Understanding Flavor at the LHC

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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]

Kfir Blum, Yuval Grossman, YN, Gilad Perez

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

Yuval Grossman, YN, Gilad Perez

arXiv:0904.0305

Oram Gedalia, Yuval Grossman, YN, Gilad Perez

arXiv:0906.1879

Helen Quinn + YN

'The Mystery of the Missing Antimatter' (PUP)

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
arXiv:0906.4215

Feng, French, Galon, Lester, YN, Shadmi, Sanford, Yu
'Identifying the SUSY theory of flavor at the LHC'

Why is flavor physics interesting?

- Flavor physics is sensitive to new physics at $\Lambda_{\text{NP}} \gg E_{\text{experiment}}$
  FCNC suppressed within the SM by $\alpha_W^n, |V_{ij}|, m_f$
- The Standard Model flavor puzzle:
  Why are the flavor parameters small and hierarchical?
  (Why) are the neutrino flavor parameters different?
- The New Physics flavor puzzle:
  If there is NP at the TeV scale, why are FCNC so small?
  The solution $\Longrightarrow$ Clues for the subtle structure of the NP

Plan of Talk

1. Introduction
   - The LHC era
2. Open questions
   - The NP flavor puzzle
   - The SM flavor puzzle
3. What will we learn?
   - Flavor@ATLAS/CMS

The LHC Era

The LHC will explore the unknown

Energy	$0.6 \to 4$ TeV
Distance	$10^{-19} \to 10^{-20}$ m
"Time"	$10^{-11} \to 10^{-13}$ s

The LHC questions

- What is the mechanism of electroweak symmetry breaking?
- What separates the electroweak scale from the Planck scale?
- What are the dark matter particles?
- What happened at the electroweak phase transition (10^{-11} second after the big bang)?
- Was the baryon asymmetry generated by TeV scale physics?

Flavor at the LHC?

- The scale of flavor dynamics is unknown
- Very likely, it is well above the LHC direct reach

But...

- If new particles that couple to the SM fermions are discovered –
  New flavor parameters can be measured
- Spectrum, flavor decomposition...
- New insights on flavor puzzles are likely

The NP Flavor Puzzle

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)

- 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 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, 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}
$A_\Gamma/y_{\rm CP}$	≤ 0.2
$S_{\psi K_S}$	0.67 ± 0.02
$S_{\psi\phi}$	≤ 1

High Scale?

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

Mixing	$\Lambda_{\rm NP}^{\rm CPC} \gtrsim$	$\Lambda_{\rm NP}^{\rm CPV} \gtrsim$
$K-\overline{K}$	1000 TeV	20000 TeV
$D-\overline{D}$	1000 TeV	3000 TeV
$B-\overline{B}$	400 TeV	800 TeV
$B_s-\overline{B_s}$	70 TeV	70 TeV

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Did we misinterpret the Higgs fine tuning problem?

Did we misinterpret the dark matter puzzle?

Small (hierachical?) flavor parameters?

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

Mixing	$\lvert z_{ij}\rvert \lesssim$	$\mathcal{I}m(z_{ij}) \lesssim$
$K-\overline{K}$	8×10^{-7}	6×10^{-9}
$D-\overline{D}$	5×10^{-7}	1×10^{-7}
$B-\overline{B}$	5×10^{-6}	1×10^{-6}
$B_s-\overline{B_s}$	2×10^{-4}	2×10^{-4}

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

How? Why? = The NP flavor puzzle

The SM Flavor Puzzle

What have we learned?

- $\Delta m^2_{21} = (7.9{\pm}0.3){\times}10^{-5}\ eV^2, \quad |\Delta m^2_{32}| = (2.6{\pm}0.2){\times}10^{-3}\ eV^2$

- $\sin^2\theta_{12} = 0.31 \pm 0.02, \quad \sin^2\theta_{23} = 0.47 \pm 0.07, \quad \sin^2\theta_{13} = 0^{+0.08}_{-0.0}$

- Neutrino-flavor is different

Smallness and Hierarchy

$$Y_t \sim 1, \quad Y_c \sim 10^{-2}, \quad Y_u \sim 10^{-5}$$
$$Y_b \sim 10^{-2}, \quad Y_s \sim 10^{-3}, \quad Y_d \sim 10^{-4}$$
$$Y_\tau \sim 10^{-2}, \quad Y_\mu \sim 10^{-3}, \quad Y_e \sim 10^{-6}$$
$$|V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004, \quad \delta_{\rm KM} \sim 1$$

- For comparison: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1$
- The SM flavor parameters have structure: smallness and hierarchy
- Why? = The SM flavor puzzle

