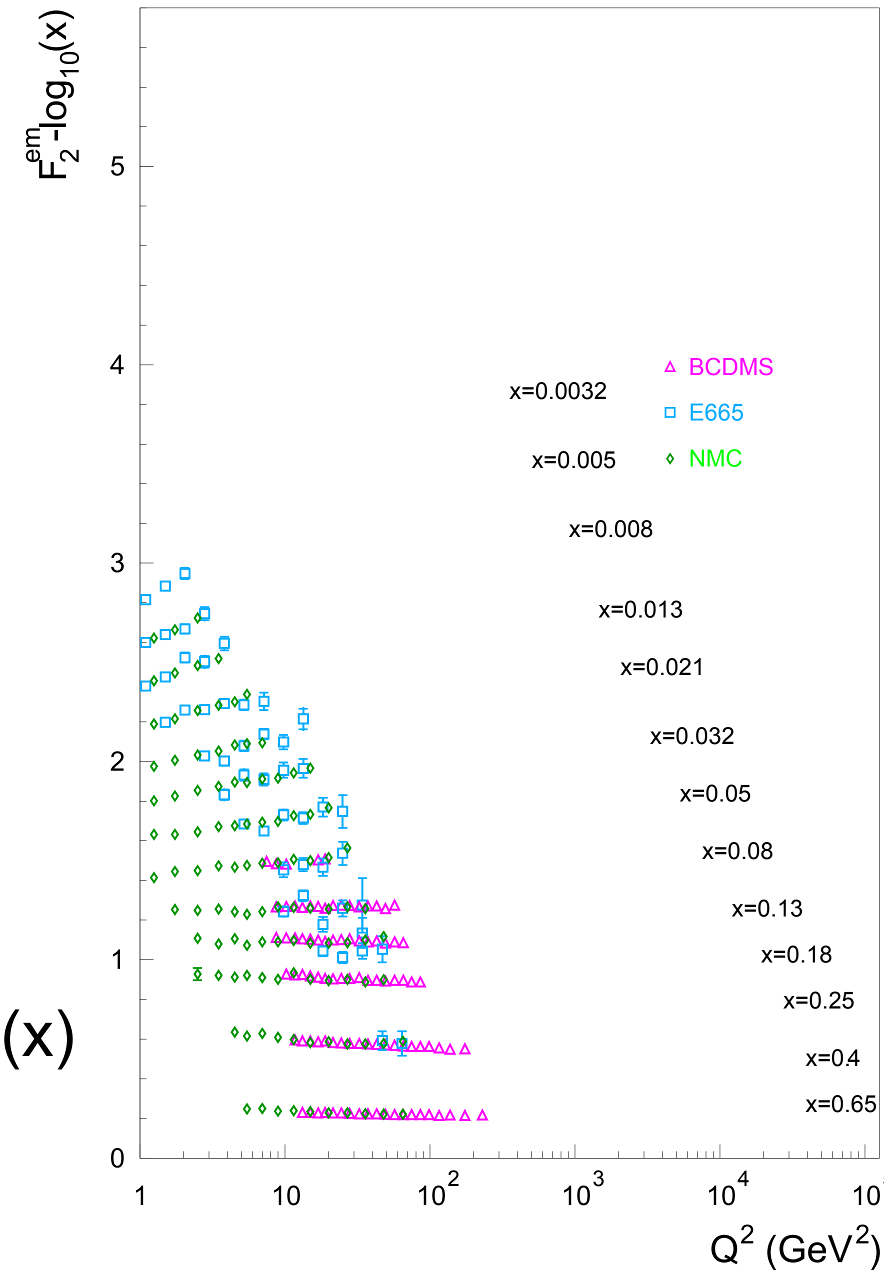

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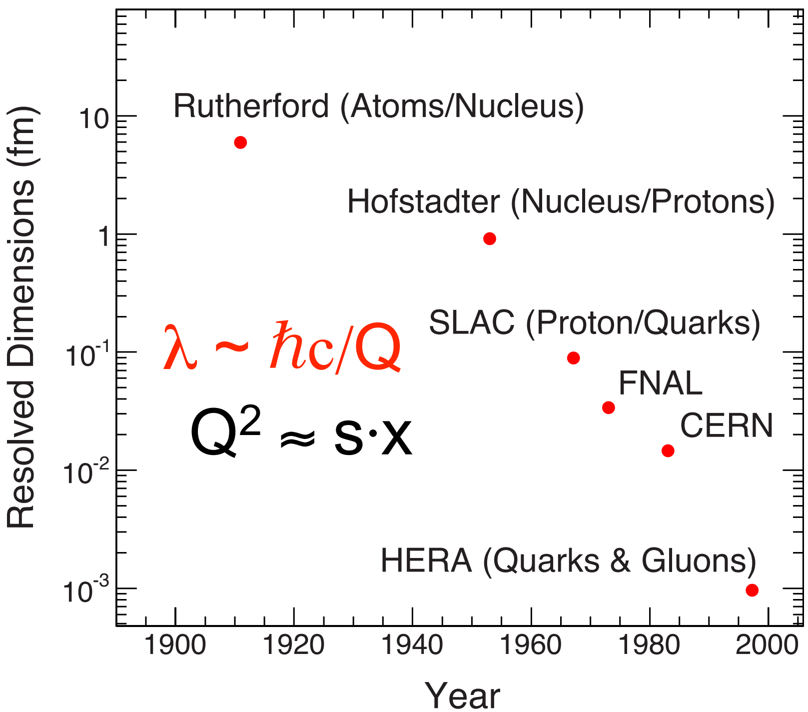
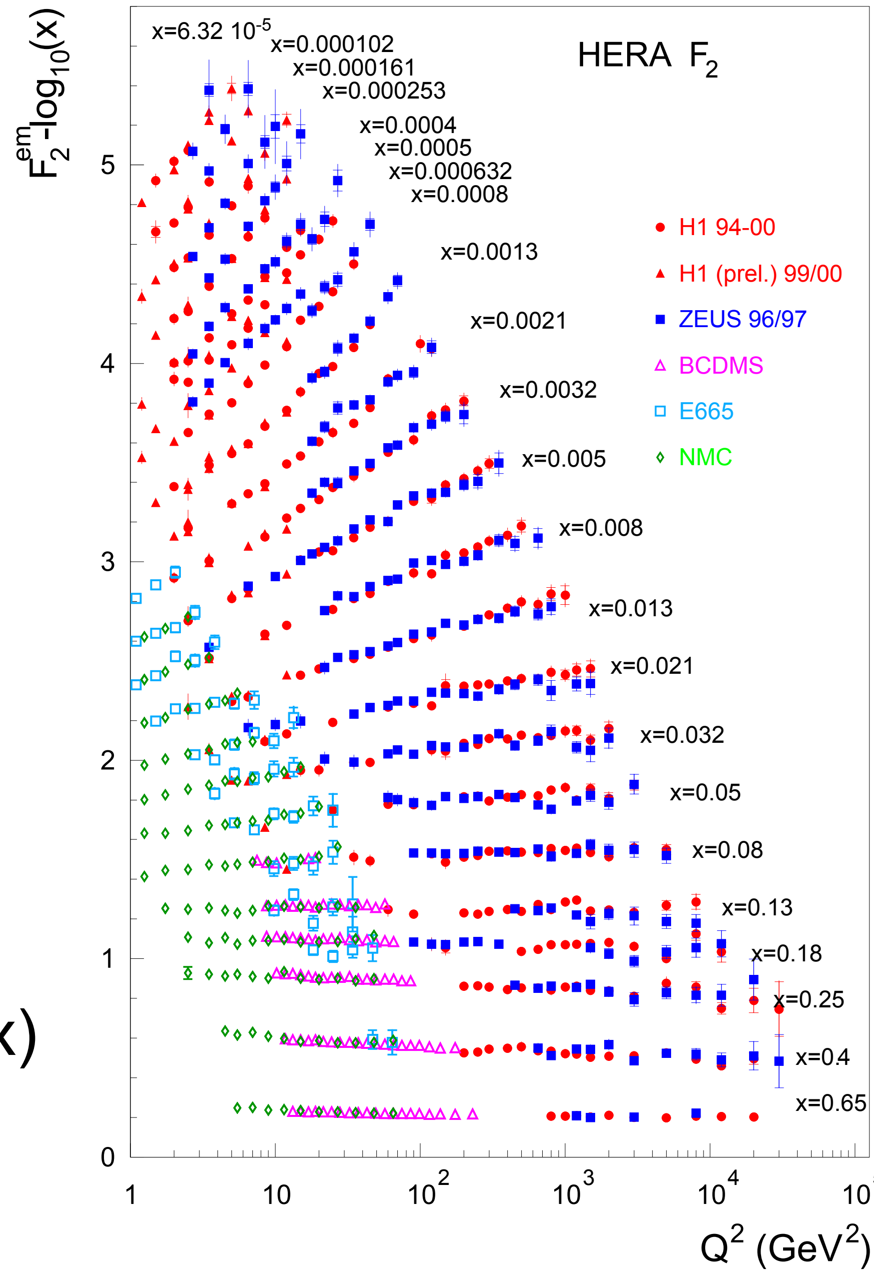




Bjorken Scaling: $F_2(x, Q^2) \neq F_2(x)$

Broken - Big Time

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

Quark and Gluon Distributions

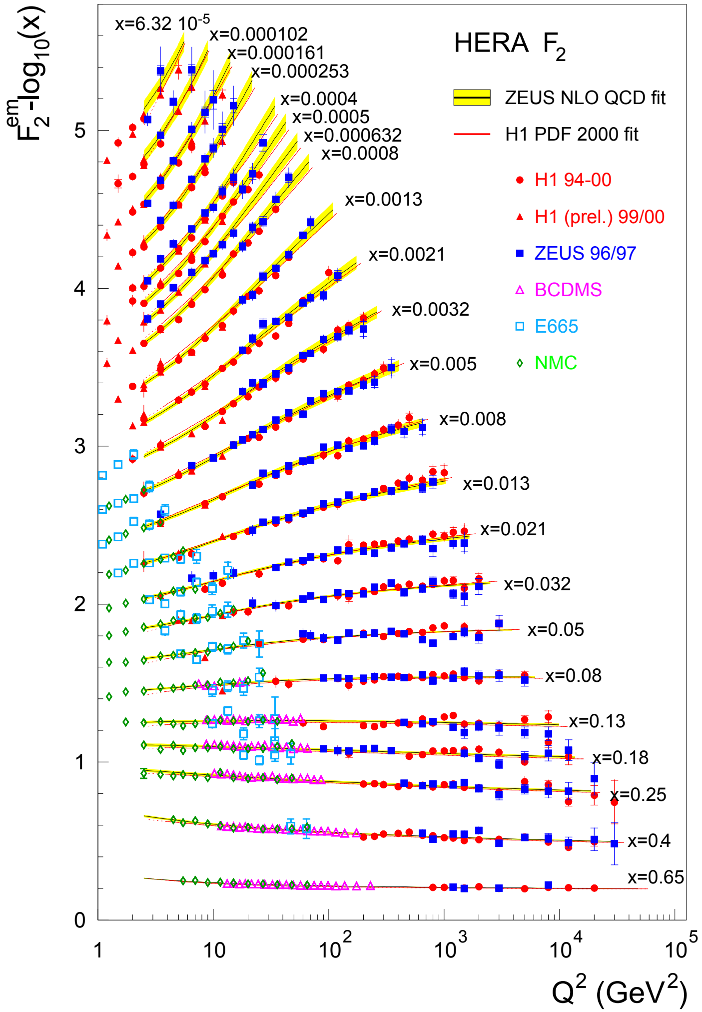
Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions.

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

Quark and Gluon Distributions

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

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



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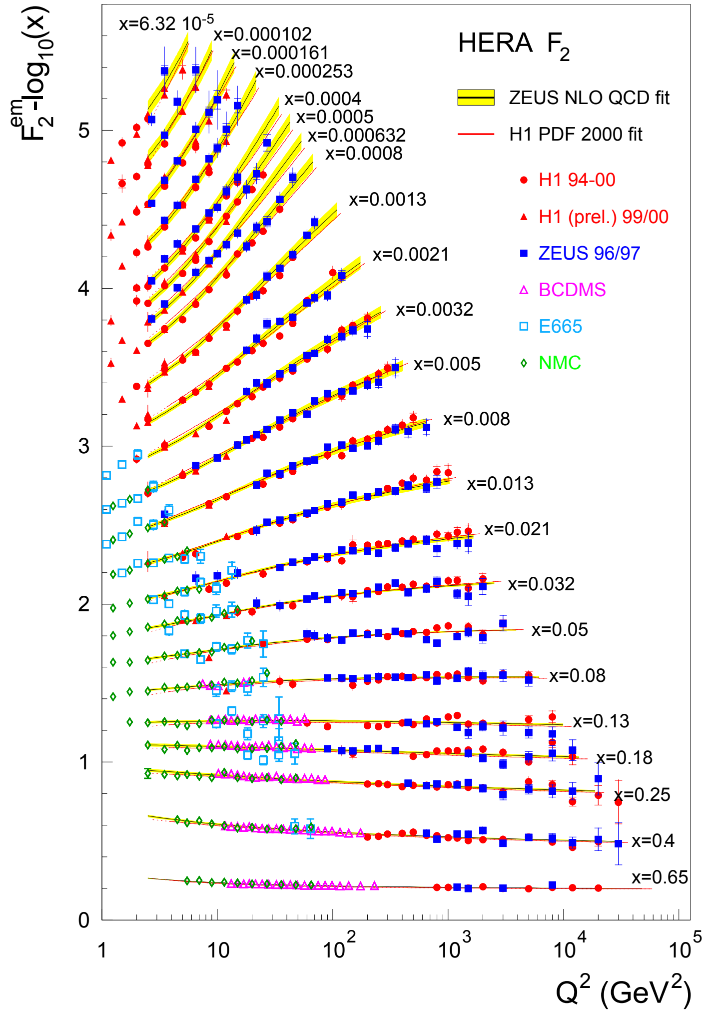

$\Rightarrow$

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

\+ pQCD+ DGLAP Evolution

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

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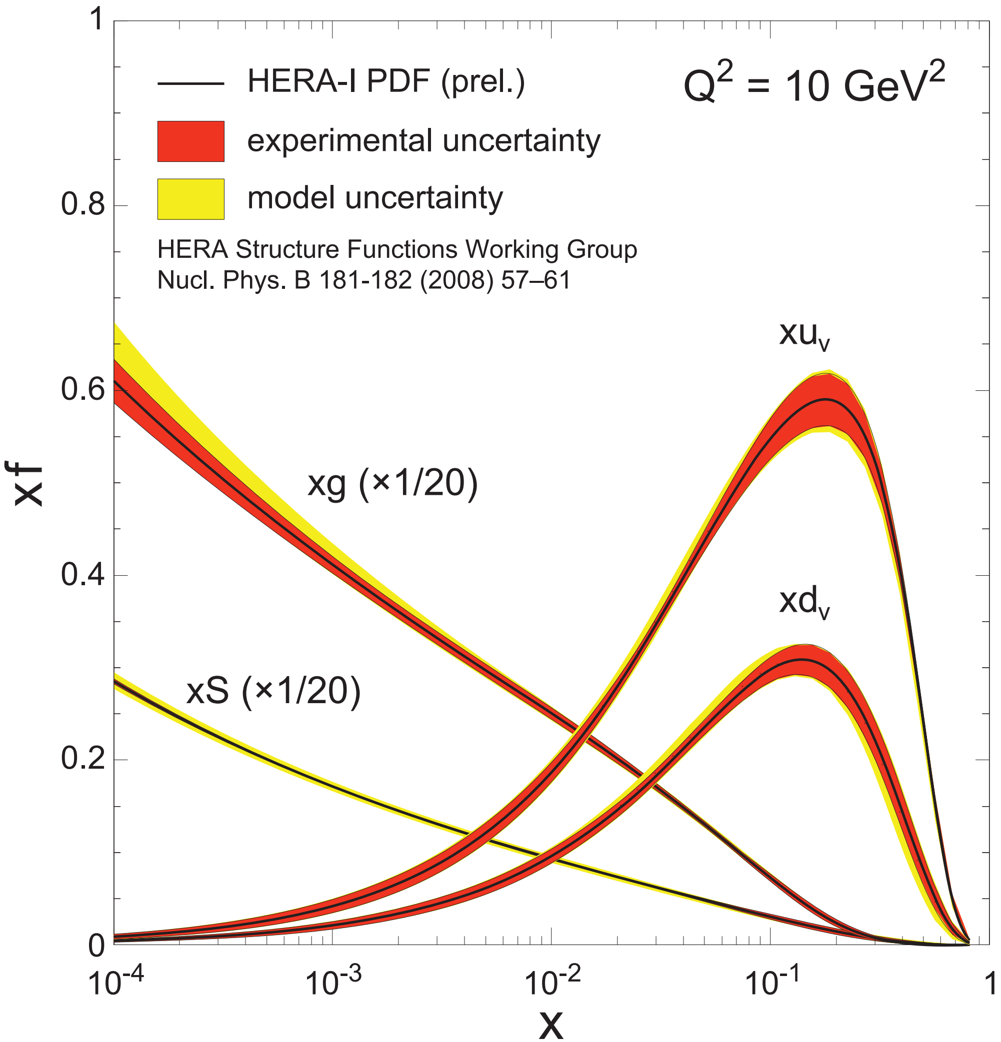

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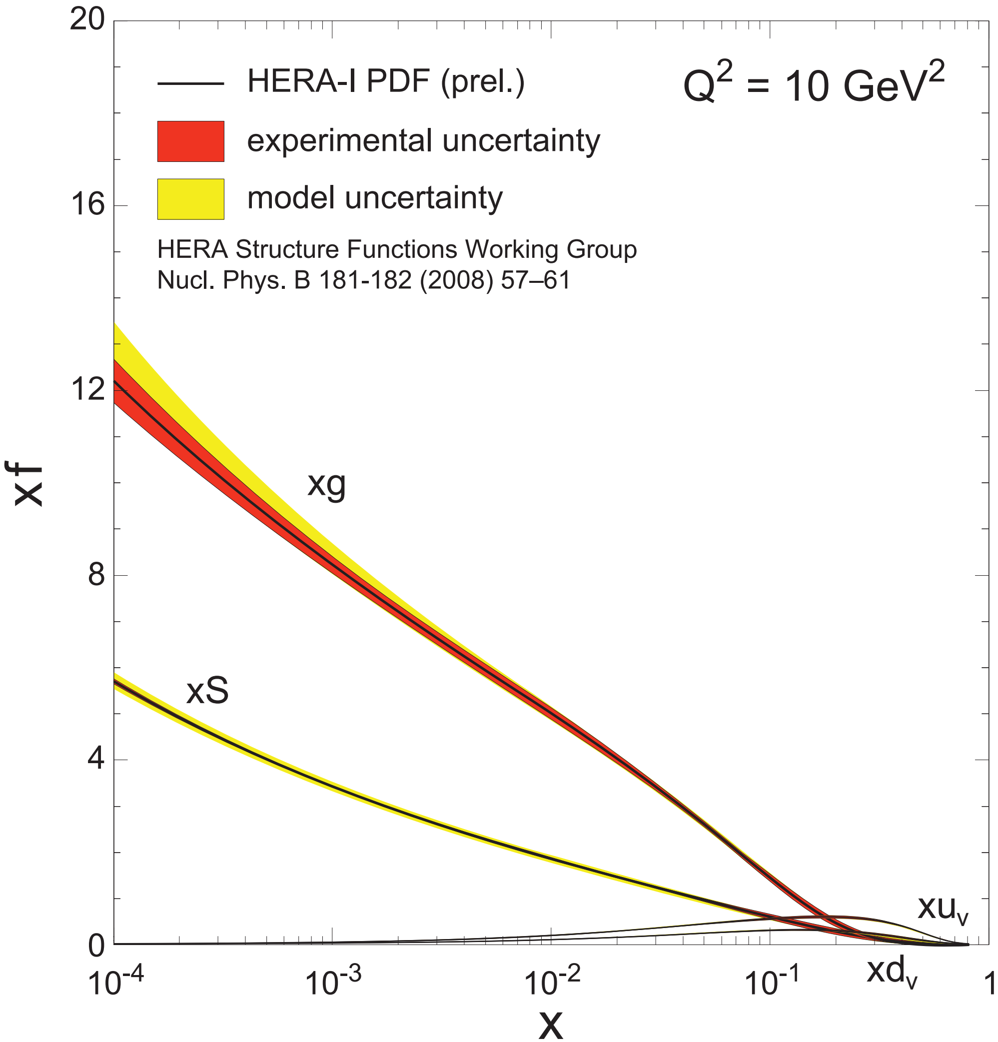
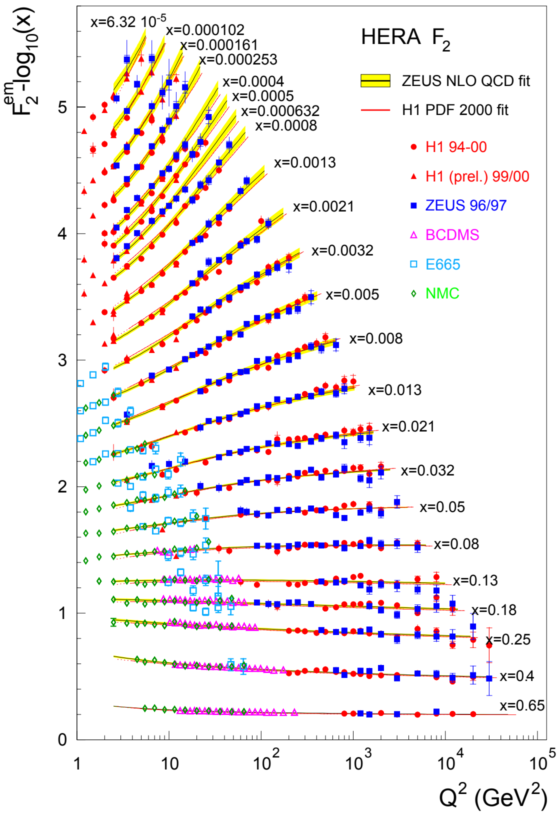


