Future Lessons from CP Violation

Fermilab

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Y. Nir

IAS, Princeton, USA

WIS, Rehovot, ISRAEL

Why is CPV Interesting?

"CPV is a mystery"

"CPV is one of the least understood aspects of the SM"

???

1. The Symmetry

2. Fermion Representations

3. Spontaneous Symmetry Breaking

The Standard Model

$$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$3 \times \{ (3,2)_{+1/6} + (3,1)_{+2/3} + (3,1)_{-1/3} + (1,2)_{-1/2} + (1,1)_{-1} \}$$

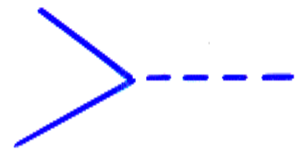
Q_{L_i} $\quad$ U_{R_i} $\quad$ d_{R_i} $\quad$ L_{L_i} $\quad$ ℓ_{R_i}

$$\langle \phi(1,2)_{+1/2} \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$G_{SM} \rightarrow SU(3)_c \times U(1)_{EM}$$

CPV in SM: Qualitatively

$$\mathcal{L}_{SM} = \mathcal{L}_{Kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

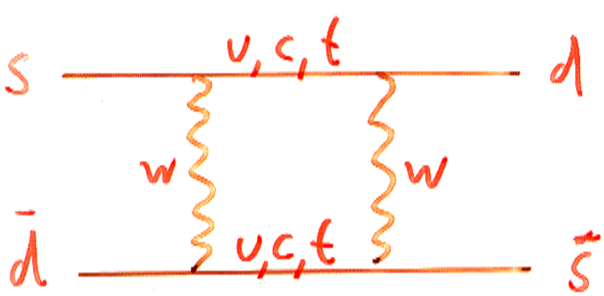
$\mathcal{L}_{Kinetic}$	$\mathcal{L}_{Higgs}$	$\mathcal{L}_{Yukawa}$
		
g_3, g_2, g_1	μ^2, λ	Y^f_{ij}
CPC	CPC	CPV

⇒ **The SM Predicts that CP is Violated**

CPV in SM, Quantitatively

Imagine that CPV has not been observed. Ask a theorist to make a naive estimate:

$\varepsilon_K = ?$

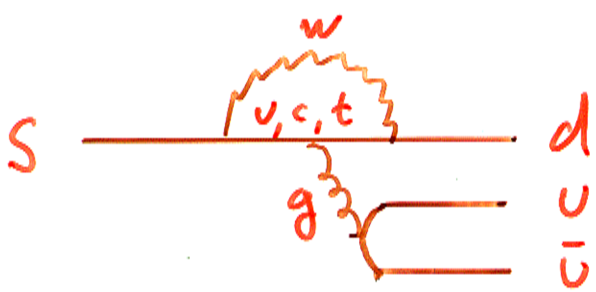


$\Rightarrow \varepsilon_K \sim 10^{-3} \sin \delta_{KM}$

↑ (CPC observables)

✓

$\varepsilon'/\varepsilon = ?$



$\Rightarrow \frac{\varepsilon'}{\varepsilon} \sim 10^{-3}$

$\left(\frac{A_2}{A_0} \times \frac{A_0^P}{A_0^T} \right)$ ↗

✓

Why is CPV interesting?

- CPV is one of the least tested aspects of the SM
- Almost any extension of the SM has new sources of CPV
- The observed baryon asymmetry of the Universe requires new CPV

⇓

It is Possible, Likely, Unavoidable that the SM picture of CPV is Incomplete

Scales

★ If $\Lambda_{CPV} \gg \Lambda_{EW}$:

GUT
ν_R

No Observable Deviations in B-Factories

Precision Flavor Measurements

★ If $\Lambda_{CPV} \sim \Lambda_{EW}$:

SUSY
LRS

Dramatic Effects Are Possible

Detailed Information on NP

★ FD CPV :

