COMHEP

5th ComHEP: Colombian Meeting on High Energy Physics

Charm, 50 Years after

COMHEP Introductory Talk

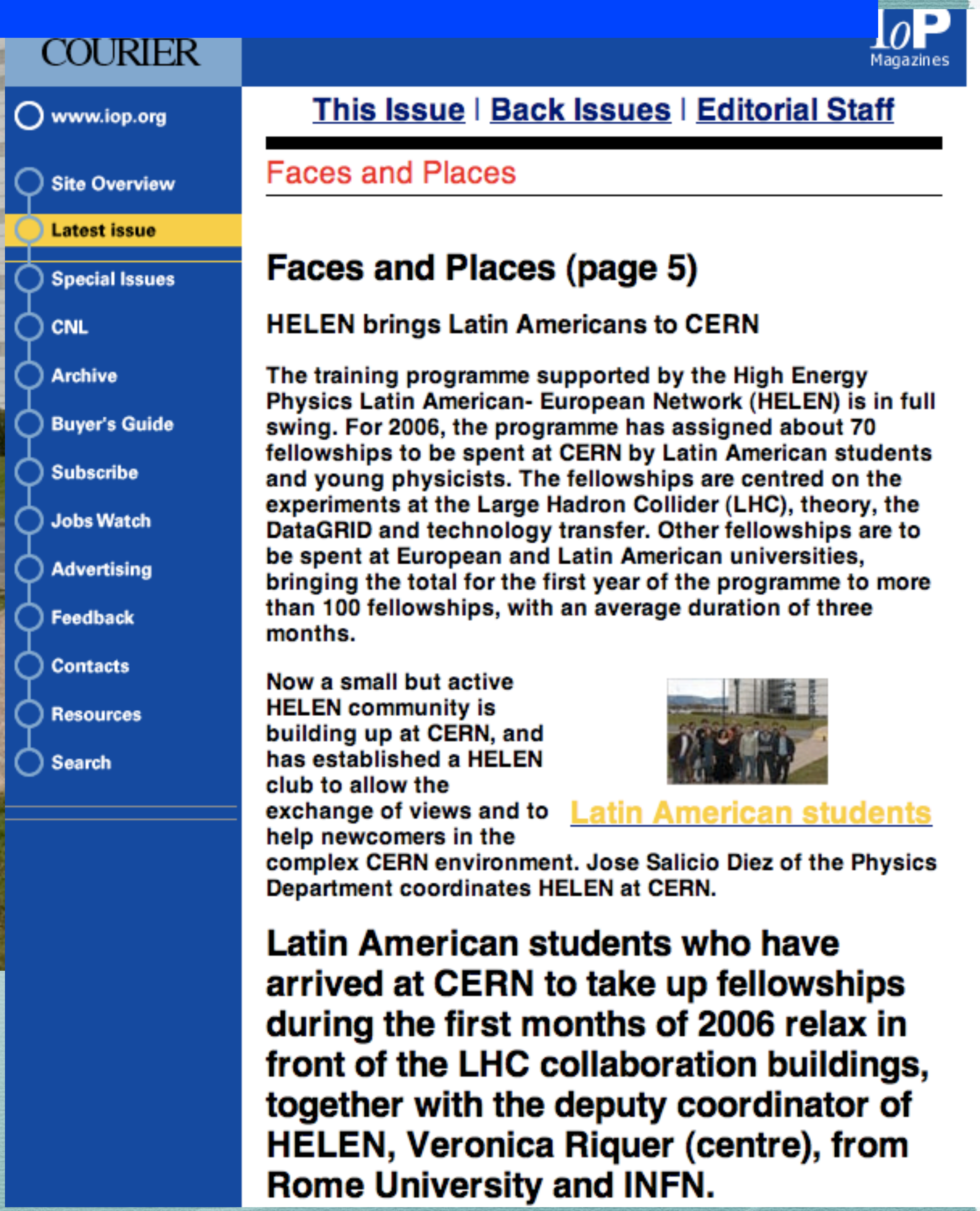
30 November 2020

Luciano Maiani

Sapienza Università di Roma and INFN

Helen was approved in spring 2005.
@ CINVESTAV, April 2005:
it is going to be like this!

The first HELEN Fellows arrive at CERN, January 2006



Faces and Places

Faces and Places (page 5)

HELEN brings Latin Americans to CERN

The training programme supported by the High Energy Physics Latin American- European Network (HELEN) is in full swing. For 2006, the programme has assigned about 70 fellowships to be spent at CERN by Latin American students and young physicists. The fellowships are centred on the experiments at the Large Hadron Collider (LHC), theory, the DataGRID and technology transfer. Other fellowships are to be spent at European and Latin American universities, bringing the total for the first year of the programme to more than 100 fellowships, with an average duration of three months.

Now a small but active HELEN community is building up at CERN, and has established a HELEN club to allow the exchange of views and to help newcomers in the complex CERN environment. Jose Salicio Diez of the Physics Department coordinates HELEN at CERN.

Latin American students

Latin American students who have arrived at CERN to take up fellowships during the first months of 2006 relax in front of the LHC collaboration buildings, together with the deputy coordinator of HELEN, Veronica Riquer (centre), from Rome University and INFN.

HELEN kids, CERN, DIC. 2006

HELEN, CERN, DIC. 2006

HELEN kids
CERN, June 2008

HELEN kids
CERN, date ??

T.D.Lee Institute, Jiao Tong Shanghai University, November 2019

CERN COURIER

CULTURE AND HISTORY | MEETING REPORT

50 years of the GIM mechanism

24 January 2020

Hong-Jian He, John Ellis, John Iliopoulos, Sheldon Lee Glashow, Verónica Riquer and Luciano Maiani at a celebration of 50 years of the GIM mechanism in Shanghai. Credit: J Liu

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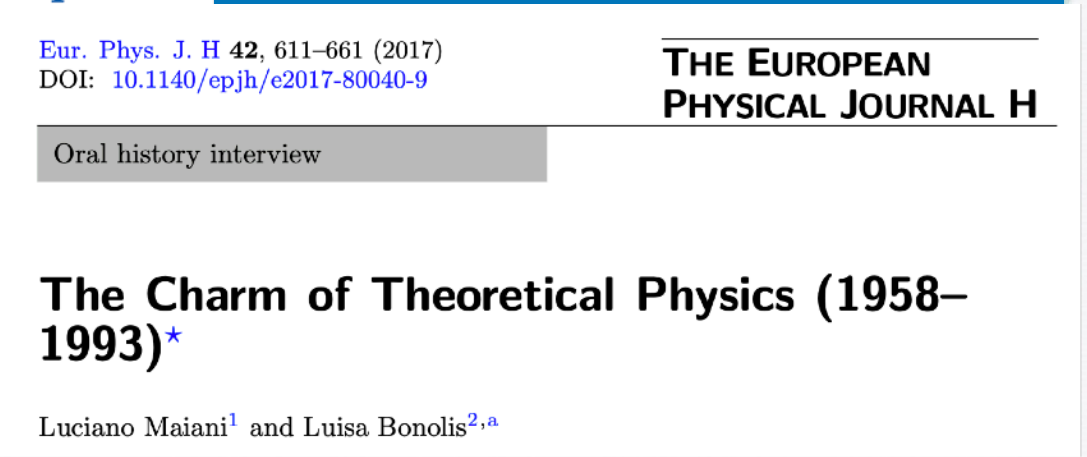
You may find my story here



Eur. Phys. J. H **42**, 611–661 (2017)
DOI: 10.1140/epjh/e2017-80040-9

THE EUROPEAN PHYSICAL JOURNAL H

Oral history interview

The Charm of Theoretical Physics (1958–1993)*

Luciano Maiani[1] and Luisa Bonolis[2,a]

Late nineteen-sixties...

...hopes of a basic theory for strong, e.m. and weak interactions

$$q = \begin{bmatrix} u \\ d \\ s \end{bmatrix}$$

- well established results:
  - -Gell-Mann-Zweig quarks in 3 flavours (baryons=qqq, etc.)
  - -u and d quark masses very small (~MeV) from chiral symmetry breaking
  - -Cabibbo theory of semileptonic decays, ΔS=0,1:

$$\mathcal{L}_F = \frac{G_F}{\sqrt{2}} J^\lambda J^+_\lambda$$

$$J^\lambda = \bar{\nu}_e \gamma^\lambda (1-\gamma_5) e + \bar{\nu}_\mu \gamma^\lambda (1-\gamma_5)\mu + \bar{u}\gamma^\lambda (1-\gamma_5) d_C$$

$$d_C = \cos\theta d + \sin\theta s$$

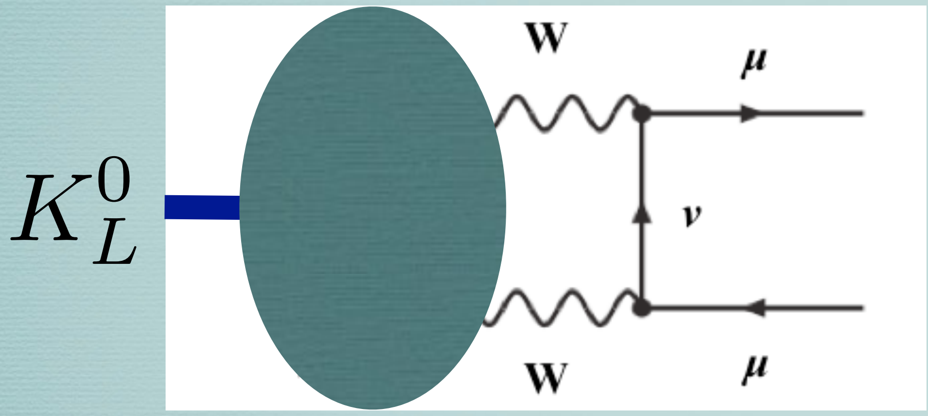
quarks: only one weak doublet:

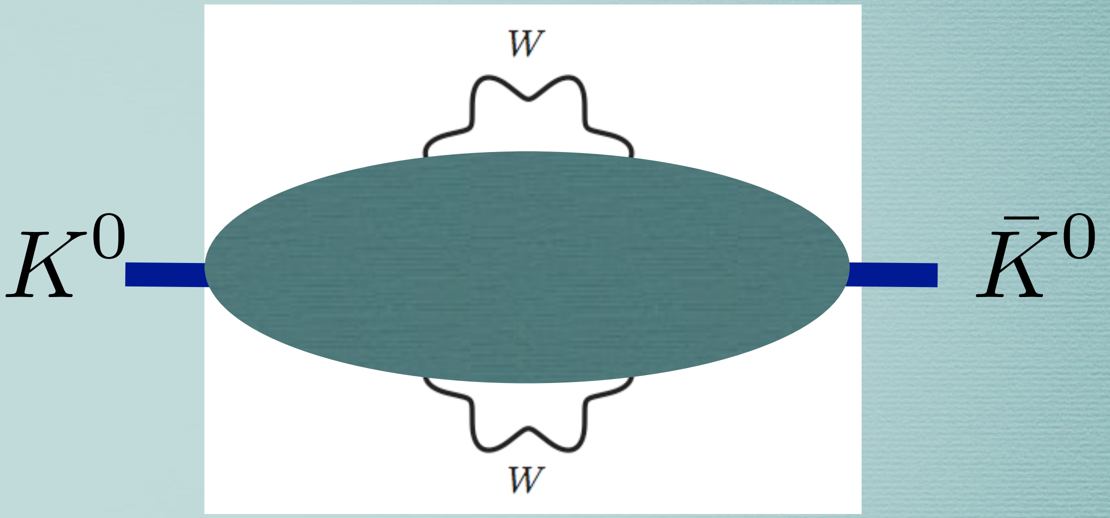
$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; (s_C)_L; d_R; u_R; s_R$$

- clouds:
  - -do quark clash with Fermi-Dirac statistics? first ideas about color (Han-Nambu)
  - -basic strong interactions: *gluon (abelian) mediated* ? *dual-like* (Veneziano model)?
  - -Fermi theory not renormalizable. W boson? strong interaction form factors?
- Schwinger ideas about EW unification+Yang-Mills
  - - Glashow’s SU(2)⊗U(1) (1961)
  - - Brout-Englert-Higgs Mechanism (1965) -> Weinberg-Salam (1967)

1. The G(GΛ²) puzzle, 1968

- The discussion on higher order weak interactions was opened in 1968 by a calculation by Boris Ioffe and Evgeny Shabalin, indicating that ΔS= ± 1 neutral currents and ΔS=2 amplitudes would result from higher order weak interactions, ***even in a theory with a charged W only***





- the amplitudes were found to be divergent, of order G(GΛ²), and in disagreement with experiments, unless limited by an ultraviolet cut-off Λ ≈ 3-4 GeV (from Δm_K);
- result is based on current algebra commutators and shows that hadron form factors cannot help: ***current commutators imply hard constituents***;
- Similar results were found by R. Marshak and coll. and by F. Low.

first attempts

- Attempts were made during 1968-69 to make the amplitude more convergent:

  - introducing more than one Intermediate Vector Boson (Gell-Mann, Low, Kroll, Ruderman) (too many were needed);

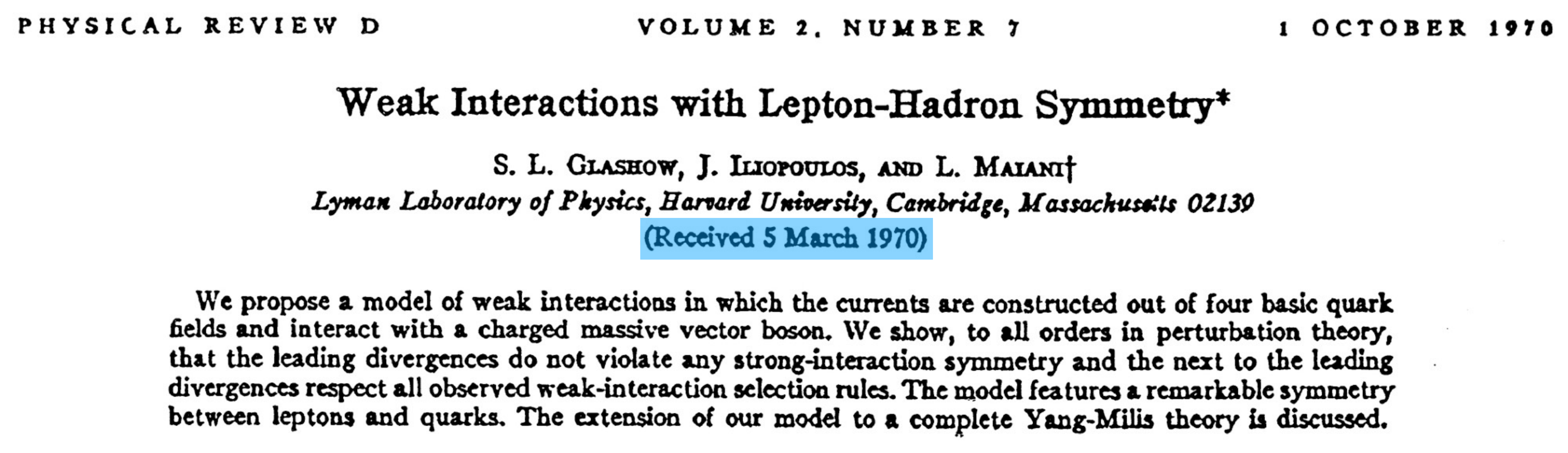
  - introducing negative metrics (ghost) states (T.D.Lee and G.C. Wick), of mass $\simeq \Lambda$!

- it was realised that quadratically divergent amplitudes of order $G\Lambda^2$ would also arise, in the IVB theory, with potential violations of strong interaction symmetries (parity, isospin, SU(3) and strangeness).

- C. Bouchiat, J. Iliopoulos and J. Prentki (1968): with chiral $SU(3) \otimes SU(3)$ breaking described by a (3,3bar) representation, leading divergent terms that violate strangeness and parity to order ($G\Lambda^2$) are of the form $\partial^\mu J_\mu$ and can be eliminated

- another line was to cancel the quadratic divergence in correspondence to a specific value of the angle, i.e. "computing" the Cabibbo angle (Gatto, Sartori, Tonin(1968); Cabibbo, Maiani (1969));

- ...but the small cutoff in the $G(G\Lambda^2)$ terms still called for an explanation.



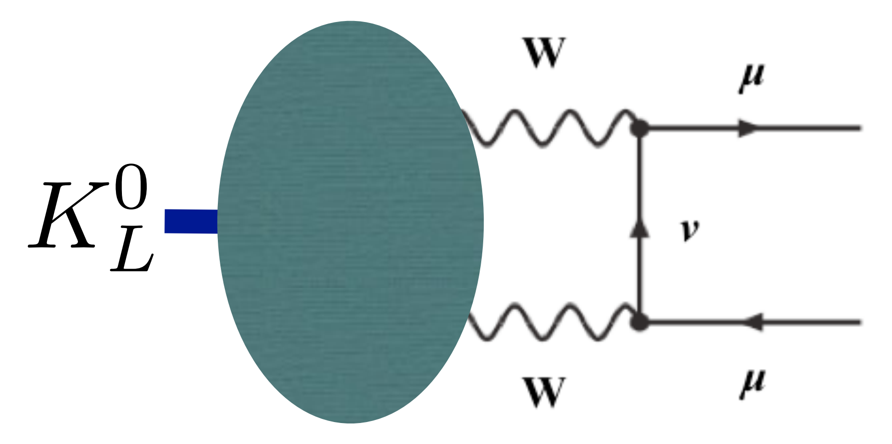
PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

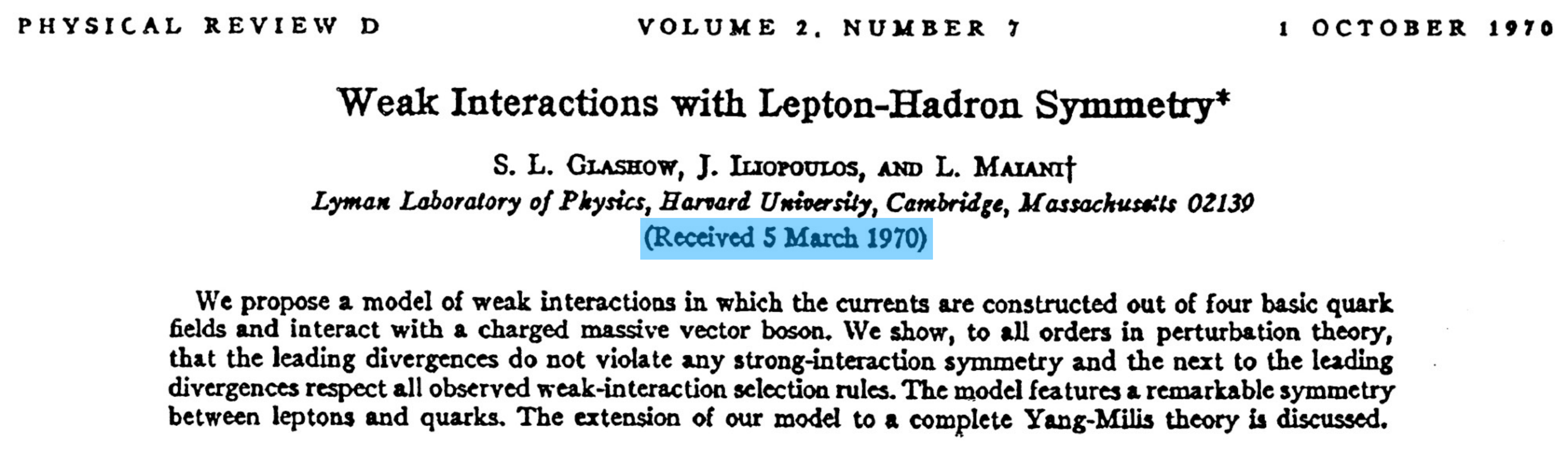
Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.





