Introduction to CP-violation in beauty and charm: general ideas

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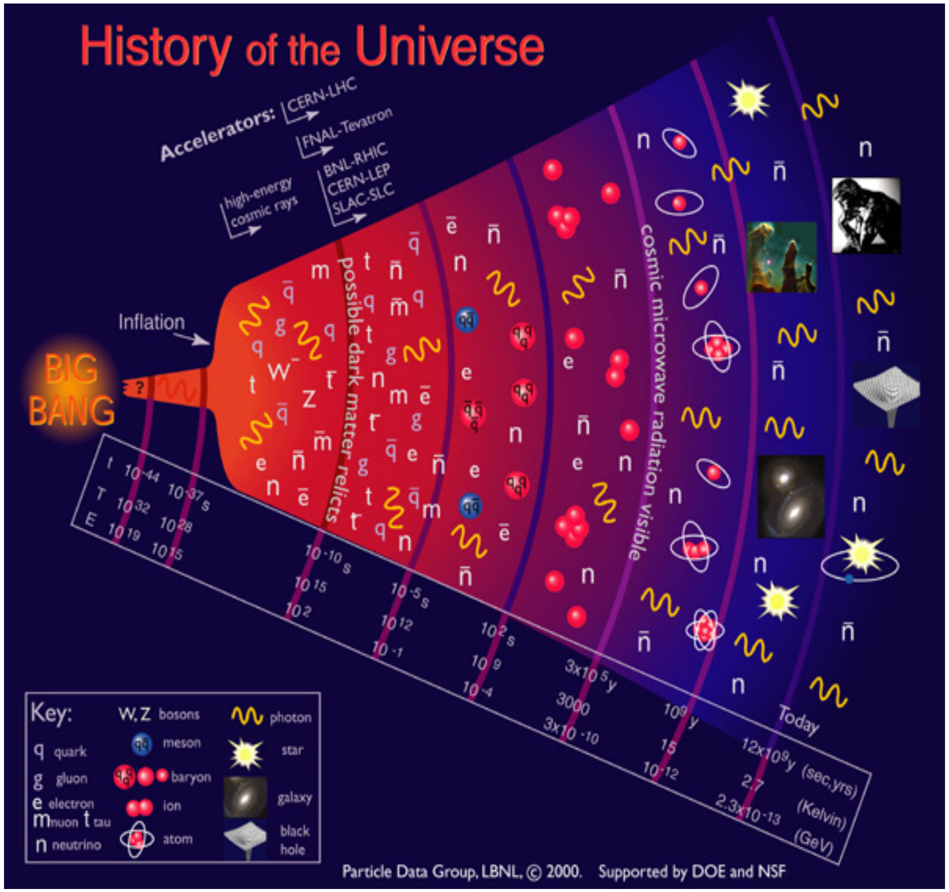
Alexey A. Petrov

Wayne State University

Standard Model does not explain how the Universe was formed…



Just after the Big Bang:

- ✓ symmetric Universe (matter and antimatter)
  - ➢ equal number of particles and antiparticles

Now:

- ✓ asymmetric Universe (matter only!)
  - ➢ dust, planets, stars, galaxies, WSU, …

Where did all the antimatter go?

Introduction: Sakharov's conditions

★ Sakharov's conditions for matter-antimatter asymmetry of the Universe

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

From the effect of S. Okubo,
At high temperature,
A fur coat is sewn for the Universe,
That fits her crooked figure.

НАРУШЕНИЕ *СР*-ИНВАРИАНТНОСТИ, *С*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

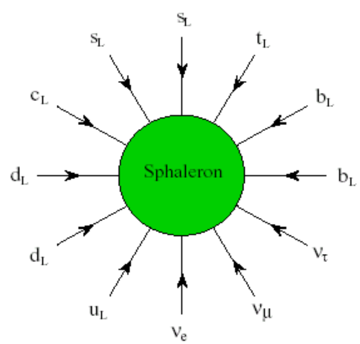
From a copy gifted to E.L. Feynberg (1967)
(effect Okubo: CP-violation in *Σ* decays)

Probably not that crooked: $\beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 3 \cdot 10^{-10}$

Introduction: Sakharov's conditions

★ Sakharov's conditions for matter-antimatter asymmetry of the Universe

✓ Baryon (and lepton) number - violating processes
to ***generate*** asymmetry



$\Delta B = 3,\ \Delta L = 3,$
$B - L$ conserved

✓ Universe that evolves out of thermal equilibrium
to ***keep*** asymmetry from ***being washed out***

✓ "Microscopic CP-violation"
to ***keep*** asymmetry from ***being compensated in the "anti-world"***

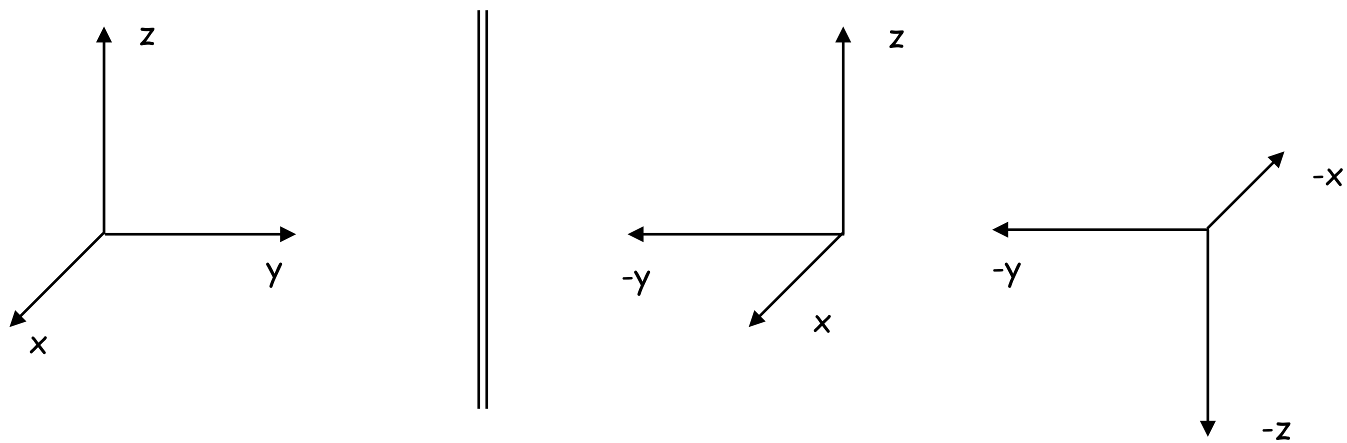
This CAN be tested experimentally

Introduction: what are C,P, & T classically?

★ The meaning of discrete symmetries in classical mechanics

- Parity [P] transformation: $\vec{r} \rightarrow -\vec{r}$

Refection through a mirror, followed by a rotation of π around an axis defined by the mirror plane.



- Time-reversal [T] transformation: $t \rightarrow -t$

Flips the arrow of time

- Charge-conjugation [C] transformation

Changes particles into antiparticles (*)

Introduction: what are C,P, & T classically?

★ The meaning of discrete symmetries in classical mechanics

Parity [P] transformation: $\vec{r} \to -\vec{r}$ || Time-reversal [T] transformation: $t \to -t$

$\vec{v} = \frac{d\vec{r}}{dt}$	odd under P	odd under T	
$\vec{p} = m\vec{v}$	odd under P	odd under T	
$\vec{F} = \frac{d\vec{p}}{dt}$	odd under P	even under T	
$\vec{L} = \vec{r} \times \vec{p}$	even under P	odd under T	(so is spin)

Q: how is this supposed to work for quantum mechanics with $[r_i, p_k] = i\delta_{ik}$?

- Lorentz force allows us to see how electric and magnetic fields react upon application of P and T

$$\vec{F}_{Lorentz} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$\vec{F}$ and $\vec{v}$ are odd under P:
$\vec{E} \to -\vec{E}$ and $\vec{B} \to \vec{B}$

$\vec{F}$ is even and and $\vec{v}$ is odd under T:
$\vec{E} \to \vec{E}$ and $\vec{B} \to -\vec{B}$

Introduction: what are C,P, & T classically?

★ The meaning of discrete symmetries in classical electrodynamics

- We can now see how equations of motion change under P and T

Under P:
$$\vec{E}(\vec{r},t) \to -\vec{E}(-\vec{r},t)$$
$$\vec{B}(\vec{r},t) \to \vec{B}(-\vec{r},t)$$
$$\nabla \to -\nabla$$
$$\vec{j}(\vec{r},t) \to -\vec{j}(-\vec{r},t)$$

Under T:
$$\vec{E}(\vec{r},t) \to \vec{E}(\vec{r},-t)$$
$$\vec{B}(\vec{r},t) \to -\vec{B}(\vec{r},-t)$$
$$\partial/\partial t \to -\partial/\partial t$$
$$\vec{j}(\vec{r},t) \to -\vec{j}(\vec{r},-t)$$

Equation	P	T	C	CPT
$\nabla\cdot\mathbf{E}=4\pi\rho$	+	+	−	−
$\nabla\cdot\mathbf{B}=0$	−	−	−	−
$\nabla\times\mathbf{B}-\frac{1}{c}\frac{\partial\mathbf{E}}{\partial t}=\frac{4\pi}{c}\mathbf{j}$	−	−	−	−
$\nabla\times\mathbf{E}+\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t}=0$	+	+	−	−

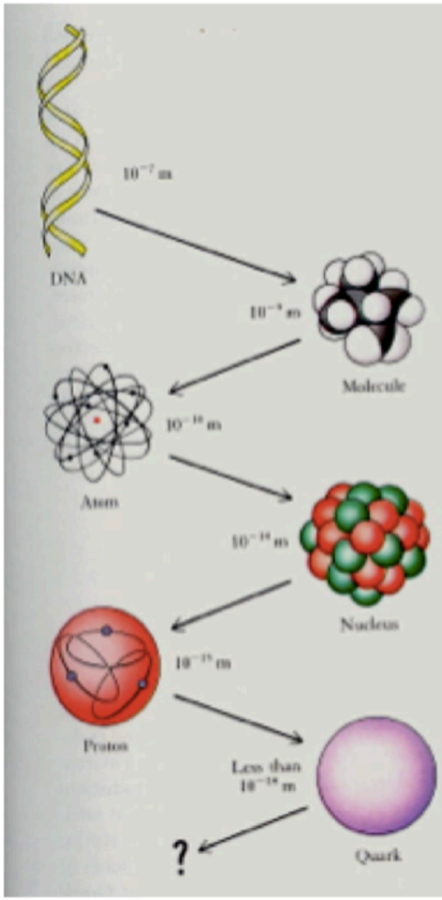
Q: What about $\vec{E}\cdot\vec{B}$?

- Technically, there is no C-parity in classical physics (no antiparticles)…

Under C:
$$\rho(\vec{r},t) \to -\rho(\vec{r},t), \quad \vec{j}(\vec{r},t) \to -\vec{j}(\vec{r},t)$$
$$\vec{E}(\vec{r},t) \to -\vec{E}(\vec{r},t), \quad \vec{B}(\vec{r},t) \to -\vec{B}(\vec{r},t)$$

(fields changed signs since their sources changed signs)

Discrete symmetries are conserved in classical E&M. Need quantum mechanics?



Molecular physics, chemistry

Atomic physics

Nuclear Physics

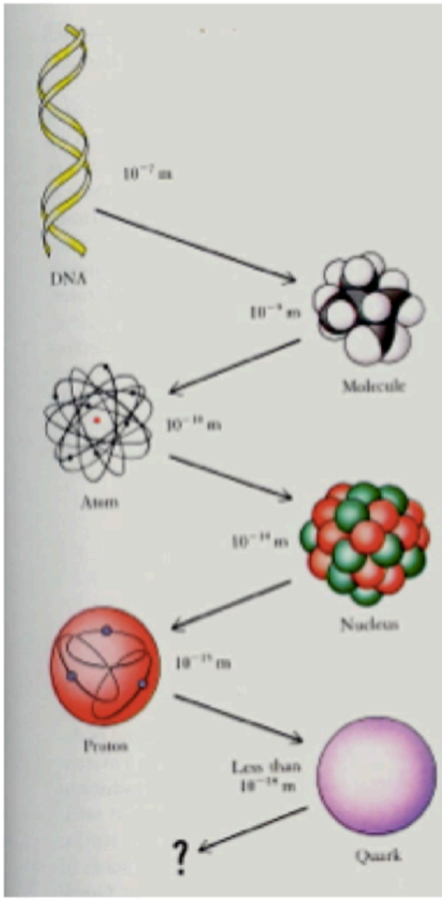
Particle physics

★ LHC:

★ Belle II/LHCb:

Can see effects of CP-violation at any scale! Where does it originate?

