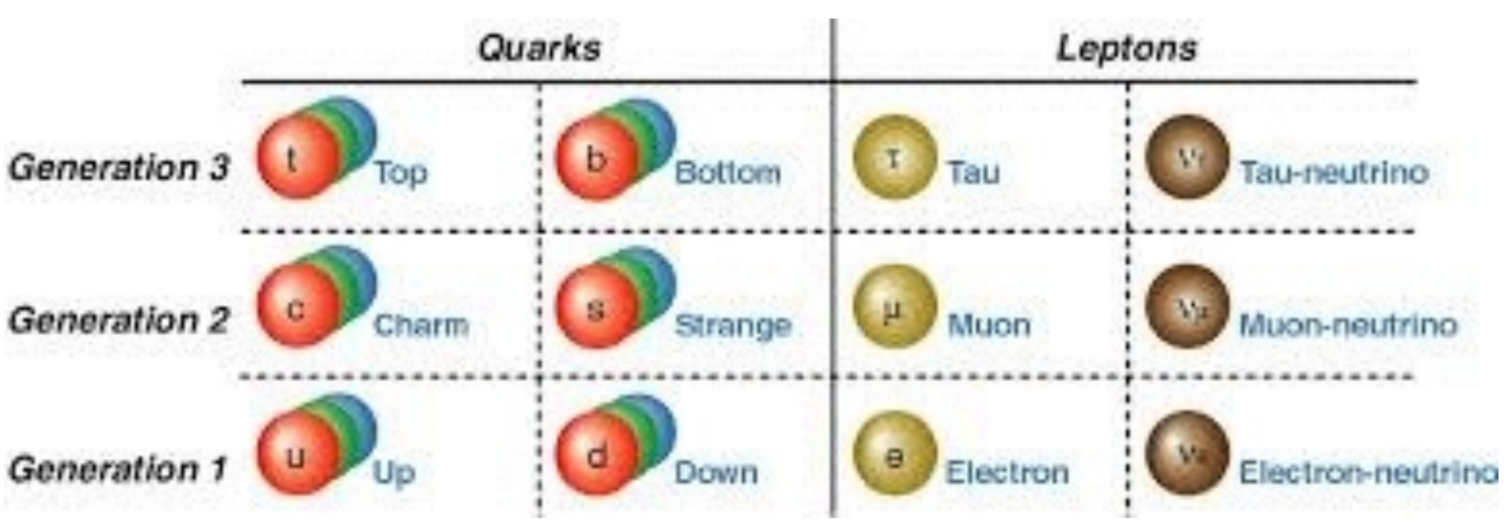
Elementary Particles, Flavour Physics and all that ...

Flavour Physics

- The term "Flavour physics" was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena.

  - **Just as ice cream has both color and flavor so do quarks**

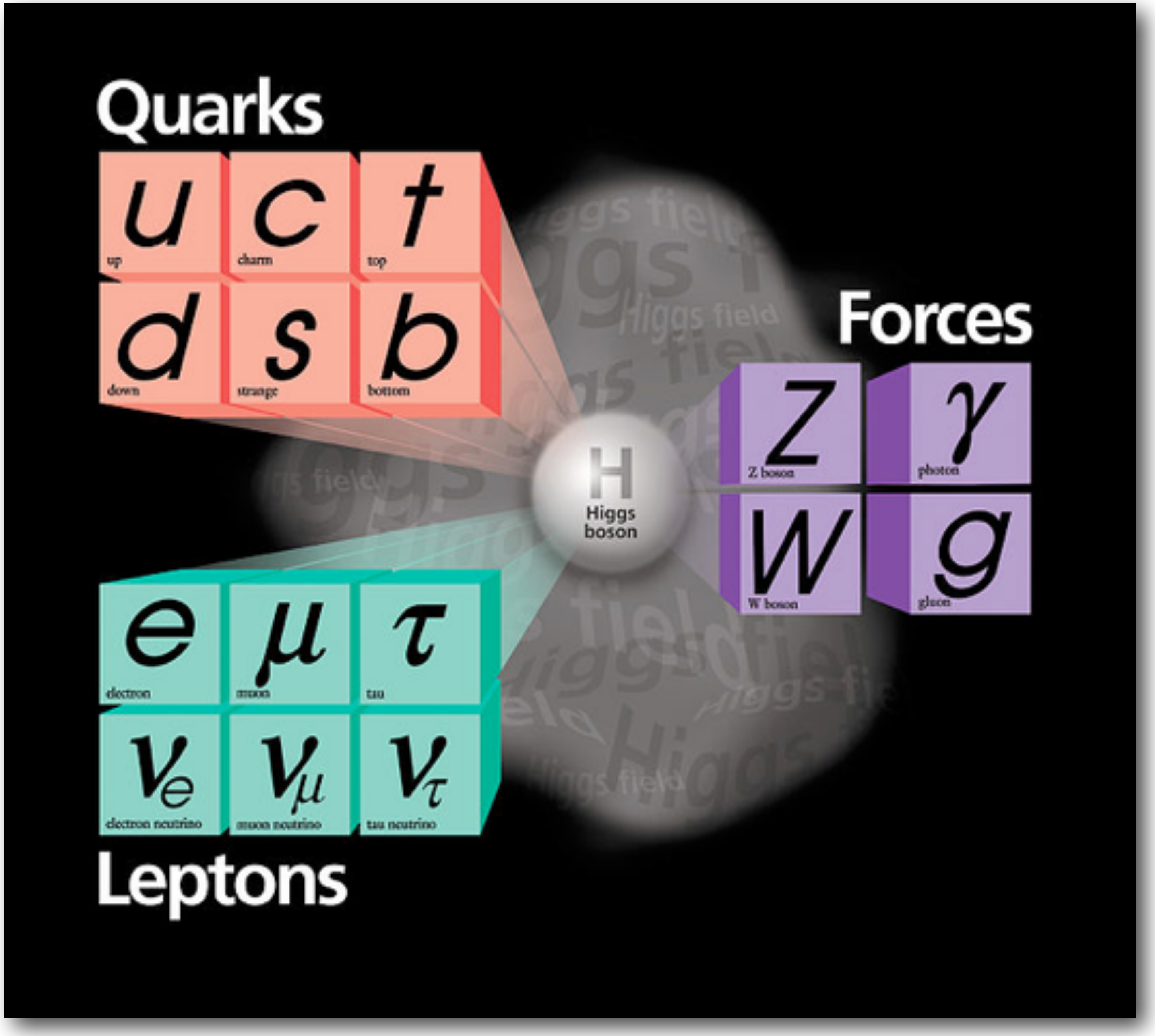


Overview

- Reminder:
  - Standard Model of particle physics
  - Symmetries and symmetry breaking
- Motivation for Flavour Physics
  - CP Violation and the Matter-Antimatter asymmetry in the universe
  - Search for rare and forbidden processes as a probe for new physics
- Present and future experimental facilities

Standard Model of Particle Physics (SM)

- **Three generations of fermions**
  - Quarks, Leptons
- **Four gauge bosons**
  - Photon (EM interaction)
  - W^+, W^-, Z^0 (weak interaction)
  - Gluon (strong interaction)
- **Higgs boson**
  - Generates mass for SM particles



Significance of the SM

- Theory allows quantitative description of all interactions of fundamental particles
  - Exception: quantum gravity effects
  - **Highly successful**
    - so far, no convincing disagreement between measurements and SM predictions
    - All predicted SM particles have been observed experimentally, including the HIGGS boson
- Despite its success, the SM has **more than 20 parameters that cannot be derived from first principles within the SM**
  - Particle masses, mixing angles, number of generations etc.
    - Expect more fundamental theory behind the SM
- Furthermore:
  - The SM fails to explain important observations in astrophysics
  - Gravity is not part of the SM
- Experimental roadmap: search for new physics (NP) beyond the standard model
  - **Energy frontier**: search for new particles at the highes possible energies: (LHC)
  - **Precision frontier**: search for the appearance of new particles in loop diagrams of rare and forbidden processes
    - **Flavour physics**

Structure of the SM

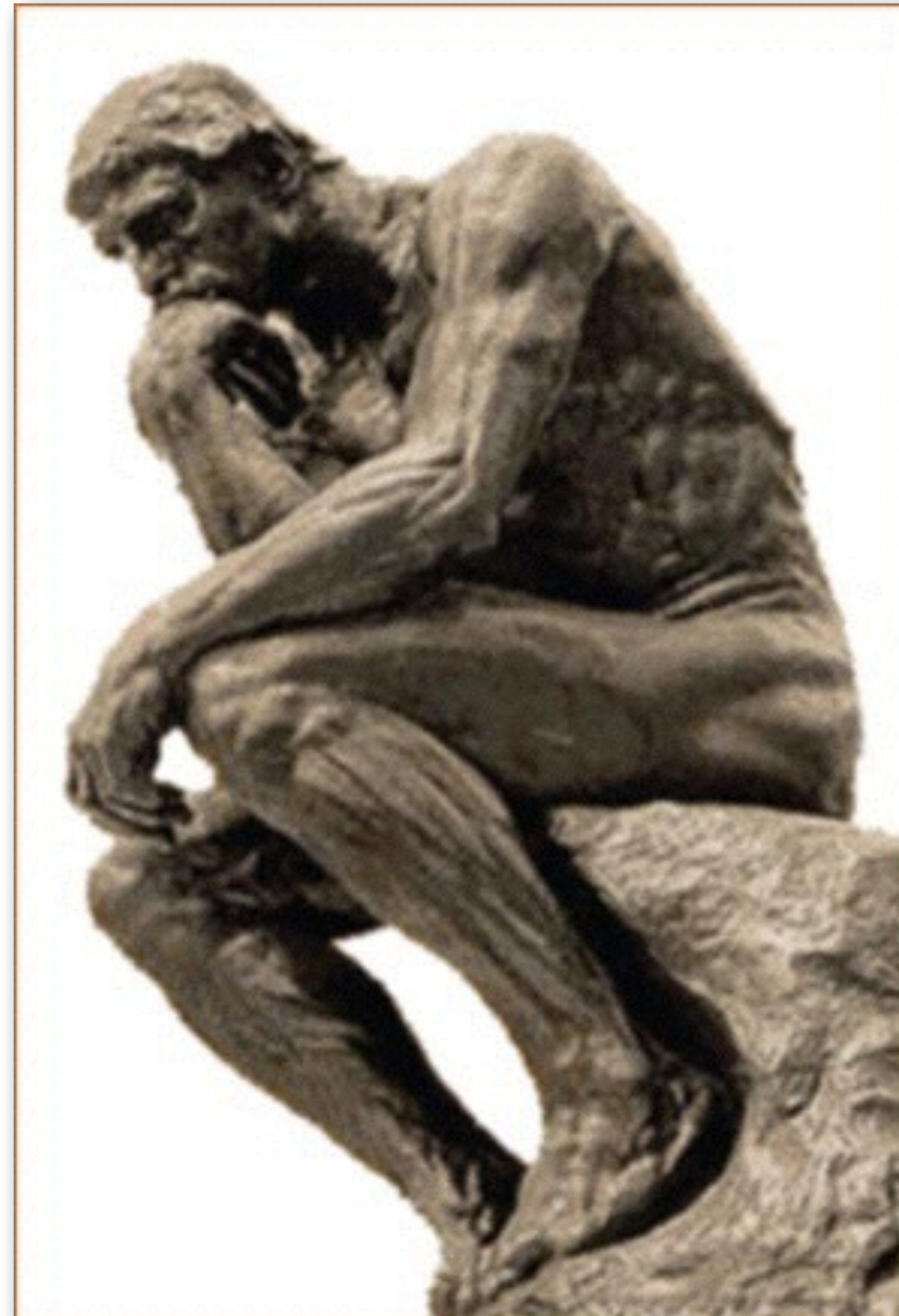
- Renormalizable relativistic quantum field theory based on non- Abelian gauge symmetry of the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Two sectors
  - Quantum Chromodynamics (QCD)
  - Electroweak Theory (EW)
- **QCD**
  - Vector gauge theory describing $SU(3)_C$ color interactions of quarks and gluons
  - Rich dynamical structure such as chiral symmetry breaking, asymptotic freedom, quark confinement, topologically non-trivial configurations
- **Electroweak Theory (EW)**
  - Describes the electromagnetic and weak interactions of quarks and leptons as a chiral non-Abelian isospin and an Abelian hypercharge gauge symmetry $SU(2)_L \times U(1)_Y$

The SM Lagrangian

$$
\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \\
\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - \\
1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$

SM has no answer to *Key Questions in physics:*

- Why are there **three generations** of quarks and leptons ?
- Why is there **much more matter than antimatter** in the universe ?
- What is the nature of **Dark Matter** ?
- How can **gravitation** be included in the picture ?
- Why do we have more than **20 free parameters** in the SM ?
- Are **neutrinos their own antiparticles** ?

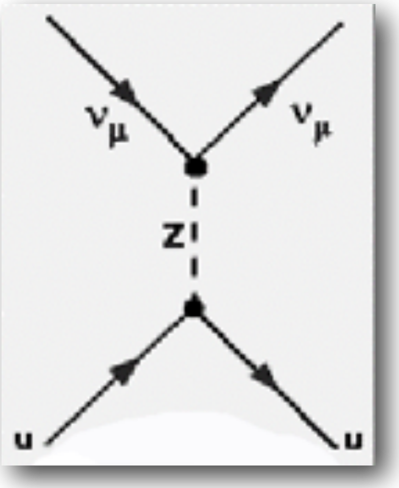


Description of Fundamental Interactions

- Fundamental interactions are mediated via the exchange of gauge bosons
- Gauge bosons of the strong interaction
  - **Gluons** (8 different combinations of color/anti-color)
- Gauge boson of the electromagnetic interaction
  - **Photon**
- Gauge bosons of the weak interaction
  - **Charged W^+, W^- bosons**
  - **Neutral Z^0 boson**
- All gauge bosons have spin s=1
- Gluons und the photon are massless
- The W, Z bosons are very heavy (about twice the mass of a Calcium nucleus !!)
- The gauge bosons are elementary particles
  - Point-like, no internal structure

Weak Interaction

- W^+,W^-, Z^0 are the gauge bosons of the weak interaction
- We call the corresponding charge the "weak charge"
- All fermions carry weak charge, i.e. they participate in the weak interaction
- Example for a scattering process mediated via weak interaction
  - Neutrino – Quark – Scattering
    - Z^0 - Exchange
      - Weak Neutral Current



- The W^+,W^-, Z^0 carry weak charge themselves
  - They interact with each other, like gluons
    - However, in the SM, there are no neutral vertices, such as ZZZ, ZZγ, Z$\gamma\gamma$

Flavor changing weak transitions: charged currents !

