cLFV & slepton flavor

and squark flavor too

Yael Shadmi

Technion

Flavor and supersymmetry: where we are (nowhere)

- no hint of (charged) flavor violation
- no hint of supersymmetry

Flavor and supersymmetry: where we are (nowhere)

stress our ***ignorance***

- leptons and quarks are not flavor blind
- we don`t know why
- a theory of flavor?
- testable?? may be very high-E (eg Froggatt Nielsen)

Flavor and supersymmetry: where we are (nowhere)

stress our ***ignorance***

- leptons and quarks are not flavor blind
- we don`t know why
- **why should sleptons and squarks be?**
- a theory of flavor?
- **any mechanism that explains lepton and quark masses → slepton and squark masses**

  (unless something erases flavor info, eg, gauge interactions..)
- testable?? may be very high-E (eg Froggatt Nielsen)
- **sleptons, squarks may be flavor-portal**

OUTLINE:

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

- – low-E constraints on slepton flavor
- – impact on LHC searches

II: top-down approach: theoretical models?

Flavored Gauge Mediation

- slepton flavor
- squark flavor
- LHC

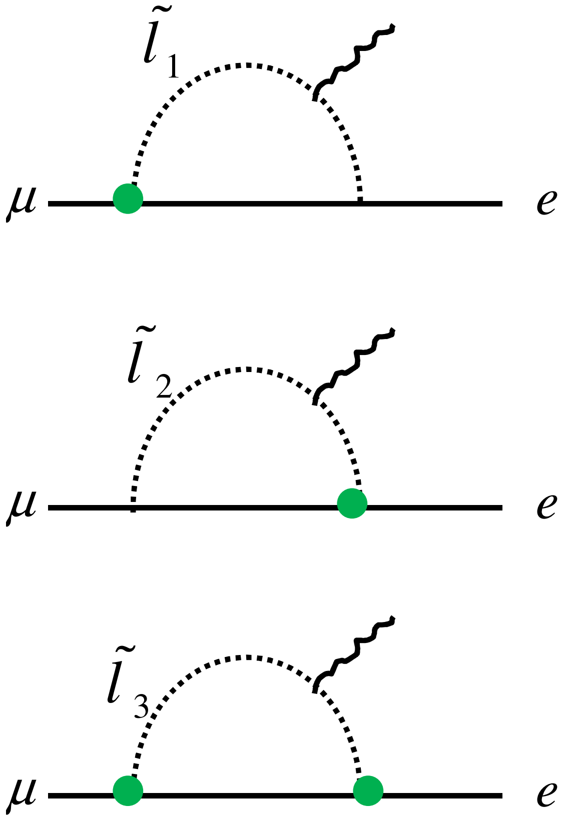
I: Simplified models for slepton flavor

Calibbi Galon Masiero Paradisi YS

low-E: no hint for (charged) LFV

	LFV Process	Present Bound	Future Sensitivity	
MEG	$\mu^+ \to e^+\gamma$	5.7×10^{-13} [31]	$\approx 6 \times 10^{-14}$ [32]	MEG
SINDRUM	$\mu^+ \to e^+e^+e^-$	1.0×10^{-12} [33]	$\mathcal{O}(10^{-16})$ [34]	Mu3e
	μ^- Au $\to e^-$ Au	7.0×10^{-13} [35]	?	
	μ^- Ti $\to e^-$ Ti	4.3×10^{-12} [36]	?	
	μ^- Al $\to e^-$ Al	–	$\mathcal{O}(10^{-16})$ [37, 38]	COMET Mu2e
BaBar	$\tau^\pm \to \mu^\pm\gamma$	4.4×10^{-8} [39]	$10^{-8} \div 10^{-9}$ [40]	Belle
Belle	$\tau^\pm \to \mu^\pm\mu^+\mu^-$	2.1×10^{-8} [41]	$10^{-9} \div 10^{-10}$ [40]	
	Electron EDM	**Present Bound**	**Future Sensitivity**	
	d_e(e cm)	8.7×10^{-29} [42]	?	

low-E:



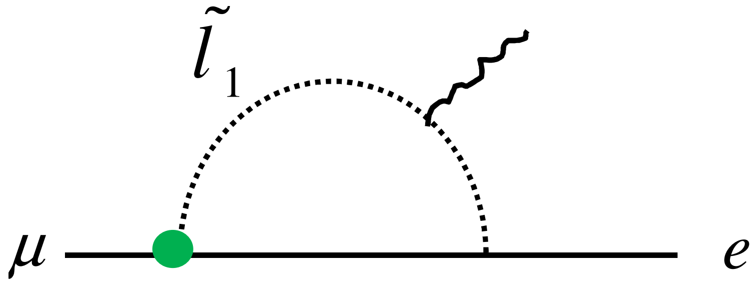
essentially constrain:

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

low-E:

the special role of Higgsinos & LR mixing

dipole amplitudes:
(LFV, g-2)



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the special role of Higgsinos & LR mixing

dipole amplitudes:
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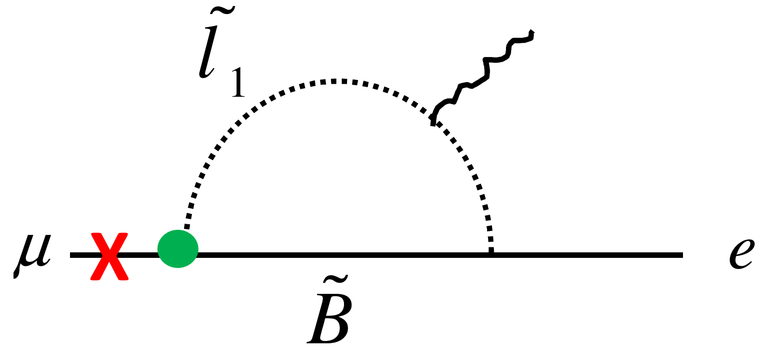
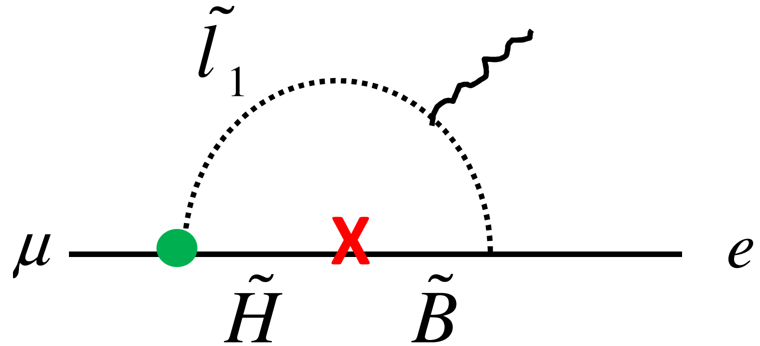
CHIRALITY FLIP



with Higgsinos:



low-E:

the special role of Higgsinos & LR mixing

dipole amplitudes:
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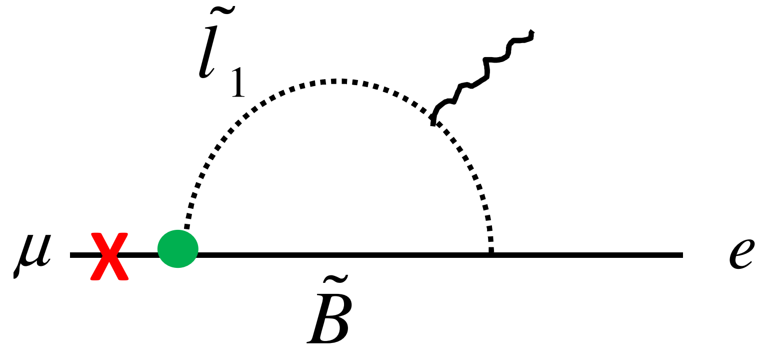
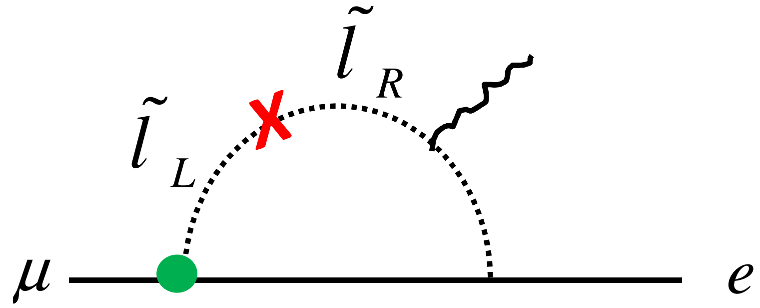


CHIRALITY FLIP

with LR mixing:



usually derive constraints in a specific model framework: eg CMSSM

high-E: no hint for supersymmetry

- LHC: (direct + 125 GeV Higgs mass):

  if supersymmetry exists near the TeV it is probably not so simple

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

  by direct LHC + Higgs mass

125 Higgs:

often need large mu-term:

? heavy Higgsinos (important contribution or decoupling)

