Physics Program at LHC

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Outline

Introductory Remarks

Brief discussion of detectors

Higgs examples, comments on precision. Very demanding of detector and machine

What might the full Higgs program accomplish?

How long must we wait for a discovery?

SUSY, models signals and examples, importance of taus. Discoveries can be made with modest luminosities: very rich program if it exists

Other new physics, extra dimensions *etc.*

Most material taken from ATLAS and CMS studies

See hep-ph/0110021 for references.

Introductory Remarks

Many LHC physics studies emphasize discovery, but there are an `enormous` number of measurements to be made.

Some can be done with $< 1\text{fb}^{-1}$, some require $> 100\text{fb}^{-1}$

10pb^{-1}: 8000 $t\bar{t}$ events and 100 jets with $E_T > 1\text{TeV}$

This is a vast multi-year program with new opportunities at each step.

Only a few examples can be given here

- Current LHC schedule – Pilot run in early 2006; Physics run $\mathbf{10}$ fb^{-1} ending in spring 2007.

Extensive Heavy Ion program Pb-Pb collisions at 1150 TeV in the center of mass and luminosity up to $\mathbf{10^{27}}$ cm^{-2} sec^{-1} with a dedicated detector (ALICE), I will not discuss this

One dedicated B-detector (LHC-b) with particle ID. Aims to exploit large B-production in particular channels that are not accessible at e^+e^- facilities $e.g.$ B_s. Extensive program (ATLAS and CMS will also do B-physics). Lack of time prevents further discussion

Multi-purpose detectors

ATLAS and CMS are aimed at "new physics"

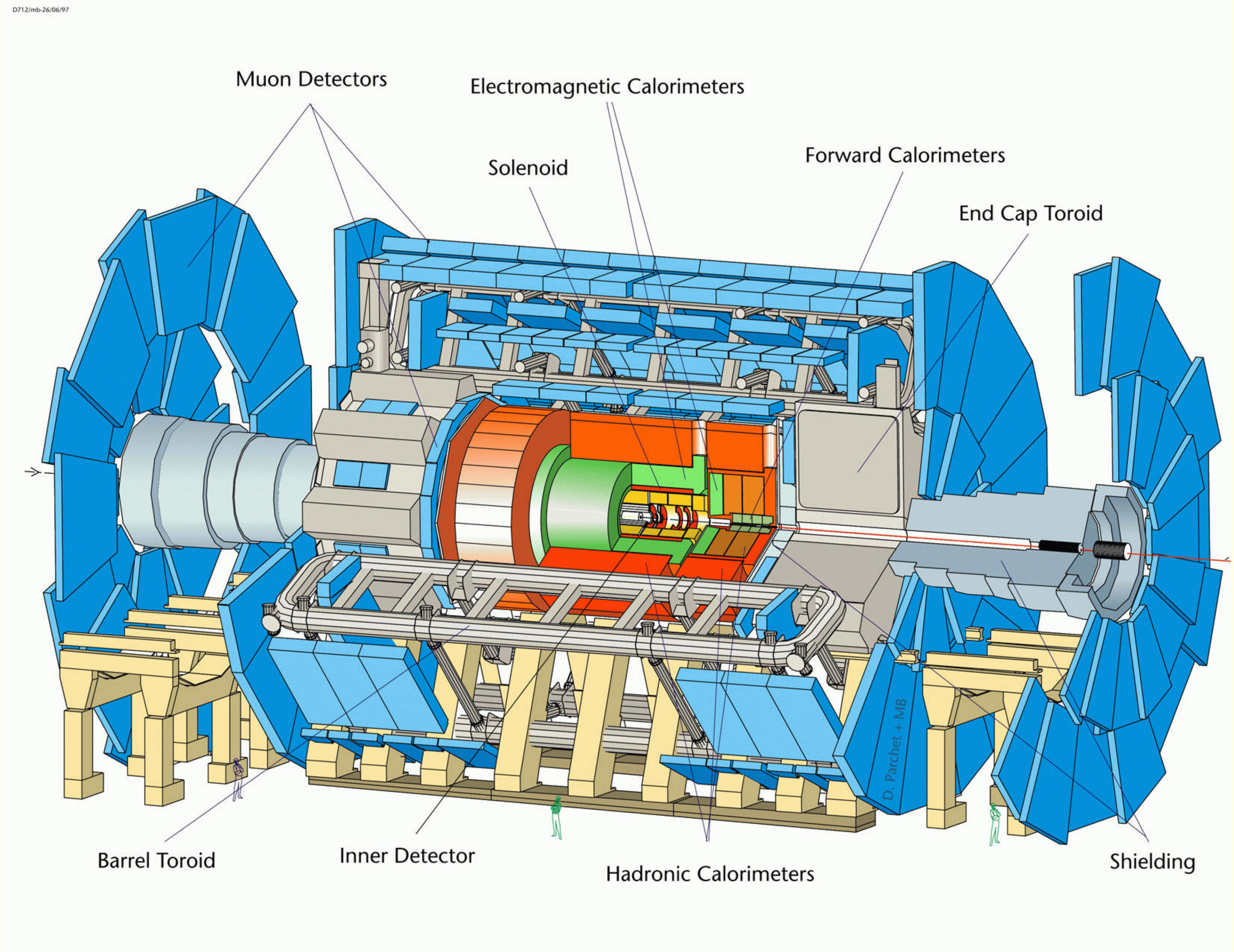
Heavy partilces are produced centrally

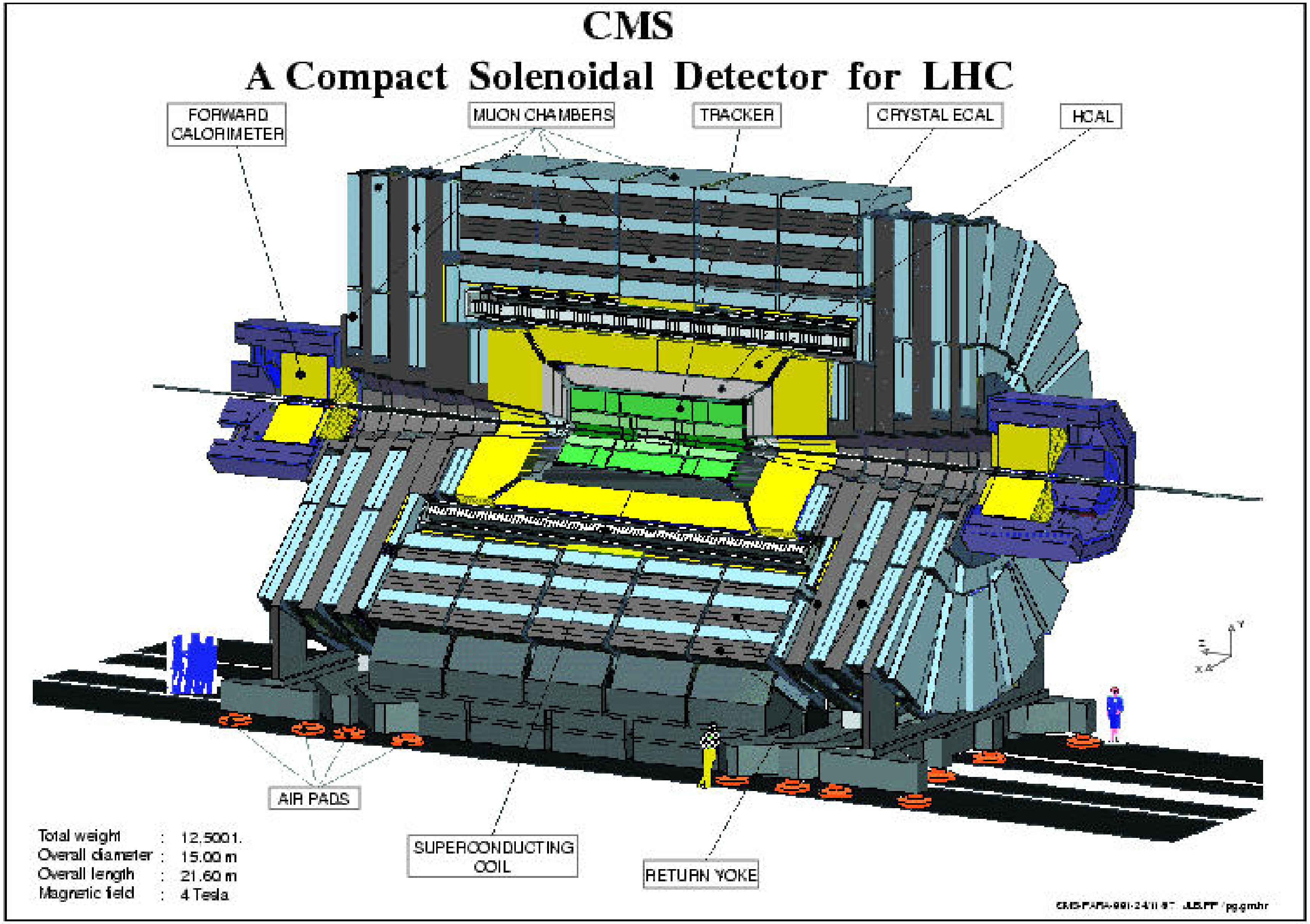
"Full acceptance" for physics objects, *i.e.* leptons and jets, missing E_T

Many detector choices driven by specific physics goals *e.g.* EM calorimiter by $H \to \gamma\gamma$

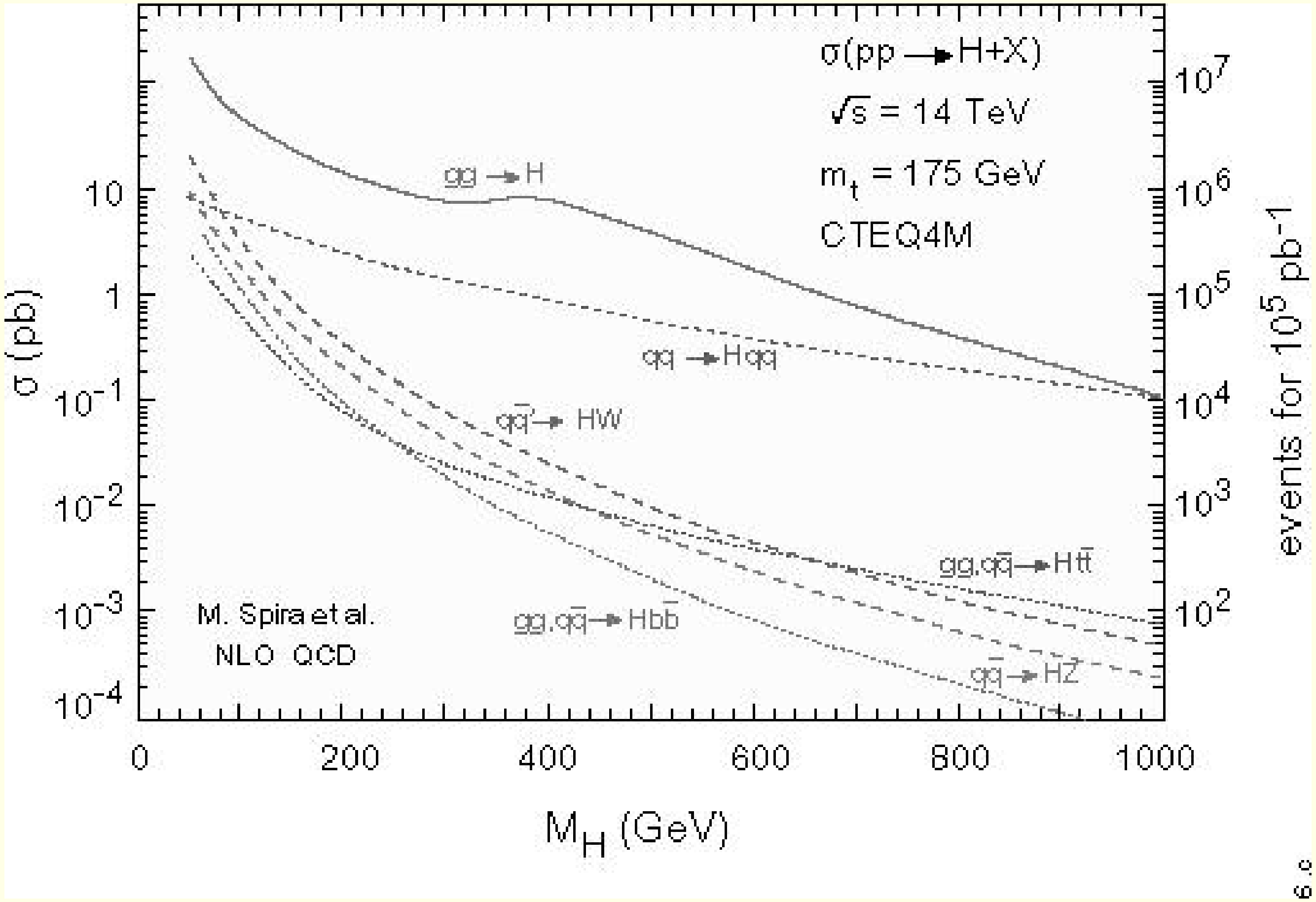
Equal response for e and μ

Physics performance of ATLAS and CMS is expected to be similar, technology choices are quite different


D712/mb-26/06/97
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

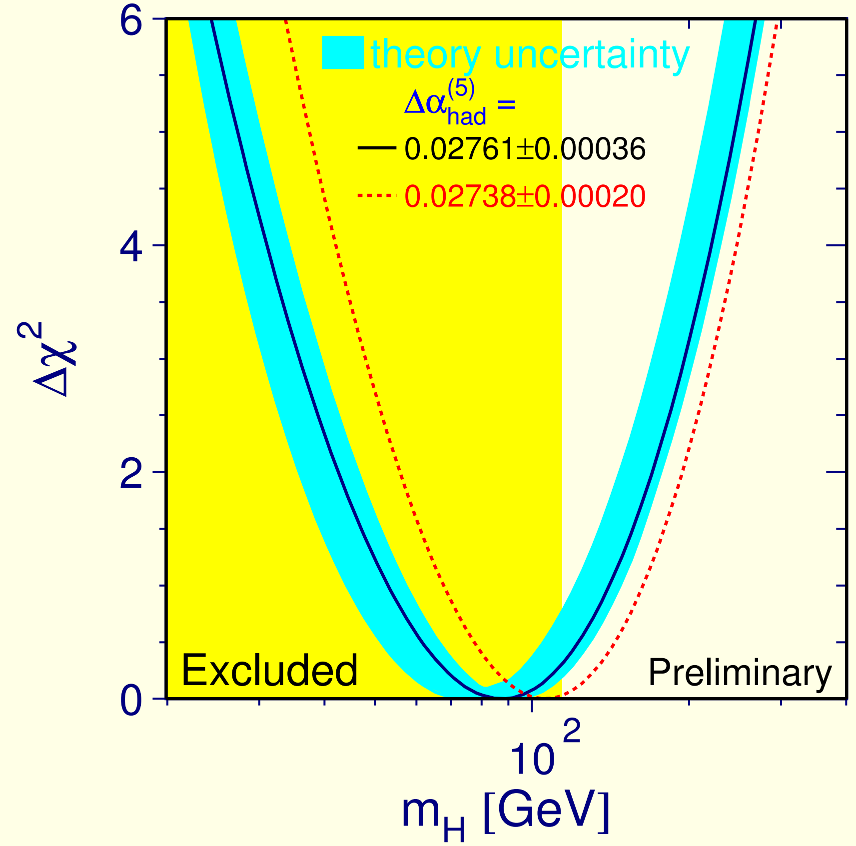

CMS
A Compact Solenoidal Detector for LHC
FORWARD CALORIMETER
MUON CHAMBERS
TRACKER
CRYSTAL ECAL
HCAL
AIR PADS
SUPERCONDUCTING COIL
RETURN YOKE
Total weight : 12,500 t.
Overall diameter : 15.00 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Standard Model Higgs



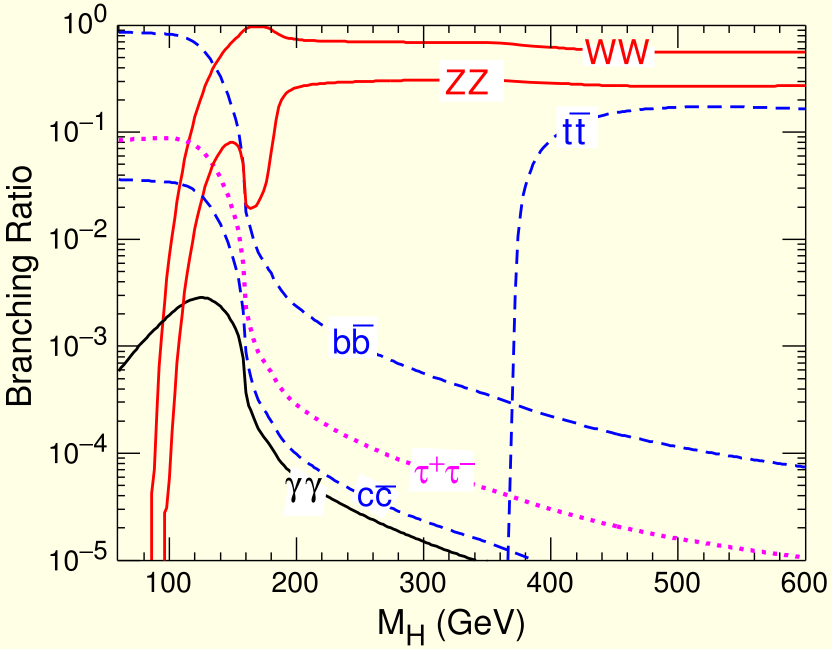
LHC searches/measurements will exploit many production mechanisms and decay modes

Constraints from LEP favor lower mass range
$M_H < 200\text{GeV}$



In this range. look for peaks in the fully reconstructed final states

- Detector resolution and signal rates are critical factors.



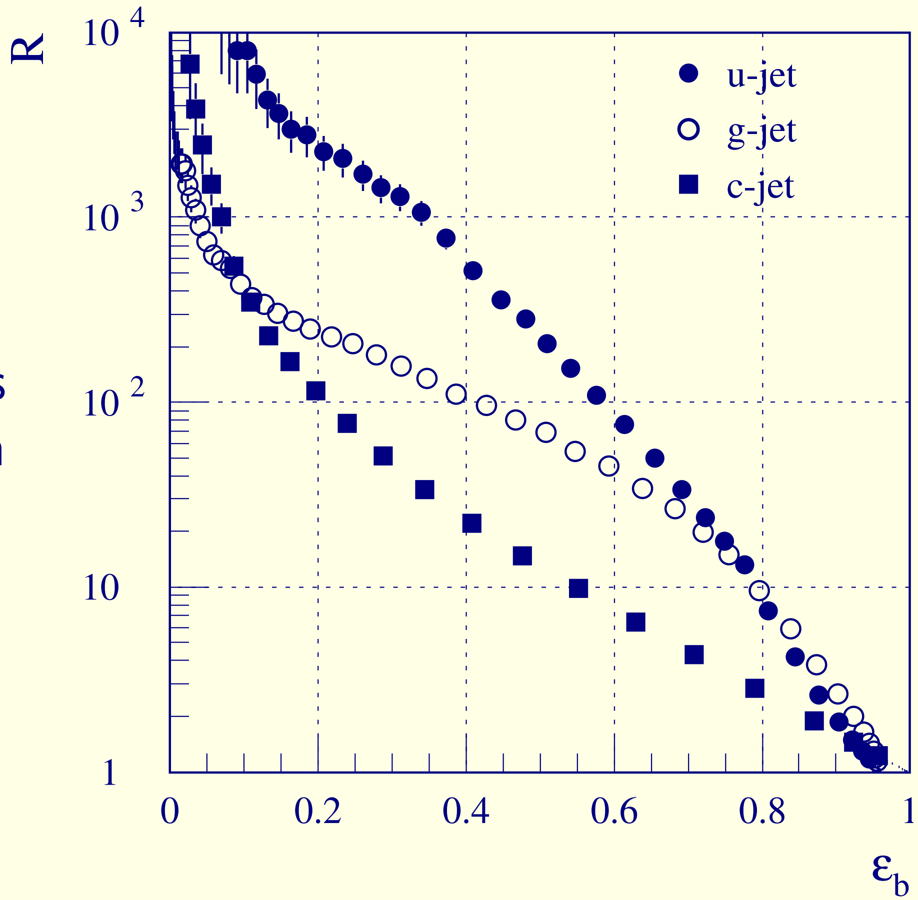
WW
ZZ
$t\bar{t}$
$b\bar{b}$
$\tau^+\tau^-$
$c\bar{c}$
$\gamma\gamma$
Branching Ratio
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
200
300
400
500
600
M_H (GeV)

- Hardest of these is $H \to b\bar{b}$

Peak is not sharp

Background arising from $t\bar{t}b\bar{b}$ is not easy to model. Must have enough data to measure background away from peak.

Depends critically upon detector's ability to tag jets with $b-quark$ with high efficiency.



