NOBLE ACTION:

QUANTUM CHROMODYNAMICS

Nobel Prize in Physics 2004: Asymptotic Freedom

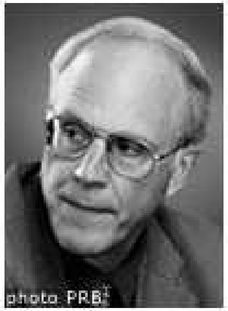
D.J.Gross, H.D.Politzer, F.Wilczek

Review of DESY's physics connection with this event
in theoretical and experimental context

⟨ Report to DPG : S.Bethke and P.M.Zerwas ⟩

The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"



David J. Gross

1/3 of the prize

USA

Kavli Institute for Theoretical Physics, University of California Santa Barbara, CA, USA

b. 1941

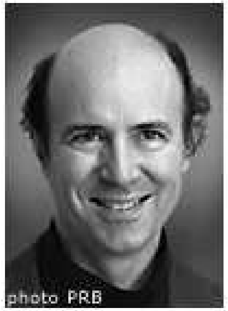
H. David Politzer

1/3 of the prize

USA

California Institute of Technology Pasadena, CA, USA

b. 1949



Frank Wilczek

1/3 of the prize

USA

Massachusetts Institute of Technology (MIT) Cambridge, MA, USA

b. 1951

OUTLINE:

1. Path to Quantum Chromodynamics
2. Asymptotic Freedom
3. Key Experiments
4. Infrared Slavery
5. Future
6. Summary

1. PATH TO QCD

Strong interaction: Force binding protons and neutrons in nuclei

$\Downarrow$

Yukawa potential $g^2 \exp[-\mu R]/R$ generated by exchange of light meson $\mu_\pi \sim 200$ MeV

$\Downarrow$

explosion of number of strongly interacting in 40's until 60's to more than one hundred "elementary particles":

baryons $P, N, \Delta, ..$ / mesons $\pi, \rho, ..$

S-Matrix Theory

- Microcausality : analytic connection of low/high energy scattering amplitudes: "s/t channel resonances"
- Unitarity : non-linear connections and absolute normalization

$\Rightarrow$ mutual connection of any particle with any other particle:

Any theory of strong interactions must necessarily incorporate these two fundamental principles – but they are not sufficient to construct the theory: democratic $\Rightarrow$ hierarchical principle

QUARK PICTURE

Gell-Mann

Zweig

After discovery of strange particles $K, ..\Lambda, ..$, isospin group SU(2) had to be extended to SU(3):

$$\text{baryons } B = 1, 8, 10 \;:\; 3 \times 3 \times 3 = 1 + 8 + 8 + 10$$

$$\text{mesons } M = 1, 8 \;:\; 3 \times \bar{3} = 1 + 8$$

Hypothesis : all hadrons are composed of constituents $[3, \bar{3}]$

quarks: $B = qqq$

$M = \bar{q}q \quad : \; S = 1/2$ and $Q = -1/3, +2/3$

Idea met with skepticism and strong attacks:

– Symmetric orbital S-wave and spin-wave baryonic ground-state not compatible with Pauli exclusion principle

– π^0 lifetime predicted too long by a factor close to 9

– fractionally charged particles not seen in any search experiment

All these problems could be solved by introducing

QUANTUM CHROMODYNAMICS

peu-á-peu over 30 years ...

COLOR

– $q \to [q_R, q_G, q_B]$: 3 distinct fermions build up symmetric baryonic ground-state

all hadrons, baryons and mesons: "white"
[confinement ad-hoc]

– $A[\pi^0 \to \bar{q}q \to \gamma\gamma]$: $\times 3$ for 3 colors
$\tau(\pi^0 \to \gamma\gamma)$ shortened by factor $3^2 = 9$

– Predictions : $R = 2$; lifetimes W, Z; Drell-Yan cross sections; and many other observables

CHROMO-STATICS $\Rightarrow$ CHROMO-DYNAMICS

Nambu: color charges may serve as sources for gluonic force fields – responsible for binding of quarks in hadrons

Fritzsch, Gell-Mann: SU(3) gauge theory formulated for canonical colors

[applied for abstracting relations between hadron currents $\sim$ solutions of QCD]

$$\Downarrow$$

QUANTUM CHROMODYNAMICS:

$SU(3)_c$ gauge field theory of the strong interaction with

– quarks, coming in 3 colors, as matter constituents

– gluons, with $3^2 - 1 = 8$ colors, as quanta of the gauge fields

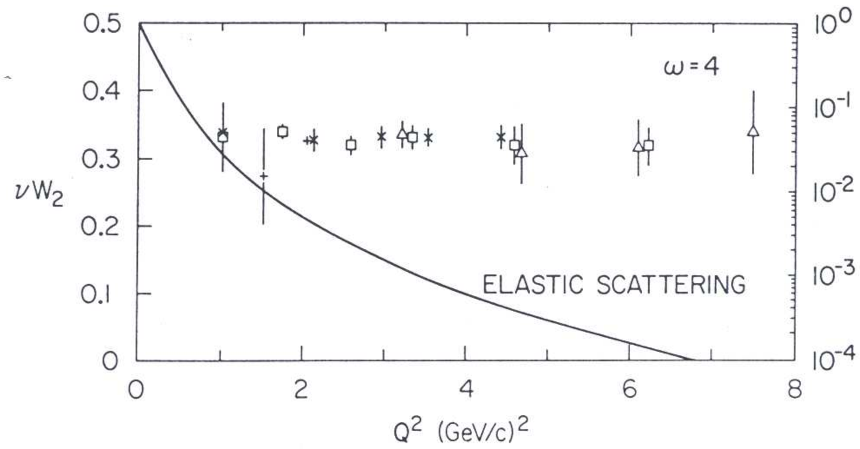
3rd component of SU(3)×SU(2)×U(1) Standard Model

$$\mathcal{L} = \bar{q}[i\partial - m - g_s G]q - \frac{1}{2} Sp\, \hat{G}^2$$

Formulating QCD as the microscopic theory of the strong interaction is one of the most important steps in the physics of the 20th century; QCD is integral part of the Standard Model: 10^{-30} cm $\sim 10^{+16}$ GeV

2. ASYMPTOTIC FREEDOM

SLAC/MIT experiments discovered Bjorken scaling in deep-inelastic eP scattering, predicted by current algebraic methods, i.e. in S-matrix theory



⇒ general conclusion: "QFT must [categorically] be dismissed"

Symanzik : need microscopic QFT in which coupling decreases with increasing energy:

"β function must be negative"

Symanzik's β function: $\partial\,\alpha_s(Q)/\partial\log Q^2 = \beta[\alpha_s]$

if β negative: $\alpha_s \to 0$ for Q large

free theory $\Rightarrow$ scaling

catalogue : Symanzik : $\lambda\phi^4$: β negative if λ negative $\leftarrow$

ruled out as vacuum instable

... : scalar, U(1) vector theories,..