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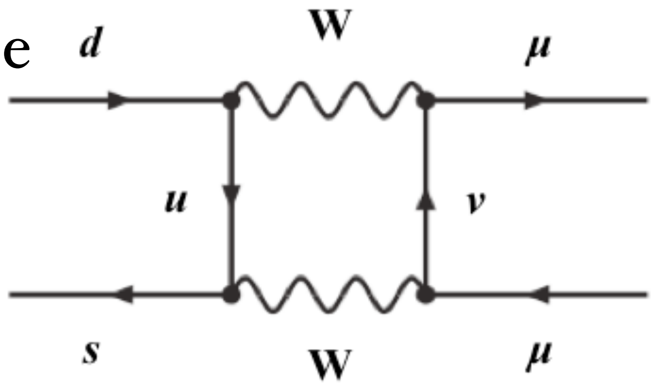
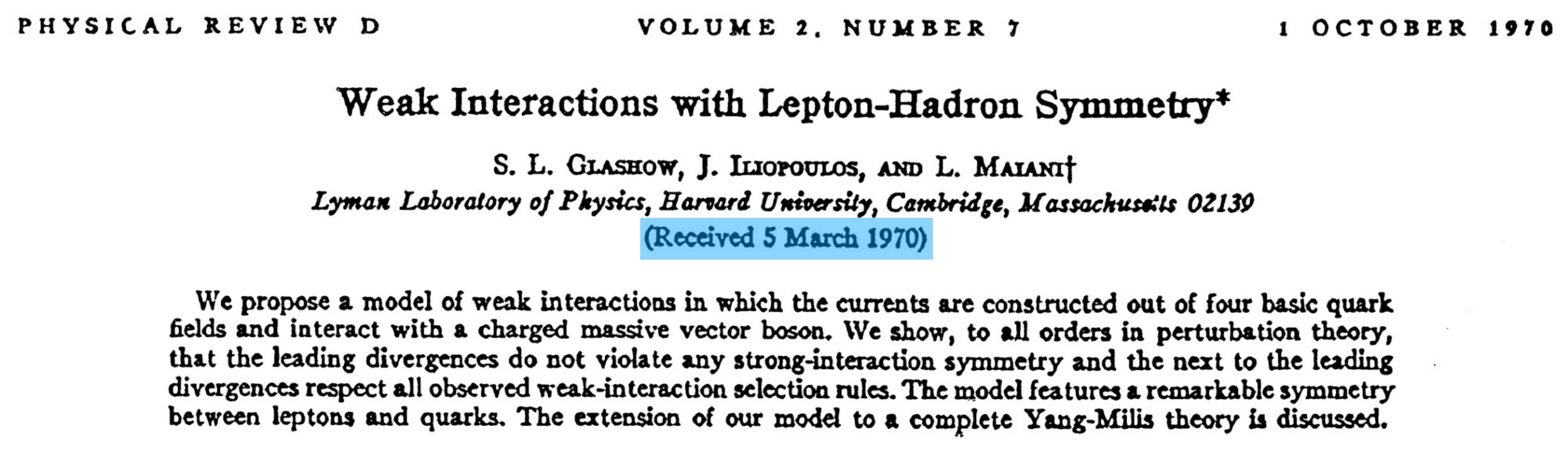
in today ‘s
common parlance





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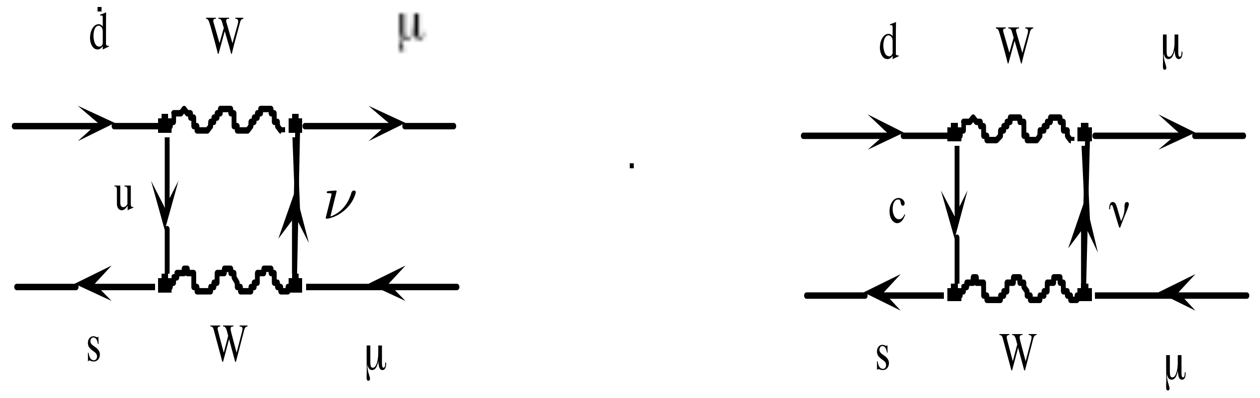
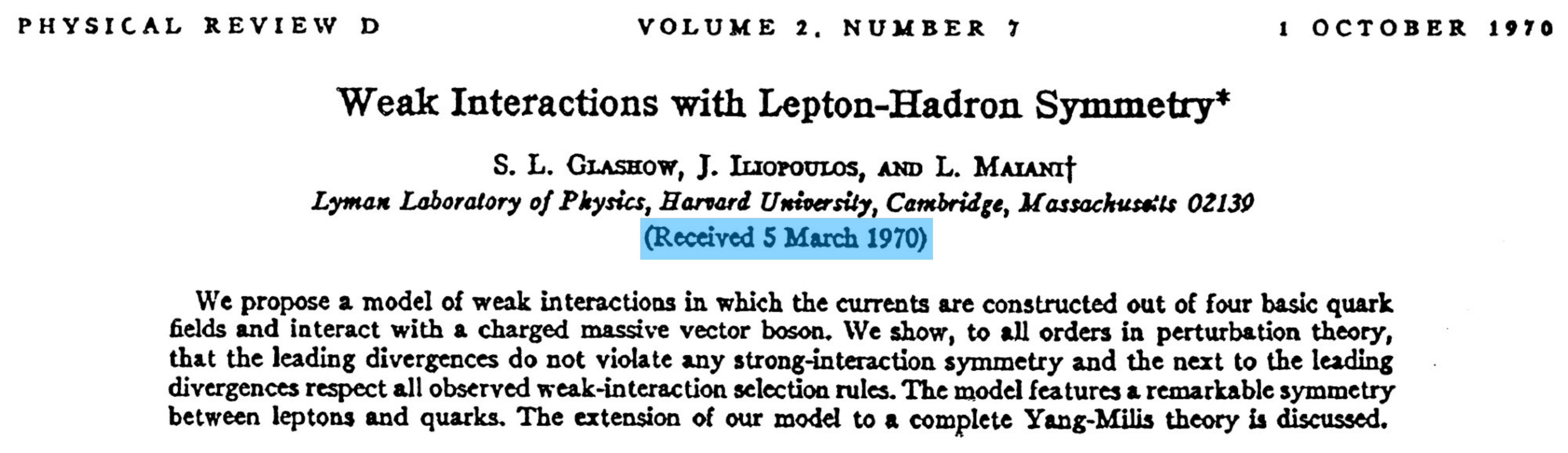


(a) (b)

GIM proposal



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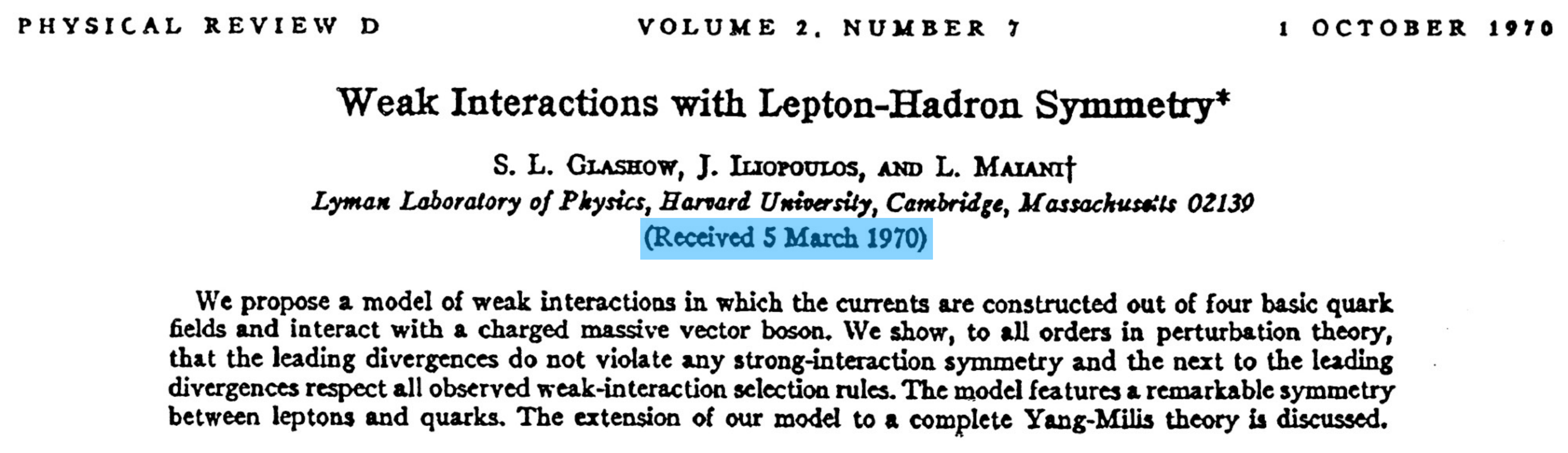
$$J^W_\mu(quark) = \bar{q} C \gamma_\mu q_L$$

$$C = \begin{pmatrix} 0 & 0 & +\cos\theta & +\sin\theta \\ 0 & 0 & -\sin\theta & +\cos\theta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$ =quark ***mixing matrix***



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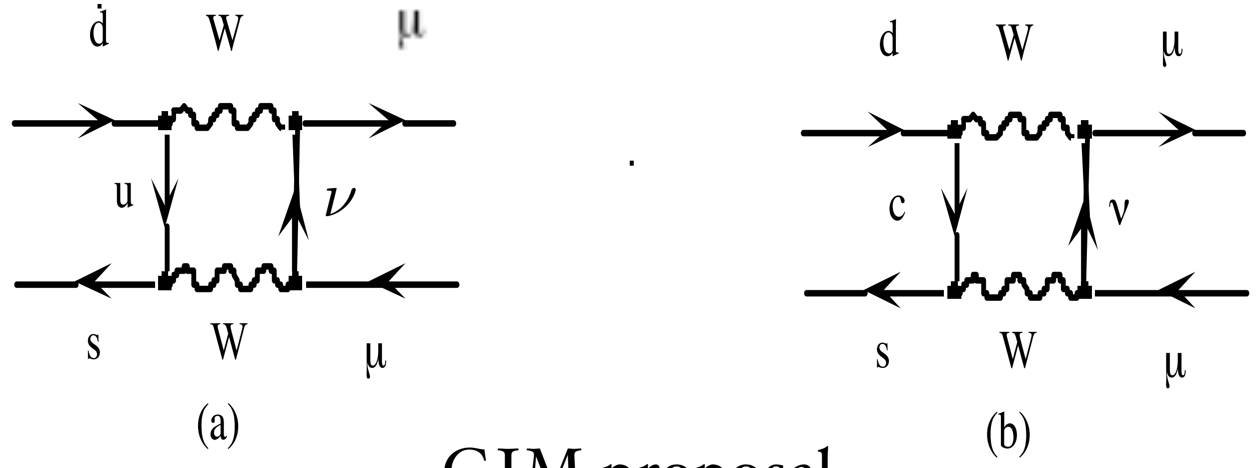

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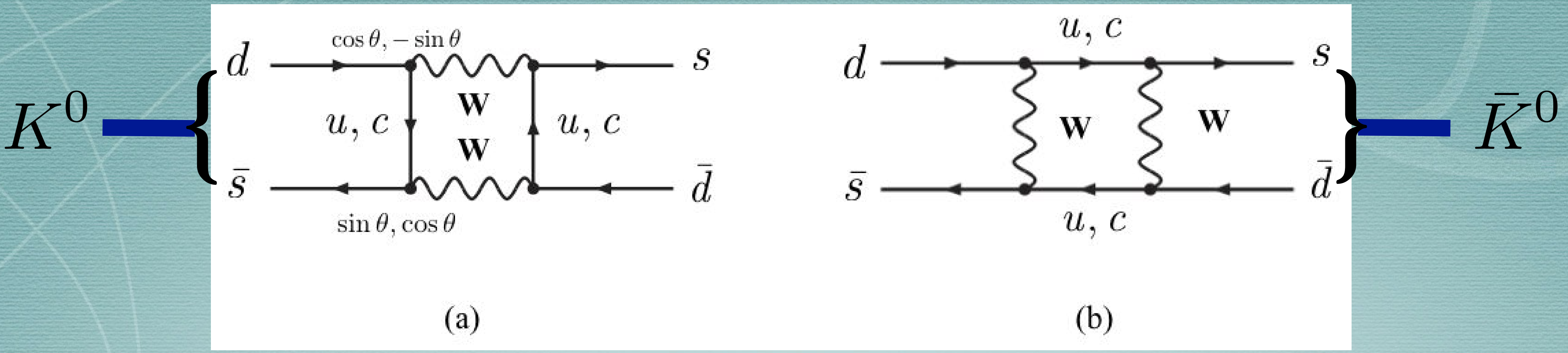
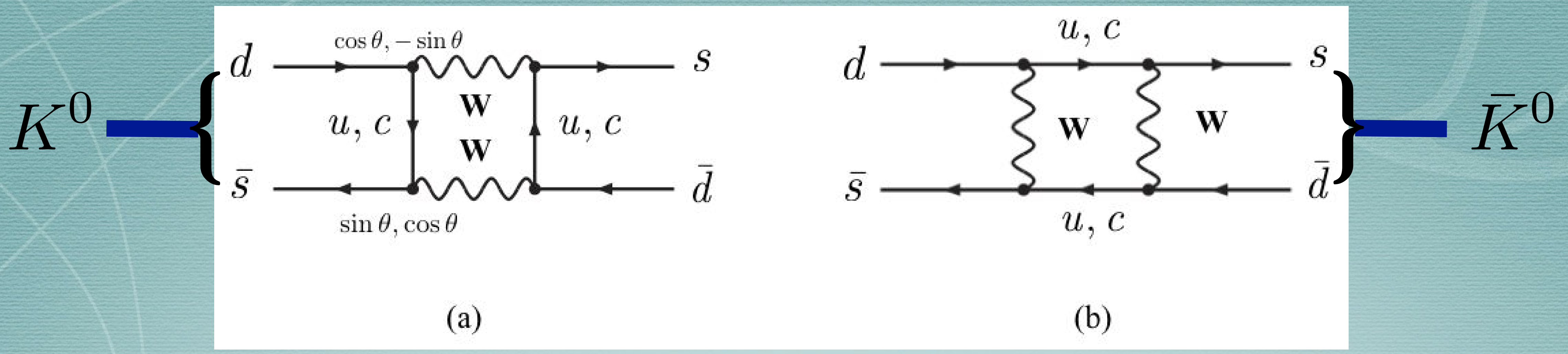
divergent amplitude for
$m_u=m_c=0$:
$\propto G(G\Lambda^2)[C,C^\dagger]$
= flavor diagonal!



- each quark line, which leads to ΔF≠ 0, carries the product of d or s couplings to u and c

$$
\begin{aligned}
A_u &= \sin\theta\cos\theta\ \ A(m_u)\\
A_c &= -\sin\theta\cos\theta\ \ A(m_c)\\
A_{\text{tot}} &= \sin\theta\cos\theta\,[A(m_u) - A(m_c)]
\end{aligned}
$$

- the subtraction makes the integral convergent
- The result vanishes for $m_c = m_u$
- the upshot is that one finds an amplitude of order $G[G(m^2_c - m^2_u)]$,
- i.e. Ioffe&Shabalin's result with: $\Lambda^2 \to m_c^2 - m_u^2 \approx (3 - 4\ \text{GeV})^2$



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- each quark line, which leads to $\Delta F \neq 0$, carries the product of d or s couplings to u and c

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Ioffe&Shabalin's result turns into a prediction of the charm quark mass, m_c=1.5-2 GeV !!

①

. . . it appears necessary to depart from the original phenomenological model of weak interactions

New weak interactions

1

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New weak interactions

2

The weak hadronic current is constructed in precise analogy with the weak lepton current, thereby revealing suggestive lepton-quark symmetry

Quark-lepton symmetry

1. *. . . it appears necessary to depart from the original phenomenological model of weak interactions* New weak interactions

2. *The weak hadronic current is constructed in precise analogy with the weak lepton current, thereby revealing suggestive lepton-quark symmetry*

   Quark-lepton symmetry

3. *. . . suitable redefinitions of the relative phases of the quarks may be performed in order to make U* [i.e. the weak interaction, matrix, note added] *real and orthogonal* No CP violation

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   No CP violation

4. *In contradistinction to the conventional (three-quark) model, the couplings of the neutral intermediary - now hypercharge conserving -cause no embarrassment. The possibility of a synthesis of weak and electromagnetic interactions is also discussed.*

   Electroweak unification is possible

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   Electroweak unification is possible

5. *Why have none of these charmed particles been seen? Suppose they are all relatively heavy, say 2 GeV. Although some of the states must be stable under strong (charm-conserving) interactions, these will decay rapidly (* 10^{-13} *sec) by weak interactions into a very wide variety of uncharmed final states (there are about a hundred distinct decay channels).*

   Since the charmed particles are copiously produced only in associated production, such events will necessarily be of very complex topology, involving the plentiful decay products of both charmed states. Charmed particles could easily have escaped notice.

   Charmed particles have to be found

can gim mechanism survive in the presence of strong interactions ?

- One may suspect that strong interactions will spoil the cancellations at the basis of GIM;
- Preparata & Weisberger: the universality relations of weak interactions are preserved by strong interactions mediated by a neutral gluon
- what seemed to be a simple curiosity (the PW theorem for the abelian gluon) became reality after the discovery of $SU(3)_{color}$ commuting with the EW group (eight gluons, all electrically neutral, anyway) and asymptotic freedom (1973).
- strong interactions, in leading order, renormalize quark EW parameters, i.e. masses and gauge couplings, and the strenght of non leptonic processes in a calculable way.

January 1970….

- By the end of January, I think we had understood all the essentials and we were very happy.
- one day, going to the Legal Sea Food for lunch, my wife Pucci joined us. Pucci told to Shelly how happy and excited I was about the new result and the work we were doing. Shelly: *He is right, this paper is going to be on all school books*
- . . .In a seminar to the experimentalists of Harvard, working at the CEA (Cambridge Electron Accelerator) Shelly opened this way: *Look, with charm we have essentially solved particle physics*.
- *Except*, he added, *for CP violation*.

Facts and predictions following GIM

- Neutrino neutral current semileptonic processes must exist

  -Flavour conserving, neutral current processes are indeed predicted, in W boson theory, or in Yang-Mills theory, to order G $[C,C^\dagger] =$ flavor diagonal;

  -in the unified theory, they appear in lowest order, mediated by Z^0

- In 1973, the Gargamelle bubble chamber collaboration at CERN observed muonless or electronless neutrino events soon recognised to be neutrino processes of the type $\nu(\bar{\nu}) + \text{Nucleous} \rightarrow \nu(\bar{\nu}) + \text{hadrons}$

  -strange particles (and, at higher energy, charmed particles) are pair produced, indicating flavour conservation in these abundant neutral current reactions.

- Quark-lepton symmetry.

  -Restoring quark-lepton symmetry was one of the basic motivations of the GIM paper and is at the basis of the partial cancellation of FCNC amplitudes.

