The decade of 1969 - 1979:
How quarks and gluons became a reality

Paul Söding

formerly

DESY
and Humboldt University zu Berlin

How we were incredibly stupid 40 years ago

Paul Söding

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DESY
and Humboldt University zu Berlin

In the **1960s**, **4 basic forces observed in nature**:

Gravitation, **Electromagnetism:** reasonably understood

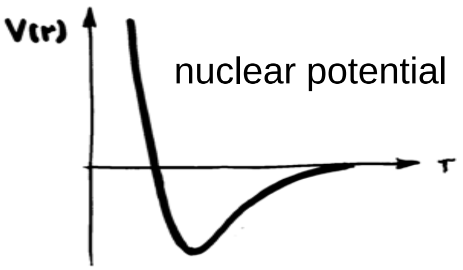
Weak interactions
(radioactivity, particle decays, neutrinos, energy procuction in stars)

phenomenological theory (Fermi, Feynman + Gell-Mann V-A)

Strong interactions (nuclear binding, hadrons):

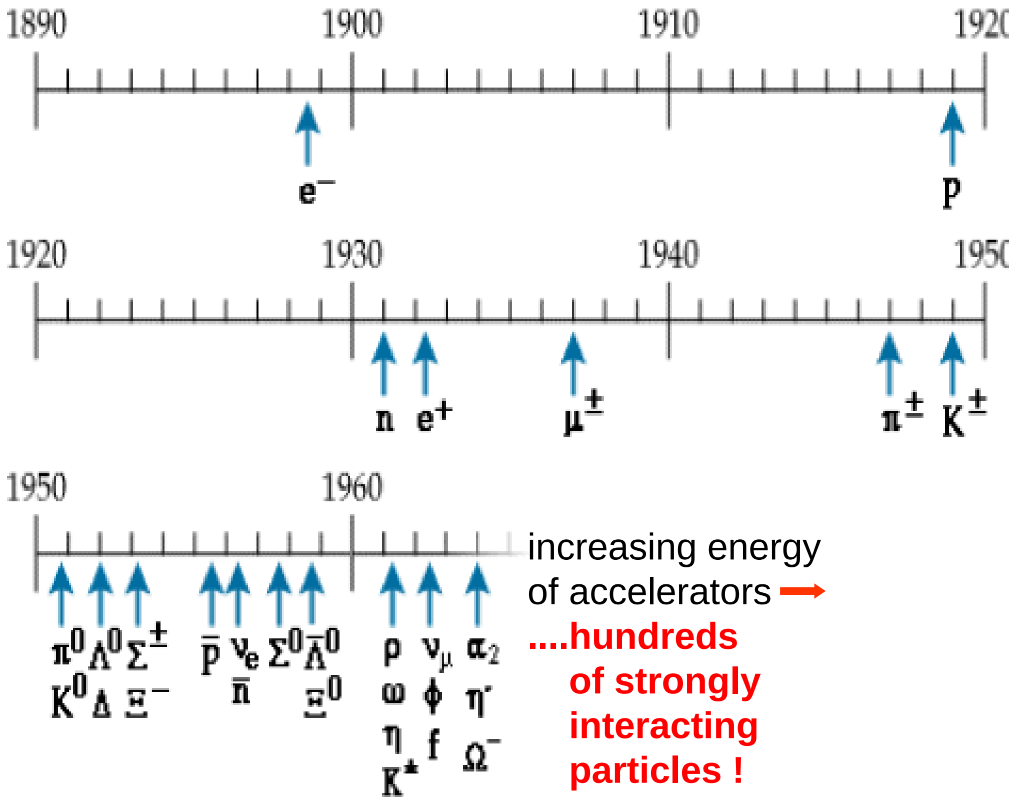
Theory: Yukawa (1935) -> Pion

but field theory
not quantitatively successful



Very mysterious:
Many “elementary particles” (mesons, baryons, resonances, strange ...)

F. Dyson: *“The correct theory will not be found in the next 100 years.”*

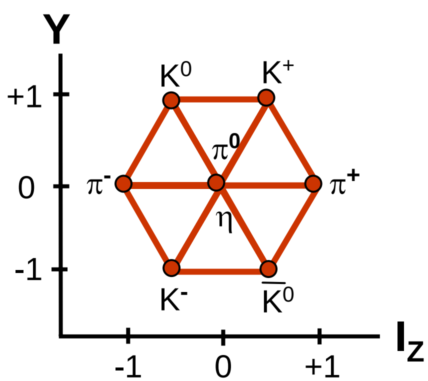

1890
1900
1910
1920
e⁻
p
1920
1930
1940
1950
n e+
μ±
π± K±
1950
1960
increasing energy
of accelerators
....hundreds
of strongly
interacting
particles !

1962:
SU(3) symmetry (Gell-Mann, Ne'eman)

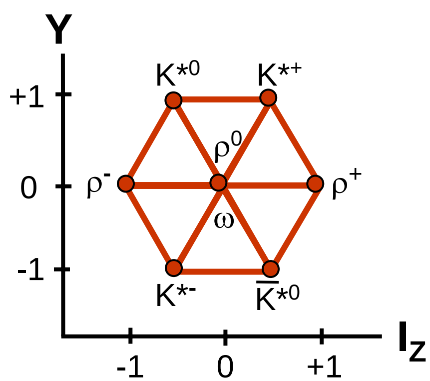
mesons

baryons

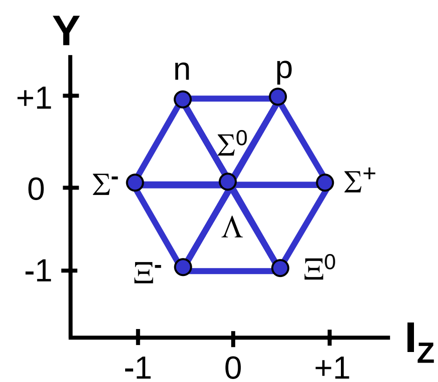
$J^P = 0^-$



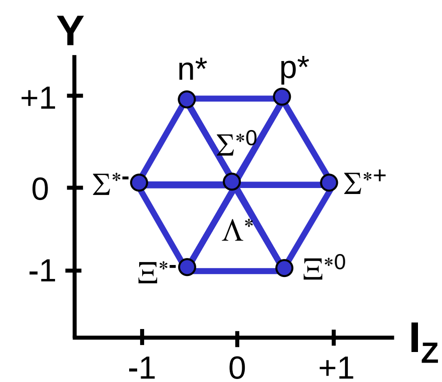
$J^P = 1^-$

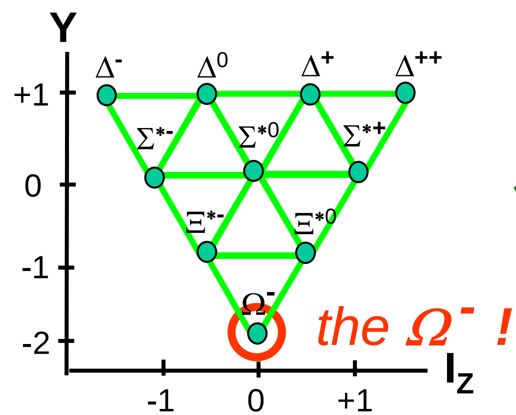


$J^P = 1/2^+$



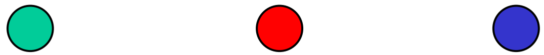
$J^P = 3/2^-$





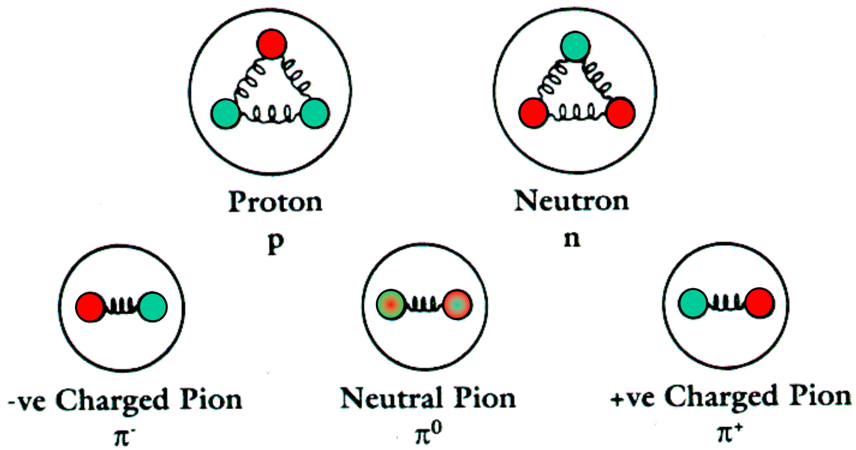
$J^P = 3/2^+$

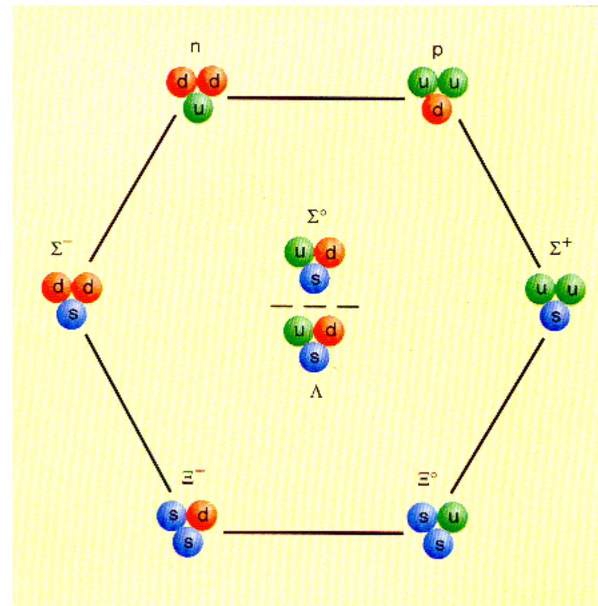
1964 Quark model (Gell-Mann, Zweig)



up *down* *strange*

can motivate the SU(3) symmetry patterns





Problems:

- wrong statistics for spin ½ quarks
- particles with charge 2/3, -1/3 not seen
- quantitative results lacking

Consensus (Gell-Mann 1972):

Quarks are ficticious, purely mathematical entities

S-matrix theory

Formulate a theory of the strong interactions using only the observable S-matrix elements, measured in scattering experiments.

A theory based on general principles such as:
Unitarity, analyticity, symmetry and self consistency requirements;
hope that these determine the S-matrix uniquely!

Microscopic dynamics (constituents, fundamental forces) irrelevant.
The way to deal with the increasing number of candidates for elementary status is to proclaim that all the hadrons are equally fundamental, all being bound states of each other:

"***Nuclear Democracy***" (emergent concept)

Successes: Dispersion relations, Regge poles
Veneziano 1968

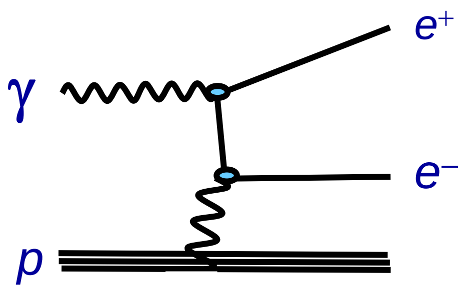
$$A(s,t) = \frac{\Gamma(-\alpha(s))\,\Gamma(-\alpha(t))}{\Gamma(-\alpha(s)-\alpha(t))}$$

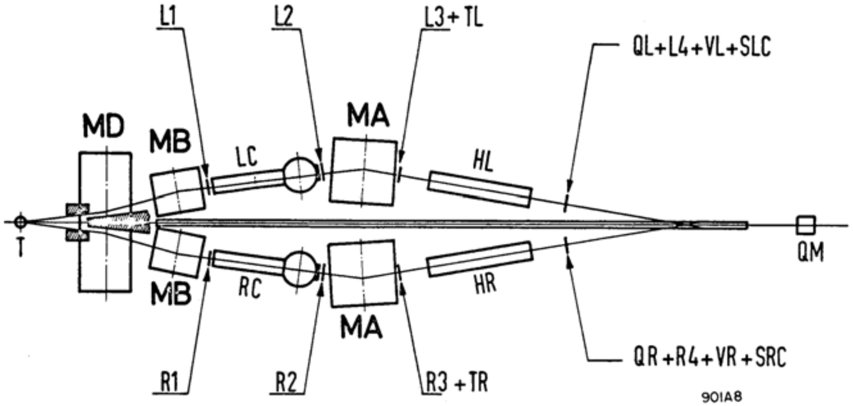
DESY in 1965: 6 GeV electrons

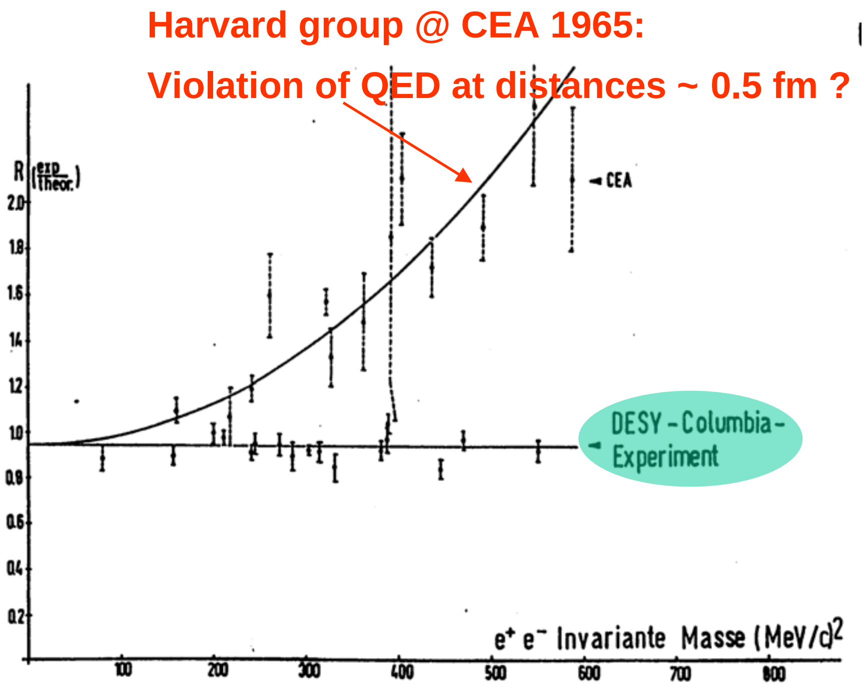
Limit to the validity of QED ?

Wide angle e⁺e⁻ pair production

DESY-Columbia collaboration
S.C.C. Ting et al. (1966)



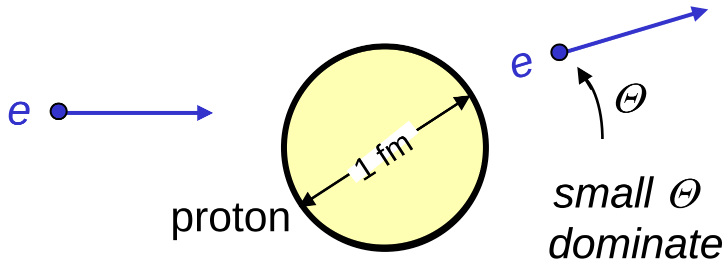


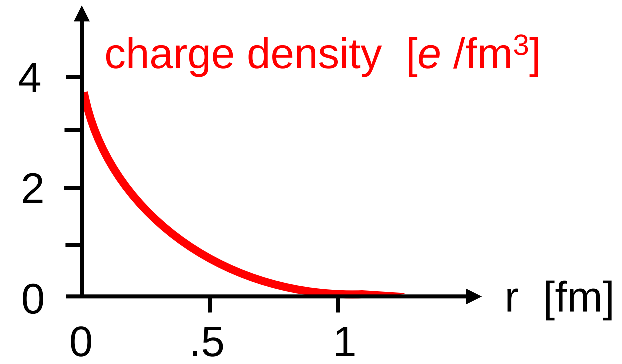


Electron scattering experiments:

DESY - 6 GeV
CEA (Cambridge Electron Accelerator) 6 GeV
SLAC (Stanford Linear Accelerator Center) - 20 GeV

