Physics 222 UCSD/225b UCSB

Lecture 16

- Supersymmetry
- A purely phenomenological perspective.

Disclaimer:
I am not an expert on SUSY !!! All you get should be looked at with some level of skepticism. I will try to indicate my sources, as well as my limitations.

Thanks to Beate Heinemann to teach me more about SUSY in a 30min phone call than I learned from hours of reading so-called "Primers" or "Introduction to" SUSY.

Logic of Today's Lecture

- Brief intro to particle content of SUSY theories.

- Brief Discussion of production mechanisms.

- Brief Discussion of decay mechanisms.

- Attempt of giving you a feel for how final state phenomenology is a result of spectroscopy and pdfs.
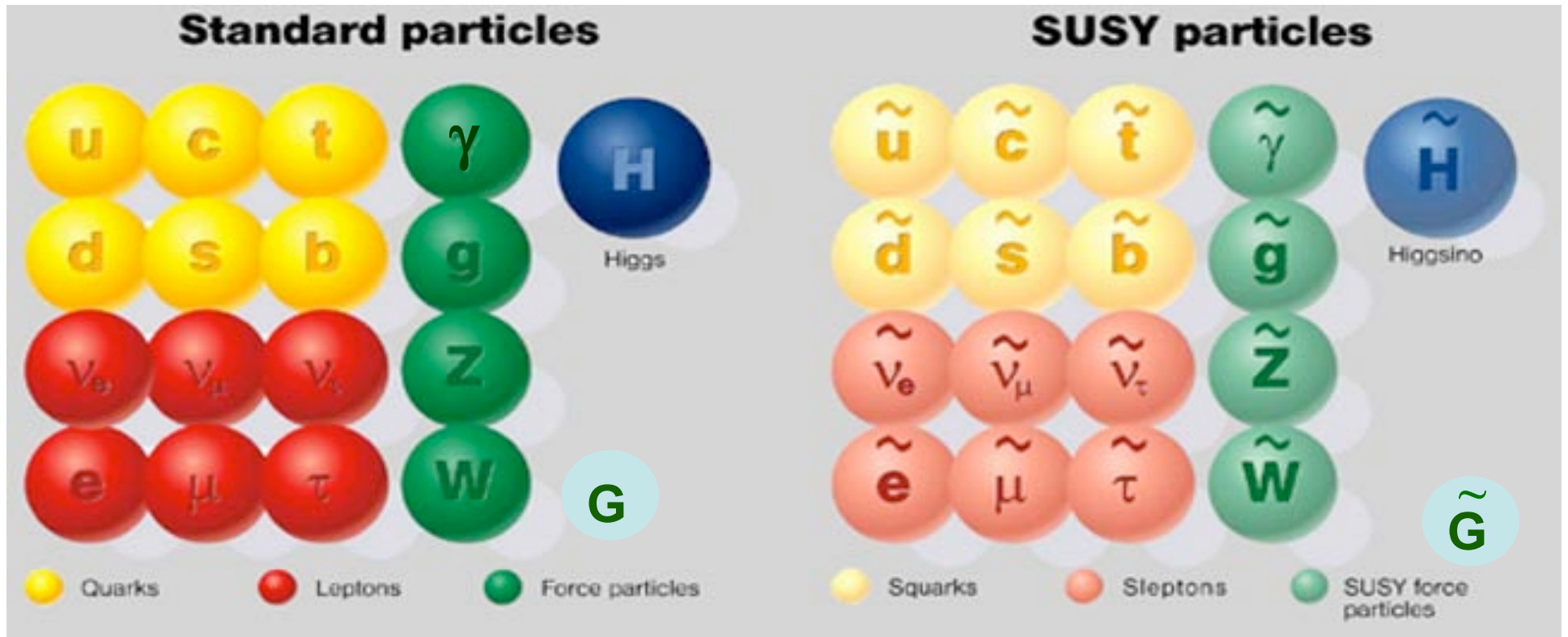
- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - Sfermions (squarks, selectron, smuon, ...): spin 0
    - gauginos (chargino, neutralino, gluino,...): spin 1/2
      - these are generically referred to as χ, and they mix in interesting ways.
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in "minimal" models!

R-Parity: $R = (-1)^{2j+3B+L}$

- The one most important principle obeyed by most SUSY models as a more or less ad hoc assumption is that R-parity is conserved.
- All SM particles have R = 1
- All SUSY particles have R = -1
- This is a multiplicative quantum number.
  - *SUSY particles are always pair produced.*
  - *The lightest SUSY particle, called LSP, can not decay*
    => MET signature is universal for all R-parity conserving SUSY.
    => The LSP is a Dark Mater candidate and (often) a WIMP.
- **One can of course construct R-Parity violating SUSY just as well.**

Seemingly Infinite Possibilities

- The "minimal" in MSSM refers to minimal number of particles. It does NOT refer to an attempt of a minimal set of new parameters.

- The most general MSSM is impossible to do anything useful with because it has too many free parameters, and too large a range of possible experimental signatures.

- The MSSM has been specialized into "branches" of phenomenology based on the SUSY breaking scheme.

- Each scheme comes with its own set of a few parameters, and some non-overlapping (i.e. distinctive) phenomenology.

