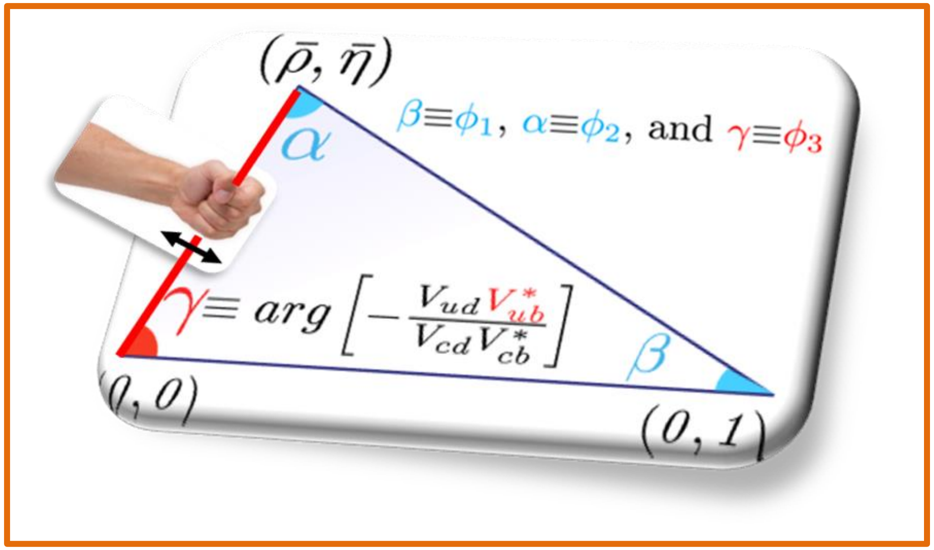
Heavy Flavour Physics: from CP violation to intensity frontiers, a new paradigm

V. Tisserand, LPC-Clermont Ferrand, France

Journées des 2 Infinis de l'IN2P3

October 2023, Monday 30th - Tuesday 31st



cnrs IN2P3 Les deux infinis

LPC Laboratoire de Physique de Clermont

UCA Université Clermont Auvergne

INTENSITY frontier GDR-InF

Credits to C. Agapopoulou, J. Charles, O. Deschamps, G. Dujany, S. Monteil, & L. Vale Silva.

Blaise Pascal 400 ans (1623-1662)

« Car, enfin, qu'est-ce que l'homme dans la nature ? Un néant à l'égard de l'infini, un tout à l'égard du néant, un milieu entre rien et tout. Infiniment éloigné de comprendre les extrêmes, la fin des choses et leur principes sont pour lui invinciblement cachés dans un secret impénétrable, également incapable de voir le néant d'où il est tiré, et l'infini où il est englouti. » (Blaise Pascal, Pensées, 1669)

Blaise Pascal 400 years (1623-1662)

"After all, what are humans in Nature? A nothingness with respect to infinity, a whole with respect to nothingness, a middle ground between nothing and everything. Infinitely far from comprehending extremes, the end of things and their principle are for him invincibly hidden in an impenetrable secret, equally incapable of seeing the nothingness from which he is drawn, and the infinity into which he is engulfed." Blaise Pascal (Thoughts, 1669)

Discrete Symmetries (CPT): why bothering ?

Among the ~ 20 Nobel Prizes in/around particle physics since WWII, seven are related to flavor transitions:

1957 Lee & Yang (theory of parity violation in weak currents)
1980 Cronin & Fitch (discovery of CP violation)
1988 Lederman (discovery of ν_μ and parity violation)
2002 Koshiba (discovery of neutrino oscillations)
2008 Kobayashi & Maskawa (mechanism of CP violation)
2013 Englert & Higgs (EW symmetry breaking)
2015 Kajita & McDonald (neutrino oscillations)

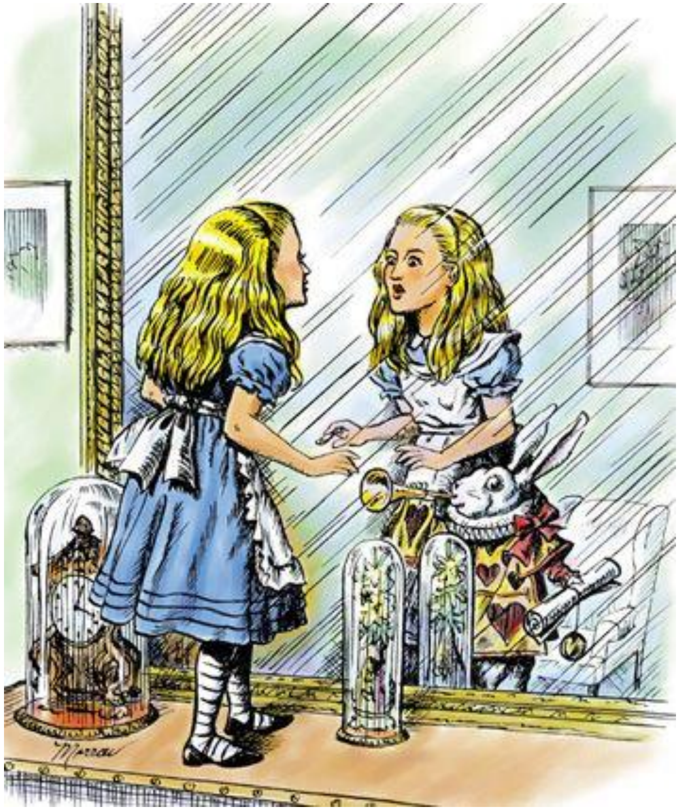
One could/should also mention:

1945: Pauli, 1949: Yukawa, 1959: Segrè & Chamberlain (anti-proton), 1960: Glaser (bubble chamber), 1965: Tomaga, Schwinger,& Feynman (QED), 1968: Alvarez (Accelerators), 1969: Gell-Mann (classification of hadrons and quarks!), 1976: Richter & Ting (the charm quark), 1978: Penzias & Wilson (cosmic ray background), 1979: Glashow, Salam, & Weinberg (EW), 1984: Rubbia & Van der Meer (W & Z), 1988: Lederman, Schwartz, & Steinberger (the neutrino mu), 1990 : Friedman, Kendall, & Taylor (dev. of quark model), 1992: Charpak (Drift Chambers), 1995: Perl & Reines (the lepton tau & neutrino detection), 1999: t'Hoft & Veltman (EW again), 2004: Gross, Politzer, & Wilczek (QCD).

→ a very important topic!

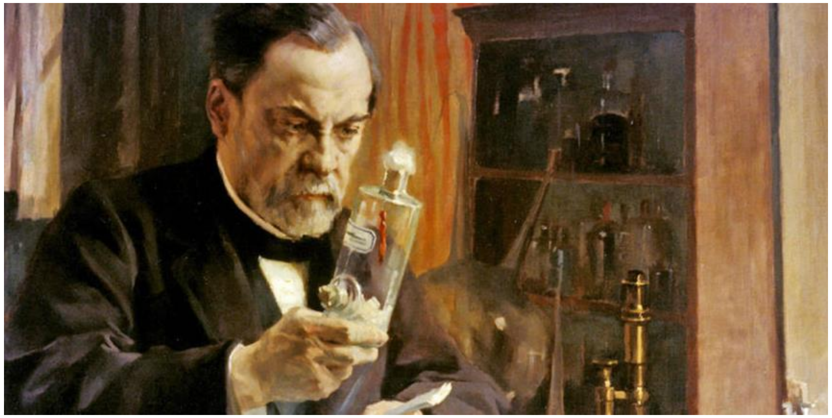
Discrete Symmetries (CPT)

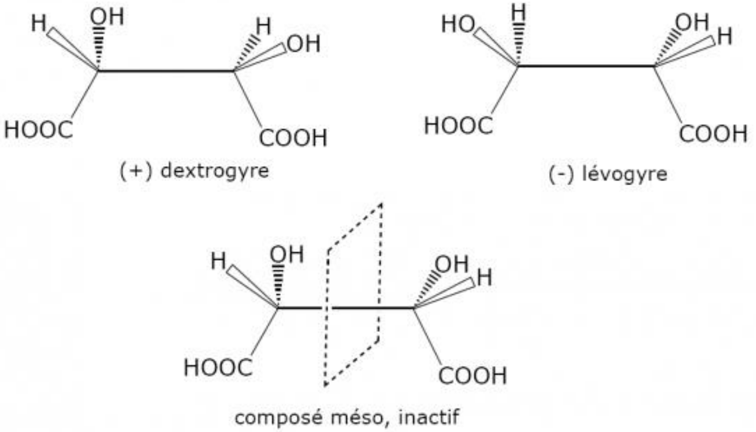
- **Parity:** is an event seen in a mirror as realistic as the original one?
- **Time reversal:** watching the film of an event backwards results in a realistic event?
- **Charge conjugation:** can we distinguish matter from antimatter?



Lewis Carroll (1871)
“Through the Looking-Glass, and What Alice Found There”

parity



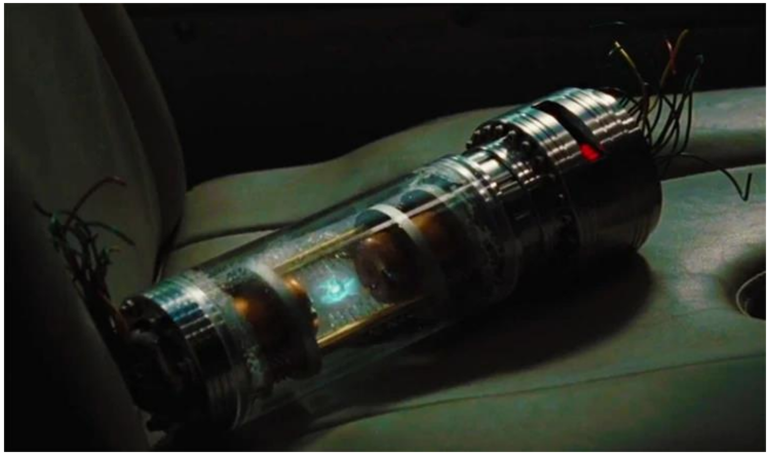


Louis Pasteur and the molecular chirality (1847-1856) [polarized light & crystallography]

Discrete Symmetries (CPT)

- **Parity:** is an event seen in a mirror as realistic as the original one?
- **Time reversal:** watching the film of an event backwards results in a realistic event?
- **Charge conjugation:** can we distinguish matter from antimatter?

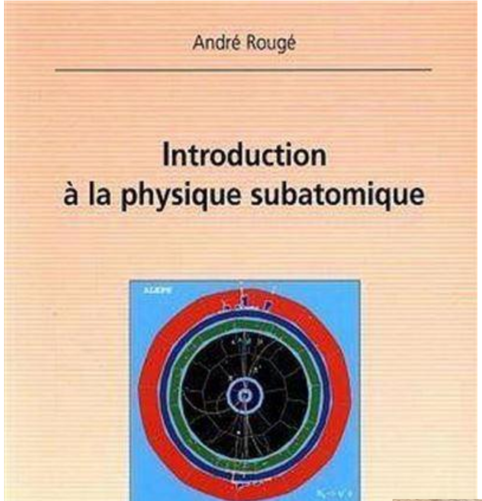
Anti-matter reactors/containers



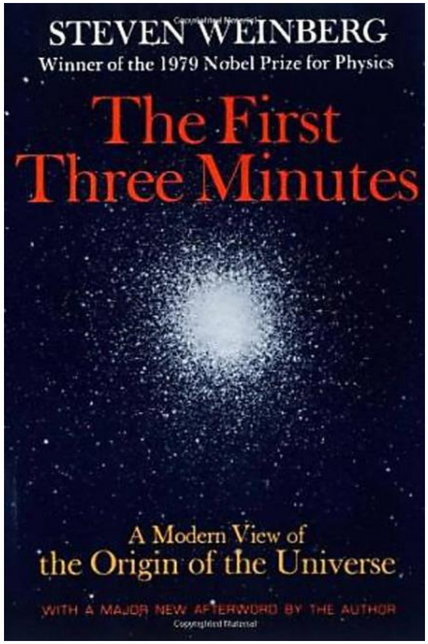
Time reversal machines

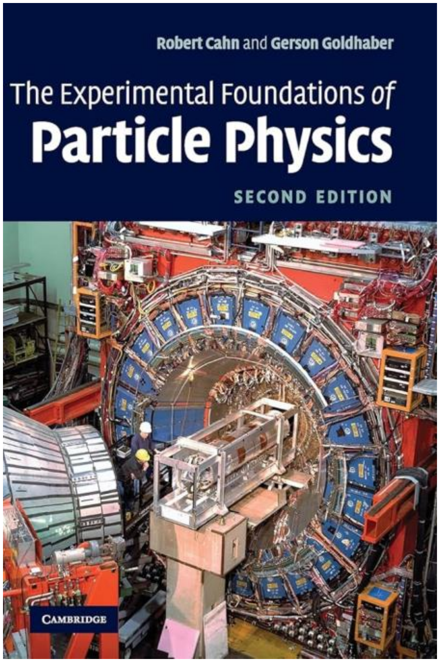
Discrete Symmetries (CPT): Some readings

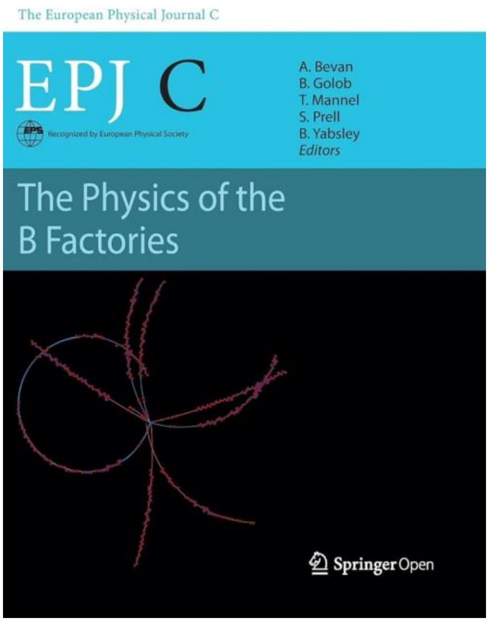
- Parity
- Time reversal
- Charge conjugation

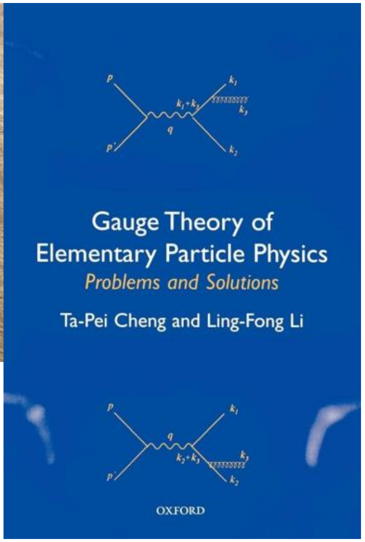


Tomes 1 & 2









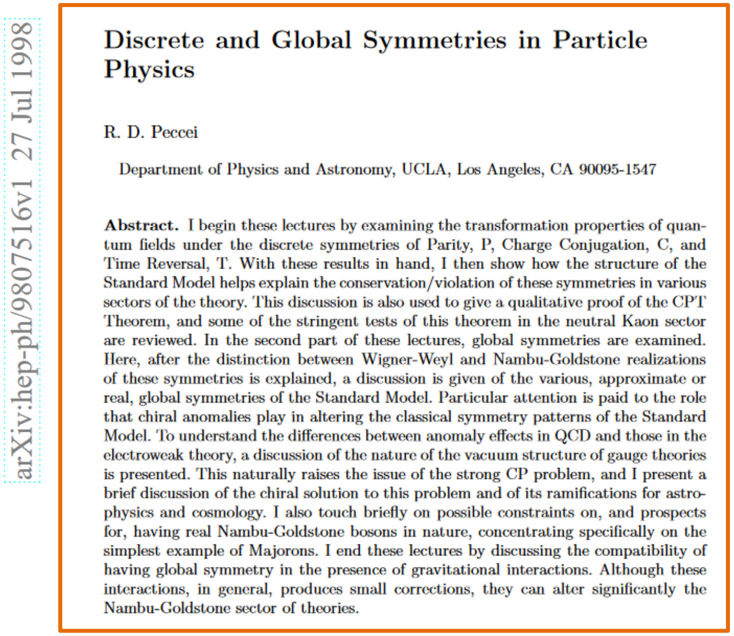
World Averages & Global Fits:

- Particle Data Group:
  https://pdg.lbl.gov/index.html
- Heavy Flavour Averaging Group:
  https://hflav.web.cern.ch
- CKMfitter:
  http://ckmfitter.in2p3.fr
- UTFit:
  http://www.utfit.org

Discrete Symmetries (CPT)

- Parity
- Time reversal
- Charge conjugation

Some readings



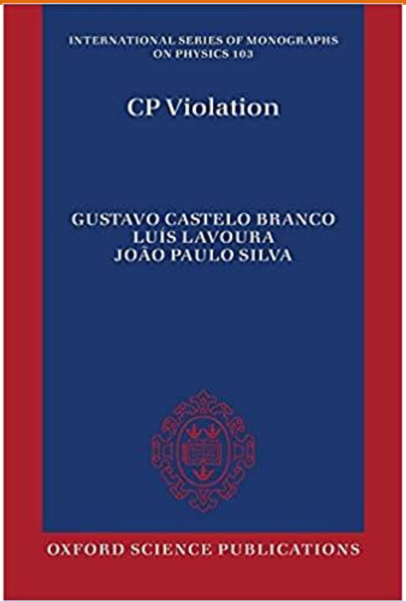
arXiv:hep-ph/9807516v1 27 Jul 1998

Discrete and Global Symmetries in Particle Physics

R. D. Peccei

Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1547

Abstract. I begin these lectures by examining the transformation properties of quantum fields under the discrete symmetries of Parity, P, Charge Conjugation, C, and Time Reversal, T. With these results in hand, I then show how the structure of the Standard Model helps explain the conservation/violation of these symmetries in various sectors of the theory. This discussion is also used to give a qualitative proof of the CPT Theorem, and some of the stringent tests of this theorem in the neutral Kaon sector are reviewed. In the second part of these lectures, global symmetries are examined. Here, after the distinction between Wigner-Weyl and Nambu-Goldstone realizations of these symmetries is explained, a discussion is given of the various, approximate or real, global symmetries of the Standard Model. Particular attention is paid to the role that chiral anomalies play in altering the classical symmetry patterns of the Standard Model. To understand the differences between anomaly effects in QCD and those in the electroweak theory, a discussion of the nature of the vacuum structure of gauge theories is presented. This naturally raises the issue of the strong CP problem, and I present a brief discussion of the chiral solution to this problem and of its ramifications for astrophysics and cosmology. I also touch briefly on possible constraints on, and prospects for, having real Nambu-Goldstone bosons in nature, concentrating specifically on the simplest example of Majorons. I end these lectures by discussing the compatibility of having global symmetry in the presence of gravitational interactions. Although these interactions, in general, produce small corrections, they can alter significantly the Nambu-Goldstone sector of theories.



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CP Violation

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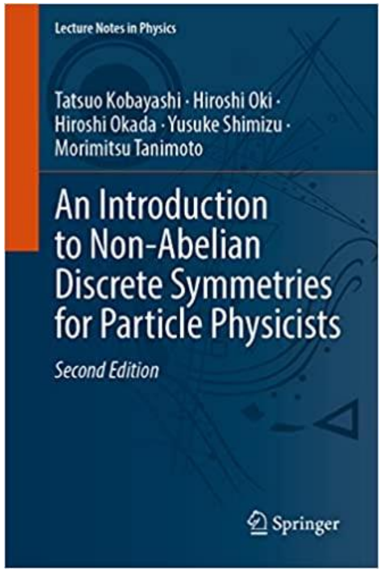
OXFORD SCIENCE PUBLICATIONS



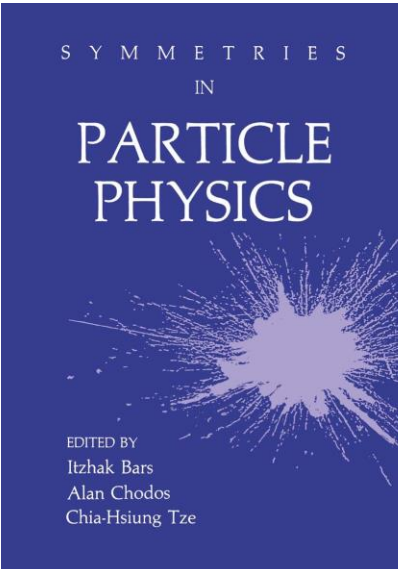
Lecture Notes in Physics

Tatsuo Kobayashi · Hiroshi Oki · Hiroshi Okada · Yusuke Shimizu · Morimitsu Tanimoto

An Introduction to Non-Abelian Discrete Symmetries for Particle Physicists

Second Edition

Springer



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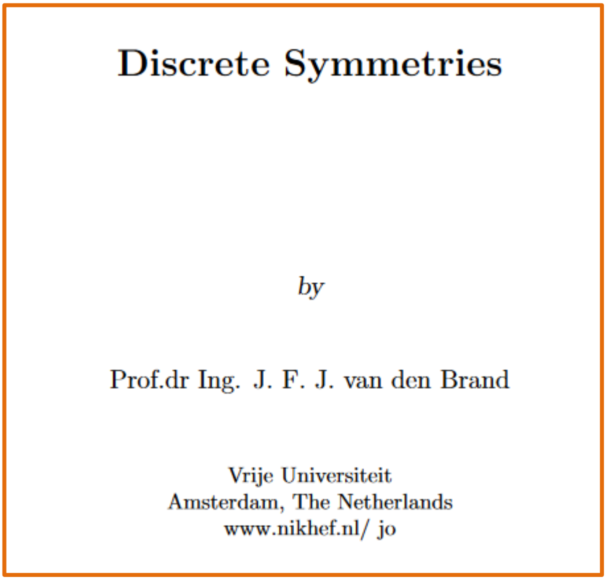


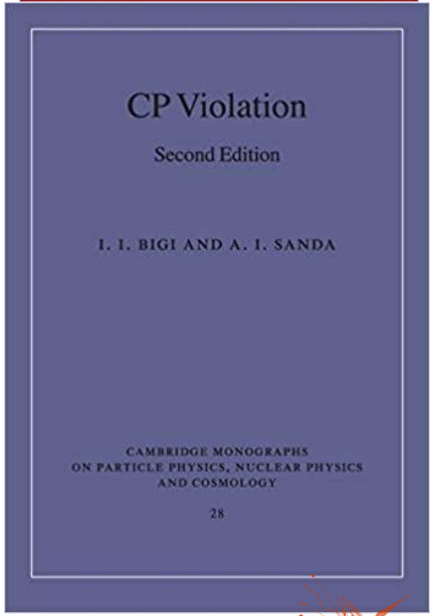
Discrete Symmetries

by

Prof.dr Ing. J. F. J. van den Brand

Vrije Universiteit
Amsterdam, The Netherlands
www.nikhef.nl/ jo

Includes problems and solutions



CP Violation

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CAMBRIDGE MONOGRAPHS ON PARTICLE PHYSICS, NUCLEAR PHYSICS AND COSMOLOGY

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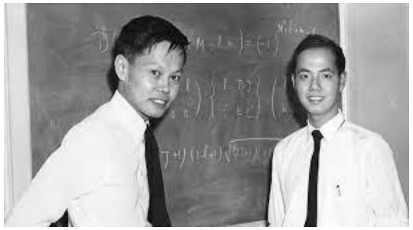
Discrete Symmetries (CPT): a bit of history (how was this built?)