$H \to \gamma\gamma$ also observable via associated production, $t\bar{t}H, WH, ZH$

Rate limited $S/B \sim 13/4$ for 100fb^{-1}

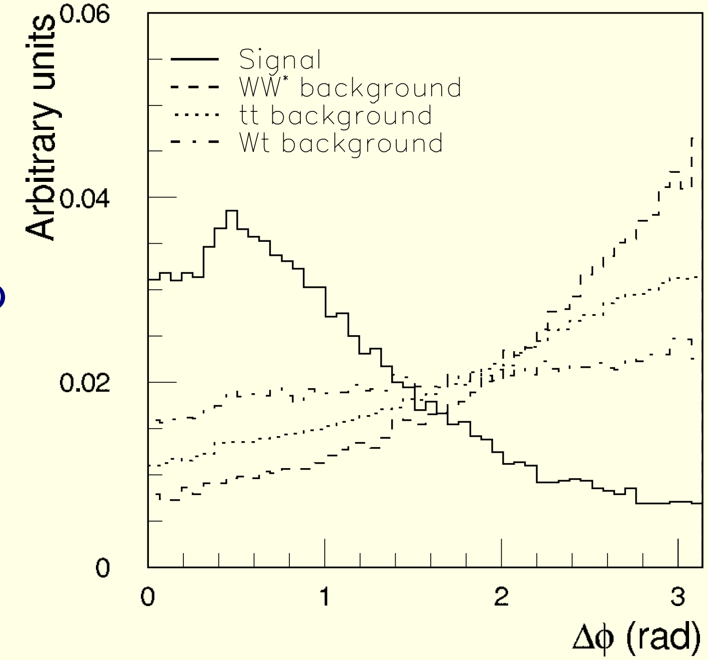
$H \to WW \to \ell\nu\ell\nu$ much harder

No mass constraint

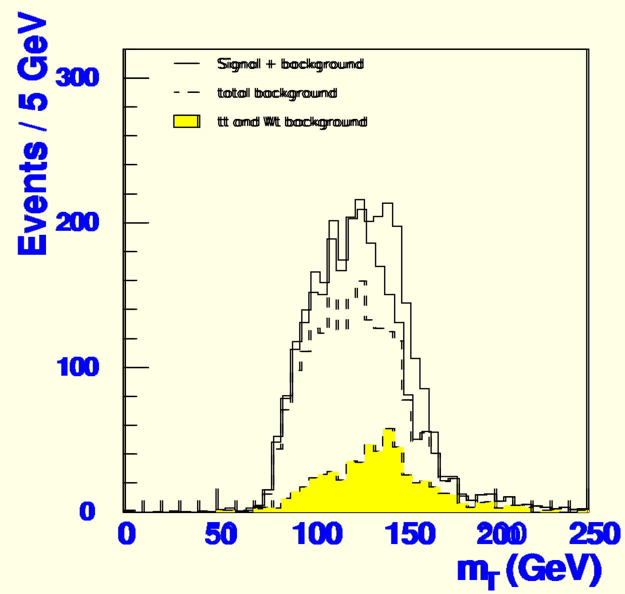
Angular correlation between leptons used to distinguish signal from background

Higgs is scalar: leptons tend to go in same direction

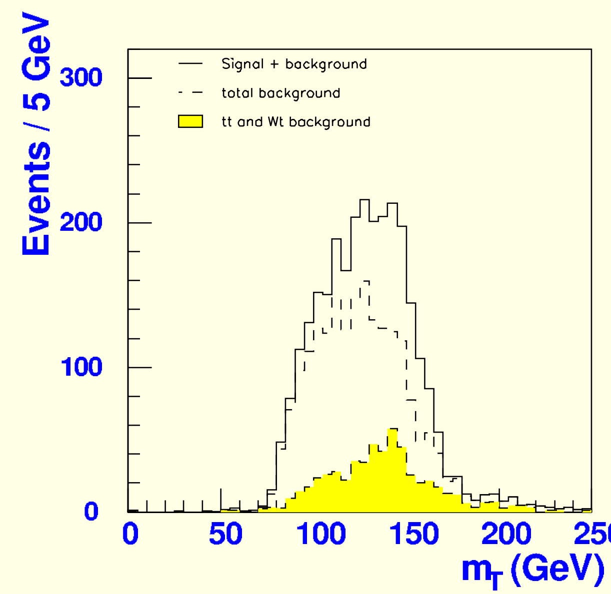
Most useful around 160 GeV: $S/B \sim 2$



Some mass sensitivity from the transverse mass made from leptons and $\not{E}_T$

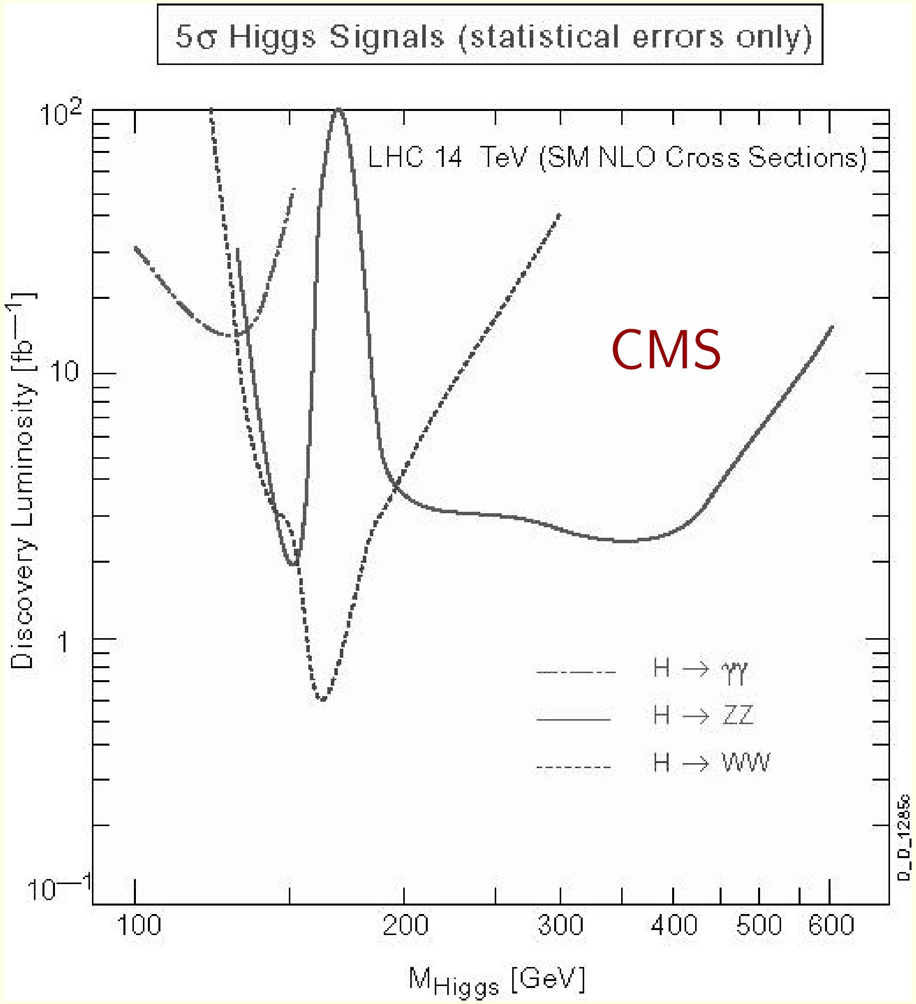


$M_H = 150$



$M_H = 170$

Higgs should be discovered by with 10fb^{-1} unless it is very heavy



Plot shows Luminosity needed for discovery

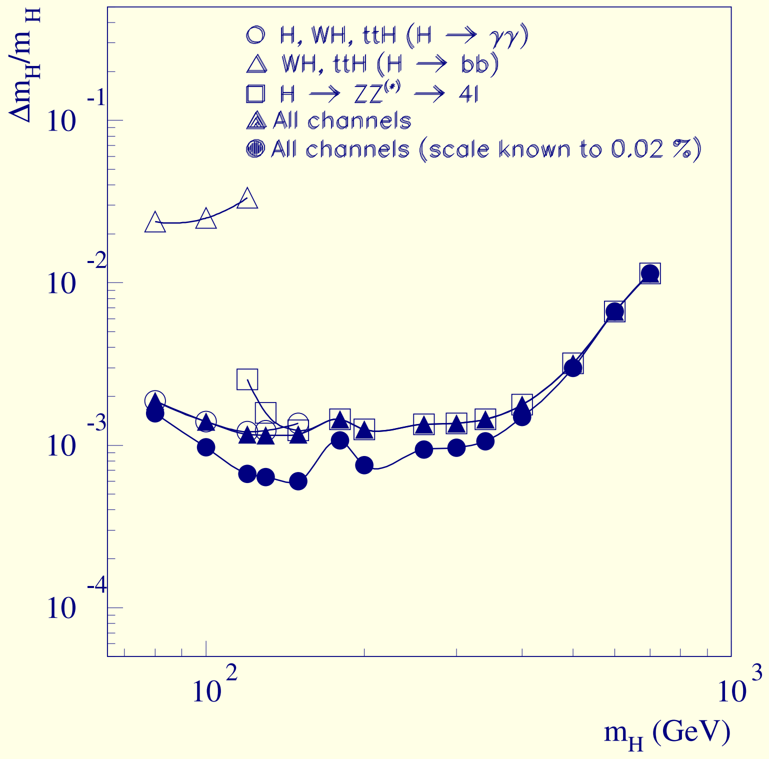
Main issue is what measurements will be available?

Precision on mass is limited by resolution at small mass and Higgs width at large mass

If you see it, mass is measured accurately (except for WW mode)

Error is $< 0.1\%$ at small mass

Intrinsic width too small to measure for $M_H \lesssim 350\mathrm{GeV}$



Observable channels depend on mass

$gg \to H \to \gamma\gamma$: $80 < M_H < 135$

$gg \to H \to ZZ \to 4\ell$: $120 < M_H < 700$

$gg \to H \to ZZ \to \ell\ell\nu\nu$: $250 < M_H < 1000$

$gg \to H \to WW \to \nu\ell\nu\ell$: $140 < M_H < 190$

$gg \to H \to WW \to \nu\ell\text{jetjet}$

$300 < M_H < 1000$

$q\bar{q} \to W/Z/t\bar{t}(\to \ell + X)H(\to \gamma\gamma)$

$100 < M_H < 130$

$q\bar{q} \to W/Z/t\bar{t}(\to \ell + X)H(\to b\bar{b})$

$100 < M_H < 125$

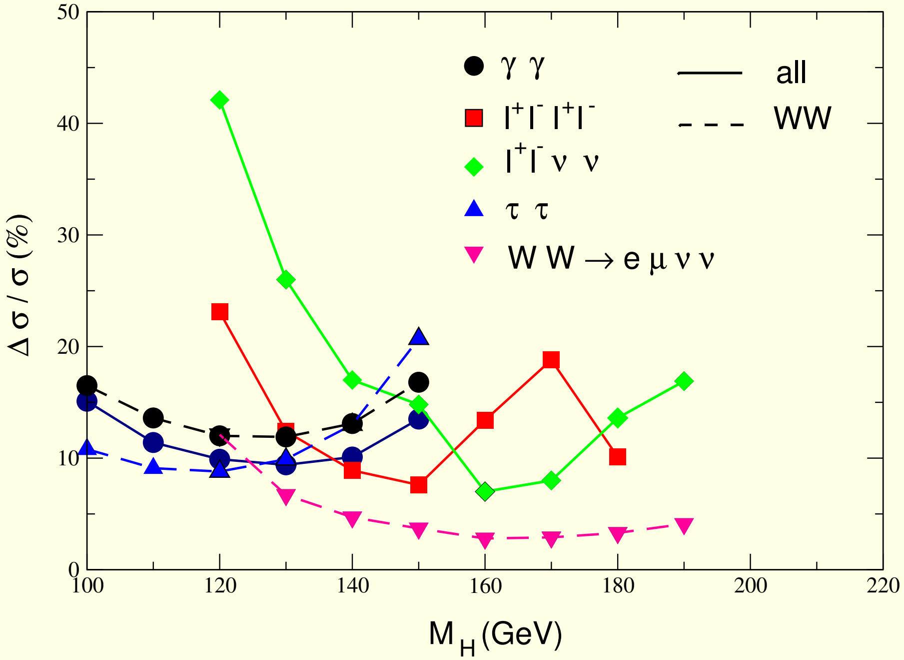
$qq \to qqH(\to \tau\tau)$: $100 < M_H < 150$

$qq \to qqH(\to \gamma\gamma)$: $100 < M_H < 140$

$qq \to qqH(\to WW \to \ell\ell\nu\nu)$

$130 < M_H < 190$

Precision on rates



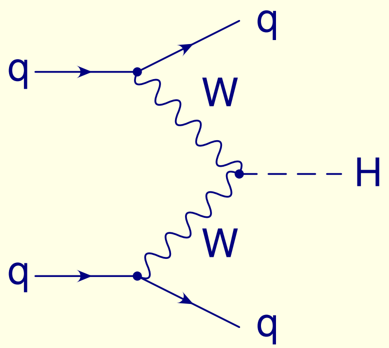
For larger masses only WW and ZZ available.

If same production process is used then ratios of couplings can be obtained directly *e.g.* $\Gamma(\tau\tau)/\Gamma(WW)$ for $M \sim 140$ GeV

Otherwise measurements depend on theory of production process.

$qq \to qqH$ `vital`

$qq \to qqH$



Vital at large masses where it dominates production
Will provide valuable information at smaller masses where it is $\sim 10\%$ of rate. Measures WWH coupling

Must be extracted from background and main Higgs process
Exploit forward jets and quiet central region
Final states $\gamma\gamma$ $e\mu\nu\nu$ and $\tau\tau$ can be reconstructed.

Event rates for $M_H = 140\mathrm{GeV}$ and $100\mathrm{fb}^{-1}$

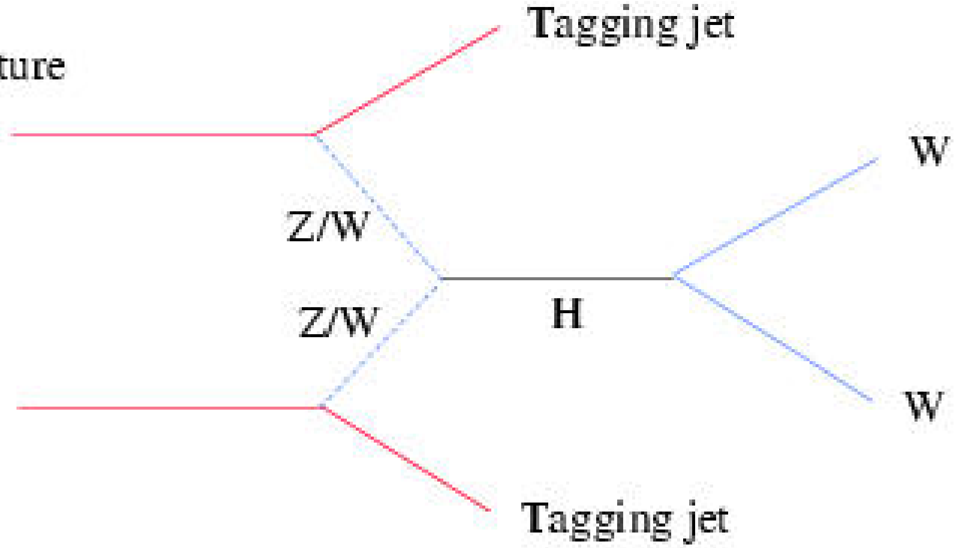
Process	Signal	Background
$\gamma\gamma$	53	51
WW	296	96
$\tau\tau$	79	27

P_T of Higgs $\sim M_W$: $\not{E}_T$ enables $\tau\tau$ mass to be reconstructed
Hence $\gamma\gamma$ and $\tau\tau$ have a mass peak
WW is most difficult

VBF Signal

Cross section ~20% of gg-production *BUT* clear signature

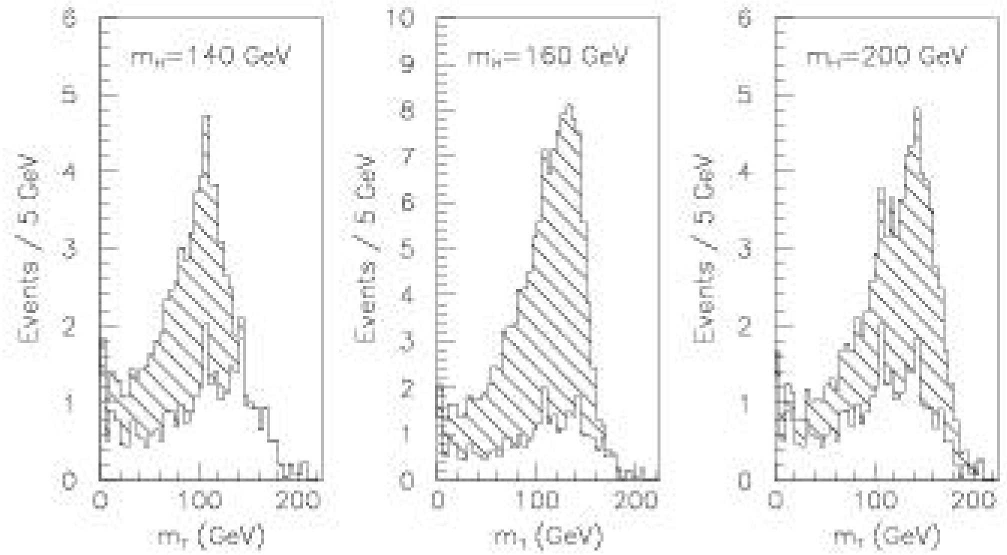
- forward tagging jets
- correlated leptons
- low hadronic activity in central region
- central Higgs production



Based on parton level study by Zeppenfeld and Rainwater hep-ph/9906218
Conclusion: >5σ observation with 5fb^{-1} at LHC in the mass range 130-200 GeV

Transverse Mass Distributions

$30fb^{-1}$



Non SM Higgs

Many possibilities.

MSSM Higgs is motivated by SUSY

Two Higgs doublets $\Rightarrow$ 5 physical states

$h, A, H, H^{\pm}$

determined by two parameters, m_h and $\tan\beta$

Other models possible, less well defined/motivated

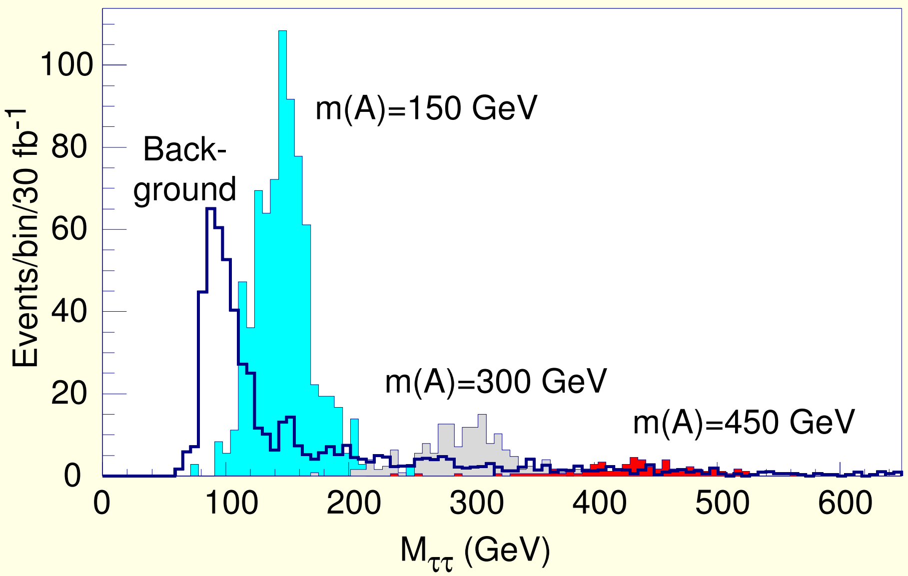
h behaves like a light SM Higgs, use above methods

H and A give new signals

Higgs production rates could be much bigger if it can be produced in the decay of something else such as squark or gluino

MSSM Higgs

New channels become available such as $A \to \tau\tau$



Uses $\tau\tau \to \ell\nu\nu_\tau h\nu_\tau$
Observed τ decay products determine τ direction
Missing E_T enables $\tau\tau$ mass reconstruction
$\Delta M/M \sim 10\%$
Background is dominated by real $\tau's$ not QCD jets

Probes large $\tan\beta$

$H^+ \to \tau\nu$

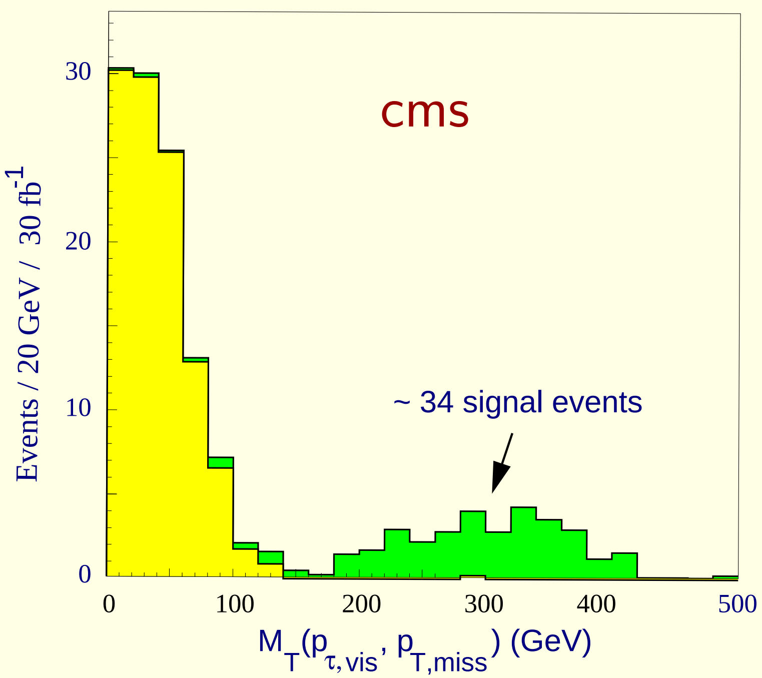
BR not small; $M_{H^+} = 400$ GeV, $\tan\beta = 30$; BR=14%

Production via $gb \to Ht$; $\sigma(H^+t) \sim 1$ pb

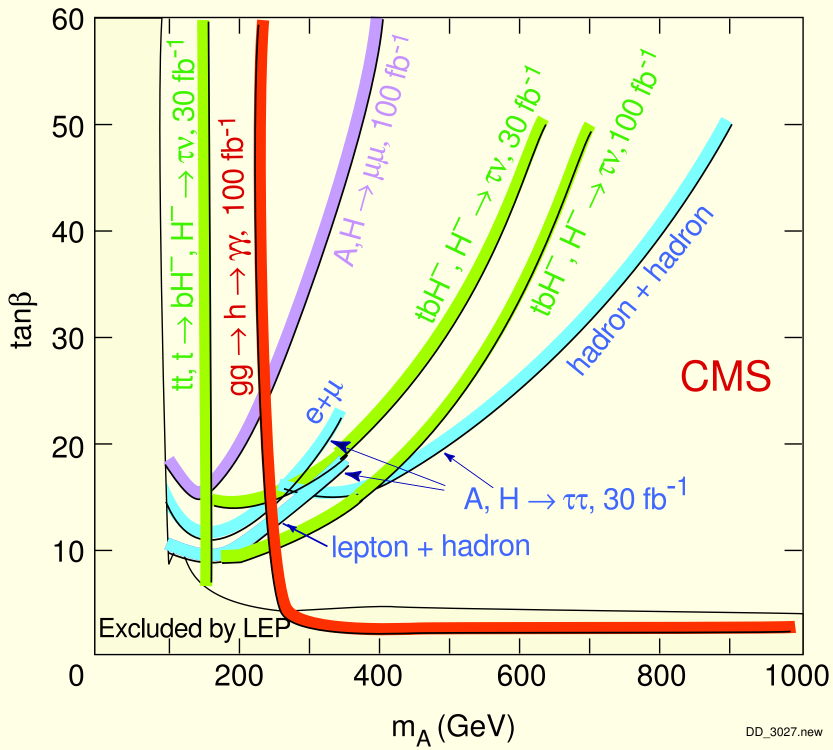
Use single prong hadronic tau decay ($p_T > 100$ GeV), plus jets and missing E_T (> 100 GeV)

Reconstruct top from jjb, $m(jj) = M_W \pm 25$, $m(jjb) = M_t \pm 25$

Signal is in transverse mass of "τ" and missing E_T



Plot has $M_{H^+} = 409$ and $\tan\beta = 40$



Note that this is $\mathbf{5\sigma}$ not 95% exclusion

$A \longrightarrow \tau\tau$ exclusion is $\sim \mathbf{450}$ GeV at $\tan\beta = 10$

Region at large M_A where only $h \longrightarrow \gamma\gamma$ is seen

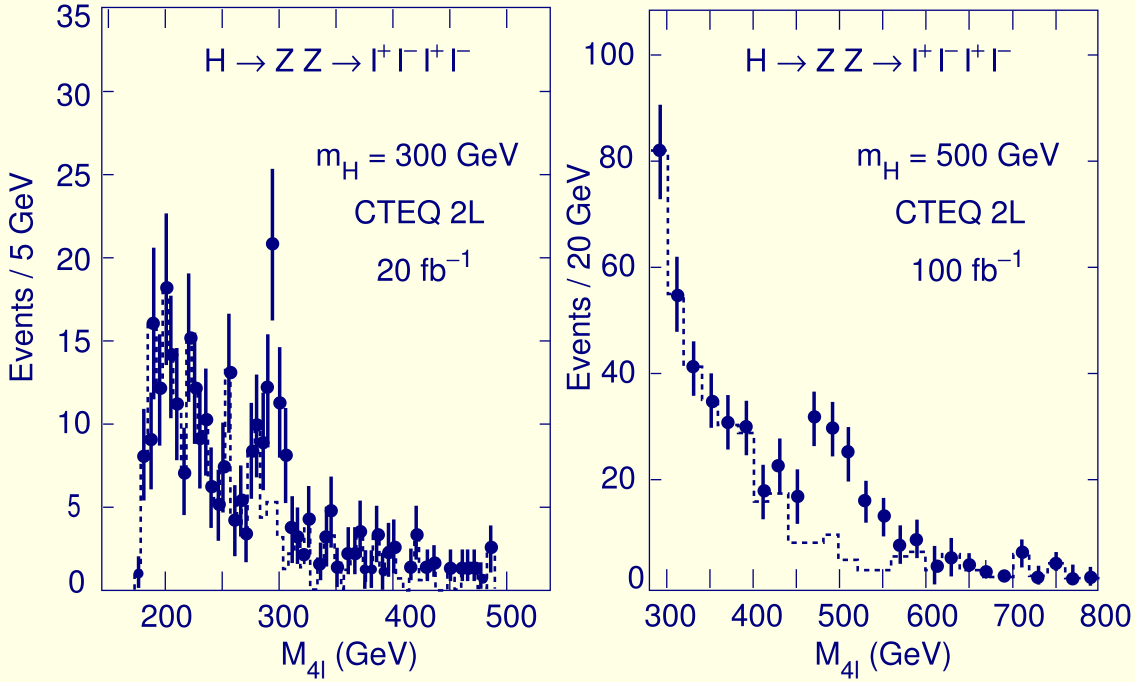
Beware of too literal an interpretation

Other measurements such as $H/A \longrightarrow \tilde{\chi}^2_0\tilde{\chi}^2_0$ may give more measurements in the large M_A region

No light Higgs??

