The Abdus Salam
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SUMMER SCHOOL ON PARTICLE PHYSICS

13 - 24 June 2005

QCD Phase Transitions and Heavy ion Collisions - Part 1

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xQCD: QCD at high energies, temperatures & baryon densities

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ICTP, Trieste, June 20th -24th, 2005

Outline of 4 lectures

- Lecture I : General Introduction, QCD at high energies.

- Lecture II: QCD at high energies-continued.

  Heavy Ion Collisions: creating hot & dense matter in the laboratory.

- Lecture III: Exploring the phase diagram of QCD

- Lecture IV: Heavy Ion Collisions at RHIC.

  What has RHIC wrought?
  What awaits at LHC?

Overall theme of lectures-

Many body / statistical QCD at

High Temperatures,

High Baryon Densities,

and yes,

at high energies…

Outstanding phenomenological questions in heavy ion collisions

- Can we learn about the universal properties of hadronic wavefunctions at high energies ? (Color Glass Condensate)

- How does the CGC melt when heated in high energy heavy ion collisions? Does the matter thermalize to form a Quark Gluon Plasma (QGP) ?

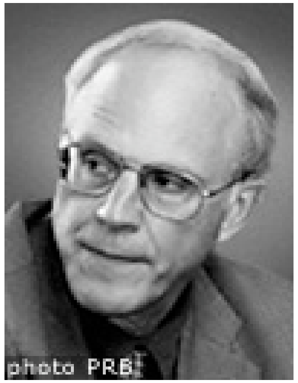
- Is the QGP formed at RHIC? What can we learn about its properties?

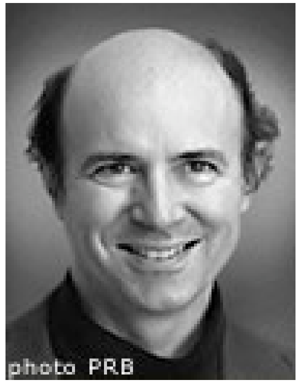
Outline of lecture I

- **QCD preliminaries**

- **What does a hadron look like at high energies?**

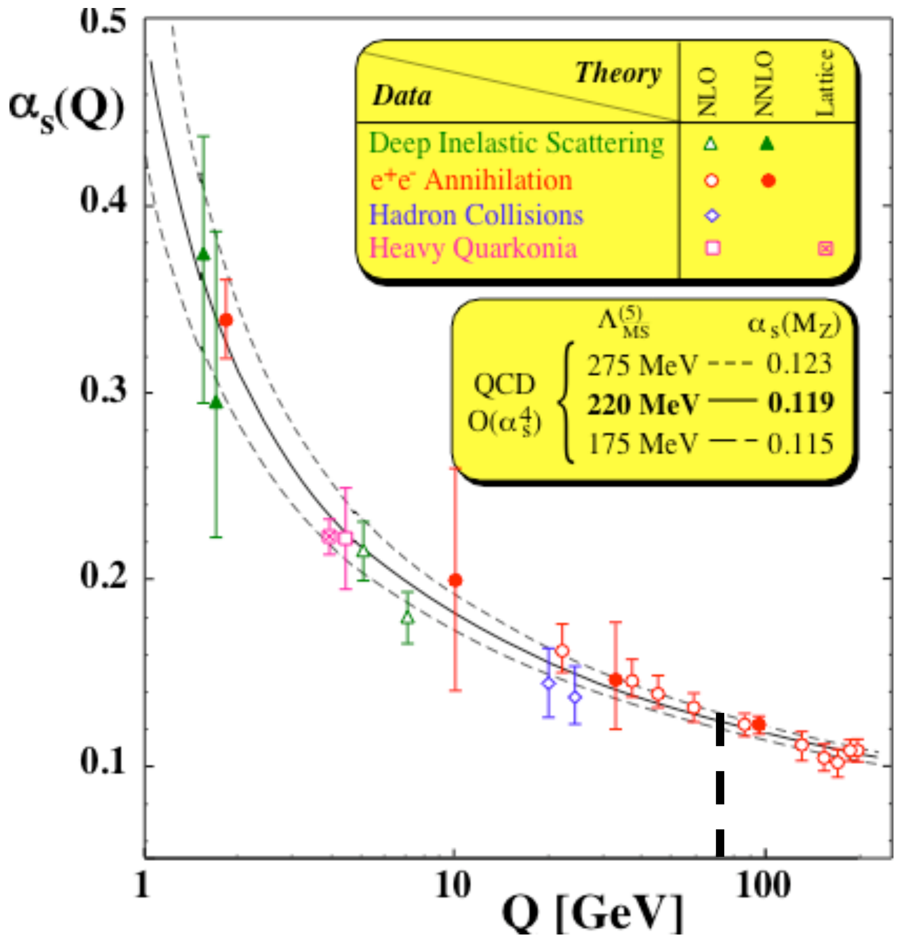
Quantum Chromodynamics (QCD) in the news…

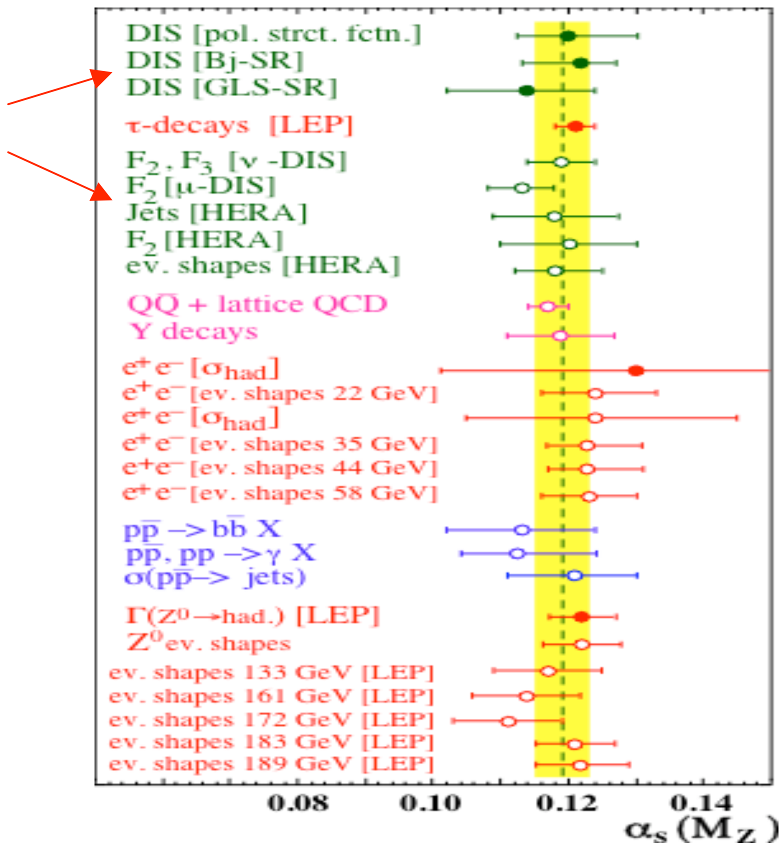




The 2004 Nobel prize in physics

For the discovery of asymptotic freedom in QCD- the theory of the strong interaction…





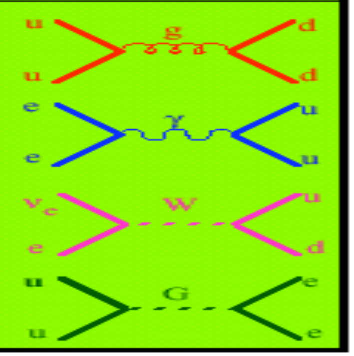
Fundamental particles and their interactions

