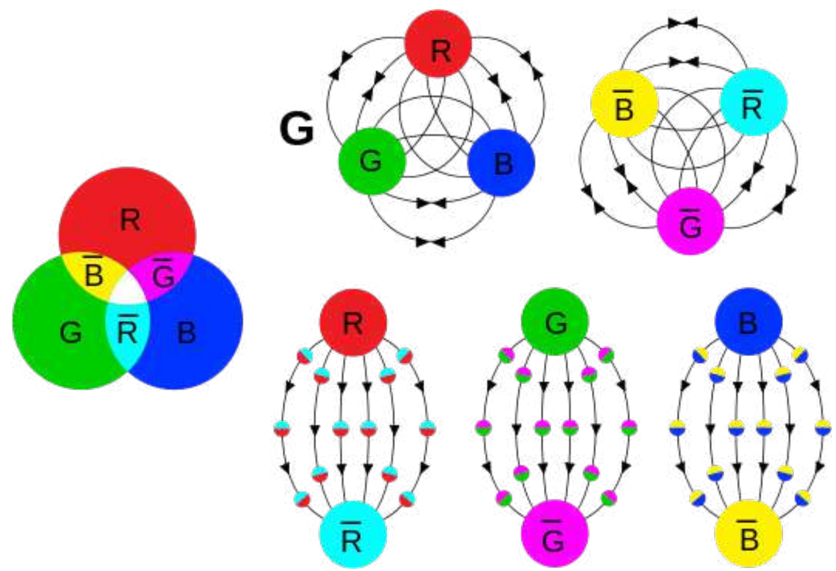
From the quark model to the strong interaction theory

Michał Praszałowicz (IFT UJ)

2020



Książki:

- F. Close, *The Infinity Puzzle*
- H. Fritzsch, *Elementary Particles*
- G. Farmelo, *The Strangest Man*
- A.K. Wróblewski, *Historia Fizyki*

Artykuły popularne:

- D.J. Gross, *Asymptotic Freedom and QCD – a Historical Perspective* Nucl. Phys. B (Proc. Suppl.) 135 (2004) 193
- H. Fritzsch, *The histoty of QCD*, CERN Courier 2012
- S. Weinberg, *Particle Physics from Rutheford to the LHC*, Phys. Today 2011
- L.B. Okun, *Physics of vacuum at ITEP and around*, hep-ph/0112032
- G. Zweig, *Concrete Quarks: the Begining of the End*, 2013, conf proc.
- I.B. Khriplovich, *Ekranowanie i antyekranowanie ładunku w teoriach cechowania*, Uspiechi. Fiz. Nauk 2010

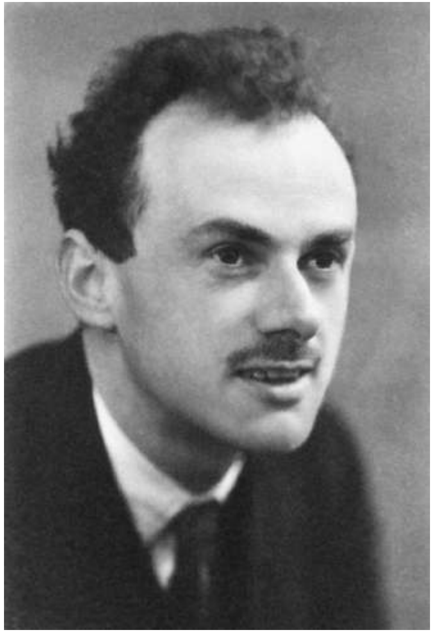
Prezentacje elektroniczne

- G. Ecker, *The early history of QCD*
- R. Baier, *QCD - a selective overview*
- H. Leutwyler, *On the history of strong interactions*
- P. Minkowski, *About the scientific life of Harald Fritzsch*

Three paths to QCD

- Development of Quantum Field Theory
- Experimental evidence
- Phenomenology of strong interactions

Quantum Field Theory



- Dirac equation 1928 (free fermions)
- quantum electrodynamics: Dirac ~1930
- weak interactions : Enrico Fermi 1933
- strong interactions : Yukawa 1935

After initial successes
serious difficulties:

- only perturbation theory
- infinities

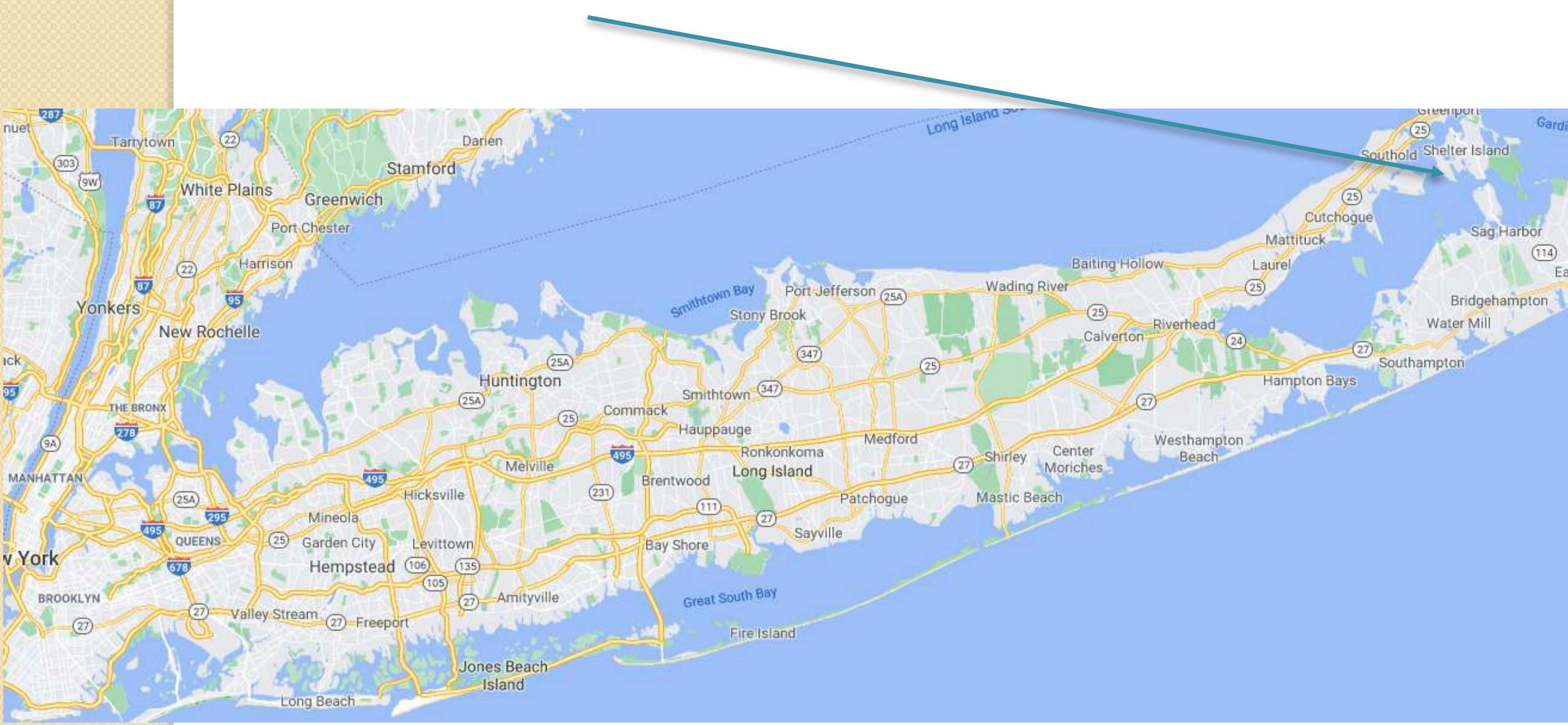
~ 1950 general belief:
field theory is fundamentaly
false, in particular it cannot
used for strong interactions

Shelter Island Conference

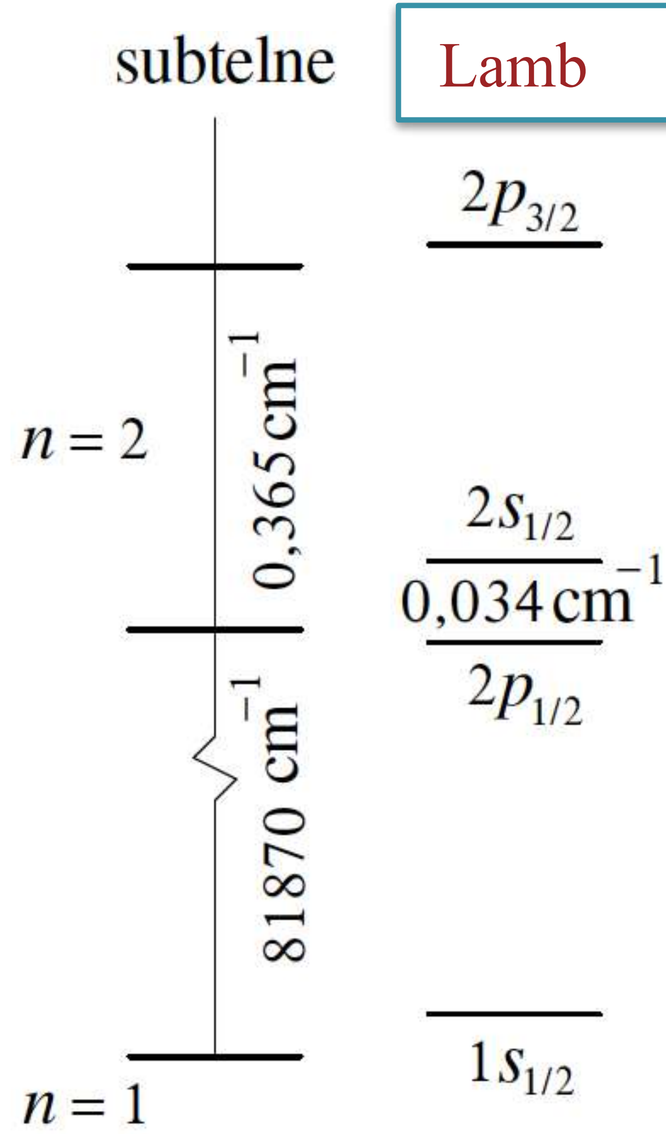
2 – 4 June 1947, 24 participants:

Hans Bethe, David Bohm, Gregory Breit, Karl K. Darrow, Herman Feshbach, Richard Feynman, Hendrik Kramer, Willis Lamb, Duncan MacInne, Robert Eugene Marshak, John von Neumann, Arnold Nordsieck, J. Robert Oppenheimer, Abraham Pais, Linus Pauling, Isidor Isaac Rabi, Bruno Rossi, Julian Schwinger, Robert Serber, Edward Teller, George Uhlenbeck, John Hasbrouck van Vleck, Victor Frederick Weisskopf, John Archibald Wheeler

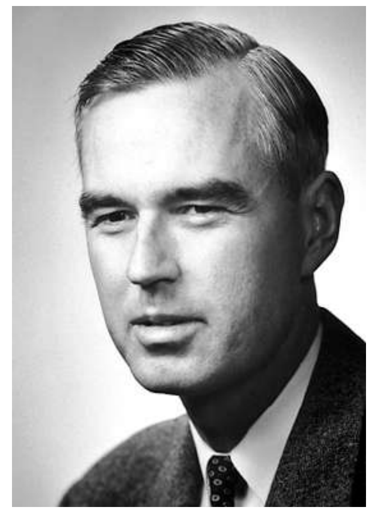
Shelter island



Shelter Island Conference



Lamb Rabi: *g* - 2

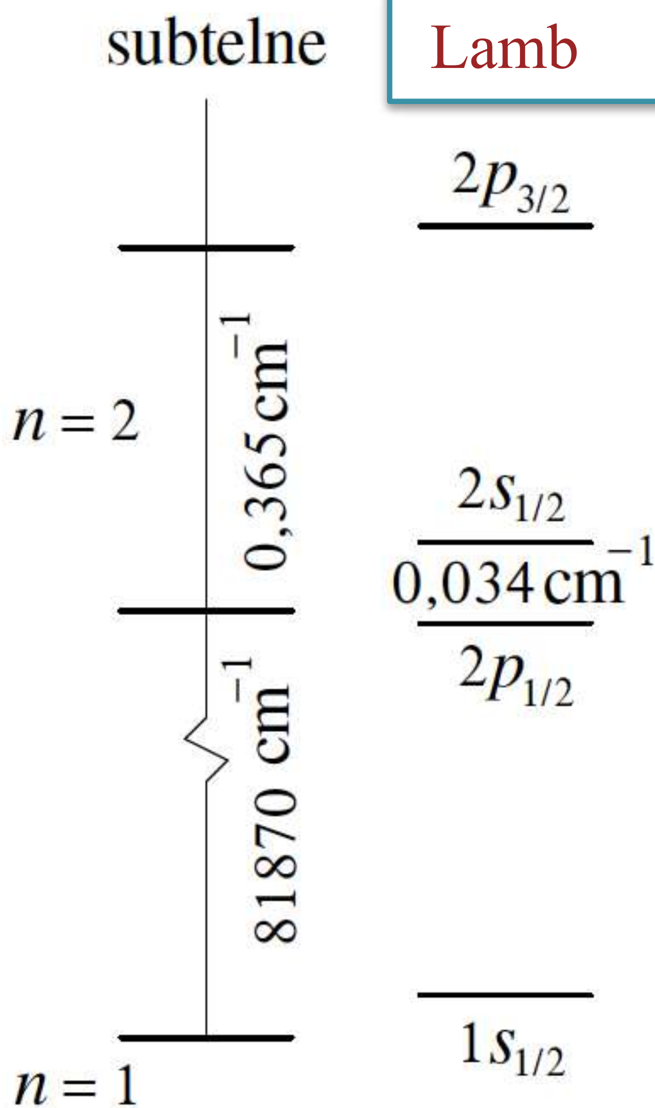


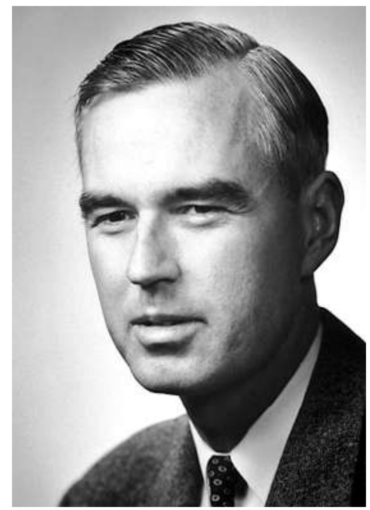
Hanse Bethe supposedly calculated on the way Back calculated the Lamba shift:

$$\Delta E_n = \frac{4Z\alpha^2}{3}\frac{1}{m^2}\int_{mZ\alpha}^{m}\frac{d\omega}{\omega}\,|\psi_n(0)|^2$$

