Flavored Supersymmetry: theory models and LHC searches

Yael Shadmi

Technion

supersymmetry and flavor:

what expt tells us

high E: LHC SUSY searches

low E: Searches for Flavor Violation

LHC SUSY searches:

informs searches
and/or interpretation

low E:

no flavor changing

→ superpartners flavor blind

LHC SUSY searches:

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generation dependent superpartner masses consistent with low E

LHC SUSY searches:

affects searches
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consistent with low E

LHC SUSY searches:

NO SUSY

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LHC SUSY searches:

NO SUSY

+ 125 GeV Higgs

? no susy

? superpartner masses different

low E:

no flavor changing

generation dependent superpartner masses consistent with low E

LHC SUSY searches:

NO SUSY

+ 125 GeV Higgs

? no susy

? superpartner masses different

affects the derivation of low-E bounds

low E:

no flavor changing

generation dependent superpartner masses consistent with low E

so:

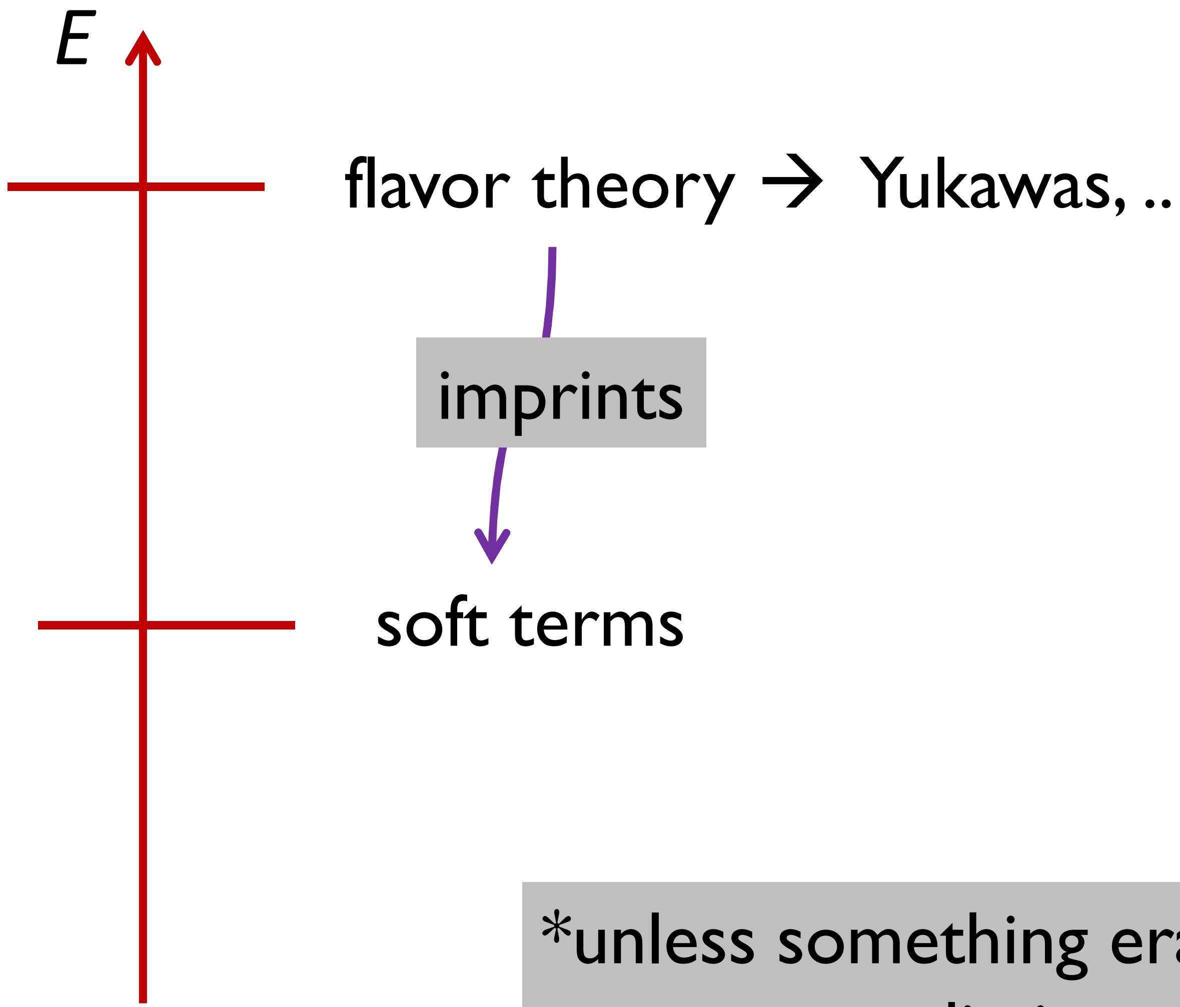
- allow for the possibility of generation-dependent superpartner masses
- consider implications for LHC searches
- derive constraints (from low-E expts) w/out theory prejudices: Simplified Models

supersymmetry and flavor:
what theory tells us:

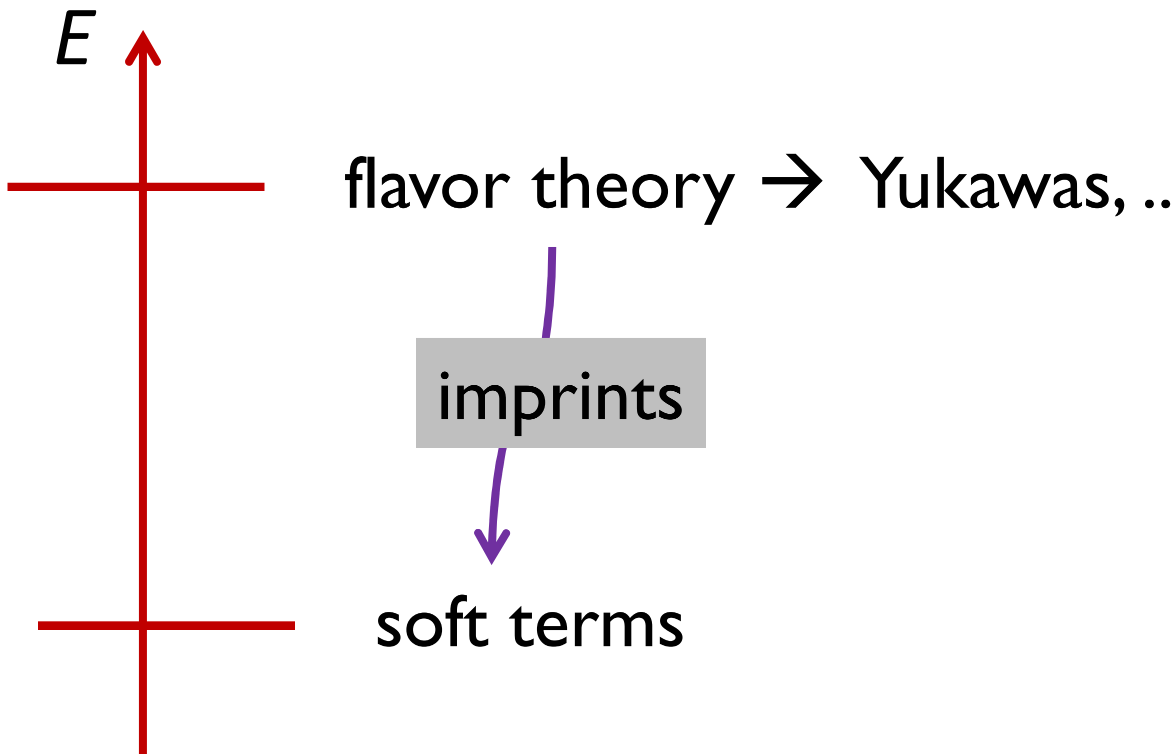
we don’t understand fermion masses

fermion masses are strange: hierarchical masses
small quark mixings

some theory of flavor ??



*unless something erases it, eg, gauge mediation



models: sfermion flavor tied to fermion parametrs

here: **Flavored Gauge Mediation**

outline

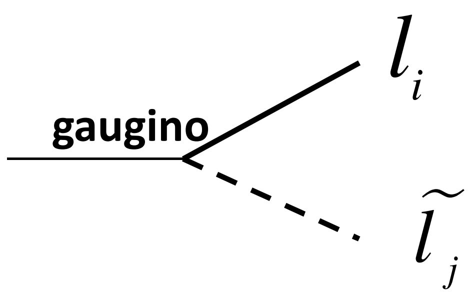
- bottom up:
  - low-E constraints
  - Simplified Models for Flavor

- top down: Flavored Gauge Mediation
  - flavor
  - Higgs mass
  - example spectra

Flavor in SUSY: relevant parameters:

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

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

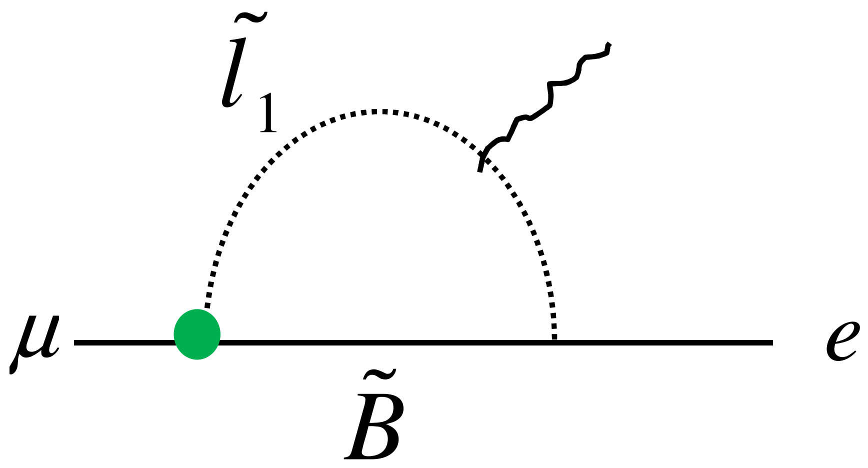


$$\propto \ K_{ij} \quad i \neq j$$

[similarly for squarks]

low-E flavor expt's essentially constrain

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



+ ...

Suppressing SUSY Flavor Violation

3 obvious approaches:
(or combination)

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

1. mass splitting
→ zero:
→ **degeneracy**

FLAVOR BLIND

or at low E:
Minimally Flavor Violating

Suppressing SUSY Flavor Violation

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

2. mixings → 0
→**alignment**

sfermion mass matrix "aligned"
with lepton mass matrix:
approximately diagonal

Suppressing SUSY Flavor Violation

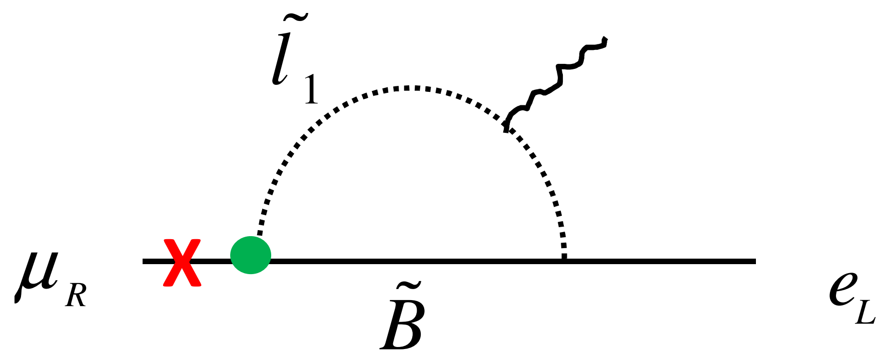
$$\delta_{ij} = \frac{\Delta m_{ij}^2 \; K_{ij}}{m^2}$$