Scale separation in physics



Molecular physics, chemistry

Atomic physics

Nuclear Physics

Particle physics

★ LHC:

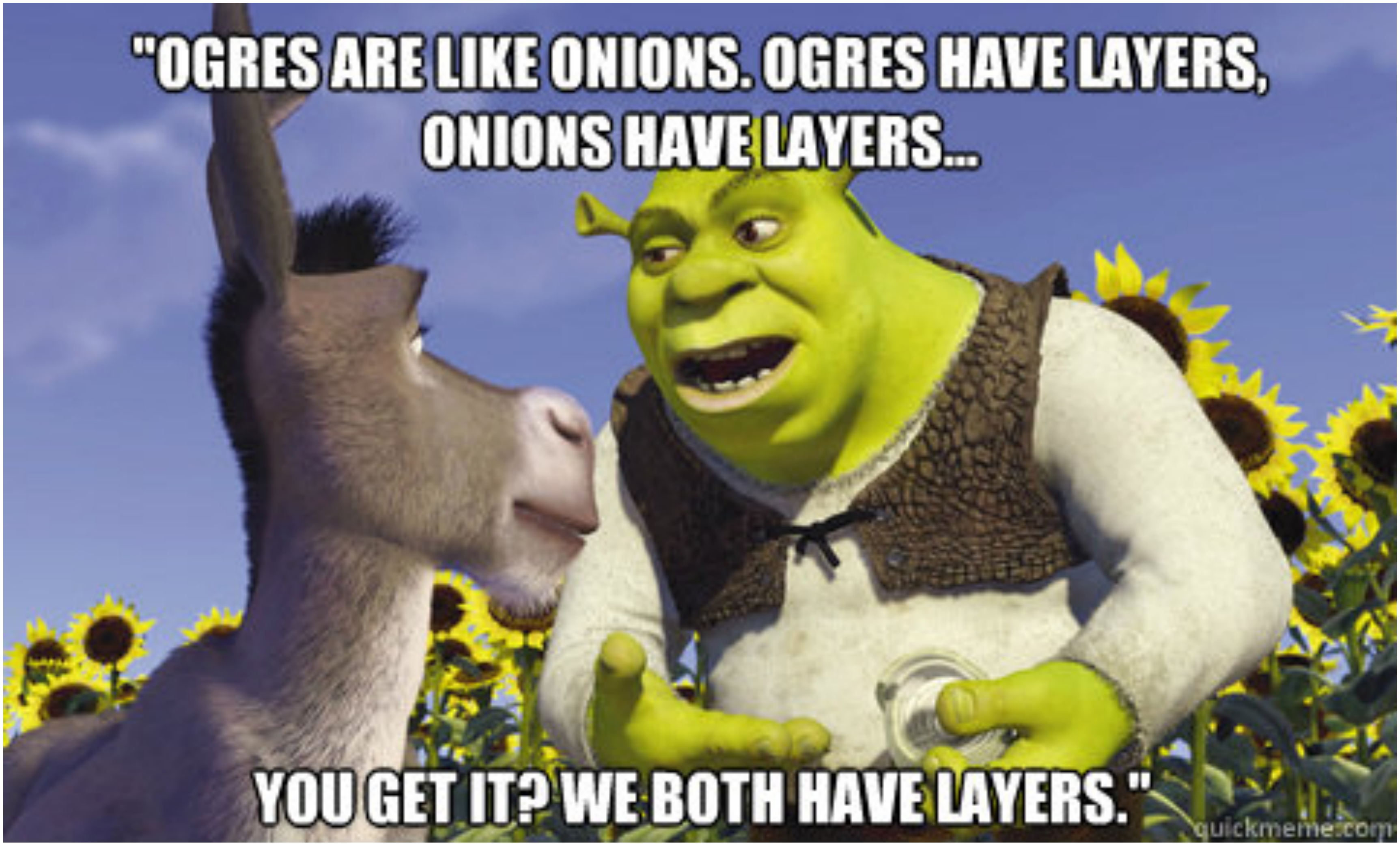
$\Delta p \cdot \Delta x \geq \hbar$: need larger machines to probe smaller scales!

★ Belle II/LHCb:

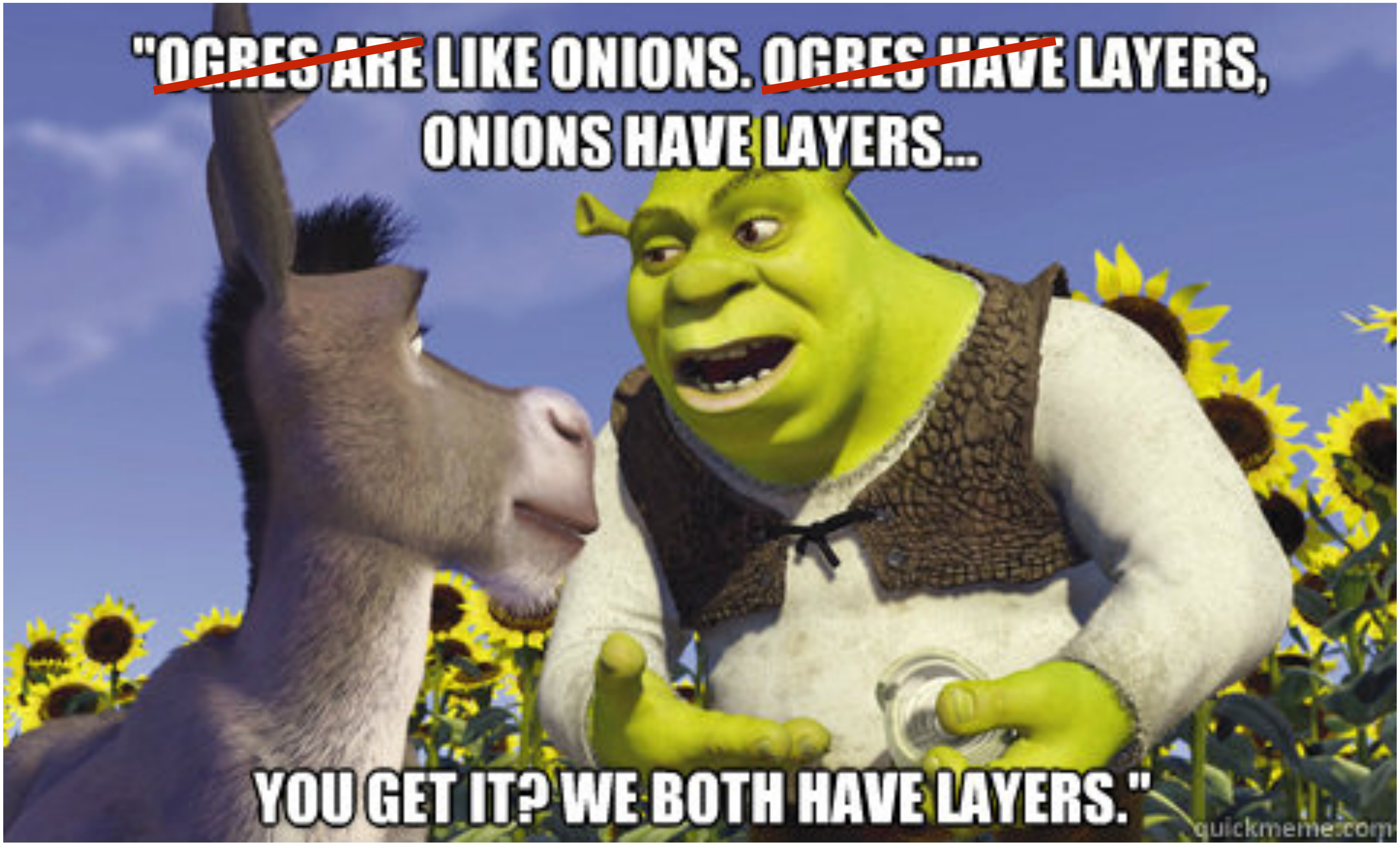
$\Delta E \cdot \Delta t \geq \hbar$: need more statistics to probe smaller scales!

Can see effects of CP-violation at any scale! Where does it originate?

A word from a philosophy guru…

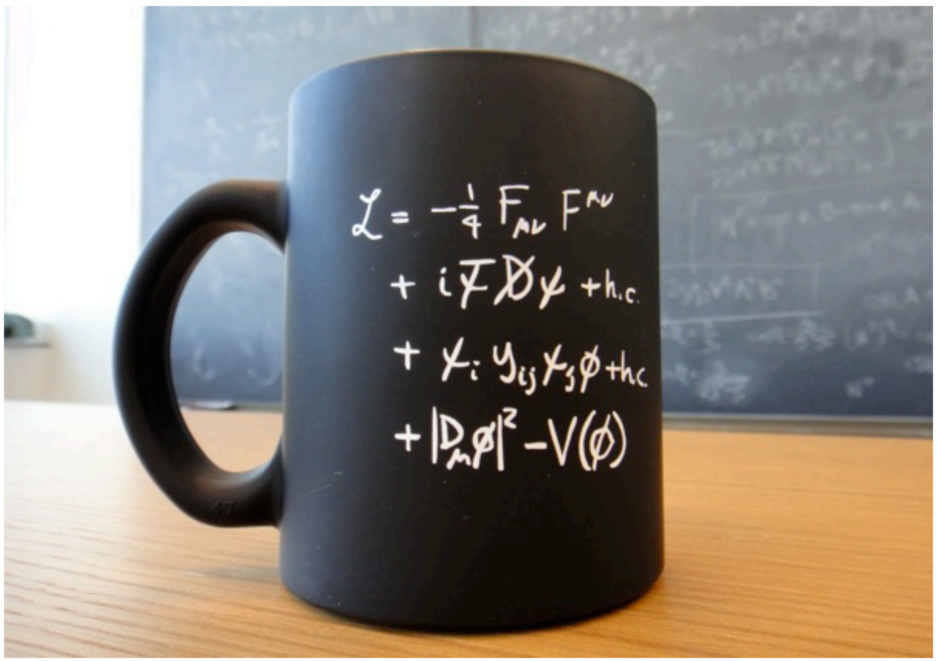


Nature is Nature has



Is this the final layer?

