SMR 1773 - 18

SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
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Supersymmetry at LHC
Part I
(SUSY at LHC)

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SUSY at LHC

- Motivation for SUSY
- Models and why we need them
- Discovering SUSY at LHC
- Properties of SUSY at LHC
- Speculations and conclusions
- LHC is not just a discovery machine, so I will discuss detailed measurements.

Apologia

- Most figures are from ATLAS or CMS simulations
  Many thanks to them
- **If there is specific topics that you would like me to discuss, speak to me after this talk and I will try to cover it in my last lecture**
- Do not wait to the end to ask questions, interrupt me as needed

Cautionary remarks

- No idea which model is correct, use model studies to draw general conclusions.
- **Difficult cases are studied more often in experimental simulations than easy ones.**
- **Studies take significant effort. Theorists beware: A model may not have been studied simply because its features are not sufficienlty demanding.**
- **Many studies attempt to determine ultimate LHC performances. Data will not appear “all at once”.**
- Identify ways to kill models before looking for some exotic feature. 1% of the events may have a very esoteric signal which is characteristic of the model, but nobody will care if the other 99% boring events rule it out!

Motivation

- Aesthetic: More symmetries are good.
- Hierarchy problem: new particles below 1 TeV
- Dark Matter: needs a stable heavy neutral particle at LHC mass scale
- Unification with Gravity
- Comes from String theory: But this does not mean SUSY is at LHC scale

But not all theorists buy any, or all, of these arguments

Problems not solved (yet?) by SUSY

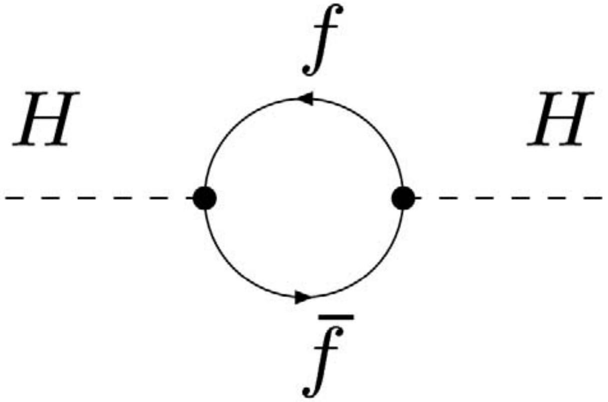
- Large number of SM parameters
- Pattern of quark masses/CP violation
- Origin of neutrino masses
- ....

Hierarchy Problem

- SM constrained at the loop level by precise data from LEP, W mass *etc*
- New particles of mass < 10 TeV are constrained: EW fits FCNC limits *etc* unless their couplings are very well prescribed.
- **Cannot add new particles LHC range unless they respect the constraints**

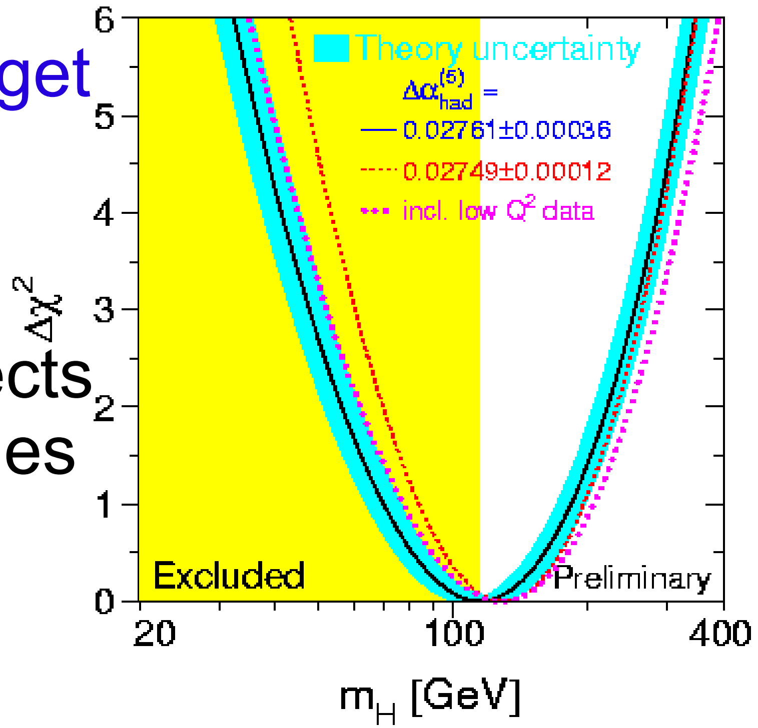
Hierarchy Problem II

- Compute corrections to Higgs mass with a momentum cut off Λ
- Three most important contributions are
- Top quark loop $\delta m_h^2 = \frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \sim (2TeV)^2$
- W loop $\delta m_h^2 \sim \alpha_w\Lambda^2 \sim -(750GeV)^2$
- Higgs loop $\delta m_h^2 \sim \frac{\lambda}{16\pi^2}\Lambda^2 \sim -(1.25m_h/100GeV)^2$
- Natural sum of these is 1 TeV
- But......



Hierarchy Problem III

- But Higgs is supposed to be <200 GeV
- “I'll just adjust bare mass to get right answer”
- “Its no big deal”
- Better is to get rid of big effects by canceling them: this implies new particles



SUSY to the rescue

- Particles must be below TeV, but must not be excluded by precision measurements
- SUSY solves it up to M_{Planck} by removing quadratic divergences. This may be overkill; Most dangerous terms are top loop, Higgs loop, W/Z loops.
- This argument implies that some SUSY particles must have mass below 1 TeV or so, specifically, Stop, Wino.
- Note that split susy models do NOT solve this problem

Basic Facts about SUSY

- SUSY is an extension of the Lorenz group, Rotations+Boosts+Q
- Q |Fermion> = |Boson>
- If only one Q (“N=1” SUSY) then for every SM particle there is a partner with $\Delta J=1/2$
- Quark, lepton ⇔squark, slepton
- Gluon ⇔gluino
- W/Z/γ ⇔ neutralinos charginos

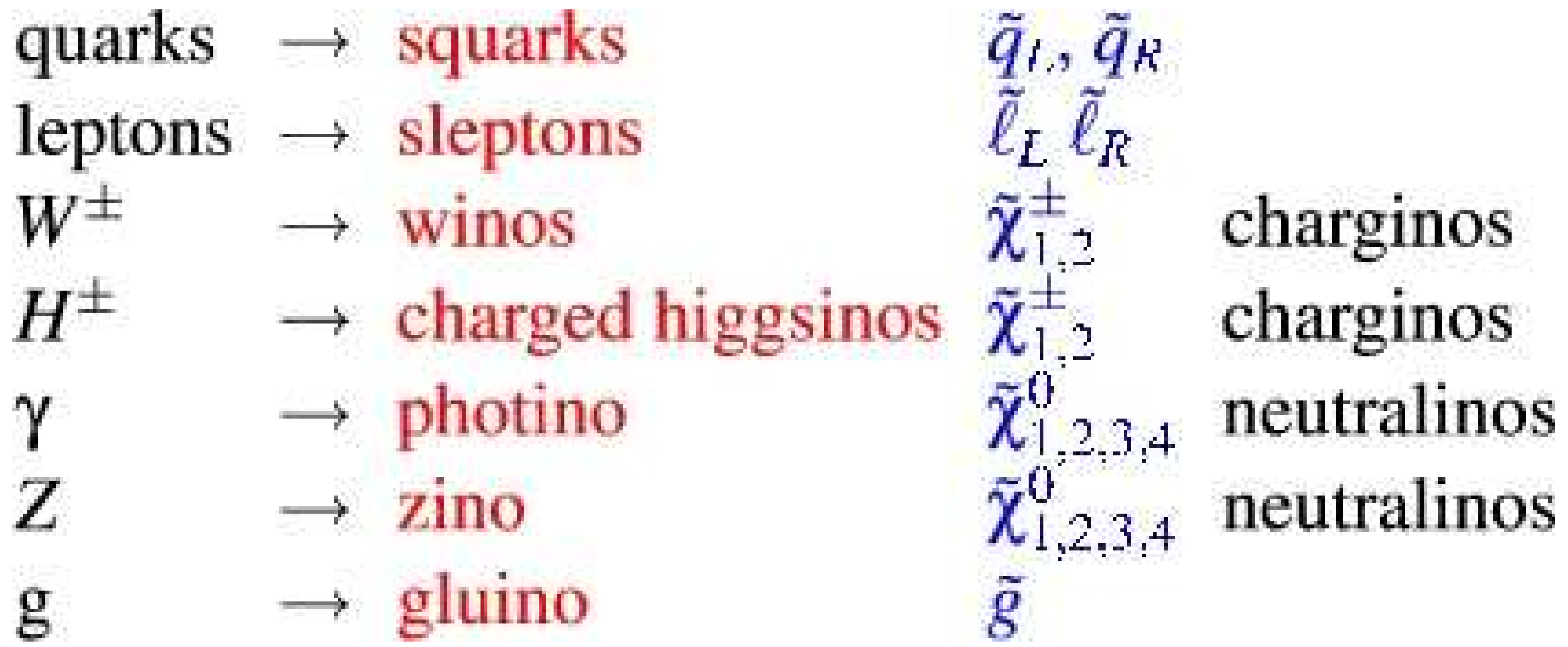
SUSY Higgs sector

- Recall SM anomalies.
- Triangle graphs that spoil renormalizibility
- Quark loops cancel lepton loops: must have same number of quark and lepton generations.
- SUSY has more fermions????
- Gauginos OK BUT
- One Higgs doublet behaves like one lepton doublet: anomaly not cancelled.
- Fixed by two doublets (H1 and H2)

SUSY Higgs sector II

- SM has 1 doublet, 4 degrees of freedom, one physical state
- SUSY has 2 doublets, 8 degrees of freedom, 5 physical states, 3 neutral, 1 charged : h, H, A, H^+
- Higgsinos can mix with charginos and neutralinos
- More complicated Higgs sectors possible

SUSY Particle summary



quarks	→	squarks	$\tilde{q}_L, \tilde{q}_R$	
leptons	→	sleptons	$\tilde{\ell}_L\ \tilde{\ell}_R$	
$W^{\pm}$	→	winos	$\tilde{\chi}^{\pm}_{1,2}$	charginos
$H^{\pm}$	→	charged higgsinos	$\tilde{\chi}^{\pm}_{1,2}$	charginos
γ	→	photino	$\tilde{\chi}^{0}_{1,2,3,4}$	neutralinos
Z	→	zino	$\tilde{\chi}^{0}_{1,2,3,4}$	neutralinos
g	→	gluino	$\tilde{g}$	

SUSY couplings

- α_s, α_w and $\sin^2\theta_W$ just like standard model
- Yukawa couplings of Higgs replaced by superpotential
-
- $\lambda^d_{ij} Q_i D_j H_1 + \lambda^u_{ij} Q_i U_j H_2 + \lambda^l_i L_i E_i H_1$
-
- Same number of params as SM
- Other terms also allowed by SU(2)xU(1)
- $\mu H_1 H_2 + \lambda^L_{ijk} Q_i D_j L_k + \lambda^B_{ijk} Q_i Q_j Q_k$
-
- M is a new mass parameter: More on red ones later