  -quark-lepton symmetry is ***mandatory*** in the unified electroweak theory for the cancellation of the Adler-Bell-Jackiw anomalies, the last obstacle towards a renormalizable theory, as shown in 1972 by C. Bouchiat, J. Iliopoulos and P. Meyer (fractionally charged and $SU(3)_{color}$ triplet quarks).

- CP violation ?

  -with 4 quarks in 2 doublets the weak coupling matrix U can be made real

  - already worried by the charm quark, GIM did not ask what would happen with even more quarks and failed to discover a simple theory of CP violation.

2. Unified theory for quarks

- The matrices:

$$\mathcal{C},\ \mathcal{C}^\dagger,\ [\mathcal{C},\ \mathcal{C}^\dagger] = 2\mathcal{C}_3,\ \text{and } Q$$

$$\mathcal{C}_3 = \begin{pmatrix} 1/2 & 0 & 0 & 0 \\ 0 & 1/2 & 0 & 0 \\ 0 & 0 & -1/2 & 0 \\ 0 & 0 & 0 & -1/2 \end{pmatrix};Q = \begin{pmatrix} 2/3 & 0 & 0 & 0 \\ 0 & 2/3 & 0 & 0 \\ 0 & 0 & -1/3 & 0 \\ 0 & 0 & 0 & -1/3 \end{pmatrix}$$

make an SU(2) ⊗ U(1) algebra without Flavor Changing Neutral Currents (FCNC) and can be taken as the generators of the unified Glashow-Weinberg-Salam theory of the Electroweak Interactions

- GIM: FCNC processes arise to order $G(Gm_c^2)$

- UV divergences are cut-offed by heavy quark exchange; if there are no additional, long distance, contributions, amplitudes may be reliably computed, due to asymptotic freedom

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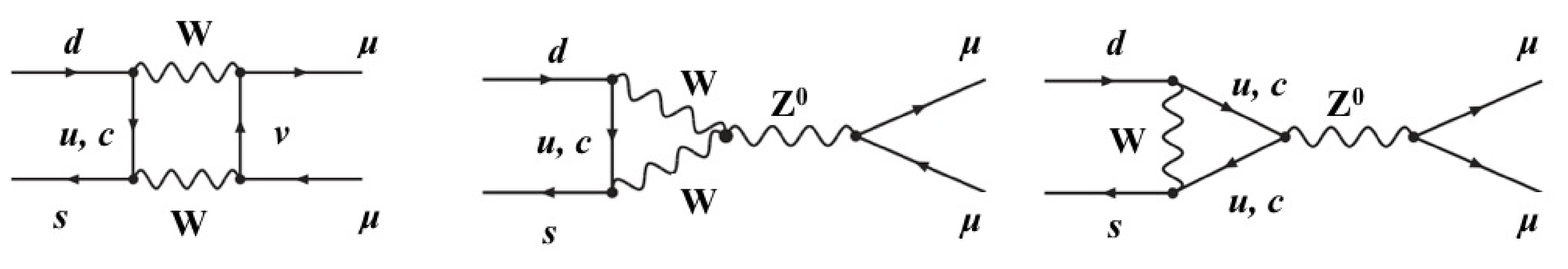
heavy quarks in FCNC provide a tool to search for new physics at high energy

M. K. Gaillard, B. W. Lee, 1974



but there is a long-distance contribution from:

$$K_L \to \gamma\gamma \to \mu^+\mu^-$$

CP violation, in brief

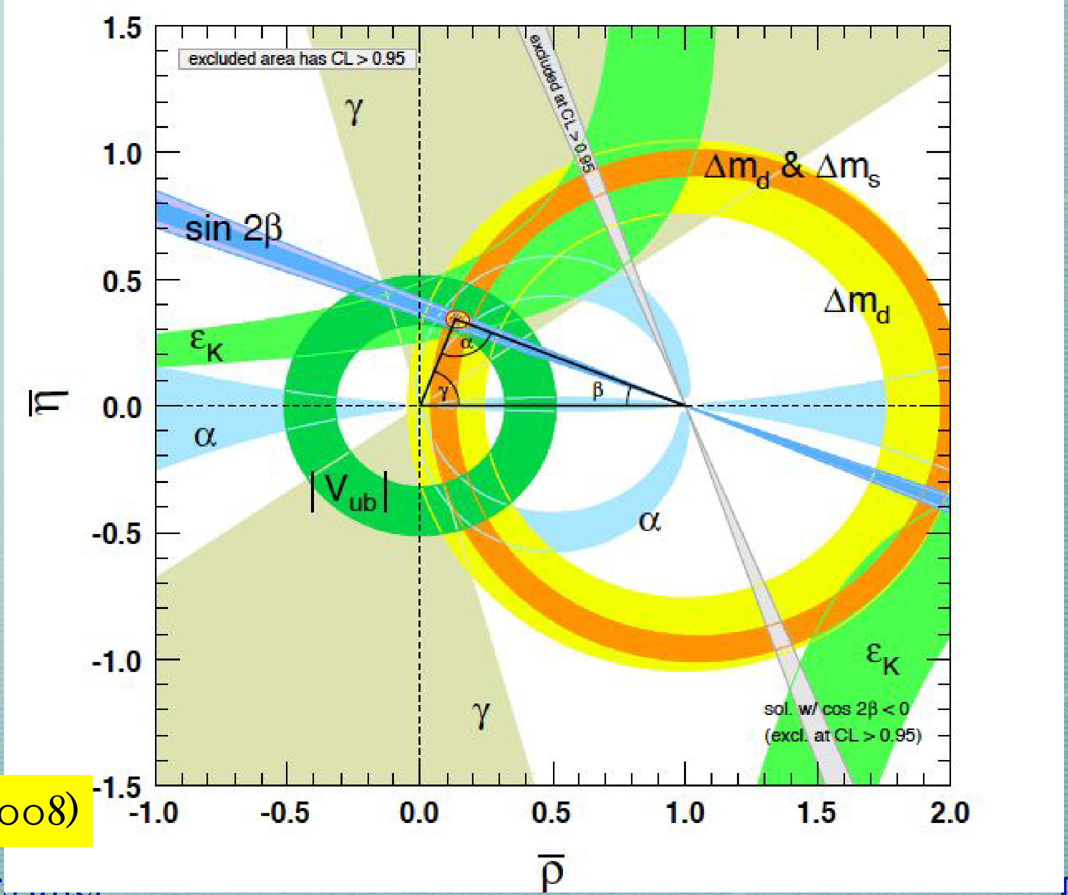
- 1973, Kobayashi and Maskawa: three left-handed quark doublets allow for one CP violating phase in the quark mixing matrix, since known as the Cabibbo-Kobayashi-Maskawa matrix;
- the phase could agree with the observed CP violation in K decays
- leads to neutron electric dipole vanishing at one loop (Pakvasa & Sugawara, Maiani, 1976);
- 1986, I. Bigi and A. Sanda predict direct CP violation in B decay;
- 2001, Belle and BaBar discover CP violating mixing effects in B-decays.

Wolfenstein's parametrization

$$U_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix}$$

U_{CKM} is in an extraordinary agreement with data

C.-Amsler *et al.* [Particle Data Group Collaboration], Phys. Lett. B**667**, (2008)



3. PRECURSORS

- Elementary particles in the Sakata model:

$$\begin{pmatrix} & p & \\ n & & \Lambda \end{pmatrix} \begin{pmatrix} & \nu & \\ e & & \mu \end{pmatrix}$$

- In 1962, after the discovery of the two neutrinos, Sakata et al. (Nagoya) and Katayama et al. (Tokyo) proposed to extend the model to a fourth baryon, called V^+:

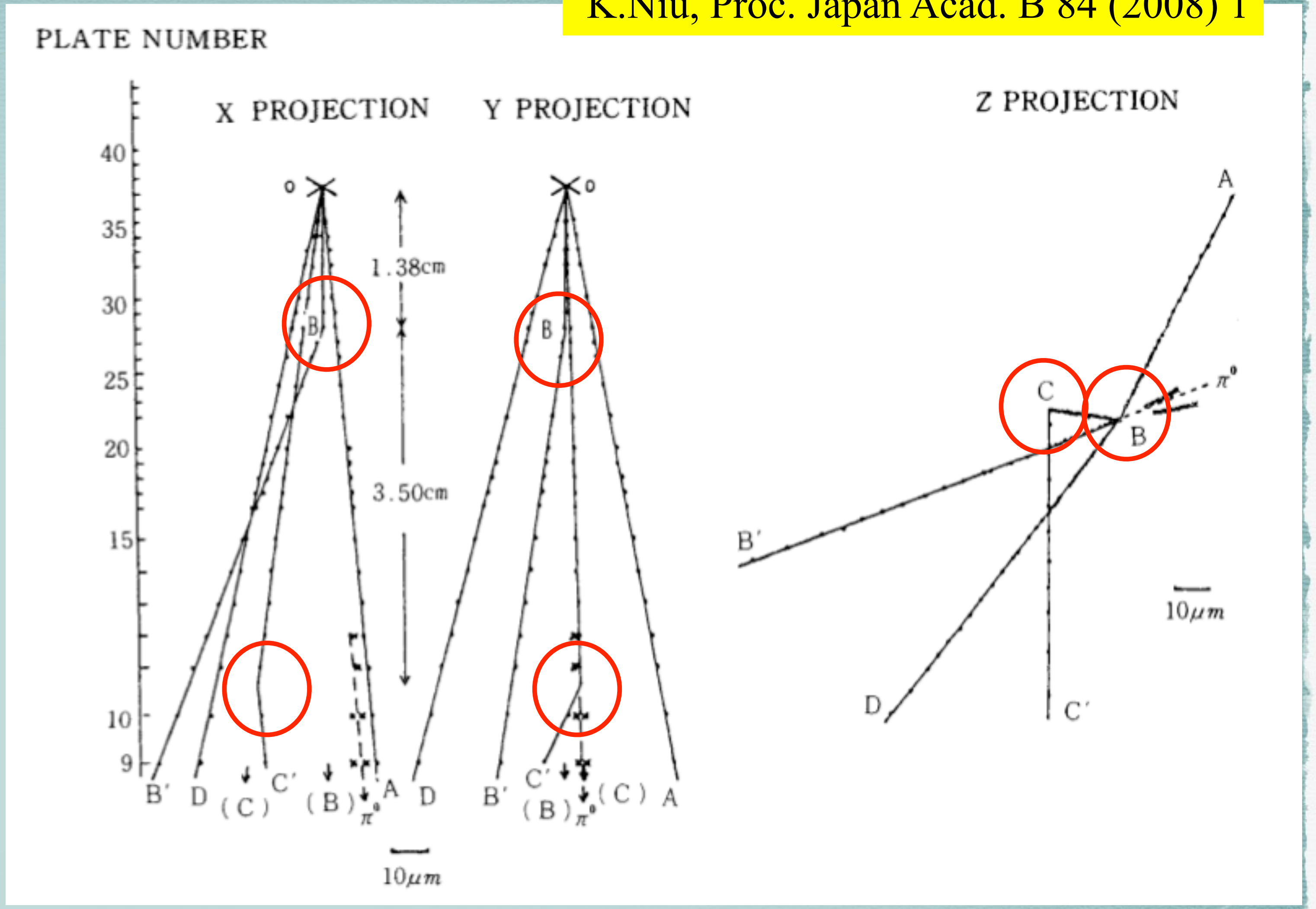
$$\begin{pmatrix} p & V^+ \\ n & \Lambda \end{pmatrix} \quad \begin{pmatrix} \nu_1 & \nu_2 \\ e & \mu \end{pmatrix}$$

a possible mixing among ν_e and ν_μ was paralleled by n-Λ mixing a-la Cabibbo, giving rise to weak couplings of p and V^+ similar to the ones we have assumed for u and c.

- In 1964, Glashow and Bjorken proposed a 4th quark and invented the name “charm”. The motivation was again lepton-quark symmetry and, in addition, they speculated that the charm quark was related to the meson φ(1020) and that it could give rise to hadrons below 1 GeV; weak couplings: $u \rightarrow d_C$ and $c \rightarrow s_C$ were assumed.

The discovery of charmed particles

- In 1971, K. Niu and collaborators observed ***kinks*** in cosmic ray emulsion events, indicating unstable particles with lifetimes of order of 10^{-12} to 10^{-13} sec. These lifetimes are in the right ballpark for charmed particles and indeed they were identified as such in Japan.
- But cosmic rays events were paid no attention in western countries.



K.Niu, Proc. Japan Acad. B 84 (2008) 1

The November Revolution

$$J/\Psi = c\bar{c} \ (3097 \text{ MeV})$$

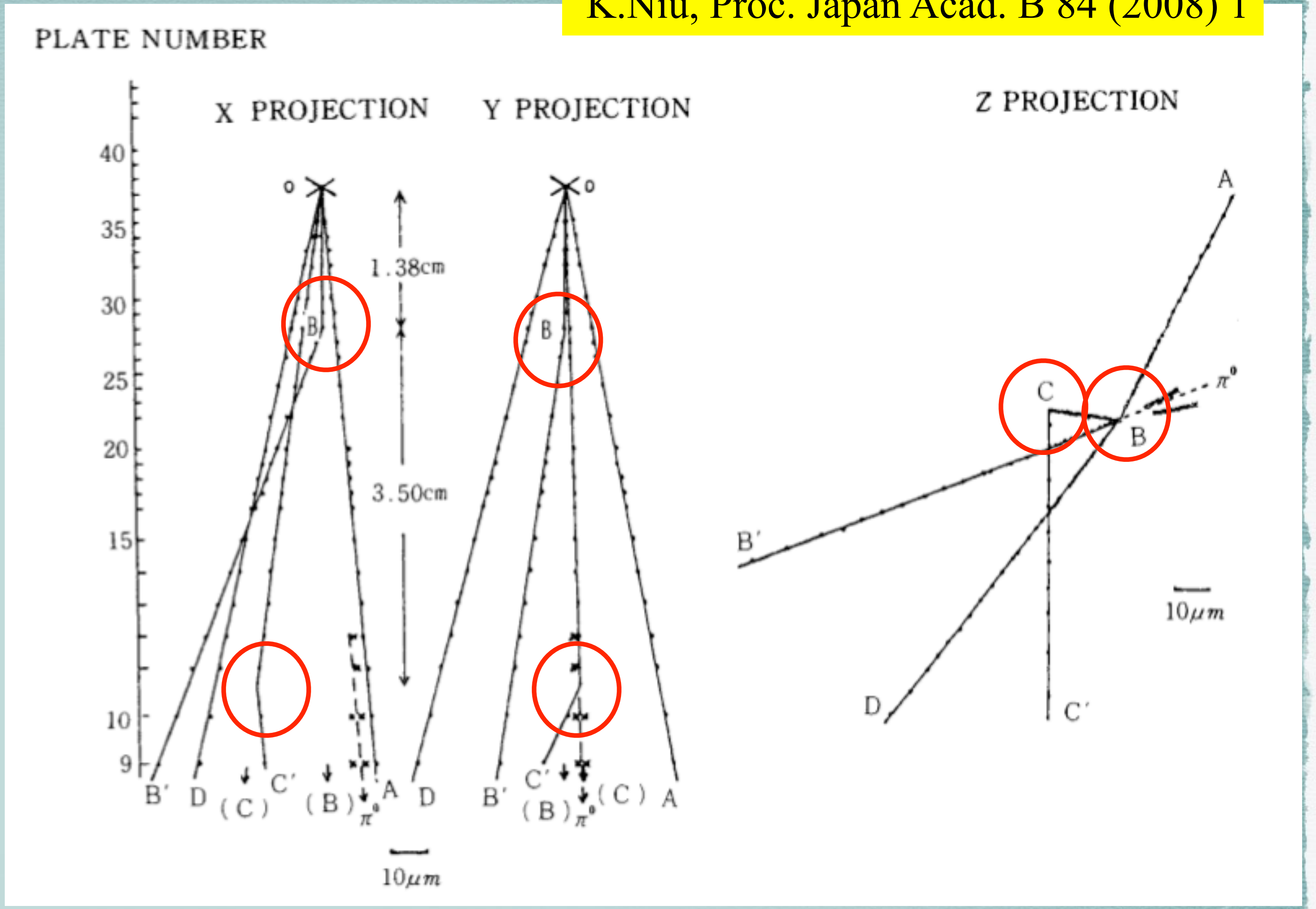
is discovered in 1974 by C. C. Ting and coll. (Brookhaven) and by B. Richter and coll. (SLAC); immediately after, was observed in Frascati.

$$D^0 = c\bar{u} \ (1865 \text{ MeV})$$

the lightest weakly decaying charmed meson, D^0, is discovered by the Mark I detector (SLAC) in 1976.

The discovery of charmed particles

- In 1971, K. Niu and collaborators observed ***kinks*** in cosmic ray emulsion events, indicating unstable particles with lifetimes of order of 10^{-12} to 10^{-13} sec. These lifetimes are in the right ballpark for charmed particles and indeed they were identified as such in Japan.
- But cosmic rays events were paid no attention in western countries.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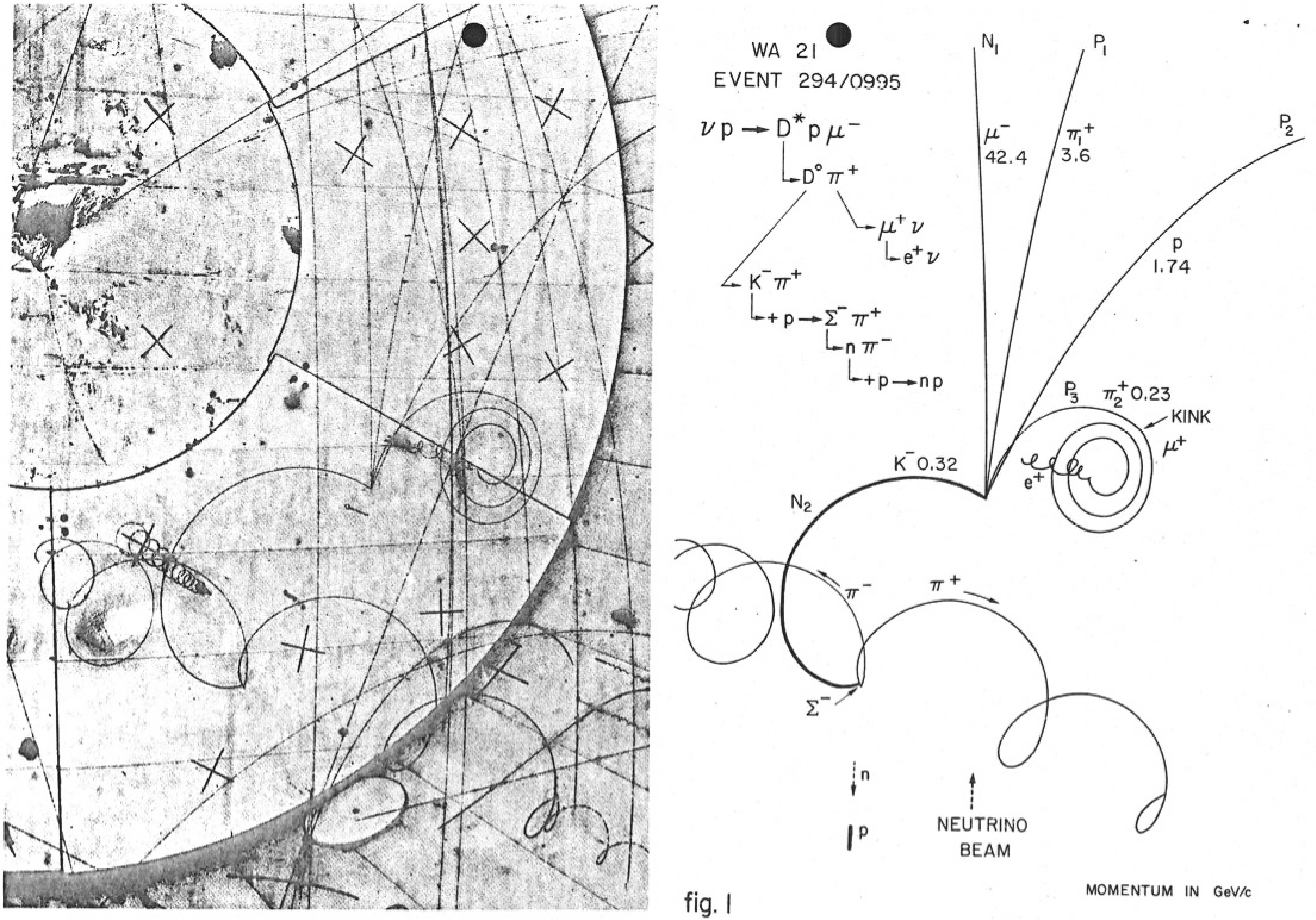
The same year, Lederman and coll. discover the Υ=(b b-bar), the first evidence of the 3rd family

The neutrino production of an excited charmed meson, D*, is captured by this spectacular picture taken at the CERN Hydrogen Bubble Chamber, with the decay chain of D* fully reconstructed

(J.Blietschau~ et al. [Aachen-Bonn-CERN-Munich-Oxford Collaboration]. *Production of Charmed Mesons in Neutrino Interactions in Hydrogen*. Physics. Lett. **86B** (1979) 108.



