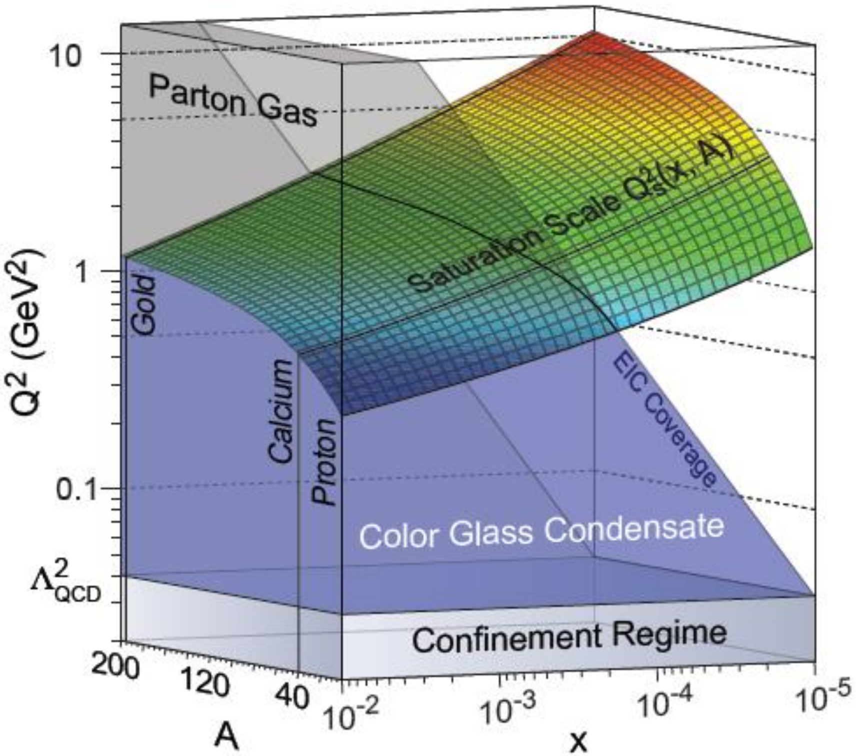
High Energy eA Scattering



Roy Lemmon

Daresbury Laboratory

LHeC UK Discussion Meeting

Liverpool University

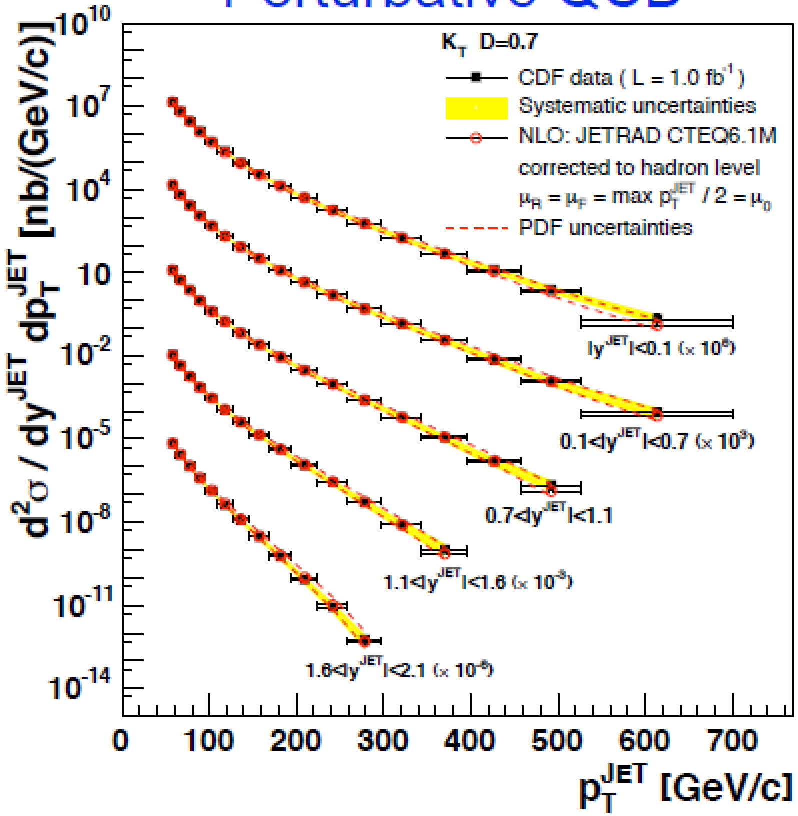
09 May 2013

Science & Technology Facilities Council

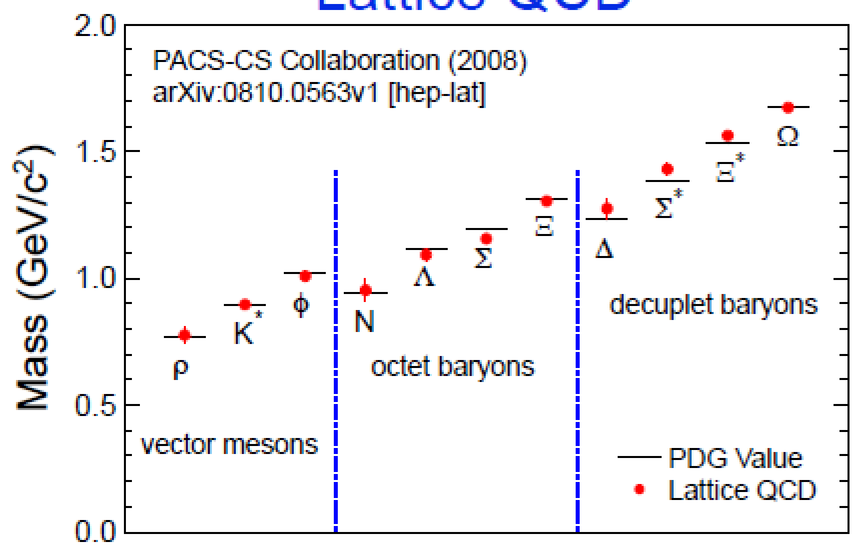
Strong Evidence that QCD is the Correct Theory

- Calculations:
  - hard processes (large m, p, Q^2) ⇒ perturbative QCD
  - everything else ⇒ Lattice QCD, effective field theories, AdS/CFT?

Perturbative QCD



Lattice QCD



Absolutely essential but also far from the full story…

New Frontier: "Gluonic" Structure of Matter

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

QCD is the "nearly perfect" fundamental theory of the strong interactions

F. Wilczek, hep-ph/9907340

New Frontier: "Gluonic" Structure of Matter

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QCD is the "nearly perfect" fundamental theory of the strong interactions

F. Wilczek, hep-ph/9907340

- "Emergent" Phenomena not evident from Lagrangian
  - Asymptotic Freedom
  - Confinement
  - Phases of QCD ($T > 0$, $\mu_B > 0$)

New Frontier: "Gluonic" Structure of Matter

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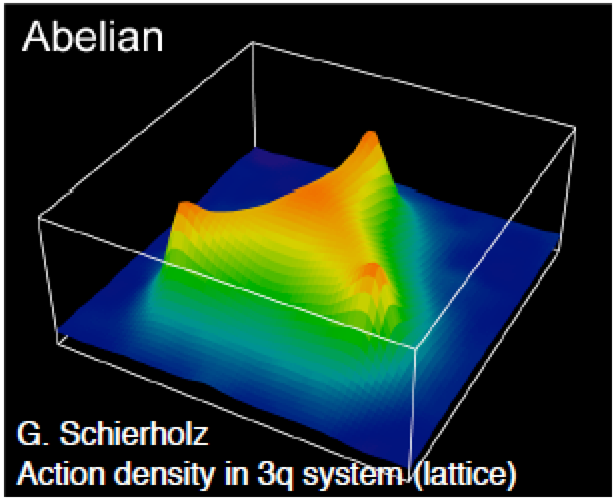
- **Gluons**
  - Self-interacting force carriers



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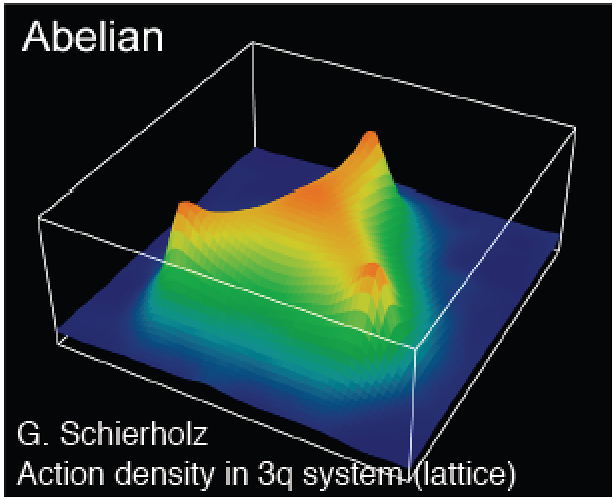
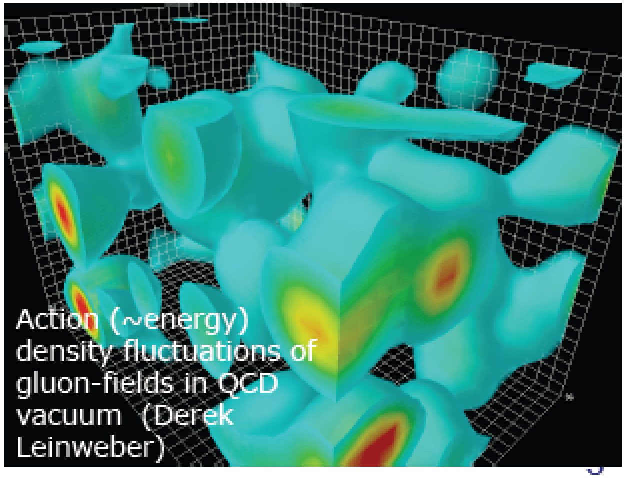
- **Gluons**
  - Self-interacting force carriers
  - Dominate structure of QCD vacuum





