Martinelli '70

Accademia dei Lincei. Roma

26 Settembre 2022

Weak interactions on the lattice with Guido

Luciano Maiani

Sapienza and CERN

1976 Polyakov Meeting
Bohr Institute. Copenhagen
Courtesy of Paolo di Vecchia

Born in Napoli, 1952, graduated in Physics at Sapienza Univ. in 1975, research associate at Laboratori Nazionali di Frascati dell'INFN (1977-87) and, from 1988, full professore in Theoretical Physics at Sapienza University of Roma.

At Universita La Sapienza in Roma:
Director of the Physics Dept., 2007- 2010, President of Ateneo della Scienza e della Tecnologia della Sapienza.

Guido has been Director of *Scuola Internazionale Superiore di Studi Avanzati* (SISSA), Trieste, 2010-2015, has chaired the *Commissione Scientifica Nazionale Fisica Teorica* of INFN, has been member of *Scientific Policy Committee*, CERN, and President of *Comitato Consultivo dell'ANVUR* (designated by ERC).

Guido Martinelli

FOLLOW

Professor of Theoretical Physics La Sapienza Roma Italy
Verified email at roma1.infn.it - Homepage
Theoretical physics

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TITLE	CITED BY	YEAR
A general method for non-perturbative renormalization of lattice operators G Martinelli, C Pittori, CT Sachrajda, M Testa, A Vladikas Nuclear Physics B 445 (1), 81-105	1087	1995
Leptonic decay of heavy flavors: A theoretical update G Altarelli, N Cabibbo, G Corbo, L Maiani, G Martinelli Nuclear Physics B 208 (3), 365-380	1084	1982
Large perturbative corrections to the Drell-Yan process in QCD G Altarelli, RK Ellis, G Martinelli Nuclear Physics B 157 (3), 461-497	1060	1979
Chiral symmetry on the lattice with Wilson fermions M Bochicchio, L Maiani, G Martinelli, G Rossi, M Testa Nuclear Physics B 262 (2), 331-355	717	1985
The ΔS= 1 effective Hamiltonian including next-to-leading order QCD and QED corrections M Ciuchini, E Franco, G Martinelli, L Reina Nuclear Physics B 415 (2), 403-459	711	1994
Vector boson production at colliders: a theoretical reappraisal G Altarelli, RK Ellis, M Greco, G Martinelli Nuclear Physics B 246 (1), 12-44	638	1984
Model-independent constraints on ΔF= 2 operators and the scale of new physics M Bona, M Ciuchini, E Franco, V Lubicz, G Martinelli, F Parodi, M Pierini, ... Journal of High Energy Physics 2008 (03), 049	602	2008
Leptoproduction and Drell-Yan processes beyond the leading approximation in chromodynamics G Altarelli, RK Ellis, G Martinelli Nuclear Physics B 143 (3), 521-545	573	1978
2000 CKM-triangle analysis a critical review with updated experimental inputs and theoretical parameters M Ciuchini, V Lubicz, G D'Agostini, E Franco, G Martinelli, F Parodi, ... Journal of High Energy Physics 2001 (07), 013	558	2001

only 500+

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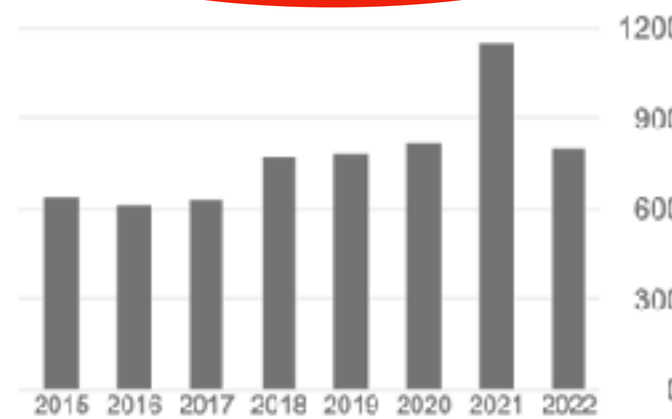

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Based on funding mandates

1. Charm semileptonic decay (1982)

- The charm quark mass is definitely larger than Λ_{QCD}, the invariant mass of the hadronic final system is also $>>\Lambda_{QCD}$, and we can use parton model + perturbative QCD to compute the semileptonic width and the energy spectrum of the emerging charged lepton.

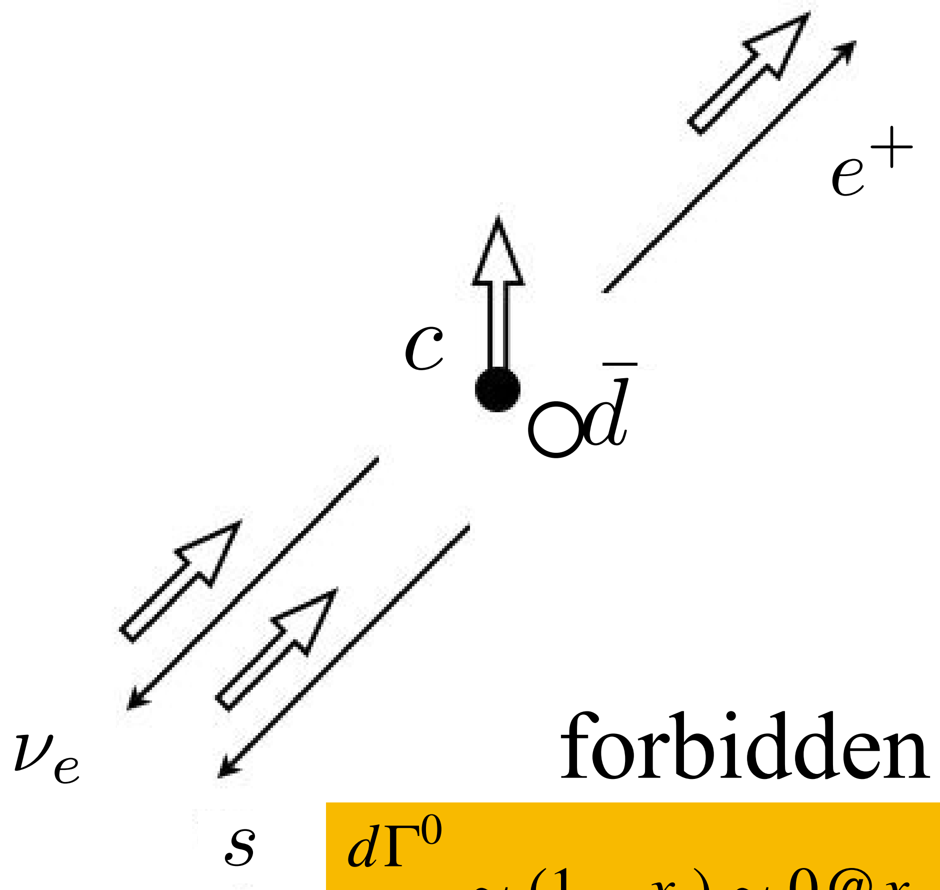
- While in Paris, Cabibbo and myself worked out the semileptonic rate of the charm quark (1978) and later (with G. Corbo') the electron energy spectrum.

