The November Revolution (and thereabouts)

- A WITNESS'S ACCOUNT

Testing

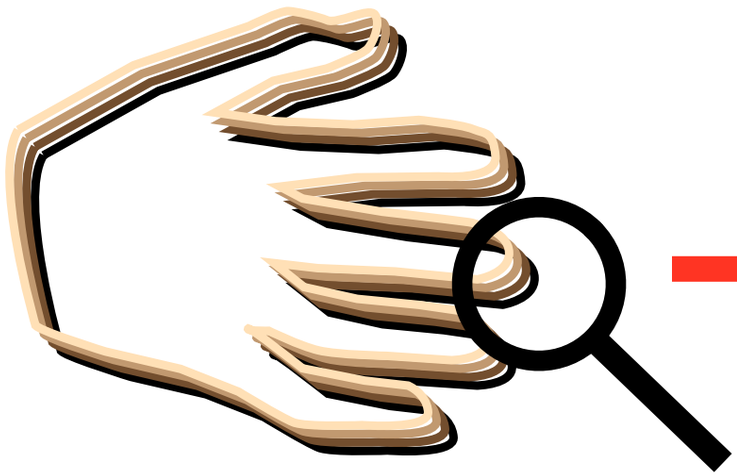
... ...

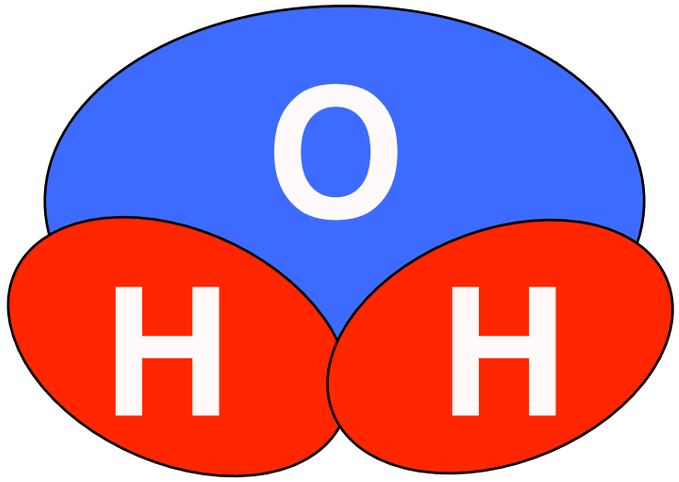
2014

CERN's 60th BD

=

Quarks' 50th BD

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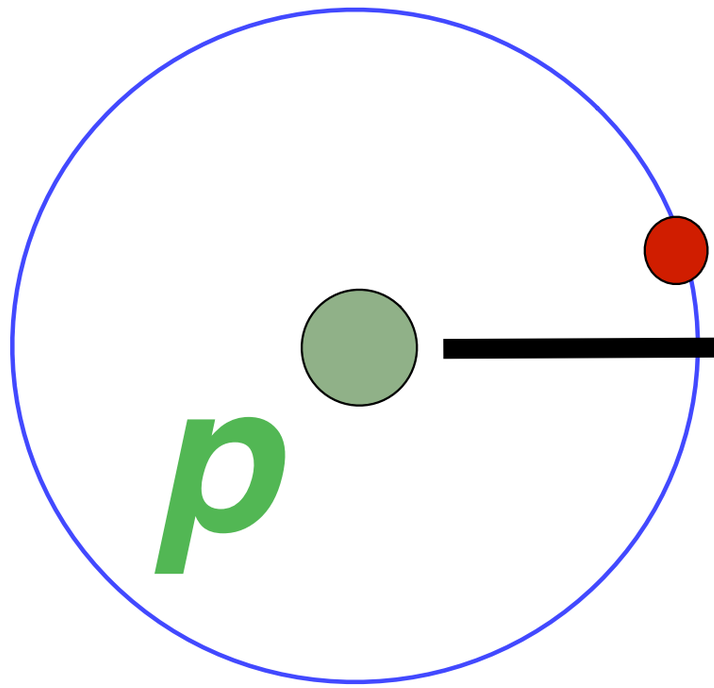
e
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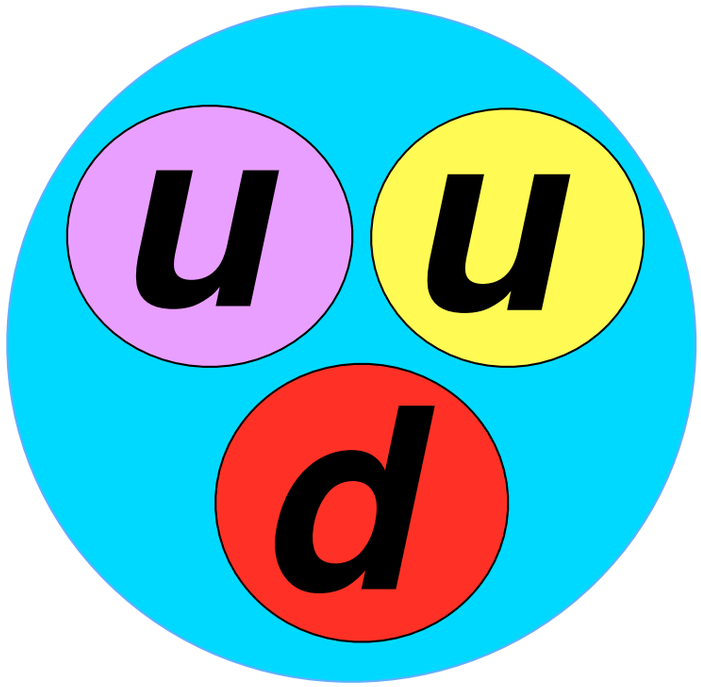
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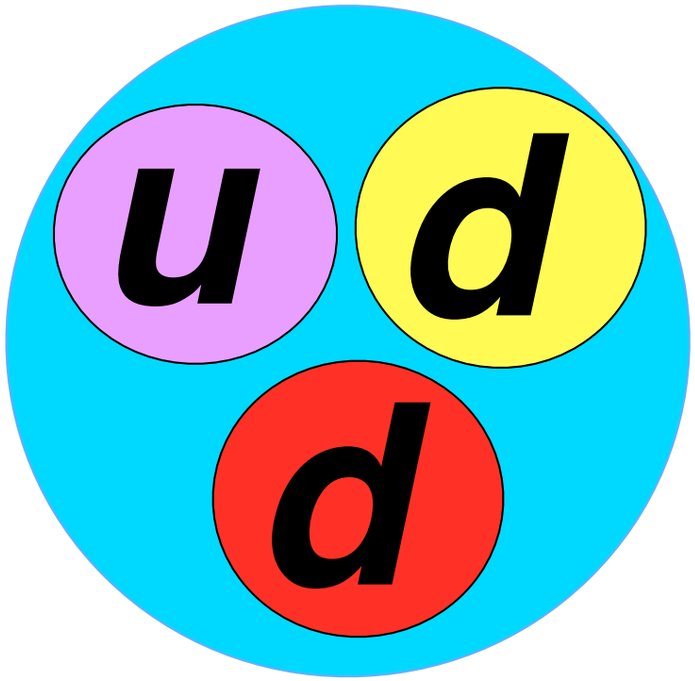

u
d
d

$$p = [u\,u\,d] \qquad \pi^+ = [u\,\bar{d}]$$

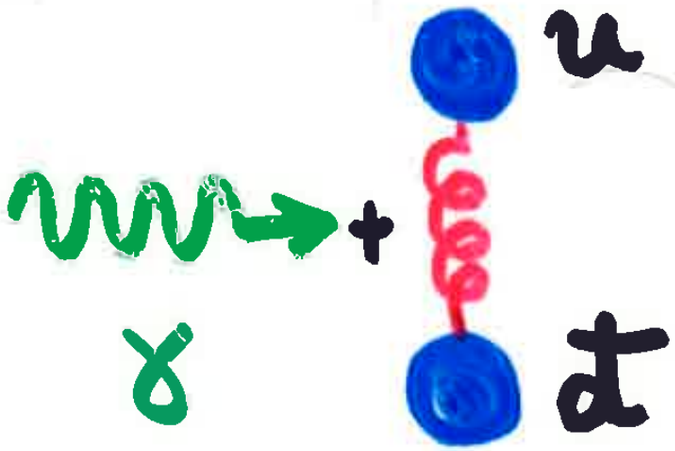
WHO INVENTED QUARKS ?

BUT **André Petermann in Nuclear Physics [63, 349, (1963)], in French! received December 30th, 1963**

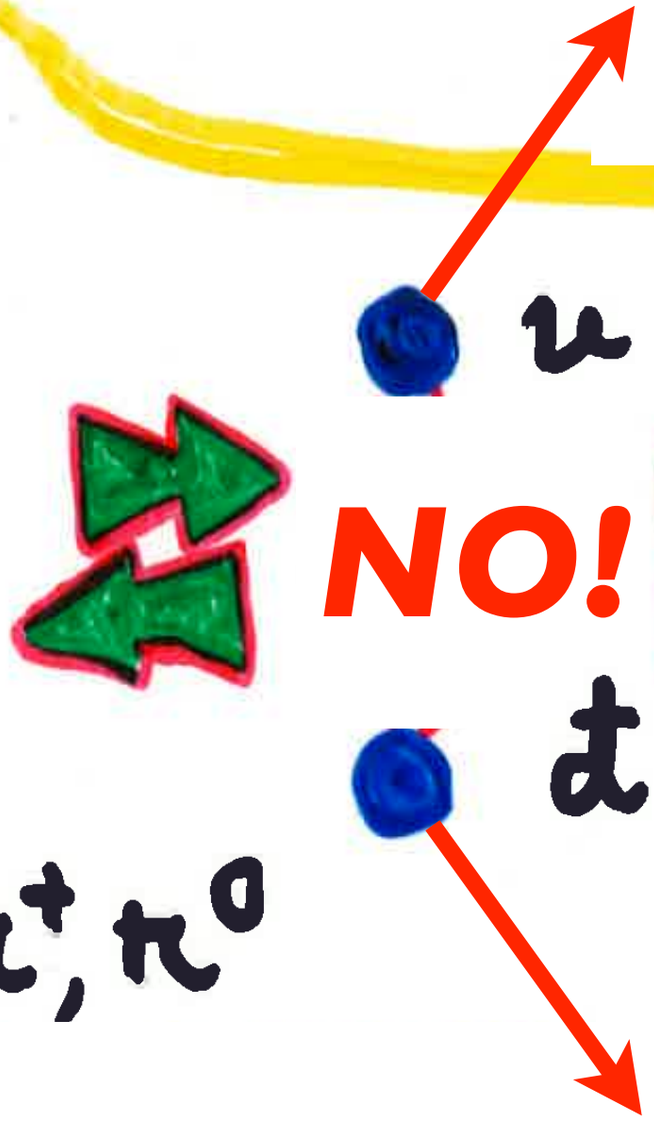
Murray Gell-Mann's paper received by Physics Letters on January 4th 1964

George Zweig's unpublished work is a CERN preprint dated January 17th 1964

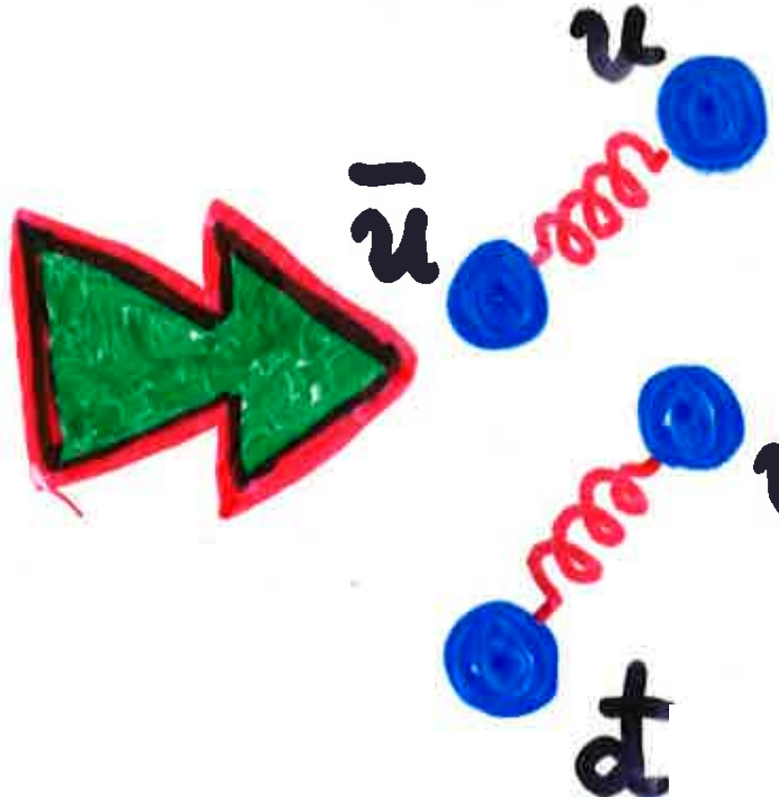
¿QUE PASA?



$\gamma + \pi^+ \rightarrow \pi^+, \pi^0$



NO!



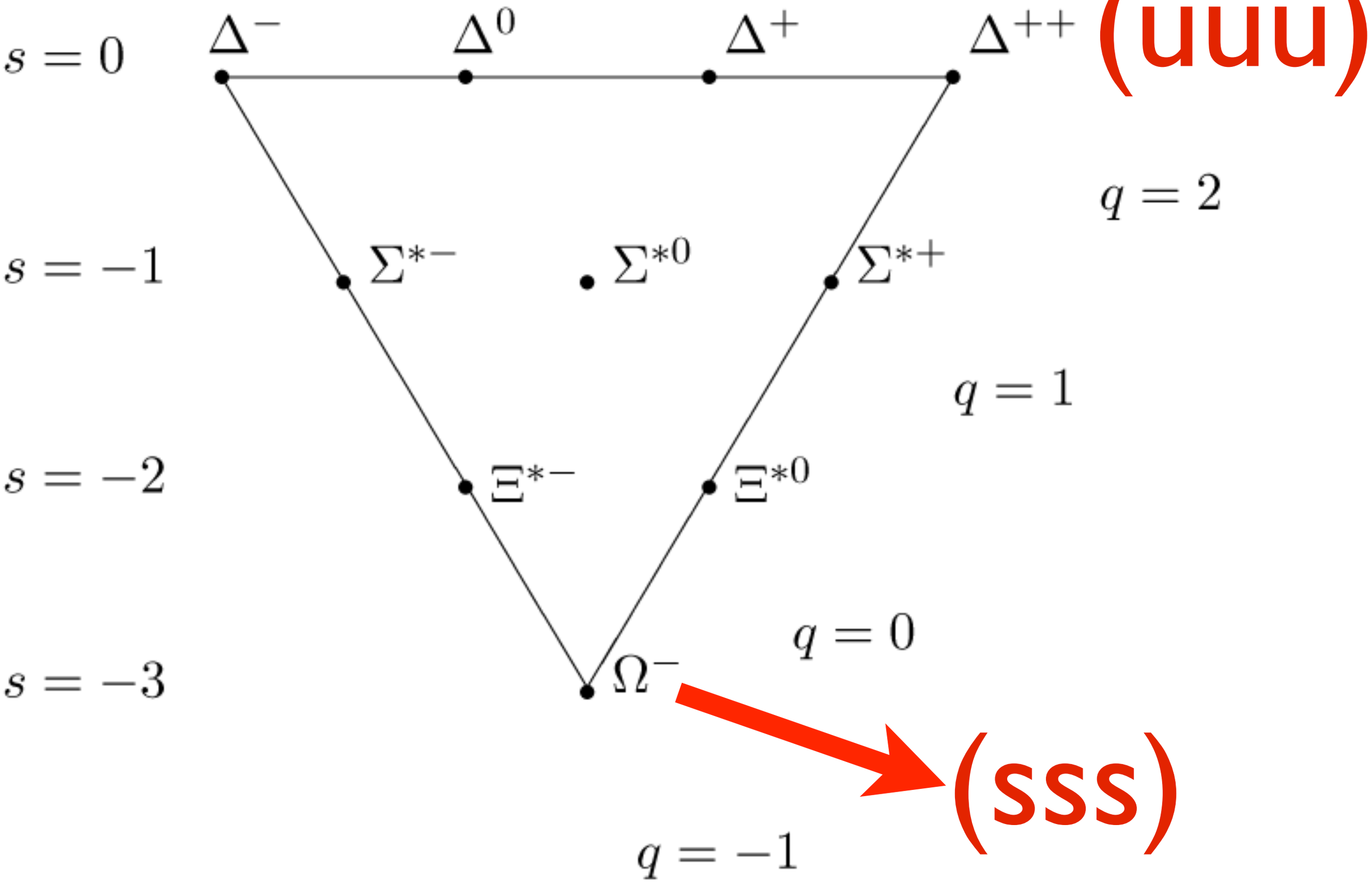
!!!

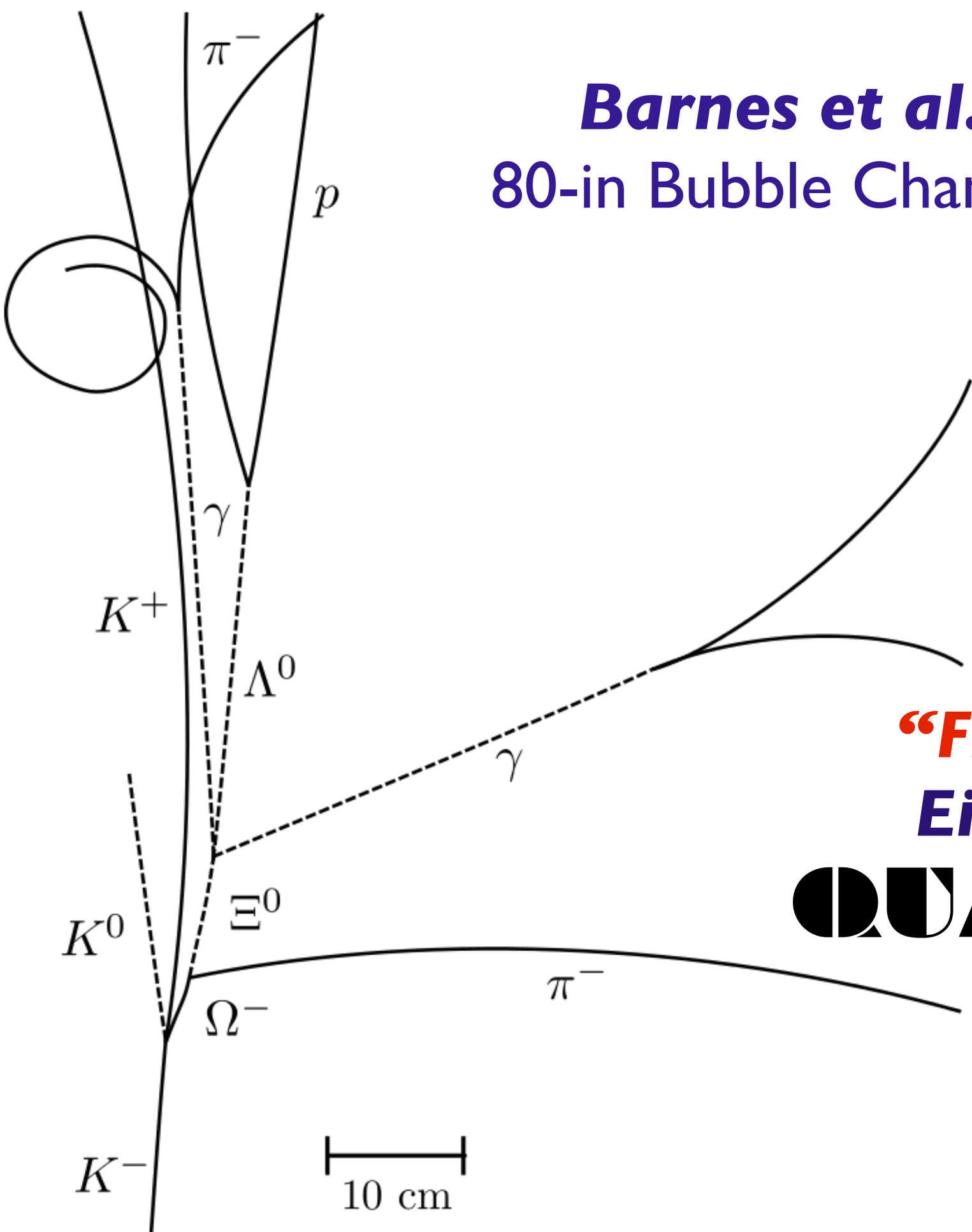
Hadrons have pieces but if you tear them to pieces

...

you don't get their pieces !!!

(qqq) ↑↑↑


$s = 0$
Δ^-
Δ^0
Δ^+
Δ^{++}
(uuu)
$q = 2$
$s = -1$
Σ^{*-}
Σ^{*0}
Σ^{*+}
$q = 1$
$s = -2$
Ξ^{*-}
Ξ^{*0}
$q = 0$
$s = -3$
Ω^-
(sss)
$q = -1$



Barnes et al. 1963

80-in Bubble Chamber BNL

"Flavour" SU(3)

Eight-fold way

QUARKS ???

WHO BELIEVED IN QUARKS ?