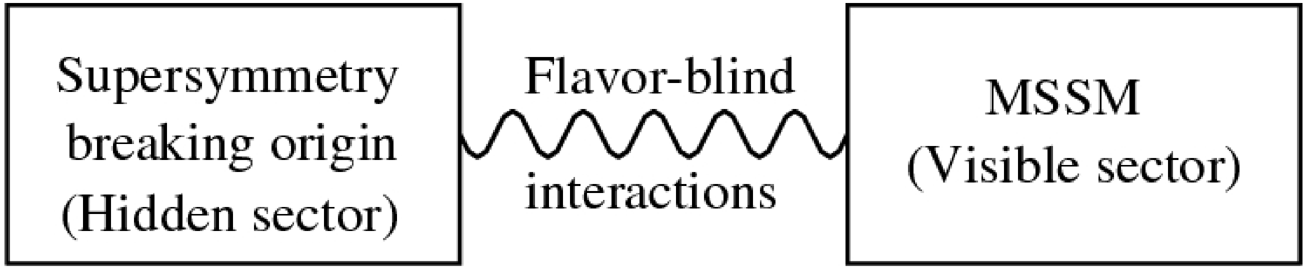
SUSY breaking

- SM also has 2 parameters in the Higgs sector
- $$-\mu h^2 + \lambda h^4$$
- These are not allowed by SUSY
- We therefore have 1 less parameter so far BUT SUSY is unbroken
- Must break to give SUSY particles mass
- Cannot break spontaneously using only the fields so far as this gives

$$\Sigma m^2_{particles} = \Sigma m^2_{sparticles}$$

SUSY breaking

- SUSY must be broken in a hidden sector



Supersymmetry breaking origin (Hidden sector)

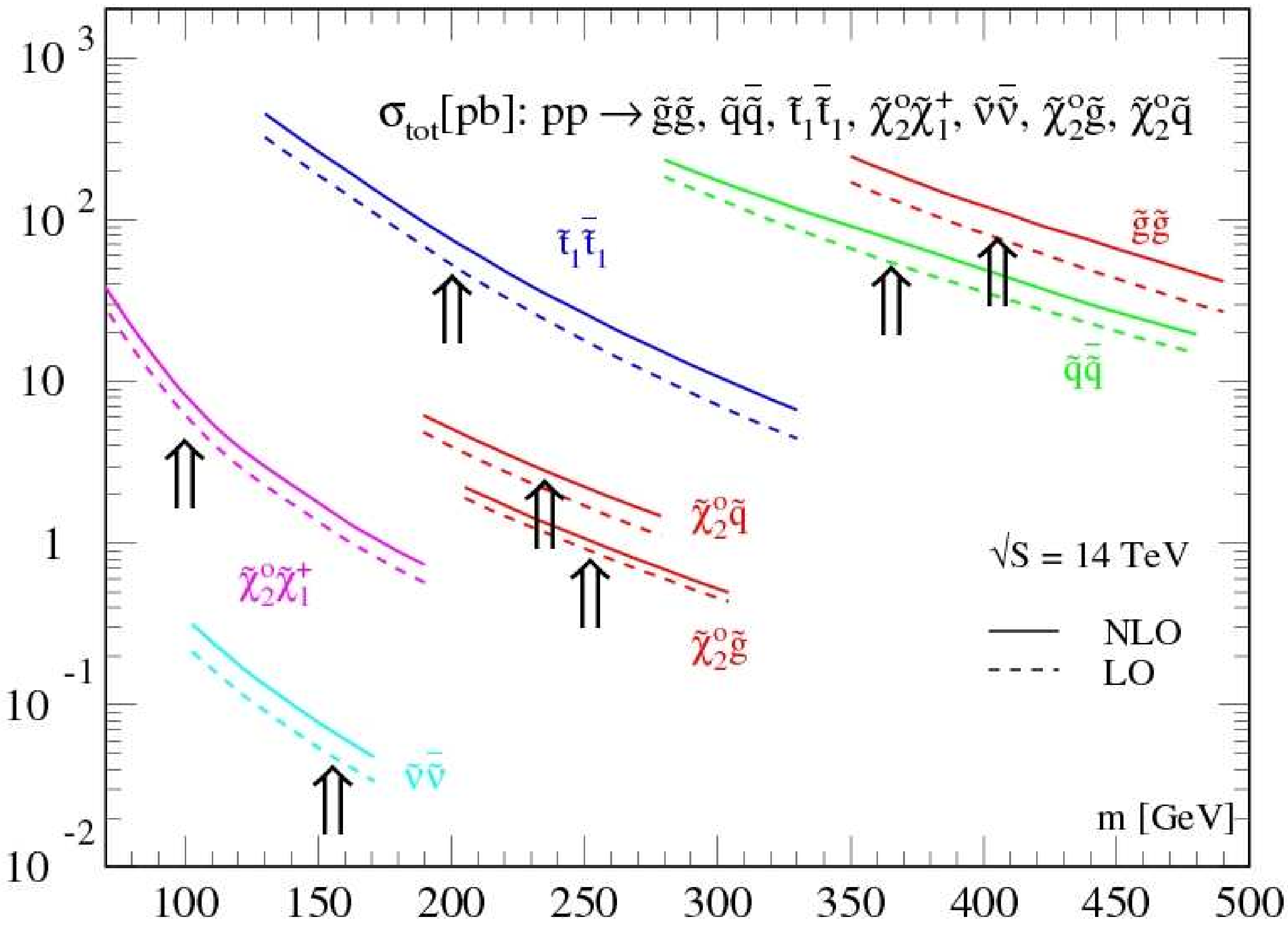
Flavor-blind interactions

MSSM (Visible sector)

Details of this determine spectrum
Goal of experiment is to measure masses and couplings
INFER susy BREAKING MECHANISM

Goal of theory is predict spectrum

Production rates at LHC



Production rates at LHC

- Squark and gluino rates given by QCD: only mass counts
- Slepton and gaugino given by EW: some dependence on couplings
- $\sigma_{SUSY} \sim 50$ pb for $m_{\tilde{q},\tilde{g}} \sim 500$ GeV
- $\sigma_{SUSY} \sim 1$ pb for $m_{\tilde{q},\tilde{g}} \sim 1000$ GeV
- Very large rates.
- Dominated by squarks and gluinos unless they are very heavy
- Everything is produced at one, so we need a model!

Production rates at LHC

- Contrast with e+e- where only a few particles might be made
- We have no idea which model of SUSY breaking might be correct
- Therefore must examine as many as possible: determine characteristic features.
- Cannot be certain that all possible signatures have been looked at.
- Start with SUGRA model

SUSY breaking in general

- Breaking must be "soft" or SUSY will not solve hierarchy
- This restricts the form of the breaking
- Masses for all sparticles
- Trilinear and bilinear scalar interactions proportional to superpotential on slide 12: A and B terms.
- This is a very large number of parameters, too many to do model independent simulations at LHC

$$\lambda^d_{ij} Q_i D_j H_1 + \lambda^u_{ij} Q_i U_j H_2 + \lambda^l_i L_i E_i H_1$$

SUSY breaking in general

$$
\begin{aligned}
-\mathcal{L}_{soft} = \; & m_1^2 \,|\, H_1 \,|^2 + m_2^2 \,|\, H_2 \,|^2 - B\mu\varepsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
& + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\
& + \frac{1}{2}\left[M_3 \bar{\tilde{g}} \tilde{g} + M_2 \overline{\tilde{\omega}_i} \tilde{\omega}_i + M_1 \bar{\tilde{b}} \tilde{b} \right] + \frac{g}{\sqrt{2} M_W} \varepsilon_{ij} \left[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\
& \left. + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.} \right] \quad .
\end{aligned}
$$

Theorists: predict these

Experiments: measure them

R-parity

- Can impose R parity. (Some theories predict this)
- All particles even; all sparticles odd
- Sparticles produced in pairs
- Lightest SUSY (LSP) particle stable: Dark Matter candidate
- R-parity forbids this
-
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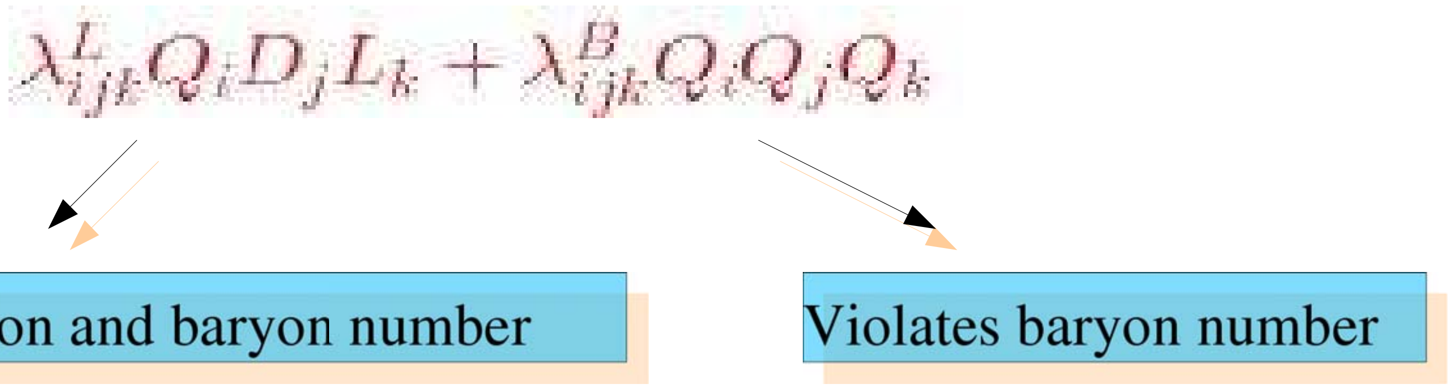


