b- and c-quarks Physics

P. Pakhlov

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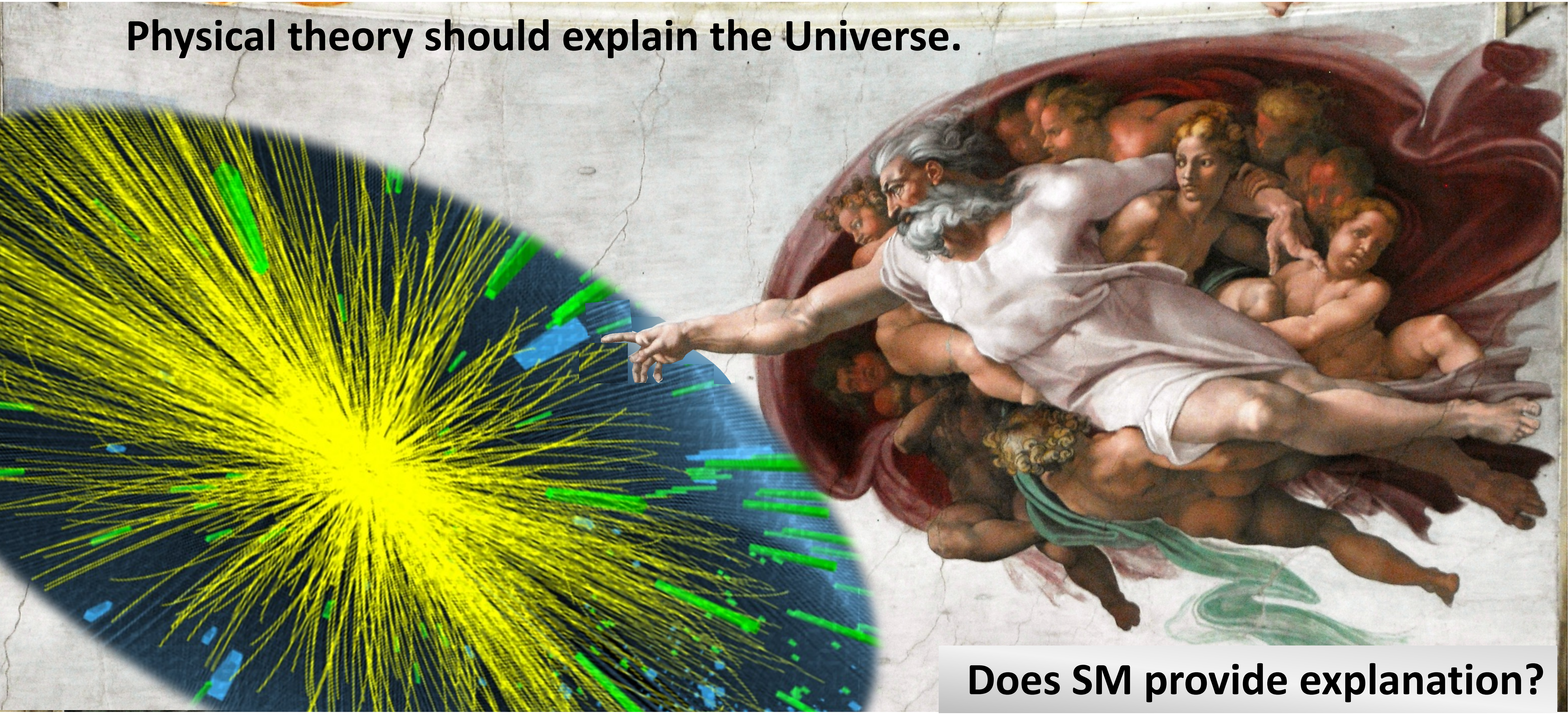
Heavy flavour Physics at LHC era?

Few years ago we dreamed about NEW rich phenomenology at the energy frontier, new puzzles and ideas, that follow from LHC new observations. LHC has brought yet only the Higgs boson but nothing else.

Flavour physics is a chance to find underground life (burrows under the palm tree)

Standard model



Standard Model: pragmatism

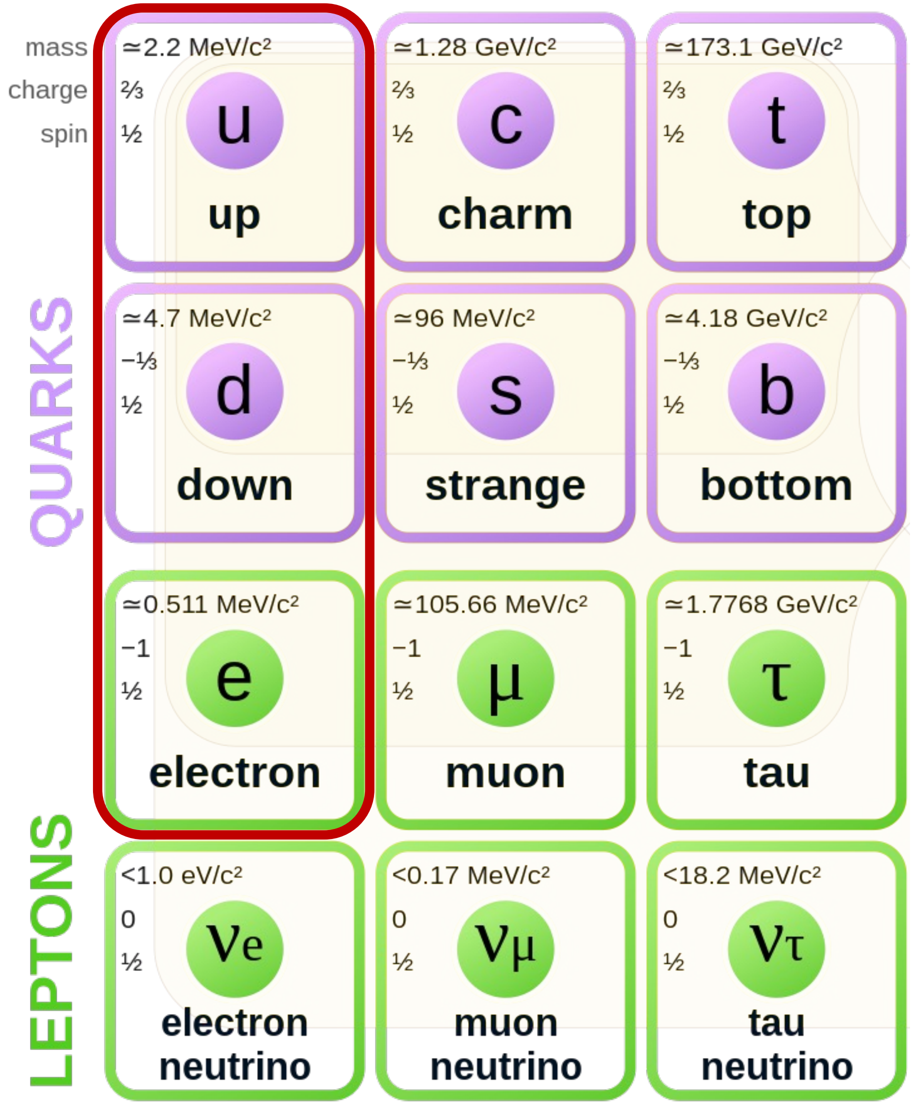
SM, a table of contents:

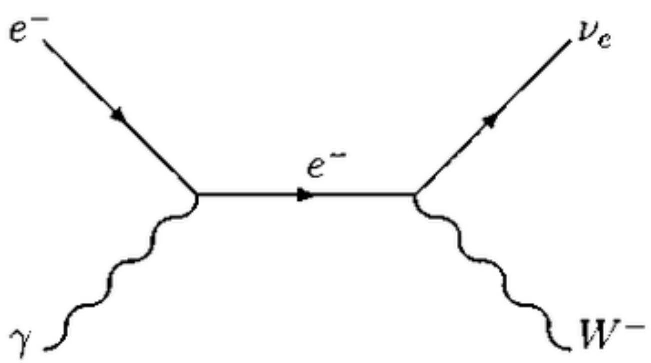
	Matter, spin = 1/2			*Forces, spin = 1*	*Vacuum, spin = 0*
mass / charge / spin					
QUARKS	≃2.2 MeV/c², ⅔, ½, u, **up**	≃1.28 GeV/c², ⅔, ½, c, **charm**	≃173.1 GeV/c², ⅔, ½, t, **top**	0, 0, 1, g, **gluon**	≃124.97 GeV/c², 0, 0, H, **higgs** (SCALAR BOSONS)
QUARKS	≃4.7 MeV/c², −⅓, ½, d, **down**	≃96 MeV/c², −⅓, ½, s, **strange**	≃4.18 GeV/c², −⅓, ½, b, **bottom**	0, 0, 1, γ, **photon**	
LEPTONS	≃0.511 MeV/c², −1, ½, e, **electron**	≃105.66 MeV/c², −1, ½, μ, **muon**	≃1.7768 GeV/c², −1, ½, τ, **tau**	≃91.19 GeV/c², 0, 1, Z, **Z boson**	
LEPTONS	<1.0 eV/c², 0, ½, ν_e, **electron neutrino**	<0.17 MeV/c², 0, ½, ν_μ, **muon neutrino**	<18.2 MeV/c², 0, ½, ν_τ, **tau neutrino**	≃80.39 GeV/c², ±1, 1, W, **W boson** (GAUGE BOSONS, VECTOR BOSONS)	

SM is a very practical theory:

It provides all ingredients to build a beautiful world

Fermions are the best bricks





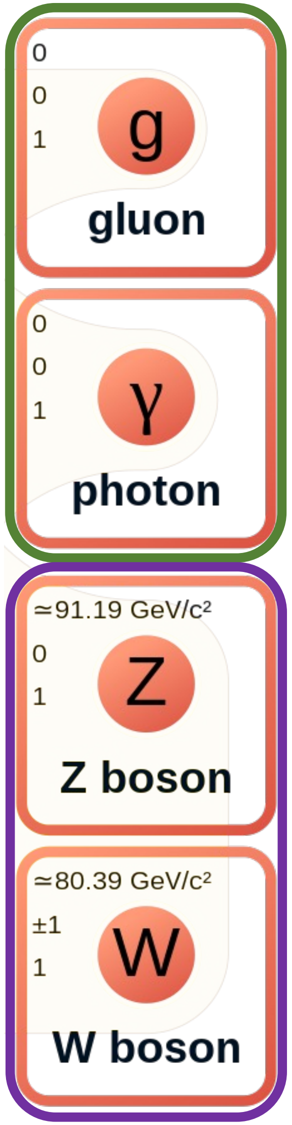
Fermions can transform into each other, but they cannot vanish or appear out of void.

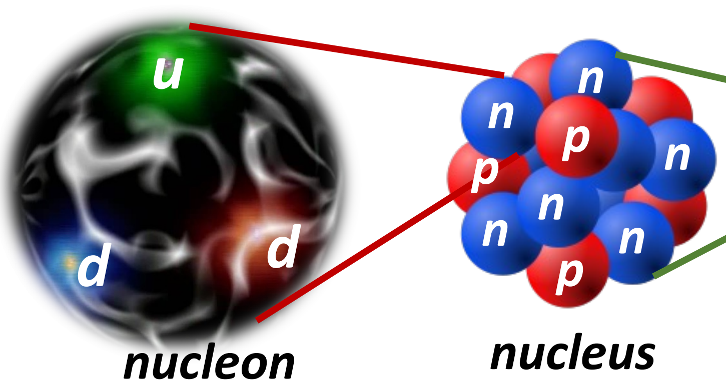
This is a good building material - it will ensure the stability of our constructure.

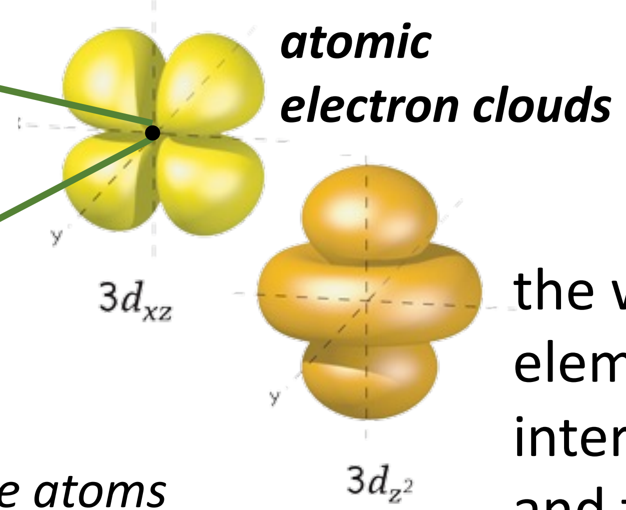
A danger: antifermions can knock out our fermion building blocks and destroy our structure. Nature must ensure that antifermions are not around. And Nature really took care of this: antimatter is not near us (probably there is just no much antifermions in our Universe at all).

Gauge bosons are cement mortar

Strong force is to build nucleons and nuclei







the whole variety of chemical elements is due to electromagnetic interactions, quantum mechanics and the Pauli principle.

Electromagnetic force is to complete atoms

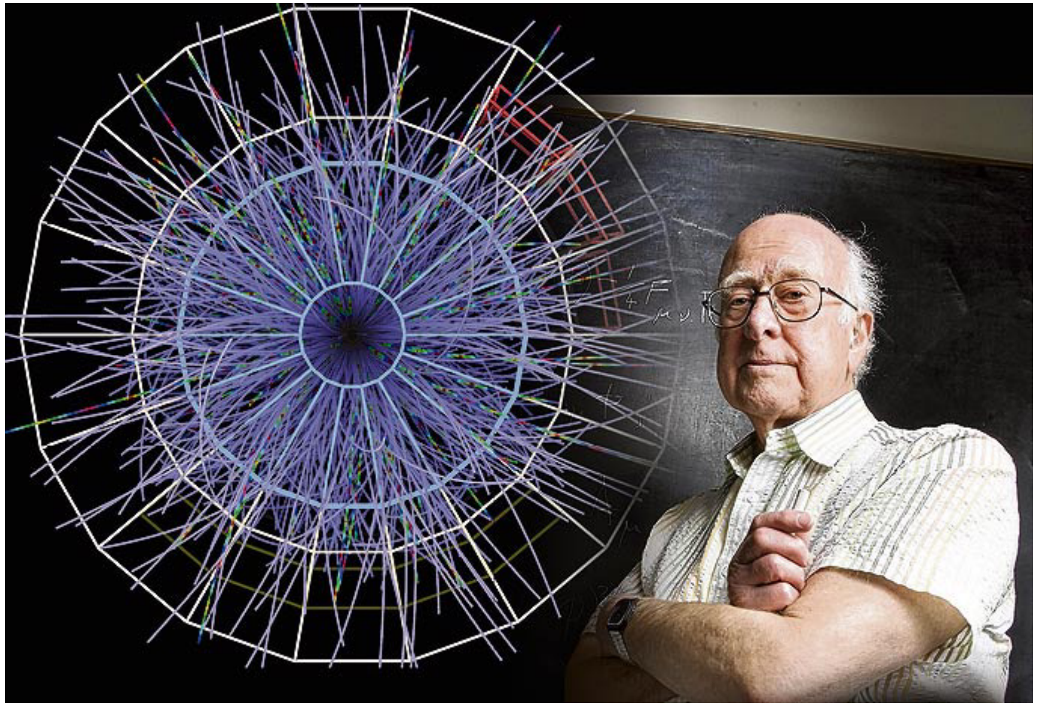
… or energy suppliers

Weak force seems not being used for construction, but supplies energy.

$$p + p \to {}^2D + e^+ + \nu_e + 0.4 \text{ МэВ}$$

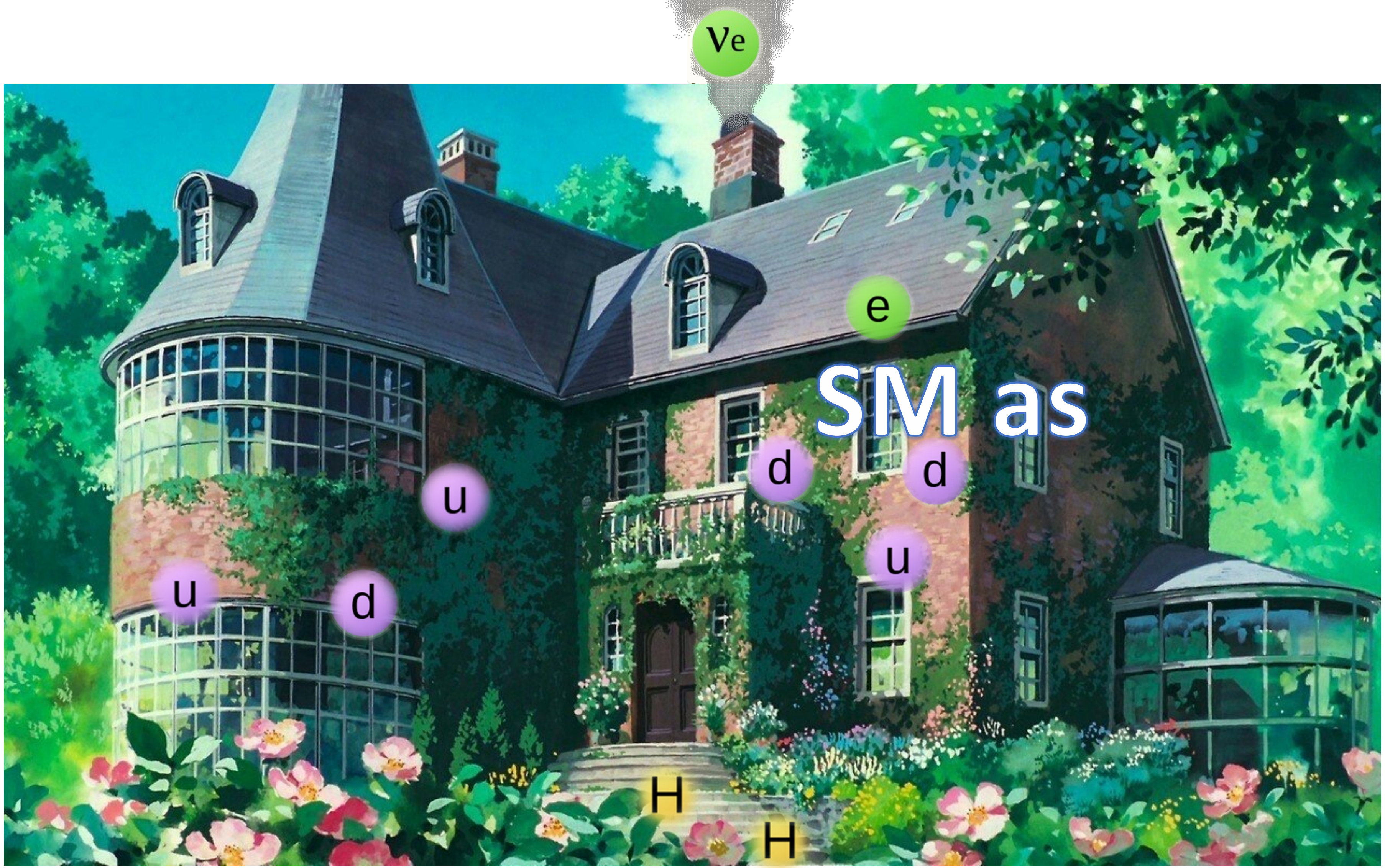
Scalar boson is footing

Ether was the postulated medium for the propagation of light. This idea (rejected in the 19th century) was revived in the 20th, although not in the form in which it was originally invented.



Higgs condensate plays a role of medium, where all other SM ingredients put in. Many of them (fermions and weak bosons) interact with Higgs field and thus are fixed in space, rather than senselessly run through it, like photons.

Does SM provide explanation for Universe?

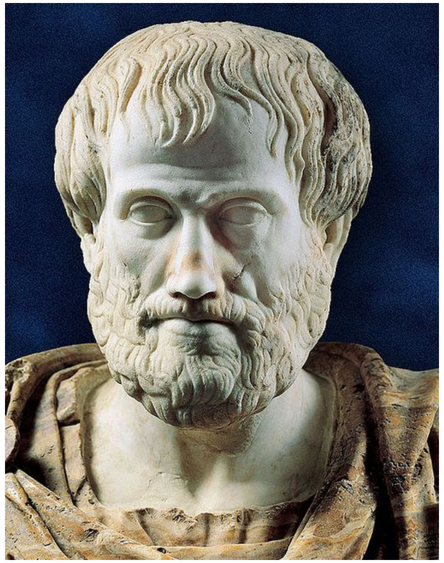


… seems to provide good training. We likely can build all objects that we see around from this small set of fundamental particles.

… and why are we unhappy?

Aristotle's principle

Nature does nothing in vain **(NDNIV)**



Does SM satisfy NDNIV?

We used almost the entire contents of the SM particle table, but two fermion generations (and all antifermions) remain unused...

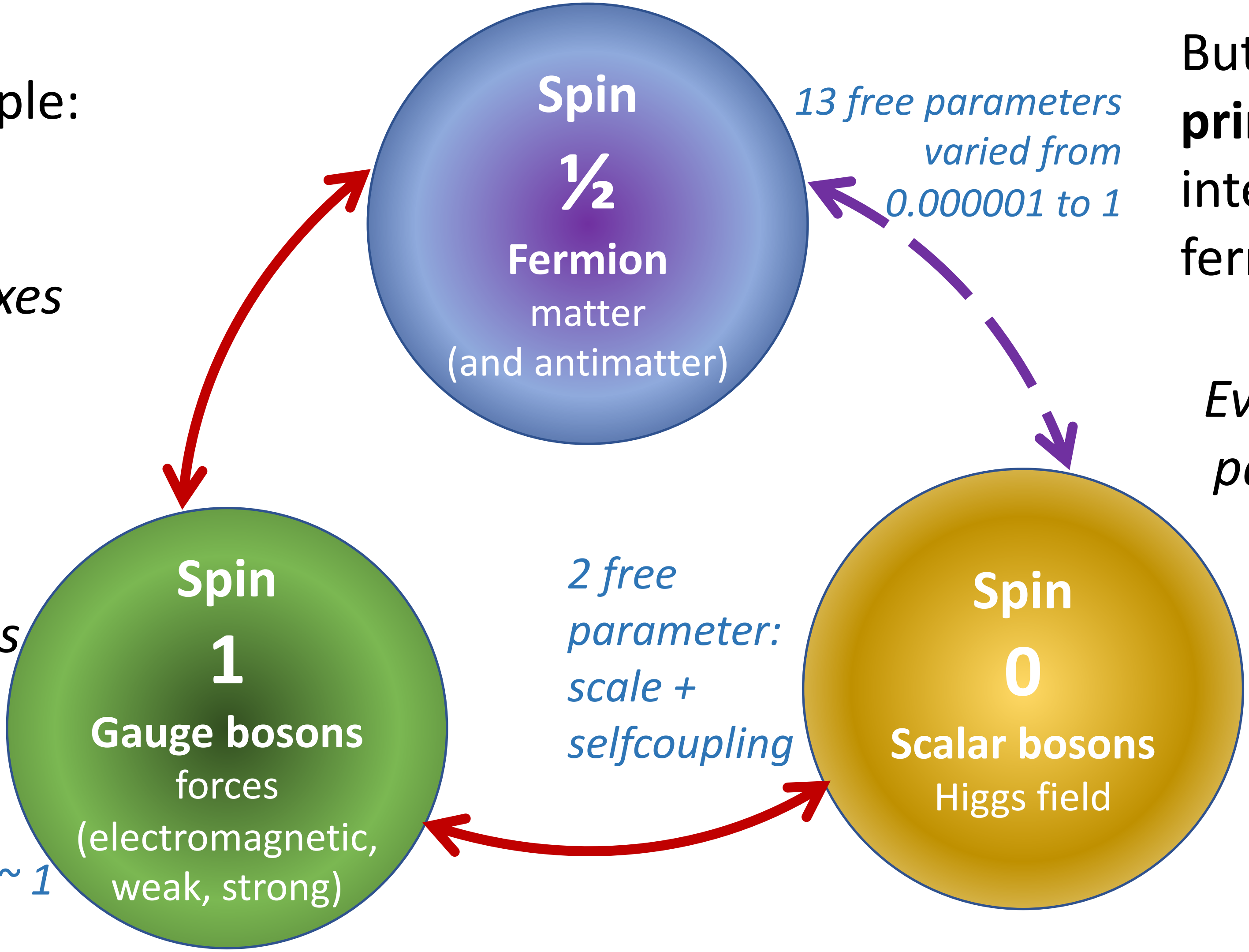
As for the macroscopic role of the particles of the second and the third generations, it seems at first glance trifling. These particles resemble the rough sketches, which the Creator has thrown out as unsuccessful, and which we with our sophisticated equipment dug in his wastebasket. Now we are starting to understand that these particles play an important role in the first moments of the Big Bang...

Lev Okun

SM contains three sectors: fermions, gauge and scalar bosons

Important SM principle:
gauge invariance

Gauge invariance fixes all interaction of gauge bosons: selfinteraction and interaction with fermions and scalars



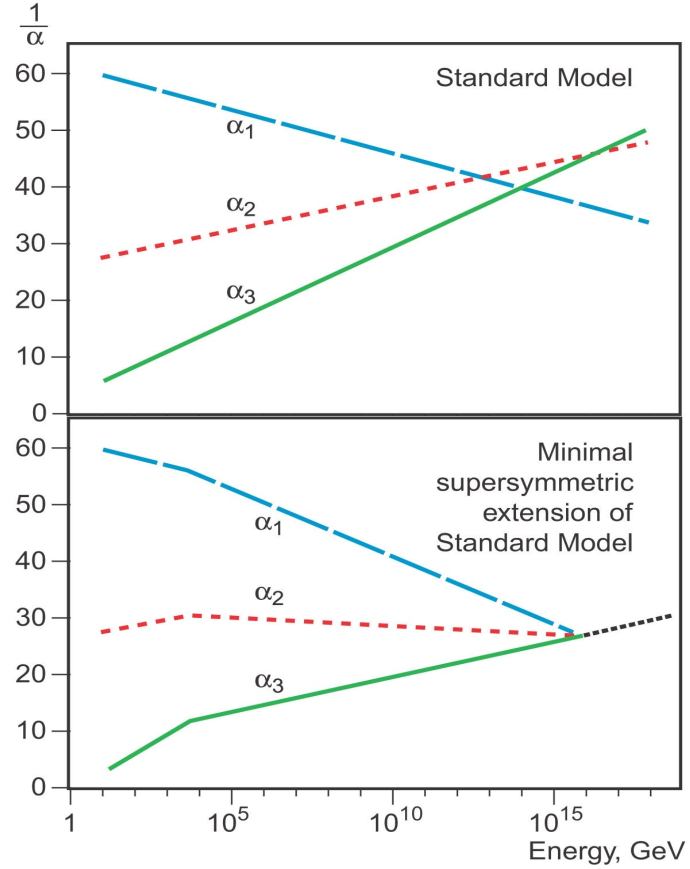
But there is **no known principle** on interaction between fermions and scalar

Even knowing all the parameters of these interactions with high accuracy, we cannot guess the principle.

SM is really built on few keystone principles, but we haven't grasped some principles yet

This is not the SM problem – this is likely a problem of lack of our creativity due to overloaded with math

Parameters of the Standard Model



- 3 gauge couplings (of the same order ~1, moreover, they are running and seem to be trending to the same value)
- 2 Higgs parameters (one is scaling parameter – we can't avoid this, another is selfcoupling ~1)
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

= 18 (+7)

after 50 years of thinking, we still have no ideas.

() = with Dirac neutrino masses

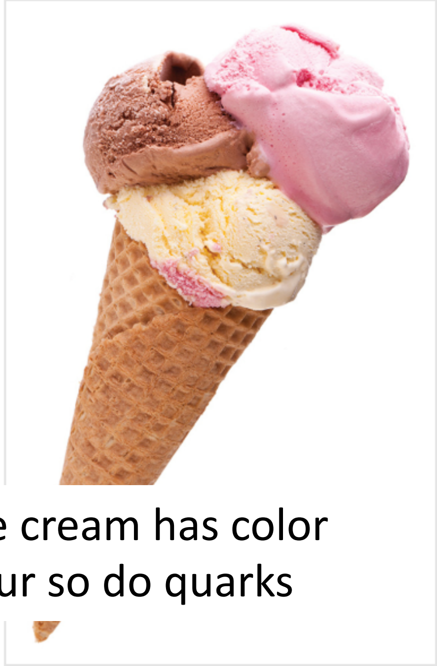
… that's why are we unhappy?

FLAVOUR PHYSICS | FEATURE

The flavour of new physics

8 May 2019

We use term "flavour" when consider fermions beyond one generation. Only the weak interaction has a power to change flavour.



Just as ice cream has color and flavour so do quarks

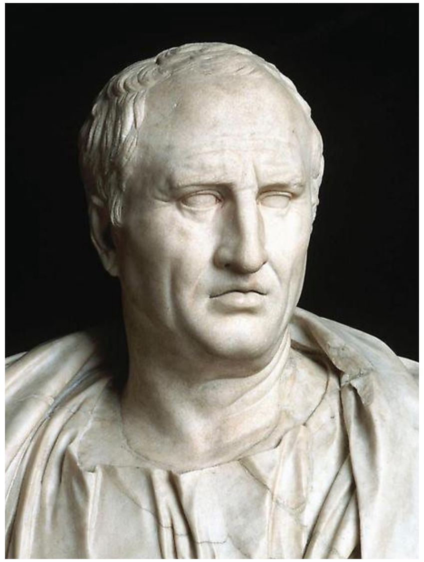
In 1971, at a Baskin-Robbins ice-cream store in Pasadena, California, Murray Gell-Mann and his student Harald Fritzsch came up with the term "flavour" to describe the different types of quarks. From the three types known at the time – up, down and strange – the list of quark flavours grew to six. A similar picture evolved for the leptons: the electron and the muon were joined by the unexpected discovery of the tau lepton at SLAC in 1975 and completed with the three corresponding neutrinos. These 12 elementary fermions are grouped into three generations of increasing mass.

This large number of free parameters is behind several of the mysteries of the SM:

- Why are there so many different fermions?
- What is responsible for their organization into generations?
- Why are there 3 (nor 2, neither 37) generations each of quarks and leptons?
- Why are there flavour symmetries?
- What breaks the flavour symmetries?
- What causes matter – antimatter asymmetry?

Unfortunately, these mysteries will not be answered in these lectures

The closer the collapse of an Empire, the crazier its laws



Marcus Tulius Cicero

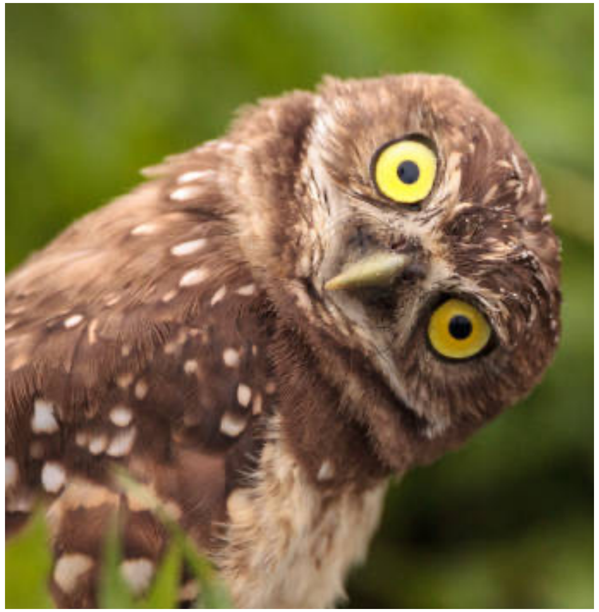
The same is true for the Theory: during 50 years, SM has to accommodate many new features: half of the second and the third generations of quarks, mixed with a complex matrix, neutrino masses, Higgs-top masses at the edge of vacuum stability, etc. These double the number of free parameters and likely indicate the sooner transition to a new Theory.

