Flavor Physics and CP Violation:
Past, Present, Future

CERN Academic Training Program
CERN, 5 April 2011

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Thanks to my low-energy-physics collaborators:

Gudrun Hiller, YN

JHEP 0803 (2008) 046 [arXiv:0802.0916]

Gudrun Hiller, Yonit Hochberg, YN

JHEP 0903 (2009) 115 [arXiv:0812.0511];
JHEP 1003 (2010) 079 [arXiv:1001.1513]

Kfir Blum, Yuval Grossman, YN, Gilad Perez

Phys. Rev. Lett. 102 (2009) 211802 [arXiv:0903.2118]

Yuval Grossman, YN, Gilad Perez

Phys. Rev. Lett. 103 (2009) 071602 [arXiv:0904.0305]

Oram Gedalia, Yuval Grossman, YN, Gilad Perez

Phys. Rev. D80 (2009) 055024 [arXiv:0906.1879]

Gino Isidori, YN, Gilad Perez

ARNPS 60 (2010) 355 [arXiv:1002.0900]

Kfir Blum, Yonit Hochberg, YN

JHEP 1009 (2010) 035 [arXiv:1007.1872]

Thanks to my high-p_t-physics collaborators:

Yuval Grossman, YN, Jesse Thaler, Tomer Volansky, Jure Zupan
Phys. Rev. D76 (2007) 096006 [arXiv:0706.1845]

Jonathan Feng, Christopher Lester, YN, Yael Shadmi
Phys. Rev. D77 (2008) 076002 [arXiv:0712.0674]

Jonathan Feng, Sky French, Christopher Lester, YN, Yael Shadmi
Phys. Rev. D80 (2009) 114004 [arXiv:0906.4215]

Feng, French, Galon, Lester, YN, Shadmi, Sanford, Yu
JHEP 1001 (2010) 047 [arXiv:0910.1618]

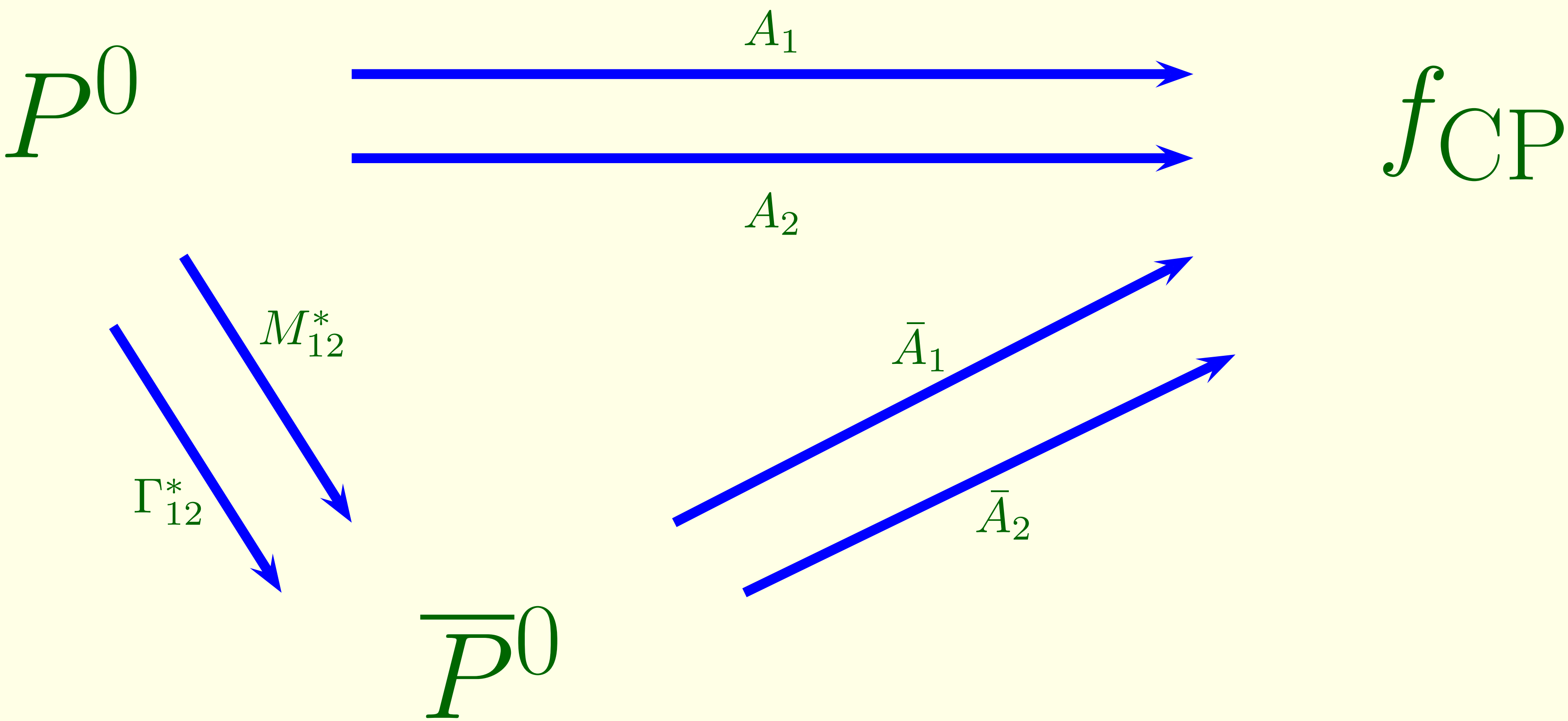
Eilam Gross, Daniel Grossman, YN, Ofer Vitells
Phys. Rev. D81 (2010) 055013 [arXiv.1001.2883]