Elastic scattering

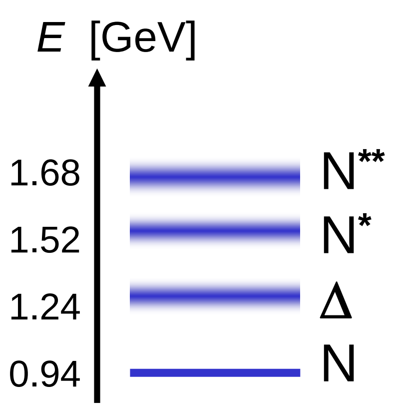




E_S = 4 ... 6 GeV
$\lambda\!\!\!^{-}$ = 0.05 fm

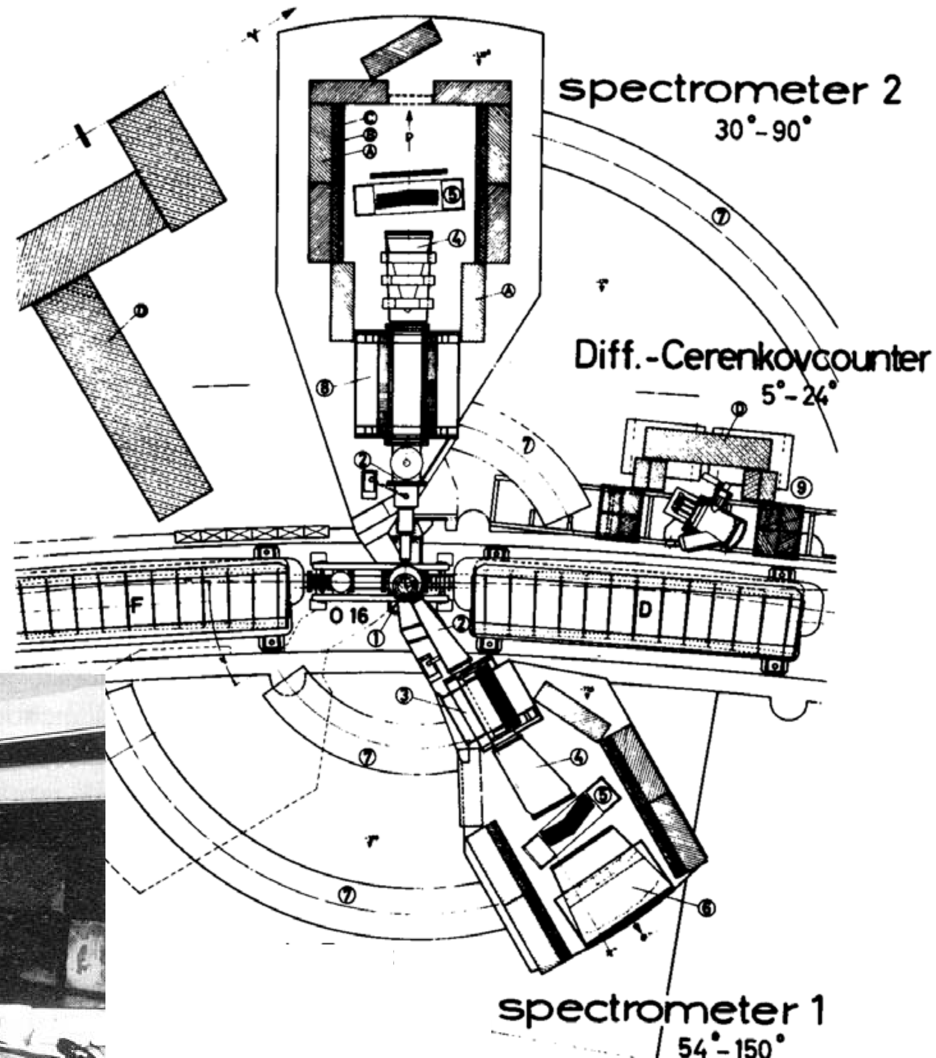
Inelastic scattering

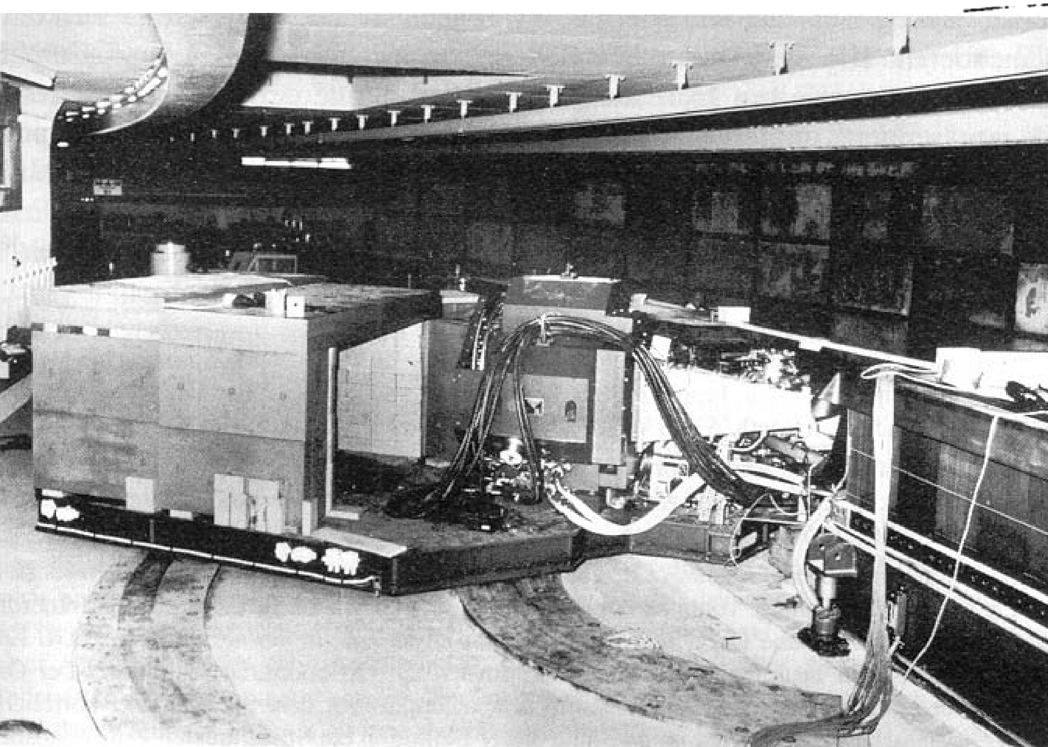
excited states
of the nucleon



Electron Proton Scattering @ DESY

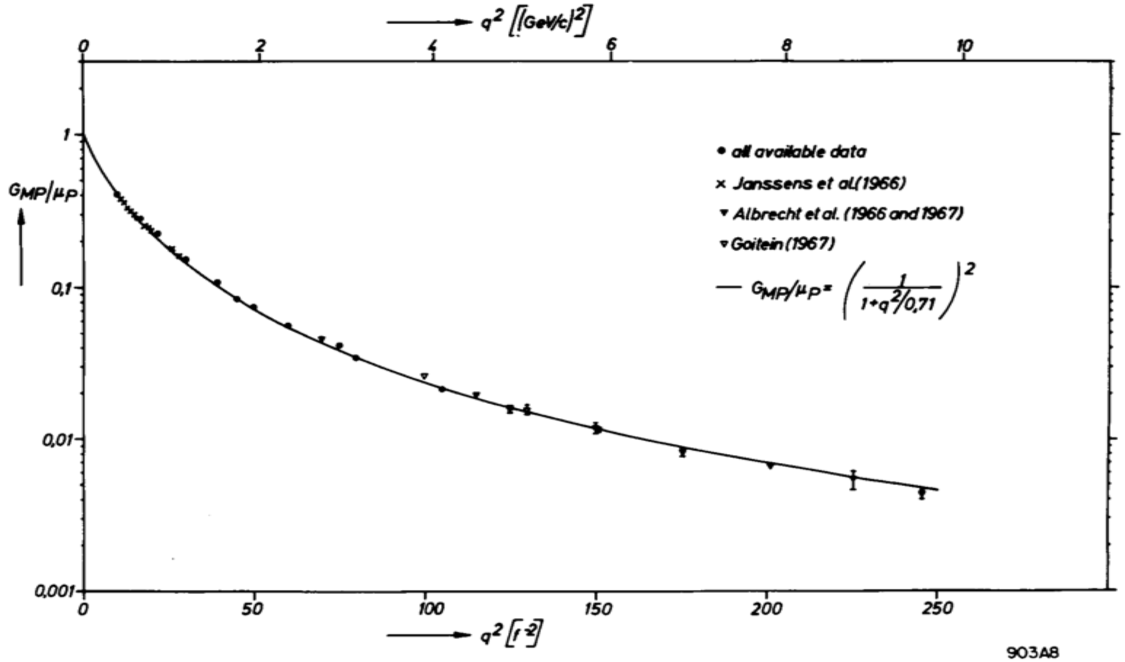
The experiment of DESY group F21



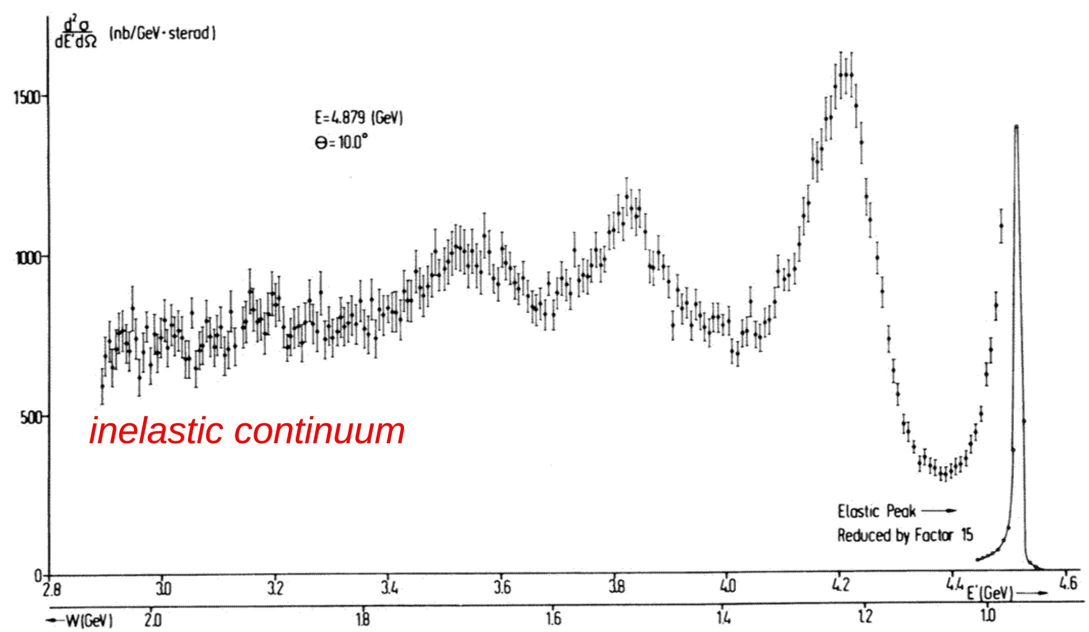


Electron Proton Scattering @ DESY 1965 - 1969

Proton magnetic form factor

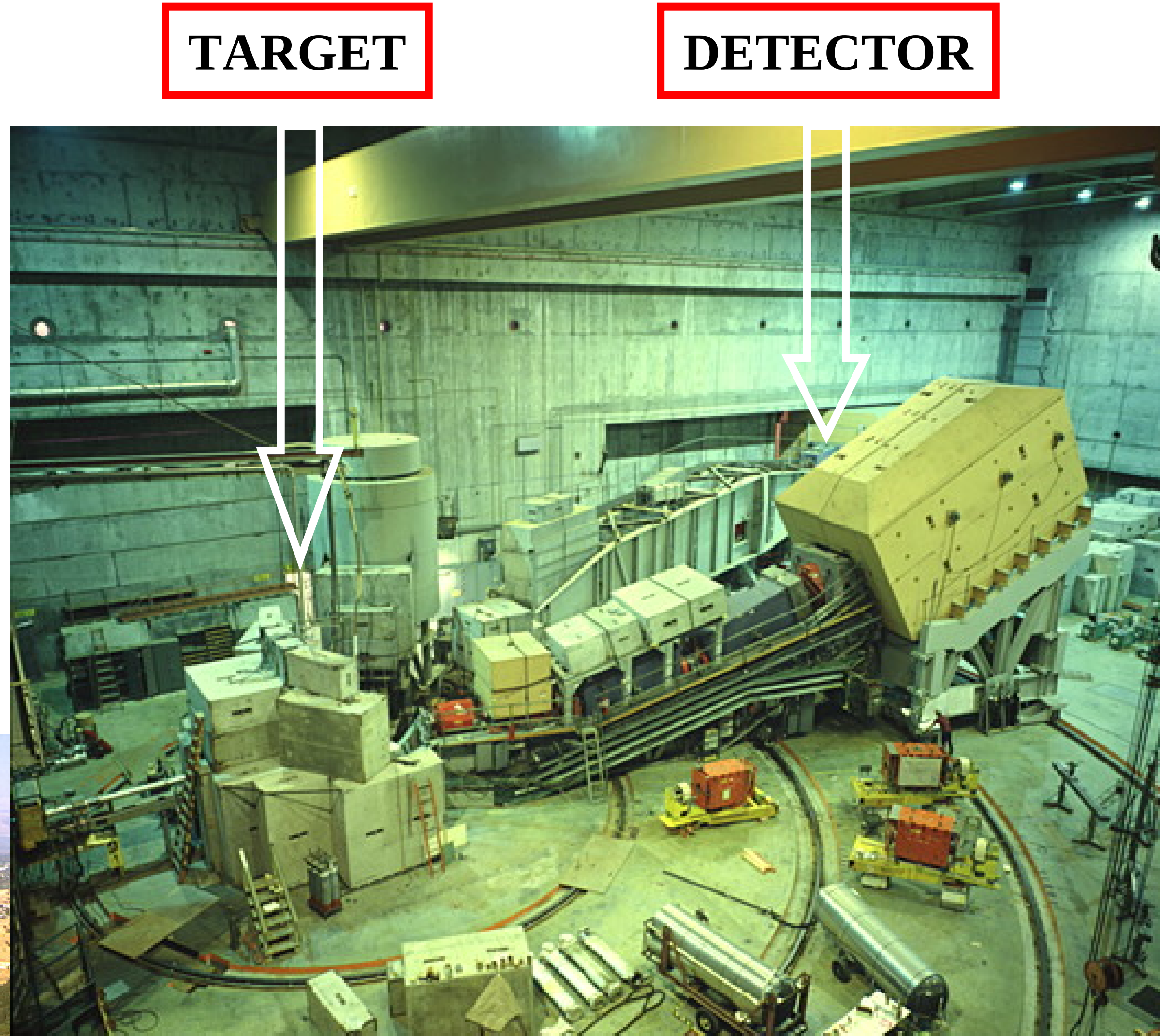


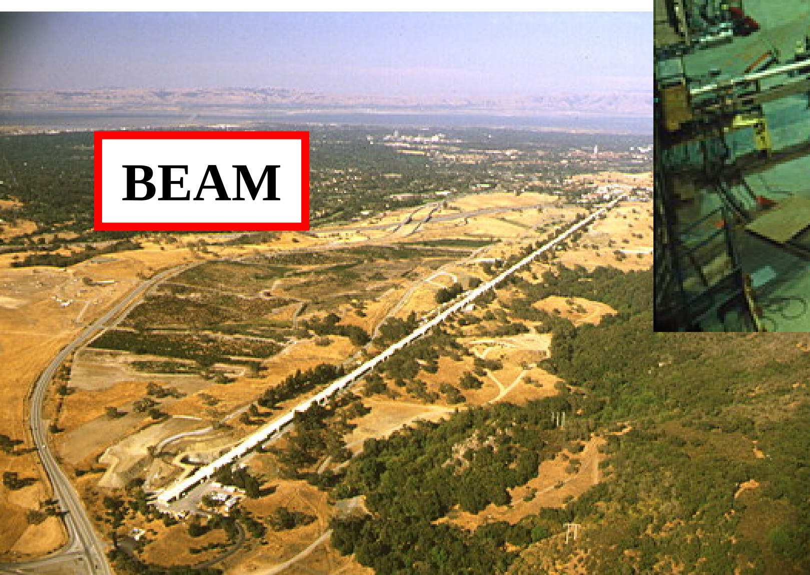
Proton resonance excitation



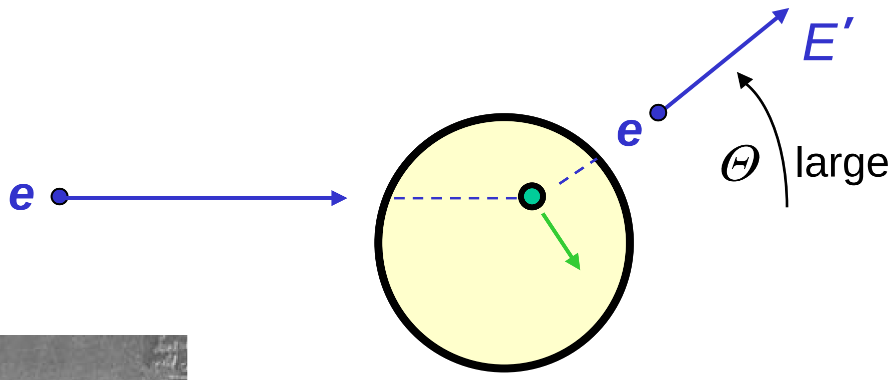
SLAC

(Stanford Linear Accelerator Center)



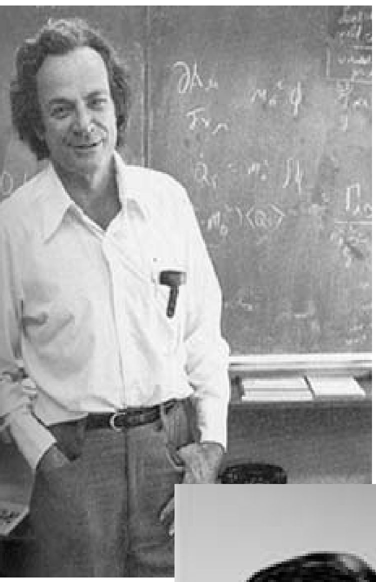


Deep inelastic electron nucleon scattering



$$\Delta E \equiv E - E' >> 1\,\mathrm{GeV}$$
$$(\cong 0.2\,\mathrm{fm})$$

$$Q^2 = (\vec{p} - \vec{p}\,')^2 - (E - E')^2$$



Feynman and Bjorken:

time resolution $\Delta t \cong \dfrac{\hbar}{\Delta E}$ (constituents moving around)

$\Rightarrow$ *Time averaging and coherence destroyed*

Recoil momentum transferred to single, quasi free constituent ("parton")

spatial resolution ~ impact parameter
~ 1 / momentum transfer Q

Measured cross section expressed in terms of a **structure function** F_2

Can depend on 2 kinematic parameters, choose Q^2 and $x = Q^2 / 2m_\mathrm{p}\Delta E$

$$\frac{d\sigma}{dQ^2 dx} \propto F_2(Q^2, x)$$

For pointlike constituents fixed in number: $F_2(Q^2, x) = \sum_{\mathrm{all}\ q,\bar{q}} e^2 \underbrace{x\, q(x)}_{\mathrm{d}n\, /\, \mathrm{d}(\ln x)}$

i.e. summed number densities of constituents weighted with (charge)^2

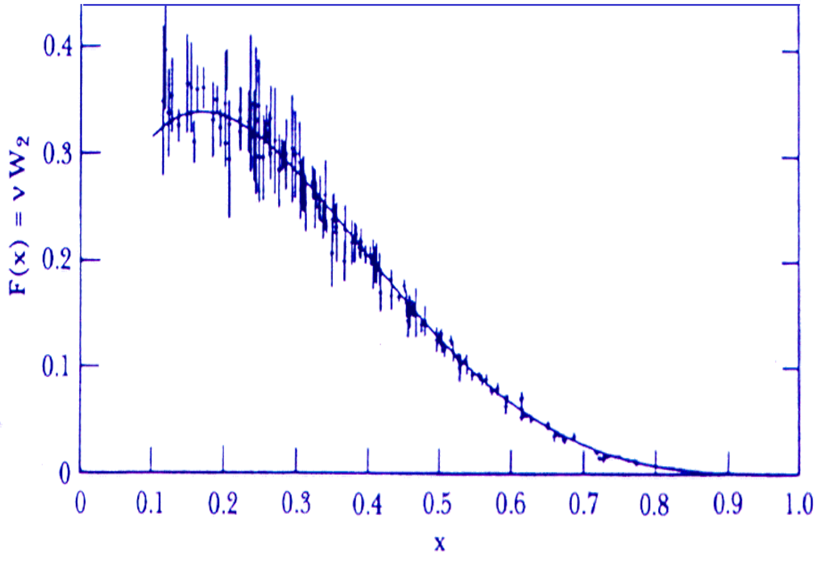
x = the fractional momentum carried by the scattering constituent

"**Scaling**": $F_2(Q^2, x)$ independent of Q^2

i.e. of the resolution $1/Q$ of the probing interaction

Experiments at SLAC (1969 . . .) :

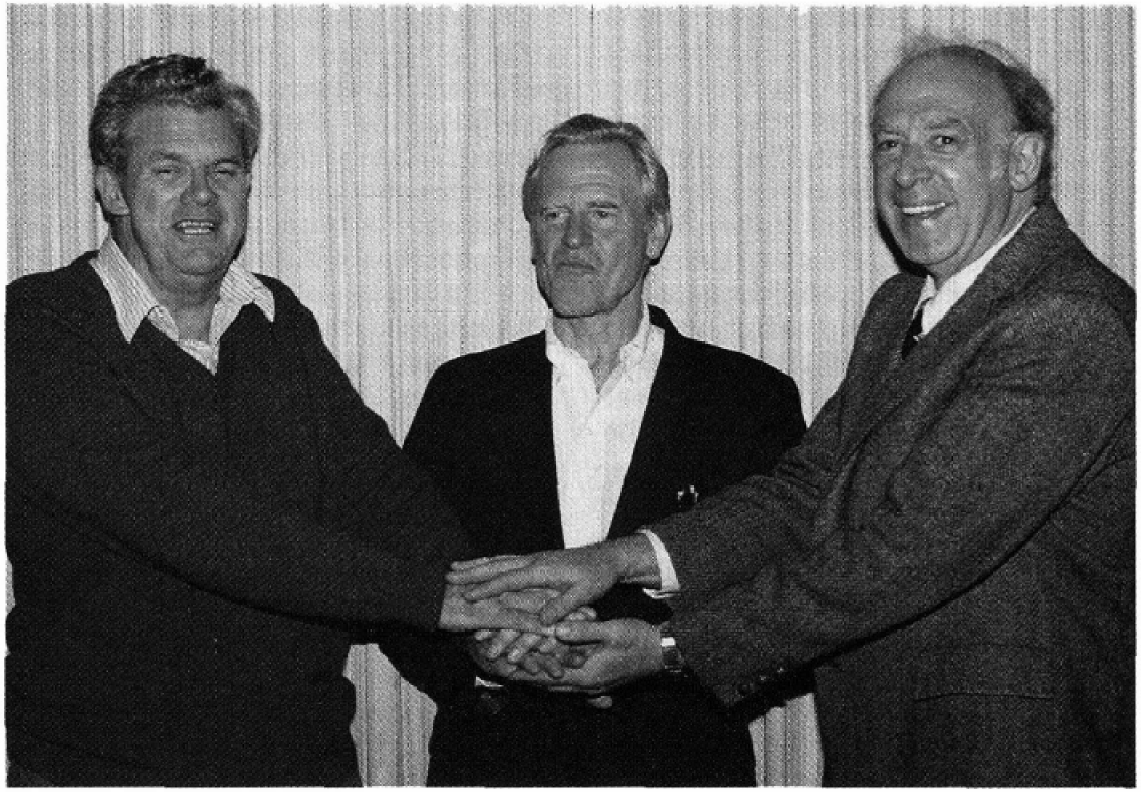
F_2 is a universal function of x for a wide range of Q^2



FRIEDMAN, KENDALL AND TAYLOR WIN NOBEL PRIZE FOR FIRST QUARK EVIDENCE

The 1990 Nobel Prize in Physics has been awarded to Jerome Friedman and Henry Kendall of MIT and Richard Taylor of SLAC "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics." The prize of $710 000, which the three recipients shared equally, was awarded in Stockholm on 10 December.

