• flavor structure in the SM
  • CP violation inherently tied with flavor
  • how do we test Kobayashi-Maskawa mechanism
STANDARD CKM UNITARITY TRIANGLE

- a test of CKM matrix unitarity

\[ V_{CKM}^\dagger V_{CKM} = V_{CKM} V_{CKM}^\dagger = 1. \]

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]

Figure 12.1: Sketch of the unitarity triangle.
1995
2021
• pick apart two measurements
• this will teach us about possible structure of CP violating observables
MEASUREMENTS

- two types of measurements shown in the CKM triangle plot
  - tree level transitions
    - less likely to be affected by new physics
  - loop level transitions
    - more likely to be affected by new physics
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MEASURING BETA
• **mixing**: flavor eigenstates ≠ mass eigenstates
• **oscillation**: initial flavor eigenstate time evolves to a different flavor eigenstate
  • because flavor eigenstate composed from two mass eigenstates
  • for instance $B^0 \sim \bar{b}d \Rightarrow \bar{B}^0 \sim b\bar{d}$
  • the oscillation frequency is $\omega = \Delta E$
• in the rest frame $\Delta E = \Delta m$
• oscillations a way to measure mass splittings
MESON MIXING: WHAT IS POSSIBLE AND WHAT IS NOT?
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• a general rule: "what is not explicitly forbidden is allowed"
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  - FCNCs forbidden at tree level, but allowed at 1 loop
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CP violation

• 3 categories of CPV observables
  • CPV in the decay: interf. between decay amplitudes
    \[ |A_f| \neq |\bar{A}_f| \]
  • CPV in mixing: interf. between \( M_{12} \) and \( \Gamma_{12} \) (different ways to oscillate \( B^0 \leftrightarrow \bar{B}^0 \))
    \[
    |q/p| \neq 1 \\
    |B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle.
    \]
  • CPV in interference between decays with and without mixing
    \[ \text{Im} \lambda_f \neq 0 \\
    \lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f}.
    \]

for kaons:
\[
p = \frac{1 + \epsilon}{\sqrt{2(1 + \epsilon^2)}} \\
q = \frac{1 - \epsilon}{\sqrt{2(1 + \epsilon^2)}}
\]
B meson mixing

- for $f$ that is a CP eigenstate, e.g., $f = J/\psi K_S$
- time dependent CP asymmetry

$$A_{f_{CP}}(t) = S_f \sin(\Delta mt) - C_f \cos(\Delta mt).$$
B meson

• for $f$ that is a CP eigenstate, e.g., $f = J/\psi K_S$

• time dependent CP asymmetry

$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta mt) - C_f \cos(\Delta mt).$$
\[ A_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t). \]

- CP eigenstate for \( f \) that is a CP eigenstate, e.g., \( f = J/\psi K_S \)
- Time dependent CP asymmetry

\[ \Gamma(\bar{B}^0(t) \to J/\psi K_S) \]
\[ \Gamma(B^0(t) \to J/\psi K_S) \]
B meson mixing

\[ A_{f_{CP}}(t) = S_f \sin(\Delta mt) - C_f \cos(\Delta mt). \]

- \( S_f \) measures CPV in interference between decays with and without mixing

\[ S_f \equiv \frac{2 \text{Im} \lambda_f}{1 + |\lambda_f|^2}, \]

- \( C_f \) is direct CPV asymmetry

\[ C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \]

\[ \lambda_f \equiv \frac{q \bar{A}_f}{p A_f}. \]
**B meson mixing**

- $q/p$ is universal for all final states $f$
  - in the SM

\[
\frac{q}{p} = e^{-i\phi_B} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}
\]

- for $B \rightarrow J/\psi K_S$ in the SM

\[
\frac{\tilde{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} + \ldots
\]

- so that the CPV parameter in the SM

\[
\lambda_{J/\psi K_S} = \frac{V_{tb}^* V_{td} V_{cb} V_{cs}^*}{V_{tb} V_{td}^* V_{cb}^* V_{cs}} = e^{i2\beta}
\]

\[
\text{Im} \lambda_{J/\psi K_S} = \sin 2\beta.
\]
\[ S_f \equiv \frac{2 \text{Im} \lambda_f}{1 + |\lambda_f|^2}, \]

**B mixing**

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MEASURING GAMMA ANGLE
MEASURING CP VIOLATION

• to measure phase $\gamma$ need to measure CP violation

• CPV an inherently quantum mechanical effect
  • governed by a phase in the Lagrangian