3. mass → infinity
taken care of by ATLAS & CMS experimentalists

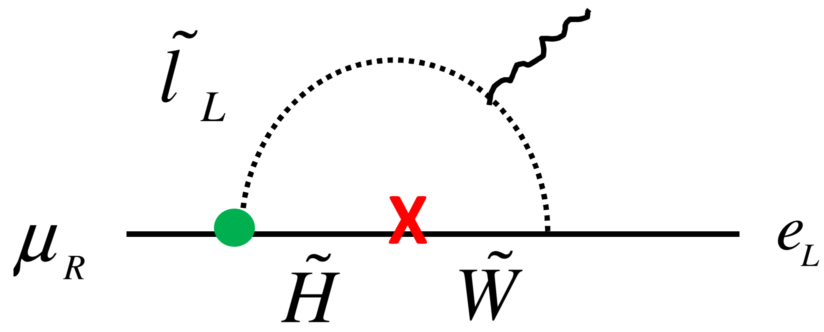
the special role of Higgsinos & LR mixing

dipole amplitudes:

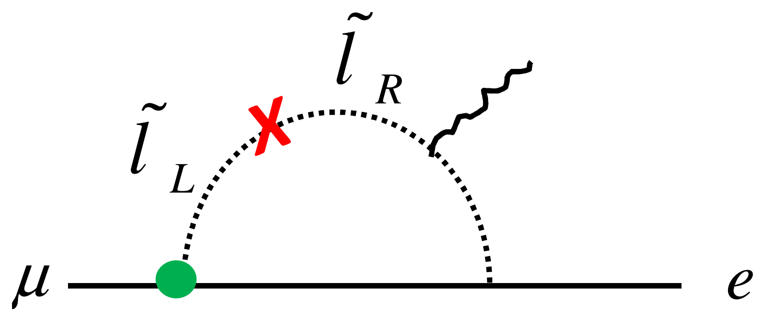
CHIRALITY FLIP



with Higgsinos:



with LR mixing:



enhancement of mu to e gamma

LHC: (direct + 125 GeV Higgs mass):

- simplest models (or ansatze) with light flavor-blind spectra largely excluded

- 125 Higgs:

often need large mu-term:

? heavy Higgsinos (important contribution or decoupling)

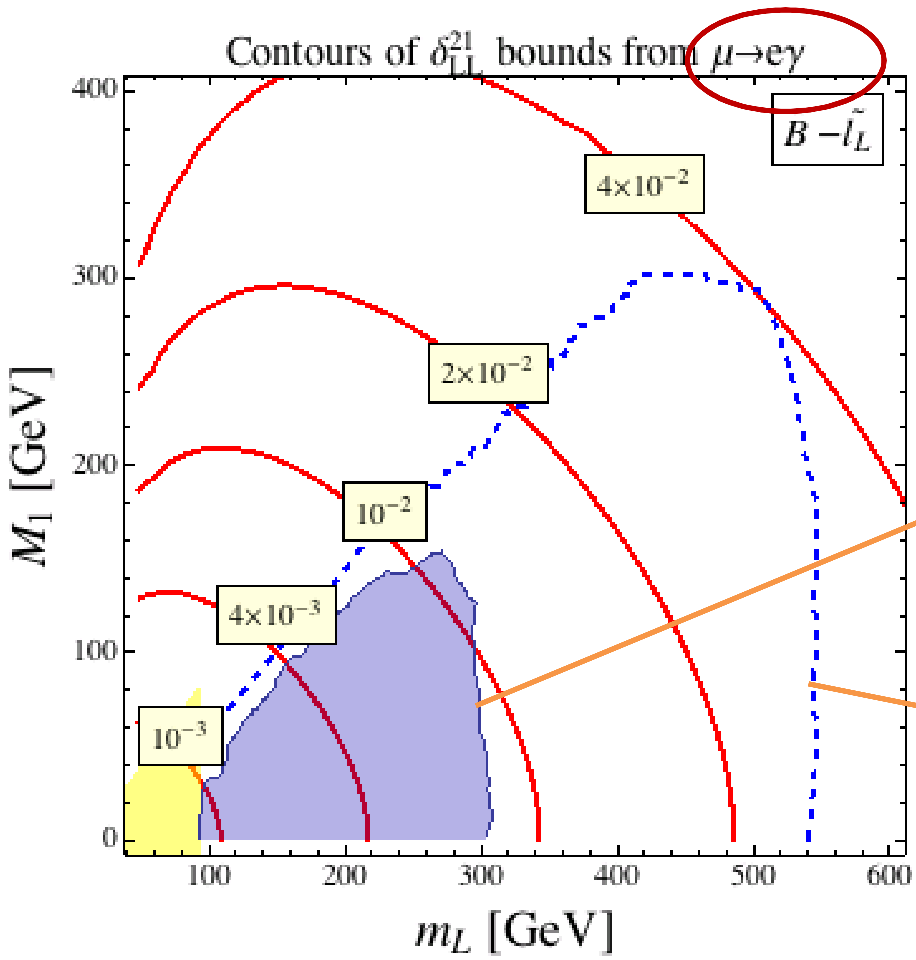
? large LR stop mixing: possibly also large LR slepton mixing to minimize theory assumptions:

a bottom-up approach: **simplified models**

\+ can directly compare to LHC searches

Calibbi Galon Masiero Paradisi YS 1502…

example: L-sleptons (selectron-smuon) + bino

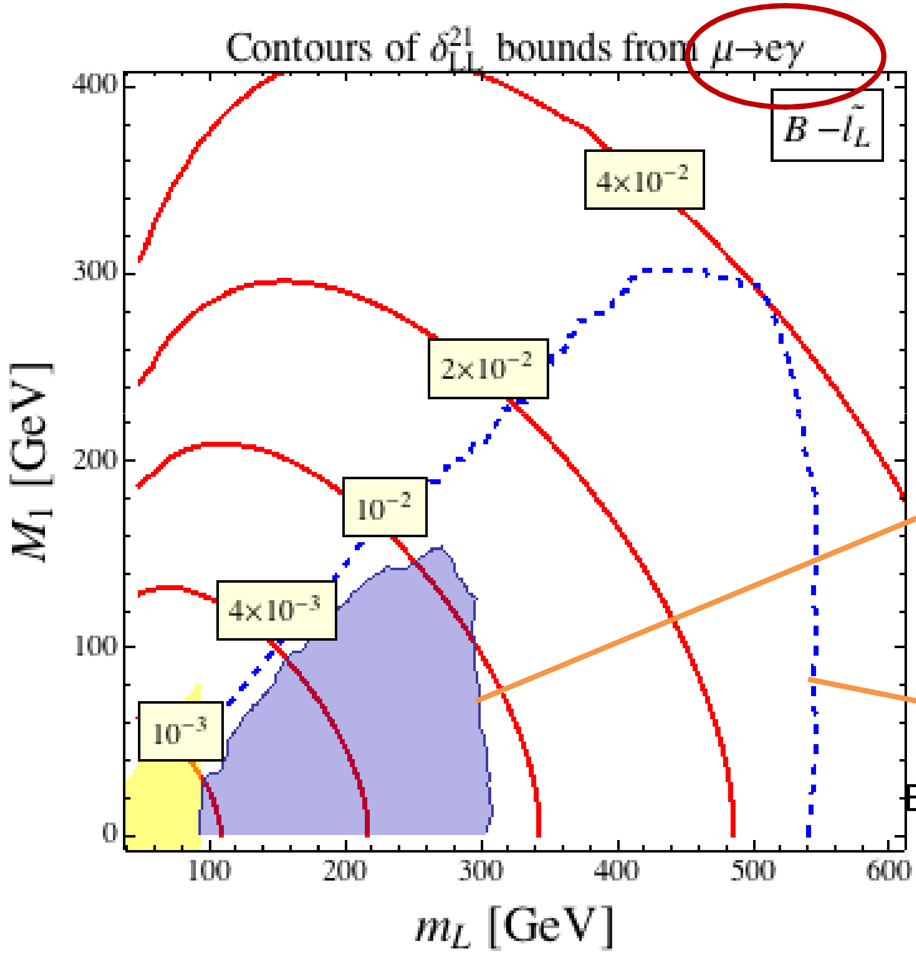


ATLAS search (Drell-Yan)
assume flavor blind selectron, smuon

projected 14 TeV

Eckel Ramsey-Musolf Shepherd Su 1408.2841

example: L-sleptons (selectron-smuon) + bino



fairly large flavor dependence allowed in 7-8 TeV

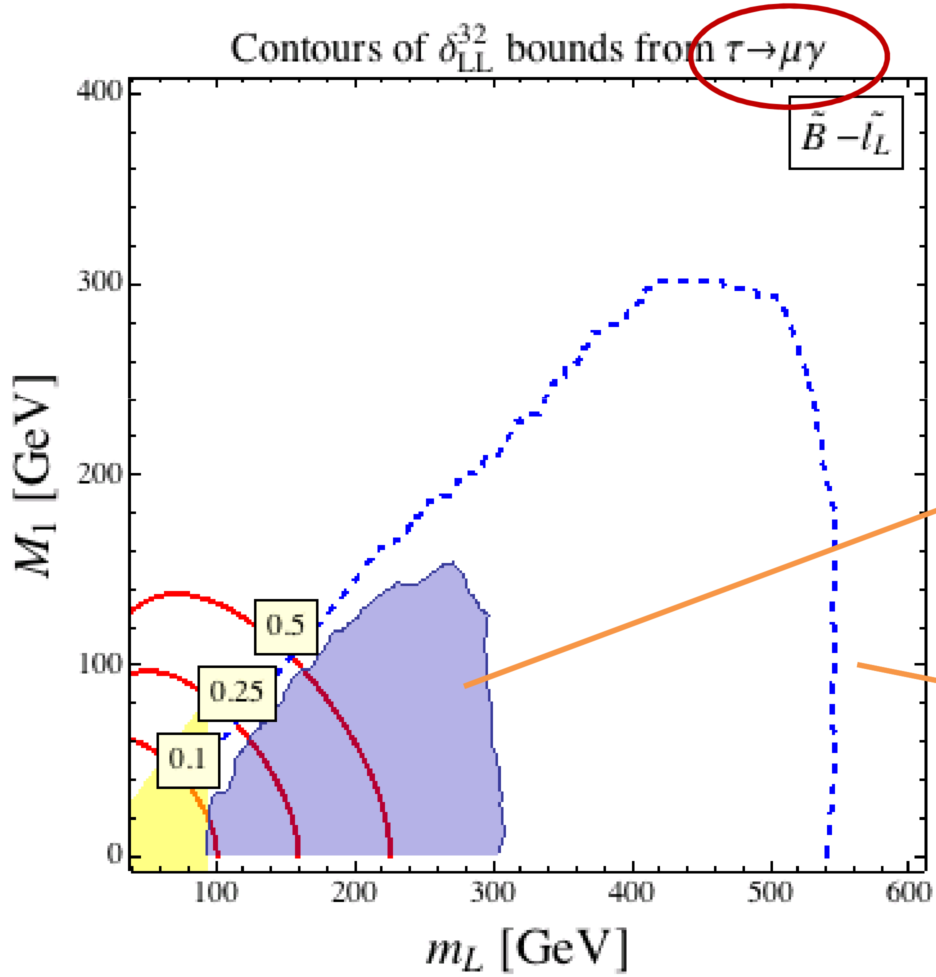
larger in run II

ATLAS search (Drell-Yan)
assume flavor blind selectron, smuon

projected 14 TeV

Eckel Ramsey-Musolf Shepherd Su 1408.2841

example: L-sleptons (smuon-stau) + bino

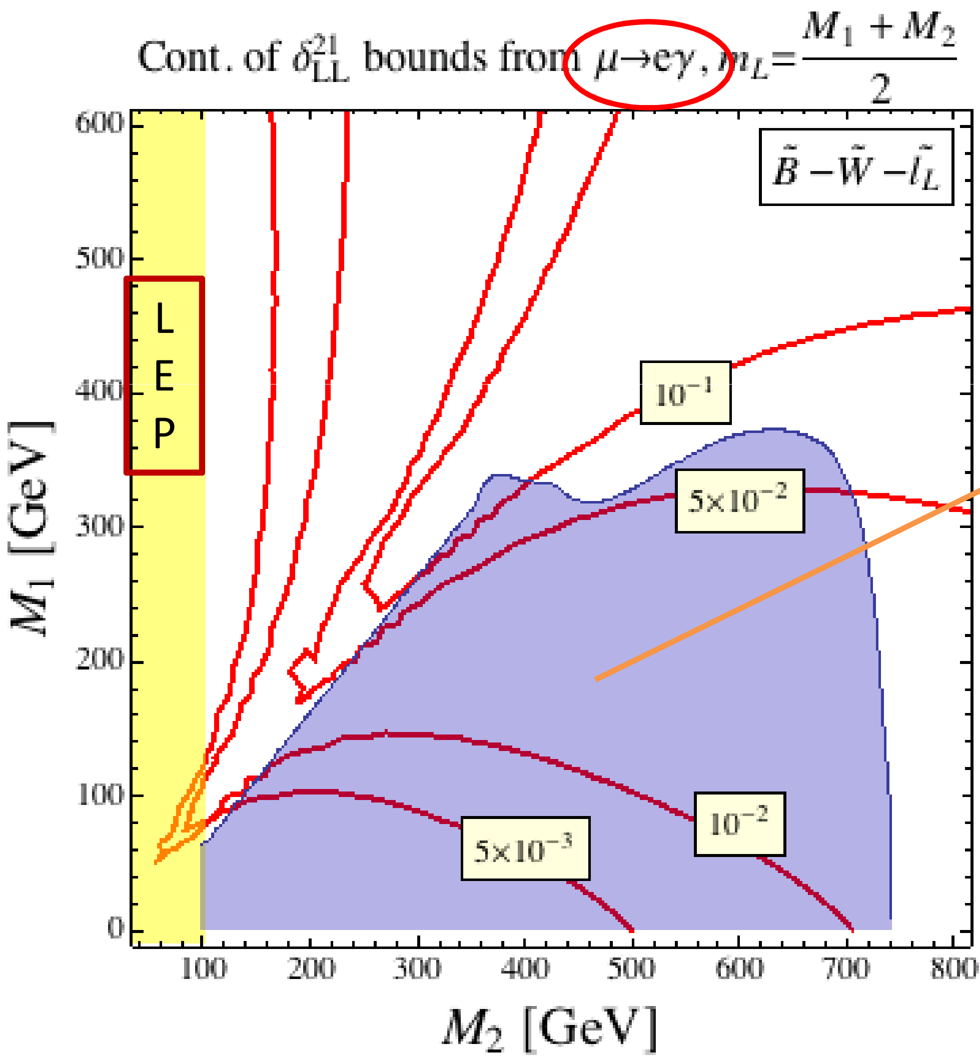


ATLAS search (Drell-Yan)
assume flavor blind selectron, smuon

projected 14 TeV

Eckel Ramsey-Musolf Shepherd Su 1408.2841

example: L-sleptons (selectron-smuon) + bino +wino



fairly large flavor dependence allowed in 7-8 TeV (accidental cancellations)

CMS search
(Chargino-Neutralino production)
assume flavor blind sleptons
(3 sleptons+3 sneutrinos)

what if the allowed slepton flavor is there?

how are LHC searches affected?

start with **Drell-Yan production**:

(here: assume slepton heavier than bino)

flavor blind: equal rates of

selectron pair production: e+e- + missing energy

smuon pair production: mu+mu- + missing energy

SFOS dileptons + missing energy

with flavor:

mass splittings + mixings

small mixing: same final state (SFOS) but different numbers of e+e- and mu+mu-

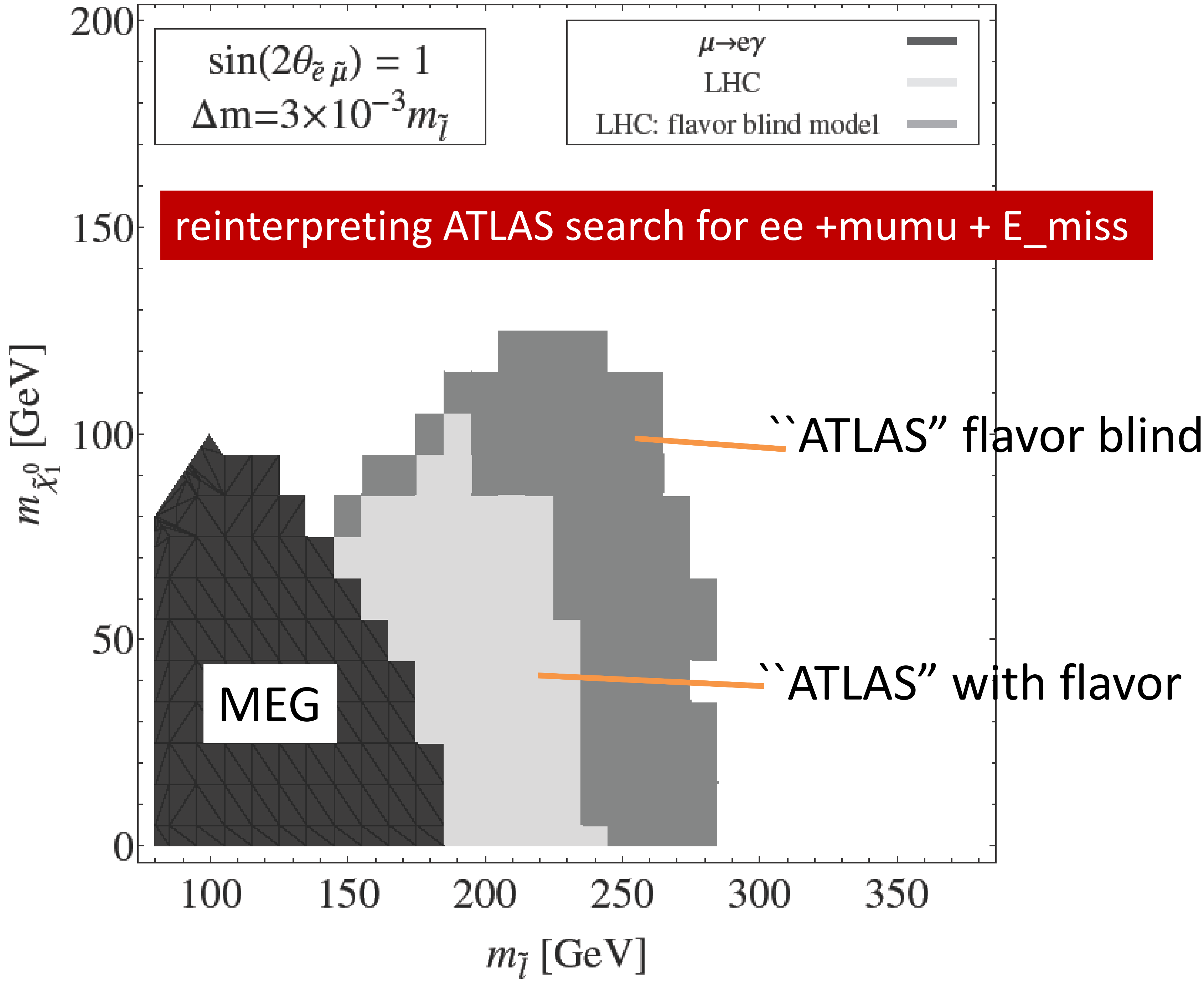
if analysis does not lump electrons and muons together: sensitive to selectron and smuon separately

with flavor:

mass splittings + mixings

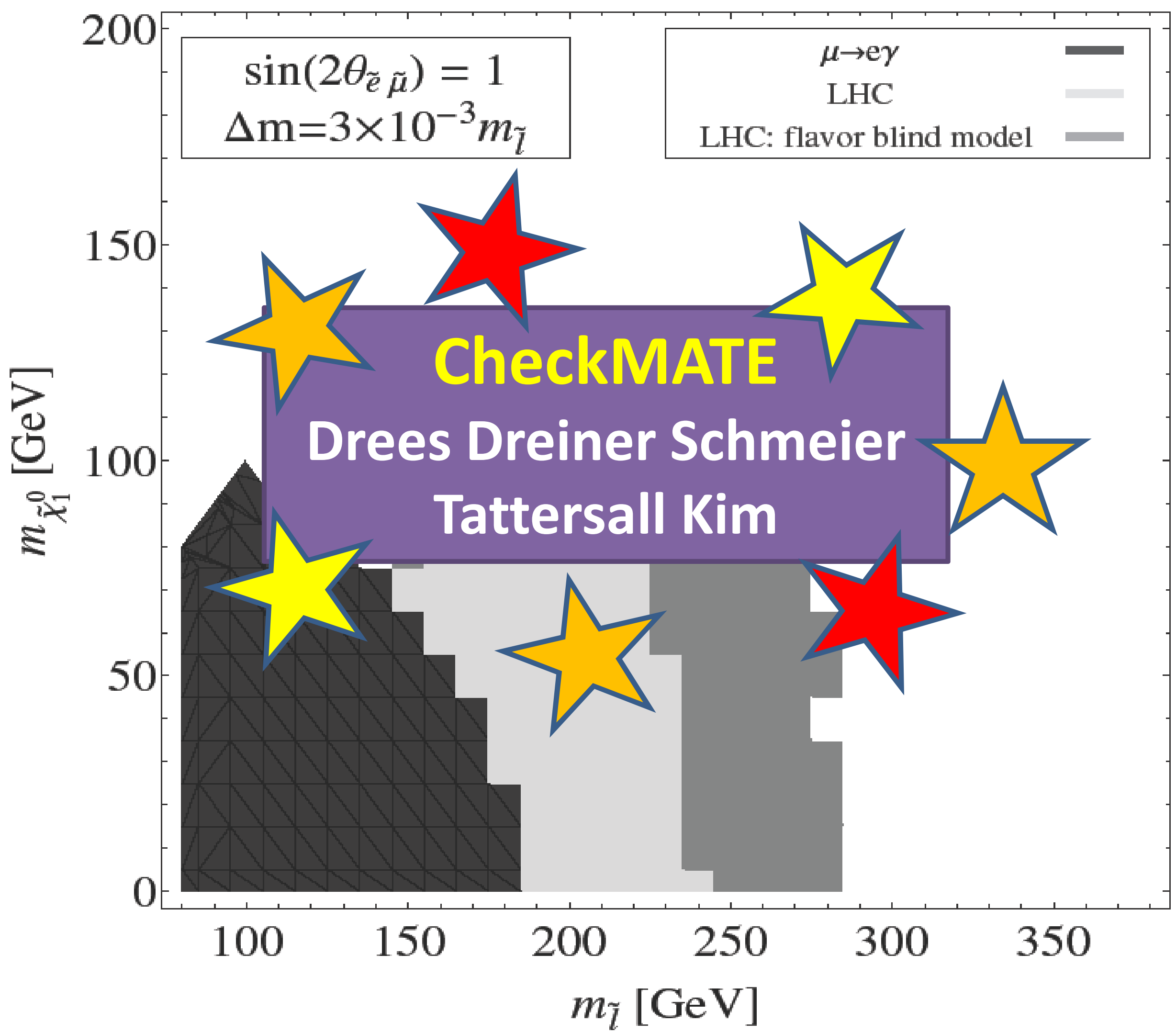
large mixing: also DFOS: e+mu- e-mu+

sensitivity deteriorates



$\sin(2\theta_{\tilde{e}\,\tilde{\mu}}) = 1$
$\Delta m = 3\times10^{-3} m_{\tilde{l}}$
$\mu\to e\gamma$
LHC
LHC: flavor blind model
reinterpreting ATLAS search for ee +mumu + E_miss
``ATLAS" flavor blind
``ATLAS" with flavor
MEG
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{l}}$ [GeV]
0
50
100
150
200
100
150
200
250
300
350

COMMERCIAL BREAK



chargino-neutralino production:

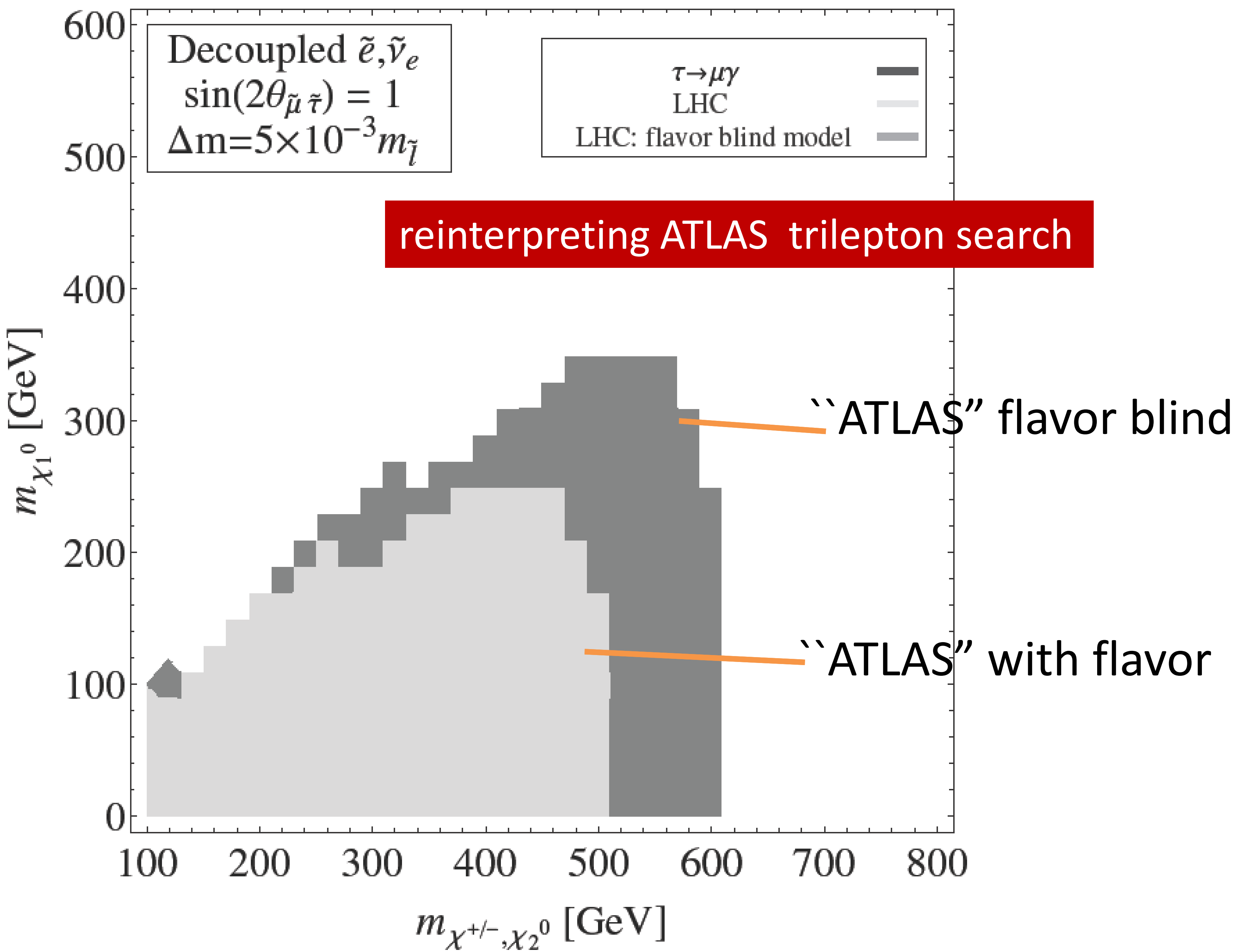
(search assumes wino > L-sleptons (6) > bino)

flavor blind: (e+e-) l+ l=e,mu,tau . . .

→ OSSF pair + another lepton but e, mu only!

some sensitivity to e-mu mixing but not much

but: sensitive to mu-tau mixings (taus lost)



Decoupled $\tilde{e}, \tilde{\nu}_e$
$\sin(2\theta_{\tilde{\mu}\tilde{\tau}}) = 1$
$\Delta m = 5\times10^{-3} m_{\tilde{l}}$
$\tau \to \mu\gamma$
LHC
LHC: flavor blind model
reinterpreting ATLAS trilepton search
``ATLAS" flavor blind
``ATLAS" with flavor
$m_{\chi_1{}^0}$ [GeV]
$m_{\chi^{+/-},\chi_2{}^0}$ [GeV]
0
100
200
300
400
500
600
700
800

theory origin? models?

Flavored Gauge Mediation

YS Szabo 2011

Abdullah Galon YS Shirman; Calibbi Paradisi; Galon Perez YS; Calibbi Pradisi Ziegler;

Ierushalmi Nepomnyashy YS (in progress)

while waiting for SUSY @ LHC..

.. *light* model building

existence proofs

Flavored **Gauge Mediation**

minimal gauge mediation

(? a sketch of gauge mediation)

can be much more general

(and.. minimal GMSB works!)

Flavored Gauge Mediation

fermion masses from a broken

abelian flavor symmetry

more satisfactory mechanisms? dynamics?

(but.. flavor symmetry works)

minimal GMSB

Dine Nelson Nir Shirman

messengers : $5 \quad \bar{5}$

doublets: $D \quad \bar{D}$

same as Higgses $D--H_D \quad \bar{D}--H_U$

can write:

$$\mathrm{W} = Y_U H_U qu + Y_D H_D qd + Y_L H_D le$$

$$+ y_U \overline{D} qu + y_D D qd + \mathrm{y}_L D le$$

$$W = Y_U H_U q u + Y_D H_D q d + Y_L H_D l e$$

$$+ y_U \bar{D} q u + y_D D q d + y_L D l e$$

- new contributions to scalar masses
- A terms (1-loop at messenger scale)

$$W = Y_U H_U q u + Y_D H_D q d + Y_L H_D l e$$

$$+ y_U \bar{D} q u + y_D D q d + y_L D l e$$

- 3x3 matrices: flavor disaster?

any mechanism that explains lepton and quark masses

→ *controls new couplings*

→ *slepton and squark masses*

YS Szabo 2011

here: up-type couplings only:

$$\mathrm{W} = Y_U H_U q u + Y_D H_D q d + Y_L H_D l e$$

$$+ y_U \bar{D} q u$$

new contributions to squark masses-squared:

(structure: spurion analysis)

2-loop:

$g^2 y_U y_U^\dagger$	$y_U y_U^\dagger y_U y_U^\dagger$	$y_U y_U^\dagger Y_U Y_U^\dagger$	...	L
$g^2 y_U^\dagger y_U$	$y_U^\dagger y_U y_U^\dagger y_U$	$y_U^\dagger Y_U Y_U^\dagger y_U$	...	R up
$Y_D^\dagger y_U y_U^\dagger Y_D$				R down

1-loop:

$$\left(\frac{F}{M^2}\right)^2$$ important at low messenger scales

$y_U y_U^\dagger$ L

$y_U^\dagger y_U$ R up

and A-term:

1-loop:

$$y_U \, y_U^\dagger Y_U \qquad Y_U \, y_U^\dagger \, y_U$$

$$y_U \, y_U^\dagger Y_D$$

flavor symmetry determines Yukawas, new coupling

if Higgses, messengers have **same** flavor charge

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

→ mass splittings **MFV-like:**

1st, 2nd generation sfermions nearly degenerate

flavor constraints ok

and large stop A-term

$$y_U \sim \begin{pmatrix} \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \\ \bullet & \lambda & 1 \end{pmatrix} \quad \text{up to order-1 coeffs;} \quad (\lambda \sim 0.2)$$

flavor: only interesting is 3rd generation

- large 33 entry: new contributions to stop mass
  possible hierarchy between stop, sbottom and other squarks
- [stop splitting: large hypercharge contributions in RGEs: sleptons pushed down]
- O(lambda) stop-scharm mixing

Higgs mass: large 33 entry:

- new contributions to stop mass
- **large stop A-term:** large stop mixing

→125 GeV Higgs with stops below 1-2 TeV

[vs pure GMSB: stops (and all) around 7-8 TeV]

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
Evans Shih Thalapillil
…

OR

if Higgses, messengers have **different** flavor charge

$$(y_U)_{ij} \neq (Y_U)_{ij}$$

→ novel squark flavor

examples:

Ierushalmi Nepomnyashy YS
in progress

MFV-like

U(1) flavor symmetry

determines:

$$Y_U \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^4 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}$$

→ masses, CKM

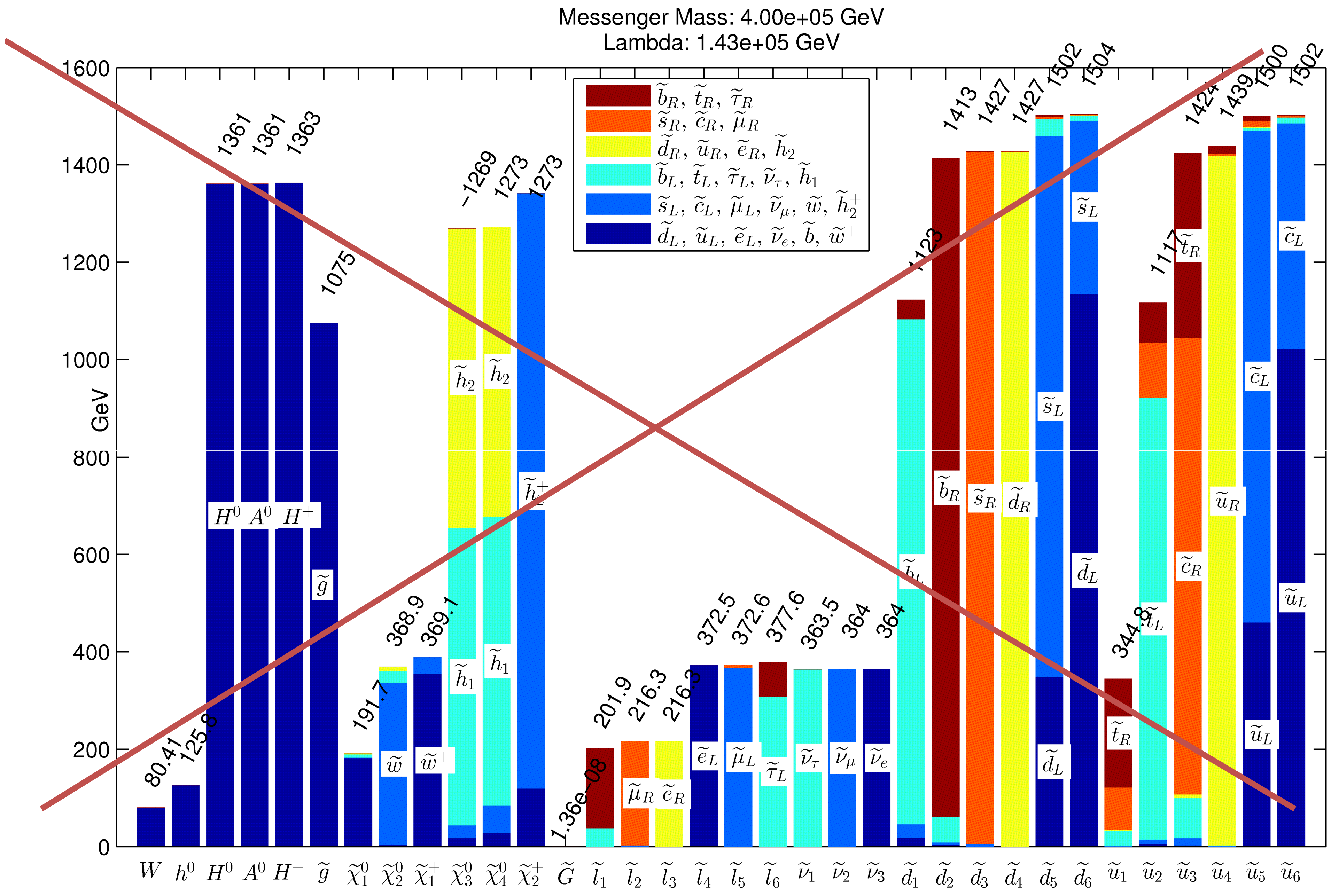
messenger U(1) charge = Higgs U(1) charge

$$y_U \sim Y_U \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^4 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}$$