SM in 1967: elegant, fresh, natural, logical.

SM in 2022: old, contradictory, unnatural, ugly.

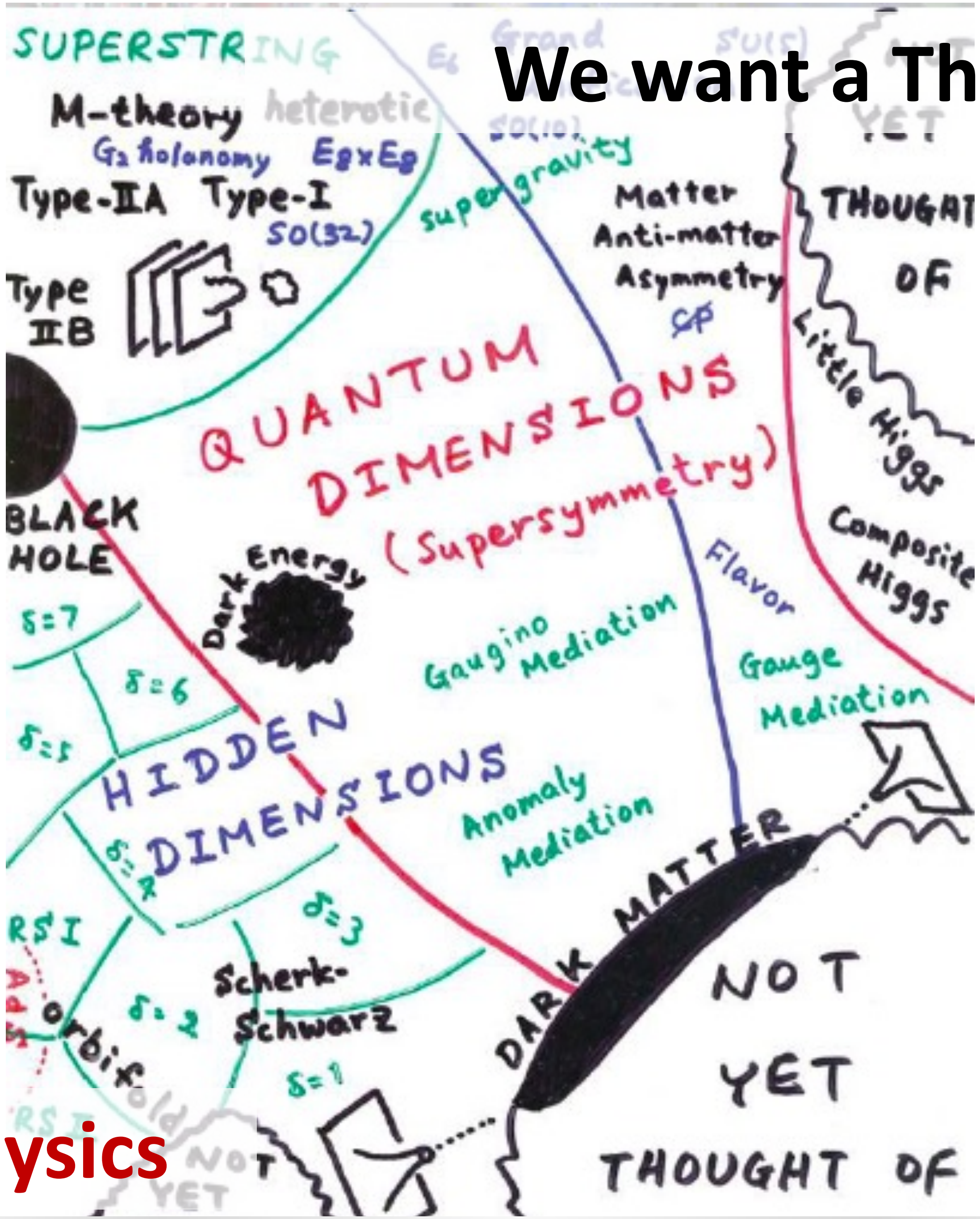
We want a Theory of Everything

that answers all questions and resolves all mysteries



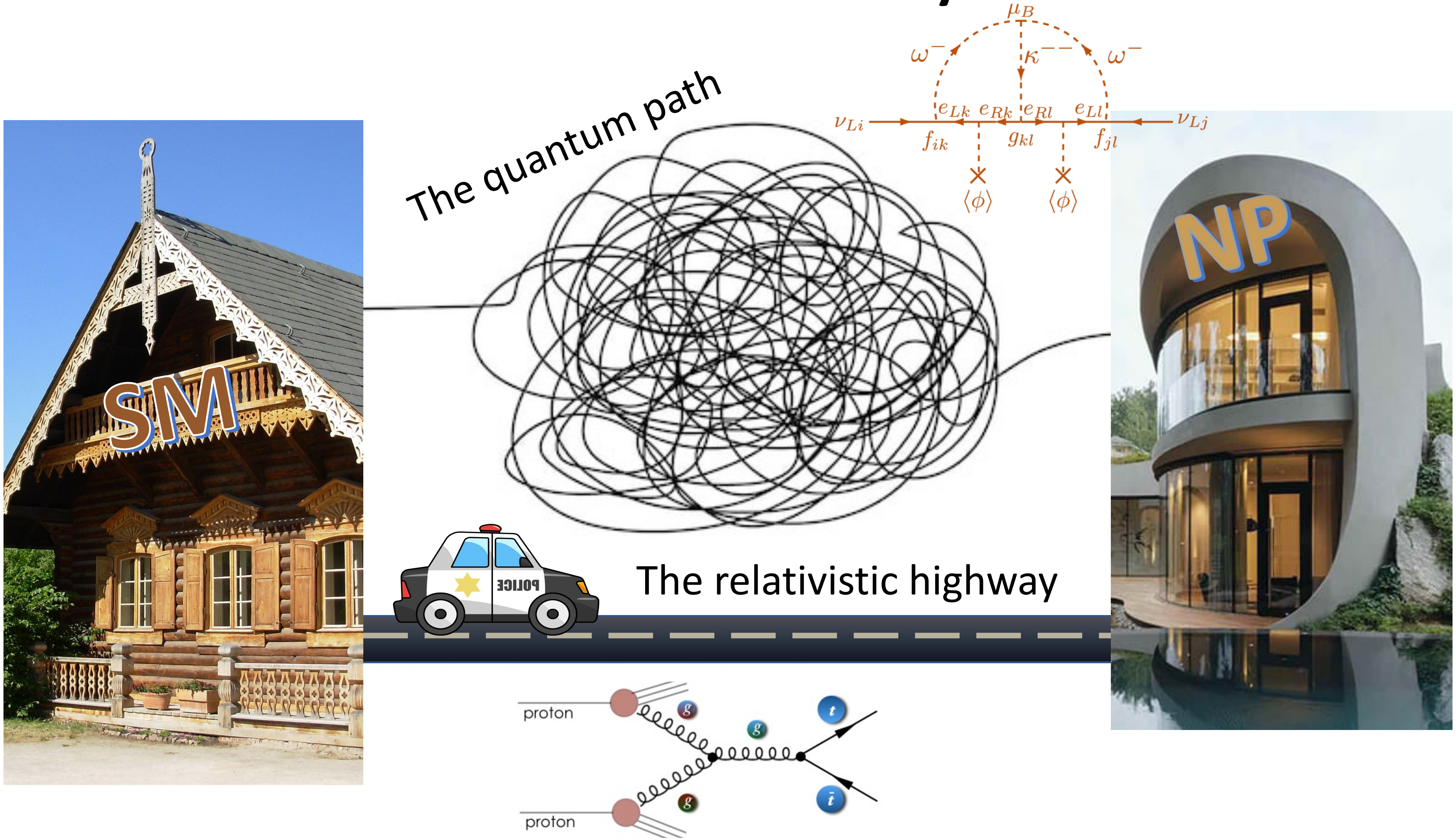
perhaps, we are too greedy…

Well, give us at least something beyond the Standard Model.

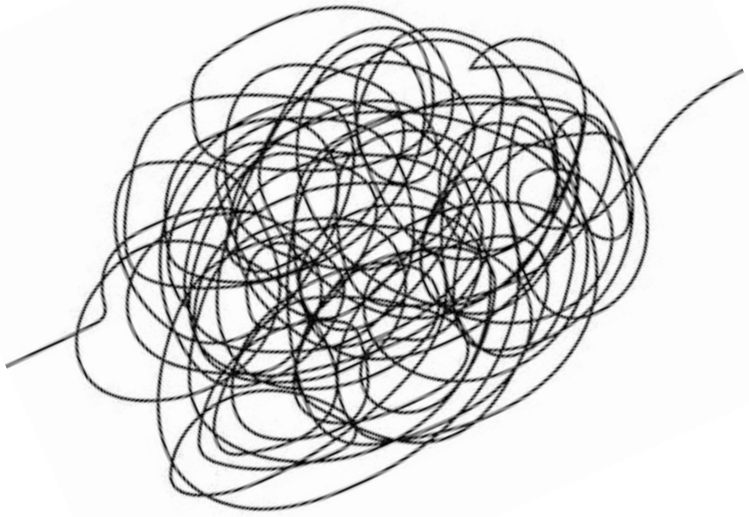


We want New Physics

How to reach New Physics?



Quantum path is easy?

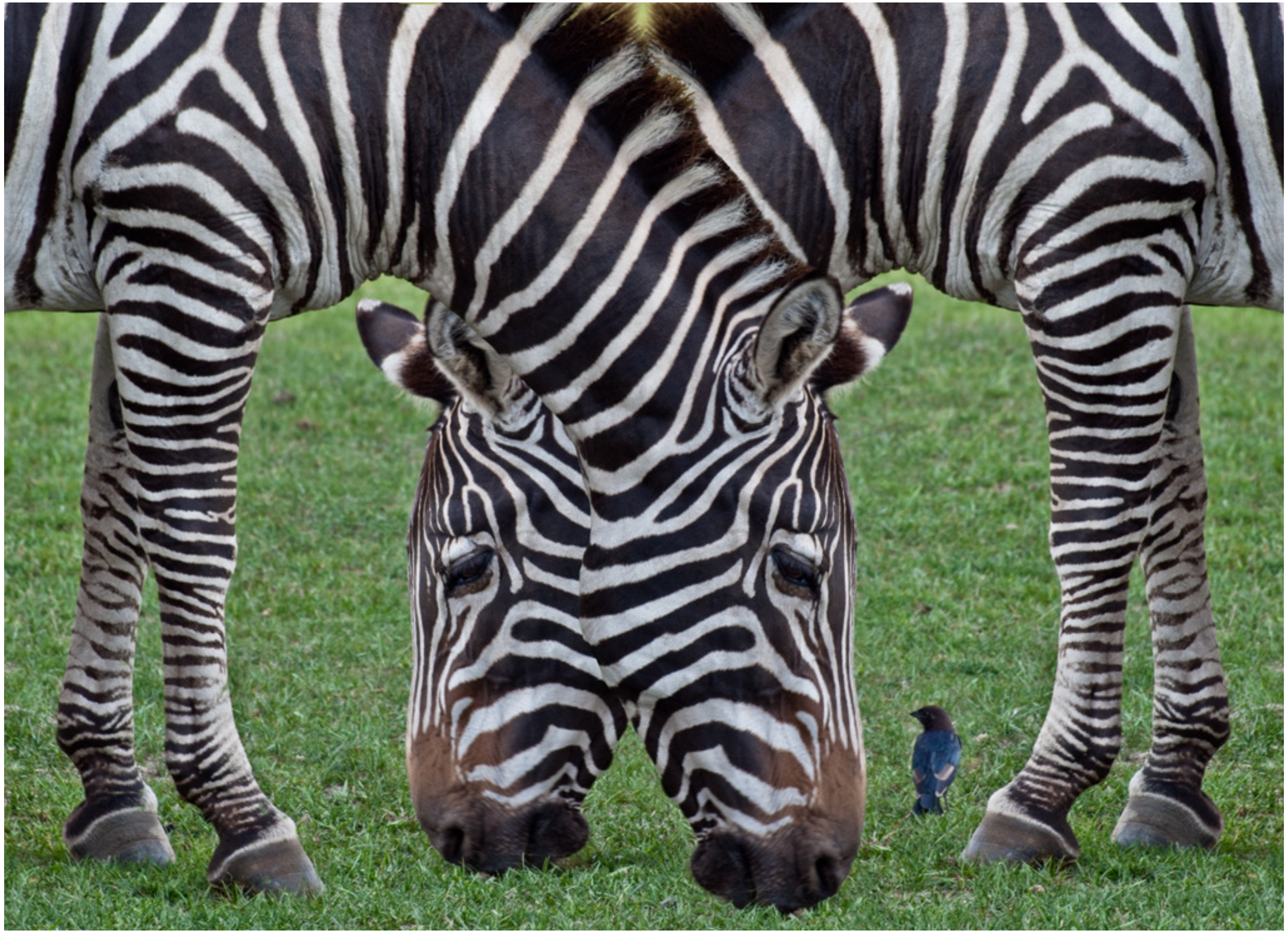


Requires:
  precise measurements
+ good idea to explain them
+ routine math work

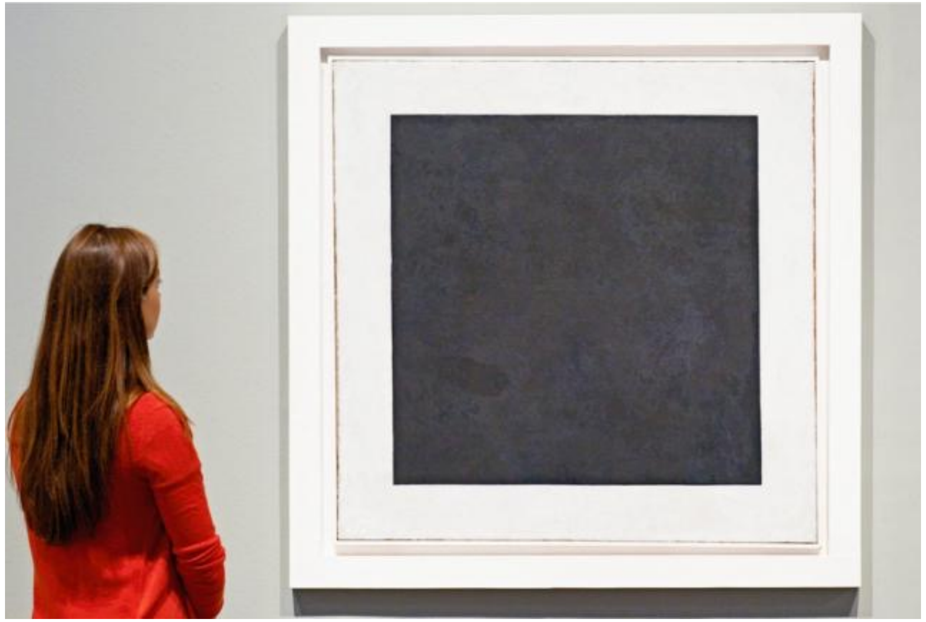
- *Charm discovery by the observation rare FCNC in the Kaon system*
- *3rd quark family seen by CPV in Kaon system*
- *the heaviness of the top quark … seen by B physics*
- *Nonobservation of many proposed/suspected NP phenomena at TeV scale from B-physics*
- *Anomalous muon magnetic moment wants to say us something…*

At least successful!

Symmetries in Nature



Interesting fact: Malevich's "Black Square" hung upside down in the Tretyakov Gallery for many years.

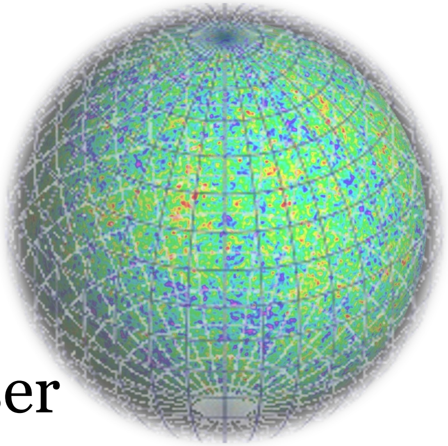


and their breaking

Symmetries

A thing is symmetrical if there is something we can do to it so that after we have done it, it looks the same as it did before.

R. Weyl



i.e. if you work without visible results, it's not because you're a loser or a loafer, it's just a symmetry!

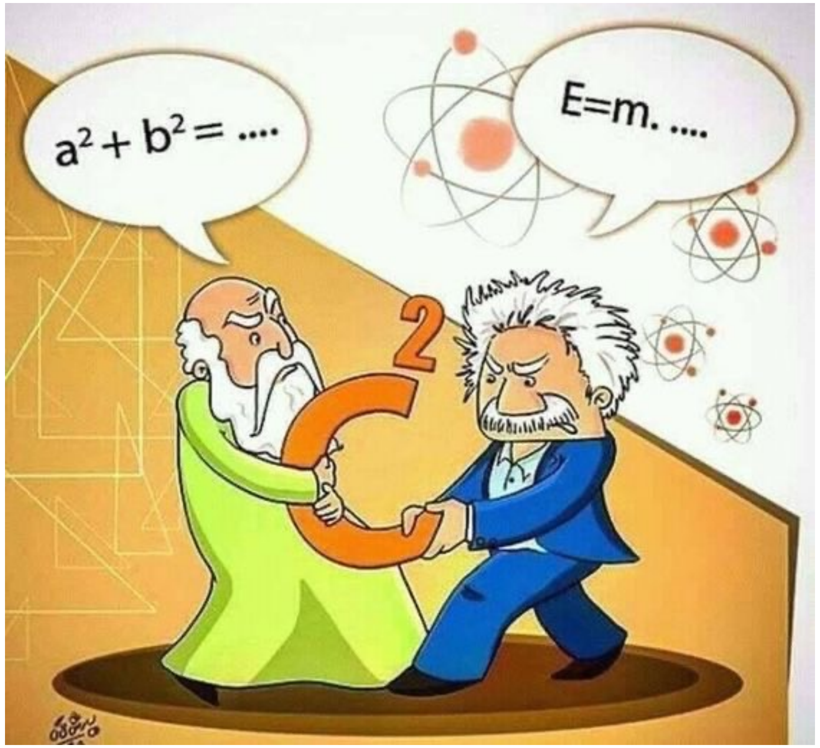
Example: pavement curbs in Moscow are being repaired regularly, while their quality unchanged: this is not a corruption, this is symmetry.

“There are two troubles in Russia: fools and roads” – this is a result of imposed symmetries under roadworks and education.

Symmetry seems to be a basic concept not only in physics!

Symmetries in Nature

Until the 20th century principles of symmetry played a little role in physics. From ancient Greeks the observed symmetries were considered as an intrinsic harmony of the laws of Nature (e.g. Pythagoras explained patterns in Nature like the harmonies of music as arising from number – the basic constituent of existence.) But nobody tried to deduce a law from the symmetry principle.



A great advance made by A. Einstein in 1905 was to put symmetry first, to regard the symmetry principle as the primary feature of Nature that constrains the allowable dynamical laws. E.g. the transformation properties of the electromagnetic field were not to be derived from Maxwell's equations, but rather were a consequence of relativistic invariance and largely dictated the form of Maxwell's equations.

Symmetries and conservation laws

A more important implication of symmetry in physics is the existence of conservation laws. Every continuous symmetry of a physical system entails a conservation law, i.e. there exists an associated time independent **conserved** quantity. This connection was revealed in 1918 by Emmy Noether through her famous theorem.

For example, the laws of energy and momentum conservation follow from the fact that experiments yield the same results wherever and whenever they are done.

It turns out that symmetries, that we like, are slave chains not allowing too much freedom!

Symmetries are restrictions

On the one hand, these restrictions sometimes are not bad thing – a certain guarantee of stability:
a brick may fall on your head, but it will do so according to the restrictions imposed by conservation laws, and this unpleasant meeting can be mitigated.

On the other hand, imposing of the maximum number of symmetries completely deprives the possibility of any dynamics in the Universe. Life completely dies (all lives, having completed a sad circle, faded away) and there is nobody to admire the perfect symmetry.

Why Nature hasn't killed all live?

Obviously, it's important to Nature to show off in front of someone! Nature seems to need an observer!

A reasonable compromise is required: restrictions are needed to avoid chaos, but some freedom must also be left for dynamics. Nature has obviously found a solution. This lecture (just the fact of it) is a proof of that.

Isn't the solution to break symmetries a little bit? This allows freezing the overall picture while allowing small movements over a static background.

Nature loves not perfect, but slightly broken symmetries?

We'll see that Nature introduces first a conservation law, but then add small violation;

violation $\ll$ *conservation*

Does Nature love not perfect, but slightly broken symmetries?

we do the same: we prefer slightly broken symmetries

Are slightly broken symmetries still symmetries?

The difference between being a circle and being nearly a circle is not a small difference; it is a fundamental change so far as the mind is concerned. There is a sign of perfection and symmetry in a circle that is not there the moment the circle is slightly off that is the end of it is no longer symmetrical.

R. Feynman

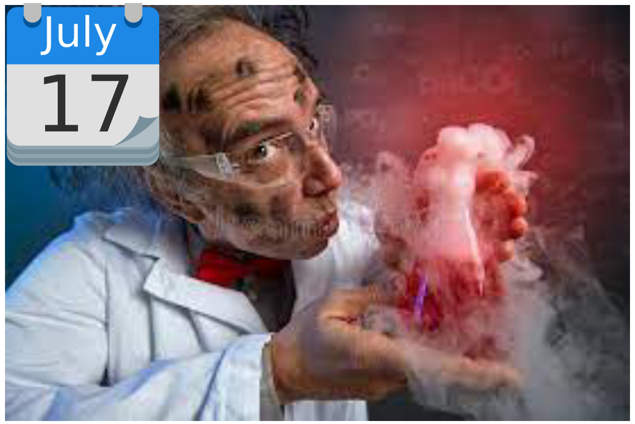
In one of his lectures, Feynman describes a gate in Japan (Nikkō Yomeimon) that at first glance is so perfectly created that it seems flawless. But if you go closer, you'll see that there is one tiny imperfection. It is rumored that the builders of that gate put the imperfection there to make sure the Gods don't get jealous and angry at the perfection of man. So, perhaps Nature is only nearly symmetrical so that we would not get jealous of its perfection!

Continues Symmetries

Those related to space-time geometry and internal.

- Time translational invariance → energy is conserved
- Invariance under a change in phase of the wave functions of charged particles → electric charge is conserved.

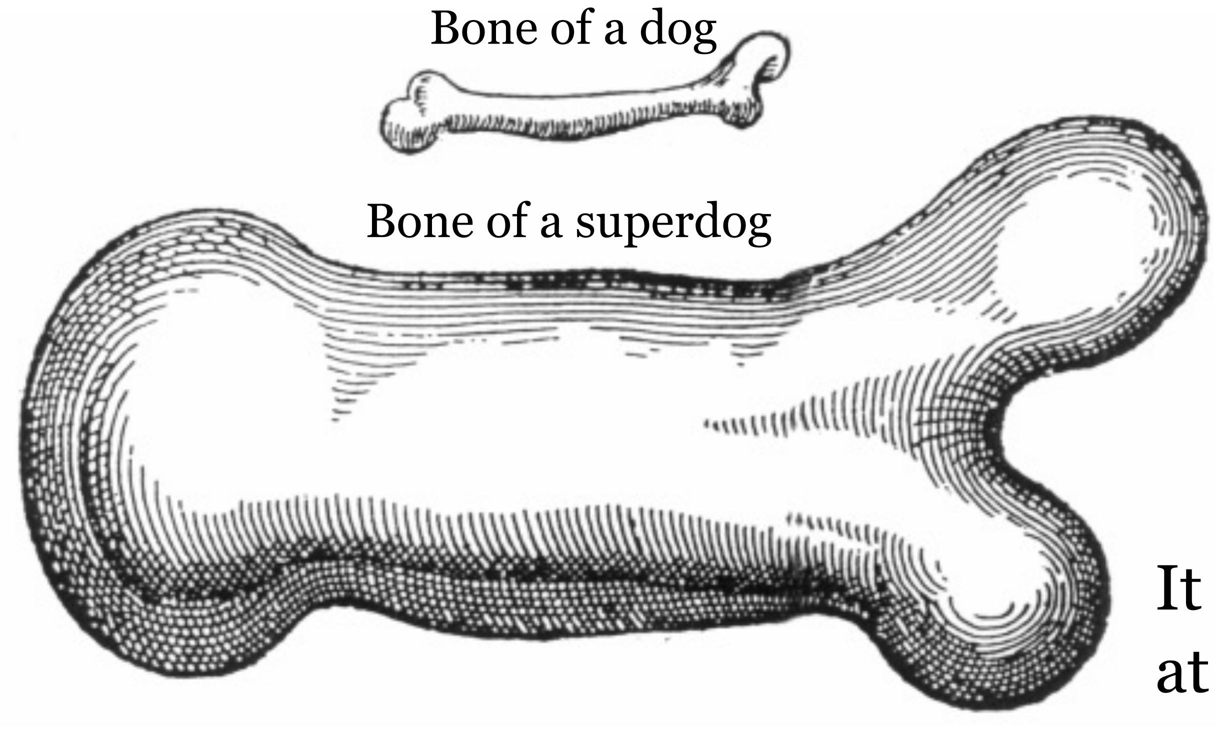
Gauge – a number of lead balls in a pound of ammunition. Gauge invariance: This number stays the same if the lead balls are colored differently. We are interested in quantity, not color.



What symmetry does not exist in nature?

Scale symmetry!

The fact that the laws of physics are not unchanged under a change of scale was discovered by Galileo. He realized that the strengths of materials were not in exactly the right proportion to their sizes.



Galileo was so impressed with this discovery that he considered it to be as important as the discovery of the laws of motion…


DISCORSI
E
DIMOSTRAZIONI
MATEMATICHE,
intorno à due nuoue scienze
Attenenti alla
MECANICA & I MOVIMENTI LOCALI,
del Signor
GALILEO GALILEI LINCEO,
Filosofo e Matematico primario del Serenissimo
Grand Duca di Toscana.
Con una Appendice del centro di grauità d'alcuni Solidi.
IN LEIDA,
Appresso gli Elsevirii. M. D. C. XXXVIII.

It is really important: the theory should contain at least one scale parameter. So SM does!

Mirror symmetry

Mirror symmetry

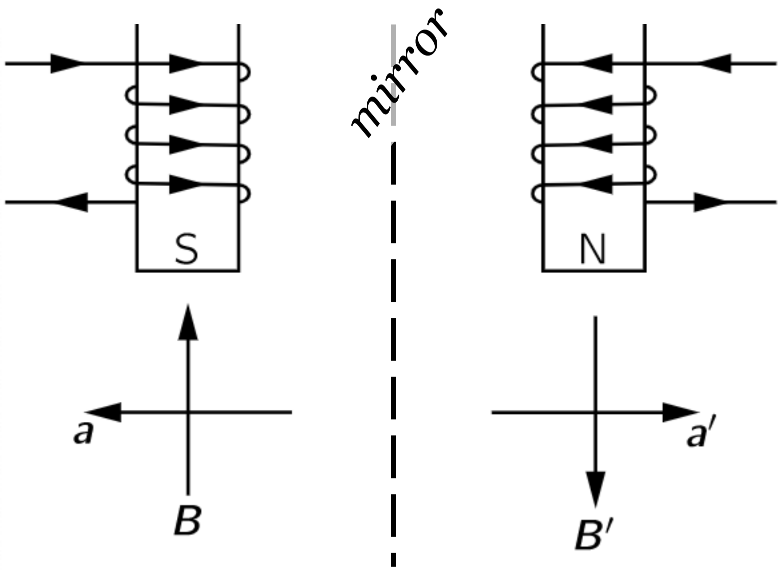
Space inversion $(x, y, z) \rightarrow (-x, -y, -z)$ inverts all space coordinates used in the description of a physical process. Equivalent to mirroring with respect to a plane, (for instance $x \rightarrow -x$) followed by a rotation around an axis perpendicular to the plane.

Parity conservation or P-symmetry implies that any physical process will proceed identically when viewed in mirror image.

Does this sound too obvious?
E.g. are there any doubts, that these two dices give the same chances to gamblers?

Mirror asymmetry is difficult to assume in pure mechanics, what about electrodynamics, where both real vector and axial vectors field exists?

Mirror symmetry



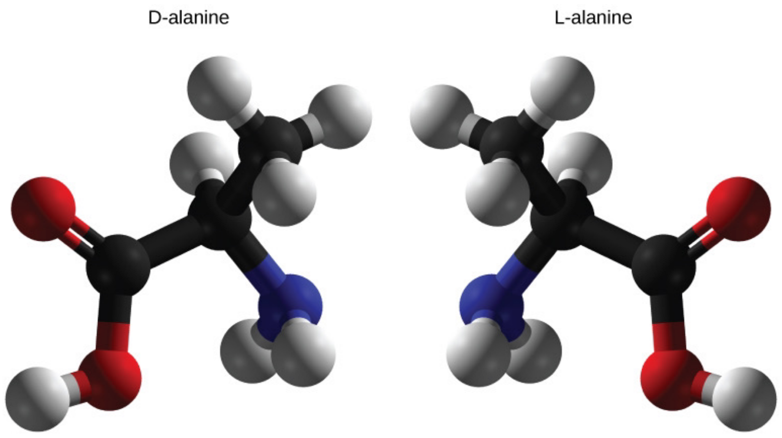
Consider electromagnet and its mirror reflection

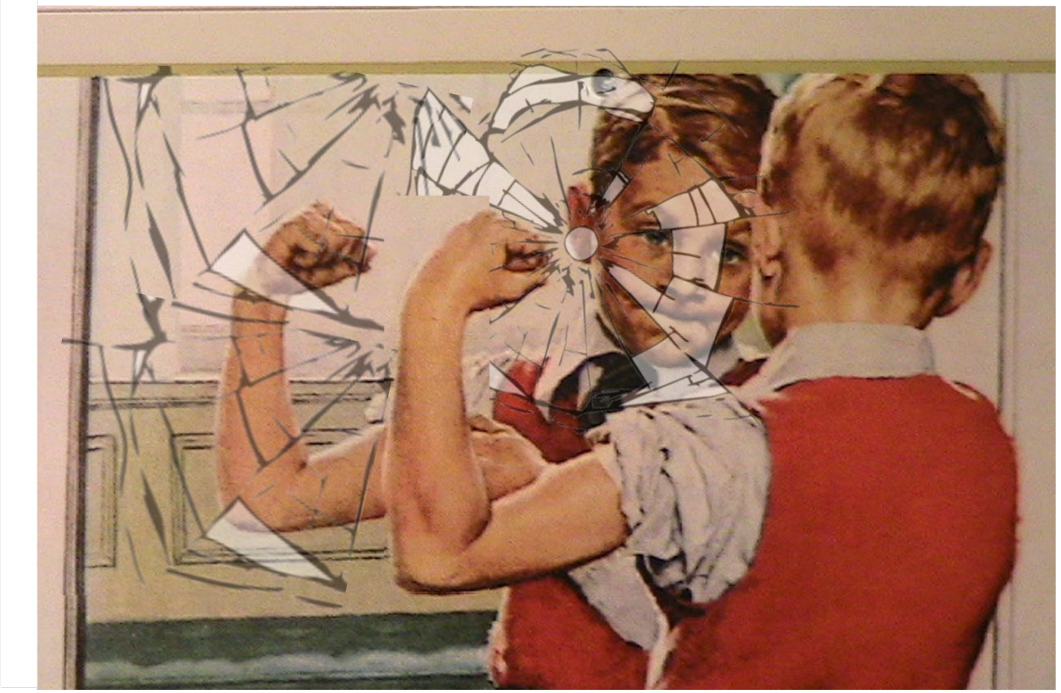
the coil will wind the other way, everything that happens inside the coil is exactly reversed, and the current goes in the opposite direction

We can see that the poles of magnets changed from north to south. Is it OK, if north in mirror becomes south? Never mind changing north to south; these too are mere conventions. Care only about phenomena. An electron moving through one field, going into the screen will deviate in the indicated direction according to the physical law. The force is reversed, and that is very good because the corresponding motions are then mirror images! *Why everything ended successfully although there seemed to be problems along the way (magnetic field behaves as axial vector, but the magnetic force is still true vector!)?*

If it's too trivial, then would you explain **Why…**

L-alanine is one of the most abundant amino acids in proteins, while D(beta)-alanine is the main component of the bacterial wall;





Is the male potency in mirror is the female beauty? Do not even try to imagine this!

