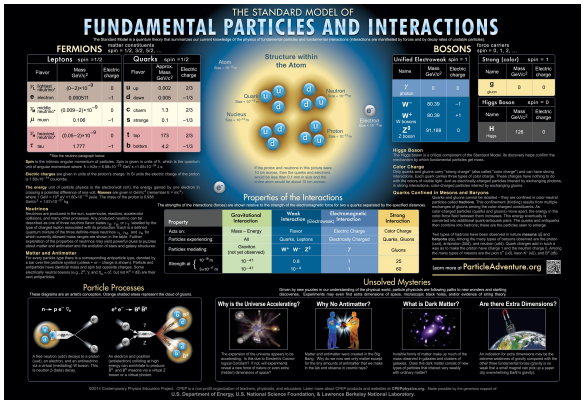
Jussara Miranda ● Salvador,BA,out/18

violação de CP

LISHEP18 A

sumário

- modelo padrão da física de partículas (MP)
  - antecedentes: zoo de partículas
    1961 quarks por Gell-Mann
    1968 espalhamento profundamente inelástico
  - férmion (constituintes da matéria)
  - bósons (mediadores de forças + Higgs)
  - anti-partículas
  - Hadrons (Barions & mesons)



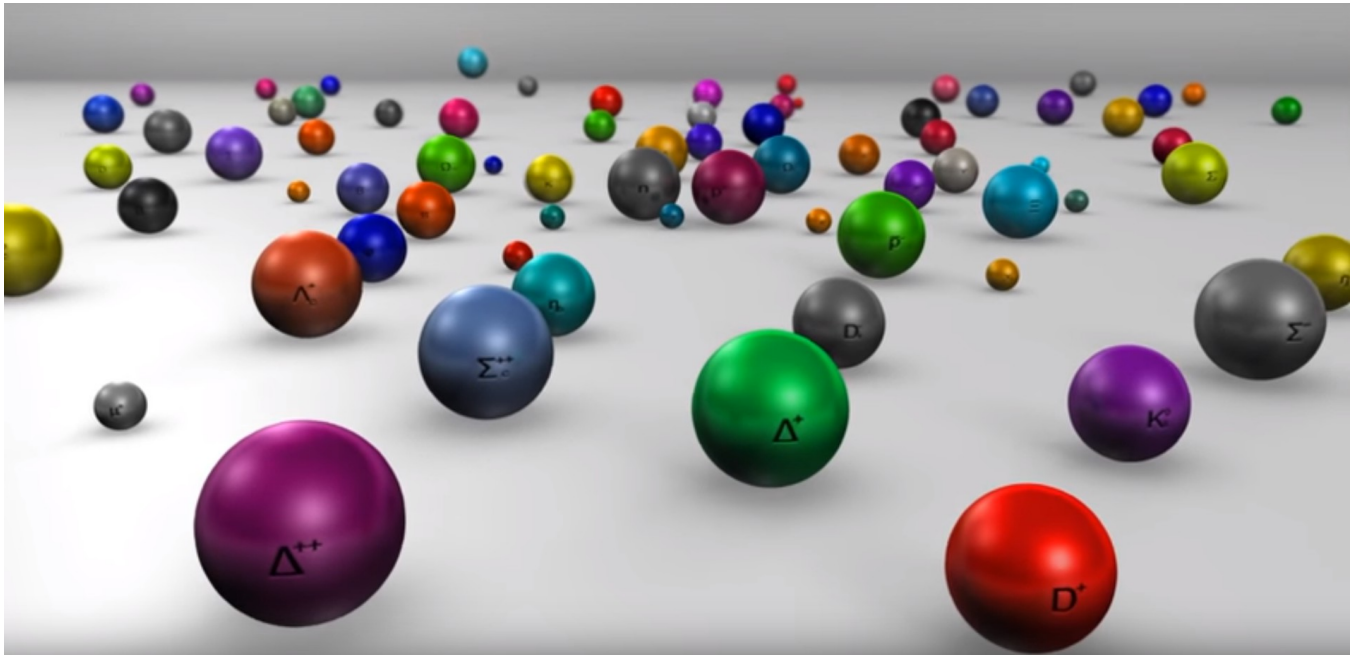
- simetrias **C,P,T**
- força fraca(ff): ~~**P**~~
  - 1956 - Lee&Yang ➡ proposta de veriticar ff sobre **P**
  - 1957 - Wu ➡ ff ~~**P**~~
  - ~~**C,P,T**~~**...CP?...CPT**
- ~~CP~~ : sistema kaons neutros
  - descoberta
- matriz de Cabbibo
- CKM: matriz de mistura de decaimentos fracos entre quarks e solução do MP para ~~CP~~
- ~~CP~~ em B→ hhh no LHCb

MP: antecedentes

- toda matéia em estado fundamental 

+ fóton +neutrinos

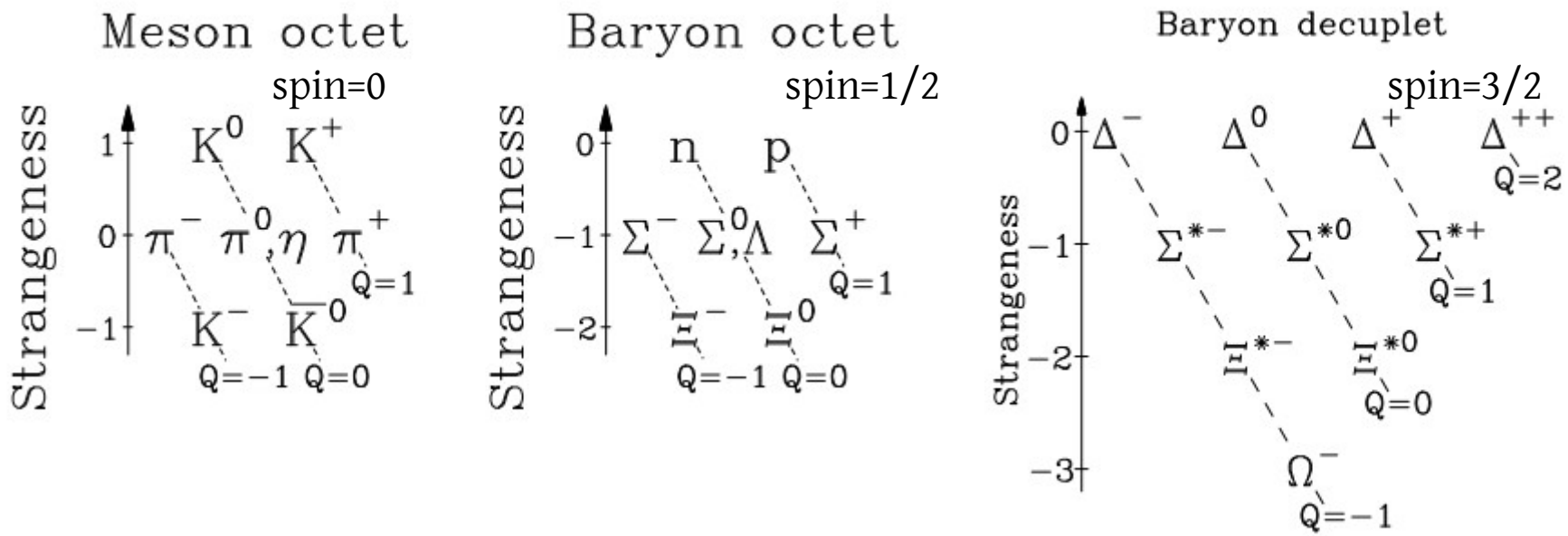
- ~1960 por raios cósmicos e aceleradores um verdadeiro *zoo* de partículas havia sido observado



MP: antecedentes

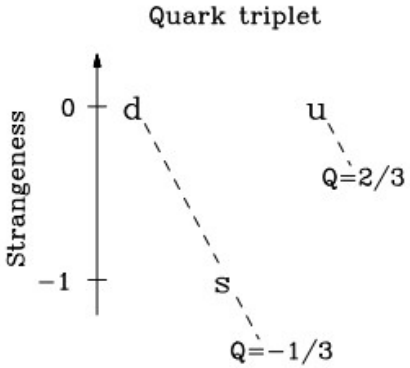
- **estranheza** ●● número quântico para classificar partículas produzidas aos pares com tempo de vida muto maior do que o esperado a julgar por suas massas

- 1961: Gell-Mann & Neeman ●● ***eighfold-way*** organiza o *zoo* em multipletos (SU_{sabor})

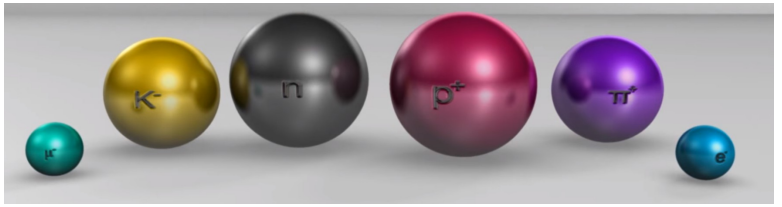


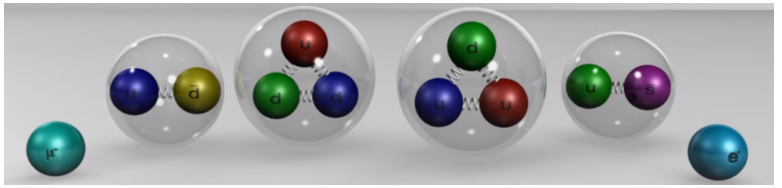
- 1964: Gell-Mann + Zweig ●● idéia de quarks "constituintes" simplifica ainda mais...

não supunham se tratar de objetos reais



●● mesons: $q\bar{q}$
●● barions: qqq





MP: antecedentes

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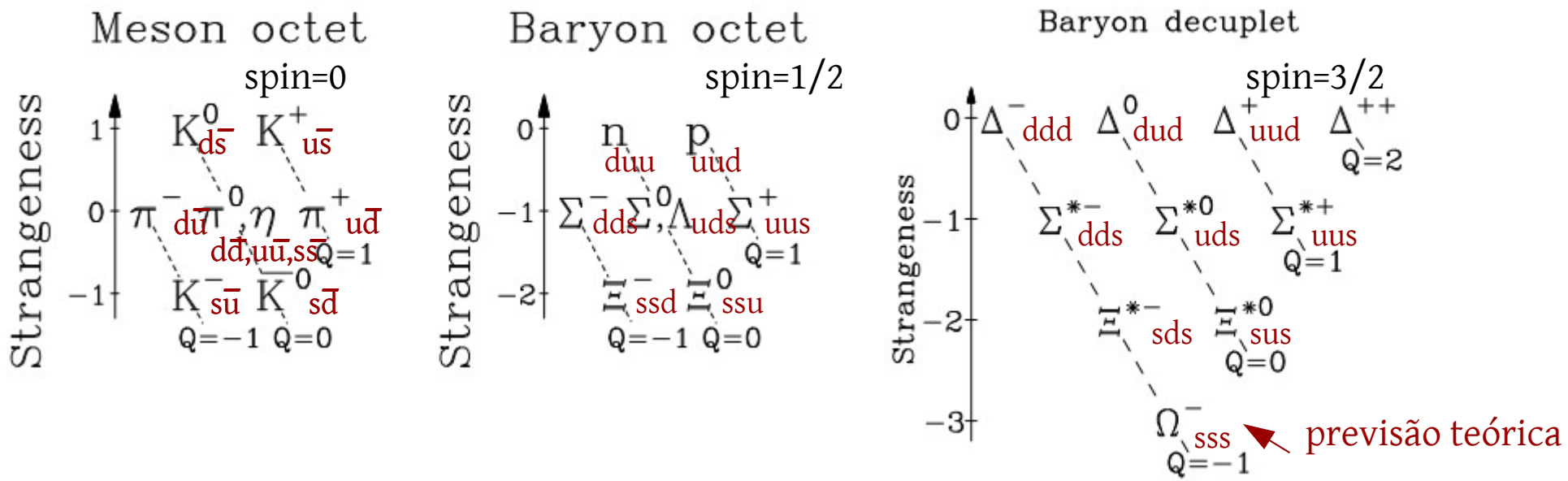

