The Physics of a Future Electron-Ion Collider

Thomas Ullrich

Workshop on High-Energy and Nuclear Physics in the ~~Far~~ Future

RHIC & AGS User Meeting 2010

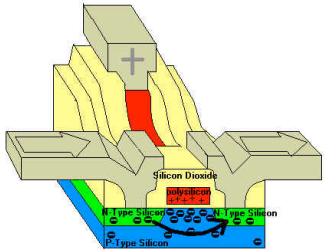
June 8, 2010

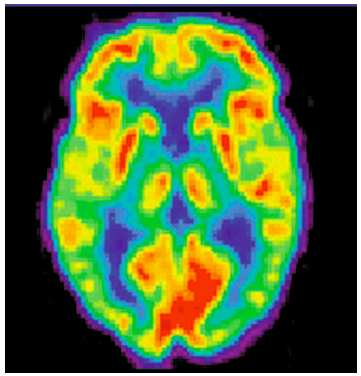
BROOKHAVEN NATIONAL LABORATORY

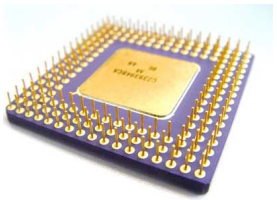
A Revolution: "*Photonic*" Structure of Matter

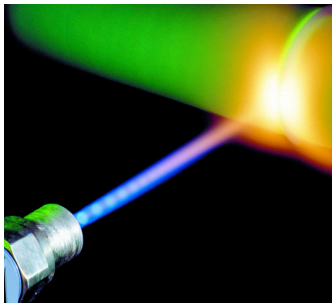
1897	Discovery of electron	Thomson
1909	Atom/Nucleus	Rutherford
1913	First Quantum Model of Atoms	Bohr
1926	Modern Quantum Model of Atom	Schrödinger, de Broglie, Heisenberg, ...
1927	Quantum field theories	Dirac, Wolfgang Pauli, Weisskopf, and Jordan
1932	Quantum mechanics as the theory of linear operators	Neumann
1947	Lamb shift ⇒ harbinger of modern QED	Lamb, Rutherford
>1947	Quantum electrodynamics (QED)	Feynman, Dyson, Schwinger, Tomonaga
~2004	g-2: $a_\mu(\text{exp}) = 11\ 659\ 208(6) \times 10^{-10}$ (0.5 ppm) $a_\mu(\text{SM}) = 11\ 659\ 181(8) \times 10^{-10}$ (0.7 ppm)	E821

A Revolution: "*Photonic*" Structure of Matter









Next Frontier: "*Gluonic*" Structure of Matter

More Questions than Answers:

How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

- Confinement of color, or why are there no free quarks and gluons at a long distance?
- How do quarks and gluons form color neutral hadrons?
- What is the quark-gluon structure inside a hadron?
- How to understand the spin of a hadron?
- What is the physics behind the QCD mass scale?

The key to the answers is **the Gluon**

- It represents the difference between QED and QCD

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
  - Confinement
  - Phases of QCD ($T > 0$, $\mu_B > 0$)

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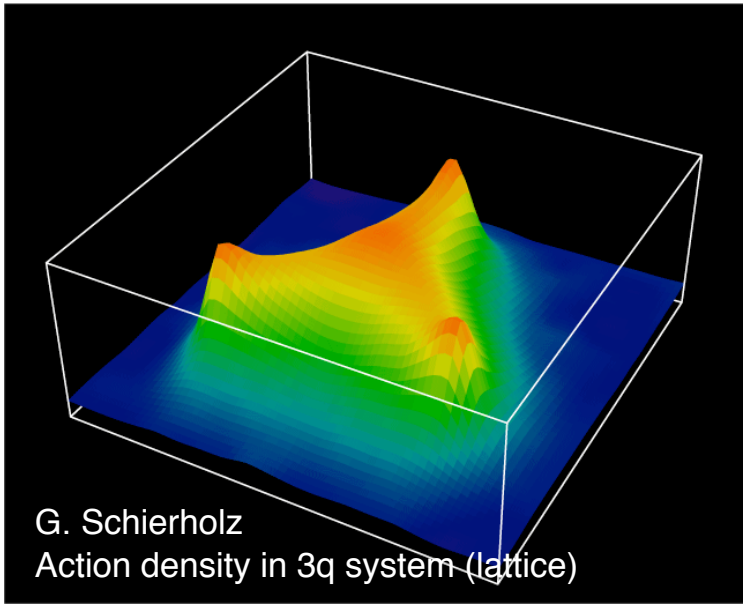
  - Confinement
  - Phases of QCD ($T > 0$, $\mu_B > 0$)

- 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



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

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- Cannot "see" the glue in the low-energy world

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

  ⇒ Experiments

(fluctuations in gluon fields)

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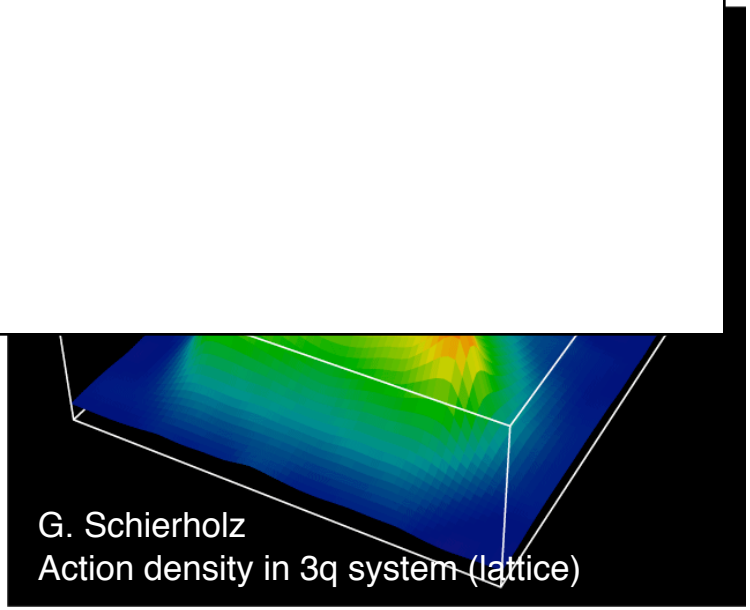

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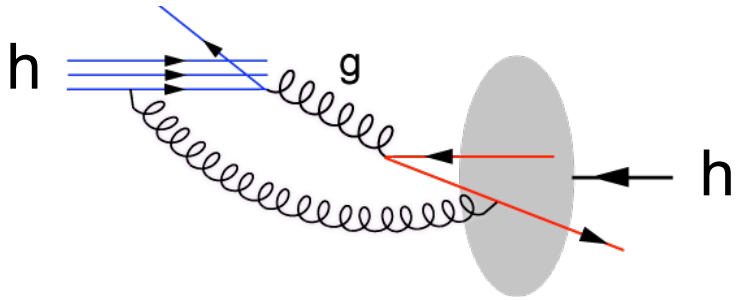
How to Study Gluons in Matter ?

Hadron-Hadron



- Test QCD
- Probe/Target interaction directly via gluons
- Lacks the direct access to parton kinematics
- Probe has complex structure

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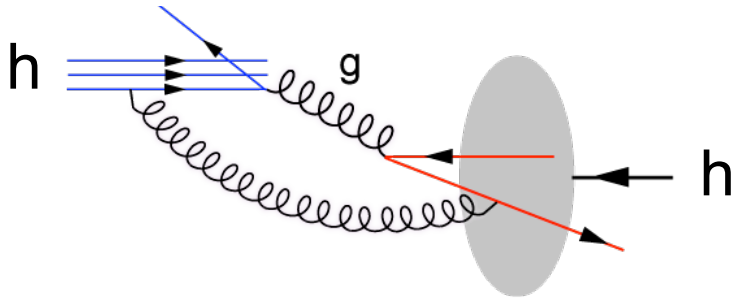

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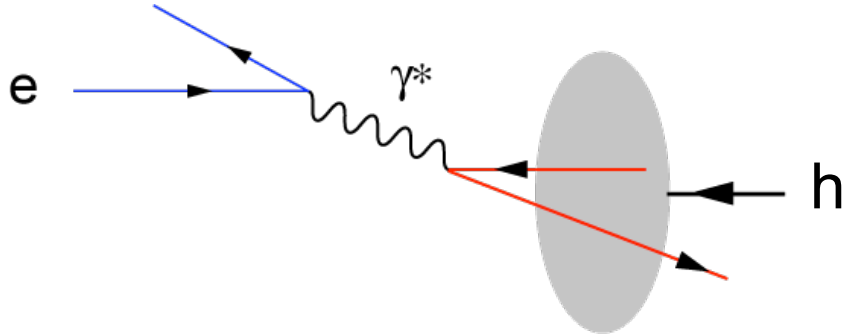

- Explore QCD & Hadron Structure
- Indirect access to glue
- High precision & access to partonic kinematics
- Probes partons w/o disturbing them or interfering with their dynamics

How to Study Gluons in Matter ?

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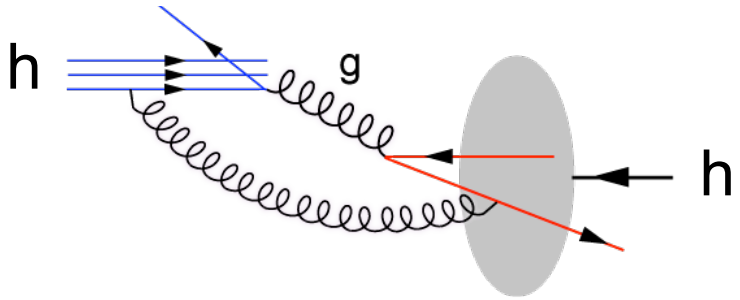

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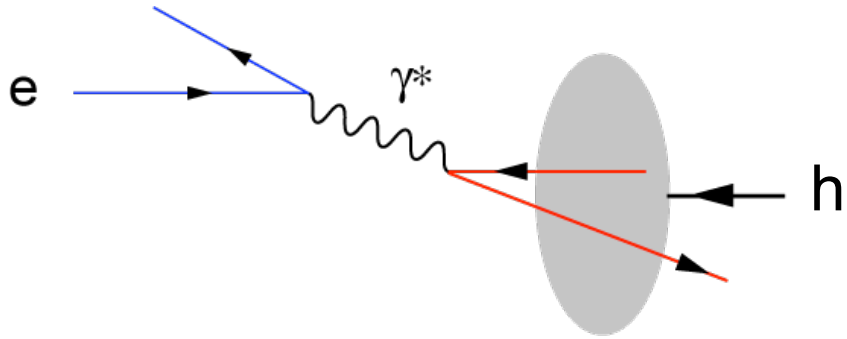

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Both are complementary but for precision ⇒ ep, eA

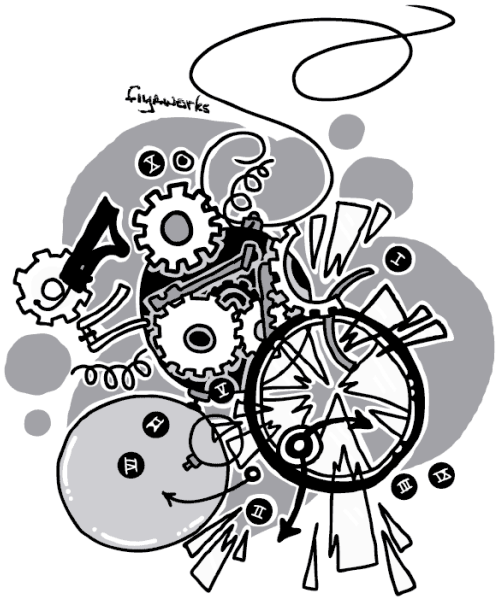
How to Study Gluons in Matter ?

Ha… Hadron … Electron Hadron (DIS)

h … h

- T…
- P… d…
- L… p…
- P… …bing …eir

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



R. Feynman

Both are complementary but for precision ⇒ ep, eA

The Electron Ion Collider

- US initiative driven by the QCD community in NP
- Colliding
  - Electrons up to 20 (30) GeV
  - Hadrons
    - protons up to 250 GeV
    - ions up to Au/U at 100 GeV
  - with unprecedented luminosities (> 100x Hera)
- Unique
  - High energy eA collisions
  - Polarized beams: e↑p↑

EIC Science Case

EIC Science Case

- What is the nature and role of gluons and their self-interactions (eA, ep)?
  - Physics of Strong Color Fields (Saturation/non-linear QCD)
  - Study the nature of color singlet excitations (Pomerons)
  - Test and study the limits of universality (eA vs. pA)

EIC Science Case

- What is the nature and role of gluons and their self-interactions (eA, ep)?

EIC Science Case

- What is the nature and role of gluons and their self-interactions (eA, ep)?

- What is the internal landscape of the nucleons?
  - What is the nature of the spin of the proton?
  - What is the Three-Dimensional Spatial Landscape of Nucleons?

EIC Science Case

- What is the nature and role of gluons and their self-interactions (eA, ep)?

- What is the internal landscape of the nucleons?

EIC Science Case

- What is the nature and role of gluons and their self-interactions (eA, ep)?
- What is the internal landscape of the nucleons?
- What governs the transition of quarks and gluons into pions and nucleons?
  - How do fast probes interact with the gluonic medium?
  - Mechanism of fragmentation?

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- Electroweak Physics (studies underway)
  - Parity Violating deep inelastic scattering (PVDIS)
  - Lepton Flavor and Number Violation

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EIC Science Case

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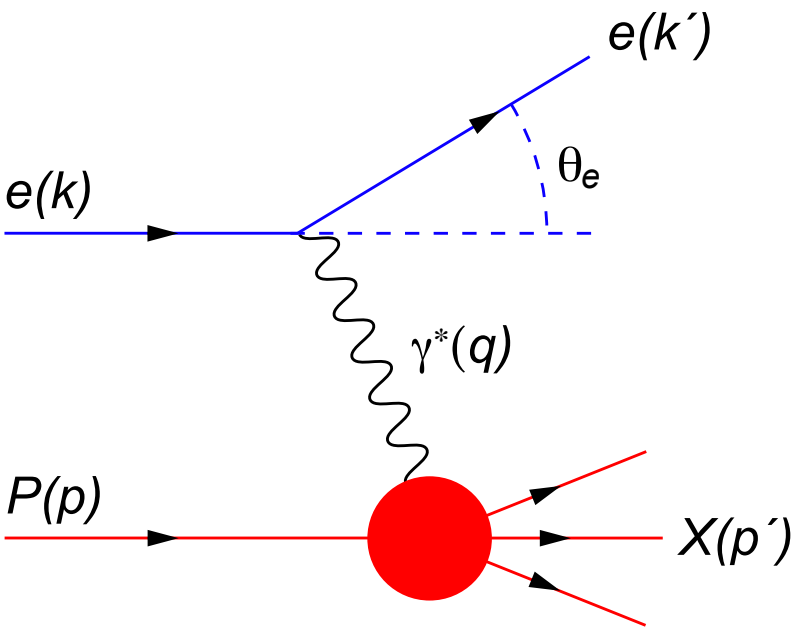
Required Measurements:

- Momentum distribution of gluons
- Spatial distribution of gluons

Deep Inelastic Scattering (DIS)



Resolution power ("Virtuality"):

$$Q^2 = -q^2 = -(k - k')^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Inelasticity:

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

p fraction of struck quark

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

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

quark+anti-quark momentum distributions

gluon momentum distribution

F_2: The Key Structure Function

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

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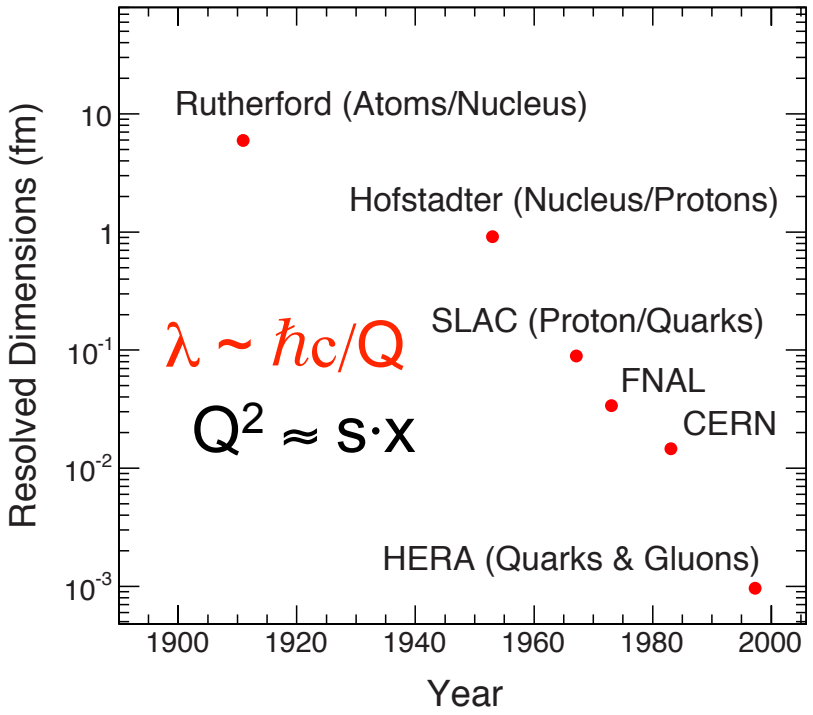

