NATIFEST

Celebrating the Science of Nati Seiberg

IAS, Princeton, NJ

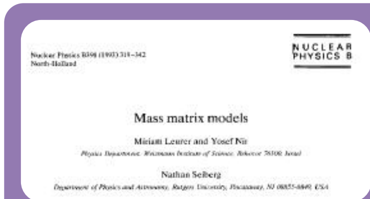
15 September 2016

A TASTE OF FLAVOR

Yossi Nir

Weizmann Institute

A brief history of our collaboration



Nuclear Physics B398 (1993) 319–342
North-Holland

NUCLEAR PHYSICS B

Mass matrix models

Miriam Leurer and Yosef Nir
Physics Department, Weizmann Institute of Science, Rehovot 76100, Israel

Nathan Seiberg
Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08855-0849, USA

Mass matrix models

- Leurer, Nir, Seiberg: Nucl. Phys. B398 (1993) 319

hysics Letters B 309 (1993) 337–343
North-Holland

Should squarks be degenerate?

Yosef Nir[1]
Weizmann Institute of Science, Physics Department, Rehovot 76100, Israel

and

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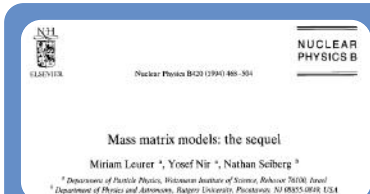
Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08855-0849, US

Should squarks be degenerate?

- Nir, Seiberg: Phys. Lett. B309 (1993) 337



NH
ELSEVIER

Nuclear Physics B420 (1994) 468–504

NUCLEAR PHYSICS B

Mass matrix models: the sequel

Miriam Leurer [a], Yosef Nir [a], Nathan Seiberg [b]

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[b] *Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08855-0849, USA*

Mass matrix models: the sequel

- Leurer, Nir, Seiberg: Nucl. Phys. B420 (1994) 468

Missing (up) Mass, Accidental Anomalous Symmetries, and the Strong CP Problem

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and

Nathan Seiberg
Department of Physics and Astronomy

Missing (up) mass

- Banks, Nir, Seiberg: hep-ph/9403203

The Flavor Puzzles

SM

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

ν

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

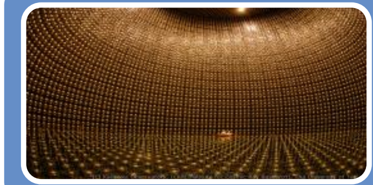
NP

- If there is TeV-scale NP, why doesn't it affect FCNC?
- Degeneracy and alignment