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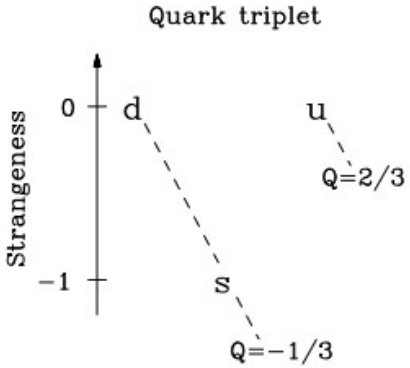

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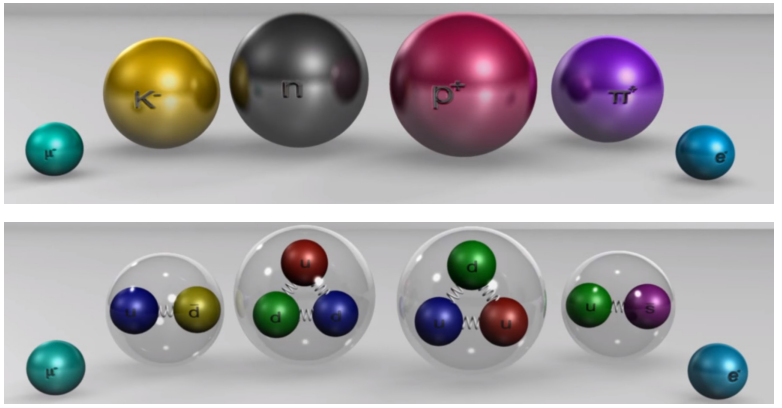
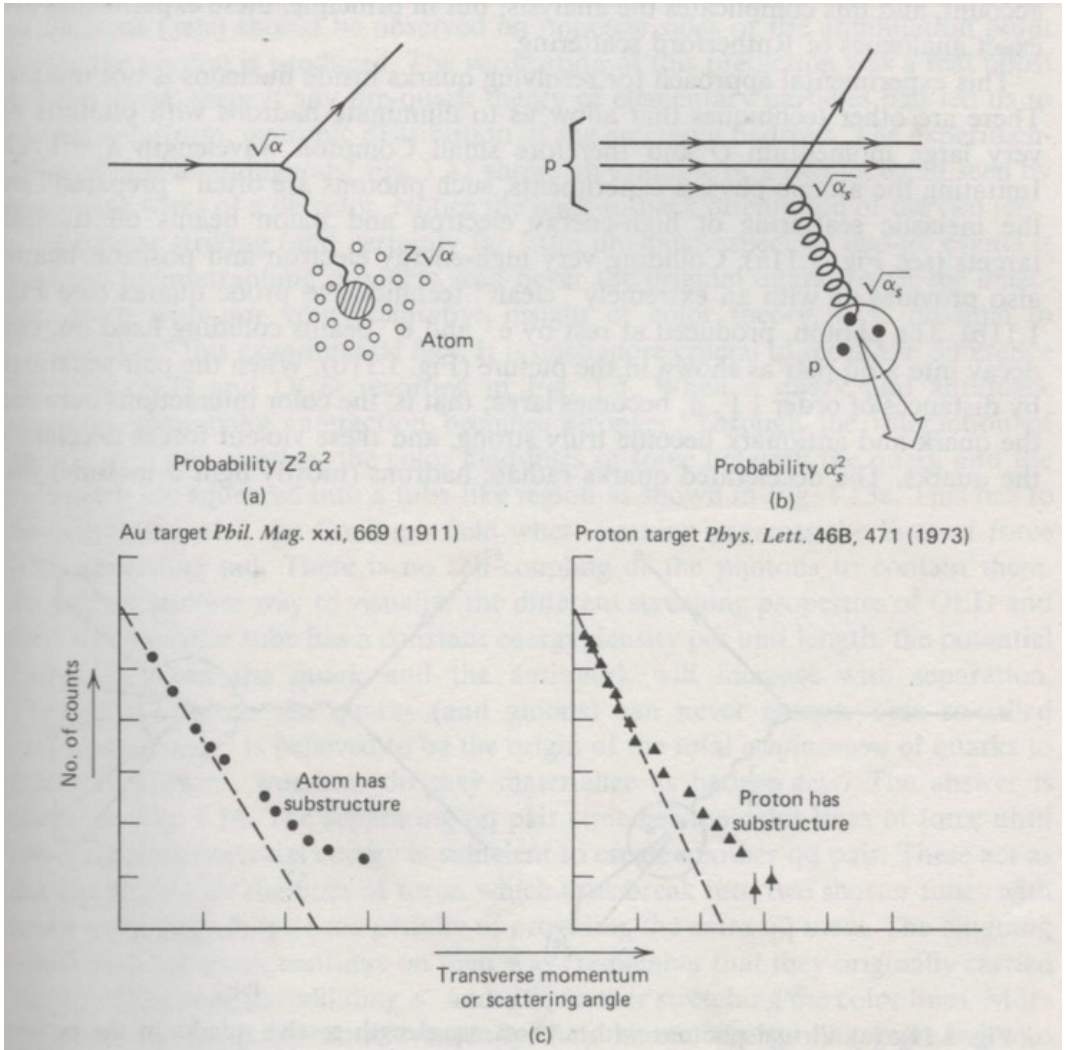


MP: antecedentes

- 1968 espalhamento profundamente inelástico.... estrutura no próton

^ E.D. Bloom; et al. (1969). "High-Energy Inelastic *e–p* Scattering at 6° and 10°". *Physical Review Letters*. **23** (16): 930–934. Bibcode:1969PhRvL..23..930B. doi:10.1103/PhysRevLett.23.930.

^ M. Breidenbach; et al. (1969). "Observed Behavior of Highly Inelastic Electron-Proton Scattering". *Physical Review Letters*. **23** (16): 935–939. Bibcode:1969PhRvL..23..935B. doi:10.1103/PhysRevLett.23.935.



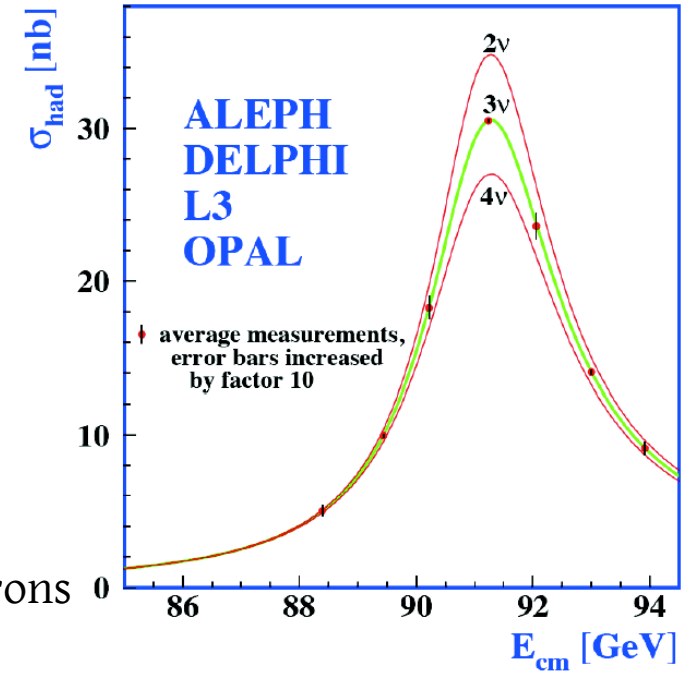
MP: férmions constituintes da matéria

- constituintes da matéria: quarks e leptons, férmions (e **anti-férmions**) de spin=1/2 constituem a matéria

●● 3 famílias

FERMIONS	matter constituents spin = 1/2, 3/2, 5/2, ...				
Leptons spin =1/2			**Quarks** spin =1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0	**u** up	0.002	2/3
e electron	0.000511	–1	**d** down	0.005	–1/3
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0	**c** charm	1.3	2/3
μ muon	0.106	–1	**s** strange	0.1	–1/3
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0	**t** top	173	2/3
τ tau	1.777	–1	**b** bottom	4.2	–1/3

Phys Rep 427 (2006)457



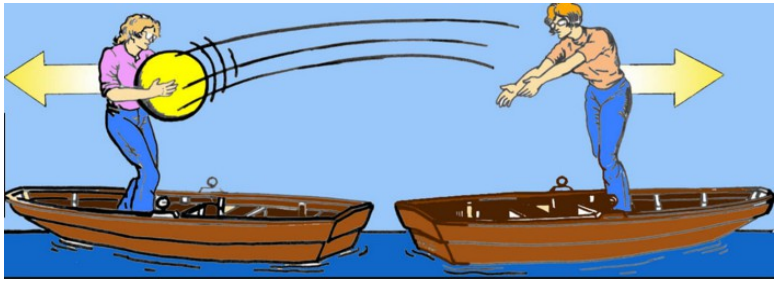
- quarks não existem isolados, são constituintes dos hadrons ... força forte aumenta com a distância

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ — Baryons are fermionic hadrons. There are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω⁻	omega	**sss**	–1	1.672	3/2

Mesons $q\bar{q}$ — Mesons are bosonic hadrons. There are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

MP: bósons, mediadores das forças

- teorias de gauge: interação se da pela troca de bósons mediadores das interações



BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

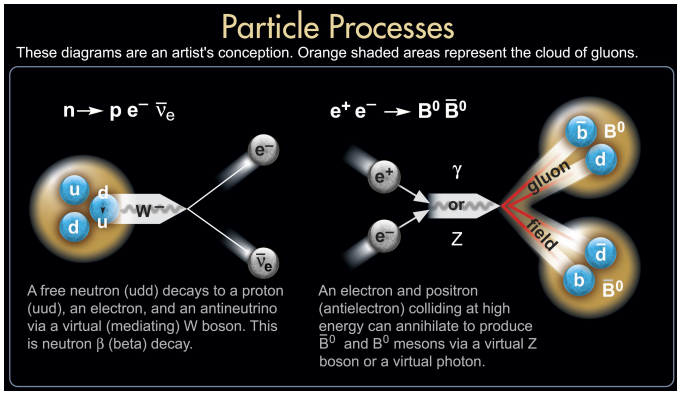
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0



Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

- ●● força forte: mantem hádrons e núcleo atômico ● não atua em léptons.
- ●● força fraca: decaimento ● troca de sabor ● atua em quarks e léptons

THE STANDARD MODEL OF
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
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Quarks spin =1/2

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*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

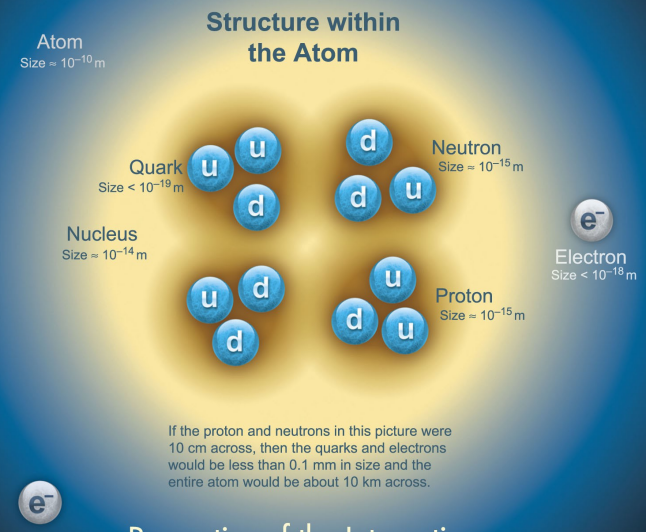
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
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Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at **ParticleAdventure.org**

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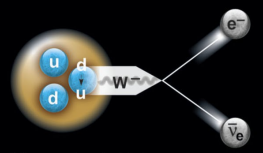
Particle Processes

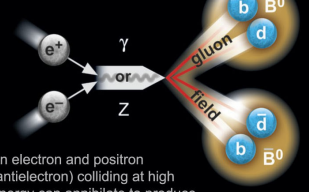
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+e^- \rightarrow B^0\bar{B}^0$

