Beyond Standard Model with ATLAS at LHC

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Outline

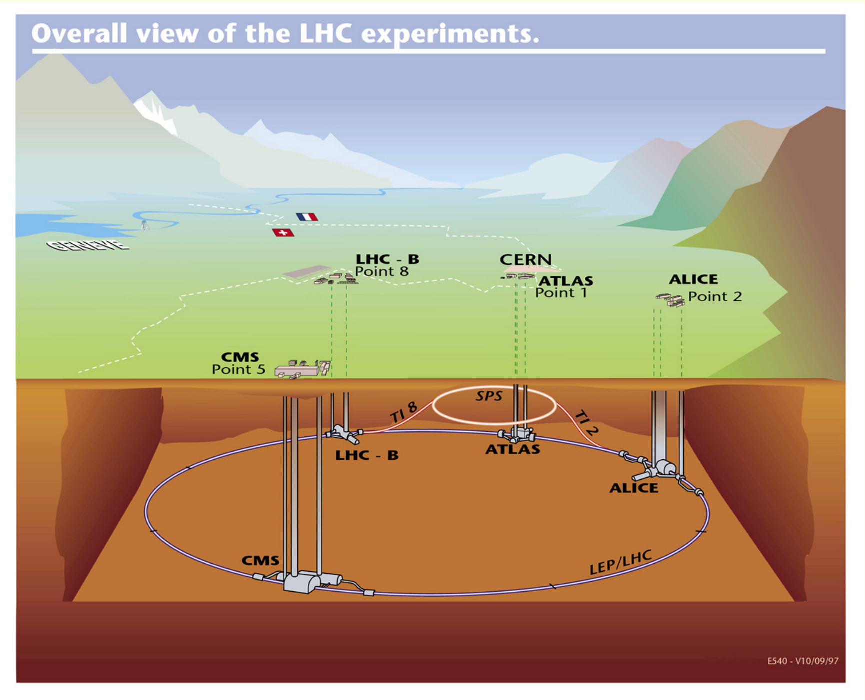
- LHC status
- ATLAS status
- Physics topics
  - SUSY
  - Extra Dimensions
  - Little Higgs Models

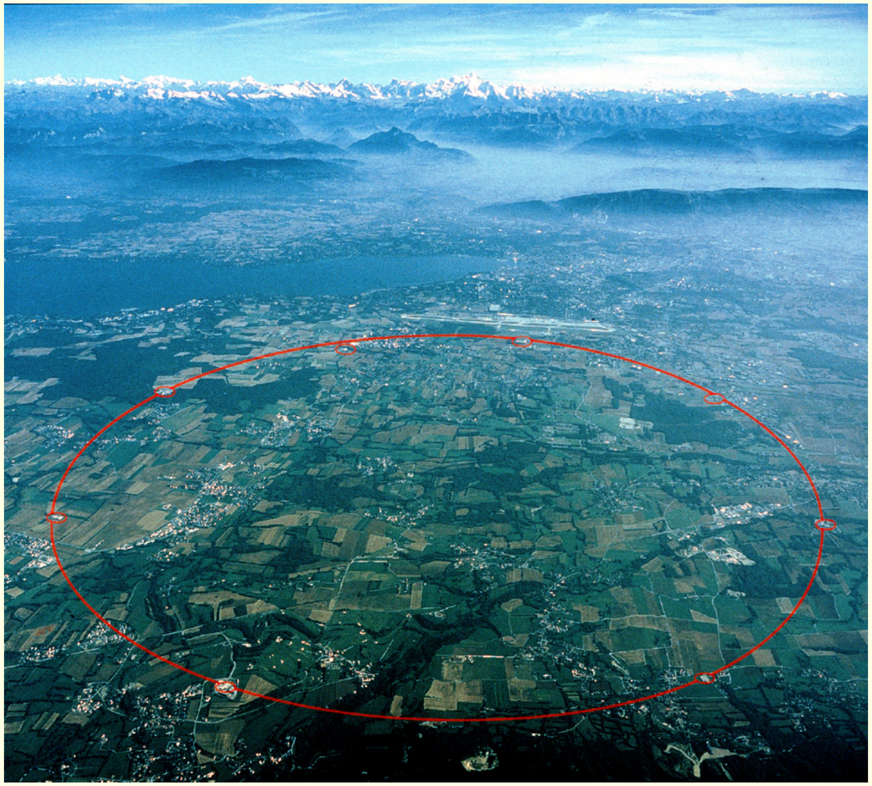
Many physics studies concentrate on "ultimate" goals.

I will give an indication of what might happen quickly

LHC Status and Schedule

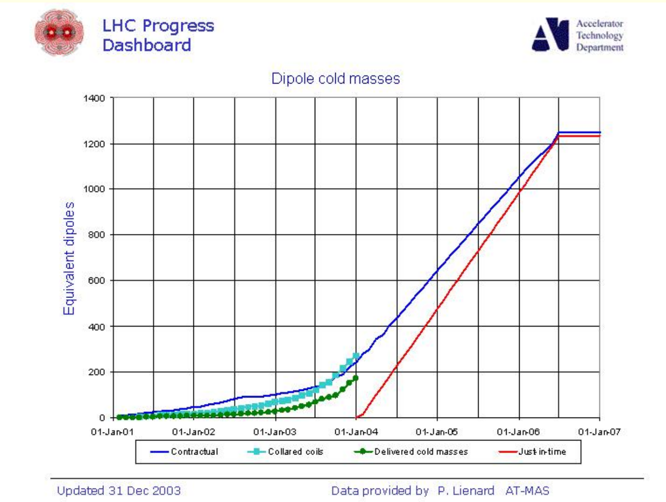
"Overall, the project's cost is stable and its schedule unchanged, foreseeing first beam in April 2007 with first collisions following in June." L. Maiani Dec 19 2003.

