The SUSY lepton-flavor portal: at dedicated CLFV experiments and the LHC

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Technion

OUTLINE

- Introduction
- Lessons from dedicated CLFV experiments: concrete models with CLFV
- Lessons from LHC
- CLFV signatures at LHC:

    meta stable charged slepton NLSP

    neutralino LSP

1st order: Flavor measurements and challenges

0th order: Flavor and searches

CLFV and NEW PHYSICS

charged leptons masses: 0.0003 : 0.06 : 1

? new physics---underlying theory of flavor

[leptons mixings: not that strange on their own]

+ quark masses and mixings

this new (flavor) physics: any scale:

eg Froggatt-Nielsen, seesaw

if high scale: not directly testable

CLFV and NEW PHYSICS

→ observable CLFV: NEW PHYSICS at low scales:

new fields:

couplings to leptons

generation dependence

``low" mass around TeV *

* haven`t said a word about EWSB

CLFV and NEW PHYSICS

→ observable CLFV: NEW PHYSICS at low scales:

new fields:

FLAVOR PORTAL

couplings to leptons

generation dependence

``low mass" around TeV

if measure generation-dependent couplings

generation-dependent masses:

→ extra handles on NEW (flavor) PHYSICS

Possible TeV Flavor Portals

- more fields with SM generation structure

  SUSY, extra-dims

or:

- new states with LFV couplings

  Z`, Higgs, extended Higgs

Possible TeV Flavor Portals

- odd under some new parity:

  Rp SUSY, KKp Extra-dims..

  affect dedicated CLFV expts at loop level

  pair produced in colliders
- no new parity:

  can affect dedicated CLFV expts at tree level

  potentially: single particle production in colliders

CLFV and NEW PHYSICS

concrete example in this talk:

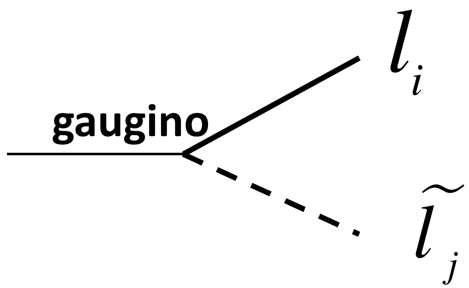
SUPERSYMMETRY

CLFV in SUSY: relevant parameters:

- sleptons: R, L

$$\tilde{l}_1,\ ..\ \tilde{l}_6\ :\quad m_1, ..., m_6$$

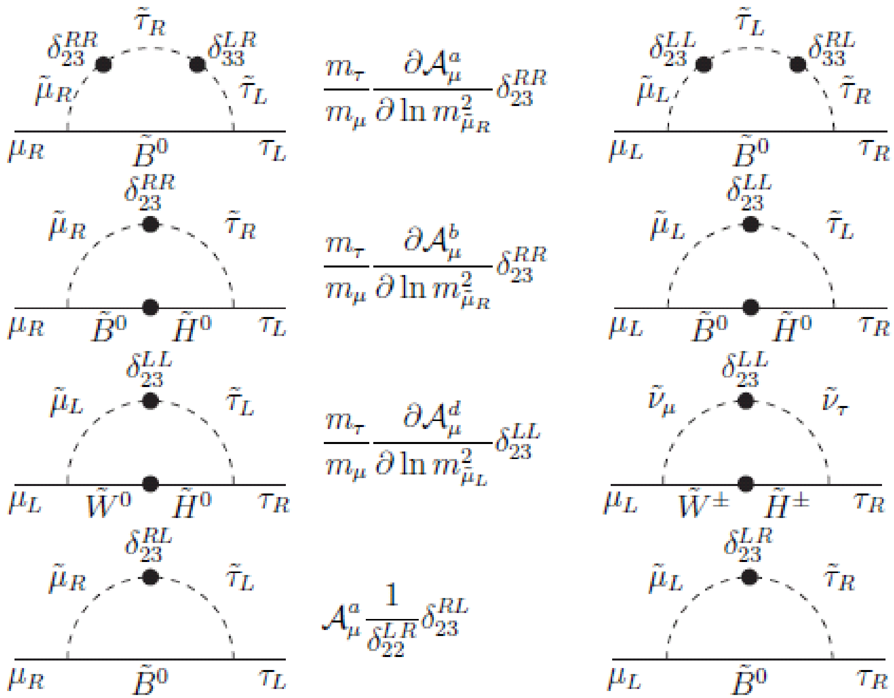
- EWK gauginos: with mixings



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

[squarks, gluinos: LHC production only]

relevant parameters:
radiative decays, lepton flavor conversion



$$\frac{m_\tau}{m_\mu}\frac{\partial \mathcal{A}^a_\mu}{\partial \ln m^2_{\tilde{\mu}_R}}\delta^{RR}_{23} \qquad \frac{m_\tau}{m_\mu}\frac{\partial \mathcal{A}^a_\mu}{\partial \ln m^2_{\tilde{\mu}_L}}\delta^{LL}_{23}$$

$$\frac{m_\tau}{m_\mu}\frac{\partial \mathcal{A}^b_\mu}{\partial \ln m^2_{\tilde{\mu}_R}}\delta^{RR}_{23} \qquad \frac{m_\tau}{m_\mu}\frac{\partial \mathcal{A}^c_\mu}{\partial \ln m^2_{\tilde{\mu}_L}}\delta^{LL}_{23}$$

$$\frac{m_\tau}{m_\mu}\frac{\partial \mathcal{A}^d_\mu}{\partial \ln m^2_{\tilde{\mu}_L}}\delta^{LL}_{23} \qquad \frac{m_\tau}{m_\mu}\frac{\partial \mathcal{A}^e_\mu}{\partial \ln m^2_{\tilde{\nu}_\mu}}\delta^{LL}_{23}$$

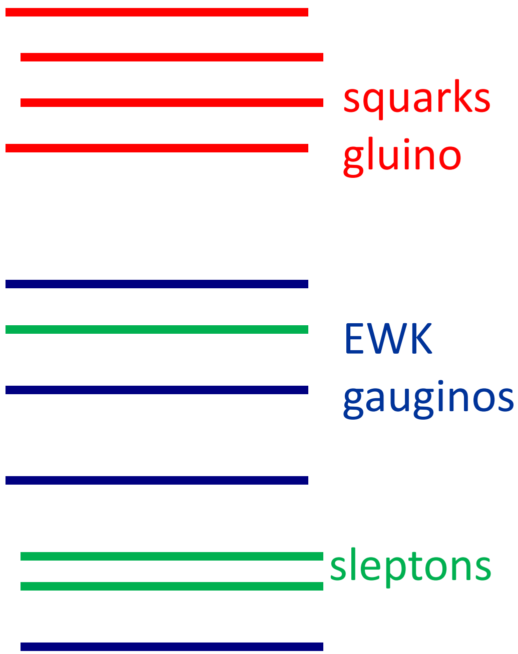
$$\mathcal{A}^a_\mu\frac{1}{\delta^{LR}_{22}}\delta^{RL}_{23} \qquad \mathcal{A}^a_\mu\frac{1}{\delta^{LR}_{22}}\delta^{LR}_{23}\,, \qquad (20)$$

gaugino masses and composition:

light/heavy Higgsinos [mu term]

R-sleptons: only couple to bino, Higgsino

relevant parameters: LHC



``only" affect production cross-section

gaugino masses and composition:

light/heavy Higgsinos, mu term

R-sleptons: only couple to bino, Higgsino:

→ small Br's

also: orderings among sleptons, gauginos

❖ neutralino LSP or slepton NLSP

CLFV in SUSY

dedicated CLFV expts essentially constrain:

$$\frac{1}{m^2} \frac{\Delta m_{ij}^2}{m^2} K_{ij}$$

- for relative mass splittings, mixings 10% currently probe masses around the TeV