Gell-Mann had introduced quarks as a mathematical concept from which relations among phenomena could be abstracted, and the underlying model then dropped. He liked to compare this to French cuisine where "a piece of pheasant meat is cooked between two pieces of veal, which are then discarded".[16] (Frank Close)

VEAL / QUARK

PHEASANT / HADRON

VEAL / QUARK

Pulling oneself up by one's own BOOTSTRAPS

HADRON = {HADRONS}

ANALITICITIE

POSITIVITIE

Talk at Berkeley

ALTHOUGH

Historical Talk :

OLD JOKES

(this one ... was not a joke)

The standard-model experimental revolution started at SLAC in 1968: quasi-point-like proton constituents (Feynman's PARTONS) *and at CERN in 1973 (weak neutral currents)*

Like nowadays,
the pace of
discovery
was very fast
in the 1970's

Discovery
"MATRIX" article

SQUELETTE D'ARTICLE POUR "DÉCOUVERTE SCIENTIFIQUE"

IL A ÉTÉ ANNONCÉ HIER QUE LE PROF. [redacted] DU LABORATOIRE [redacted] ET LE PROF. [redacted] DU LABO [redacted] ET LEURS COLLABORATEURS ONT ÉTABLI L'EXISTENCE D'UNE NOUVELLE (EAU) [redacted]

IL S'AGIT D'UNE DÉCOUVERTE D'UNE TRÉS GRANDE IMPORTANCE, QUI CONSTATE LA THÉORIE DE [redacted] QUI AVAIENT PRÉDIT UN(E) TEL(LLE) [redacted] COMME CONSÉQUENCE DE [redacted]

UNE AUTRE ÉCOLE INTERPRÉTE LE NOUVEAU(LLE) [redacted] COMME UNE MANIFESTATION DU RECHERCHÉ [redacted]

SQUELETTE D'ARTICLE POUR "DÉCOUVERTE SCIENTIFIQUE"

IL A ÉTÉ ANNONCÉ HIER QUE LE PROF. LAGARRIGUE DU LABORATOIRE D'ORSAY ET LE PROF. MUSSET DU LABO DU CERN ET LEURS COLLABORATEURS ONT ÉTABLI L'EXISTENCE D'UNE NOUVELLE (EAU) FORCE "FAIBLE"

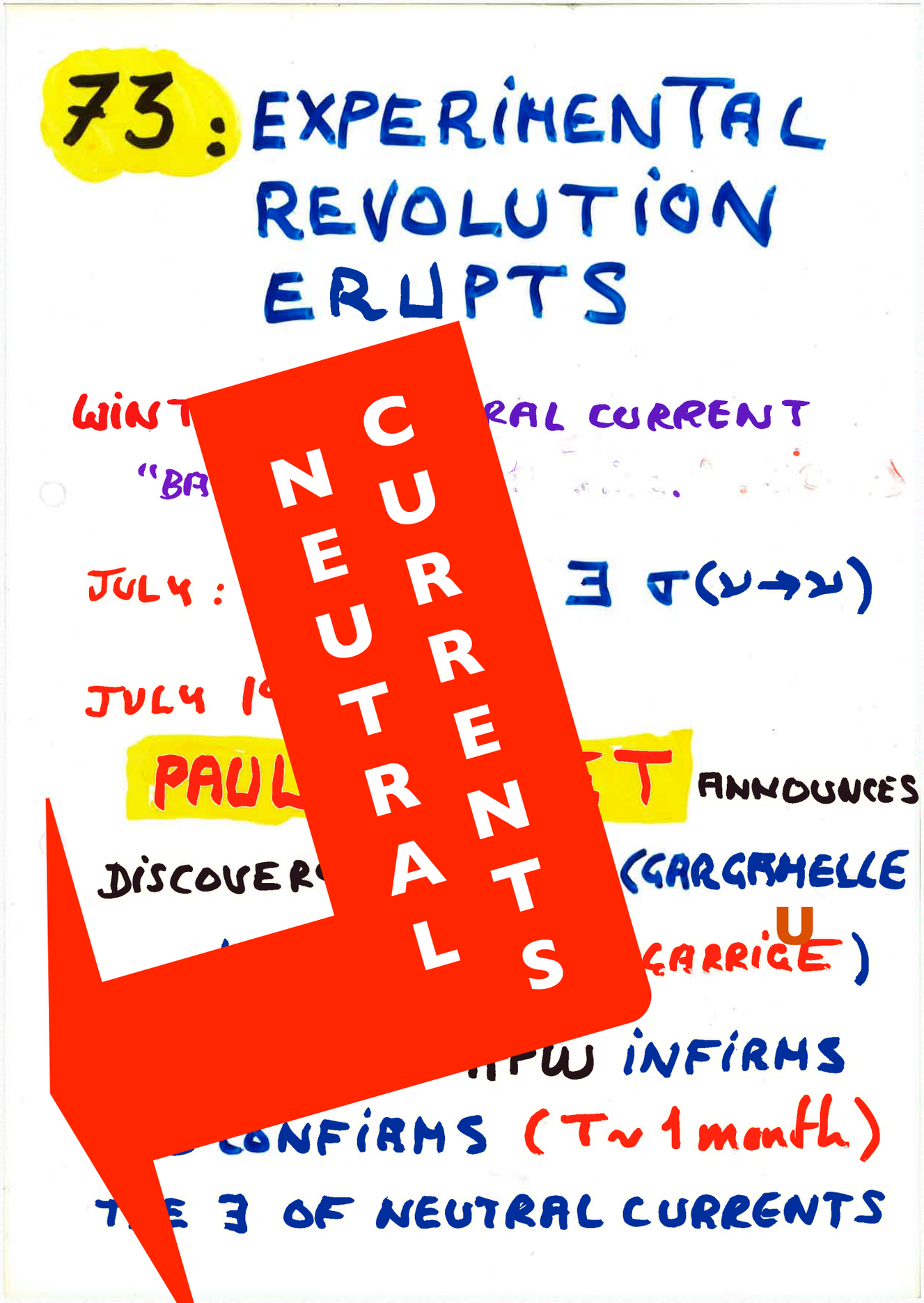
IL S'AGIT D'UNE DÉCOUVERTE D'UNE TRÉS GRANDE IMPORTANCE, QUI CONSTATE LA THÉORIE DE GLASHOW, WEINBERG ET SALAM QUI AVAIENT PRÉDIT UN(E) TEL(LLE) FORCE COMME CONSÉQUENCE DE UNIFICATION DES FORCES FONDAMENTALES

UNE AUTRE ÉCOLE INTERPRÉTE LE NOUVEAU(LLE) FORCE COMME UNE MANIFESTATION DU RECHERCHÉ ERREUR DES COMPÉTITEURS

CERN 1973

TH: FIRST EVIDENCE FOR THE EXISTENCE OF CHARM

Z ??



SQUELETTE D'ARTICLE POUR "DÉCOUVERTE SCIENTIFIQUE"

IL A ÉTÉ ANNONCÉ HIER QUE LE PROF. RUBBIA DU LABORATOIRE CERN ET LE PROF. DARRIULAT DU LABO DU CERN ! ET LEURS COLLABORATEURS ONT ÉTABLI L'EXISTENCE D'UNE NOUVELLE (EAU) PARTICULE

IL S'AGIT D'UNE DÉCOUVERTE D'UNE TRÉS GRANDE IMPORTANCE, QUI CONSTATE LA THÉORIE DE GLASHOW, SALAM ET WEINBERG QUI AVAIENT PRÉDIT UN(E) TEL(LLE) PARTICULE COMME CONSÉQUENCE DE L'UNITÉ DES FORCES FONDAMENTALES

UNE AUTRE ÉCOLE INTERPRÉTE LE NOUVEAU(LLE) PARTICULE COMME UNE MANIFESTATION DU RECHERCHÉ

● ● ●

WITH THE INESTIMABLE HELP OF VAN DER MEER

How do things WORK ?

$$Q[p] = +1 \quad Q[e] = -1$$

$$H = (p\,e) \quad \Rightarrow \quad Q[H] = 0$$

$$Q[u] = 2/3 \quad Q[d] = -1/3$$

$$\pi^+ = [u\,\bar{d}] \quad \Rightarrow \quad Q[\pi^+] = 1$$

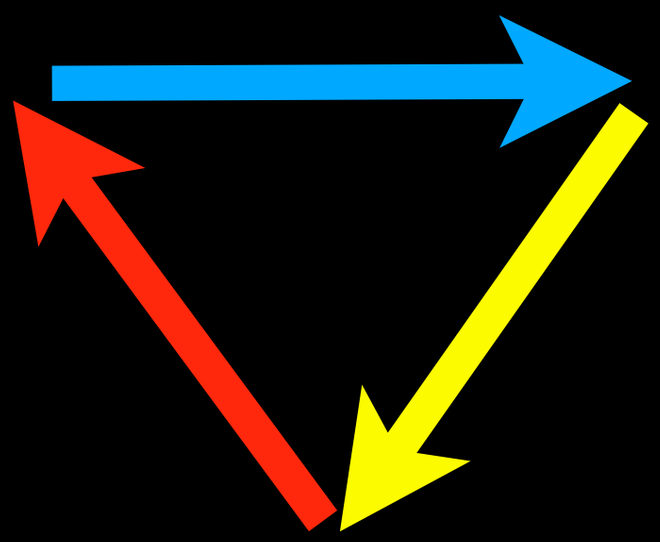
$$p = [u\,u\,d] \quad \Rightarrow \quad Q[p] = 1$$

$$C[q] = R, B, Y \Rightarrow C[\pi^+] = 0$$

$$\pi^+ = [u_R\, \bar{d}_{\bar{R}} + u_B\, \bar{d}_{\bar{B}} + u_Y\, \bar{d}_{\bar{Y}}]$$

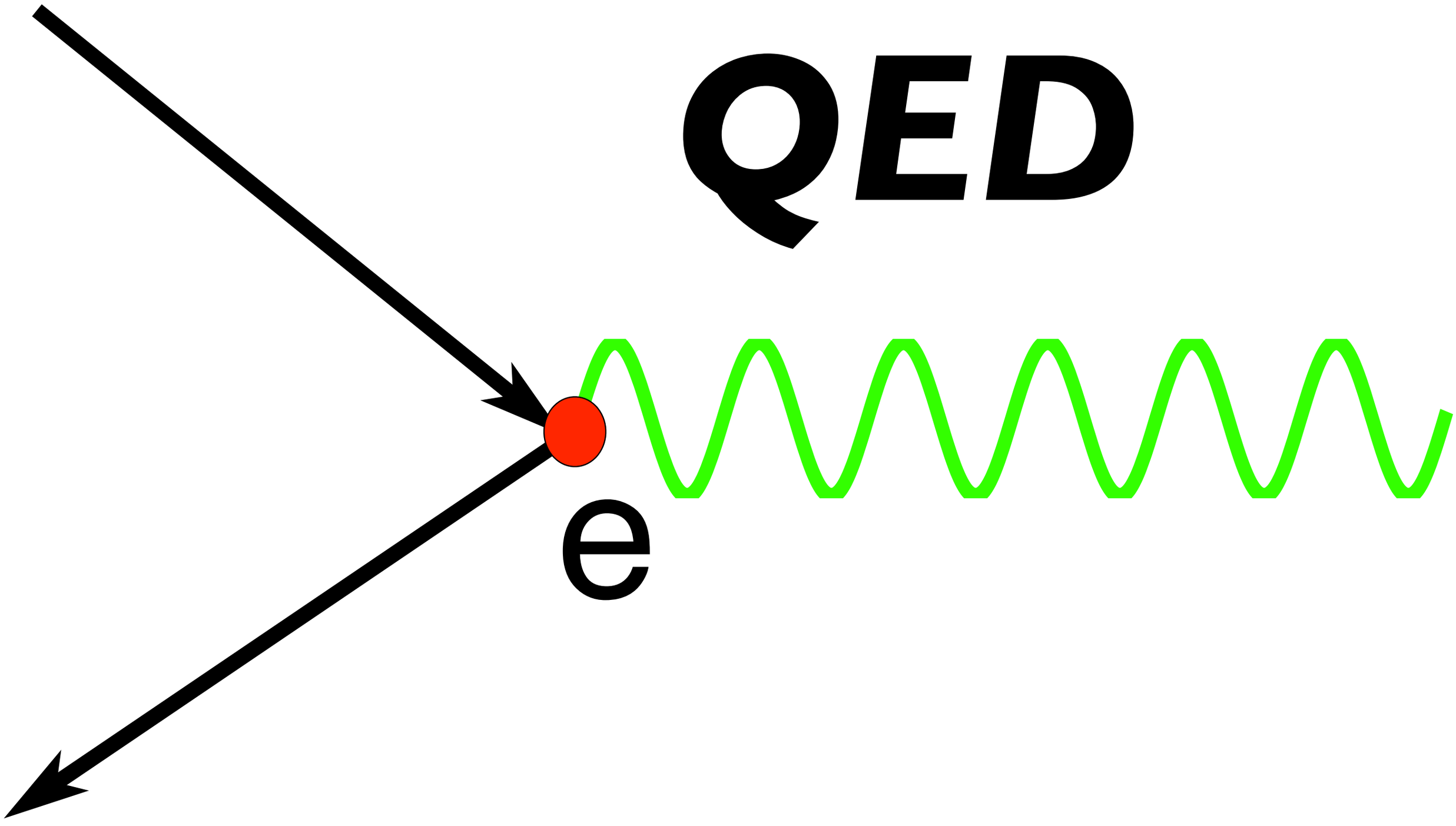
$$p = [u_R\, u_B\, d_Y \pm \text{perms}]$$

$$\Rightarrow C[p] = RBY???$$



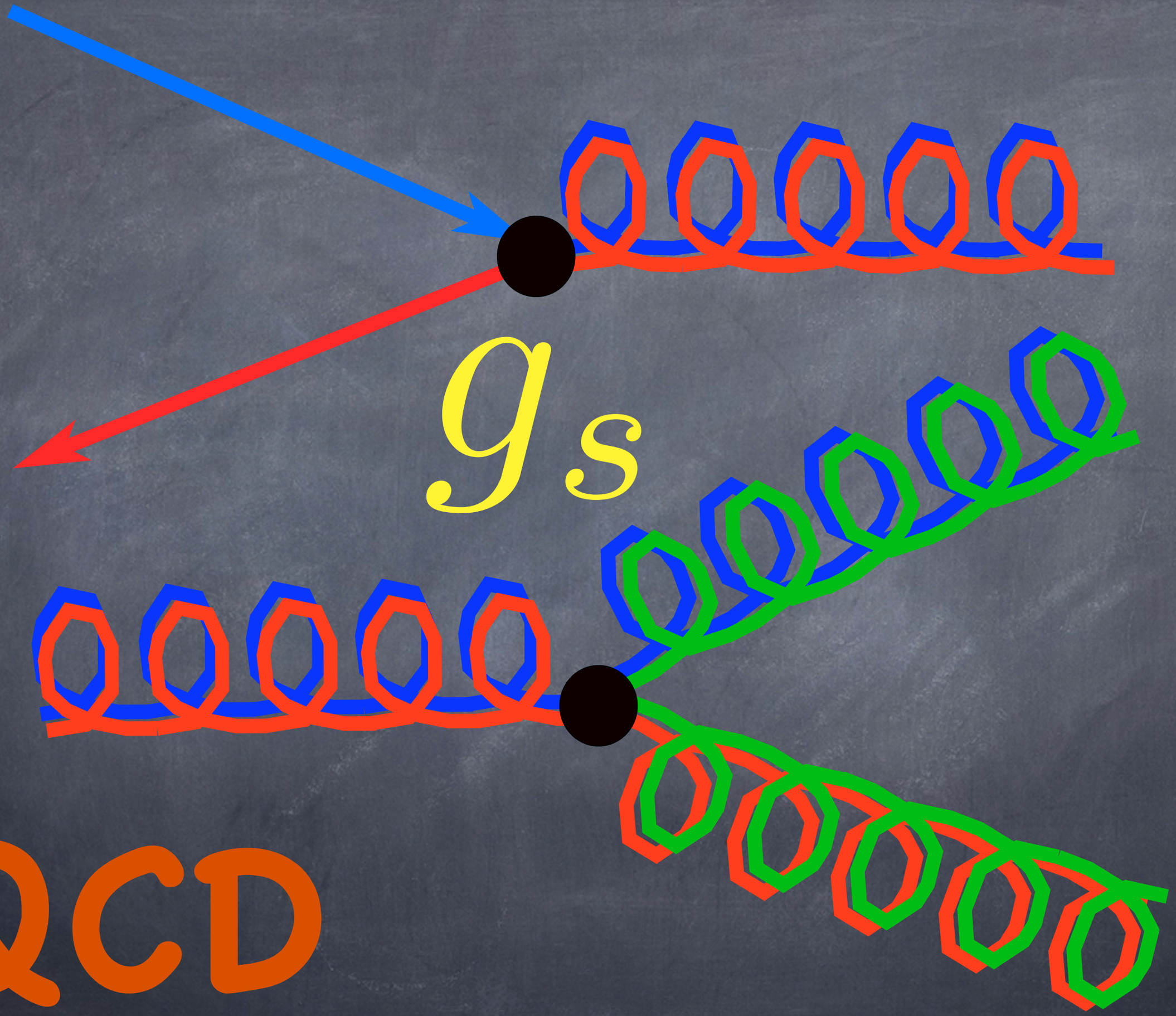
$$\Rightarrow C[p] = 0\,!!!!$$

QED

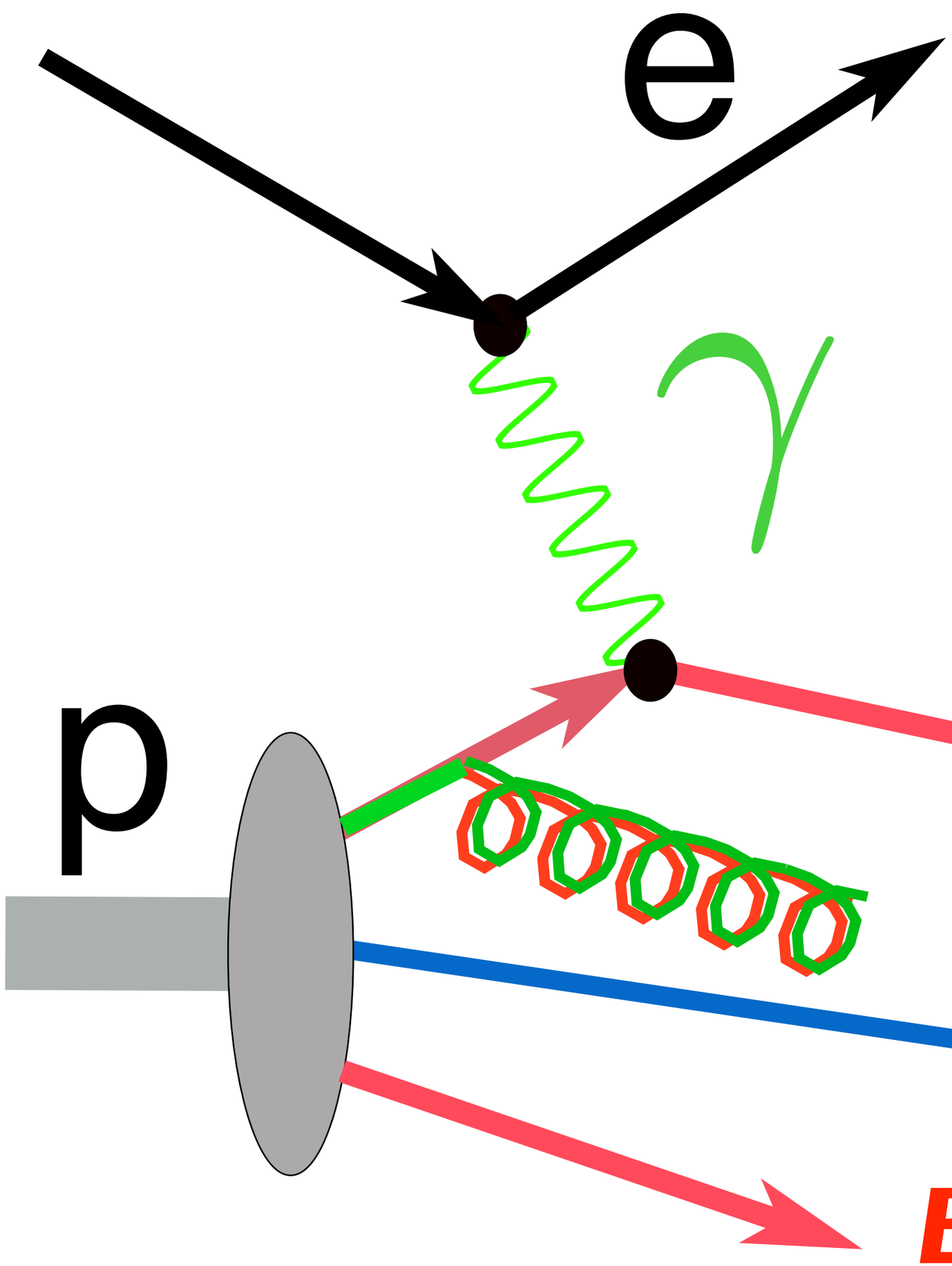


QED

1965



QCD



SLAC / MIT circa 1965

18/5

ν/e

BEFORE THAT

(AUDIENCE DUMP EXPERIMENT)

ASYMPTOTIC FREEDOM

Politzer &
Gross & Wilczec
1973

A PROPERTY OF QCD [THE STRONG INTERACTIONS]

ROUGHISSIMA
≈
DEFINITIO

IN PROCECESS FOR WHICH ALL THE RELEVANT MOMENTAE ARE LARGE ($\gtrsim 1$ GeV)

THE STRONG INTERACTIONS GET WEAKER AND TREATABLE IN PERT. THEORY.

TROUBLE : FEW OF SUCH PROCECESS. [EX : e^+e^- ANNIHIL
CNEX : $\sigma(\pi p)$

WHY THE NAME ?

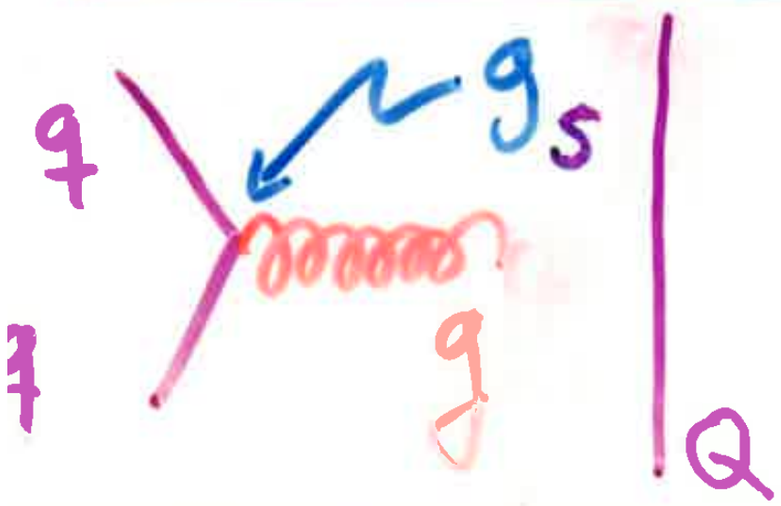
WHY THE NAME ?

FREEDOM : REFERS TO THE FACT THAT THE THEORY IS **NOT** TRIVIAL FREE FIELD TH.

(Like with politicians...)

ASYMPTOTIC : REFERS TO THE FACT THAT THE PREDICTIONS ARE FOR FINITE, RATHER SMALL, NON ASYMPTOTIC ENERGIES

HOW WILL IT WORK ?



THE QUARK-GLUON (AND G-G) COUPLING CONSTANT g_s IS NOT A CONSTANT

$g_s \sim \frac{1}{\log Q}$

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.