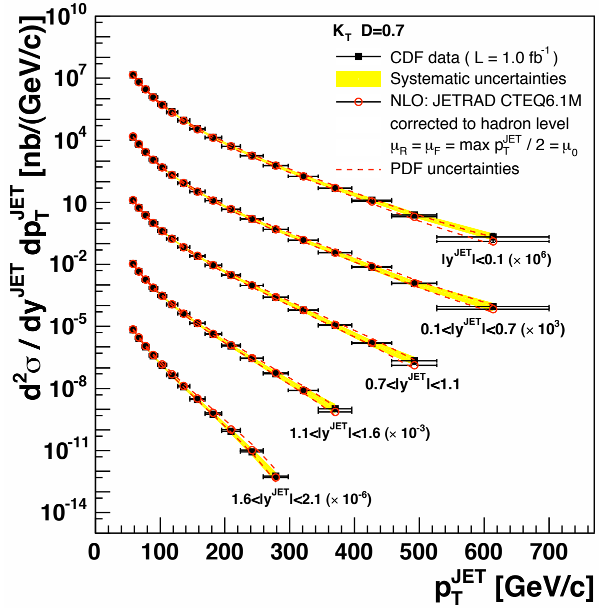
Proton is almost entirely glue by x<0.1 (for Q^2 = 10 GeV^2)

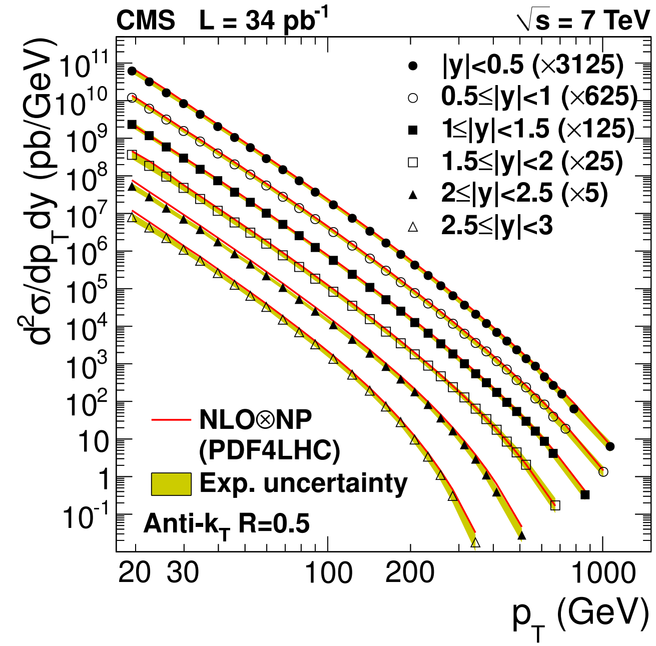
Perturbative QCD: Benchmark for New Physics

Structure functions measured at HERA ep collider



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





At large momenta, the weak QCD coupling (asymptotic freedom!) enables systematic computations

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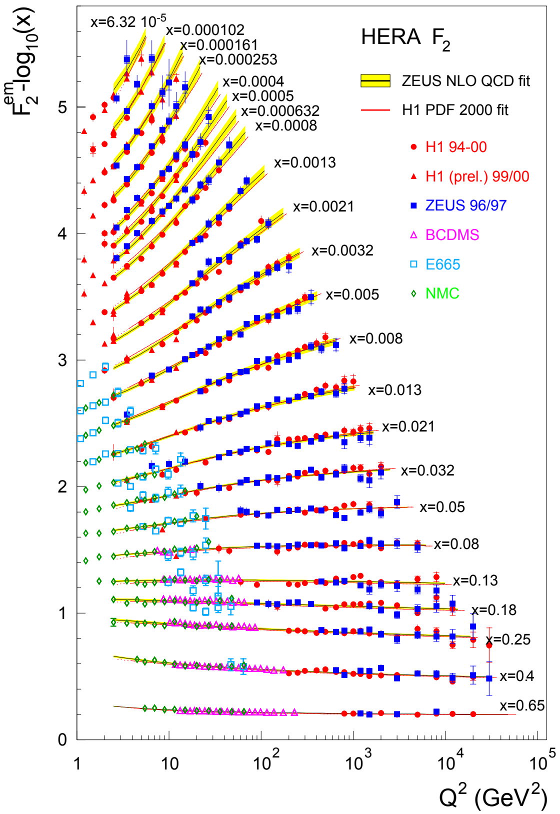

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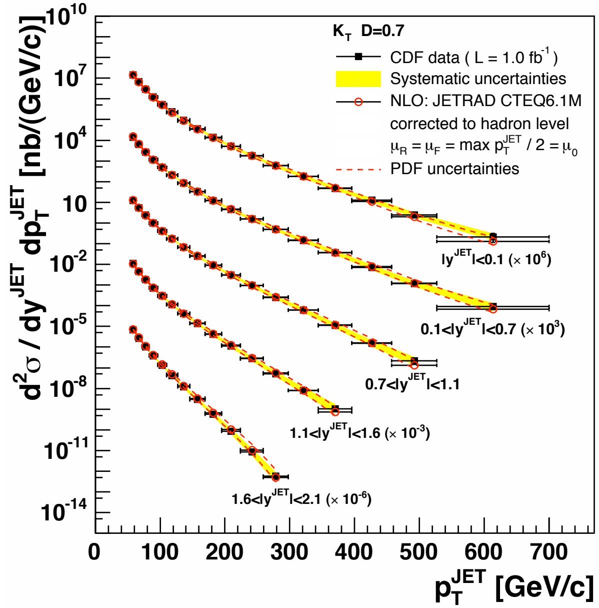
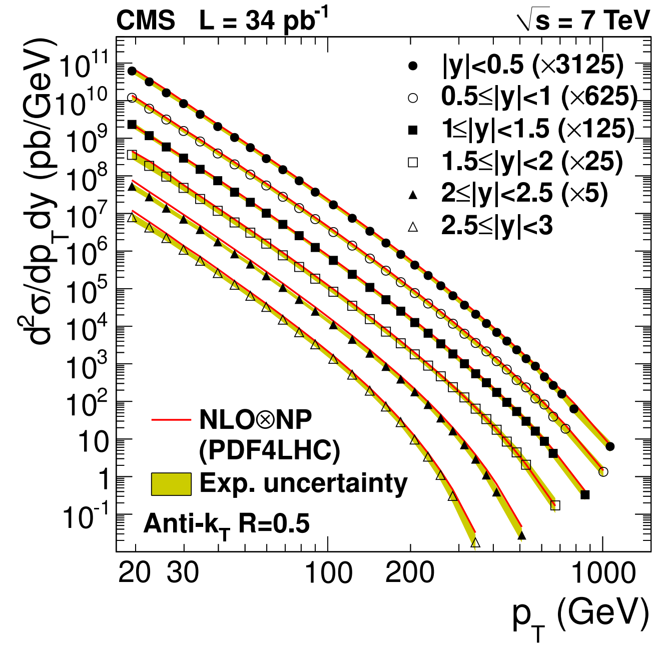
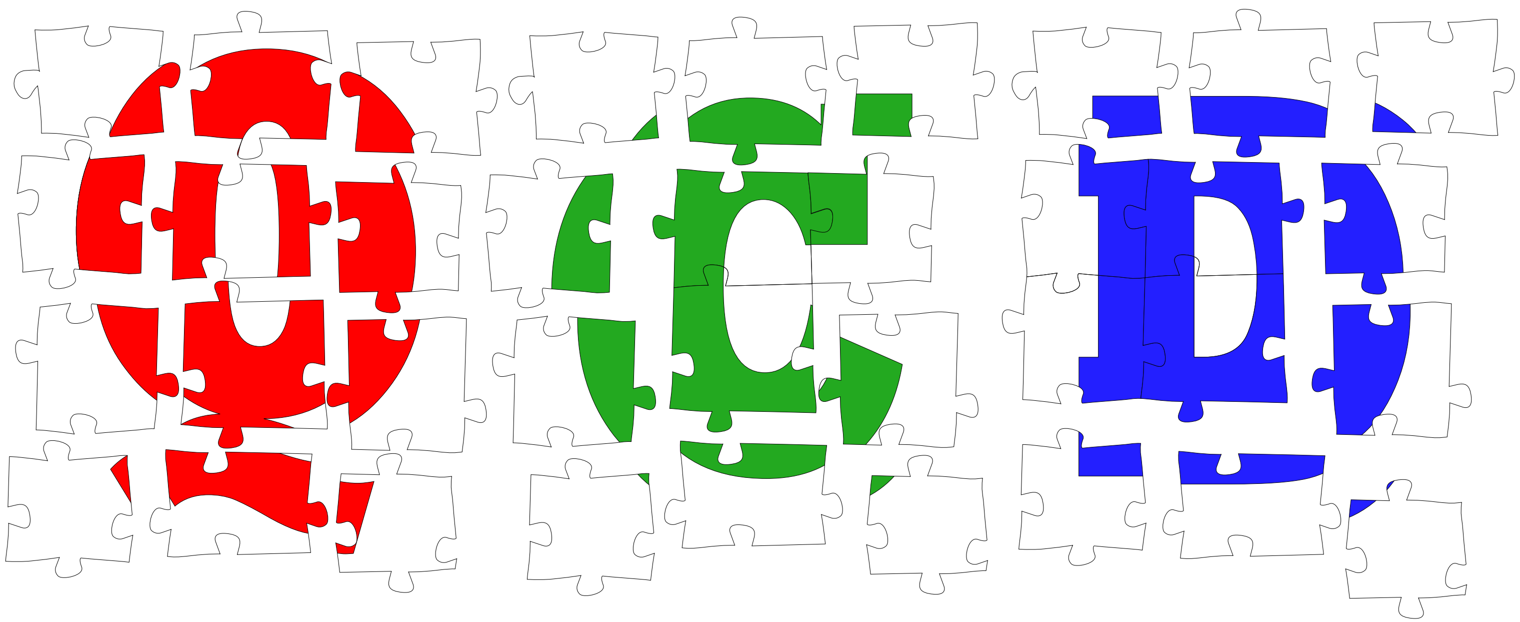




At large momenta, the weak QCD coupling (asymptotic freedom!) enables systematic computations

Are we done?

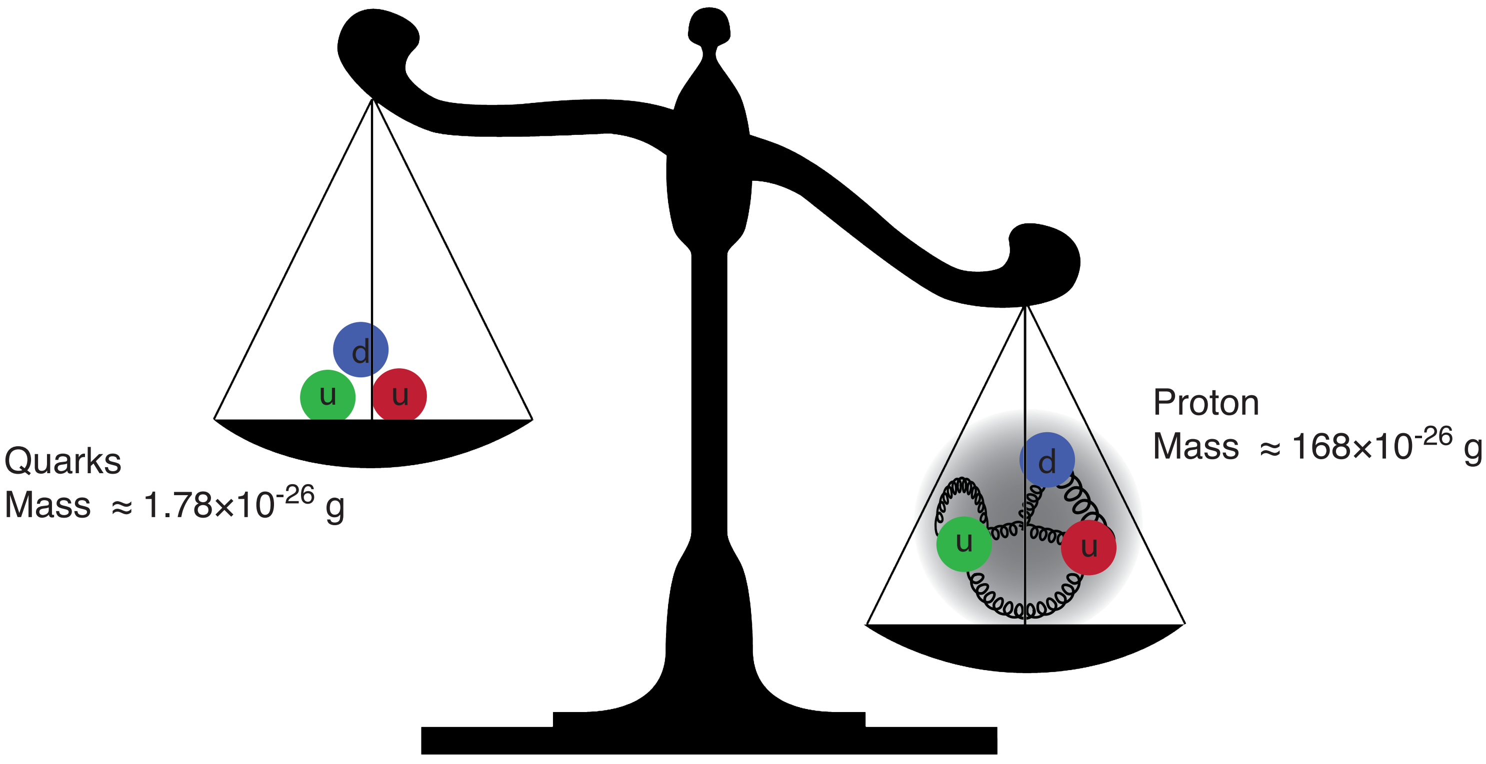
The Frontiers of Our Ignorance



... 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 how?

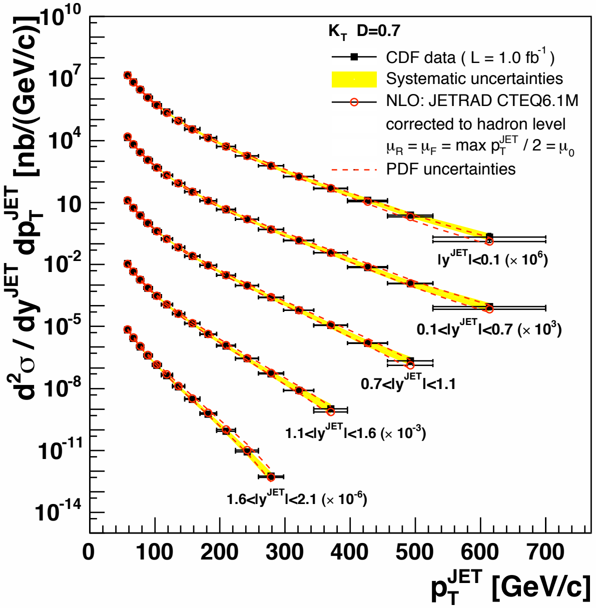
Scattering in the Strong Interactions

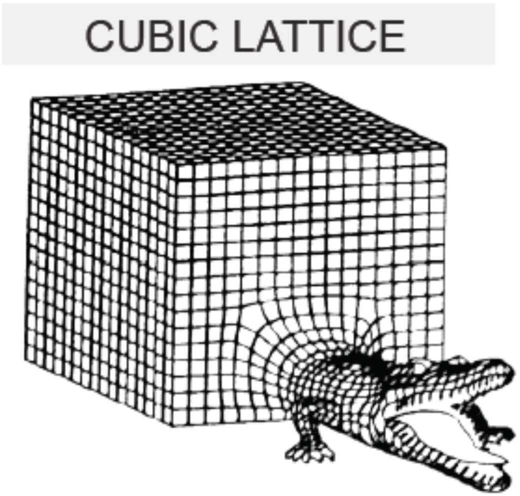
Perturbative QCD:

- 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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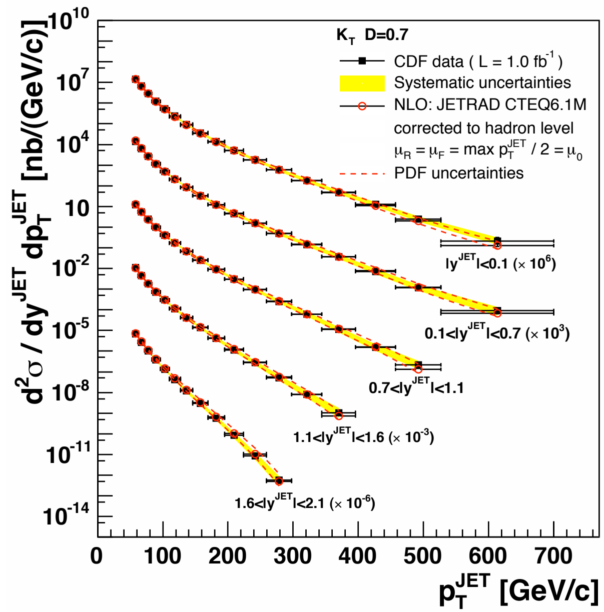
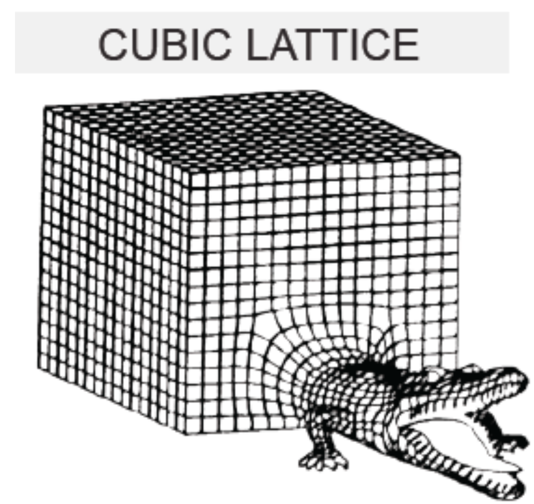
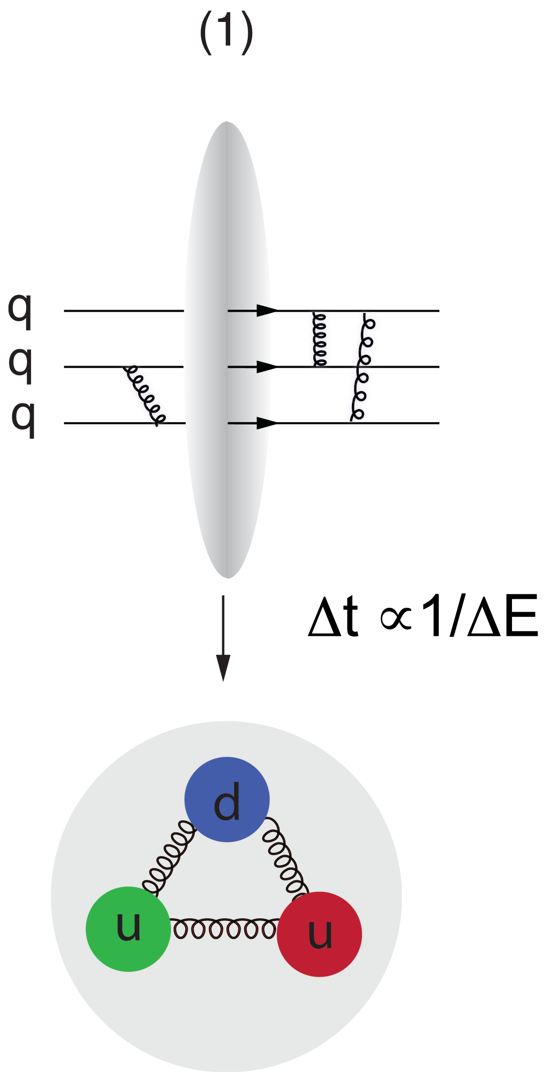


Instead ⇒ Effective theories:

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



A Look Inside the Boosted Proton



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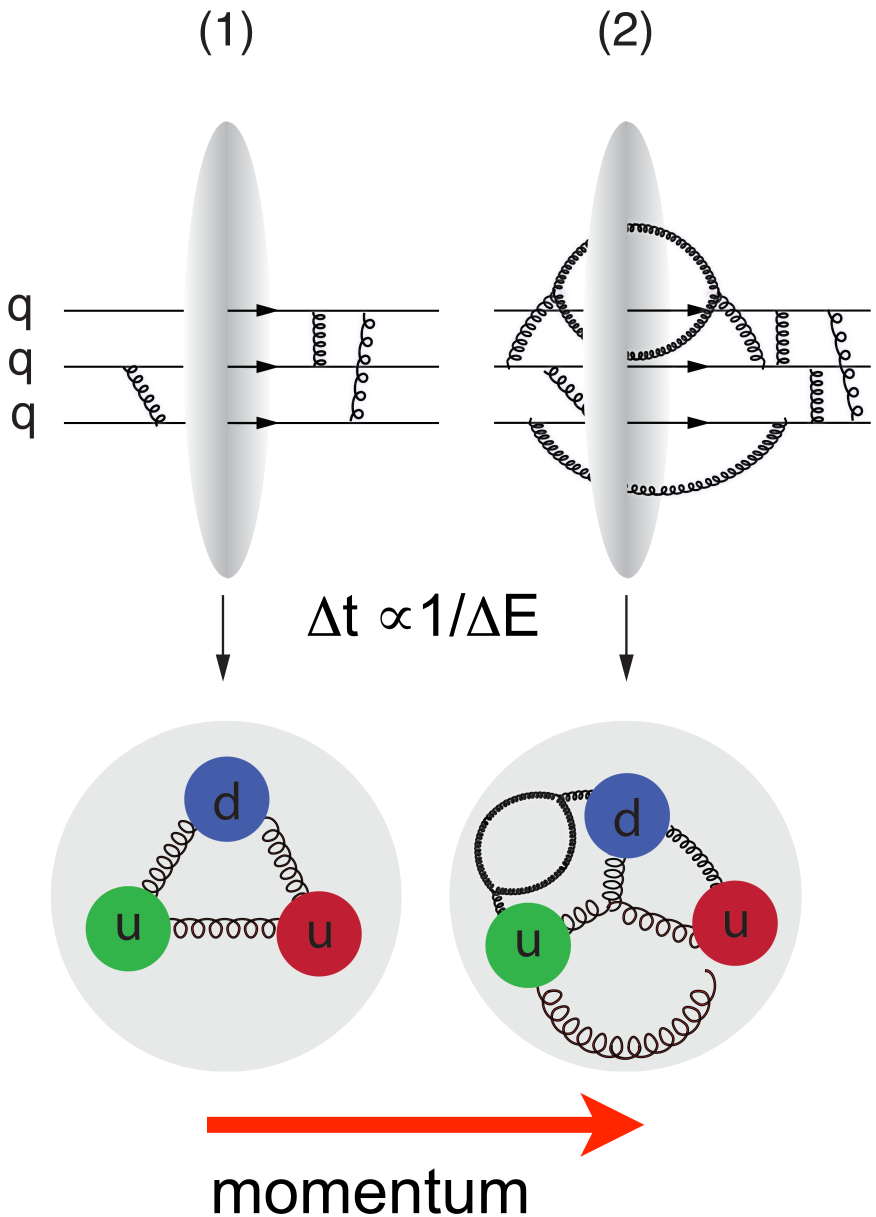

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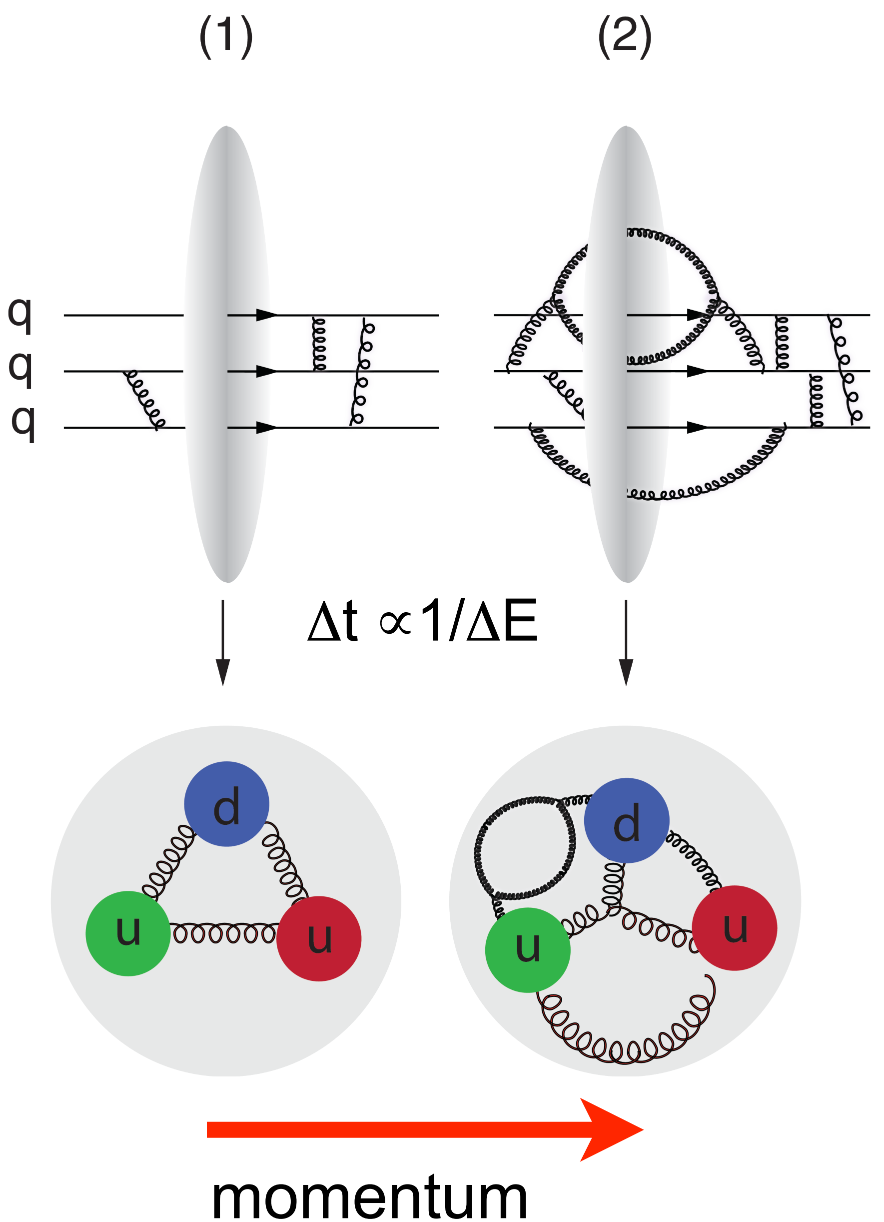
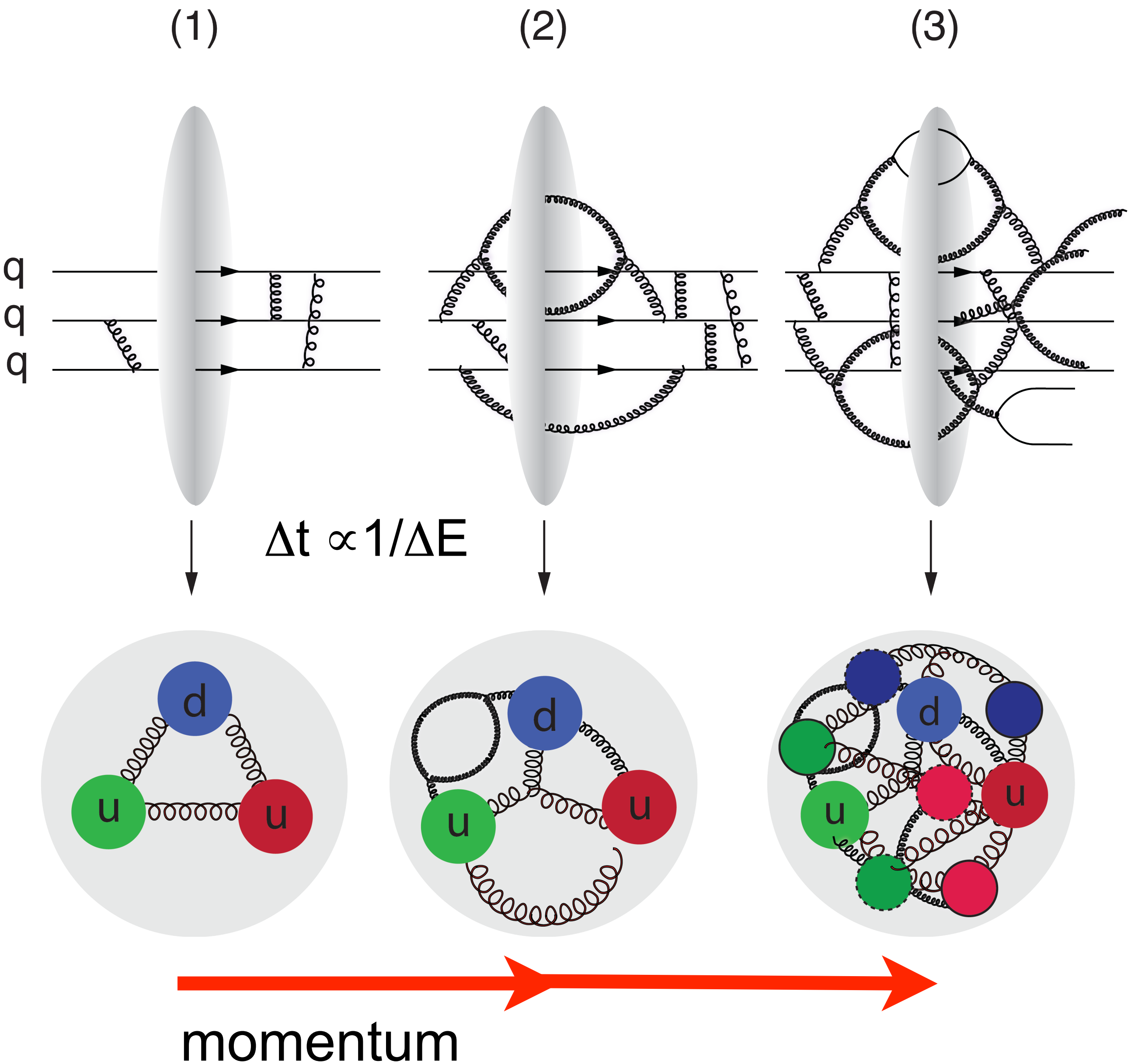


In QCD, the proton is made up of quanta that fluctuate in and out of existence

- 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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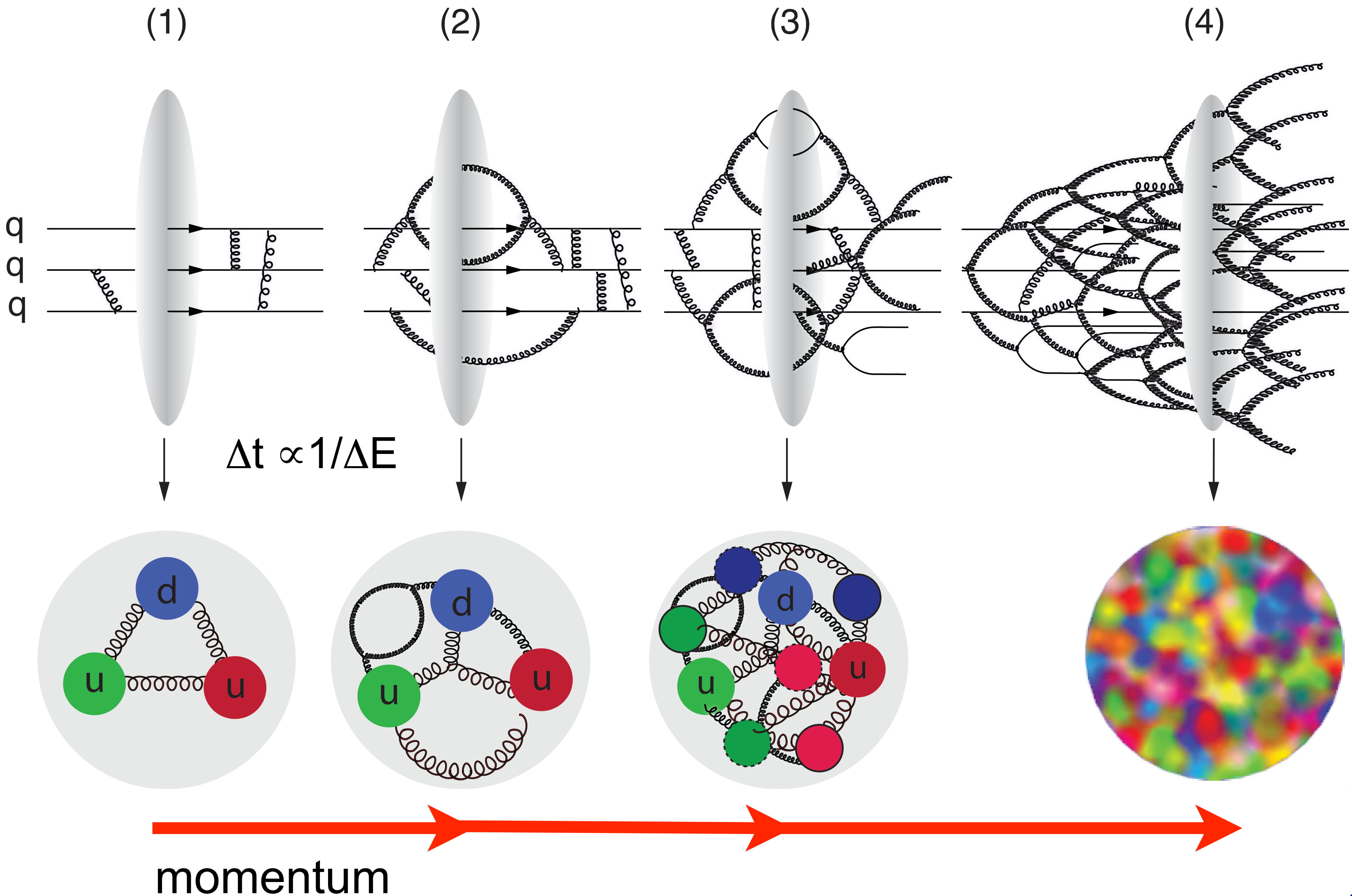

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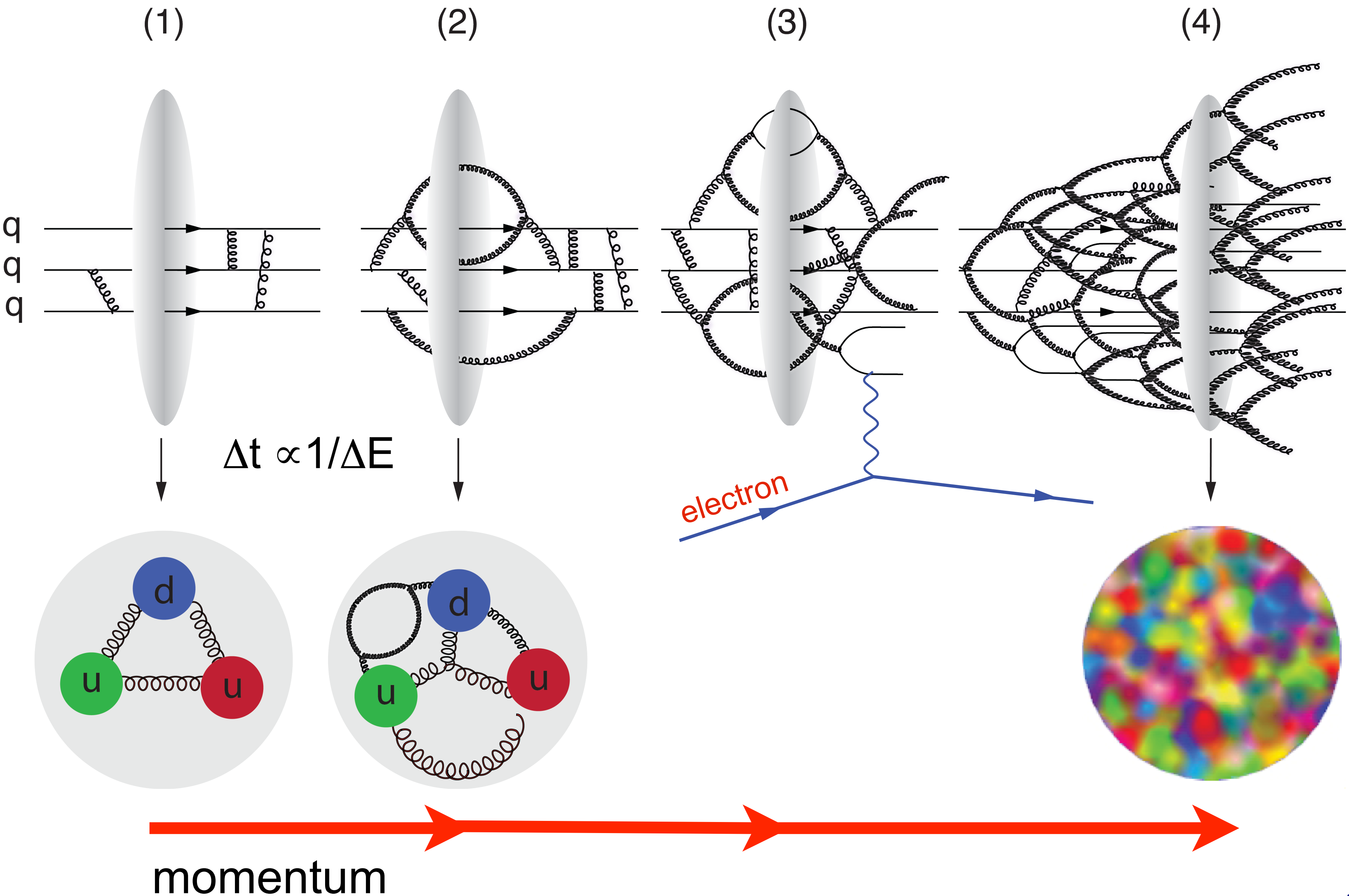
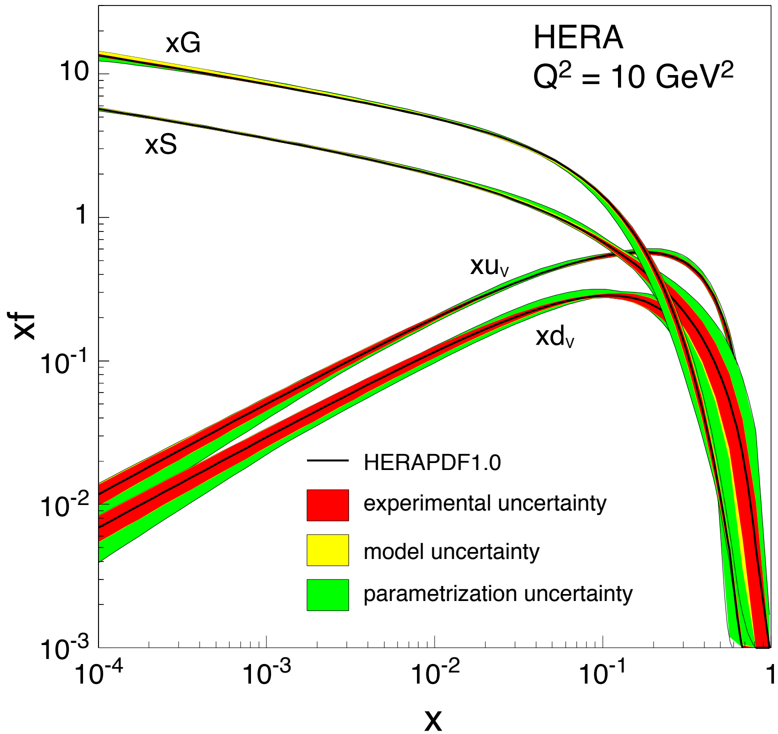


A Look Inside the Boosted Proton

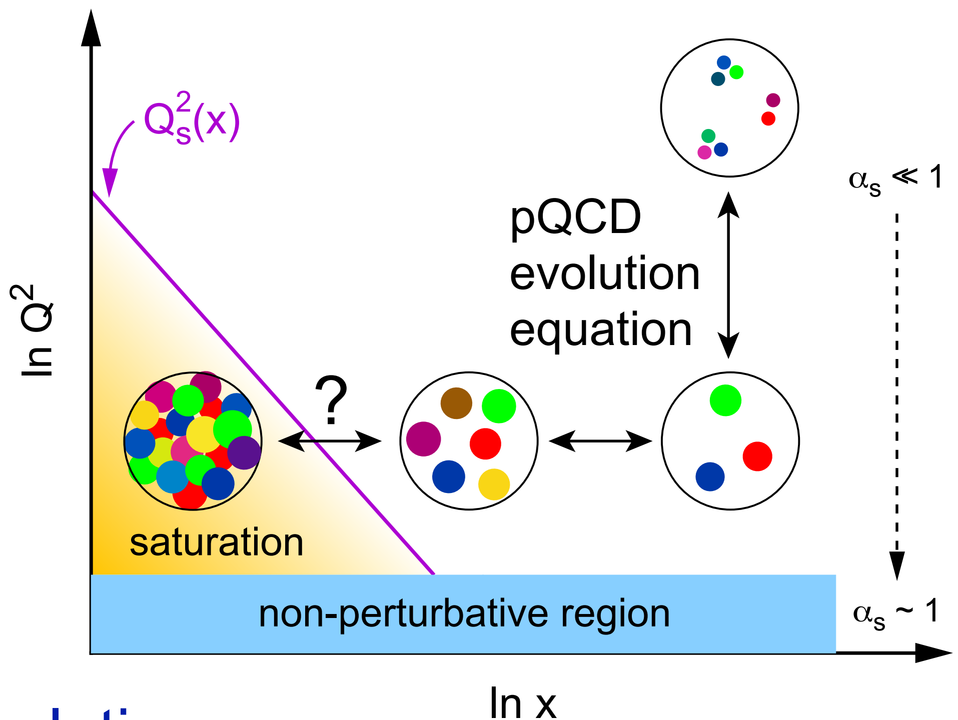
Gluon Saturation (I)

Is the proton a runaway popcorn machine at high energies ?



Explosion of gluon density violates unitarity!