A Taste of Flavor: Plan of Talk

Quarks

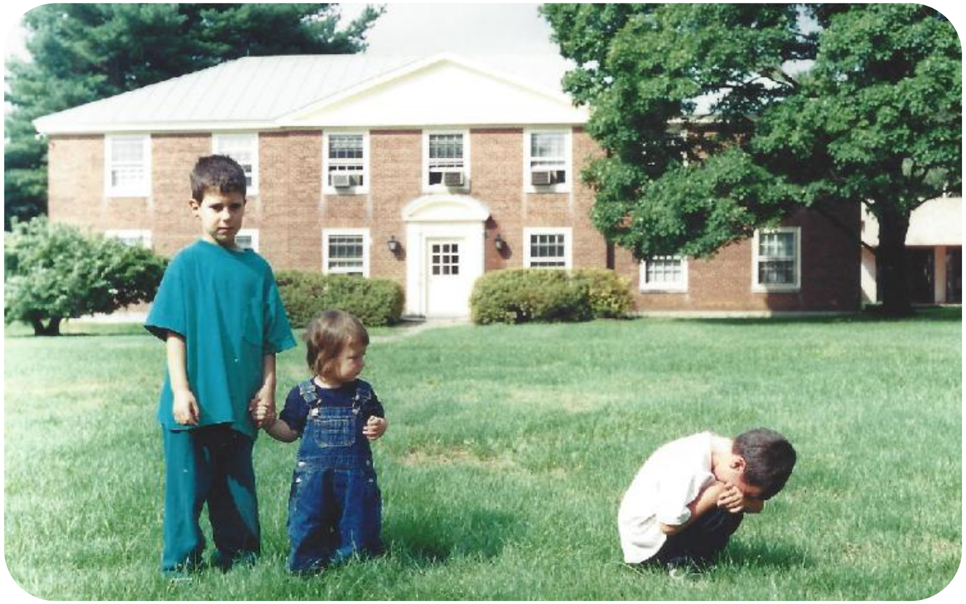
Squarks



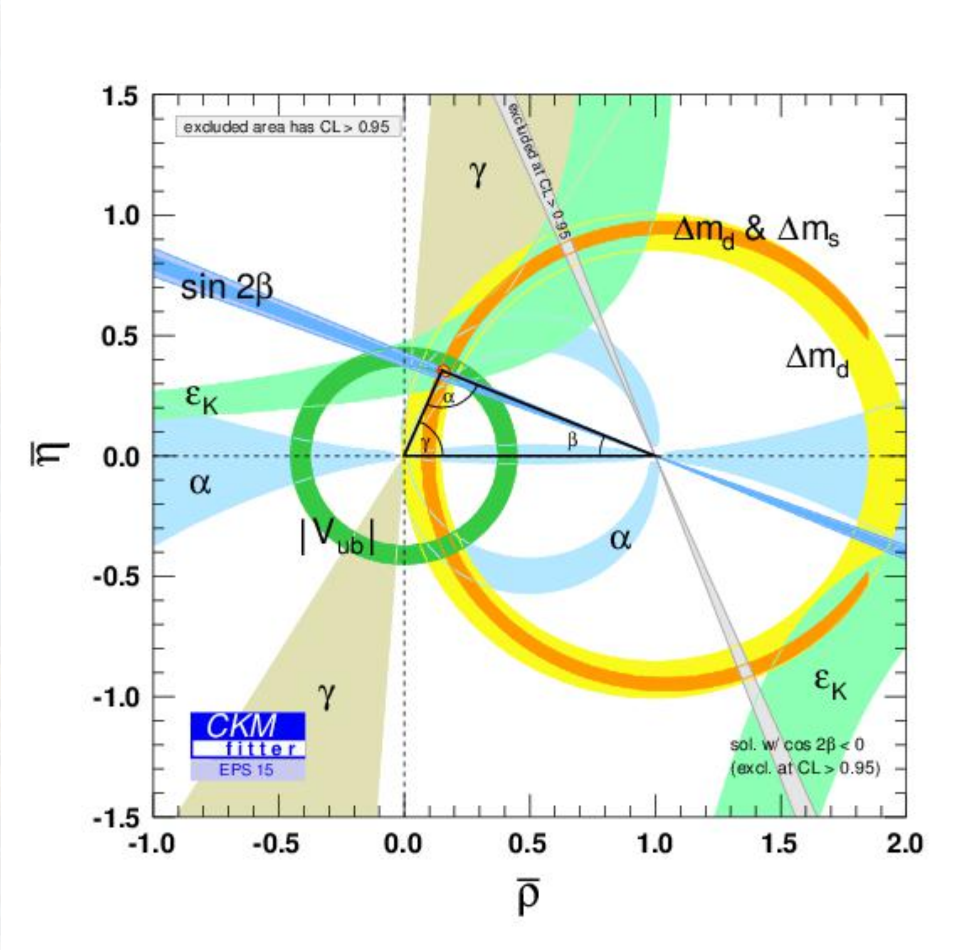
Neutrinos

Higgs

Quarks



Quark Data



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
$|V_{ub}|$
α
γ
ε_K
CKM fitter
EPS 15
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

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 $\varepsilon\uparrow n$
- Can be embedded in a full high energy theory with a scalar singlet and vector-like fermions

FN predictions

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

- $|V_{us}| \geq m_u / m_c \,, m_d / m_s$
- $|V_{cb}| \geq m_c / m_t \,, m_s / m_b$
- $|V_{ub}| \geq m_u / m_t \,, m_d / m_b$