• need interference to be sensitive to it
INTERMEZZO

• not all phases are CP violating
• think of double slit experiment
  • a phase difference between two waves due to different paths
**STRONG PHASES VS. WEAK PHASES**

- **weak phases**: phases that appear in the Lagrangian
  - these violate the CP
- **strong phases**: phases that are CP conserving
  - for instance from rescattering of particles, due to QCD interactions
  - thought experiment:
    \[ \pi^+\pi^0 \rightarrow \rho^+ \rightarrow \pi^+\pi^0 \text{ scattering vs. } \pi^-\pi^0 \rightarrow \rho^- \rightarrow \pi^-\pi^0 \text{ scattering} \]

\[ A \propto \frac{1}{p^2 - m^2 + i m \Gamma} \]
CP VIOLATION IN THE DECAY

• direct CPV asymmetry

\[ A_f \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{1 - |A/\bar{A}|^2}{1 + |A/\bar{A}|^2}. \]

• assume two interfering contributions

\[ A = a_1 e^{i\phi_1+i\delta_1} + a_2 e^{i\phi_2+i\delta_2}, \]
\[ \bar{A} = a_1 e^{-i\phi_1+i\delta_1} + a_2 e^{-i\phi_2+i\delta_2}. \]

• for simplifying assumption \( a_2/a_1 \ll 1 \)

\[ A_f = \frac{a_2}{a_1} \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1) + \mathcal{O}(a_2^2/a_1^2). \]

• direct CP asymmetry nonzero only if

  • there are at least two interfering amplitudes
  • both strong and weak phase diff. nonzero
**OBTAINING GAMMA**

- use interference between $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$


$$e^{i\gamma} = \frac{\varrho + i\eta}{\varrho^2 + \eta^2} = \arg(V_{ub}^*) ,$$
OBTAINING GAMMA

• use interference between $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$

$e^{i\gamma} = \frac{\rho + i\eta}{\rho^2 + \eta^2} = \text{arg}(V^*_{ub})$

THE UPSHOT

• CPV an inherently quantum mechanical effect
  • governed by a phase in Lagrangian
• KM mechanism the dominant origin of CPV
  • measurements point to a consistent picture
    \[ A = 0.813(9), \quad \lambda = 0.225(2), \]
    \[ \tilde{\rho} = 0.157(7), \quad \tilde{\eta} = 0.348(9) \]
• since \( \tilde{\rho} \lesssim \tilde{\eta} \) the CKM weak phase is large, \( \mathcal{O}(1) \)

\[ e^{i\gamma} = \frac{\tilde{\rho} + i\tilde{\eta}}{\tilde{\rho}^2 + \tilde{\eta}^2} = \arg(V_{ub}^*), \]

• tests will be significantly improved in the near future
THE FUTURE: TREE PROCESSES @ LHCB

Akar et al, 1812.07638
THE FUTURE: TREE PROCESSES @ LHCb

Akar et al, 1812.07638
strong CP problem and axions
BACK TO THE GENERAL RULE...

• a general rule: "what is not explicitly forbidden is allowed"
• SM Lagrangian obeys this rule
• given field content + gauge symmetries write all possible (renormalizable) terms
• all these coefficients are known to be nonzero except one
STRONG CP PROBLEM

• Lorentz and gauge invariance allow

\[ \mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}_{\alpha,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_{\alpha\mu} G_{\alpha\rho} \]

• naively one would expect \( \theta \sim \mathcal{O}(1) \)

• experimentally though

\[ d_n \approx 4 \times 10^{-16} \bar{\theta} \, e \text{ cm} \quad |d_n|_{\text{exp}} < 3 \times 10^{-26} \, e \text{ cm} \]

• why \( \bar{\theta} \) so small?