SUSY Flavor Assumptions

traditonally (theory+pre LHC):

- physics of EWSB (fine tuning)

→ scale set by fine tuning: colored particles especially stops below TeV

- sleptons from strong production + cascade decays (since lighter in virtually all models)

SUSY Flavor Assumptions

- Flavor-blind or Minimally Flavor Violating (MFV)

  really the case in GMSB, gMSB, AMSB

  ansatz in mSUGRA CMSSM

→underlying assumptions in many searches:

1^{st}, 2^{nd} generations degenerate; no mixing

but **overkill:** CONCRETE, calculable models with CLFV potentially observable

and there are neutrinos too:

neutrino mixing: in many frameworks

→ large (L) slepton mixing

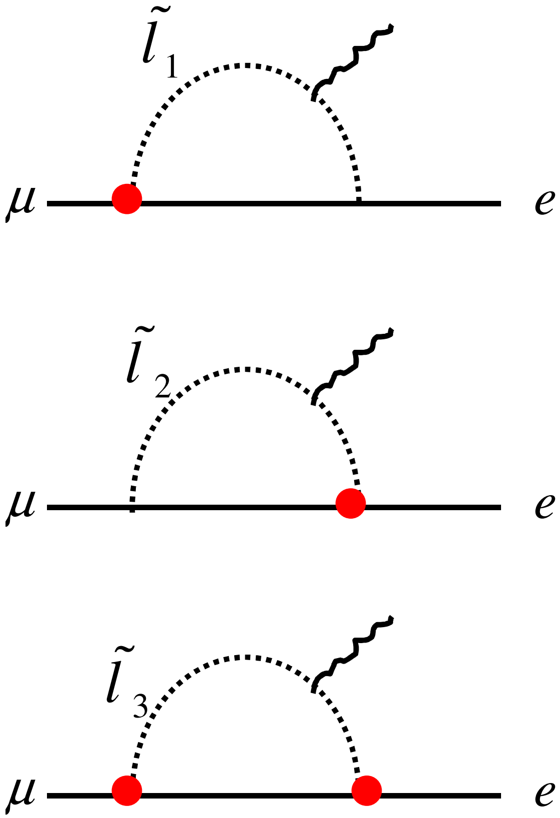
cMSSM + seesaw

pure alignmemmt with Abelian flavor symm

high-scale GMSB with RGE effects above messenger scale

high-scale GMSB + seesaw messengers

Suppressing SUSY CLFV
(a model building guide)



essentially constrains:

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

Suppressing SUSY CLFV (0^{th} order)

3 obvious approaches:

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

or combination

1. degeneracy: slepton mass matrix proportional to identity

2. alignment: slepton mass matrix "aligned" with lepton mass matrix: approximately diagonal **Nir Seiberg**

3. all sleptons or just 1^{st}, 2^{nd} generations heavy

Effective SUSY **Cohen Kaplan Nelson; Dvali Pomarol 96**

aka Natural SUSY **Brust Katz Lawrence Sundrum …**

not observable at LHC

unforunately: already taken care of by Nature ..

models with combination of degeneracy and alignment

- Hybrid models: GMSB + Planck suppressed contributions
  Feng Lester Nir YS

  (high scales only)
- AMSB + Planck suppressed contributions

  (high scales only)
  Gross-Hiller
- Flavored Gauge Mediation: GMSB with matter-messenger couplings
  YS Szabo

  (also important for Higgs mass) Abdullah Galon YS Shirman

quark flavor: Calibbi Paradisi Ziegler

$$m^2_{slepton} = \text{GMSB} + \text{something else}$$

$$\# \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{F}{M_{mess}}\right)^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **Hybrid models:** SUB-DOMINANT Planck suppressed operators: in principle arbitrary texture: but aligned with SM Yukawa

- **Flavored Gauge Mediation:** contribution of messenger-lepton coupling (analog of SM Yukawa); new coupling aligned with SM Yukawa (**fully calculable in terms of new coupling**→ signs known)

$$m^2_{slepton} = \text{GMSB} + \text{something else}$$

$$\# \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{F}{M_{mess}}\right)^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **Hybrid models:** Planck suppressed operators: in principle arbitrary texture: but aligned with SM Yukawa
- **Flavored Gauge Mediation:** contribution of messenger-lepton coupling (analog of SM Yukawa); fully calculable; new coupling aligned with SM Yukawa

FN Flavor symmetry (fermion masses)

up to order-1 coeffs

- **Hybrid models:** soft terms controlled by flavor symmetry
  (as in original alignment)
  high scale

- **Flavored Gauge Mediation:**
  new (superpotential) couplings controlled by flavor symmetry
  high or low scales

Suppressing SUSY CLFV
(beyond 0^{th} order)

- loops involve EW gauginos:

→ make (some) EW gauginos heavy

(with sleptons still light)

R-symmetric models (Dirac gauginos)

Kribs Poppitz Weiner

Fox Nelson Weiner

Suppressing SUSY CLFV
(beyond 0^{th} order)

- radiative decays require chirality flip:

  in bino diagrams: on slepton line

  → make A-terms small

  pure GMSB

  Flavorful SUSY (relies on extra dim) Nomura Stolarski

  Higgsophobic supersymmetry breaking

  R-symmetric models (A terms forbidden)

  otherwise: chirality flip on gaugino line

  → make gauginos Dirac R-symmetric

CLFV expts implications

(a rough model building guide)

- generic feature of models above:

  small LR mixings (small A terms)
- main bounds on LL, RR
- for model guidelines: *overall picture*: instructive to state bounds parametrically in terms of flavor spurion

  lambda ~ 0.1--0.2

  [O(1) not determined by models; bounds vary over parameter space]

- scale with overall soft-mass

$$\delta \sim \tilde{m}^2 \sqrt{Br}$$

Process	Present Bounds
$BR(\mu \to e\,\gamma)$	1.2×10^{-11}
$BR(\mu \to e\,e\,e)$	1.1×10^{-12}
$BR(\mu \to e \text{ in Nuclei (Ti)})$	1.1×10^{-12}
$BR(\tau \to e\,\gamma)$	1.1×10^{-7}
$BR(\tau \to e\,e\,e)$	2.7×10^{-7}
$BR(\tau \to e\,\mu\,\mu)$	$2. \times 10^{-7}$
$BR(\tau \to \mu\,\gamma)$	6.8×10^{-8}
$BR(\tau \to \mu\,\mu\,\mu)$	2×10^{-7}
$BR(\tau \to \mu\,e\,e)$	2.4×10^{-7}

MEGA → MEG $5.7 \cdot 10^{-13}$

SINDRUM

SINDRUM II $7 \cdot 10^{-13}$

$3.3 \cdot 10^{-8}$

BaBar
BELLE

$4.4 \cdot 10^{-8}$

Ciuchini Masiero Paradisi Silvestrini Vempati Vives 0702144
Paradisi 0505046

$$\delta_{12}^{LL} \leq \lambda^4 \qquad \delta_{12}^{RR} \leq \lambda^2 \qquad \delta_{23}\ ,\ \delta_{13} \leq \lambda$$

$$(\delta_{23}^{LL}\ \delta_{13}^{LL} \leq \lambda^4)$$

$$\delta_{12}^{LL} \le \lambda^4 \qquad \delta_{12}^{RR} \le \lambda^2 \qquad \delta_{23}\ ,\ \delta_{13} \le \lambda$$

$$\delta_{23}{}^{LL}\ \delta_{13}{}^{LL} \le \lambda^4$$

Ciuchini Masiero Paradisi Silvestrini Vempati Vives 0702144
Paradisi 0505046

- main change: factor 5 improvement in delta12 !!
- but: more inputs:

CMSSM with squarks around 600 GeV
sleptons 400 GeV
gauginos below 150 GeV

- still: only care about sleptons, gauginos

1-2 relative mass splitting X mixing below 10^(-4) !!
and * potentially* observable !

