SUSY and other searches at LHC

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Outline

- **Beyond the Standard Model physics**
  Huge variety of models being studied in ATLAS & CMS

- **In this talk I will concentrate mainly on phenomenology of**
  Supersymmetry
  and give a quick overview of
  Micro Black holes
  Extra Dimensions

Supersymmetry

<u>MSSM particle spectrum :</u>

5 Higgs bosons : h, H, A, $H^{\pm}$

quarks	$\rightarrow$	squarks	$\tilde{u}$, $\tilde{d}$, etc.
leptons	$\rightarrow$	sleptons	$\tilde{e}$, $\tilde{\mu}$, $\tilde{\nu}$, etc.
$W^{\pm}$	$\rightarrow$	winos	$\rightarrow \chi^{\pm}_1, \chi^{\pm}_2$ 2 charginos
$H^{\pm}$	$\rightarrow$	charged higgsino	
γ	$\rightarrow$	photino	$\rightarrow \chi^{0}_{1,2,3,4}$ 4 neutralinos
Z	$\rightarrow$	zino	
h, H	$\rightarrow$	neutral higgsino	
g	$\rightarrow$	gluino	$\tilde{g}$

Masses not known. However charginos/neutralinos are usually lighter than squarks/sleptons/gluinos.

Present limits : $m_{\tilde{l}, \chi^{\pm}}$ > 90-100 GeV LEP

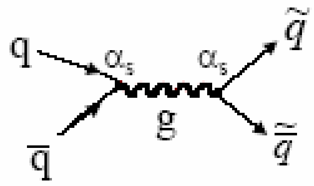
$m_{\tilde{q}, \tilde{g}}$ > 250 GeV Tevatron Run 1

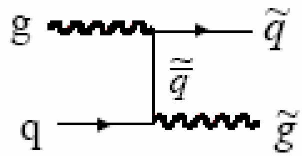
400 GeV Tevatron Run 2

Production of SUSY particles

- Squarks and gluinos produced via strong processes
  → large cross-section

Ex.:





$m_{\tilde{q},\tilde{g}} \sim 1$ TeV $\sigma \sim 1$ pb → 10^4 events per year

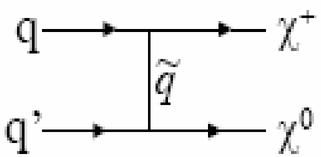
500 GeV **σ~10 pb** produced at low L

~100 events/day

~1000 events/day

- Charginos, neutralinos, sleptons produced via electroweak processes → much smaller rate

Ex.

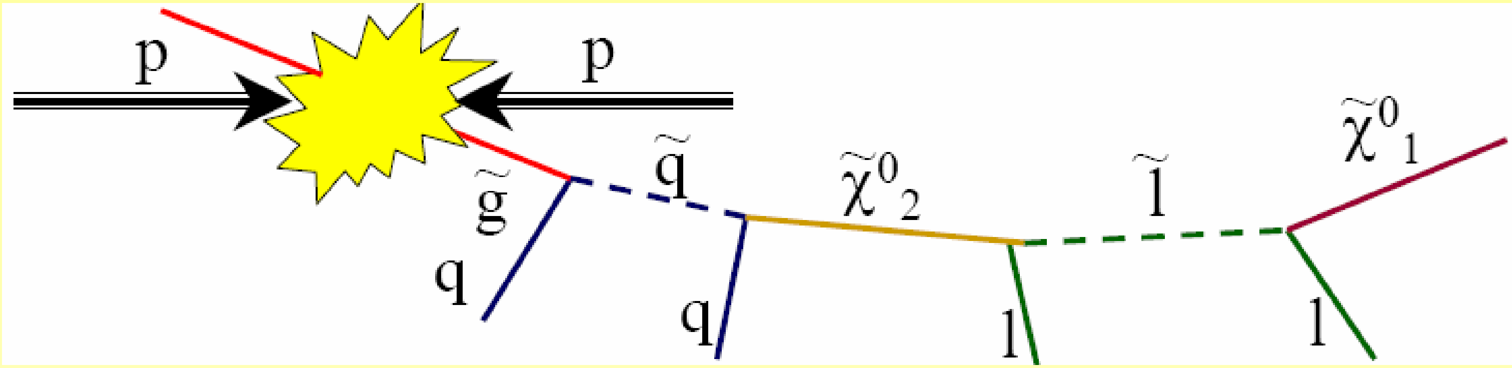


$\sigma \approx$ pb $m_\chi \approx 150$ GeV

$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ are dominant SUSY processes at LHC if kinematically accessible

SUSY signatures

- Q: What do we expect SUSY events @ LHC to look like?
- A: Here is a typical decay chain:



- **Strongly interacting sparticles (squarks, gluinos) dominate production**
- **Heavier than sleptons, gauginos etc.   cascade decays to LSP**

Everything is produced at once!

- **Long decay chains and large mass differences between SUSY states**

Many high pT objects observed (leptons, jets, b-jets)

- **If R-Parity conserved LSP (lightest neutralino in mSUGRA) stable and sparticles pair produced**

Large ETmiss signature

- **Closest equivalent SM signature t→Wb**

SUSY: what are we looking for?

Use mSUGRA model as baseline (Probably wrong but well defined!)

⇔ 5 parameters

- 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(μ) (superpotential has $\mu H_1 H_2$)

  A_0 (trilinear Higgs-sfermion-sfermion coupling)

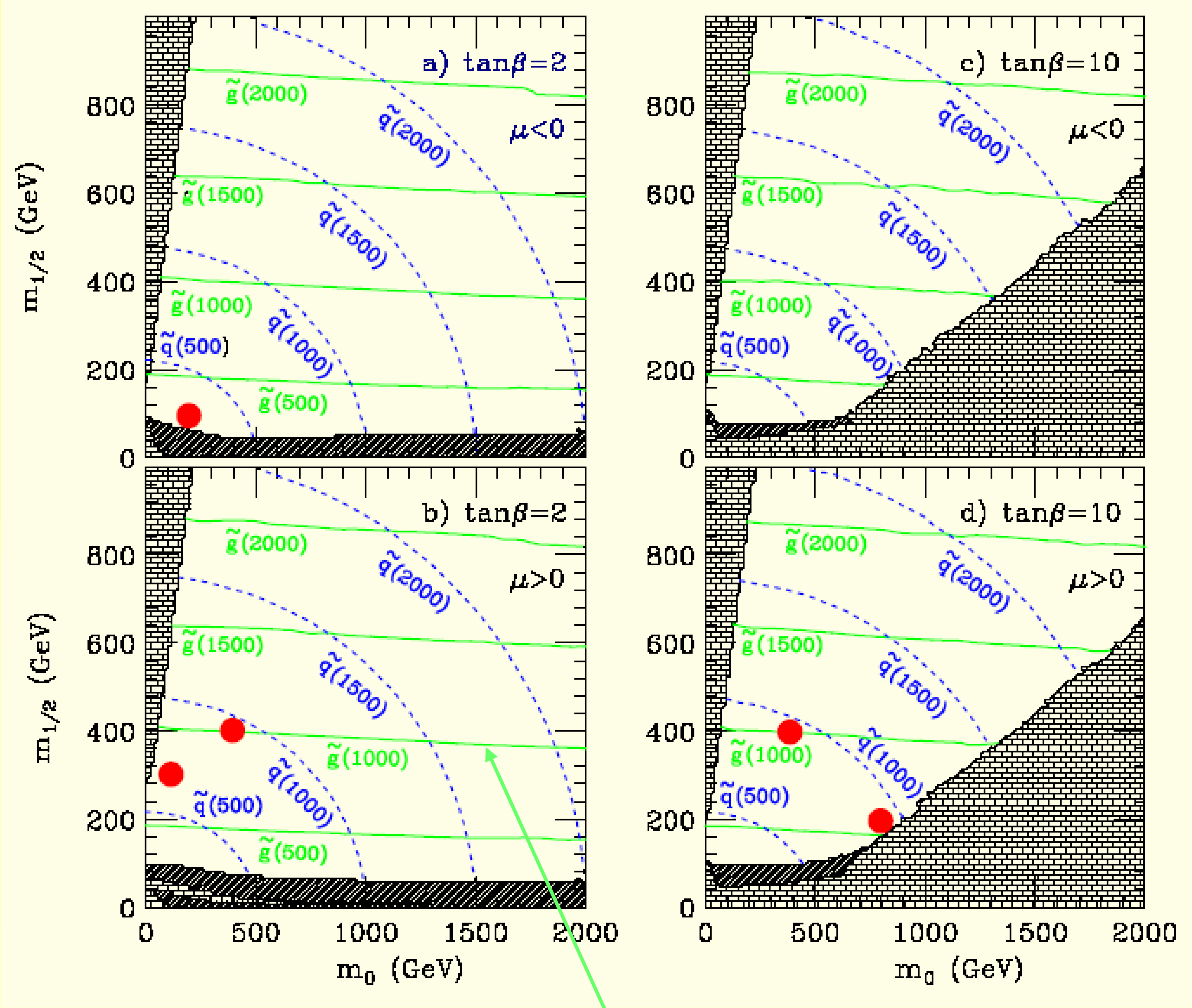
→ Full mass spectrum and decay table predicted

- Gluino mass strongly correlates with $m_{1/2}$, slepton mass with m_0
- Trilinear term A_0, important only for 3rd generation
- R parity conservation

  sparticles are produced in pairs

  all events have 2 LSP's ⇒ missing E_T
- Gravitino has mass in TeV region: irrelevant to colliders

SUSY: what are we looking for?



Contours of fixed gluino and squark mass

SUSY: where to look?