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

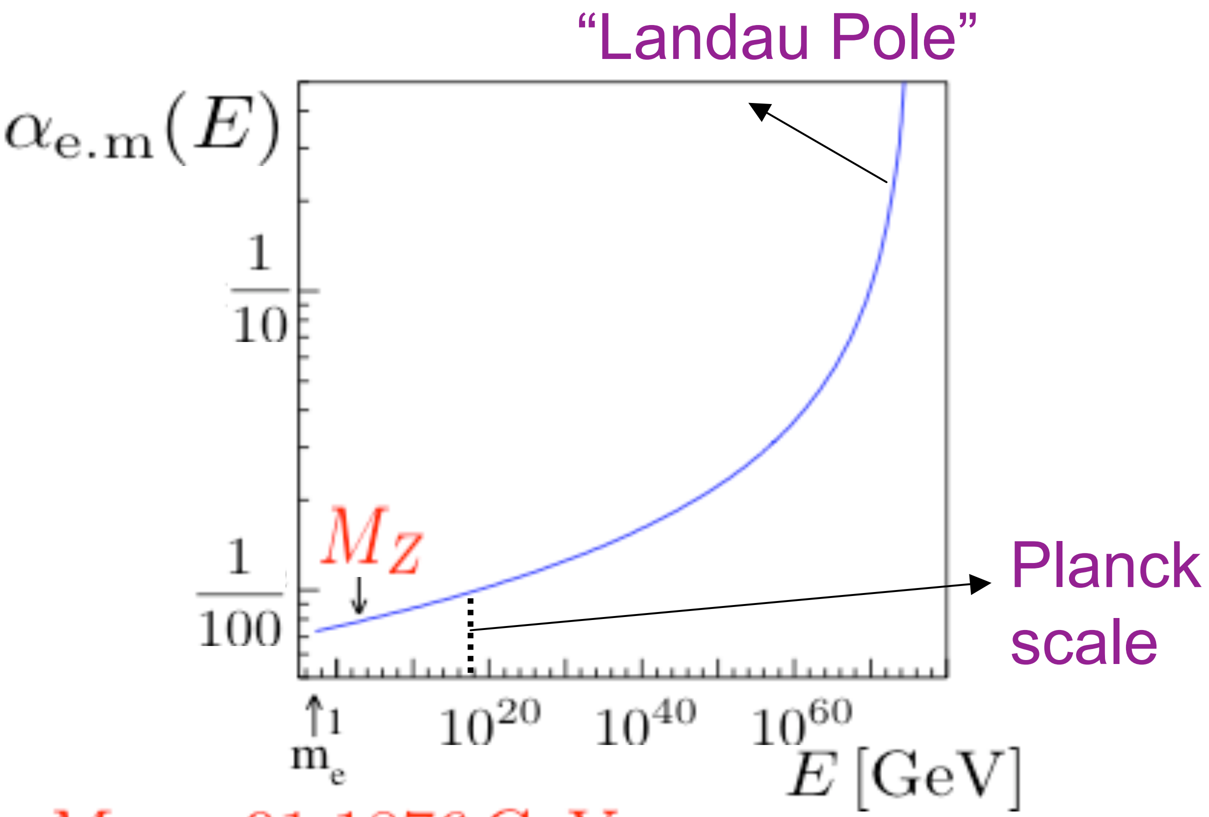
All masses in GeV units

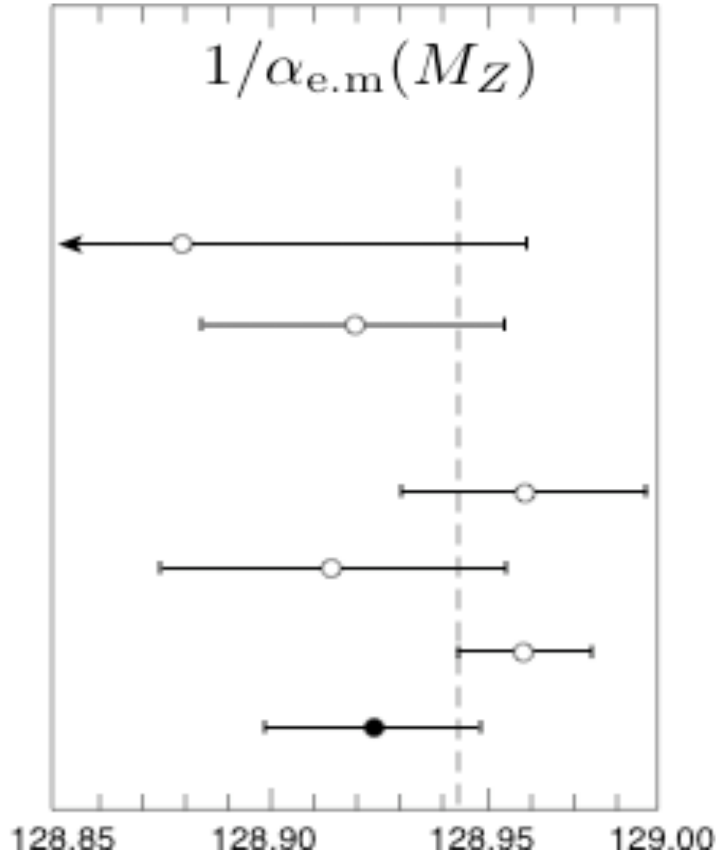
QCD →

QED ↗

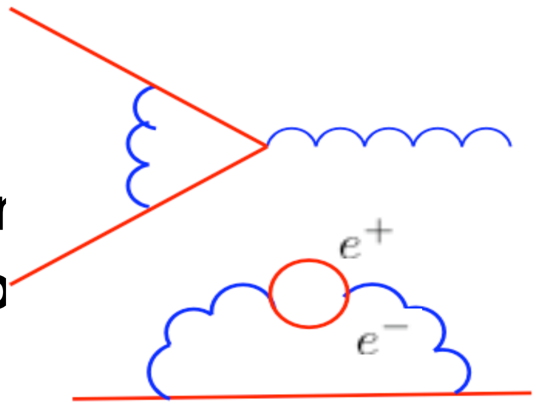
Interaction	exchanged boson	relative strength	example
Strong	Gluon (g)	1	
Electromagnet.	Photon (γ)	$\frac{1}{137}$	
Weak	W^+, W^-, Z^0	10^{-14}	
Gravitation	Graviton (G) ?	10^{-40}	

The RUNNING COUPLING CONSTANT IN QED



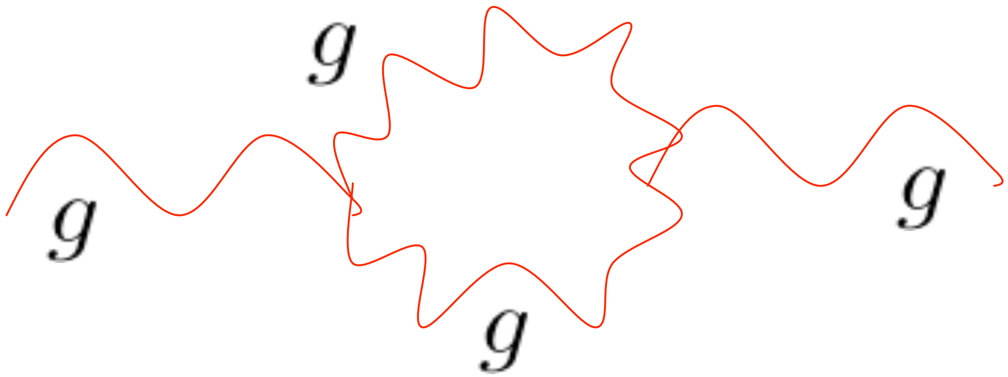


$M_Z \approx 91.1876\,\mathrm{GeV}$



Simple reason for rur **of e.m charges by**
virtual excitations fro

In QCD, one has "anti-screening" because colored gluons can interact with each other…



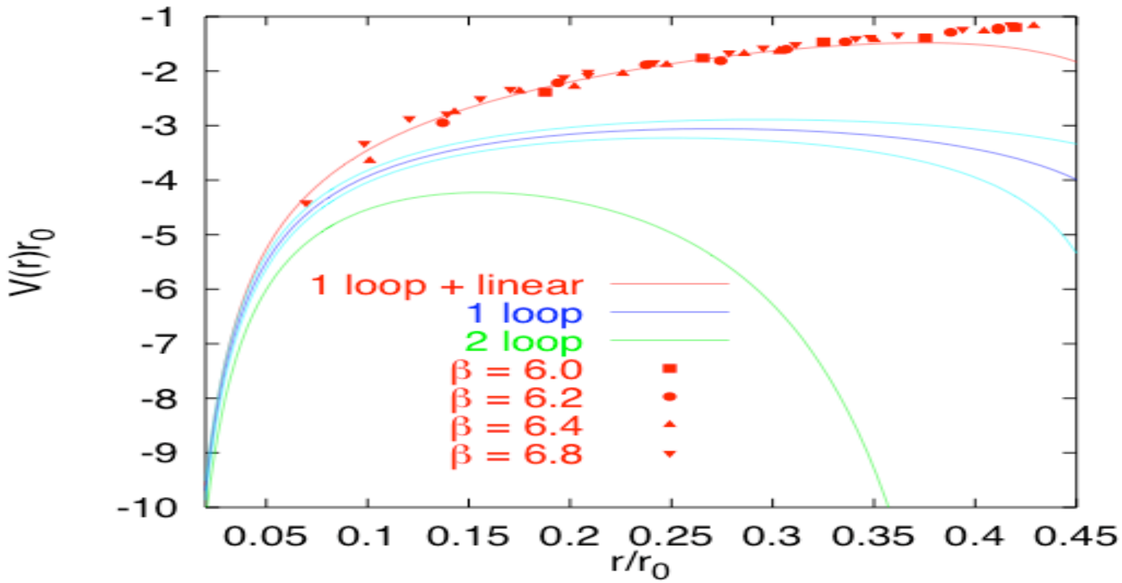
Photons do not self-interact in QED

The coupling between color charges gets weaker at high energies- or short distances…

Infrared Slavery

$$V(r) = \sigma r - \frac{e}{r}$$

$\sigma = 425\ \mathrm{MeV}^2\ ;\ e \approx 0.5$



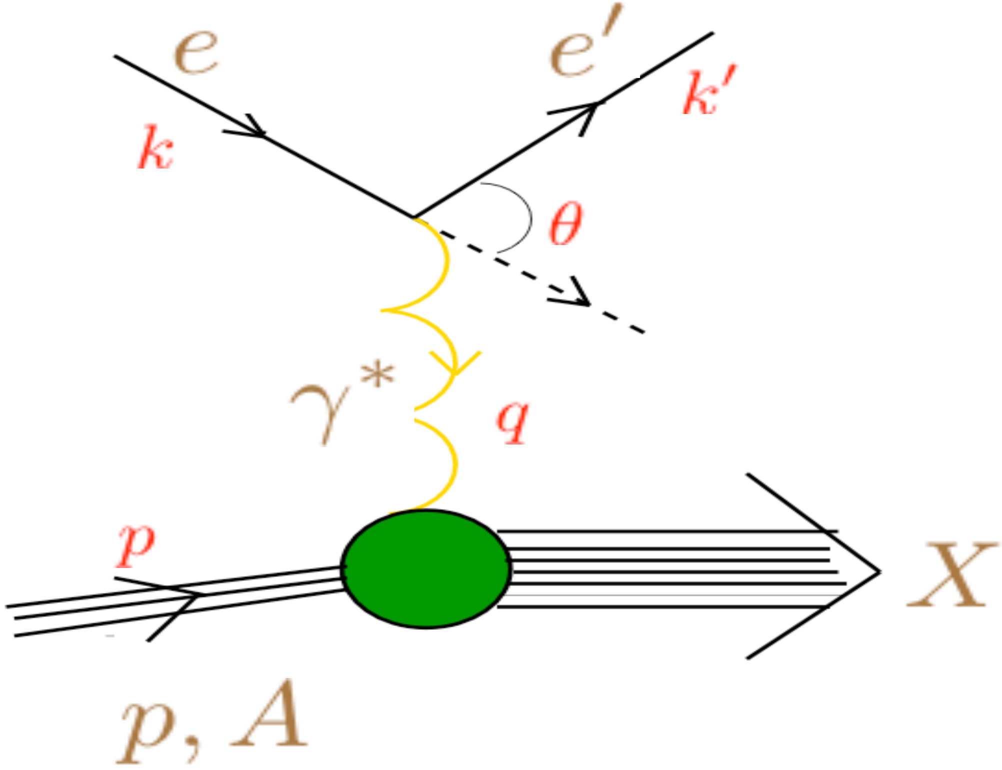
Potential between static quark-anti-quark pair grows linearly at large distances -

provides intuitive picture of confinement

DEEPLY INELASTIC SCATTERING

THE SIMPLEST WAY TO STUDY QCD AT SMALL DISTANCES…

R. Hofstader



Kinematic Invariants:

Center of mass energy square S

Momentum resolution square Q^2

x_{Bj} -an invariant to be defined shortly

$$x_{\mathrm{Bj}} \approx \frac{Q^2}{s}$$

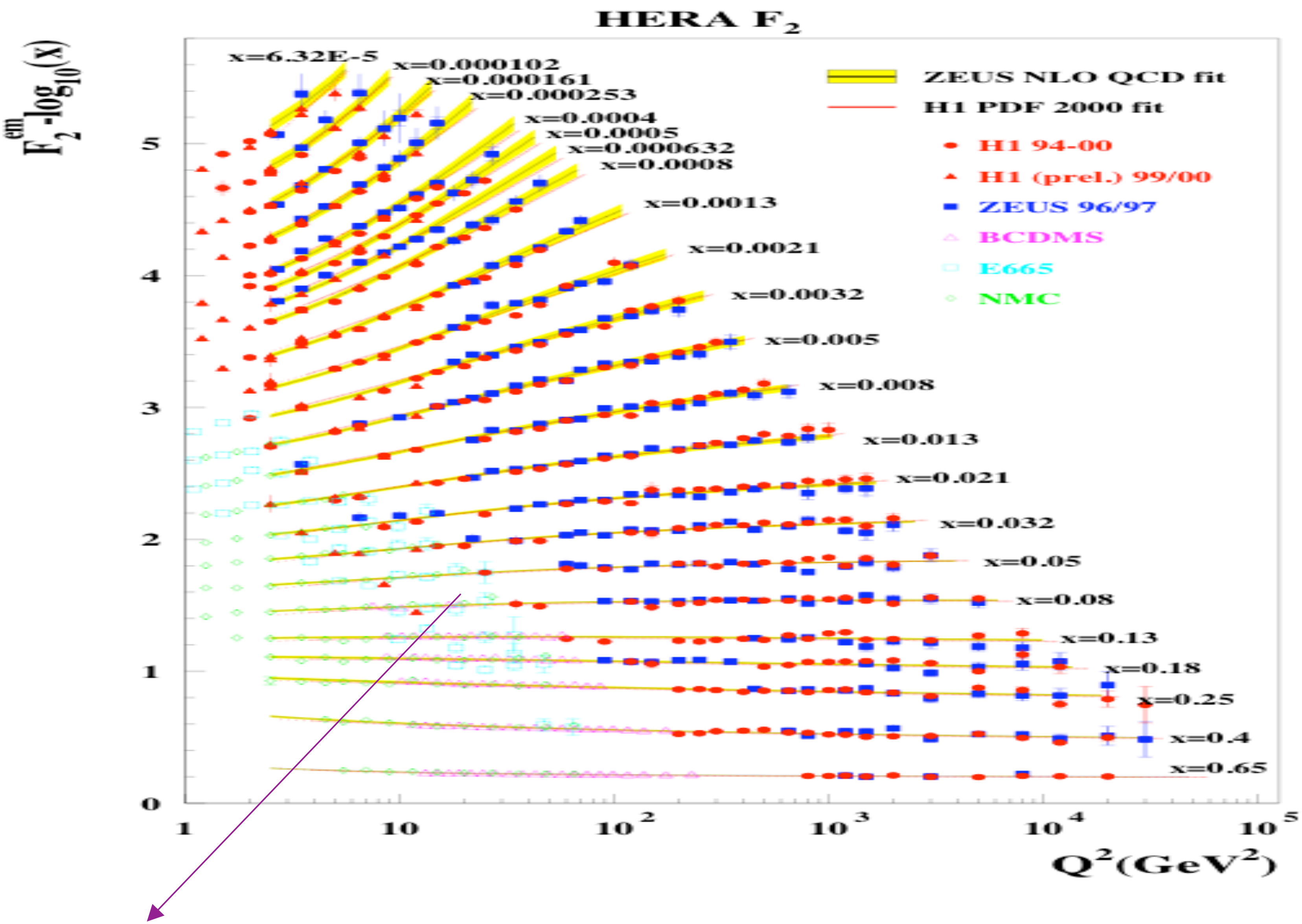
DIS inclusive cross-section:

$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{\mathrm{em.}}}{xQ^4}\left[y^2 x F_1(x,Q^2) + (1-y)F_2(x,Q^2)\right]$$

Structure functions

Rutherford cross-section

Nobel to Friedman, Kendall, Taylor

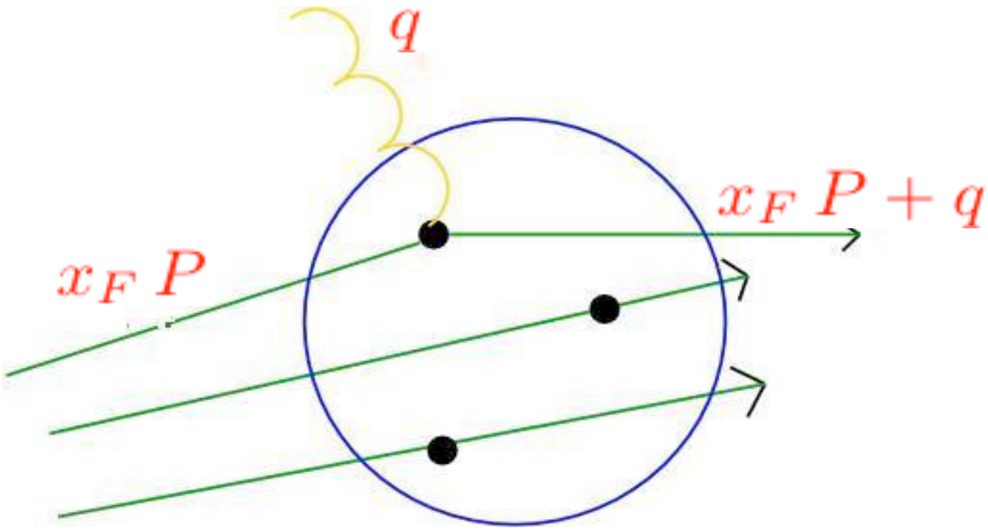


Bj-scaling - apparent scale invariance of structure functions…

- **Feynman and Bjorken explanation of scaling puzzle…**

Parton model

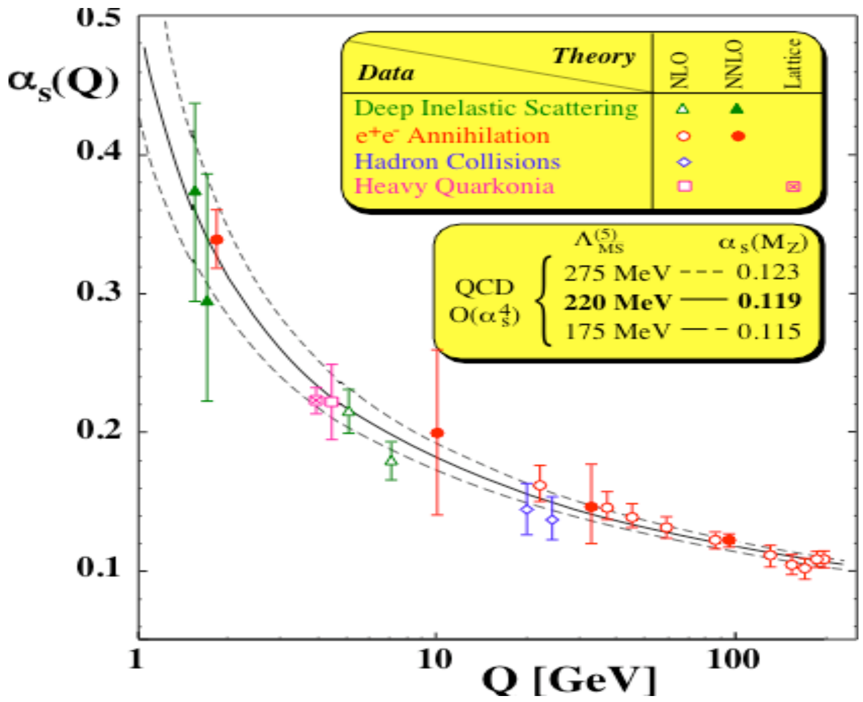
Parton constituents of proton are "quasi-free" on interaction time scale 1/q



$$(x_F P + q)^2 = m_q^2 \approx 0 \longrightarrow \boxed{x_F \approx \frac{Q^2}{s}}$$

$x_{\rm Bj} =$ Fraction of hadron momentum carried by a parton…

Puzzle resolved in QCD

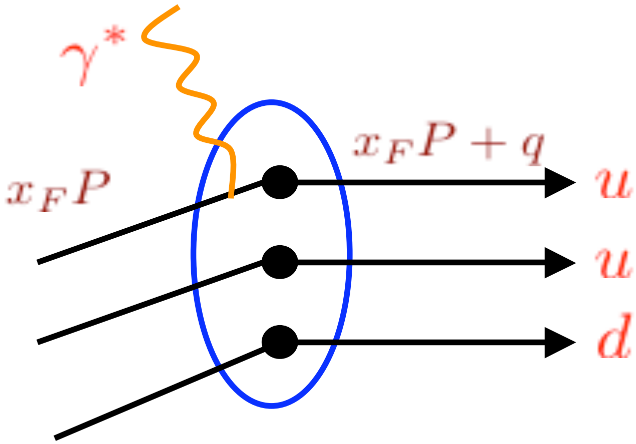


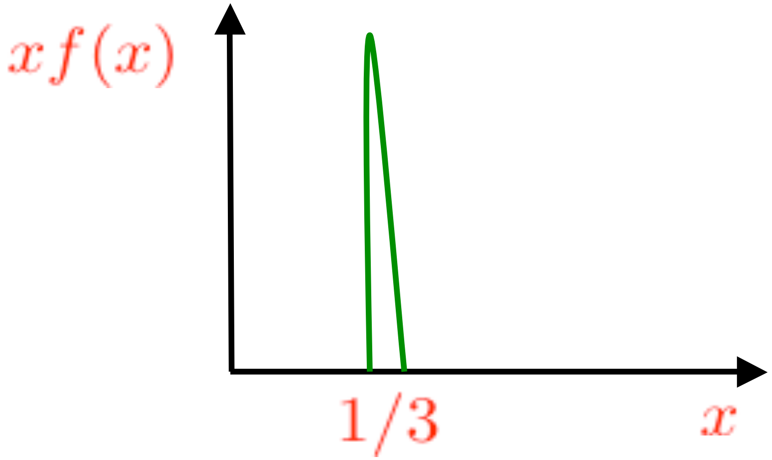
QCD $\neq$ Parton model

Logarithmic scaling violations

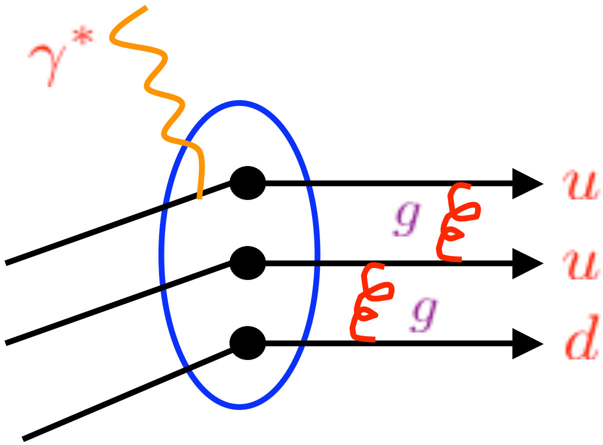
$$F_2(x,Q^2) = \sum_{\substack{q=u,c,t\\ d,s,b}} e_q^2 \left(x\, q(x,Q^2) + x\, \bar{q}(x,Q^2) \right)$$