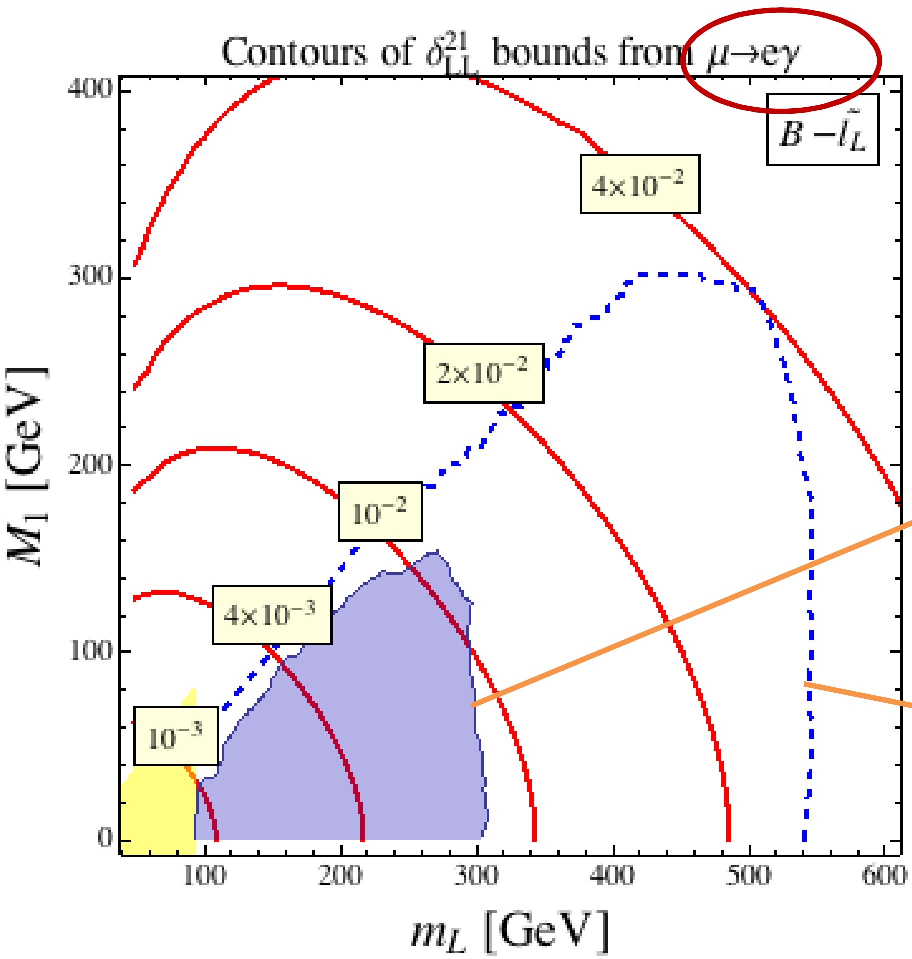
$$\sim M_1 \tan\beta / \mu$$

? 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

1st example: L-sleptons (selectron-smuon) + bino

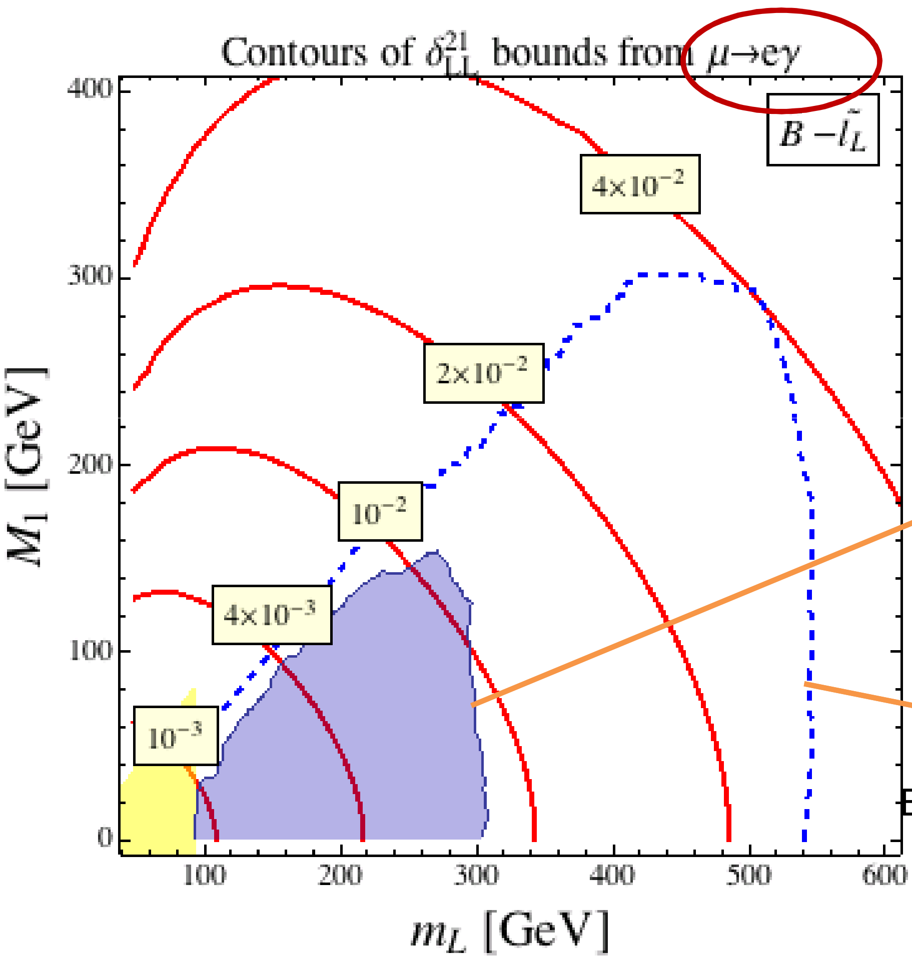


ATLAS search (Drell-Yan)
assume flavor blind selectron, smuon

projected 14 TeV

Eckel Ramsey-Musolf Shepherd Su 1408.2841

1st example: L-sleptons (selectron-smuon) + bino



fairly large flavor dependence allowed in 7-8 TeV

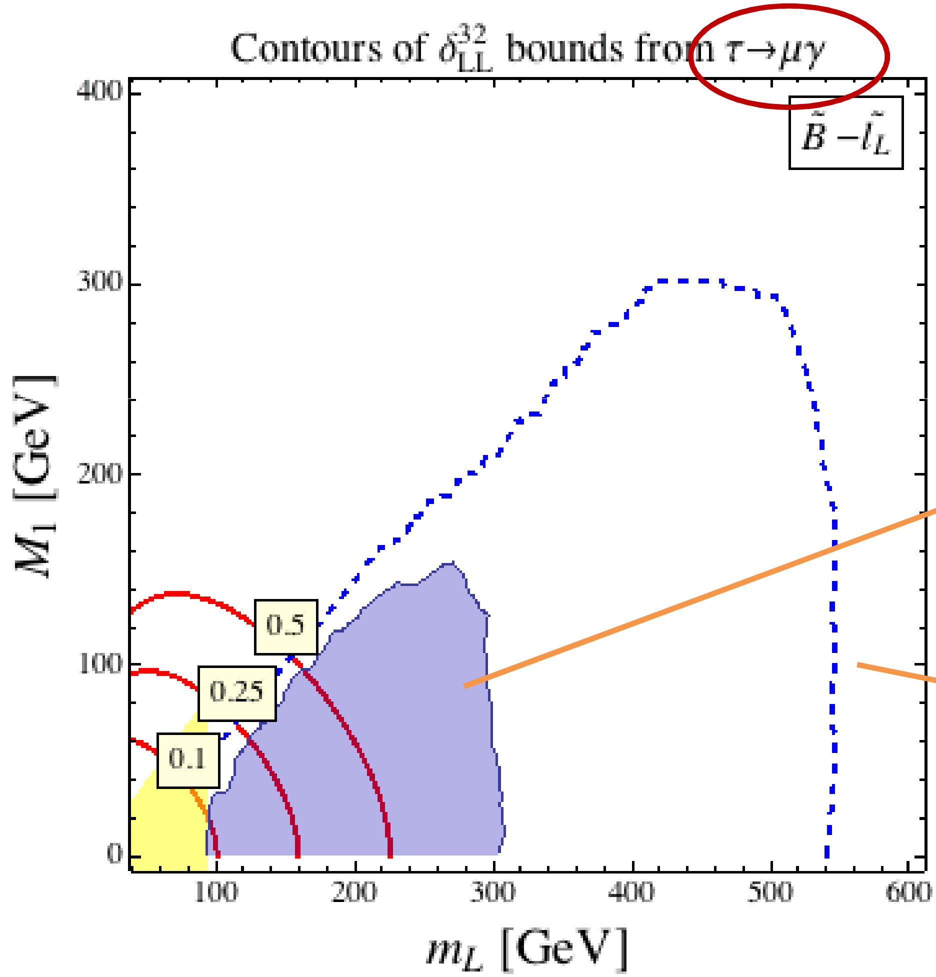
larger in next run

