The Interplay between Flavor and LHC High pT Physics

Yael Shadmi

Technion

The Flavor of the Past

FLAVOR → HIGH pT LHC

searches for
NEW PHYSICS
=
origin of EWSB

NEW PARTICLES
around TeV

The Flavor of the Past

FLAVOR

dedicated flavor expt's constraining

NEW PHYSICS

→

HIGH pT LHC

searches for

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The Flavor of the Past

FLAVOR

dedicated low-E flavor expt's
constra
NEW P

→

HIGH pT LHC

ches for
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NEW PARTICLES
around TeV

NEW PHYSICS
is
FLAVOR BLIND
(at least approximately)
(or MFV: Minimally Flavor Violating)

The Flavor of the Past

NEW PHYSICS
is
FLAVOR BLIND
(at least approximately)

crucial assumption for LHC searches

example here: supersymmetry

but is this assumption justified?

after all:

quarks are not degenerate
leptons are not degenerate

far from it: **masses span orders of magnitude**
mixings of different sizes

= **THE STANDARD MODEL FLAVOR PUZZLE**

after all:

quarks are not degenerate
leptons are not degenerate

WHY SHOULD SQUARKS, SLEPTONS be ?

paraphrasing Nir-Seiberg "Should squarks be degenerate?"

and an innocent astrophysicist in Aspen this summer

WHY SHOULD SQUARKS, SLEPTONS be ?

same for SM partners in other extensions of SM

where spacetime symmetry enlarged

e.g. extra dim's (flat, warped, UED..)

global symmetry = G_{FLAVOR} x 4d Lorentz

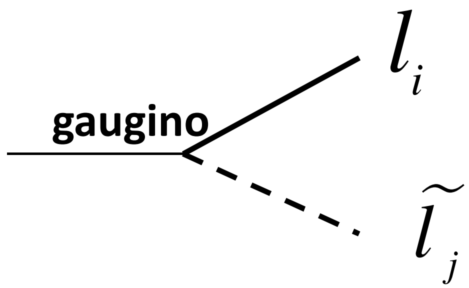
→ SUSY, 5d..

untouched:
3 copies of new particles
accompanying SM 3 generations

Flavor in SUSY: relevant parameters:

eg sleptons: $\tilde{l}_1, \, .. \, , \tilde{l}_6$

- 6 masses: $m_1, .., m_6$
- mixings:



$$\propto \; K_{ij} \quad i \neq j$$

[similarly for squarks]

The Flavor of the Past

FLAVOR → HIGH pT LHC

dedicated flavor expt's

essentially constrain

$$\delta_{ij} = \frac{\Delta m^2_{ij} \; K_{ij}}{m^2}$$

$$[\mathrm{Br} \sim \frac{1}{m^2} \; \frac{\Delta m^2_{ij}}{m^2} \; K_{ij}]$$

Suppressing SUSY Flavor Violation

(a model builder guide)

3 obvious approaches:
(or combination)

$$\delta_{ij} = \frac{\Delta m_{ij}^2 \; K_{ij}}{m^2}$$

1. decrease mass splitting:
→ **degeneracy**
sfermion mass matrix proportional to identity

FLAVOR BLIND
at low E: MFV

Suppressing SUSY Flavor Violation

(a model -builder guide)

3 obvious approaches:
(or combination)

$$\delta_{ij} = \frac{\Delta m^2_{ij} \; K_{ij}}{m^2}$$

2. decrease mixings:
→ **alignment**
sfermion mass matrix "aligned"
with lepton mass matrix:
approximately diagonal **Nir Seiberg**

Suppressing SUSY Flavor Violation

3 obvious approaches:
(or combination)

(a model-builder guide)

$$\delta_{ij} = \frac{\Delta m^2_{ij} \; K_{ij}}{m^2}$$

3. increase masses:
taken care of by high-pT LHC experimentalists

m goes up ← HIGH pT LHC

- by direct searches
- by Higgs mass

more room for

flavor dependence:

Δm^2_{ij} K_{ij} can be larger

m goes up ← HIGH pT LHC

- by direct searches
- by Higgs mass

in MSSM: need large loop corrections to Higgs mass

- large LR stop mixings
- large stop masses

→ generically: whole spectrum pushed up

eg pure GMSB: superpartners around 8 TeV (!)

m goes up ← HIGH pT LHC

entire spectrum??

just 1st, 2nd generation: ``Natural SUSY"??