The Froggatt-Nielsen (FN) mechanism

- Approximate "horizontal" symmetry (e.g. $U(1)_H$)
- Small breaking parameter $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- $\mathbf{10}(2,1,0), \quad \bar{\mathbf{5}}(0,0,0)$

$$\Downarrow$$

$$Y_t : Y_c : Y_u \sim 1 : \epsilon^2 : \epsilon^4$$
$$Y_b : Y_s : Y_d \sim 1 : \epsilon : \epsilon^2$$
$$Y_\tau : Y_\mu : Y_e \sim 1 : \epsilon : \epsilon^2$$
$$|V_{us}| \sim |V_{cb}| \sim \epsilon, \quad |V_{ub}| \sim \epsilon^2, \quad \delta_{\rm KM} \sim 1$$

$$+$$

$$m_3 : m_2 : m_1 \sim 1 : 1 : 1$$
$$|U_{e2}| \sim 1, \quad |U_{\mu 3}| \sim 1, \quad |U_{e3}| \sim 1$$

Testing FN with Neutrinos

- The data:
  - $\Delta m^2_{21} = (7.9\pm0.3)\times10^{-5}\ eV^2, \quad |\Delta m^2_{32}| = (2.6\pm0.2)\times10^{-3}\ eV^2$
  - $\sin^2\theta_{12} = 0.31\pm0.02, \quad \sin^2\theta_{23} = 0.47\pm0.07, \quad \sin^2\theta_{13} = 0^{+0.08}_{-0.0}$
- The tests:
  - $s_{23}\sim 1, \quad m_2/m_3 \sim \epsilon^x$?
    Inconsistent with FN
  - $s_{23}\sim 1, \quad s_{12}\sim 1, \quad s_{13}\sim\epsilon^x$?
    Inconsistent with FN
  - $\sin^2 2\theta_{23} = 1-\epsilon^x$?
    Inconsistent with FN

Neutrino Mass Anarchy

- Facts:
  - $\sin\theta_{23} \sim 0.70 >$ any $|V_{ij}|$
  - $\sin\theta_{12} \sim 0.56 >$ any $|V_{ij}|$
  - $m_2/m_3 \gtrsim 1/6 >$ any m_i/m_j for charged fermions
  - $\sin\theta_{13} \sim 0.1$ is still possible
- Possible interpretation:
  - Neutrino parameters are all of $O(1)$ (no structure):
    Neutrino mass anarchy
  - Consistent with FN
  - Close to GUT+FN predictions:
    $s_{23} \sim \frac{m_s/m_b}{|V_{cb}|} \sim 1; \quad s_{12} \sim \frac{m_d/m_s}{|V_{us}|} \sim 0.2; \quad s_{13} \sim \frac{m_d/m_b}{|V_{ub}|} \sim 0.5$

Structure is in the eye of the beholder

$$|U|_{3\sigma} = \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & 0.0-0.2 \\ 0.25-0.53 & 0.47-0.73 & 0.56-0.79 \\ 0.21-0.51 & 0.42-0.69 & 0.61-0.83 \end{pmatrix}$$

- Tribimaximal-ists:

$$|U|_{\rm TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

- Anarch-ists:

$$|U|_{\rm anarchy} = \begin{pmatrix} \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \end{pmatrix}$$

What will we learn?

Flavor Physics at the LHC era

- If ATLAS/CMS observe no NP...
- and flavor factories observe no NP...

Flavor Physics at the LHC era

- If ATLAS/CMS observe no NP...
- but flavor factories observe NP...
  - We may have misinterpreted the fine-tuning problem
  - We may have misinterpreted the dark matter puzzle
  - Flavor will provide the only clue for an accessible scale of NP

Flavor Physics at the LHC era

ATLAS/CMS will, hopefully, observe NP at $\Lambda_{\rm NP} \lesssim TeV$;

In combination with flavor factories, we may...