GMSB

No Observable Effects in B-Factories

Plan of Talk

1. The SM Picture of CPV

   Predictive, Unique, Testable

2. Probing NP with CPV

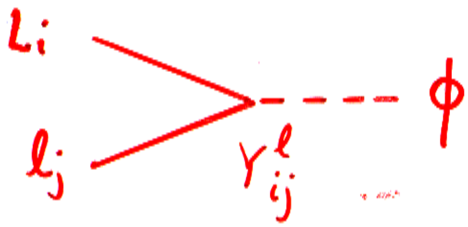
   Detailed Information

3. Open Questions

   Future Experimental Answers

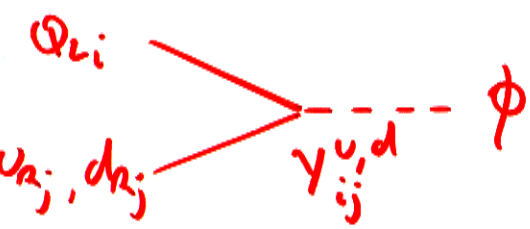
How Many Phases? (SM)

Lepton Sector



	Real	Imaginary
Yukawa Y^{ℓ}_{ij}	9	9
$G_{global}(Y^{\ell}=0) = U(3)_L \times U(3)_{\bar{\ell}}$	-6	-12
$G_{global}(Y^{\ell}\neq 0) = U(1)_e \times U(1)_\mu \times U(1)_\tau$		+3
	3	0

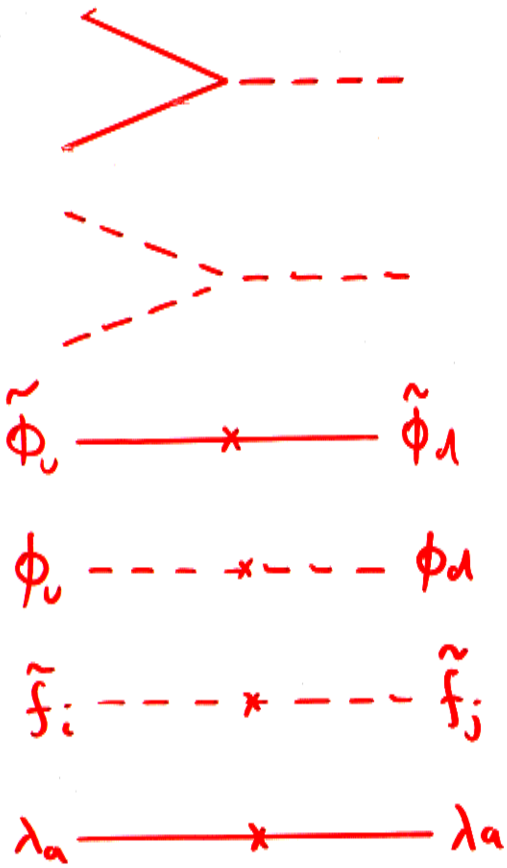
Quark Sector



	Real	Imaginary
Yukawa $Y^{u,d}_{ij}$	18	18
$G_{global}(Y^{q}=0) = U(3)_Q \times U(3)_{u_R} \times U(3)_{d_R}$	-9	-18
$G_{global}(Y^{q}\neq 0) = U(1)_B$		+1
	9	1

A Single Source of CPV δ_{KM}

How Many Phases? (SUSY)



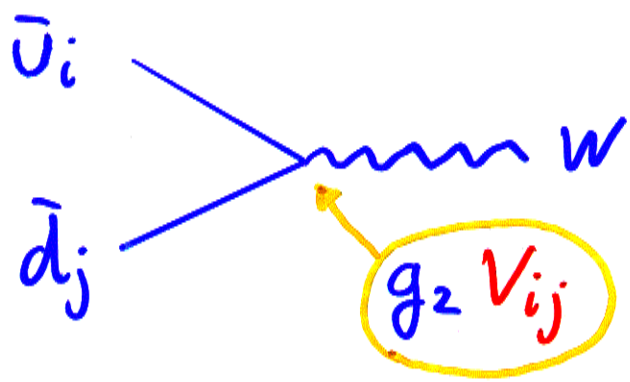
	R	I
Yukawa A - Terms μ - Term B - Term $\tilde{m}_0^2$ - Terms $m_{1/2}$ - Terms	95	74
$G_{global}(Y, A, \mu, B, \tilde{m}_0^2, m_{1/2} = 0) = U(3)^5 \times U(1)_{PQ} \times U(1)_R$	-15	-32
$G_{global}^{SUSY)} = U(1)_B \times U(1)_L$		+2
	80	44

> The MSSM (with R_p) gives 43 new CPV phases (in addition to δ_{KM})

Where Can CPV Be Observed ?