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

projected 14 TeV

Eckel Ramsey-Musolf Shepherd Su 1408.2841

1st example: L-sleptons (smuon-stau) + bino

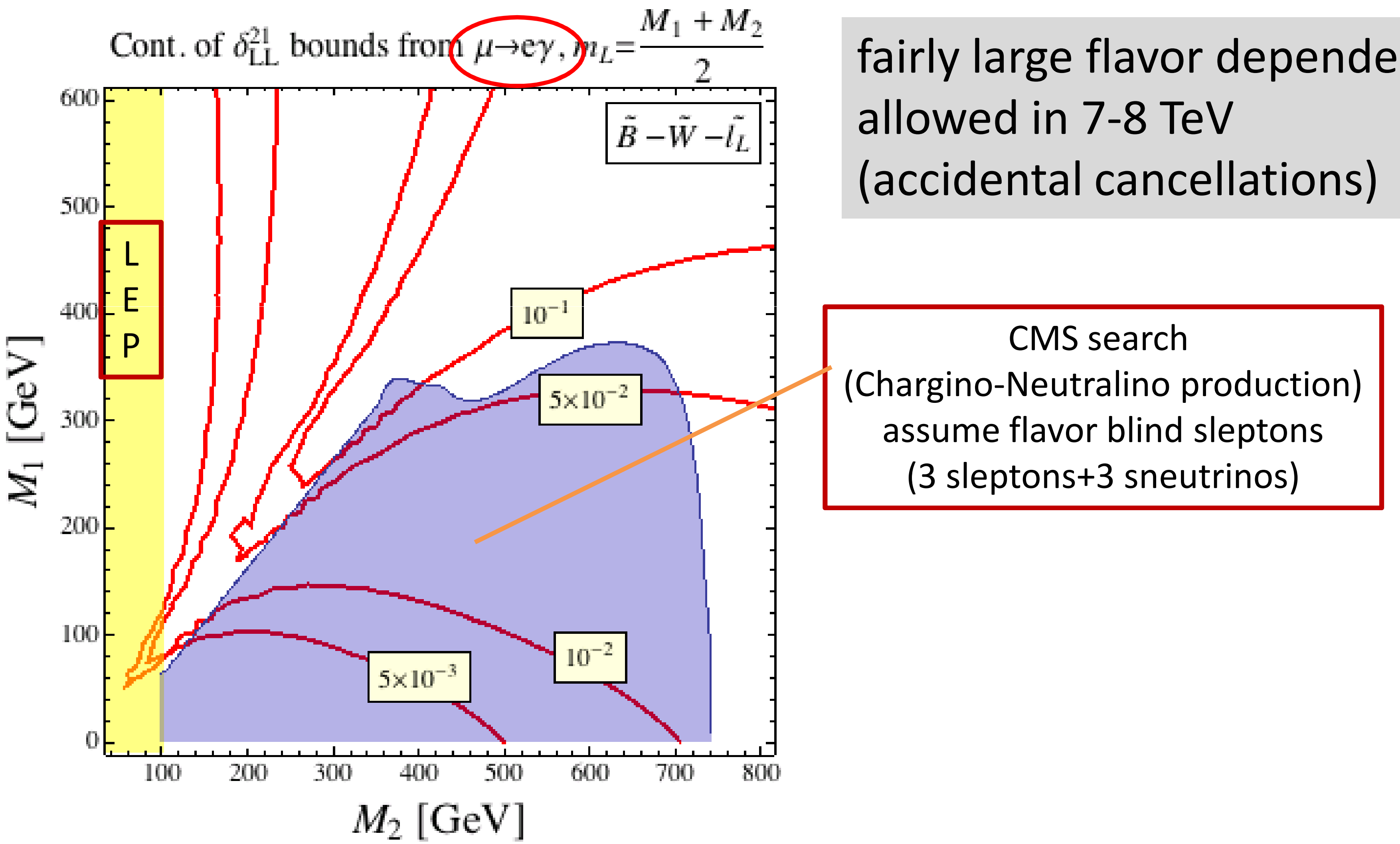


ATLAS search (Drell-Yan)
assume flavor blind selectron, smuon

projected 14 TeV

Eckel Ramsey-Musolf Shepherd Su 1408.2841

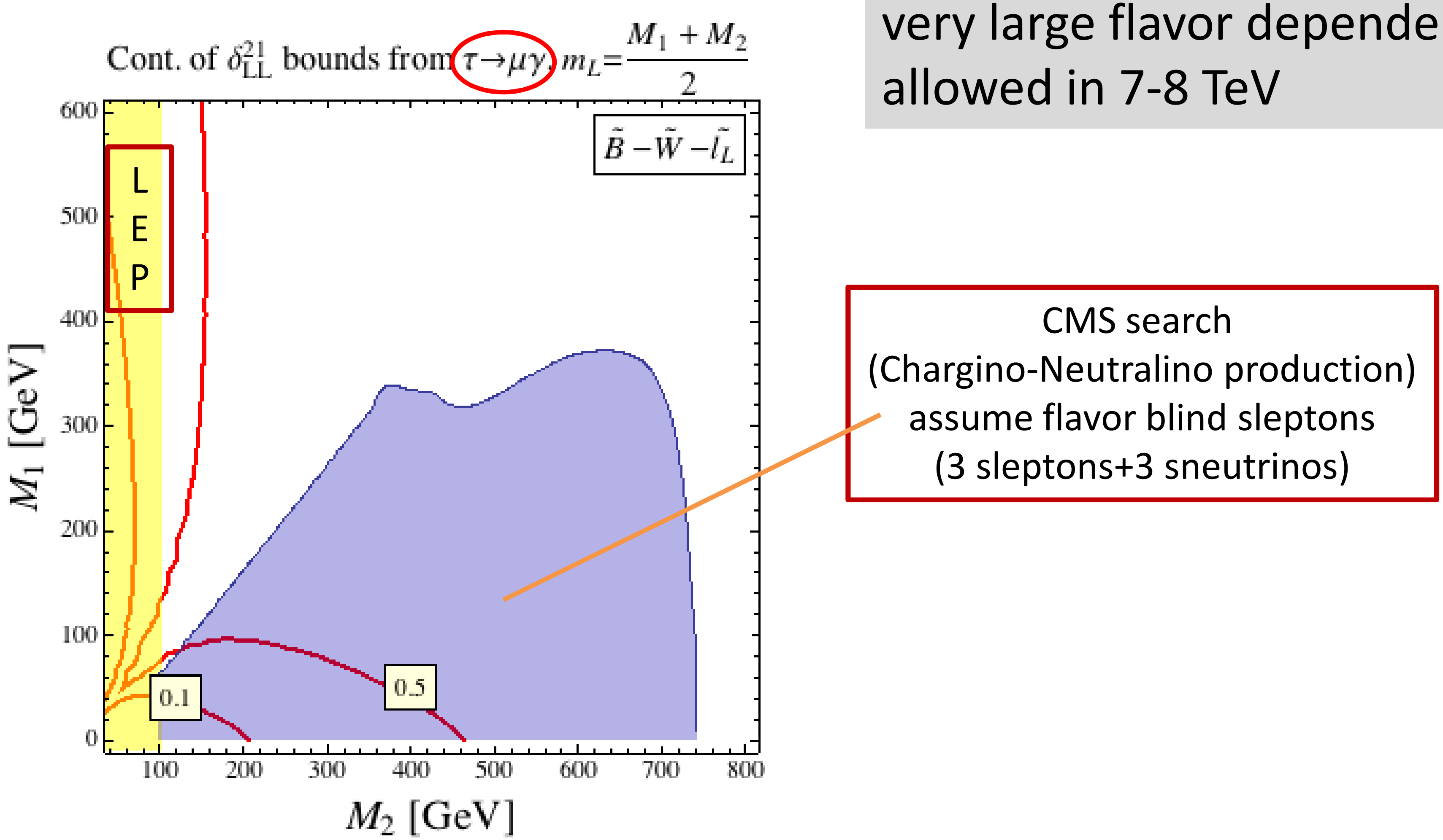
2nd example: L-sleptons (selectron-smuon) + bino +wino



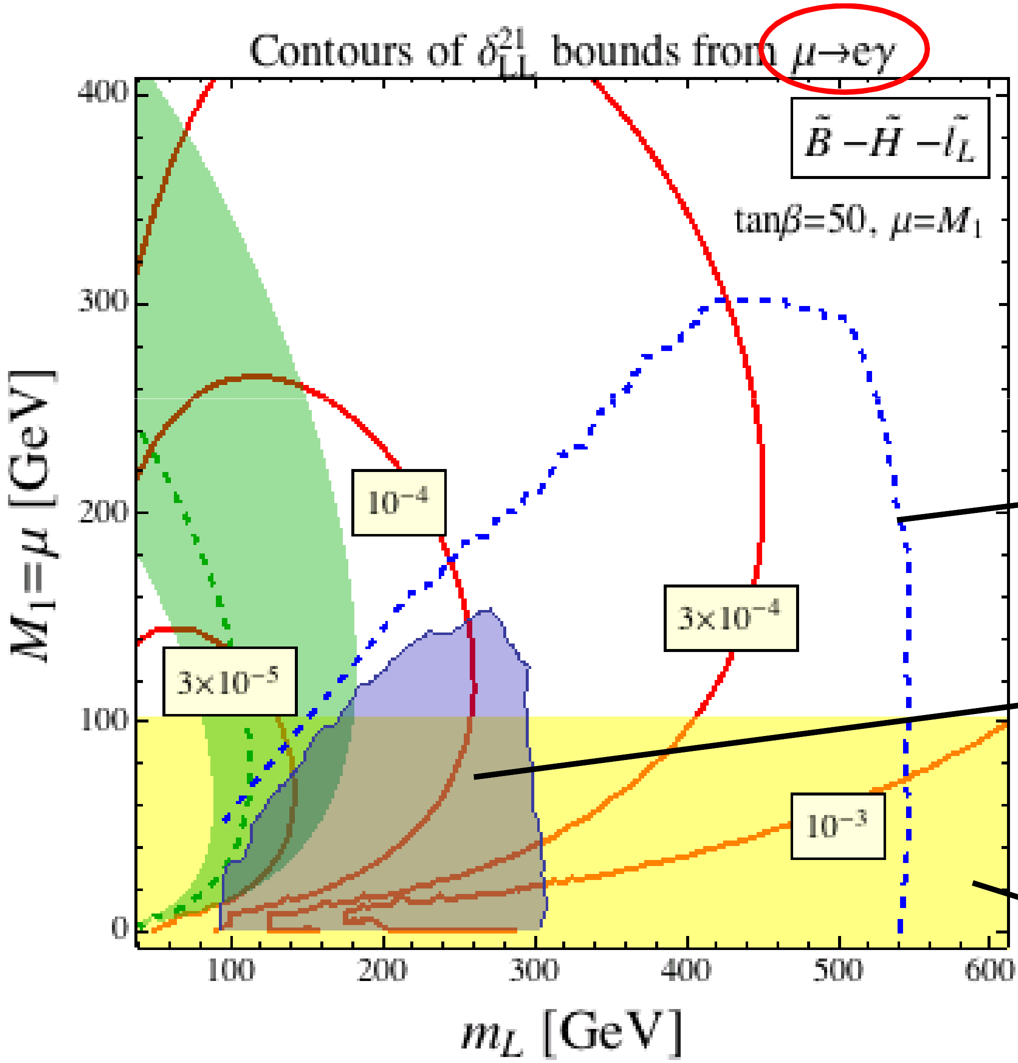
fairly large flavor dependence
allowed in 7-8 TeV
(accidental cancellations)

