Flavour Physics: A Taster

CERN Summer Student Lecture Programme 2022

Lecture 1 of 3: What? Why? How?

20-22 July 2022

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University of Edinburgh

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Introduction

First of three lectures on flavour physics

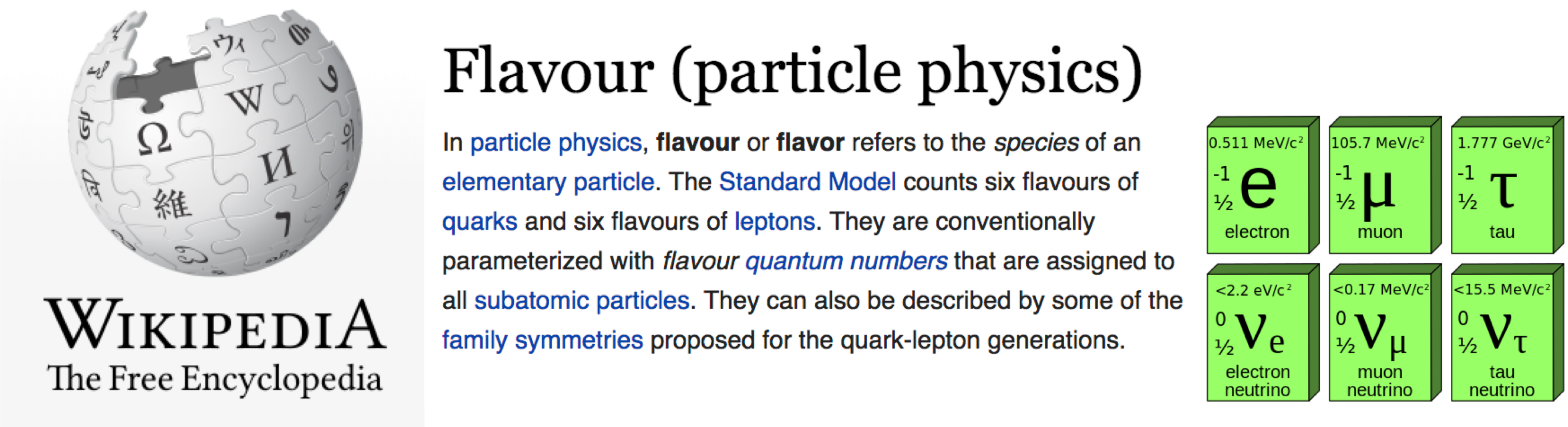
Today we focus on the foundations and motivations of the subject

- What is flavour physics and why does it matter?
  - Quantum loops & indirect searches for new physics
- Why do we live in a universe full of matter?
  - Discrete symmetries in nature
- How can we use precision measurements to observe new physics
  - Example: Neutral meson oscillations

Cover the foundations of the subject with some history
⇒ Leads us up to the modern era – subject of the next 2 lectures

Part I: What is flavour physics?

What is flavour?



WIKIPEDIA
The Free Encyclopedia

Flavour (particle physics)

In particle physics, **flavour** or **flavor** refers to the *species* of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with *flavour quantum numbers* that are assigned to all subatomic particles. They can also be described by some of the family symmetries proposed for the quark-lepton generations.

Coined by Gell-mann and Fritsch on visit to ice cream parlour (Pasadena, 1971)

"Just as ice cream has both color and flavor so do quarks."

Flavour physics

Bosons
⇒ “Forces”

g (x8)
γ
$W^{\pm}$
Z^0

H

Fermions
⇒”Matter”

u
d

Quarks
(3 colours)

e^-
ν_e

Leptons

(+ antimatter equivalent)

Flavour physics

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(3 colours)

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(+ antimatter equivalent)

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(3 colours)

τ^{-}
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Leptons

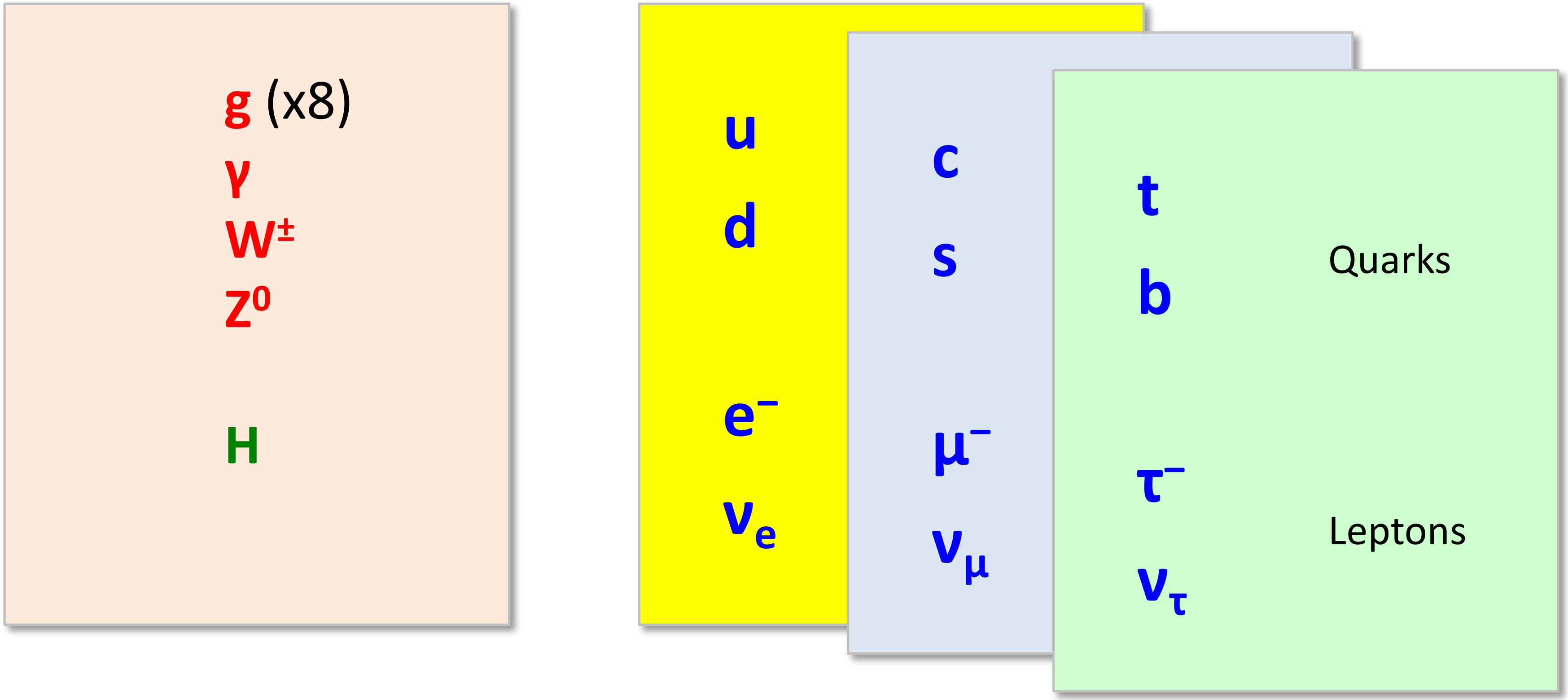
(+ antimatter equivalent)

Flavour physics

Bosons
⇒ “Forces”

Fermions
⇒”Matter”

Why so many fermions?
Why structured into ‘families’?
Why 3?



g (x8)
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d

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c
s

μ^-
ν_μ

t
b

τ^-
ν_τ

Quarks

Leptons

Why do we observe flavour ‘symmetries’?
Why are they imperfect (=broken)?

Flavour symmetries: some history

1932: Discovery of neutron ⇒ Looks like a neutral counterpart of proton
Same mass, same coupling to strong interaction

Same year, Heisenberg proposed neutron and proton are an ‘**isospin doublet**’

⇒ Two quantum states of the same particle (like spin-⇑ and spin-⇓ electron)

p: $(I;\ I_z) = (\tfrac{1}{2}\ ;\ \mathbf{+\tfrac{1}{2}})$ ⇑

n: $(I;\ I_z) = (\tfrac{1}{2}\ ;\ \mathbf{-\tfrac{1}{2}})$ ⇓

Also later used for pions, which form isospin triplet: $(\pi^+, \pi^0, \pi^-) = (+1, 0, -1)$

Flavour symmetries: some history

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Same year, Heisenberg proposed neutron and proton are an '**isospin doublet**'

⇒ Two quantum states of the same particle (like spin-⇑ and spin-⇓ electron)

p: $(I;\, I_z) = (½\, ;\, +½)$ ⇑

n: $(I;\, I_z) = (½\, ;\, -½)$ ⇓

Proved a very useful concept making successful predictions

Works because u and d quarks have 'similar' masses (compared to QCD scale)
⇒ But masses **not** identical. **Broken symmetry!**

Many such near-symmetries in flavour physics, with interesting implications

A Rich Field

Parameters of the Standard Model:

- 3 gauge couplings
- 2 Higgs parameters
- 6 quark masses
- 3 (+3) lepton masses
- 3 quark mixing angles + 1 phase ⇒ CKM matrix
- (3 lepton mixing angles + 1 phase) ⇒ PMNS matrix

(…): with Dirac neutrino masses

A Rich Field

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Flavour parameters

(…): with Dirac neutrino masses

Just a Taste…

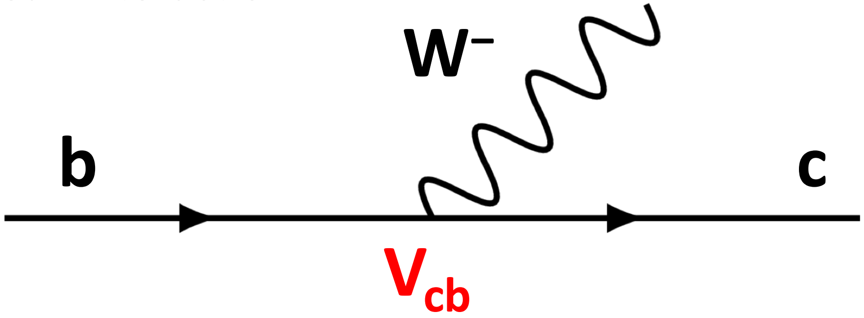
Flavour physics is a wide topic!

- Neutrinos
- Charged leptons
- Kaon (strange) physics
- Charm and beauty physics
- (Some) top quark physics

In 3 lectures, no time to cover everything – will give a selected, biased, sample of topics, mainly focusing on quark sector

Heavy (quark) flavour physics

Quarks change flavour through the charged weak interaction

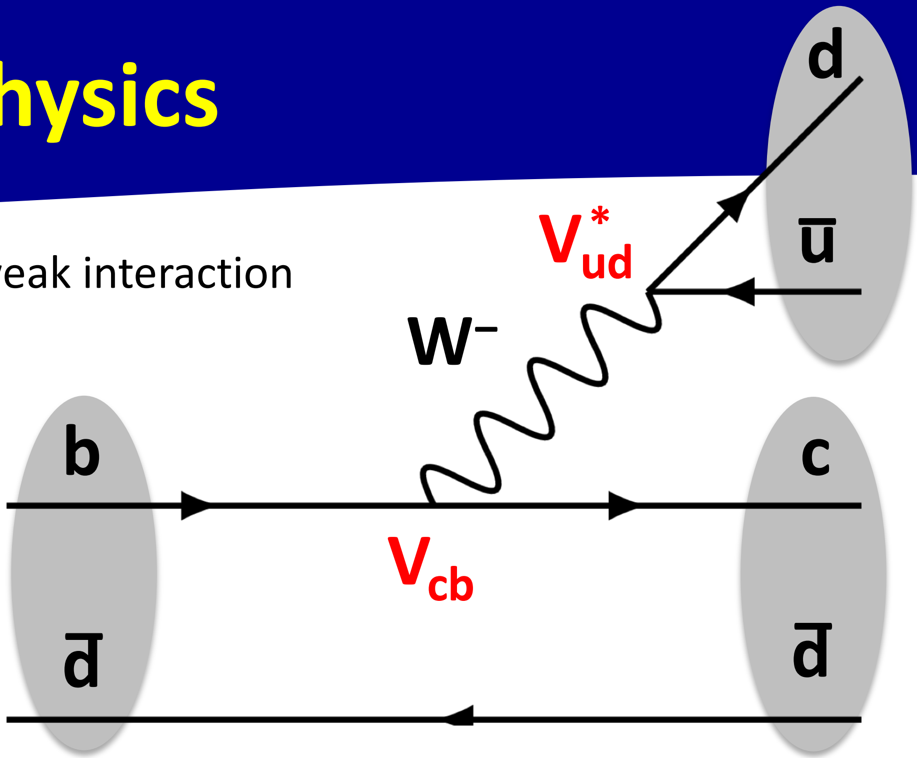


Heavy (quark) flavour physics

Quarks change flavour through the charged weak interaction

But… they are bound by the strong interaction into hadrons

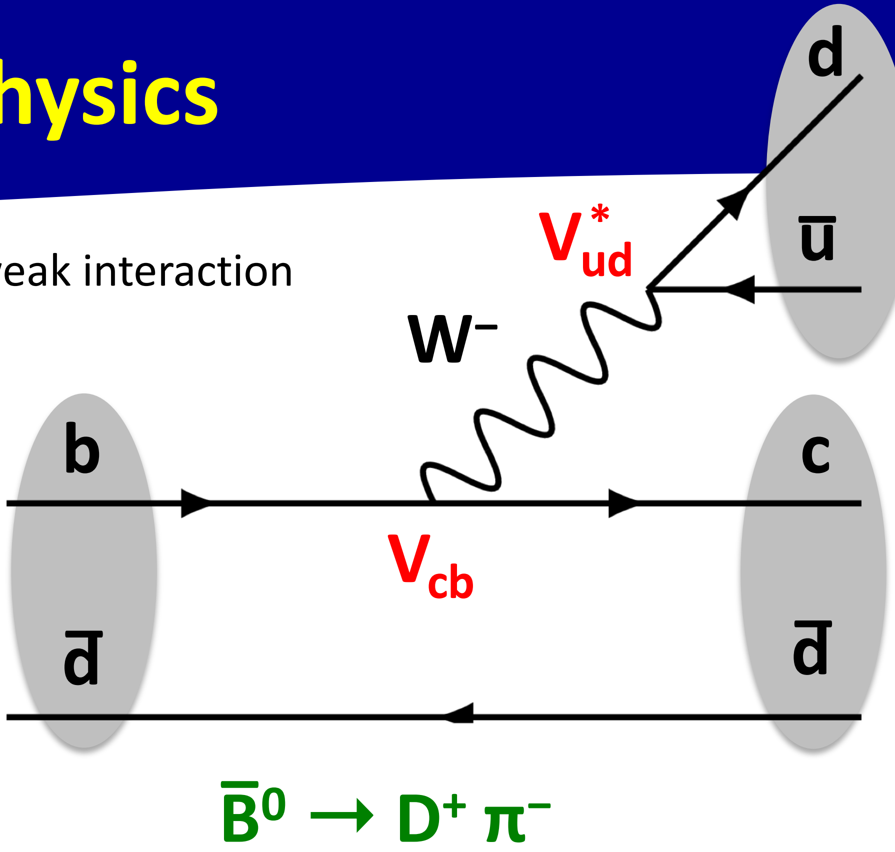
⇒ Many possible quark combinations, many possible decays to different final states