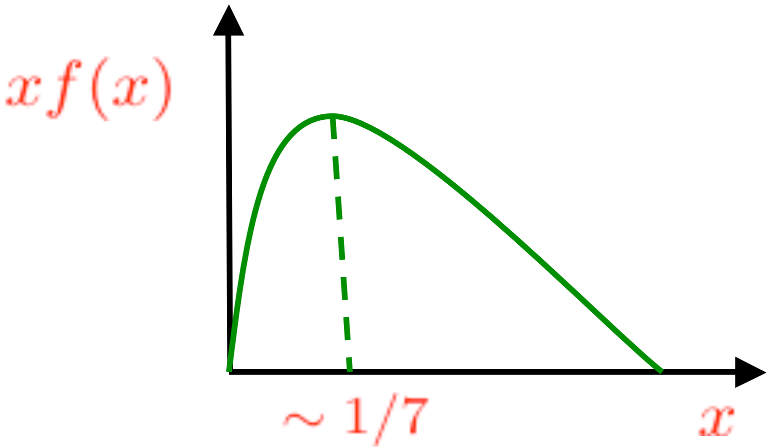
The Hadron at high energies: I



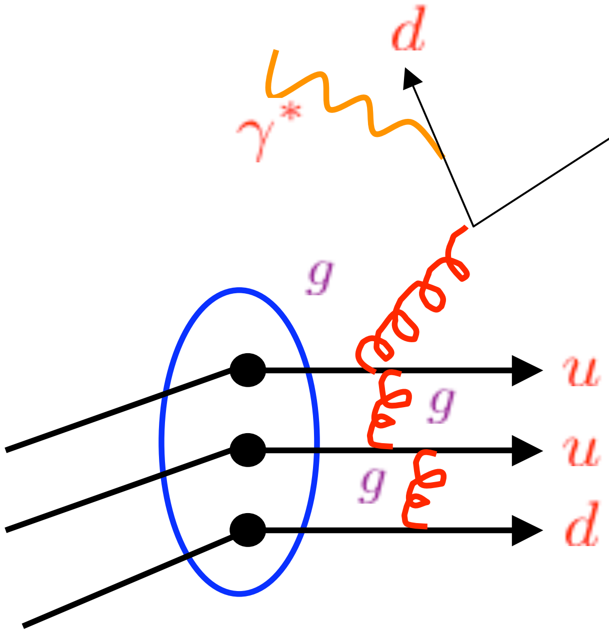


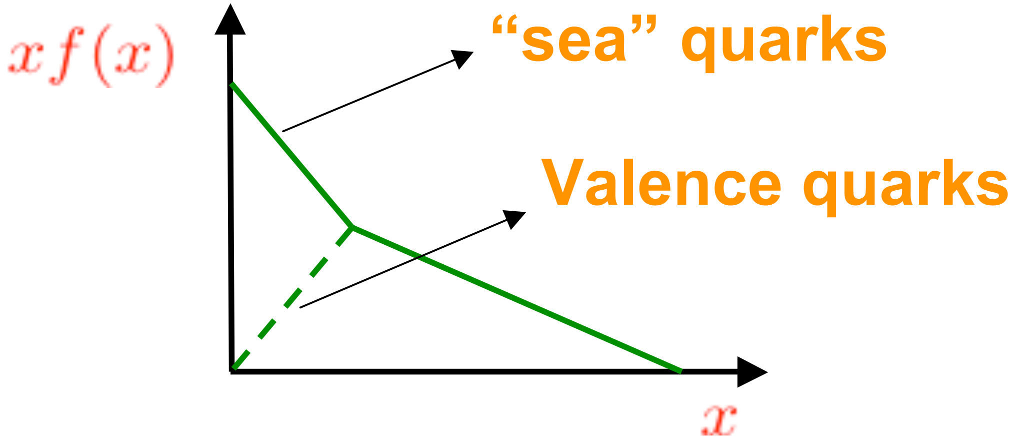
Parton model





QCD-logarithmic corrections





"X"-QCD--RG evolution

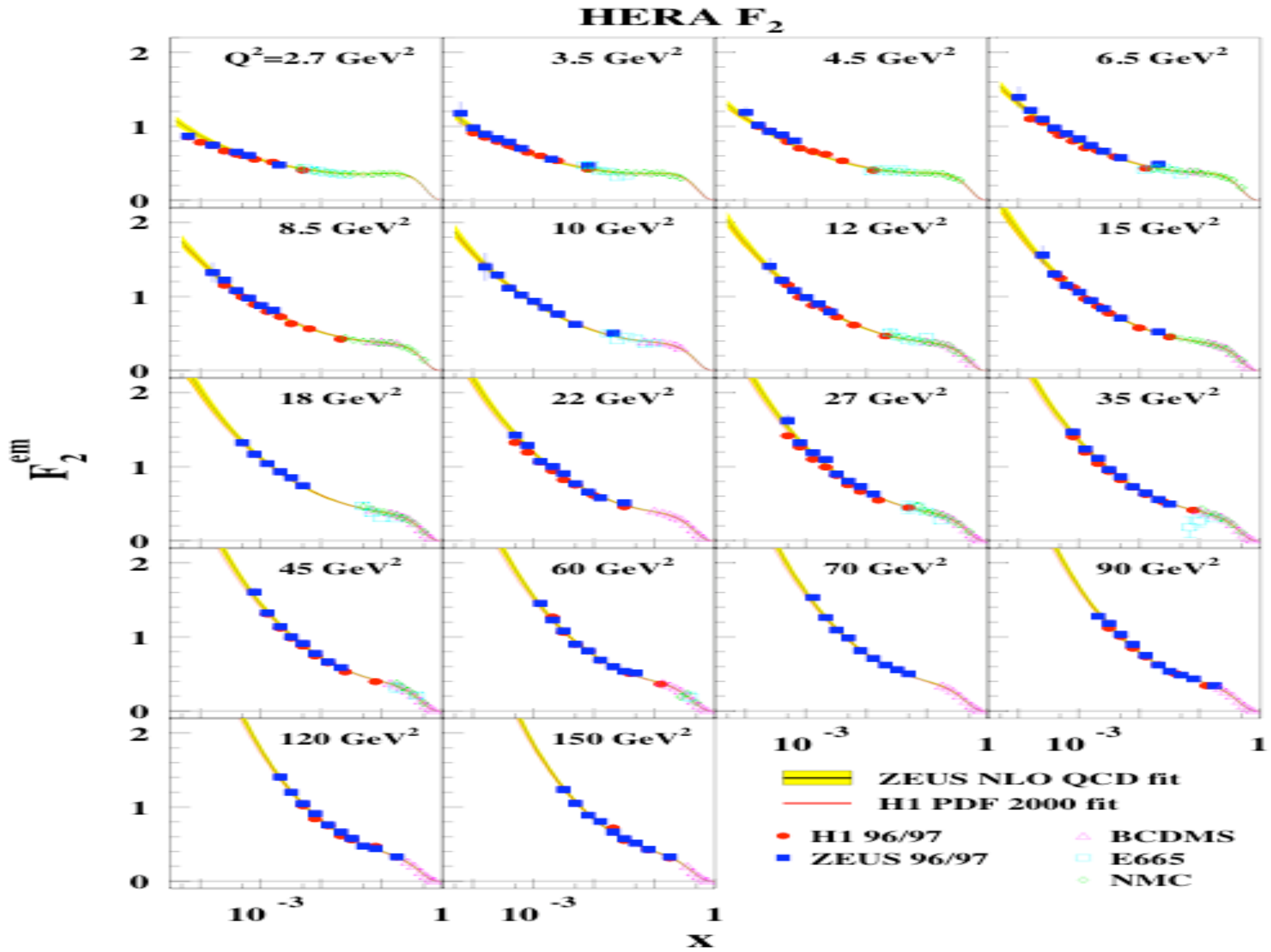
$$\int_0^1 \frac{dx}{x}\,(xq(x) - x\bar{q}(x)) = 3$$

# of valence quarks

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

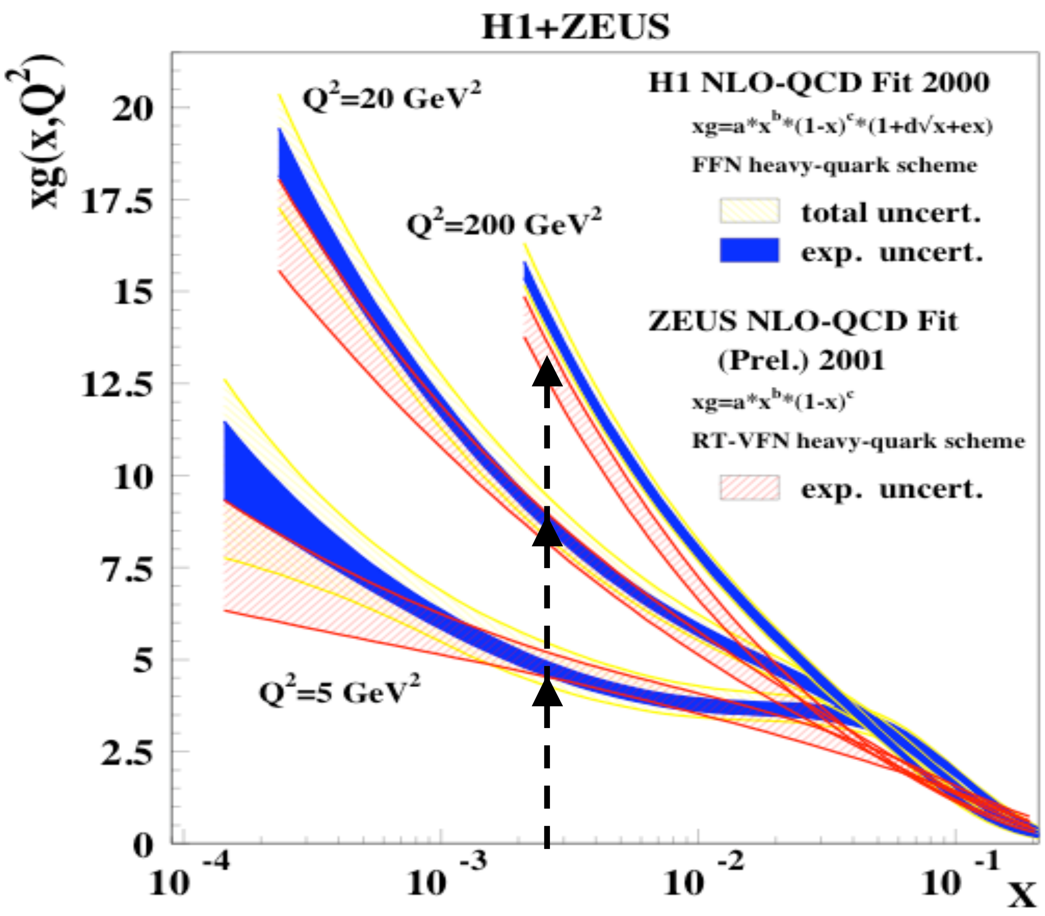
 # quarks…

Renormalization group (RG) evolution:



DGLAP evolution: Linear RG in Q^2

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi



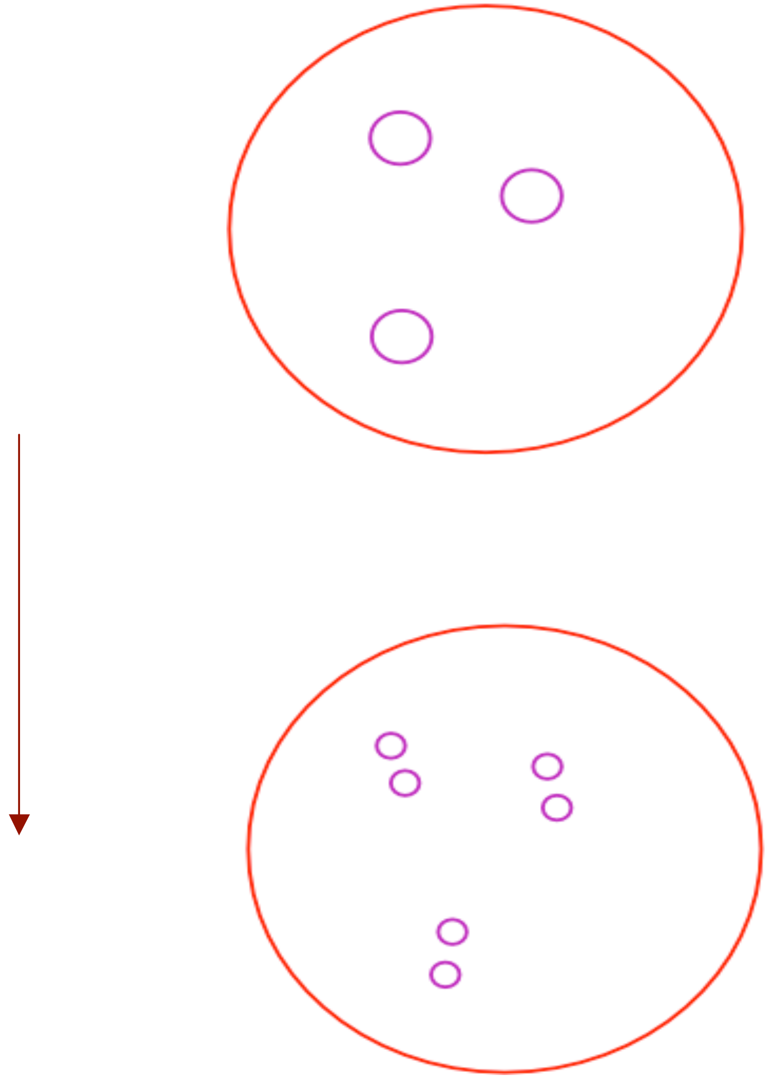
Sum large # of Bremsstrahlung logs -

# of gluons grows rapidly at small x…

Resolving the hadron
-DGLAP evolution

increasing

Q^2



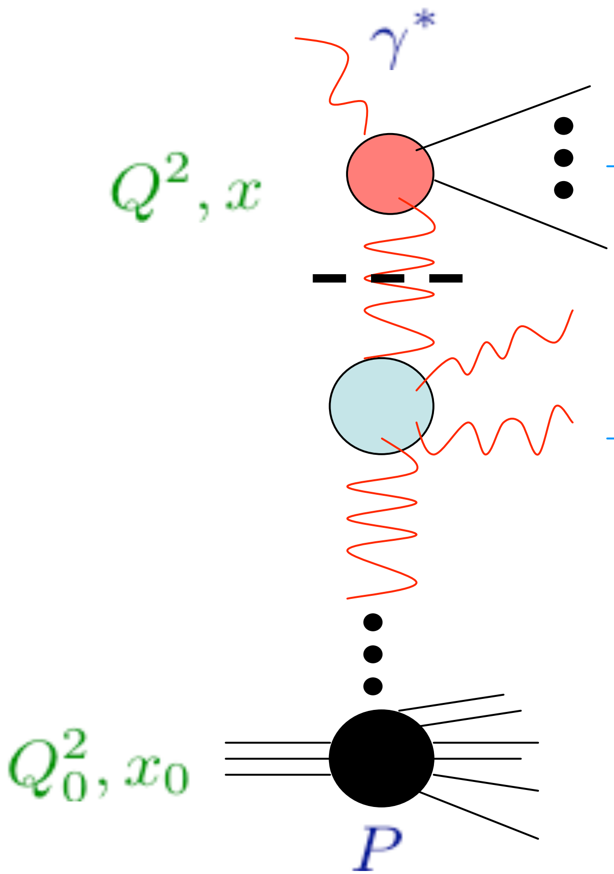
But… the phase space density decreases
-the proton becomes more dilute

Much of the discussion in pQCD has focused on the Bjorken limit:

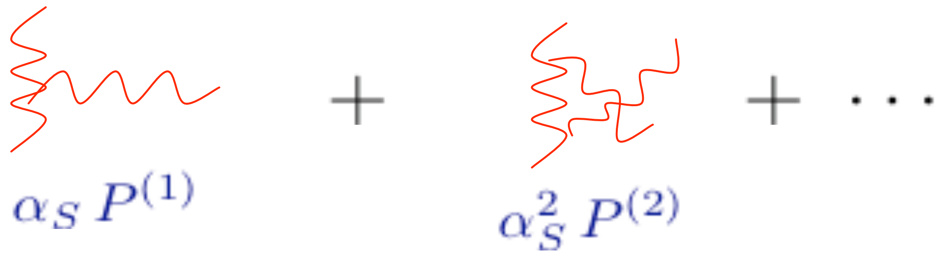
$$Q^2 \to \infty\, ;\, s \to \infty\, ;\, x_{\mathrm{Bj}} \approx \frac{Q^2}{s} = \text{fixed}$$

Asymptotic freedom,
the Operator Product Expansion (OPE)
& Factorization Theorems:
machinery of precision physics in QCD…

STRUCTURE OF HIGHER ORDER CONTRIBUTIONS IN DIS



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



+ higher twist (power suppressed) contributions…

- Coefficient functions - C - computed to NNLO for many processes, e.g., gg -> H Harlander, Kilgore; Ravindran,Van Neerven,Smith; …
- Splitting functions -P - computed to 3-loops recently! Moch, Vermaseren, Vogt

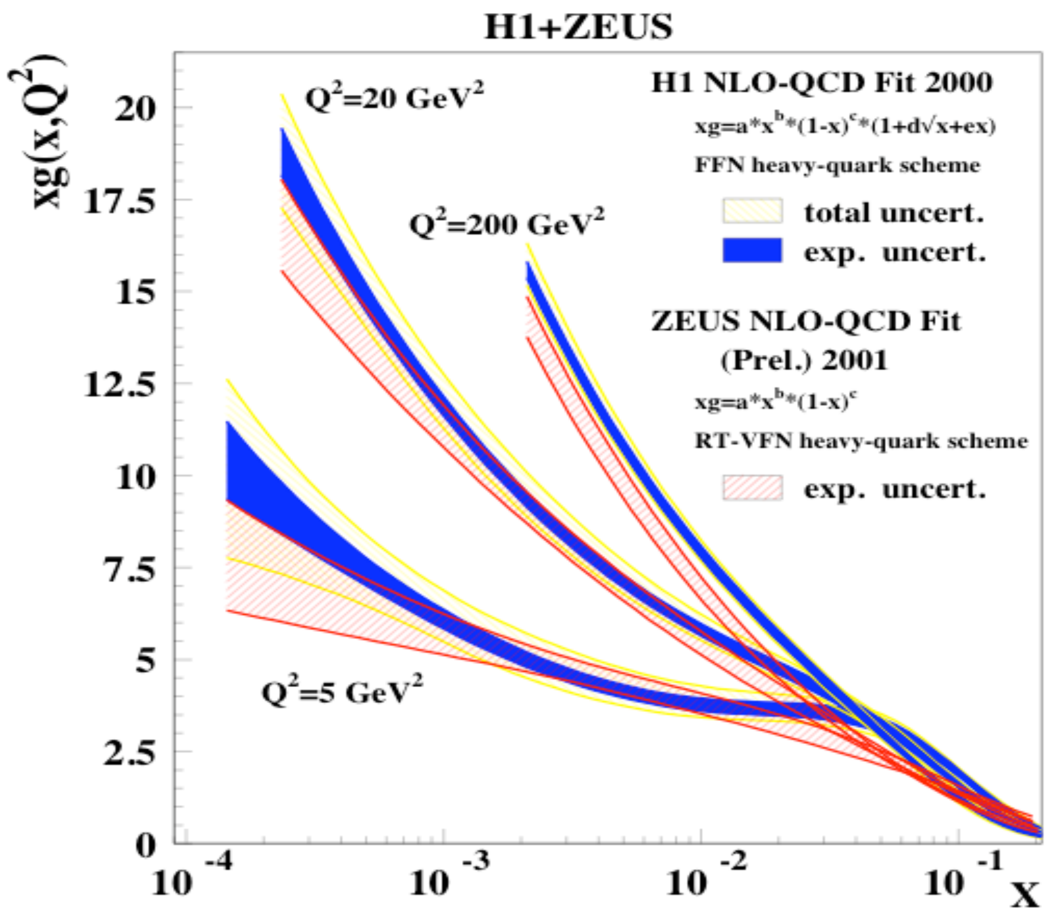
The other interesting limit-is the Regge limit of QCD:

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

Physics of strong fields in QCD,
multi-particle production-
novel universal properties of theory in this limit ?