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

very large flavor dependence allowed in 7-8 TeV



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



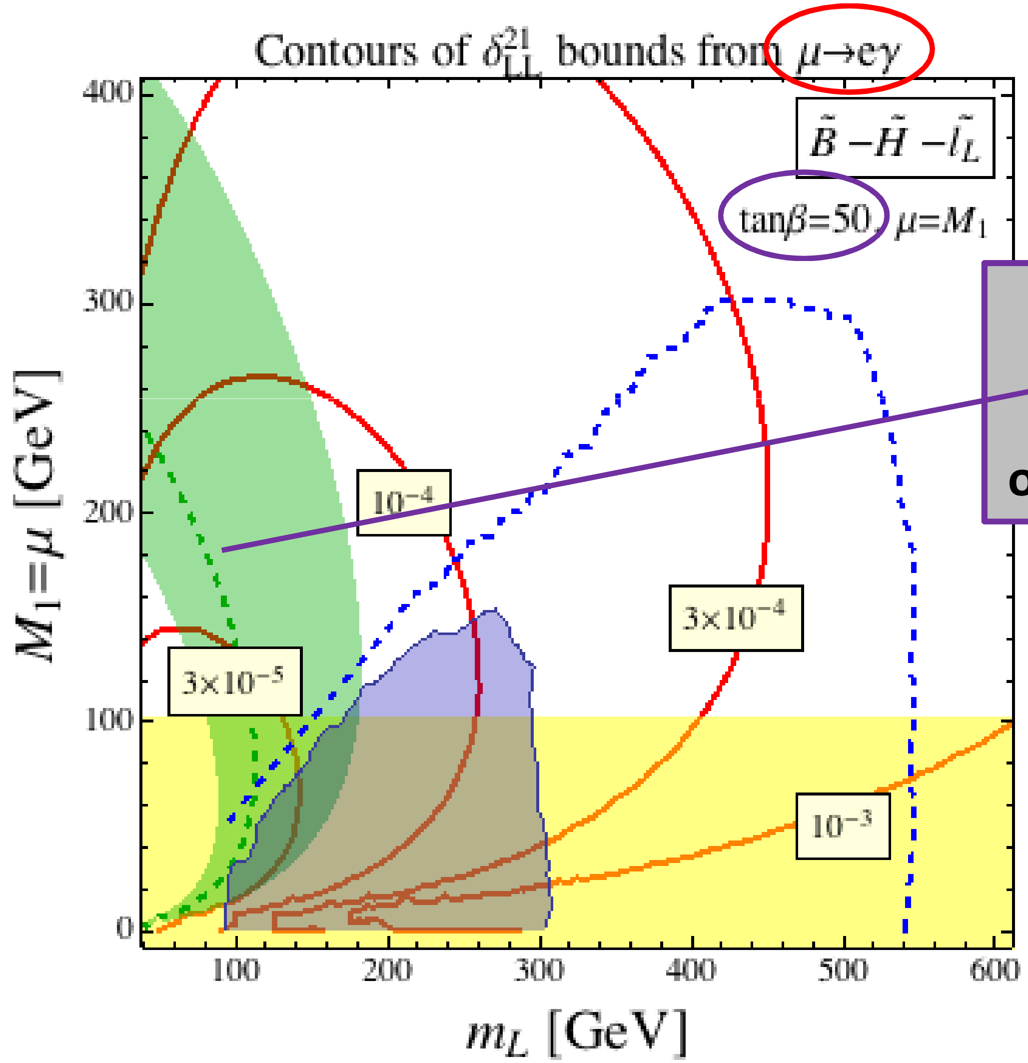
projected 14 TeV

Eckel Ramsey-Musolf Shepherd Su 1408.2841

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

LEP

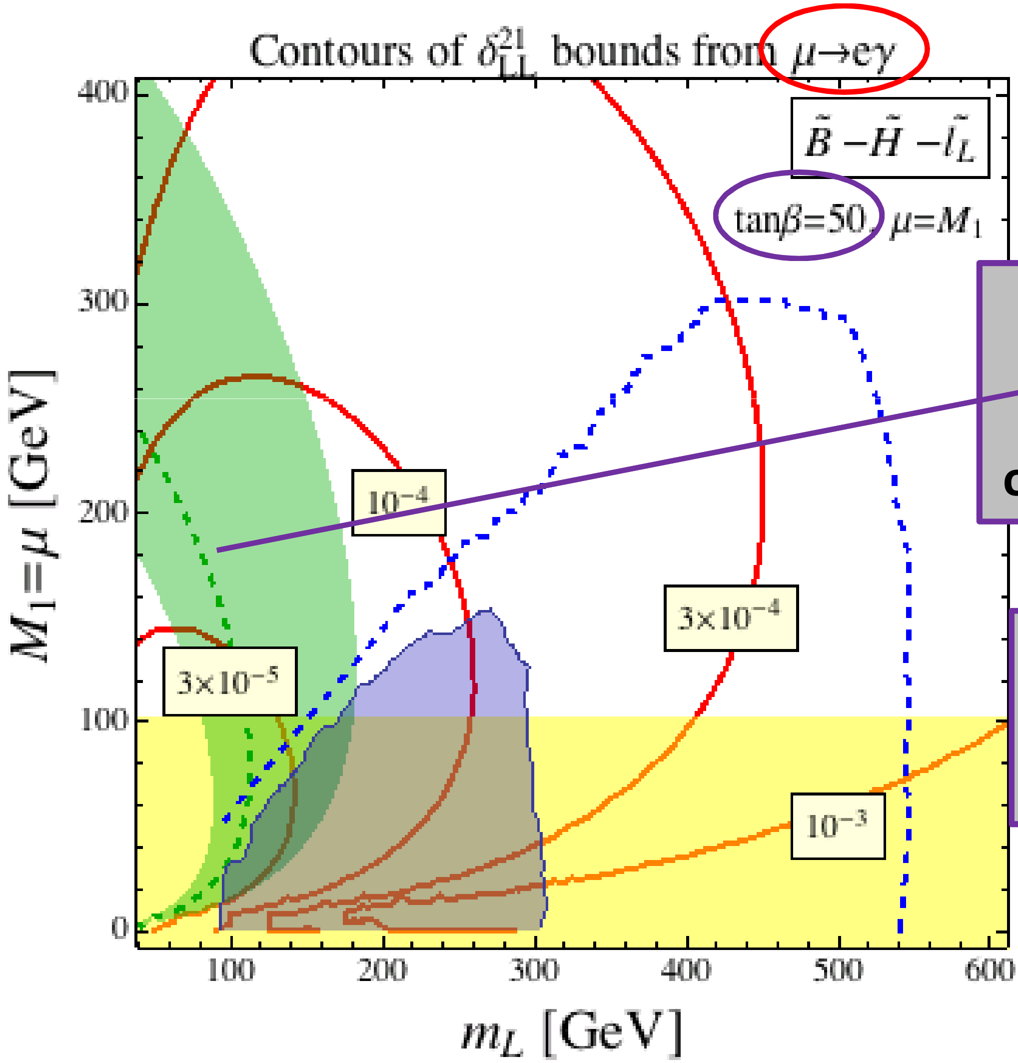
3rd example: L-sleptons (selectron-smuon) + bino +**higgsino**



g-2
motivates choice of tanbeta

otherwise limits weaker by 50/tanbeta

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



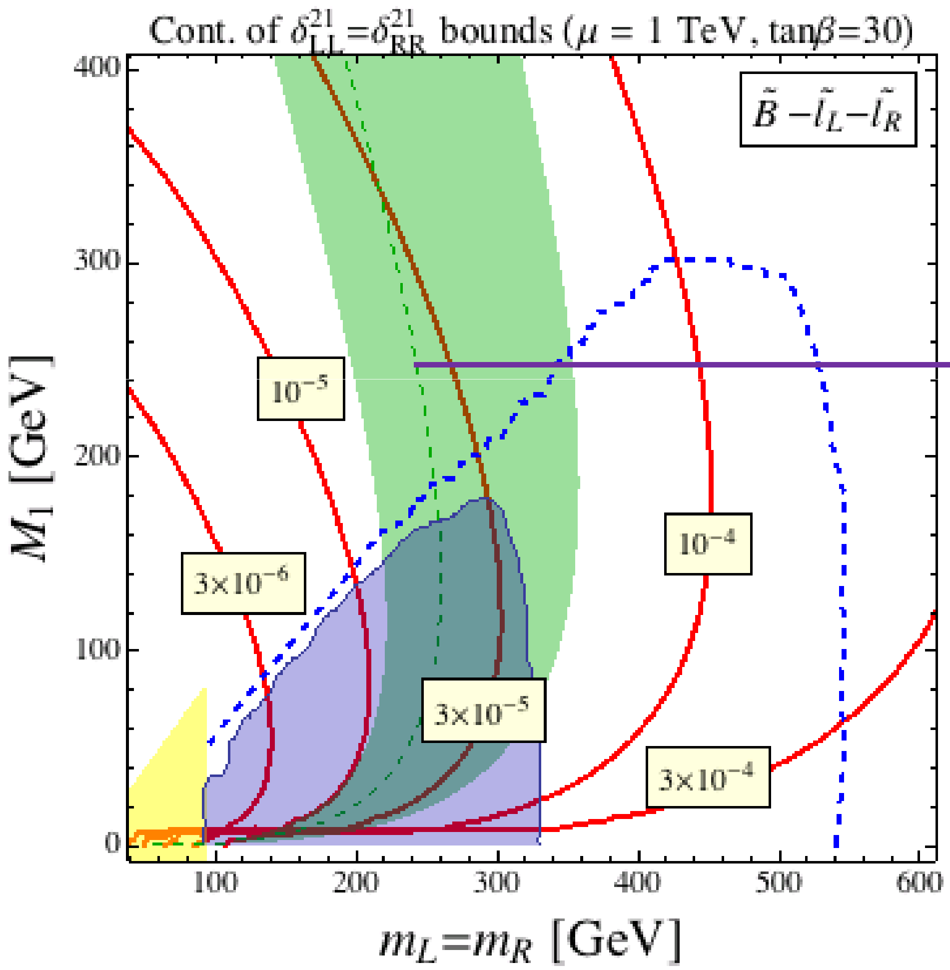
g-2
motivates choice of tanbeta

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)