They both are sailed in internet-shops:

- L-alanine promotes male potency,
- D-alanine is a cosmetic product.

…are their prices different?

The first hadronic flavour: strange

Physicists guessed correctly with the name of the hadrons that arrived in 1947 from cosmic rays. Strange particles brought the most surprises, related to symmetries.

Isospin

+1/2	$K^+(\bar{s}u)$	$\overline{K^0}(s\bar{d})$
-1/2	$K^0(\bar{s}d)$	$K^-(s\bar{u})$
	-1	+1 Strangeness

Why are these particles strange?

– produced (always in pair) as copiously as the π's;

– lifetime is $\sim 10^{-10}$ s;

Produced through strong interaction, decay through weak interaction

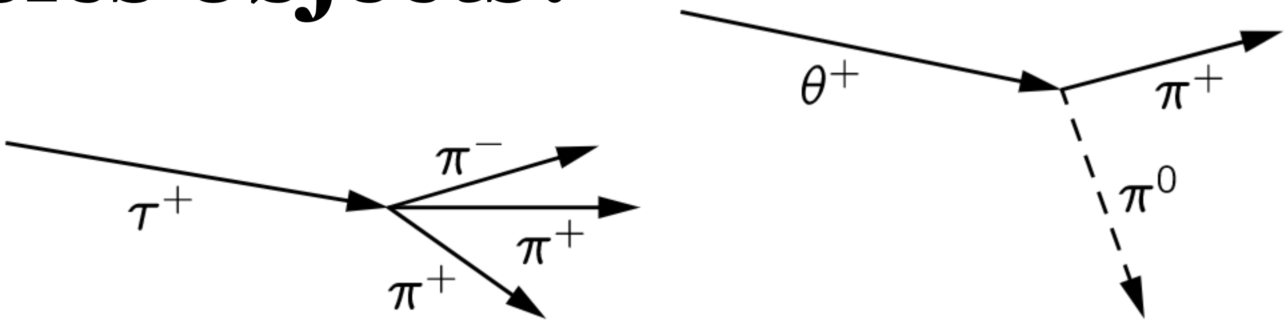
There should be a reason to inhibit the decay through strong interactions.

Introduce a new quantum number, call it "strangeness" and then wait for new strangeness.

Living objects do not respect mirror symmetry

it's a biology problem but physics has nothing to do with it?
Yes! until physics faces the same problem itself!

What about physics objects?



In 1950th we had a particle called a τ^+, decaying into three π's, and a θ^+, which decays into two π's. The τ and the θ are equal in mass within the experimental error; their lifetimes were found to be almost exactly the same; moreover, whenever they were produced, they were made in the same proportions, ~14% τ's & ~86% θ's. Definitely, they are the same particle that have two decay modes. But, parity conservation says, it was *impossible* to have these both modes come from the same particle.

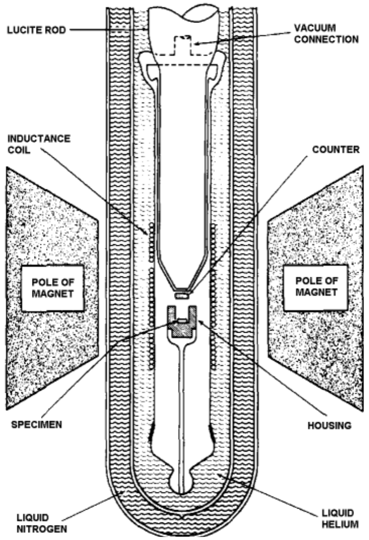
P-violation in weak decays

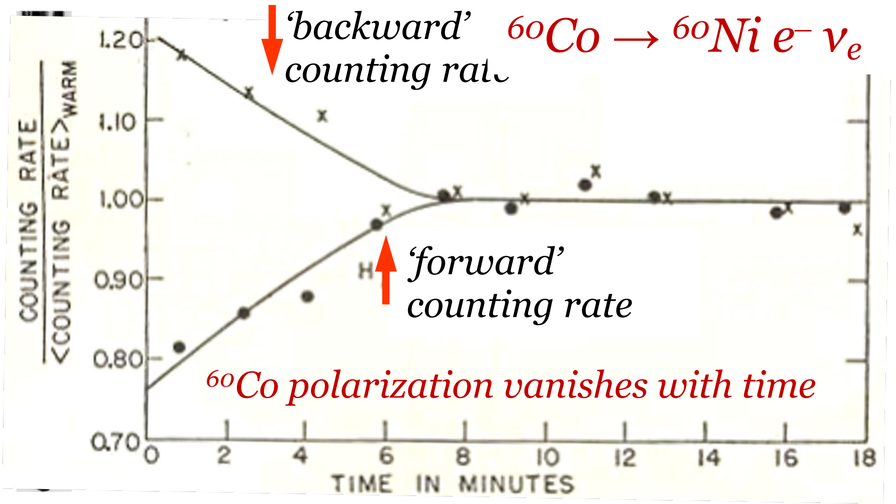
Miss Wu following the suggestions of Lee and Yang using a *very strong magnet* at a *very low temperature* found that the atoms of cobalt lined up in a field whose B vector points upward, emit electrons in a downward direction.

Doesn't sound very stupendously?

Let's say otherwise: If we were to put it in a corresponding experiment in a "mirror", in which the cobalt atoms would be lined up in the opposite direction, they would spit their electrons *up*, not *down;* the action is *unsymmetrical.*

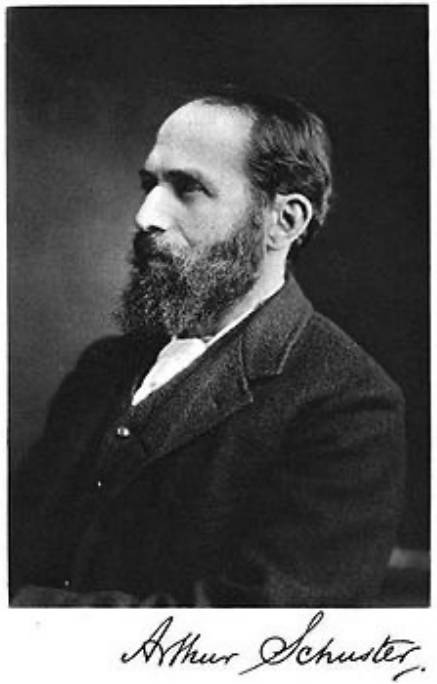
The Wu experiment (1956)





Electrons are preferentially emitted opposite to ^{60}Co spin

north and south are still mere conventions? No, Cobalt distinguishes them..



Antimatter

Was proposed 30 years before Dirac's derivation by A. Schuster (1898, immediately after electron discovery). In letters to "Nature" he conjectured: *"…if there is negative electricity, why not negative gold, as yellow as our own?…"*. He coined the concept of "antimatter", hypothesized antiatoms, and whole antimatter solar systems, which would yield energy if the atoms meet with atoms of normal matter (annihilation).

Although Schuster's conjectures were not taken seriously for 30 years, he made a correct conclusion based on symmetry considerations! He just couldn't find convincing arguments.

Antimatter

Was discovered theoretically by P. Dirac (1928) in merging quantum mechanics to special relativity.

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Charge conjugation symmetry

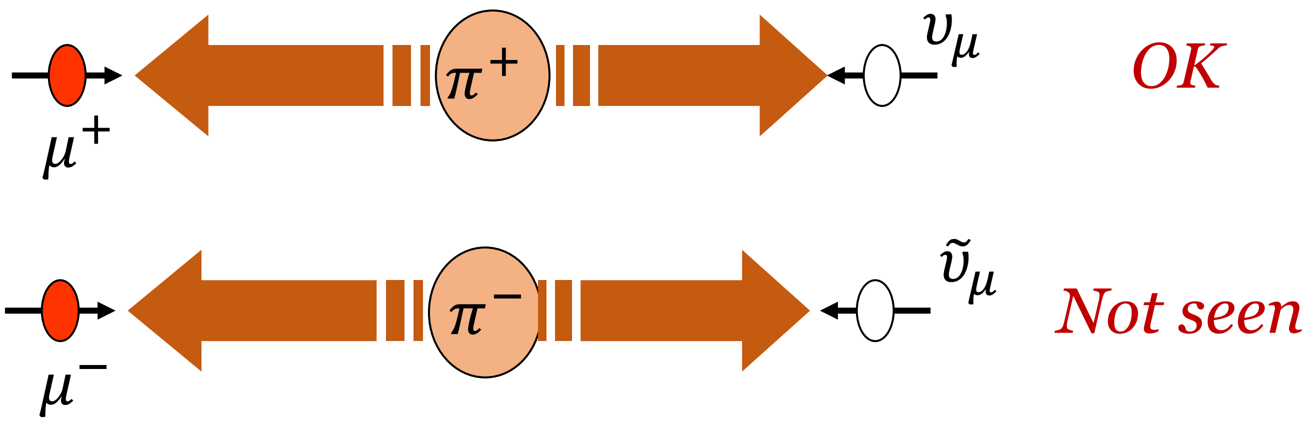
Charge conjugation (C) is the mathematical transformation that turns a particle into its antiparticle: $\psi \xrightarrow{C} i(\bar{\psi}\gamma_0\gamma_2)^T$

Symmetry under charge conjugation (C-symmetry) suggests that experiments made with particles and antiparticles would give the same result. It is true for a wide range of phenomena – nuclear forces, electrical phenomena, and even such weak ones like gravitation – over a tremendous range of physics, all the laws for these seem to be symmetrical.

C symmetry is broken by the weak interactions, just like P

Lederman (1956)

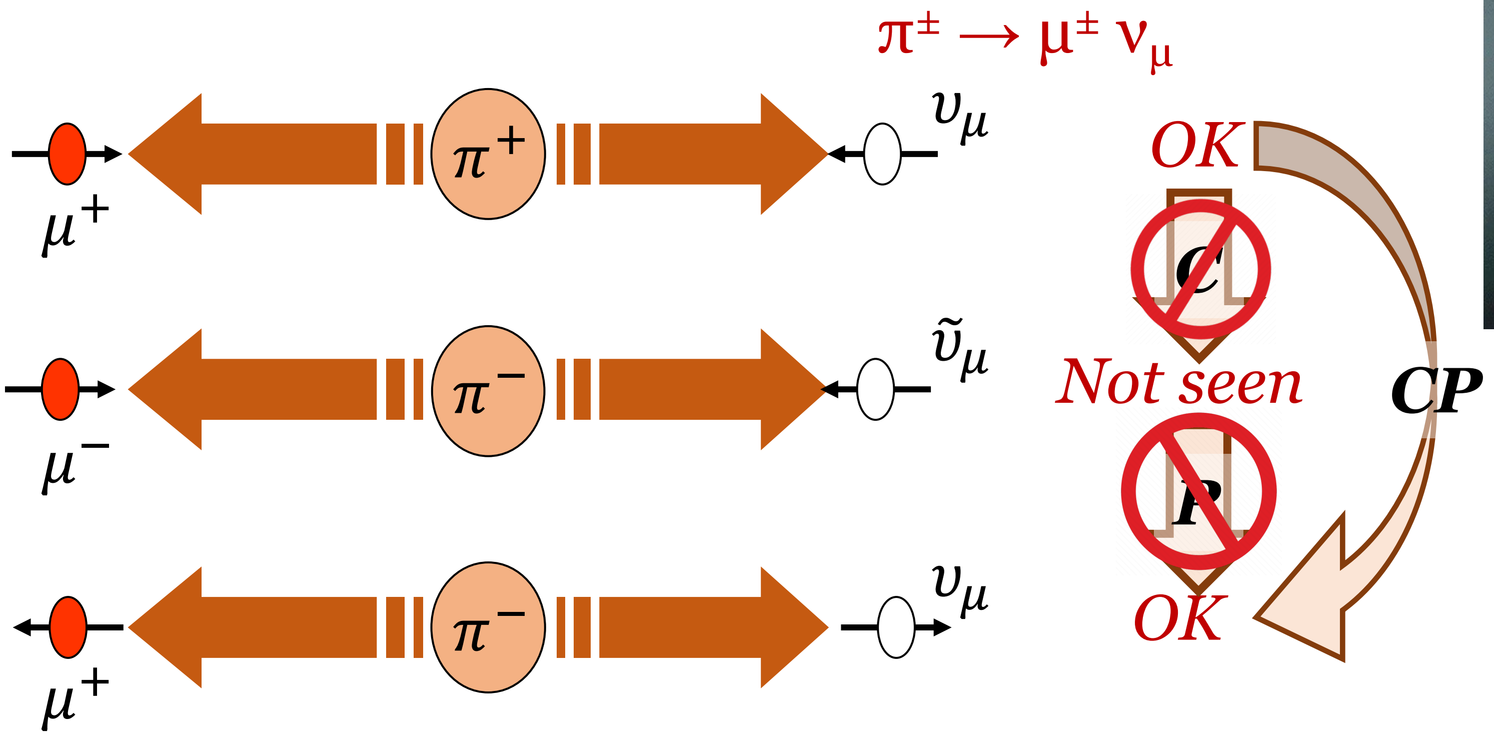
$\pi^\pm \to \mu^\pm \nu_\mu$



results of experiment and C-flipped experiment are not the same!

But before experimental evidence, C-violation was suggested theoretically: Ioffe-Okun-Rudik & Oehme-Lee-Yang (1956): the way of P-violation suggested by Lee-Yang leads to C-violation: Pseudoscalar product (L•P) is invariant under T, therefore by CPT-theorem while T is conserved, C-parity have to be violated together with P.

CP is a restored symmetry?



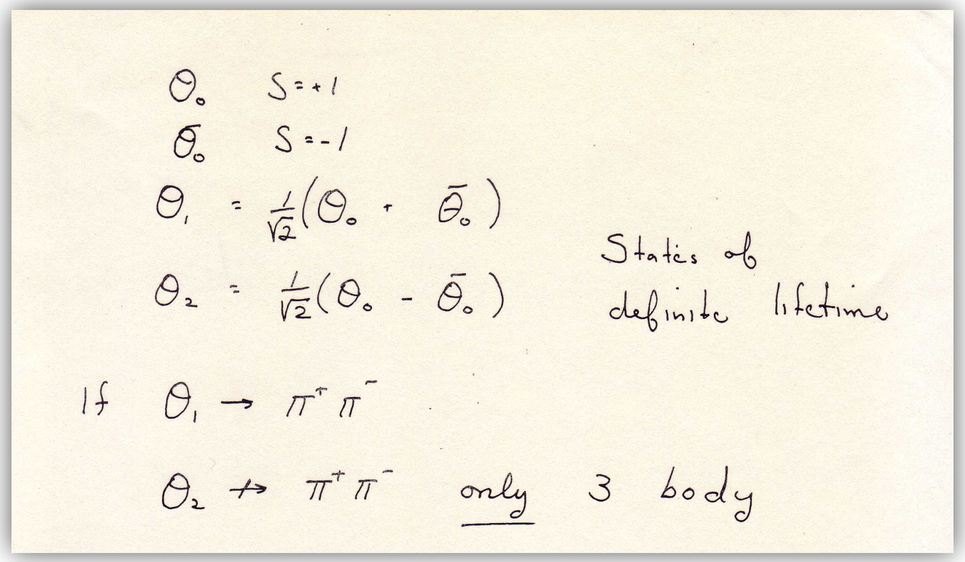
The idea of exact CP-symmetry supports the idea of two-component massless neutrinos.

L.Landau (1956) introduced CP symmetry as a mean to restore broken C and P symmetries.

Landau insisted on strict CP conservation to have beautiful world with no matter-antimatter difference.

More strangeness from strange

K^0 and $\bar{K}^0$ are not are CP eigenstates, but their mixture $K_S = {}^1/_{\sqrt{2}}\,(K^0 + \bar{K}^0)$ and $K_L = {}^1/_{\sqrt{2}}\,(K^0 - \bar{K}^0)$ are CP eigenstates with CP= $+1$ and -1, correspondingly.



θ_0 $S=+1$

$\bar{\theta}_0$ $S=-1$

$\theta_1 = \frac{1}{\sqrt{2}}(\theta_0 + \bar{\theta}_0)$

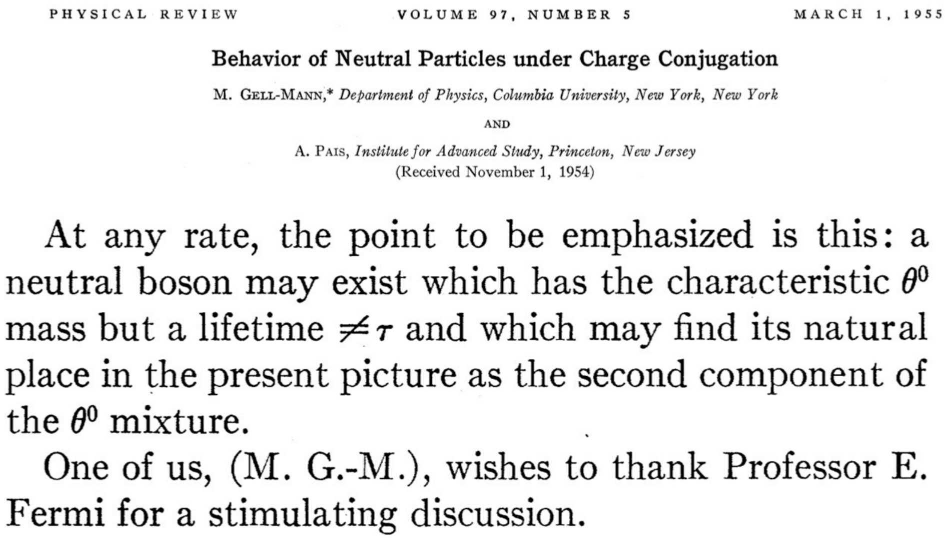
$\theta_2 = \frac{1}{\sqrt{2}}(\theta_0 - \bar{\theta}_0)$

States of definite lifetime

If $\theta_1 \to \pi^+\pi^-$

$\theta_2 \not\to \pi^+\pi^-$ only 3 body

Gell-Mann & Pais (1952) (but relying on C-symmetry) concluded that K_S and K_L are physical particles that have their own (different) masses and lifetimes. CP-odd state could decay 3-body only and, thus, has much greater lifetime than CP-even one.



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

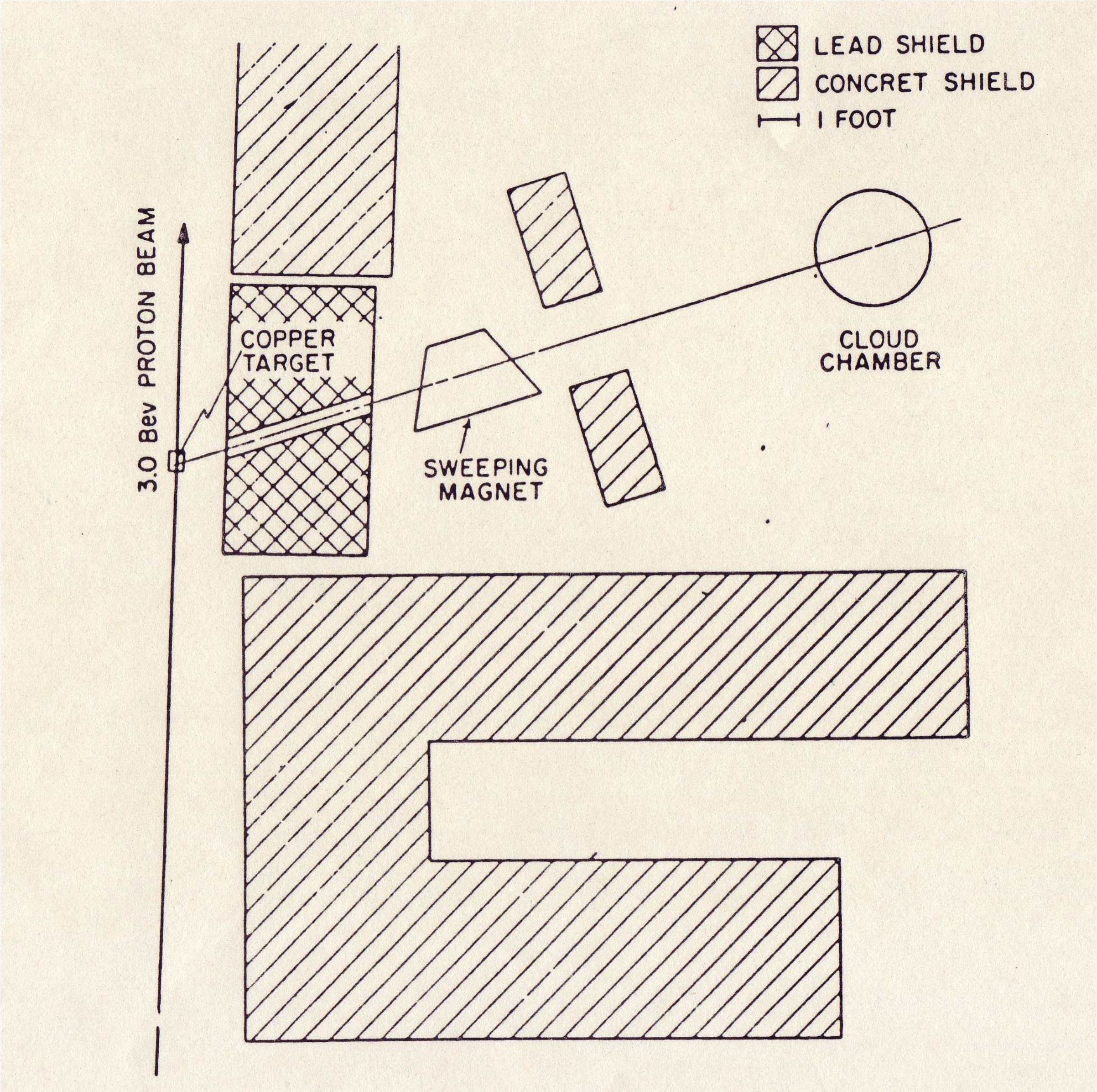
A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

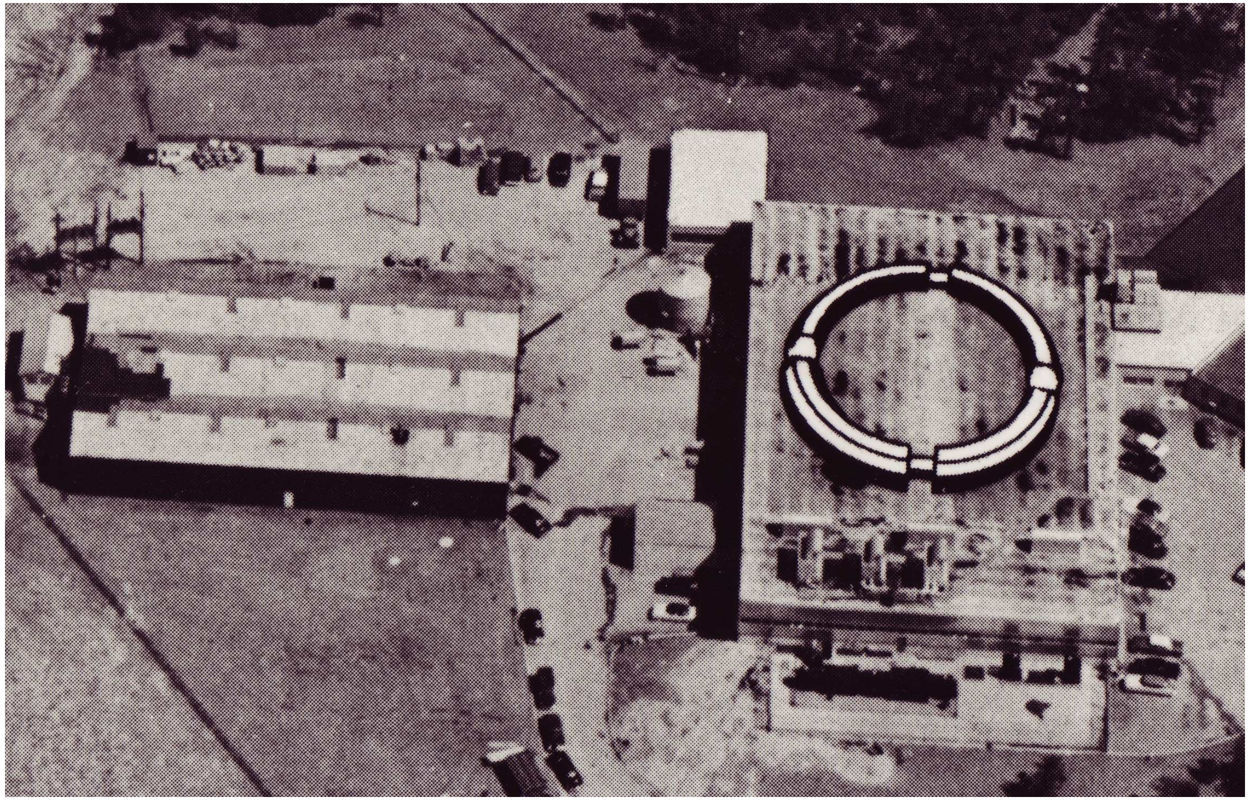
(Received November 1, 1954)

At any rate, the point to be emphasized is this: a neutral boson may exist which has the characteristic θ^0 mass but a lifetime $\neq \tau$ and which may find its natural place in the present picture as the second component of the θ^0 mixture.

One of us, (M. G.-M.), wishes to thank Professor E. Fermi for a stimulating discussion.

Observation of 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)

CP violation

VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our results on the charge ratio and the degree of the 2π-decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in K^0 decay.

Perhaps, the saddest story in JINR history

One more looser…

PHYSICAL REVIEW VOLUME 132, NUMBER 5 1 DECEMBER 1963

Anomalous Regeneration of K_1^0 Mesons from K_2^0 Mesons*

L. B. Leipuner, W. Chinowsky,† and R. Crittenden
Brookhaven National Laboratory, Upton, New York

and

R. Adair,‡ B. Musgrave,§ and F. T. Shively†
Yale University, New Haven, Connecticut

(Received 13 March 1963; revised manuscript received 27 August 1963)

A beam of 1.0-BeV/c K_2^0 mesons passing through liquid hydrogen in a bubble chamber was seen to generate K_1^0 mesons with the momentum and direction of the original beam. The intensity of K_1^0 production was far greater than that anticipated from conventional mechanisms, and the suggestion is made that the K_1^0 mesons are produced by coherent regeneration resulting from a new weak long-range interaction between

PROPOSAL FOR K^0_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^0_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^0_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits,

… found too large (few %) CP-violation. But this was a big motivation for the final success.

Happy end

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§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

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. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as

$$\frac{K_L \to \pi^+\pi^-}{K_S \to \pi^+\pi^-} \approx \frac{1}{500}$$

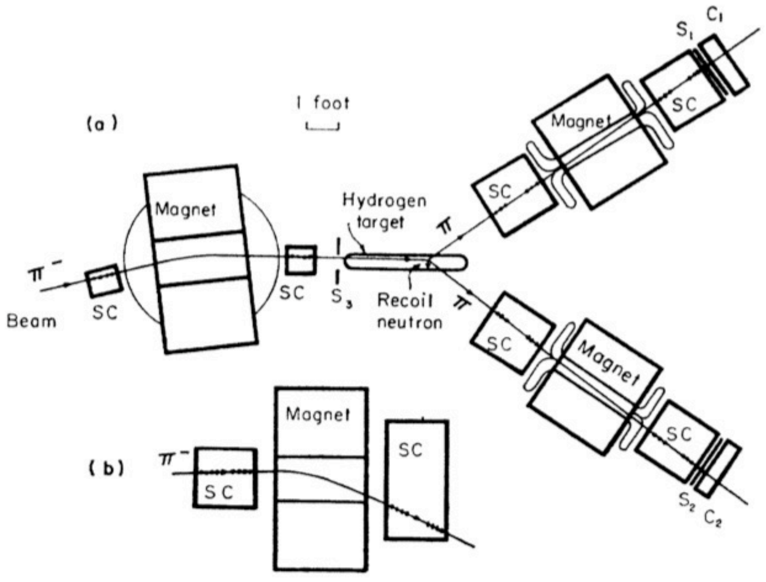
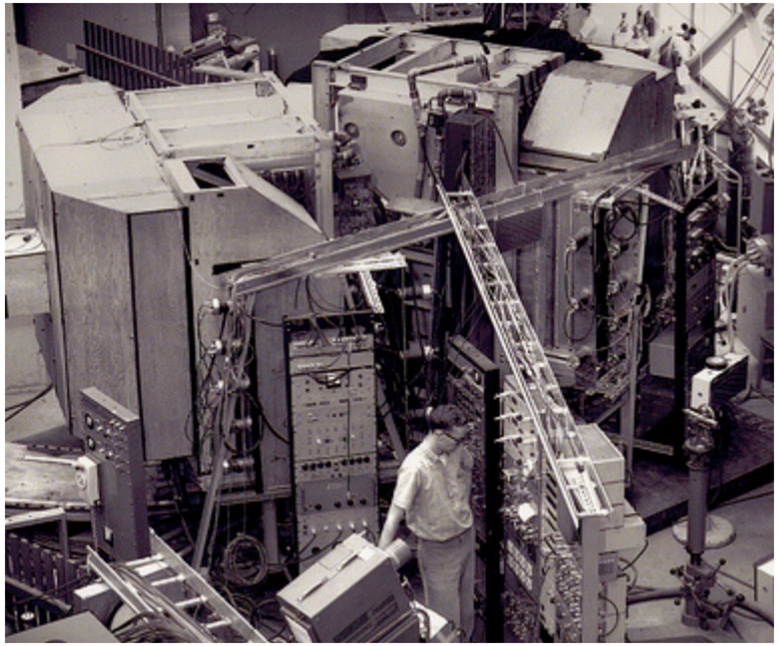
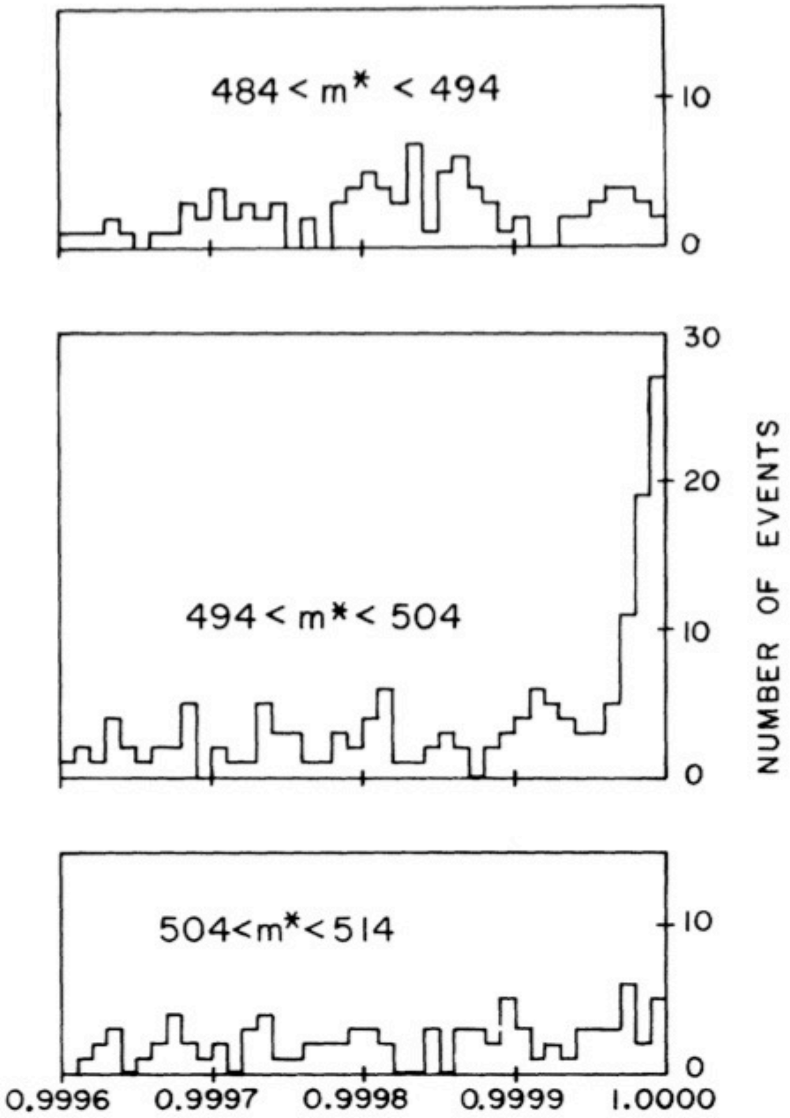


FIG. 1. Schematic views of the experimental apparatus.

