12 Best Reasons to Like CP Violation

SSI 2012
The Electroweak Scale:
Unraveling the Mysteries at the LHC

SLAC, California
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1st REASON

1st REASON

$\boxed{\text{Otherwise we would not be here}}$

The Baryon Asymmetry

$$\boxed{Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (8.75 \pm 0.23) \times 10^{-11}}$$

- Antimatter disappeared from the Universe: $n_{\bar{b}}/s \approx 0$
- Matter has survived: $n_b/s \sim 10^{-10}$

Sakharov Conditions

- The baryon asymmetry can be dynamically generated ('baryogenesis') provided that

1. Baryon number is violated;
2. CP and C are violated;
3. Departure from thermal equilibrium.

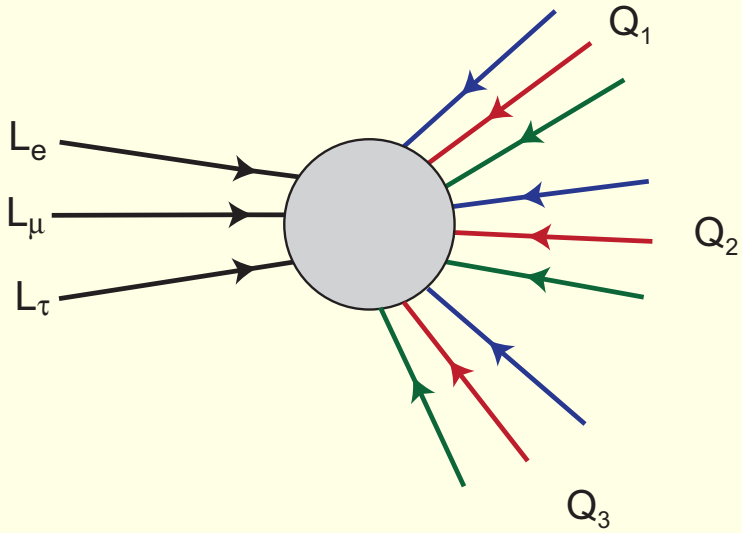
If CP were not violated, neither matter nor antimatter would have survived

2nd REASON

2nd REASON

$$\boxed{\text{A window to } t_{\text{universe}} < 10^{-11}\ \text{s}}$$

SM $B + L$ violation



$$T = 0 \qquad \Gamma \propto e^{-8\pi^2/g^2}$$

$$T \gg T_{\rm EWPT} \qquad \Gamma \propto 250\alpha_w^5 T$$

- $\Gamma_{B+L\ \text{violation}} > H$ for $T_{\rm EWPT} < T < 10^{12}$ GeV
- Baryon number is no longer violated after $t \sim 10^{-11}$ seconds
- Electroweak baryogenesis: $t \sim 10^{-11}$ seconds
- Leptogenesis: $t \lesssim 10^{-27}$ seconds

3rd REASON

3rd REASON

$\boxed{\text{It proves the SM wrong}}$

SM CP violation

- CP violated within the SM only if

$$\begin{aligned} J_{CP} &\equiv (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \\ &\times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \\ &\times s_{12}s_{23}s_{13}c_{12}c_{23}c_{13}s_\delta \neq 0 \end{aligned}$$

- The baryon asymmetry is therefore proportional to J_{CP}:

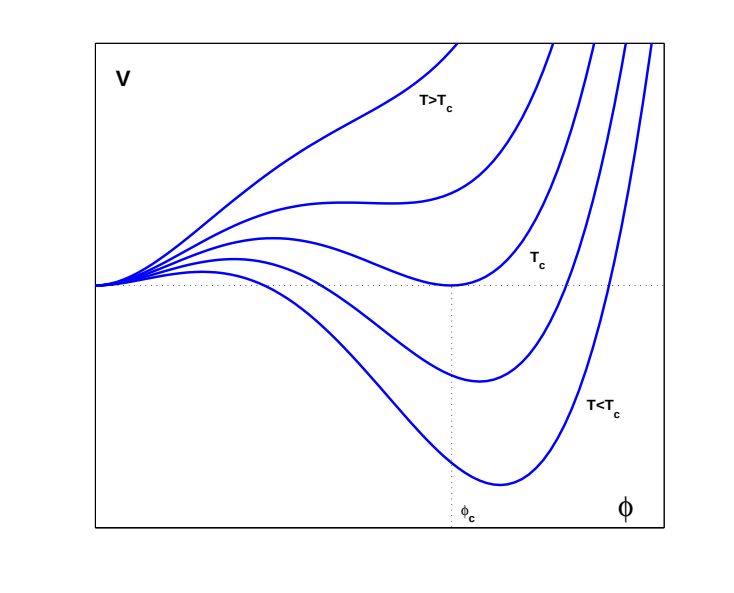
$$\left(\frac{n_b}{n_\gamma}\right)^{\rm SM} \propto \frac{J_{CP}}{T_c^{12}} \sim 10^{-20} \quad \Longleftrightarrow \quad \left(\frac{n_b}{n_\gamma}\right)^{\rm obs} \sim 10^{-9}$$

$$\boxed{\text{The KM mechanism cannot produce large enough baryon asymmetry}}$$

$\Longrightarrow$ There must exist sources of CPV beyond the KM phase

SM EWPT

Need a strongly 1st-order PT



SM EWPT

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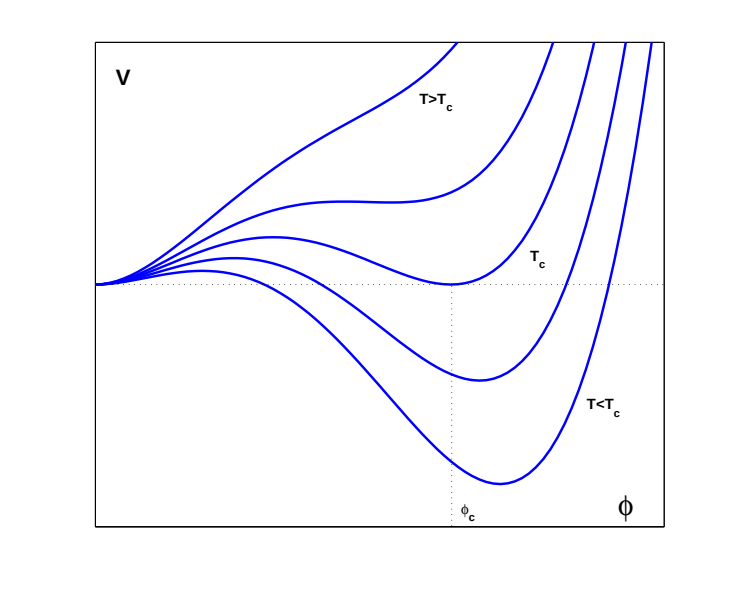
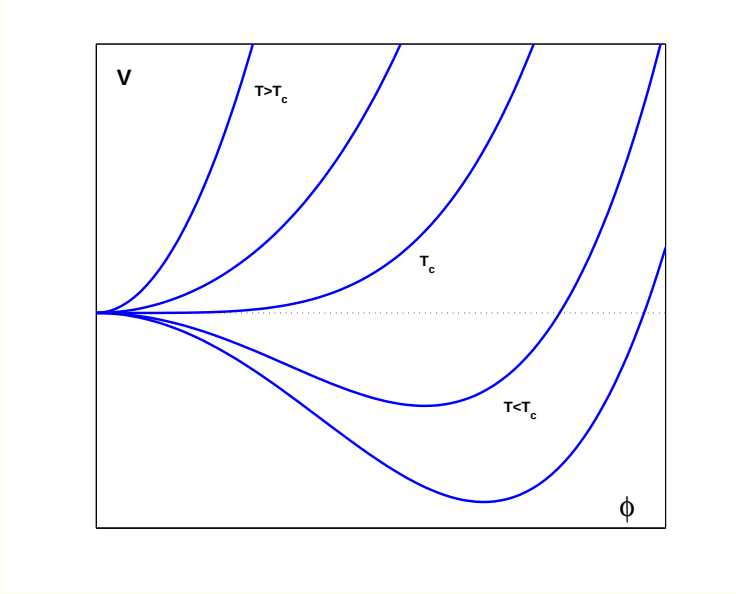