β always positive

! class not studied for technical reasons:

nonabelian gauge field theories

1973: β function discovered to be negative in QCD

Gross, Politzer, Wilczek

QCD: theory of strong interactions incorporating Bj scaling

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

1973: β function discovered to be negative in QCD

Gross, Politzer, Wilczek

QCD: theory of strong interactions incorporating Bj scaling

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

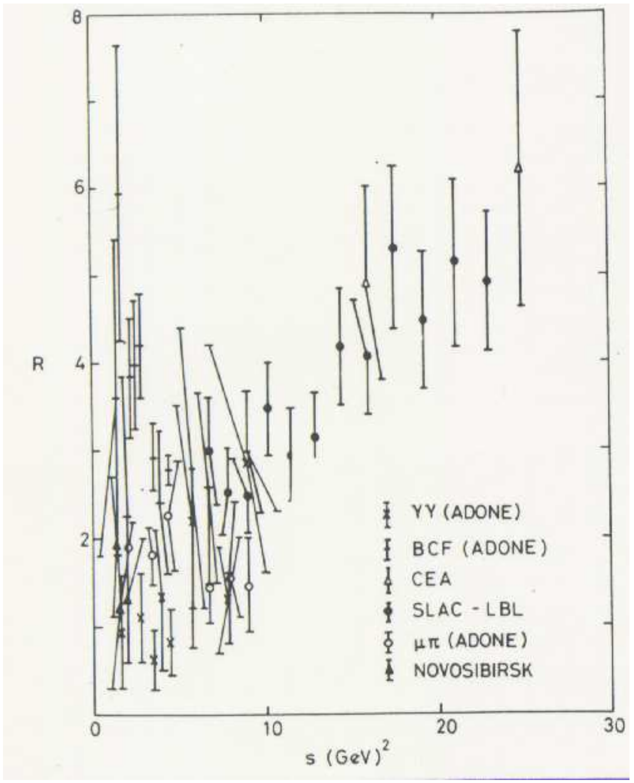
1973: β function discovered to be negative in QCD

Gross, Politzer, Wilczek

QCD: theory of strong interactions incorporating Bj scaling

Comment : 't Hooft at the '72 Marseille Conference : β in non-abelian theories negative

Comment : At the time of the publication $\beta_{QCD} < 0$, scaling was believed dead by many theorists and experimentalists as a result of strong indications at CEA and SPEAR that $\sigma(e^+e^- \to hads) \neq const/s$



Symanzik's β-function in QCD :

$$\beta[\alpha_s] = -\beta_0 \frac{\alpha_s^2}{2\pi} - \beta_1 \frac{\alpha_s^3}{4\pi^2} - \beta_2 \frac{\alpha_s^4}{64\pi^3} - \dots$$

$$\beta_0 = 11 - \tfrac{2}{3} n_f \quad \rightarrow \quad -\beta_0 < 0$$ Gross, Politzer, Wilczek

$$\beta_1 = 51 - \tfrac{19}{3} n_f$$ Caswell, Jones

$$\beta_2 = 2857 - \tfrac{5033}{9} n_f + \tfrac{325}{27} n_f^2$$ Tarasov, Vladimirov, Zharkov

$$\beta_3 = \dots$$ Larin, van Ritbergen, Vermaseren

QCD coupling :

$$\boxed{\alpha_s(Q) = 4\pi / [\beta_0 \log \frac{Q^2}{\Lambda^2} + \beta_1' \log\log \frac{Q^2}{\Lambda^2} + \dots]}$$

origin of asymptotic freedom : anti-screening *over* screening
for virtual $q\bar{q}/gg$ pairs in vacuum

color susceptiblity [Pauli + Landau terms] :

$$\chi = \frac{(-)^{2S}}{2\pi}[(2S)^2 - \tfrac{1}{3}] \quad < \quad 0 \quad \text{for quarks}$$

$$> \quad 0 \quad \text{for gluons} \qquad \Leftarrow$$

$$\chi = \tfrac{1}{2\pi}[11 - \tfrac{2}{3}n_f] \quad > \quad 0 \quad \text{for 3 families}$$

$\Rightarrow$ vacuum : color-paramagnetic medium $\mu > 1$
color-dielectric parameter $\epsilon = 1/\mu < 1$

$\Rightarrow$ anti-screening of charges $\Leftarrow$ Khriplovich in SU(2)

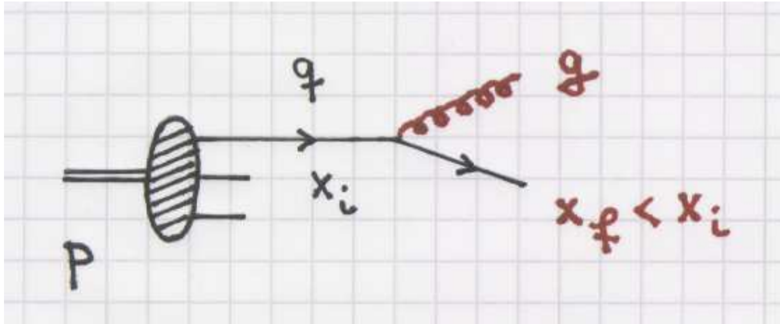
origin of AF is the gauge interaction of $S = 1$ gluons with a color probe:
color self-interaction of the gluons

3. KEY EXPERIMENTS : QCD/AF

3.1 SCALING VIOLATION IN LEPTON-NUCLEON DIS :

perturbative gluon radiation :
quarks lose momentum →

- depletion at large x
- turning point at $x \sim 0.25$
- accumulation at small x

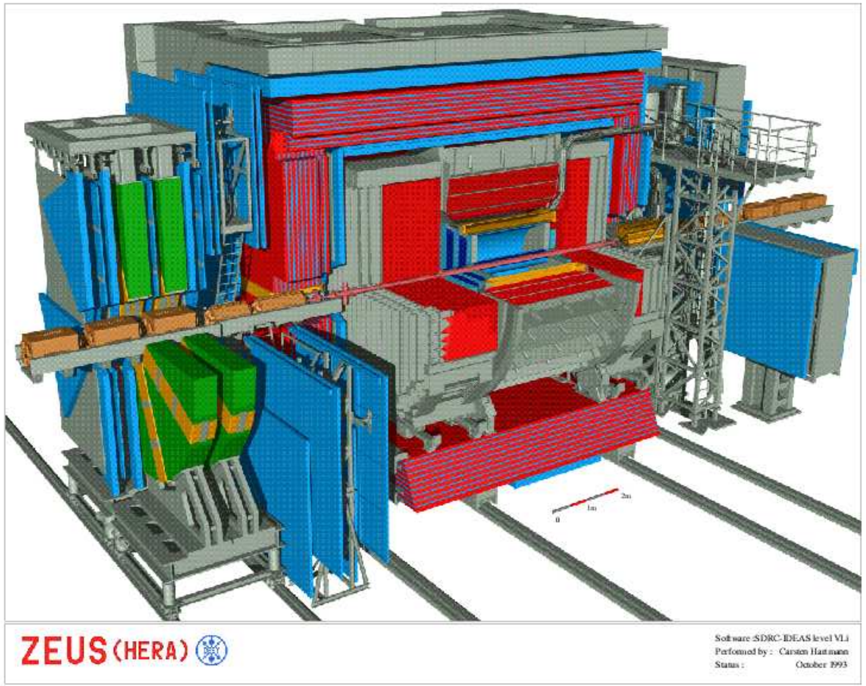


AF prediction :

$$F_2 \sim \alpha_s(Q)^d$$
$$\sim \exp[-d \log \log Q]$$

large lever arm in Q needed :

provided by FT ... HERA



3.2 SCALING VIOLATION IN LEPTON-NUCLEON DIS :

AF prediction :

$$F_2 \sim \alpha_s(Q)^d$$
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large lever arm in Q needed :