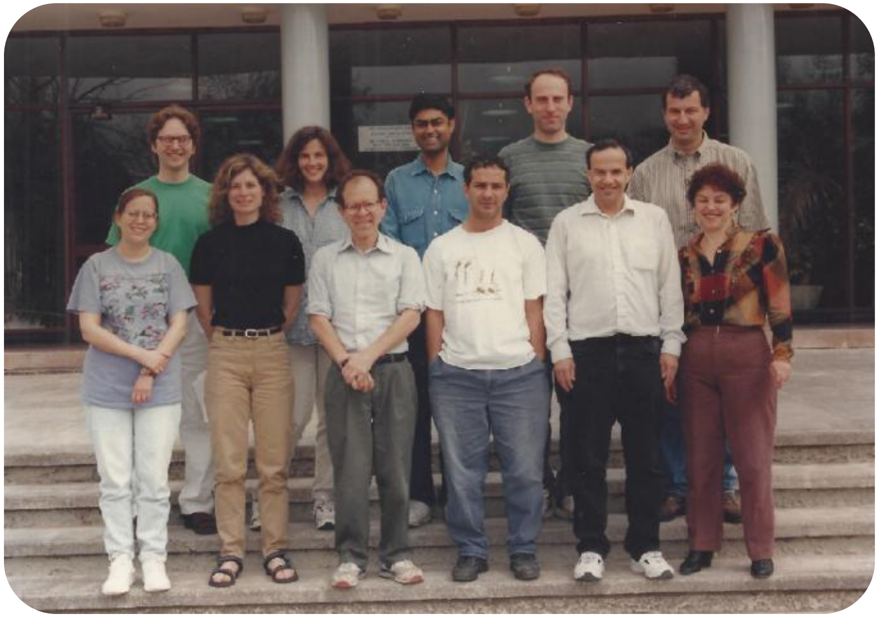
- $\boldsymbol{V}_{CKM} \sim \mathbf{1}$ (when mass-ordered)

Can we make progress?

- NP that couples to quarks/leptons

  $\Longrightarrow$ 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
- $h \Longrightarrow$ The "NP" is already here!
  - Y_{ij} are new flavor parameters that can be measured