$m_H \sim 126$ GeV



- $\langle\phi\rangle : 0 \to v$ continuously and uniformly in space
- The $B + L$ violating processes switch off slowly
- The baryon asymmetry is erased

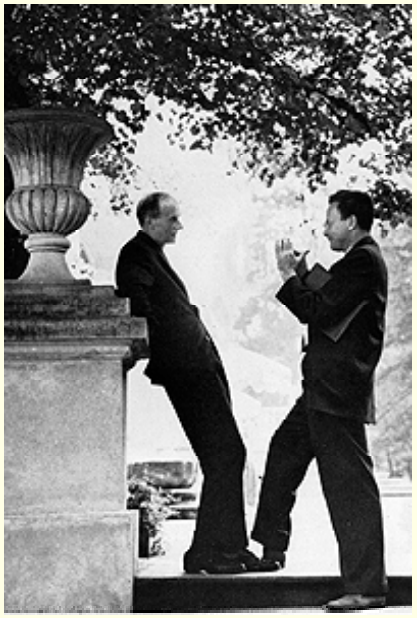
$$\boxed{\text{The SM EWPT is not of the right kind}}$$

4th REASON

4th REASON

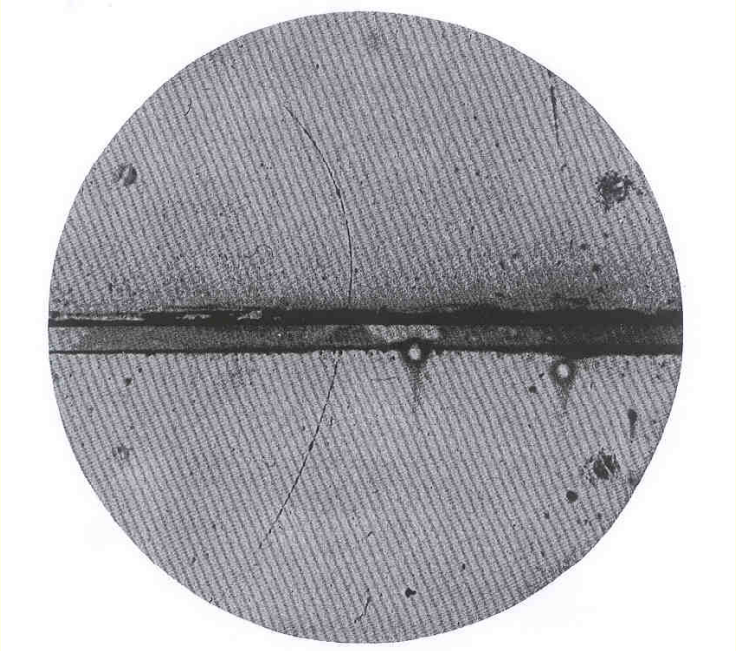
Theory preceding experiment

1928: Dirac's Equation



- Dirac wanted to understand the electron
- Special relativity + quantum mechanics
  $\Longrightarrow$ Dirac Equation: $i\gamma \cdot \partial\psi = m\psi$
- Two solutions:
  electron e^- and "anti-electron" e^+
- $\boxed{\text{CP}}$

1932: Anderson's positron



5th REASON

5th REASON

Experiment preceding theory

1964: CP is violated!