$$\lambda^L_{ijk} Q_i D_j L_k + \lambda^B_{ijk} Q_i Q_j Q_k$$

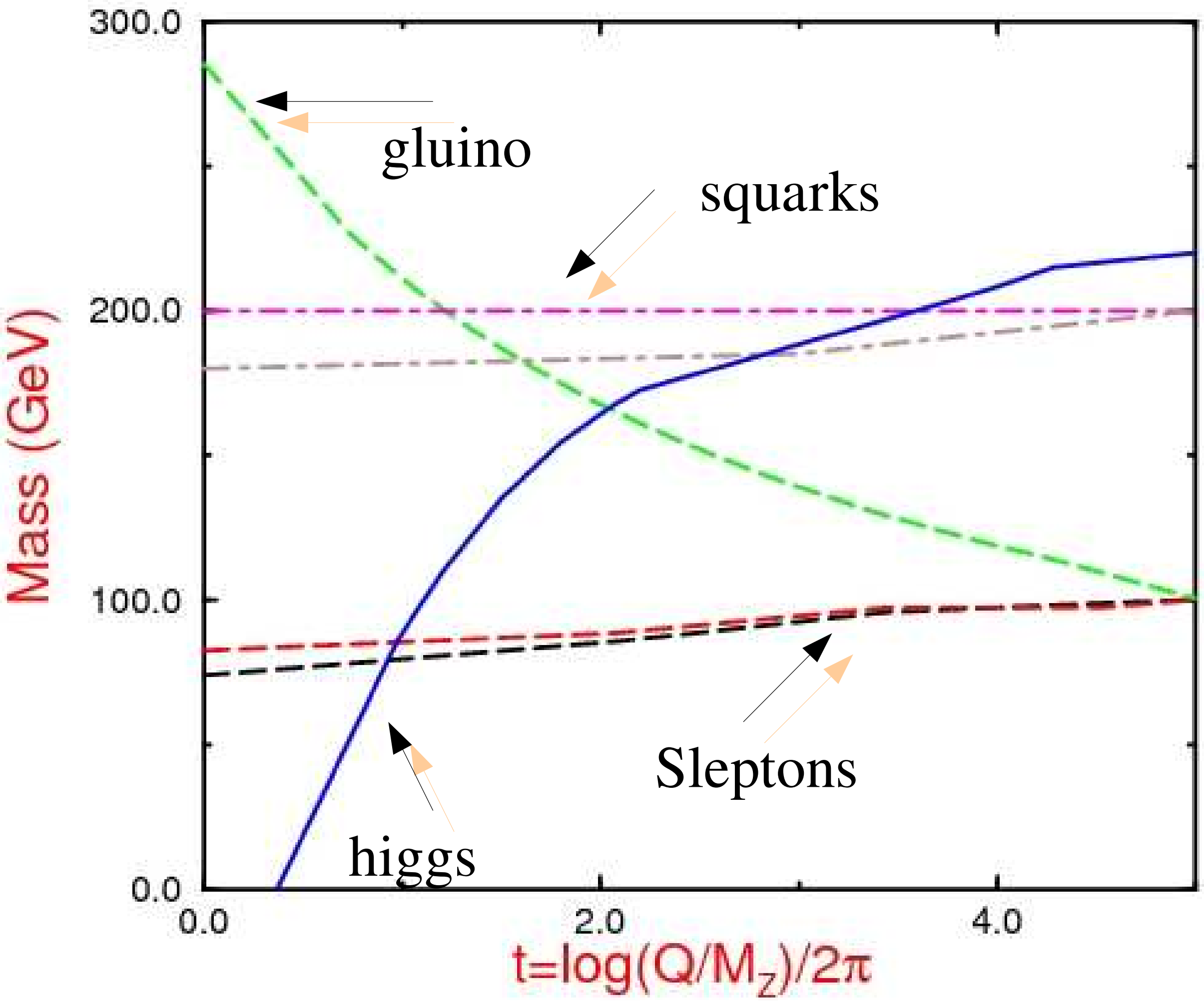
Violates lepton and baryon number

Violates baryon number

Features of SUGRA model

- Assume that gravity is responsible for transmission of SUSY breaking at some very high scale.
- Gravity knows nothing about flavor: all squark, slepton and higgs masses same m_0
- R Parity
- All gaugino masses same: $m_{1/2}$
- All A same, one B
- Only 6 parameters
- Apply SM radiative corrections to get spectrum at low energy

Evolution of masses



Breaking of EW symmetry

- Evolve parameters down to low energy
- Biggest effects from strong interactions and top quark yukawa.
- Gauge coupings cause masses to increase, Yukawas cause decrease
- Breaking of EW triggered by $m^2(H_2)<0$. Note that this requires a large top mass
- Contrast with SM

Model parameters

- $m^2(H_1)<0$ at low energy: triggers EW symmetry breaking
- Higgs Vevs v1(m_0,$m_{1/2}$, μ...) and v2(m_0,$m_{1/2}$, μ...)
- Z mass is given in terms of fundamental parameters: replace B by M_Z
- Introduce $\tan\beta$=v1/v2 and use this to replace μ
- Fundamental parameters are m_0,$m_{1/2}$$\tan\beta$, A, sign($\mu$)
- A is mostly irrelevant, except for third generation

Mass spectra

$$M_{\tilde{g}} \sim 2.7 m_{1/2}$$

$$m_{\tilde{e}_l}^2 \sim m_0^2 + 0.49 m_{1/2}^2 - 0.27 \cos 2\beta M_Z^2$$
$$m_{\tilde{e}_r}^2 \sim m_0^2 + 0.15 m_{1/2}^2 - 0.23 \cos 2\beta M_Z^2$$
$$m_{\tilde{u}_r}^2 \sim m_0^2 + 4.5 m_{1/2}^2 + 0.15 \cos 2\beta M_Z^2$$
$$m_{\tilde{u}_l}^2 \sim m_0^2 + 5.0 m_{1/2}^2 - 0.35 \cos 2\beta M_Z^2$$

Mass spectra comments

- Gluinos not much heavier than squarks
- Right sleptons lightest
- Sleptons lighter than squarks
- Third generations mix (more later)

Mass spectra

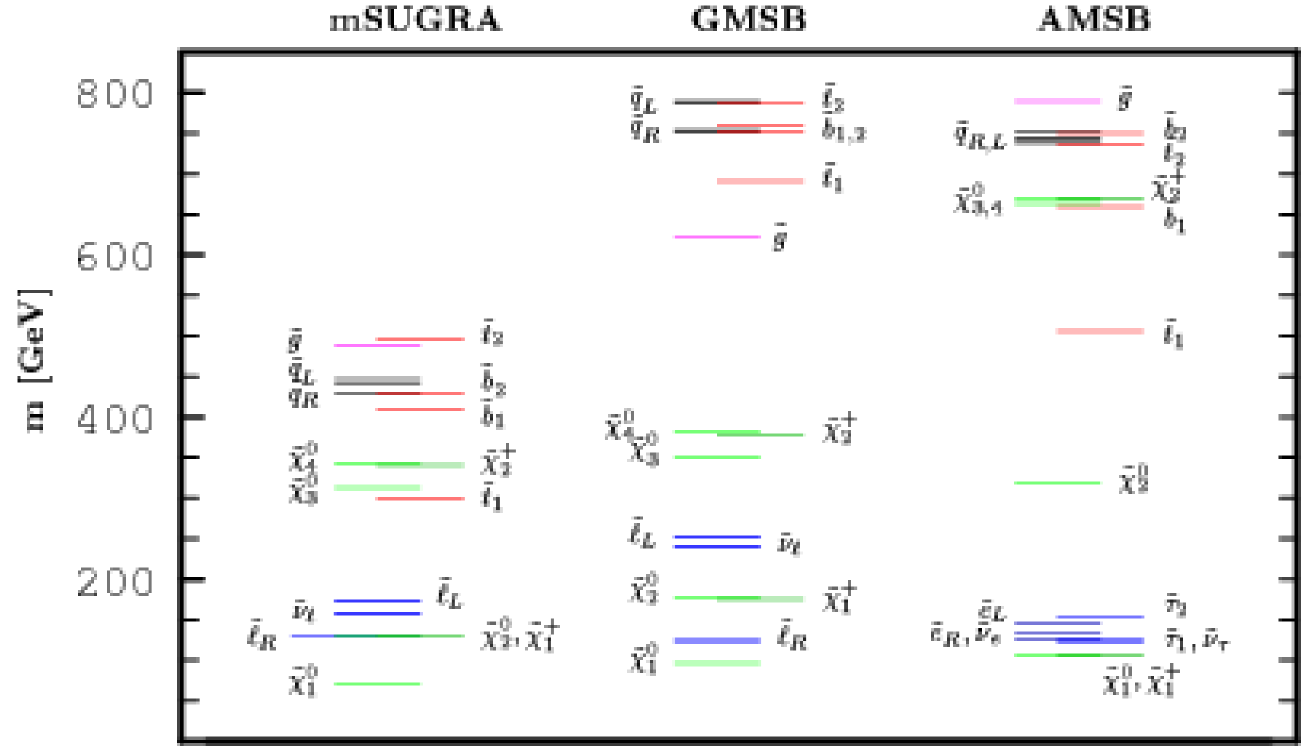
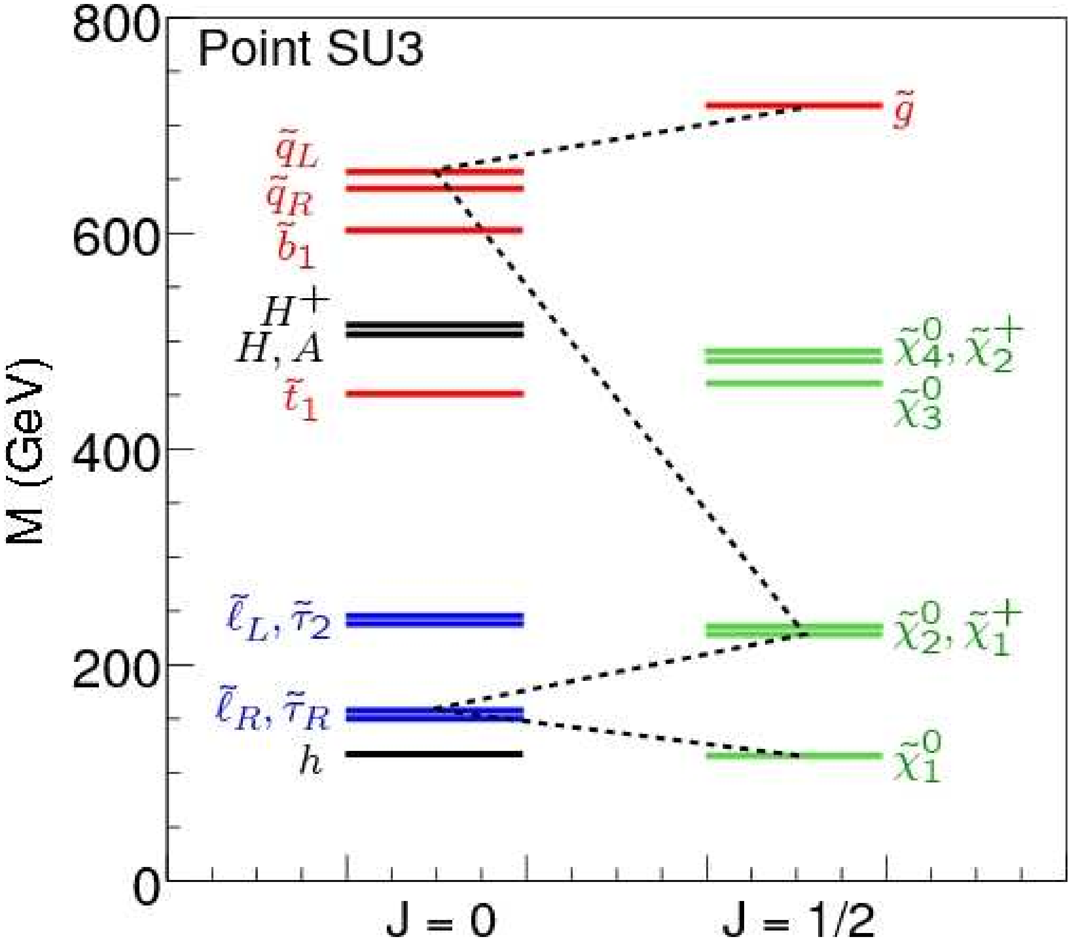
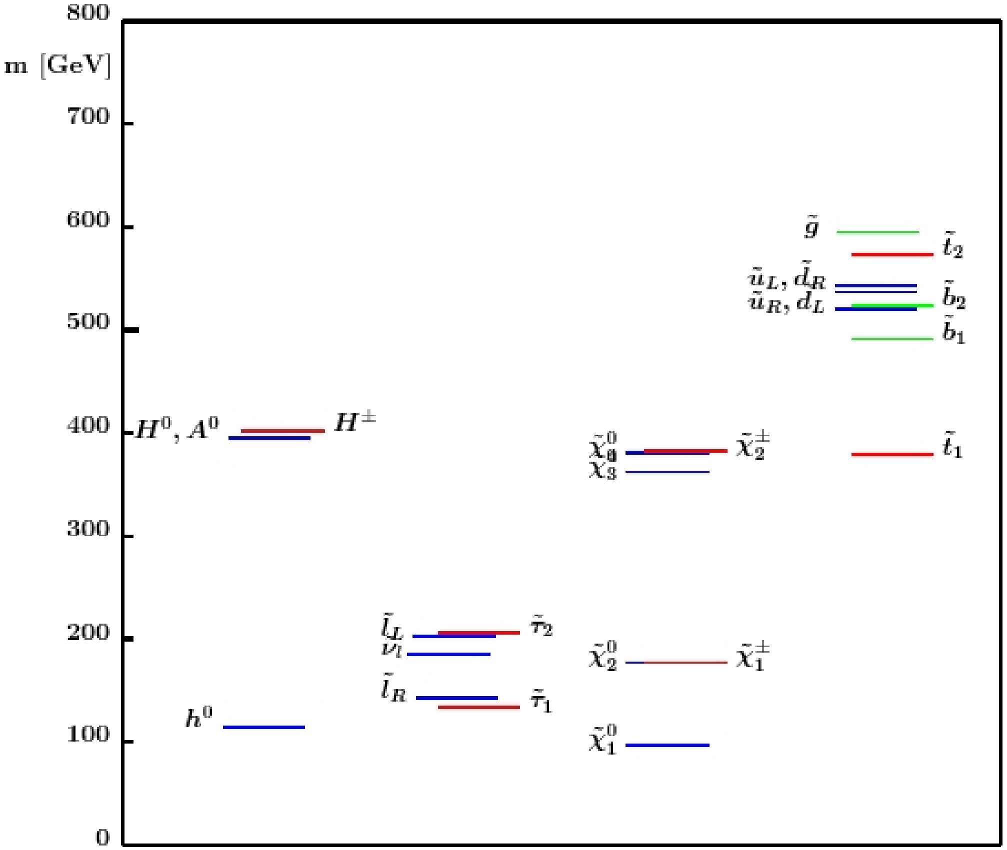