- After discovery of the b quark, with even a larger mass, we thought our formulae for the energy lepton spectrum near the end point could be used to determine the Cabibbo-Kobayashi-Maskawa matrix element V_{ub}, not determined by the total rate (dominated by the $b \to c$ transition).

- Paolo Franzini (then still in Cornell with CLEO) observed however that the lepton end point in b decay corresponds to small hadron masses and therefore non perturbative QCD corrections come in.

Semileptonic decays of c vs. b quarks

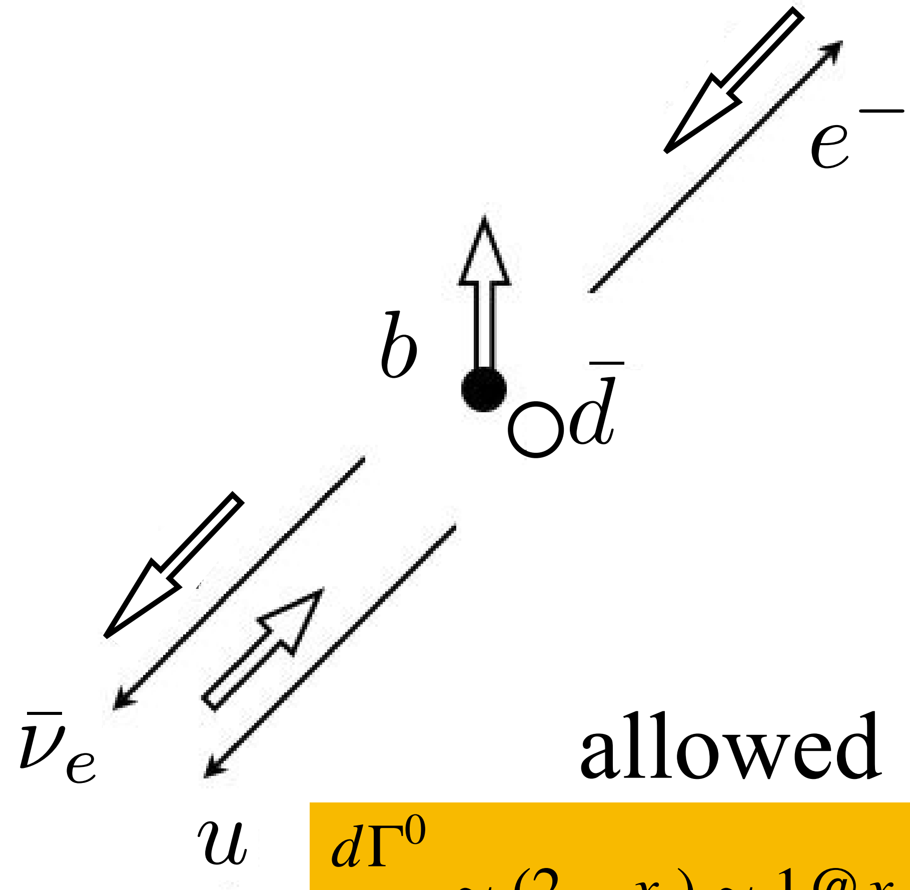
Charged lepton energy end point configurations in c and b decay



forbidden

$$\frac{d\Gamma^0}{dx_e} \sim (1 - x_e) \sim 0 \,@\, x_e \to 1$$

charm decay is dominated by inelastic, large mass, hadron configurations: perturbative QCD corrections are adequate.



allowed

$$\frac{d\Gamma^0}{dx_e} \sim (2 - x_e) \sim 1 \,@\, x_e \to 1$$

beauty decay is dominated by small mass, hadron configurations: resummation of perturbative QCD corrections is required.

QCD experts get in

- The two Guidos, Altarelli and Martinelli, came in, with the crucial resummation of the perturbative terms and the result provided a valuable (and much used) tool in the estimate of V_{ub} from inclusive rates:

G. Altarelli, N. Cabibbo, G. Corbo, L. Maiani and G. Martinelli, *Leptonic Decay of Heavy Flavors: A Theoretical Update*, Nucl. Phys. B 208 (1982) 365.

- The other side of the story:

an alternative method is to obtain V_{ub} from ***exclusive rates*** provided by the lattice computation of the the form factor of B meson → light flavoured vector meson.

Inclusive average:
$|V| = (4.25 \pm 0.12^{+0.15}_{-0.14} \pm 0.23) \times 10^{-3}$
Lattice QCD: $|Vub| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3}$
see:
Ceccucci (CERN), Z. Ligeti (LBNL), Y. Sakai (KEK)
CKM Quark-Mixing Matrix (PdG 2021)

2. Weak Interactions on the Lattice (1984)

- After Ken Wilson's papers, early lattice QCD work was focussed on the calculation of the hadron spectrum.
- Exceptional work was done in Italy, starting from conception and realization of the APE supercomputer (N. Cabibbo, G.Parisi and coll.)
- An example of the preparatory work done in Italy for hadron spectroscopy is:

Hadron spectroscopy in lattice QCD

F Fucito, G Martinelli, C Omero, G Parisi, R Petronzio, F Rapuano

Nuclear Physics B 210 (3), 407-421 (1982)

- Cabibbo, Martinelli and Petronz started a new turn in 1983: a lattice QCD calculation of mesonic matrix elements of four-quark operators

Weak interactions on the lattice

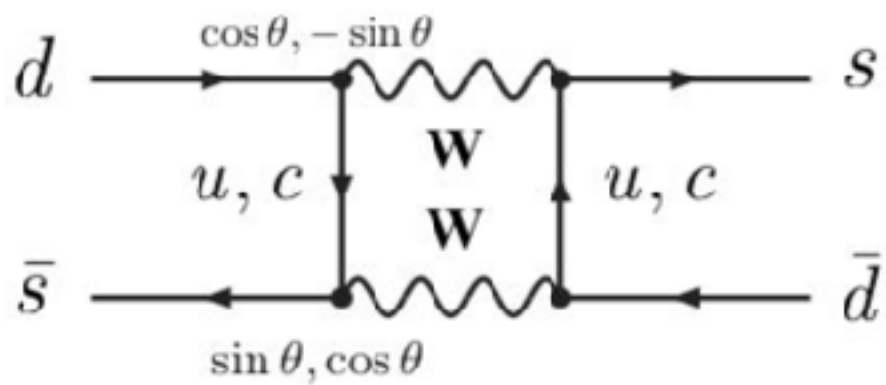
N Cabbibo, G Martinelli, R Petronzio Nuclear Physics B 244 (2), 381-391 (1984)