New Frontier: "Gluonic" Structure of Matter

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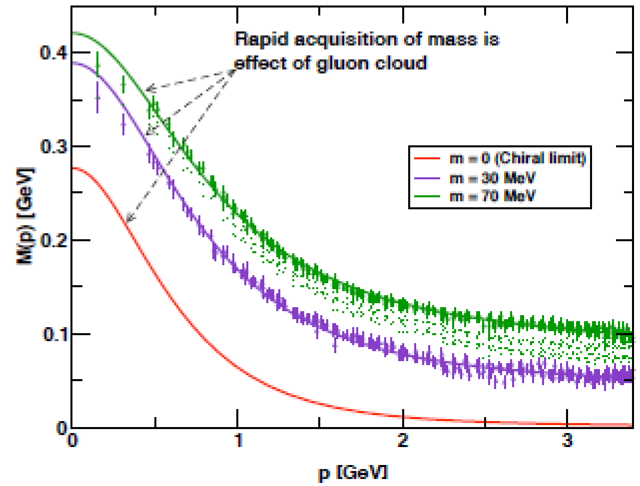
- **Gluons**
  - Self-interacting force carriers
  - Dominate structure of QCD vacuum
  - Responsible for >94% if visible mass in universe
    - Quenched QCD explains mass spectrum to ± 10%
  - Determine essential features of QCD

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

Bhagwat et al., nucl-th/0710.2059



Chiral Pertubation Theory

In chiral SU(3) limit:

M_p = 880 MeV

Meißner, hep-ph/0501009

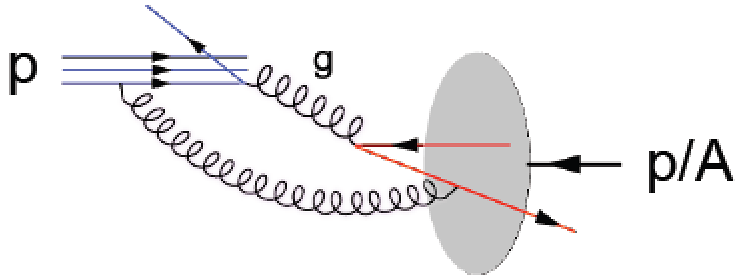
Sum Rules & Trace Anomaly

Quark kinetic + potential energy = only 1/3 of M_p

J. Ji, PRL 73, 1071

How to Study Gluons in Matter ?

Hadron-Hadron



- Test QCD
- Probe/Target interaction directly via gluons
- lacks the direct access to partons kinematics
- probe has complex structure

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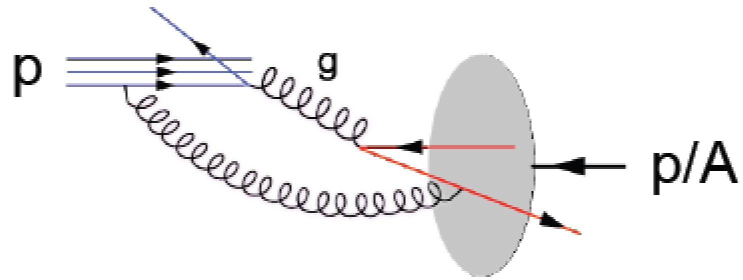

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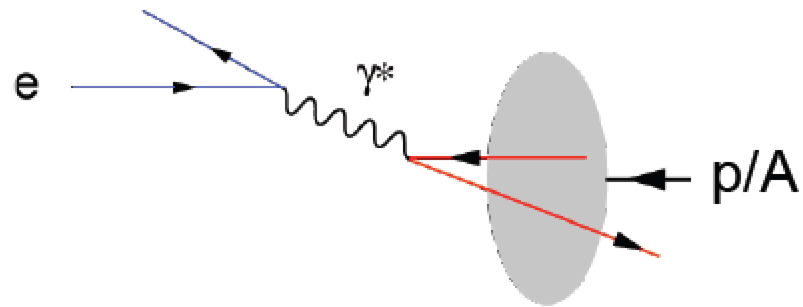
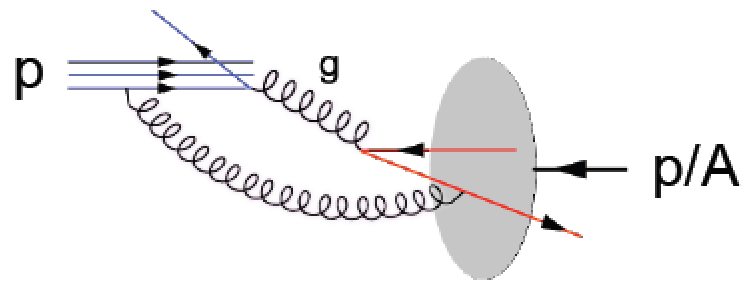
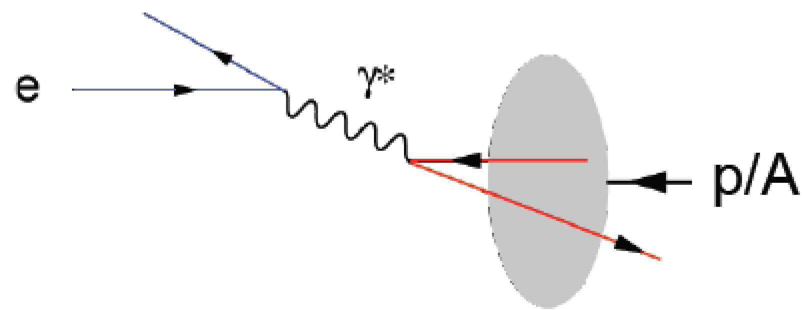
Electron-Hadron (DIS)



- Explore QCD & Hadron Structure
- Indirect access to glue
- High precision & access to partonic kinematics
- probe point-like

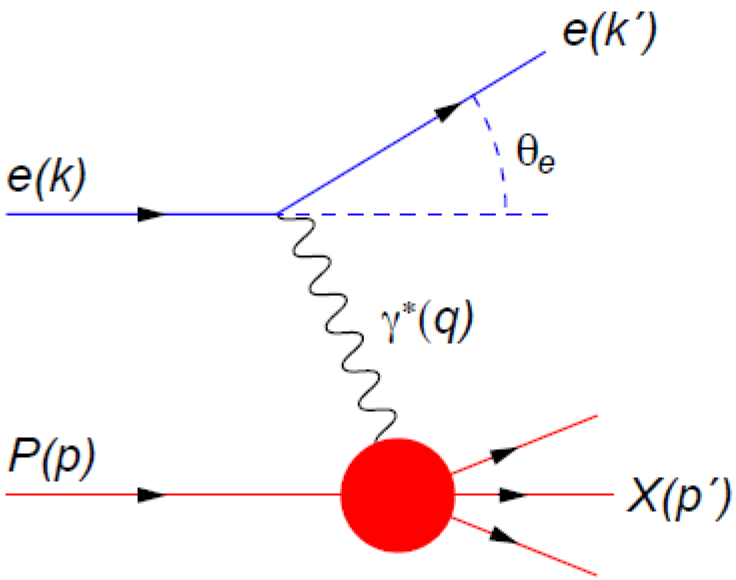
How to Study Gluons in Matter ?

Hadron-Hadron	Electron-Hadron (DIS)
	
• Test QCD • Probe/Target interaction directly via gluons • lacks the direct access to partons kinematics • probe has complex structure	• Explore QCD & Hadron Structure • Indirect access to glue • High precision & access to partonic kinematics • probe point-like

Both are complementary and provide excellent information on properties of gluons in the nuclear wave functions

Precision measurements ⇒ ep, eA

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

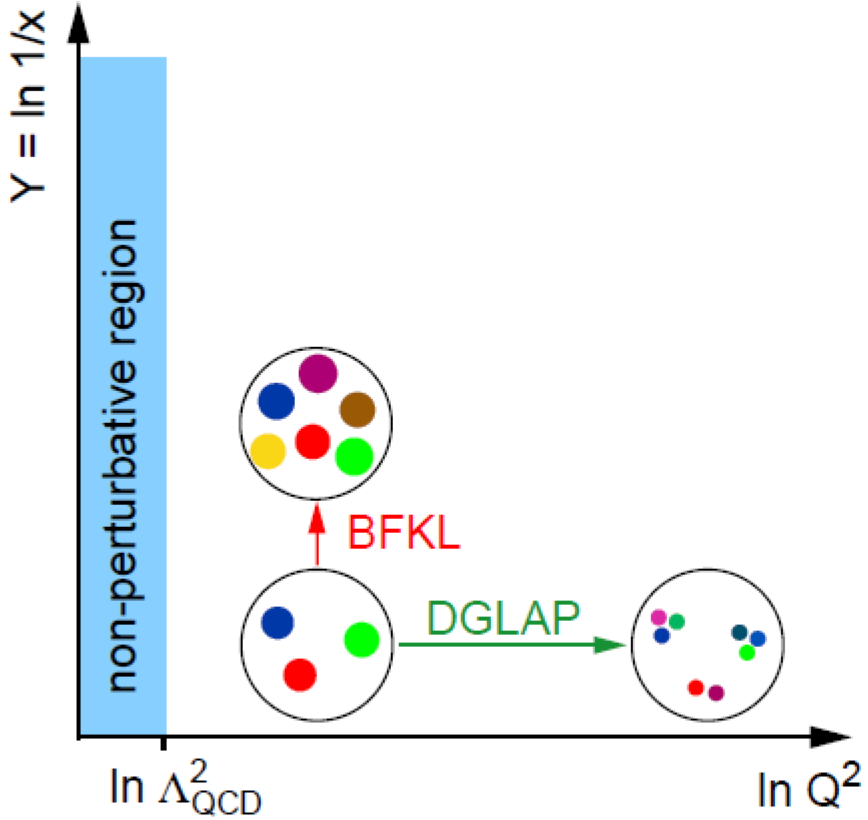
$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

