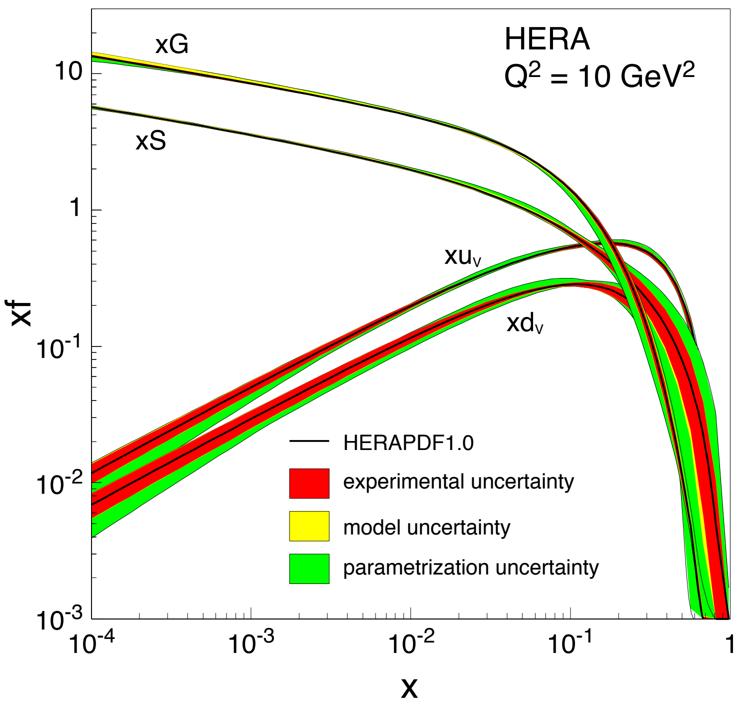
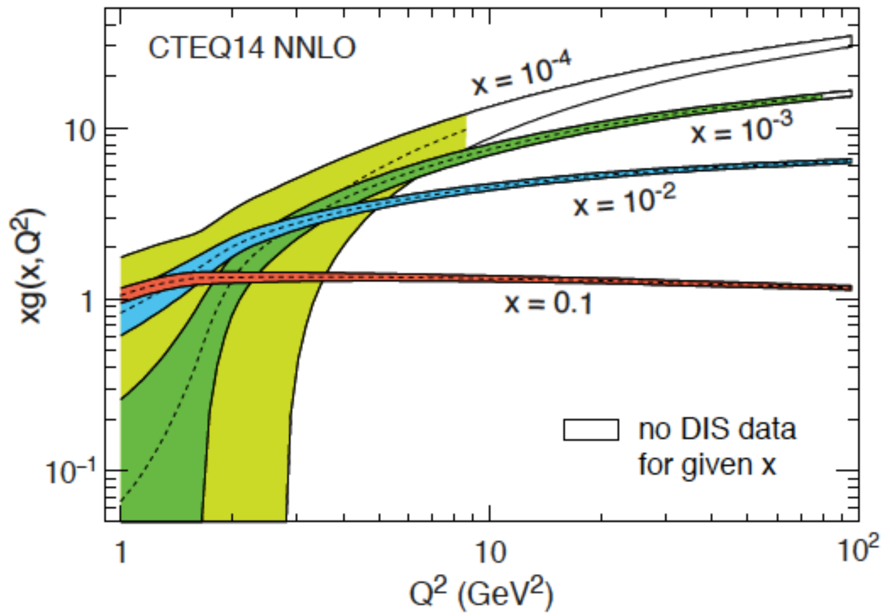
GLUON SATURATION AT LOW X

Kai Schweda

GLUON DENSITY IN THE PROTON

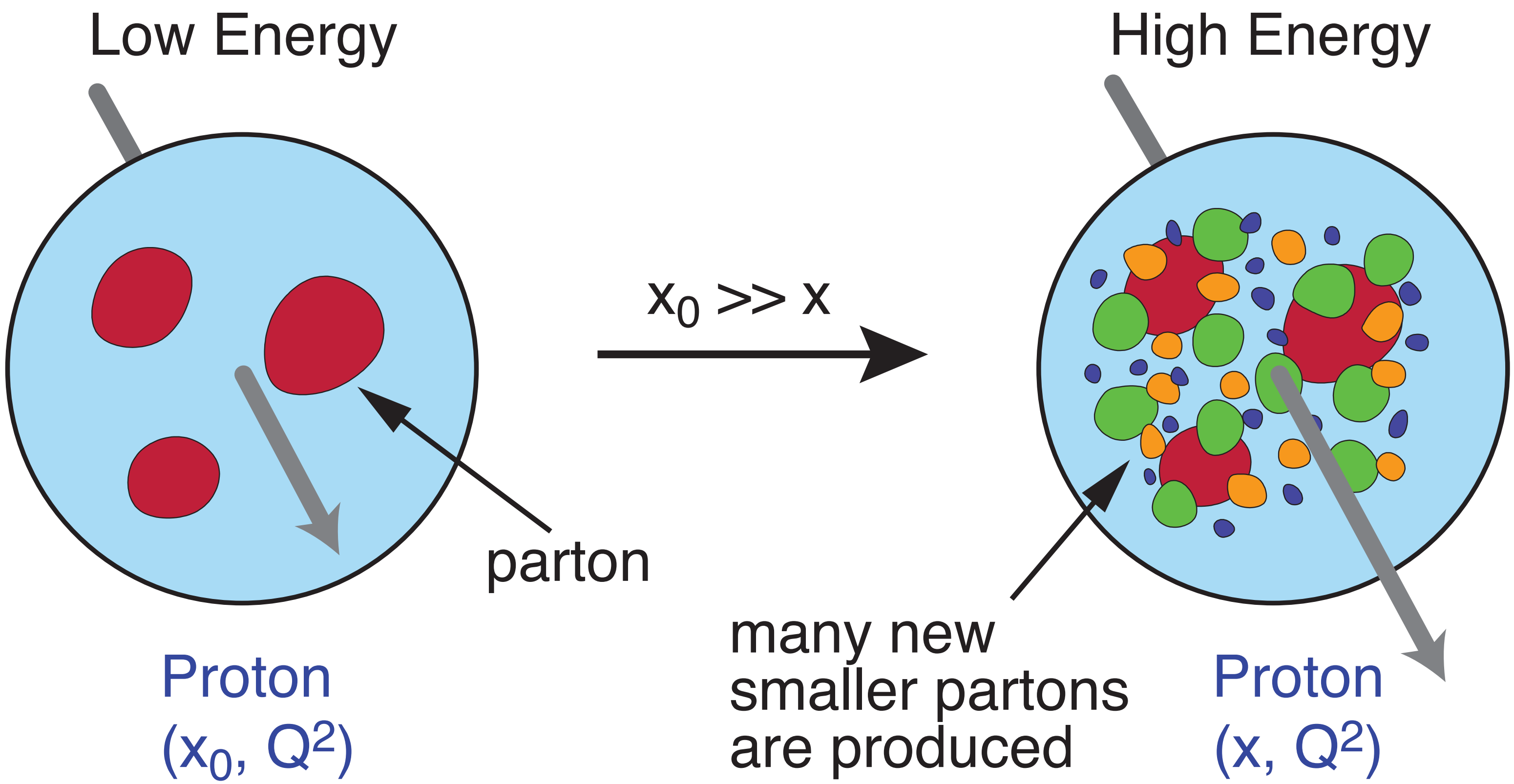




- gluon density grows at low x ~1/x
- gluon density grows with larger Q^2

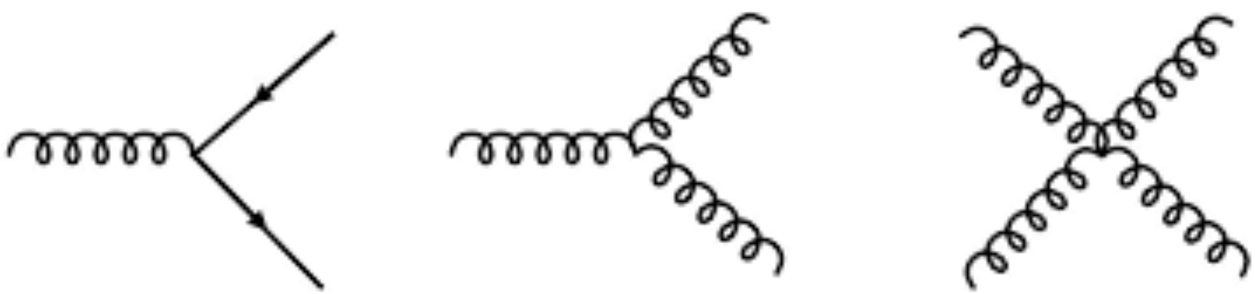
e.g., top quark pair production at LHC: $x = \frac{2m_t}{\sqrt{s}} \approx 0.03$

