Introduction to the Physics of Particle Flavors

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Belle II Explorer

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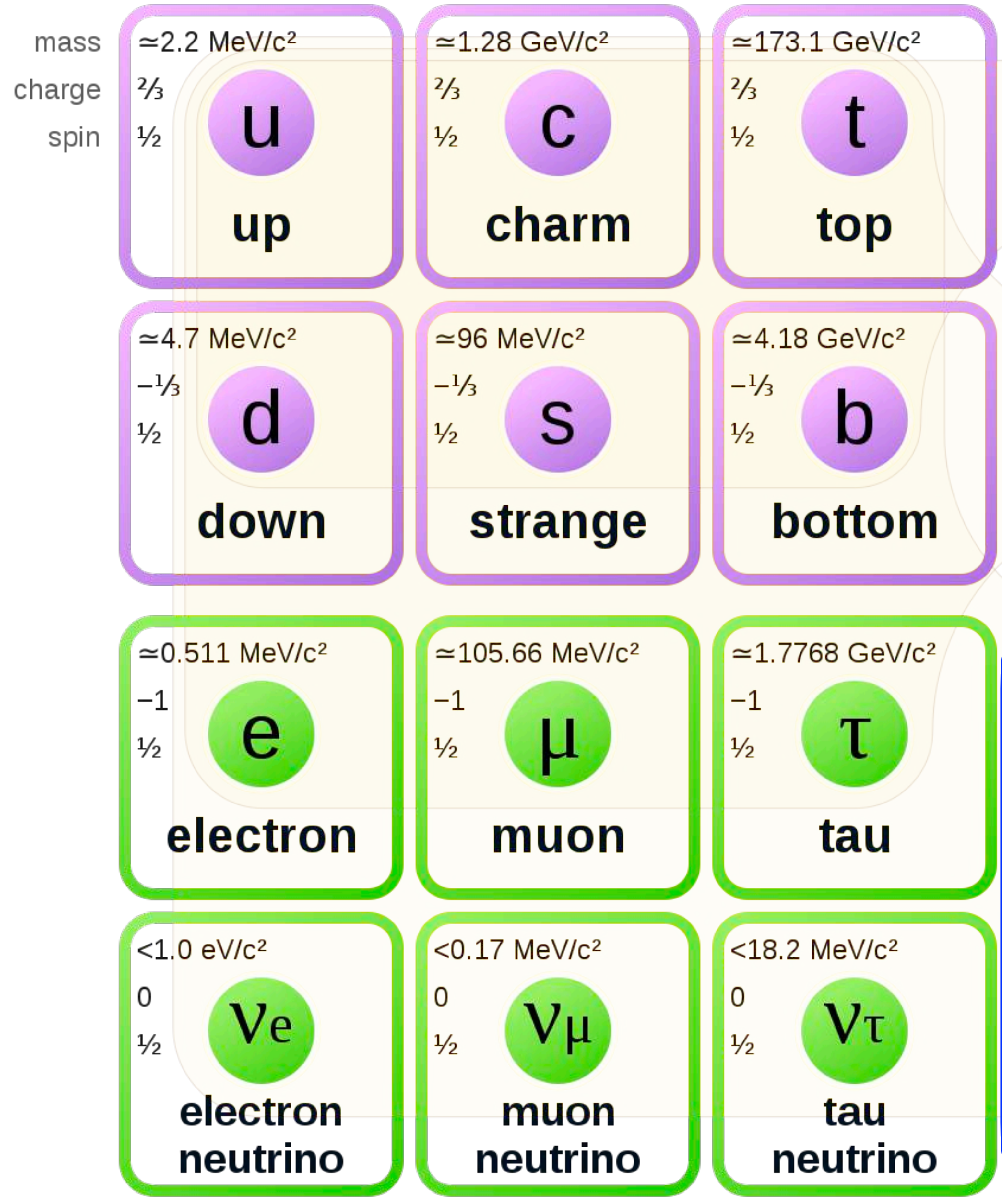
UNIVERSITY OF Cincinna

Belle II

What is flavor?

- **Flavor**: indicates the different types of Standard Model (SM) fermions, both quarks and leptons.



up type quarks

down type quarks

charged leptons

neutrinos

WIKIPEDIA
The Free Encyclopedia

Flavour in particle physics

Flavour quantum numbers

- Isospin: **I** or I_3
- Charm: C
- Strangeness: S
- Topness: T
- Bottomness: B'

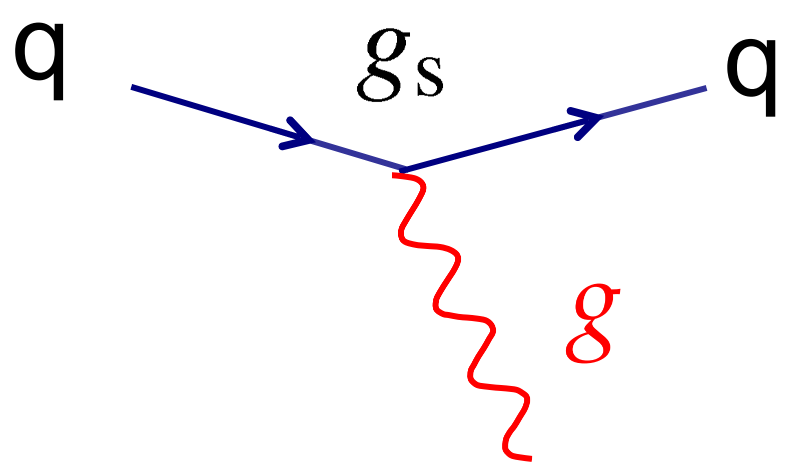
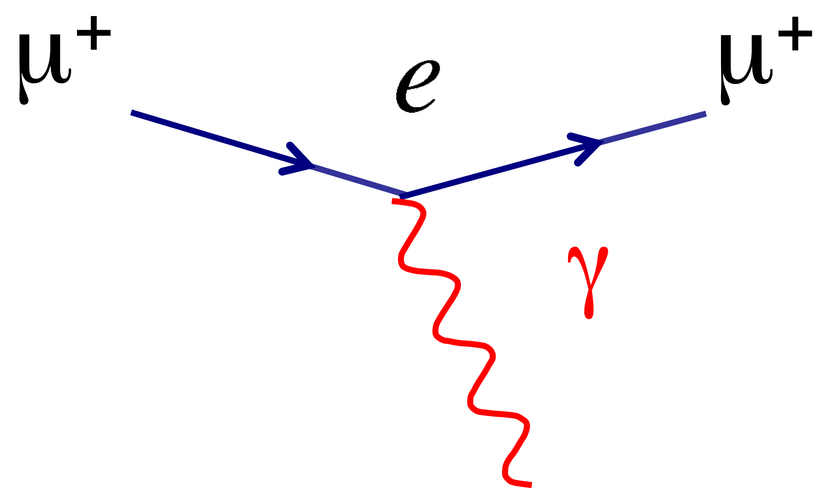
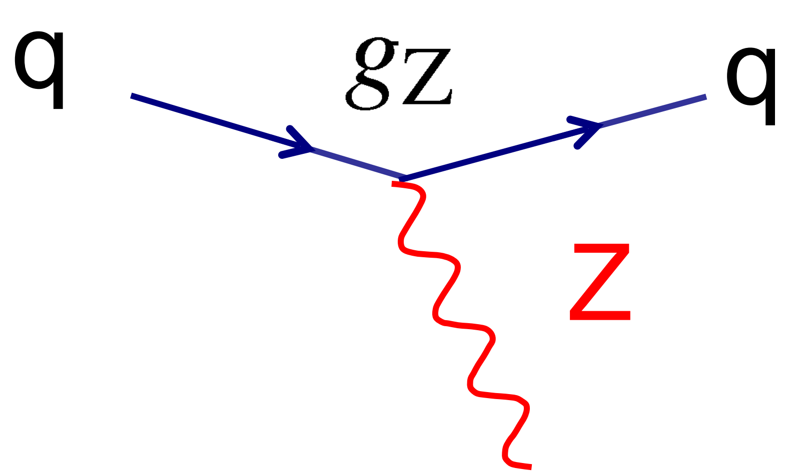
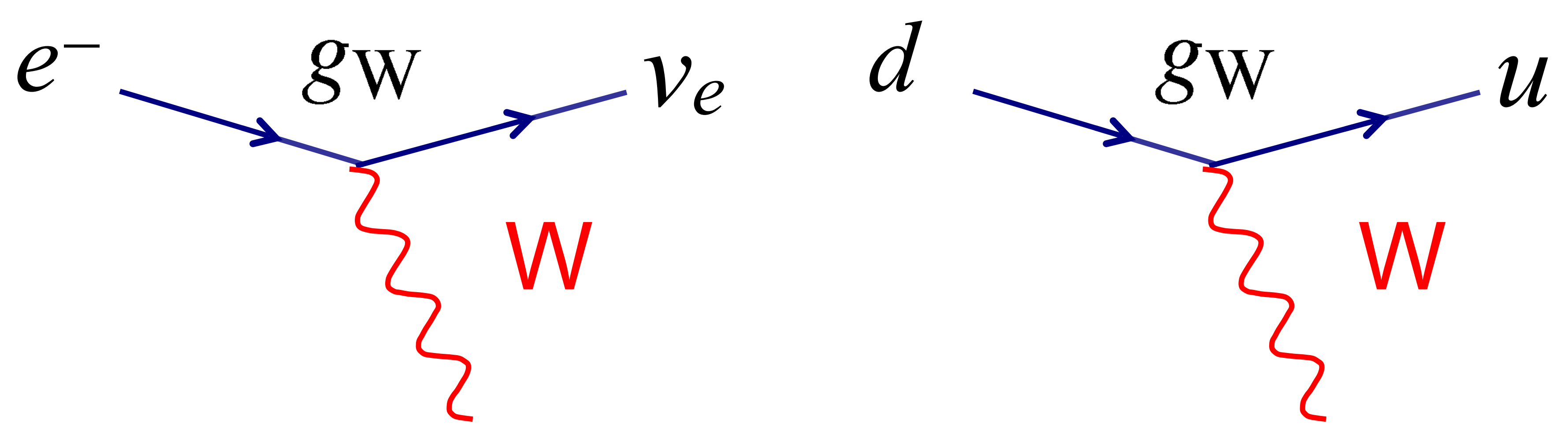
Related quantum numbers

- Baryon number: B
- Lepton number: L
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations

Standard Model Vertices

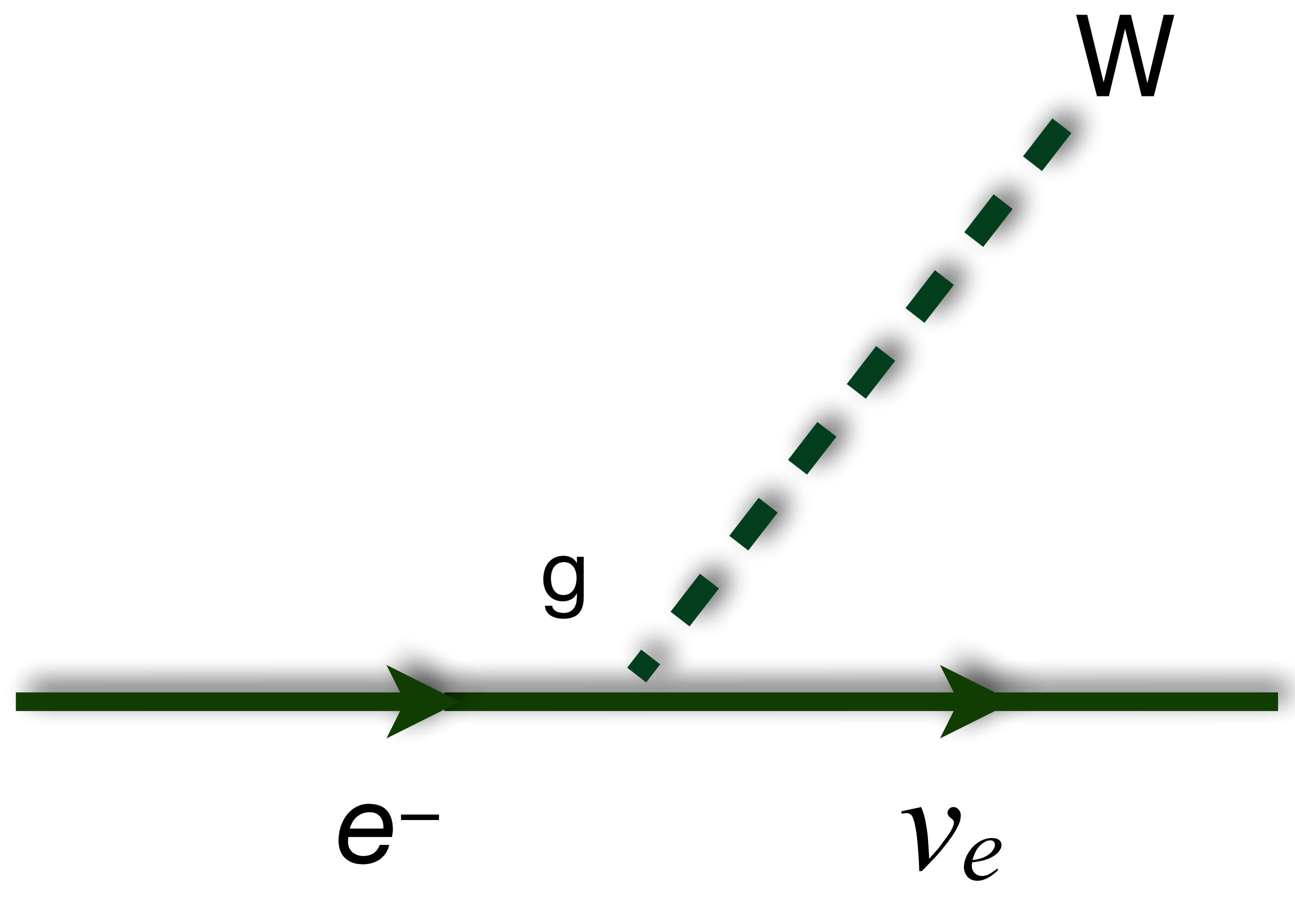
- Interaction of gauge bosons with fermions described by SM vertices
- Properties of the gauge bosons and nature of the interaction between the bosons and fermions determine the properties of the interaction

Strong Interaction	Electromagnetism	Weak Interactions	
STRONG	EM	Neutral WEAK	Charged WEAK
			
Only quarks	All charged fermions	All fermions	All fermions
Never changes flavor	Never changes flavor	Never changes flavor	**Always changes flavor**