Figure 3.0.1: *Examples of mass spectra in mSUGRA, GMSB and AMSB models for* $\tan\beta = 3$, *sign* $\mu > 0$. *The other parameters are* $m_0 = 100$ *eV*, $m_{1/2} = 200\,GeV$ *for mSUGRA;* $M_{mess} = 100\,TeV$, $N_{mess} = 1$, $\Lambda = 70\,TeV$ *for GMSB; and* $m_0 = 200\,GeV$, $m_{3/2} = 35\,TeV$ *for AMSB.*

Mass spectra



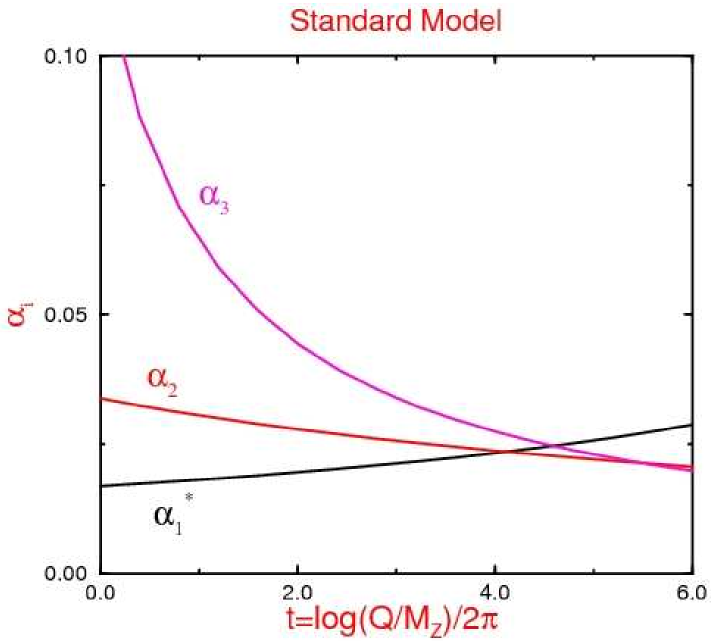
Mass spectra



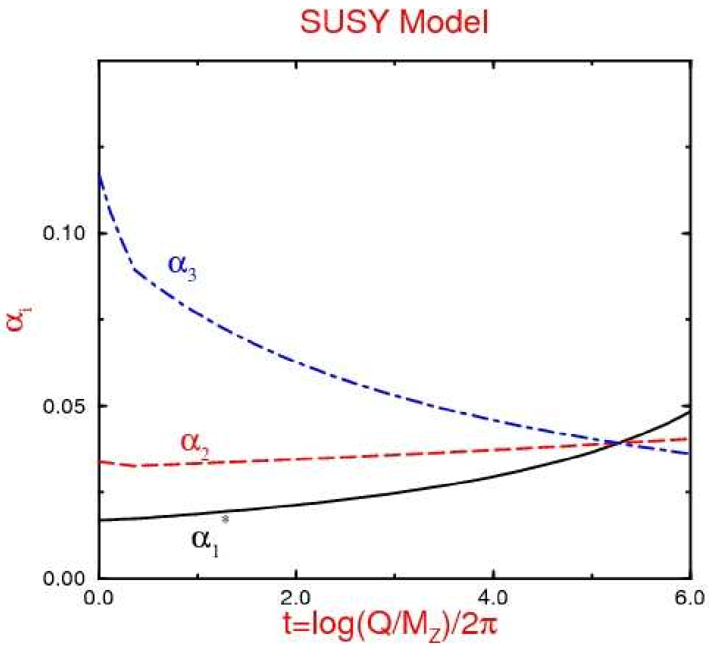
Decays

- Cascade down.
- Decay rates: strong, left weak, right weak in that order
- 2 body beats 3 body

Another argument for SUSY



Standard Model

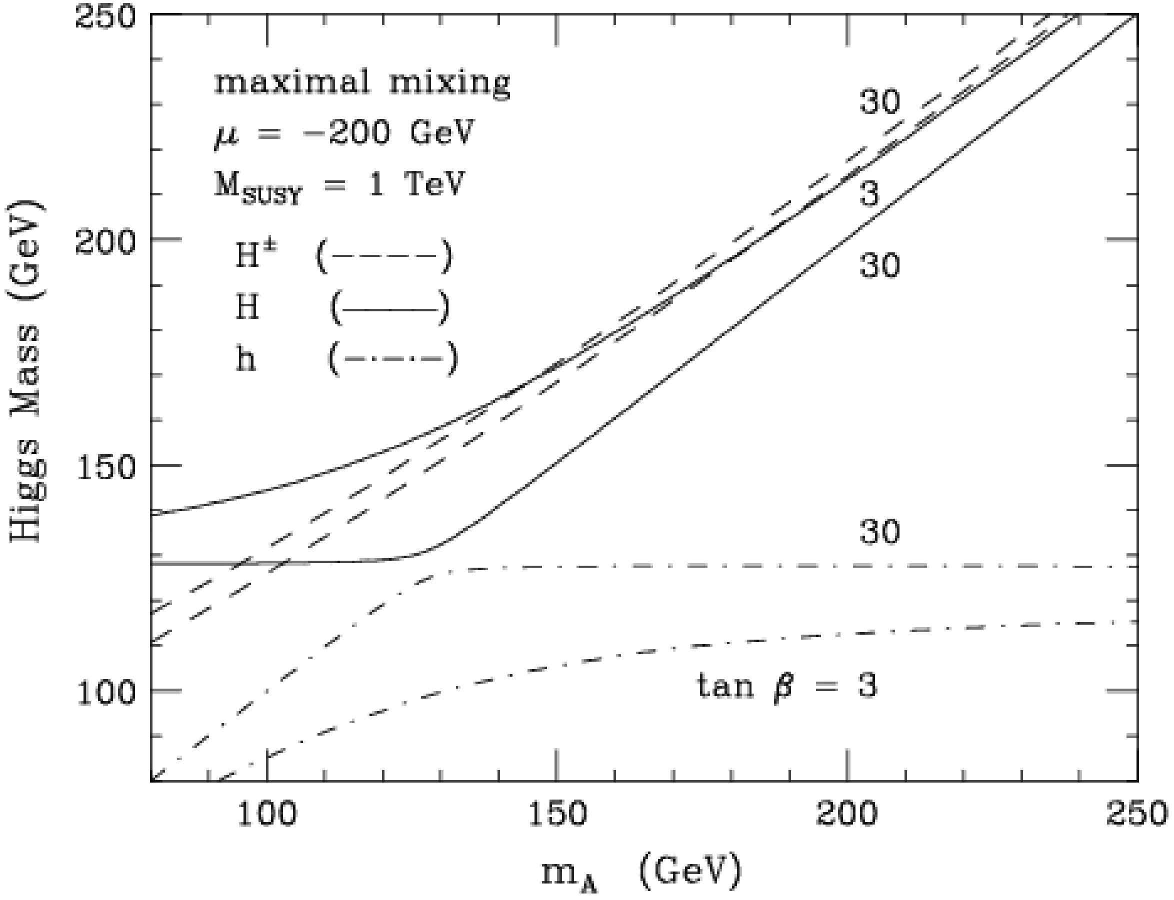


SUSY Model

Higgs masses

- In SM Higgs mass can be large: scales with self coupling
- Self coupling in SUSY is not a free parameter
- Higgs masses are constrained
- Lightest (h_0) < 135 GeV
- True in MSSM (not restricted to SUGRA)
- Lightest Higgs can be heavier if we have more Higgs bosons (NMSSM) etc.