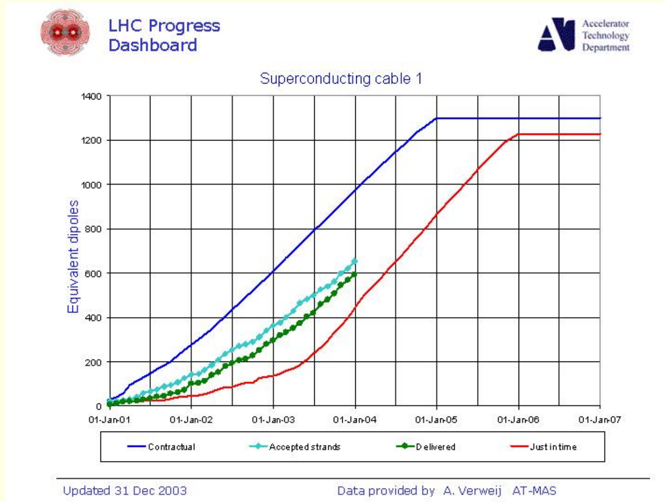


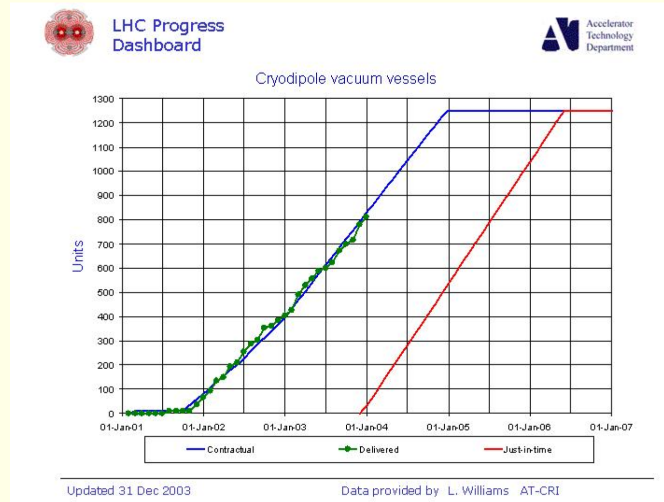


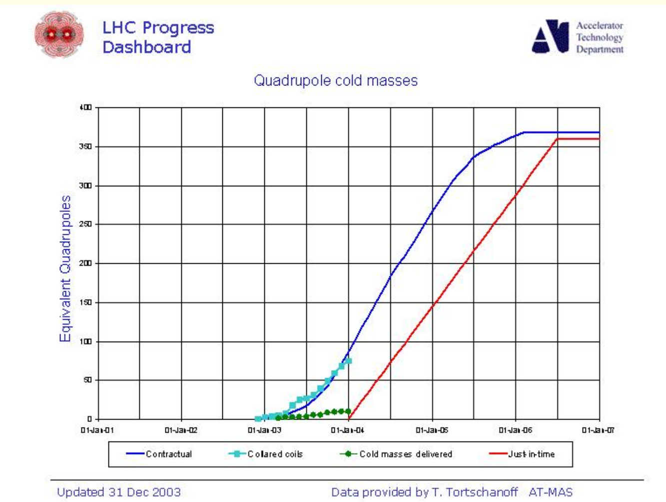
Status is updated monthly at

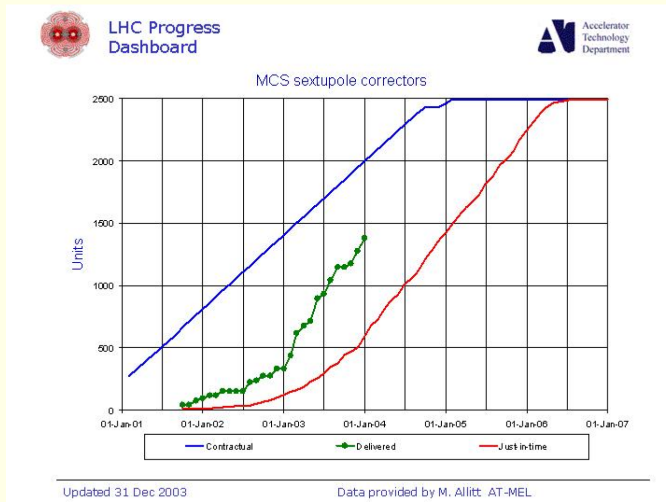
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/DashBoard/index.as