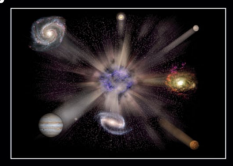


An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

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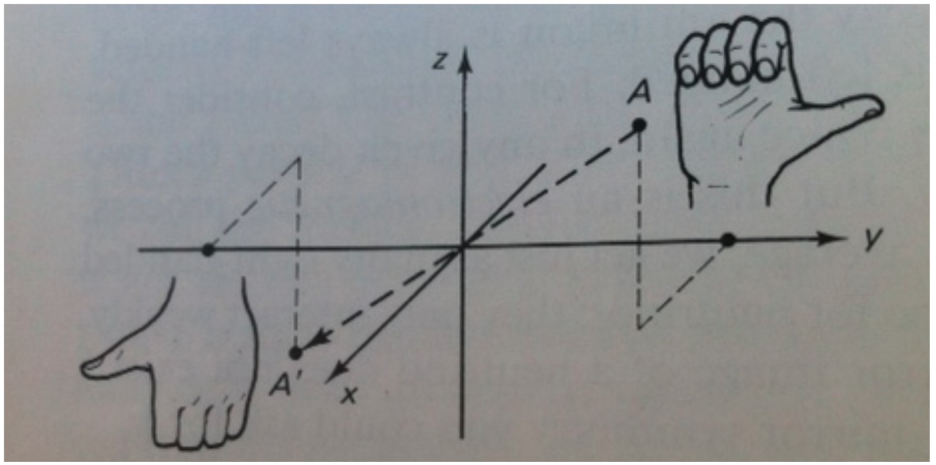
Jussara Miranda ● Salvador,BA,out/18

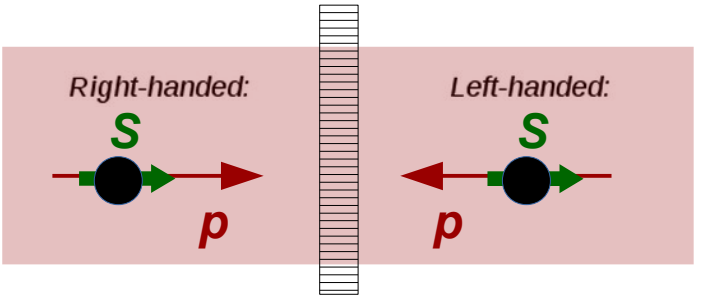
Carga q ⟷ -q
Paridade **r** ⟷ -**r**
Tempo t ⟷ -t

até ~1950 pensava-se que estas eram simetrias fundamentais em todas as leis da física

- **P**



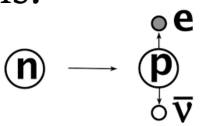
●● quanticamente spins são paralelos ou anti-paralelos à direção do movimento ➡ helicidade troca de sinal sob **P**



espelho

força fraca(ff): ~~P~~

- ff é responsável pelos decaimentos de quarks e leptons.
  - proposta por Fermi para explicar o decaimento β



- ff e **P** ?

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

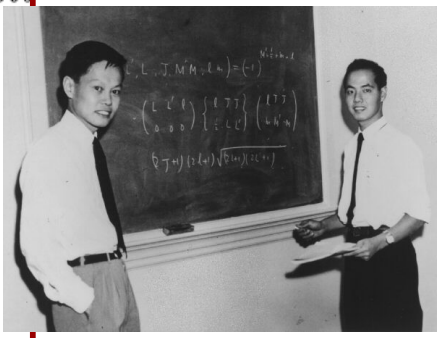
AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

high degree of accuracy, but that for the weak interactions (i.e., decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence. (One might even say that the present $\theta-\tau$ puzzle may be taken as an indication that parity conservation is violated in weak interactions. This argument is, however, not to



Θ-τ puzzle

$\theta^+ \rightarrow \pi^+ \pi^0$ +1† $m_\theta = m_\tau$

$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-$ -1 $\tau_\theta = \tau_\tau \approx 10^{-8}$s

se as interações fracas não conservam P

$\theta^+ = \tau^+ = K^+$

Proposição: *observar spin de produtos de decaimentos radiativo de núcleos polarizados*

†$P_\pi = -1$; $P_{2\pi} = +1$; $P_{3\pi} = -1$

força fraca(ff): ~~P~~

● 

Phys. Rev. 105 (1957) 1413

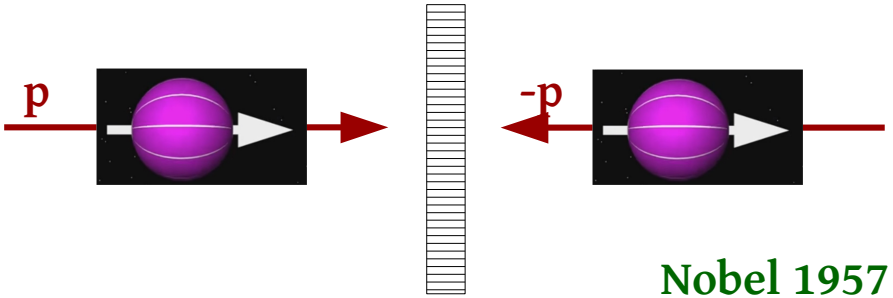
Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

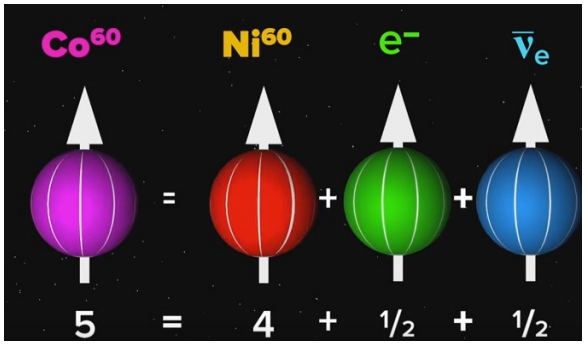
E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

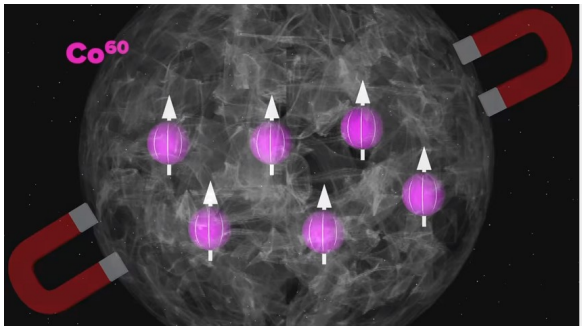


Nobel 1957

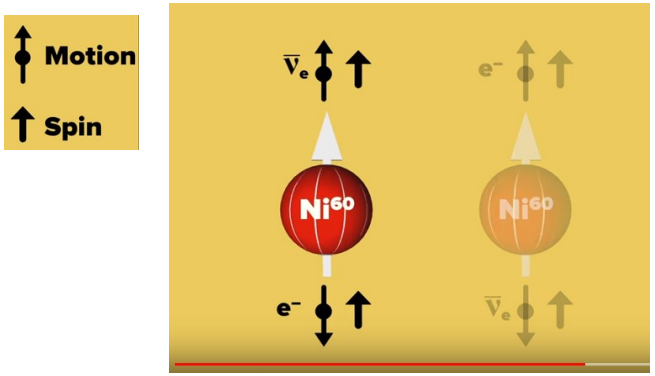
●●decaimento radiativo do Co^{60}



●● polarizado



●●elétrons e neutrinos movem-se na direção no núcleo em sentidos opostos.

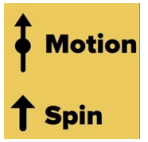


●● no caso de conservação de paridade não existiria sentido preferencial na emissão dos elétrons

Wu observa que os elétrons se movem no sentido oposto à polarização do Co^{60}

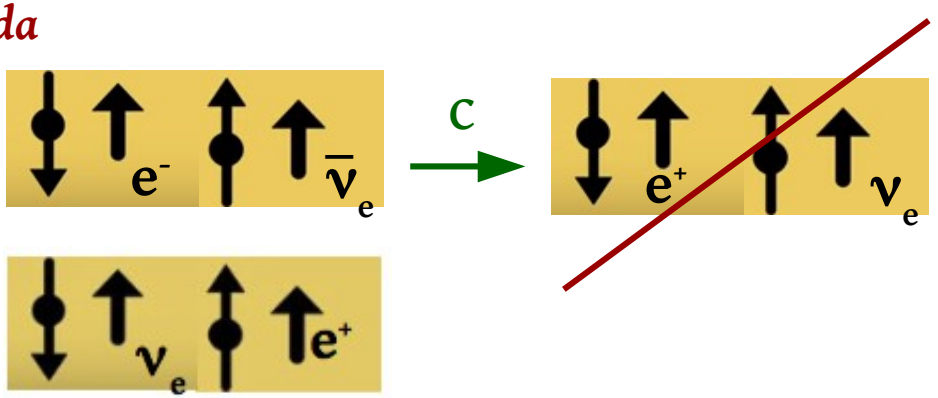
força fraca(ff): ~~P~~,~~C~~,~~T~~...CP?...CPT

- força fraca não só viola **P**, viola maximamente ➡

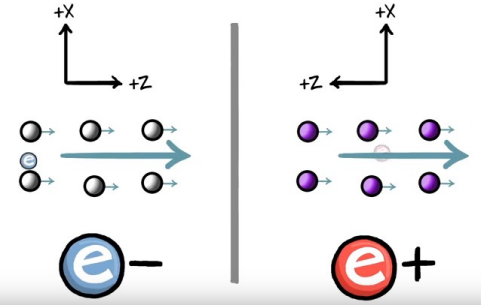


a força fraca só interage com anti-neutrinos (anti-partículas) de mão-direita e neutrinos (partículas) de mão-esquerda

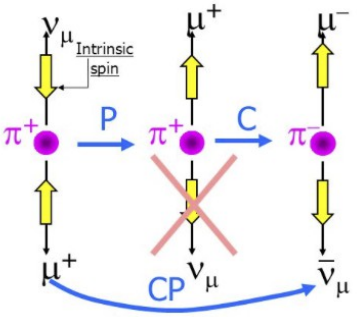
- força fraca viola maximamente **C** ➡



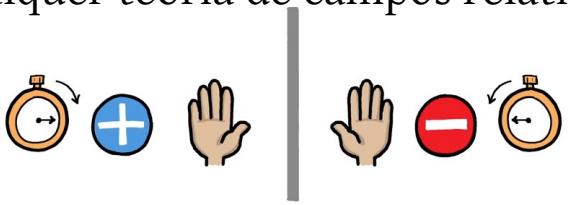
- **CP**??



●● força fraca viola "minimamente" **CP**



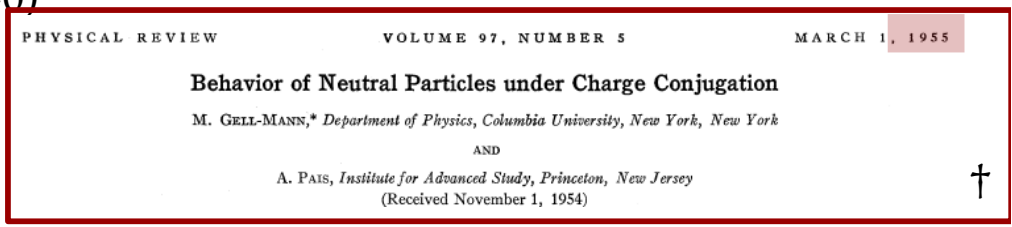
- **CPT** TEOREMA : qualquer teoria de campos relativística é invariante por **CPT**



$\not{C}P$: sistema kaons neutros

Jussara Miranda ● Salvador,BA,out/18

- partículas estranhas:
  - ●● produzidas aos pares em interações fortes ($\Delta S=0$)
  - ●● decaem por interações fracas $|\Delta S|=1$



PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. GELL-MANN,* *Department of Physics, Columbia University, New York, New York*

AND

A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

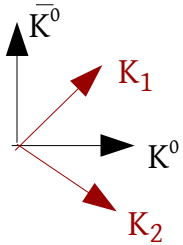
†

- $K^0(d\bar{s})$: $S=+1$ ●● $K^0 \to 2\pi$
- $\bar{K}^0(\bar{d}s)$: $S=-1$ ●● $\bar{K}^0 \to 2\pi$

➡ $K^0 \xrightarrow{|\Delta S|=2} 2\pi \to \bar{K}^0$

partícula anti-partícula mix por interações fracas

- troca de base:



$K_1 = \sqrt{½}\,(K^0 - \bar{K}^0)$

$K_2 = \sqrt{½}\,(K^0 + \bar{K}^0)$

Decaimento	amplitude
$K^0 \to 2\pi$	A
$\bar{K}^0 \to 2\pi$	$-A$
$K_1 \to 2\pi$	$-\sqrt{2}A$
$K_2 \to 2\pi$	0

CPT

➡ $\tau_{K_1} \ll \tau_{K_2}$

dois tempos de vida distintos no sistema de kaons neutros.

como K2 não se acopla a 2π, (modo mais facilmente atingível) ele terá ***tempo de vida maior***

K_1 e K_2 are não são partícula e anti-partícula; não têm S bem definido. São eles os "objetos" que efetivamente decaem

K^0 e $\bar{K}^0$ são produzidos
K_1 e K_2 decaem

previsão teórica existência de dois mésons neutros

†na época ainda conhecidos como θ

$\cancel{CP}$: sistema kaons neutros

Jussara Miranda ● Salvador,BA,out/18

- $P|K^0\rangle = -|K^0\rangle \qquad P|\bar{K}^0\rangle = -|\bar{K}^0\rangle$
  $C|K^0\rangle = |\bar{K}^0\rangle \qquad C|\bar{K}^0\rangle = |K^0\rangle$
  $CP|K^0\rangle = -|\bar{K}^0\rangle \qquad CP|\bar{K}^0\rangle = -|K^0\rangle$

K_0 e $\bar{K}_0$ não são auto-estados de CP

$CP|K_1\rangle = |K_1\rangle \qquad CP|K_2\rangle = -|K_2\rangle$

assumindo CP ➡ $K_1 \rightarrow 2\pi \qquad K_2 \rightarrow 3\pi^\dagger$

$K_1 = \sqrt{½}\,(K^0 - \bar{K}^0)$

$K_2 = \sqrt{½}\,(K^0 + \bar{K}^0)$

- se CP então podemos associar K_1 com K_S e K_2 com K_L que são efetivamente observados no laboratório (auto-estados de massa)

observação dos K_L

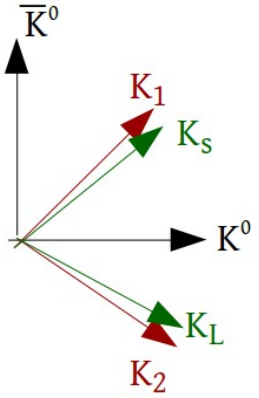
Observation of Long-Lived Neutral *V* Particles*

K. Lande, E. T. Booth, J. Impeduglia, and L. M. Lederman,
Columbia University, New York, New York
and
W. Chinowsky, *Brookhaven National Laboratory, Upton, New York*
(Received July 30, 1956)

se CP então $K_L \not\rightarrow 2\pi$

resumo

força forte	$K^0, \bar{K}^0$	composição de quarks
auto-estados CP	K_1, K_2	$CP\|K_{1,2}\rangle = +,-\|K_{1,2}\rangle$
auto-estados de massa	K_S, K_L	propagação



$\dagger CP_\pi = -1;\ CP_{2\pi} = +1;\ C\,P_{3\pi} = -1$

CP: descoberta

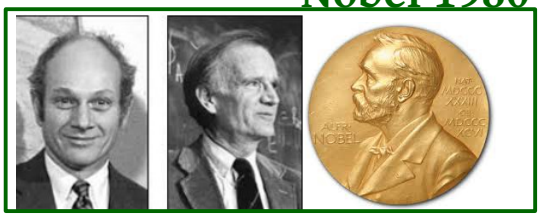
Jussara Miranda ● Salvador,BA,out/18

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§

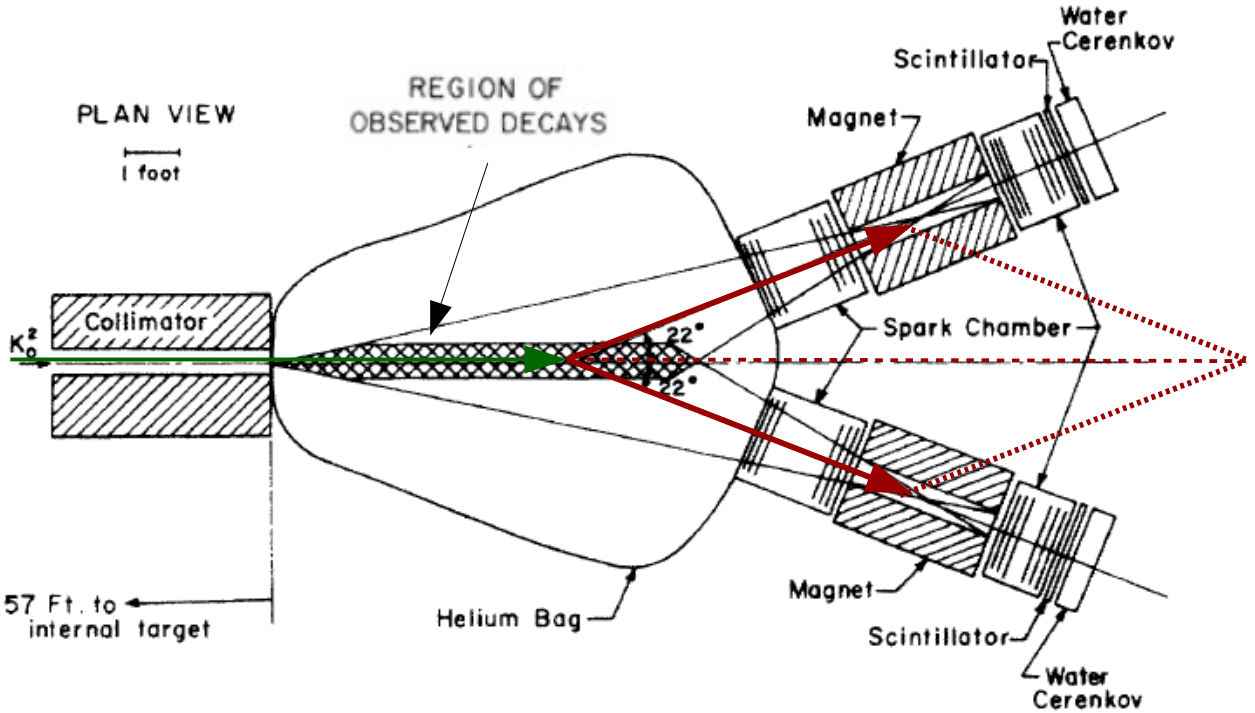
Nobel 1980



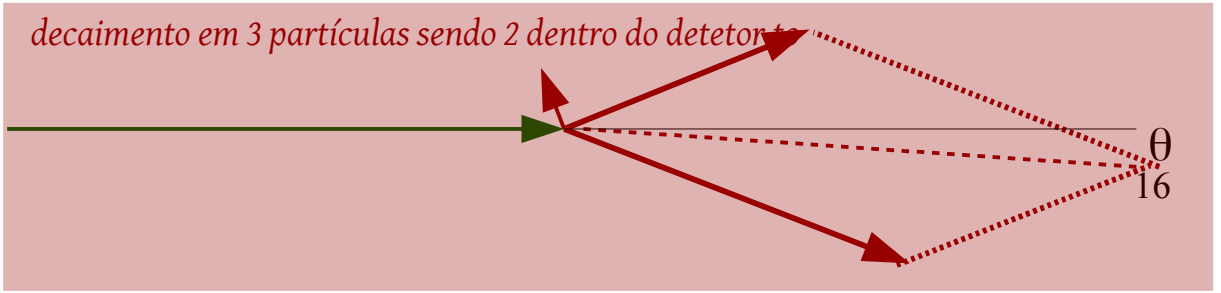
The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion.

In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV.

An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the K_1^0 mesons produced by coherent regeneration have the same momentum and direction as the K_2^0 beam, the K_1^0 decay simulates the direct decay of the K_2^0 into two pions. The regenerator was successively placed at intervals of 11 in.



decaimento em 3 partículas sendo 2 dentro do detetor



‡The Discovery of CP Violation: a Surprise -- Prof. Jim Cronin 30 video: http://cds.cern.ch/record/1228545/

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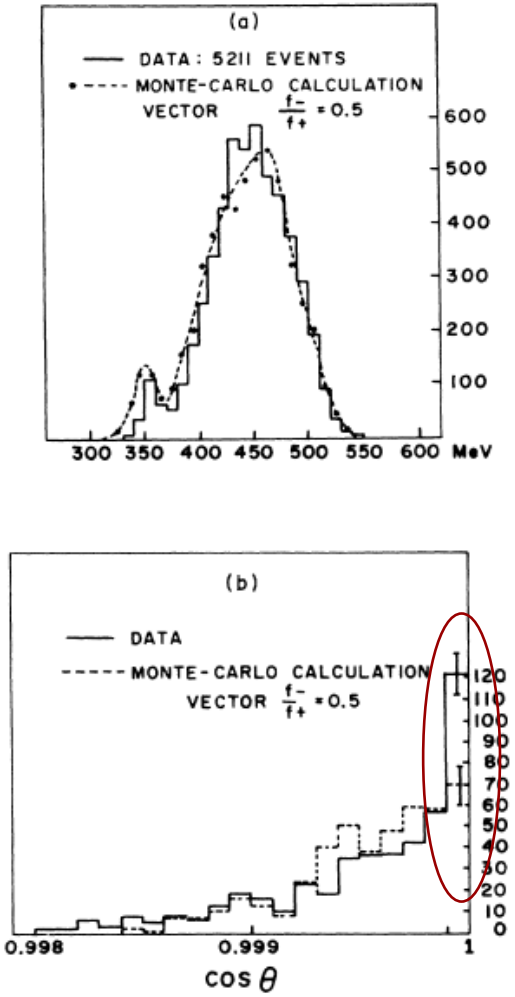


FIG. 2. (a) Experimental distribution in m^* compared with Monte Carlo calculation. The calculated distribution is normalized to the total number of observed events. (b) Angular distribution of those even in the range $490 < m^* < 510$ MeV. The calculated curv is normalized to the number of events in the complete sample.

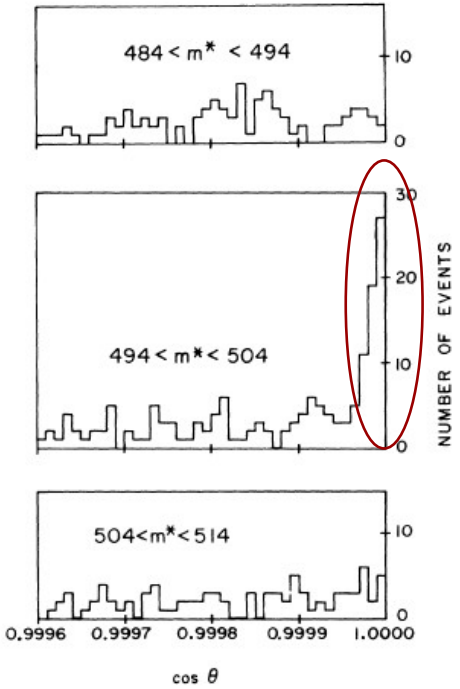


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

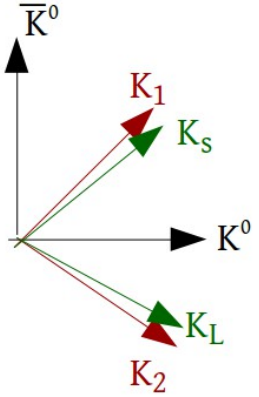
After subtraction of background, 45 ± 10 events are observed in the forward peak at the K^0 mass. We estimate that ~10 events can be expected from coherent regeneration. The number of events remaining (35) is entirely consistent with the decay data when the relative target volumes and integrated beam intensities are taken into account. This number is substantially smaller (by more than a factor of 15) than one would expect on the basis of the data of Adair et al.[4]

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation.