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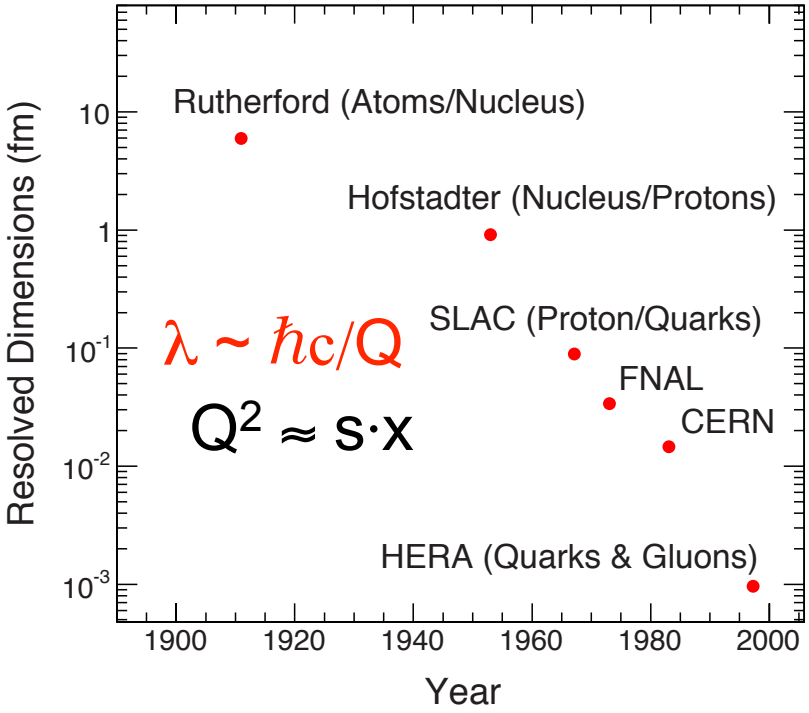

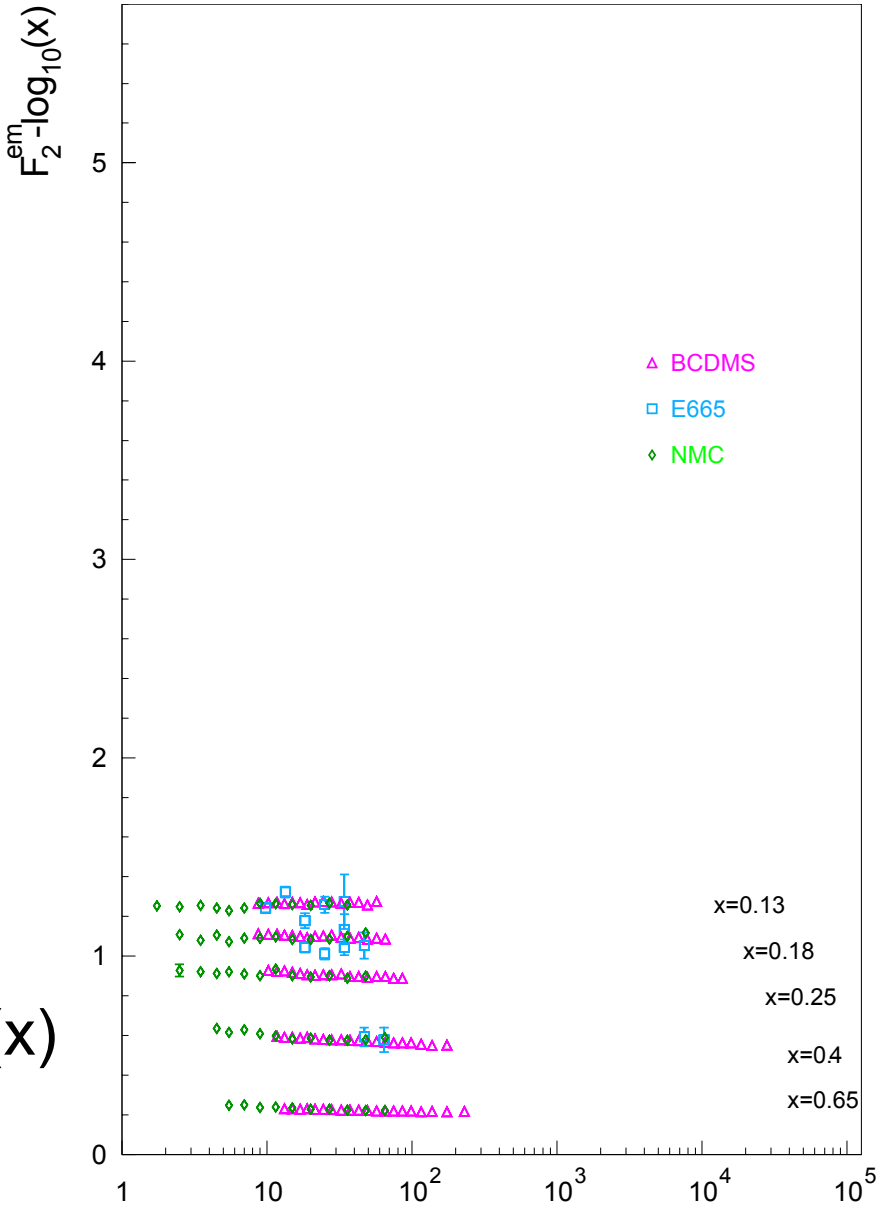

Bjorken Scaling: $F_2(x, Q^2) \to F_2(x)$

virtual photon interacts with a single essentially free quark

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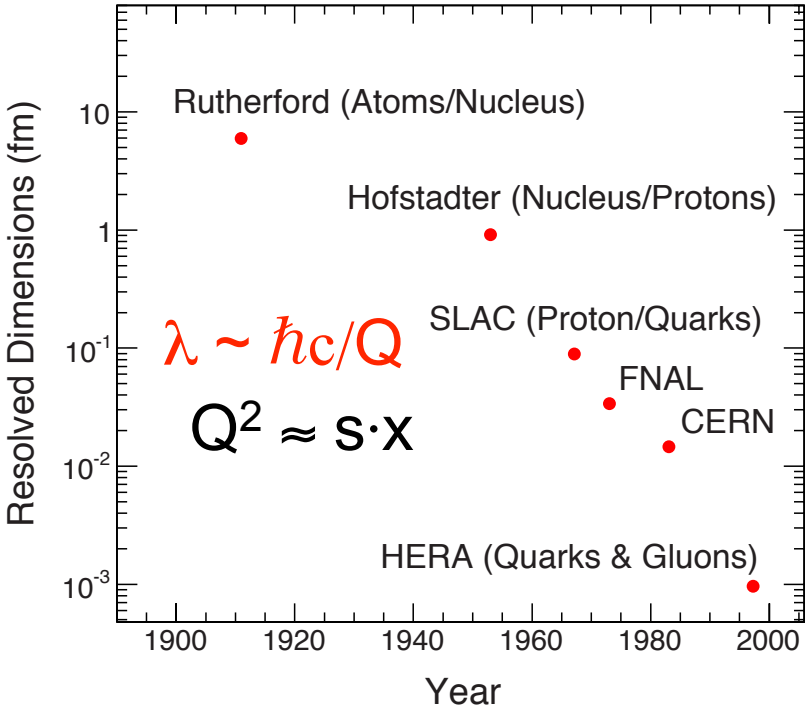

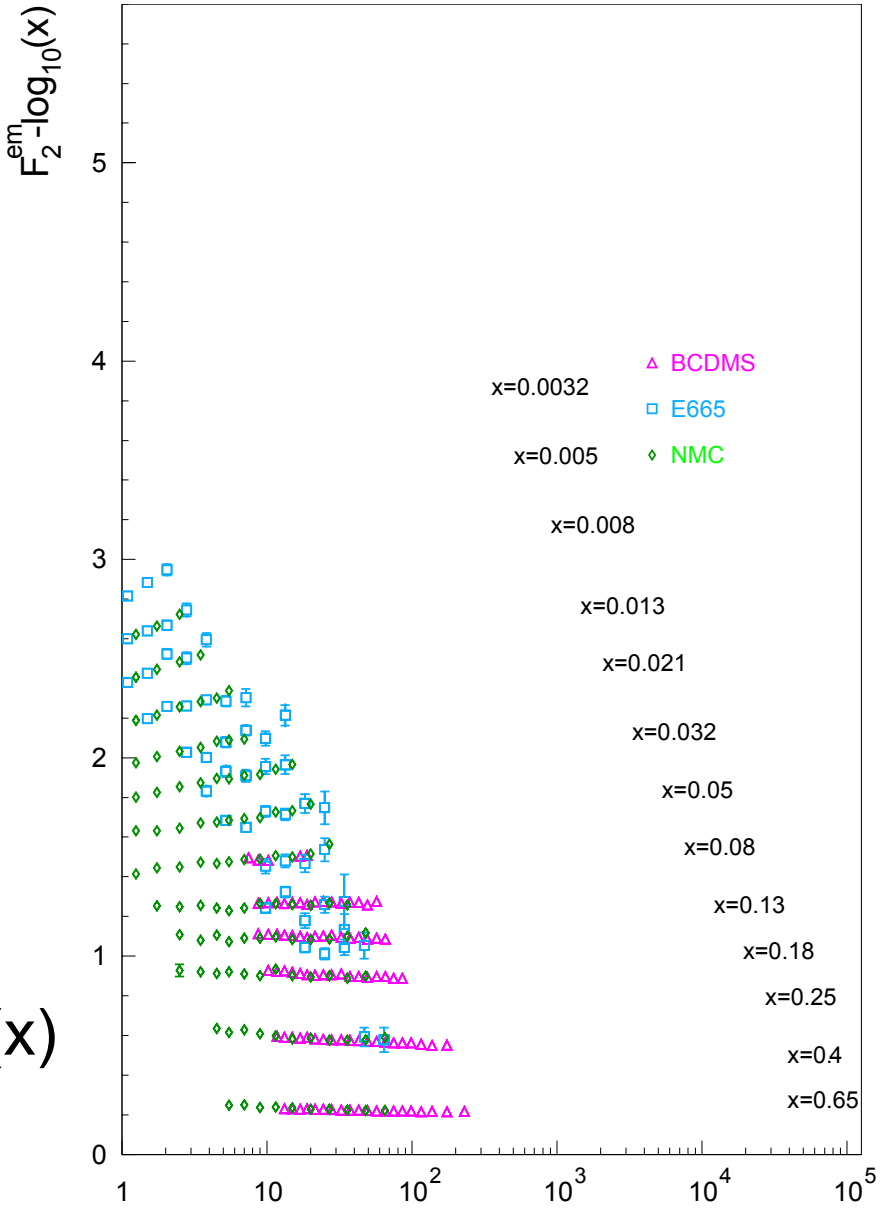

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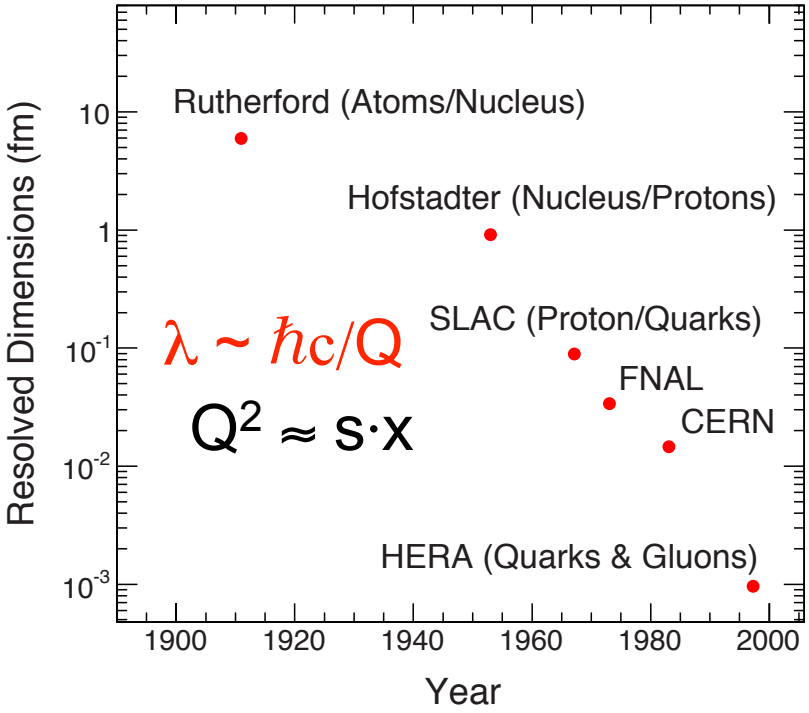

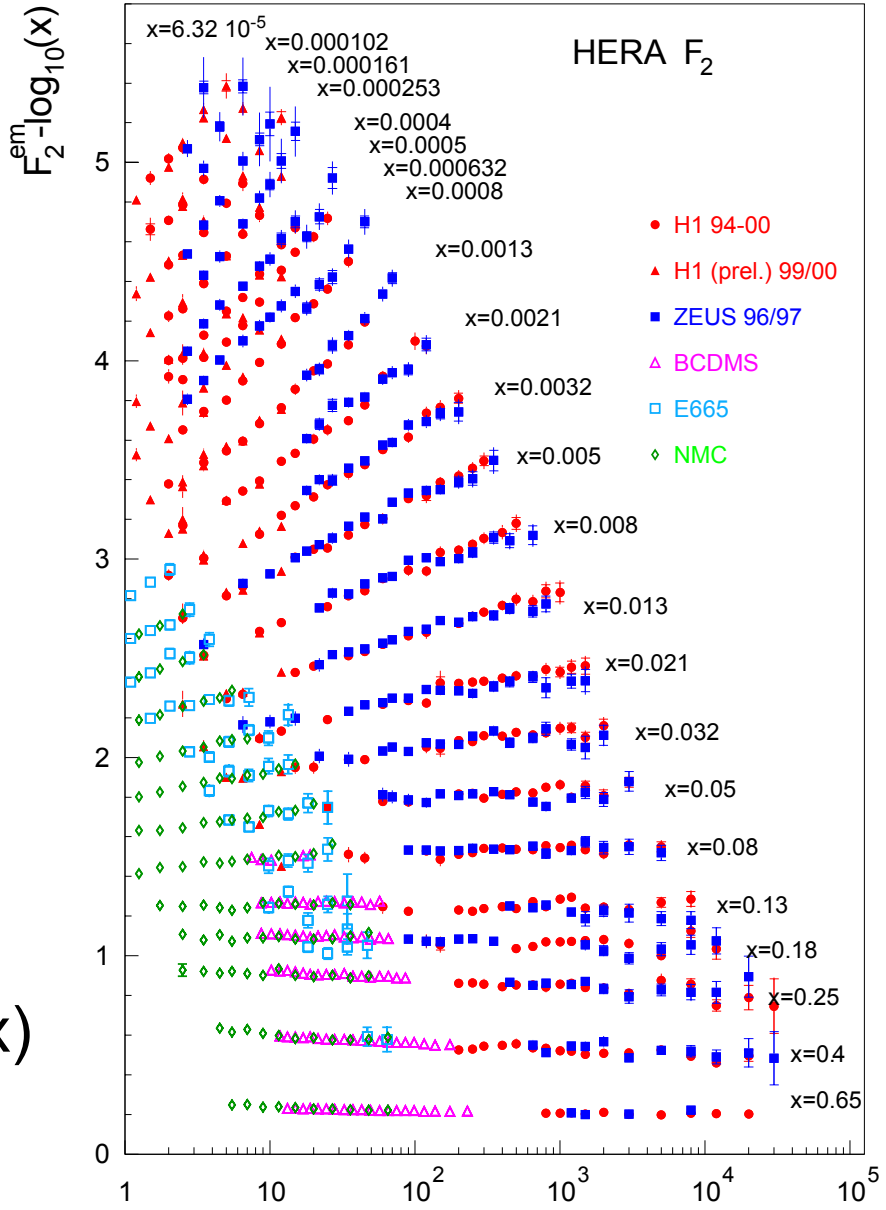

Bjorken Scaling: $F_2(x, Q^2) \neq F_2(x)$

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

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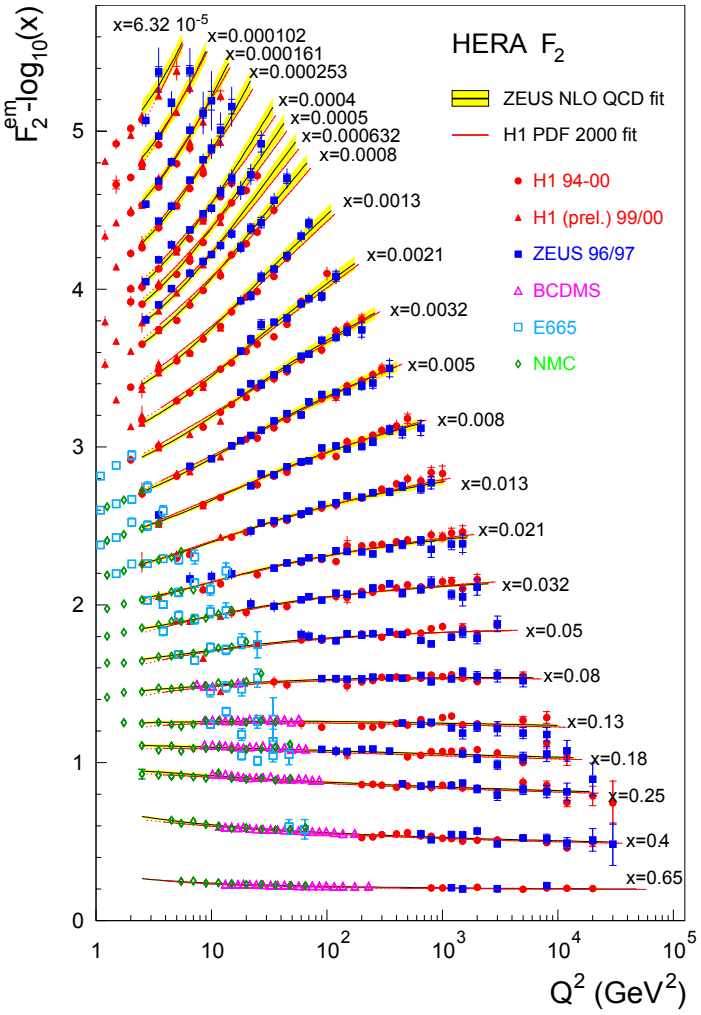

