NATIFEST

Celebrating the Science of Nati Seiberg
IAS, Princeton, NJ
15 September 2016

A TASTE OF FLAVOR

Yossi Nir
Weizmann Institute
A brief history of our collaboration

Mass matrix models

Should squarks be degenerate?

Mass matrix models: the sequel

Missing (up) mass
- Banks, Nir, Seiberg: hep-ph/9403203
The Flavor Puzzles

• Why is there structure in the charged fermion flavor parameters?
• Smallness and hierarchy

• Why is the neutrino flavor structure different?
• Neither smallness nor hierarchy

• If there is TeV-scale NP, why doesn’t it affect FCNC?
• Degeneracy and alignment
A Taste of Flavor: Plan of Talk

- Quarks
- Squarks
- Neutrinos
- Higgs
Quark Data
The FN Mechanism

- A horizontal Abelian symmetry, \( e.g. \, U(1) \)
- Explicitly broken by a small parameter \( \varepsilon(-1) \)
- Selection rule: A term that carries charge \( n \) is suppressed by \( \varepsilon^n \)
- Can be embedded in a full high energy theory with a scalar singlet and vector-like fermions
FN predictions

- $|V_{ub}| \sim |V_{us} V_{cb}|$

- $|V_{us}| \geq \frac{m_{\uparrow u}}{m_{\downarrow c}} , \frac{m_{\downarrow d}}{m_{s}}$

- $|V_{cb}| \geq \frac{m_{\downarrow c}}{m_{t}} , \frac{m_{s}}{m_{b}}$

- $|V_{ub}| \geq \frac{m_{\downarrow u}}{m_{t}} , \frac{m_{\downarrow d}}{m_{b}}$

- $\mathbf{VCKM} \sim 1$ (when mass-ordered)
Can we make progress?

• NP that couples to quarks/leptons

  ⟹ New flavor parameters that can be measured

• The NP flavor structure can be
  – MFV
  – Related but not identical to SM
  – Unrelated to SM or even anarchical

• The NP flavor puzzle:
  – With ATLAS/CMS we are likely to understand it

• The SM flavor puzzle:
  – Progress possible if structure neither MFV nor unrelated to SM

• $h \Rightarrow$ The “NP” is already here!

  – $Y_{ij}$ are new flavor parameters that can be measured
Squarks
### Squark Data

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experiment</th>
</tr>
</thead>
</table>

The quark data, again

\[ \Rightarrow (\Delta m_{\text{13}} / m_{\text{22}})_{K_{\text{13}}} < 0.07 \]
Naïve FN predictions

• Squark masses are only RGE-degenerate

\[
|V_{\downarrow ij}^{\uparrow LL}| \sim |(V_{\downarrow CKM})_{ij}|
\]

\[
|V_{\downarrow ij}^{\uparrow RR}| \sim \left(\frac{m_{\downarrow i}}{m_{\downarrow j}}\right)/ |(V_{\downarrow CKM})_{ij}|
\]

• Quark-Squark alignment
  Alternative to squark degeneracy
Holomorphic Zeros

- Take the breaking parameter $\varepsilon$ to be a spurion
- In superpotential – You can employ $\varepsilon^n$ but not $(\varepsilon^\dagger)^n$
- FN symmetry can induce holomorphic zeros in the Yukawa couplings
- Quark-squark alignment can be stronger than the naïve estimate
- If K-mixing constraints satisfied $\rightarrow$ D-mixing close to the bound
Naturalness versus supersymmetric non-renormalization theorems

Nathan Seiberg
Department of Physics and Astronomy, Rutgers University

Received 1 October 1993
Editor: M. Dine

Ooguri: This was the beginning of the modern approach to supersymmetric field theory.

Seiberg: This was one element. The second element was influenced by my work with Yossi Nir, where we used spurious and the fact that the superpotential had to be holomorphic in them.

Ooguri: Was that the first time the spurious technique was used in supersymmetric theory?

Seiberg: Spurions had appeared earlier, especially in the context of supersymmetric breaking. I think the new point here was to view all the ordinary supersymmetric coupling constants as spurions by viewing them as background superfields. And the main application was to derive the non-renormalization theorem.
Neutrinos
### V Data

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$(7.5 \pm 0.2) \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
</tr>
<tr>
<td>$</td>
<td>U_{e2}</td>
</tr>
<tr>
<td>$</td>
<td>U_{\mu3}</td>
</tr>
<tr>
<td>$</td>
<td>U_{e3}</td>
</tr>
</tbody>
</table>
Surprise, Surprise...