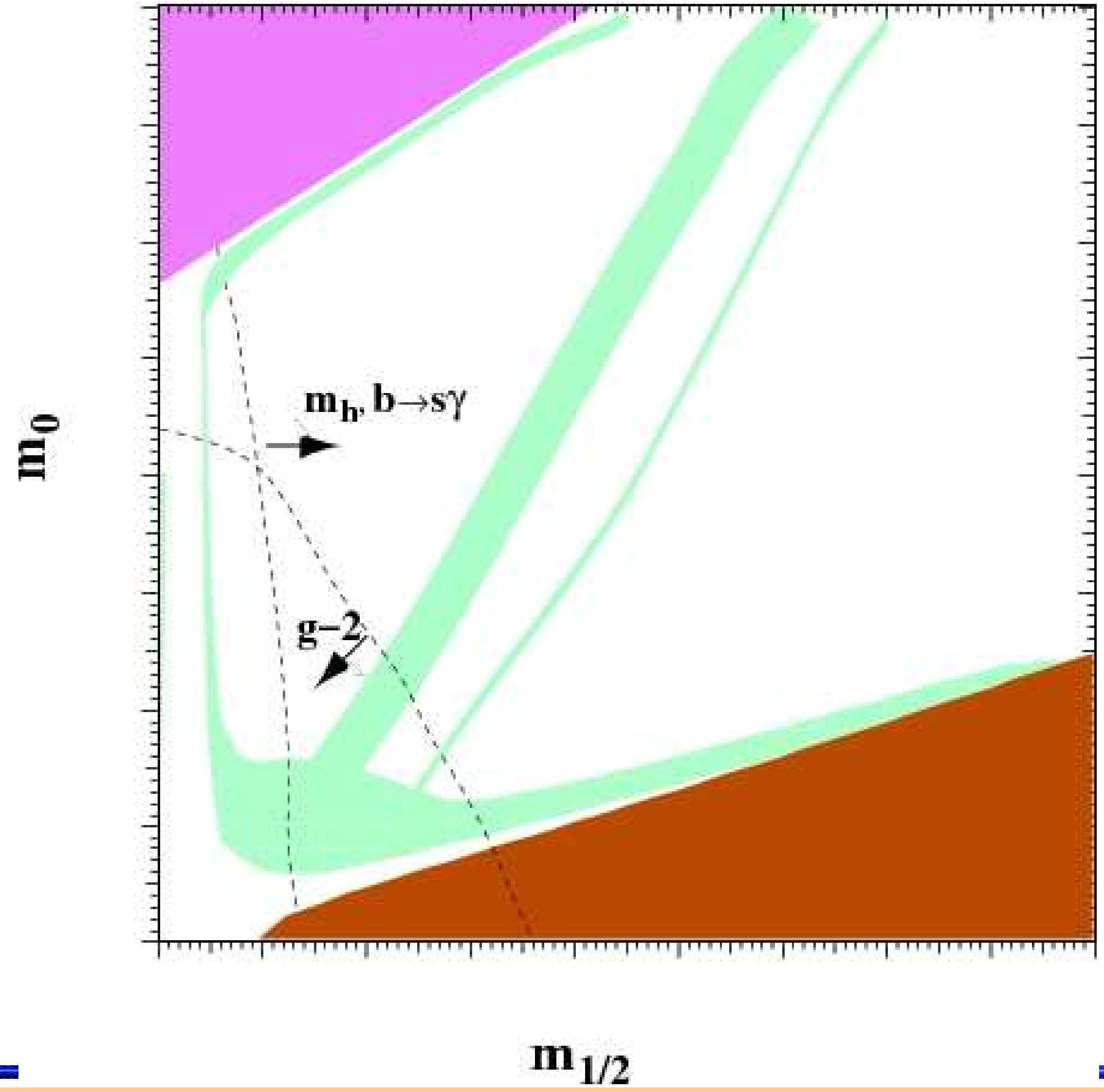
Higgs masses in MSSM



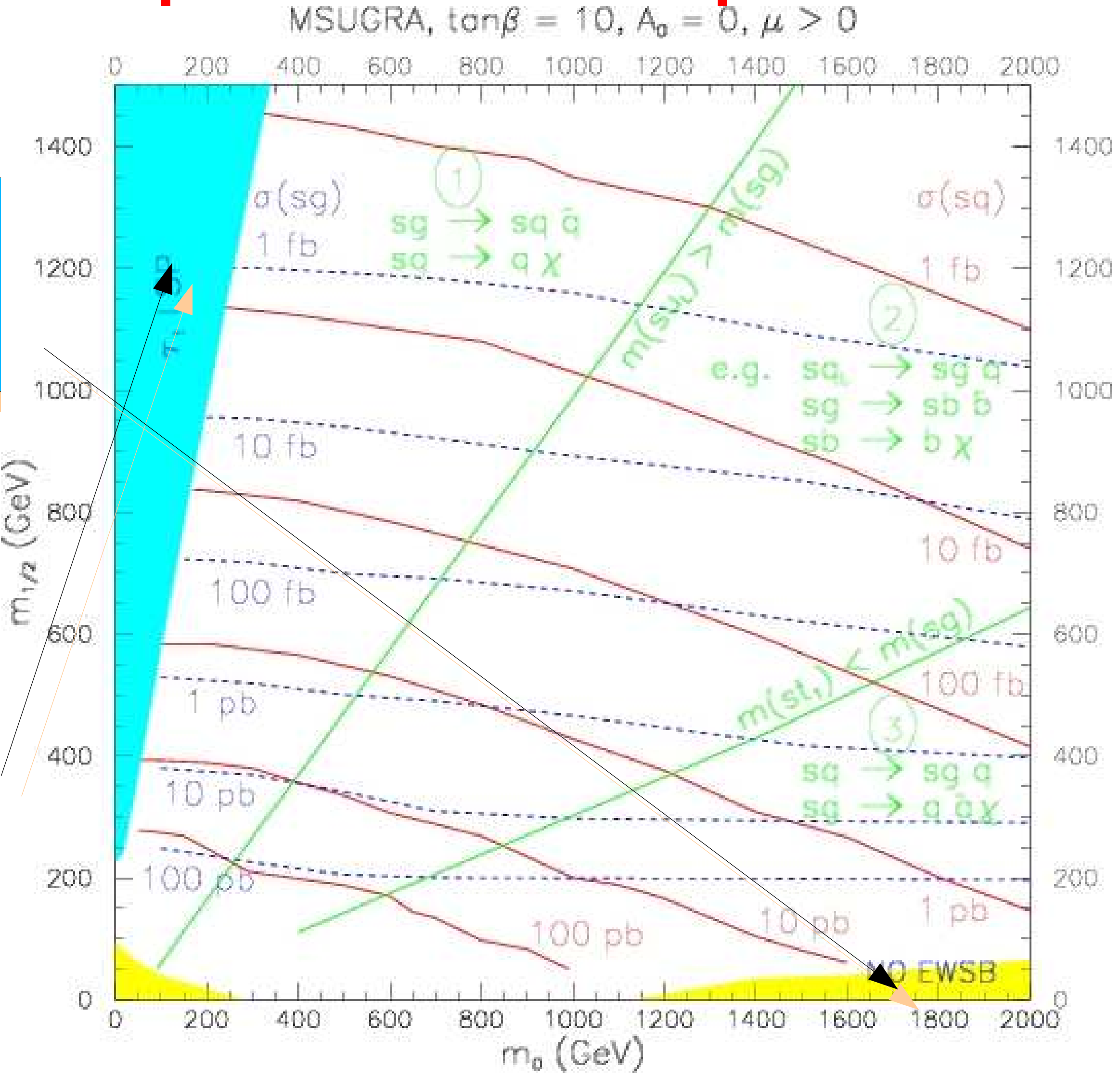
What is the LSP?

- R parity good, stable
- Cannot be charged (expt constraint)
- Sneutrinos, gauginos/Higgsinos, gravitino
- In SUGRA, gauginos/Higgsinos with mass O(100) GeV and weak interactions
- Produced at the end of all decay chains: two in every event: exits detector leading to missing Et
- Could be dark matter, details very model dependent (most analyses in SUGRA)

SUGRA and Dark Matter



SUGRA parameter space



No electro weak symmetry breaking

QED broken

Charged lsp

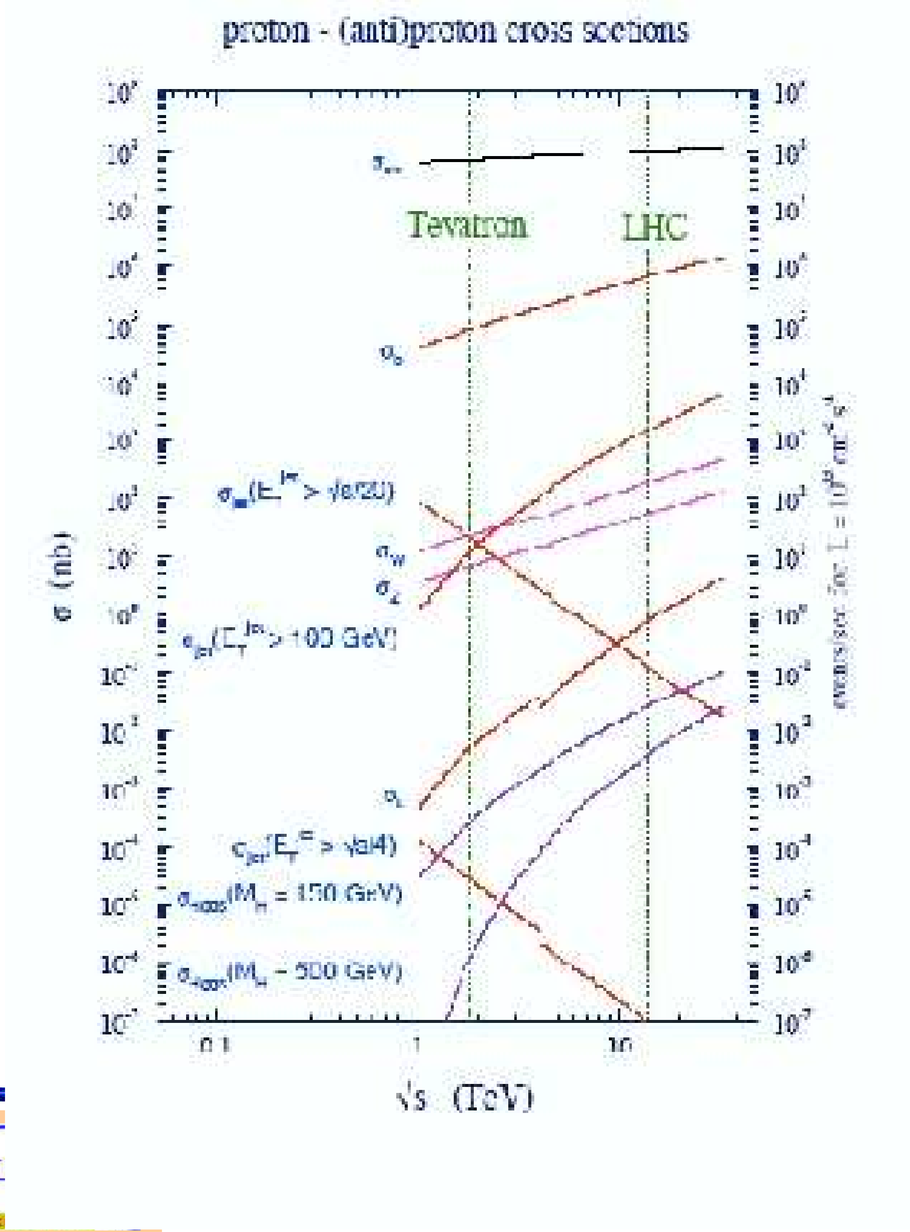
Characteristic features of SUGRA

- Squark and gluino production dominates
- Cascade decays to SM particles and LSP
- Many high pt jets from decays
- Leptons from charginos/neutralinos in decay chain
- Missing Et: 2 LSP per event
- “Spherical” events
- Copious b-jets
- These are general features of “new physics”