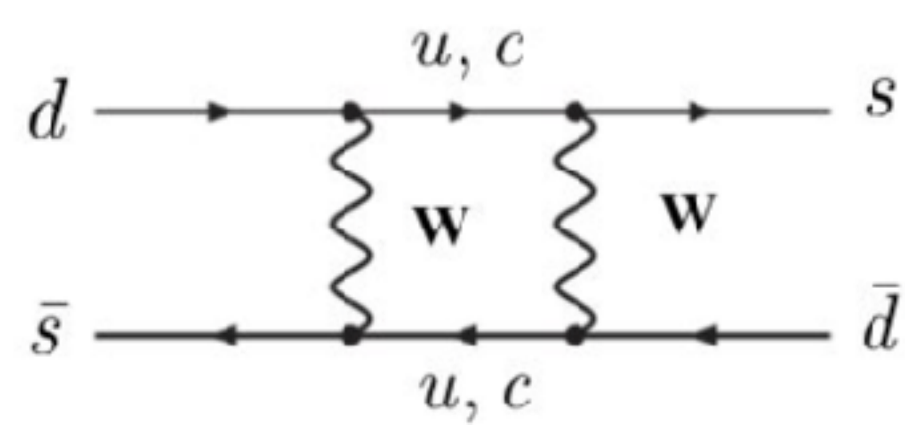
A long story, going back to the works of Ioffe & Shabalin, Low…the GIM Mechanism…

- Ioffe and Shabalin
- F. Low (1967-1968)

$$m_{K_1} - m_{K_2} = \frac{1}{2m_K}\left(\frac{G}{\sqrt{2}}\right)^2 \frac{\Lambda^2}{8\pi^2}\langle K^0 \,|\, j_\mu^{K^0}(0) j_\mu^{K^0}(0) \,|\, \overline{K^0} \rangle,$$

- GIM (1970)





$$\Lambda^2 \sim m_c^2;\;\; j_\mu \cdot j_\mu = (\bar{s}\gamma_\mu(1-\gamma_5)d)(\bar{s}\gamma^\mu(1-\gamma_5)d);$$

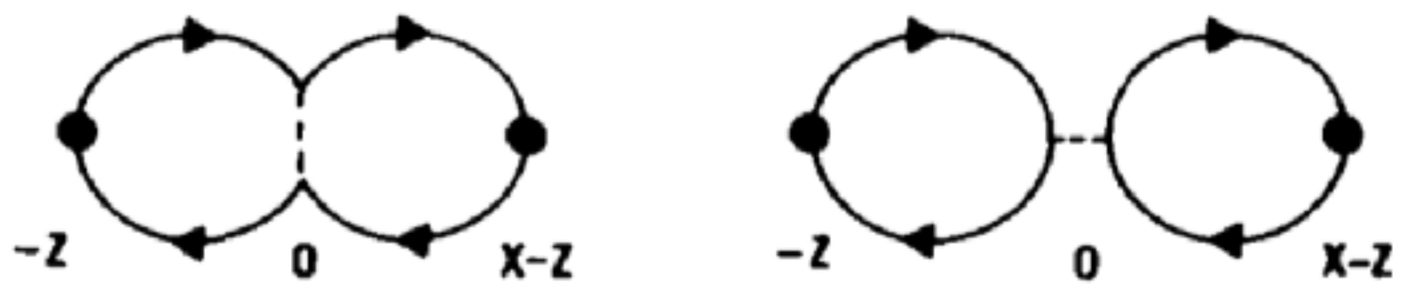
- Gaillard & Lee (1974): Vacuum saturation

$$< K^0 \,|\, (\bar{s}\gamma_\mu(1-\gamma_5)d)(\bar{s}\gamma^\mu(1-\gamma_5)d) \,|\, \bar{K}^0 > \propto f_K^2 m_K^2$$

What you have to put on the lattice…and CMP result

- The operator in the origin of coordinates
- propagators from origin to anywhere

$$\pm \sum_{y,z} \langle \mathrm{Tr}\, \{ S(-z) S^{+}(-z) \gamma^{\mu}_{L,R} S(y) S^{+}(y) \gamma^{\mu}_{L} \} \rangle_{U} \delta(y_0 + z_0 - t)$$



(a) (b)

CMP:

As a second test we have evaluated the $K_0 - \bar{K}_0$ matrix element

$$\frac{\langle K_0 | (\bar{s}\gamma_\mu (1-\gamma_5) d)(\bar{s}\gamma_\mu (1-\gamma_5) d) | \bar{k}_0 \rangle}{m^2} = (4a^2)(10 \pm 1) 10^{-2} \quad [\sim 7.7 \times 10^{-2}] .$$

Shifman, Vainstein, Zhakarov, vacuum saturation in QCD (1976)

Cabibbo, Martinelli, Petronzio (1983)

The fact that our results are close to those obtained by a well-accepted approximation scheme is a clear indication of the validity of the method.

An exciting program for non-leptonic weak interactions

Cabibbo, Martinelli, Petronzio (1983): **We are confident that our method can lead to an accurate determination of matrix elements which are essential for the theoretical predictions of important physical quantities, such as $\Delta T = \frac{3}{2}$ rates for K meson decays and $K - \bar{K}$ mixing, including *CP* violation. A new method is, however, required for a full evaluation of the $O_{5,6}$ matrix elements.**

New groups got into the game

C. W. Bernard, T. Draper, A. Soni, H. D. Politzer and M. B. Wise,
Chiral Perturbation Theory and the $\Delta I = 1/2$ Rule, UCLA/84/TEP/14, Calt 68-1211, (1984)
R. C. Brower, G. Maturana, M. Belen Gavela and R. Gupta,
Calculation of Weak Transitions in Lattice, Phys. Rev. Lett. **53** (1984), 1318

- Focus on chiral symmetry in lattice QCD:
- It is broken on the lattice by the Wilson term….