The Standard Model of particle physics is a remarkably simple and powerful construct



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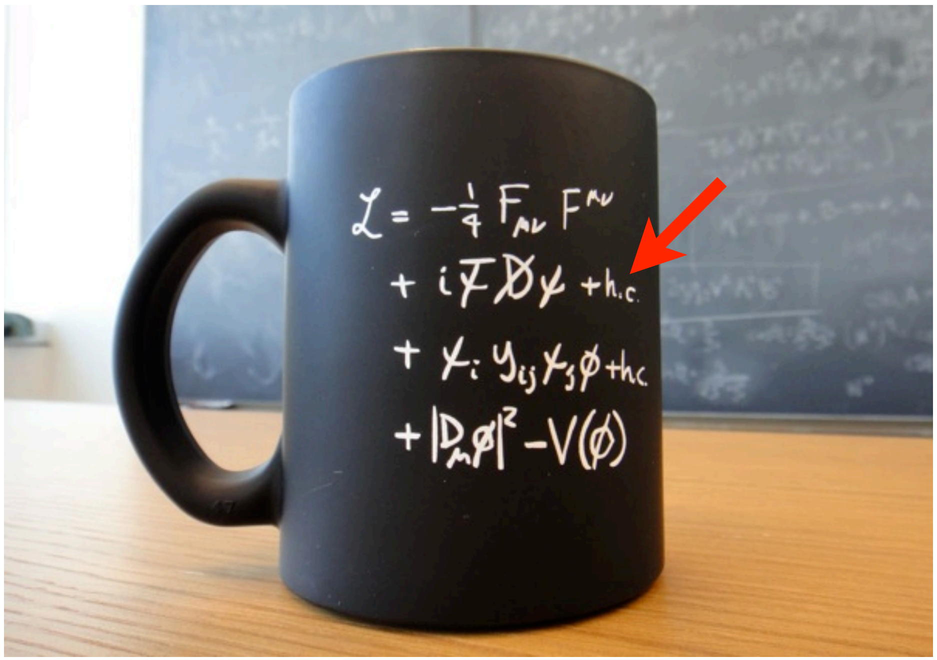

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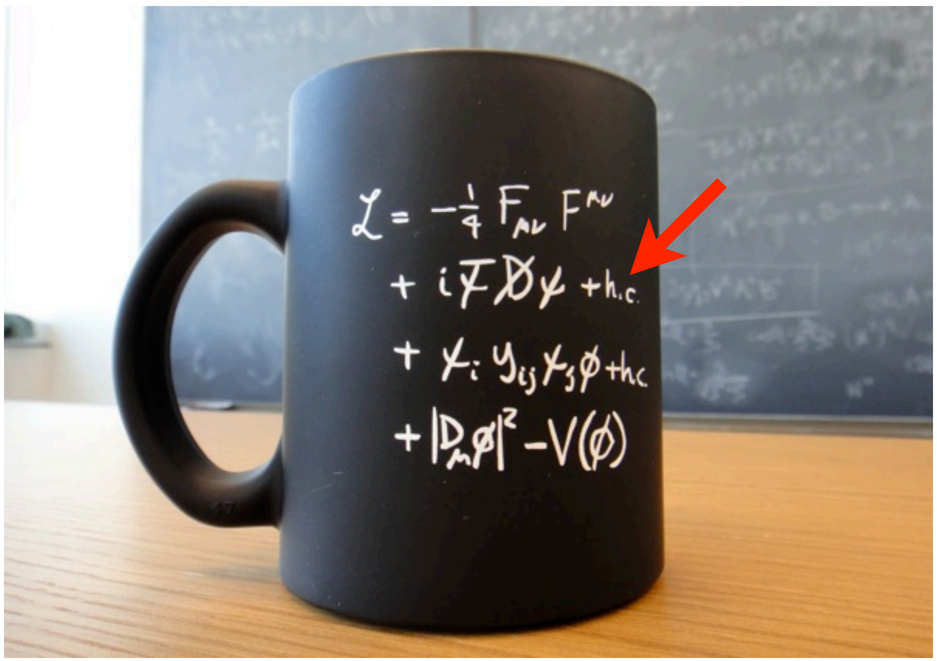

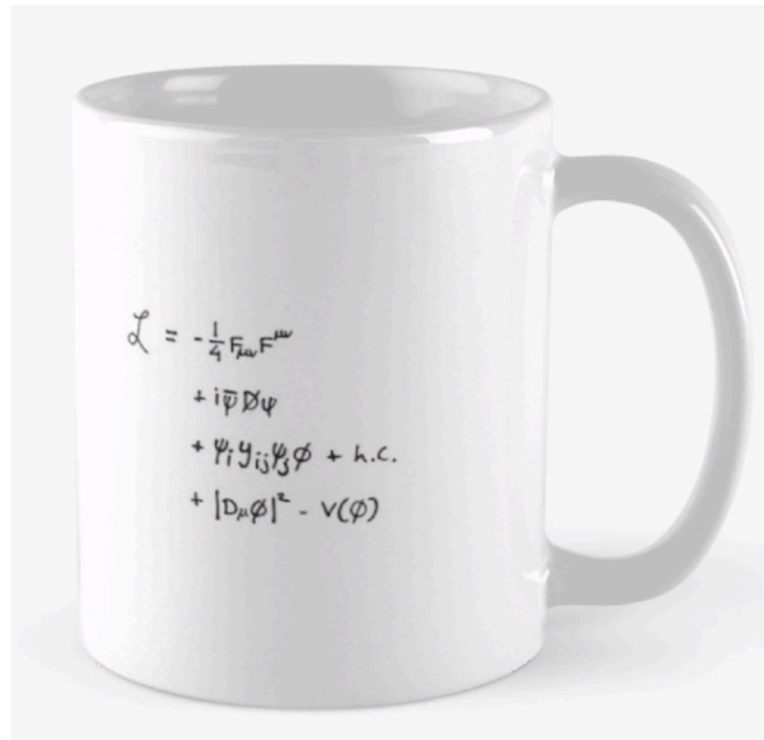

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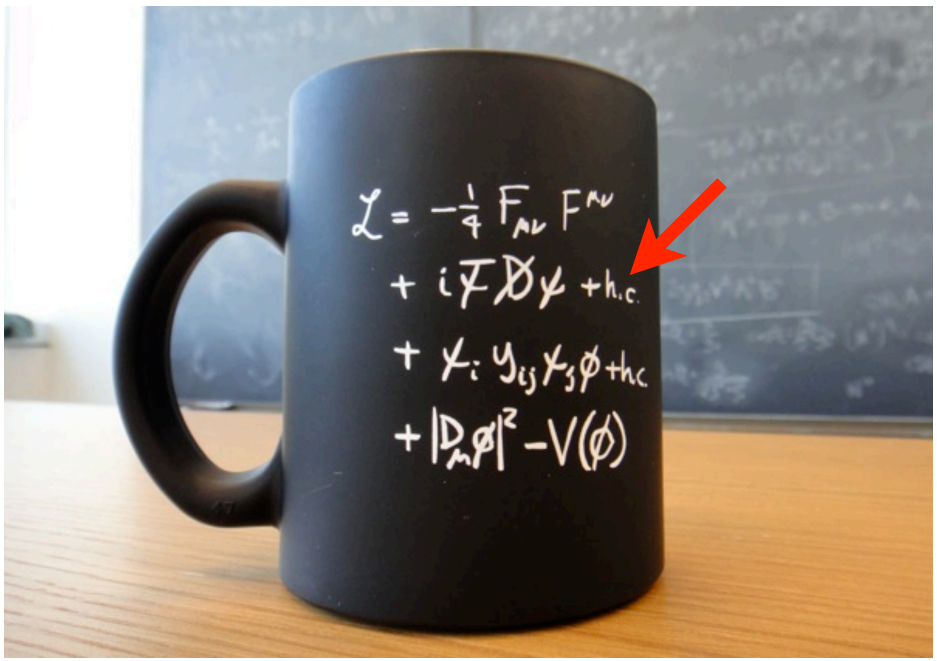

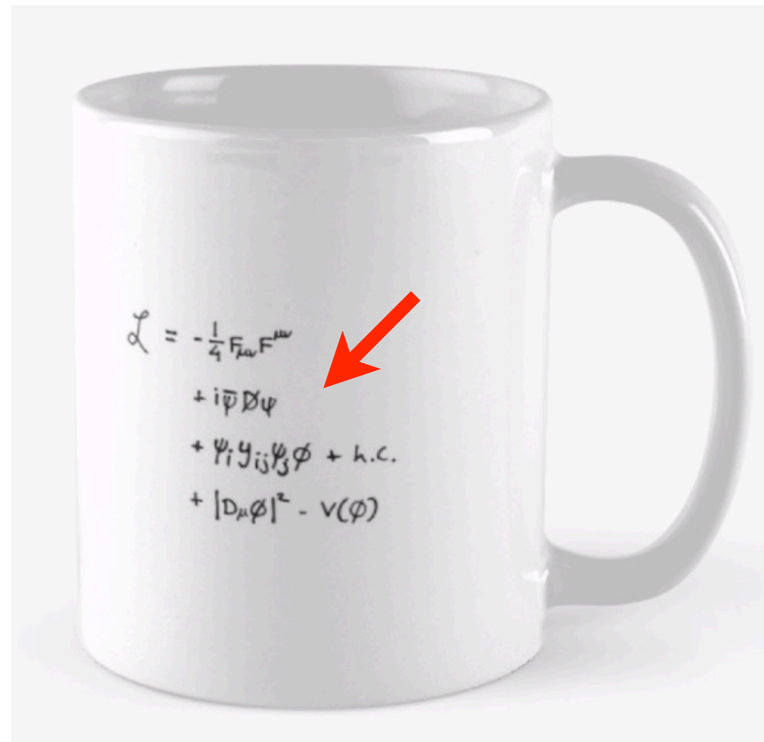

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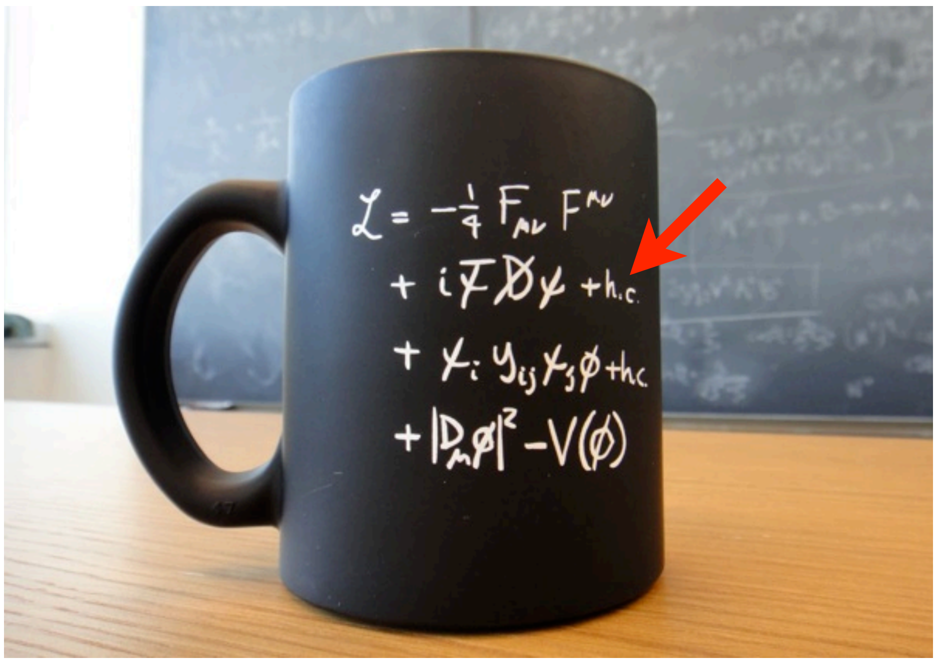

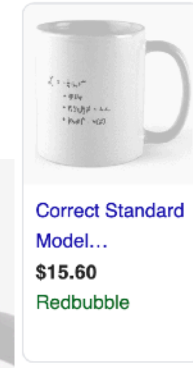

Standard Model

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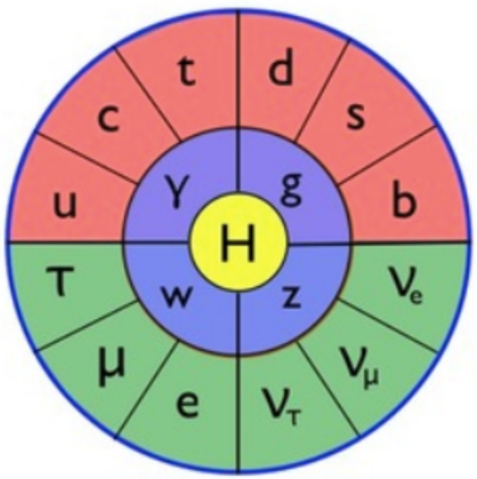

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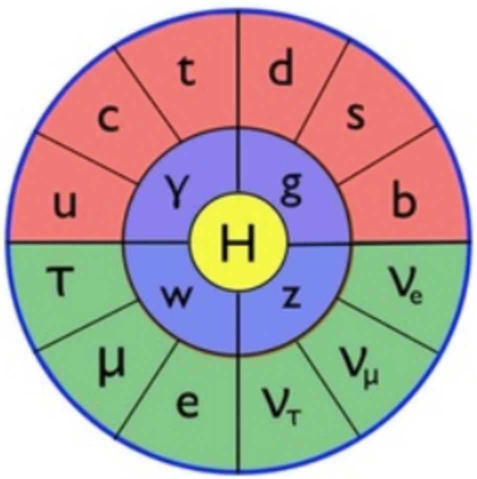