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

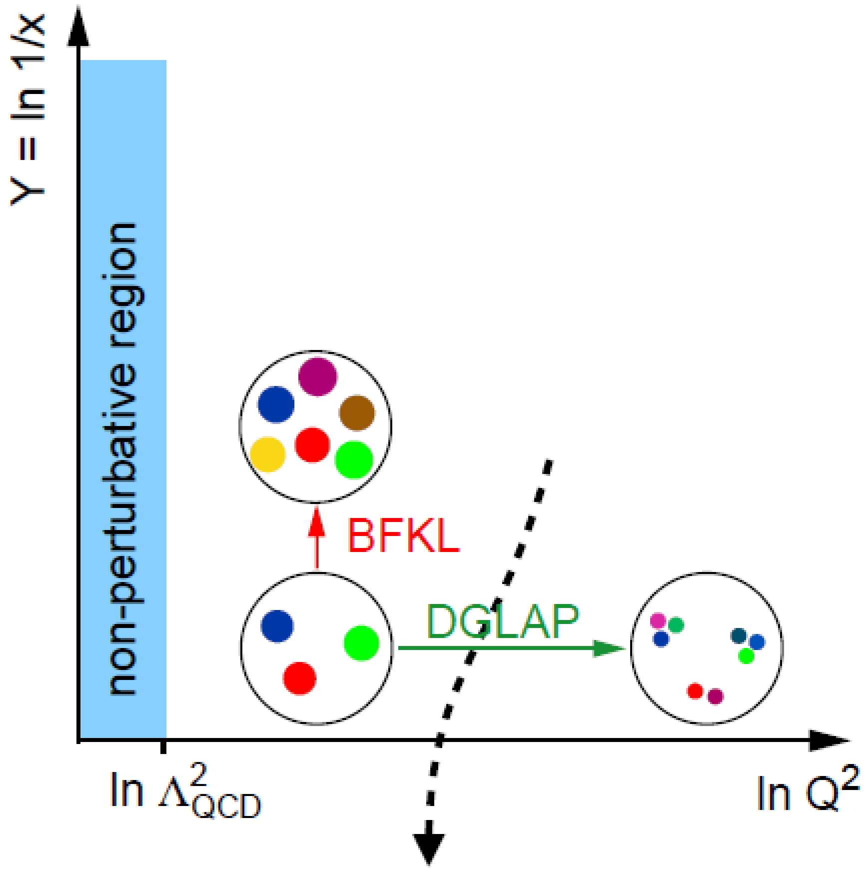
quark+anti-quark momentum distributions

gluon momentum distribution

Regimes of the Hadronic Wave Function

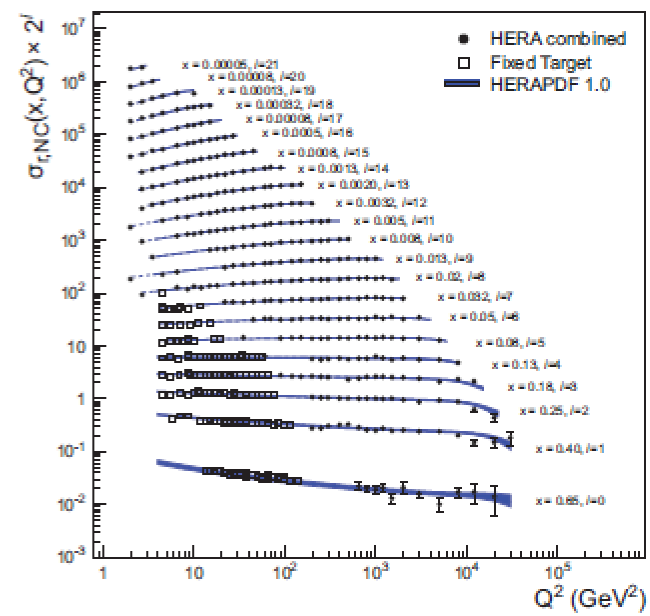


Regimes of the Hadronic Wave Function



pQCD and DGLAP & BFKL evolution works with high precision (⇒HERA)

$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$
$$\approx F_2(x,Q^2)$$



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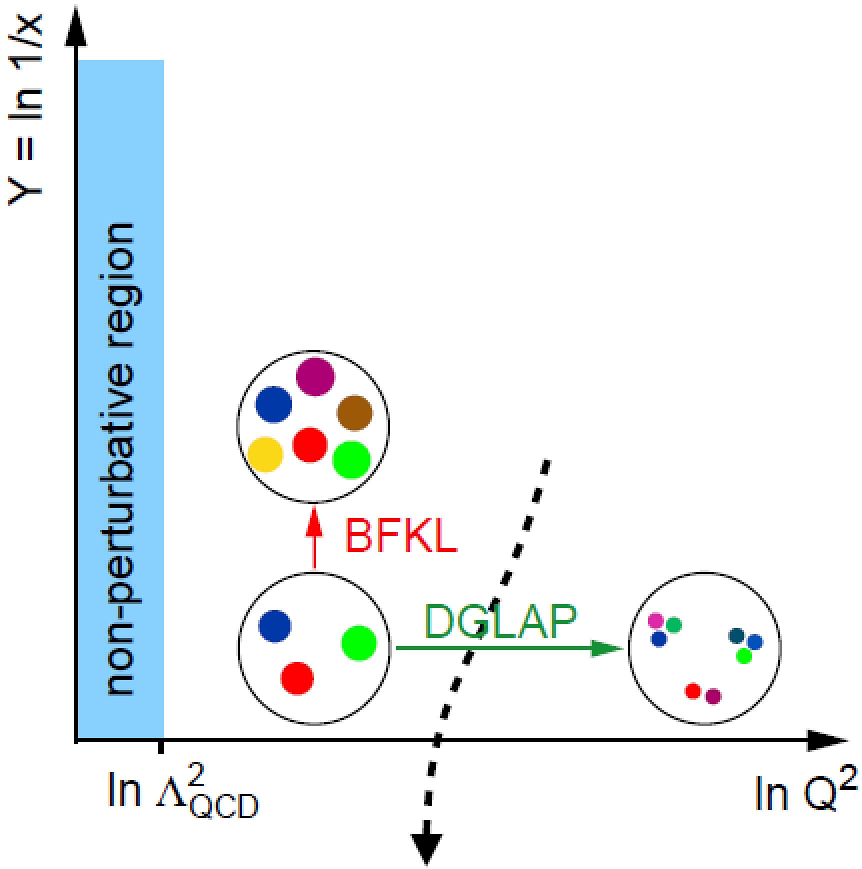


pQCD and DGLAP & BFKL evolution works with high precision (⇒HERA)

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

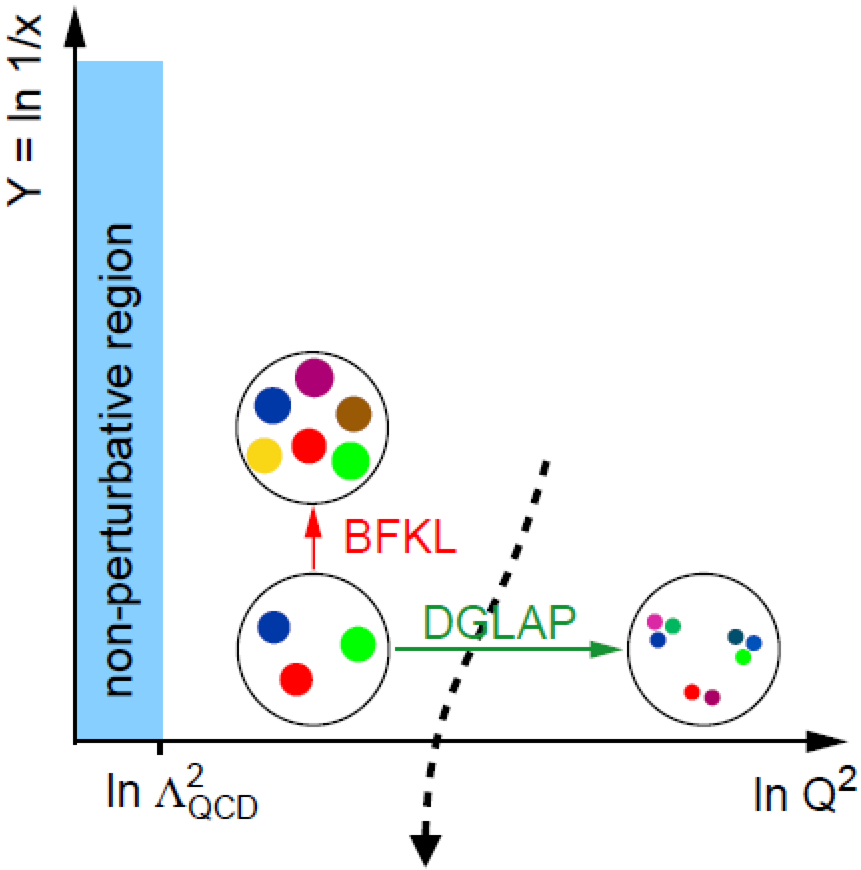
In LO: Number density for a parton with x, Q^2 in proton