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

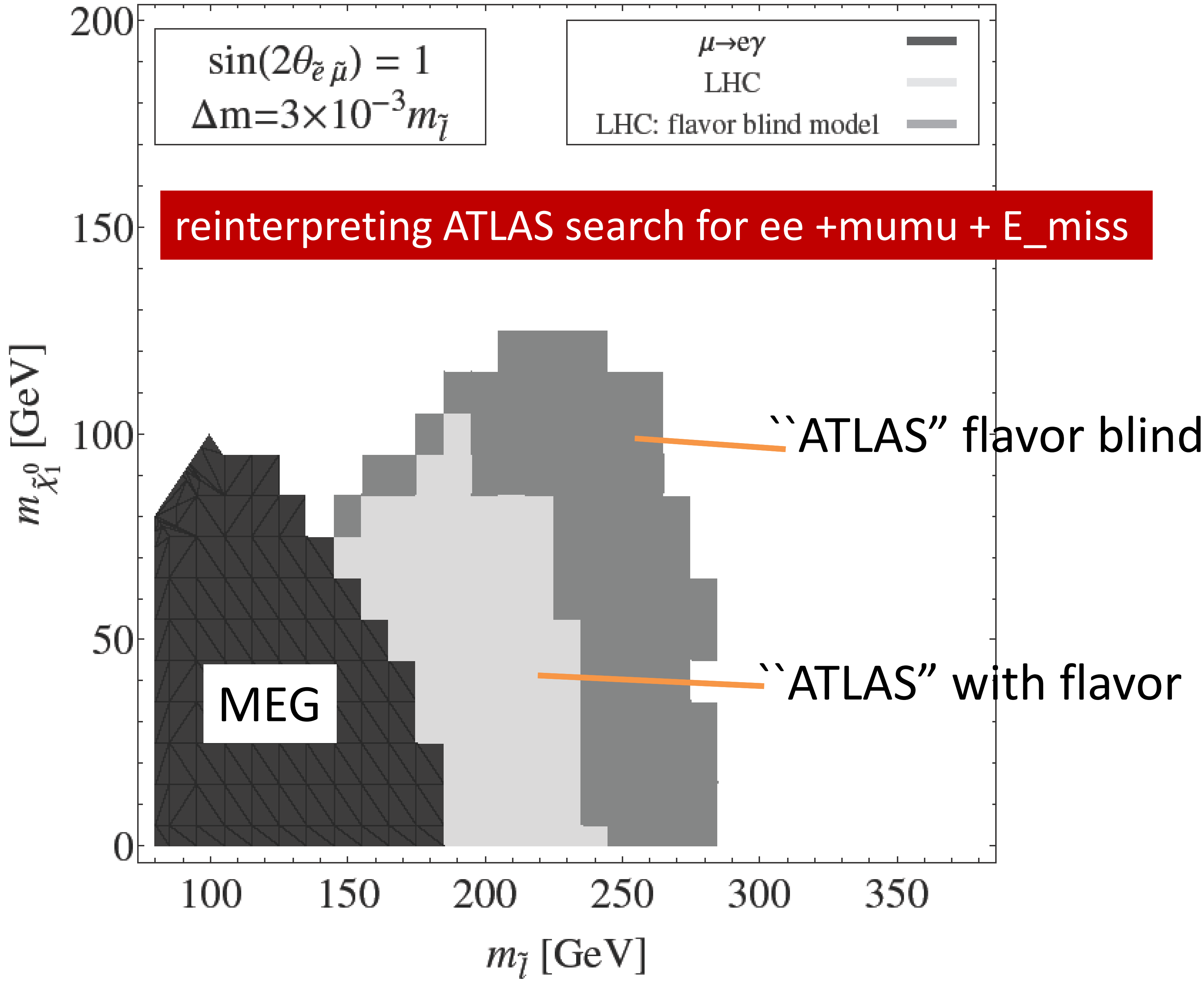
small mixing: same final state (SFOS) but different numbers of e+e- and mu+mu-

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

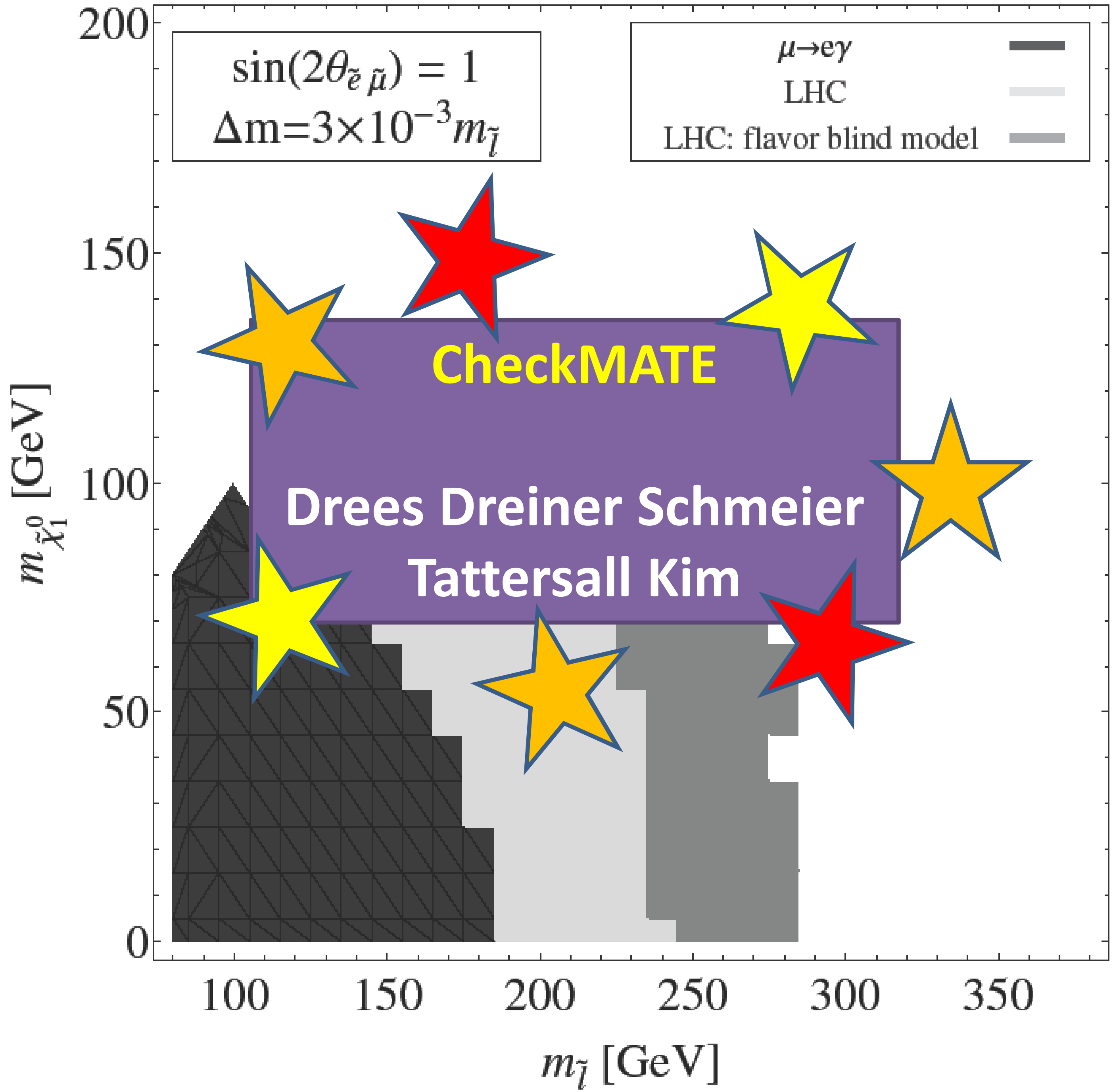
mass splittings + mixings

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]



$\sin(2\theta_{\tilde{e}\,\tilde{\mu}}) = 1$
$\Delta m = 3\times10^{-3} m_{\tilde{l}}$
$\mu\to e\gamma$
LHC
LHC: flavor blind model
CheckMATE
Drees Dreiner Schmeier
Tattersall Kim
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{l}}$ [GeV]
0
50
100
150
200
100
150
200
250
300
350

chargino-neutralino production:

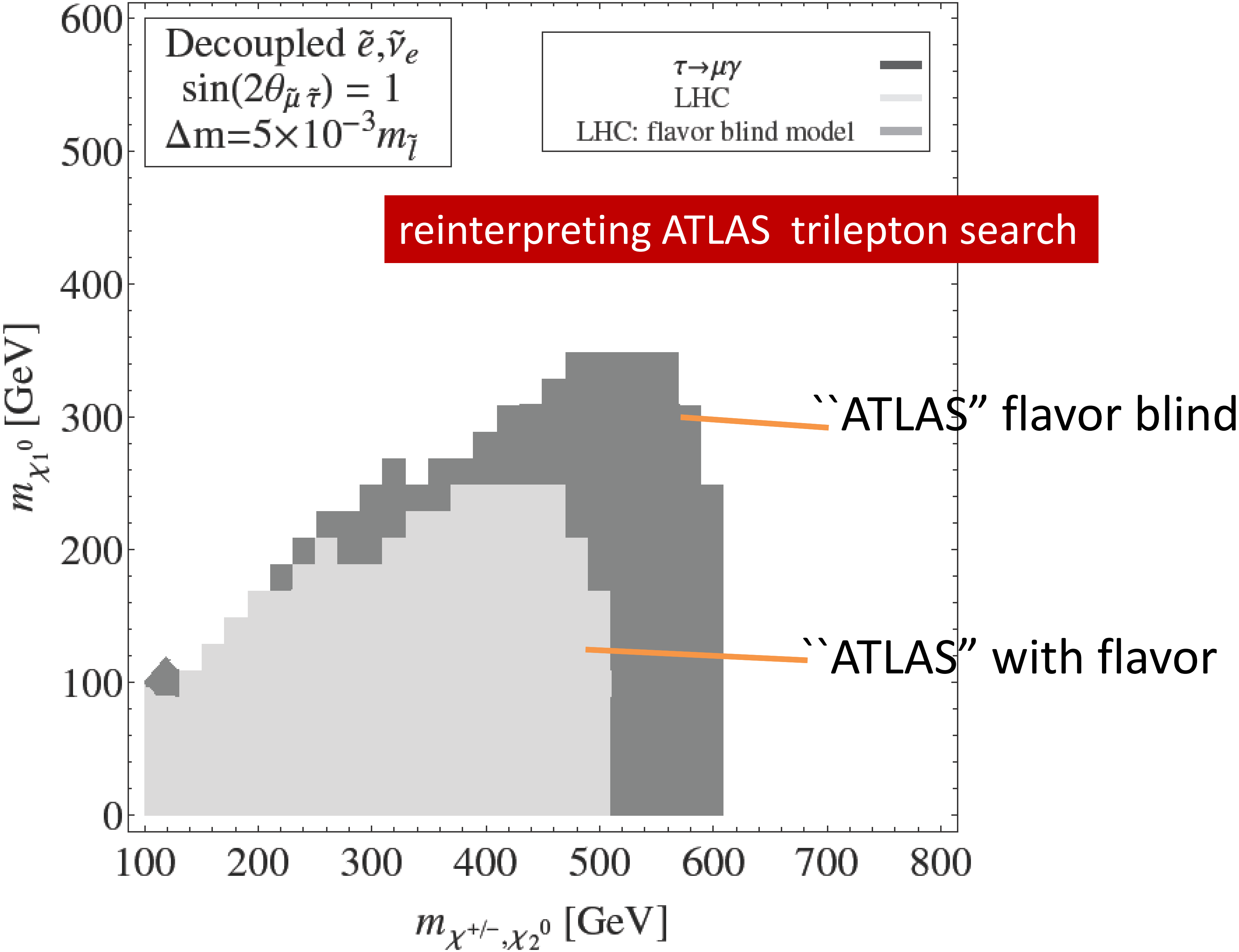
(search assumes wino > L-sleptons (6) > bino)

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

sensitivity 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
600
500
400
300
200
100
0
100
200
300
400
500
600
700
800
$m_{\chi_1{}^0}$ [GeV]
$m_{\chi^{+/-},\chi_2{}^0}$ [GeV]

theory origin? models?

Flavored Gauge Mediation

YS Szabo 1103.0922

gauge mediated SUSY breaking (GMSB)

- beautiful: concrete model, MFV
- in trouble:
  - direct searches (+ EWK searches: EWK << colored)
  - no A-terms → no LR stop mixing → heavy stops

    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

[MFV: Chacko Ponton 2001]

[seesaw: Brignole Joaquim Rossi 2006]

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

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

squarks

squarks **sleptons**

- contributions to scalar masses-squared
  negative in large parts of parameter space
- A terms

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

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

3x3 matrix: new contributions to soft terms

if arbitrary structure: flavor disaster

any mechanism that explains lepton and quark masses → slepton and squark masses

YS Szabo 1103.0922

flavor dependent slepton masses

YS Szabo 1103.0922

- spurion expansion: $Y_L, \quad y_L \qquad SU(3)_L \times SU(3)_e$
- with eg flavor symmetry determining the structure of these spurions

→slepton mass splittings and mixings

already saw impact on LHC searches

also kinematic edges

Galon YS

moving on to **squarks:**

flavor important for LHC searches:

Mahbubani Papucci Perez Ruderman Weiler

- production: dominated by u, d squarks
  (unless gluino very heavy)
- detection:
  - efficiency goes up with squark mass (more missing energy)
  - stops: if mixed with other squarks: efficiency goes down

Blanke Giudice Paradisi Perez Zupan

simplest example:
MFV-**like** models

YS Szabo

Abdullah Galon YS Shirman

★ Ierushalmi Nepomnyashy YS (in progress)

Calibbi Paradisi Ziegler

$$W = Y_U H_U qu + \ldots$$

$$+ y_U \bar{D} qu + \ldots$$

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

realization: U(1) flavor symmetry

Ierushalmi Nepomnyashy YS

Higgses, messengers: same (zero) U(1) charge

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

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

flavor: only interesting is 3rd generation

- large 33 entry: new contributions to stop mass
  possible hierarchy between stop and other squarks

- but note: O(lambda) stop-scharm mixing

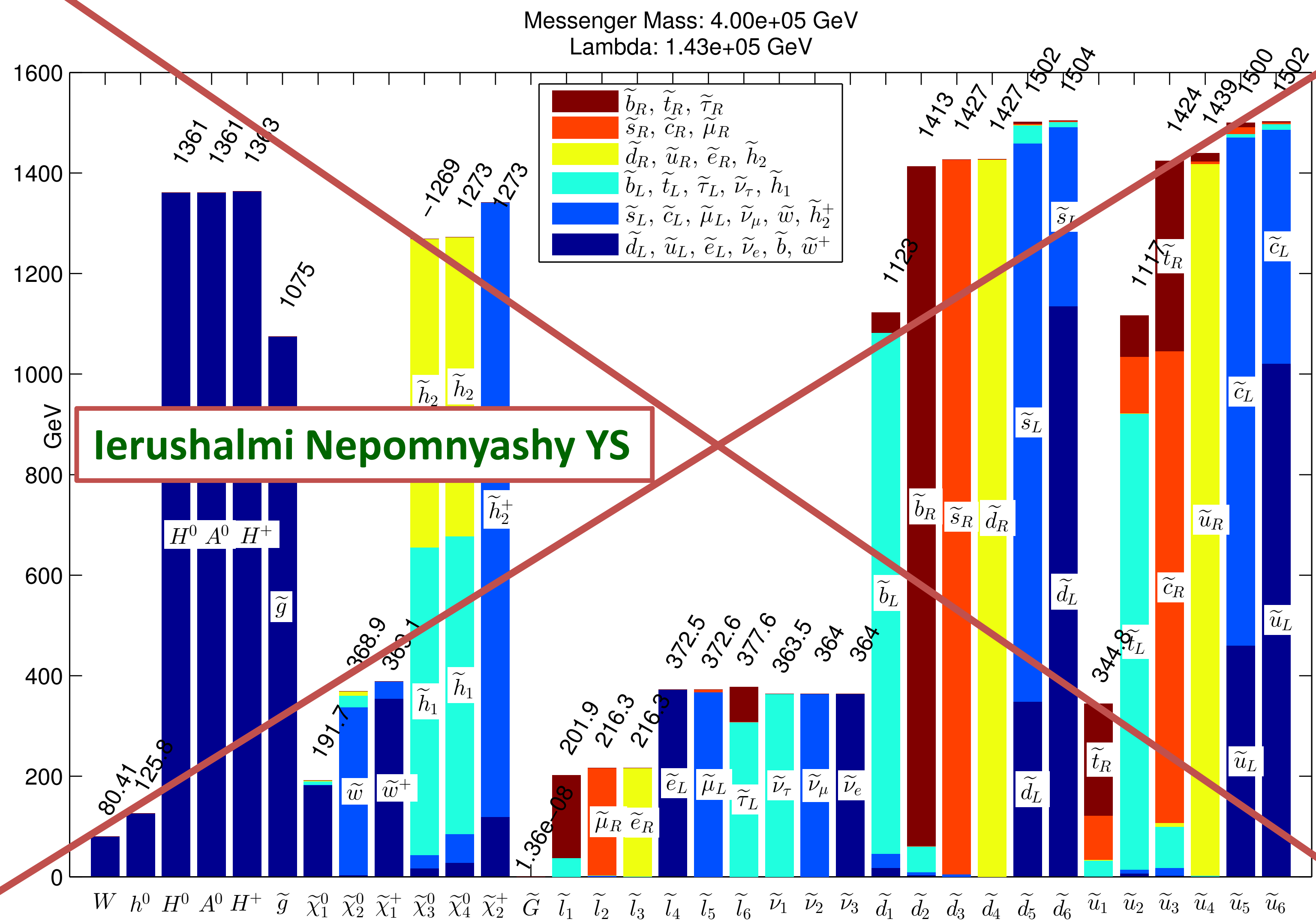
- [stop splitting: large hypercharge contributions
  in RGEs: sleptons pushed down]