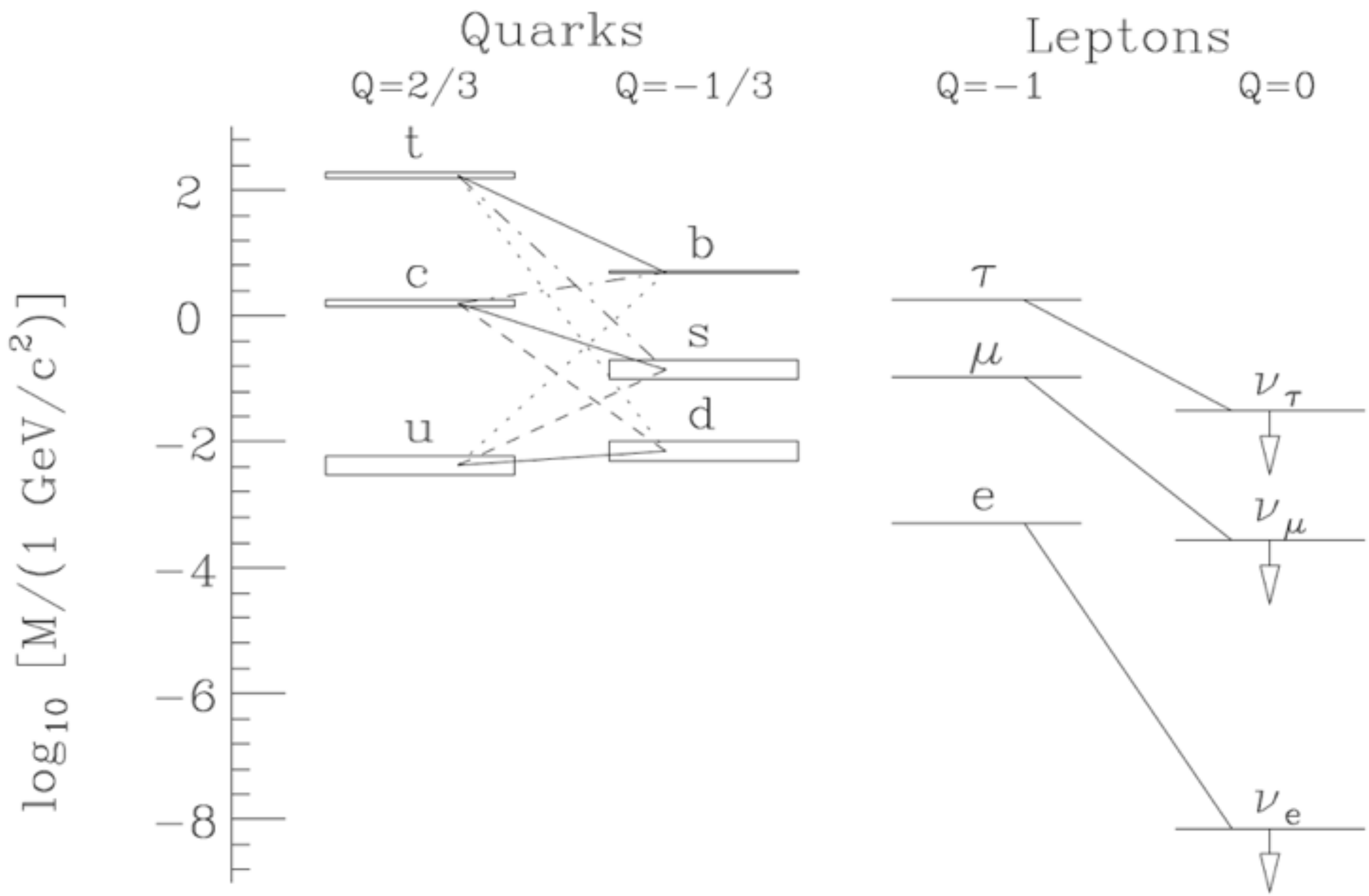


Figure 1. *Patterns of charge-changing weak transitions among quarks and leptons. The strongest inter-quark transitions correspond to the solid lines, with dashed, dot-dashed, and dotted lines corresponding to successively weaker transitions.*

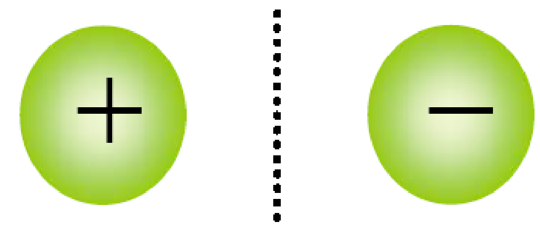
Symmetries in Particle Physics

- Space, time translation and rotation symmetries are all **continuous symmetries**
  - Each symmetry operation associated with one ore more continuous parameter
  - Each continuous symmetry implies a conserved quantum number (**Noether Theorem**)
    - Space translation invariance => momentum conservation
    - Rotational invariance = > angular momentum conservation
    - Time translation invariance => Energy conservation

Discrete Symmetries

Charge conjugation C

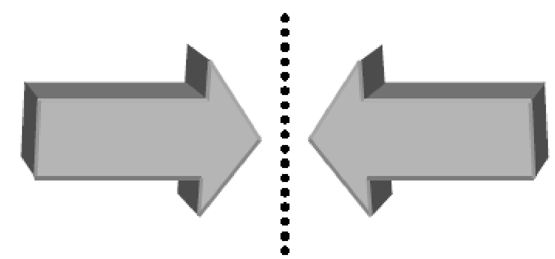
Particle ⇔ Anti-particle



$e^- \rightarrow e^+$

$\gamma \rightarrow \gamma$

Parity P

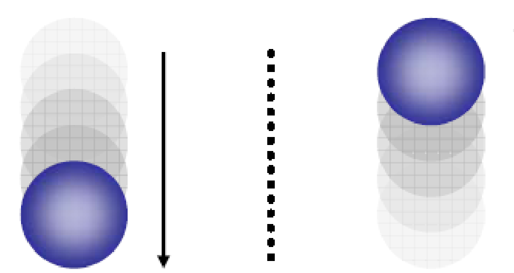


$\vec{r} \rightarrow -\vec{r}$

$\vec{p} \rightarrow -\vec{p}$

$\vec{L} \rightarrow \vec{L}$

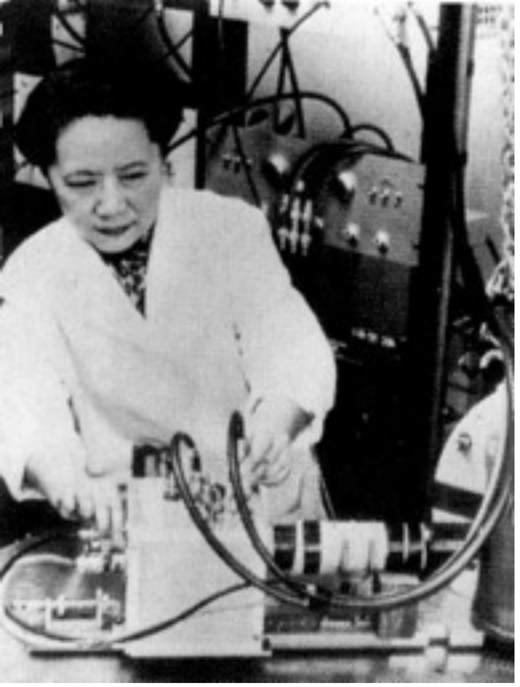
Time inversion T



$t \rightarrow -t$

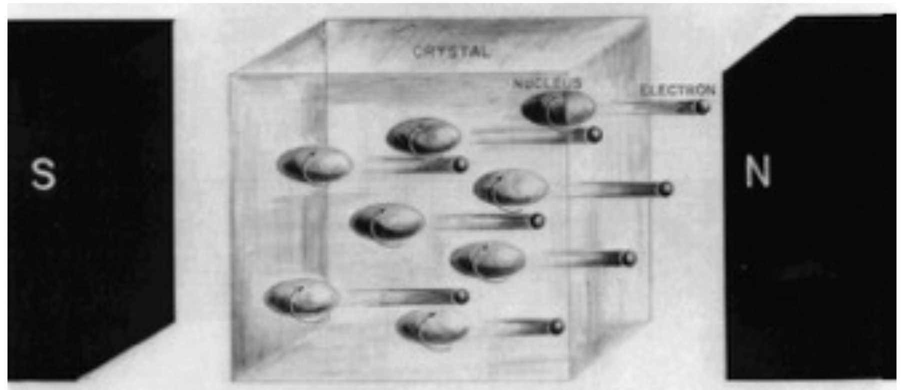
Interesting question:

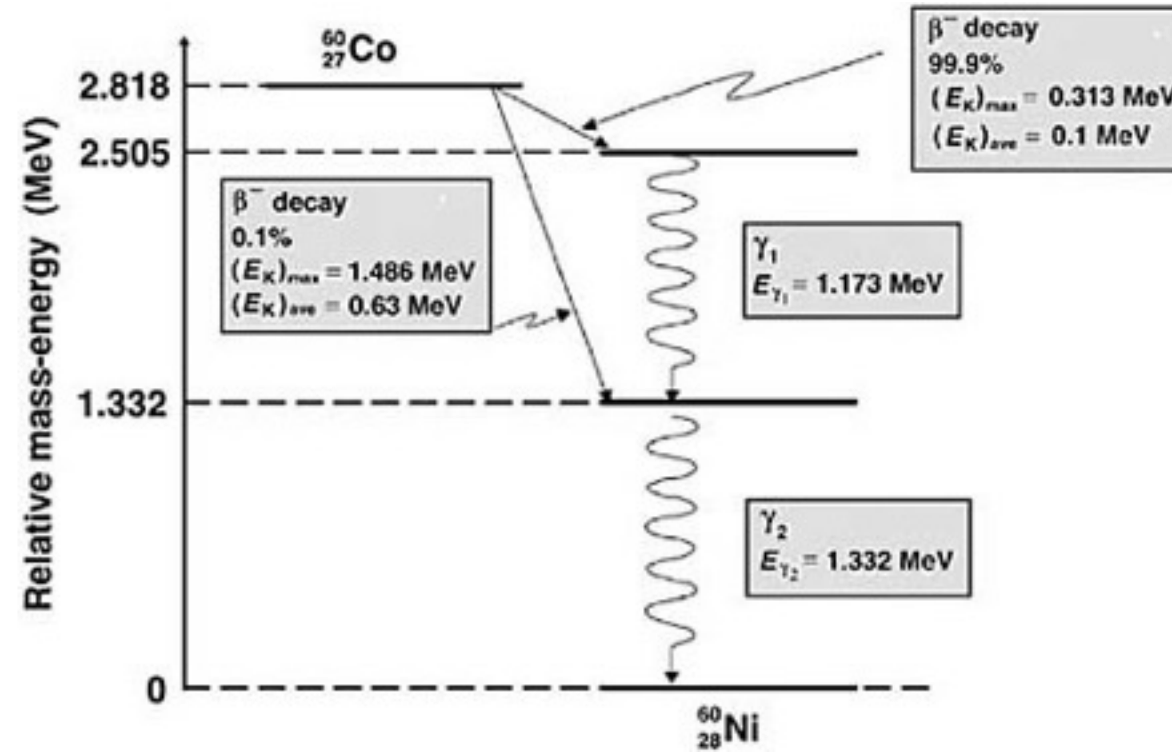
- Do all processes in particle physics exhibit these symmetries ?
  - Answer: C,P,T individually conserved only for the EM and strong interactions. **However, all interactions conserve CPT**

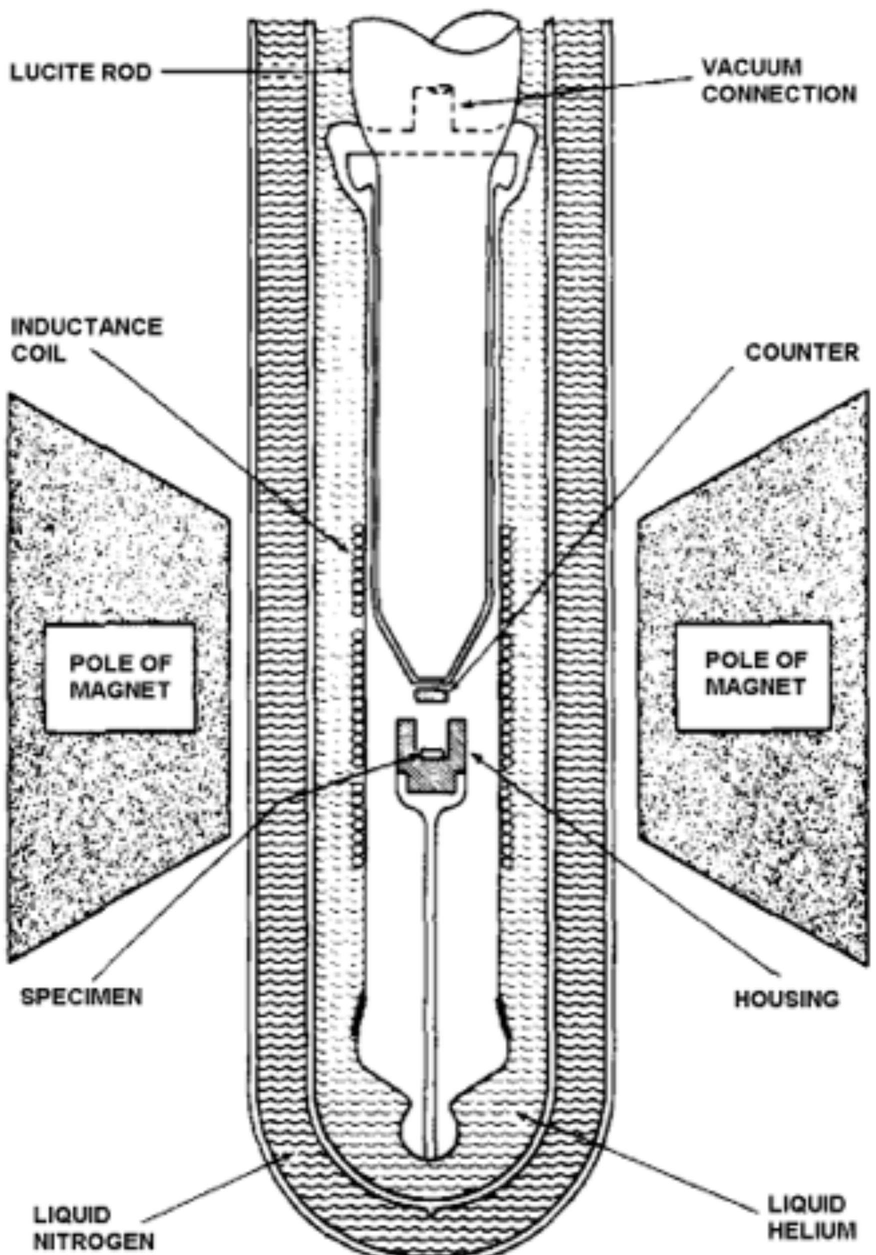


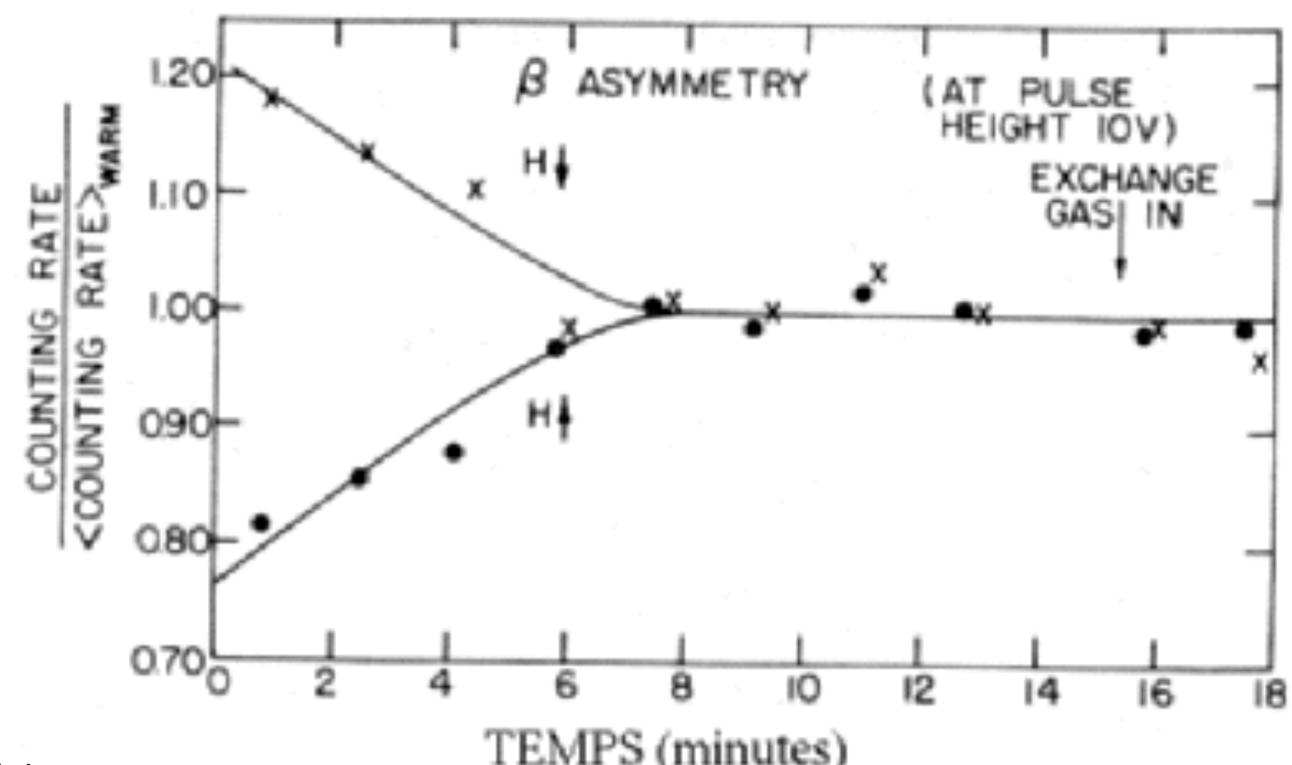
Wu - Experiment Parity violation in beta decay