• strong CP problem
STRONG CP PROBLEM

• several peculiar things about this term

\[ \mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_{a}^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_{a}^{\mu\nu} G_{a}^{\rho\sigma} \]

• setting it simply to zero by postulating CP invariance not satisfactory
  • the other known CPV param., CKM weak phase is $\mathcal{O}(1)$
• there is no such term for QED or weak $\text{SU}(2)_L$ gauge group*
• physically observable is the combination

\[ \bar{\theta} \equiv \theta + \arg \det(\mathcal{M}_u \mathcal{M}_d) \]

• note: if $m_u = 0$ can set $\bar{\theta} = \theta = 0$

*for QED can be integrated out by parts, for $\text{SU}(2)_L$ can be set to zero through B+L transfrom, see e.g., Fileviez Perez, Patel, 1402.6340
AXION

• axion solution to the strong CP problem:
  • if $\bar{\theta}(x)$ is a dynamical field with no other potential but $\bar{\theta}G\bar{G}$
  • the rest of QCD is CP conserving
    • $\Rightarrow$ non-perturbative
      QCD dynamics generates the potential with a minimum at $\bar{\theta}(x) = 0$
• new ultra-light particle - axion
  • PNGB of spontaneously broken global symmetry, anomalous under QCD

Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)
THE AXION MASS

• the couplings to gluons generates mass for the axion

\[ V_{\text{eff}} = \frac{a}{f} \alpha_s \left( \frac{\pi}{8} \right) G_{\mu\nu}^{a} \tilde{G}_{\alpha,\mu\nu} \]

\[ \xrightarrow{\text{non-PT effects}} V(a) \sim -m_{\pi}^2 f_{\pi}^2 \cos \frac{a}{f} \]

\[ m_a \sim m_{\pi} f_{\pi} / f \]

• larger \( f \) means lighter axion

\[ m_a = 5.7 \, \text{\( \mu \)eV} \left( \frac{10^{12} \text{GeV}}{f_a} \right) \]
AXION AS DARK MATTER

• axion can be a viable cold DM candidate
  • essentially stable for $m_a \lesssim 20$ eV
  • the production of axions in the early universe from misalignment mechanism
  • correct relic abundance for

$$10^{-8} \text{ eV} \lesssim m_a \lesssim 10^{-3} \text{ eV}$$
SEARCHING FOR AXIONS

• often minimal interactions assumed:

\[ \mathcal{L} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G} + \frac{E}{N} \frac{\alpha_{em}}{8\pi} \frac{a}{f_a} F\tilde{F}, \]

• searching for axion through its coupling to photons

\[ g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \]

\[ g_{a\gamma\gamma} \sim \frac{E}{N} \frac{1}{10^{16} \text{GeV}} \frac{m_a}{\mu\text{eV}} \]

• Primakoff conversion of photons (affects e.g. star cooling)

\[ \gamma + Ze \rightarrow a + Ze \]

• in static B conversion \( a \rightarrow \gamma \), photon of frequency \( m_a \), resonantly enhanced in microwave cavities of size \( 1/m_a \)

• lab searches also through couplings to nucleons : CASPER (bounds also from Supernova 1987A)

• in general axion couples to all SM fields

• many more constraints, including FCNC transitions
- Lab searches also through couplings to nucleons: CASPEr (bounds also from Supernova 1987A)
- In general, axion couples to all SM fields
  - Many more constraints, including FCNC transitions
ORIGIN OF MATTER-ANTIMATTER ASYMMETRY
MATTER DOMINANCE?

- Universe is made of matter not anti-matter

\[ \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10} \]

- what mechanism in the evolution of the Universe is responsible?

- Sacharov conditions
  - out of equilibrium
  - B violation
  - C and CP violation
CREATING MATTER-ANTIMATTER ASYMMETRY

• baryogenesis
  • create baryon asymmetry
  • since B-L conserved this also creates lepton asymmetry (through sphalerons)

• leptogenesis
  • create lepton asymmetry

• darkogenesis
  • create baryon or lepton asymmetry in dark sector
  • transfer to visible sector
LEPTOGENESIS

for a review see e.g., Davidson et al, 0802.2962

• maybe the simplest setup
  • new physics ingredients for neutrino see-saw already suffice

• heavy neutrinos decay out of equilibrium
  • CP asymmetry from interference of tree + loop diagrams

• 6 unremovable phases in Yukawa couplings, 3 of which are observable in PMNS

• generically requires heavy neutrinos, above $10^{10}$ GeV
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BARYOGENESIS

for a review, see, e.g., J. Cline, 1807.08749; hep-ph/0609145

• high scale baryogenesis
  • out of equilibrium decay of heavy states that violate B and CP
  • e.g. decays of GUT leptoquarks
• electroweak baryogenesis
  • in principle possible in the SM, if Higgs lighter and more CPV
  • new physics to make phase transition strong first order, additional CPV
    • out of equilibrium: creation of bubbles and their expansion
    • CPV: the higgs Yukawas in the wall
    • B viol.: sphalerons
**BARYOGENESIS**