- Understand how the NP flavor puzzle is (not) solved
  $\Longrightarrow$ Probe NP at $\Lambda_{\rm NP} \gg TeV$
- Get hints about the solution to the SM flavor puzzle

Gauge+Gravity Mediation

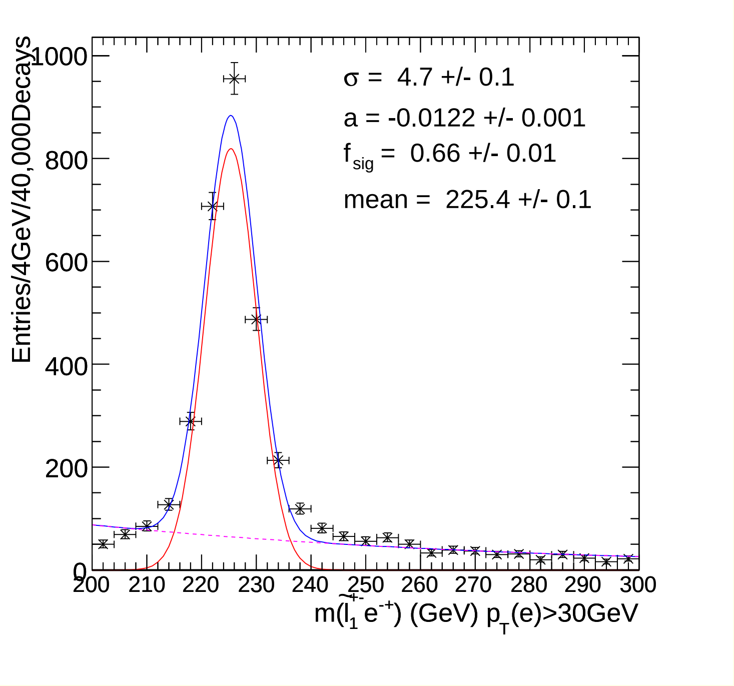
- Example: High (but not too high) scale gauge mediation
  - Gravity mediation sub-dominant but non-negligible
  - $r = \frac{\text{gravity}-\text{med}}{\text{gauge}-\text{med}} \sim \left(\frac{m_M}{m_{\rm Pl}}\right)^2 \left(\frac{4\pi}{\alpha_3(m_M)}\right)^2 \frac{3}{8n_M}$
  - $\widetilde{M}^2_{\tilde{Q}_L}(m_M) = \tilde{m}^2_{\tilde{Q}_L}(\mathbf{1} + rX_{\tilde{Q}_L})$
  - Degeneracy depends on r

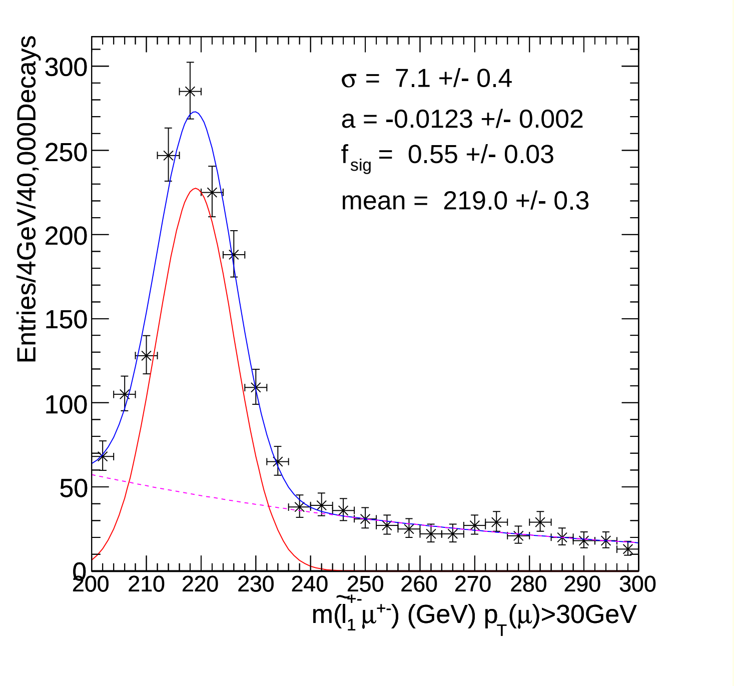
Assume: The flavor structure of X determined by FN:

- $X_{\tilde{Q}_L} \sim \begin{pmatrix} 1 & V_{us} & V_{ub} \\ \cdot & 1 & V_{cb} \\ \cdot & \cdot & 1 \end{pmatrix}; \quad X_{\tilde{D}_R} \sim \begin{pmatrix} 1 & \frac{m_d/m_s}{V_{us}} & \frac{m_d/m_b}{V_{ub}} \\ \cdot & 1 & \frac{m_s/m_b}{V_{cb}} \\ \cdot & \cdot & 1 \end{pmatrix}$
- Mixing depends only on X which is related to the SM flavor

Measuring small mass splitting + mixing

$\chi_1^0 \to \tilde{\ell}_1^{\pm} e^{\mp}$ or $\tilde{\ell}_2^{\pm} \mu^{\mp}$; $\tilde{\ell}_2^{\pm} \to \tilde{\ell}_1^{\mp} (\ell^{\pm}\ell^{\pm})_{\rm soft}$ or $\tilde{\ell}_2^{\pm} \to \tilde{\ell}_1^{\pm} (\ell^{\pm}\ell^{\mp})_{\rm soft}$