To read some discussion of scenarios:

hep-ph/0202233

"The Snowmass Points and Slopes: Benchmarks for SUSY searches."

The 3 favorite Breaking Scenarios

- **mSugra** = minimal supergravity
  - The most popular scenario among experiments !!!
  - Often referred to as *"the MSSM"*
- GMSB = Gauge mediated Susy breaking
- AMSB = anomaly mediated Susy breaking
- These are the three most popular implementations of SUSY breaking schemes.
- They share a fair bit of phenomenology, but differ in some important aspects.
- Let's look at some of these differences.

GMSB

- The second lightest SUSY particle, also called NLSP is either a neutralino or a slepton.

- Neutralino as NLSP:
  - Decays into a photon and a gravitino (m ~ keV).
  - *Collider signature is 2 photons & MET*
  - Tevatron Results, e.g. hep-ex/0504004

- Slepton as NLSP:
  - Decays into a lepton and a gravitino.
  - *Collider signature is 2 opp. Charge leptons & MET.*
  - e.g. hep-ph/9712499

- In both cases, *the lifetime of the NLSP may vary over a large range, leading to delayed photons or leptons as possible signatures*.

AMSB

- The NLSP and LSP are nearly degenerate in mass. NSLP = charged and LSP = neutral.
  - Significant lifetime for the NLSP => CHAMPs, CHArged Massive Particles.
  - *Collider signature is a 100GeV or more charged massive particle that moves slowly through the detector, leaving behind large minimim ionizing energy.*
 - We see it in the detector via ToF and dE/dx.

mSUGRA

- There are 4 parameters, and a sign that define the phenomenology.
- For fun, check out:

  http://kraml.web.cern.ch/kraml/comparison/
- It allows you to choose values for the parameters of mSUGRA, and it calculates for you the masses, and branching fractions of all SUSY particles.
- Let's start by taking a look at these mass spectra. We follow Snowmass Points & Slopes here.

For the rest of this lecture we focus on mSUGRA unless explicitly stated otherwise.

This means that the LSP is the lightest neutralino.