To get them use:

- F_2 (quark)
- $dF_2/d\ln Q^2$ (Gluon)
- pQCD+ DGLAP Evolution

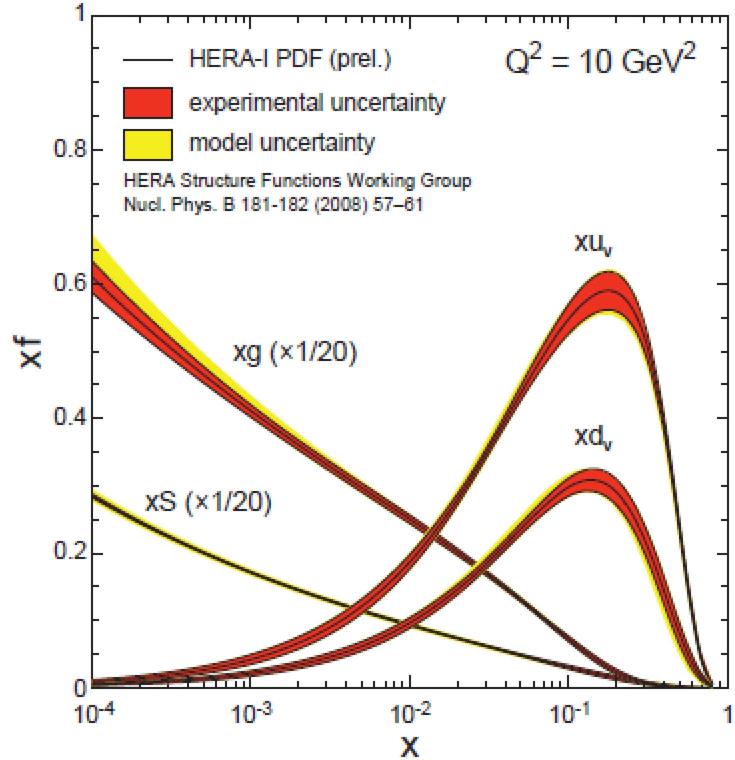
$$f(x, Q_1^2) \rightarrow f(x, Q_2^2)$$

Regimes of the Hadronic Wave Function



pQCD and DGLAP & BFKL evolution works with high precision (⇒HERA)

HERA taught us that glue dominates for x < 0.1



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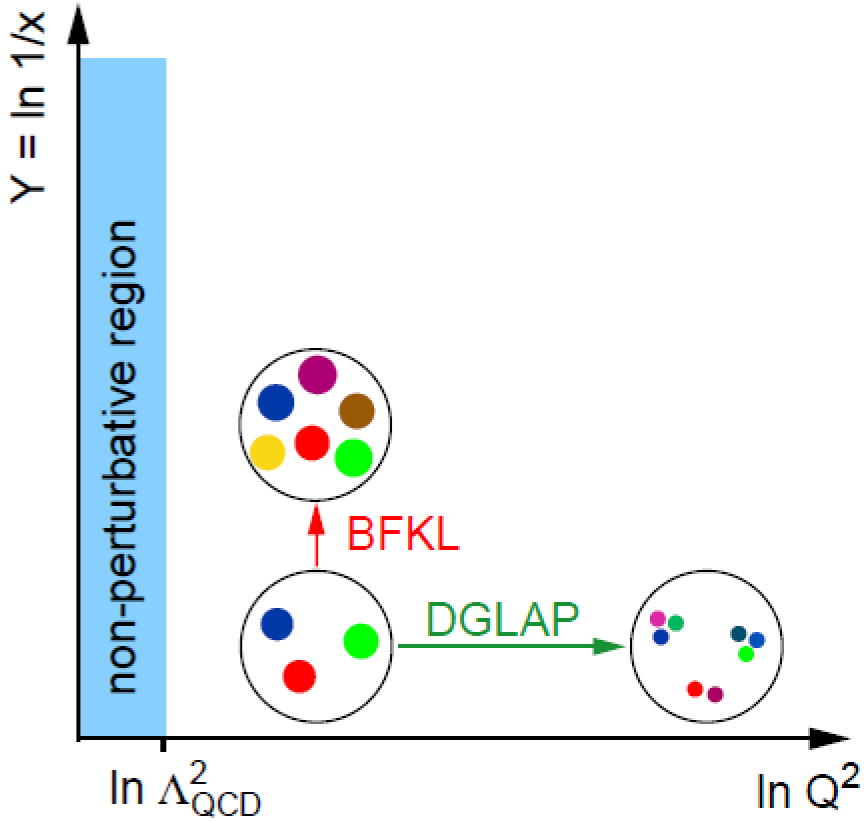
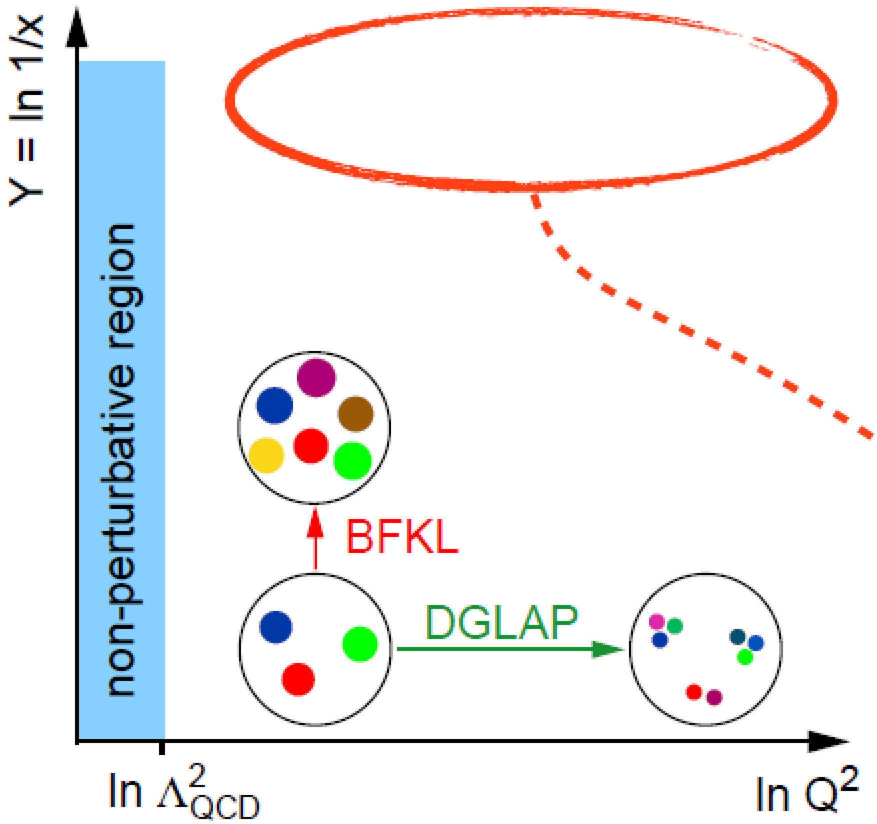


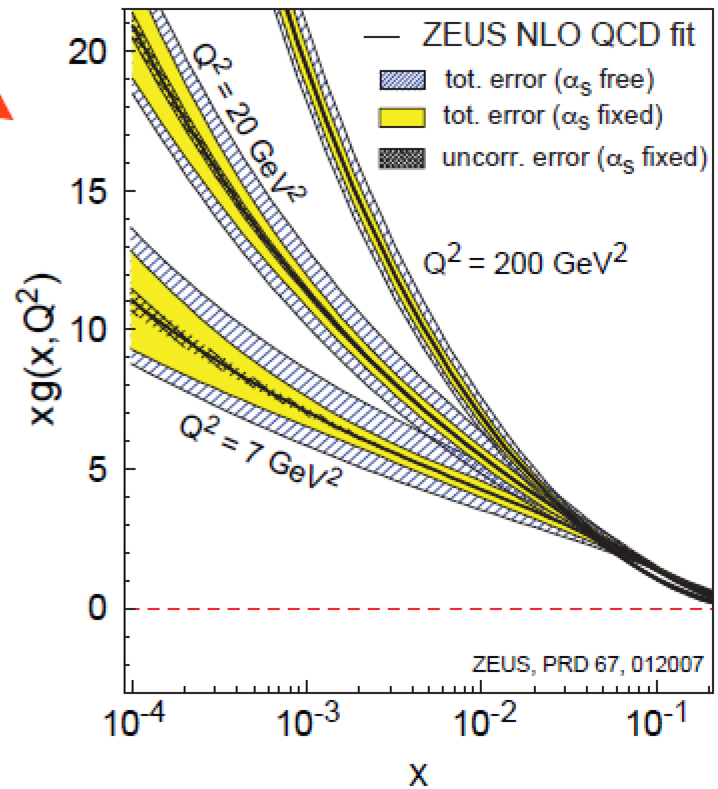
However DGLAP & BFKL evolution have their limits

