An Introduction to High Energy Nuclear Collisions

QCD under extreme conditions

Jamal Jalilian-Marian
Baruch College, City University of New York

many thanks to the organizers
and
colleagues whose slides I have “borrowed”

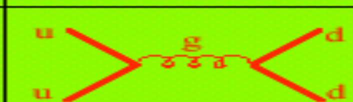
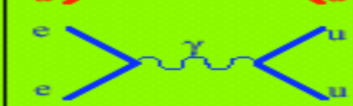
Fundamental particles and their interactions

QUARKS S=1/2		LEPTONS S=1/2		GAUGE BOSONS S=1
Q = −2/3	Q = −1/3	Q = −1	Q = 0	quanta
u u u m=(1-4) 10^{-3}	d d d m=(5-8) 10^{-3}	e m=5.11 10^{-4}	ν_e m<3 10^{-9}	g_1 …… g_8 m< a few 10^{-3}
c c c m=1.0-1.4	s s s m=0.08-0.15	μ m=0.10566	ν_μ m<1.9 10^{-4}	γ m<2 10^{-25}
t t t m=174.3±5.1	b b b m=4.0-4.5	τ m=1.7770	ν_τ m<18.2 10^{-3}	$W^{\pm}$, Z^0 m_W=80.432 ±0.39, m_Z=91.1876 ±0.0021

All masses in GeV units

QCD → Strong

QED → Electromagnet.

Interaction	exchanged boson	relative strength	example
Strong	Gluon (g)	1	
Electromagnet.	Photon (γ)	$\frac{1}{137}$	
Weak	W^+, W^-, Z^0	10^{-14}	
Gravitation	Graviton (G) ?	10^{-40}	

An Introduction to High Energy Nuclear Collisions

Lecture I: *What is a nucleus?*

Deeply Inelastic Scattering (DIS), Parton Model, QCD, Structure Functions

Lecture II: *What does a nucleus look like at high energy?*

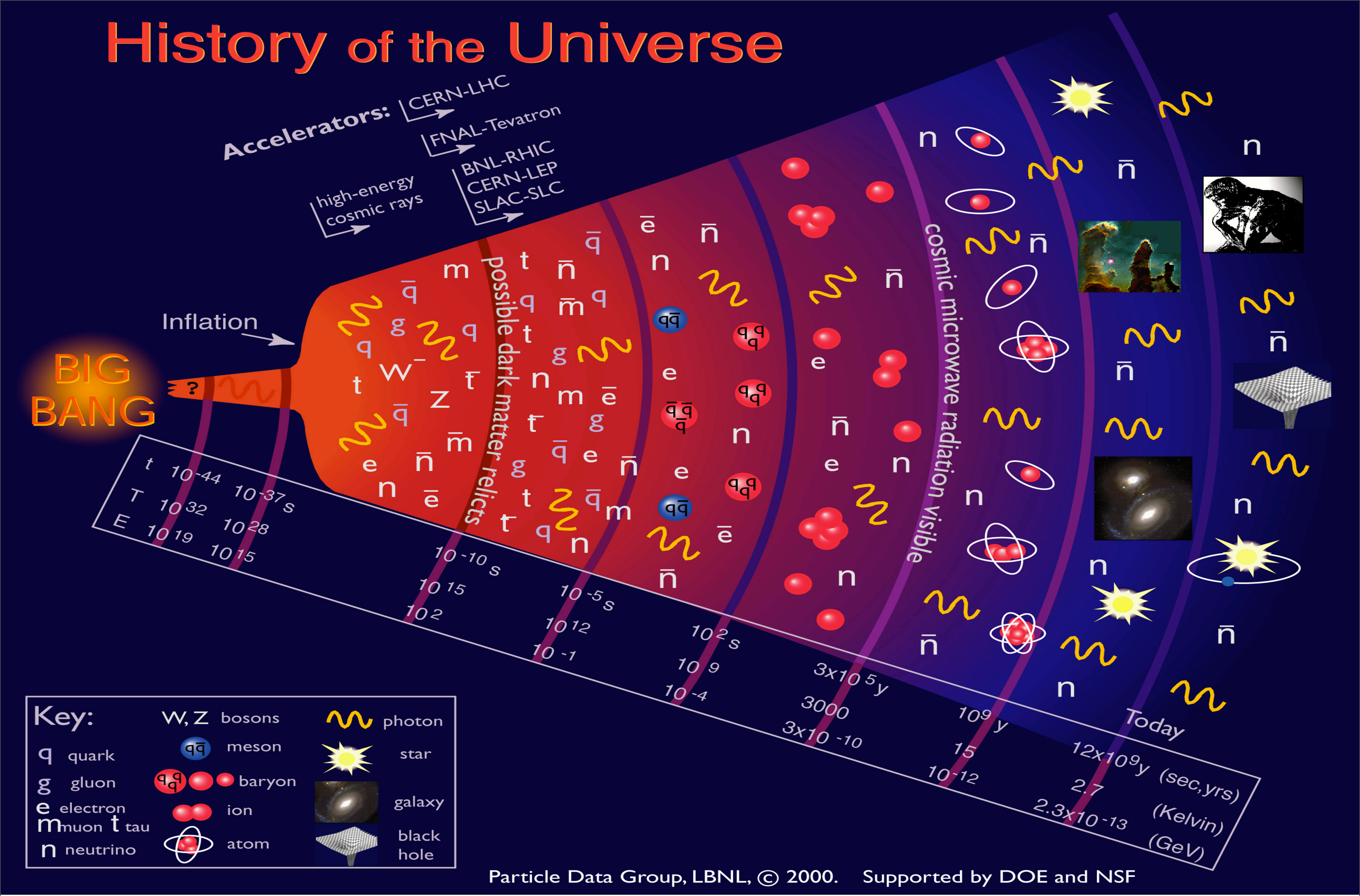
QCD at small x, Renormalization Group, Saturation, Color Glass Condensate

Lecture III: *Particle production in H.E. nuclear collisions*

Classical fields, particle production, Instability, Thermalization?

WHY?

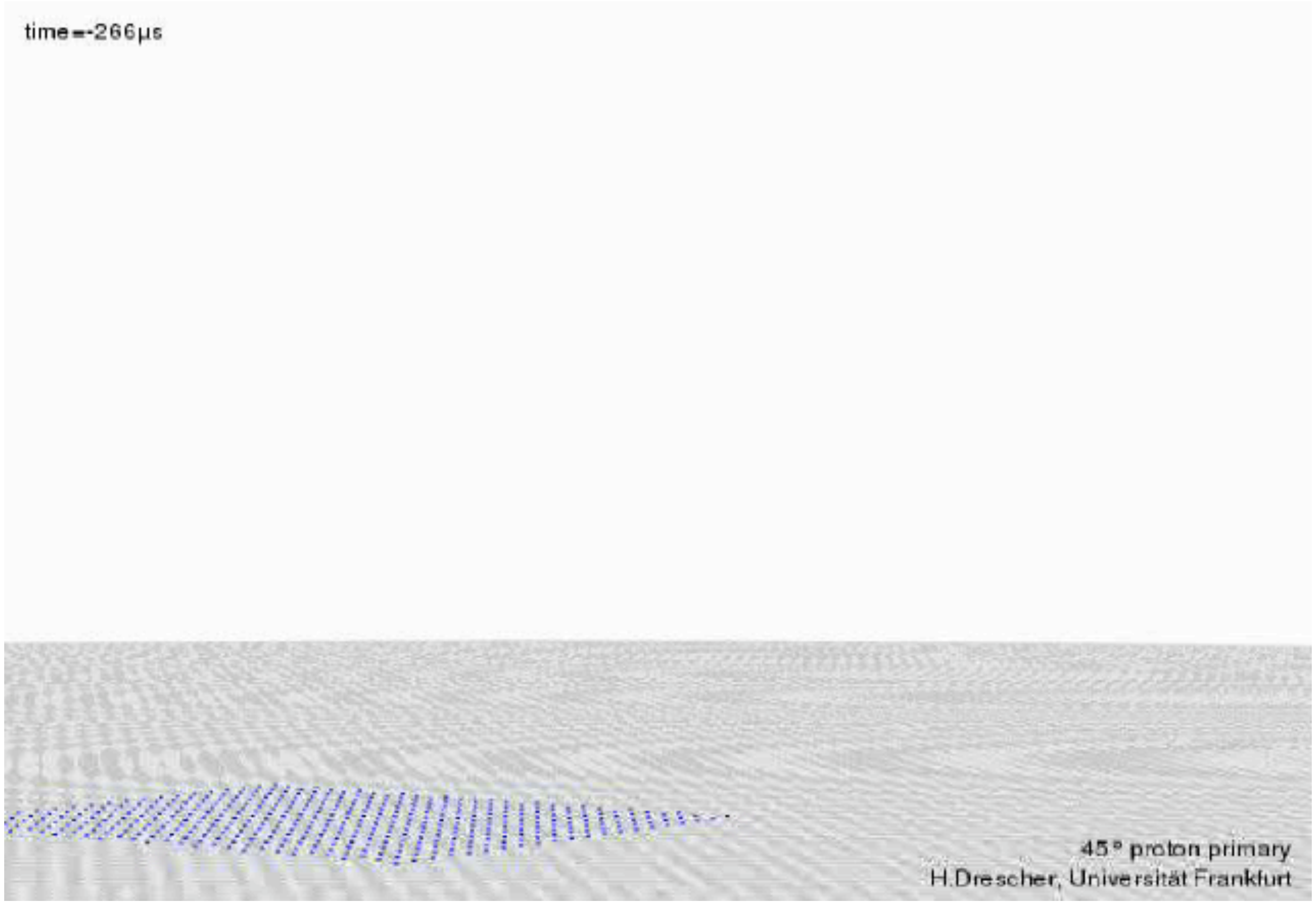
- ***Early Universe***
  - *A hot and dense soup (Quark-Gluon Plasma)*
    - **Can we recreate this in lab and study its properties ?**
  - *Strong interactions in the extreme limit*
    - **Can we probe/learn about new aspects of strong interactions ?**

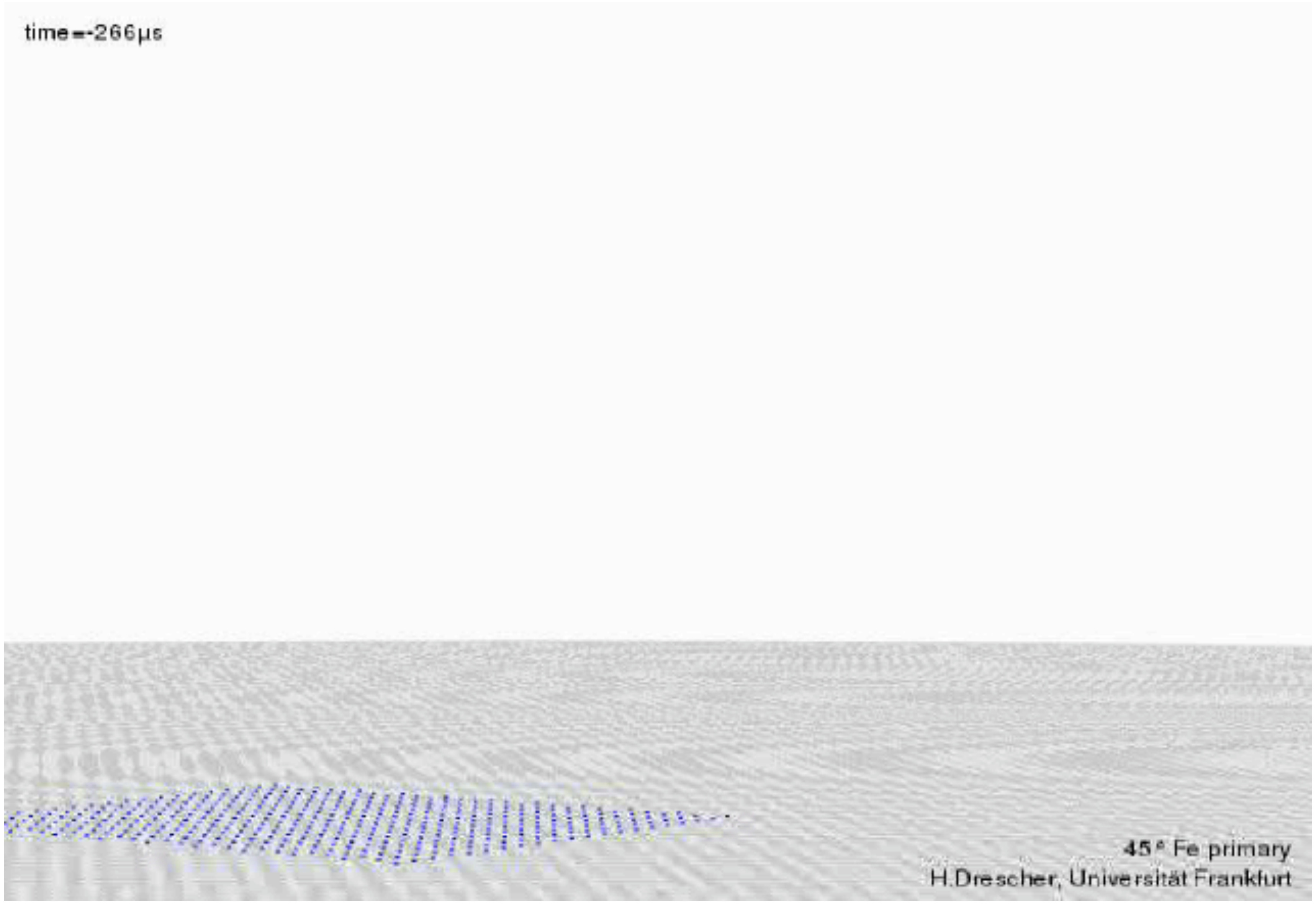


Few microseconds after the Big Bang the entire Universe was in a QGP state

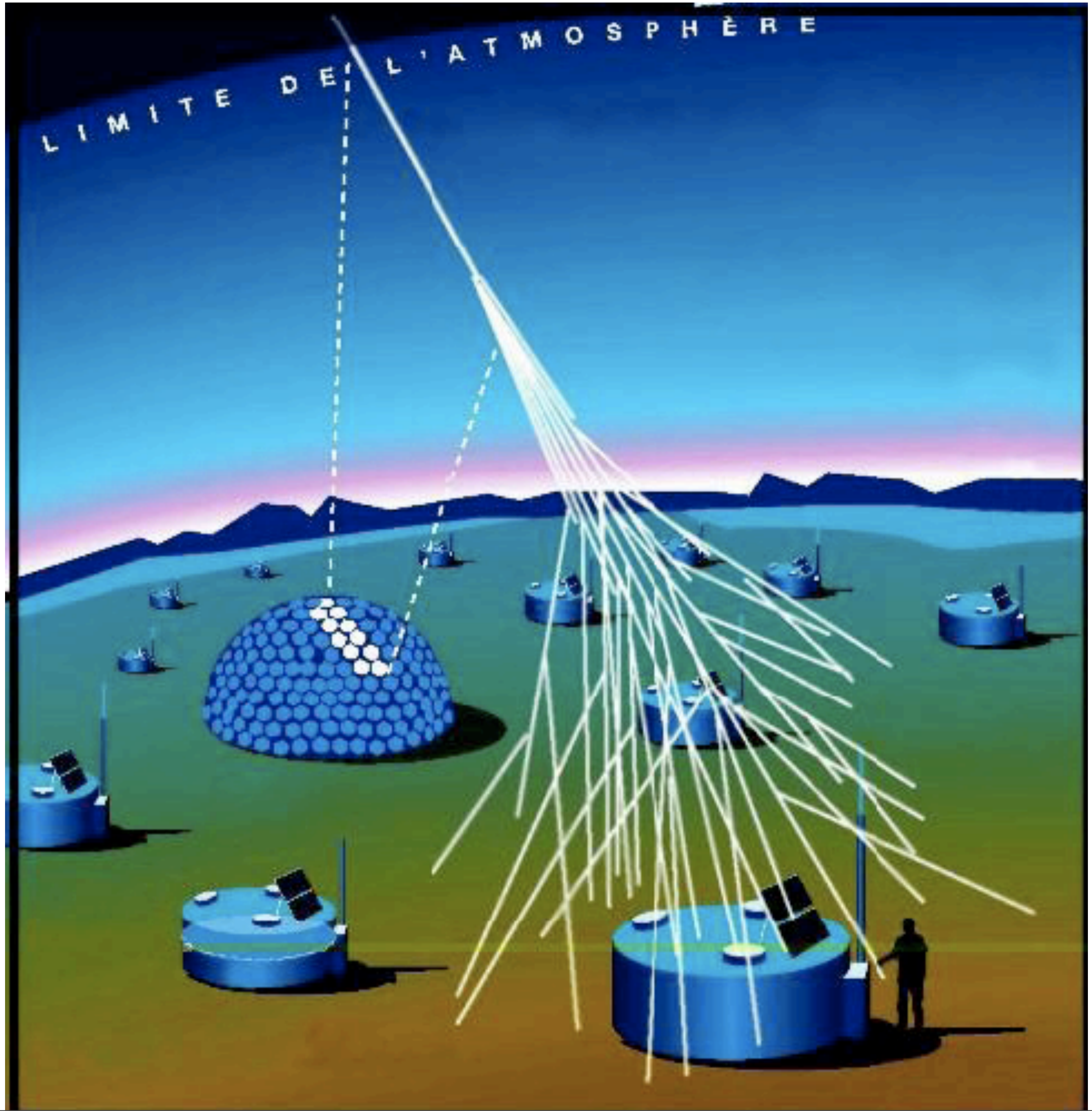
WHY?

- ★ ***Ultra-high energy cosmic rays***
  - ★ *What is their source?*
    - ★ **A window into new physics ?**
  - ★ *How do they interact?*
    - ★ **Can they shed light on extreme limit of strong interactions ?**

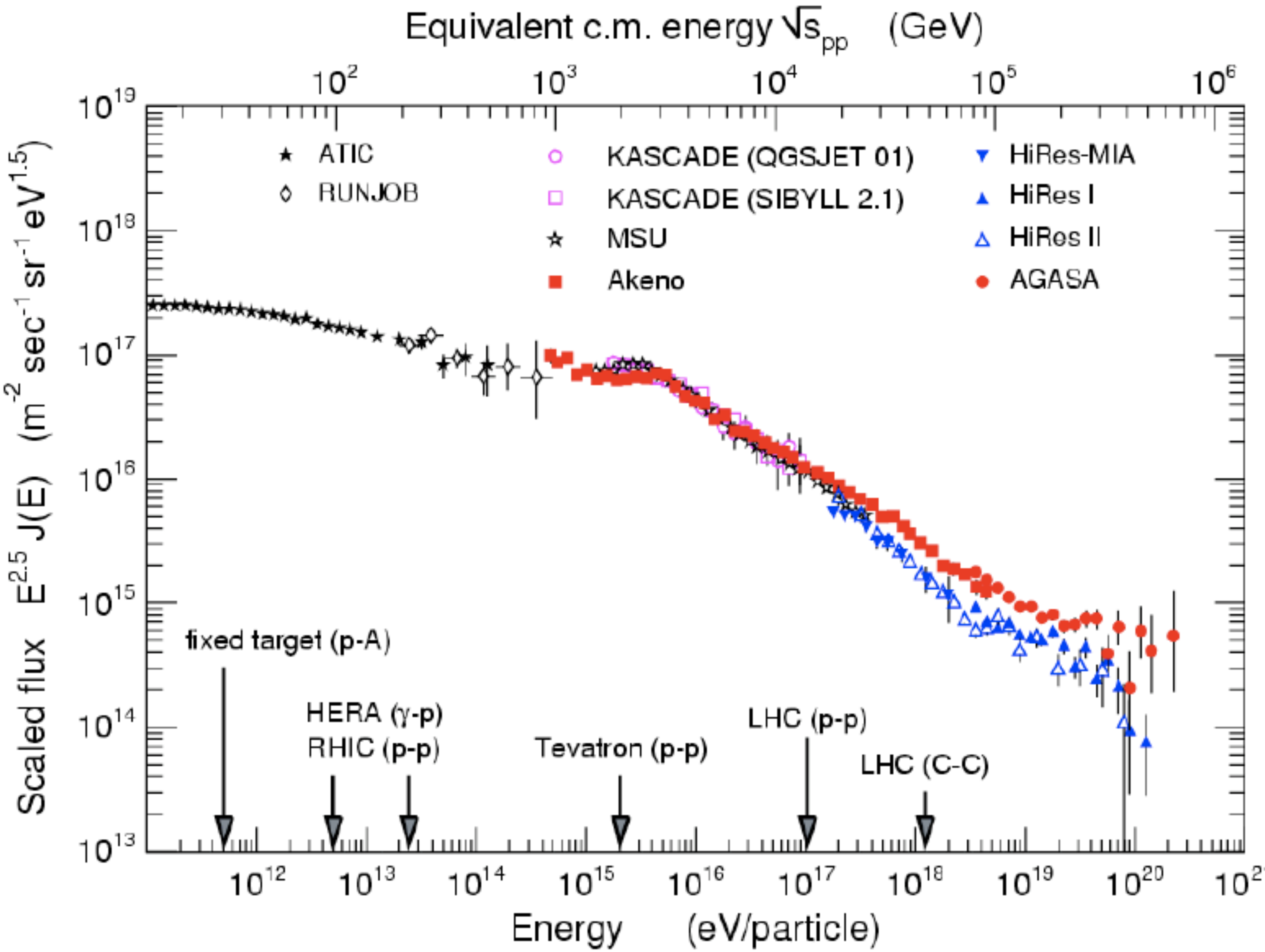

time=-266µs
45° proton primary
H.Drescher, Universität Frankfurt


time=-266µs
45° Fe primary
H.Drescher, Universität Frankfurt

Ultra-High Energy Cosmic Rays



The flux of cosmic rays on earth

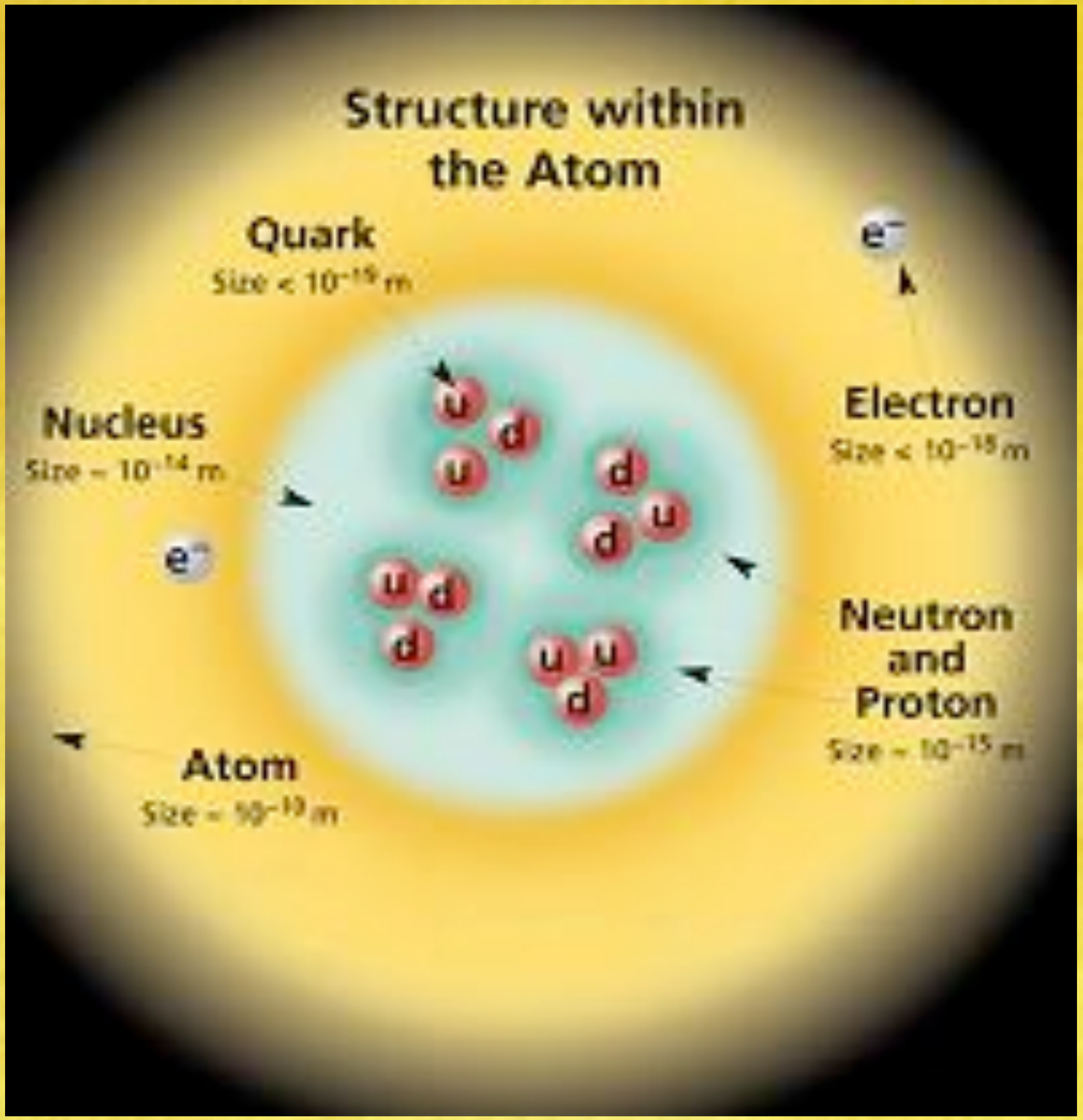


Quantum ChromoDynamics (QCD)