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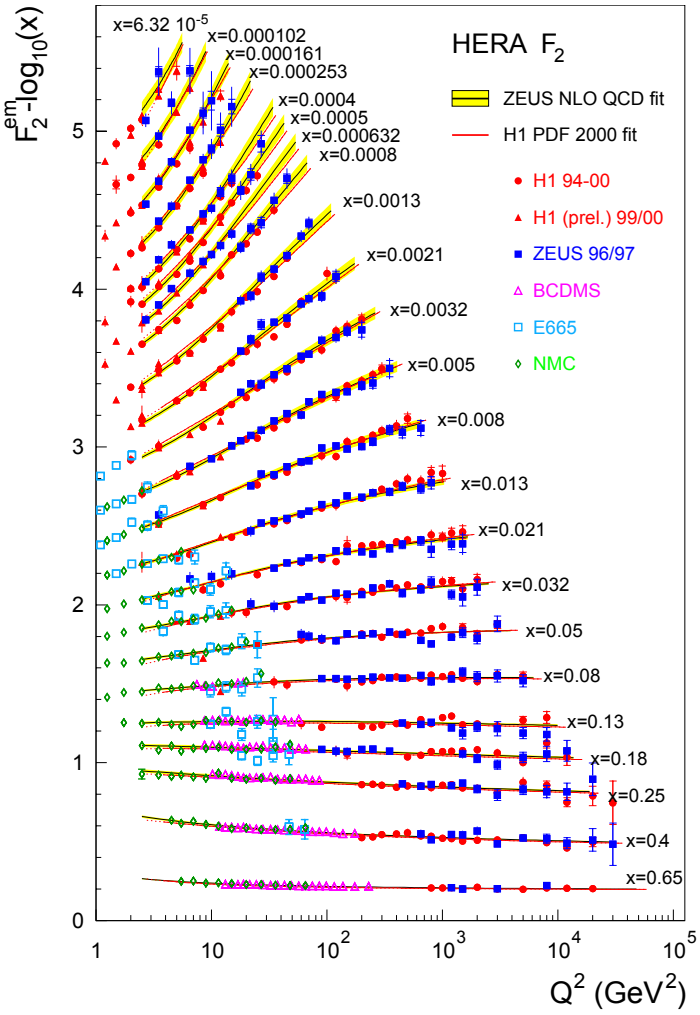

$\Rightarrow$ • F_2
• $dF_2/d\ln Q^2$ + pQCD+ DGLAP Evolution

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

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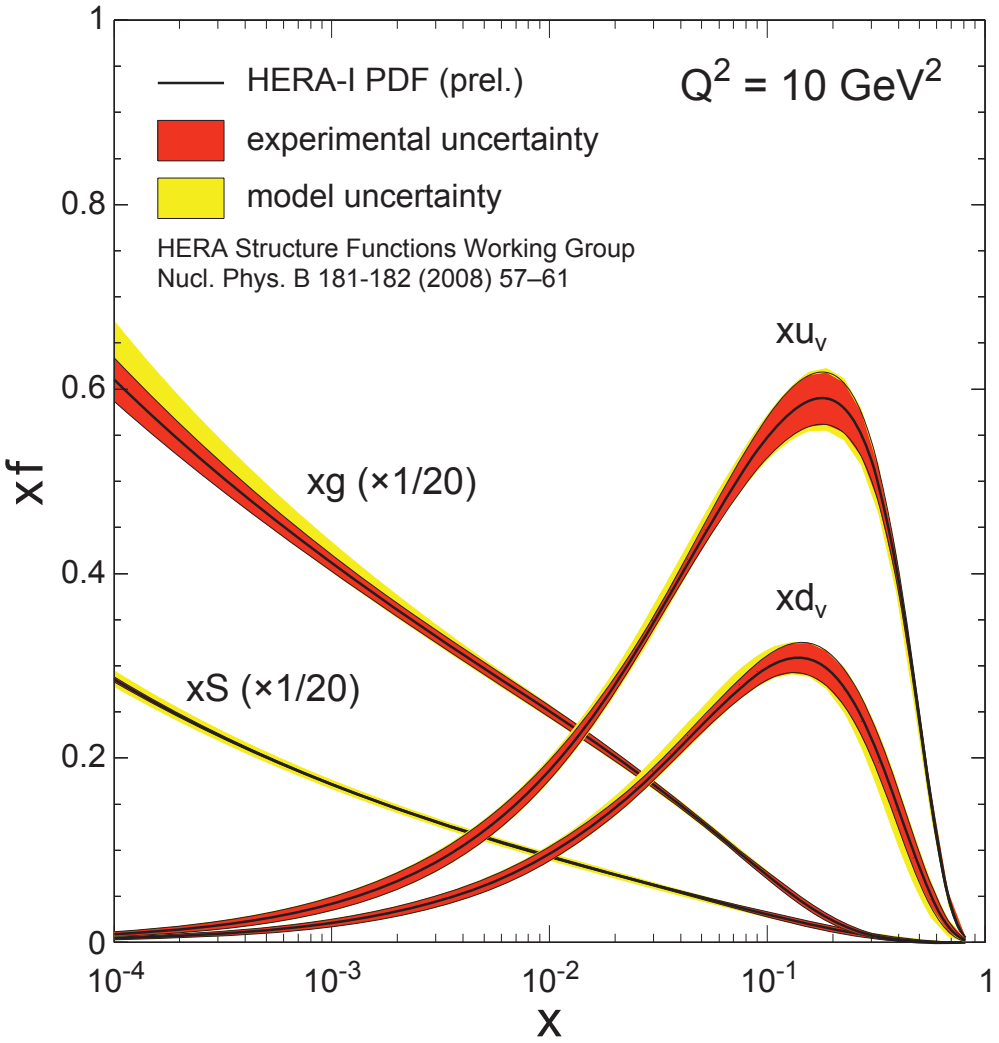

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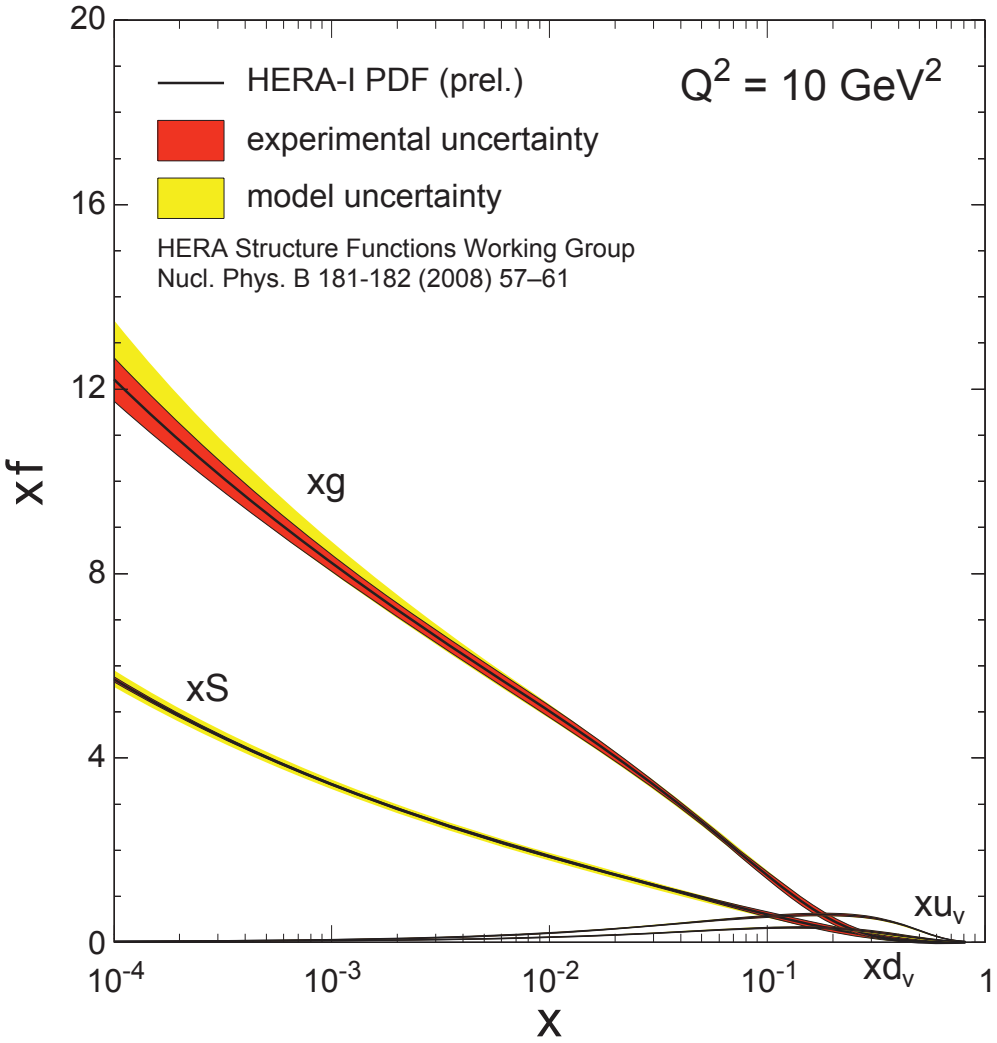
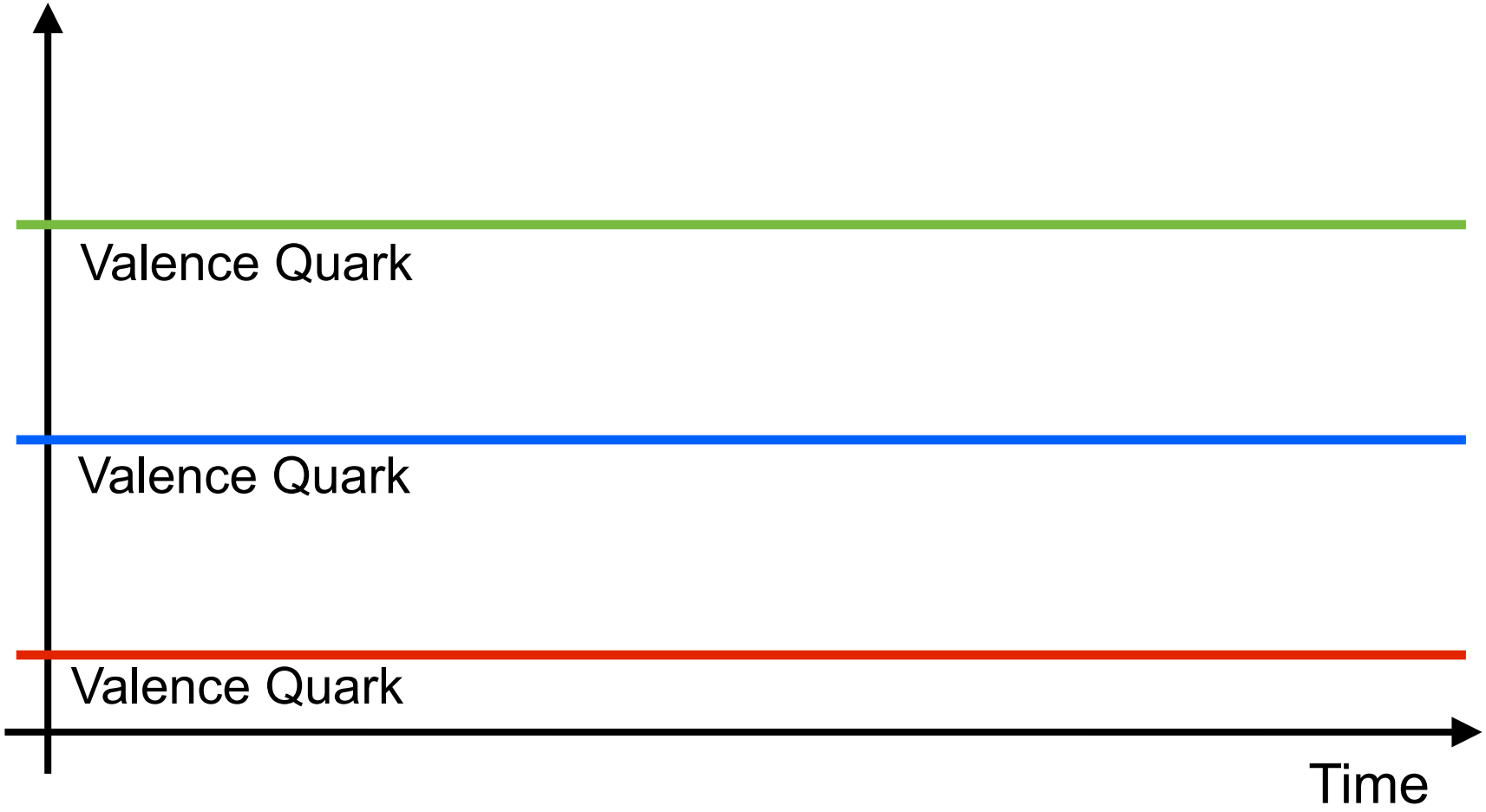


Proton is almost entirely glue by x<0.1 (for Q^2 = 10 GeV^2)

Evolving Picture of Proton



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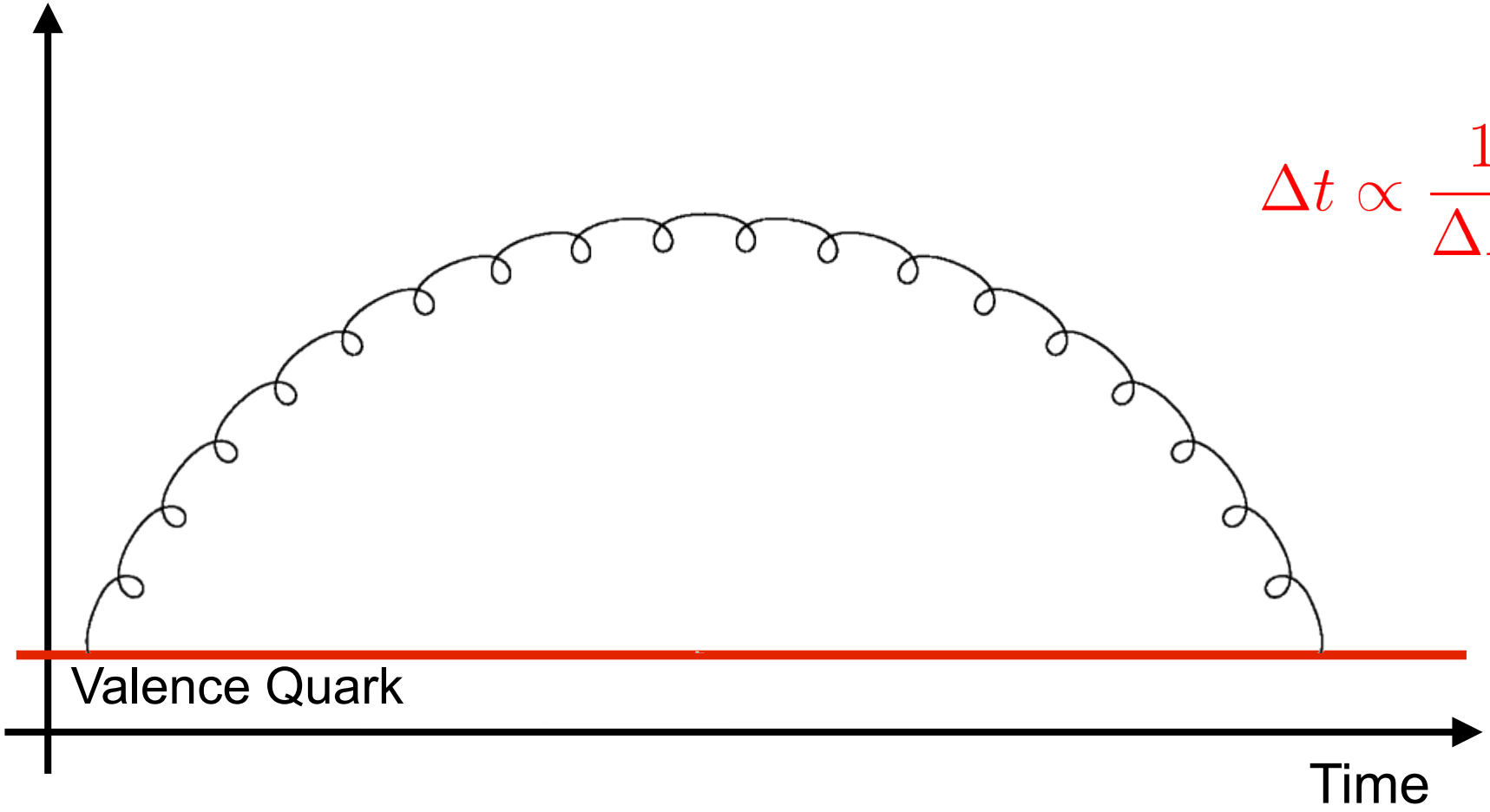