Variety of models:

R-symmetric models:

full analysis of mu-e   Fok Kribs

mu to e gamma, mu to eee

* mu to e conversion (no chirality flip)

large selectron-smuon mass splitting

with mixings of 0.1 in most of parameter space

even maximal mixings in some wedges

Flavorful SUSY

Nomura Stolarski

Nomura Papucci Stolarski

mu-e mass splittings: O(0.01)

stau: O(1) splittings

fermion masses from 5th dimension

Brummer Fichet Kraml

colored particles above LHC reach, R-sleptons 500 GeV

mass splittings O(0.2) mixings O(0.1)

FGM, hybrid (degeneracy + alignment)

- R-sleptons: small mixings:
  12, 23 at few percent or below
  relative mass splittings up to O(1)
- L-sleptons:
  relative mass splitting O(1) with no mixing
  or: O(1) mixing with negligible splittings

  * in between: mass splittings and mixings of a few percent (LHC study)

- FGM: can be MFV-like: new coupling similar to Yukawa: mass splittings as in MFV but mixings of few percent
  largest effects naturally on selectron

Moral:

- different classes of concrete models with CLFV
- CLFV can be controlled by structure of model
- often saturating current bounds
- often related to mechanism which generates fermion masses:
- if measured in combination of LHC and low-E experiments: extra handles on underlying flavor theory

main question

low-E LHC interplay:

viable models with observable CLFV at LHC ?

SUSY Lessons from LHC

1. NO SUSY:

   [colored particles roughly above 1-1.5 TeV]

? because no SUSY: fine tuning

? because it`s around the corner: some degree of fine tuning

? because searches optimized for wrong models (flavor??)

Lessons from LHC (2)

Higgs! (compatible with SUSY)

but 125 GeV very hard in SUSY

- **MSSM**: generically:

heavy stops → **MFV models**: all squarks heavy

except in tuned corners of parameter space with

tanbeta ~ 50, large stop mixing

either entire spectrum pushed up

or: large hierarchy between colored, non-colored

stronger than direct searches!!

- large mu → heavy Higgsinos

  (affects CLFV constraints+

  LHC slepton production)

concrete MSSM models: GMSB:

no A terms → no stop mixing (only by RGE)

stops (+ squarks) around 8 TeV

FGM models:

new matter-messenger couplings can generate top A-term! 2 TeV stops, gluinos

sub-TeV sleptons, EWK gauginos

L-sleptons can be lighter than R-sleptons

(driven by new stop contributions)

- or beyond MSSM: modify Higgs couplings NMSSM (Higgsinos → CLFV bounds)

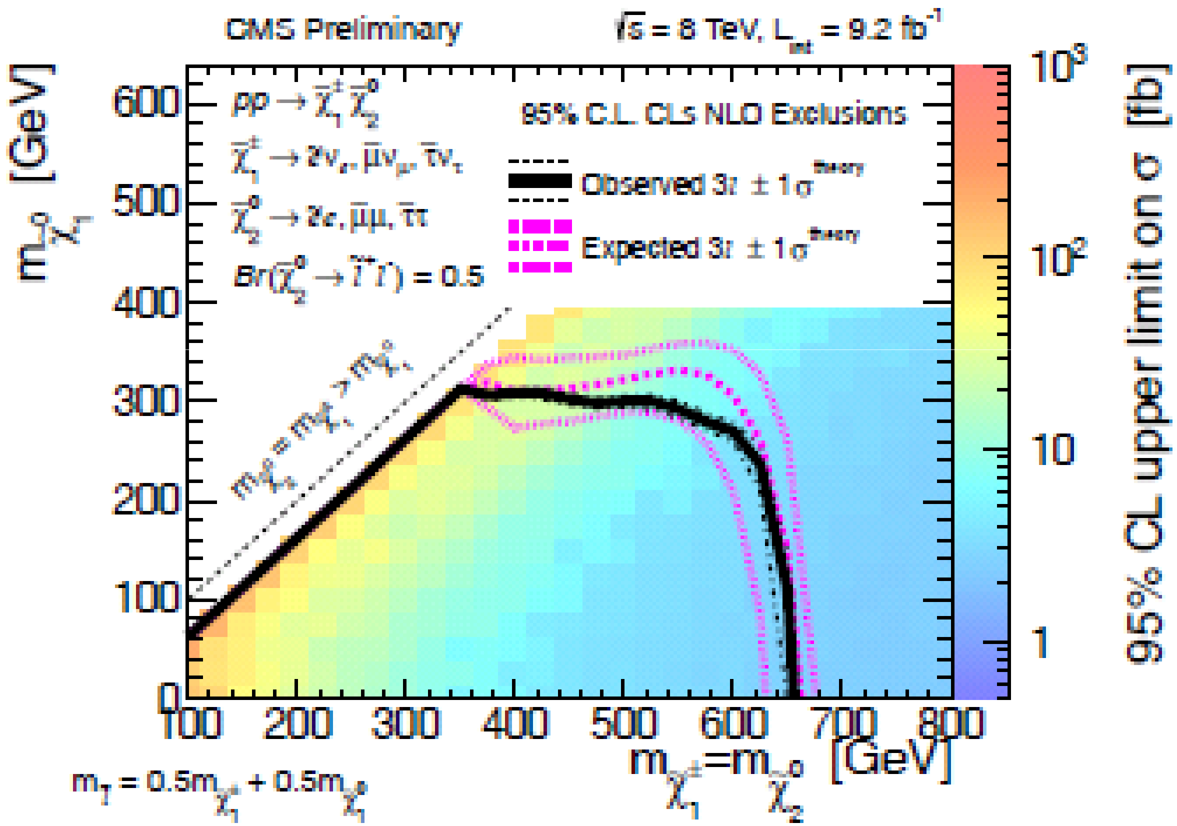
sleptons may be taking center stage:

EWK gaugino
pair production

(Drell-Yan)