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

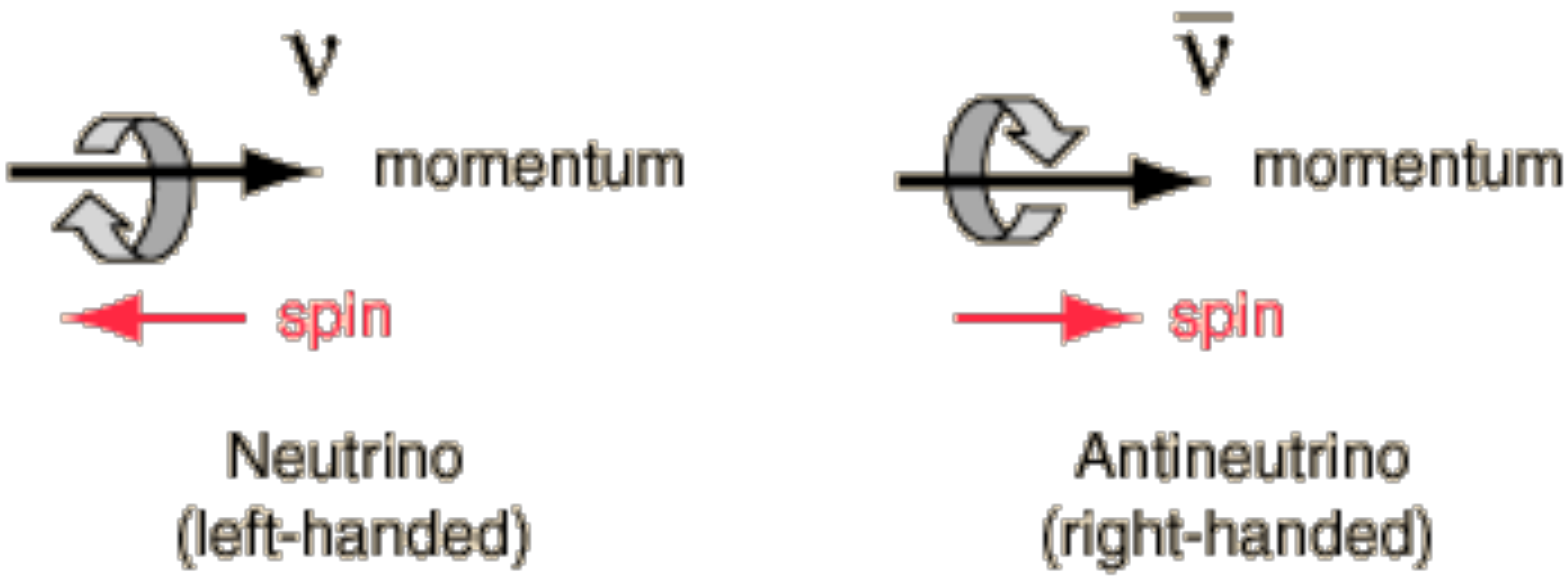








Important Concept: Neutrino Helicity



$$H = \frac{\vec{s} \times \vec{p}}{|\vec{s}| \times |\vec{p}|} \qquad \nu : H = -1 \qquad \bar{\nu} : H = +1$$

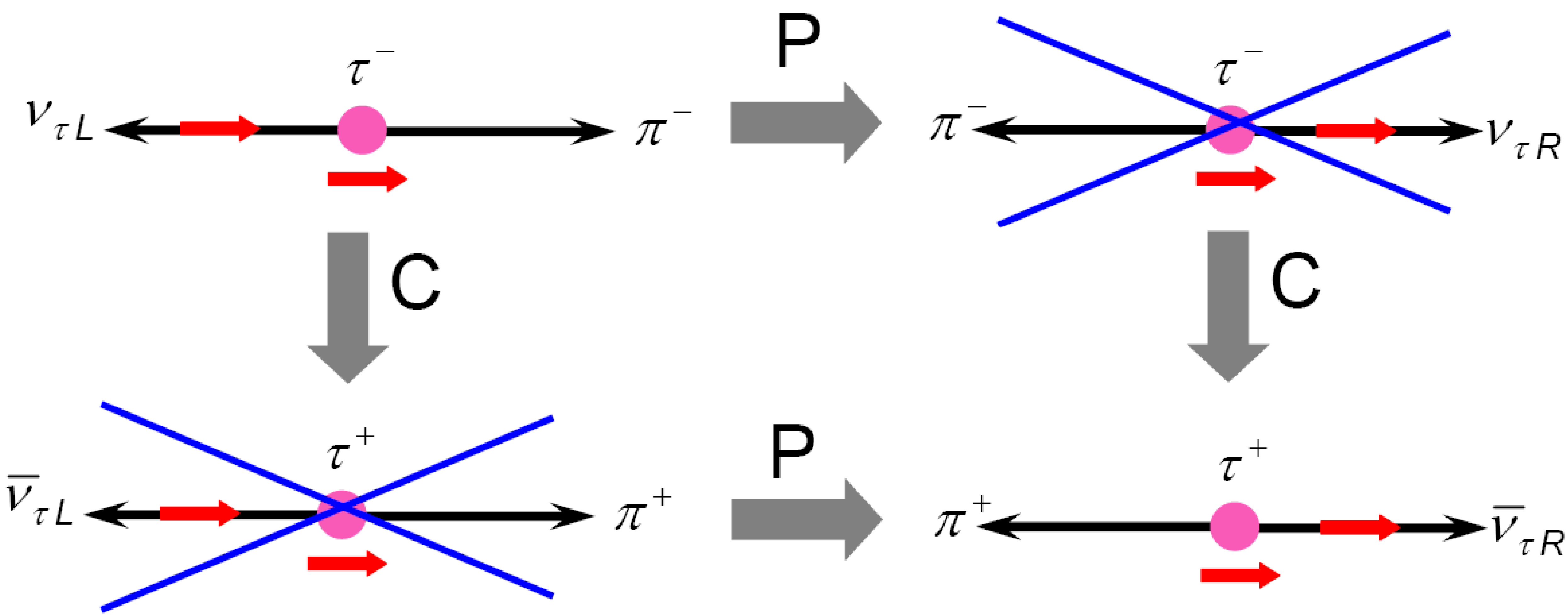
Measurement of neutrino helicity: Goldhaber experiment

M. Goldhaber, L. Grodzins, and A. W. Sunyar, Helicity of Neutrinos, Physical Review 109, 1015–1017 (1958)

Interpretation of Wu Experiment

- Neutrinos and antineutrinos come with a fixed helicity
  - **Neutrinos are always left-handed**
    - Spin points in *opposite* direction as momentum vector
  - **Antineutrinos are always right-handed**
    - Spin points into *same* direction as momentum vector
  - Note: this makes only strict sense if the neutrinos are mass-less
    - Otherwise, consider Lorentz transformation into a system moving faster than the (massive) neutrino
    - Electrons are almost mass-less
      - They are mostly left-handed and positrons are mostly right-handed
  - **Weak interaction (W, Z boson exchanges) couples to left-handed particles and right-handed antiparticles only**
    - This violates Parity !

C, P and CP in Weak Interactions



The weak interaction violates C and P maximally.
But CP was thought to be a good symmetry, until 1964.

CP Violation in the System of Neutral K Mesons

Decay of neutral K Mesons

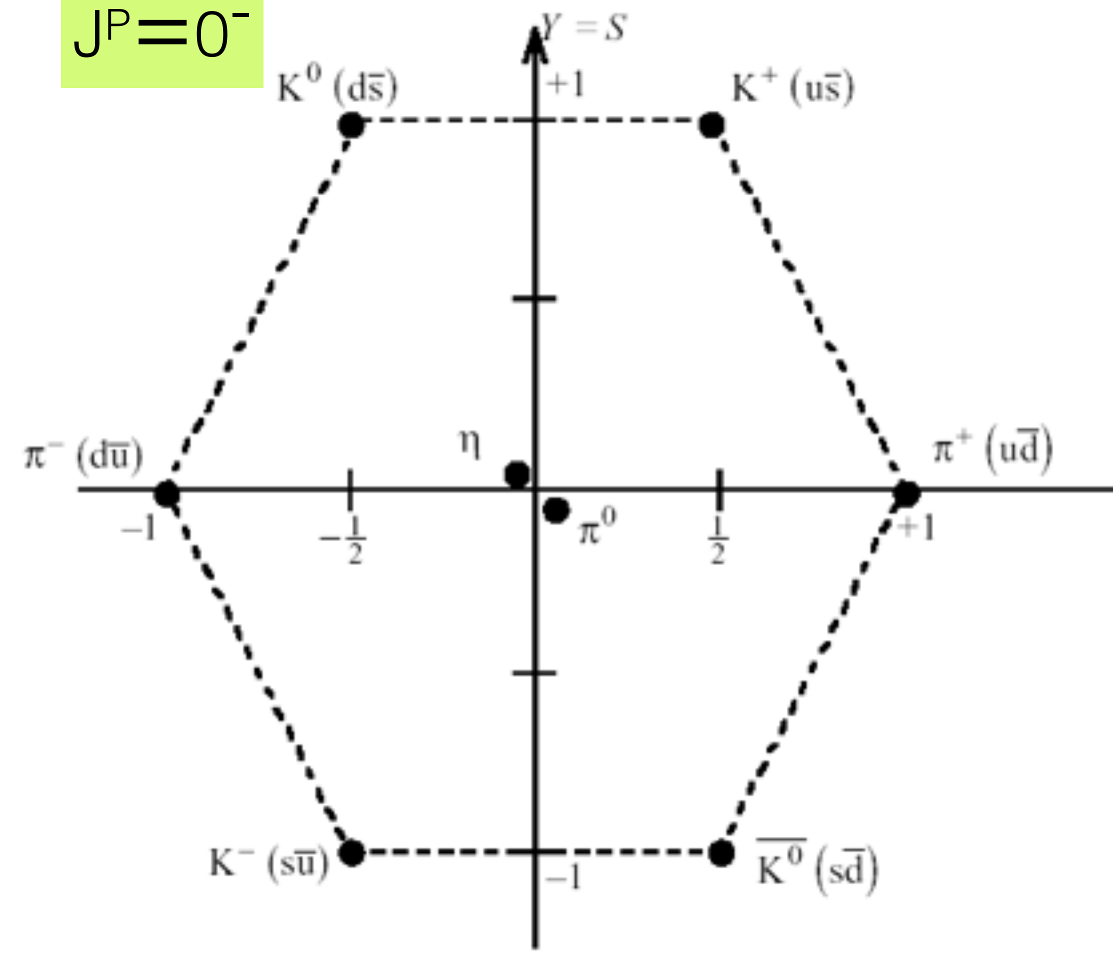
Eigenstates of P
Not Eigenstates of C, CP:

$$\mathbf{P}\left|\mathbf{K}^0\right\rangle = -\left|\mathbf{K}^0\right\rangle \qquad \mathbf{P}\left|\bar{\mathbf{K}}^0\right\rangle = -\left|\bar{\mathbf{K}}^0\right\rangle$$

$$\mathbf{C}\left|\mathbf{K}^0\right\rangle = \left|\bar{\mathbf{K}}^0\right\rangle \qquad \mathbf{C}\left|\bar{\mathbf{K}}^0\right\rangle = \left|\mathbf{K}^0\right\rangle$$

$$\mathbf{CP}\left|\mathbf{K}^0\right\rangle = -\left|\bar{\mathbf{K}}^0\right\rangle \qquad \mathbf{CP}\left|\bar{\mathbf{K}}^0\right\rangle = -\left|\mathbf{K}^0\right\rangle$$

$J^P = 0^-$



Construct Eigenstates of CP:

$$\left|K_1\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right) \qquad \left|K_2\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right)$$

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

Decay Properties

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

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

$$CP|K_1\rangle = |K_1\rangle$$

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

$$|K_1\rangle \to 2\pi$$

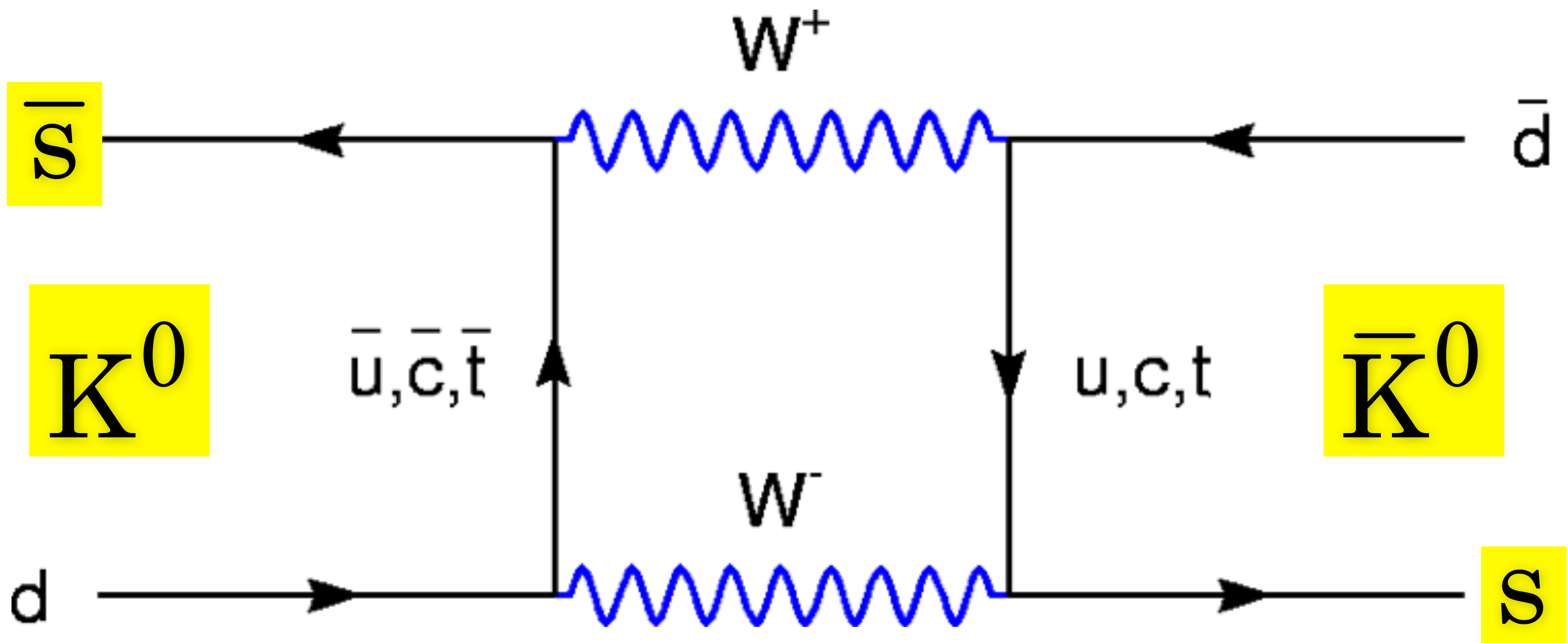
$$|K_2\rangle \to 3\pi$$

Short-lived
(lots of phase space)

long-lived
(small phase space)