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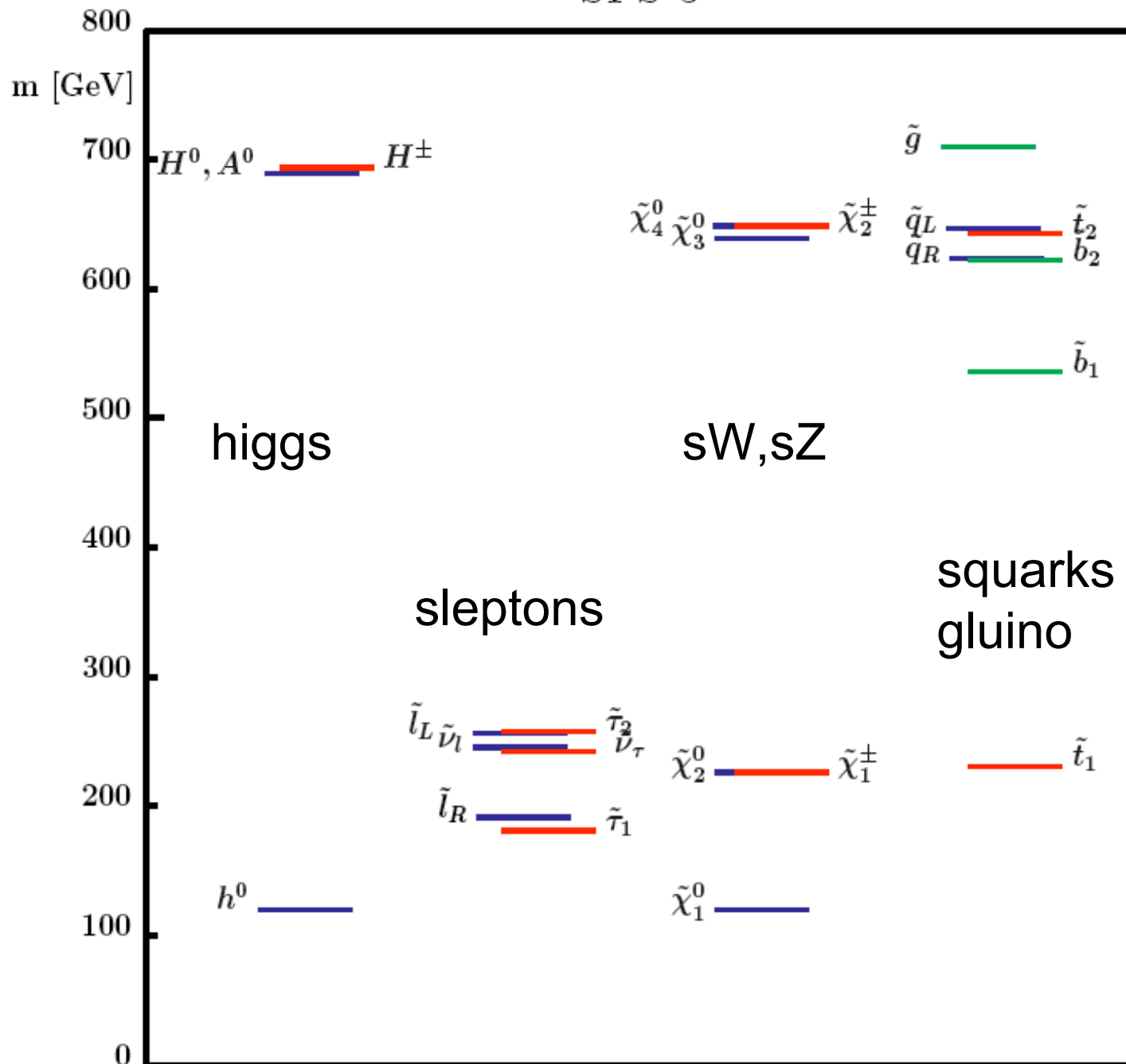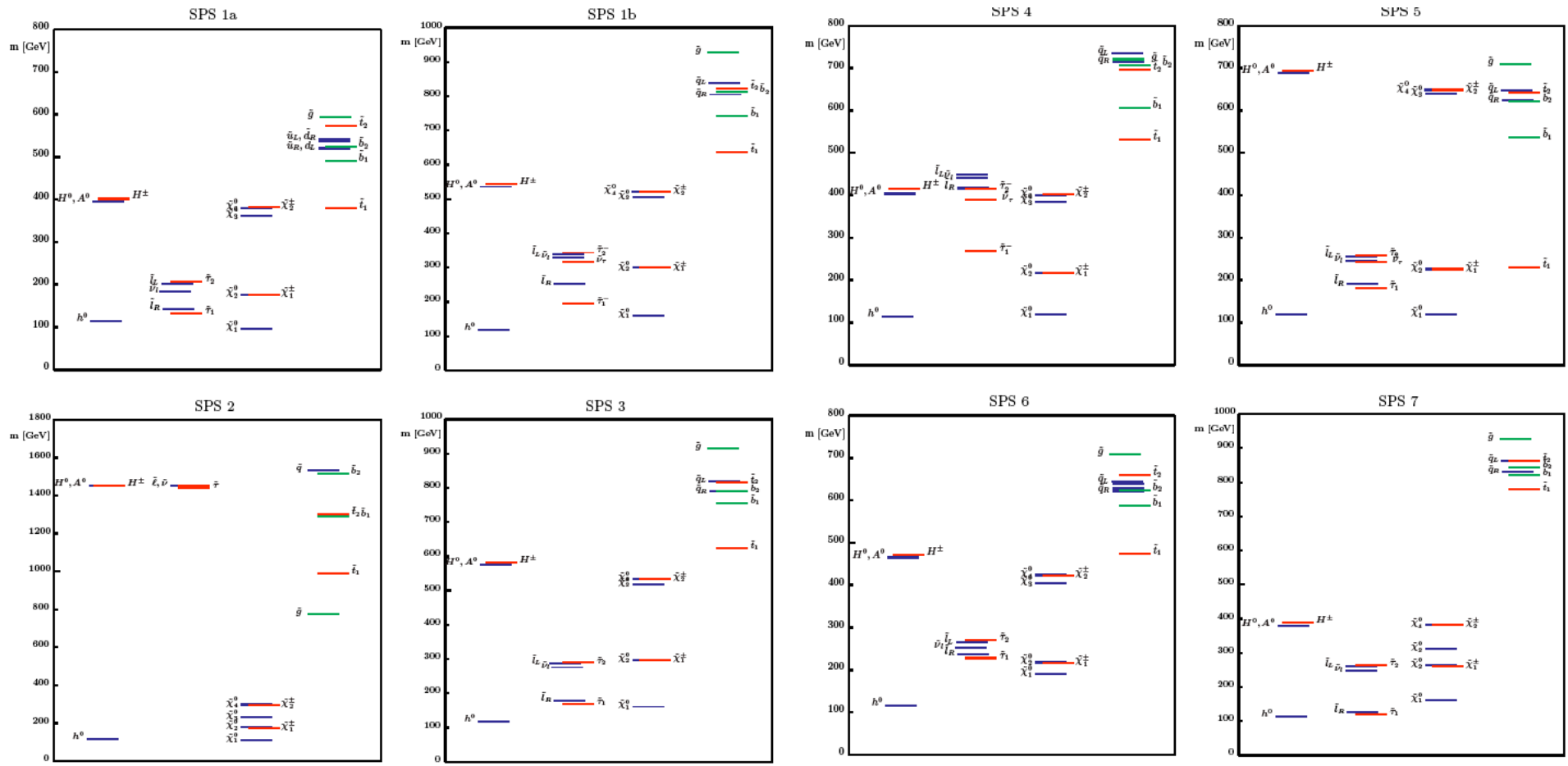
You're not supposed to be able to read these spectra.
The points to take away are:
=> All points have one low mass higgs, the rest high mass.
=> All points have gluinos and squarks
   (except stop in SP5) at high masses
=> Everything else is all over the place!