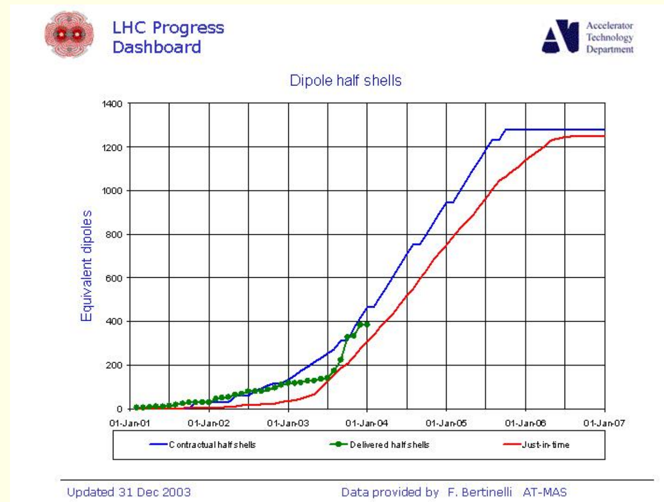




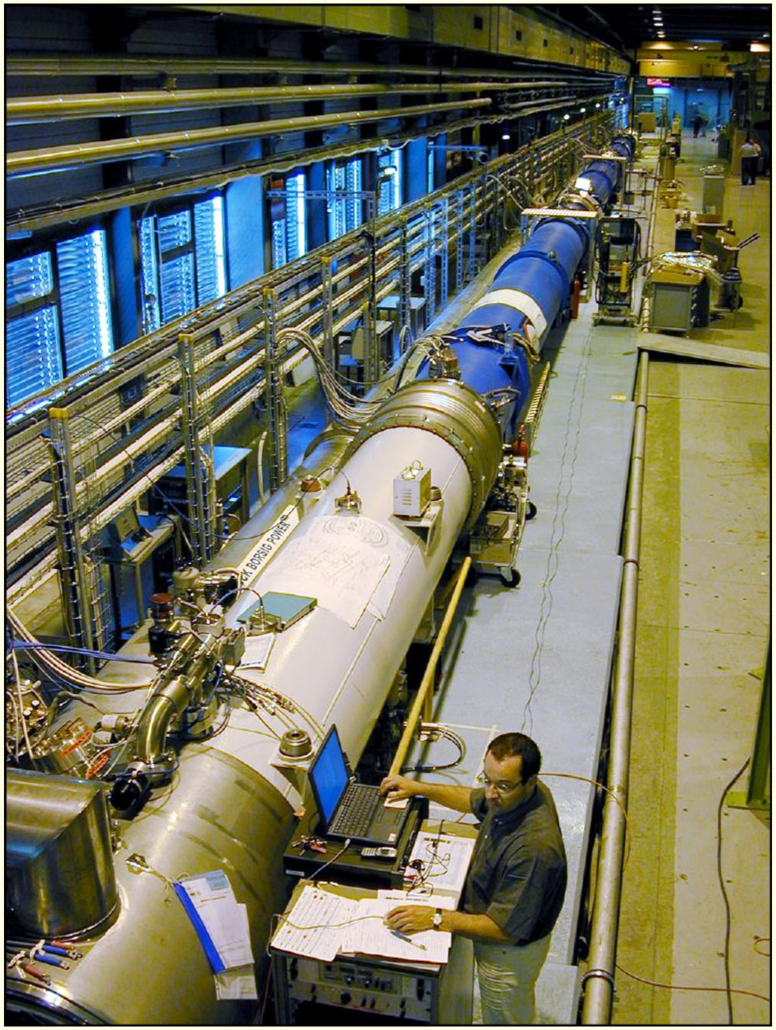








First magnet installed into transfer line December 2003



String Test 2001

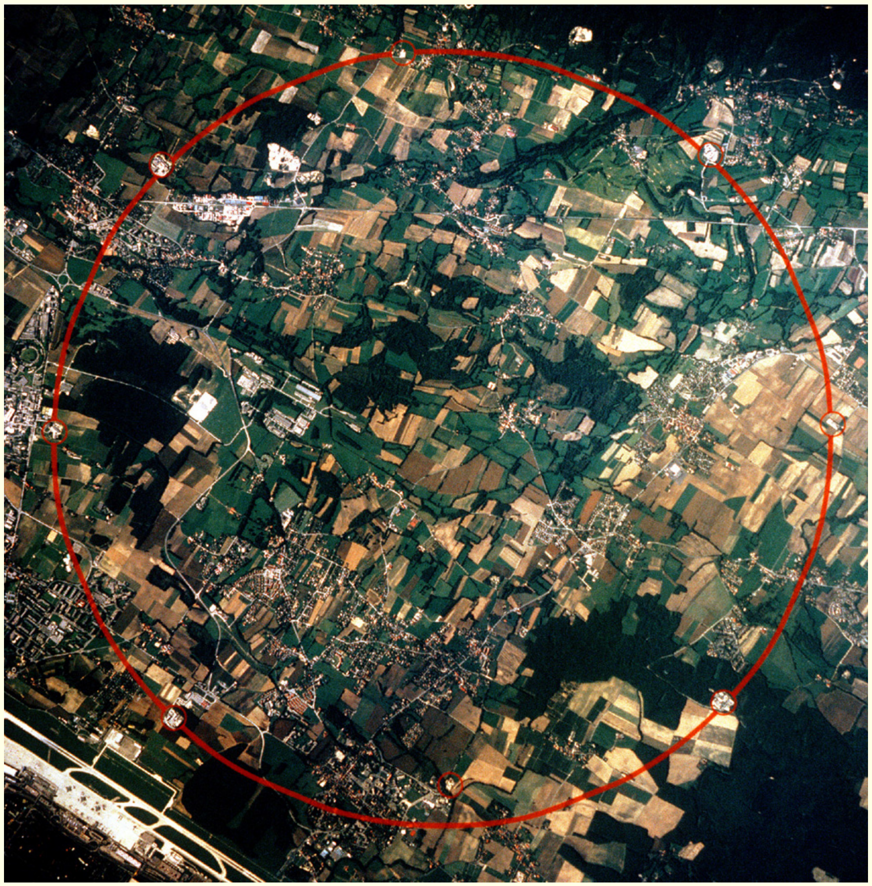
Transfer magnets awaiting installation

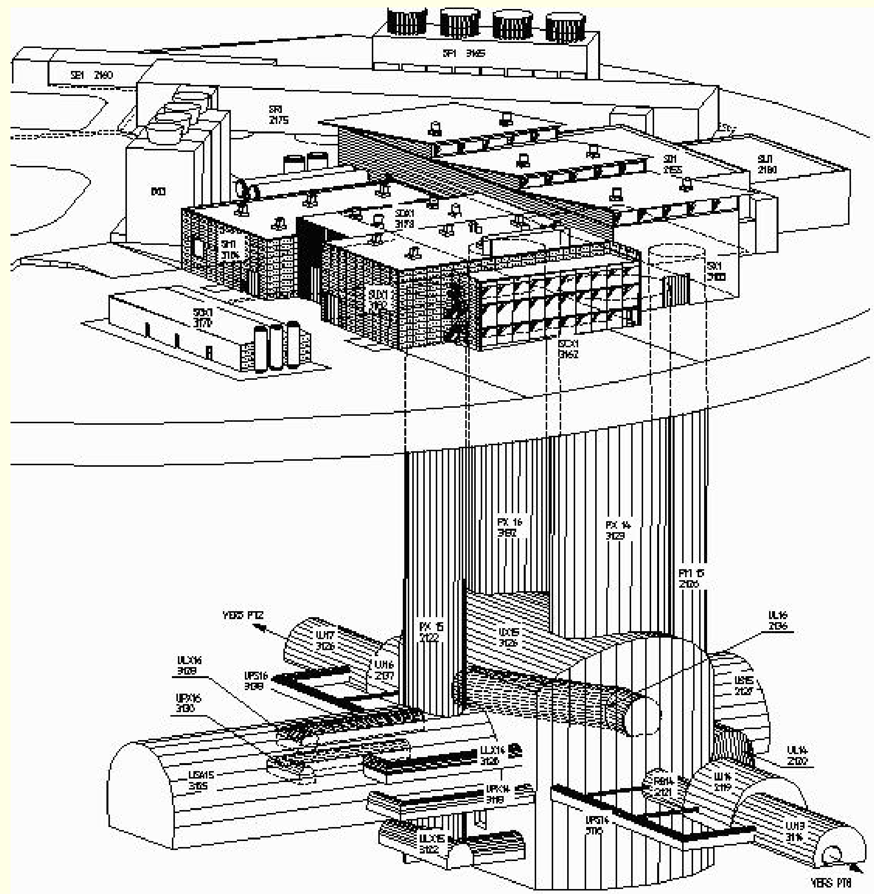
LHC operation

- Single Beam operation – April 2007
- Collisions – June 2007
- Operation in "low luminosity mode" for 3 years 2×10^{33} cm^{-2} sec^{-1}
- 1 month per year of heavy ion running.
- Full luminosity in ~ 2010 10^{34} cm^{-2} sec^{-1}, multiple interactions per crossing cause some degradation in performance $e.g.$ b-tagging.
- Some ATLAS elements have been staged and will not be available at turn-on. Middle layer of pixels, some muon chambers, little impact at low luminosity.
- Trigger/DAQ staging means less rate – impacts $b-$physics: Could be restored with extra funding.

Atlas–Buildings and location

Surface building – across street from CERN main gate

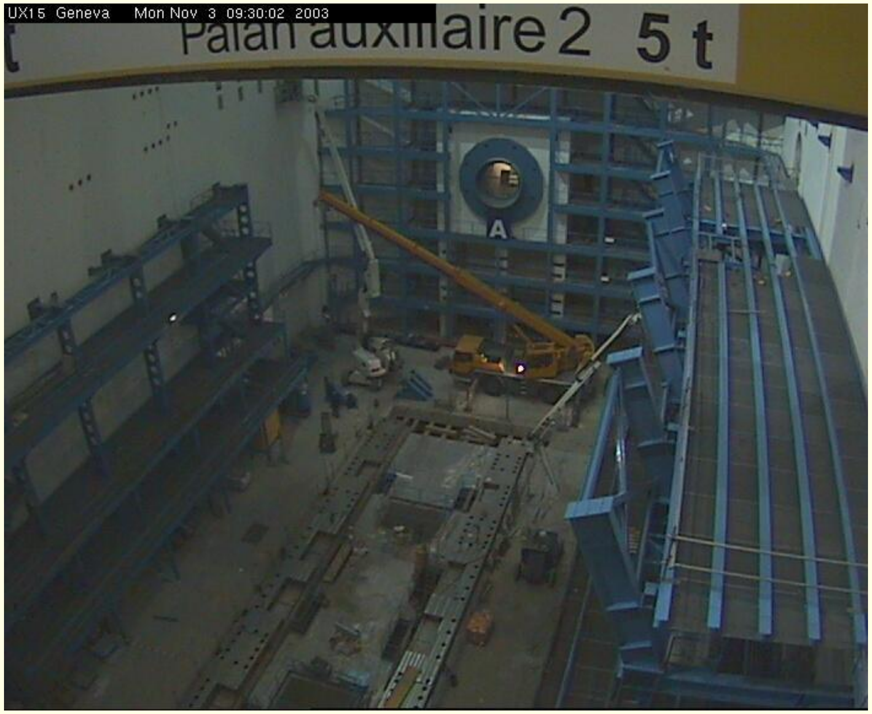




Above


Chemin de Bel-Horizon

Below


UX15 Geneva Mon Nov 3 09:30:02 2003
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Last weeks photos