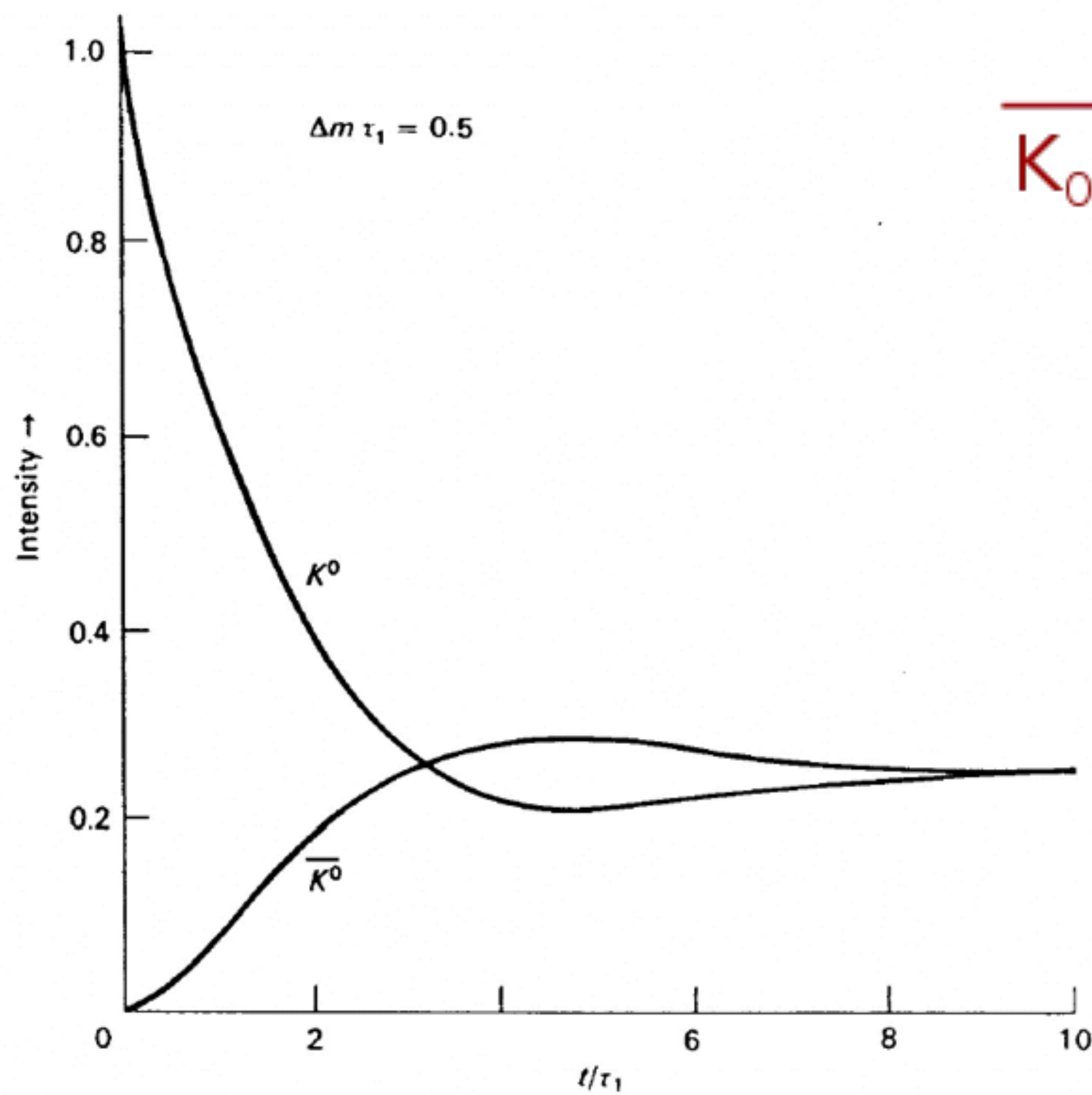
Strangeness - Oscillations

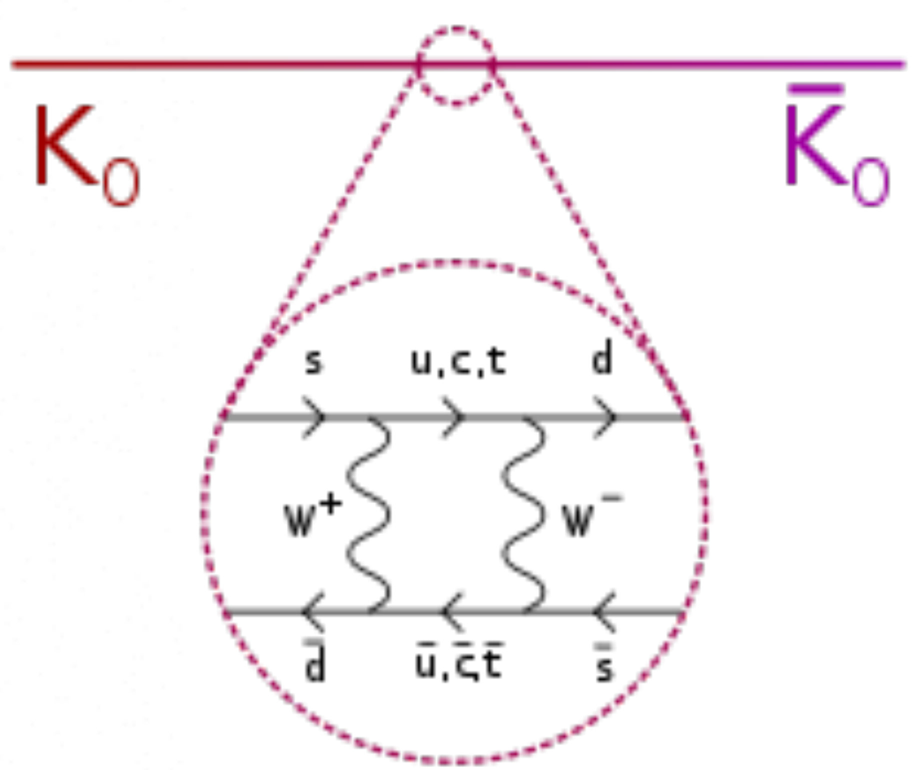
- This box diagram allows a K^0 to convert into its antiparticle
  - Strangeness changes from +1 to –1 !



- A hadronic interaction conserve strangeness and produce either K^0 or its antiparticle
- The week interaction will mix these states via the box diagram
- Experiment shows oscillations

Strangeness - Oscillations



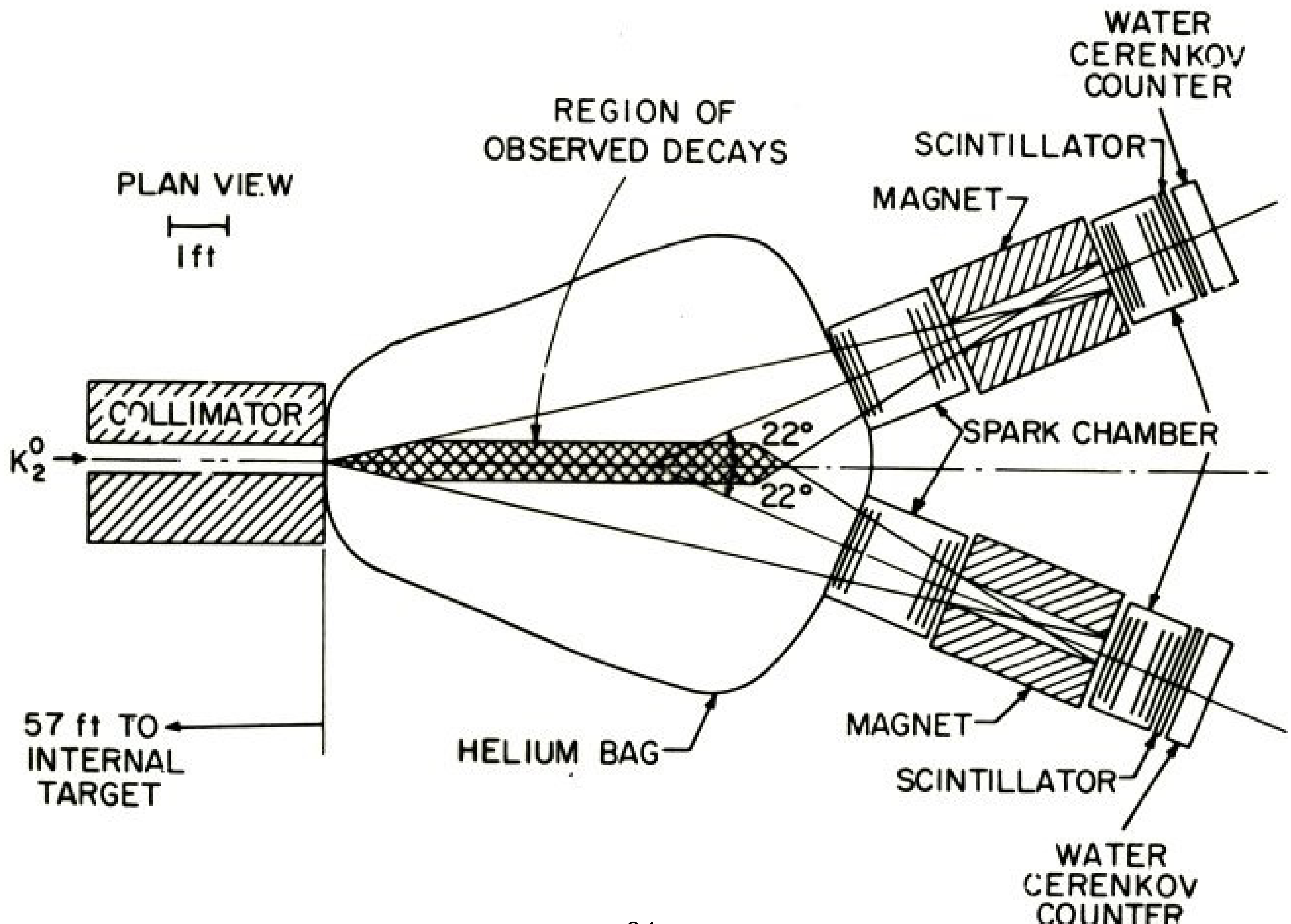


Consequence of different lifetimes

- If we start with a beam of neutral kaons at time zero, this will be converted into a virtually pure K_2 beam after some time
- The characteristic oscillation time is given by the difference between the masses of K_1 and K_2: $\Delta m = 3.5 \times 10^{-6}$ eV
  - Note: K_1 ist NOT the antiparticle of K_2 !!!
- Result
  - If we look at decays at some point which is sufficiently far away from the production target, we should see only the decay of long-lived K_2 into 3 pions
  - The observation of a decay into 2 pions would mean that CP is not conserved
    - Test : Experiment by Cronin und Fitch (1964)

Fitch – Cronin – Experiment: Observation of CP – Violation

Christenson, Cronin, Fitch, Turlay, Physical Review Letters, Volume 13, Number 4, 27 July 1964

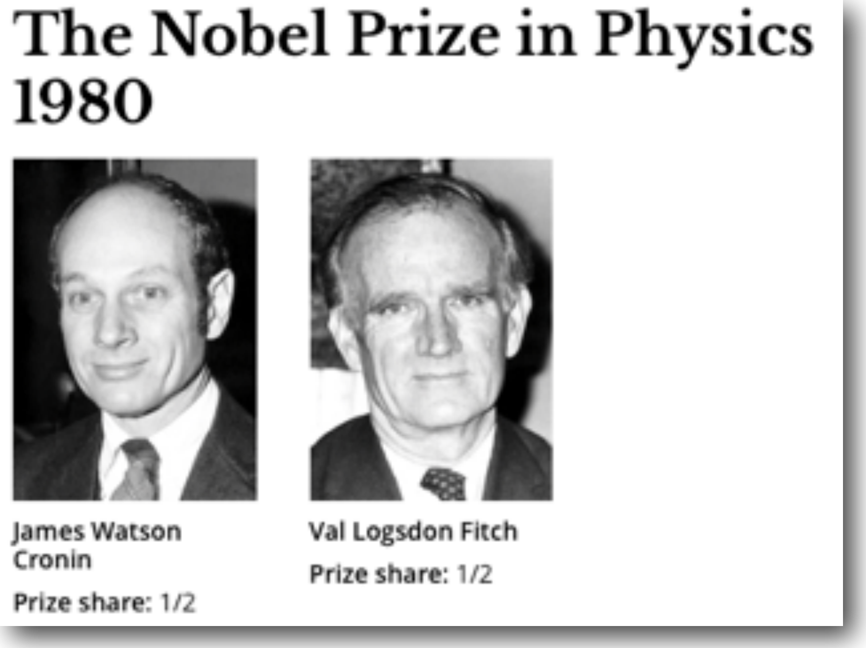


CP – Violation for neutral K – Mesons observed

- Fitch – Cronin – Experiment:
  - In 45 out of 22700 K_2 – decays they observed CP-violating 2π –decays
  - One way to describe this is by modifying the eigenstate of the long-lived component in the following way:

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

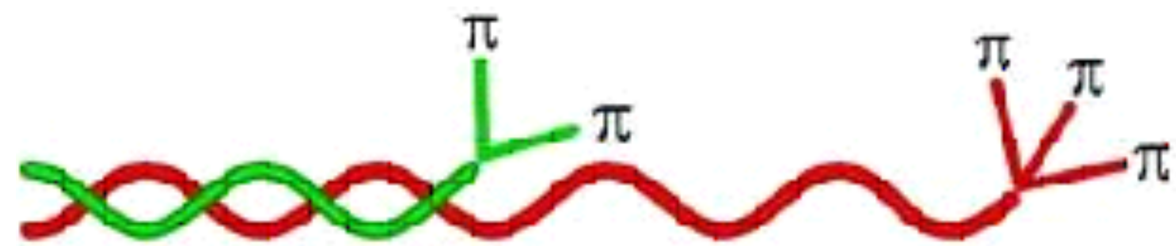
$$|\varepsilon| \approx 2.3 \cdot 10^{-3}$$