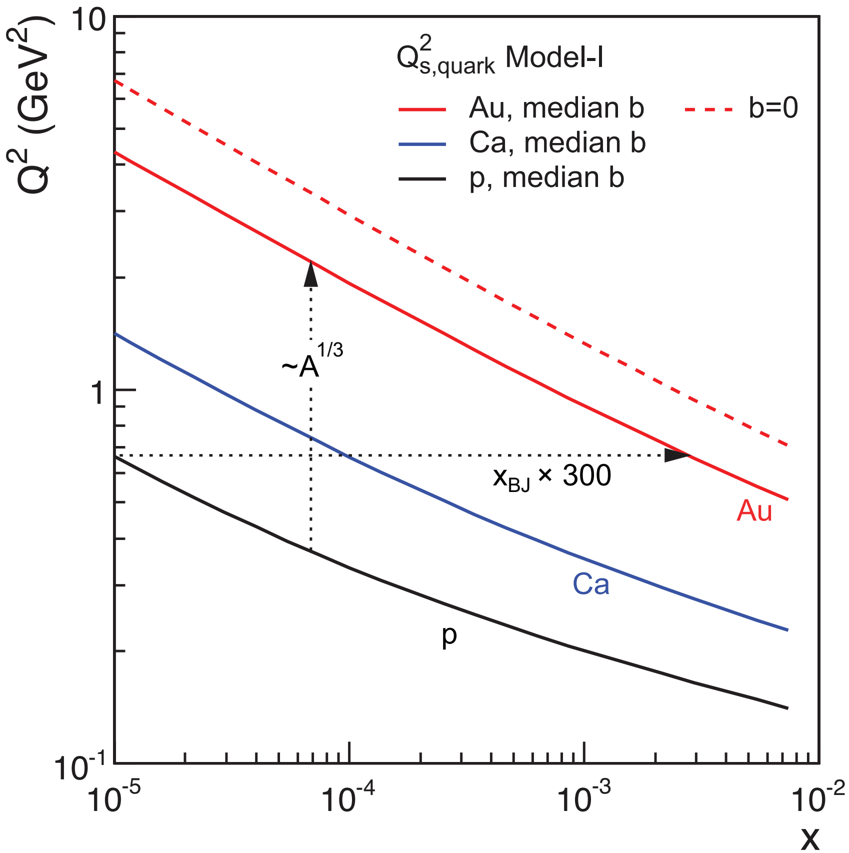
Cross-sections must be finite

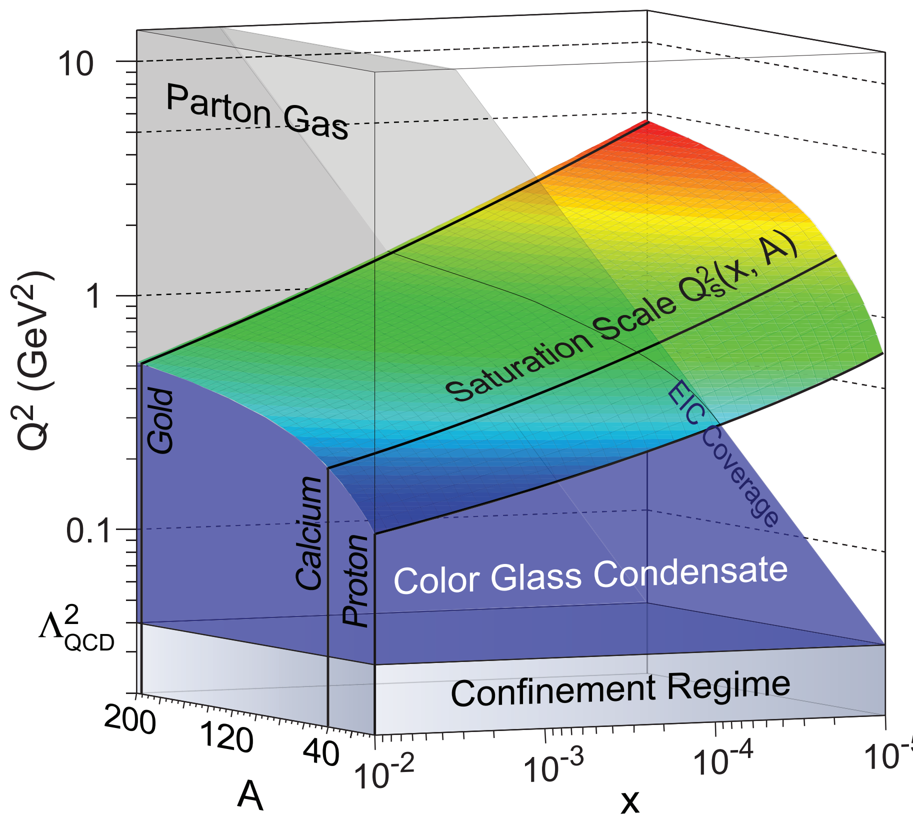


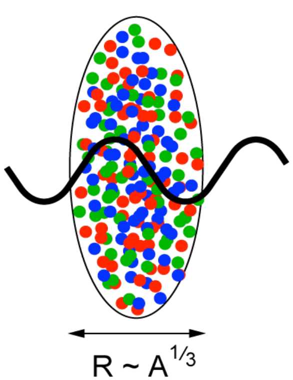
New Approach: Non-Linear Evolution

- Recombination compensates gluon splitting
- New evolution equations at low-x & low to moderate Q^2
- Saturation of gluon densities characterized by scale $Q_s(x)$

Gluon Saturation (II)





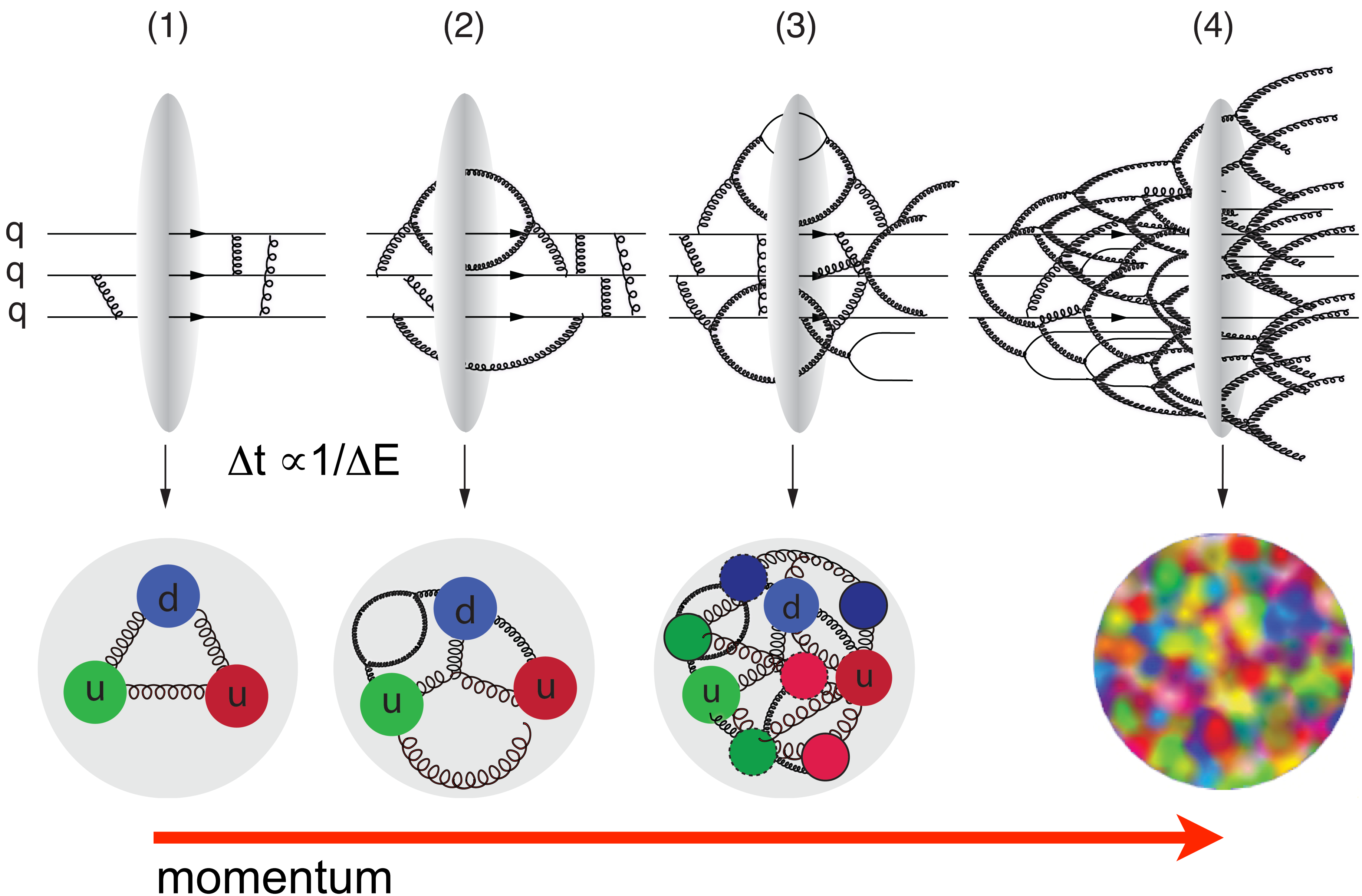


$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A:

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

A Look Inside the “Saturated” Proton



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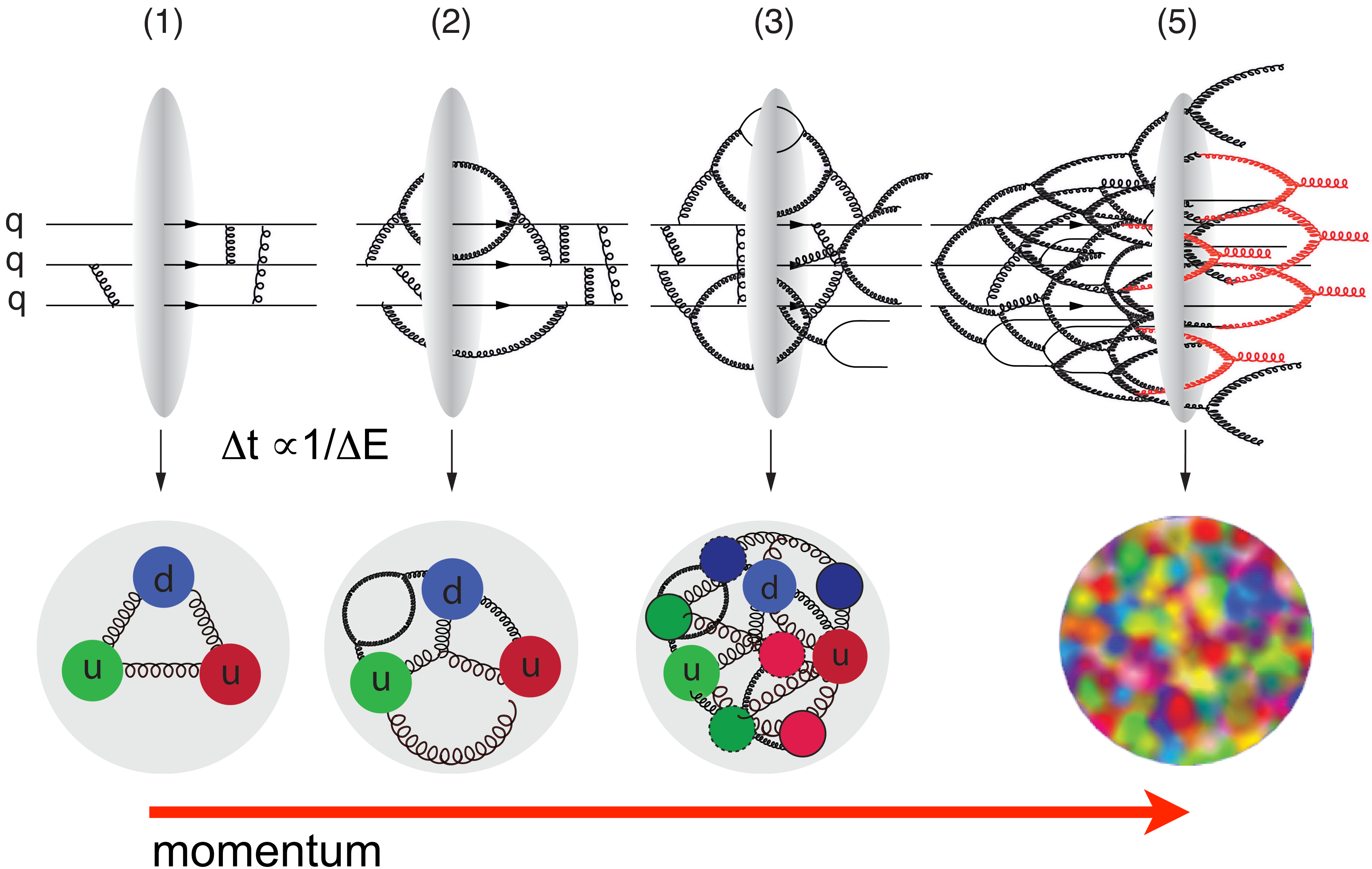

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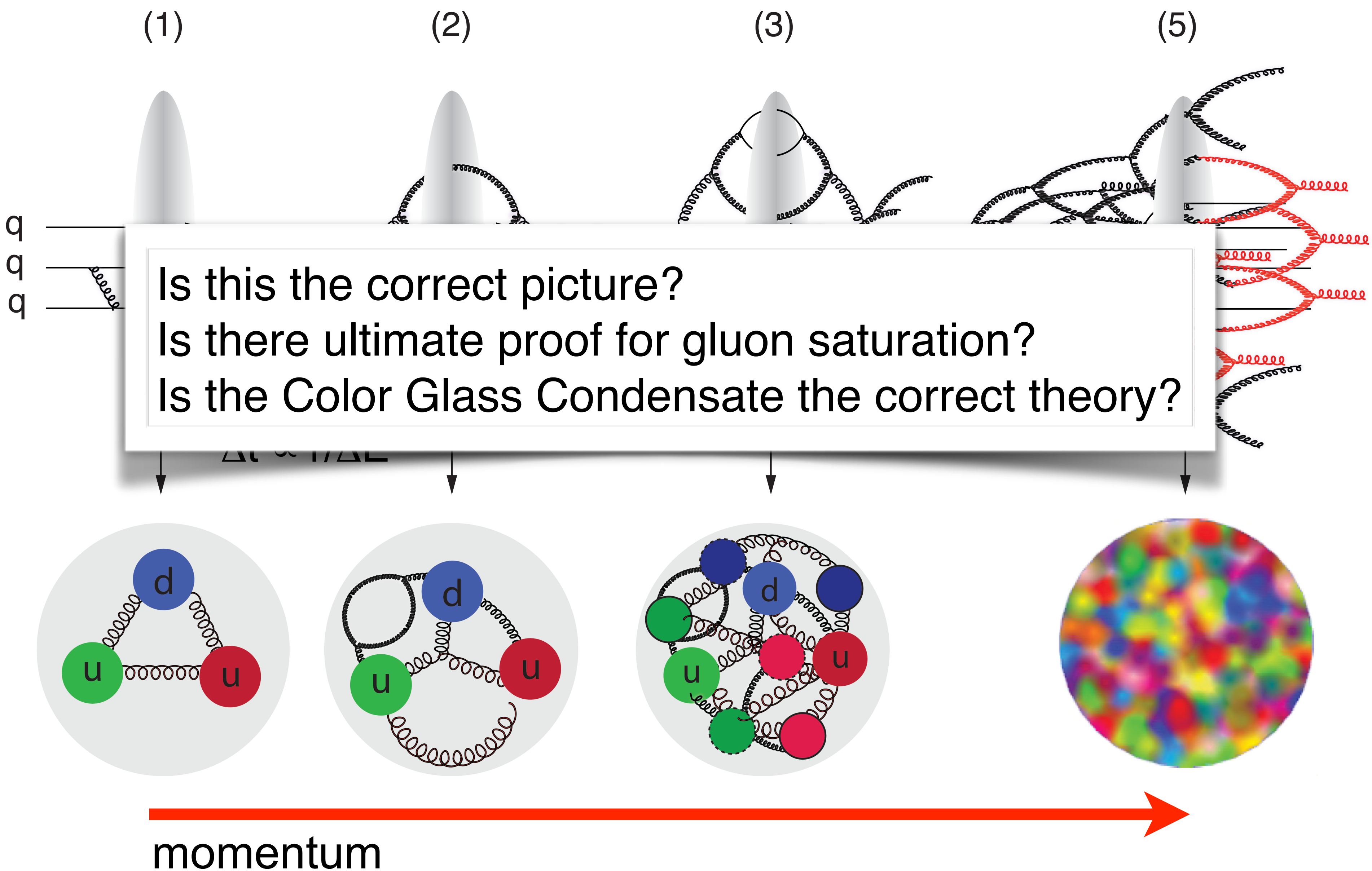
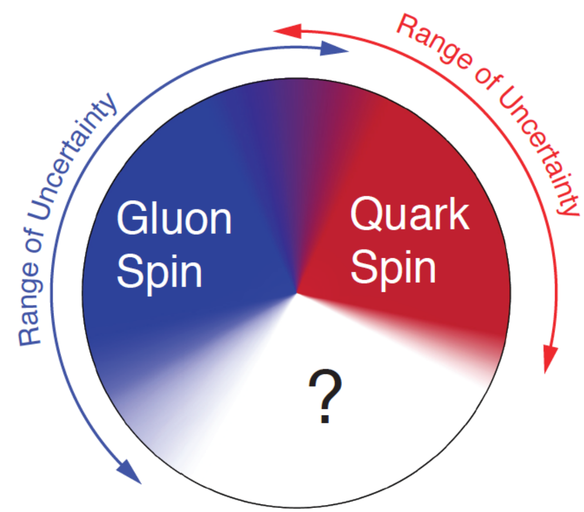


Is this the correct picture?
Is there ultimate proof for gluon saturation?
Is the Color Glass Condensate the correct theory?

Key Topic in ep: Proton Spin Puzzle

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



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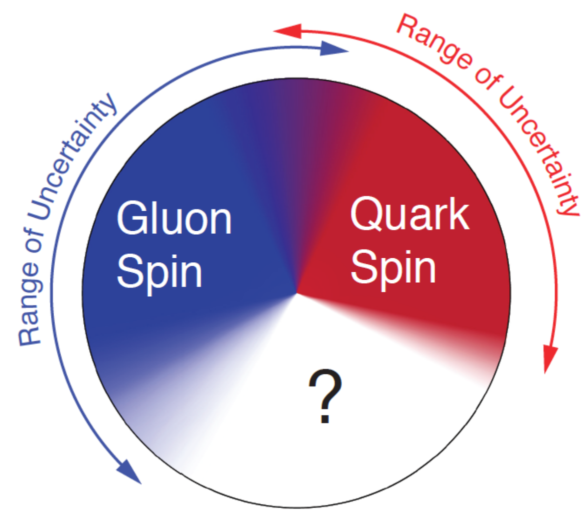

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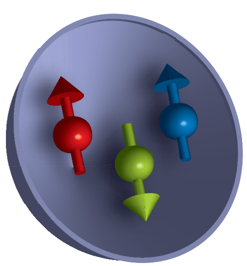
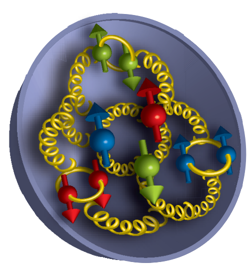
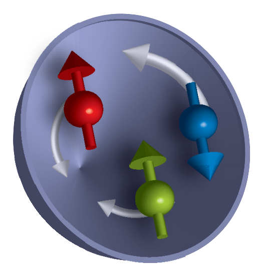
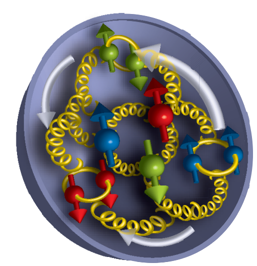
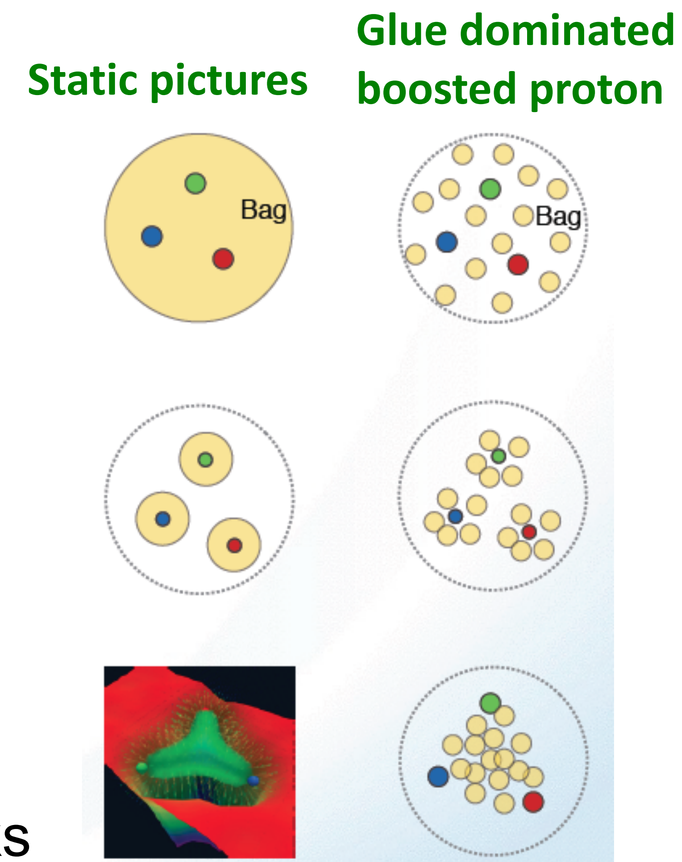
It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

	Spin of Quarks		Spin of Gluons		Angular Momentum of Quarks		Angular Momentum of Gluons
½ =		+		+		+	

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?



- Bag Model:
  - Field energy distribution is wider than the distribution of fas moving light quarks
- Constituent Quark Model:
  - Gluons hide inside massive quarks
  - Distribution similar to valence quark distribution
- Lattice Gauge Theory:
  - (with slow moving quarks)
  - gluons are more concentrated than quarks

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?