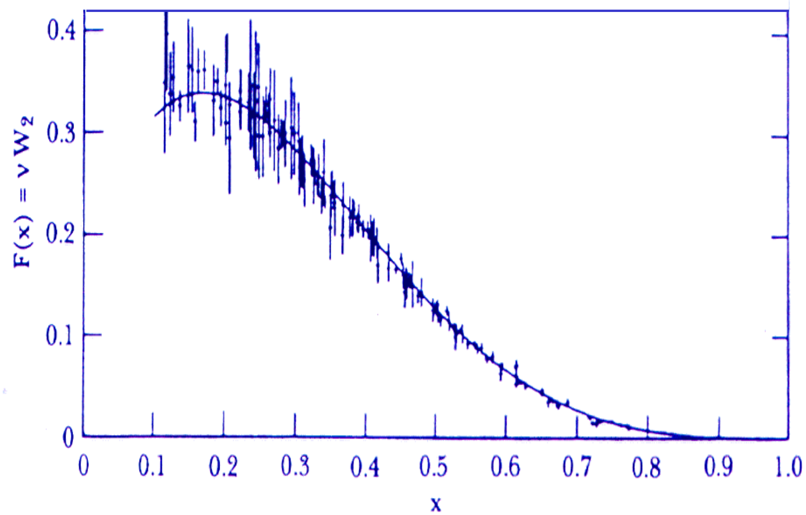
Friedman, Kendall and Taylor were honored for a series of experiments from 1967 and 1973 that used the then-new two-mile electron linear accelerator at Stanford to study deep inelastic scattering of electrons from protons and neutrons. The SLAC experiments were somewhat analogous to the experiment by Ernest Rutherford that gave evidence for a hard core within the atom: Just as



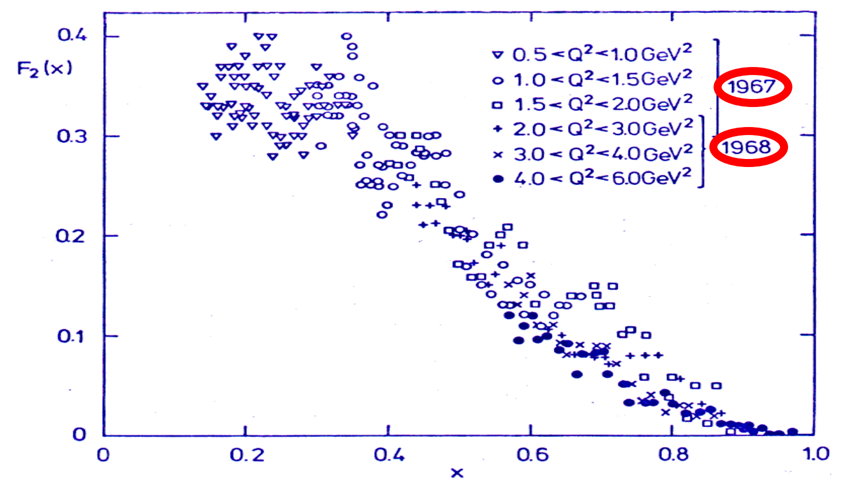
Could / should DESY have done it ?

The electron energy was much lower, but . . .

SLAC



DESY (reanalysis)



You may well call it stupidity . . .

But even by 1972, quarks were still not accepted as real

Feynman: *"The greatest challenge is to get some evidence of quark quantum numbers in high energy collisions."*

Leading textbook:

278 *Elementary Particle Physics*

there be a particle associated with each field.[1] If such quark particles existed, at least one of them would have to be stable, because baryon conservation would forbid the decay into "ordinary" particles. A search for new particles of this type has so far proved unsuccessful. In view of this failure and the difficulty of inventing a mechanism which would bind a quark and an antiquark, or three quarks, but not two quarks, for example, we will not discuss the quark model further.[2] The statement is also true

Getretner Quark wird breit, nicht stark.

(J. W. von Goethe, West-östlicher Divan)

General preoccupation:

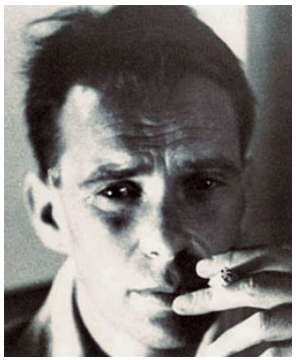
Hadron spectroscopy and high energy hadronic interactions

Signs were already appearing on the wall . . .
. . . understood by very few (if any)

e^+e^- colliding beams

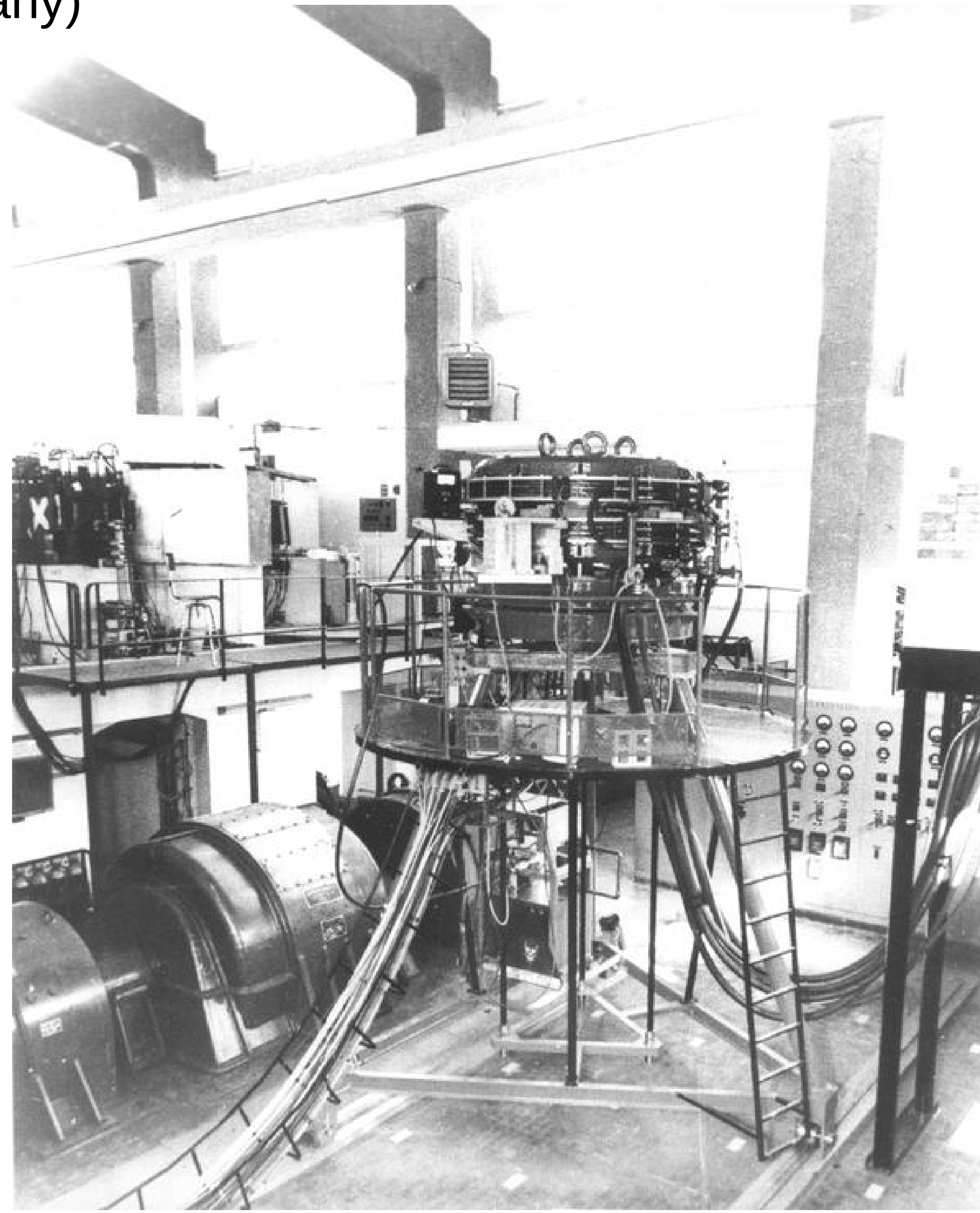
were to bring the breakthrough!

Early pioneer:
B. Touschek (Frascati)



"**Ada**" (1960 - 62)
e^+e^- 250 MeV
$L = 10^{24}\ cm^{-2}\ s^{-1}$

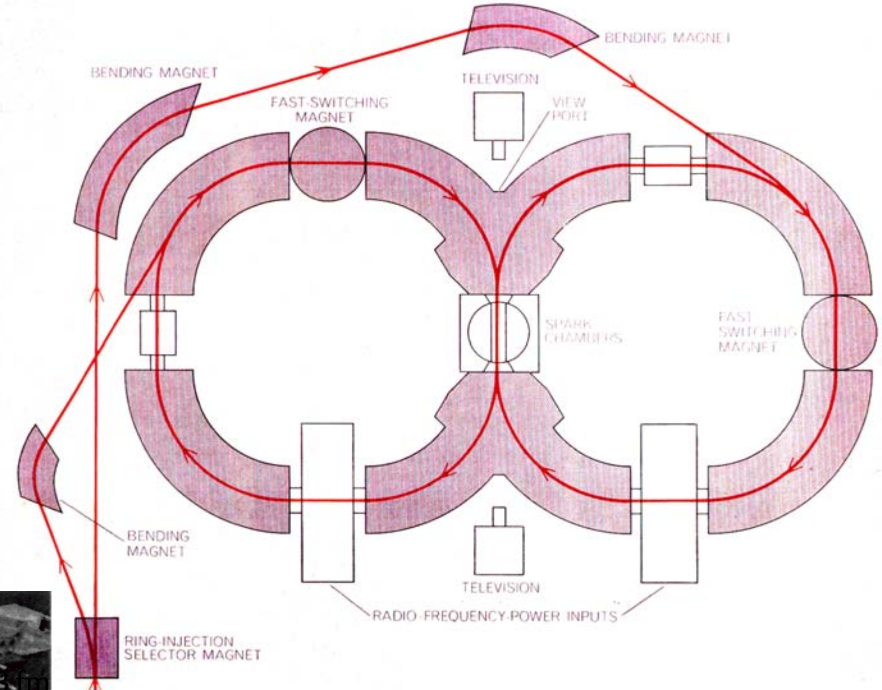
Also V. Budker (Novosibirsk)

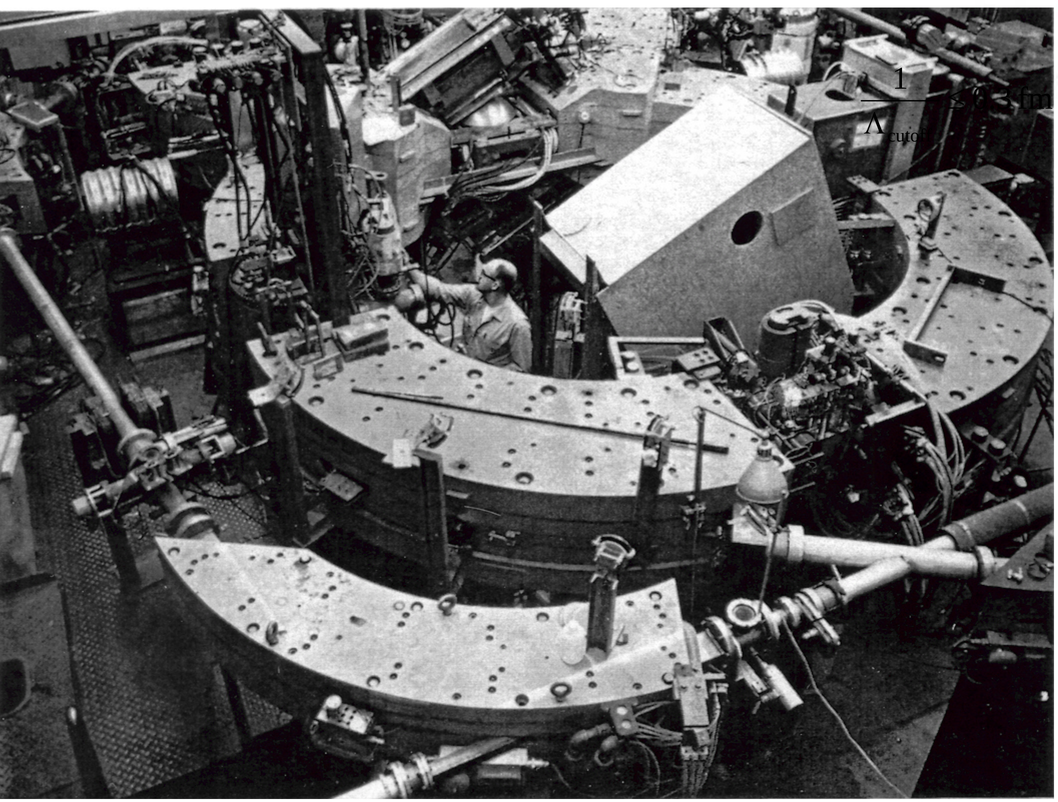


B. Richter et al, Stanford 1964 - 66:

“Unique tool for testing QED”

e^-e^- 600 MeV 400 events

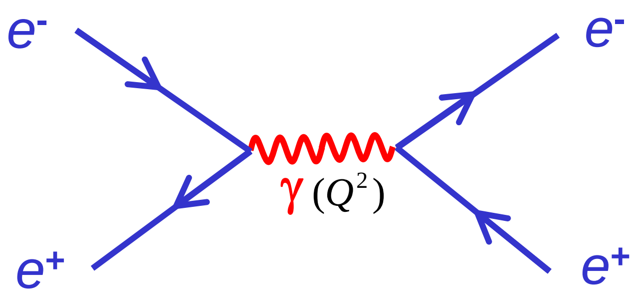




$$\frac{1}{\Lambda_{\text{cutoff}}} \leq 0.3\,\text{fm}$$ (“*smaller than r_P*”)

e^+e^- colliding beams

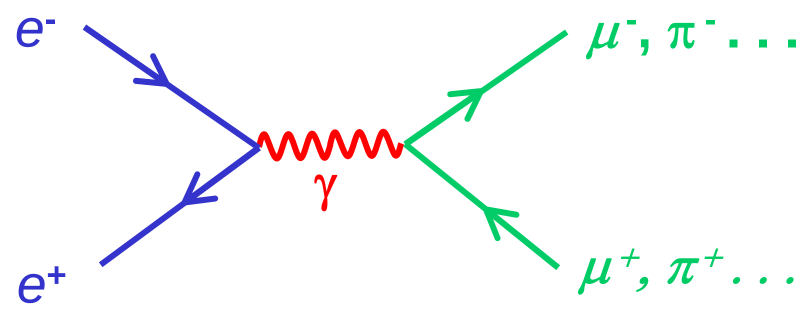
QED



timelike photon propagator $\sim \frac{1}{Q^2}$

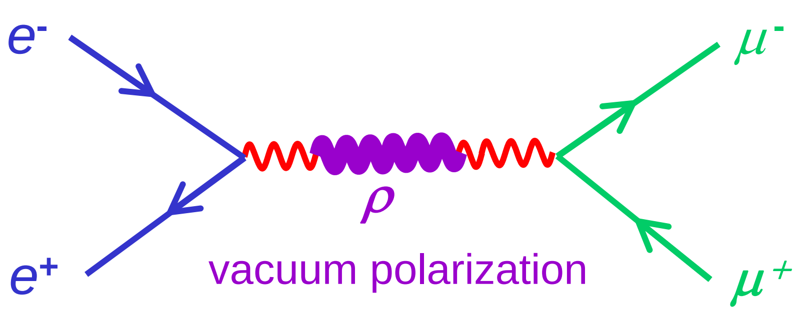
(Coulomb law at very small distances)

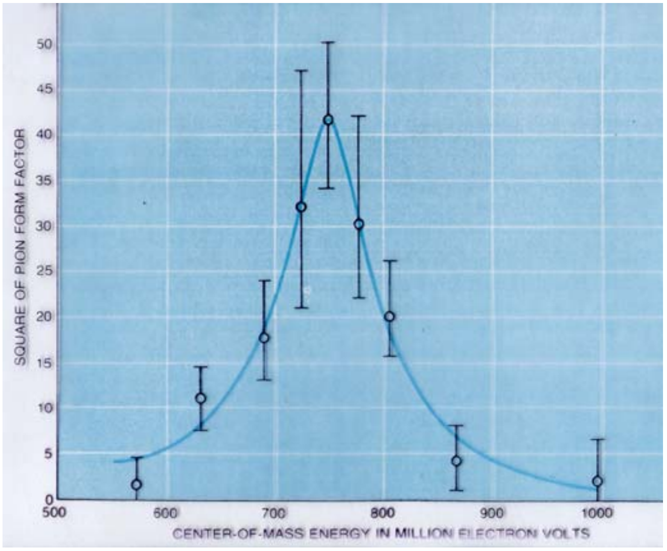
alchemy



"What is the muon?"
"Does it have structure?"