- **E. Noether's** first theorem **(1915)** states that every differentiable symmetry of the action of a physical system with conservative forces has a corresponding conservation law.
- **('32) C.D. Anderson & P.A.M. Dirac** the positive electron (*positron*): antiparticles exist !
- CPT invariance theorem **J. Wigner ('51) + G. Lüders & W. Pauli ('54) + J.S. Bell ('55)**

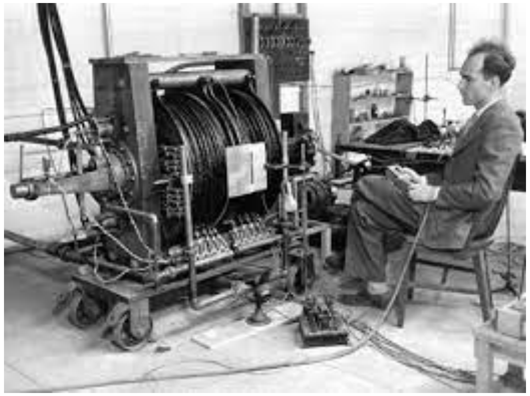


Just after **T.-D.Yang & C.-N.Lee**
The experiments of Particle-Nuclear physicist **C.-S. Wu ('57) and M. Goldhaber ('58)** proved that weak interactions are not P-invariant.

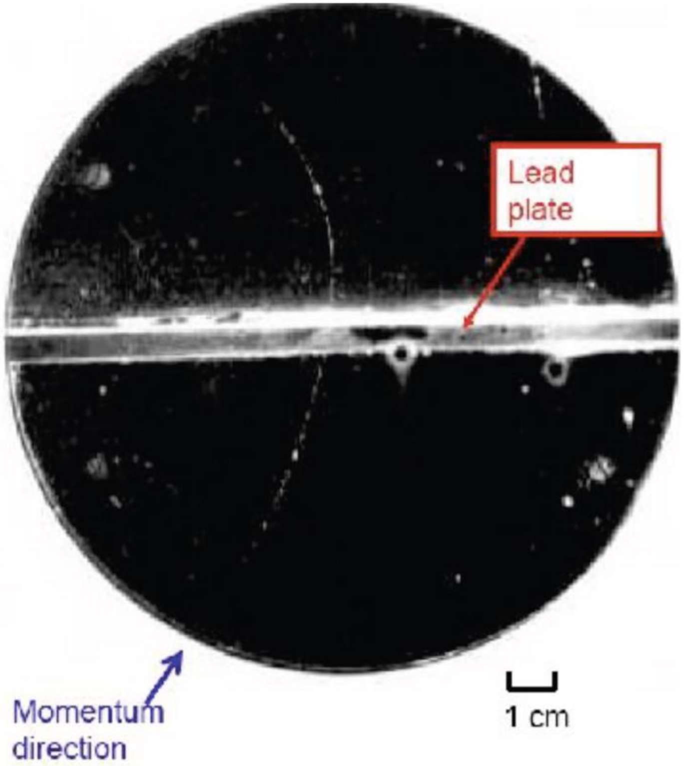
The Tau-Theta puzzle(60s), **R.Dalitz**, **N. Cabibbo's** mixing angle λ ('63) & Evidence for CP violation in the decay of neutral K-mesons observed by **J. Cronin & V. Fitch ('64)+ J.H. Christenson, & R. Turlay**

Anti-matter exits !

- **In 1929, P.A.M. Dirac solves the free motion of a relativistic spin 1/2 particle (electron or proton).** It happened that there should exist a solution of negative energy, which he interpreted as an antiparticle.
- **Anderson at work: discovery of the positron in 1932.**



- The radius of curvature is smaller above the plate. The particle is slowed down in the lead → the particle is incoming from the bottom.
- The magnetic field direction is known:
  → positive charge
- From the density of the drops one can measure the ionizing power of the particle→ minimum ionizing particle.
- Similar ionizing power before and after the plate → same particle on the 2 sides.
- Curvature measurement after the lead: particle of ~23MeV → it is not a non-relativistic proton because it would have lost all its energy after ~5mm (a track of ~5 cm is observed).



The C, P, and T symmetries

The Standard Model has been defined without imposing by hand global nor discrete symmetries; still, these symmetries are present, *e.g.* baryonic and leptonic global continuous symmetries, and *CPT* discrete symmetry from general properties of local and Lorentz-invariant Quantum Field Theories (Schwinger, Lüders & Pauli).

C is the charge conjugation transformation particle $\leftrightarrow$ antiparticle

P is the spatial parity transformation $(t, \mathbf{x}) \to (t, -\mathbf{x})$

T is the time reversal transformation $(t, \mathbf{x}) \to (-t, \mathbf{x})$

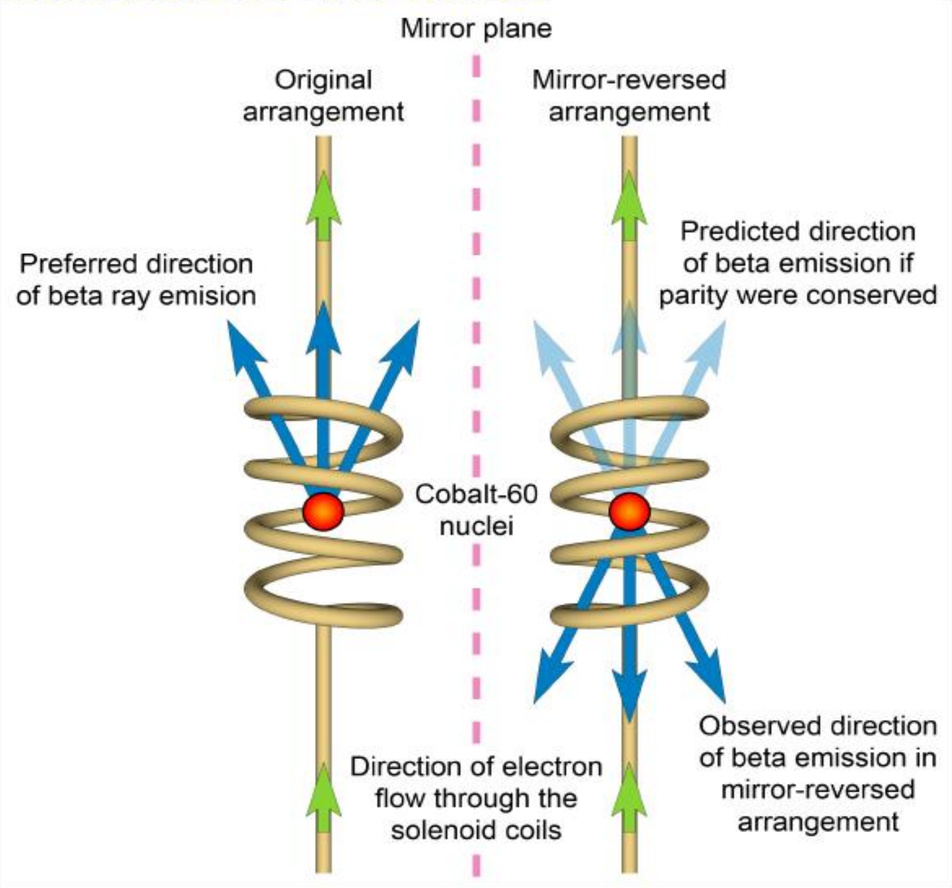
the product *CPT* is a mathematical exact invariance of any "viable" quantum field theory

The precise transformation rules for the fields can be found in textbooks.

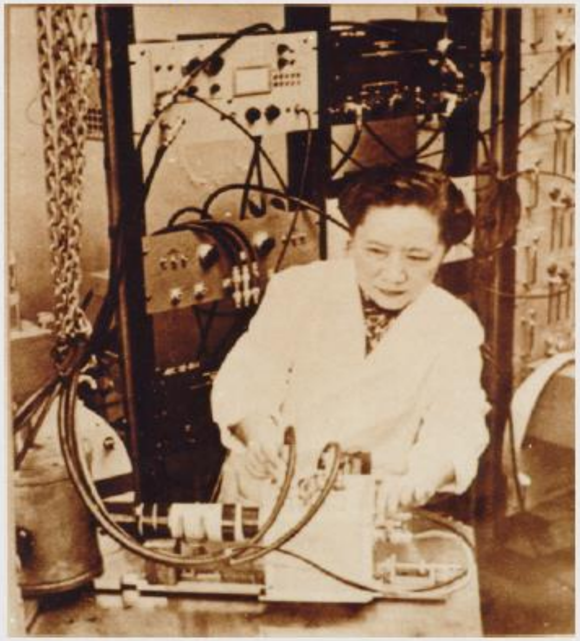
Intuitively the distinction between left and right could be thought as a human invention, and so fundamental physics was postulated to be *P*-invariant.

Parity violation in Cobalt weak decay

This is however not true (not even macroscopically: there are chiral molecules with chirality-dependent biological properties): weak interactions are chiral.



Wu experiment 1956-57



Immediately confirmed by Lederman & Garwin in pion decay by measuring muon magnetic moments

+ $\Gamma(\pi^+ \to e^+ \nu_e)/\Gamma(\pi^+ \to \mu^+ \nu_\mu) = (1.230 \pm 0.004) \times 10^{-4}$

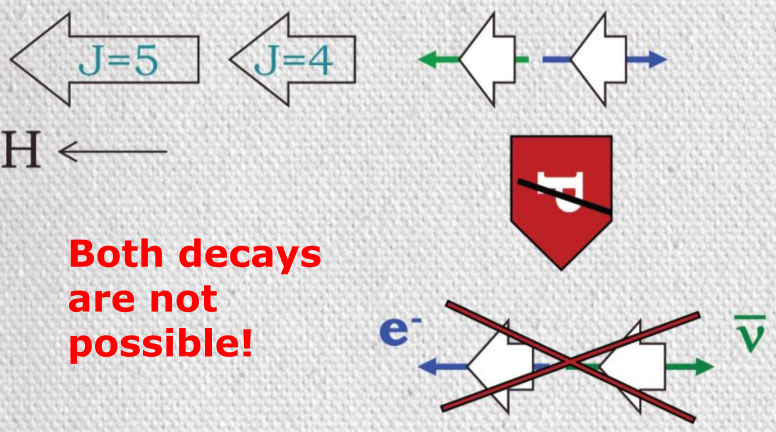
➔ V-A interactions (helicity suppression) [LINK]

(see also B^0 to $l^+\nu$ decays !)

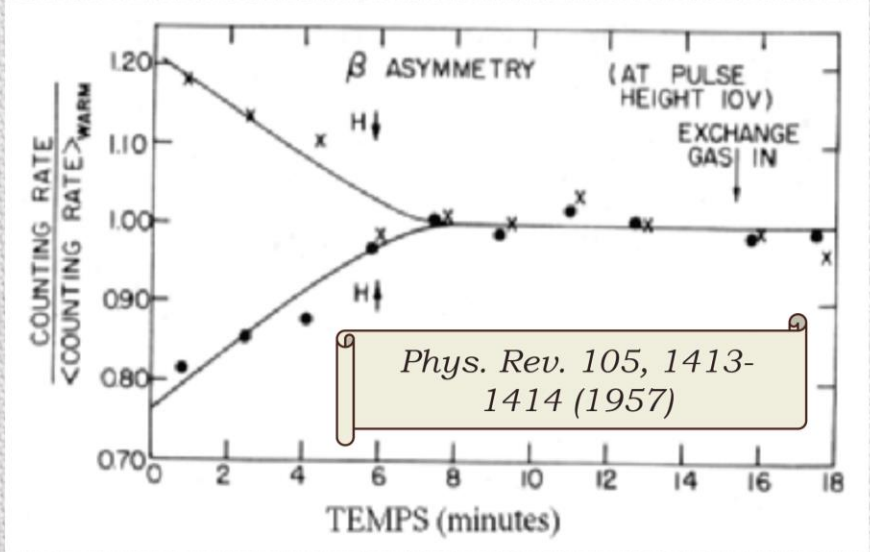
Parity violation in weak interaction

- C.S. Wu experiment (1957)

$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}^* + \bar{\nu} + e^-$



Both decays are not possible!



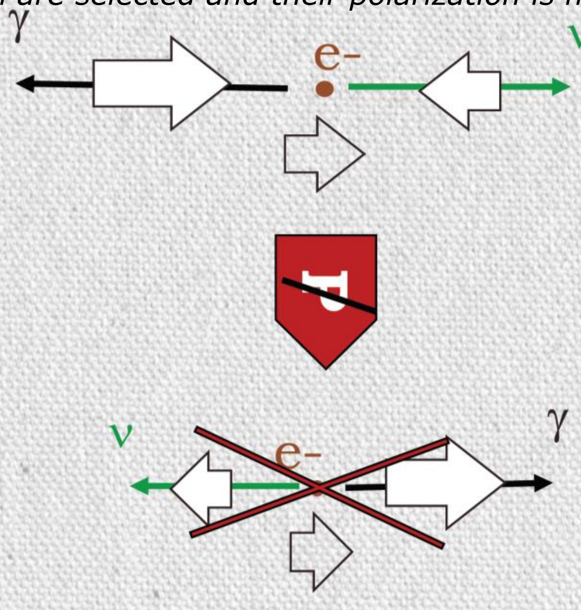
Phys. Rev. 105, 1413-1414 (1957)

- Goldhaber experiment (1958)

$^{152}\mathrm{Eu}\ (J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*\ (J=1) + \nu$

$\rightarrow {}^{152}\mathrm{Sm}\ (J=0) + \gamma + \nu$

The spins of all final state particles are constrained. The gammas aligned with the ^{152}Sm are selected and their polarization is measured.



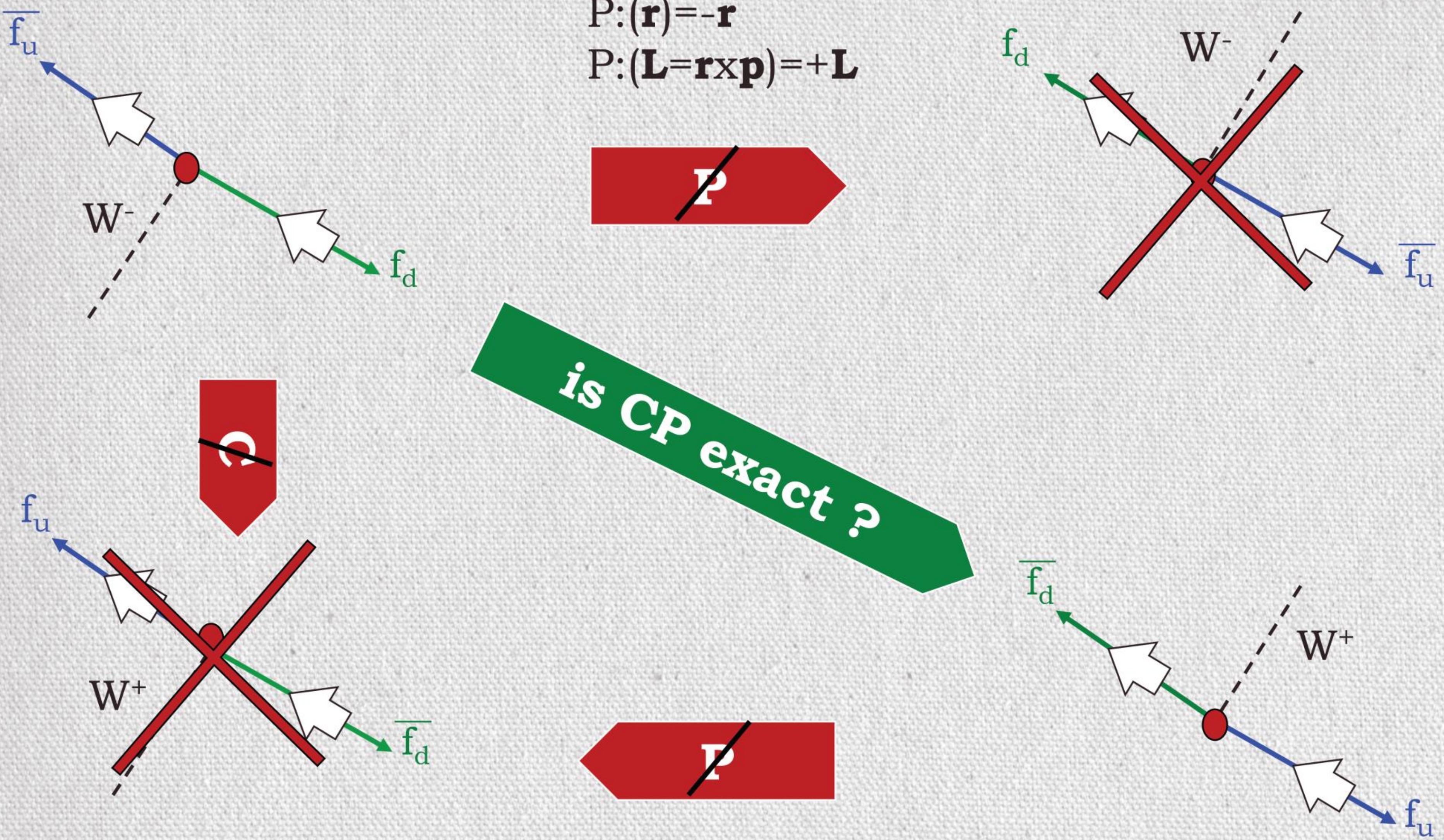
Phys. Rev. 109, 1015 (1958)

Neutrinos are definitely left-handed!

Lee, Yang Nobel 1957

Weak interaction maximally violates C and P

Is CP an exact symmetry ?