Production Mechanism at LHC

- SUSY particles are pair produced.
- Squarks and gluino couple just like quarks and gluons.
  - Production is entirely driven by sum of masses of the pair and PDFs for gluons and sea/valence quarks in proton.
- Weak sector of SUSY different
  - Have twice as many particles
  - may mix differently from standard model.
  - Produced via electroweak coupling to quarks, not gluons!
  => *Smaller cross sections than squarks and gluinos!*
- Slepton sector of SUSY
  - Produced via ewk from q qbar -> sl$^+$sl$^-$ via s-channel.
  => *Smaller cross sections than squarks and gluinos!*

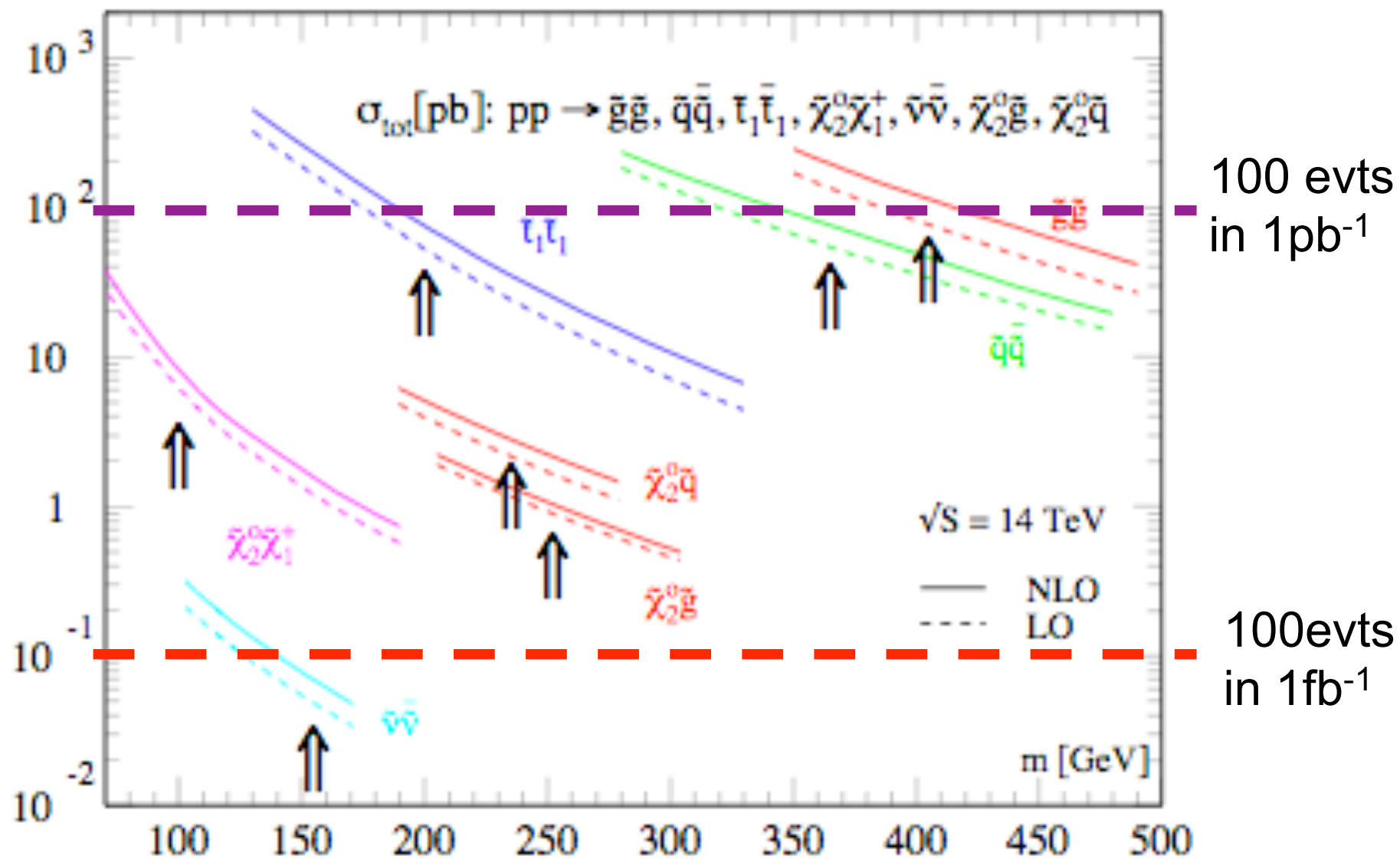# Most Important Plot for understanding SUSY Phenomenology at LHC
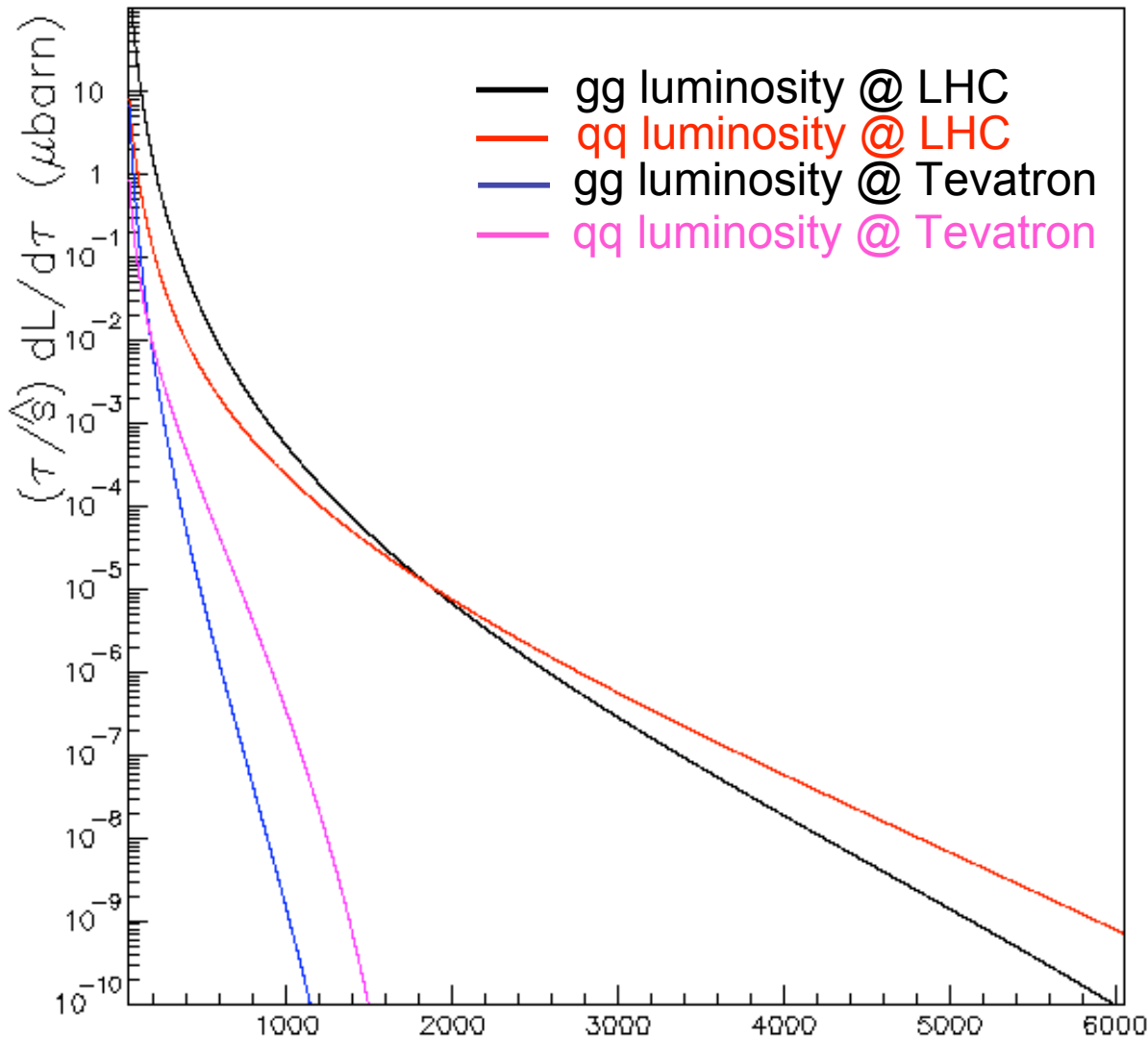
Parton-Parton Luminosity of LHC and Tevatron !