The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as

$$K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$$

$$|\epsilon| \cong 2.3 \times 10^{-3}$$



6 meses depois o resultado foi confirmado por outro experimento

$\not{CP}$: observação

- obsercação $\not{CP}$ ⟷ acoplamento complexo ➡ *requer interferência!!*

lagrangiana : $\mathcal{L} \sim g_{ji}\,\varphi_i\varphi_j + g_{ij}^*\,\varphi_i^\dagger\varphi_j^\dagger$

CP atua nos campos: $\varphi_i\varphi_j$ ➡ $\varphi_i^\dagger\varphi_j^\dagger$

CP é uma simetria do sistema se $g_{ji} = g_{ij}^*$

●● **amplitude:**

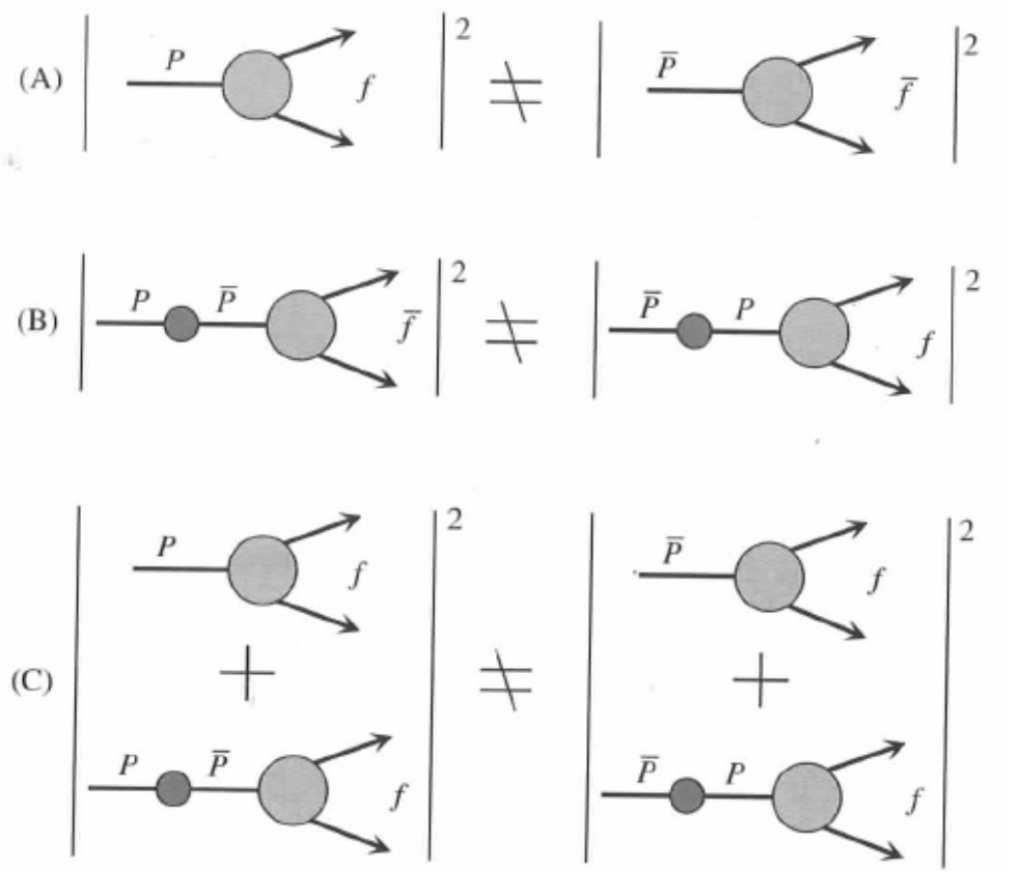
$A = |A_1|\,e^{i\phi} + |A_2|e^{i\alpha}$ ⟷ $\bar{A} = |A_1|\,e^{-i\phi} + |A_2|e^{i\alpha}$

●● **observável:**

$|\bar{A}|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\alpha+\phi)$

$|A|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\alpha-\phi)$

- $\not{CP}$ pode ser observada de diversas formas:



(A) $\not{CP}$ direta sem presença de mixing: **mésons carregados**

(B) $\not{CP}$ no mixing. $\mathbf{P^0, \bar{P}^0 \to l^\pm X}$

(C) $\not{CP}$ no termo de interferência. $\mathbf{B^0, \bar{B}^0 \to J/\psi\, K_s}$

no $K_L \to \pi\pi$ *,(B) e (C) contribuem*

todas as possíveis formas de manifestação de $\not{CP}$ *já foram observadas*

●Cabibbo Kobayashi Maskawa

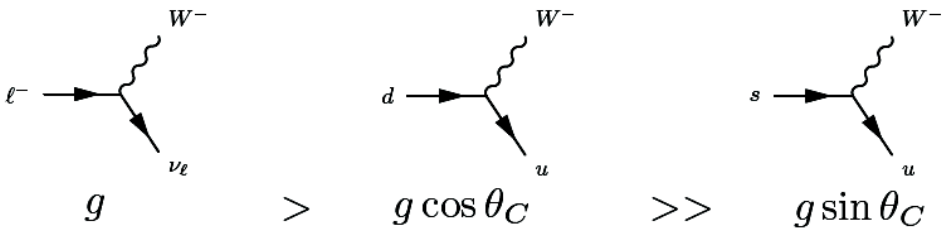
VOLUME 10, NUMBER 12 PHYSICAL REVIEW LETTERS 15 JUNE 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

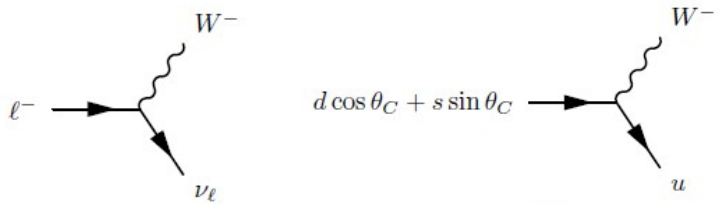
Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

60' :

			Q			Q
W-	υ_e	υ_μ	0	u		+2/3
	e	μ	-1	d	s	-1/3



universalidade das interações fracas



$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L, \begin{pmatrix}u\\ d'\end{pmatrix}_L = \begin{pmatrix}u\\ d\cos\theta_C + s\sin\theta_C\end{pmatrix}_L$$

charme não havia sido descoberto!!!!

● para **unificar as interações fracas** nos setores de quarks e lepton e acomodar as taxas de decaimento observadas, Cabibbo introduziu o ângulo de mistura θ_c

To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$
$$= \tan^2\theta M_K(1 - M_\mu{}^2/M_K{}^2)^2/M_\pi(1 - M_\mu{}^2/M_\pi{}^2)^2. \quad (3)$$

From the experimental data, we then get[5,6]

$$\theta = 0.257. \quad (4)$$

$p \to ne^+\nu_e$ (^{14}O)	$u \to de^+\nu_e$	$G^2\cos^2\theta_C$
$\pi^- \to \pi^0 e^-\bar{\nu}_e$	$d \to ue^-\bar{\nu}_e$	$G^2\cos^2\theta_C$
$K^- \to \pi^0 e^-\bar{\nu}_e$	$s \to ue^-\bar{\nu}_e$	$G^2\sin^2\theta_C$
$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$	—	G^2

● no setor leptônico não há mistura de famílias

Cabibbo Kobayashi Maskawa

- **KM** propoem a extensão no esquema de Cabibbo para acomodar $\not{CP}$.
  - •• acoplamento complexo requer uma matriz de mistura 3X3.

KM propoem uma terceira família no setor de quarks‡ antes da segunda estar "completa"†.

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

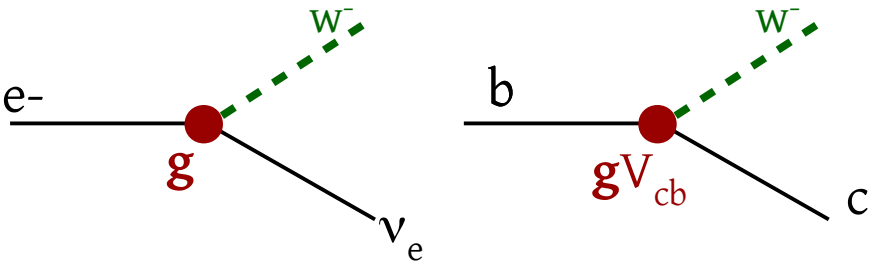
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

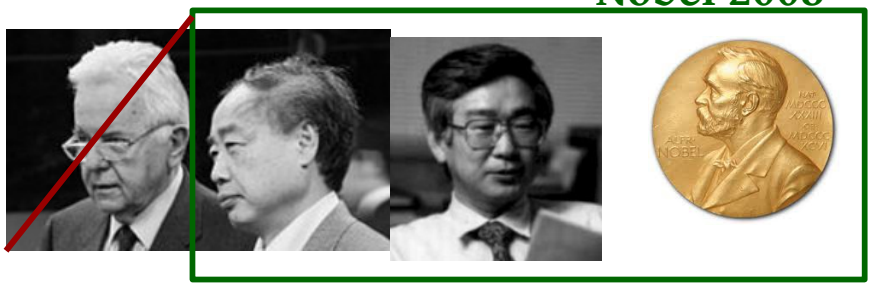
$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}\quad\begin{pmatrix}u\\ d'\end{pmatrix}\begin{pmatrix}c\\ s'\end{pmatrix}\begin{pmatrix}t\\ b'\end{pmatrix}$$

➡ dubletos da interação fraca (I^W=1/2)

$$\begin{pmatrix}d'\\ s'\\ b'\end{pmatrix} = \underbrace{\begin{bmatrix}V_{ud} & V_{us} & V_{ub}\\ V_{cd} & V_{cs} & V_{cb}\\ V_{td} & V_{ts} & V_{tb}\end{bmatrix}}_{V_{CKM}}\begin{pmatrix}d\\ s\\ b\end{pmatrix}$$



Nobel 2008



†quark ***c*** proposto por G.I.M. (1970).
J/ψ (***cc***)observado em novembro/1974
‡terceira família: ϒ(***bb***) observado em 1977
e o quark ***t*** *em* 1994

Cabibbo Kobayashi Maskawa

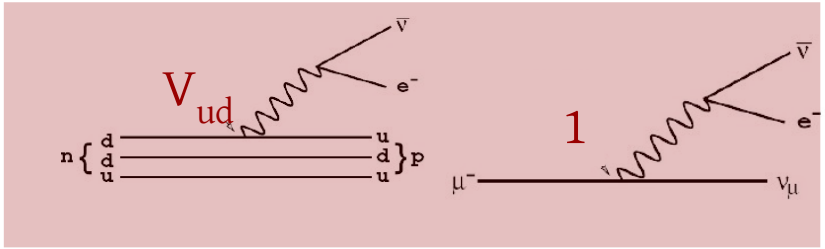
- matriz complexa N X N ➡ $2N^2$ parâmetros V_{CKM} N=3
- Vínculos:
  unitariedade: $V^{*T}V = I$ ➡ N^2 vínculos
  fases arbitárias:
  $|q_j\rangle \rightarrow e^{-\varphi_j}|q_j\rangle$ ➡ 2N-1 fases irrelevantes
- parâmetros independentes: N^2-2N-1

V_{CKM} : 4 parâmetros ➡ 3 ângulos + 1 fase complexa irredutível

precisamos verificar se este esquema faz sentido!

*na verdade os elementos da matriz CKM podem ser medidos de diversas formas. a comparação dos resultados servem como **verificação** do esquema e/ou fazer **previsões***

- **magnitudes** são obtidas comparando taxas de decaimento:



$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix}$$

$n \to pe\upsilon$ $K_L \to \pi e\upsilon$ $D \to Kl\upsilon$ $B \to \pi l\upsilon$ $B \to Dl\upsilon$ $D \to \pi l\upsilon$ oscilações B_d B_s† $t \to Wb$

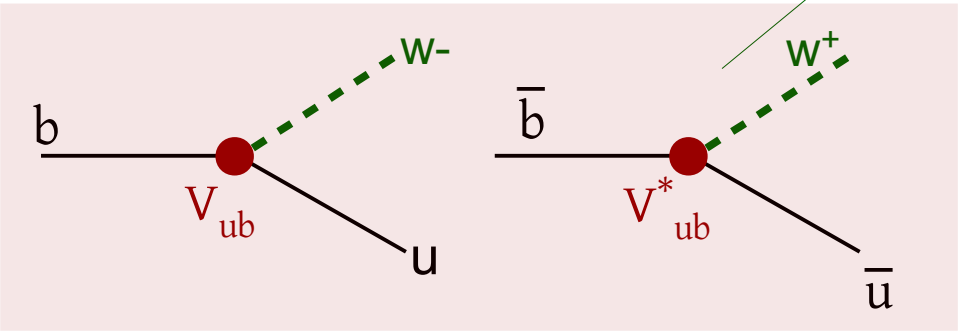
$$V_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

† não se pode medir por taxa de decaimento
pq sento t muito pesado não chega a hadronizar

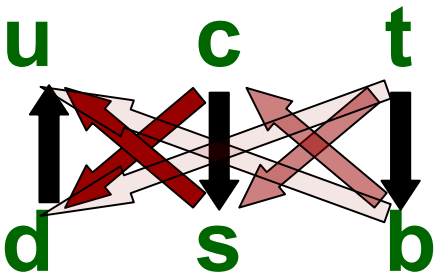
● Wolfenstein: parametrização conveniente baseada na hierarquia das transições:

●● CKM escrita como expansão em $\lambda = \sin\theta_c$

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\,.$$



*os menores acoplamentos são os **complexos***
espera-se $\not{CP}$ um efeito pequeno!