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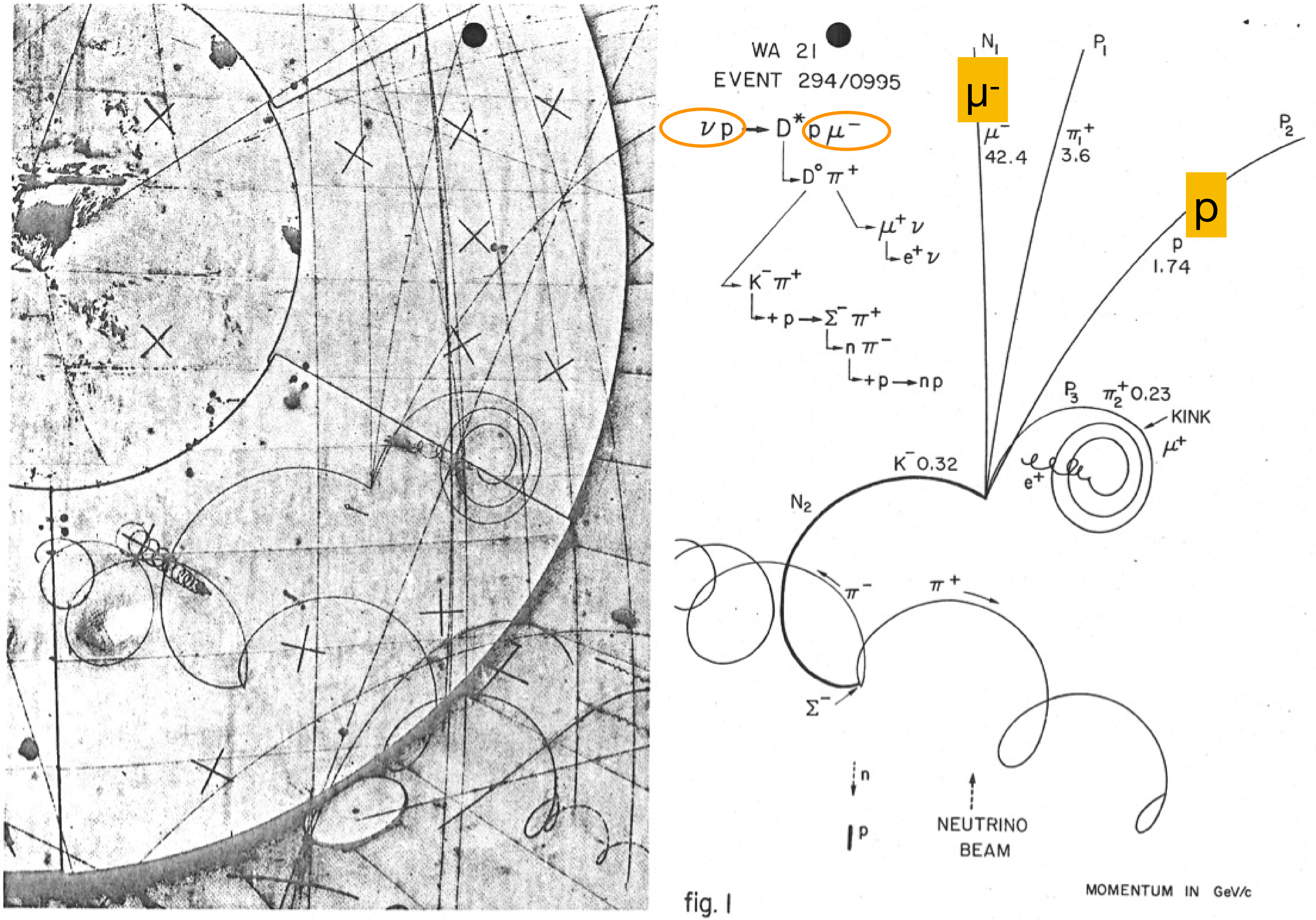

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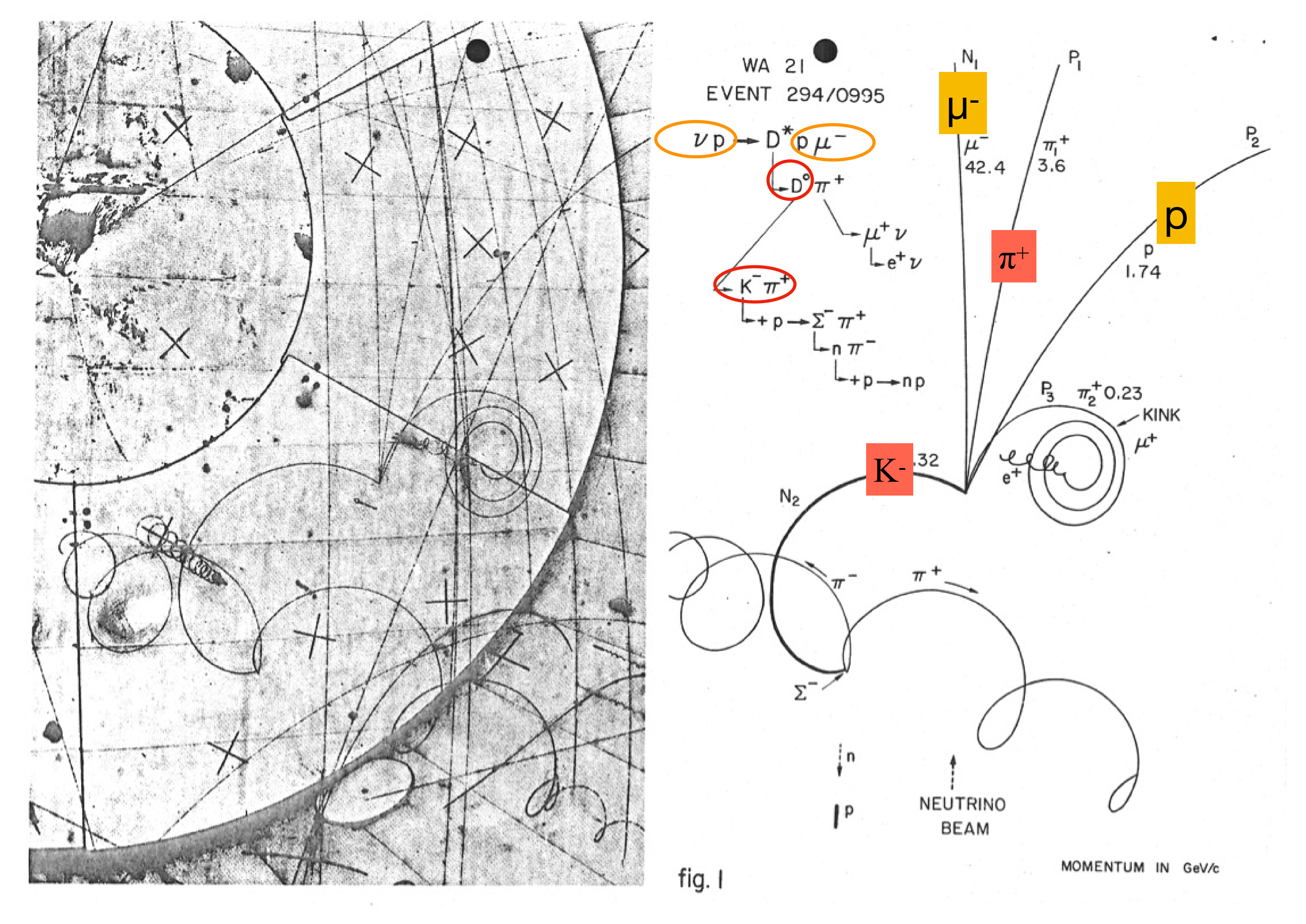

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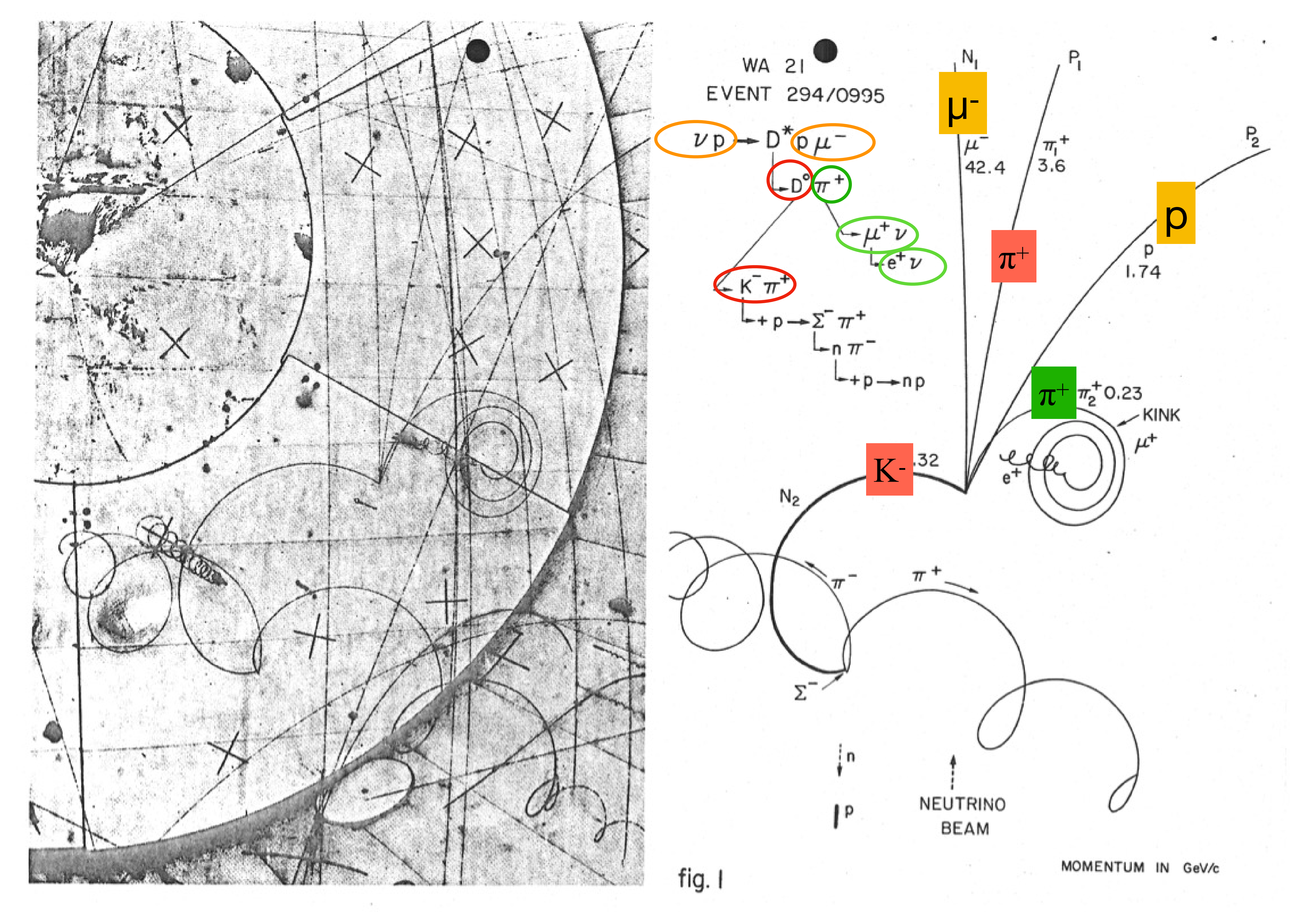

fig. I

4. Heavy and very heavy quarks in QCD

- Λ_{QCD}~300 MeV sets the scale of the strong interactions and gives an absolute meaning to quark heaviness:
  - $m_q < \Lambda_{QCD}$, light quarks
  - $m_q >, >> \Lambda_{QCD}$, heavy (m_c~1.7 GeV) and very heavy (m_b~5 GeV) quarks
- Inclusive semileptonic decay of heavy quarks
  - $m_c \rightarrow e^+ \nu_e +$ anything

is a *deep inelastic* process, and the strong corrections to free quark decay can be computed in perturbation theory.

- the semileptonic rate, therefore the lifetime, was computed to first order in the strong coupling (Cabibbo, Maiani, 1978)
- and the electron energy distribution by Cabibbo, Corbo', &Maiani, and by Ali & Pietarinen (1979).

N. Cabibbo et al. / Semileptonic charm decay

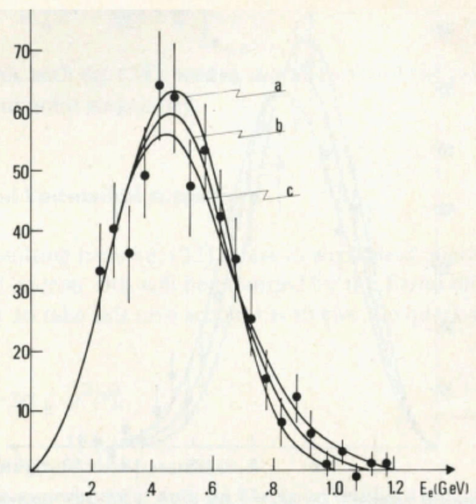

Fig. 5. Same as in fig. 4, with M_c = 1.75 GeV, and P_F = 0.30 0.45, 0.60 GeV (curves a, b, c respectively).

1979

A. Ali, E. Pietarinen / Semileptonic decays of heavy quarks in QCD 527

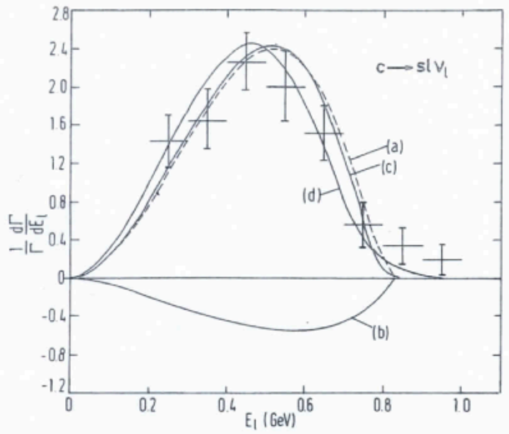

Fig. 3. Inclusive lepton energy spectrum from charm quark decay. (a) Free-quark model result; (b) O(α_s) contribution from one gluon corrections; (c) one gluon corrected spectrum; (d) combined effect of c-quark Fermi motion and one-gluon corrections. The curves (a)–(c) correspond to m_c = 1.8 GeV, m_s = 0.5 GeV and (9) to m_c = 1.7 GeV, m_s = 0.5 GeV and ΔP_c = 0.6 GeV. Data points are from ref. [6].

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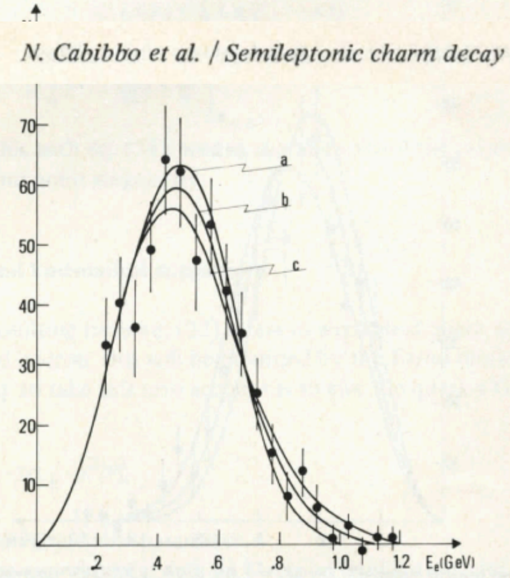
N. Cabibbo et al. / Semileptonic charm decay



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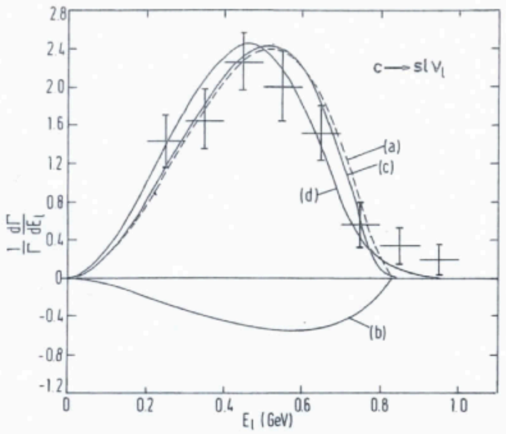

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PHYSICAL REVIEW D **81,** 052007 (2010)

Measurement of absolute branching fractions of inclusive semileptonic decays of charm and charmed-strange mesons

(CLEO Collaboration)

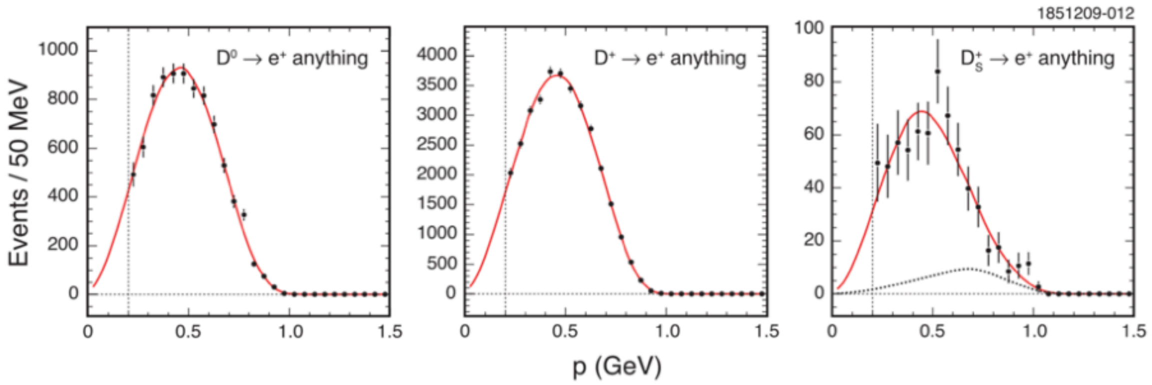

FIG. 3 (color online). Inclusive laboratory frame electron spectra obtained from data, shown as points with statistical uncertainties. The vertical dashed lines indicate the PID momentum cutoff at 200 MeV. Extrapolated spectra are shown as solid curves. The dashed curve in the D_s^+ spectrum plot is the expected contribution from $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$ from leptonic $D_s^+ \rightarrow \tau^+ \nu_\tau$ decay.

more modern data, e.g. CLEO, 2010.