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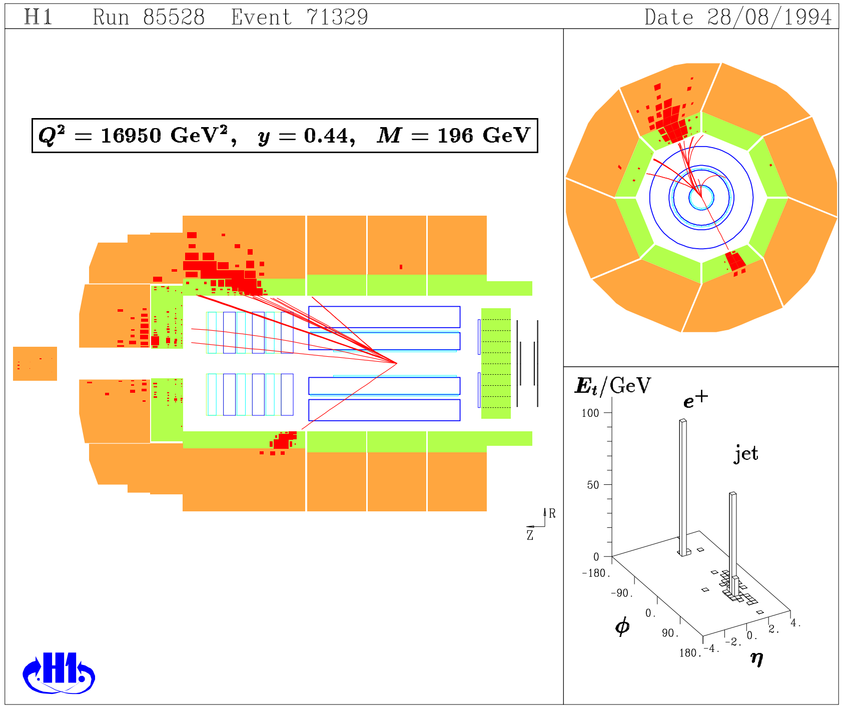

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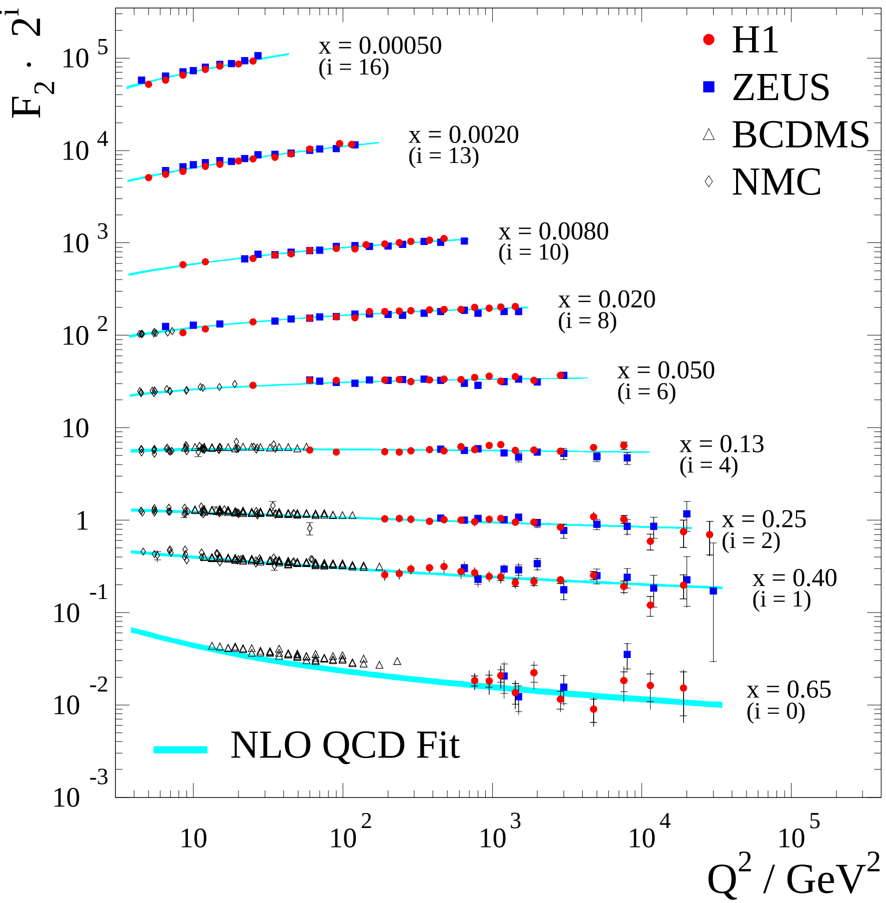
[Shekelyan ea]



AF prediction :

$$F_2 \sim \alpha_s(Q)^d$$
$$\sim \exp[-d \log \log Q]$$

large lever arm in Q needed :