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CONCLUSIONS

• CKM matrix weak phase the only observed source of CP violation
• active program to measure whether CPV in neutrino sector
• successful baryogenesis and/or resolution of strong CP problem require new physics
BACKUP SLIDES
THE AXION MECHANISM

- field without a potential: Goldstone boson $\theta = a/f$
  - need a new global U(1) symmetry that is spontaneously broken
  - experimentally the scale of spontaneous breaking $\sim f$ required to be large

- a simple example: single scalar field, with Mexican hat potential $V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$
  - parametrize $\phi = [f + s(x)] \exp[i\bar{\theta}(x)]$
  - shift symmetry $\bar{\theta} \rightarrow \bar{\theta} + \alpha$

- two directions
  - massless Goldstone boson: $\bar{\theta}$
  - massive scalar boson: $s$

- nontrivial requirement: coupling of $\bar{\theta} = a/f$ to $G\bar{G}$
  - achieved if U(1) anomalous with respect to QCD
AXION COUPLINGS

- in general the axion will couple to all the SM fields

\[ \mathcal{L} = \frac{\alpha_s}{8\pi f} G \tilde{G} + \frac{E}{N} \frac{\alpha_{em}}{8\pi f} F \tilde{F} + \sum_{\psi=e,u,d,\ldots} m_\psi \frac{a}{f} (\lambda_\psi \bar{\psi} \psi + i \lambda'_\psi \bar{\psi} \gamma_5 \psi) + \ldots \]

  - to solve strong CP problem only coupling to $G \tilde{G}$ needed
  - all the couplings are controlled by the scale of spontaneous symmetry breaking $\sim f$
    - experimentally $f$ required to be large, well above $10^{10}\text{GeV}$
  - $E, N, \lambda_\psi, \lambda'_\psi$, are UV model dependent parameters
    - in general expected to be $O(1)$
    - axion only feebly couples to the SM particles
AXIFLAVON

- so far axion solved
  - the strong CP problem
  - dark matter
- can be even more ambitious
  - the SM flavor problem
- a common solution: axiflavon
STANDARD MODEL FLAVOR PUZZLE

- where does the hierarchical structure of charged lepton masses come from?
- the mixing patterns in quark and lepton sectors?
- possible that due to spontaneously broken $U(1)$ symmetry
  - **axiflavon** the related Goldstone boson

\[
\begin{align*}
\text{width} & \quad \text{height} \\
10^1 & \quad 10^0 \\
10^{-1} & \quad 10^{-2} \\
10^{-3} & \quad 10^{-4} \\
10^{-5} & \quad 10^{-6} \\
-1 & \quad -\frac{1}{3} \\
\frac{2}{3} & \\
\end{align*}
\]

plot due to E. Stamou
AXIFLAVON: COUPLINGS TO FERMIONS

- crucial new ingredient flavor violating couplings to fermions
  - in the minimal model up to $O(1)$ uncertainties

\[ d_j \quad \cdots \cdots \quad a \sim \frac{\sqrt{m_i m_j}}{f_a} \sim \frac{m_a}{\mu eV} \times 10^{12} \text{GeV} \]

- observation of such couplings (in addition to usual axion searches) a smoking gun for axiflavon
SEARCHING FOR AXIONS

natural axion as DM window

1 Superradiance
2 SN1987A
3 H.E.S.S., Fermi–LAT
4 Globular Cluster
5 ADMX
6 White dwarfs

$K^+ \rightarrow \pi^+ a$
ADMX–II
ADMX–HF
CASPEr–II
IAXO
ABRA–Res
ABRA–Broad
TWO WAYS OF SEARCHING FOR BSM IN FLAVOR

• measuring rare decays
  • e.g., $b \rightarrow s l^+ l^-$

• measuring meson mixing amplitudes
  • e.g., $B_d - \bar{B}_d$ mixing
TWO WAYS OF SEARCHING FOR BSM IN FLAVOR

• measuring rare decays
  e.g., $b \rightarrow s l^+ l^-$

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  e.g., $B_d - \bar{B}_d$ mixing
**EFFECTIVE HAMILTONIAN**

- effective hamiltonian for $B$ mixing

\[
\mathcal{H}_{\text{eff}} = \frac{1}{8m_W^2} \frac{g^4}{16\pi^2} \eta_B S_0 (V_{tb}^* V_{td})^2 (\bar{b}_L \gamma^\mu d_L) (\bar{b}_L \gamma_\mu d_L) + \text{h.c.}
\]

1.26 QCD corrections + loop function

- for $B_s$ mixing instead

\[
\mathcal{H}_{\text{eff}} = \frac{1}{\Lambda_{\text{MFV}}^2} (V_{tb}^* V_{td})^2 (\bar{b}_L \gamma^\mu d_L) (\bar{b}_L \gamma_\mu d_L) + \text{h.c.}
\]

$\Lambda_{\text{MFV}} \simeq 6.0$ TeV.