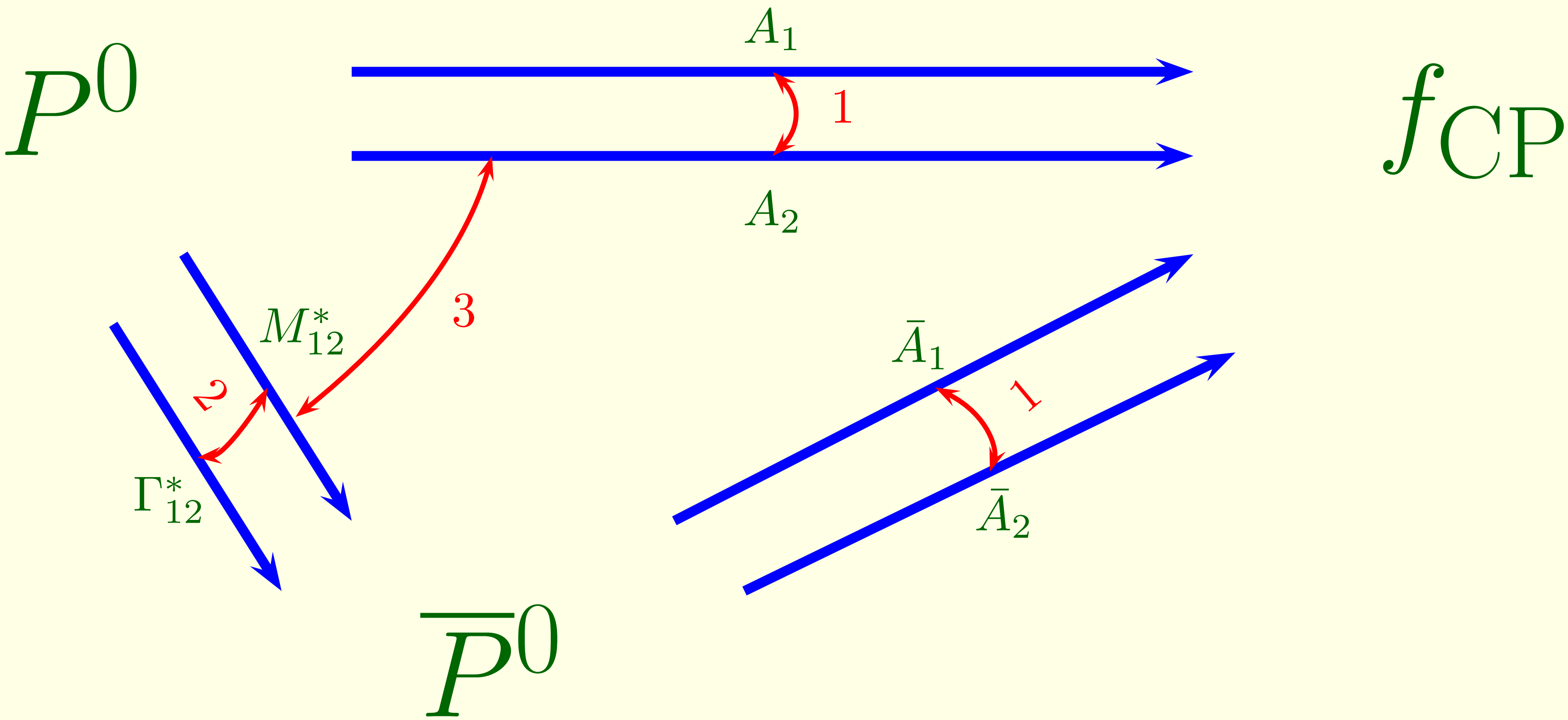
Helen Quinn + YN
'The Mystery of the Missing Antimatter' (PUP)

Plan of Lectures

1. Lecture1
   (a) What is flavor and why is it interesting?
   (b) Flavor in the Standard Model
2. Lecture2
   (a) Lessons from the B-factories
   (b) The NP flavor puzzle
3. Lecture3
   (a) Minimal Flavor Violation ($a_{\rm SL}^b,\ A_{\rm FB}^{t\bar t}$)
   (b) The SM flavor puzzle
   (c) Neutrino flavor surprises
4. Lecture4
   (a) Flavor@LHC
   (b) Baryogenesis@LHC

What have we learned?