Not likely in context of standard model, but ...

$H \rightarrow ZZ \rightarrow 4\ell$ eventually runs out of rate



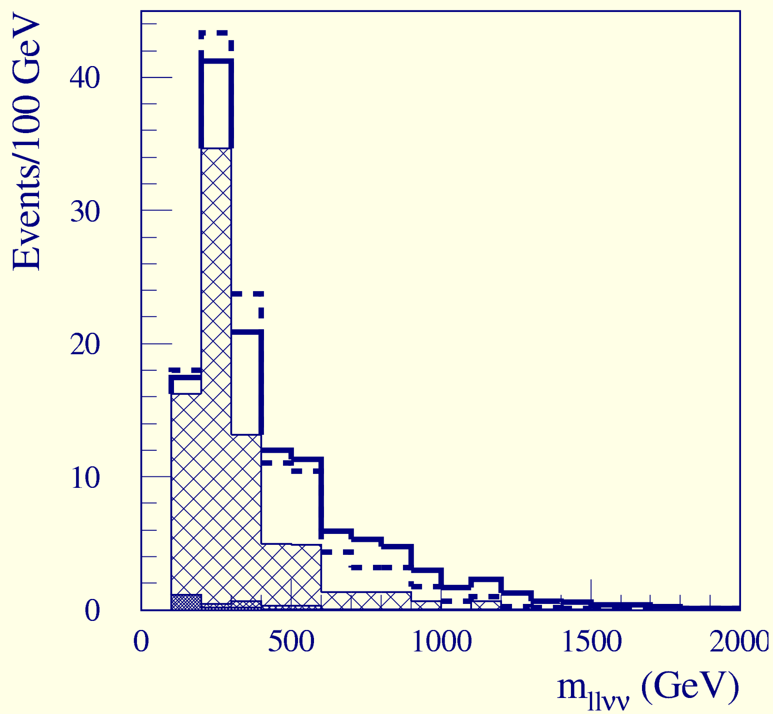
$H \rightarrow ZZ \rightarrow \nu\nu\ell\ell$ must be used or $H \rightarrow WW \rightarrow \ell\nu + jets$

Higgs heavier than $\sim 800 GeV$ meaningless

must be other new physics

Strongly coupled WW

Simplest models have few signatures.
K-matrix produces excess of events in WW at large mass: No mass peak so signal is hard to extract.
W^+W^+ is cleanest final state
Two isolated positive leptons with $M(\ell\ell) > 100$ GeV
≤ 3jets two of which have $|\eta| > 2$



Plot shows mass of $\ell\ell\not{E}_T$
Event rates are small $S/B \sim 50/75$ for 300 fb^{-1}
Should be possible to establish signal, but measurements will be hard

Resonant models are easier

SUSY in hadron colliders

Inclusive signatures provide evidence up to $\mathbf{2.5}$ TeV for squarks and gluinos.

Everything is produced at once; squarks and gluinos have largest rates.

Production of Sparticles with only E-W couplings (e.g sleptons, Higgs) may be dominated by decays not direct production.

Must use a consistent model for simulation
cannot discuss one sparticle in isolation.

Makes studies somewhat complicated and general conclusions difficult to draw.

LHC Strategies different from Tevatron where weak gaugino production probably dominates

Studies shown here are not optimized

Large event rates are used to cut hard to get rid of standard model background.

Dominant backgrounds are combinatorial from SUSY events themselves.

Studies shown here are not optimized; large event rates are exploited to cut hard to get rid of standard model background.

Full program difficult to estimate, depends on masses and branching ratios

General remarks

Huge number of theoretical models

Most general SUSY model has > 100 parameters Simulation has concentrated on cases that are qualitatively different; some examples were chosen in the expectation that they would be hard.

Model determines the masses, decays and signals.
A Model must be used for simulation in order to understand the problems of reconstruction – Background to SUSY is SUSY itself

Analysis does not depend on a particular model

SUSY production is dominated by gluinos and squarks

Other susy particles produced in their decays

Therefore observation of direct production of sleptons and weak gauginos is difficult but not impossible

Final states with e, μ, τ, γ, $\not{E}_T$ studied

Characteristic SUSY signatures at LHC

Not all present in all models

$\not{E}_T$

High Multiplicity of large p_t jets

Many isolated leptons

Copious b production

Large Higgs production

Isolated Photons

Quasi-stable charged particles

N.B.Production of heavy objects implies subset these signals

Important for triggering considerations

I show only examples, many cases have been studied

(SUGRA, GMSB, broken R parity ....)

Simplest models have few parameters; $m_{1/2}$ and m_0 determine gluino and slepton masses.

SUGRA Model

Grandaddy of SUSY models

Unification all scalar masses (m_0) at GUT scale

Unification all gaugino masses ($m_{1/2}$) at GUT scale

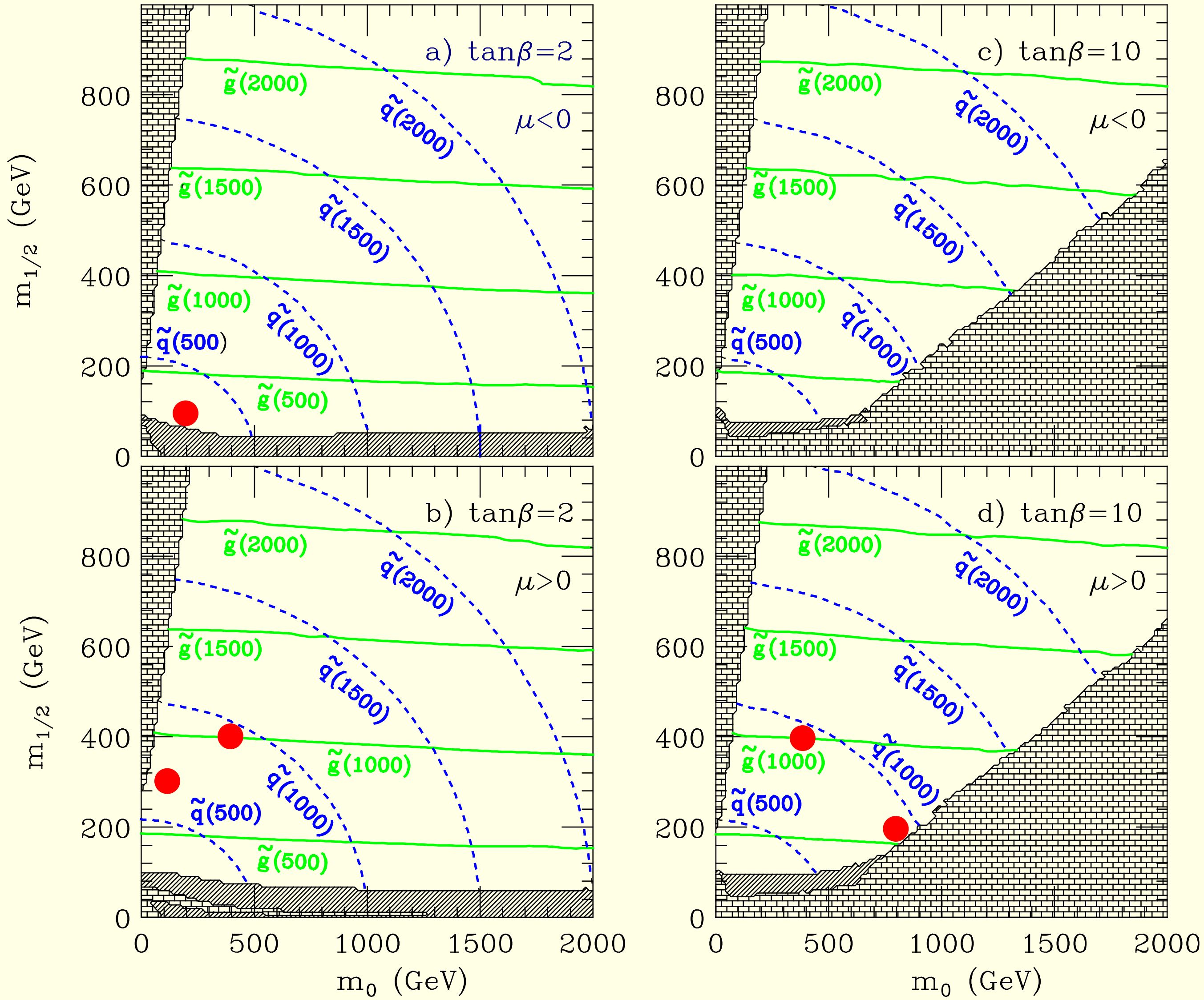
Three more parameters $\tan\beta = v_1/v_2\ sign(\mu)$ (superpotential has $\mu H_1 H_2$) and Trilinear term A, important only for 3^{rd} generation

Full mass spectrum and decay table predicted

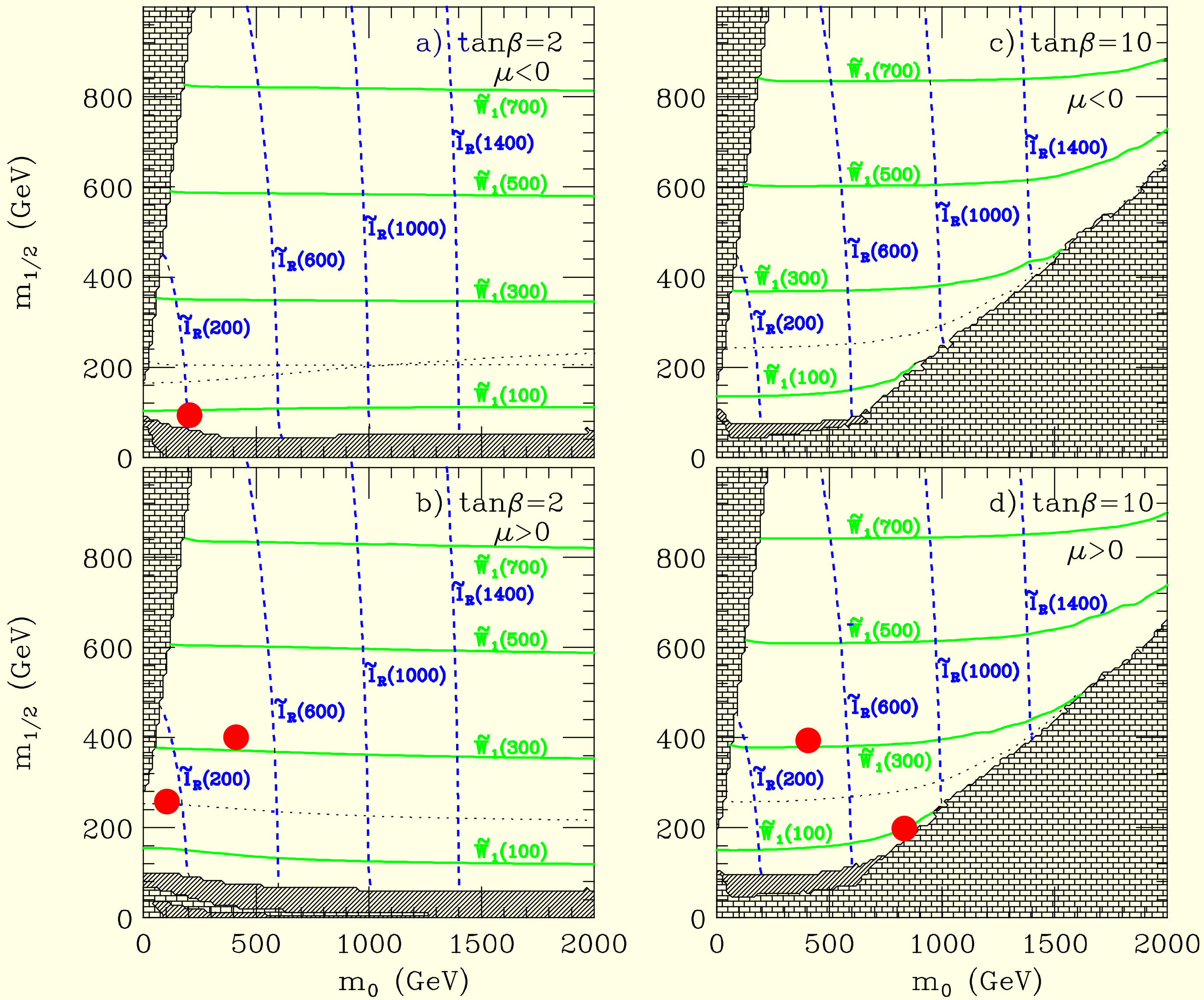
Gluino mass strongly correlates with $m_{1/2}$, slepton mass with m_0.

R parity good – neutral LSP stable – all events have 2 LSP's in them
$\Rightarrow$ missing E_T

Can relax unification assumption – more parameters



Contours of fixed *gluino* and squark mass



Contours of fixed *wino* and slepton mass

Several SUGRA cases studied in detail In one case unification assumptions were relaxed to investigate how signals changed (New signals appeared, old ones stayed) Some cases were restudied assuming that R-Parity was broken

$\Rightarrow$ LSP decayed inside detector.

Note typically large rates

Table 1: SUGRA parameters for the six LHC points.

Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	$\mathrm{sgn}\,\mu$	σ (pb)
1	400	400	0	2.0	$+$	2.9
2	400	400	0	10.0	$+$	2.9
3	200	100	0	2.0	$-$	1300
4	800	200	0	10.0	$+$	28
5	100	300	300	2.1	$+$	15
6	200	200	0	45	$-$	99

Point	1	2	3	4	5	6
$\tilde{g}$	1004	1009	298	582	767	540
$\tilde{\chi}_1^{\pm}$	325	321	96	147	232	152
$\tilde{\chi}_2^{\pm}$	764	537	272	315	518	307
$\tilde{\chi}_1^0$	168	168	45	80	122	81
$\tilde{\chi}_2^0$	326	321	97	148	233	152
$\tilde{\chi}_3^0$	750	519	257	290	497	286
$\tilde{\chi}_4^0$	766	538	273	315	521	304
$\tilde{u}_L$	957	963	317	918	687	511
$\tilde{u}_R$	925	933	313	910	664	498
$\tilde{d}_L$	959	966	323	921	690	517
$\tilde{d}_R$	921	930	314	910	662	498
$\tilde{t}_1$	643	710	264	594	489	365
$\tilde{t}_2$	924	933	329	805	717	517
$\tilde{b}_1$	854	871	278	774	633	390
$\tilde{b}_2$	922	930	314	903	663	480
$\tilde{e}_L$	490	491	216	814	239	250
$\tilde{e}_R$	430	431	207	805	157	219
$\tilde{\nu}_e$	486	485	207	810	230	237
$\tilde{\tau}_1$	430	425	206	797	157	132
$\tilde{\tau}_2$	490	491	216	811	239	259
$\tilde{\nu}_\tau$	486	483	207	806	230	218
h^0	111	125	68	117	104	112
H^0	1046	737	379	858	638	157
A^0	1044	737	371	859	634	157
$H^{\pm}$	1046	741	378	862	638	182

General Features

In general $m_{squark} > m_{slepton}$, $m_{gluino} > m_{\widetilde{W}}$

Splitting between $m_{\widetilde{e_l}}$ and $m_{\widetilde{e_r}}$

Stop is usually lightest squark

Lightest SUSY particle (LSP) stable if R-parity good.

LSP must be neutral if stable

SUSY particles produced in pairs even if R-parity broken.

SUSY production is dominated by gluinos and squarks.

Not necessarily true for Tevatron. Stable LSP $\Rightarrow$ Missing E_T

Background for SUSY usually other SUSY, not Standard Model.

Gauge Mediated Model

Aims to solve FCNC problem by using gauge interactions instead of Gravity to transmit SUSY breaking Messenger Sector consists of some particles (X) that have SM interactions and are aware of SUSY breaking.

$M_i^2 = M^2 \pm F_A$ Simplest X is complete SU(5) **5** or **10** to preserve GUT

Fundamental SUSY breaking scale $F > F_A$, but $\sqrt{F} \lesssim 10^{10}$ GeV or SUGRA breaking will dominate Gaugino masses at 1-loop

$$M_{\tilde{g}} \sim \alpha_s N_X \Lambda$$

Squark and Slepton masses at 2-loop

$$M_{\tilde{e}} \sim \alpha_W \sqrt{N_X} \Lambda$$

True LSP is a (almost) massless Gravitino

Sparticles decay as in SUGRA, then "NLSP" decays to $\tilde{G}$

lifetime model dependent

NLSP does not have to be neutral

6 parameters

Λ, M, N_5, $\tan\beta$,

$sign\mu$

$10\,\mathrm{TeV} \lesssim \Lambda \equiv F_A/M \lesssim 400\,\mathrm{TeV}$: Scale for SUSY masses.

$M > \Lambda$: Messenger mass scale.

$N_5 \geq 1$: Number of equivalent $5 + \bar{5}$ messenger fields.

$1 \lesssim \tan\beta \lesssim m_t/m_b$: Usual ratio of Higgs VEV's.

$\mathrm{sgn}\,\mu = \pm 1$: Usual sign of μ parameter.

$C_{\mathrm{grav}} \geq 1$: Ratio of $M_{\tilde{G}}$ to value from F_A, controls lifetime of NLSP.

Point	Λ (TeV)	M_m (TeV)	N_5	$\tan\beta$	$\mathrm{sgn}\,\mu$	$C_{\mathrm{grav}} \geq 1$	σ (pb)
G1a	90	500	1	5.0	$+$	1.0	7.6
G1b	90	500	1	5.0	$+$	10^3	7.6
G2a	30	250	3	5.0	$+$	1.0	23
G2b	30	250	3	5.0	$+$	5×10^3	23

Sparticle	G1	G2	Sparticle	G1	G2
$\tilde{g}$	747	713			
$\tilde{\chi}_1^\pm$	223	201	$\tilde{\chi}_2^\pm$	469	346
$\tilde{\chi}_1^0$	119	116	$\tilde{\chi}_2^0$	224	204
$\tilde{\chi}_3^0$	451	305	$\tilde{\chi}_4^0$	470	348
$\tilde{u}_L$	986	672	$\tilde{u}_R$	942	649
$\tilde{d}_L$	989	676	$\tilde{d}_R$	939	648
$\tilde{t}_1$	846	584	$\tilde{t}_2$	962	684
$\tilde{b}_1$	935	643	$\tilde{b}_2$	945	652
$\tilde{e}_L$	326	204	$\tilde{e}_R$	164	103
$\tilde{\nu}_e$	317	189	$\tilde{\tau}_2$	326	204
$\tilde{\tau}_1$	163	102	$\tilde{\nu}_\tau$	316	189
h^0	110	107	H^0	557	360
A^0	555	358	$H^\pm$	562	367

Mass spectrum more spread out than in SUGRA

$m(squark)/m(slepton)$ bigger

Anomaly mediated model

Superconformal anomaly always present

predicts sparticle masses in terms of $m_{3/2}$ Randall, Sundrum, Luty, Giudice, Wells, Murayama

Simplest version predicts tachyonic sleptons!

Some other SUSY breaking mechanism must be present to get realistic spectrum

Add universal squark masses (mAMSB) or new very heavy fields (DAMSB) (similar to gauge mediated), both variants are in ISAJET.

AMSB only – Most important feature $M_3 > M_1 > M_2 \Rightarrow$ LSP is a $\tilde{W}^0$ and almost degenerate with $\tilde{\chi}_1^+$ $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \pi^+$ with $c\tau < 10$ cm DAMSB has very short lifetime and bigger mass difference Wells, Paige

Sleptons are lighter than squarks $\tilde{q}_r \to \tilde{\chi}_2^0 q$ and $\tilde{q}_l \to \tilde{\chi}_1^0 q$, *i.e. opposite* to SUGRA and GMSB.

Gravitino mass is $\sim$ TeV, irrelevant to LHC.

AMSB has 4 parameters m_0, $m_{3/2}$, $\tan\beta$, $sign\mu$

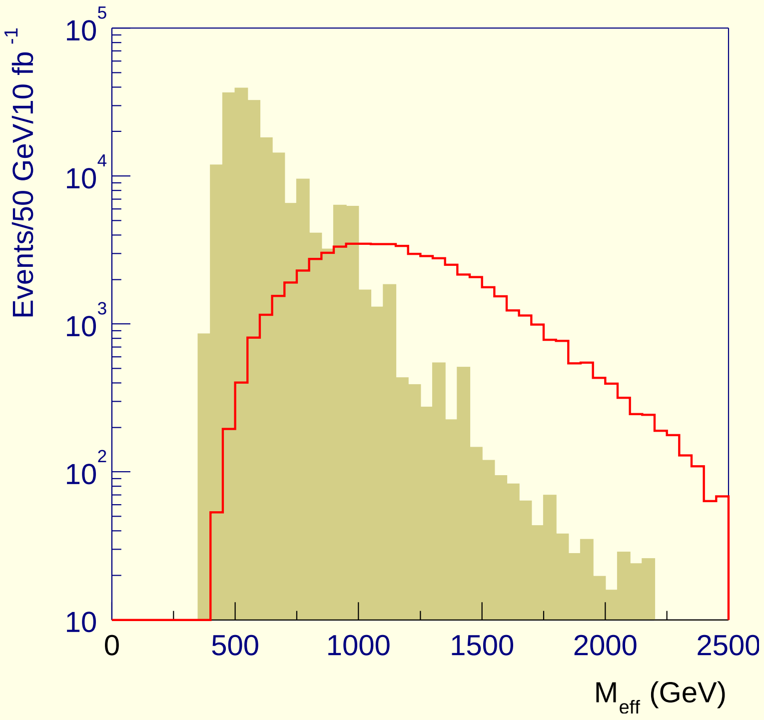
DAMSB has 5 parameters M_0, $m_{3/2}$, ,n $\tan\beta$, $sign\mu$. n is the number of new fields at mass M.