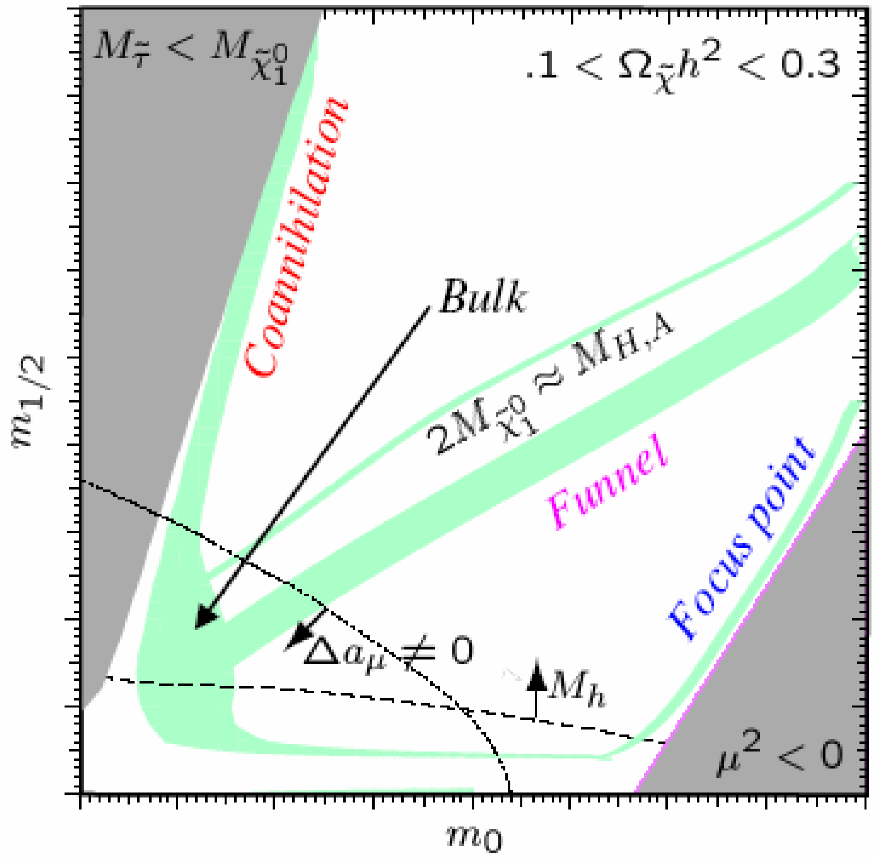
TeV-scale SUSY gives qualitatively right cold dark matter. Detailed calculation $\Rightarrow$ need enhanced annihilation. Use mSUGRA as guide (qualitative picture — no mass scale):

Coannihilation: Light $\tilde{\tau}_1$ in equilibrium with $\tilde{\chi}_1^0$, so annihilate via $\tilde{\chi}_1^0 \tilde{\tau}_1 \to \gamma\tau$.

Bulk: bino $\tilde{\chi}_1^0$; light $\tilde{\ell}_R$ enhances annihilation.

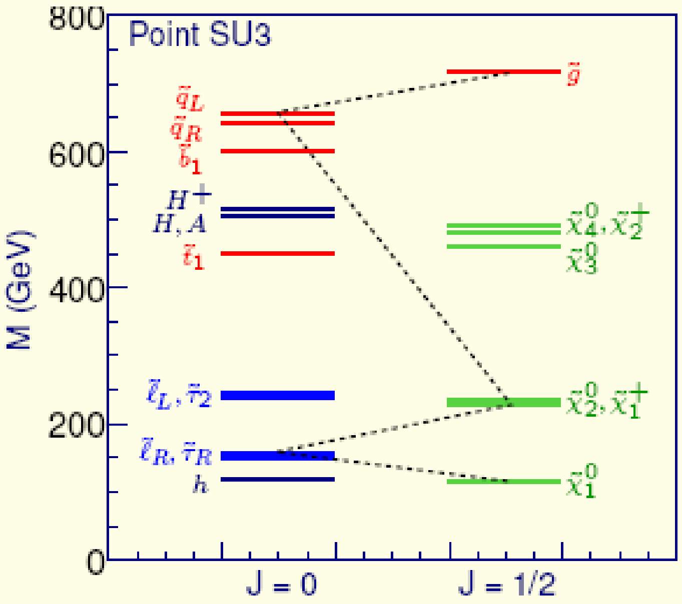
Funnel: H, A poles enhance annihilation for $\tan\beta \gg 1$.

Focus point: Small μ^2, so Higgsino $\tilde{\chi}_1^0$ annihilate. Heavy s-fermions, so small FCNC.

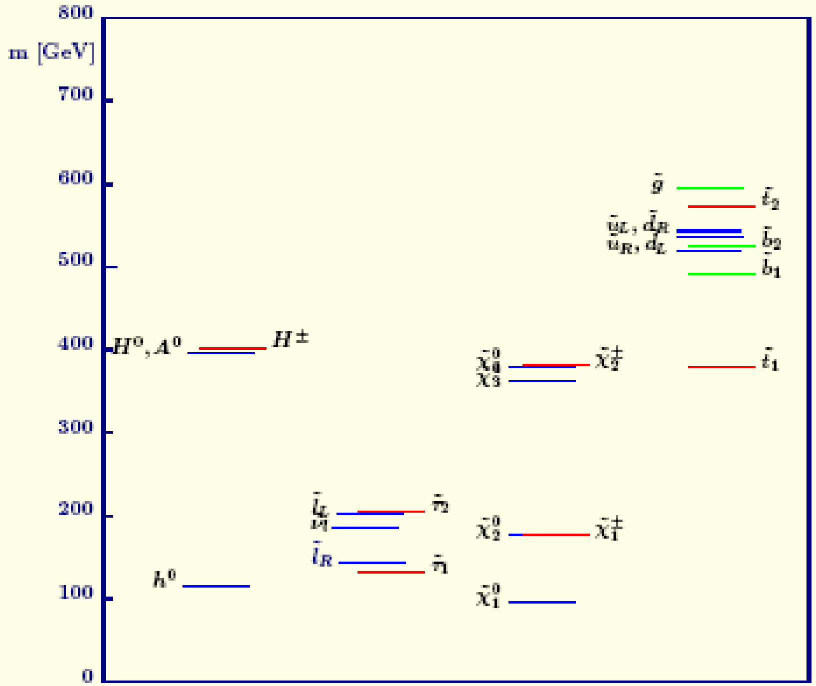


Choose benchmark points in allowed regions

Two typical spectra



Used in ATLAS studies: important decays shown



SPS1a: used in many LHC/ILC comparisons

Inclusive analysis

Select events with at least 4 jets and Missing E_T

A simple variable

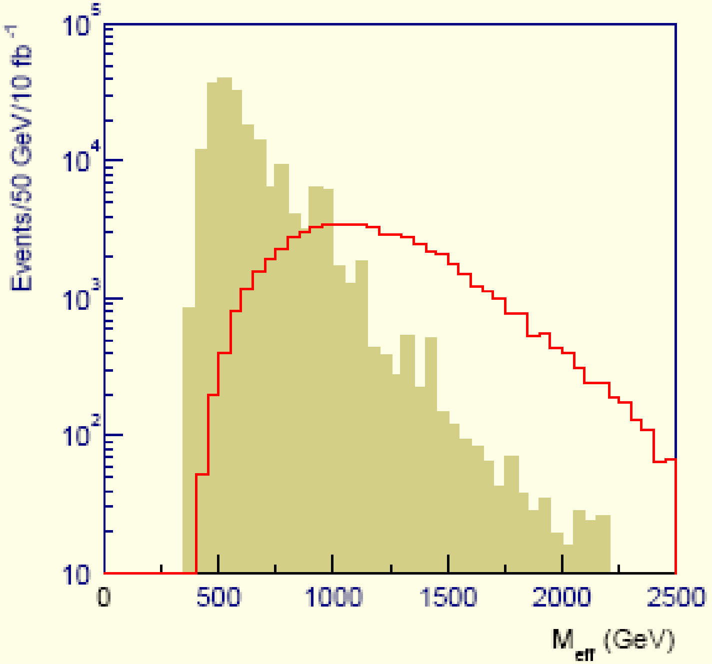
$M_{\text{eff}} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not{E}_T$

At high M_{eff} non-SM signal rises above background note scale

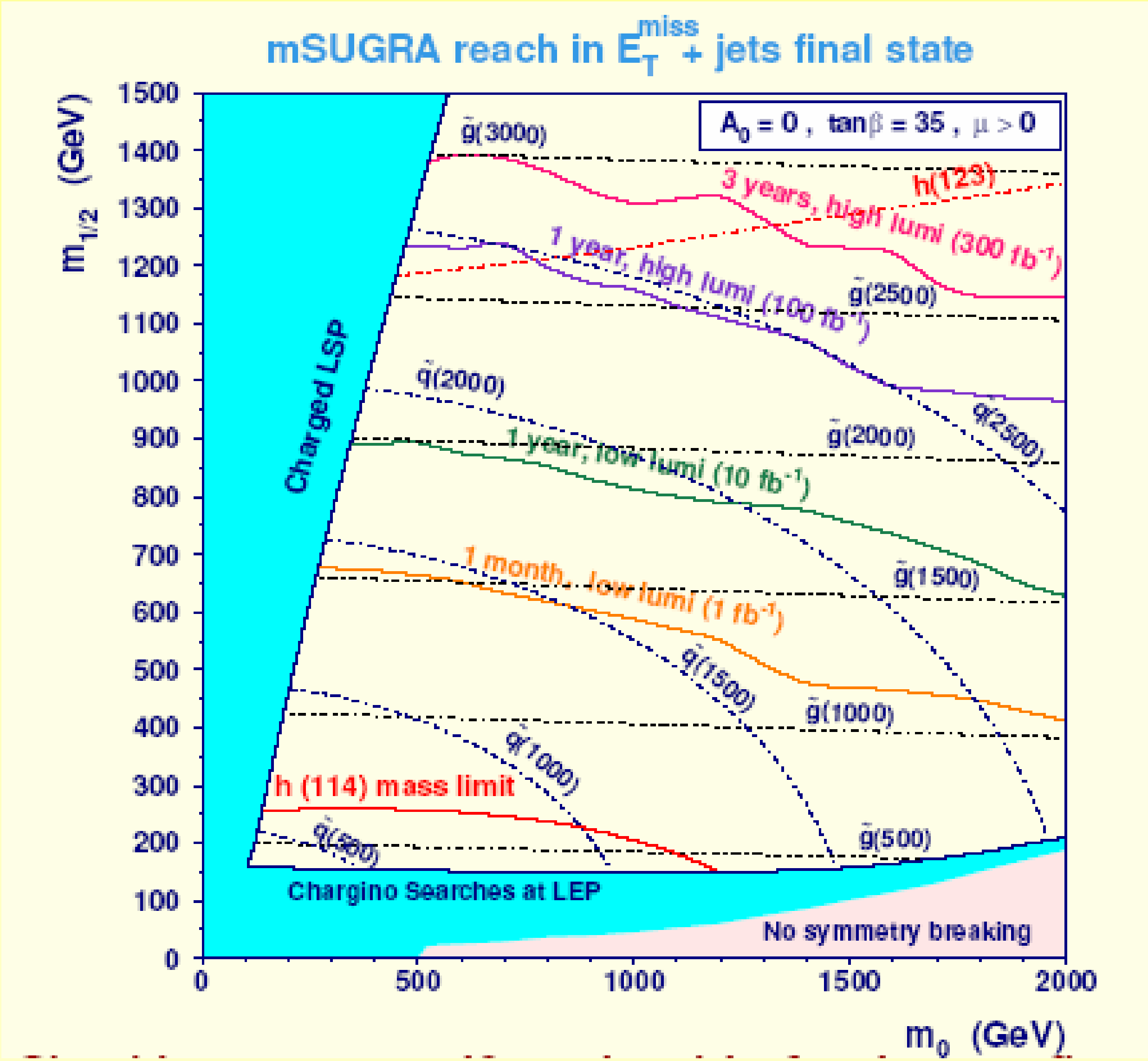
Peak in M_{eff} distribution correlates well with SUSY mass scale