3D Imaging:

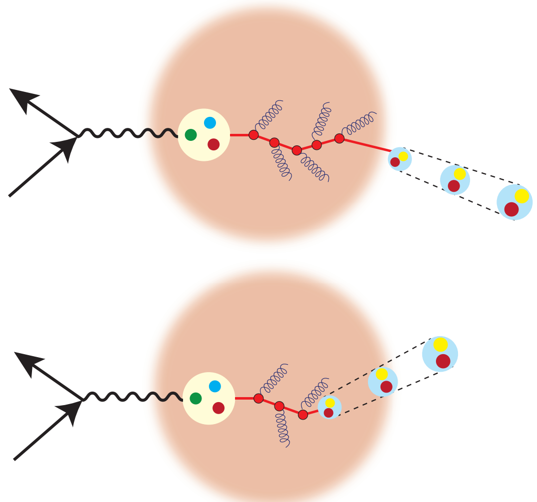
- **Transverse Momentum Distributions (TMDs):**
  - 2D+1 picture in momentum space (k_T)
- **Generalized Parton Distributions (GPDs):**
  - 2D+1 picture in coordinate space (b_T)

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

Electron-Ion Collider

Investigate with precision universal dynamics of gluons

Central themes:

- Probing the momentum-dependence of gluon densities and the onset of saturation in nucleons and nuclei
- Mapping the transverse spatial and spin distributions of partons in the gluon-dominated regime
- Provide novel insight into propagation, attenuation and hadronization of colored probes

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Ultimate QCD machine:

- The world's first polarized electron-polarized proton collider
- The world's first electron-heavy ion collider
- Luminosities: a hundred to up to a thousand times HERA
- Fine resolution inside proton down to 10^{-18} meters

US Electron Collider: Accelerator Designs

- **eRHIC (BNL)**
  - Add ERL+FFAG Recirculating e Rings to RHIC facility
  - Electrons up to 21.2 GeV
  - Protons up to 255 GeV
  - Ions (Au) up to 100 GeV/u
  - $L \approx 4\times10^{33}$ cm^{-2} s^{-1} ($\sqrt{s}$=126 GeV)

- **MEIC (JLab)**
  - Figure-8 Ring-Ring Collider, use of CEBAF
  - Electrons 3-12 GeV
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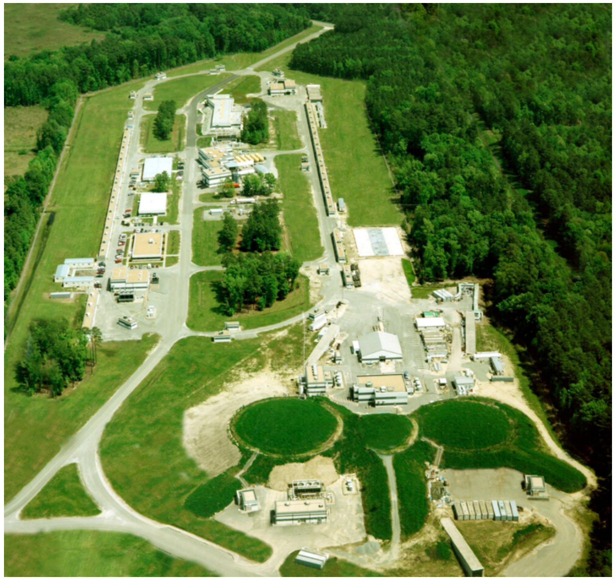
  - $L \approx 2.4\times10^{34}$ cm^{-2} s^{-1}/A ($\sqrt{s}$=22 GeV)



eRHIC: arXiv:1409.1633, MEIC: arXiv:1209.0757

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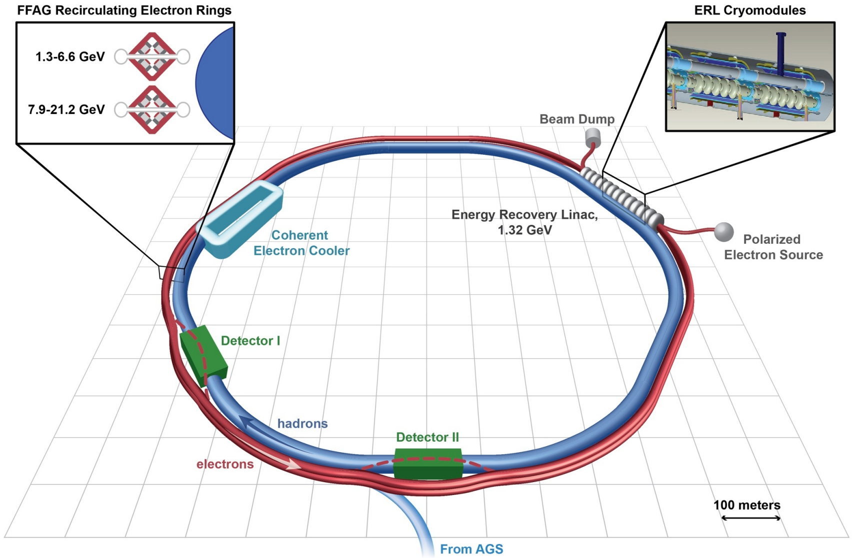

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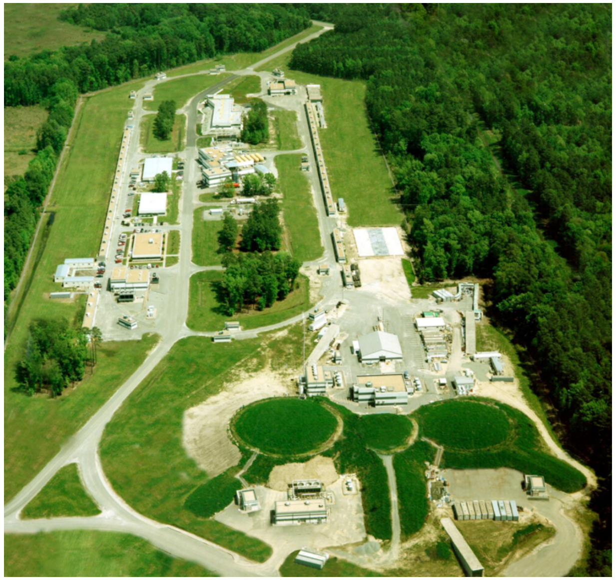

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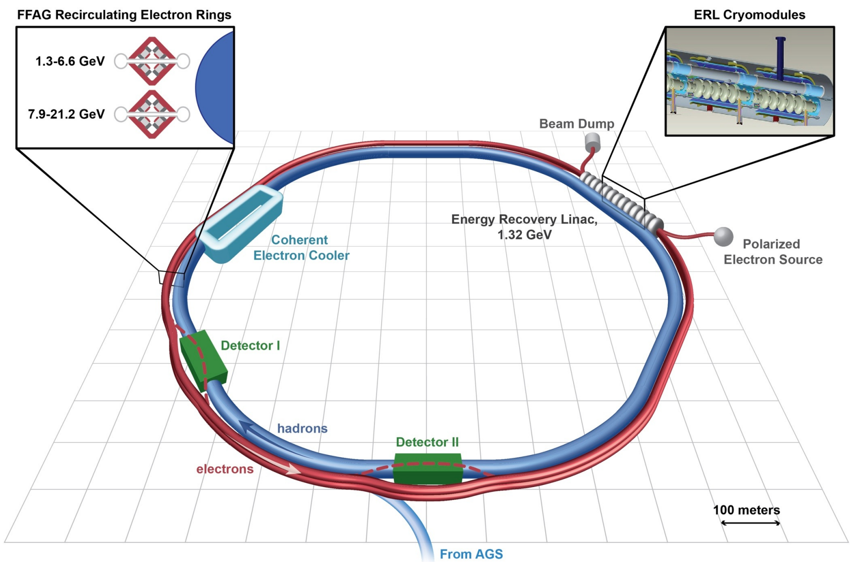

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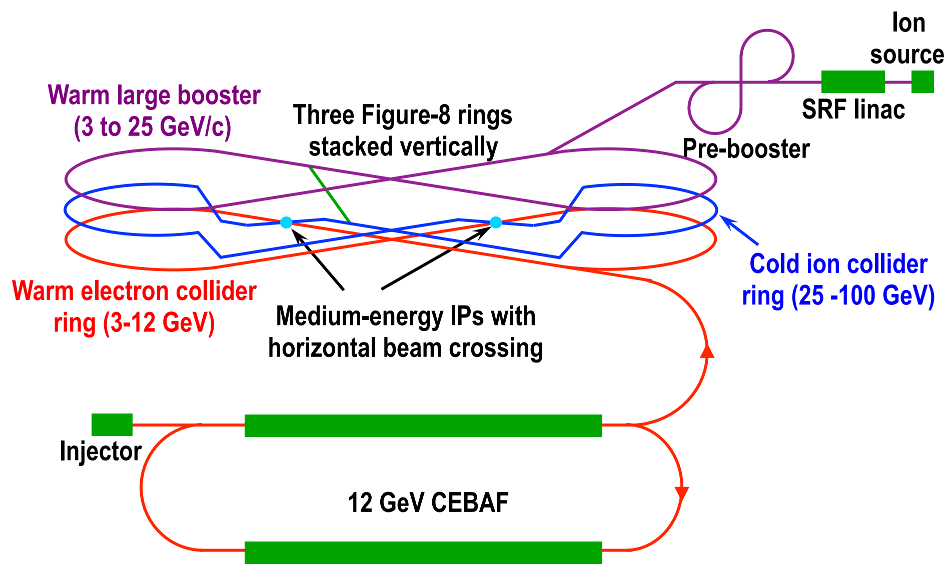

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Examples of Key Measurements at an EIC

EIC: Longitudinal Spin of the Proton (I)

Inclusive Measurement:
e+p → e′+X

$$\frac{1}{2}\left[\frac{\mathrm{d}^2\sigma^{\rightleftarrows}}{\mathrm{d}x\,\mathrm{d}Q^2} - \frac{\mathrm{d}^2\sigma^{\rightrightarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}\right] \simeq \frac{4\pi\,\alpha^2}{Q^4} y\,(2-y)\,g_1(x,Q^2)$$

Leading Order:

$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\,\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

$$\Delta\Sigma(Q^2) = \int_0^1 dx\;g_1(x,Q^2)$$ (Quark Spin)

Higher Order:

$$\frac{dg_1}{d\log Q^2} \propto \Delta g(x,Q^2)$$ (Gluon Spin)

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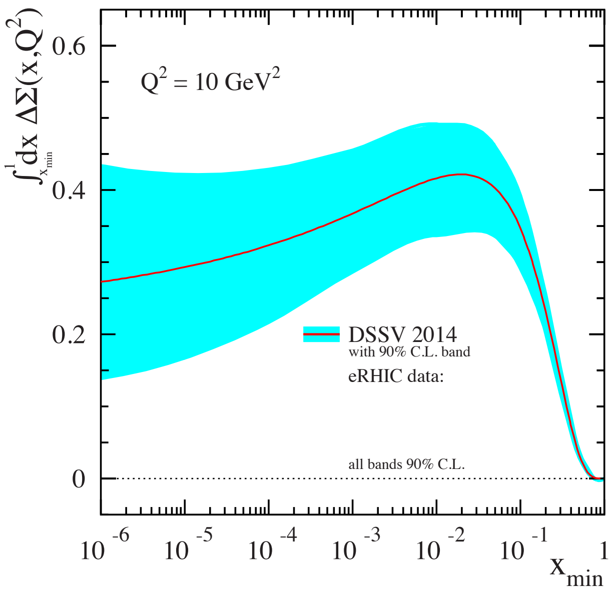
Quark Spin



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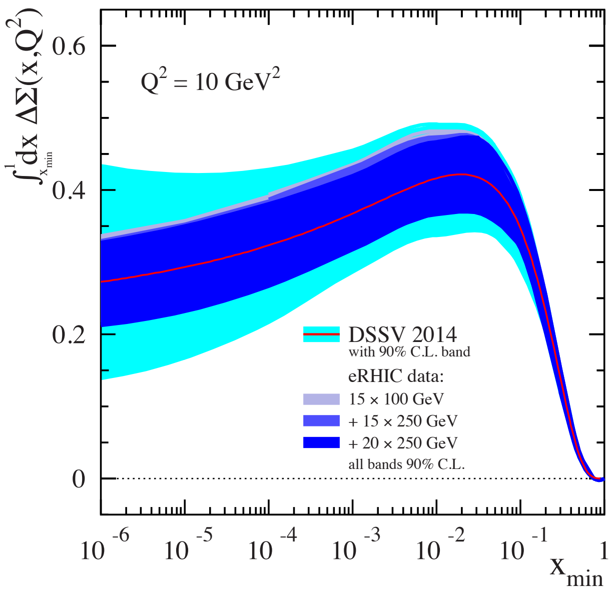
Quark Spin



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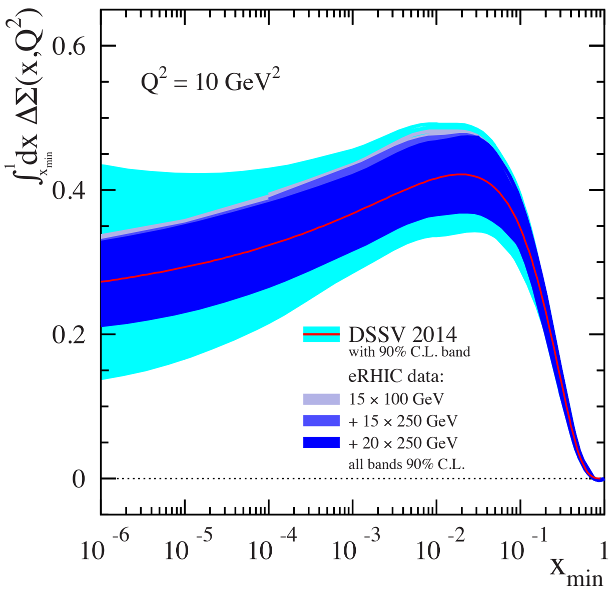
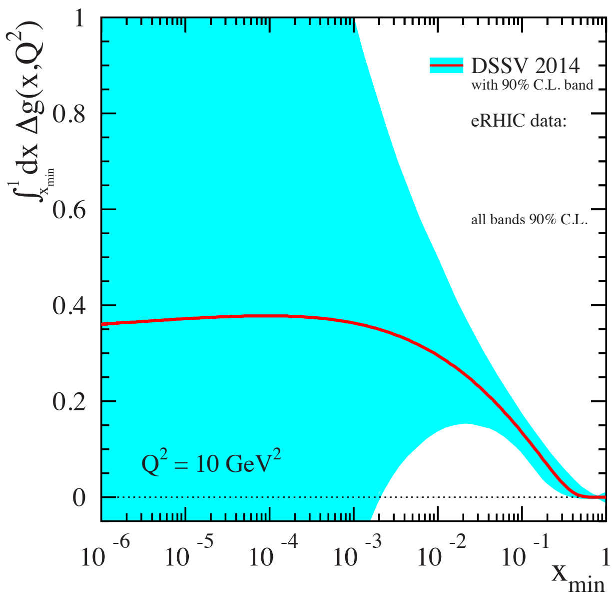
Quark Spin



Gluon Spin

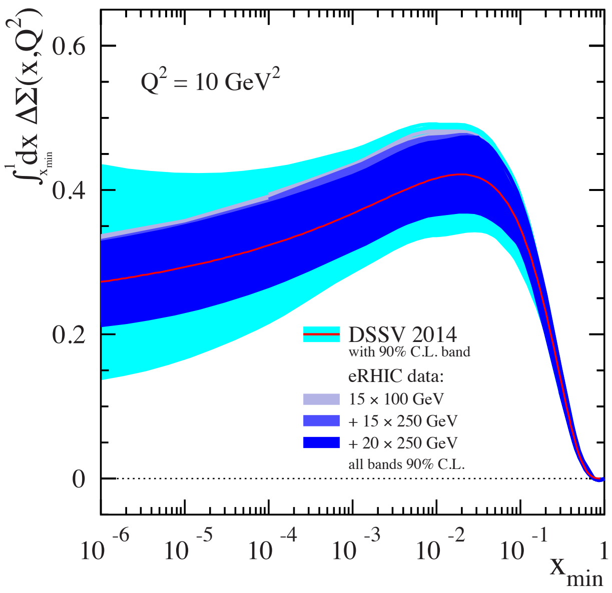


EIC: Longitudinal Spin of the Proton (I)

Inclusive Measurement:
e+p → e′+X

$$\frac{1}{2}\left[\frac{\mathrm{d}^2\sigma^{\rightleftarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}-\frac{\mathrm{d}^2\sigma^{\rightrightarrows}}{\mathrm{d}x\,\mathrm{d}Q^2}\right]\simeq\frac{4\pi\,\alpha^2}{Q^4}y\,(2-y)\,g_1(x,Q^2)$$

Quark Spin



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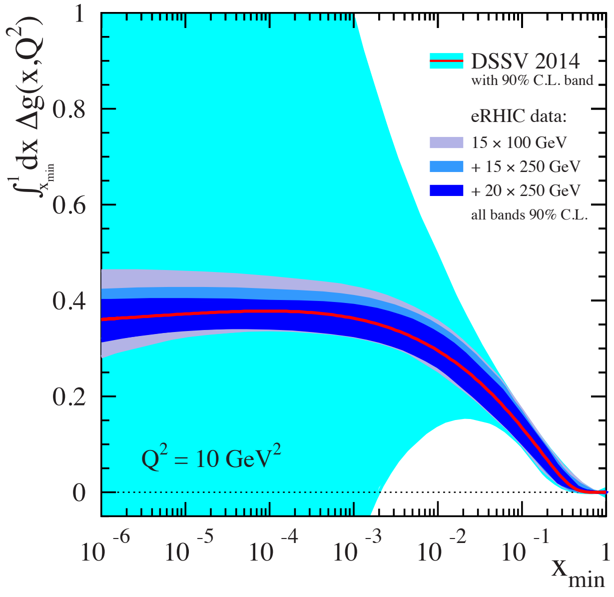

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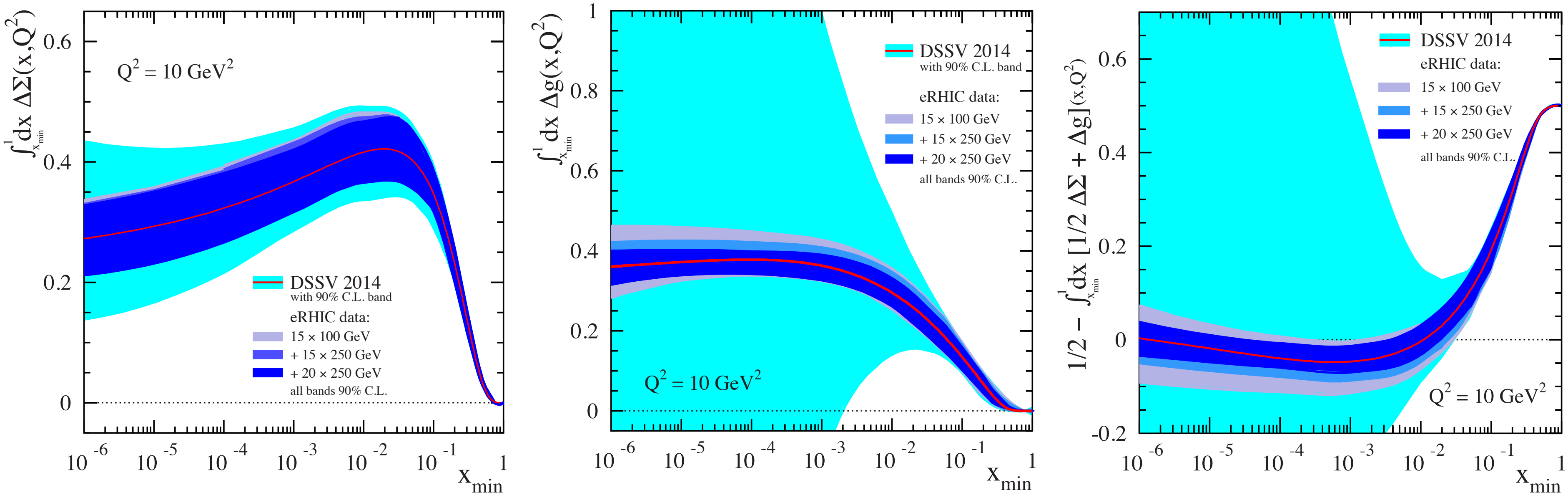
Quark Spin | Gluon Spin | ½-Gluon-Quark Spin



For $\int\mathcal{L}dt$ = 10 fb^{-1} and 70% polarization

Current knowledge (DSSV): uses strong theoretical constraints

EIC projections do not ⇒ test w/o assumptions

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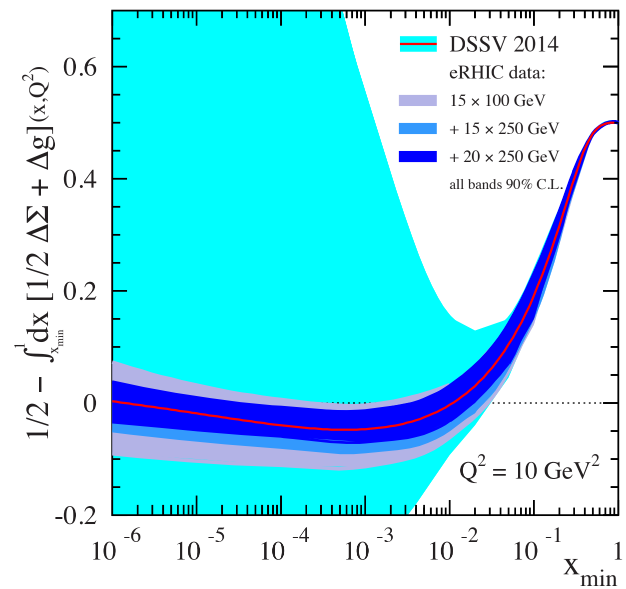
½-Gluon-Quark Spin