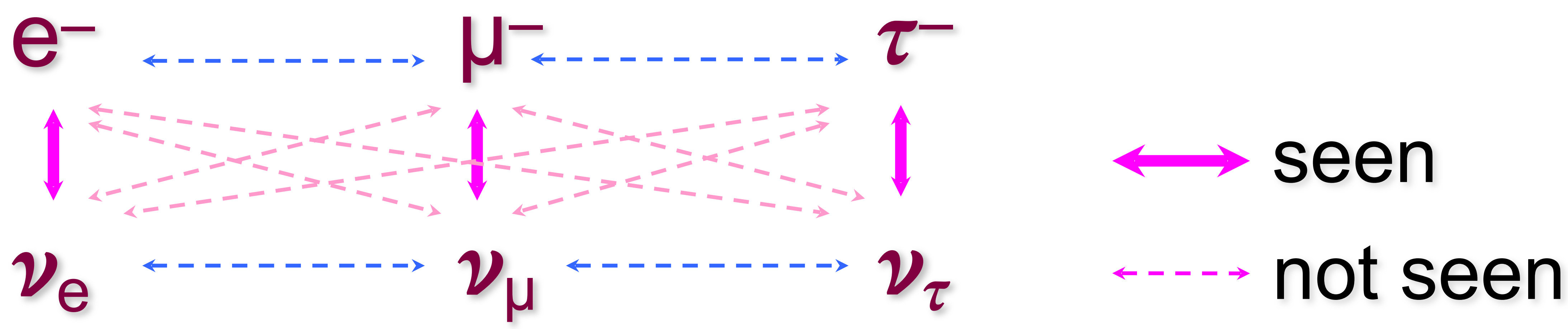
Flavor Change

Only the weak interaction allows flavor change

Leptons: no generation crossing



$W^\pm$ "charged current"



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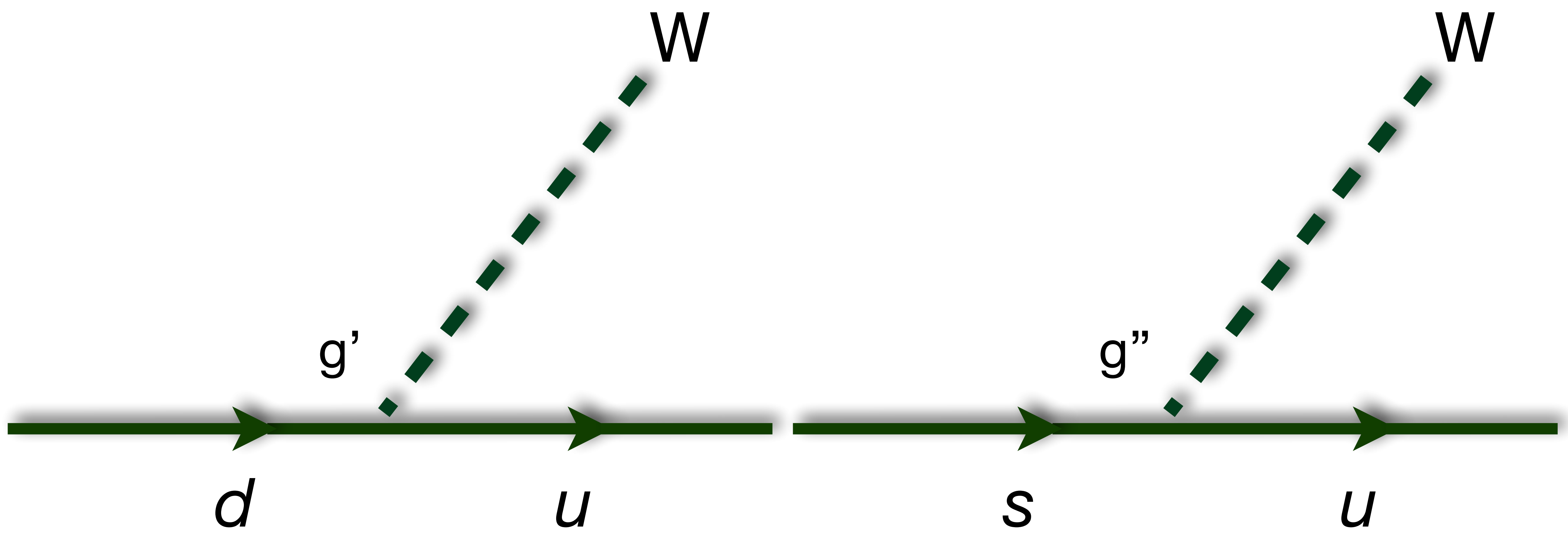
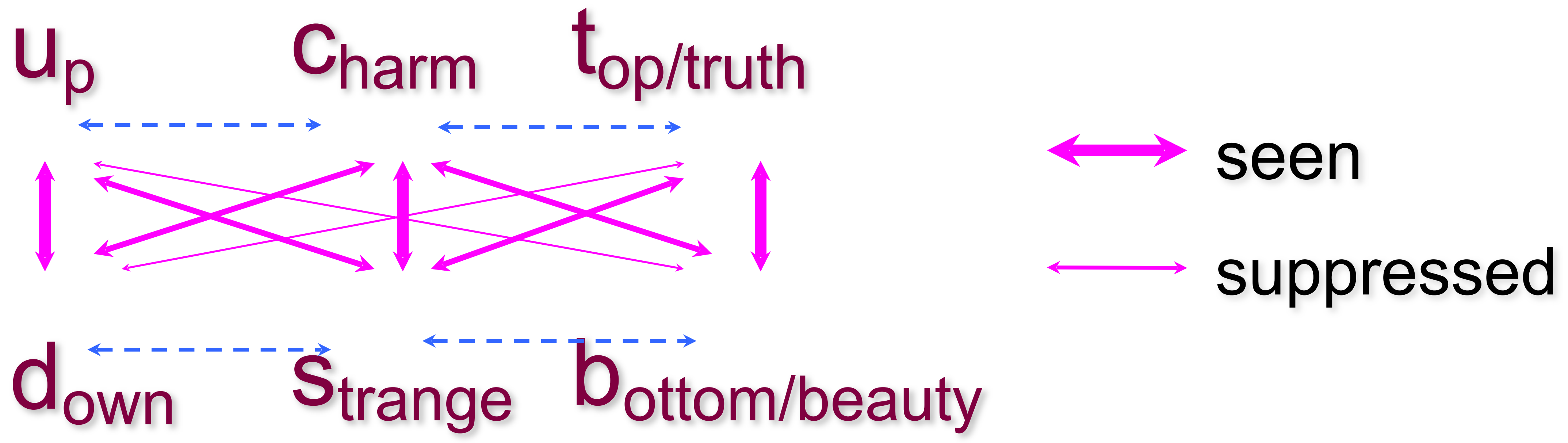




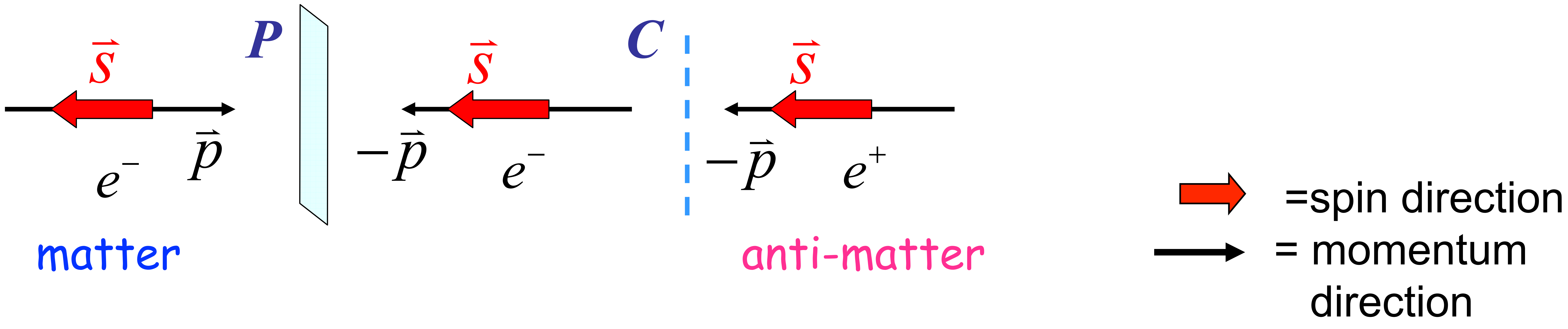
Why do we study flavor physics?

- Obtain deeper understanding of the fundamental flavor structure of the nature.

- Charge Parity (*CP*) violation and its connection to the matter dominated Universe. (*Matter-antimater asymmetry of universe requires CP-violating interactions (Sakharov 1967)*)

- Discover effects of new particles and forces beyond the Standard Model – even particles too massive to be produced at the high energy colliders.

What is CP?

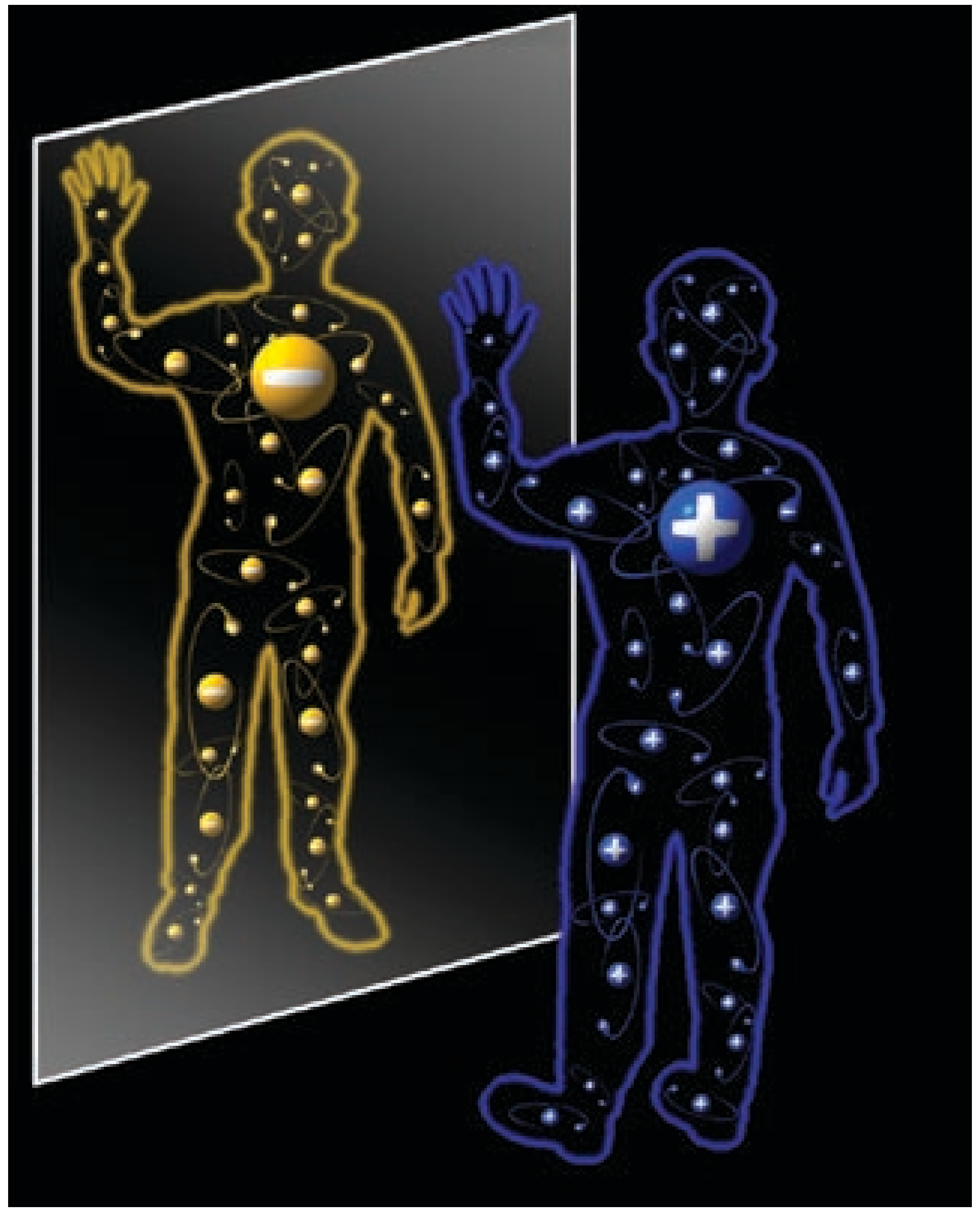


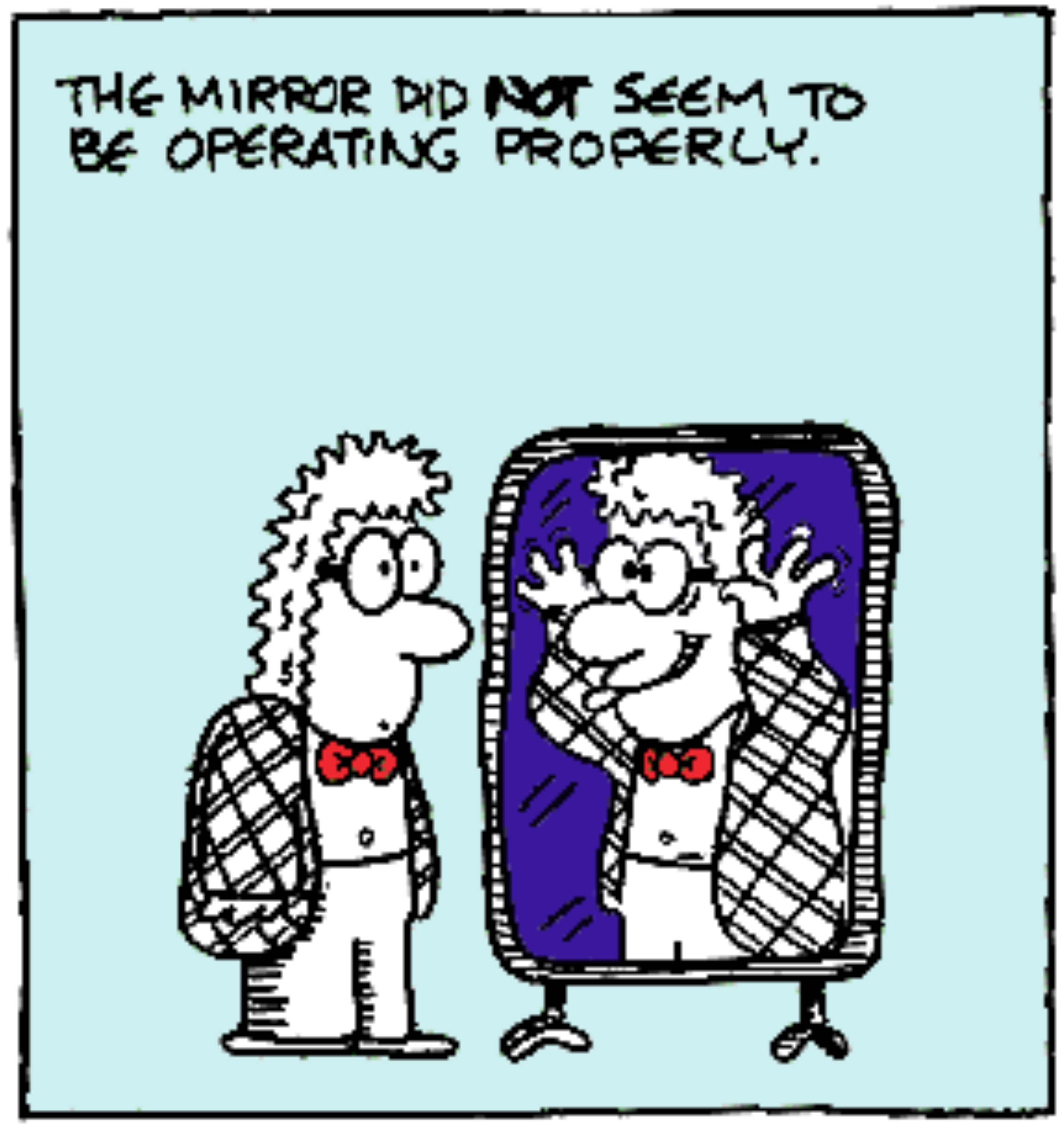
- Parity, P
  - $(\vec{r} \rightarrow -\vec{r}\ , \vec{p} \rightarrow -\vec{p}\ , \vec{L} \rightarrow \vec{L}\ )$
- Charge Conjugation, C
  - $e^- \rightarrow e^+$, $K^+ \rightarrow K^-$
- CP is the product of the C and P operators.
  - CP transformation converts a particle into its anti-particle.