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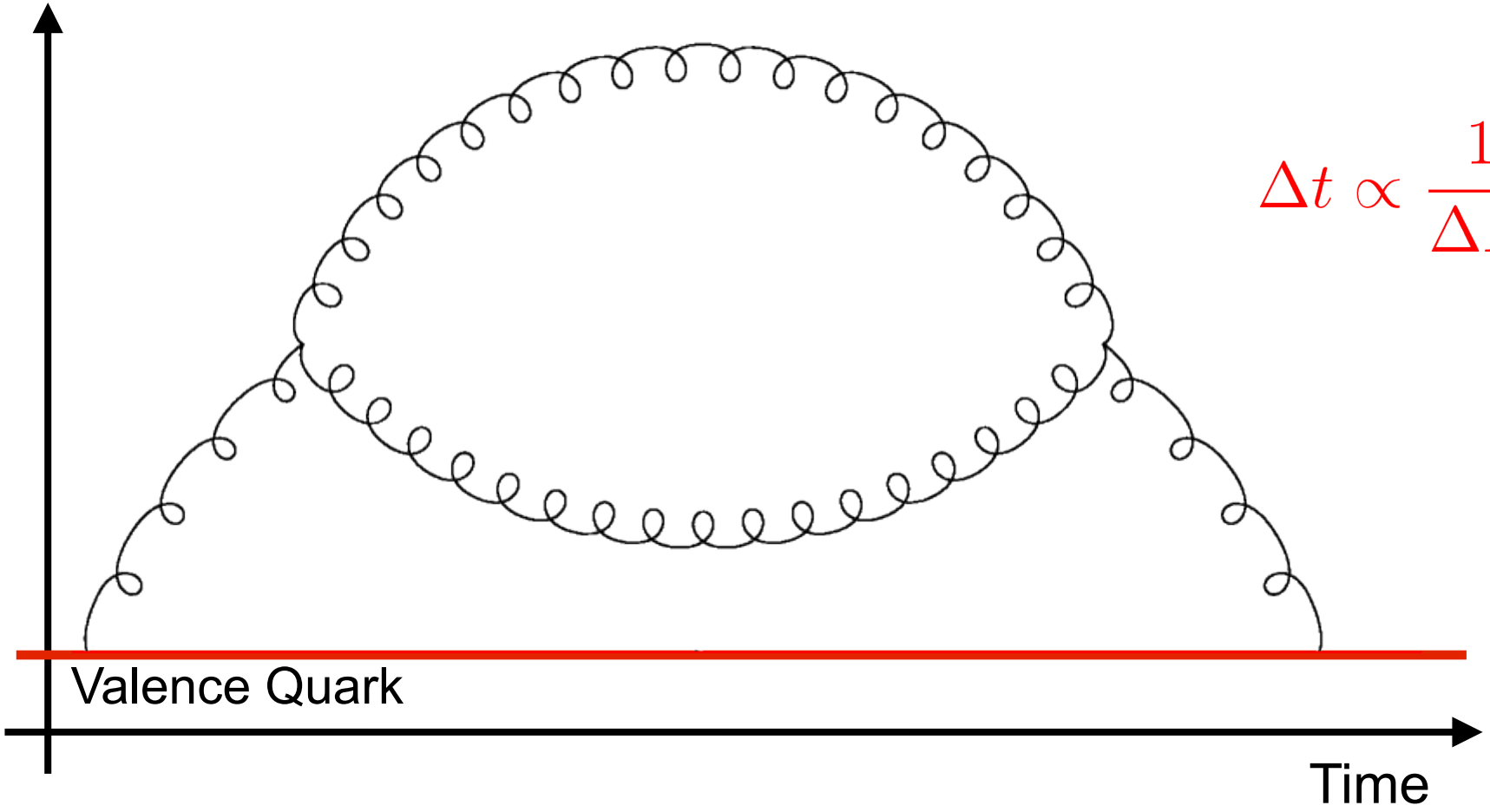

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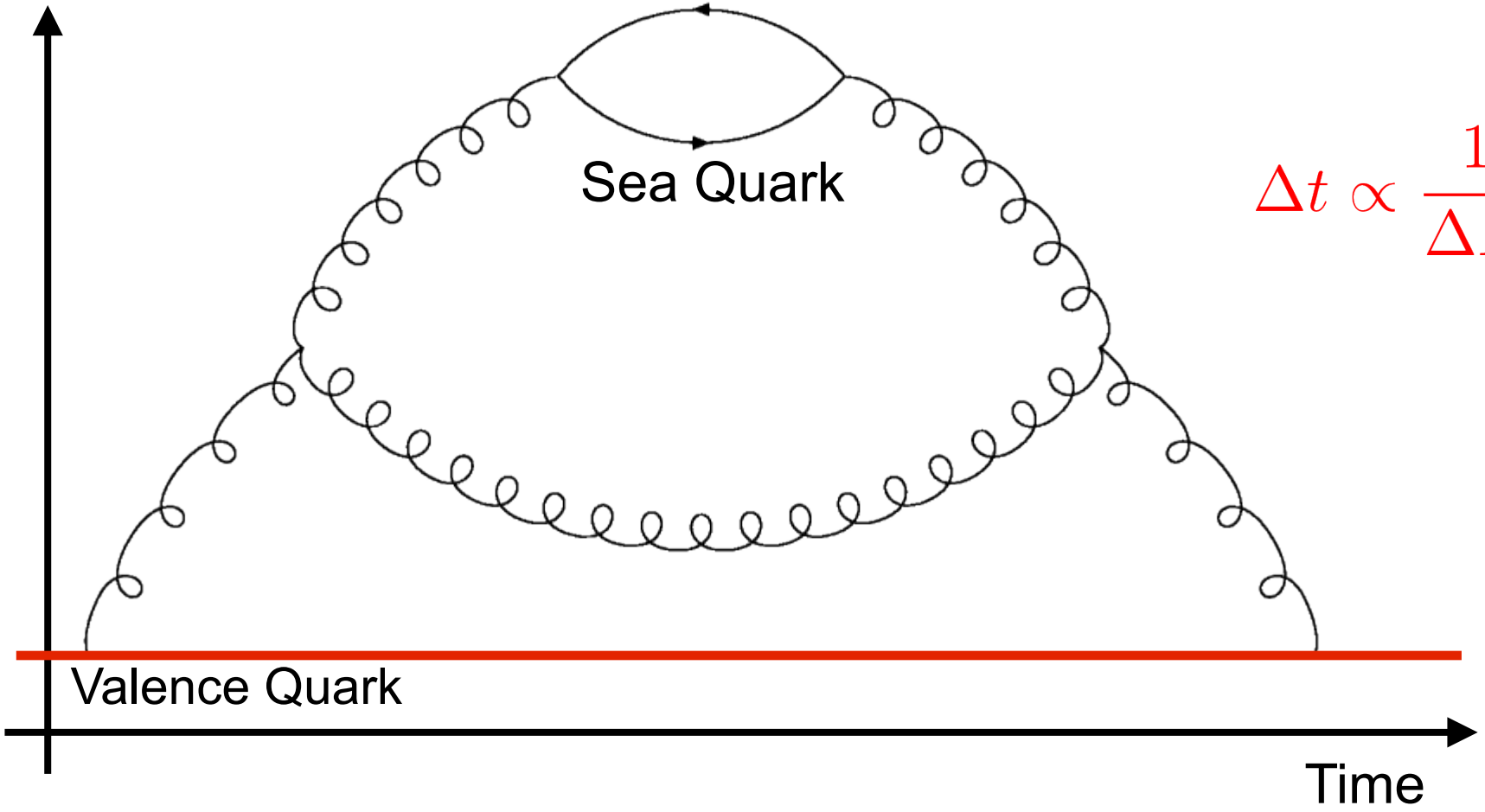

$$\Delta t \propto \frac{1}{\Delta E}$$

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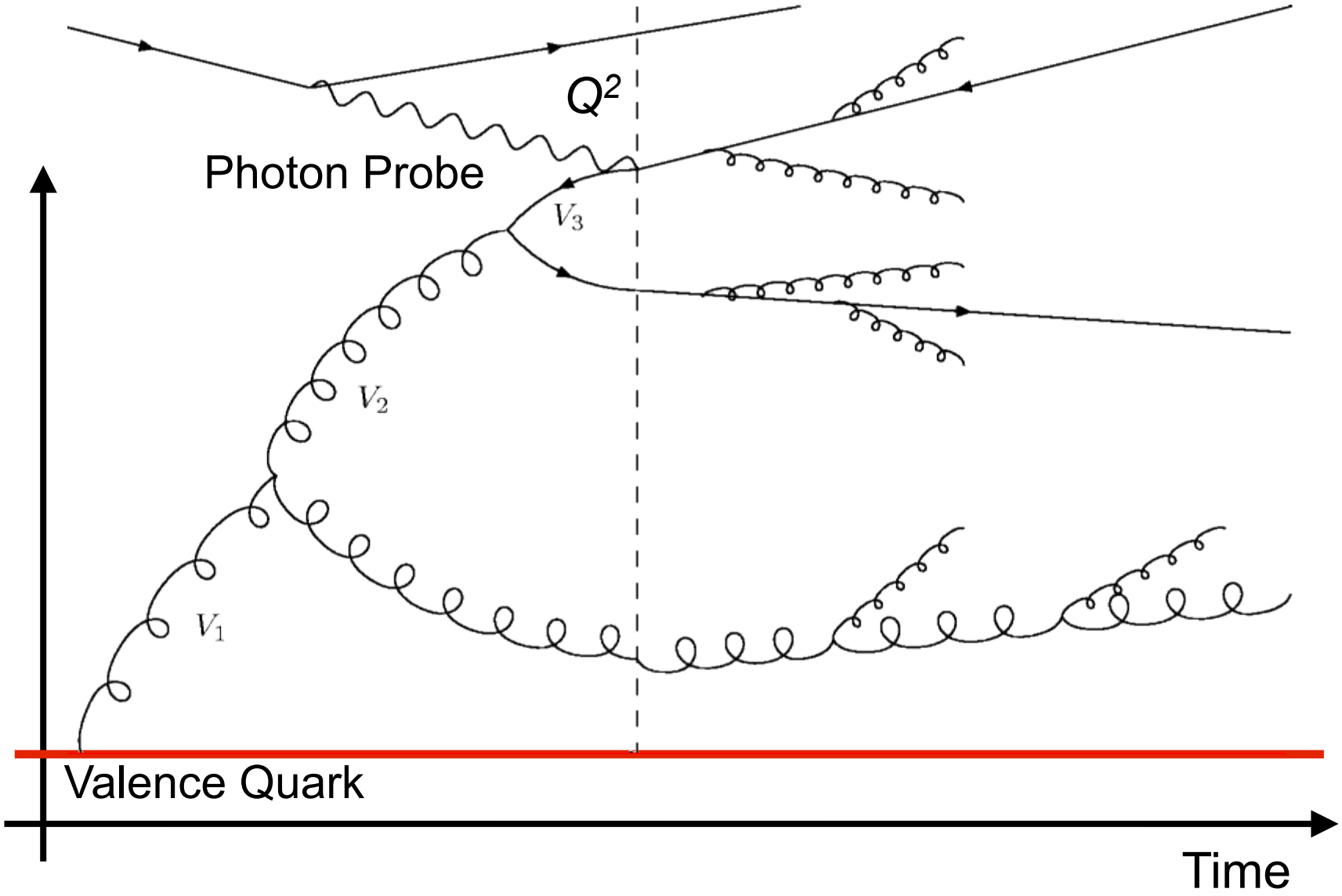
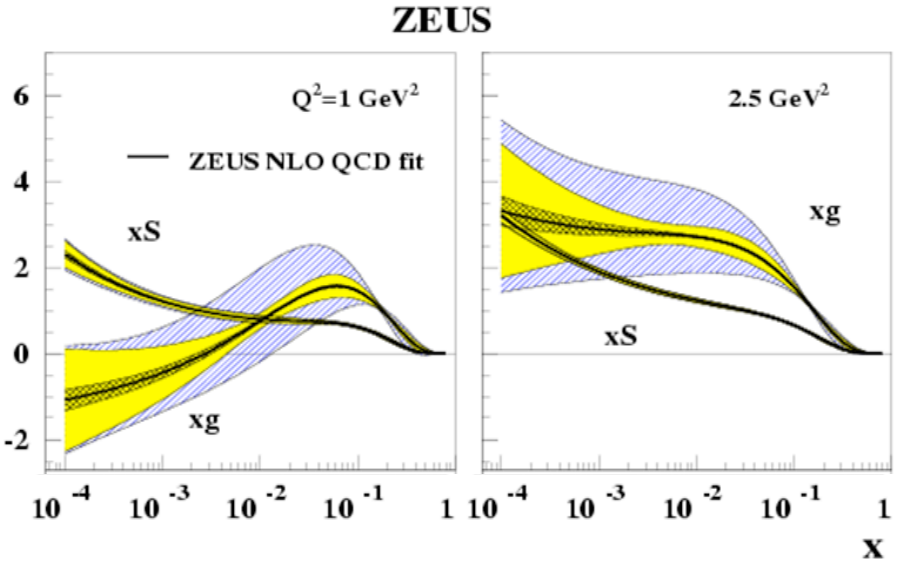


Issues with our Current Understanding

Linear DGLAP Evolution Scheme

- Low Q^2
  - $G(x, Q^2) < Q_{sea}(x, Q^2)$?
  - $G(x, Q^2) < 0$?