The Physical Parameters Are Those of the Mass Basis

★ The Only Complex Parameters Are



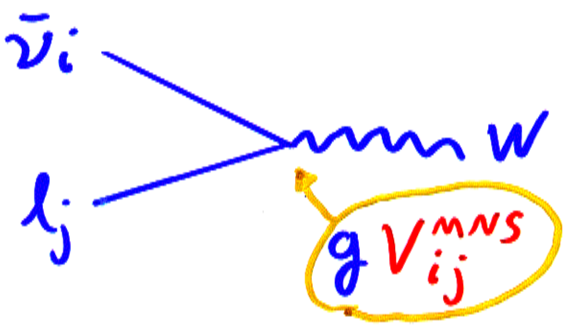
But, if any $V_{ij} = 0$, there are no complex parameters

SM: CPV appears only in

- ★ Flavor Changing
- ★ Charged Current (W-mediated) Int's
- ★ of Quarks !

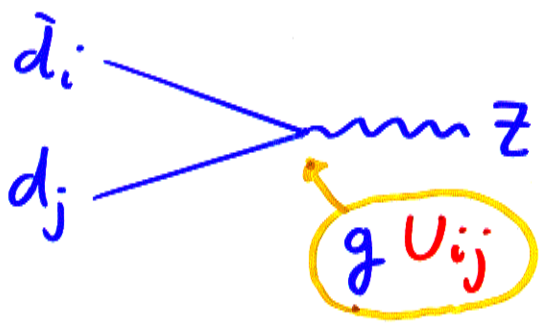
New Physics

$M_\nu \neq 0$ (AN, SN, K2K...)



⇨ 3 New Phases in CC Lepton Int's!