- $|U_{\mu 3}| > \text{any } |V_{ij}|$
- $|U_{e 2}| > \text{any } |V_{ij}|$
- $|U_{\downarrow e 3}| = O(|U_{\downarrow e 2} U_{\mu 3}|)$
- $m_2/m_3 > 1/6 > \text{any } m_i/m_j$ for charged fermions
- Neither smallness nor hierarchy
  $\Rightarrow$ The neutrino flavor puzzle
TBM ↔ Anarchy

- Experimentalists:
  \[ U\downarrow 3\sigma = (\boxed{0.80-0.85&0.51-0.58&0.14-0.16@0.22-0.52&0.44-0.70&0.61-0.79@0.25-0.53&0.57-0.71&0.59-0.78} ) \]

  \[ U\downarrow TBM = (\boxed{2/\sqrt{6} &1/\sqrt{3} &0@1/\sqrt{6} &1/\sqrt{3} &1/\sqrt{2} @1/\sqrt{6} &1/\sqrt{3} &1/\sqrt{2}} ) \]

- Tribimaximal-ists:

- Anarch-ists:
  \[ U\downarrow\text{anarchy} = (\boxed{O(0.6)&O(0.6)&O(0.6)@O(0.6)&O(0.6)@O(0.6)&O(0.6)&O(0.6) } ) \]
FN and neutrinos

- Simplest + SU(5)-consistent assignment:
  - $Q, U, E = 10$: $(2, 1, 0)$
  - $D, L = 5$: $(0, 0, 0)$

- $m_u / m_c \sim m_c / m_t \sim \varepsilon_2$
- $m_d / m_s \sim m_s / m_b \sim \varepsilon$
- $|V_{us}| \sim |V_{cb}| \sim \varepsilon, \ |V_{ub}| \sim \varepsilon^2$

- $m_e / m_\mu \sim m_\mu / m_\tau \sim \varepsilon$
- $m_1 / m_2 \sim m_2 / m_3 \sim 1$
- $|U_{\mu 2}| \sim |U_{\mu 3}| \sim |U_{\mu 3}| \sim 1$

- Charged fermion hierarchy + Neutrino anarchy
The Higgs Boson
# Higgs Data

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\gamma\gamma}$</td>
<td>1.14 ± 0.18</td>
</tr>
<tr>
<td>$R_{ZZ^*}$</td>
<td>1.17 ± 0.23</td>
</tr>
<tr>
<td>$R_{WW^*}$</td>
<td>0.99 ± 0.15</td>
</tr>
<tr>
<td>$R_{b\bar{b}}$</td>
<td>0.7 ± 0.3</td>
</tr>
<tr>
<td>$R_{\tau\tau}$</td>
<td>1.09 ± 0.23</td>
</tr>
<tr>
<td>$R_{\mu\mu}$</td>
<td>&lt; 7</td>
</tr>
<tr>
<td>$R_{ee}$</td>
<td>&lt; $4 \times 10^5$</td>
</tr>
</tbody>
</table>
SM: \( Y \downarrow F = (\sqrt{2}/v) M \downarrow F \)

- Proportionality
  - \( y \downarrow i \equiv Y \downarrow ii \propto m \downarrow i \)

- Factor of proportionality
  - \( y \downarrow i / m \downarrow i = \sqrt{2}/v \)

- Diagonality
  - \( Y \downarrow ij = 0 \text{ for } i \neq j \)
Proportionality?

- $y_t, y_b, y_\tau$ not far from SM
- $y_{3rd}/m_{3rd} \sim \sqrt{2}/\nu$
- $y_e, y_\mu < y_\tau$

- The beginning of Higgs flavor physics
However, Diagonality?

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experiment</th>
<th>$\sqrt{Y_{ij}^2 + Y_{ji}^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(t \rightarrow ch)$</td>
<td>$\leq 0.0046$</td>
<td>$\leq 0.13$</td>
</tr>
<tr>
<td>$\text{BR}(h \rightarrow \tau\mu)$</td>
<td>$\leq 0.015$</td>
<td>$\leq 0.004$</td>
</tr>
</tbody>
</table>

- $\text{BR}(h \rightarrow \tau\mu) = \begin{cases} (8.4 \pm 3.7) \times 10^{-3} & \text{CMS} \\ (5.3 \pm 5.1) \times 10^{-3} & \text{ATLAS} \end{cases}$

- What if $\text{BR}(h \rightarrow \tau\mu) \ll \text{BR}(h \rightarrow \tau\tau)$?
• $U(1)\downarrow\mu \times U(1)\downarrow\tau$ broken
  ▪ $\Lambda\downarrow LFV \ll \Lambda\downarrow LNV$?

• $BR(h\rightarrow\tau\mu) \sim BR(h\rightarrow\tau\tau)$
  ▪ FCNC at tree level?