- If CP is a good symmetry:
  - Mass eigenstates = CP eigenstates
  - Two neutral kaon states: $K_S = K_{CP=+}, \quad K_L = K_{CP=-}$
  - $K_S \to \pi\pi, \quad K_L \not\to \pi\pi$

- 1964, Cronin and Fitch:
  Experimental discovery of $K_L \to \pi\pi$
  - $\boxed{\text{CPV}}$

6th REASON

6th REASON

Predicting the third generation

Kobayashi and Maskawa (I)

CP violation $\leftrightarrow$ Complex couplings:

- Hermiticity: $\mathcal{L} \sim g_{ijk}\phi_i\phi_j\phi_k + g^*_{ijk}\phi^\dagger_i\phi^\dagger_j\phi^\dagger_k$
- CP transformation: $\phi_i\phi_j\phi_k \leftrightarrow \phi^\dagger_i\phi^\dagger_j\phi^\dagger_k$
- CP is a good symmetry if $g_{ijk} = g^*_{ijk}$

The number of real and imaginary quark flavor parameters:

- With two generations:
  $2 \times (4_R + 4_I) - [3 \times (1_R + 3_I) - 1_I] = 5_R + 0_I$
- With three generations:
  $2 \times (9_R + 9_I) - [3 \times (3_R + 6_I) - 1_I] = 9_R + 1_I$
- The two generation SM is CP conserving
  The three generation SM is CP violating

Kobayashi and Maskawa (II)

- $\boxed{\text{A third generation is predicted to exist}}$
- All flavor violation in V = The CKM matrix
  $\mathcal{L}_W = \frac{g}{\sqrt{2}}\overline{U_L}V\gamma^\mu D_L W_\mu^+ + \text{h.c.}$
- V unitary with 3 real (λ, A, ρ) and 1 imaginary (η) parameters:

$$V \simeq \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho + i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho+i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- η - the only source of CP violation
- A very predictive theory of CP violation:
  Easily falsiable

7th REASON

7th REASON

$$\boxed{\text{QCD is CP invariant}}$$

$S_{\psi K_S}$

B^0 ψK_S

$\overline{B^0}$

- Babar/Belle: $A_{\psi K_S}(t) = \frac{\frac{d\Gamma}{dt}[\overline{B^0_{\rm phys}}(t)\to\psi K_S] - \frac{d\Gamma}{dt}[B^0_{\rm phys}(t)\to\psi K_S]}{\frac{d\Gamma}{dt}[\overline{B^0_{\rm phys}}(t)\to\psi K_S] + \frac{d\Gamma}{dt}[B^0_{\rm phys}(t)\to\psi K_S]}$
- Theory: $A_{\psi K_S}(t)$ dominated by interference between $A(B^0 \to \psi K_S)$ and $A(B^0 \to \overline{B^0} \to \psi K_S)$
- $\Longrightarrow A_{\psi K_S}(t) = S_{\psi K_S} \sin(\Delta m_B t)$
- Babar/Belle: $S_{\psi K_S} = 0.68 \pm 0.02$

$S_{\psi K_S}$ in the SM

- $$\boxed{S_{\psi K_S} = \mathcal{I}m\left[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}\right] = \frac{2\eta(1-\rho)}{\eta^2+(1-\rho)^2} = \sin 2\beta}$$
- All hadronic parameters cancel in $A_{\psi K_S}(t)$ (and $S_{\psi K_S}$) as a result of the CP invariance of QCD
- The approximations involved are better than one percent!
- Similar theoretical cleanliness in CPV observables:
  $K \to \pi\nu\bar{\nu}, \quad B \to DK$

8th REASON

8th REASON

$$\boxed{\text{QCD is not CP invariant}}$$

The $\theta_{\rm QCD}$ puzzle

- $\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\theta_{\rm QCD} G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}$
- $d_n \sim 3.6 \times 10^{-16}\ \theta_{\rm QCD}\ e$ cm
- $d_n^{\rm exp} < 2.9 \times 10^{-26}\ e$ cm
- $\Longrightarrow\ \theta_{\rm QCD} < 10^{-10}$
  - PQ symmetry?
  - Spontaneous CP violation?
  - $m_u = 0$?