Triggering

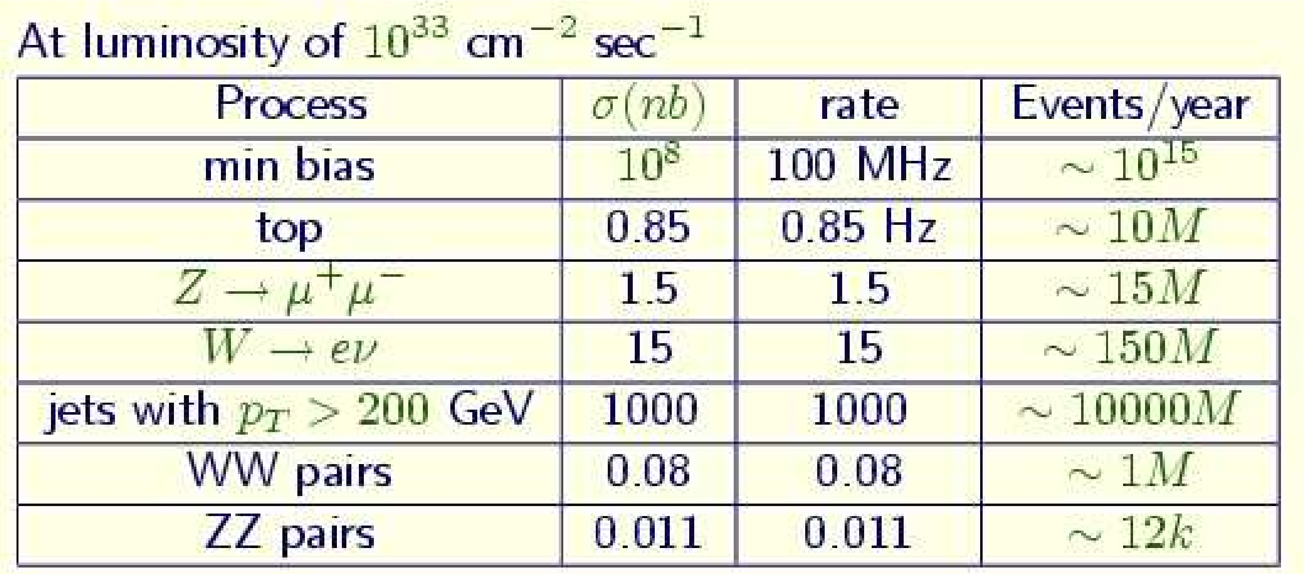
- Total cross section at LHC implies 100Mhz of events at “low luminosity”
- Must trigger and accept only a subset of this
- Must cover all physics
- Need high efficiency for rare physics
- Need redundancy
- Avoid “model driven” triggers
- Be careful not to miss anything
- Basic LHC trigger menus have not changed for many years: robust against new theory models

Rates



- Tevatron shown for comparison
- The two falling curves are jets with energies that scale with beam energy
- Huge range of rates

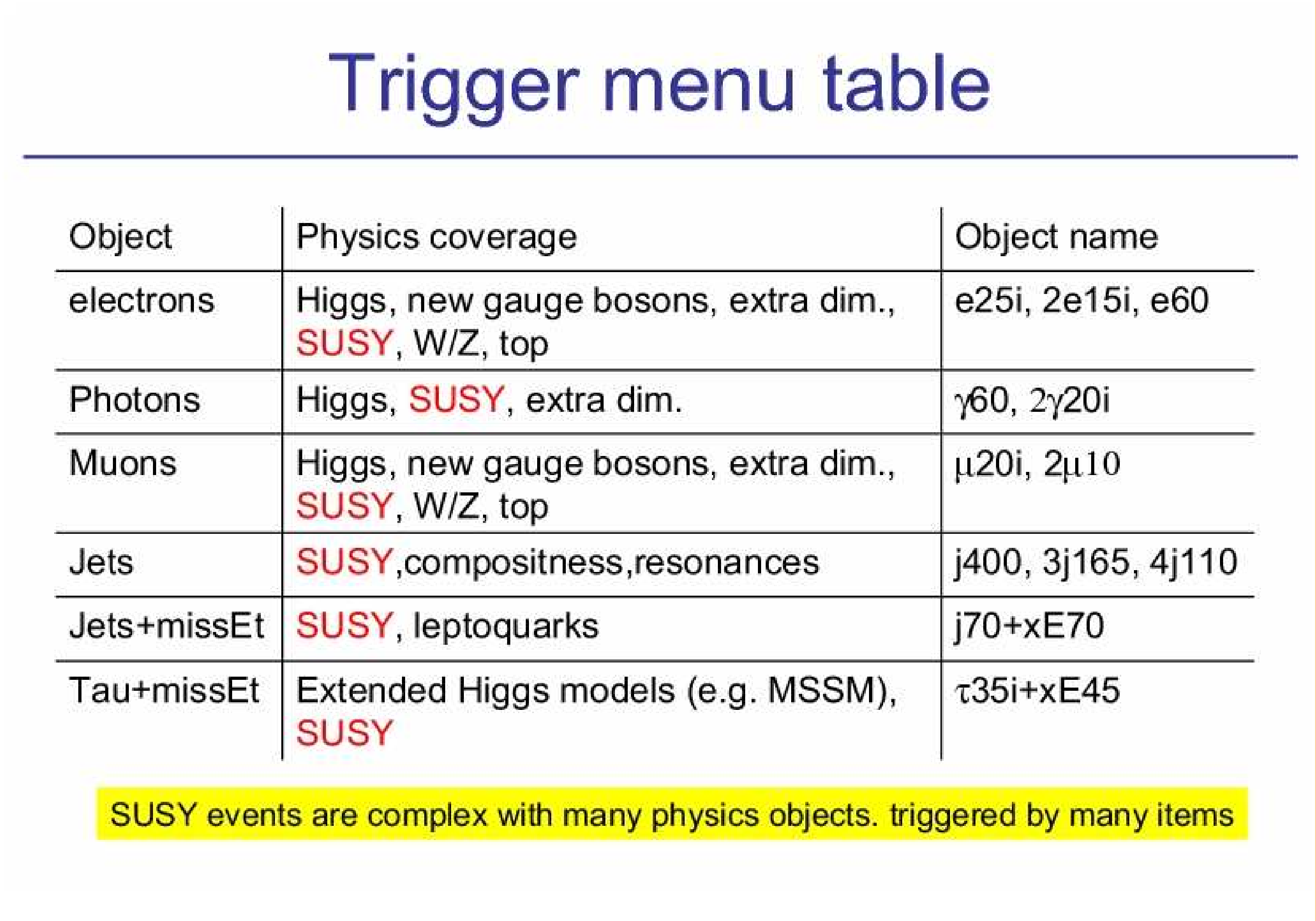
Rates



At luminosity of 10^{33} cm^{-2} sec^{-1}

Process	$\sigma(nb)$	rate	Events/year
min bias	10^8	100 MHz	$\sim 10^{15}$
top	0.85	0.85 Hz	$\sim 10M$
$Z \rightarrow \mu^+\mu^-$	1.5	1.5	$\sim 15M$
$W \rightarrow e\nu$	15	15	$\sim 150M$
jets with $p_T > 200$ GeV	1000	1000	$\sim 10000M$
WW pairs	0.08	0.08	$\sim 1M$
ZZ pairs	0.011	0.011	$\sim 12k$

Triggering



Trigger menu table

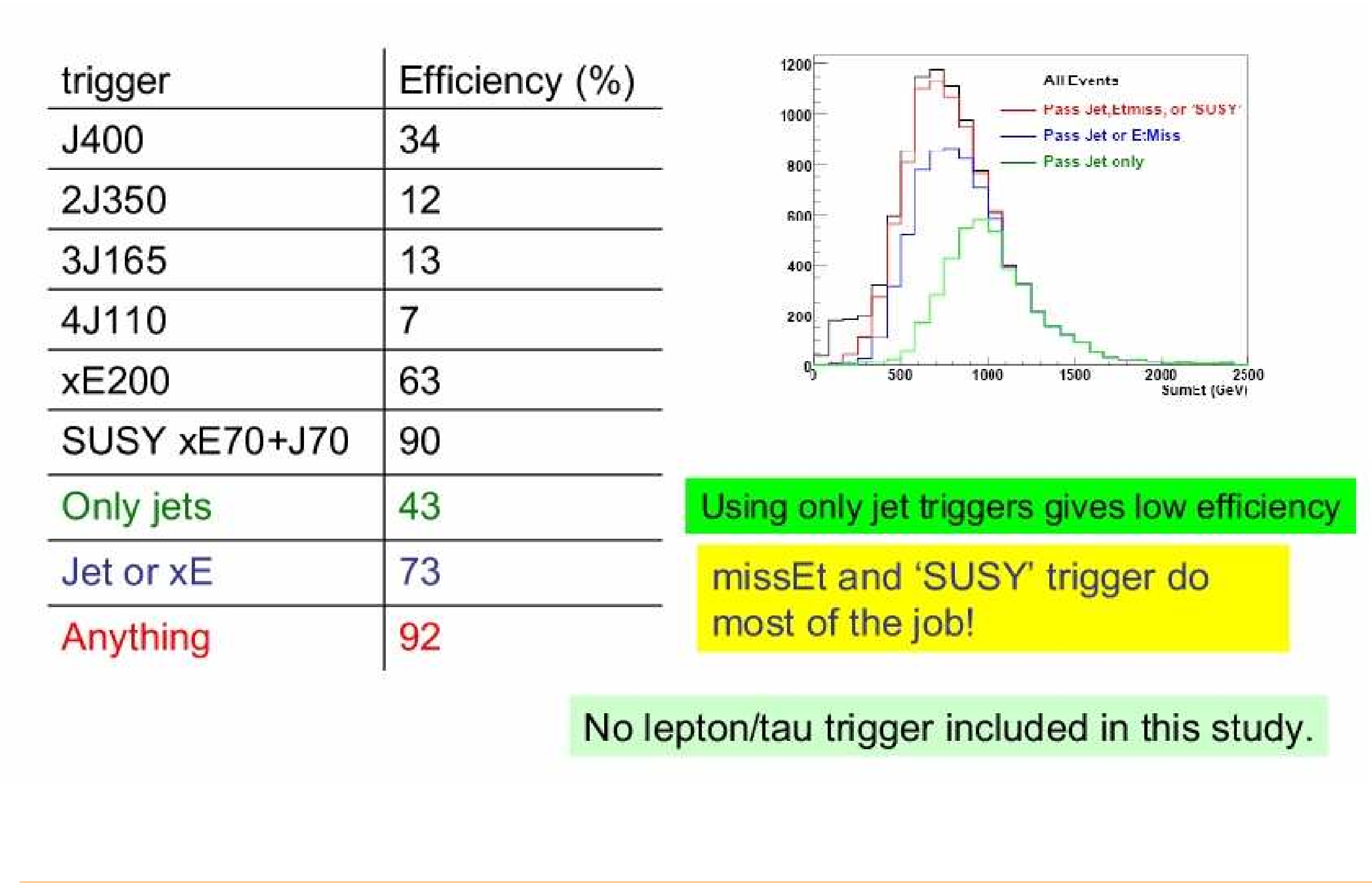
Object	Physics coverage	Object name
electrons	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	e25i, 2e15i, e60
Photons	Higgs, SUSY, extra dim.	γ60, 2γ20i
Muons	Higgs, new gauge bosons, extra dim., SUSY, W/Z, top	μ20i, 2μ10
Jets	SUSY,compositness,resonances	j400, 3j165, 4j110
Jets+missEt	SUSY, leptoquarks	j70+xE70
Tau+missEt	Extended Higgs models (e.g. MSSM), SUSY	τ35i+xE45