EWK gaugino production (model independent) CMS

chargino neutralino production

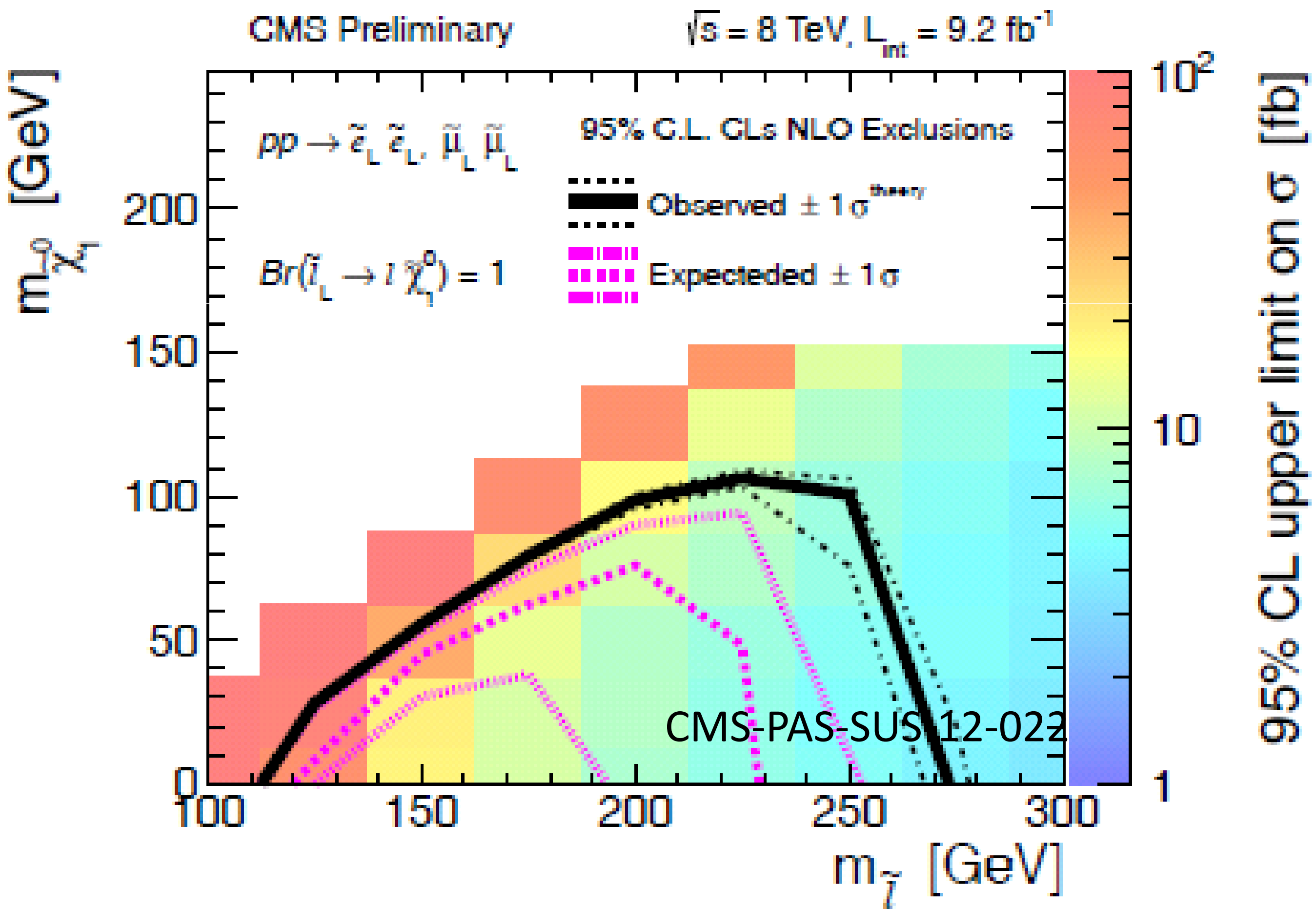


chi1, N2 to 600 GeV with N1 to 250

sleptons around 400

Drell-Yan production (model independent)

CMS



Can CLFV be observable at LHC?

- neutralino LSP
- charged slepton NLSP

SLEPTON LSP
(long-lived)

Charged slepton NLSP

- decays to gravitino: lifetime can be very large: decays outside detector
- NLSP in large parts of GMSB parameter space (messenger pairs >1)
- high scale models too: if gravitino light enough

CLFV at LHC: long-lived sleptons

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

CLFV case study:

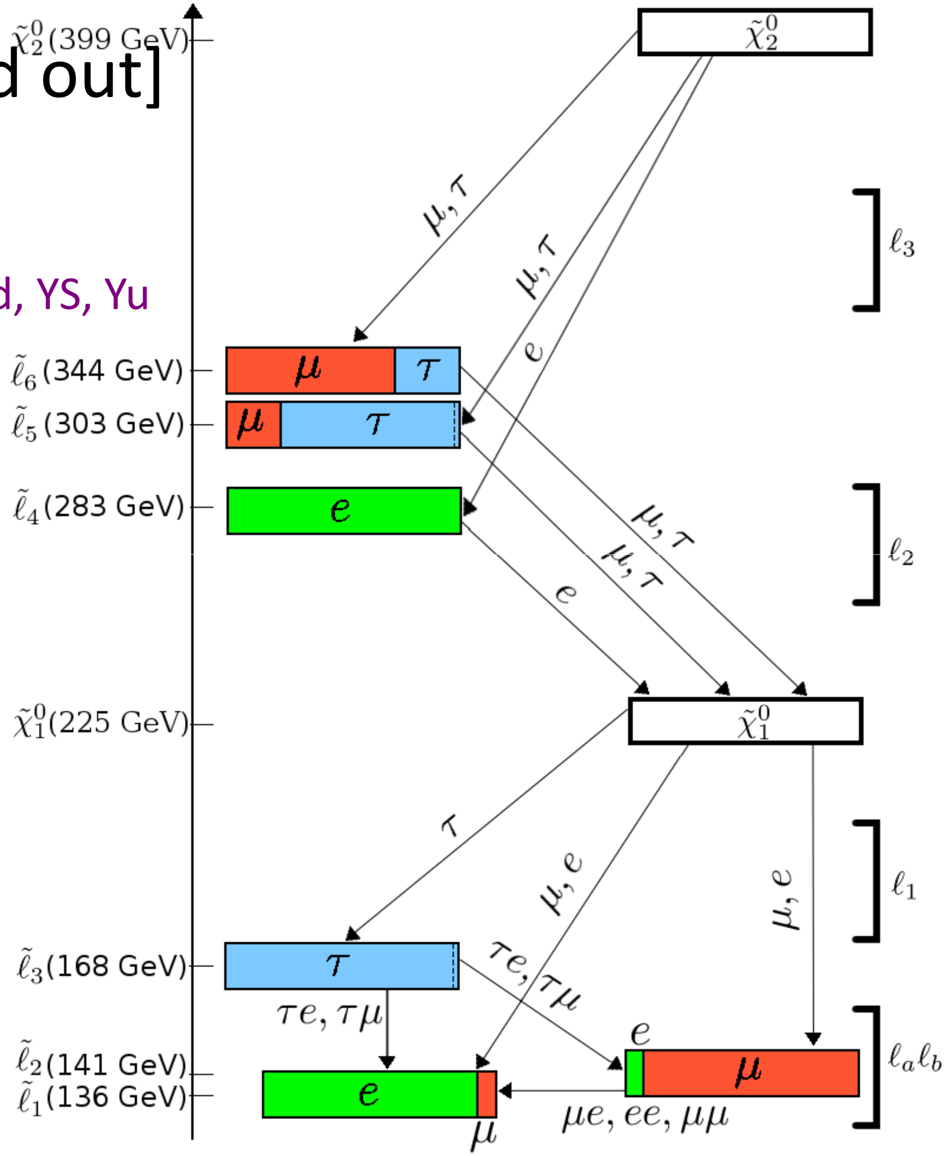
[Illustrative purposes: ruled out]