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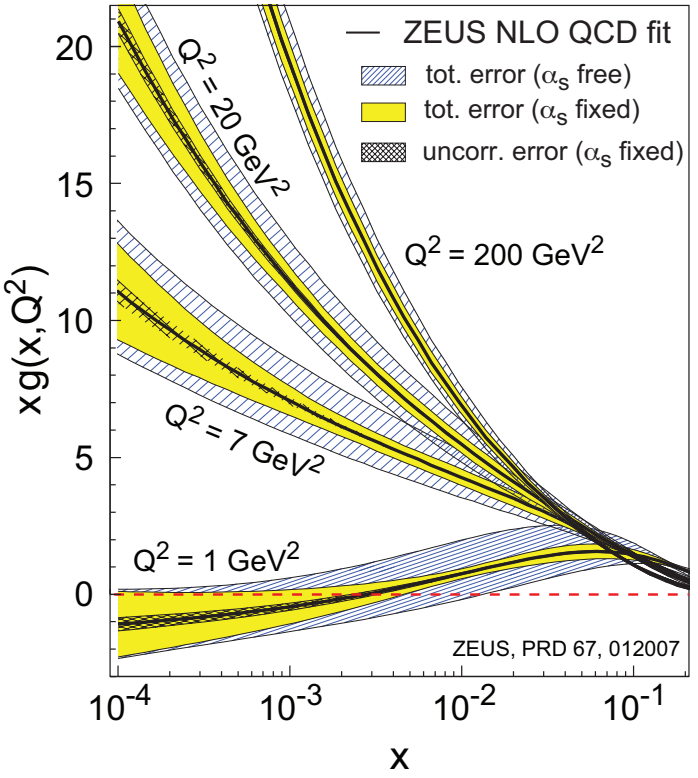
- Large Q^2
- built in high energy "catastrophe"
- G rapid rise violates unitary bound



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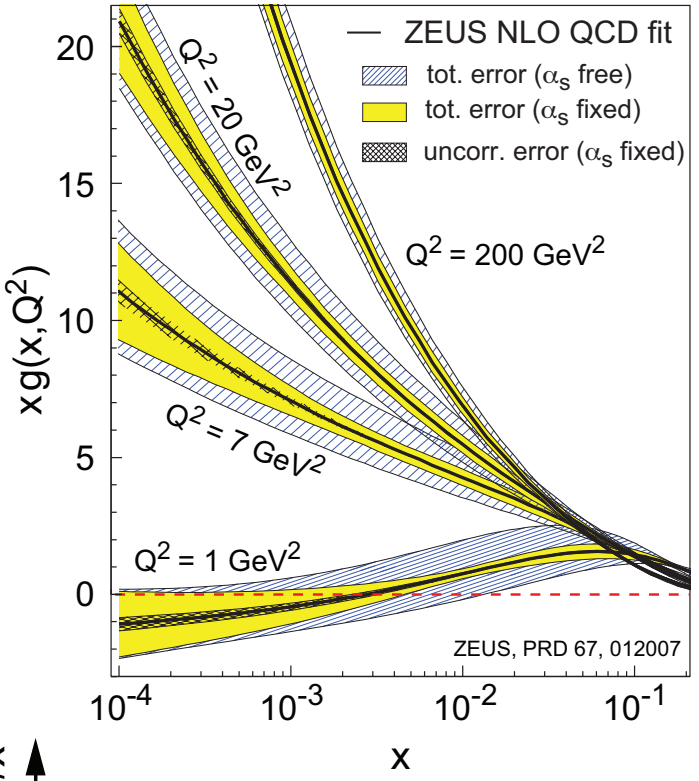
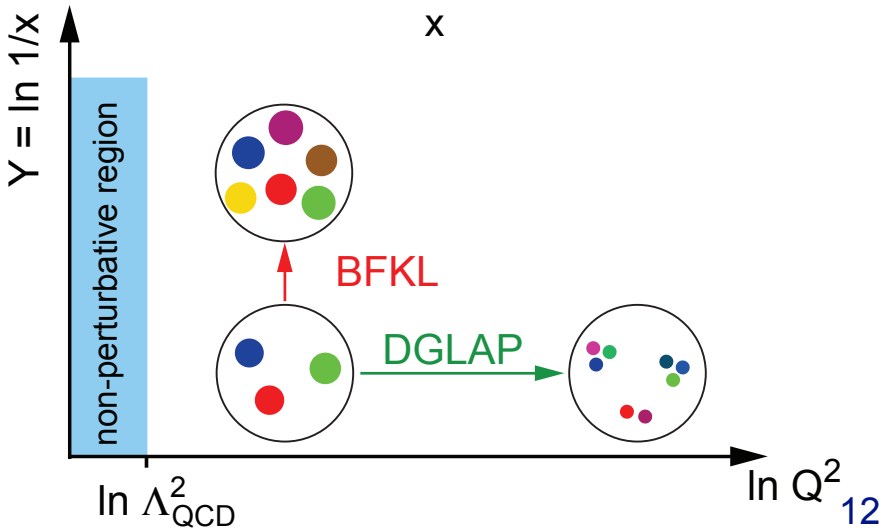


Linear BFKL Evolution Scheme

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



Issues with our Current Understanding

Linear DGLAP Evolution Scheme

- Low
  - G
  - G
- Larg
- built
- G ra

Something's wrong:

Gluon density is growing too fast

$\Rightarrow$ Must saturate (gluons recombine)

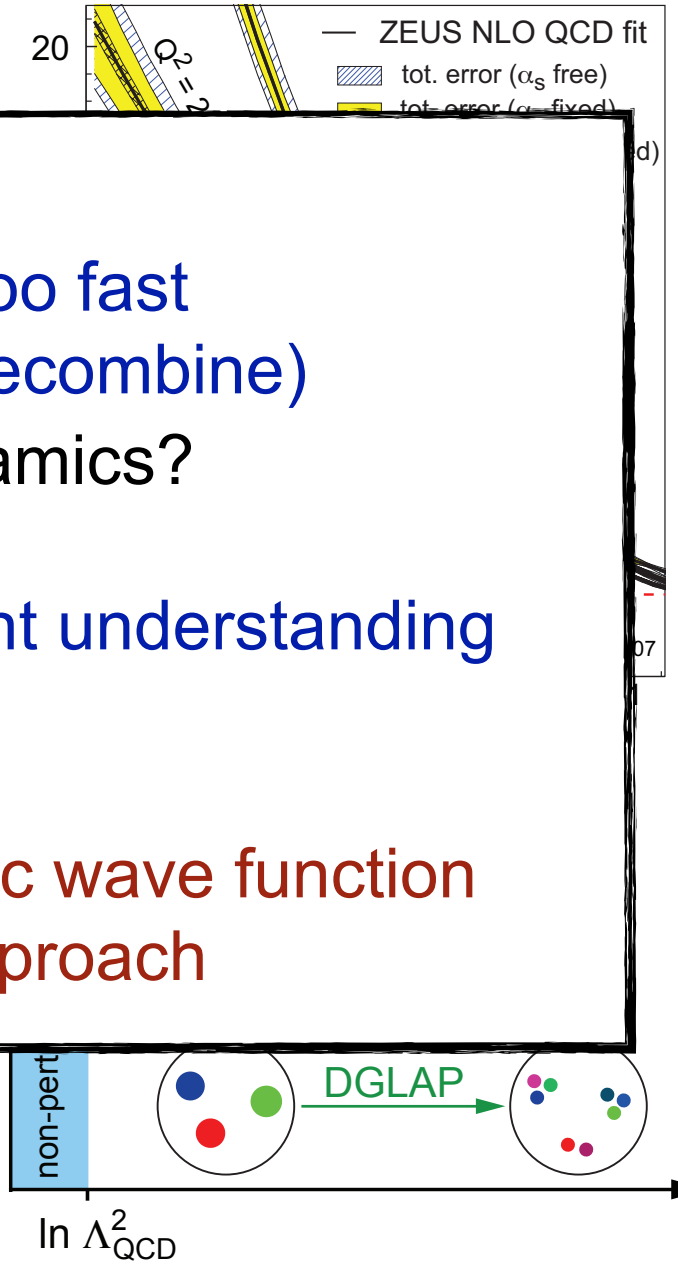
What's the underlying dynamics?

Strong hints that our current understanding of QCD is incomplete.

Low-x realm of the hadronic wave function require a complete new approach

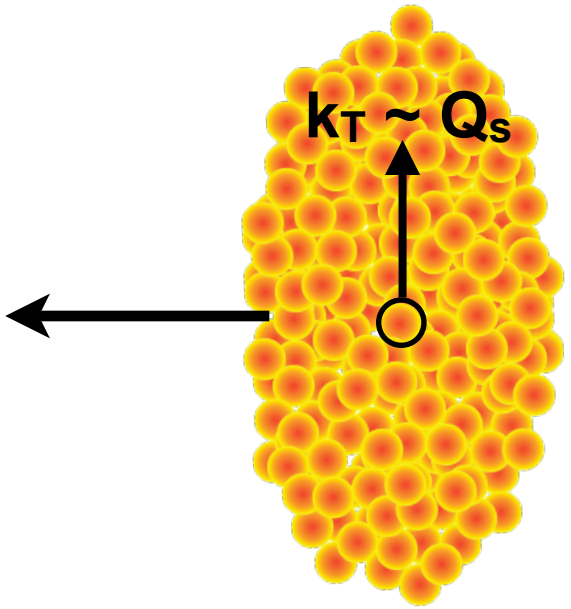
Linea

- Den pow
- Can densities & σ rise forever?
- Black disk limit: $\sigma_{total} \leq 2 \pi R^2$



Saturation/Color Glass Condensate

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 $k_T \sim Q_S$

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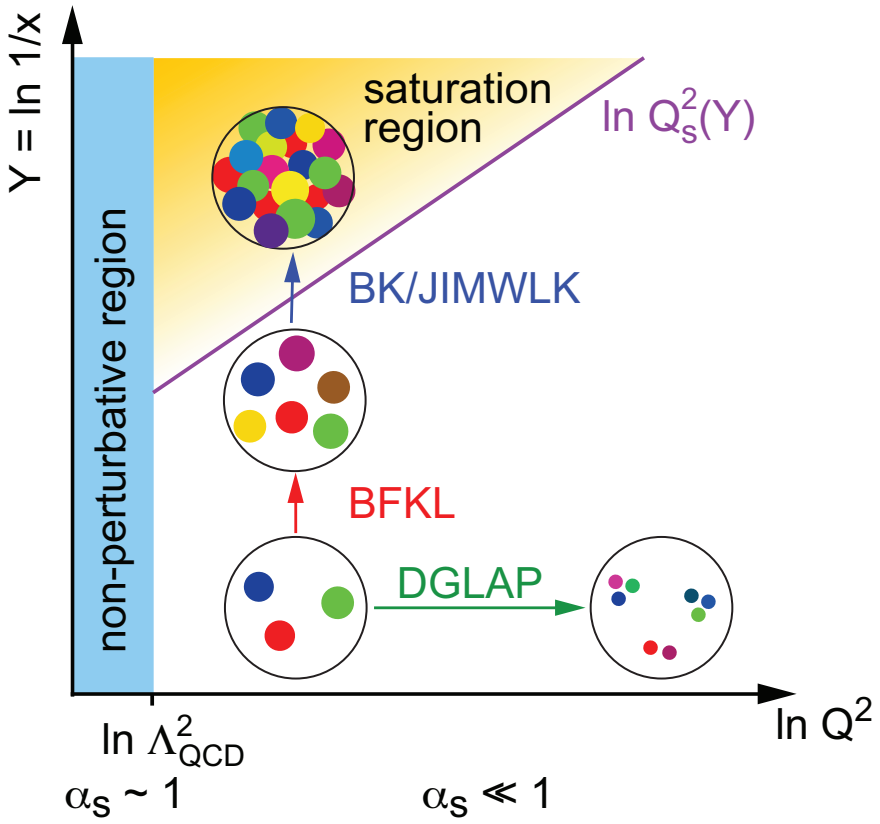

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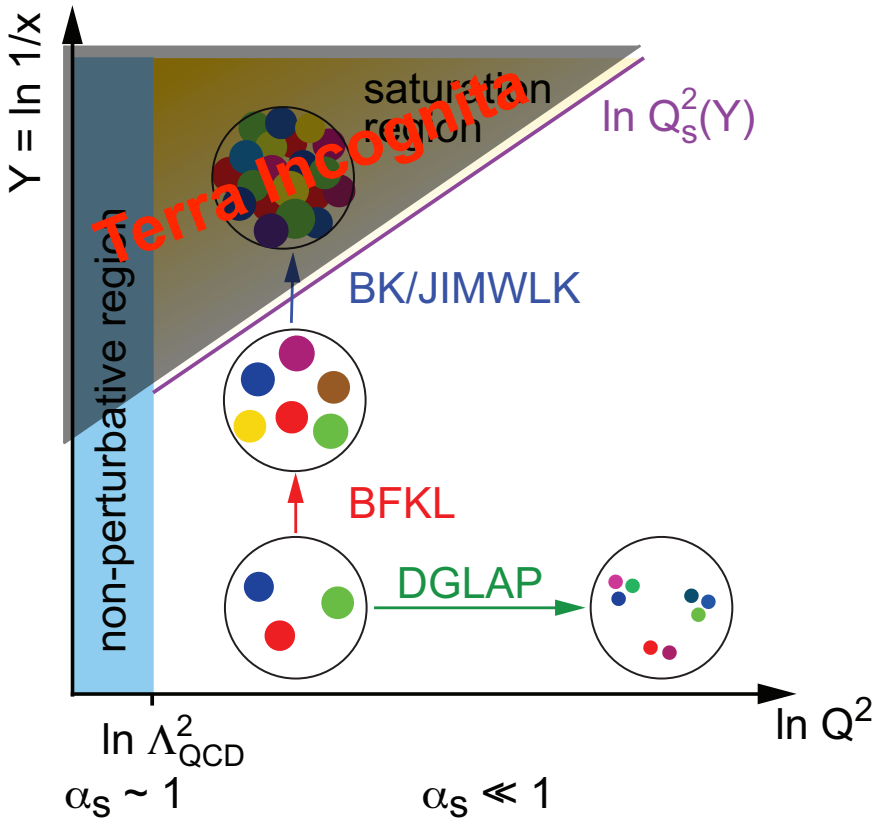

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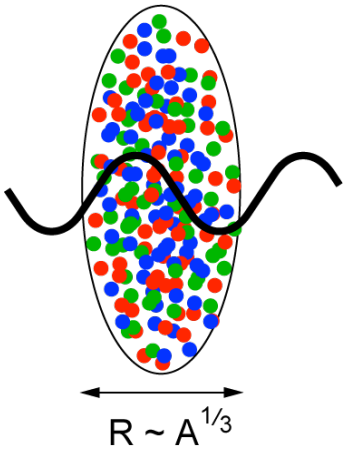
Raison d'être for e+A

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



"Expected"
Nuclear Enhancement Factor
(Pocket Formula):

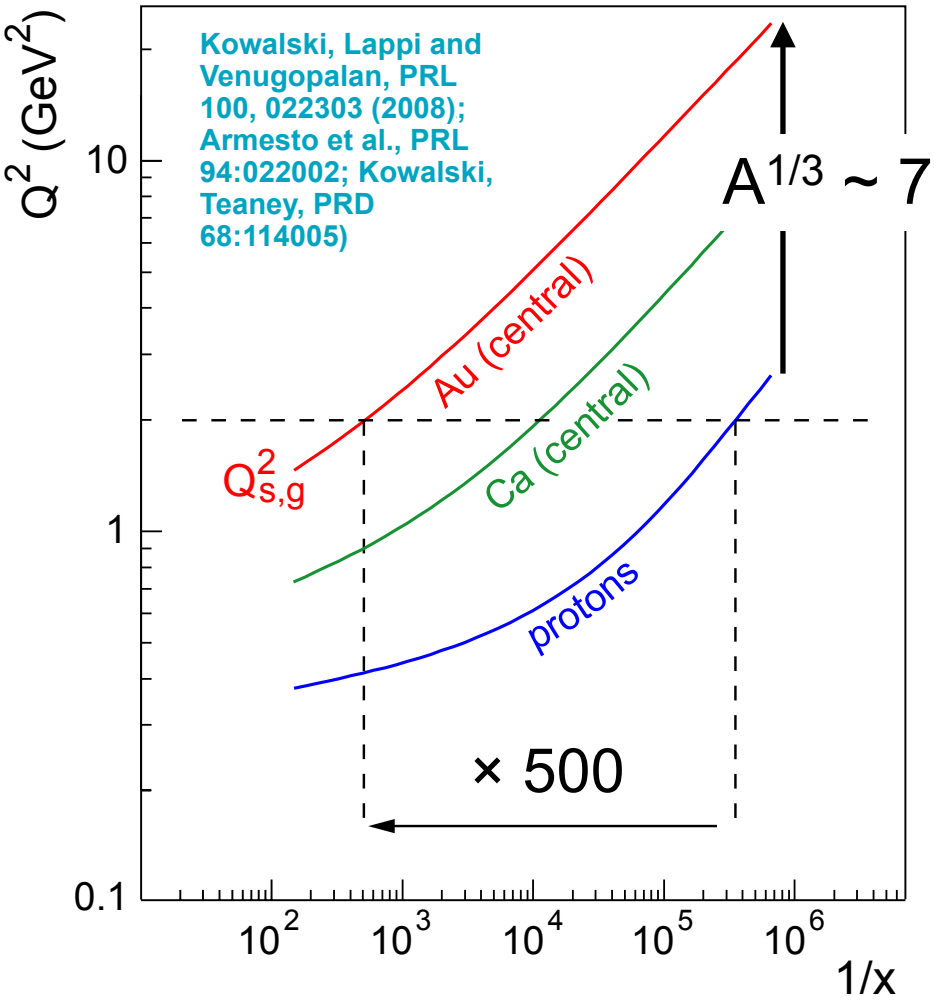
$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A $\Rightarrow$ non-linear QCD regime reached at significantly lower energy in nuclei

eA: Key to Studying Saturation

Electron-Ion Collider (EIC)

- Instead extending x, Q reach ⇒ increase Q_s
- More sophisticated analyses (constrained by data) confirm pocket formula