the theory of strong interactions: hadrons, nuclei

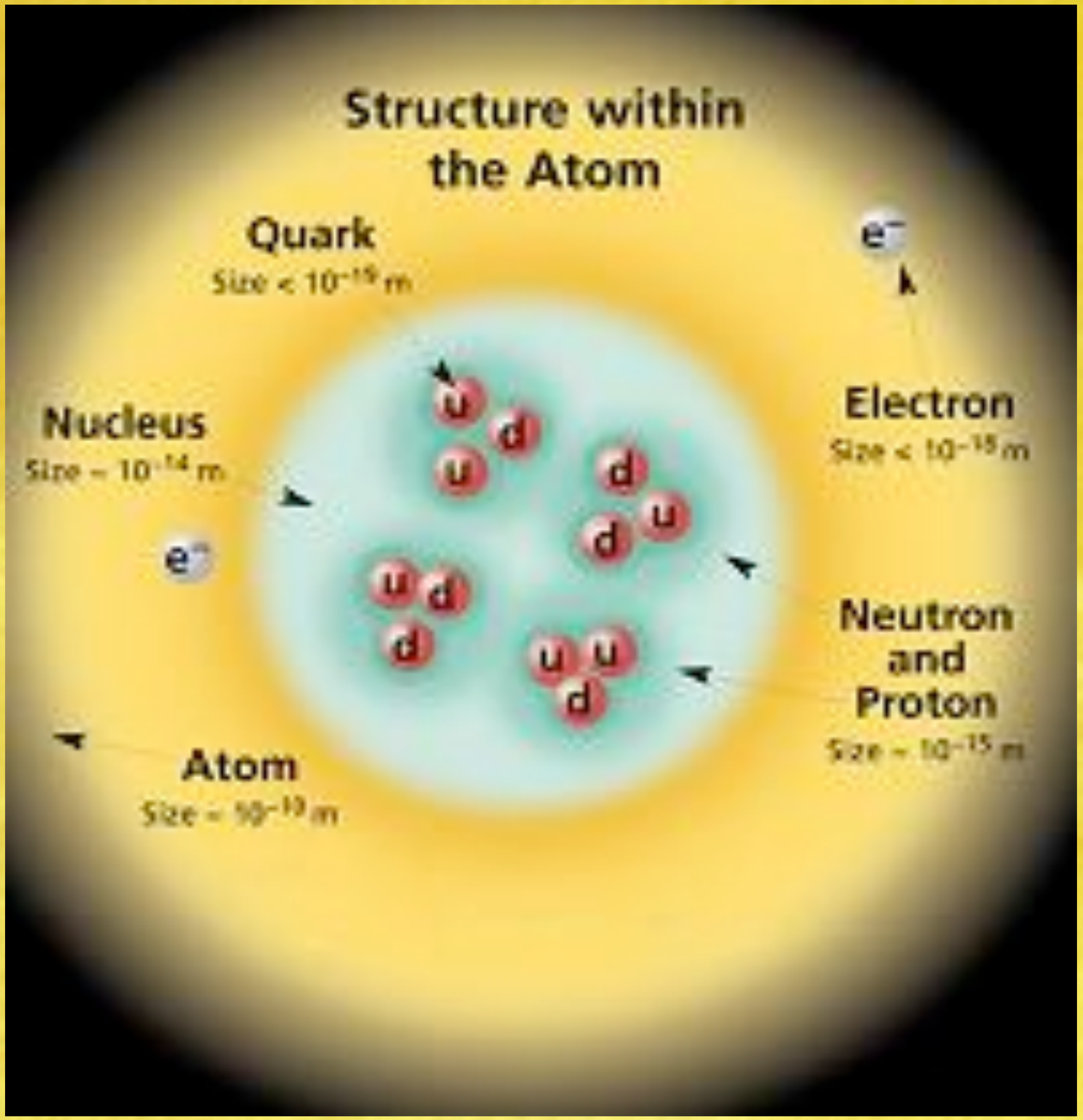
Quantum ChromoDynamics (QCD)

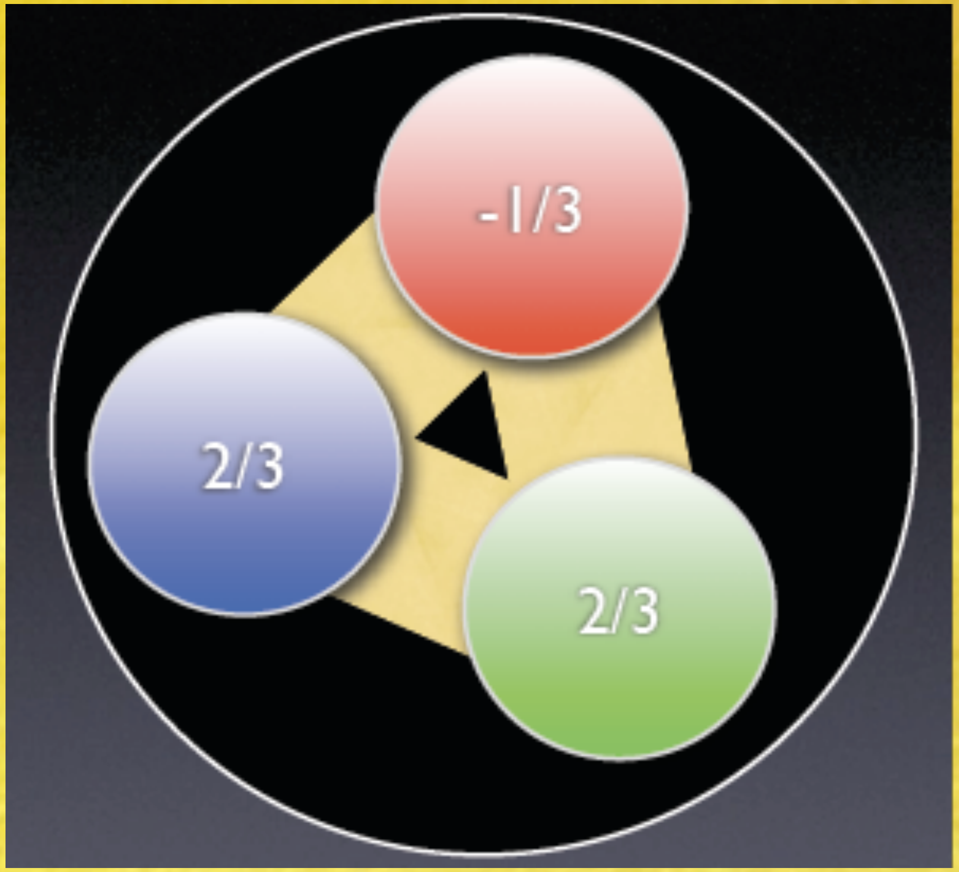
the theory of strong interactions: hadrons, nuclei



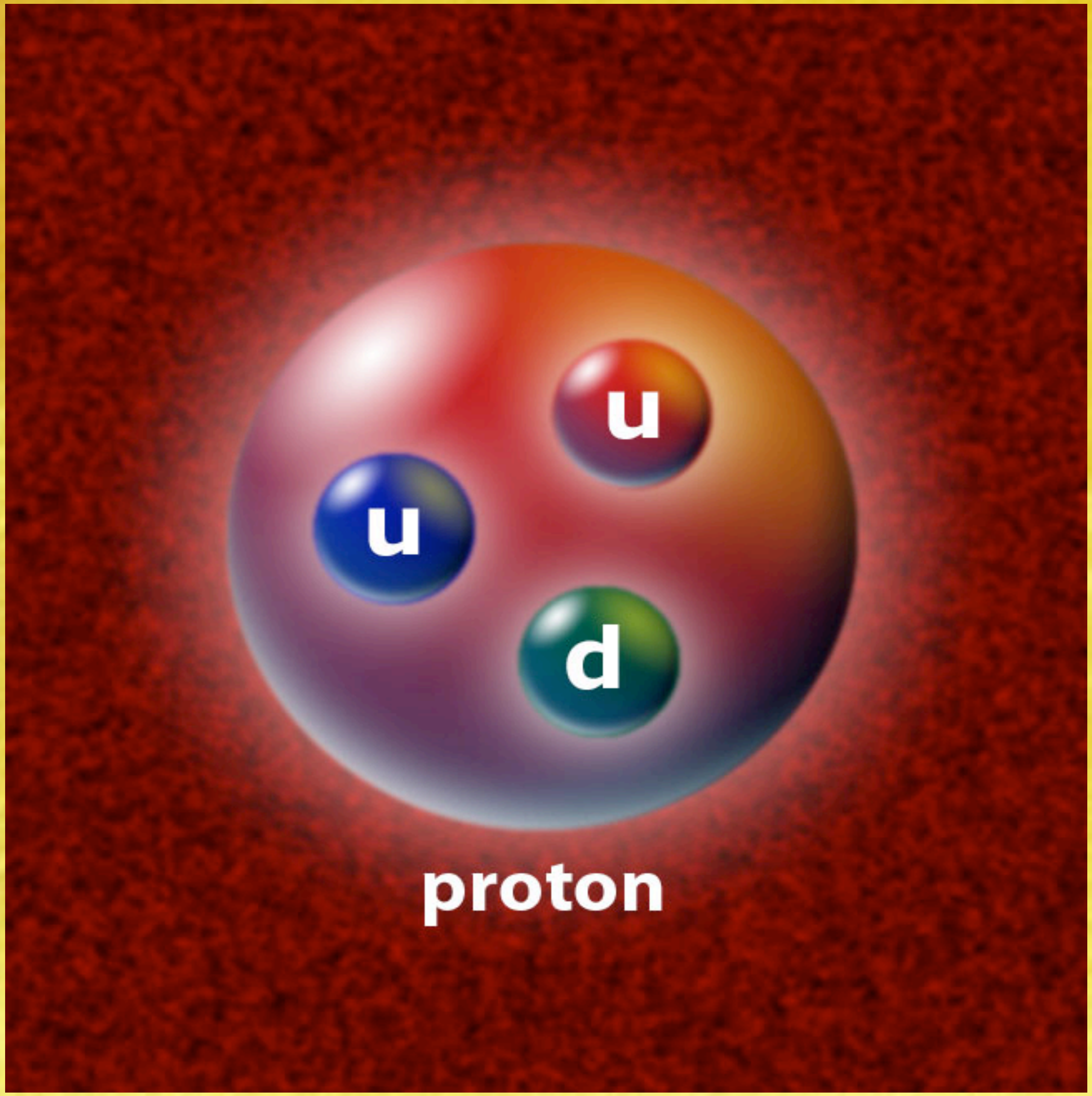
Quantum ChromoDynamics (QCD)

the theory of strong interactions: hadrons, nuclei

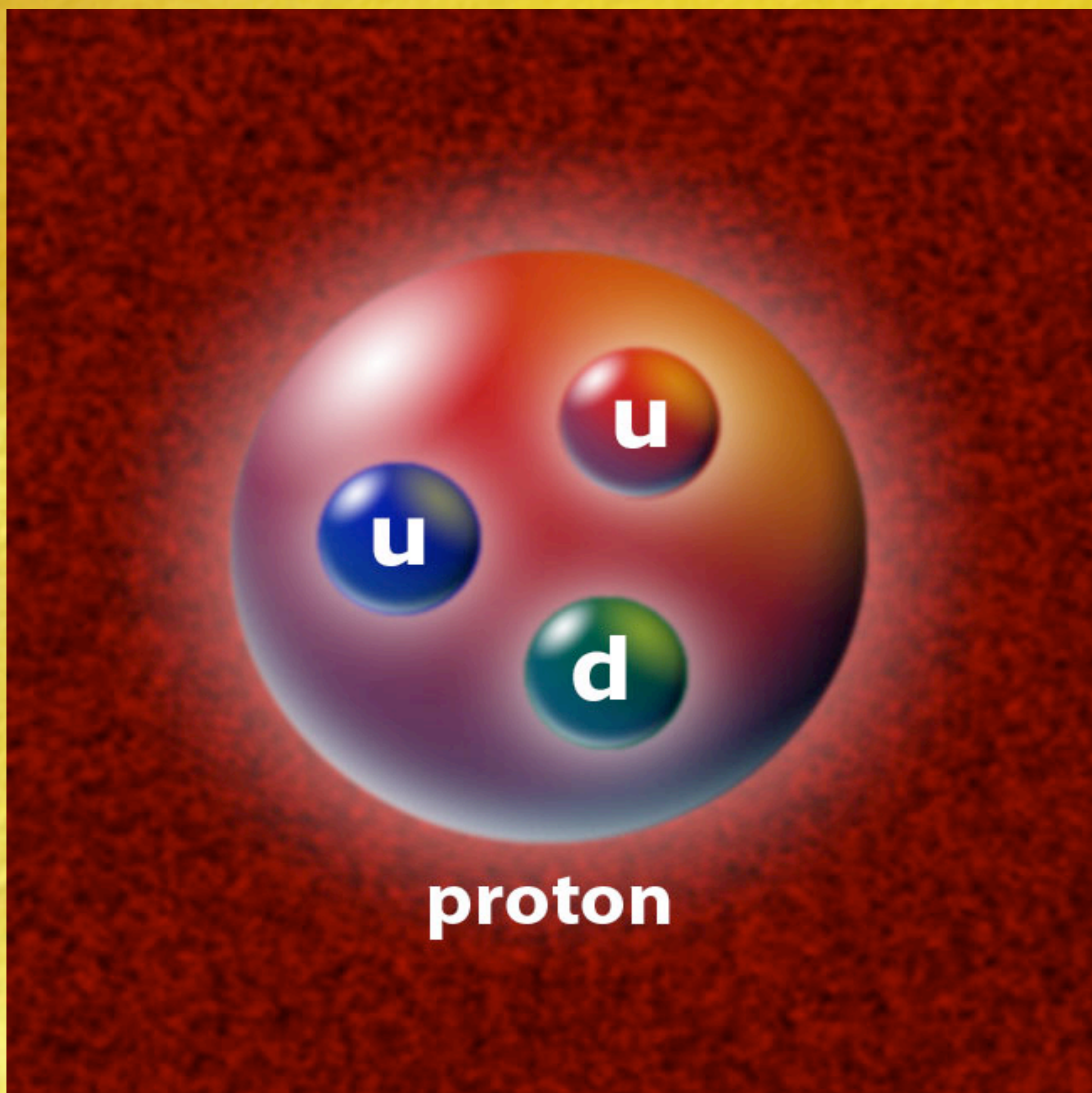




pre-QCD: Quarks

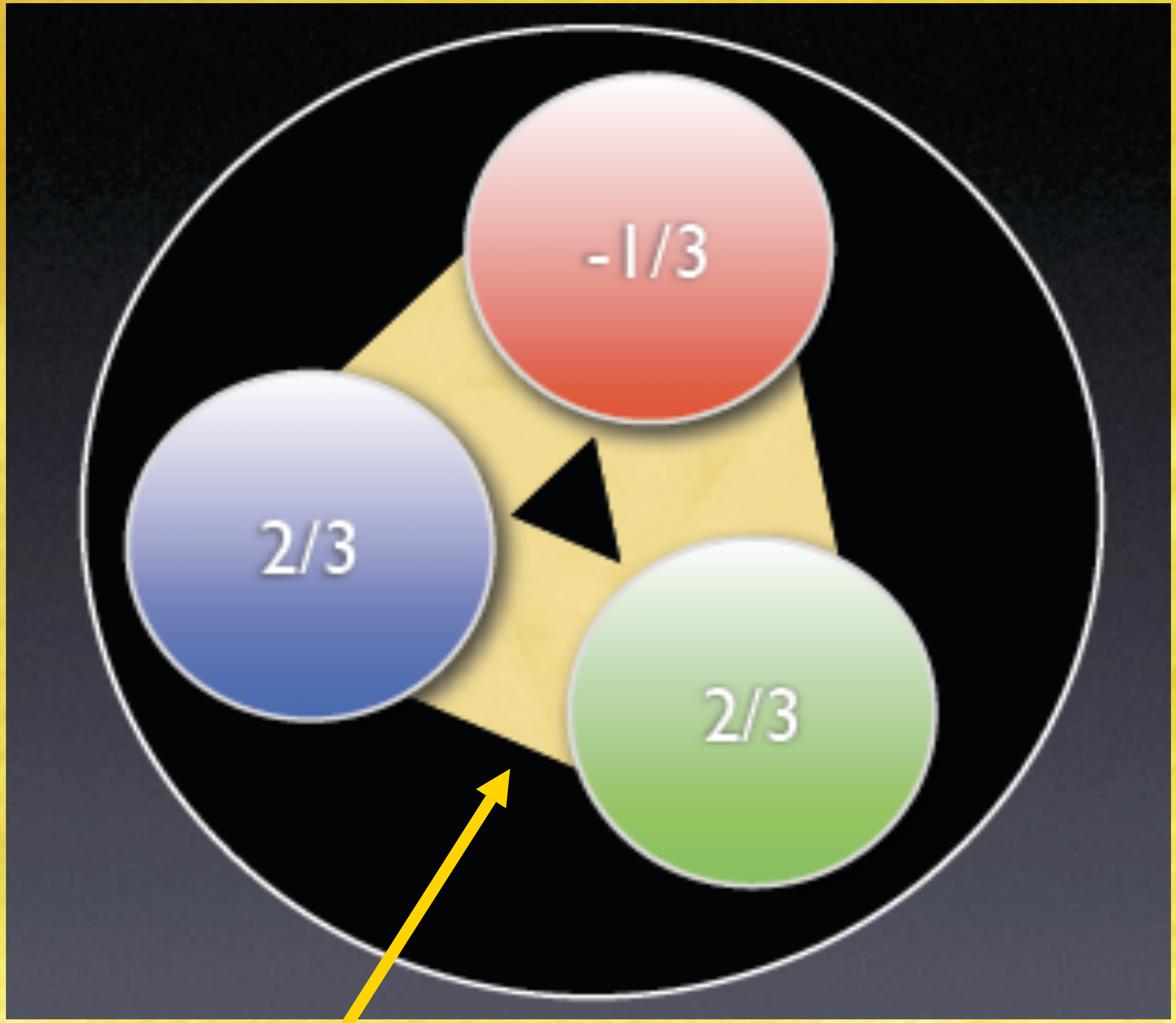


pre-QCD: Quarks



Gell-Mann and Ne'eman

pre-QCD: Yang-Mills

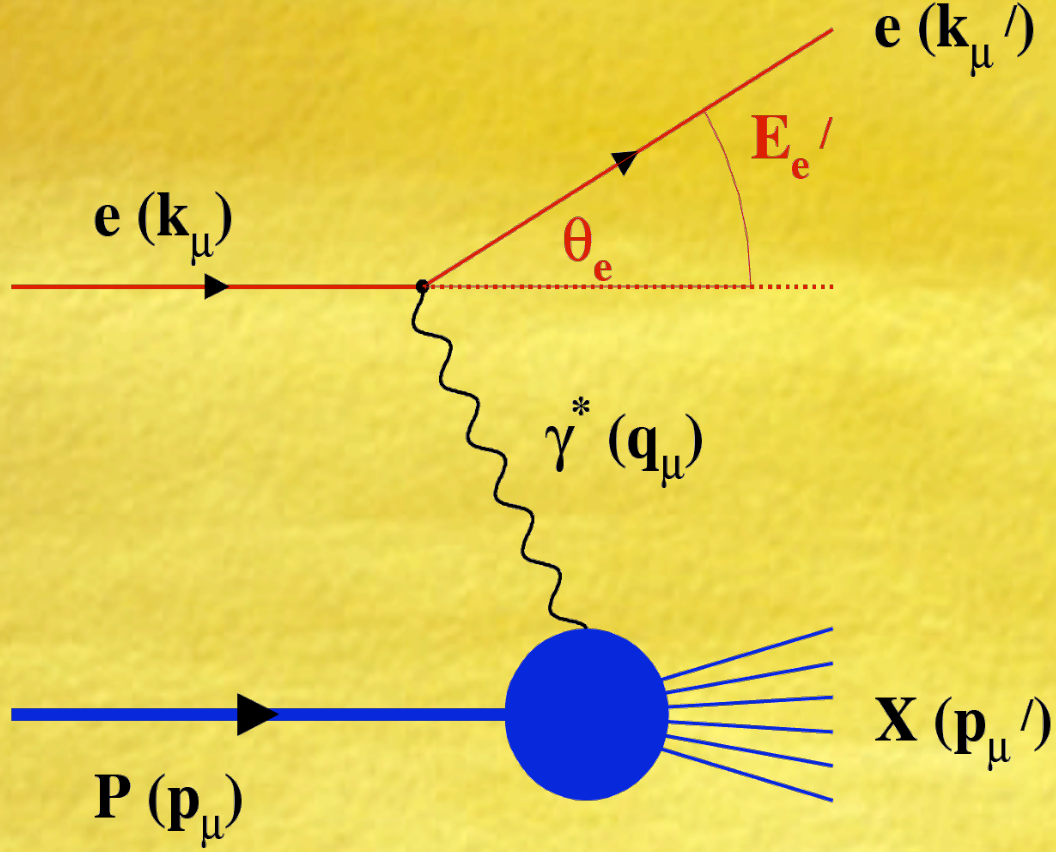


gluons

Yang and Mills

Deeply Inelastic Scattering (DIS)

probing hadron structure



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power

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

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

Measure of inelasticity

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

Measure of momentum fraction of struck quark

DIS

$$\frac{d\sigma}{dx dQ^2} \propto L_{\mu\nu} W^{\mu\nu}$$

Hadronic tensor:

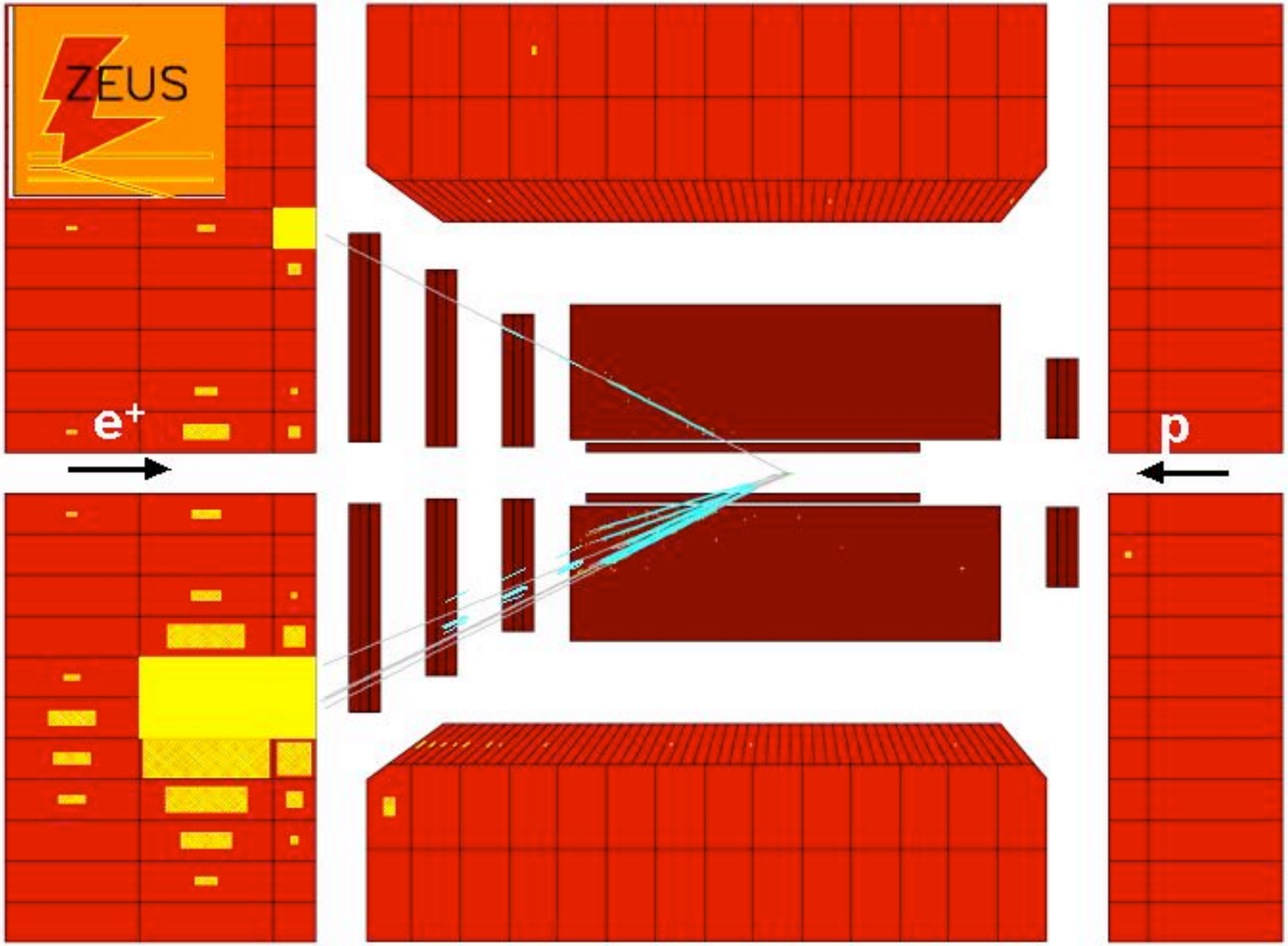
$$W^{\mu\nu} = 2 \text{ Disc. } T^{\mu\nu}(q^2, P \cdot q) = \frac{1}{2\pi} \text{ Im.} \int d^4x \, e^{iq\cdot x} \langle P | T(J^\mu(x) J^\nu(0)) | P \rangle$$

$$J^\mu(x) = \bar{\psi}\gamma^\mu\psi$$

hadronic tensor can be written in terms of two structure functions, F_2, F_L

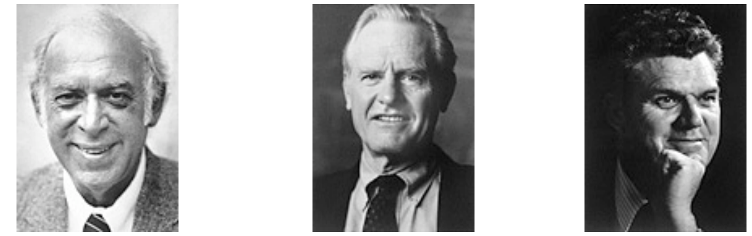
$$\frac{d^2\sigma^{eh\to eX}}{dx dQ^2} = \frac{4\pi\alpha_{em}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2)\right]$$

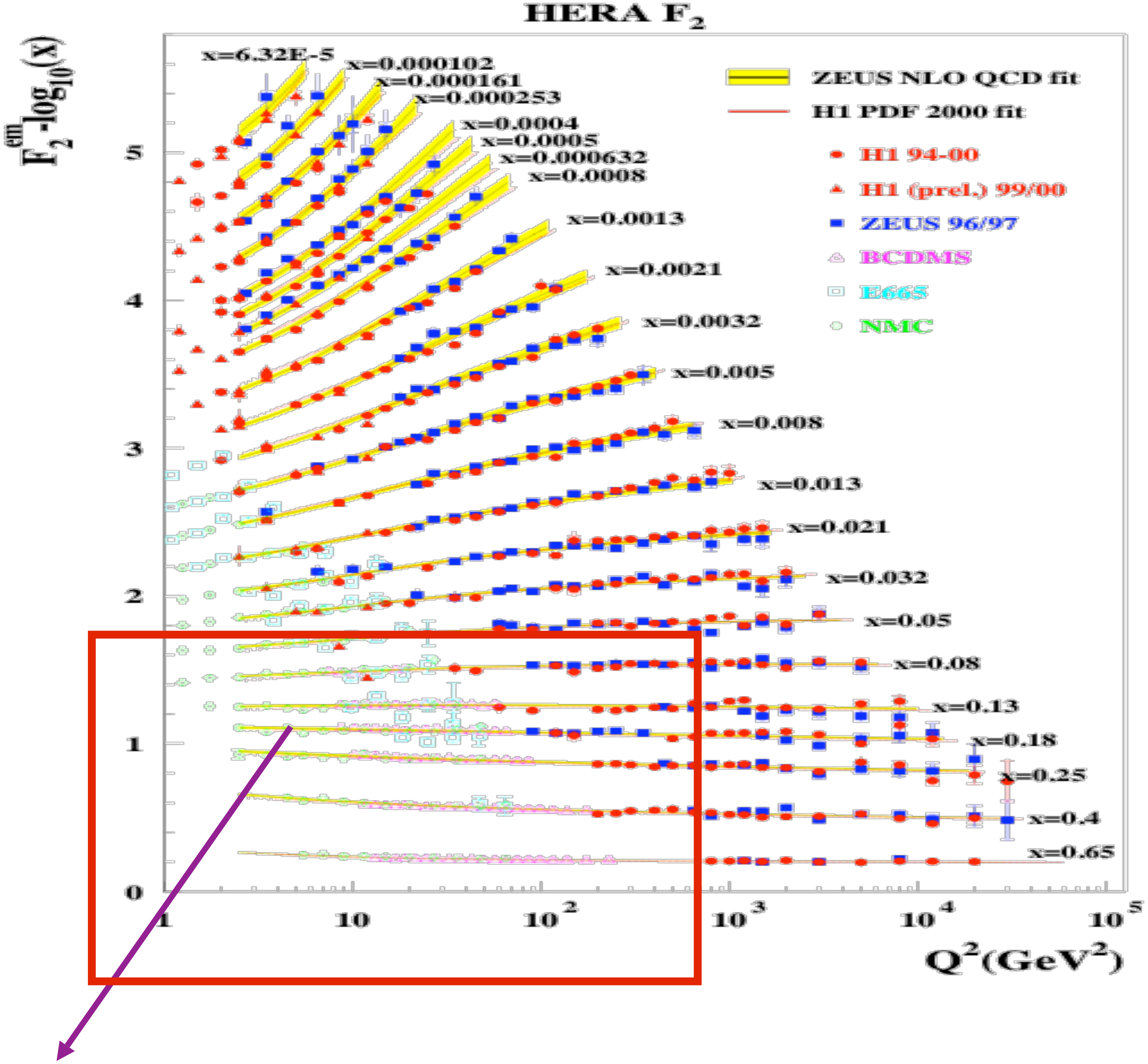
A Deep Inelastic electron-proton Scattering event



ZEUS at DESY

Nobel to Friedman, Kendall, Taylor



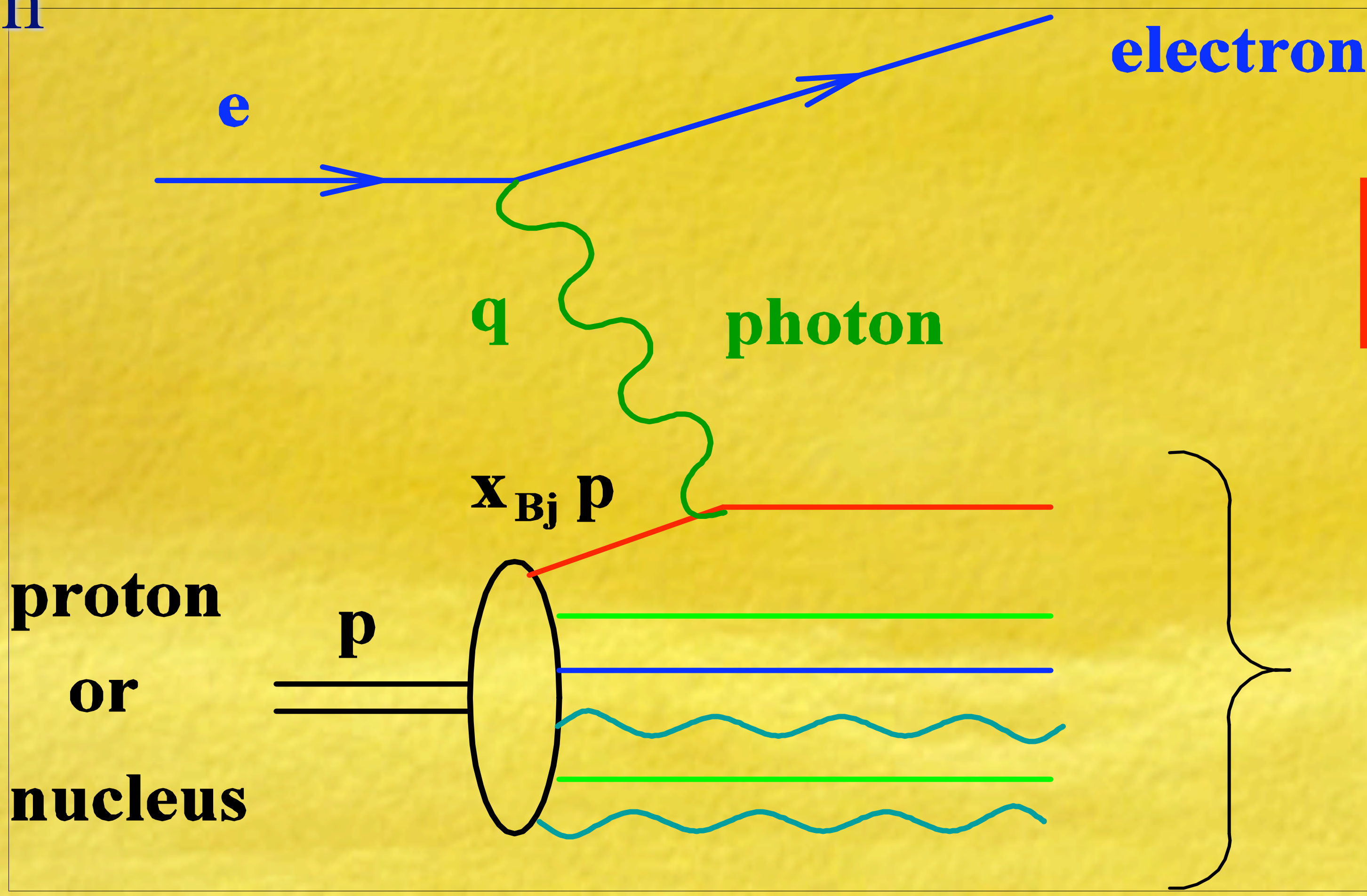


Bj-scaling: apparent scale invariance of structure functions

Parton Model: Bjorken & Feynman

Bjorken

Feynman



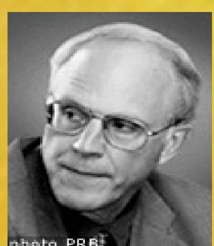
$$Q^2 \to \infty\,;\ s \to \infty\,;\ x_{\rm Bj} \approx \frac{Q^2}{s} = \text{fixed}$$

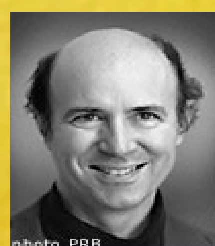
Parton constituents of hadron are "quasi-free" on time scale 1/q

x_{Bj} = Fraction of hadron momentum carried by a parton

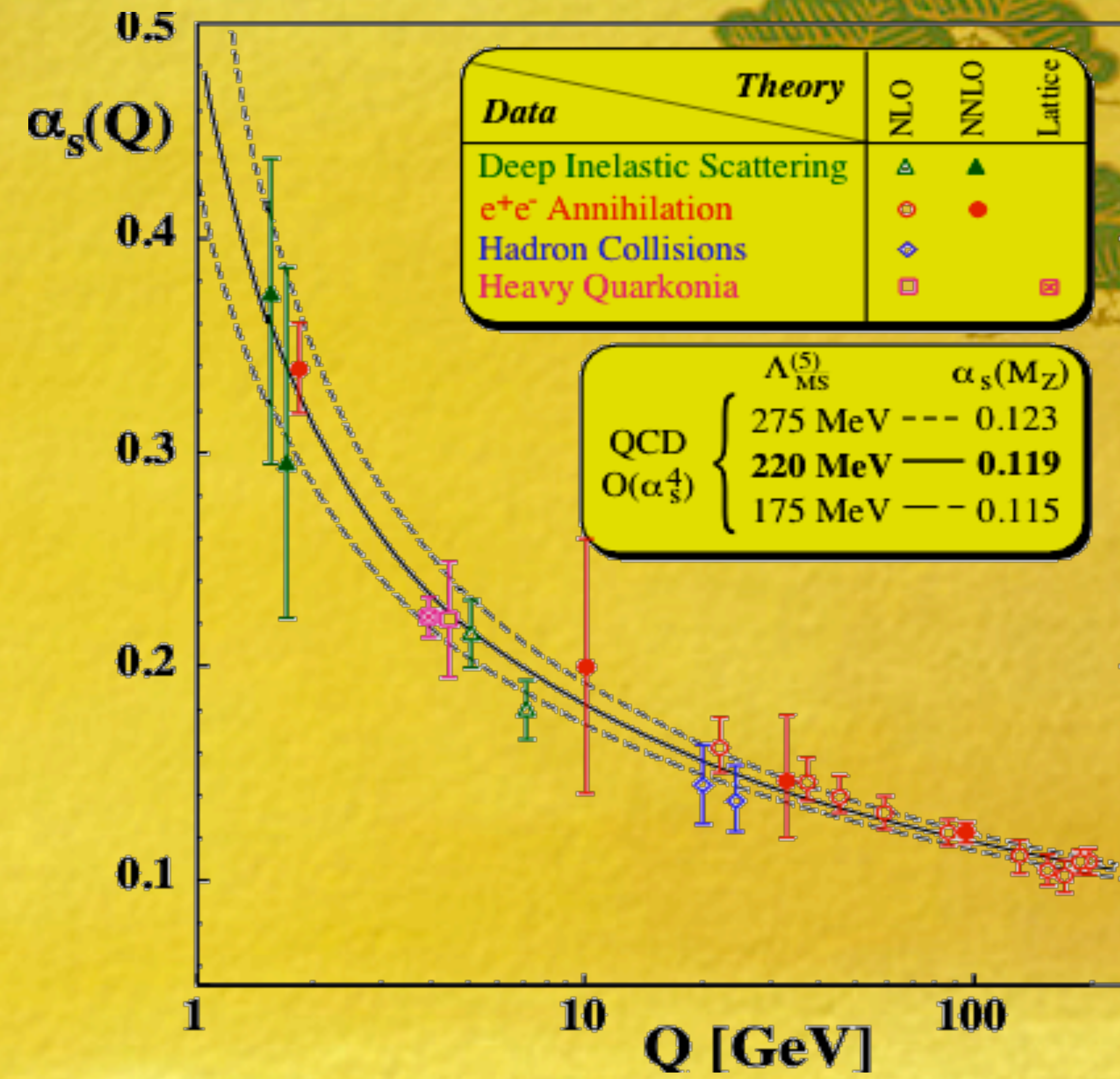
$$F_2 \sim e^2\,[xq\,(x) + x\bar{q}\,(x)]$$