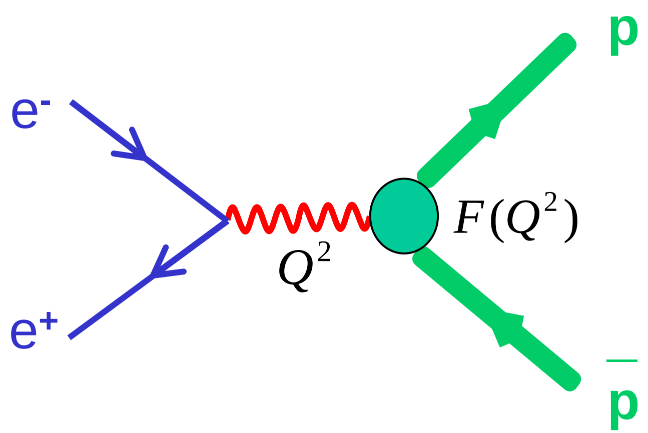
Vector meson formation (Novosibirsk 1967):





... I feel that this is an important step forward and I may quote Budker, who thinks that a few years from now a considerable portion (he thinks of 20%) of high energy physics will have come from storage rings. I think so too - only more so. (Touschek 1969)

Orthodoxy:
Prospects of e^+e^- colliders not very promising



$$\sigma \sim \frac{1}{Q^2} \left| F(Q^2) \right|^2$$

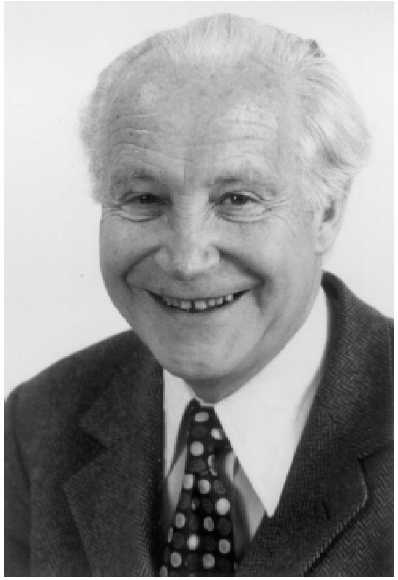
even QED processes are becoming small

decreases with high power of Q^2 (charge in hadrons smeared out)

⟹ ***"3 GeV is the highest practical energy!"***

Frascati (Touschek): ADONE
CEA (Cambridge Electron Accelerator): “Bypass”
Stanford: SPEAR

DESY Hamburg:
Doppelring "DORIS" 2 x 3 GeV

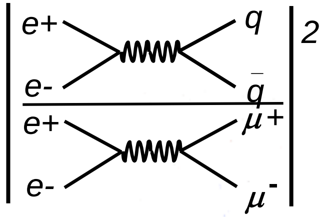


Willibald Jentschke

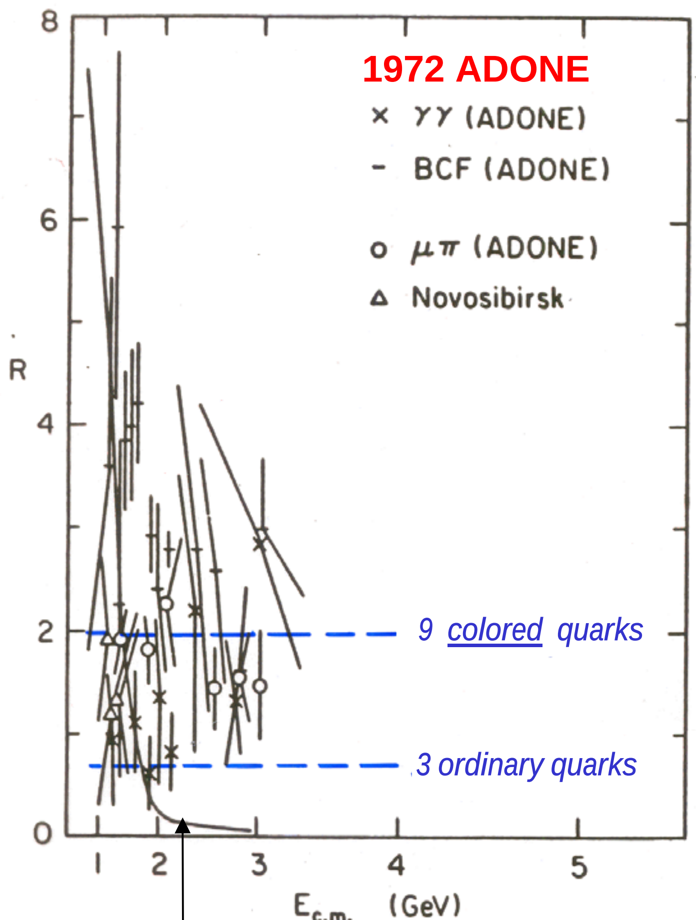
Erich Lohrmann

under construction 1969 - 1974

$$R \equiv \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} \equiv \left| \quad \right|^2 = e_d^2 + e_u^2 + e_s^2 = \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{2}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 = \tfrac{2}{3}$$



with 3 colors: **2**



prediction for hadron production

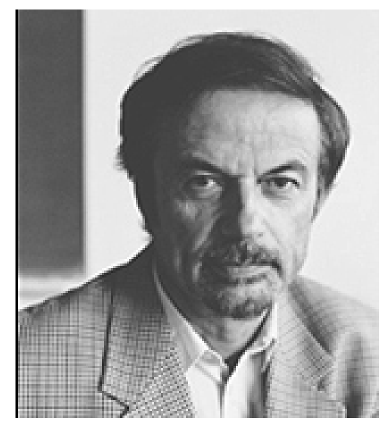
Dramatic:

Rate of hadron production remains large (i.e. of same order as muon production) up to 3 GeV

Even much larger than for 3 pointlike quarks !

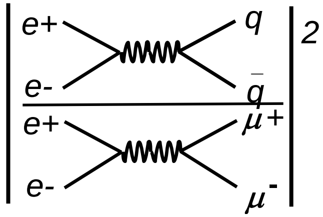
Fritzsch und Gell-Mann 1972:

Colored quarks !



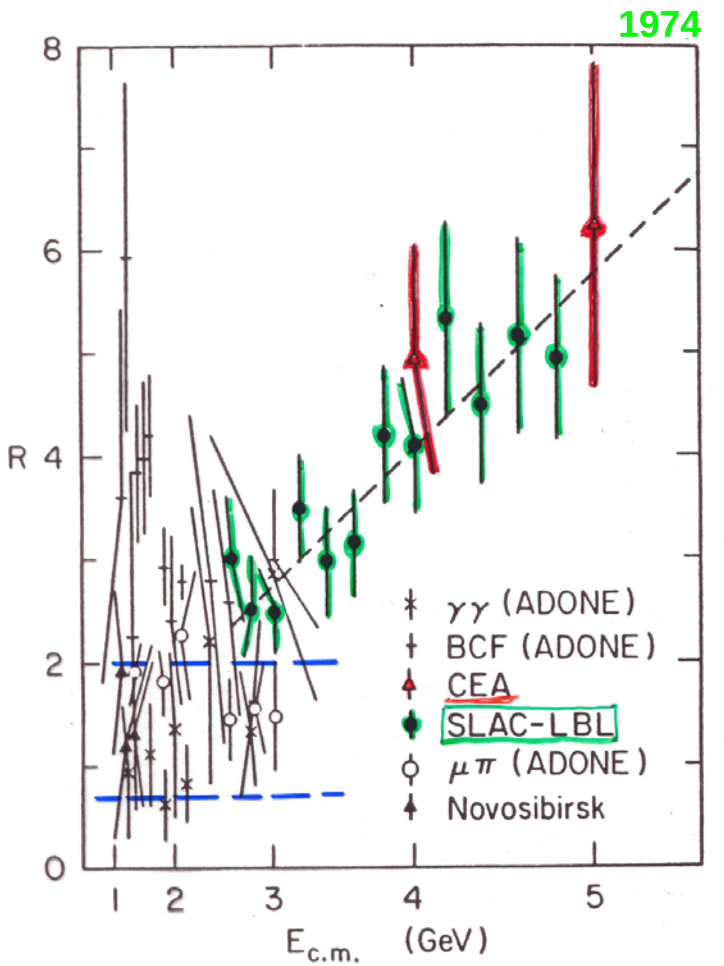
Harald Fritzsch

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



$$= e_d^2 + e_u^2 + e_s^2 \quad = \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{2}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 = \tfrac{2}{3}$$

with 3 colors: **2**



Data from the **CEA-bypass**
and from **SPEAR**:

Even colored quarks excluded!

. . . a complete mystery!

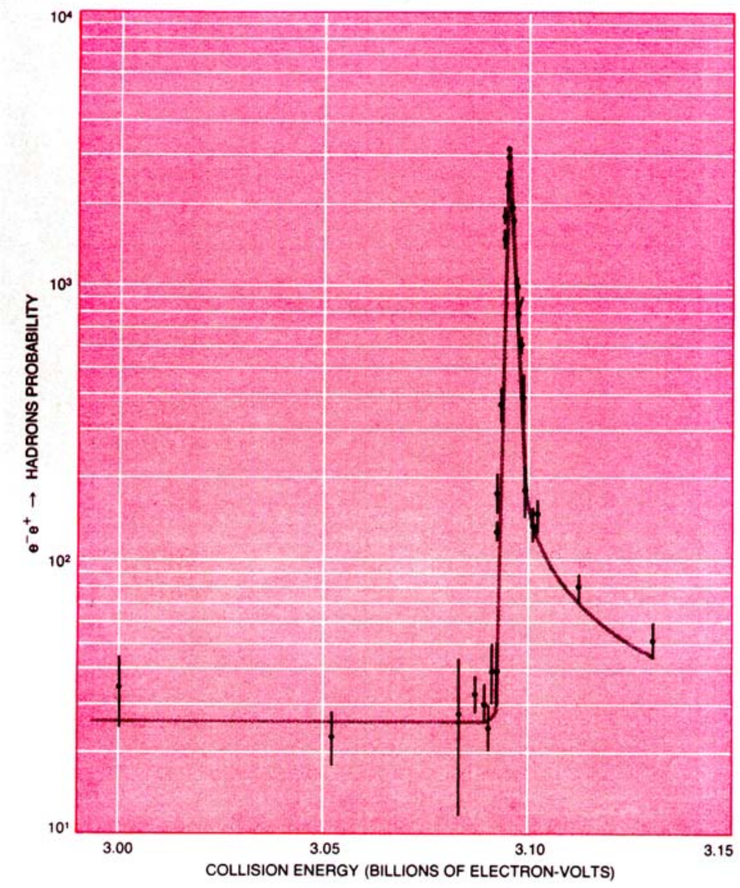
Choices for the value of *R*

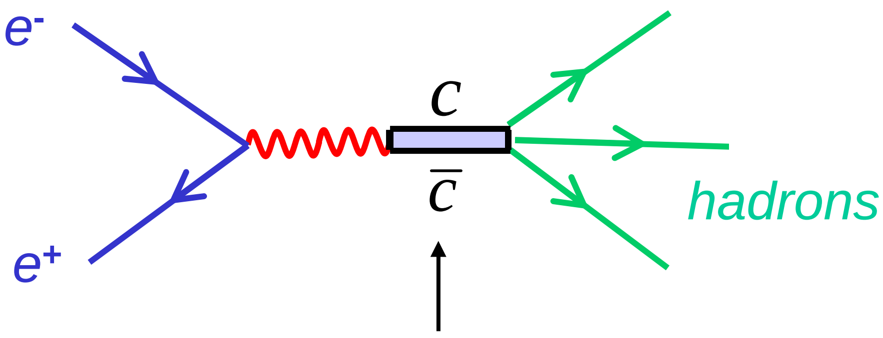
(J. Ellis' menu of 1974)

Value	Model	
0.36	Bethe-Salpeter bound quarks	Bohm *et al.*, Ref. 42
2/3	Gell-Mann-Zweig quarks	
0.69	Generalized vector meson dominance	Renard, Ref. 49
~ 1	Composite quark	Raitio, Ref. 43
10/9	Gell-Mann-Zweig with charm	Glashow *et al.*, Ref. 31
2	Colored quarks	
2.5 to 3	Generalized vector meson dominance	Greco, Ref. 30
2 to 5	Generalized vector meson dominance	Sakurai, Gounaris, Ref. 47
3-1/3	Colored charmed quarks	Glashow *et al.*, Ref. 31
4	Han-Nambu quarks	Han and Nambu, Ref. 32
5.7 ± 0.9	Trace anomaly and ρ dominance	Terazawa, Ref. 27
$5.8^{+3.2}_{-3.5}$	Trace anomaly and ϵ dominance	Orito *et al.*, Ref. 25
6	Han-Nambu with charm	Han and Nambu, Ref. 32
6.69 to 7.77	Broken scale invariance	Choudhury, Ref. 18
8	Tati quarks	Han and Nambu, Ref. 32
8 ± 2	Trace anomaly and ϵ dominance	Eliezer, Ref. 26
9	Gravitational cut-off, Universality	Parisi, Ref. 40
9	Broken scale invariance	Nachtmann, Ref. 39
16	$SU_{12} \times SU_{12}$ gauge models	Fritzsch and Minkowski, Ref. 34
35-1/3	$SU_{16} \times SU_{16}$ gauge models	Fritzsch and Minkowski, Ref. 34
~ 5000	High Z quark	Yock, Ref. 73
70,383	Schwinger's quark	Yock, Ref. 73
∞	∞ of partons	Cabibbo and Karl, Ref. 9 Matveev and Tolkachev, Ref. 35 Rozenblit, Ref. 36

The "November Revolution"

SPEAR, Nov 11, 1974





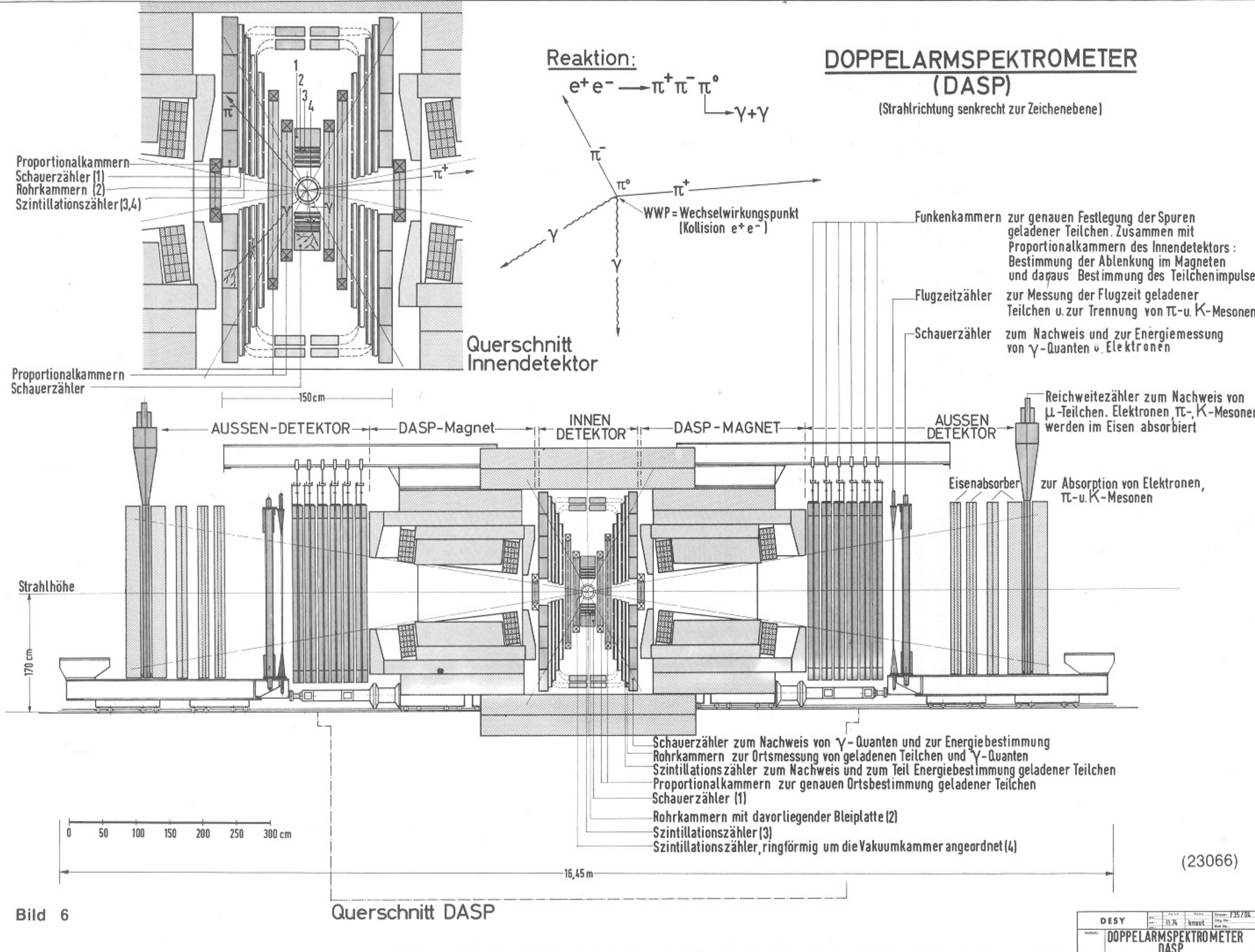
bound state of *<u>charm anticharm</u>* *quarks*

"J/ψ"

At Frascati, it is confirmed at ADONE just a few days later.

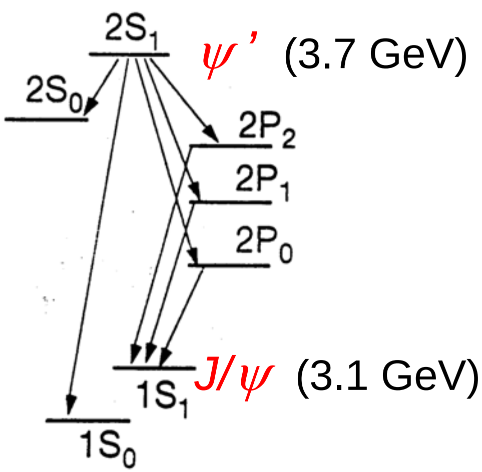
At DESY, DORIS is just starting up, and the J/ψ is quickly found.