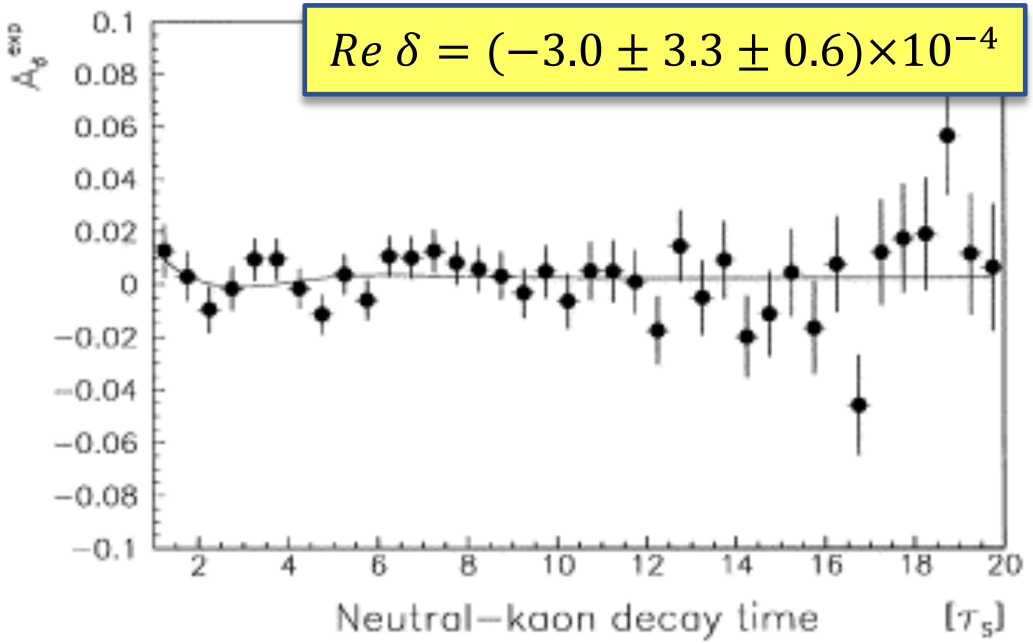




CPT symmetry

We know three discrete symmetries: C, P, and T. C and P are maximally violated by weak interaction. CP are better conserved: only small violation has been observed. What about full combination: CPT?

Antimatter was introduced in a way, that any Lorentz invariant local field theory must have the CPT symmetry. But Nature may not care, how we introduced antimatter…

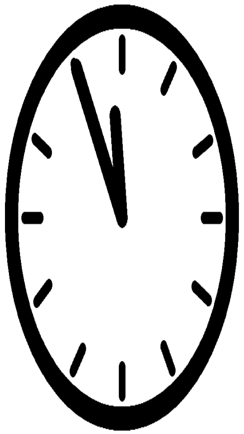


CPT test: check the of mass and lifetimes of particle and antiparticle.

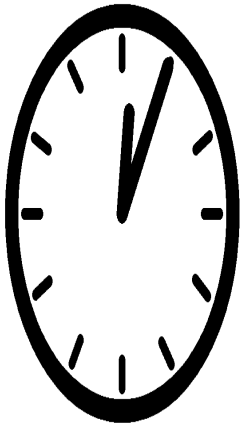
$$\frac{M_{\bar{K}^0} - M_{K^0}}{M_K} < 7.2\times 10^{-19}$$

CPT is the only one of the discrete symmetries that has remained (so far) unbroken.

Time reversal



T symmetry or time-reversal invariance. Suppose you had a movie of some physical process. If the movie were run backwards through the projector, could you tell from the images on the screen that the movie was running backwards?



In everyday life there is an obvious "time arrow" from the past to the future. Irreversibility is due to the very large number of particles involved, while at individual molecules level, we would not be able to discern whether this is working forward or backwards. The everyday ”time arrow" does not seem to have a counterpart in the microscopic world…

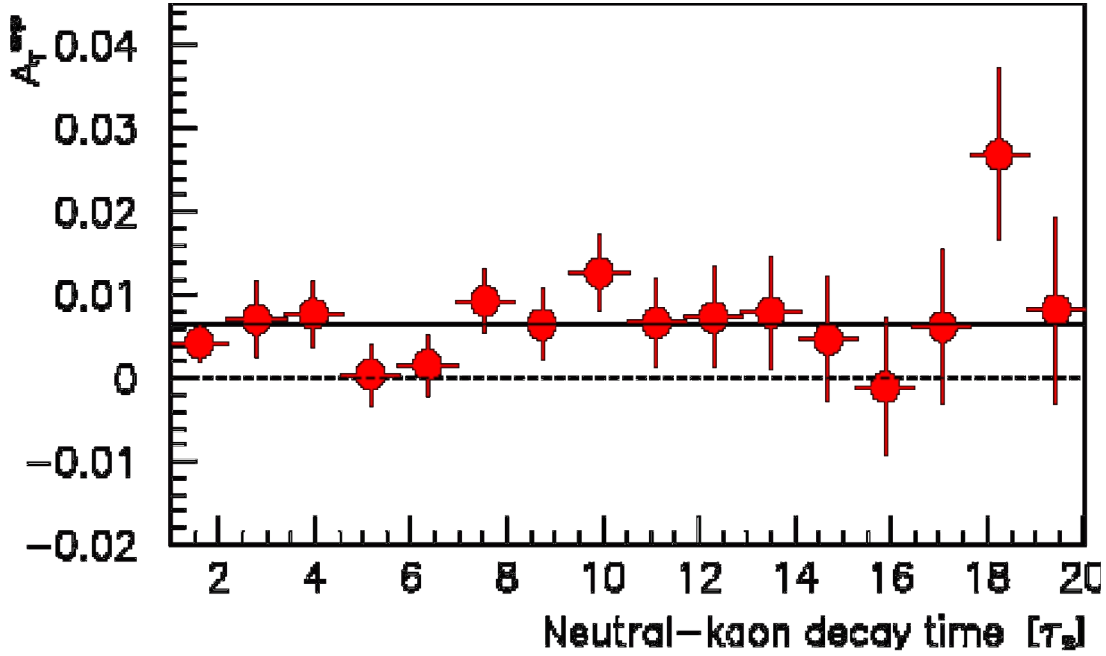
The classical laws are good to describe the interactions of two bodies, but when we talk about 10^{24} bodies, we should use Statistical mechanics… Somewhere in between 1 and 10^{24} particles, time finds arrow?

CPT and Time reversal

CPT symmetry and CP violation give a hint that T symmetry should be violated?

Search for particle and nuclei electric dipole moment. Only upper limits set so far.

Direct search for difference of rates for direct and inversed processes:
CPLEAR search's for a difference in the rates $K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$



$$A_T = \frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)}$$

$$A_T = (6.6 \pm 1.6) \times 10^{-3}$$

First direct evidence (~4 sigma) for T-violation

It turns out that the weak forces distinguish between the past and the future.

CP violation and Universe evolution

Big Band seemingly started from matter-antimatter symmetric initial state. Why didn't matter and antimatter annihilate all at the beginning? If they avoided annihilation, where the rest of antimatter lurks now?

Are there antimatter dominated regions of the Universe? Possible signals:

- Photons produced by matter-antimatter annihilation at domain boundaries

  not seen nearby anti-galaxies ruled out

- Cosmic rays from anti-stars

  best prospect: Anti-^{4}He nuclei (searches ongoing...)

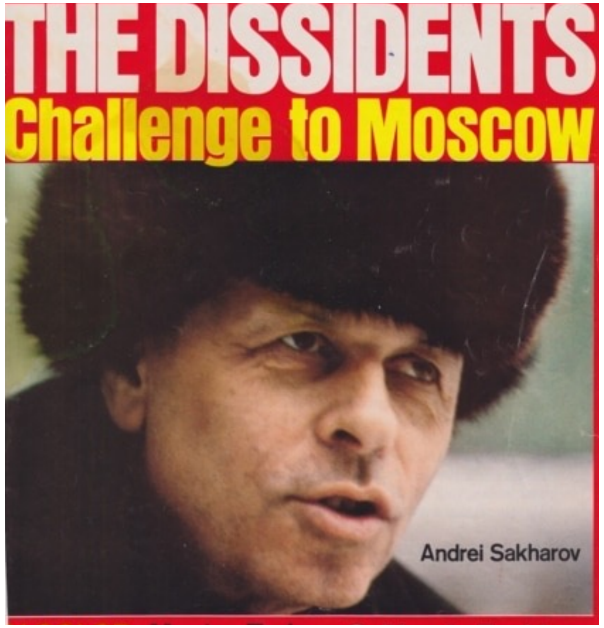
Sakharov conditions…

Necessary for evolution of matter dominated universe, from symmetric initial state (1967):

I. baryon number violation

II. C & CP violation

III. thermal inequilibrium



Sakharov's ideas changed attitudes toward CP violation. Before 1967, the violation of symmetry between matter and antimatter seemed to spoil the beautiful picture of the world. After Sakharov's paper it became clear that the world exists thanks to this violation.

Suppose equal amount of matter (X) and antimatter ($\overline{\mathrm{X}}$)

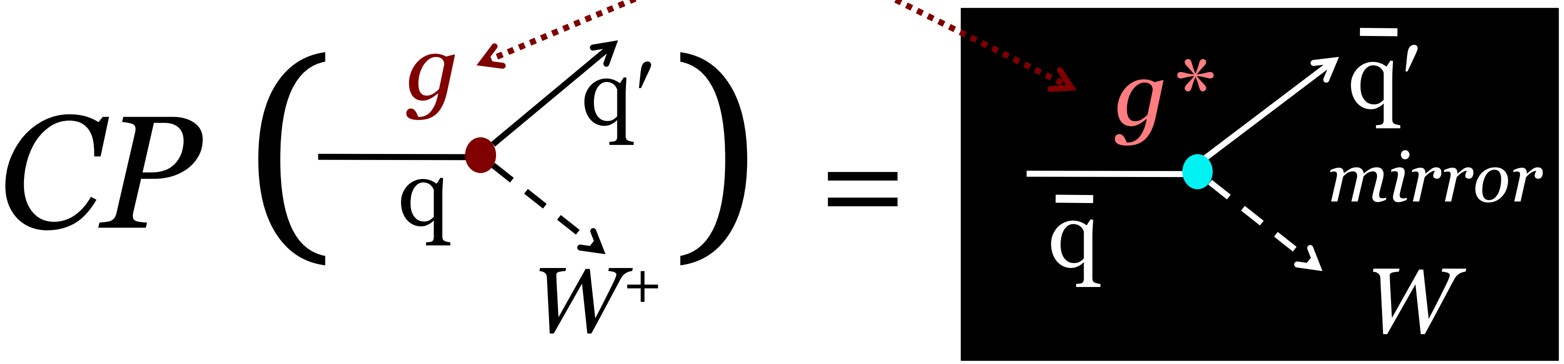
X decays to A(baryon number N_A) and B(baryon number N_B) with probabilities p and $(1-p)$

$\bar{X}$ decays to $\bar{A}$(baryon number $-N_A$) and $\bar{B}$(baryon number $-N_B$) with probabilities $\bar{p}$ and $(1-\bar{p})$

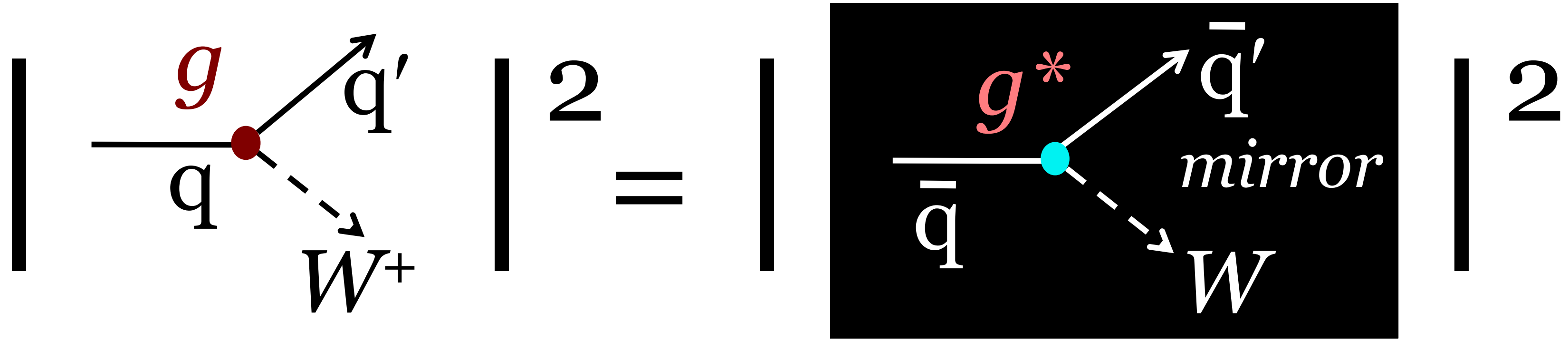
Generated BAU: $\Delta N = pN_A + (1-p)N_B - \bar{p}N_A - (1-\bar{p})N_B = (p-\bar{p})(N_A - N_B) \neq 0$

How to enable CP Violation in QFT?

what about different “charges” $g \neq g^*$?



However, even if g complex, in the rate calculations its phase is not seen:



Oh, it's hard work

as $|g|^2 = |g^*|^2$

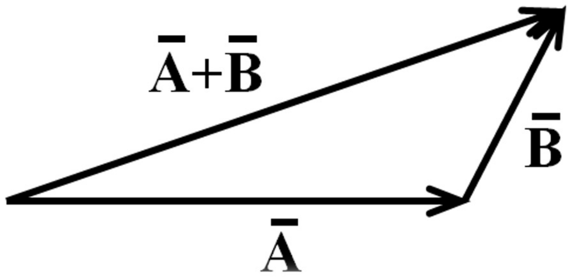
What about two competing amplitudes?

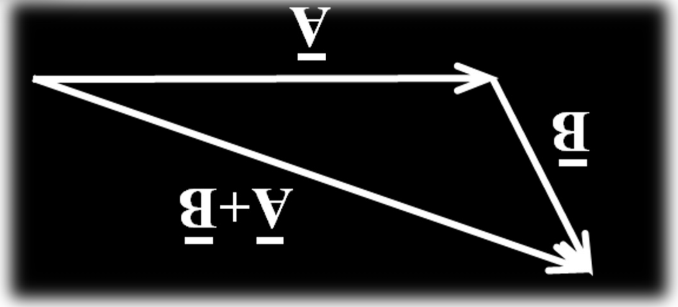
A-real; $B=|B|\,e^{i\varphi}$

$\bar{A}=A$; $\bar{B}=|B|\,e^{-i\varphi}$

still not working

$|A+B| = |\bar{A}+\bar{B}|$





need a reference phase difference that is not changed under CP

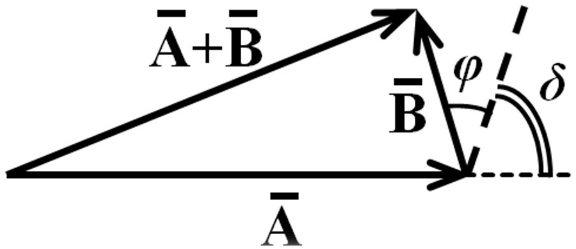
A-real; $B=|B|\,e^{i(\delta+\varphi)}$

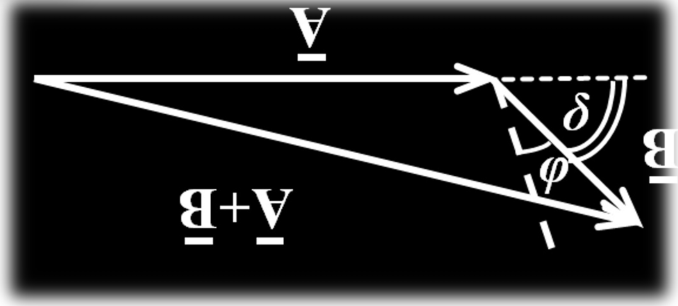
$\bar{A}=A$; $\bar{B}=|B|\,e^{i(\delta-\varphi)}$

e.g. strong interaction can provide this phase δ

successful

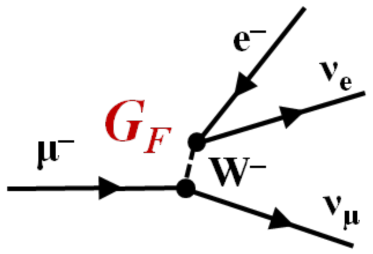
$|A+B| \neq |\bar{A}+\bar{B}|$





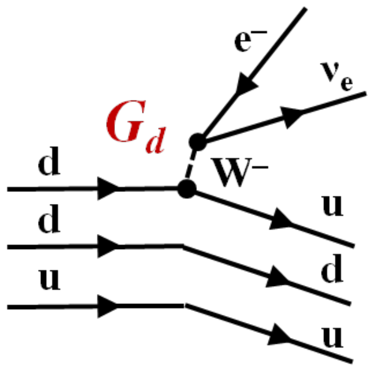
We have done half of the job, but we still do not know how to introduce weak phase

Flavour hints

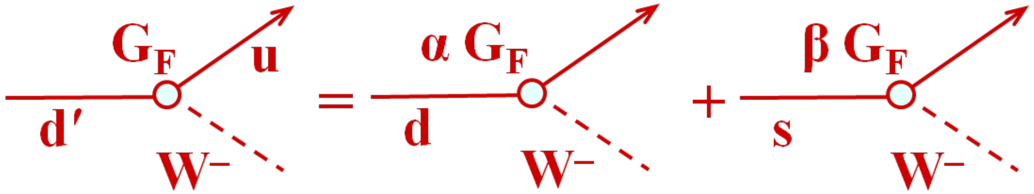


Problem: different weak charges for leptons and quarks:

d→u	s→u
$G_d \approx G_F$	$G_s \approx 0.05\, G_F$

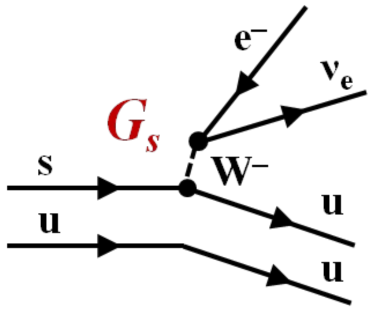


Cabibbo solution: $d' = \alpha\, d + \beta\, s$

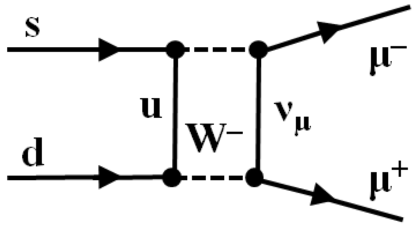


Unitarity: probabilities add up to 1 with $\alpha^2 + \beta^2 = 1$ $(\alpha = \cos\theta_C, \beta = \sin\theta_C)$

successfully explains many decays, but there is one important exception which Cabibbo could not describe: $K^0 \to \mu^+\mu^-$ observed rate was MUCH lower than expected ~ $g^8(\cos^2\theta_C \sin^2\theta_C)$



Solution to K^0 decay problem in 1970 by Glashow, Iliopoulos and Maiani: postulate existence of 4th quark.
Two 'up-type' quarks decay into rotated 'down-type' states: restore symmetry between up and down; and between leptons and quarks generations!



CP violation from quark mixing?

$$L_{W^\pm} = -\frac{g}{\sqrt{2}}(\bar{u},\,\bar{c})_L \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_L \gamma^\mu W_\mu^- + h.c.$$

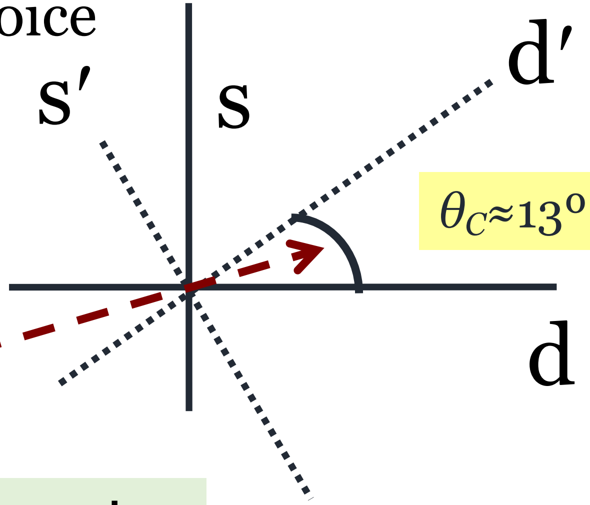
$$\begin{bmatrix} \alpha & \beta \\ -\beta^* & \alpha^* \end{bmatrix}$$

Quark mixing is done by a mixing matrix. Nothing (and nobody) prevents this matrix from being complex! Why not take the complex phase from this matrix as an effective complex weak charge for CP violation?

Alas! Nothing (and nobody) prevents to multiply all u-quarks in the Universe by $e^{i\alpha}$, then multiply all d- and s-quarks by $e^{i\beta}$ and $e^{i\gamma}$. With a proper choice of α, β, γ, we remove all complex phases from the mixing matrix.

It is easy to check by counting parameters for 2×2 matrix:

8 real parameters – 4 unitarity conditions – 3 free quark phases = 1 (Cabibbo angle)



2×2 matrix is REAL! – not enough freedom to introduce imaginary part

The Kobayashi-Maskawa idea

For 3×3 matrix:

18 real parameters
– 9 unitarity conditions
– 5 free quark phases
= 4 (3 Euler angles
+1 phase)

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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)

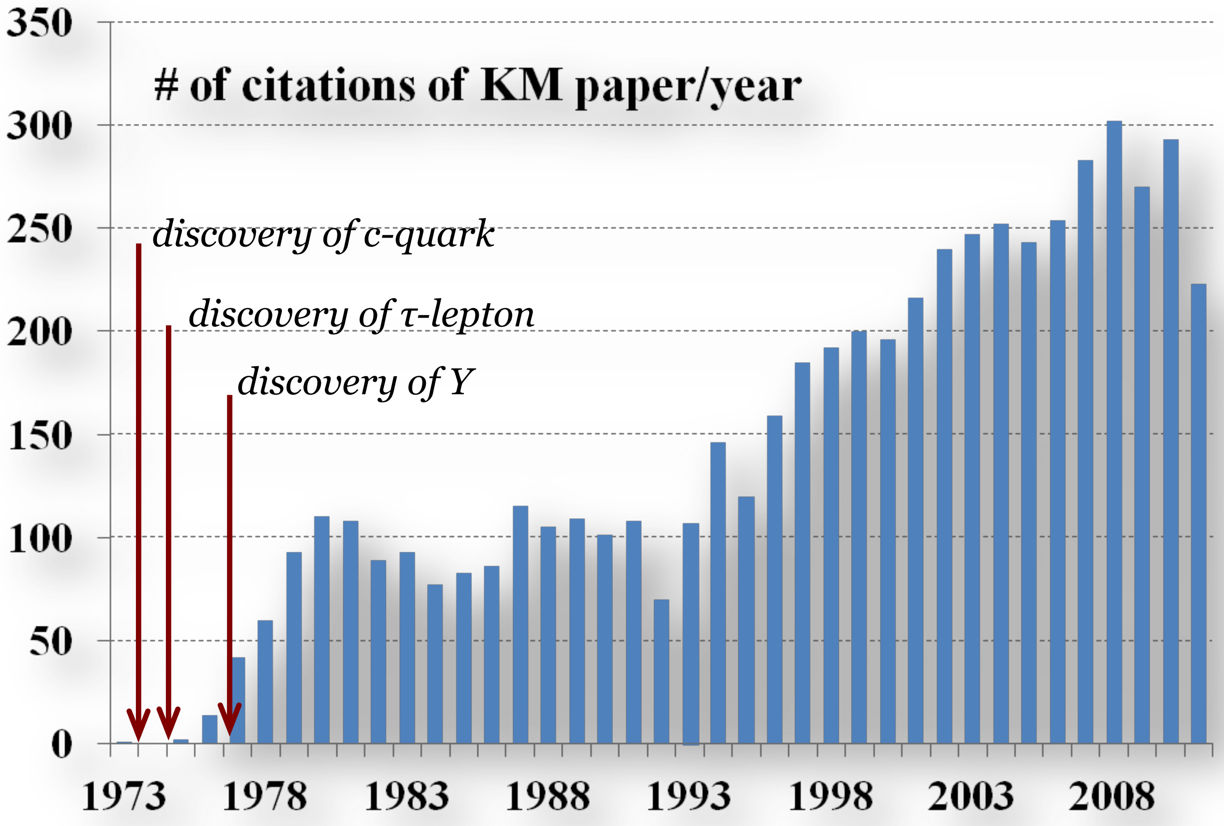
In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Wasn't this too trivial idea to try with 3 generations?

Too trivial idea of 3 generations?

It took

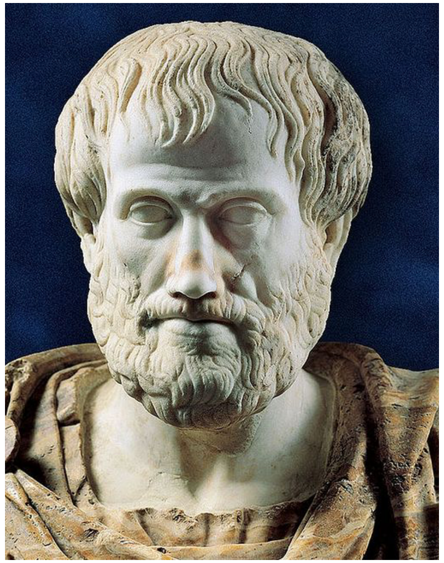
- 8 years to come to this “trivial” hypothesis after CP violation observation;
- 2 years after GIM mechanism with full 2-generations proposal…



- *0 citations in 2 year after publication*
- *Accepted as reasonable hypothesis only after discovery of the 3-rd generation of leptons*
- *~30 years to be finally accepted as a true theory*
- *more than 7000 citations for 40 years*
- *the 3^{d} place in topcited articles rank*

Aristotle's principle

***Nature does nothing in vain* (NDNIV)**



Does SM satisfy NDNIV?

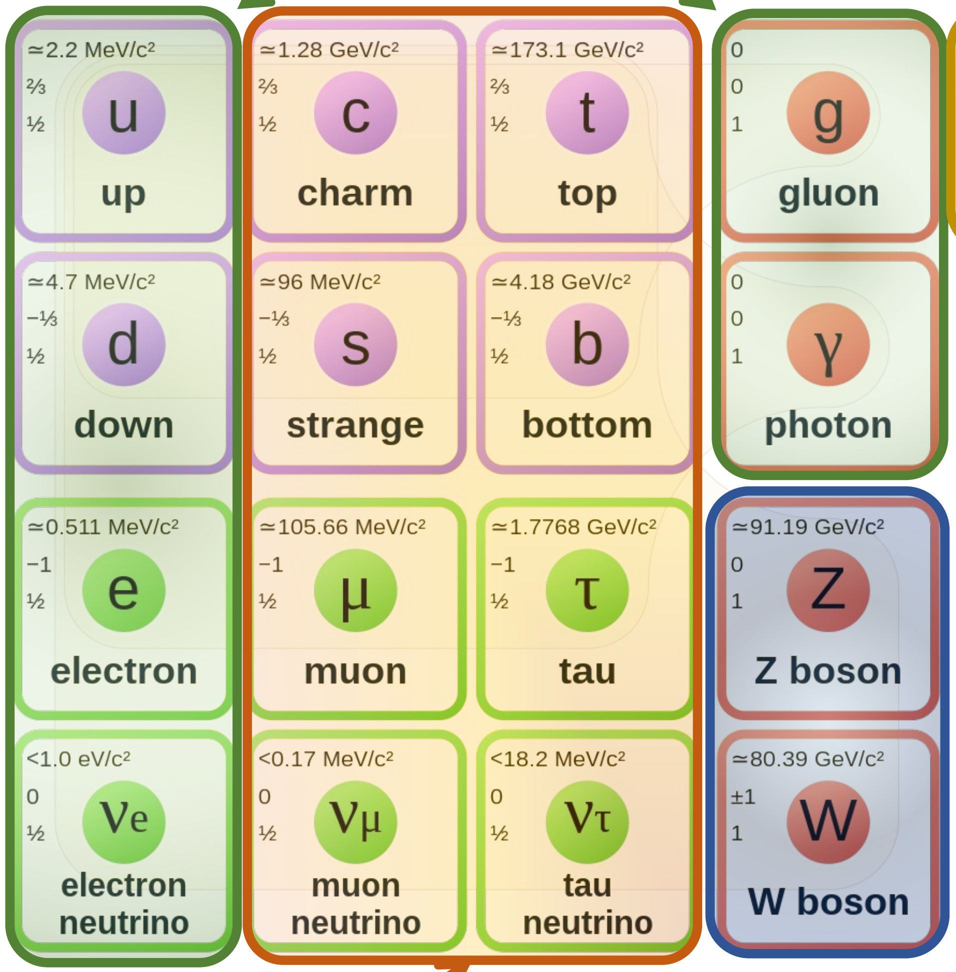
We used almost the entire contents of the SM particle table, but two fermion generations (and all antifermions) remain unused…

As for the macroscopic role of the particles of the second and the third generations, it seems at first glance trifling. These particles resemble the rough sketches, which the Creator has thrown out as unsuccessful, and which we with our sophisticated equipment dug in his wastebasket. Now we are starting to understand that these particles play an important role in the first moments of the Big Bang…

Lev Okun

Aristotle’s (NDNIV) principle

Are constituents of stars, planets and all we can see



fills all space, provides an independent 'transmission' substance, gives masses, breaks symmetries

Provides energy, are required to violate symmetries

Are required to remove antimatter

It turns out that two extra generations are needed to remove antimatter. Natural question: Why did antimatter even have to be created, and then to be removed in such a complicated way?