$m(\tilde{\ell}_1^{\pm} e^{\mp}) = m_{\chi_1^0}$

$m(\tilde{\ell}_1^{\pm} \mu^{\pm}) = m_{\chi_1^0} - E_{\rm shift}$

$$\Delta m = \frac{2 m_{\chi_1^0} m_{\tilde{\ell}}}{m_{\chi_1^0}^2 + m_{\tilde{\ell}}^2} E_{\rm shift}$$

Solving the NP Flavor Puzzle

If ATLAS/CMS observe squarks and sleptons...

- Determine the sfermion mass scale ($\tilde{m}$)
- Determine the sfermion mass splitting ($m_{\tilde{f}_j} - m_{\tilde{f}_i}$)
- Determine the sfermion flavor decomposition (K_{ij})

$$\Downarrow$$

Learn how the SUSY flavor suppression is obtained

Physics at $\Lambda_{\rm NP} \gg \Lambda_{\rm LHC}$

If ATLAS/CMS determine sfermion mass splittings...

- Find the ratio between gravity- and gauge-mediated contributions (r)
- Determine the messenger scale of gauge mediation (m_M)
- Find the hierarchy between the GMSB and see-saw scales

$$\Downarrow$$

Probe physics at $m_M \sim 10^{15}\ GeV$

Solving the SM Flavor Puzzle?

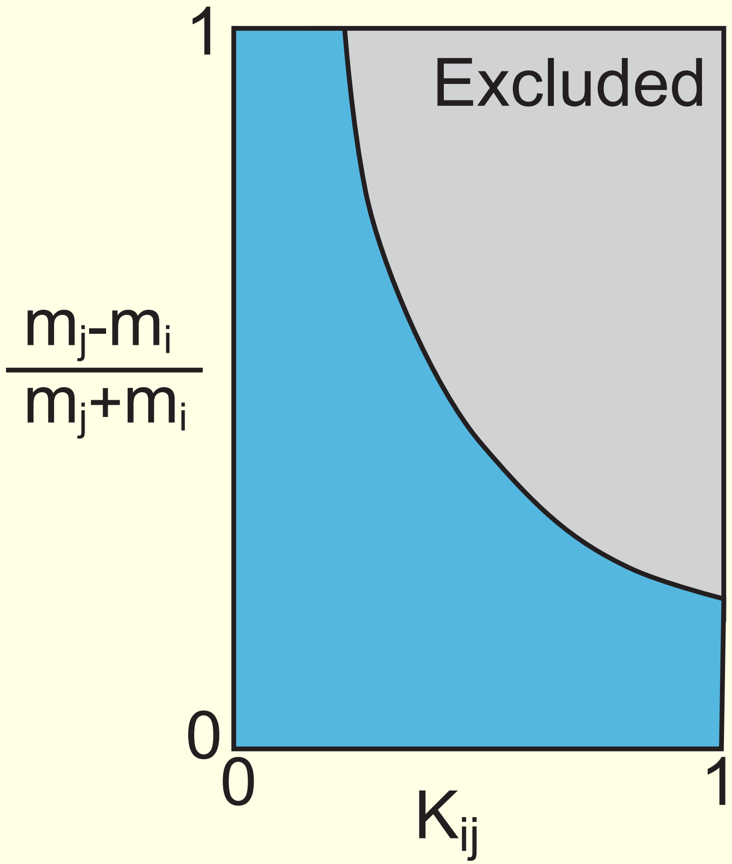
If ATLAS/CMS determine sfermion flavor decomposition...

- Determine X of $\tilde{M}^2 = \tilde{m}^2(\mathbf{1} + rX)$
- Does X have the FN-predicted structure?