P:(**r**)=-**r**

P:(**L**=**r**x**p**)=+**L**

Well, it's a good symmetry in π decay !

$$\Gamma(\pi^+ \to \ell^+ \nu_\ell) = \Gamma(\pi^- \to \ell^- \bar{\nu}_\ell)$$

MIXING of neutral mesons

$$\left|F_{L(H)}\right\rangle = p\left|F^0\right\rangle \pm q\left|\bar{F}^0\right\rangle$$

$$\text{if } \left|\frac{q}{p}\right| = 1 \;\Rightarrow\; \mathcal{P}\left[F^0(t) \to \bar{F}^0\right] = \mathcal{P}\left[\bar{F}^0(t) \to F^0\right] = \left|g_-(t)\right|^2$$

CP is conserved in mixing

$$|q|^2 + |p|^2 = 1 \;\Rightarrow\; \frac{q}{p} = e^{i\theta} \text{ and } |q| = |p| = 1/\sqrt{2}$$

$$\left|F_L\right\rangle = \frac{\left|F^0\right\rangle + e^{i\theta}\left|\bar{F}^0\right\rangle}{\sqrt{2}}$$

$$\left|F_H\right\rangle = \frac{\left|F^0\right\rangle - e^{i\theta}\left|\bar{F}^0\right\rangle}{\sqrt{2}}$$

The physical states are eigenstates of the *CP* operator (and orthogonal)

$$(CP)^2\left|f\right\rangle = \left|f\right\rangle \;\Rightarrow\; \text{eigenvalues : } \sigma_{CP} = \pm 1$$

$$\mathrm{CP}\left|F^0\right\rangle = e^{i\kappa}\left|\bar{F}^0\right\rangle$$

$$\mathrm{CP}\left|\bar{F}^0\right\rangle = e^{-i\kappa}\left|F^0\right\rangle$$

Arbitrary phase in the *CP* operator

With κ=Θ

$$CP\left|F_L\right\rangle = +\left|F_L\right\rangle$$

$$CP\left|F_H\right\rangle = -\left|F_H\right\rangle$$

$$\left[CP, \hat{H}\right] = 0$$

Experimentally :

Slight CP-violation **is observed in K⁰ mixing**

No *CP*-violation observed **in B⁰ and B$_s$ mixing**

$$1 - \left|\frac{q}{p}\right| = \begin{cases} K^0 & : +(4.448 \pm 0.024) \times 10^{-3} \\ B^0 & : -(1.0 \pm 0.8) \times 10^{-3} \\ B_s & : -(0.3 \pm 1.4) \times 10^{-3} \end{cases}$$

Discovery of CP violation in the MIXING of neutral kaons

Cronin, Fitch (1964 – Nobel 1980)

AGS – Brookhaven National Laboratory

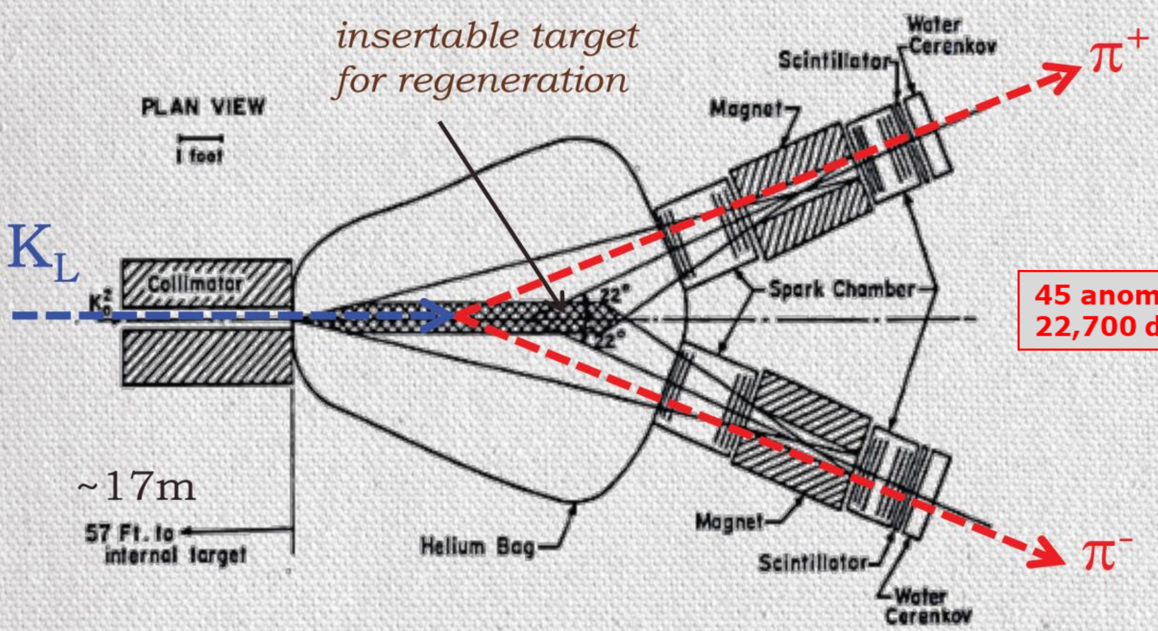
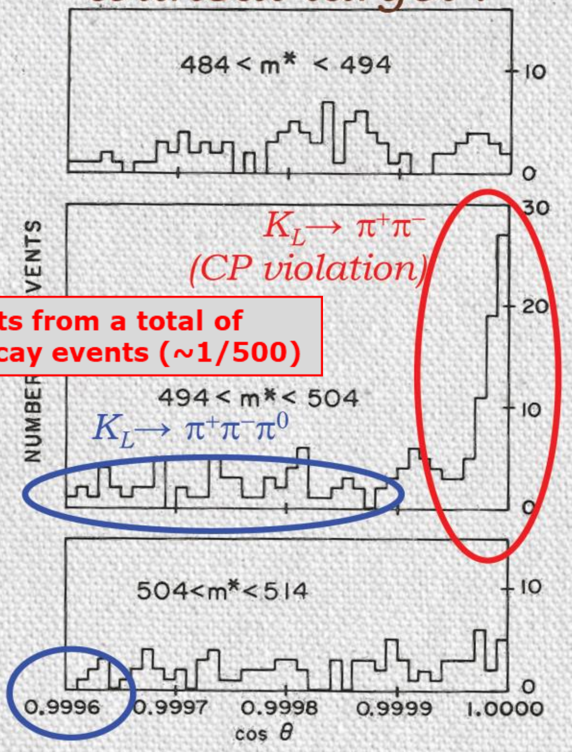


Fig. 9a. Set-up used to detect $K_2 \to \pi^+\pi^-$.

Phys. Rev. Lett. 13, 138 (1964)

without target !



45 anomalous events from a total of 22,700 detected decay events (~1/500)

FIG. 2.3. Forward angular distributions for three ranges of m^*, found by Christenson et (1964).

K_S regeneration experiment (insertable target)

$n \to K^0 n$ (mostly elastic scattering)

$$|K_L\rangle \sim \left(|K^0\rangle - |\bar{K}^0\rangle\right)/\sqrt{2}$$

$n \to \Lambda\pi^0$

$\bar{K}^0$ is absorbed faster than K^0 in matter (destroying K_L coherence) → K^0 remains → K_S is back (mixed with K_L)

Discovery of CP violation in the MIXING of neutral kaons

Physical states

(denoted Short and Long)

$K_S \to \pi\pi \qquad \tau_{K_S} \sim 89\,ps$

$K_L \to \pi\pi\pi \qquad \tau_{K_L} \sim 51\,ns$

$$CP|\mathrm{n}\pi\rangle = (-1)^{\mathrm{n}}|\mathrm{n}\pi\rangle$$

CP eigenstates :

$$\sqrt{2}|K_{CP=+1}\rangle = |K^0\rangle + |\bar{K}^0\rangle$$

$$\sqrt{2}|K_{CP=-1}\rangle = |K^0\rangle - |\bar{K}^0\rangle$$

$$CP|K^0_\pm\rangle = \pm|K^0_\pm\rangle$$

If *CP* is conserved :

$K_S = K_{CP=+1} \to \pi\pi$

$K_L = K_{CP=-1} \to \pi\pi\pi$

Observation of

$$K^0_L \to \pi^+\pi^-$$

CP is (slightly) violated in K^0 system

$$|\eta_{+-}| = \left|\frac{A(K^0_L \to \pi^+\pi^-)}{A(K^0_S \to \pi^+\pi^-)}\right| = (2.232 \pm 0.011)\times 10^{-3}$$

Are CP-eigenstates mixed in physical states ?

$$|K_S\rangle = p|K^0\rangle + q|\bar{K}^0\rangle = \left(|K_{CP=+1}\rangle + \varepsilon_K|K_{CP=-1}\rangle\right)\Big/\sqrt{1+|\varepsilon_K|^2}$$

$$|K_L\rangle = p|K^0\rangle - q|\bar{K}^0\rangle = \left(|K_{CP=-1}\rangle + \varepsilon_K|K_{CP=+1}\rangle\right)\Big/\sqrt{1+|\varepsilon_K|^2}$$

$$\Rightarrow \frac{q}{p} = \frac{1-\varepsilon_K}{1+\varepsilon_K}$$

|q/p| differs from 1
→ CPV in mixing !

$$|\varepsilon_K| = (2.228 \pm 0.011)\times 10^{-3} \approx |\eta_{+-}|$$

CP is (slightly) violated in K^0 **mixing**

Summary on Discovery of CP violation in the MIXING of neutral kaons

If P is not conserved, why not postulate that CP is the "correct" interpretation of the left-right symmetry ?

CP was also found to be violated in 1964 (Cronin & Fitch) in kaon decays.

$$|K^0\rangle = \bar{s}d\,, \qquad |\bar{K}^0\rangle = CP|K^0\rangle = s\bar{d}$$

CP-eigenstates

$$|K_\pm\rangle = (1/\sqrt{2})(|K^0\rangle \pm |\bar{K}^0\rangle)$$

If CP were conserved, only $K_+ \to \pi\pi$ and $K_- \to \pi\pi\pi$ would be allowed

$$K_\pm \equiv K_{S,L}, \qquad \tau(K_S) \ll \tau(K_L)$$

but $K_L \to \pi\pi$ was observed at the 10^{-3} level !

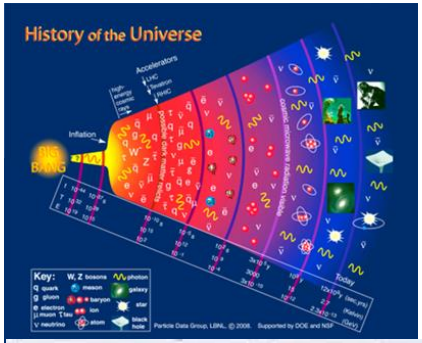
CP-asymmetries $\varepsilon_K \sim (K_L \to \pi\pi)/(K_S \to \pi\pi)$,

$\varepsilon' \sim (K_L \to \pi^+\pi^-) - (K_L \to \pi^0\pi^0)$

ε_K is indirect CP, while ε' comes from direct CP-violation in decay (found different from zero in 1999). See KTeV@FNAL and NA48@CERN

Discrete Symmetries (CPT): a bit of history (how was this built?)

HEP Big-Bang



A. Sakahrov conditions Cosmological baryongenesis ('67):

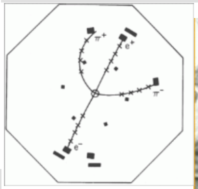
- Baryon number B violation.
- C-symmetry and CP-symmetry violation.
- Interactions out of thermal equilibrium.

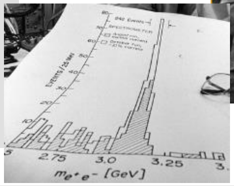
+ Kuzmin, Rubakov, Shaposhnikov '85

GIM Mechanism ('70)

M.K. Gaillard & B.W. Lee rare kaons **('74)**

➔ a VIP **(very important paper, a must read)**





The Charm of **B. Richter and S. Ting ('74)** J/ψ

Strong CP problem

Axion **('77) Peccei-Quinn**

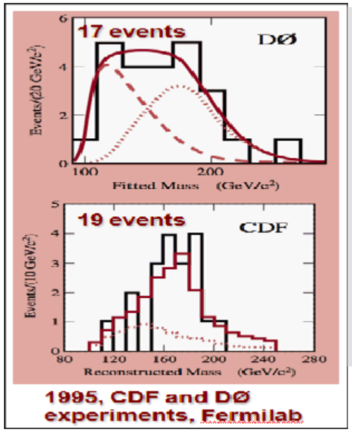
The beauty of **Lederman ('77)**

Oups Leon: ϒ

Kobayashi & Maskawa ('73)

B^0-B^0bar oscillation

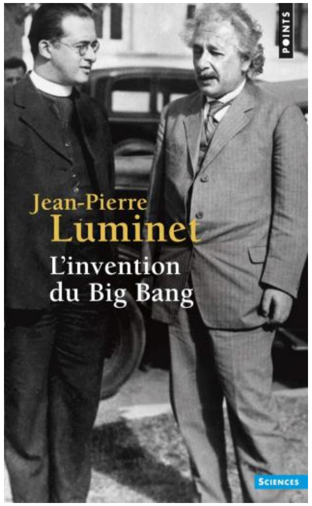
UA1 and Argus ('87): χ & Δm_d

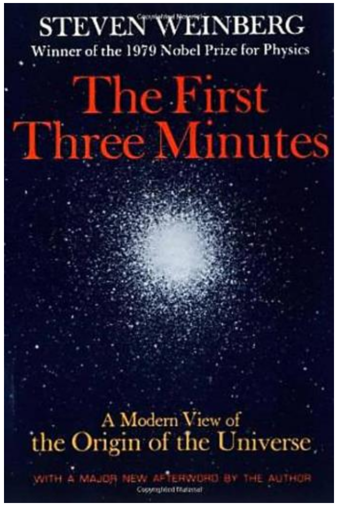


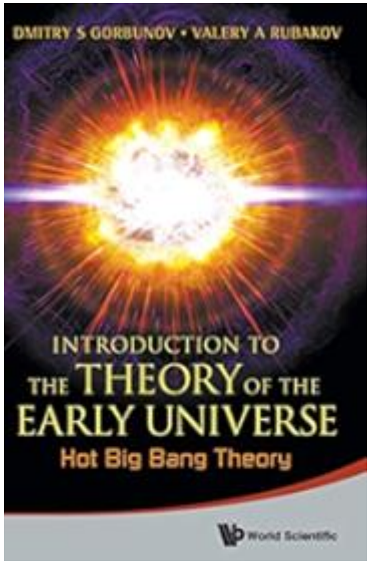
1995, CDF and DØ experiments, Fermilab

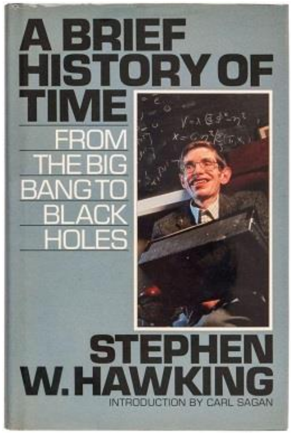
The top discovery at **FermiLab ('94) & CDF in 2006** measures the B_s oscillation Δm_s

About 3 minutes about the Big Bang









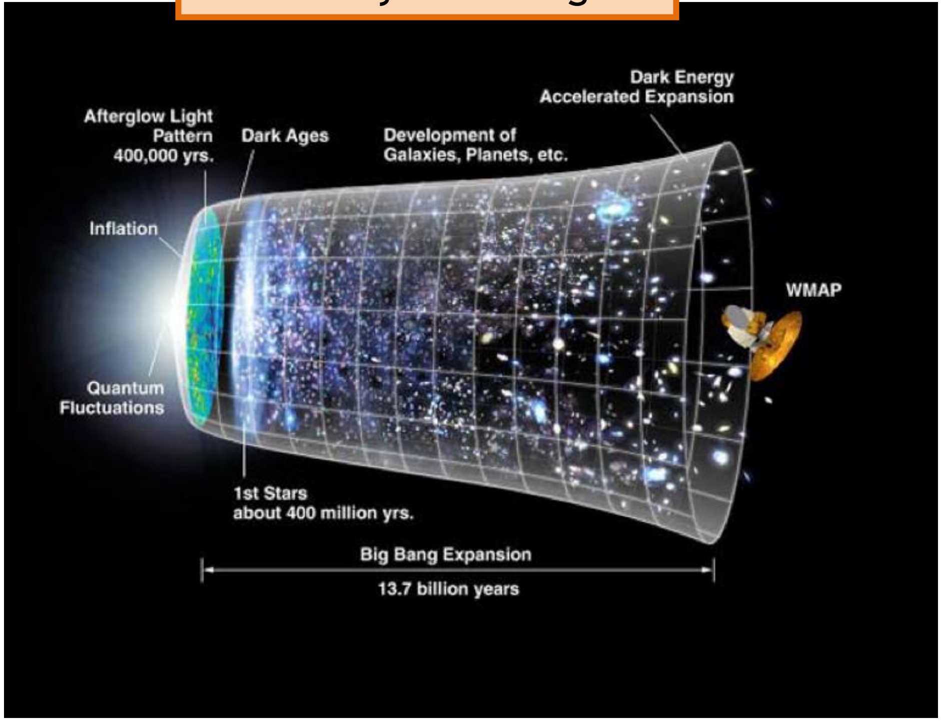
"Sorry Doc, we had a load of Anti-Matter around 13 billion years ago, but it got lost when we moved"

The Big Bang (expression by F. Hoyle at the BBC 1950)

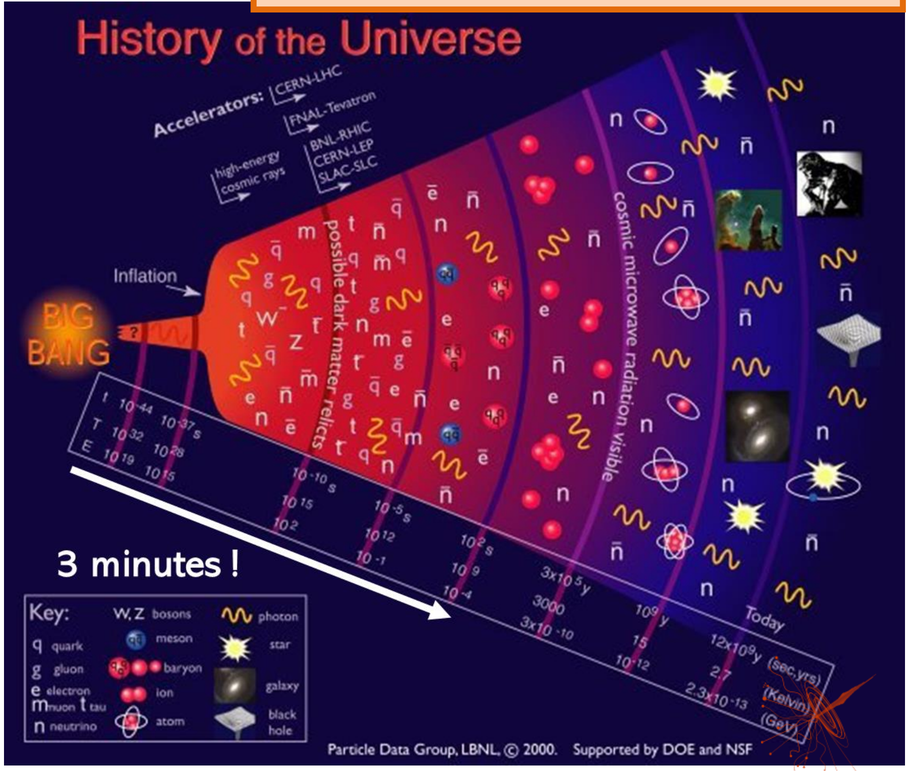
The cosmological model of the Big Bang, or the expansion of the Universe, was introduced by physicists A. Friedman and G. Lemaître in the 1920s, following Einstein’s theory of general relativity. It was later experimentally confirmed by astronomer E. Hubble in 1929 (RedShift), paper in 1948 by R. Alpher & G. Gamow on formation of elements in the early Universe (nucleosynthesis) and again in 1965 by A.A. Penzias and R.W. Wilson (a relic 3°K cosmic background radiation).

The fact that our Universe is mainly made of matter is then a quite long-standing enigma confronting the Big Bang theory, which naively predicts that the same amount of matter and anti-matter was evident in the early Universe.

As seen by cosmologists



As seen by subatomic physicists



Well, is CP-violation a fundamental phenomenon ?

A slight asymmetry matter / antimatter is enough to explain the matter dominance of our Universe

10,000,000,000 antiprotons or antineutrons… for
10,000,000,001 protons or neutrons.

Peace Nobel **prize 1975**

Because it is one of the three ingredients for baryogenesis (10^9 times more photons than baryons in the universe - vanishingly small quantities of antimatter): Sakharov 1967

1. baryon number violating interactions
2. *C*- and *CP*-violation
3. deviation from thermal equilibrium

Actually the SM interactions to be described later contain these ingredients, but in way too small quantities.

Warning: it is actually not proven that cosmological *CP*-violation has something to do with elementary particle physics.

See International Workshop on the Origin of Matter-Antimatter Asymmetry,
École de Physique des Houches, 12-17 February 2023

Is our Universe telling us something, is CP violation we observe large enough ?

- a key parameter to measure how badly/happily asymmetric is the situation. The ratio of baryons to photons. It is observed to be an apparently small number:

$$\boxed{n = \frac{N_b}{n_\gamma} \sim 10^{-10}}$$

- I choose here heuristic arguments to predict the baryon abundance from the magnitude of CP violation (using the Jarlskog parameter J~$\mathcal{O}(10^{-5})$, *don't worry we will be back on it soon*)

[A convincing derivation can be found in https://arxiv.org/pdf/hep-ph/9312215.pdf]:

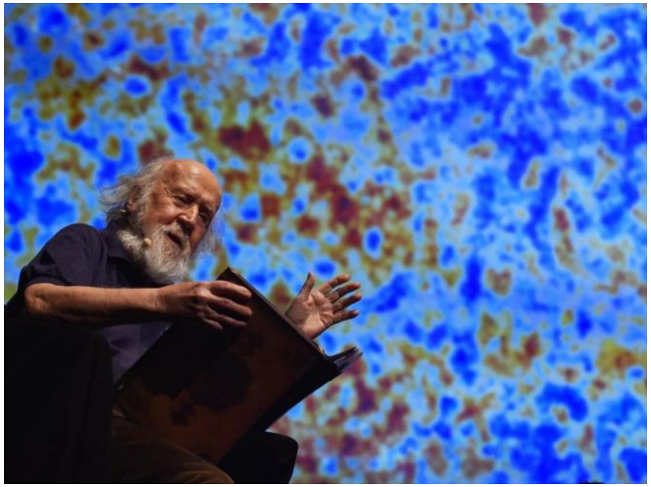
$$n \sim \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_t^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}{T_{\mathrm{EW}}^{12}} . J$$

$$n \sim 10^{-21}$$

Take home message ➔ The SM is short by several orders of magnitude to explain what we observe. There must be additional CP-violating phases / phenomena.