Feng, French, Lester, Nir, YS

Feng, Galon, Sanford, YS, Yu

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

- reconstruct masses in stages: bottom-up
- 14 TeV 100 1/fb
- but: too conservative:
  NLSP beta < 0.8
  (huge drop)
- no tau information
- still very encouraging



one challenging (but very plausible) example:

quasi-degenerate sleptons

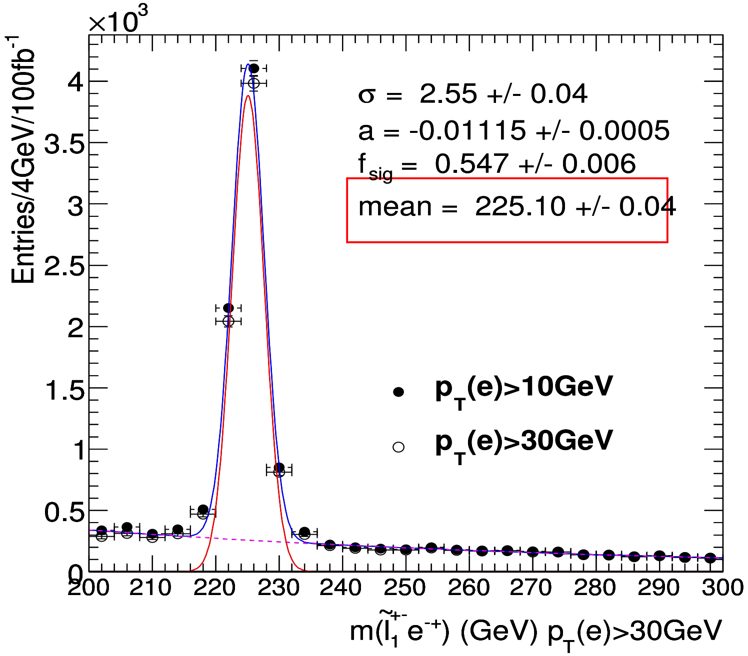
here NLSP = mainly R selectron 136 GeV

next slepton = mainly R muon 141 GeV

with 6% mixing

neutralino at 225 GeV

can we tell that there are 2 distinct slepton states? measure mass difference? mixing?



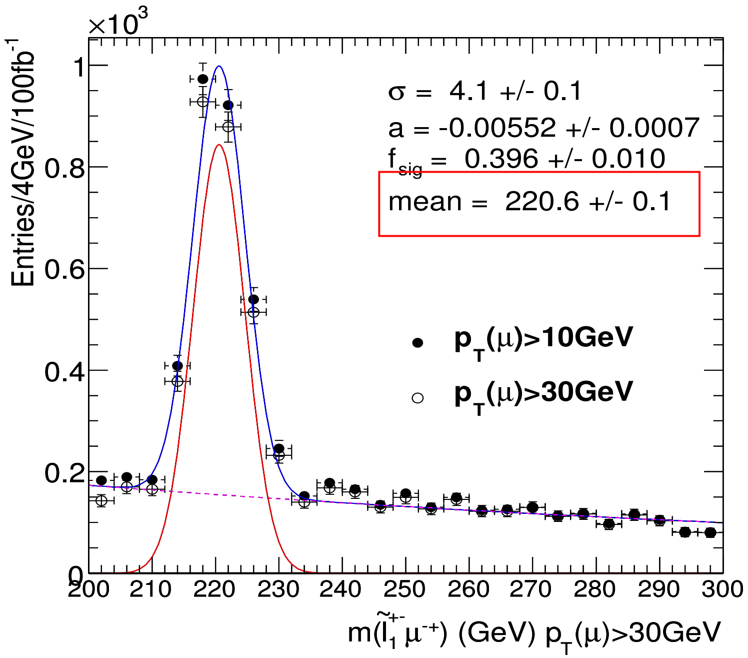
$$\text{recall:}\quad \tilde{l}_1 \sim \tilde{e} \qquad (96\%)$$

$$\tilde{l}_2 \sim \tilde{\mu} \qquad (96\%)$$

dominantly $\chi_1^0 \rightarrow \tilde{l}_1\, e$

true neutralino peak

OS

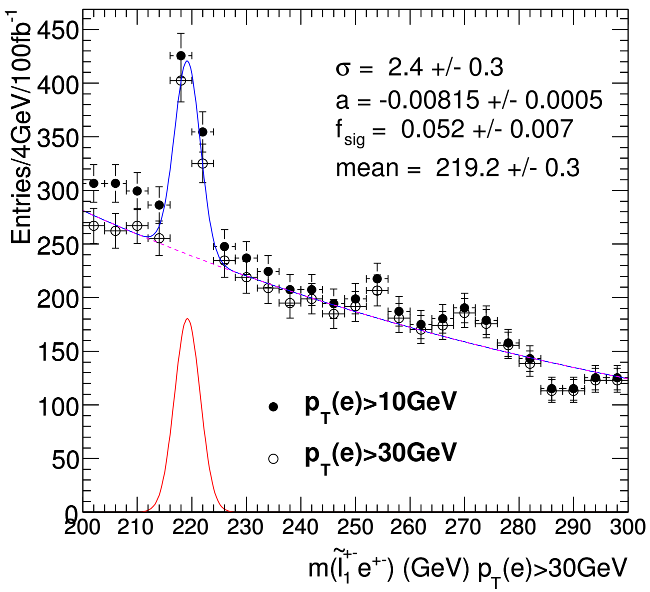


dominantly

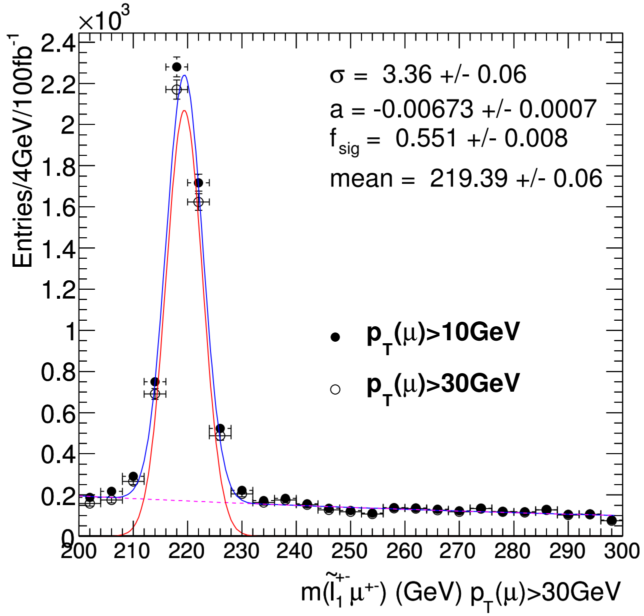
$$\chi_1^0 \rightarrow \tilde{l}_2\, \mu$$

$$\rightarrow \tilde{l}_1\, \mu + \text{ soft leptons}$$

shifted neutralino peak



SS



neutralino decays through slepton2 only: just shifted peak

mass difference: from shift in peak locations (kinematics)