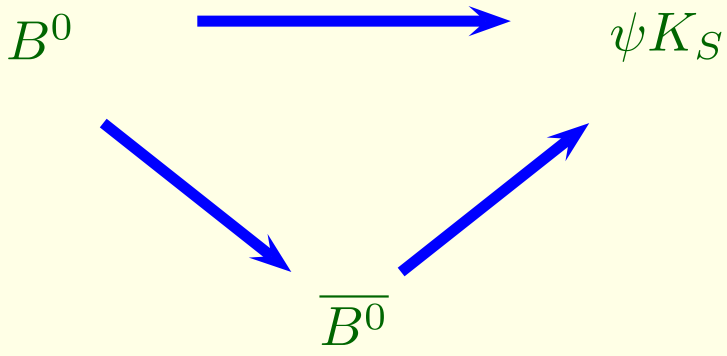

P^0
A_1
A_2
f_{CP}
M_{12}^*
Γ_{12}^*
$\bar{A}_1$
$\bar{A}_2$
$\overline{P}^0$



1	Decay	$\lvert\bar{A}/A\rvert \neq 1$	$\frac{\bar{A}}{A} = \frac{\bar{A}_1+\bar{A}_2}{A_1+A_2}$	$\mathcal{A}_{K^\mp\pi^\pm}$	$P^\pm \to f^\pm$
2	Mixing	$\lvert q/p\rvert \neq 1$	$\frac{q}{p} = \frac{2M_{12}^*-i\Gamma_{12}^*}{\Delta M-i\Delta\Gamma}$	$\mathcal{R}e\ \varepsilon$	$P^0, \overline{P}^0 \to \ell^\pm X$
3	Interference	$\mathcal{I}m\lambda \neq 0$	$\lambda = \frac{M_{12}^*}{\lvert M_{12}\rvert}\frac{\bar{A}}{A}$	$S_{\psi K_S}$	$P^0, \overline{P}^0 \to f_{\rm CP}$

What have we learned?

$S_{\psi K_S}$



- 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 $A(B^0 \to \overline{B^0} \to \psi K_S)$
- $\Longrightarrow A_{\psi K_S}(t) = S_{\psi K_S} \sin(\Delta m_B t)$
  $\Longrightarrow S_{\psi K_S} = \mathcal{I}m \left[\frac{A(B^0 \to \overline{B^0})}{|A(B^0 \to \overline{B^0})|} \frac{A(\overline{B^0} \to \psi K_S)}{A(B^0 \to \psi K_S)} \right]$

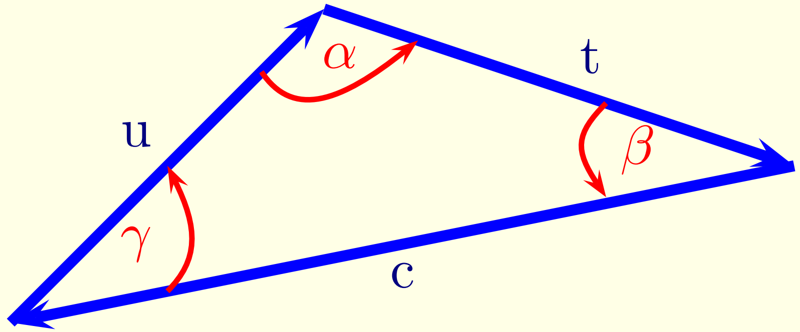
$S_{\psi K_S}$ in the SM

- $$S_{\psi K_S} = \mathcal{I}m\left[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}\right] = \frac{2\eta(1-\rho)}{\eta^2+(1-\rho)^2}$$
- In the language of the unitarity triangle:
  $S_{\psi K_S} = \sin 2\beta$
- The approximations involved are better than one percent!
- Experiments: $S_{\psi K_S} = 0.671 \pm 0.024$

The Unitarity Triangle

- A geometrical presentation of $\boxed{V_{ub}^* V_{ud} + V_{tb}^* V_{td} + V_{cb}^* V_{cd} = 0}$

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



The Unitarity Triangle

- A geometrical presentation of $\boxed{V_{ub}^{*}V_{ud} + V_{tb}^{*}V_{td} + V_{cb}^{*}V_{cd} = 0}$

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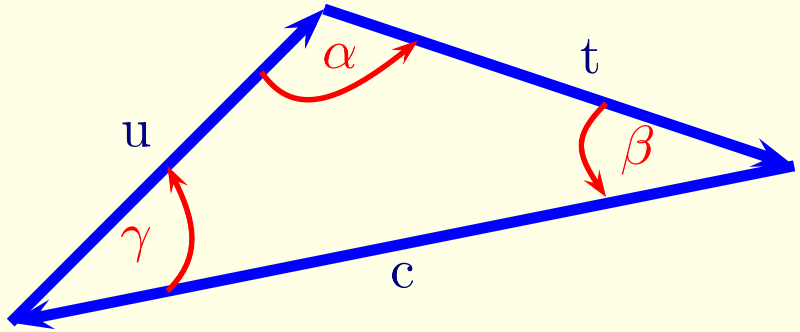
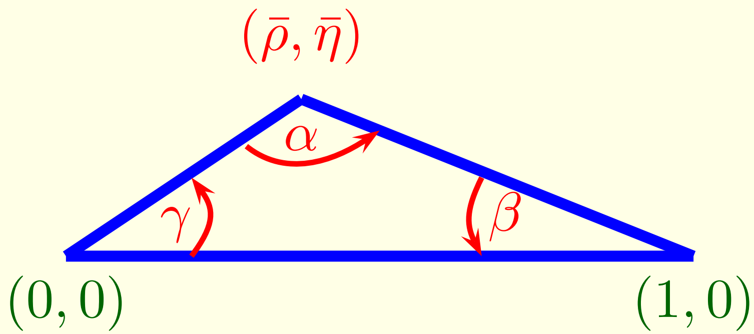