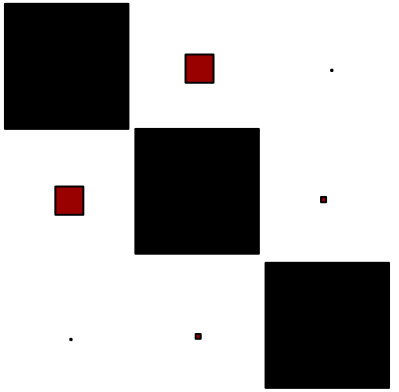
acoplamento por geração

1st to 2nd $\sim\lambda$

2nd 3rd $\sim\lambda^2$

1st to 3rd $\sim\lambda^3$

$$V_{\rm CKM} = \begin{matrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{matrix} \sim$$



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●relações de unitariedade

$$V^{*T}V = I \Longleftrightarrow \sum_j V_{ij} V^*_{jk} = \delta_{ik}$$

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

●● dentro de cada linha ou (coluna)

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$

$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1$$

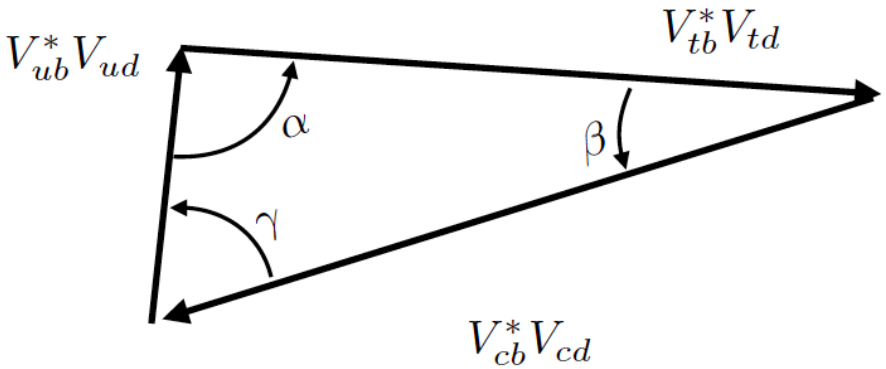
$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

●● entre colunas diferentes†:

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0 \Rightarrow \sim O(\lambda^3) + O(\lambda^3) + O(\lambda^3)$$

esta combinação particular produz um triângulo de lados ~equivalentes associados ao B^0

3 números complexos cuja soma é nula ➡ *triângulo no plano complexo*



$$\alpha = \arg\left(-\frac{V^*_{tb}V_{td}}{V^*_{ub}V_{ud}}\right)$$

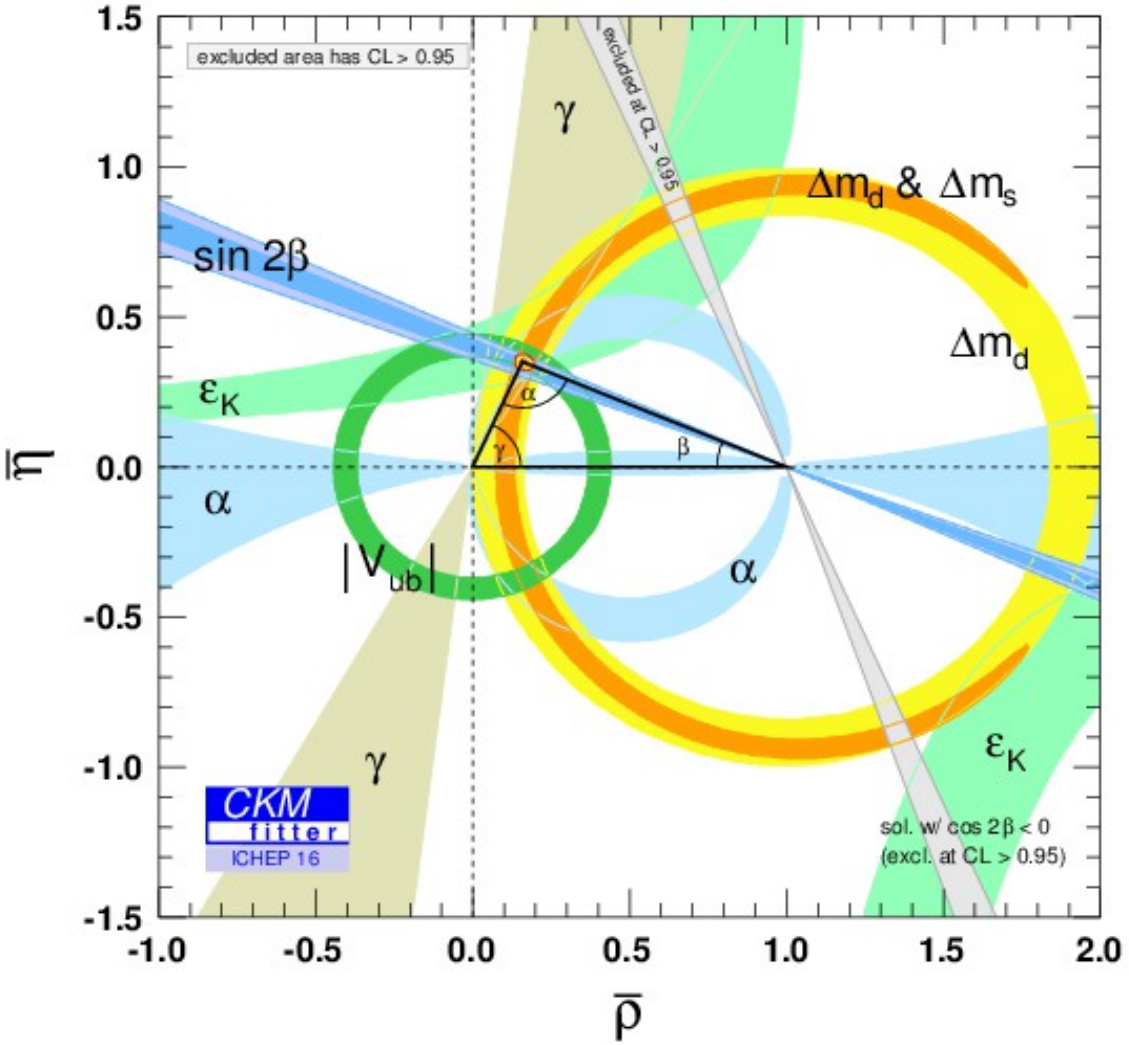
$$\gamma = \arg\left(-\frac{V^*_{ub}V_{ud}}{V^*_{cb}V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V^*_{cb}V_{cd}}{V^*_{tb}V_{td}}\right)$$

o triângulo 'sd' associado ao K^0 é $\sim O(\lambda) + O(\lambda) + O(\lambda^5)$

os ângulos internos estão associados à $\not{CP}$

†podemos construir muitas mais relações, mas estas são as mais uteis



$|V_{ud}|$, $|V_{us}|$

$|V_{cb}|$, $|V_{ub}|_{SL}$

$B \to \tau\nu$

Δm_d, Δm_s

ϵ_K

$\sin 2\beta$

α

γ

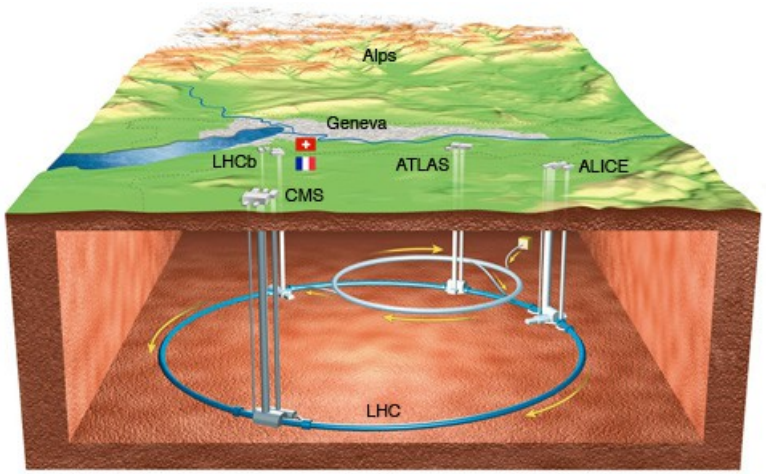
parametrização de Wolfenstein

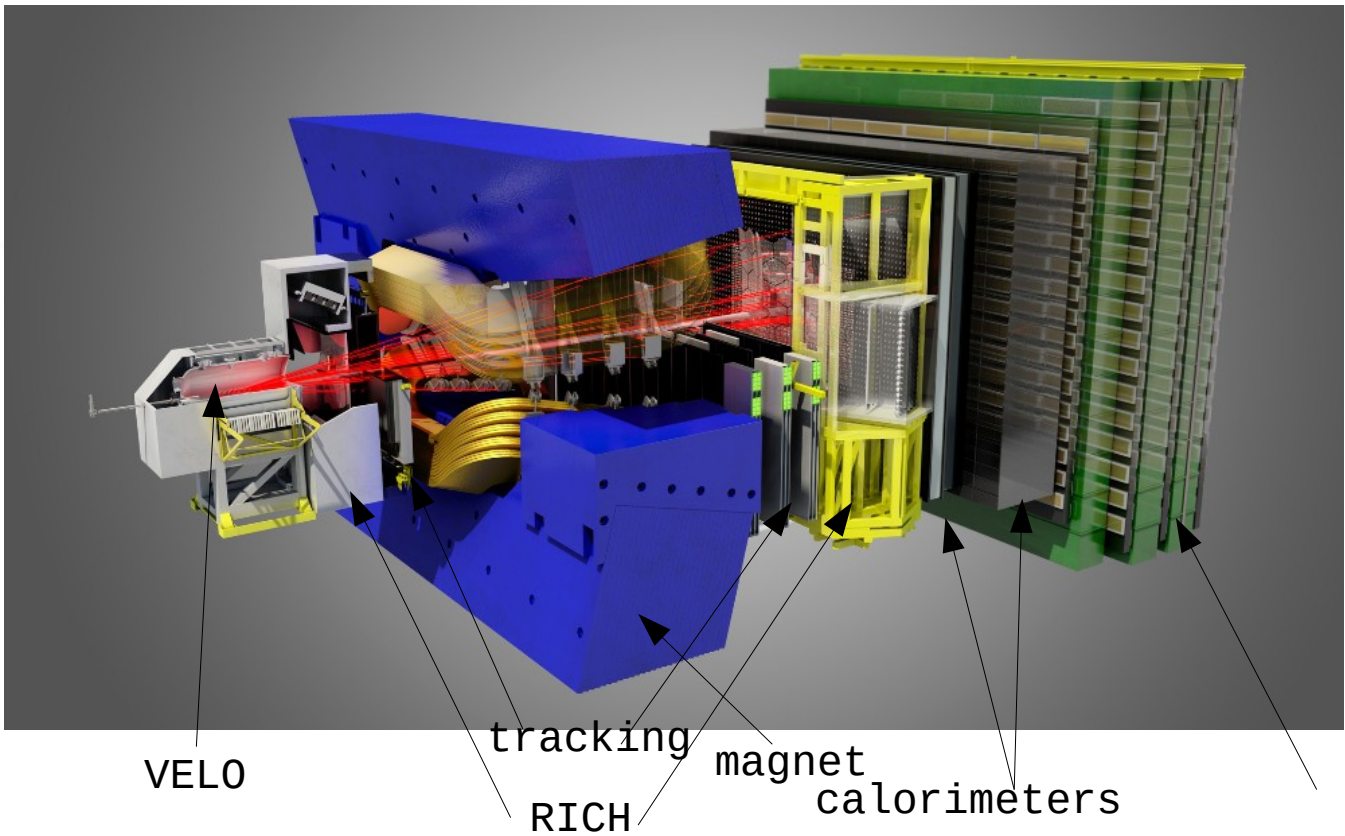
Observable	± 2 σ
A	0.825 [+0.014 -0.027]
λ	0.22509 [+0.00059 -0.00058]
ρbar	0.160 [+0.024 -0.014]
ηbar	0.350 [+0.015 -0.015]

Existe uma solução consistente com a proposta de CKM!!!

