

Theory of CP Violation

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CP as Natural Symmetry of Gauge Theories

P and C alone are *not* natural symmetries:
consider chiral gauge theory:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \psi_L^\dagger i \bar{\sigma} D \psi_L (+\psi_R^\dagger i \sigma \partial \psi_R)$$

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- \mathcal{L} violates P: right-handed fermions do not couple to gauge bosons
- \mathcal{L} violates C: left-handed antifermions do not couple to gauge bosons
- \mathcal{L} preserves CP: both left-handed fermions and right-handed antifermions couple to gauge bosons

Massless gauge theories are invariant under CP and T.

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But CP IS violated!

CP violation in K decays known since 1964; observed in B decays in 1999.

Origin in SM: Yukawa interactions:

$$\mathcal{L}_{\text{SM}} = \underbrace{\mathcal{L}_G(\psi, W, \phi)}_{\substack{\text{kinetic} \\ \text{energy} + \\ \text{gauge IA}}} + \underbrace{\mathcal{L}_H(\phi)}_{\substack{\text{Higgs potential} \\ \rightarrow \text{spontaneous} \\ \text{symmetry} \\ \text{breaking}}} + \underbrace{\mathcal{L}_Y(\psi, \phi)}_{\substack{\text{Yukawa IA} \\ \rightarrow \text{fermion} \\ \text{masses}}}$$

gauge sector scalar sector

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Origin in SM: Yukawa interactions:

$$\mathcal{L}_Y = -\lambda_d^{ij} \bar{Q}_L^i \cdot \Phi d_R^j - (\lambda_d^{ij})^* \bar{d}_R^j \Phi^\dagger \cdot Q_L^i + \dots$$

λ_d : general, not necessarily symmetric or Hermitian matrices (Yukawa couplings), not constrained by gauge symmetry

CP: $\lambda_d \leftrightarrow \lambda_d^* \Rightarrow$ (explicit) CP violation if λ_d complex

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Next generation of accelerators (LHC 2007/8):

- direct Higgs searches
 - indirect effects: CP in B decays
- } complementary tests of the scalar sector!

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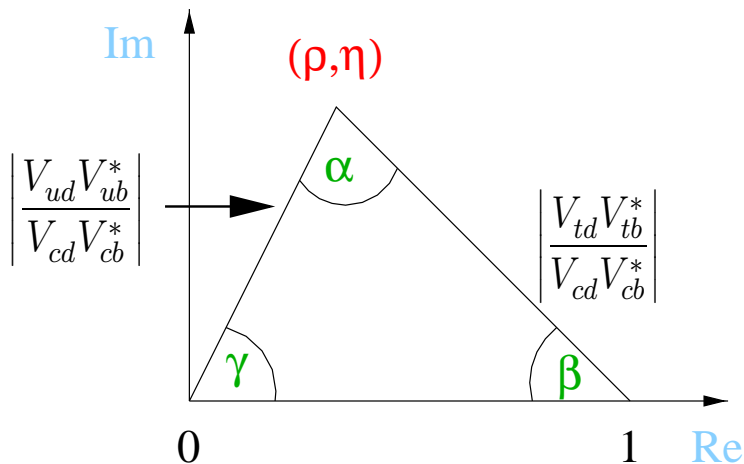
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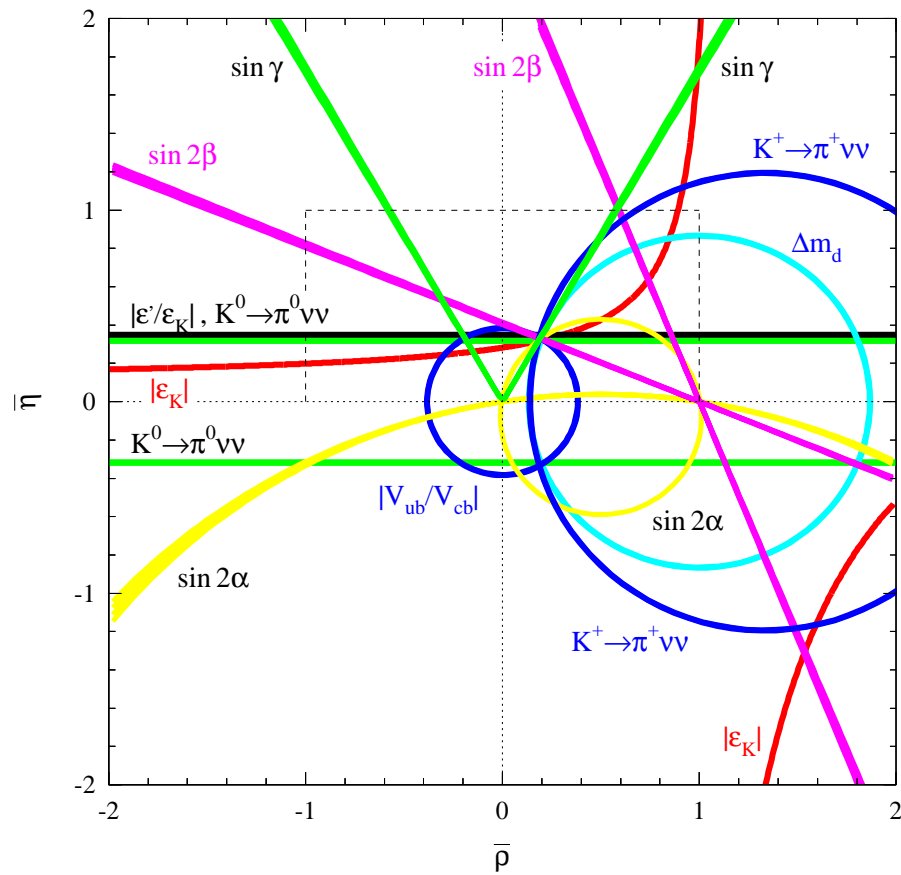
Visualise unitarity relation