Regimes of the Hadronic Wave Function



However DGLAP & BFKL evolution have their limits

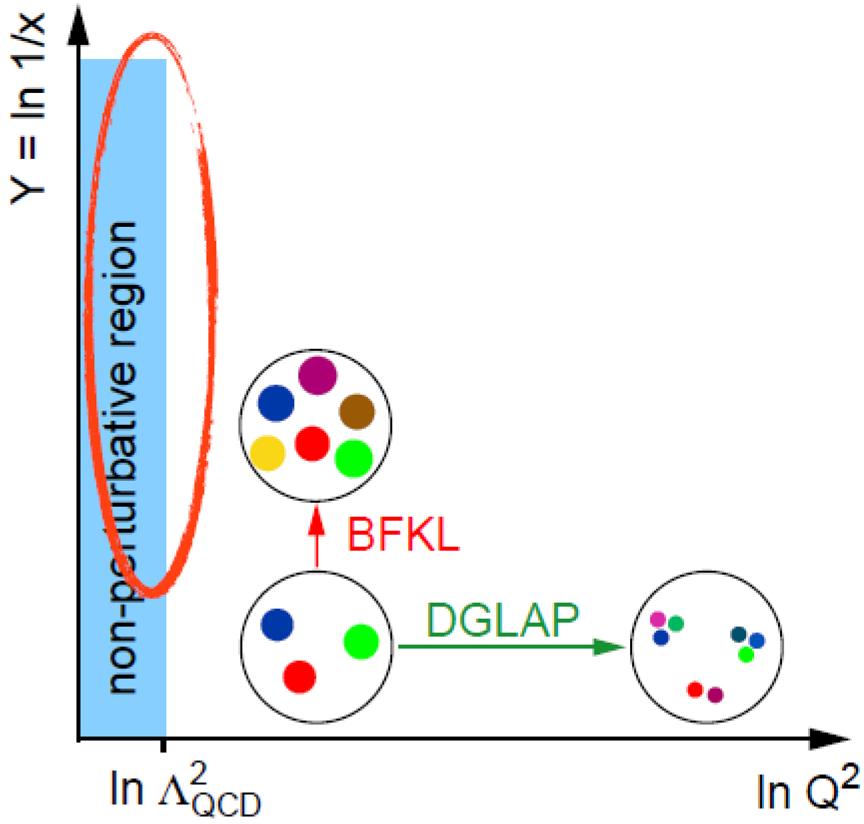
Gluon self-interaction has dramatic consequences at small x:



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

⇒ Need to tame/saturate evolution

Regimes of the Hadronic Wave Function



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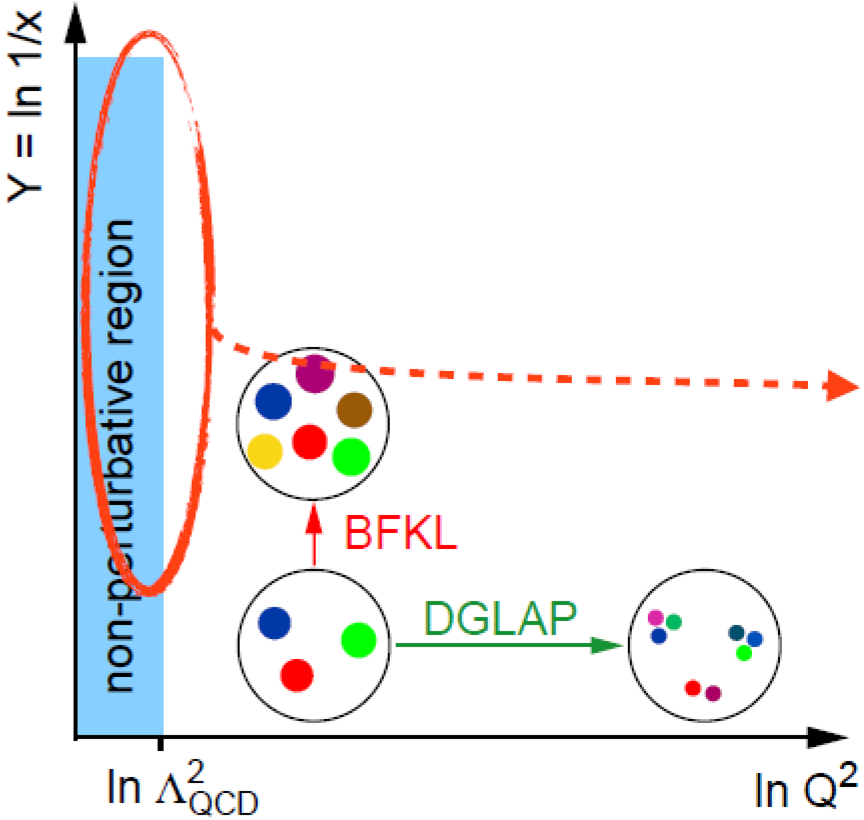
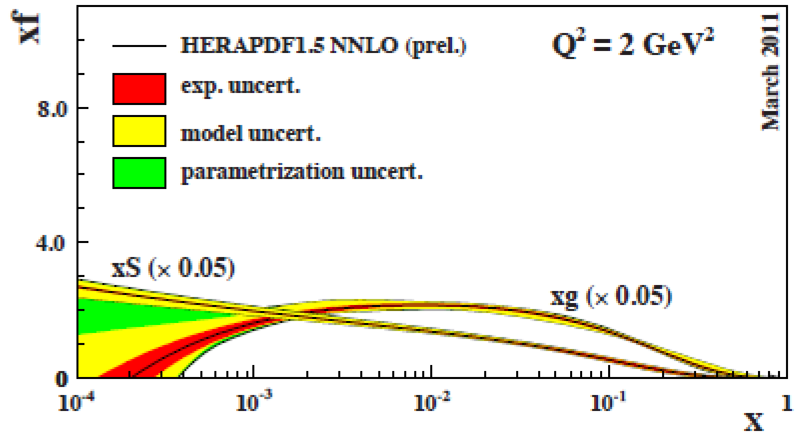


Issue: To what Q^2 is pQCD applicable?

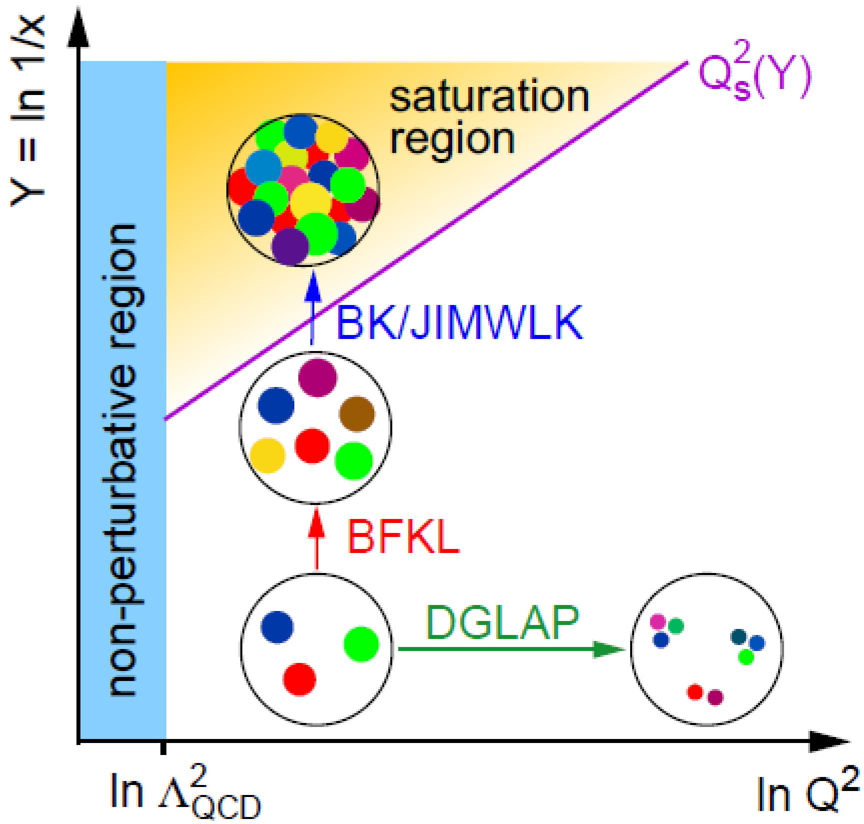
However DGLAP & BFKL evolution have their limits



Hints at low-Q^2 that things are not in order

- $xG(x,Q^2) < 0$ (OK in NLO)
- $xG(x,Q^2) < xQ_{sea}(x,Q^2)$?