THE NUCLEON AT HIGH ENERGY



"Color Glass Condensate"

GLUON SELF INTERACTION

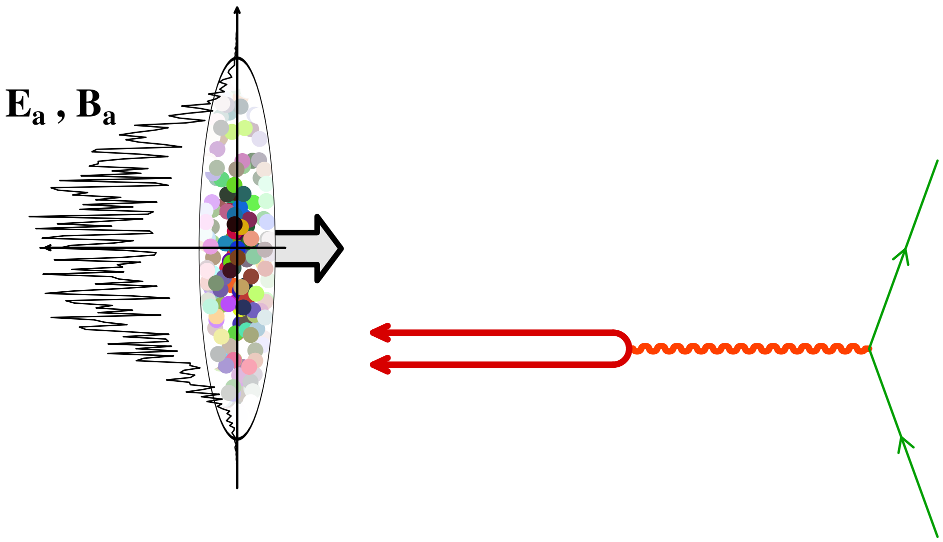


Analogous to photon exchange of QED

3-gluon vertex

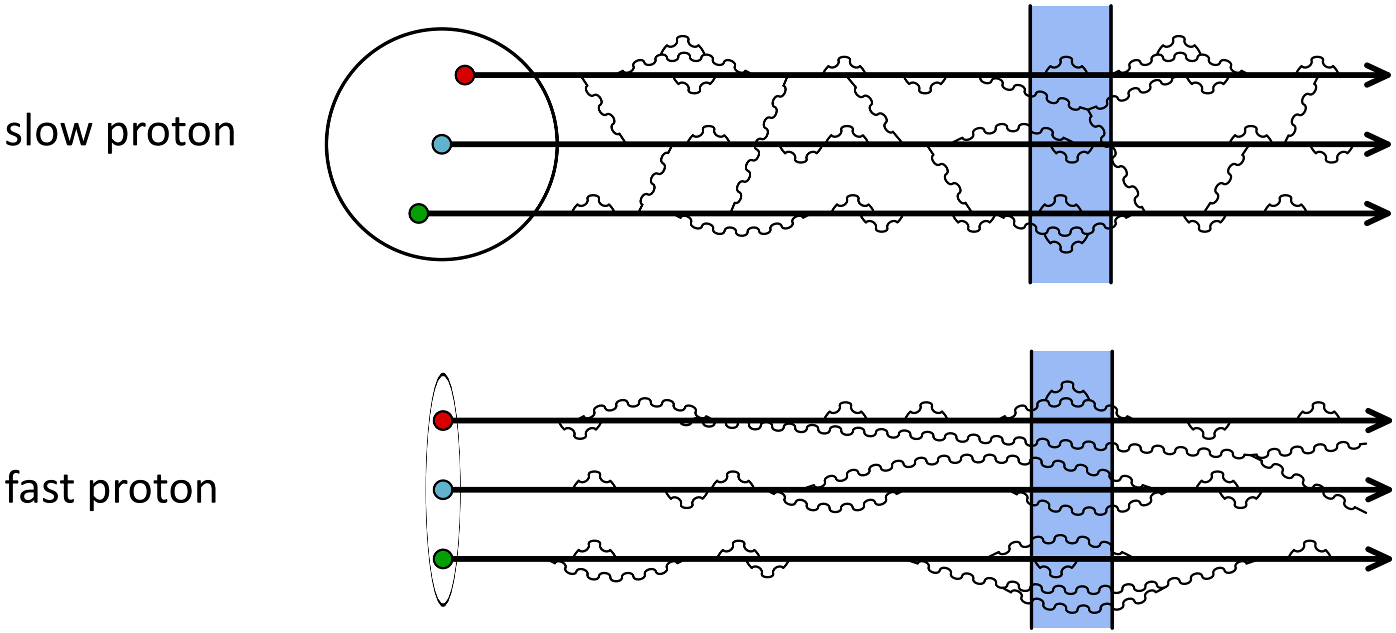
4-gluon vertex

COLOR DIPOLE MODEL



in deep inelastic scattering, virtual photon splits into quark-antiquark dipole
dipole scattering amplitude $N(x, r_T)$ probes gluon density
at distance $r_T \sim 1/Q$, transverse to the beam direction

TIME DILATION



all gluons interact coherently with projectile along beam direction

Lorentz contraction $R \rightarrow R/\gamma$

all nucleons seen by low-x gluons with large longitudinal wavelength

overlap in transverse plane —> high parton density

—> large occupation number of color charges

—> classical gluon field

L. D. McLerran and R. Venugopalan, Phys. Rev. D49, 2233 (1994).

GLUON DENSITY AT LOW-X - BFKL EVOLUTION

$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_S K_{\mathrm{BFKL}} \otimes N(x, r_T),$$

I. I. Balitsky and L. N. Lipatov, Sov. J. Nucl. Phys. 28, 822 (1978),
E.A. Kuraev, L.N. Lipatov and V.S. Fadin,Sov. Phys. JETP45 (1977) 199.

$$N \sim (1/x)^{\lambda} \to \sigma_{\mathrm{tot}} \sim s^{\lambda}$$

However, black disk limit in quantum mechanics

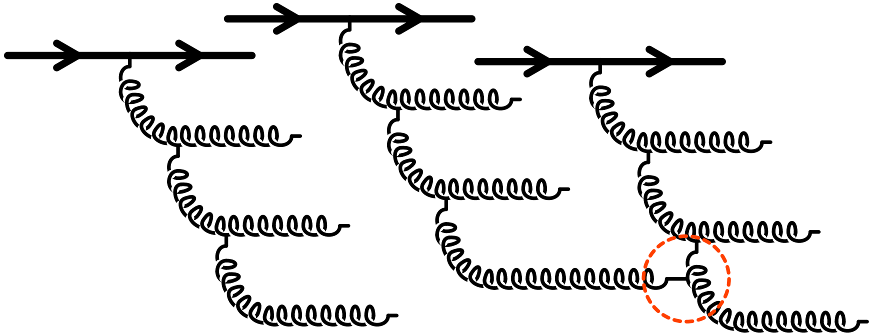
$$\sigma_{\mathrm{tot}} \leq 2\pi R^2$$

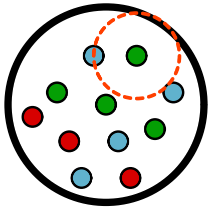
In QCD, Froissart-Martin bound

$$\sigma_{\mathrm{tot}} \leq \ln^2 s$$

M. Froissart, Phys. Rev. 123, 1053 (1961).

TAMING THE POWER-LAW GROWTH





F. Gelis, arXiv:1211.3327

$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_S K_{\mathrm{BFKL}} \otimes N(x, r_T) - \alpha_S [N(x, r_T)]^2$$