5. Hidden charm and beauty hadrons reveal *tetraquarks* and *pentaquarks*

- Heavy quark pairs ar difficult to be created or destroyed inside hadrons by QCD forces.
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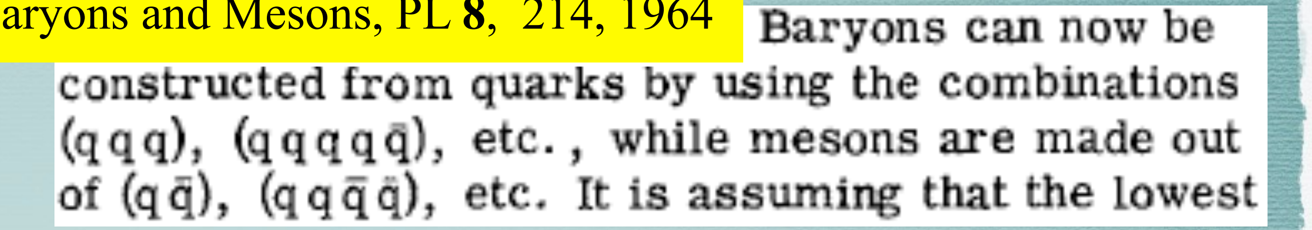
M. Gell-Mann, A Schematic Model of Baryons and Mesons, PL **8**, 214, 1964



Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

There are indeed new valence quark configurations !!

- These are exotic X, Y, Z mesons and the pentaquarks discovered over the last decade

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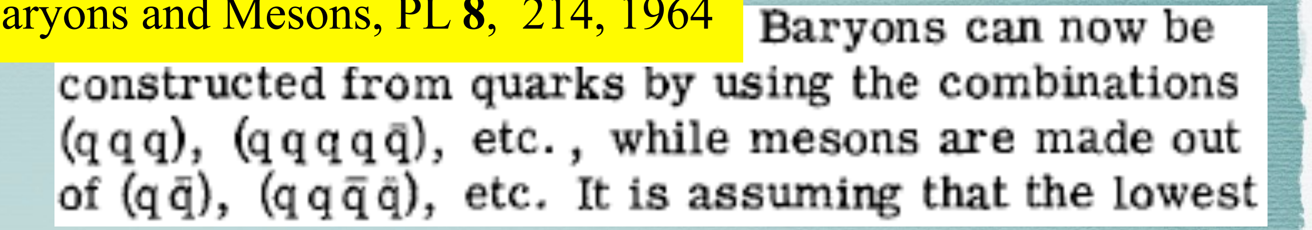

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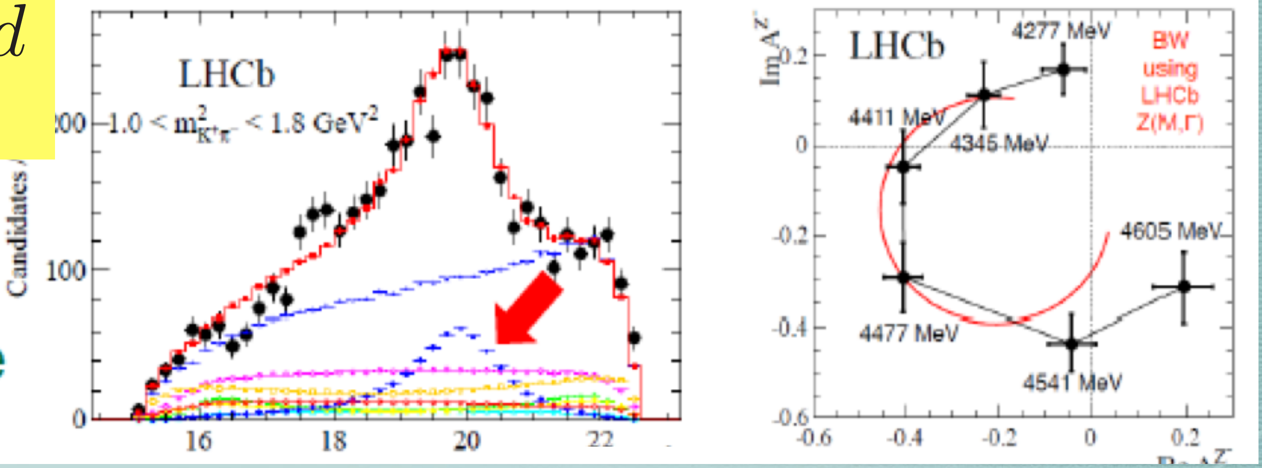
valence quark composition: $c\bar{c}u\bar{d}$

1. Confirm Belle's observation of 'bump'
2. Can NOT be built from standard states
3. Textbook phase variation of a resonance

[PRL 112 (2014) 222002]



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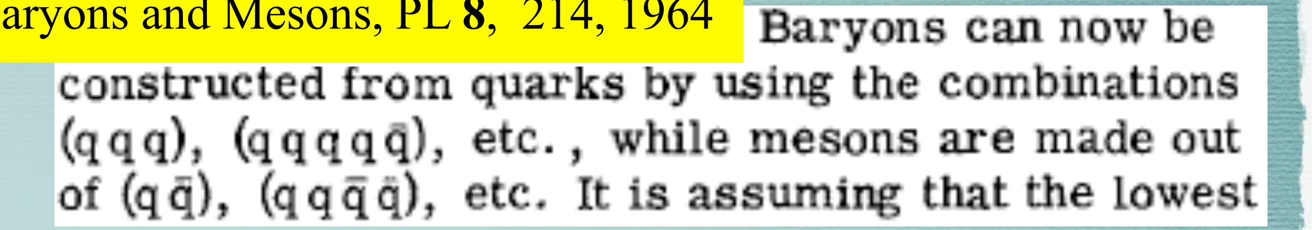
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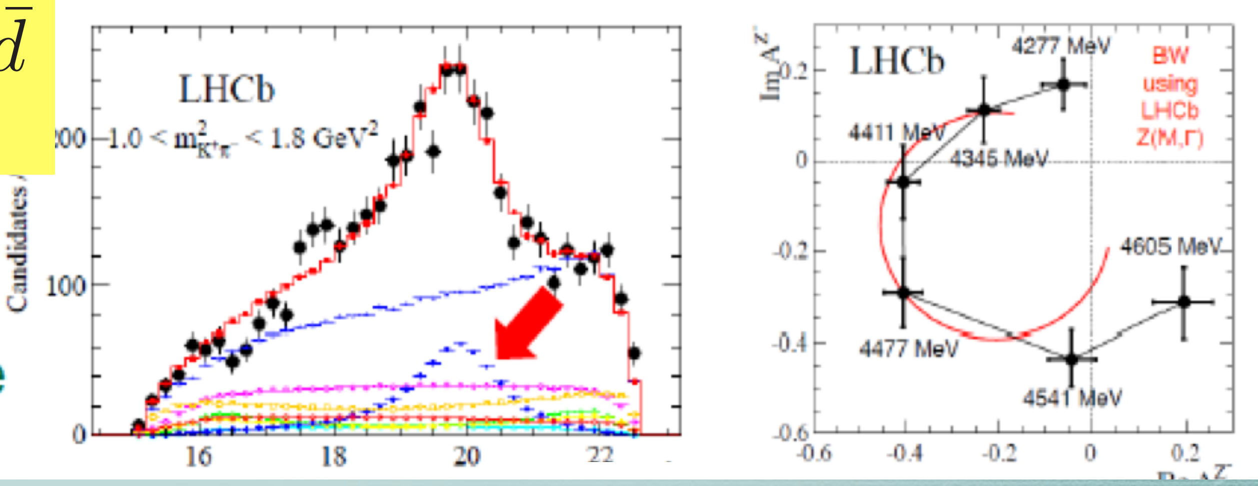
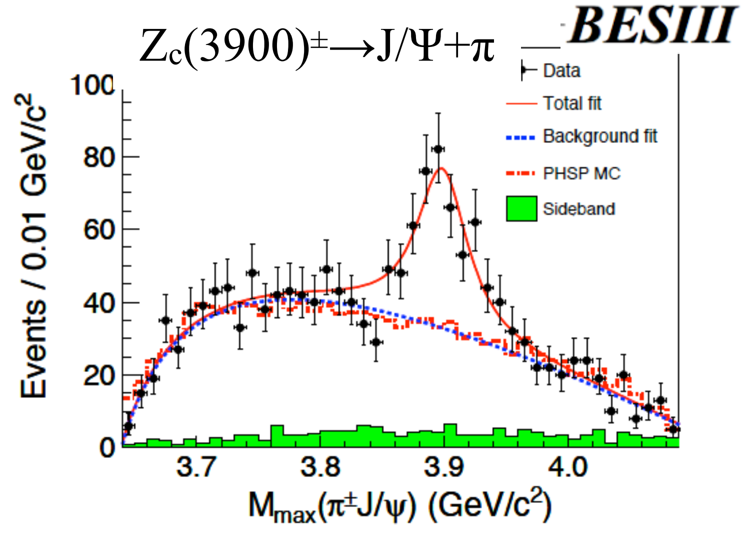
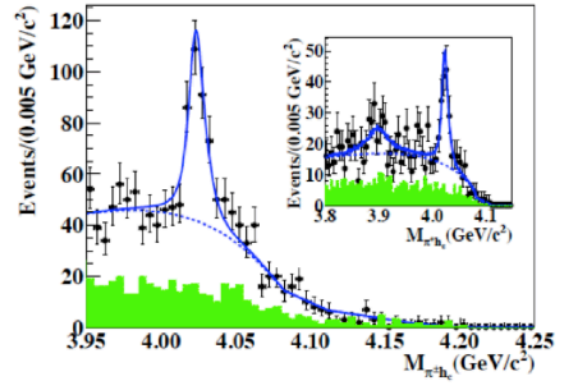


$Z_c(3900)^\pm \to J/\Psi + \pi$



e BESIII

$Z_c(4020)^\pm \to h_c + \pi$



BESIII: PRL111, 242001

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 η_c decay modes. 8.9σ

$M(Z_c(4020)) = 4022.9 \pm 0.8 \pm 2.7$ MeV;

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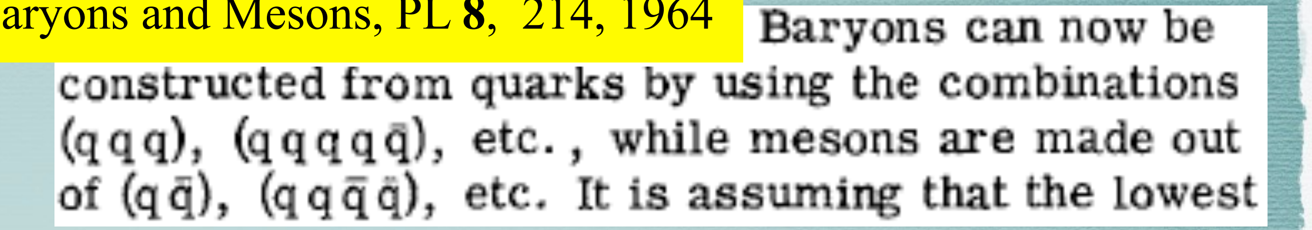
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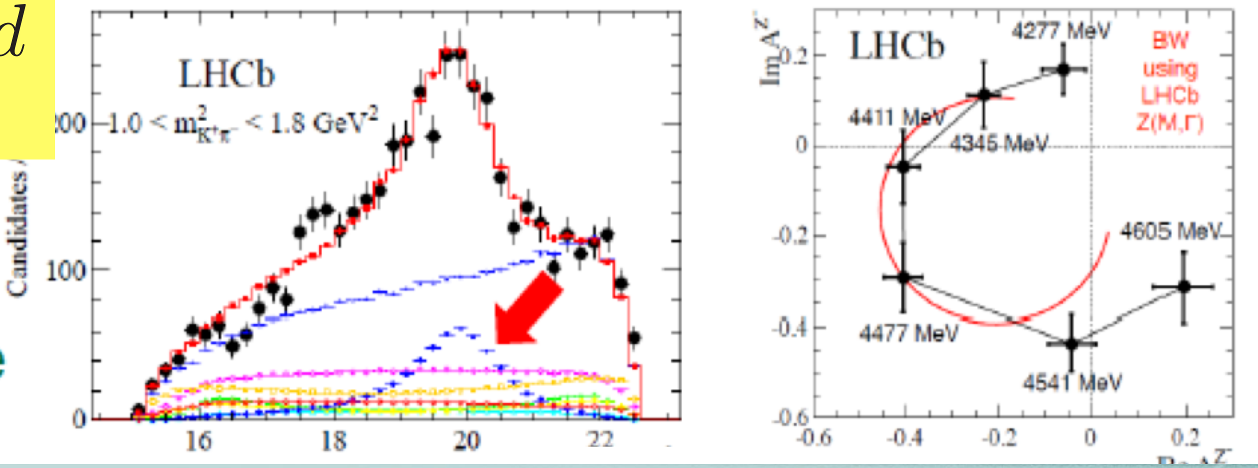

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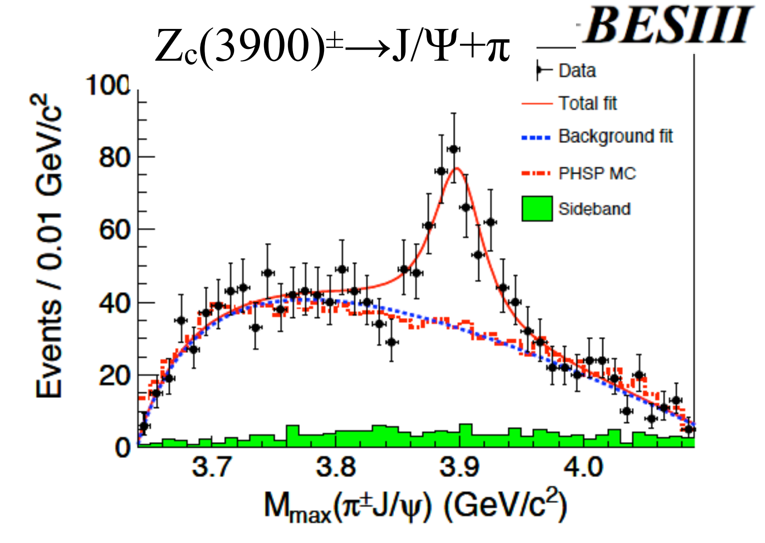

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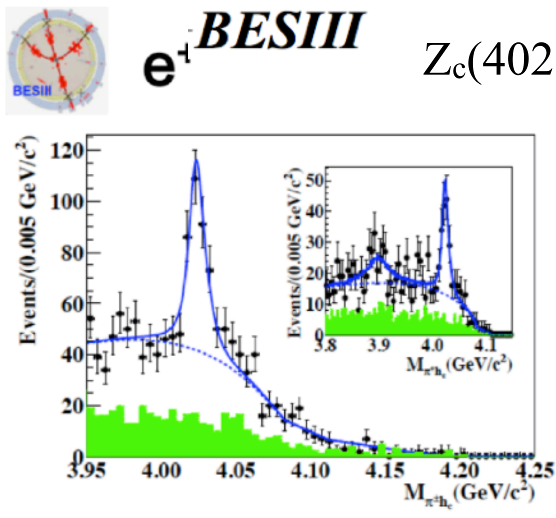

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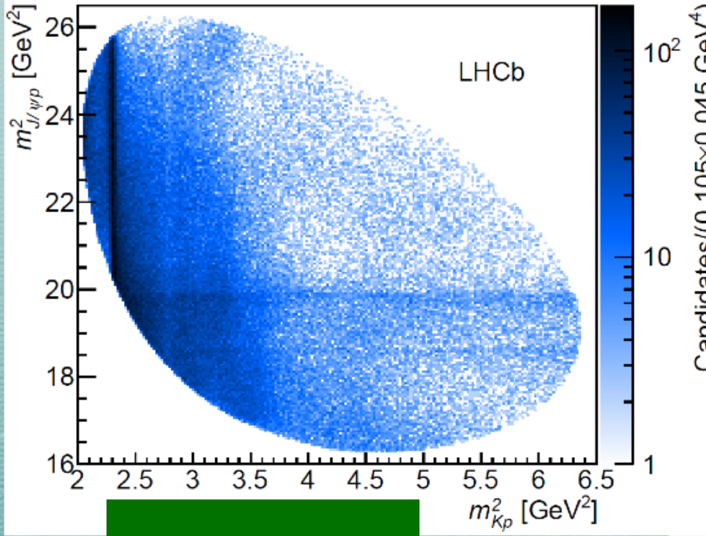
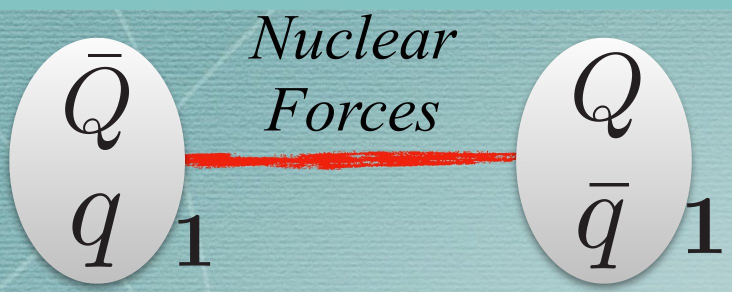


Pentaquarks

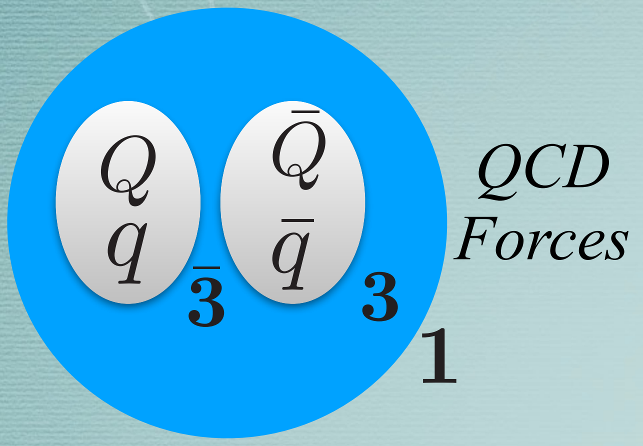
$\mathcal{P}^+ = c\bar{c}uud$

No consensus, yet



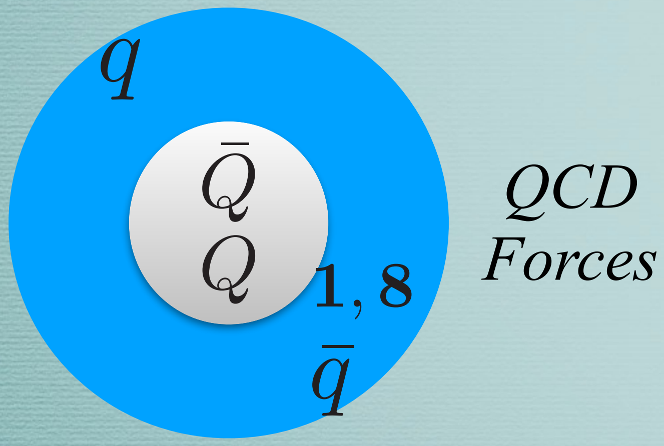
Hadron Molecule

F-K. Guo, C. Hanhart, U-G Meißner, Q. Wang, Q. Zhao, and B-S Zou, arXiv 1705.00141 (2017)



Compact Diquark-Antidiquark

L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 71 (2005) 014028; **D 89** (2014) 114010.