Regimes of the Hadronic Wave Function



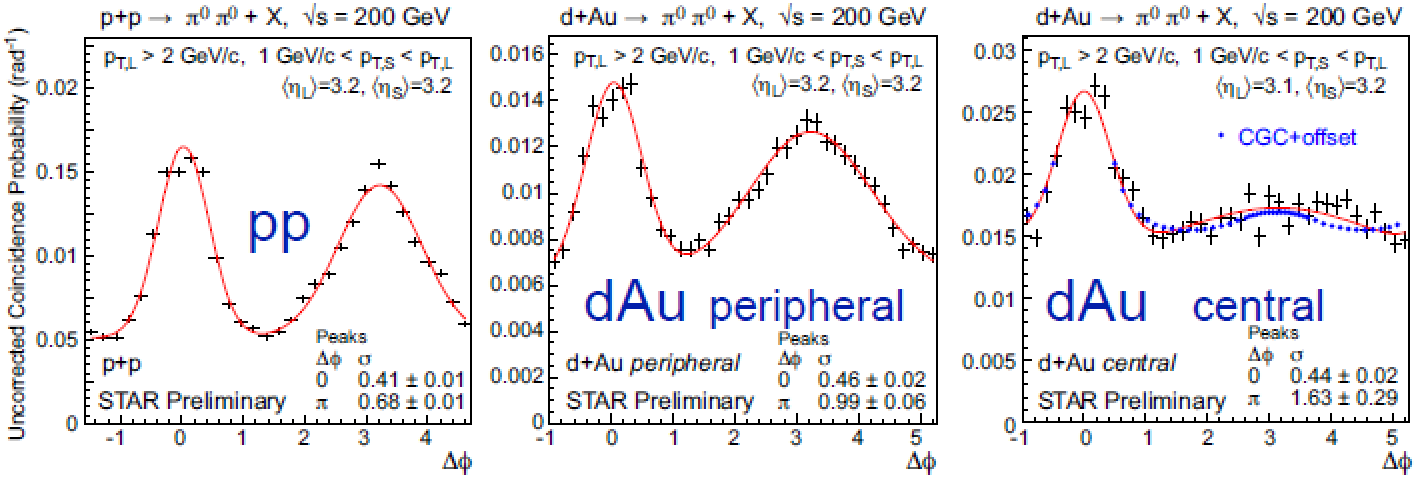
New Approach:
Non-Linear Evolution

- McLerran-Venugopalan Model:
  - Weak coupling description of wave function
  - Gluon field $A_\mu \sim 1/g \Rightarrow$ gluon fields are strong classical fields!
- BK/JIMWLK: non-linear effects $\Rightarrow$ saturation characterized by $Q_s(x)$
- Wave function is Color Glass Condensate in IMF description

Hints For a New Regime of QCD

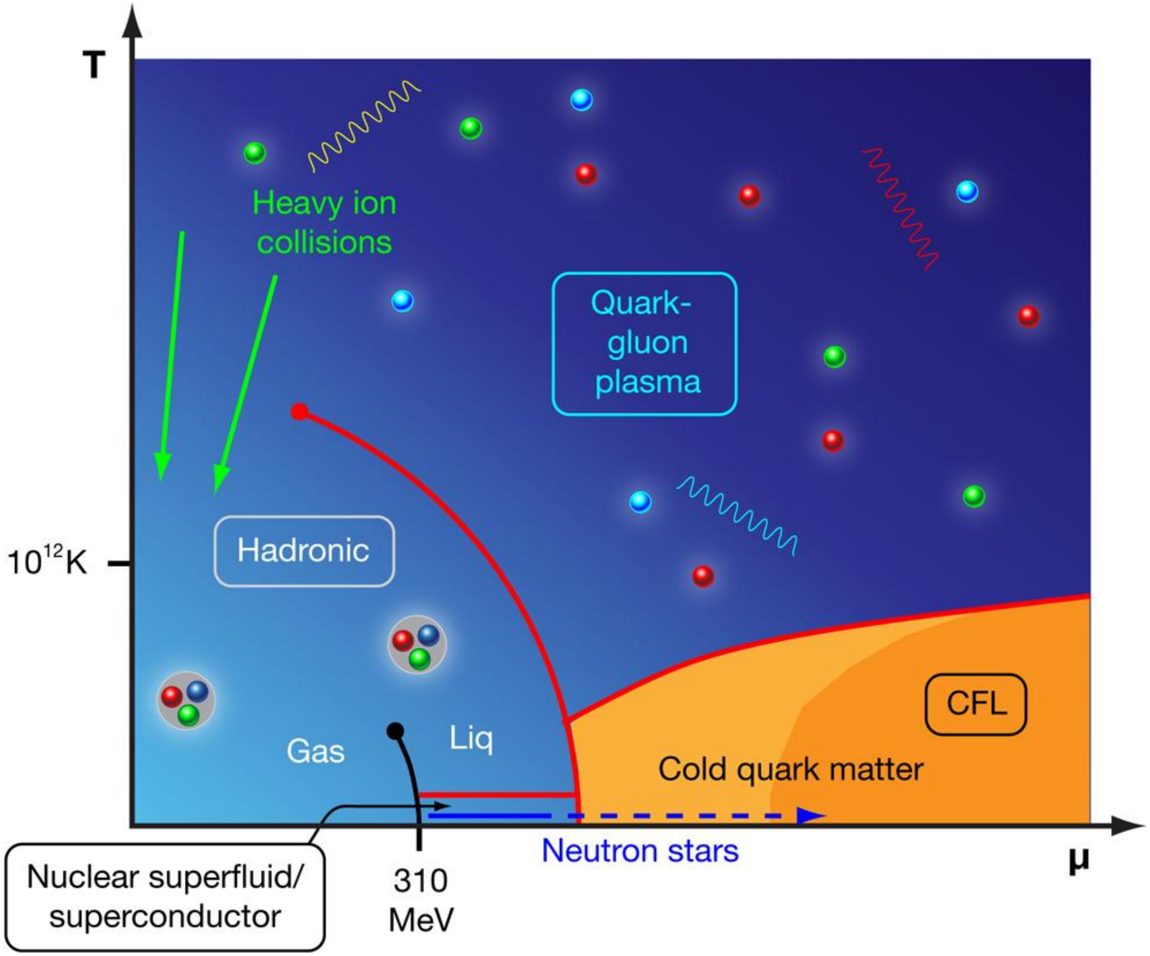
However

- at small x and/or at small Q^2 at Hera deviations become apparent (Caola, Forte, Rojo '11)
  - non-linear evolution, gluon saturation, higher twist effects ?
- (p)QCD fails to describe large diffractive cross-sections and their energy independence
- Recent p+A results (hadron spectra & dihadrons) at η>3 (low x) cannot be explained unless invoking saturation effects ⇒ non-linear QCD

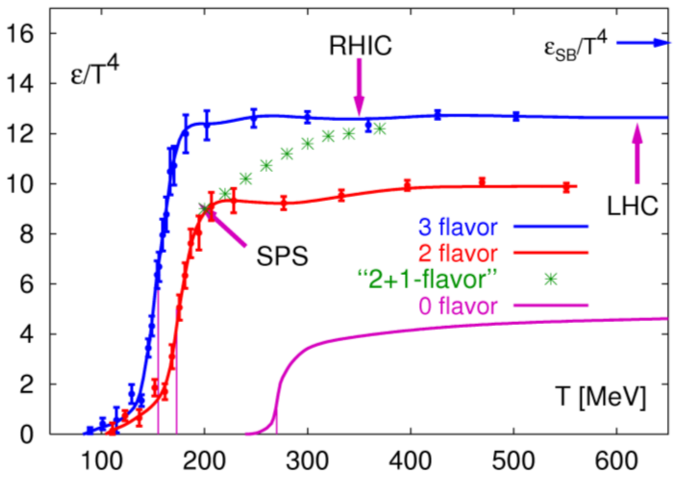


arXiv:1008.3989

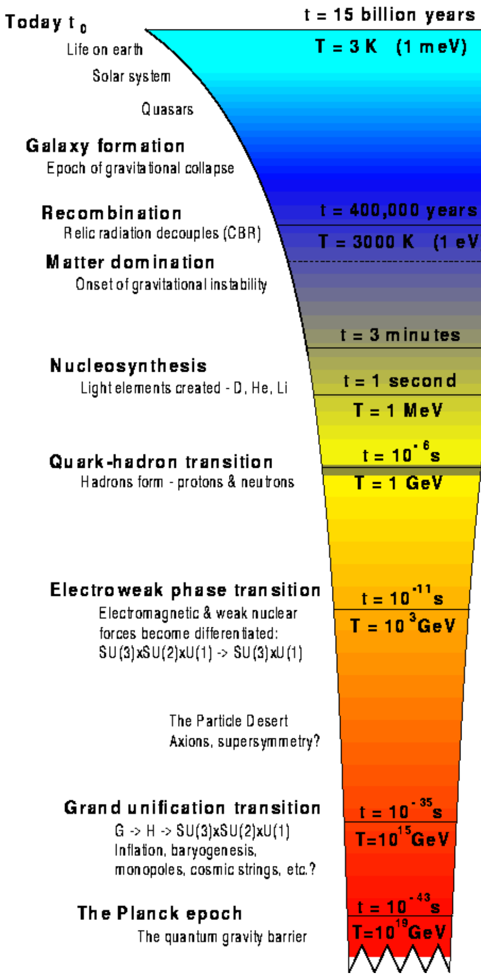
Phases of QCD



- Equation of State
- Transport Properties
- Phase Transitions



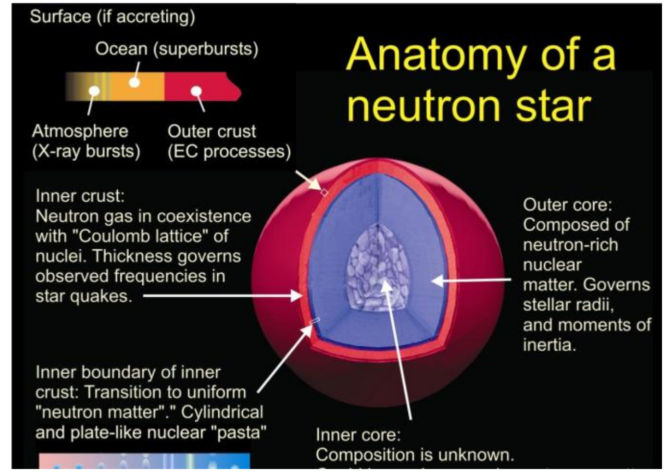
Connections in Cosmology and Astrophysics