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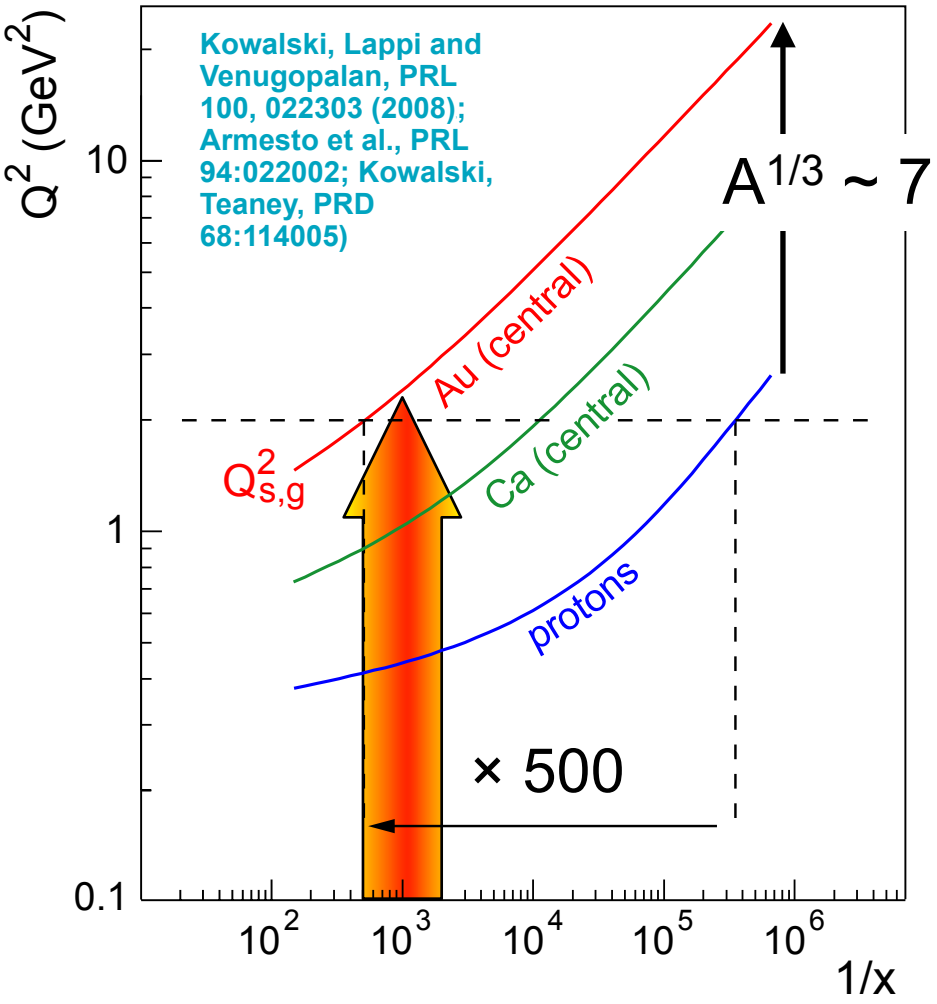
- **Strong hints** of saturation from RHIC: x ~ 10^{-3} in Au
- p: **No hints** at Hera up to x=$6.32 \cdot 10^{-5}$, Q^2 = 1-5 GeV^2



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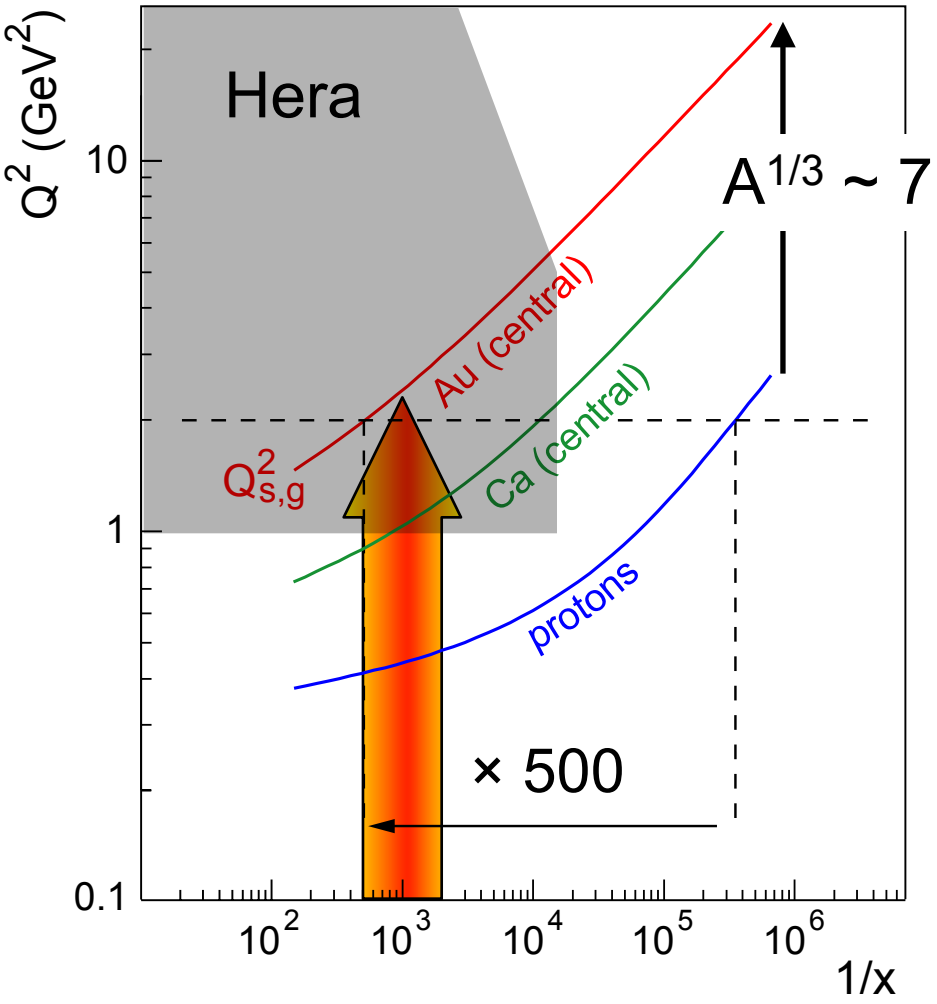

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Finding RHIC and Hera & Q_s scalings consistent

Measurements & Techniques

- Gluon Distribution $G(x,Q^2)$
  - Scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
    - day 1 measurements (inclusive DIS)
  - $F_L \sim xG(x,Q^2)$
    - requires running at wide range of $\sqrt{s}$
  - 2+1 jet rates
    - sensitive dominantly to large x
  - Diffractive vector meson production $([xG(x,Q^2)]^2)$
    - most sensitive method

- Space-Time Distribution
  - Exclusive diffractive VM production (J/ψ, ϕ, ρ) at $Q \sim 0$ (photoproduction)
    - Gluonic form factor of nuclei

EIC Science Case

- What is the nature and role of gluons and their self-interactions (eA, ep)?
- What is the internal landscape of the nucleons?
- What governs the transition of quarks and gluons into pions and nucleons?
- Electroweak Physics (studies underway)

EIC Science Case

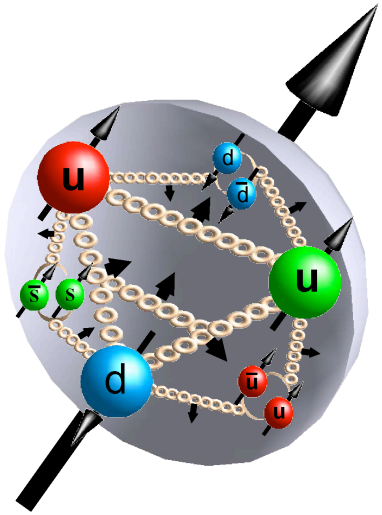
- What is the nature and role of gluons and their self-interactions (eA, ep)?
- What is the internal landscape of the nucleons?

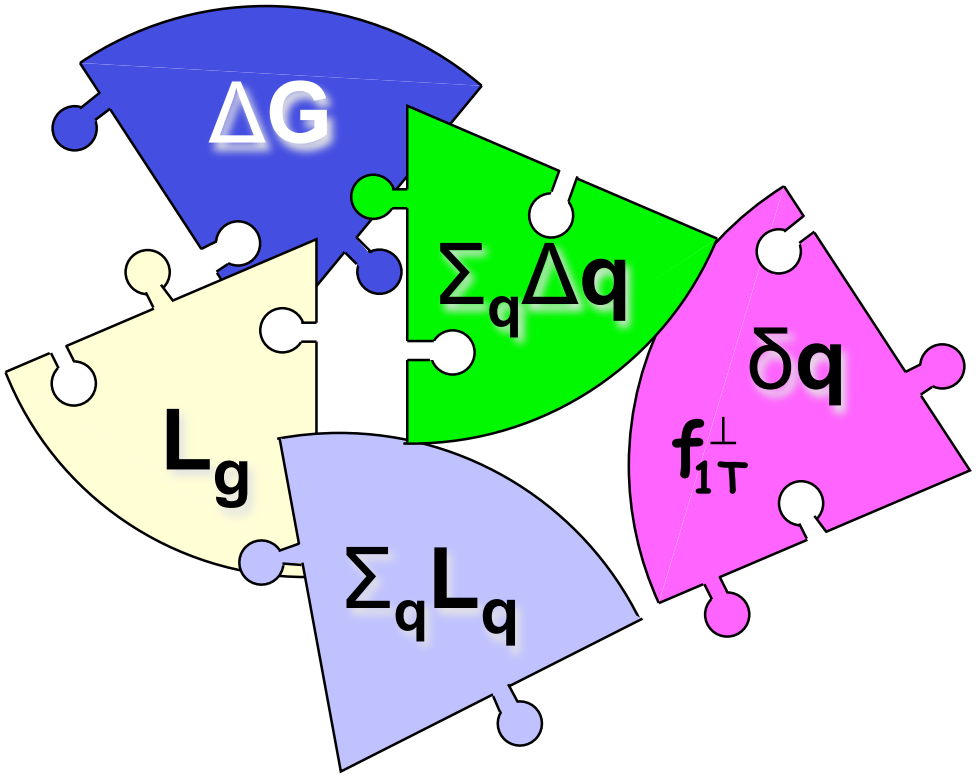
Required Measurements:

- Exclusive and Semi-inclusive Measurements
- Polarized beams: $e\uparrow p\uparrow$ $e\uparrow He^{3}\uparrow$ (polarized n!)

Nature of Spin of the Proton ?

Is the proton looking like this?





Longitudinal Helicity Sum Rule:

Gluon spin

$$\frac{1}{2}\hbar = \underbrace{\sum_q \frac{1}{2} S_q}_{\text{Total u+d+s quark spin}} + \overbrace{S_g} + \underbrace{\sum_q L_q + L_g}_{\text{Angular momentum}}$$

(IMF only)

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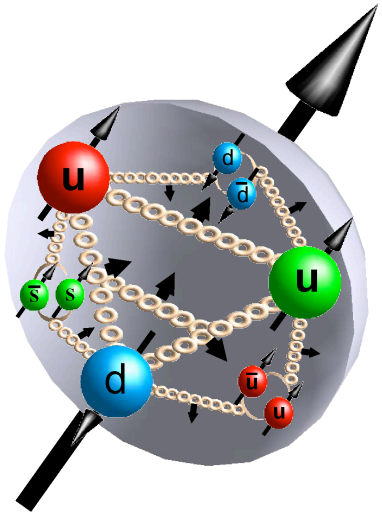

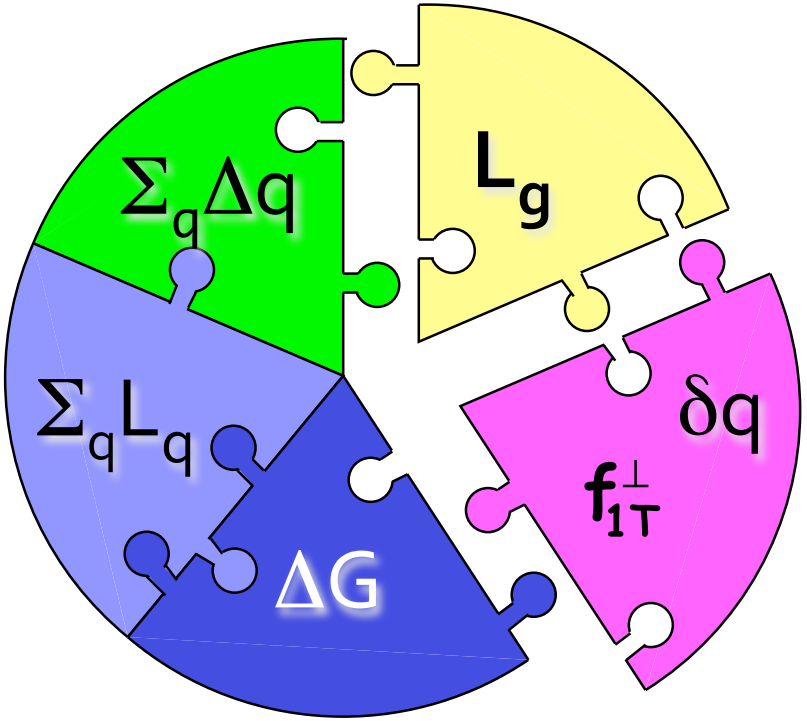

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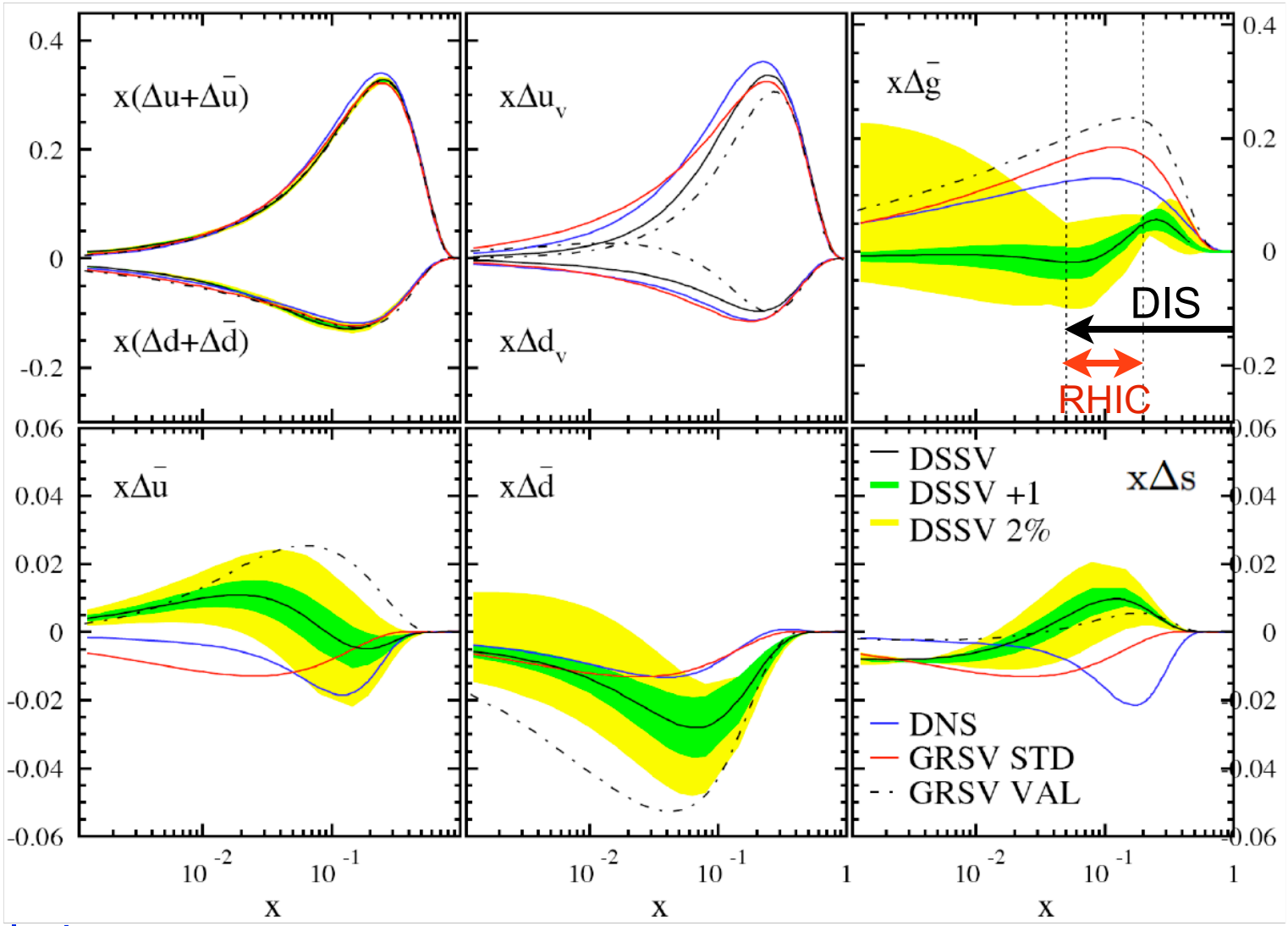
What Do We Know? NLO Fits to World Data



Includes:

World Data from DIS, SIDIS, pp (incl. Hermes, Compass, RHIC)

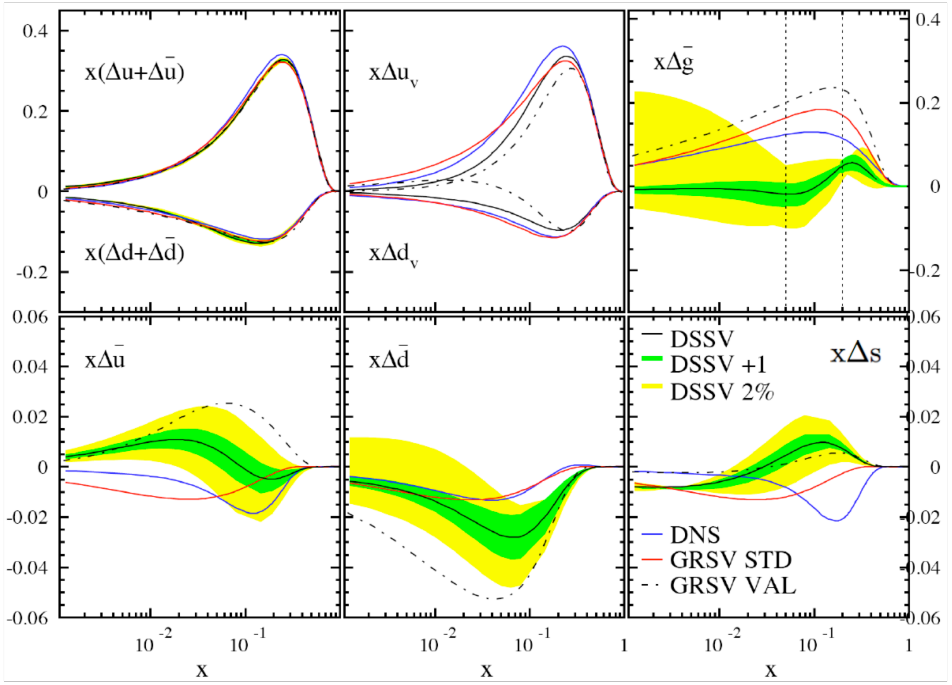
What Do We Know? NLO Fits to World Data

DSSH: D. De Florian et al. arXiv:0804.0422

	Δu_v	Δd_v	$\Delta \bar{u}$	$\Delta \bar{d}$	Δs	Δg	$\Delta\Sigma$
DSSV	0.813	-0.458	0.036	-0.115	-0.057	-0.084	0.242

Big questions:

- $\Delta G = \int \Delta g(x)\, dx$
  - no measurements below $x \sim 5 \cdot 10^{-2}$
- How do we access L_q and L_g in the IMF?



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Impact of EIC: g_1

$$\sigma = \sigma[F_2(x,Q^2), F_L(x,Q^2),\ g_1(x,Q^2), g_2(x,Q^2)]$$

- longitudinal polarization probes mainly g_1
- g_1 has partonic interpretation like F_1 but now in terms of pol. PDFs

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

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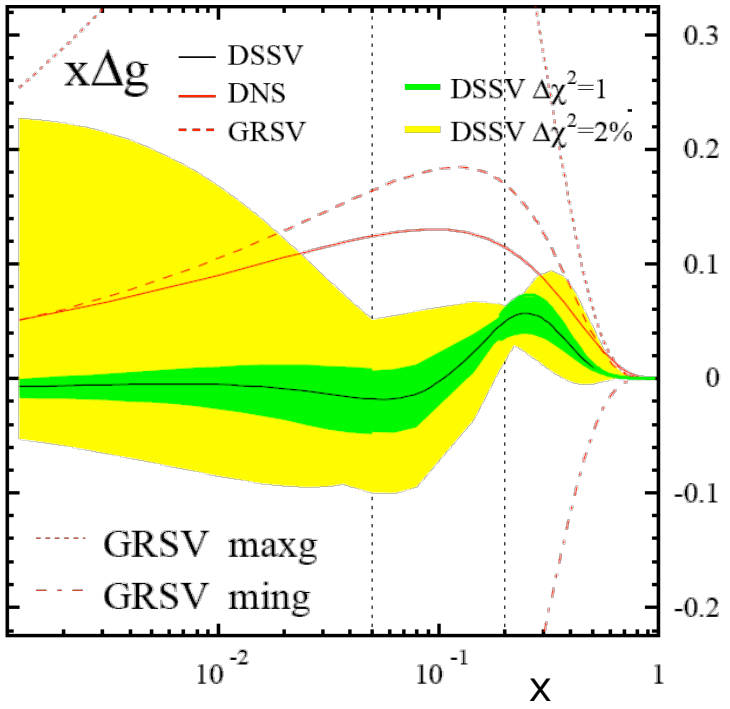

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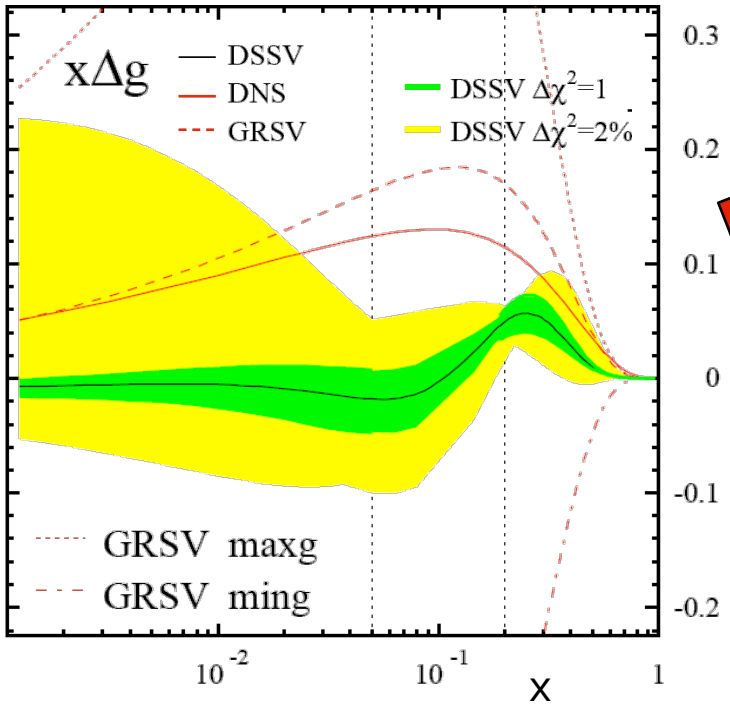

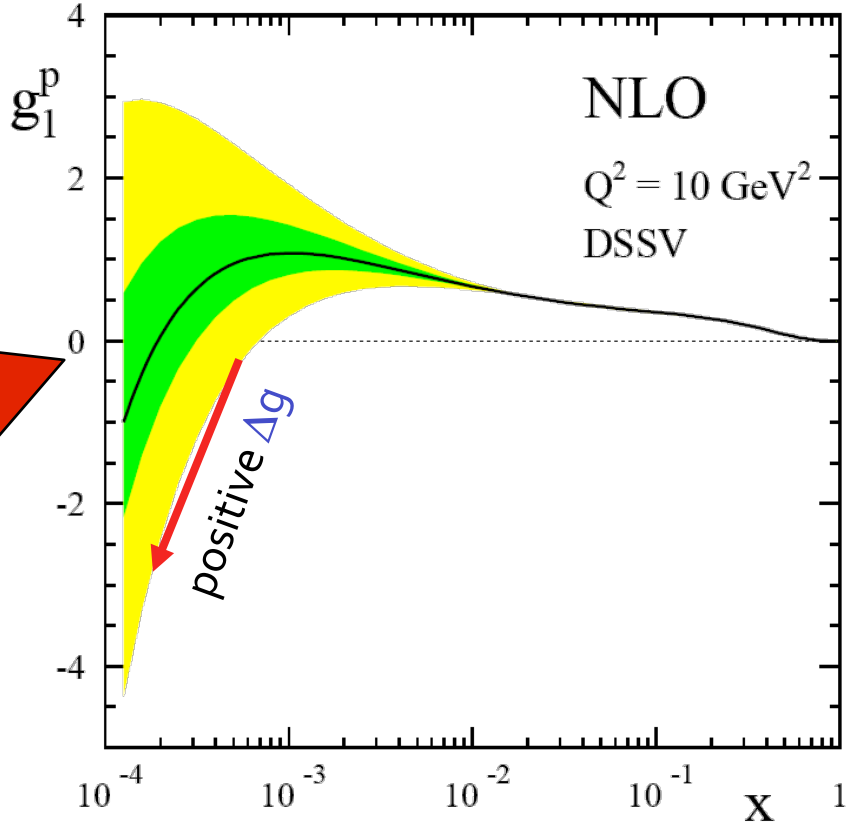

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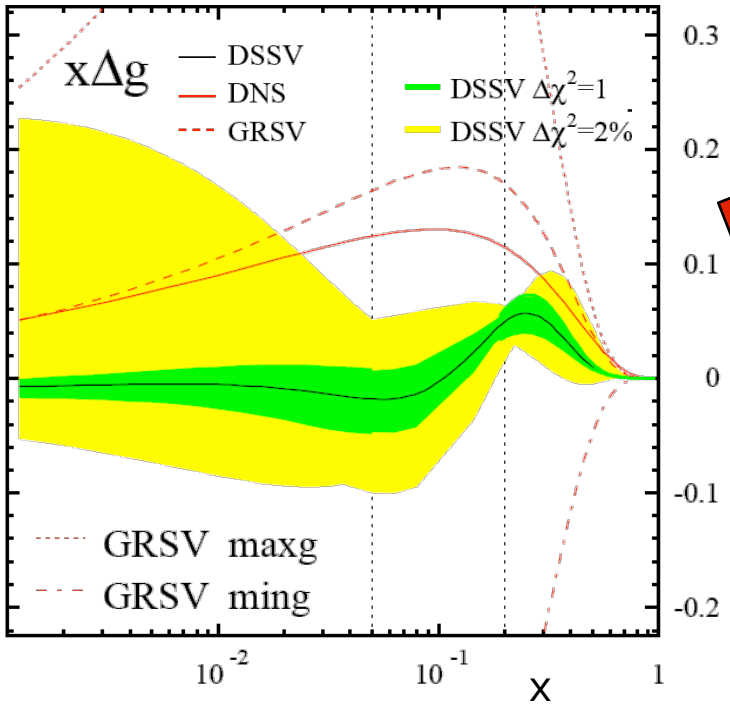

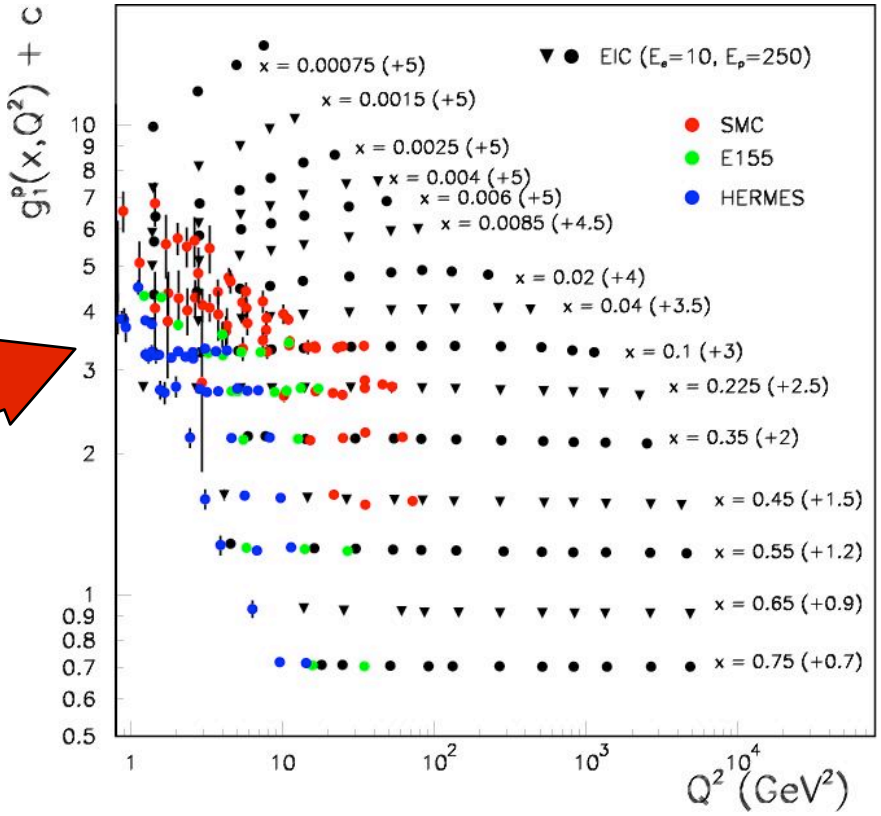

Anticipated precision for one beam energy combination
Integrated Lumi: 5fb^{-1} ~ 1 week data taking

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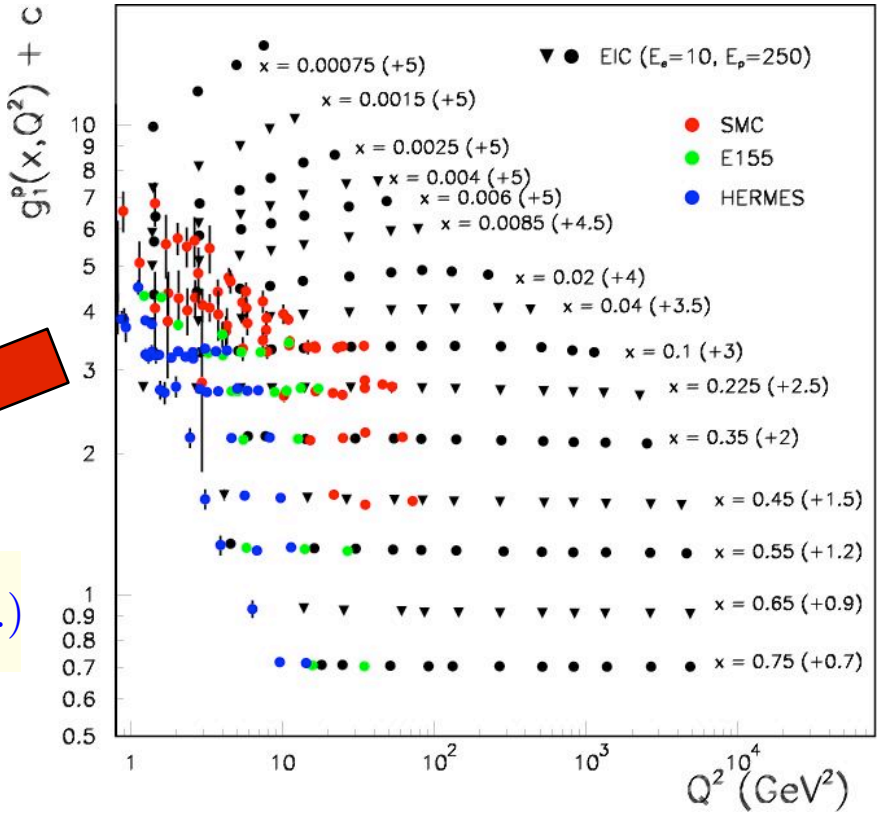
$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$

- Constraints ΔG down too x ~ 10^{-3}-10^{-4}
- Allows precision study of Bjorken sum rule

$$\int_0^1 dx[g_1^p(x,Q^2) - g_1^n(x,Q^2)] = \frac{g_A}{6}(1 - \frac{\alpha_s}{\pi} - ...)$$

(rare example of a well understood fundamental quantity in QCD)



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Beyond Spin: Full 3D Imaging of Proton

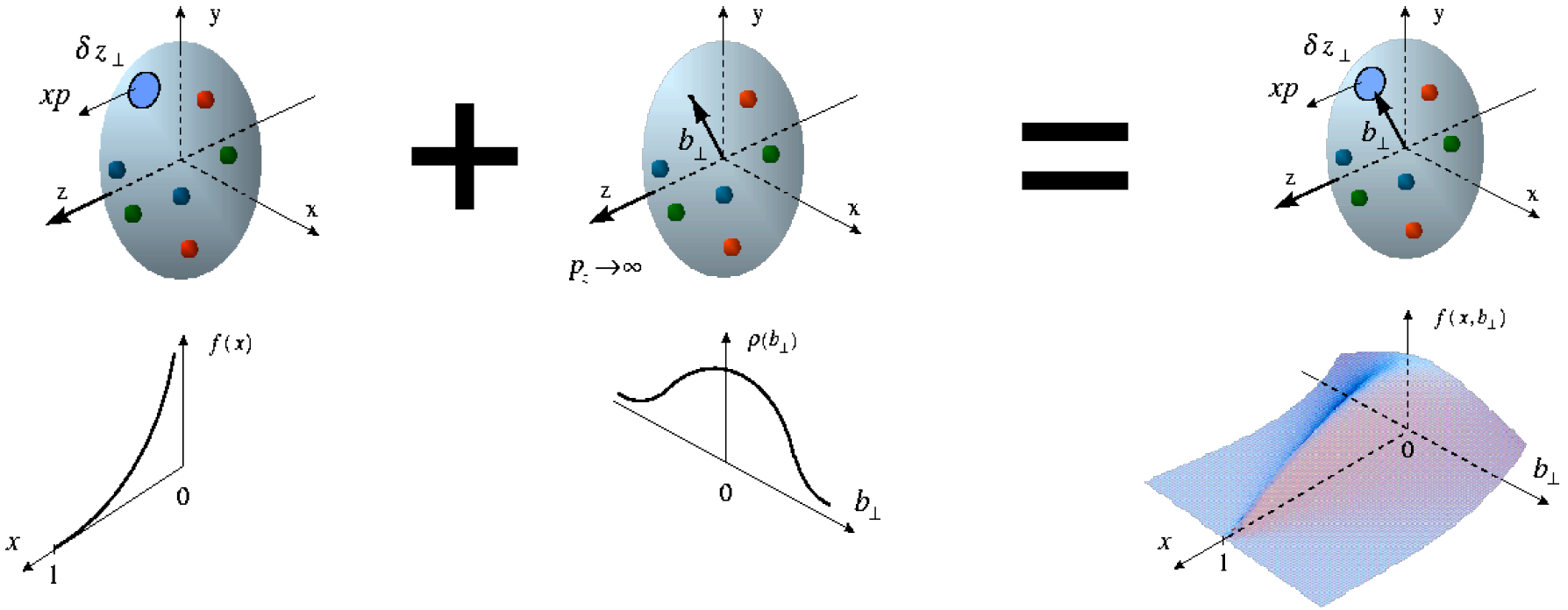
Generalized Parton Distributions

X. Ji, D. Mueller, A. Radyushkin (1994-1997)

Structure functions, quark longitudinal momentum (PDF) & helicity distributions

Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs



GPDs $\Rightarrow$ Orbital Momentum L

GPDs: $H^q, E^q, \tilde{H}^q, \tilde{E}^q$ (~ = pol.)