HadroCharmonium (1)
Quarkonium Adjoint Meson (8)

S. Dubynskiy, S. and M. B.Voloshin, Phys. Lett. **B 666**,(2008) 344.

E. Braaten, C. Langmack and D. H. Smith, Phys. Rev. **D 90** (2014) 01404

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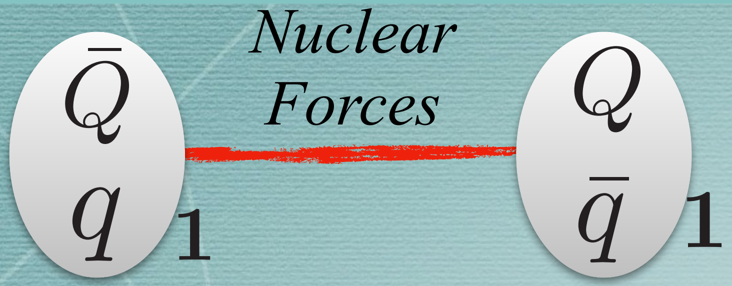

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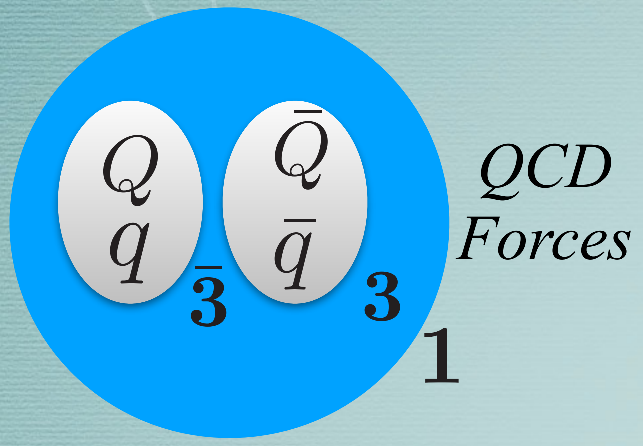

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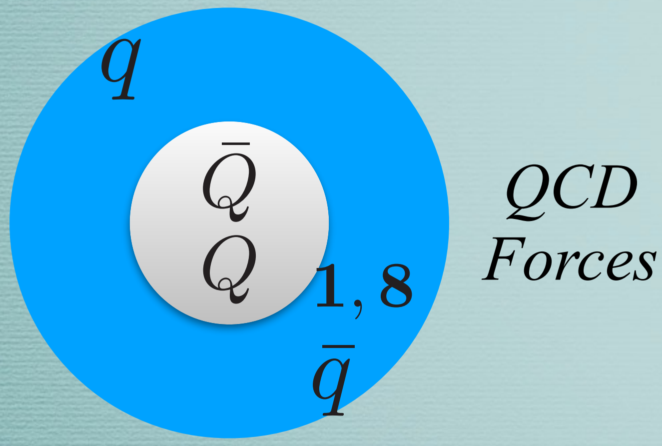

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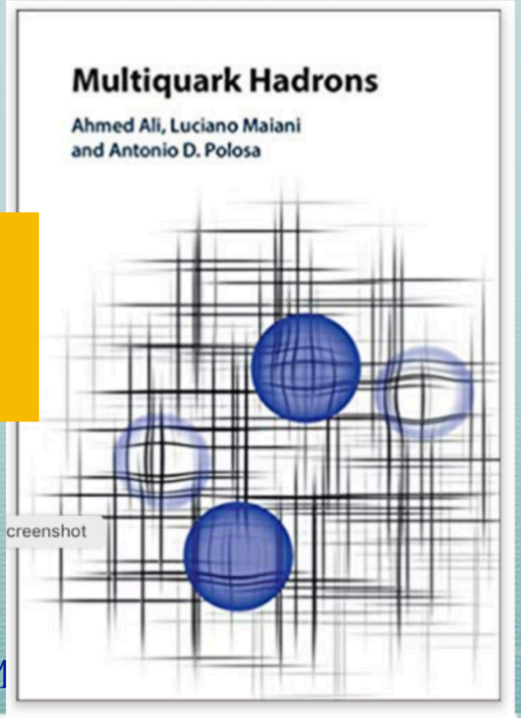
For a review, see:
A. Ali, L. Maiani and A.D. Polosa, *Multiquark Hadrons*, Cambridge University Press (2019)

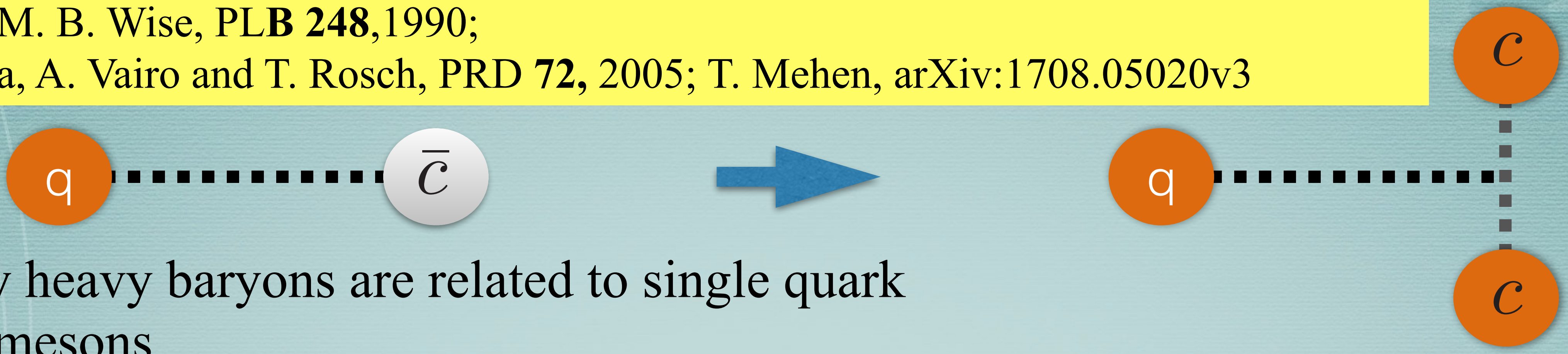


Multiquark Hadrons

Ahmed Ali, Luciano Maiani
and Antonio D. Polosa

The new sensation: doubly heavy baryons

M. Savage, M. B. Wise, PL**B 248**,1990;
N. Brambilla, A. Vairo and T. Rosch, PRD **72,** 2005; T. Mehen, arXiv:1708.05020v3

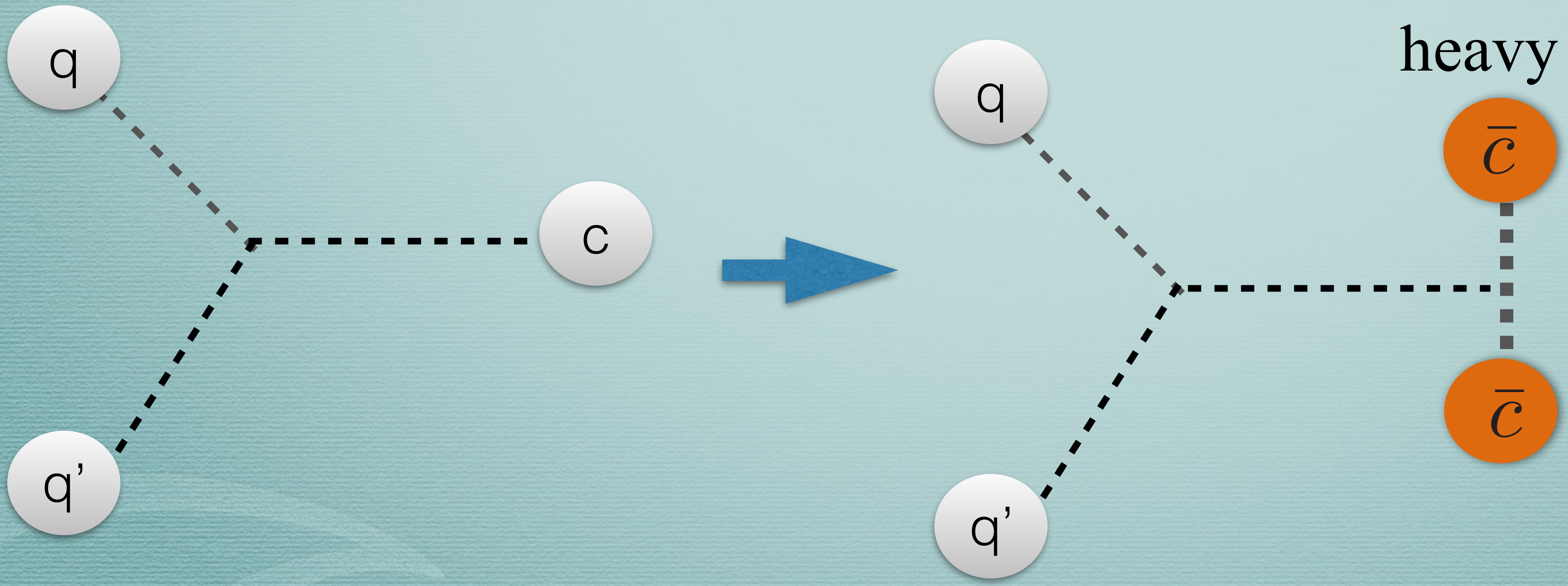


- Doubly heavy baryons are related to single quark heavy mesons
- QCD forces are mainly spin independent, so there is an approximate symmetry relating masses of DH baryons to SH mesons: e.g.

$$M(\Xi^*_{cc}) - M(\Xi_{cc}) = \frac{3}{4}[M(D^*) - M(D)]$$

similarly: single heavy quark baryons….

…. are related to doubly heavy tetraquark



Esposito, M. Papinutto, A. Pilloni, A. D. Polosa, and N. Tantalo, Phys. Rev. D88, 054029 (2013)
M. Karliner and J. L. Rosner, arXiv:1707.07666 [hep-ph].
E. J. Eichten and C. Quigg, arXiv:1707.09575 [hep-ph].

Double Beauty tetraquarks may be stable for strong decays

predicted :
M. Karliner and J. L. Rosner, arXiv:1707.07666 [hep-ph].
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- Q-value for the decay $T_{bb} \to BB\gamma$ ***is negative***, as confirmed by different calculations!
- only allowed: weak decays of constituent quarks

$QQ'\bar{u}\bar{d}$	Q. Model(K&R)	Q. Model(E&Q)	Lattice	Born-Oppen$^{(a)}$
$cc\bar{u}\bar{d}$	$+140$	$+102$	$-23 \pm 11^{(*)}$	0
$cb\bar{u}\bar{d}$	~ 0	$+83$	$+8 \pm 23^{(**)}$	-64
$bb\bar{u}\bar{d}$	-170	-121	$\begin{bmatrix} -143 \pm 34^{(*)} \\ -143(1)(3)^{(**)} \end{bmatrix}$	-141

(*) Junnarkar et al. arXiv:1810.12285, (**) A. Francis arXiv:1810.10550, arXiv:1607.05214;
(a) L. Maiani, M. Polosa, V. Riquer, PR **D** 100, 014002 (2019). See Exotic Workshop@TDLI

- ***confirmed*** by Lattice QCD and Born-Oppenheimer calculations.

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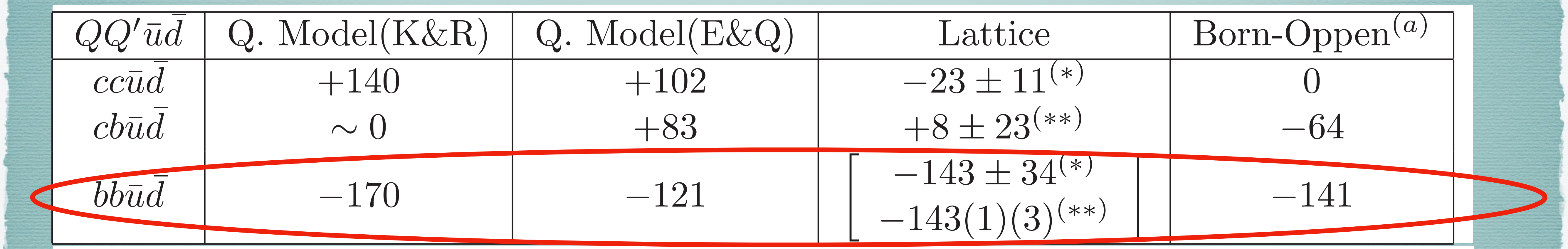

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(*) Junnarkar et al. arXiv:1810.12285, (**) A. Francis arXiv:1810.10550, arXiv:1607.05214;
(a) L. Maiani, M. Polosa, V. Riquer, PR **D** 100, 014002 (2019). See Exotic Workshop@TDLI

- ***confirmed*** by Lattice QCD and Born-Oppenheimer calculations.

Double Beauty tetraquarks may be stable for strong decays

predicted :
M. Karliner and J. L. Rosner, arXiv:1707.07666 [hep-ph].
E. J. Eichten and C. Quigg, arXiv:1707.09575 [hep-ph].

- Q-value for the decay $T_{bb} \to BB\,\gamma$ ***is negative***, as confirmed by different calculations!
- only allowed: weak decays of constituent quarks

$QQ'\bar{u}\bar{d}$	Q. Model(K&R)	Q. Model(E&Q)	Lattice	Born-Oppen$^{(a)}$
$cc\bar{u}\bar{d}$	$+140$	$+102$	$-23 \pm 11^{(*)}$	0
$cb\bar{u}\bar{d}$	~ 0	$+83$	$+8 \pm 23^{(**)}$	-64
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- ***confirmed*** by Lattice QCD and Born-Oppenheimer calculations.
- Cross sections may not be so forbidding: doubly charmed baryons have been observed at LHC and bb pairs observed at LEP.

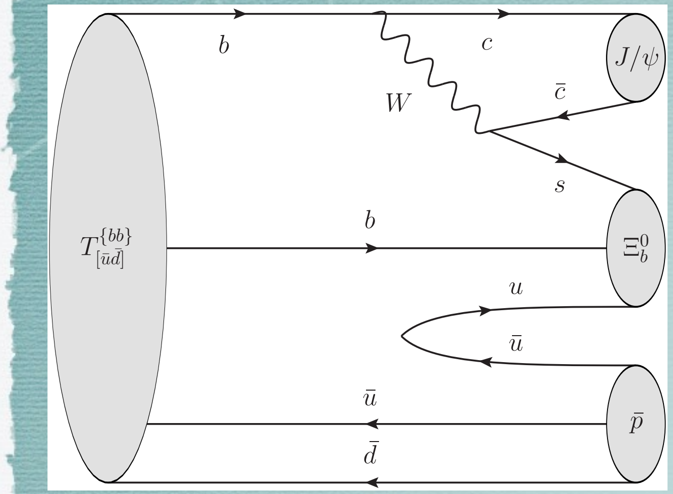
$$\mathcal{B}(Z^0 \to b\bar{b}b\bar{b}) = (3.6 \pm 1.3) \times 10^{-4}\ \text{(LEP)}$$
$$\mathcal{B}(Z^0 \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + X) = (1.4^{+1.1}_{-0.5})\ 10^{-6}$$

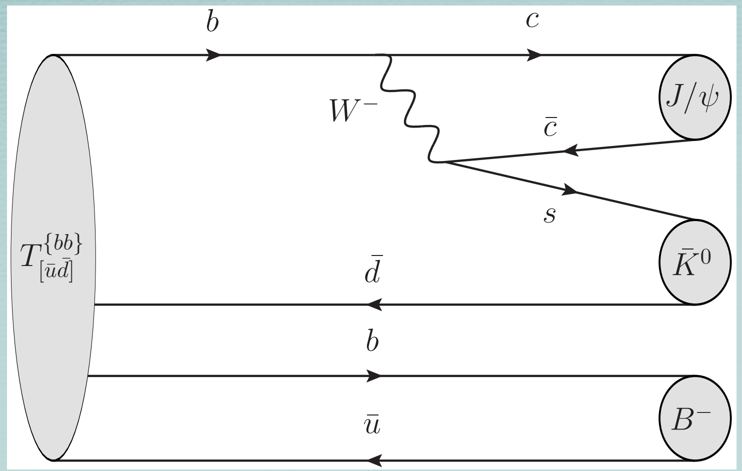
$$\frac{\mathcal{B}(Z \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + X)}{\mathcal{B}\left(Z \to (\Xi^0_{bb}, \Xi^-_{bb}, \Omega^-_{bb}) + X\right)} \sim 1:6$$

A. Ali and coll., DESY 18-061 years after

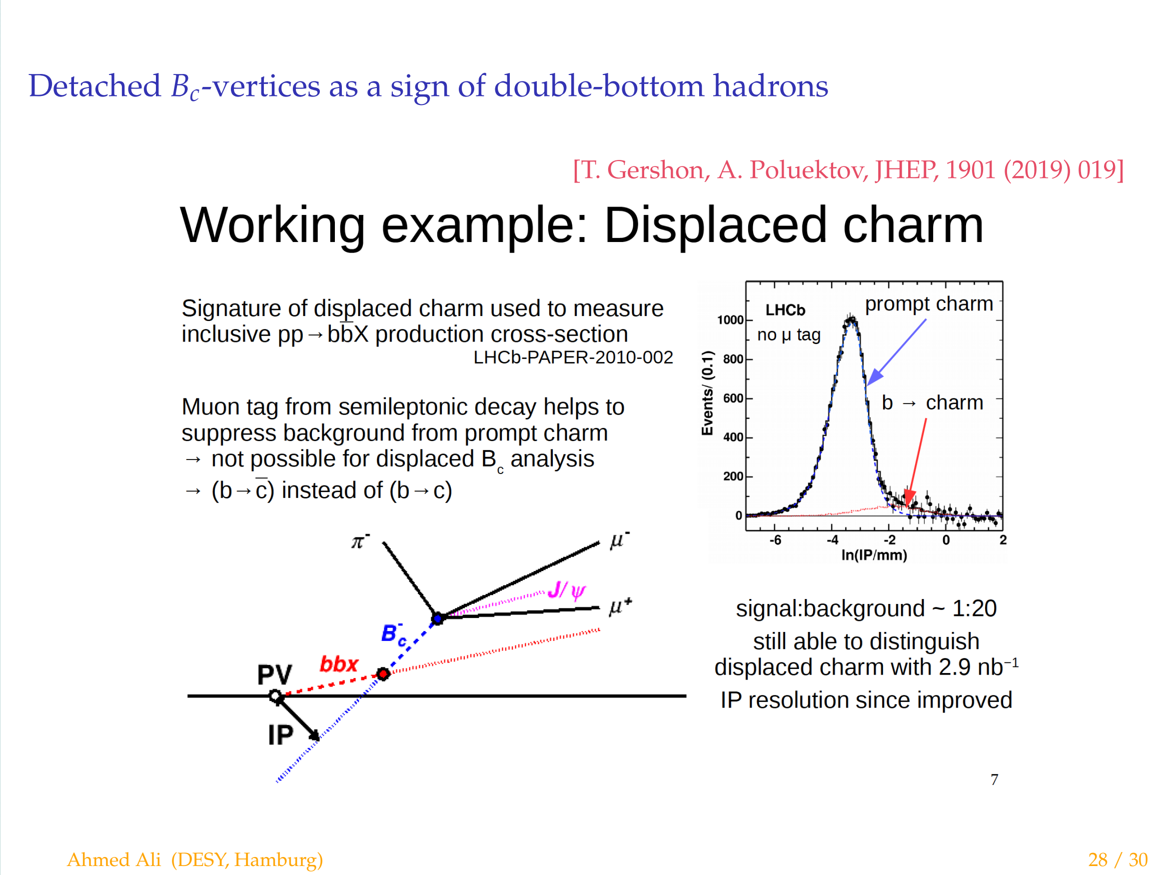
spectacular weak decays!

$$T^{(bb)}_{[\bar{u}d]} \to J/\Psi \; \Xi^0_b \; p \qquad\qquad T^{(bb)}_{[\bar{u}d]} \to J/\Psi \; K^0 \; B^-$$





- LHC-High Energy
- Tera Z factory (FCC-ee, CepC) ?