LHC Beam is at A and C

In the center is the support structure for the detector

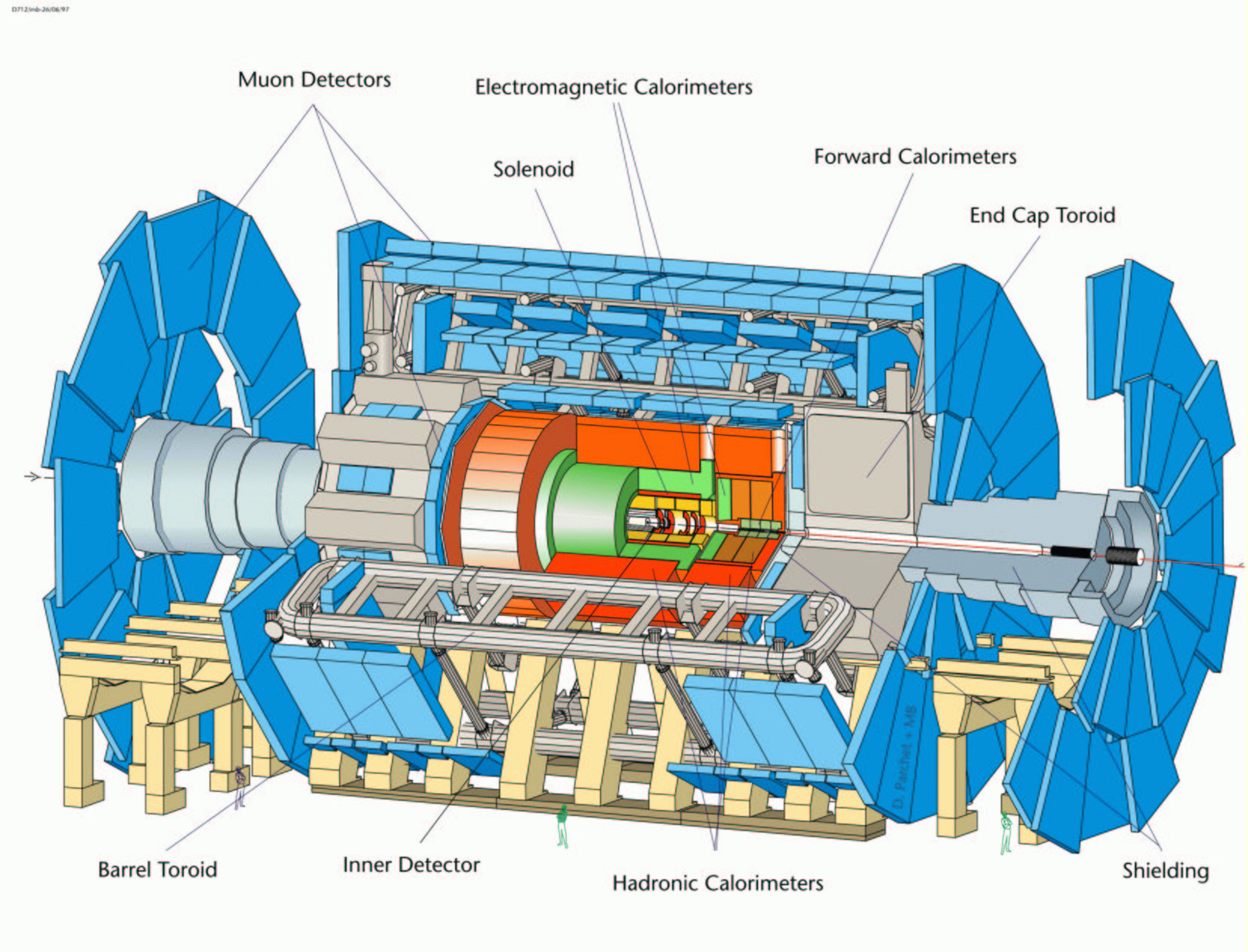
Overview of ATLAS

ATLAS and CMS are aimed at "new physics"

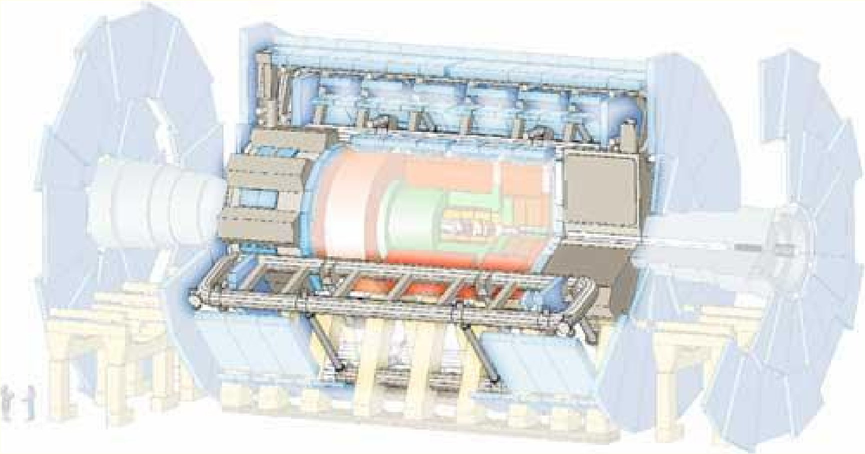
"Full acceptance" for physics objects, *i.e.* leptons and jets, missing E_T

Many detector choices driven by specific physics goals (*e.g.* LiAr Calorimeter) Equal response for e and μ

Physics performance is expected to be similar to CMS, 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