CP Symmetry, Particles - Antiparticles

"*CP*-mirror," a device that returns the mirror image of the anti-matter.

CP is violated IF particles and anti-particles behave differently!





What is different about the weak interaction?

Only the weak interaction allows flavor change

CP is violated in weak interactions

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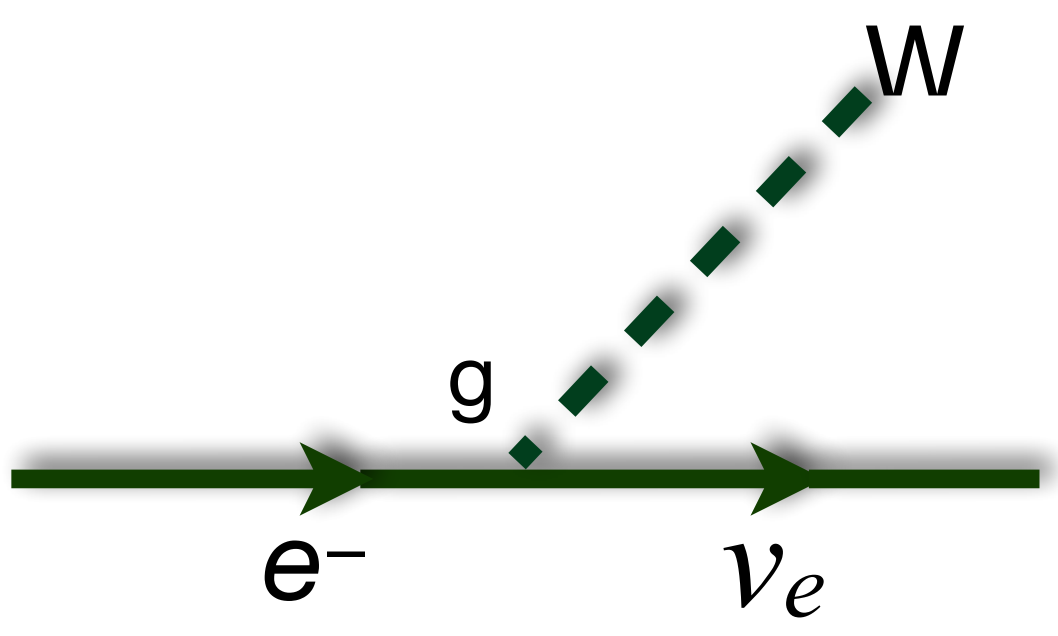

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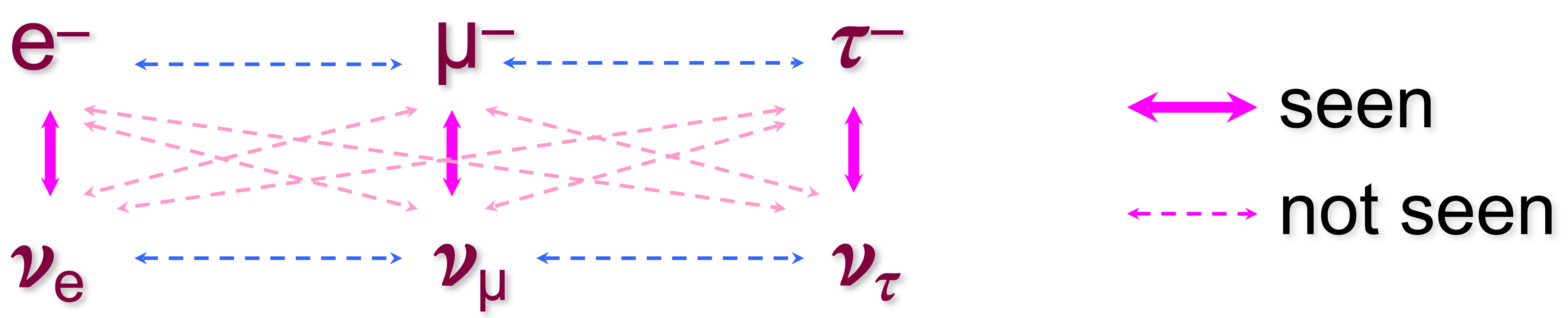

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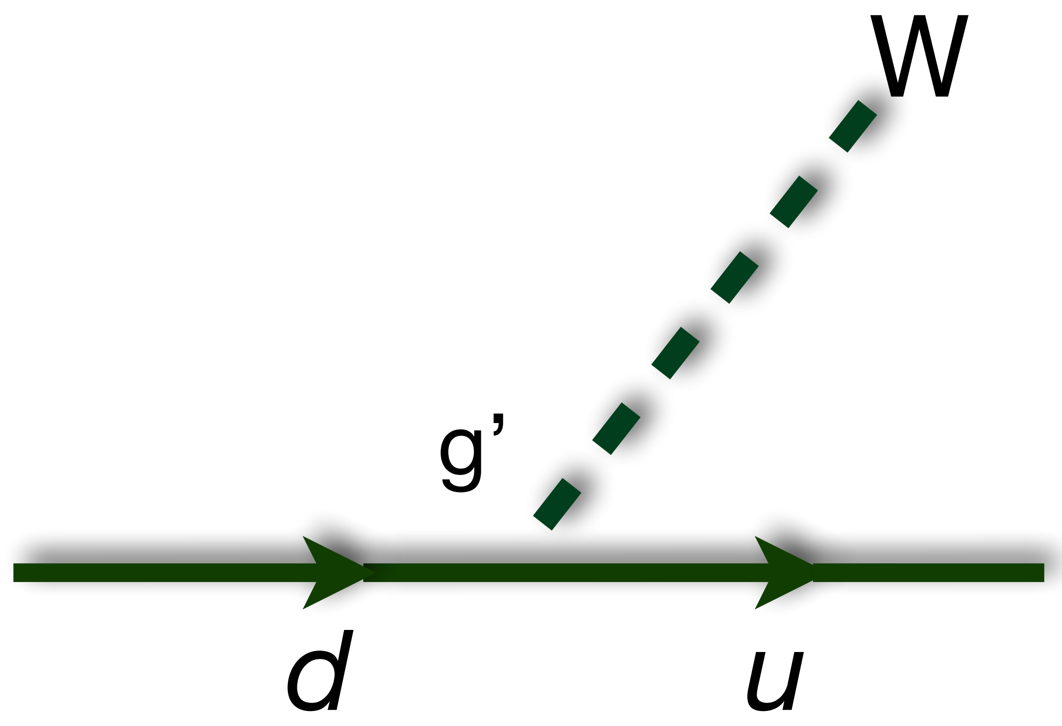

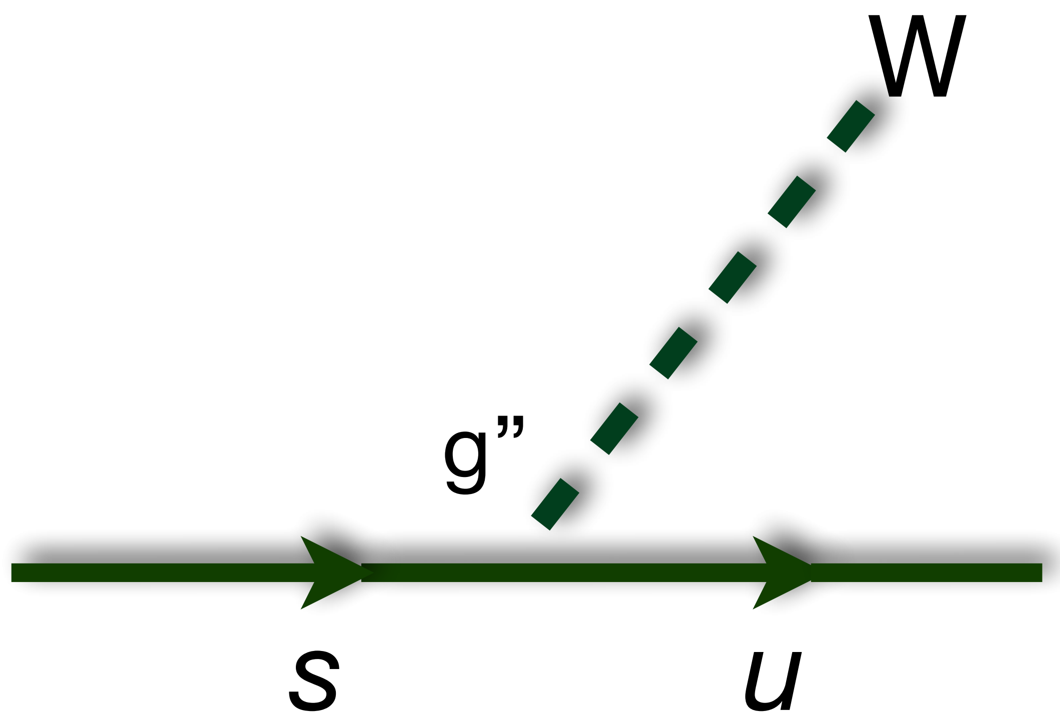

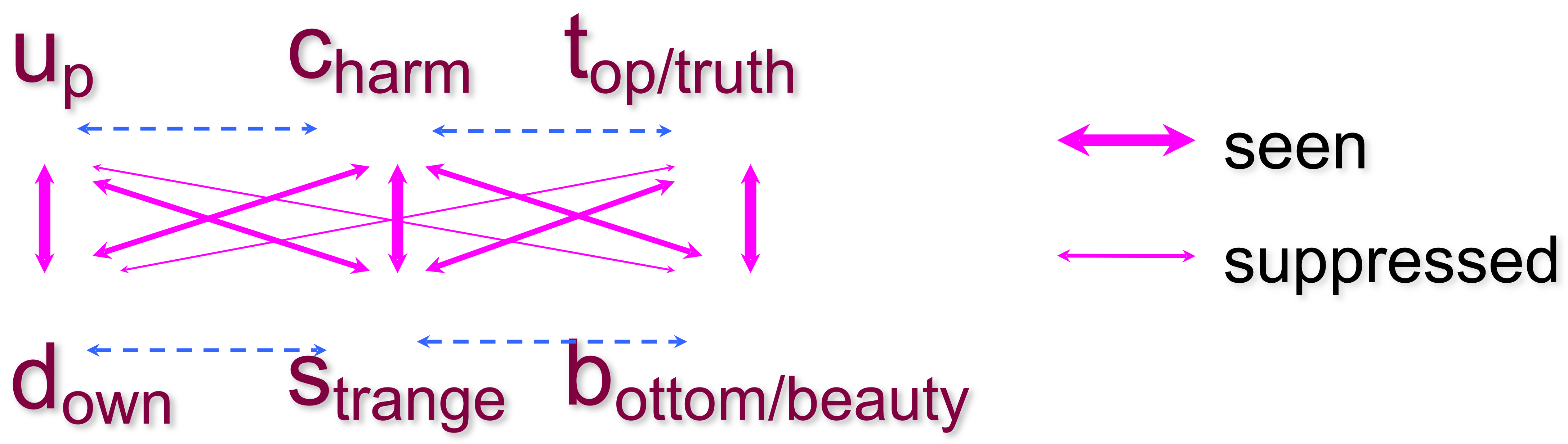

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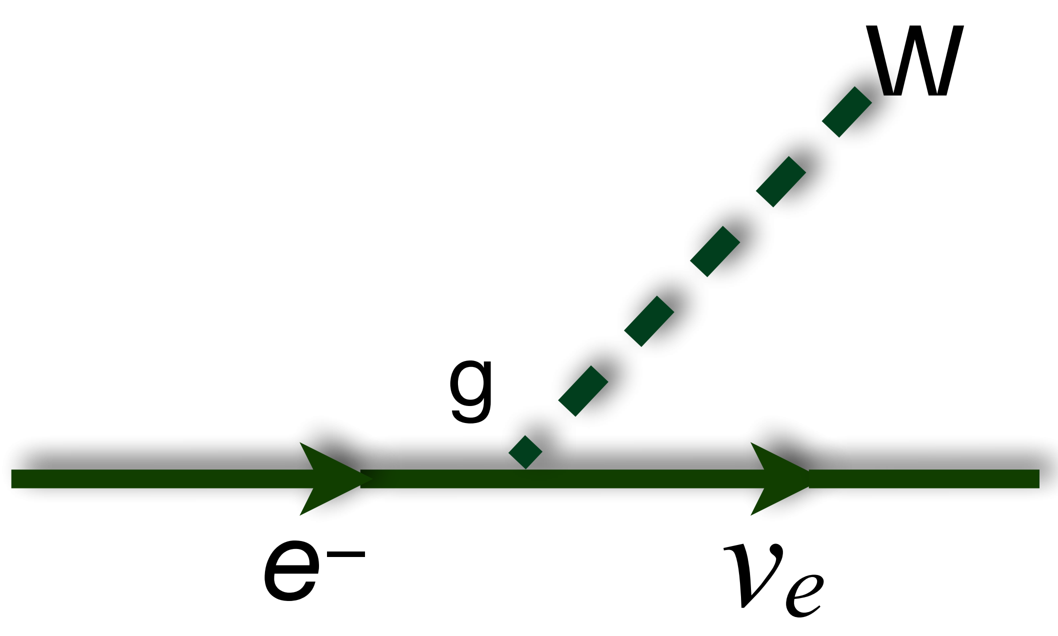