$$\sum V_{dj} V_{jb}^* = 0$$

as triangle in complex plane:

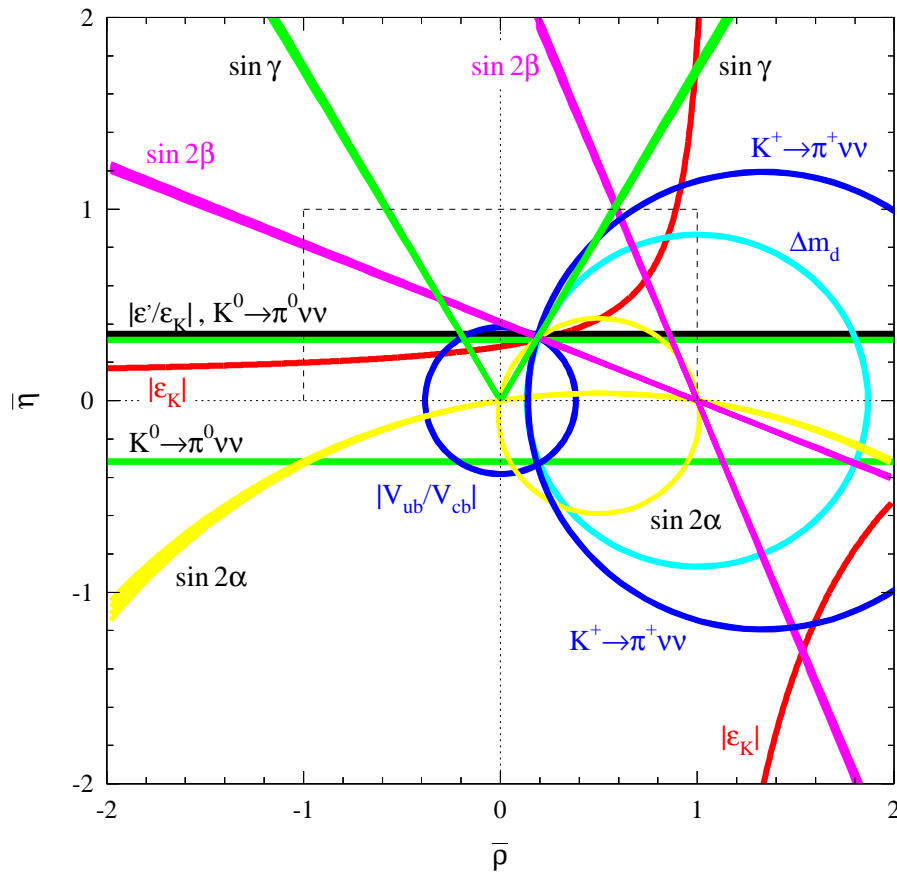
unitarity triangle (UT)