- Rescale and rotate: $\boxed{A\lambda^3\left[(\rho + i\eta) + (1 - \rho - i\eta) + (-1)\right] = 0}$

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



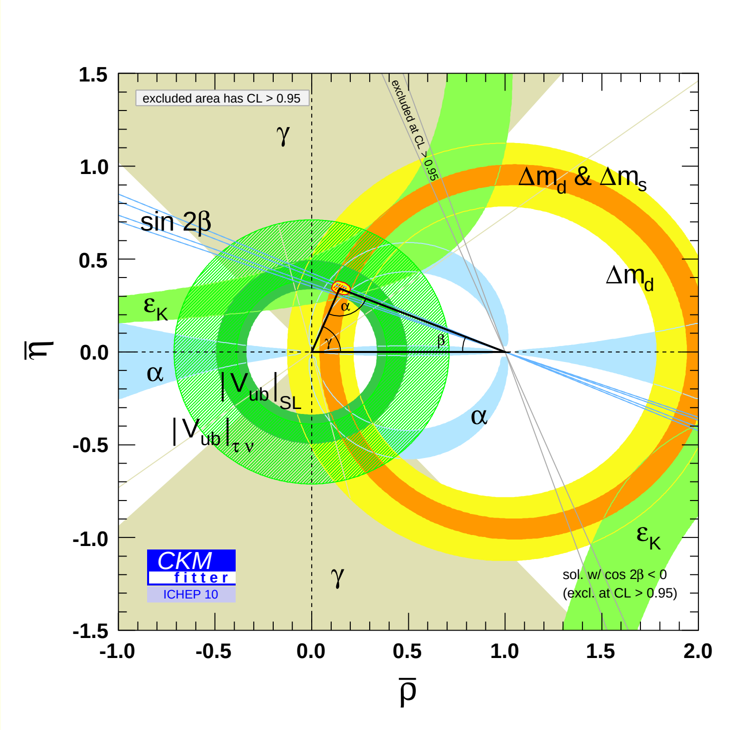
Wolfenstein (83); Buras *et al.* (94)

$\alpha \equiv \phi_2; \quad \beta \equiv \phi_1; \quad \gamma \equiv \phi_3$

Testing CKM – Take I

- Assume: CKM matrix is the only source of FV and CPV
- 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

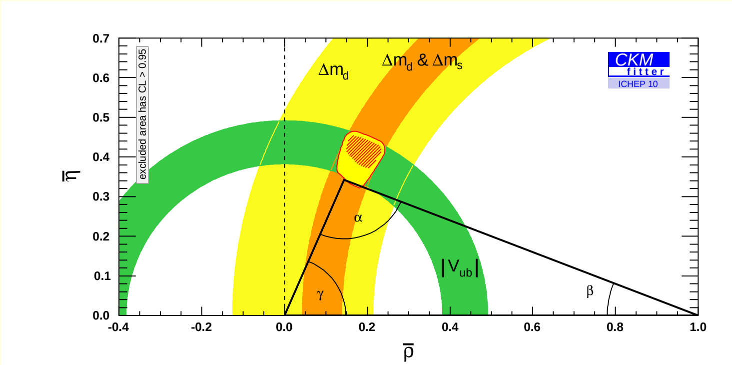
The B-factories Plot

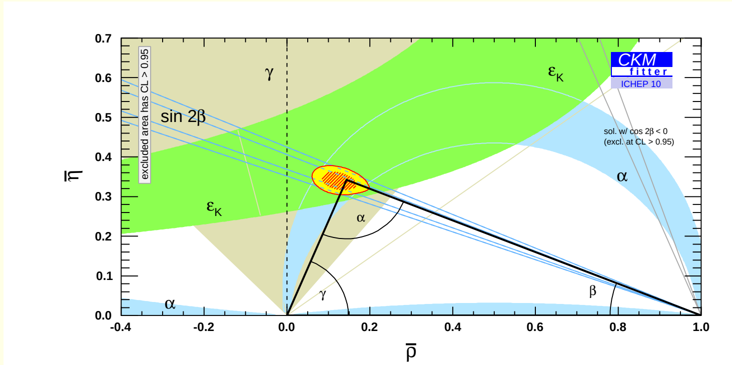


CKMFitter

Very likely, the CKM mechanism dominates FV and CPV

CPC vs. CPV





Very likely, the KM mechanism dominates CP violation

$S_{\psi K_S}$ with NP

- Reminder: $S_{\psi K_S} = \mathcal{I}m\left[\frac{A(B^0\to\overline{B^0})}{|A(B^0\to\overline{B^0})|}\frac{A(\overline{B^0}\to\psi K_S)}{A(B^0\to\psi K_S)}\right]$
- New physics contributions to the tree level decay amplitude - negligible
- New physics contributions to the loop + CKM suppressed mixing amplitude could be large
- Define $h_d e^{2i\sigma_d} = \frac{A^{\rm NP}(B^0\to\overline{B}^0)}{A^{\rm SM}(B^0\to\overline{B}^0)}$