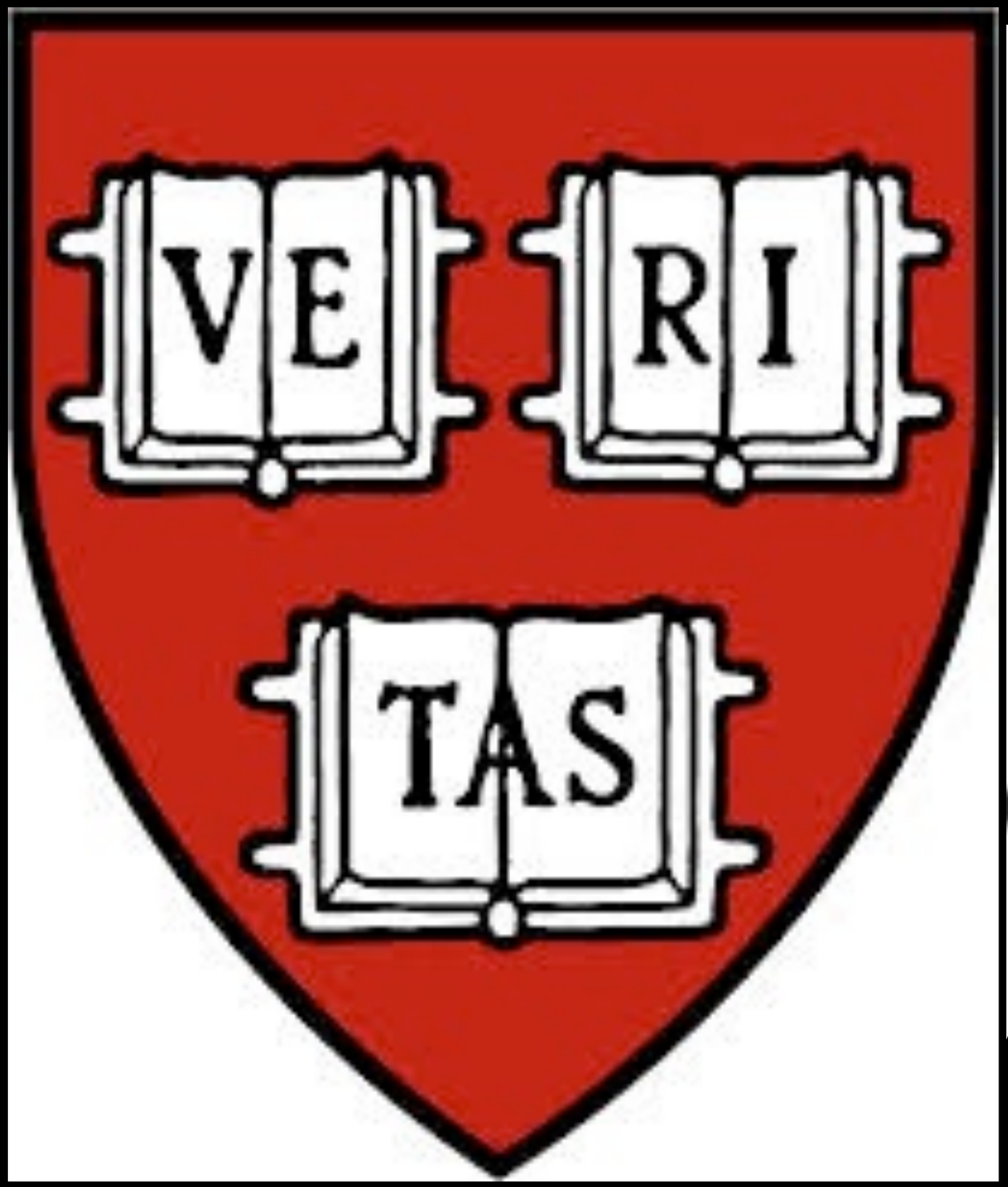
Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

(Received 27 April 1973)

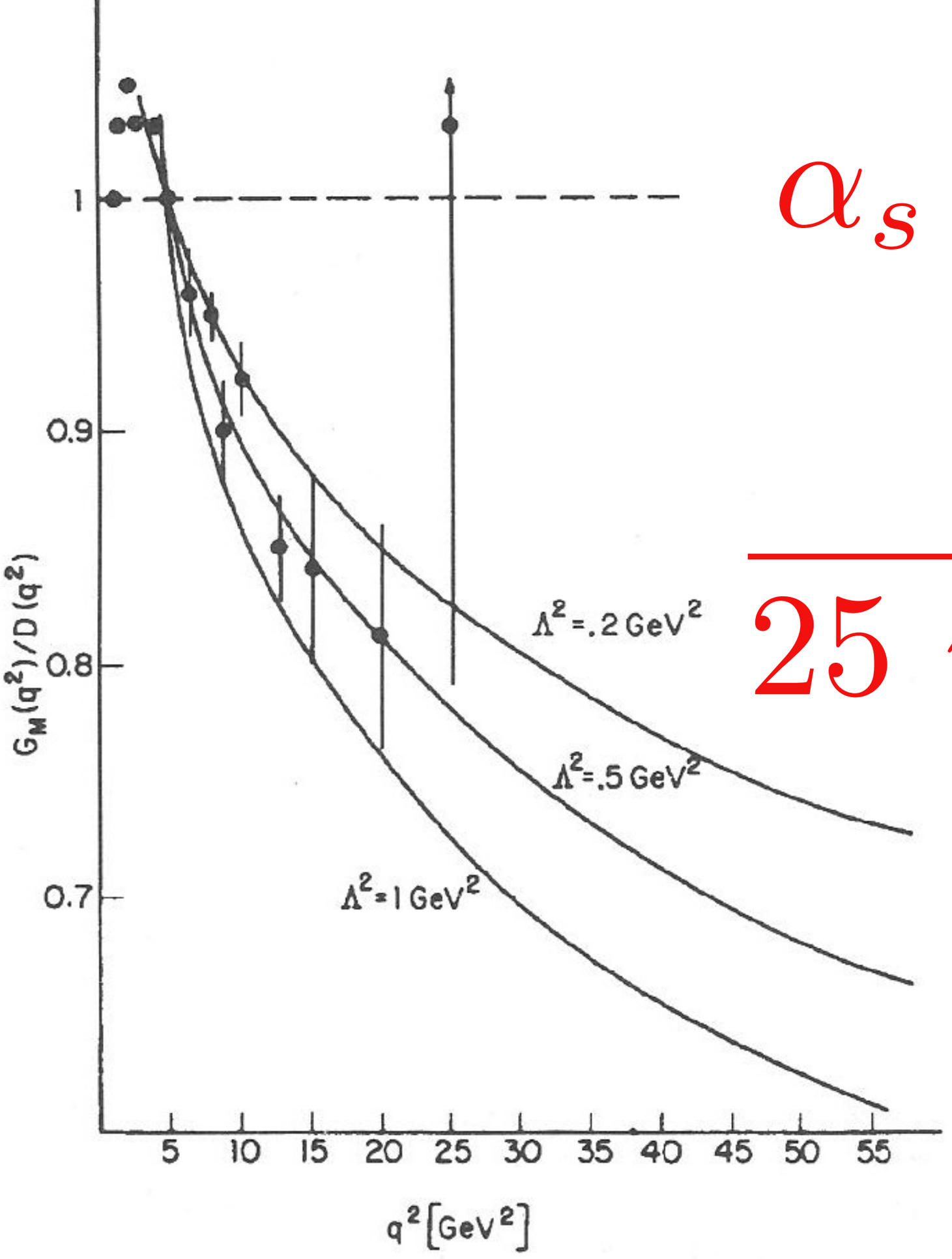
It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.



God Went to Princeton

A. De Rujula, S.L. Glashow, H.David Politzer (Harvard U.),
S.B. Treiman, Frank Wilczek, A. Zee (Princeton U.)

Phys.Rev. D10 (1974) 1649



$$\alpha_s \equiv \frac{g_s^2}{4\pi} = \frac{12}{25\,\pi \ln[q^2/\Lambda^2]}$$

ADR PRL 26/3/74

Gross & Treiman
PRL 25/3/74

error bars?

1/3, 1/2 ?? :

$$\frac{1}{2}mv^2$$

Frequent reference to work by ADR et al.

Oscar Wilde:

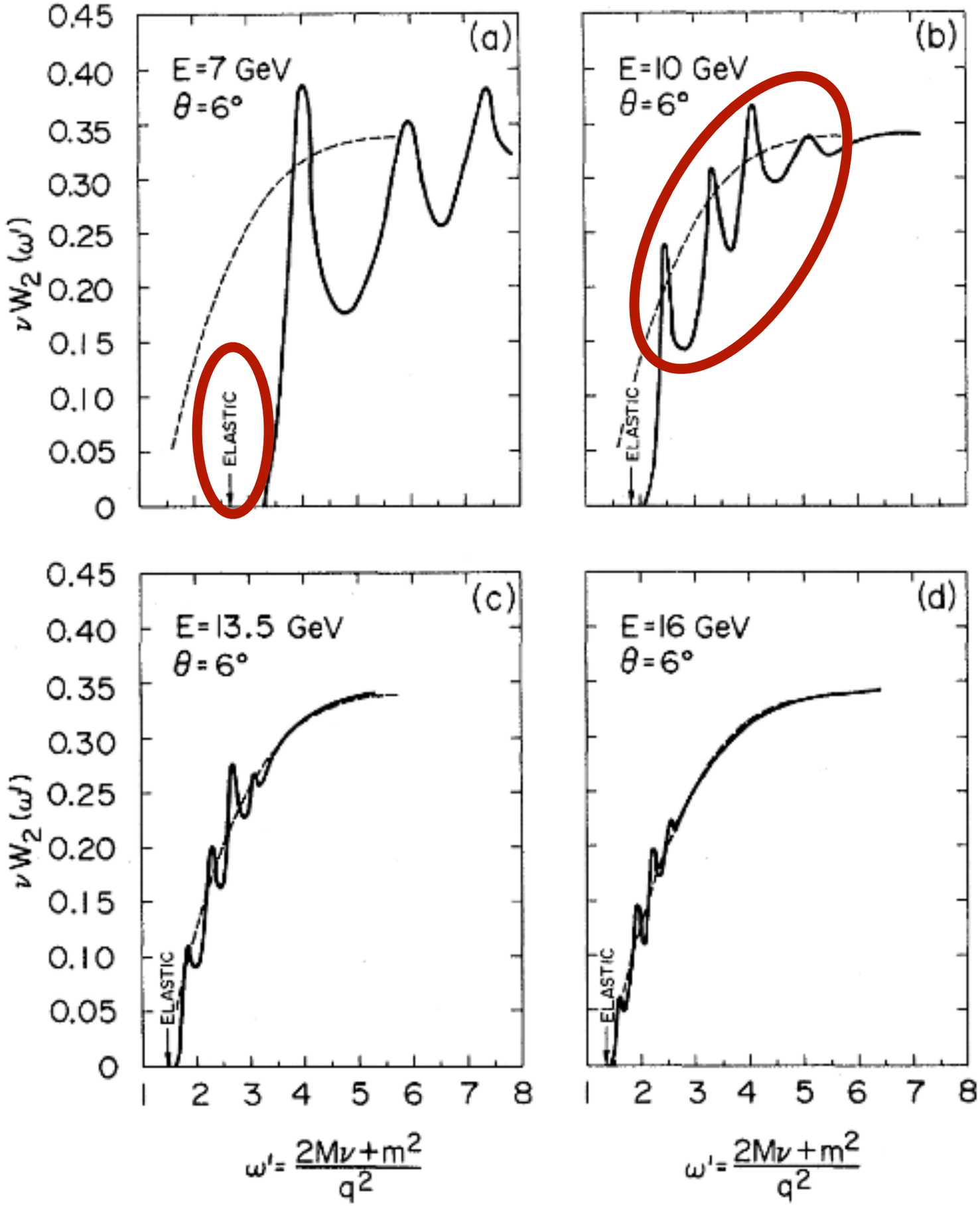
Memory... is the diary that we all carry about with us.

Golda Meir:

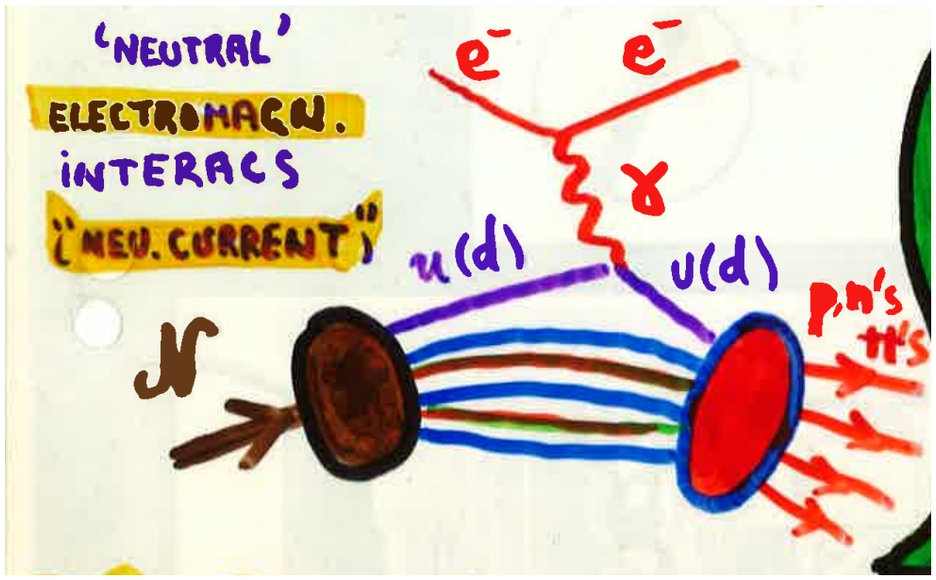
Don't be humble... you're not that great.

unlike

“et al.”



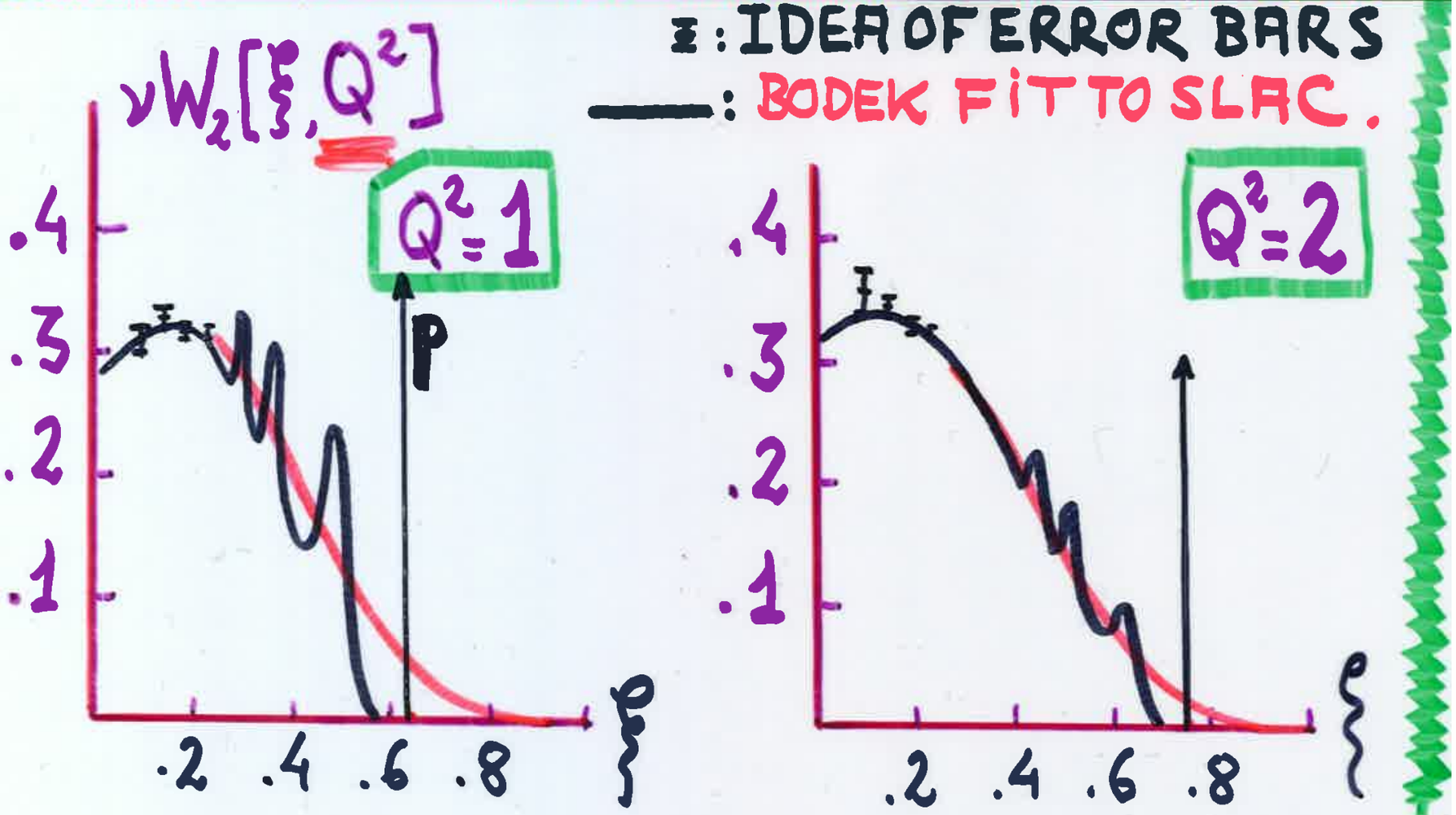
Bloom-Gilman duality



Dashed: *At high transfer of momentum the proton behaves as if made of charged point-like “PARTONS”*

H.DeR, H.GEORGI, H.D.POLITZER

"DEMYTHIFICATION OF ELECTROPRODUCTION LOCAL DUALITY AND PRECOCIOUS SCALING"



BLACK: *fit to DATA*

RED: LEADING TWIST QCD, i.e.

INCLUDE LEADING $(Ln[Q^2/\Lambda^2])^d$ EVOL.

DROP Λ^2/Q^2 EFFECTS

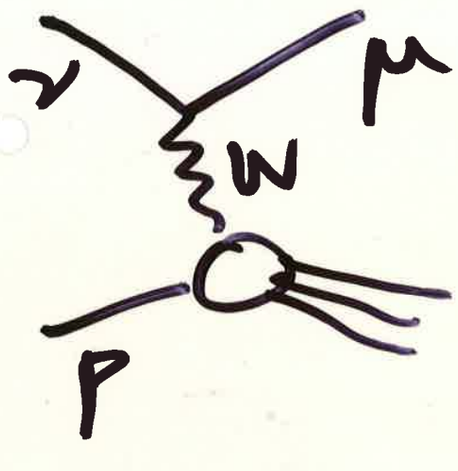
ξ is Nachtman's variable, OPE

IRONY

THIS WAS IGNORED (AND SUBS. FORGOTTEN)

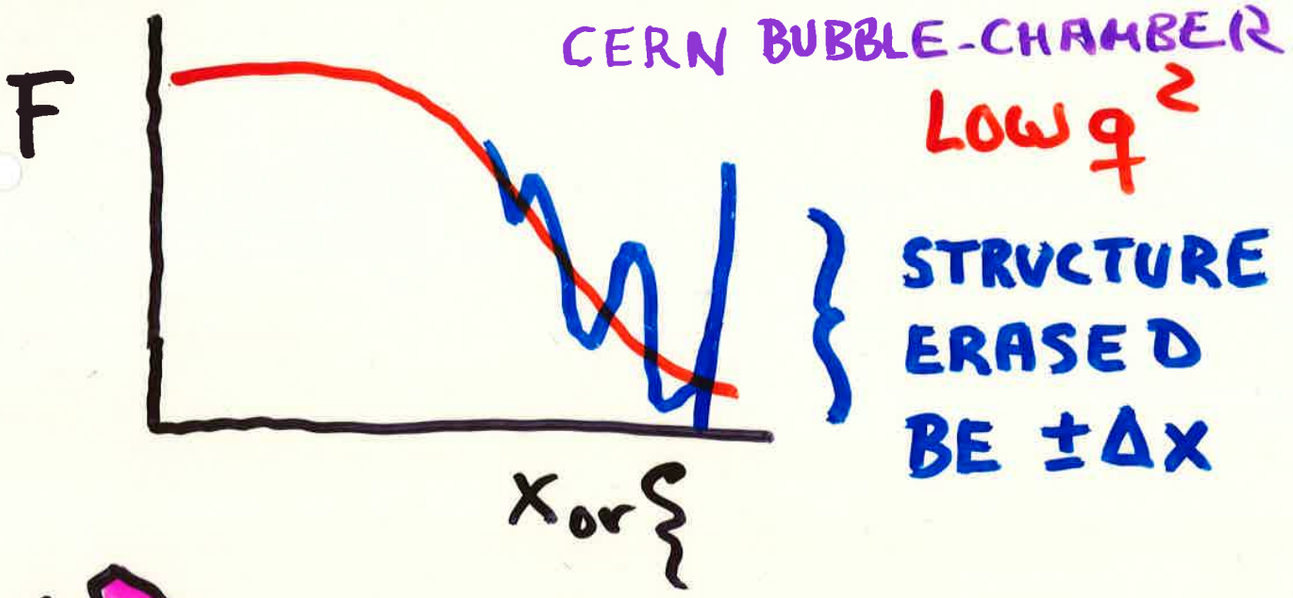
TILL $\nu \to \mu$ DIS EXPS

UNLIKE $e \to e$



ν-ENERGY NOT MEASURABLE

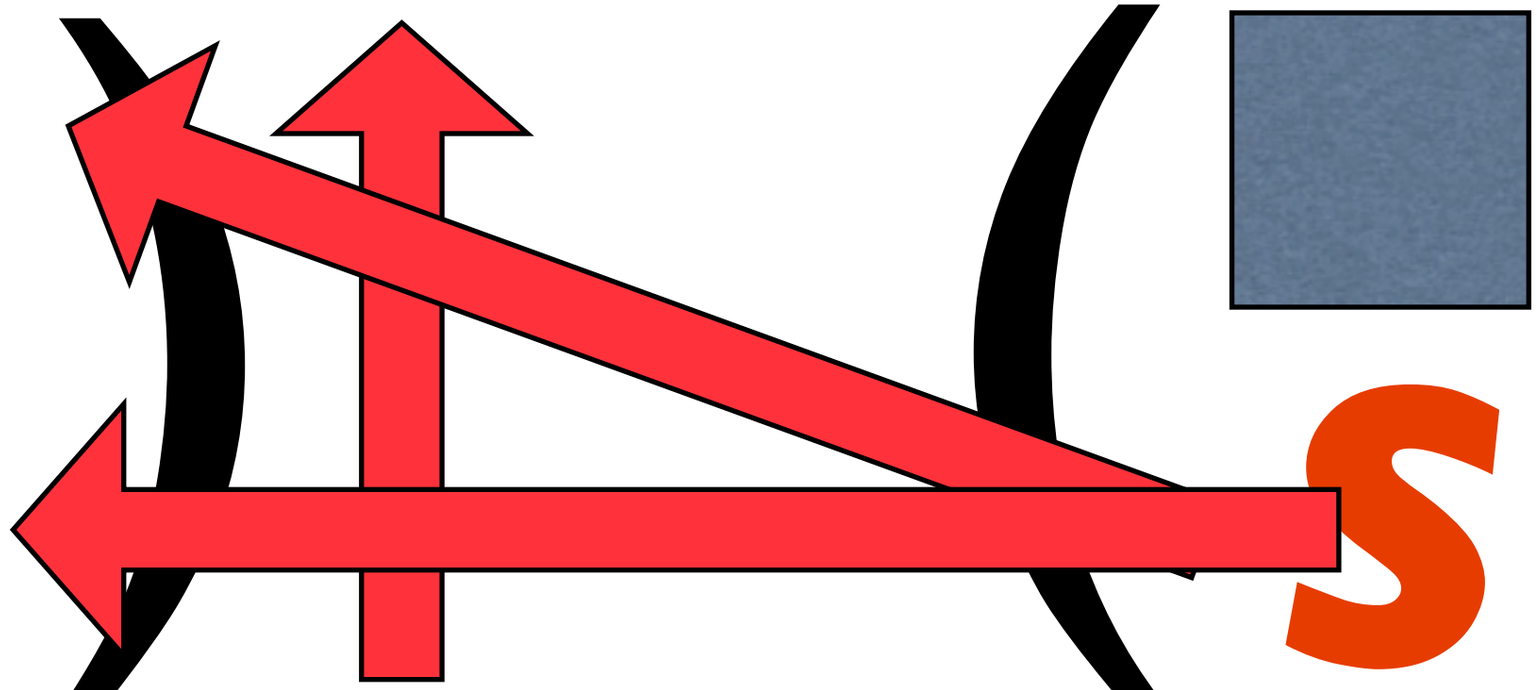
X-RESOLUT NOT GOOD



DATA BAD ENOUGH TO LOOK LIKE NAIVEST QCD EXPECTS

QCD evolution was accepted as a precise prediction because the data were *NOT* precise

That is why I recalled the "demythifycation" of B&G

$\begin{pmatrix} u \\ d \end{pmatrix}$  $\begin{pmatrix} \square \\ s \end{pmatrix}$

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ GIM $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$

DEUTSCHLAND

SU(2) x U(1)

GLASHOW

1963

SSB

HKHEGB

1964

> 1966 M_1

???