Detached B_c-vertices as a sign of double-bottom hadrons

[T. Gershon, A. Poluektov, JHEP, 1901 (2019) 019]

Working example: Displaced charm

Signature of displaced charm used to measure inclusive pp → bbX production cross-section
LHCb-PAPER-2010-002

Muon tag from semileptonic decay helps to suppress background from prompt charm
→ not possible for displaced B_c analysis
→ (b → $\bar{c}$) instead of (b → c)

signal:background ~ 1:20
still able to distinguish displaced charm with 2.9 nb^{-1}
IP resolution since improved

7

Ahmed Ali (DESY, Hamburg)

28 / 30

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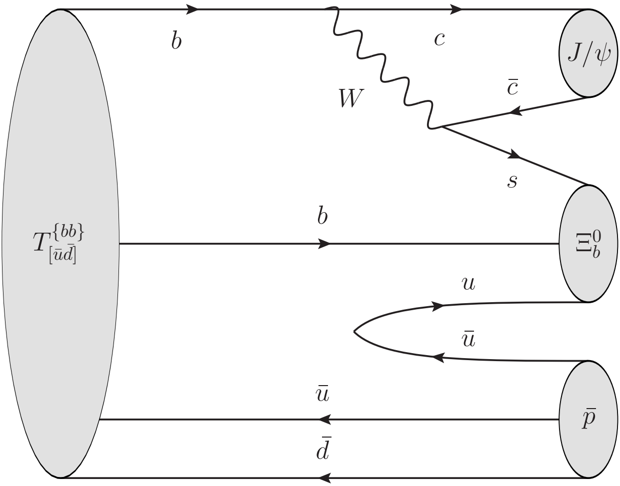

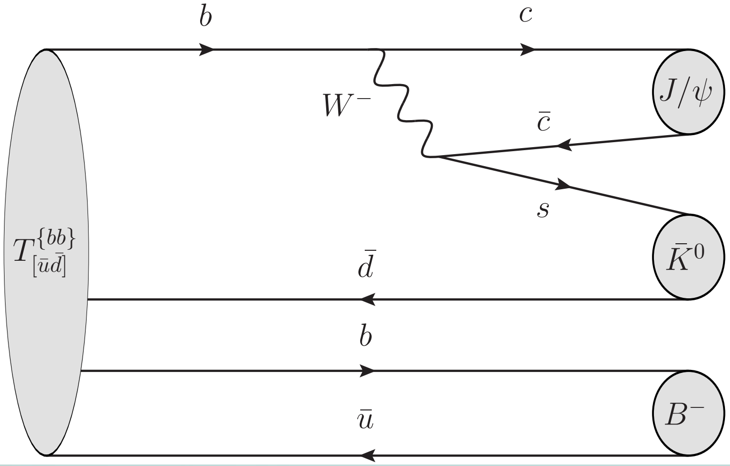

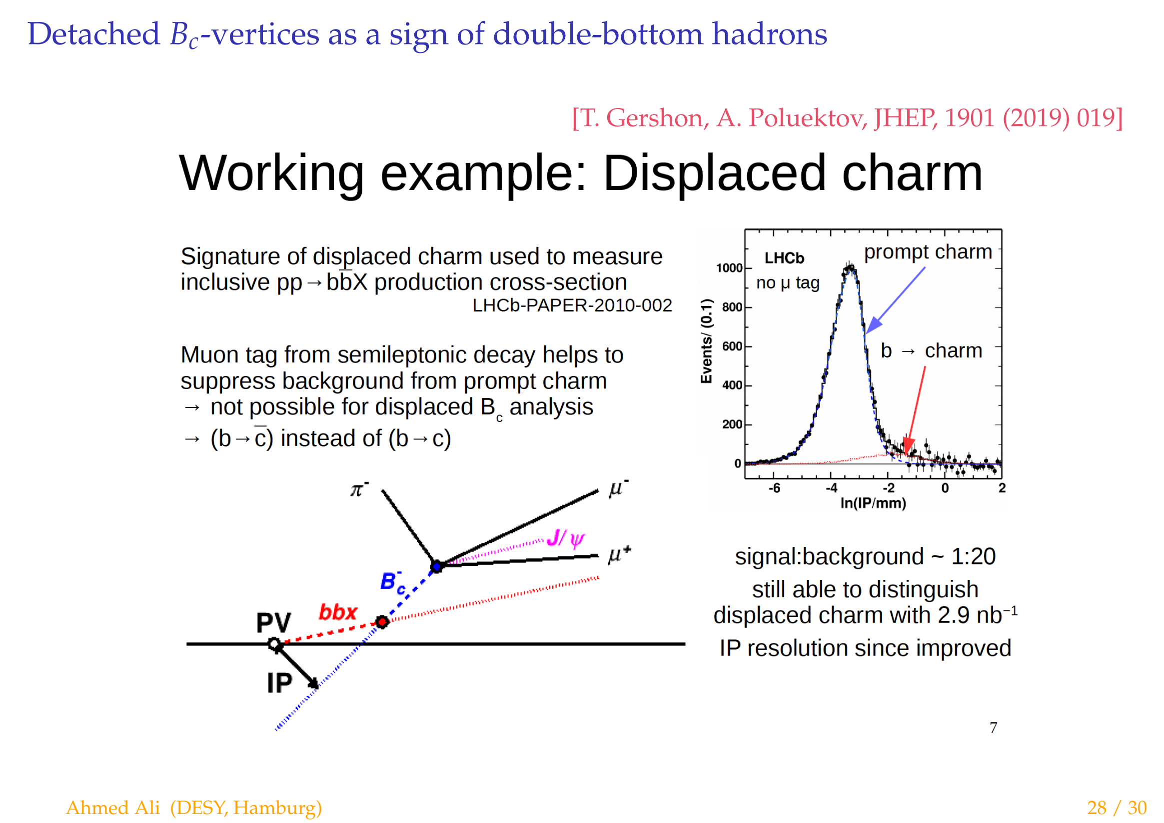
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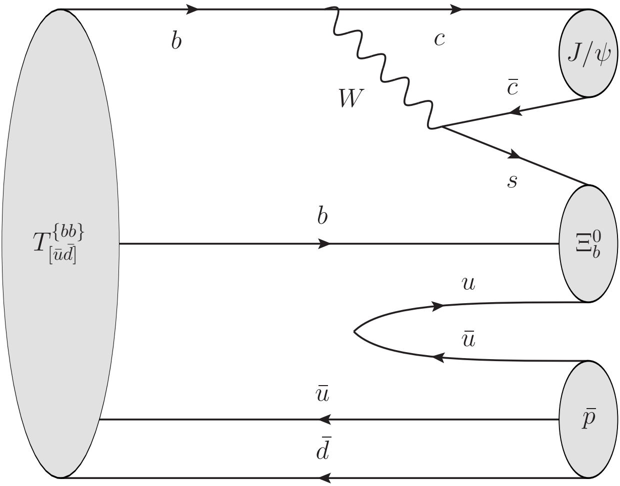

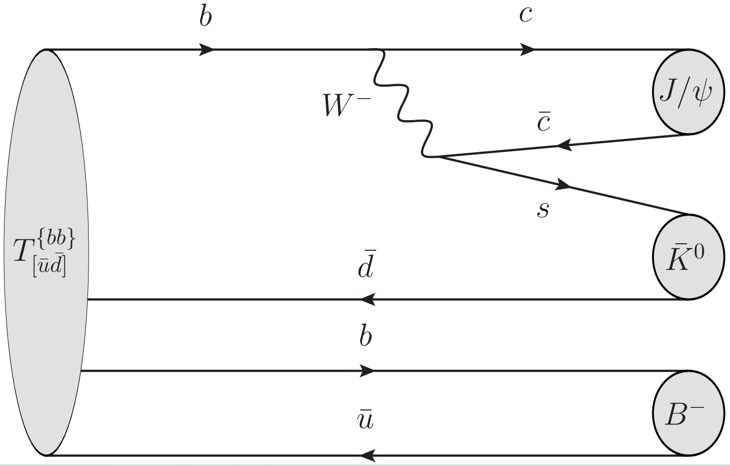

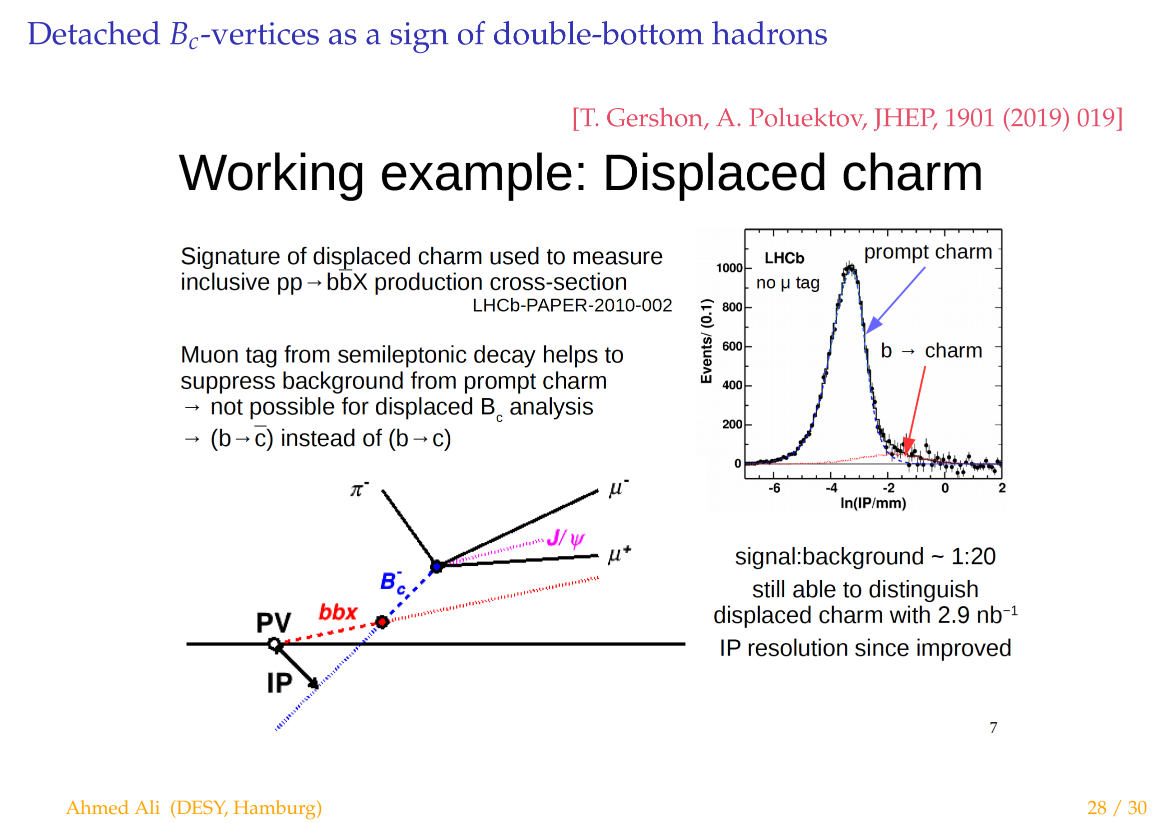

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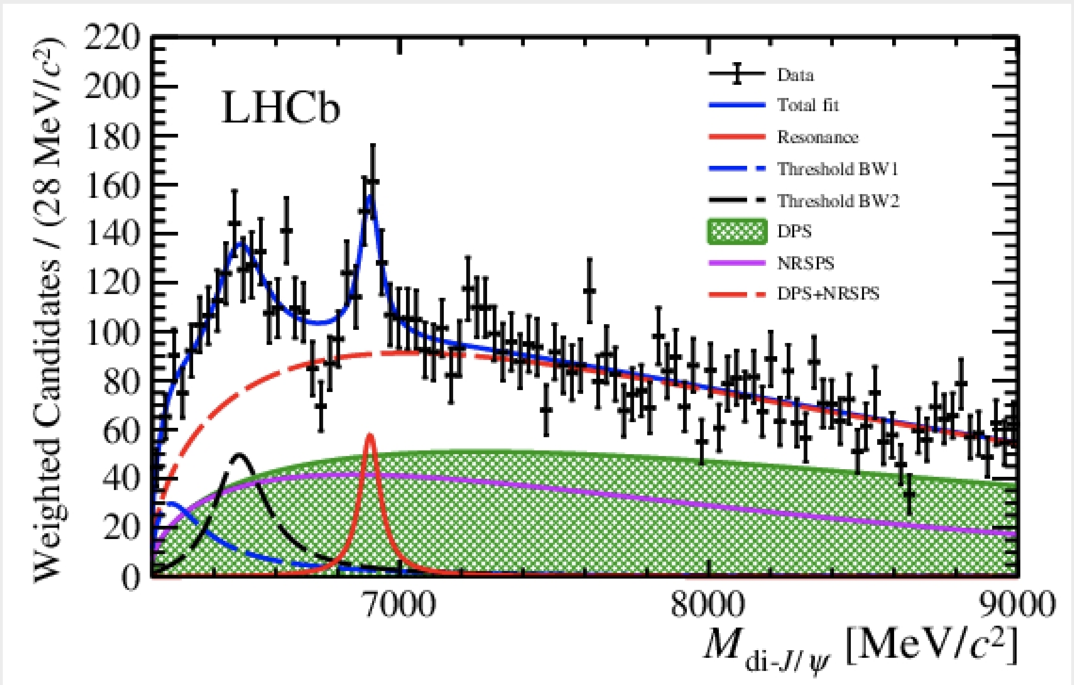
A new territory for experiments
and for non perturbative methods in QCD

27

A game changer! LHCb has observed J/ψ- pair resonances (June 2020)



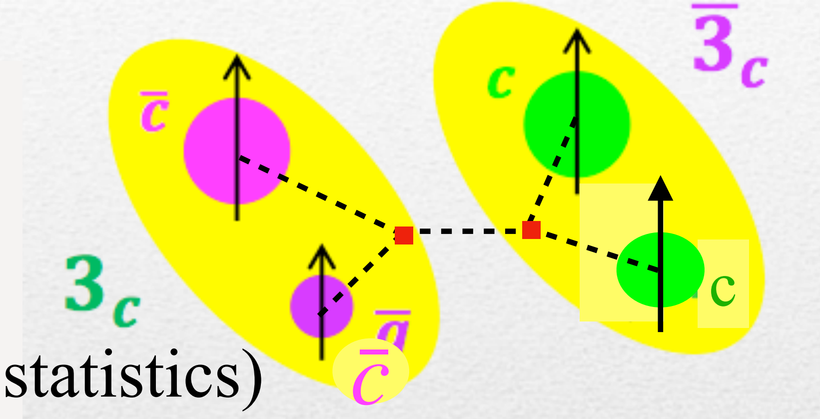
R. Aaij, C. Abellan Beteta, T. Ackernley, et al. (LHCb Collaboration). Observation of structure in the J/ψ pair mass spectrum. arXiv:2006.16957, 2006 Sci. Bull. 2020, 65.

Little doubt that these resonances are tetraquarks

Tetraquark constituent picture of di-J/Ψ resonances

$$[cc]_{S=1}[\bar{c}\bar{c}]_{S=1}$$

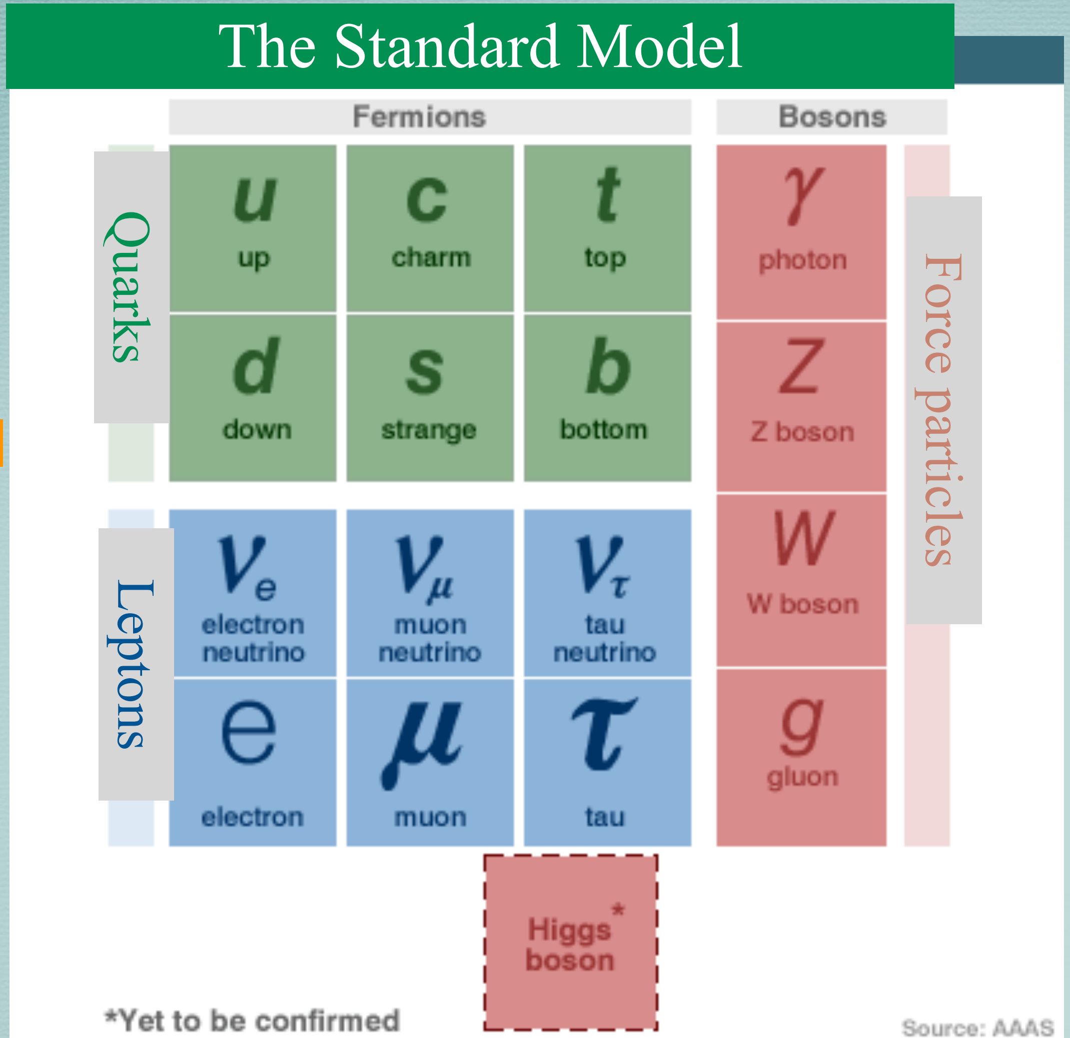
- [cc] in color $\bar{\mathbf{3}}$
- total spin of each diquark, S=1 (color antisymmetry and Fermi statistics)



production and decays: C. Becchi, et al, Phys.Lett.B 811 (2020) 135952

5. Constituents of matter and fundamental forces (circa 2016)

Murray Gell-Mann



The Standard Model

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force particles
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	