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

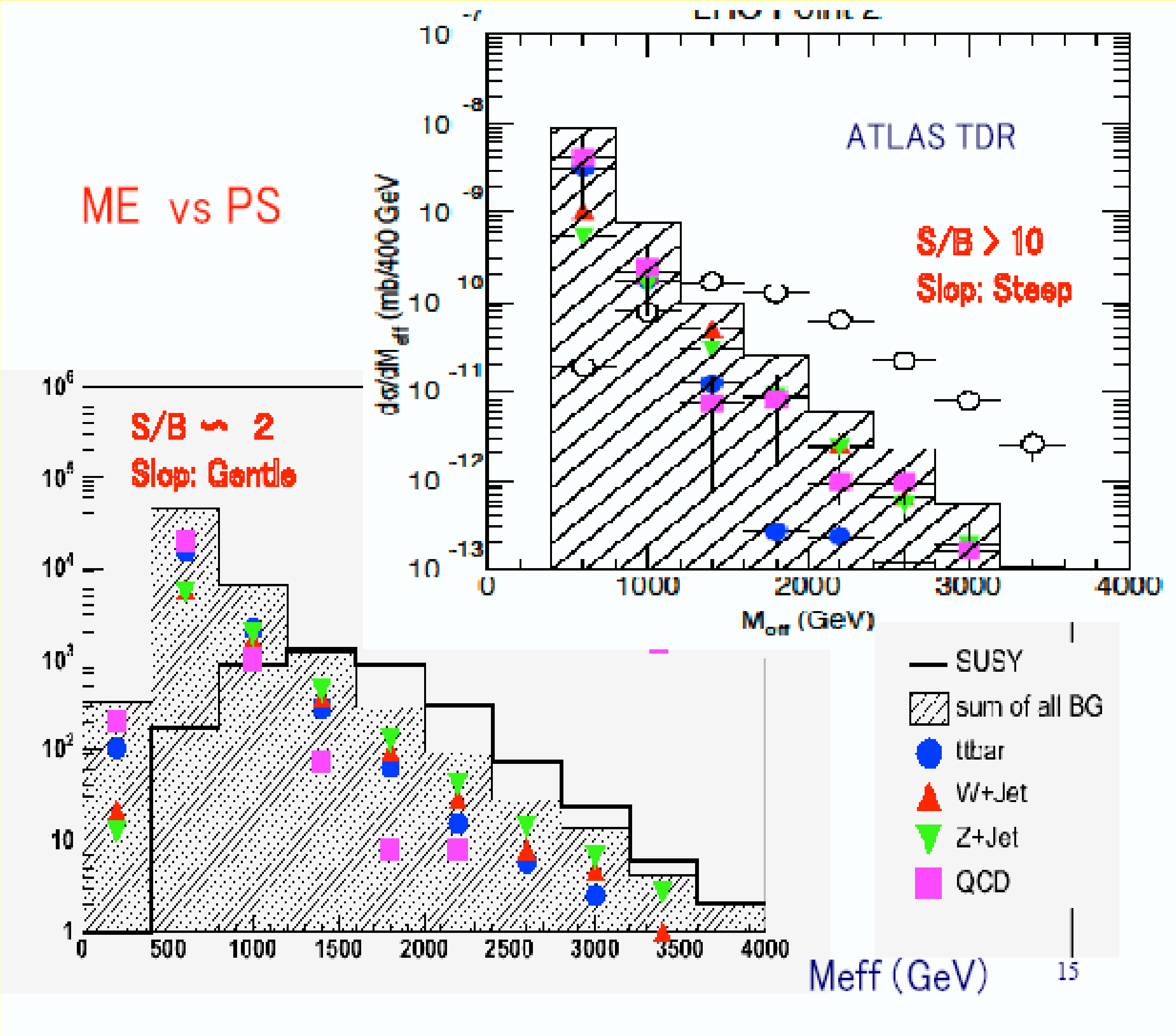
Will determine gluino/squark masses to $\sim 15\%$



Sensitivity



How robust is it?



May lower reach slightly

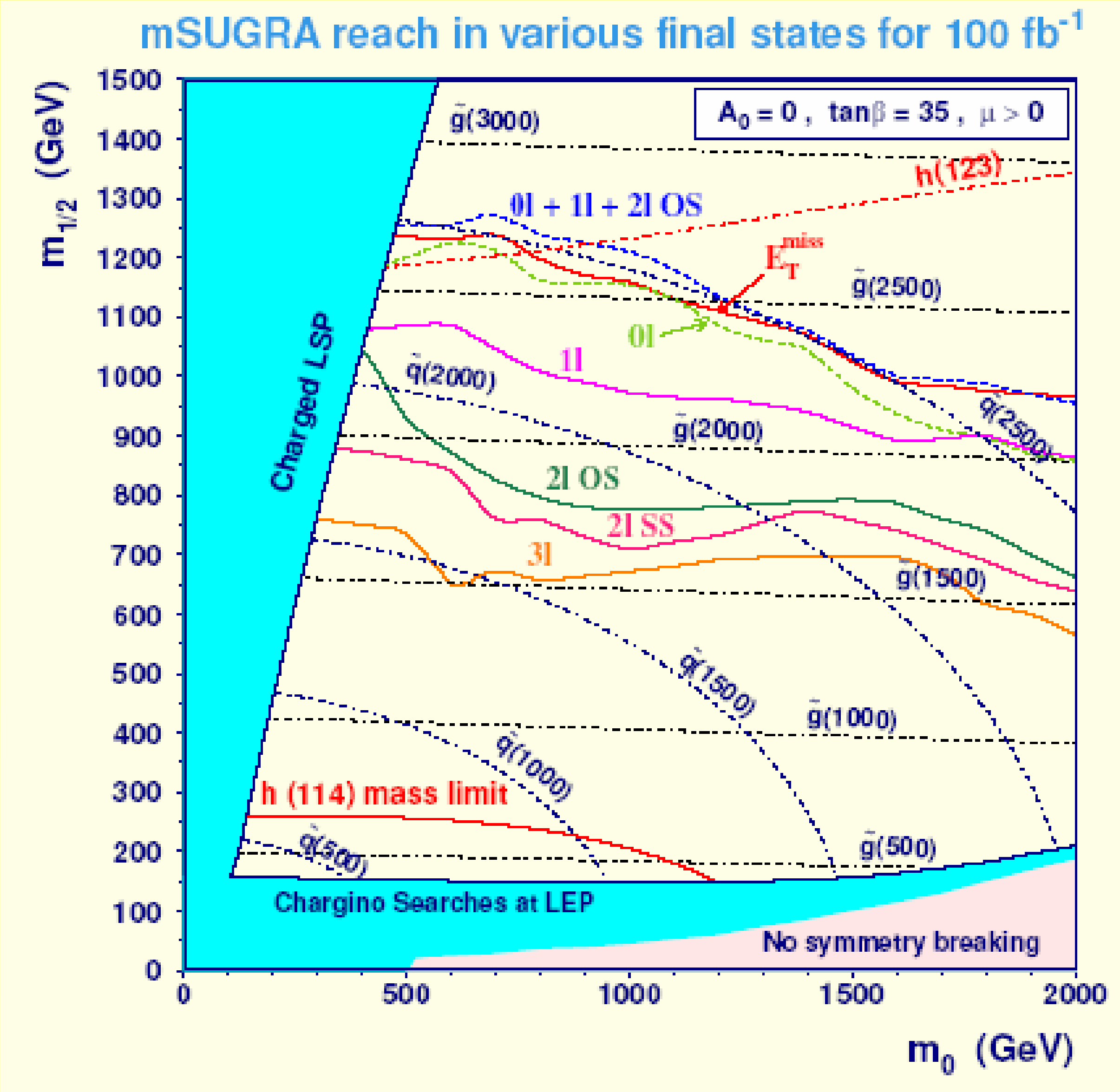
Plot shows all jet state

Signal in Lepton+jets+miss

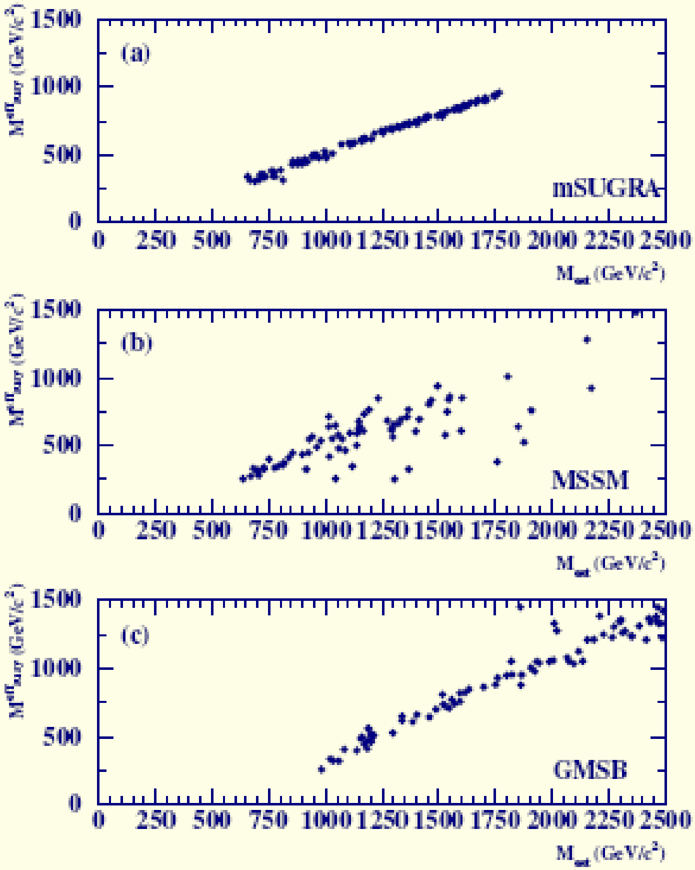
is more robust

Include leptons for robustness

CMS



Measurement of "M_{SUSY}"