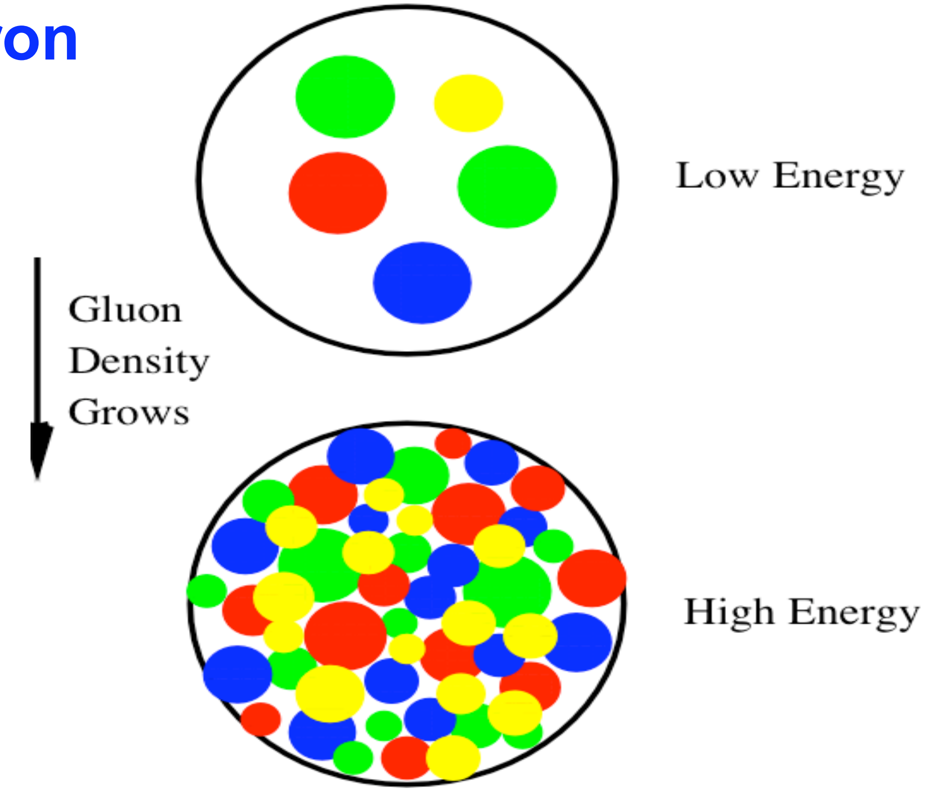
BFKL evolution: Linear RG in x

Balitsky-**F**adin-**K**uraev-**L**ipatov



of gluons grows even more rapidly…

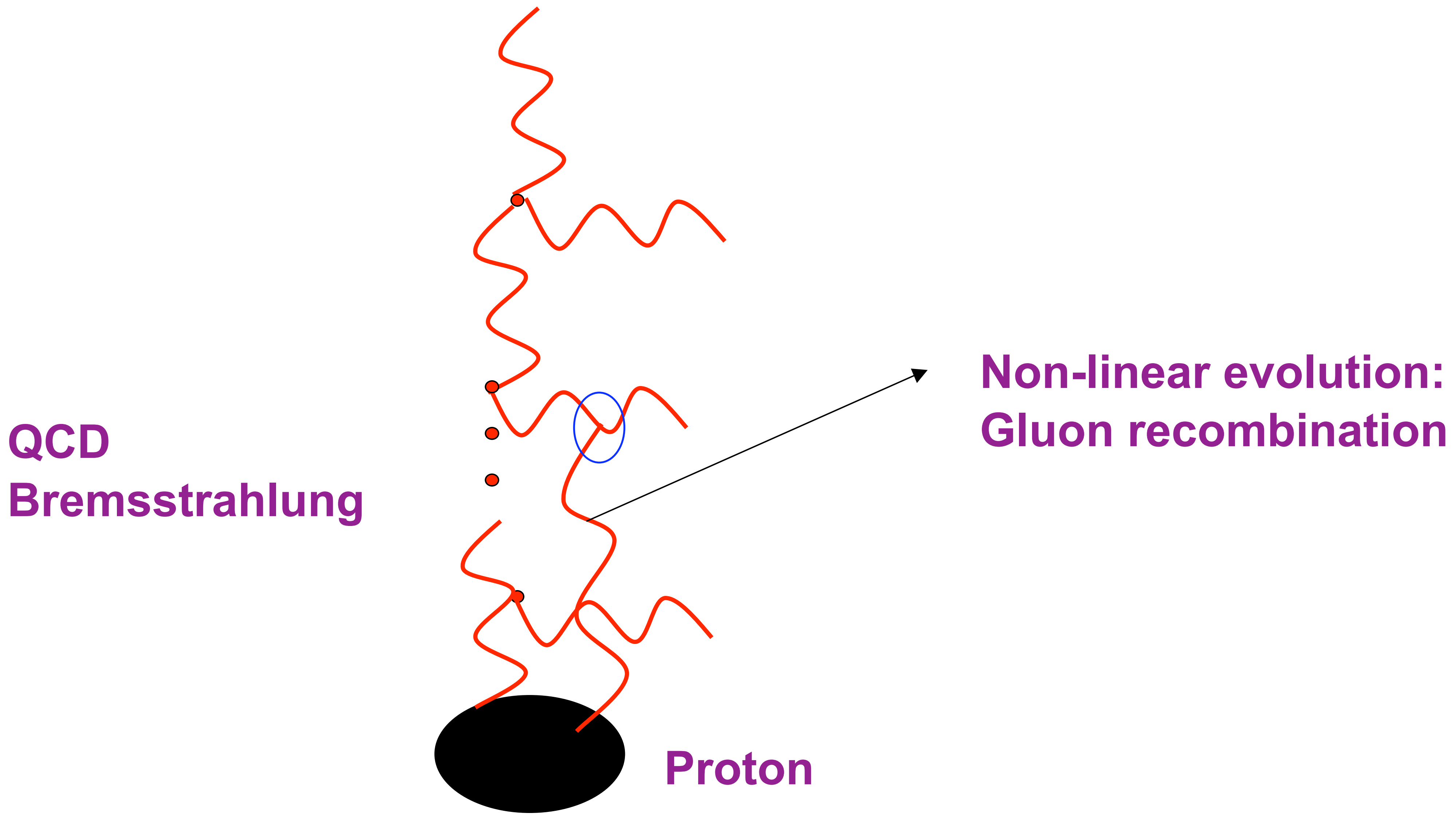
Resolving the hadron
-BFKL evolution



– Large x

– Small x

Gluon density saturates at f= $\dfrac{1}{\alpha_S}$



Proton is a dense many body system at high energies

Mechanism for parton saturation:

Competition between "attractive" bremsstrahlung and "repulsive" recombination effects.

Maximal phase space density =>

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

Saturated for

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

- Higher twists (power suppressed-in Q^2)

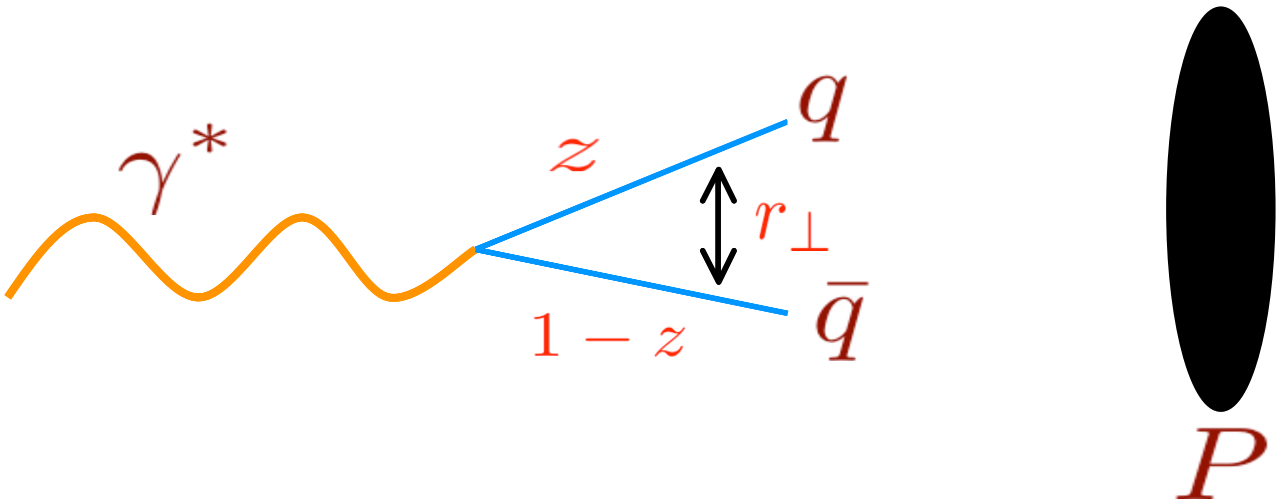
  are important when: $Q^2 \approx Q_s^2(x) >> \Lambda^2_{\rm QCD}$

- Leading twist "shadowing" of these contributions can extend up to at small x.

$$Q^2 >> Q_s^2(x)$$

Need a new organizing principle- beyond the OPE- at small x.

Golec-Biernat & Wusthoff's model



$$\sigma_{\mathrm{T,L}}^{\gamma^*,P} = \int d^2 r_\perp \int dz \, |\psi_{\mathrm{T,L}}(r_\perp, z, Q^2)|^2 \, \sigma_{q,\bar{q},P}(r_\perp, x)$$

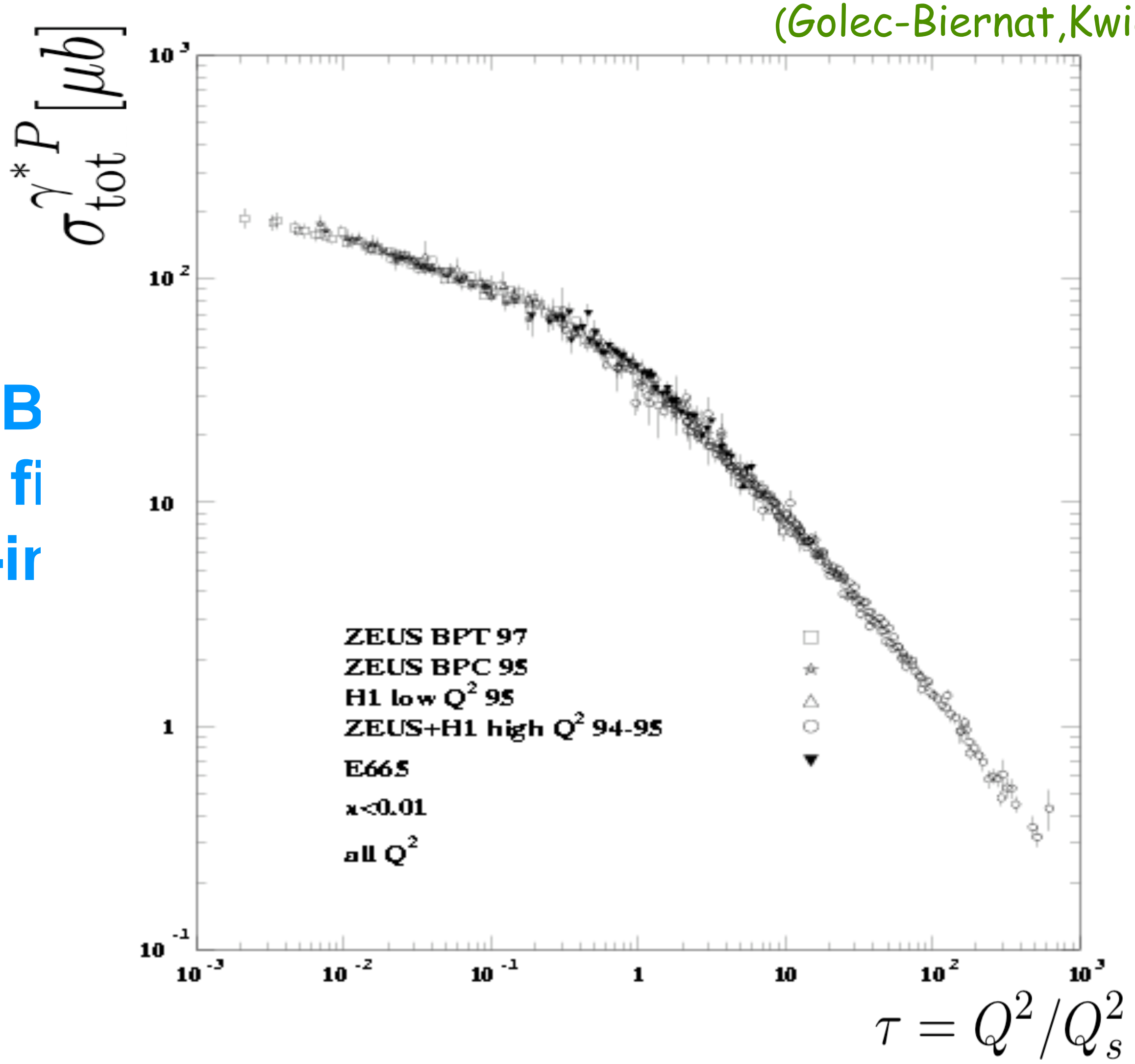
where $\sigma_{q\bar{q}P}(r_\perp, x) = \sigma_0 \left[1 - \exp\left(-r_\perp^2 \, Q_s^2(x)\right)\right]$

& $$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

Parameters: $Q_0 = 1\,\mathrm{GeV}\,;\, \lambda = 0.3\,;\, x_0 = 3 \cdot 10^{-4}$

Geometrical scaling at HERA

(Golec-Biernat,Kwiecinski,Stasto)