SUSY events are complex with many physics objects. triggered by many items

Triggering for SUSY

- SUSY will contribute to most triggers
- Note very large QCD jet rates, SUSY efficiency will be low using jets unless mass gaps are very large
- Missing Et is very important
- Leptonic trigger are very effective. Trigger effic very high for leptons from W/Z

Explicit example



trigger	Efficiency (%)
J400	34
2J350	12
3J165	13
4J110	7
xE200	63
SUSY xE70+J70	90
Only jets	43
Jet or xE	73
Anything	92

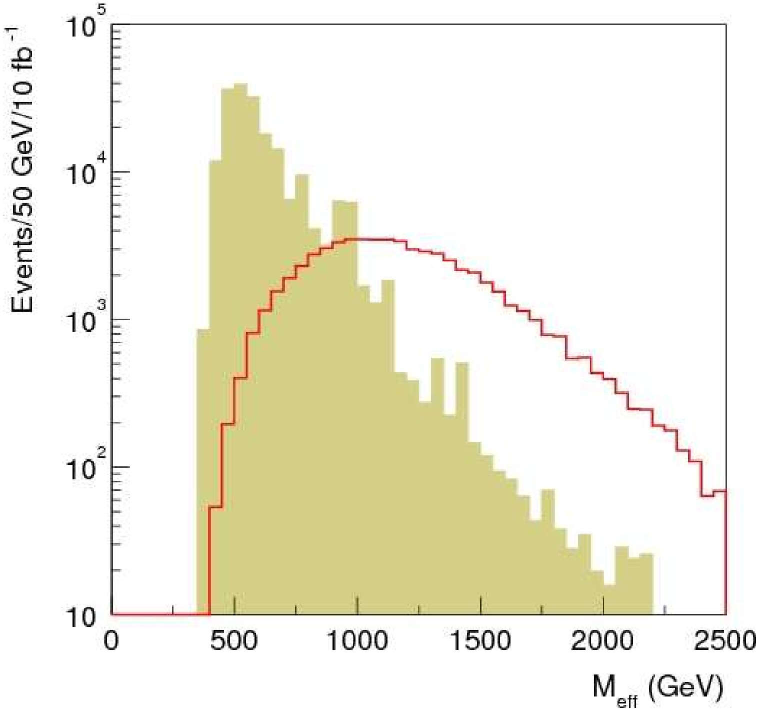
Using only jet triggers gives low efficiency

missEt and 'SUSY' trigger do most of the job!

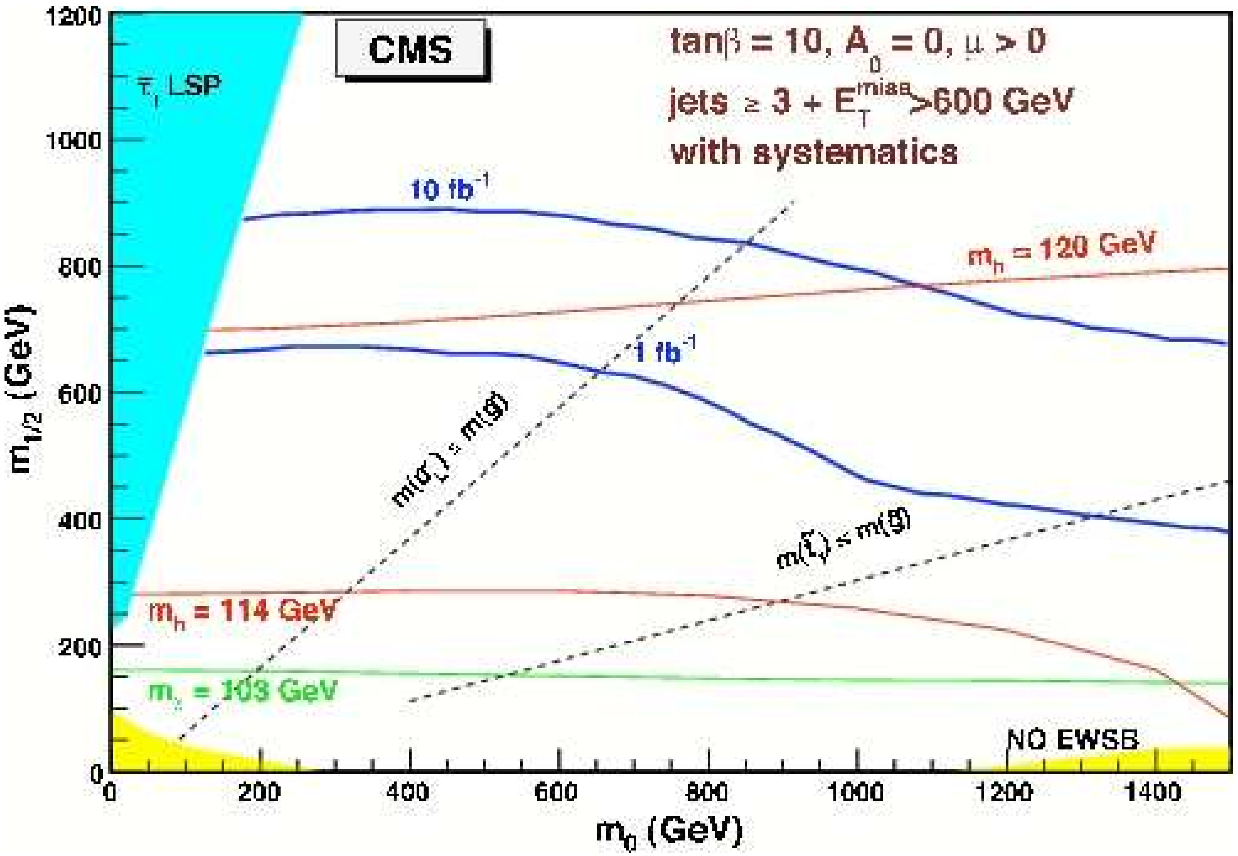
No lepton/tau trigger included in this study.

Inclusive searches

- At least 4 jets and etmiss
- $M_{eff}=pt_1+pt_2+pt_3+pt_4+etmiss$
- Peak correlates somewhat to mass of gluino/squark
- Very large rates
- More on background estimates later. Must measure and understand them before any discovery