Higgs boson*

*Yet to be confirmed

Source: AAAS

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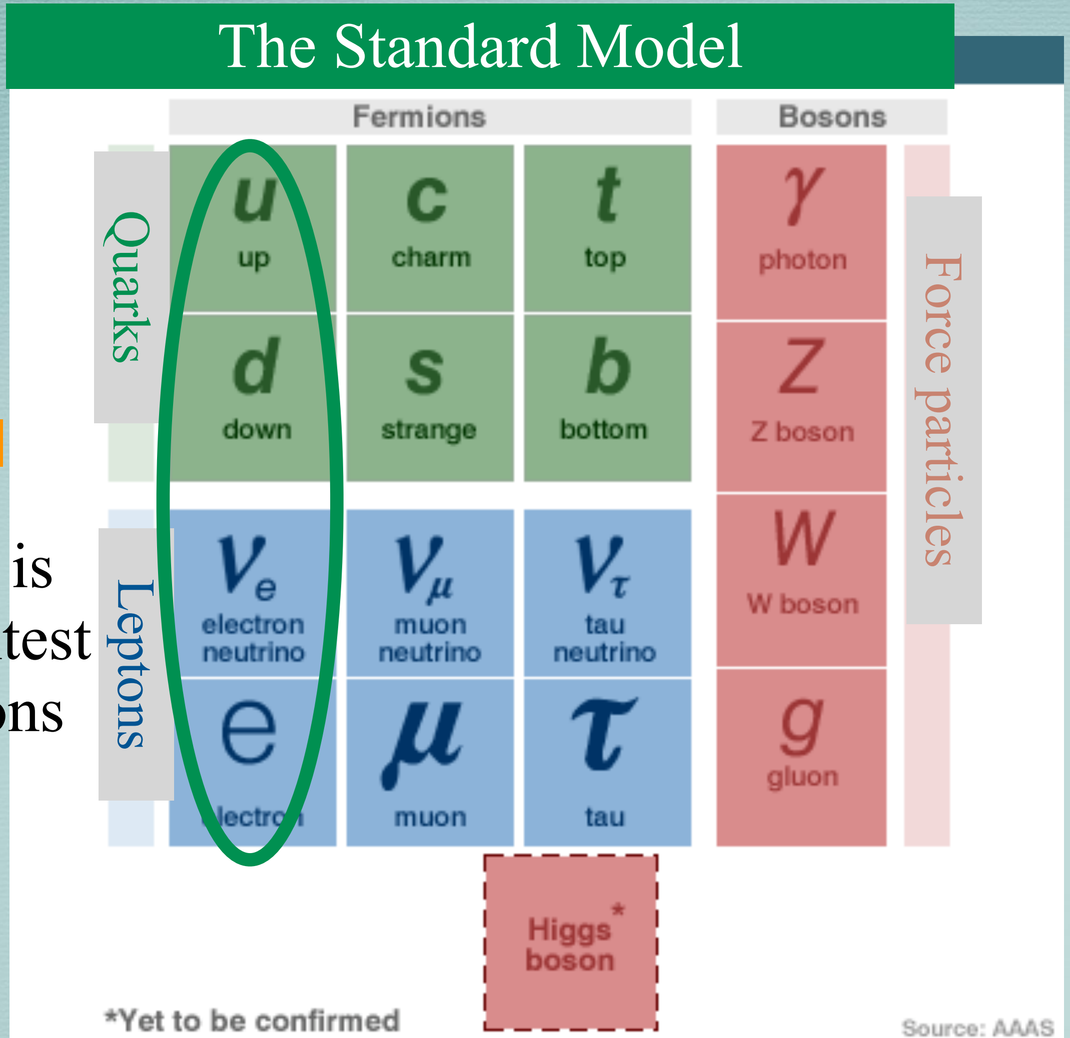
Ordinary matter is made of the lightest quarks and leptons



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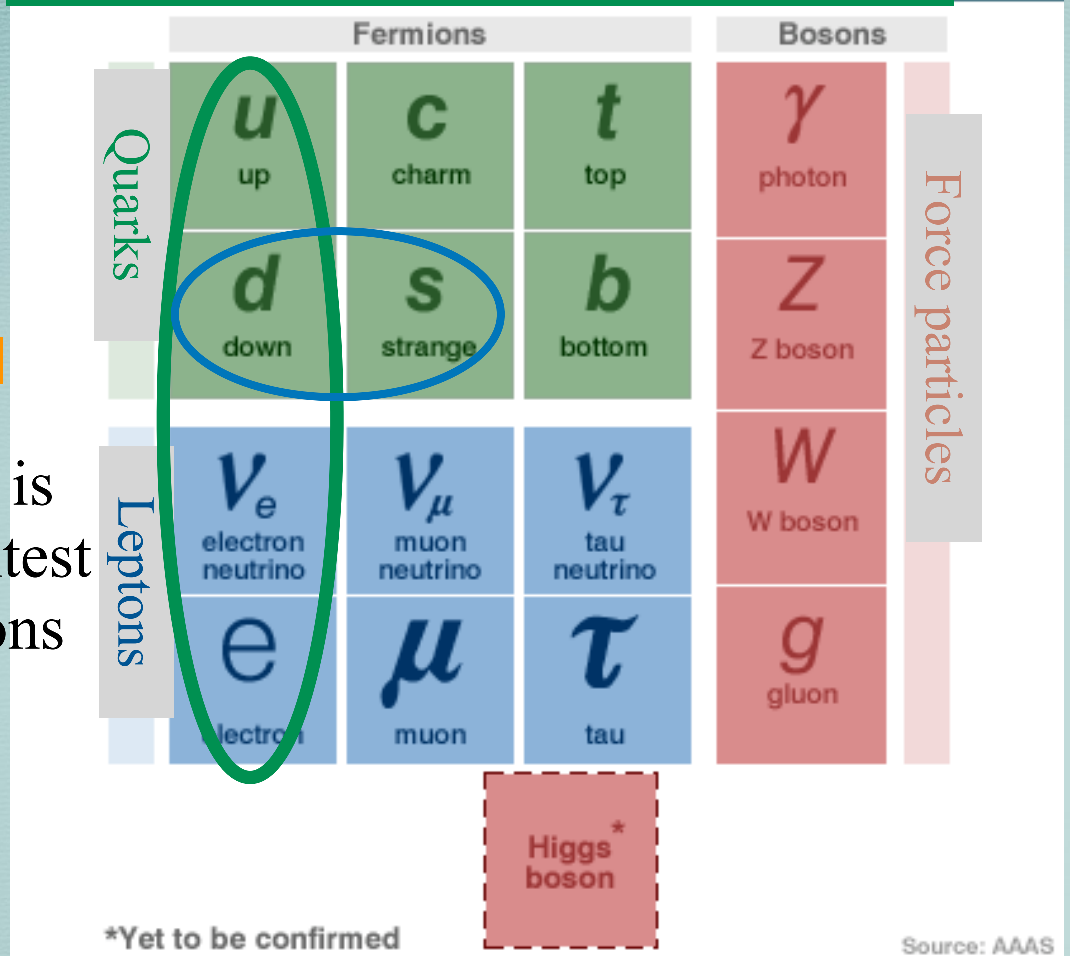

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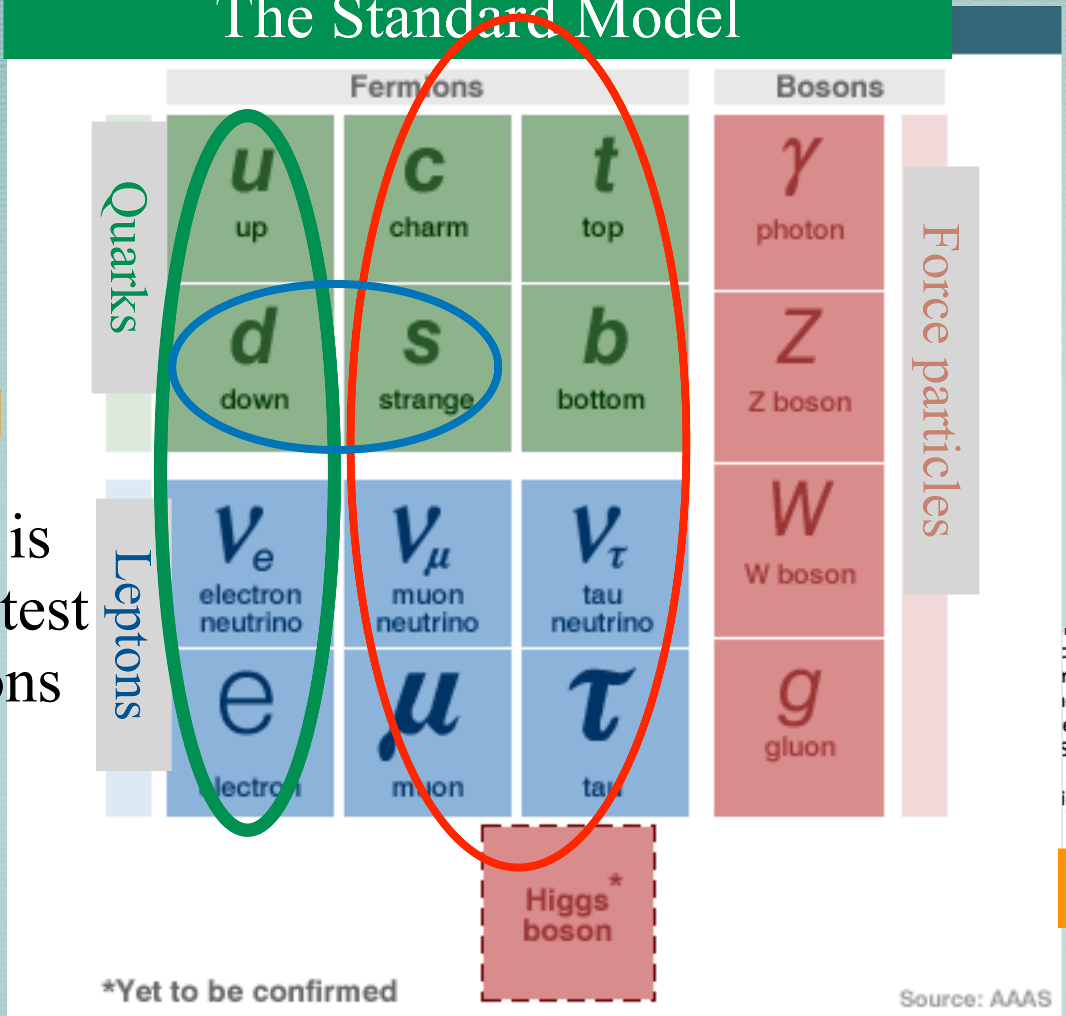

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Heavier quarks are unstable: what is their role in the Universe?

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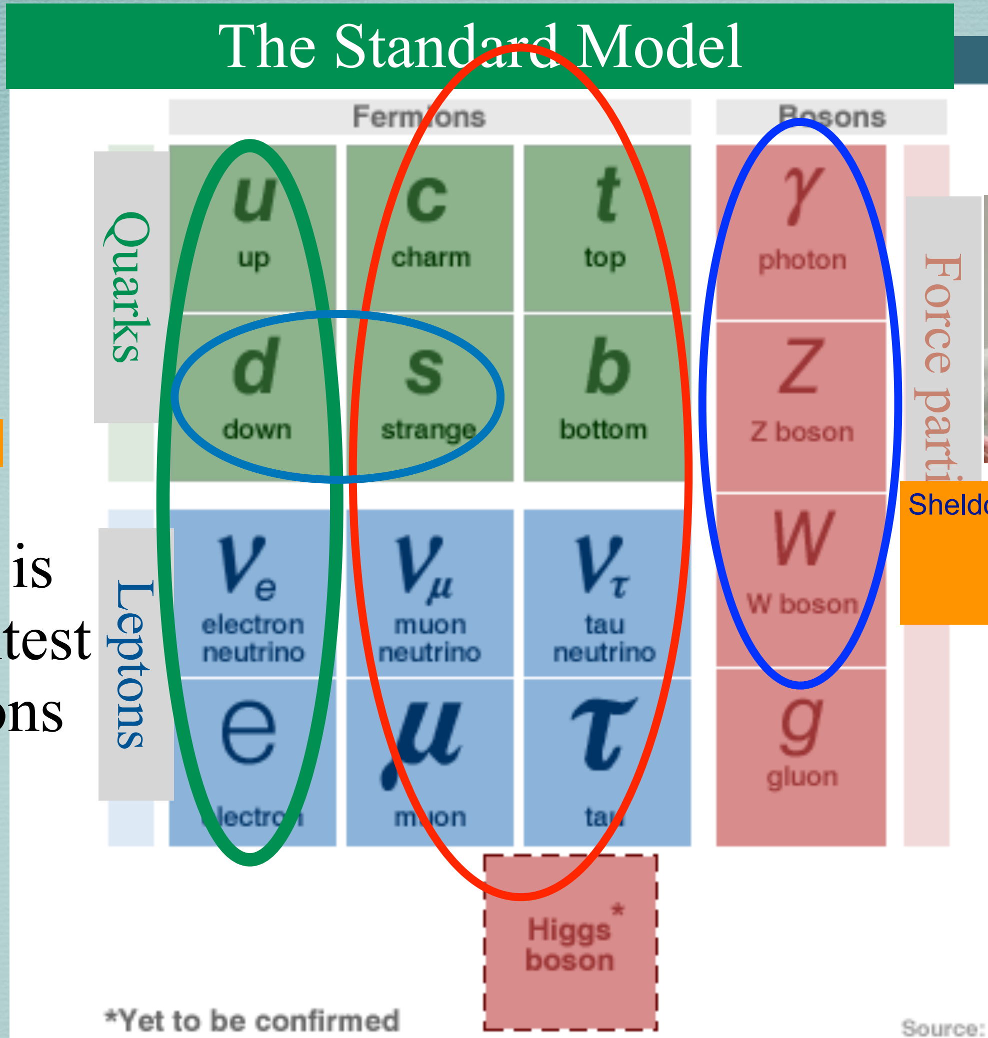

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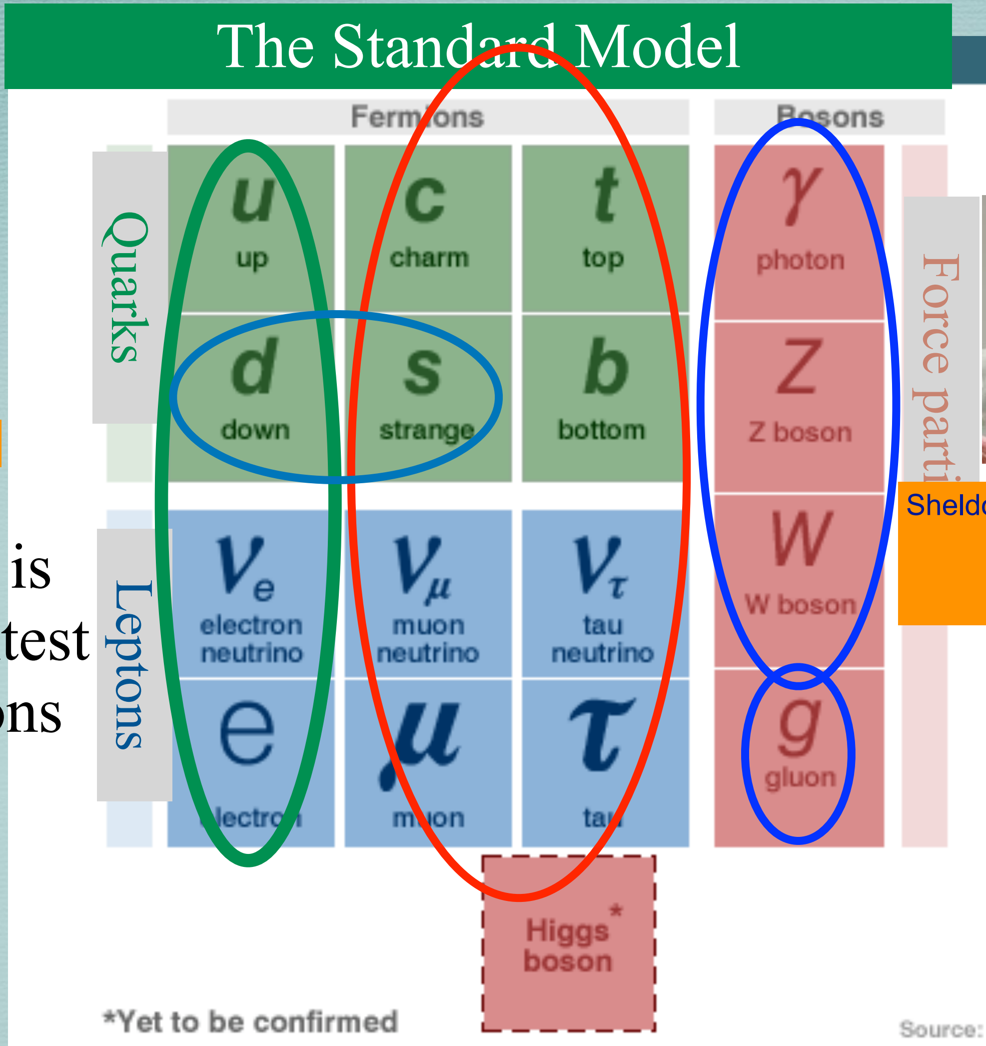

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Strong interactions between quarks are mediated by neutral vector mesons (gluons) coupled to color, and are asymptotically free
Gross&Wilczeck, Politzer (1973)

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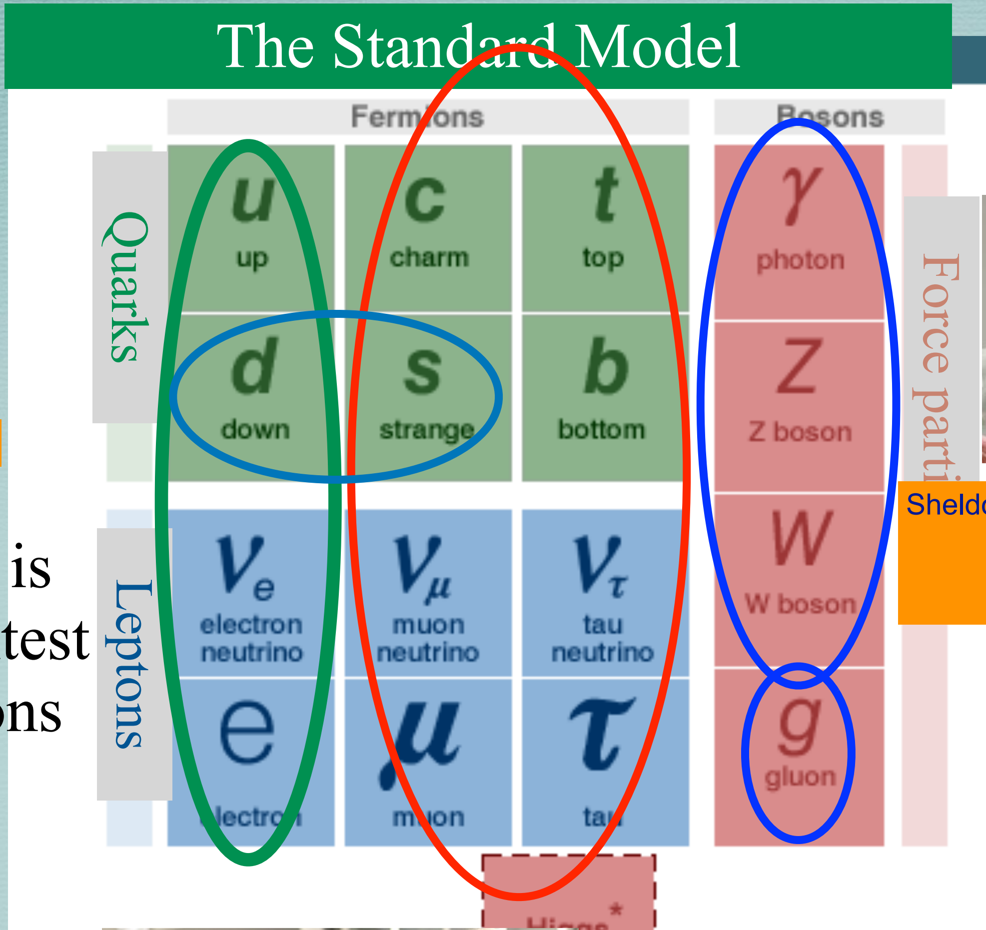

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Summing Up

- It has been a pleasure to come back to old memories.
- 50 years after, GIM is alive and well
- it is an efficient tool to search for flavour changing processes beyond the Standard Theory:

$$K^+ \to \pi^+ \nu \bar{\nu};\ K_L \to \pi^0 \nu \bar{\nu}, B_d \to \mu^+ \mu^-;\ b \to s\gamma;$$

$$\mu \to e\gamma;\ \mu + N \to e + \cdots$$

- due to QCD, heavy quarks are a good indicators of the dynamics of hadron spectroscopy
- weakly decaying doubly heavy tetraquarks anticipated at future colliders;
- fully charm tetraquarks discovered: amenable to a theoretical description? a second charmonium ?

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Thank You !