With $D_L(3,1)_{-1/3} + D_R(3,1)_{-1/3}$

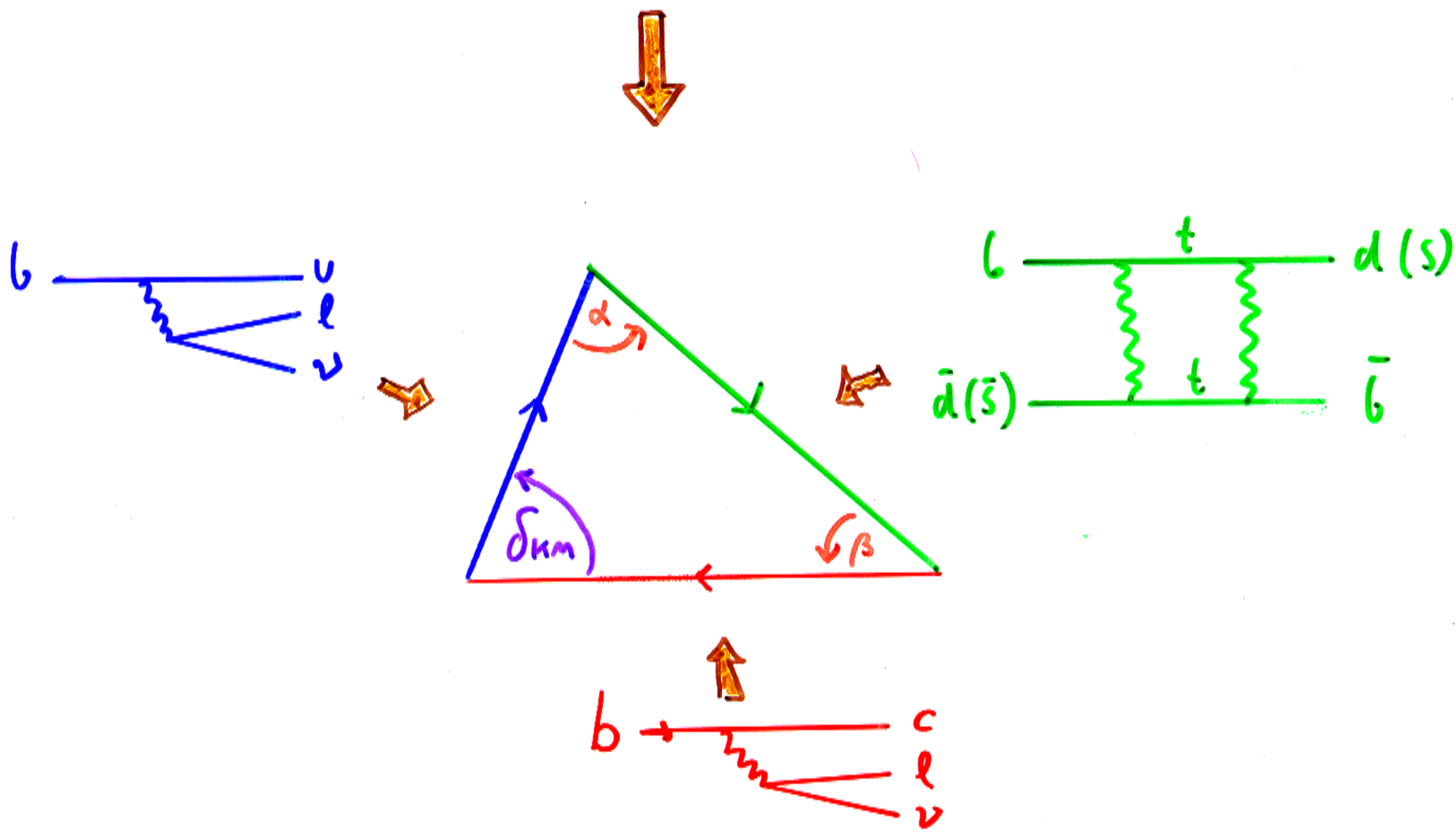


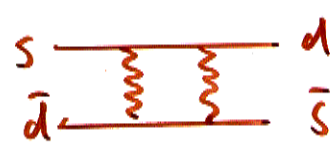
⇨ 3 New Phases in NC int's!

⋮

How Large is δ_{KM} ?

$$V_{cd}V_{cb}^* + V_{ud}V_{ub}^* + V_{td}V_{tb}^* = 0$$

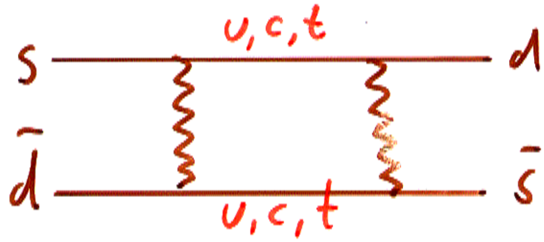


$\varepsilon_K \sim \mathrm{Im}$  $\propto$ Area (△)

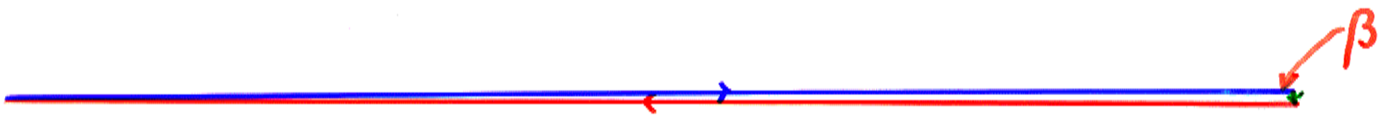
$$\sin^2 \delta_{KM} \approx 0.3 - 1.0$$

★ CP is not an approximate sym of the SM

Why is ε_K Small ?