Magnet system

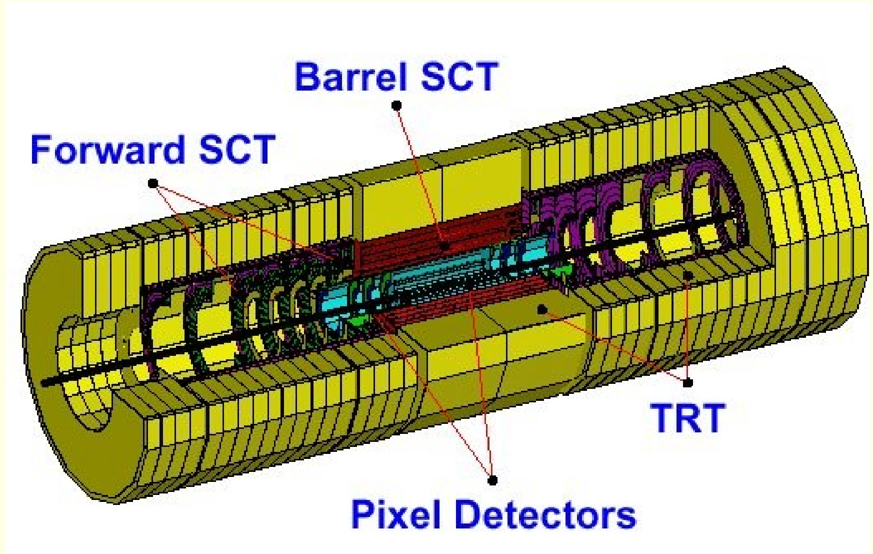


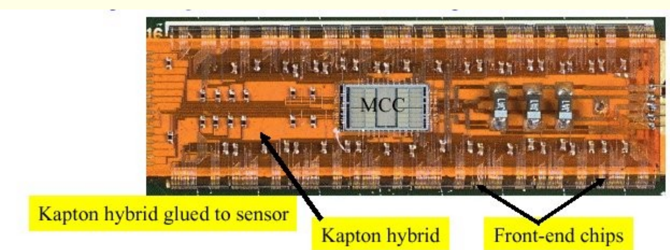
Solenoid – Central tracking

Muon endcap

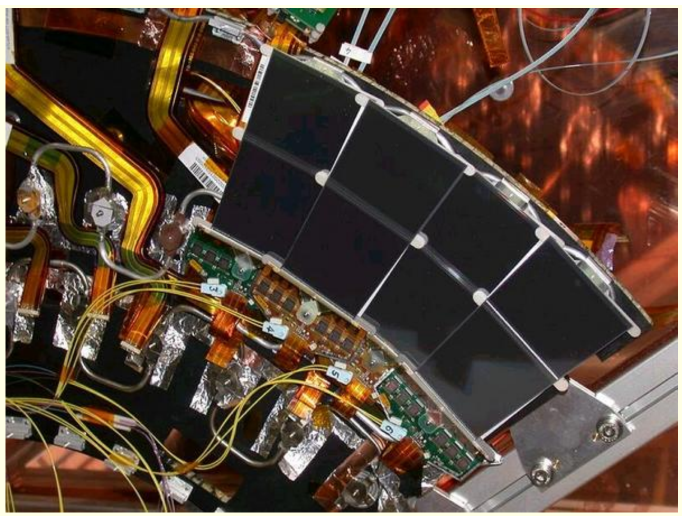
Central toroid under assembly

Inner Detector





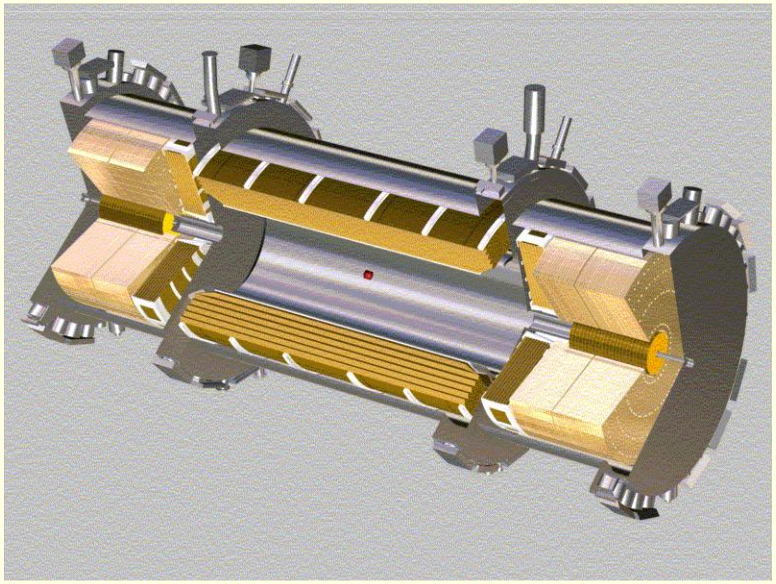
Pixel Hybrid



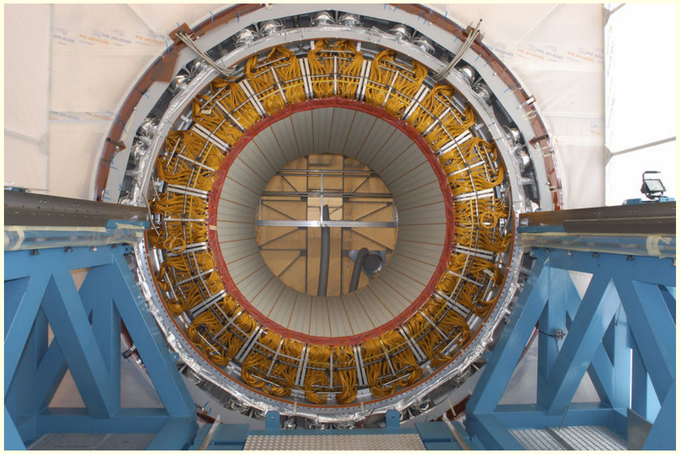
Forward Si Strip Module

Forward TRT wheel

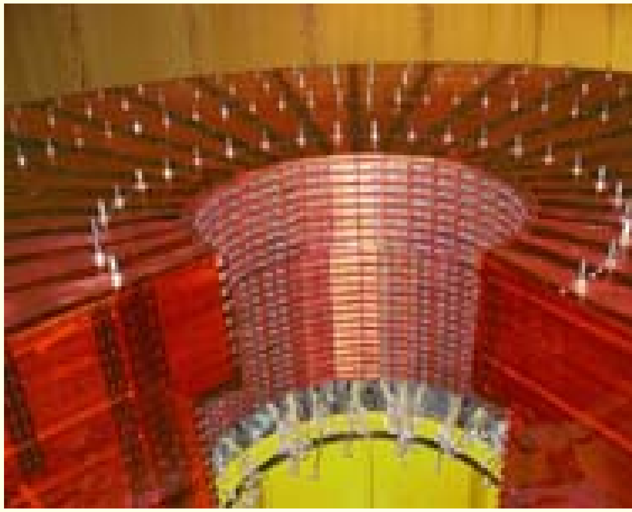
LiAr (EM) Calorimeter



Barrel EM

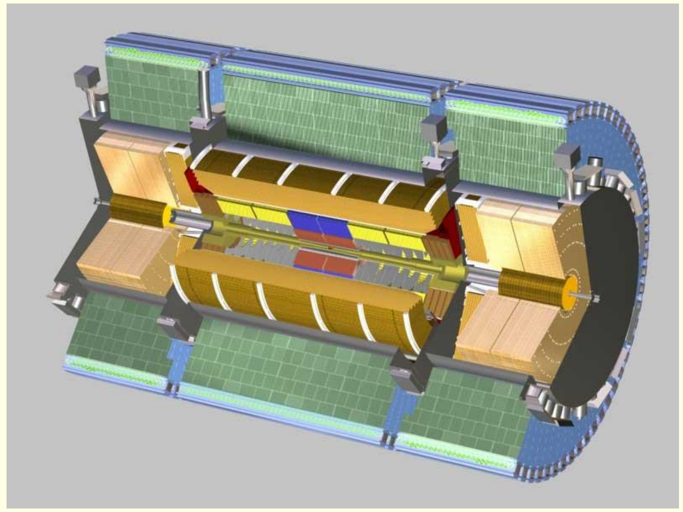


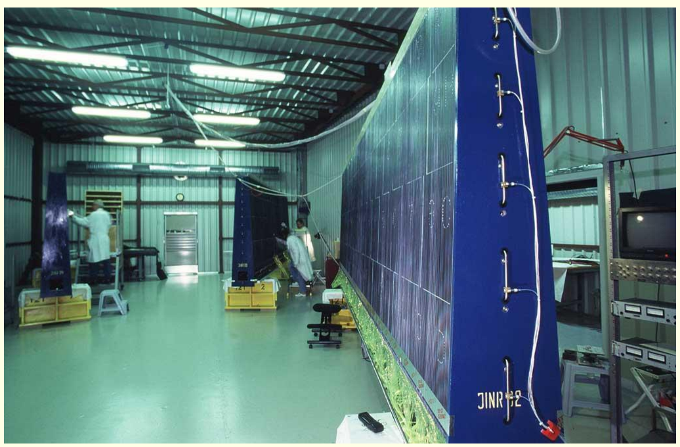
Barrel Cryostat



hadronic end cap

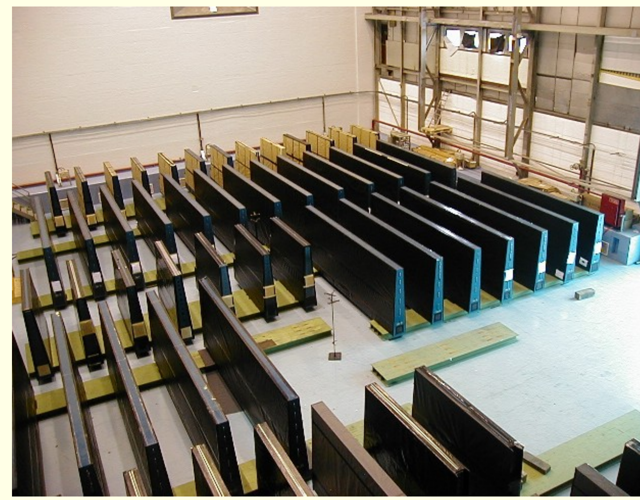
Tile (Hadronic) Calorimeter





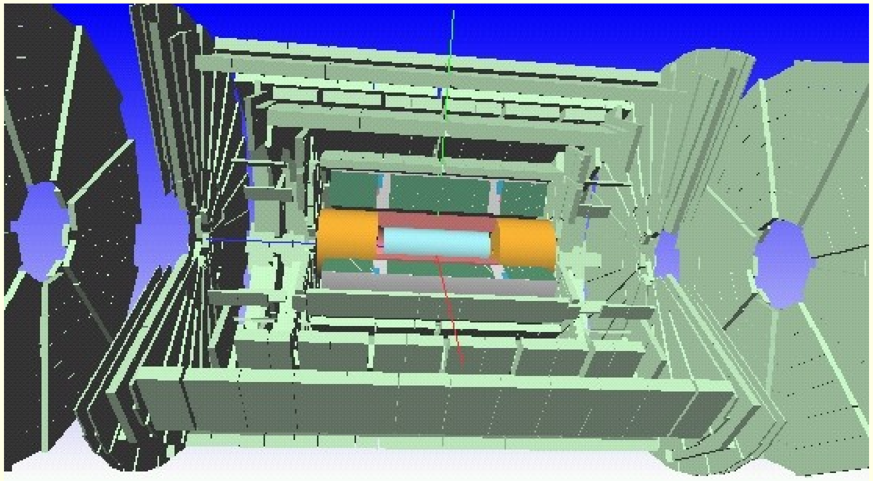
Single element

Barrel



Sections in storage

Muons



Characteristic New physics signatures at LHC

Not all present in all models

Heavy objects decay into Standard Model particles with high energy

$\not{E}_T$ from ν or other new particles

High Multiplicity of large p_t jets

Many isolated leptons – from W, Z or directly produced

Copious b production – "democratic decays?"

Large Higgs production – this may be a standard model particle

Isolated Photons

Quasi-stable charged particles – like a heavy muon.

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

Important for triggering considerations

Backgrounds – Measuring and Calculating

At present, we rely on MC for signal and background estimates

There are uncertainties in rates from PDF's, higher order QCD

Most of these do no matter at the moment, They will matter once data appears

My concern: underlying and min-bias events

Affects process that need forward jet tagging $e.g.$ $WW - scattering$ or central jet veto

Will be measured once data exists and MC will be tuned to agree...

Little Higgs Models

All data consistent with SM ($g-2$???)

New particles of mass $\lesssim 10\mathrm{TeV}$ are constrained EW fits, FCNC limits *etc*

Calculate with a cut off $\Lambda = 10TeV$

top loop $\delta m_h^2 = \frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \sim (2TeV)^2$

W/Z loops $\delta m_h^2 \sim \alpha_w \Lambda^2 \sim -(750GeV)^2$

Higgs loop $\delta m_h^2 \sim \frac{\lambda}{16\pi^2}\Lambda^2 \sim -(1.25m_h)^2$

$m_h^2 \sim (100GeV)^2$

Fine tuning of Higgs mass seems to require something else $\sim 1\mathrm{TeV}$

Most dangerous terms are top loop, Higgs loop, W/Z loops

Solve these and problem is $\gtrsim 10\mathrm{TeV}$ where we know nothing

SUSY solves it up to $\sim M_{Planck}$ by removing all quadratic divergences.