Combining information on ΔΣ and Δg constrains angular momentum



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EIC: Nuclear Structure Functions (I)

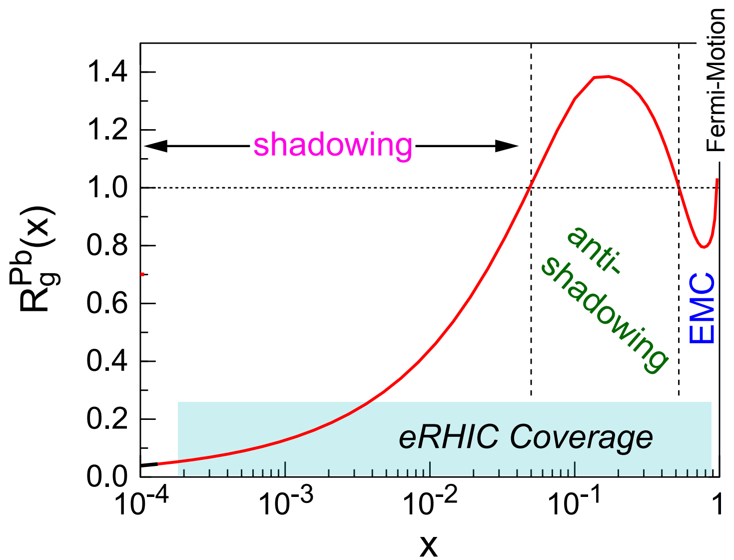
Inclusive DIS on eA:

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

quark+anti-quark **gluon**

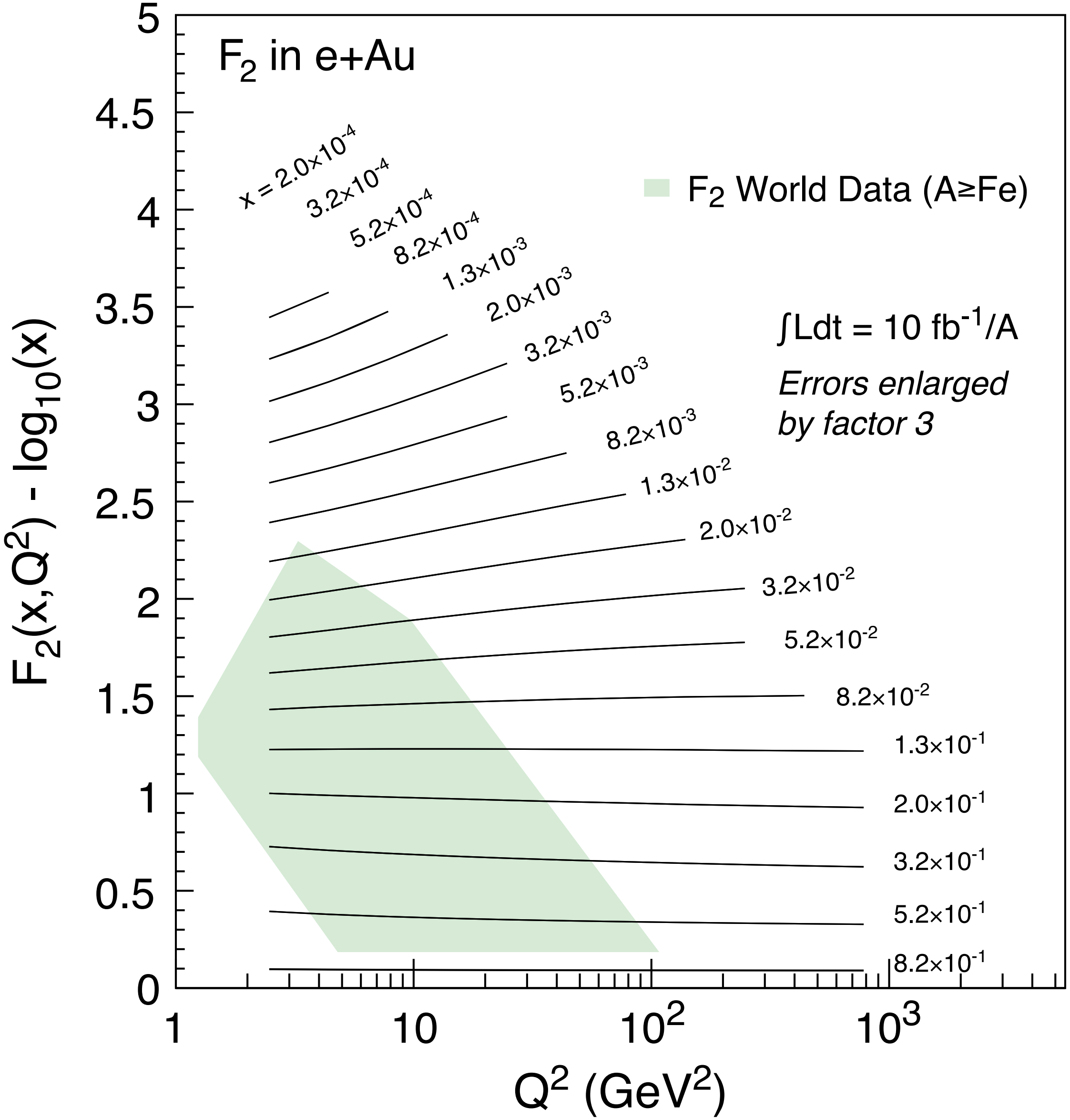
F_2 and F_L are benchmark measurements:
Theory/models have to be able to describe the structure functions and their evolution.

Leading twist pQCD models parameterize the observed suppression of the structure function with decreasing x using *nuclear parton distribution functions* (nPDFs)



Aim at extending our knowledge on structure functions into the realm where gluon saturation effects emerge

EIC: Nuclear Structure Functions (II)



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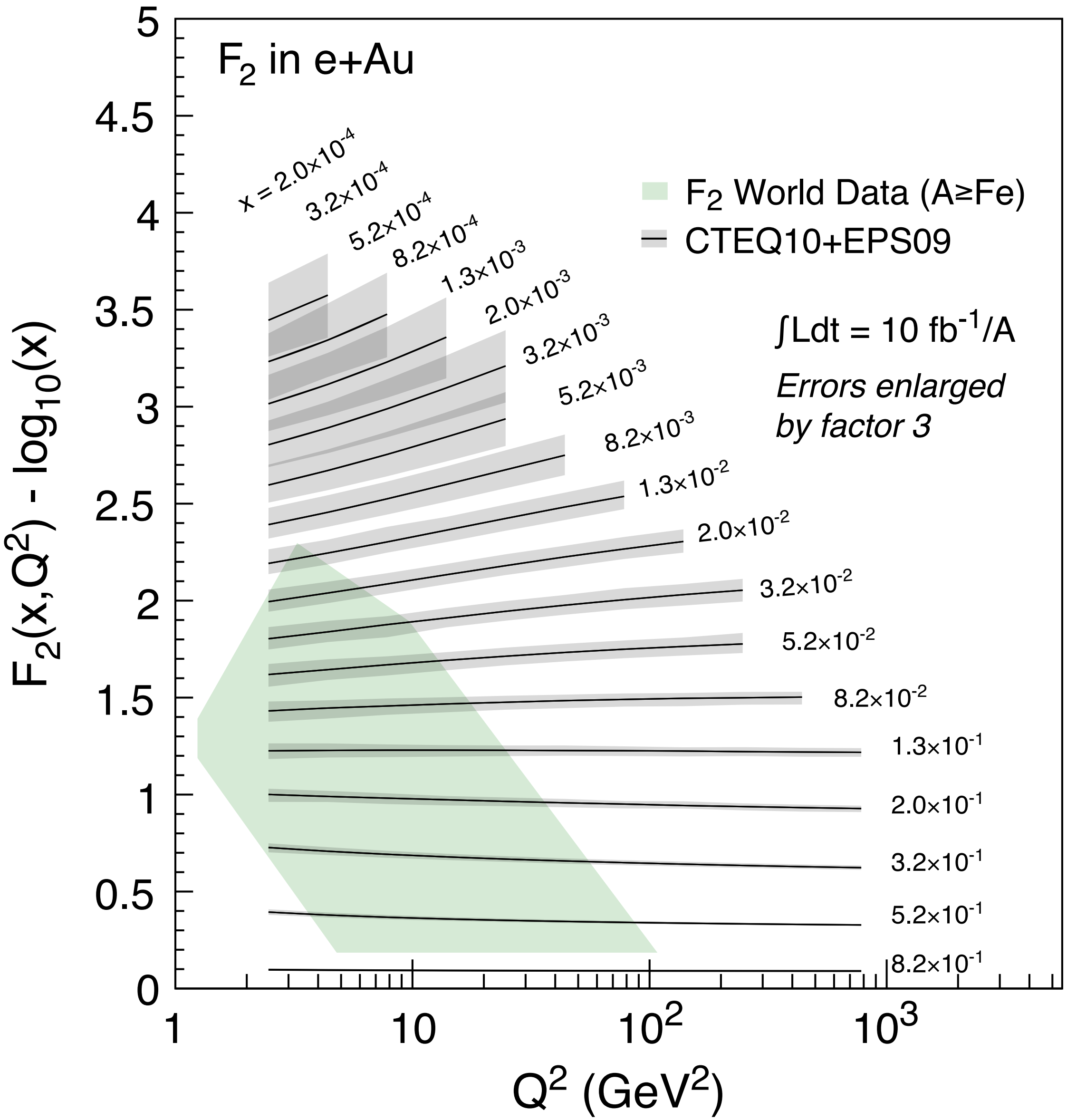

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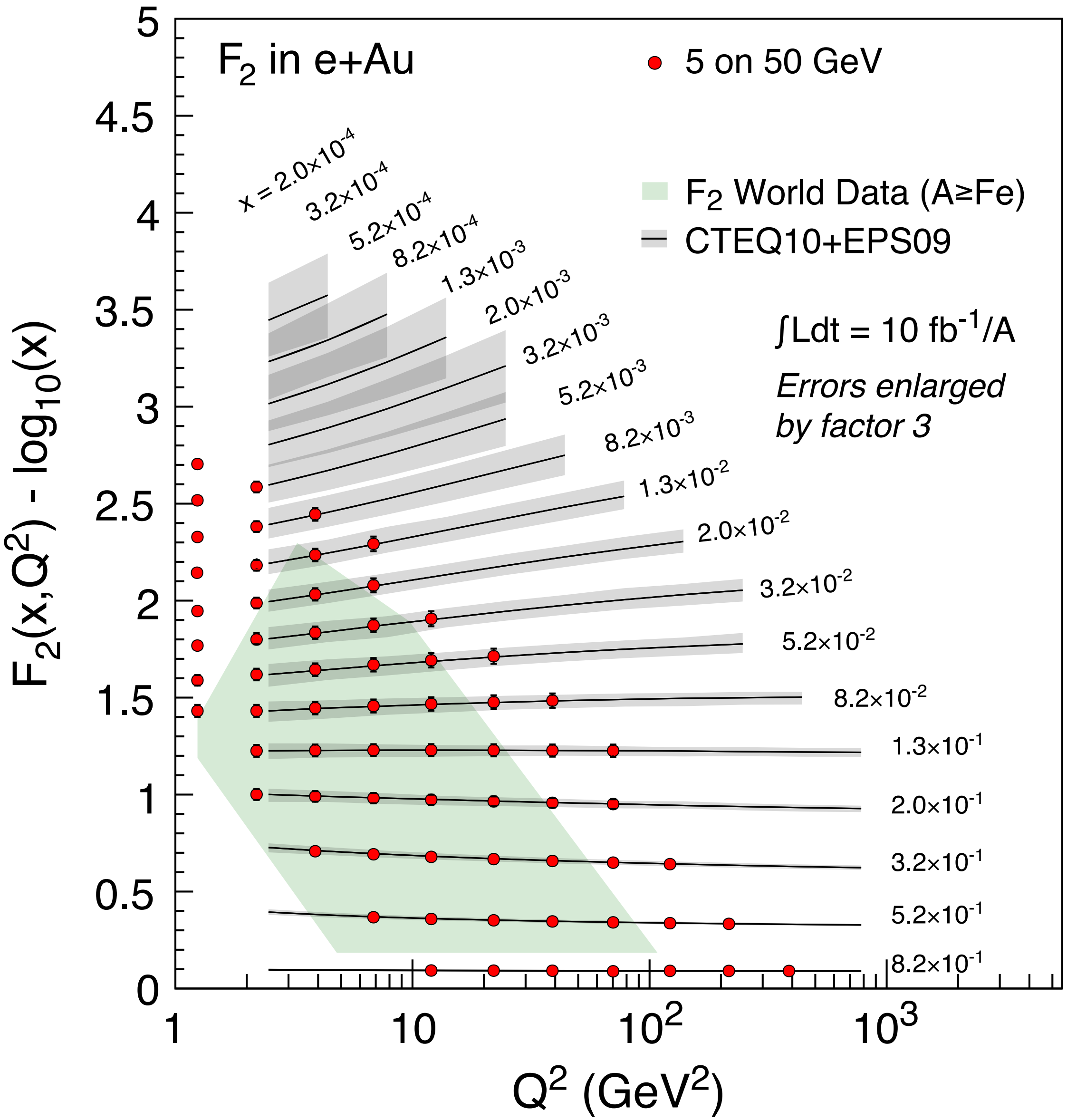

- Assume 3% systematic uncertainty
- Systematic uncertainties dominate, not $\mathcal{L}$ hungry

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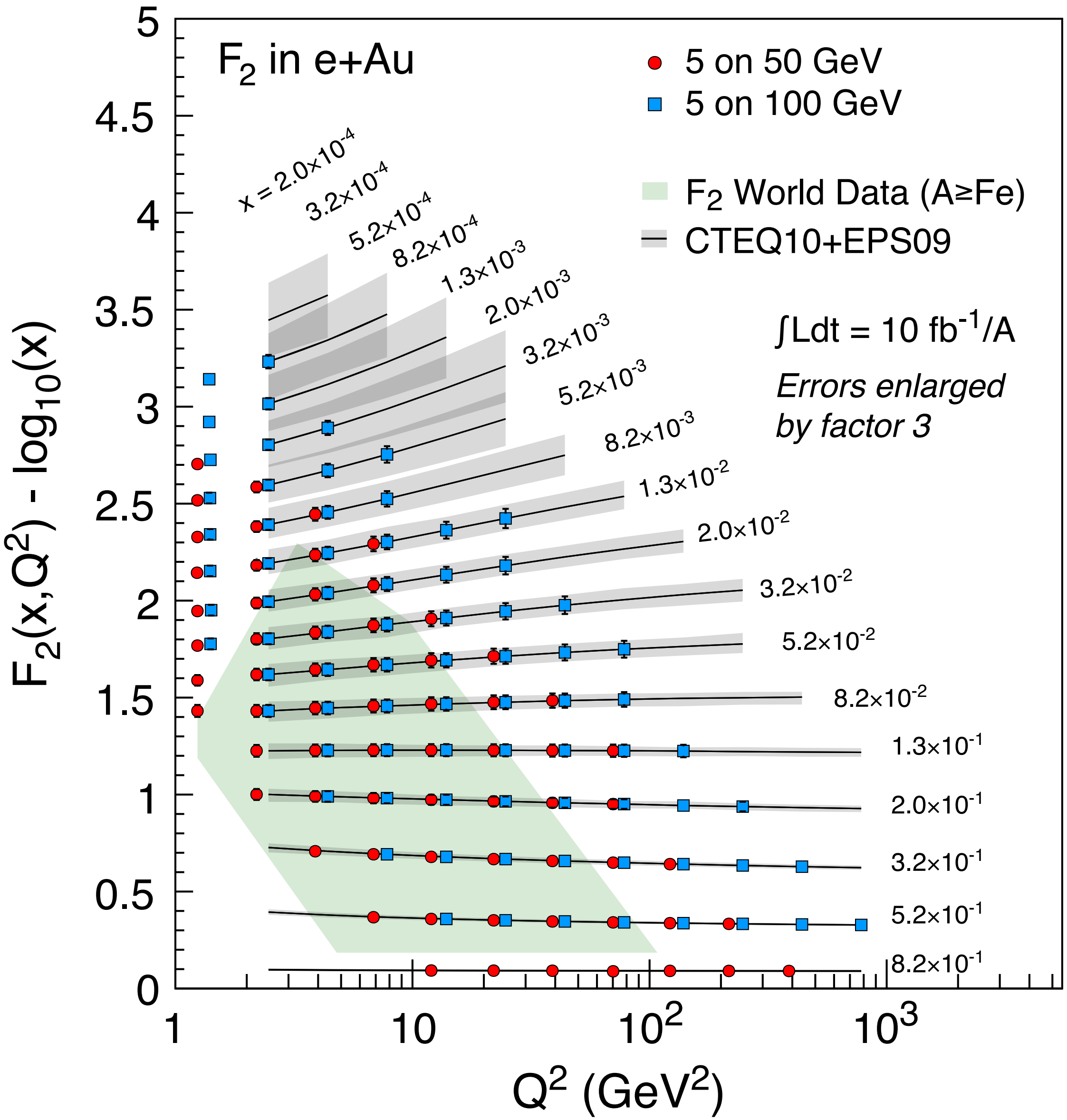

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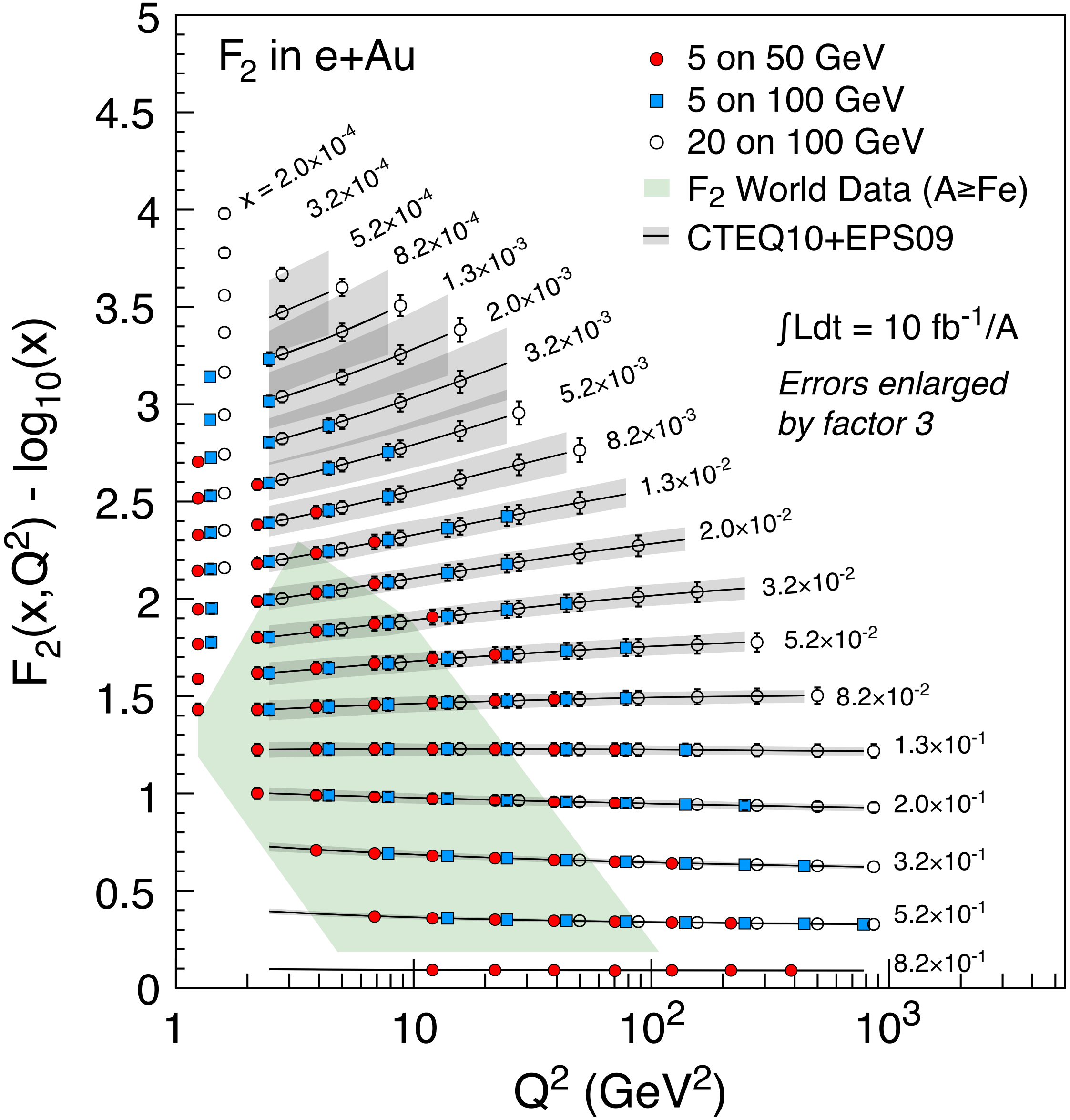

