Why can’t we see quarks?

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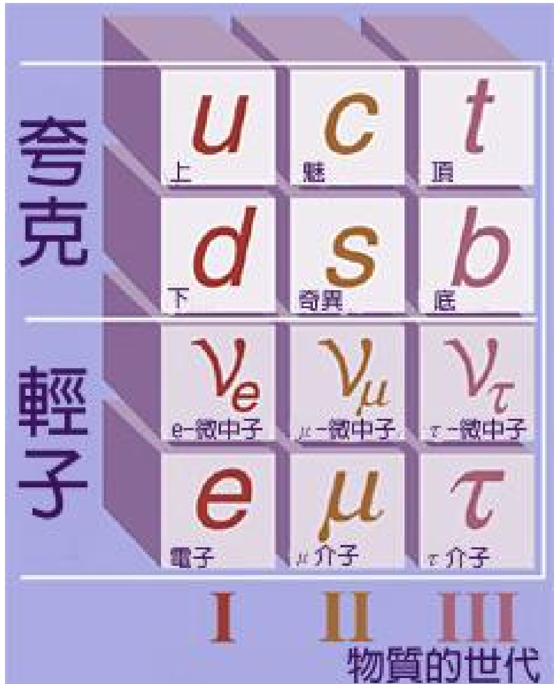
Outlines

- Introduction
- Strong Interaction
- Asymptotic Freedom
- Confinement
- Gribov’s Confinement
- Conclusion

Introduction

Understood composition of our universe

Elementary particles



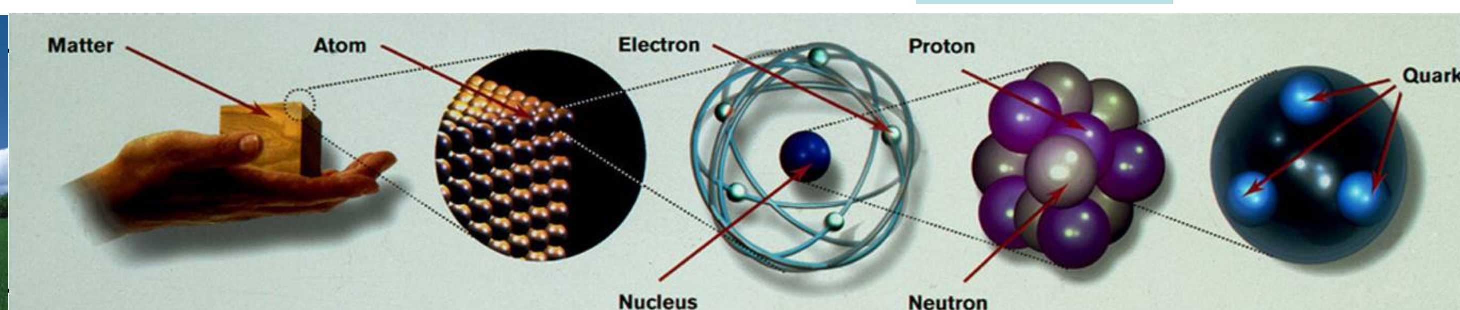
+反物質

+

EM

Higgs
（未被發現）

Strong

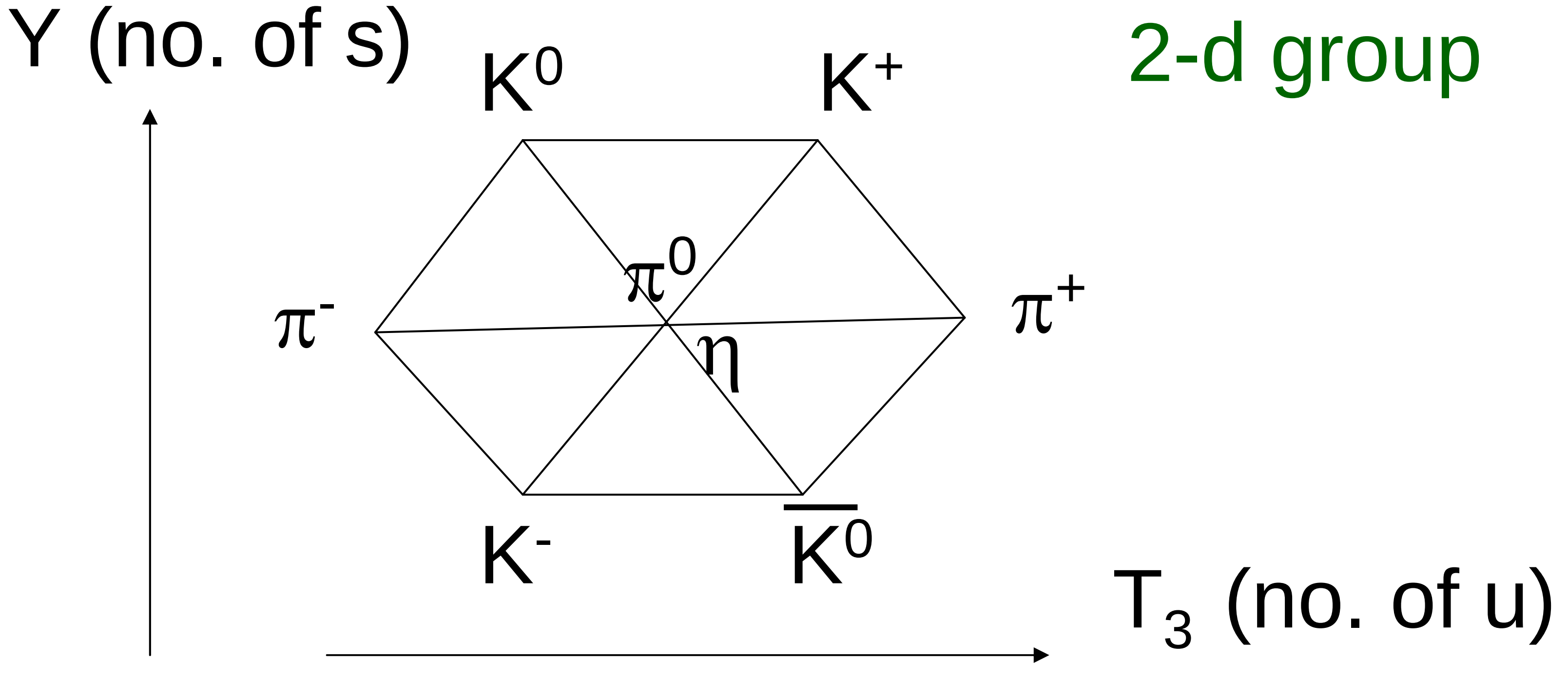


Quark Model

- Chemical "elements" are classified according to proton numbers, leading to the periodic table.
- Many "elementary" particles were found in 60's. There should exist more elementary particles.
- Gell-Mann proposed that "elementary" particles are composed of quarks (1964).
- "Elementary" particles were classified, and new particles were predicted.

Eightfold Ways

- Quark was only a math identity, not real.
- DIS at SLAC indicated the existence of “quarks” inside a proton at the end of 60’s.