SM is free of unnecessary meaningless components and thus, satisfies NDNIV!

This table seems to be necessary and sufficient for our Universe.

“Flavour” physicsc is about fermions beyond one generation.

i.e. flavour quark physics is about *s*-, *c*-, *b*- and only to a small extent about *t*-quarks

- Kaon physics still alive: there are few experiments in the worlds with kaon, e.g. at JPARC (Japan). They are mainly to study VERY RARE ($Br \sim 10^{-10} - 10^{-12}$) kaon decays.
- *t*-quarks does not produce hadrons (decays before hadronization). $Br(t \to bW) \sim 100\%$. Some interesting studies are foreseen at linear collider in future.
- *b*- and *c*-physics are the main object of the modern flavour physics.
  - *b*-hadrons decays: rich of interesting SM phenomena (quantum path): large mixing, large CP violation, electroweak penguin loop decays.
  - c-hadrons decays: all SM interesting are highly suppressed by GIM and CKM.

Which are more interesting? If for NP searches *c*-physics is better: there is nor SM background.

Cabibbo-Kobayashi-Maskawa matrix

generalization on the 3-generations case: weak quark mixing 3×3 matrix

$$L_{W^\pm} = -\frac{g}{\sqrt{2}}(\bar{u}, \bar{c}, \bar{t})_L V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \gamma^\mu W_\mu^- \ldots \qquad V_{CKM} = V_L^u \cdot V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

KM-parameterization

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3 + \sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3 + \cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3 - \cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}$$

PDG-reparameterization

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

CPV in the KM Model

KM ansatz is a necessity for CP-violation

Sufficiency for CPV in KM ansatz:

$$(m_t^2 - m_c^2)\times(m_t^2 - m_u^2)\times(m_c^2 - m_u^2)$$
$$\times(m_b^2 - m_s^2)\times(m_b^2 - m_d^2)\times(m_s^2 - m_d^2)\times J_{CP} \neq 0$$

where J_{CP} is Jarlskog determinant

$$J_{CP} = \left|\mathrm{Im}\left(V_{i\alpha}V_{j\beta}V_{i\beta}^*V_{j\alpha}^*\right)\right| \;\; (i \neq j, \alpha \neq \beta)$$

Why are quarks required to have different masses?

Elements values (PDG)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 0.9743 & 0.2253 & 0.0035 \\ 0.2252 & 0.9734 & 0.0412 \\ 0.0087 & 0.0404 & 0.9991 \end{pmatrix} \pm \begin{pmatrix} 0.0002 & 0.0007 & 0.0002 \\ 0.0007 & 0.0002 & 0.0010 \\ 0.0003 & 0.0010 & 0.0001 \end{pmatrix}$$

Almost identity

Almost diagonal

Almost symmetric

observe hierarchy
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$
where $\lambda = \sin\theta_C \approx 0.23$

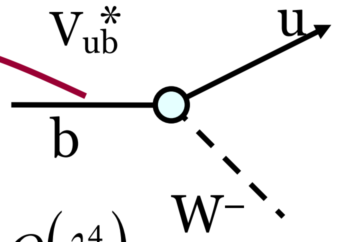
$$J_{CP} = s_{12}s_{13}s_{23}c_{12}c_{13}c_{23}\sin\delta = (2.96^{+0.20}_{-016})\times 10^{-5}$$

CPV is tiny in SM; it is not enough to produce BAU

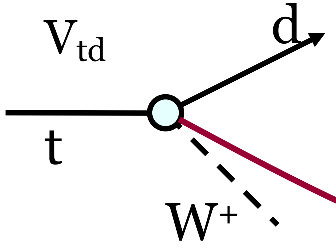
Wolfenstein parameterization

$$\lambda = s_{12} = \sin\theta_{12} \approx 0.23 \quad A = \frac{s_{23}}{s_{12}^2} \approx 0.8 \quad \rho = \frac{s_{13}\cos\delta}{s_{12}s_{23}} \quad \eta = \frac{s_{13}\sin\delta}{s_{12}s_{23}}$$

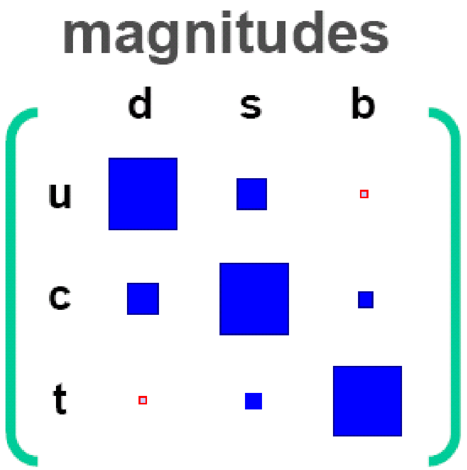
(expansion on a small parameter λ)



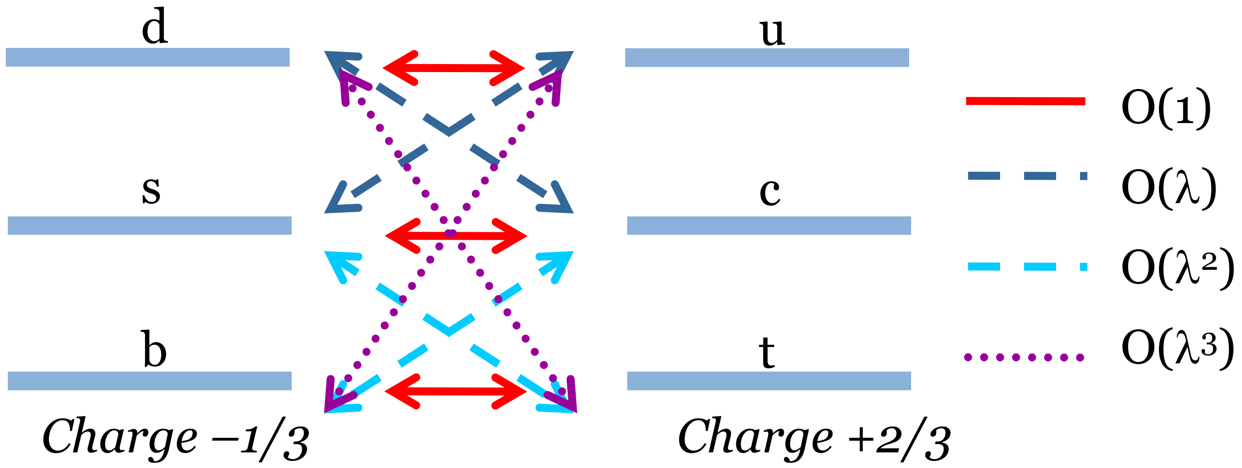
$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

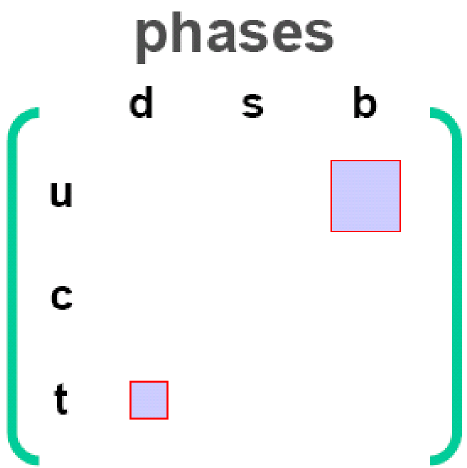


CPV phases are in the corners



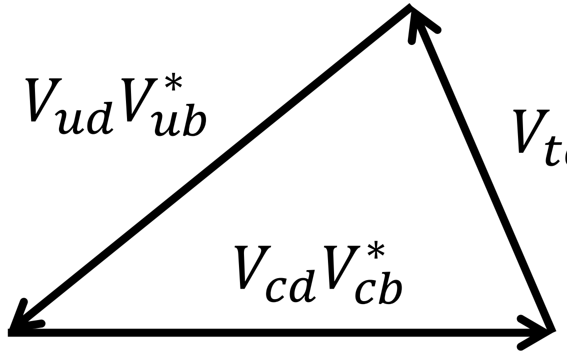
Reflects hierarchy of strengths of quark transitions





Unitarity triangle

Unitarity condition of CKM matrix $V_{\text{CKM}}^{\dagger} \cdot V_{CKM} = V_{CKM} \cdot V_{\text{CKM}}^{\dagger} = 1$ gives 9 constrains $V_{ij}V_{ik}^{*} = \delta_{jk}$; 3 corresponds to $j = k$ and says that the probability for each quark to couple to W^{-} is summed up to 1; 6 unitarity conditions, when $j \neq k$, can be represented by triangles in the complex plane:



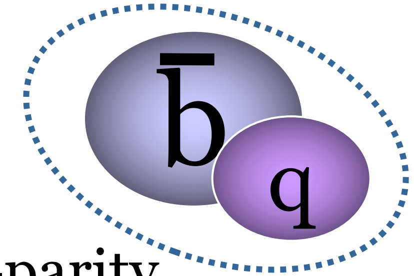
- All six triangles have the same area = ½ Jarlskog determinant
- 4 are degenerated (almost squeezed to a line)
- Only in two triangles all three sides of the same order $O(\lambda^3)$
- These two are related to the 3rd quark generation

$$\underbrace{V_{ud}V_{ub}^{*}}_{(\rho+i\eta)A\lambda^3} + \underbrace{V_{cd}V_{cb}^{*}}_{-A\lambda^3} + \underbrace{V_{td}V_{tb}^{*}}_{(1-\rho-i\eta)A\lambda^3} = 0 \qquad \underbrace{V_{ud}^{*}V_{td}}_{(1-\rho-i\eta)A\lambda^3} + \underbrace{V_{us}^{*}V_{ts}}_{-A\lambda^3} + \underbrace{V_{ub}^{*}V_{tb}}_{(\rho+i\eta)A\lambda^3} = 0$$

B-mesons

What are B mesons?

name	quarks	charge	mass (GeV)	lifetime (10^{-12}s)
B_d^0 or B^0	$\bar{b}d$	0	5.2796	1.519
B_u^+ or B^+	$\bar{b}u$	+1	5.2793	1.641
B_s^0	$\bar{b}s$	0	5.3668	1.463
B_c^+	$\bar{b}c$	+1	6.277	0.45



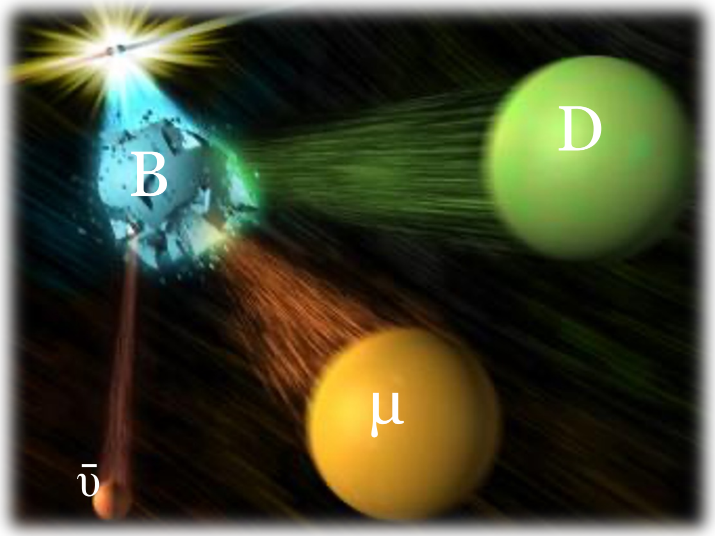
Spin-parity
$J^P = 0^-$

How are they produced?

- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ is the cleanest process (large $B\bar{B}$ /other cross section; no extra particles; quantum correlations)
- also at hadron machines: $pp \to B + \bar{B} +$ anything

How are they decay?

- usually to charm $b \to c$, $e.g.$ $B \to D\mu\bar{\upsilon}, D^*\pi$, etc
- much rarely to light quarks $B \to \pi\pi$ ($\frac{|b\to c|^2}{|b\to u|^2} \sim 100$)



Neutral mesons oscillations

Time evolution of B^0 and $\bar{B}^0$ can be described by an effective Hamiltonian:

$$i\frac{\partial}{\partial t}\Psi = H\Psi$$

Hamiltonian is just a numerical (complex) matrix 2×2

$$\Psi(t) = a(t)\left|B^0\right\rangle + b(t)\left|\bar{B}^0\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

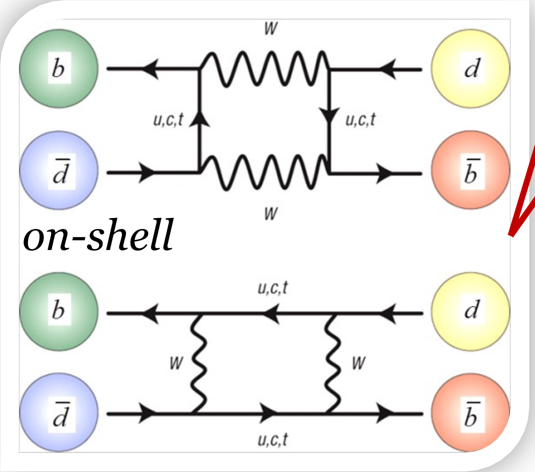
$$H = \underbrace{\begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix}}_{\text{hermitian}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & 0 \\ 0 & \Gamma \end{pmatrix}}_{\text{hermitian}}$$

Here we still have no mixing (no off-diagonal terms); note, that Hamiltoniam is not Hermitian! because of decay, probability of observing either B^0 or B^0 must decrease with time $\Rightarrow \Gamma > 0$

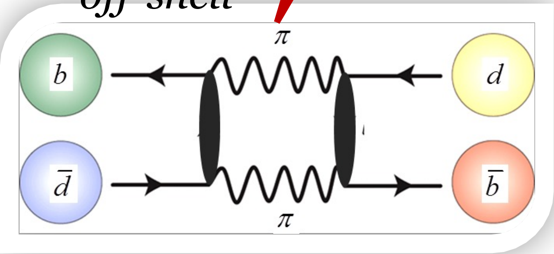
Add mixing

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\text{hermitian}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\text{hermitian}}$$

note, $M_{21} = M_{12}^*$ and $\Gamma_{21} = \Gamma_{12}^*$ from CPT invariance



off-shell

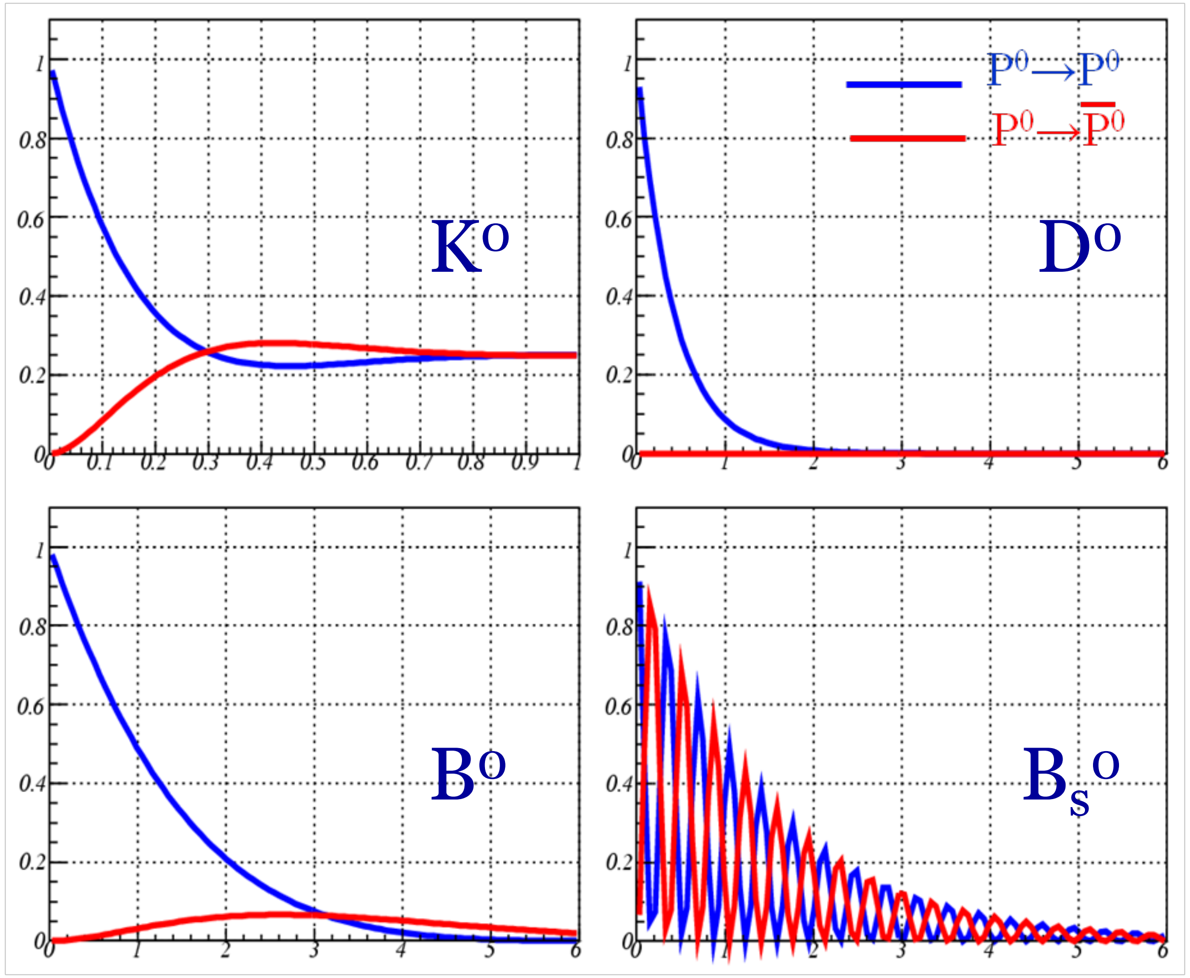


off-diagonal M term is due to off-shell states like box diagram

off-diagonal Γ is due to on-shell states, e.g. ππ, DD…

We know 4 neutral mesons that can oscillate

Probability to find P^0 or $\bar{P}^0$, when start with pure P^0-beam



Their oscillations looks so much different…
but this is just different numerical values

$$m = \frac{m_1 + m_2}{2}, \quad \Delta m = m_1 - m_2$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}, \quad \Delta\Gamma = \Gamma_1 - \Gamma_2$$

	<τ> [s]	Δm	x=Δm/Γ	y=ΔΓ/2Γ
K^0	2.6×10^{-8}	5.29 ns^{-1}	$\Delta m/\Gamma_S$=0.49	~1
D^0	0.41×10^{-12}	0.001 fs^{-1}	~0	0.01
B^0	1.53×10^{-12}	0.507 ps^{-1}	0.78	~0
B_s^0	1.47×10^{-12}	17.8 ps^{-1}	12.1	~0.05

x=Δm/Γ measures, how many times
meson oscillates before decay (average lifetime)

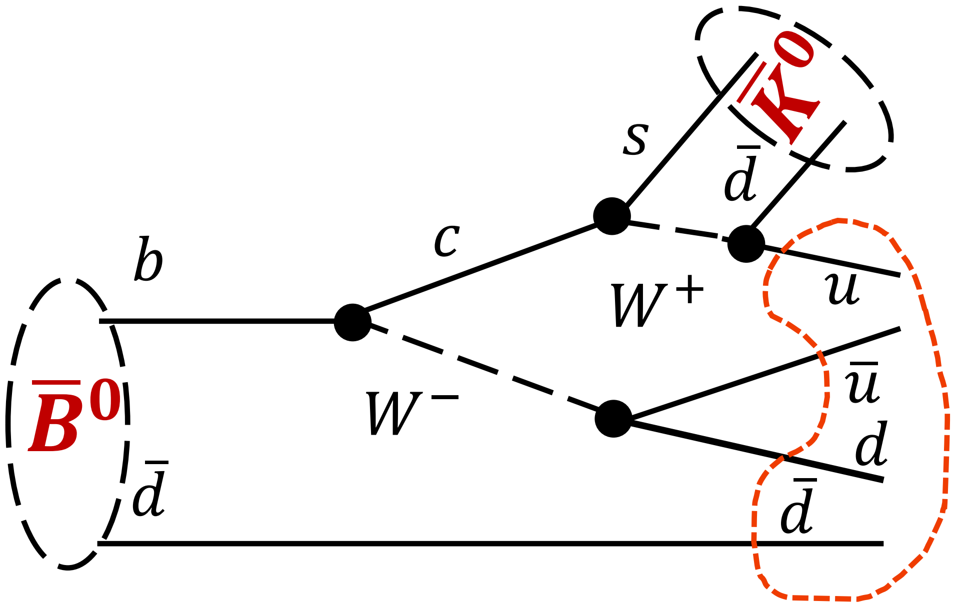
How to study CP violation in B mesons

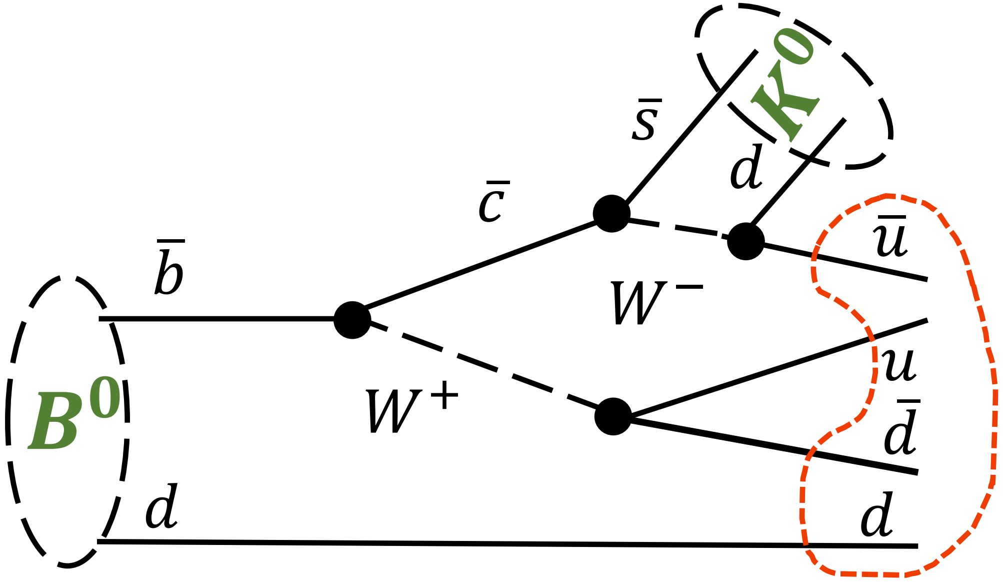
- No "K_L" methods applicable!
  - Lifetime difference is tiny, $\tau(B_H) - \tau(B_L)/\tau(B)$ ~1%: no way to work with a beam of long lived B's.
  - Semileptonic asymmetry also vanishes.
- New ideas required!
  - Sanda & Carter (1980): consider a final state f common for both B^0 and $\bar{B}^0$:

$$B^0 \to f_{\text{common}} \leftarrow \overline{B}^0$$

  - … in this place you can diagnose: they are crazy! In 1980, B mesons had not been discovered yet, only little can be hypothesized about their decay and lifetimes, but $B^0\bar{B}^0$ mixing was certainly expected to be tiny, as top quark was theoretically proven to be lighter than 20 GeV! The evidence was so compelling that the finance ministers of many countries are allocating billions of dollars, marks, oku-yens to build an experiment for top observation and expected Nobel prize…

Carter-Sanda idea





In 1980 nobody could think of golden mode ($J/\psi\ K_S^0$). But Carter & Sanda realized that two succeeding CKM-favored W emitions may result in (almost, up to s-d replacement) same quark configuration. s-d difference is hidden in K_S^0. Thus, both B^0 and $\bar{B}^0$ decay into the indistinguishable final state (even if intermediate states D^0 / $\bar{D}^0$ are different). They estimated the CP violation effect may be as large as 10% (obviously, they pulled the effect up), but the Nature is very generous: in reality the effect is ~100%.

How to measure CPV at e^+e^- collider?

The source of B mesons is the $\Upsilon(4S)$, which has $J^{PC} = 1^{--}$.
The $\Upsilon(4S)$ decays to two bosons with $J^P = 0^-$.
Quantum Mechanics (application of the Einstein-Rosen-Podolsky Effect) tells us that for a C = –1 initial state (Y(4S)) the rate asymmetry:

$$A = \frac{N_{(B_1 \to f_{CP})(\bar{B}_2 \to \bar{f}_{fl})} - N_{(B_1 \to f_{CP})(B_2 \to f_{fl})}}{N_{(B_1 \to f_{CP})(\bar{B}_2 \to \bar{f}_{fl})} + N_{(B_1 \to f_{CP})(B_2 \to f_{fl})}} = 0$$

However, if we measure the time dependence of A we find:

$$A(t_1,t_2) = \frac{N(t_1,t_2)_{(B_1 \to f_{CP})(\bar{B}_2 \to \bar{f}_{fl})} - N(t_1,t_2)_{(B_1 \to f_{CP})(B_2 \to f_{fl})}}{N(t_1,t_2)_{(B_1 \to f_{CP})(\bar{B}_2 \to \bar{f}_{fl})} + N(t_1,t_2)_{(B_1 \to f_{CP})(B_2 \to f_{fl})}} \propto \sin 2\phi_{CP}$$

Need to measure the time dependence of decays to “see” CP violation using the B’s produced at the $\Upsilon(4S)$.

B-meson’s decay flight is only 20μm in $\Upsilon(4S)$ rest frame. No chance to measure such small distance with modern detectors…

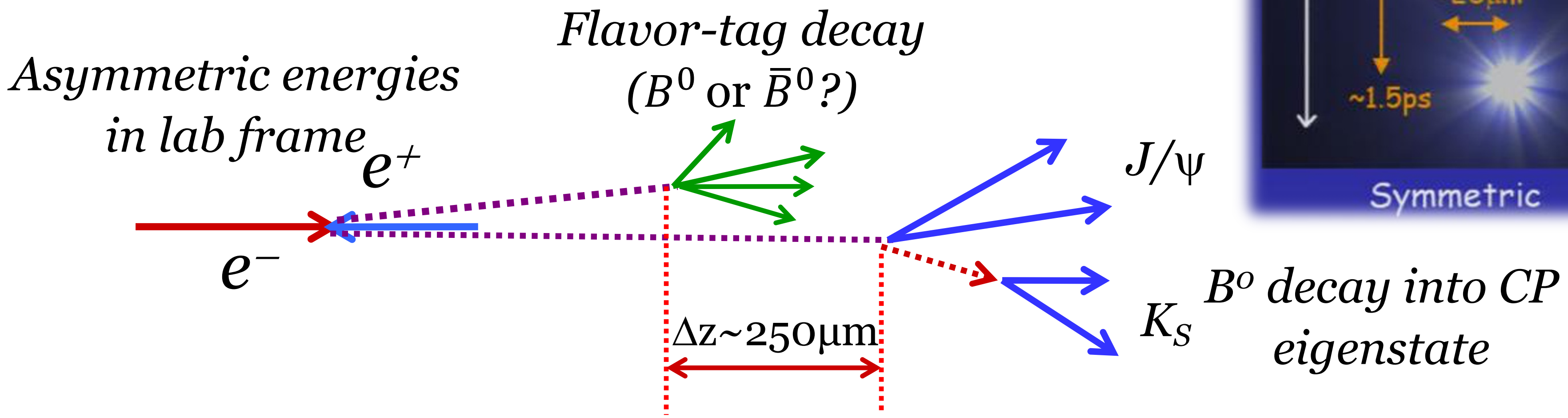
$\Rightarrow$ this kills good idea? No! just requires new idea:

Asymmetric e^+e^- collider

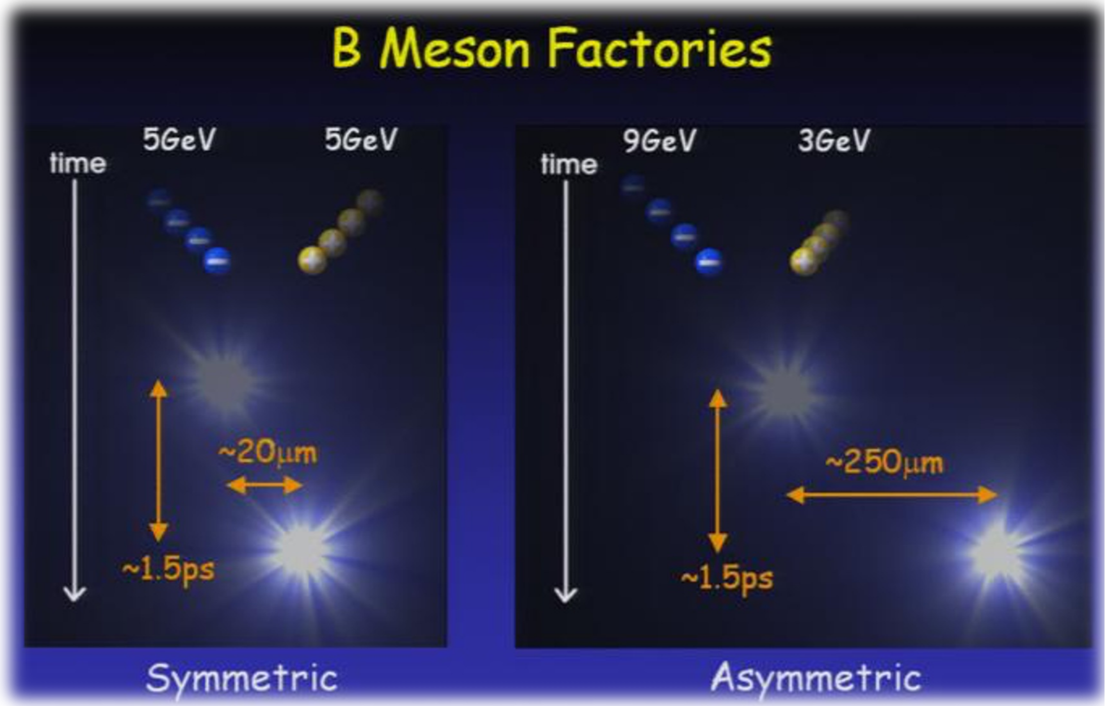
Impossible to reconstruct B-decay vertex because they are too slowly in $\Upsilon(4S)$ frame?

Let's make the $\Upsilon(4S)$ to move fast in the laboratory frame, then B-mesons have a sizable path; we need that accelerating electrons and positrons have different energies, but the Energy of center of mass = $M(\Upsilon(4S))$, $2\sqrt{E_+E_-} = M(\Upsilon(4S))$

We can measure t-dependent asymmetry at $\Upsilon(4S)$!