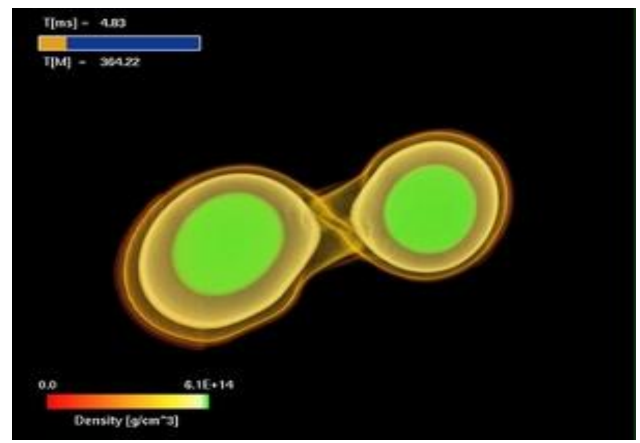


$\varepsilon \sim 1\ \text{GeV/fm}^3$

$\varepsilon \sim 10^{10}\ \text{GeV/fm}^3$

Early Universe





Neutron Stars and Binary Mergers

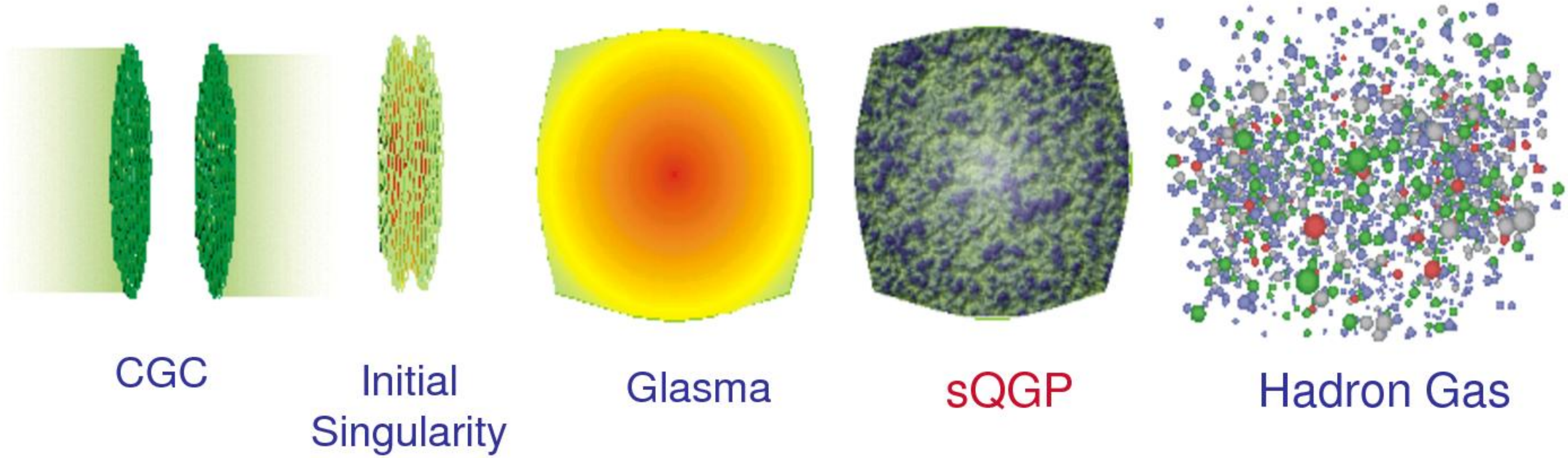
LIGO Laser Interferometer Gravitational-Wave Observatory

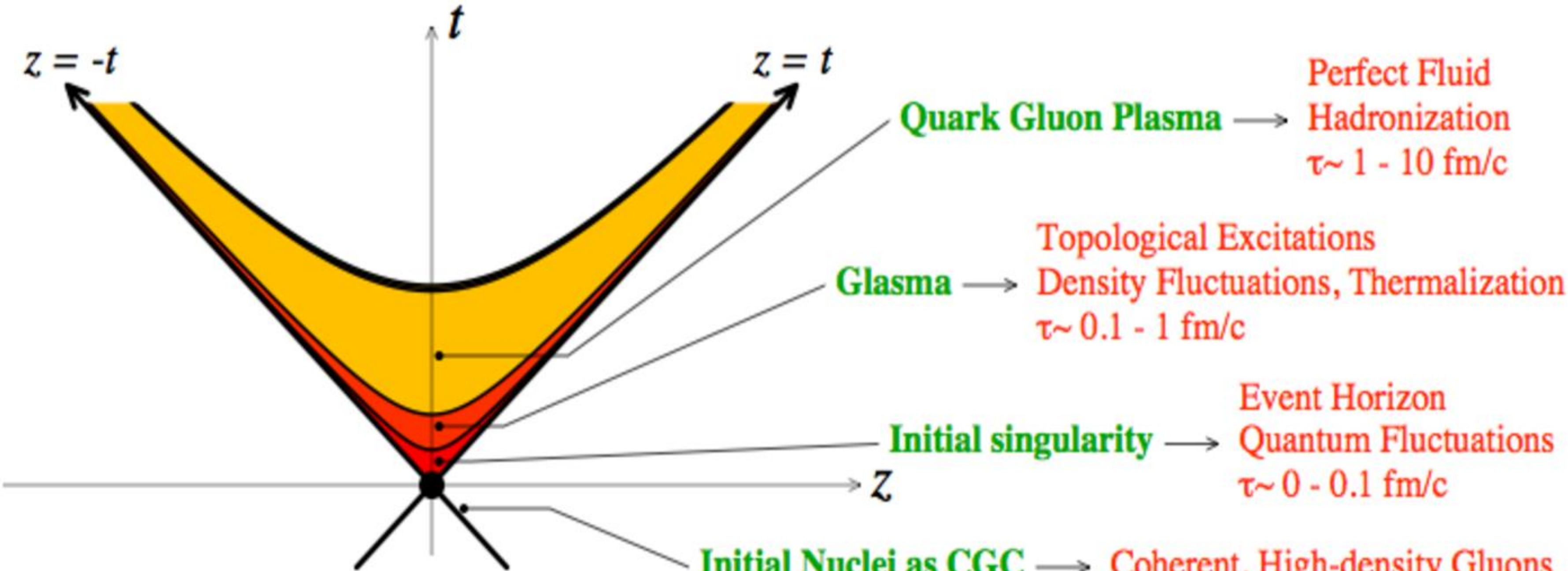
SKA

LISA Pathfinder

Theoretical Aspects of the Color Glass Condensate and Glasma

Art due to S. Bass



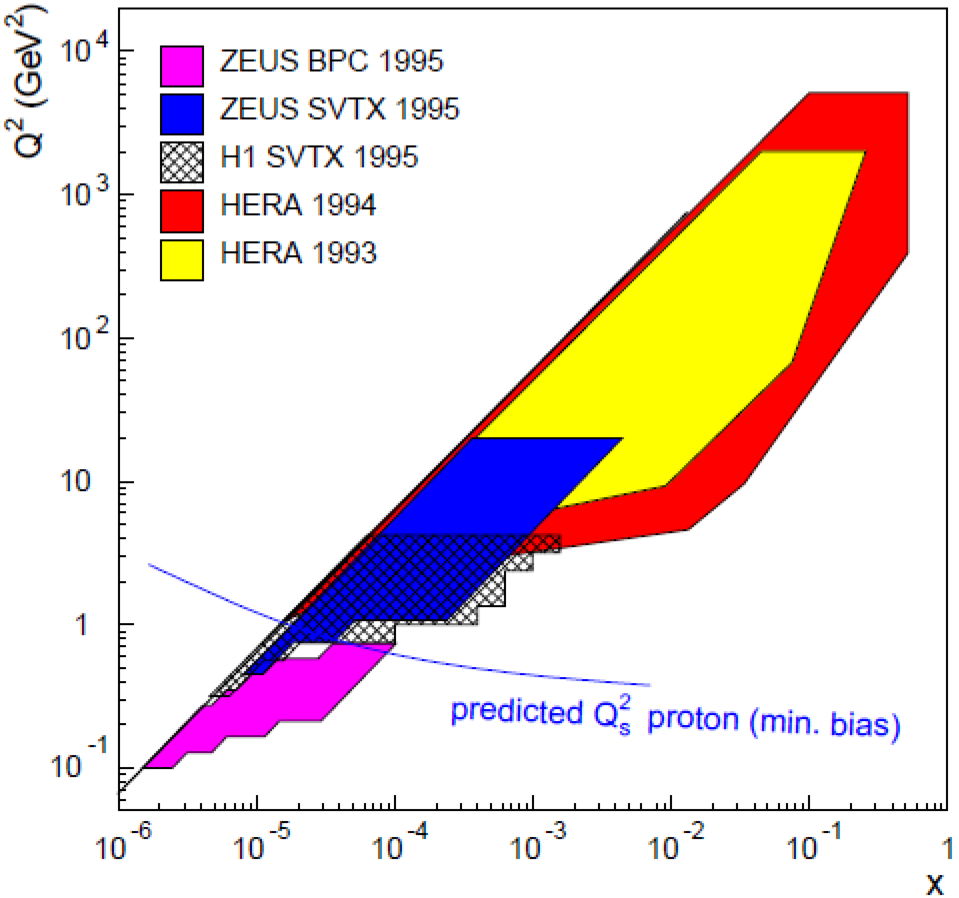


Reaching the Saturation Region

HERA (ep):