We need to have enough √s to pair produce susy.

What we learned so far

- ## Susy is pair produced.
  - Colored spartons larger Xsect than colorless.
- ## Xsect depends on sparticle masses
  - Typically large mass diff. for mSUGRA:
    - m(colored) >> m(colorless)
  - Increase in energy => increased reach for color
  - Increase in lumi => colorless catch up later
- ## GMSB and AMSB are different in that NLSP dominates the phenomenology.

LHC Production cross sections

$\sigma_{tot}[pb]$: $pp \to \tilde{g}\tilde{g}, \tilde{q}\bar{\tilde{q}}, \tilde{\tau}_1\bar{\tilde{\tau}}_1, \tilde{\chi}_2^0\tilde{\chi}_1^+, \tilde{\nu}\bar{\tilde{\nu}}, \tilde{\chi}_2^0\tilde{g}, \tilde{\chi}_2^0\tilde{q}$

100 evts
in 1pb^{-1}

$\tilde{\tau}_1\bar{\tilde{\tau}}_1$

$\tilde{g}\tilde{g}$

$\tilde{q}\bar{\tilde{q}}$

$\tilde{\chi}_2^0\tilde{q}$

$\tilde{\chi}_2^0\tilde{\chi}_1^+$

$\tilde{\chi}_2^0\tilde{g}$

$\sqrt{S}$ = 14 TeV

—— NLO

- - - LO

100 evts
in 1fb^{-1}

$\tilde{\nu}\bar{\tilde{\nu}}$

m [GeV]

Sparticle Decays

- Decay chains depend crucially on the spectrum of masses !!!

- Basic ideas the same as in SM, just translate the names, and conserve R-parity.
  - Gluino decays to quark & squark
  - Squarks decay to Wino ("W") or Bino ("Z") & quark if allowed
    - Otherwise to LSP & quark
  - Wino decays to slepton & neutrino or LSP & W
  - Bino decays to slepton & lepton or sneutrino & neutrino, or dilepton/quark-antiquark (incl.Z) & LSP.
  - Slepton decays to Bino/LSP & lepton or Wino & neutrino.

  Let's look at these one at a time, and try to explain.

Gluino decays

- Decay is driven by R-parity conservation, color flow, and kinematics (=allowed phase space).