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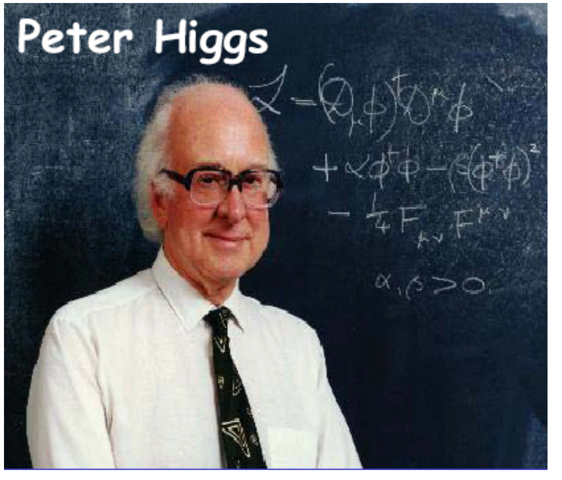

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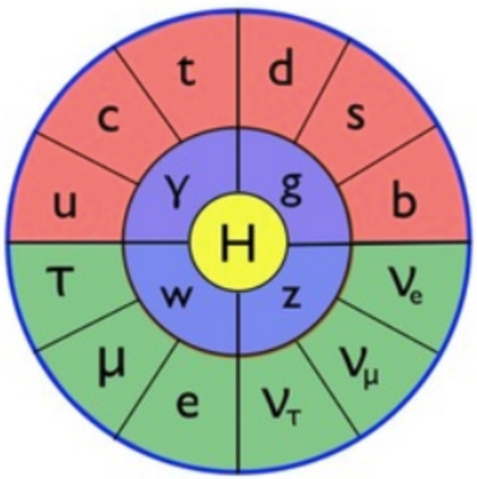

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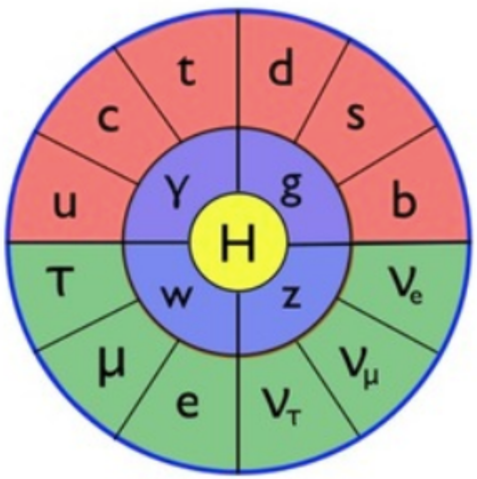
= **Standard Model**

The Standard Model of particle physics is a remarkably simple and powerful construct



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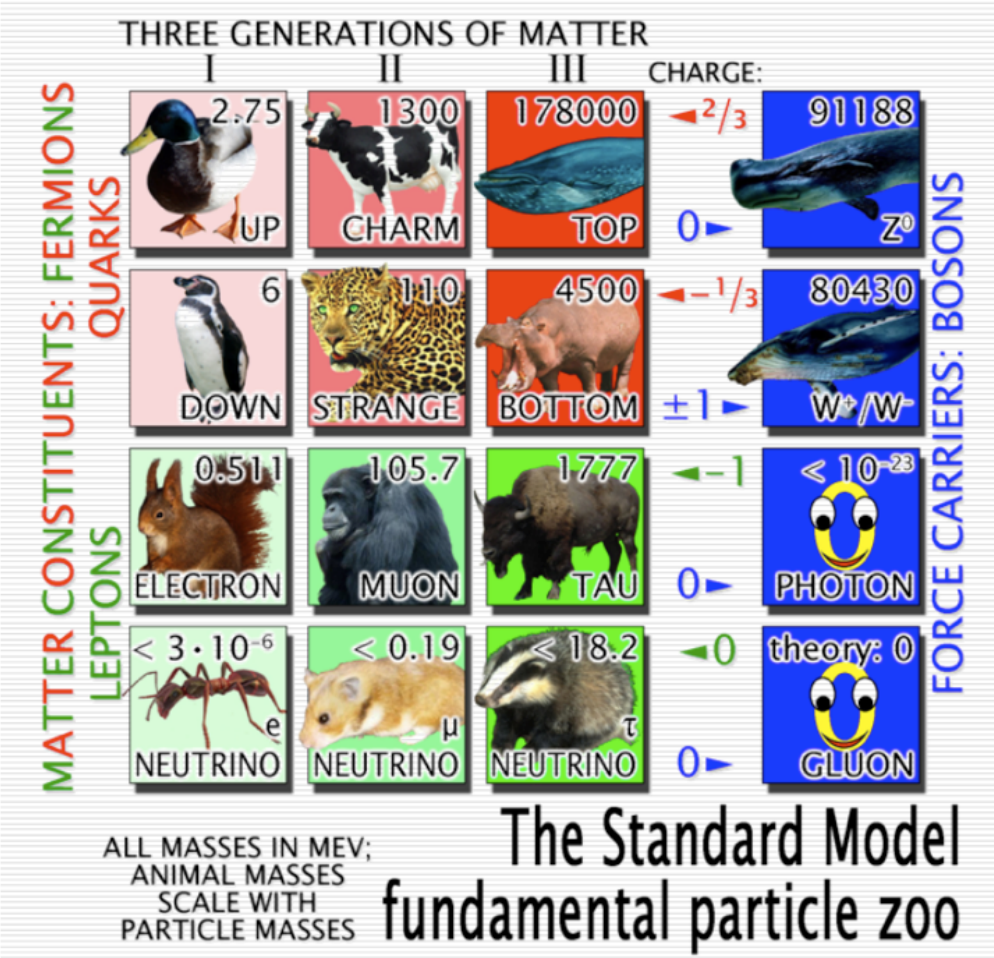
= **Standard Model**

$$\mathcal{L}_{SM} = \sum_{\psi} \overline{\psi}\gamma^{\mu}\left(i\partial_{\mu} - \frac{g_1}{2}Y_W B_{\mu} - \frac{g_2}{2}\vec{\tau}_L \vec{W}_{\mu}\right)\psi + \mathcal{L}_{B,\ kin} + \mathcal{L}_{W,\ kin} + \mathcal{L}_{Higgs}$$

- ★ Symmetries require all particles to be massless!
- ★ Part of this equation is related to particle masses: Higgs sector
- ★ Part of this equation is related to matter interaction with Higgs: flavor sector

(Flavorful) problems with the Standard Model



E. Lunghi

★ Ratios of masses of quarks and leptons

- quarks

$$\frac{m_d}{m_u} \simeq 2 \,, \quad \frac{m_s}{m_d} \simeq 21 \,,$$
$$\frac{m_t}{m_c} \simeq 267 \,, \quad \frac{m_c}{m_u} \simeq 431 \,, \quad \frac{m_t}{m_u} \simeq 1.2 \times 10^5 \,.$$

- leptons

$$\frac{m_\tau}{m_\mu} \simeq 17 \,, \quad \frac{m_\mu}{m_e} \simeq 207 \,.$$

Flavor Problem:

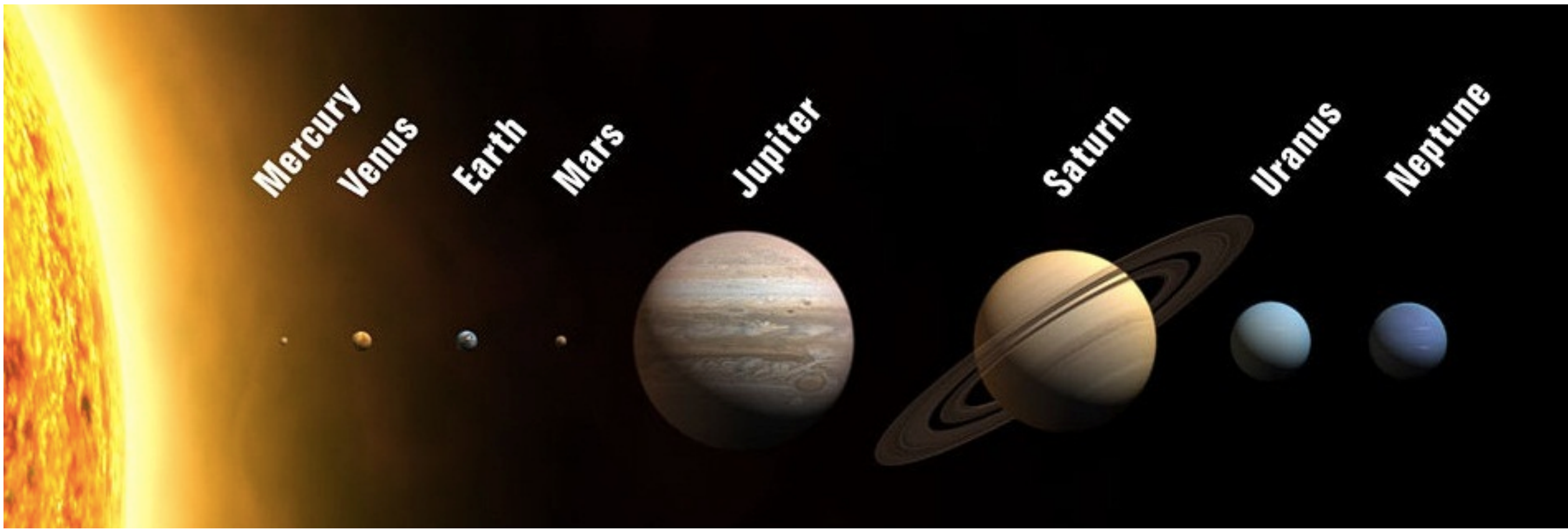
★ Why generations? Why only 3? Are there only 3?

★ Why hierarchies of masses and mixings?

★ Can there be transitions between quarks/leptons of the same charge but different generations?

Do studies of CP-violation lead to better understanding of flavor? Or vice-versa?

Another view of a flavor problem



Why is $M_{Jupiter} \gg M_{Mercury}$?

Introduction: what is CP(T) quantum-mechanically?

★ Let us consider a (convention-dependent) example

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$$P\left|\Psi\left(\vec{r}, s\right)\right\rangle = \pm\left|\Psi\left(-\vec{r}, s\right)\right\rangle$$

$$\Gamma(K^+ \to \mu_L^+ \nu_{\mu L}) = \Gamma(K^+ \to \mu_R^+ \nu_{\mu R})$$

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T: time reversal $\mathcal{T}: \quad \vec{t} \to -\vec{t}$

$$\Gamma(K^+ \to \mu_L^+ \nu_{\mu L}) = \Gamma(\mu_L^+ \nu_{\mu L} \to K^+)$$

★ Helicity is a projection of a particle's spin along the direction of its momentum

- important (frame-dependent) concept in weak particle physics

$$h = \frac{\vec{s} \cdot \vec{p}}{|\vec{s}||\vec{p}|}$$

pseudoscalar

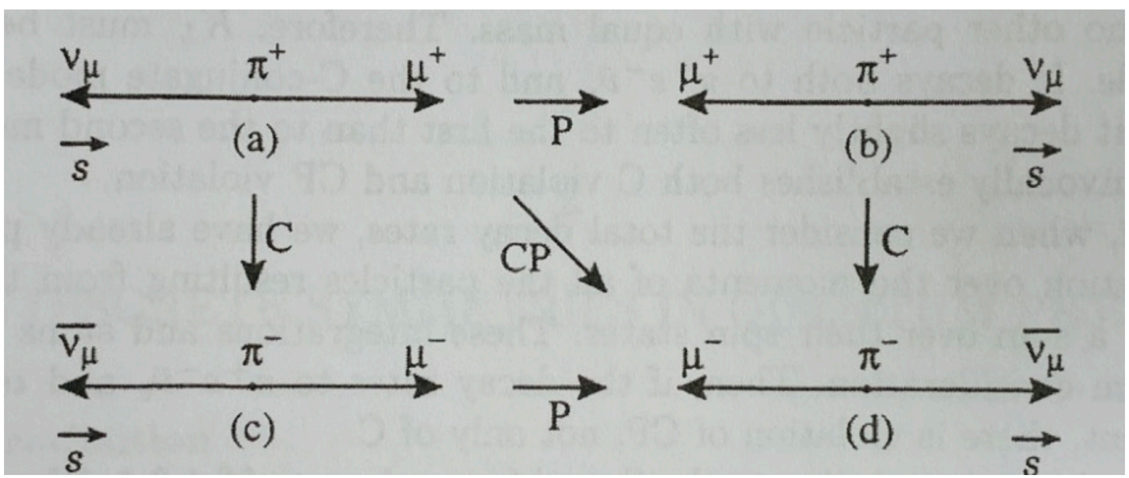
- for massless particles helicity is equivalent to chirality
- under C, P, and T it transforms as

$$h \to -h \quad \text{under P}$$
$$h \to h \quad \text{under C}$$
$$h \to h \quad \text{under T}$$

Can Standard Model violate CP?