9th REASON

9th REASON

Richness of experimental results*

A brief history

- 1964 – 2000
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$

A brief history

- 1964 – 2000
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$
- 2000 – 2012
  - $S_{\psi K_S} = +0.68 \pm 0.02$
  - $S_{\phi K_S} = +0.74 \pm 0.12$, $S_{\eta' K_S} = +0.59 \pm 0.07$, $S_{f_0 K_S} = +0.69 \pm 0.11$
  - $S_{K^+K^-K_S} = +0.68 \pm 0.10$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.36 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{D^+D^-} = -0.98 \pm 0.17$, $S_{D^{*+}D^{*-}} = -0.77 \pm 0.10$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.087 \pm 0.008$
  - $\mathcal{A}_{D_+K^\pm} = +0.19 \pm 0.03$

10th REASON

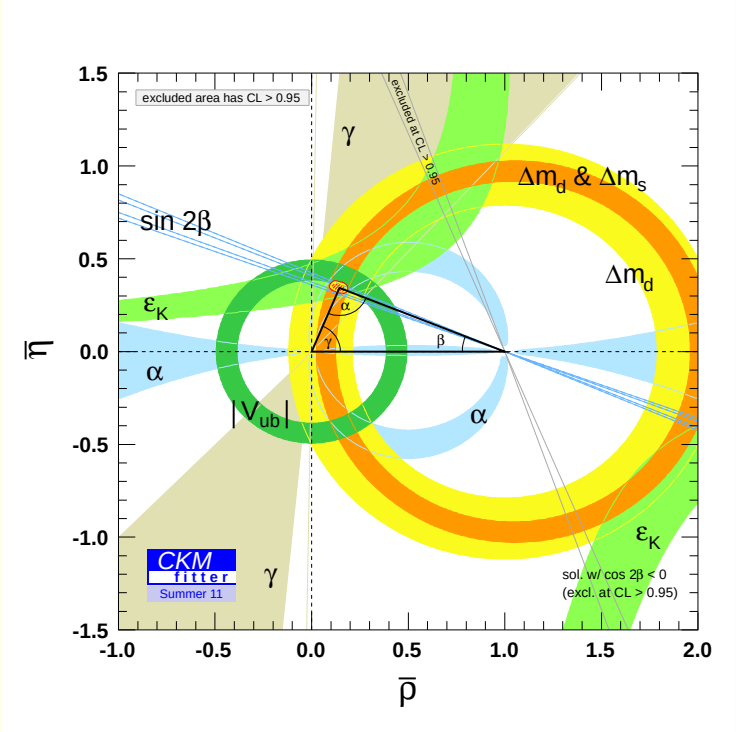
10th REASON

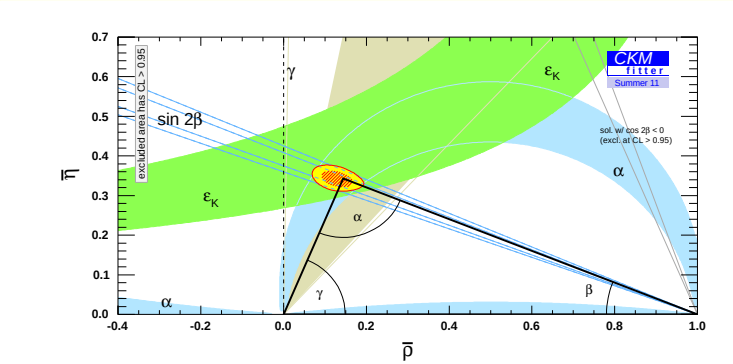
Beauty of theoretical methods*

Testing CKM – Take I

- Assume: CKM matrix is the only source of FV and CPV
  $\Longrightarrow$ Four CKM parameters: λ, A, ρ, η
- λ known from $K \to \pi \ell \nu$
  A known from $b \to c \ell \nu$
- Many observables are $f(\rho, \eta)$:
  - $b \to u \ell \nu \implies \propto |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \implies \propto |V_{td}/V_{ts}|^2 \propto (1-\rho)^2 + \eta^2$
  - $S_{\psi K_S} \implies \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$
  - $S_{\rho\rho}(\alpha)$
  - $\mathcal{A}_{DK}(\gamma)$
  - ϵ_K
- Beautiful theory: Isopsin, HQS, HQET, SCET...