- If m(squark) < m(gluino):

  => Gluino -> squark & quark

  QCD is flavor blind:

  squark & quark same flavor (except for mixing).

  all flavors equal rate (except for phase space -> lower mass means larger rate)

- If m(squark) > m(gluino):

  => Gluino decays via virtual squark or loops

Gluino and heavy flavor

- For large part of parameter space in mSUGRA, gluino production dominates at LHC.

- As gluino decay is flavor blind, this means that you get significant top and bottom production.

- If stop and sbottom are furthermore lighter than the other squarks you get a lot of top and bottom.

- If furthermore the other squarks have m(squark) > m(gluino) then (almost) every event has bottom and/or top.

Several of the benchmark points studied in CMS are like this!

Simple numeric argument

- 1/3 of all (s)quarks lead to bottom
- Gluino dominates, and doesn't care about flavor.

  $\Rightarrow$ 1/3 of all gluinos will lead to at least one b-quark.

    (6 quarks, 2 of which lead to b-quark => 2/6 = 1/3)

  $\Rightarrow$ there are 2 gluinos per event.

  $\Rightarrow (2/3)^2 = 40\%$ is the "natural" fraction of gluino-gluino without b-quarks.

- Let's call it 50/50 because there are also slepton-slepton and wino-bino production.

Roughly 50% of all susy events ought to have >= 1 b-quark
Unless, there is a good kinematic reason not to !!!

Reasons not to have b-quark

- If the gluino, stop, and sbottom masses all were significantly higher than the other squarks, then kinematics would disfavor the production of b-quarks in susy decay chains.
  - Have not seen an example of this yet in literature.
- If all colored objects were so much higher in mass than the "electroweak sparticles" and sleptons, then gluino/squark production in general is kinematically disfavored.
  - Have seen examples of that discussed in GMSB.
  - Have not verified the details yet, but assume naively that such scenarios lead to more lepton, W, Z production than standard mSugra.
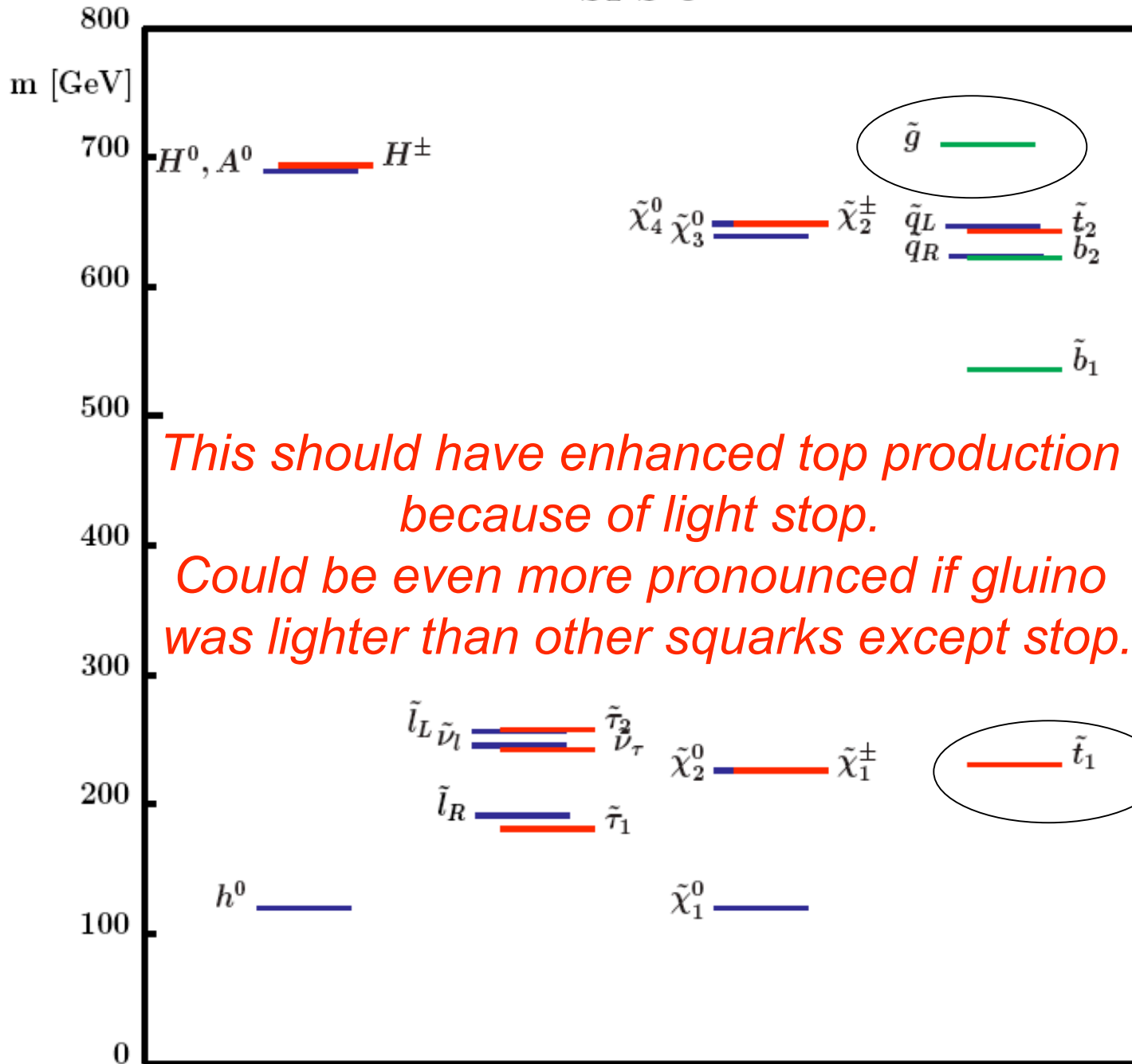
Squark Decay

- Same as in standard model, except neutral currents are allowed as well.