Experimental Determination of UT

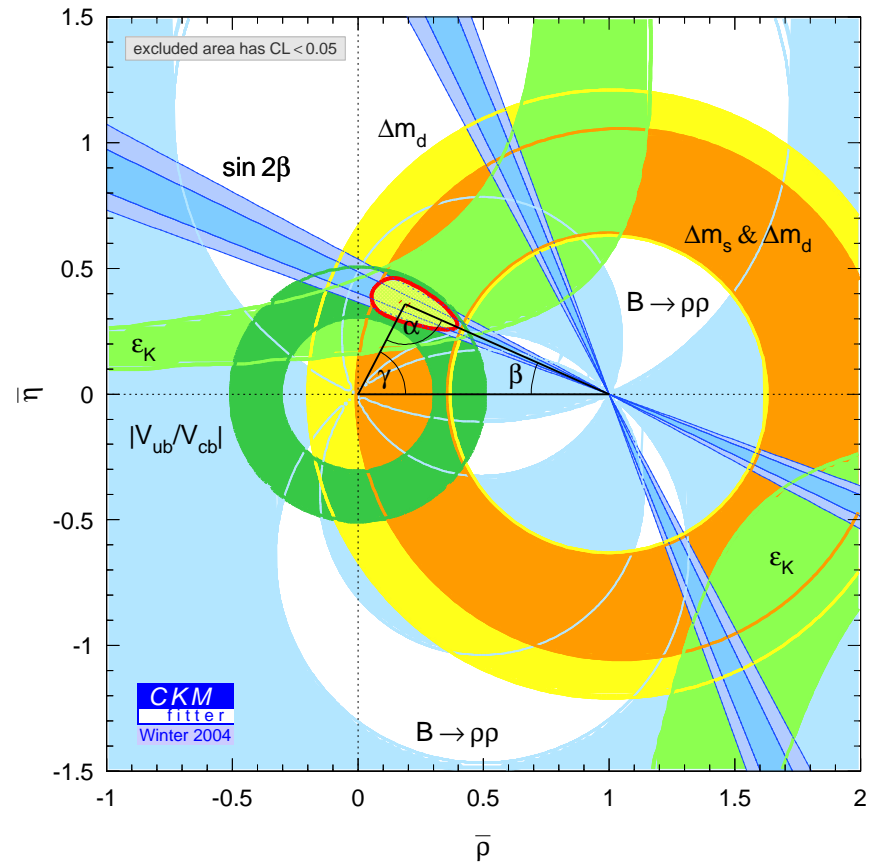


The ideal...

Experimental Determination of UT



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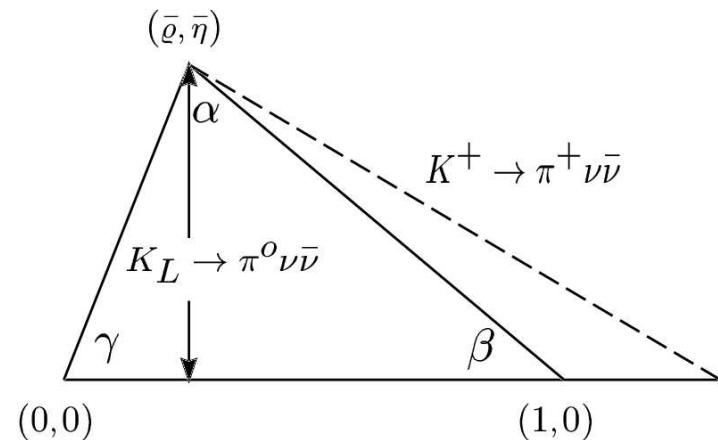
The reality...

UT from K Decays

Experimentally favoured: ϵ_K : th. uncertainty from $B_K, m_t, |V_{cb}|$

Theoretically favoured: $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}), B(K_L \rightarrow \pi^0 \nu \bar{\nu})$

- 😊 hadronic matrix elements from $K \rightarrow \pi \ell \nu$
- 😊 SD dominated (W-box, Z-penguin)
- 😊 QCD corrections known to NLO: small residual scale-dependence
- 😞 BR $\sim O(10^{-11})$
- 😊 complete determination of UT
- 😞 with strong dependence on $|V_{cb}|$ and (less strong) on m_t



npQCD potentially more dangerous than in B decays (ϵ'/ϵ etc.)