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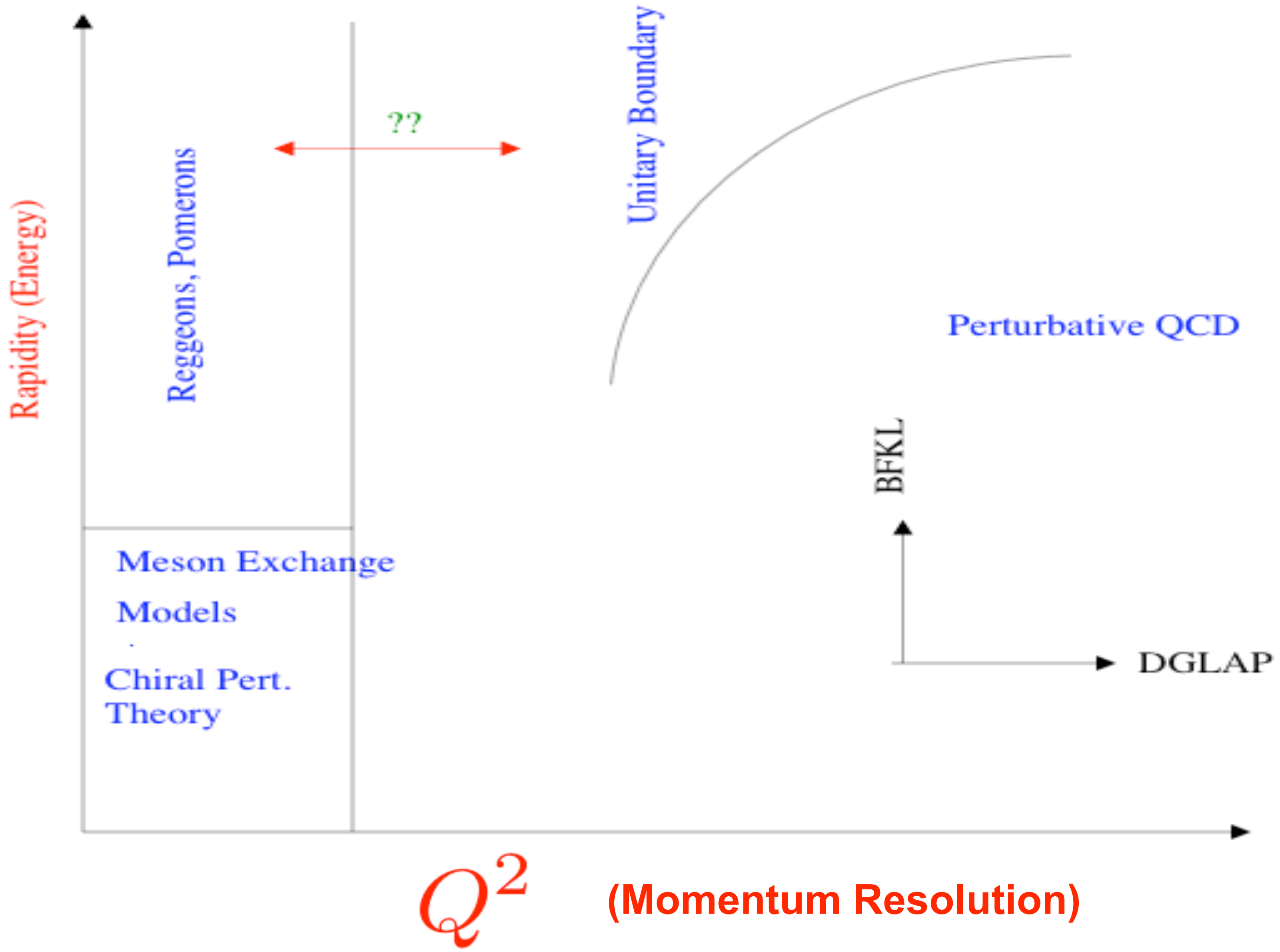
Scaling seen for all x < 0.01 and $0.045 < Q^2 < 450\,\mathrm{GeV}^2$