provided by FT ... HERA

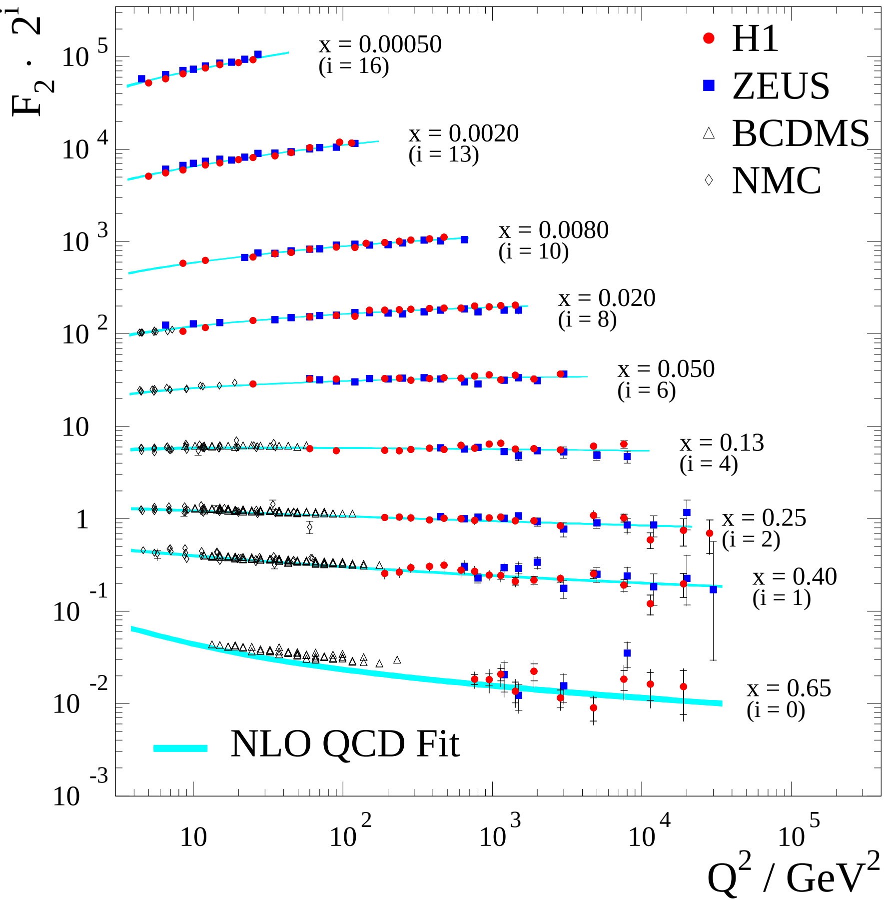
splitting functions :

$$\gamma = \gamma_0 \frac{\alpha_s}{4\pi} + \gamma_1 \frac{\alpha_s^2}{16\pi^2} + \gamma_2 \frac{\alpha_s^3}{64\pi^3} + ..$$

Gross, Wilczek, Georgi, Politzer

Altarelli ea; van Neerven ea

Moch, Vermaseren, Vogt

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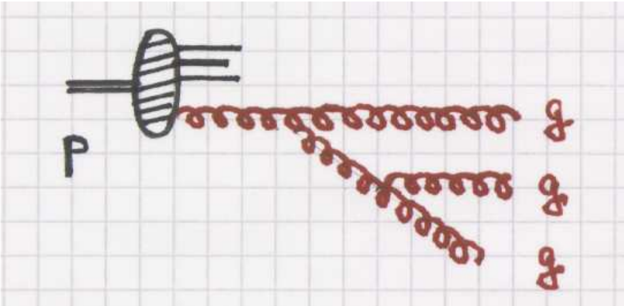
3.2′ LARGE NUMBER OF GLUONS IN PROTON

expected in gluon cascade picture [⇐ De Rujula, Glashow, Politzer, Treiman, Wilczek, Zee]



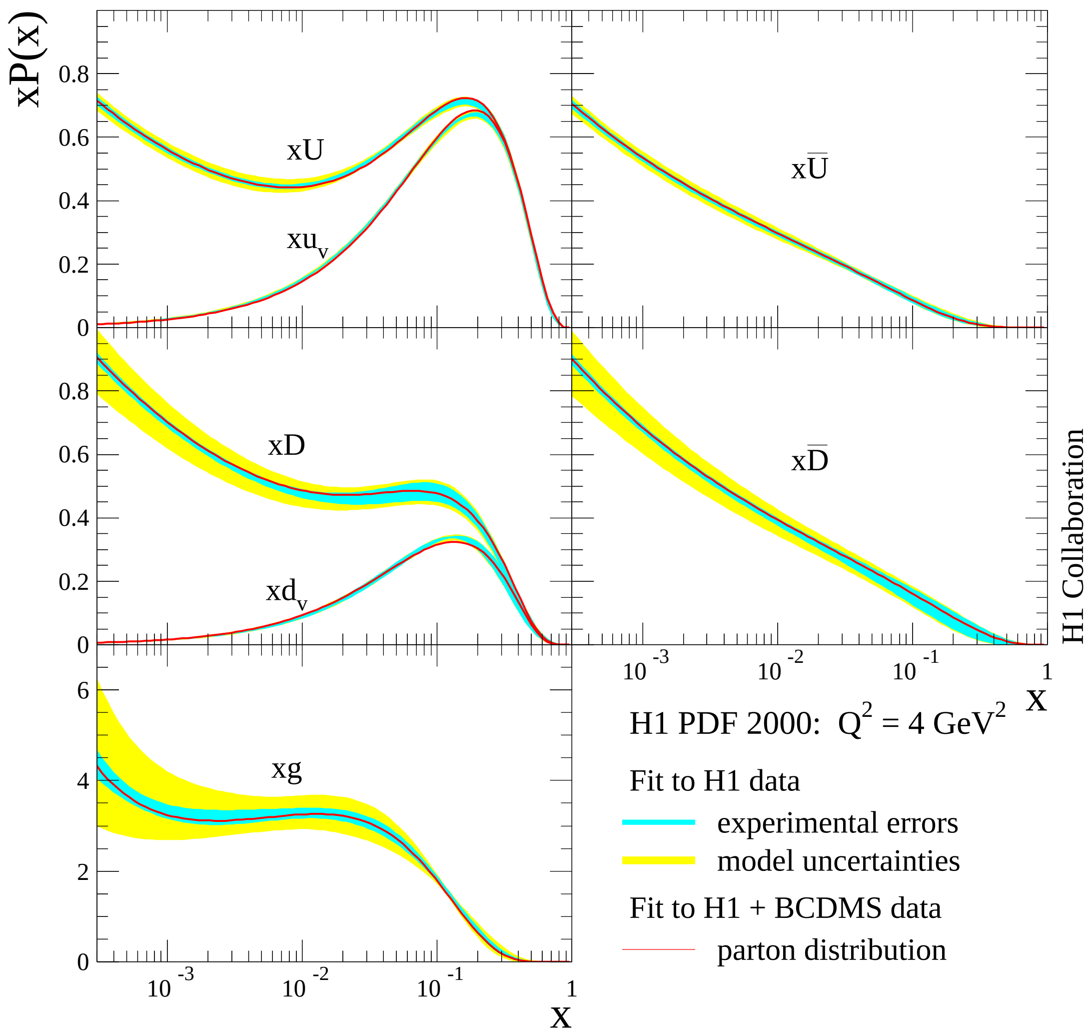
large g color charge $\rightarrow$
rapid splitting $g \rightarrow gg$:

densely populated cascade of gluons

$$\partial g(x,Q^2)/\partial \log Q^2 = \frac{\alpha_s}{2\pi} \int dz P_{gg}(z) \int dy g(y,Q^2)_{|x=zy}$$

$$xg(x,Q^2) \sim \exp\, 2\sqrt{\frac{4C_A}{\beta_0} \log\frac{1}{x} \log\log\frac{Q^2}{\Lambda^2}}$$