The Case for B Physics

- large number of different decay channels, sensitive to different weak phases

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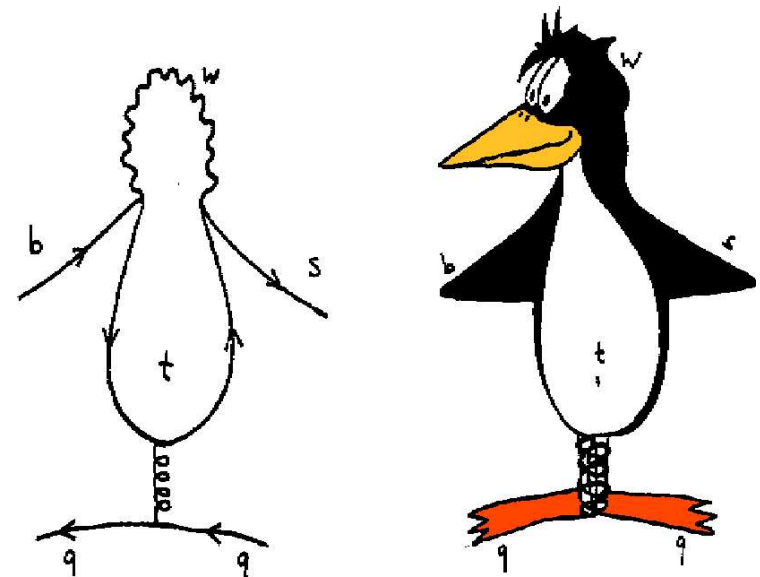
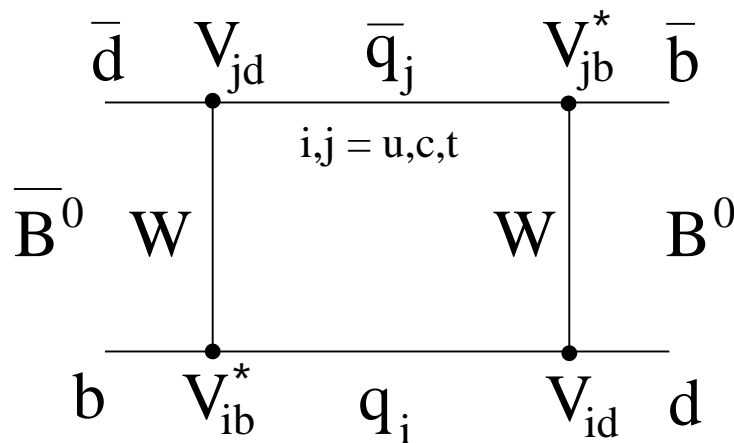
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- large number of different decay channels, sensitive to different weak phases
- expect sizeable CP asymmetries thanks to non-squashed unitarity triangles (in contrast to K decays)
- GIM-suppression largely relaxed thanks to $m_t \gg m_c, m_u$
 → large and **theoretically clean effects** from $B^0-\bar{B}^0$ mixing: → large penguin contributions:



Manifestations of CP Violation

- CP violation in the decay (direct CP violation):

$$|\mathcal{A}(B \rightarrow F)| \neq |\mathcal{A}(\bar{B} \rightarrow \bar{F})|$$

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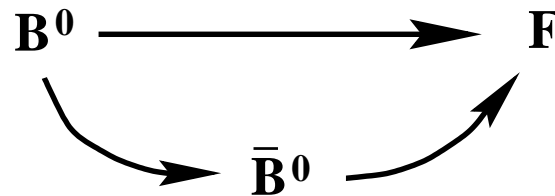
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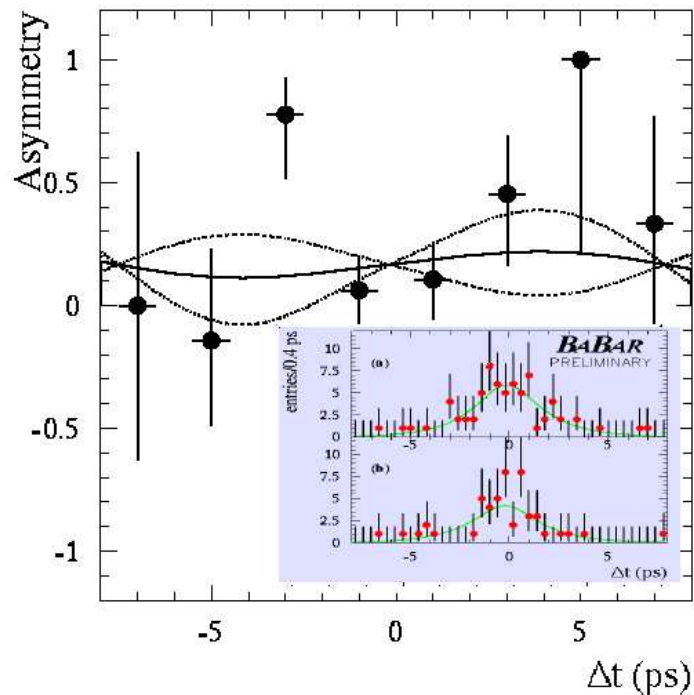
- CP violation in the