$$\Downarrow$$

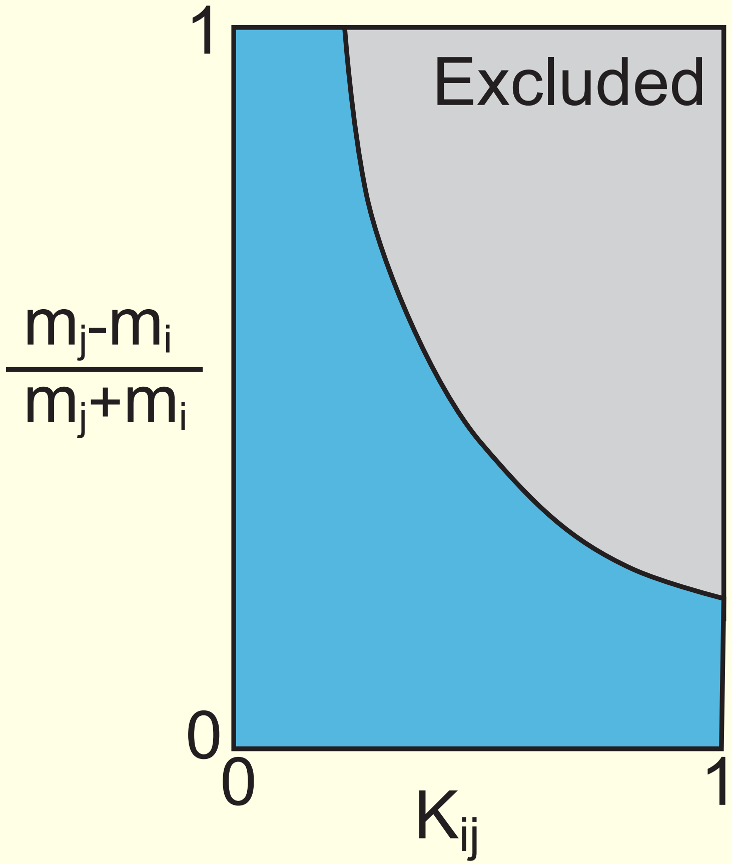
Test theories that explain the SM flavor structure

The NP flavor plane

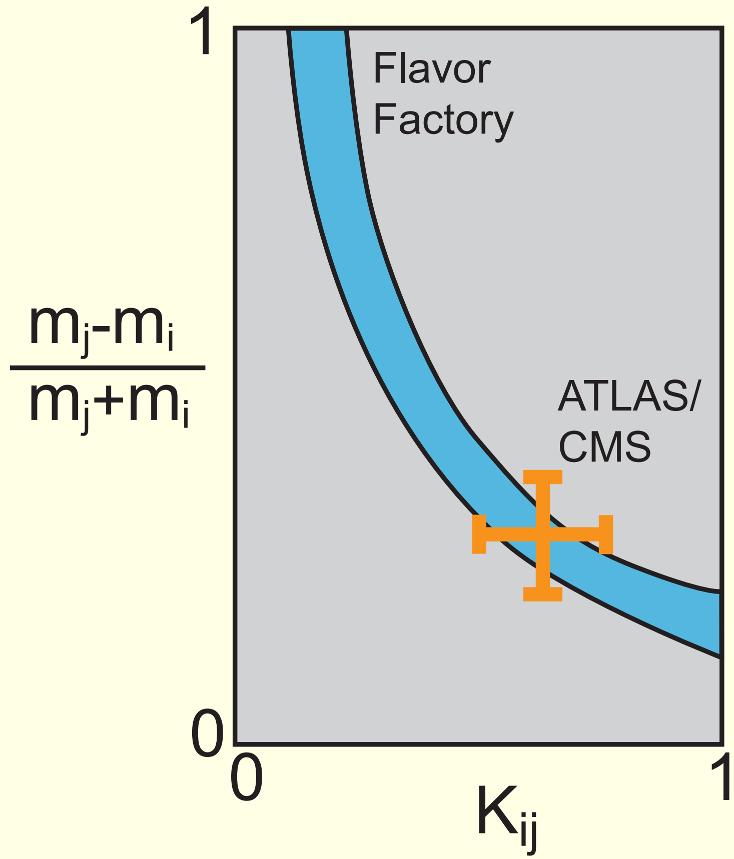


Flavor Factories

The NP flavor plane



Flavor Factories



FF+ATLAS/CMS

What will we learn?

- ATLAS/CMS and flavor factories give complementary information
- In the absence of NP at ATLAS/CMS –
  flavor factories will be crucial to find $\Lambda_{\rm NP}$
- With NP at ATLAS/CMS –
  The NP flavor puzzle is likely to be understood
  $\Longrightarrow$ A probe of physics at $\Lambda_{\rm NP} \gg \Lambda_{\rm LHC}$
- With supersymmetry –
  The SM flavor puzzle may be solved

Backup Transparencies

A brief history of FV

- $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu) \implies$ Charm [GIM, 1970]
- $\Delta m_K \implies m_c \sim 1.5\ GeV$ [Gaillard-Lee, 1974]
- $\varepsilon_K \neq 0 \implies$ Third generation [KM, 1973]
- $\Delta m_B \implies m_t \gg m_W$ [Various, 1986]

Why is CPV interesting?