Can arrange ad-hoc cancellations by adding a few particles but need a symmetry

Little Higgs models (2)

- Models try to arrange new particles to cancel these effects
- Do this by extending the symmetries of the Standard Model so that the cancellations are forced by the new symmetries – SUSY is best example
- Need a theory with a broken global symmetry to get a massless Goldstone boson.
- Must break the symmetry "in a small way" so that this Goldstone Boson can have interactions and a VEV and play the role of the Higgs.
- Will solve the hierarchy problem; cancellations will appear as needed.
- The models are not simple (they may be "elegant") and not complete.

Arkani-Hamed, Georgi, Burdman, Schmalz, ...

LHC signals

What is the minimal stuff??

- Something to cancel the top loop.
  In the example this is T decays via $T \to Zt$, $T \to Wb$, $T \to ht$ with BR in the proportion $1:2:1$
  Ratio is test of model

- Something to deal with the W loop
  In the example this is the gauge bosons of the other $SU(2) \times U(1)$.
  Once the masses are specified their couplings have one free parameter (θ)

- Something to deal with the H loop
  In the example here this is the Higgs triplet ϕ which is produced via WW fusion

- Very small effects $< 5\%$ in $h \to gg$ and $h \to \gamma\gamma$

Masses and decays are model dependent. Higgs sector is most model dependent

Expected range of masses

- Fine tuning means that $f = \frac{\Lambda}{4\pi} < 1TeV(\frac{m_H}{200GeV})^2$
- $m_T < 2TeV(\frac{m_H}{200GeV})^2$
- $M_{W_H} < 6TeV(\frac{m_H}{200GeV})^2$
- $m_\phi < 10TeV$

New Quark

Properties determined by two parameters λ_1/λ_2 and mass.

Two production mechanisms $qb \to q'T$ and $gg \to T\overline{T}$: Former depends on $t - T$ mixing and therefore on λ_1/λ_2

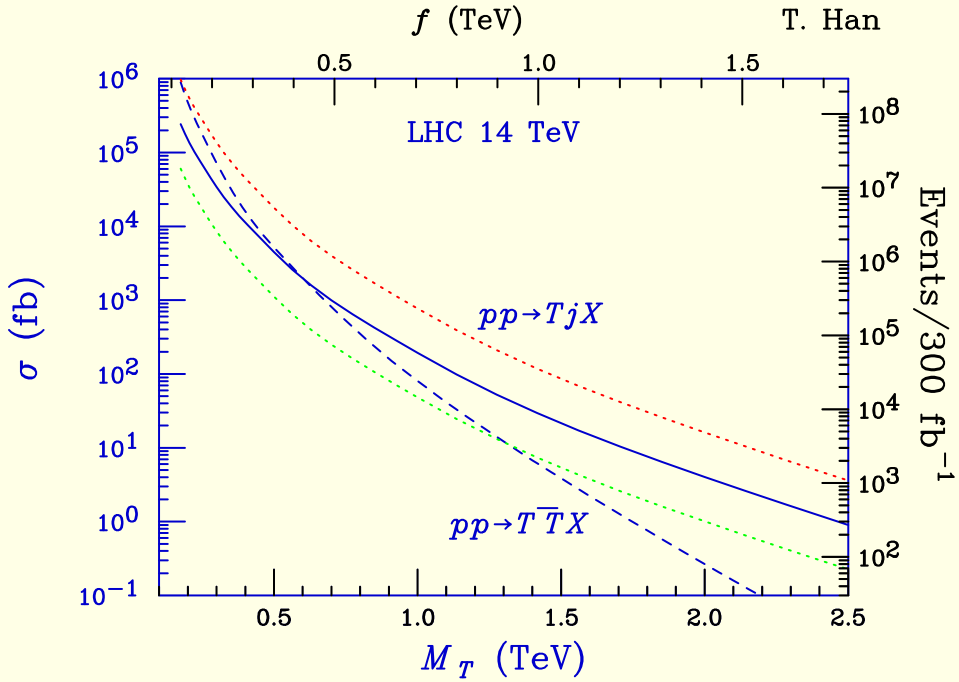


Figure from Han

Single production dominates at large masses

Three single production curves are for $\lambda_1/\lambda_2 = 2, 1, 0.5$

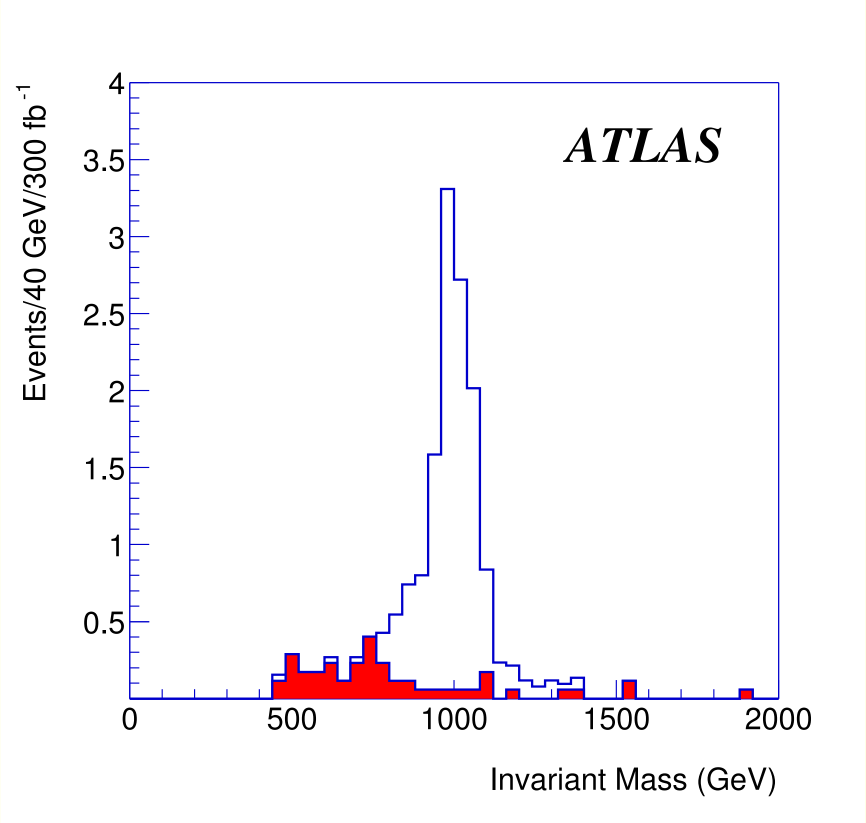
Width is small

Single Production is used in the following: note recoil jet.

$T \to Zt$

Reconstruct from $Z \to \ell^+\ell^-$ and $t \to b\ell\nu$

Three isolated leptons (either e or μ) with $p_T > 40$ GeV and $|\eta| < 2.5$ one of which has $p_T > 100$ GeV
No other leptons with $p_T > 15$ GeV
One pair of leptons within 10 GeV of Z mass.
$\not{E}_T > 100$ GeV
At least one tagged $b-$ jet with $p_T > 30$ GeV