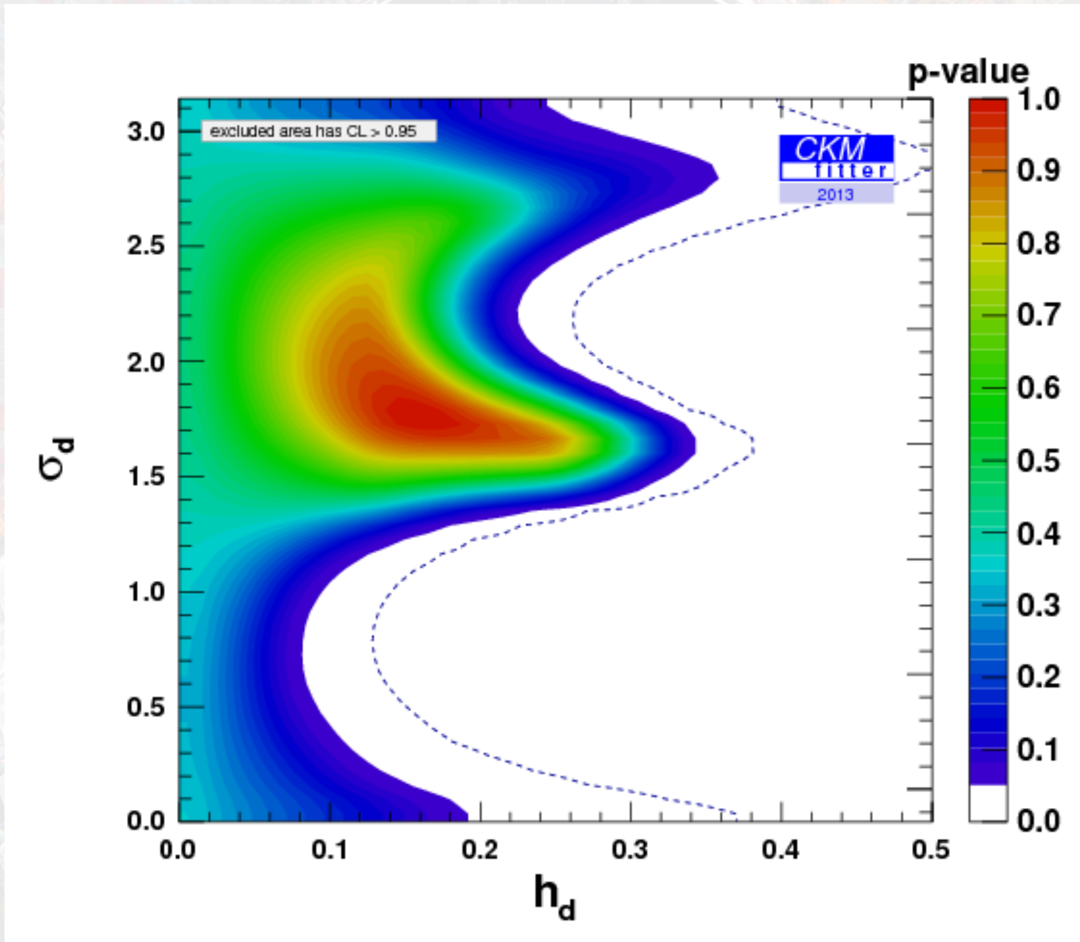
Squarks



Squark Data

Observable	Experiment

The quark data, again



$$\Rightarrow (\Delta m_{13}^2/m^2)_{K_{13}} < 0.07$$

Naïve FN predictions

- Squark masses are only RGE-degenerate

- $|V_{ij}^{LL}| \sim |(V_{CKM})_{ij}|$
- $|V_{ij}^{RR}| \sim (m_i/m_j)/|(V_{CKM})_{ij}|$

- **Quark-Squark alignment**

  Alternative to squark degeneracy

Holomorphic Zeros

- Take the breaking parameter ε to be a spurion
- In superpotential – You can employ ε^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 → D-mixing close to the bound

QFT and Phenomenology

Naturalness versus supersymmetric non-renormalization theorems

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Received 1 October 1993
Editor: M. Dine

We give an intuitive proof of a new non-renormali
tively and non-perturbatively. The superpotential is n
rections. However, these non-perturbative correctior
Certain invariant terms are not generated. This violati

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 spurions and the fact that the superpotential had to be holomorphic in them.

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

Seiberg: Spurions had appeared earlier, especially in the context of supersymmetry 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.

New tools for low energy dynamical supersymmetry breaking

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(Received 7 August 1995)

We report the construction of large new classes of models which break supersymmetry dynamically. We then turn to model building. Two of the principal obstacles to constructing simple models of dynamical supersymmetry breaking are the appearance of Fayet-Iliopoulos D terms and difficulties in generating a μ term for the Higgs fields. Among the new models are examples in which symmetries prevent the appearance of Fayet-Iliopoulos terms. A gauge singlet field, which may play a role in explaining the hierarchy in quark and lepton parameters, can generate a suitable μ term. The result is a comparatively simple model, with a low energy structure similar to that of the MSSM, but with far fewer arbitrary parameters. We begin the study of the phenomenology of these models.

vided by supersymmetry. Any supersymmetric model generates the operator (6) via box diagrams with intermediate gluinos and squark doublets. The various factors that enter z_1^K and z_1^D can be identified as follows:

$$\Lambda_{\rm NP} = \tilde{m}_Q \equiv (m_{\tilde{Q}_1} + m_{\tilde{Q}_2})/2, \qquad \lambda_{12}^2 = \frac{\alpha_s^2}{54} g(m_{\tilde{g}}^2/\tilde{m}_Q^2),$$
$$\delta_{12} = (m_{\tilde{Q}_2} - m_{\tilde{Q}_1})/(m_{\tilde{Q}_1} + m_{\tilde{Q}_2}), \tag{30}$$

where $m_{\tilde{Q}_i}$ is the squark-doublet mass, $m_{\tilde{g}}$ is the gluino mass, and $g(m_{\tilde{g}}^2/\tilde{m}_Q^2)$ is a known function (see, e.g., [6]) with, for example $g(1) = 1$. Taking $\tilde{m}_Q \leq 1$ TeV, and $m_{\tilde{g}} \approx \tilde{m}_Q$ (which gives $\lambda_{12} \approx 0.014$), leads to

$$\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \lesssim \begin{cases} 0.034 & \text{maximal phases} \\ 0.27 & \text{vanishing phases} \end{cases}. \tag{31}$$

Neutrinos

ν Data

Observable	Experiment
Δm^2_{21}	$(7.5 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2$
$\lvert\Delta m^2_{32}\rvert$	$(2.5 \pm 0.1) \times 10^{-3}\ \mathrm{eV}^2$
$\lvert U_{e2}\rvert$	0.55 ± 0.01
$\lvert U_{\mu 3}\rvert$	0.67 ± 0.03
$\lvert U_{e3}\rvert$	0.148 ± 0.003