- ✓ Strong and electromagnetic interactions conserve C, P and T
- ✓ All interactions (local QFT) conserve combination CPT
- ✓ Weak interactions violate P and C…
  what about CP?

$$\Gamma(K^{+} \to \mu^{+}_{L} \nu_{\mu L}) = \Gamma(K^{-} \to \mu^{-}_{R} \overline{\nu_{\mu R}})$$



Branco, Lavoura, Silva

C,P, &T in Quantum Field Theory

★ The meaning of discrete symmetries in Quantum Field Theory

- C and P are unitary operators: $C^\dagger = C^{-1}$ and $P^\dagger = P^{-1}$
  - … and if they are good symmetries, they commute with the Hamiltonian,

$$[C, \mathcal{H}] = 0 \quad \text{and} \quad [P, \mathcal{H}] = 0$$

  - for the scattering matrix $S = 1 + iT$,

$$CSC^\dagger = S \quad \text{and} \quad PSP^\dagger = S$$

  - note, however that weak interactions break both, so $[C, \mathscr{H}_W] \neq 0$, $[P, \mathscr{H}_W] \neq 0$

- … but T is anti-unitary: $$i\frac{\partial\psi}{\partial t} = -\frac{\vec{\nabla}^2}{2m}\psi$$

T-odd T-even

only possible if T also switched $i \to -i$, and $\psi \to \psi^*$!

  - recall that an anti-unitary operator A=UK, where $U^\dagger = U^{-1}$ and $K[\alpha|\psi_1\rangle + \beta|\psi_2\rangle] = \alpha^*|\psi_1^\dagger\rangle + \beta^*|\psi_2^\dagger\rangle$
  - it interchanges in- and out- states in the S-matrix: $TST^{-1} = S^\dagger$

C,P, &T in Quantum Field Theory

★ The meaning of discrete symmetries in Quantum Field Theory

- Quantum fields in QFT are Hermitian operators
  - written as linear combinations of creation/annihilation operators

$$[CP]\phi(\vec{r},t)[CP]^\dagger = exp(i\alpha)\phi^\dagger(-\vec{r},t)$$
$$[CP]\psi(\vec{r},t)[CP]^\dagger = exp(i\beta)\gamma_0 C A^T \psi^{\dagger T}(-\vec{r},t)$$
$$[CP]\overline{\psi}(\vec{r},t)[CP]^\dagger = -exp(-i\beta)\psi^T(-\vec{r},t)C^{-1}\gamma_0$$

$$A\gamma_\mu = \gamma_\mu^\dagger A$$
$$\gamma_\mu C = -C\gamma_\mu^T$$

- We can summarize actions of discrete symmetries on fermonic currents:

	P	T	C	CP	CPT
$\overline{\psi}\chi$	$\overline{\psi}\chi$	$\overline{\psi}\chi$	$\overline{\chi}\psi$	$\overline{\chi}\psi$	$\overline{\chi}\psi$
$\overline{\psi}\gamma_5\chi$	$-\overline{\psi}\gamma_5\chi$	$\overline{\psi}\gamma_5\chi$	$\overline{\chi}\gamma_5\psi$	$-\overline{\chi}\gamma_5\psi$	$-\overline{\chi}\gamma_5\psi$
$\overline{\psi}\gamma_L\chi$	$\overline{\psi}\gamma_R\chi$	$\overline{\psi}\gamma_L\chi$	$\overline{\chi}\gamma_L\psi$	$\overline{\chi}\gamma_R\psi$	$\overline{\chi}\gamma_R\psi$
$\overline{\psi}\gamma_R\chi$	$\overline{\psi}\gamma_L\chi$	$\overline{\psi}\gamma_R\chi$	$\overline{\chi}\gamma_R\psi$	$\overline{\chi}\gamma_L\psi$	$\overline{\chi}\gamma_L\psi$
$\overline{\psi}\gamma^\mu\chi$	$\overline{\psi}\gamma_\mu\chi$	$\overline{\psi}\gamma_\mu\chi$	$-\overline{\chi}\gamma^\mu\psi$	$-\overline{\chi}\gamma_\mu\psi$	$-\overline{\chi}\gamma^\mu\psi$
$\overline{\psi}\gamma^\mu\gamma_5\chi$	$-\overline{\psi}\gamma_\mu\gamma_5\chi$	$\overline{\psi}\gamma_\mu\gamma_5\chi$	$\overline{\chi}\gamma^\mu\gamma_5\psi$	$-\overline{\chi}\gamma_\mu\gamma_5\psi$	$-\overline{\chi}\gamma^\mu\gamma_5\psi$
$\overline{\psi}\gamma^\mu\gamma_L\chi$	$\overline{\psi}\gamma_\mu\gamma_R\chi$	$\overline{\psi}\gamma_\mu\gamma_L\chi$	$-\overline{\chi}\gamma^\mu\gamma_R\psi$	$-\overline{\chi}\gamma_\mu\gamma_L\psi$	$-\overline{\chi}\gamma^\mu\gamma_L\psi$
$\overline{\psi}\gamma^\mu\gamma_R\chi$	$\overline{\psi}\gamma_\mu\gamma_L\chi$	$\overline{\psi}\gamma_\mu\gamma_R\chi$	$-\overline{\chi}\gamma^\mu\gamma_L\psi$	$-\overline{\chi}\gamma_\mu\gamma_R\psi$	$-\overline{\chi}\gamma^\mu\gamma_R\psi$
$\overline{\psi}\sigma^{\mu\nu}\chi$	$\overline{\psi}\sigma_{\mu\nu}\chi$	$-\overline{\psi}\sigma_{\mu\nu}\chi$	$-\overline{\chi}\sigma^{\mu\nu}\psi$	$-\overline{\chi}\sigma_{\mu\nu}\psi$	$\overline{\chi}\sigma^{\mu\nu}\psi$

Branco, Lavoura, Silva

Theoretical ideas for CP-violation

★ In any quantum field theory CP-symmetry can be broken

- recall terms like $\overrightarrow{E} \cdot \overrightarrow{B}$ for E&M; can write a similar one for QCD!

$$\mathcal{L} = \mathcal{L}_{QCD} + \frac{\theta g^2}{32\pi^2} G_a^{\mu\nu} \widetilde{G}_{a\mu\nu}$$

- … but this is a problem, as a combination

$$\bar{\theta} = \theta + Arg \left[det M \right] \quad \text{with} \quad -\mathcal{L}_M = \overline{q_{Ri}} M_{ik} q_{Lk} + h.c.$$

- …is observable as an electric dipole moment of a neutron:

$$d_n \simeq e m_q \bar{\theta} / M_n^2 \approx 10^{-16} \bar{\theta} \ ecm$$

★ A variety of proposed solutions exist (axions, anthropic, etc)

Static observables for CP-violation

I. Intrinsic particle properties

✓ electric dipole moments:

$$\vec{d} = \int d^3x \; \vec{x}\rho(\vec{x})$$

should be (anti-)alligned with spin $\vec{s}$!

Experimental limits:

Particle	Exp Limit, e cm	Theory (SM), e cm
neutron	$\lvert d_n\rvert < 6.3 \times 10^{-26}$	$\lvert d_n\rvert \sim 10^{-32}$
electron	$\lvert d_e\rvert < 4 \times 10^{-27}$	$\lvert d_e\rvert \sim 10^{-37}$
muon	$\lvert d_\mu\rvert < 7 \times 10^{-19}$	$\lvert d_\mu\rvert \sim 10^{-35}$

$$d_n \simeq e m_q \bar{\theta}/M_n^2 \approx 10^{-16}\bar{\theta} \; ecm$$

$$\vec{d} \xrightarrow{\mathcal{T}} \vec{d} \quad || \quad \vec{s} \xrightarrow{\mathcal{T}} -\vec{s}$$

however

$$\vec{d} \xrightarrow{\mathcal{P}} -\vec{d} \quad || \quad \vec{s} \xrightarrow{\mathcal{P}} \vec{s}$$

thus, if $\vec{d} \neq 0 \Rightarrow \mathcal{T}$ or $\mathcal{CP}$ is broken

Low energy strong interaction effects might complicate predictions, but $\bar{\theta} < 10^{16}$!
We will not be discussing it here.

Theoretical ideas for CP-violation

★ In any quantum field theory CP-symmetry can be broken

1. Explicitly through dimension-4 (or higher) operators ("hard")

   Example: Standard Model (CKM): $\bar{\psi}_i \psi_k \overset{CP}{\Rightarrow} \bar{\psi}_k \psi_i,\ \varphi \overset{CP}{\Rightarrow} \varphi$

   $$\mathcal{L}_{Yuk} = \zeta_{ik} \bar{\psi}_i \psi_k \varphi + H.c. \overset{CP}{\not\Rightarrow} \mathcal{L}_{Yuk}$$

2. Explicitly through dimension <4 operators ("soft")

   Example: SUSY, 2HDM, ...

3. Spontaneously (CP is a symmetry of the Lagrangian, but not of the ground state)

   Example: multi-Higgs models, left-right models $\langle \Phi \rangle = \begin{pmatrix} k & 0 \\ 0 & k' e^{i\eta} \end{pmatrix}$

★ These mechanisms can be probed in quark transitions

Aside: no spontaneous CP-violation in SM

★ One can show that SM (or other 1HDMs) cannot spontaneously break CP

- In order to spontaneously break CP, a scalar doublet (Higgs) must have a VEV, which is independent of $\vec{r}$ and t

- One can perform an SU(2) rotation to bring the doublet to be

$$\langle 0|\phi|0\rangle = \begin{pmatrix} 0 \\ ve^{i\theta} \end{pmatrix}$$

- Recall that under CP transformation

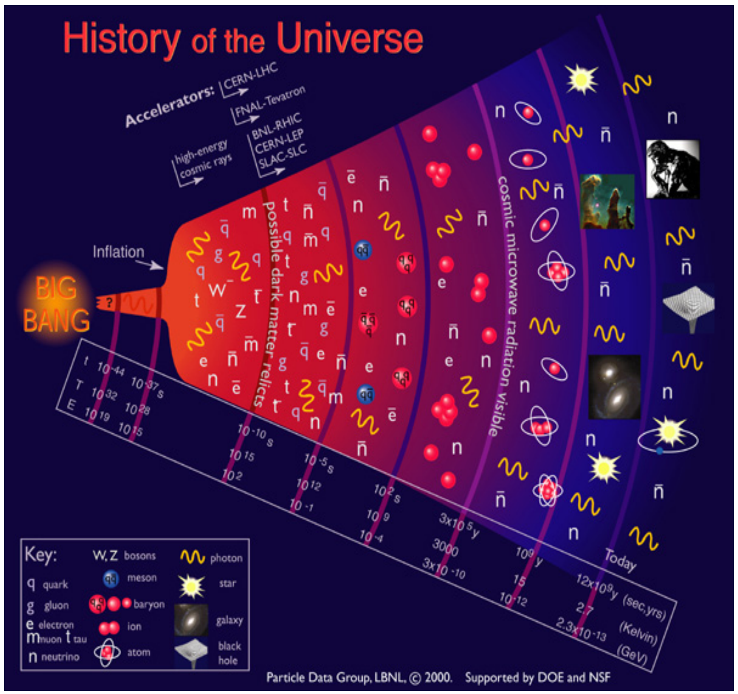
$$[CP]\phi(\vec{r},t)[CP]^\dagger = exp(i\alpha)\phi^\dagger(-\vec{r},t)$$

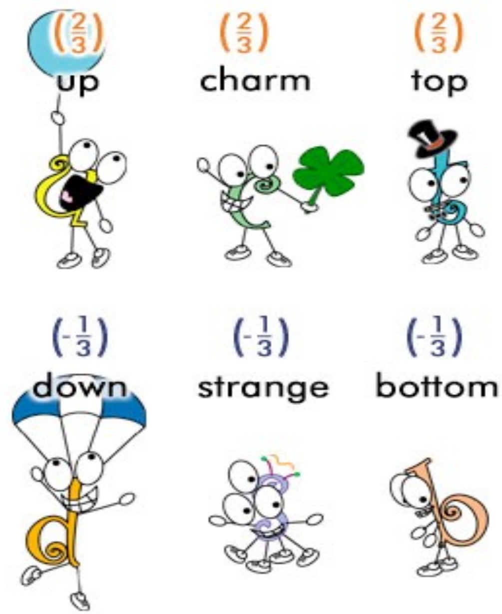
- Choosing $\alpha = 2\theta$ we can always make it invariant under CP-transformation!