2-d group

Ionization of an Atom

- Atom is a bound state of a nucleus and electrons.
- They are bounded by Coulomb's potential energy, electromagnetic (EM) interaction,

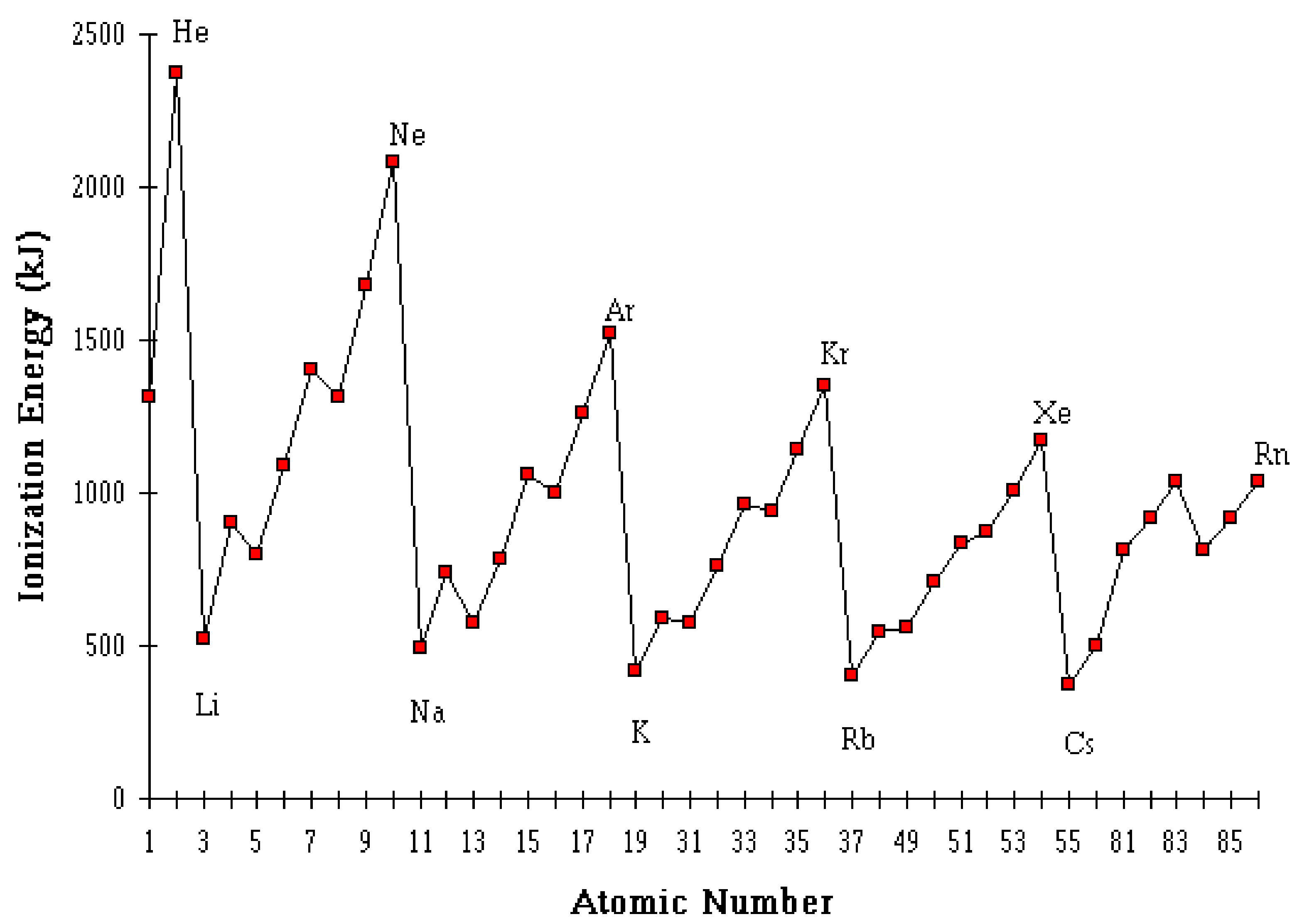
$$V(r) = ((+Z)\ e)\ (-e)\ /r$$

- Can see a free electron via ionization

$$A(\mathrm{g}) \rightarrow A^{+}(\mathrm{g}) + e^{-}(\mathrm{g})$$

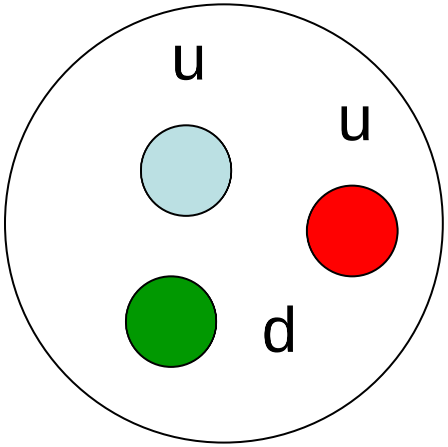
- Ionization energy is finite.

Ionization Energy



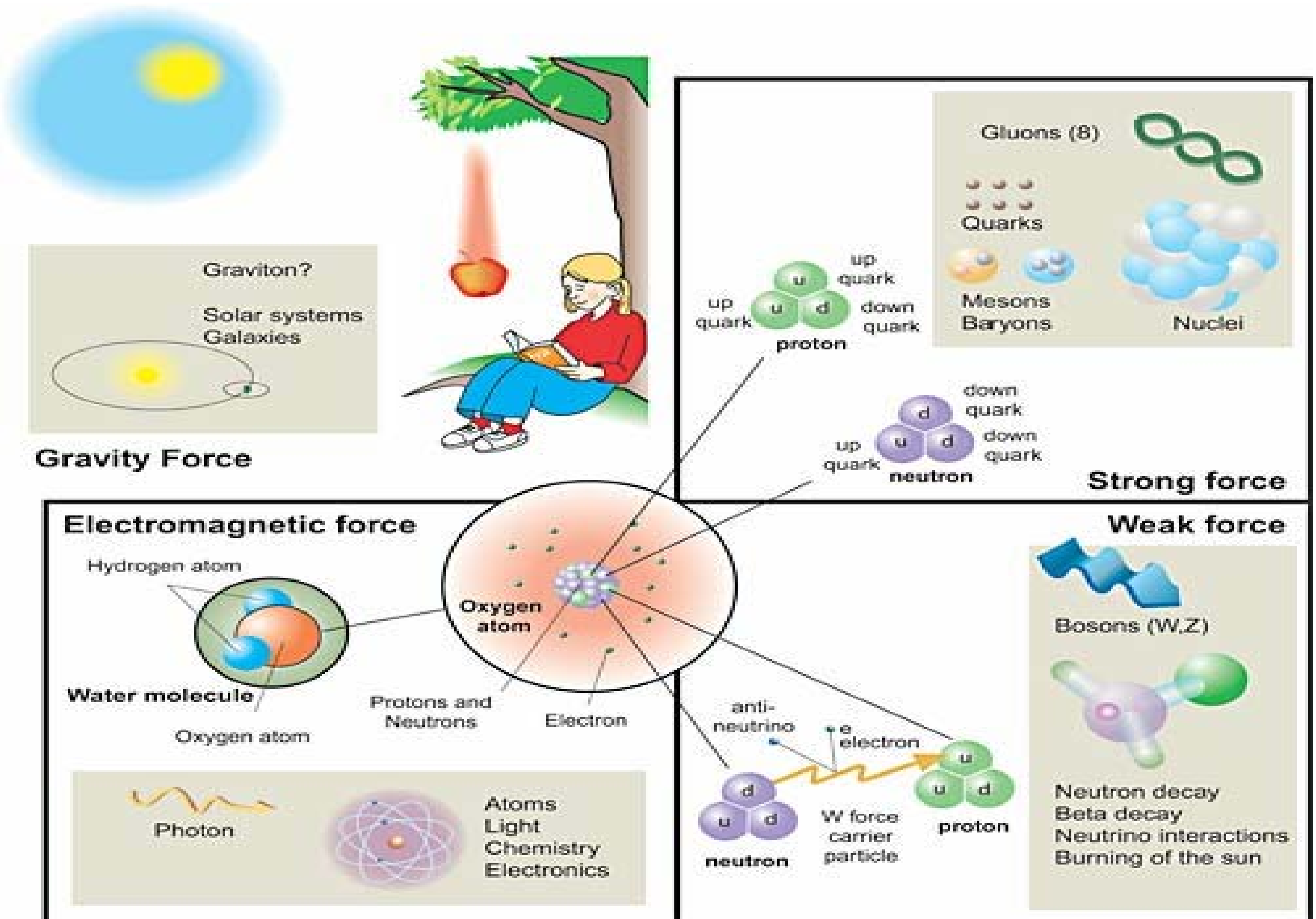
Confinement of Quarks

- Hadron is a bound state of quarks, such as pion, proton, neutron,…
- They are bounded by strong interaction, color potential energy.
- Never see free quarks, no matter how much energy is supplied.
- Why is the confinement?