The B-factories Plot



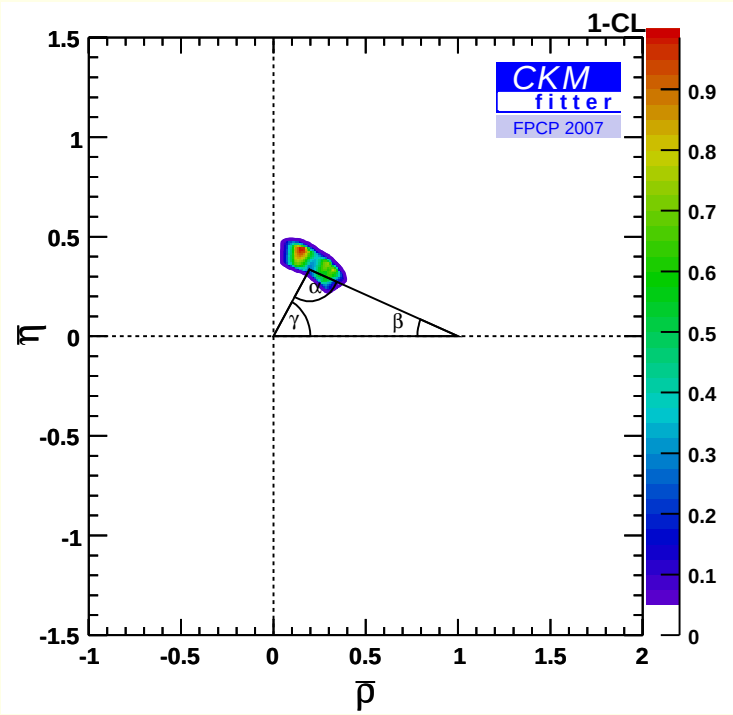


Very likely, the CKM mechanism dominates FV and CPV

Testing CKM - take II

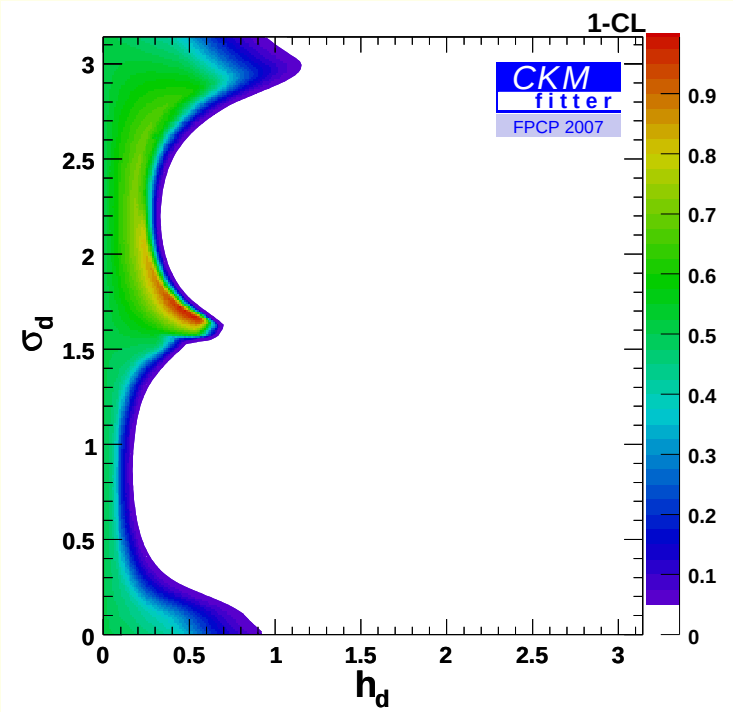
- Assume: New Physics in leading tree decays - negligible
- Allow arbitrary new physics in loop processes
- Consider only tree decays and $B^0 - \overline{B}^0$ mixing
- Define $h_d e^{2i\sigma_d} = A^{\rm NP}(B^0 \to \overline{B})/A^{\rm SM}(B^0 \to \overline{B})$
  $\Longrightarrow$ Four parameters: ρ, η (CKM), h_d, σ_d (NP)
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}^d_{\rm SL}$
- Fit to η, ρ, h_d, σ_d
- Find whether $\eta = 0$ is allowed
  If not $\Longrightarrow$ The KM mechanism is at work
- Find whether $h_d \gg 1$ is allowed
  If not $\Longrightarrow$ The KM mechanism is dominant

$\eta \neq 0$?