STILL DON'T KNOW

should SUSY be flavor blind?

not just a question for theorists:

important for SUSY (or other “New Physics”) searches

should SUSY be flavor blind? **NO**

lots of recent progress:

- flavor-dependent sfermions consistent
  with high-pT LHC, low-E results
- THEORY: concrete and viable models with flavor-dependent
  sfermions
  new approaches to
  - suppressing low-E FV
  - generating large mass splittings

- implications for SUSY (or other "New Physics") searches and needless to say:

theory prejudices (eg wrt flavor) should
be seriously reconsidered given
the dismal failure of theoretical predictions so far:

no TeV-scale flavor-blind SUSY
(the cMSSM ansatz; GMSB, AMSB..)

The Flavor of the Future ??

FLAVOR → HIGH pT LHC

dedicated low E flavor expt's
co
NE

for
SICS
WSB
NEW PARTICLES
around TeV

``NEW PHYSICS" (eg SUSY)
may be
FLAVOR dependent

searches for NP should take that into account

The Flavor of the Future ??

FLAVOR

the underlying theory of flavor

←

HIGH pT LHC

TeV-scale flavor-dependent spectra

The Flavor of the Future ??

FLAVOR	←	HIGH pT LHC
the underlying theory of flavor		TeV-scale flavor-dependent spectra

- flavor – the structure of fermion masses **is** a puzzle
- the explanation (in terms of a flavor theory) may involve high scales, beyond the reach of direct or indirect experiments

The Flavor of the Future ??

FLAVOR

the underlying theory of flavor

←

HIGH pT LHC

TeV-scale flavor-dependent spectra

=

The TeV FLAVOR PORTAL

rest of talk:

1. implications for SUSY searches
2. SUSY models with flavor dependent spectra

production:

jet + missing energy searches:

8 degenerate squarks (1^{st}, 2^{nd} generation)

*[but dominated by **up** + down squarks]:*

Mahbubani Papucci Perez Ruderman Weiler 1212.3328

talk by Zupan

if not: up (or down) squarks can be somewhat heavier than rest and bounds evaded

detection:

- *neutralino LSP*

- *charged slepton NLSP (Long Lived)*
  gauge mediation, …

detection: neutralino LSP

– *missing energy based searches: efficiency goes up with squark mass*

Mahbubani Papucci Perez Ruderman Weiler 1212.3328:

** single charm squark at 400 GeV **

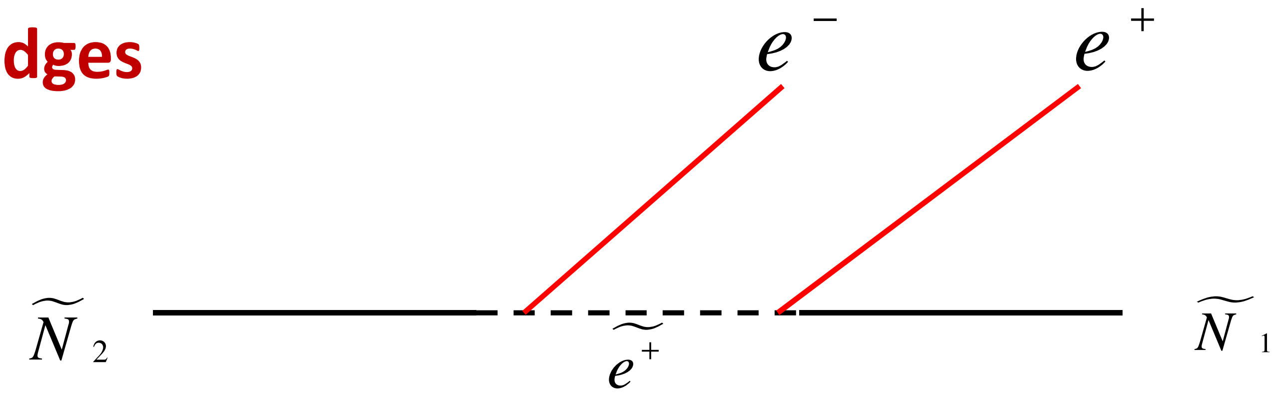
– *event shapes: distorted too: different scales*