About 3 minutes about the Big Bang

« Une des plus grandes découvertes scientifiques est que l'Univers a une histoire. Depuis Aristote, on pensait l'Univers éternel et statique, existant depuis toujours et se répétant indéfiniment. Mais depuis le début du XX^{ème} siècle, on sait que l'Univers n'a pas toujours existé, qu'il a un âge et évolue. »

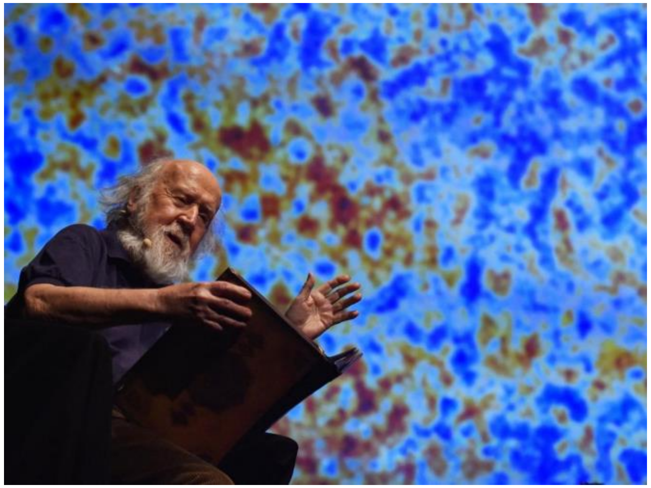


H. Reeves
(1932-2023)

About 3 minutes about the Big Bang

«One of the greatest scientific discoveries is that the Universe has a history. Since Aristotle, the Universe has been thought to be eternal and static, existing forever and repeating itself indefinitely. But since the beginning of the twentieth century, we know that the Universe has not always existed, that it has an age and is evolving. »

H. Reeves
(1932-2023)



CP-violation

There are 3 types of CP-violations !

- **CP-violation in mixing, or indirect CPV:**

  Unequal transition probabilities between flavour eigenstates

  ➔ $P(K^0 \to \overline{K^0}) \neq P(\overline{K^0} \to K^0)$

  $|q/p| \neq 1$ (seen in kaons 1964)

- **CP-violation in decay, or direct CPV:**

  Unequal CP-conjugate decay rates ➔ $\Gamma(B^0 \to f) \neq \Gamma(\overline{B^0} \to \bar{f})$

  (seen in kaons, B^0, B^+, B_s, not yet in B-baryons)

- **CP-violation in the interference between mixing and decay:** Time-dependent or time-integrated difference of decay rates of initial flavour eigenstates ➔

  $$\boxed{\Gamma(B_{(\rightsquigarrow \bar{B})} \to f) \neq \Gamma(\bar{B}_{(\rightsquigarrow B)} \to f)}$$

  (seen in Kaons and in B^0 (BaBar and Belle 2002))

CP-violation in neutral B-mesons mixing ?

Defining the (time-independent) *asymmetry* of *mixed probabilities* :

$$A_{CP}=\frac{\mathcal{P}\left[\bar{F}^0(t)\to F^0\right]-\mathcal{P}\left[F^0(t)\to\bar{F}^0\right]}{\mathcal{P}\left[\bar{F}^0(t)\to F^0\right]+\mathcal{P}\left[F^0(t)\to\bar{F}^0\right]}=\frac{\left(\left|\frac{p}{q}\right|^2-\left|\frac{q}{p}\right|^2\right)\times\left|g_-(t)\right|^2}{\left(\left|\frac{p}{q}\right|^2+\left|\frac{q}{p}\right|^2\right)\times\left|g_-(t)\right|^2}=\frac{1-\left|\frac{q}{p}\right|^4}{1+\left|\frac{q}{p}\right|^4}$$

B-hadrons are produced as $b\bar{b}$ at $\Upsilon(4S)$ B-factories and TeVatron/LHC proton machines

This asymmetry can be measured using flavour-specific semi-leptonic (SL) decays

$$B^0\to D^-l^+\nu_l$$

$$\bar{B}^0\to D^+l^-\bar{\nu}_l$$

(BR~10%)

For instance, looking at the lepton in SL decays of ($B^0\bar{B}^0$) pairs:

- if opposite sign leptons : B^0 and $\bar{B}^0$ haven't oscillated (or both did have)
- if same sign leptons : either B^0 (--) or $\bar{B}^0$ (++) have oscillated

Counting the pairs of $B^0\bar{B}^0$ producing a pair of positive (N^{++}) and negative (N^{--}) leptons

$$A_{SL}=\frac{N^{++}-N^{--}}{N^{++}+N^{--}}=\frac{\mathcal{P}\left[\bar{B}^0\to B^0\right]\cdot\mathcal{P}\left[B^0\not\to B^0\right]-\mathcal{P}\left[\bar{B}^0\not\to\bar{B}^0\right]\cdot\mathcal{P}\left[B^0\to\bar{B}^0\right]}{\mathcal{P}\left[\bar{B}^0\to B^0\right]\cdot\mathcal{P}\left[B^0\not\to B^0\right]+\mathcal{P}\left[\bar{B}^0\not\to\bar{B}^0\right]\cdot\mathcal{P}\left[B^0\to\bar{B}^0\right]}=A_{CP}$$

$$A_{SL}^{\exp}(B^0)=-(0.21\pm0.17)\%$$

$$A_{SL}^{\exp}(B_s)=-(0.06\pm0.21)\%$$

World-average
[Cleo, BaBar, Belle,D0, LHCb]

CP-violation in neutral B-mesons mixing ?

Defining the (time-independent) *asymmetry* of *mixed probabilities* :

$$A_{CP} = \frac{\mathcal{P}\left[\bar{F}^0(t)\to F^0\right]-\mathcal{P}\left[F^0(t)\to \bar{F}^0\right]}{\mathcal{P}\left[\bar{F}^0(t)\to F^0\right]+\mathcal{P}\left[F^0(t)\to \bar{F}^0\right]} = \frac{\left(\left|\frac{p}{q}\right|^2-\left|\frac{q}{p}\right|^2\right)\times\left|g_-(t)\right|^2}{\left(\left|\frac{p}{q}\right|^2+\left|\frac{q}{p}\right|^2\right)\times\left|g_-(t)\right|^2} = \frac{1-\left|\frac{q}{p}\right|^4}{1+\left|\frac{q}{p}\right|^4}$$

This asymmetry can be me
flavour-specific semi-lepto

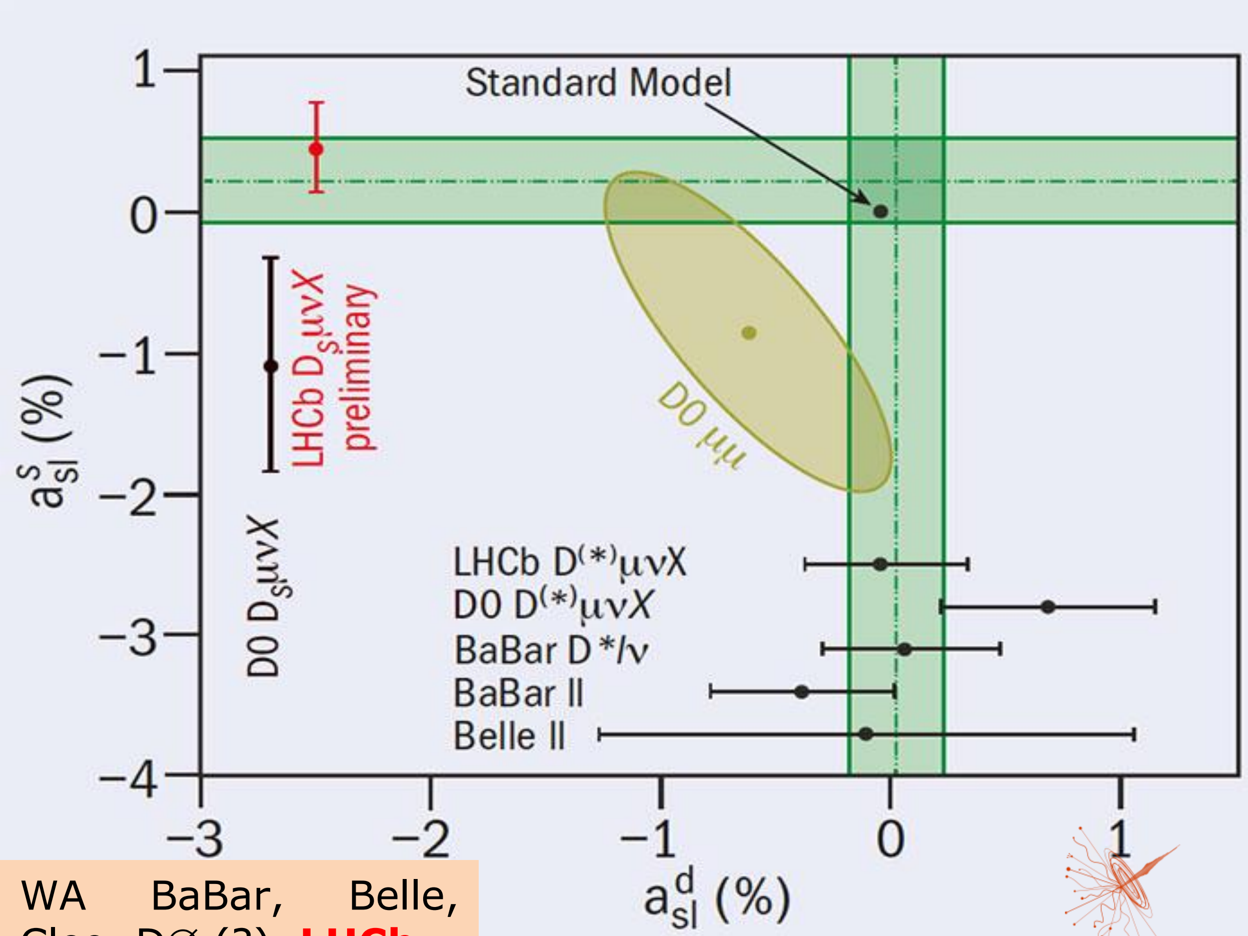
For instance, looking at

- if opposite sign lepto
- if same sign leptons

Counting the pairs of $B^0\bar{B}$
producing a pair of positiv
and negative (N^{--}) leptons

$$A_{SL}^{\exp}(B^0) = -(0.21\pm0.17)\%$$

$$A_{SL}^{\exp}(B_s) = -(0.06\pm0.21)\%$$



WA BaBar, Belle, Cleo, D∅ (?), **LHCb**

CP-violation in B-mesons decays

Defining the (time-independent) charge *asymmetry* in flavour-specific decay modes $(\bar{f} \neq f)$:

$$\boxed{A_{dir} = \frac{N\left(\bar{F} \to \bar{f}\right) - N\left(F \to f\right)}{N\left(\bar{F} \to \bar{f}\right) + N\left(F \to f\right)}}$$

in case of neutral mesons :

$$\begin{cases} N(\bar{F}^0(t) \to \bar{f}) \propto \left|\left\langle \bar{f} \middle| \mathcal{H} \middle| \bar{F}^0(t) \right\rangle\right|^2 = \left|g_+(t)^2\right| \times \left|\bar{\mathcal{A}}_f\right|^2 \\ N(F^0(t) \to f) \propto \left|\left\langle f \middle| \mathcal{H} \middle| F^0(t) \right\rangle\right|^2 = \left|g_+(t)^2\right| \times \left|\mathcal{A}_f\right|^2 \end{cases}$$

$$\Rightarrow A_{dir} = \frac{\left|\bar{\mathcal{A}}_f\right|^2 - \left|\mathcal{A}_f\right|^2}{\left|\bar{\mathcal{A}}_f\right|^2 + \left|\mathcal{A}_f\right|^2} = \frac{\left|r_f\right|^2 - 1}{\left|r_f\right|^2 + 1}$$

where $\left|r_f\right| = \left|\dfrac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}\right|$ measures CPV *in decay*

For neutral mesons, the knowledge of the initial flavour is irrelevant, in the limit of no CPV in mixing (no flavour-tagging needed !)

$$\begin{cases} N(F^0 + \bar{F}^0 \to \bar{f}) \propto \left(\mathcal{P}\left[\bar{F}^0(t) \to \bar{F}^0\right] + \mathcal{P}\left[F^0(t) \to \bar{F}^0\right]\right) \times \left|\bar{\mathcal{A}}_f\right|^2 \\ N(F^0 + \bar{F}^0 \to f) \propto \left(\mathcal{P}\left[F^0(t) \to F^0\right] + \mathcal{P}\left[\bar{F}^0(t) \to F^0\right]\right) \times \left|\mathcal{A}_f\right|^2 \end{cases} \Rightarrow A_{dir} = \frac{N\left(F \to \bar{f}\right) - N\left(F \to f\right)}{N\left(F \to \bar{f}\right) + N\left(F \to f\right)}$$

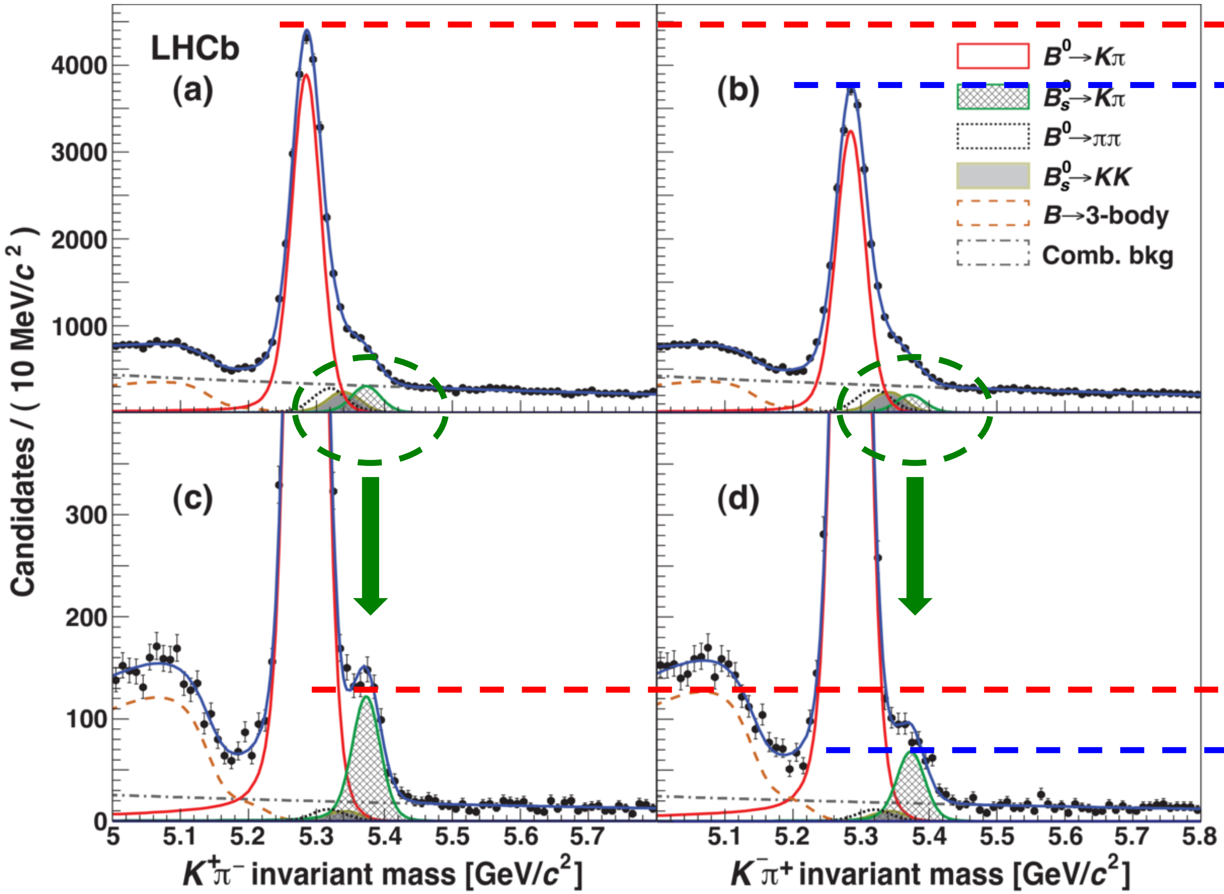
// //

[CPT] [CP in mixing]

CP-violation in B-mesons decays has been observed!

Direct CP violation has been observed in several flavour-specific decay modes of B^0, B^+ (BaBar, Belle(2002), LHCb) or B_s decays (LHCb, 2013)

e.g. LHCb 2013 : $B^0 \to K^+\pi^-$ and $B_s \to K^-\pi^+$



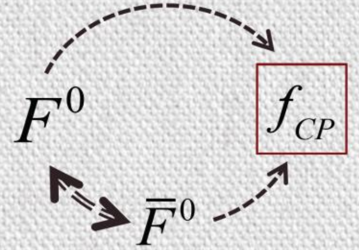
$A_{CP}(B^0 \to K^+\pi^-)=$
$-(8.0\pm0.7\pm0.3)\%$

$$\boxed{A_{dir} = \frac{\bar{N}-N}{\bar{N}+N}}$$

$A_{CP}(B_s \to K^-\pi^+)=$
$+(27\pm4\pm1)\%$

CP-violation in interference between mixing and decay

In case of neutral F^0 mesons decaying into a CP-eigenstate ($\overline{f}_{CP} = f_{CP}$)



$$\begin{tikzcd}F^0 \arrow[rr, bend left, dashed] \arrow[d, leftrightarrow, dashed] & & \boxed{f_{CP}} \\ & \overline{F}^0 \arrow[ur, dashed] & \end{tikzcd}$$

The asymmetry is time-dependent:

$$a_{CP}(t) = \frac{N(\overline{F}^0(t) \to f_{CP}) - N(F^0(t) \to f_{CP})}{N(\overline{F}^0(t) \to f_{CP}) + N(F^0(t) \to f_{CP})}$$

and interference between mixed & unmixed decays enter in the game:

$$\boxed{\begin{aligned} N\left(F^0(t) \to f_{CP}\right) &\propto \left|\left\langle f_{CP}\middle|\mathcal{H}\middle|F^0(t)\right\rangle\right|^2 = \left|g_+(t)\mathcal{A}_f + g_-(t)\tfrac{q}{p}\overline{\mathcal{A}}_f\right|^2 \\ N\left(\overline{F}^0(t) \to f_{CP}\right) &\propto \left|\left\langle f_{CP}\middle|\mathcal{H}\middle|\overline{F}^0(t)\right\rangle\right|^2 = \left|g_+(t)\overline{\mathcal{A}}_f + g_-(t)\tfrac{p}{q}\mathcal{A}_f\right|^2 \end{aligned}}$$

introducing
the observable:

$$\lambda_f = \left(\frac{q}{p}\right)\left(\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f}\right) = \frac{q}{p}\,\mathrm{r}_f$$

$$\boxed{a_{CP}(T) = \frac{S_f \sin(xT) - C_f \cos(xT)}{\cosh(yT) + A_\Delta \sinh(yT)}}$$

with

$$\underbrace{\boxed{C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}} \quad \boxed{S_f = \frac{2\mathcal{Im}(\lambda_f)}{1+|\lambda_f|^2}}}_{\text{CP-violating terms}} \quad \underbrace{\boxed{A_\Delta = \frac{2\mathcal{Re}(\lambda_f)}{1+|\lambda_f|^2}}}_{\sqrt{1-C_f^2-S_f^2}}$$

CP-violating terms

*$a_{CP}(t) \neq 0$ if $C_f \neq 0$ **or** $S_f \neq 0$*

$T = \Gamma t$
$xT = \Delta m t$
$yT = \Delta\Gamma t/2$

CP-violation in interference between mixing and decay

$$\boxed{C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}$$

Direct CP-violation term

in case of no CPV in mixing ($|q/p|=1$) we have:

$$|\lambda_f| = |r_f| = \left|\frac{\bar{A}_f}{A_f}\right| \Rightarrow \boxed{C_f = \frac{1-|r_f|^2}{1+|r_f|^2} = \frac{|A_f|^2-|\bar{A}_f|^2}{|A_f|^2+|\bar{A}_f|^2} = -A_{dir}}$$

$$\boxed{S_f = \frac{2\mathcal{Im}(\lambda_f)}{1+|\lambda_f|^2}}$$

CP-violation in interference between mixing & decay ("A_{mix}")
generates CP-violation even when neither CPV in mixing ($|q/p|=1$) nor in decay ($|\bar{A}_f/A_f|=|r_f|=1$) in case of a non-vanishing phase between q/p and r_f

$$\boxed{\lambda_f = e^{i\phi} \Rightarrow S_f = \sin(\phi)\ ;\ C_f = 0}$$

S_f (C_f) are sometime called 'time-(in)dependent *CP* asymmetries' and ϕ the 'mixing angle'

$$\boxed{A_\Delta = \frac{2\mathcal{Re}(\lambda_f)}{1+|\lambda_f|^2}}$$

experimentally relevant when $\Delta\Gamma/2\Gamma \neq 0$ (e.g. in B_s decay rate)

$$\boxed{\lambda_f = e^{i\phi} \Rightarrow A_\Delta = \cos(\phi)}$$

In any case: $\boxed{C_f^2 + S_f^2 = 1 - A_\Delta^2}$ :: no CPV implies $A_\Delta = \pm 1$