THEORY LAID DORMANT 5 MORE DARK-AGE YEARS, BUT

FOR

SALAM 68
WEINBERG 67
} H+G

CITATIONS

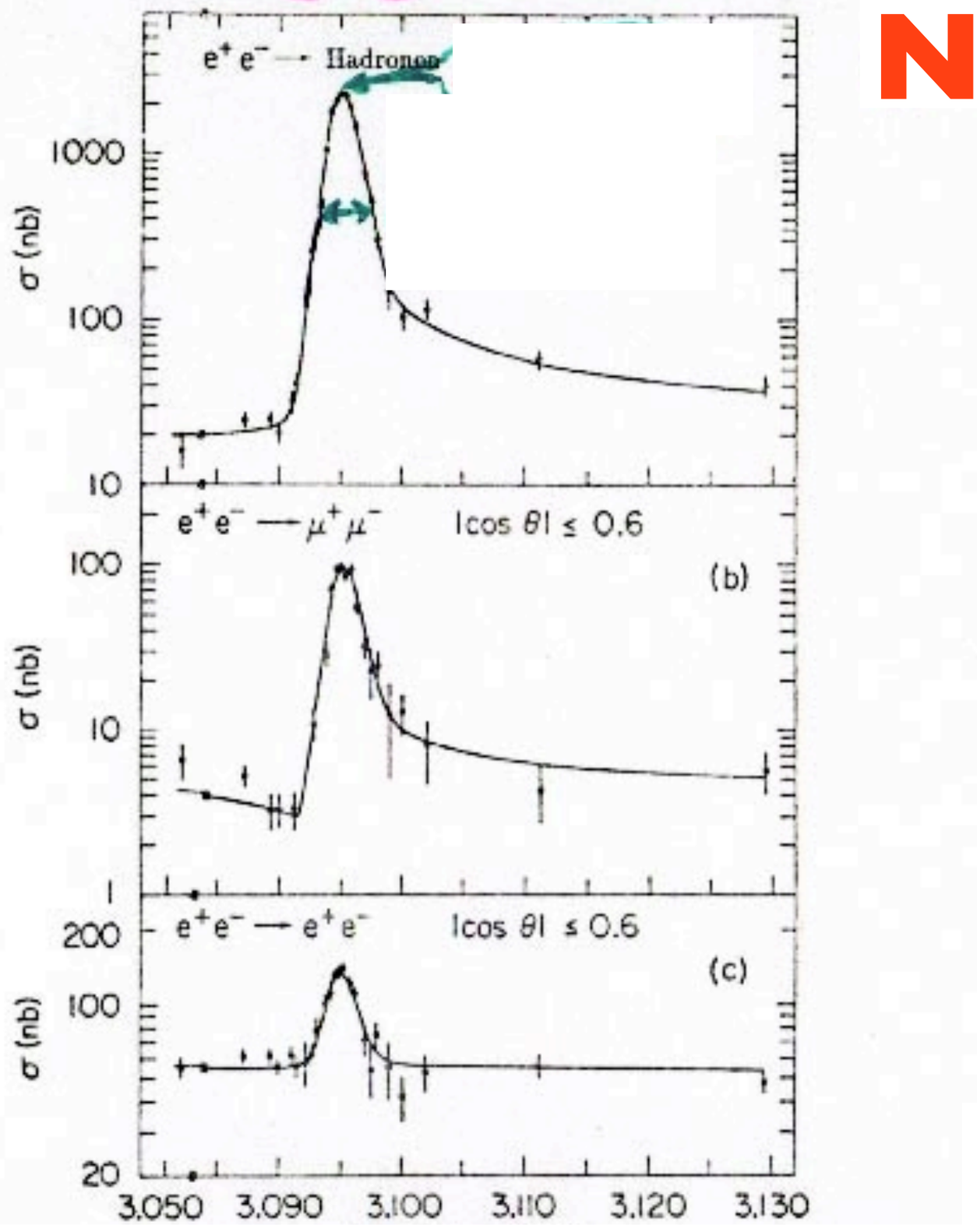
67 : 0
68 : 0
69 : 0
70 : 1
71 : 4
72 : 64
73 : 162

't HOOFT

SPONTANEOUSLY BROKEN NON-ABELIAN GAUGE THS ARE RENORMALIZABLE

SC : GERARD'S KISS TRANSMOGRIFIED STEVE'S FROG INTO AN ENCHANTED PRINCE

NOVEMBER 1974



Augustin et al.

SLAC, Nov 13, Ψ

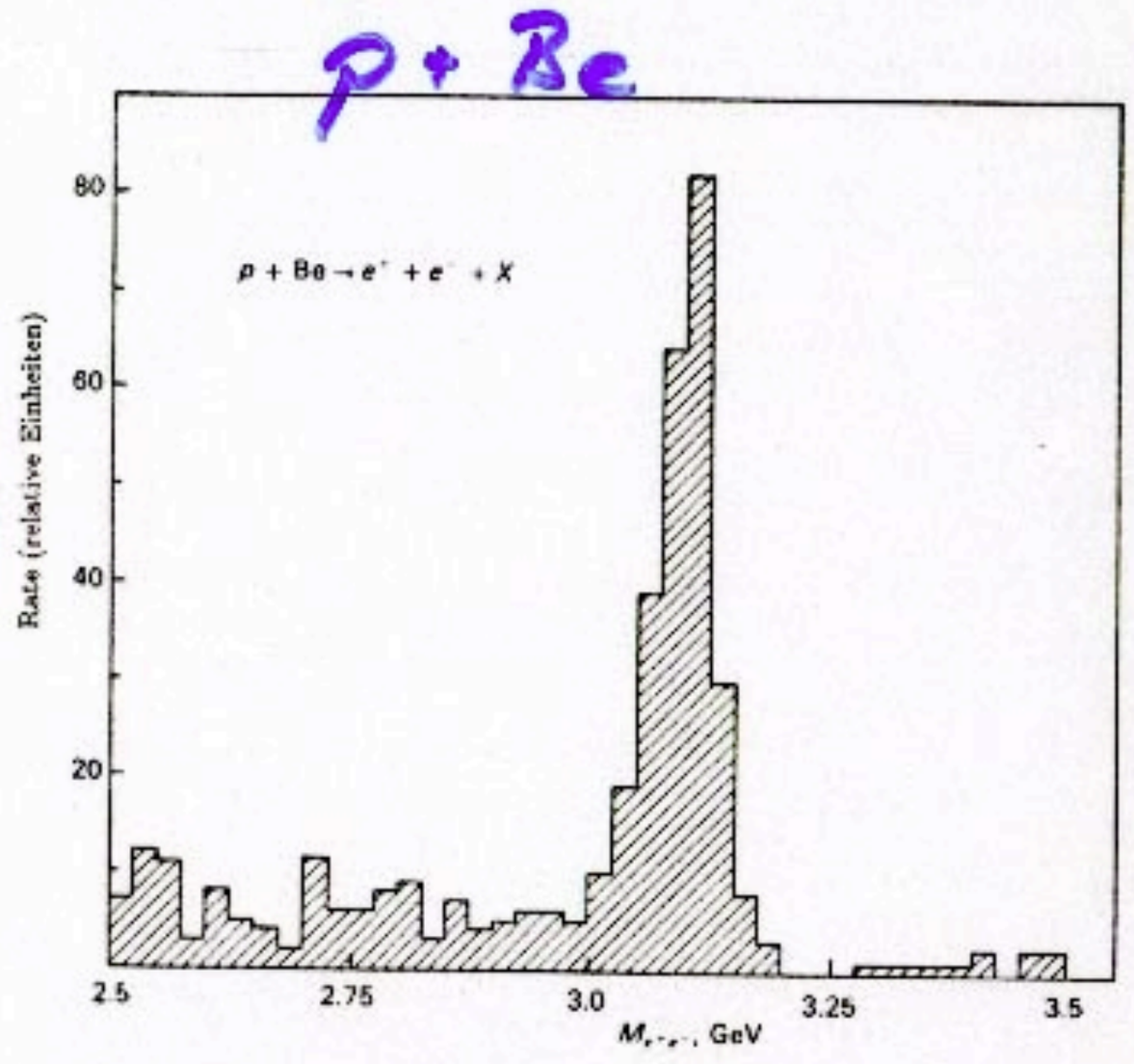


Abbildung 5.10 Die Ergebnisse von Aubert et al. (1974) zeigen die schmale J/ψ-Resonanz in der Verteilung der invarianten Masse des e^+e^--Paars, das in inklusiven Reaktionen von Protonen an einem Berylliumtarget erzeugt wurde. Dies Experiment wurde am 28 GeV-AGS des Brookhaven National Laboratorys ausgeführt.

Aubert et al.

BNL, Nov 12, J

PERIODISTAS VAGOS

MATRIZ PARA ARTICULO "DESCUBRIMIENTO CIENTIFICO"

SE ANUNCIO AYER EN UNA CONFERENCIA DE PRENSA QUE EL PROF _____ DEL LABORATORIO _____ Y EL PROF. _____ DEL LABORATORIO _____ Y SUS COLABORADORES HAN ESTABLECIDO LA EXISTENCIA DE UN(A) NUEVA(O) _____. ES ESTE UN DESCUBRIMIENTO DE GRAN IMPORTANCIA, QUE CORROBORA LA TEORIA DE _____ Y SUS COLABORADORES, QUE HABIAN PREDICHO TAL _____ COMO CONSECUENCIA DE _____.

OTRA ESCUELA INTERPRETA LA (EL) NUEVA(O) _____ COMO UNA MANIFESTACION DEL AÑORADO _____

MATRIZ PARA ARTICULO "DESCUBRIMIENTO CIENTIFICO" (NOV 74)

SE ANUNCIO AYER EN UNA CONFERENCIA DE PRENSA QUE EL PROF. TING DEL LABORATORIO BNL (BROOKHAVEN) Y EL PROF. RICHTER DEL LABORATORIO SLAC (STANFORD) Y SUS COLABORADORES HAN ESTABLECIDO LA EXISTENCIA DE UN(A) NUEVA(O) PARTICULA. ES ESTE UN DESCUBRIMIENTO DE GRAN IMPORTANCIA, QUE CORROBORA LA TEORIA DE SHELDON LEE GLASHOW Y SUS COLABORADORES, QUE HABIAN PREDICHO TAL PARTICULA COMO CONSECUENCIA DE LA EXISTENCIA DE QUARKS ENCANTADOS.

OTRA ESCUELA INTERPRETA LA (EL) NUEVA(O) PARTICULA COMO UNA MANIFESTACION DEL AÑORADO COLOR NO CONFINADO Unconfined Colour

FEVERISH REACTION

Phys. Rev. Lett. 34, many, (1975)

Published

6 January 1975

PRL

Are the New Particles Baryon-Antibaryon Nuclei?

Alfred S. Goldhaber and Maurice Goldhaber

Interpretation of a Narrow Resonance in e+ e- Annihilation

Julian Schwinger

Possible Explanation of the New Resonance in e+ e- Annihilation

S. Borchardt, V. S. Mathur, and S. Okubo

Model with Three Charmed Quarks R. Michael Barnett

Heavy Quarks and e+ e- Annihilation Thomas Appelquist and H. David Politzer

Is Bound Charm Found? A. De Rújula and S. L. Glashow

Possible Interactions of the J Particle

H. T. Nieh, Tai Tsun Wu, and Chen Ning Yang

Remarks on the New Resonances at 3.1 and 3.7 GeV

C. G. Callan, R. L. Kingsley, S. B. Treiman, F. Wilczek, and A. Zee

Is the 3104-MeV Vector Meson the psi - Charm or the W0?

G, Altarelli, N. Cabibbo, R. Petronzio, L. Maiani, G. Parisi

MASS VERSUS LIFETIME ALL PARTICLES

LIFETIME IN SECONDS

∞?

10^{3}

10^{-5}

10^{-10}

10^{-15}

10^{-20}

10^{-25}

γ, ν, e p n μ $\pi^{\pm}$ K^{L} K^{+} K_S Λ Σ^{+} Ξ^{0} Ξ^{-} Ω^{-} Σ^{0} π^{0} η

8 ?

STABLE

DEC. WEAKLY

DEC. ELECTROMAGNETICALLY

DEC. STRONGLY

● MESONS

× BARYONS

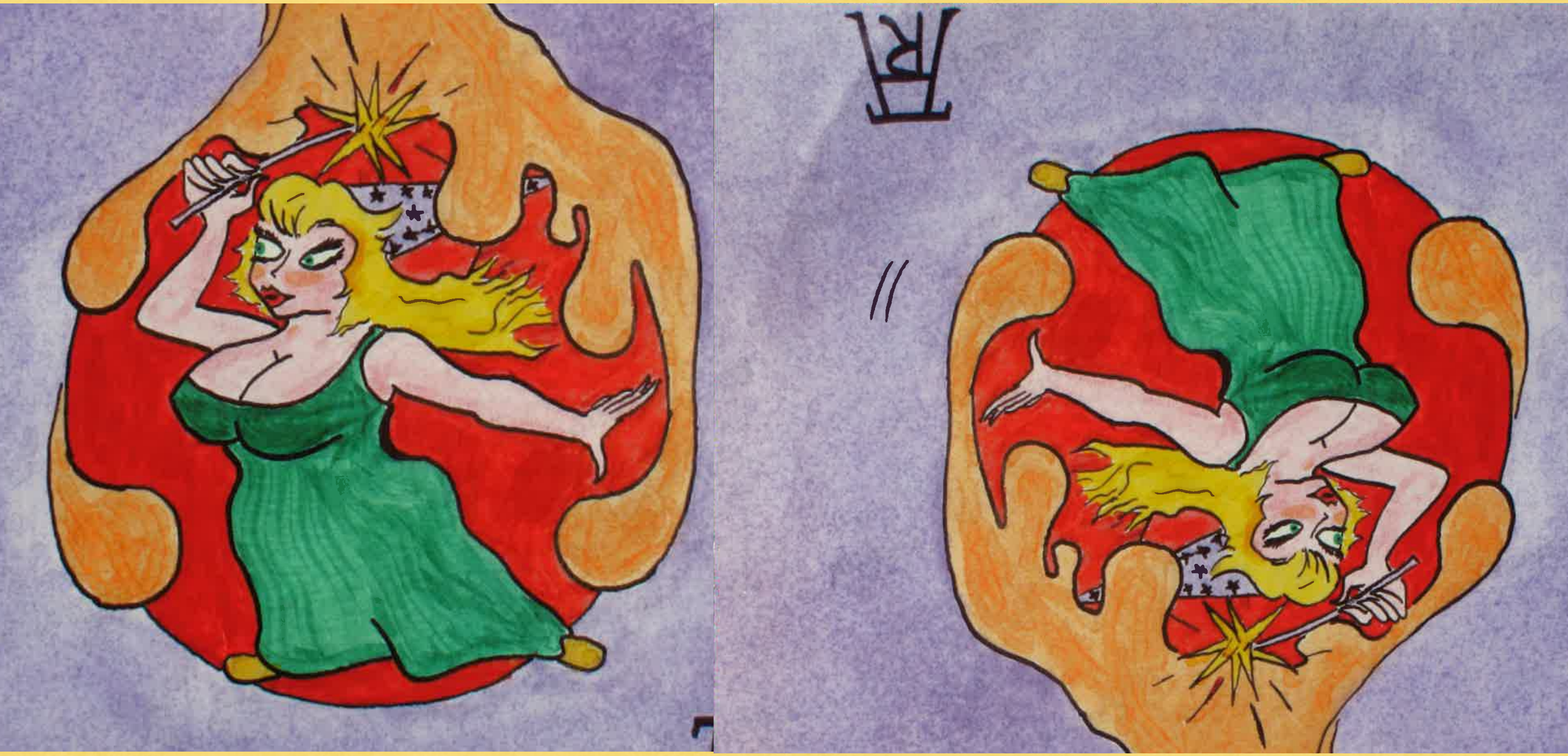
SEMIWEAK DECAY OF NEUTRAL WEAK BOSON Z

J ψ'

1 2 3 4

Mass GeV/c^2 →

CHARMONIUM (name):
A VERY DISCREET CHARM



ONLY TWO GROUPS BET ONLY FOR THE CORRECT INTERPRETATION :

Heavy Quarks and $e^+ e^-$ Annihilation*

Thomas Appelquist† and H. David Politzer‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 19 November 1974)

The effects of new, heavy quarks are examined in a colored quark-gluon model. The e^+e^- total cross section scales for energies far above any quark mass. However, it is much greater than the scaling prediction in a domain about the nominal two–heavy-quark threshold, despite $\sigma_{e^+e^-}$ being a weak-coupling problem above 2 GeV. We expect spikes at the low end of this domain and a broad enhancement at the upper end.

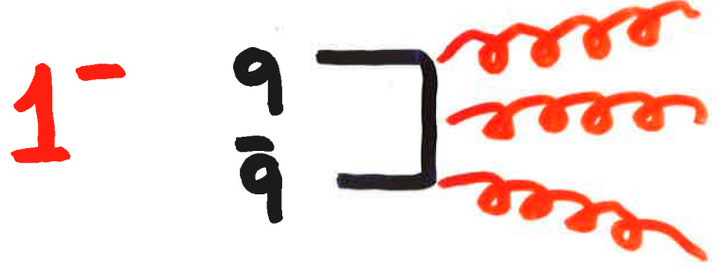
Is Bound Charm Found?*

A. De Rújula
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

and

S. L. Glashow†
Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 27 November 1974)

We argue that the newly discovered narrow resonance at 3.1 GeV is a $^3S_1$ bound state of charmed quarks and we show the consistency of this interpretation with known meson systematics. The crucial test of this notion is the existence of charmed hadrons near 2 GeV.