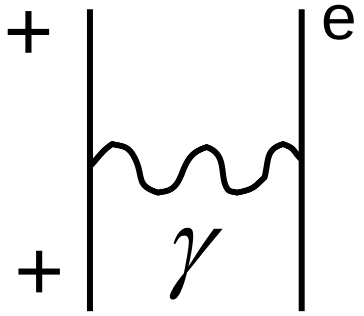
Strong Interaction

4 fundamental interactions



Electric Charges & Photons

- EM interaction between electric charges through exchanging photons.
- Electron carries an electric charge, but a photon does not.
- No EM interaction between photons.
- All electric charges add into electric neutrality.

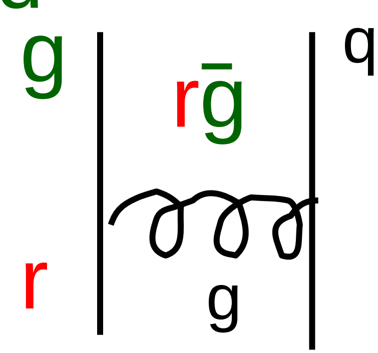


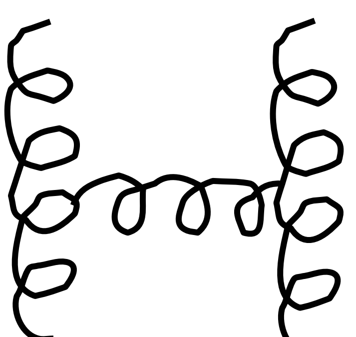
Gauge Field Theories

- Describe interactions in the view point of group theory (Yang, Mills 1954)
- Symmetry dictates interaction!
- EM (QED)   weak   strong (QCD)
- U(1)   SU(2)   SU(3)
- It was a math model at that time.
- Effect of gluon emission → (3X3 matrix) (red blue green)

Color Charges & Gluons

- Strong interaction between color charges through exchanging gluons.
- Both quark and gluon carry color charges.
- Strong interaction between gluons.
- Electric charges: positive and negative; color charges: red, blue, green
- All color charges add into color neutrality.



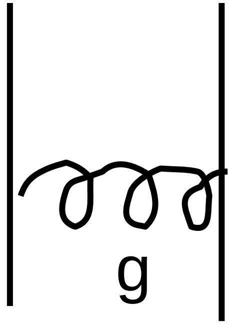


Non-abelian Gauge

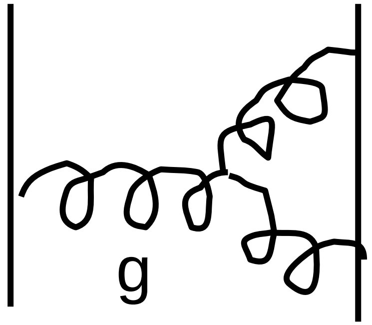
- EM is dictated by abelian U(1) gauge symmetry under the local transformation $\psi(x) \to \exp(i\alpha(x))\psi(x)$, $A_\mu(x) \to A_\mu(x) - \partial_\mu \alpha(x)$.
- Field tensor (electric and magnetic fields) $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.
- Strong interaction is dictated by SU(3) symmetry under $\psi(x) \to \exp(iT^a \alpha^a(x))\psi(x)$
- T^a is a color 3X3 matrix (a=1,…8).
- Field tensor $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$.
- f^{abc}: structure constants of SU(3).

Nonlinearity of QCD

- Gluon-gluon interaction corresponds to nonlinearity of QCD.
- Field strength between two quarks:



linear



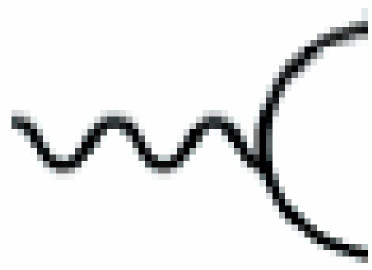
nonlinear

Asymptotic Freedom

Gross, Politzer, Wilczek

Nobel prize 2004

Vaccum $\neq$ empty



$$\Delta t \Delta E \sim h$$

Violate energy conservation $\Delta E \neq 0$

Impossible in classical mechanics $h = 0$

Allowed in quantum mechanics

As long as electrons exist in

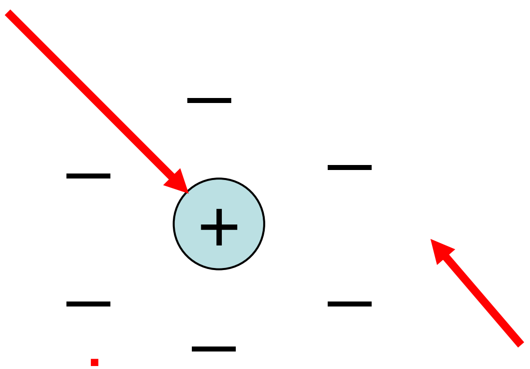
A sufficiently short time. $\Delta t \to 0$

Vacuum Polarization

Electron and positron pop out from the vacuum

Short distance
(high energy)

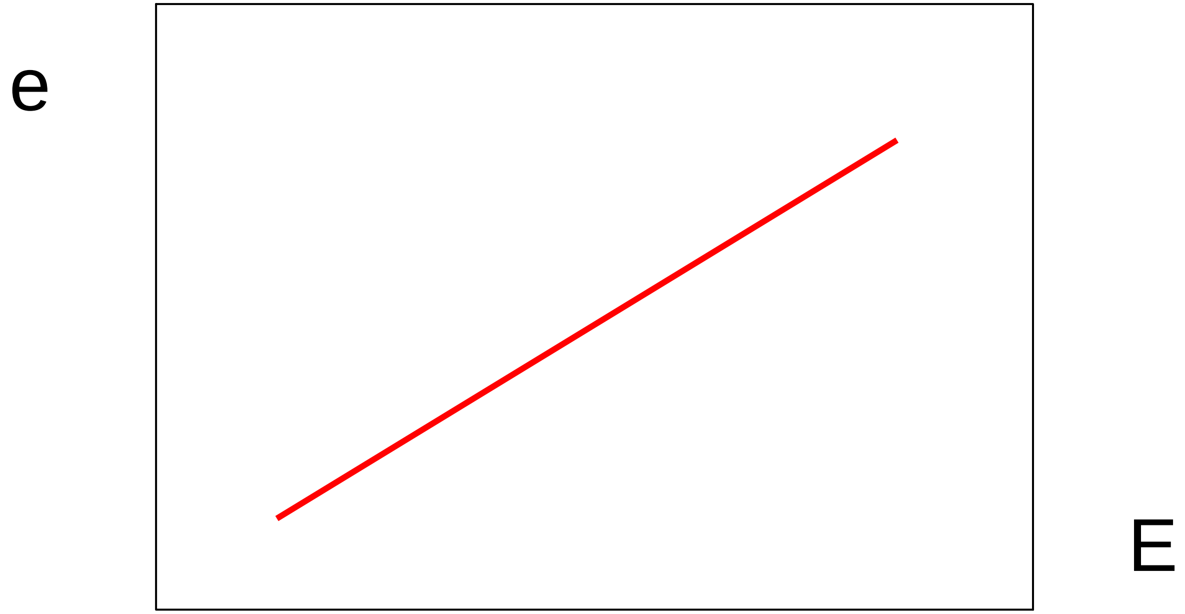
More positive
charge



Measured e varies
with energies

Long distnace
(low energy)
less positive
charge

EM interaction ⇨ screening effect



Precision measurement of hydrogen atom's energy levels has confirmed this effect, Lamb shift (Nobel prize,1955)