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

- large 33 entry: new contributions to stop mass

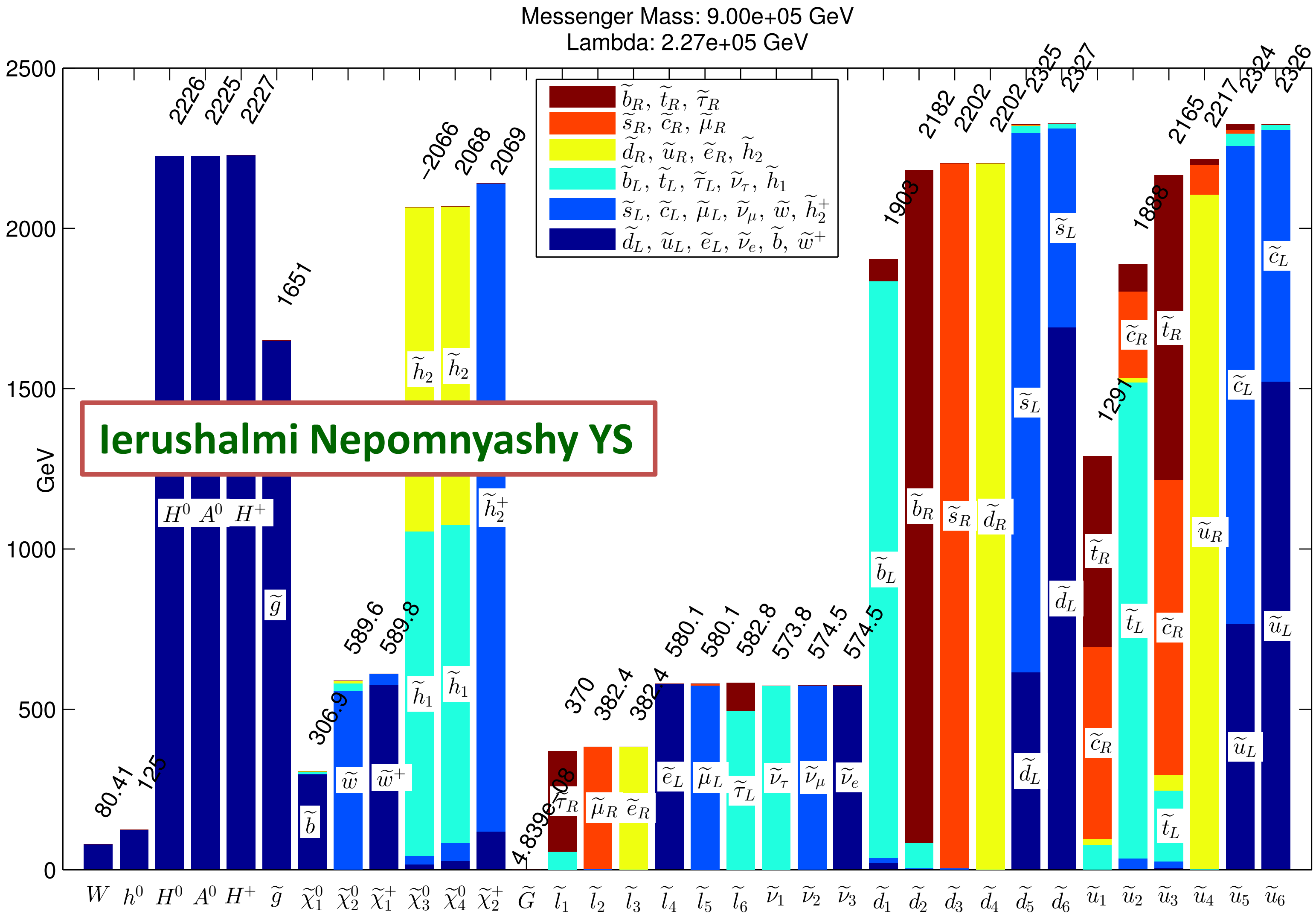
  + large stop A-term → Higgs mass

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
…



125 GeV Higgs
with light spectrum

very light stop
large stop-charm mix



125 GeV Higgs
with light spectrum

light
stop-charm mixture

{

2 comments on MFV(-like)

1) MFV-like: Y and y parametrically the same but not the same: sfermion mixing can be large

2 comments on MFV(-like)

2) Magic**F**lavor**V**iolation: M is not for MAGIC!

MFV is an ansatz unless something generates it:
as in GMSB, AMSB

or here flavor symmetry →Y and y parametrically the same

}

MFV-like: 1st 2nd generation squark masses essentially degenerate

(new couplings similar to Yukawas)

to obtain larger mass splittings:

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

examples with or without 125 GeV Higgs

(latter case: need extra ingredient eg NMSSM but small effect on squark flavor)

realization: U(1)xU(1) flavor symmetry

Galon Perez YS
Ierushalmi Nepomnyashy YS

Higgses: zero U(1) charge

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

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alignment in 1-2

realization: U(1)xU(1) flavor symmetry

Galon Perez YS
Ierushalmi Nepomnyashy YS

Higgses: zero U(1) charge

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

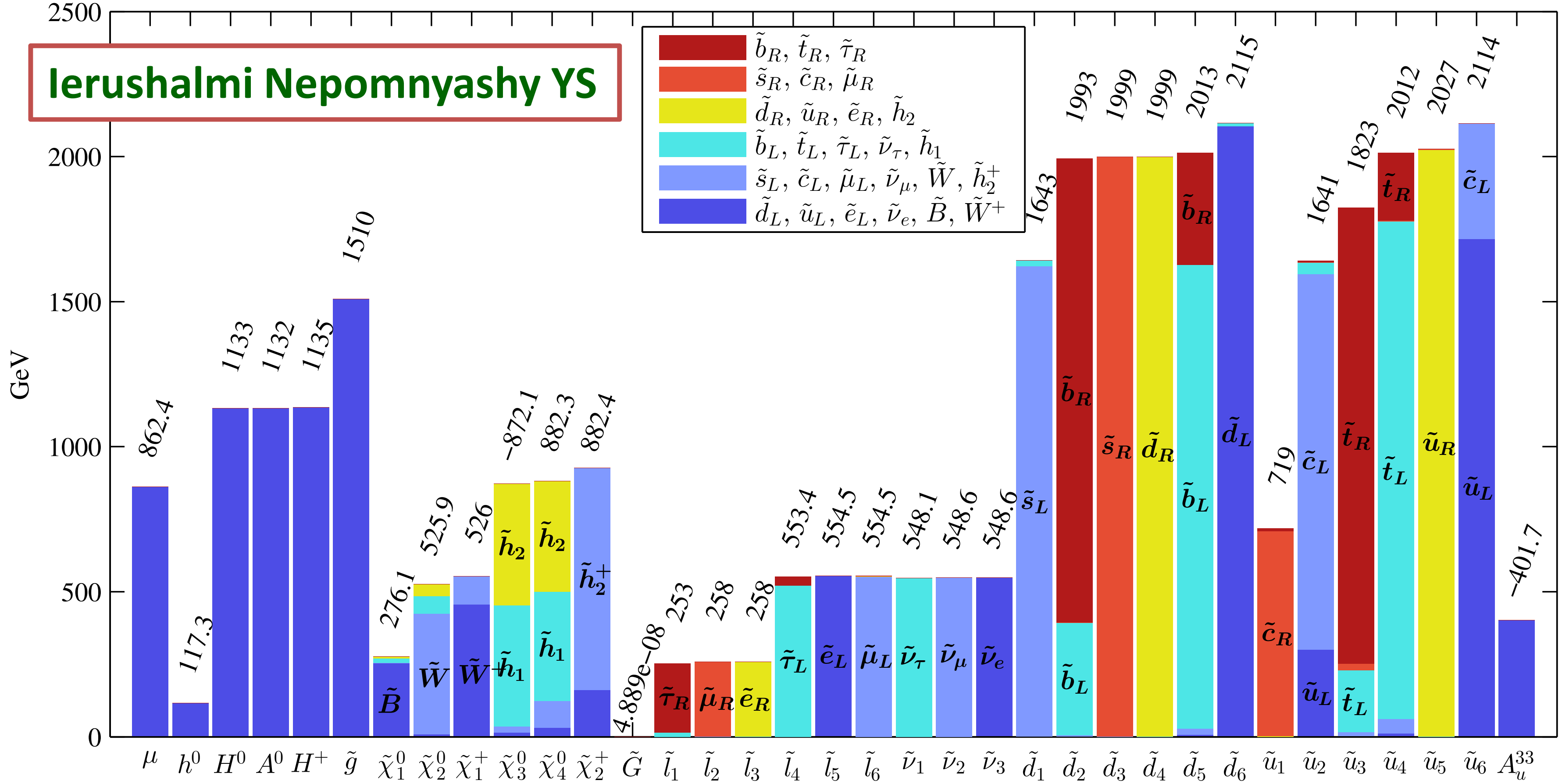
messenger has different charges: (-1,-2):

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

→ only affect scharm masses

(mixings only from SM Yukawas: note 32)