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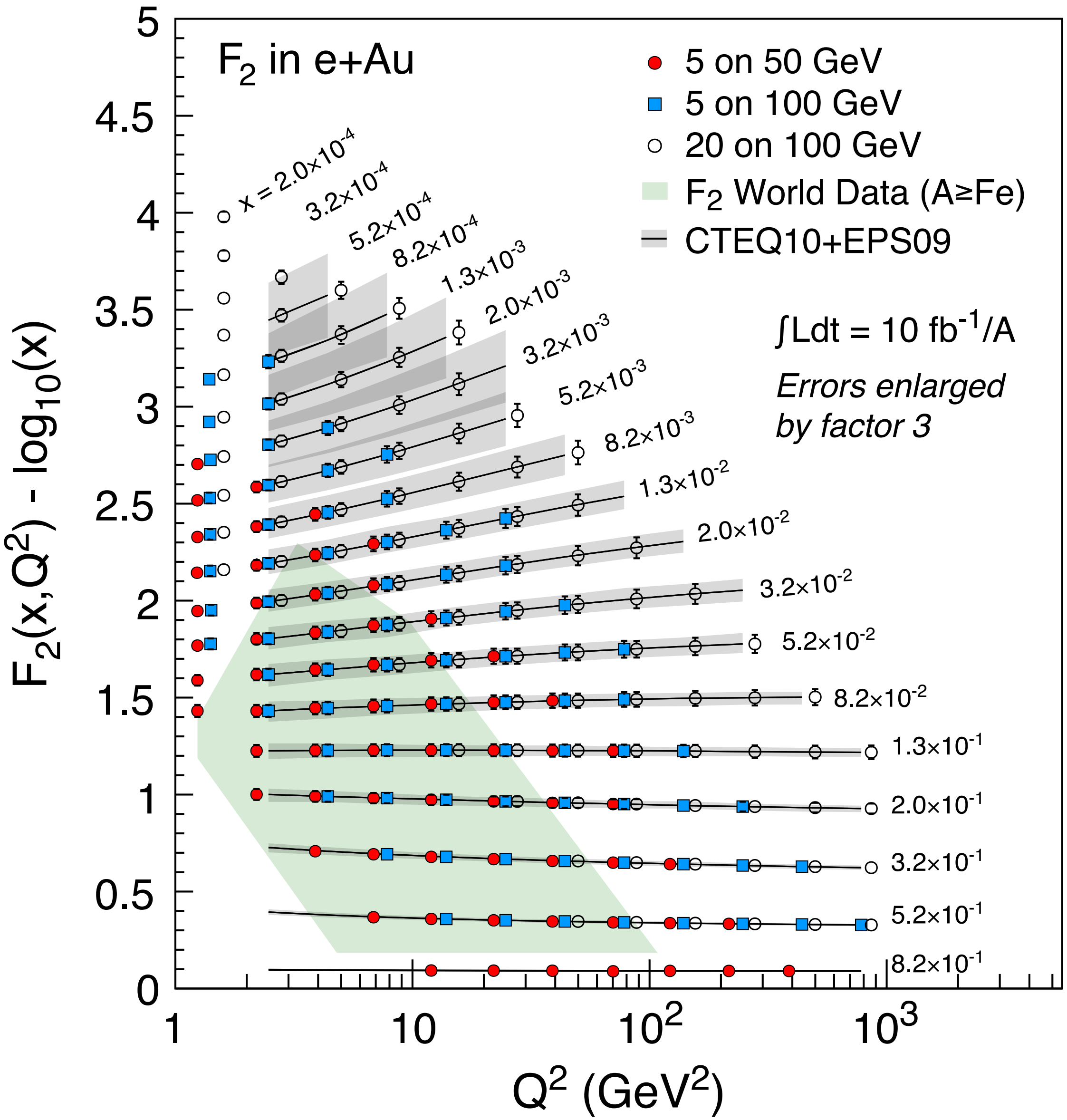

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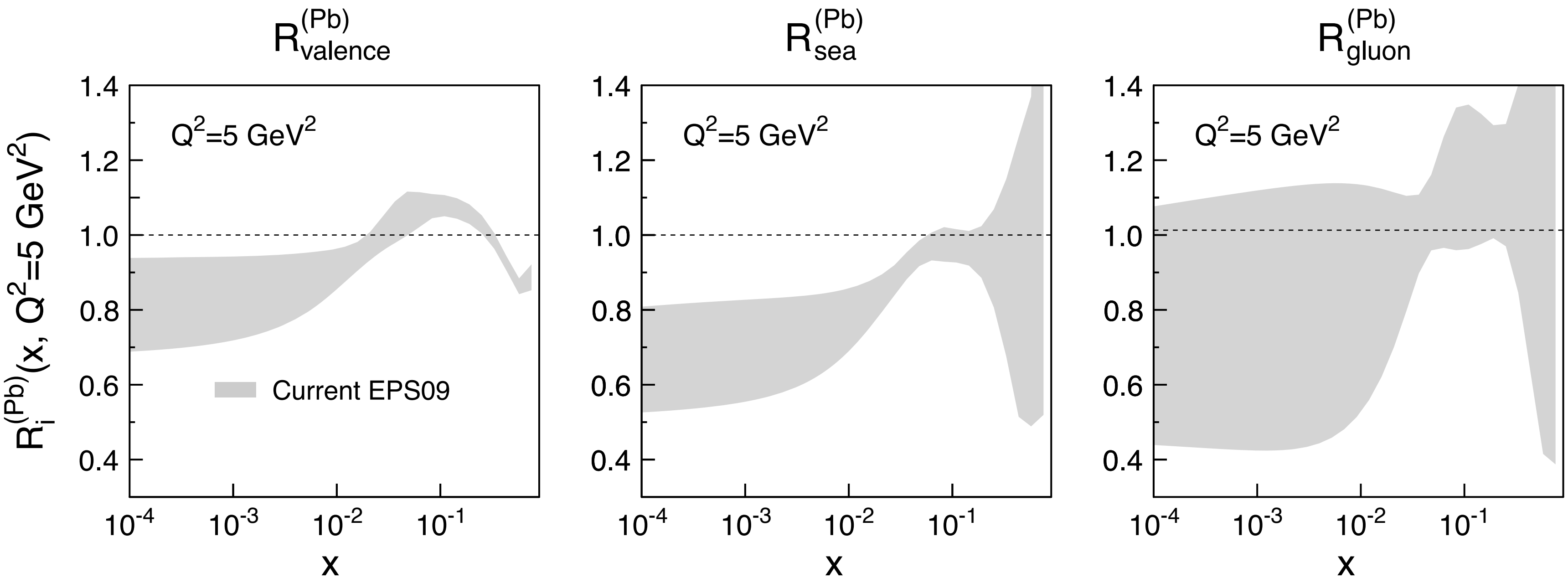
Also studied:

- F_L
  - statistics hungry
  - requires runs at various $\sqrt{s}$
- $F_{2,charm}$
  - provides compelling alternative to F_L, sensitive to glue

EIC: Impact on Knowledge on nPDFs



- Ratio of PDF(Pb)/PDF(p)
  - Without EIC, large uncertainties for sea quarks and gluons
  - Adding in EIC, pseudo-data significantly reduces the uncertainties, particularly at small-x
  - Fitting the charm pseudo-data has a dramatic effect at high-x
  - Something *p*A at RHIC & LHC will not be able to address

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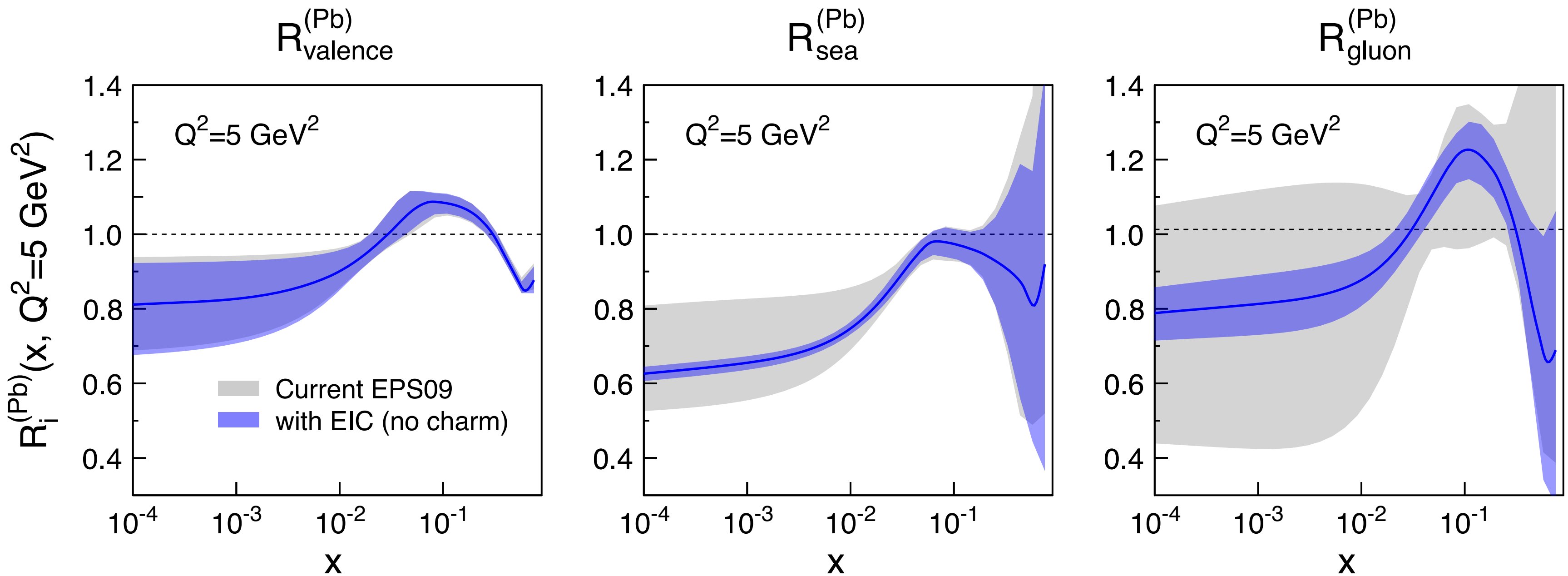

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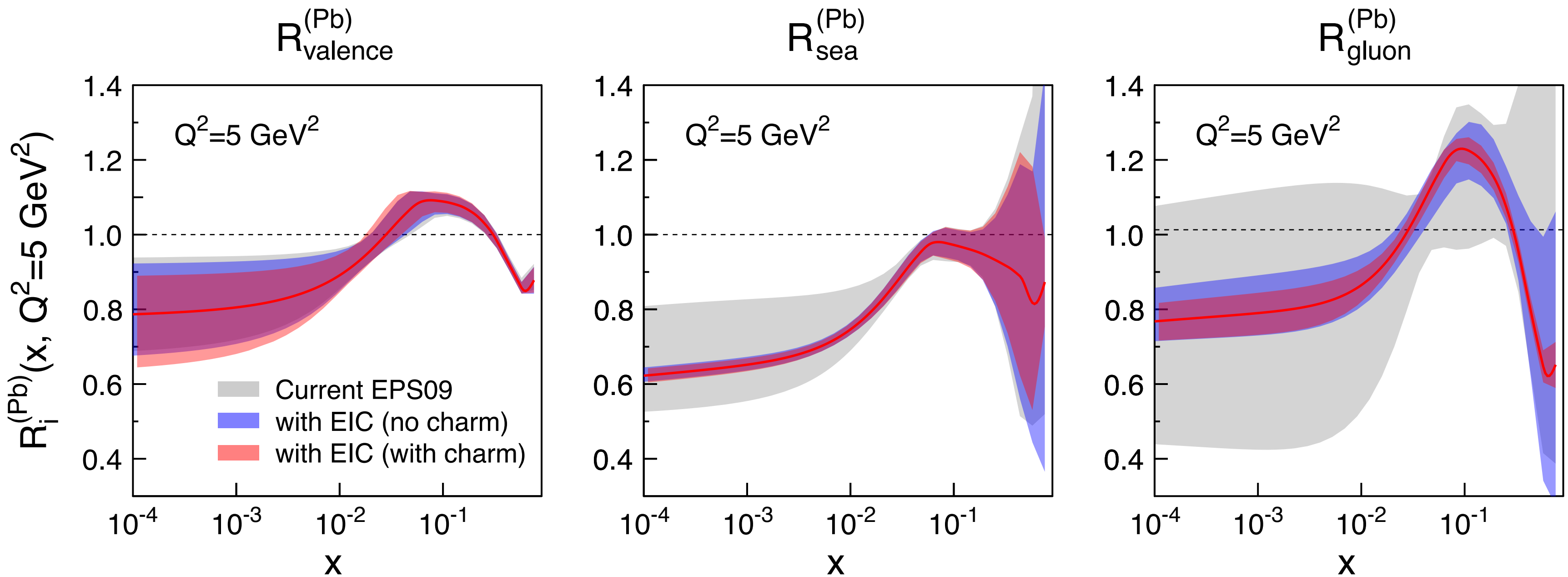

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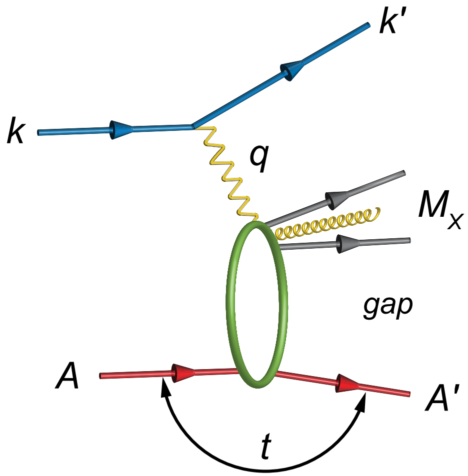
EIC: Diffractive Events in eA

Diffractive physics will be a major component of the eA program at an EIC



- High sensitivity to gluon density: $\sigma \sim [g(x,Q^2)]^2$ due to color-neutral exchange
- Only known process where spatial gluon distributions of nuclei can be extracted

- 2 Types: Coherent (A stays intact) & Incoherent (A breaks up)
- Experimental challenging to identify
  - Rapidity gap $\Rightarrow$ hermetic detector
  - Breakup needs to be detected $\Rightarrow$ n and γ in Zero Degree Calorimeter, spectator tagging (Roman Pots), IR design!

See also talks by Vadim and Elke

EIC: Spatial Gluon Distribution from $d\sigma/dt$

1950-60: Measurement of charge (proton) distribution in nuclei
Ongoing: Measurement of neutron distribution in nuclei
EIC $\Rightarrow$ Gluon distribution in nuclei

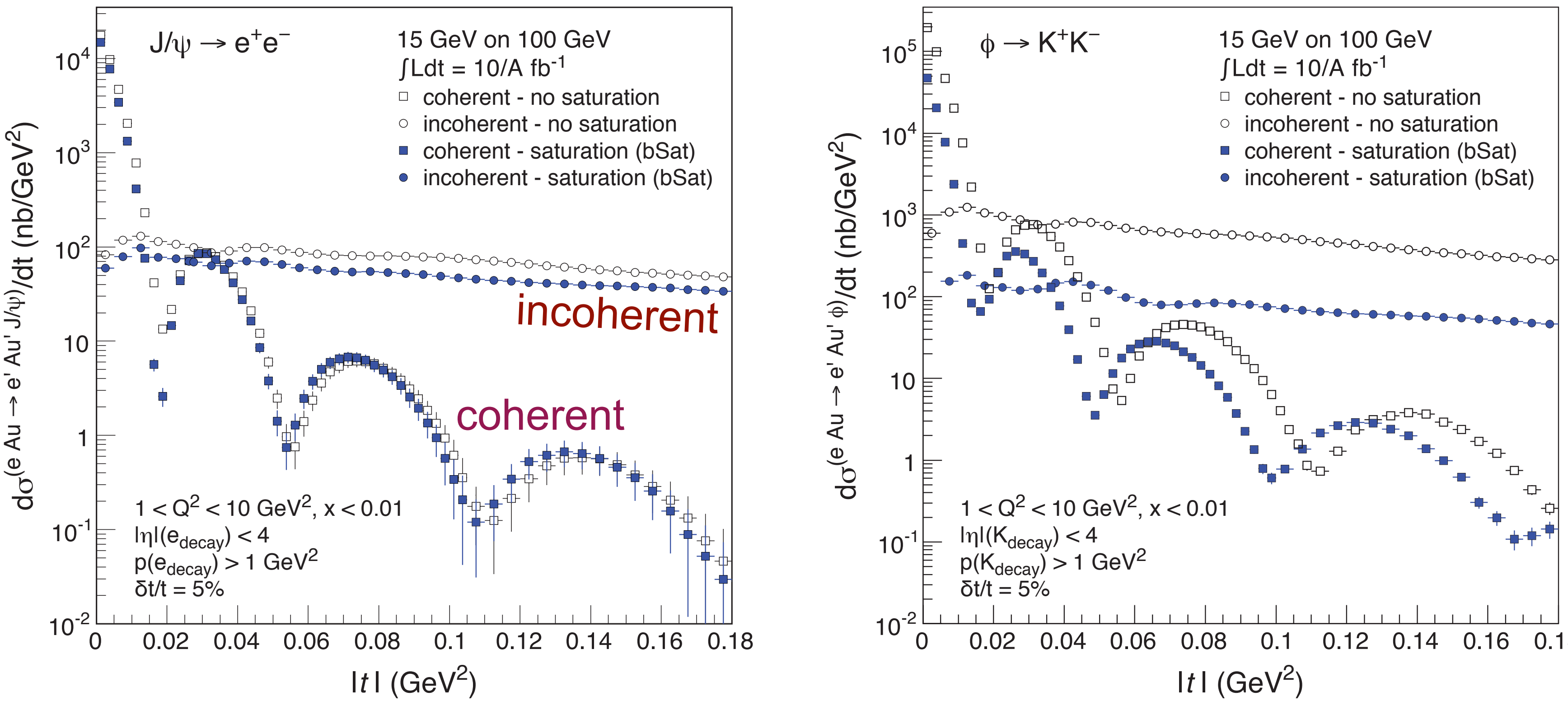
Method:

Diffractive vector meson production: $e + Au \to e' + Au' + J/\psi, \phi, \rho$

- Momentum transfer $t = |\mathbf{p}_{Au}-\mathbf{p}_{Au'}|^2$ conjugate to b_T

EIC: Spatial Gluon Distribution from dσ/dt

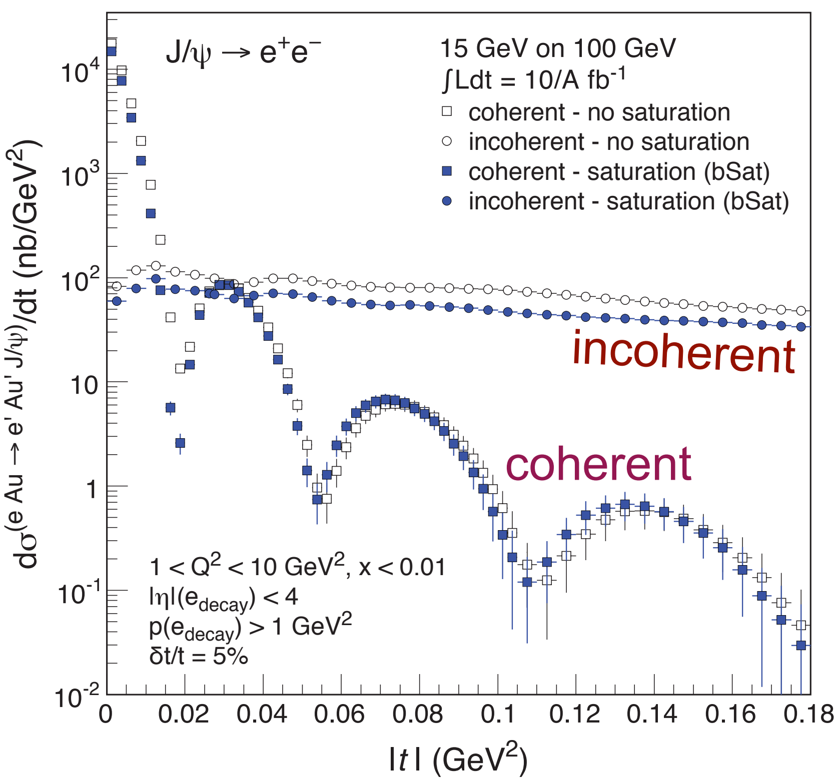
Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$



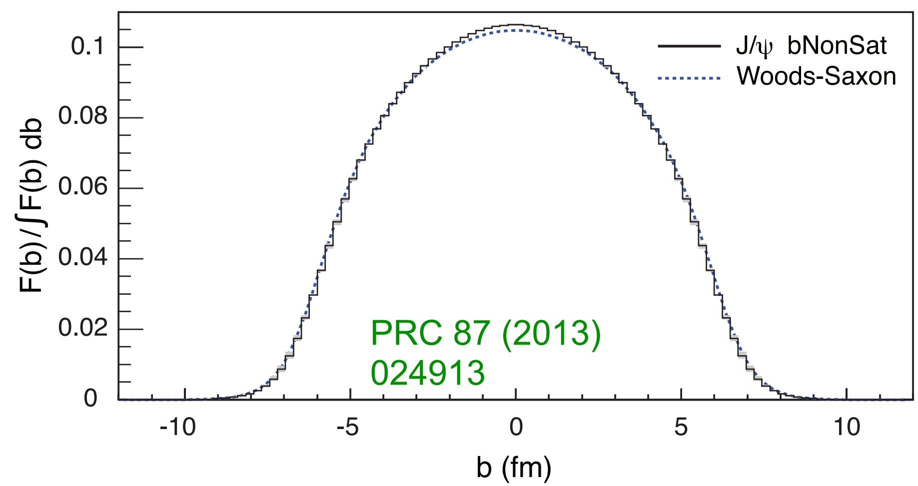
- dσ/dt: diffractive pattern known from wave optics
- ϕ sensitive to saturation effects, smaller J/ψ shows no effect
- J/ψ perfectly suited to extract source distribution

EIC: Spatial Gluon Distribution from dσ/d*t*

Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$



Fourier Transform



- Converges to input F(b) rapidly: $|t| < 0.1$ almost enough
- Recover accurately any input distribution used in model used to generate pseudo-data (here Wood-Saxon)
- Systematic measurement requires $\int \mathcal{L}dt \gg 1\ fb^{-1}/A$

Take Away Message

EIC, with its high energy, high luminosity eA and polarized ep collisions, will provide answers to long-standing fundamental questions in QCD

- **ep:** Precision studies of structure functions, TMDs, and GPDs will lead to the most comprehensive picture of the nucleon ever: its flavor, spin, and spatial structure
- **eA:** Unprecedented study of matter in a new regime of QCD. New capabilities open a new frontier to study the saturation region, measure the gluonic structure of nuclei, and investigate color propagation, and fragmentation using the nucleus as analyzer.