Anti-screening of QCD

Vacuum ≠ empty,
full of gluons

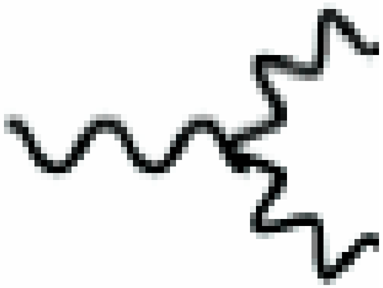
quark

anti-quark

Screening

Gluon carries color

gluon

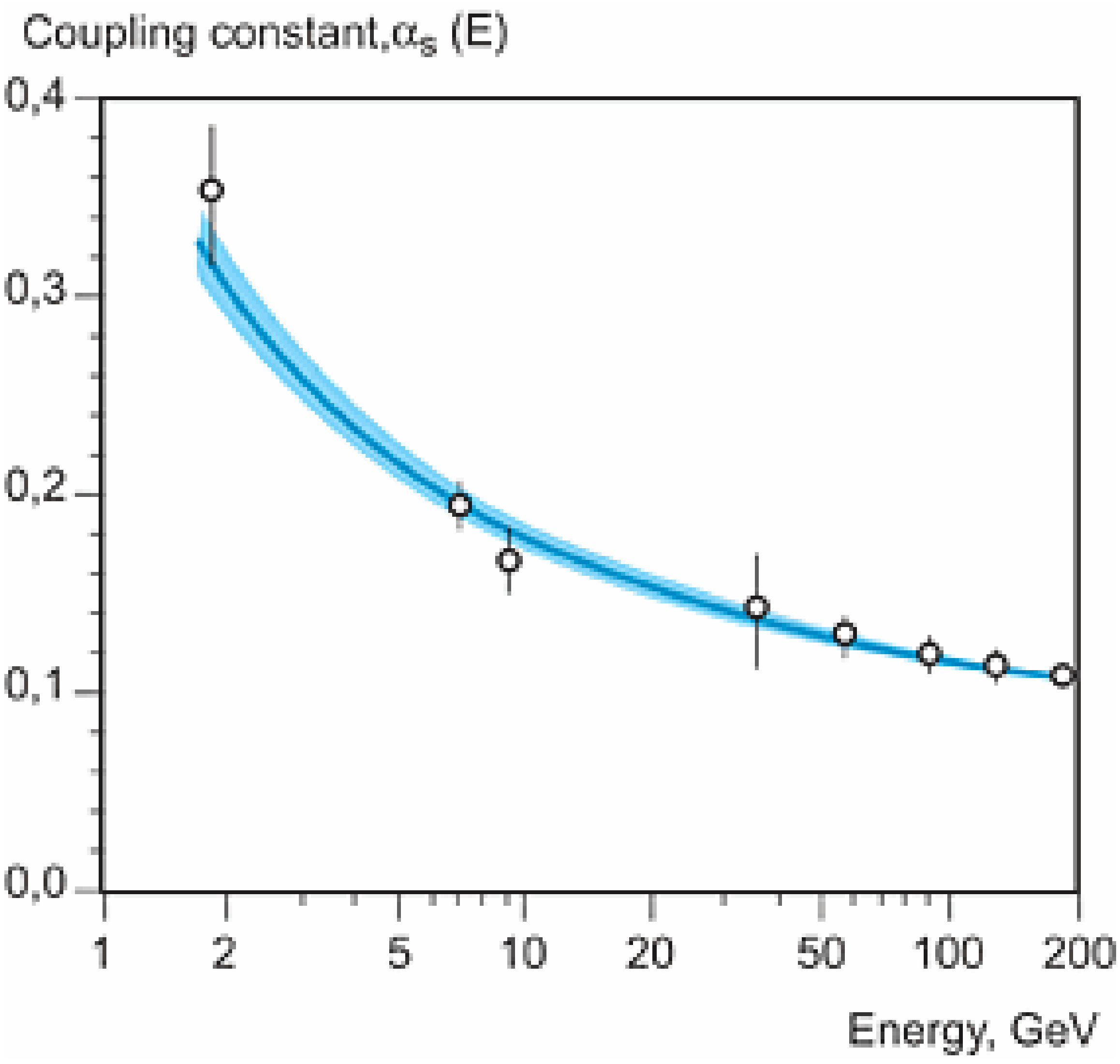


gluon

gluon

Anti-screening

Anti-screening > screening



Coupling decreases (freedom)

Opposite to EM

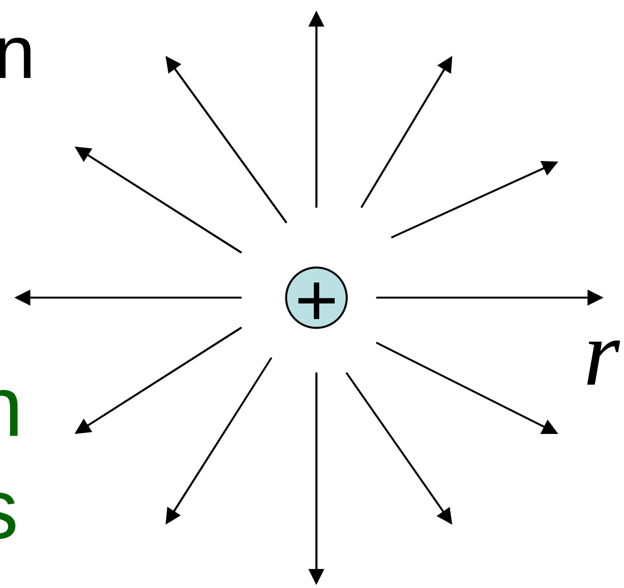
High energy (asymototic)

Confinement

Next Nobel prize in QCD

Coulomb's Law

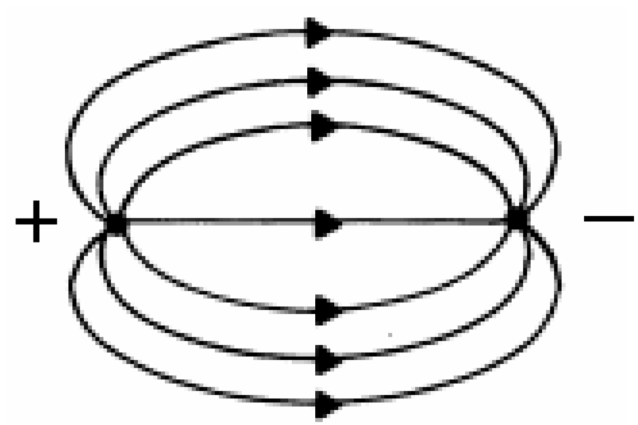
photon



gravity, EM force $\propto \frac{1}{r^2}$

potential $\propto \frac{1}{r}$

Interaction decreases with r.

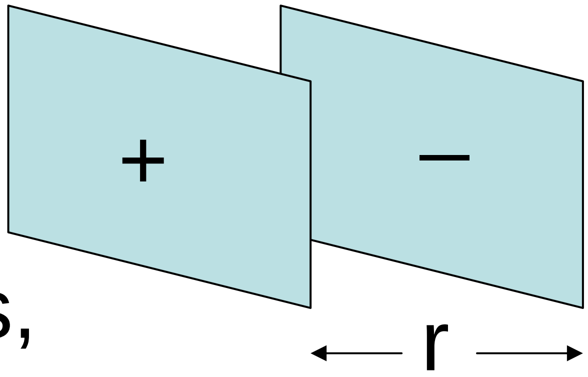


can separate the charge pair.

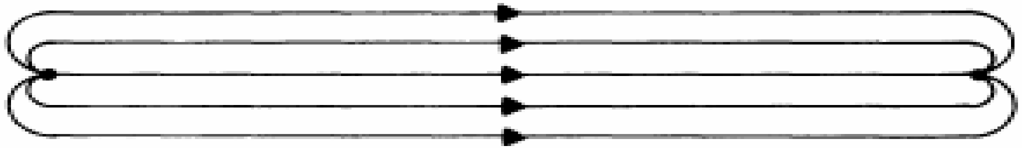
Flux Tube

- To produce a strong potential, consider 1-dim QED
- E=constant, $V \propto r$
- Field lines are parallel
- To separate the two plates, infinite energy is needed

  $\Rightarrow$ confinement



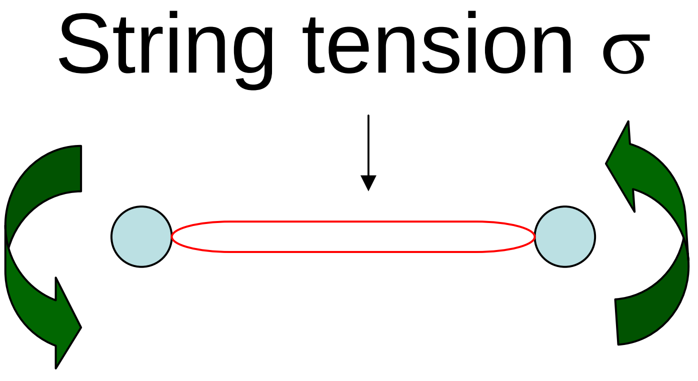
- Conjecture: field lines between a pair of quarks are deformed into a tube.