H. Nielsen, M. Nonomiya (1981)

- and so must it be…otherwise the singlet axial current in QCD could not be anomalous ($\pi^0 \to \gamma\gamma$!!!)
- but in the continuum limit ***chiral symmetry for non anomalous currents has to be recovered***. This was shown by the Roma group:

M. Bochicchio, L. Maiani, G. Martinelli, G. C. Rossi and M. Testa,
Chiral Symmetry on the Lattice with Wilson Fermions
Nucl. Phys. B **262** (1985), 331

Now: a fully fledged industry

Pseudoscalar meson couplings and non-leptonics

- During the 1980s, the decay constants of the pseudoscalar mesons, π, K, D, D_s have been successfully computed in Lattice QCD by the groups listed before, in particular by the Roma-Paris (Orsay)-Southampton group.
- A large effort by us and by the UCLA group (C. Bernard, A. Soni and coll.) went to lattice calculations of $K \to \pi$ non-leptonic decay amplitudes with $\Delta I = 3/2,\ 1/2$, following
  - the QCD renormalization group results (Lee and Gaillard, Altarelli and Maiani 1974)
  - the successive the penguin diagram analysis (Shifman, Vainstein and Zakharov)
  - the chiral symmetry prescriptions in Bochicchio et al and:
    - use the LG and AM hamiltonian at lattice level;
    - work with $a^{-1} > 2$ GeV i.e. dynamical charm quarks to justify the use of LG-AM hamiltonian (renormalised at a momentum scale $\mu >> m_c$;
    - let SVZ penguins develop non perturbatively by QCD interactions on the lattice:

L. Maiani, G. Martinelli, G. C. Rossi and M. Testa, Nucl. Phys. B **289** (1987), 505

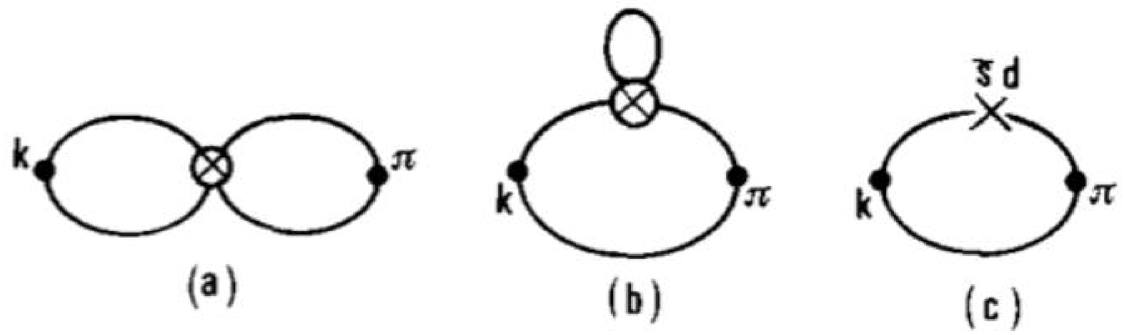


Fig. 2. The "eight" (a), "eye" (b), and counterterm (c) diagrams for K–π three-point correlations.

"eye" (b) develops the penguin
(c) is the counterterm to be added to obtain the physical penguin

non-leptonics (cont'd)

- We obtined very encouraging results for $\Delta I = 3/2,\ K^+ \to \pi^+\pi^0$ amplitude

$$\frac{< K|H_W|\pi^+\pi^0 >}{m_K} = (7 \pm 2) \cdot 10^{-8}$$

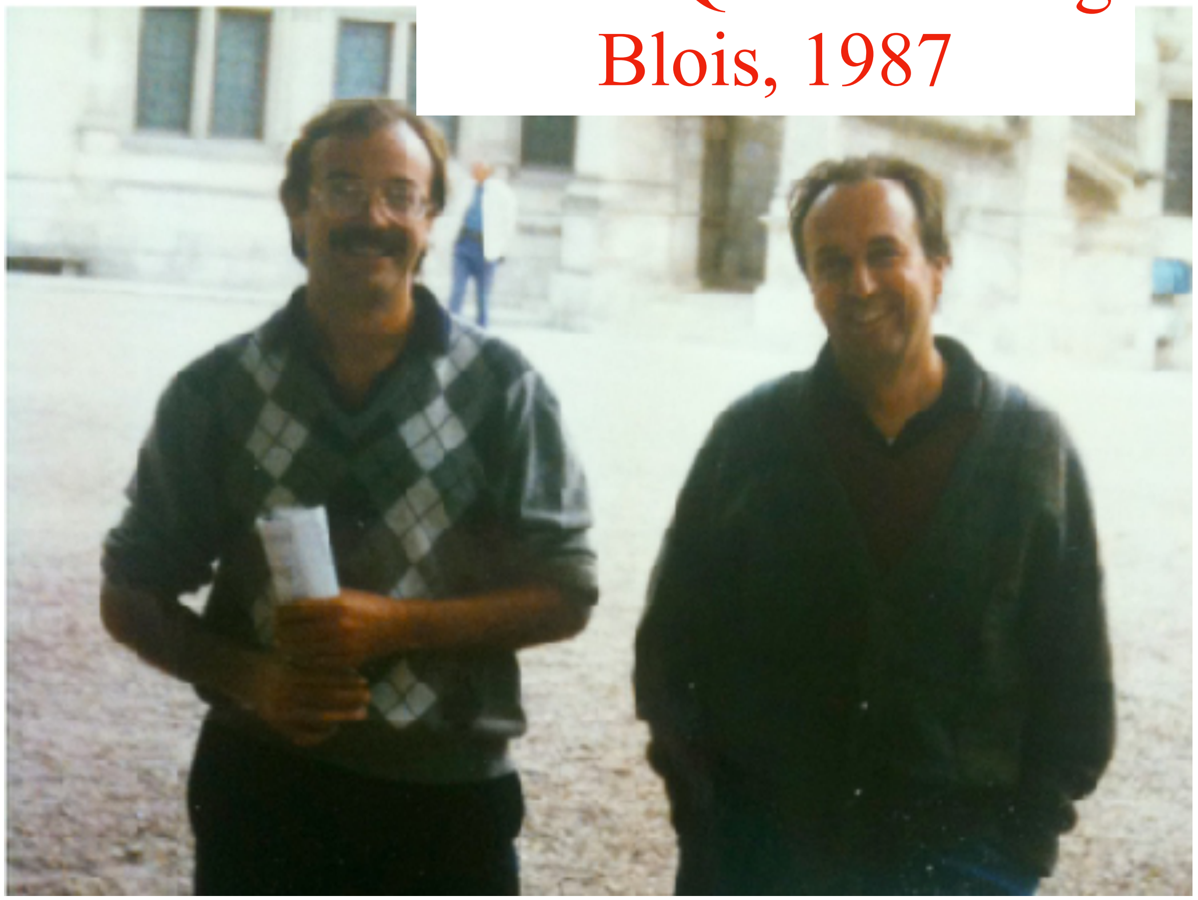
M. B. Gavela, L. Maiani, S. Petrarca, F. Rapuano, G. Martinelli, O. Pene, C. T. Sachrajda, Nucl. Phys. B **306** (1988) 677.