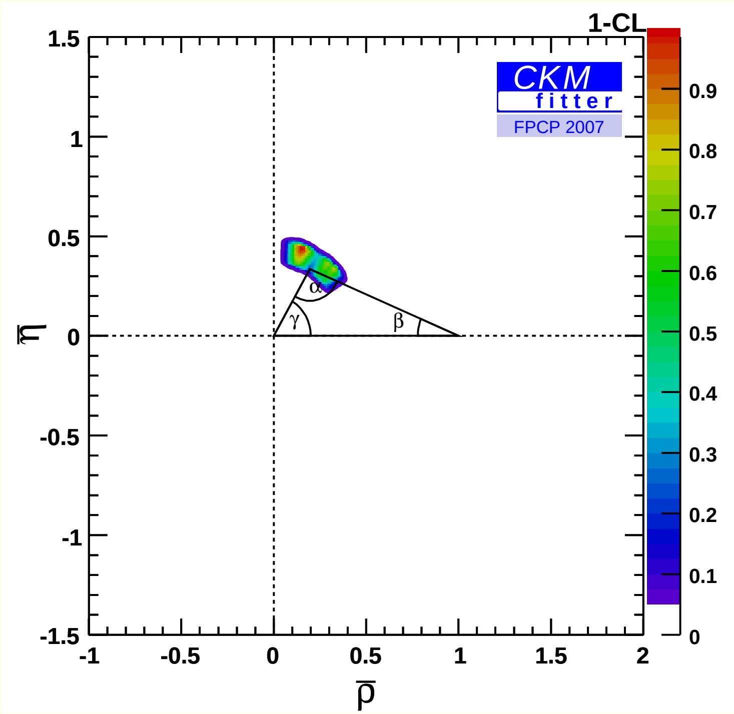
  $r_d e^{2i\theta_d} = 1 + h_d e^{2i\sigma_d} = \frac{A^{\rm full}(B^0\to\overline{B}^0)}{A^{\rm SM}(B^0\to\overline{B}^0)}$
- $\boxed{S_{\psi K_S} = \sin[2(\beta+\theta_d)] = f(\rho,\eta,h_d,\sigma_d)}$

Testing CKM - take II

- Assume: New Physics in leading tree decays - negligible
- Allow arbitrary new physics in loop processes
- Use only tree decays and $B^0 - \overline{B}^0$ mixing
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}_{\rm SL}^d$
- 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

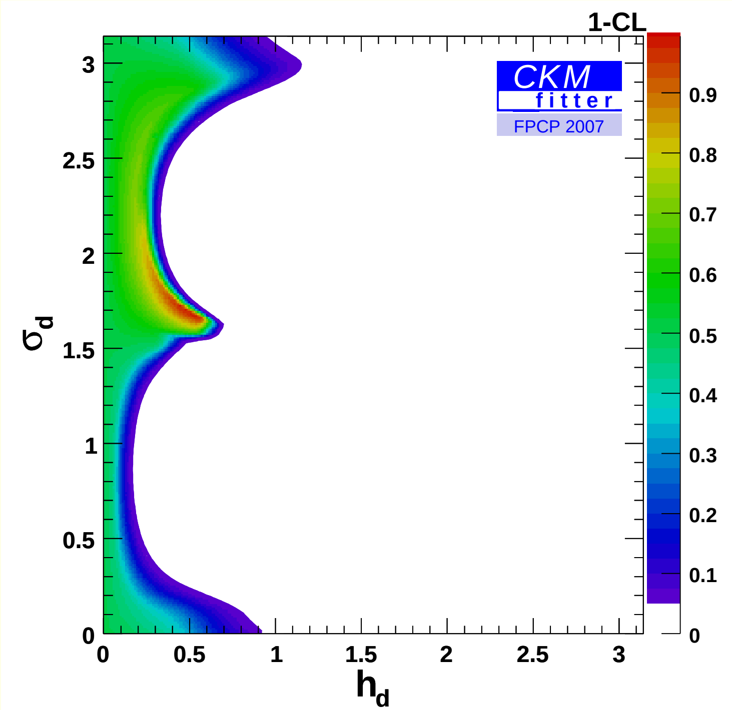
What have we learned?

$\eta \neq 0$?



- The KM mechanism is at work

$h_d \ll 1$?



- The KM mechanism dominates CP violation
- The CKM mechanism is a major player in flavor violation

Is CPV in $K \to \pi\pi$ small because of flavor?