Shelter Island Conference

Lamb   Rabi: g - 2





Hanse Bethe supposedly
calculated on the way
Back calculated
the Lamba shift:

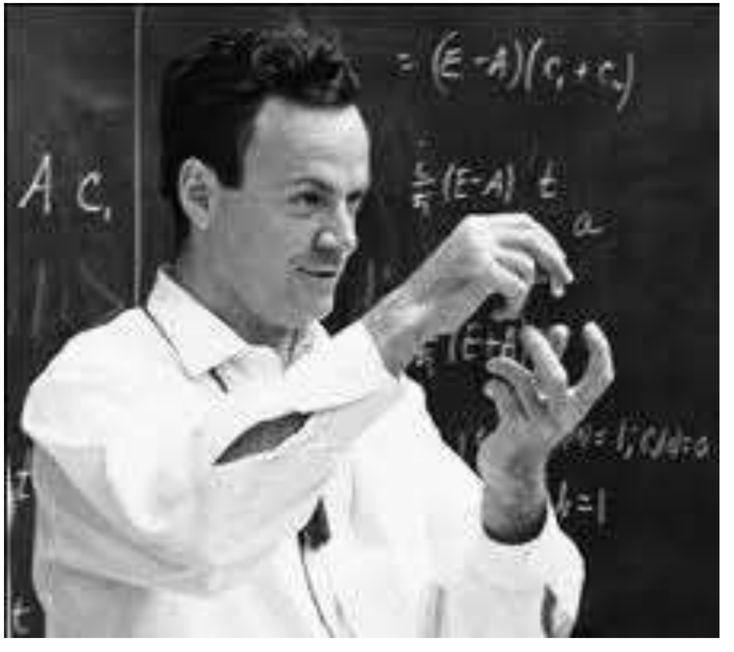
$$\Delta E_n = \frac{4Z\alpha^2}{3}\frac{1}{m^2}\ln\left(\frac{1}{Z\alpha}\right)|\psi_n(0)|^2$$

Pocono Mountain Confernce

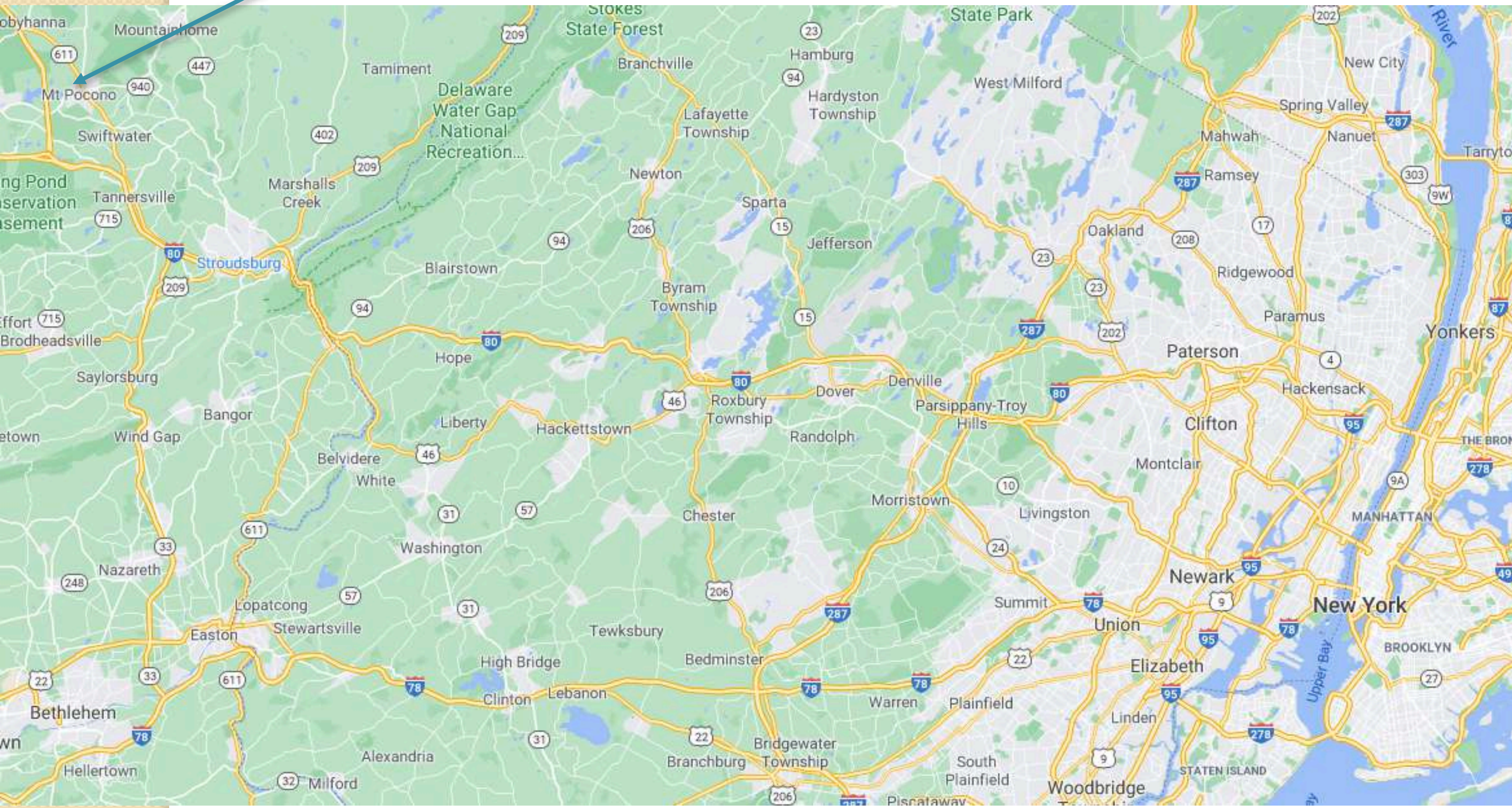
30.3 – 2.4.1948 + Niels Bohr, Paul Adrien Dirac

first day: strange particles + accelerator in Berkeley

second day: Schwinger's lecture on renormalization until late afternoon, then Feynman



Mt. Pocono



Mountainhome
Mt Pocono
Swiftwater
Tannersville
Stroudsburg
Brodheadsville
Saylorsburg
Bangor
Wind Gap
Nazareth
Easton
Bethlehem
Hellertown
Tamiment
Marshalls Creek
Delaware Water Gap National Recreation...
Stokes State Forest
Branchville
Lafayette Township
Newton
Blairstown
Hope
Liberty
Belvidere
White
Washington
Lopatcong
Stewartsville
High Bridge
Clinton
Lebanon
Alexandria
Milford
Hackettstown
Byram Township
Roxbury Township
Chester
Tewksbury
Bedminster
Branchburg
Bridgewater Township
Hamburg
Hardyston Township
Sparta
Jefferson
Dover
Randolph
Denville
Parsippany-Troy Hills
Morristown
Livingston
Summit
Union
Warren
Plainfield
South Plainfield
Piscataway
State Park
West Milford
Oakland
Mahwah
Ramsey
Ridgewood
Paramus
Paterson
Hackensack
Clifton
Montclair
Newark
Elizabeth
Linden
Woodbridge
New City
Spring Valley
Nanuet
Yonkers
THE BRONX
MANHATTAN
New York
BROOKLYN
STATEN ISLAND
Upper Bay

Renormalization in QED

Sin-Itiro Tomonaga published in 1943 a paper on renormalization in QED

Freeman Dyson w 1948 r showed equivalence of schemes By Schwinger, Feynman and Tomonaga, who received Noble Prize in 1965 r.

Renormalization in QED

Not everyone is convinced
it is commonly believd that renormalization is
the "dirty trick",
Dirac never accepted renormalization,
Fermi and Yukawa's theories are not renormalizable

D.J. Gross, Nucl. Phys. B (Proc. Suppl.) 135 (2004) 193-211:
To quote Feynman, speaking at the 1961 Solvay conference:
"I still hold to this belief and do not subscribe to the philosophy of renormalization."

Field theory is not considered a serious theoretical tool.
Instead one uses:
S matrix theory, bootstrap,
current algebra, dual models, phenomenology

"My own feeling is that we have learned a great deal from field theory... that I am quite happy to discard it as an old, but rather friendly, mistress who I would be willing to recognize on the street if I should encounter her again. From a philosophical point of view and certainly from a practical one the S-matrix approach at the moment seems to me by far the most attractive."

Marvin Goldberger, konferencja Solvay, 1961

[D.J. Gross, Nucl. Phys. B (Proc. Suppl.) 135 (2004) 193-211]

Marvin Goldberger

Goldberger was a professor of physics at Princeton University 1957 - 1977.
He received the Dannie Heineman Prize for Mathematical Physics in 1961.
In 1963 was elected to the U.S. National Academy of Sciences.
In 1965 he was elected a Fellow of the American Academy of Arts and Sciences.
From 1978 through 1987 he served as president of Caltech.
He was the Director of the Institute for Advanced Study from 1987 to 1991.
From 1991 to 1993 he was a professor of physics at the University of California, Los Angeles.
From 1993 until his death in November, 2014, he served on the faculty of the University of California, San Diego,
Goldberger also served as Dean of Natural Sciences for UC San Diego from 1994 to 1999.

In physics mostly known from so called Goldberger-Treiman relation:

and it is obeyed to 10% accuracy. $$g_{\pi NN} F_\pi = G_A M_N$$

Yang-Mills Theory (1954)

$$\psi(x) \to \psi'(x) = e^{-i\theta(x)}\psi(x),$$

$$A_\mu(x) \to A'_\mu(x) = A_\mu(x) + \frac{1}{q}\partial_\mu\theta(x)$$

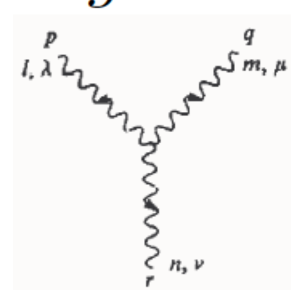
Yang-Mills Theory (1954)

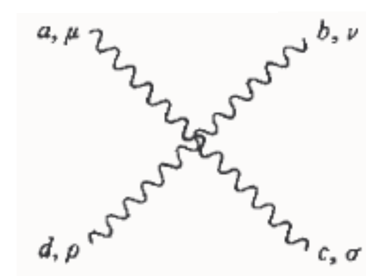
$$\Psi(x) \to \Psi'(x) = U(x)\Psi(x) \qquad U(x) = e^{-i\theta_m(x)T^m}$$

$$\boldsymbol{A}'_\mu(x) = U(x)\boldsymbol{A}_\mu(x)U^\dagger(x) + \frac{i}{g}\left[\partial_\mu U(x)\right]U^\dagger(x)$$

$$\boldsymbol{A}_\mu(x) = T^m A^m_\mu(x)$$

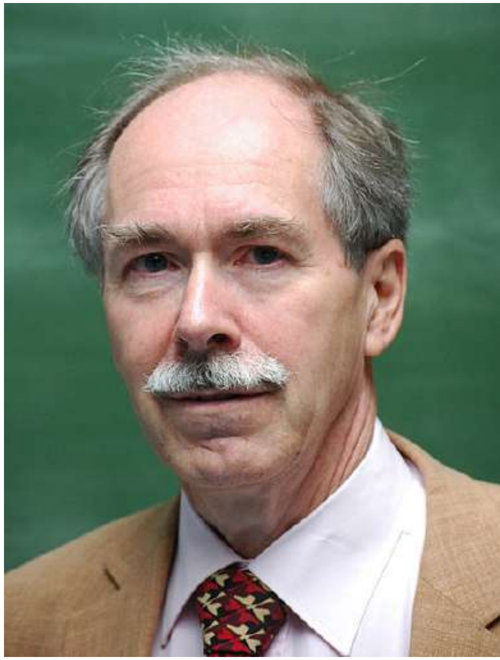
„photons” are selfinteracting,
it was not known if such theory
is renormalizable