Balitsky-Kovchegov evolution (BK), valid at large N_c

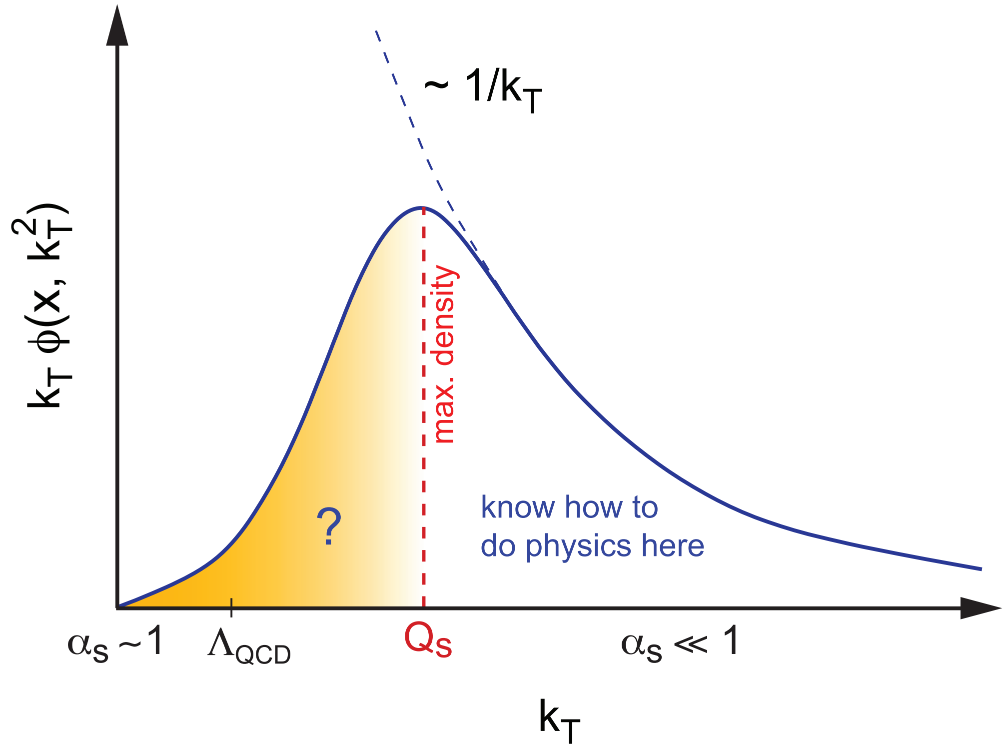
I. Balitsky, Nucl. Phys. B463, 99 (1996),
Y. V. Kovchegov, Phys. Rev. D60, 034008 (1999).

generalized by JIMWLK evolution equation ("gym-walk")

E. Iancu, A. Leonidov, and L. D. McLerran, Phys. Lett. B510, 133 (2001),
J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, Phys. Rev. D59, 014014 (1998).

When gluon recombination (quadratic term) comparable to splitting (linear term), parton density stops growing with decreasing x → saturation scale $Q_s^2 \sim (1/x)^\lambda$