$\bar{B}^0 \rightarrow D^+ \pi^-$

Heavy (quark) flavour physics

Quarks change flavour through the charged weak interaction



$\bar{B}^0 \rightarrow D^+ \pi^-$

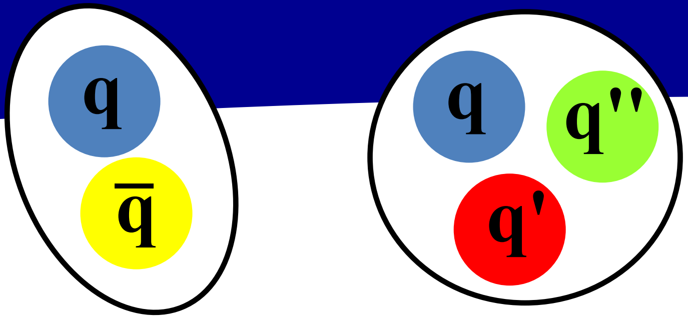
But… they are bound by the strong interaction into hadrons

⇒ Many possible quark combinations, many possible decays to different final states

Cannot observe weak interaction in isolation – makes theoretical predictions tougher
⇒ Also lots of hadrons to remember (or refer to PDG booklet!)

But… leads to **better sensitivity** to new particles and non-SM effects
Enables wide programme of measurements to over-constrain the SM parameter-space

[The particle zoo]



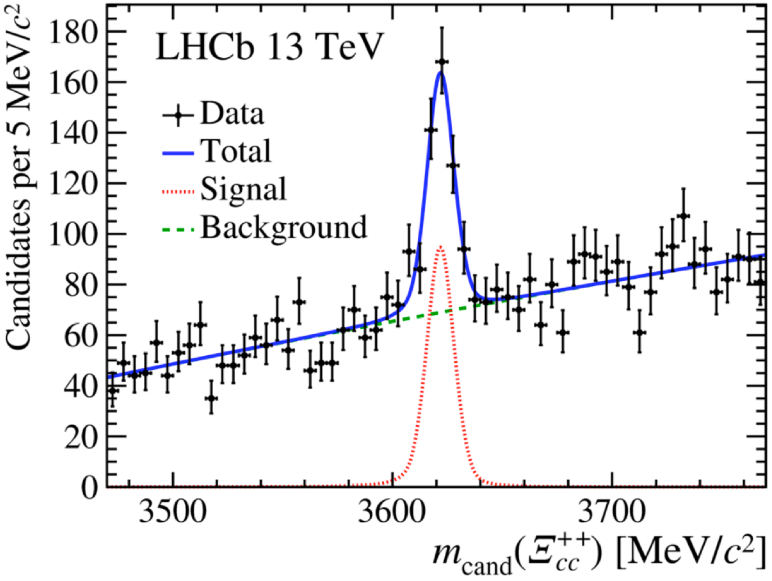
With 5 quarks forming hadrons:

25 possible mesons
⇒ All now discovered (last was **$B_c^\pm$** in 1998)

35 possible baryons
⇒ Many still not observed – **in 2017 LHCb discovered Ξ_{cc}^{++} (ccu) baryon**
12 other undiscovered baryons with >1 heavy (=b or c) quarks

Also additional ‘excited’ states (just like atoms) with different masses & properties

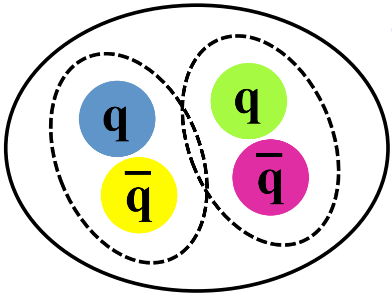
https://doi.org/10.1103/PhysRevLett.119.112001



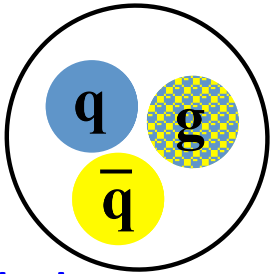
Discovering new states, and measuring their properties (masses, lifetimes, decays) gives powerful tool to study and improve QCD calculations

[The particle zoo]

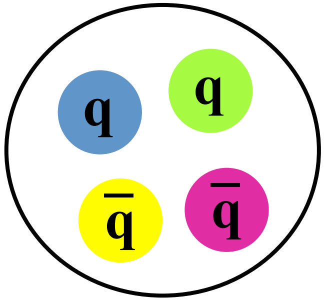
Long standing puzzle – why only mesons and baryons? Why not other combinations of quarks and gluons?



dimeson molecule

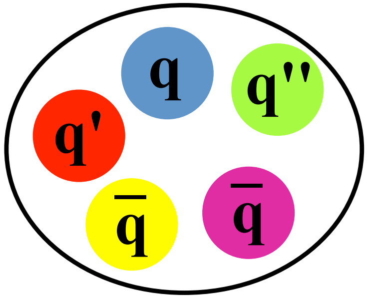


quark-gluon hybrid



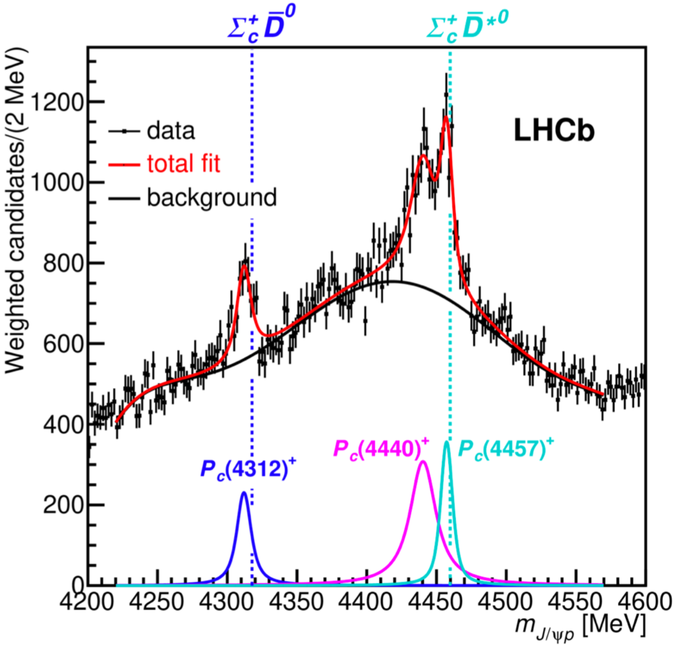
tetraquark

pentaquark



In **2015**, LHCb made first discovery of (two!) pentaquark states (uudc$\bar{c}$)

In **2019**, two became three →



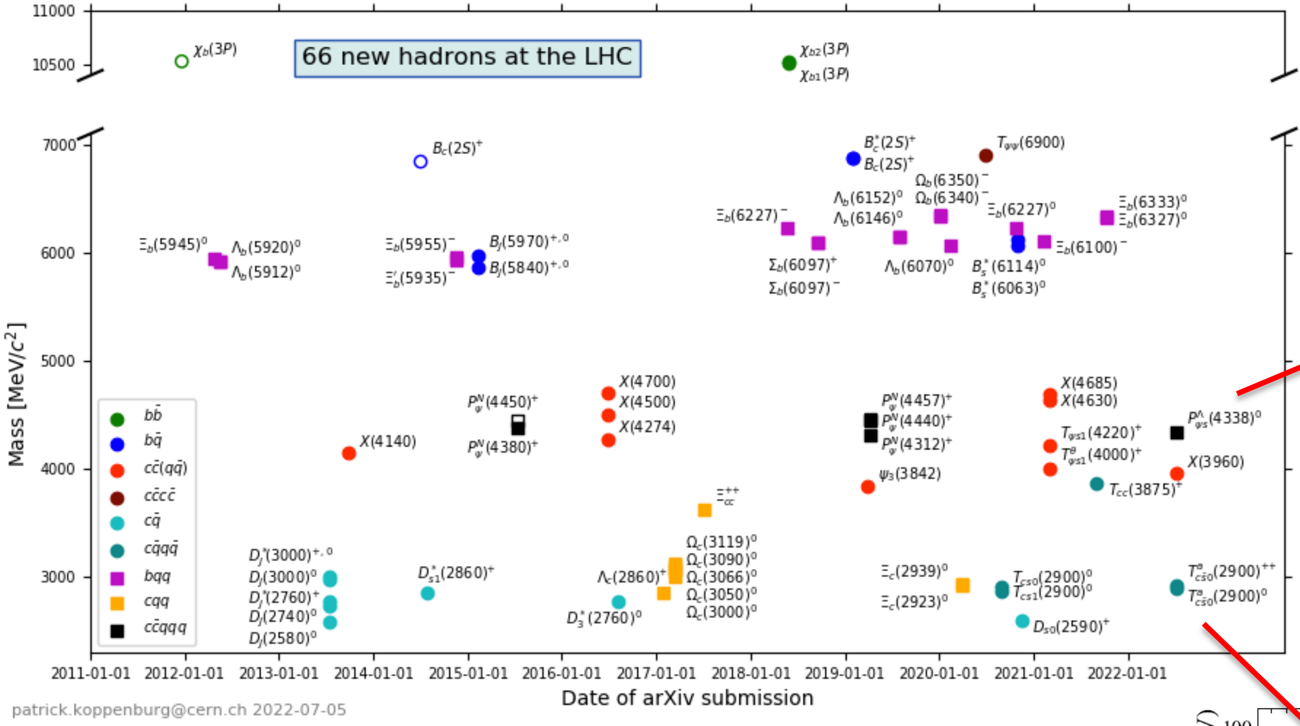
https://doi.org/10.1103/PhysRevLett.122.222001

Since then, many other tetra- and pentaquark candidates have been observed.

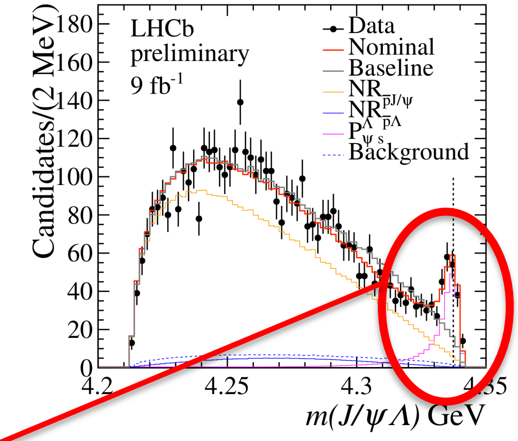
A new field opening up!

[The particle zoo]

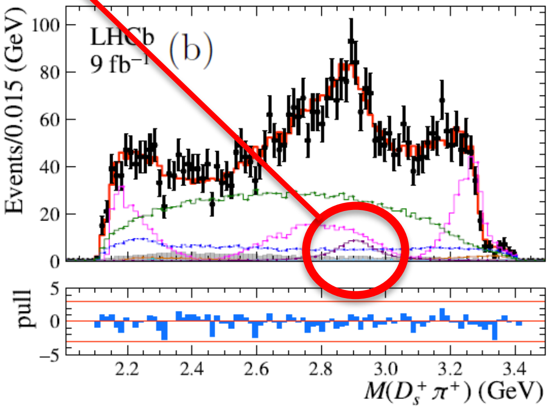
https://www.nikhef.nl/~pkoppenb/particles.html



patrick.koppenburg@cern.ch 2022-07-05



Latest arrivals:
https://indico.cern.ch/event/1176505/



The power of flavour

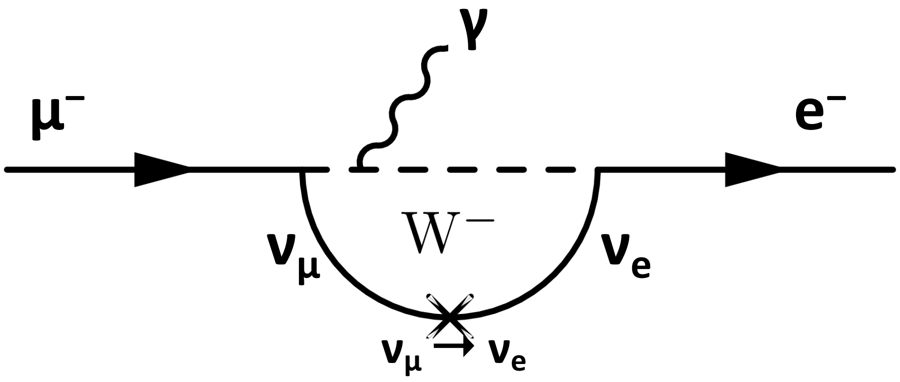
- Gain deeper understanding of the underlying **flavour structure** of the Standard Model (and beyond?)