Asymptotic Freedom

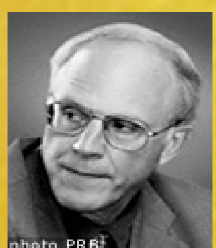


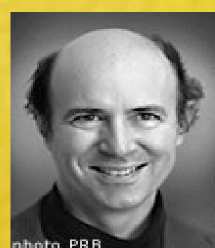


Gross, Wilczek, Politzer

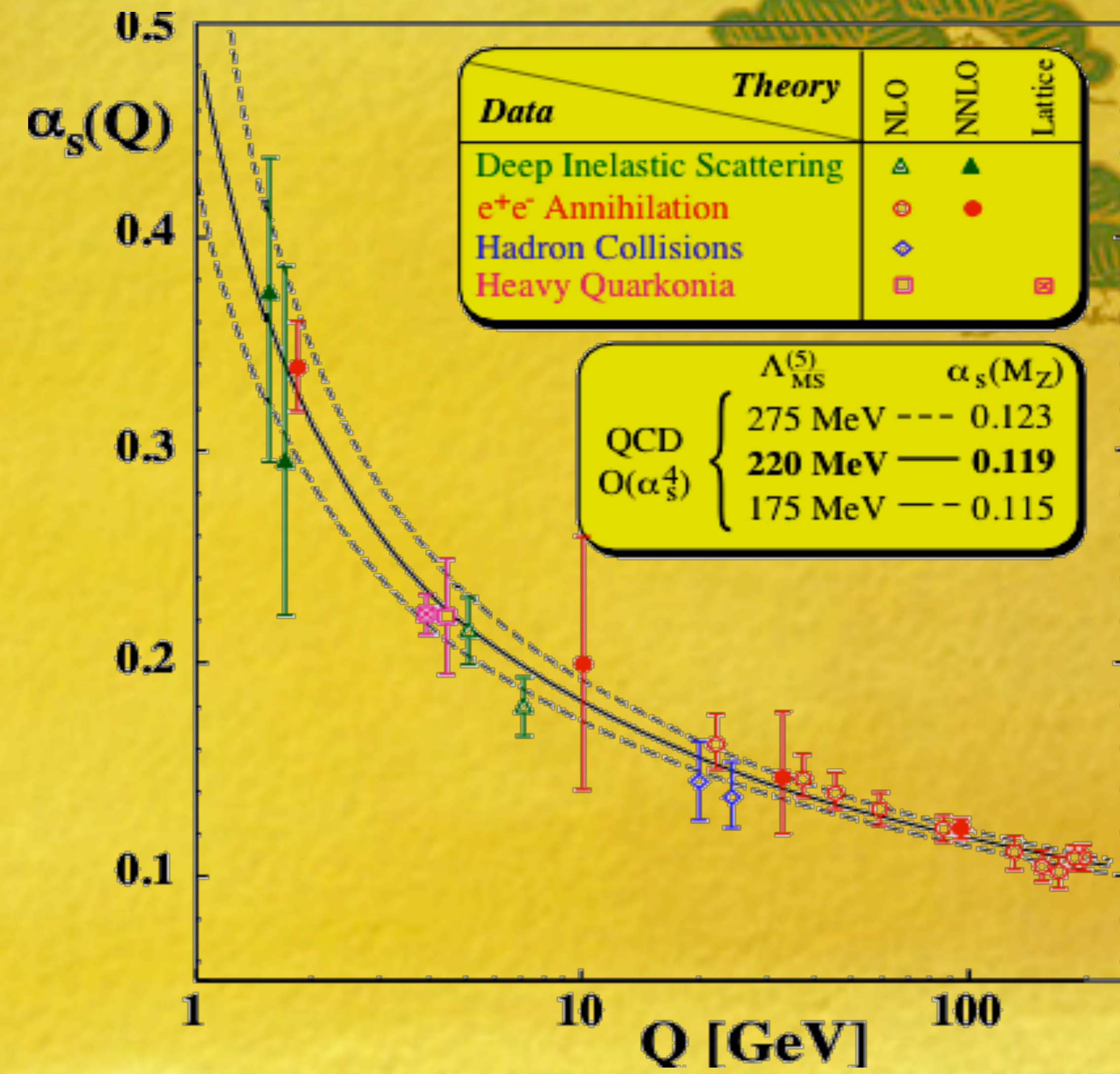


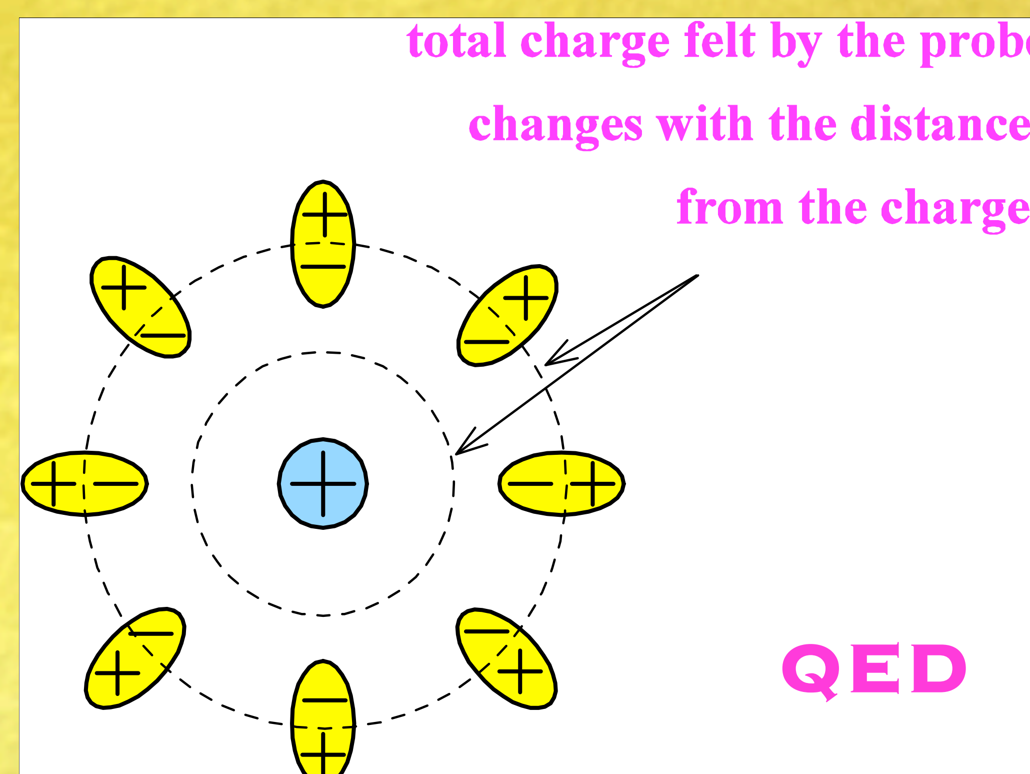
Asymptotic Freedom



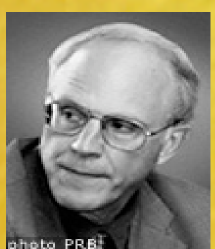


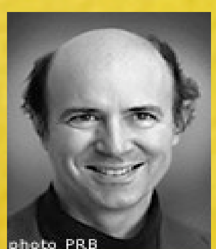
Gross, Wilczek, Politzer

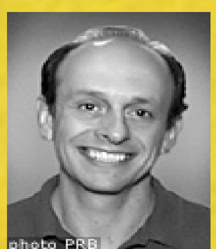




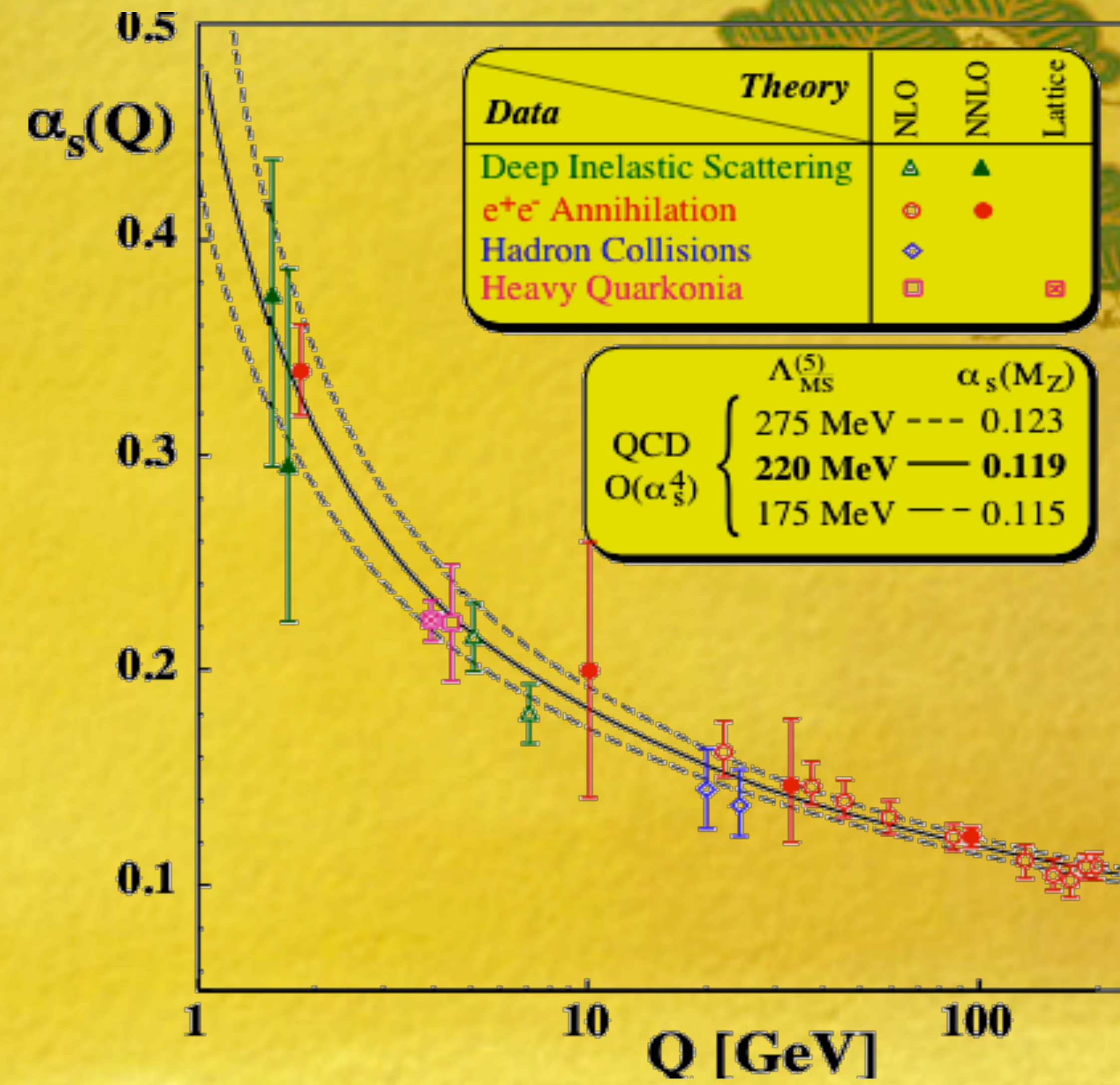
Asymptotic Freedom







Gross, Wilczek, Politzer



$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

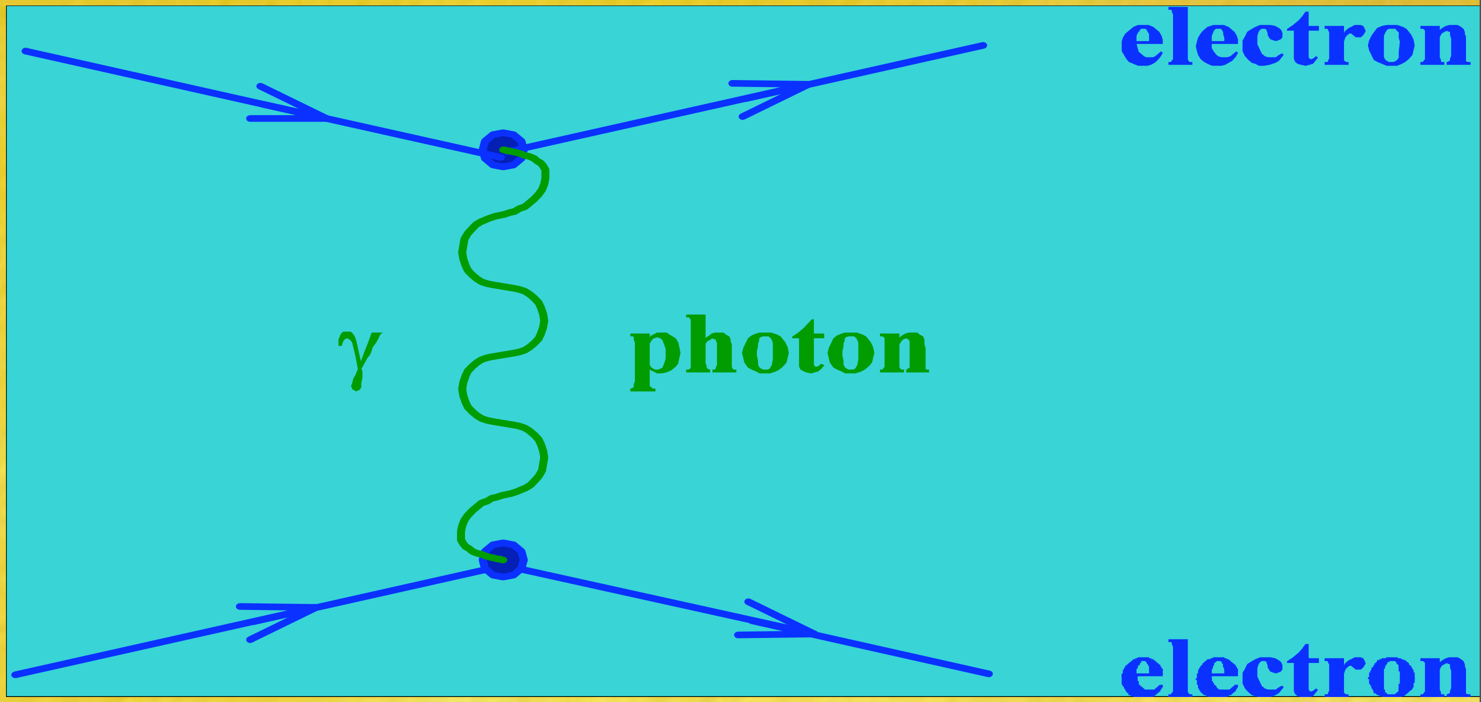
$$= \bar{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_i - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu$$

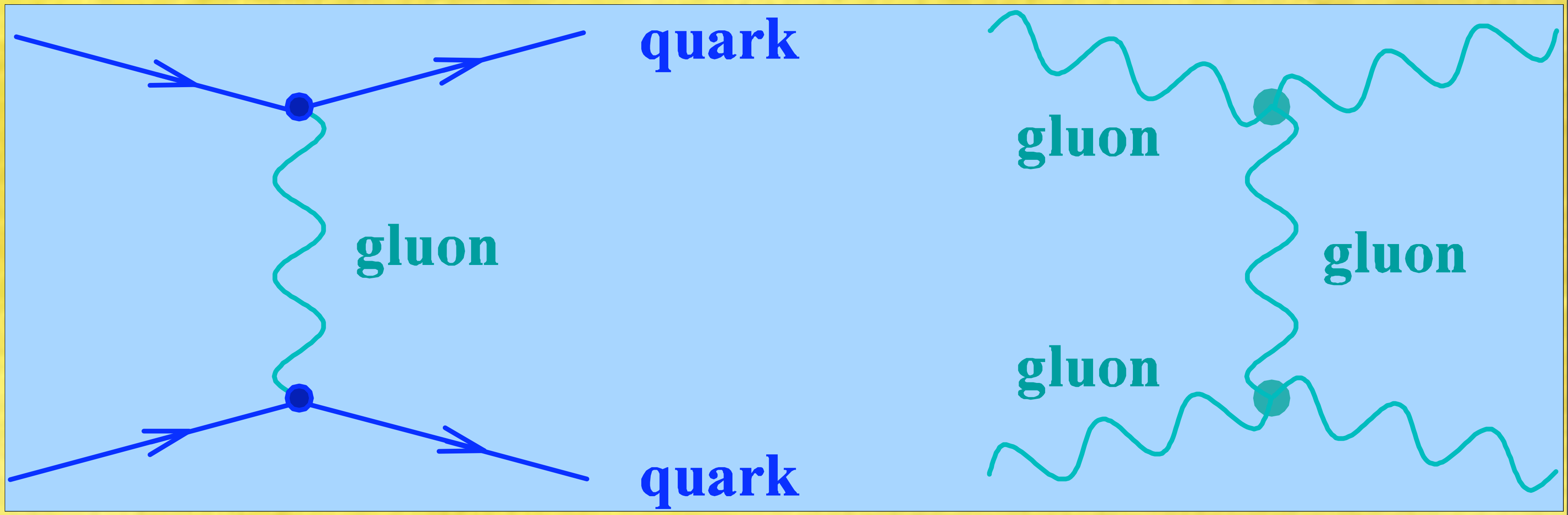
Perturbative QCD

expansion in α_s

QED:
photons don't interact



QCD:
gluons interact

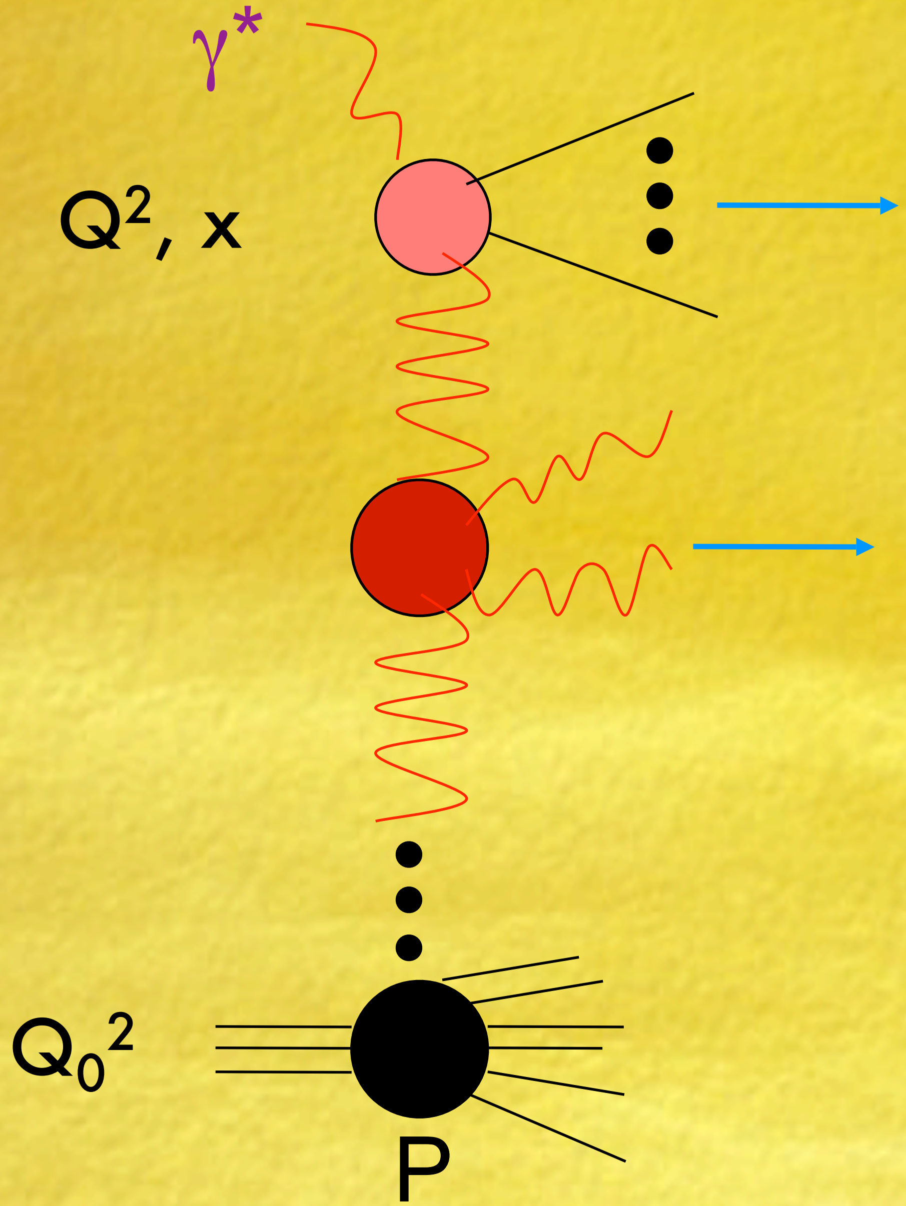


The Bjorken limit

$$Q^2 \to \infty\,;\, s \to \infty\,;\, x_{\mathrm{Bj}} \approx \frac{Q^2}{s} = \mathrm{fixed}$$

* Operator Product Expansion (OPE)
  Factorization theorems
  machinery of precision physics in QCD

Structure of higher order contributions in pQCD



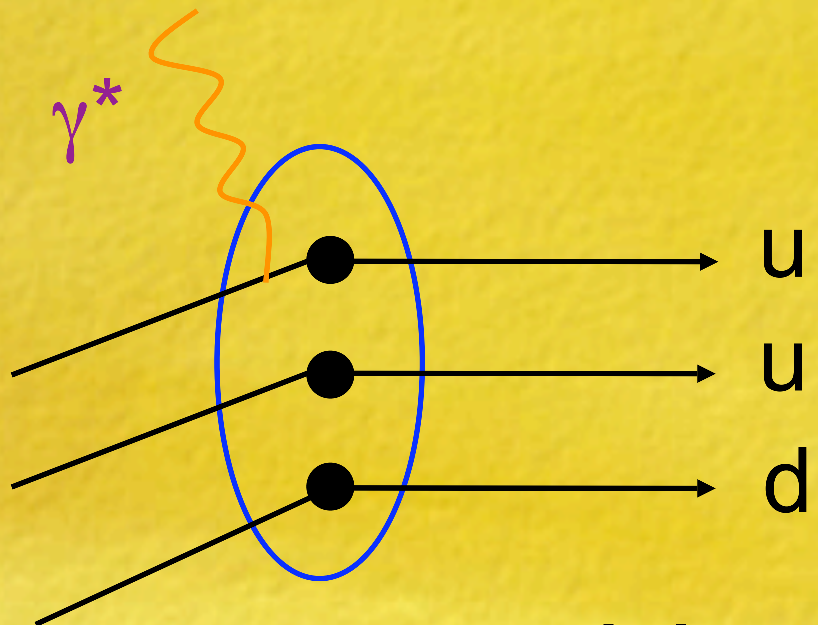
$$C_2(x, \alpha_S) = \delta(1-x) + \alpha_S C_2^{(1)}(x) + \alpha_S^2 C_2^{(2)} + \cdots$$

$\alpha_S P^{(1)}$ $\alpha_S^2 P^{(2)}$

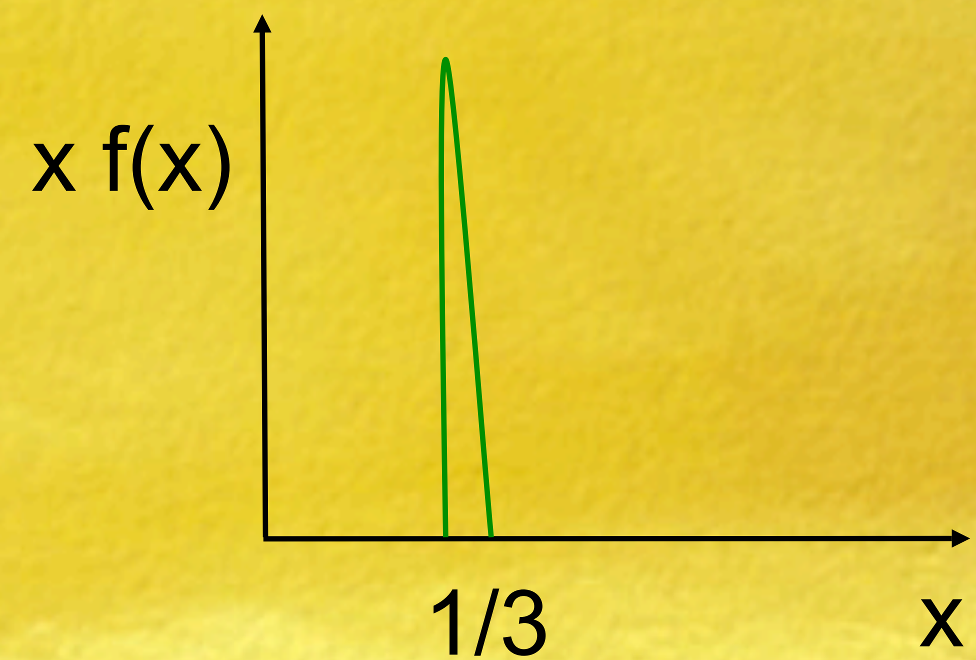
+ higher twist (power suppressed) contributions…

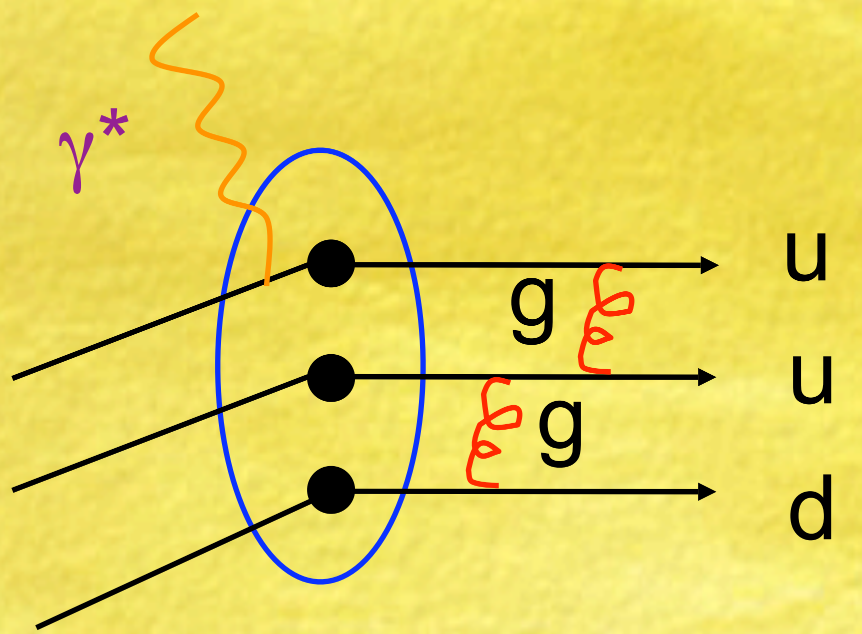
- Coefficient functions C - computed to NNLO for many processes
- Splitting functions P - computed to 3-loops