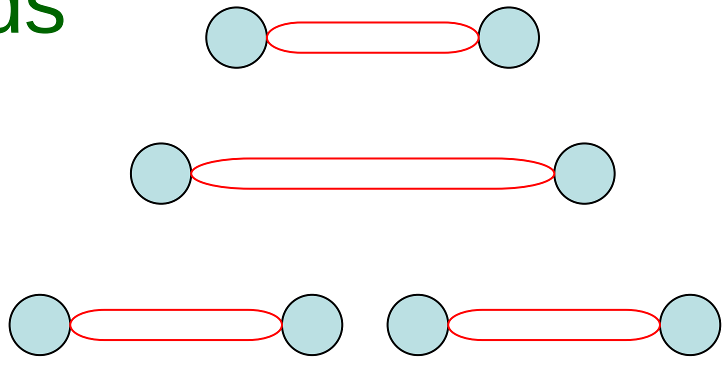
String Model

- Regge trajectory
- $J = E^2/2\pi\sigma$

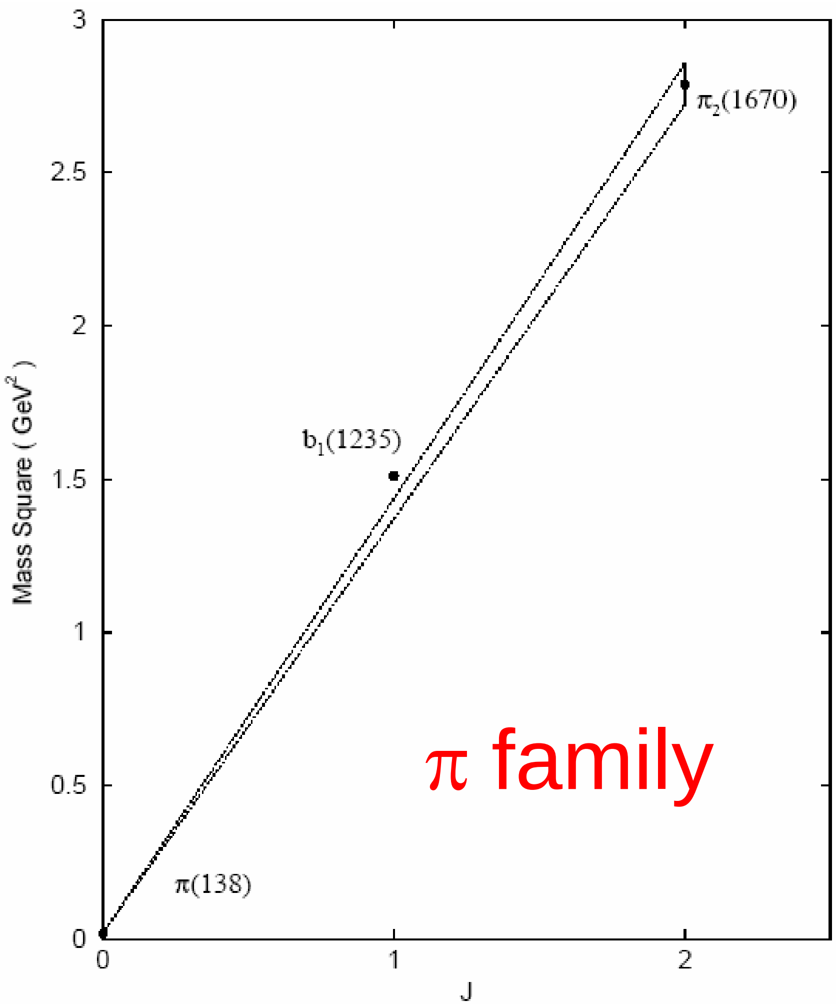
spin, mass

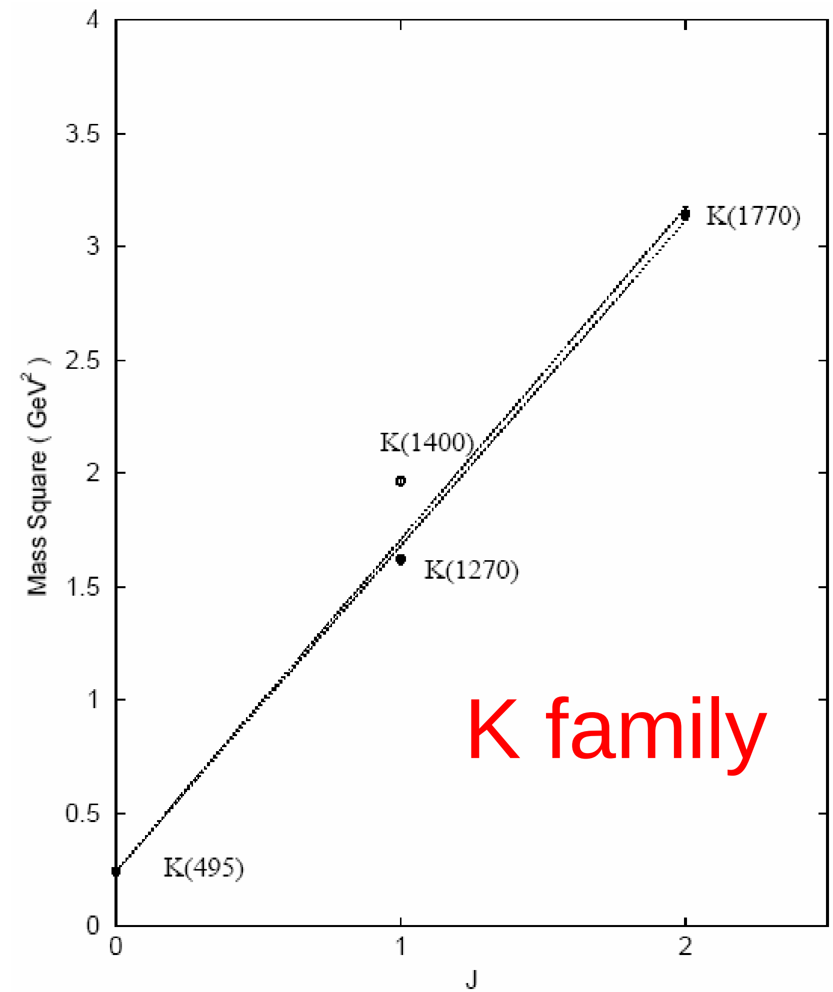


- Multiplicity
- As dosed energy exceeds the mass of quark pair, string breaks, and new pair appears