★ Thus we need multi-Higgs doublet models to realize spontaneous CP breaking

Observation of CP-violation?

★ CP-violation has been firmly established with the down-type quarks





★ Down-type quark system: consistent with SM!

★ What about up-type quark system? Hope: signs of New Physics?

CKM picture of CP-violation

★ CP violation in the Standard Model is related to mass generation

- masses are generated through Yukawa terms (quarks)

$$-\mathcal{L}_Y = Y_{ij}^d \overline{Q_{Li}^f} H D_{Rj}^f + Y_{ij}^u \overline{Q_{Li}^f} \widetilde{H} U_{Rj}^f + h.c. \quad \text{with} \quad Q_{Li}^f = \begin{pmatrix} U_{Li}^f \\ D_{Li}^f \end{pmatrix}$$

- after spontaneous symmetry breaking $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H^0 \end{pmatrix}$

$$-\mathcal{L}_M = (M_d)_{ij} \overline{D_{Li}^f} D_{Rj}^f + (M_u)_{ij} \overline{U_{Li}^f} U_{Rj}^f + h.c. \quad \text{with} \quad (M_q)_{ij} = \frac{v}{\sqrt{2}} (Y^q)_{ij}$$

- … but mass matrices above are NOT diagonal! For for both q = {u,d}:

$$V_{qL} M_q V_{qR}^\dagger = M_q^{\text{diag}} \quad \text{with} \quad \begin{aligned} q_{Li} &= (V_{qL})_{ij}\, q_{Lj}^f \\ q_{Ri} &= (V_{qR})_{ij}\, q_{Rj}^f \end{aligned}$$

What is the physical effect of this diagonalization?

CKM picture of CP-violation

★ Charged current interactions: the only source of flavor violation in SM

- since left and right matrices are different: charge current part of $\mathcal{L}$:

$$-\mathcal{L}^q_{W^\pm} = \frac{g}{\sqrt{2}} \overline{u}_{Li} \gamma^\mu \left[V_{uL} V^\dagger_{qR} \right]_{ij} d_{Lj} W^+_\mu + h.c.$$

$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$ (CKM matrix)

- Cabibbo-Kobayashi-Maskawa (CKM) matrix is unitary: $VV^\dagger = 1$ (N^2 relations)
- Counting the number of parameters: N×N
  - N×N complex matrix contains $2N^2$ real parameters
  - N×N unitary matrix contains $2N^2 - N^2 = N^2$ real parameters (phases and angles)
  - can rephrase up and down quarks: 2N-1 relations: $N^2 - (2N-1) = (N-1)^2$ parameters
  - … which represent ${}_NC_2=N(N-1)/2$ angles and $(N-1)(N-2)/2$ phases

2 generations: 1 angle and 0 phases; 3 generations: 3 angles and 1 phase!
(No CPV) (CPV)

CKM picture of CP-violation

★ There is a single phase of the CKM matrix for 3-generation SM

- … but there are MULTIPLE ways to parameterize CKM matrix
  - Wolfenstein parameterization (parameters: λ ~ 0.22, A ~ 0.83, ρ ~ 0.15, η ~ 0.35)

$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

  - Buras-Wolfenstein parameterization (with $\bar{\rho} = \rho(1-\lambda^2/2)$ and $\bar{\eta} = \eta(1-\lambda^2/2)$)

$$V = \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{bmatrix}$$

(note $\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$)

  - "PDG" parameterization (in terms of rotation angles)

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

CKM picture of CP-violation

★ There is a single phase of the CKM matrix for 3-generation SM

- Even though there are MULTIPLE ways to parameterize CKM matrix

$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

(Wolfenstein)

- ...there exists a parameterization-independent quantity,

$$Im\left[V_{ij}V_{kl}V^\dagger_{il}V^\dagger_{kj}\right] = J_{CKM}\sum_{m,n=1}^{3}\epsilon_{ilkm}\epsilon_{jlkm} \quad \text{with} \quad J_{CKM} \simeq \lambda^6 A^2 \eta$$

- Since CP-violation appears from imaginary parts of Yukawas, there is a condition for CP-violation to be present in the SM:

(Jarlskog)

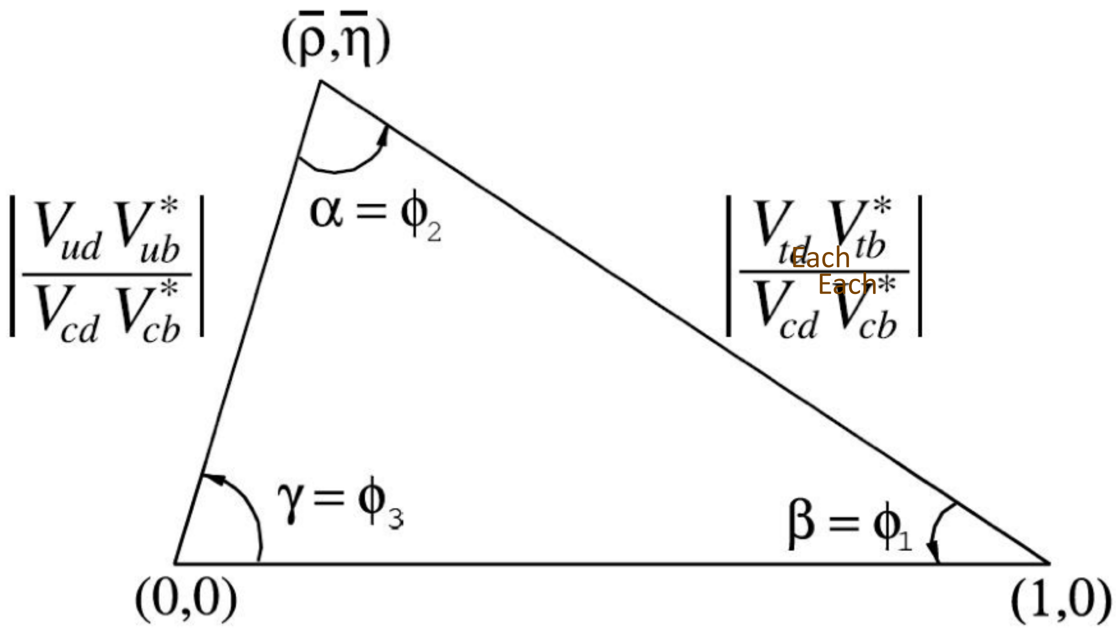
$$\Delta m^2_{tc}\Delta m^2_{tu}\Delta m^2_{cu}\Delta m^2_{bs}\Delta m^2_{bd}\Delta m^2_{sd}J_{CKM} \neq 0 \quad \text{with} \quad \Delta m^2_{ij} = m^2_i - m^2_j$$

i.e. no mass degeneracies or zero (or π) angles/phases

CKM picture of CP-violation

★ There is a single phase of the CKM matrix for 3-generation SM

- off-diagonal terms in unitarity relations VV⁺=1 look like triangles in a complex plane (*ρ*,*η*), e.g. $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ Each term is $\mathcal{O}(\lambda^3)$



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

- angles are

$$\phi_1(\beta) = arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$$ phase of V_{td} in Wolfenstein param

$$\phi_2(\alpha) = arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$$

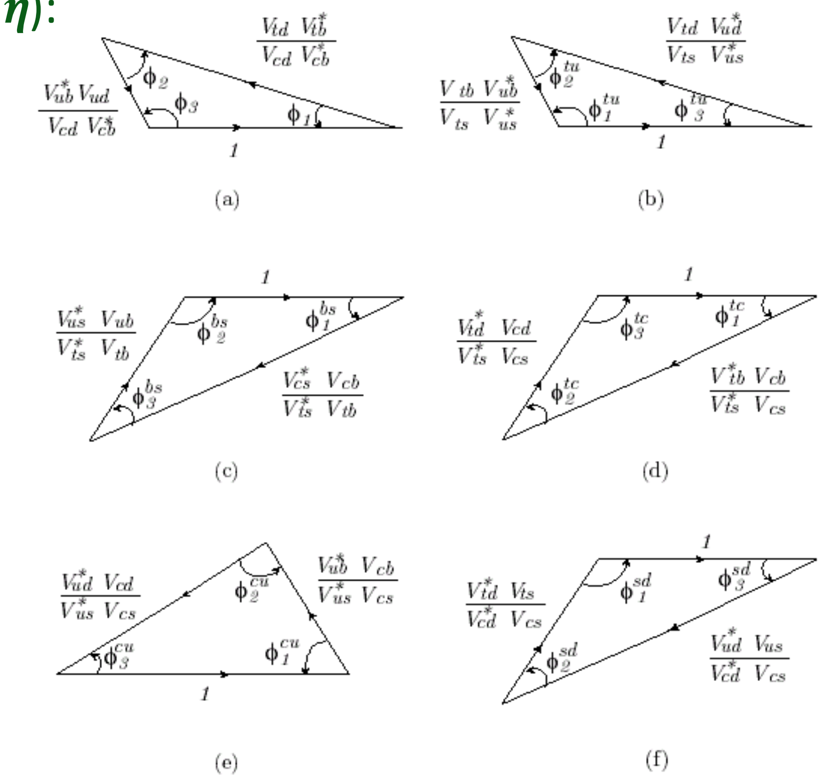
$$\phi_3(\gamma) = arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$$ phase of V_{ub} in Wolfenstein param

CKM picture of CP-violation

★ There is a single phase of the CKM matrix for 3-generation SM

- off-diagonal terms in unitarity relations $VV^{+}=1$ look like triangles in a complex plane (ρ,η):

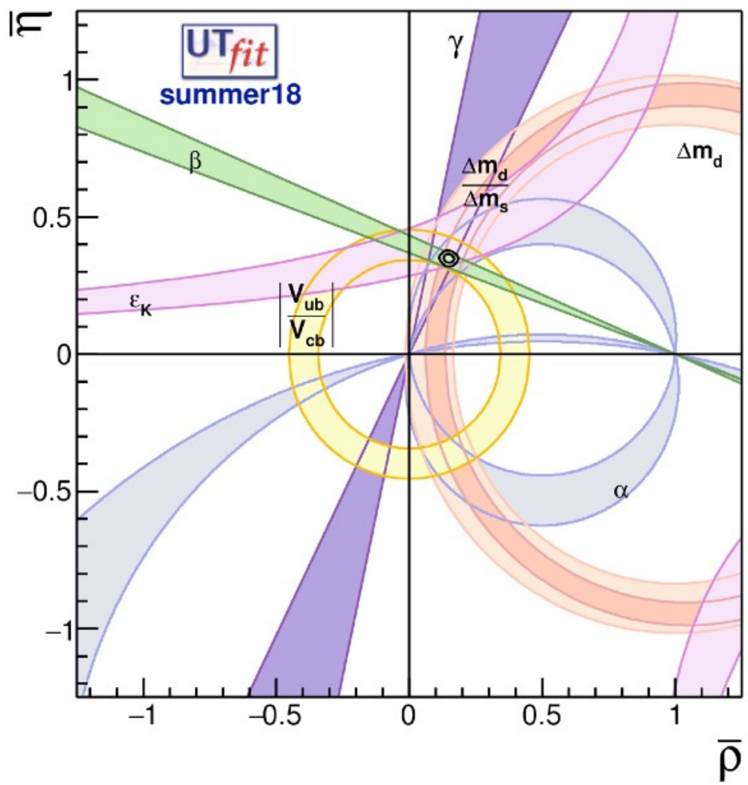
$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