Pier Oddone (1987) proposed the idea of asymmetric B-factory



Asymmetric energy e^+e^- collider

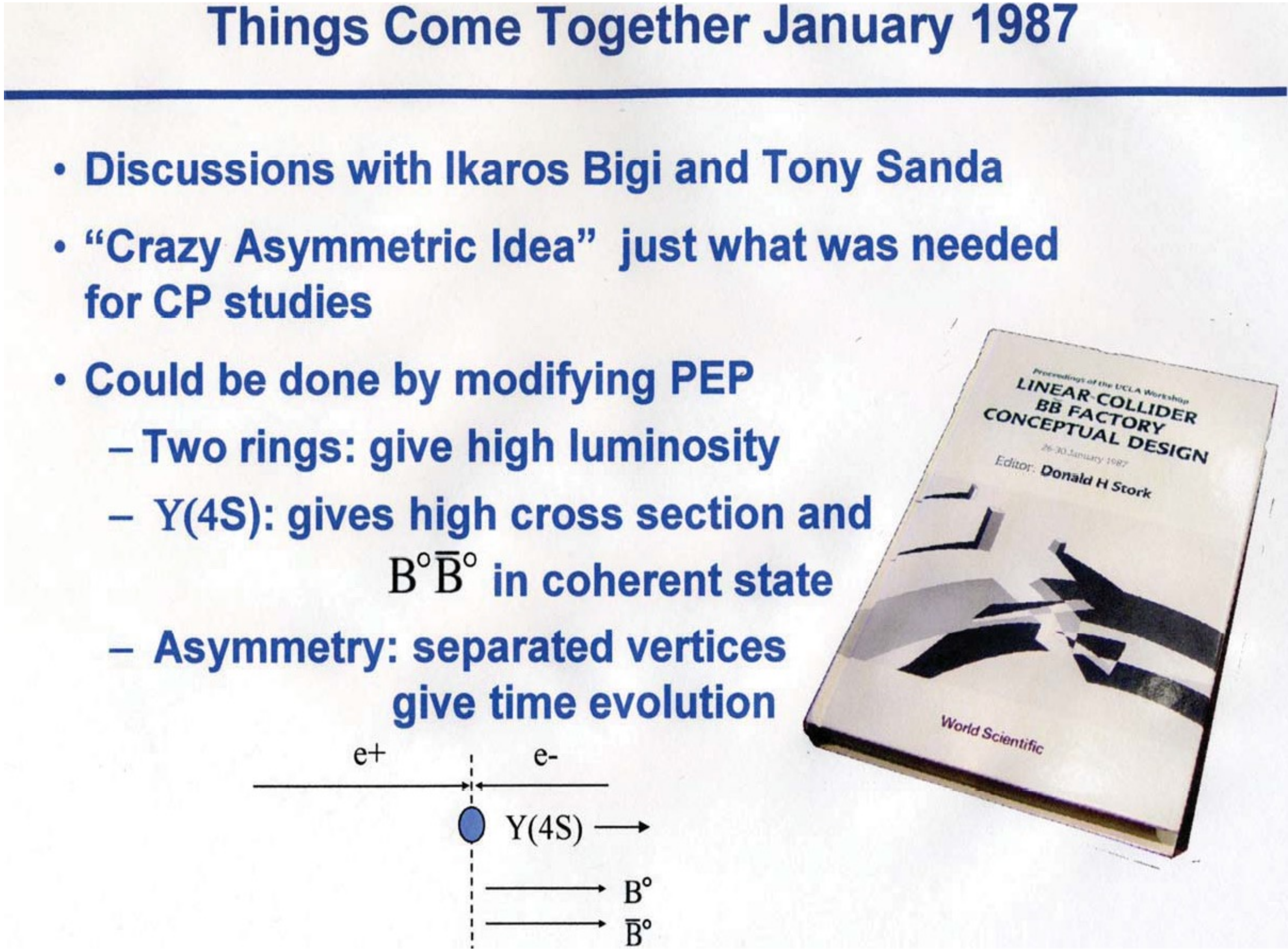
$$a_{CPV}(\Delta t) = \frac{\Gamma_{\bar{B}\to\bar{f}}(\Delta t) - \Gamma_{B\to f}(\Delta t)}{\Gamma_{\bar{B}\to\bar{f}}(\Delta t) + \Gamma_{B\to f}(\Delta t)} =$$

$$= S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$

Proposed by P. Oddone for realization at SLAC;

The idea led to **21** conceptual design projects of asymmetric B-factories throughout the world.

Two collider, PEP-II and KEKB, were ultimately built.



Asymmetric B-factory

TABLE 1.

Future $b\bar{b}$ factories and sweat shops. None of the luminosities shown in the Table have been achieved. Factors of two difference in luminosity are not significant.

E_{CM} GeV	Class	$E_1 \times E_2$ GeV × GeV	$\sigma_{b\bar{b}}$	Peak L proposed $cm^{-2}sec^{-1}$	$b\bar{b}$ events/yr 10^7 sec @ peak L	References
$\Upsilon(4S)$	CM RING	5 × 5	1 nb	5×10^{32}	$5 \cdot 10^6$	SIN Proposal[1]
	CM LINEAR	5 × 5		10^{33}	10^7	Amaldi & Coignet[2]
	BOOSTED LINEAR	2 × 12.5		5×10^{32}	$5 \cdot 10^6$	Sessler & Wurtele[3]
	BOOSTED RING	2 × 12.5		5×10^{32}	$5 \cdot 10^6$	Oddone[4]
Continum 20 GeV	RING		0.1 nb	5×10^{33}	$5 \cdot 10^6$	Bloom[5]
	LINEAR			10^{34}	10^7	Amaldi & Coignet[2]
Z^0	LINEAR SLC	45 × 45	5 nb	5×10^{30}	$2.5 \cdot 10^5$	SLC Study[6]
	LEP	45 × 45		2×10^{31}	$8 \cdot 10^5$	LEP Study[7]
	RING IMAGINARY	45 × 45		5×10^{33}	$2.5 \cdot 10^8$	

DETECTOR CONSIDERATIONS

P. Oddone
Lawrence Berkeley Laboratory

1 INTRODUCTION

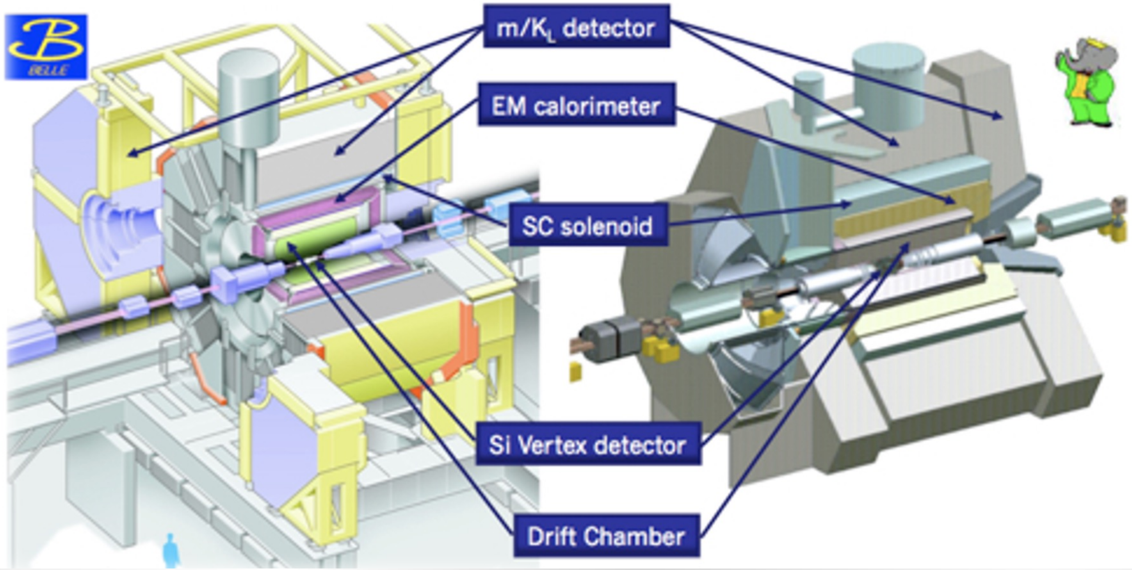
This short note is drawn in large part from the joint deliberations of the detector and physics groups at this workshop. There were many "full time" and "part time" members, among them C. Adolphsen, P. Avery, I. Bigi, E. Bloom, C. Buchanan, G. Coignet, H. Harari, W. Hofmann, N. Lockyer, I. Peruzzi, M. Piccolo, T. Sanda, P. Schlein, A. Soni, D. Stork, S. Weseler, H. Yamamoto, and T. Ypsilantis. In our deliberations we tried to under-

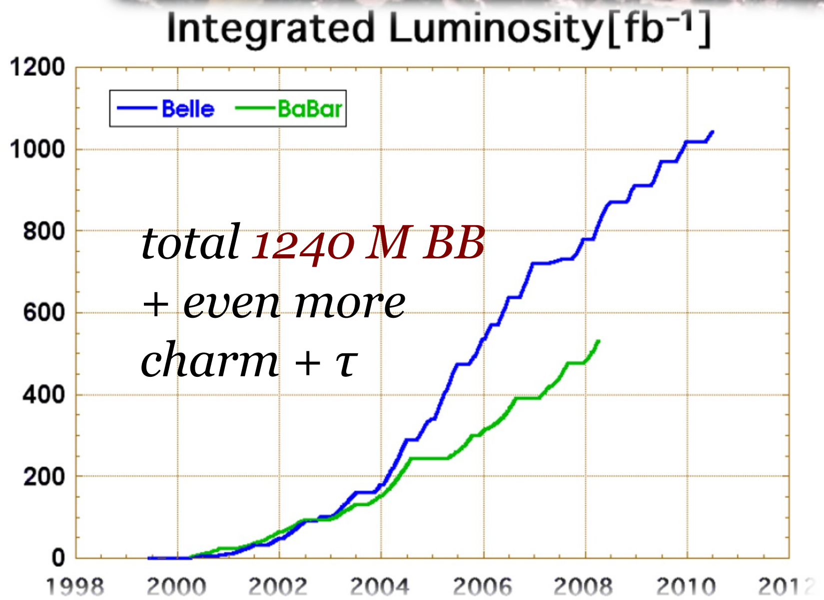
The idea of an Asymmetric B-Factory can be realized relatively economically at SLAC, where a powerful injector, an existing tunnel, and a ring of magnets suitable for the high energy ring already exist. The requirements for the accelerator are,

From Sanda's memories: "I went to KEK.
People said that Oddone's idea is crazy and that the beam will blow up!

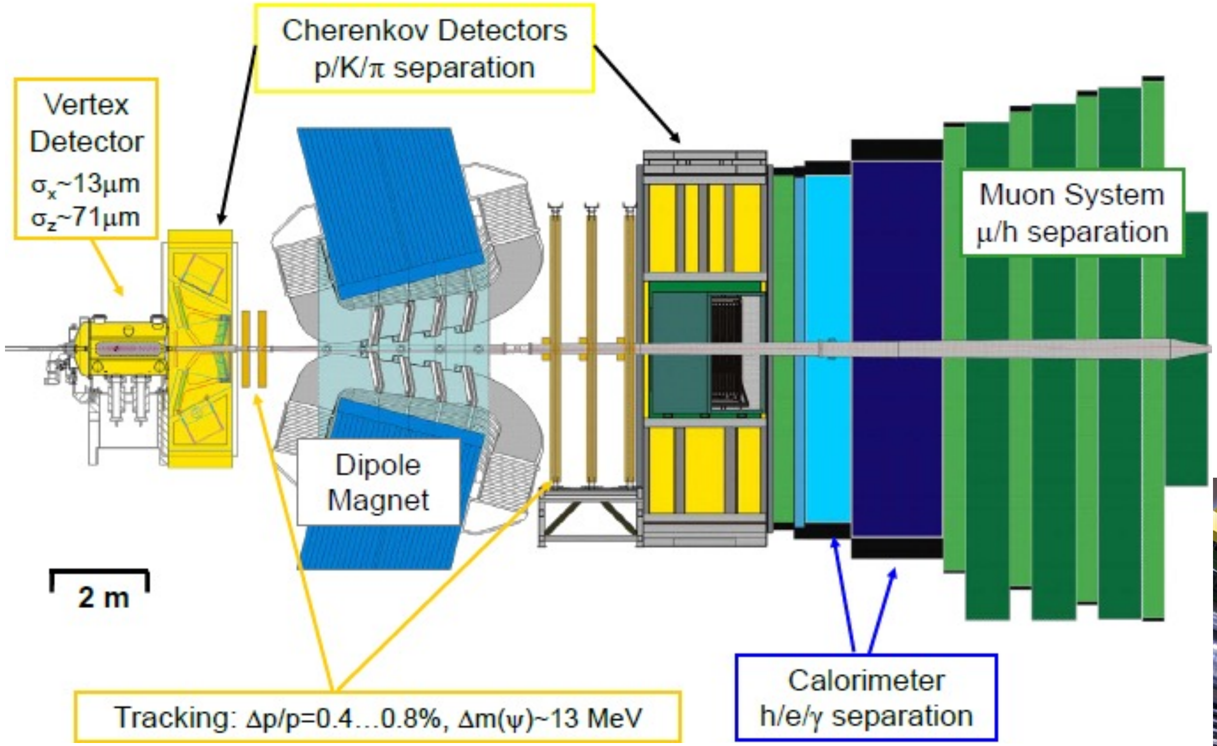
e^+e^- Asymmetric B-factories

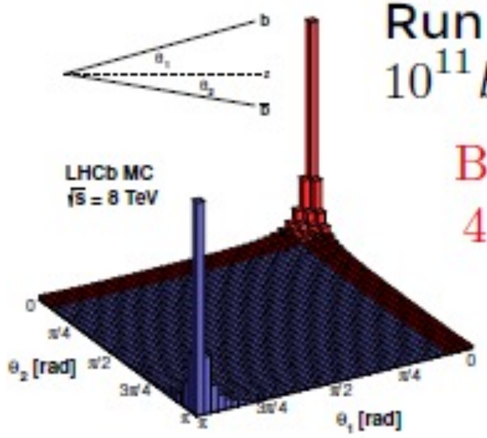
world highest luminosities





LHCb



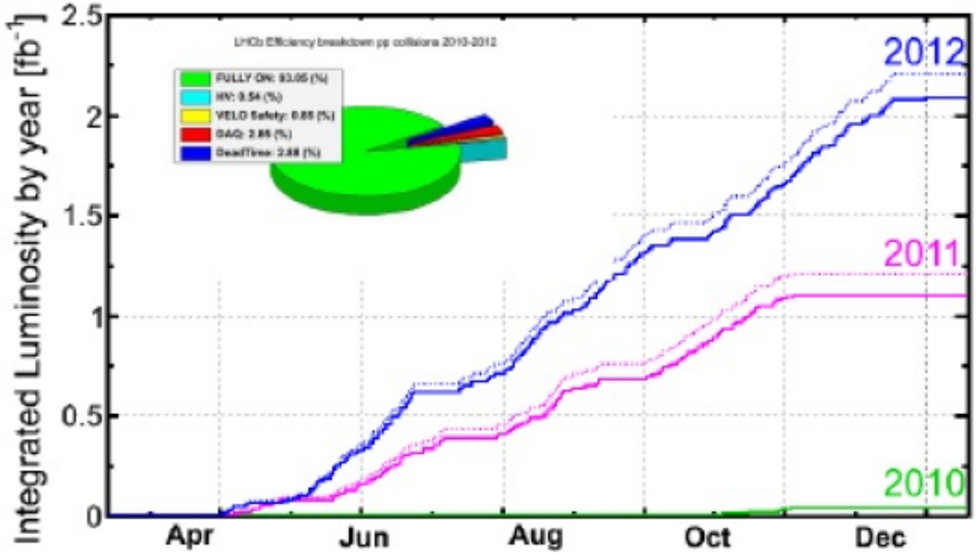


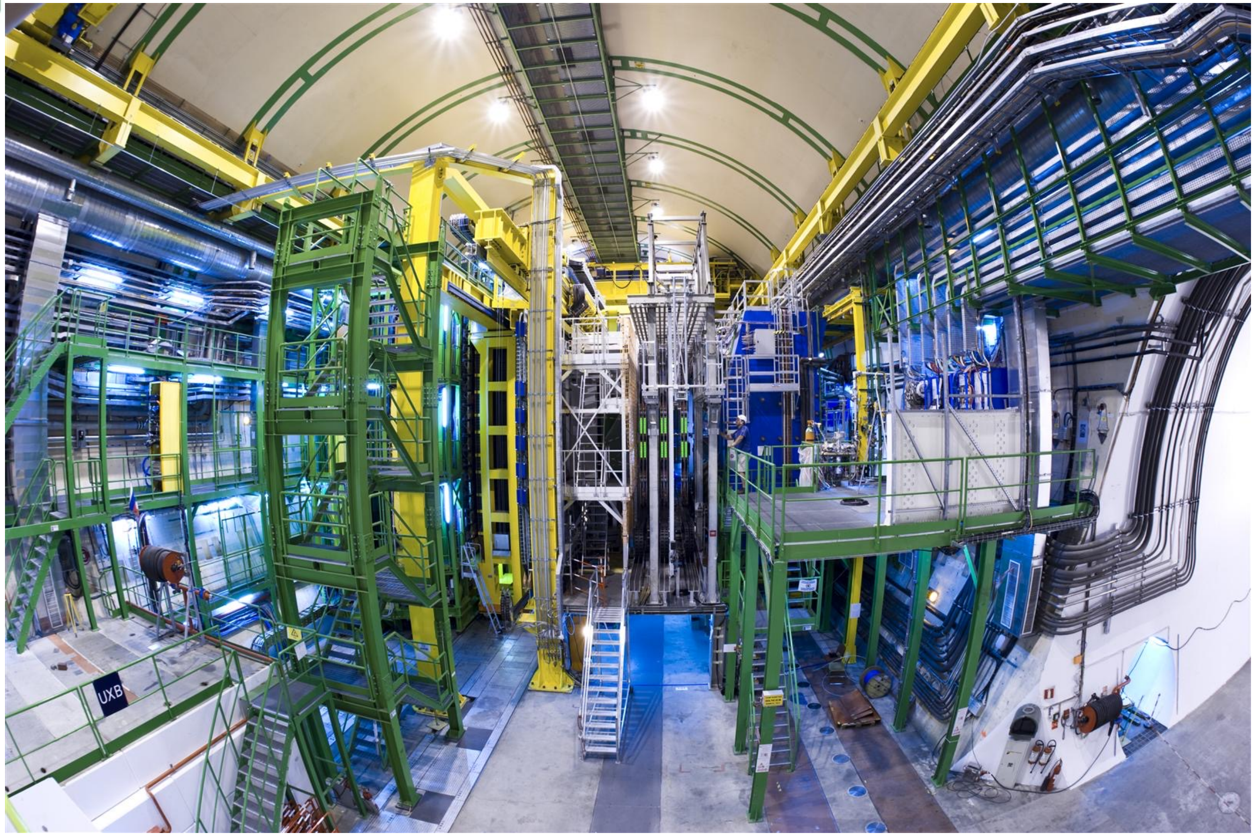
Run I: $3\ fb^{-1}$

$10^{11}\ b\bar{b}$ pairs

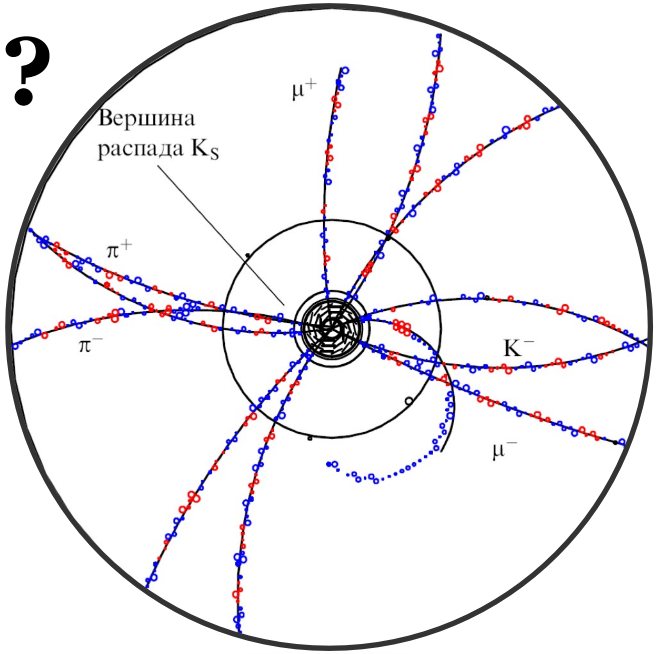
$B : \Lambda_b : B_s^0$

$4 : 2 : 1$





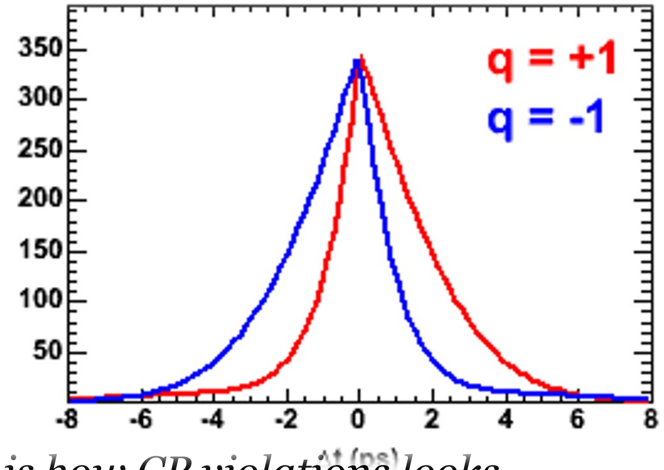
How to measure CPV at B-factories?



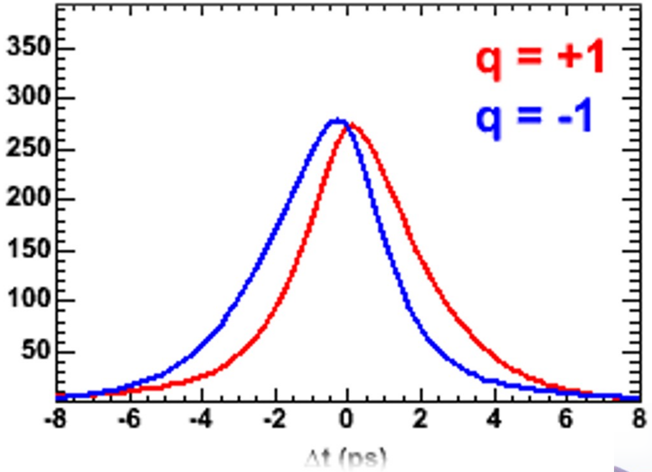
Reconstruct decay of one B-meson into CP eigenstate, e.g. $B \to J/\psi\, K_S$

Reconstruct the decay of the other B-meson to determine its flavor ("tag"). Partial reconstruction is sufficient

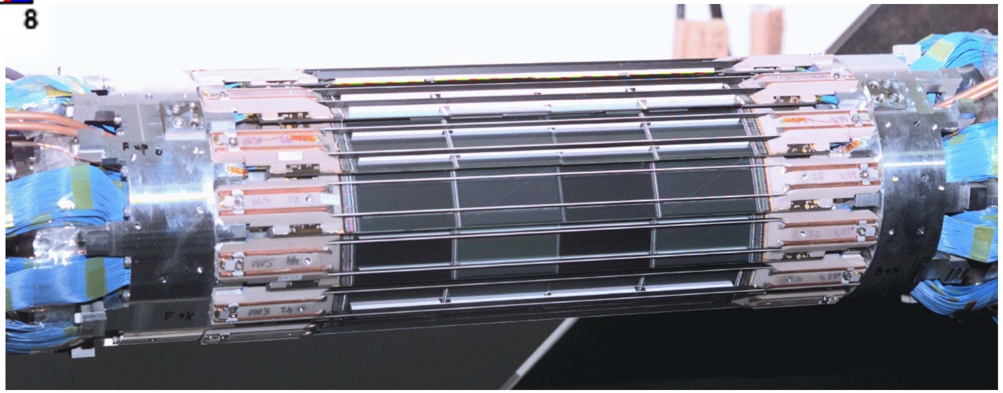
Measure the distance (L) between the two B meson decays vertices and convert to proper time $\Delta t = L/(\beta\gamma c)$



This is how CP violations looks with ideal detector…



with real one the proper time is smeared by finite vertex detector resolution, while sometimes we the flavor is ascribed incorrectly…

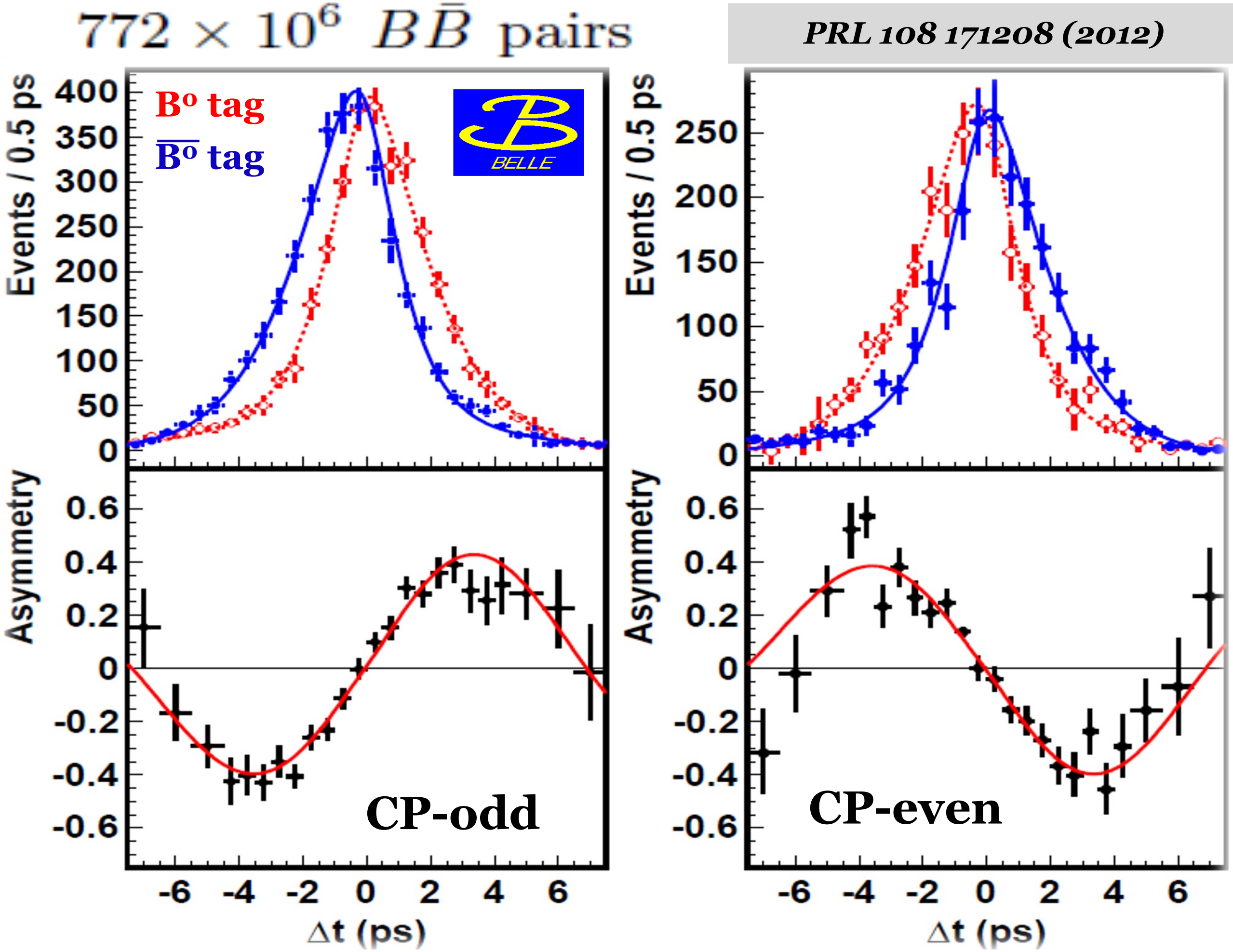


Extract CP asymmetry from the measured Δt distributions for tagged B^0 and $\bar{B}^0$:

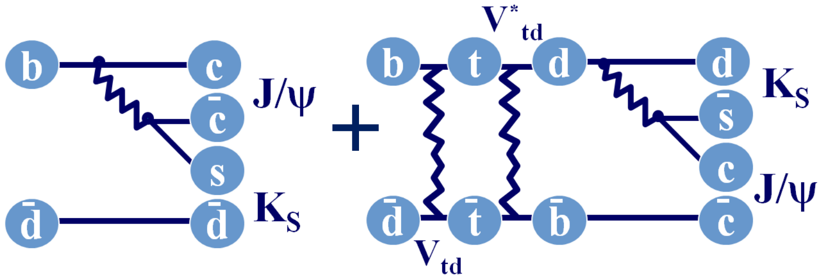
$$dN/d\Delta t \sim e^{-\Gamma|\Delta t|}\,[1 \pm \xi_{cp}\, \mathbf{A} \sin(\Delta m\, \Delta t)]$$

Precise measurement of sin(2β) in $B^o \to ccK^o$

PRL 108 171208 (2012)



$Y(4S) \to \bar{B^o}B^o \to f_{CP} f_{tag}$



Decay rate:

$$\frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 + q\left[\mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t)\right]\right\}$$

SM: S = –ξ sin(2β)

A = 0 (direct CPV)

sin(2β)

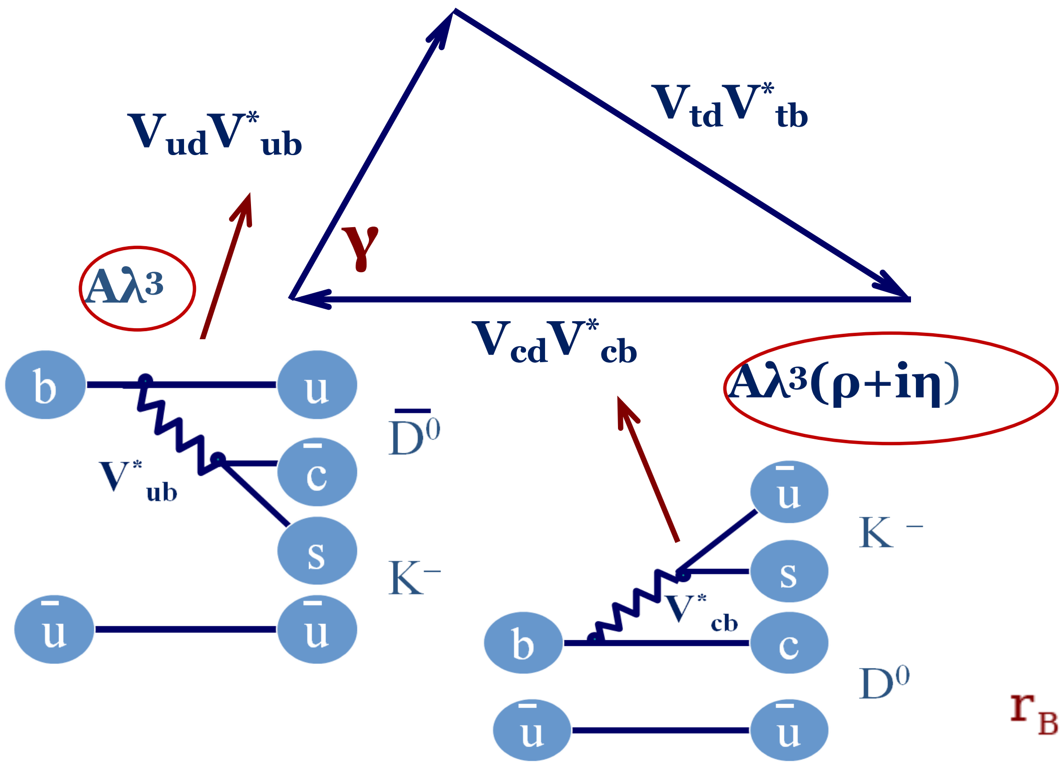
Belle II		LHCb	
$5\ ab^{-1}$	$50\ ab^{-1}$	$8\ fb^{-1}$ (2018)	$50\ fb^{-1}$
0.4°	0.3°	0.6°	0.3°