$\not{CP}$: $B^{\pm}\rightarrow hhh(h=K^{\pm},\pi^{\pm})$ no LHCb

- **LHCb:** um dos quatro experimetos LHC ●●(run1 pp @ ~7 TeV)
  ●●$\int L$ =3fb^{-1} (2011/2012)
- **objetivo principal:** física dos sabores e $\not{CP}$ ➡otimizado para mésons B (e D)●●alta estatística
- **participação brasileira:** CBPF, UFRJ, PUC-Rio,UFTM





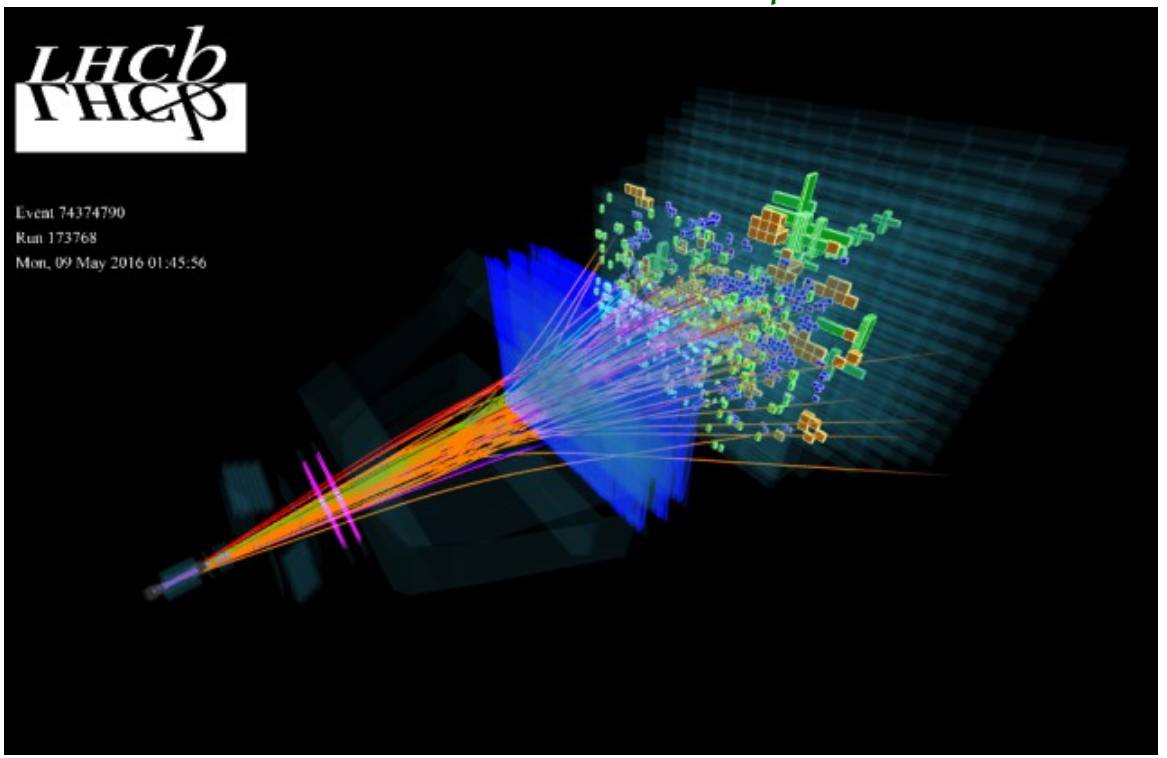
Jussara Miranda ● Salvador,BA,out/18

- $E=mc^2$ •• $m=m0\gamma$ •• $\gamma= 1/\sqrt{(1-v^2/c^2)}$

- numa colisão: **E** ➡ **m**

uma infinidade de partículas† são criadas e decaem para outras mais estáveis que deixam rastro nos detetores

evento típico do run 2 LHCb



- tipicamente podemos observar:
  $K^{\pm}$ $p^{\pm}$ $\pi^{\pm}$ $e^{\pm}$ $\mu^{\pm}$ γ

- "observar"‡: posição (traço; vértice)
  momento,
  carga,
  identidade

a cada colisão produz-se (em tempo real) uma lista de partículas observadas para definir se são ***potencialmente interessantes***

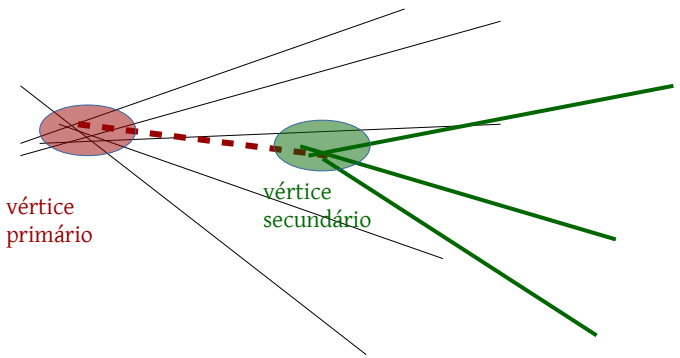
†todas as partículas de "interesse" não chegam aos detetores, as "reconstruimos" a partir do produto de seus decaimentos
‡medir com uma probablilidade ou erro

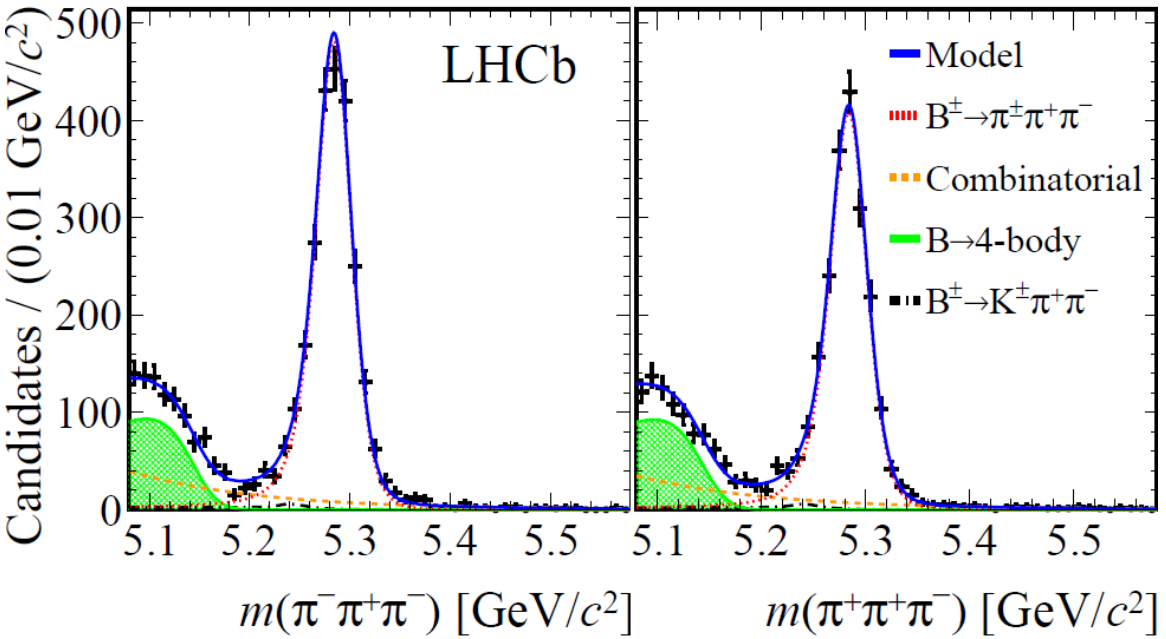
$\cancel{CP}$: $B^{\pm}\rightarrow hhh$ no LHCb

- quadrimomento : $p=(E/c,\mathbf{p})$
- massa invariante: $m^2c^2=p^2=E^2/c^2-\mathbf{p}^2$

- $M\rightarrow m_1,m_2$ ●● $M^2 = (E_1+E_2)^2 - |\mathbf{p}_1+\mathbf{p}_2|^2$

- **observação do sinal de interesse (B→ hhh)**: massa invariante da combinação de 3 traços carregados + **critérios de seleção†** para eliminar combinações espúrias (background)





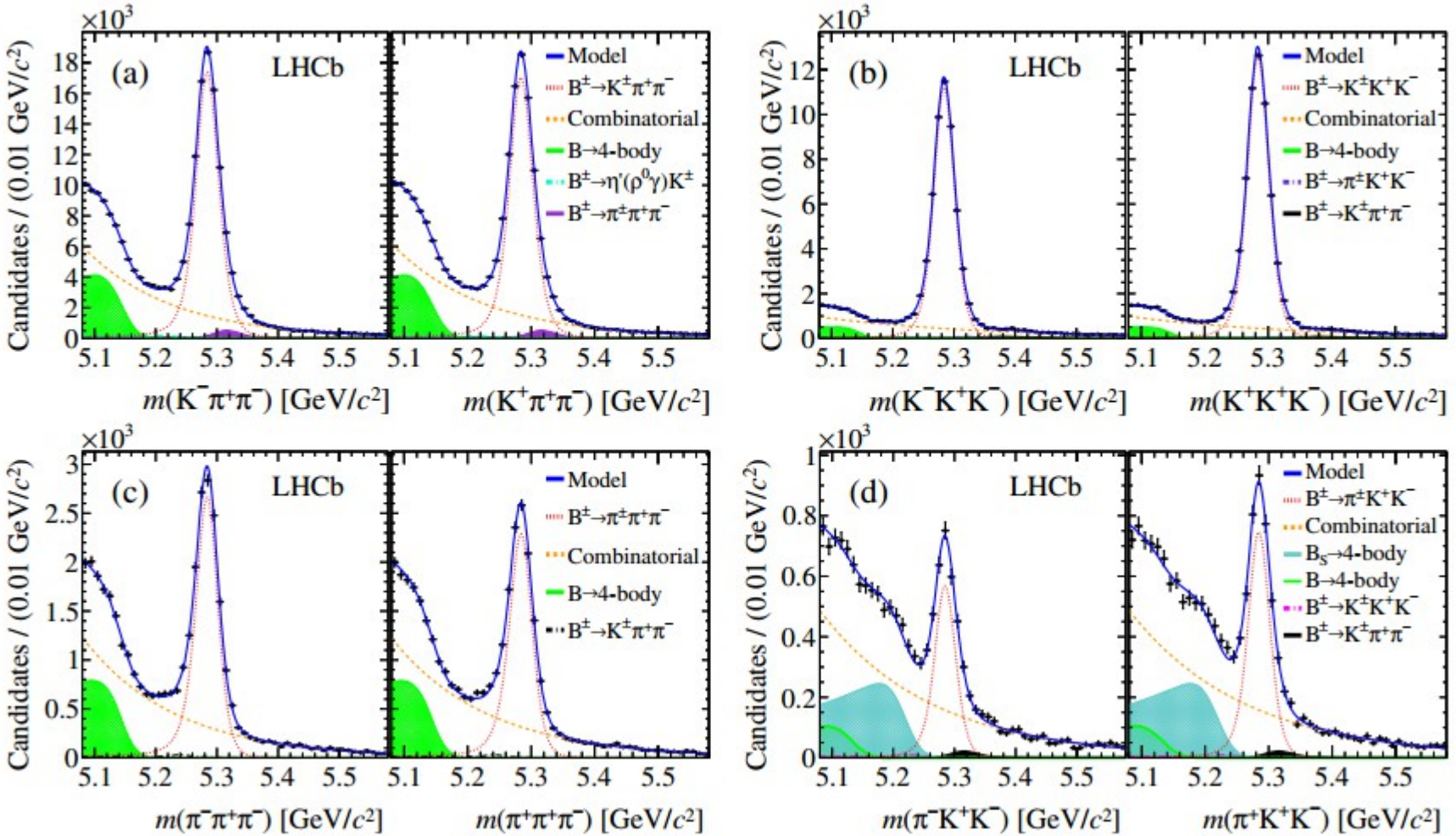
† que exploram as características do decaimento de interesse