$\varepsilon_K \propto \mathrm{Im}$ 

$$V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$$



$$\varepsilon_K \propto \left| \frac{V_{td}V_{ts}^{*}}{V_{ud}V_{us}^{*}} \right| \cdot \sin\beta$$

$O(10^{-3})$ $\quad$ $O(1)$

SM: ε_K is small not because CPV is small but rather because the effect is screened by small flavor violation

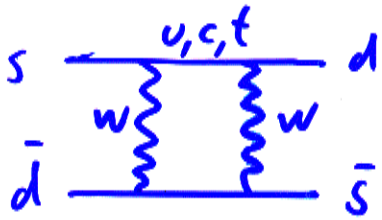
(CPV is large in various B_d decays)

SUSY + Approximate CP

Within SUSY, it is possible that all

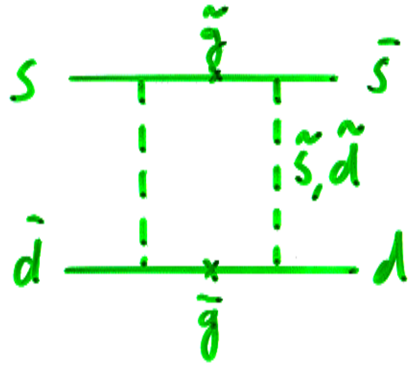
$$\phi_{CPV} \ll 1$$

The SM



Cannot Account for ε_K

SUSY



Must Account for ε_K

Eyal, YN, NPB528(98)21 [9801411]

SUSY + Approx CP: ε_K is small because All CPV phases are small

⇒ Prediction: All CPV Asymmetries Are Small (e.g. $B \to \psi K_S$)

☆ Approx CP is also possible in the LRS framework (requires $M(W_R) \lesssim 20$ TeV)

CPV in SM

- Explicit $(Y_{ij}^{q} \neq Y_{ij}^{q*})$
- A Single Source (δ_{KM})
- Only in CC interactions of Quarks
- Vanishes in the absence of FC int's
- CP Not an approximate sym $(\delta_{KM} = O(1))$

✗ NP

Possibly...

☆ Spontaneous $\left(\arg \frac{\langle\phi_1\rangle}{\langle\phi_2\rangle} \neq 0\right)$