CP-violation in interference between mixing and decay
in a more compact view

CP violation parameters enter the decay rate to specific final states

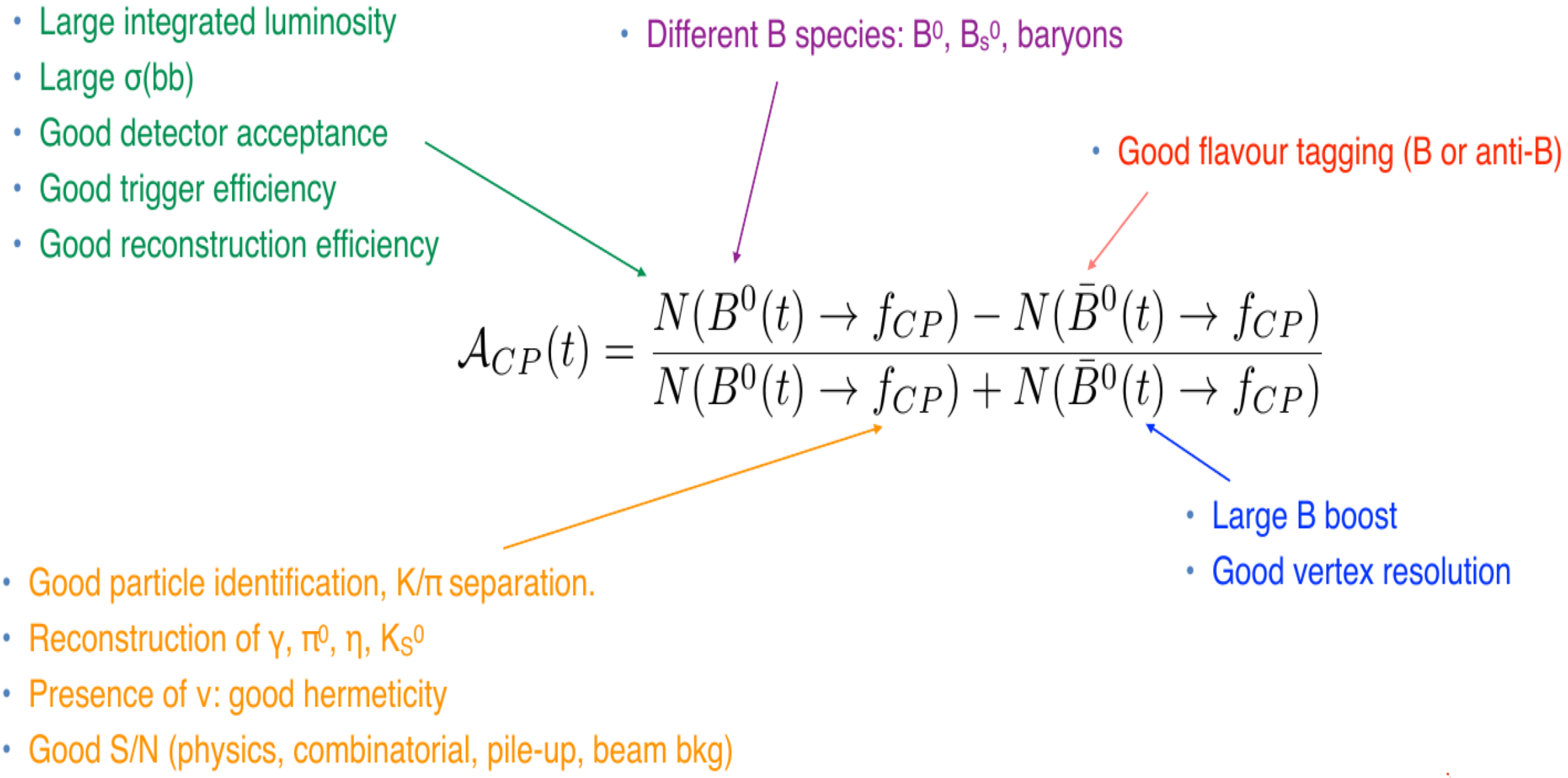
$$\Gamma_{B^0\to f} = \frac{1}{2}e^{-\Gamma t}|A_f|^2(1+|\lambda_f|^2)\left\{\cosh\left(\frac{\Delta\Gamma}{2}t\right) + A_{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t\right) + C\cos(\Delta m\, t) - S\sin(\Delta m\, t)\right\}$$

They can be extracted by measuring asymmetries (time integrated or time dependent)

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{B^0\to f} - \Gamma_{\overline{B}^0\to f}}{\Gamma_{B^0\to f} + \Gamma_{\overline{B}^0\to f}} \propto S\sin(\Delta m\, t) - C\cos(\Delta m\, t)$$

$$\begin{tikzcd}
B^0 \arrow[rr, bend left] \arrow[dr, bend right] & & f \\
& \overline{B}^0 \arrow[ur, bend right] &
\end{tikzcd}$$

CP-violation in interference between mixing and decay
Typical experimental performance drivers, to extract the observables



- Large integrated luminosity
- Large σ(bb)
- Good detector acceptance
- Good trigger efficiency
- Good reconstruction efficiency

- Different B species: B^0, B_s^0, baryons

- Good flavour tagging (B or anti-B)

$$A_{CP}(t) = \frac{N(B^0(t) \to f_{CP}) - N(\bar{B}^0(t) \to f_{CP})}{N(B^0(t) \to f_{CP}) + N(\bar{B}^0(t) \to f_{CP})}$$

- Large B boost
- Good vertex resolution

- Good particle identification, K/π separation.
- Reconstruction of γ, π^0, η, K_S^0
- Presence of ν: good hermeticity
- Good S/N (physics, combinatorial, pile-up, beam bkg)

Observation of CP-violation in interference in B^0 decays

Neutral B^0 system :

Damping: $y_d = \Delta\Gamma_d / 2\Gamma_d \sim 0$

No CPV in mixing: $|q/p| \sim 1$

$$\Rightarrow \quad a_{CP}(T) = S_f \sin(xT) - C_f \cos(xT)$$

"Golden mode" : CP final states with a single dominating amplitude

:: no CPV in decay :: $C_f \sim 0$.

$$\Rightarrow \quad a_{CP}(T) = S_f \sin(xT)$$

:: pure effect of CPV in interference

$$B^0 \to J/\psi K_s$$

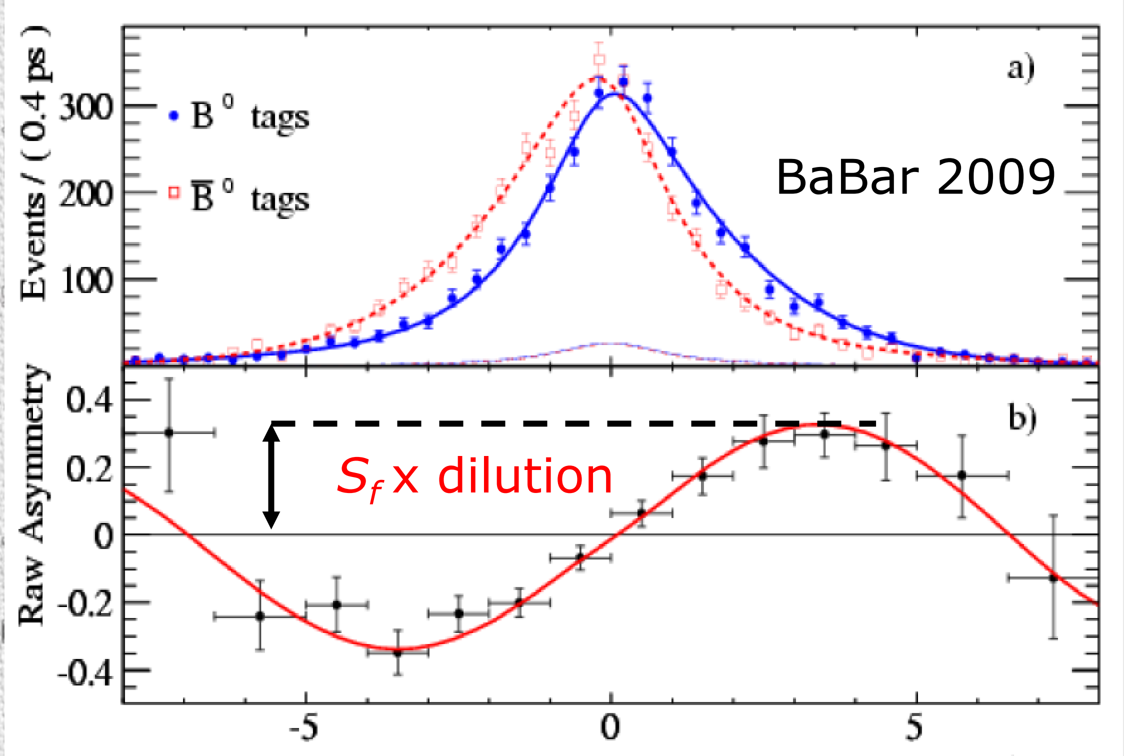
First observation of CPV other than in K^0 system (2001)

$$\lambda_{J/\psi K_s} \sim -e^{-2i\beta} \Rightarrow S_f = \sin(2\beta)$$

'mixing angle'

$$\beta = (21.85 \pm 0.68)^\circ$$

[BaBar, Belle, CDF, LHCb]



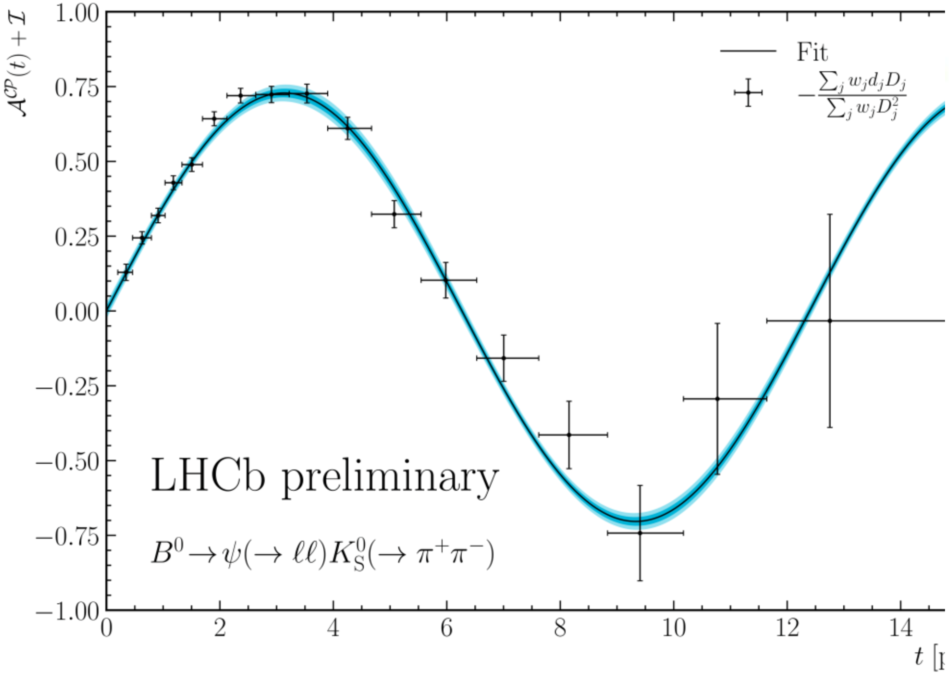
BaBar 2009

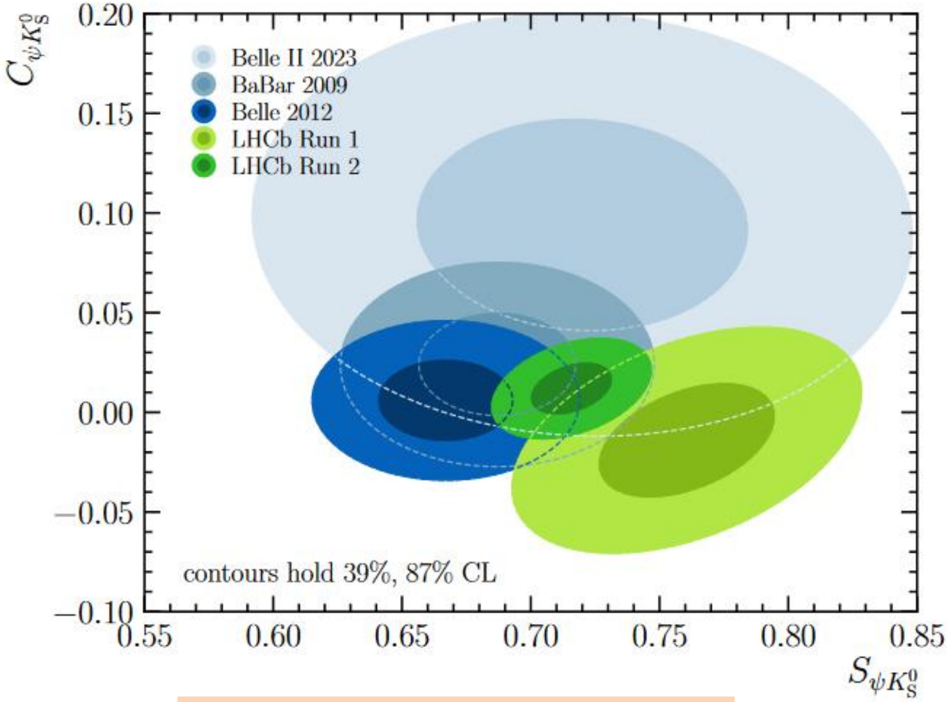
S_f x dilution

First "measurement" : L3 (1998, LEP) : $\sin 2\beta = (3.2 \pm 2.1)$!!

Observation of CP-violation in interference in B^0 decays

Hot off the press LHCb CERN seminar June 2023: https://indico.cern.ch/event/1281612/





Combination of $B^0\to J/\psi\, K^0_S$ modes

$$S^{\text{Run 1+2}}_{J/\psi\, K^0_S} = 0.724 \pm 0.014\,(\text{stat+syst})$$
$$C^{\text{Run 1+2}}_{J/\psi\, K^0_S} = 0.013 \pm 0.012\,(\text{stat+syst})$$

HFLAV 23:
S_{WA}= 0.708±0.011
C_{WA}= 0.006±0.010

β/ϕ_1 =(22.54±0.31)°

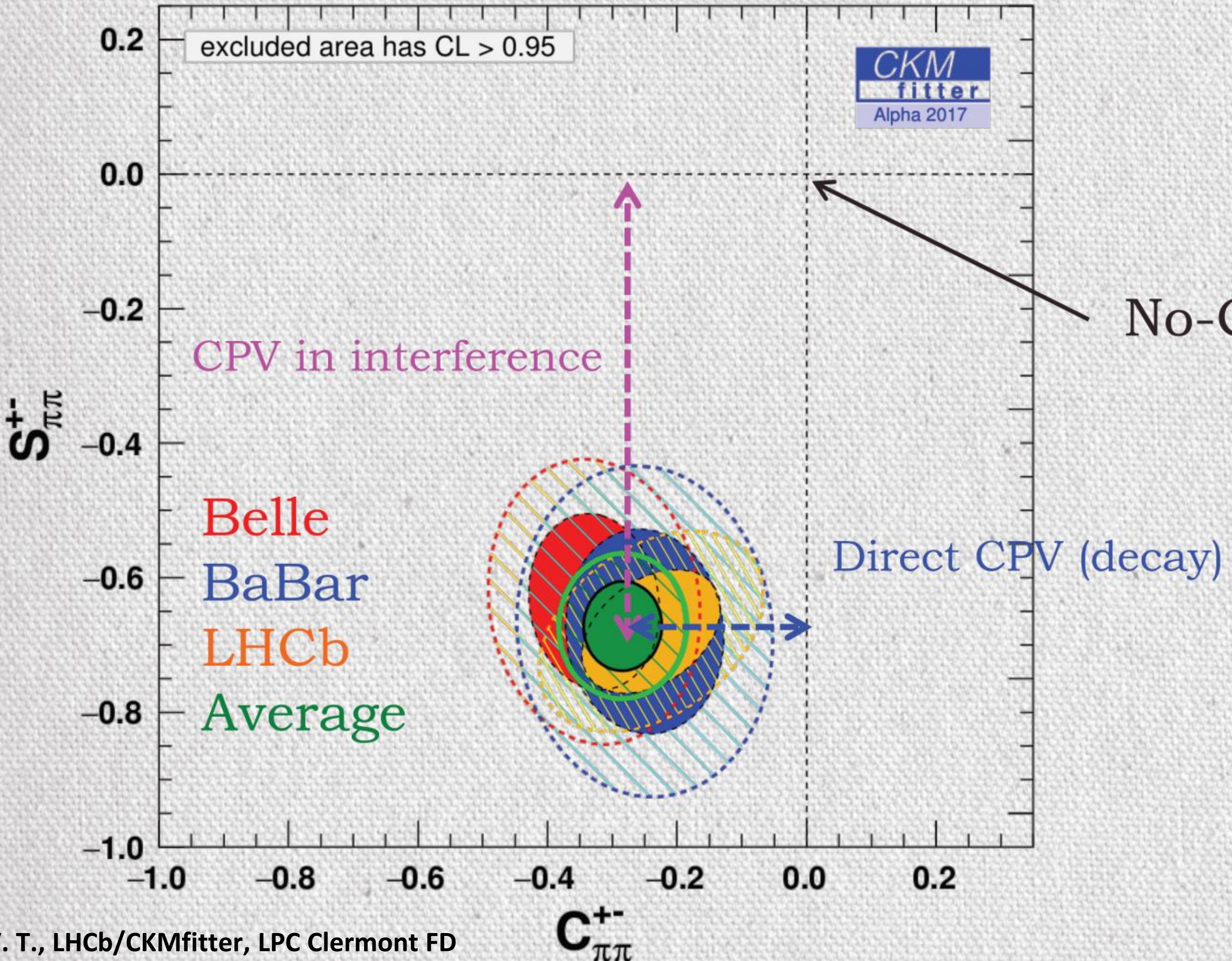
Observation of CP-violation in interference in B^0 decays

CP-violating parameter S_f observed in many other B^0 decay modes

Example: $\boxed{B^0 \to \pi^+\pi^-}$

'penguin' pollution also induces CPV in decay

$$\boxed{a_{CP}(T) = S_f \sin(xT) - C_f \cos(xT)}$$



CPV in interference

Belle

BaBar

LHCb

Average

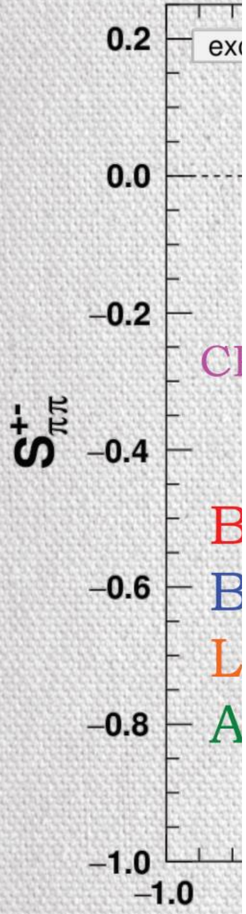
Direct CPV (decay)

No-CPV hypothesis

Obse ecays

CP-violati nodes

Example in decay



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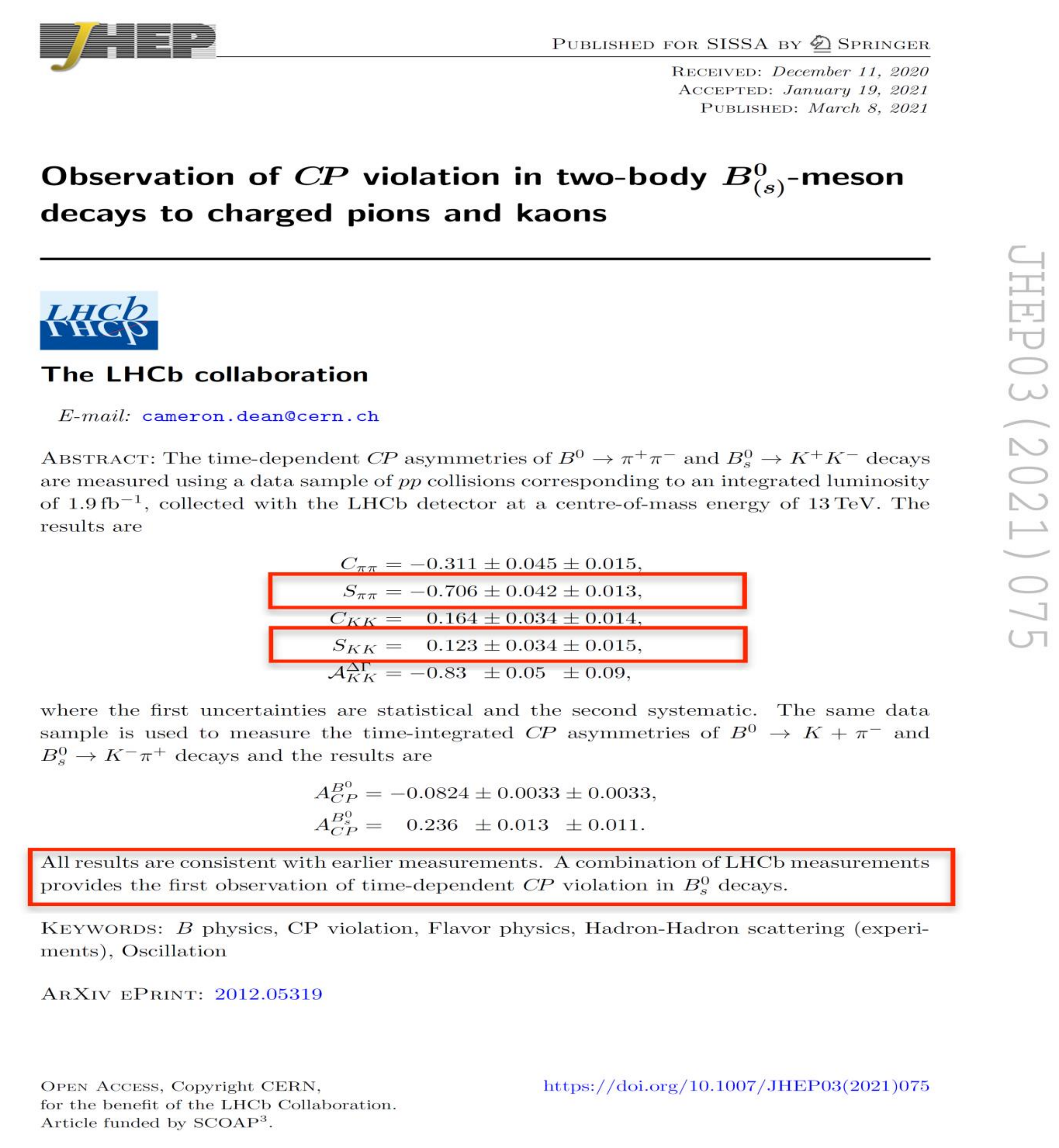

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Observation of CP violation in two-body $B^0_{(s)}$-meson decays to charged pions and kaons

The LHCb collaboration

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ABSTRACT: The time-dependent CP asymmetries of $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays are measured using a data sample of pp collisions corresponding to an integrated luminosity of 1.9 fb^{-1}, collected with the LHCb detector at a centre-of-mass energy of 13 TeV. The results are

$$\begin{aligned} C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015, \\ \boxed{S_{\pi\pi} = -0.706 \pm 0.042 \pm 0.013,} \\ C_{KK} &= 0.164 \pm 0.034 \pm 0.014, \\ \boxed{S_{KK} = 0.123 \pm 0.034 \pm 0.015,} \\ \mathcal{A}^{\Delta\Gamma}_{KK} &= -0.83 \pm 0.05 \pm 0.09, \end{aligned}$$

where the first uncertainties are statistical and the second systematic. The same data sample is used to measure the time-integrated CP asymmetries of $B^0 \to K+\pi^-$ and $B^0_s \to K^-\pi^+$ decays and the results are

$$\begin{aligned} A^{B^0}_{CP} &= -0.0824 \pm 0.0033 \pm 0.0033, \\ A^{B^0_s}_{CP} &= 0.236 \pm 0.013 \pm 0.011. \end{aligned}$$

All results are consistent with earlier measurements. A combination of LHCb measurements provides the first observation of time-dependent CP violation in B^0_s decays.