interference of decays with and without mixing

$$\mathcal{A}(B \rightarrow F) \neq \mathcal{A}(\bar{B} \rightarrow F)$$



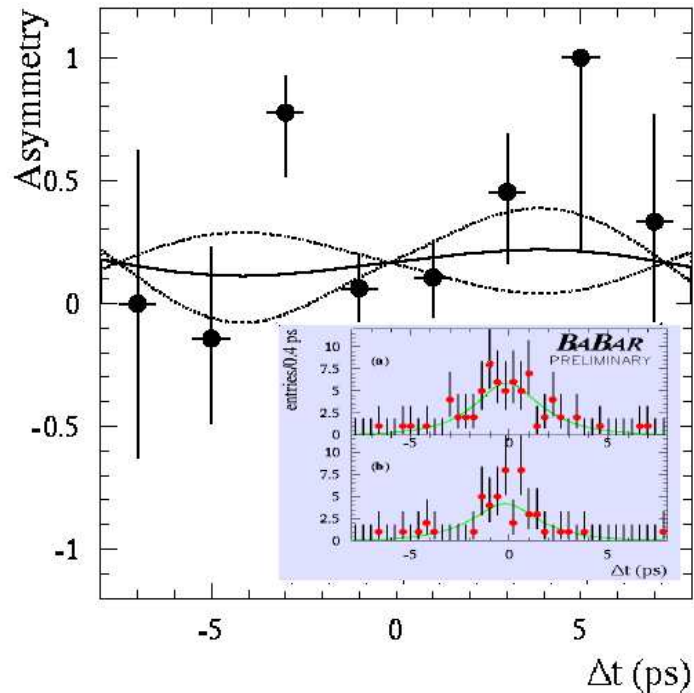
Time-dependent CP Asymmetries



Measure time-dependent CP asymmetry:

$$\frac{\Gamma(B_q^0(t) \rightarrow F) - \Gamma(\bar{B}_q^0(t) \rightarrow F)}{\Gamma(B_q^0(t) \rightarrow F) + \Gamma(\bar{B}_q^0(t) \rightarrow F)} = \left\{ \mathcal{A}_{\text{CP}}^{\text{dir}}(B_q \rightarrow F) \cos(\Delta M_q t) + \mathcal{A}_{\text{CP}}^{\text{mix}}(B_q \rightarrow F) \sin(\Delta M_q t) \right\}$$

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In general $\mathcal{A}_{\text{CP}}^{\text{dir}}$ and $\mathcal{A}_{\text{CP}}^{\text{mix}}$ dependent on hadronic matrix elements.

Special case: one **single** weak amplitude dominant:

$$\mathcal{A}_{\text{CP}}^{\text{mix}} = \text{Im} \left(\mp e^{-i\phi_q} \right) \longrightarrow \text{“gold-plated” decay} \quad (\text{e.g. } B \rightarrow J/\psi K_S)$$

→ measure mixing phase ϕ_q with small theoretical uncertainty

The Big Picture

Alternative scenarios of CP violation

Recall: CP violation happens in the scalar sector

→ combination of several mechanisms:

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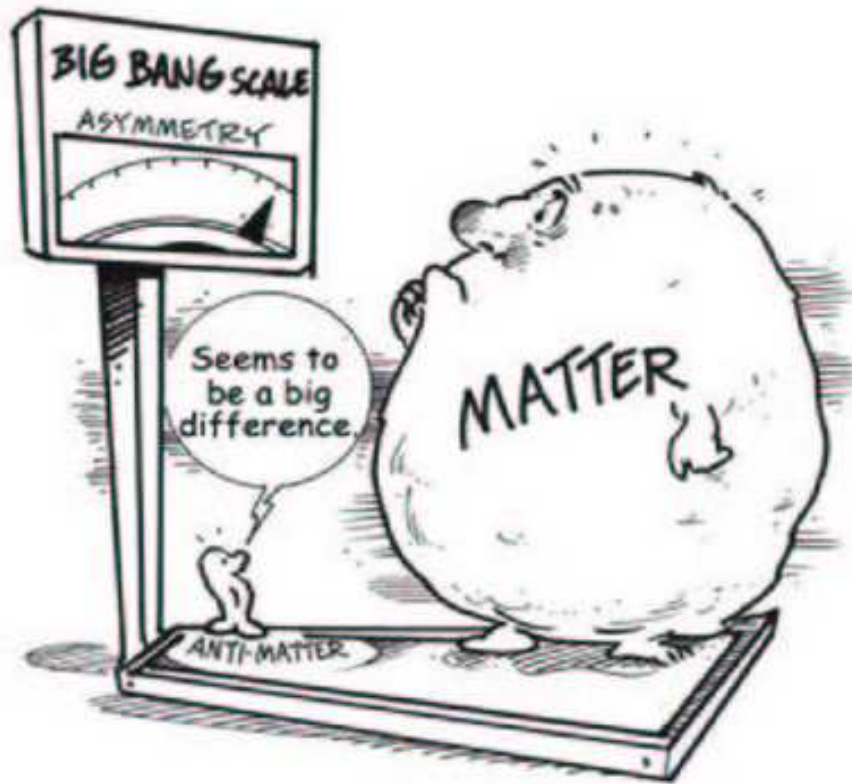
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- electric dipole moment of neutron problematic

The Truly Big Picture

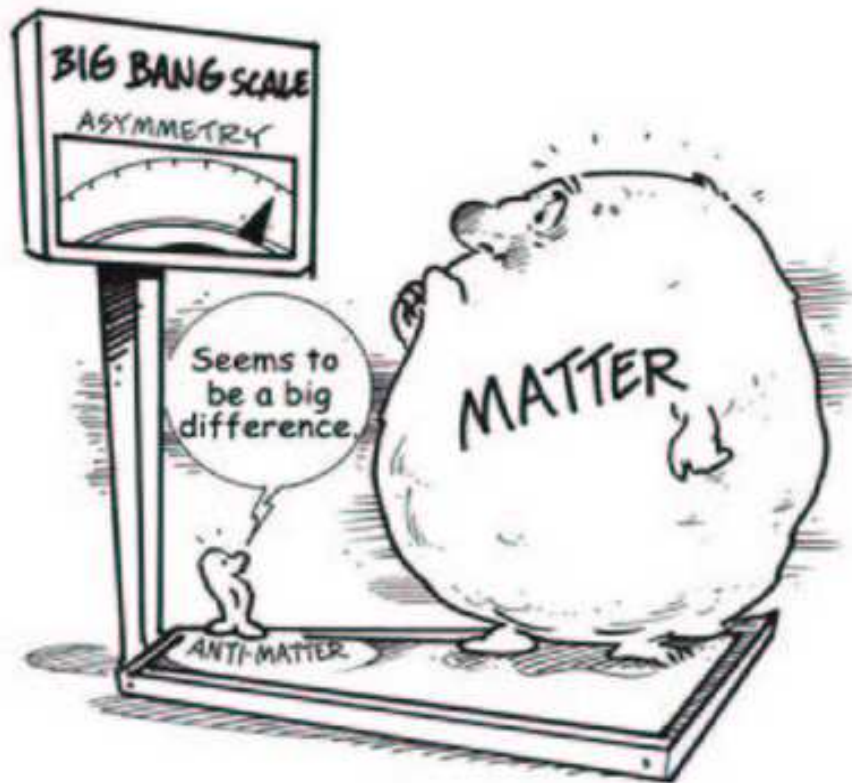
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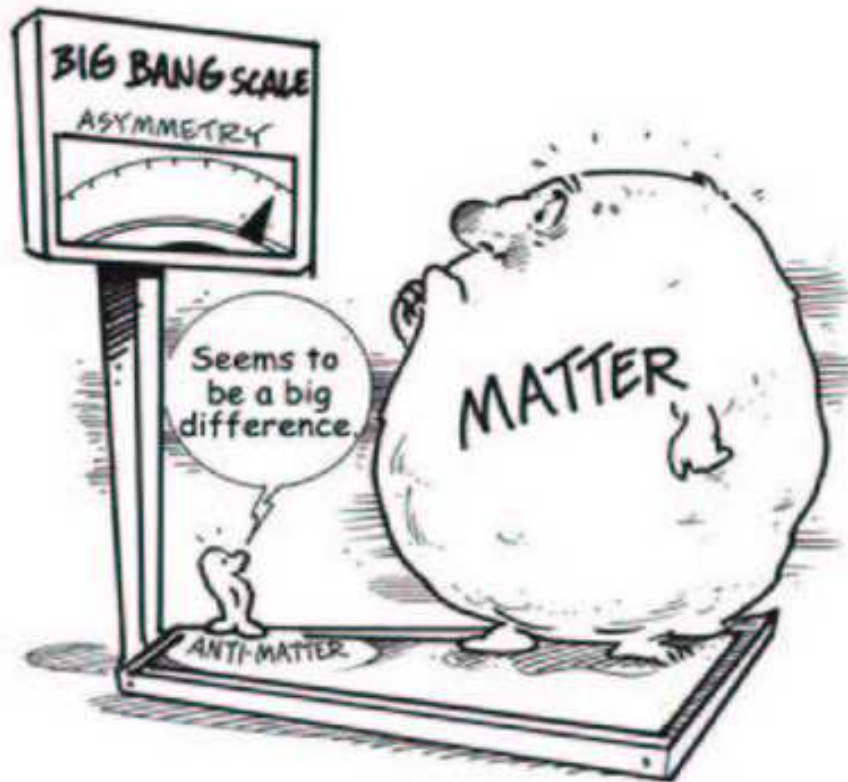