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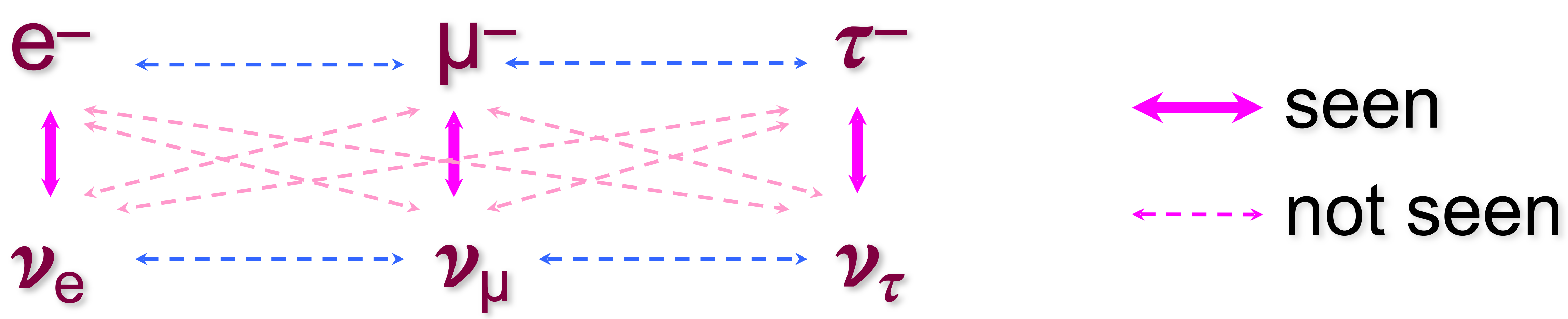
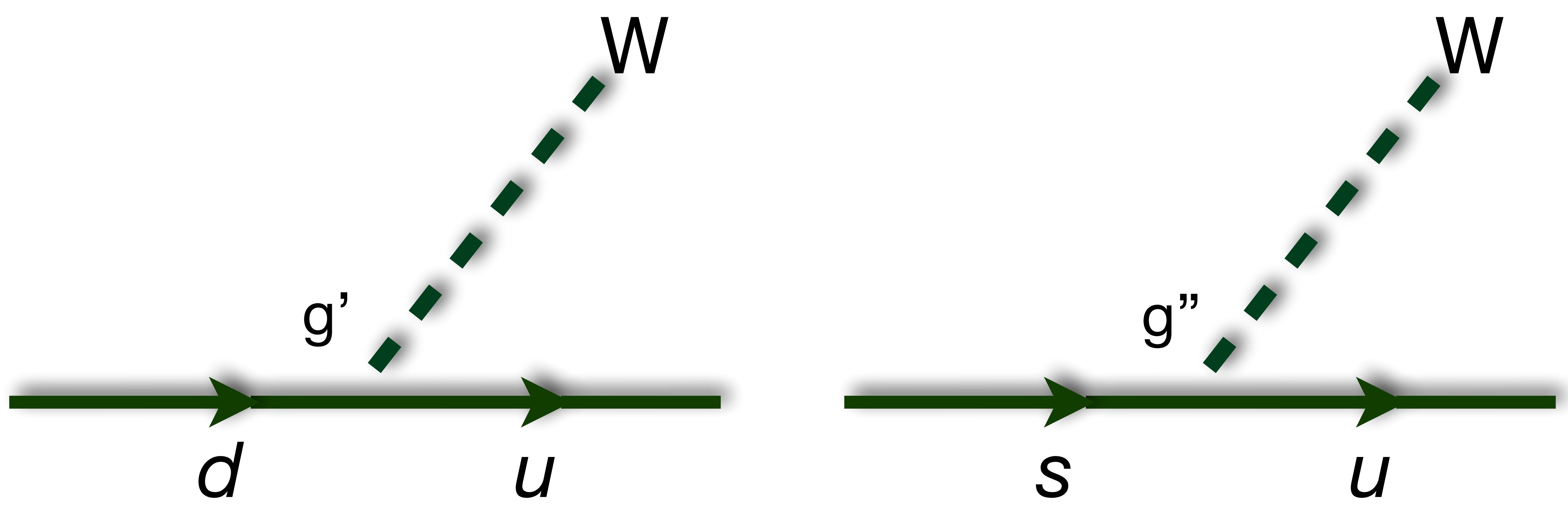
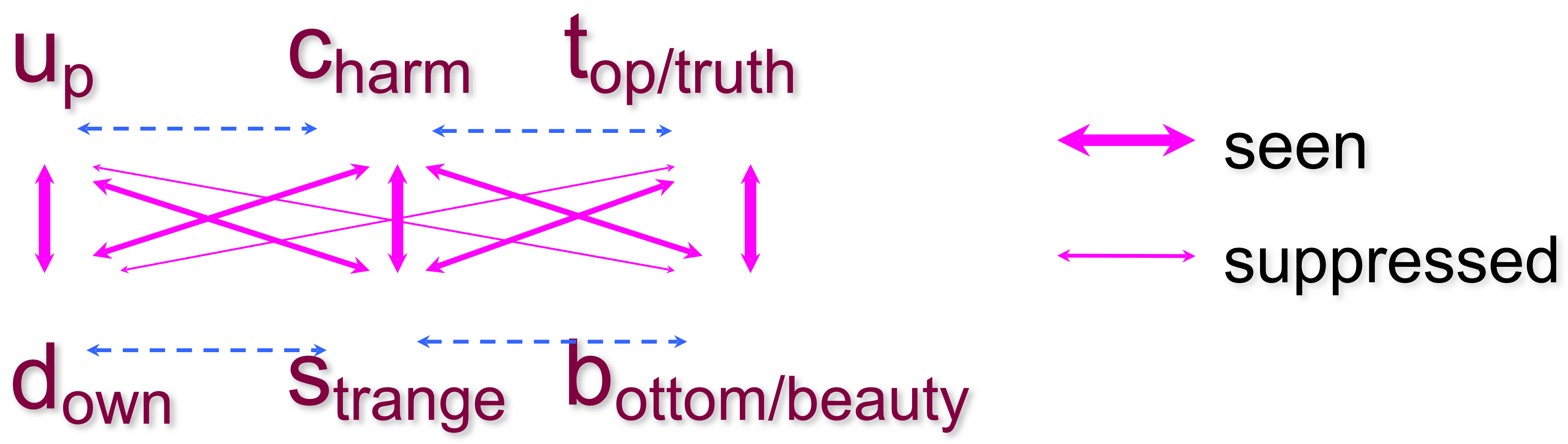


the pattern was not initially understood

Quarks: generation crossing





Quark Mixing

The solution was suggested by Cabibbo in 1963, perfected by Glashow, Illiopoulos, and Maiani (GIM) in 1970, and a an explanation for CP violation is proposed by Kobayashi and Maskawa (KM) in 1973:

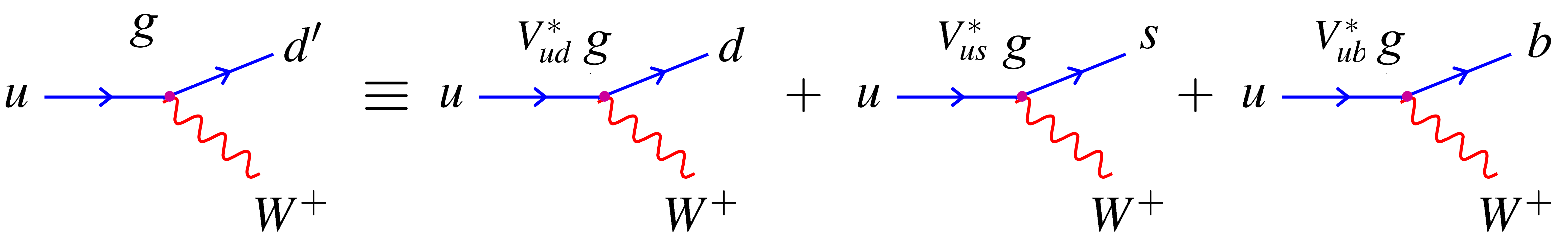
Instead of $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$ the weak force couples the pairs $\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}$

where d', s', and b' are linear combinations of the physical quarks d, s, and b

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

Cabibbo Kobayashi Maskawa (CKM) Matrix

e.g.



Universal weak coupling g must be multiplied by element of CKM matrix V_{ij}.

Quark Mixing

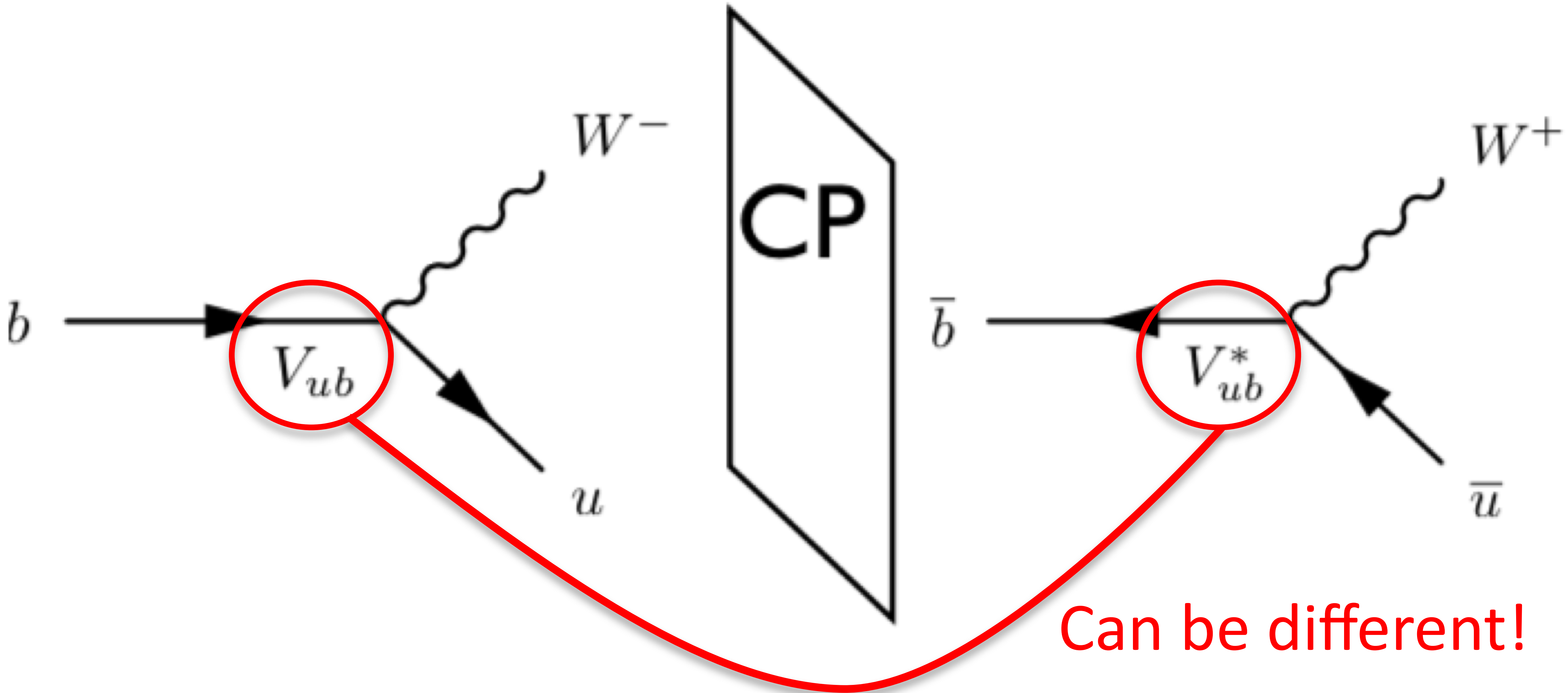
(Kobayashi-Maskawa **1973**)

Kobayashi and Maskawa proposed the explanation for CP violation in weak interactions prior to discovery of bottom and top quarks.

Explicit parameterization (Wolfenstein)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \underbrace{\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{bmatrix}}_{V_{CKM}} + \mathcal{O}(\lambda^4)$$

irreducibly complex $\Rightarrow$ ***CP* Violation!**



Quark Mixing

CP-violation measured in B-decays: 2002

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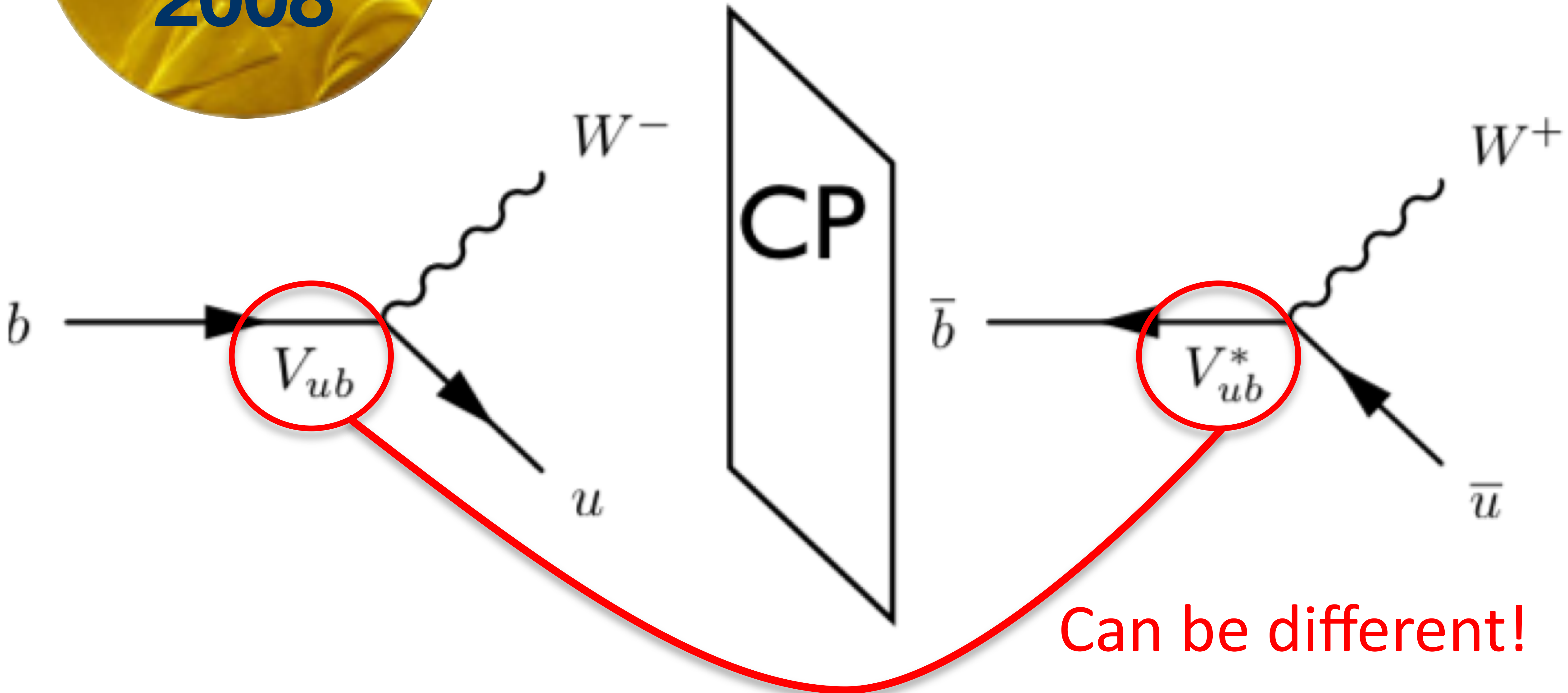