KEYWORDS: B physics, CP violation, Flavor physics, Hadron-Hadron scattering (experiments), Oscillation

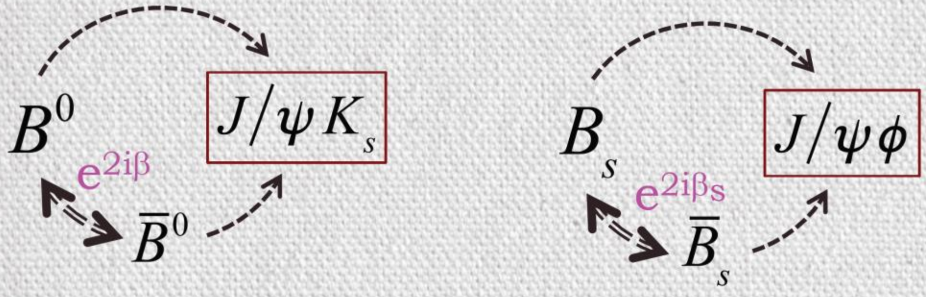
ARXIV EPRINT: 2012.05319

https://doi.org/10.1007/JHEP03(2021)075

JHEP03(2021)075

Evidence of CP-violation in interference in B_s decays

The equivalent golden decay mode in the B_s system is $\boxed{B_s \to J/\psi\phi}$

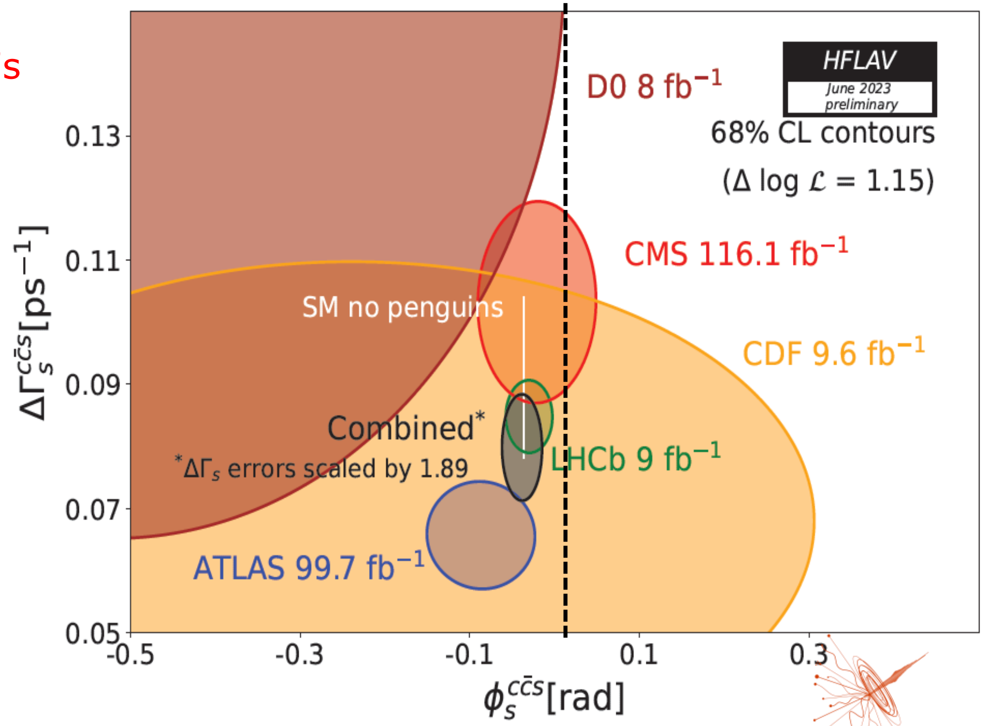


Finite width-splitting in B_s has to be taken into account: $2y_s = \Delta\Gamma_s/\Gamma_s = 0.135 \pm 0.08$

$\phi_s \equiv -2\beta_s$ is a very small angle in B_s

- $\phi_s^{J/\psi KK} = -0.050 \pm 0.017$ rad → improved by 23%
- $\phi_s^{c\bar{c}s} = -0.039 \pm 0.016$ rad → improved by 15%
- Consistent with the prediction of Global fits assuming SM:[3]

$$\phi_s^{\text{CKMfitter}} \approx \left(-0.0368^{+0.0006}_{-0.0009}\right) \text{rad}, \quad \phi_s^{\text{UTfitter}} = -0.0370 \pm 0.0010$$



https://indico.cern.ch/event/1281612/

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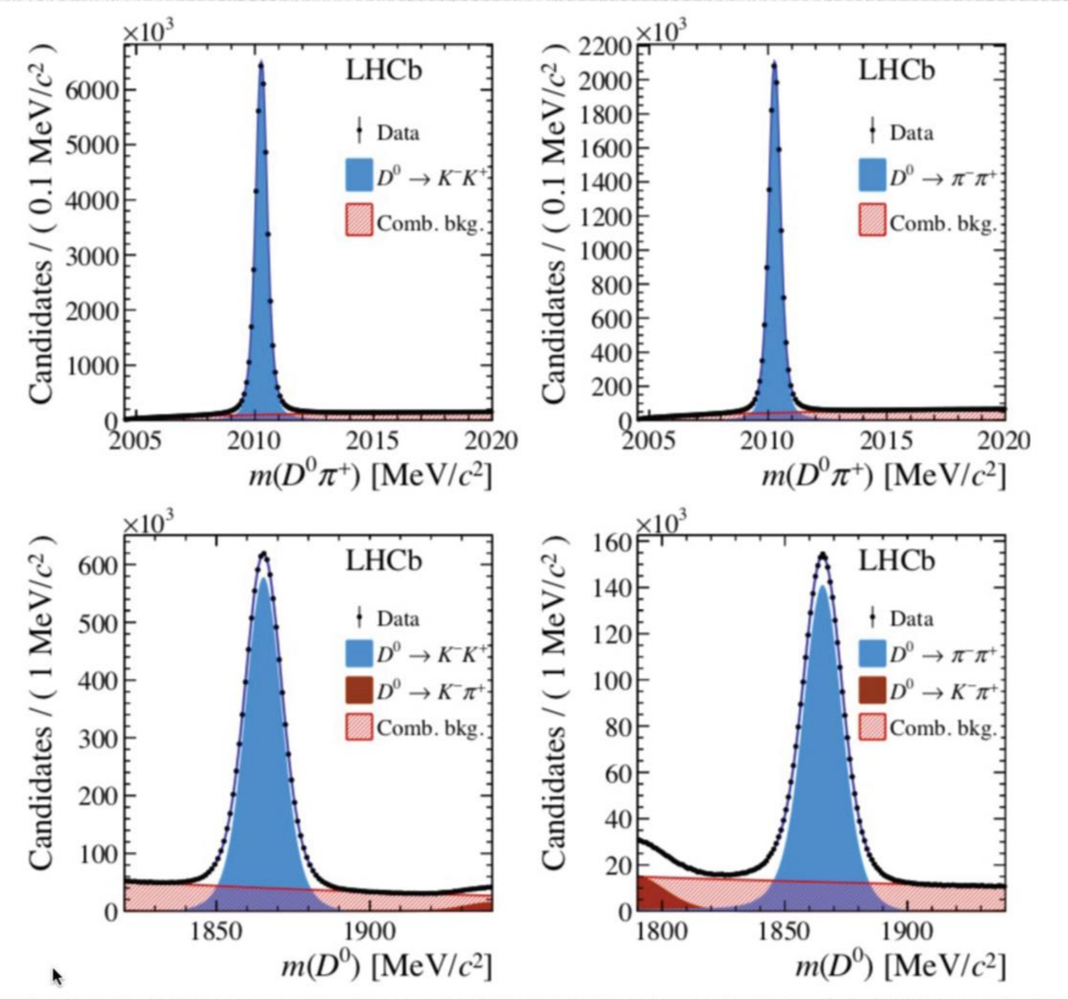
[3] Ignoring penguin contribution.

Observation of CP-violation also in Charmed D^0 meson decays !

March 2019 update (LHCb)

ΔA_{CP} = A(KK)-A(ππ)
=(-0.154±0.029)%

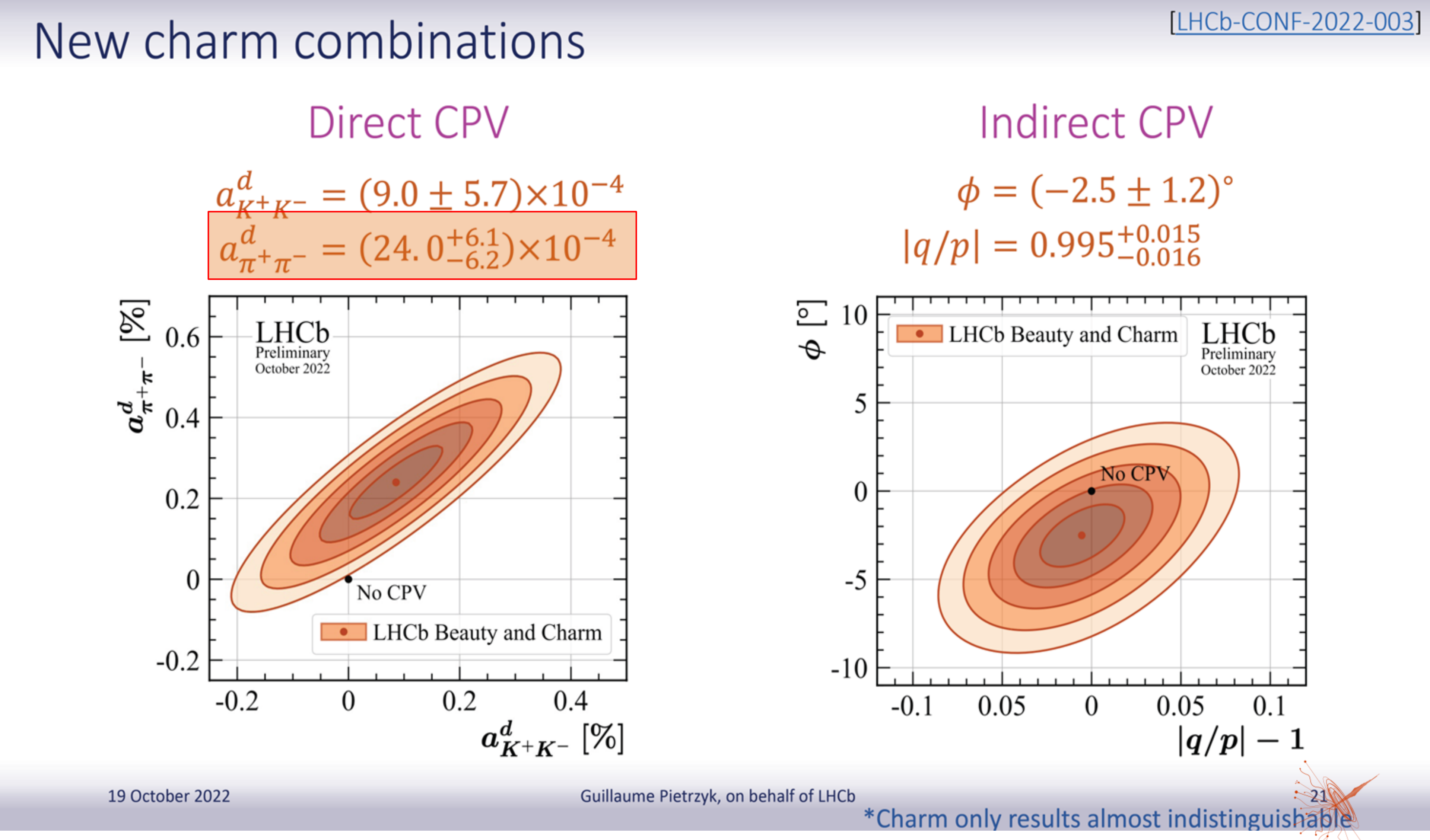
Observation of (direct) CP violation in the D^0 system at 5.3σ



Observation of CP-violation also in Charmed meson decays !

Very low mixing probability in the D^0 system

$A_{f_{CP}}$ measures the direct CP violation only



[LHCb-CONF-2022-003]

New charm combinations

Direct CPV

$$a^d_{K^+K^-} = (9.0 \pm 5.7)\times 10^{-4}$$

$$\boxed{a^d_{\pi^+\pi^-} = (24.0^{+6.1}_{-6.2})\times 10^{-4}}$$

Indirect CPV

$$\phi = (-2.5 \pm 1.2)^\circ$$

$$|q/p| = 0.995^{+0.015}_{-0.016}$$

19 October 2022

Guillaume Pietrzyk, on behalf of LHCb

21

*Charm only results almost indistinguishable

Summary of 3 types of CP-violations

The ratio q/p is not an observable (CP-phase convention dependent)

The ratio $\bar{A}_f/A_f$ is not an observable (CP-phase convention dependent)

Observables:

$$\left|\frac{q}{p}\right|$$

$$K^0 \longrightarrow \bar{K}^0 \neq \bar{K}^0 \longrightarrow K^0$$

CP-violation in mixing when $|q/p| \neq 1$

[observed in neutral Kaons system (1964)]

$$\left|\frac{\bar{A}_f}{A_f}\right| = |r_f|$$

CP-violation in decay when $|r_f| \neq 1$

[observed in K^0, B^0, B^+, B_s, D decays]

$$B^0 \longrightarrow K^+\pi^- \neq \bar{B}^0 \longrightarrow K^-\pi^+$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

CP-violation in interference when $Arg(\lambda_f) \neq 0$

[observed in K^0 and B^0 decays]

$$\begin{tikzcd} B^0 \arrow[rr] \arrow[dr] & & f_{CP} & \neq & \bar{B}^0 \arrow[rr] \arrow[dr] & & f_{CP} \\ & \bar{B}^0 \arrow[ur] & & & & B^0 \arrow[ur] & \end{tikzcd}$$

Flavour Physics (rewind): a bit of history

Antiquity

1896 discovery of the radioactivity of the uranium (Becquerel)

1898 thorium, polonium, radium (Curie^2)

1899 distinction between α and β decay (Rutherford)

1930 "invention" of the neutrino (Pauli)

Middle Age

1951-1954 CPT conservation theorem (Schwinger, Lüders & Pauli)

1956-1957 postulate and discovery of parity violation (Lee & Yang, Wu et al., Garwin & Lederman)

1964 discovery of charge × parity violation (Cronin & Fitch)

1973 mechanism(s) of CP violation in the "Standard" model (Kobayashi & Maskawa)

Modern Era

1998 discovery of time-reversal violation (CPLEAR)

1998 discovery of neutrino oscillations (Super-Kamiokande)

1999 direct CP violation in the kaon system (KTeV, Na48)

2001 mixing-induced CP violation in the B system (BaBar, Belle)

2004 direct CP violation in the B system (BaBar, Belle)

Postmodern Era

2008 Nobel Prize to Kobayashi and Maskawa for their successful mechanism of CP violation in the Standard Model

2014 first discovery of very rare FCNC decay $B_s \to \mu\mu$ (LHCb, CMS)

since $\sim$ 10 years a few hints against the SM are showing up (and down)

Quark Flavour Physics : the various experiments for the last 60 years

Kaon physics :

Cronin-Fitch (AGS, BNL)	1964	: discovery of indirect CP violation
NA31 (SPS, CERN)	1986-1987	: evidence of direct CP violation
CPLear (Lear, CERN)	1990-1996	
NA48 (SPS, CERN)	1991-2004	: discovery of direct CP violation
KTEV (Tevatron, FNAL)	1996-2001	: discovery of direct CP violation
E787/E949 (AGS, BNL)	1994-2003	
KL0E (Daϕne, Frascati)	2000-2006	
E391a (KEK)	2004-2005	
KLOE-2	2014-...	
Koto (J-Parc)	2013-...	
NA62 (SPS, CERN)	2015-...	

Heavy flavours (beauty, charm & tau) :

Cleo/Cleo-c (CESR, Cornell)	1979-2008	: FCNC
Argus (DorisII, DESY)	1982-1992	: B^0 oscillation (1987)
B-factories : BaBar (PEPII-SLAC)	2000-2010	: CP violation in B^0
Belle (KEKB, KEK)	2000-2010	& CKM metrology & ...
LHCb (LHC, CERN)	2010-2018	: CP violation in B_s ...
Belle-2	2018-...	**2018 (April 25 - 1st collisions)**
LHCb upgrade	~~2021-~~...	**2022 (July 05)**

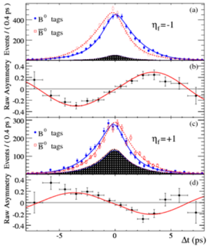
flavour physics is also part of the physics program of the 'General Purpose Detectors' in High Energy physics => important contributions in this area from D0/CDF (Fermilab), LEP experiments (CERN), SLD (SLAC), CMS/Atlas (LHC CERN), ...