- Within the SM, a single CP violating parameter η:
  In addition, QCD = CP invariant ($\theta_{\rm QCD}$ irrelevant)
  Strong predictive power (correlations + zeros)
  Excellent tests of the flavor sector
- η cannot explain the baryon asymmetry – a puzzle:
  There must exist new sources of CPV
  Electroweak baryogenesis? (Testable at the LHC)
  Leptogenesis? (Window to $\Lambda_{\rm seesaw}$)

A brief history of CPV

- $1964 - 2000$
  - $|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.67 \pm 0.26) \times 10^{-3}$

A brief history of CPV

- 1964 – 2000
  - $|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.67 \pm 0.26) \times 10^{-3}$
- 2000 – 2009
  - $S_{\psi K_S} = +0.67 \pm 0.02$
  - $S_{\eta' K_S} = +0.61 \pm 0.07$, $S_{\pi^0 K_S} = +0.57 \pm 0.17$, $S_{\rho^0 K_S} = +0.63 \pm 0.17$, $S_{f_0 K_S} = +0.62 \pm 0.11$
  - $S_{K^+K^-K_S} = -0.74 \pm 0.11$
  - $S_{\pi^+\pi^-} = -0.61 \pm 0.08$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{D^+D^-} = -0.89 \pm 0.26$
  - $\mathcal{A}_{K^\mp\rho^0} = +0.37 \pm 0.11$, $\mathcal{A}_{\eta K^\mp} = -0.27 \pm 0.09$, $\mathcal{A}_{f_2 K^\mp} = -0.68 \pm 0.20$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.098 \pm 0.012$, $\mathcal{A}_{\eta K^{*0}} = +0.19 \pm 0.05$
  - ...

Flavor@GeV $\Longrightarrow$ NP@TeV

A recent example [Blum et al, 0903.2118, PRL in press]

- $\frac{\Delta m_K}{m_K} = (7.01 \pm 0.01) \times 10^{-15}; \quad \epsilon_K = (2.23 \pm 0.01) \times 10^{-3}$
- $\frac{\Delta m_D}{m_D} = (8.6 \pm 2.1) \times 10^{-15}; \quad A_\Gamma = (1.2 \pm 2.5) \times 10^{-3}$
- Consider $\frac{1}{\mathrm{TeV}^2} \left[\overline{Q_{Li}}(X_Q)_{ij}\gamma_\mu Q_{Lj}\right]^2$
- Take $Y_d = \lambda_d, \quad Y_u = V^\dagger \lambda_u, \quad X_Q = V_d^\dagger \mathrm{diag}(\lambda_1, \lambda_2) V_d$
- $K + D \Longrightarrow$ Degeneracy: $\lambda_2 - \lambda_1 \leq 0.004 - 0.0005$
  - Supersymmetry: $\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \leq 0.27 - 0.034$
  - RS-I: $\sqrt{\frac{\mathrm{TeV}}{m_{\mathrm{KK}}}} f_{Q_2} \lesssim 0.06 - 0.02.$

A beautiful relation

- Assume no direct CP violation
- A surprising relation: $\boxed{y \tan\phi = x(1-|q/p|)}$

Grossman et al., arXiv:0904.0305

$$\Downarrow$$

K $$\arg(\epsilon) = \arctan(-x/y)$$

B_s $$A^s_{\rm SL} = -2|y/x| S_{\psi\phi}/(1-S^2_{\psi\phi})^{1/2}$$

D $$(1-|q/p|)/\tan\phi = y/x$$

Flavor Violation (FV)

- $\mathcal{L}_{\text{kinetic+gauge}} + \mathcal{L}_{\text{Higgs}}$ has a large global symmetry:
  $G_{\text{global}} = [U(3)]^5$
- $\mathcal{L}_{\text{Yukawa}} = \overline{Q_L}_i Y^u_{ij} \tilde{\phi} U_{Rj} + \overline{Q_L}_i Y^d_{ij} \phi D_{Rj} + \overline{L_L}_i Y^e_{ij} \phi E_{Rj}$
  breaks $G_{\text{global}} \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
- Flavor physics:
  interactions that break the $[SU(3)]^5$ symmetry

$$\Downarrow$$

- $Q_L \to V_Q Q_L, \quad U_R \to V_U U_R, \quad D_R \to V_D D_R$
  $=$ Change of interaction basis
- Can be used to reduce the number of parameters in Y^u, Y^d

Kobayashi and Maskawa

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

CP violation = a single imaginary parametr in the CKM matrix:

- V unitary with 3 real (λ, A, ρ) and 1 imaginary (η) parameters:

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

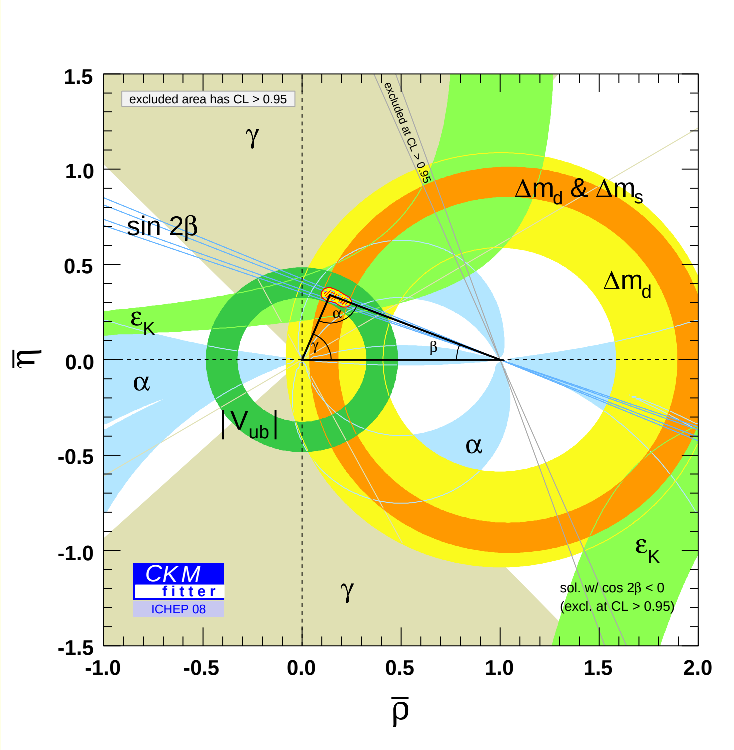
$S_{\psi K_S}$

- 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 $A(B^0 \to \overline{B^0} \to \psi K_S)$
- $\Longrightarrow A_{\psi K_S}(t) = S_{\psi K_S} \sin(\Delta m_B t)$
  $\Longrightarrow S_{\psi K_S} = \frac{1}{|A(B^0\to\overline{B^0})|} \mathcal{I}m \left[\frac{A(B^0\to\overline{B^0})A(\overline{B^0}\to\psi K_S)}{A(B^0\to\psi K_S)}\right]$
- SM: $\boxed{S_{\psi K_S} = \mathcal{I}m\left[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}\right] = \frac{2\eta(1-\rho)}{\eta^2+(1-\rho)^2}}$
- The approximations involved are better than one percent!
- Experiments: $S_{\psi K_S} = 0.671 \pm 0.024$