The CKM Matrix and "Unitarity Triangle(s)"

- Unitarity condition: $(V_{CKM})^{\dagger}\, V_{CKM} = \mathbf{1} \;\Leftrightarrow\; \sum_j V_{ij} V^*_{jk} = \delta_{ik}$

- The 9 unitarity conditions of the 3×3 generations CKM matrix:

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

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multiply *

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- The 6 complex "**Unitarity Triangles**" involve different physics processes

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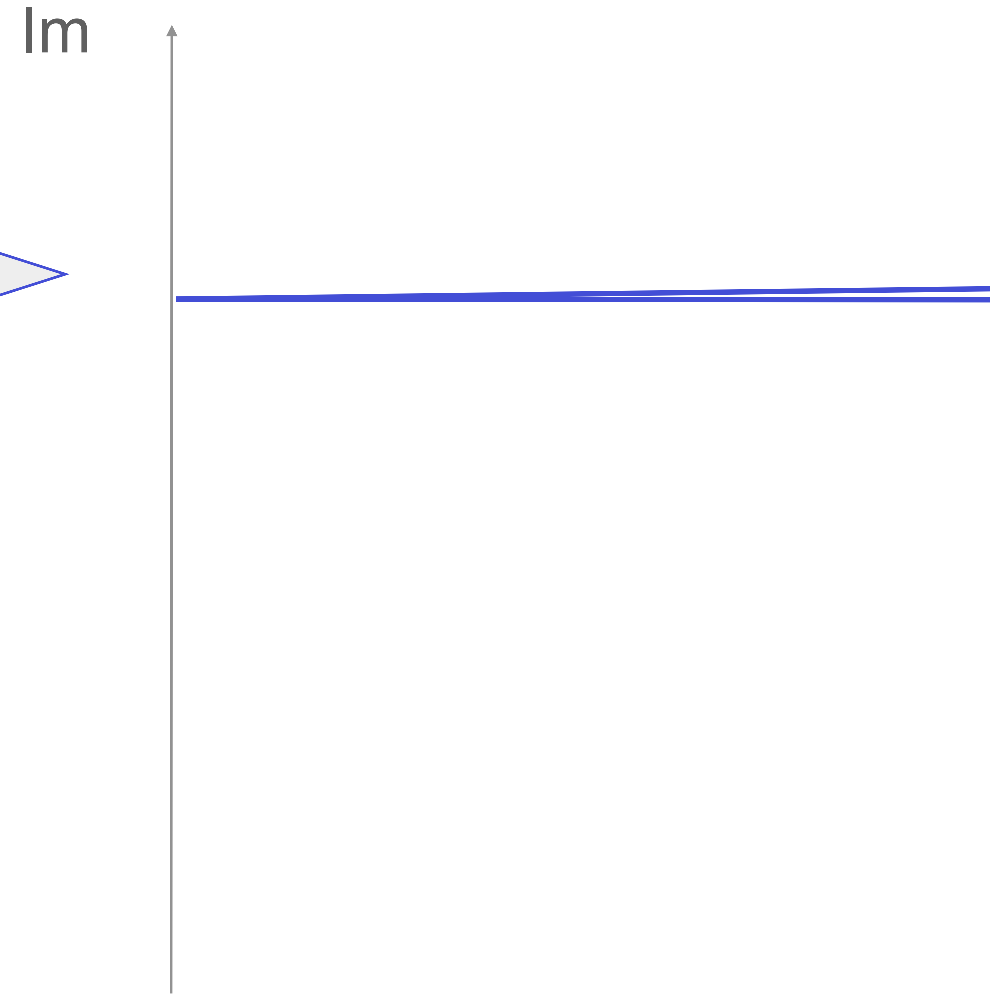
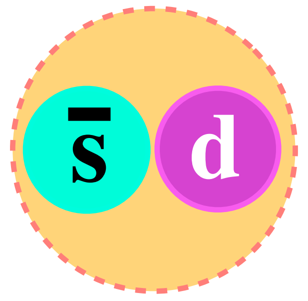


K^0 system



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multiply

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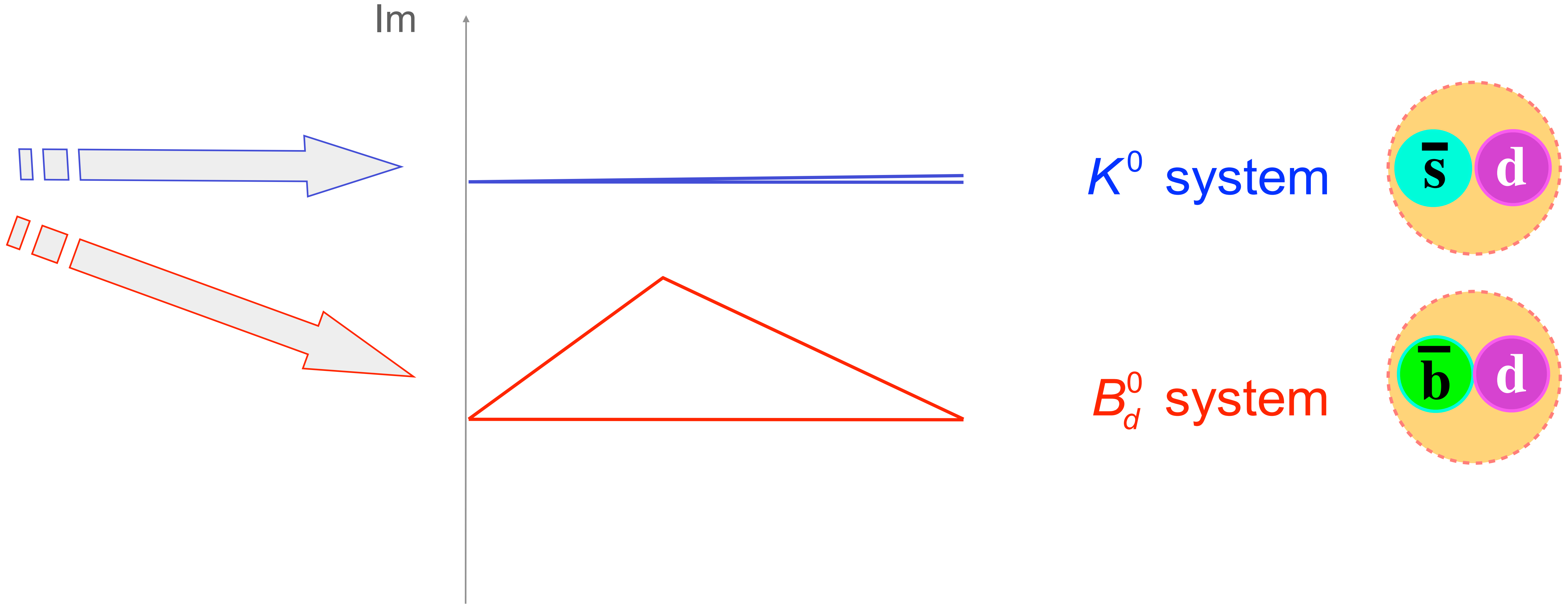

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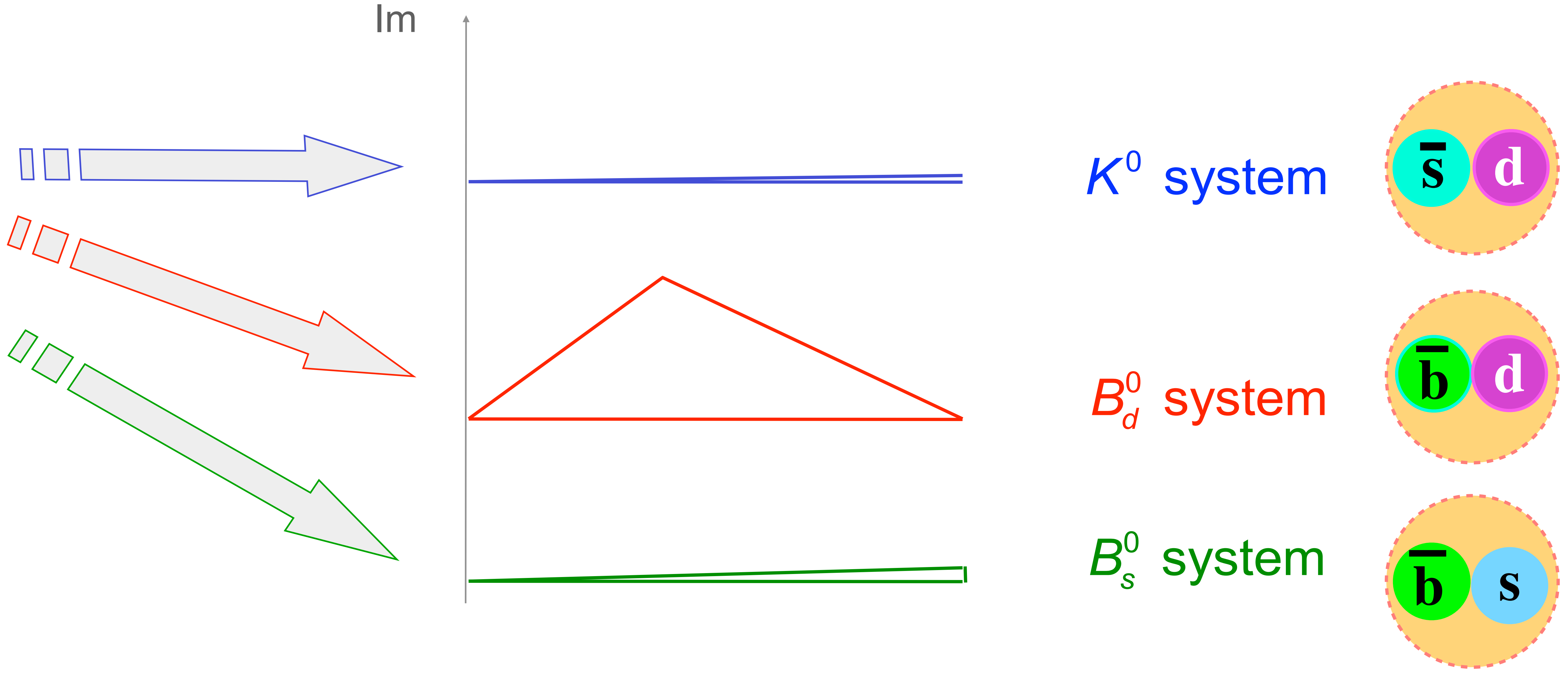

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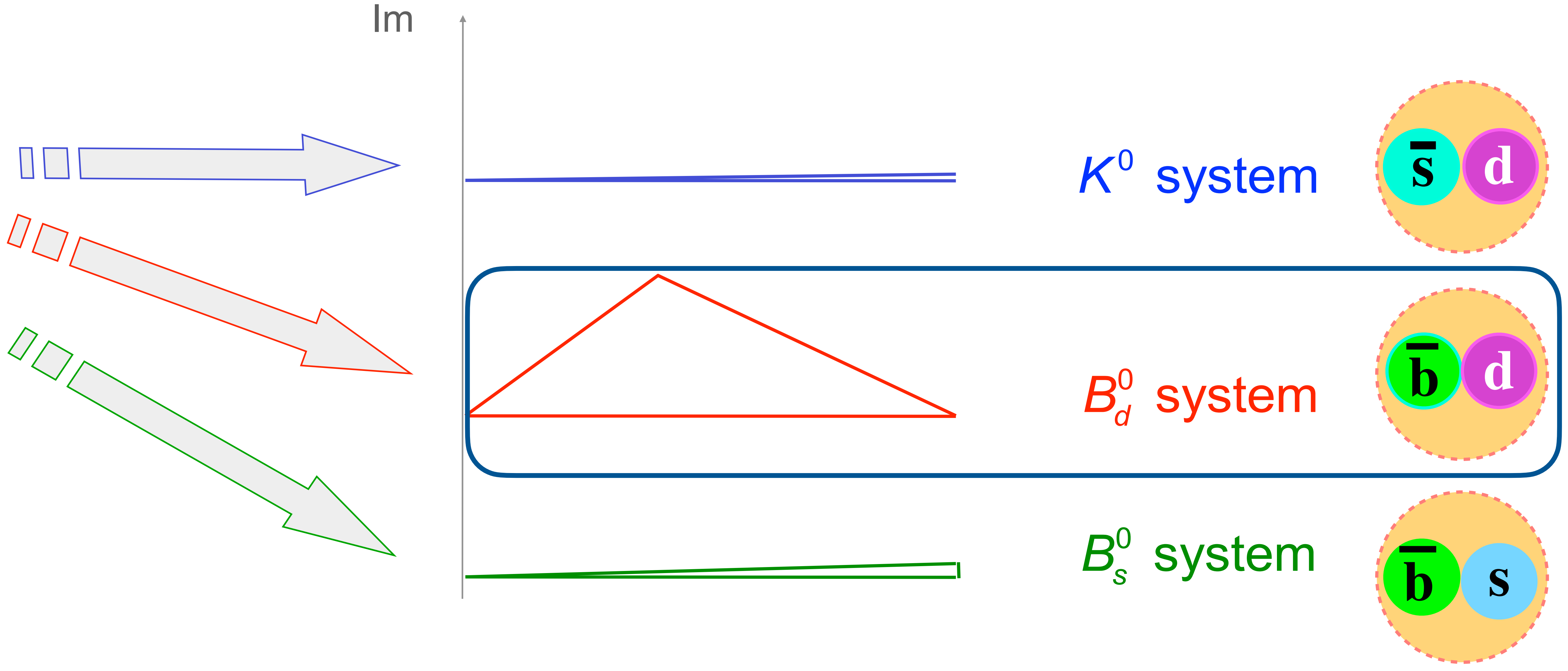
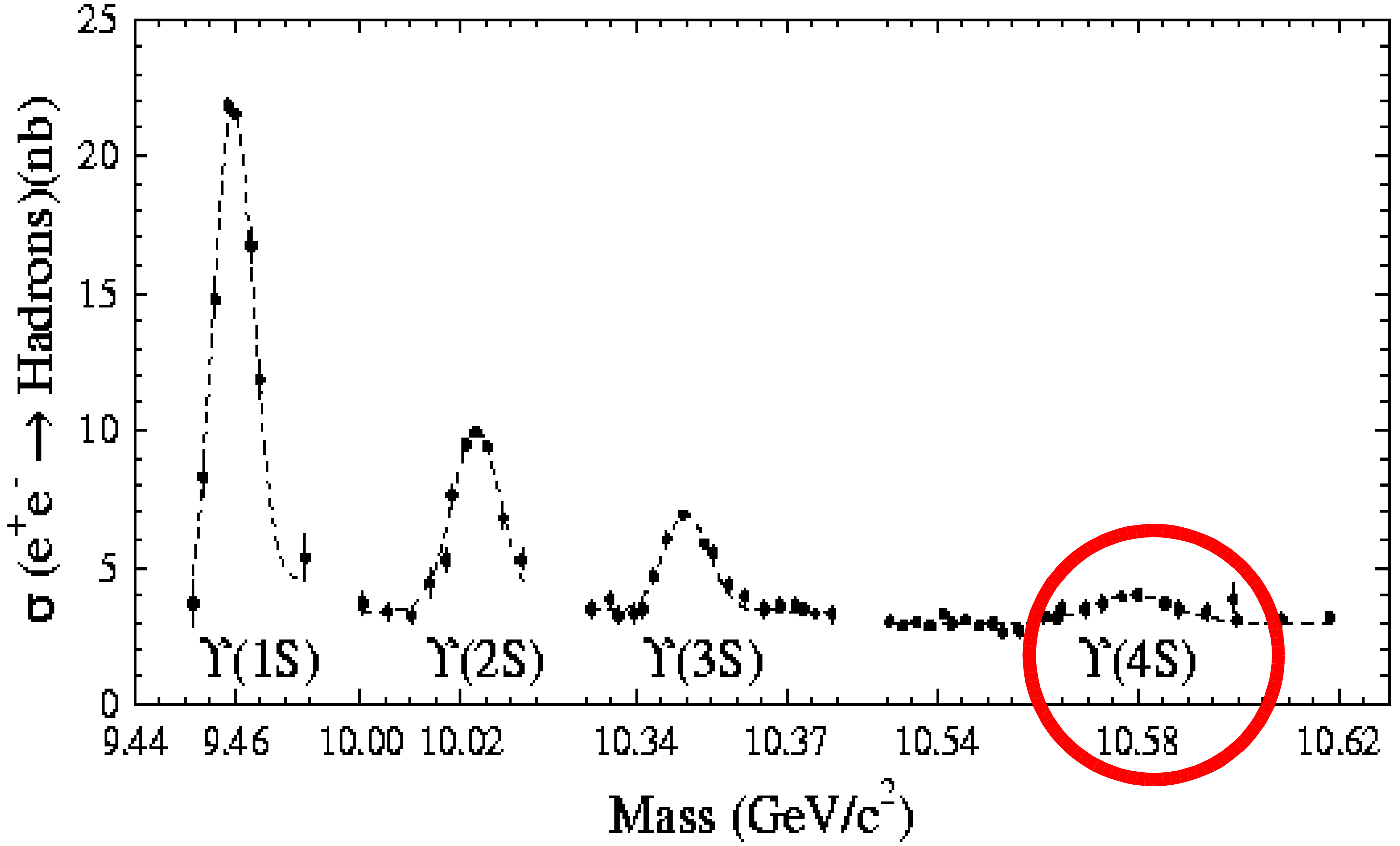