Discrete Symmetries (CPT)

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
CP* violation in *K
meson decays
J. W. Cronin,
V. L. Fitch *et al.*



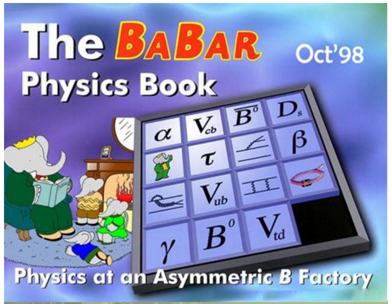
1973
The CKM matrix
M. Kobayashi and
T. Maskawa

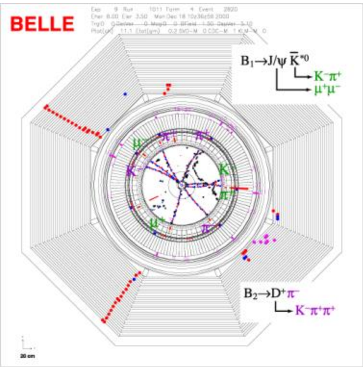
2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

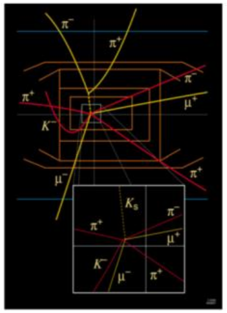
+ D oscillation BaBar 2007

TODAY

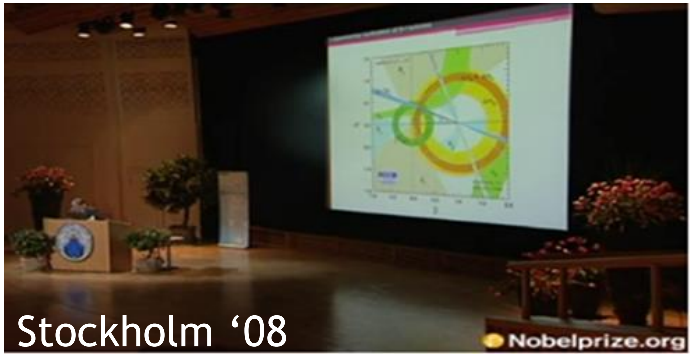
2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration



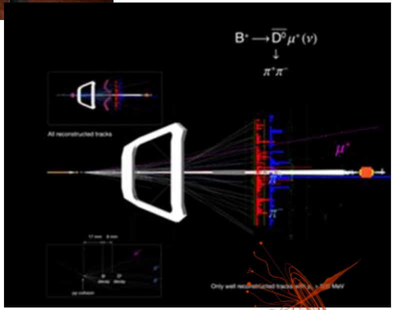




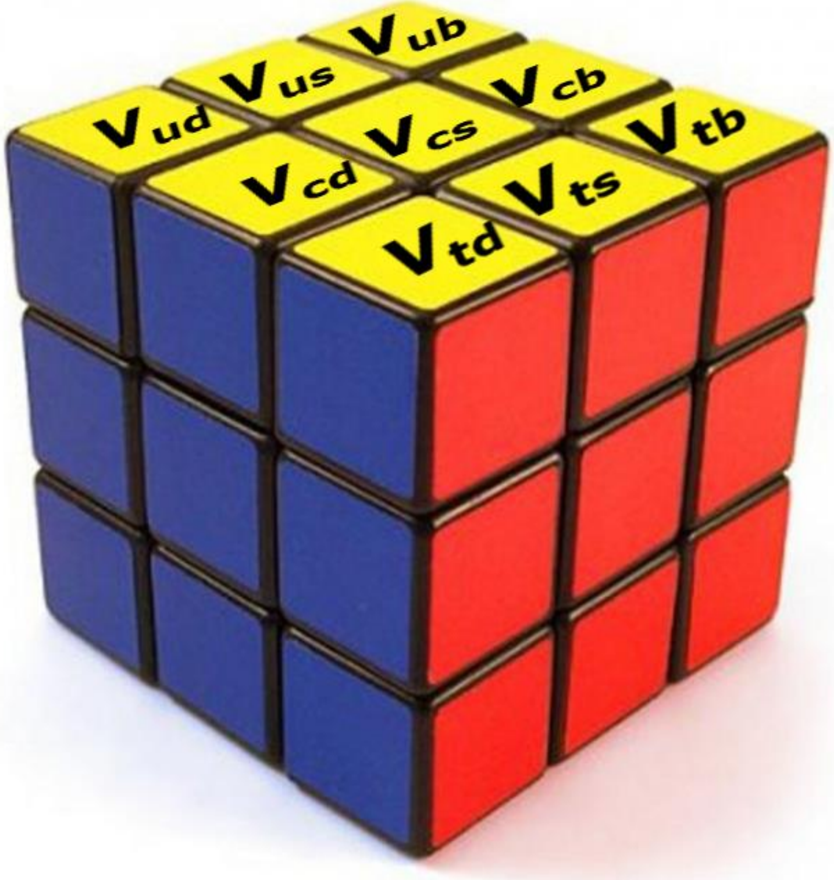

LHCb Moriond EW '19


Stockholm '08

Nobelprize.org



The CKM MATRIX
Cabibbo-Kobayashi-Maskawa



The *Rubik's Cube* is a 3-D combination puzzle originally invented in 1974 by Hungarian sculptor and professor of architecture Ernő *Rubik*.

The Cabibbo 2x2 MATRIX

- Cabibbo angle (1963)

Quark-lepton universality in weak transitions can be preserved by introducing the mixing angle Θ_c

with $\sin(\Theta_c) \sim 0.22$ ($\Theta_c \sim 13°$)

Pure leptonic decay $\Gamma(\mu^+ \to e^+ \bar{\nu}_\mu \nu_e) \propto g^4$

Semi-leptonic $\Delta S=0$ $\Gamma(n \to p e^- \bar{\nu}_e) \propto g^4 \cos^2(\theta_c)$

Semi-leptonic $\Delta S=1$ $\Gamma(\Lambda \to p e^- \bar{\nu}_e) \propto g^4 \sin^2(\theta_c)$

$$\begin{pmatrix} u' \\ d' \end{pmatrix}_{EW} = \begin{pmatrix} u \\ d\cos(\theta_c) + s\sin(\theta_c) \end{pmatrix}$$

$$\begin{array}{c} \Delta S=1 \\ \Delta S=0 \end{array} \quad \frac{\Gamma(K^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)} \sim \tan^2(\theta_c) \sim 1/20$$

Problem:

unobserved Strangeness-Changing-Neutral-Current transitions are allowed

$$\langle d'|J_{NC}|d'\rangle = \cos^2(\theta_c)\langle d|J_{NC}|d\rangle + \sin^2(\theta_c)\langle s|J_{NC}|s\rangle + \boxed{\cos(\theta_c)\sin(\theta_c)\left(\langle d|J_{NC}|s\rangle + \langle s|J_{NC}|d\rangle\right)}$$

$$\frac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^+ \to \mu^+\nu_\mu)} = \frac{7.2\times10^{-9}}{6.4\times10^{-1}} \neq \tan^{-1}(\theta_c) \quad !!$$

Glashow Illiopoulos Maiani: GIM mechanism (1970)

the **GIM mechanism** is the mechanism through which **flavour-changing neutral currents (FCNCs)** are suppressed in loop diagrams. It also explains why weak interactions that change strangeness by 2 ($\Delta S = 2$ transitions) are suppressed, while those that change strangeness by 1 ($\Delta S = 1$ transitions) are allowed, but only in charged current interactions.

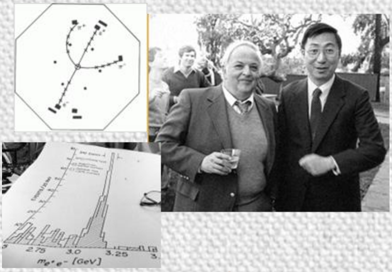
FCNC are suppressed by adding a new doublet (with a new up-type quark)

$$\begin{pmatrix} u' \\ d' \end{pmatrix}_{EW} = \begin{pmatrix} u \\ d\cos(\theta_c)+s\sin(\theta_c) \end{pmatrix} \qquad \begin{pmatrix} c' \\ s' \end{pmatrix}_{EW} = \begin{pmatrix} c \\ s\cos(\theta_c)-d\sin(\theta_c) \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \end{pmatrix}_{EW} = \begin{pmatrix} \cos(\theta_c) & \sin(\theta_c) \\ -\sin(\theta_c) & \cos(\theta_c) \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Unitary rotation : FCNC cancelation thanks to $UU^{+} = I$

$$\langle d'|J_{NC}|d'\rangle + \langle s'|J_{NC}|s'\rangle = \langle d|J_{NC}|d\rangle + \langle s|J_{NC}|s\rangle$$



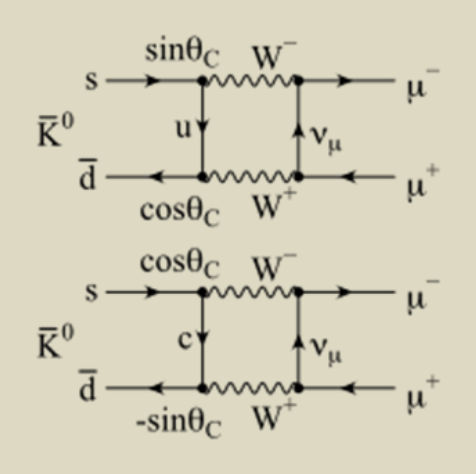
Charmonium meson (J/Ψ) observed in 1974

The November 1974 Revolution

Still a problem : the 2x2 unitary matrix conserves CP

Kaon Mixing, again, and GIM !

The smallness is set by the mass-squared difference of the different virtual quarks exchanged in the box diagram, originally the *u*-*c* quarks, on the scale of the *W* mass.
The smallness of this quantity accounts for the suppressed induced FCNC, dictating a rare decay $K_L \to \mu^- \mu^+$, illustrated.
If that mass difference were ignorable, the minus sign between the two interfering box diagrams (itself a consequence of unitarity of the Cabibbo matrix) would lead to a complete cancellation, and thus a null effect.

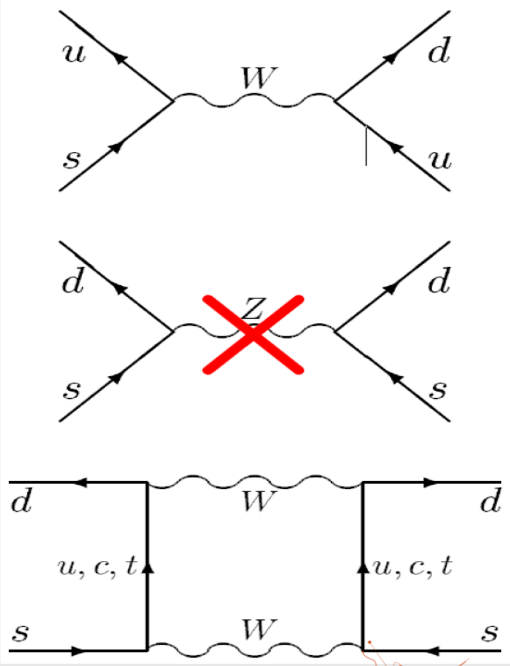


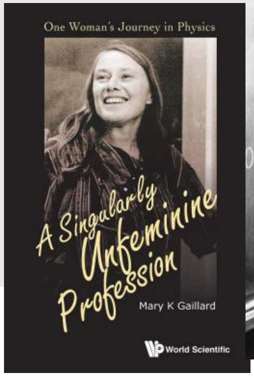
M.K. Gaillard & B.W. Lee rare kaons ('74)

➔ **a VIP (very important paper, a must read)**

Rare decay modes of the K mesons in gauge theories
Phys. Rev. D 10, 897 – Published **1 August 1974**

Kaon mixing is the prototype for FCNC transitions. It was used to predict the value of the charm mass from the value of Δm_K (Gaillard & Lee 1974).

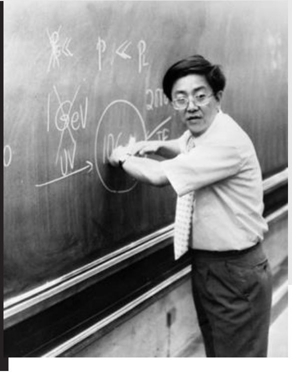



One Woman's Journey in Physics

A Singularly Unfeminine Profession

Mary K Gaillard

World Scientific



CPV in the Electroweak model of particle physics

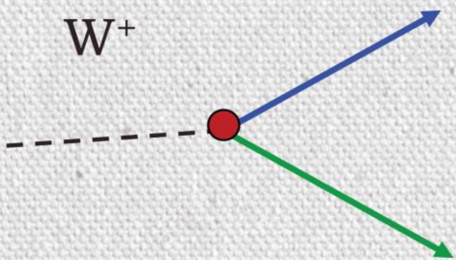
quarks acquire mass via the Yukawa coupling $M_{U(D)} = \frac{<vev>}{\sqrt{2}} g_{U(D)}$

$\mathbf{M_{U(D)}}$: 3x3 mass matrix for Up- (Down-) type quarks

Diagonalised with **unitary** (complex) rotation matrices, **U** and **D**, resp.

Neutral currents **unaffected** by flavour mixing (unitarity): $UU^+ = DD^+ = I$

Charged currents **affected** by flavour mixing: $UD^+ = (DU^+)^+ = V_{CKM}$



$$|u_i'\rangle_{EW} = U_{ui}|u\rangle + U_{ci}|c\rangle + U_{ti}|t\rangle$$

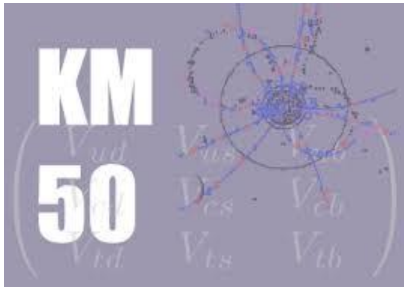
$$|\bar{d}_i'\rangle_{EW} = D^*_{id}|\bar{d}\rangle + D^*_{is}|\bar{s}\rangle + D^*_{ib}|\bar{b}\rangle$$

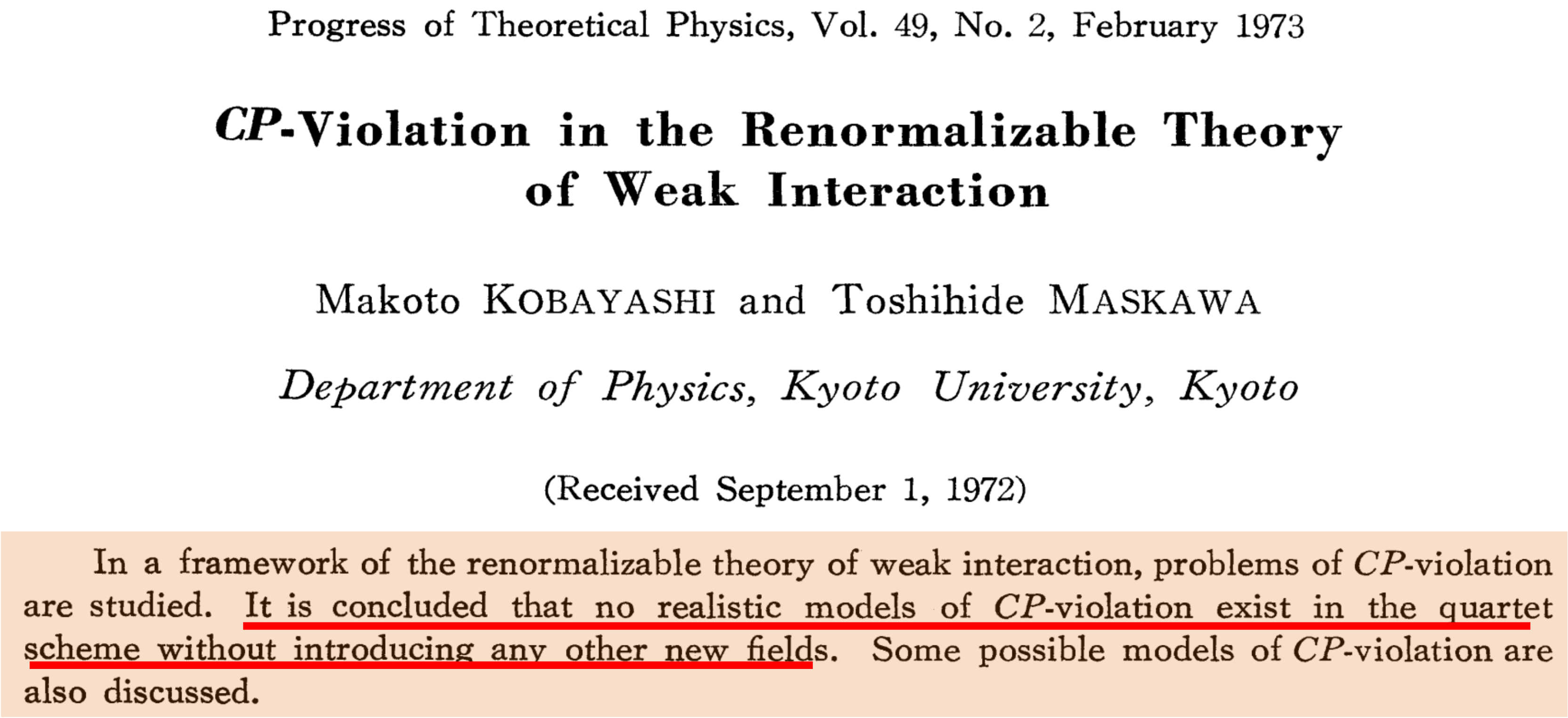
$$V_{ud} = \sum_{i=1}^{3} U_{ui} D^*_{id}$$

In case an unabsorbable **complex phases** appear in the flavour mixing

$|u_i'\bar{d}_i'\rangle_{EW} \neq CP|d_i'\bar{u}_i'\rangle_{EW}$ ➡ **CP is violated**

The Kobayashi-Maskawa mechanism : CKM 1972-1973





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)

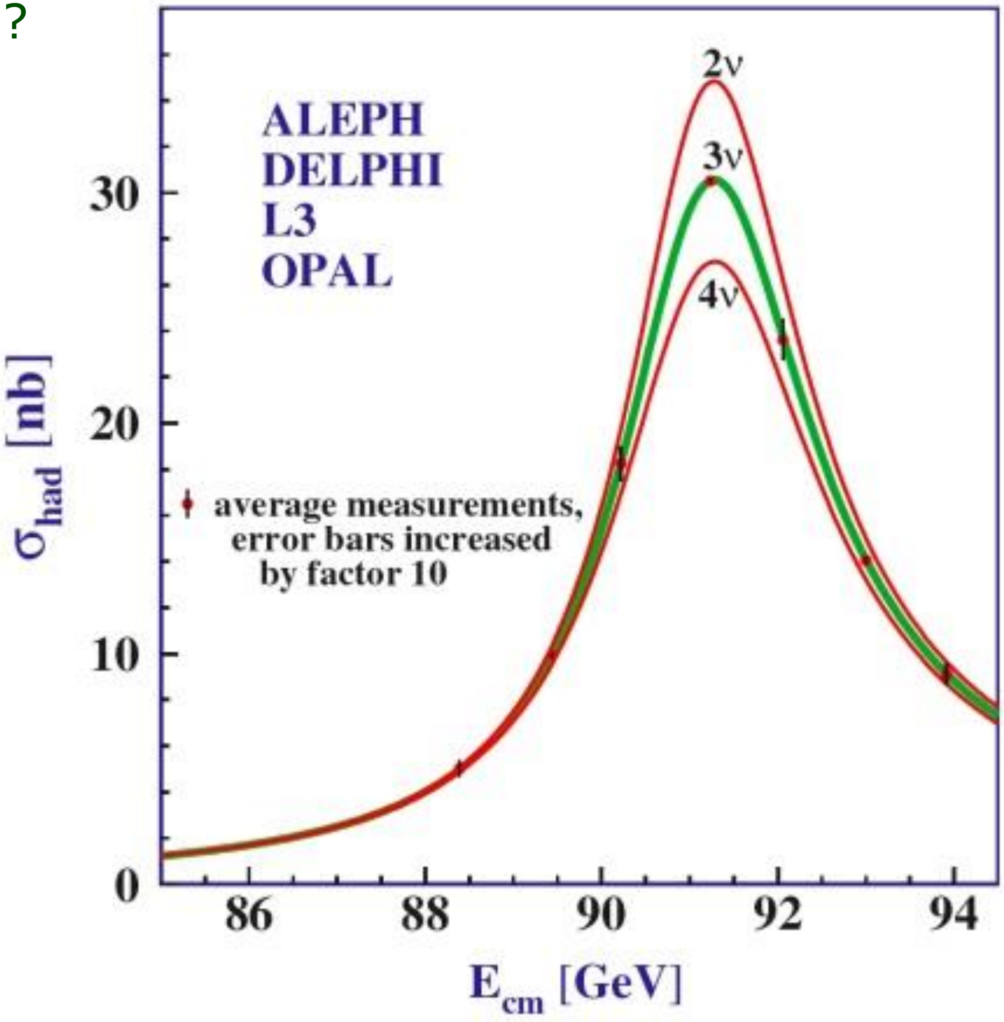
In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

It predicted 3 families of quarks, while, only u, d, s were seen !

3 families !

From parameter counting n = 3 is the minimal number of families that are needed to generate CP-violation through the KM mechanism.

It also happens that n = 3 is the number of massless neutrinos found at LEP, and more generally the number of observed fermion generation: is it a coincidence ?



N_ν=2.984±0.008

The Kobayashi-Maskawa mechanism : CKM1973

- V_{CKM} unitary complex matrix encoding the quark flavour mixing

  n generations: $2n^2$ real parameters / n^2 unitary relations and 2n-1 rephasing

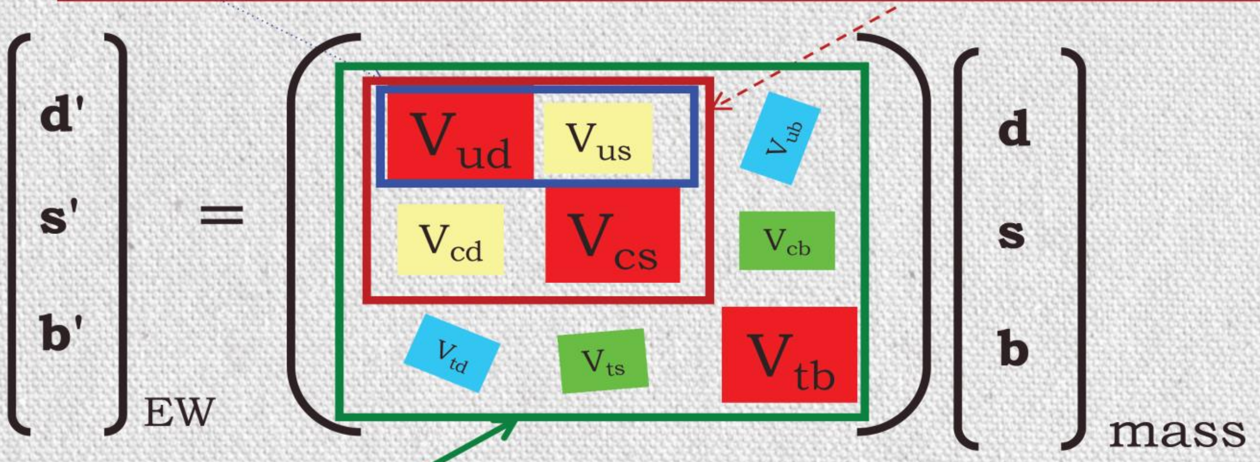
  ⇒ $(n-1)^2$ real parameters

  ⇒ $C(2,n)=n(n-1)/2$ Euler angles **and $(n-1)(n-2)/2$ complex phase(s)**

  ⇒ 3 quarks generations : 3 real parameters + **1 CP-violating phase**

Cabibbo model (1963) : $|d'\rangle_{EW} = \cos(\Theta_c)\,|d\rangle + \sin(\Theta_c)\,|s\rangle$ to preserve the universality of weak interaction. $\sin(\Theta_c) \sim 0.22$

Glashow-Iliopoulos-Maiani (1970) : $|s'\rangle_{EW} = \cos(\Theta_c)\,|s\rangle - \sin(\Theta_c)\,|d\rangle$
FCNC suppression via 2x2 unitarity => 4th quark needed
Richter-Ting : charmonium discovery (1974) – Nobel 1976



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

Kobayashi-Maskawa (1972): 3rd familly to account for CP-violating phase - Nobel 2008
Botomium (1977) and top quark discovery (1995) at Fermilab

Parametrisation of the CKM Matrix

With the mixing angles $\cos, \sin(\theta_{ij}) \equiv c_{ij}, s_{ij}$ the CKM matrix is the product of three 2x2 rotation matrices with one phase

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

However it will experimentally be found that $s_{12} \sim \lambda \sim 0.2$, $s_{23} \sim \lambda^2 \sim 0.04$, $s_{13} \sim \lambda^3 \sim 0.008$.