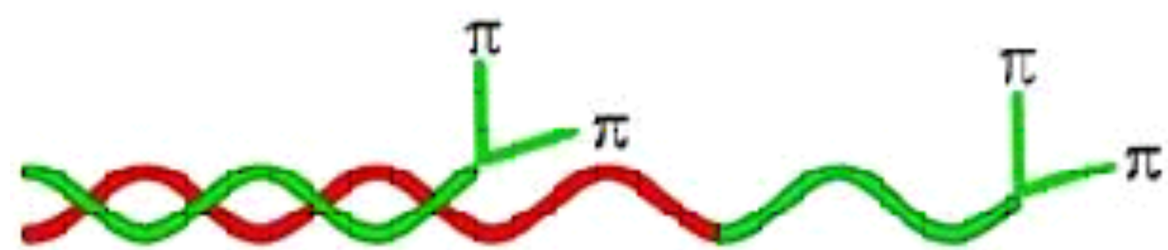
- The mixing parameter ε is small
- CP Violation is a small effect (unlike parity violation !)
- CP Violation via mixing is also called indirect CP violation
- In addition to indirect CP violation there could be a direct CP violation

Direct vs. Indirect CP Violation

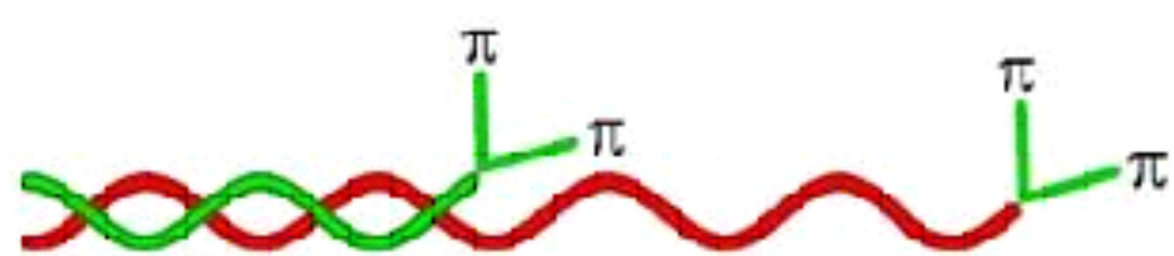
- CP conserving decays of K_S and K_L



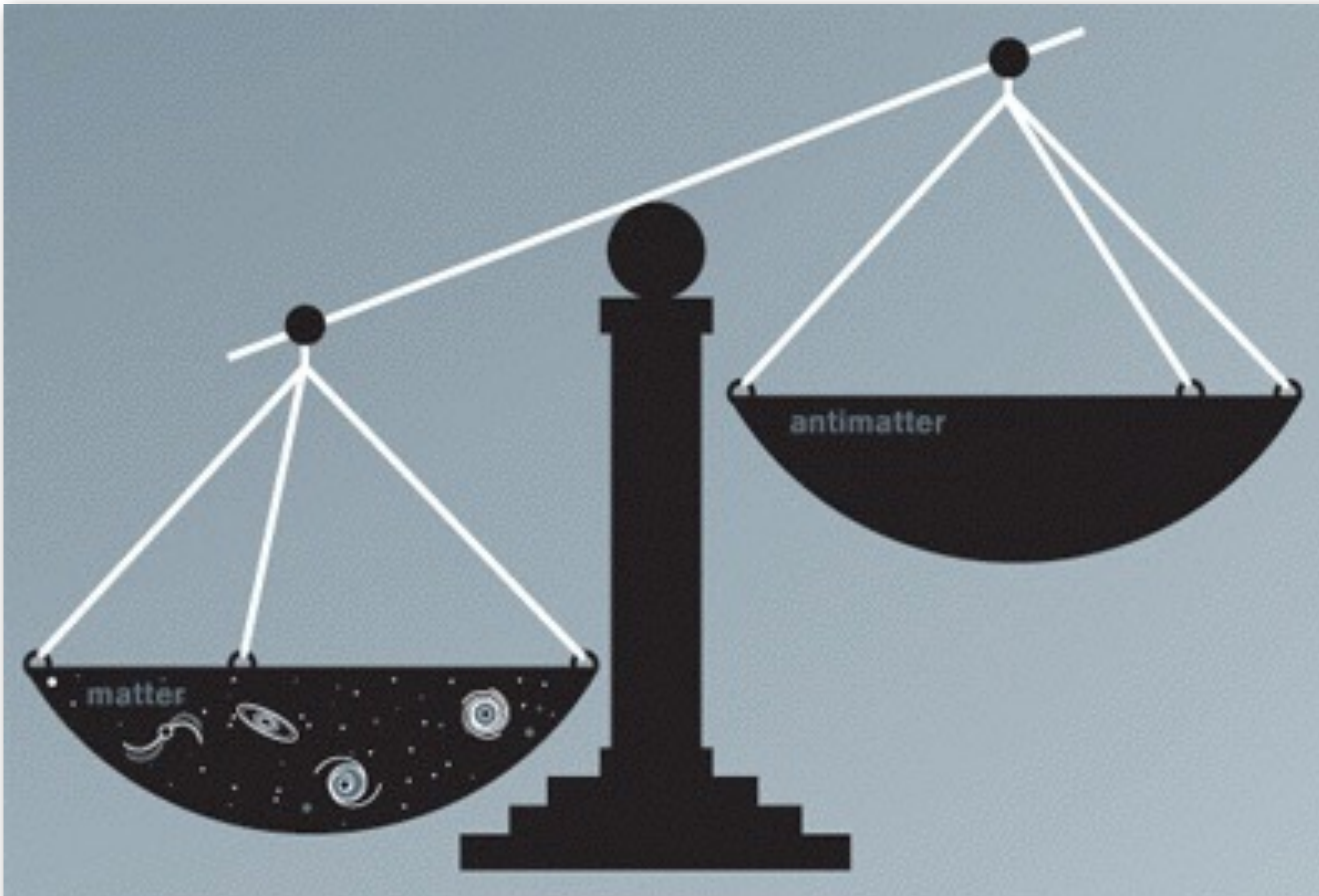
- Indirect CP violation
  - mixing of states with different CP parity
    - described by the parameter ε



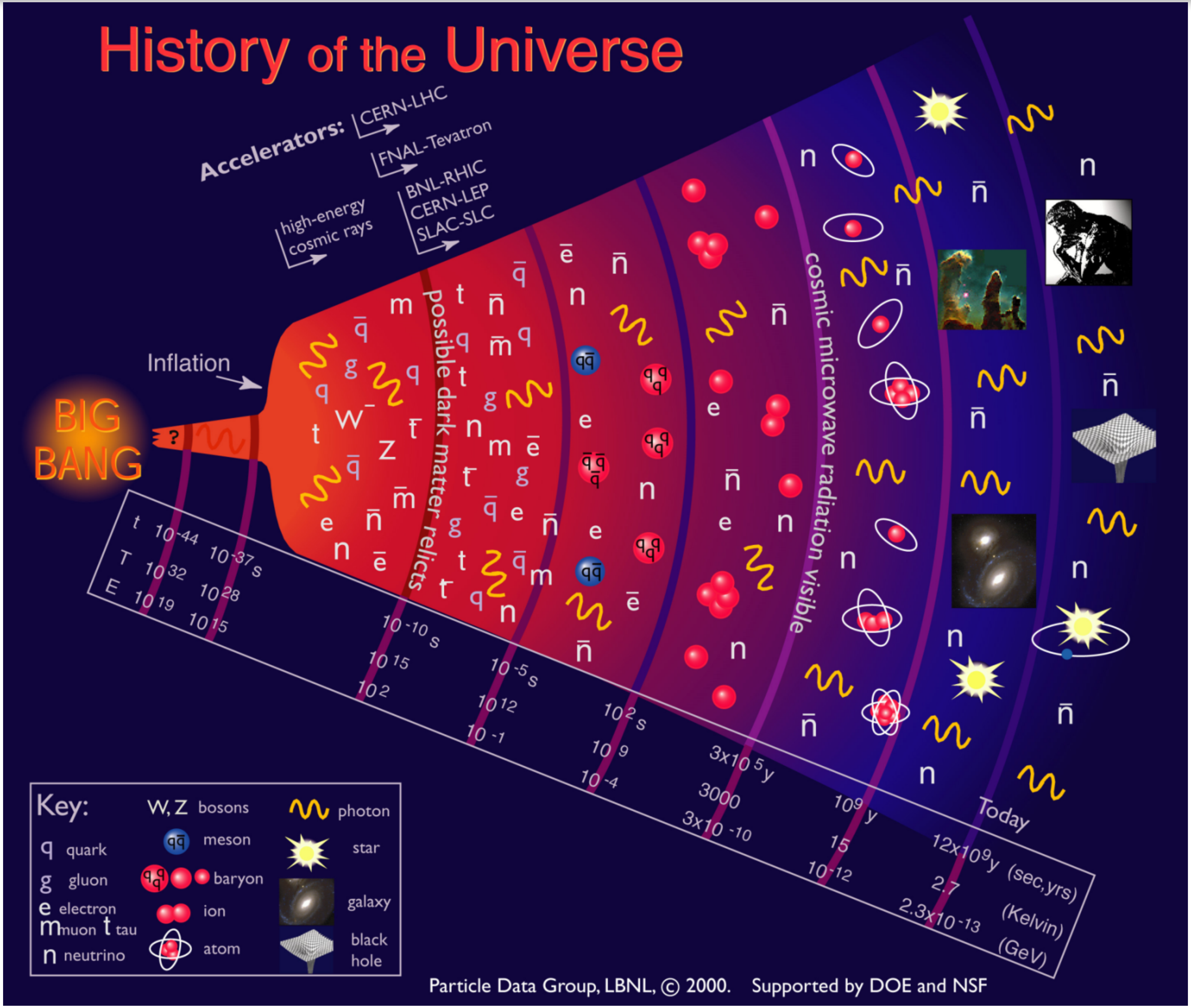
- Direct CP violation
  - caused by CP violating decay amplitude
    - described by the parameter ε'



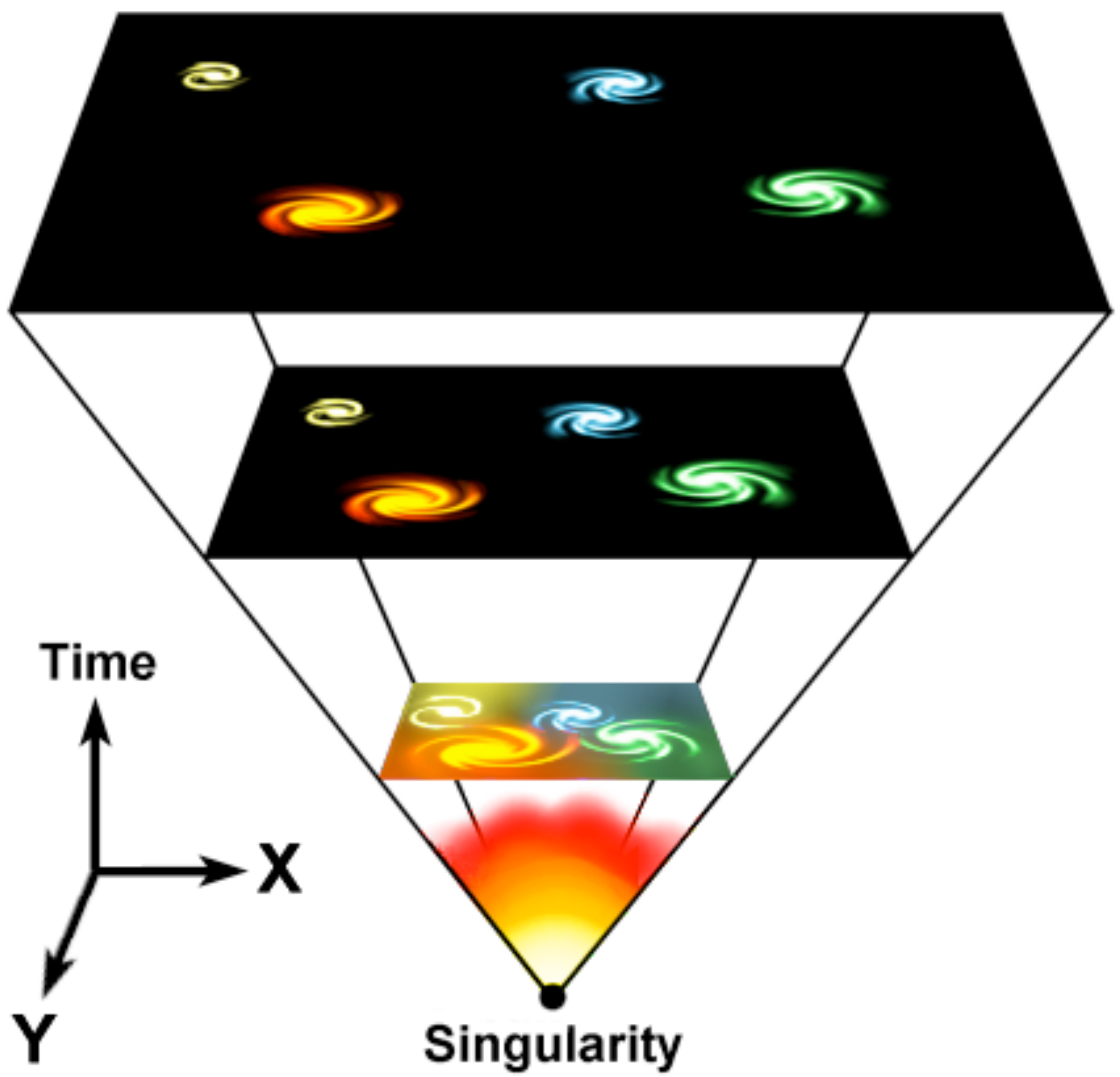
CP Violation and Symmetry of Matter/Antimatter



Matter and Antimatter in the Universe



History of Antimatter



Today:

$(N(\text{baryon}) - N(\text{antibaryon}))/N_\gamma \sim 10^{-10}$

(almost) no antimatter !

?

Shortly after BIG BANG:

Equal amount of
matter and antimatter

The Sakharov Conditions:

Three necessary conditions for matter/antimatter asymmetry

- Baryon number violating process

$$X \rightarrow p^+ e^-$$

- C and CP violation

$$\Gamma(X \rightarrow p^+ e^-) \neq \Gamma(\overline{X} \rightarrow p^- e^+)$$

- Deviation from thermal equilibrium

$$\Gamma(X \rightarrow p^+ e^-) \neq \Gamma(p^+ e^- \rightarrow X)$$

However, the observed CP violation in the K-System is too small to explain the matter/antimatter asymmetry in the Universe

- **Search for other sources of CP violation among the SM particles**
- **Search for new particles (NP)**

CP Violation in the SM: Quark Mixing

$$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}\begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}\begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}$$

In the Standard Model, leptons can only transition *within* a generation (NOTE: probably not true!)

$$\begin{pmatrix}u \\ d\end{pmatrix}\begin{pmatrix}c \\ s\end{pmatrix}\begin{pmatrix}t \\ b\end{pmatrix}$$

Although the rate is *suppressed*, quarks can transition *between* generations.