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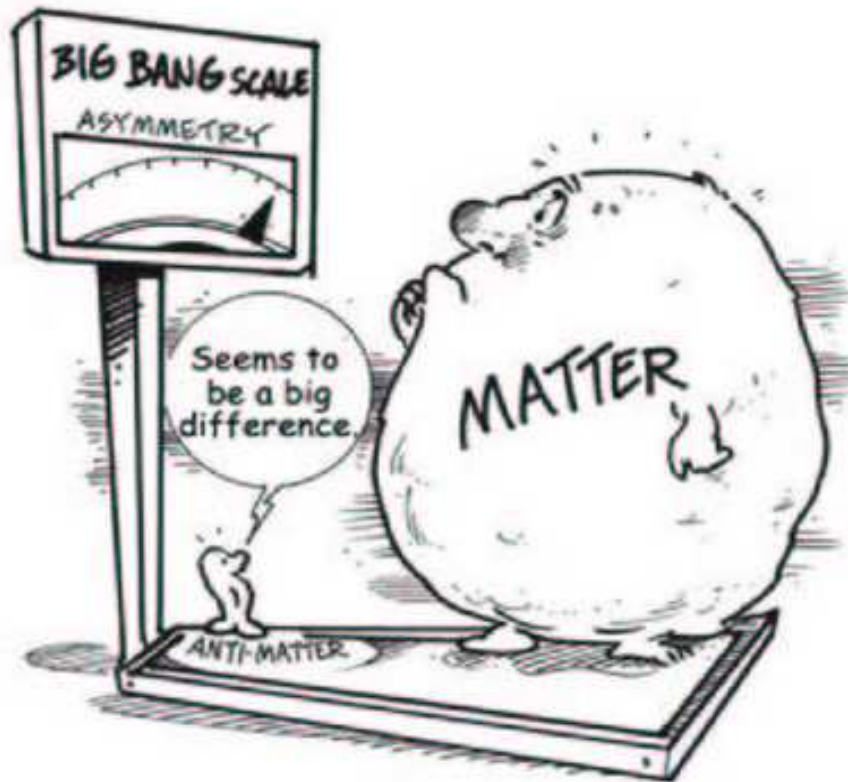