- to be compared with the experimental value of [expt: $3.7 \cdot 10^{-8}$]

- Preliminary results have been presented at the Blois Conference on Lattice QCD

M. B. Gavela, L. Maiani, S. Petrarca, G. Martinelli and O. Pene, *First Results for the Amplitude in K Decays, With Quenched Lattice QCD and Wilson Fermions*, Phys. Lett. B **211** (1988), 139

Lattice QCD Meeting
Blois, 1987



- However, high statistics is required for the non-perturbative subtractions needed to isolate the $\Delta I = 1/2,\ K \to \pi$ amplitude
- this made the calculation not possible with the then available computer power and we could not continue the program;
- our UCLA competitors, as well, could not make progresses on $\Delta I = 1/2$ amplitudes for a long time.

3. The pseudoscalar coupling of B mesons on the lattice (1991)

- In the calculations of the 1980s, the value of the inverse lattice spacing (a^{-1}) was generally taken between 1-3 GeV. Thus, on these lattices, it was not possible to simulate hadrons containing the b-quark ($m_b > a^{-1}$).

- An interesting technique for the study of heavy-quark physics on the lattice was proposed by E. Eichten and B. Hill (*Phys. Lett*. B **234** (1990), 511):
- expand the heavy-quark propagator in inverse powers of the quark mass and take the leading term, corresponding to propagation only along the time direction

$$\text{Action} = b^\dagger(i\partial_0 + gA_0)b$$

- coupling the static b to a fully dynamical light quark, it became possible to consider the local heavy-light axial current $A_0 = b^\dagger(x)\gamma_0\gamma_5 q(x)$ in Lattice QCD.
- To compute the pseudoscalar coupling f_B from the correlation function $G(x) = < A_0(x)A_0(0) >$, one has to isolate the one-particle intermediate state (i.e. the ground state B meson) and:

$$< 0 | A_0 | B > = f_B p_0$$

- The first calculation of f_B in the static limit was done by the Roma-Southampton group (Allton, Sachrajda, Lubicz, Maiani and Martinelli) on a lattice with $a^{-1} = 2$ GeV with the surprising result

$$310 \pm 25 \pm 50 \text{ MeV}$$

with $f_B > f_D$, contrary to expectation.

f_B , M_{top} and $\sin 2\beta$

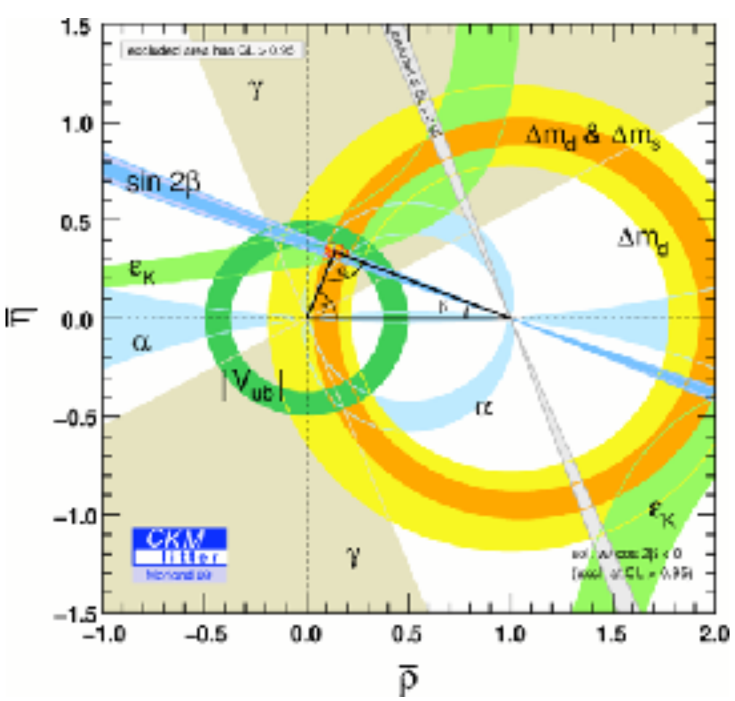
- We realized soon a totally unexpected effect of the large value of f_B .
- Combined with a high value of the top quark mass, above the lower limit then available (100 GeV), a large f_B had the effect to push the CP-violating asymmetry in $B \to J/\Psi + K_S$ decays to a much larger level than previously estimated.
- We found that

$M_{top} > 140$ GeV and 200 GeV $< f_B <$ 300 MeV would lead to values

$$\sin(2\beta) = 0.6 - 0.8$$

M. Lusignoli, L. Maiani, G. Martinelli and L. Reina, Nucl. Phys. B 369 (1992) 139.

The lower bound to the asymmetry is, in this case, about a factor 5 larger than previously found, which corresponds to about a factor 25 reduction in the luminosity required for a given statistical error in the asymmetry measurement.
....We wait eagerly for new data from Fermilab to tell us if the t-quark is below 130 GeV. or not..



All went well
Present world average, including some other measurements, is
$\sin 2\beta = 0.699 \pm 0.017$. CKM Quark-Mixing Matrix (PdG 2021)

Top quark was observed in 1994,
$M_{top} = 173$ GeV

…at present

f_P	Allton et al.[a] (1991)	Lattice[d] (2021)	from $P^+ \to \tau^+ \nu_\tau$ [e] (2008)
f_D	$180 \pm 25 \pm 30$ MeV	212.0 ± 0.7 MeV	$205.8 \pm 8.5 \pm 2.5$ MeV
f_B	$310 \pm 25 \pm 50$ [b] MeV $260 \pm 25 \pm 50$ [c] MeV	190.0 ± 1.3 MeV	216 ± 22 MeV
$f_P\sqrt{M_P} = A(1 - \frac{C}{M_P})$	$C = 1.2$ GeV	$C = 0.76$ GeV	$C = 0.93$ GeV

Table 1:

Notes:

a: C. S. Allton, *et al.*, *A Lattice Computation of the B-Meson Decay Constant*, Nucl. Phys. B **399** (1991) 598.

b: lattice spacing $a^{-1} = 2$ GeV.

c: lattice spacing $a^{-1} = 1.8$ GeV, determined using the values of f_π and f_K.

d: dynamical quark flavours on the lattice: u, d, s, c. Flavour Lattice Averaging Group (FLAG) 2021, arXiv:2111.09849.