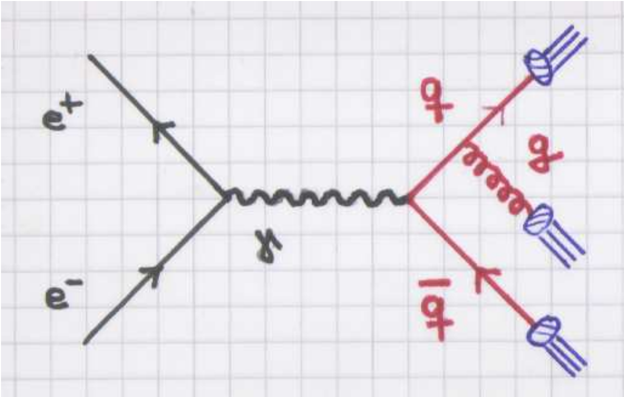
borne out by HERA



3.2 PETRA GLUON JETS

AF gauge theories: quark color charges accelerated after the production $\rightarrow$

emit color synchrotron light = gluons



$\Leftarrow$ Polyakov : original idea

Ellis, Gaillard, Ross : adjusted to QCD

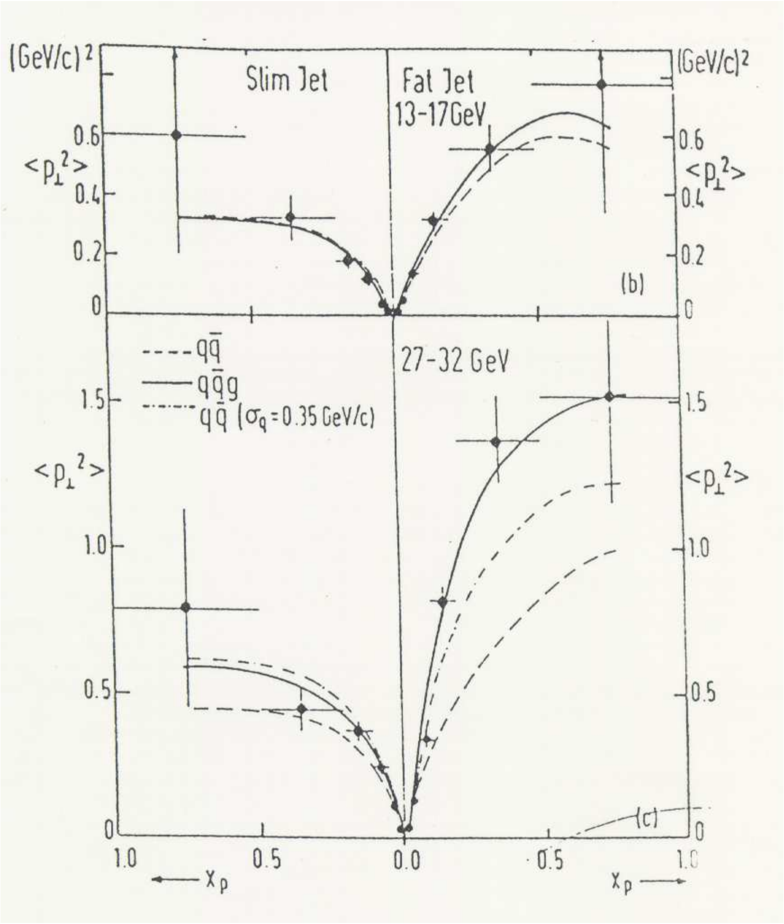
Ali, Kramer, Schierholz, Walsh & coll : theoretical basis of analyses, h.o.

Classical sequence of experimental proof :

- quark jets widen in trv.mom.

- only on one side [Pluto →]

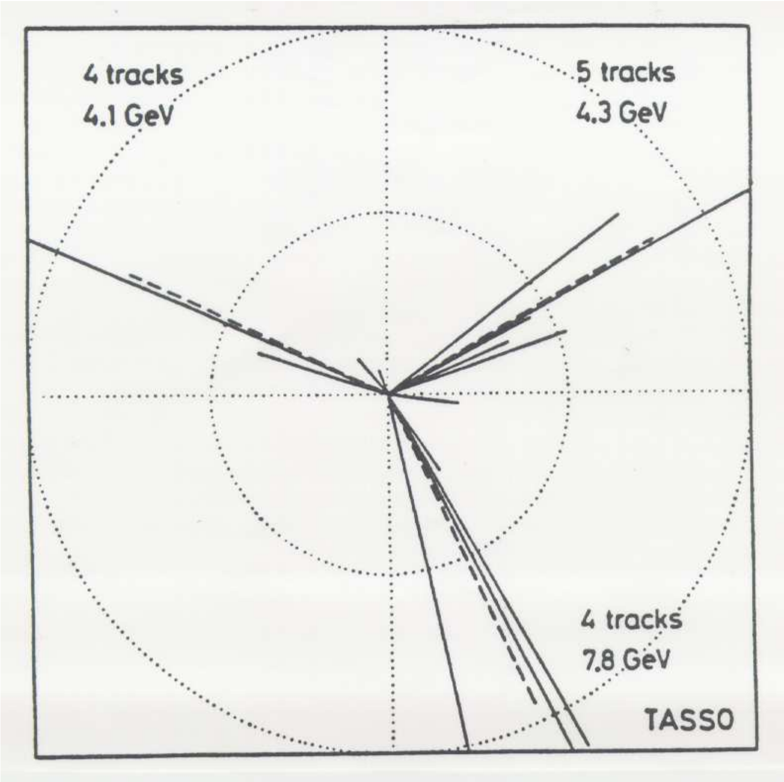
- 3-jet events appear



Classical sequence of experimental proof :

- quark jets widen
- only on one side
- 3-jet events appear :

first TASSO 3-jet event:



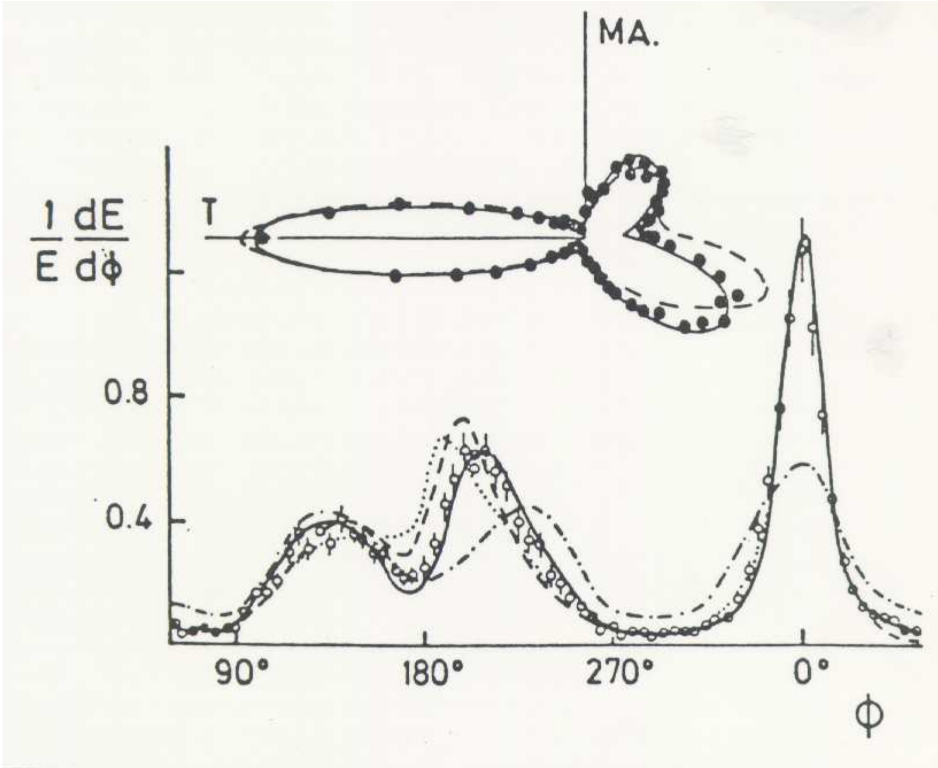
Classical sequence of experimental proof :