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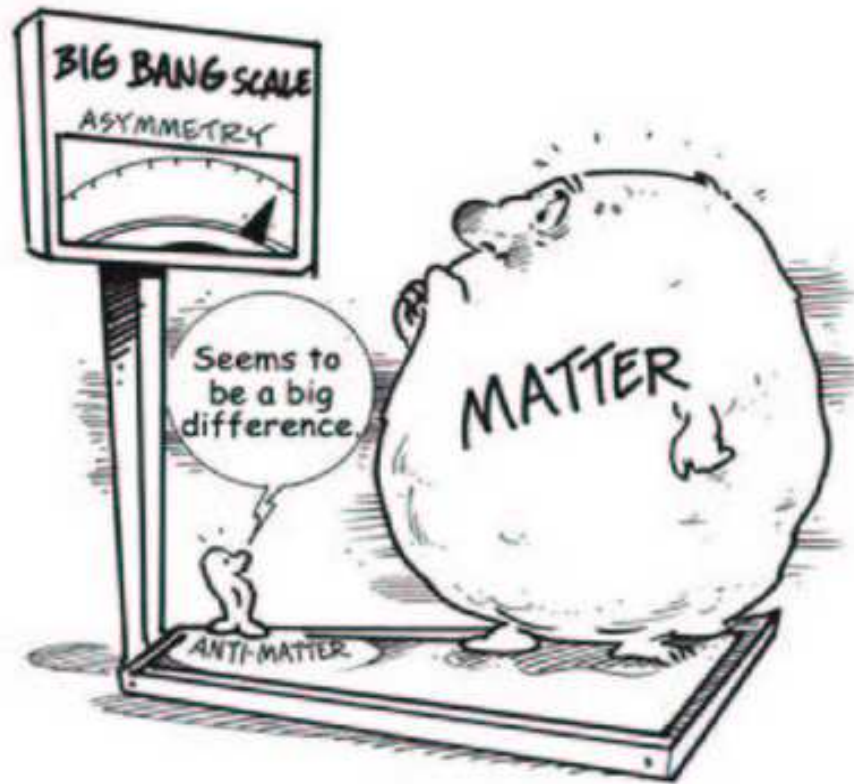
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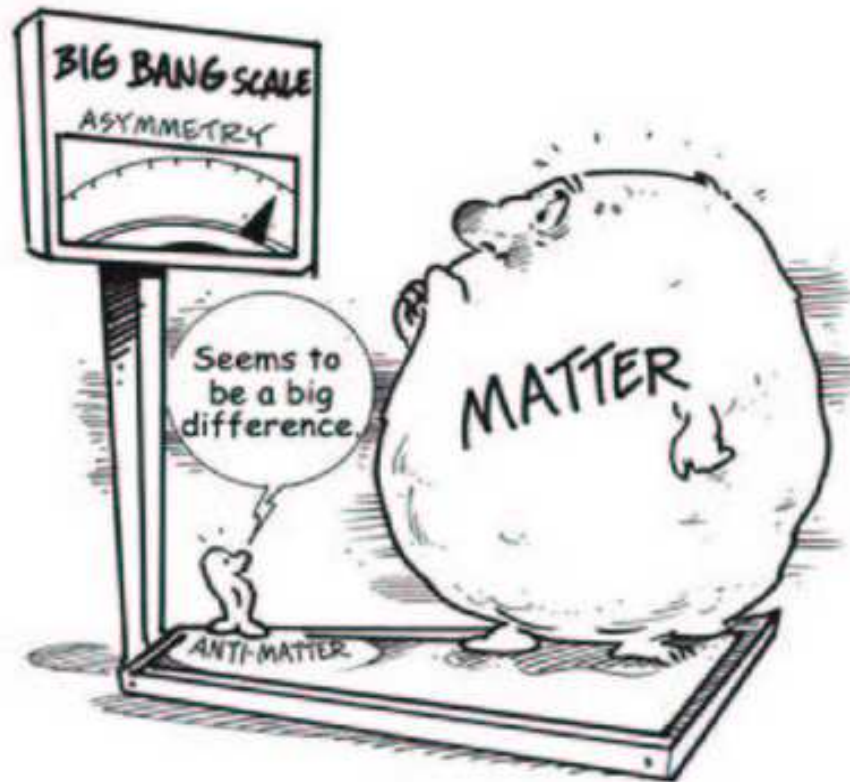


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GUT baryogenesis?

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Leptogenesis?

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Electroweak baryogenesis?

Outlook

- CP violation related to scalar sector
- nonstandard sources of CP violation to show up as inconsistencies of measurements of parameters of UT
- extraction of UT angles α , β , γ from experiment often hampered by nonperturbative QCD
 - QCD factorisation? (Beneke, Buchalla, Neubert, Sachrajda)
 - Phenomenological methods? (Fleischer, Gronau)
- B/K physics to give indirect hints at new physics
→ complementary to results of direct searches
- exciting times for theorists and experimentalists alike!