$\not{CP}$: $B^{\pm}\to hhh$ no LHCb

● assimetria total CP

$$A_{CP} \equiv \frac{\Gamma[B^- \to f^-] - \Gamma[B^+ \to f^+]}{\Gamma[B^- \to f^-] + \Gamma[B^+ \to f^+]},$$

et al. PHYSICAL REVIEW D **90,** 112004 (2014)



$$A_{CP}(B^{\pm} \to K^{\pm}\pi^+\pi^-) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007, \quad A_{CP}(B^{\pm} \to \pi^{\pm}\pi^+\pi^-) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007,$$

$$A_{CP}(B^{\pm} \to K^{\pm}K^+K^-) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007, \quad A_{CP}(B^{\pm} \to \pi^{\pm}K^+K^-) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007,$$

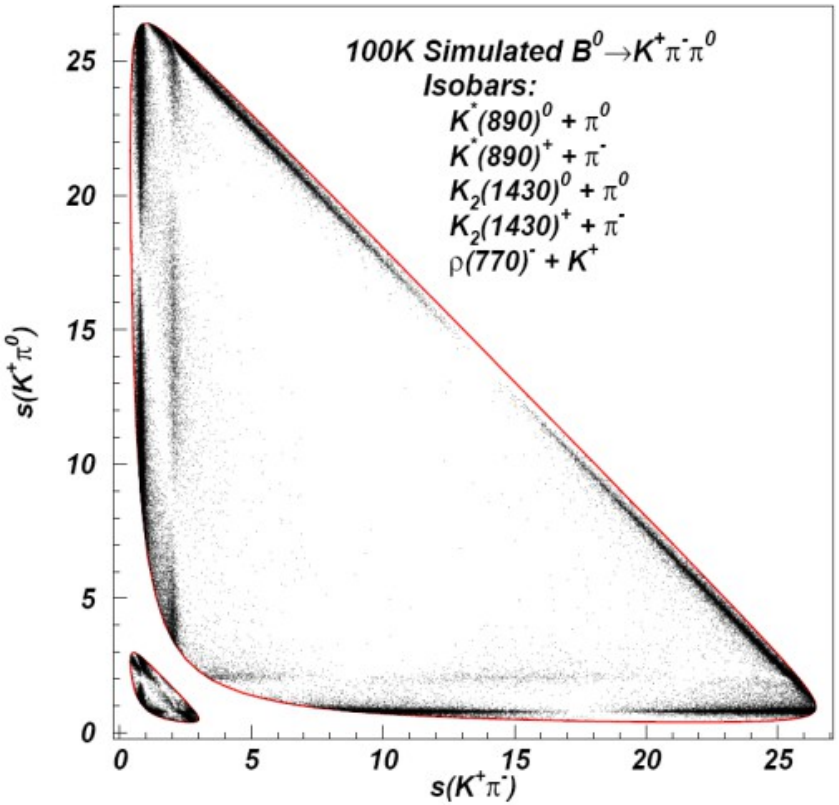
medida mais simples possível ... contagem de eventos

$\not{CP}$: $B^{\pm} \rightarrow hhh$ no LHCb

- elaborando... explorar $\not{CP}$ na dinâmica do decaimento
  ...estado **resonante** intermediário

- B → intermediate state → h_1, h_2, h_3

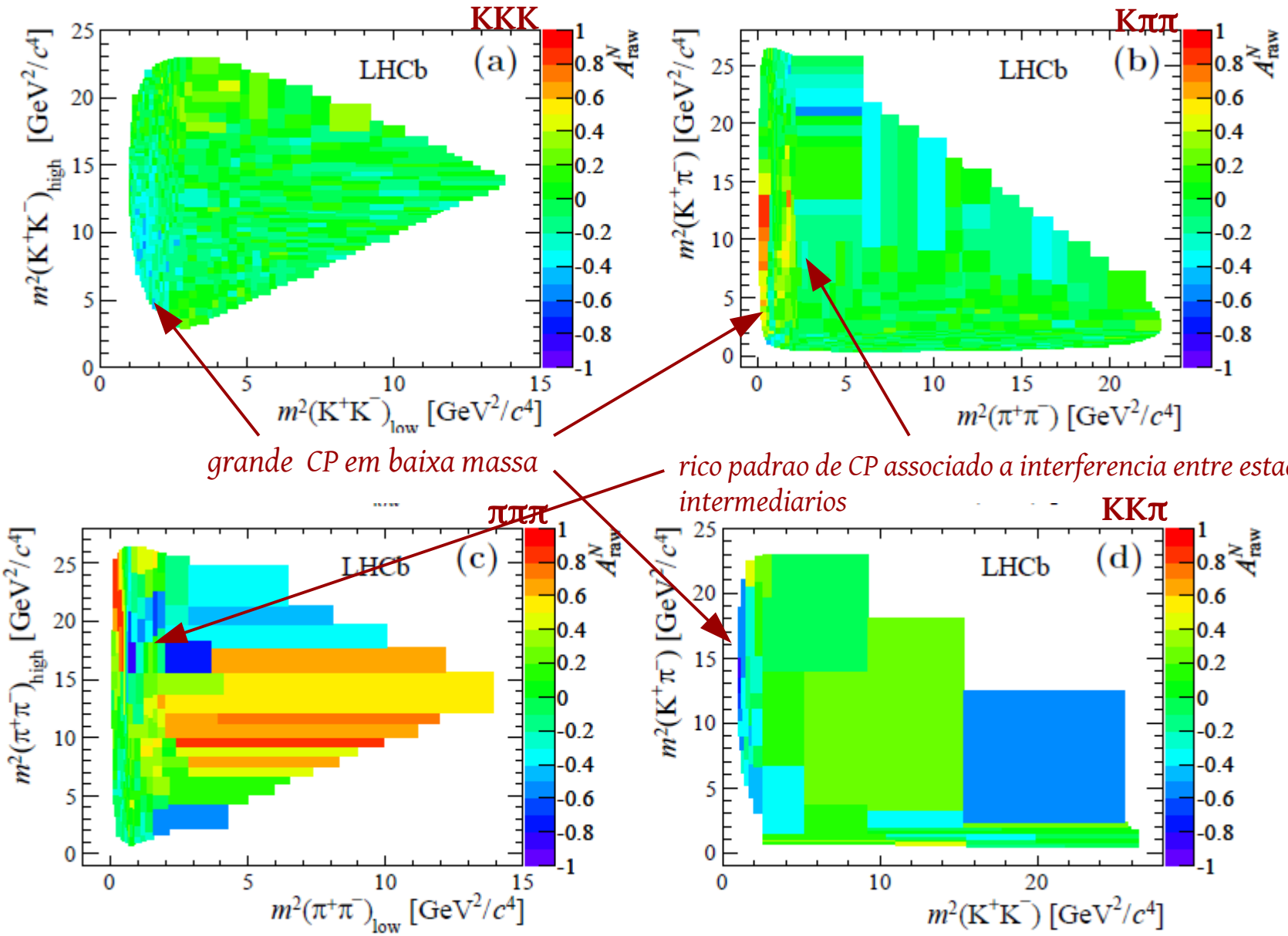
- sistema com dois graus de liberdade: m^2_{12} X m^2_{23}
- DALITZ PLOT :
  - m^2_{12} X m^2_{23} *é o espaço de fase do decaimento em 3 corpos*
  - "retrato" do decaimeto



- $d\Gamma(m^2_{12}, m^2_{23}) \propto |\mathcal{A}|^2 \, dm^2_{12} \, dm^2_{23}$

CP: $B^{\pm} \to hhh$ no LHCb

- medir a assimetria em regiões no espacço de fase....

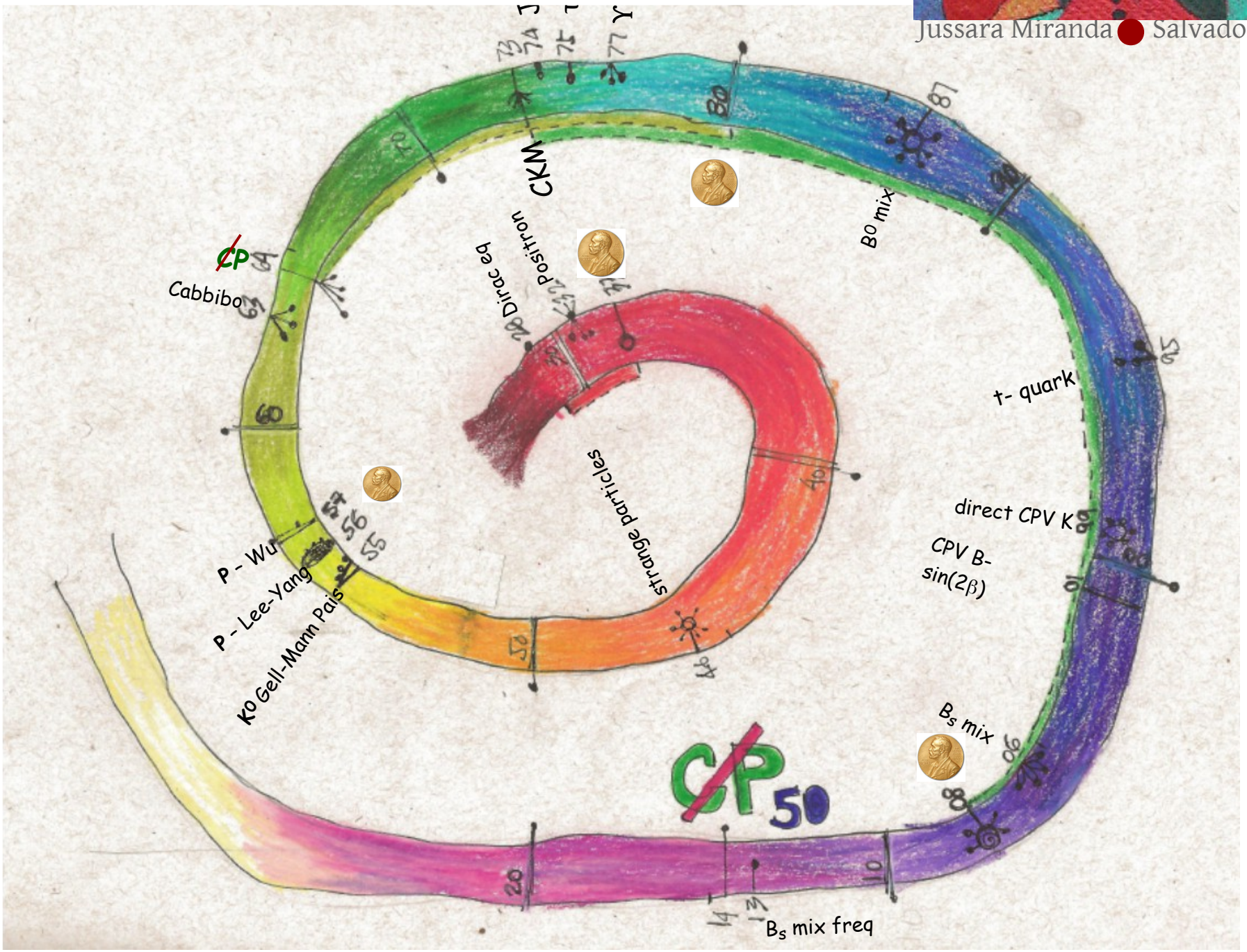


grande CP em baixa massa

rico padrao de CP associado a interferencia entre estados intermediarios

podemos elaborar ainda mais propondo um modelo de amplitude...

conclusões


CP
Cabbibo
CKM
Dirac eq
positron
B0 mix
t- quark
direct CPV K0
CPV B-
sin(2β)
Bs mix
Bs mix freq
strange particles
P - Wu
P - Lee-Yang
K0 Gell-Mann Pais
CP 50