Proton structure functions

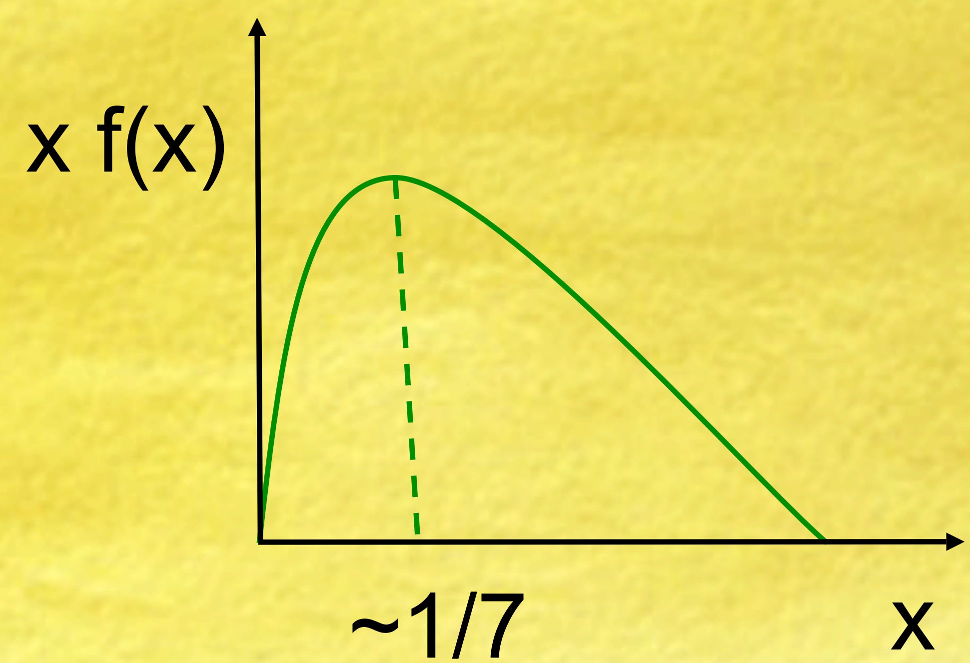


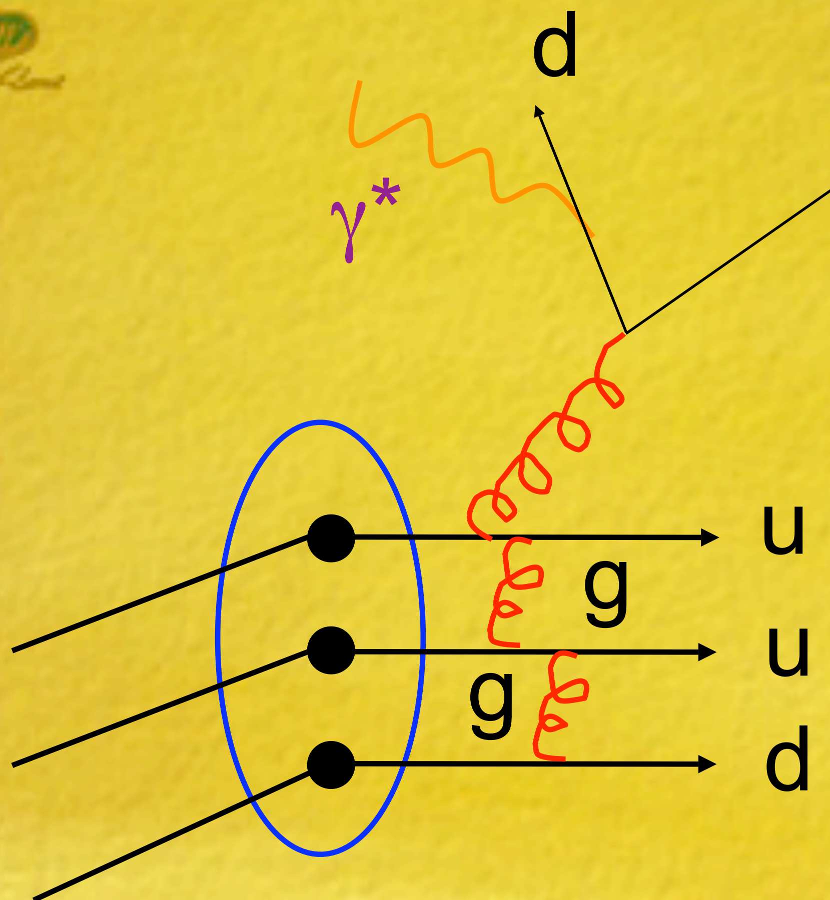
Parton model

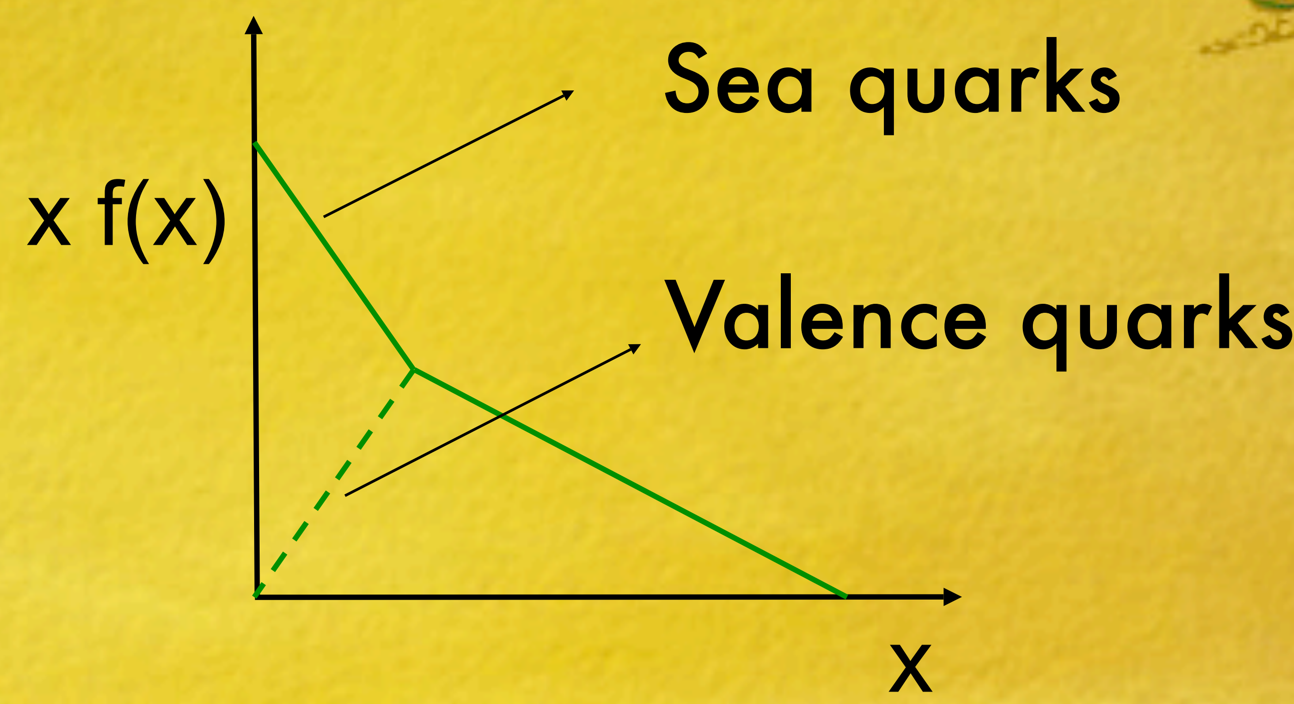




QCD - corrections







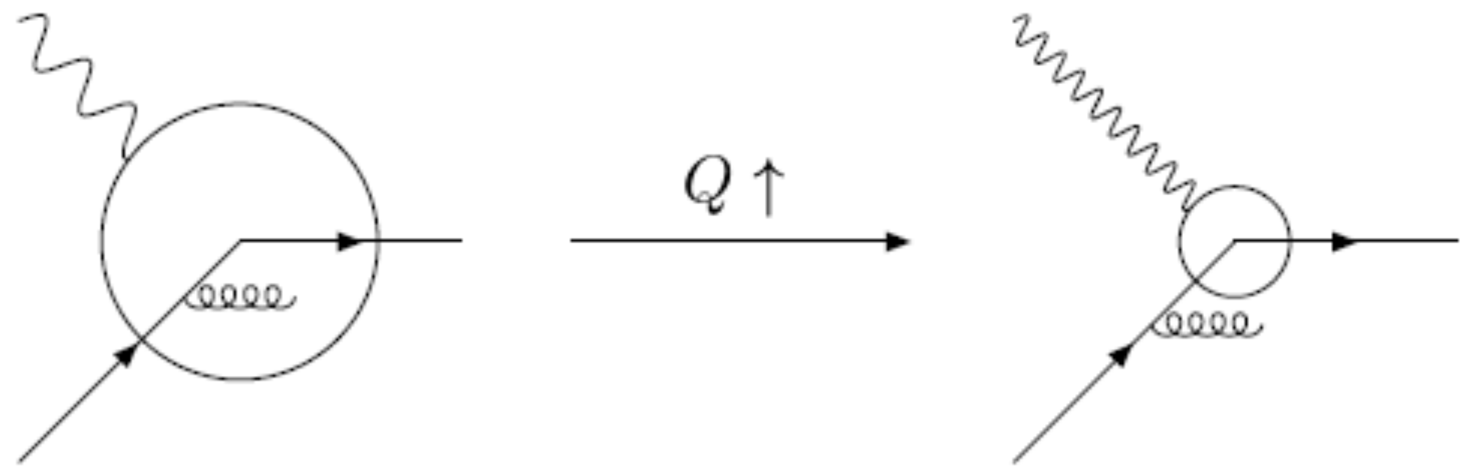
"x-QCD"- small x evolution

$$\int_0^1 \frac{dx}{x}\,(xq(x) - x\bar{q}(x)) = 3$$ → # of valence quarks

$$\int_0^1 \frac{dx}{x}\,(xq(x) + x\bar{q}(x)) \to \infty$$ → # of quarks

DIS: resolution scale

- As Q increases, the photon sees more and more of the inner structure of the nucleus A



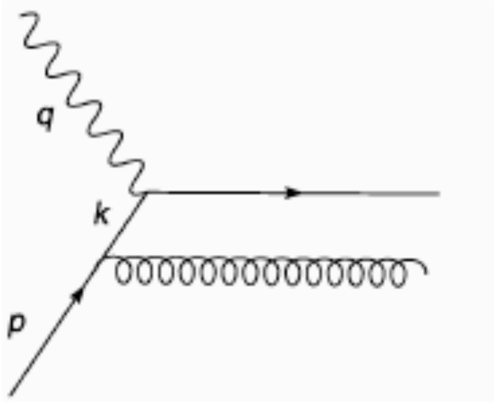
- Thus at higher Q, more constituents with smaller values of the Feynman x
- A rapid increase of $G(x, Q^2)$ at small x is measured

Structure functions: DGLAP

One gluon emission gives the logarithmic Q^2 dependence

$$\alpha_s \int^{Q^2} \frac{dk_\perp^2}{k_\perp^2} \quad \sim \quad \alpha_s \ln Q^2$$

$$\rightarrow \quad q(x, Q^2) \sim \frac{\alpha_s}{2\pi}\left(P(x) \ln Q^2 + \cdots\right)$$



Change of the resolution scale Q^2

→ evolution equation for the parton distribution functions

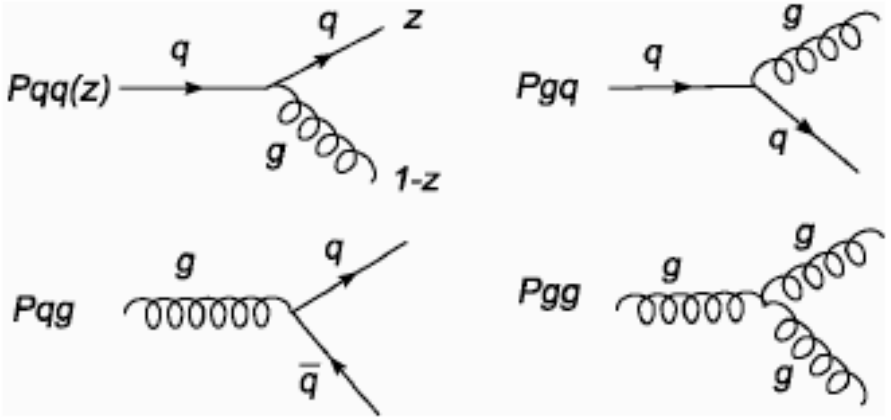
DGLAP equation (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)

$$Q^2 \frac{\partial}{\partial Q^2} \begin{pmatrix} q_i(x, Q^2) \\ g(x, Q^2) \end{pmatrix} = \frac{\alpha_s}{2\pi} \sum_{q_j, \bar{q}_j} \int_x^1 \frac{dz}{z} \begin{pmatrix} P_{q_i q_j}(\frac{x}{z}) & P_{q_i g}(\frac{x}{z}) \\ P_{g q_j}(\frac{x}{z}) & P_{gg}(\frac{x}{z}) \end{pmatrix} \begin{pmatrix} q_j(z, Q^2) \\ g(z, Q^2) \end{pmatrix}$$

"Splitting function" $P_{ij}(x)$:

a probability of finding a parton of type ***"i"*** in a parton of type ***"j"***.

The equation for the change of "transverse resolution"



DGLAP at small x

Splitting functions at leading order $O(\alpha_S{}^0)$ $(x \neq 1)$

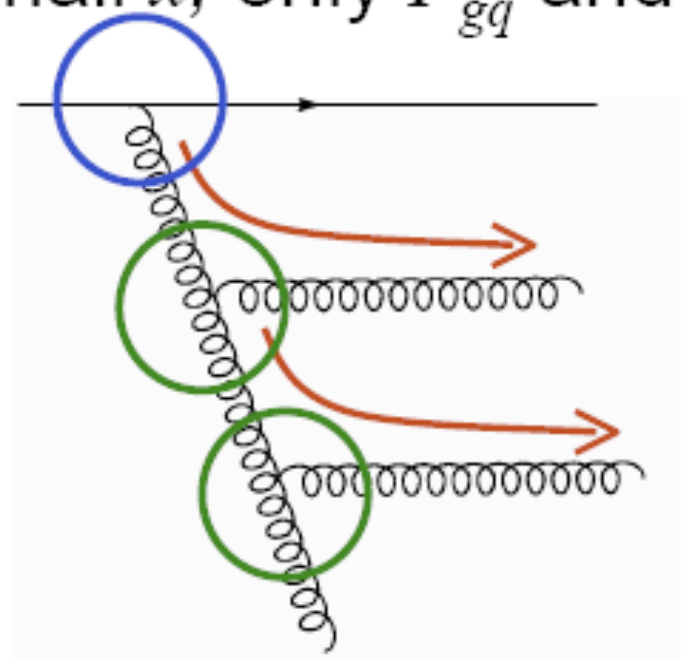
$$P_{qq}^{(0)}(x) = C_F \frac{1+x^2}{1-x}$$

$$P_{qg}^{(0)}(x) = \frac{1}{2}\left[x^2 + (1-x)^2\right]$$

$$P_{gq}^{(0)}(x) = C_F \frac{1+(1-x)^2}{x}$$

$$P_{gg}^{(0)}(x) = 2C_A\left[\frac{x}{1-x} + \frac{1-x}{x} + x(1-x)\right]$$

At small x, only P_{gq} and P_{gg} are relevant.

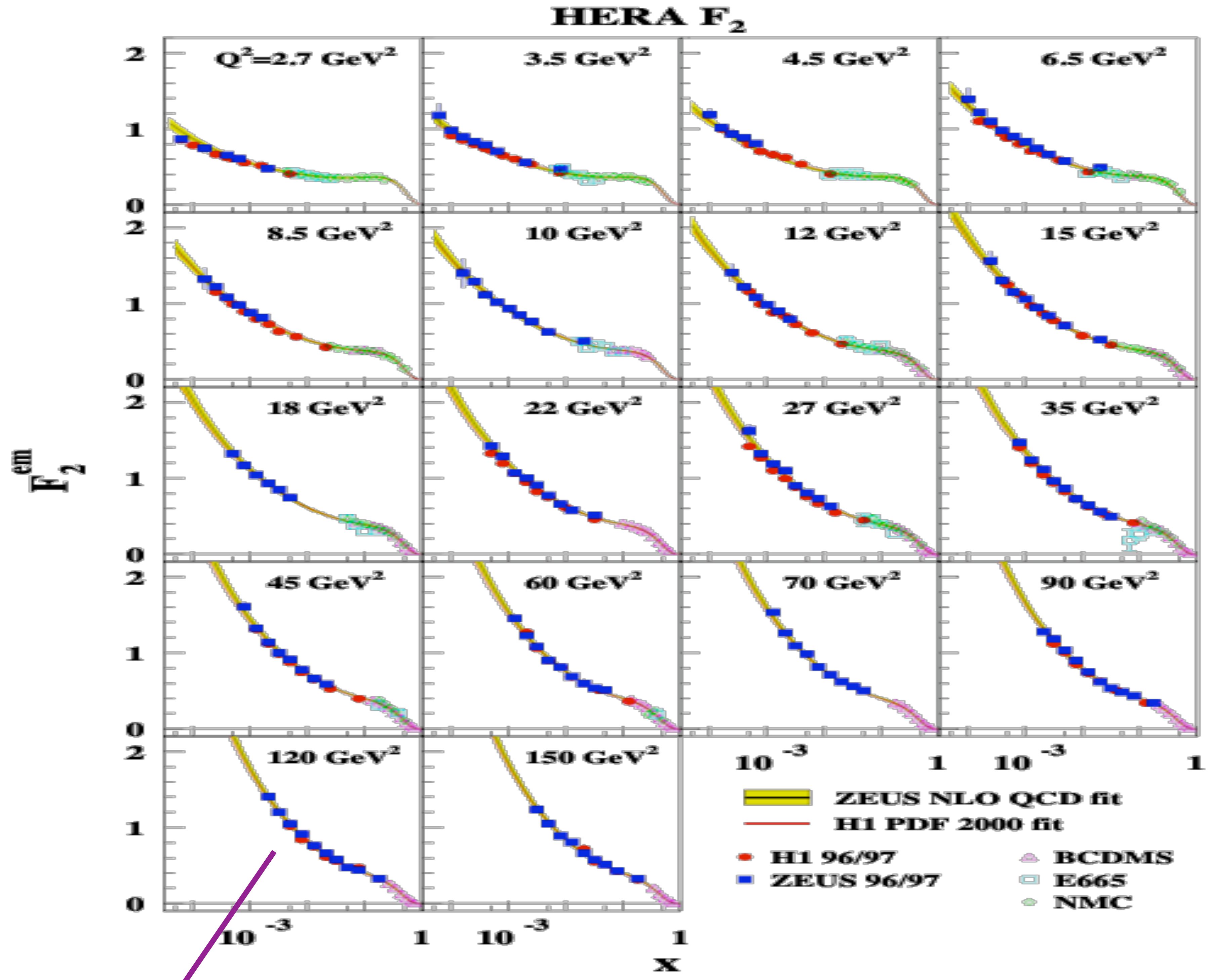


→ Gluon dominant at small *x*!

The double log approximation (DLA) of DGLAP is easily solved.