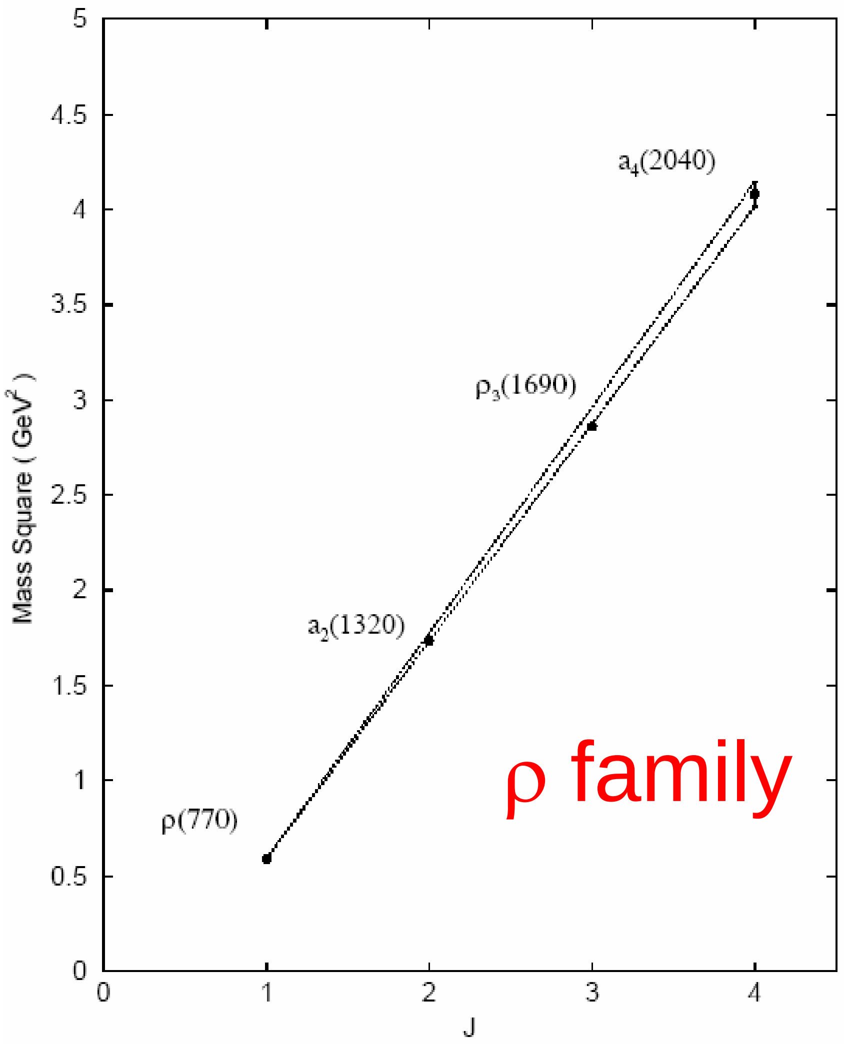


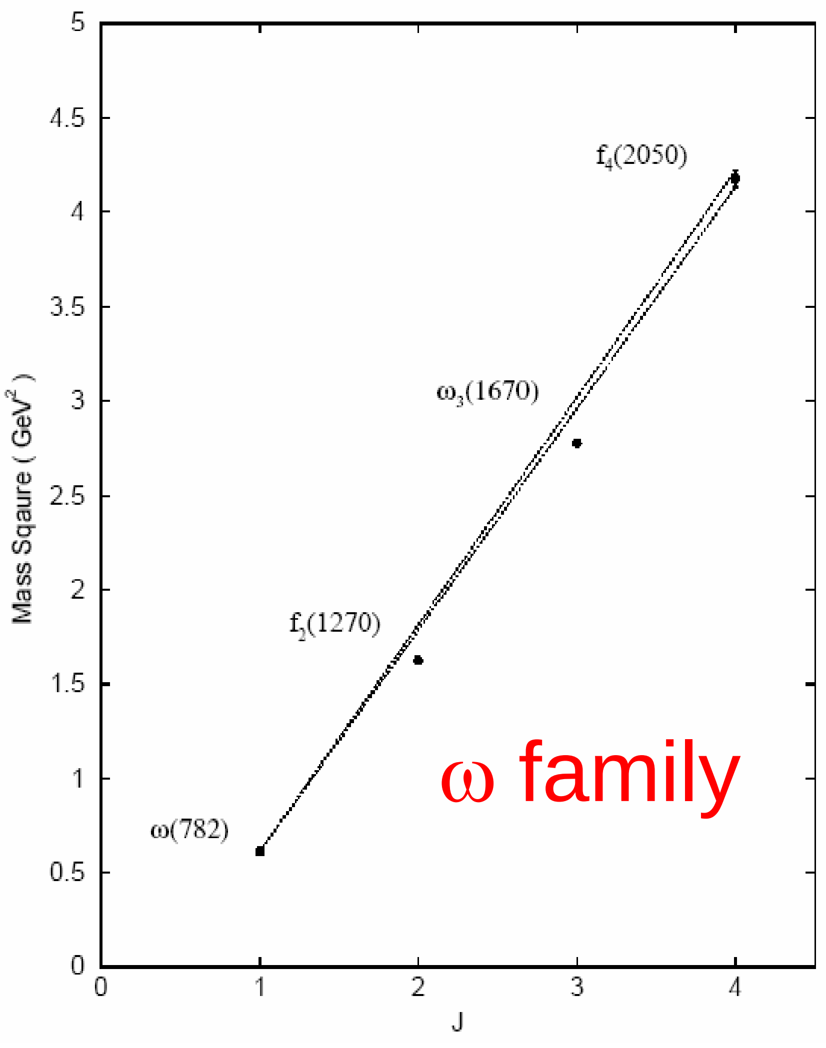
Regge Trajectory



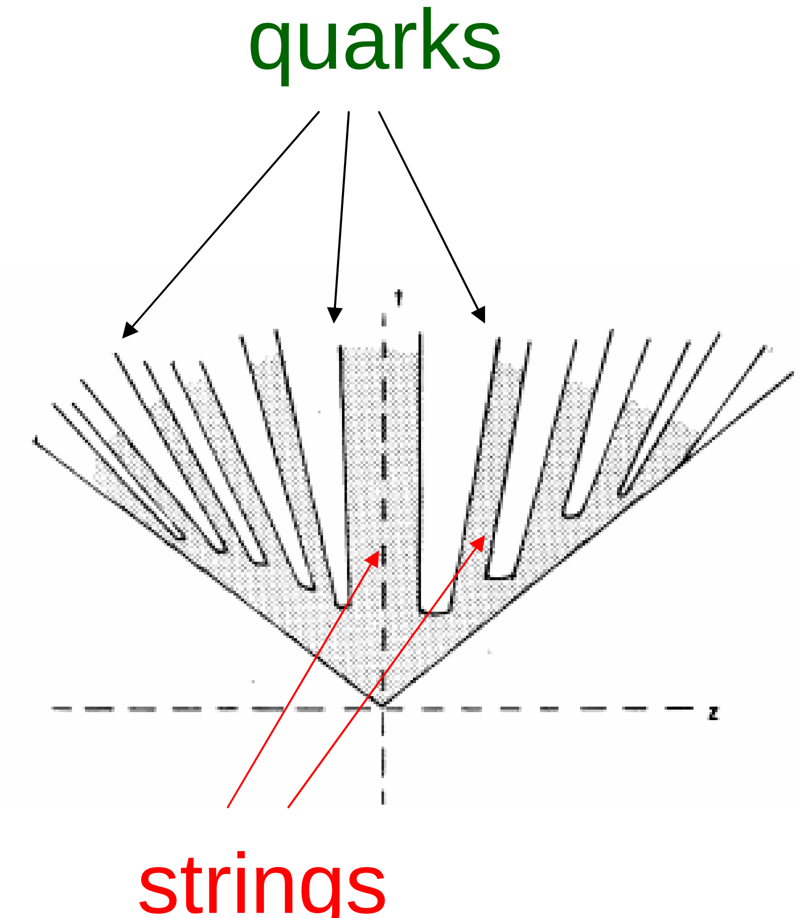


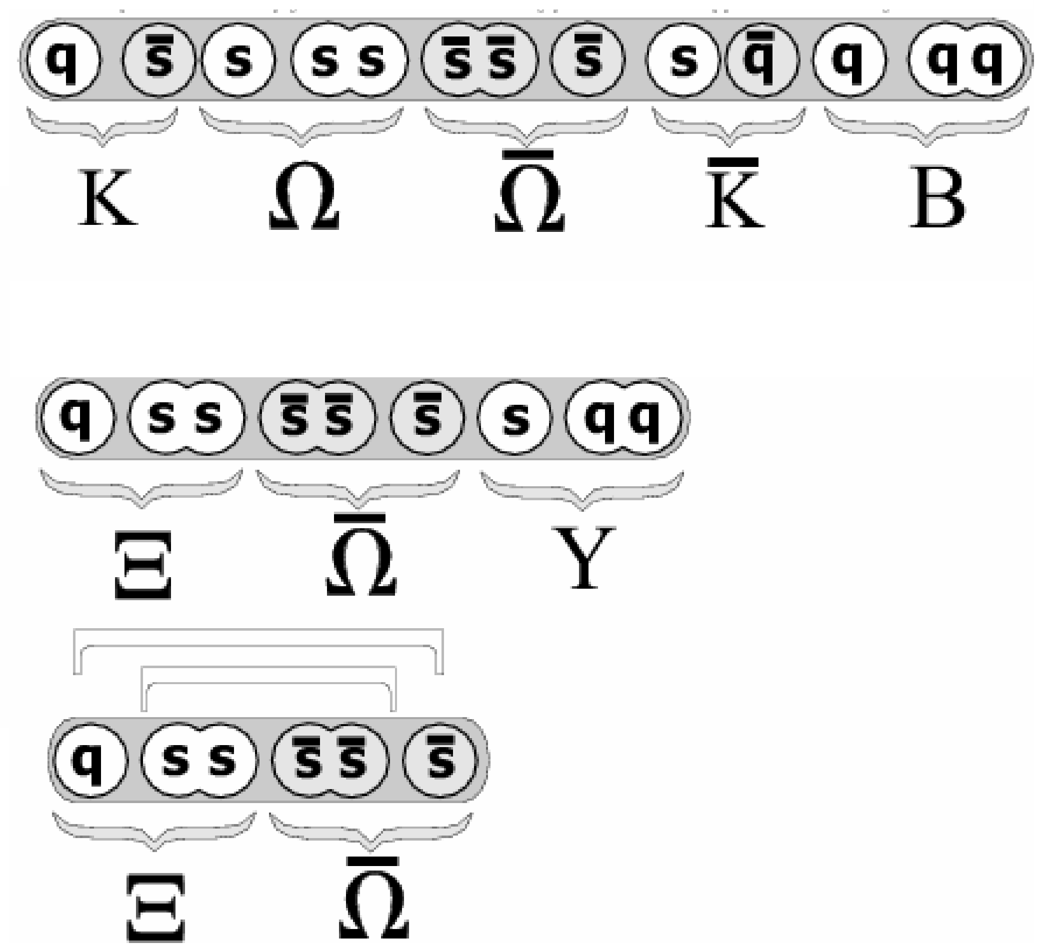
Regge Trajectory