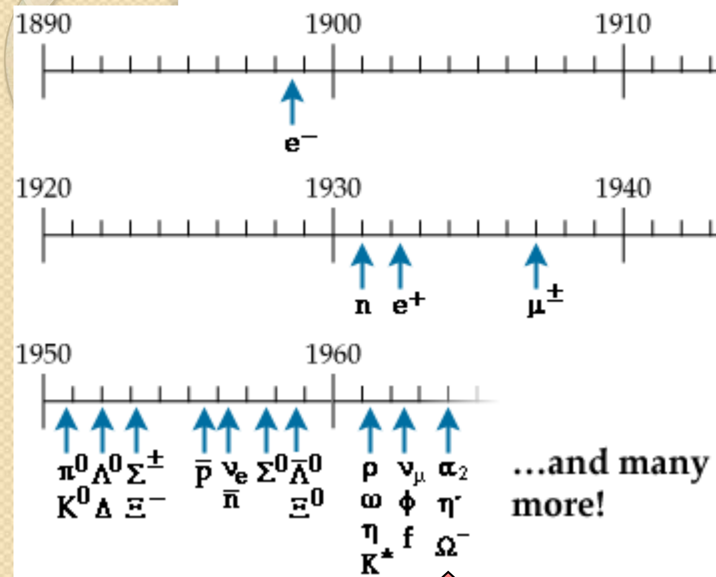


Renormalization of YM theory

1971: 't Hooft, Veltman student proves renormalization based on the method of Feynman functional integrals

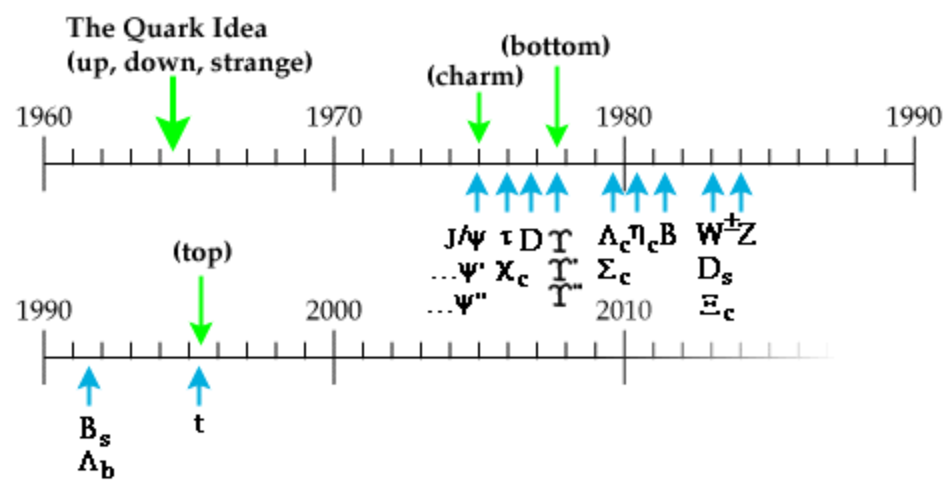


Elementary particles?



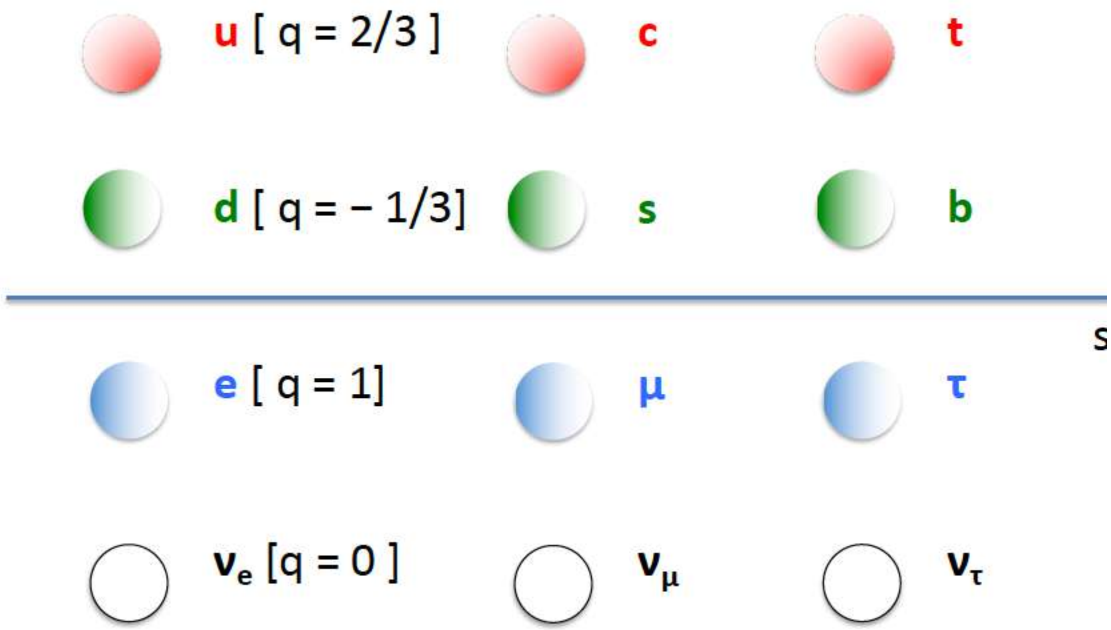
with that number of particles produced artificially in accelerators, it's hard consider them elementary

The quark model predicted Ω



and many others

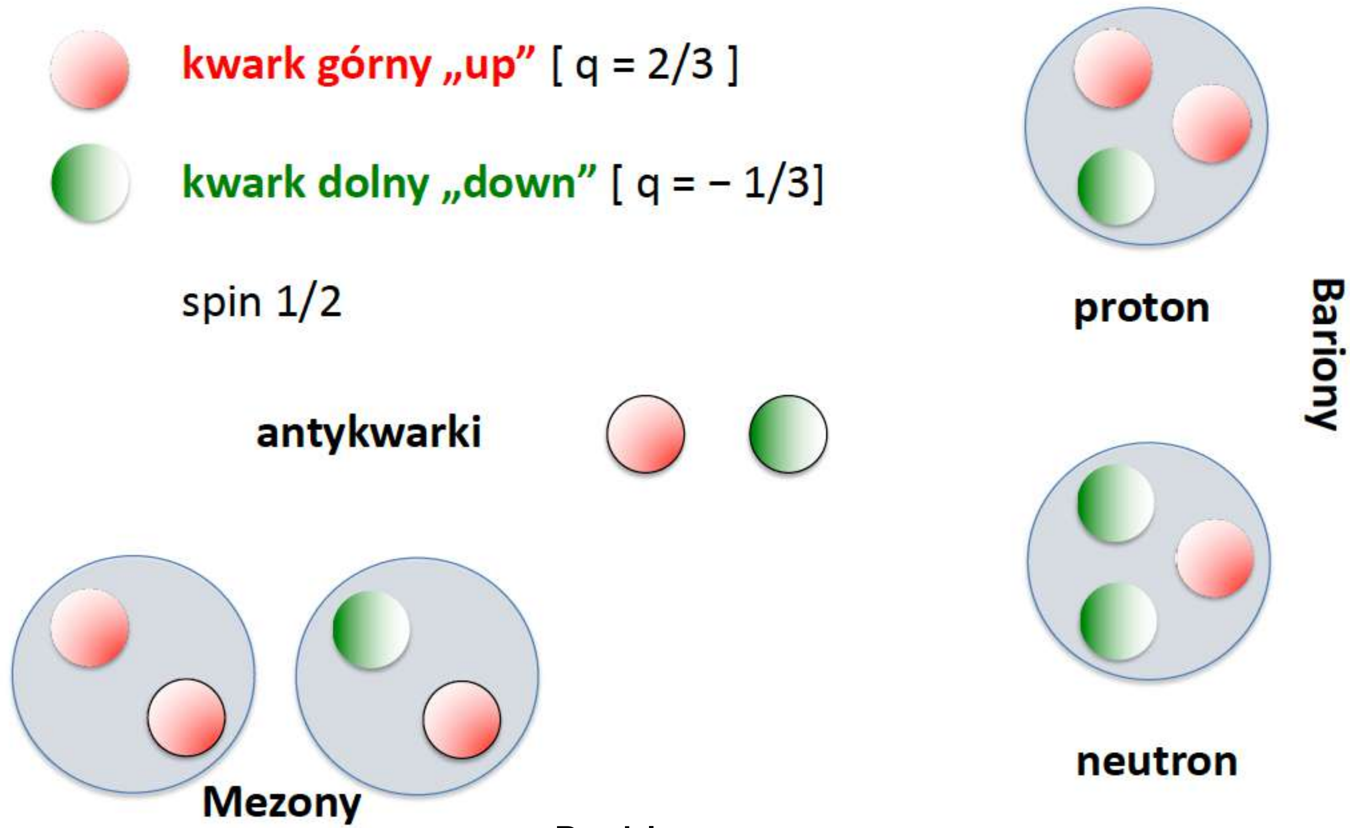
Quark Model



quarks

leptons

Quark Model



Problems:
Why only these combinations?
Statistics…

Statistics

$$\Delta^{++} = u\uparrow\, u\uparrow\, u\uparrow \;\rightarrow\; u\uparrow\, u\uparrow\, u\uparrow$$

$$\Delta^{-} = d\uparrow\, d\uparrow\, d\uparrow \;\rightarrow\; d\uparrow\, d\uparrow\, d\uparrow$$

$$\Omega^{-} = s\uparrow\, s\uparrow\, s\uparrow \;\rightarrow\; s\uparrow\, s\uparrow\, s\uparrow$$

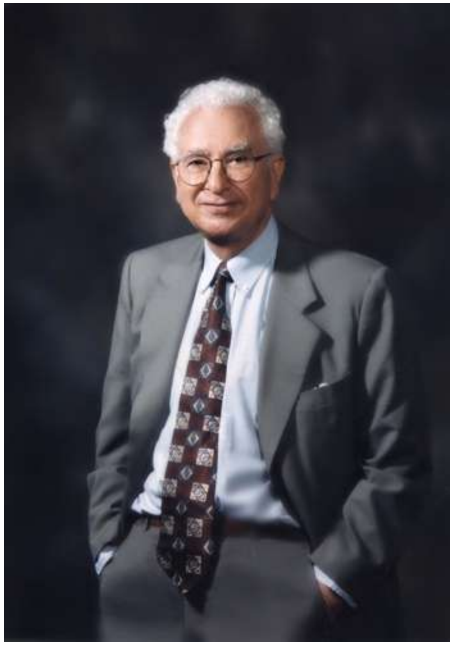
Global symmetry (as isospin) – only „white" states allowed

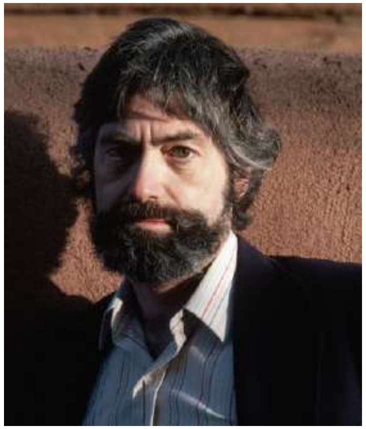
Geenberg, Nambu, Han, Gell-Mann, Fritzsch, …

Quark Model

Murray Gell-Mann 1972 (!):

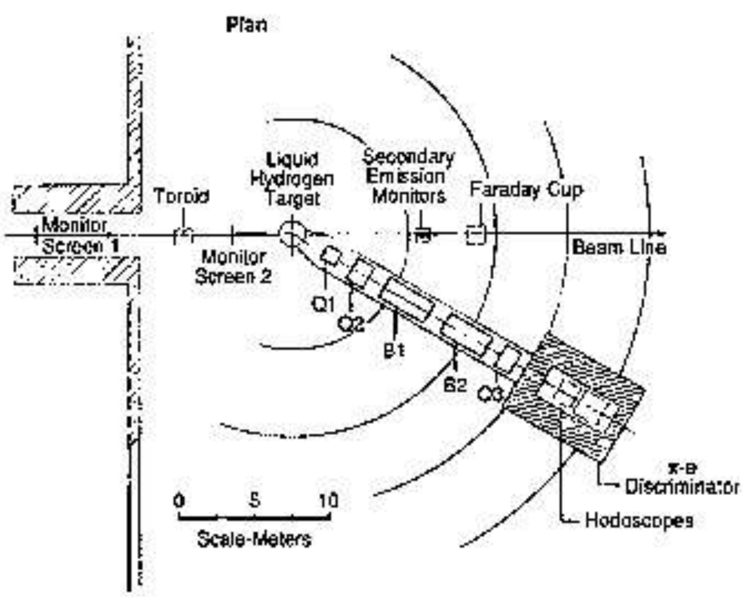
"Let us end by emphasizing our main point, that it may well be possible to construct an explicit theory of hadrons, based on quarks and some kind of glue, treated as fictitious, but with enough physical properties abstracted and applied to real hadrons to constitute a complete theory. Since the entities we start with are fictitious, there is no need for any conflict with the bootstrap or conventional dual parton point of view."