The CKM Matrix

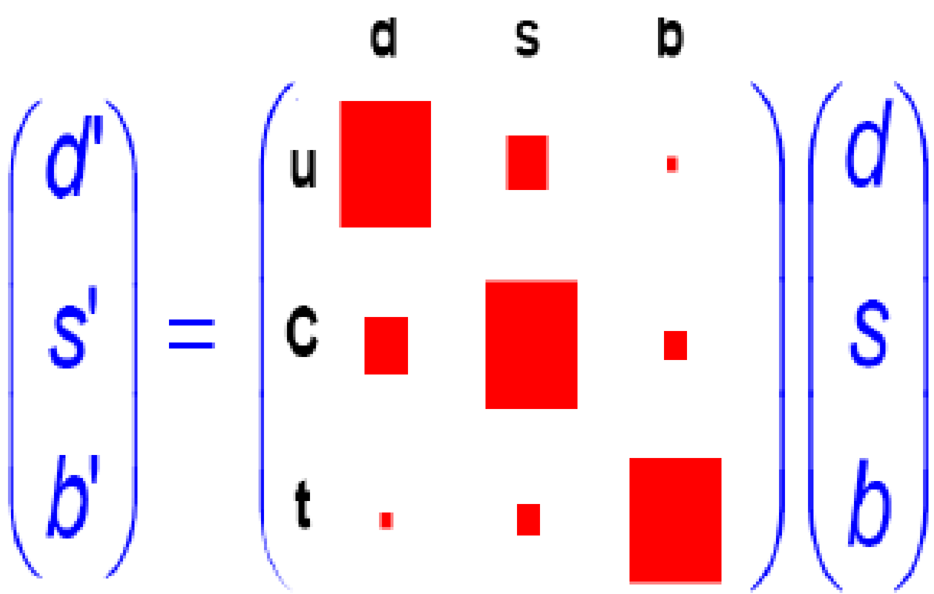
- The weak quark eigenstates are related to the strong (or mass) eigenstates through a unitary transformation.

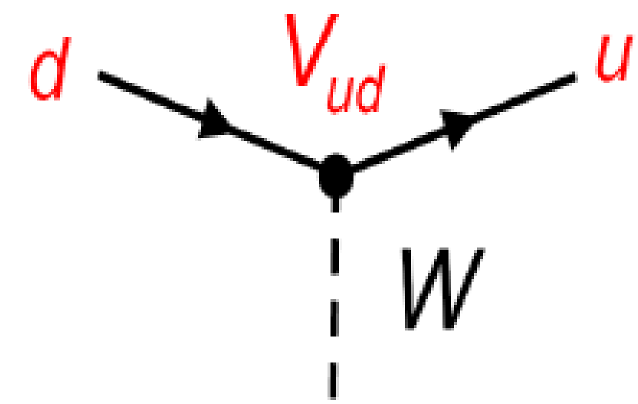
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \Longrightarrow \begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$

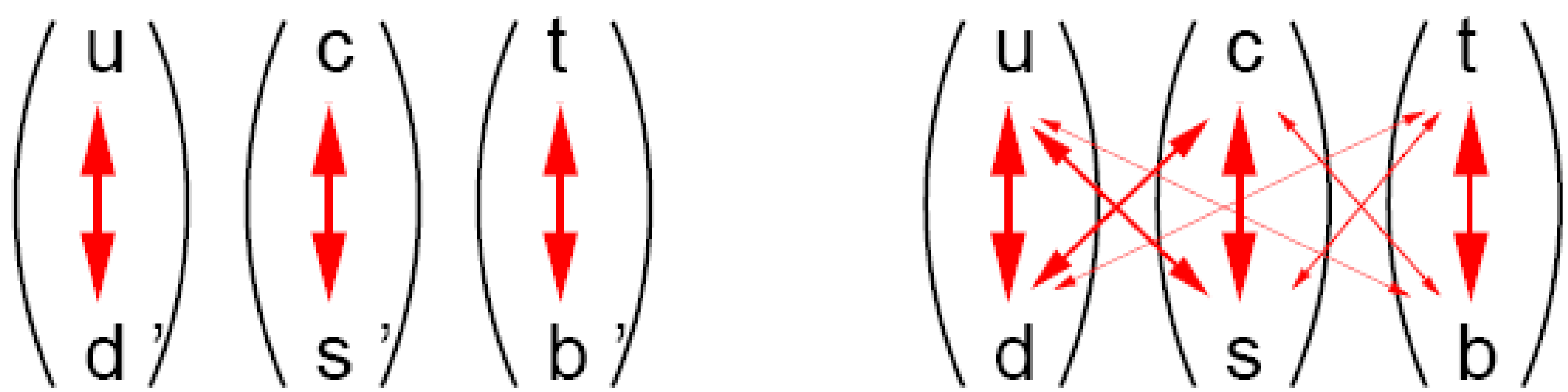
Cabibbo-Kobayashi-Maskawa (CKM) Matrix

- CP violation in the SM requires.
  - **Existence of a complex phase in this matrix**
    - Only possible, if there are at least 3 generations of quarks
      - We would not exist if there would be no b, t - quarks in nature !!!

Size of the CKM matrix elements







Diagonal elements of CKM matrix are close to one.

Only small of diagonal contributions.

Mixing between quark families is “CKM suppressed”.

Wolfenstein Parameterization

The CKM matrix is an SU(3) transformation, which has four free parameters. Because of the scale of the elements, this is often represented with the "Wolfenstein Parameterization"

$$\cong \begin{bmatrix} \boxed{\begin{matrix} 1-\lambda^2/2 & \lambda \\ -\lambda & 1-\lambda^2/2 \end{matrix}} & \begin{matrix} A\lambda^3(\rho - i\eta) \\ A\lambda^2 \end{matrix} \\ \begin{matrix} A\lambda^3(1-\rho-i\eta) & -A\lambda^2 \end{matrix} & 1 \end{bmatrix}$$

First two generations *almost* unitary.

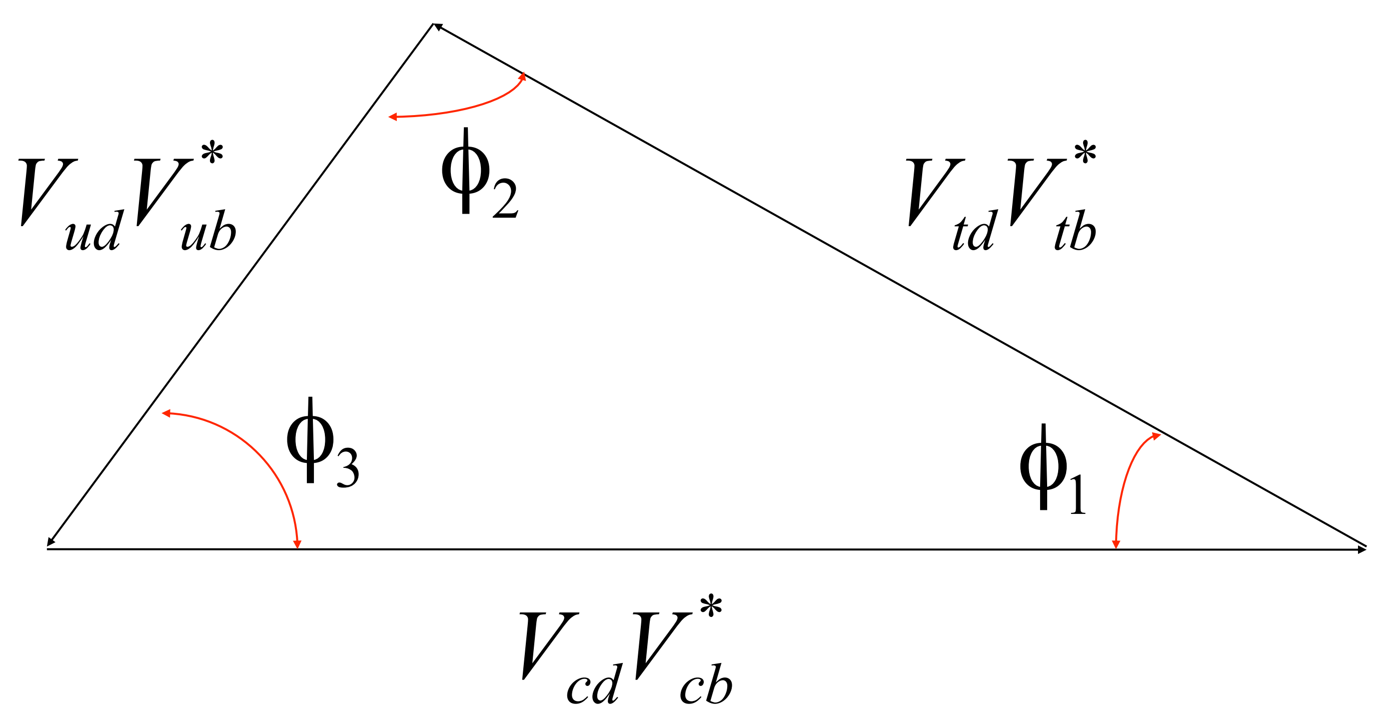
CP Violating phase

"The" Unitarity Triangle

- Unitarity imposes several constraints on the matrix, but one...

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

results in a triangle in the complex plane with sides of similar length $\left(\approx A\lambda^{3}\right)$, which appears the most interesting for study



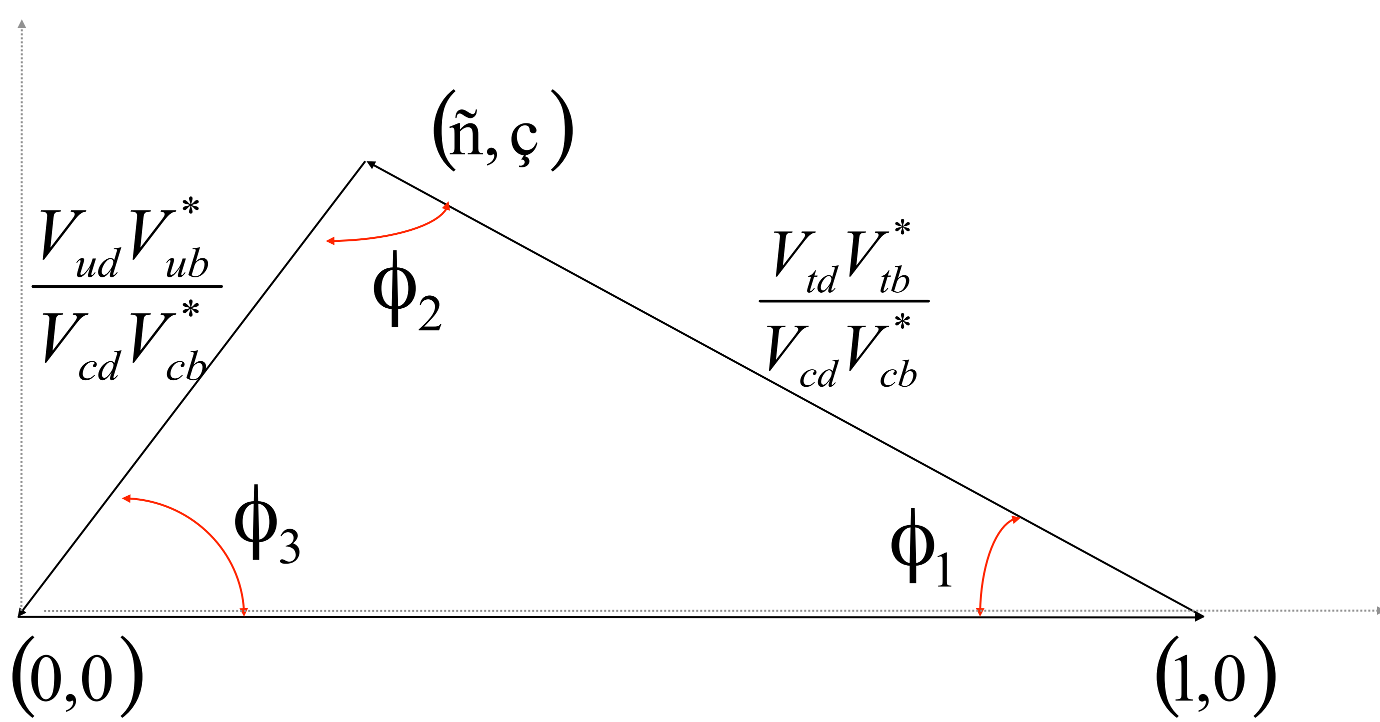
$$(\text{Note! in US}: \ \phi_1 \equiv \beta,\ \phi_2 \equiv \alpha,\ \phi_3 \equiv \gamma)$$

The ρ–η Plane

- Remembering the Wolfenstein Parameterization

$$\cong \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

we can divide through by the magnitude of the base….