– *lepton-based searches:*

assume degenerate smuon-selectron:

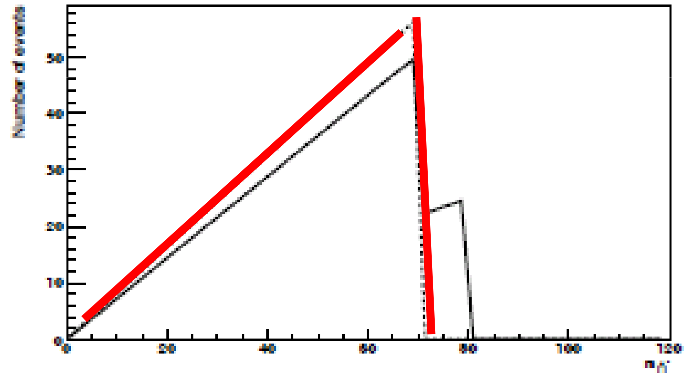
❖ *eg kinematic edges: split and ``mixed”* Galon YS

kinematic edges



endpoint of dilpeton invariant mass:

$$m_{ll}^2|_{endpoint} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}}^2}.$$



m_{ll}

→ triangle shape

peak in invariant mass distribution

- extract superpartner masses
- discovery: enhance signal over bgnd
- ee, mu-mu identical [flavor subtraction: ee +mumu-2emu]

but what if not MFV:

smuon, selectron can have different masses

Allanach Conlon Lester
Buras Calibbi Paradisi

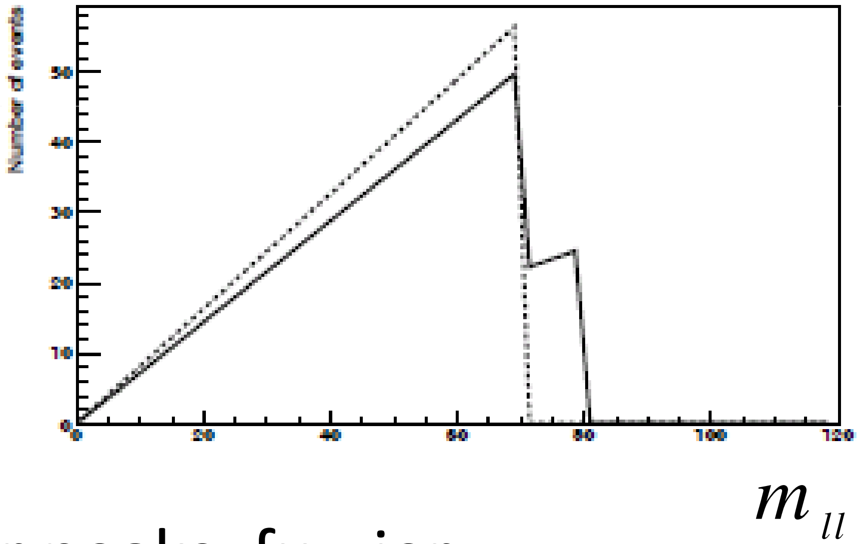
mixing Galon YS

also: Grossman Martone Robinson: widths

$$\tilde{l}_1 = \cos\theta\,\tilde{e} - \sin\theta\,\tilde{\mu}$$
$$\tilde{l}_2 = \sin\theta\,\tilde{e} + \cos\theta\,\tilde{\mu}$$

$$m_{\tilde{l}_1} = m_{\tilde{l}}\,, \qquad m_{\tilde{l}_2} = m_{\tilde{l}} + \Delta m$$

$$e^+e^-, \mu^+\mu^-, e^+\mu^-, \mu^+e^-$$



each distribution: 2 lower peaks, fuzzier
flavor subtraction dilutes signal

detection: Long Lived Slepton NLSP

flavor heaven
(high pT)

- (SM) background free
- no missing energy:
  → events fully reconstructible
  → FV: each event ends with 2 charged sleptons : mass measured (eg TOF) neutralino decays = flavor analyzer