• $Y \downarrow E \not\propto M \downarrow E$
  ▪ Not the SM Higgs?
\[ \Lambda \downarrow LFV \ll \Lambda \downarrow LNV? (d=5) \]

- d=5: \[ Y_{ij} \uparrow N / \Lambda \downarrow LNV \ L \downarrow i \ L \downarrow j \ \phi \phi \]
- Explain neutrino mass and mixing
- Break \[ U(1) \downarrow e \times U(1) \downarrow \mu \times U(1) \downarrow \tau \ (LFV) \]
- Break total lepton number (LNV)
- \( h \rightarrow \tau \mu \) allowed, but...
  - Loop suppression \( \sim \alpha \uparrow 2 \uparrow 2 \)
  - Mixing suppression \( \sim |U_{\mu3}| \uparrow 2 \uparrow 2 \)
  - GIM suppression \( \sim (\Delta m_{23} \uparrow 2 \uparrow 2 / m_{W} \uparrow 2) \uparrow 2 \)
- \( BR(h \rightarrow \tau \mu) \sim 10^{\uparrow -50} \)
\( \Lambda \downarrow LFV \ll \Lambda \downarrow LNV ? (d=6) \)

- d=6: \( Z \downarrow ij \uparrow e / \Lambda \downarrow LFV \uparrow 2 \ (\phi \uparrow + \phi) \phi L \downarrow i \ E \downarrow j \)

- \( Y \downarrow E \uparrow h = (\sqrt{2} M \downarrow E / v) + (v \uparrow 2 / 2 \Lambda \uparrow 2) Z \uparrow e \)

- For \( \Lambda \downarrow LFV / \sqrt{Z} \downarrow \mu \tau \uparrow e \sim \text{few TeV} : \)
  - \( BR(h \rightarrow \tau \mu) \sim 0.01 \)
FCNC at tree level?

• All models with no bare mass terms and with NFC: \( h \to \tau \mu \) loop-suppressed
• With loop suppression:
  \[
  \left( \frac{v^2}{\Lambda^2} \right) \left( \frac{\alpha}{4\pi} \right) X_{\tau \mu} \sim y_{\tau \tau} \sim 10^{1-2}
  \]
  Very challenging model building
• MSSM – excluded
• Models with tree-level \( Y_{\tau \mu}^h \neq 0 \) favored
  ▪ Vector-like leptons
  ▪ Multi-Higgs doublets
• Vector-like leptons:
  – Strongly disfavored by the $\tau \rightarrow \mu \mu \mu$ bound

• Two Higgs doublet models:
  – $Y_{\downarrow E} \uparrow h = s \downarrow \alpha - \beta \left( \sqrt{2} M_{\downarrow E} / v \right) + c \downarrow \alpha - \beta \ Y_{\downarrow E} \uparrow A$
  – $Y_{\downarrow E} \uparrow A$ arbitrary

• 2HDM = the favored option
• $BR(\mu \rightarrow e\gamma) < 5 \times 10^{-13}$
  $\Rightarrow Y_{\downarrow e\mu\uparrow h} \leq 1.2 \times 10^{-6}$

• **FN:**
  $Y_{\downarrow e\mu\uparrow h} / y_{\downarrow \mu\tau\uparrow h} \sim y_{\downarrow \mu} |U_{\downarrow e2}| / y_{\downarrow \tau}$ / $U_{\downarrow \mu3}$ / $\sim 0.05$

  $\Rightarrow Y_{\downarrow \mu\tau\uparrow h} \leq 3 \times 10^{-5}$

• If $BR(h \rightarrow \tau\mu) \sim 0.01$
  $\Rightarrow Y_{\downarrow \mu\tau\uparrow h} \sim 3 \times 10^{-3}$

• **FN will be excluded**
What if $BR(h\to \tau\mu)\sim 0.01$?

- **Natural flavor conservation (NFC)**
  - A solution of the 2HDM flavor puzzle
  - Will be excluded

- **Minimal flavor violation (MFV)**
  - A solution to the NP flavor puzzle
  - Will be excluded

- **Froggatt-Nielsen (FN)**
  - A solution to the SM and NP flavor puzzles
  - Will be excluded

- In principle, measuring $h\to \tau\tau, \mu\mu, \tau\mu$ can distinguish NFC/MFV/FN
Flavored Conclusions

Quarks: smallness, hierarchy
⇒ Approximate symmetry?

Squarks: degeneracy, alignment
⇒ Flavor paradise, but where are they?

Neutrinos: anarchy
⇒ Knowing more does not necessarily mean understanding better

Higgs: diagonality? proportionality?
⇒ a new opportunity for flavor
Final comments

• The collaboration with Nati has taught me precious lessons about how to ask scientific questions, how to search for the answers, and how to notice the unexpected.

• I learned about mentoring the younger generation and about being generous in sharing scientific insights.

I am privileged to have worked with him.