- Sensitive to effects of new particles and forces beyond the standard model – **even particles too massive to be produced at the LHC**
(invisible in direct searches)

- May explain the ‘**matter dominance**’ of the universe – one of the big mysteries linking particle physics and cosmological observations
⇒ “CP violation”

Flavour as a probe of new physics

An example: search for $\mu \rightarrow e\gamma$

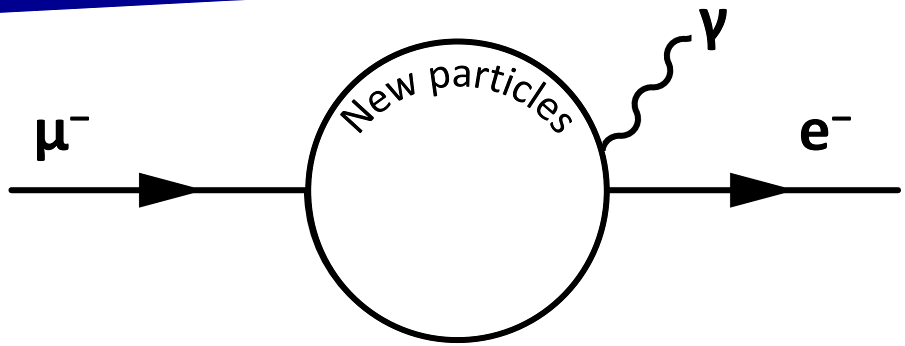


In the SM, almost forbidden – only allowed due to neutrino oscillations
⇒ Rate suppressed by $(m_\nu/M_W)^4$
⇒ $< 1/10^{50}$ muons decay this way!

Many new theories predict significant enhancements to rate – can be additional contributions from new particles "in the loop"

Flavour as a probe of new physics

An example: search for μ→eγ



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Observe μ→eγ ?

Yes: Discover new physics!
No: Place limits on masses and couplings of new particles

Flavour as a probe of new physics

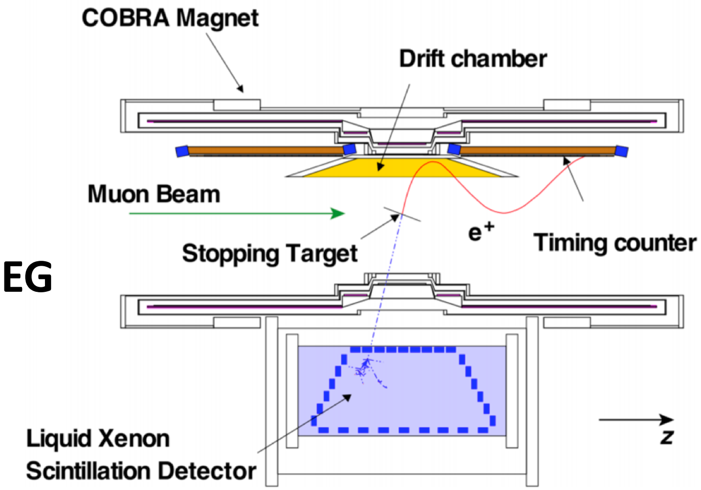
An example: search for $\mu \to e\gamma$

Best current measurements from MEG experiment at PSI facility

Deliver μ^+ beam onto plastic target, and search for back-to-back photon and positron

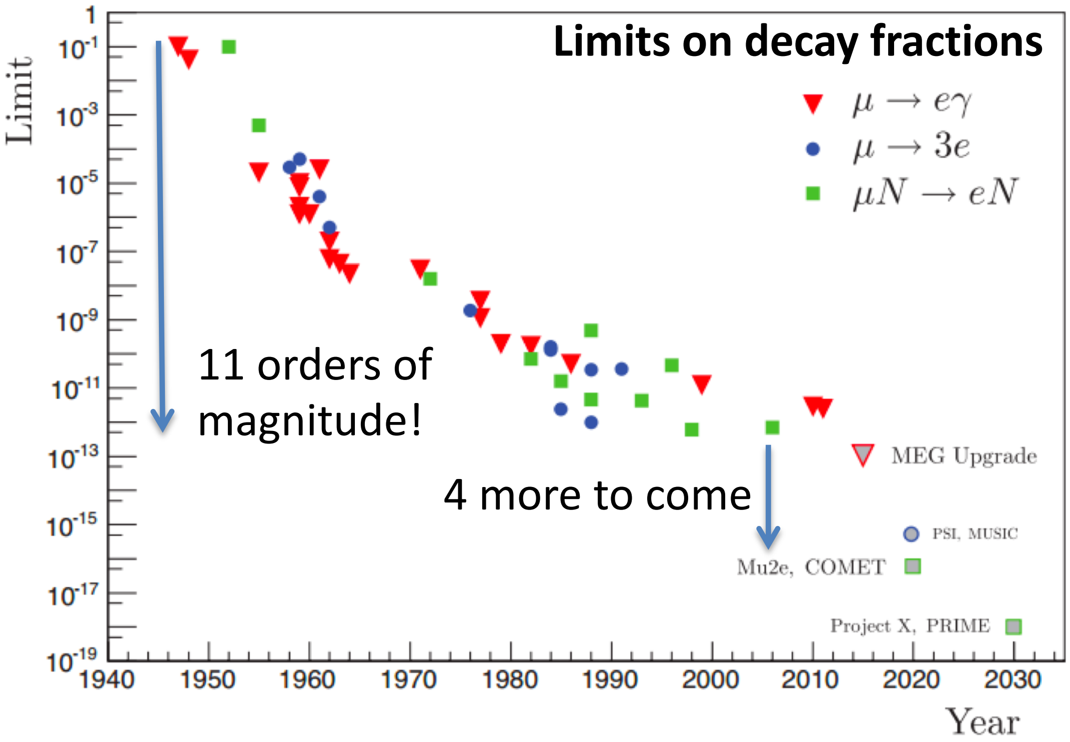
Huge background from $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$

MEG



https://doi.org/10.1016/j.physrep.2013.07.002

Limits on decay fractions



11 orders of magnitude!

4 more to come

Future planned experiments (Mu2e, Comet) will improve sensitivity by factor 10,000

Flavour as a probe of new physics

Lessons from history:

‘Indirect’ effects of new physics often appear before particles are directly discovered:

- GIM mechanism → predict charm quark existence **4 years** before discovery
- CP violation in kaons → prediction of **bottom** & **top** quarks
- B meson mixing → top quark **much more massive** than expected

Part II: Symmetries of nature

Symmetries in physics

Physical systems can exhibit both continuous and discrete symmetries

> *For every continuous symmetry there exists a corresponding conservation law*
>
> **Noether's theorem**

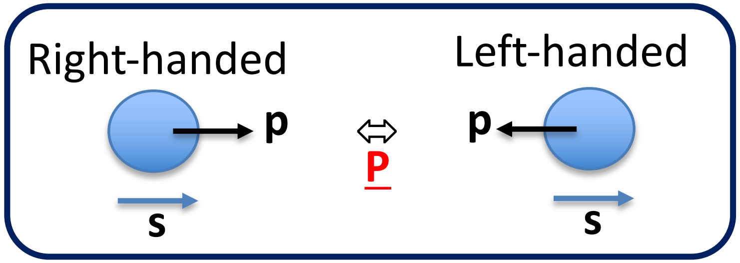
Laws of physics invariant under:		Conservation of:
Spatial translations	⟷	Momentum
Time translations	⟷	Energy
Rotations	⟷	Angular momentum

Emmy Noether
(1882-1935)

What about *discrete* symmetries?

⇒ It turns out that these are very important in particle physics!

Discrete symmetries



Parity (P): reflect all spatial points through origin

$x \Leftrightarrow -x \quad y \Leftrightarrow -y \quad z \Leftrightarrow -z$ ⇒ (polar) vectors change sign $\quad \mathbf{x} \Leftrightarrow -\mathbf{x} \quad \mathbf{p} \Leftrightarrow -\mathbf{p}$

⇒ axial vectors unchanged $\quad \mathbf{L} = \mathbf{x} \times \mathbf{p} \Leftrightarrow (-\mathbf{x}) \times (-\mathbf{p}) = \mathbf{L}$

Changes ‘handedness’ of particles with spin

Charge conjugation (C): transform all particles ⇔ antiparticles

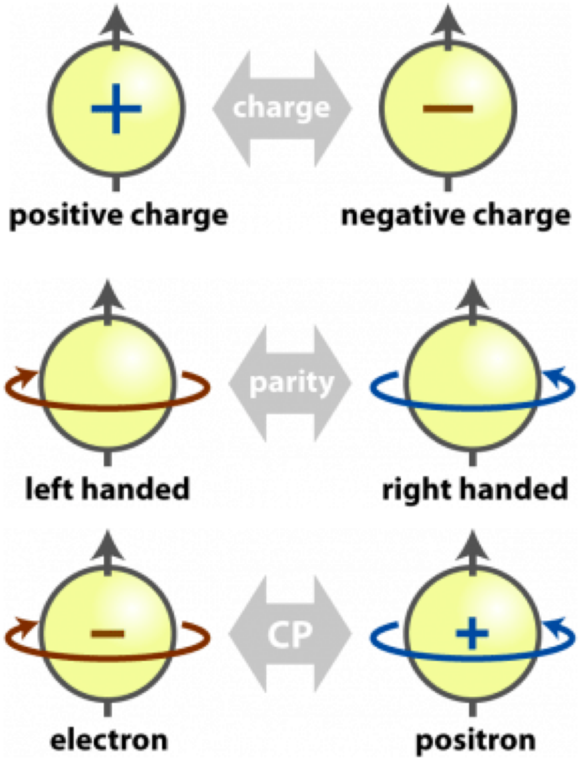
$e^- \Leftrightarrow e^+ \qquad K^- \Leftrightarrow K^+ \qquad \nu \Leftrightarrow \bar{\nu} \qquad \gamma \Leftrightarrow \gamma$

Time reversal (T): Reverse any motion in system

$t \Leftrightarrow -t \qquad \mathbf{p} \Leftrightarrow -\mathbf{p} \qquad \mathbf{x} \Leftrightarrow \mathbf{x} \qquad \mathbf{L} = \mathbf{x} \times \mathbf{p} \Leftrightarrow (\mathbf{x}) \times (-\mathbf{p}) = -\mathbf{L}$

CP violation: Some history

Flip Tanedo, Quantum Diaries



Can combine symmetries like operators, e.g.

CP: apply **P** operator then **C** operator on system

Left-handed particle ⇔ Right-handed antiparticle

Situation in 1950s: measurements indicate strong and EM interactions symmetric under both C and P.

What about weak interaction? – could C and/or P symmetries be violated?

The "θ-τ puzzle"…

Parity in the weak interaction

The "θ-τ puzzle"

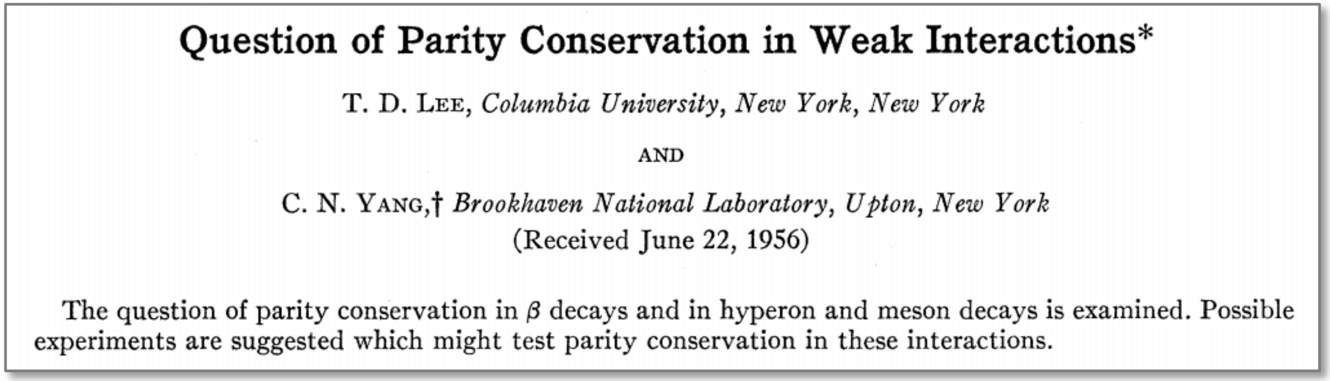
In 1950s, two new strange particles observed:

$$\left.\begin{array}{l}\theta^+ \rightarrow \pi^+\pi^0 \\ \tau^+ \rightarrow \pi^+\pi^+\pi^-\end{array}\right\}$$

2π and 3π states have **opposite parity** eigenvalues
but… θ,τ have **same masses, spins, lifetime**

Did nature give us two identical particles with opposite parity?

OR… **are θ and τ same particle? ("charged kaon", K$^+$)**
⇒ weak interaction violates parity conservation!