- Can be studied at EIC using hard exclusive processes
- 1st moments can be calculated on lattice
- GPDs are defined in the proton rest frame (not IMF!)
- Ji's Sumrule:

$$\frac{1}{2} = J_z^q + J_z^g = \frac{1}{2}\sum_q \Delta q + \sum_q L_z^q + J_z^g$$

$$J_z^q = \frac{1}{2}\sum_q \Delta q + \sum_q L_z^q$$

$$= \frac{1}{2}\int x(H^q + E^q)dx \,\Big|_{t\to 0}$$

Note: No separation between Δg and L_g

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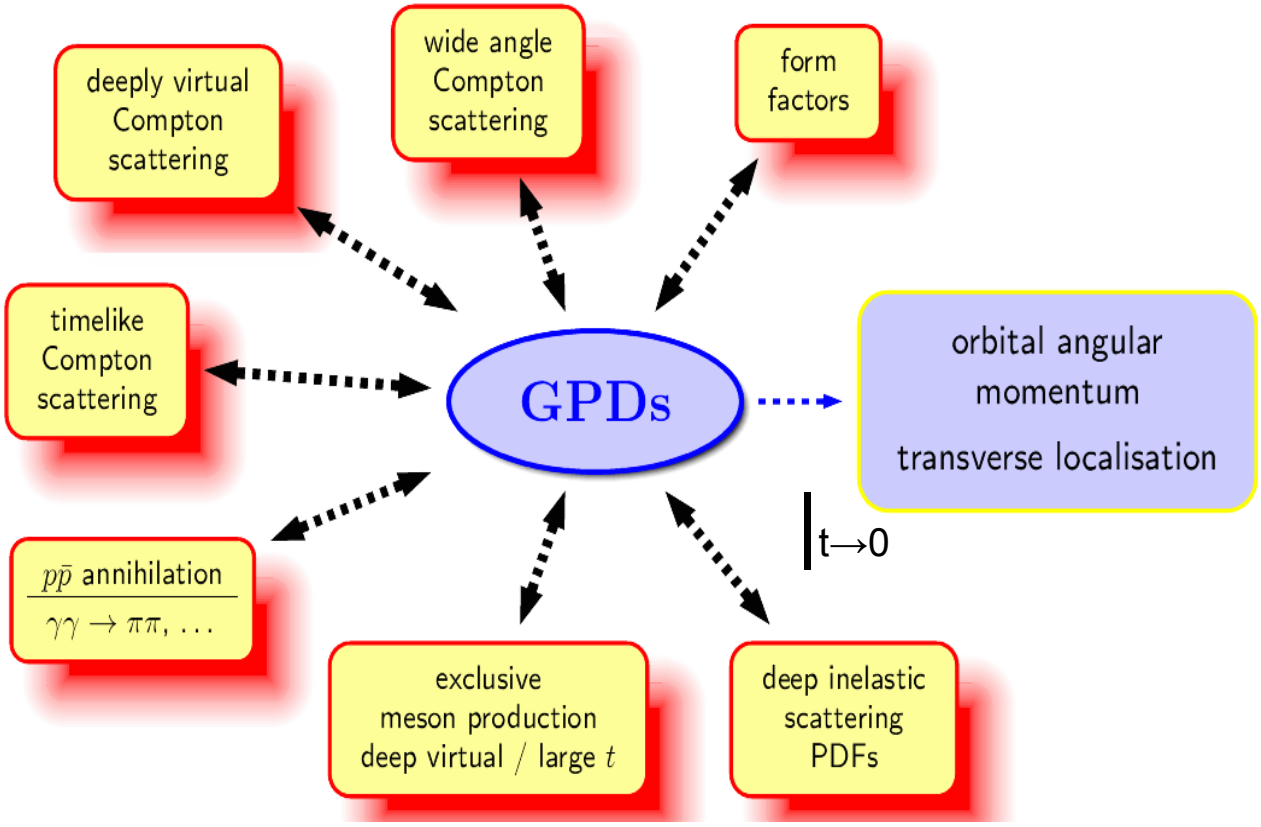
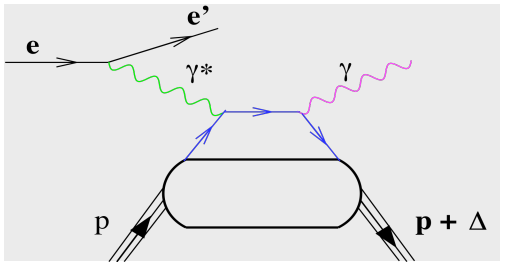
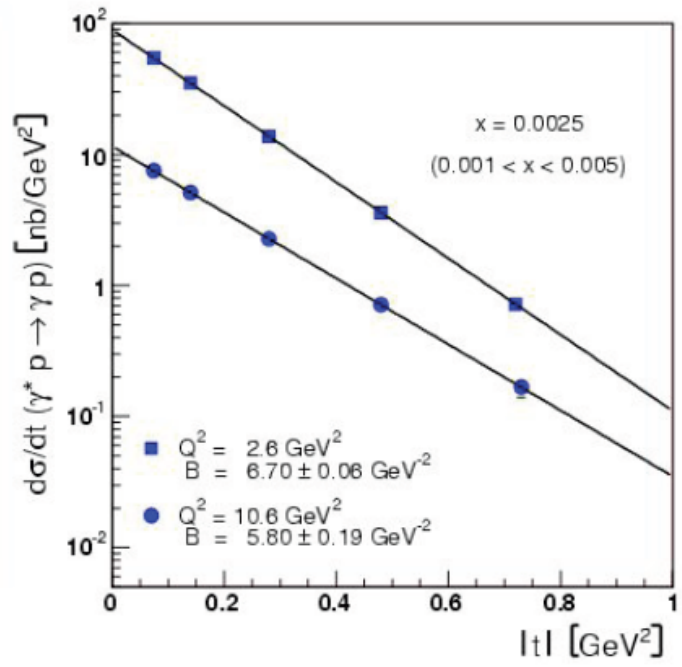
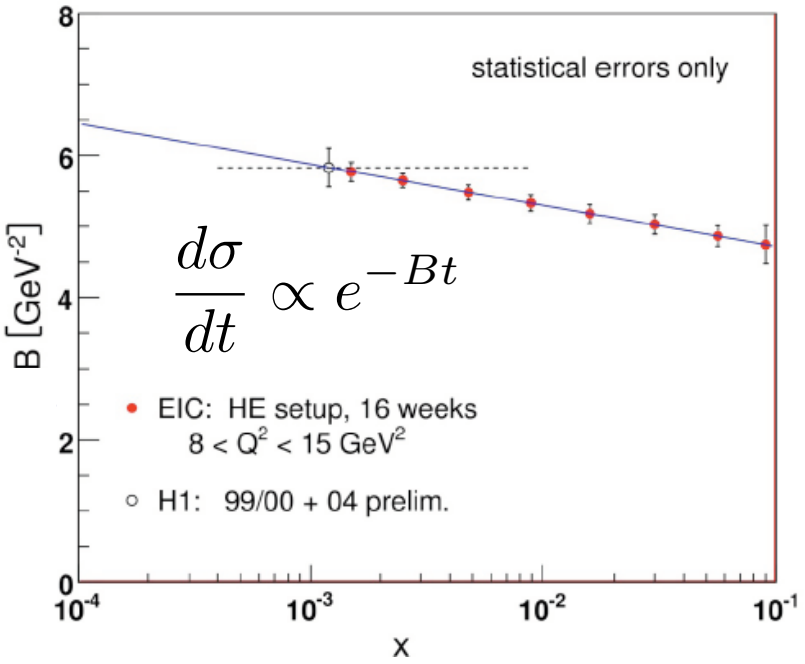


Measurements to Constraint GPDs

- Quantum number of final state selects different GPDs:
  - DVCS (γ): H, E, $\tilde{H}$, $\tilde{E}$
  - pseudo-scaler mesons: $\tilde{H}$, $\tilde{E}$
  - vector-mesons: H, E
- Need wide x and Q^2 range to extract GPDs
- Need sufficient luminosity to bin in multi-dimensions

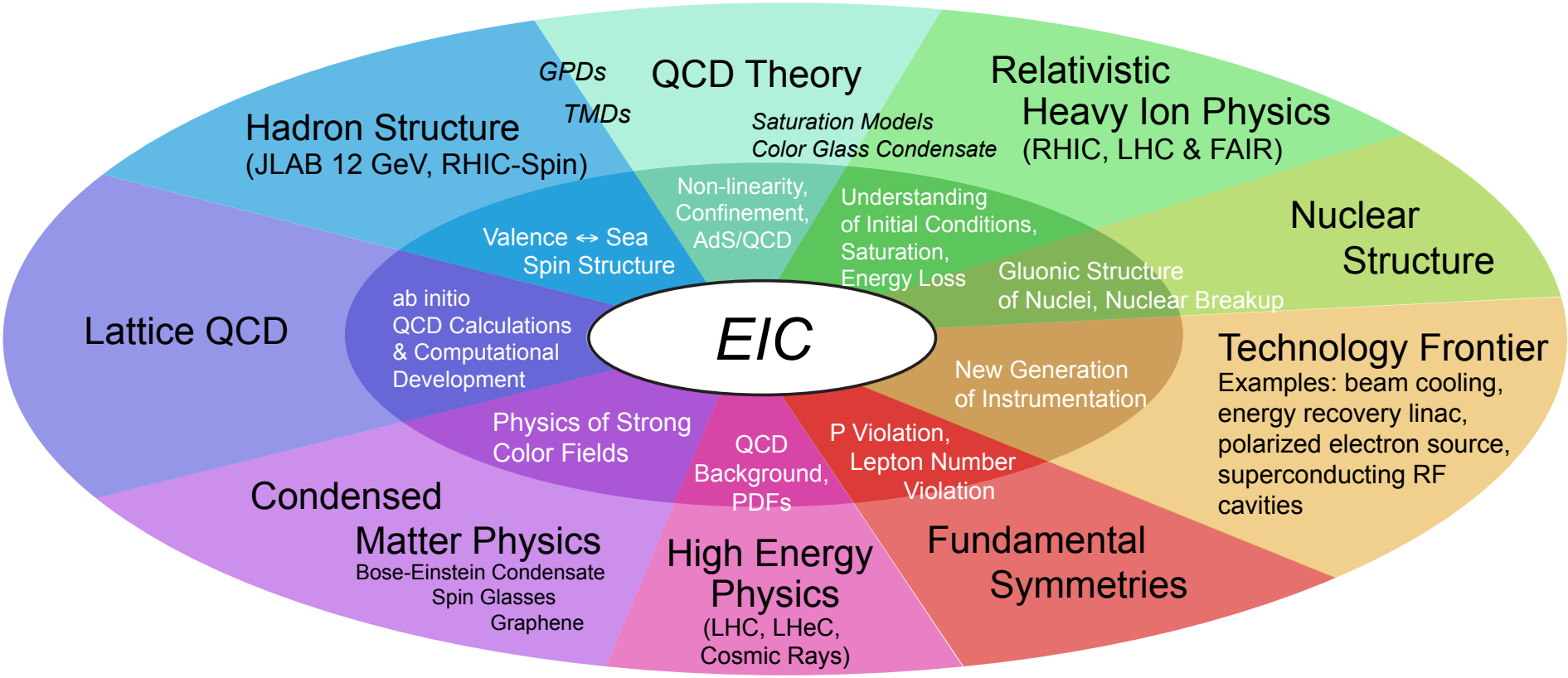






EIC Science Case

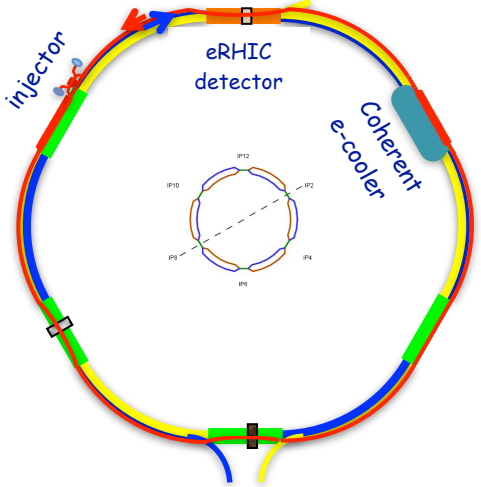
A unique opportunity for fundamental physics:



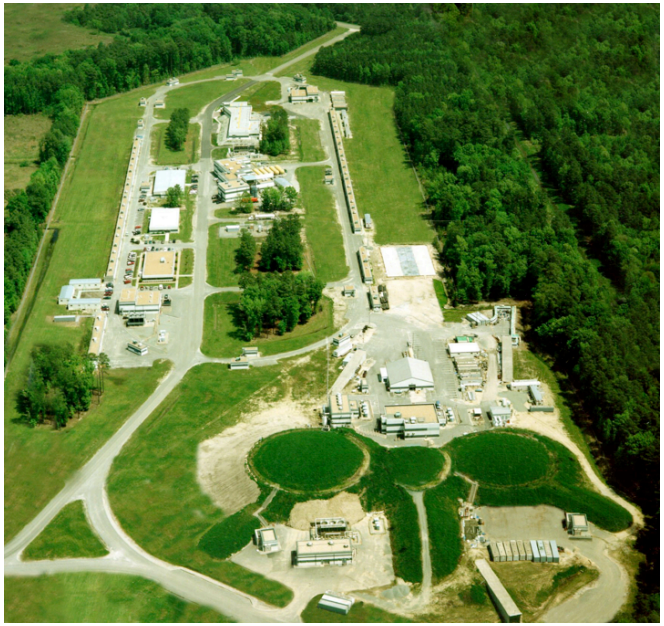
- Increasing Global Interest in ep/eA Facilities
  - LHeC (CERN)
  - EIC (BNL/JLAB)
  - ENC (FAIR)

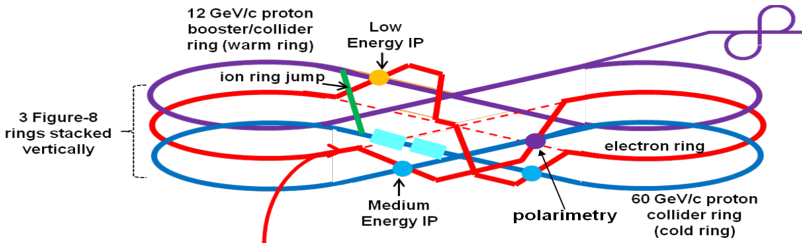
EIC Concepts: BNL & JLAB

eRHIC = RHIC + Energy-Recovery Linac



ELIC = CEBAF + Hadron Ring





See talk by Vladimir Litvinenko

EIC Outlook

NSAC Long Range Plan 2007

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

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- Next Key Event:
  - INT Workshop: Gluons and the Quark Sea at High Energies: Sep-Nov, 2010 ⇒ Science Case for EIC