Belle 2012: $B \to ccK^o{}_S$ & $B \to J/\psi K^o{}_L$

$\sin(2\beta) = 0.667 \pm 0.023 \pm 0.012\ (0.9^\circ)$

$A_f = 0.006 \pm 0.016 \pm 0.012$

Direct CPV and angle γ

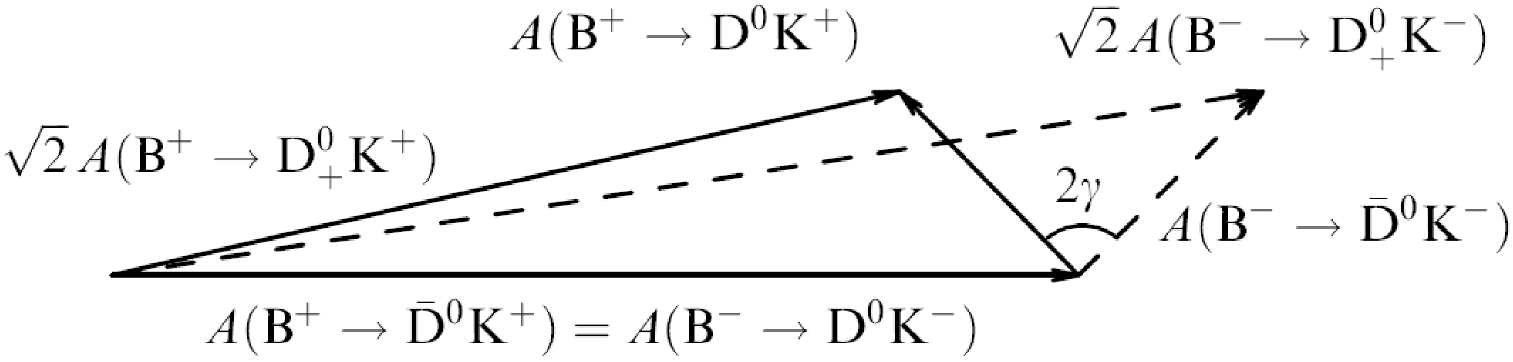


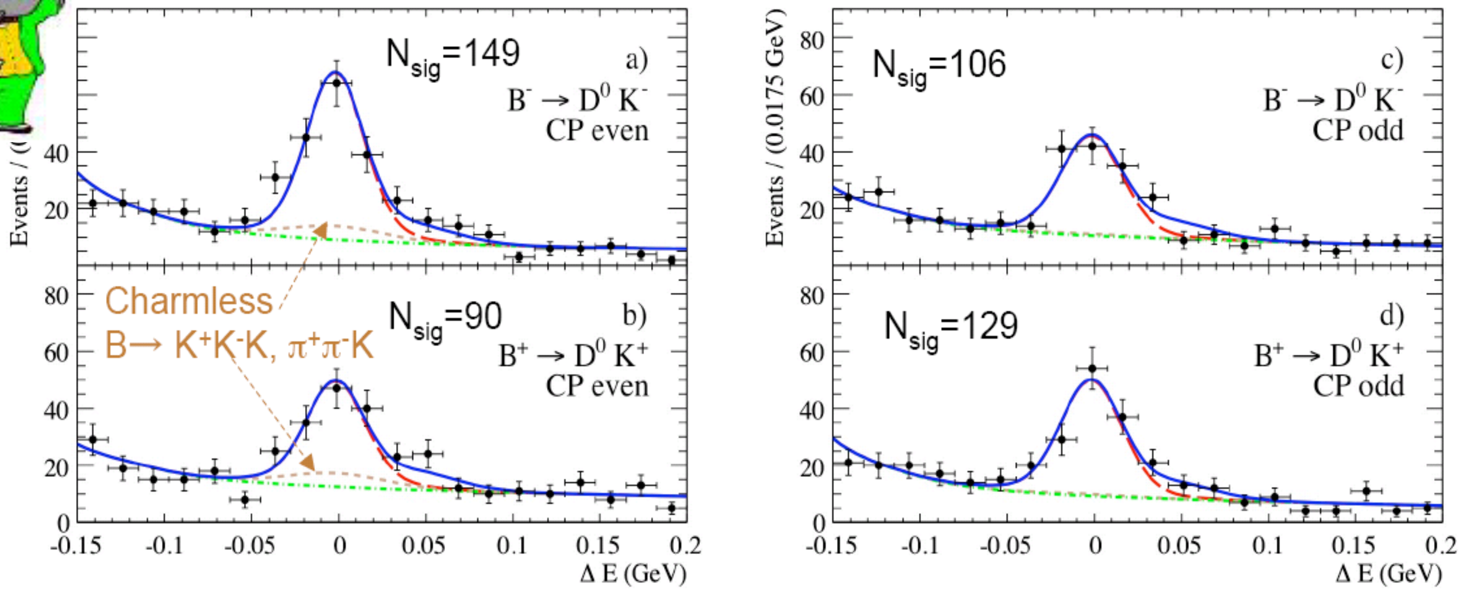
$B \to DK$: the angle between two amplitudes is really γ, but the final states are different $D^0 \neq \overline{D}^0$

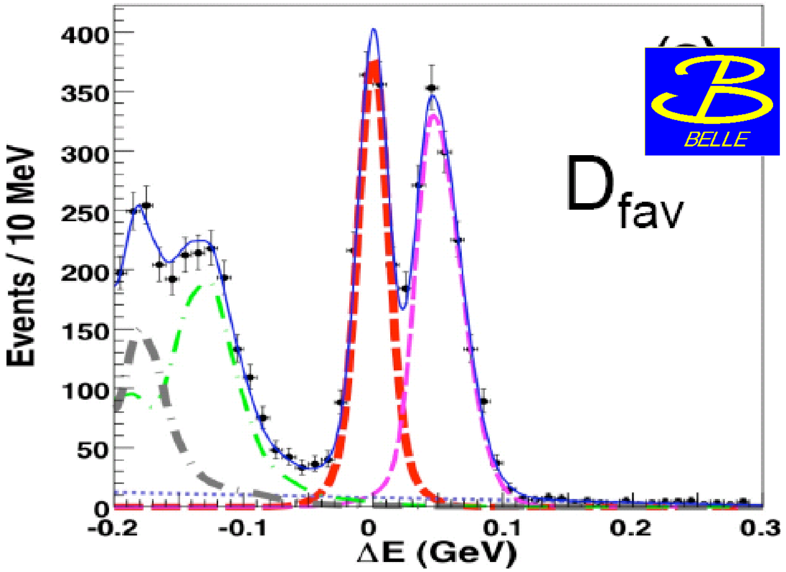
$$r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub} V^*_{cs}|}{|V_{cb} V^*_{us}|} \times [\text{color supp}] = 0.1 - 0.2$$

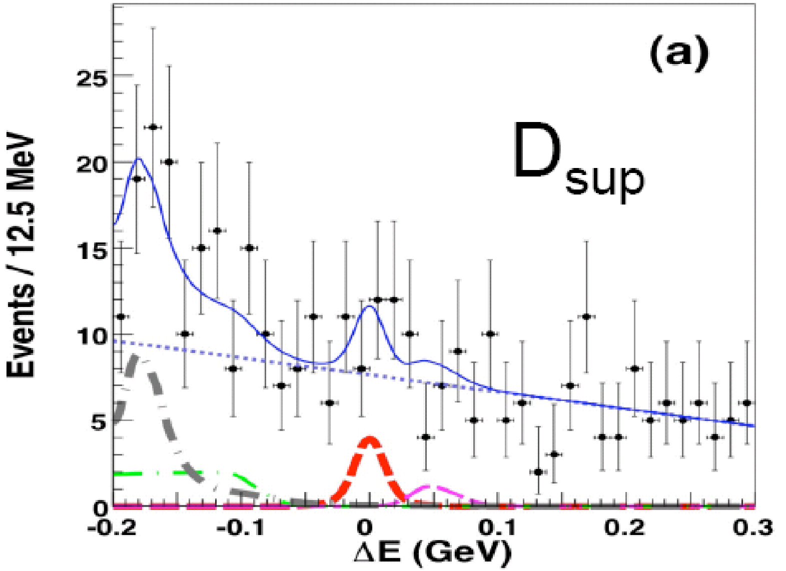
- GLW method: use D^0 decays into two-body CP eigenstates, *e.g.* $D^0 \to K^+K^-$
- ADS method: D^0 decays into final state typical for $\overline{D}^0$ *e.g.* $D^0 \to K^+\pi^-$
- Belle/GGSZ method: Dalitz analysis of 3-body final state, *e.g.* $D^0 \to K_S^0\pi^+\pi^-$

γ from GLS and ADS methods





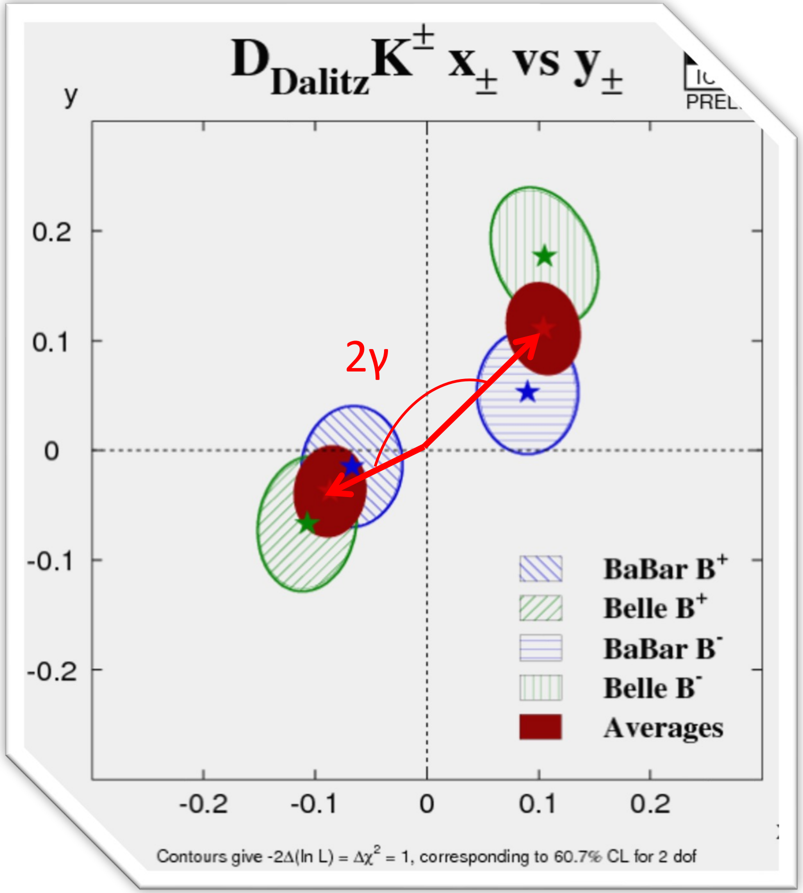


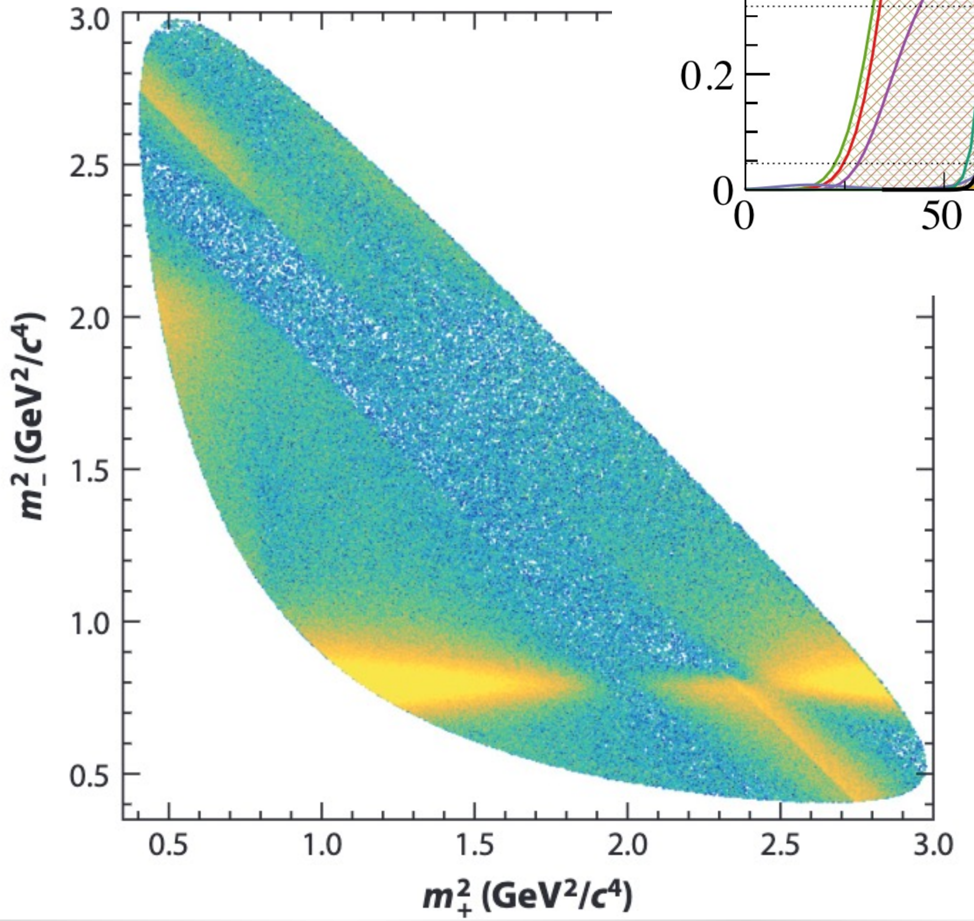


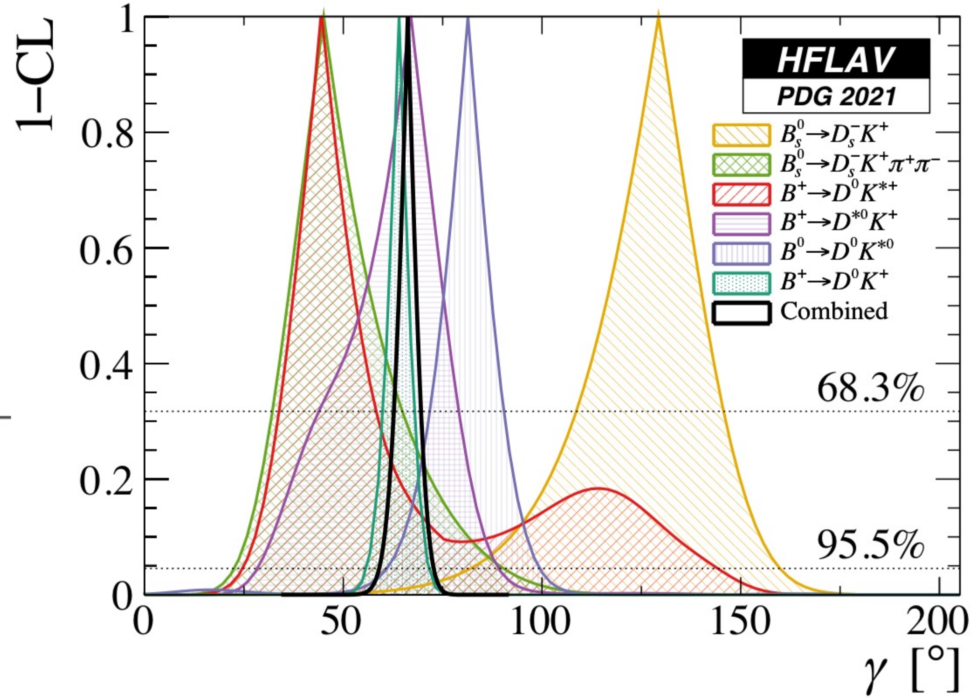
γ Belle/GGSZ method

Measure B⁺/B⁻ asymmetry across Dalitz plot

$$A_{\pm} = f\left(m_{+}^{2}, m_{-}^{2}\right) + r_B e^{\pm i\gamma} e^{i\delta} f\left(m_{-}^{2}, m_{+}^{2}\right)$$







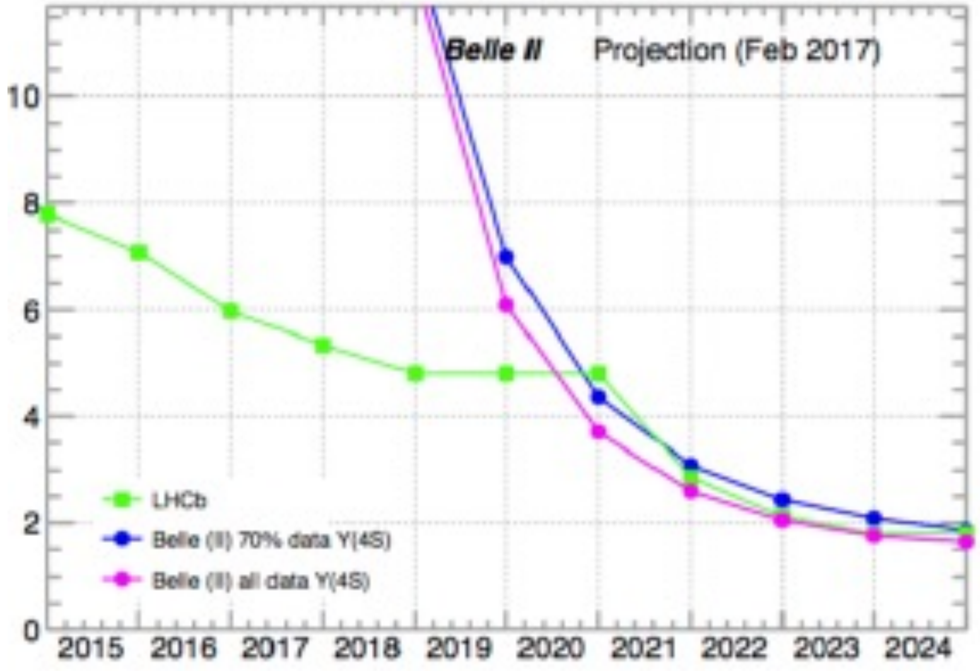
$\gamma = (66.2^{+3.4}_{-3.6})^{\circ}$

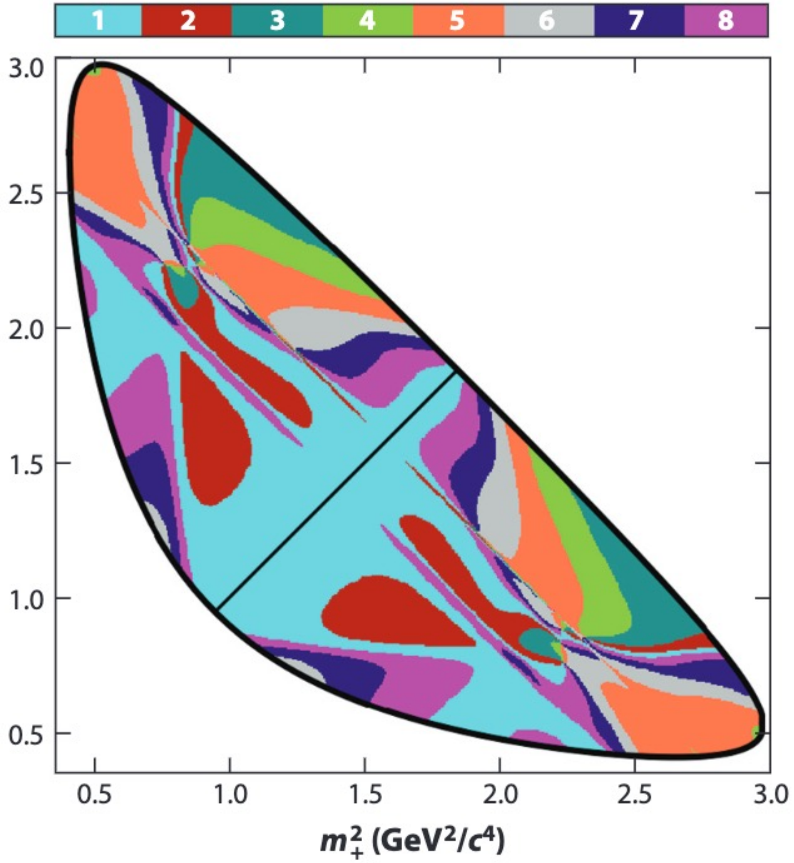
γ at Belle II and LHCb

Continue in future with these two methods.
But model uncertainties will become critical for Dalitz method with more data and reduced statistical errors. Propose to use $D^0 \to K_S^0\pi^+\pi^-$ binned plot from CP tagged data at charm-factory.
Need input from Super charm-tau factory.

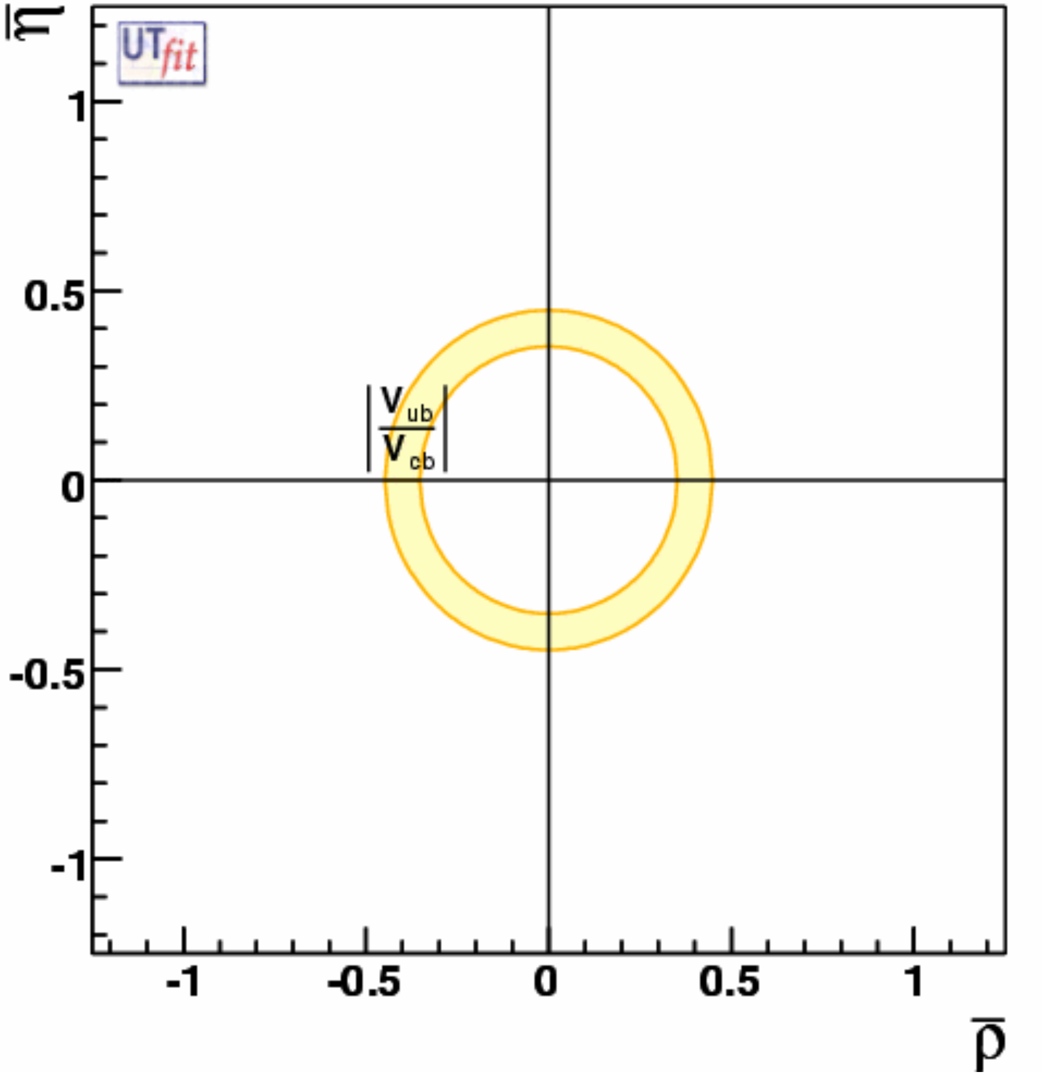
Sensitivity of Belle II and LHCb upgrade

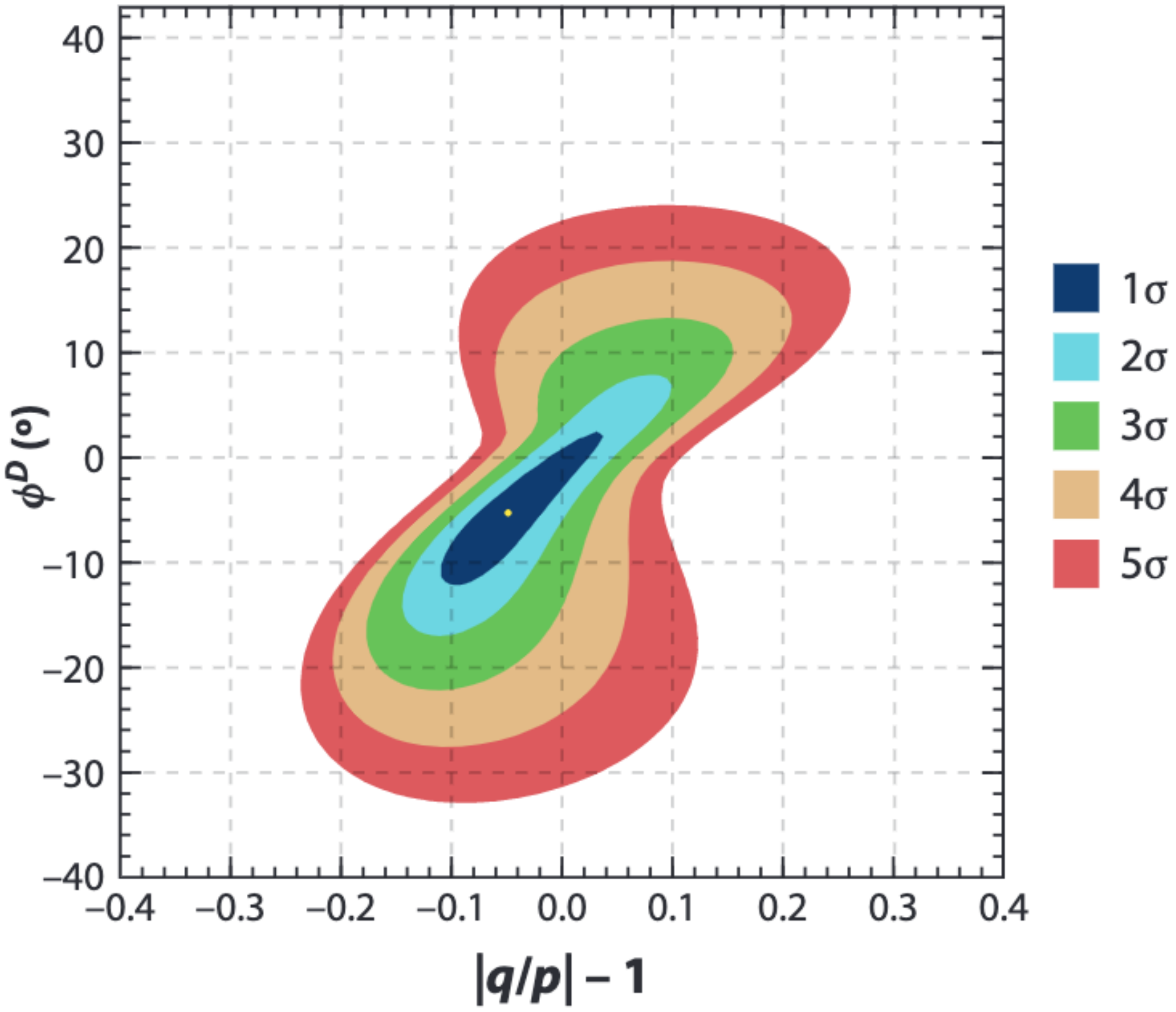
	LHCb	Belle II
$B \to DK$ with $D \to h^+h^-$	1.3°	2.0°
$B \to DK$ with $D \to K_S^0\pi^+\pi^-$	1.9°	2.0°
Total	**1.1°**	**1.5°**
Time dependent $B_s \to D_sK$	2.4°	





Compare b- and c-physics





Better chance to defend PhD

Better chance to get Nobel prize

First CP violation in charm at LHCb

The asymmetry

$$A_{CP}(f;\,t) \equiv \frac{\Gamma(D^0(t)\to f)-\Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f)+\Gamma(\overline{D}^0(t)\to f)}$$

is sensitive to both direct and indirect CP violation.