Question of Parity Conservation in Weak Interactions*

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

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

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

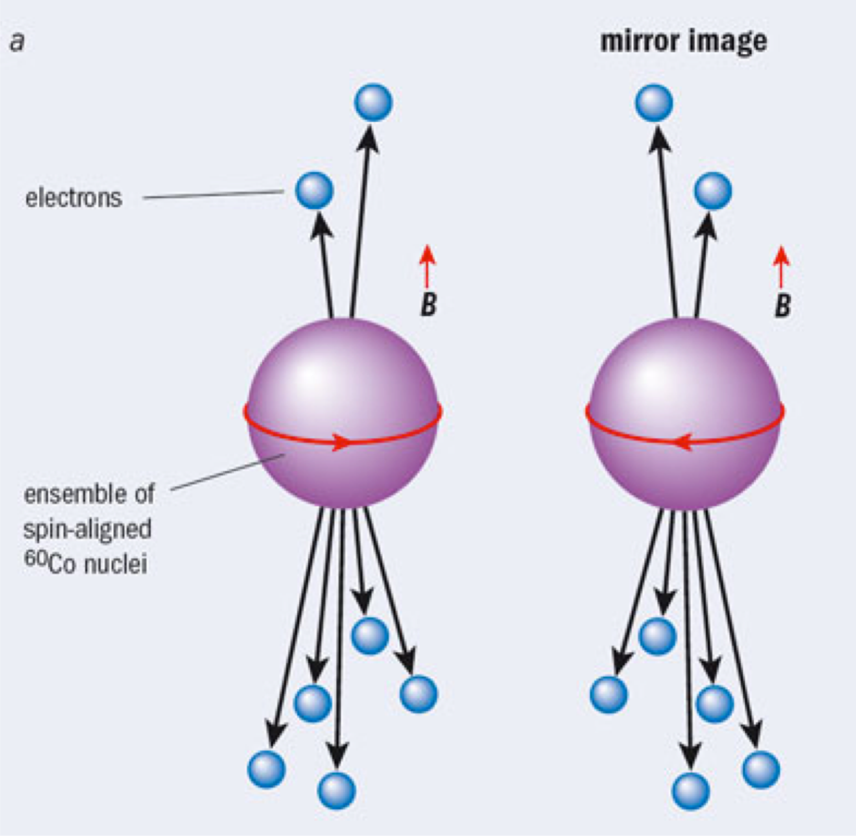
https://journals.aps.org/pr/abstract/10.1103/PhysRev.104.254

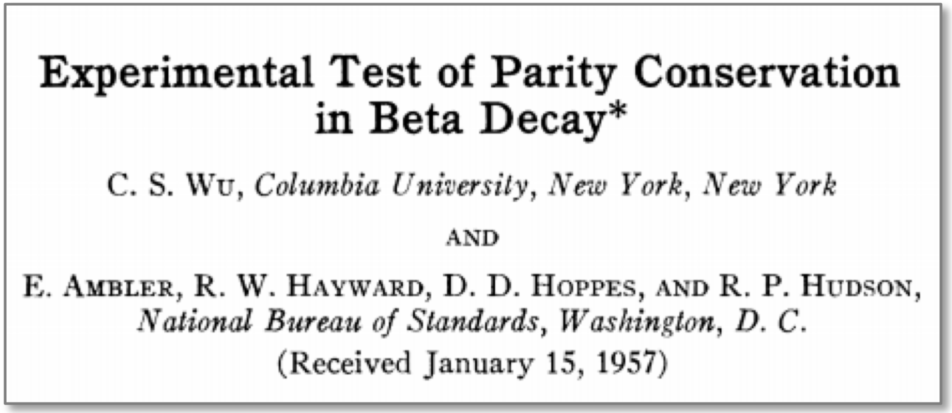
Lee and Yang propose experimental tests ⇒
Does weak interaction differentiate right from left?


1957

Parity is violated in the weak interaction!

Discovery of P-violation





Experimental Test of Parity Conservation in Beta Decay*

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

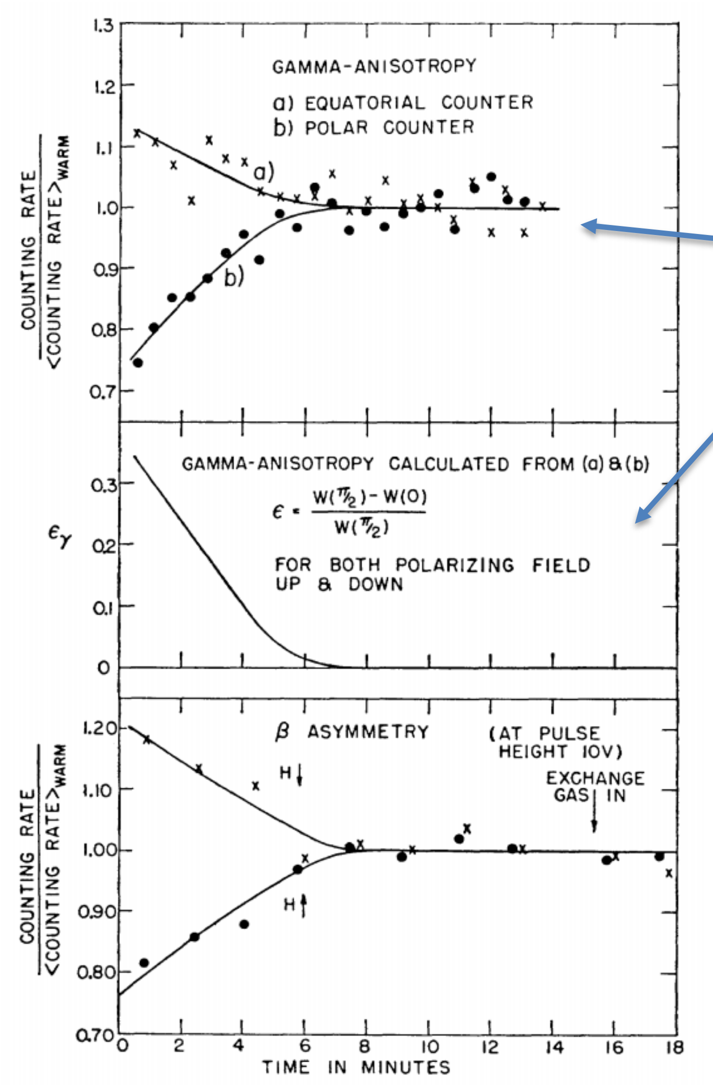
AND

E. AMBLER, R. W. HAYWARD, D. D. HOPPES, AND R. P. HUDSON,
National Bureau of Standards, Washington, D. C.
(Received January 15, 1957)

https://journals.aps.org/pr/abstract/10.1103/PhysRev.105.1413

Wu et al discovered P-violation in β-decays of Co^{60}
(use polarized nuclei to set ‘axis’ and look for preferred direction of electrons – need to cool to 0.01K)

Parity violation: Wu's results (1957)



Decaying neutron has known spin orientation (relaxes over time as system warms up)

(Use associated gamma decays to track polarization of system)

Conservation of angular momentum sets emission direction of left and right-handed particles

⇒ Electrons emitted in one direction only

– Consistent with 100% being left-handed

P and C violated, what about CP?

We now know that β-decays **maximally violate** P-symmetry
⇒ No right-handed neutrinos

They also **maximally violate** C-symmetry
⇒ No left-handed antineutrinos

But… product of **CP** operators apparently conserved
⇒ same for left-handed neutrinos & right-handed antineutrinos
(Landau, 1957) https://www.sciencedirect.com/science/article/pii/0029558257900615

Or is it? …

CP symmetry & neutral kaon system

$K^0 : \bar{s}d$

$\bar{K}^0 : s\bar{d}$

Ground-state: $S = 0$, $L = 0$

Parity (P): $\mathbf{P}|K^0\rangle = -|K^0\rangle$ $\mathbf{P}|\bar{K}^0\rangle = -|\bar{K}^0\rangle$

$q\bar{q}$ has intrinsic parity $(-1)^{L+1}$

Charge conjugation (C):

$\mathbf{C}|K^0\rangle = -|\bar{K}^0\rangle$ $\mathbf{C}|\bar{K}^0\rangle = -|K^0\rangle$

CP: $\mathbf{CP}|K^0\rangle = |\bar{K}^0\rangle$ $\mathbf{CP}|\bar{K}^0\rangle = |K^0\rangle$

⇒ K^0 and $\bar{K}^0$ are not CP-eigenstates.

CP symmetry & neutral kaon system

We can construct CP eigenstates as superposition of flavor eigenstates

$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)$

$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$

$\mathbf{CP}|K_1\rangle = +1|K_1\rangle$ **CP-even**

$\mathbf{CP}|K_2\rangle = -1|K_2\rangle$ **CP-odd**

CP symmetry & neutral kaon system

If CP is conserved, it commutes with Hamiltonian
⇒ **CP eigenstates = mass eigenstates**
(well-defined masses and lifetimes)

$|K_1\rangle = |K_S^0\rangle$ $|K_2\rangle = |K_L^0\rangle$
"K short" "K long"

Finally, note: $\mathbf{CP}|\pi^+\pi^-\rangle = +1|\pi^+\pi^-\rangle$ and $\mathbf{CP}|\pi^+\pi^-\pi^0\rangle = -1|\pi^+\pi^-\pi^0\rangle$

⇒ Expect $K_S^0 \rightarrow \pi^+\pi^-$ More phase-space: shorter lifetime (0.089ns)
⇒ discovered in 1947 (Rochester & Butler)

$K_L^0 \rightarrow \pi^+\pi^-\pi^0$ Less phase-space: longer lifetime (51.7 ns)
⇒ discovered in 1956 (Gellman)

“Cronin & Fitch” experiment

Designed to investigate ‘regeneration’ effects in K_L^0 (=K_2) beam

Exploit lifetime difference:
All K_1 decay quickly

Pure K^0 beam
(flavor eigenstate)

$\xrightarrow{\text{wait}}$

Pure K_2 beam
(CP eigenstate)

$$|K^0\rangle = \frac{1}{\sqrt{2}}\big(|K_1\rangle + |K_2\rangle\big)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\big(|K^0\rangle - |\overline{K}^0\rangle\big)$$

Now insert some material **M** into beam:
Matter, not antimatter

$K^0 + p \rightarrow K^+ + n$ (amplitude f)

$\overline{K}^0 + n \rightarrow K^- + p$ (amplitude $\overline{f}$)

$$\mathbf{M}|K_2\rangle = \frac{1}{\sqrt{2}}\big(f|K^0\rangle - \overline{f}|\overline{K}^0\rangle\big) = \frac{1}{2}(f - \overline{f})|K_1\rangle + \frac{1}{2}(f + \overline{f})|K_2\rangle$$