  $\Rightarrow$ S-up -> Wino+ & down (+2/3 -> +1 & -1/3)

  $\Rightarrow$ S-up -> Bino & up (+2/3 -> 0 & +2/3)

- Flavor assignment is messy because of mixing matrices in Wino,Bino, stop, and sbottom sector.

- If kinematically allowed, we can also have:

  $\Rightarrow$ S-up -> gluino & up (dominates if allowed!)

Many other rare decays as well, of course. Sometimes, "rare decays" dominate because of kinematics.

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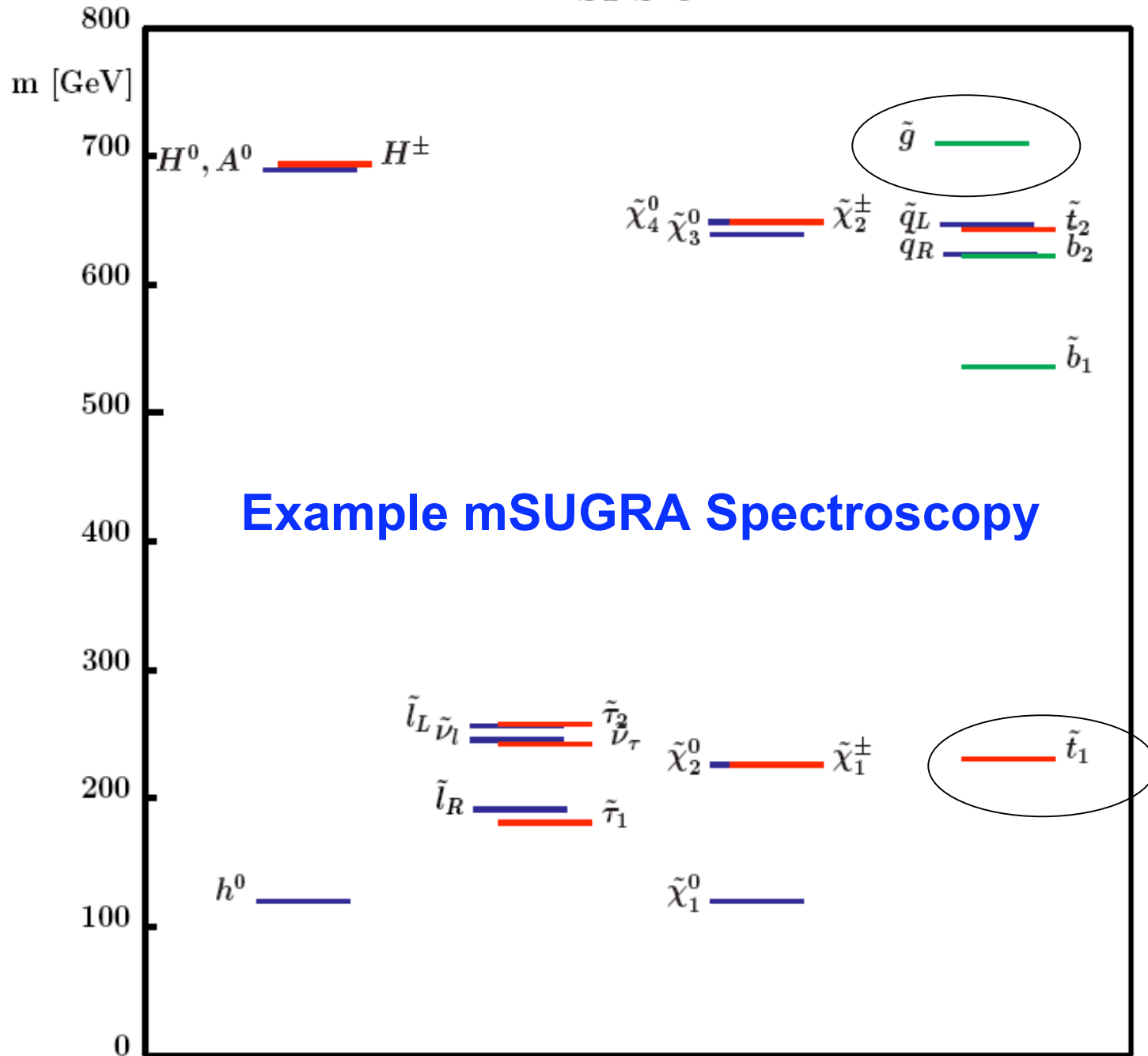
Example mSUGRA Spectroscopy

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Where e's and mu's come from

- First of all, many come from W and Z decays.
- Some come from chargino decays
  - Wino -> sneutrino & lepton
- Some come from neutralino decays
  - Bino -> slepton & lepton
- Some come from slepton decays
  - Slepton -> bino & lepton
- Some come from sneutrino decays
  - Sneutrino -> Wino & lepton

Lot's of options,
details depend on masses and model!!!