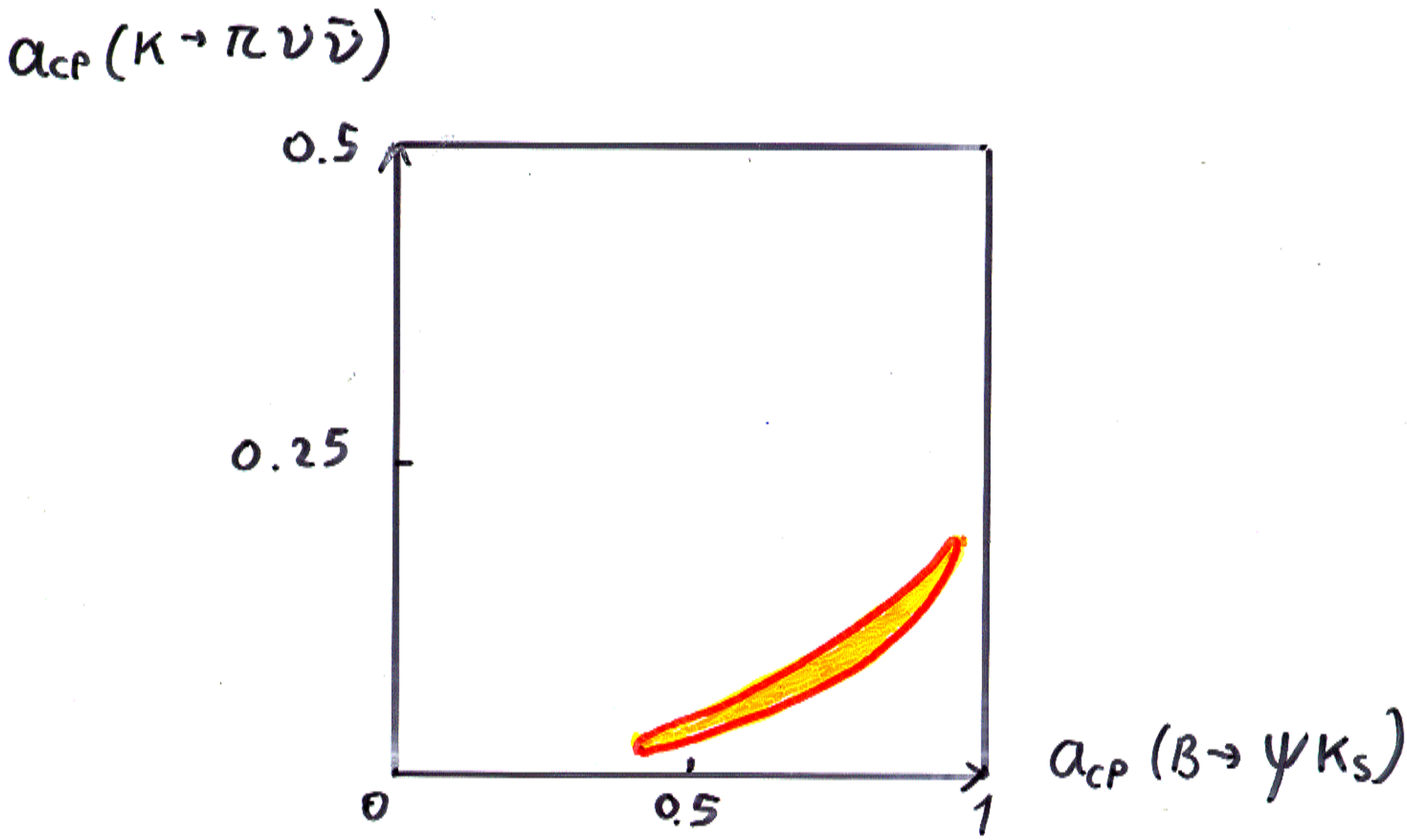
☆ Many Independent Sources

☆ Lepton Int's ; NC int's ; New Sectors

☆ FD (e.g. $\mu\phi_u\phi_d$, $\mu \neq \mu^*$)

☆ CP is an approx sym $(10^{-3} \lesssim \phi_{CP} \ll 1)$

Correlations



YN, M.P. Worah, PLB 423 (1998) 319 hep-ph/9711215

Y. Grossman, YN, PLB 398 (1997) 163 hep-ph/9701313

Testing the SM

The SM Picture of CPV is Unique and Predictive

1. Correlations

   $B \to \psi K_S$ vs. $B \to \phi K_S$; $B \to \psi K_S$ vs. $K \to \pi \nu \bar{\nu}$...

2. Zeros

   $\nu_i \to \nu_j$; $B_s \to D_s^+ D_s^-$; d_N ...

In the Near Future

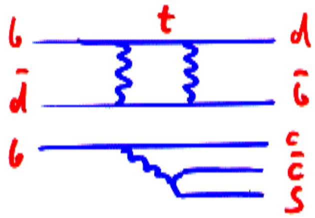
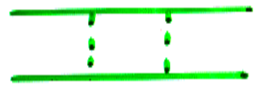
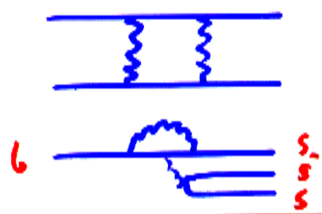
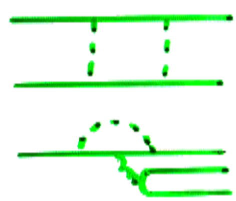
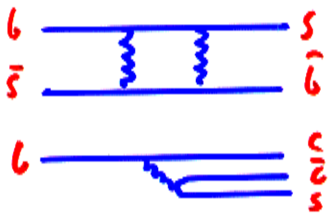
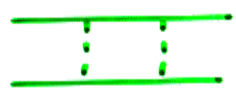
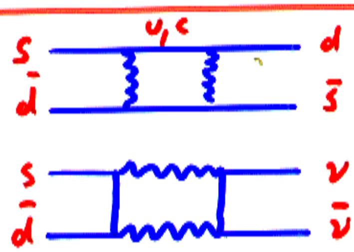
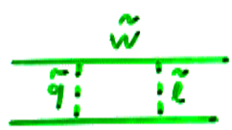
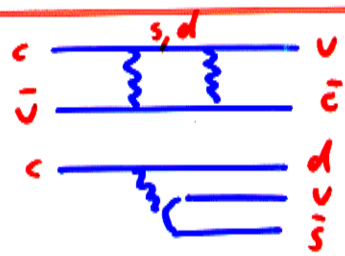
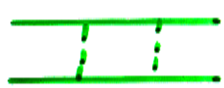
B-Factories, HERA-B, TeVatron, LHC-B