GLUON TRANSVERSE MOMENTUM DISTRIBUTION

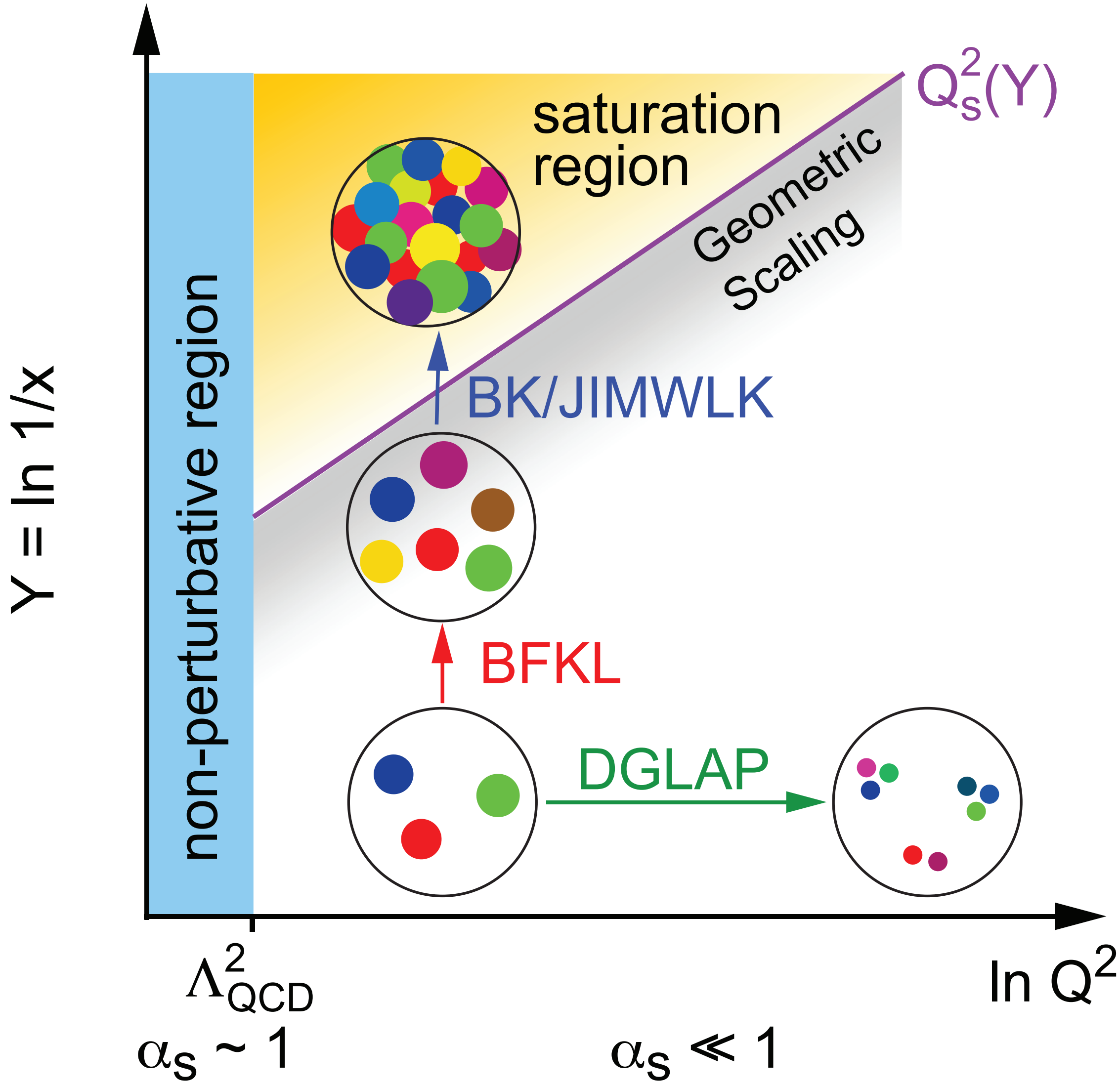


Thickness of large nucleus proportional to radius $R \sim A^{1/3}$

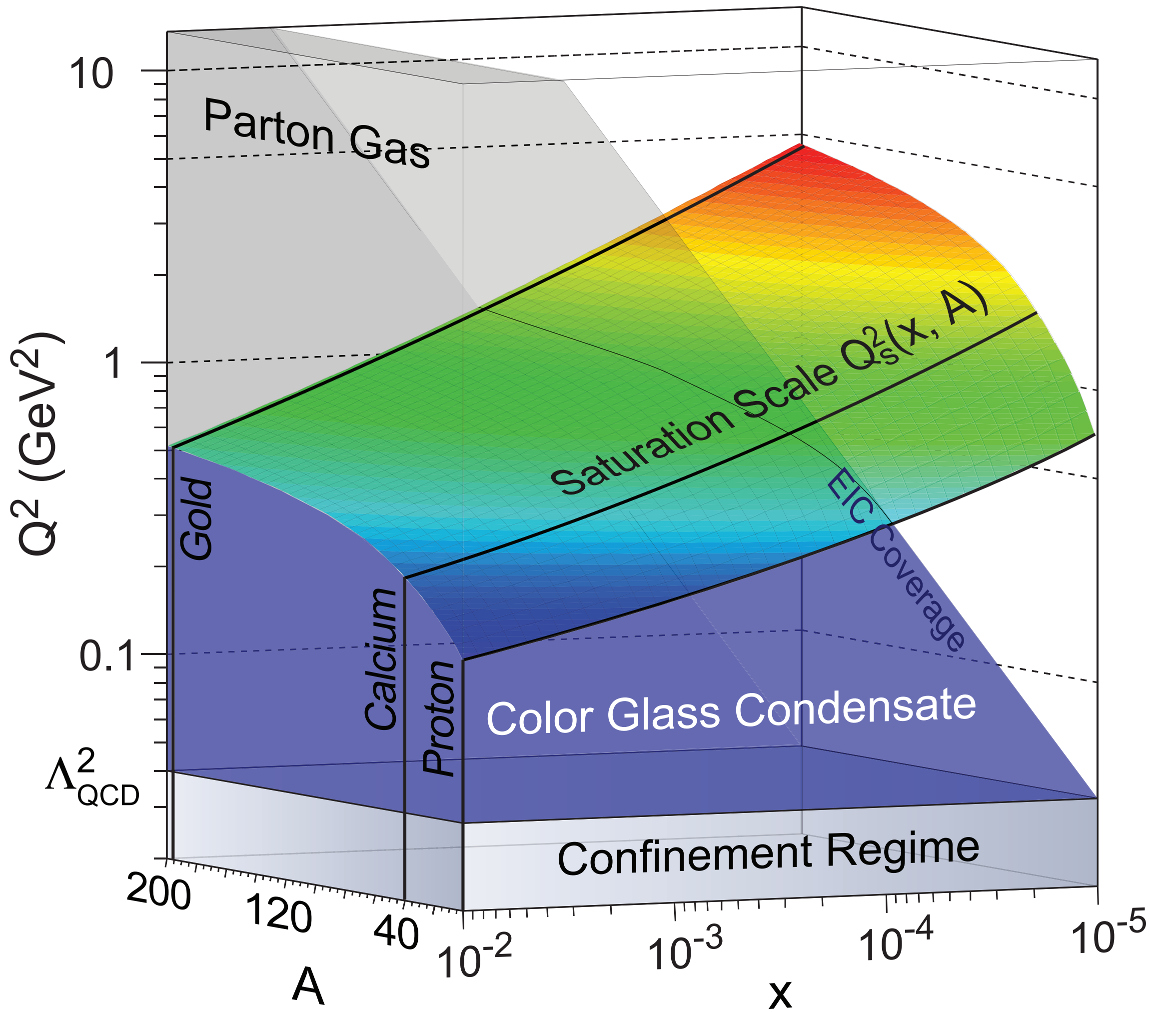
$Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda}$, e.g. gold nucleus $A = 197,\ A^{1/3} \approx 6$ (oomph factor), λ = 0.2 … 0.3

$Q_s^2 \gg \Lambda_{QCD}^2 \ \rightarrow\ \alpha_s(Q_s^2) \ll 1$ and also: $\lambda \approx 1/3 \rightarrow Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$