-- increase of gluon distribution at small x

$$F_2(x,Q^2) = \sum_{\substack{q=u,c,t \\ d,s,b}} e_q^2 \left(x\,q(x,Q^2) + x\,\bar{q}(x,Q^2) \right)$$

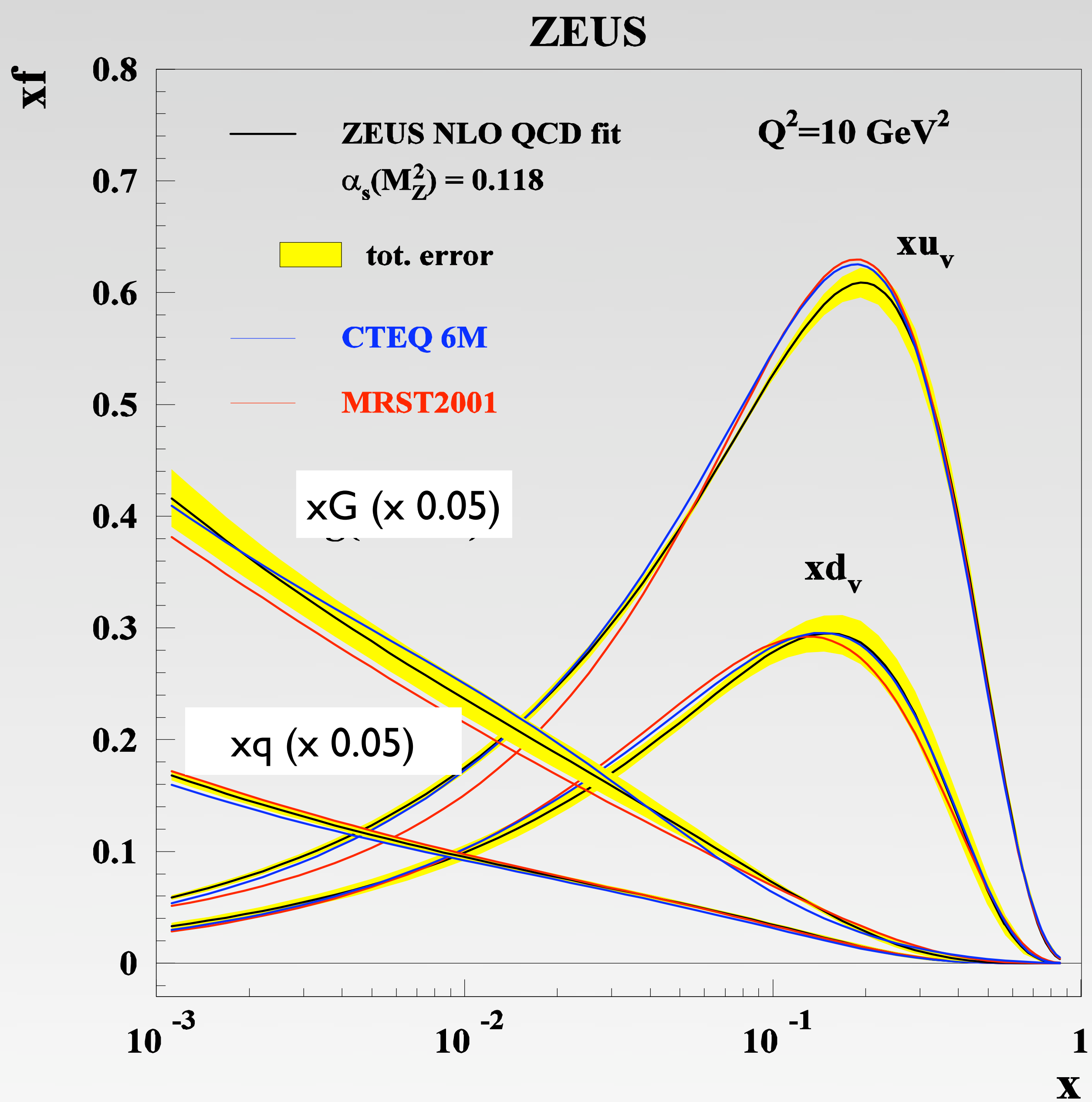


Structure functions grow rapidly at small x

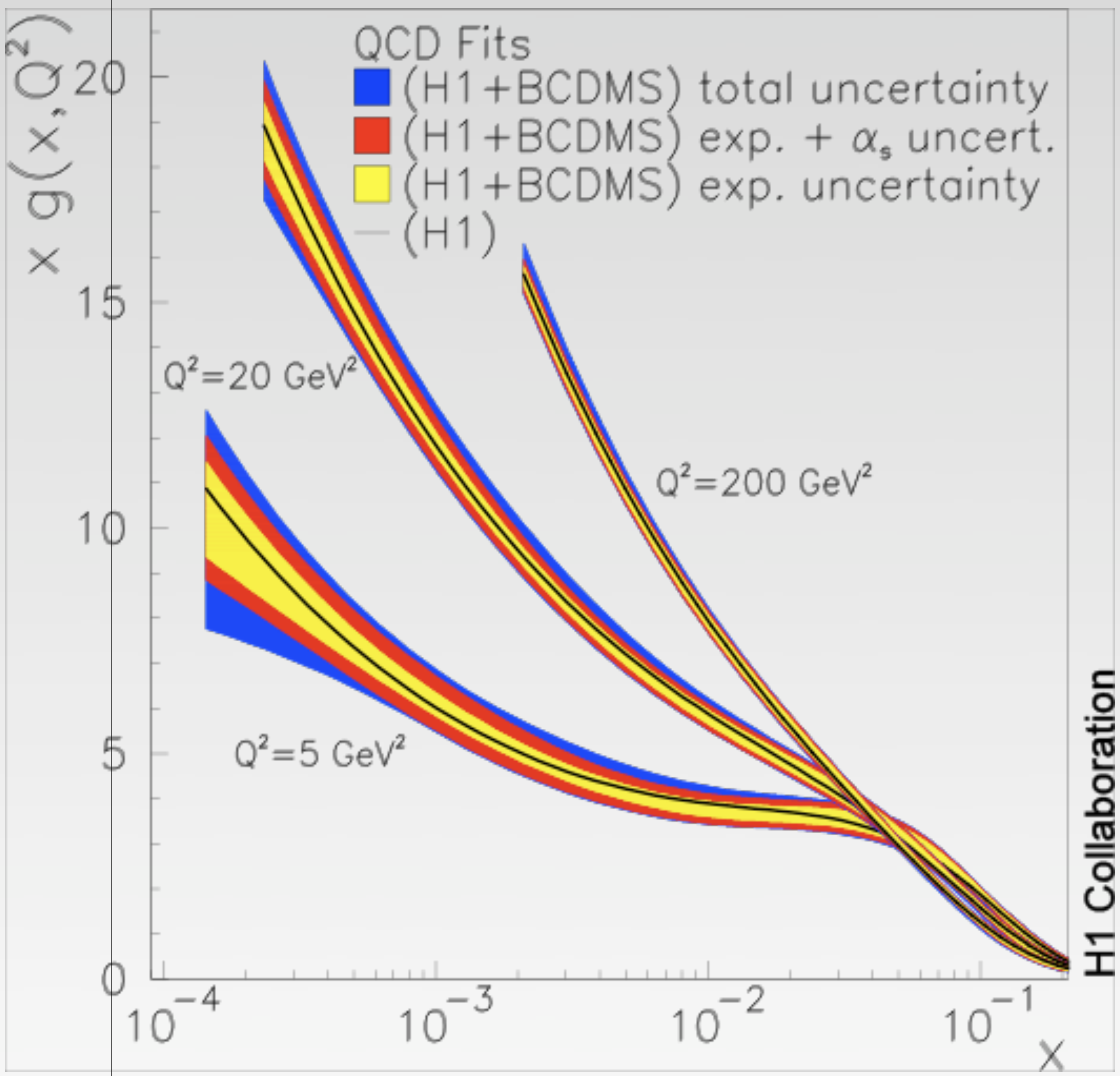
What have we learned at HERA?

(protons)

Gluons and Quarks



Gluons only



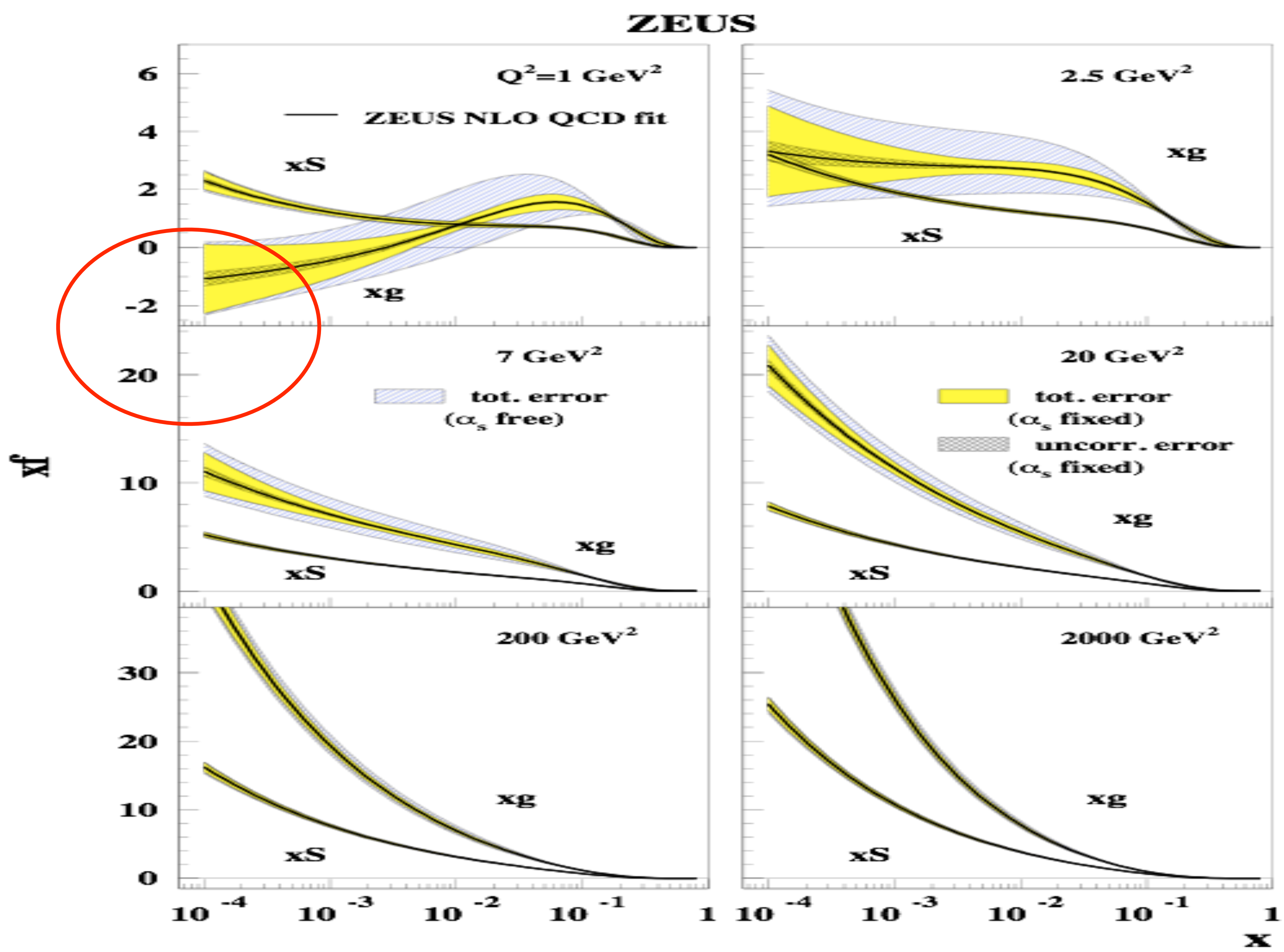
what happens when x ---> 0 ?

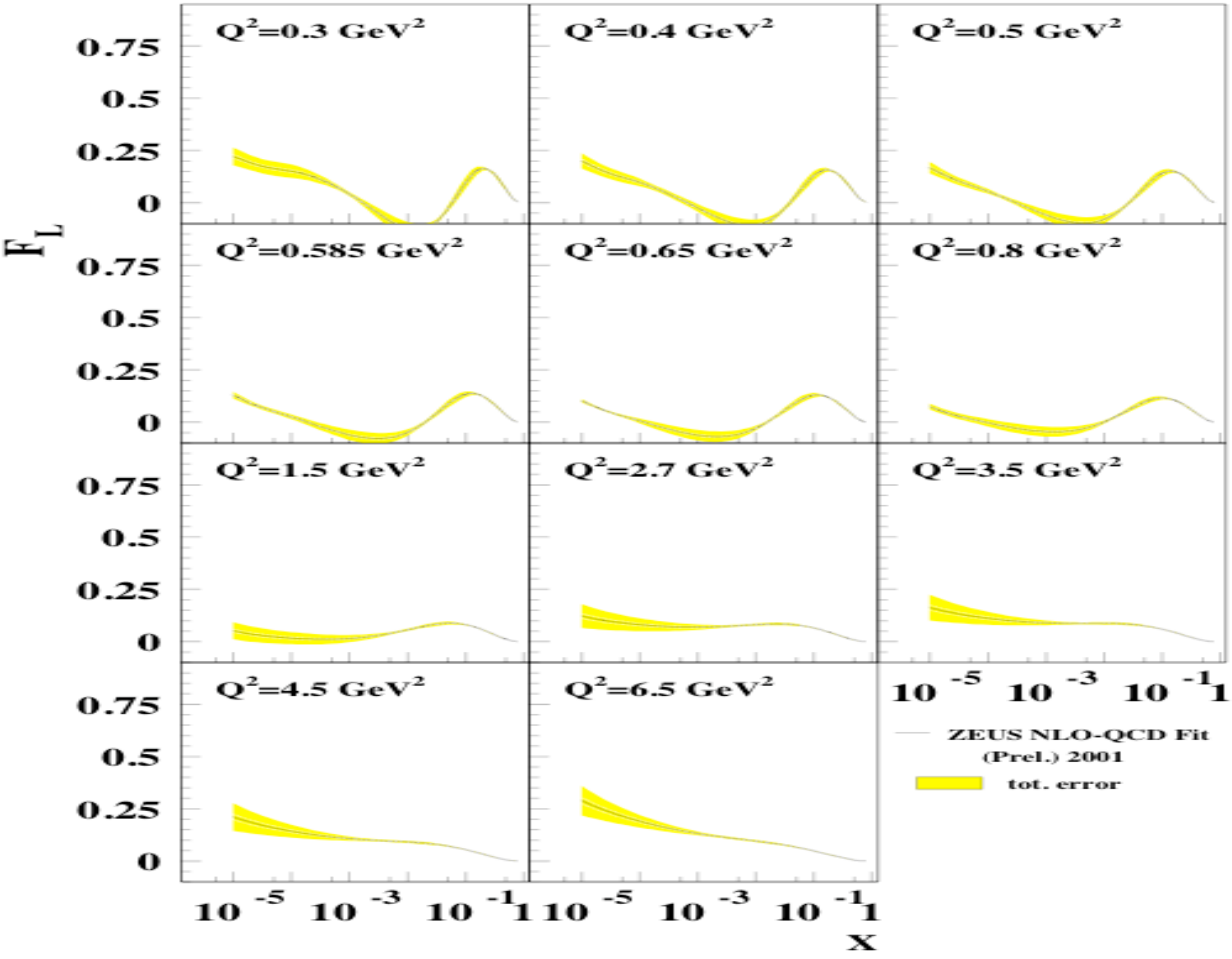
Resolving the hadron

Ren.Group-DGLAP evolution
(sums large logs in Q^2)

Phase space density decreases
(# partons / area / Q^2)
proton becomes more dilute...

Where may the standard "DGLAP" picture fail ?