$m_{3/2}$ is the gravitino mass

Sparticle	AMSB	DAMSB	Sparticle	AMSB	DAMSB
$\tilde{g}$	815	500			
$\tilde{\chi}_1^{\pm}$	101	145	$\tilde{\chi}_2^{\pm}$	658	481
$\tilde{\chi}_1^0$	101	136	$\tilde{\chi}_2^0$	322	152
$\tilde{\chi}_3^0$	652	462	$\tilde{\chi}_4^0$	657	483
$\tilde{u}_L$	754	432	$\tilde{u}_R$	758	384
$\tilde{d}_L$	757	439	$\tilde{d}_R$	763	371
$\tilde{t}_1$	516	306	$\tilde{t}_2$	745	454
$\tilde{b}_1$	670	371	$\tilde{b}_2$	763	406
$\tilde{e}_L$	155	257	$\tilde{e}_R$	153	190
$\tilde{\nu}_e$	137	246	$\tilde{\tau}_2$	166	257
$\tilde{\tau}_1$	140	190	$\tilde{\nu}_\tau$	137	246
h^0	107	98	H^0	699	297
A^0	697	293	$H^{\pm}$	701	303

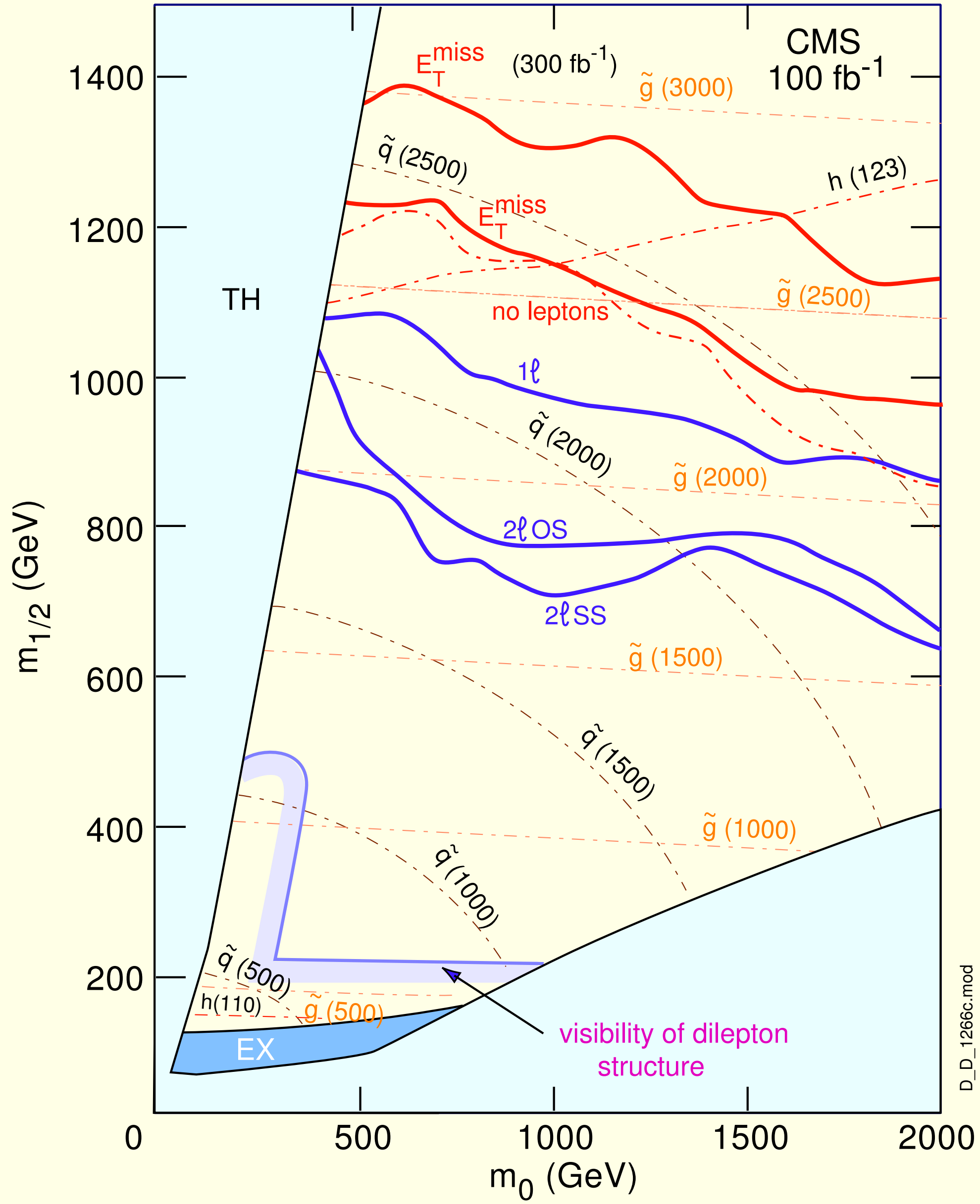
Inclusive analysis

Select events with at least 4 jets and Missing E_T
A simple variable
$M_{\rm eff} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not{E}_T$
At high $M_{\rm eff}$ non-SM signal rises above background note scale
Peak in $M_{\rm eff}$ distribution correlates well with SUSY mass scale
$M_{\rm SUSY} = \min(M_{\tilde{u}}, M_{\tilde{g}})$

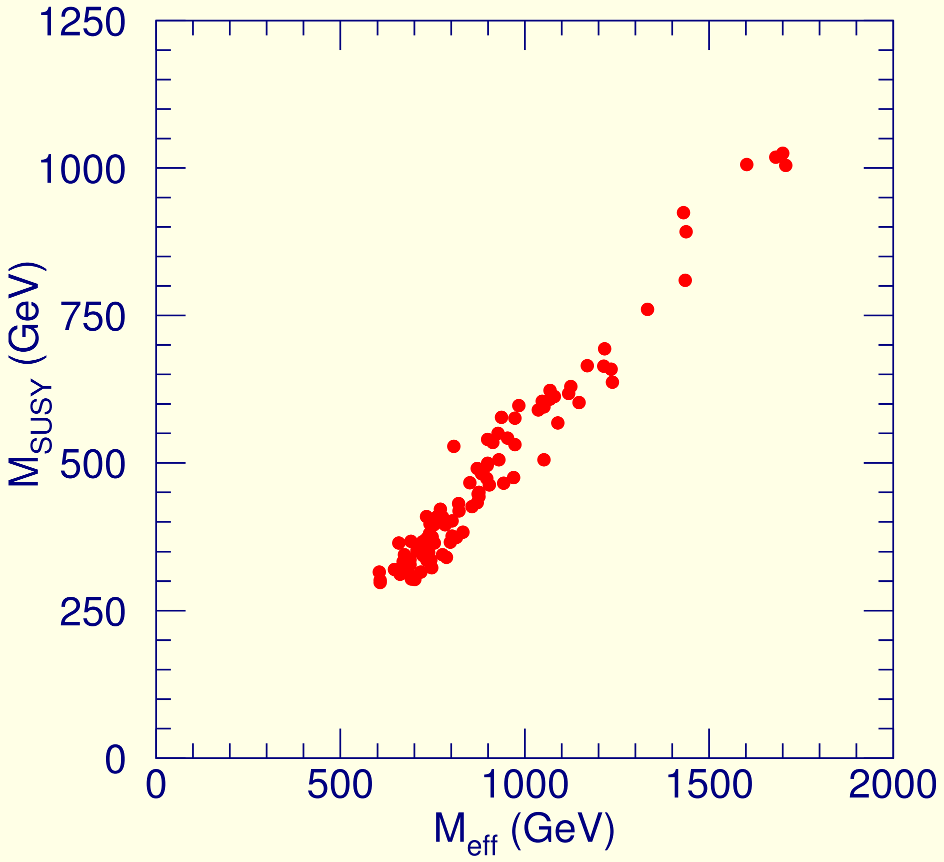


Will determine gluino/squark masses to $\sim 15\%$

Inclusive signals provide large search reach
shown for SUGRA model



Peak in M_{eff} distribution correlates well with SUSY mass scale



$$M_{\mathrm{SUSY}} = \min(M_{\tilde{u}}, M_{\tilde{g}})$$

Use this and similar global distributions to establish that new physics exists and determine its mass scale

Method is slightly model dependent

Generalizations to other models

Similar method works in GMSB and MSSM

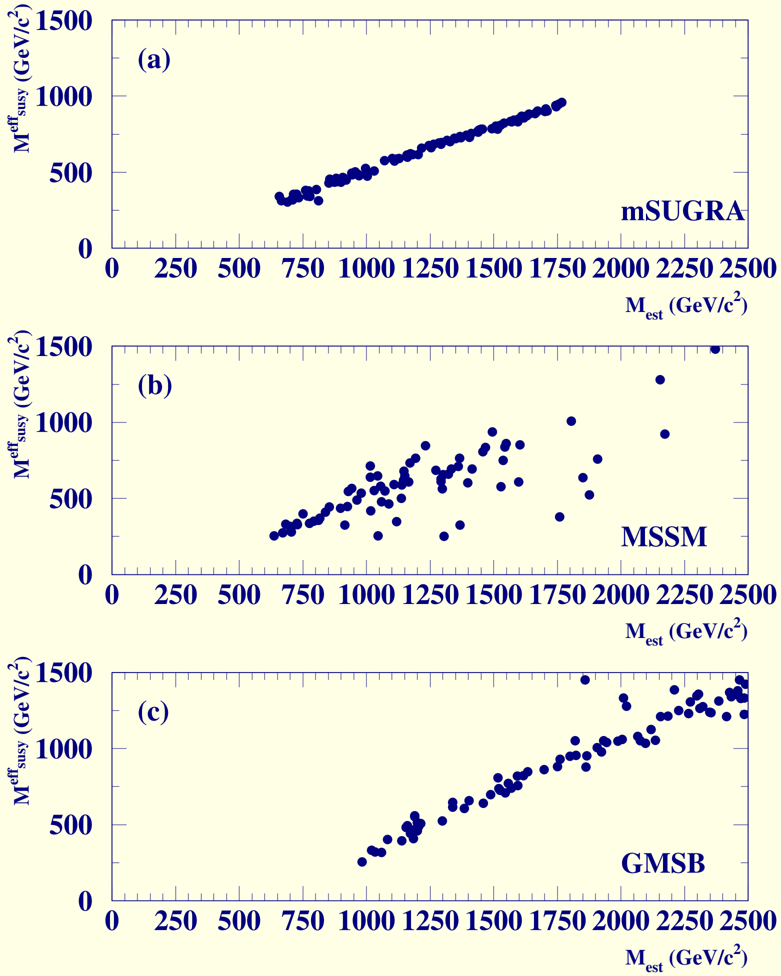
In MSSM, 15 parameters were varied

Events selected to have no isolated leptons, at least 4 jets, large missing E_T

More global variables were used; best is

$$\sum_{jets} |E_T| \text{ or } \sum_{jets} |E_T| + \not{E}_T$$

Error is bigger in MSSM



Model	Var	$\bar{x}$	σ	$\sigma/\bar{x}$	Prec. (%)
mSUGRA	1	1.585	0.049	0.031	2.9
	2	0.991	0.039	0.039	3.8
	3	1.700	0.043	0.026	2.1
	4	1.089	0.030	0.028	2.5
	5	1.168	0.029	0.025	2.1
MSSM	1	1.657	0.386	0.233	23.1
	2	0.998	0.214	0.215	21.1
	3	1.722	0.227	0.132	12.8
	4	1.092	0.143	0.131	12.8
	5	1.156	0.176	0.152	14.8
GMSB	1	1.660	0.149	0.090	8.1
	2	1.095	0.085	0.077	6.6
	3	1.832	0.176	0.096	9.0
	4	1.235	0.091	0.074	6.1
	5	1.273	0.109	0.086	7.9

$\sigma(M_{susy} < 13\%)$

Not optimized

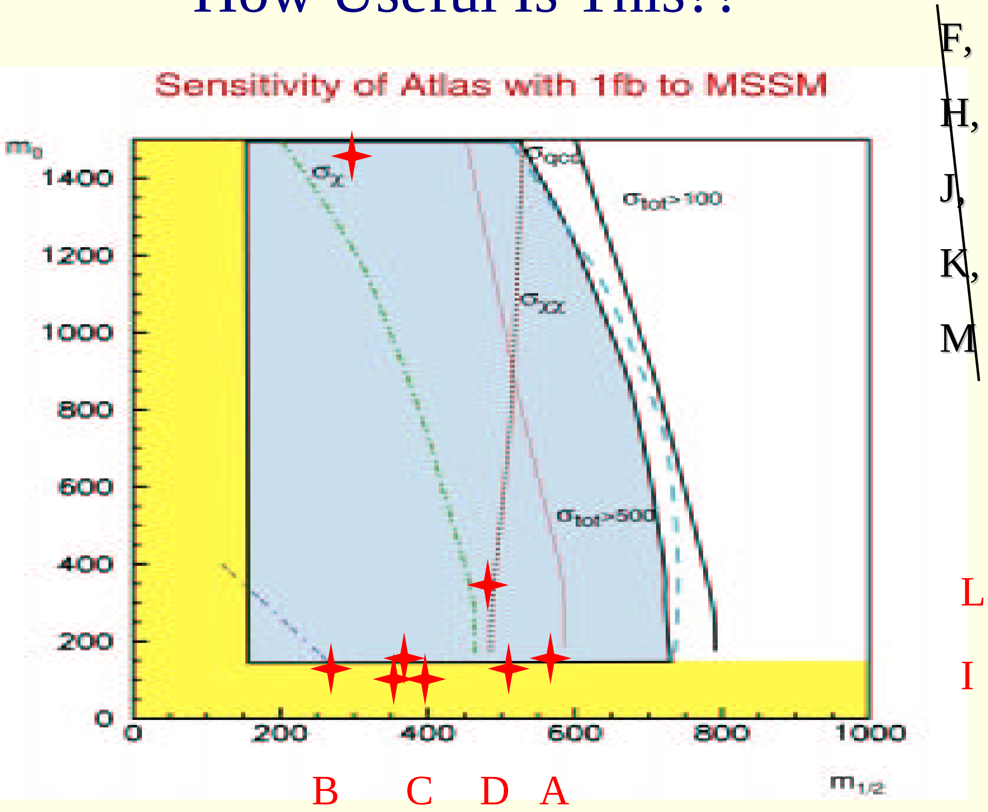
Leptonic channels not used

More work on "global signatures" needed

What about 1fb^{-1}

.

How Useful Is This??



Covers "preferred region"

Now for examples of specific final states...

Characteristic Decays

Illustrate techniques by choosing examples from case studies.

Both $\tilde{q}$ and $\tilde{g}$ produced; one decays to the other

Weak gauginos ($\widetilde{\chi_i^0}, \widetilde{\chi_i^{\pm}}$) then produced in their decay. $e.g.$ $\widetilde{q_L} \rightarrow \tilde{\chi}_2^0 q_L$

Two generic features
$\chi_2^0 \rightarrow \chi_1^0 h$ or
$\chi_2^0 \rightarrow \chi_1^0 \ell^+ \ell^-$ possibly via intermediate slepton $\chi_2^0 \rightarrow \widetilde{\ell^+} \ell^- \rightarrow \chi_1^0 \ell^+ \ell^-$
Former tends to dominate if kinematically allowed.

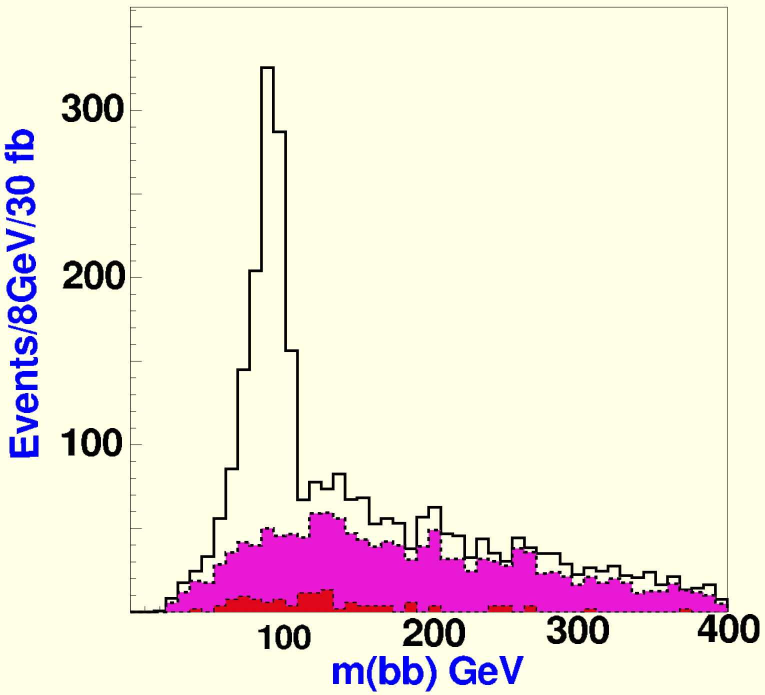
Use these characteristic decays as a starting point for mass measurements

Many SUSY particles can then be identified by adding more jets/leptons

Decays to Higgs bosons

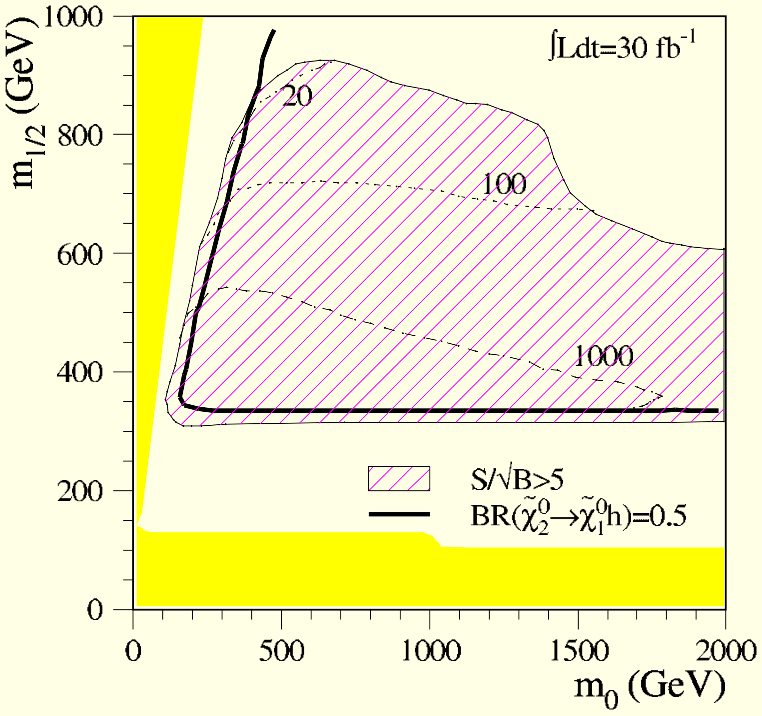
If $\chi_2^0 \rightarrow \chi_1^0 h$ exists then this final state followed by $h \rightarrow b\bar{b}$ results in discovery of Higgs at LHC.
In these cases $\sim 20\%$ of SUSY events contain $h \rightarrow b\bar{b}$

Event selection
$\not{E}_T > 300\,\mathrm{GeV}$
≥ 2 jets with $p_T > 100\,\mathrm{GeV}$ and ≥ 1 with $|\eta| < 2$
No isolated leptons (suppresses $t\bar{t}$)
Only 2 b-jets with $p_{T,b} > 55$ GeV and $|\eta| < 2$
$\Delta R_{b\bar{b}} < 1.0$ (suppresses $t\bar{t}$)
Clear peak in $b\bar{b}$ mass
Very small standard model background (pale)
Dominant background is other SUSY decays (dark)



Generally applicable

This method works over a large region of parameter space in the SUGRA Model
Hatched region has $S/\sqrt{B} > 5$
Contours show number of reconstructed Higgs
Channel is closed at low $m_{1/2}$



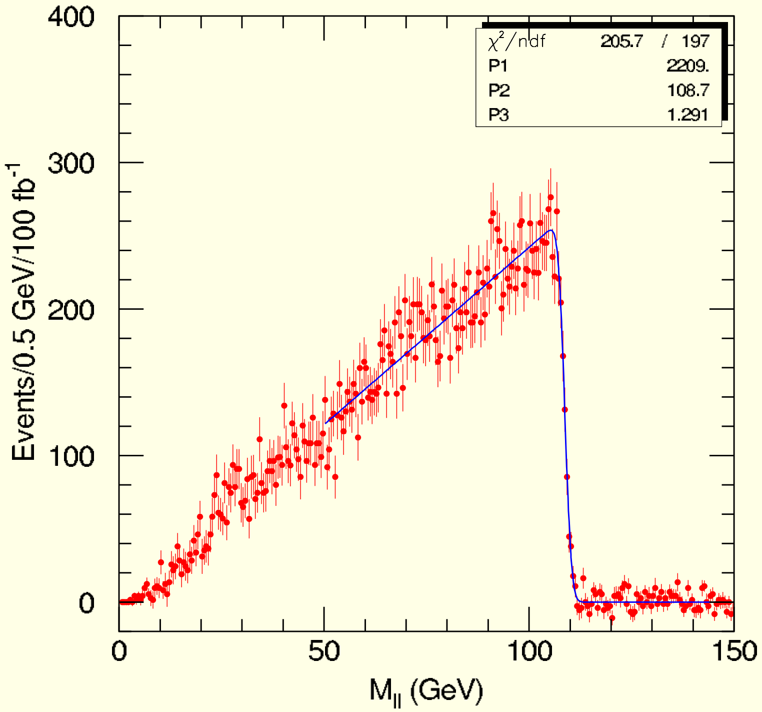
Over rest of parameter space, leptons are the key...

Starting with Leptons

Isolated leptons indicate presence of t, W, Z, weak gauginos or sleptons

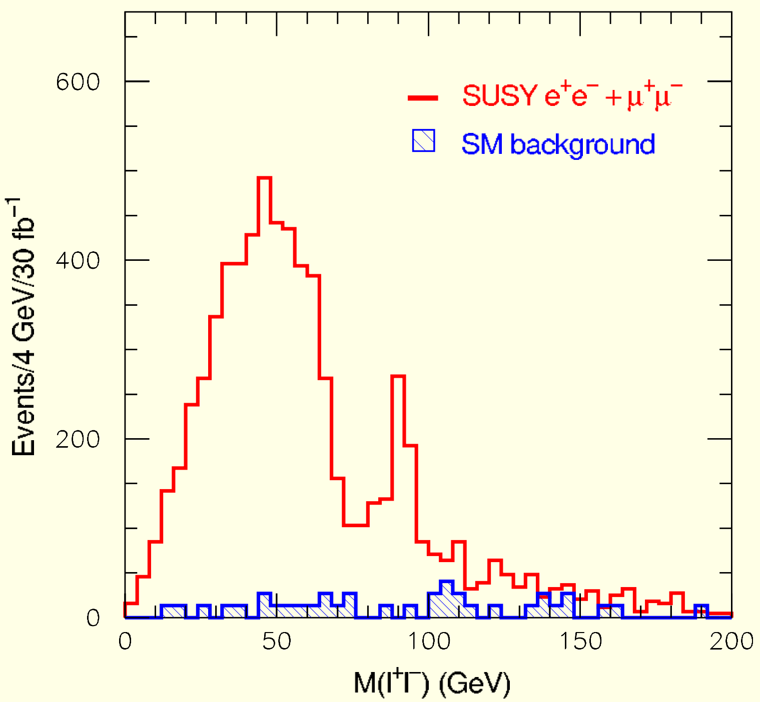
Key decays are $\tilde{\chi}_2 \rightarrow \tilde{\ell}^+\ell^-$ and $\tilde{\chi}_2 \rightarrow \tilde{\chi}_1\ell^+\ell^-$

Mass of opposite sign same flavor leptons is constrained by decay



Decay via real slepton: $\tilde{\chi}_2 \rightarrow \tilde{\ell}^+\ell^-$

Plot shows $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$

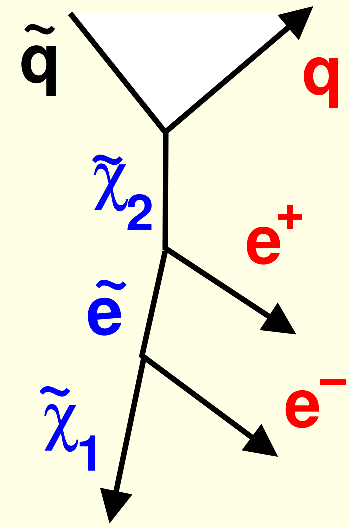


Decay via virtual slepton: $\tilde{\chi}_2 \rightarrow \tilde{\chi}_1\ell^+\ell^-$

and Z from other SUSY particles

Building on Leptons

Decay $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\tilde{\ell}\ell \to q\ell\ell\tilde{\chi}_1^0$



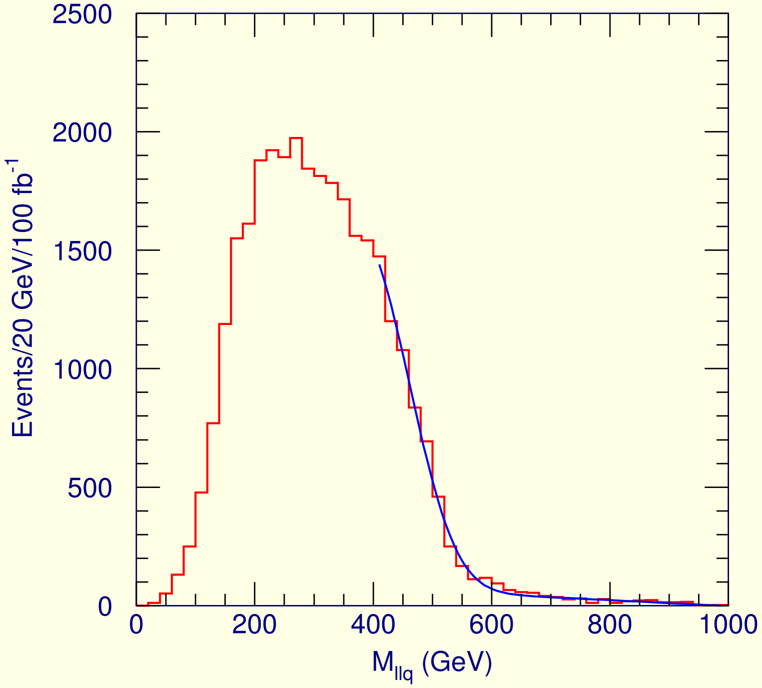
Identify and measure decay chain

- 2 isolated opposite sign leptons; $p_t > 10$ GeV
- ≥ 4 jets; one has $p_t > 100\ GeV$, rest $p_t > 50$ GeV
- $\not{E}_T > max(100, 0.2M_{eff})$