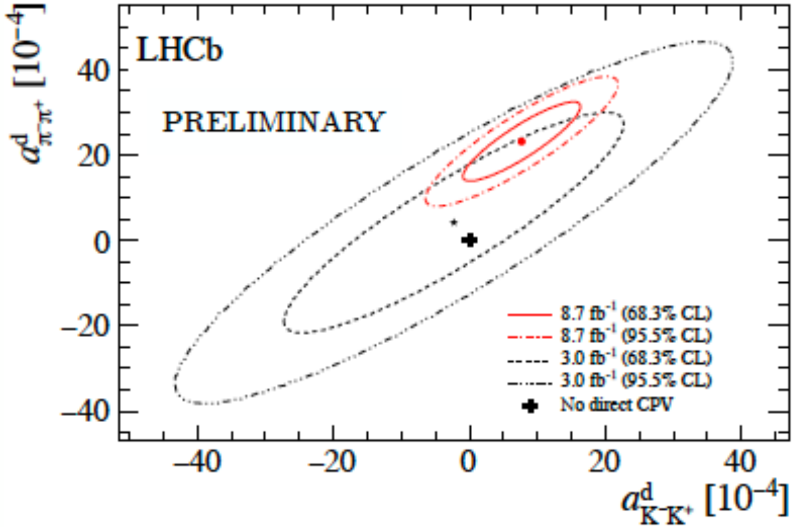
Time integrated measurement: huge statistics from

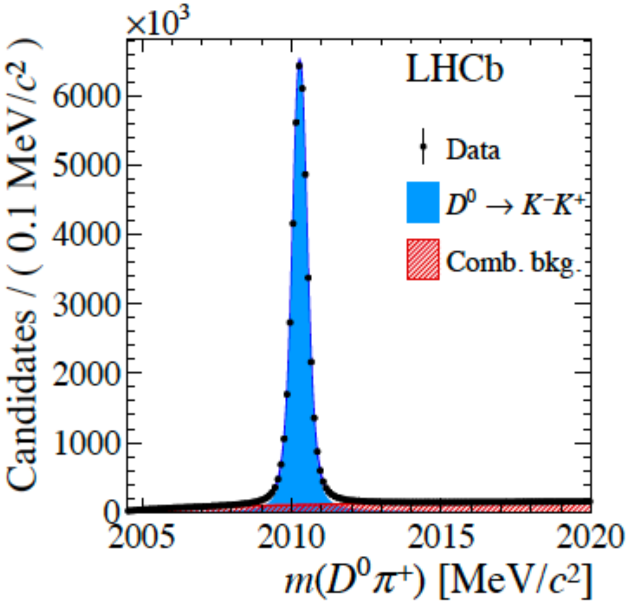
$$\overline{B}\to D^0\mu^-\overline{\nu}_\mu X \qquad D^{*+}\to D^0(f)\pi^+$$

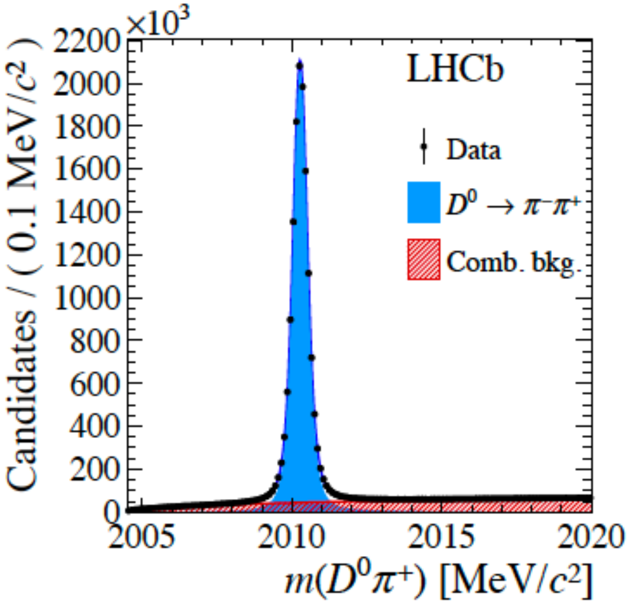
$$A_{CP}(f)\approx a_{CP}^{\rm dir}(f)-\frac{\langle t(f)\rangle}{\tau(D^0)}A_\Gamma(f)$$

the mean decay time $D^0\to f$

Strong suppression of the systematic uncertainties by measuring the difference







$$\Delta A_{CP} \equiv A_{CP}(K^-K^+)-A_{CP}(\pi^-\pi^+)$$

The result (including LHCb Run 1):

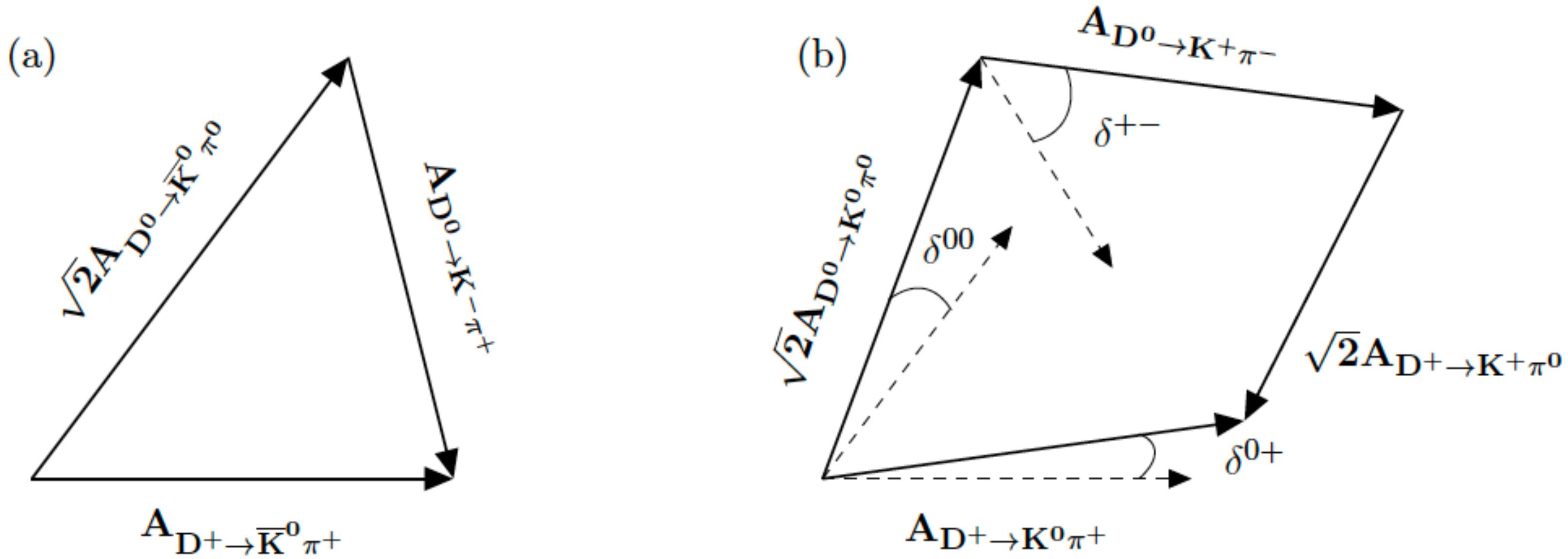
$$\Delta A_{CP} = (-15.4\pm 2.9)\times 10^{-4}$$

5.3 standard deviations. The first observation of CP violation in the decay of charm hadrons.

CPV in charm: NP or QCD tricks?

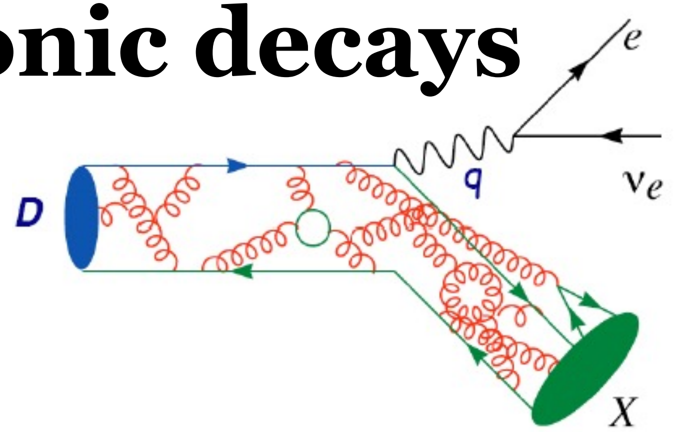
- CP violation is by a factor of 10 larger than SM expectations.
- NP contribution or QCD enhancement of penguin amplitudes?

To answer this question, QCD sum rules should be tested: for this we need not only measure sides of the three(quadr)angle, but also angles!

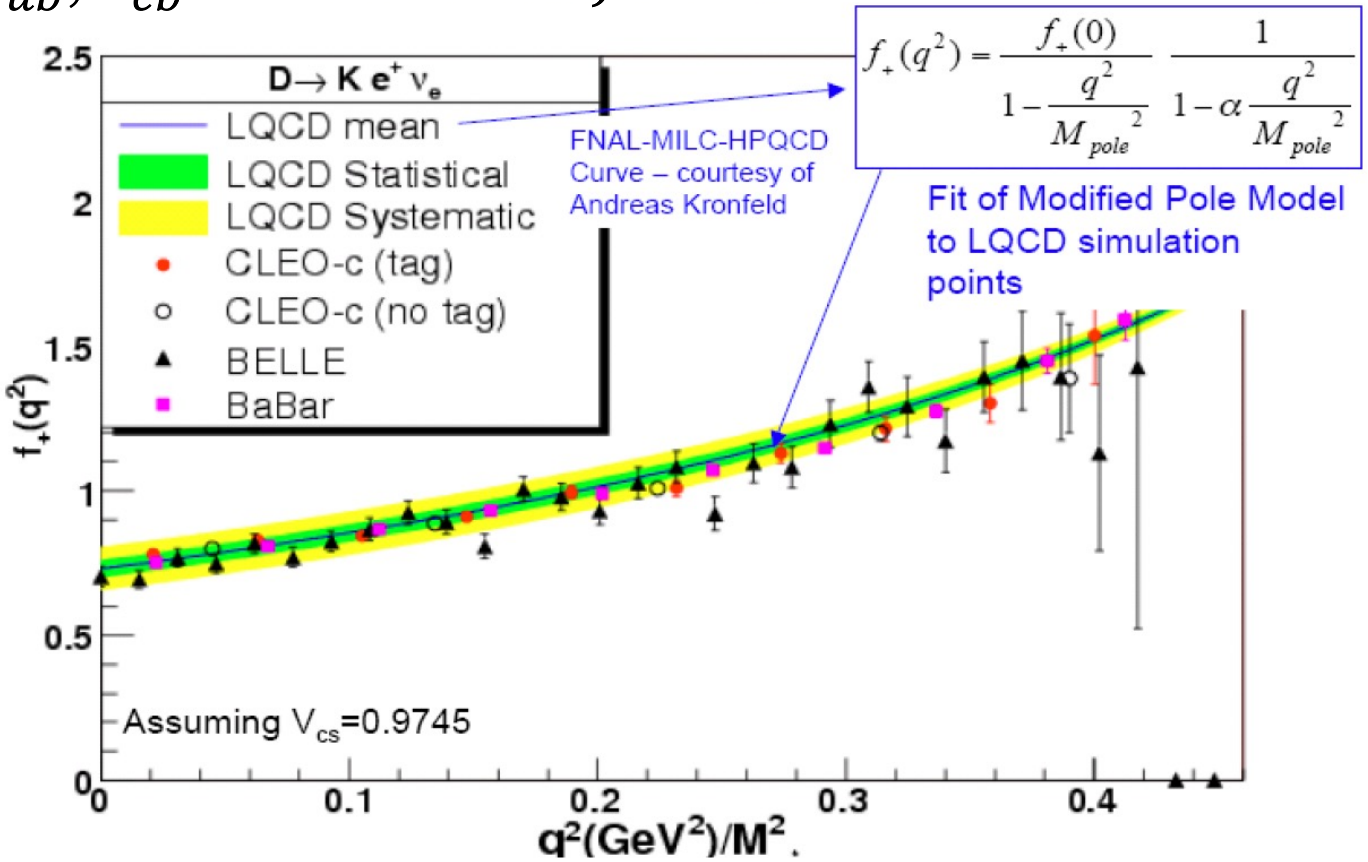


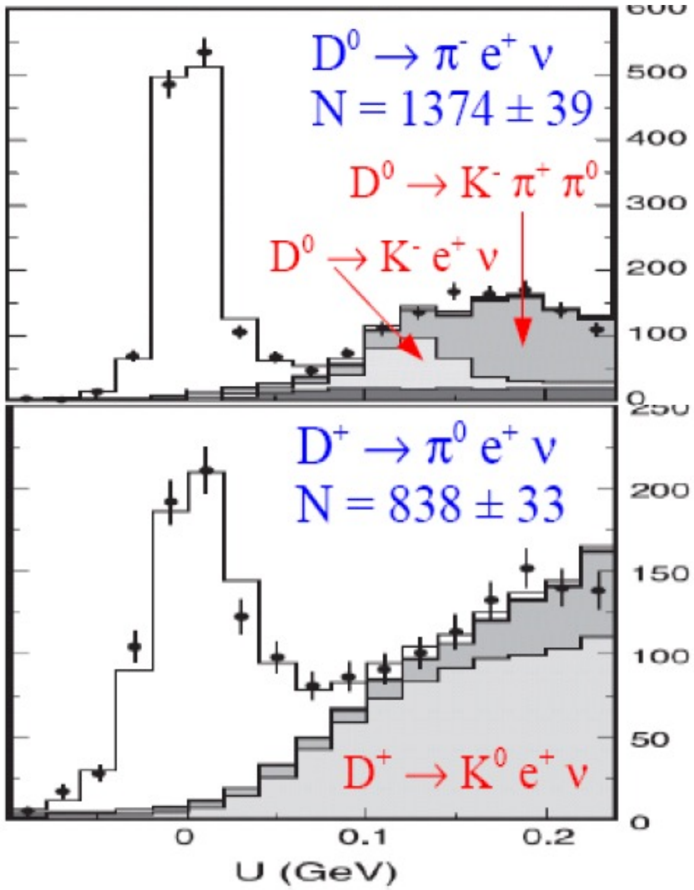
Such analysis is possible at Super Charm-tau Factory: coherent $D^0\overline{D}^0$ pair production; possibility to study $D^0 \to K^0\ X$ at large K^0 lifetimes.

Precise measurement of semileptonic decays



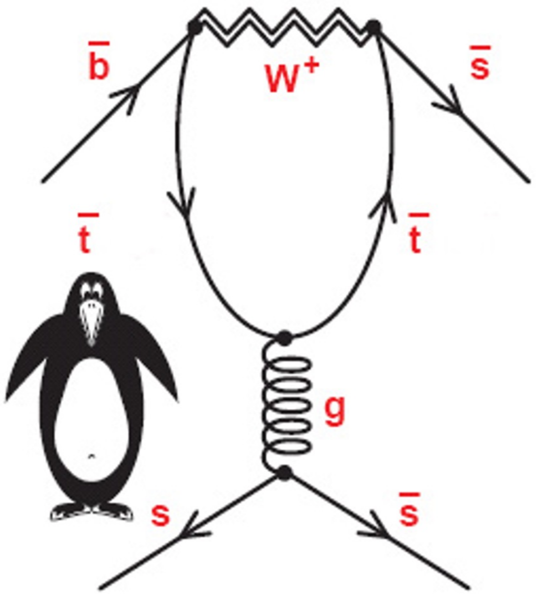
Provides measurement of transition form-factors. Test (and perhaps correction) of LQCD, to be used in overall CKM precision test (extrapolation for V_{ub}, V_{cb} measurement)

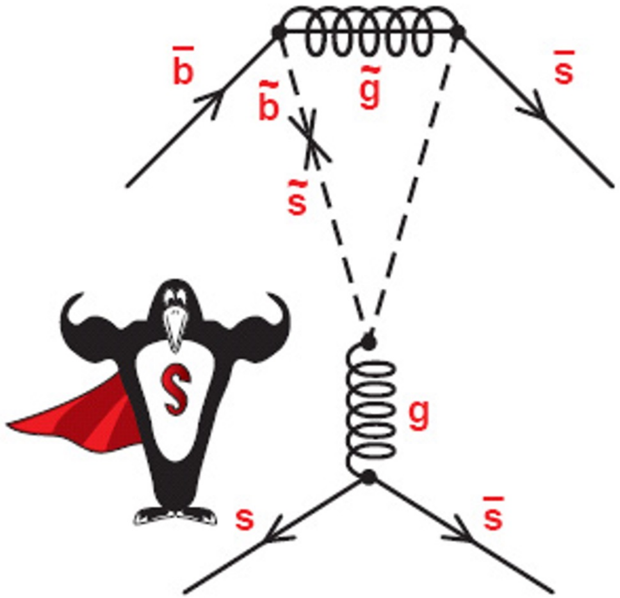




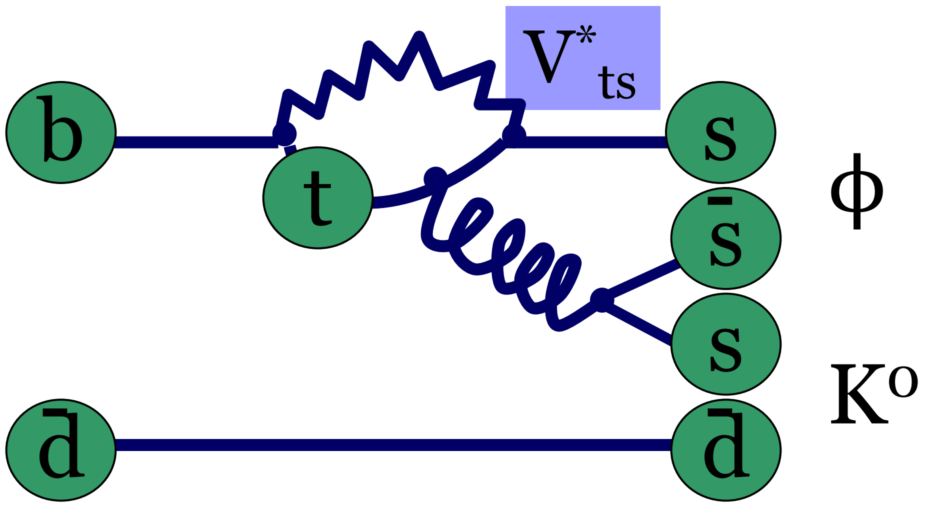
The curious name penguin goes back to a game of darts in a Geneva pub in the summer of 1977, involving theorists John Ellis, Mary K. Gaillard, Dimitri Nanopoulos and Serge Rudaz (all then at CERN) and experimentalist Melissa Franklin (then a Stanford student, now a Harvard professor). Somehow the telling of a joke about penguins evolved to the resolution that the loser of the dart game would use the word penguin in their next paper. It seems that Rudaz spelled Franklin at some point, beating Ellis (otherwise we might now have a detector named penguin); sure enough the seminal 1977 paper on loop diagrams in B decays [3] refers to such diagrams as penguins. This paper contains a whimsical acknowledgment to Franklin for "useful discussions" [4].

Search for Super-Penguins?





Testing loops!



CP asymmetry should be ~ sin2β

$$\frac{\bar{A}}{A} = \frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}} = \frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}$$

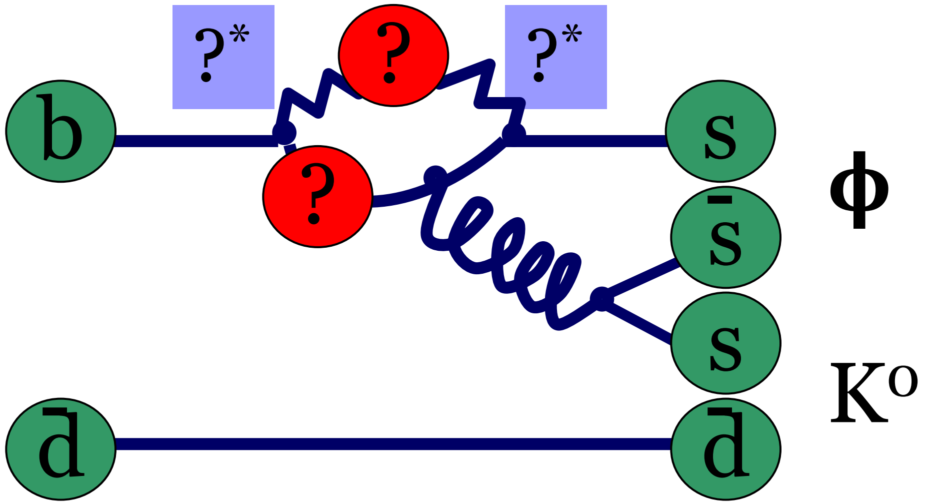
No tree contribution!

Theoretical uncertainty ~ 0.01-0.03 much smaller than the current exp errors!

All our previous measurements test new physics contribution to the box diagram and check the consistency with pure tree (where no big contribution from NP expected)

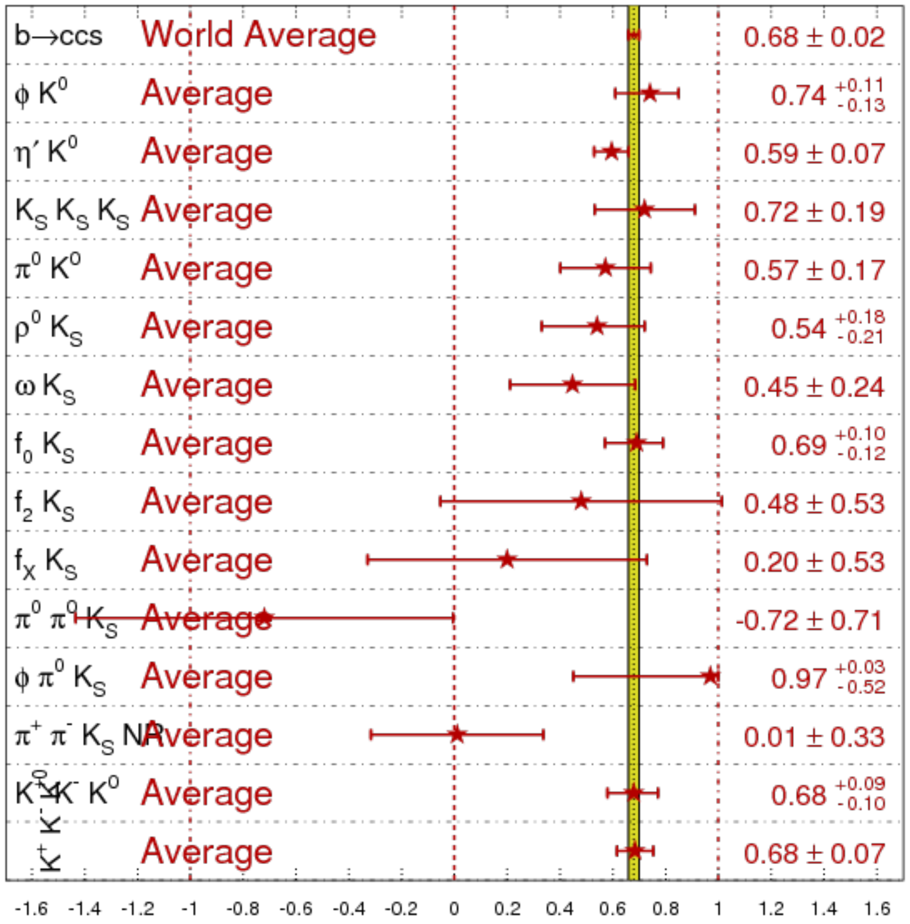
This one really give access to the loop. If any (heavy) particles (with extra to KM phases) are involved in the loop we can see the effect!

$$\sin 2\varphi^{\text{eff}} \neq \sin 2\beta$$



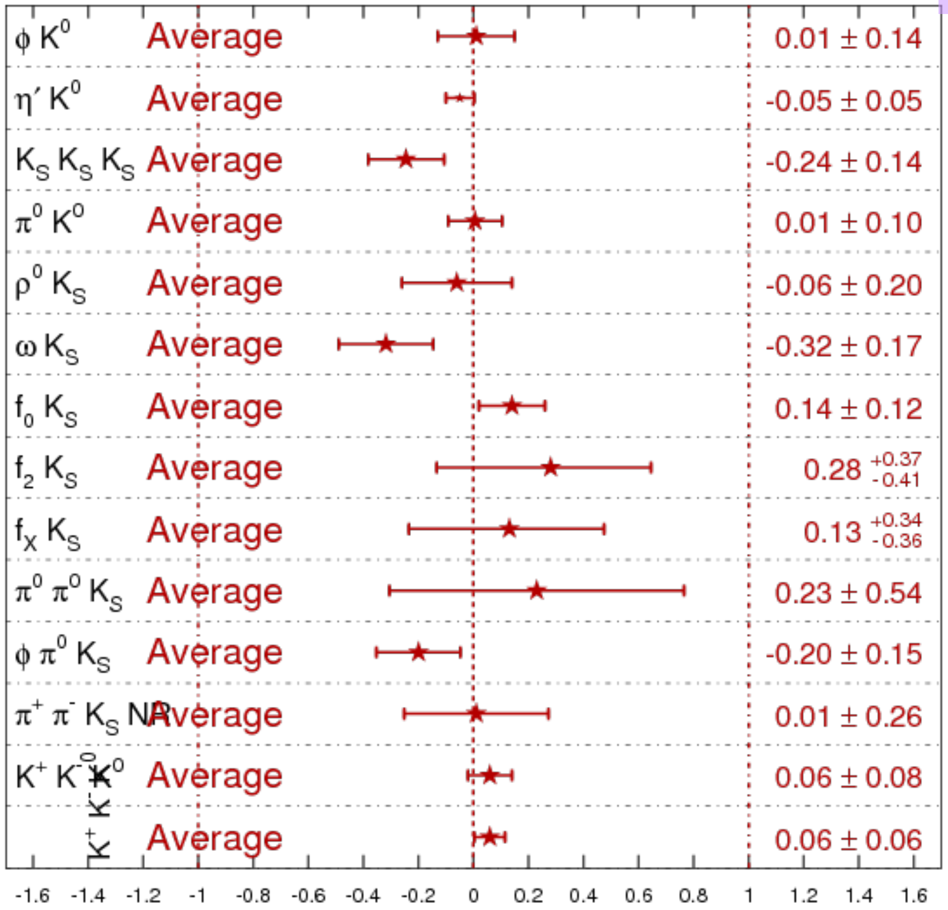
2006: exciting 3.5 σ discrepancy!

$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$



$C_f = -A_f$

$A_{CP} \approx 0$

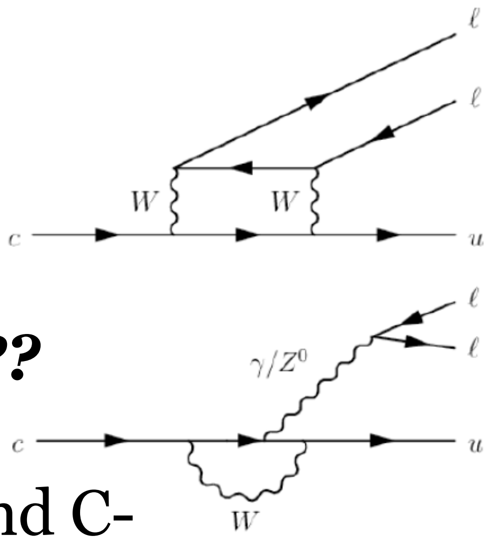


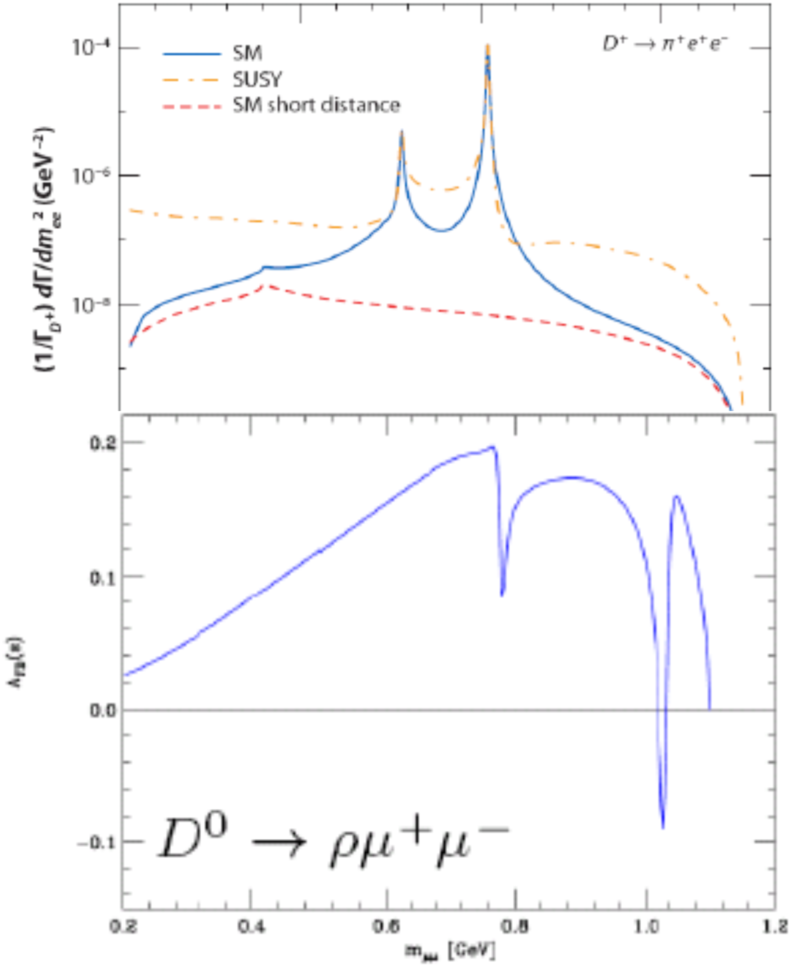
$\sin 2\beta = 0.68 \pm 0.02 \approx 0.68 \pm 0.07 = \sin 2\phi^{eff}$

now: disappointing nice agreement

Rare decays: $D \to X\ell^+\ell^-$

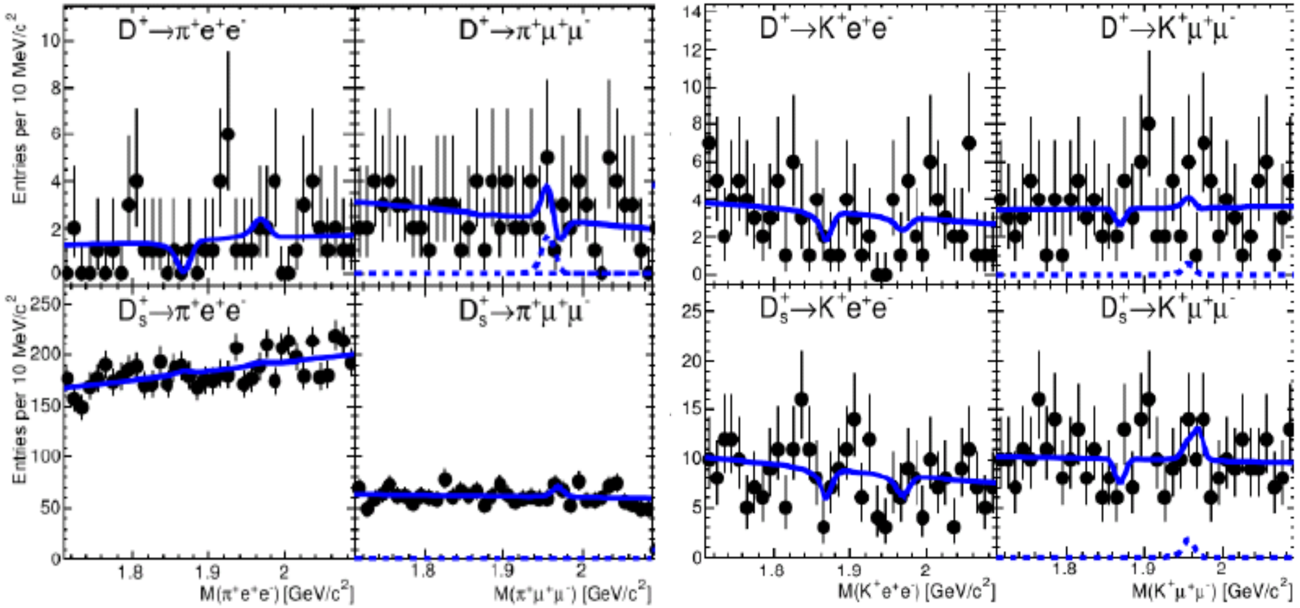
- In SM GIM and CKM suppression ($Br{\sim}10^{-8}$)
- long-distance contribution $D \to XV \to X\ell\ell$
- NP can enhance penguin loop





How to distinguish QCD from NP?

Lepton charge asymmetry, due to P- and C-violating contribution from W and Z in the loop.



Summary

The current era is the most exciting one in charm physics for many decades. Neutral mixing and CP-violation in charm, long feared to be too small for experimental study, are now observed, and the next goals are firmly in sight. The most urgent tasks are to establish whether the parameter x, and hence the mass splitting in the neutral charm system, is of a similar magnitude to y, or instead vanishing; to make further measurements of direct CP-violation, in particular those that will help elucidate whether the size of A_{CP} is compatible with SM expectations; and finally to intensify the search for CP-violation associated with $D^0 - \overline{D}^0$ oscillations.

But the most important!

From the past experience: many good ideas come to mind in bar, wine clubs etc…
The success of Super charm-tau Factory depends on whether life and freedom can be organized here, at Sarov technopark.