- quark jets widen

- only on one side

- 3-jet events appear :

MarkJ energy-flow:



Classical sequence of experimental proof :

- quark jets widen
- only on one side
- 3-jet events appear
- more details: $spin_g = 1$, fragmentation, ...

Bj: Any skeptic must agree now: GLUONS DO EXIST!

EPS PRIZE 1995 : P.Soeding, B.H.Wiik, G.Wolf, S.L.Wu

SPECIAL EPS PRIZE: Jade, MarkJ, Pluto, Tasso

Classical sequence of experimental proof :

- quark jets widen
- only on one side
- 3-jet events appear
- more details: $spin = 1$, fragmentation, ...

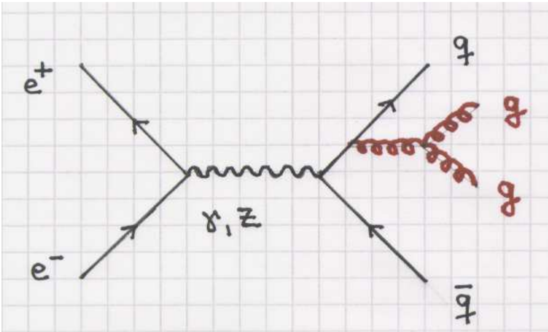
Bj: Any sceptic must agree now: GLUONS DO EXIST!

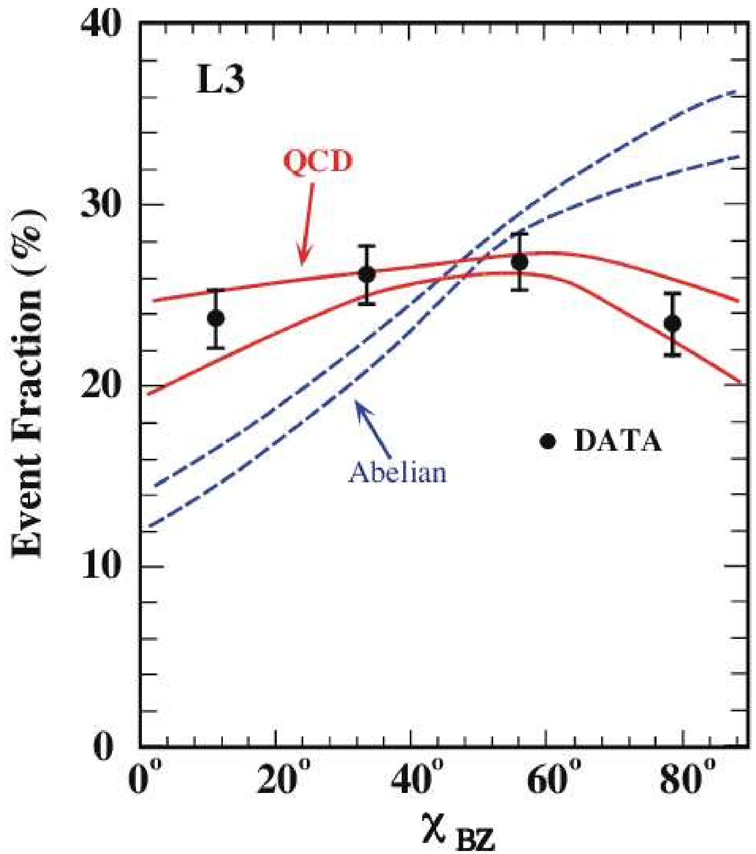
Comment :

DORIS/Pluto: topologies in Υ decays distinctly different from hadron final states in e^+e^- continuum and compatible with $\Upsilon \rightarrow ggg$ decays – but jet energies very low: heavy weight on MC tools

3.3 GLUON SELF-COUPLING FROM 4-jet EVENTS /LEP

gluon self-coupling $\Rightarrow$ AF





obs. in 4j : $e^+e^- \rightarrow q\,\bar{q}\,g_{|lin.pol}$

$g \rightarrow q'\bar{q}'$ perp.

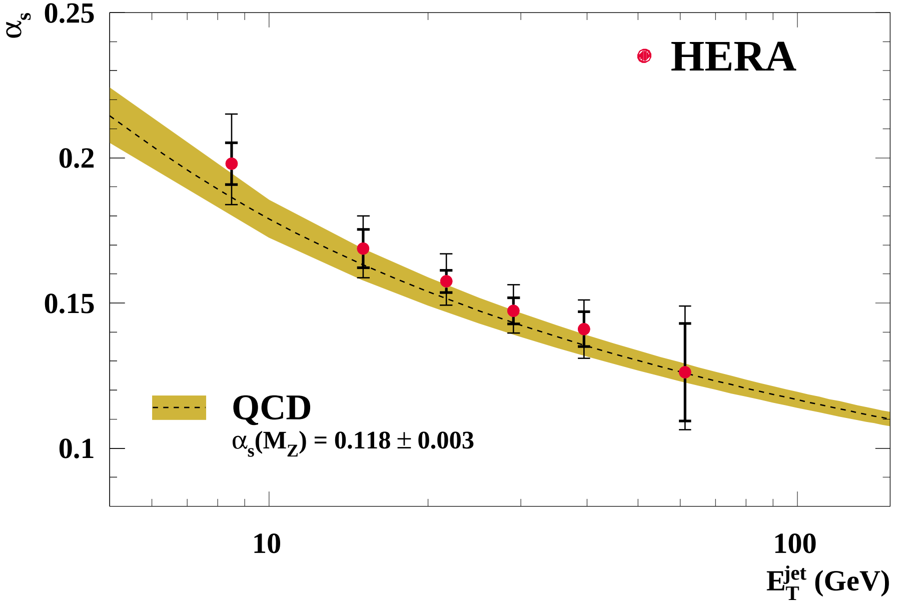
$g \rightarrow gg$ parallel

$C_A = 3 \;\rightarrow\; 2.89 \pm 0.21 \;\neq\; 0$

$$\alpha_s(Q^2) = 4\pi/[(11 - \tfrac{2}{3}n_f)\log Q^2/\Lambda^2 + \beta_1' \log\log Q^2/\Lambda^2 + ...]$$