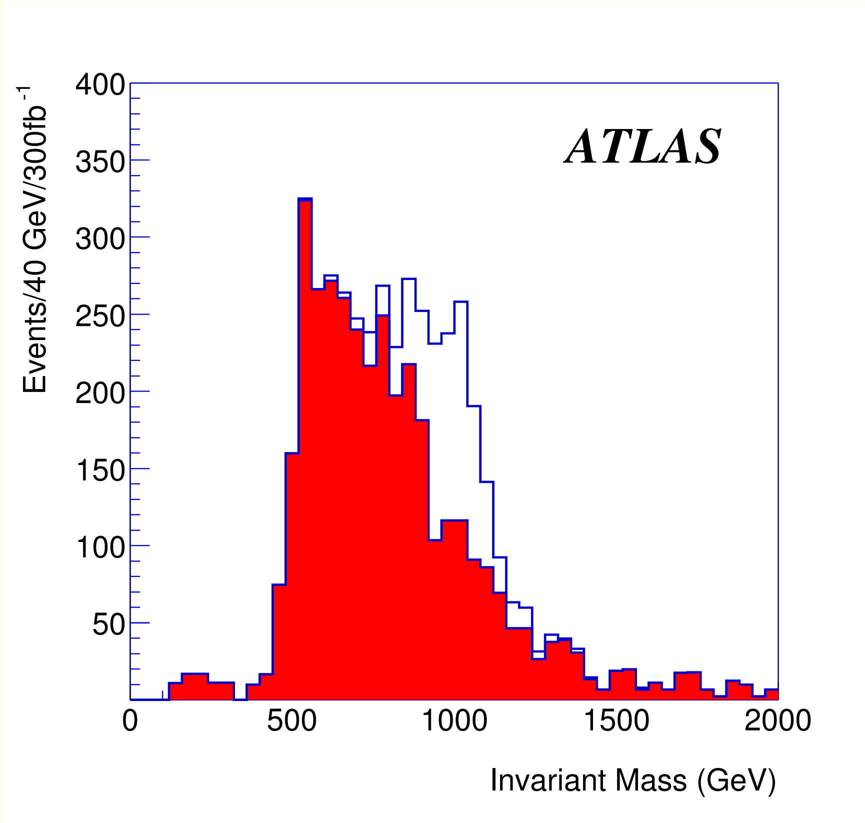


Background is dominated by tbZ

$T \to Wb$

Reconstruct from $T \to b\ell\nu$

One isolated lepton (either e or μ) with p_T >100 GeV and $| \eta |< 2.5$
No other leptons with $p_T >$ 15 GeV No more than 2 jets with $p_T >$ 50 GeV and $M(j1, j2) > 200$ GeV
$\not{E}_T > 100$ GeV
at least one tagged $b-$ jet with $p_T >$ 200 GeV

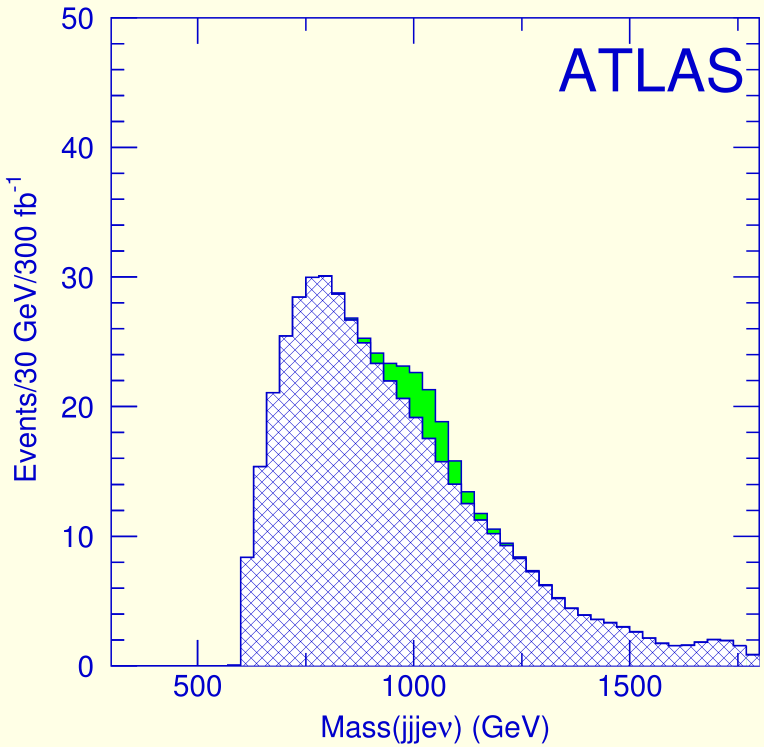


Background is dominated by $t\bar{t}$

$T \to ht$

Reconstruct from $h \to b\bar{b}$ and $t \to b\ell\nu$

One isolated e or μ with $p_T > 100$ GeV and $\mid \eta \mid < 2.5$.
Three jets with $p_T > 130$ GeV.
Four jets with $p_T > 15$ GeV.
At least one jet tagged as a$b-$jet
Mass of dijet system within 20 GeV of Higgs mass (assumed to be 120 GeV)



Background dominated by $t\bar{t}$

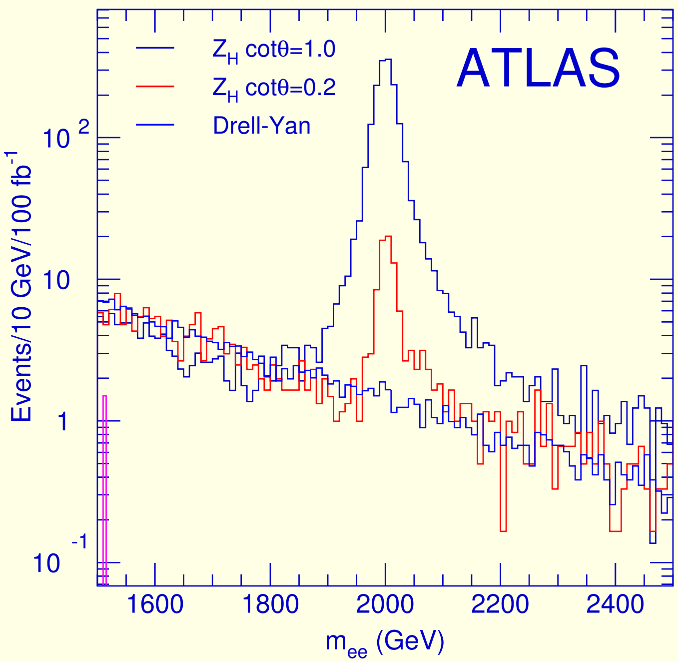
New Bosons

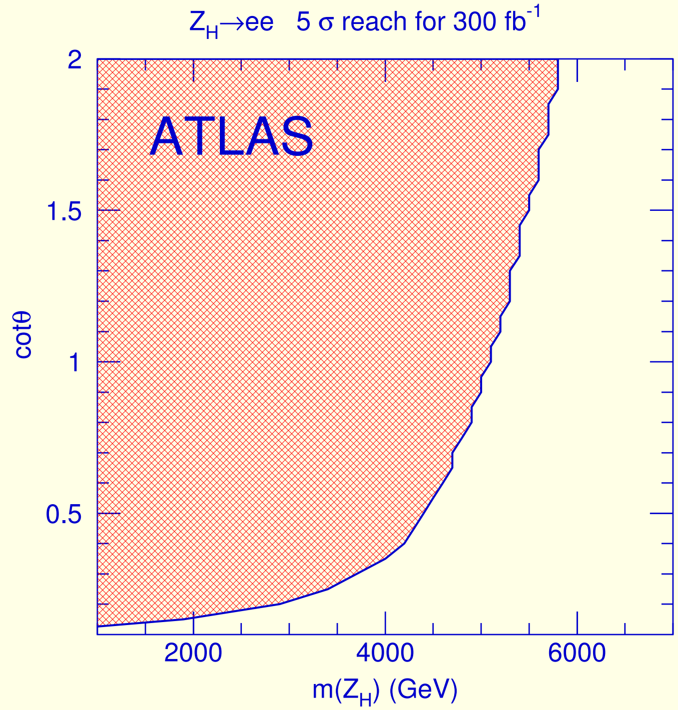
Expect two neutral and two charged: $Z_H, A_H, W_H^{\pm}$
Model has two additional couplings corresponding to the extra $SU(2) \times U(1)$,

Bosons will be discovered via leptonic decays **But critical test is cascades such as** $Z_H \to Zh$