Model	Var	x	σ	σ/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

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

“Quasi” exclusive analysis

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

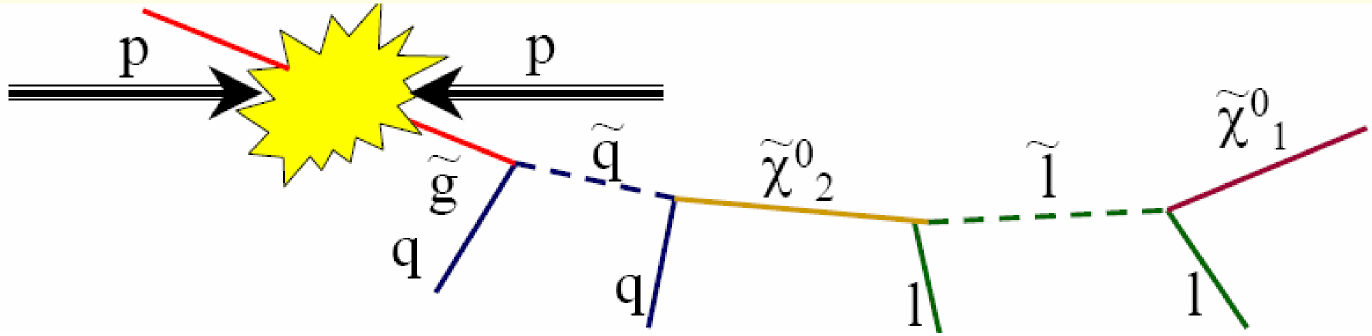
$\chi_2^0 \rightarrow \chi_1^0 h$ or

$\chi_2^0 \rightarrow \chi_1^0 \ell^+ \ell^-$ 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

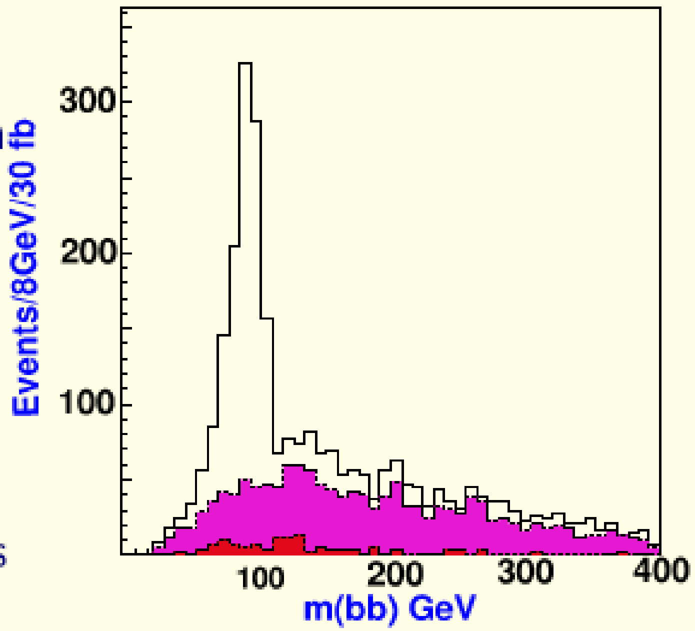
Many SUSY particles can then be identified by adding more jets/leptons



Decays to Higgs boson

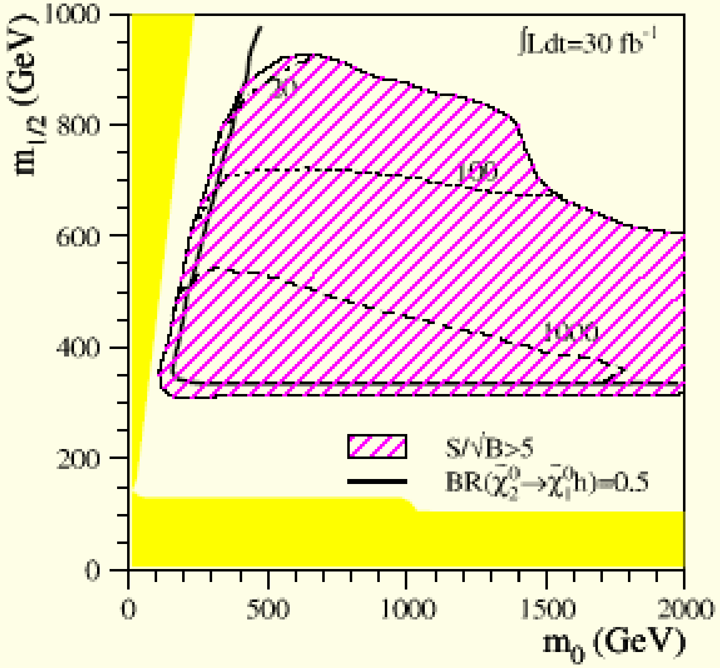
If $\chi_2^0 \to \chi_1^0 h$ exists then this final state followed by $h \to b\bar{b}$ results in discovery of Higgs at LHC.
In these cases $\sim 20\%$ of SUSY events contain $h \to b\bar{b}$

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
Dominant background is other SUSY decays



Decays to Higgs boson (2)

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 $m_{1/2}$



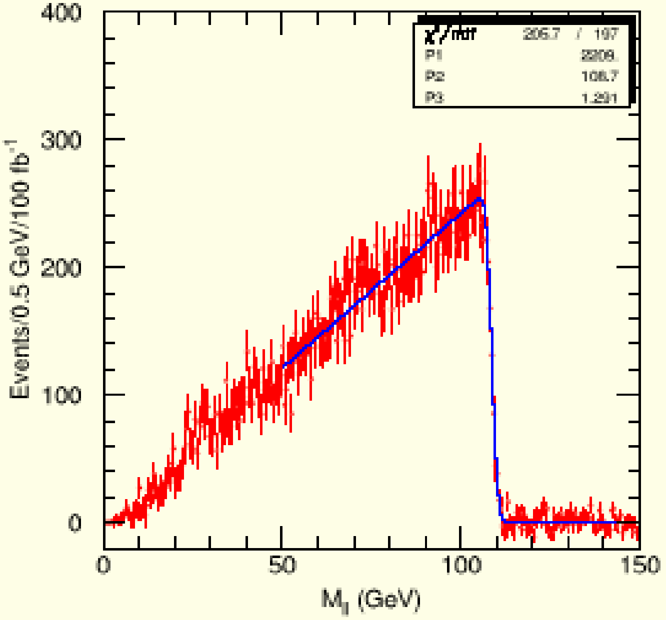
Over rest of parameter space, leptons are the key...

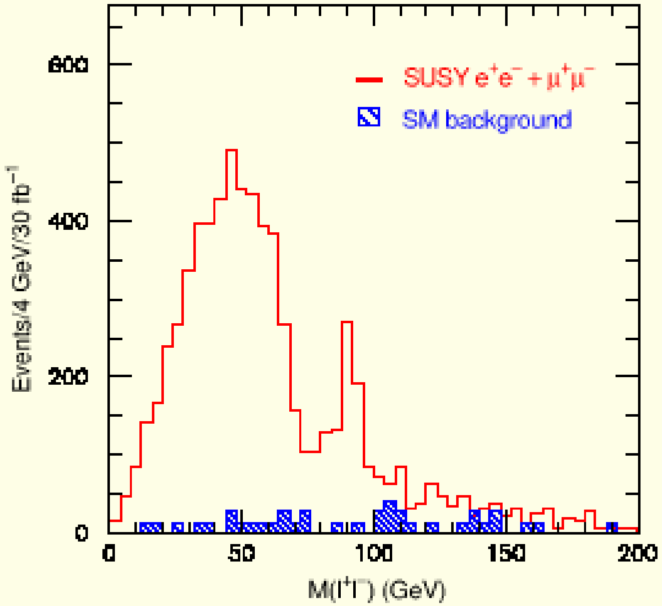
Decays to leptons

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

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

Mass of opposite sign same flavor leptons is constrained by decay





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

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

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

and Z from other SUSY particles

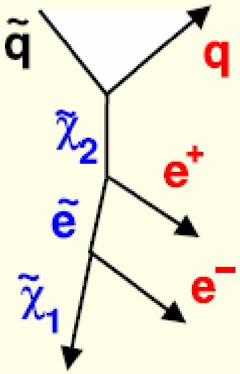
$$M_{\ell\ell}^{\max} = \sqrt{\frac{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}}^2)(M_{\tilde{\ell}}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{\ell}}^2}}$$

$$M_{\ell\ell}^{\max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$$

$\Rightarrow$ Information on neutralinos and slepton masses

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

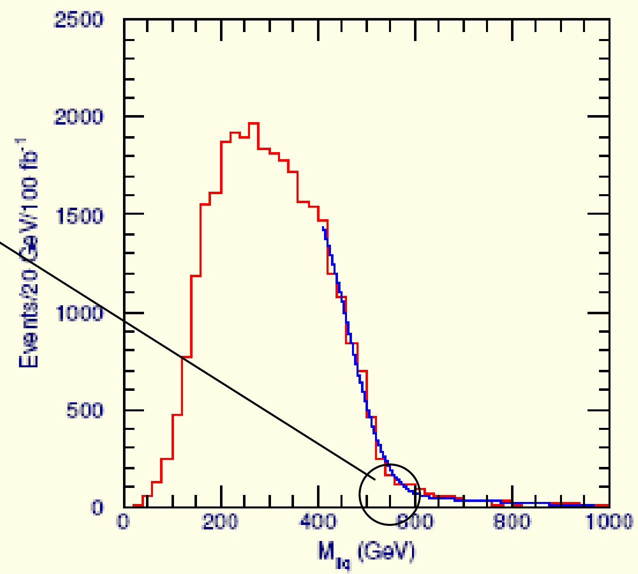
Mass of $q\ell\ell$ system has max at

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

Take 2 hardest jets in event

Choose the one that gives the smallest $\ell\ell q$ mass

Plot the $M_{\ell\ell q}$ mass and look for maximum



⇒ Information on neutralinos and squark masses

"Model independent" mass fits

- Combine measurements from edges from different jet/lepton combinations to obtain 'model independent' mass measurements.
- Example of precision in one of the points

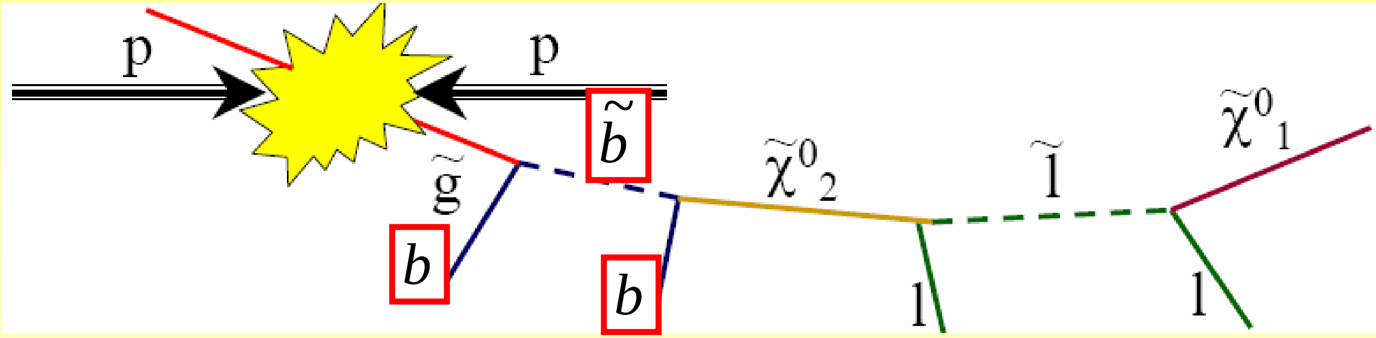
Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	$\pm$ 3%
$\tilde{\chi}^0_2$	$\pm$ 6%
$\tilde{l}_R$	$\pm$ 9%
$\tilde{\chi}^0_1$	$\pm$ 12%

Keep going up the chain ...