Feng, French, Lester, Nir, YS
Feng, Galon, Sanford, YS, Yu
Feng, French, Galon, Lester, Nir, Sanford, YS, Yu

detection: Long Lived Slepton NLSP

flavor heaven
(high pT)

smaller lifetime: lhcb:
Strassler's talk

- (SM) background free
- no missing energy:
  → events fully reconstructible
  → FV: each event ends with 2 charged sleptons : mass measured (eg TOF) neutralino decays = flavor analyzer

Feng, French, Lester, Nir, YS
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Theory

can we have non-degenerate sfermions ?

(and flavor-violating processes under control)?

$$\delta_{ij} = \frac{\Delta m^2_{ij} \; K_{ij}}{m^2}$$

2. decrease mixings:

→ **alignment**

sfermion mass matrix "aligned"

with lepton mass matrix:

approximately diagonal **Nir Seiberg**

FLAVORED GAUGE MEDIATION

low-scale supersymmetric alignment

YS, Szabo 1103.0922 : general setup, sleptons

Abdullah, Galon, YS, Shirman 1209.4904: Higgs mass

Galon, Perez, YS 1306.6631: squarks

gauge mediated SUSY breaking (GMSB)

messengers = new heavy fields

with SUSY breaking at tree level

charged under SU(3)xSU(2)xU(1)

→ MSSM soft breaking masses from messenger loops

gauge mediated SUSY breaking (GMSB)

- beautiful: concrete model, MFV
- in trouble:
  - direct searches (+ EWK searches: EWK << colored)
  - Higgs mass: superpartners around 8 TeV

minimal GMSB : messengers :

same charges as Higgses

Dine Nelson Nir Shirman

$$T + D \qquad \bar{T} + \bar{D}$$

$$H_D \qquad H_U$$

in principle:

$$W = H_U qu + H_D qd + H_D le$$

$$+ \bar{D}qu + Dqd + Dle$$

messenger-matter couplings

$$+Y_U H_U qu + Y_D H_D qd + Y_L H_D le$$

$$+\, y_U \bar{D}_1 qu \;+\, y_D\, D_2 qd \;+\; y_L D_2 le$$

up squarks:
focus on these today

Abdullah Galon YS Shirman
Galon Perez YS

down squarks, sleptons

Shadmi Szabo

3x3 matrices: new contributions to soft terms
arbitrary structure: flavor disaster

- *A terms*
- *scalar masses-squared*

  negative in large parts of parameter space

- *usually **forbid** messenger-matter couplings by **imposing** some global symmetry*
- *[Chacko-Ponton (2001): MFV model from 5d setup (but easy to get in 4d too)]*
- *but: non-trivial Yukawas hint at some flavor theory*

same flavor theory would necessarily control the new couplings

simplest example:
MFV-**like** models

YS Szabo

Abdullah Galon YS Shirman

Calibbi Paradisi Ziegler (squark flavor)

$$W = Y_U H_U q u + \dots$$

$$+ \, y_U \bar{D} q u \; + \; \dots$$

if $H_U, \ \bar{D}$: *same properties under flavor theory*

$$\longrightarrow \boxed{(y_U)_{ij} \approx (Y_U)_{ij}}$$

mass splittings MFV-like:

1st, 2nd generation sfermions nearly degenerate

✓ *flavor constraints obeyed*

non-degenerate spectra:

$H_U, \ \bar{D}$: *different properties under flavor theory* *simple realization: flavor symmetries*

flavor symmetry controls

a. fermion masses

b. messenger-matter couplings

U(1)xU(1) flavor symmetry

broken by small parameter $\lambda \sim 0.2$

different masses given by powers of λ

example: light charm, strange squarks

$$Y_U \sim \begin{pmatrix} \lambda^6 & \lambda^4 & 0 \\ 0 & \lambda^3 & \lambda^2 \\ 0 & 0 & 1 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} \lambda^6 & 0 & 0 \\ 0 & \lambda^4 & \lambda^4 \\ 0 & \lambda^2 & \lambda^2 \end{pmatrix}$$

$$y_U \sim \begin{pmatrix} \lambda^4 & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

only affects
2nd generation

↓

lower charm
strange masses

$$\frac{\Delta m^2}{m^2_{GMSB}} = -1$$

- *M=500 TeV: up, down squarks near 2 TeV*
  gluino 1.5 TeV
  R charm 900 GeV
- *M=400 TeV: up, down squarks near 1.5 TeV*
  gluino 1.2 TeV
  R charm 670 GeV

huge mass differences: flavor constraints?