mixing: counting events in each peak

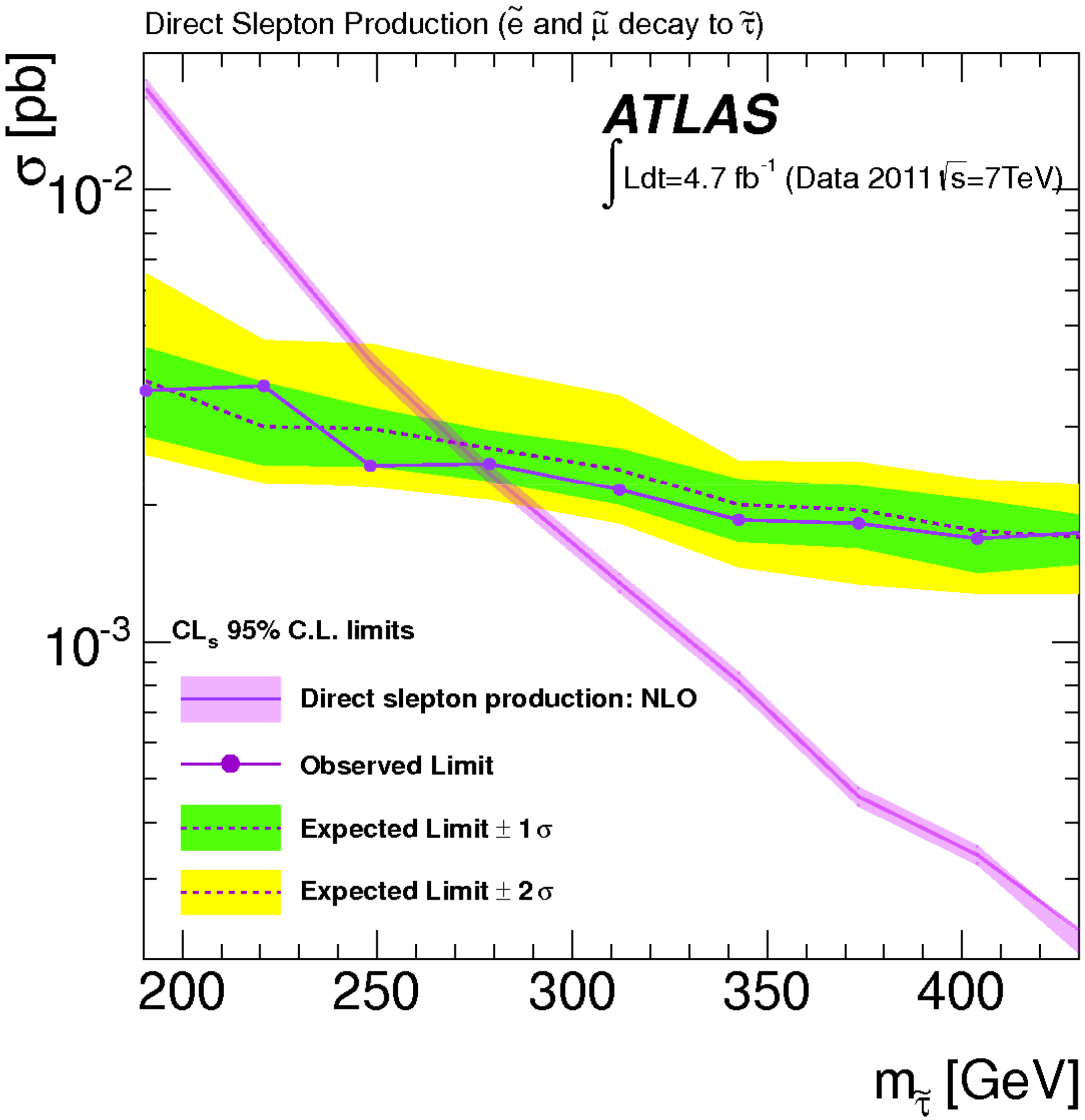
Long Lived Sleptons

- lots of progress on trigger, reconstruction at ATLAS, CMS
- TOF in muon detectors: Tarem et al

  high efficiency for roughly 0.6<beta<0.95
- for faster ones---typical in cascades: distinguish from muons using mother particle decay (neutralino → slepton + lepton) Galon YS Tarboush Tarem

  more relevant for 14 TeV

Long Lived Sleptons: Drell-Yan bound



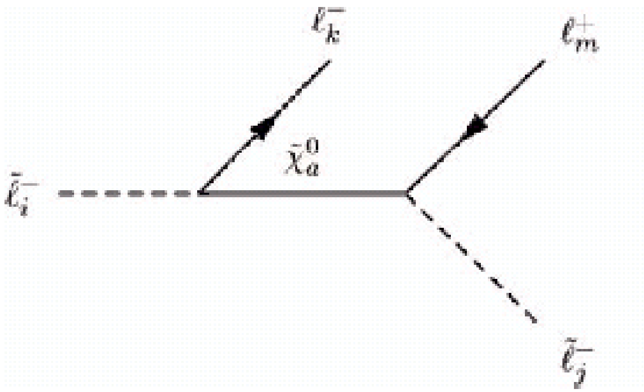
- R-handed sleptons
- higher reach if include gaugino production: but more model dependende

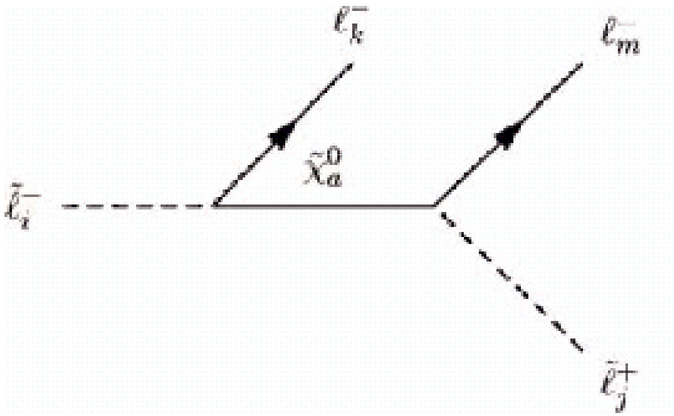
consider extreme case:

just Drell-Yan production of lightest sleptons (L or R)

only 3 body decays:

Feng Galon YS Sanford Yu





OS leptons or SS leptons (Majorana neutralino)

LFC: only different flavor leptons: e-tau, e-mu, tau-e

LFV: + same flavor too: ee ..

- mass difference above ~ 10-20 GeV: fairly easy

measure masses m1, m2; mixings?

- mass difference below that:

soft leptons (if lightest slepton is stau

LFV helps: e or mu instead of tau)

or both long-lived

- statistics may be very limited (low efficiency at very low beta)
- low-E signal (exclusion): important complementary information

Neutralino LSP

missing ET

much more challenging

- 1^{st} order questions: measuring flavor effects:
  masses, mixings
- 0^{th} order questions: effects on discovery
  as scale goes up: more room for mixings,
  relative mass splittings ← dedicated CLFV expts

effects on discovery:

1. (lepton) counting experiments:

eg look for leptons from neutralino decay

Opposite Sign Same Flavor (OSSF)

assumes Lepton Flavor Conservation

2. special variables: eg kinematic edges

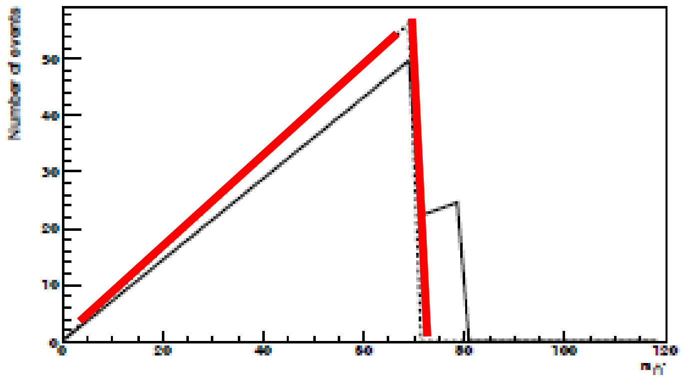
$$\tilde{\chi}_2^0 \to \tilde{l}^\pm l_j^\mp \to \tilde{\chi}_1^0 l_j^\mp l_i^\pm .$$

endpoint of dilpeton invariant mass:

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

→ triangle shape

and peak in invariant mass distribution:



- important tool for extracting information about superpartner masses:

  crucial for flavor measurements!