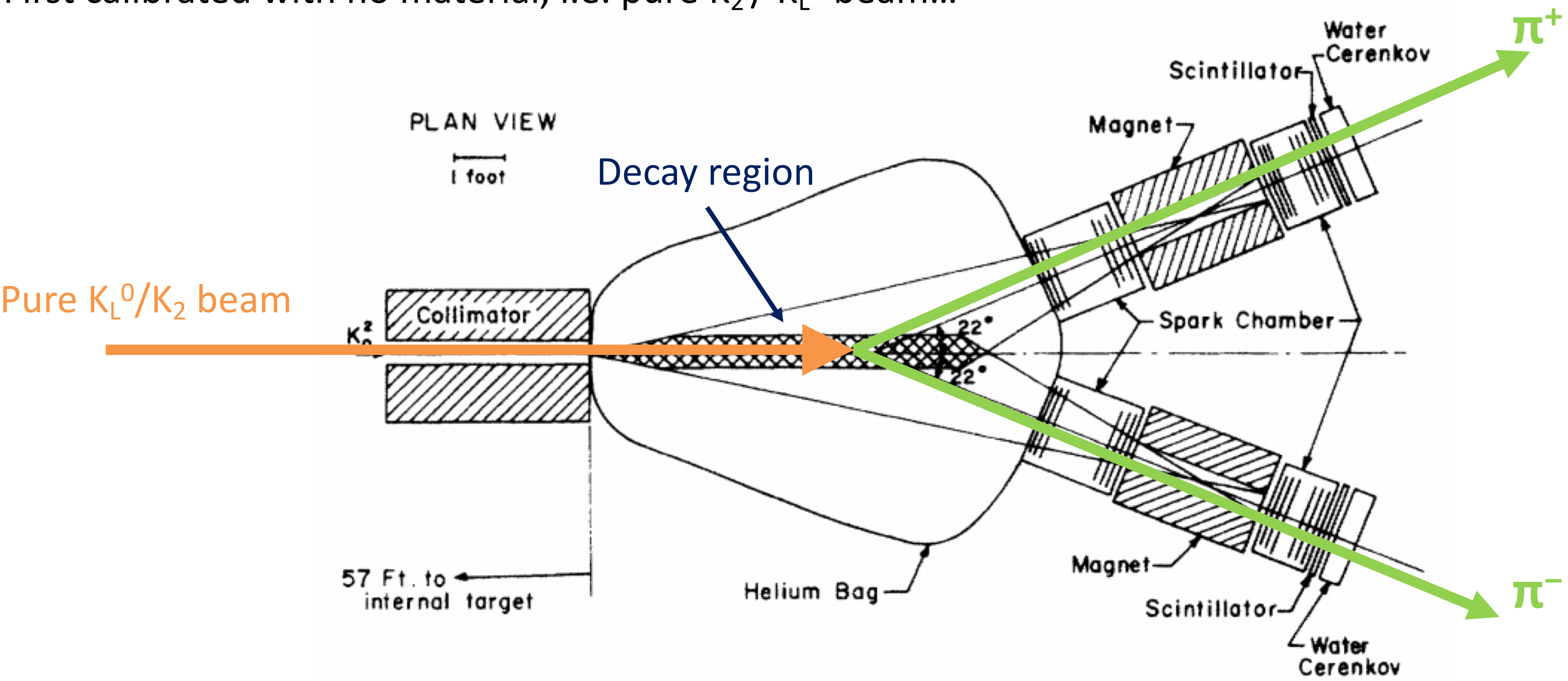
⇒ K_1 (=K_S^0) is regenerated

“Cronin & Fitch” experiment

Look for kaon decays to $\pi^+\pi^-$, and measure momenta

Plan to insert material to regenerate K_1 / K_S^0

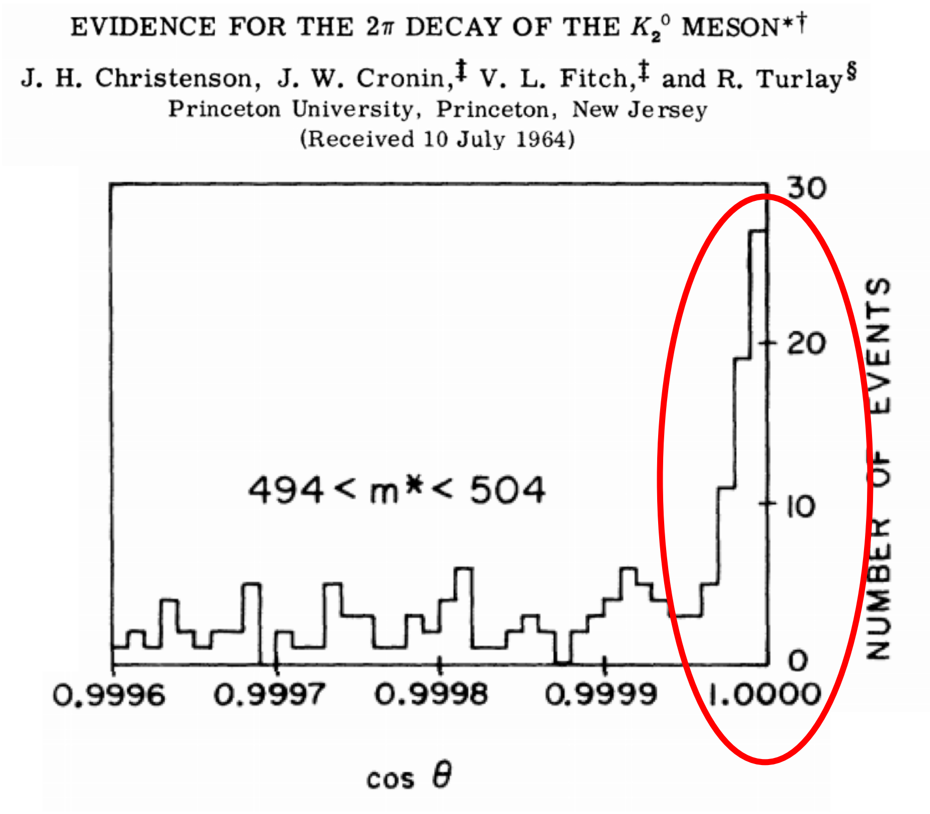
First calibrated with no material, i.e. pure K_2 / K_L^0 beam…



https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.13.138

CP is violated!

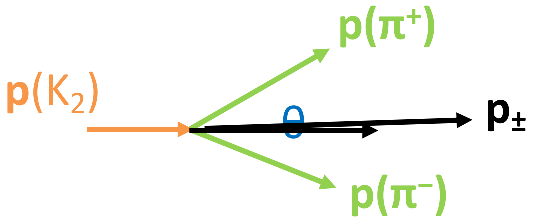
Measure pion momenta ⇒ compute angle between p(K_2) and $\mathbf{p}_\pm$ = p(π^+) + p(π^-)



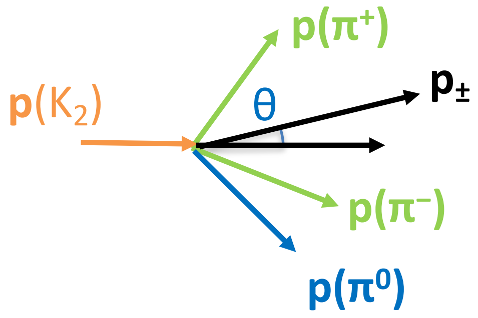
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.13.138



$K_2 \rightarrow 2\pi$:
θ = 0°
⇒ cos(θ) = 1



$K_2 \rightarrow 3\pi$:
θ ≠ 180°
⇒ cos(θ) ≠ 1

- Clear peak observed at cos(θ) = 1
- CP violating process $K_2 \rightarrow \pi^+\pi^-$
- 0.2% effect (1/500 K_2 decays)

What does this mean for kaons?

We've been assuming CP symmetry so far… Now we know that this is not the case.

CP eigenstates ≠ mass eigenstates ~~$|K_S^0\rangle = |K_1\rangle$ $|K_L^0\rangle = |K_2\rangle$~~

But – CP violation is small (0.2%), so this is a good first-order approximation

$$|K_S^0\rangle = \frac{1}{\sqrt{(1+|\varepsilon|^2)}}\left(|K_1\rangle + \varepsilon|K_2\rangle\right) \qquad |K_L^0\rangle = \frac{1}{\sqrt{(1+|\varepsilon|^2)}}\left(\varepsilon|K_1\rangle + |K_2\rangle\right)$$

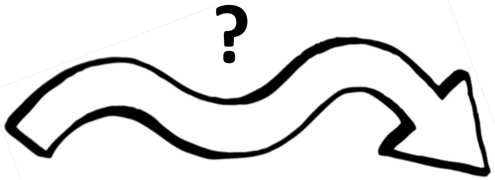
This is the part which decays to $\pi^+\pi^-$

Where **ε = 0.2%** quantifies the level of CP violation

What does this mean for the Universe?

Our very existence is a puzzle…

Big bang ⇒
matter and antimatter
created equally



Current universe ⇒
dominated by matter

What happened?
Where did the antimatter go?

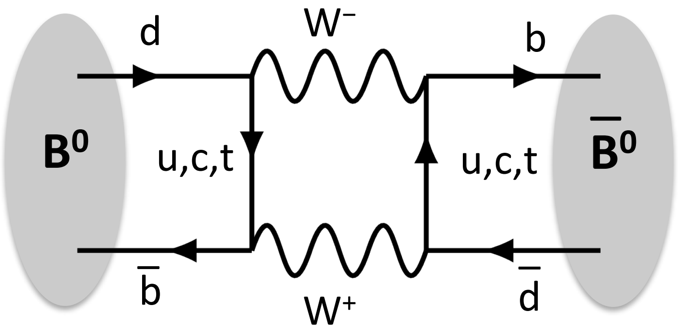
Sakharov (1967) proposed three conditions necessary to explain matter dominance:

- **Baryon number violation** ⇒ No evidence (proton lifetime > 2.1×10^{29} years)
- **C and CP violation** ⇒ Discovered, but far too small to explain matter dominance
- **State out of thermal equilibrium** ⇒ Plausible scenarios

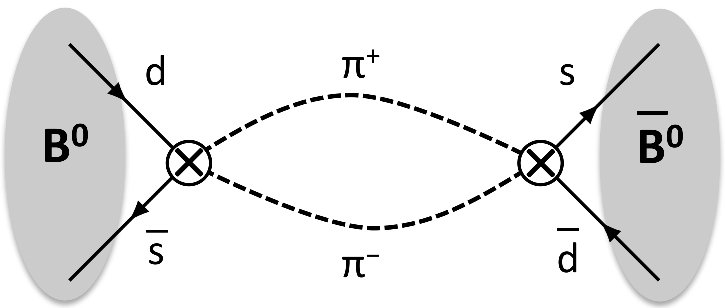
https://ufn.ru/en/articles/1991/5/h/

Part III: Neutral meson mixing

Meson mixing: the ultimate loop experiment



"short-distance"
(=virtual particle exchange)



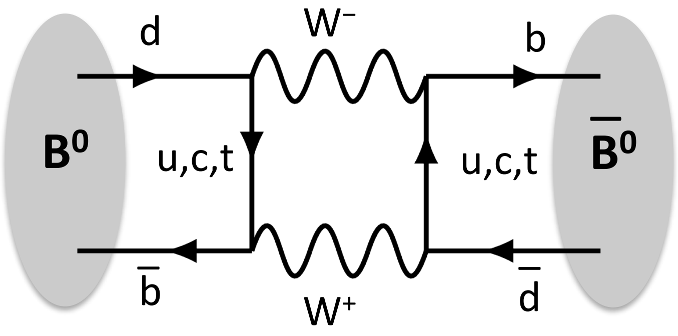
"long-distance"
(=real particle exchange)

Four possible mesons…

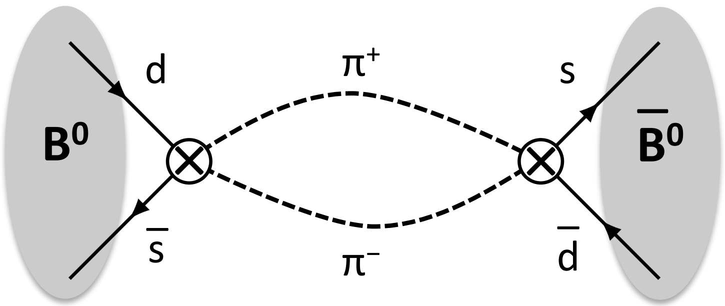
Any neutral meson
where $M \neq \overline{M}$

K^0 (ds)
B^0 (db)
B_s^0 (sb)
D^0 (uc) ← only one with up-type quarks

Meson mixing: the ultimate loop experiment



"short-distance"
(=virtual particle exchange)



"long-distance"
(=real particle exchange)

Time evolution of particle given by Schrödinger-like equation:

$$i\frac{\partial}{\partial t}|\Psi\rangle = H|\Psi\rangle = (M - \frac{i}{2}\Gamma)|\Psi\rangle$$

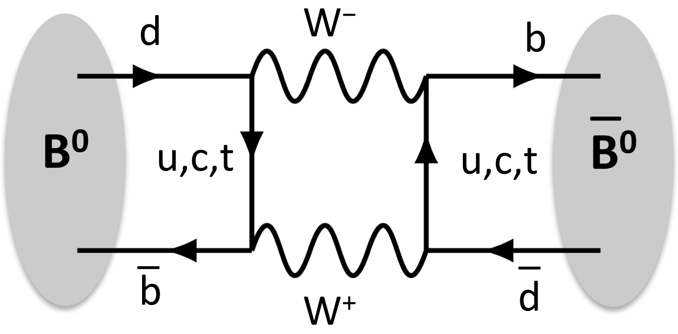
mass

(real part of potential
– conserves probability)

decay rate (=1/τ)

(imaginary part of potential
– allows decays to be included)

Meson mixing: the ultimate loop experiment



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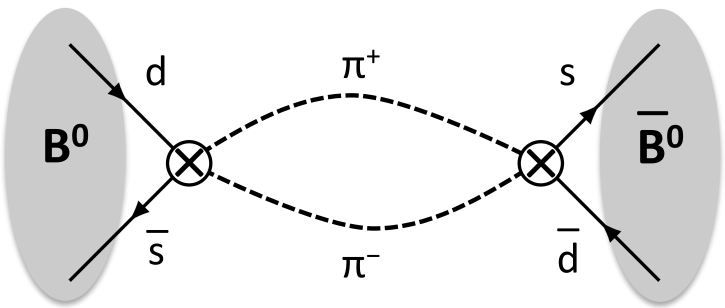


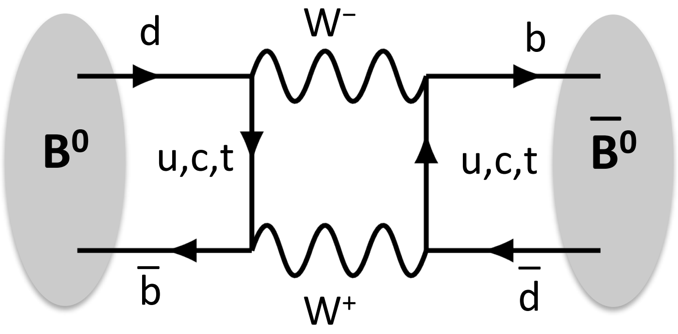
"long-distance"
(=real particle exchange)

For two-meson system, replace M,Γ with 2×2 matrices:

$$|\Psi\rangle = \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & 0 \\ 0 & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

Meson mixing: the ultimate loop experiment



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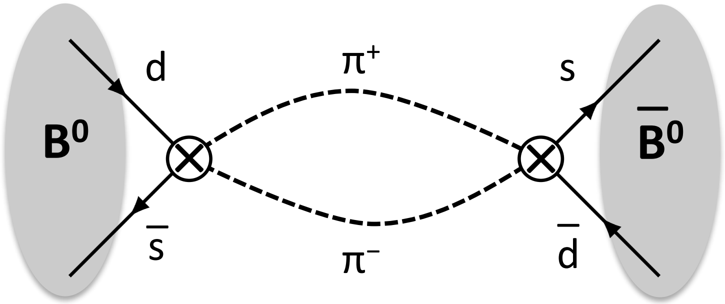
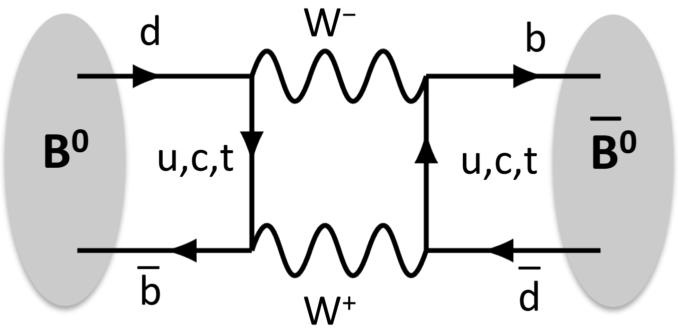


"long-distance"
(=real particle exchange)

"CPT theorem": $M_{11} = M_{22} = M$
$\Gamma_{11} = \Gamma_{22} = \Gamma$

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & 0 \\ 0 & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

Meson mixing: the ultimate loop experiment



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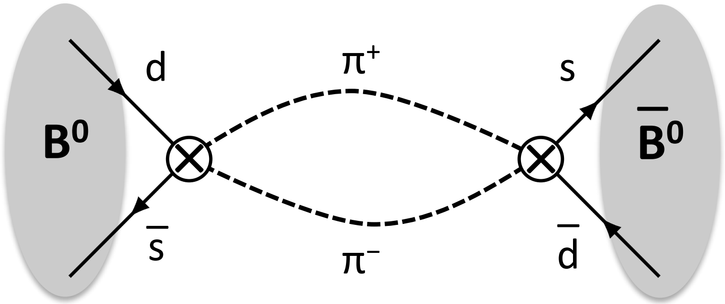