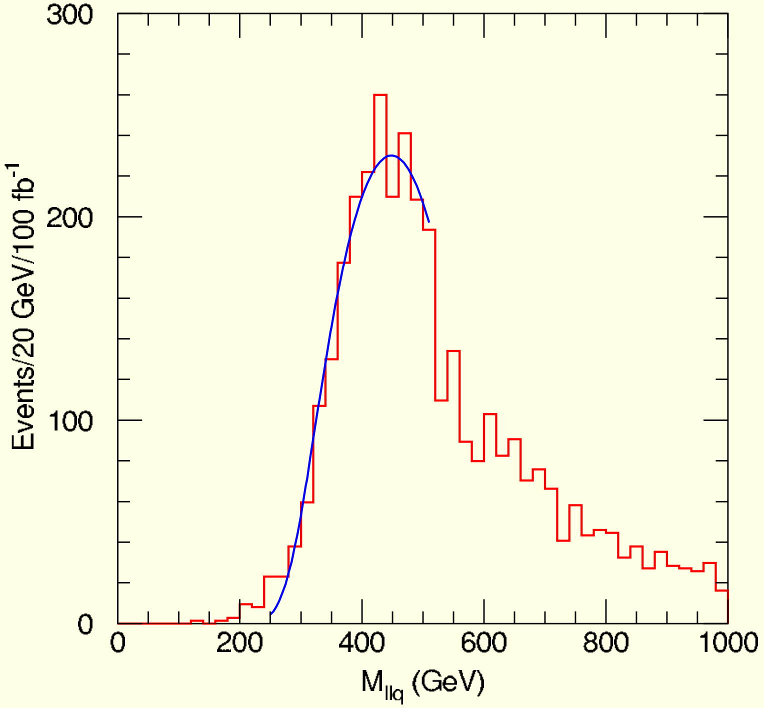
Mass of $q\ell\ell$ system has max at

$$M_{\ell\ell q}^{\max} = [\frac{(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{\chi}_2^0}^2}]^{1/2} = 552.4\,\mathrm{GeV}$$

and min at 271 GeV



smallest mass of possible $\ell\ell jet$ combinations



largest mass of possible $\ell\ell jet$ combinations

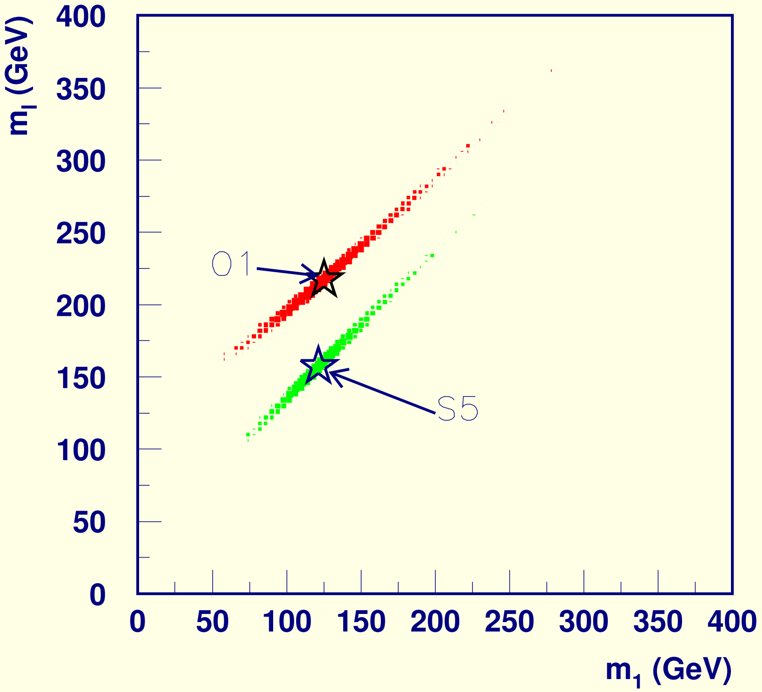
Kinematic structure clearly seen

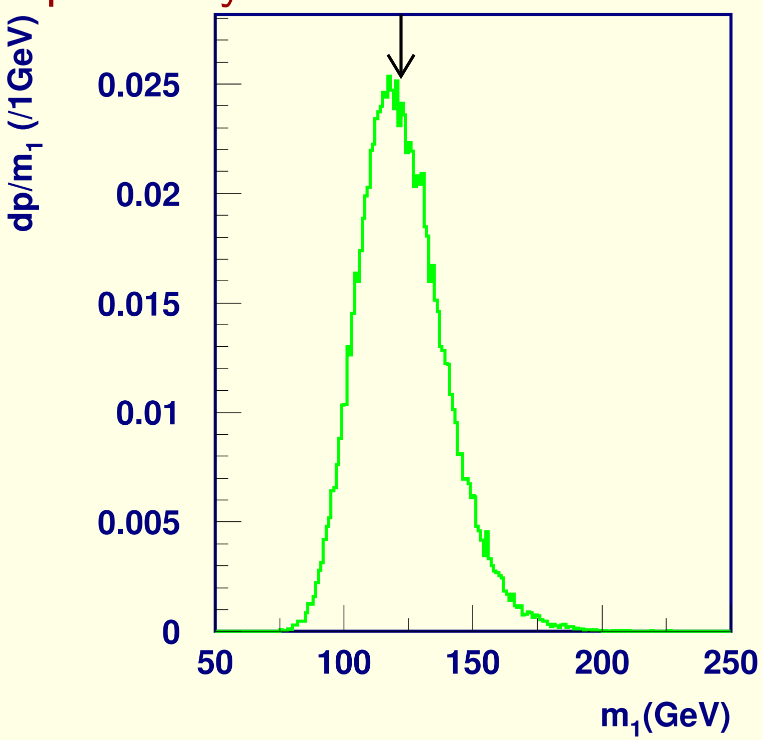
Can also exploit ℓjet mass

Can now solve for the masses. Note that no model is needed

Very naive analysis has 4 constraints from $lq, llq_{upper}, llq_{lower}, ll$ masses
4 Unknowns, $m_{\tilde{q_L}}, m_{\tilde{e_R}}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}$

Errors are 3%, 9%, 6% and 12% respectively





correlations $m_{\tilde{e_R}}$ vs. $m_{\tilde{\chi}_1^0}$

LSP mass

Mass of unobserved LSP is determined

Errors are strong correlated and a precise independent determination of one mass reduces the errors on the rest.

Final states with taus

Large $\tan\beta$ implies that $m(\tilde{\tau}) < m(\tilde{\mu})$

Taus may be the only produced leptons in gaugino decay.

Leptonic tau decays are of limited use – where did lepton come from?

Use Hadronic tau decays, using jet shape and multiplicity for ID and jet rejection.

Full simulation study used to estimate efficiency and rejection

Rely on Jet and $E_t(miss)$ cuts to get rid of SM background

Measure "visible" tau energy

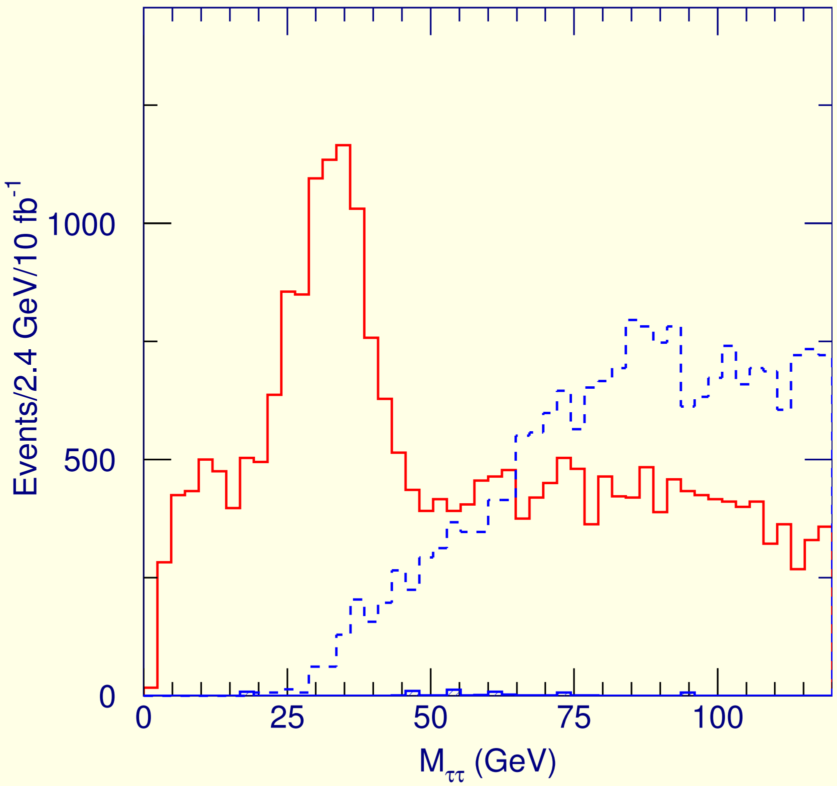
Event selection

≥ 4 jets, one has $p_t > 100$ GeV, rest $p_t > 50$ GeV

No isolated leptons with $p_t > 10$ GeV

$\not{E}_T > max(100, 0.2M_{eff})$

Look at mass of observed tau pairs



Real signal visible above fakes (dashed) and SM (solid)

Can use peak position to infer end point in decay $\tilde{\chi}_2^0 \to \tau\tau\tilde{\chi}_1^0$ (61 GeV)

Estimate 5% error

Large $\tan\beta \Rightarrow$ light sbottom – Look for these

$$\tilde{g} \to b\tilde{b} \to bb\tau^{\pm}\tau^{\mp}\tilde{\chi}_1^0$$

Previous sample with 2 $b-$jets having $p_t > 25$ GeV

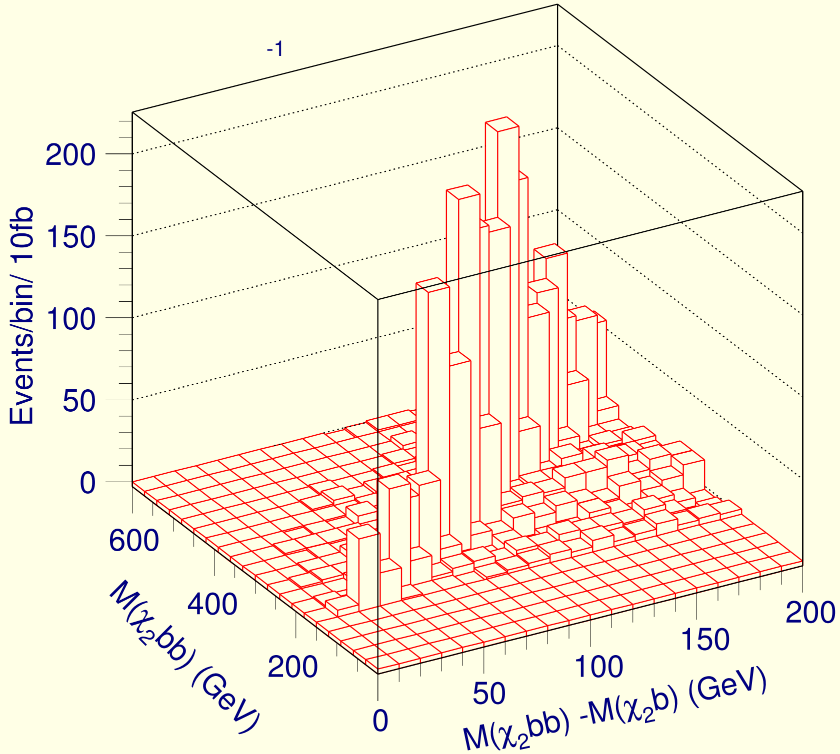
Lots of missing E_T: tau decays and $\tilde{\chi}_1^0$'s

Select $40 < m_{\tau\tau} < 60$ GeV

Combine with b jets

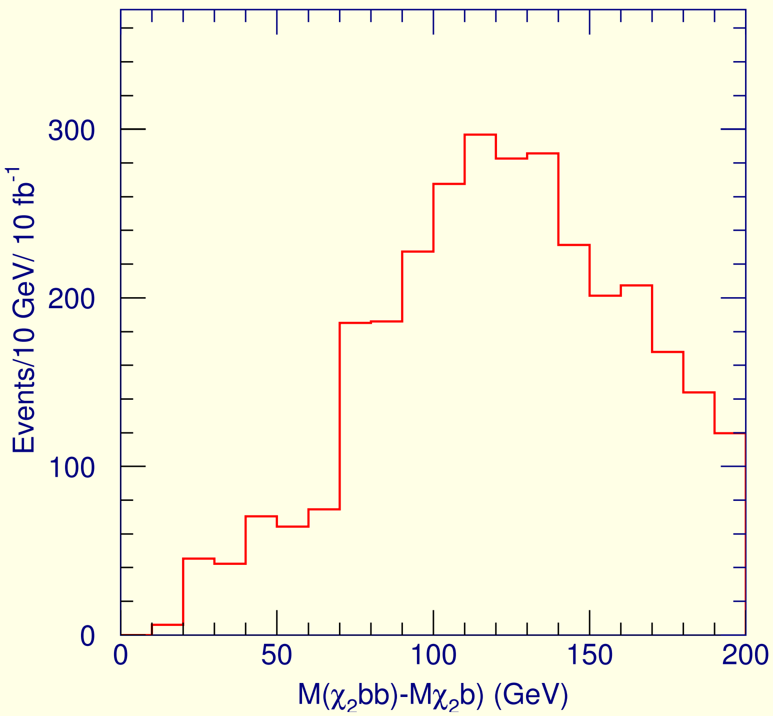
Look at $\tau\tau bb$ and $\tau\tau b$: should approximate gluino and sbottom use partial reconstruction technique assuming mass of $\tilde{\chi}_1^0$

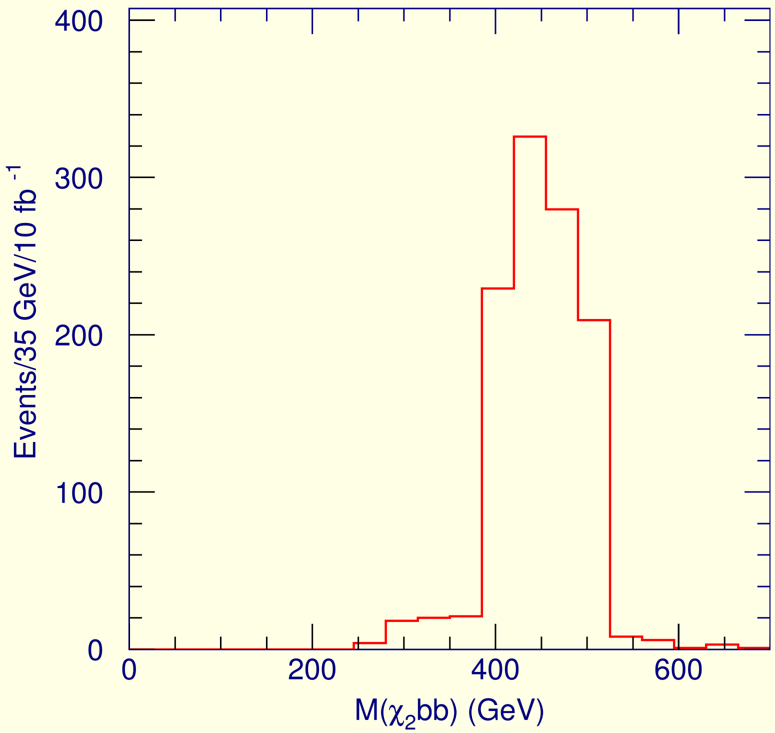
Peaks are low; should be expected due to missing energy



Plot of $m(\tilde{\chi}_2^0 bb)$ vs $m(\tilde{\chi}_2^0 bb) - m(\tilde{\chi}_2^0 b)$

Projections





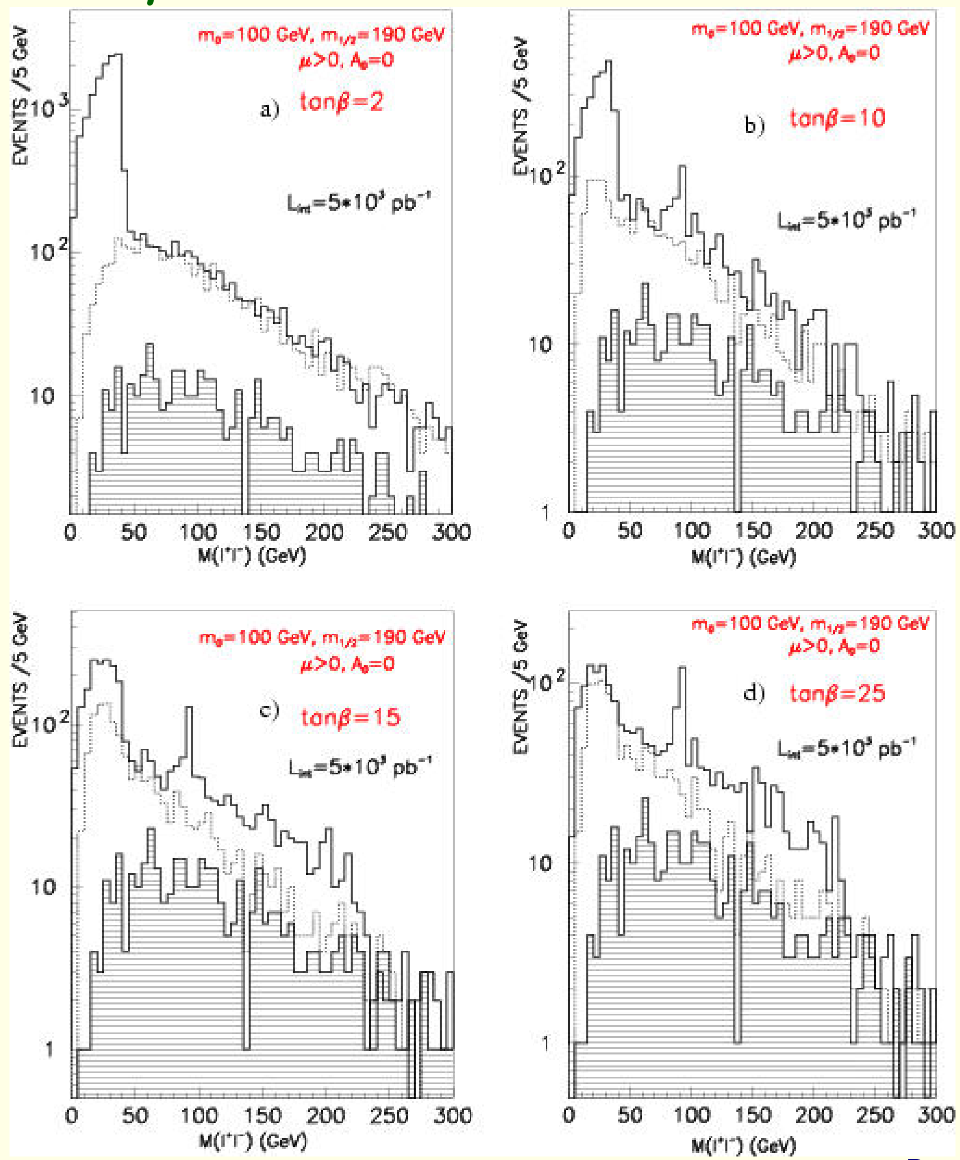
gluino-sbottom
should be 160 GeV

gluino
540 GeV

Lepton Universality

$e/\mu/\tau$ universality must be tested Large $\beta \Rightarrow m_{\tilde{\tau}} < m_{\tilde{e}}$
Expect larger rate of $\tau^+\tau^-$ and hence $\mu^+ e^-$

Plot of invariant mass distributions
$\mu^+ e^-$ (dashed) and $\mu^+\mu^-$ (solid) from SUSY cascades *vs.* $\tan\beta$
$\mu^+\mu^-$ structure less distinct at large $\tan\beta$



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Denegri, Majerotto, Rurua

Explicit flavor violation is also possible

Neutrino oscillations imply lepton number is violated

Atmospheric muon neutrino deficit implies $\nu_{mu} \leftrightarrow \nu_\tau$ with maximal mixing

In a SUSY model, expect significant flavor violation in slepton sector

Simplest model of lepton number violation involves addition of right handed neutrino N with SUSY conserving Majorana mass mNN and coupling to lepton left doublet and Higgs of the form LNH

Including only $\mu \leftrightarrow \tau$ mixing gives

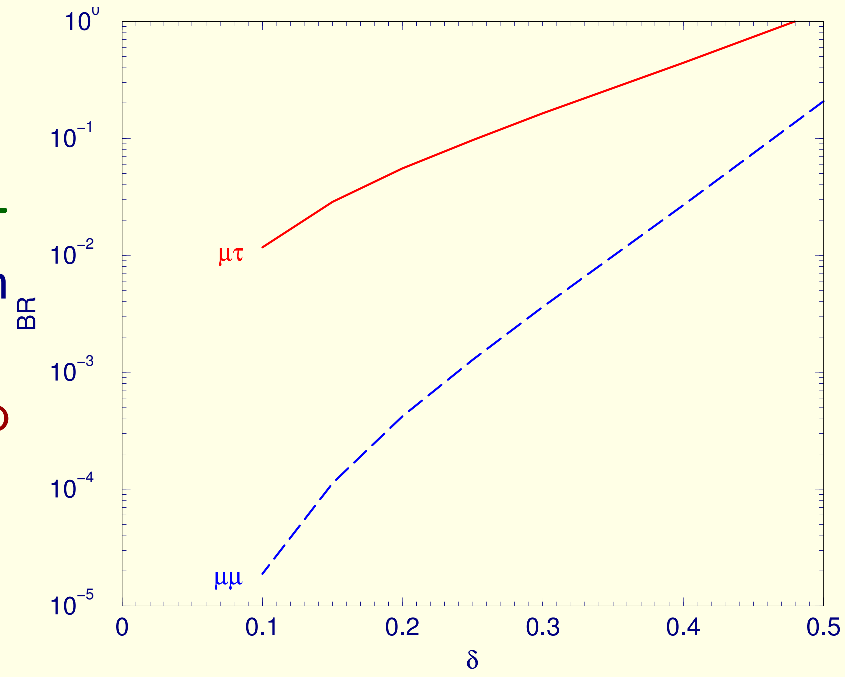
$$M^2_{\tilde{\ell}\tilde{\ell}} = \begin{bmatrix} M_L^2 + D_L & 0 & 0 & 0 & 0 & 0 \\ 0 & M_L^2 + D_L & M^2_{\mu\tau} & 0 & 0 & 0 \\ 0 & M^2_{\mu\tau} & M^2_{\tau_L} + D_L & 0 & 0 & m_\tau \bar{A}_\tau \\ 0 & 0 & 0 & M_R^2 + D_R & 0 & 0 \\ 0 & 0 & 0 & 0 & M_R^2 + D_R & 0 \\ 0 & 0 & m_\tau \bar{A}_\tau & 0 & 0 & M^2_{\tau_R} + D_R \end{bmatrix}$$

Atmospheric neutrinos suggest maximal mixing *i.e.* $\delta = \mathcal{O}(1)$

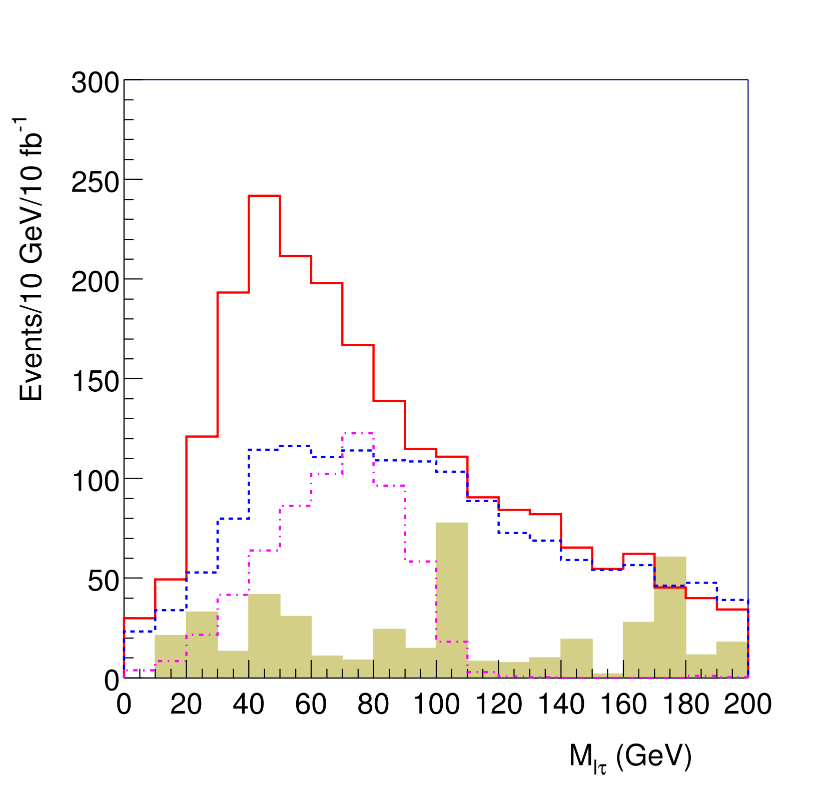
Two types of flavor violation production ($\tilde{\chi}_2^0 \to \tilde{\tau}\mu$) and decay ($\tilde{\tau} \to \tilde{\chi}_1^0\mu$).