- The KM mechanism is at work

$h_d \ll 1$?



- The KM mechanism dominates CP violation
  Complete alternatives (superweak, approximate CP) excluded
- The CKM mechanism is a major player in flavor violation

11th REASON

11th REASON

$\boxed{\text{Hints of new physics?}}$

Charm, Bottom, Top 'anomalies'

- LHCb+CDF+...: $\Delta A_{\rm CP} = (-0.66 \pm 0.15) \times 10^{-2}$
  SM(?): $\Delta A_{\rm CP} \lesssim 10^{-3}$

- D0: $A^b_{\rm SL} = (-7.9 \pm 1.7 \pm 0.9) \times 10^{-3}$
  SM: $A^b_{\rm SL} = (-0.23 \pm 0.06) \times 10^{-3}$

- CDF+D0: Forward-backward asymmetry in $t\bar{t}$ production

Observable	Experiment	SM
$A^t_{\rm FB}$	0.18 ± 0.04	~ 0.08
$A^\ell_{\rm FB}$	0.15 ± 0.04	~ 0.02
$A^t_{\rm FB}(m_{t\bar{t}} > 450)$	0.28 ± 0.06	$0.10 - 0.15$

12th REASON

12th REASON

$\boxed{\text{Otherwise I would not be here today}}$

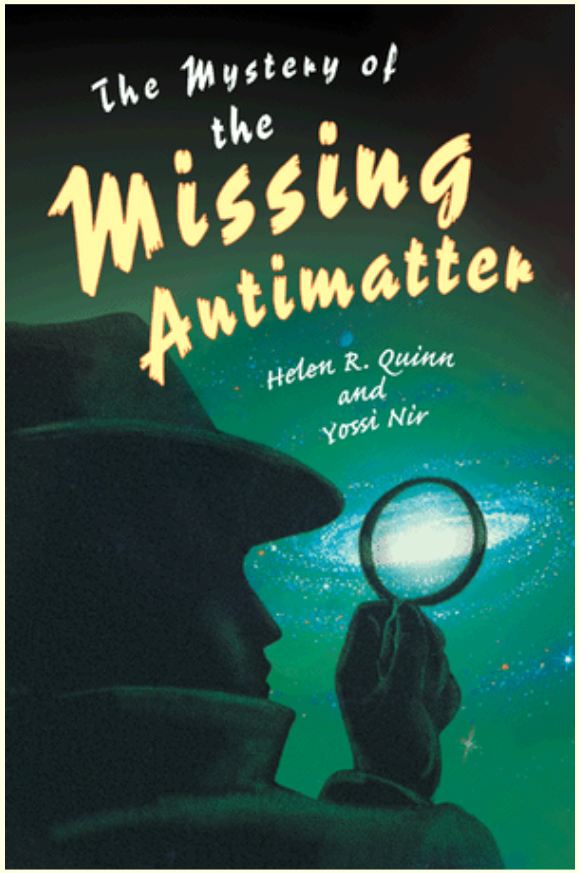
SSI

- SSI 1992: CP violation
- SSI 1999: CP violation in and beyond the SM
- SSI 2010: Leptogenesis

SSI12: 12 best reasons to like CPV

- Otherwise we would not be here
- A window to the Univesre at $t < 10^{-11}$ second
- It proves the SM wrong
- CP: An example of theory preceding experiment
- CPV: An example of experiment preceding theory
- Predicting the third generation
- QCD is CP invariant
- QCD is not CP invariant
- Richness of experimental results
- Beauty of theoretical methods
- Hints of new physics?
- Otherwise I would not be here today

A book


The Mystery of
the
Missing
Antimatter
Helen R. Quinn
and
Yossi Nir

Nobel festivities