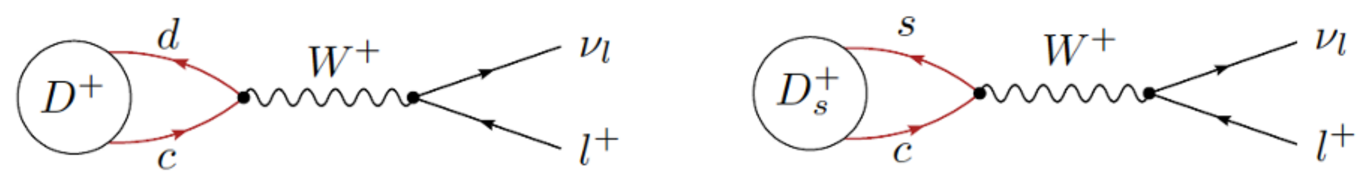
e: J. Rosner, S. Stone, *Decay Constants of Charged Pseudoscalar Mesons*, arXiv:0802.1043.

- In QCD, one expects the asymptotic scaling law: $f_P\sqrt{M_P} = const.$ for large quark mass.
- Setting: $f_P\sqrt{M_P} = A(1 - \frac{C}{M_P})$, one would expect $C = \mathcal{O}(\Lambda_{QCD}) \sim 0.25$ GeV
- A sizeable deviation was seen by Allton et al. and is confirmed in more recent estimates of f_B vs f_D (see Table)….???…

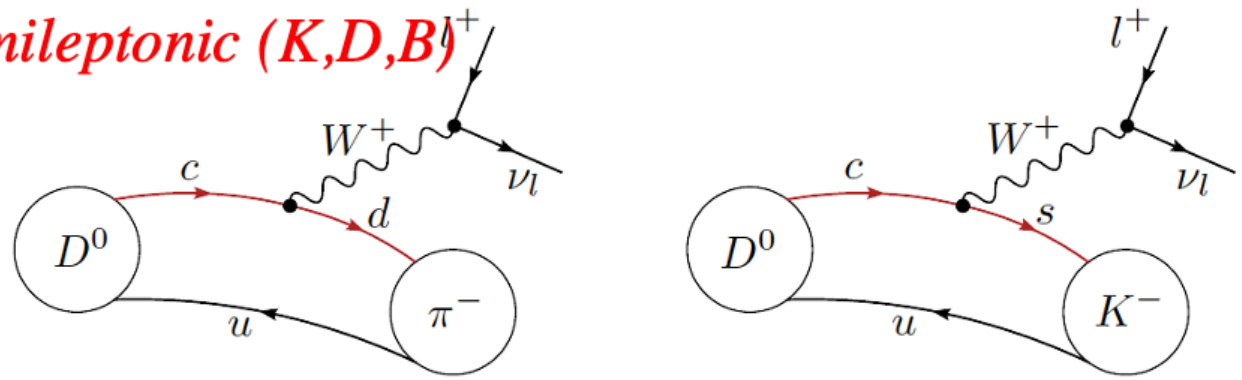
Guido' summary figure: Weak Interactions on the Lattice

Guido Martinelli. *QCD and Supercomputers*, in: *Bruno Touscheck 100 YEARS,* Roma, Frascati 2-4 December 2021; Luisa Bonolis, Luciano Maiani, Giulia Pancheri Editors, Springer (2022)

Leptonic (π,K,D,B)

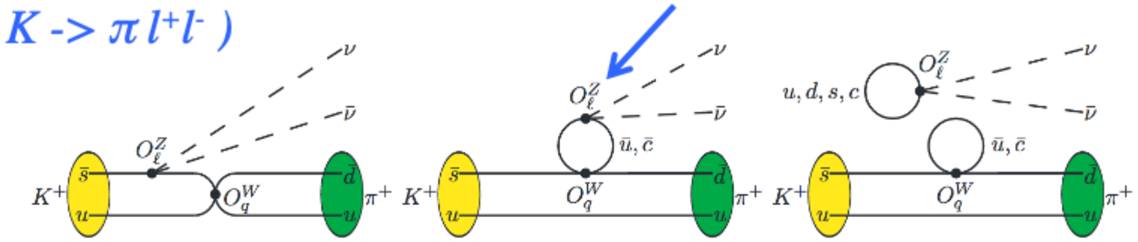


Semileptonic (K,D,B)



(some) Radiative and Rare *long distance effects*

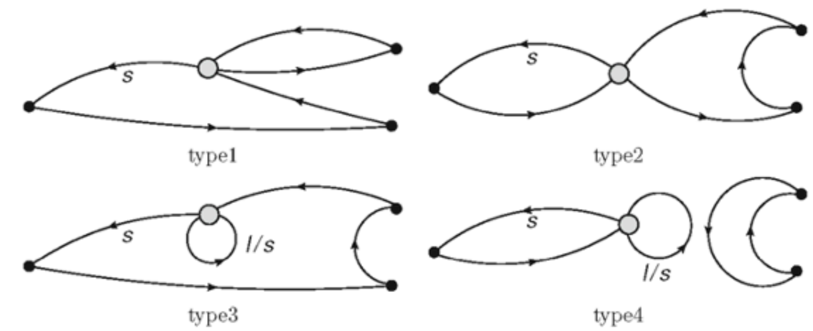
(also K -> π l⁺l⁻)



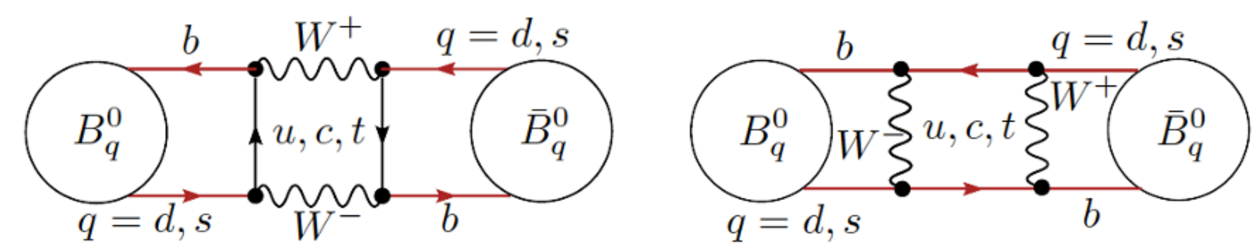
connected diag. self-loop diag. disconnected diag.

Non-leptonic *B -> ππ,Kπ, etc. No !*

but only below the inelastic threshold (may be also 3 body decays)



Neutral meson mixing (local)



+ some long distance contributions to K and D neutral meson mixing + short distance contributions to B-> K(*) l⁺l⁻

Synthetic overview of the amplitudes most frequently computed for Weak Interaction Phenomenology

Left panel: Leptonic, Semi-leptonic and Radiative decays (also for baryons and electromagnetic transitions not shown in the figure).

Right Panel: Non-leptonic decays of Kaons, Neutral meson mixing of B_q mesons (D meson and Kaon mixing not shown in the figure).