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 flavor-factories plot



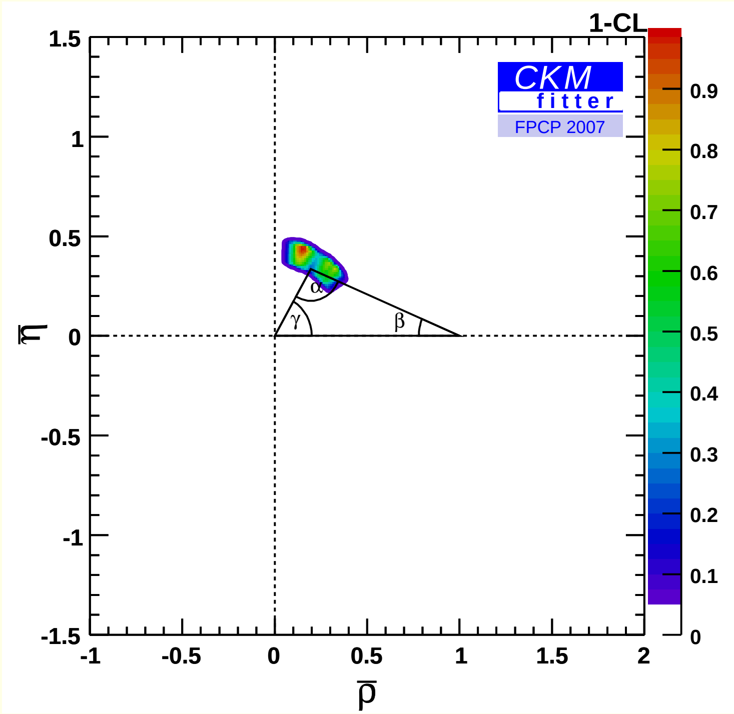
CKMFitter

Very likely, the CKM mechanism dominates FV and CPV

Testing CKM - take II

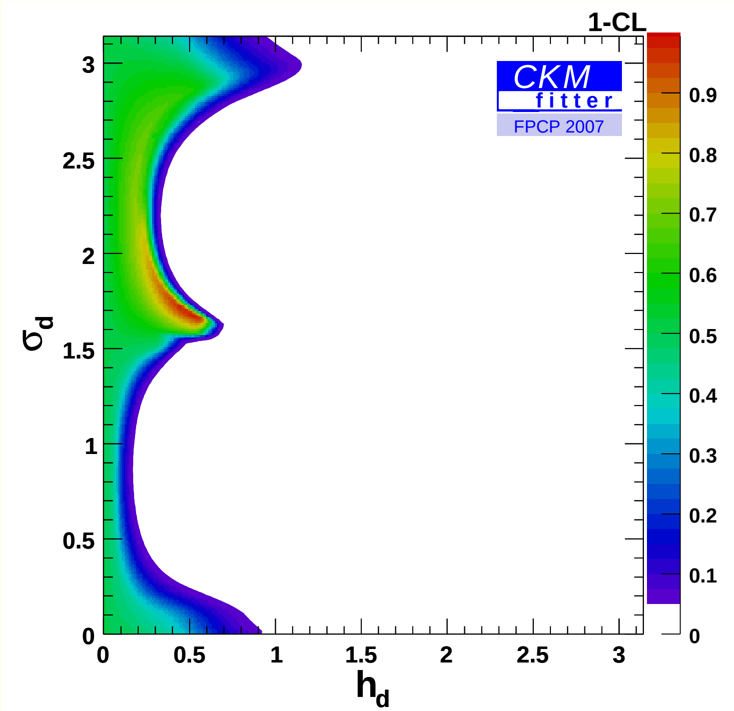
- Assume: New Physics in leading tree decays - negligible
- Allow arbitrary new physics in loop processes
- Use only tree decays and $B^0 - \overline{B}^0$ mixing
- Define $h_d e^{2i\sigma_d} = \frac{A^{\rm NP}(B^0 \to \overline{B})}{A^{\rm SM}(B^0 \to \overline{B})}$
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}^d_{\rm SL}$
- Fit to $\boxed{\eta}$, ρ, $\boxed{h_d}$, 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
- The CKM mechanism is a major player in flavor violation

Minimal flavor violation (MFV)

- MFV = the only source of FV are the SM Yukawa matrices
- MFV $\Longrightarrow$ NP@TeV scale is consistent with FCNC constraints
- Most likely, an approximation
- Predictions:
  - Spectrum: often MFV implies degeneracies
  - Mixing: the third generation is approximately decoupled
- Example: Gauge mediated supersymmetry breaking
  - Squark spectrum: $2+1$
  - Squark decays: $\tilde{q}_{1,2} \to q_{1,2}, \quad \tilde{q}_3 \to q_3$
- In principle, testable in ATLAS/CMS

The FN mechanism: Predictions (quarks)

- In the quark sector: 8 FN charges, 9 observables
- One prediction that is independent of charge assignments:
  $\boxed{|V_{ub}| \sim |V_{us}V_{cb}|}$
  Experimentally correct to within a factor of 2
- In addition, six inequalities:
  $|V_{us}| \gtrsim \frac{m_d}{m_s}, \frac{m_u}{m_c}; \quad |V_{ub}| \gtrsim \frac{m_d}{m_b}, \frac{m_u}{m_t}; \quad |V_{cb}| \gtrsim \frac{m_s}{m_b}, \frac{m_c}{m_t}$
  Experimentally fulfilled
- When ordering the quarks by mass:
  $V_{CKM} \sim \mathbf{1}$ (diagonal terms not suppressed parameterically)
  Experimentally fulfilled

The FN mechanism: Predictions (leptons)

- In the lepton sector: 5 FN charges, 9 observables
- Four predictions that are independent of charge assignments:
  $\boxed{m_{\nu_i}/m_{\nu_j} \sim |U_{ij}|^2}$
  $|U_{e3}| \sim |U_{e2}U_{\mu3}|$
- In addition, three inequalities:
  $|U_{e2}| \gtrsim \frac{m_e}{m_\mu}; \quad |U_{e3}| \gtrsim \frac{m_e}{m_\tau}; \quad |U_{\mu3}| \gtrsim \frac{m_\mu}{m_\tau}$
- When ordering the leptons by mass:
  $U \sim \mathbf{1}$