Simultaneously observed at BNL in pp collisions



DOPPELARMSPEKTROMETER
(DASP)
(Strahlrichtung senkrecht zur Zeichenebene)
Reaktion:
e⁺e⁻ → π⁺π⁻π° → γ+γ
WWP = Wechselwirkungspunkt (Kollision e⁺e⁻)
Proportionalkammern
Schauerzähler (1)
Rohrkammern (2)
Szintillationszähler (3,4)
Proportionalkammern
Schauerzähler
Querschnitt Innendetektor
150 cm
Funkenkammern zur genauen Festlegung der Spuren geladener Teilchen. Zusammen mit Proportionalkammern des Innendetektors: Bestimmung der Ablenkung im Magneten und daraus Bestimmung des Teilchenimpulses.
Flugzeitzähler zur Messung der Flugzeit geladener Teilchen u. zur Trennung von π- u. K-Mesonen
Schauerzähler zum Nachweis und zur Energiemessung von γ-Quanten u. Elektronen
Reichweitezähler zum Nachweis von μ-Teilchen. Elektronen, π-, K-Mesonen werden im Eisen absorbiert
AUSSEN-DETEKTOR
DASP-Magnet
INNEN DETEKTOR
DASP-MAGNET
AUSSEN DETEKTOR
Eisenabsorber zur Absorption von Elektronen, π- u. K-Mesonen
Strahlhöhe
170 cm
Schauerzähler zum Nachweis von γ-Quanten und zur Energiebestimmung
Rohrkammern zur Ortsmessung von geladenen Teilchen und γ-Quanten
Szintillationszähler zum Nachweis und zum Teil Energiebestimmung geladener Teilchen
Proportionalkammern zur genauen Ortsbestimmung geladener Teilchen
Schauerzähler (1)
Rohrkammern mit davorliegender Bleiplatte (2)
Szintillationszähler (3)
Szintillationszähler, ringförmig um die Vakuumkammer angeordnet (4)
0 50 100 150 200 250 300 cm
16,45 m
(23066)
Querschnitt DASP
DESY
11.74 knaut
F35706
DOPPELARMSPEKTROMETER DASP

Bild 6

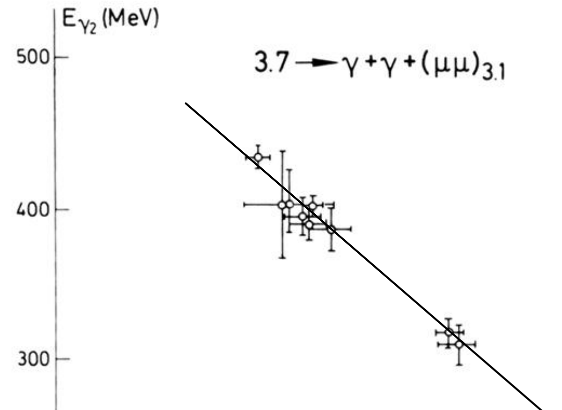


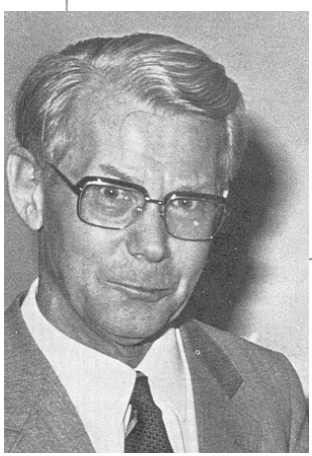
"Charmonium" = bound $c\bar{c}$ system

$$V(r) = -\frac{4}{3}\frac{\alpha_S}{r} + k\,r, \quad k \approx 1\,\mathrm{GeV/fm}$$

DESY in June 1975:
The DASP experiment at DORIS sets the final keystone:
Observing the photon transitions

$\Rightarrow$ Discovery of the *P* wave states of charmonium

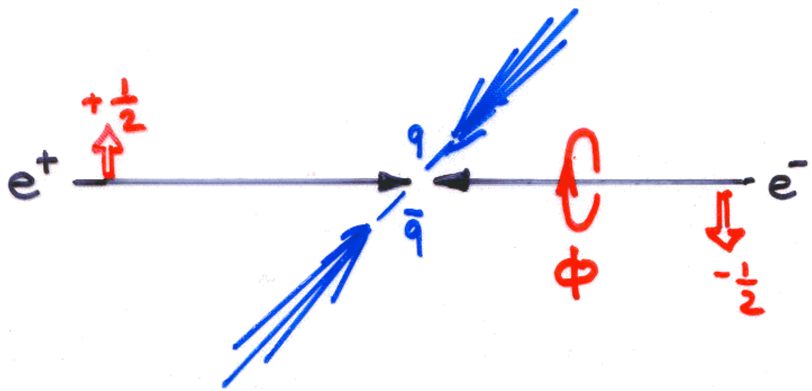




"From now on it is impossible not to believe in the quarks!"

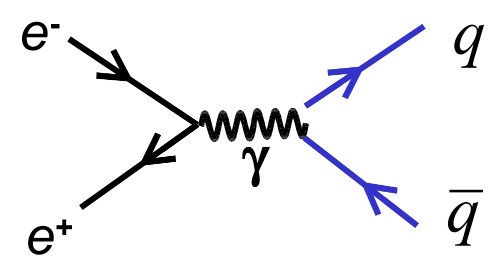
Gross, Wilczek, Politzer 1973
t'Hooft, Symanzik 1972

The discovery of the Jets (SPEAR 1975)

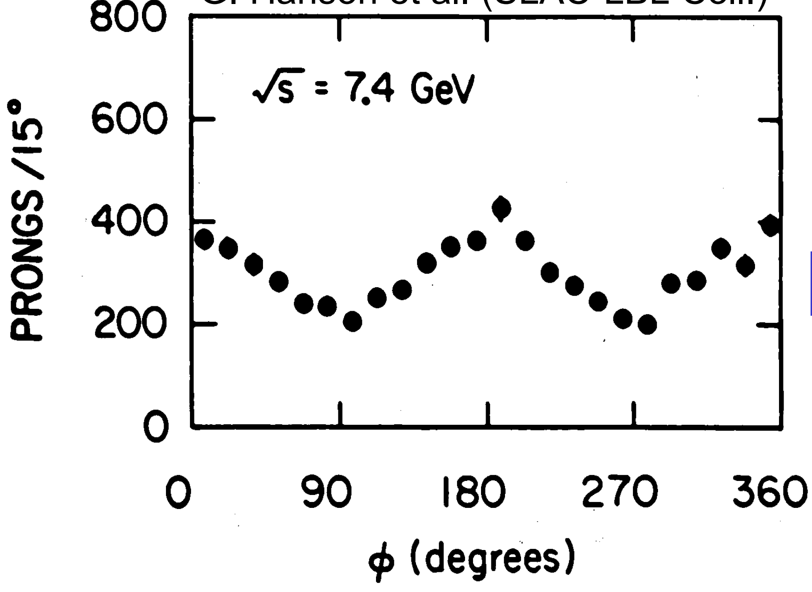


For $s = \frac{1}{2}$:

$$\frac{d\sigma}{d\cos\theta \; d\phi} \sim 1 + \cos^2\theta + P^2 \sin^2\theta \, \cos 2\phi$$



G. Hanson et al. (SLAC-LBL Coll.)



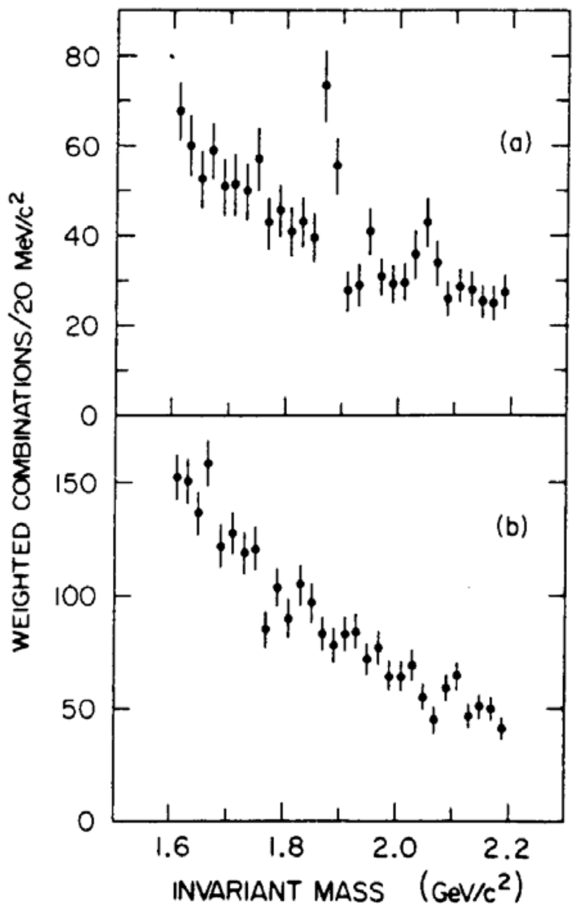
The hadrons are indeed coming from **pair-produced fermion parents**

In hadronic interactions, no compelling evidence for jets; some even doubt that they exist at all.

Charmed particles (*D* mesons)

discovered 1976 by the
SLAC-LBL collaboration @ SPEAR

$$D^+ \to K^-\pi^+\pi^+$$

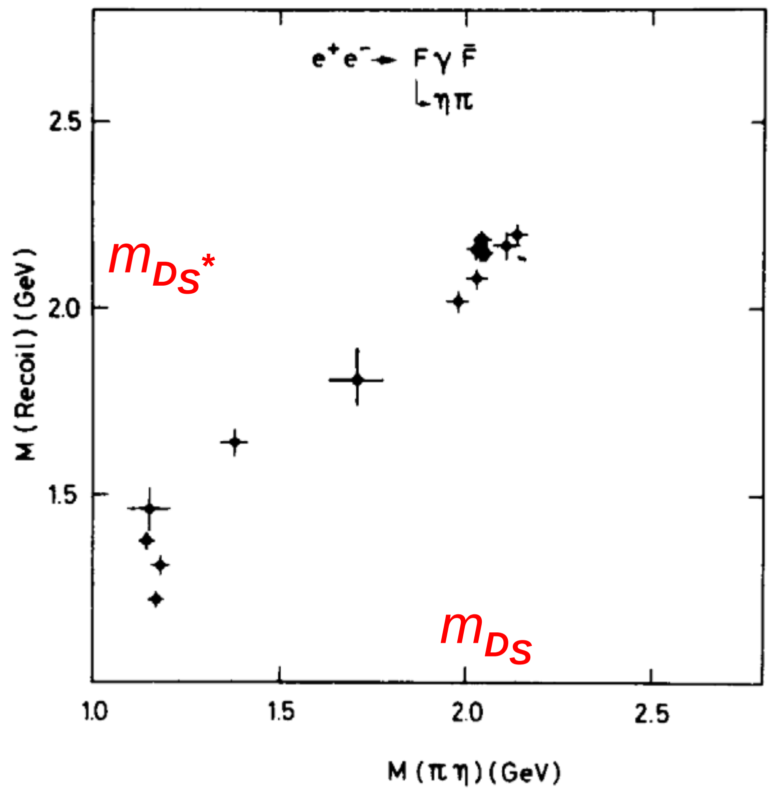


Charmed-strange (D_S) mesons

1977 first evidence
by DASP @ DORIS

$$e^+e^- \to D_S\,\overline{D}_S^{\,*}$$

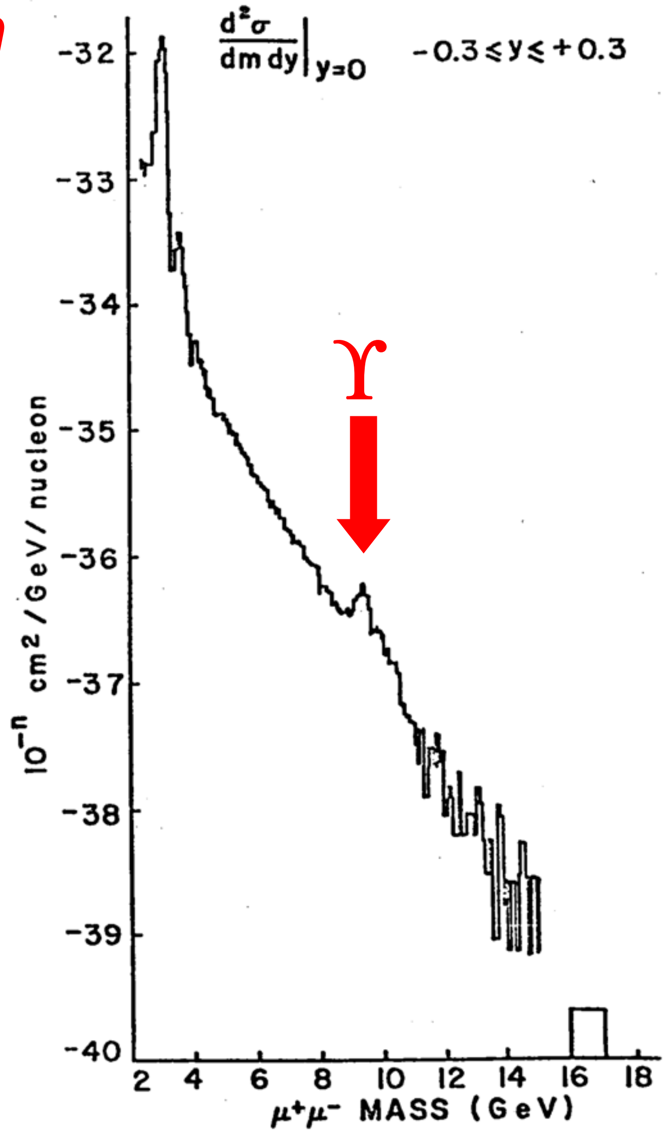
$$D_S \to \eta\pi \qquad \overline{D}_S^{\,*} \to \gamma\,\overline{D}_S$$



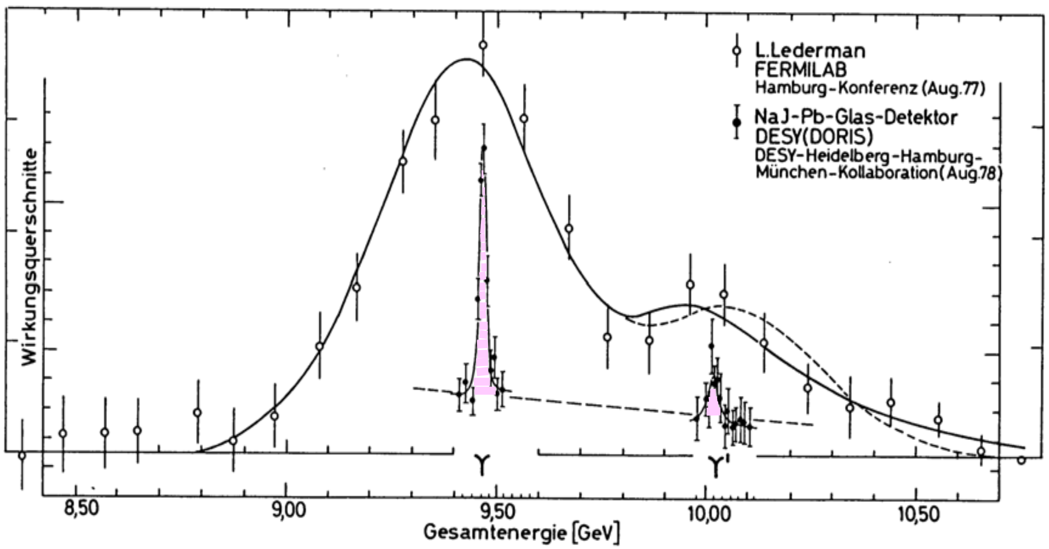
Discovery of the 5th quark, *bottom*

at Fermilab (S. Herb et al 1977)

400 GeV *p* + *nucleus* $\longrightarrow$ $\mu^+\mu^-$ + *anything*



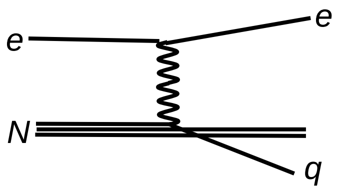
One year later at DESY,
with the upgraded DORIS e^+e^- collider:



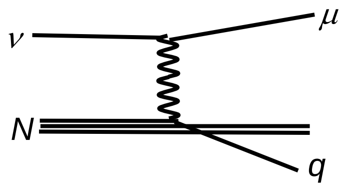
$\Rightarrow$ definitely a new quark with fractional charge

Two further lessons from deep inelastic scattering:

electrons



neutrinos



$$F_2(Q^2, x) = \sum_{\text{all } q,\bar{q}} e^2 \underbrace{x\, q(x)}_{\mathrm{d}n\,/\,\mathrm{d}(\ln x)}$$

measures the mean squared charge of the constituents;
for the quarks in nuclei:

$$\langle e^2 \rangle = \frac{1}{2}\left[\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = \frac{5}{18}$$

For neutrinos no factor e^2
the structure function simply
counts the quarks

$$\frac{F_2^{\,electron}}{F_2^{\,neutrino}} = \frac{5}{18}$$, <u>confirmed !</u>

Callan-Gross sum rule:

$$\int_0^1 F_2(x)\, dx = \underbrace{\sum_{\text{all } q,\bar{q}} e^2 \int_0^1 x\,(q+\bar{q})\, dx}_{\text{mean squared charge of all constituents}} = \begin{cases} 0.18 \text{ (proton)} \\ 0.12 \text{ (neutron)} \end{cases}$$

~ 50 % of the nucleon momentum is flavor-blind:
***uncharged partons ("gluons")* in addition to the quarks**

1973: DESY discusses bigger *ep* or e^+e^- collider "PETRA":

3 - 4 GeV $\Rightarrow$ 30 - 40 GeV !

Proposal of 1974:

- "Test QED"
- "Search for weak-em interference effects"
- "Investigate $\gamma\,\gamma$ interaction processes"

Quarks only mentioned once:

"*Should* quarks exist, rates may stay large at high energy."

Gluons not mentioned at all.

1976: Funding of PETRA appears and construction starts.