Let us make this hierarchy explicit by defining the exact version of the Wolfenstein parametrization

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

$$\bar{\rho} + i\bar{\eta} \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

CKM is a mixing matrix CKM → unitarity relations

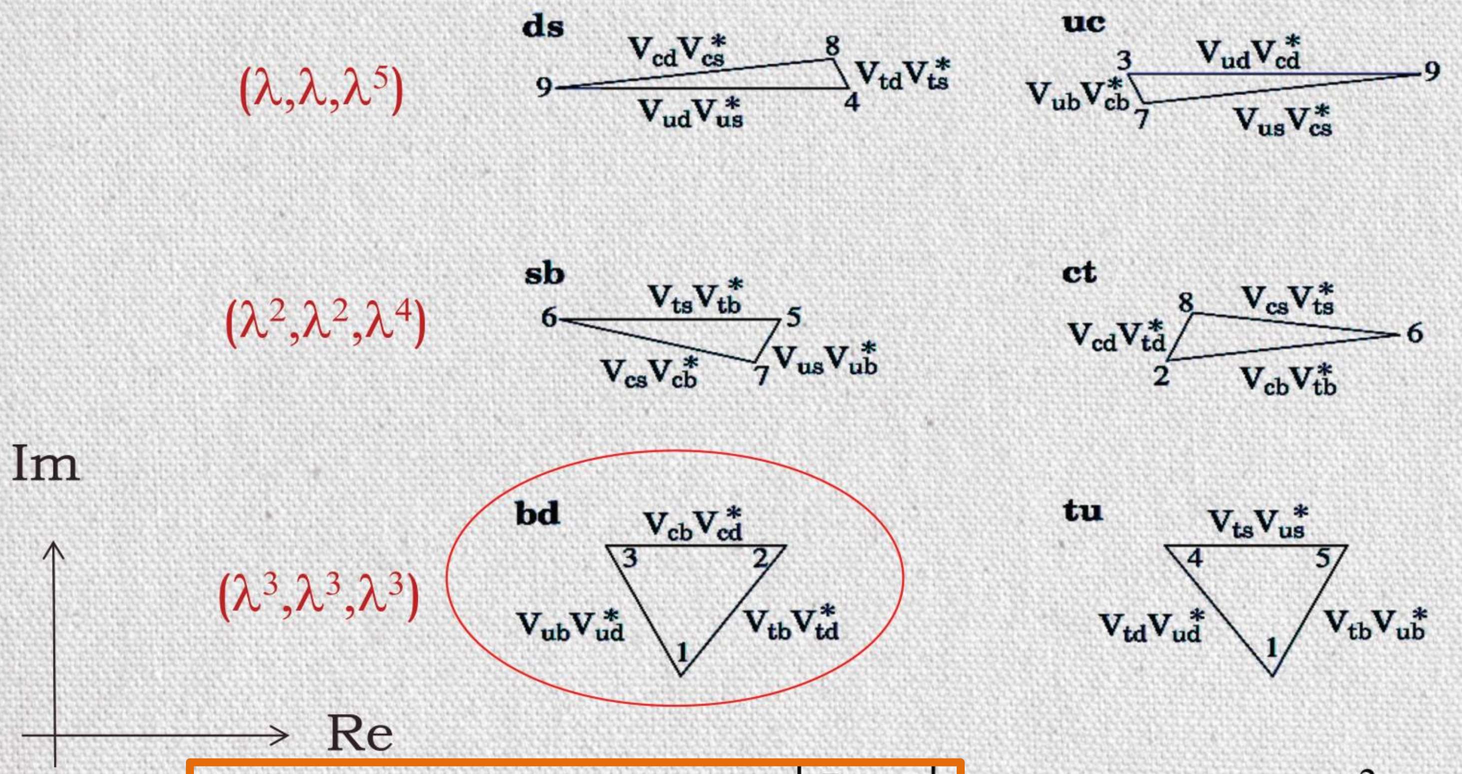
3 identities

6 triangular relations:

$$(u_i):\ \left|V_{u_i d}\right|^2+\left|V_{u_i s}\right|^2+\left|V_{u_i b}\right|^2=1$$

$$(d_1,d_2):\ V_{ud_1}V_{ud_2}^*+V_{cd_1}V_{cd_2}^*+V_{td_1}V_{td_2}^*=0$$

$$(u_1,u_2):\ V_{u_1 d}V_{u_2 d}^*+V_{u_1 s}V_{u_2 s}^*+V_{u_1 b}V_{u_2 b}^*=0$$



Jarlskog invariant

$$\boxed{\text{ANY triangles area}=\frac{\left|J_{CKM}\right|}{2}}=\frac{1}{2}A^2\lambda^6\eta\left(1-\frac{\lambda^2}{2}\right)+O(\lambda^{10})$$

Quantifying the level of CPV: it's driven by the Jarlskog invariant !

$$det([M_U, M_D]) = -2i \frac{\prod_{u_k \neq u_l}(m_{u_k} - m_{u_l}) \prod_{d_k \neq d_l}(m_{d_k} - m_{d_l})}{m_t^3 m_b^3} \times J_{CKM}$$

CP violation in flavour mixing requires :

1. no degeneracy of quark masses (separately for U- and D-type)
2. Jarlskog invariant $J_{CKM} \neq 0$

$$J_{CKM} = \sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\cos(\theta_{13})\boxed{\sin(\delta)}/8$$

$$= A^2\lambda^6\boxed{\eta}(1-\frac{\lambda^2}{2}) + O(\lambda^{10})$$

$$\max(J_{CKM}) = \frac{1}{6\sqrt{3}} \approx 0.1$$

$$(\theta_{12} = \theta_{23} = 45°; \theta_{13} = 35.26°; \delta = 90°]$$

where we see that three generation mixing ((12), (23), (13)) and CP-violating phase (δ) are necessary ingredients for CP violation.

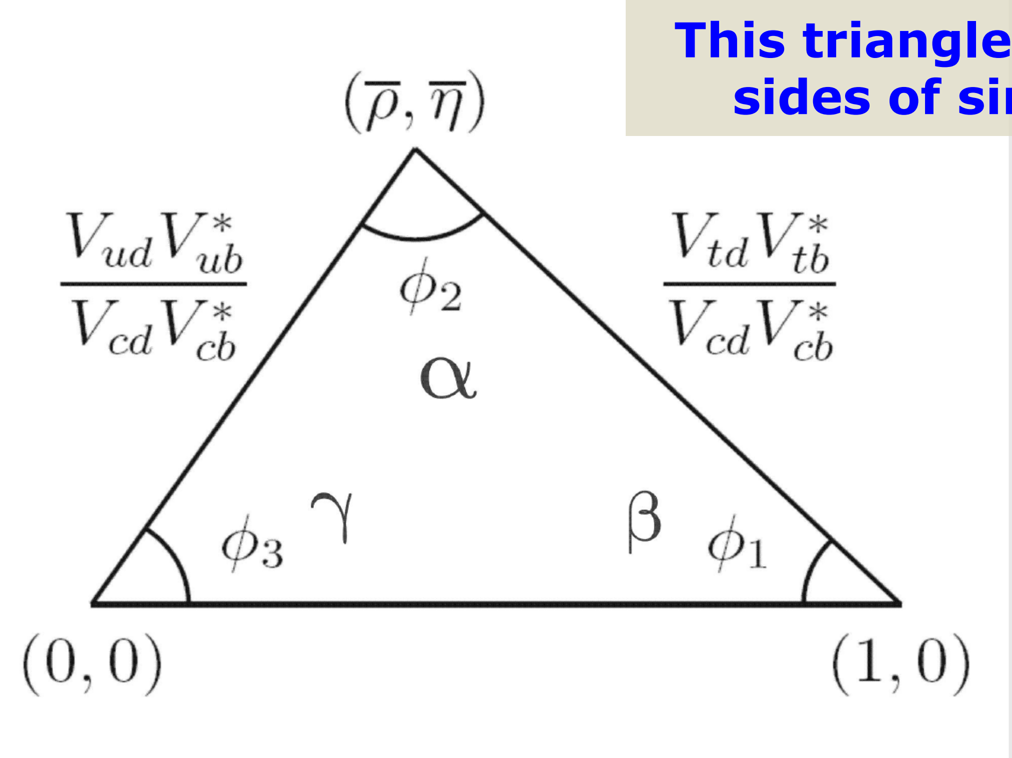
Experimentally : J ~ $3\text{x}10^{-5}$ due to strong hierarchy in V_{CKM} elements

➔ CP is 'weakly' violated in quark mixing

The "natural" Unitarity Triangle of the CKM Matrix

3×3 unitarity implies six triangle relations in the complex plane; because of the λ suppression, four of these triangles are quasi-flat, and the remaining two are almost degenerate. One defines "the" Unitarity Triangle by

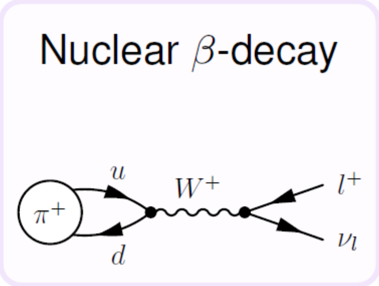
$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

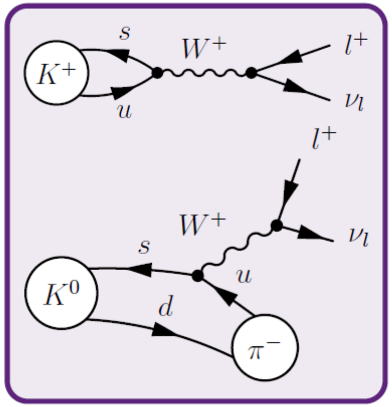


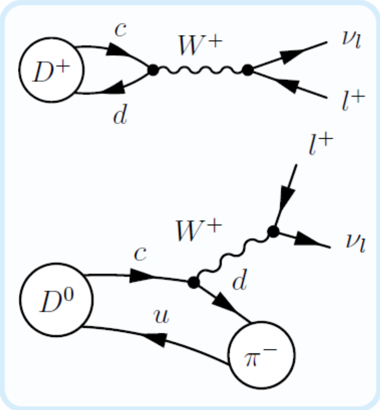
This triangle has angles/ sides of similar sizes

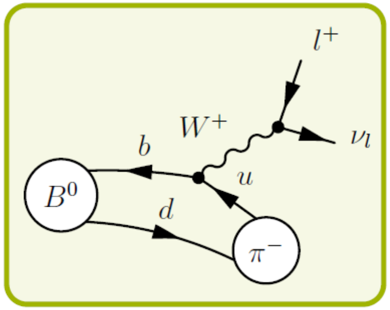
NB: $\beta, \alpha, \gamma = \phi_1, \phi_2, \phi_3$ in the Japanese notation

Determining the elements of the CMK matrix
Explores a large physics range !

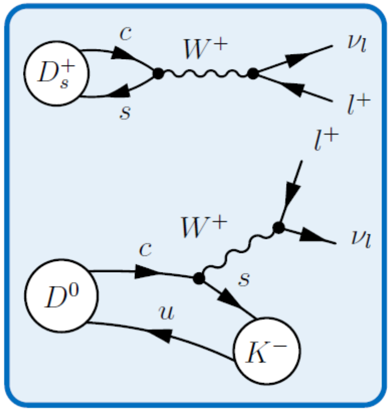

Nuclear β-decay

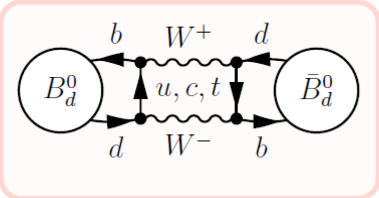


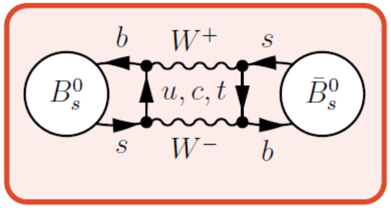


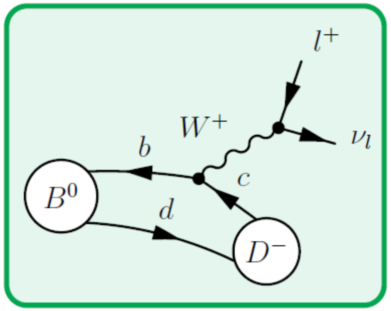


$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

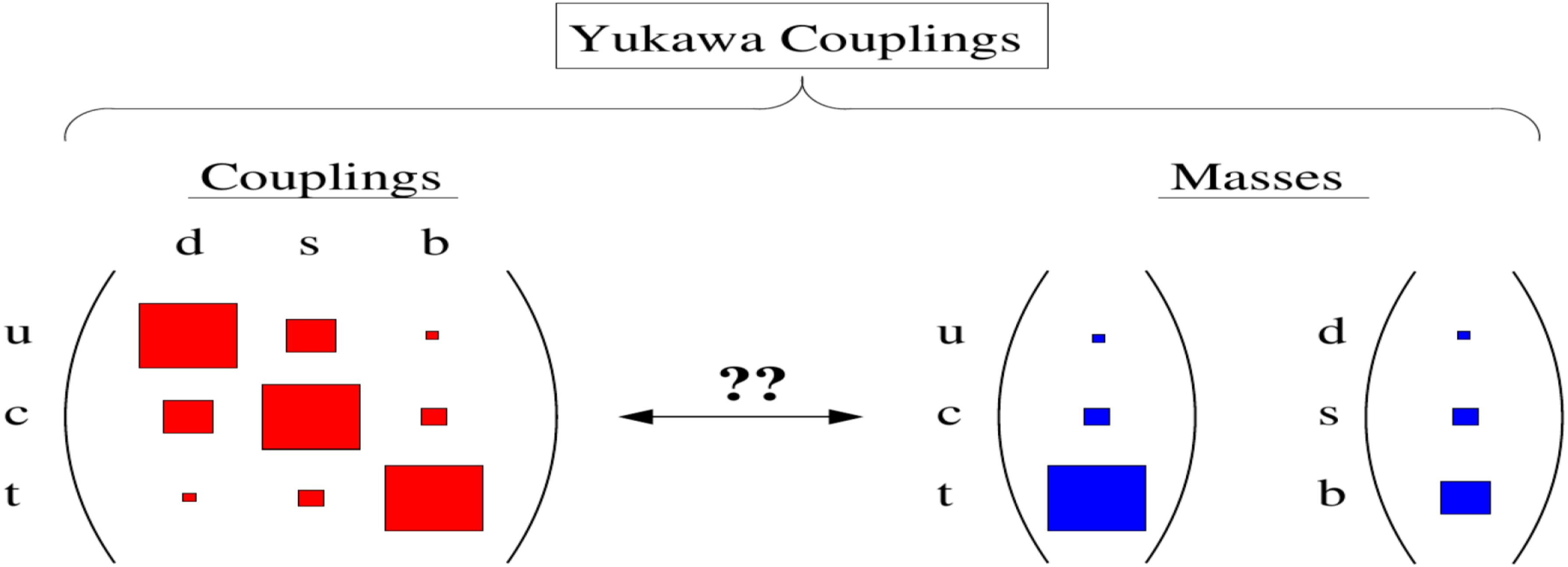




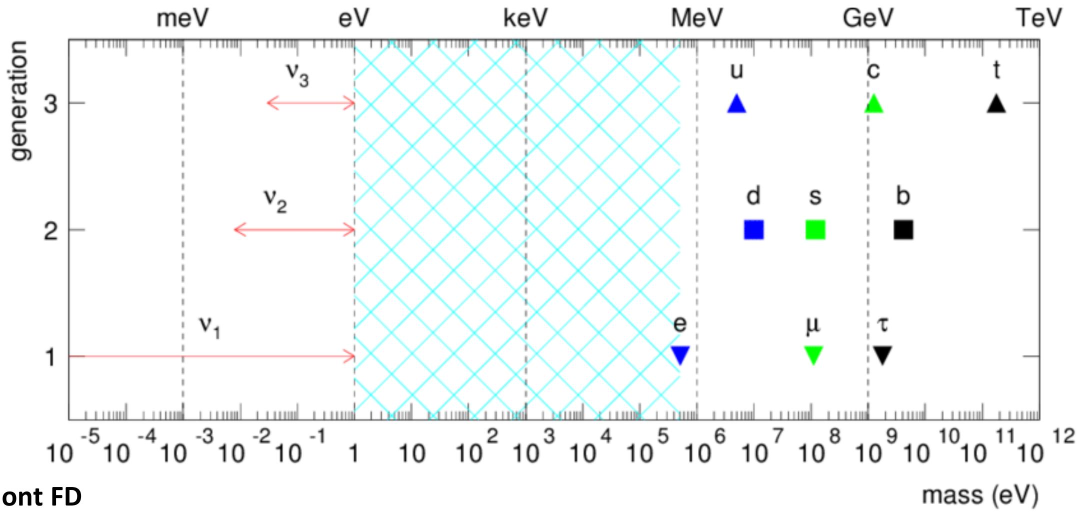




Strong hierarchy in couplings



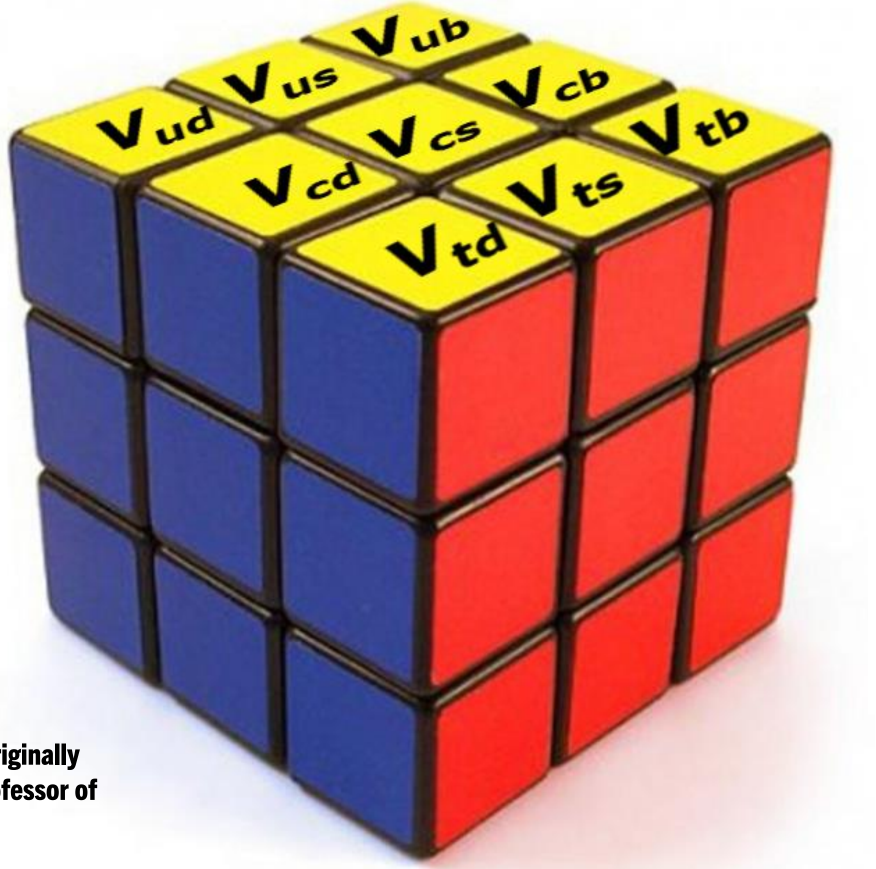
Sign of an underlying mechanism?



Note: the Yukawa of the quark top is almost 1 (this is the natural particle of EW !)

The CKM MATRIX

Cabibbo-Kobayashi-Maskawa



END OF DAY 1

The ***Rubik's Cube*** is a 3-D combination puzzle originally invented in 1974 by Hungarian sculptor and professor of architecture Ernő ***Rubik***.