Surprise, Surprise…

- $|U_{\mu 3}| > any\,|V_{ij}|$
- $|U_{e2}| > any\,|V_{ij}|$

- $|U_{e3}| = O(|U_{e2}\,U_{\mu 3}|)$

- $m_2/m_3 > 1/6 > any\ m_i/m_j$ for charged fermions

- Neither smallness nor hierarchy
  $\Longrightarrow$ The neutrino flavor puzzle

TBM ↔ Anarchy

- Experimentalists:

$$U_{3\sigma} = \begin{pmatrix} 0.80-0.85 & 0.51-0.58 & 0.14-0.16 \\ 0.22-0.52 & 0.44-0.70 & 0.61-0.79 \\ 0.25-0.53 & 0.57-0.71 & 0.59-0.78 \end{pmatrix}$$

$$U_{TBM} = \begin{pmatrix} 2/\sqrt{6} & 1/\sqrt{3} & 0 \\ 1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

- Tribimaximal-ists:

- Anarch-ists:

$$U_{anarchy} = \begin{pmatrix} O(0.6) & O(0.6) & O(0.6) \\ O(0.6) & O(0.6) & O(0.6) \\ O(0.6) & O(0.6) & O(0.6) \end{pmatrix}$$

FN and neutrinos

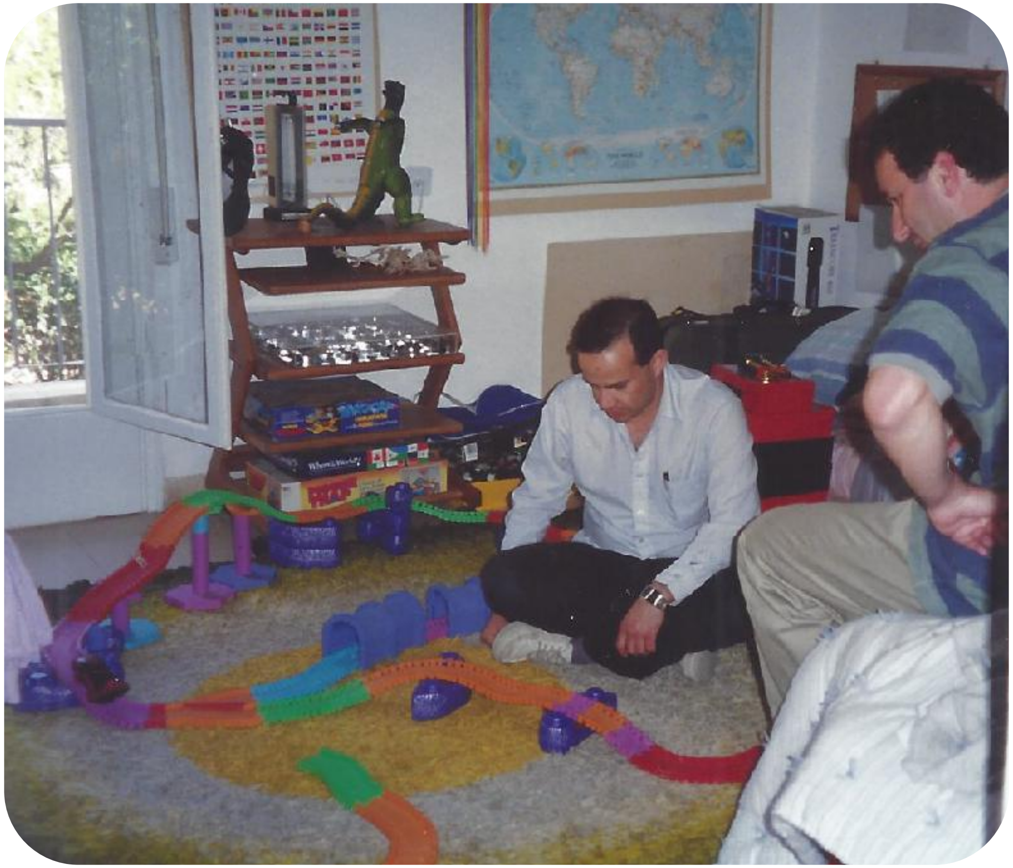
- Simplest + SU(5)-consistent assignment:
- Q,U,E = **10**: (2,1,0)
- D,L = $\bar{\mathbf{5}}$: (0,0,0)