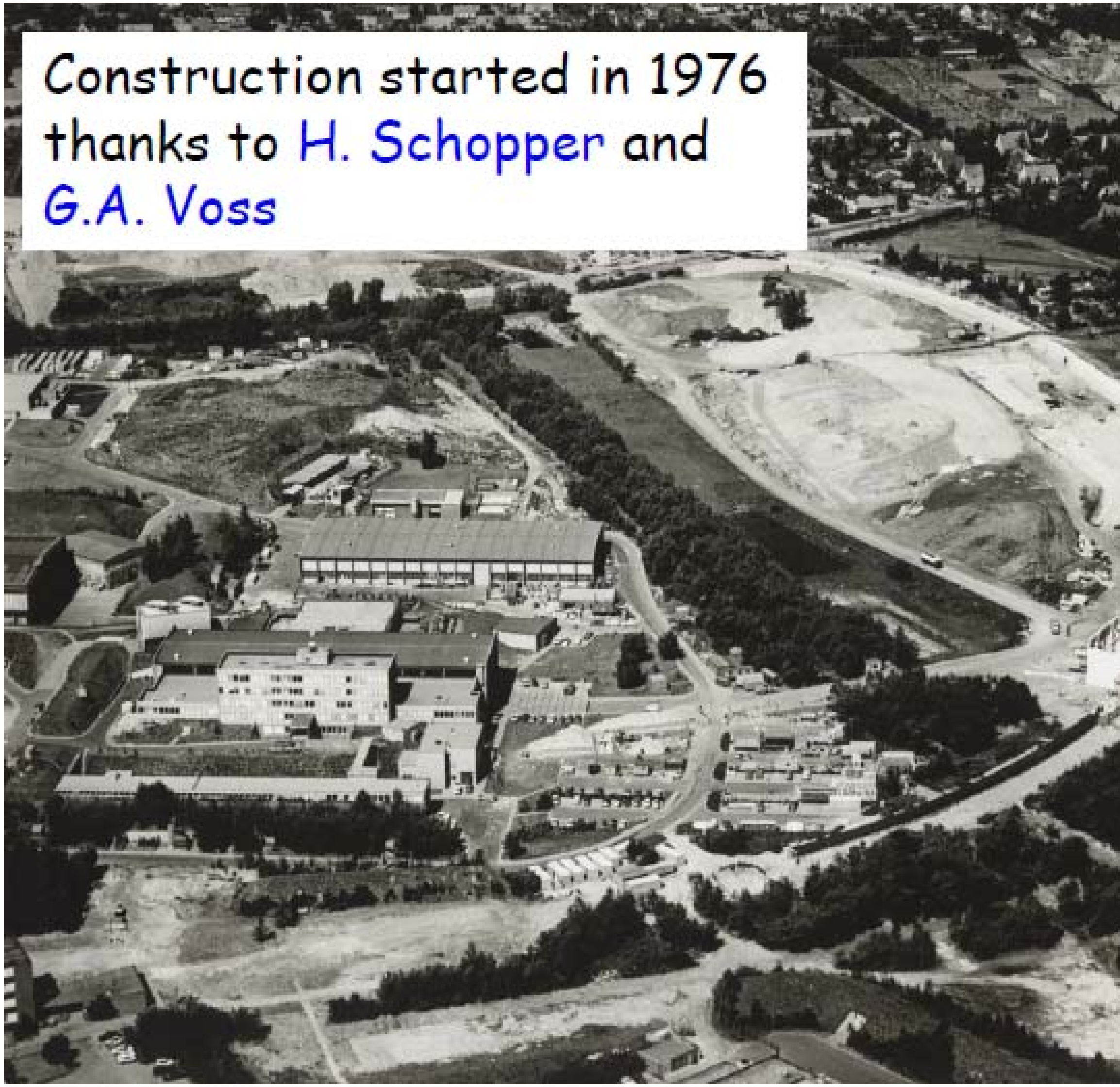
Int'l meeting in Frascati on future PETRA experiments:

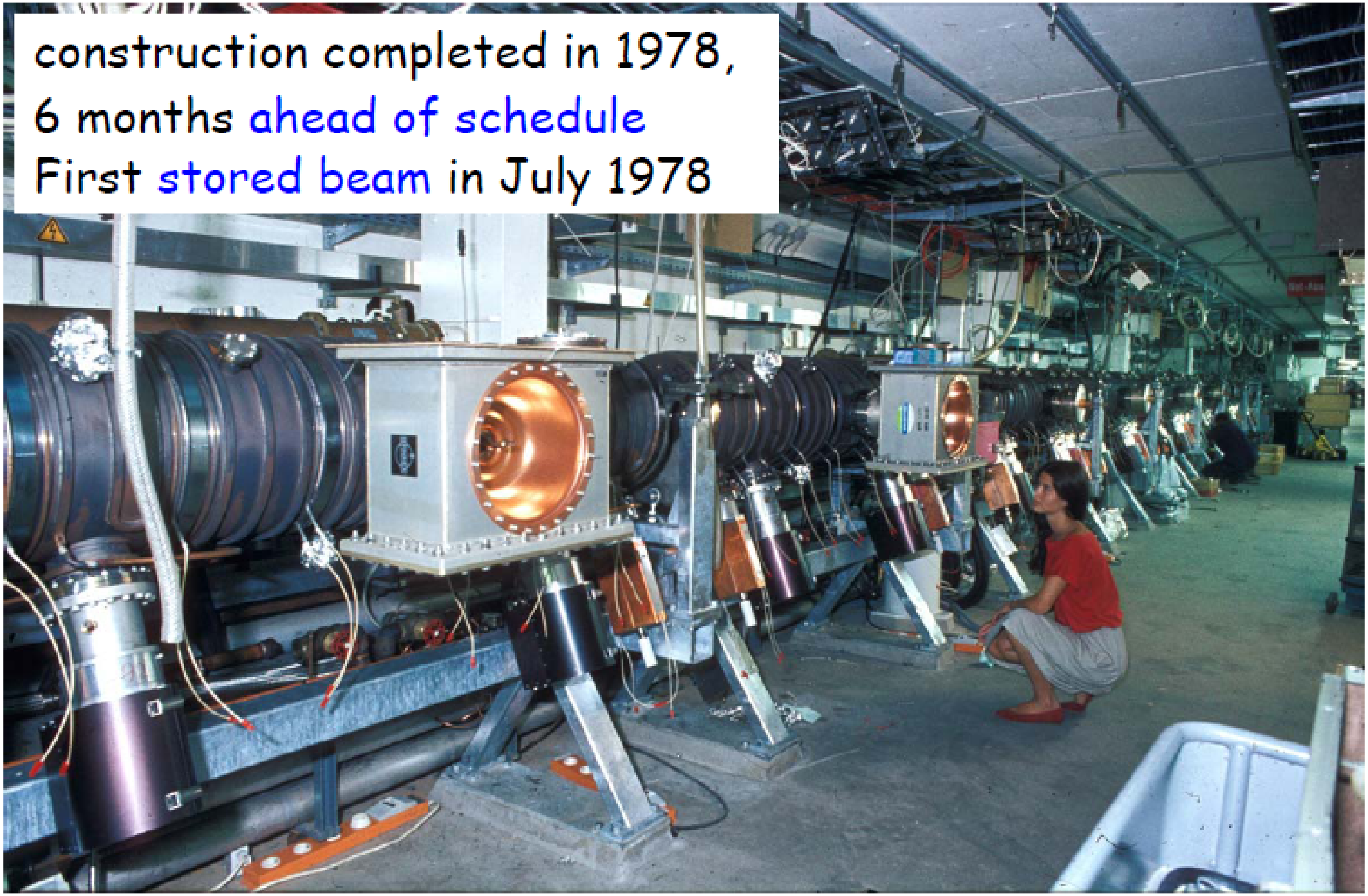
In 630 pg of proceedings, the word "*gluon*" doesn't appear once.

Under "weird options" a possibility is mentioned

that a jet might split into two.

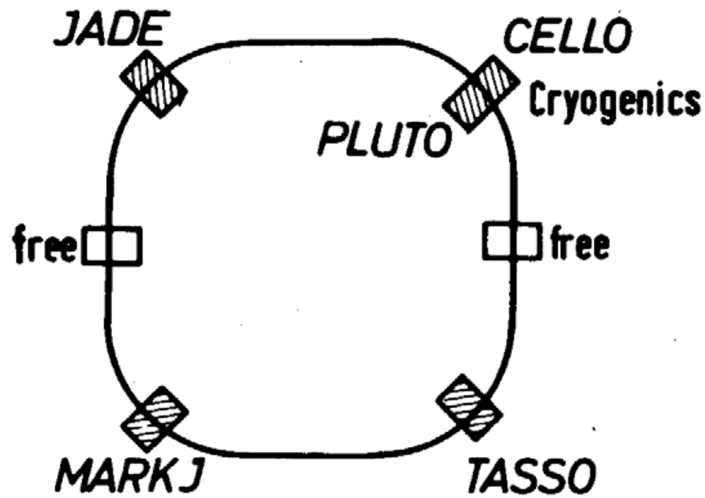
Construction of PETRA



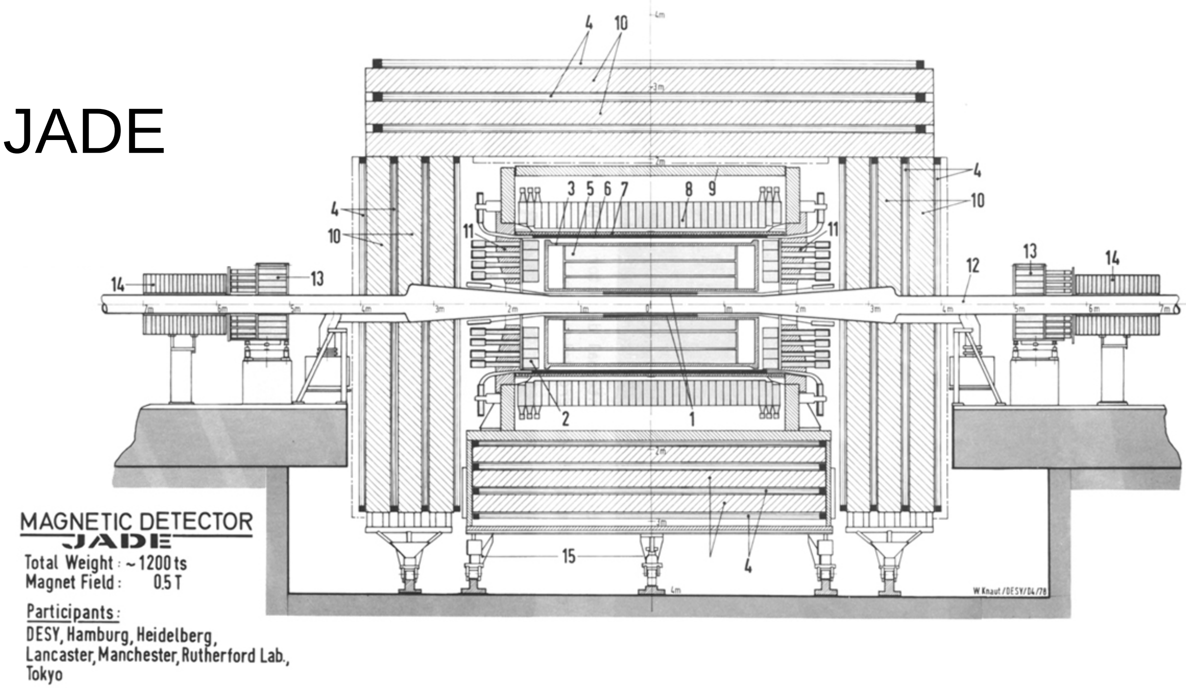


First collisions seen in November 1978

The detectors
at the PETRA e^+e^- ring

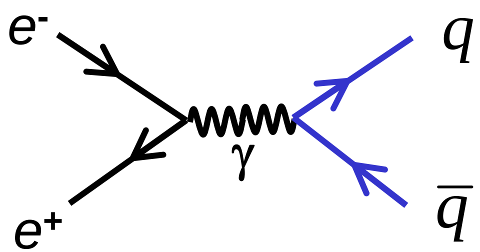


JADE

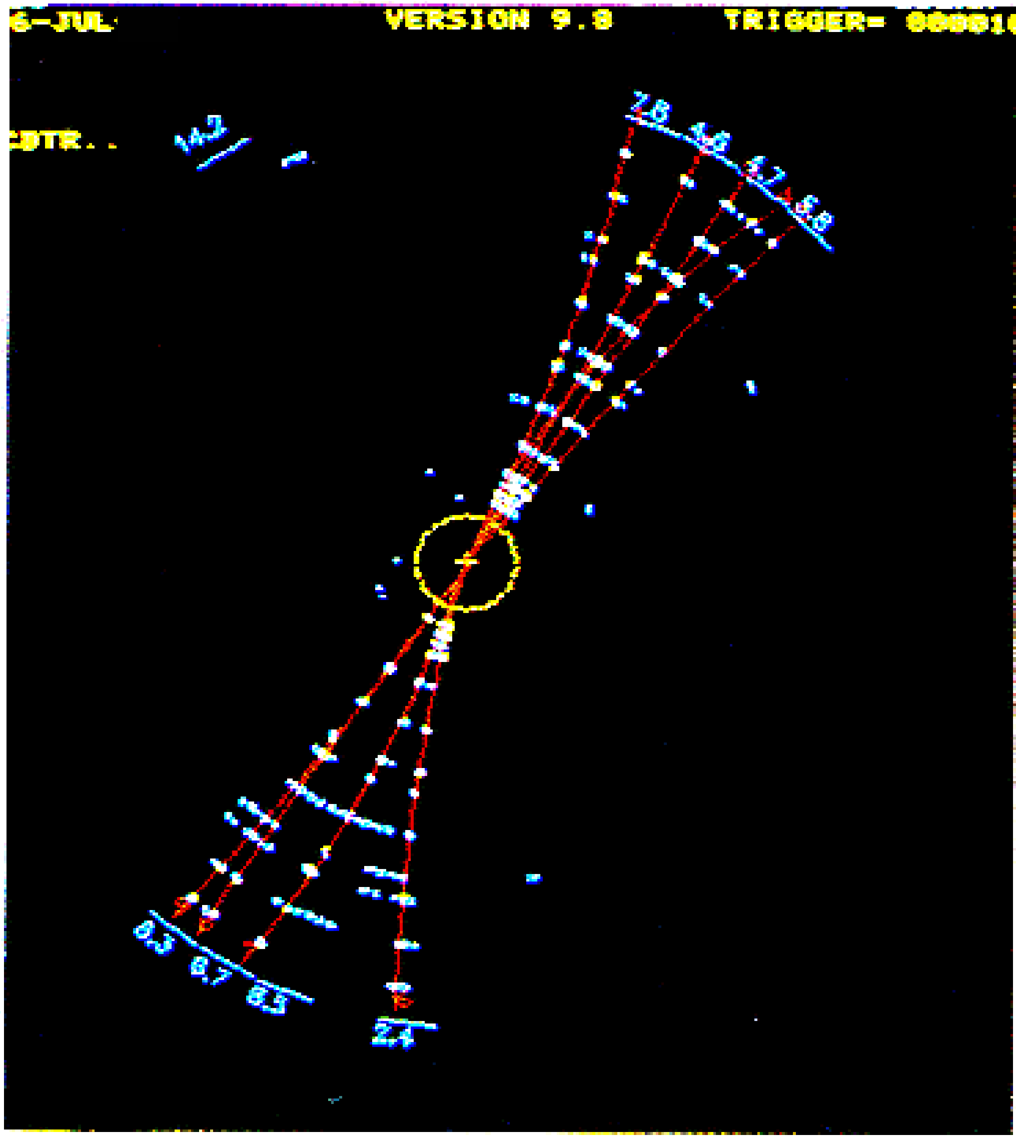


Jets:
seeing is believing !

In PETRA at ~ 30 GeV, two-jet events abound, with a rate as expected for 5 quark-antiquark pairs.



Jets
established as the observable substitutes for the quarks



Angular distribution: s = ½

Gluons

1976 J. Ellis, M. K. Gaillard, G. G. Ross:

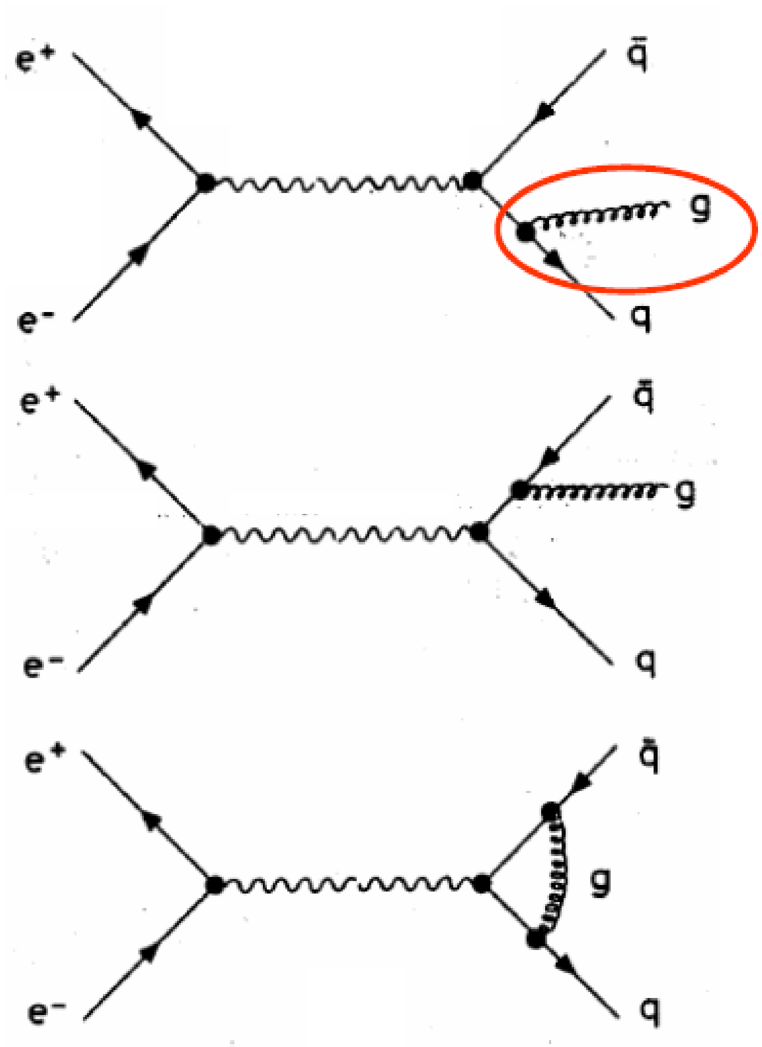
"Search for Gluons in *e+e*$^-$ Annihilation"**!**

The basis of the prediction was field theory, i.e. that the outgoing quarks radiate field quanta (gluons)

The probability for radiation is ~ $\alpha_s(q^2)/\pi$, which at PETRA energy is ~ 10%.

-> 3-jet events

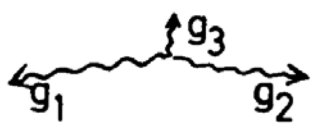
"Gluon bremsstrahlung"



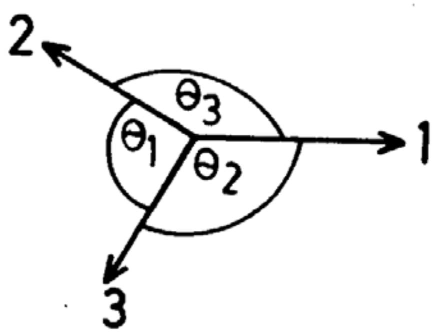
Gluons?