This physics is tied to a future high-energy electron-ion collider

It cannot be done without.

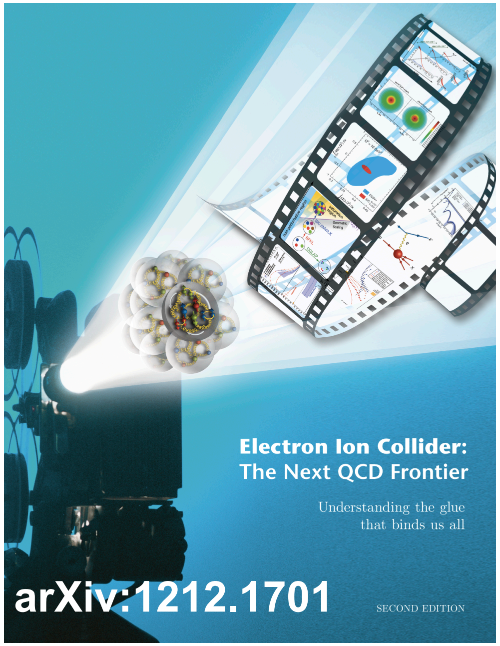
Take Away Message

EIC, with i… …arized ep collisions, … …lamental questions

- **ep:** Pre… …nd GPDs will lead to t… …n ever: its flavor, s…
- **eA:** Unp… …of QCD. New ca… …ration region, … …nvestigate color pr… …us as analyze…

This phys… …-ion collider

For more:



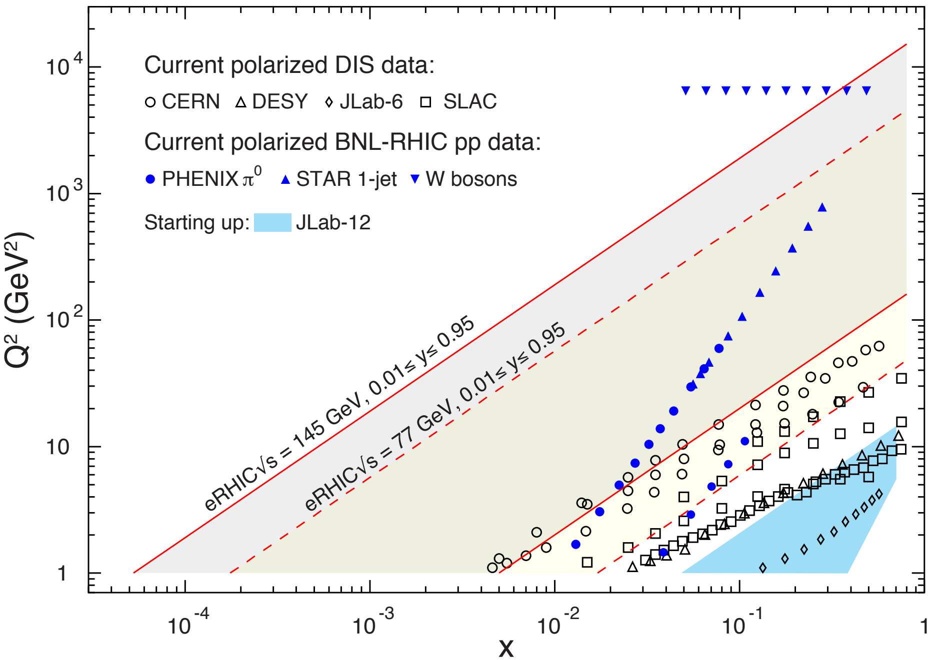
and …

Scientific American
May 2015
The Glue That Binds Us
by R. Ent, R. Venugopalan, TU

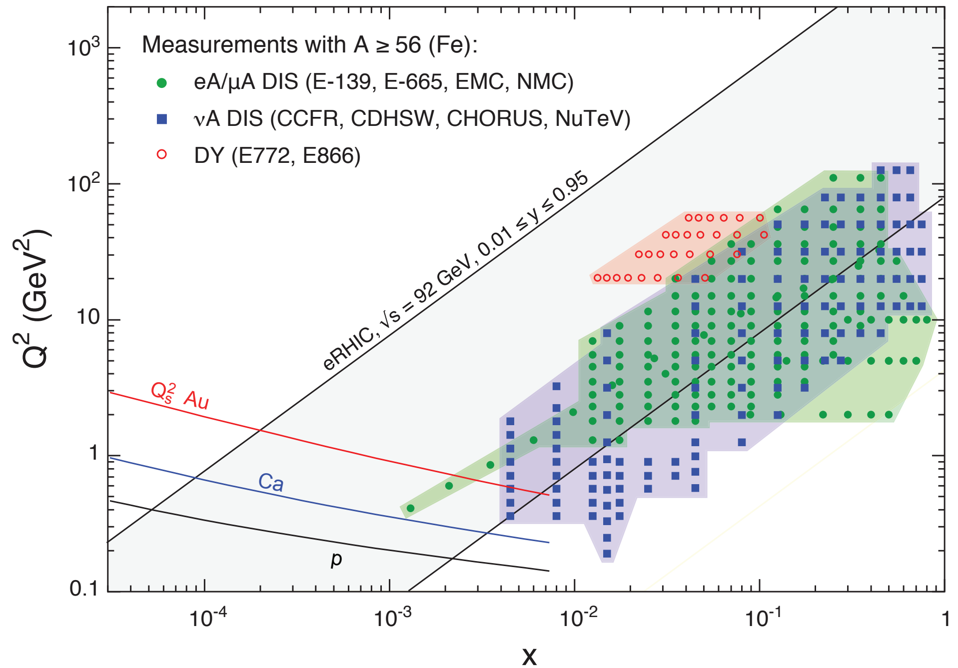
Additional Slides

EIC Kinematic Reach

polarized ep



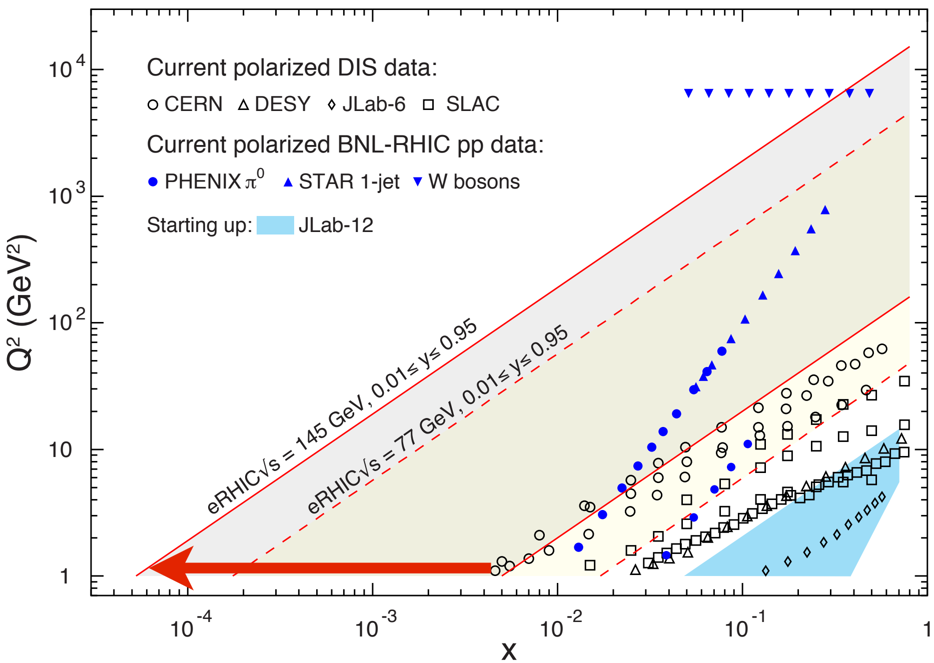
eA (A ≥ Fe)



- $Q^2 = x\, y\, s \Rightarrow\ \sqrt{s}$ important for low-x reach and Q^2 lever arm to test evolution
- Acceptance is typically limited due to experimental constraints to $0.01 < y < 0.95 \Rightarrow$ acceptance band
- EIC (here eRHIC) reaches unknown territory

EIC Kinematic Reach

polarized ep



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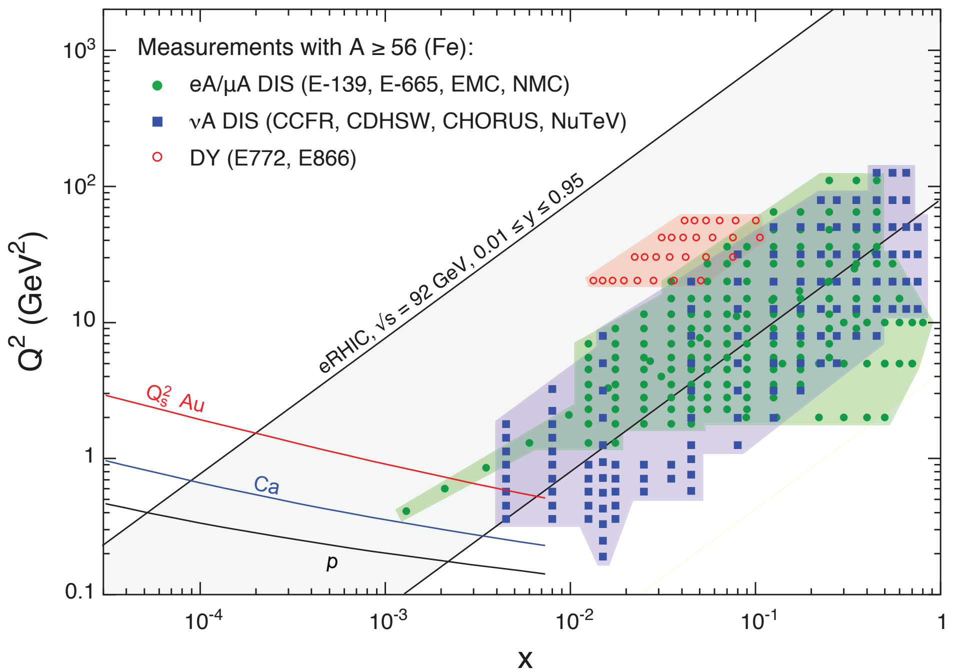

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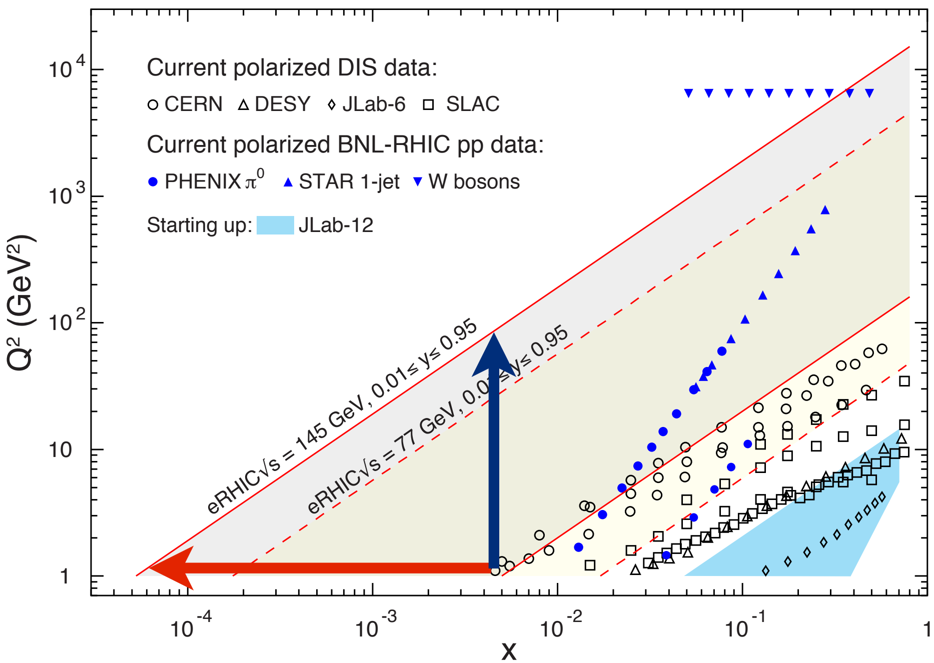

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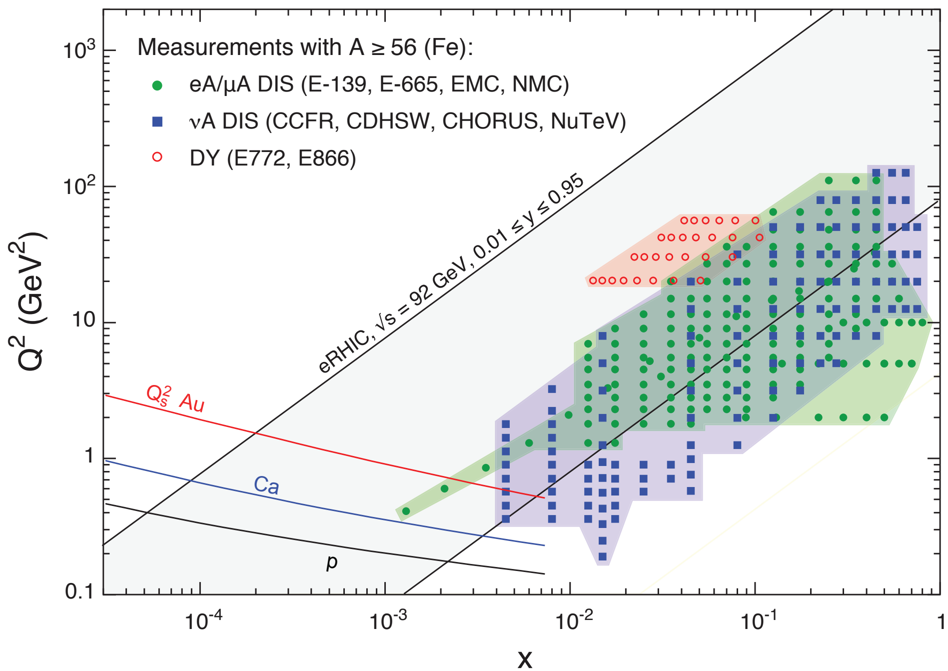

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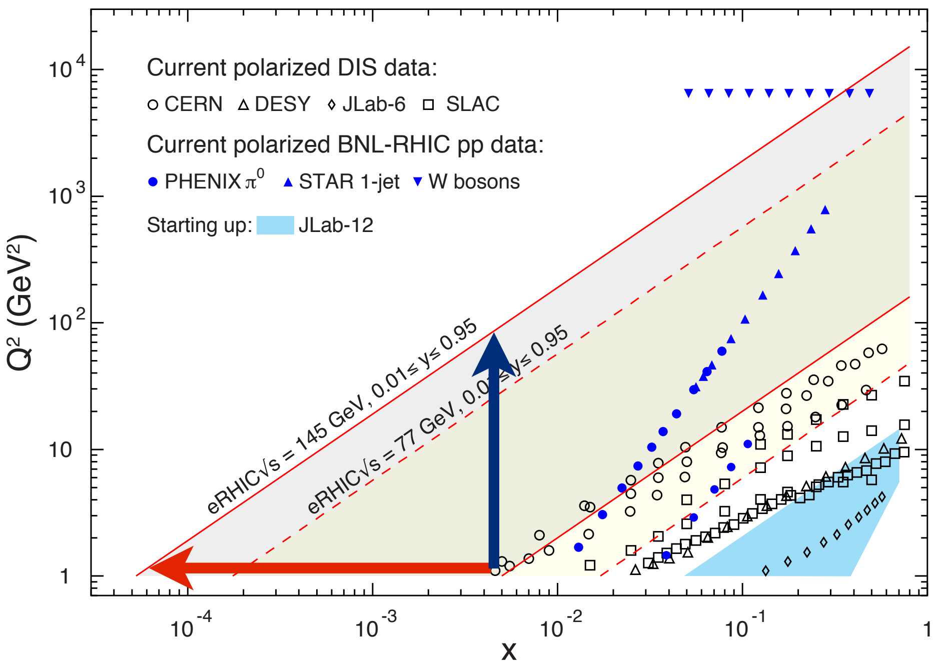

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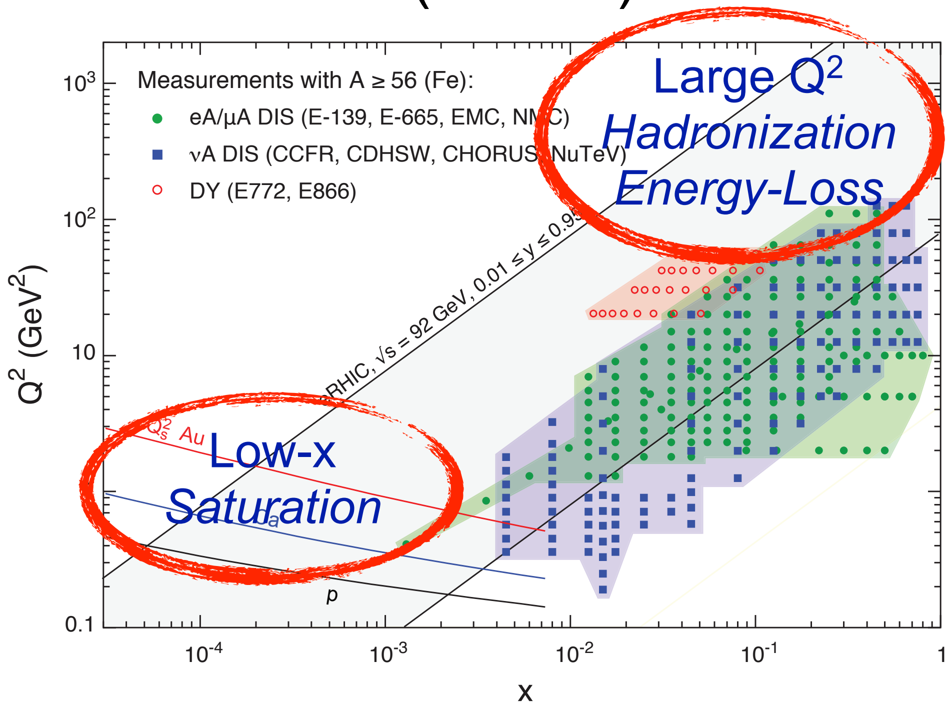

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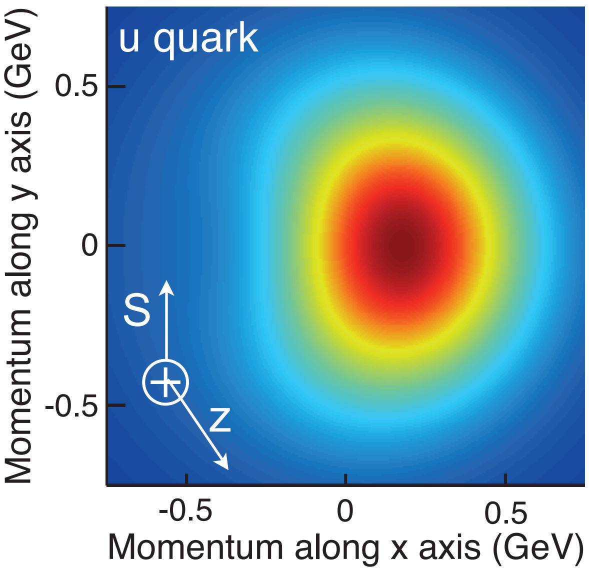
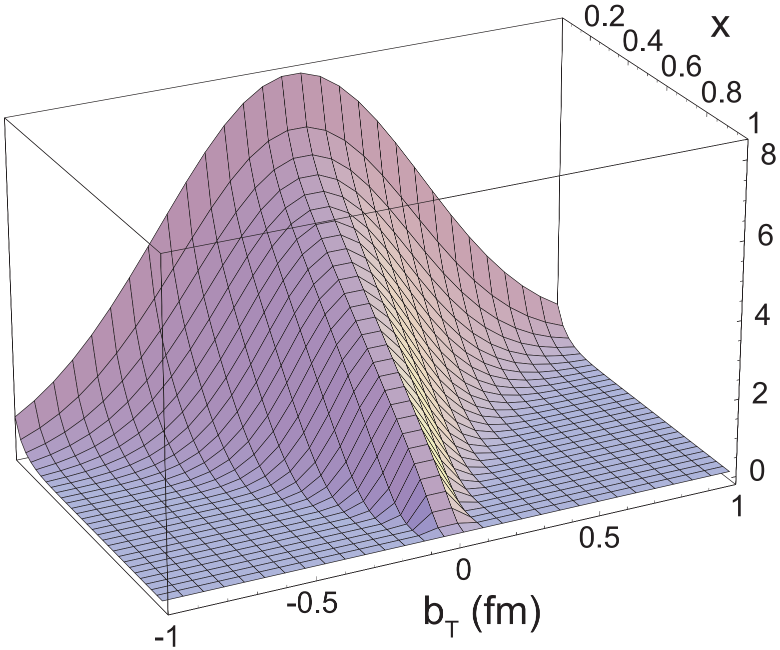
3D Imaging at an EIC: TMDs & GPDs

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



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



EIC - Status

- April ’14: Nuclear Science Advisory Committee charged by DOE/NSF to create NP Long Range Plan
- September ’14: Town Meeting of QCD community (incl. BNL and JLab) support EIC (highest priority for new construction)
- January ’15: NSAC sub-panel EIC cost estimate review
- April ’15: LRP Resolution Meeting
- October ’15: LRP submitted to DOE/NSF
- Site selection expected after positive LRP decision