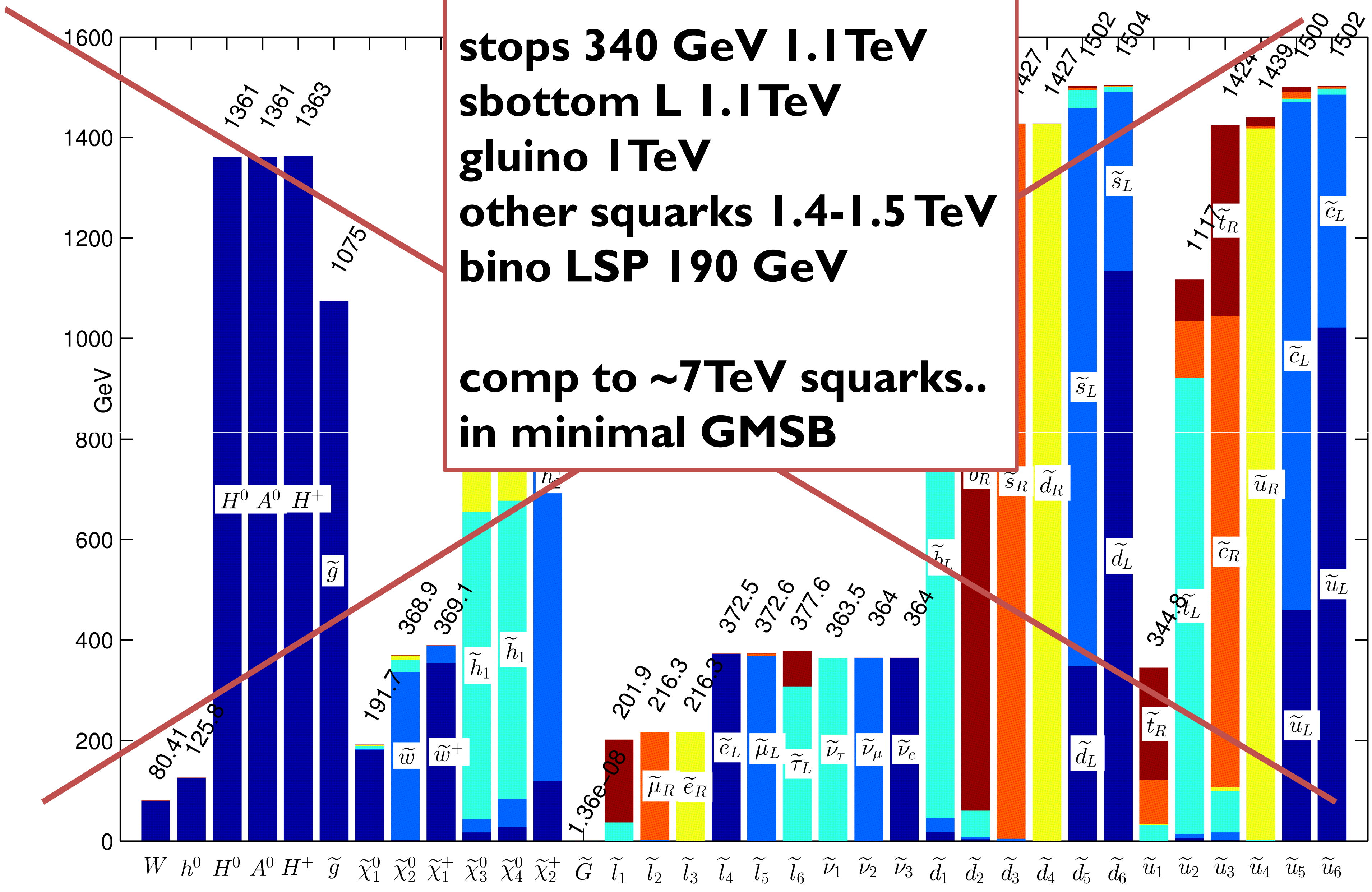
→ new contributions to stops, sbottom_L, masses

→ large stop A term

→ possibly large stop-charm mixing

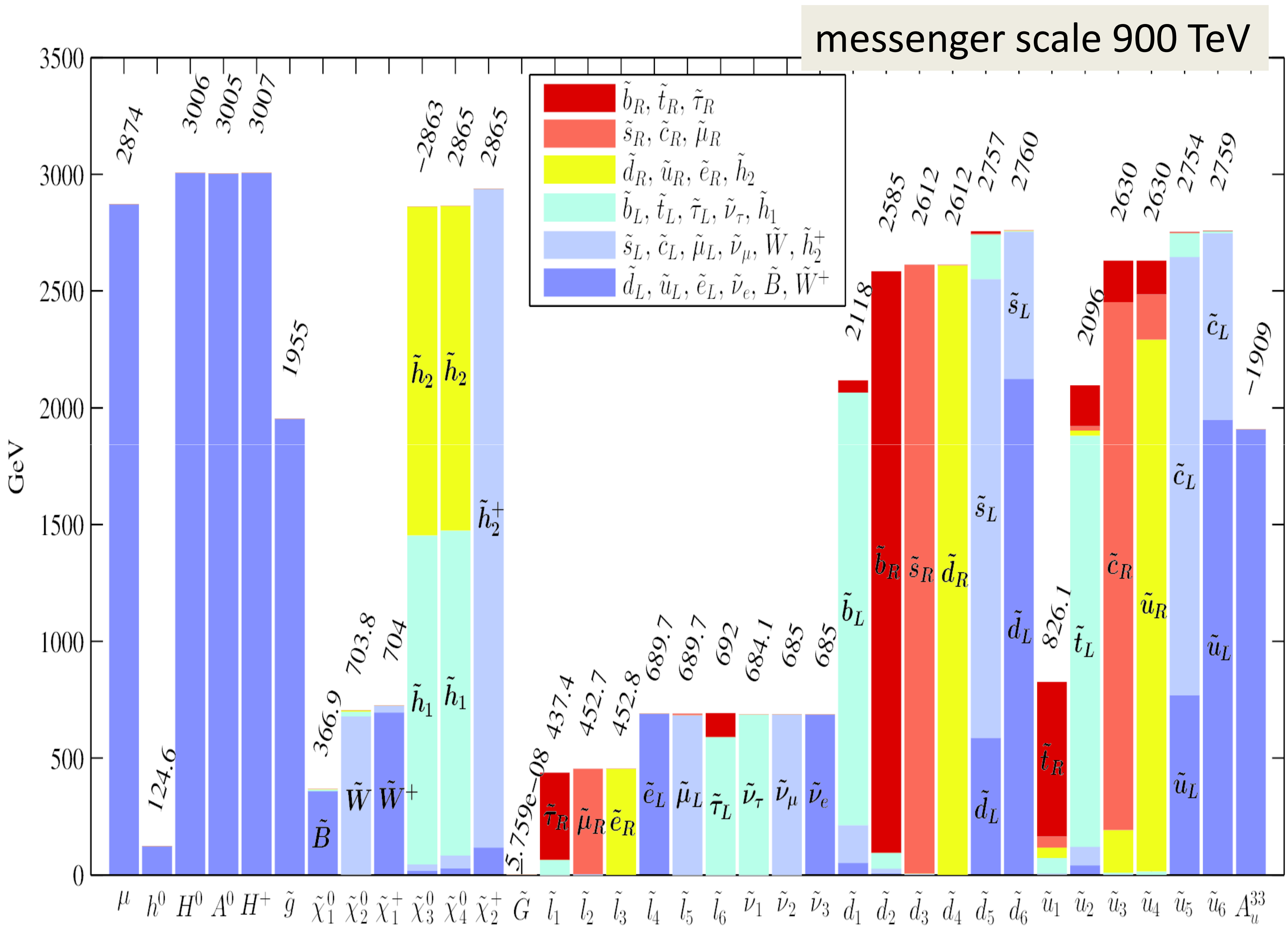


Messenger Mass: 4.00e+05 GeV
Lambda: 1.43e+05 GeV
GeV
$\widetilde{b}_R, \widetilde{t}_R, \widetilde{\tau}_R$
$\widetilde{s}_R, \widetilde{c}_R, \widetilde{\mu}_R$
$\widetilde{d}_R, \widetilde{u}_R, \widetilde{e}_R, \widetilde{h}_2$
$\widetilde{b}_L, \widetilde{t}_L, \widetilde{\tau}_L, \widetilde{\nu}_\tau, \widetilde{h}_1$
$\widetilde{s}_L, \widetilde{c}_L, \widetilde{\mu}_L, \widetilde{\nu}_\mu, \widetilde{w}, \widetilde{h}_2^+$
$\widetilde{d}_L, \widetilde{u}_L, \widetilde{e}_L, \widetilde{\nu}_e, \widetilde{b}, \widetilde{w}^+$
W h^0 H^0 A^0 H^+ $\widetilde{g}$ $\widetilde{\chi}_1^0$ $\widetilde{\chi}_2^0$ $\widetilde{\chi}_1^+$ $\widetilde{\chi}_3^0$ $\widetilde{\chi}_4^0$ $\widetilde{\chi}_2^+$ $\widetilde{G}$ $\widetilde{l}_1$ $\widetilde{l}_2$ $\widetilde{l}_3$ $\widetilde{l}_4$ $\widetilde{l}_5$ $\widetilde{l}_6$ $\widetilde{\nu}_1$ $\widetilde{\nu}_2$ $\widetilde{\nu}_3$ $\widetilde{d}_1$ $\widetilde{d}_2$ $\widetilde{d}_3$ $\widetilde{d}_4$ $\widetilde{d}_5$ $\widetilde{d}_6$ $\widetilde{u}_1$ $\widetilde{u}_2$ $\widetilde{u}_3$ $\widetilde{u}_4$ $\widetilde{u}_5$ $\widetilde{u}_6$
80.41 125.8 1361 1361 1363 1075 191.7 368.9 369.1 -1269 1273 1273 1.36e-08 201.9 216.3 216.3 372.5 372.6 377.6 363.5 364 364 1123 1413 1427 1427 1502 1504 344.8 1117 1424 1439 1500 1502
0 200 400 600 800 1000 1200 1400 1600



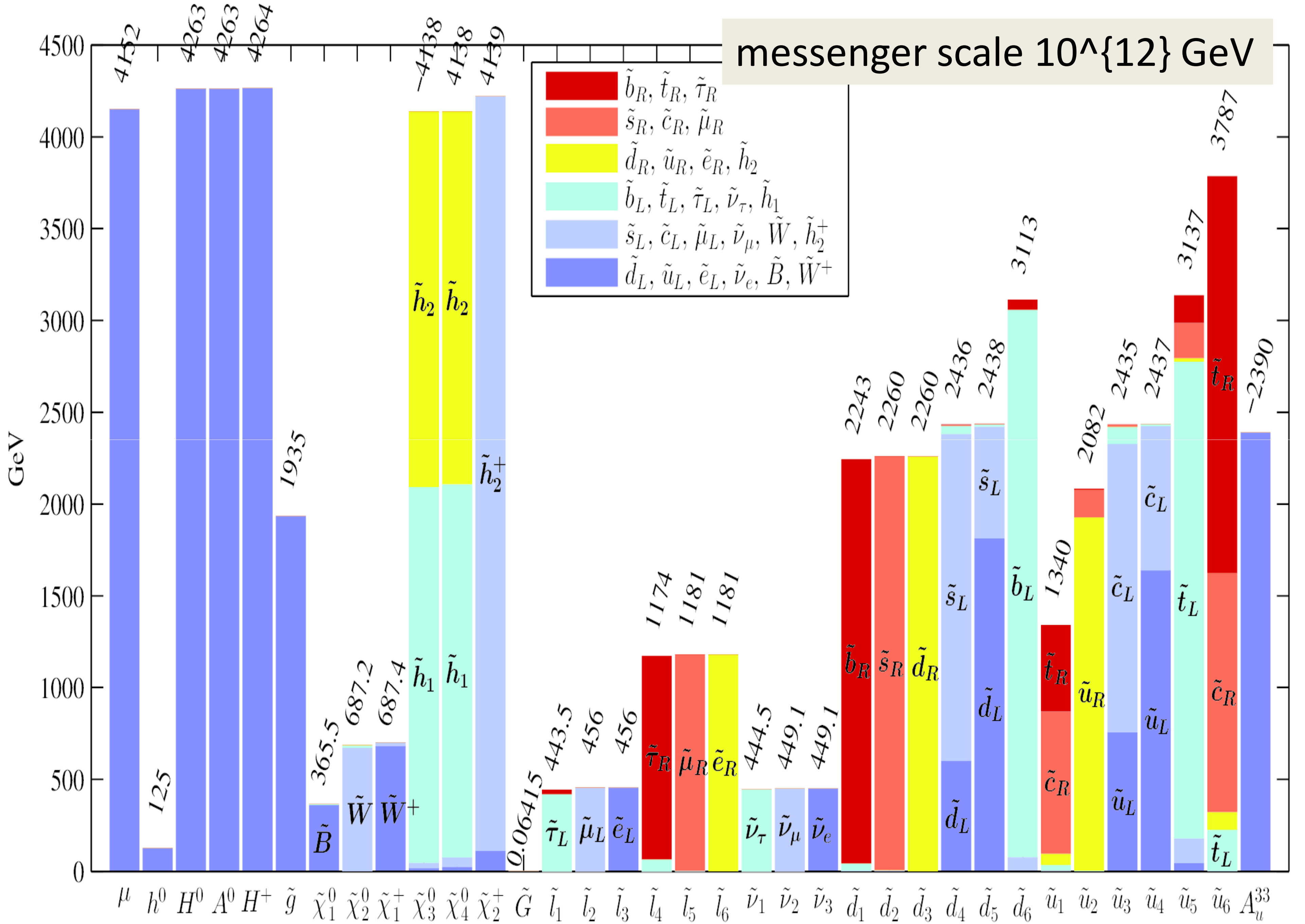
stops 340 GeV 1.1TeV
sbottom L 1.1TeV
gluino 1TeV
other squarks 1.4-1.5 TeV
bino LSP 190 GeV