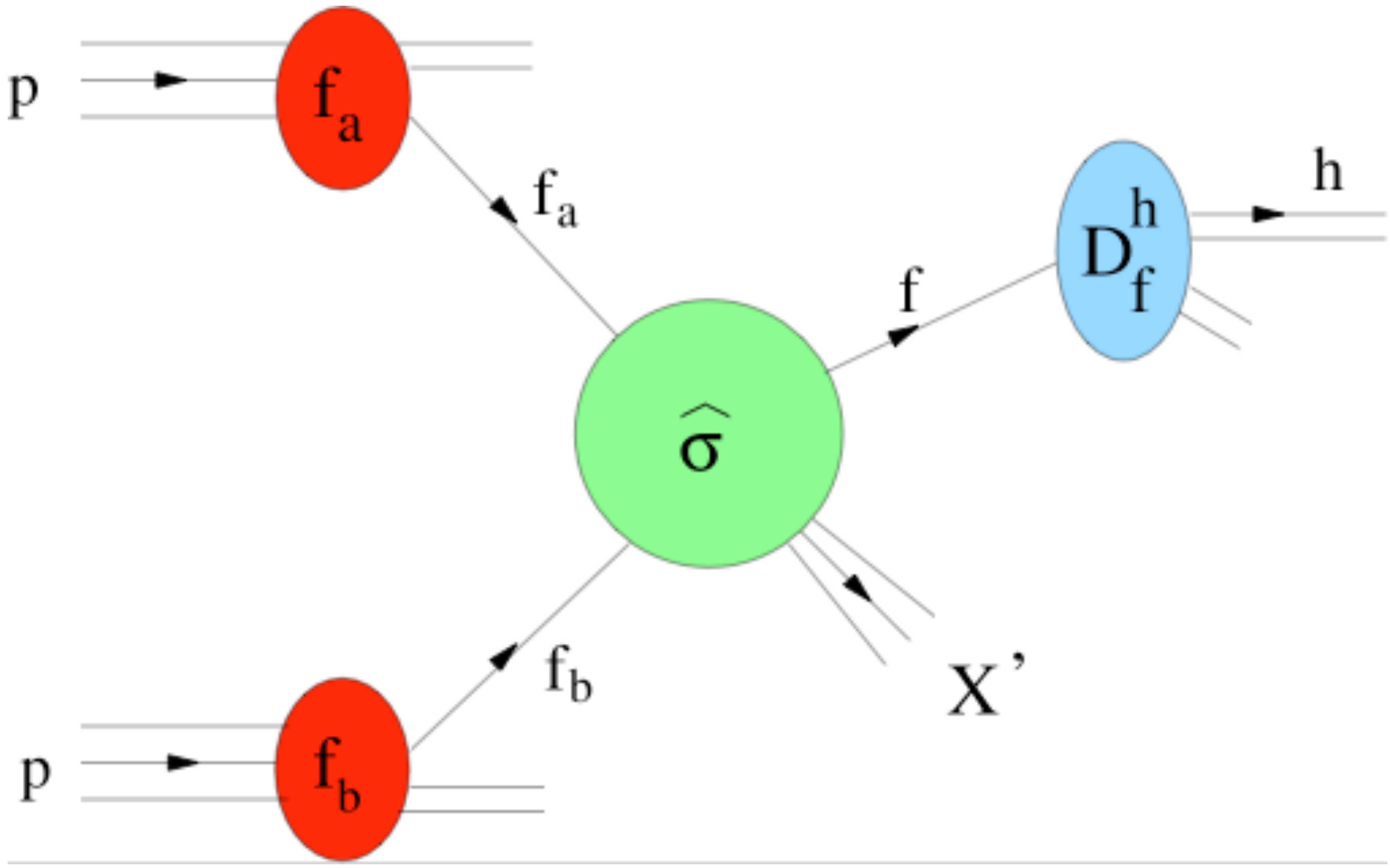




F_L ($\propto \alpha_S\, x\, G(x, Q^2)$) is a positive definite quantity

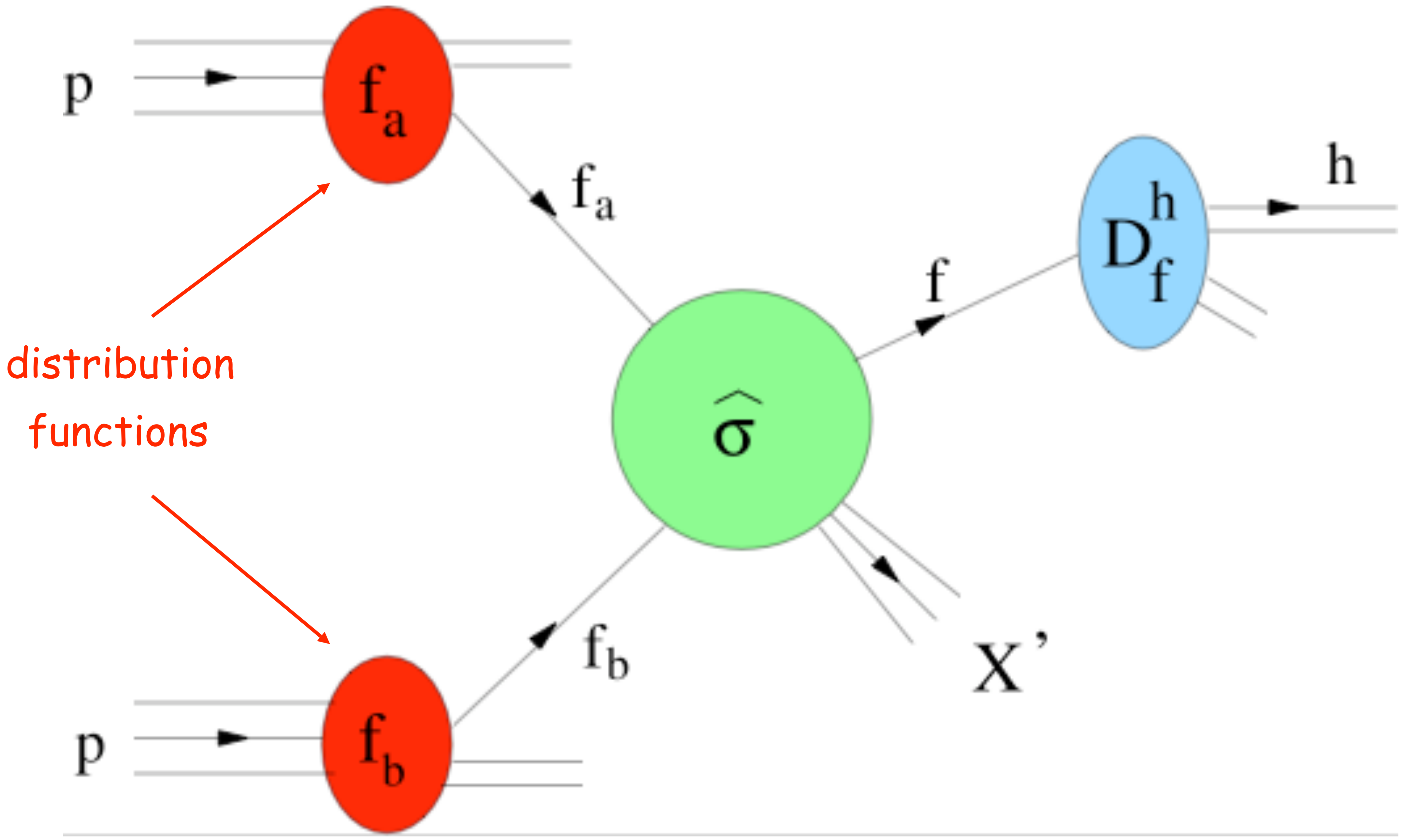
pQCD in proton-proton Collisions

factorization: separation of long and short distances



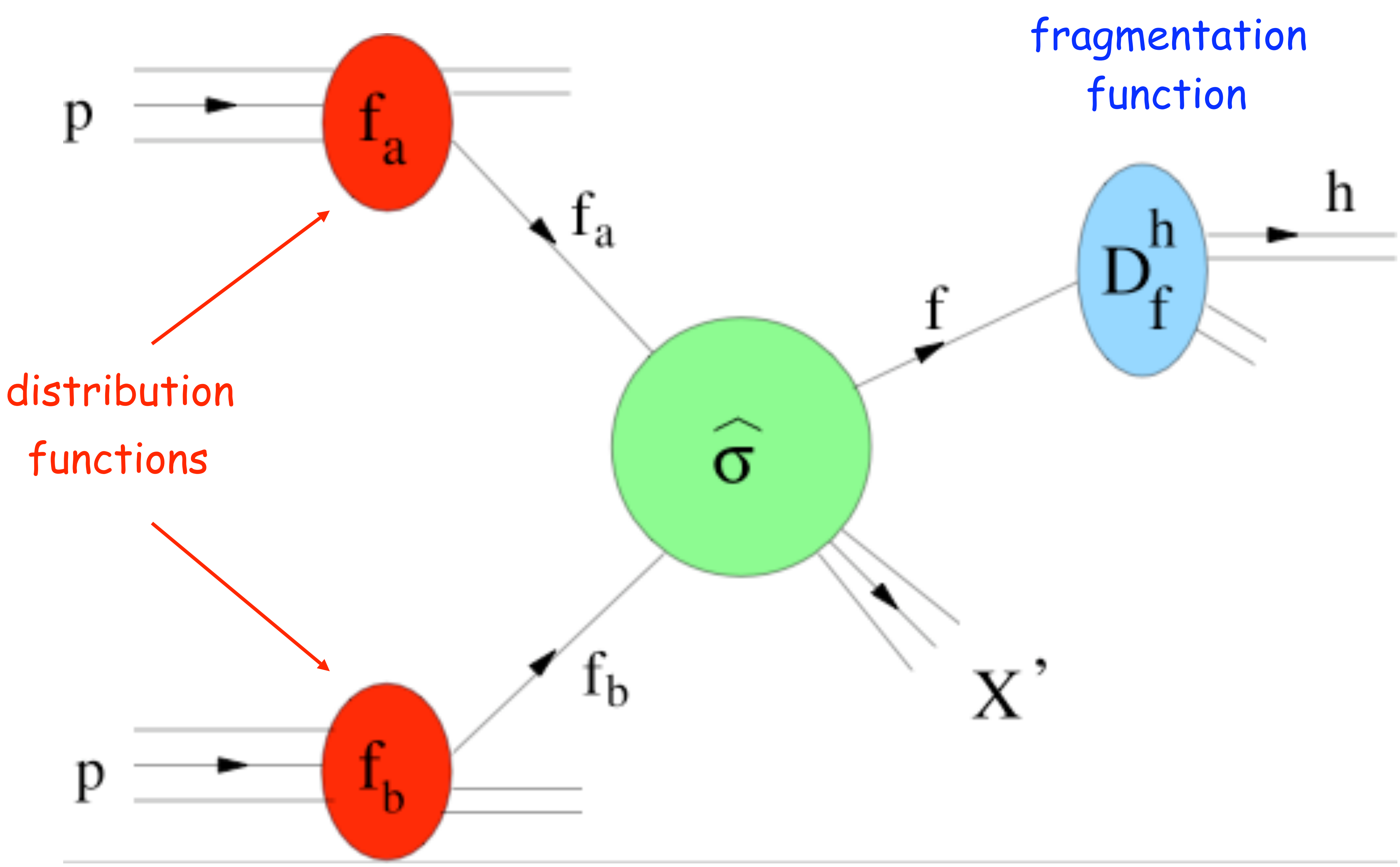
pQCD in proton-proton Collisions

factorization: separation of long and short distances



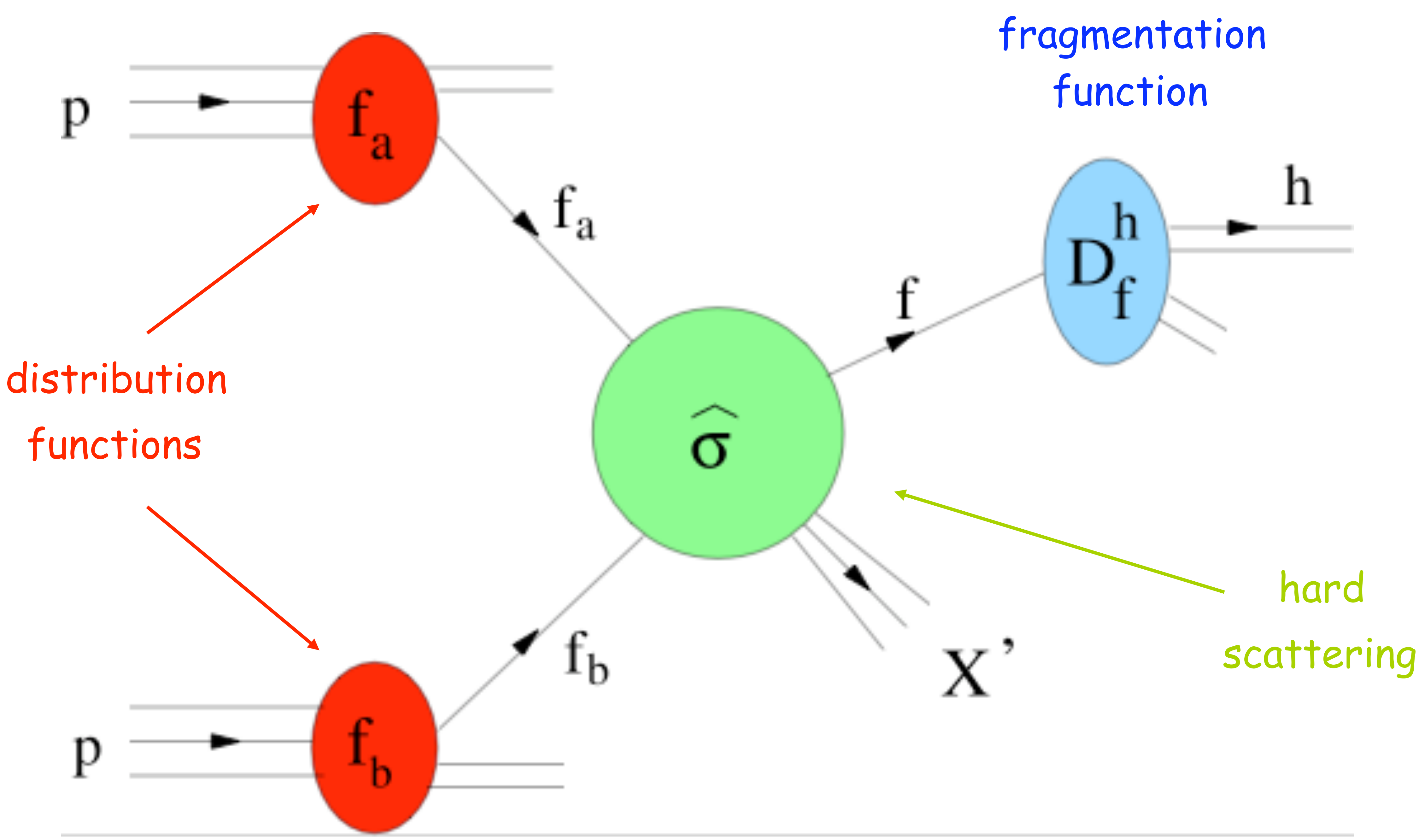
pQCD in proton-proton Collisions

factorization: separation of long and short distances



pQCD in proton-proton Collisions

factorization: separation of long and short distances

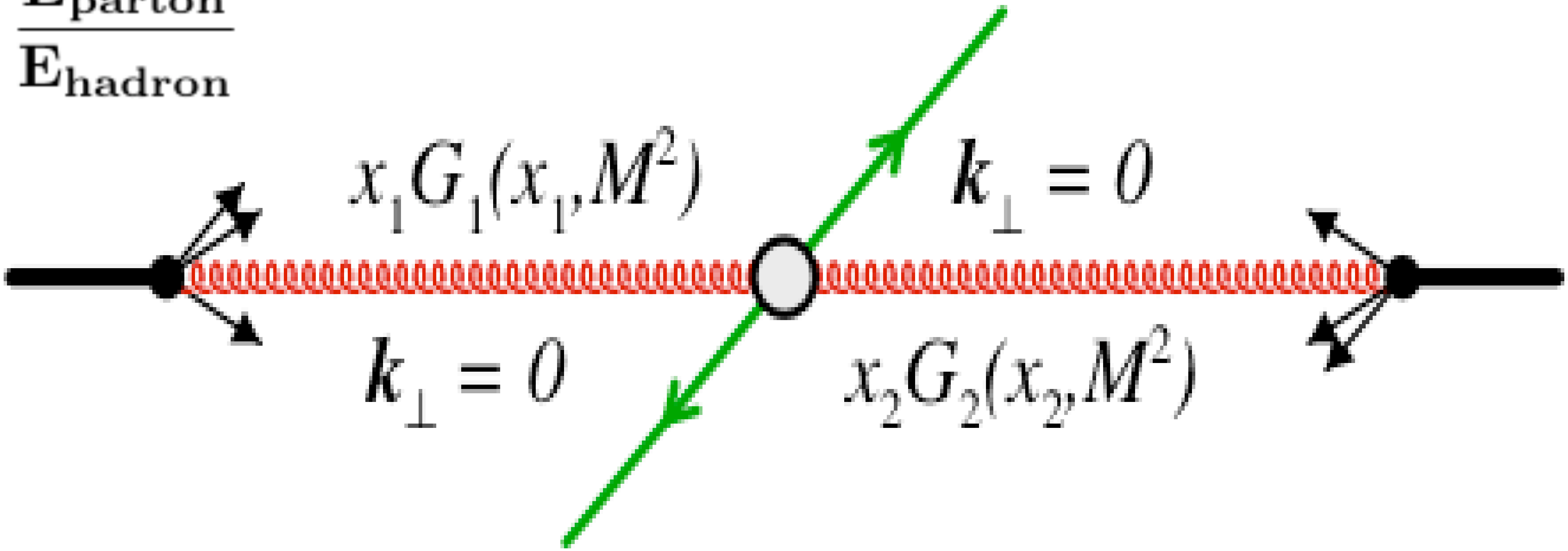


collinear factorization

Incoherence: independent probabilities

$$\mathbf{M \sim \sqrt{S} \gg \Lambda_{QCD}}$$

$$\mathbf{X \equiv \frac{E_{parton}}{E_{hadron}}}$$

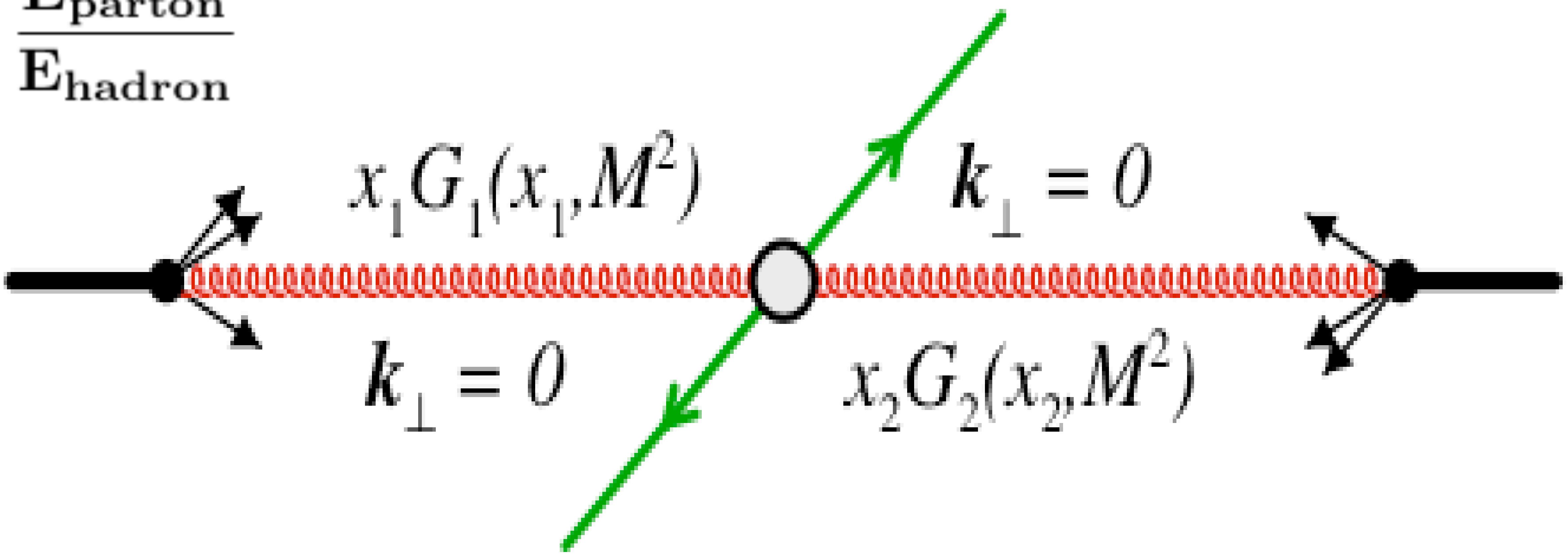


collinear factorization

Incoherence: independent probabilities

$$\mathbf{M} \sim \sqrt{\mathbf{S}} \gg \Lambda_{\mathbf{QCD}}$$

$$\mathbf{X} \equiv \frac{\mathbf{E_{parton}}}{\mathbf{E_{hadron}}}$$



Incoming partons have k_t=0

Quark and gluon distributions are universal, evaluated at hard scale

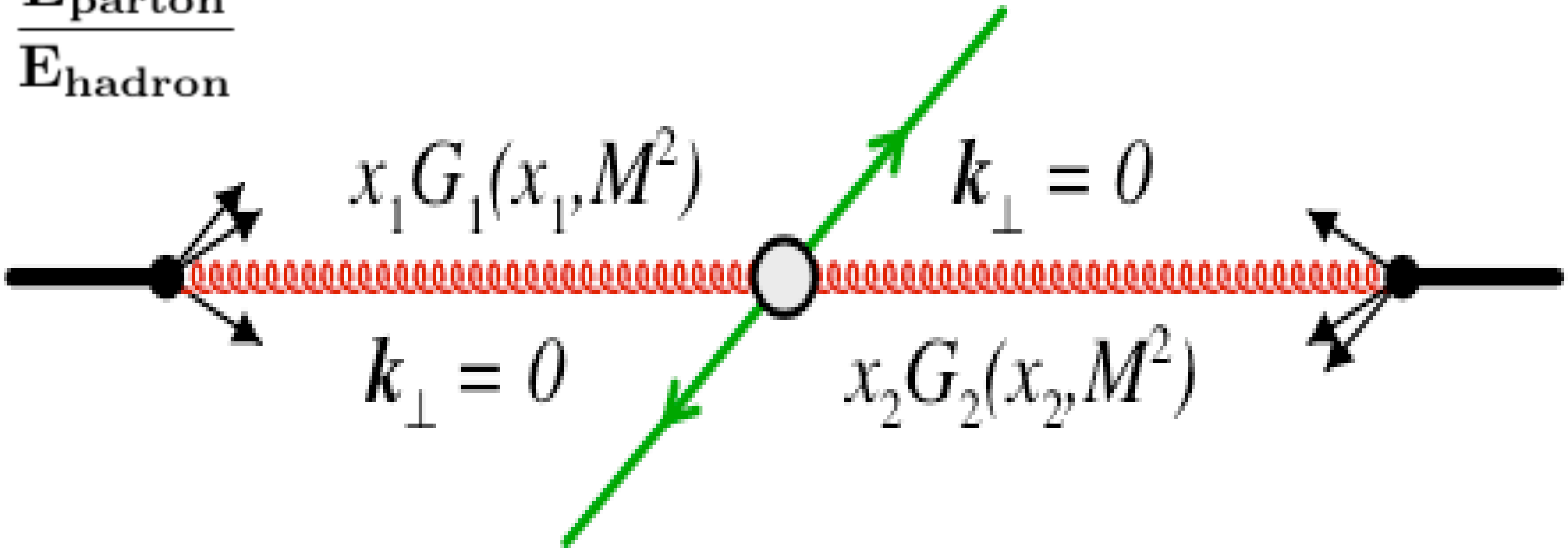
Factorization theorems are proven to all order in α_s

collinear factorization

Incoherence: independent probabilities

$$\mathbf{M} \sim \sqrt{\mathbf{S}} \gg \Lambda_{\mathbf{QCD}}$$

$$\mathbf{X} \equiv \frac{\mathbf{E_{parton}}}{\mathbf{E_{hadron}}}$$



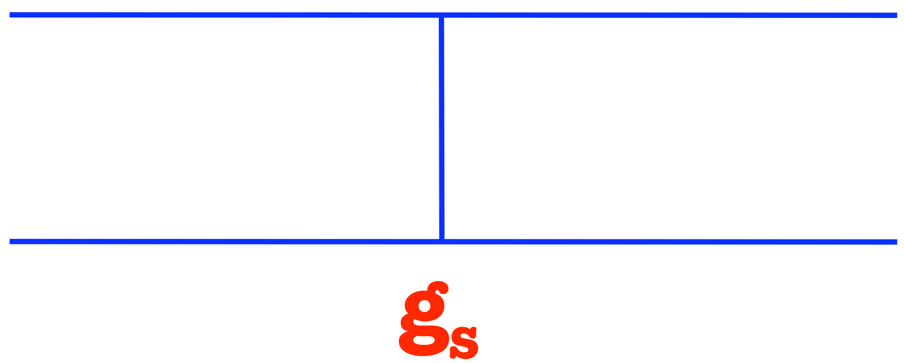
$$d\sigma = \int dx_1\, dx_2\, dz\, f_a^{H1}(x_1, M^2)\, f_b^{H2}(x_2, M^2)\, D_c^h(z, M^2)$$

$$\otimes \quad d\hat{\sigma}_{ab}^c(x_1 P_{H1}, x_2 P_{H2}, P_h/z, M^2)$$

partonic cross sections

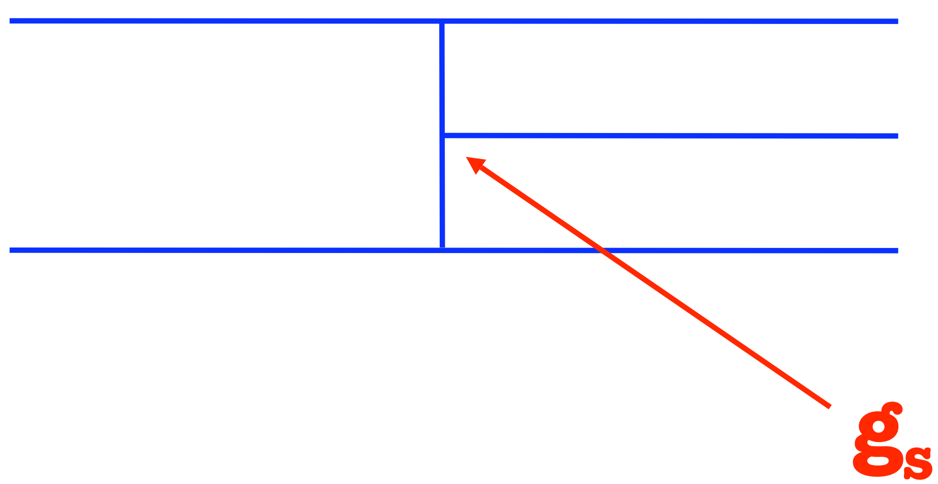
calculable in pQCD

α_s^2



+

α_s^3

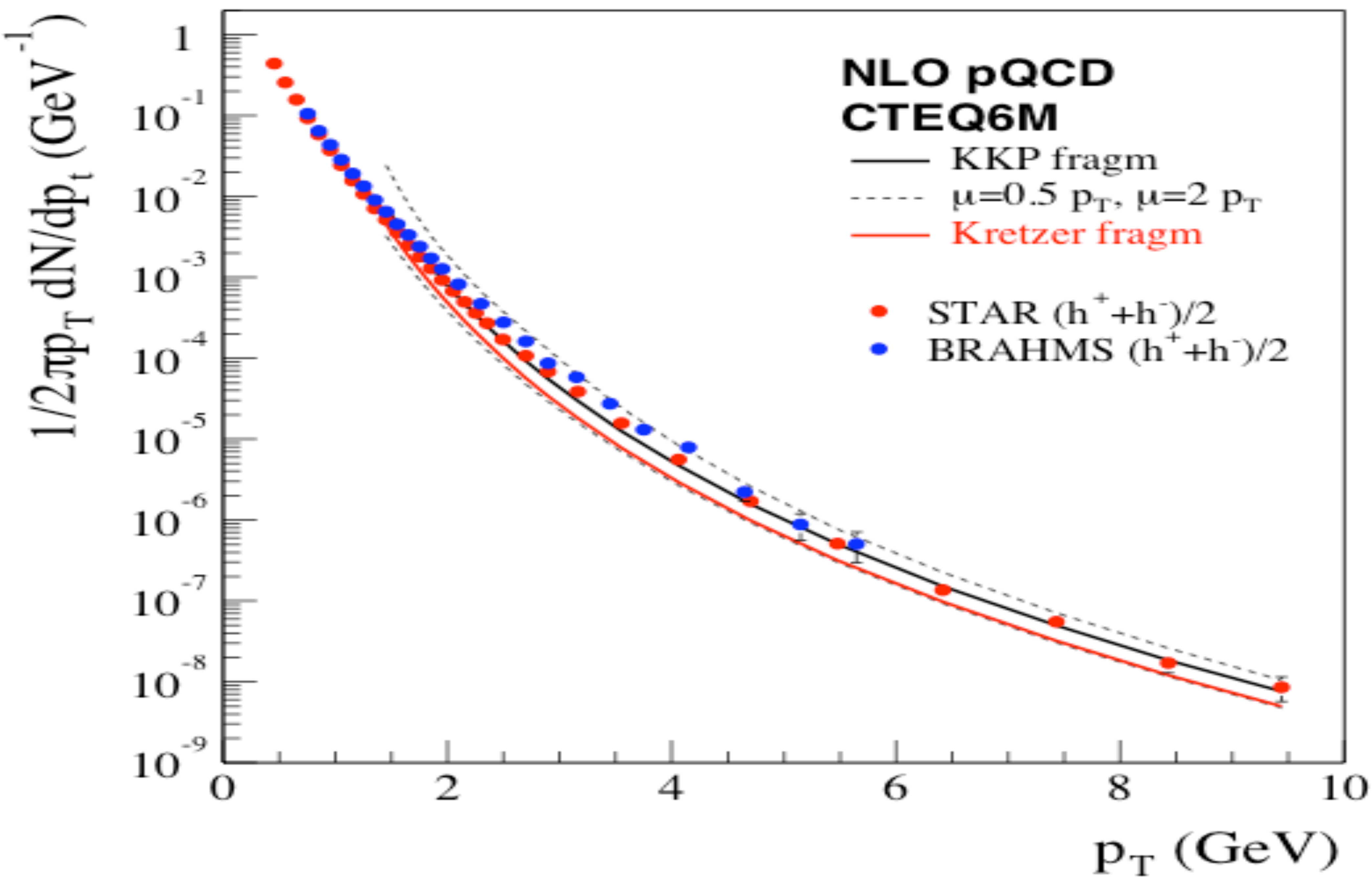


systematic expansion
in the coupling constant

process
dependent

pQCD in pp Collisions at RHIC

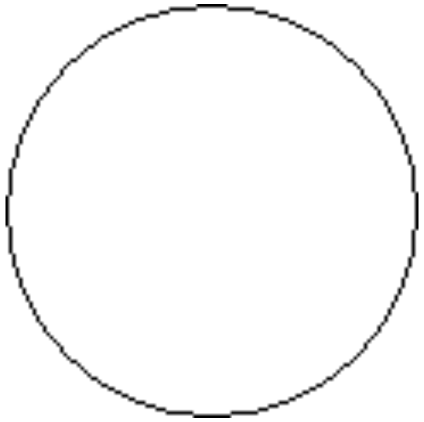
pQCD in pp Collisions at RHIC



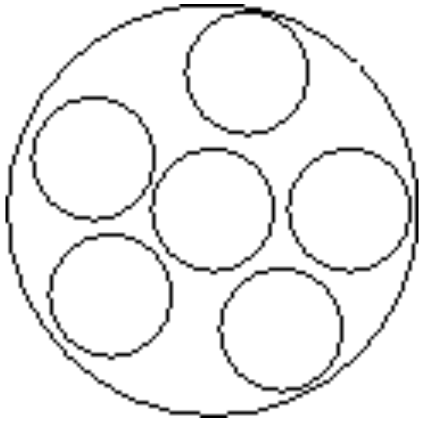
STAR

How about a nucleus ?