SM:

- $\epsilon \sim 10^{-3}$, $\epsilon' \sim 10^{-5}$ because of flavor suppression
- Some CP violating phases are order one

Approximate CP:

- All CPV phases are small
- All CP asymmetries are small

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- $\epsilon \sim 10^{-3}$, $\epsilon' \sim 10^{-5}$ because of flavor suppression
- Some CP violating phases are order one

Approximate CP:

- All CPV phases are small
- All CP asymmetries are small

B Physics: $S_{\psi K} \sim 0.7$

$\Longrightarrow$ Some CP violating phases are indeed $\mathcal{O}(1)$

Is CP violated in $\Delta B = 1$ processes?

SM:

• Indirect $(A(M^0 \to \overline{M}^0))$ and direct $(A(M \to f))$ CP violations are both large

Superweak:

• There is no direct $(A(M \to f))$ CP violation

K Physics: $\epsilon'/\epsilon = (1.67 \pm 0.26) \times 10^{-3}$

$\Longrightarrow$ CP is violated in $\Delta S = 1$ processes $(s \to u\bar{u}d)$

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K Physics: $\epsilon'/\epsilon = (1.67 \pm 0.26) \times 10^{-3}$

$\Longrightarrow$ CP is violated in $\Delta S = 1$ processes $(s \to u\bar{u}d)$

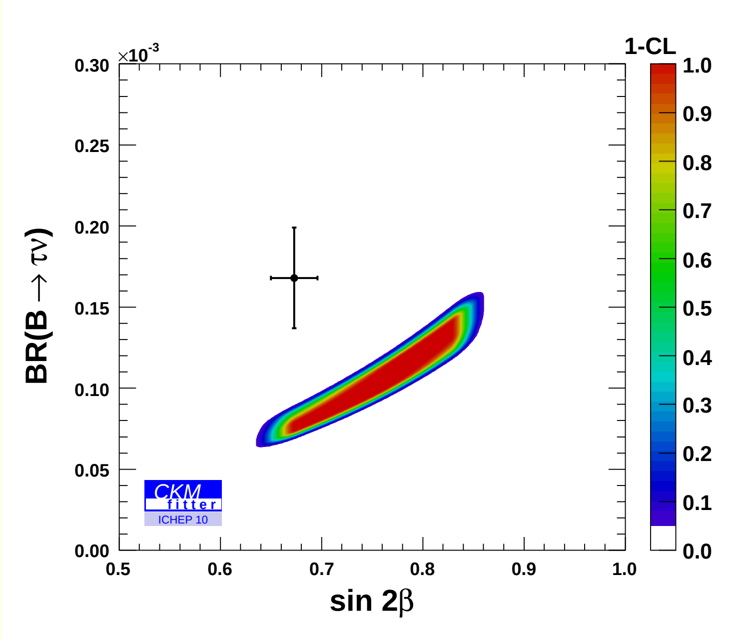
B Physics: $\mathcal{A}_{K^\mp \pi^\pm} = -0.098 \pm 0.012$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$, $\mathcal{A}_{K^\mp \rho^0} = 0.37 \pm 0.11$

$\Longrightarrow$ CP is violated in $\Delta B = 1$ processes $(b \to u\bar{u}s,\ b \to u\bar{u}d)$

Several $\sim 3\sigma$ tensions

- $S_{\psi K}$ *vs.* $\sin 2\beta$ from global fit
- $\mathrm{BR}(B \to \tau\nu)$ *vs.* prediction from global fit
- a_{SL} *vs.* (almost) null prediction of the SM

$\sin 2\beta \;\Leftrightarrow\; \mathbf{BR}(B \to \tau\nu)$



CKMFitter

What have we learned?

- The KM phase is different from zero (SM violates CP)
- The KM mechanism is the dominant source of the CP violation observed in meson decays
- Complete alternatives to the KM mechanism are excluded (Superweak, Approximate CP)
- CP violation in D, B_s may still hold surprises

- No evidence for corrections to CKM
- NP contributions to the observed FCNC are at most comparable to the CKM contributions
- NP contributions are very small in $s \to d$, $c \to u$, $b \to d$, $b \to s$

The NP Flavor Puzzle

The SM = Low energy effective theory

1. Gravity $\Longrightarrow \Lambda_{\rm Planck} \sim 10^{19}\ GeV$
2. $m_\nu \neq 0 \Longrightarrow \Lambda_{\rm Seesaw} \leq 10^{15}\ GeV$
3. m_H^2-fine tuning; Dark matter $\Longrightarrow \Lambda_{\rm NP} \sim\ TeV$

$$\Downarrow$$

- The SM = Low energy effective theory
- Must write non-renormalizable terms suppressed by $\Lambda_{\rm NP}^{d-4}$
- $\mathcal{L}_{d=5} = \frac{y_{ij}^\nu}{\Lambda_{\rm seesaw}} L_i L_j \phi\phi$
- $\mathcal{L}_{d=6}$ contains many flavor changing operators