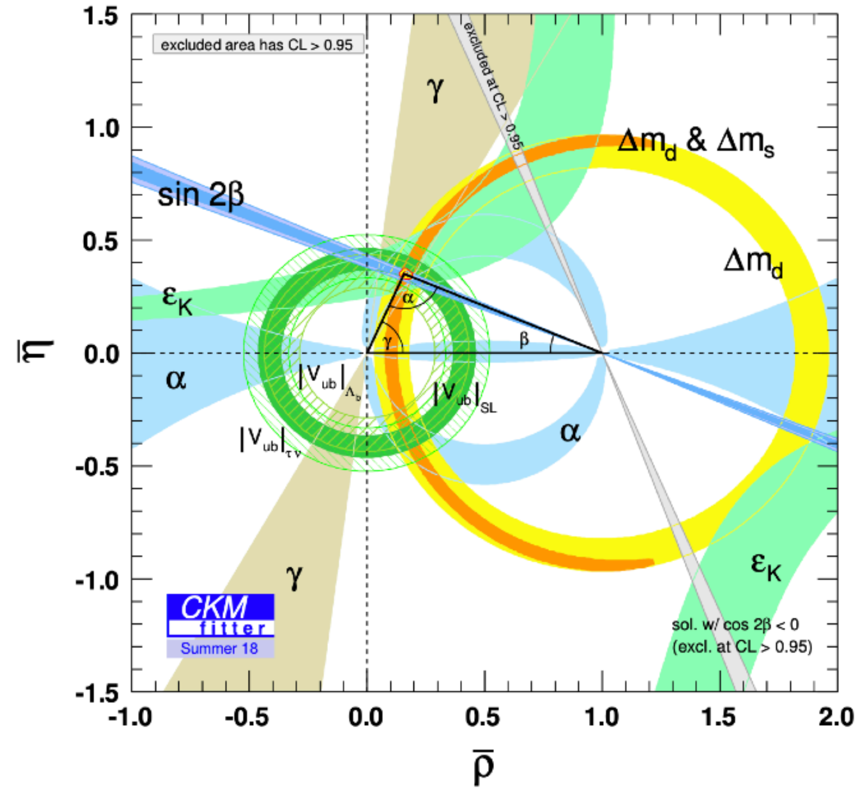


- … but regardless of the lines/columns used all these triangles have the same area $A = J_{CKM}/2$ (useful cross-check for NP studies)!

★ There is a single phase of the CKM matrix for 3-generation SM

- triangle parameters can be determined via a variety of ways…



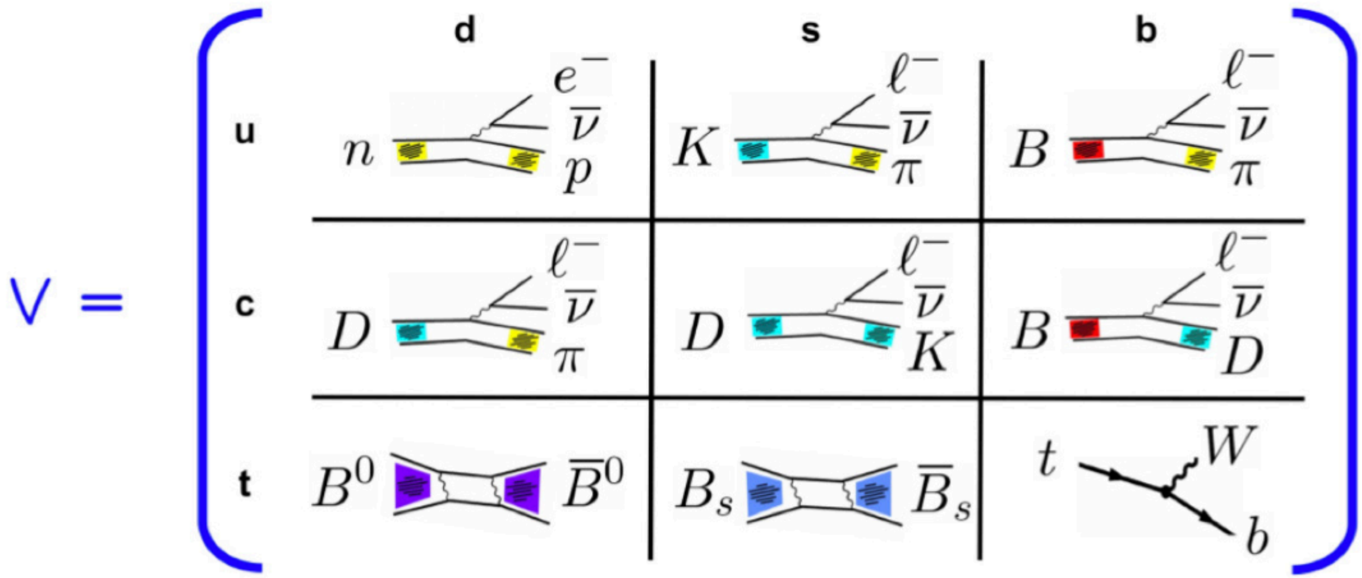


- … and even though any triangle can be completely defined by two measurements: an angle and two sides (or 3 sides or 3 angles)

Using SM CP-violation to study NP

★ There is a single phase of the CKM matrix for 3-generation SM

- triangle parameters can be determined via a variety of ways...



E. Vale Silva

- ... and even though any triangle can be completely defined by two measurements: an angle and two sides (or 3 sides or 3 angles)
- ... we keep measuring the "triangle parameters" trying to find inconsistencies!

Recipe for searches for New Physics

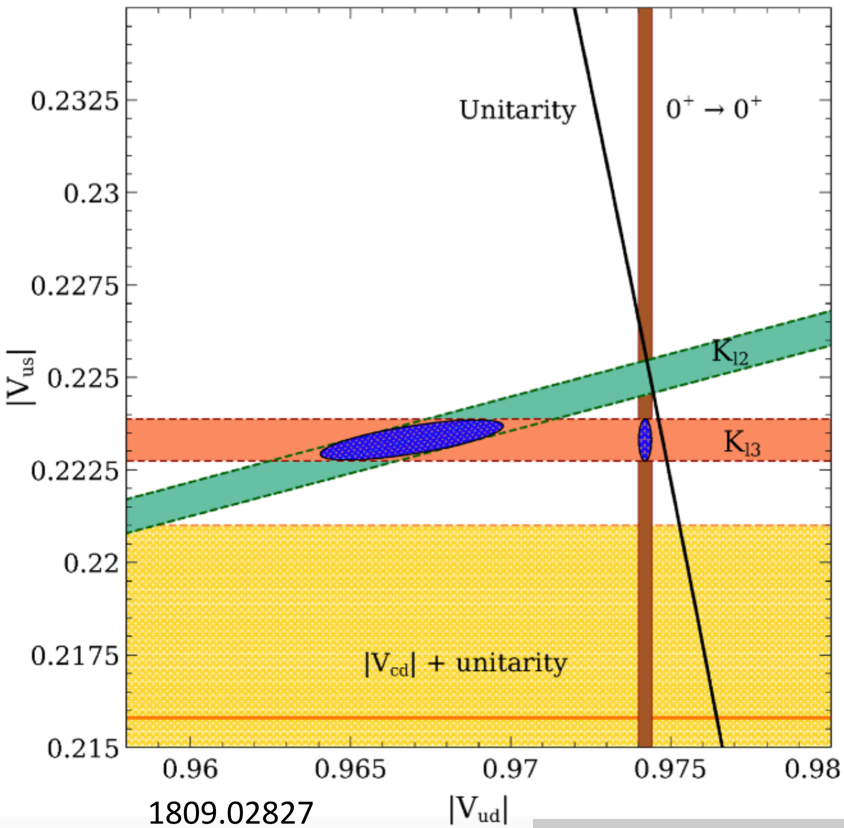
1. Measure as many processes that depend on CKM parameters independently
2. Interpret those measurements assuming there is no NP contribution and extract the CKM parameters
3. Build CKM triangles out of those CKM parameters. If a triangle does not close, then no-NP assumption was incorrect and there is a (possible) presence of New Physics

Realistically, one does not even need triangles…

Current issues with “experimental unitarity”

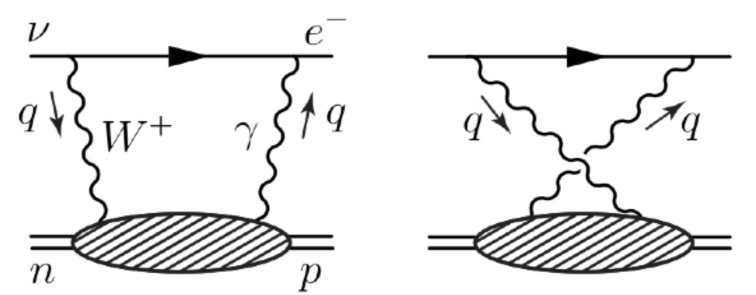
★ CKM parameters extracted from various decays are used to check unitarity

- Measurements with no CP-violation: first row unitarity



1809.02827

$$\Delta_u \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$$



Choice of $f_+(0)$		V_{us}	$\Delta_{CKM} = V_{ud}^2 + V_{us}^2 - 1$	
N_f = 2+1	0.9677(27)	**0.2238(8)**	**−0.0019(5)**	$= -4.2\sigma$
N_f = 2+1+1	0.9698(17)	**0.2233(6)**	**−0.0021(4)**	$= -5.4\sigma$

CKM angle measurements at Belle II

Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to J/\psi K_S^0$	ϕ_1	★★★	5-10	★★	★★	★	★
$B \to \phi K_S^0$	ϕ_1	★★	>50	★★	★★★	★	★★★
$B \to \eta' K_S^0$	ϕ_1	★★	>50	★★	★★★	★	★★★
$B \to \rho^\pm \rho^0$	ϕ_2	★★★	>50	★	★★★	★	★
$B \to J/\psi \pi^0$	ϕ_1	★★★	>50	★	★★★	-	-
$B \to \pi^0 \pi^0$	ϕ_2	★★	>50	★★★	★★★	★★	★★
$B \to \pi^0 K_S^0$	$S_{\rm CP}$	★★	>50	★★★	★★★	★★	★★

Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
GGSZ	ϕ_3	★★★	>50	★★	★★★	★	★★
GLW	ϕ_3	★★★	>50	★★	★★★	★	★★
ADS	ϕ_3	★★	>50	★★	★★★	★	★★★
Time-dependent	$\phi_3 - \phi_2$	★★	-	★★	★★	★	★

How to observe CP-violation?

★ There exists a variety of CP-violating observables

1. "Static" observables (flavor-conserving), such as electric dipole moment

2. "Dynamical" observables (flavor-violating):

   a. Transitions that are forbidden in the absence of CP-violation

   $$CP\left[\text{initial state}\right] \neq CP\left[\text{final state}\right]$$

   b. Mismatch of transition probabilities of CP-conjugated processes

   $$\Gamma\left(D \to f\right) \neq \Gamma\left(\overline{D} \to \overline{f}\right)$$

   c. Various asymmetries in decay distributions, etc.