"ABUSUS NON TOLLIT USUM"

$$\Gamma_{J/\psi}(\text{HADS}) \sim \frac{3}{2}\frac{M_J}{M_\varphi}\left[\frac{\alpha_s(3\text{GeV})}{\alpha_s(1\text{GeV})}\right]^6 *$$

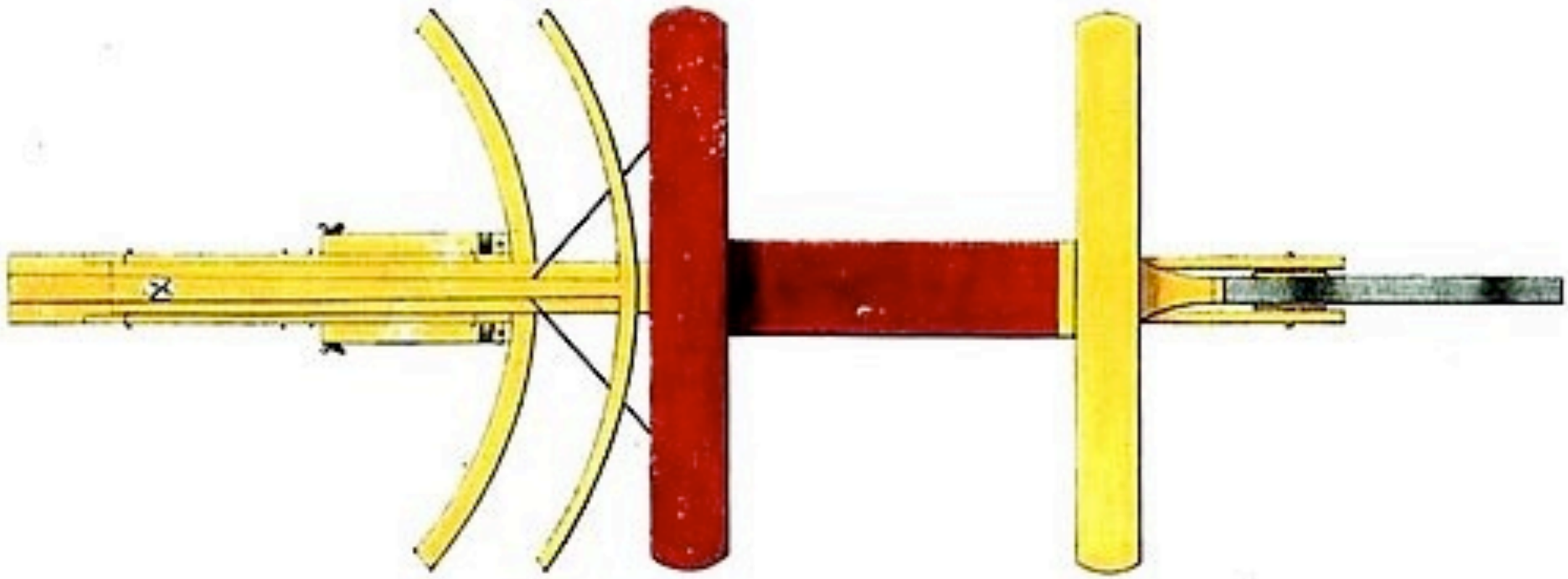
$$\Gamma(\varphi \to 3\pi) \sim 42\,\text{keV}$$

... HOW TO FIND LESS DISCREETLY CHARMED PARTICLES IN

J/ψ

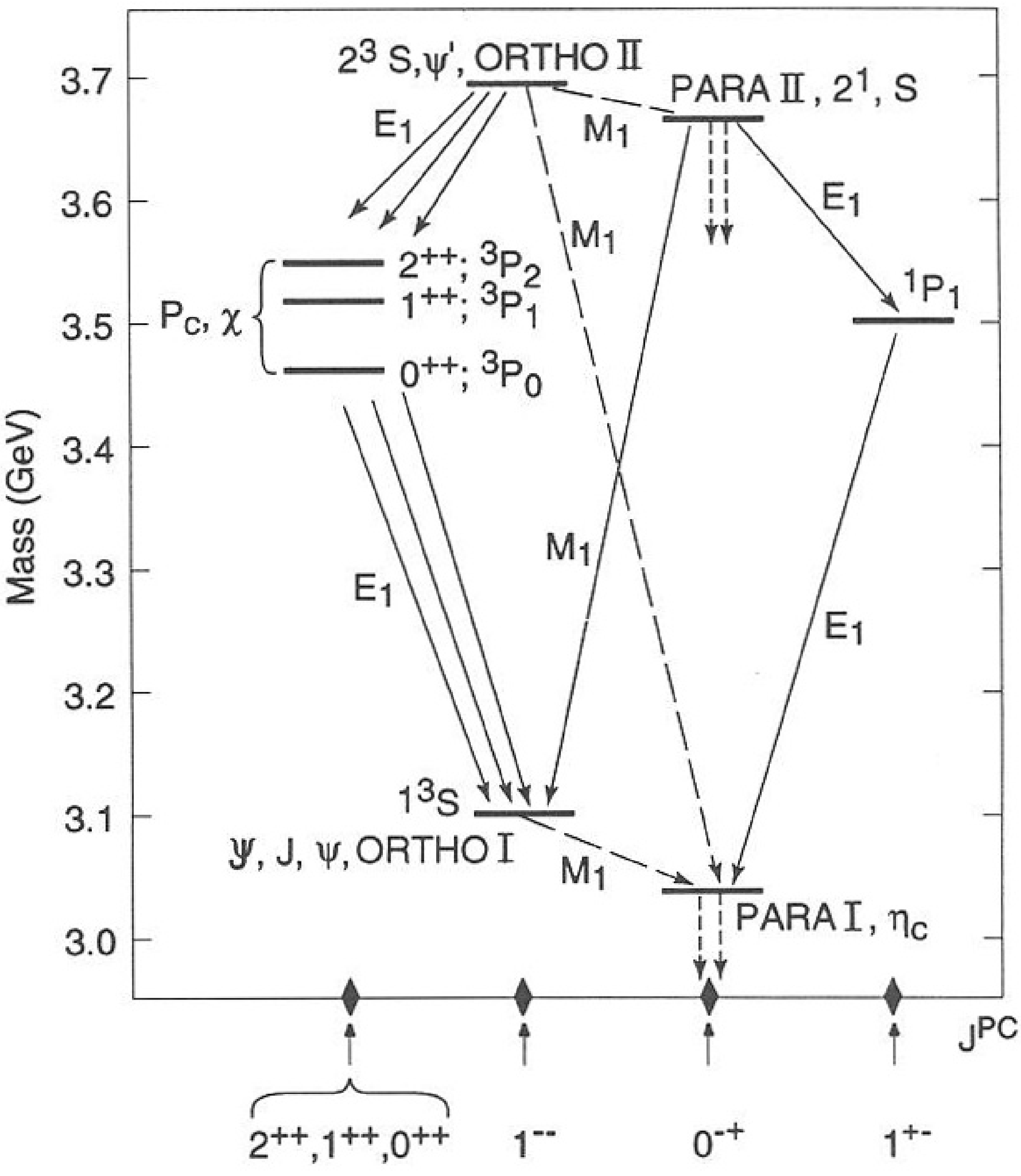
e^+e^- ANNIHILATION
J-SCATTERING
PP COLLISIONS
PHOTOPRODUCTION

Sleep -Less Night



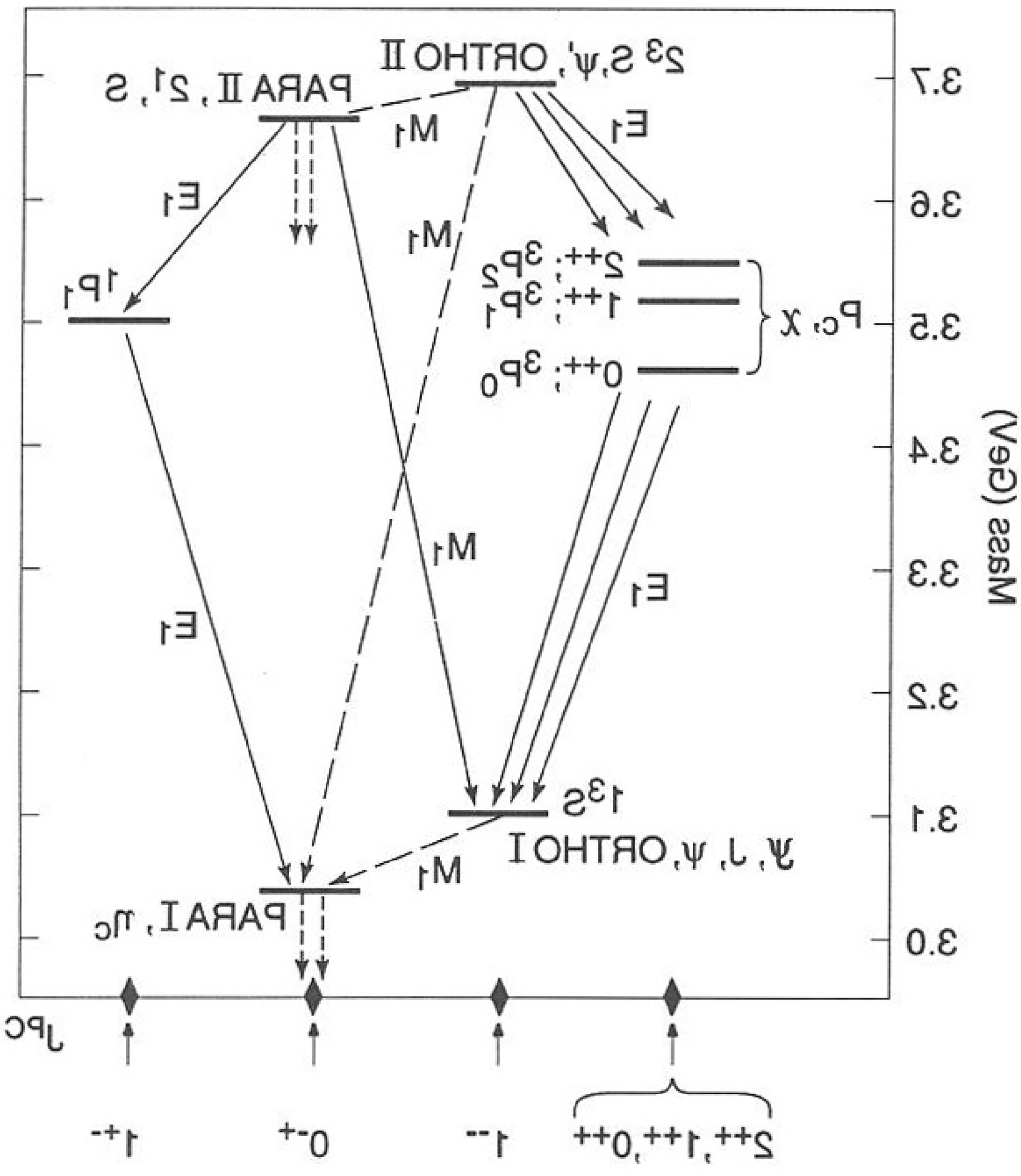
DIE LAUFMASCHINE DES Freiherrn Carl von Drais.

[illegible] Hegrist del. et sculp. Mannheim 1817



HARVARD

Appelquist
ADR
Glashow
Politzer



CORNELL

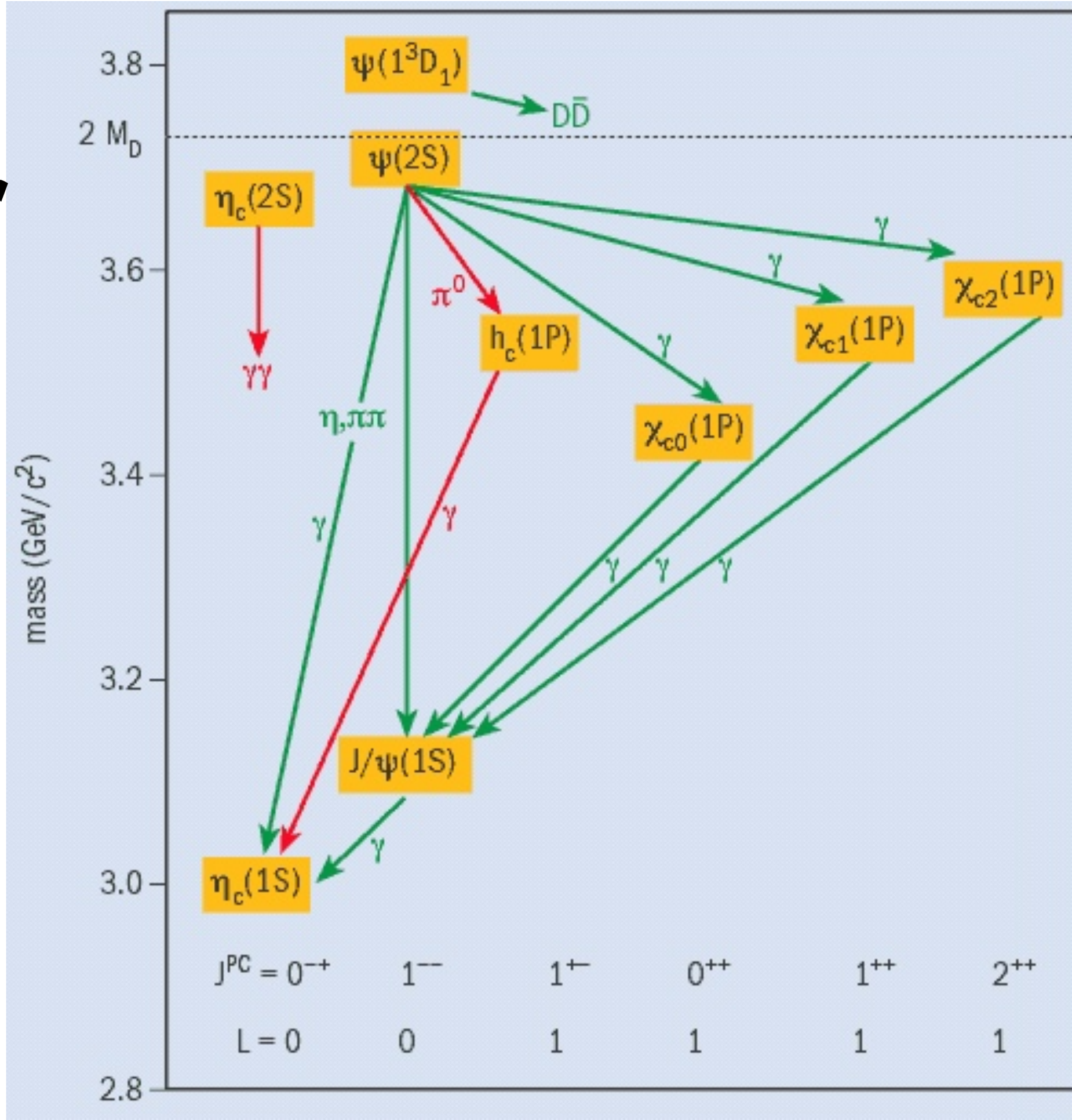
Ken Wilson's Coulomb + linear potential routines

Eichten
Gottfried
Kinoshita
Kogut
Lane, Yan

Yet another year of lean cows

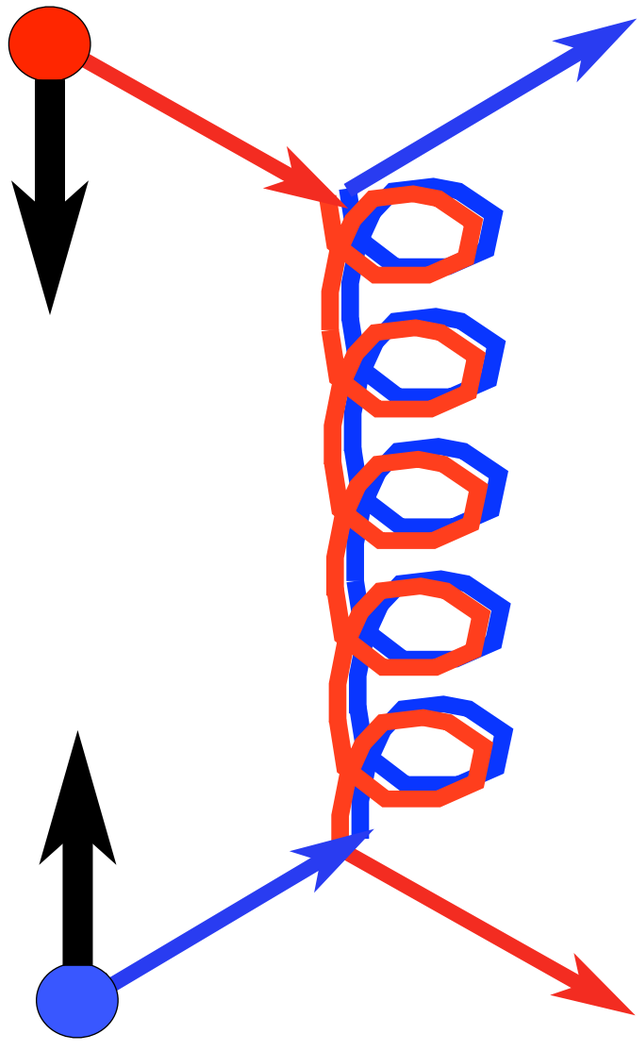
DESY

SLAC



DGG, 1975

Constituent Quarks + QCD "Hyperfine"



WE EXPLAIN (TOO WELL!) SPLITTINGS BETWEEN HADRONS IN SAME MULTIPLET

[eg Σ-Λ $[uds]_{J=\frac{1}{2}}$]

AS "CHROMO HYPERFINE"

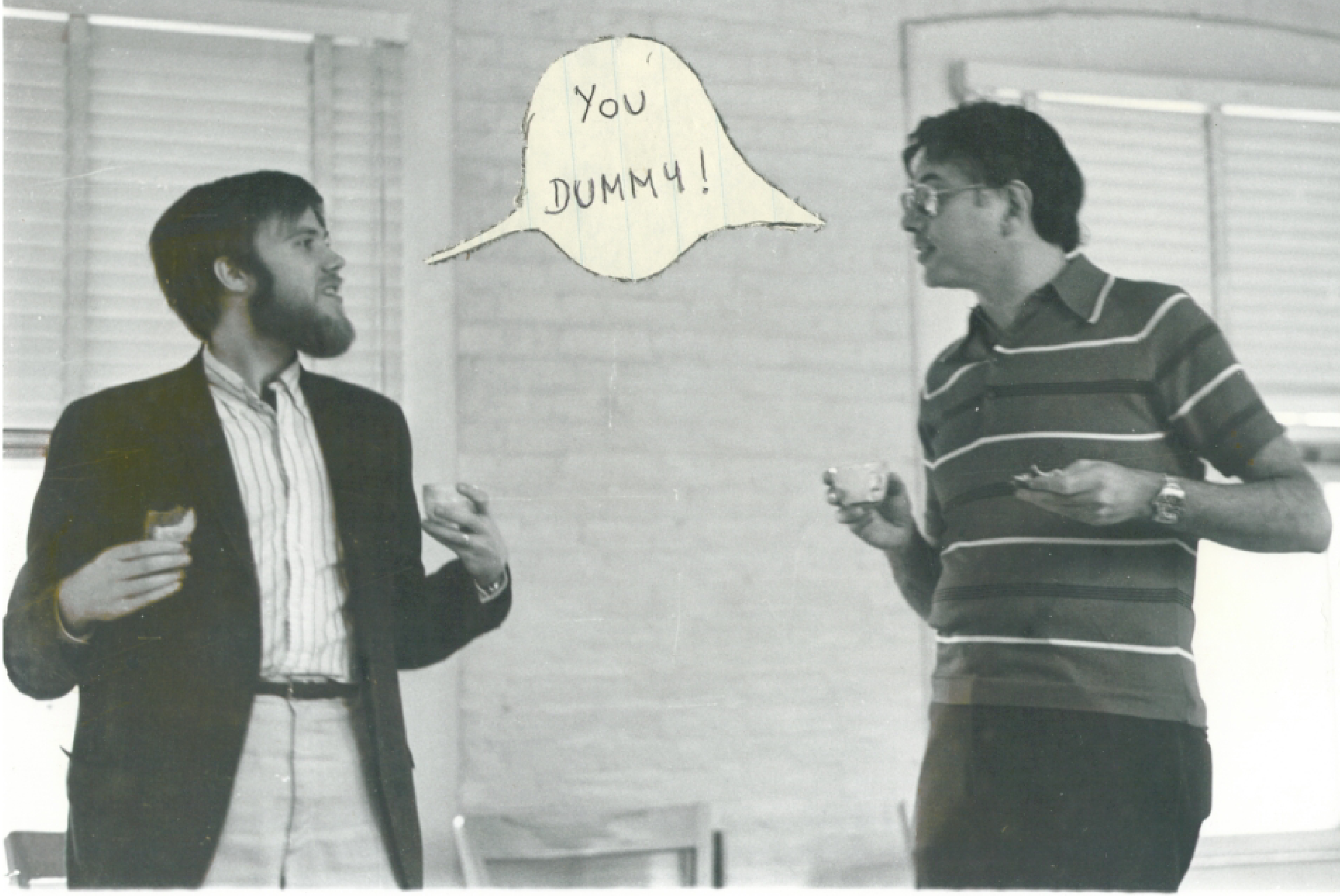
RELATIVISTIC VERSION

MIT

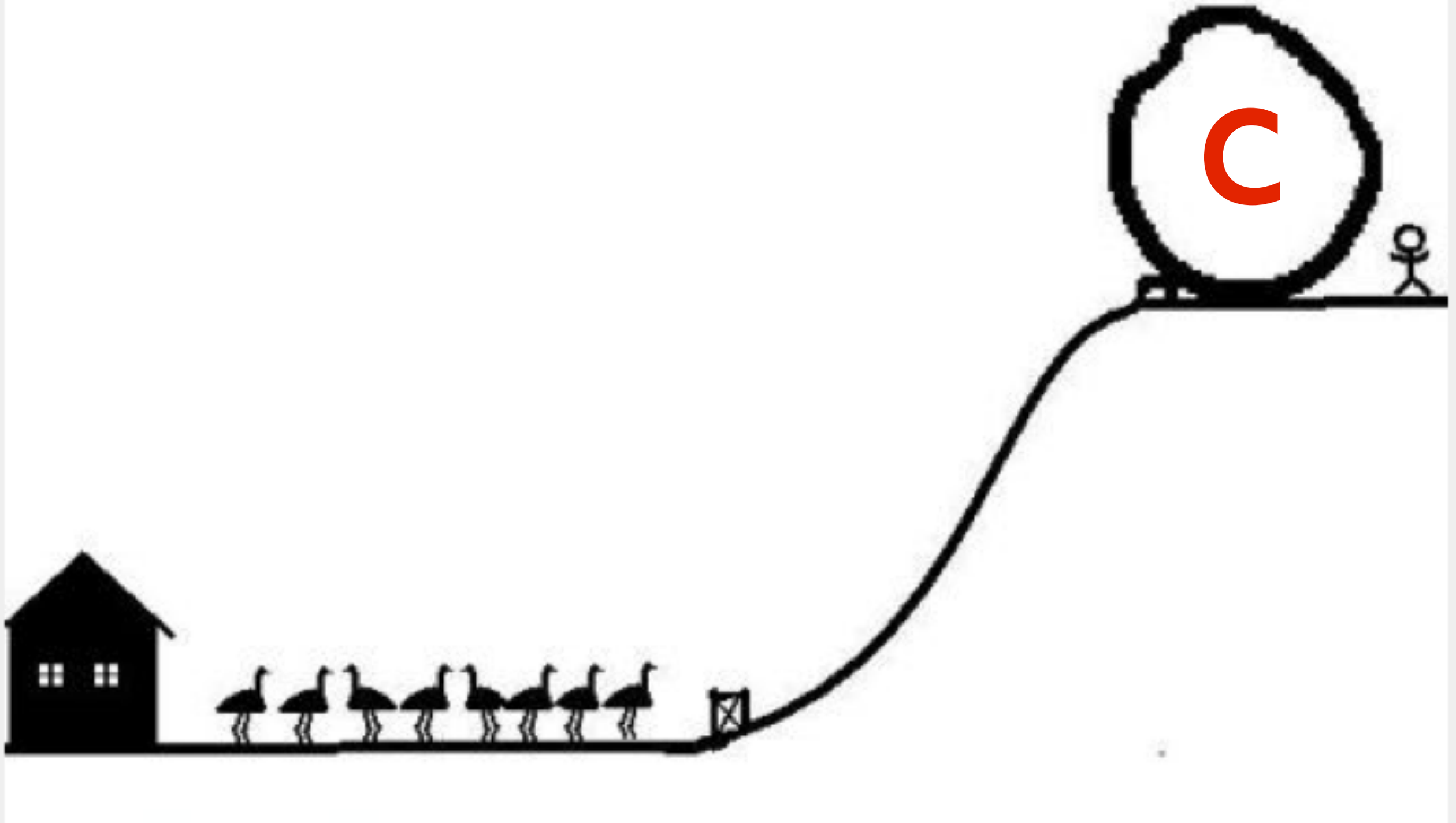
De Grand, Jaffe, Johnson, Kiskis, 1975

Once upon a time, there was a controversy in particle physics. There were some physicists[1] who denied the existence of structures more elementary than hadrons, and searched for a self-consistent interpretation wherein all hadron states, stable or resonant, were equally elementary. Others,[2] appalled by the teeming democracy of hadrons, insisted on the existence of a small number of fundamental constituents and a simple underlying force law. In terms of these more fundamental things, hadron spectroscopy should be qualitatively described and essentially understood just as are atomic and nuclear physics.