Lattice QCD computed also some long distance contributions to K and D neutral meson mixing and short distance contributions to $B \to K^{(*)}\ell^+\ell^-$ decays, not shown in the figure.

Thirty years later….
Unanticipated hadrons: what are they?

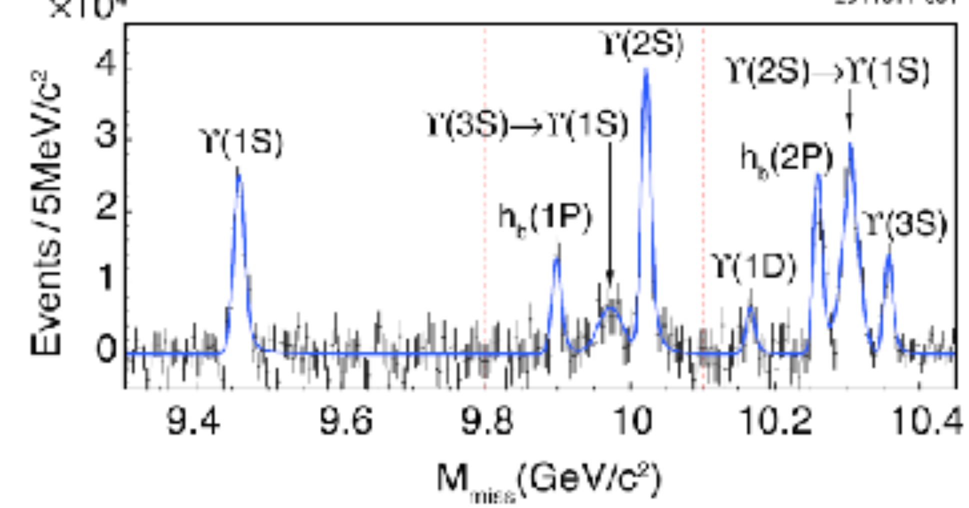
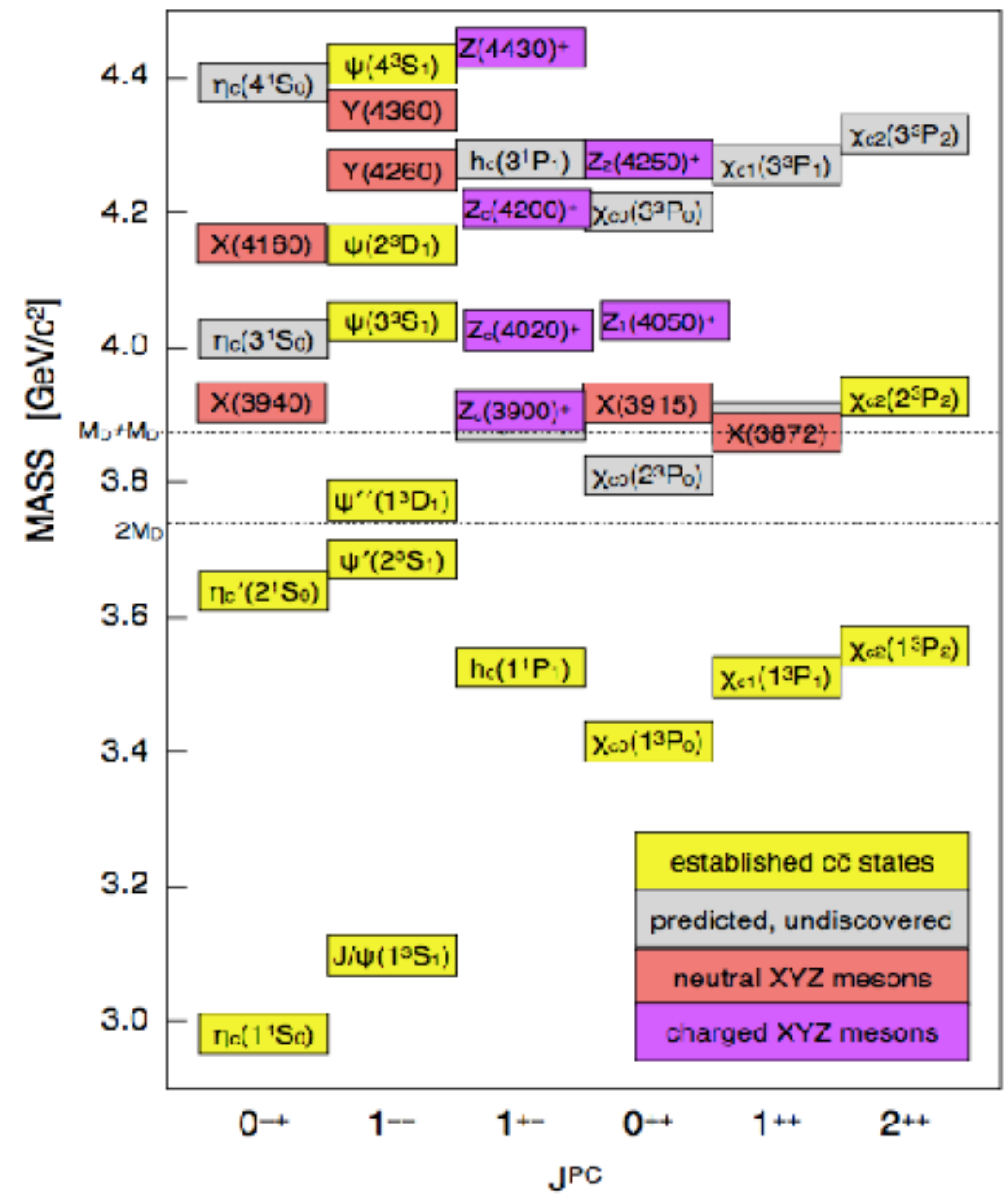


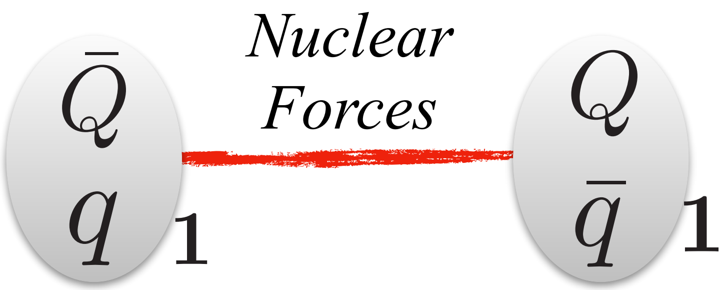
Figure 1: From Belle [31], the mass recoiling

The virtues of heavy quarks
($m_Q >> \Lambda_{QCD}$ *):*

- the inclusive decays are calculable deep inelastic processes;
- $c\bar{c}$ or $b\bar{b}$ bound states involve short distance forces: a calculable spectrum of charmonia/ bottomonia;
- inside hadrons, $c\bar{c}$ or $b\bar{b}$ pairs are not easily created or destroyed: a hadron decay into J/Ψ or $\Upsilon + \ldots$ indicates a valence $c\bar{c}$ or $b\bar{b}$ pair $\rightarrow$ heavy-quark counting is possible.