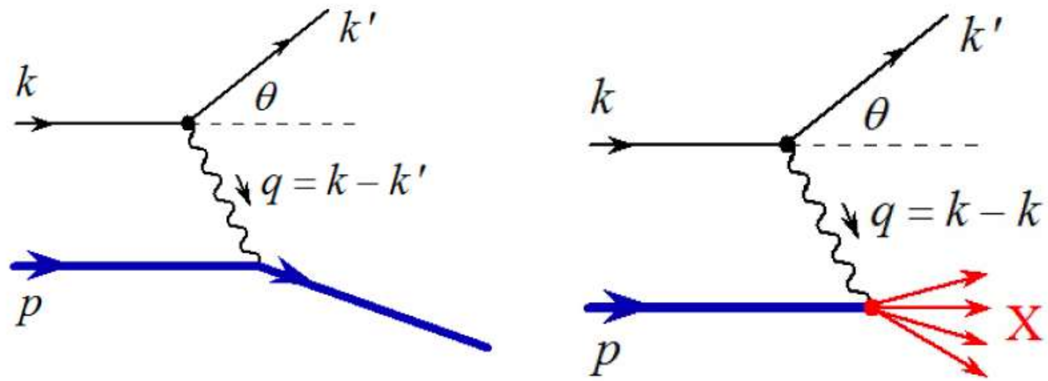


SLAC

SLAC built in1967
Length ~ 2 miles
Energy: 20 GeV



Deep inelastic scattering



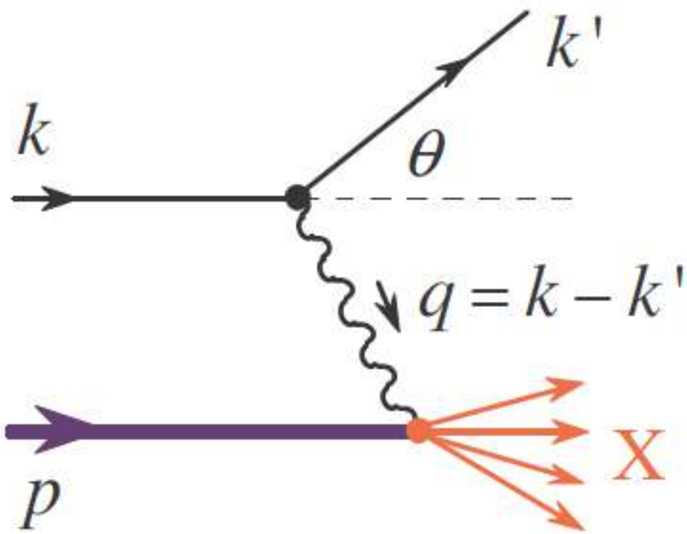
$$q^2 = -2\omega\omega'(1-\cos\theta) = -4\omega\omega'\sin^2\frac{\theta}{2}, \qquad \nu = \omega - \omega'$$

In elastic case ν and Q are not independent:

$$\delta((p+q)^2 - M^2) = \delta(2M\nu - Q^2) = \frac{1}{2M}\delta\left(\nu - \frac{Q^2}{2M}\right)$$

(for the proton at rest: p = (M,0,0,0))

Deep inelastic scattering



$$-q^2 = 4\omega\omega' \sin^2\frac{\theta}{2}$$

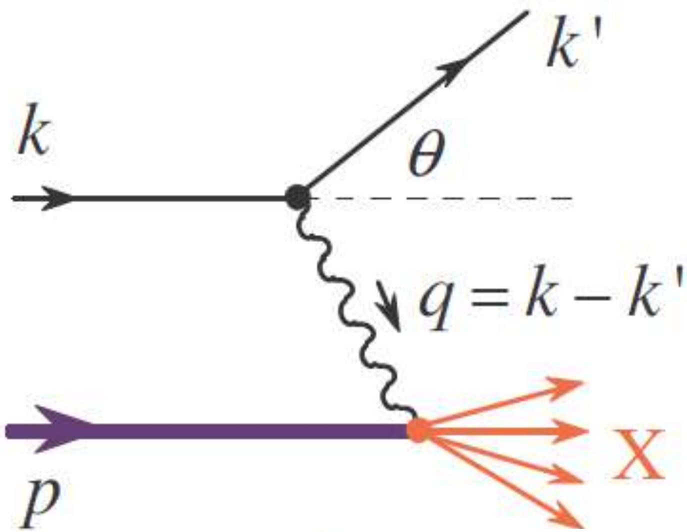
$$q \cdot p = M(\omega - \omega') = M\nu$$

Bjorken variable → $x = \frac{Q^2}{2M\nu}$

$$\frac{d\sigma}{dQ^2 d\nu} =$$

$$= \frac{\pi\alpha^2}{4\omega^3\omega' \sin^4\frac{\theta}{2}} \left\{ W_2(Q^2,\nu)\cos^2\frac{\theta}{2} + 2W_1(Q^2,\nu)\sin^2\frac{\theta}{2} \right\}$$

Deep inelastic scattering



$$-q^2 = 4\omega\omega' \sin^2\frac{\theta}{2}$$

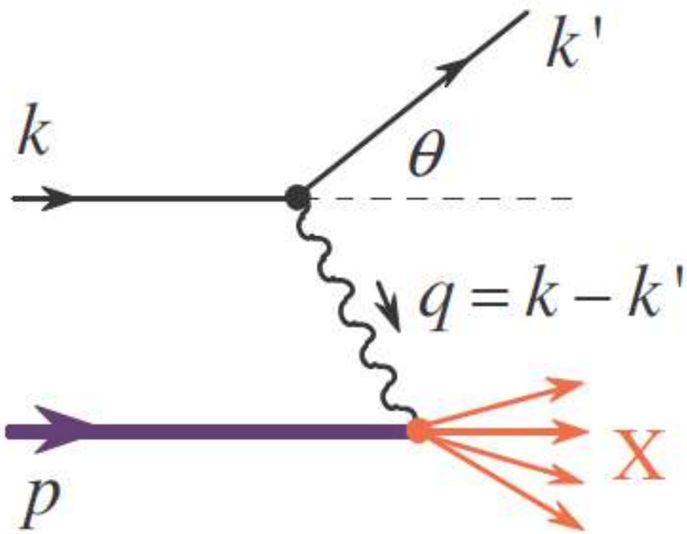
$$q \cdot p = M(\omega - \omega') = M\nu$$

Bjorken variable → $x = \dfrac{Q^2}{2M\nu}$

$$\frac{d\sigma}{dQ^2 d\nu} = \left\{\cos^2\frac{\theta}{2} + \frac{Q^2}{2M^2}\sin^2\frac{\theta}{2}\right\}$$ ← **ELASTIC**

$$= \frac{\pi\alpha^2}{4\omega^3\omega'\sin^4\frac{\theta}{2}}\left\{W_2(Q^2,\nu)\cos^2\frac{\theta}{2} + 2W_1(Q^2,\nu)\sin^2\frac{\theta}{2}\right\}$$

Bjorken scaling



$$-q^2 = 4\omega\omega' \sin^2\frac{\theta}{2}$$

$$q \cdot p = M(\omega - \omega') = M\nu$$

Bjorken variable → $x = \frac{Q^2}{2M\nu}$

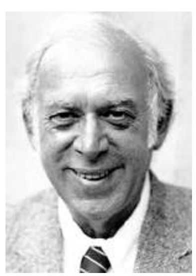
$$MW_1(Q^2,\nu) = F_1(x)$$
$$\nu W_2(Q^2,\nu) = F_2(x)$$

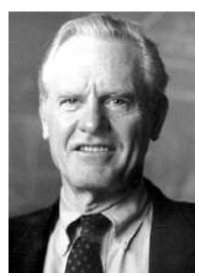
$$\frac{d\sigma}{dQ^2 d\nu} = \frac{\pi\alpha^2}{4\omega^3\omega' \sin^4\frac{\theta}{2}}\left\{W_2(Q^2,\nu)\cos^2\frac{\theta}{2} + 2W_1(Q^2,\nu)\sin^2\frac{\theta}{2}\right\}$$

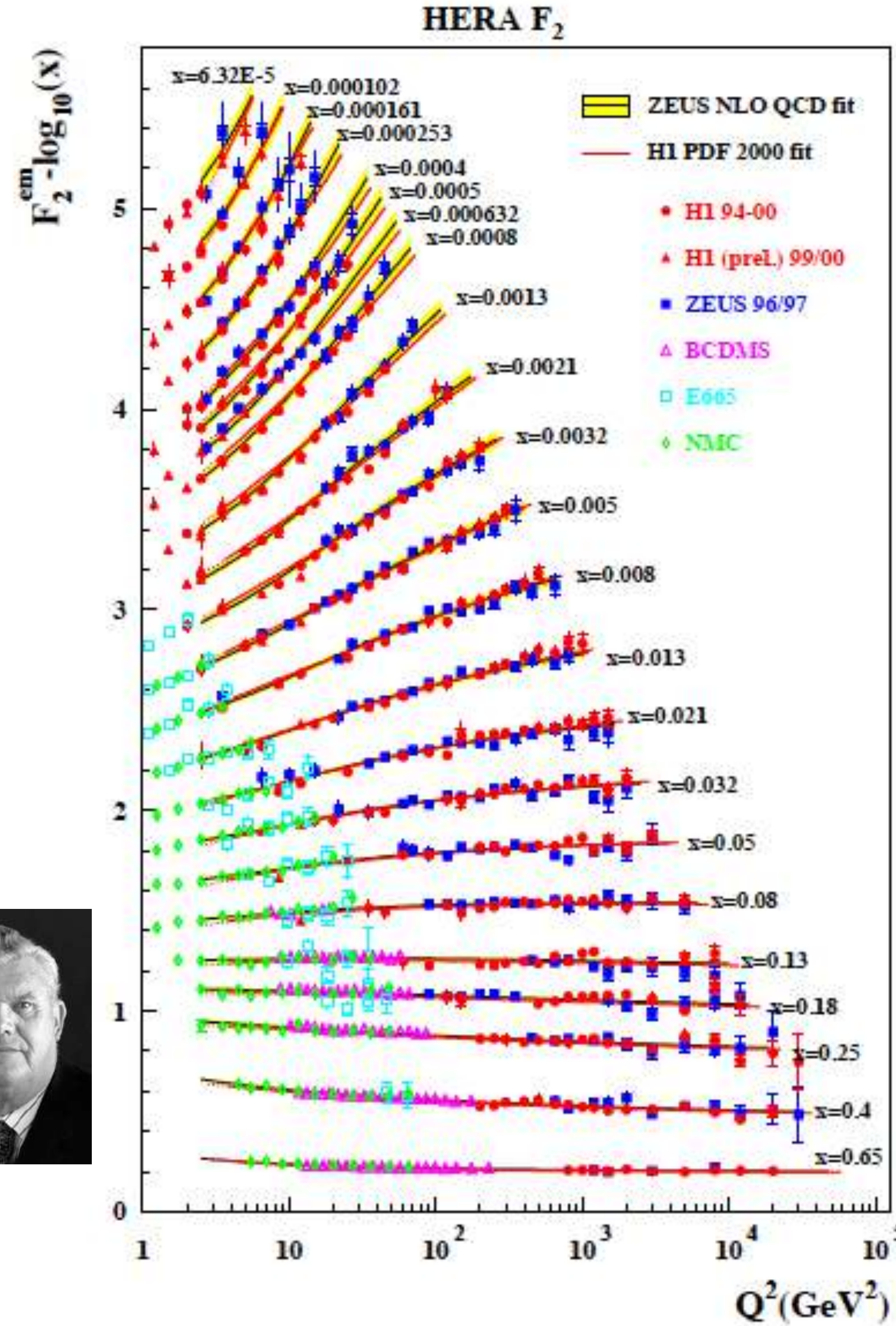
1968: convinced by James Bjorken analysis of has been made DIS

Interpretation was given by Richard Feynman

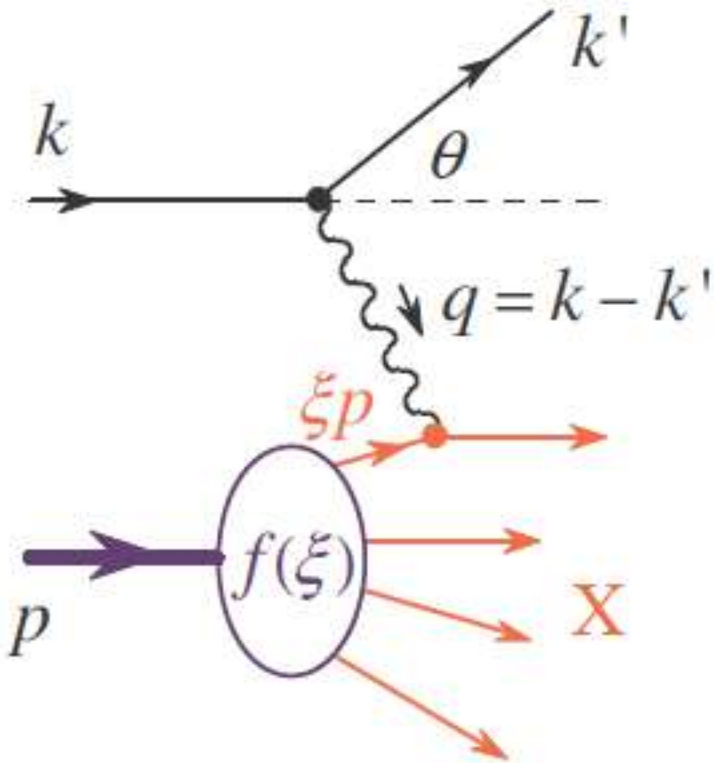
Nobel 1990:
Jerome Friedman (MIT)
Henry Kendall (MIT)
Richard Taylor (SLAC)







Feynman parton model



neglecting masses

$$(\xi p + q)^2 = 0$$

$$2\xi\, pq + q^2 = 0$$

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

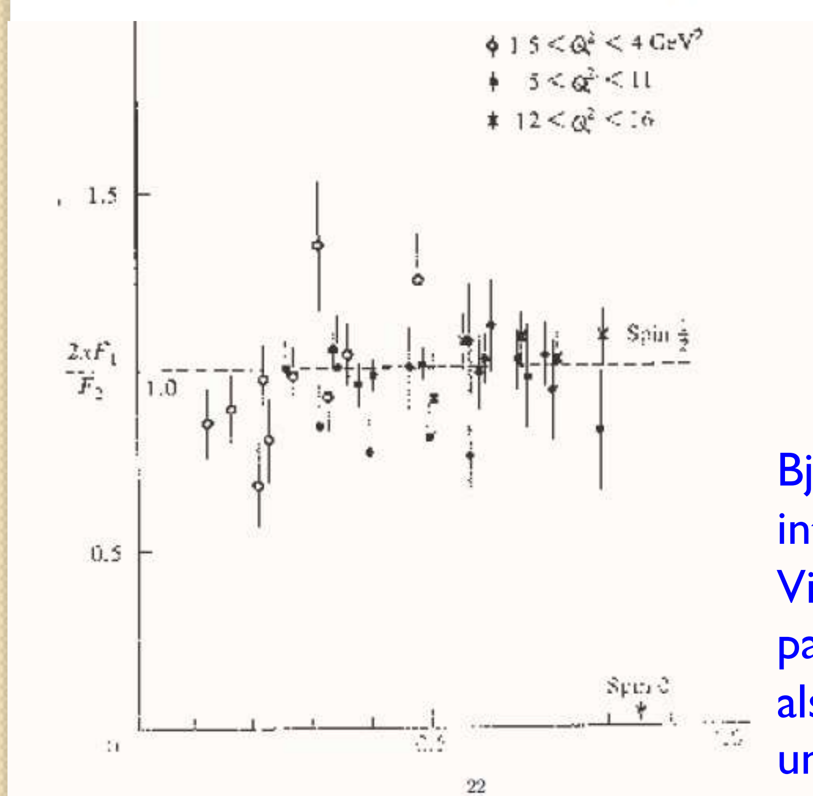
- Are partons quarks?
- Why are they free?