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

- $m_e/m_\mu \sim m_\mu/m_\tau \sim \varepsilon$
- $m_1/m_2 \sim m_2/m_3 \sim 1$
- $|U_{e2}| \sim |U_{\mu3}| \sim |U_{e3}| \sim 1$

- Charged fermion hierarchy + Neutrino anarchy

The Higgs Boson



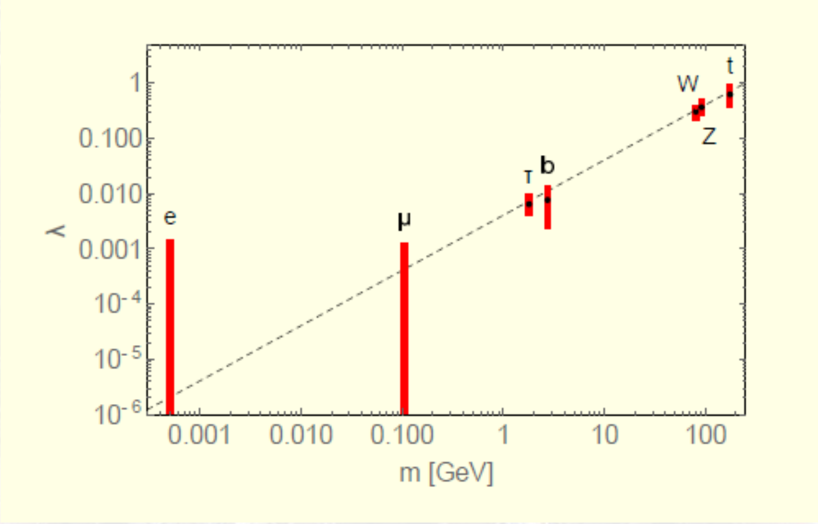
Higgs Data

Observable	Experiment
$R_{\gamma\gamma}$	1.14 ± 0.18
R_{ZZ^*}	1.17 ± 0.23
R_{WW^*}	0.99 ± 0.15
$R_{b\bar{b}}$	0.7 ± 0.3
$R_{\tau\tau}$	1.09 ± 0.23
$R_{\mu\mu}$	< 7
R_{ee}	$< 4 \times 10^5$

SM: $Y_F = (\sqrt{2}/v) M_F$

- Proportionality
  - $y_i \equiv Y_{ii} \propto m_i$
- Factor of proportionality
  - $y_i / m_i = \sqrt{2}/v$
- Diagonality
  - $Y_{ij} = 0$ for $i \neq j$

Proportionality?



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

- The beginning of Higgs flavor physics

Diagonality?

Observable	Experiment	$\sqrt{Y_{ij}^2 + Y_{ji}^2}$
$BR(t \to ch)$	≤ 0.0046	≤ 0.13
$BR(h \to \tau\mu)$	≤ 0.015	≤ 0.004

However,

- $BR(h \to \tau\mu) = \begin{cases} (8.4 \pm 3.7) \times 10^{-3} & \text{CMS} \\ (5.3 \pm 5.1) \times 10^{-3} & \text{ATLAS} \end{cases}$
- What if $BR(h \to \tau\mu) \not\ll BR(h \to \tau\tau)$?

Exciting x 3

- $U(1)_{\mu} \times U(1)_{\tau}$ broken
  - $\Lambda_{LFV} \ll \Lambda_{LNV}$?
- $BR(h \to \tau\mu) \sim BR(h \to \tau\tau)$
  - FCNC at tree level?
- $Y_E \;\; not \propto M_E$
  - Not the SM Higgs?

$\Lambda_{LFV} \ll \Lambda_{LNV}?(d=5)$

- d=5: $\frac{Y_{ij}^N}{\Lambda_{LNV}} L_i L_j \phi\phi$
- Explain neutrino mass and mixing
- Break $U(1)_e \times U(1)_\mu \times U(1)_\tau$ (LFV)
- Break total lepton number (LNV)
- $h \to \tau\mu$ allowed, but…
  - Loop suppression $\sim \alpha_2^2$
  - Mixing suppression $\sim |U_{\mu 3} U_{\tau 3}|^2$
  - GIM suppression $\sim (\Delta m_{23}^2 / m_W^2)^2$
- $BR(h \to \tau\mu) \sim 10^{-50}$

$\Lambda_{LFV} \ll \Lambda_{LNV}$? $(d=6)$

- d=6: $\frac{Z_{ij}^{e}}{\Lambda_{LFV}^{2}} (\phi^{\dagger} \phi)\phi L_{i} E_{j}$

- $Y_{E}^{h} = \left(\frac{\sqrt{2} M_{E}}{v}\right) + \left(\frac{v^{2}}{2\Lambda^{2}}\right) Z^{e}$

- For $\Lambda_{LFV}/\sqrt{Z_{\mu\tau}^{e}} \sim$ few TeV:
  - $BR(h \to \tau\mu) \sim 0.01$

FCNC at tree level?