Personal Conclusion

- There's very little that can't happen in SUSY.

- We better watch out, be ready to look for anything that might show up.

- mSUGRA and thus the benchmark points studied in great detail in CMS, is by no means representative of susy phenomenology!

- Don't get too biased by the fantasies of what might be there in nature at the TeV scale.

- Given the overall excitement about SUSY, many people in the community will assume SUSY exists as soon as a non-standard MET signal is observed. However, to actually prove that we indeed have seen SUSY will take years, if not decades. To fully understand the SUSY breaking mechanism will take high energy colliders beyond the LHC.

Sally Dawson

Modifying the MSSM: NMSSM

- Simplest modification of MSSM: add Higgs singlet S
- Superpotential $W = \lambda H_1 H_2 S + \dfrac{\kappa}{3} S^3$
  - $\lambda <S> H_1 H_2$ naturally generates $\mu H_1 H_2$ term
- At tree level, lightest Higgs mass bound becomes:
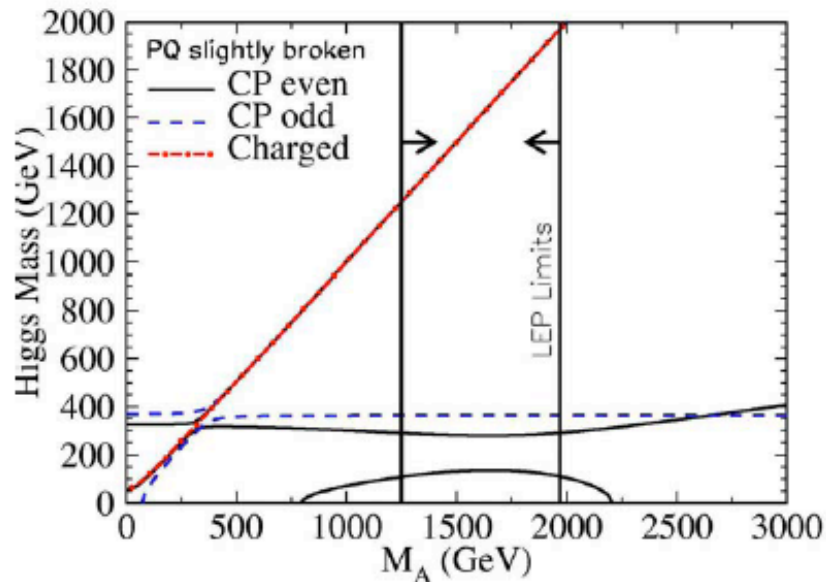
$$M_H^{\ 2} \leq M_Z^{\ 2} \cos^2 2\beta + v^2 \lambda^{\ 2} \sin^2 2\beta$$

- Assume couplings perturbative to M_{GUT}
  - $M_H < 150$ GeV with singlet Higgs
- Phenomenology very different from MSSM

Sally Dawson

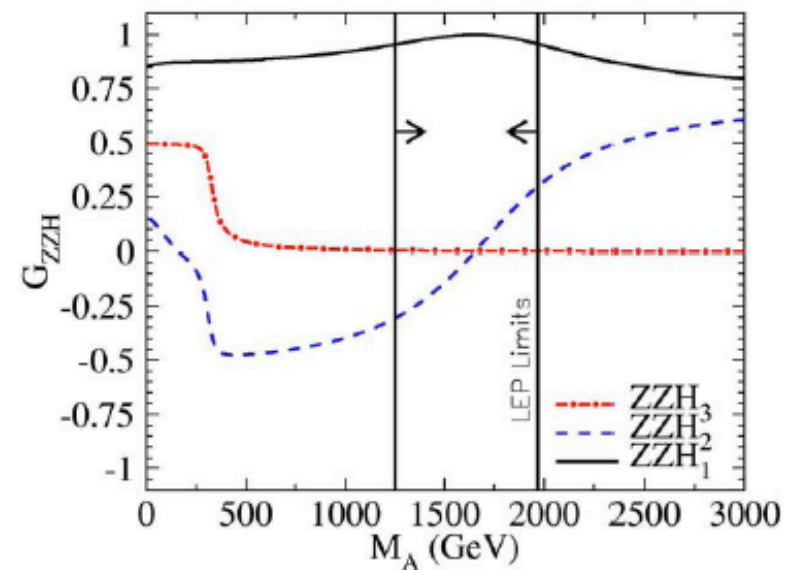# NMSSM Higgs Mass Spectrum

Typical Scenario:

ZZH couplings suppressed

(Evade LEP bounds on M_H)

➢Spectrum of light Higgs: 2 light scalars, 1 light pseudoscalar

➢Heavy, roughly degenerate H_3, A_2, $H^\pm$

Very different from MSSM!

New Decays:

$A_1 \rightarrow H_1 H_1$, $H_2 \rightarrow A_1 A_1$

Ellwanger, Gunion, Hugonie, hep-ph/0503203

Miller, Nevzorov, Zerwas, hep-ph/0304049

Choi, Miller, Zerwas, hep-ph/0407209