– jet measurements... HERA

[Shekelyan ea]



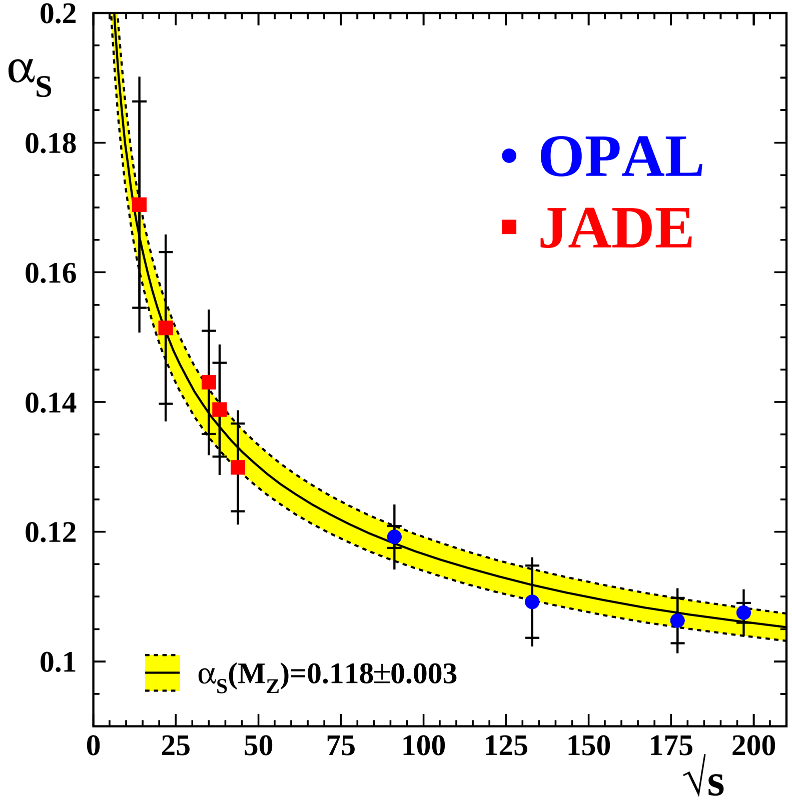
3.4 ASYMPTOTIC FREEDOM: The running of α_s

$$\alpha_s(Q^2) = 4\pi/[(11 - \tfrac{2}{3}n_f)\log Q^2/\Lambda^2 + \beta_1' \log\log Q^2/\Lambda^2 + ...]$$

– jet measurements etc at HERA

– and PETRA $\Rightarrow$ LEP

[Bethke ea]

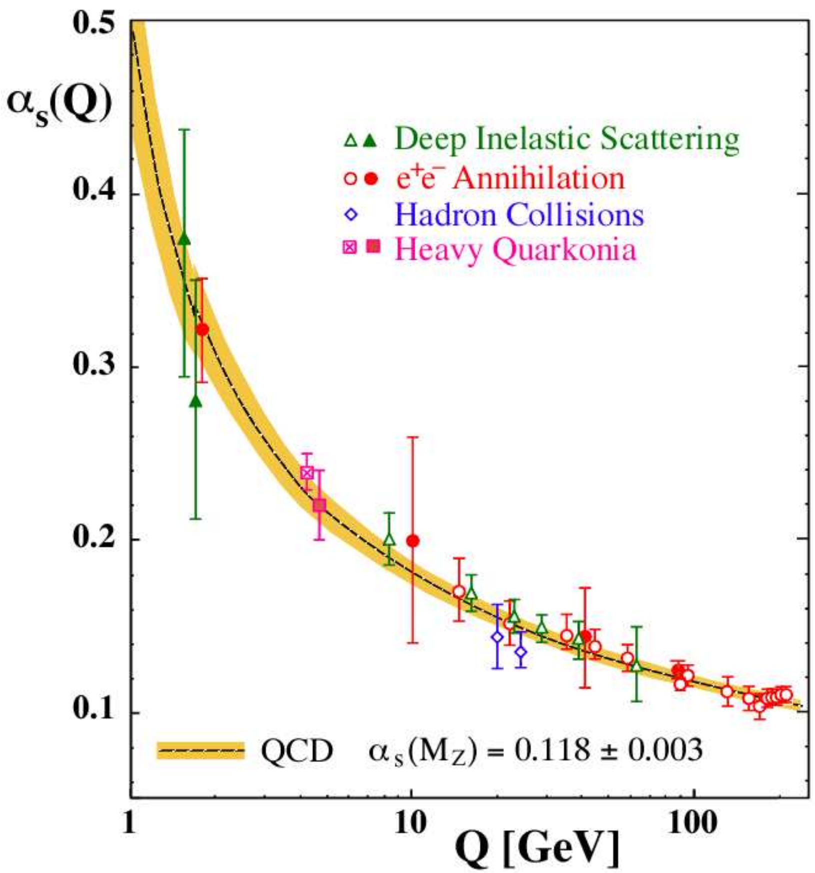


$$\alpha_s(Q^2) = 4\pi/[(11 - \tfrac{2}{3}n_f)\log Q^2/\Lambda^2 + \beta_1' \log\log Q^2/\Lambda^2 + ...]$$

– jet measurements etc at HERA

– and PETRA $\Rightarrow$ LEP

– α_s summary $\leftarrow$ Bethke



AF has been observed

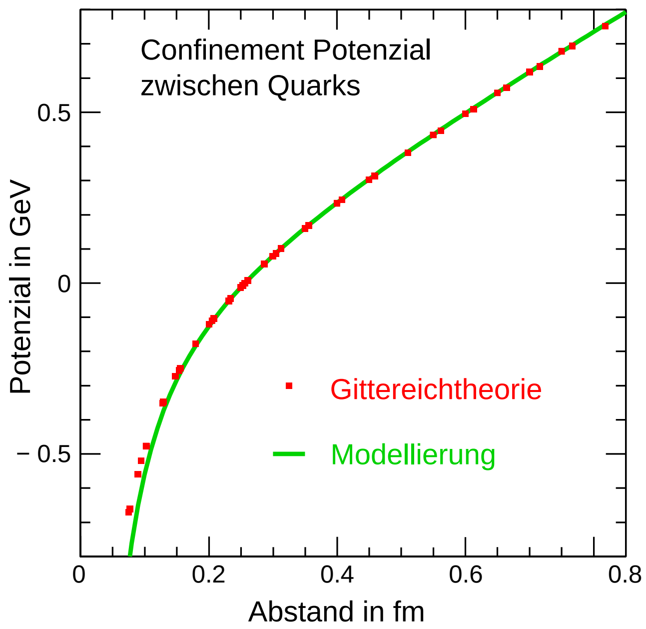
suggestive: ultraviolet freedom $\sim$ infrared slavery

short distances large distances

interquark potential: $V(R) = -\frac{\alpha}{R} + \sigma R$

Feynman path integration of QCD equations of motion numerically on discretized space-time: "lattice QCD"

compelling evidence for confinement of quarks in QCD [Sommer ea:] :