... to get to gluino

- using for example sbottom

  require identify b-jets



- or reconstructed top quarks ...

Decay chains like $\tilde{g}$ -> $t\ \tilde{t}_1$ -> $t\ b\ \tilde{\chi}^{\pm}_j$

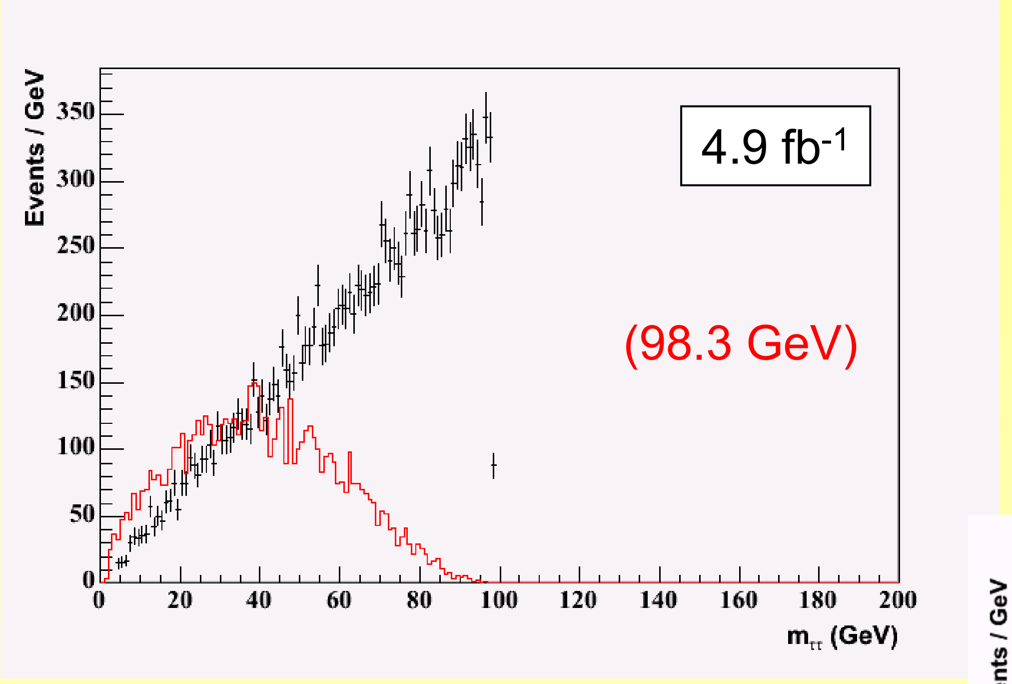
What about Tau leptons?

- Tau signatures are important in much of the mSUGRA parameter space, particularly at high tanβ
- At some points in the parameter space (e.g. funnel) can only observe kinematic endpoints in τ invariant mass distributions
- Taus provide independent information even if lepton signatures are available
- Tau ID is much harder than electron or muon ID, particularly for soft taus (e.g. co-annihilation point)

  $\Rightarrow$ typically achieve τ/jet $\sim$ 100 for a tau reconstruction efficiency of 50%

- measure $m_{\tau\tau}$ from visible decay products

End points with Tau leptons



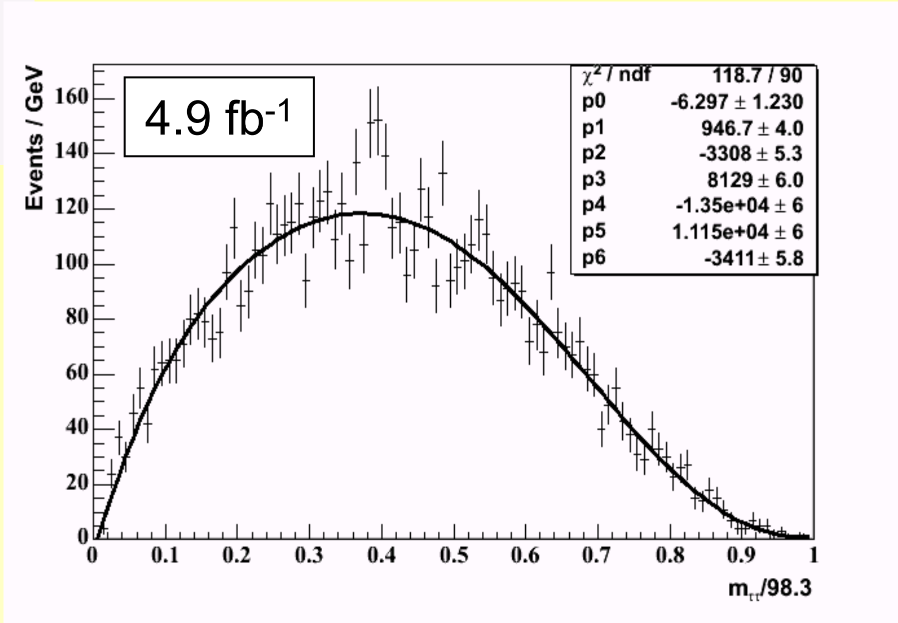
- Black points: MC truth

⇒ note the triangular shape

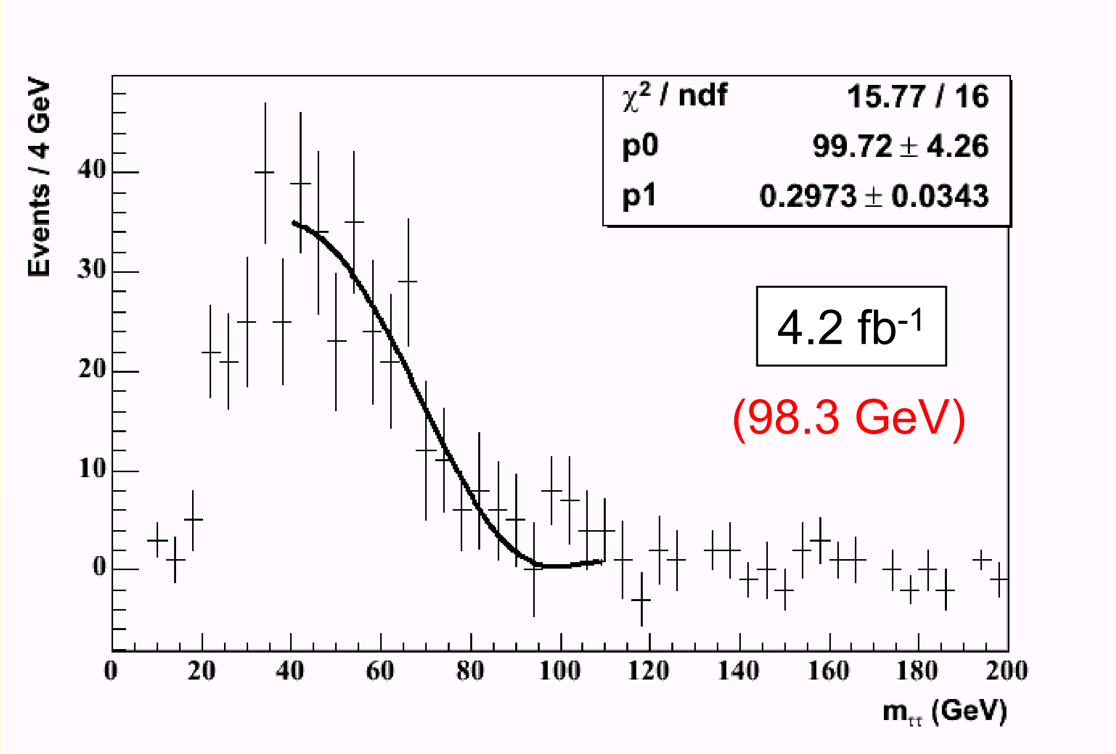
- Red line: distribution from the non-leptonic decay products

⇒ (distorted shape)

- Can fit this distorted distribution with, for example, a polynomial (see right)



End points with Tau leptons (2)



- Can take MC fit and apply it to the reconstructed distribution
- Have fitted the background subtracted distribution using the width and normalisation as parameters

- End points with Taus can be fitted, but loss of precision ...

Right squarks

Right handed squarks difficult as rarely decay via 'standard' $\tilde{\chi}^0{}_2$ chain

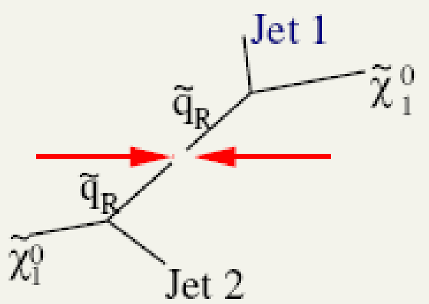
- **Typically BR ($\tilde{q}_R \rightarrow \tilde{\chi}^0{}_1 q$) > 99%.**

s-tranverse mass. Definition

- Select Events:

  $pp \rightarrow X + \tilde{q}_R \tilde{q}_R \rightarrow X + q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$

  - 2 Jets with P_T >200GeV
  - Δ(j1-j2)>1
  - Missing E_T >400GeV

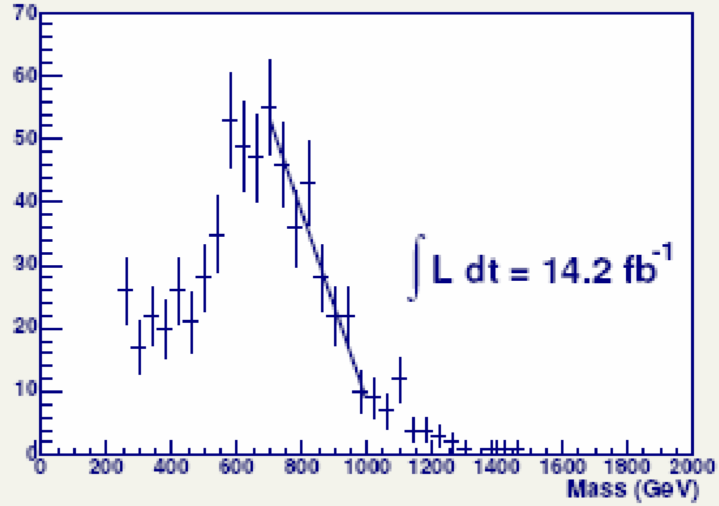


- Partition $\vec{\not{E}}_T = \vec{\not{E}}_{T,1} + \vec{\not{E}}_{T,2}$ in all possible ways and compute:

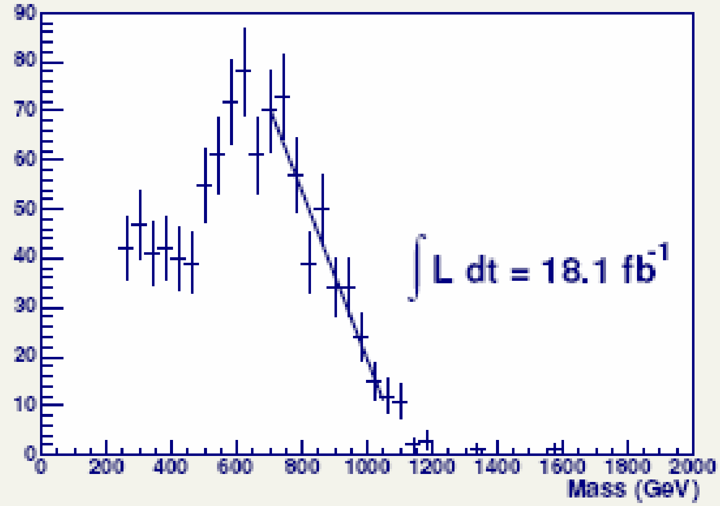
$$M_T^2 = \min_{\not{E}_{T,1}, \not{E}_{T,2}} \left[\max\{ m_T^2(P_{T,j1}, \not{E}_{T,1}, M_{\tilde{\chi}_1^0}), m_T^2(P_{T,j2}, \not{E}_{T,2}, M_{\tilde{\chi}_1^0}) \} \right]$$

- M_T^2 depends on the choice of $M(\tilde{\chi}_1^0)$

Right squarks (2)



From the fit: $M(\tilde{q}_R) = 1056 \pm 181$GeV
Generator: $M(\tilde{q}_R) = 1190$GeV



From the fit: $M(\tilde{q}_R) = 1113 \pm 164$GeV
Generator: $M(\tilde{q}_R) = 1210$GeV

here, use true $\tilde{\chi}_0^1$ mass

Worse when using $\tilde{\chi}_0^1$ obtained from dilepton analysis

SUSY - Summary

Analyses to date have concentrated on first steps in analysis:

- Observe signal over SM background.
- Identify specific decay chains and use kinematic properties like endpoints to determine masses.

Much more potential information from rates, branching ratios, and event properties. Requires understanding of acceptance corrections in complex events.

Eventual goal is to reconstruct weak-scale SUSY breaking Lagrangian. Then extrapolate to high scale with RGE to understand SUSY breaking mechanism. Highly non-trivial task.

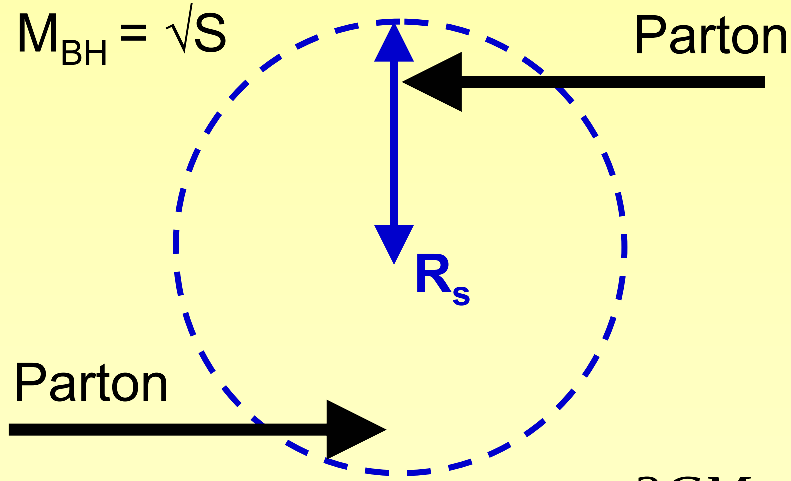
Some examples of different physics

If M_{pl} ~ O(1 TeV) → Black Hole Production possible at LHC

N.Arkani-Hamed, S. Dimopoulos and G.R.Dvali [hep-ph/9803315]
S.Dimopoulos and G. Landsberg [hep-ph/0106295]

- $\sigma \sim \pi R_S^2 \sim O(100)$pb
- LHC → Black Hole Factory
- BH lifetime ~ $10^{-27} - 10^{-25}$ sec
- Decays with equal probability to all particles via Hawking Radiation

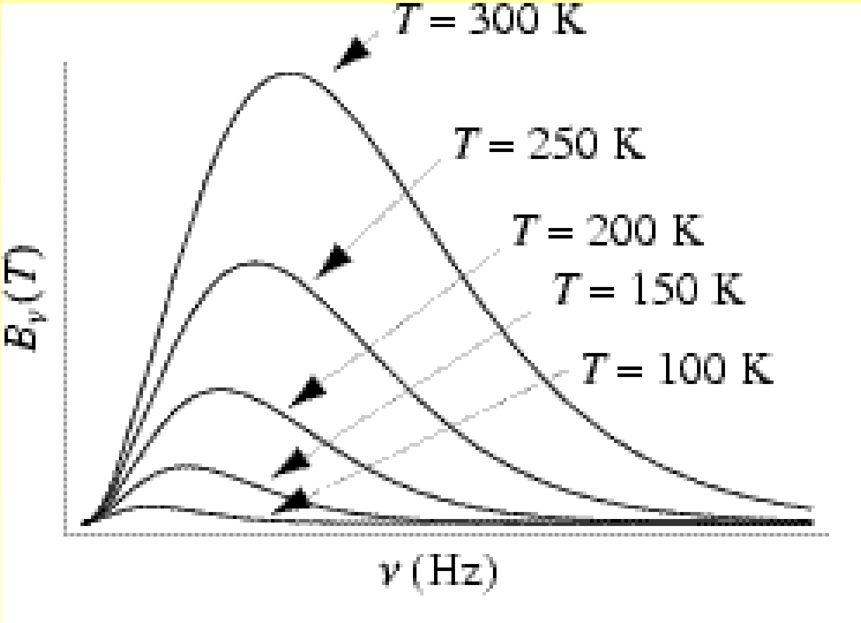
Large theoritical uncertainties
... still quite speculative



Rs = Schwarzschild radius $= \frac{2GM_{BH}}{c^2}$

Black Hole decay

- Decay via Hawking Radiation
- Emit particles following an approximately black body thermal spectrum



$$T_H = \frac{1+n}{4\pi \cdot R_{BH}} \approx \frac{1+n}{M_{BH}^{1/(1+n)}}$$

n = number of extra dimensions

- Spectrum modified by Grey Body factors
- Black Hole might not maintain Thermal equilibrium

- Astronomic BH -- **COLD** -- No Evaporation
- Micro BH -- **HOT** -- Evaporation

Black Hole event in ATLAS

BH evaporates into

(q and g : leptons : Z and W : ν and G : H) = (72%:11%:8%:6%:2%:1%)

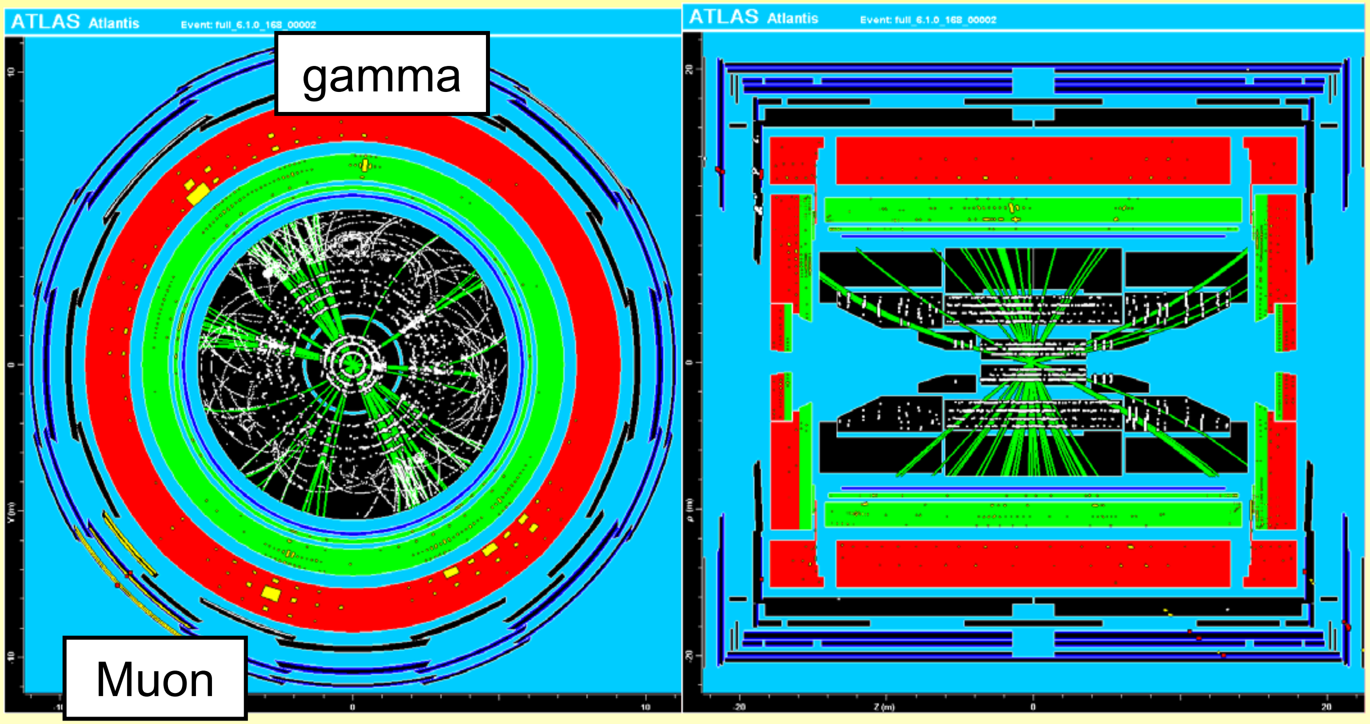
(hadron : lepton) is (5 : 1) accounting for t, W, Z and H decays