A very suggestive observation by PLUTO @ DORIS on the $\Upsilon(1S)$:

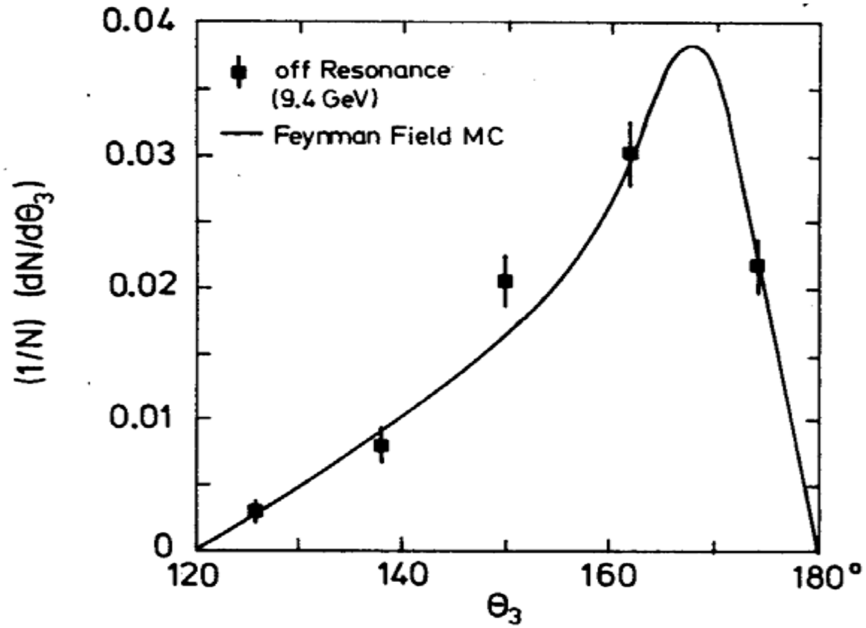
A strongly changing event topology off - on resonance

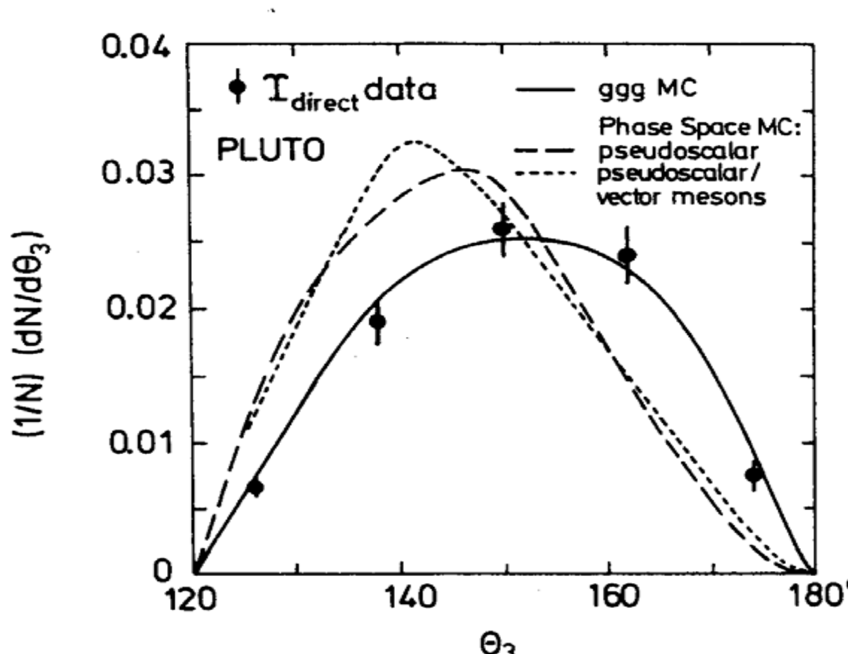


Most probable configuration for $T \rightarrow 3g$ decay.



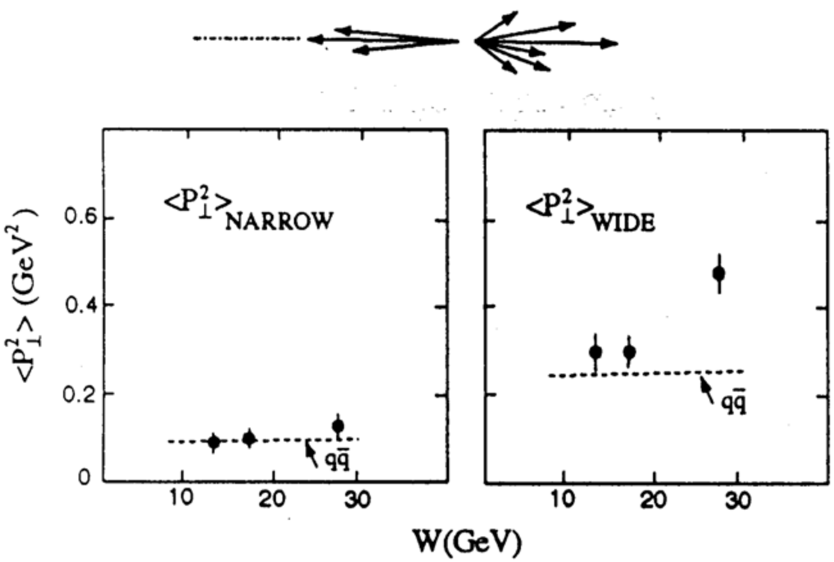
Schematic diagram for the $T \rightarrow 3g$ decay.



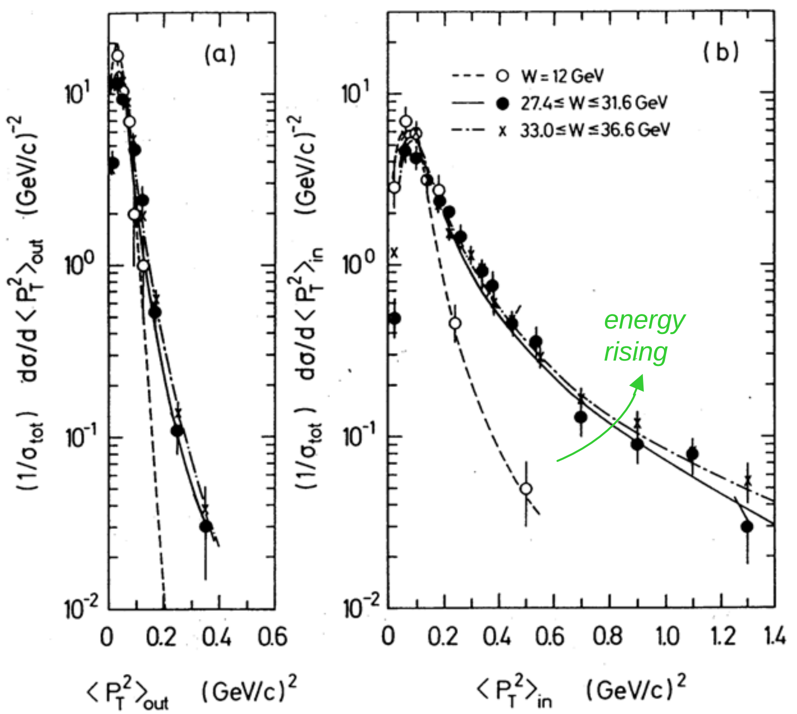


Only days after PETRA reached an energy of 27 GeV, the TASSO experiment demonstrated evidence for

one-sided jet broadening



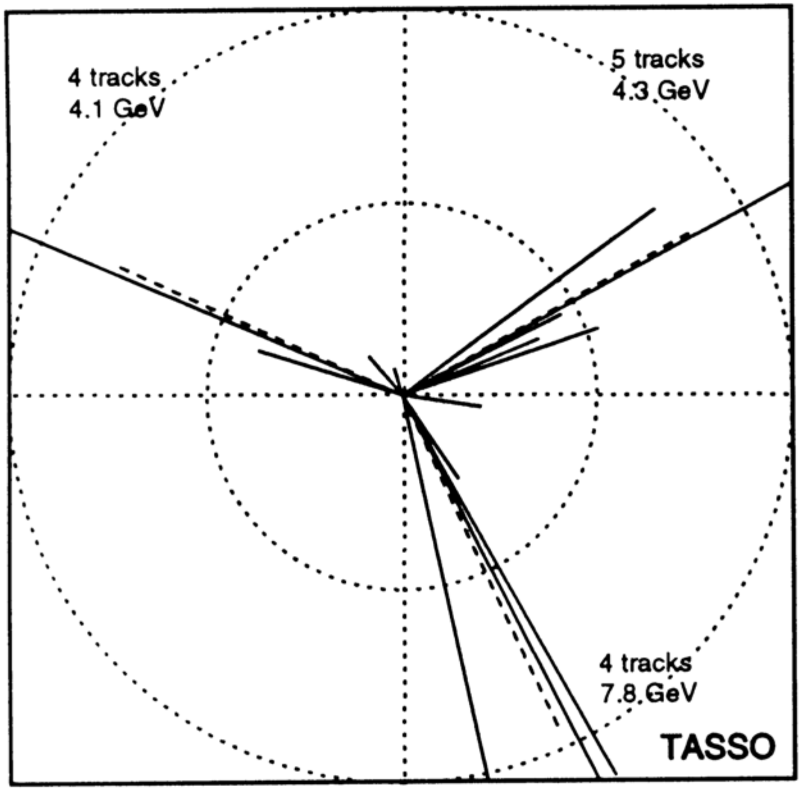
Planarity of the event pattern



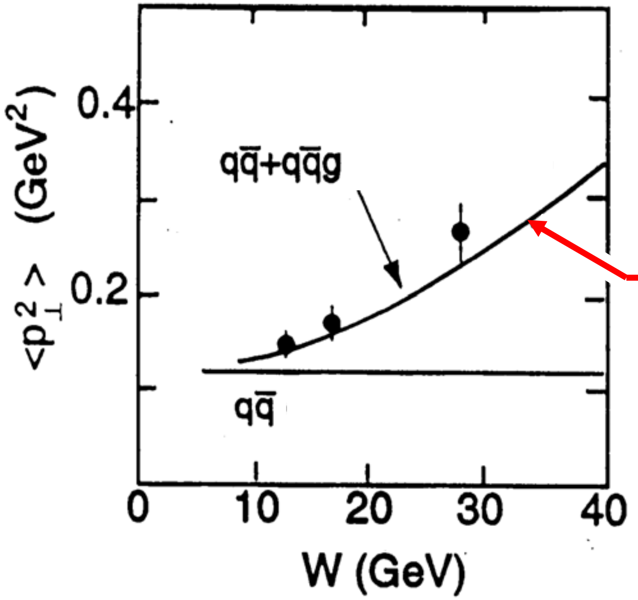
Detailed quantitative predictions for gluon bremsstrahlung by
P. Hoyer, P. Osland, H. G. Sander, T. F. Walsh, P. M. Zerwas (Nucl.Phys. B161 (1979) 349)
and by G. Kramer + *friends*, A. Ali + *friends*.

Three-jet events

S. L. Wu and G. Zobernig:
Algorithm to recognize and analyze planar events and 3-jet patterns



Quantitative analysis shows consistency with gluon bremsstrahlung, excludes new heavy quark.

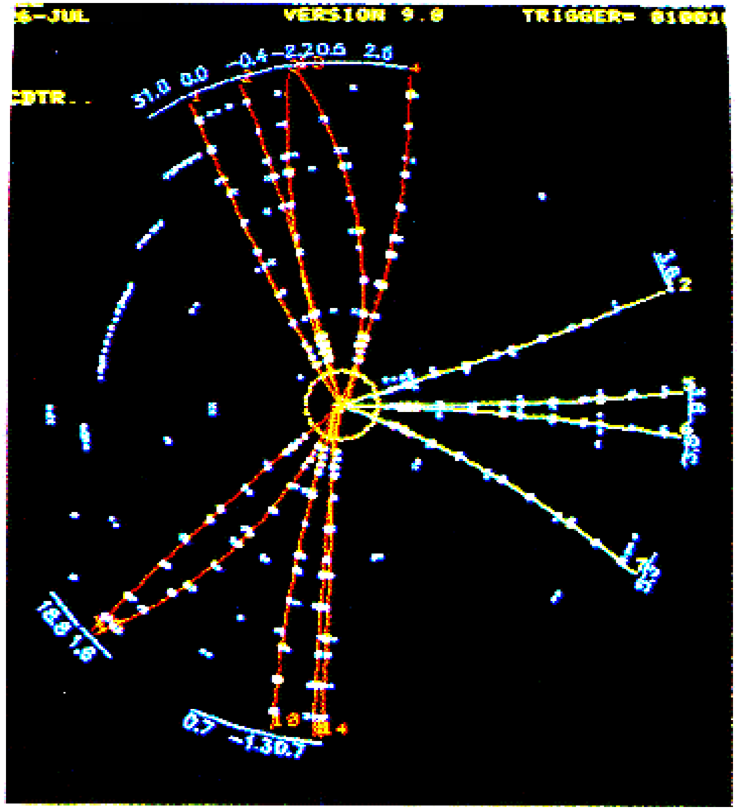


gluons!

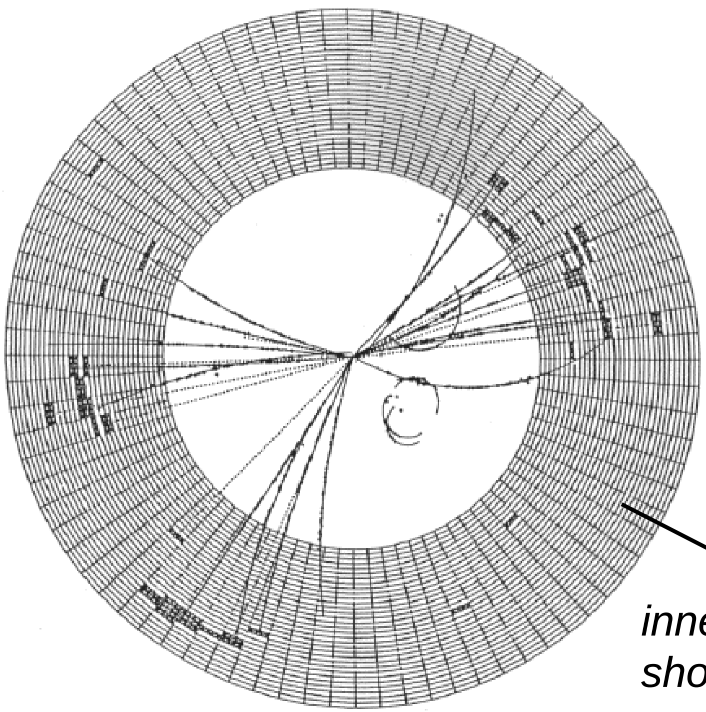
Rate allows first determintation of the quark-gluon coupling strength

$\alpha_s \sim 0.18$

Sometimes the 3 jets were almost directly visible:



TASSO



inner surface of shower counter

JADE

Within 2 months, all four PETRA experinents
had demonstrated the three-jet event shapes

~10 % of the hadron production at ~ 30 GeV
is in the form of three-jet events

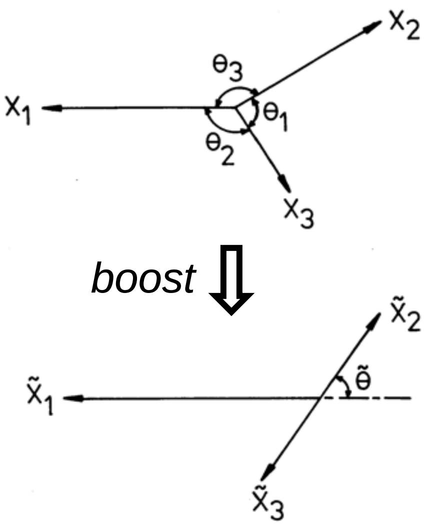
August 1979 Lepton Photon Symposium @ FNAL :

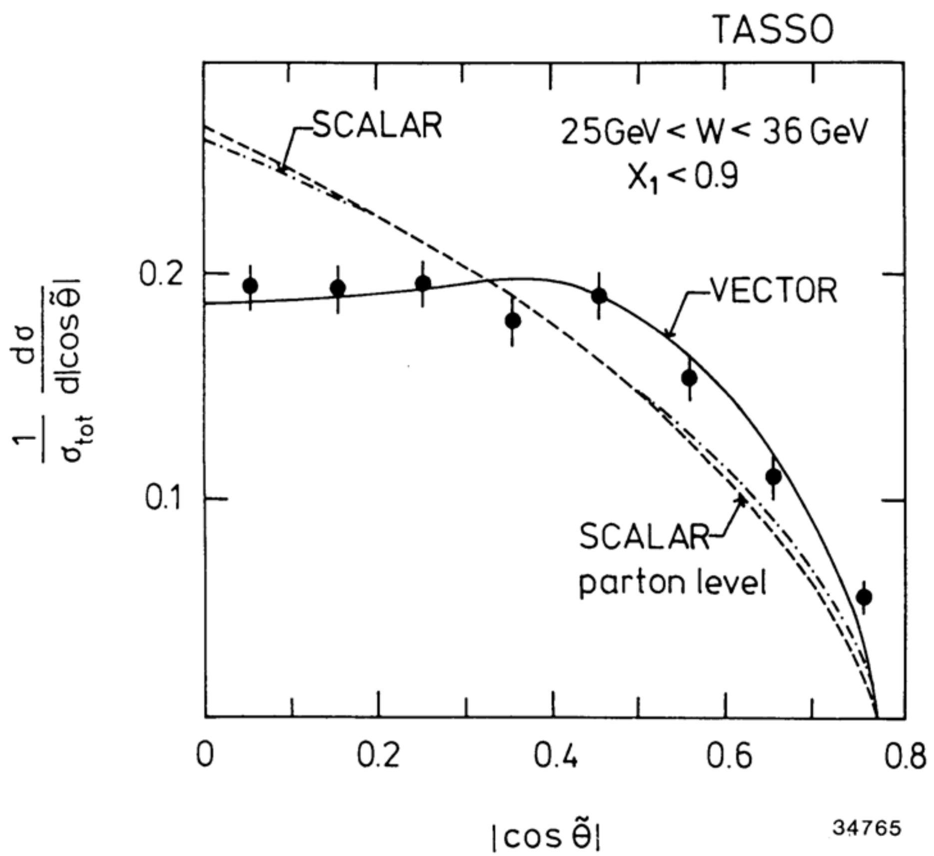
Haim Harari (concluding talk):

" . . . we will all agree that the gluon was discovered in the summer of 1979."