- All models with no bare mass terms and with NFC: $h\to\tau\mu$ loop-suppressed
- With loop suppression:
  - $(v^2/\Lambda^2)(\alpha_W/4\pi)X_{\mu\tau}\sim y_\tau\sim 10^{-2}$ Very challenging model building
- MSSM – excluded
- Models with tree-level $Y_{\tau\mu}^h\neq 0$ favored
  - Vector-like leptons
  - Multi-Higgs doublets

h not the SM Higgs?

- Vector-like leptons:
  - Strongly disfavored by the $\tau\to\mu\mu\mu$ bound
- Two Higgs doublet models:
  - $Y_E^h = s_{\alpha-\beta}\left(\sqrt{2}M_E/v\right) + c_{\alpha-\beta}Y_E^A$
  - Y_E^A arbitrary
- 2HDM = the favored option

FN and Higgs

- $BR(\mu \to e\gamma) < 5\times 10^{-13}$

  $\Longrightarrow Y_{e\mu}^{h} \leq 1.2\times 10^{-6}$

- FN: $Y_{e\mu}^{h} / y_{\mu\tau}^{h} \sim y_{\mu} |U_{e2}| / y_{\tau} |U_{\mu 3}| \sim 0.05$

  $\Longrightarrow Y_{\mu\tau}^{h} \leq 3\times 10^{-5}$

- If $BR(h \to \tau\mu) \sim 0.01$

  $\Longrightarrow Y_{\mu\tau}^{h} \sim 3\times 10^{-3}$

- 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

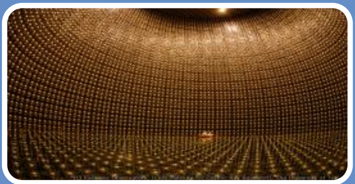
Flavored Conclusions

Quarks: smallness, hierarchy

$\Longrightarrow$ Approximate symmetry?

Squarks: degeneracy, alignment

$\Longrightarrow$ Flavor paradise, but where are they?



Neutrinos: anarchy $\Longrightarrow$ Knowing more does not necessarily mean understanding better

Higgs: diagonality? proportionality?

$\Longrightarrow$ 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


Seiberg 1982 Weizmann


Harari 1965 Hebrew


Lipkin 1950 Princetonn


Neeman 1962 Imperial


Salam 1952 Cambridge


Kemmer 1935 Zürich

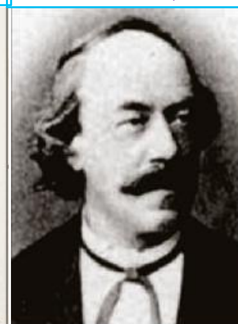

Pauli 1921 LMU München


Wentzel 1921 LMU


Sommerfeld 1891 Königsberg


Lindemann 1873 Nürnberg

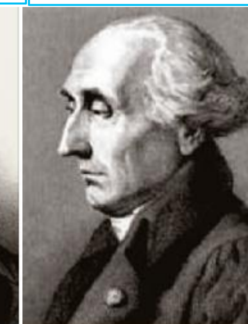

Klein 1868 Bonn


Lipschitz 1853 Berlin


Dirichlet 1827 Bonn


Fourier 1800 EP Paris


Poisson 1800 ENS Paris


Lagrange 1756


Euler 1726 Basel


Bernoulli 1690 Basel


Bernoulli 1684 Basel


Malebranche 1672 Paris


Leibniz 1666 Leipzig


Weigel 1650 Leipzig


Müller 1604 Leipzig


Meurer 1582 Leipzig


Steinmetz 1550 Leipzig


Rheticus 1535 Halle


Copernicus 1499 Bologna

Novara 1483 Firenze


Regiomontanus 1457 Leipzig


Peuerbach 1440 Wien


Gmunden 1406 Wien


Langenstein 1363 Paris