1) Bootstrap 2) Gell-Mann, Zweig, Petermann



They had their cake and eat it too


C

3/4

	DGG PREDICTION (1975)	EXPERIMENT	
$D[c\bar{u}]_{J=0}$	1830 ± 30	1870	
$D^*_{J=1} - D$	130	140	
$\Lambda_c^+[c\underbrace{ud}_{I=0}]_{J=1/2}$	2250 ± 50	2260 ± 20	?
$\Sigma_c[c\underbrace{qq}_{I=1}] - \Lambda_c$	160	160 ± 10	?
$\Sigma_c^*(J=3/2) - \Lambda_c$	220	~ 220	?
$F[c\bar{s}]_{J=0}$	1975	2041	(HΩ!)

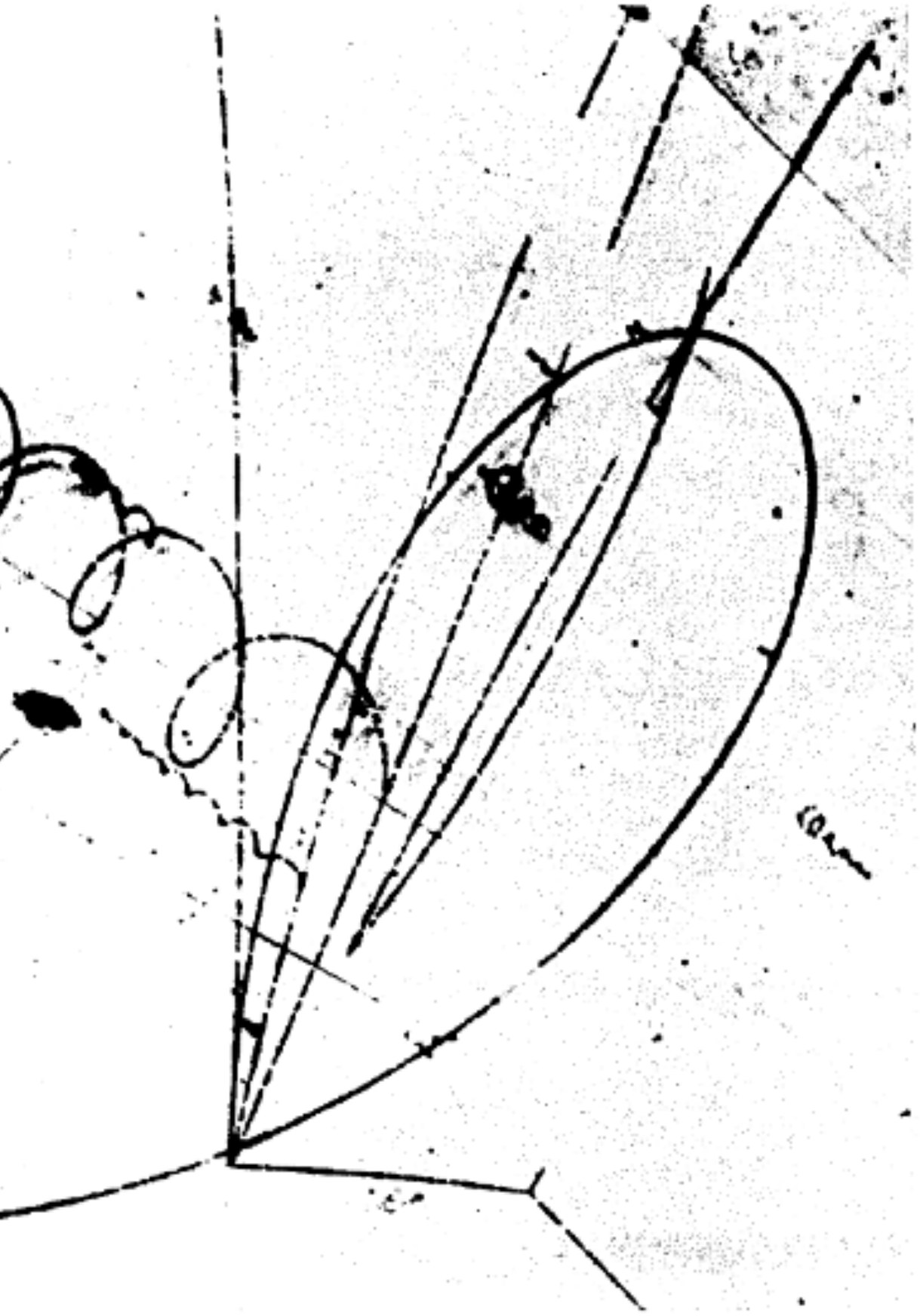
7 %
WRONG

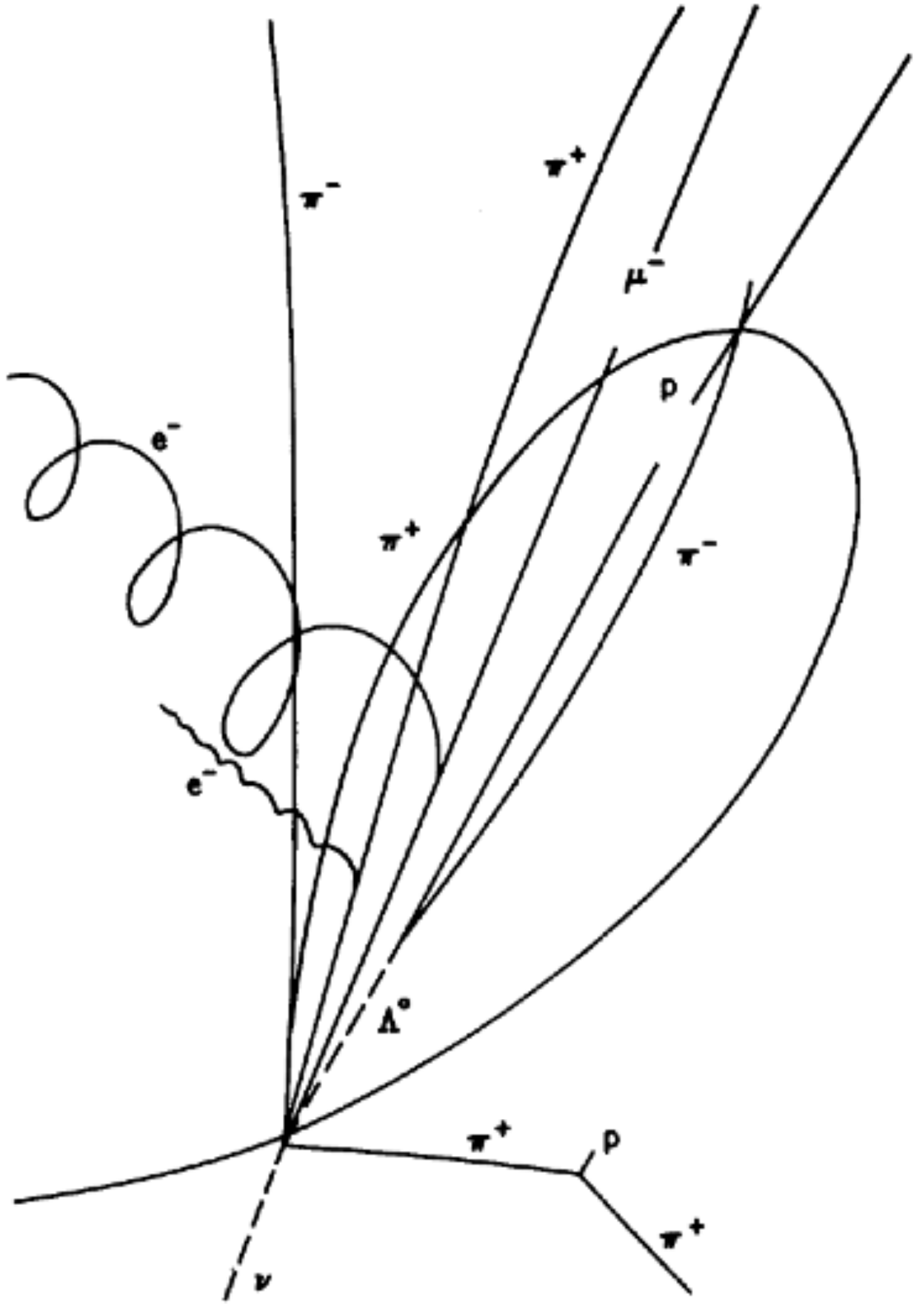
(cqq)

???

3 %
WRONG

Brookhaven Bubble Chamber, 1975





$$\nu_\mu\, p \to \mu^-\ \Sigma_c^{++}[uuc]$$

$$\boxed{\Sigma_c^{++}} \to \pi^+\ \Lambda_c^+[udc]$$

$$\boxed{\Lambda_c^+} \to \pi^+\ \pi^+\ \pi^-\ \Lambda^0$$

$$\Lambda[uds] \to \pi^-[d\bar{u}]\ p[uud]$$

total recoiling hadron mass ($\Lambda\pi^+\pi^+\pi^+\pi^-$) 2426 ± 12 MeV.[12]

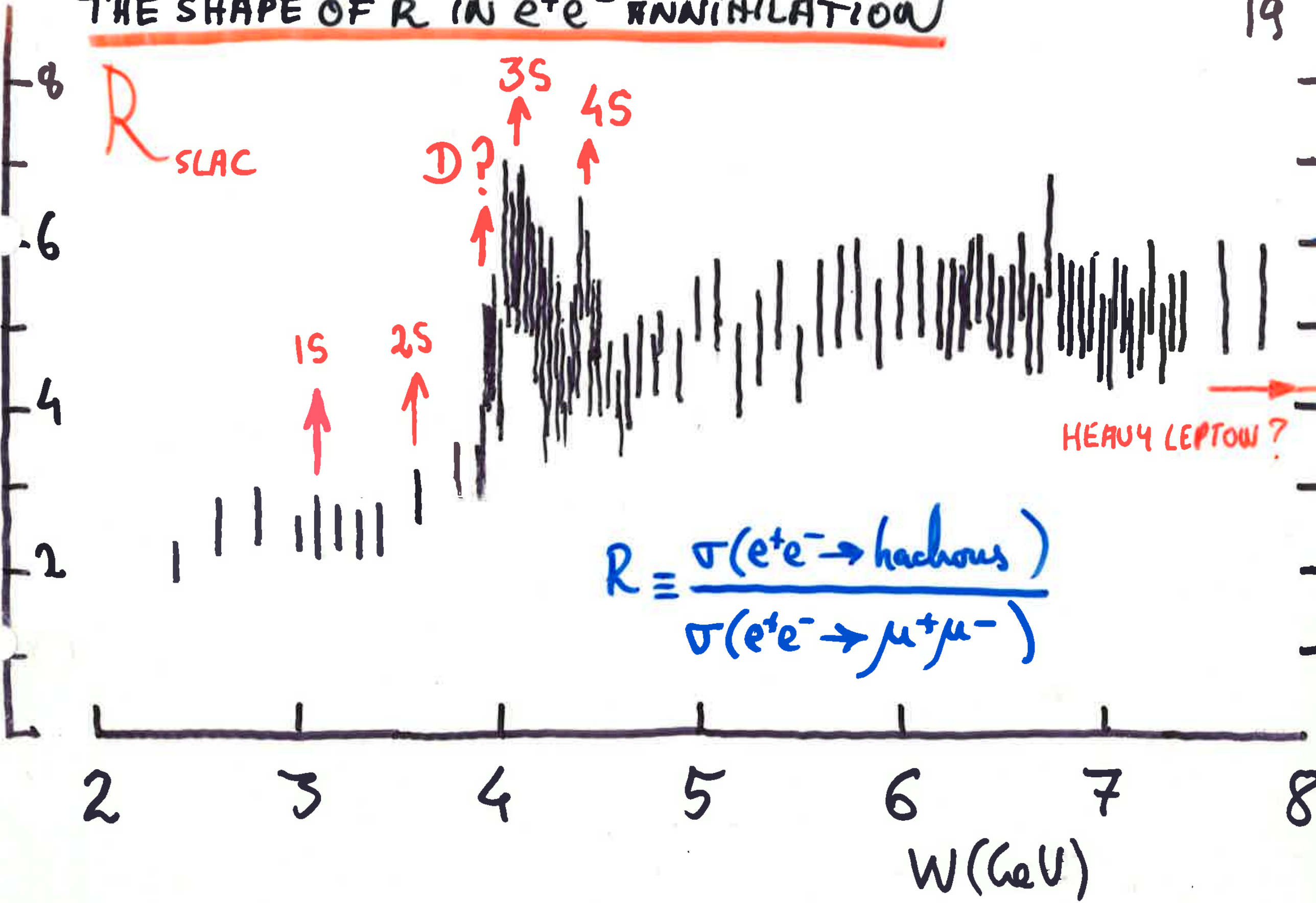
This mass is in reasonable agreement with the values predicted by De Rujula, Georgi, and Glashow[13] for the lowest-lying charmed-baryon states of charge +2, 2420 MeV ($J^P = \frac{3}{2}^+$, $I = 1$, Σ_C^*)

Nick Samios et al., 1975

There are three π^+'s and thus three possible mass differences derivable from this event; these are observed to be 166 ± 15 MeV, 338 ± 12 MeV, and 327 ± 12 MeV. The first of these differences is in remarkable agreement with the 160 MeV predicted for the decay of a spin-$\frac{1}{2}$ charmed baryon Σ_C decaying into a charmed Λ_C.

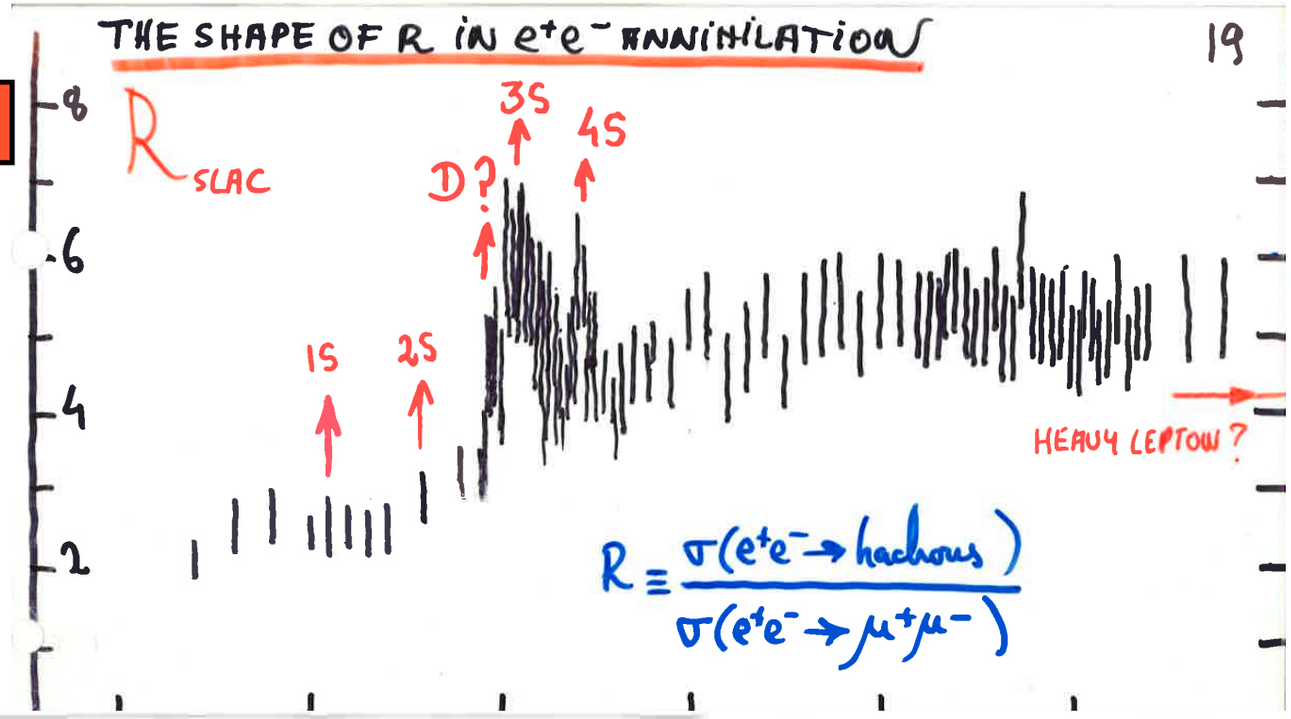
$\Lambda_c^+[udc]$

THE SHAPE OF R IN e^+e^- ANNIHILATION



ANALYTIC CONTINUATION

TO $Q^2 < 0$, WHERE PERTURBATIVE QCD NO DOUBT WORKS



Counting quarks in e^+e^- annihilation*

A. De Rújula and Howard Georgi†
The Physics Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 28 October 1975)

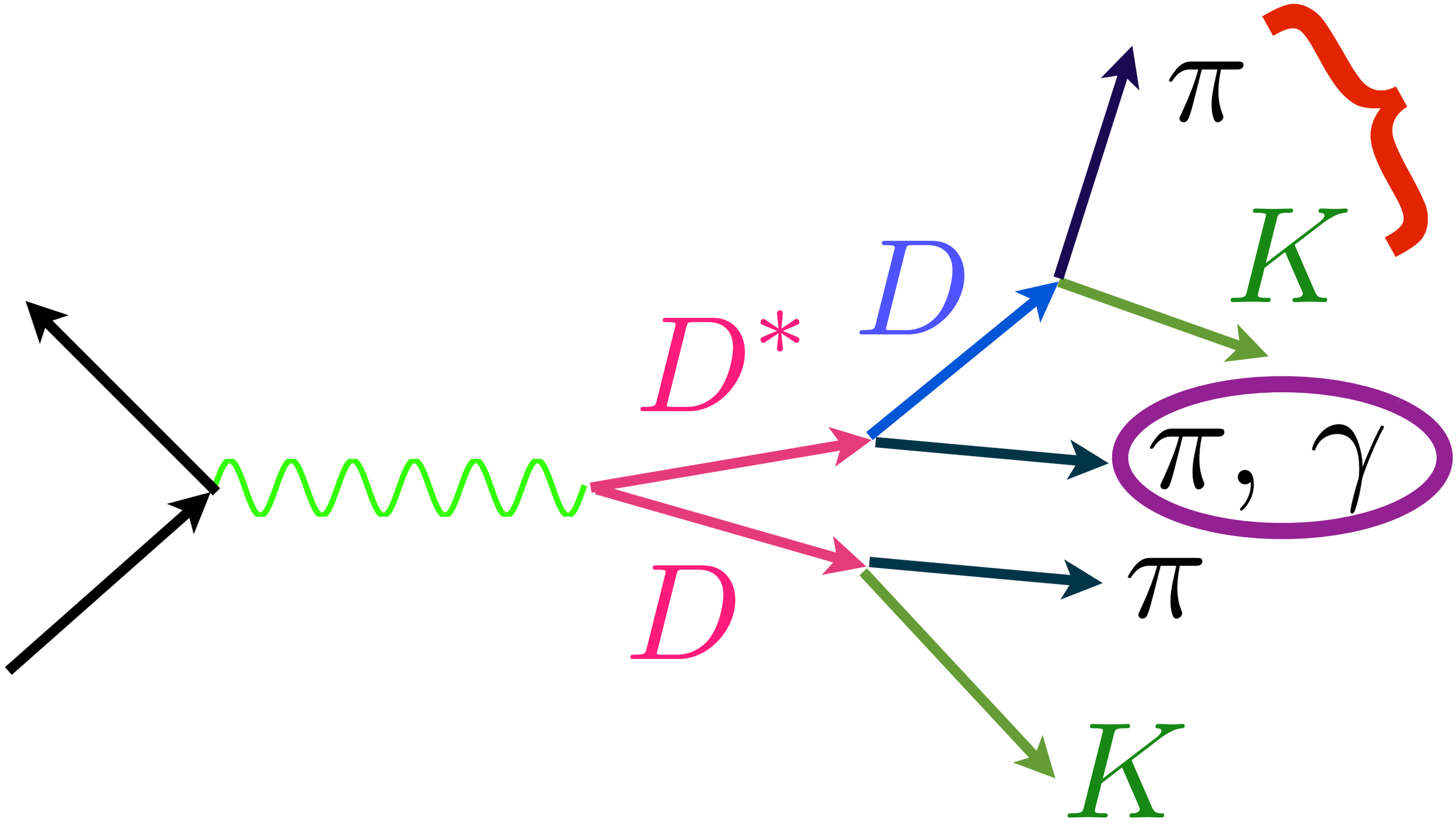
A comparison of asymptotically-free-quark-model predictions and e^+e^- annihilation data can be made by using a dispersion relation to continue the data into the spacelike region. We make this comparison for several models, including when appropriate the effect of heavy-quark masses. We conclude that the "old" theory with no charm is excluded, the standard model with charm is acceptable if heavy leptons are produced, and six-quark models are viable if no heavy leptons are produced.