Parton spin

Callan – Gross relation for spin 1/2:

$$\frac{d\sigma}{dQ^2 d\nu} = \frac{\pi\alpha^2}{4\omega^3\omega' \sin^4\frac{\theta}{2}} \left\{ W_2(Q^2,\nu)\cos^2\frac{\theta}{2} + 2W_1(Q^2,\nu)\sin^2\frac{\theta}{2} \right\}$$

$$MW_1(Q^2,\nu) = F_1(x)$$
$$\nu W_2(Q^2,\nu) = F_2(x)$$

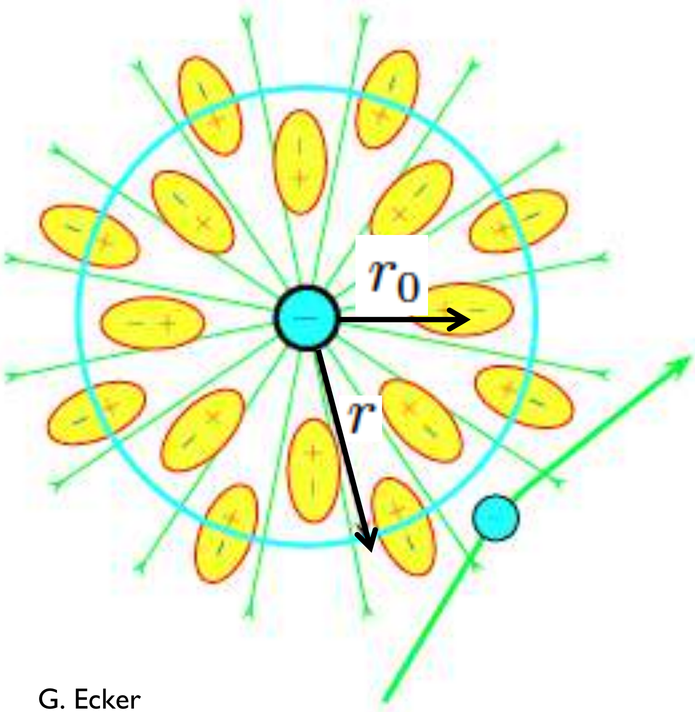


$$F_2(x) = 2xF_1(x)$$

Bj scaling goes unnoticed,
interest in ep scattering is negligible.
Vienna 1968: Friedman's talk at the parallel session attended onlyby a few people,
also Panofski's plenary paper goes unnoticed

Vacuum polarization

- Are partons quarks? - yes
- Why are they free?



G. Ecker

charge screening in QED

$$r\frac{de_{\text{eff}}(r)}{dr} = -\beta(e_{\text{eff}})$$

$$-\int_{e_{\text{eff}}(r_0)}^{e_{\text{eff}}(r)} \frac{de_{\text{eff}}}{\beta(e_{\text{eff}})} = \ln\frac{r}{r_0} > 0$$

$$\beta > 0 \rightarrow e_{\text{eff}}(r_0) > e_{\text{eff}}(r)$$

$$\beta < 0 \rightarrow e_{\text{eff}}(r_0) < e_{\text{eff}}(r)$$

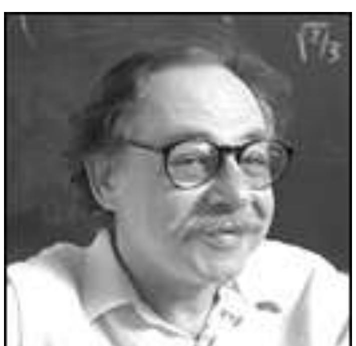
For the parton model to make sense beta function should be negative

Asymptotic freedom

1973: Gross & Wilczek at Princeton and Politzer (student of Coleman, on sabattical in Princeton) at Harvard calculated beta function for Yang-Mills th.

Gross:

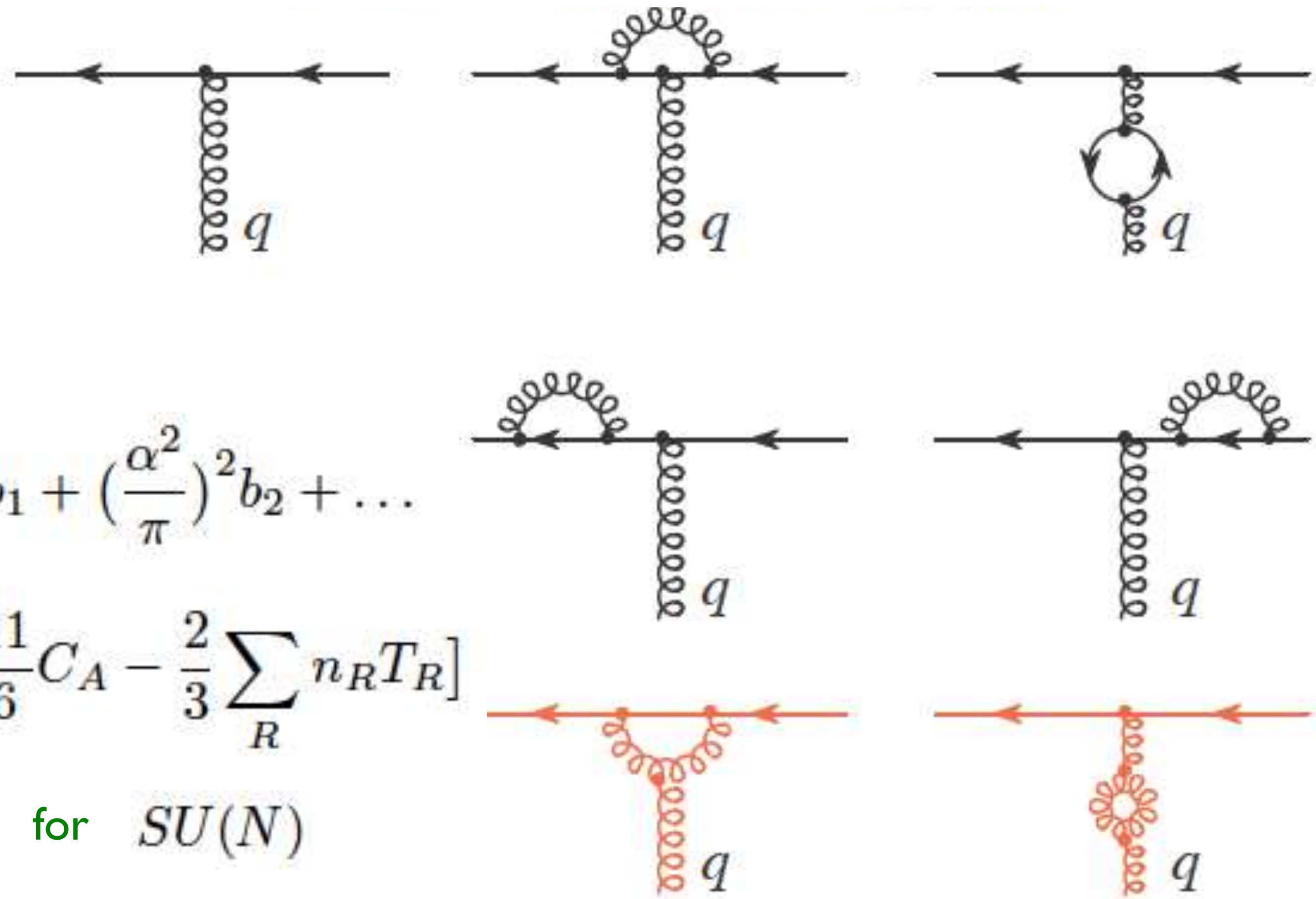
For me the discovery of asymptotic freedom was totally unexpected. Like an atheist who has just received a message from a burning bush, I became an immediate true believer. Field theory wasn't wrong–instead scaling must be explained by an asymptotically free gauge theory



Nobel 2004

Asymptotic freedom

quark-guon vertex corrections



$$\alpha = \frac{g^2}{4\pi}$$

$$\beta(\alpha) = \frac{\alpha^2}{\pi} b_1 + (\frac{\alpha^2}{\pi})^2 b_2 + \ldots$$

$$b_1 = -[\frac{11}{6} C_A - \frac{2}{3} \sum_R n_R T_R]$$

$C_A = N$ for $SU(N)$

$T_F = \frac{1}{2}$

Asymptotic freedom (prehistory)

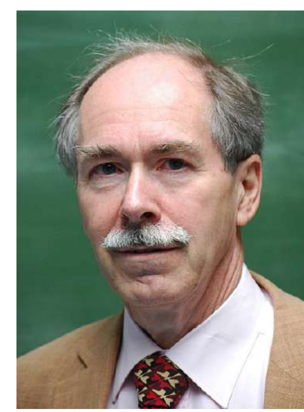
$$b_1 = -[\frac{11}{6}C_A - \frac{2}{3}\sum_R n_R T_R]$$

- 1965 Mikhail Terentyev & Vlasimir Vanyashin (ITEP)
  error: 11× 2 = 22, they had= 21

Ваняшин В С, Терентьев М В *ЖЭТФ* **48** 565 (1965) [Vanyashin V S, Terentyev M V *Sov. Phys. JETP* **21** 375 (1965)]

- 1969 Iosif Khripovich (Novosibirsk)
  (Coulomb gauge)

Хриплович И Б *ЯФ* **10** 410 (1969) [Khriplovich I B *Sov. J. Nucl. Phys.* **10** 235 (1970)]



- 1972 Gerald ‘t Hooft
  at the conference in Marseille discussion after Kurt Symanzik’s lecture (not in proceedings)

Color

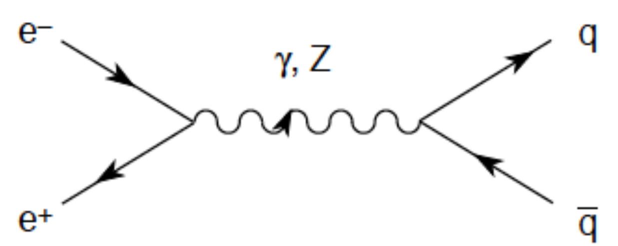
$$\Delta^{++} = u\uparrow u\uparrow u\uparrow \;\rightarrow\; u\uparrow u\uparrow u\uparrow$$

$$\Delta^{-} = d\uparrow d\uparrow d\uparrow \;\rightarrow\; d\uparrow d\uparrow d\uparrow$$