"long-distance"
(=real particle exchange)

But… particles mix between states by above processes… need off-diagonal elements

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

⇒ Flavour states are not eigenstates of Hamiltonian – no well defined mass or lifetime

Meson mixing: time dependence

⇒ Flavour states are not eigenstates of Hamiltonian…

Orthogonality

But… can express mass eigenstates in flavour basis:

$$\begin{aligned} |B_H\rangle &= p|B^0\rangle + q|\bar{B}^0\rangle \\ |B_L\rangle &= p|B^0\rangle - q|\bar{B}^0\rangle \end{aligned}$$

Define parameters:

$$\Delta m = m_H - m_L$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

Heavy and light eigenstates then have energies:

$$\begin{aligned} E_H &= M + \tfrac{1}{2}\Delta m + \tfrac{1}{2}i(\Gamma - \Delta\Gamma) \\ E_L &= M - \tfrac{1}{2}\Delta m + \tfrac{1}{2}i(\Gamma + \Delta\Gamma) \end{aligned}$$

So we can write time-dependent solutions for stationary states:

$$|B(t)\rangle = |B(0)\rangle\, e^{-iEt}$$

$$\begin{aligned} |B_H(t)\rangle &= |B_H\rangle e^{-i(M+\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma-\Delta\Gamma))t} \\ |B_L(t)\rangle &= |B_L\rangle e^{-i(M-\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma+\Delta\Gamma))t} \end{aligned}$$

Meson mixing: time dependence

We care about time-dependence of flavor states B^0 and $\bar{B}^0$. Can determine this from:

$$|B_H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$
$$|B_L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

and

$$\begin{aligned} |B_H(t)\rangle &= |B_H\rangle e^{-i(M+\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma-\Delta\Gamma))t} \\ |B_L(t)\rangle &= |B_L\rangle e^{-i(M-\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma+\Delta\Gamma))t} \end{aligned}$$

With a bit of algebra, we get:

B^0 at t=0
$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \left(\frac{q}{p}\right) g_-(t)|\bar{B}^0\rangle$$

$\bar{B}^0$ at t=0
$$|\bar{B}^0(t)\rangle = \left(\frac{p}{q}\right) g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle$$

where $g_\pm(t)$ gives time dependence:

$$\begin{aligned} g_+(t) &= e^{-imt}e^{-\Gamma/2t}\left[\cosh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} - i\sinh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right], \\ g_-(t) &= e^{-imt}e^{-\Gamma/2t}\left[-\sinh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} + i\cosh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right] \end{aligned}$$

Meson mixing: time dependence

Take the simple case:

- We identify the production flavor of the meson as B^0
- What is the probability of observing the meson as $\bar{B}^0$ as a function of time?

$$\mathbf{P(B^0 \rightarrow \bar{B}^0) = |\langle \bar{B}^0(t)|B^0\rangle|^2}$$

$$\Rightarrow \quad P(B^0 \rightarrow \bar{B}^0) \;=\; |g_+(t)\underbrace{\cancel{\langle \bar{B}^0|B^0\rangle}}_{\substack{= 0 \\ \text{(}\underline{\text{ortho}}\text{normal basis)}}} + (p/q)^* g_-(t)^* \underbrace{\langle B^0|B^0\rangle}_{\substack{= 1 \\ \text{(ortho}\underline{\text{normal}}\text{ basis)}}}|^2$$

Plug in $g_-(t)$ from last slide

$$= \quad |p/q|^2|g_-(t)|^2$$

$$= \quad \tfrac{1}{2}\,|p/q|^2\,\mathbf{e^{-\Gamma t}}\left[\cosh(\Delta\Gamma t/2) - \cos(\Delta m t)\right]$$

Exponential decay with lifetime $1/\Gamma$

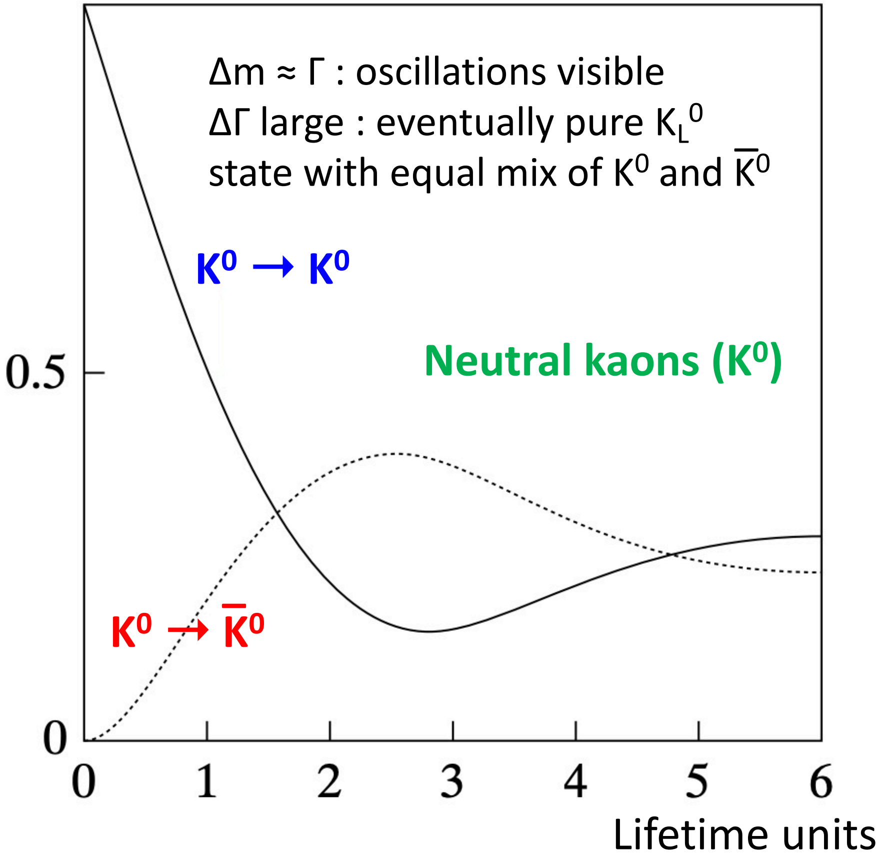
+ive sign if meson doesn't oscillate

Oscillation with angular frequency Δm

Meson mixing: four different systems

K^0 mixing

- Discovered implicitly in 1950s
  (K_L^0 and K_S^0 clearly different particles)



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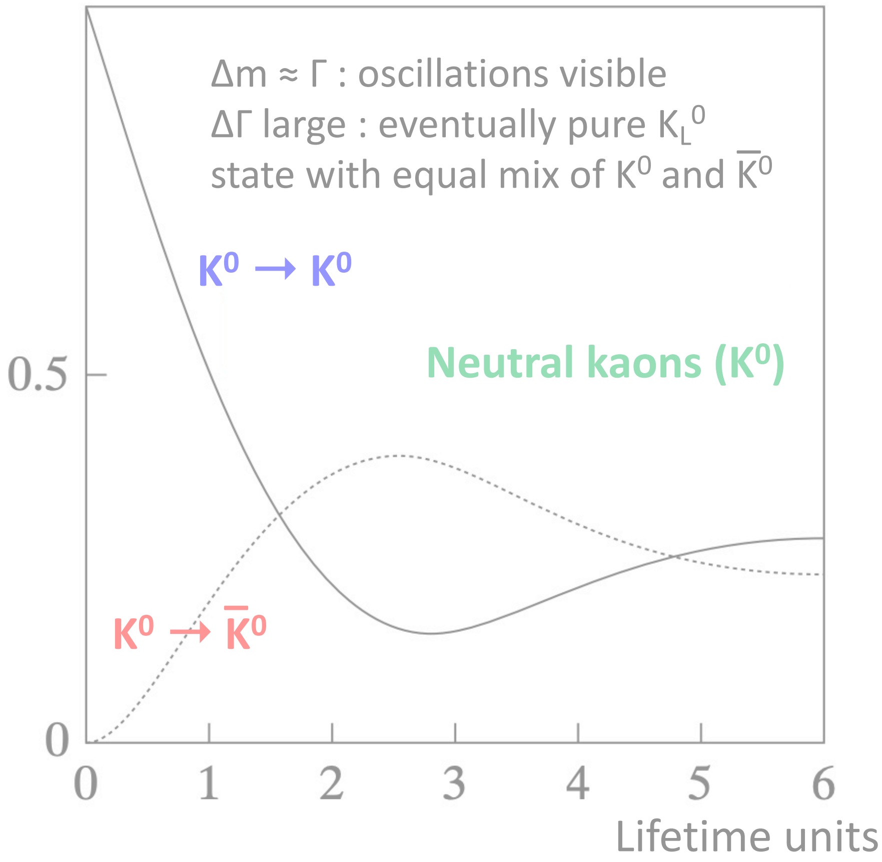
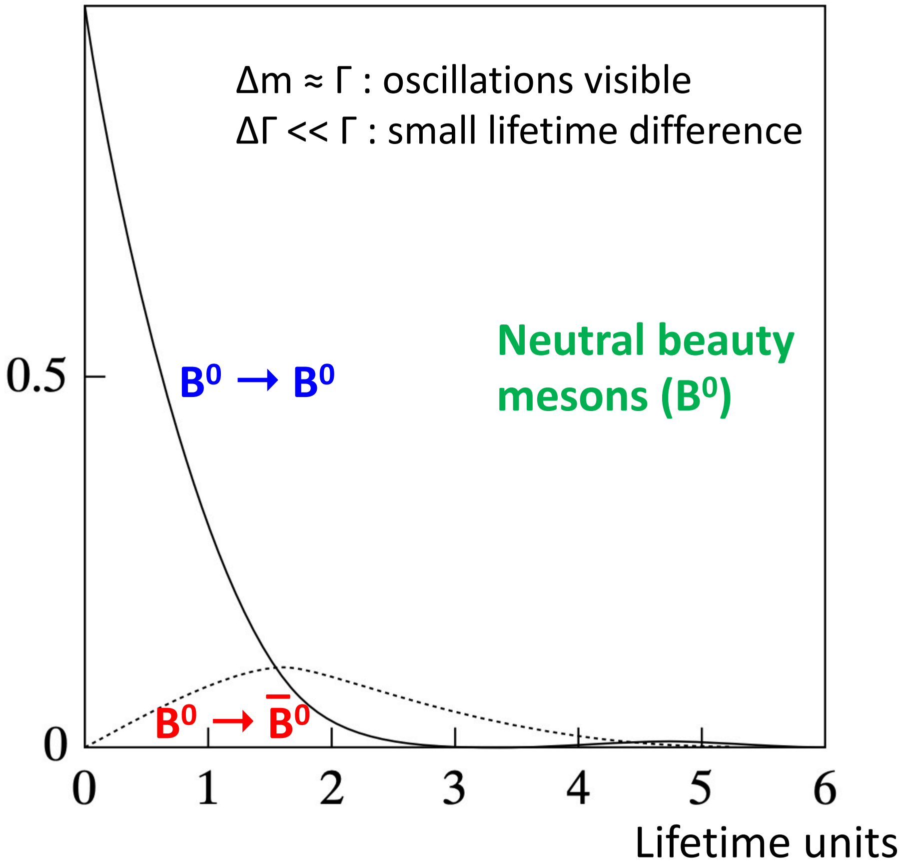


$\Delta m \approx \Gamma$: oscillations visible
$\Delta\Gamma$ large : eventually pure K_L^0 state with equal mix of K^0 and $\overline{K}^0$

B^0 mixing

- Discovered in 1987 by Argus experiment

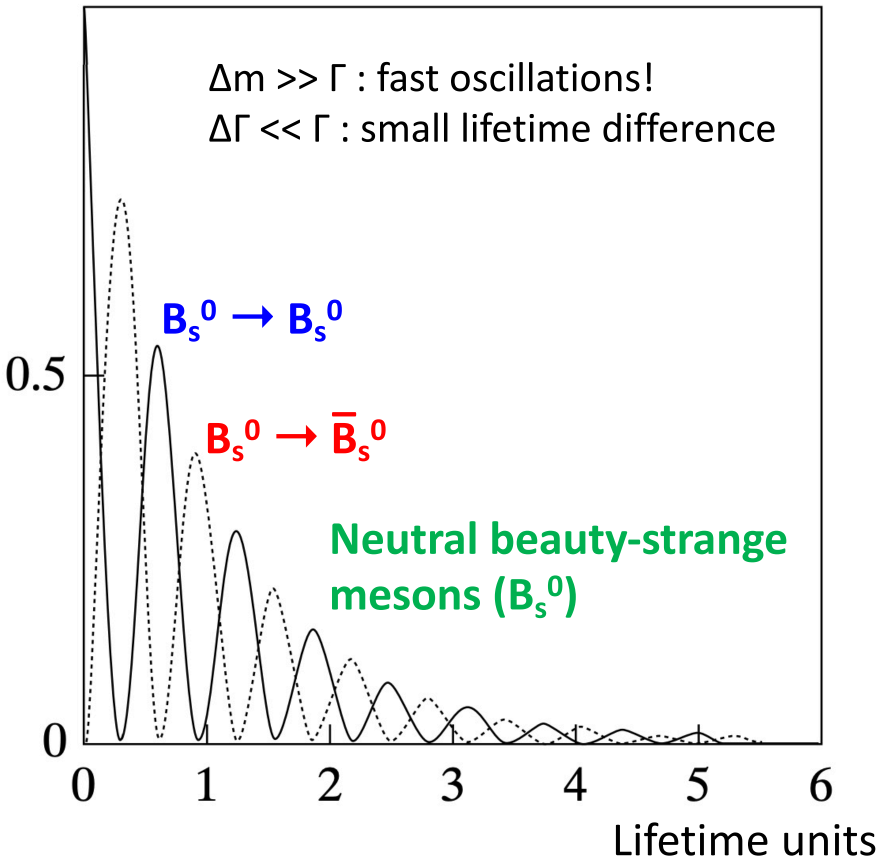


$\Delta m \approx \Gamma$: oscillations visible
$\Delta\Gamma << \Gamma$: small lifetime difference