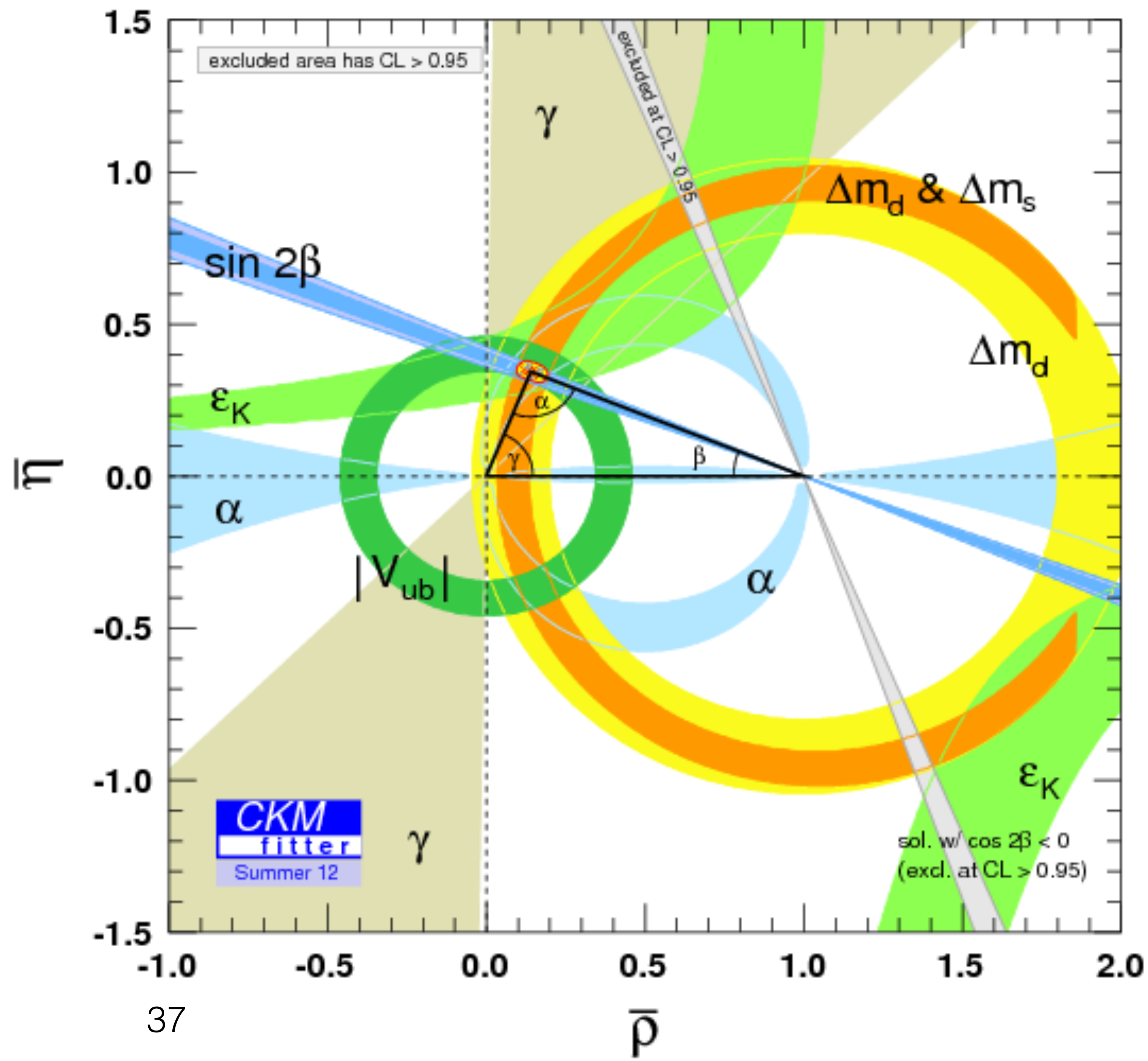


CP violation is generally discussed in terms of this plane

The Unitarity Triangle

Current knowledge of UT:
(from CKMFitter) http://ckmfitter.in2p3.fr

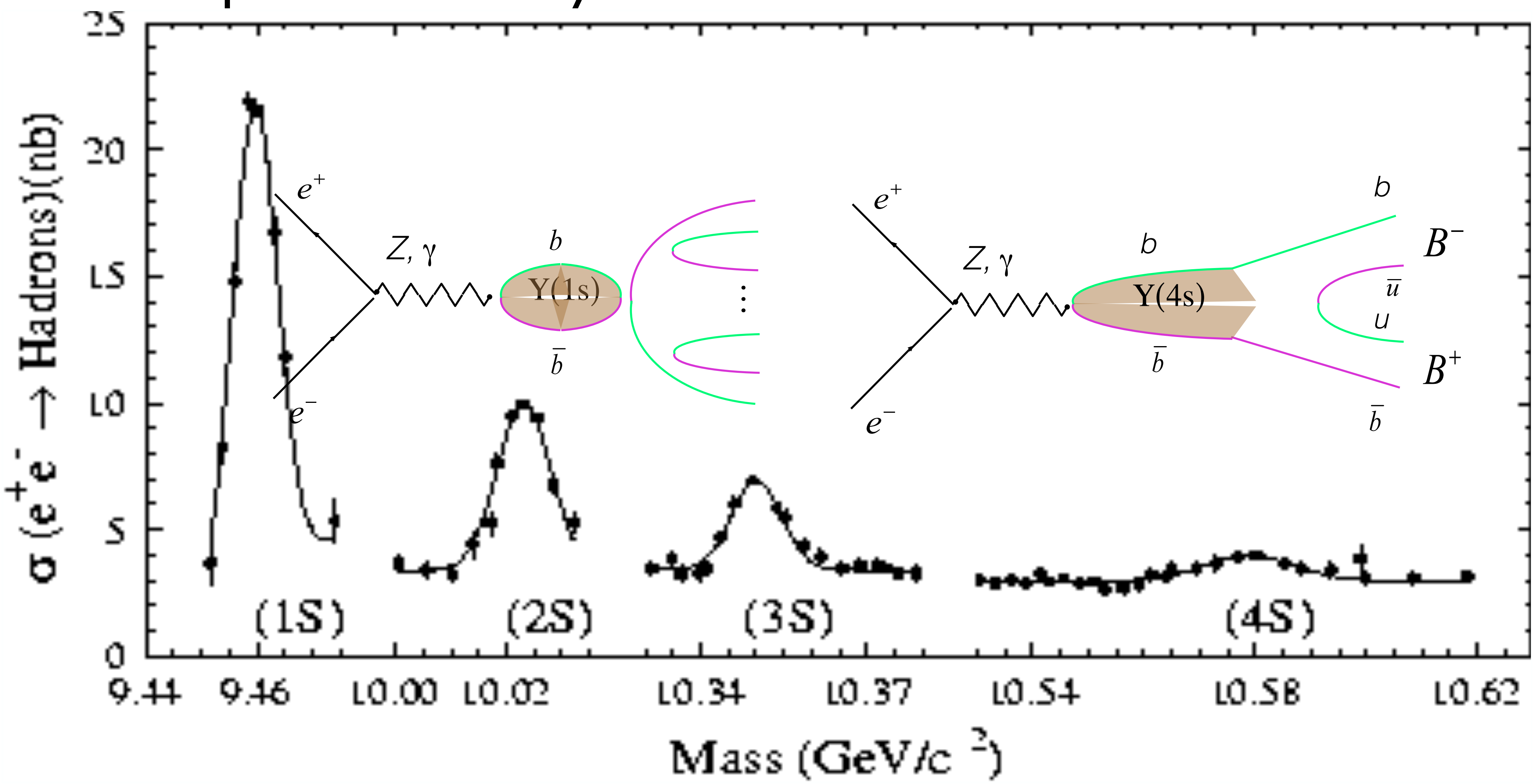
- Shows the size of the CP violation
  - no CPV means no triangle
- Presents our knowledge of CKM parameters
- Shows how consistent the measurements are!



CP Violation in the B System

How to make B Mesons ?

- Example: $e^+ e^-$ Colliders at ~ 10.56 GeV
- High luminosity lots of collisions ~ 10^7 Bs/year
  - Production of Υ(4s) –> B anti B mesons ~ 100%
    - Width of Υ(4s) = 10 MeV
    - B mesons produced nearly at rest



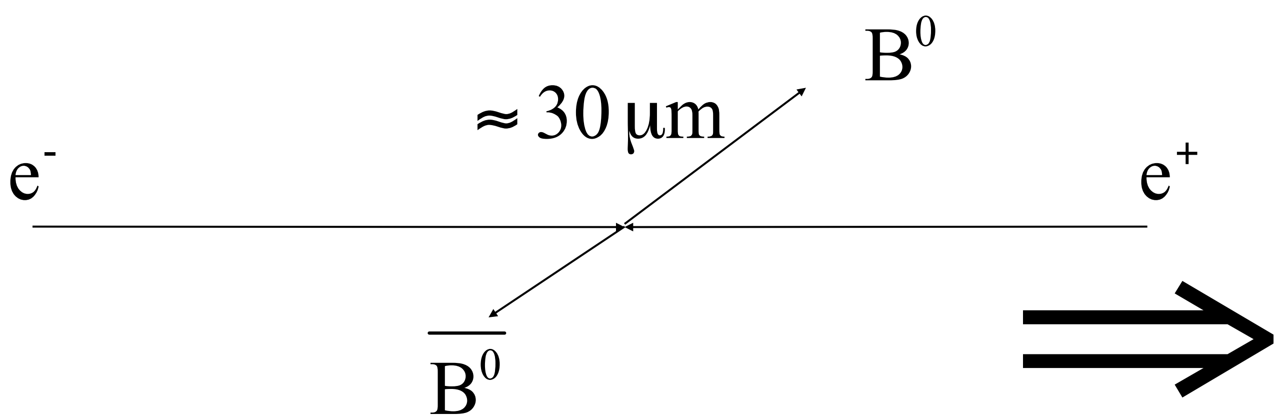
The Basic Idea: Measure time-dependent asymmetries

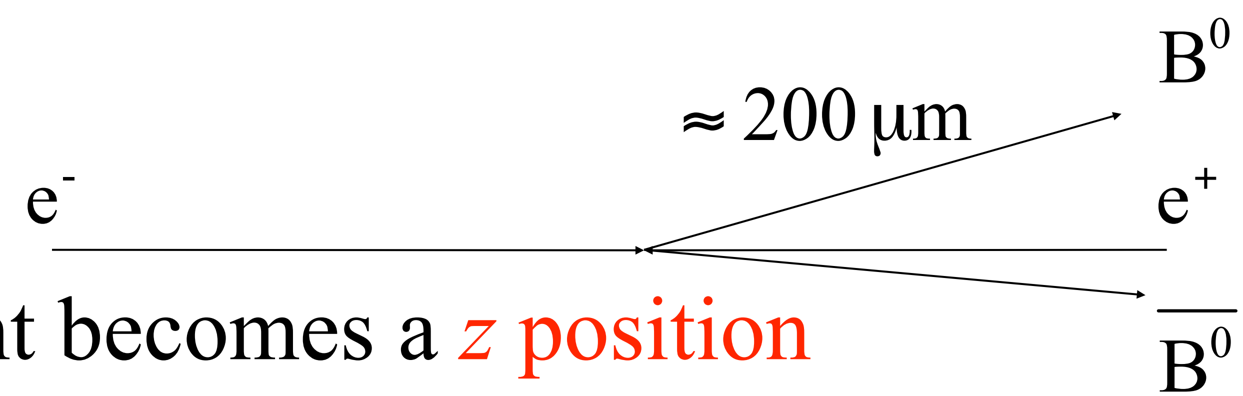
- We can create $B^0\overline{B^0}$ pairs at the $\Upsilon(4S)$ resonance.
- Problem: both CP eigenstates have about the same lifetime
- Even though both *B'*s are mixing, if we tag the decay of one of them, the other must be the CP conjugate *at that time*.
    - Measure the time dependent decay of one B relative to the time that the first one was tagged .
- PROBLEM: At the $\Upsilon(4S)$ resonance, B's only go about 30 μm in the center of mass, making it difficult to measure time-dependent mixing.

The Clever Trick

- If the collider is *asymmetric*, then the entire system is Lorentz boosted.

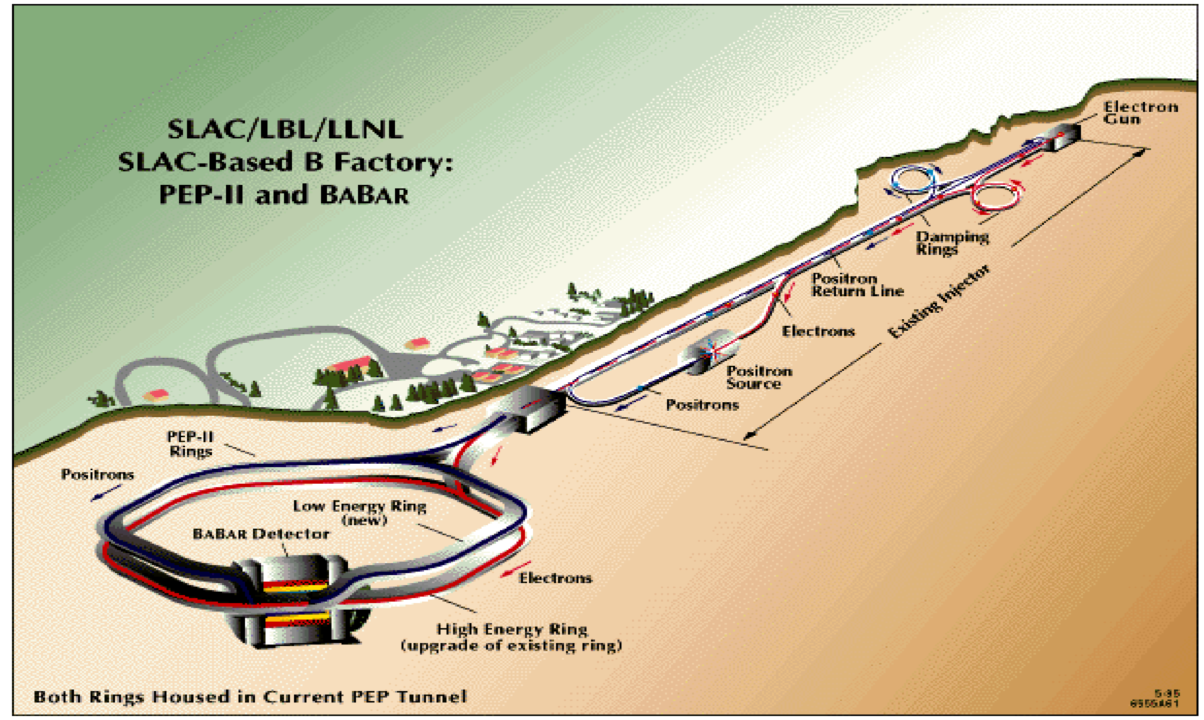
- In the Belle Experiment, 8 GeV e^- are collided with 3.5 GeV e^+





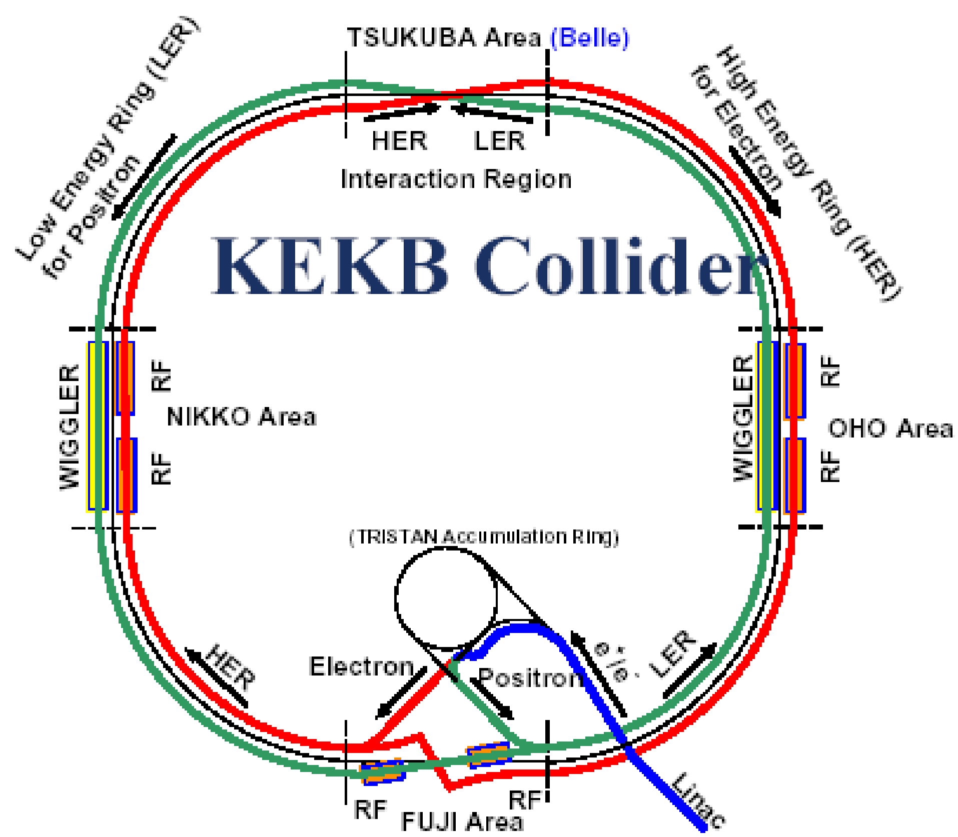
  - So now the time measurement becomes a *z* position measurement.