$\lambda^3)^2$

$\Lambda_{\text{MFV}}^2$
NEW PHYSICS IN MIXING

- measuring mixing amplitude precisely can probe for new physics
- can parametrize the new physics contributions as

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \mathcal{H}_{\text{eff}}^{\text{NP}}$$

$$M_{12} = M_{12}^{\text{SM}} + M_{12}^{\text{NP}} = M_{12}^{\text{SM}} \left(1 + h_{d,s} e^{i\sigma_{d,s}}\right)$$

$$M_{12} = \frac{1}{2m_B} \langle \bar{B}_d^0 | \mathcal{H}_{\text{eff}} | B_d^0 \rangle^*$$

$$\left(V_{tb}^* V_{td}\right)^2 \quad \left(V_{tb}^* V_{ts}\right)^2$$
BOUNDS ON NEW PHYSICS IN MIXING

- ~20% corrections relative to the SM allowed at present
- to be reduced to ~5%

$B^0 - B\bar{0}$

$B_s - B\bar{s}$

Charles et al, 1309.2293

J. Zupan  CP violation: lecture 3
BOUNDS ON NEW PHYSICS IN MIXING

- ~20% corrections relative to the SM allowed at present
- to be reduced to ~5%

\[ B^0 - \bar{B}^0 \]

\[ B_s - \bar{B}_s \]

Charles et al, 1309.2293
WHAT SCALE?

- what does this mean in terms of bounds on NP masses?
- assume for instance, that NP has the same \((V-A)\times(V-A)\) structure as the SM

\[ H_{\text{eff}} = \left( \frac{(V_{tb}^*V_{tq})^2}{\Lambda_{\text{MFV}}^2} + \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2} \right) (\bar{b}_L\gamma^\mu q_L) (\bar{b}_L\gamma_\mu q_L) + \text{h.c.} \]

- e.g., could be due to \(Z'\) exchange

\[ H_{\text{eff}} = i(g_{Z'})^2 (\bar{b}_L\gamma^\mu q_L) \frac{-ig^{\mu\nu}}{q^2 - m_{Z'}^2} (\bar{b}_L\gamma_\nu q_L) \]

- \(h_d < 20\%\) correction to the SM gives, for \(C_{\text{NP}} = 1\)

\[ \Lambda_{\text{NP},B_d} \gtrsim 1500 \text{ TeV}, \quad \Lambda_{\text{NP},B_s} \gtrsim 300 \text{ TeV}, \]

- the difference entirely due to \(V_{ts} \approx 5V_{td}\)
LOW ENERGY PRECISION BOUNDS

• an impressive progress on flavor bounds in last 10 years $c\bar{u} \leftrightarrow b\bar{s}$
• in $D, B_s$ mixing
• also from $\varepsilon_K \leftrightarrow \varepsilon_{B_s}$

$$\frac{1}{\Lambda^2}(\bar{b}_L \gamma^\mu d_L)(\bar{b}_L \gamma_\mu d_L)$$

2007 $\rightarrow \sim$ now
progress on flavor bounds in last 10 years

\[ Q_{1, q} = (\bar{b}_L \gamma^\mu q_L)(\bar{b}_L \gamma^\mu q_L), \]
\[ Q_{2, q} = (\bar{b}_R q_L)(\bar{b}_R q_L), \]
\[ Q_{3, q} = (\bar{b}_R^\alpha q_\beta)(\bar{b}_R^\beta q_\alpha), \]
\[ Q_{4, q} = (\bar{b}_R q_L)(\bar{b}_L q_R), \]
\[ Q_{5, q} = (\bar{b}_R^\alpha q_\beta)(\bar{b}_L^\beta q_\alpha), \]

\[ \frac{1}{\Lambda^2}(\bar{b}_L \gamma^\mu d_L)(\bar{b}_L \gamma^\mu d_L), \]

in \( D, B_s \) mixing

also from \( \varepsilon_K \) 

\[ \varepsilon_K \sim \bar{b} s \]