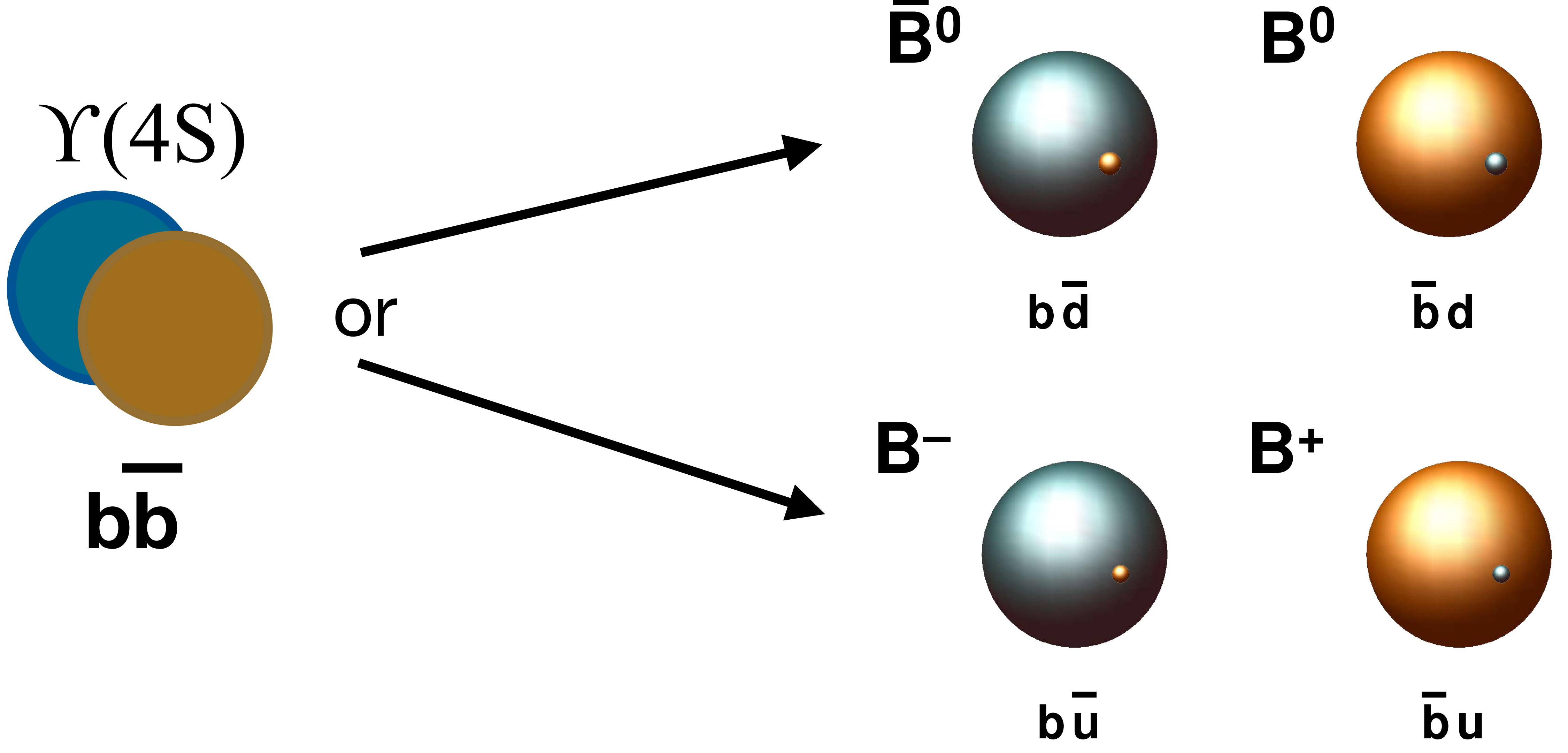
height measures the amount of CP violation

One Way to Produce *B*'s

Use e^+e^- annihilations at **Upsilon (4S) [Υ(4S)]** particle which decays to ***B*** mesons

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$





$m_{\Upsilon(4S)} \sim 10.58$ GeV $\qquad m_{B^0} \sim m_{B^-} \sim 5.28$ GeV

The Υ(4S) - a clean source of *B* meson *pairs*

Equal amounts of matter and anti-matter

B Factory - Super KEKB and BELLE II detector

B-Factory experiments [Belle at KEK(Japan), BaBar at SLAC (Stanford)] (1999-2009)

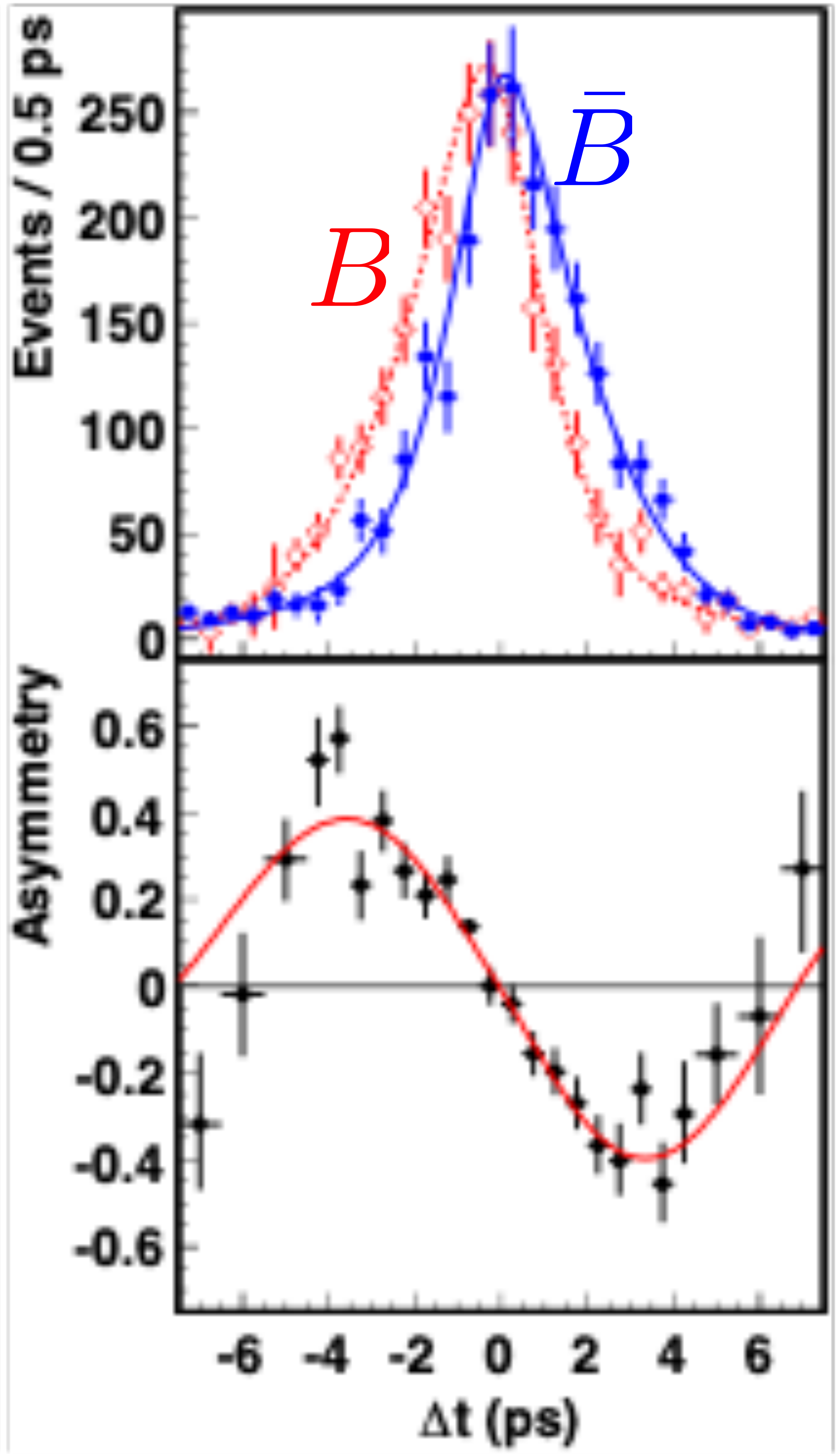
- CP asymmetry observed in diverse processes in B decay

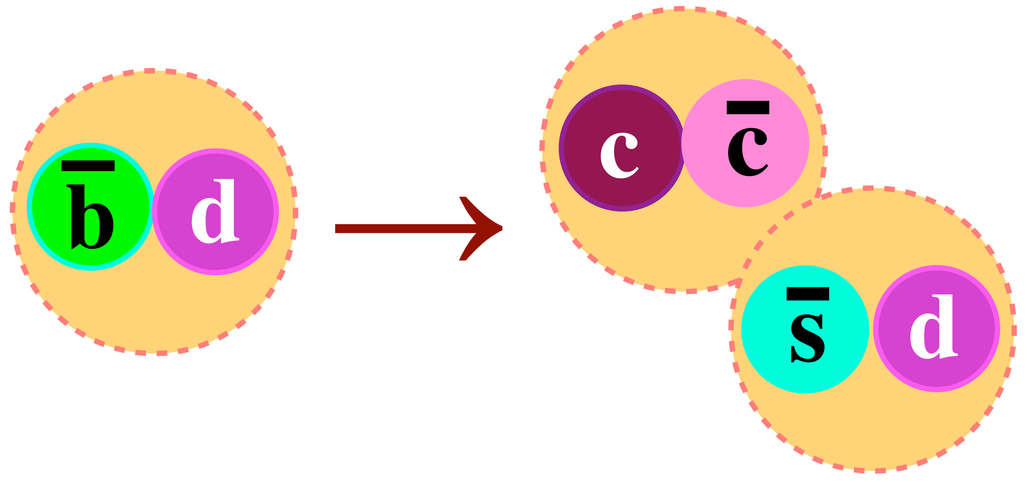
-> many measurements, (over)constrain CKM, confirm unitarity

Next generation B factory, BELLE II detector at Super KEKB will be covered by Dr. Seema Choudhury

Measurement of CP Violation in $B^0 \to J/\psi\, K_s^0$

PRL 108, 171802 (2012)