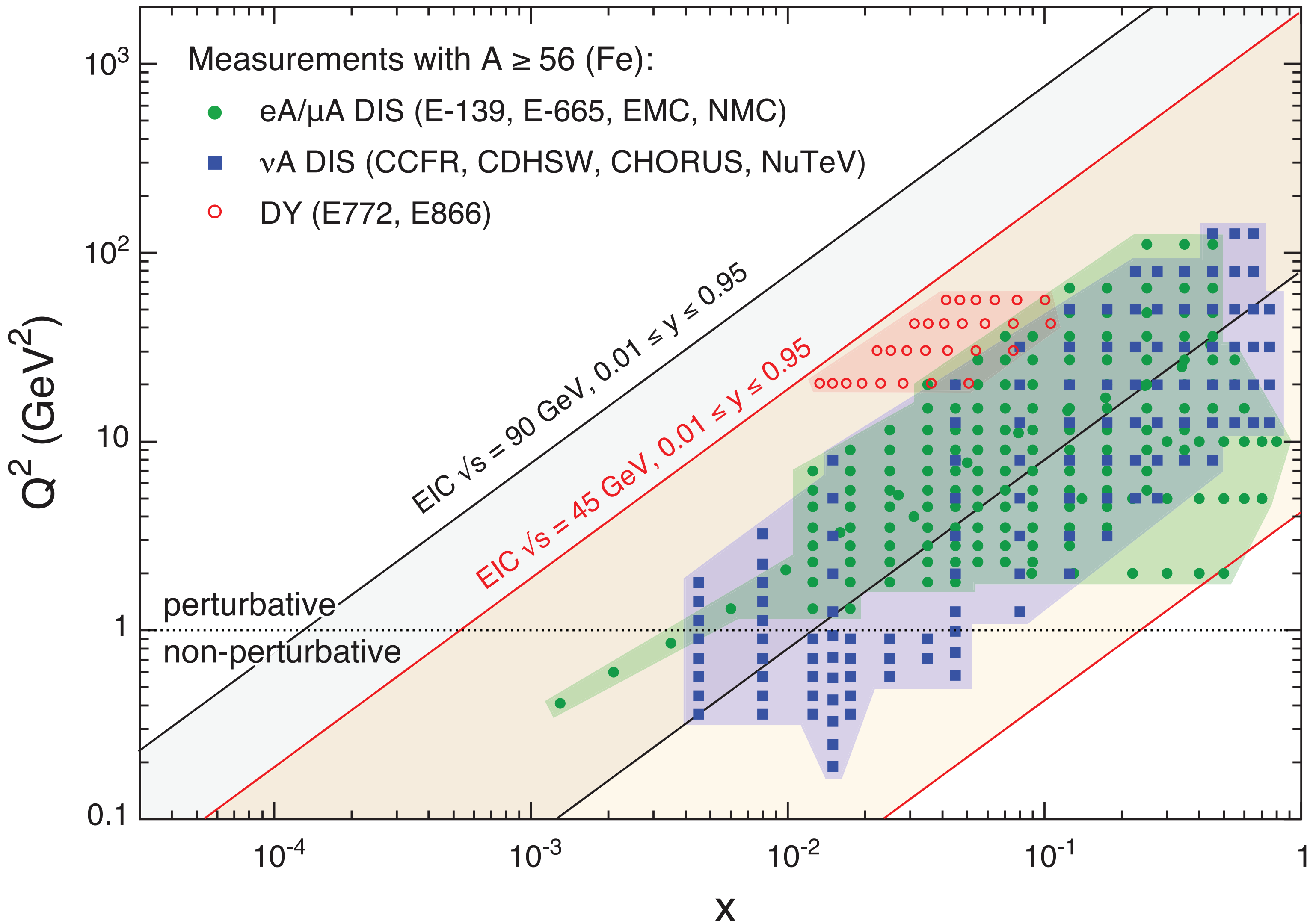
EVOLUTION IN X - Q² PLANE



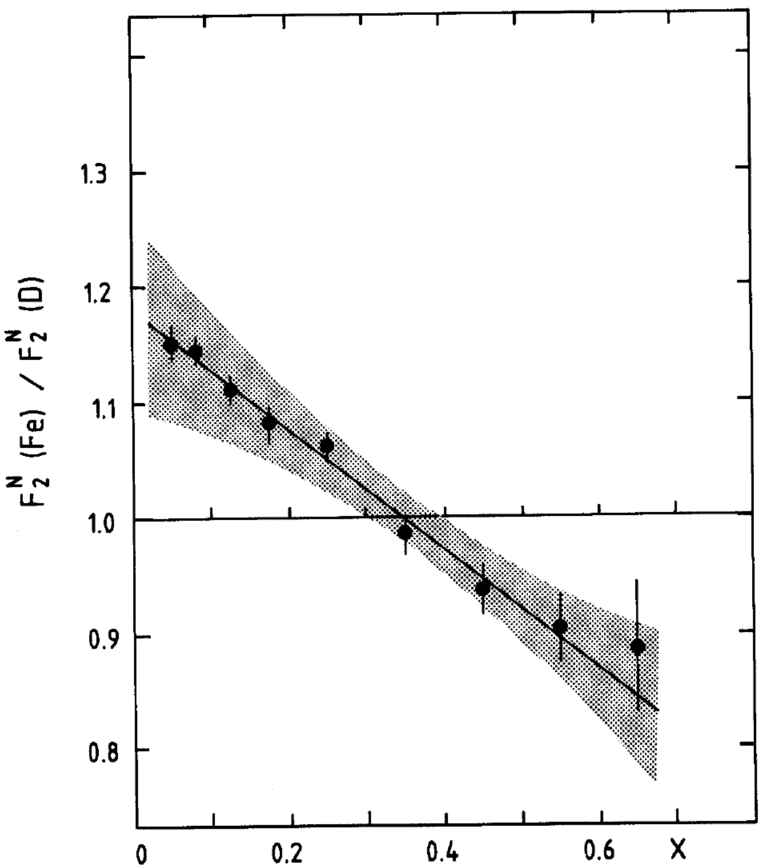
SATURATION SCALE Q_S



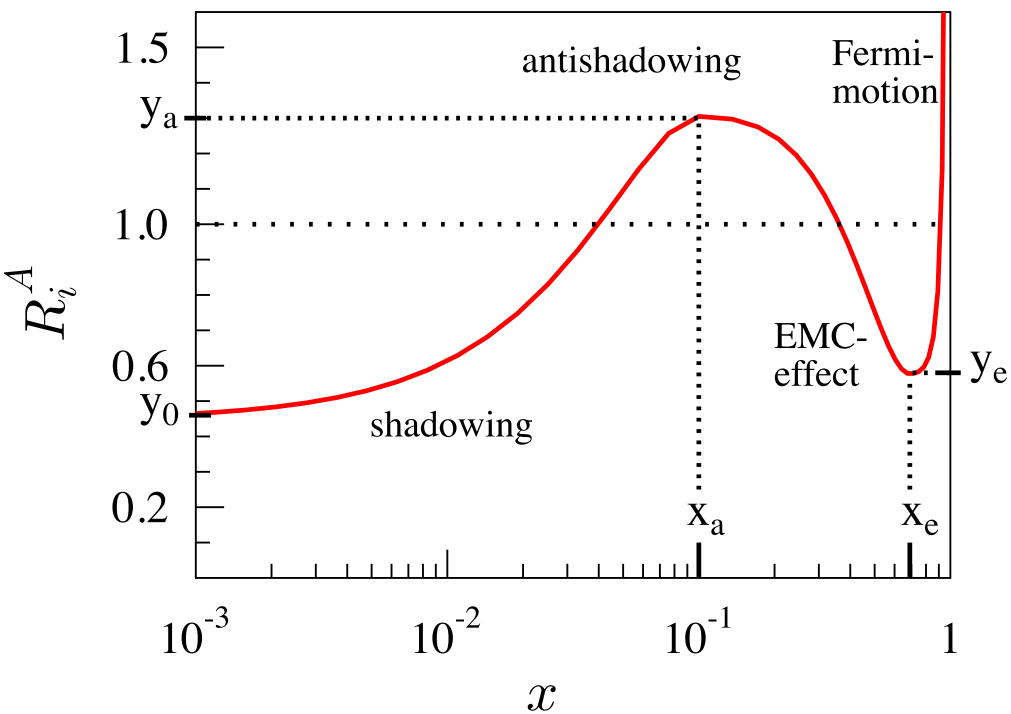
KINEMATIC RANGE - ELECTRON ION COLLIDER



PARTON DISTRIBUTION IN NUCLEI - EMC DISCOVERY



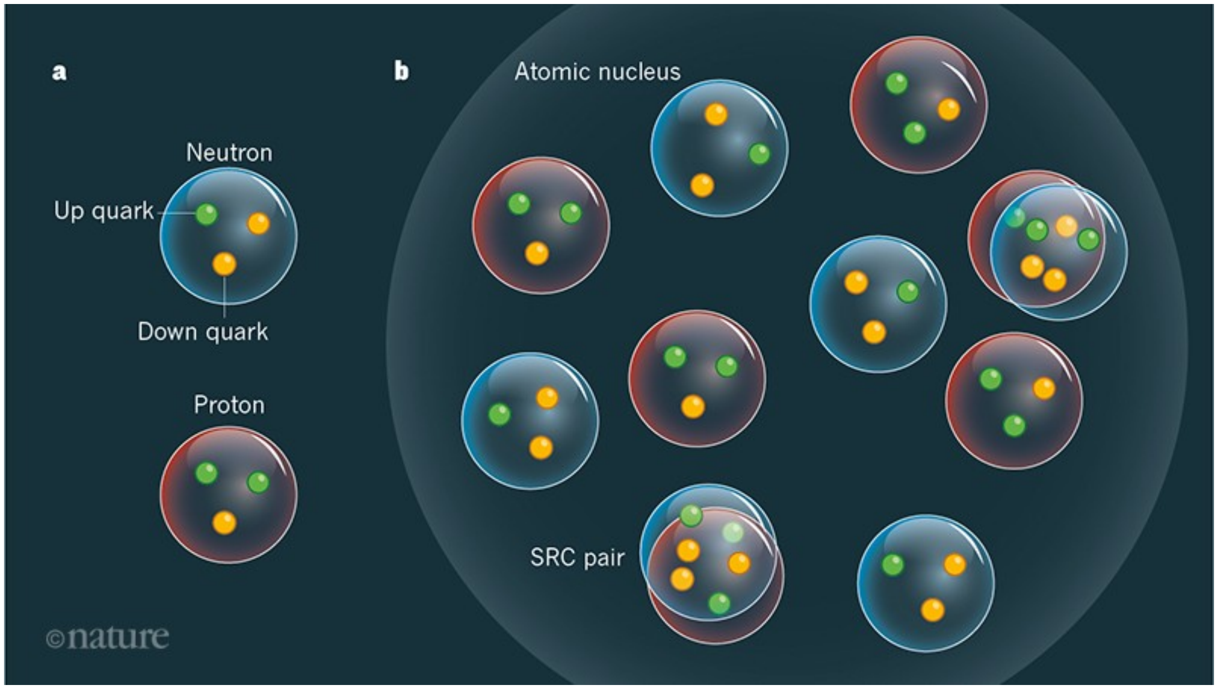
EMC Collab., Phys. Lett. B. **123B** (1983) 275



$$R_2(x, Q^2) \equiv \frac{F_2^A(x, Q^2)}{A\, F_2^p(x, Q^2)}$$

parton distributions modified in nuclei when compared to free nucleon
likely due to short range correlations of nucleon pairs