Despite high energy range:

- F_2, $G_p(x, Q^2)$ outside the saturation regime
- Need also Q^2 lever arm!
- Only way in ep is to increase $\sqrt{s}$
- Would require an ep collider at $\sqrt{s}$ ~ 1-2 TeV



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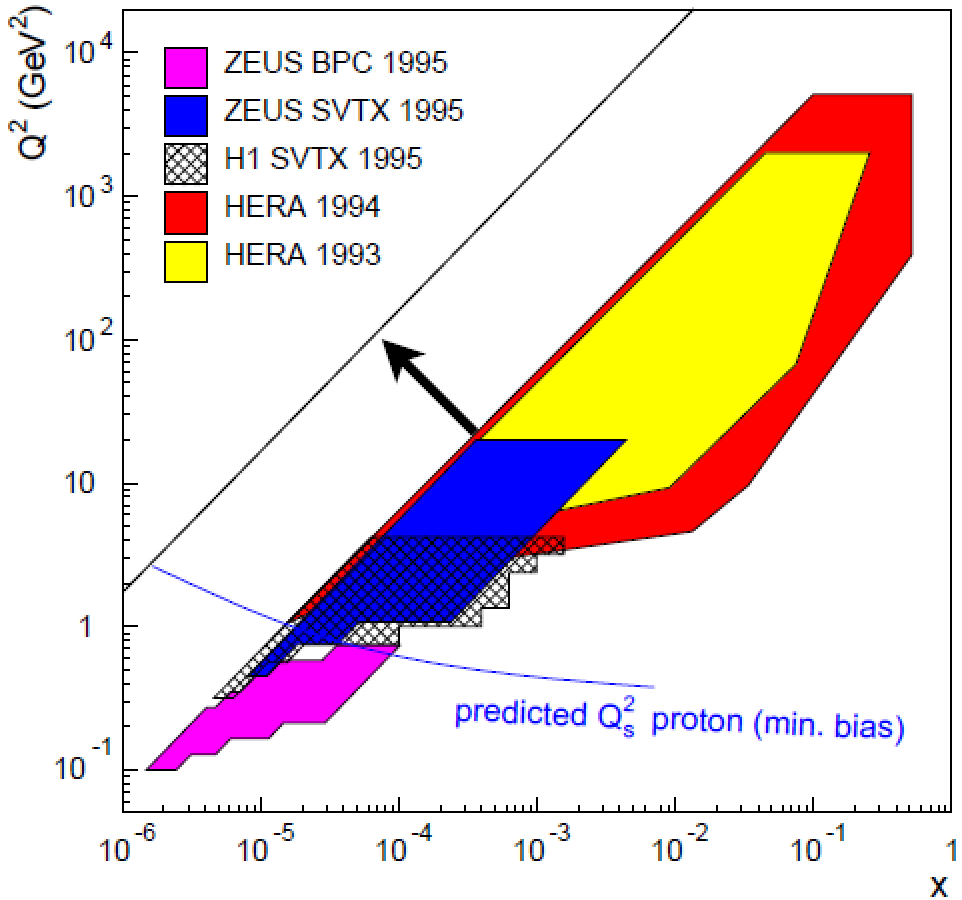

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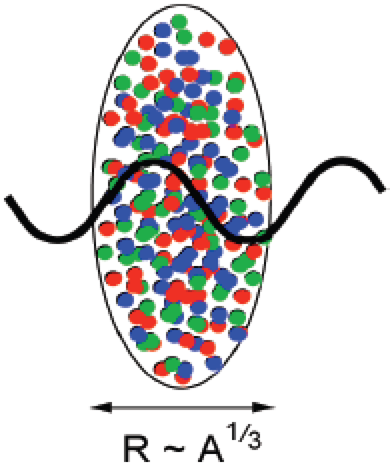

$L \sim (2m_N x)^{-1} > 2\,R_A \sim A^{1/3}$

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

Different approach (eA):

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

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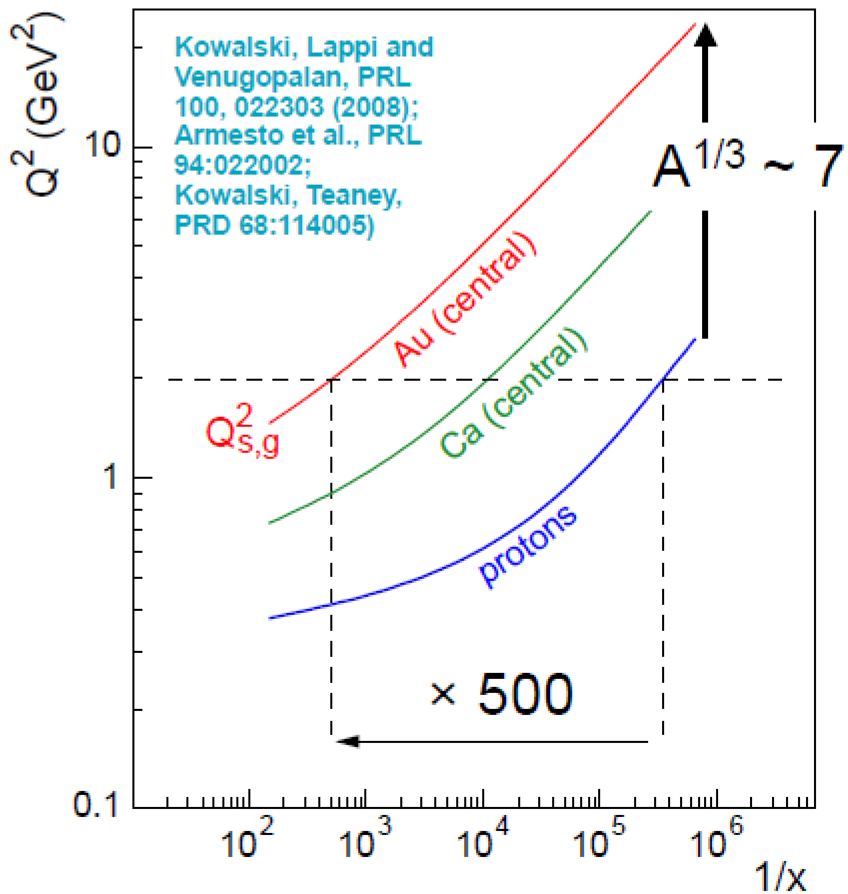

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$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x} \right)^{1/3}$$

Enhancement of Q_S with A ⇒ saturation regime reached at significantly lower energy in nuclei

e+A Science Matrix & Golden Measurements

Result of 2 month INT workshop in Seattle in fall '10 on EIC physics:

Primary new science deliverables	What we hope to fundamentally learn	Basic measurements	Typical required precision	Special requirements on accelerator/ detector	What can be done in phase I	Alternatives in absence of an EIC	Gain/Loss compared with other relevant facilities	Comments
integrated nuclear gluon distribution	The nuclear wave function throughout x-Q^2 plane	F_L, F_2, F_L^c, F_2^c	What HERA reached for F2 with combined data	displaced vertex detector for charm	stage 1: large-x & large-Q^2 need full EIC, for F_L and F_2^c	p+A at LHC (not as precise though) & LHeC	First experiment with good x, Q^2 & A range	This is fundamental input for A+A collisions
k_T dependence of gluon distribution and correlations	The non-linear QCD evolution - Qs	SIDIS & di-hadron correlations with light and heavy flavors		Need low-pt particle ID	SIDIS for sure TBD: saturation signal in di-hadron p_T imbalance	1) p+A at RHIC/LHC, although e+A needed to check universality 2) LHeC	Cleaner than p+A: reduced background	
b dependence of gluon distribution and correlations	Interplay between small-x evolution and confinement	Diffractive VM production and DVCS, coherent and incoherent parts	50 MeV resolution on momentum transfer	hermetic detector with 4pi coverage low-t: need to detect nuclear break-up	Moderate x with light and heavy nuclei	LHeC	Never been measured before	Initial conditions for HI collisions – eccentricity fluctuations

e+A Science Matrix & Golden Measurements

Key Measurement (benchmark for simulations):

- Nuclear gluons at small-x
  - Inclusive structure functions (F_2, F_L, F_2^c, F_L^c)
  - Di-hadrons (and di-jet) imbalance
  - Exclusive diffractive production (J/ψ, ϕ, ρ and DVCS)
    - coherent & incoherent
- Nuclear gluons at larger-x
  - Gluon anti-shadowing / EMC effect
- Jets and hadronization
  - Use nuclei to test in-medium fragmentation, pQCD energy loss and parton showers

Summary

eA collisions allow us to:

- **Explore the Physics of Strong Colour Fields**
    - **Measure properties (momentum and space-time) of glue with high precision**
    - **Explore non-linear QCD**
    - **Unambiguously establish gluon saturation**
    - **Determine initial conditions for heavy ion programme (sQGP) at RHIC/LHC**
    - **Existence of universal saturation regime ?**
- **Partonic origin of nuclear forces**
- **Insights into nature of colour singlet excitations (Pomerons)**

High energy eA scattering open a new precision window into fundamental questions in QCD