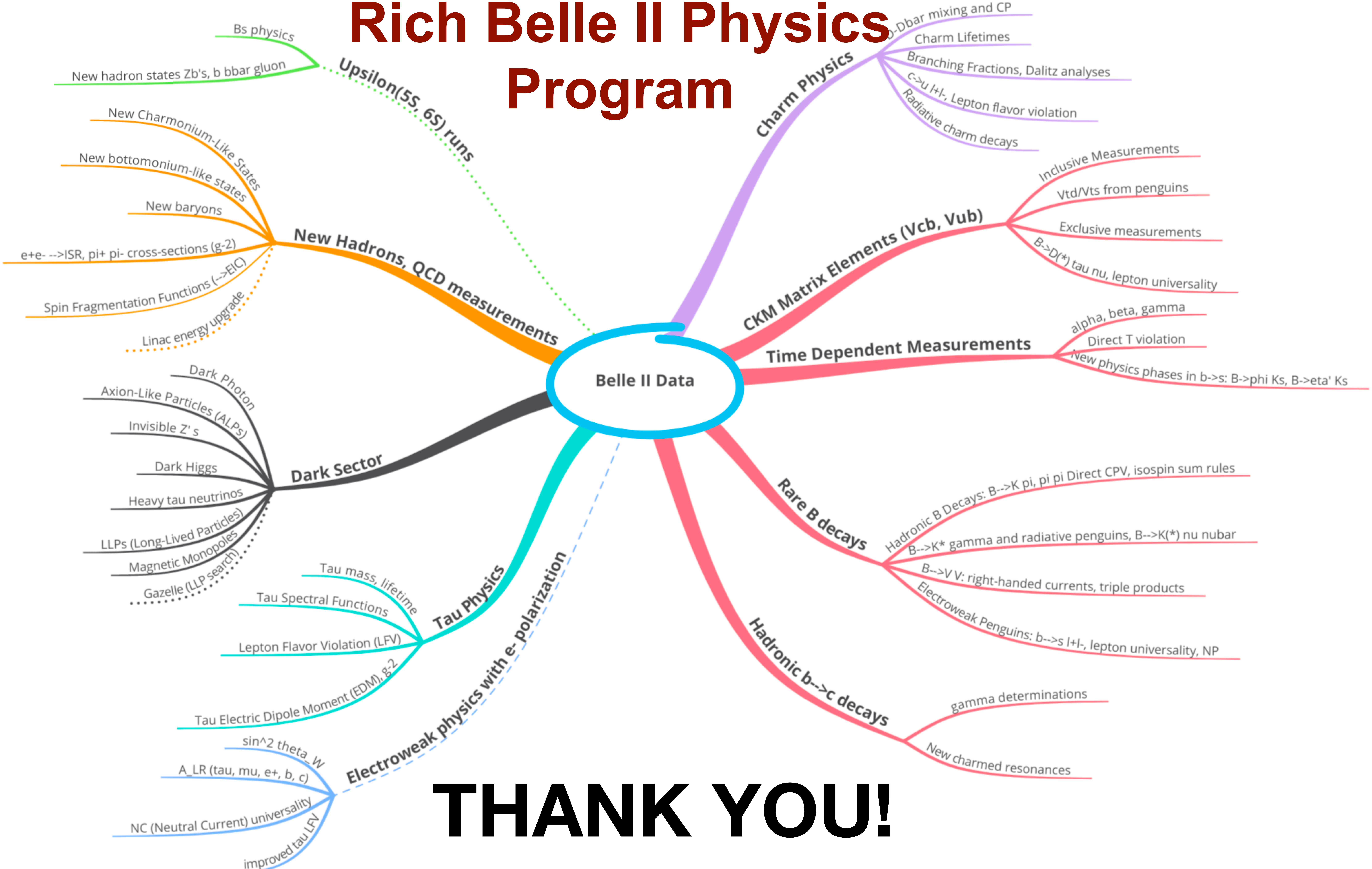
- Top plot shows the decay time distribution for B^0 and anti-B^0. Matter and anti-matter are essentially different.
- If CP were conserved in nature, the bottom distribution would be completely flat.

Belle collected
7.7×10^8 B events
for this plot

CP Violation and the Standard Model

- However, the Standard Model sources of *CP* violation cannot explain the matter dominance of the universe.
- We have to search for new sources of *CP* violation
  ⇒ New physics beyond the Standard Model.

Rich Belle II Physics Program



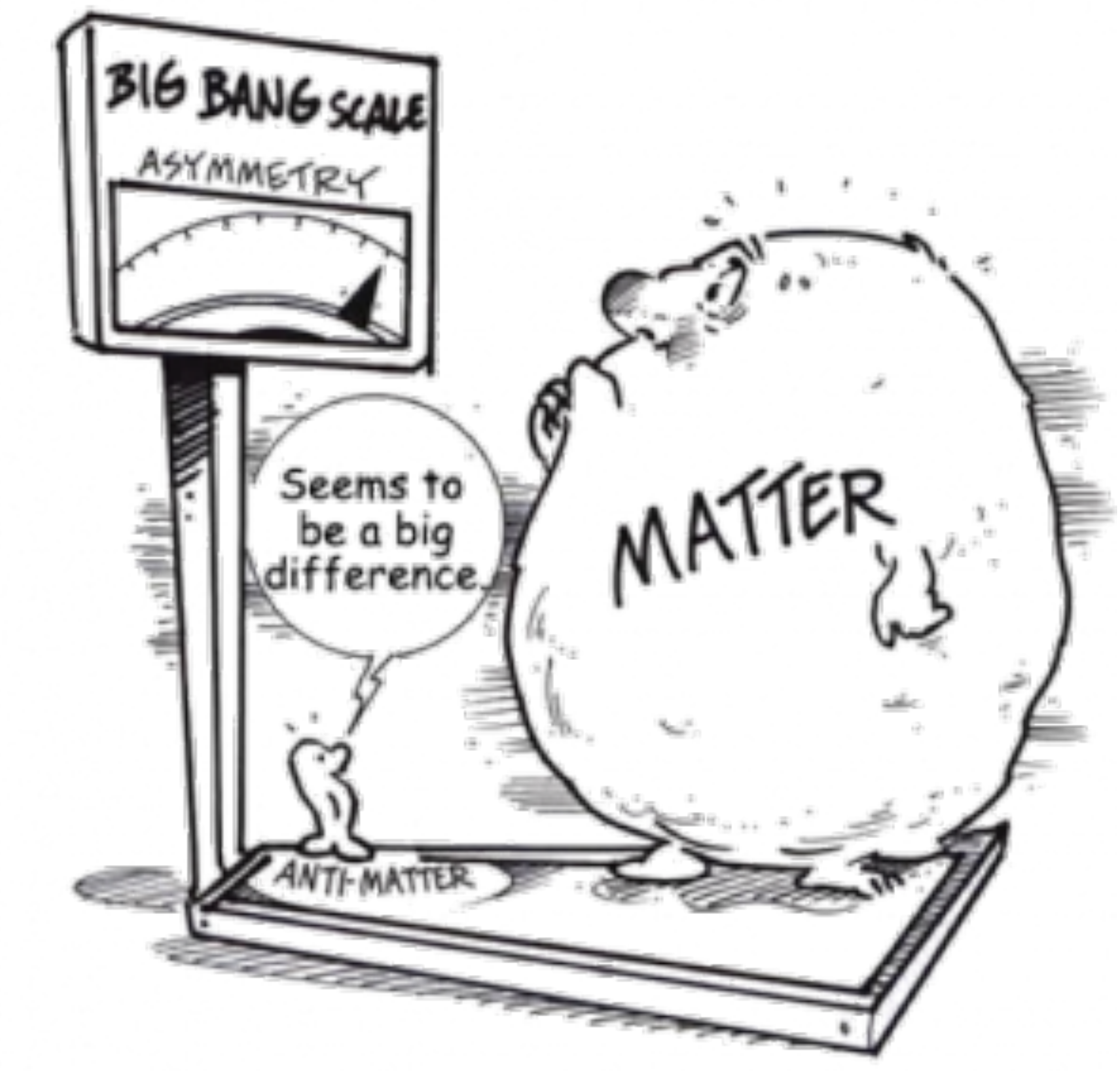
THANK YOU!

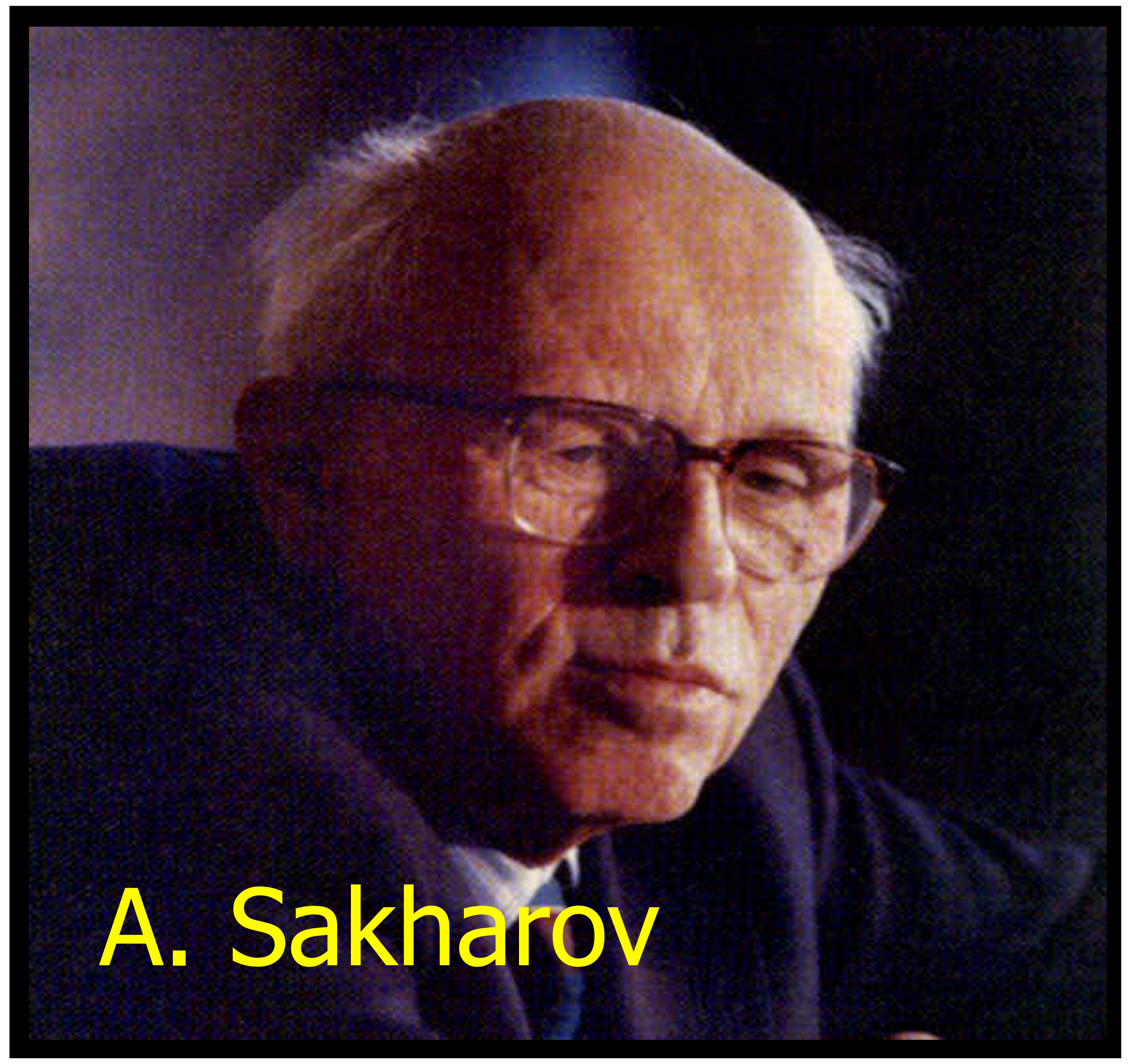
Extra

Asymmetric Universe of Matter

To generate this initial asymmetry three conditions must be met (Sakharov, 1967):

- Baryon number violation
- *Charge* and *Charge Parity* violation
- Departure from thermal equilibrium; in thermal equilibrium any baryon number violating process will be balanced by the inverse reaction




A. Sakharov

Symmetries in Physics

There are two main types of symmetries in physics: continuous and discrete.

Emmy Noether
(1882-1935)

- For every continuous symmetry there exists a corresponding conservation law.

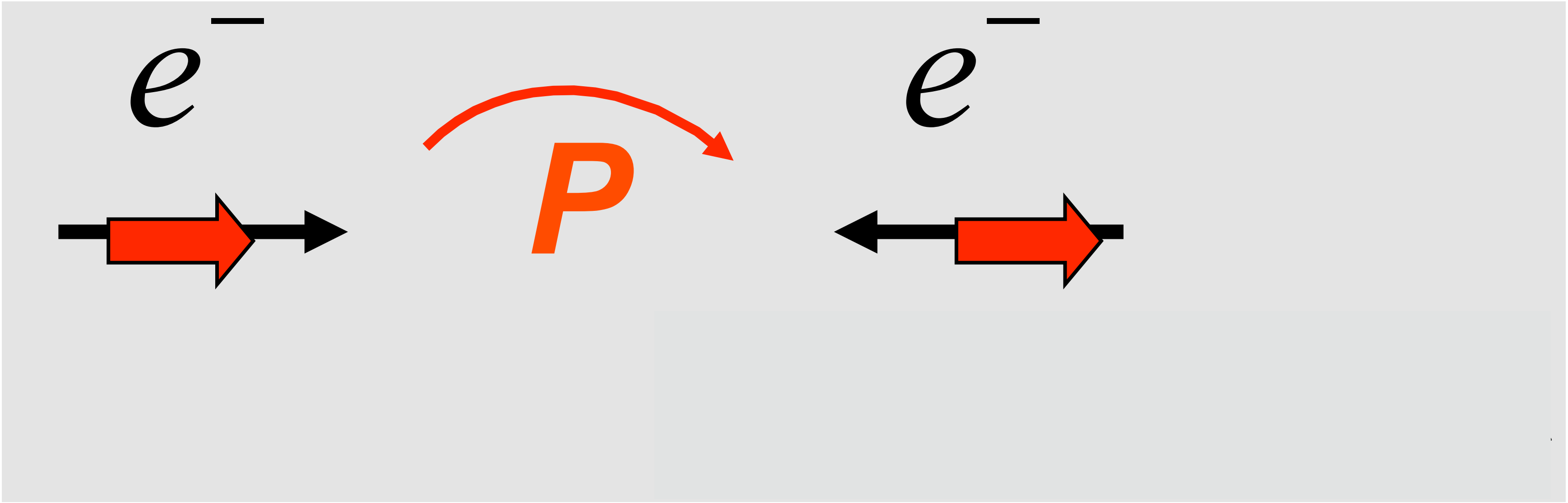
Noether's Theorem

Laws of physics invariant under		Conservation of
Spatial Translations	⟷	Momentum
Time Translations	⟷	Energy
Rotations	⟷	Angular Momentum

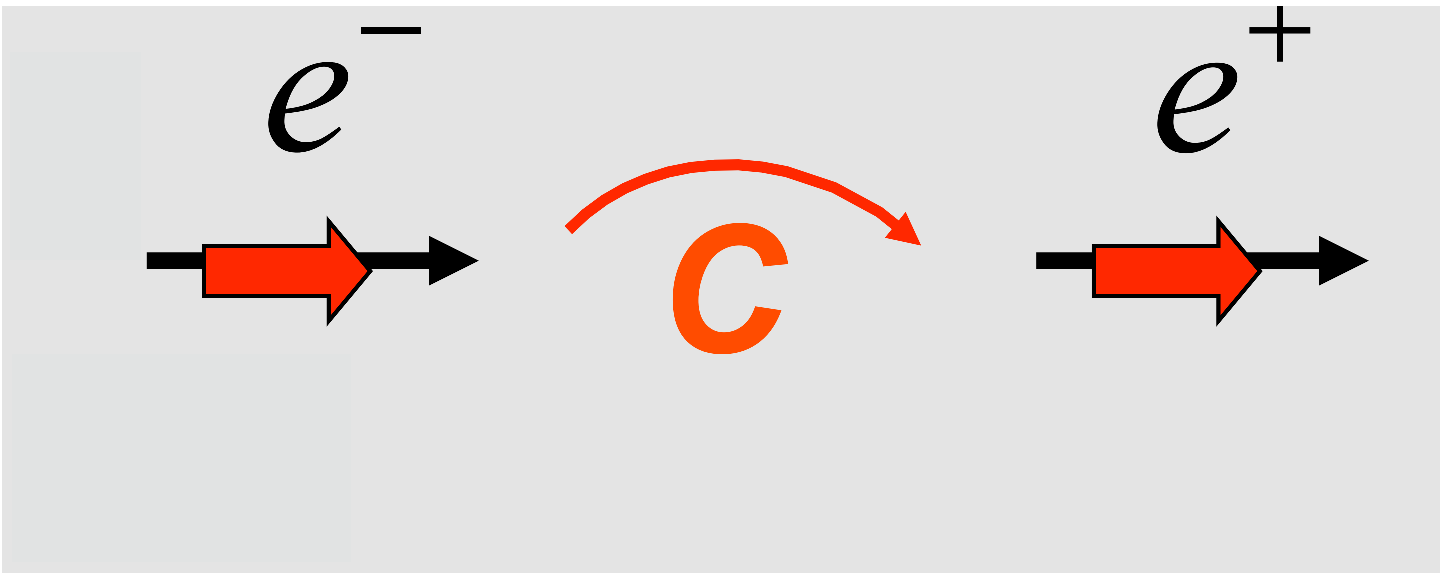
- Discrete symmetries are very important in particle physics!