  [often assume excellent resolutions claimed in original (flavor blind) studies below 0.01m]

- but for detection too: peaks over flat background

  [eg: Eckel Shepherd Su 2011:

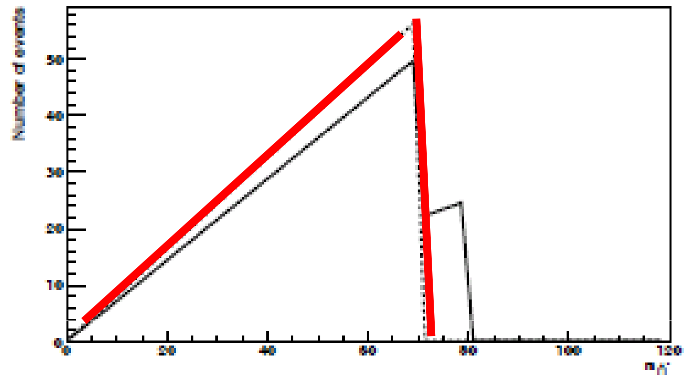
  enhance reach for L-sleptons :

  ~ 600 GeV at 14 TeV at 100 /fb]

$$\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l_j^{\mp} \to \tilde{\chi}_1^0 l_j^{\mp} l_i^{\pm}.$$

slepton= selectron , smuon

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



usual assumption: MFV:

1) slepton= smuon: mu mu only

2) slepton=selectron: ee only

3) selectron, smuon degenerate: same endpoint

→ e-e, mu-mu, distributions identical:
each looks like a single triangle

use flavor-subtracted distribution to reduce bgnd:

$$N_{ee} + N_{\mu\mu} - N_{e\mu} - N_{\mu e}$$

but what if not MFV:

smuon, selectron can have different masses

Allanach Conlon Lester
Buras Calibbi Paradisi

LFV: mixing

Galon YS

also: Grossman Martone Robinson: widths

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

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

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

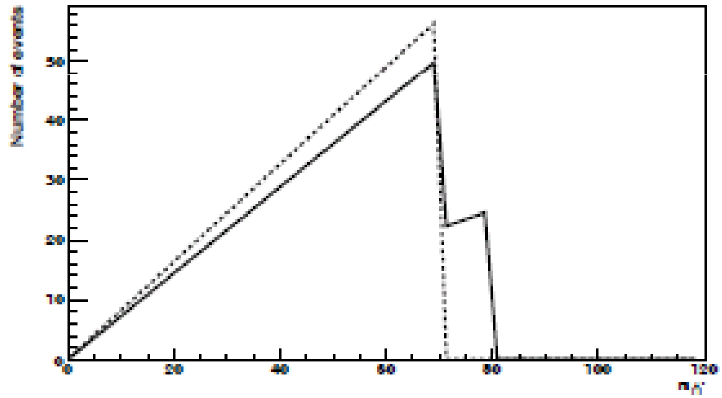
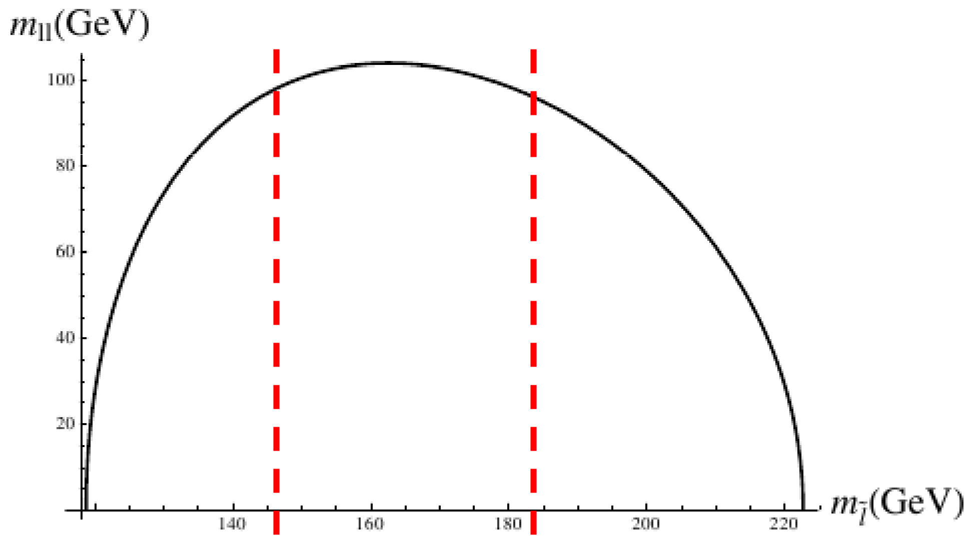


Fig. 1. The l^+l^- invariant mass distribution ($l = e, \mu$) for degenerate sleptons (dashed) and for sleptons of different masses (solid).

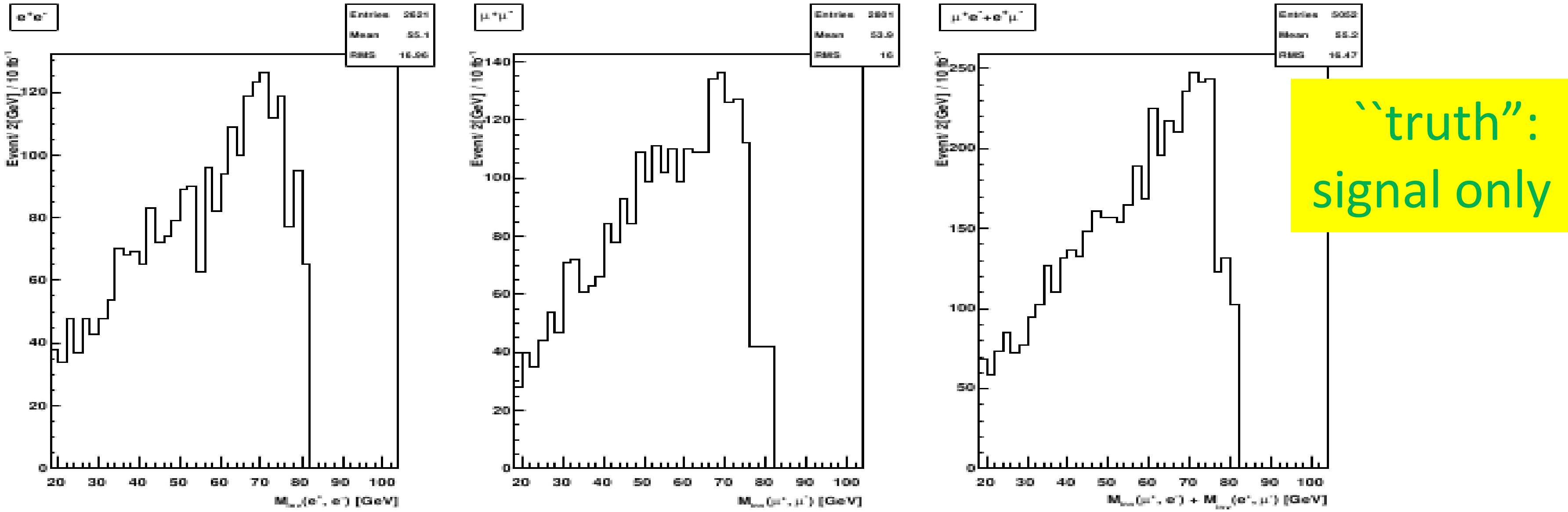
slepton mass splitting can be greatly enhanced
but also reduced in edge splitting:
140 – 185 → less than 5GeV
= optimal region with hard leptons