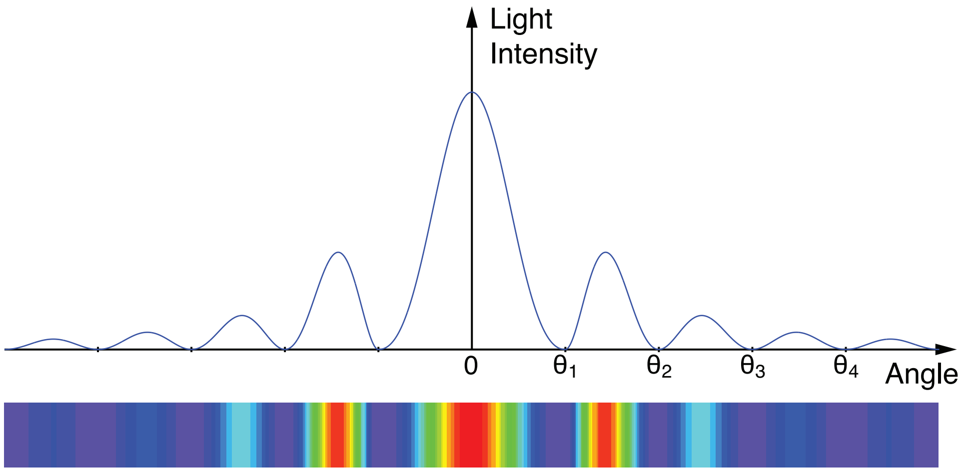
MODIFICATION OF NUCLEON INSIDE NUCLEUS



Measurement at CEBAF demonstrates that the EMC effect is related to close-proximity Short Range Correlated (SRC) nucleon pairs in nuclei.

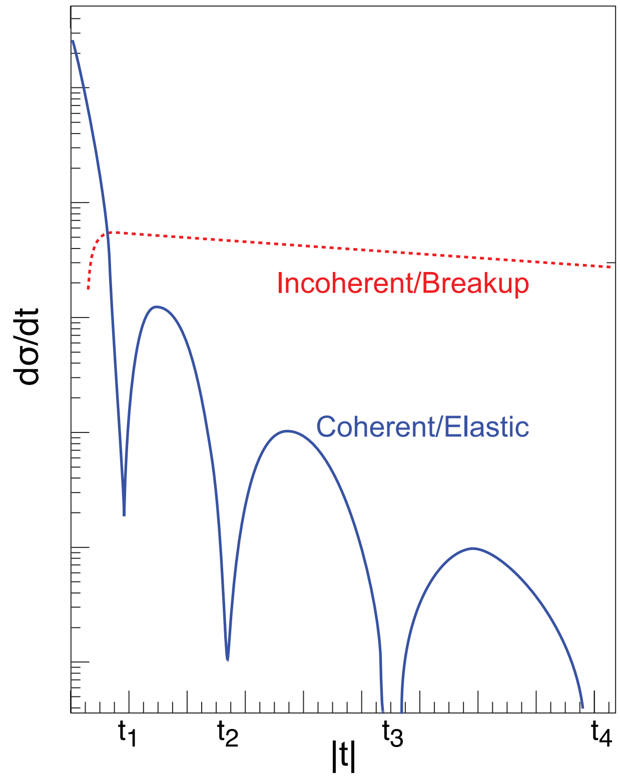
CLAS Collab., Nature. **566** (2019) 354.