comp to ~7TeV squarks..
in minimal GMSB



messenger scale 900 TeV
GeV
$\tilde{b}_R, \tilde{t}_R, \tilde{\tau}_R$
$\tilde{s}_R, \tilde{c}_R, \tilde{\mu}_R$
$\tilde{d}_R, \tilde{u}_R, \tilde{e}_R, \tilde{h}_2$
$\tilde{b}_L, \tilde{t}_L, \tilde{\tau}_L, \tilde{\nu}_\tau, \tilde{h}_1$
$\tilde{s}_L, \tilde{c}_L, \tilde{\mu}_L, \tilde{\nu}_\mu, \tilde{W}, \tilde{h}_2^+$
$\tilde{d}_L, \tilde{u}_L, \tilde{e}_L, \tilde{\nu}_e, \tilde{B}, \tilde{W}^+$

- Higgs mass: large stop mixing: stops at 830GeV, 2TeV
- heavy spectrum with gluino 2 TeV, squarks 2-2.8 TeV
- bino LSP at 370 GeV
- note:
  RGE: high flavor scale to messenger scale
  reduces y_{33}



messenger scale 10^{12} GeV
$\tilde{b}_R, \tilde{t}_R, \tilde{\tau}_R$
$\tilde{s}_R, \tilde{c}_R, \tilde{\mu}_R$
$\tilde{d}_R, \tilde{u}_R, \tilde{e}_R, \tilde{h}_2$
$\tilde{b}_L, \tilde{t}_L, \tilde{\tau}_L, \tilde{\nu}_\tau, \tilde{h}_1$
$\tilde{s}_L, \tilde{c}_L, \tilde{\mu}_L, \tilde{\nu}_\mu, \tilde{W}, \tilde{h}_2^+$
$\tilde{d}_L, \tilde{u}_L, \tilde{e}_L, \tilde{\nu}_e, \tilde{B}, \tilde{W}^+$
GeV
μ h^0 H^0 A^0 H^+ $\tilde{g}$ $\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_1^+$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$ $\tilde{\chi}_2^+$ $\tilde{G}$ $\tilde{l}_1$ $\tilde{l}_2$ $\tilde{l}_3$ $\tilde{l}_4$ $\tilde{l}_5$ $\tilde{l}_6$ $\tilde{\nu}_1$ $\tilde{\nu}_2$ $\tilde{\nu}_3$ $\tilde{d}_1$ $\tilde{d}_2$ $\tilde{d}_3$ $\tilde{d}_4$ $\tilde{d}_5$ $\tilde{d}_6$ $\tilde{u}_1$ $\tilde{u}_2$ $\tilde{u}_3$ $\tilde{u}_4$ $\tilde{u}_5$ $\tilde{u}_6$ A_u^{33}
4152 125 4263 4263 4264 1935 365.5 687.2 687.4 −4138 4138 4139 0.06415 443.5 456 456 1174 1181 1181 444.5 449.1 449.1 2243 2260 2260 2436 2438 3113 1340 2082 2435 2437 3137 3787 −2390

similar spectrum: but large stop-scharm mixing

recall 32 up Yukawa O(lambda)

stop searches: efficiency deteriorates

Blanke Giudice Paradisi Perez Zupan

so far MFV-like
now to different structures

can we have large effects in 1, 2 generations ??

with U(1) flavor symmetry:

O(lambda Cabbibo) mixing in fermion masses

cannot have 1-2 mass splittings

for large mass splittings:

must suppress 1-2 mixing: **alignment**

→ 2 U(1)s

U(1)xU(1) flavor symmetry

$$Y_U \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ 0 & \lambda^3 & \lambda^2 \\ 0 & \lambda & 1 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} \lambda^6 & 0 & \lambda^5 \\ 0 & \lambda^4 & \lambda^4 \\ 0 & 0 & \lambda^2 \end{pmatrix}$$ **~ diagonal**

→ fermion masses, CKM

``holomorphic zero" (need lambda dagger)

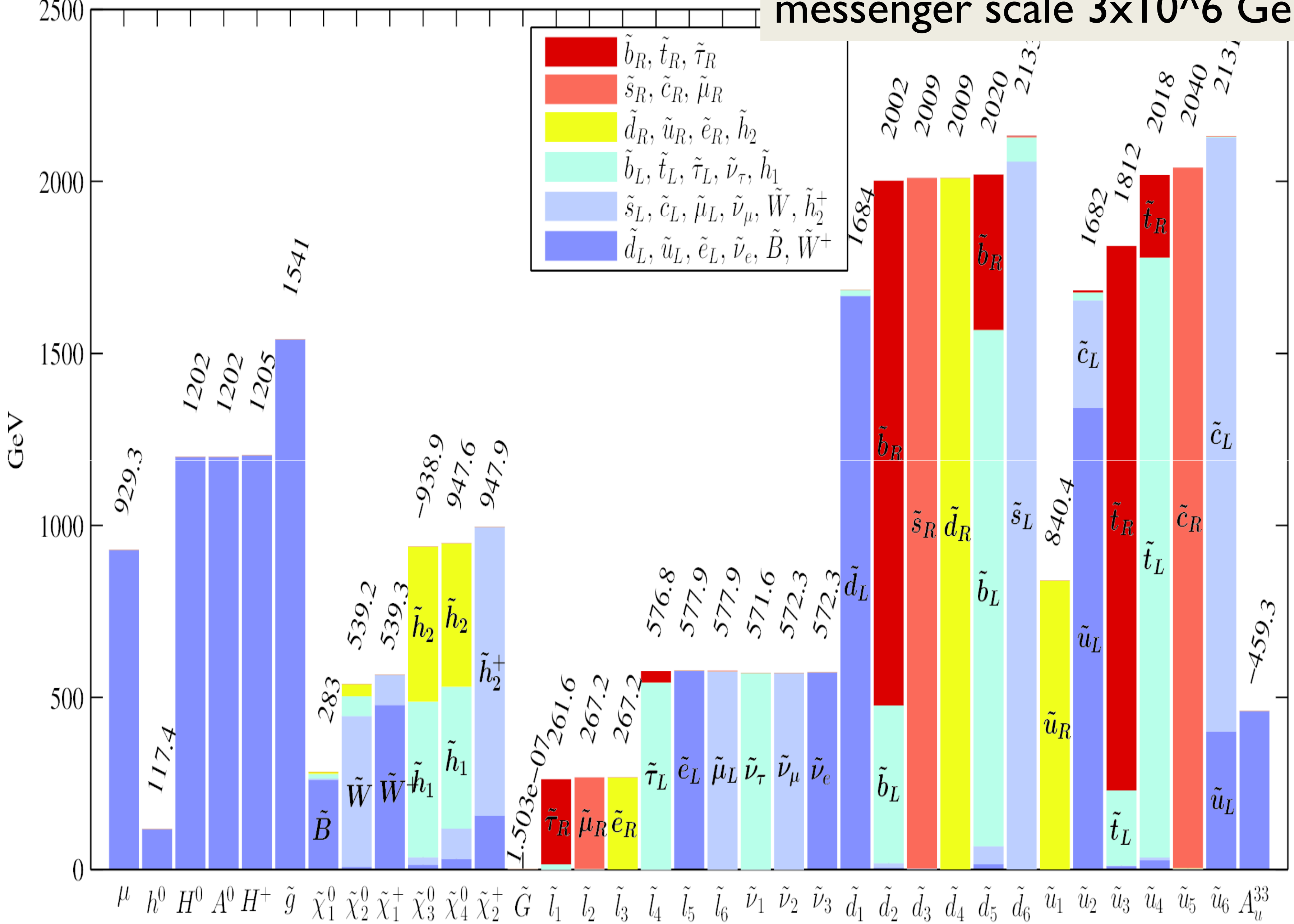
(here: Higgs charge 0)

take messenger charges: (0,-6) (different from Higgs!)

$$y_U \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

→ only affects up, down squark masses!

messenger scale 3x10^6 GeV



a non-degenerate spectrum:

up-R at 840 GeV
all other squarks 1.6-2 TeV
gluino 1.5TeV

no 8-fold degeneracy of 1st, 2nd generations
different efficiency for different masses

Mahbubani Papucci Perez Ruderman Weiler

in this specific example: slepton LSP

another U(1)xU(1) example

same SM charges as before (Higgs zero)

→ same Yukawas as before

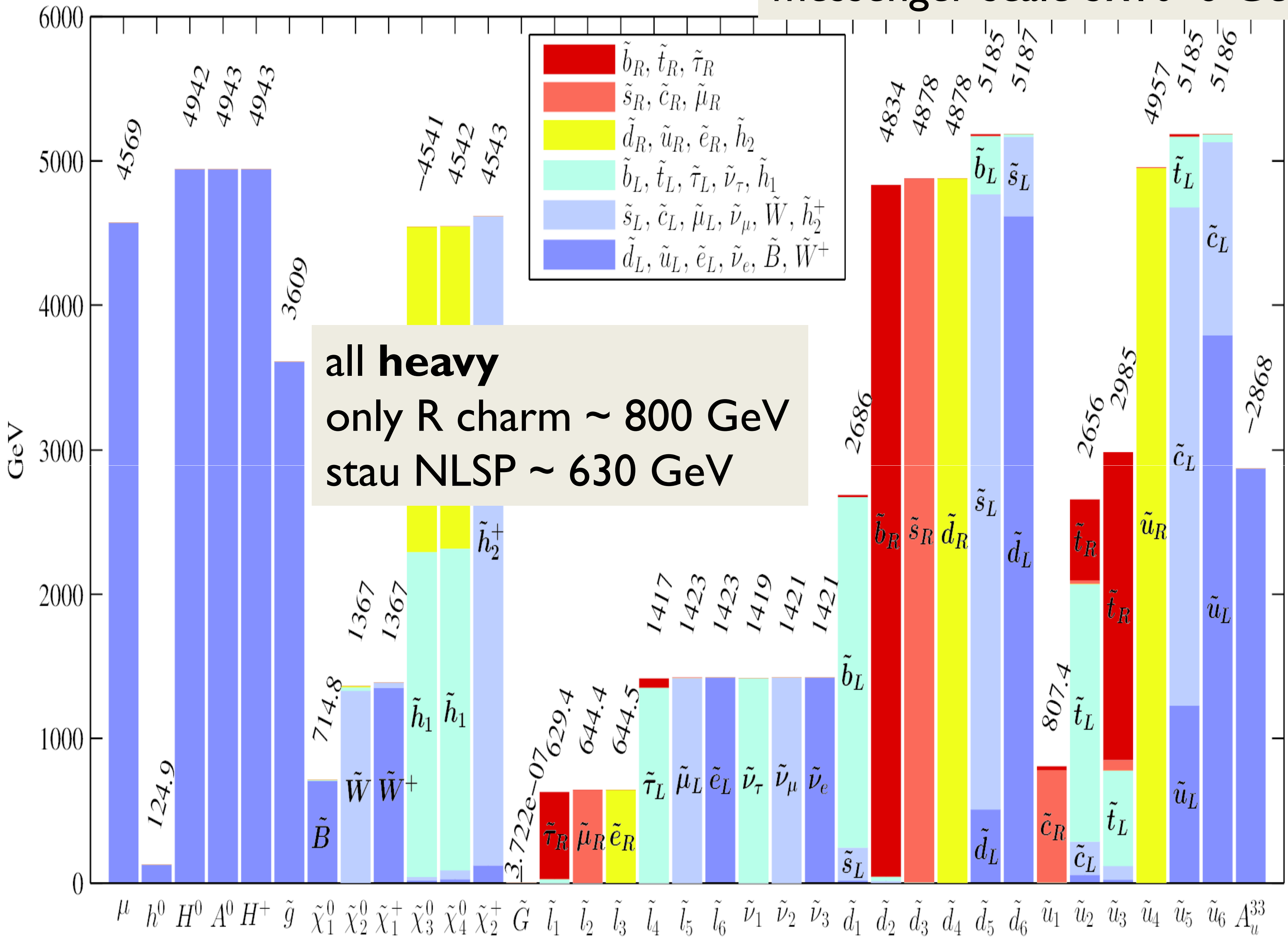
but different messenger charges (-1,0):