★ Depending on the initial and final states, these observables can be affected by SM and BSM sources of CP-violation

★ LHCb: initial state is NOT CP-symmetric, nonzero $D\overline{D}$ production asymmetry

How to observe CP-violation: easy

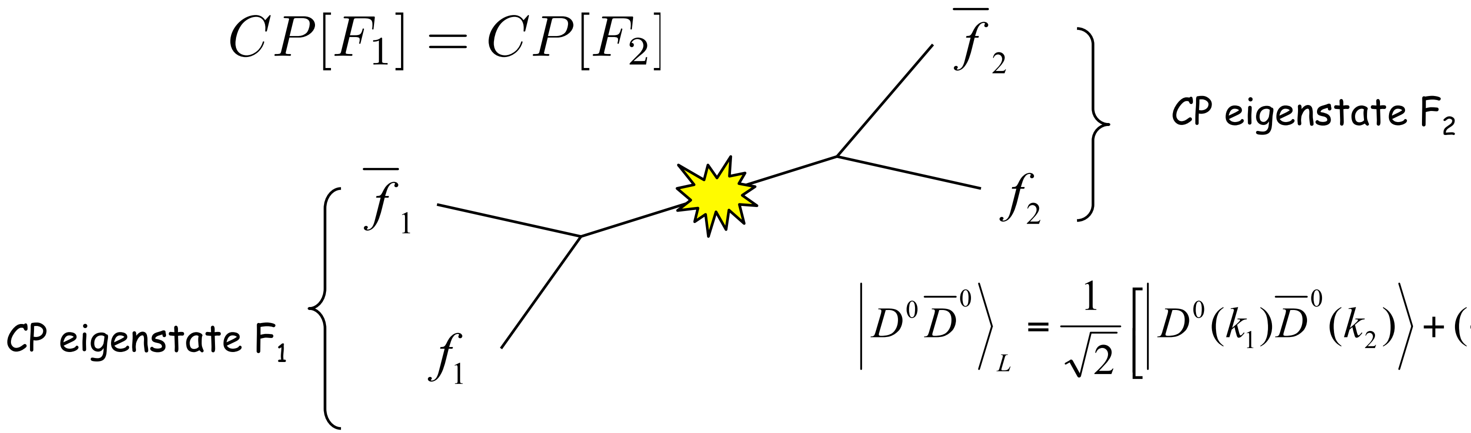
τ-charm factory

★ Recall that CP of the states in $D^0\overline{D^0} \to (F_1)(F_2)$ are anti-correlated at ψ(3770):

★ a simple signal of CP violation: $\psi(3770) \to D^0\overline{D^0} \to (CP_\pm)(CP_\pm)$

I. Bigi, A. Sanda; H. Yamamoto; Z.Z. Xing; D. Atwood, AAP

$$CP[F_1] = CP[F_2]$$



$$\left|D^0\overline{D}^0\right\rangle_L = \frac{1}{\sqrt{2}}\left[\left|D^0(k_1)\overline{D}^0(k_2)\right\rangle + (-1)^L\left|D^0(k_2)\overline{D}^0(k_1)\right\rangle\right]$$

$$\Gamma_{F_1F_2} = \frac{\Gamma_{F_1}\Gamma_{F_2}}{R_m^2}\left[\left(2+x^2+y^2\right)\left|\lambda_{F_1}-\lambda_{F_2}\right|^2 + \left(x^2+y^2\right)\left|1-\lambda_{F_1}\lambda_{F_2}\right|^2\right]$$

★ CP-violation in the **rate** → of the second order in CP-violating parameters.

★ Cleanest measurement of CP-violation!

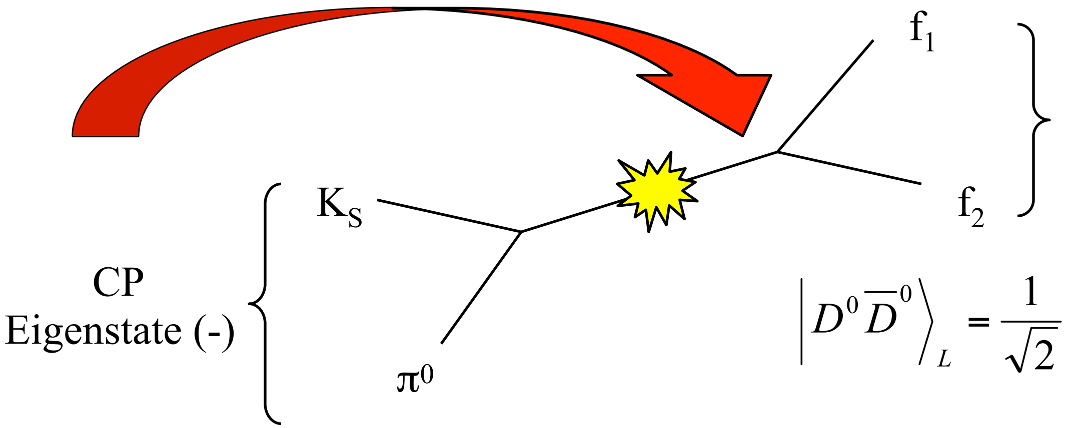
$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

AAP, Nucl. Phys. PS 142 (2005) 333
hep-ph/0409130

What if F1 or F2 is not a CP-eigenstate

τ-charm factory

- ★ If CP violation is neglected: mass eigenstates = CP eigenstates
- ★ CP eigenstates do NOT evolve with time, so can be used for "tagging"



$$D_{CP(+)} \to f_1 f_2$$

$$\left| D^0 \overline{D}^0 \right\rangle_L = \frac{1}{\sqrt{2}} \left[\left| D^0(k_1) \overline{D}^0(k_2) \right\rangle + (-1)^L \left| D^0(k_2) \overline{D}^0(k_1) \right\rangle \right]$$

- ★ τ-charm factories have good CP-tagging capabilities

CP anti-correlated ψ(3770): $\mathrm{CP(tag)}\ (-1)^L = \underbrace{[\mathrm{CP}(K_S)\ \mathrm{CP}(\pi^0)]}_{(-)}\ (-1) = +1$

CP correlated ψ(4140)

Can measure (y cos ϕ): $B^l_\pm = \dfrac{\Gamma(D_{CP\pm} \to X l \nu)}{\Gamma_{tot}}$

$$y \cos\phi = \frac{1}{4}\left(\frac{B^l_+}{B^l_-} - \frac{B^l_-}{B^l_+}\right)$$

D. Atwood, A.A.P., hep-ph/0207165
D. Asner, W. Sun, hep-ph/0507238

How to observe CP-violation: hard

- How can CP-violation be observed in beauty/charm system?
  - can be observed by comparing CP-conjugated decay rates in various ways, both with and w/out time dependence

$$a_{\rm CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})},$$

  - can manifest itself in flavor ΔF=1 transitions (direct CP-violation)

$$\Gamma(D \to f) \neq \Gamma(CP[D] \to CP[f])$$

dCPV

  - or in ΔF=2 transitions (indirect CP-violation): mixing $\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D^0}\right\rangle$

$$R_m^2 = |q/p|^2 = \left|\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - (i/2)\Delta\Gamma}\right|^2 = 1 + A_m \neq 1$$

CPVmix

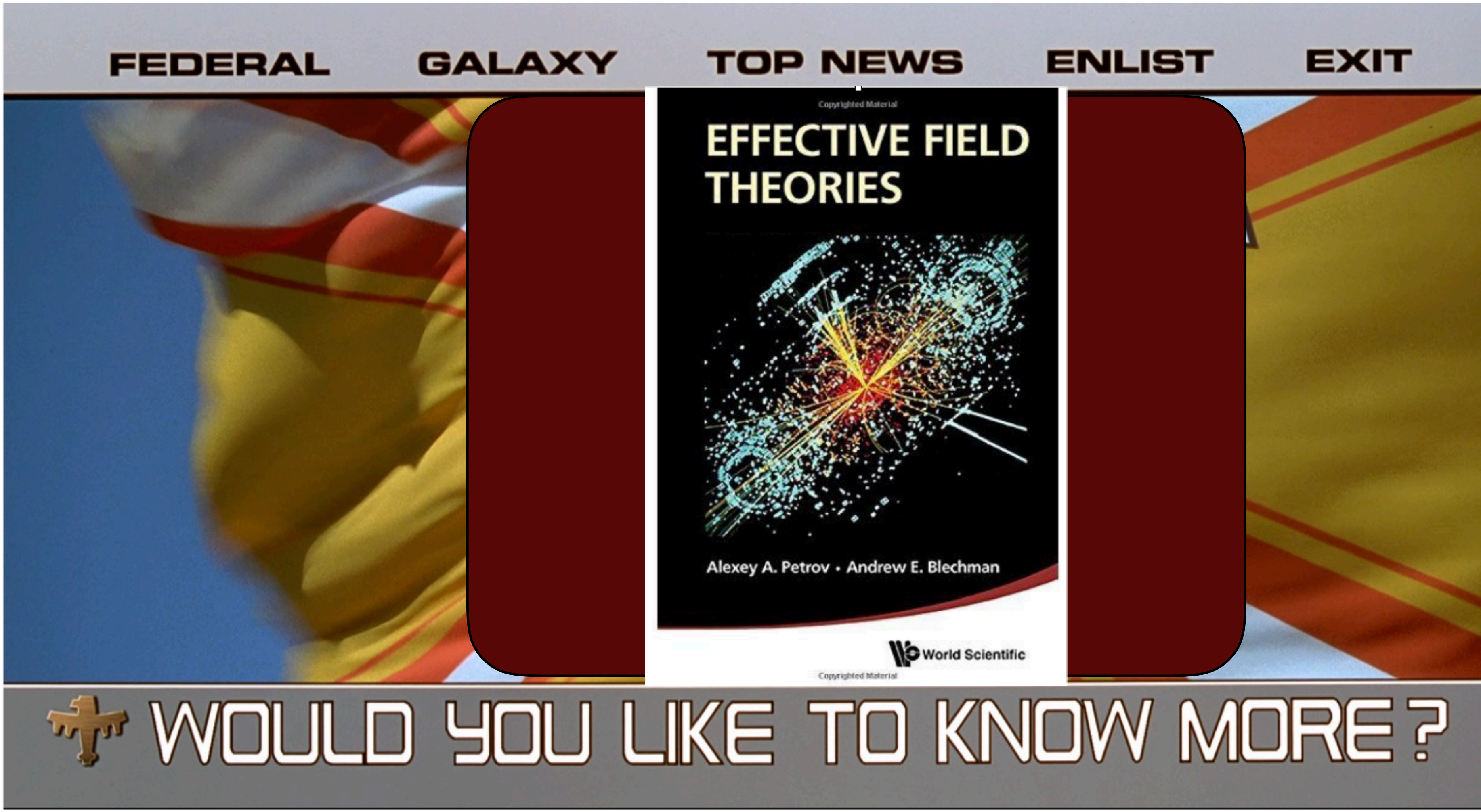
  - or in the interference b/w decays (ΔF=1) and mixing (ΔF=2)

$$\lambda_f = \frac{q}{p}\frac{\overline{A_f}}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A_f}}{A_f}\right|$$

CPVint

Things to take home

- Indirect effects of New Physics at flavor factories help to distinguish among models possibly observed at the LHC
  - a combination of bottom/charm sector studies
  - don't forget measurements unique to tau-charm factories
- Flavor provides great opportunities for New Physics studies
  - independent experimental access to up- and down-type quark sectors
- Observation of CP-violation in the current round of experiments could have provided a "smoking gun" signals for New Physics
  - But latest observation seem to be (broadly) consistent with Standard Model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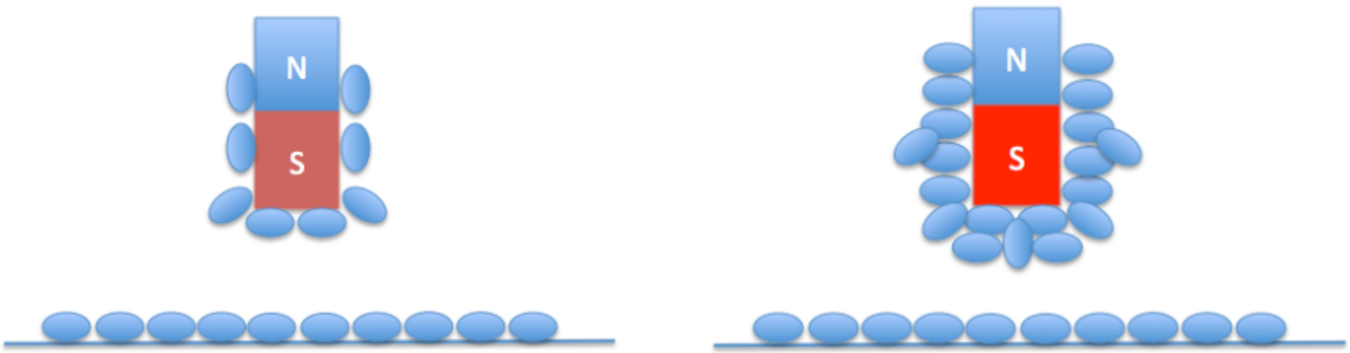
Alexey A. Petrov • Andrew E. Blechman
World Scientific
WOULD YOU LIKE TO KNOW MORE?


EXTRA!

Imagine all particles as tiny (almost) massless magnets…



Particle masses depend on the strength of our "magnets"!

Moreover, since the filings are self-interacting, they would clump into bunches ("particles") if disturbed: just like Higgs bosons!