flavor constraints?

mixings are small: squark, quark matrices aligned

$$Y_U \sim \begin{pmatrix} \lambda^6 & \lambda^4 & 0 \\ 0 & \lambda^3 & \lambda^2 \\ 0 & 0 & 1 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} \lambda^6 & 0 & 0 \\ 0 & \lambda^4 & \lambda^4 \\ 0 & \lambda^2 & \lambda^2 \end{pmatrix}$$

$$y_U \sim \begin{pmatrix} \lambda^4 & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

to first approximation:

$$Y_U \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$y_U \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

flavor constraints?

mixings are small: squark, quark matrices aligned

$$Y_U \sim \begin{pmatrix} \lambda^6 & \lambda^4 & 0 \\ 0 & \lambda^3 & \lambda^2 \\ 0 & 0 & 1 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} \lambda^6 & 0 & 0 \\ 0 & \lambda^4 & \lambda^4 \\ 0 & \lambda^2 & \lambda^2 \end{pmatrix}$$

no down L
12 mixings

$$y_U \sim \begin{pmatrix} \lambda^4 & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

reason why needed 2 U(1)s:

with single U(1): just Cabibbo suppressed note on CP:

one dominant entry in new matrix y:

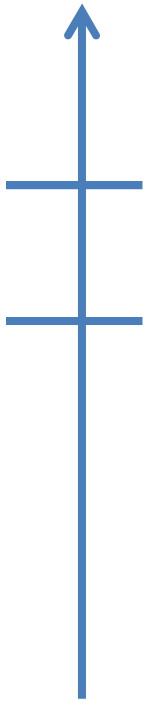
→ no new phase to leading order:

because $y_U^+ y_U$ or $y_U y_U^+$

(phases enter at higher order in λ)

original alignment models: high scale SUSY breaking:

SUSY breaking scale must be ABOVE flavor scale



SUSY scale: soft masses generated

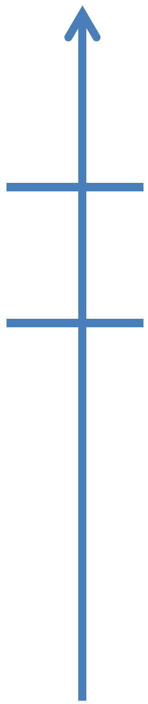
flavor symmetry broken

RGE: large universal contribution from gluino mass

→ $$\frac{\Delta m}{m} \leq 0.15$$

here: ``supersymmetric alignment":

flavor symmetry controls superpotential coupling y



flavor symmetry broken: y determined

SUSY scale=messenger scale:
soft masses generated

→ *messenger scale can be low*

→ *no large (universal) RGE gluino contribution:*

→ ***much larger mass differences possible***

(in high scale models only 10-20%)

and 125 GeV Higgs

Abdullah Galon YS Shirman

MFV: Evans Ibe Yanagida
Kang Li Liu Tong Yang

+ different couplings: Craig Knapen Shih Zhao
Albaid Babu
Craig Knapen Shih
Evans Shih

- *pure GMSB: no A terms*
- *large Higgs mass → large stop masses → large squark masses 8-10 GeV*

but see Feng Kant Profumo Sanford: 3 loop

Flavored Gauge Mediation: A-terms at messenger scale

large stop A-term

→ colored superpartners below 2 TeV

rich flavor structure:

- light charm, strange (here)
- heavy up

…

different patterns of mass splittings, mixings

+ viable and concrete models (not ansatze!)

flavor-dependent superpartners just waiting to be discovered..

The Flavor of the Future ??

FLAVOR

the underlying theory of flavor

←

LHC

TeV-scale flavor-dependent spectra

=

The TeV FLAVOR PORTAL