DIFFRACTIVE PATTERNS - LIGHT WAVES VERSUS MATTER WAVES



$$\theta_i \sim 1/(kR)$$

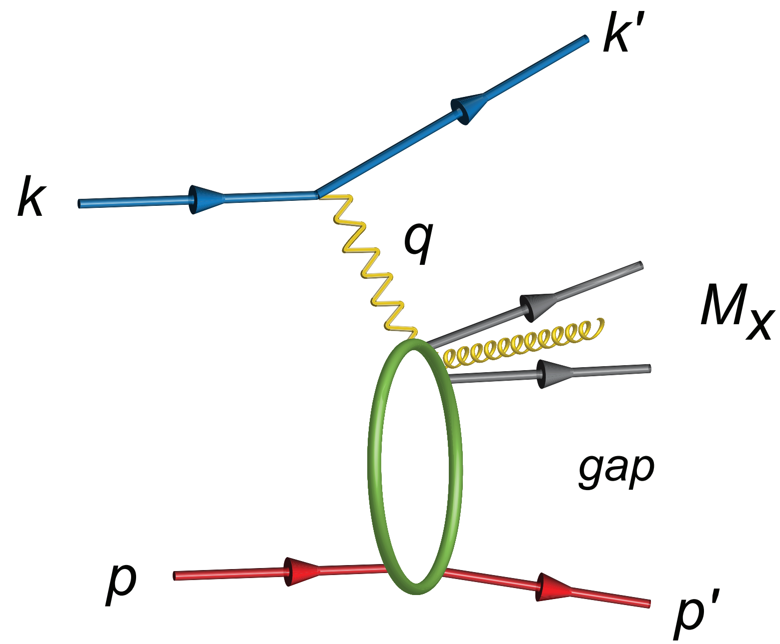
nucleon breaks up



both nuclei stay intact

$$|t_i| \sim 1/(R^2)$$

DIFFRACTIVE SCATTERING

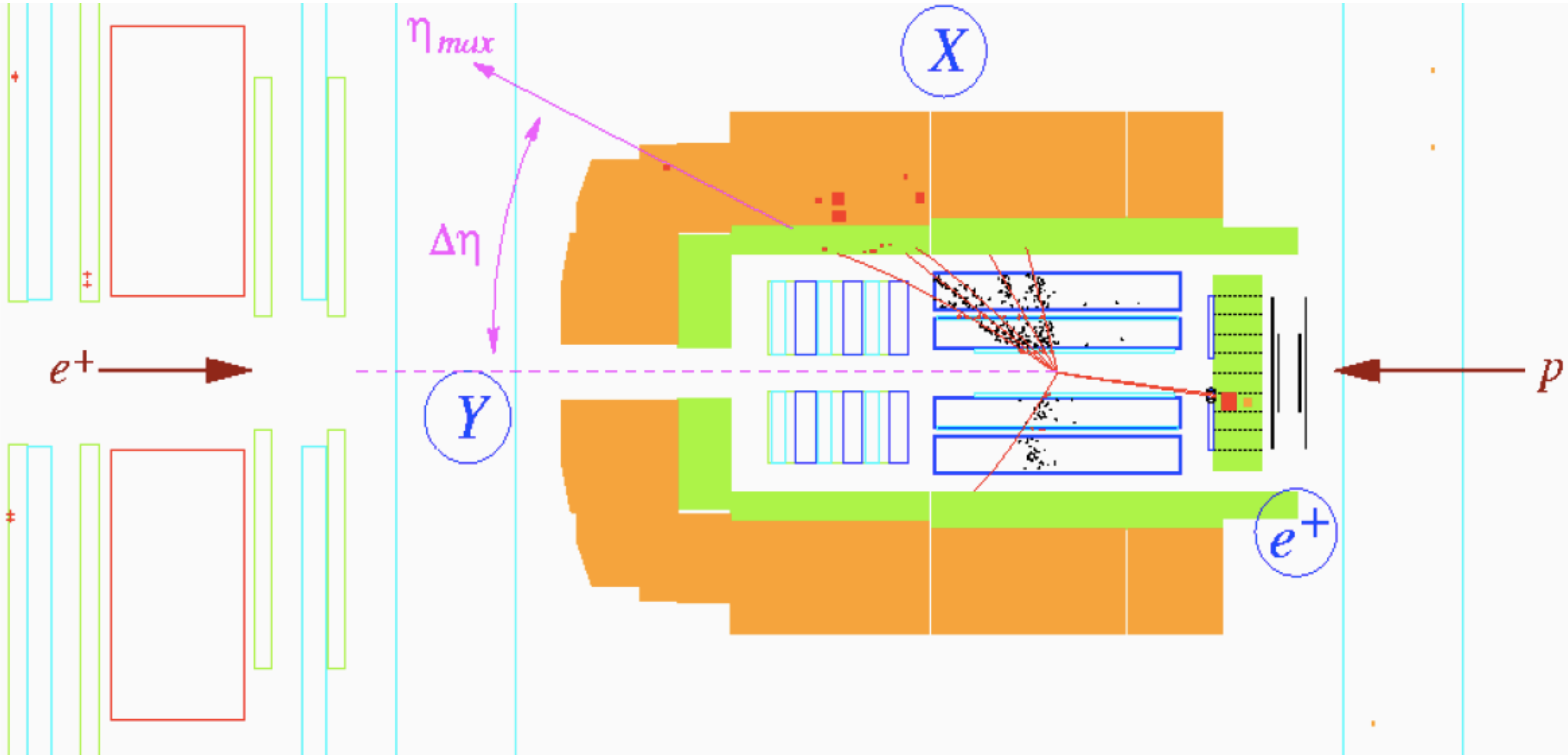


$$\frac{d^4\sigma}{dx_B\, dQ^2\, dM_X^2\, dt} = \frac{4\pi\alpha^2}{Q^6}\left[\left(1-y\right) F_2^{D,4}(x, Q^2, M_X^2, t) + xy^2 F_1^{D,4}(x, Q^2, M_X^2, t)\right].$$

- k, k’: four momenta of the incoming and outgoing lepton (e,μ)
- p, p’: four momentum of the incoming and outgoing nucleon
- t = (p-p’)^2: square of the four momentum transfer at the hadronic vertex
- squared invariant mass of hadronic system X: W^2 = (p-p’ + k-k’)^2

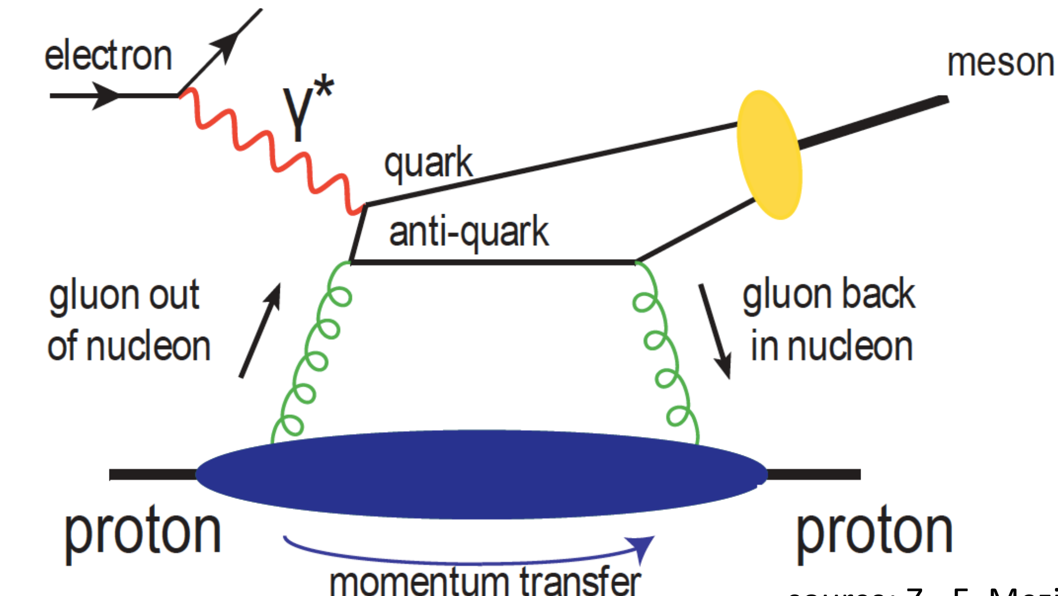
- pseudo-rapidity : η = ln(tan(θ/2)), θ is angle of X w.r.t. beam axis
- nucleon stays intact, large gap in η between nucleon and X

DIFFRACTIVE EVENT AT HERA



System Y is the proton + some small energy

HOW TO ACCESS GLUONS?

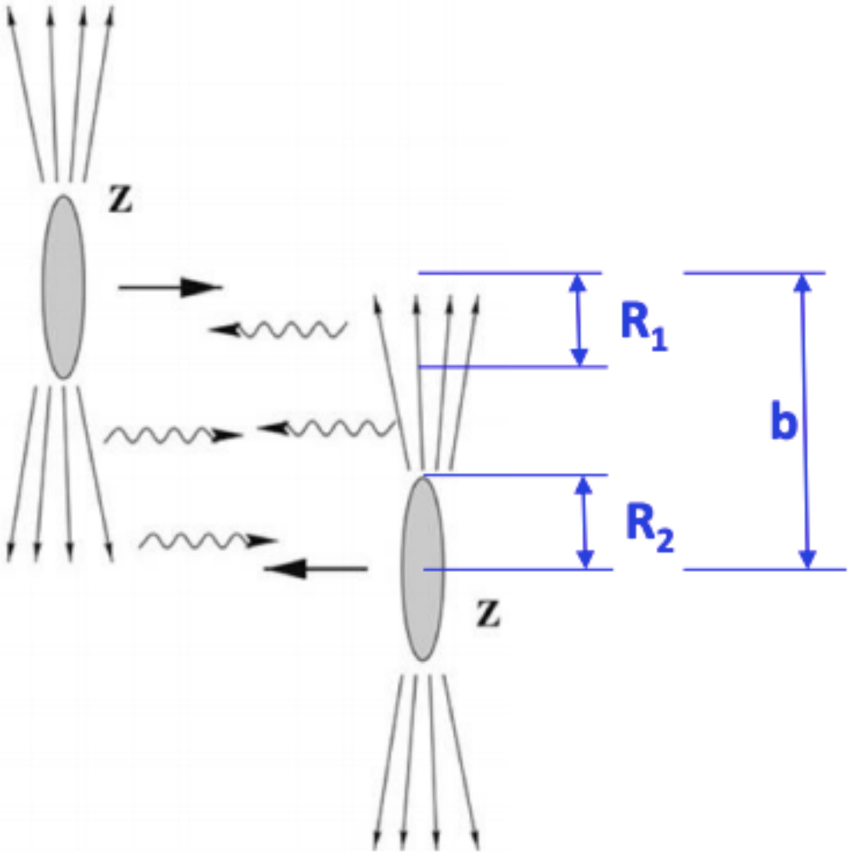


source: Z.-.E. Meziani

- Virtual photon splits into a heavy quark-antiquark pair, e.g. charm-anticharm
- Quarks carry color charge, interact with the gluons in the proton

- Color neutral process, 2 gluon exchange, Regge trajectory, Pomeron
- Experimentally: detect heavy vector-mesons in the final state, e.g. $J/\psi \longrightarrow e^+e^-, \mu^+\mu^-$, D mesons
- Experimentally clean signature, little background or other physics sources