Discrete Symmetries

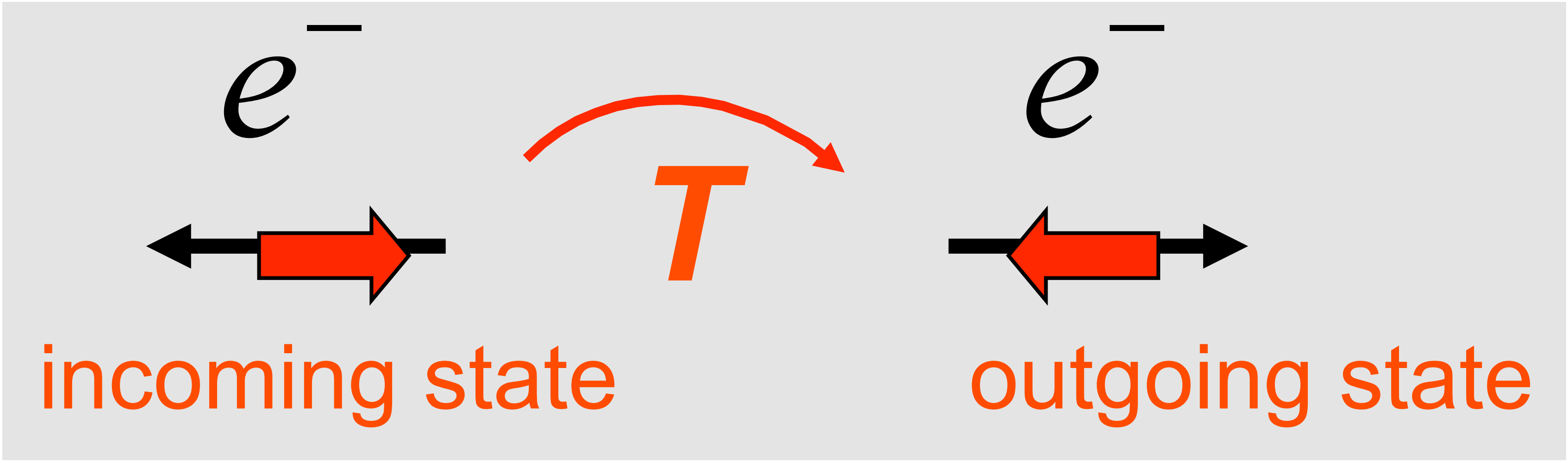
- Parity, ***P***
- Parity reflects a system through the origin.
  - $(\vec{r} \to -\vec{r}, \vec{p} \to -\vec{p}, \vec{L} \to \vec{L})$

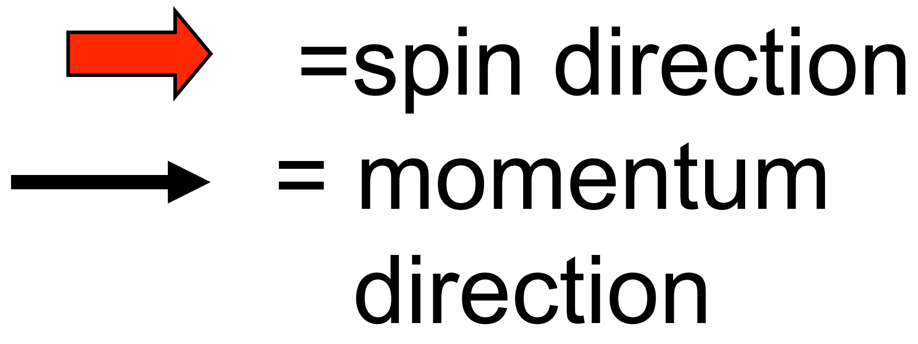


- Charge Conjugation, ***C***
- ***C*** changes the sign of all the “internal” quantum numbers.
  - $e^- \to e^+, K^+ \to K^-, p \to \overline{p}, \gamma \to \gamma$



- Time reversal, ***T***
- ***T*** reverse any motion in system.
  - $t \to -t, \vec{p} \to -\vec{p}, \vec{L} \to -\vec{L}$



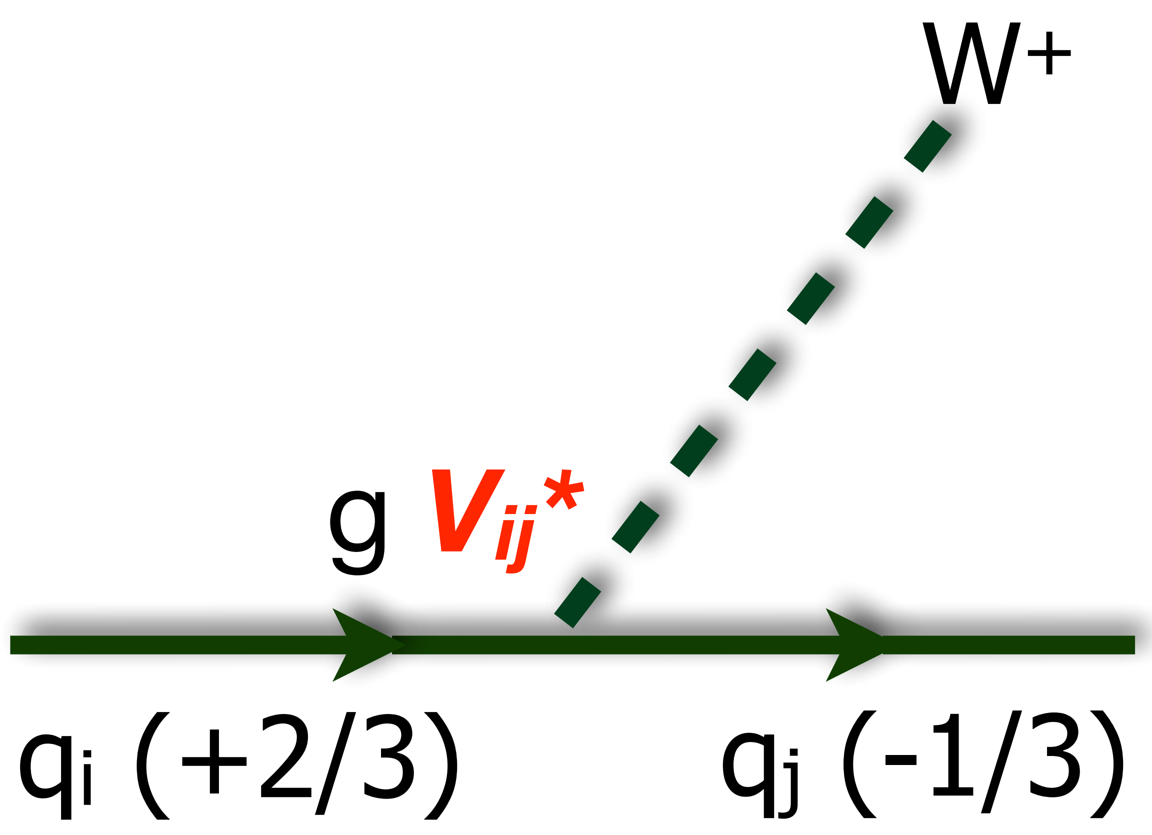


Quark Mixing

(Kobayashi-Maskawa 1973)

Kobayashi and Maskawa proposed a daring explanation for CP violation in weak interactions.

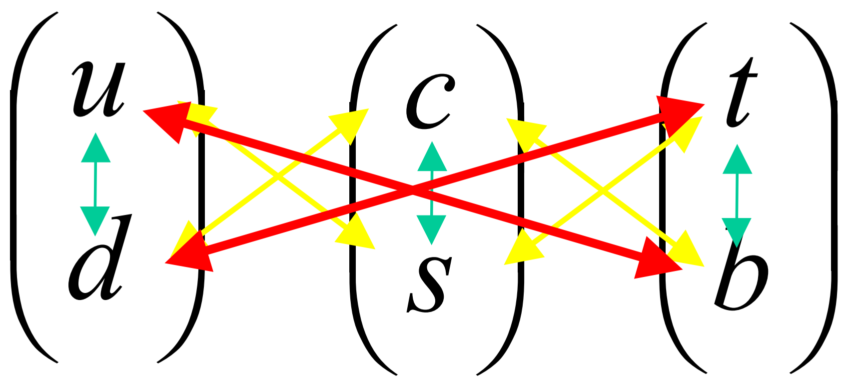
- Need at least **3 Generation of Quarks** (then not known).
- Get a CP-violating phase $e^{i\delta}$, if one assumes three families.



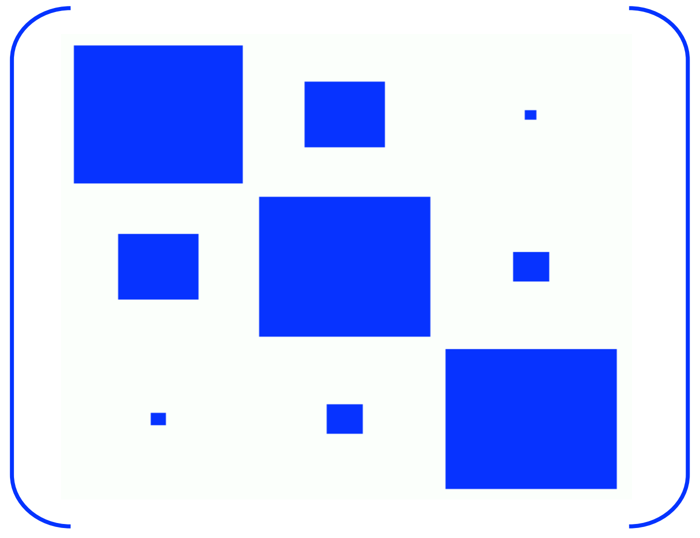
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo Kobayashi Maskawa (CKM) matrix

Allowed
suppressed
doubly suppressed

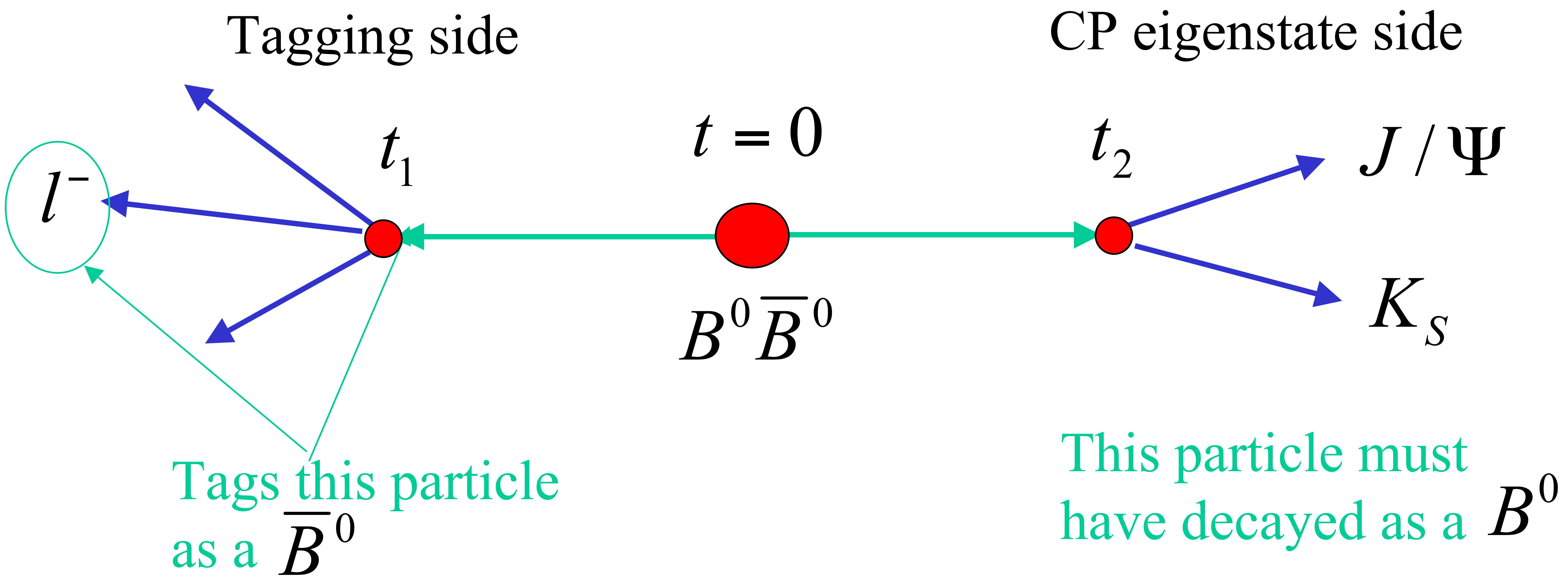


$|V_{ij}| =$



relative magnitudes

Quantum Weirdness



If $t_1 = t_2$, then the particle on the CP eigenstate must be a B^0. Note that the tagging information is communicated across space instantaneously despite the fact that the *B*'s could be separated by a finite distance (a few hundred microns). This is an example of quantum entanglement (the EPR paradox).

Time Dependent *CP* Violation in B Decays