New Physics

- The effects of new physics at a high energy scale $\Lambda_{\rm NP}$ can be presented as higher dimension operators

- For example, we expect the following dimension-six operators:

$$\frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2+\frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2+\frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2+\frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2$$

- New contribution to neutral meson mixing, *e.g.*

$$\frac{\Delta m_B}{m_B}\sim\frac{f_B^2}{3}\times\frac{|z_{bd}|}{\Lambda_{\rm NP}^2}$$

- Generic flavor structure $\equiv z_{ij}\sim 1$ or, perhaps, $\mathrm{loop-factor}$

Some data

$\Delta m_K/m_K$	7.0×10^{-15}
$\Delta m_D/m_D$	8.7×10^{-15}
$\Delta m_B/m_B$	6.3×10^{-14}
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}
ϵ_K	2.3×10^{-3}
A_Γ	≤ 0.2
$S_{\psi K_S}$	0.67 ± 0.02
$S_{\psi\phi}$	≤ 1

High Scale?

- For $z_{ij} \sim 1$ (and $\mathcal{I}m(z_{ij}) \sim 1$), $\Lambda_{\rm NP} \gtrsim \frac{10^{-4}}{\sqrt{\Delta m/m}}\ TeV$

		$\Lambda_{\rm NP} \gtrsim$
$\Delta m_K/m_K$	7.0×10^{-15}	1000 TeV
$\Delta m_D/m_D$	8.7×10^{-15}	1000 TeV
$\Delta m_B/m_B$	6.3×10^{-14}	400 TeV
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	70 TeV
ϵ_K	2.3×10^{-3}	20000 TeV
A_Γ	≤ 0.004	3000 TeV
$S_{\psi K_S}$	0.67 ± 0.02	800 TeV
$S_{\psi\phi}$	≤ 1	70 TeV

High Scale

- For $z_{ij} \sim 1$, $\Lambda_{\rm NP} \gg 1000\ TeV$

- For $z_{ij} \sim \alpha_2^2$, $\Lambda_{\rm NP} \gg 100\ TeV$

High Scale

- For $z_{ij} \sim 1$, $\Lambda_{\rm NP} \gg 1000\ TeV$
- For $z_{ij} \sim \alpha_2^2$, $\Lambda_{\rm NP} \gg 100\ TeV$

$$\Downarrow$$

- Did we misinterpret the Higgs fine tuning problem?
- Did we misinterpret the dark matter puzzle?

Small (hierachical?) flavor parameters?

- For $\Lambda_{\rm NP} \sim 1\ TeV$, $z_{ij} \lesssim 10^8(\Delta m_{ij}/m)$

		$z_{ij} \lesssim$
$\Delta m_K/m_K$	7.0×10^{-15}	9×10^{-7}
$\Delta m_D/m_D$	8.7×10^{-15}	6×10^{-7}
$\Delta m_B/m_B$	6.3×10^{-14}	5×10^{-6}
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	2×10^{-4}
		$\mathcal{I}m(z_{ij}) \lesssim$
ϵ_K	2.3×10^{-3}	4×10^{-9}
A_Γ	≤ 0.004	1×10^{-7}
$S_{\psi K_S}$	0.67 ± 0.02	1×10^{-6}
$S_{\psi\phi}$	≤ 1	2×10^{-4}

Small (hierachical?) flavor parameters

- For $\Lambda_{\rm NP} \sim TeV$, $\mathcal{I}m(z_{sd}) < 6 \times 10^{-9}$

- For $\Lambda_{\rm NP} \sim TeV$, $|z_{bs}| < 2 \times 10^{-4}$

Small (hierachical?) flavor parameters

- For $\Lambda_{\rm NP} \sim \; TeV$, $\mathcal{I}m(z_{sd}) < 6 \times 10^{-9}$

- For $\Lambda_{\rm NP} \sim \; TeV$, $|z_{bs}| < 2 \times 10^{-4}$

$$\Downarrow$$

- The flavor structure of NP@TeV must be highly non-generic
  Degeneracies/Alignment

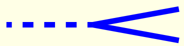
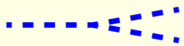
- How? Why? = The NP flavor puzzle

How does the SM ($\Lambda_{\rm SM} \sim m_W$) do it?