SQUELETTE D'ARTICLE POUR "DÉCOUVERTE SCIENTIFIQUE"

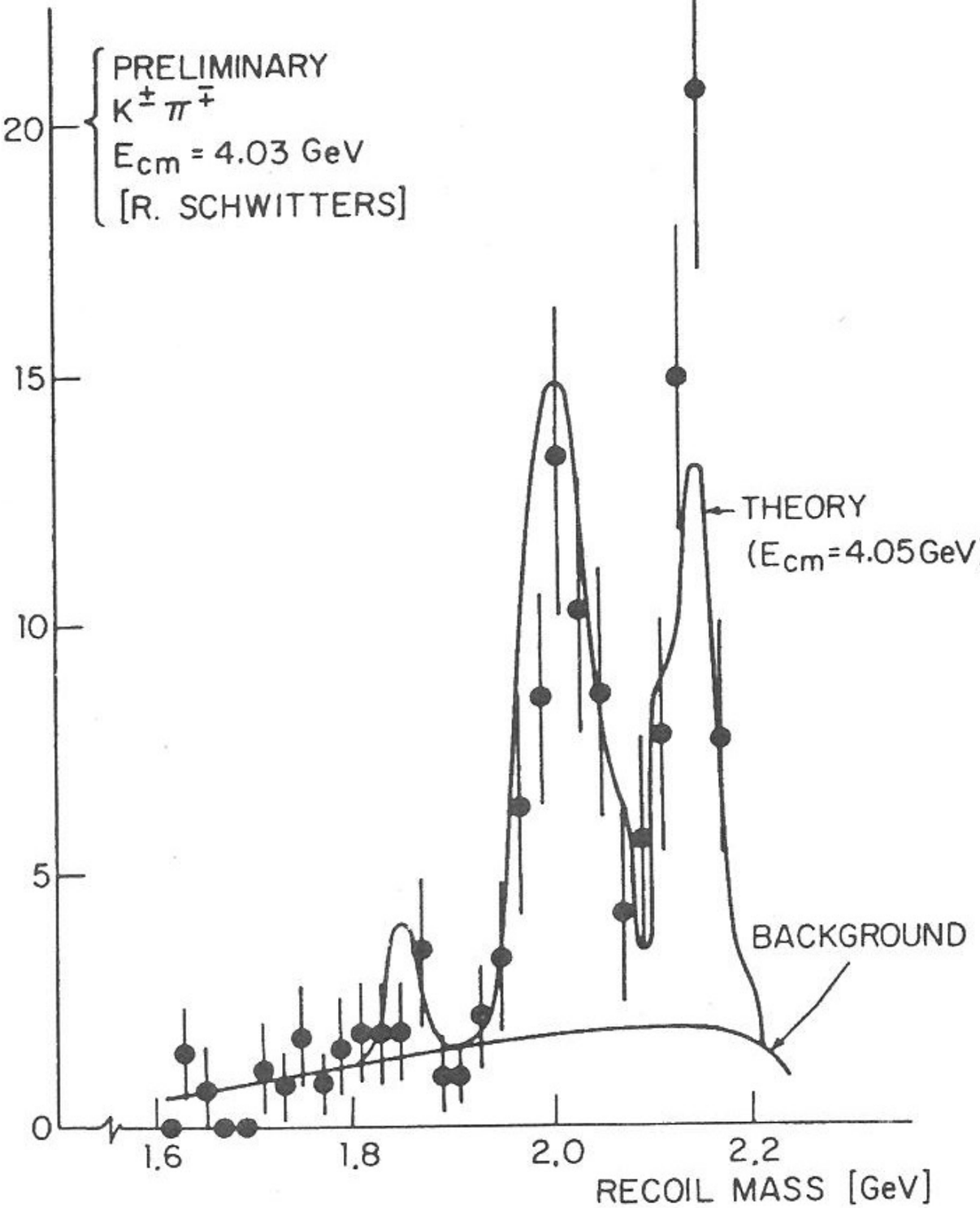
IL A ÉTÉ ANNONCÉ HIER QUE LE PROF. PERL DU LABORATOIRE SLAC ET LE PROF. XXX DU LABO _____ ET LEURS COLLABORATEURS ONT ÉTABLI L'EXISTENCE D'UNE NOUVELLE (EAU) PARTICULE

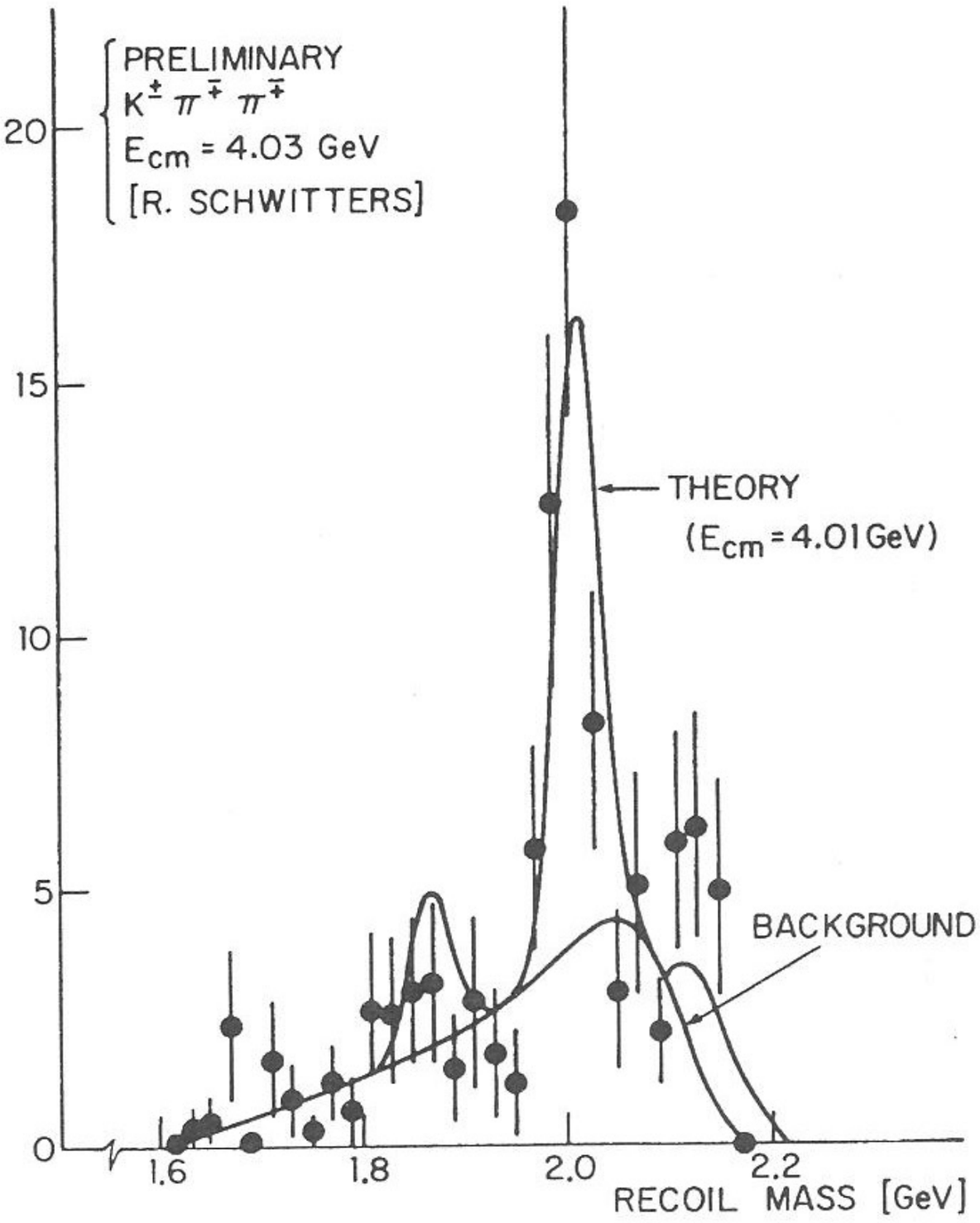
IL S'AGIT D'UNE DÉCOUVERTE D'UNE TRÉS GRANDE IMPORTANCE, QUI CONSTATE LA THÉORIE DE _____ ?????????????????? QUI AVAIENT PRÉDIT UN(E) TEL(LLE) PARTICULE COMME CONSÉQUENCE DE _____ ??????????????????

UNE AUTRE ÉCOLE INTERPRÉTE LE NOUVEAU(LLE) PARTICULE COMME UNE MANIFESTATION DU RECHERCHÉ _____ LE CULOT DE SLAC



Masses and Branching Ratios predicted by theory


PRELIMINARY
$K^{\pm}\pi^{\mp}$
E_{cm} = 4.03 GeV
[R. SCHWITTERS]
THEORY
(E_{cm}=4.05GeV)
BACKGROUND
20
15
10
5
0
1.6
1.8
2.0
2.2
RECOIL MASS [GeV]


PRELIMINARY
$K^{\pm}\pi^{\mp}\pi^{\mp}$
E_{cm} = 4.03 GeV
[R. SCHWITTERS]
THEORY
(E_{cm}=4.01GeV)
BACKGROUND
20
15
10
5
0
1.6
1.8
2.0
2.2
RECOIL MASS [GeV]

DGG

SQUELETTE D'ARTICLE POUR "DÉCOUVERTE SCIENTIFIQUE"

IL A ÉTÉ ANNONCÉ HIER QUE LE PROF. G. GOLDHABER DU LABORATOIRE SLAC ET LE PROF. XXX DU LABO _____ ET LEURS COLLABORATEURS ONT ÉTABLI L'EXISTENCE D'UNE NOUVELLE (EAU) PARTICULE

IL S'AGIT D'UNE DÉCOUVERTE D'UNE TRÉS GRANDE IMPORTANCE, QUI CONSTATE LA THÉORIE DE GLASHOW ILIOPOLOUS & MAIANI QUI AVAIENT PRÉDIT UN(E) TEL(LLE) PARTICULE COMME CONSÉQUENCE DE L'EXISTENCE DE QUARKS ENCHANTES

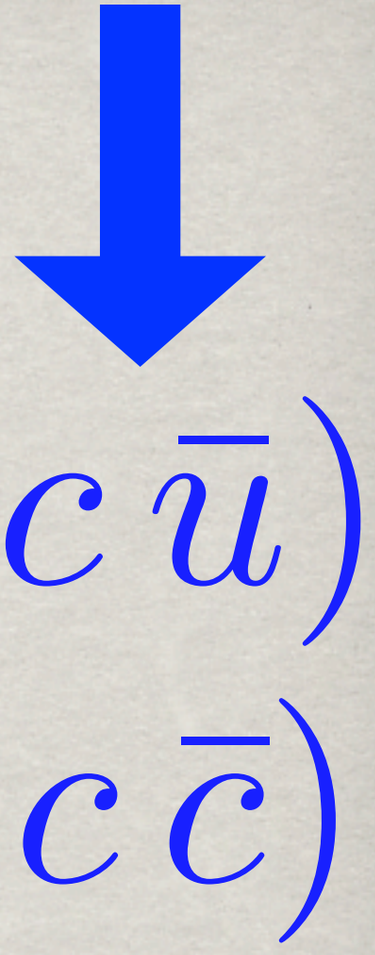
UNE AUTRE ÉCOLE INTERPRÉTE LE NOUVEAU(LLE) PARTICULE COMME UNE MANIFESTATION DU RECHERCHÉ

CA: UNFATHOMABLE NATURE OF NATURE

I SEEM TO BE
OBSESSED WITH THE PRESS

AM I THE ONLY
ONE AROUND
HERE ?

EVEN THE MOST FORMAL THEORIST AND THE MOST CABLE-CONNECTING EXPERIMENTALIST UNDERSTANDS (pe), $(e^+ e^-)$



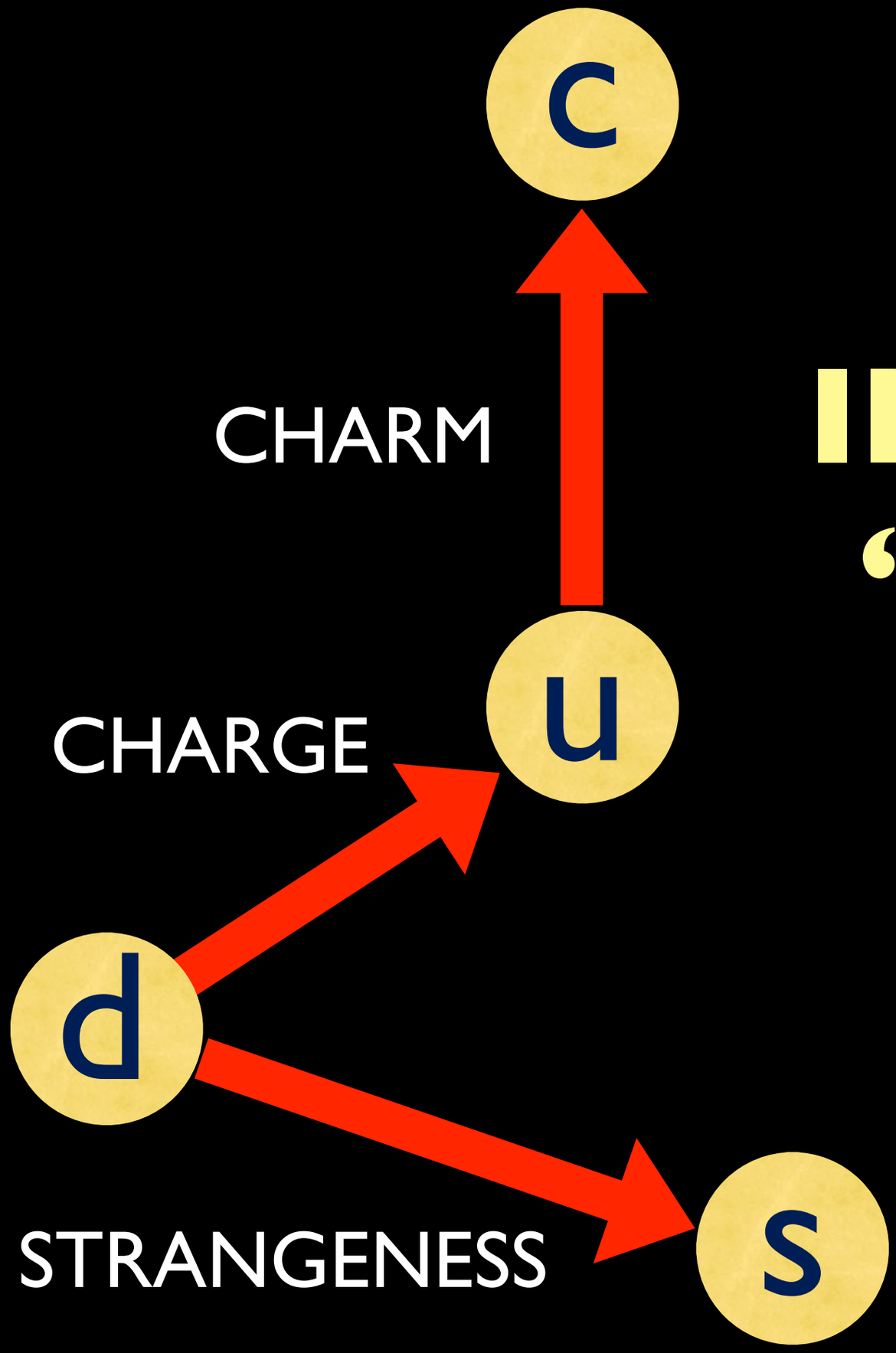
IT TOOK ASYMPTOTIC FREEDOM & A FOURTH (CHARMED) QUARK TO HAVE THE SM BECOME THE STANDARD LORE

THE SU(2)xU(1) STANDARD-MODEL EXPERIMENTAL REVOLUTION ...

STARTED AT CERN WITH THE DISCOVERY OF NEUTRAL CURRENTS

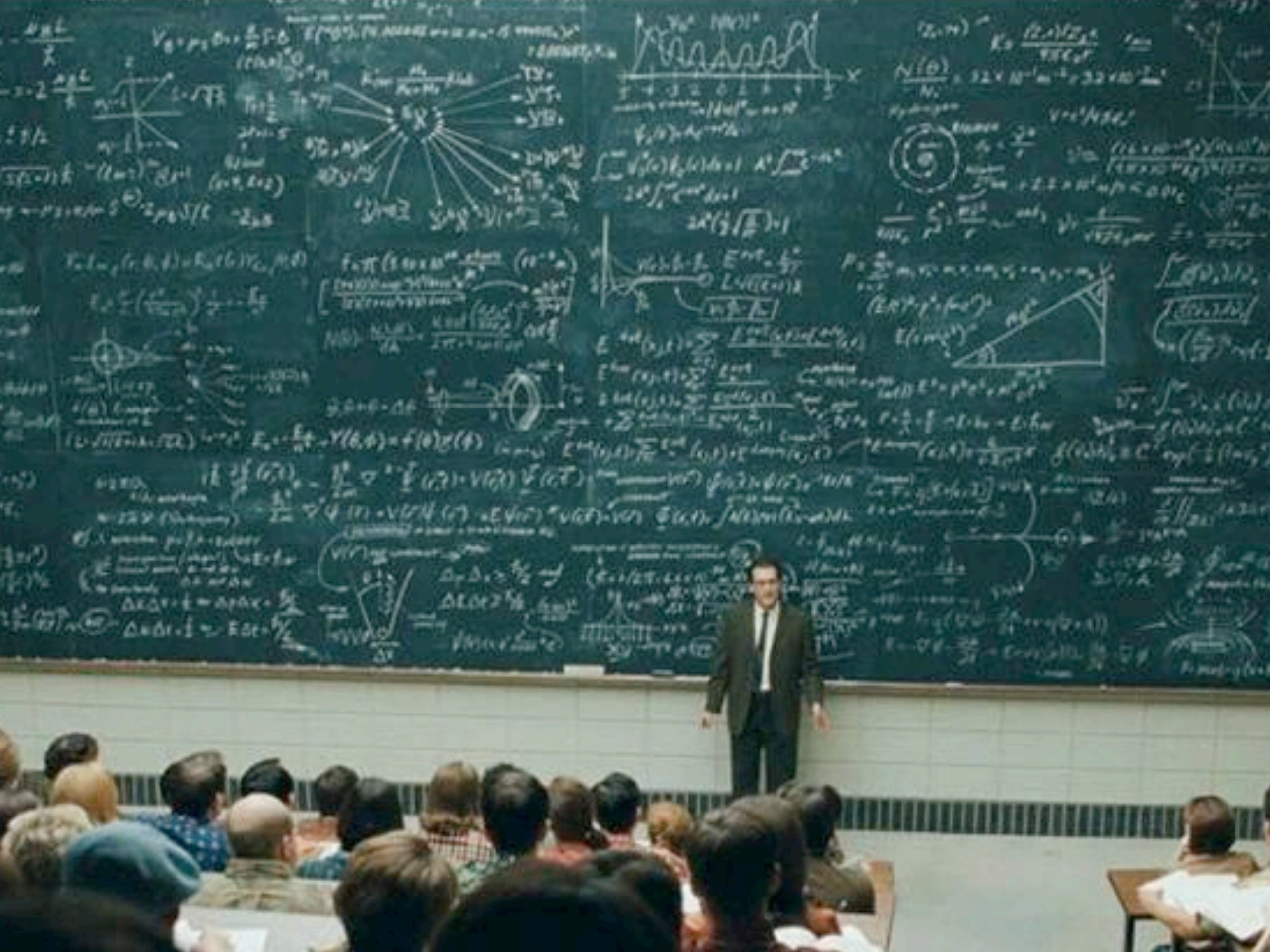
... CULMINATED WITH THE DISCOVERY OF W and Z, THE COUNTING OF NEUTRINOS, PRECISION PHYSICS AT LEP *(which made the SM a STANDARD THEORY)*, AND THE DISCOVERY OF THE H-BOSON

MANY OTHER THINGS (some of which I have described) ... HAPPENED ELSEWHERE



QUANTUM NUMBERS IN ABSTRACT "INTERNAL" SPACE, i.e.