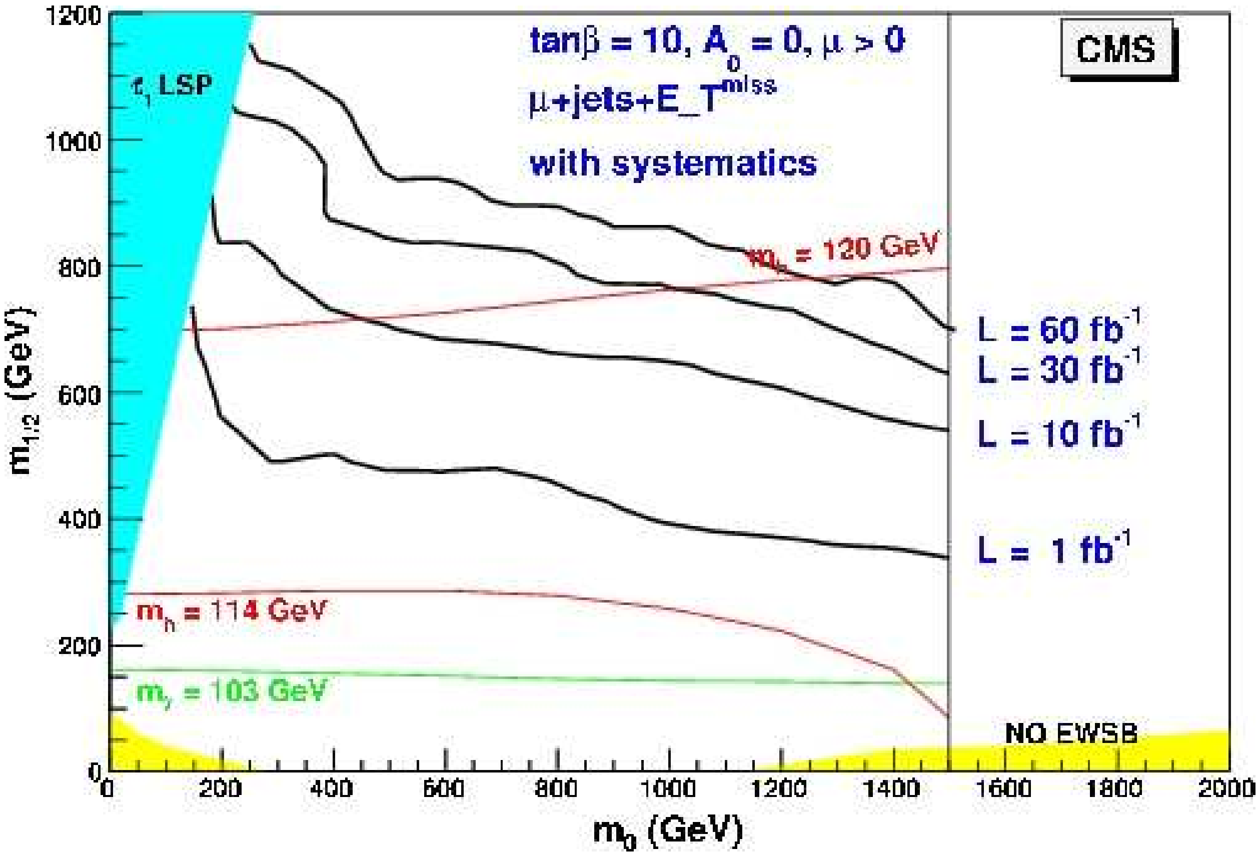


Mass reach



Energy is more important than luminosity

Mass reach

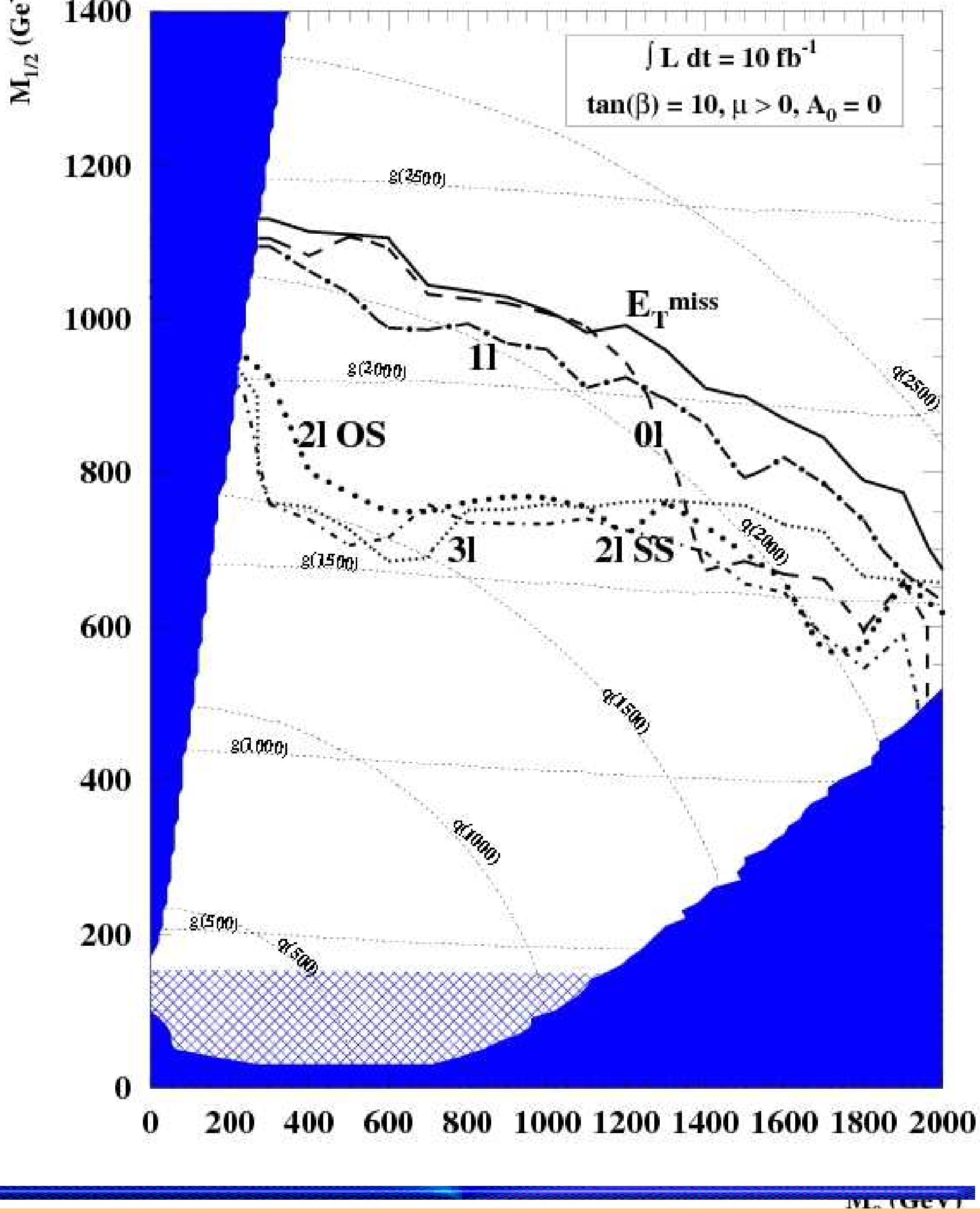


Jets plus muons

Mass reach

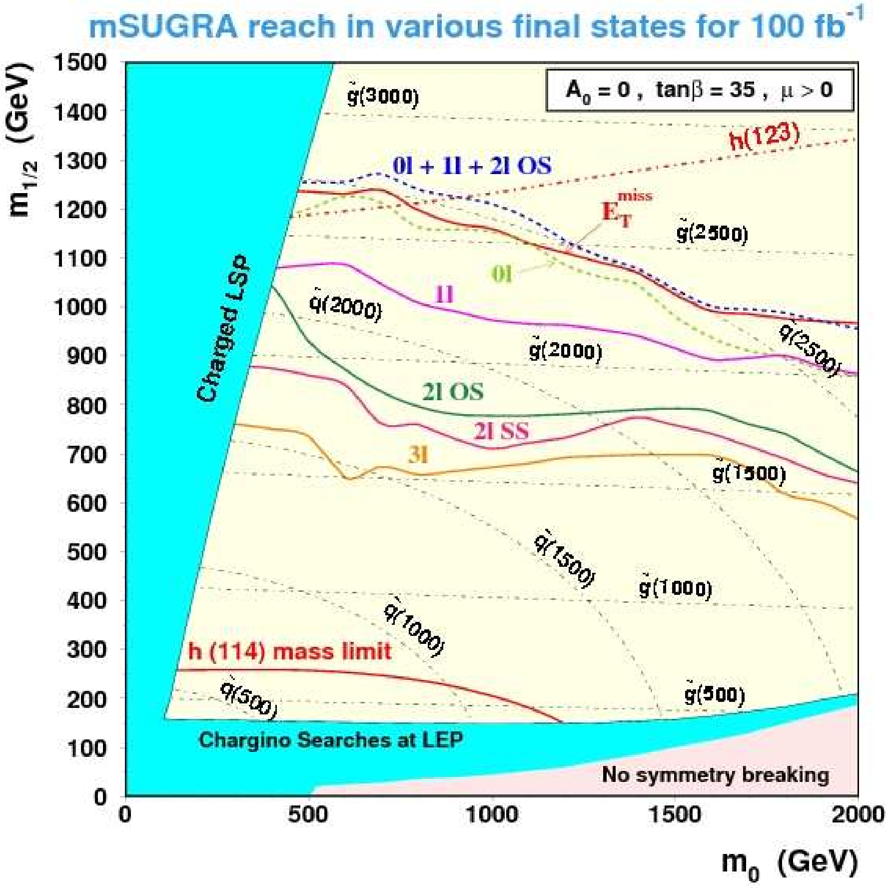
Can also require one or more leptons

May be more robust



Mass reach

Reach increases slowly with luminosity



A very clean final state

- Gluinos are majorana particles

$$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^{+}q\bar{q}\tilde{\chi}^{-}$$

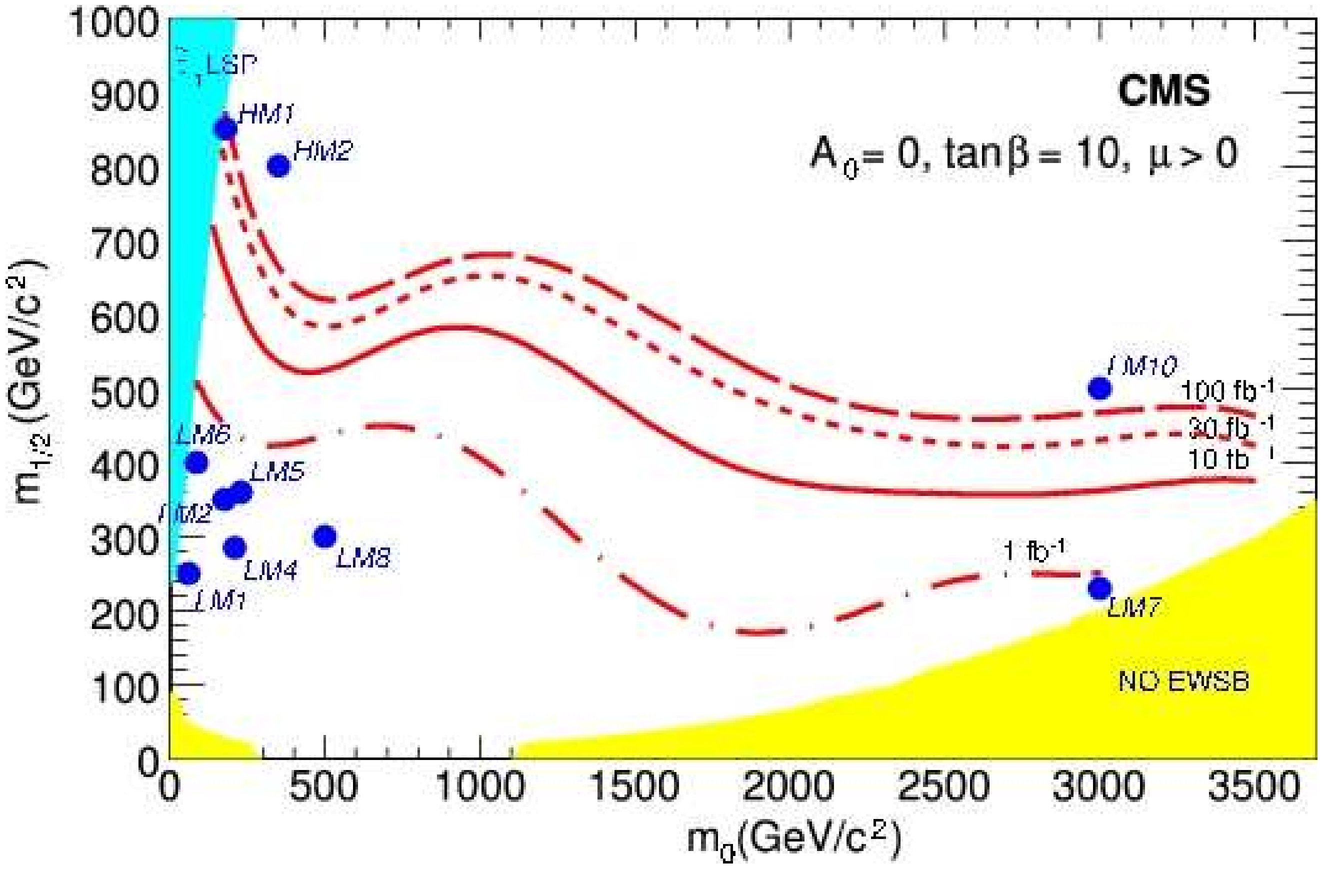
AND

$$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^{+}q\bar{q}\tilde{\chi}^{+} \quad \tilde{\chi}^{+} \rightarrow \ell^{+}\nu\tilde{\chi}_{1}^{0}$$

Dominant background sources of isolated lepton pairs give only opposite sign

$$t\bar{t} \rightarrow W^{+}W^{-}b\bar{b}$$

Same sign muons



Next time

- Background issues
- Mass measurements
- Other models and their characteristics