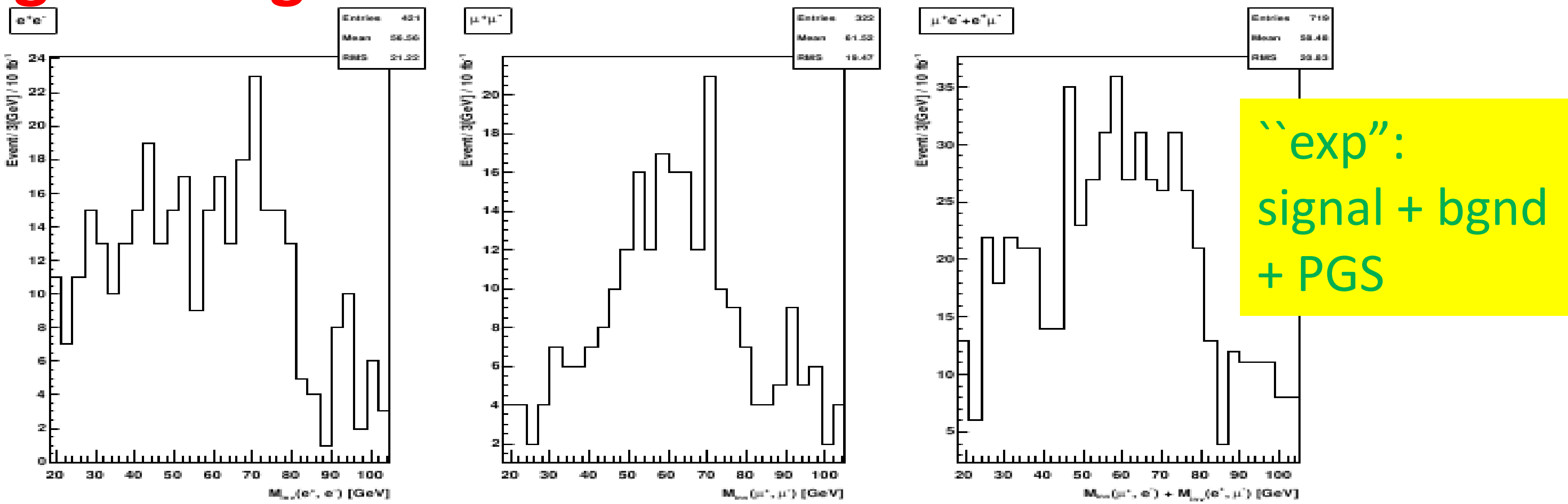
- large edge splitting: smaller peaks
- LFV: each distribution contains both edges
- in a real detector: fuzzier structure
- cant use flavor subtraction
- example: took SU3 benchmark study:
  [resolution in edge around 1 GeV at 14 TeV
  with 1fb-1]
  deformed R selectron, smuon

slepton1: 131 GeV → EP= 76 GeV
slepton2: 134 GeV → EP= 82 GeV

large mixing



(a) Truth distributions 2 GeV per bin



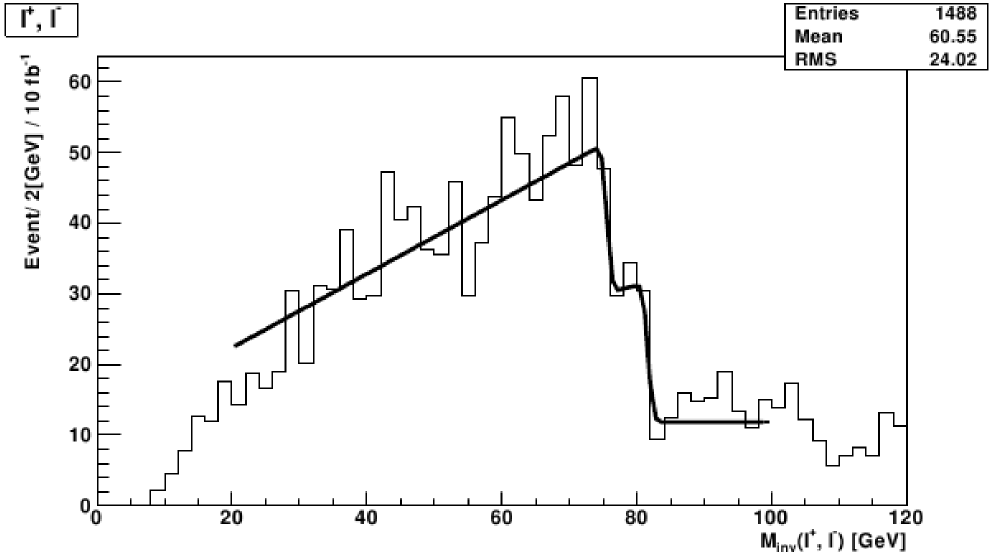
(b) ”Experimental” distributions 3 GeV per bin

heights of different distributions
depend on mixing, phase space

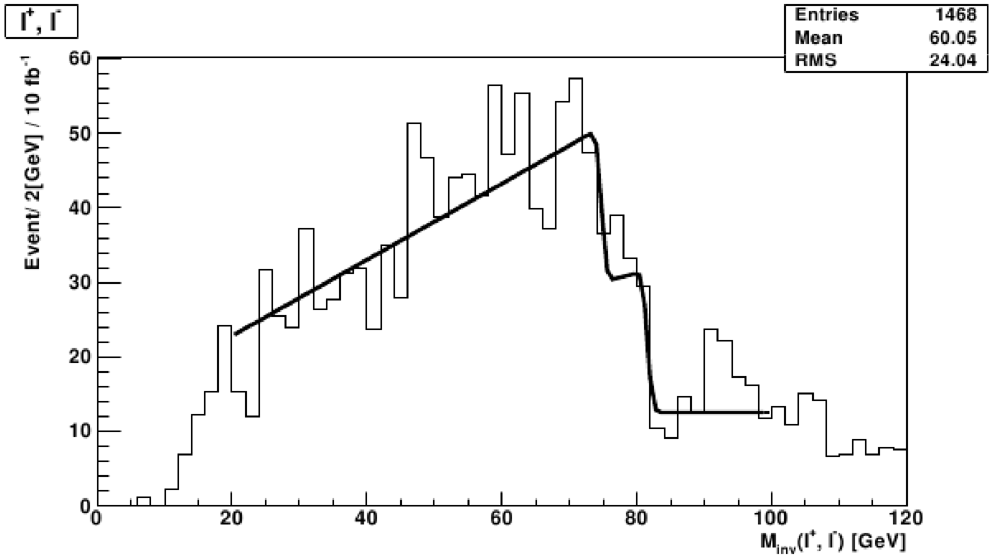
$$\frac{N(e^\pm \mu^\mp)}{N(e^+e^-)} = \frac{2(1+R)\cos^2\theta\sin^2\theta}{\cos^4\theta + R\sin^4\theta}$$
$$\frac{N(\mu^+\mu^-)}{N(e^+e^-)} = \frac{R\cos^4\theta + \sin^4\theta}{\cos^4\theta + R\sin^4\theta},$$

but: locations of endpoint are the same in
ee, mu mu, e mu (kinematics only)

flavor-**added** distribution more sensitive



(a) Model 1–small mixing



(b) Model 2–large mixing

can use
flavor-*added* distribution
to detect 2 endpoints

then return to separate ones
to fit mixings

10 fb-1: resolution around
1GeV
(can probably do better)

- for discovery: MFV is a dangerous assumption
- flavor measurements: large mixing makes measurement of masses more challenging

back to 1st order questions:

Kinematic edges as signal of LFV at LHC

[again: illustrative purposes: ruled out already]

Buras Calibbi Paradisi

CMSSM with selectron-smuon splittings from

23 slepton mixing: (selectron-smuon mixing small)

RR: delta_23=0.1 → selectron-smuon relative mass splitting up to 4%

LL: delta_23=0.01 → selectron-smuon relative mass splitting around 1%

study: accessible at 14TeV LHC 100fb-1 but colored particles at or below TeV

To Conclude

- Concrete SUSY models with CLFV

  CLFV controllable

  Currently probed by both low-E expts and LHC

- As SUSY scale pushed higher by

  direct searches + 125 GeV Higgs

  EWK production may play important role

→ CLFV LHC searches: less sensitivity

but low-E unaffected!

- flavor measurements at LHC possible but non-trivial

especially with lower statistics given heavy squarks, gluinos

any input from low-E experiments important

- here: focused on mu, e at LHC: tau even harder
- FLAVOR is important even for searches: especially with lepton-only signatures

THANK YOU