$B \to$; $B_s \to$; $D \to$

LBL : $K_L \to \pi^0 \nu \bar{\nu}$: $P_\perp^\ell$: d_N, d_e :

$\nu_i \to \nu_j$

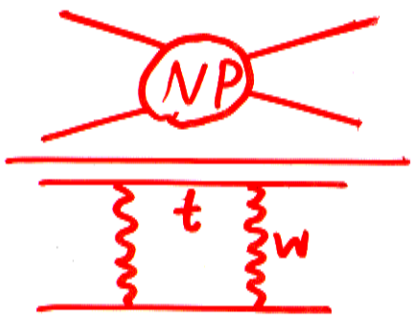
Probing New Physics

CPV in	SM	NP	Probes
$B \to \psi K_s$			Down 1 & 3 gen's $\Delta B = 2$
$B \to \phi K_s$			Down 1&2 & 3 gen's $\Delta B = 2$, $\Delta B = 1$
$B_s \to D_s^+ D_s^-$			Down 2&3 gen's $\Delta B = 2$
$K \to \pi \nu \bar{\nu}$			Down 1&2 gen's $\Delta S = 1$
$D \to K\pi$			Up 1 & 2 gen's $\Delta C = 2$
d_N	0 (3 Loops)		FD

$a_{\psi K_S}$ and New Physics

$a_{\psi K_S} = 0.79^{+0.41}_{-0.44}$ — CDF, hep-ex/9909003

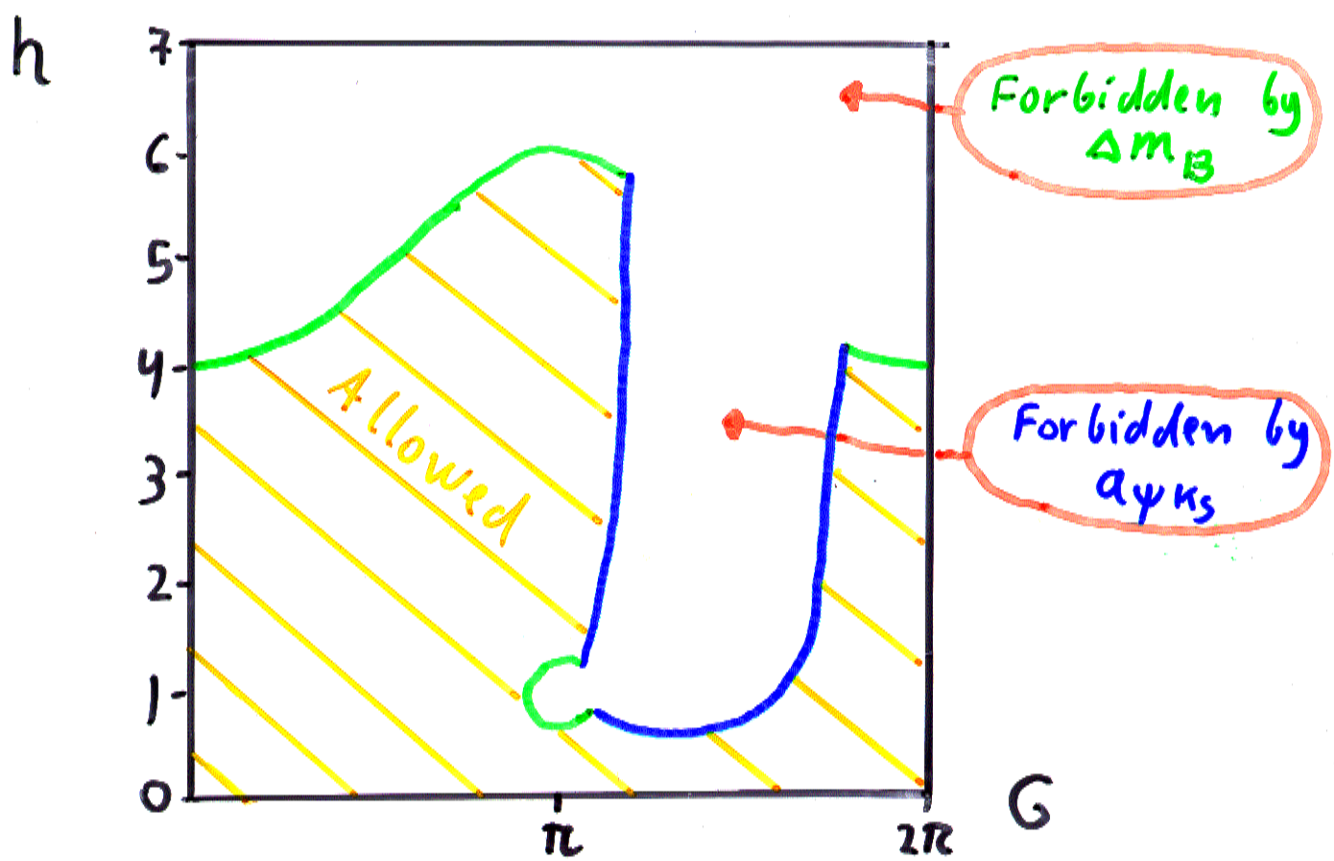
$a^{SM}_{\psi K_S} \sim 0.50 - 0.85$ — Plaszczynski, Schune hep-ph/9911280