Meson mixing: four different systems

B_s^0 mixing

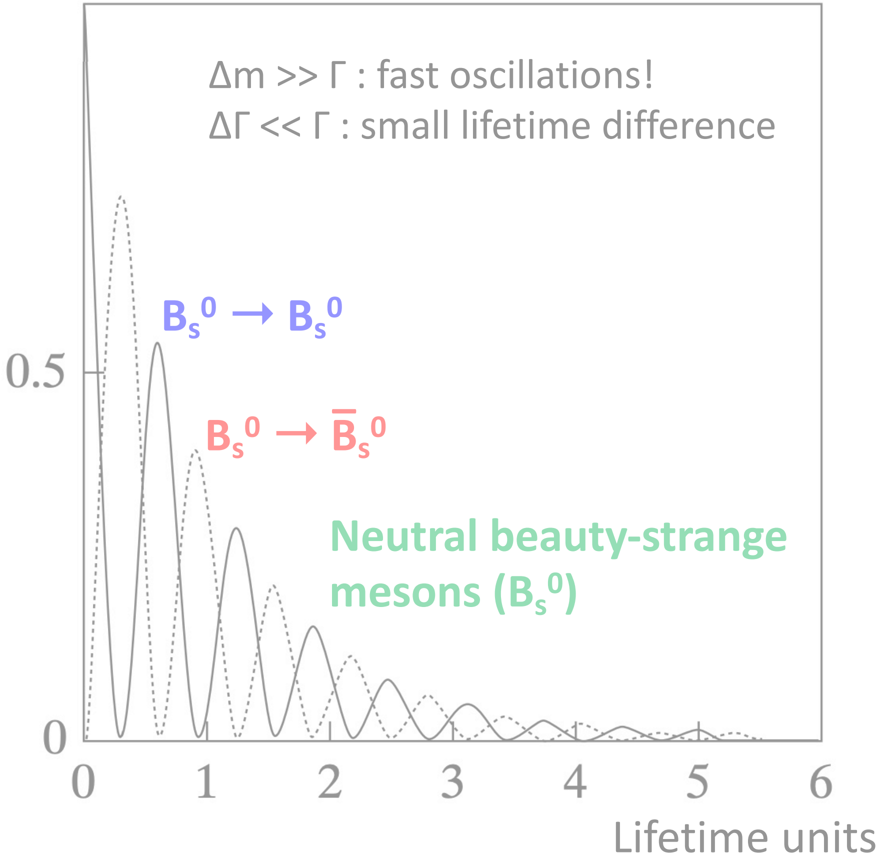
- Discovered in 2006 by CDF experiment



Meson mixing: four different systems

B_s^0 mixing

- Discovered in 2006 by CDF experiment



Δm >> Γ : fast oscillations!
ΔΓ << Γ : small lifetime difference

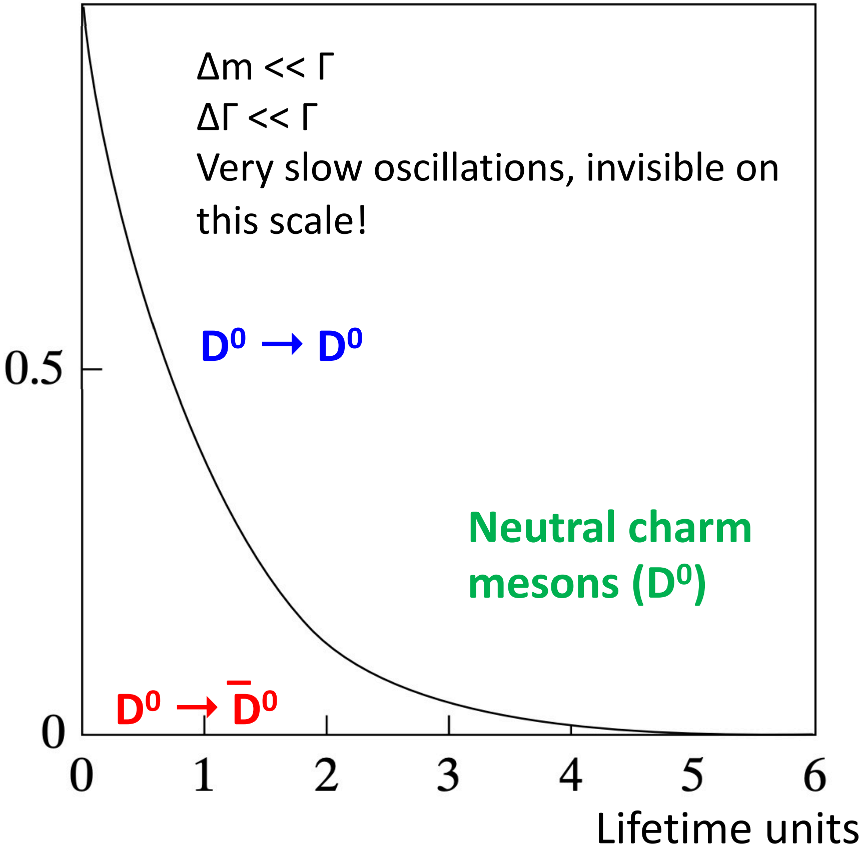
$B_s^0 \rightarrow B_s^0$

$B_s^0 \rightarrow \bar{B}_s^0$

Neutral beauty-strange mesons (B_s^0)

D^0 mixing

- ΔΓ ≠ 0 discovered by Belle/Babar/LHCb in 2007-2013
- **In 2021**: Δm measured >5σ from zero



Δm << Γ
ΔΓ << Γ
Very slow oscillations, invisible on this scale!

$D^0 \rightarrow D^0$

$D^0 \rightarrow \bar{D}^0$

Neutral charm mesons (D^0)

Meson mixing: kaon experiments

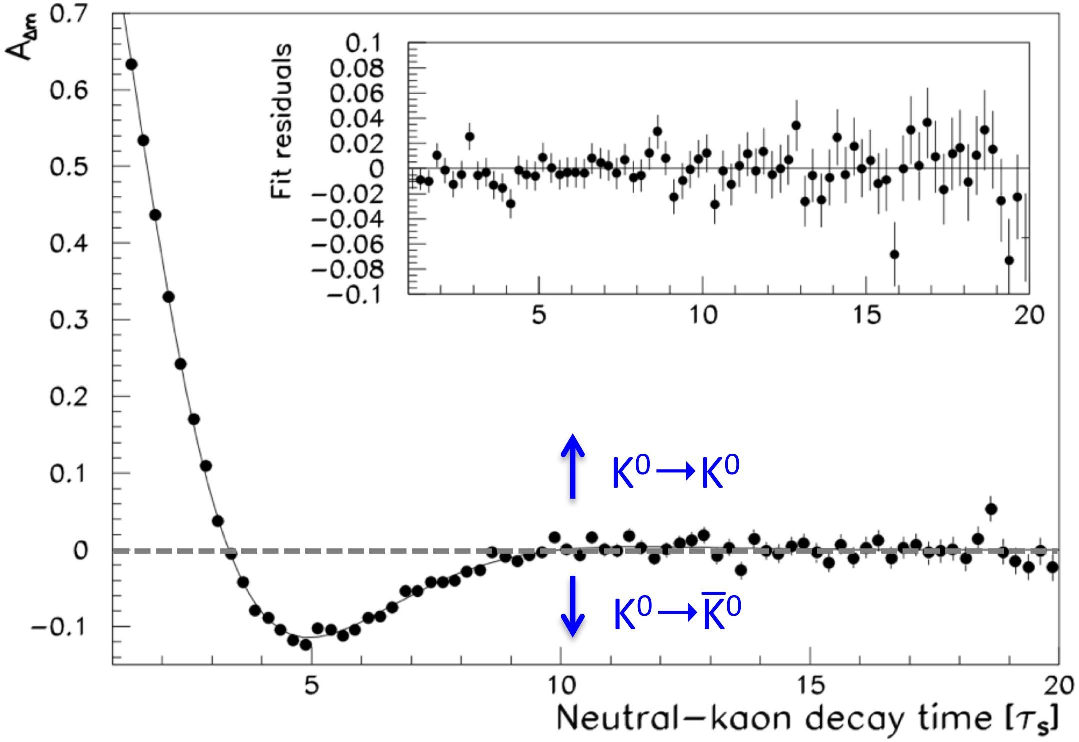
Production: $p\bar{p} \to K^0\pi^+\mathbf{K^-}$ ($\bar{K}^0\pi^-\mathbf{K^+}$)

Decay (e.g.): $K^0 \to \pi^-\mathbf{e^+}\nu_e$

Identify final and initial kaon flavour states

CPLEAR Experiment
(results from 1998)

http://weblib.cern.ch/record/368703



At long decay times, only K_L^0 remains - equal probability to decay as K^0 or $\bar{K}^0$

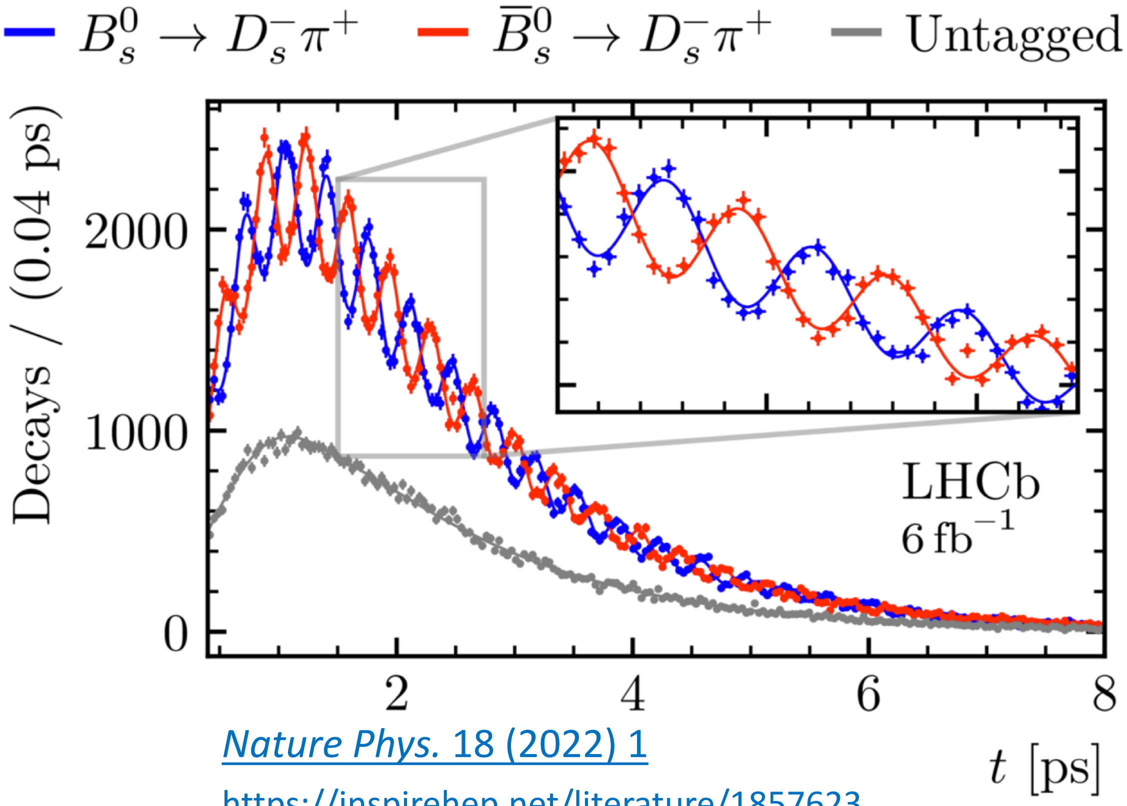
Meson mixing: beauty experiments

Same principles used for studies of B^0 and B_s^0 mixing
⇒ need to ‘tag’ flavour at production and decay

$\Delta m_s = (17.7656 \pm 0.0057)\ \mathrm{ps}^{-1}$
(0.03% precision!)