$$y_U \sim \begin{pmatrix} 0 & \lambda^3 & \lambda^2 \\ 0 & \lambda^2 & 0 \\ 0 & \textcircled{1} & 0 \end{pmatrix}$$

large contribution to

- L-stop, sbottom
- R-scharm
- stop A term

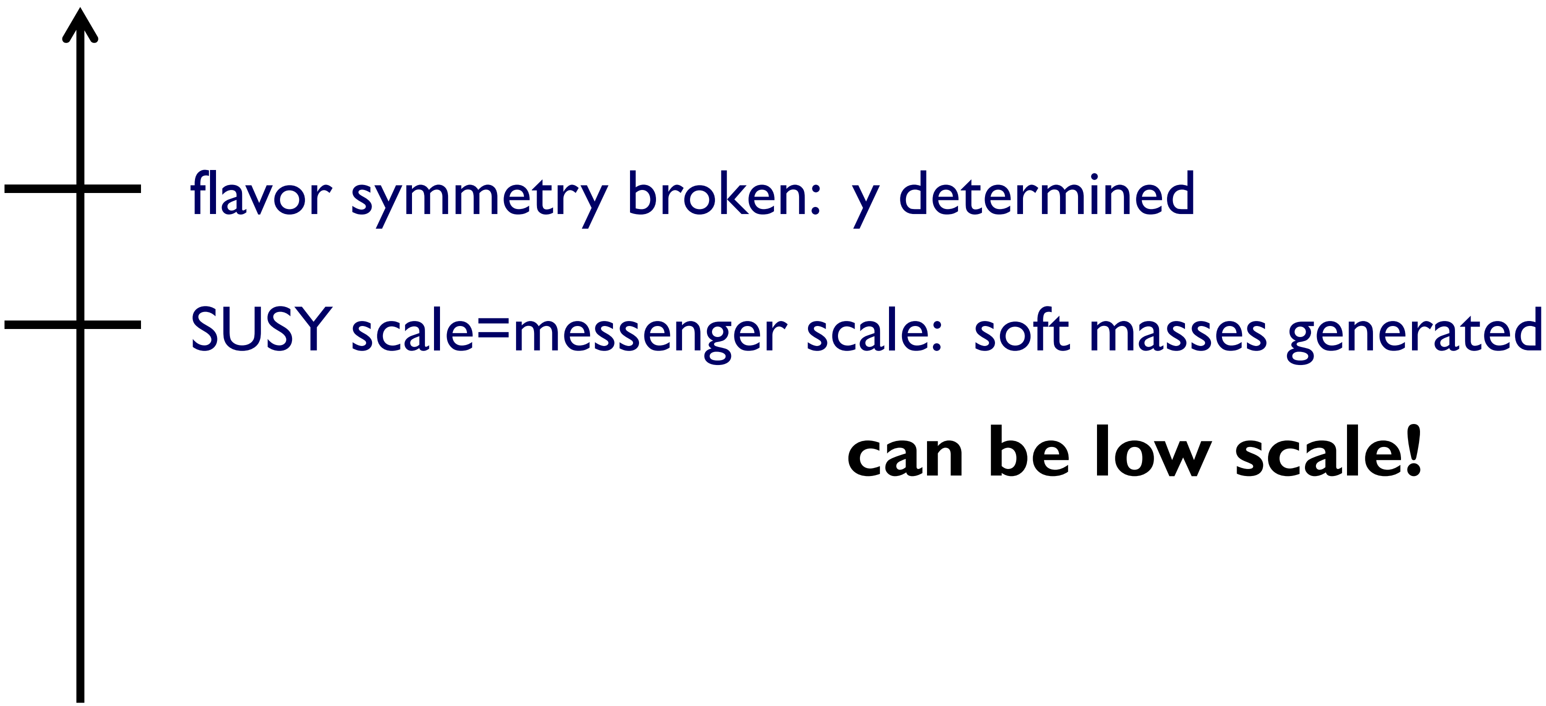
messenger scale 3x10^6 GeV



all **heavy**
only R charm ~ 800 GeV
stau NLSP ~ 630 GeV

flavor constraints: alignment sometimes at play but ``**supersymmetric** alignment":

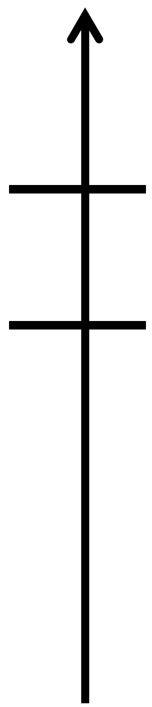
flavor symmetry controls **superpotential** coupling y



vs original alignment models – high scale only

Nir Seiberg

SUSY breaking scale above flavor scale



SUSY scale: soft masses generated

flavor symmetry broken

long time to run: gluino → degeneracy

so:

LHC searches: sfermions can have flavor
(in **concrete** calculable models)

1st and 2nd generations can be affected too

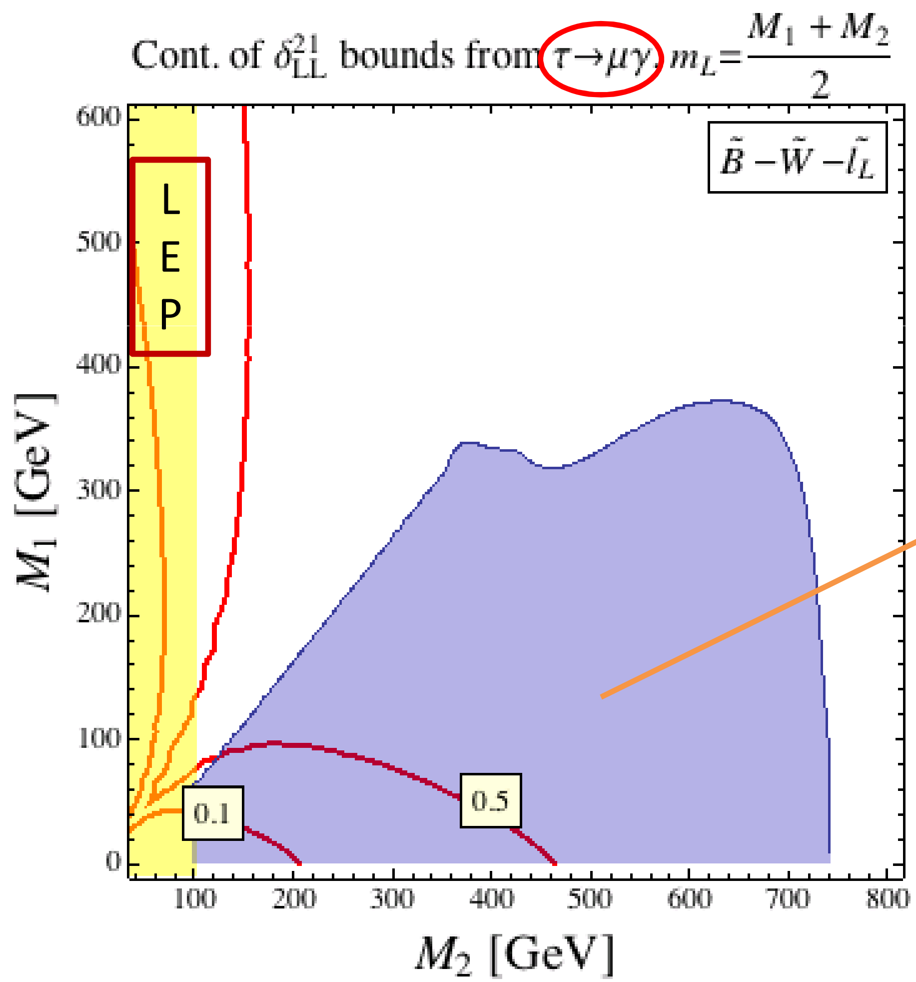
flavor symmetry there to explain fermion masses

automatically controls sfermion masses examples here:

- often large stop-charm mixing
- bino OR slepton NLSP
- decay length a few mm or more (GMSB)

``intermediate" region important to cover thank you!

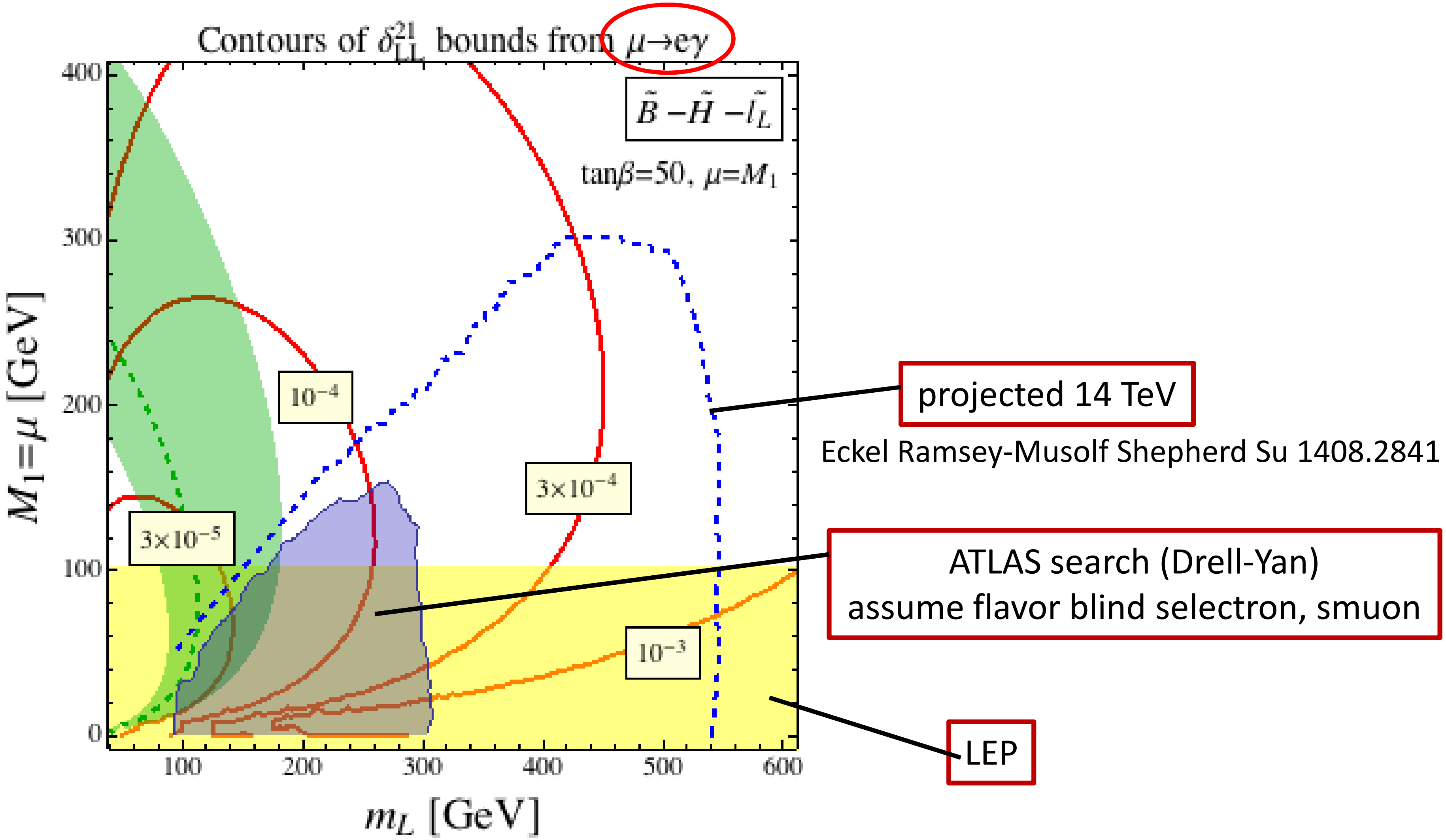
2nd example: L-sleptons (smuon+stau) + bino +wino