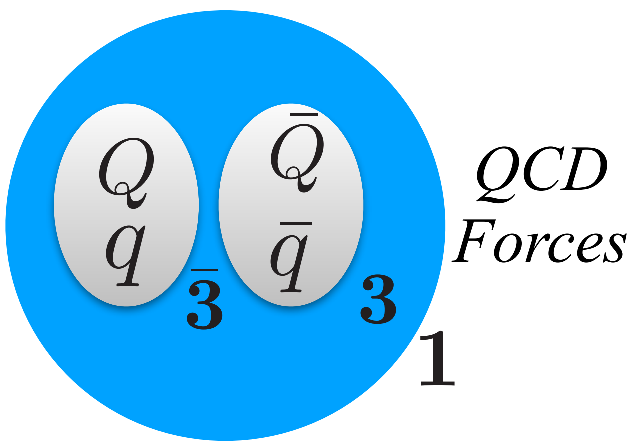


No consensus, yet



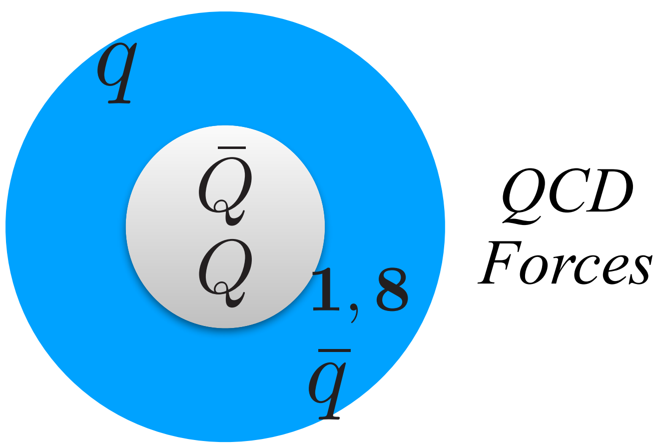
Hadron Molecule

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

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

The new sensation: doubly heavy tetraquarks

- Doubly heavy tetraquarks have been anticipated long ago
- $\mathcal{T}_c^+ = cc\bar{u}\bar{d}$ seen by LHCb (2021)

Esposito, Papinutto, Pilloni, Polosa, Tantalo, Phys. Rev. D88, 054029 (2013)

- The possibility has been raised that $I = 0,\ J^P = 1^+,\ \mathcal{T}_{bb}^- = bb\bar{u}\bar{d}$ be stable under strong and e.m. decays

M. Karliner and J. L. Rosner, PRL **119** (2017) 202001. E. J. Eichten and C. Quigg, PRL **119** (2017) 202002.; S. Q. Luo et al. Eur. Phys. J. C **77** (2017) 709.

- extended calculations of $\mathcal{T}_{cc}$ and $\mathcal{T}_{bb}$ mass have been presented, in the Born-Oppenheimer approximation, analytical

L. Maiani, A. D.Polosa and V. Riquer, Phys. Rev. **D100** (2019) 074002,

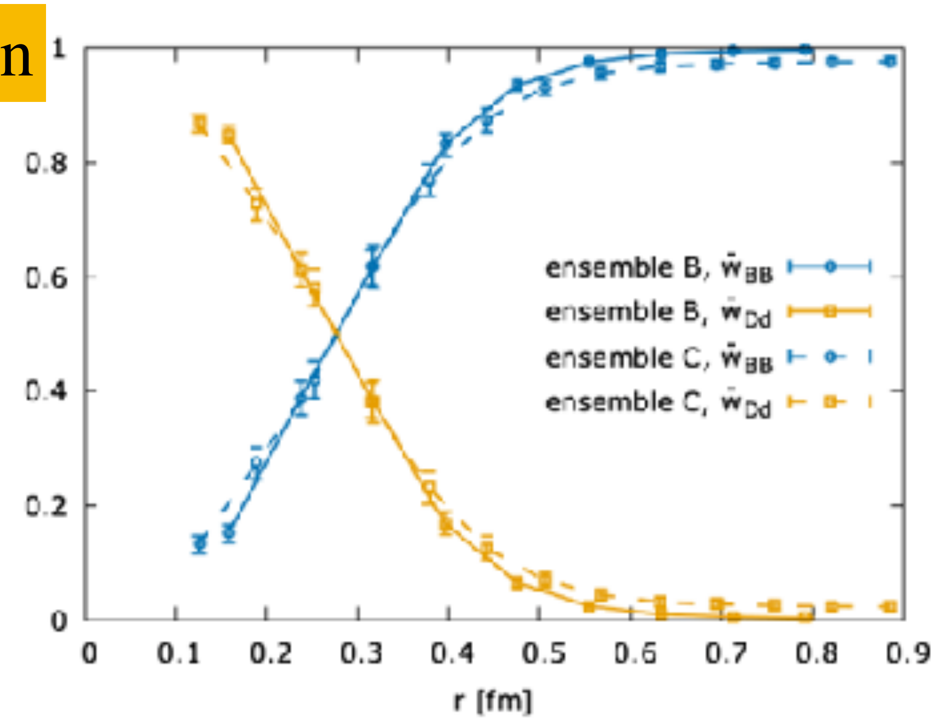
- A recent lattice QCD calculation shows a deeply bound 6 b-quarks dibaryon:$[bb][bb][bb]$

N. Mathur et al. ArXiv:2205.02862

Radiography of the double beauty tetraquark on lattice

$Dd = [bb][\bar{q}\bar{q}];\ BB = \text{Meson} - \text{Meson}$

- Projection of the lattice $[bb][\bar{q}\bar{q}]$ result over Dd (yellow) or BB (blue) gives a picture of the space arrangement of light quarks at a given bb distance, R
- Mainly $[bb]_{\bar{3}}[\bar{q}\bar{q}]_3$ at the peak of the bb wave function ~0.2 fm.



← B_1B_1 = Meson-Meson

← $Dd = [bb][\bar{q}\bar{q}]$

P.Bicudo et al. Phys. Rev. **D 103** (2021) 114506

Post classical, unanticipated hadrons in QCD Lattice: the challenge of the coming years?

Congratulations to Guido
and
Thank You !