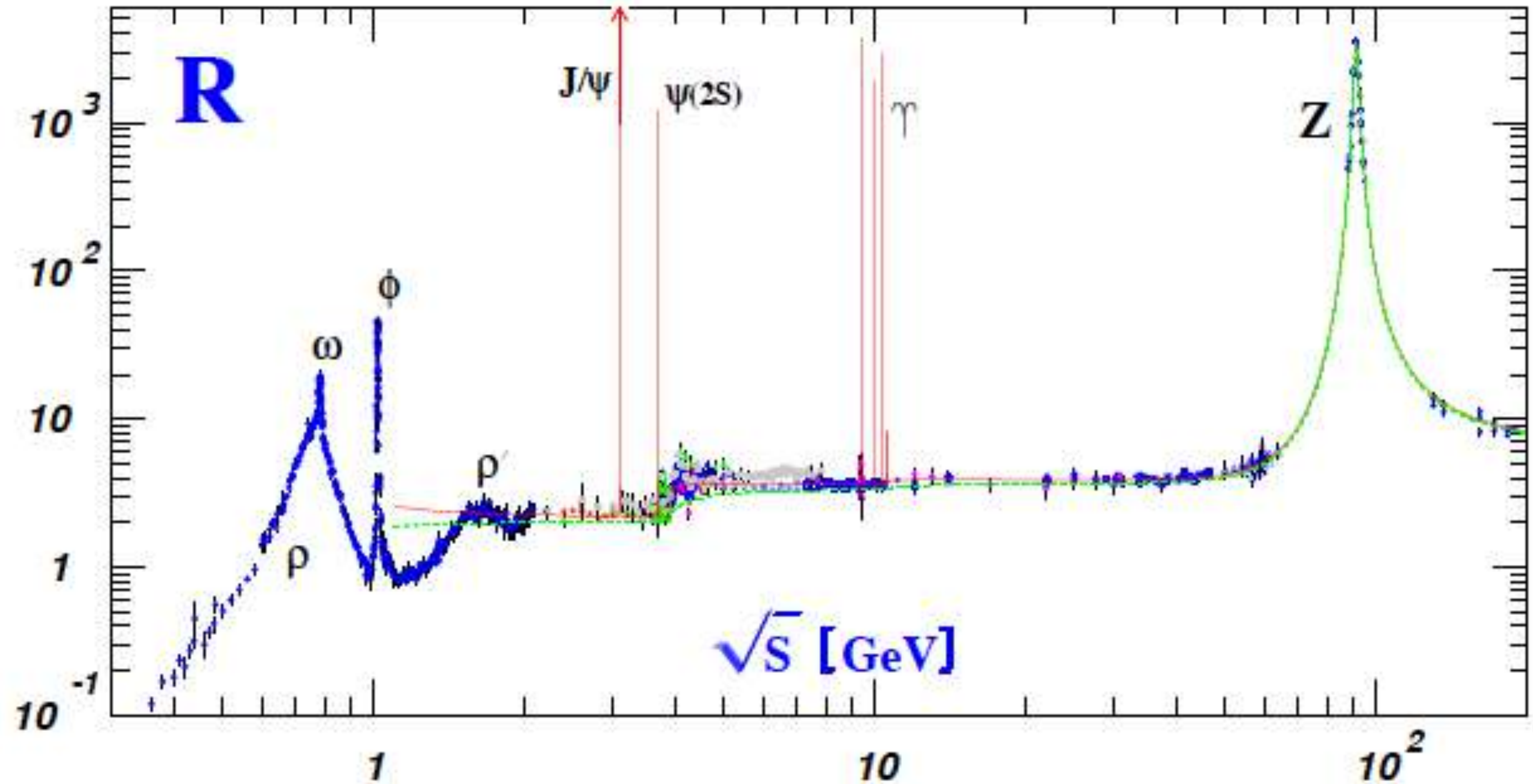
$$\Omega^{-} = s\uparrow s\uparrow s\uparrow \;\rightarrow\; s\uparrow s\uparrow s\uparrow$$

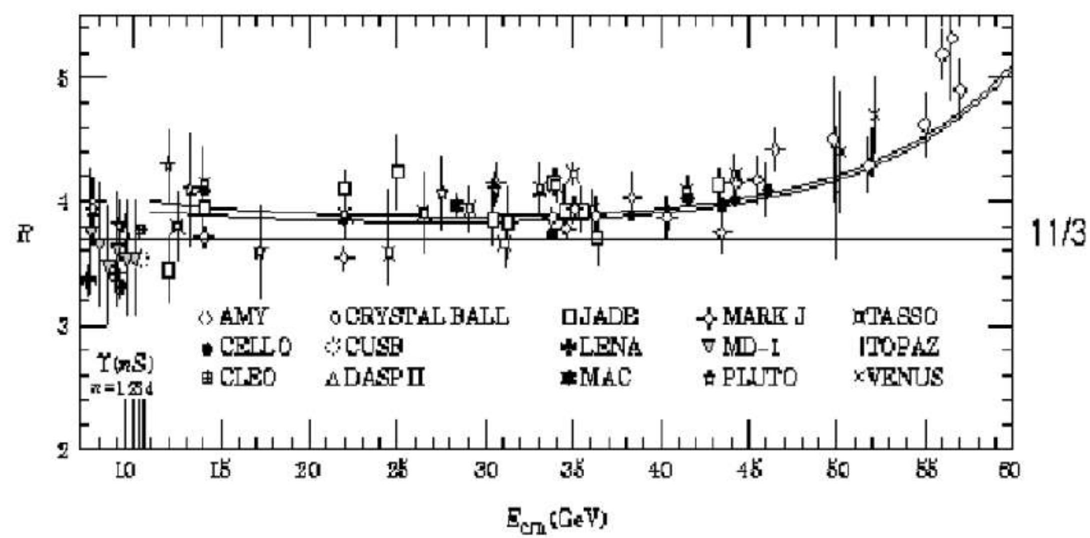
Geenberg, Nambu, Han, Gell-Mann, Fritzsch, …

$$R_{e^+e^-} \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



$$R_{e^+e^-} \approx N_C \sum_{f=1}^{N_f} Q_f^2 = \begin{cases} \frac{2}{3} N_C = 2\,, & (N_f = 3 \;:\; u,d,s) \\ \frac{10}{9} N_C = \frac{10}{3}\,, & (N_f = 4 \;:\; u,d,s,c) \\ \frac{11}{9} N_C = \frac{11}{3}\,, & (N_f = 5 \;:\; u,d,s,c,b) \end{cases}$$


R
J/ψ
ψ(2S)
ϒ
Z
φ
ω
ρ
ρ′
√s [GeV]
10^3
10^2
10
1
10^-1
1
10
10^2


R
11/3
AMY
CRYSTAL BALL
JADE
MARK J
TASSO
CELLO
CUSB
LENA
MD-1
TOPAZ
CLEO
DASP II
MAC
PLUTO
VENUS
ϒ(nS)
E_cm (GeV)

Quantum Chromodynamics

It became clear that a good theory to describe the strong interactions is Yang – Mills theory based on local SU(3) mentioned in an article from1973 by Gross and Wilczek

- 1973

CALT 68-409
AEC RESEARCH AND
DEVELOPMENT REPORT

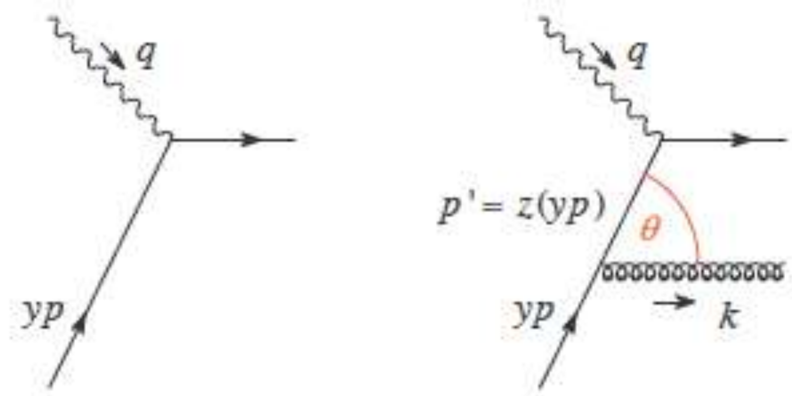
Advantages of the Color Octet Gluon Picture*

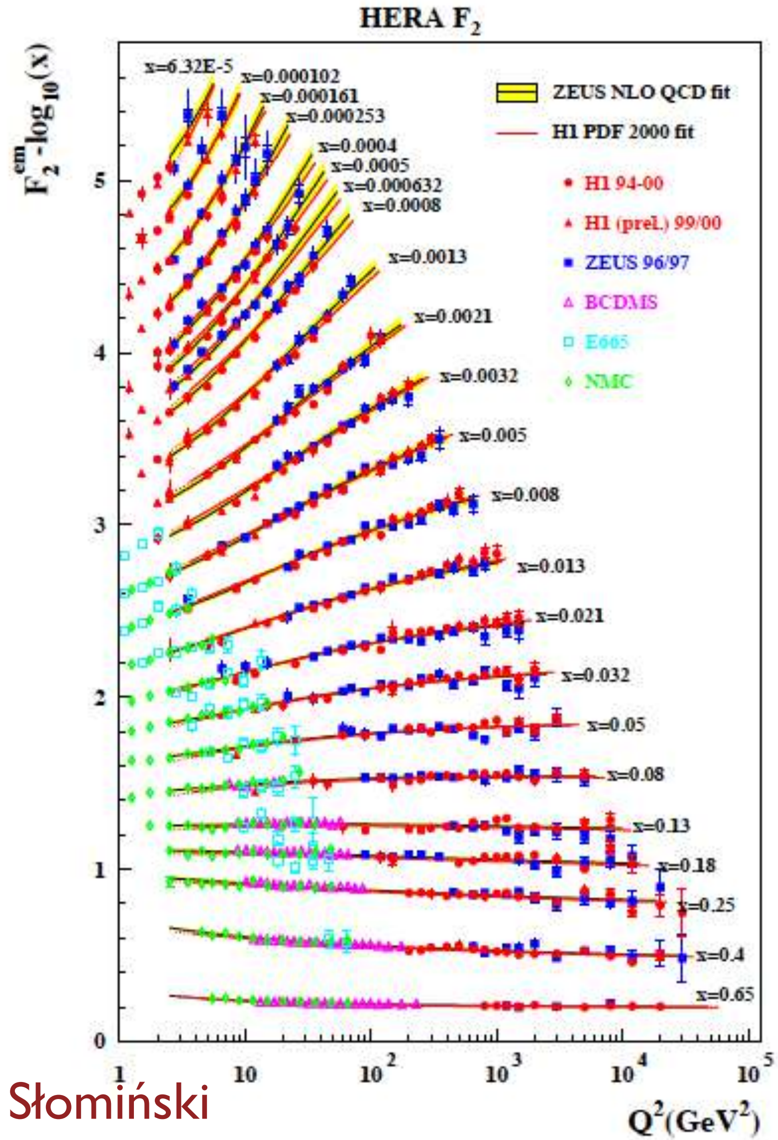
HARALD FRITZSCH†, MURRAY GELL-MANN and HEINRICH LEUTWYLER††

California Institute of Technology, Pasadena, California 91109

The name QCD first appeared in the review by Marciano i Pagels (1978), where it is attributed to Gell-Mann.