B_s^0 case special due to very fast oscillations – need detector with very precise time reconstruction

LHCb designed to have excellent time resolution
⇒ could have seen oscillations up to $\Delta m_s = 60\mathrm{ps}^{-1}$

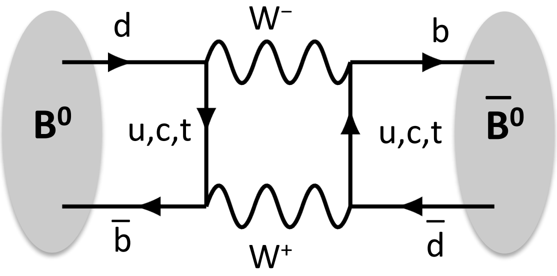


Nature Phys. 18 (2022) 1
https://inspirehep.net/literature/1857623

Δm and ΔΓ in the SM (and beyond)

Δm dictated by short-distance amplitude

⇒ depends on CKM matrix elements and quark masses
Sets the oscillation frequency



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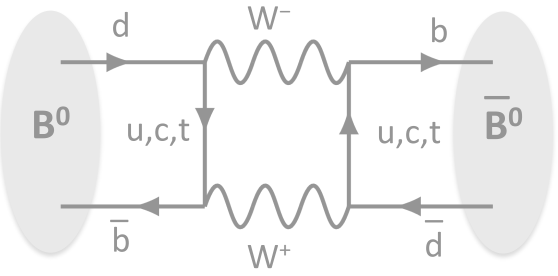


ΔΓ value set by allowed and forbidden decays for mass (≈CP) states

⇒ e.g. ΔΓ is very large for kaons since
$K_L^0 \to \pi\pi$ channel highly suppressed

$$\begin{aligned} K^0 &\to \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0 \\ \overline{K^0} &\to \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0 \end{aligned}$$

$$\begin{aligned} K^0 &\to \mu^-\mu^+,\ e^-e^+ \\ \overline{K^0} &\to \mu^+\mu^-,\ e^+e^- \end{aligned}$$

$$\begin{aligned} K^0 &\to \pi^-\mu^+\nu_\mu,\ \pi^-e^+\nu_e \\ \overline{K^0} &\to \pi^+\mu^-\overline{\nu_\mu},\ \pi^+e^-\overline{\nu_e} \end{aligned}$$

Outlook: CP violation and the SM

The standard model does allow for CP violation in quark and lepton sectors

However, standard model sources of CP violation cannot explain the matter dominance of the universe

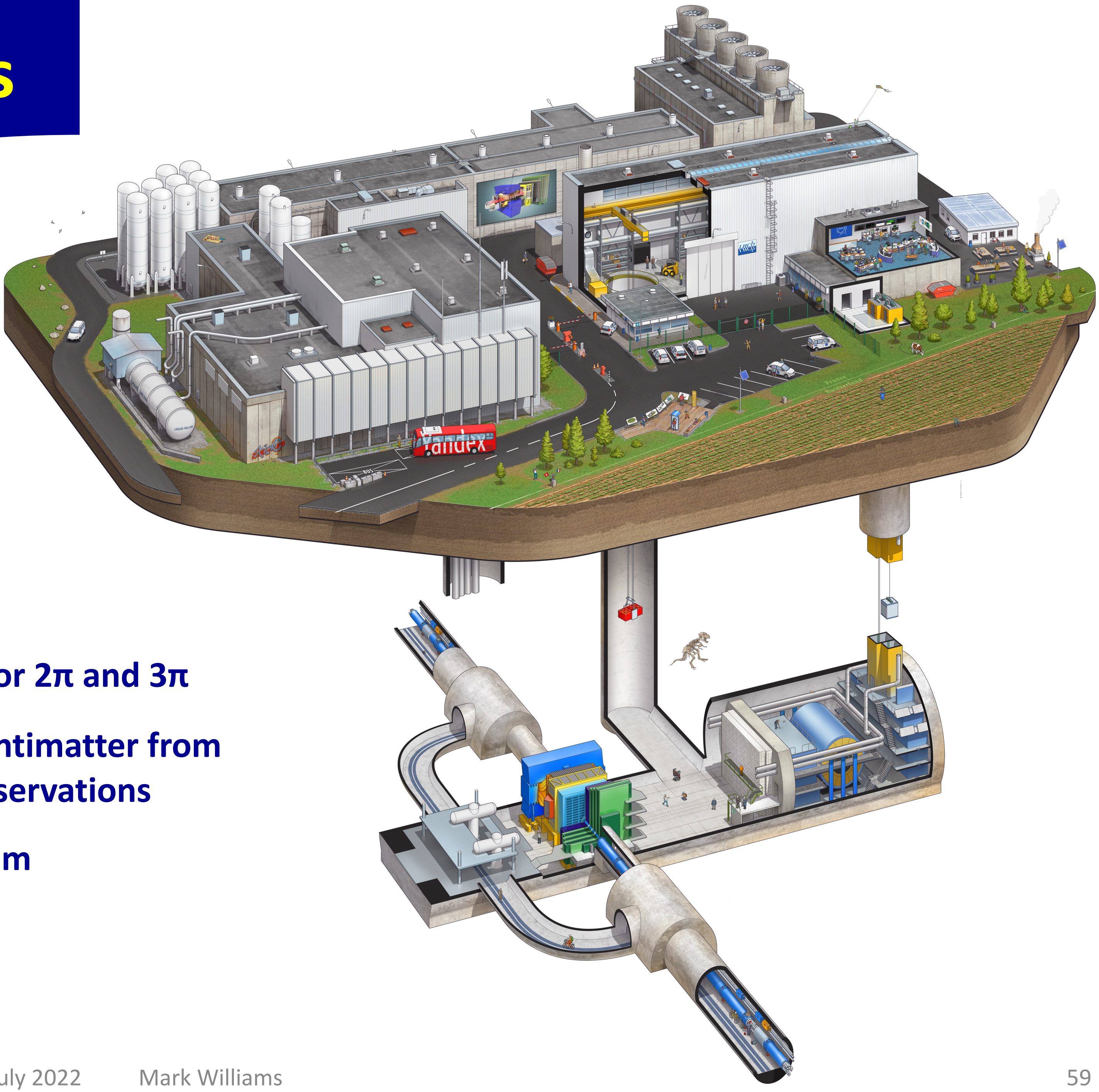
Why? Essentially because the SM is a low-energy theory, and the quarks and leptons are light. In the high energies of the early universe any CP-violating transitions would have been finely balanced by the reverse processes.

We need new sources of CP violation, beyond the SM, associated with large energy (=mass) scales.

One of the major challenges of flavour physics is searching for, and precisely measuring, CP violation, and comparing with SM predictions

⇒ That's where we will start in tomorrow's lecture

Extra Slides



- CPT Theorem
- CP eigenvalues for 2π and 3π
- Constraints on antimatter from astrophysical observations
- Strong CP problem

CPT Theorem

Combination of C,P, and T operators: $\mathbf{CPT}|\psi(r,t)\rangle \rightarrow |\bar{\psi}(-r,-t)\rangle$

Converts particle into antiparticle with reversed space and time coordinates

> *Any Lorentz invariant local quantum field theory is invariant under the combination of C, P and T*
>
> **CPT theorem**

Consequence: Particles have the same mass and lifetime as their antiparticles

If CPT symmetry is violated, so is special relativity!
All of the standard model relies on it being true

CP of pionic final states

$\pi^0\pi^0$:

- Spin 0 to 2 spin 0 particles: $\ell = 0$

$$\begin{aligned} P(\pi^0\pi^0) &\rightarrow \pi^0\pi^0 \\ C\pi^0 &\rightarrow \pi^0 \\ CP(\pi^0\pi^0) &\rightarrow +1(\pi^0\pi^0) \end{aligned}$$

$\pi^+\pi^-$:

- Spin 0 to 2 spin 0 particles: $\ell = 0$

$$\begin{aligned} P\left(\pi^+(\vec{p})\,\pi^-(-\vec{p})\right) &\rightarrow \pi^+(-\vec{p})\pi^-(\vec{p}) \\ C\pi^\pm &\rightarrow \pi^\mp \\ CP\left(\pi^+\pi^-\right) &\rightarrow +1(\pi^+\pi^-) \end{aligned}$$

$\pi^0\pi^0\pi^0$:

- Any two π^0 combo must have even ℓ (Bose stats)
- $J = 0$ so ℓ of 3^{rd} π^0 also even wrt other two
- But π has intrinsic parity $P = -1$

$$\begin{aligned} P(\pi^0\pi^0\pi^0) &\rightarrow (-1)^3\pi^0\pi^0\pi^0 \\ C\pi^0 &\rightarrow \pi^0 \\ CP(\pi^0\pi^0\pi^0) &\rightarrow -1(\pi^0\pi^0\pi^0) \end{aligned}$$

$\pi^+\pi^-\pi^0$:

- Small Q suggests $\ell = 0$. If so, same argument as above
- Both CP states allowed but $CP(\pi^+\pi^-\pi^0) = -(\pi^+\pi^-\pi^0)$ state highly dominant

2π states have $CP = +1$ and 3π states have $CP = -1$

Meson mixing: time dependence

Solve characteristic equation
det(**H** – E**I**) = 0 to find eigenvalues
(energies E) and eigenstates

$$\begin{aligned}(\Delta M)^2 - \frac{1}{4}(\Delta\Gamma)^2 &= 4\left|M_{12}\right|^2 - \left|\Gamma_{12}\right|^2 \ , \\ \Delta M \cdot \Delta\Gamma &= -4\mathrm{Re}\left(M_{12}\Gamma_{12}^*\right) \ , \\ \frac{p}{q} &= -\frac{\Delta M + \frac{i}{2}\Delta\Gamma}{2M_{12} - i\Gamma_{12}} \ .\end{aligned}$$

⇒ obtain expressions relating Δm, ΔΓ, q/p
in terms of Hamiltonian parameters M_{12},Γ_{12}

System fully characterised by two real parameters **Δm** & **ΔΓ**
and one complex number **(q/p)**

When performing measurements of meson mixing and CP violation, these are the quantities you will see listed in publications

How do we know there is no antimatter?

Could there be ‘antimatter galaxies’ or even whole regions of the universe?

- Boundaries between matter and antimatter regions ⇒ copious photon production from annihilation…

✗ **Not seen**

- Cosmic rays from anti-stars and other astrophysical anti-objects (e.g. anti-He^4 nuclei)…

? Searches ongoing – no observations yet

How do we know there is no antimatter?

Could there be ‘antimatter galaxies’ or even whole regions of the universe?

(2006 – 2016)

PaMeLa a Payload for Antimatter Matter Exploration and Light–nuclei Astrophysics

(2011 –)

Delivered to the International Space Station by space shuttle Endeavour in May 2011, AMS-2 was installed on the station’s truss by astronauts using the robot arms on both shuttle and station.

AMS-2 LOCATION ON SPACE STATION

PRESSURIZED CREW MODULES

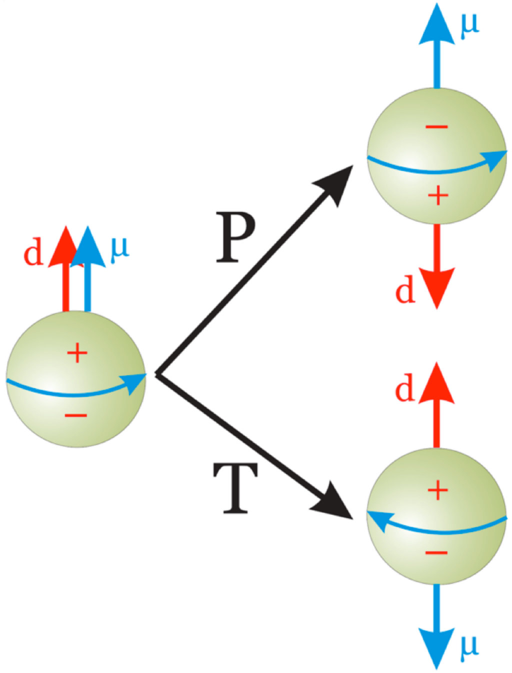
Strong CP violation

In most general Lagrangian (w/ Lorentz invariance, local gauge symmetry) there is a term which includes CPV in QCD…

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \boxed{\theta}}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m e^{i\theta'\gamma_5})\psi$$

If θ≠0, there is CP violation in the strong interaction

But… we don't see any – very strict limits from neutron electric dipole moment (EDM) measurements)



EDM ⇒ negative and positive charges have different charge distributions

Current limits would place the +/− charges <10μm apart **if the neutron were earth sized!**

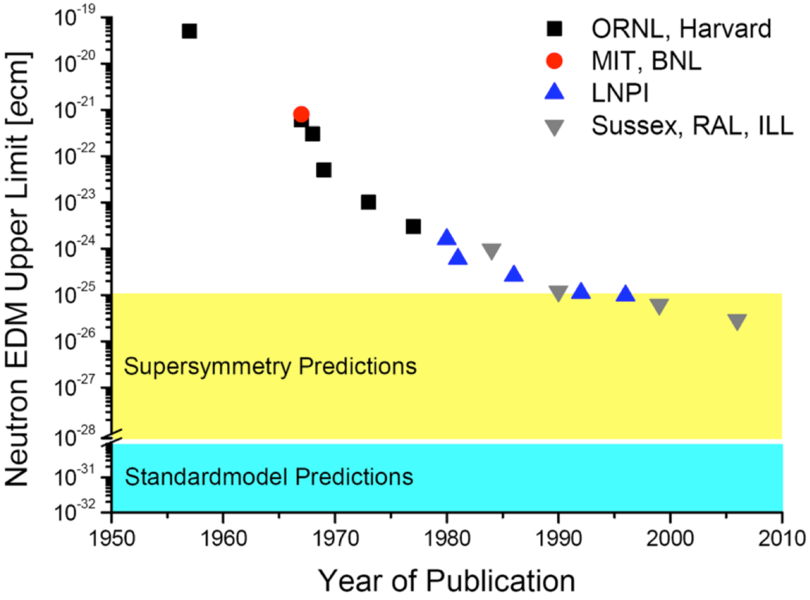
Strong CP violation

So why no strong CPV? **“Strong CP problem”**

$\theta < 10^{-9}$

- Why so small? Is it exactly zero?
- Is it forbidden by some symmetry?

Several SM extensions explain strong CP conservation
e.g. Peccei Quinn theory (predicts ‘axion’)



Experiments searching for axions (convert to photons in strong magnetic field)
– e.g. **CAST @ CERN Point-8**

3 different types of CP violation

Three ways to satisfy the criteria for CPV: >1 interfering amplitudes

CP violation in decay:

$$\boldsymbol{\Gamma(i\to f) \neq \Gamma(\bar{i}\to\bar{f})}$$

Possible for any decay

CP violation in meson mixing:

$$\boldsymbol{\Gamma(M^0\to\bar{M}^0) \neq \Gamma(\bar{M}^0\to M^0)}$$

i.e. $|q/p| \neq 1$

CP violation in interference between mixing and decay:

(to common final state f)

$$\boldsymbol{\Gamma(M^0(\to\bar{M}^0)\to f) \neq \Gamma(\bar{M}^0(\to M^0)\to f)}$$

requires $\arg(q/p) \neq 0$

Only possible for neutral mesons