$\equiv h e^{iG}$

Barenboim, Eyal, YN PRL 83 (99) 4486 [9905397]

Eyal, YN JHEP 09 (99) 013



If Deviations from the SM Predictions are Observed...

We Can Ask Whether the NP that is responsible to these deviations is related to...

- ☆ The Down Sector? Up? Both?
- ☆ $\Delta B=1$ Processes? $\Delta B=2$? Both?
- ☆ The Third Generation? All Gen's?
- ☆ FC int's? FD? Both?

⇓

CPV is an excellent probe of New Physics

OPEN QUESTIONS

• Why Are ε and ε' Small?

SM: Small Mixing Angles

NP: Small Phases?

Expt: $a_{CP} \sim O(1)$ ⇒ ~~Approx CP~~

SUSY + Approx CP
LRS + Approx CP

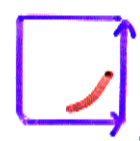
$B \to \psi K_S$
$K \to \pi \nu \bar{\nu}$
$B^{\pm} \to K^{\pm} \pi^0$
⋮

• What Is the Number of Independent Phases?

SM: One (δ_{KM})

NP: 44 (MSSM); 6 (LRS); 3 (Extra d)? ...

Expt: Correlations: $B \to \psi K_S \overset{?}{=} B \to \phi K_S$



Zeros: $B_s \to \psi \phi$, $D \to K\pi$ ...

• Why Is CP Violated?

SM: Explicit Breaking by Yukawa's

NP: Spontaneous? (LRS, Multi-Doublet..)

Expt: Difficult...

OPEN QUESTIONS

- Is CPV restricted to FC interactions?

  SM: Yes

  NP: FD CPV (susy!)

  Expt: EDM's, $t\bar{t}$ production...

- Is CPV restricted to Quark interactions?

  SM: Yes

  NP: No if $m_\nu \neq 0$

  Expt.: $P(\nu_i \to \nu_j)$ vs. $P(\bar{\nu}_i \to \bar{\nu}_j)$

- Is CPV restricted to Weak interactions?

  SM: Only $W^\pm$ mediated

  NP: Scalar-mediated? Strong (susy)? ...

  Expt.: Transverse Lepton Polarization

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Conclusions

- CPV is one of the least tested aspects of the SM
- The SM picture of CPV is unique, predictive and testable
- Soon we will know much more...