Corrections to Bjorken scaling

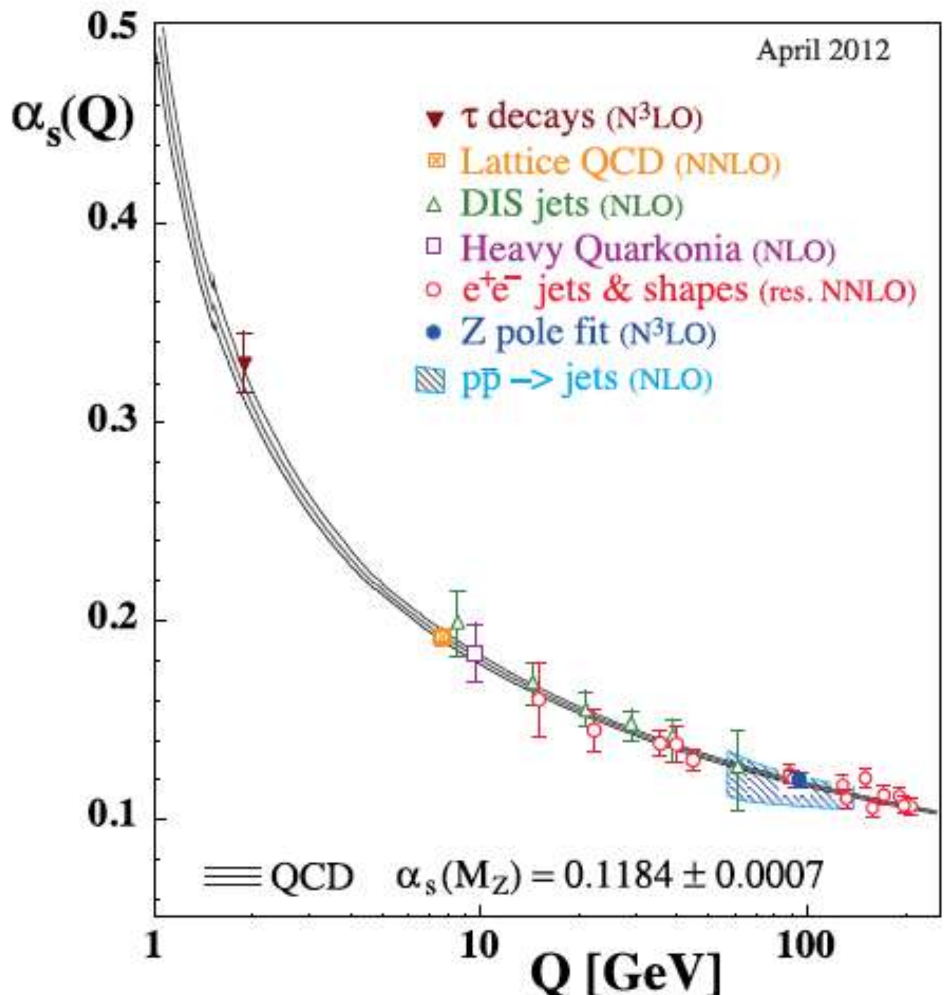




Evolution equations (DGLAP):
Altarelli, Parisi,
Dokshitzer, Gribov, Lipatov

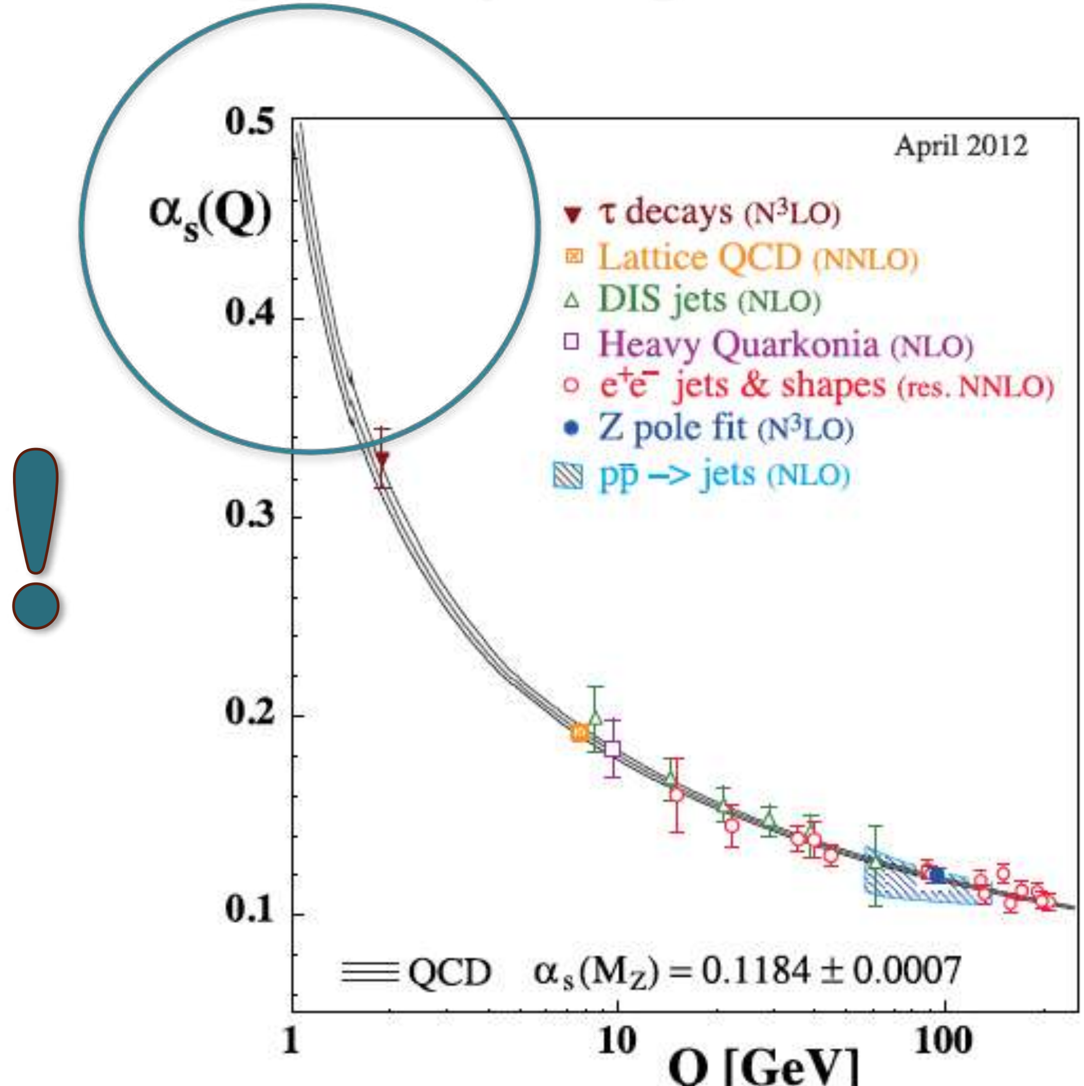
higher order corections:
Curci, Furmański, Petronzio; Furmański, Słomiński

Running coupling constant



G. Ecker

Running coupling constant

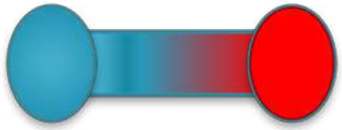


G. Ecker

Confinement

For long distances, the coupling constant increases.

Quark-gluon string



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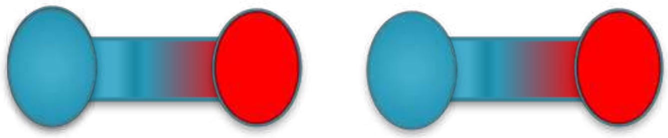

Confinement

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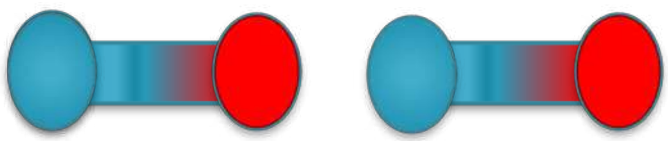
Quark-gluon string

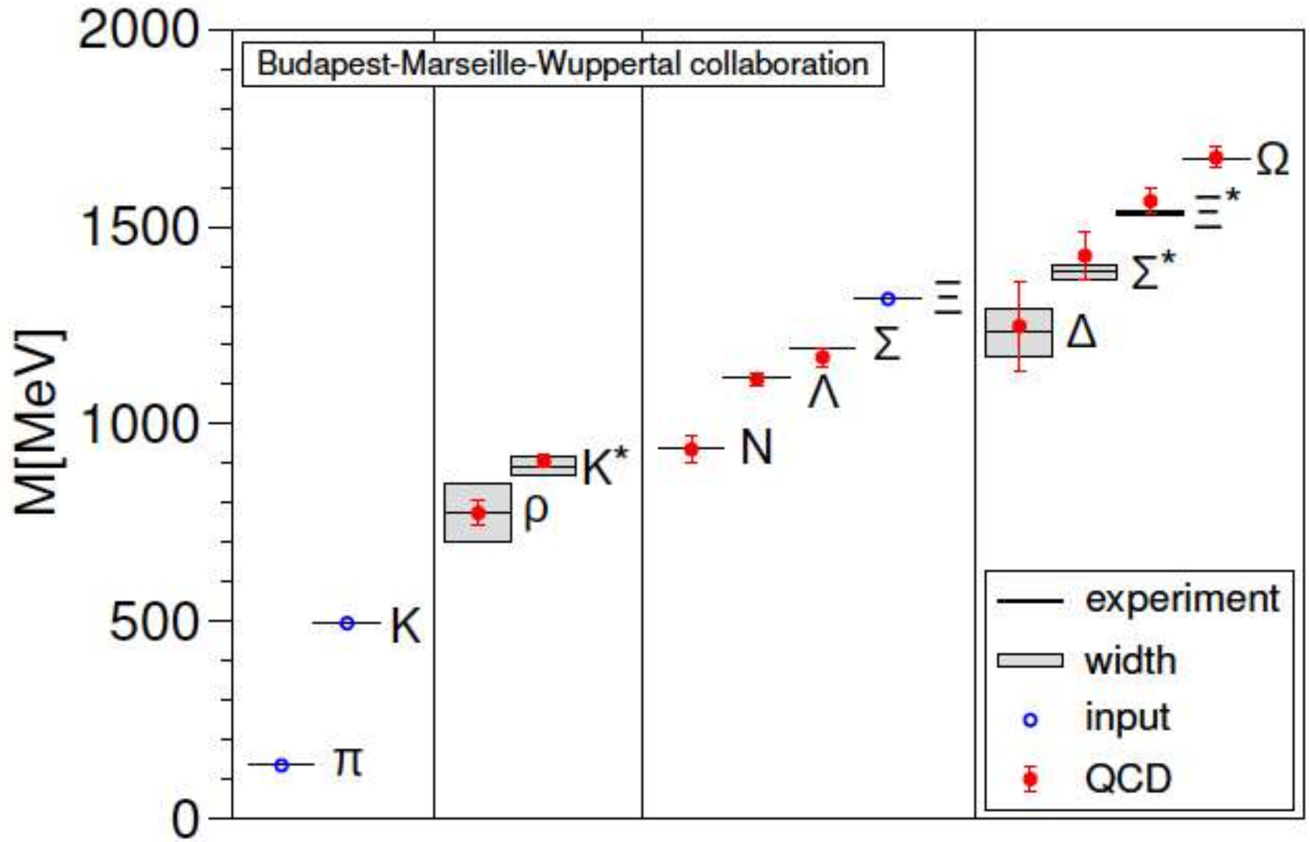


New nonperurbative techniques in field theory:

- FT on the lattice (Kenneth Wilson, 1974)
- Classical solutions (eg. instantons, 1975:
  Belavin, Polyakov, Tyupkin, Schwarz, ‘t Hooft,)
- Sum rules
- Effective models
- AdS/CFT correspondence

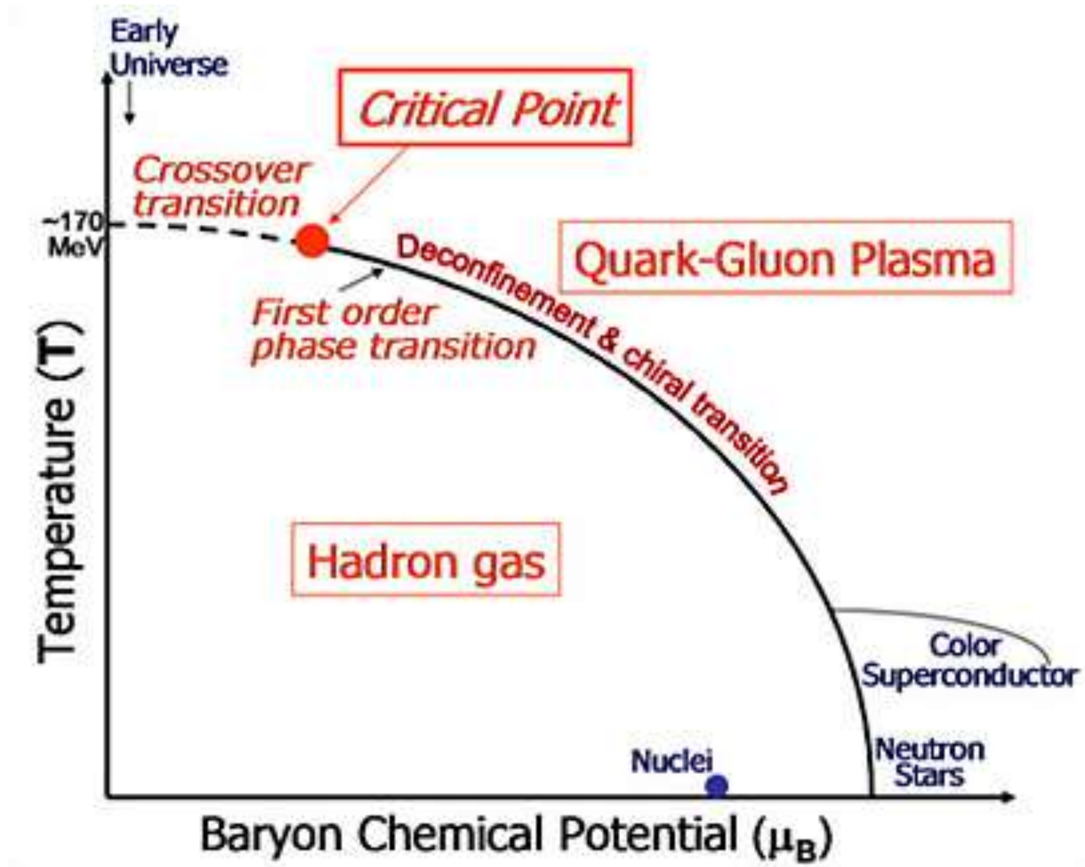
Lattice QCD

Wilson 1974, first simulations Creutz 1981



Zoltan Fodor, Zakopane 2011

Phase trasition confinement – deconfinement



Phase trasition confinement – deconfinement

Literature: discrepancies between T_c

Bielefeld-Brookhaven-Riken-Columbia Collaboration:

M. Cheng et.al, Phys. Rev. D74 (2006) 054507

T_c from $\chi_{\bar{\psi}\psi}$ and Polyakov loop, from both quantities:

T_c=192(7)(4) MeV

Bielefeld-Brookhaven-Riken-Columbia merged with MILC: 'hotQCD'