Ierushalmi Nepomnyashy YS



light scharm

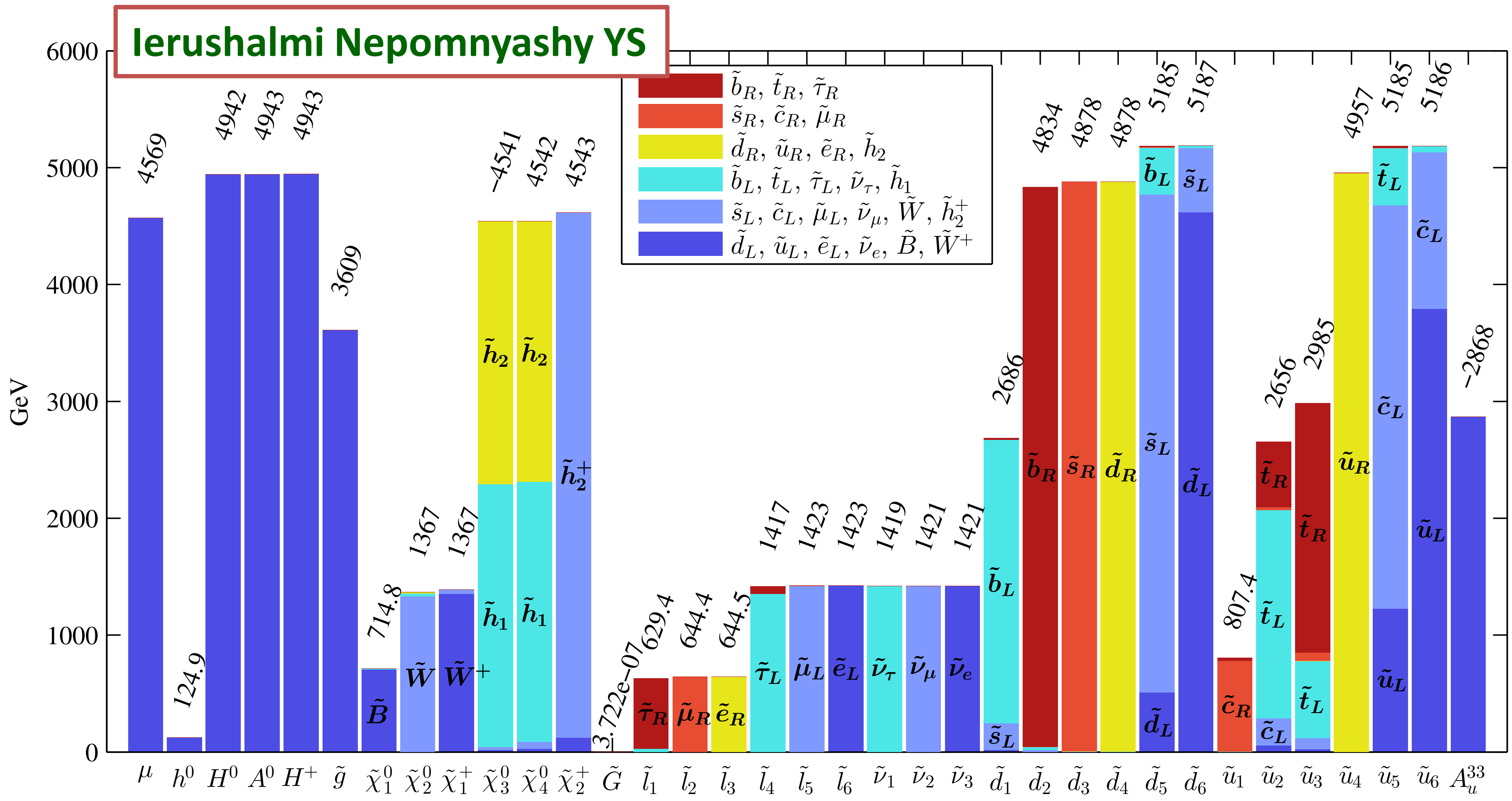
realization: U(1)xU(1) flavor symmetry

Higgses: zero U(1) charge

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

messenger has different charges (-1,0):

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



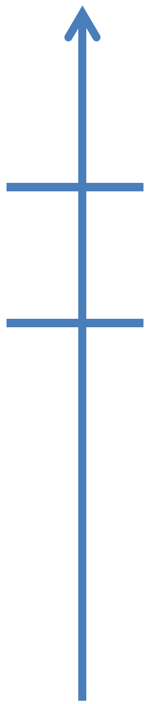
Higgs mass driven by very heavy stops + rest

only light: scharm

flavor constraints: alignment sometimes at play but

``supersymmetric alignment”:

flavor symmetry controls superpotential coupling y



flavor symmetry broken: y determined

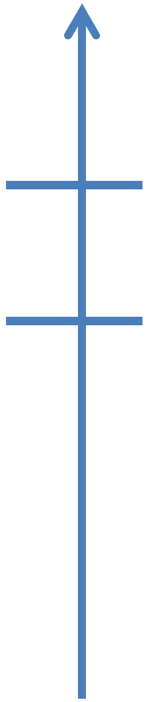
SUSY scale=messenger scale:
soft masses generated

can be low scale!

vs original alignment models: high scale SUSY breaking:

Nir Seiberg

SUSY breaking scale must be ABOVE flavor scale



SUSY scale: soft masses generated

flavor symmetry broken

RGE: large universal contribution from gluino mass

→ $$\frac{\Delta m}{m} \leq 0.15$$

→ messenger scale can be low

→ no large (universal) RGE gluino contribution:

→ **much larger mass differences possible**

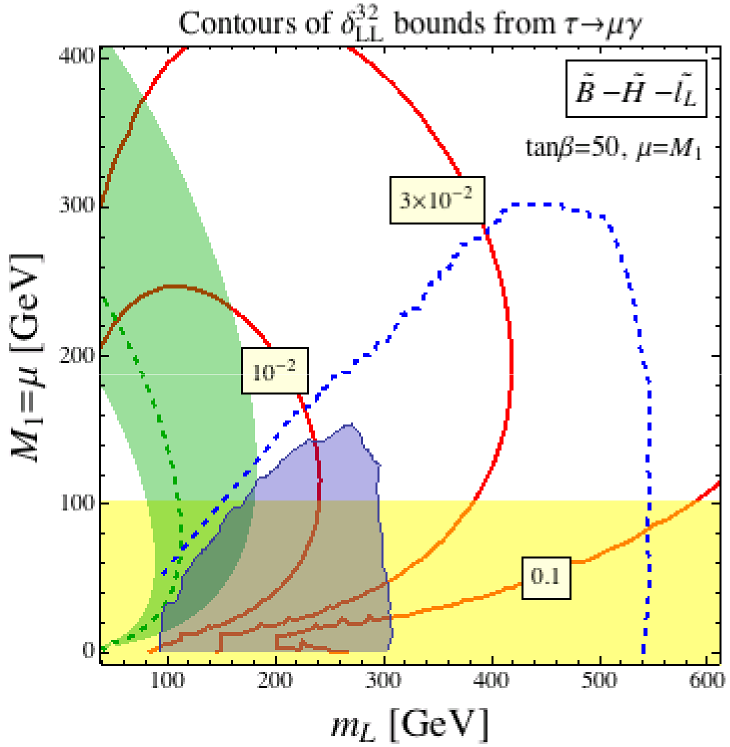
(in high scale models only 10-20%)

To conclude:

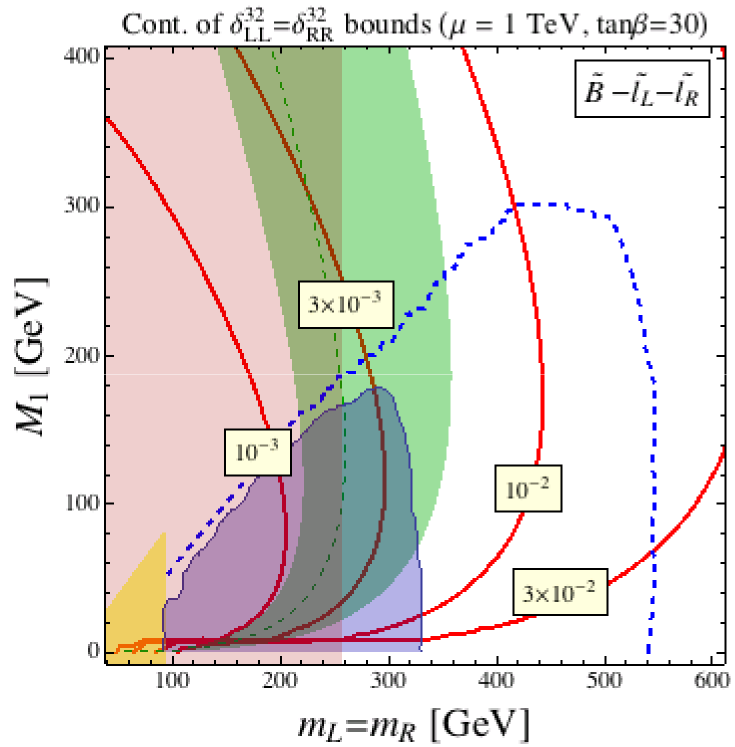
should think about sfermion flavor:

- fermion flavor motivates sfermion flavor
- sfermion flavor (if there) will teach us about the flavor puzzle
- sfermion flavor can affect LHC SUSY searches
- without too many assumptions about SUSY (haven't had much luck so far): simplified model approach
- but real models exist, eg Flavored Gauge Mediation (and no M for Magic..)

thank you!



Contours of δ_{LL}^{32} bounds from $\tau \to \mu\gamma$
$\tilde{B} - \tilde{H} - \tilde{l}_L$
$\tan\beta=50,\ \mu=M_1$
3×10^{-2}
10^{-2}
0.1
$M_1=\mu$ [GeV]
m_L [GeV]
0
100
200
300
400
500
600



Cont. of $\delta^{32}_{LL}=\delta^{32}_{RR}$ bounds (μ = 1 TeV, tanβ=30)
$\tilde{B}-\tilde{l}_L-\tilde{l}_R$
3×10^{-3}
10^{-3}
10^{-2}
3×10^{-2}
M_1 [GeV]
$m_L=m_R$ [GeV]
0
100
200
300
400
500
600