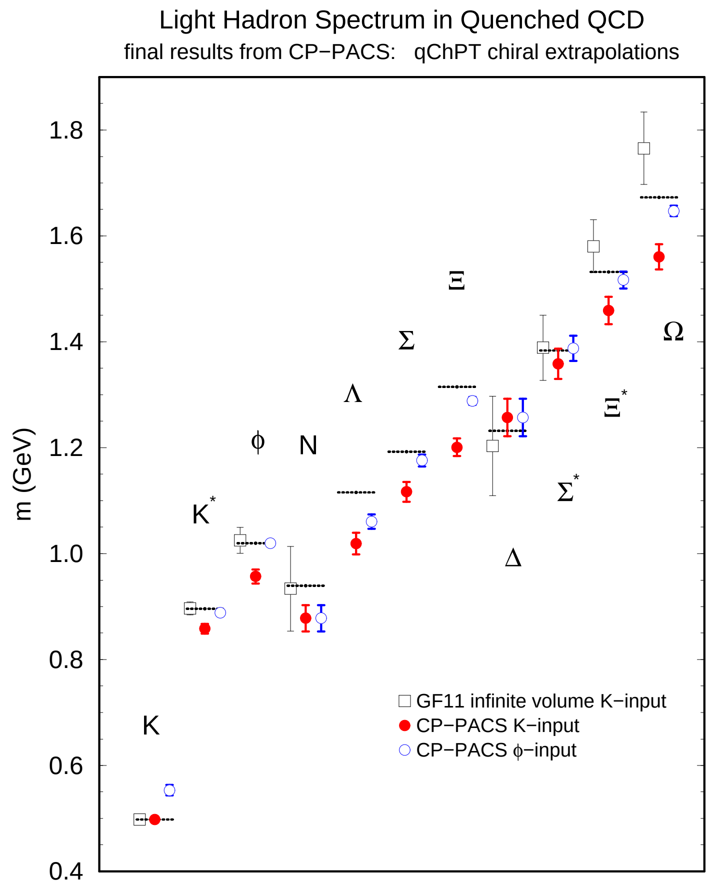


Last of the big three questions on quarks solved in QCD!

infrared slavery :

Feynman path integration of QCD
in “lattice QCD” $\Rightarrow$

compelling explanation of hadronic spectrum in QCD [CP-PACS]



pres. precision of QCD coupling : $\alpha_s(M_Z^2)^{\overline{MS}}_{n_f=5} = 0.118 \pm 0.003$ Bethke

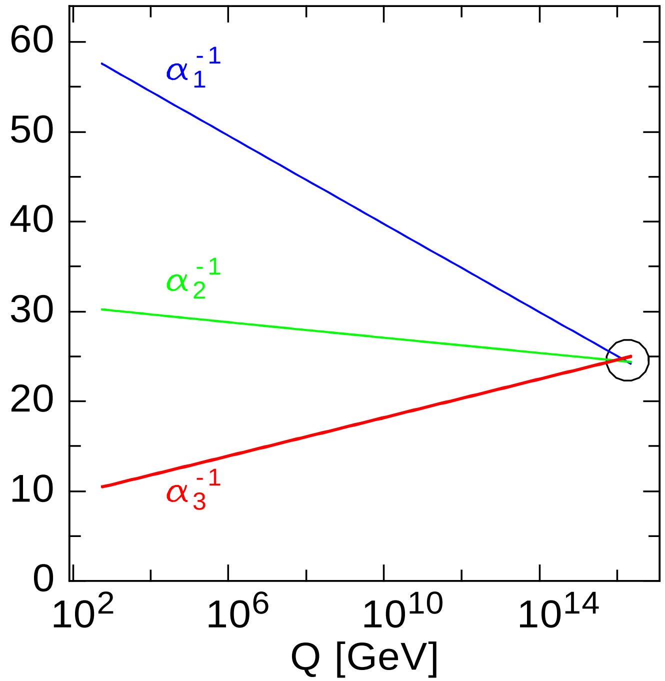
GigaZ at ILC [$\leftarrow$ TESLA] : improved to $\Delta\alpha_s = \pm 0.001$

- provocative question : cui bono?
- provocative answer : ultimate unfication of forces:
  explore physics near scales where gravity
  joins particle physics

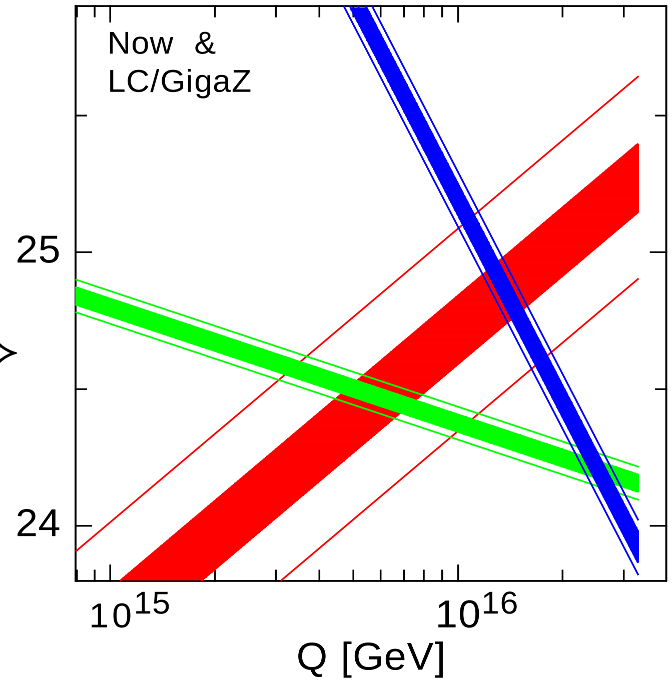
path : extrapolation of $\alpha_i(Q)$ $i =$ SU(3),SU(2),U(1) to high energies :
couplings close to each other [SUSY] at energy $M_U = 2 \cdot 10^{16}$ GeV :

suggestive for Grand Unification :

GigaZ sensit. GUT/PL scales :



$\Rightarrow$



⇑ DESY retrospective :

– essential elements of theoretical base and physical consequences

– discovery of gluon jets at PETRA led to undisputed acceptance of QCD as the microscopic theory of the strong interactions

– HERA/PETRA measurm. confirm classical predictions of QCD: α_s running / scaling violations / large g number at small x

⇑ DESY perspective :

exploit the exciting consequences of α_s precision measurement at TeV Linear Collider ILC – *explore a new physics frontier*