NOT THE FOGGIEST IDEA



TH basis of today's discussion: Gauge Theories

C.-N. Yang & R.L. Mills, *Conservation of isotopic spin and isotopic gauge invariance*, Phys. Rev. **96** (1954) 191. **Non-Abelian GTs**

M. Gell-Mann, H. Fritzsch & J. Leutwyler, *Advantages of the color-octet gluon picture*, Phys. Lett. **B47** (1973) 365. **QCD SU(3) Non-Abe GT**

R. Utiyama, Phys. Rev. **101** (1956) 1597. **GR is a Non-Abe GT**

S.L. Glashow, *Partial symmetries of weak interactions*, Nucl. Phys. **22** (1961) 579. **SU(2) x U(1) Weak + Electromagnetic**

S. Weinberg, *A model of leptons*, Phys. Rev. Lett. **19** (1967) 1264.

A. Salam & J.C. Ward, *Electromagnetic and weak interactions*, Phys. Lett. **13** (1964) 168; **SU(2) x U(1) with SSB, à la HHKEGB**

A. Salam, in *Elementary Particle Theory*; ed. N. Svartholm (Stockholm, 1968).

G. 't Hooft, *Renormalizable Lagrangians for massive gauge field theories*, Nucl. Phys. **35** (1971) 167. **SU(2) x U(1) with SSB ...**

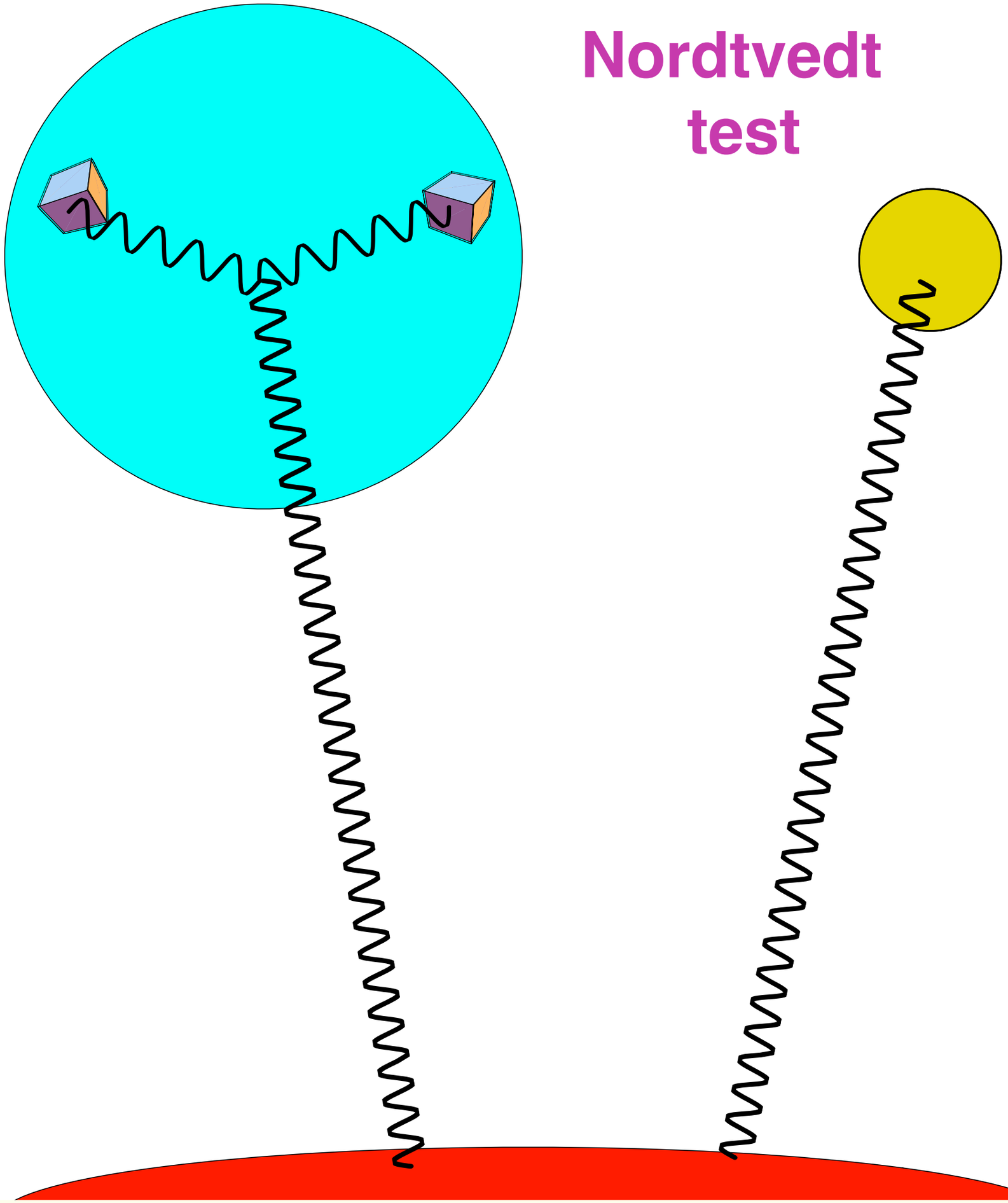
G. 't Hooft & M.J.G. Veltman, *Regularization and renormalization of gauge fields*, Nucl. Phys. **B44** (1972) 189. **... is renormalizable**

S.L. Glashow, J. Iliopoulos & L. Maiani, Phys. Rev. **D2** (1970) 1285. **GIM**

H.D. Politzer, Phys. Rev. Lett. **26** (1973) 1346. **QCD's Asymptotic Freedom**

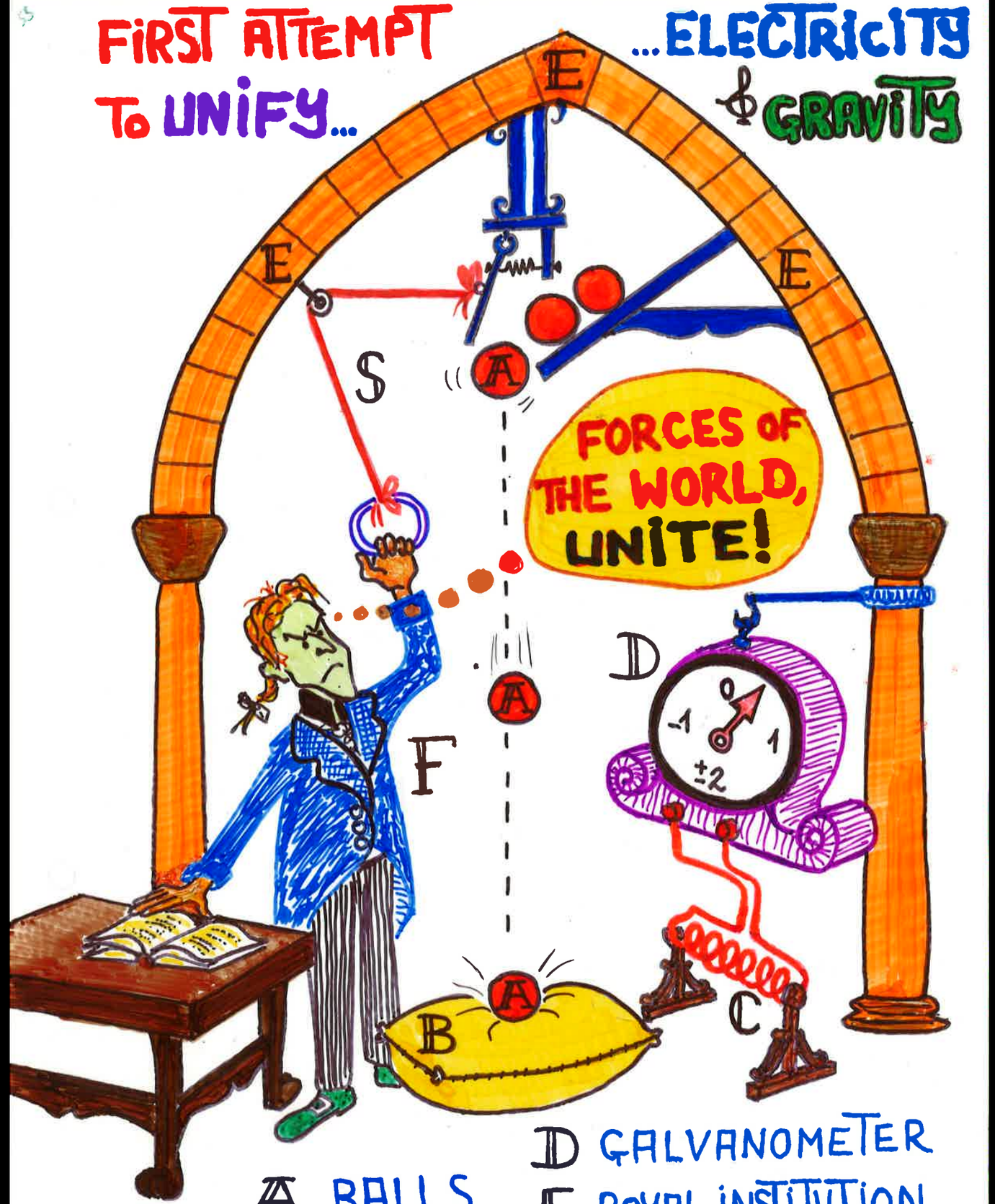
D. Gross & F. Wilczek, Phys. Rev. Lett. **26** (1973) 1343.

Nordtvedt test



FIRST ATTEMPT TO UNIFY...

...ELECTRICITY & GRAVITY



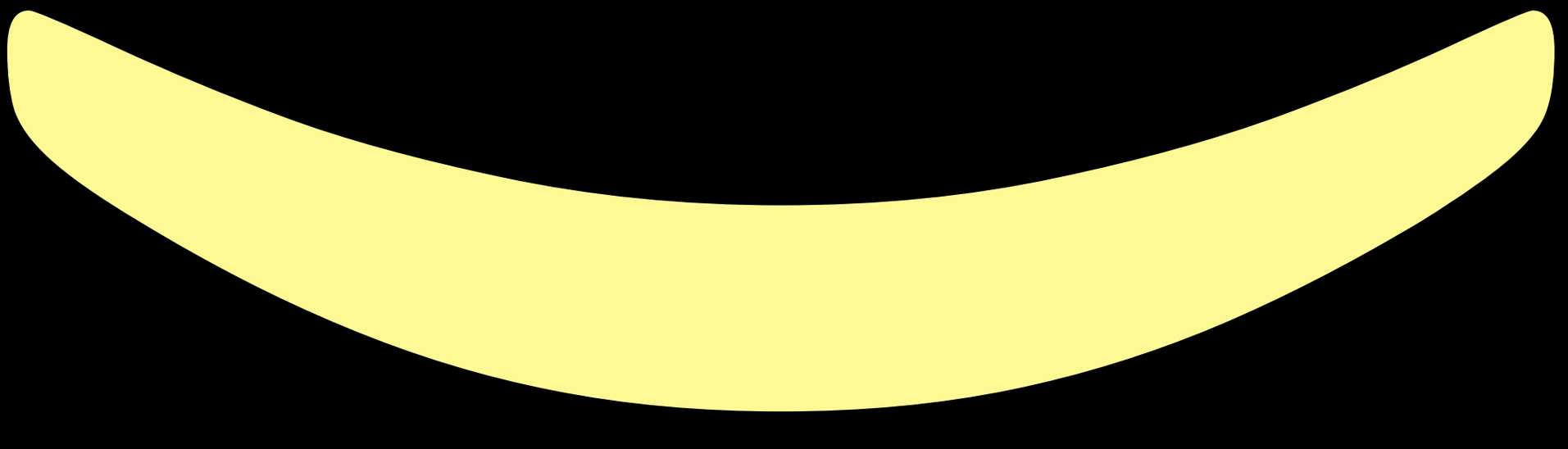
A BALLS
B CUSHION
C COIL
D GALVANOMETER
E ROYAL INSTITUTION
F M. FARADAY
S STRING

M. FARADAY (ON THE FAILURE OF HIS ELECTRO-GRAVITATIONAL EXPS.)

"Here end my trials for the present. The results are negative. They do not shake my strong feeling of the existence of a relation between gravity and electricity, though they give no proof that such a relation exists".

ROYAL INSTITUTION

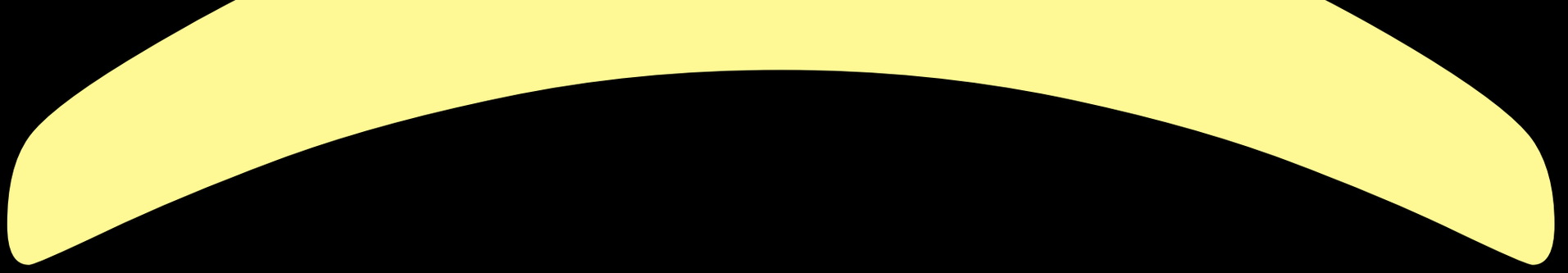
(July 19, 1850)



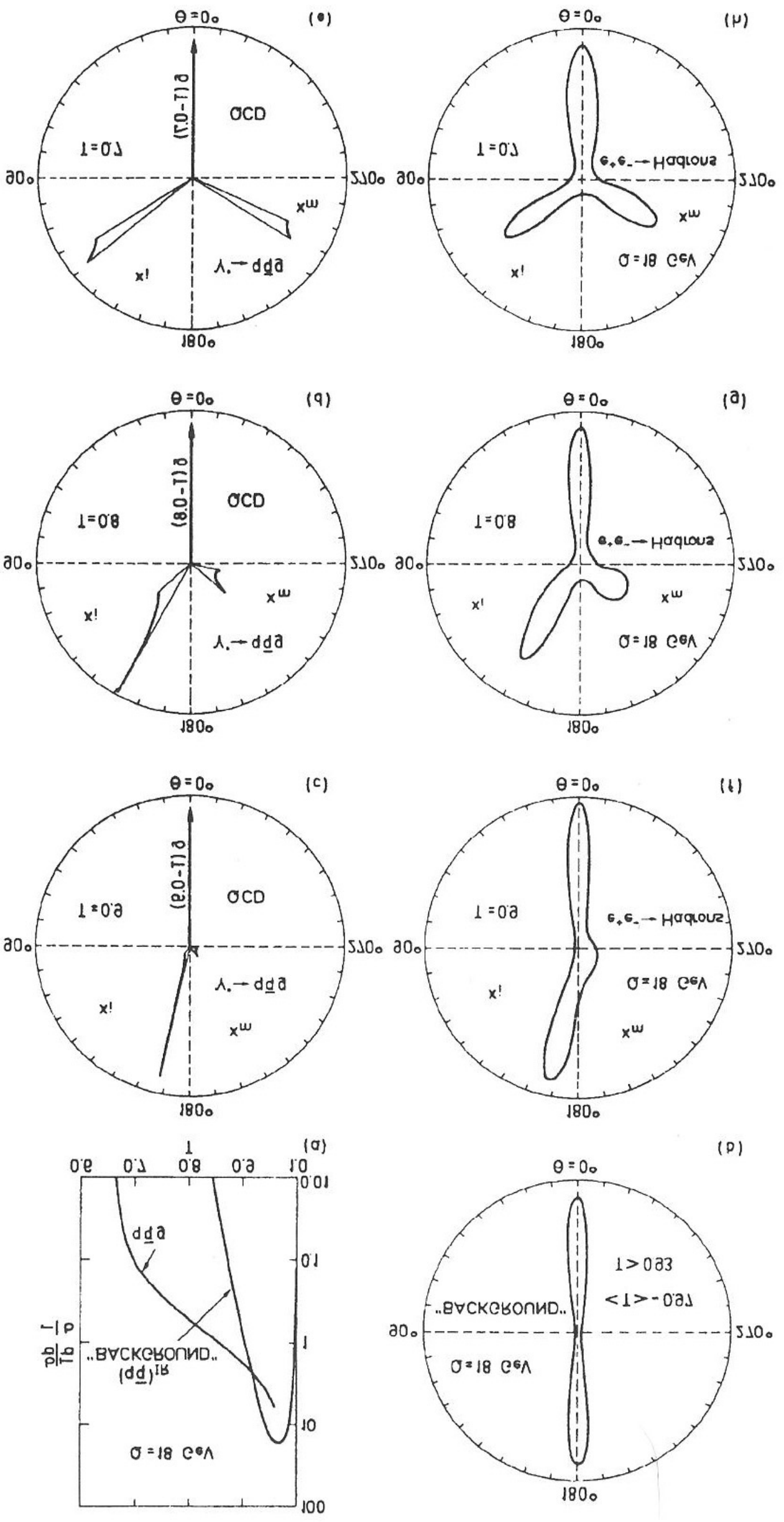
$$\begin{pmatrix} u \\ d \end{pmatrix}\begin{pmatrix} c \\ s \end{pmatrix}\begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

Materia ≠ Antimateria

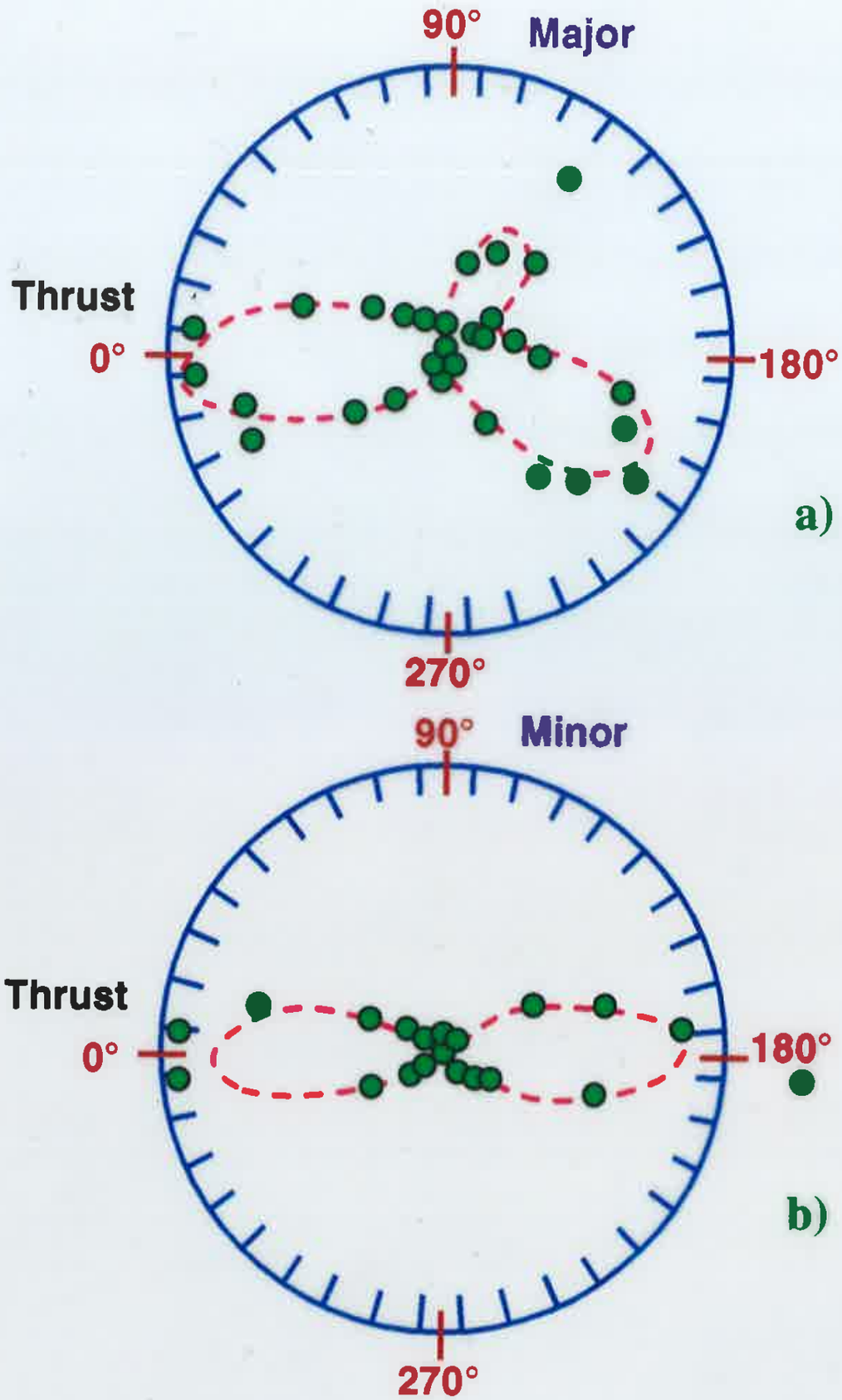


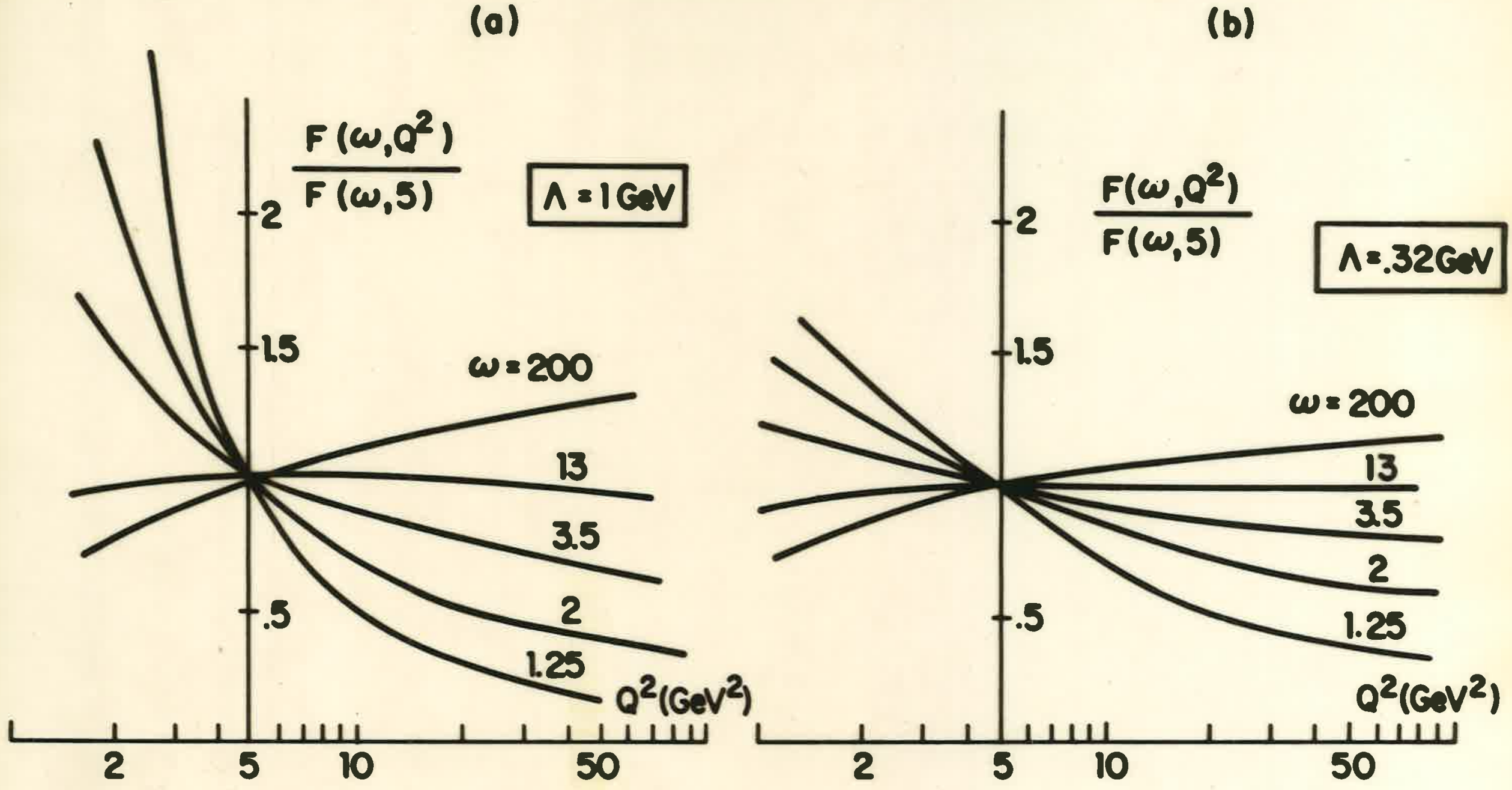
RA



(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
θ = 0°
90°
180°
270°
T
0.1
0.6
0.8
1.0
0.01
0.1
1
10
100
σ = 18 GeV
"BACKGROUND"

MARK J





G. Parisi: "Mellin" transform of the OPE moments of structure functions $\int_0^1 x^n F(x,Q^2)\,dx$ (SFs) into SFs $F(x,Q^2)$