Branching ratio for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\mu\tau$ and for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\mu\mu$ through an intermediate $\tilde{\tau}_1$

Must use hadronic tau decays to distinguish



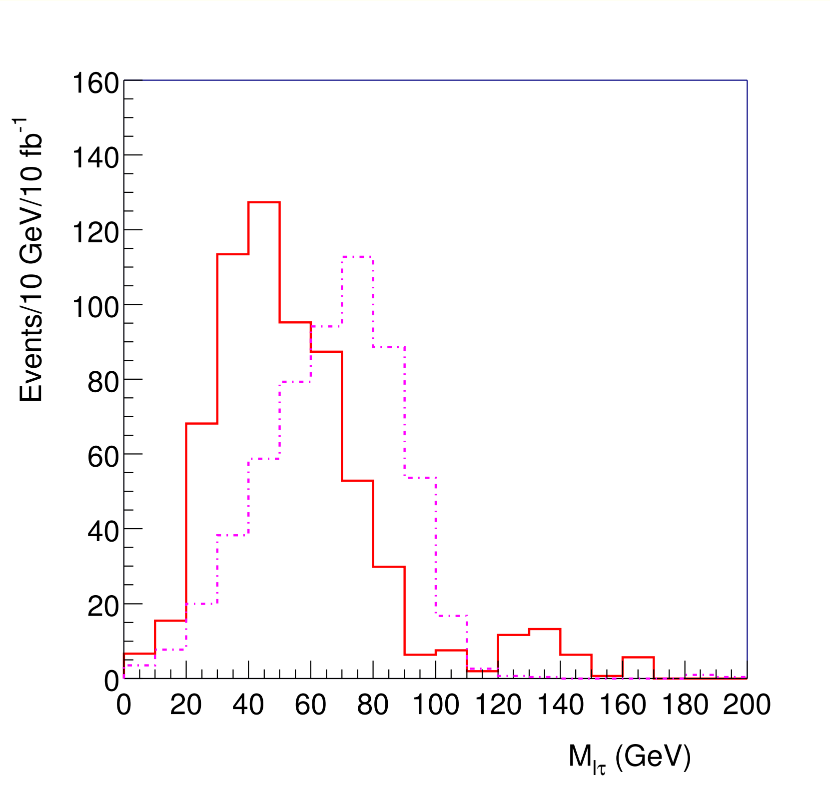
Signal for lepton number violation comes by comparing $\mu\tau_h$ and $e\tau_h$ final states



$\ell^\pm\tau_h^\mp$ signal (red), $\ell^\pm\tau_h^\pm$ signal (blue), $\mu^\pm\tau_h^\mp$ from LFV decays with $BR = 10\%$ (magenta), and Standard Model $\ell^\pm\tau_h^\mp$

Lepton number violating decay $\widetilde{\chi}_2^0 \rightarrow \mu\tau_h\widetilde{\chi}_1^0$ give harder $\mu\tau$ mass distribution than that from $\widetilde{\chi}_2^0 \rightarrow \tau\tau\widetilde{\chi}_1^0 \rightarrow \mu\tau_h\widetilde{\chi}_1^0$

Subtraction removes background



$\ell^{\pm}\tau_h^{\mp} - \ell^{\pm}\tau_h^{\pm}$ (red) and $\mu^{\pm}\tau_h^{\mp}$ from LFV decays with $BR = 10\%$ (magenta)
Signal is established from $E = N(\mu^{\pm}\tau_h^{\mp}) - N(e^{\pm}\tau_h^{\mp})$
10 fb^{-1} and 5σ implies BR=2.3% or $\delta \sim 0.1$ well within value needed for neutrino data

Sensitive provided that $\widetilde{\chi}_2^0$ production is large enough (large fraction of parameter space More sensitive than $\mu \rightarrow e\gamma$

R-parity broken

Implies either Lepton number or Baryon number is violated and LSP decays

Either $\widetilde{\chi}_1^0 \to qqq$, or $\widetilde{\chi}_1^0 \to q\bar{q}\ell$ or $\widetilde{\chi}_1^0 \to \ell^+\ell^-\nu$

First two have no $\not{E}_T$, last 2 have more leptons and are straightforward

First case is hardest, Global S/B is worse due to less $\not{E}_T$ Example, SUGRA with $\widetilde{\chi}_1^0 \to qqq$ Leptons are essential to get rid of QCD background

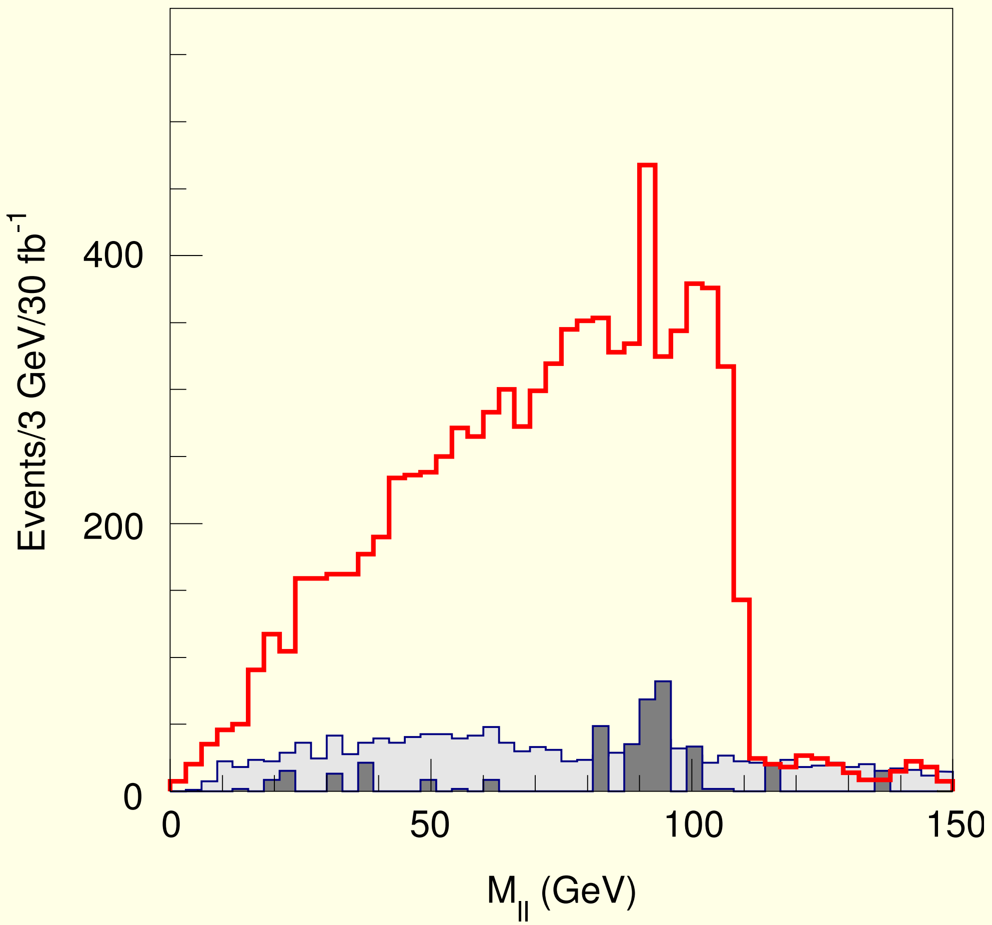
≥ 8 jets with $p_t > 50$ GeV

2 OSSF isolated leptons.

$S_T > 0.2$, selects "ball like" events

$\Sigma_{jets+leptons} E_T > 1$ TeV

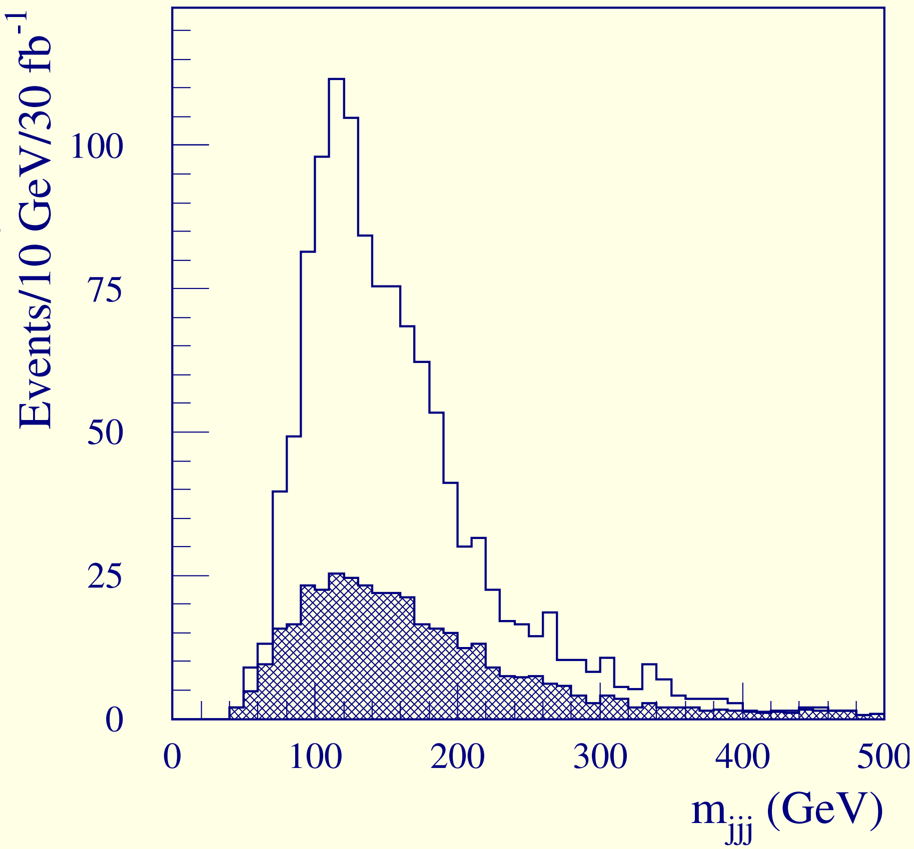
Dilepton mass still shows clear structure with small background from $\tilde{\chi}^0_2 \to \ell^+\ell^-\tilde{\chi}^0_1$



As nothing is lost, should be possible to reconstruct $\tilde{\chi}^0_1$

Difficult because jet multiplicity is very high and $\tilde{\chi}^0_1$ mass is usually small, so jets are soft

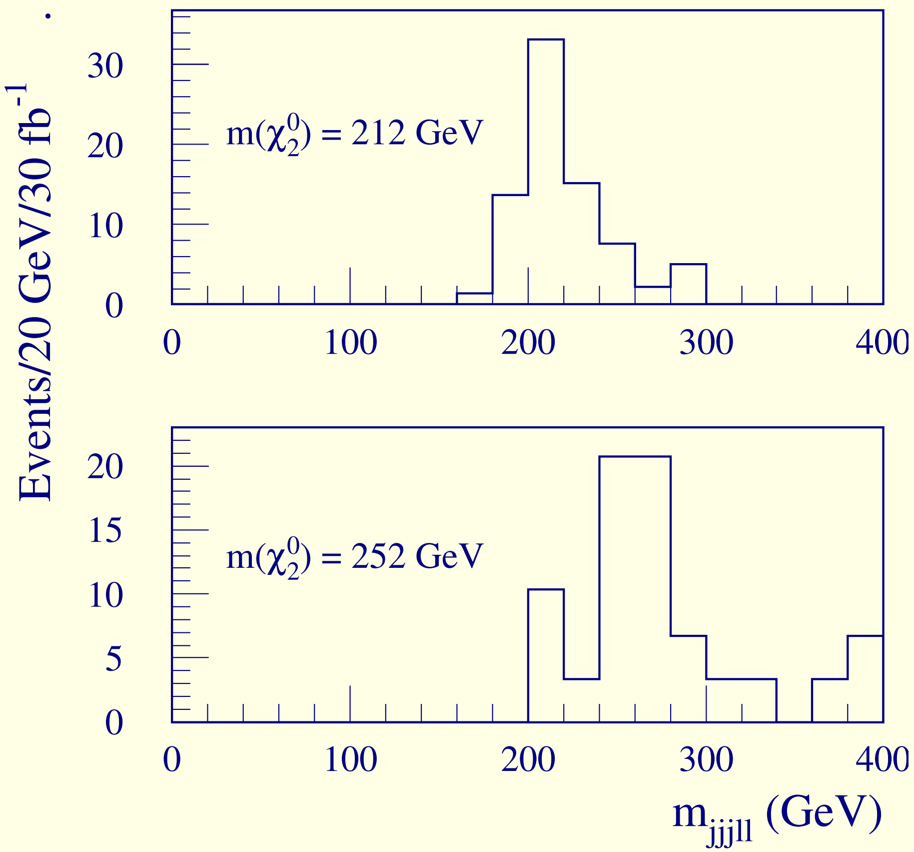
$\geq \mathbf{8}$ jets with $p_t > \mathbf{17.5}$ GeV, $\leq \mathbf{8}$ jets with $p_t > \mathbf{25}$ GeV
2 jets with $p_t > \mathbf{100(200)}$ GeV and $\mid \eta \mid < \mathbf{2}$
1 or 2 leptons with $p_t > \mathbf{20}$ GeV
Sphericity cut
combine 6 slowest jets into 2 sets of 3;
require $M(jjj)_1 - M(jjj)_2 < \mathbf{20}$ GeV



Nominal mass 122 GeV

Can cut around peak and combine with either leptons or quarks

reconstruct $\tilde{q}_R \to q\widetilde{\chi}_1^0(\to qqq))$ and $\chi_2^0 \to \ell\ell\widetilde{\chi}_1^0$



Plot shows $\widetilde{\chi}_2^0$

Note that tight cuts imply low event rate (analysis not optimized)

New signals in GMSB

Lightest superpartner is unstable and decays to Gravitino ($\tilde{G}$)

Either neutral

$\chi_1^0 \to \gamma \tilde{G}$: $c\tau \sim C^2 (100 \text{ GeV}/M_{\chi_1^0})^5 (\Lambda/180\text{TeV})^2 (M_M/180\text{TeV})^2 \text{mm}$

$\Rightarrow$ extra photons or similar signals to SUGRA depending on lifetime

Or charged

Almost always slepton: $\tilde{e_R} \to e\widetilde{G}$

No Missing E_T if $c\tau$ large, events have a pair of massive stable charged particles ("G2b")

Large lepton multiplicity if $c\tau$ small ("G2a").

Discovery and measurement in these cases is trivial

In case "G2b", every decay product can be measured

In case "G1a" $\widetilde{G}$ momenta can be inferred and events fully reconstructed.

GMSB case 1a: Event selection (not optimized)

Decay $\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0 \to \ell^+\ell^-\gamma\tilde{G}$ is key
Lifetime of $\widetilde{\chi}_1^0$ is short

Find jets

$$M_{\text{eff}} \equiv \not{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} \,.$$

Require

$M_{\text{eff}} > 400\,\text{GeV}$;

$\not{E}_T > 0.1 M_{\text{eff}}$.

Looking for

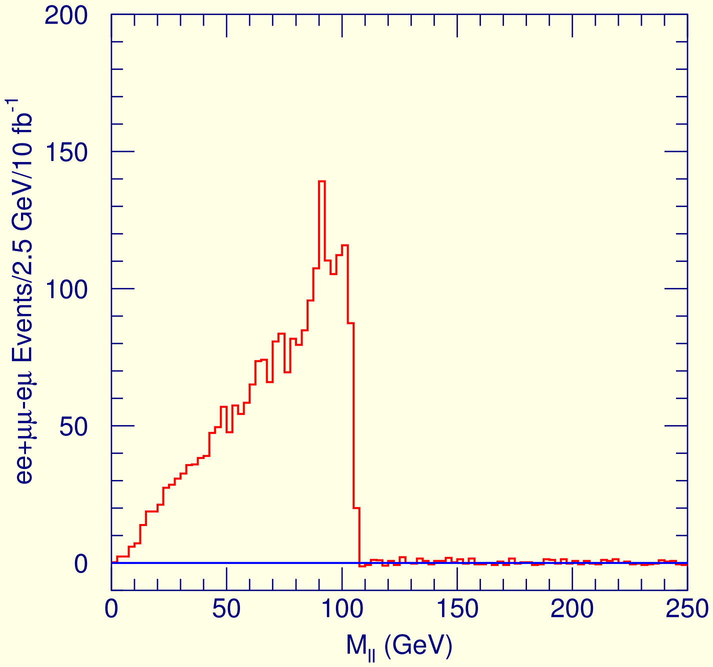
$$\widetilde{\chi}_2^0 \to \widetilde{\ell}^\pm\ell^\mp \to \widetilde{\chi}_1^0\ell^\pm\ell^\mp \to \widetilde{G}\gamma\ell^\pm\ell^\mp \,,$$

Electrons and photons : $p_T > 20\,\text{GeV}$

Muons : $p_T > 5\,\text{GeV}$.

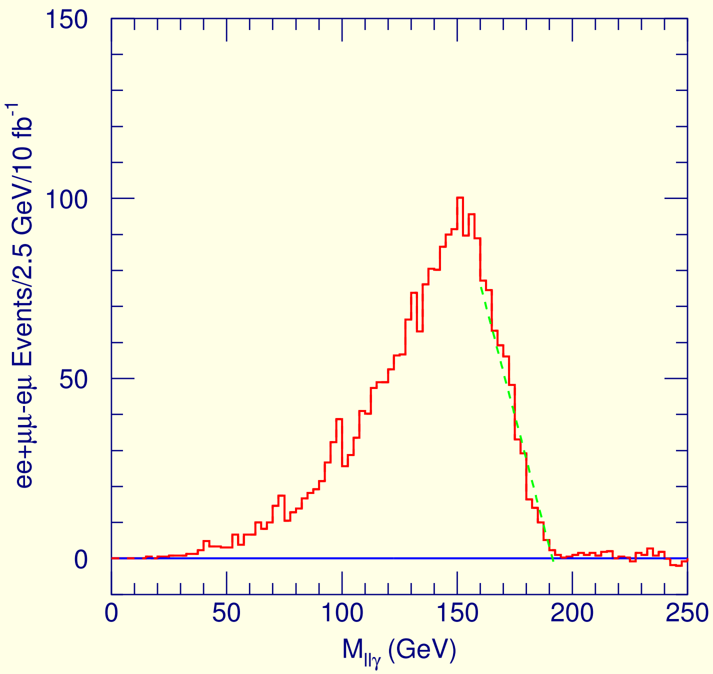
Require at least 2 photons and two leptons.

Dilepton mass distribution, flavor subtracted $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$



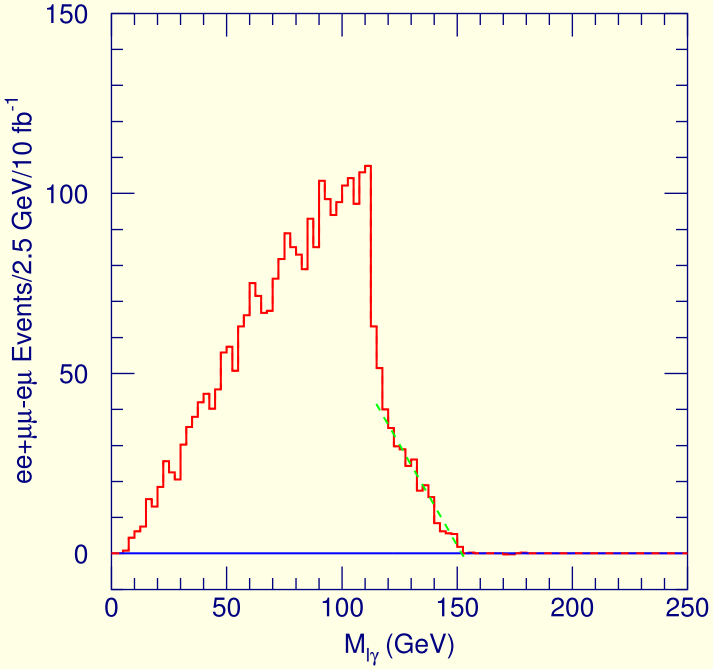
End is at

$$M_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{M_{\tilde{\ell}_R}}{M_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{\ell}_R}}\right)^2} = 105.1\,\mathrm{Ge}$$



Form $\ell^+\ell^-\gamma$ mass and take smallest combination. Linear vanishing at

$$\sqrt{M^2_{\tilde{\chi}^0_2} - M^2_{\chi^0_1}} = 189.7\,\mathrm{GeV}\,,$$



Form $\ell^{\pm}\gamma$ mass also. Two structures at

$$\sqrt{M^2_{\tilde{\ell}_R} - M^2_{\chi^0_1}} = \mathbf{112.7}\,\mathrm{GeV}$$

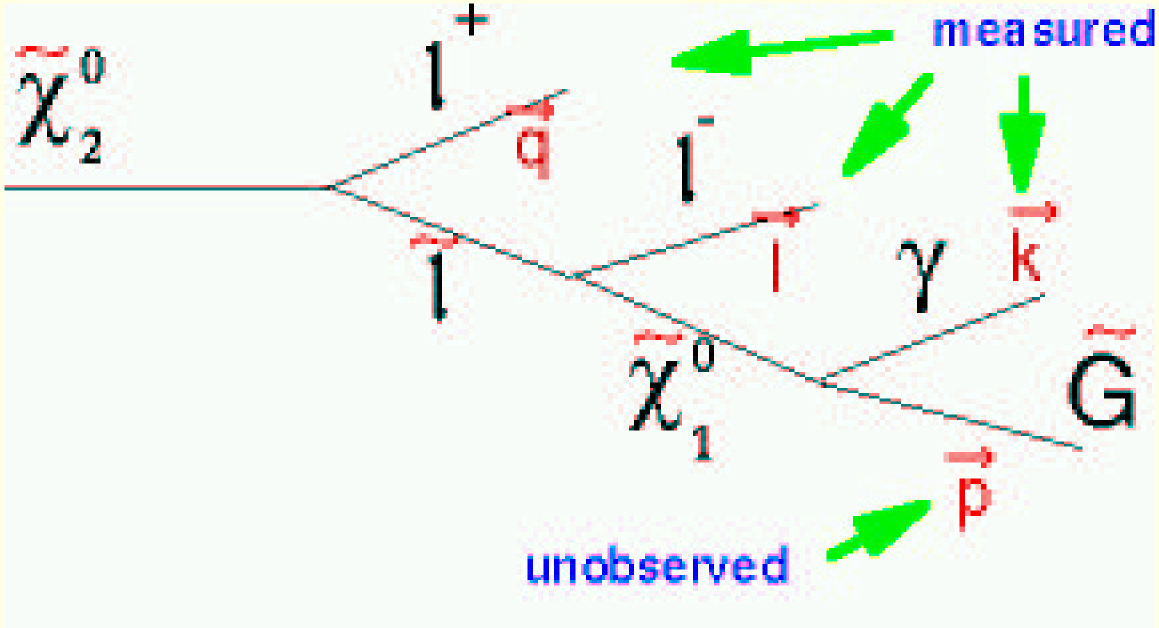
and

$$\sqrt{M^2_{\chi^0_2} - M^2_{\tilde{\ell}_R}} = \mathbf{152.6}\,\mathrm{GeV}$$

These four measurements are sufficient to determine the masses of the particles ($\widetilde{\chi}_2^0$, $\widetilde{\ell}_R$, and $\widetilde{\chi}_1^0$) in this decay chain without assuming any model of SUSY breaking.