		$z_{ij} \sim$	$z_{ij}^{\rm SM}$
$\Delta m_K/m_K$	7.0×10^{-15}	5×10^{-9}	$\alpha_2^2 y_c^2 \lvert V_{cd}V_{cs}\rvert^2$
$\Delta m_D/m_D$	8.7×10^{-15}	5×10^{-9}	Long Distance
$\Delta m_B/m_B$	6.3×10^{-14}	7×10^{-8}	$\alpha_2^2 y_t^2 \lvert V_{td}V_{tb}\rvert^2$
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	2×10^{-6}	$\alpha_2^2 y_t^2 \lvert V_{ts}V_{tb}\rvert^2$
		$\frac{\mathcal{I}m(z_{ij})}{\lvert z_{ij}\rvert} \sim$	$\frac{\mathcal{I}m(z_{ij}^{\rm SM})}{\lvert z_{ij}^{\rm SM}\rvert}$
ϵ_K	2.3×10^{-3}	$\mathcal{O}(0.01)$	$\mathcal{I}m \frac{y_t^2 (V_{td}^* V_{ts})^2}{y_c^2 (V_{cd}^* V_{cs})^2} \sim 0.01$
A_Γ	≤ 0.004	≤ 0.2	0
$S_{\psi K_S}$	0.67 ± 0.02	$\mathcal{O}(1)$	$\mathcal{I}m \frac{V_{tb}V_{td}^*}{V_{tb}^* V_{td}} \frac{V_{cb}^* V_{cd}}{V_{cb} V_{cd}^*} \sim 0.7$
$S_{\psi\phi}$	≤ 1	≤ 1	$\mathcal{I}m \frac{V_{tb}V_{ts}^*}{V_{tb}^* V_{ts}} \frac{V_{cb}^* V_{cs}}{V_{cb} V_{cs}^*} \sim 0.02$

- Does the new physics know the SM Yukawa structure? (MFV)

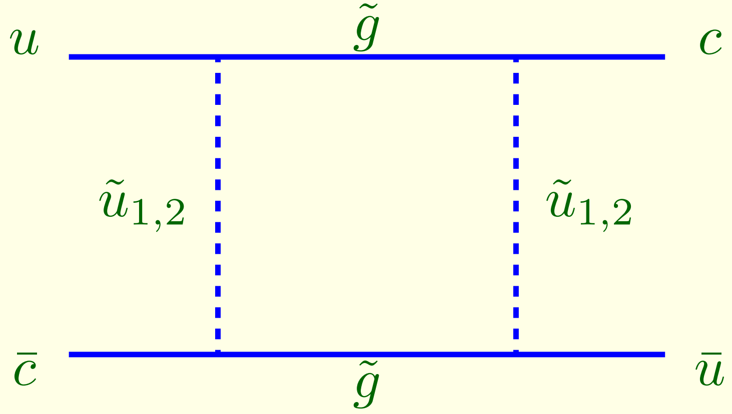
Supersymmetry for Phenomenologists

		FV	CPV
	Y	$+$	$+$
	μ	$-$	$+$
	A	$+$	$+$
	$m_{\tilde{g}}$	$-$	$+$
	$m^2_{\tilde{f}}$	$+$	$+$
	B	$-$	$+$

80 real + 44 imaginary parameters

The $D^0 - \overline{D^0}$ mixing challenge

Take, for example, the contribution from the first two generations of squark doublets to $D - \bar{D}$ mixing:



$\Lambda_{\rm NP} = m_{\tilde{Q}}$

$z_{cu} \sim 3.8 \times 10^{-5} \frac{(\Delta m^2_{\tilde{Q}})^2}{m^4_{\tilde{Q}}} (K^{u_L}_{21} K^{u_L *}_{11})^2$

$$\Longrightarrow \frac{TeV}{m_{\tilde{Q}}} \times \frac{\Delta m^2_{\tilde{Q}}}{m^2_{\tilde{Q}}} \times \sin 2\theta_u \leq 0.05 - 0.10$$

How can Supersymmetry do it?

$$\boxed{\frac{TeV}{\tilde{m}} \times \frac{\Delta\tilde{m}_{ij}^2}{\tilde{m}^2} \times K_{ij} \ll 1}$$

Why? = The SUSY flavor puzzle

How can Supersymmetry do it?

$$\boxed{\frac{TeV}{\tilde{m}} \times \frac{\Delta\tilde{m}^2_{ij}}{\tilde{m}^2} \times K_{ij} \ll 1}$$

Why? = The SUSY flavor puzzle

- Solutions:
  - Heaviness: $\tilde{m} \gg 1\ TeV$
  - Degeneracy: $\Delta\tilde{m}^2_{ij} \ll \tilde{m}^2$
  - Alignment: $K_{ij} \ll 1$
  - Split Supersymmetry
  - Gauge-mediation
  - Horizontal symmetries

Gauge Mediated Supersymmetry Breaking

Gauge interactions generate universal soft squark and slepton masses:

- $\widetilde{M}^2_{\tilde{q}_L} = \tilde{m}^2 \mathbf{1} + D_{q_L} \mathbf{1} + v_q^2 Y_q Y_q^\dagger$
- RGE: $\tilde{m}^2_{\tilde{Q}_L}(m_Z) = \tilde{m}^2(r_3 \mathbf{1} + c_u Y_u Y_u^\dagger + c_d Y_d Y_d^\dagger)$
- Strong $[\mathcal{O}(10^{-4})]$ degeneracy between $\tilde{Q}_{L1} - \tilde{Q}_{L2}$; CKM-size alignment
- The only source of flavor violation = The SM Yukawa couplings
- An example of minimal flavor violation (MFV)
- MFV solves all SUSY flavor problems

Intermediate Summary II

- How does new physics at TeV suppress its flavor violation?
- Degeneracy? Alignment?
- Is the flavor structure of the NP related to the SM Yukawa structure?