S.B. Giddings, S. Thomas, Phys.Rev.D65(2002)056010

Decay of 6.1 TeV Black Hole

High multiplicity events

small missing E_T

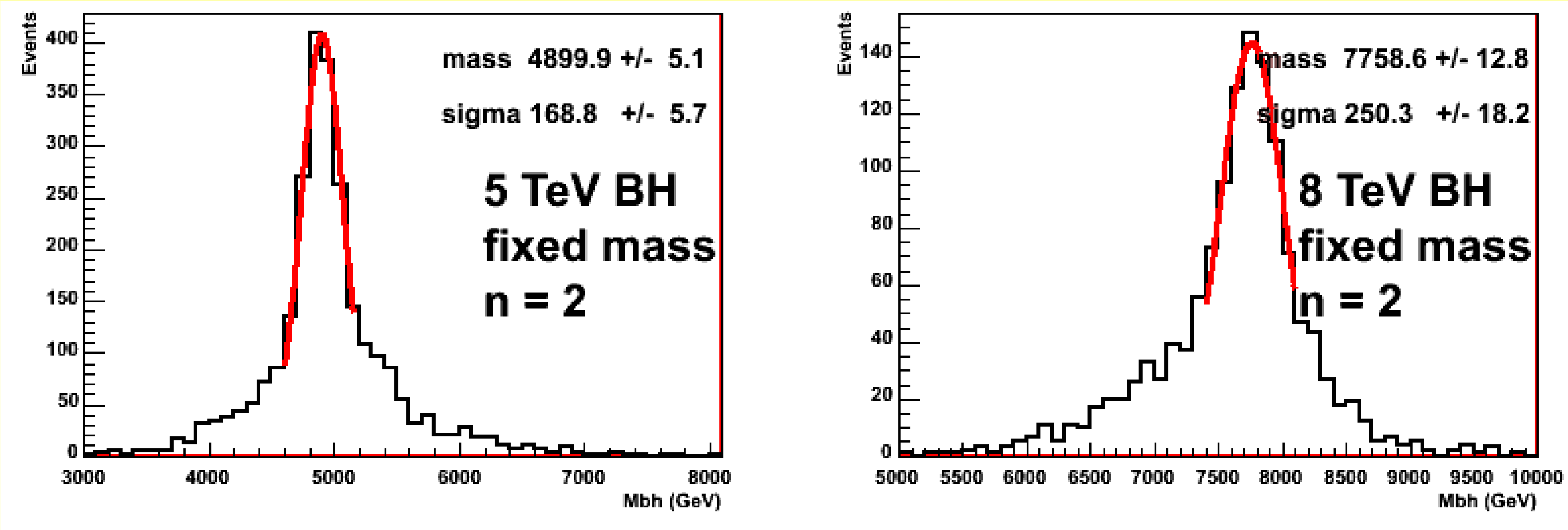


Reconstruction of black holes

Mass Reconstructed by summing 4-momenta of all decay products

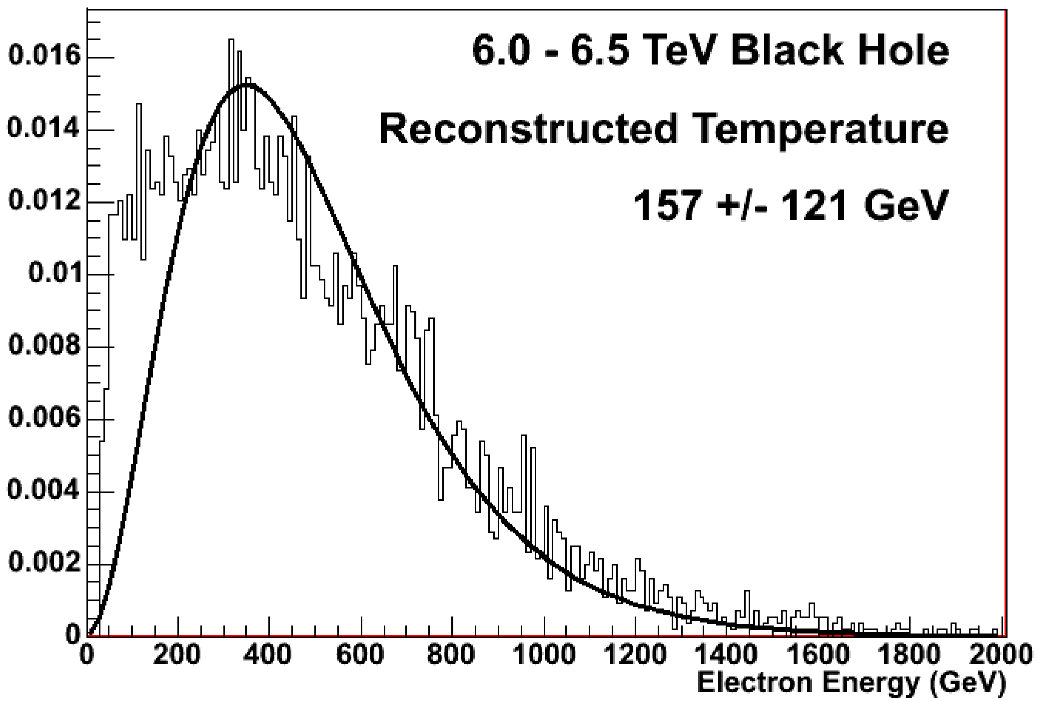
The following cuts were applied:

- Minimum of 4 jets
- PT of 3 leading jets > 500, 400, 300 GeV respectively
- Missing E_T < 100 GeV
- Eta < 2.5



Measuring temperature

Temperature reconstructed by fitting black body spectrum to electron energy distribution

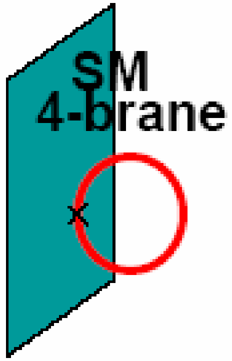


Problems

- Electrons are boosted by Black hole recoil
- Electrons are not all from the event horizon (secondaries)
- Theoretical uncertainties over Temperature variation during decay

Extra Dimensions

- M-theory/Strings → compactified Extra Dimensions (EDs)
- Q: Why is gravity weak compared to gauge fields (hierarchy)?
- A: It isn't, but gravity 'leaks' into EDs.
- Possibility of Quantum Gravity effects at TeV scale colliders!
- Variety of ED models studied (a few examples follow):

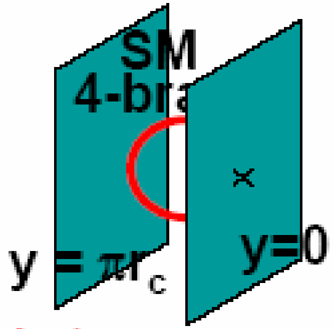


Large (>> TeV^{-1})

- Only gravity propagates in the EDs, $M^{eff}_{Planck} \sim M_{weak}$
- Signature: Direct or virtual production of Gravitons

TeV^{-1}

- SM gauge fields also propagate in EDs
- Signature: 4D Kaluza-Klein excitations of gauge fields



Warped

- Warped metric with 1 ED
- $M^{eff}_{Planck} \sim M_{weak}$
- Signature: 4D KK excitations of Graviton (also Radion scalar)

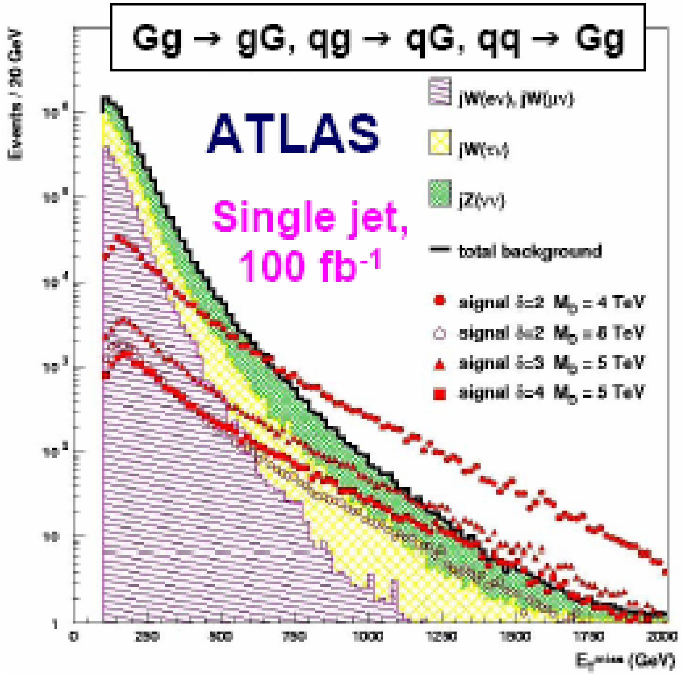
Large Extra dimensions (>> TeV^{-1})

Antoniadis, Benakli and Quiros, PLB331 (1994) 313; Arkani-Hamed, Dimopoulos and Dvali, PLB429 (1998) 263

- **With δ EDs of size R, observed Newton constant related to fundamental scale of gravity M_D:**

$$G_N^{-1} = 8\pi R^{\delta} M_D^{2+\delta}$$

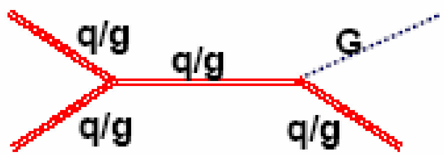
- **Search for direct graviton production in jet(γ) + E_T^{miss} channel.**



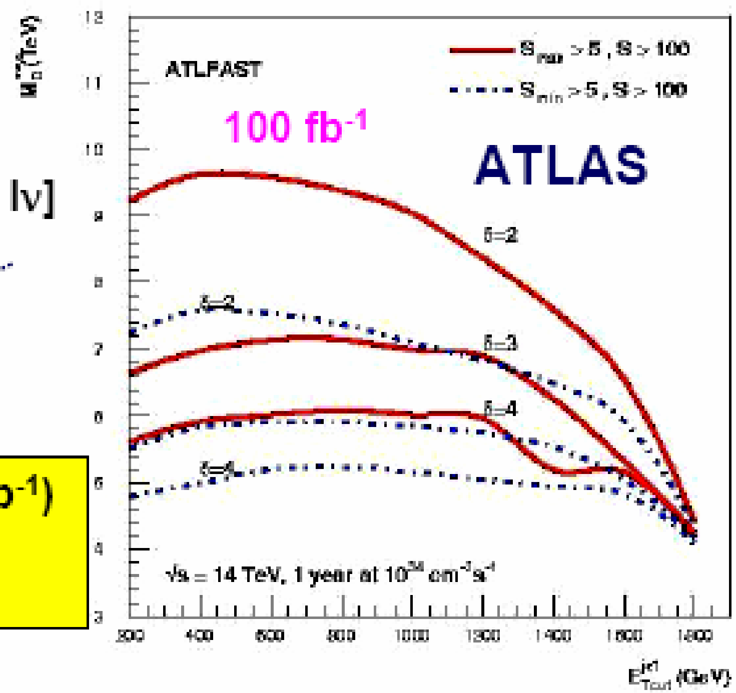
Signal : graviton + 1 jet production

Main background:

Jet + Z(W) [$Z \to \nu\nu$, $W \to l\nu$]