Verify the vector (spin-1) nature of the gluon (J. Ellis + I. Karliner)

angular correlations between the three jets

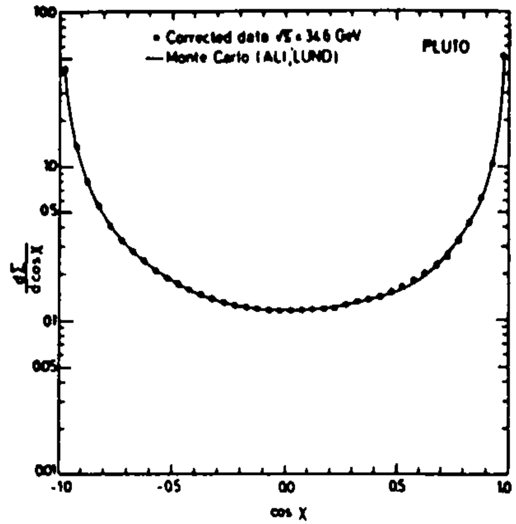


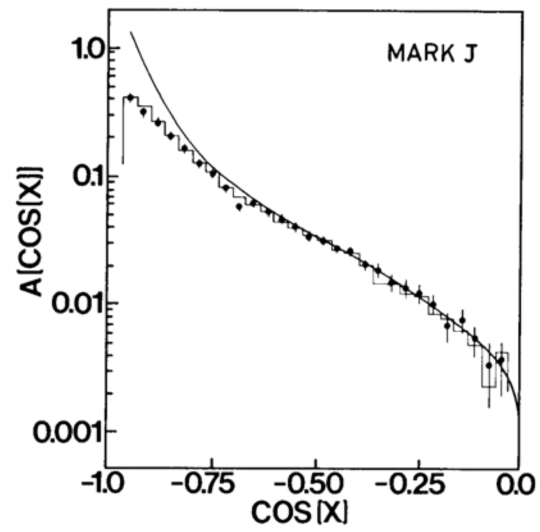


Comparison with QCD to 2nd order:

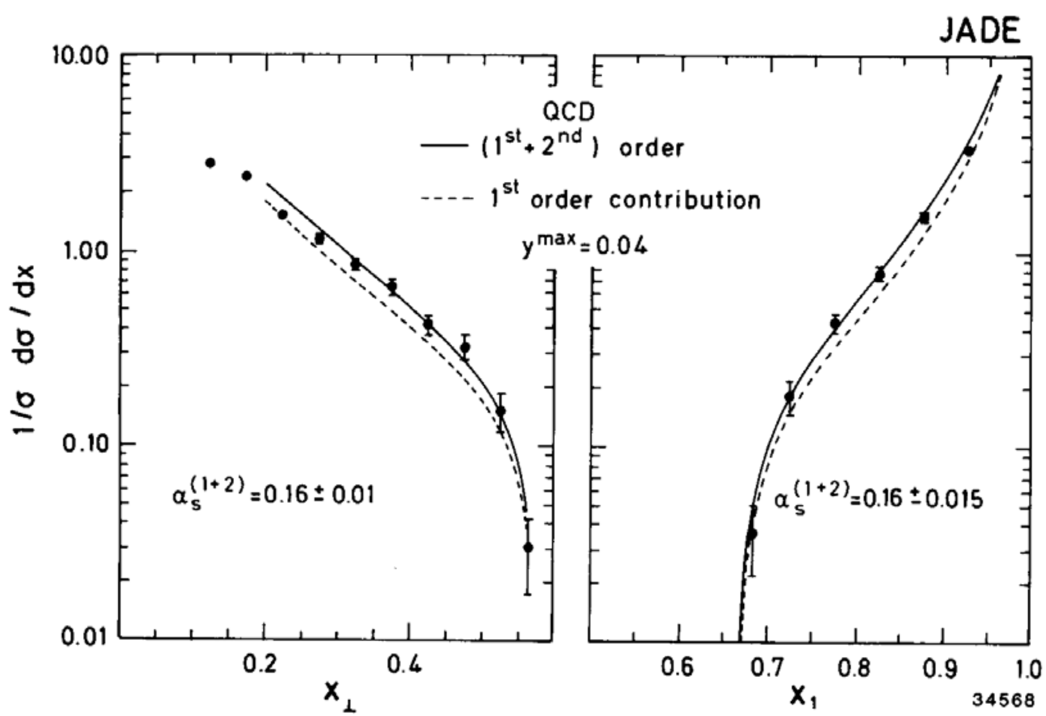
G. Kramer et al
A. Ali et al
. . .

E - E correlations



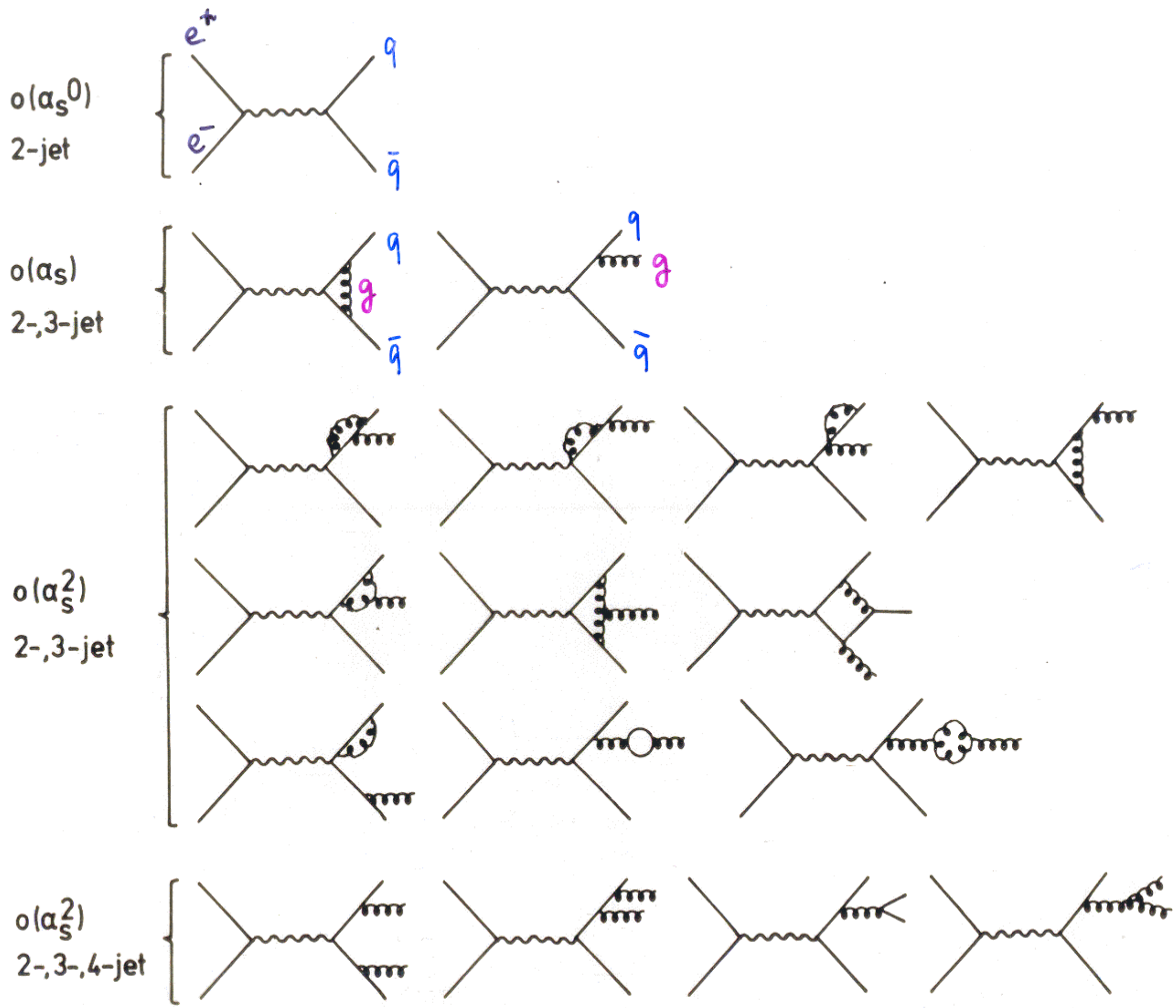


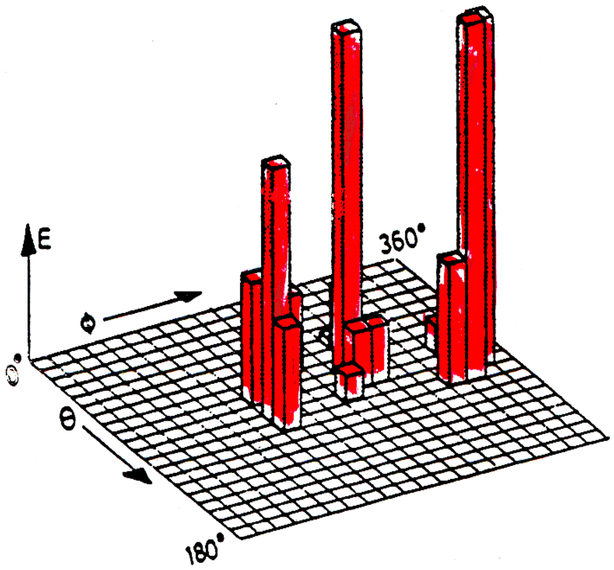
Jet fractional energy



consistent values for α_s

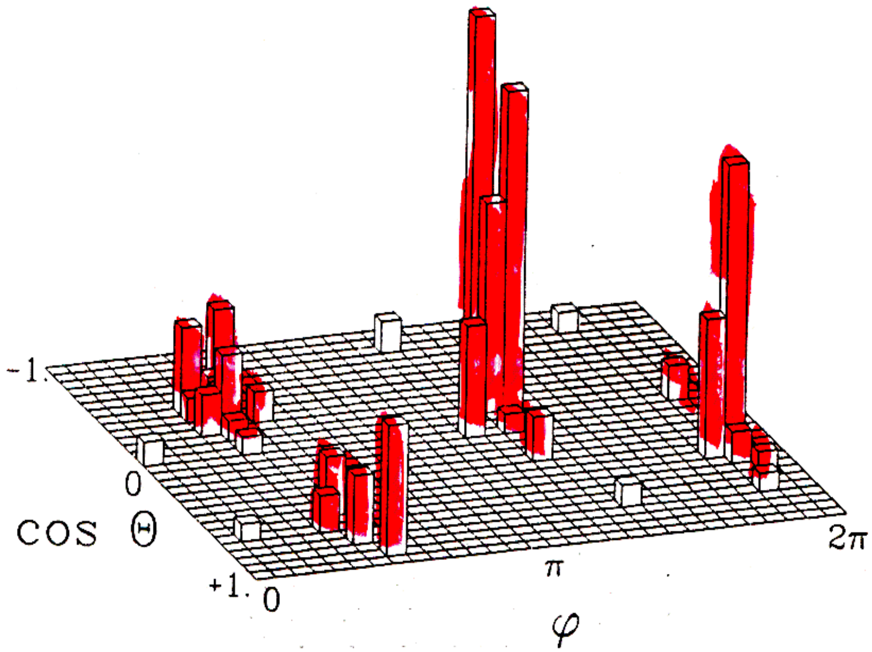
Feynman diagrams for $e^+e^- \Rightarrow jets$





“Lego” plot of 3-jet event

4-jet event

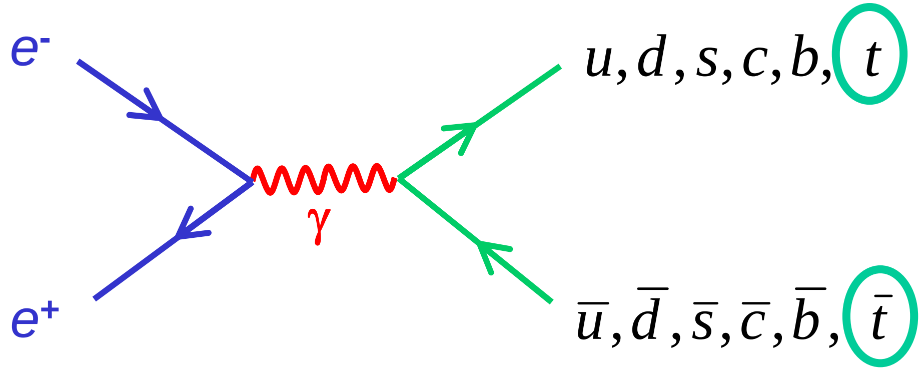


JADE

Where is the top quark ?

Thresholds:

pions (*u, d*)	0.3 GeV
strange (*s*)	1 GeV
charmed (*c*)	3 GeV
bottom (*b*)	10 GeV



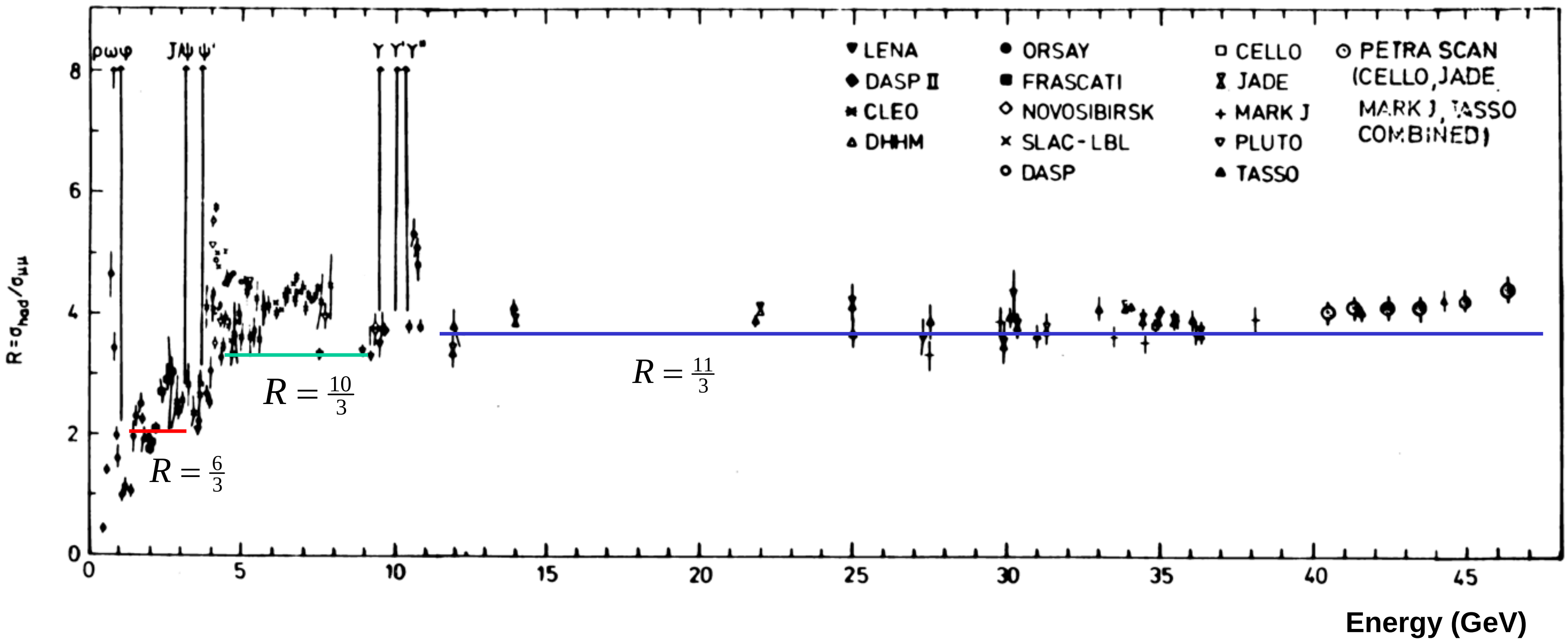
⇨ The *top* is a sure bet at 30 - 40 GeV

A great and careful effort: NOTHING!

Perkins' law: *Fermions are discovered in the U.S.*
bosons in Europe

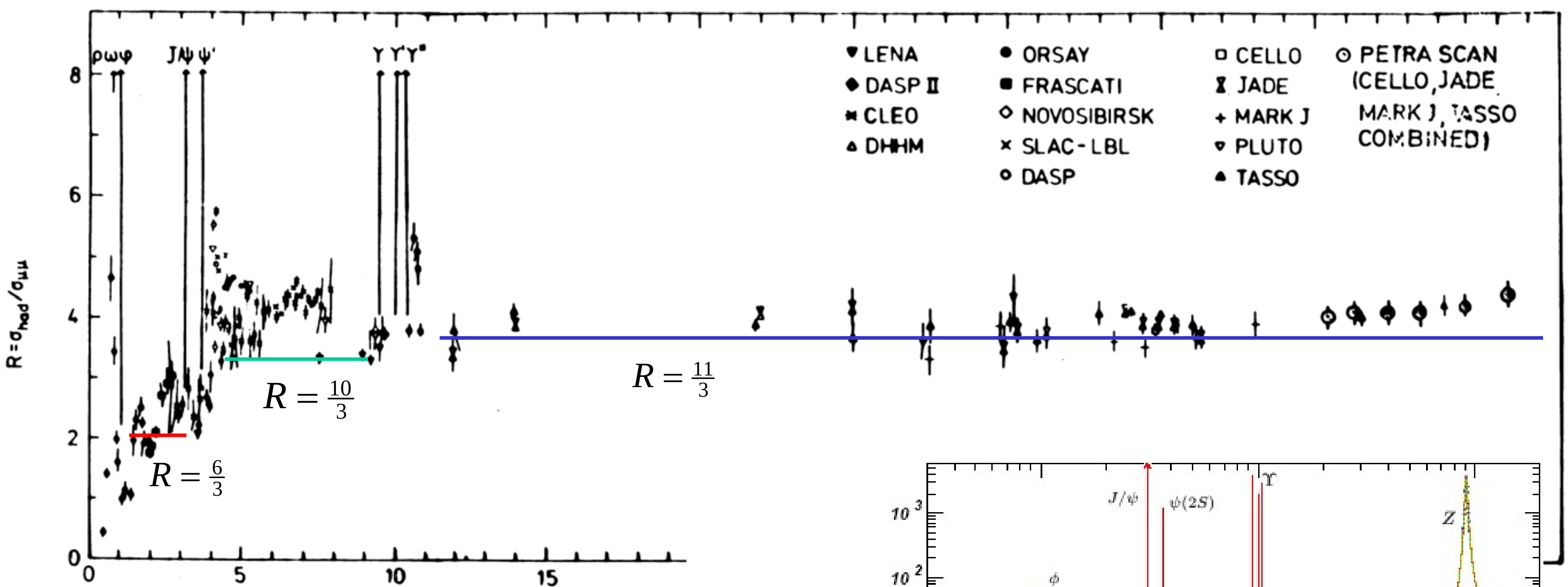
$$R = \frac{\sigma_{hadron}}{\sigma_{\mu\mu}} = \left\{ e_d^2 + e_u^2 + e_s^2 + e_c^2 + e_b^2 \right\} \times 3 = \frac{11}{3}$$

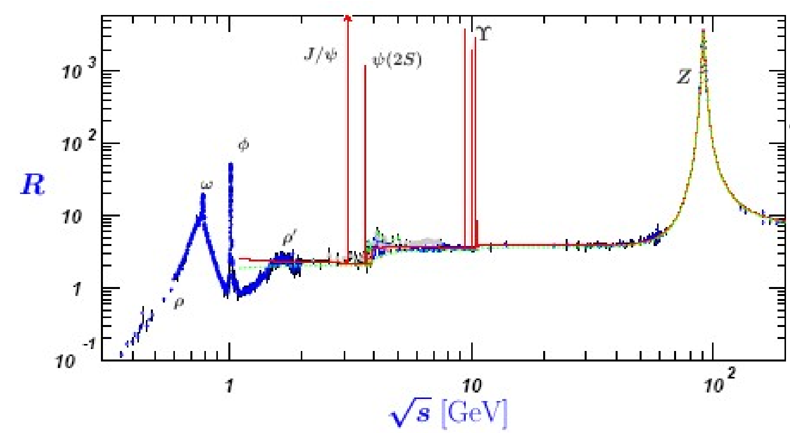
$\frac{1}{9}$ $\frac{4}{9}$ $\frac{1}{9}$ $\frac{4}{9}$ $\frac{1}{9}$ colors



Constancy of R over a wide energy range $\Rightarrow$ quarks have no form factor, i.e. they act pointlike (down to at least 10^{-16} cm)

$$R = \frac{\sigma_{hadron}}{\sigma_{\mu\mu}} = \left\{ \underset{\frac{1}{9}}{e_d^2} + \underset{\frac{4}{9}}{e_u^2} + \underset{\frac{1}{9}}{e_s^2} + \underset{\frac{4}{9}}{e_c^2} + \underset{\frac{1}{9}}{e_b^2} \right\} \times \underset{\text{colors}}{3} = \frac{11}{3}$$





	invented	real
antiparticles	1928	1932
neutrino	1933	1956
pion	1935	1947
quarks	1964	1974
gluon	1969	1979
weak bosons	1967	1983
higgs	1964	