ULTRA-PERIPHERAL COLLISIONS OF TWO NUCLEI

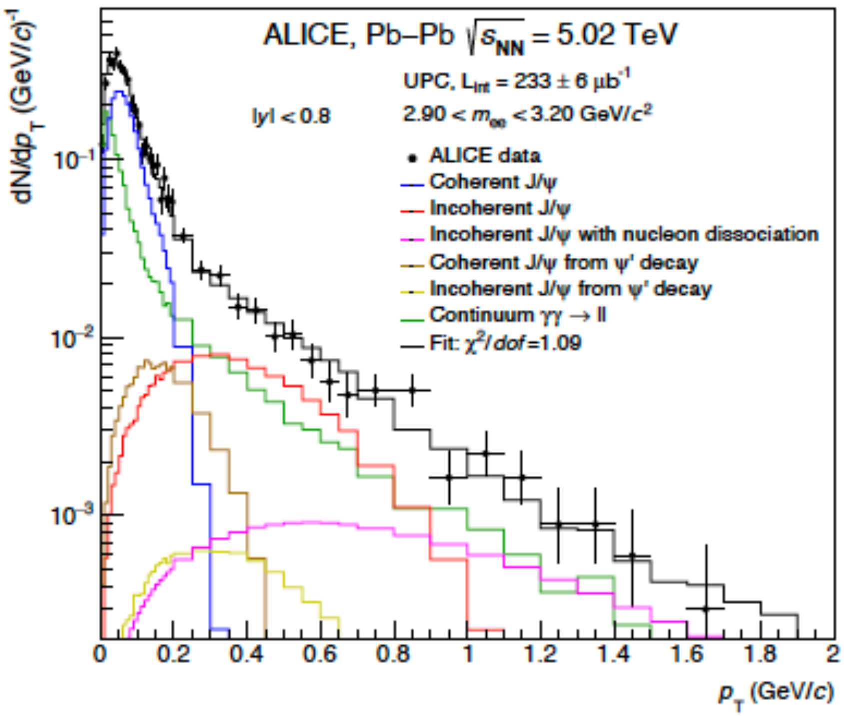


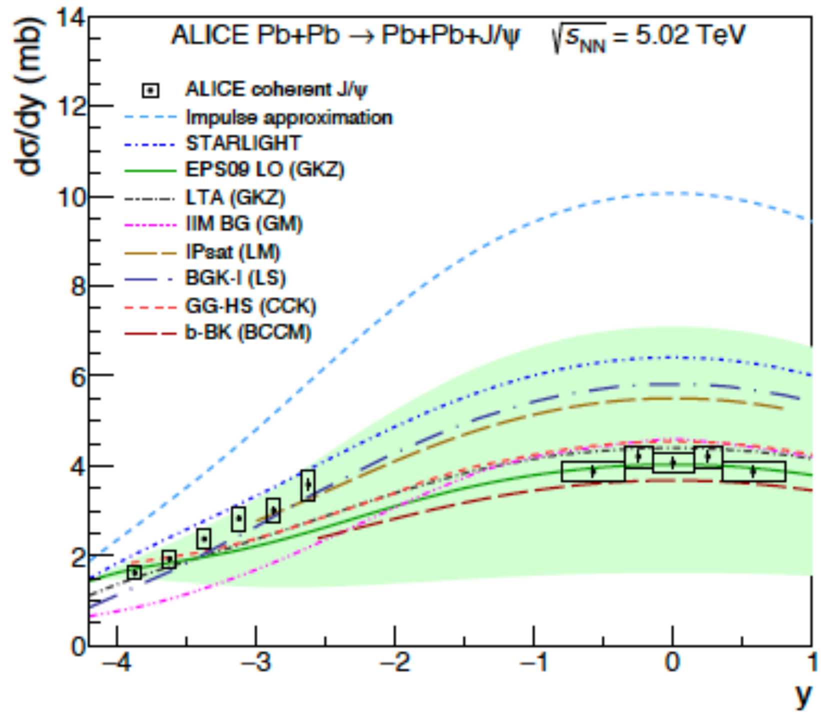
Quasi-real photon field

Photon flux $\propto Z^2$

EXPERIMENTAL OBSERVABLES

https://arxiv.org/abs/2101.04577





Suppression with respect to radiation off free nucleon

→ Nuclear **shadowing, nuclear PDF** (nPDF)

$<p_T>$ ~ $1/R_{Pb}$ ~ 60 MeV/c, coherent interactions: ultra-low p_T

$x = m_V / s_{NN} \cdot exp(-y)$, down to $x = 6 \cdot 10^{-4}$

Production quadratically sensitive to gluon distribution

PARTON DENSITY IN NUCLEI

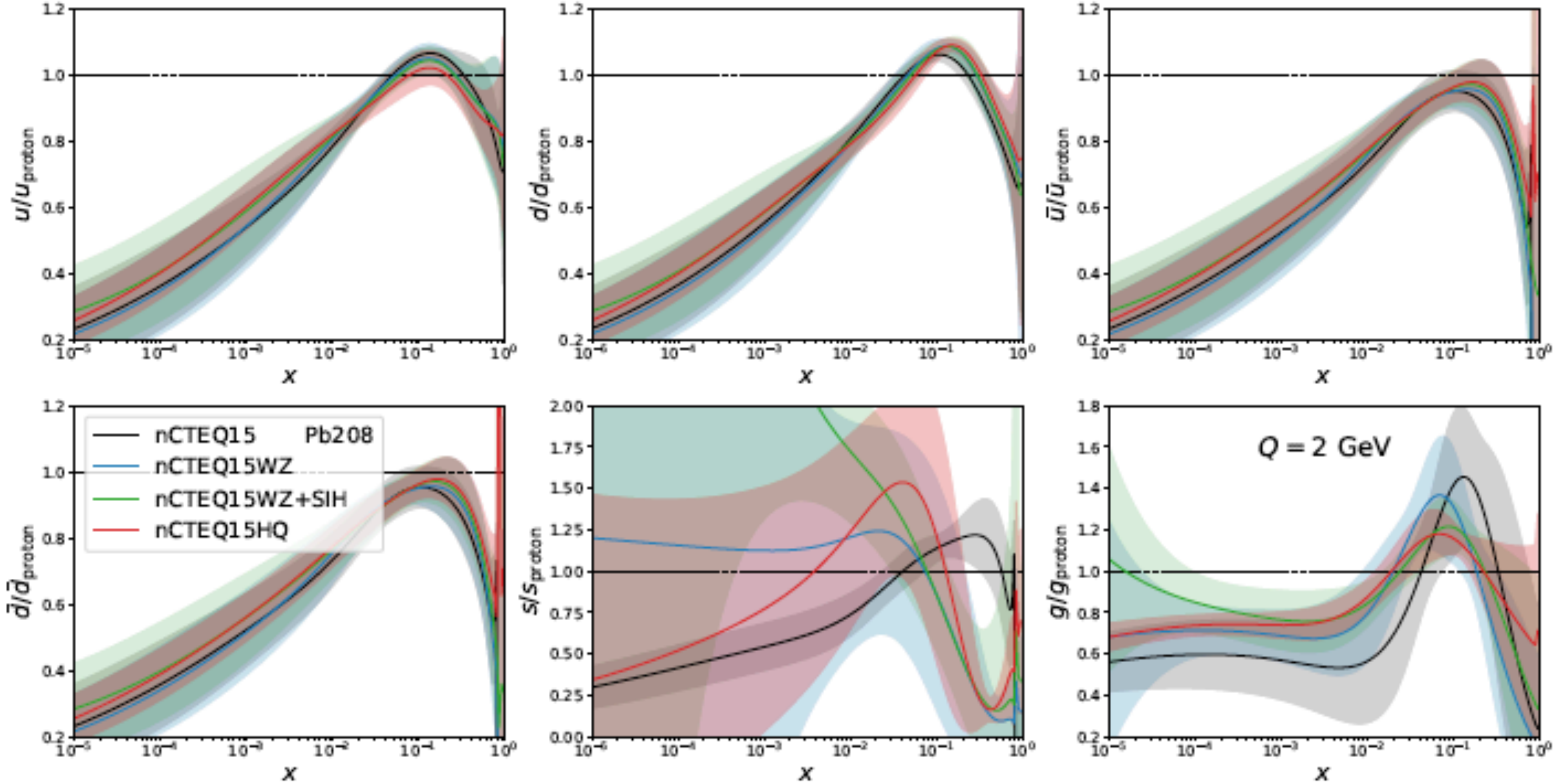


FIG. 5: Ratio of lead and proton PDF from different nCTEQ15 versions. The baseline nCTEQ15 fit is shown in black, nCTEQ15WZ in blue, nCTEQ15WZSIH in green, and the new fit in red.

https://arxiv.org/abs/2204.09982