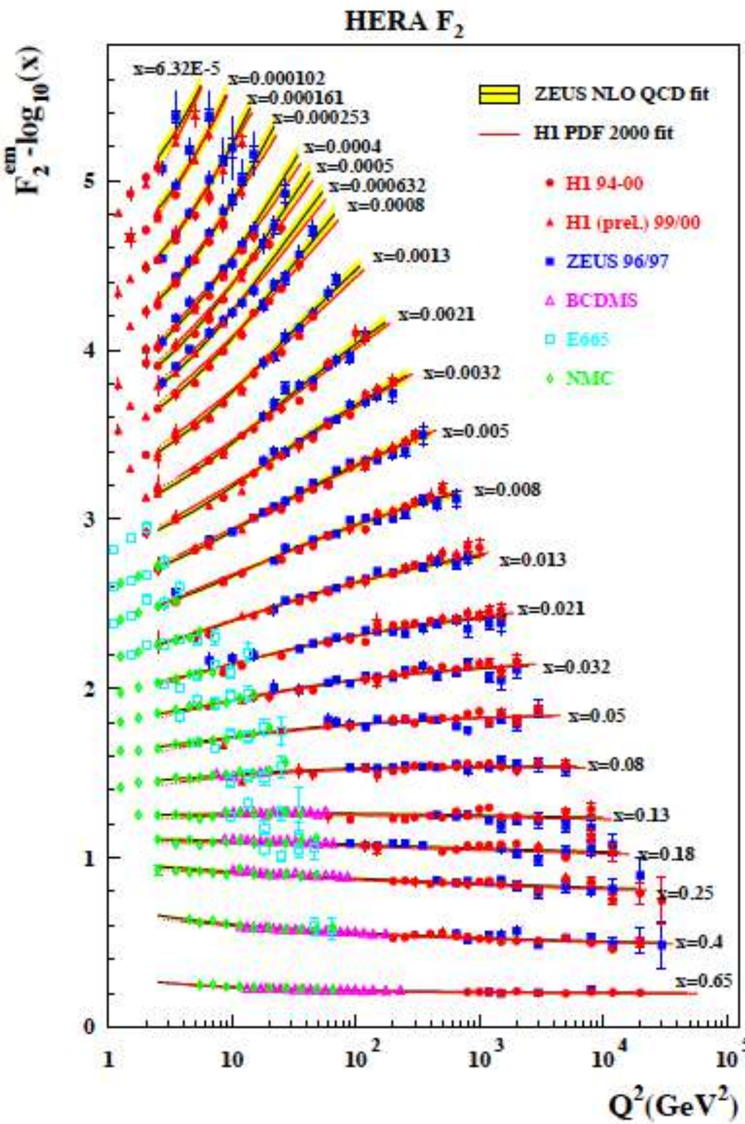
Wuppertal-Budapest group: WB

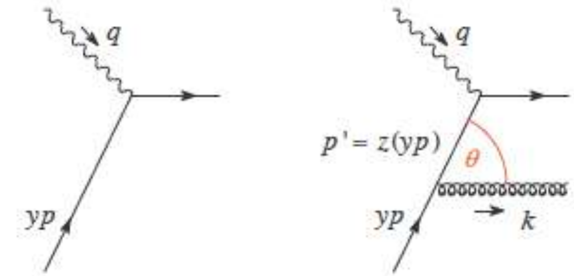
Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, Phys. Lett. B. 643 (2006) 46

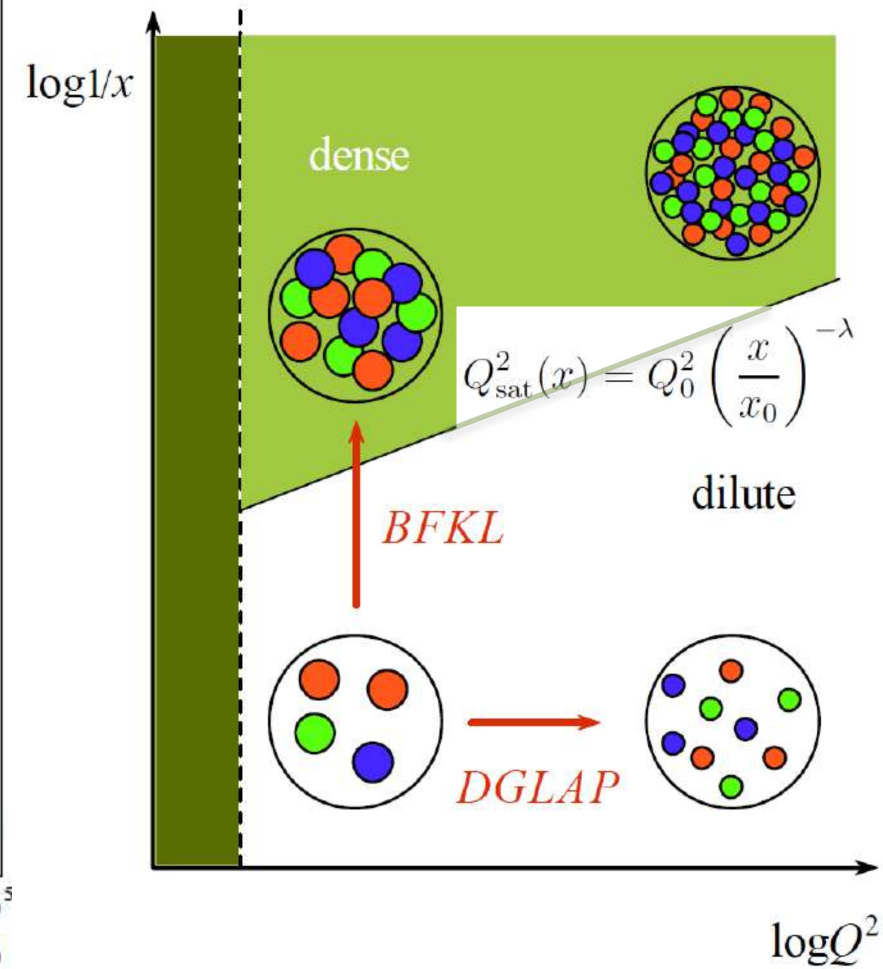
chiral susceptibility: T_c=151(3)(3) MeV

Polyakov and strange susceptibility: T_c=175(2)(4) MeV

Evolution eqs.







Effective QCD

up and down masses are of the order of a few MeV, why proton mass is ~ 1000 MeV, requiring quark masses to be of the order of 350 MeV?

Sponteneous chiral symmetry breaking.

In short: proton mass if fully generated by strong interactions, not by the Higgs mechanism quark mass.

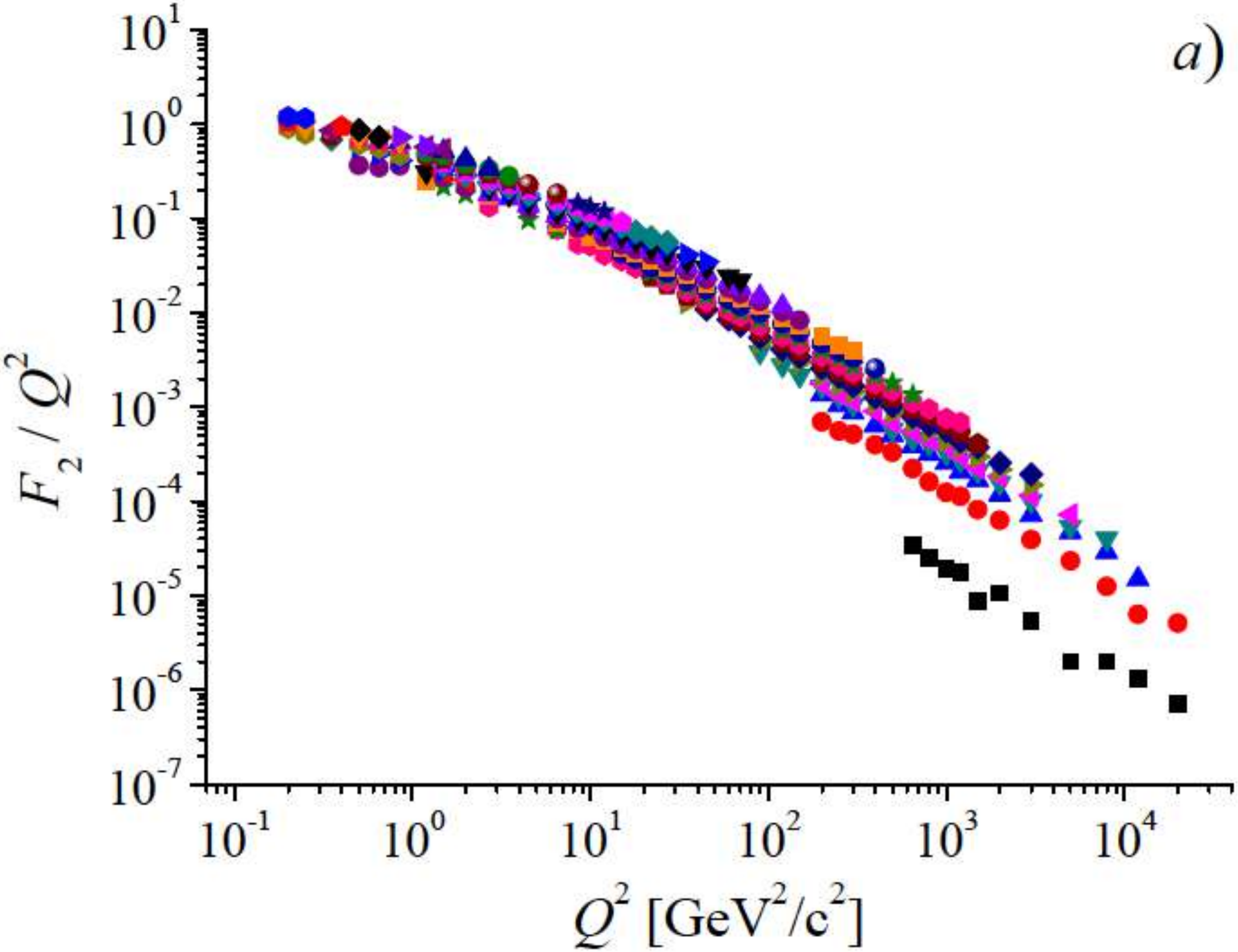
Effective QCD is a realization of the chiral symmetry breaking in terms of effective degrees of freedom: Goldstone bosons, i.e. pseudoscalar mesons

Saturation, geomerical scaling

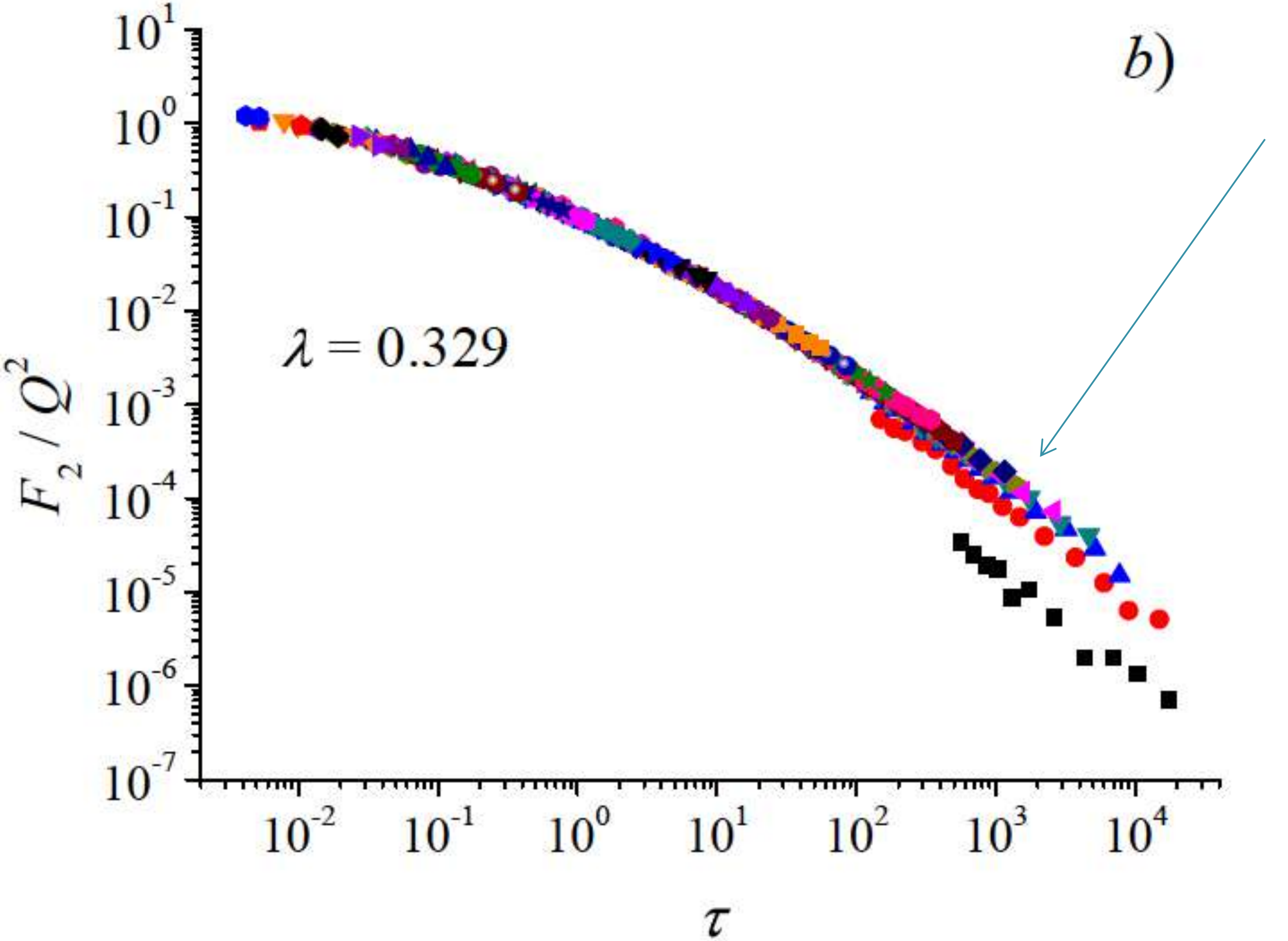
Geometric scaling for the total γ^* p *cross-section in the low* x *region*.
A.M. Stasto, K. J. Golec-Biernat , J. Kwiecinski PRL 86 (2001) 596-599

$$\sigma_{\gamma^* p}(x, Q^2) = \sigma_{\gamma^* p}\left(\frac{Q^2}{Q^2_{\mathrm{sat}}(x)}\right)$$

Saturation, geomerical scaling



Saturation, geomerical scaling



Summary

- Trimumph of Quantum Field Theory
- Dedidaced experiments"
- Progress - fighting prejudices and habits
- New tools: computers
- What was once a discovery is part of today "engineering"

Dziękuję