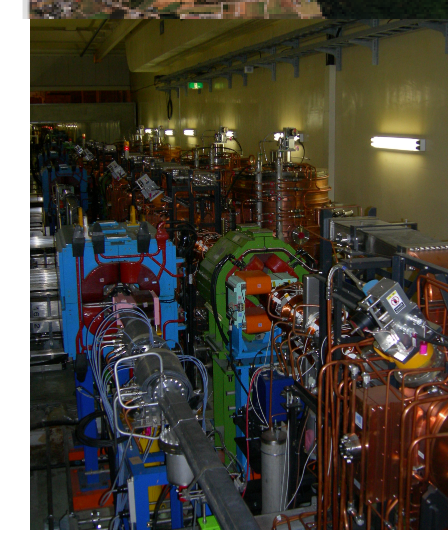
PEP-II and KEKB



PEP-II

- 9 GeV e^- on 3.1 GeV e^+
- Υ(4S) boost: $\beta\gamma = 0.56$



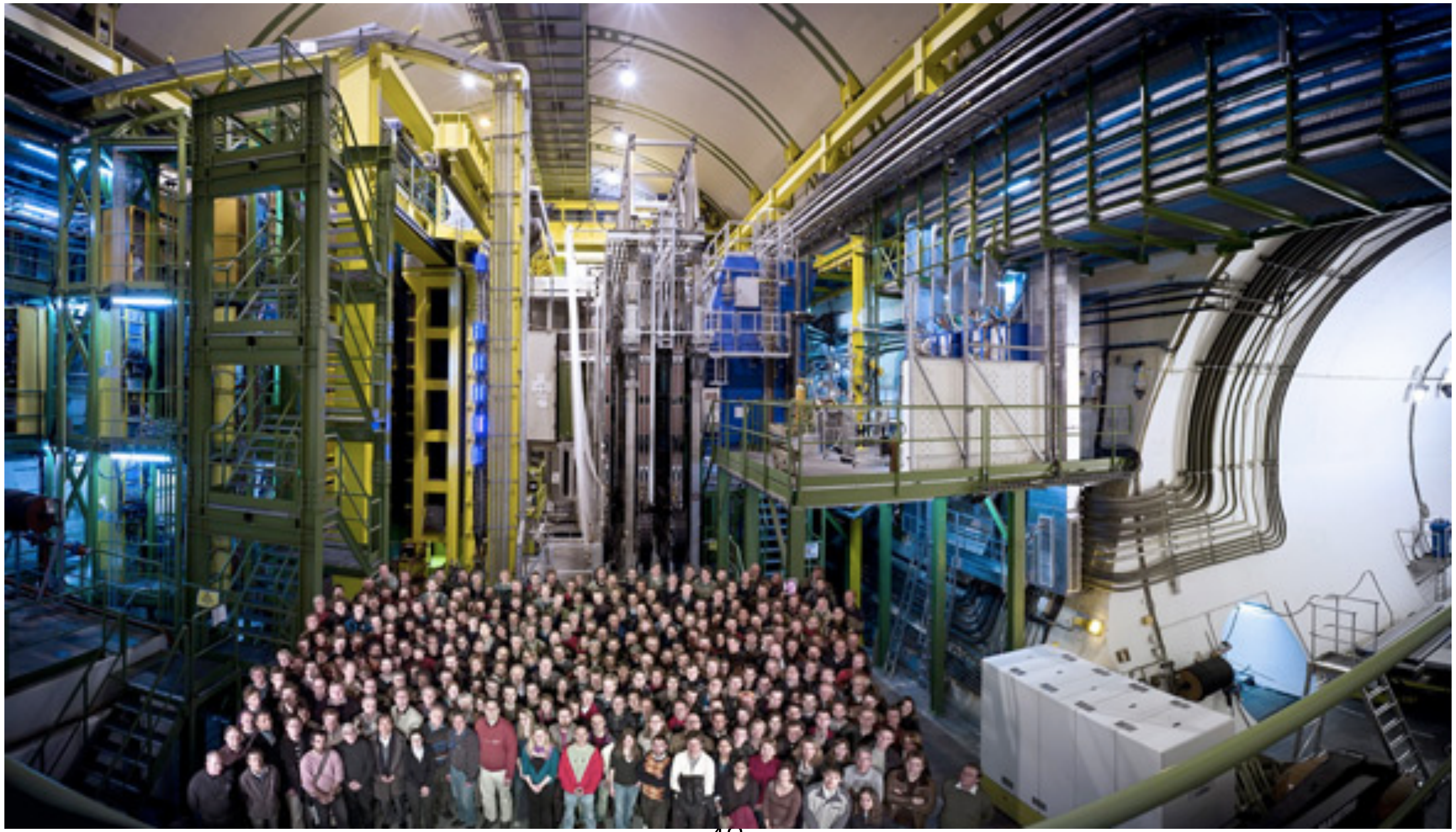


KEKB

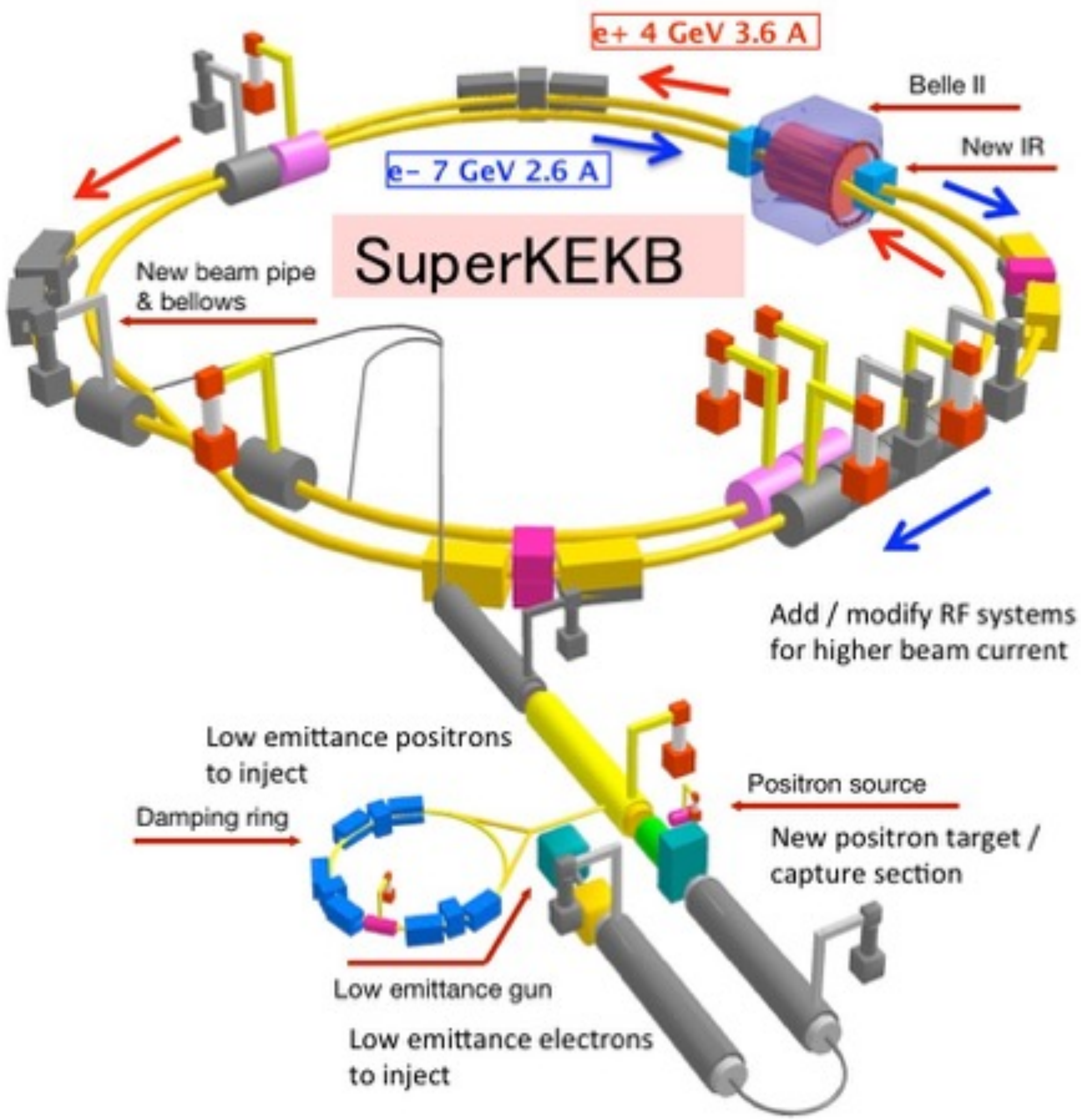
- 8 GeV e^- on 3.5 GeV e^+
- Υ(4S) boost: $\beta\gamma = 0.425$

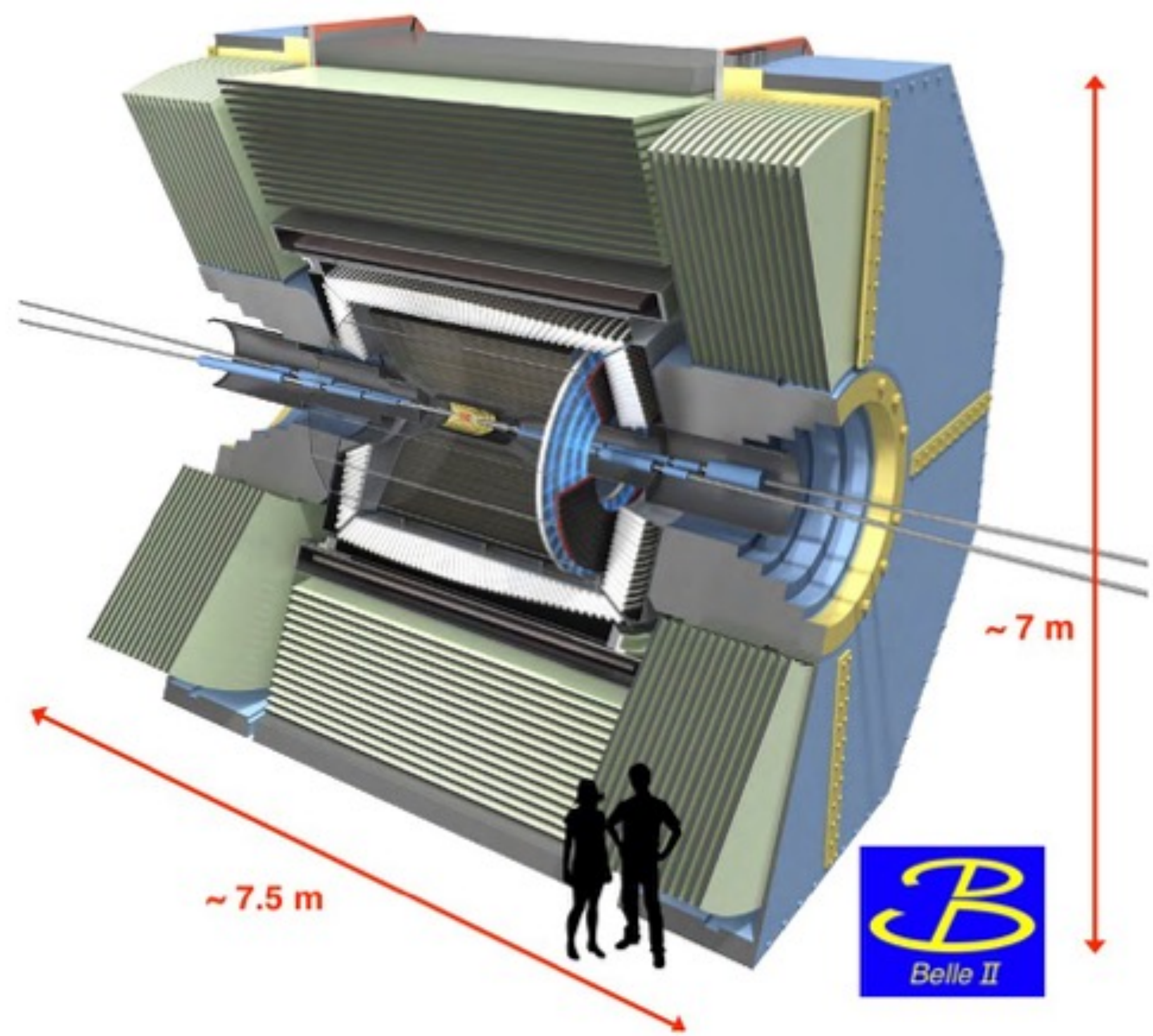
Hadronic B-Factory: LHCb@CERN

- Alternative: produce B mesons with high energy hadrons
  - Large cross sections for b quark proaction
  - Large Lorentz boost can be achieved at forward rapidities
- Disadvantage: large background from hadrons



Future Facility: Belle II @ SuperKEKB



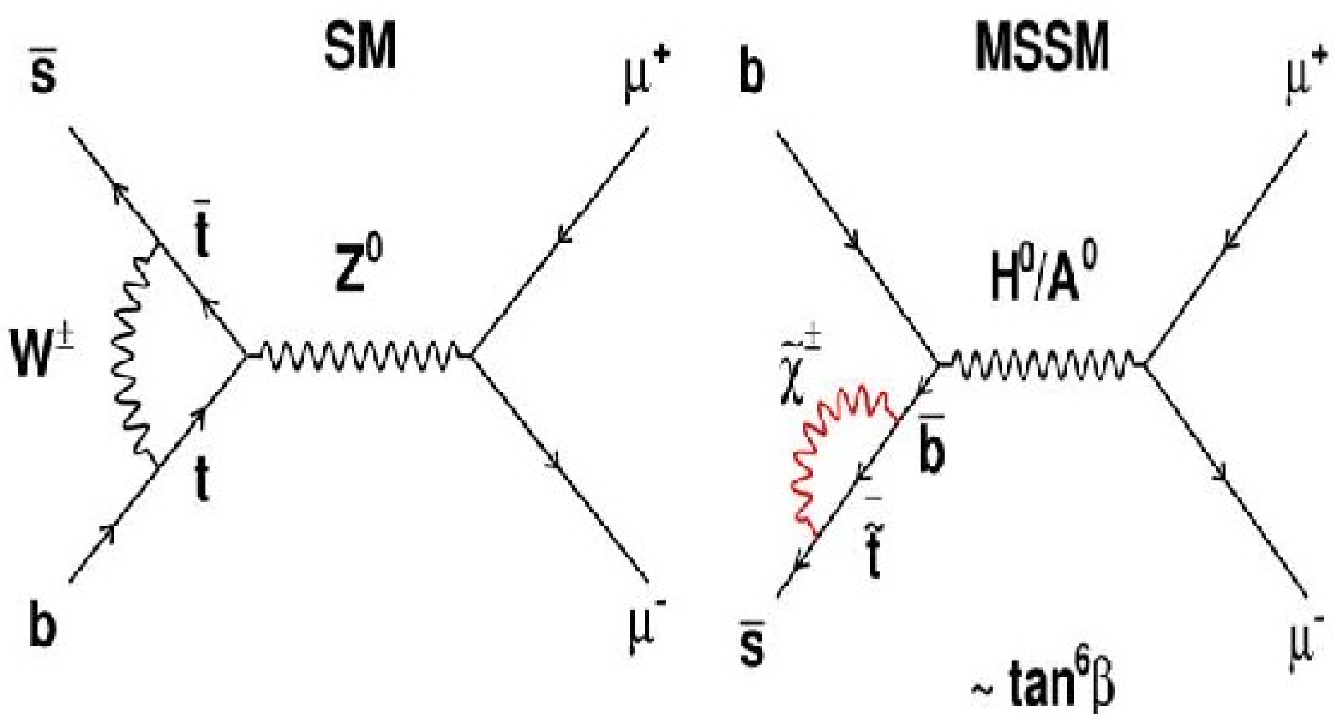


Luminosity: Belle x 40, much better detector

Search for new physics: rare decays

- In the SM, there are no flavour-changing neutral currents (no direct transition from b-quarks to s quarks via Z^0 emission)

- These processes can, however, occur via loop diagrams:



$B_{(s)}^0 \rightarrow \mu^+\mu^-$ **CMS, LHCb**

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

SM: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$.

$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

SM: $\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$.

- If we have sufficient precision (statistics) to see this process, we can compare to the expected SM rate
    - Any deviation might be a pointer to new physics

Summary

- The Standard Model of particle physics has been challenged by a very large number of different experiments. So far, no convincing contradiction was found
- We know, however, that the SM cannot be the final word, because it has a many parameters and fails to explain essential features of nature
  - Matter/Antimatter asymmetry in the universe, dark matter, the apparent existence of exactly 3 generations of quarks and leptons, the smallness of the neutrino masses, etc.
- To make progress, we have to search for new physics, for instance for particles, which do not appear in the standard model
  - Direct searches at the largest accessible energies. These experiments are limited by the maximum reachable energy (currently13 TeV @ LHC)
  - Indirect searches by precision flavor physics, where particles appear in loops and modify SM processes. Here, our sensitivity is not limited by the reachable energy but by the precision of the experiments:
- Both approaches will either find evidence for new physics or rule out existing theories of physics beyond the standard model