A point particle: λ_T >> 10 fm

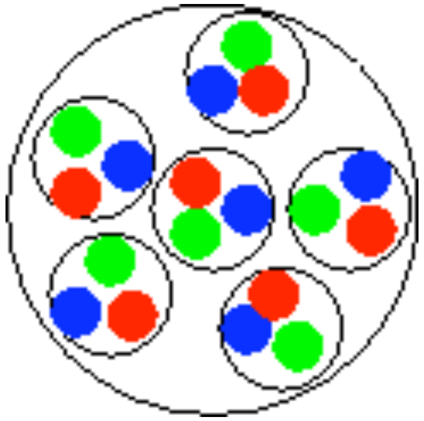


A collection of nucleons: $\lambda_T \sim 1$ fm



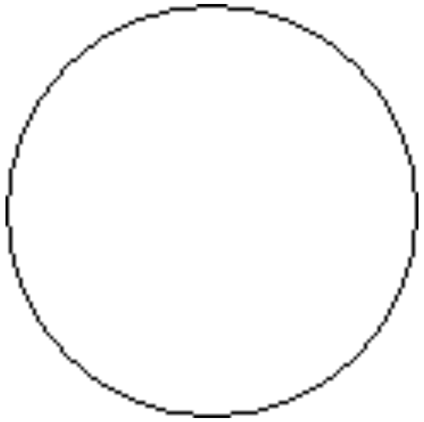
A system of quarks and gluons:

λ_T << 1 fm

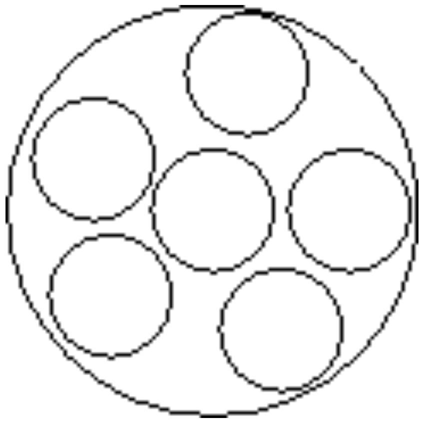


How about a nucleus ?

A point particle: λ_T >> 10 fm

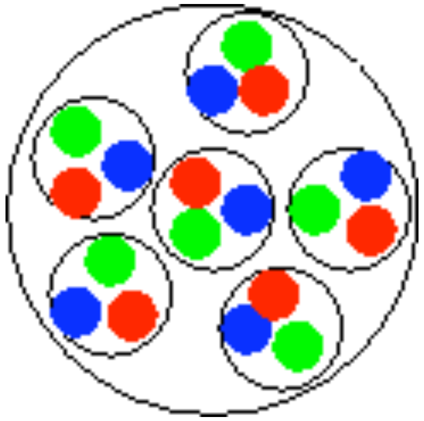


A collection of nucleons: $\lambda_T \sim 1$ fm



A system of quarks and gluons:

λ_T << 1 fm



depends on the resolution$_T$ scale!

How about scattering of nuclei?

RHIC, LHC

How about scattering of nuclei?

RHIC, LHC

I) modification of initial state: "nuclear shadowing"

How about scattering of nuclei?

RHIC, LHC

I) modification of initial state: “nuclear shadowing”

II) modification of hard scattering: multiple scattering

How about scattering of nuclei?

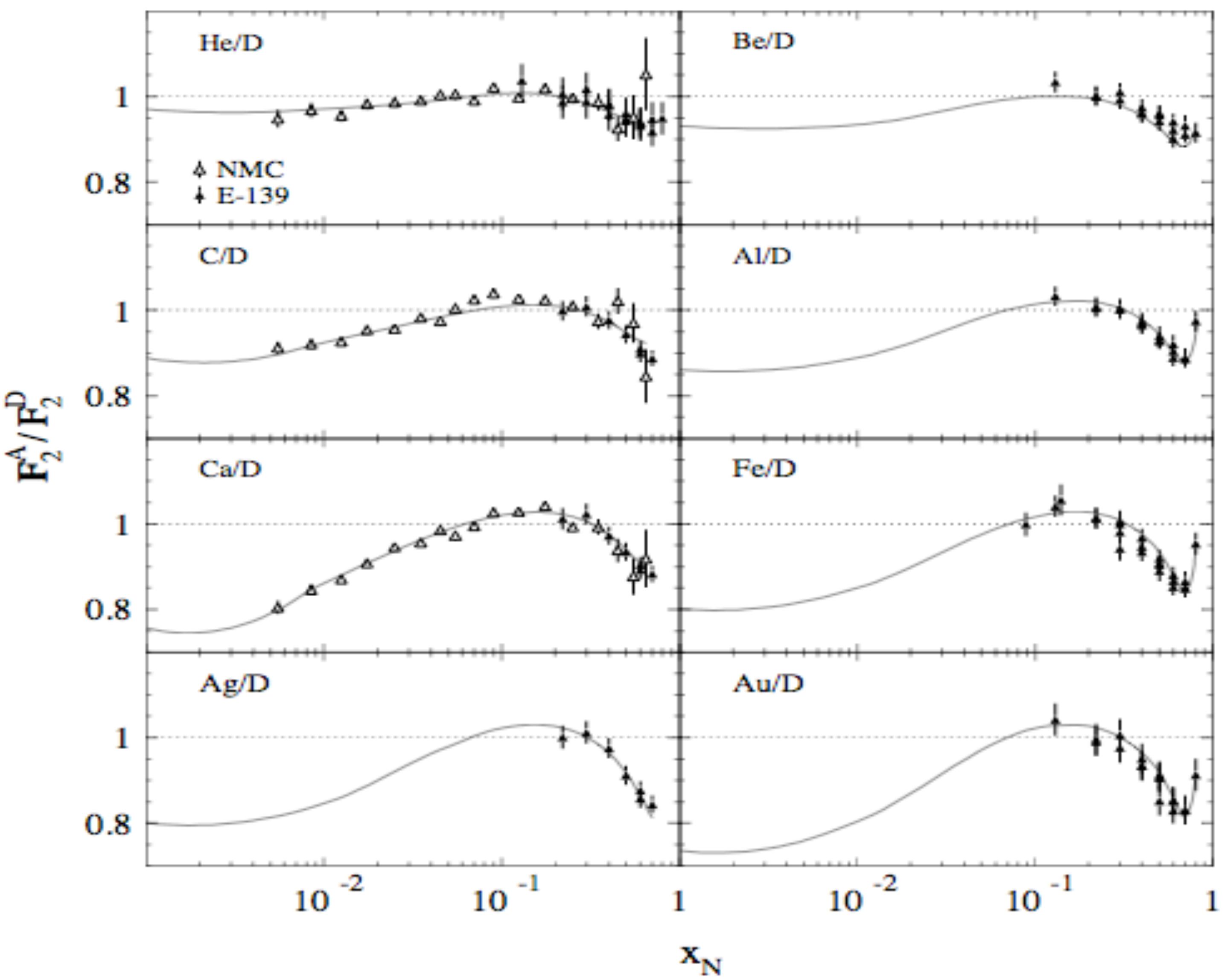
RHIC, LHC

I) modification of initial state: “nuclear shadowing”

II) modification of hard scattering: multiple scattering

III) modification of fragmentation functions?

Modification of the nuclear structure functions (shadowing)



can one understand shadowing from pQCD?

Beyond pQCD in Bj limit

- ★ Works great for inclusive, high Q^2 processes
- ★ Higher twists important when Q^2 is low
- ★ Problematic for diffractive/exclusive processes
- ★ Formalism not designed to treat shadowing, multiple scattering, diffraction, energy loss, impact parameter dependence, thermalization...

The Regge-Gribov limit

$$x_{\mathrm{Bj}} \to 0\,;\; s \to \infty\,;\; Q^2(>> \Lambda^2_{\mathrm{QCD}}) = \mathrm{fixed}$$

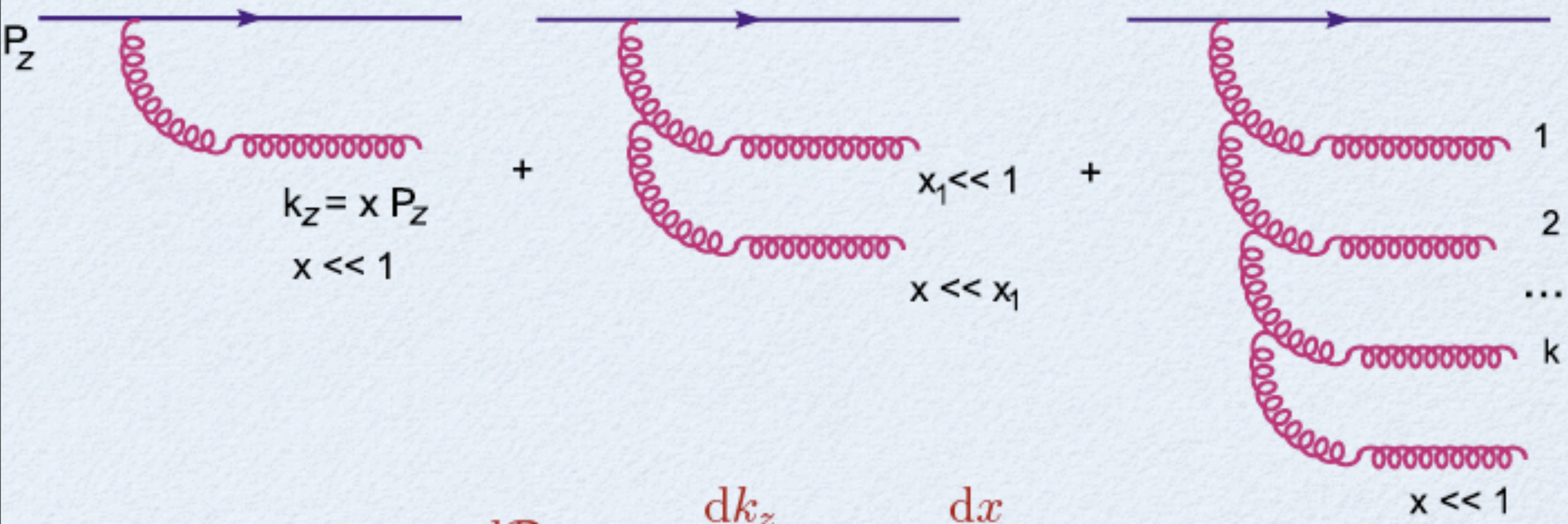
Physics of strong fields in QCD

Multi-particle production

Novel universal properties of QCD

BFKL evolution

- The infrared sensitivity of bremsstrahlung favors the emission of 'soft' (= small–x) gluons



$$\mathrm{d}\mathcal{P} \propto \alpha_s \frac{\mathrm{d}k_z}{k_z} = \alpha_s \frac{\mathrm{d}x}{x}$$

- The 'price' of an additional gluon:

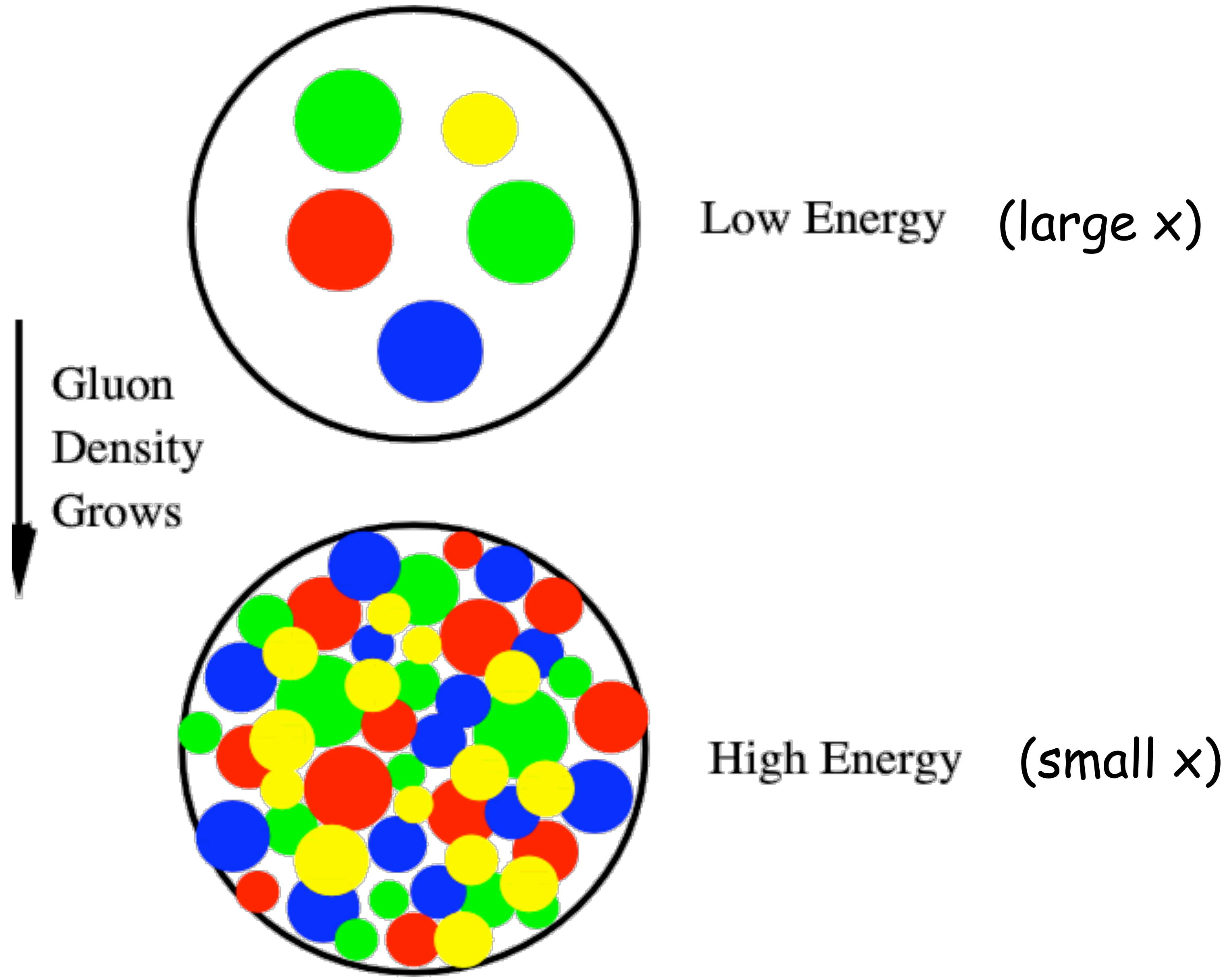
$$\mathcal{P}(1) \propto \alpha_s \int_x^1 \frac{\mathrm{d}x_1}{x_1} = \alpha_s \ln \frac{1}{x}$$

number of gluons grows fast

$$n \sim e^{\alpha_s \, ln 1/x}$$

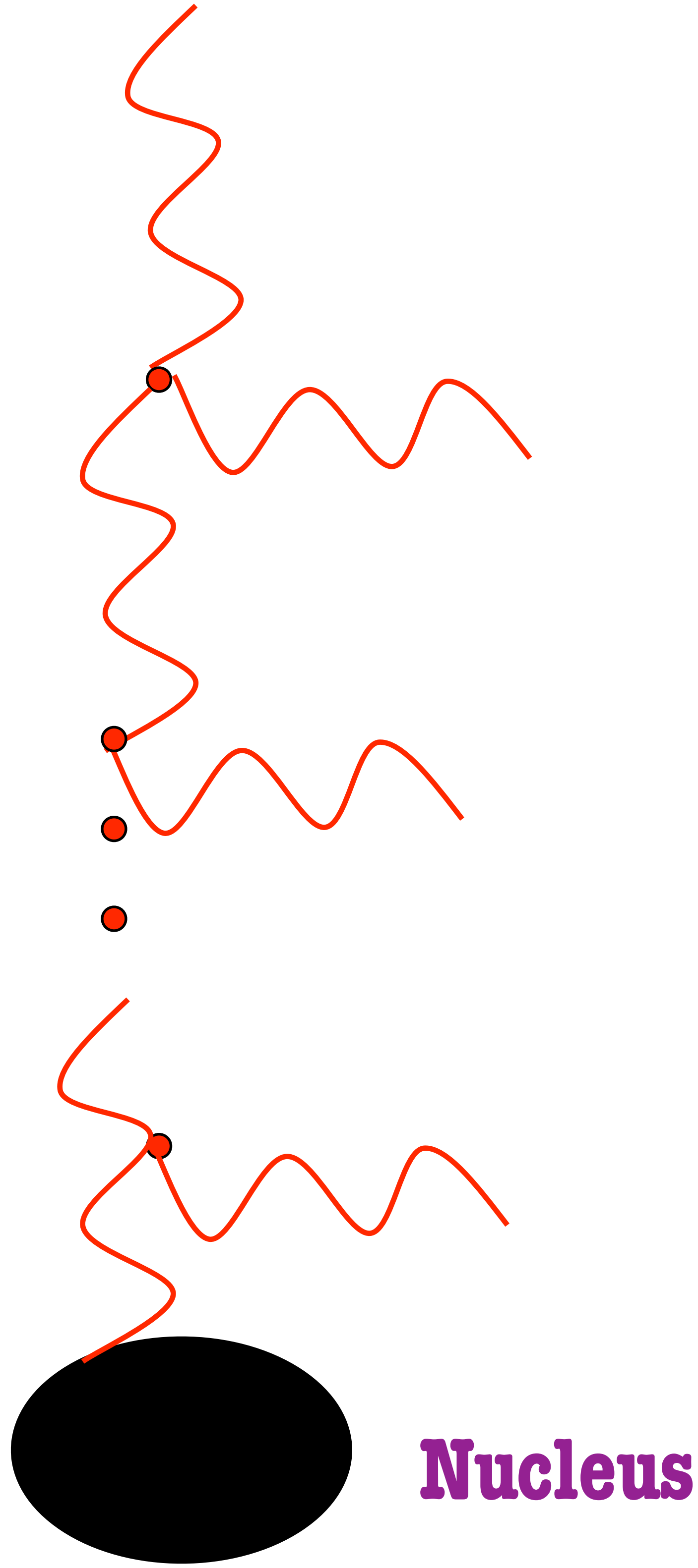
Resolving the hadron

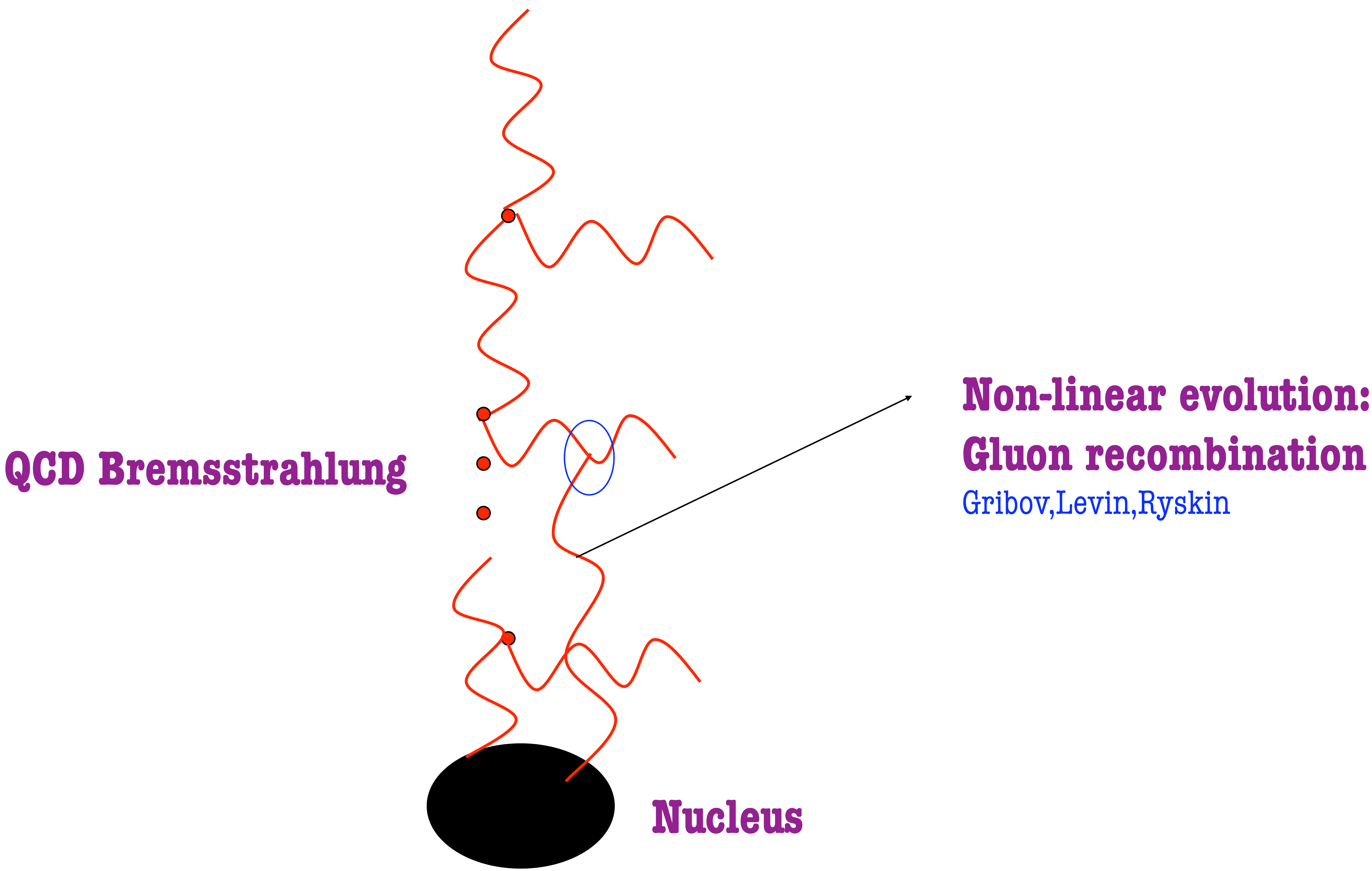
Ren.Group-BFKL evolution
(sums large logs in x)



Gluon density saturates at $f = 1/\alpha_S$
- strongest E&M fields in nature…

QCD Bremsstrahlung




QCD Bremsstrahlung
Non-linear evolution:
Gluon recombination
Gribov,Levin,Ryskin
Nucleus

Parton Saturation

★ Competition between attractive bremsstrahlung and repulsive recombination effects

Maximum occupation number (f = 1/α_S) =>

$$\frac{1}{2(N_c^2-1)}\,\frac{x\,G(x,Q^2)}{\pi R^2\,Q^2} = \frac{1}{\alpha_S(Q^2)}$$

This relation is saturated for

$$Q = Q_s(x) >> \Lambda_{\rm QCD} \approx 0.2\ \mathrm{GeV}$$

Need a new organizing principle to explore this novel physics regime of high energy QCD