very large flavor dependence allowed in 7-8 TeV

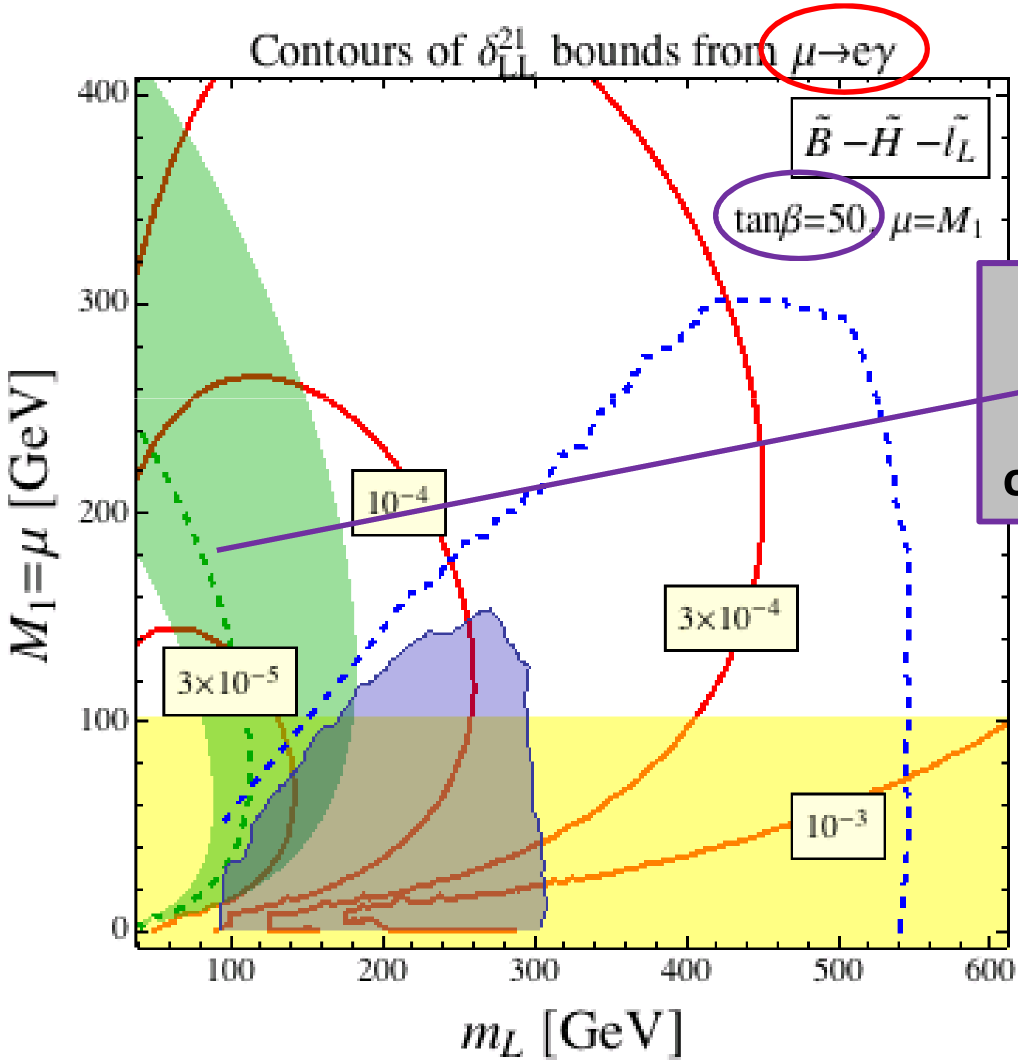
CMS search
(Chargino-Neutralino production)
assume flavor blind sleptons
(3 sleptons+3 sneutrinos)

3rd example: L-sleptons (selectron-smuon) + bino + **higgsino**



Eckel Ramsey-Musolf Shepherd Su 1408.2841

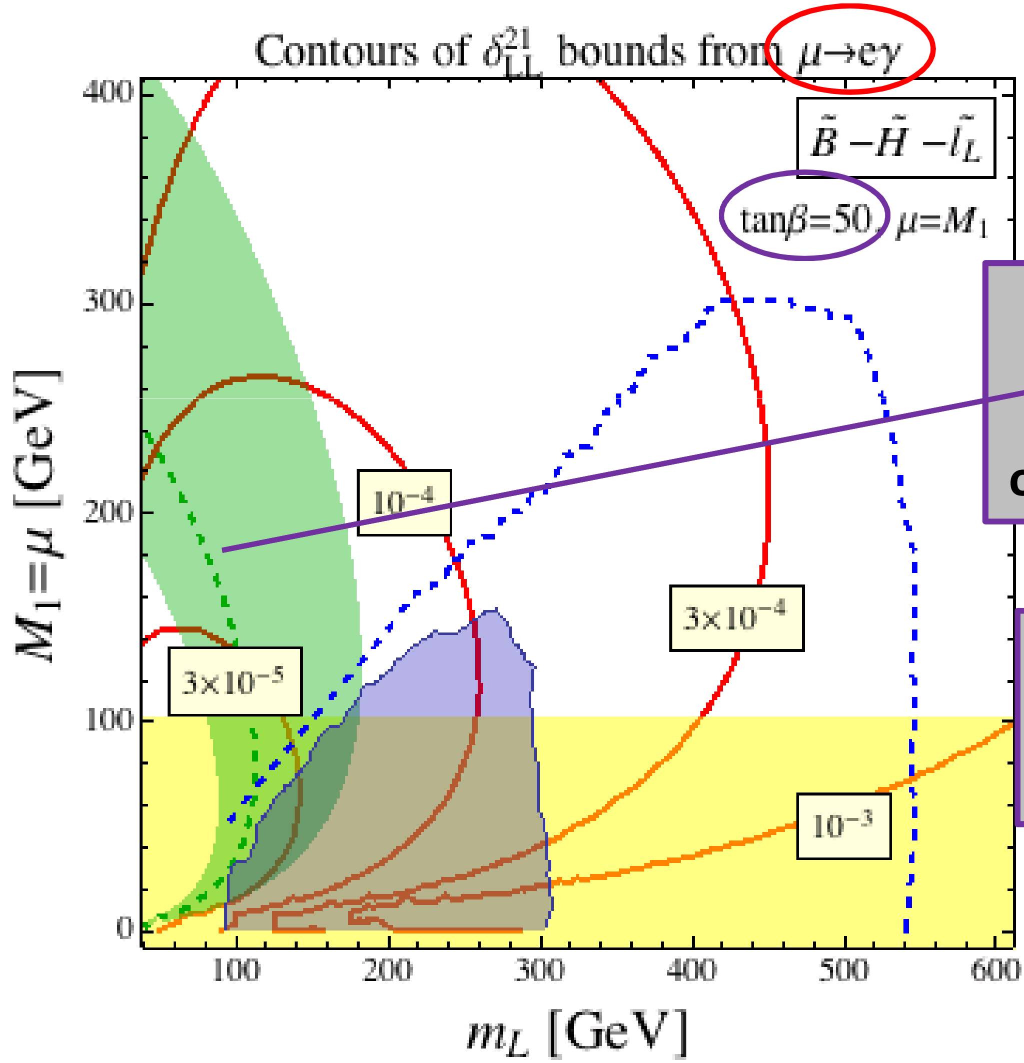
3rd example: L-sleptons (selectron-smuon) + bino +**higgsino**



g-2
motivates choice of tanbeta

otherwise limits weaker by 50/tanbeta

3rd example: L-sleptons (selectron-smuon) + bino +**higgsino**



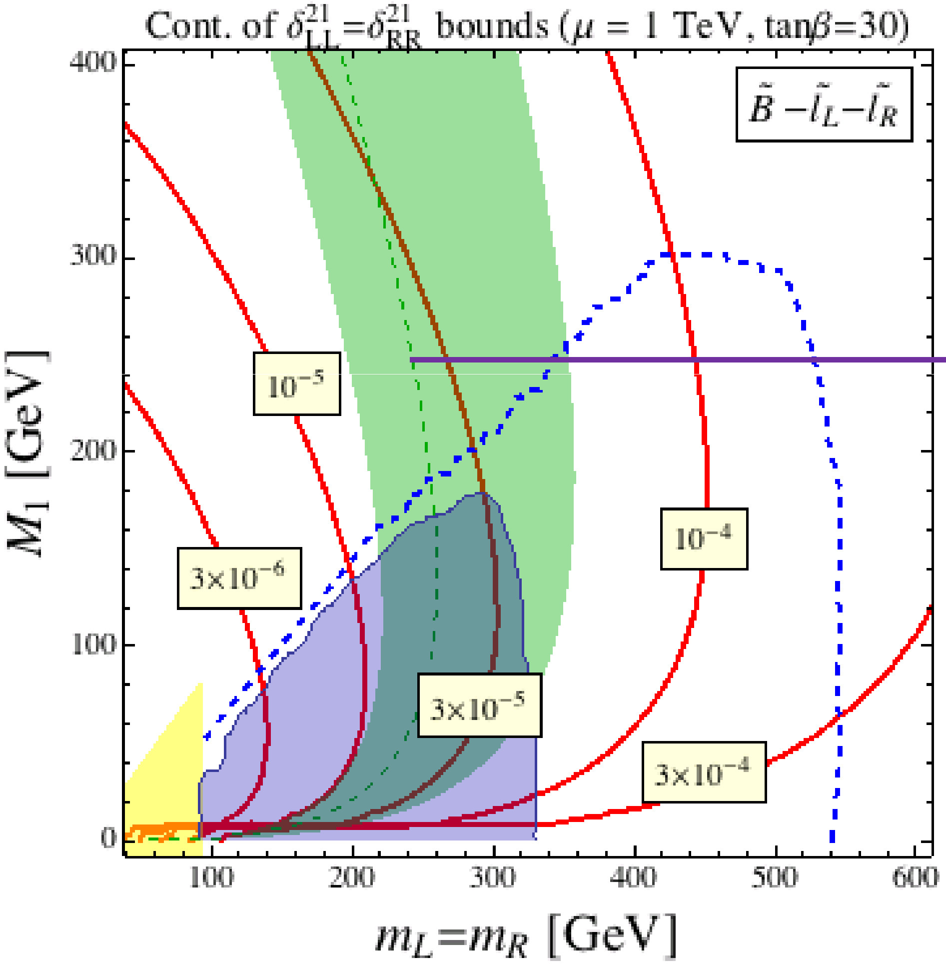
g-2
motivates choice of tanbeta

otherwise limits weaker by 50/tanbeta

g-2, mu to e gamma, both enhanced by bino-higgsino mixing mu tanbeta

4th example: **L+R** sleptons (selectron-smuon) + bino

effect of LR mixing



g-2
motivates choice of tanbeta

otherwise limits weaker by 30/tanbeta

g-2, mu to e gamma, both enhanced by LR mixing
(assume = mu tanbeta
no A terms)