Multiplicity dn (No. particles)/dy (rapidity)

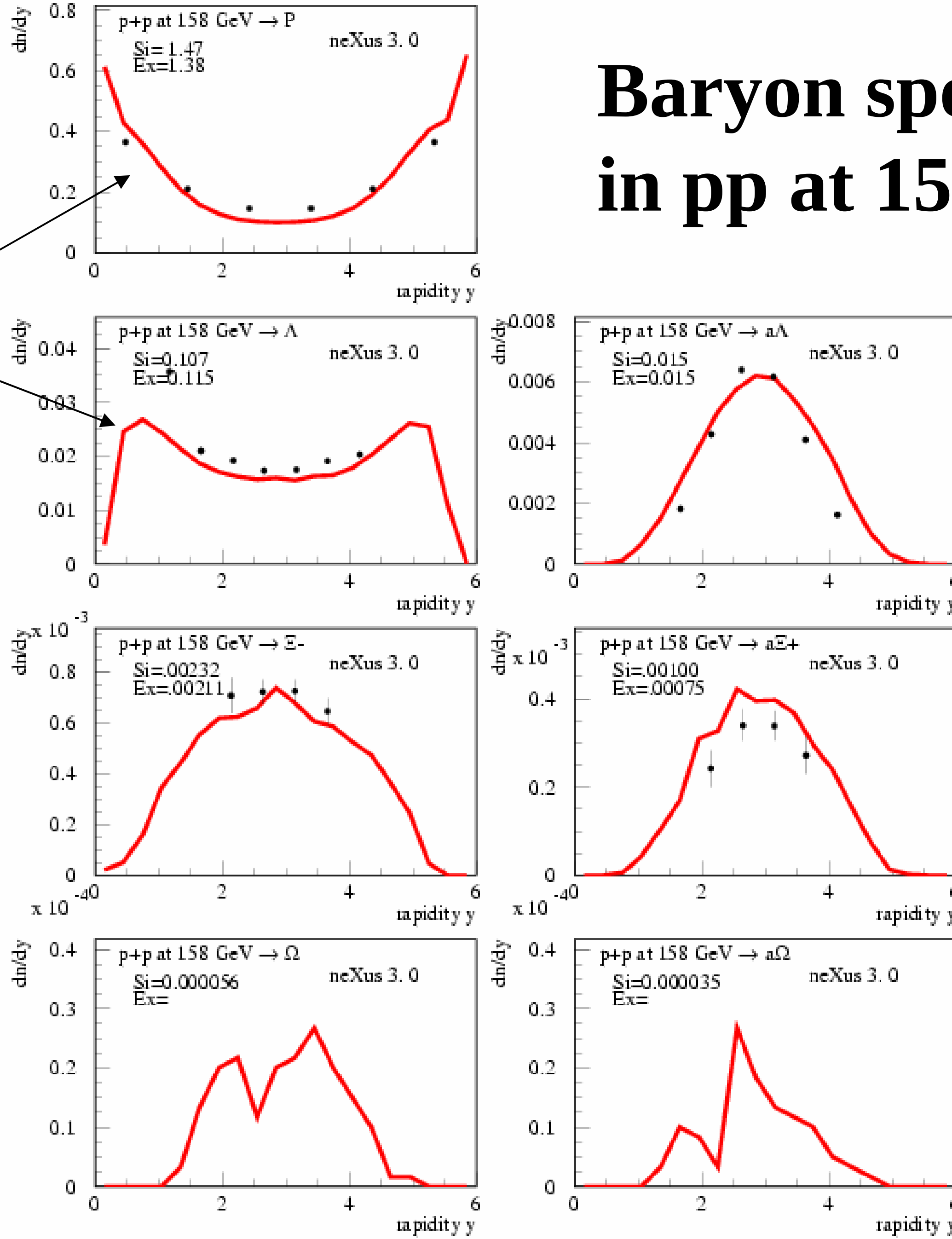




Baryon spectra in pp at 158 GeV

Leading particles

(mainly from remnants)



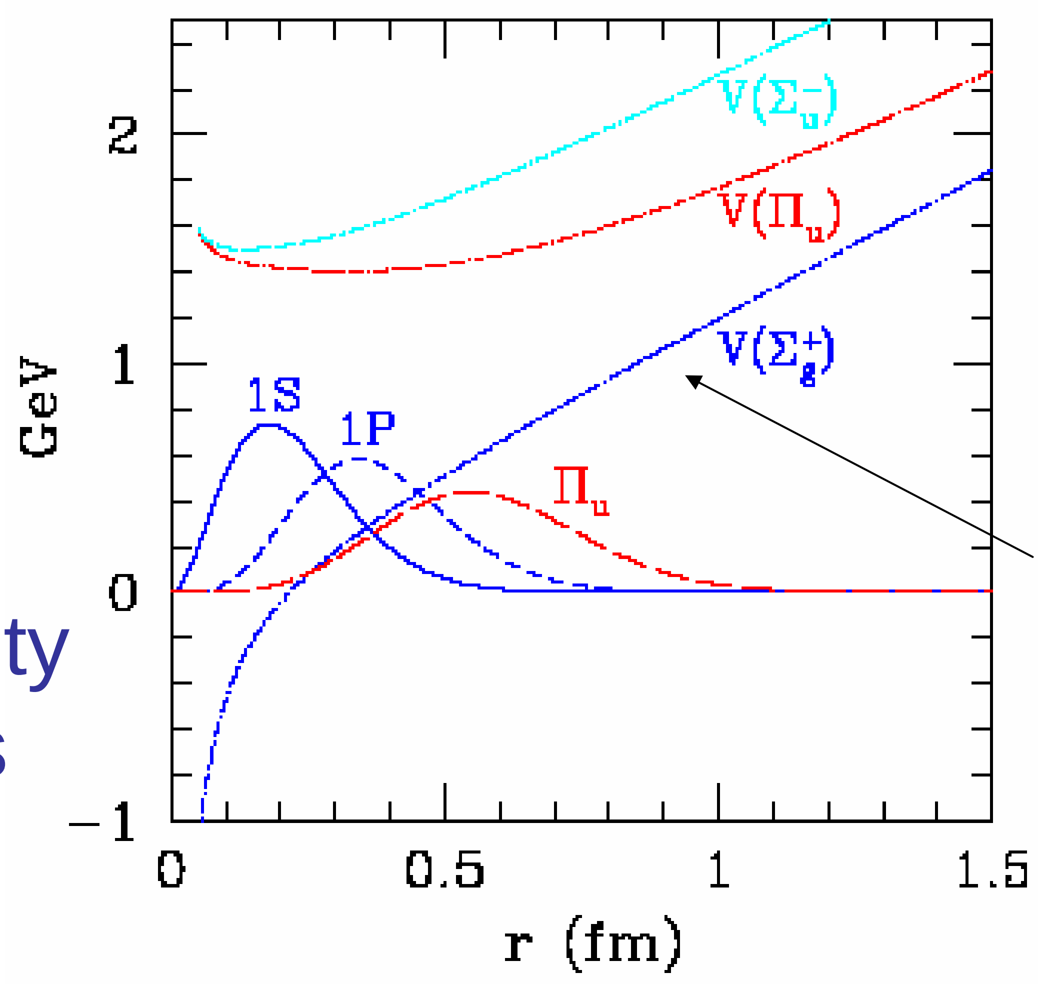
Gribov-Regge Theory: (FM Liu et al)