Now use this to reconstruct the decay chain and measure the $\widetilde{G}$ momenta despite the fact that there are two in each event and both are invisible!

Full reconstruction of SUSY events



Know masses $\Rightarrow$ can calculate p assuming $p^2 = 0$:

$$
\begin{aligned}
2p_0k_0 - 2\vec{p}\cdot\vec{k} &= M^2_{\tilde{\chi}^0_1} \\
2p_0l_0 - 2\vec{p}\cdot\vec{l} &= M^2_{\tilde{\ell}_R} - M^2_{\tilde{\chi}^0_1} - 2k\cdot l \\
2p_0k_0 - 2\vec{p}\cdot\vec{q} &= M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}_R} - 2(k+l)\cdot q
\end{aligned}
$$

0C fit with 2×2 solutions.

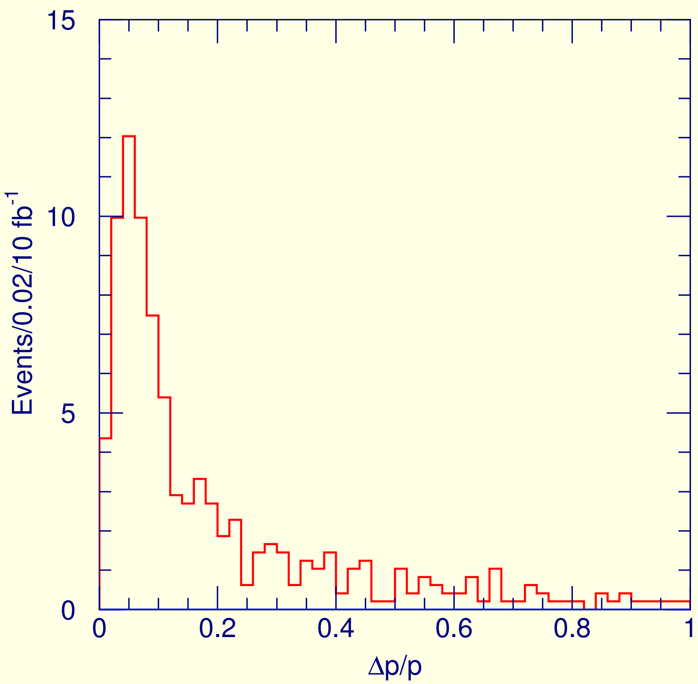
Event has two of these decays so require 4 leptons and 2 gammas

Calculate missing E_T

Form a χ^2 using measured missing E_T to resolve ambiguities

$$\chi^2 = \left(\frac{\not{E}_x - p_{1x} - p_{2x}}{\Delta \not{E}_x}\right)^2 + \left(\frac{\not{E}_y - p_{1y} - p_{2y}}{\Delta \not{E}_y}\right)^2 .$$

use $\Delta \not{E}_x = \Delta \not{E}_x = 0.6\sqrt{E_T} + 0.03 E_T$.



Compare to generated $\widetilde{G}$ momenta

Plot shows all solutions with $\chi^2 < 10$

$\Delta\vec{p} = \vec{p}_{\tilde{G}} - \vec{p}_{reconst}$

$\Delta|\vec{p}|/|\vec{p}| \sim 10\%$

Squark and Gluino Masses

Use measured $\tilde{\chi}_2^0$ momenta and combine with jets
$\tilde{q} \to \tilde{g}q \to \tilde{\chi}_2^0 \bar{q}qq$
Require at least 4 jets with $p_T > 75\,\mathrm{GeV}$

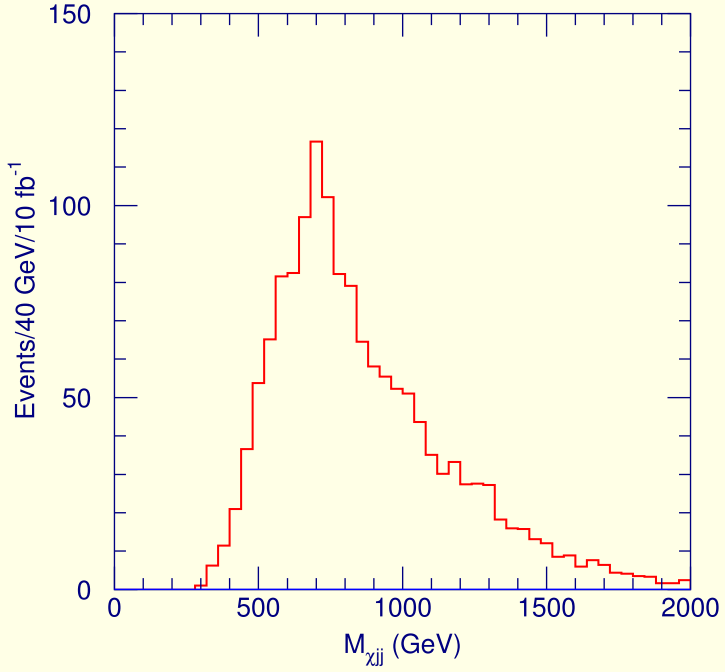


Figure shows mass of $\tilde{\chi}_2^0$+2 jets;
peak is below gluino mass (747 GeV);
no correction applied for small jet cone.

Much easier than the SUGRA cases; masses measured directly

Measuring the fundamental scale of SUSY breaking

Lifetime of $\widetilde{\chi}_1^0 \to \tilde{G}$ is important as it measures the fundamental scale of SUSY breaking

Measure lifetime of χ_1^0 ($\to \widetilde{G}\gamma$) using Dalitz decay $\chi_1^0 \to e^+e^-\gamma\widetilde{G}$

Works for short lived $\widetilde{\chi}_1^0$

Statistics limited ($\sim$few-K events)

Measure lifetime of χ_1^0 ($\to \widetilde{G}\gamma$): photon pointing.

Angular resolution of photons from primary vertex (ATLAS)

$\Delta\theta \sim 60mr/\sqrt{E}$ Detailed study of efficiency for non-pointing photons

Important for long lived $\widetilde{\chi}_1^0$

Decays are uniformly distributed in the detector

Cross check from time delay of decay

Failure to see photons $\Rightarrow c\tau > 100$ km or $\sqrt{F} \geq 10^4$ TeV

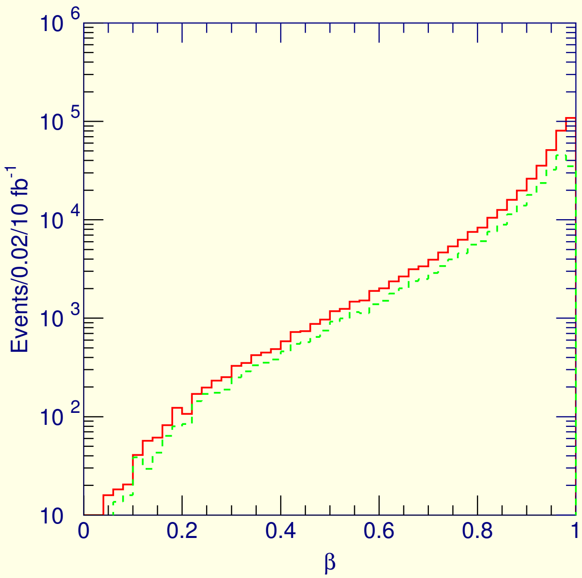
Sleptons are produced at the end of decay chains $\Rightarrow$ large velocity

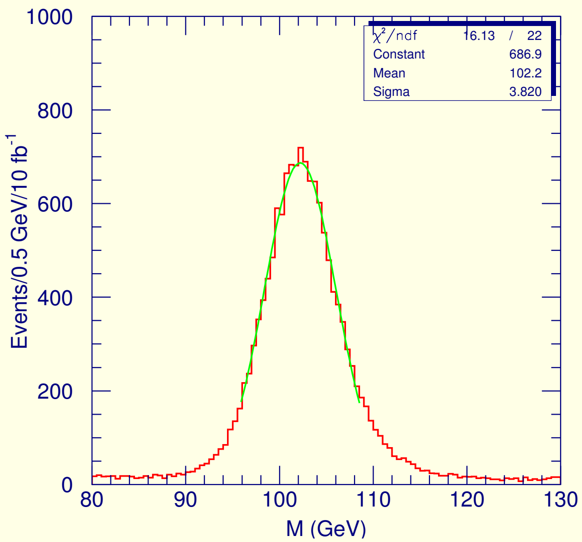
Most of these will pass the Muon Trigger

Measure the velocity using TOF in Muon system, then infer mass

Time resolution $\sim \mathbf{65}$ ns

$\Rightarrow \boldsymbol{\Delta M/M \sim 3\%}$ for $\boldsymbol{M = 100}$ GeV



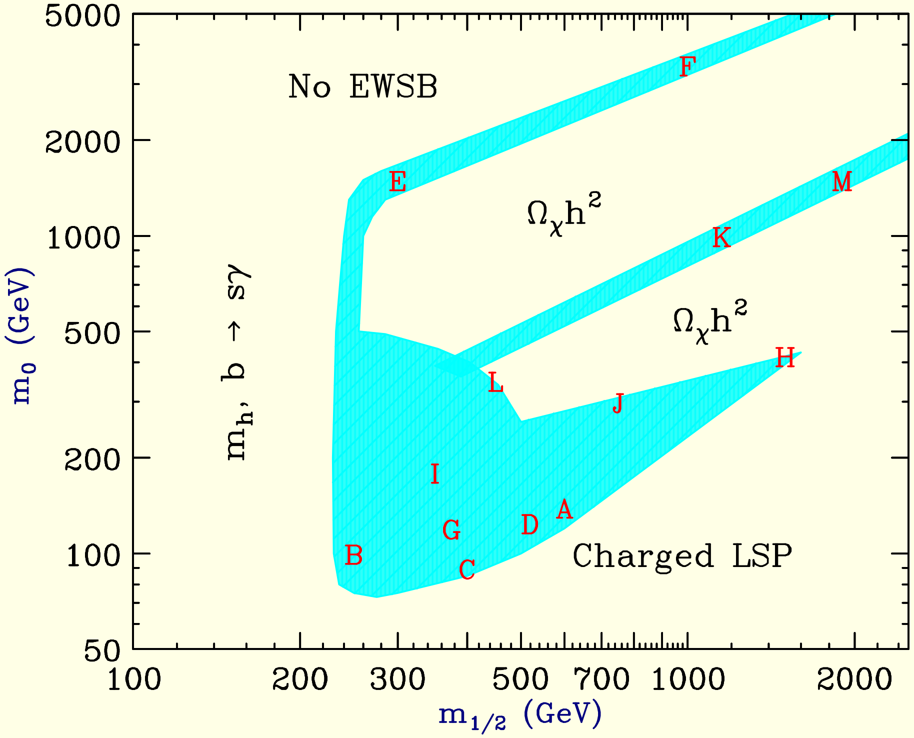


velocity $\qquad\qquad$ $\boldsymbol{\Delta M/M}$

How Heavy could sparticles be?

Rigorous bound impossible
In sugra model

Battaglia *et.al*



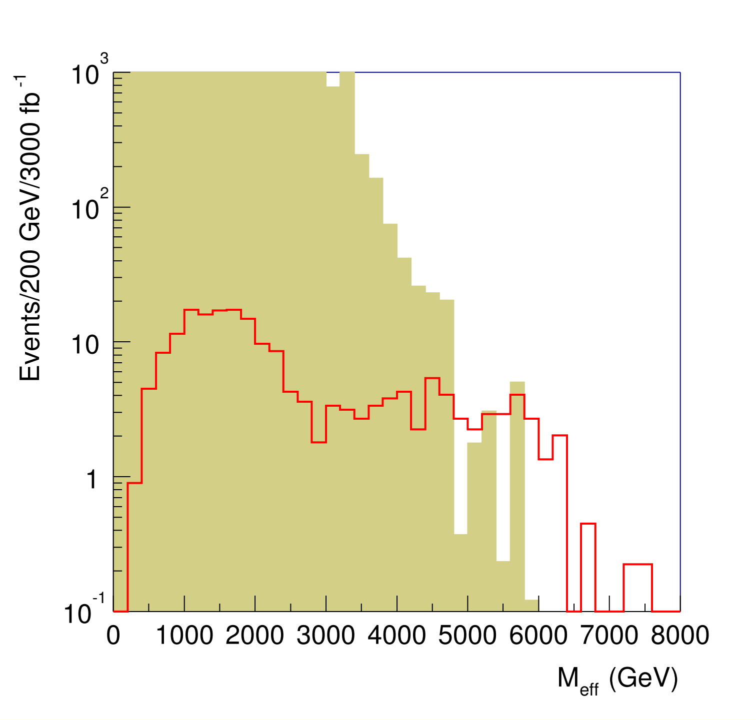
Allowed regions using all constraints
High masses are reachable only in fine tuned regions and are not natural

To reach the very high mass regions, more luminosity or energy may be needed

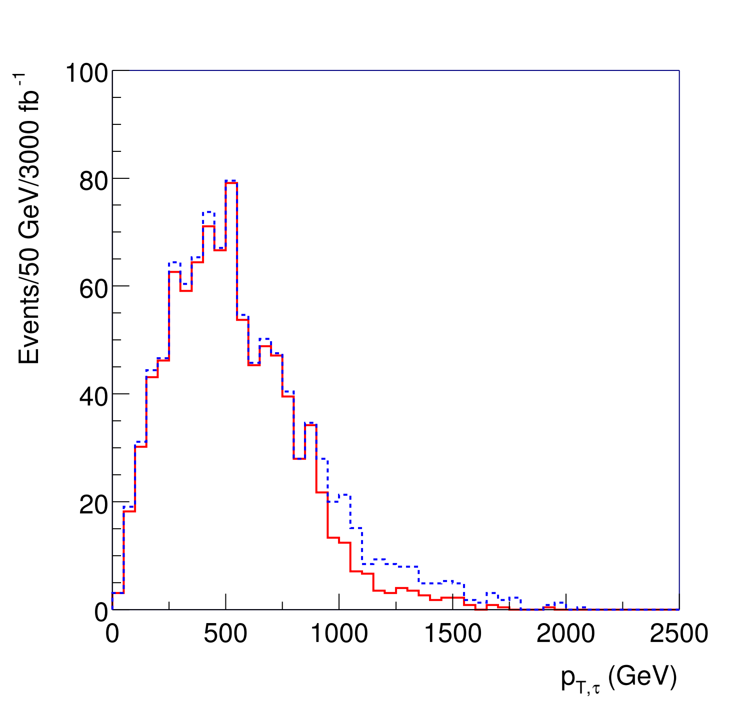
An extreme case

Extreme cases are F, M and H.

Effective mass distribution should be sensitive to Point M if there is a luminosity upgrade
Note Scale



Point H is very special stau and LSP almost degenerate ⇒ quasi stable stau
Plot shows P_t distribution of staus
Red line shows slow ones

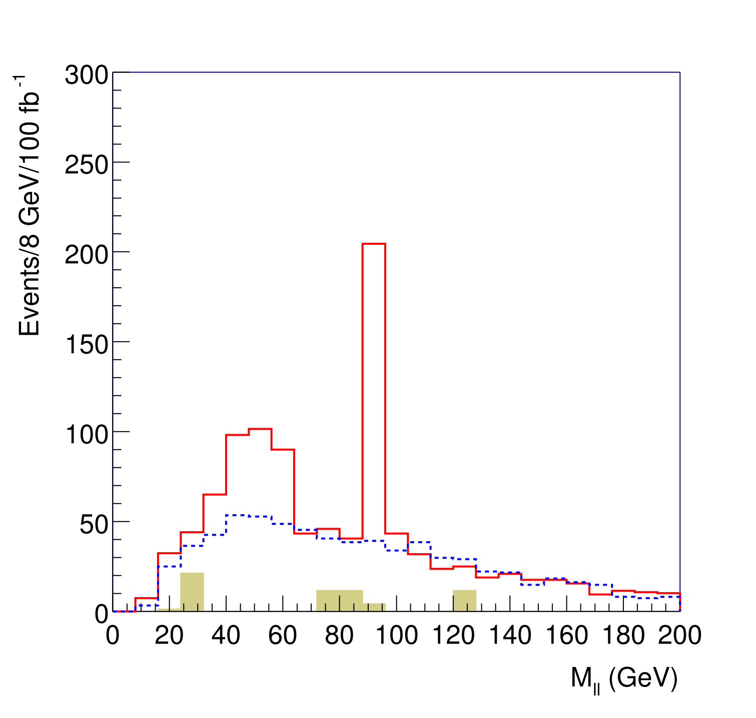


SUSY – Heavy Scalars

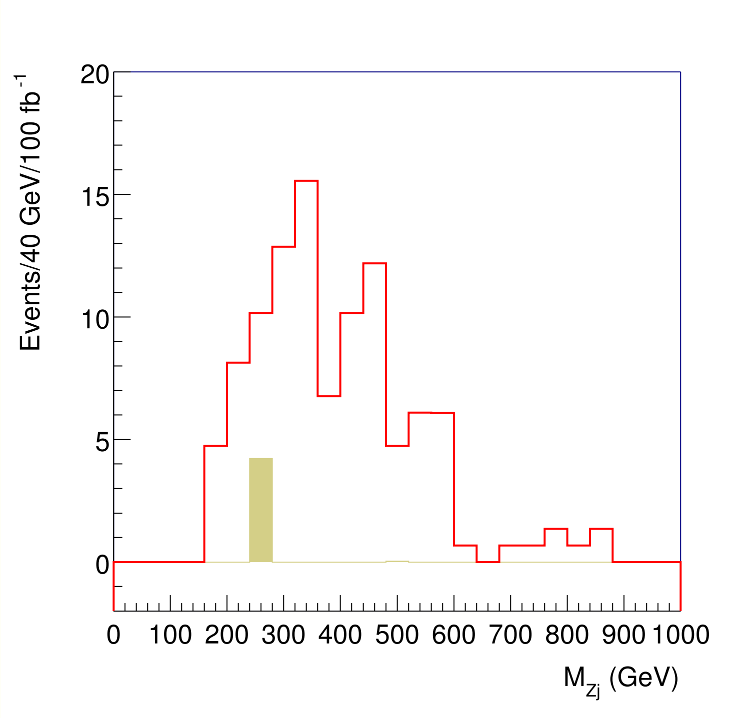
May accomodate FCNC constraints

Only $\tilde{g}, h, \widetilde{\chi}_i$ can be produced with significant rates

$\tilde{g}$ decays to $\widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0$ and $\widetilde{\chi}^+$ with significant rates. Signals are complicated



Dilepton structure
solid $\ell^+\ell^-$ dashed $\ell^+\ell^+$



Gluino extracted from $Z(\rightarrow \ell^+\ell^-)\mathrm{jet}$
endpoint at $\mathbf{602}$ GeV

Some Scenarios

Light SUSY: Can extrapolate from existing studies.

Straightforward ($\mathbf{10}$ fb^{-1}, measure masses to $< \mathbf{10\%}$)

$\tilde{g}$, $\tilde{q}_l$, $\tilde{q}_r$, $\tilde{b}_1$, $\tilde{b}_2$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$, $\tilde{\chi}_1^+$, $h(?)$, $\tilde{e}_r$, $\tilde{\mu}_r$, $\tilde{\tau}_1$

Difficult ($\mathbf{100}$ fb^{-1}, measure masses to $< \mathbf{20\%}$)

h, $H/A(?)$ $\tilde{e}_l$, $\tilde{\mu}_l$

May be impossible (At least nobody knows how at the moment)

$\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$ (Production rates too small) H^+ $\tilde{\chi}_2^+$

Heavy SUSY: Work is underway No firm conclusions

Straightforward ($\mathbf{10}$ fb^{-1}, measure masses to $< \mathbf{10\%}$)

h, Susy discovered $\tilde{g}$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$

Difficult ($\mathbf{100}$ fb^{-1}, measure masses to $< \mathbf{20\%}$)

$\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$,

Some hint for squarks may be possible, but no-none has demonstrated it.

Impossible

All sleptons, H^+, H, A

Extra Dimensions

Many theories ($e.g.$ string) predict extra dimensions of size R

What is R?. Old ideas $\Rightarrow 1/M_P$. Unobservable.

Larger value of R can allow scale of Gravity to be smaller — Arkani-Hamed...

$$G_N = 8\pi R^\delta M_D^{-(2+\delta)}$$

$M_D \sim 1$ TeV $R \sim 10^{32/\delta-16}$ mm

m Attractive because no hierarchy between M_W and M_D

But hierarchy between $1/R$ and M_W still exists

Compactified dimension implies tower of states with $\Delta m \sim 1/R$

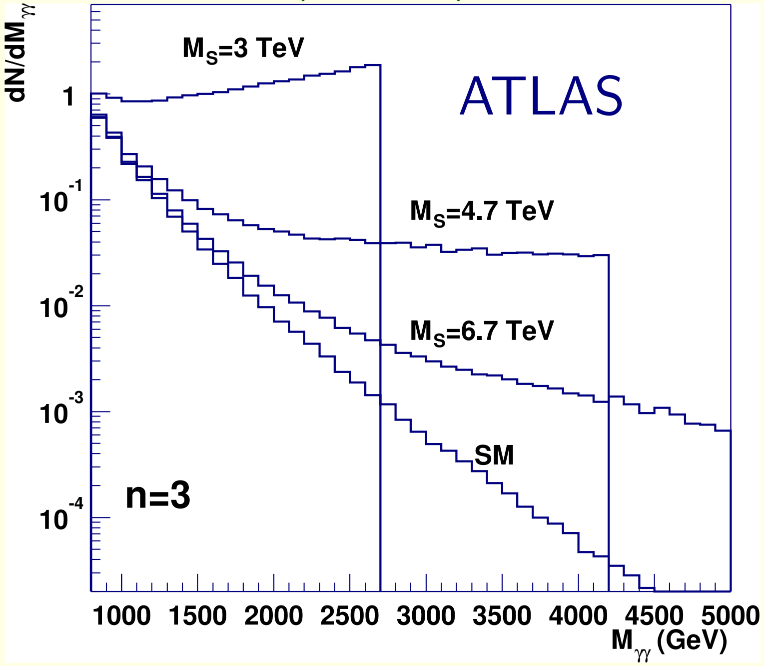
$\Rightarrow$ Standard Model fields must be stuck in $d = 4$ But many graviton (G) excitations can exist.

In simplest models processes such as $qg \longrightarrow qG$ or $q\overline{q} \longrightarrow \gamma G$ give missing energy signatures or distortions in rates due to exchanges

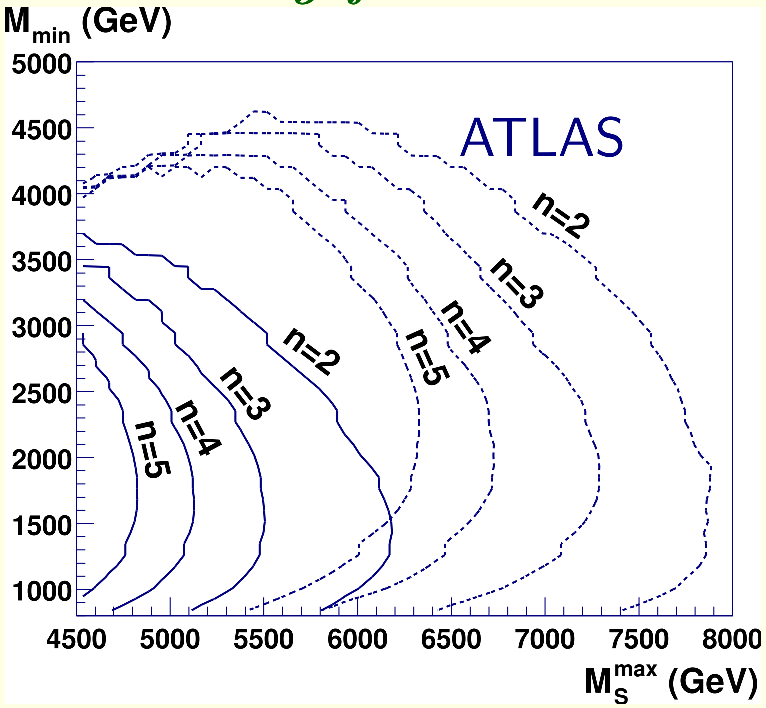
Studies have focused on jets $+ \not{E}_T$, $\gamma + \not{E}_T$, $\gamma\gamma$, and $\ell\ell$ final states.