M_D^{max} (E_T>1 TeV, 100 fb^{-1})
= 9.1, 7.0, 6.0 TeV
for δ=2,3,4



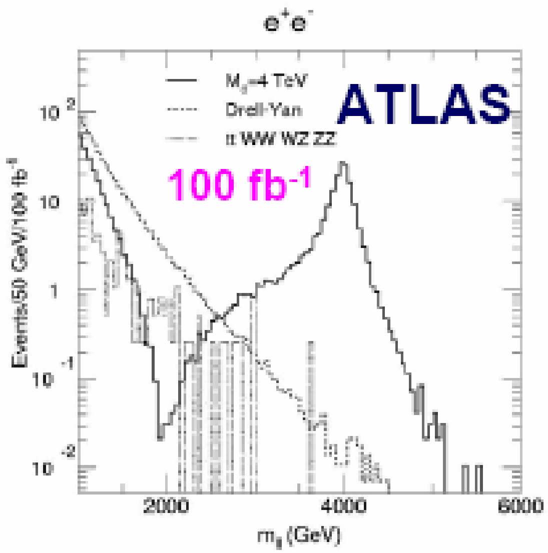
TeV^{-1} scale Extra Dimensions

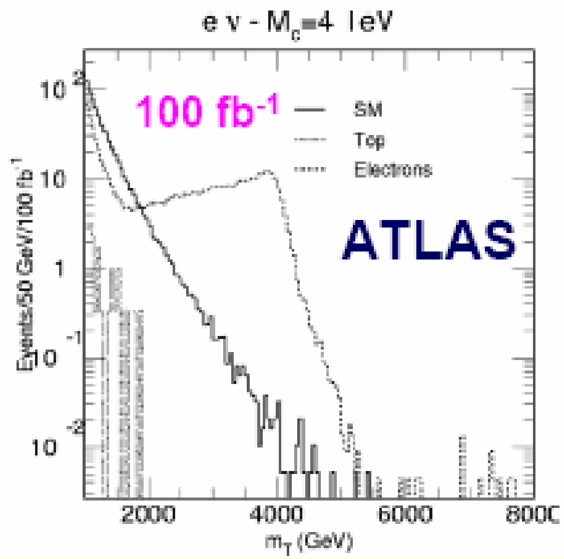
- Usual 4D + small (TeV^{-1}) EDs + large EDs (>> TeV^{-1})
- SM fermions on 3-brane, SM gauge bosons on 4D+small EDs, gravitons everywhere.
- 4D Kaluza-Klein excitations of SM gauge bosons (here assume 1 small ED).
- Masses of KK modes given by:

$$M_n^2=(nM_c)^2+M_0^2$$

  for compactification scale M_c and SM mass M_0
- Look for l^+l^- decays of γ and Z^0 KK modes.
- Also $l\nu$ decays (m_T) of $W^{+/-}$ KK modes.

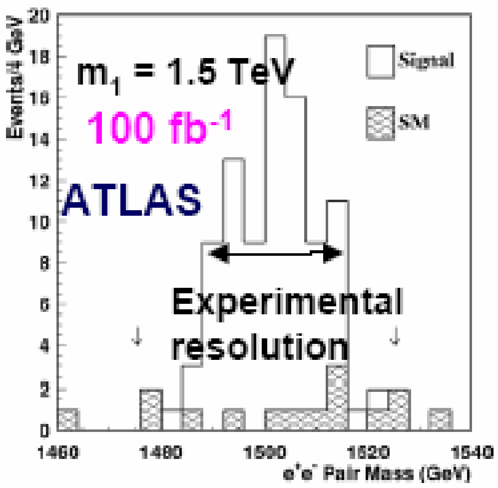
> - 5σ reach for 100 fb^{-1} ~ 5.8 TeV (Z/γ)
>   ~ 6 TeV (W)
> - For 300 fb^{-1} l^+l^- peak detected if M_c < 13.5 TeV (95% CL).

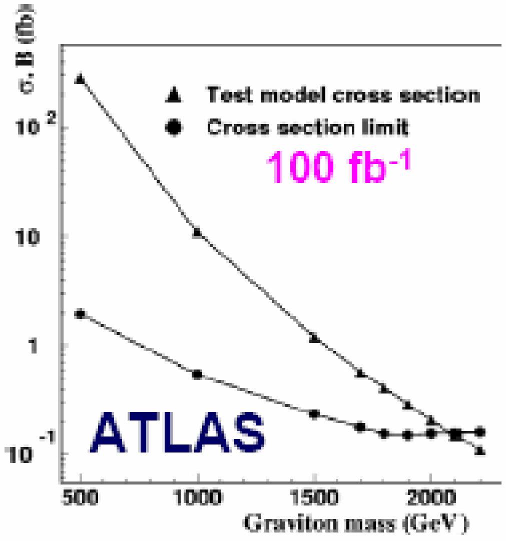


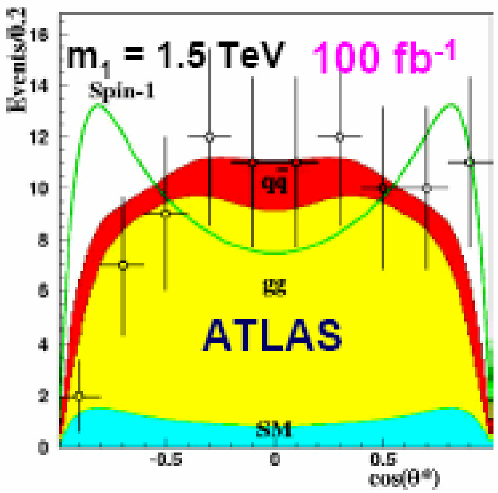


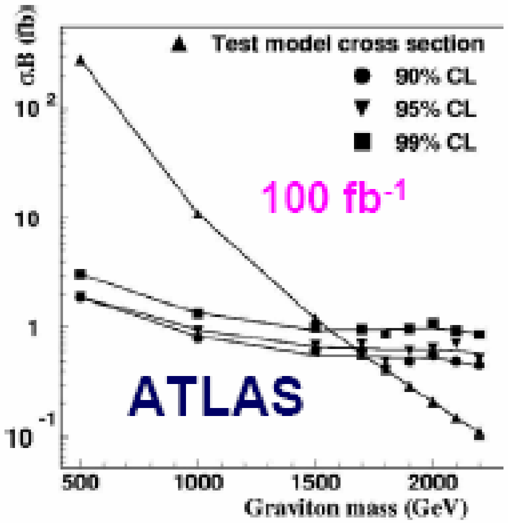
Warped Extra Dimensions

- Search for gg(qq) → $G^{(1)}$ → e^+e^-. Study using test model with k/M_{Pl}=0.01 (narrow resonance).
- Signal seen for mass in range [0.5,2.08] TeV for k/M_{Pl}=0.01.
- Measure spin (distinguish from Z') using polar angle distribution of e^+e^-.
- Measure shape with likelihood technique.
- Can distinguish spin 2 vs. spin 1 at 90% CL for mass up to 1.72 TeV.









Conclusion

- **Much work on Beyond the Standard Model Physics being carried out by both ATLAS and CMS.**
- **Lots of input from both theorists and experimentalists**
- **LHC and detector performance should in general give access to energy scales ~ a few TeV.**
- **Different phenomenology for different models**
  - **first discovery of signals beyond SM**
  - **then try to identify what is the physics and constraint the theory**
- **Depending on the physics it may be more or less easy but in general all the "power" of the detector will be needed**
- **Get to best performance of such large complex detectors will not be easy and will need an "army" of people**

Back-up slides

Beyond SM - Problem

- How do you think one can measure the efficiency of b-jet tagging with LHC data?

  Think of standard mode process copiously produced ...

Beyond SM - Problem

- How to distinguish between black hole production and SUSY

  many jets, leptons, missing ET

Little Higgs Model (2001)

(see hep-ph/0301040)

- Quadratic divergences

bosons ⟷ new fermions
cancellations
fermions ⟷ new bosons

Supersymmetry

Little Higgs

bosons ⟷ new bosons
cancellations
quark t ⟷ new quark t

- Symmetries and pseudo-Goldstone bosons

	big scale		electroweak scale
global symmetry	SU(5)	symmetry breaking →	SO(5)
local symmetry			$SU(2)_L \times U(1)_Y$

Goldstone bosons massless → electroweak symmetry breaking → pseudo-Goldstone bosons "light" mass

- To note

effective model up to Λ=10 TeV, compatible with experimental constraints

New particules

- Heavy gauge bosons

Z_H W_H A_H

- Heavy quark top

T

- Heavy Higgses

ϕ^0 ϕ^+ ϕ^{++}

NB : SM Higgs remains with the same properties (BR ...)

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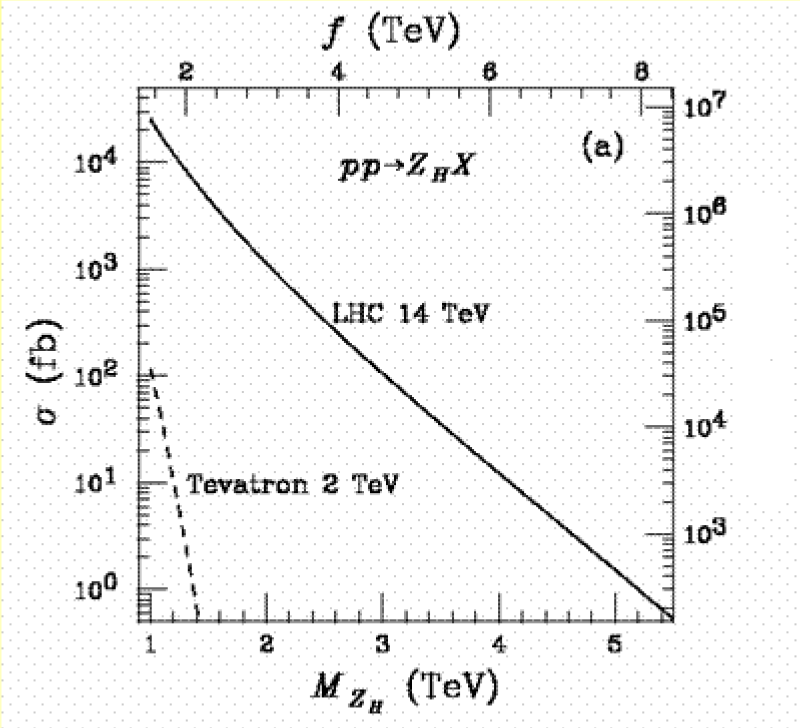
Beyond SM - Problem

- Heavy Gauge Bosons $Z_H \rightarrow$ Z H and $W_H \rightarrow$ W H



background:

tt,WZ,ZZ

- **Heavy Top=1000 GeV, Higgs=120 GeV, 200 fb**
  Higgs→bb
- **Φ++→W+W+ produced by Vector Boson Fusion mechanism WWqq,WZ,WZqq,Wtt Mass~few TeV**