Data: NA49

Lattice QCD (Juge et al.)

different gluonic excited states

Radial Probability densities



Fit to $V_0+e/r+\kappa\ r$

Static quark potentials

Gluon propagator

- Gluon propagator $D_{\mu\nu}^{ab}(r)=\langle A^a_\mu(r)A^b_\nu(0)\rangle$ represents the amplitude for a gluon propagating from 0 to r.
- $D_{\mu\nu}^{ab}(r)$ gives the distribution of a gluon in space for a non-abelian gauge theory.
- $D_{00}(r)=V(r)$, the Coulomb potential.
- $D_{00}(k)\propto 1/k^2$ in an abelian theory, Fourier transform gives $D_{00}(r)\propto 1/r$
- $D_{ij}(k)$ describes a physical gluon (transverse polarizations) in Coulomb gauge $\nabla\cdot A^a=0$ $(k\cdot A^a=0)$.

Infrared Behaviors

$D_{00}(k) \propto 1/k^4$

$D_{00}(r) \propto r$

long-range

Coulomb potential

$D_{ij}(k) \propto k^{0.5}$

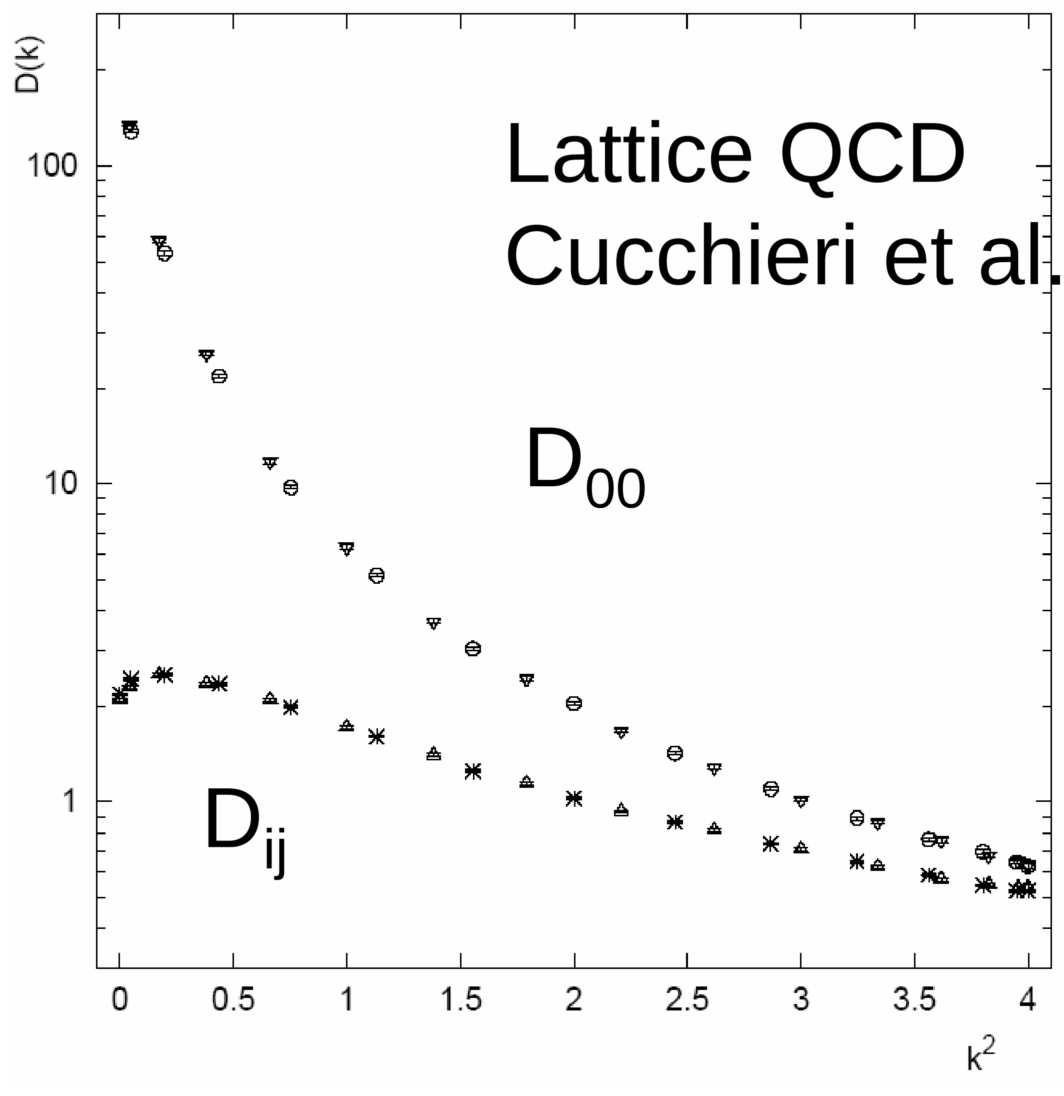
$D_{ij}(r) \propto r^{-3.5}$

suppression of

physical gluon

Consistent with

flux tube picture



The Mechanism?

- Analytical studies always need introduction of free parameters, like condensate (Szczepaniak).
- It is not a full understanding.
- Large coupling constant is not responsible for the linear potential.
- It still leads to the Coulomb's potential 1/r.
- The mechanism should be the nonlinearity of QCD.

Gribov’s Confinement

1930-1997

Supercritical States

- A supercrtitical nucleus with Z>137 (large EM coupling) makes vacuum unstable.
- Electron (negative energy) and positron (positive energy) are created.
- Electron falls into the nucleus to form a bound state, reducing Z into Z-1.

$$N(Z) \rightarrow N(Z-1)+e^{+}$$

- The process repeats until vacuum is stable.

QED Confinement

- The bound state has a lower energy due to absorption of the negative-energy e^-.
- Assume that the bound state drops into the negative-energy spectrum of vacuum.
- The negative-energy spectrum is filled up.
- It is impossible to separate the e^- from the nucleus due to Pauli exclusion principle.
- This is the Gribov's picture of confinement.

QCD Confinement?

- Apply the same picture to QCD. The coupling reaches the critical value at low energy.
- A bound state is formed: q $\rightarrow$ M(qq) + q
- Really work? There seems no difference between QED and QCD.
- The naïve idea indeed fails.
- A new term must be added into Gribov's equation by hand….

Conclusion

- QCD is dictated by the non-abelian gauge group SU(3).
- QCD is nonlinear, ie., a gluon interacts with a gluon. A gluon carries colors.
- Nonlinearity gives the anti-screening, leading to asymptotic freedom.
- Nonlinearity deforms the field lines into a tube, leading to the string model, the linear potential, and the confinement.
- Full understanding of confinement is not yet available.

致謝

感謝清華大學物理系的邀請