Virtual effects from graviton exchange show up as excesses in the production rates

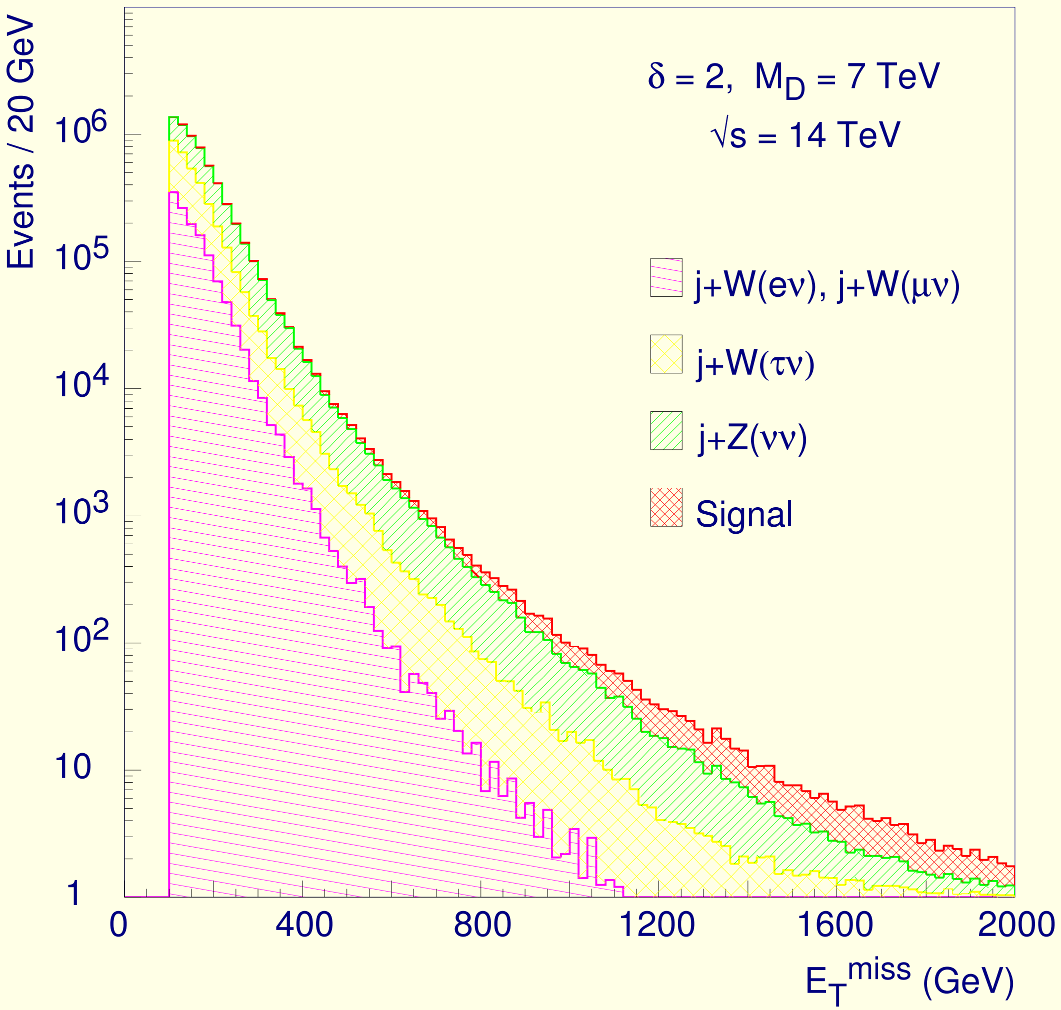
$\gamma\gamma$ *Events/GeV*/10 fb^{-1}



Sensitivity for **10** *and* **100** fb^{-1}



ADD extra dimensions produce $\mathrm{jets} + \not{E}_T$, $\gamma + \not{E}_T$ signals from graviton emission



red region is signal from jets for $\mathbf{100}\ \mathrm{fb}^{-1}$

Sensitivity

$\boldsymbol{\delta}$	$\boldsymbol{M_D^{max}}$ (TeV)
2	**9**
3	**7**
4	**6**

Warped Extra Dimensions – Randall Sundrum models

Model of 5-dim space with two branes of 4-dim. SM fields are stuck on one brane. Metric is "non-factorizible"

$$ds^2 = e^{-kR\phi}\eta_{\mu,\nu}dx^\mu dx^\nu + R^2 d\phi^2$$

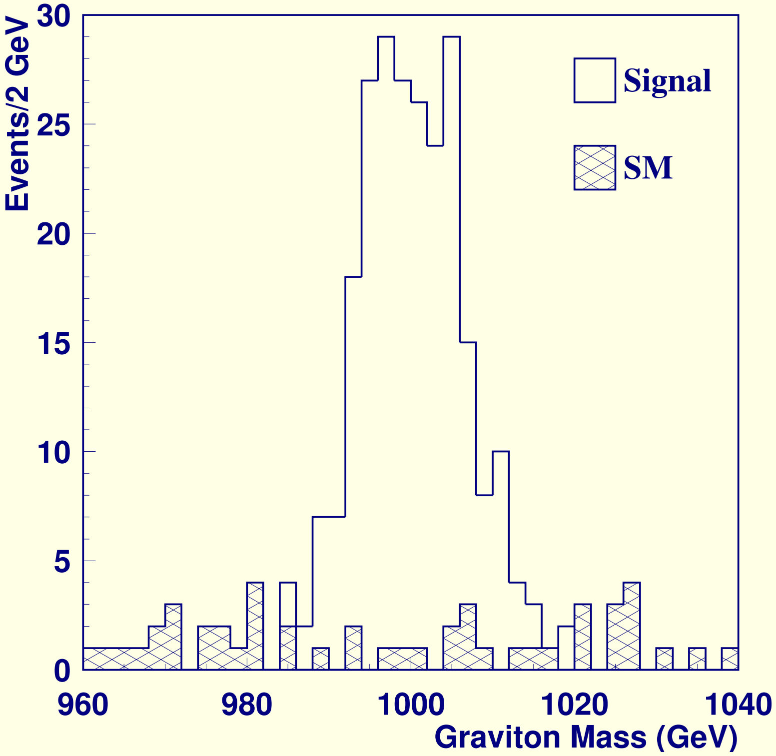
Scale $\Lambda = ke^{-kR\pi}$ in 4-D world

Can get $\Lambda \sim 1$ TeV with $Rk \sim 12$ and $k \sim M_P$

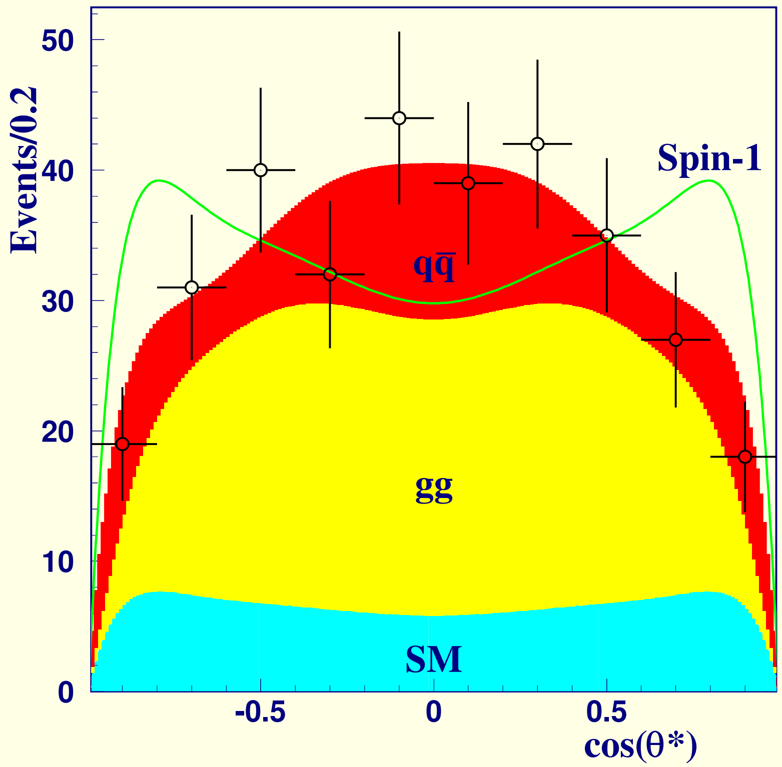
Graviton excited states have mass gaps of order Λ

Properties are determined by k/M_P.

Simple models have $k/M_P \sim 0.01$; excited states are then narrow and weakly coupled



Look for a resonance in dilepton final states *e.g.* $gg \longrightarrow e^+e^-$ Discovery limit is $\sim$ $\mathbf{1.8 TeV}$ for 100 fb^{-1}



Resonance is Spin-2, confirm this by looking at lepton angular distribution
Can determine spin properties for $M < 1.4 TeV$ for 100 fb^{-1}

Introduction

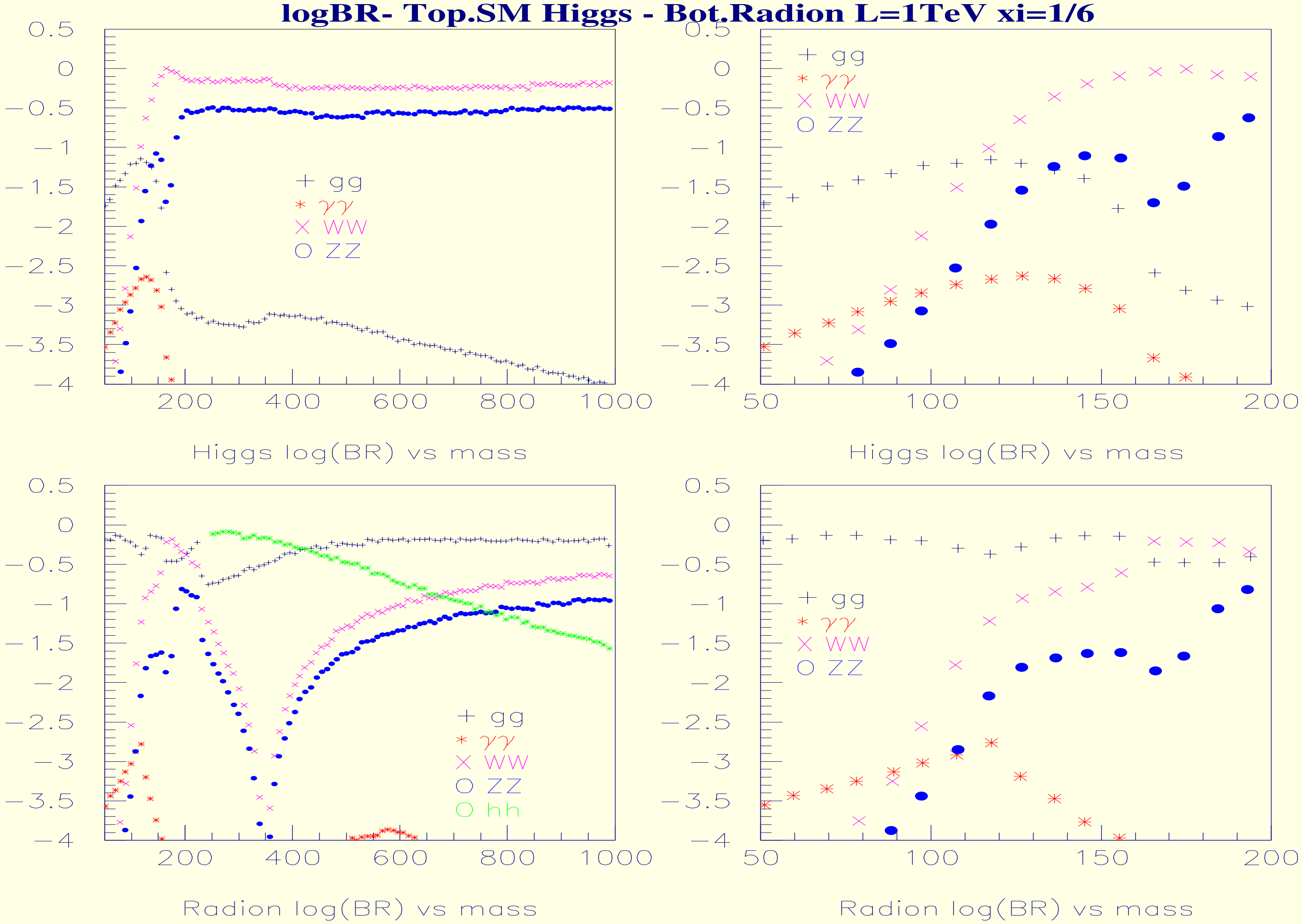
Radion

- radial excitations of compactified dimensions
- 0^{++} state, Higgs-like

Which model ?

- present in ADD LED (KK tower), not discussed here
- in Randall-Sundrum non-factorizable geometry model
  - a single massless mode
  - mass dynamically generated (model-dependant)
  - Goldberger+Wise mechanism:
    - stabilization of brane separation
    - avoid fine-tuning of r_c, gives $k\pi r_c \sim 35$
    - $m_\varphi < m_{G^{(1)}}$

Radion Branching Ratios



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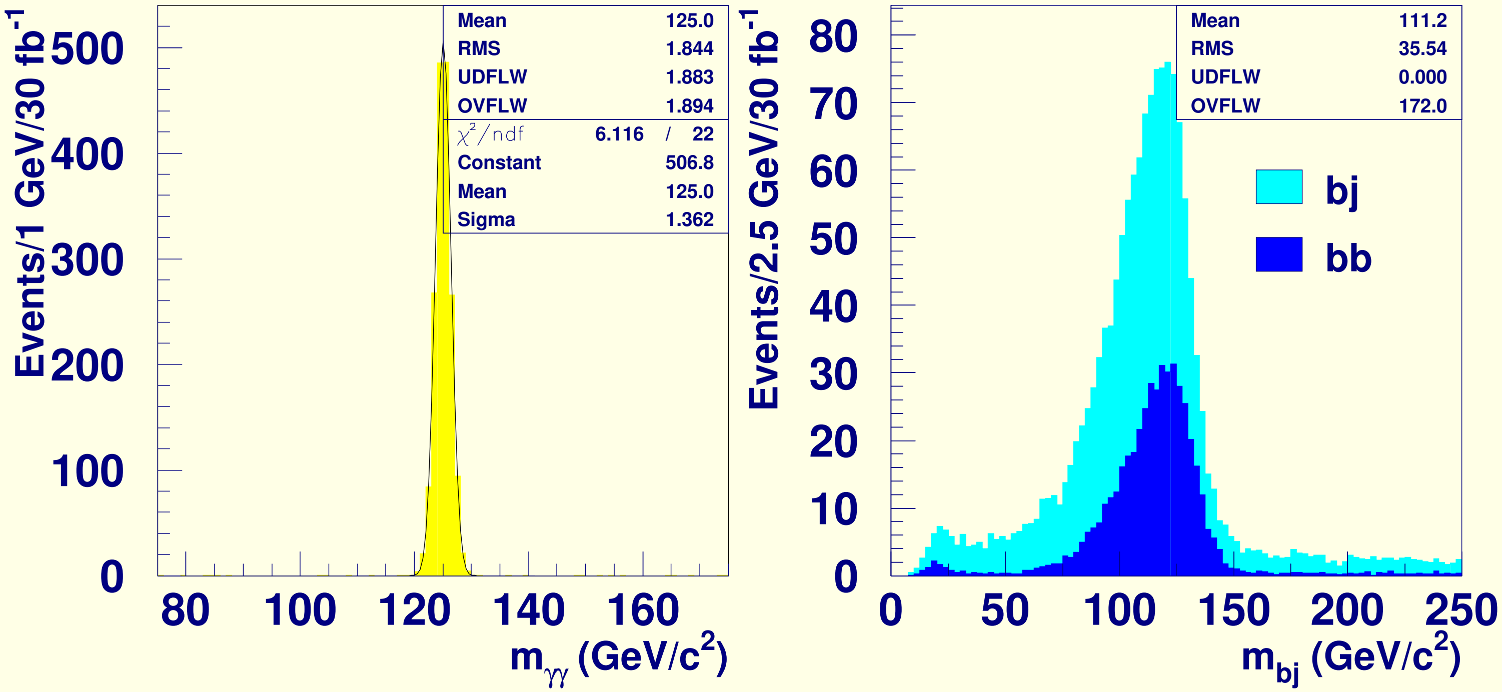
$\varphi \to hh \to \gamma\gamma b\bar{b}$

Reconstructed Higgs mass

$m_\varphi = 300$ GeV/c^2 $\quad m_h = 125$ GeV/c^2 $\quad \xi = 0 \quad \Lambda = 1$ TeV



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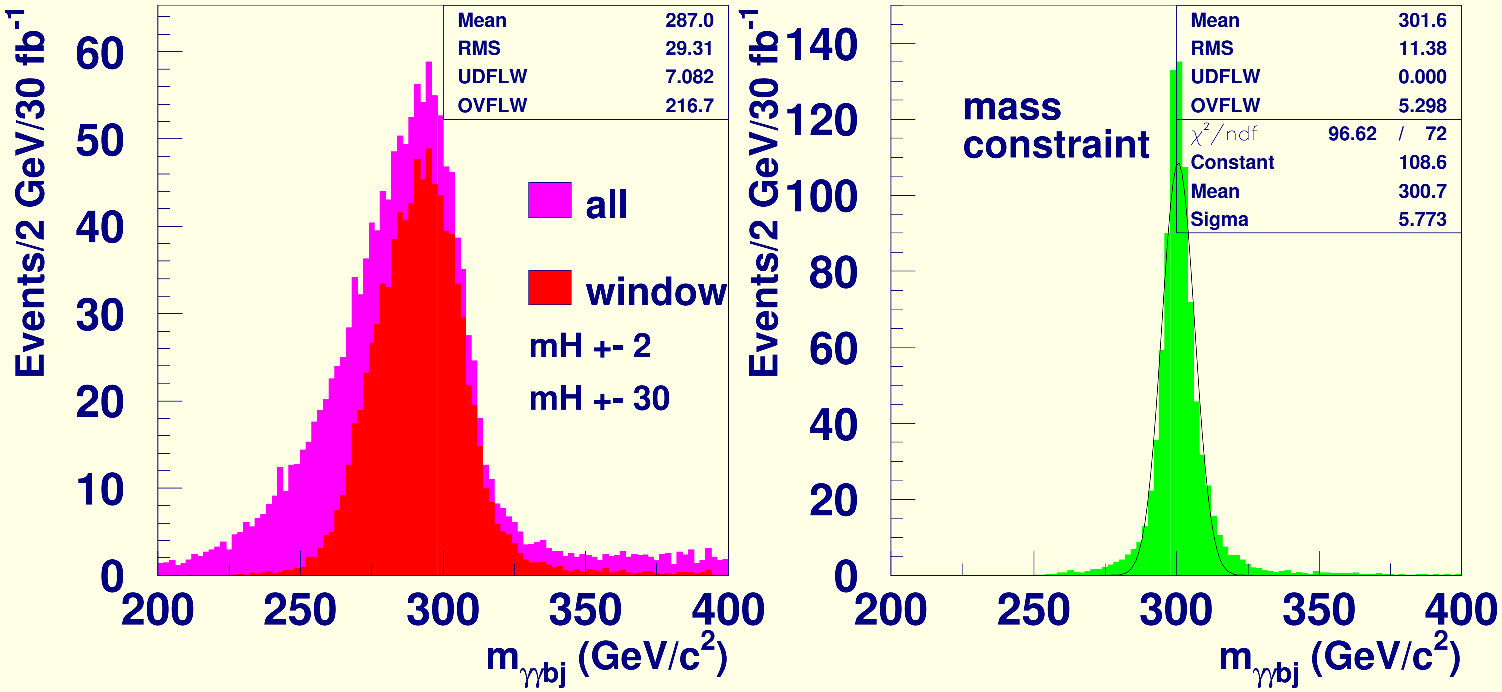
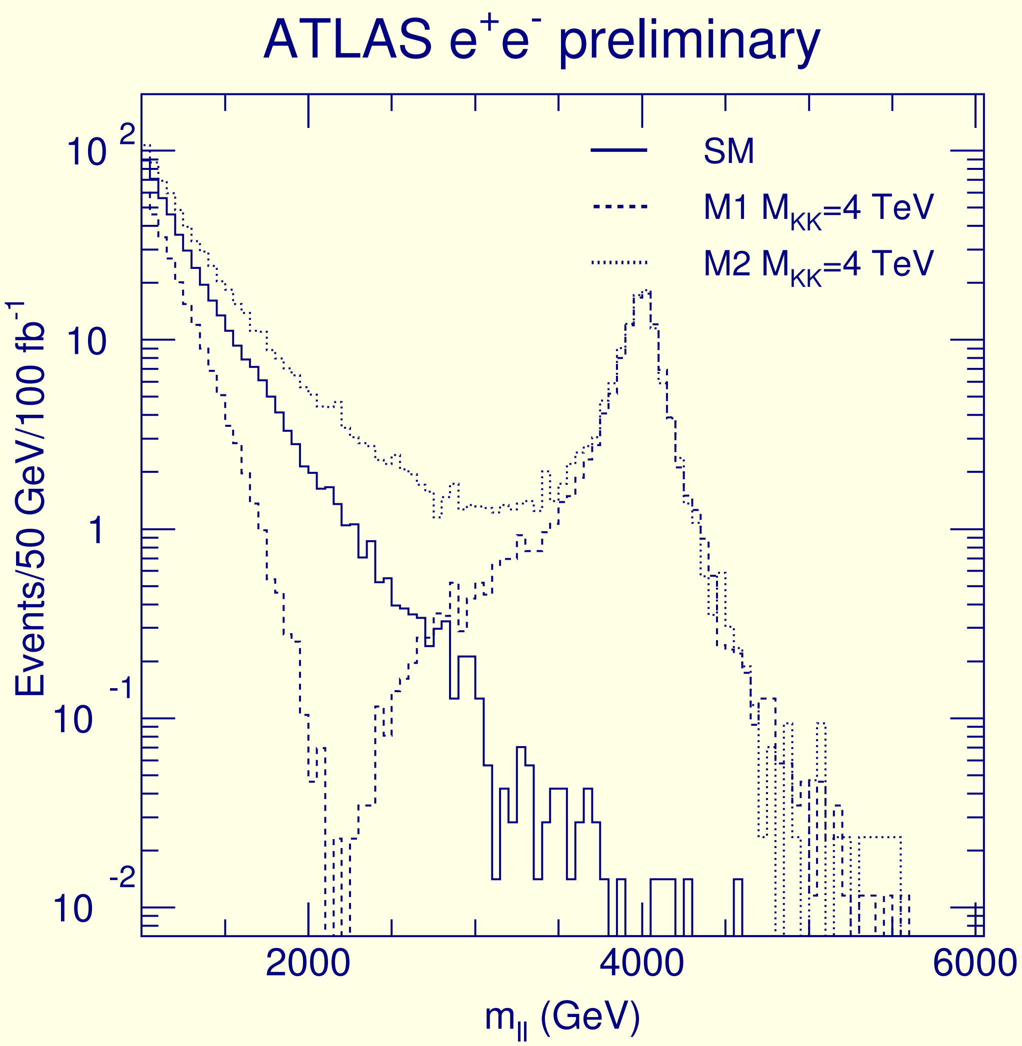


Can also have standard model fields in extra dim.

Excitations of SM particles



Insufficient reach to see second resonance

General Summary after a few years of LHC

Higgs – will have been found and several measurements made

$c\bar{c}$ and gg modes unobservable: Branching ratio measurements $\sim 10\%$

SUSY – Model dependent See above

Extra Dimensions –

$M \sim 5$ TeV probed

Ultimate LHC limit will not have been reached

Full luminosity needed to establish signal

Strong – WW

Indirect evidence – No Higgs seen

Conclusions

- LHC will open up new high energy frontier, find Higgs, measure many of its properties.
- In addition, LHC is a QCD factory, b-factory and top factory
- If susy exists, it's a susy factory, many sparticles will be discovered and masses measured. The underlying model will be tightly constrained
- Some physics could benefit from luminosity greater than $\mathbf{10^{34}}$; a modest machine upgrade could deliver this, but detectors will need upgrading to exploit it fully
  Examples: Extend search reach, measure more SUSY decays.
- An exciting time ahead