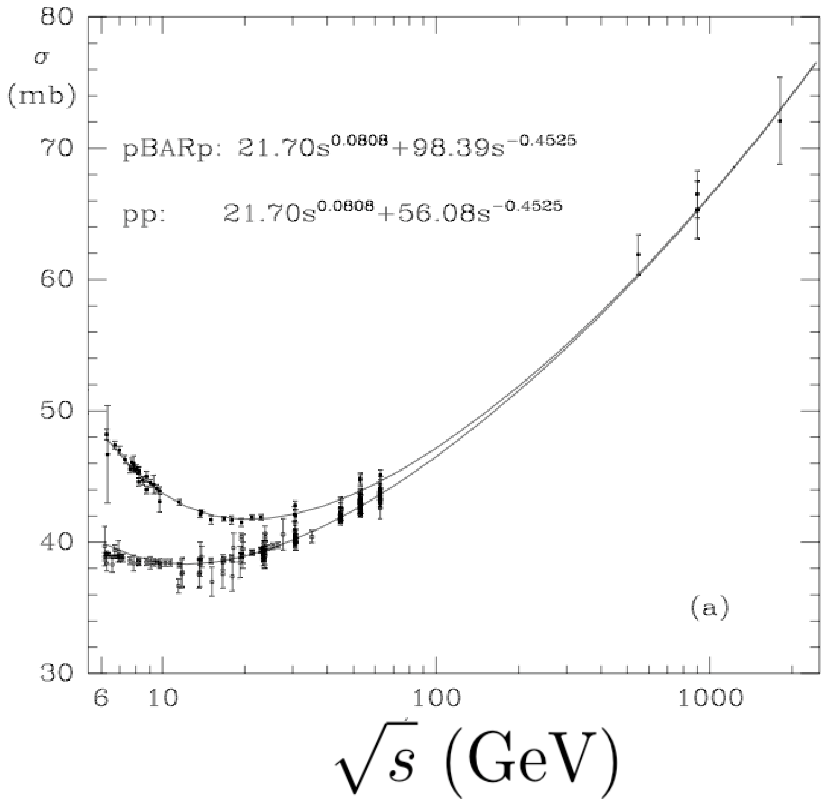
Road map of the strong interactions

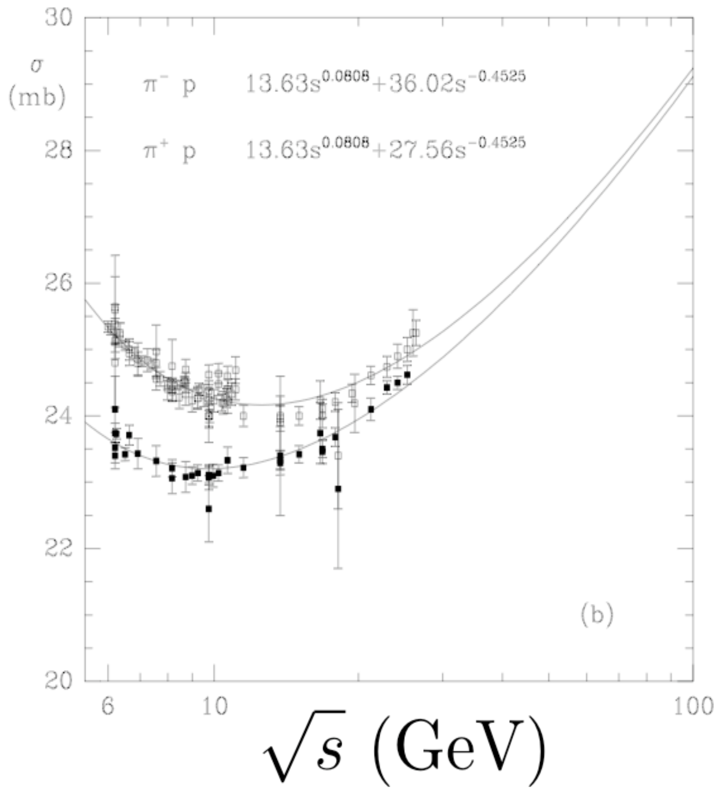


Total Cross-sections

$$\sigma(s)$$

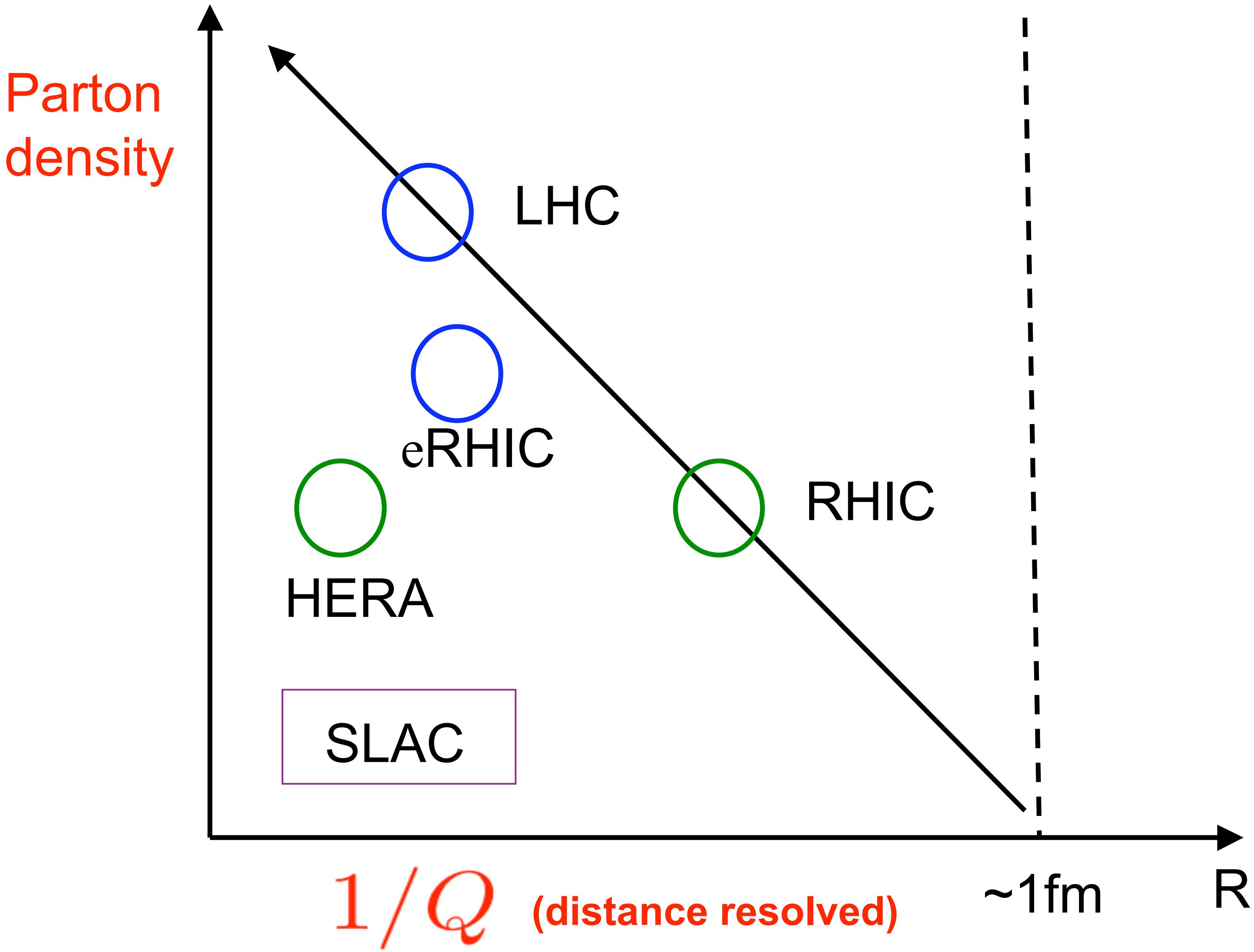
Donnachie & Landshoff



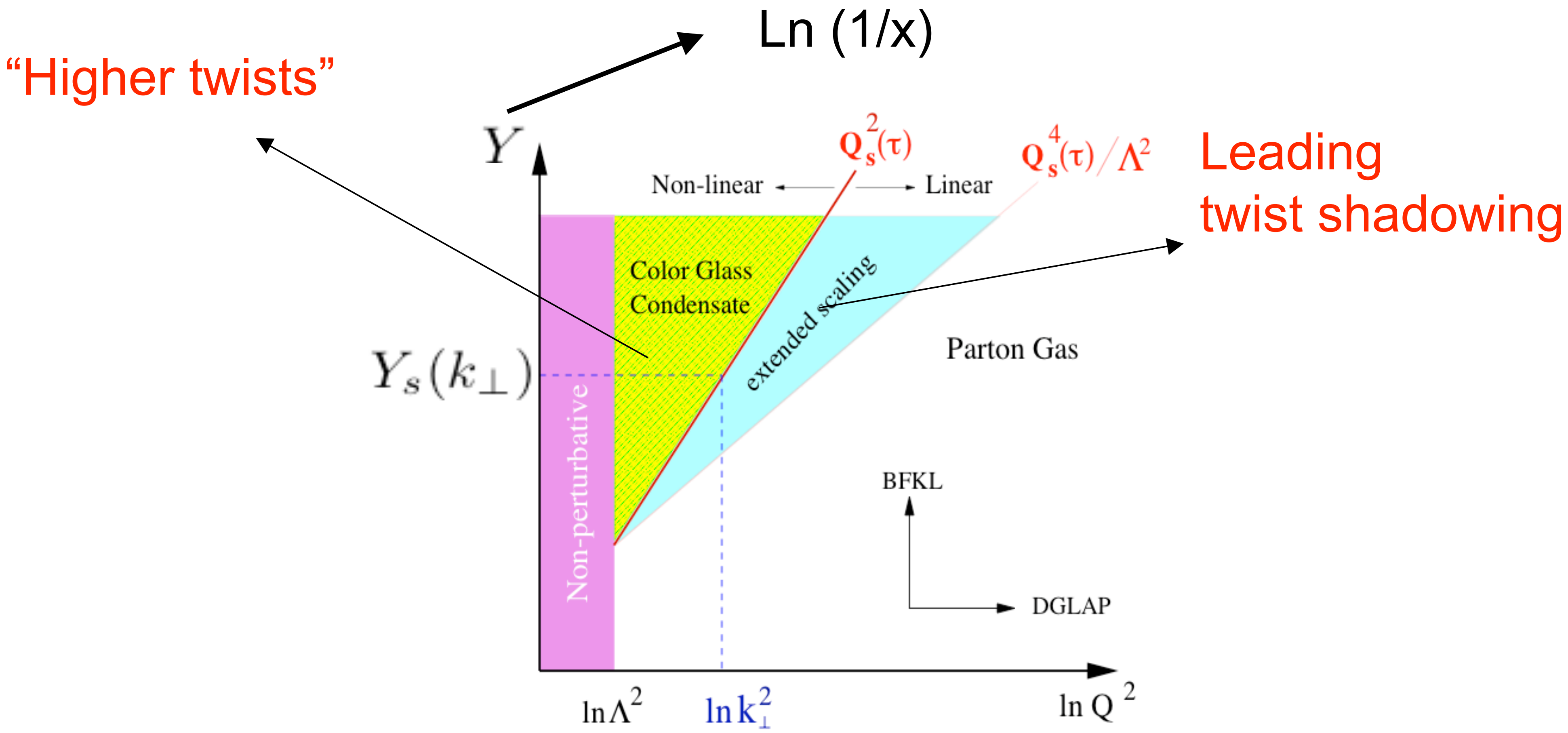


$$\sigma(s) = As^{0.0808} + Bs^{-0.4525}$$

Current and future colliders

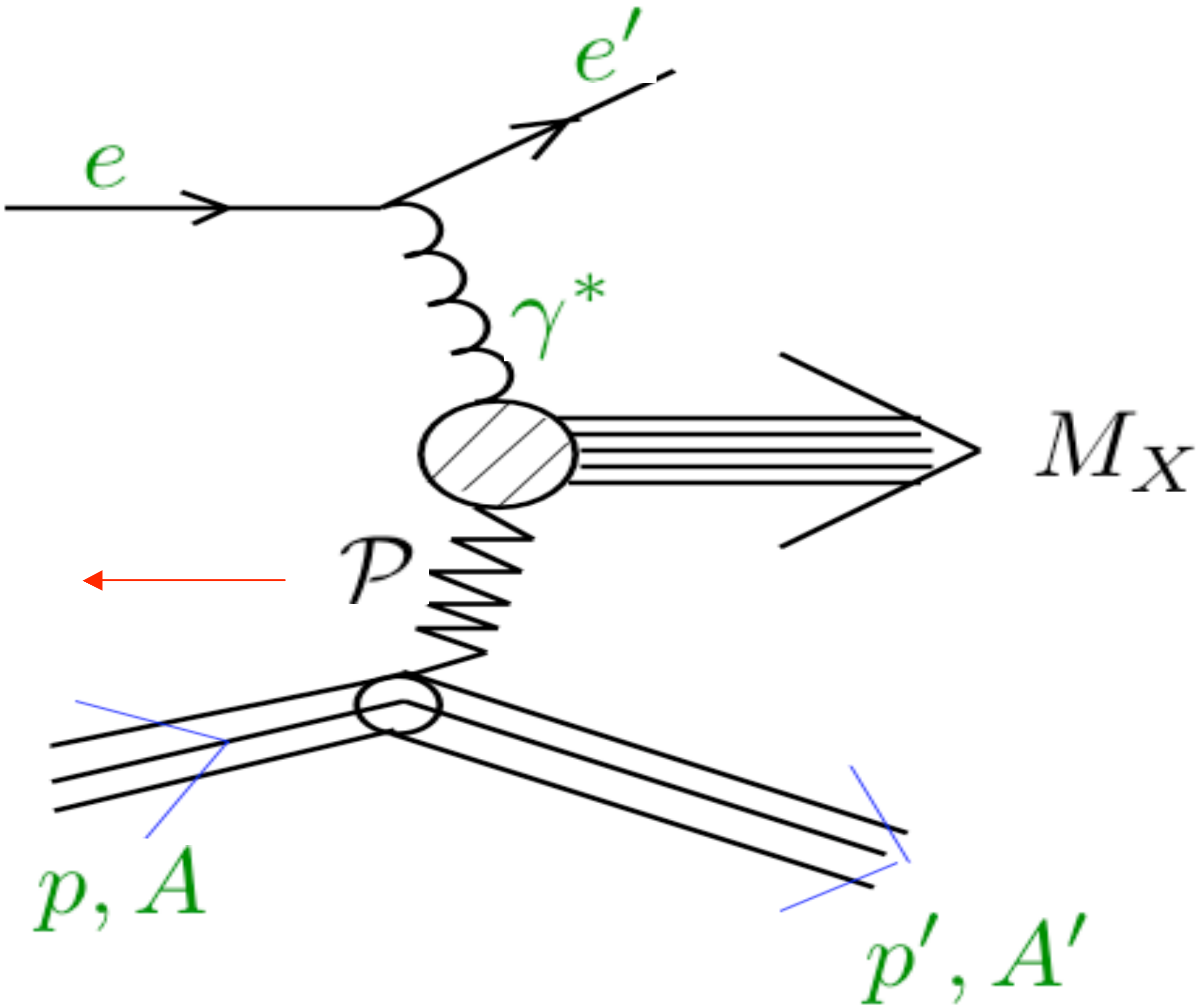


Novel regime of QCD evolution at high energies



Extra Slides

Hard diffractive processes

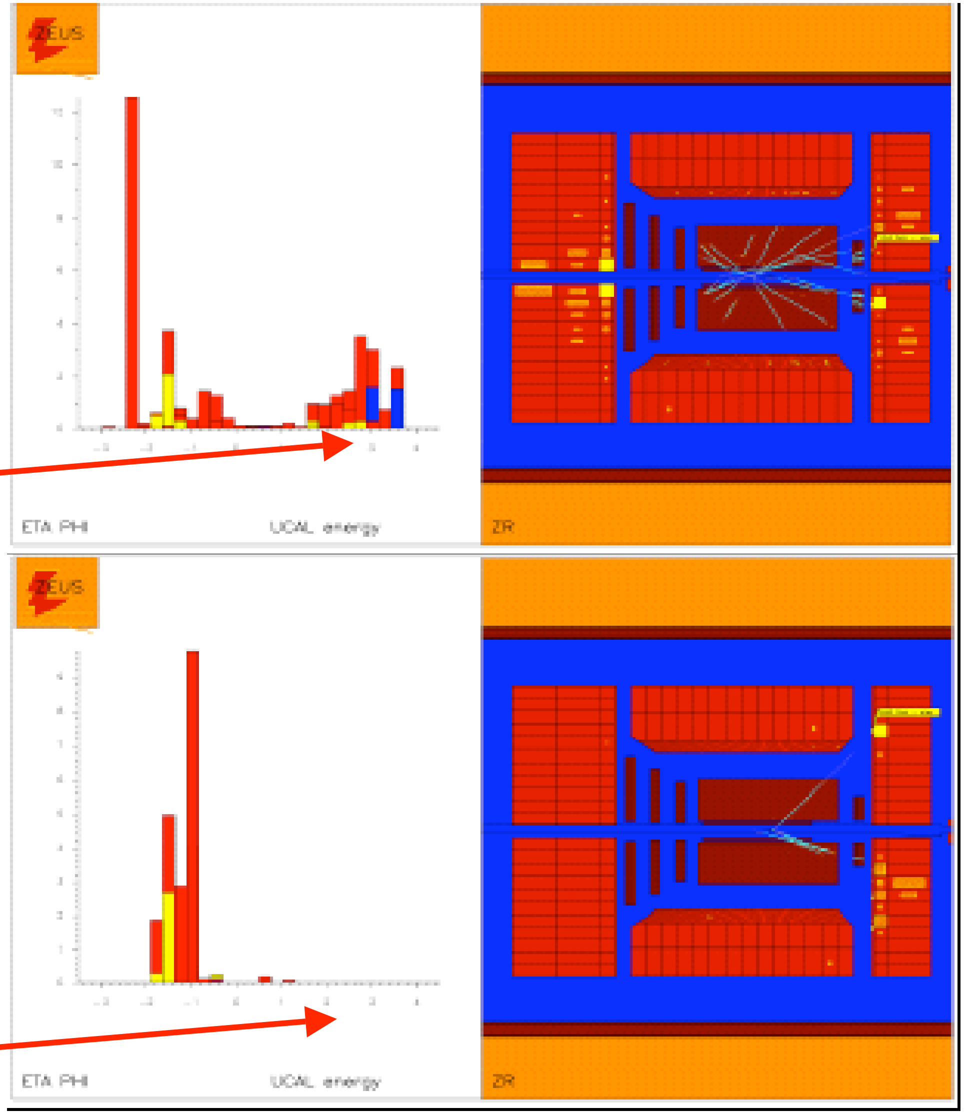


"Pomeron"
exchange

Diffractive Surprises at HERA

‘Standard DIS event’

Detector activity in proton direction



Diffractive event

No activity in proton direction

Approximate 10% of events are hard diffractive events!

Comparison with Data

FS model with/without saturation and **IIM CGC model** hep-ph /0411337.