New Bosons – Leptonic decays

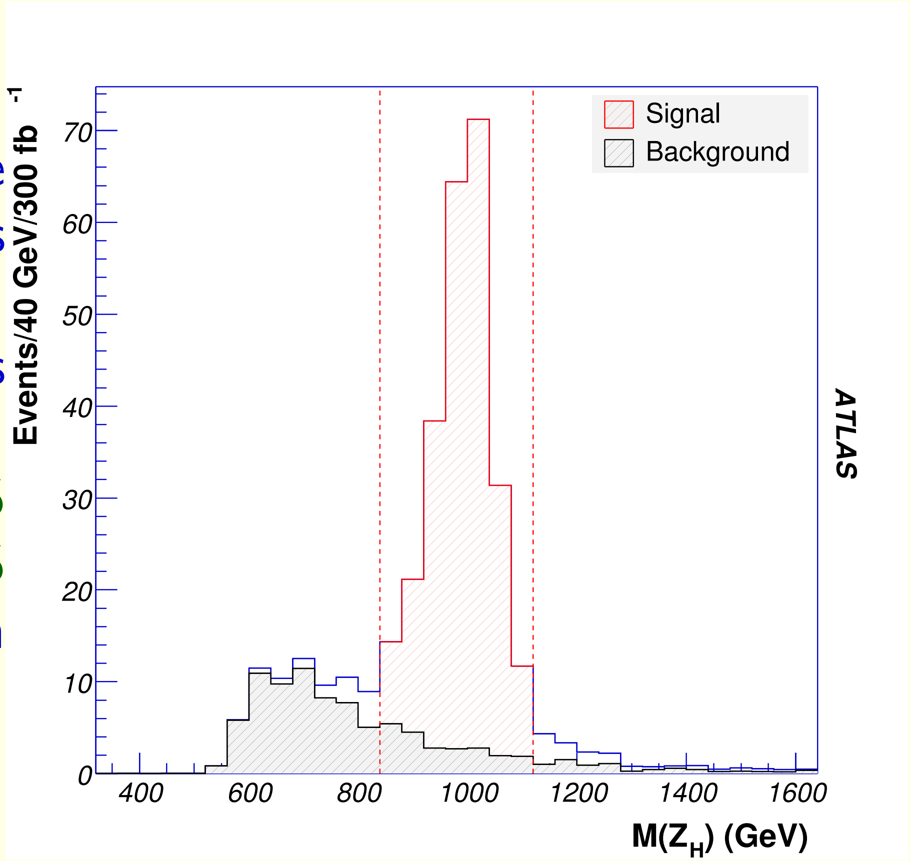
Clear signal over Drell-Yan background. Plot shows 2 TeV mass for Z_H





New Bosons – Cascade decay $Z_H \to Zh \to \ell^+\ell^- b\bar{b}$

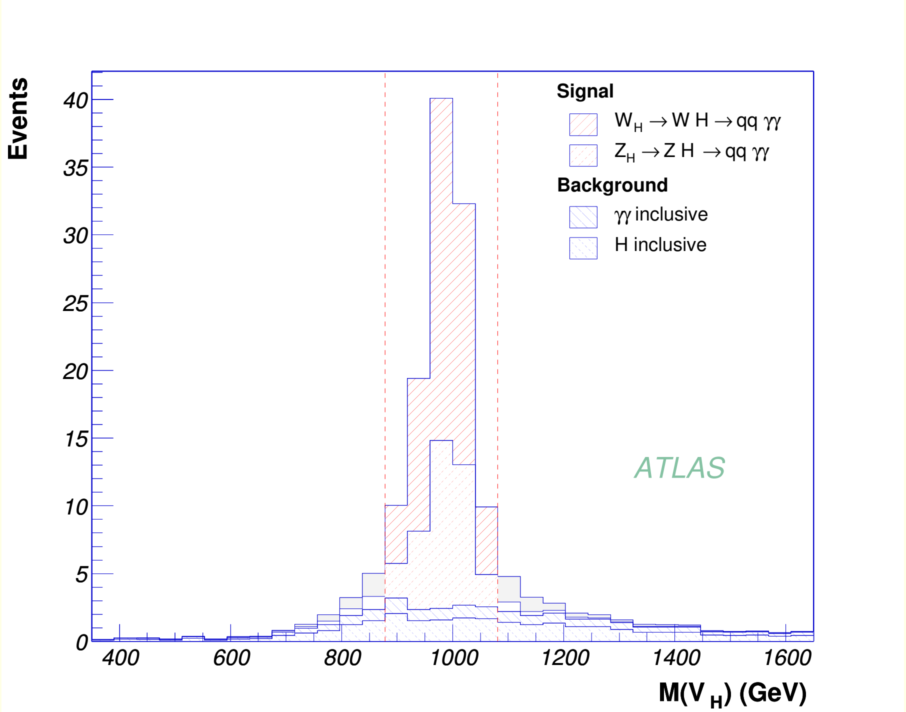
Two leptons of opposite charge and same flavor with $p_T > 6(5)$ GeV for muons (electrons) and $\mid \eta \mid < 2.5$
The lepton pair should have a mass between 76 and 116 GeV
Two reconstructed $b-jets$ with $p_T > 25$ and $\mid \eta \mid < 2.5$, which are within $\Delta R < 1.5$
The $b-jet$ pair should have a mass between 60 and 180 GeV



$Z_H \to Zh$, $h \to \gamma\gamma$

Must use all hadronic mode of Z: Cannot distinguish W_H from Z_H

Two isolated photons one having $p_T(1) > 25$ GeV, $p_T(2) > 40$ GeV.
$M(\gamma\gamma) = m_h \pm 2\sigma$
The jet pair with invariant mass closest to M_W is selected.
Pair has a combined $p_T > 200$ GeV

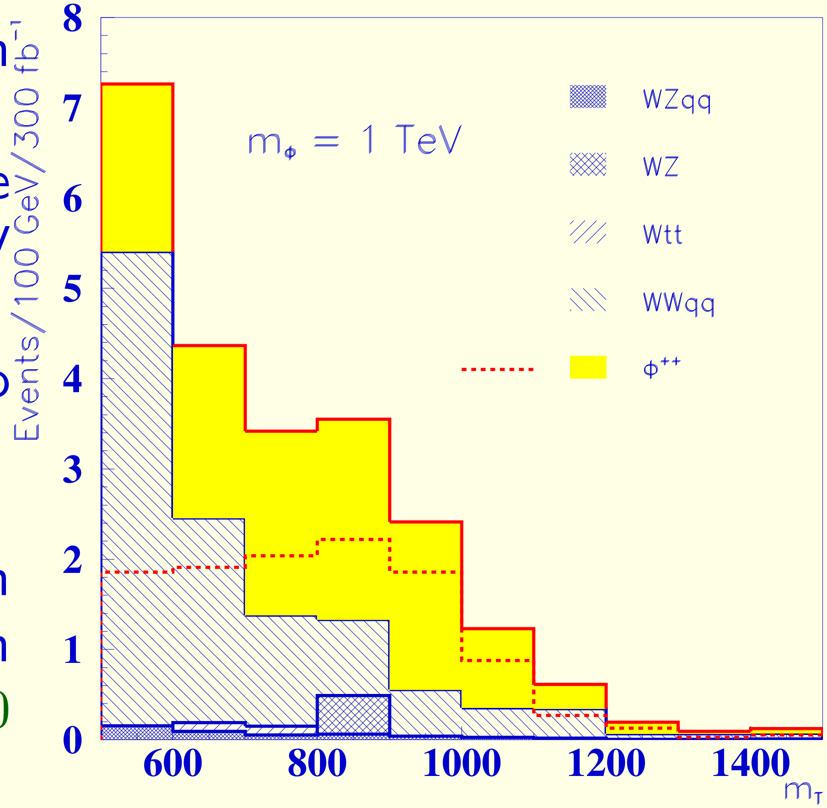


Can also extract signal via Jacobian peak in the P_T dist of Higgs

Extra Higgs

ϕ^{++} produced by WW fusion: So must use the forward tagging jets

Two reconstructed positively charged isolated leptons (electrons or muons) with $| \eta |< 2.5$
One of the leptons was required to have $p_T > 150$ GeV and the other $p_T > 20$ GeV
$|p_{T1} - p_{Ts}| > 200$ GeV
the difference in pseudorapidity of the two leptons $|\eta_1 - \eta_2| < 2.$
$\not{E}_T > 50$ GeV
Two jets each with $p_T > 15$ GeV, with rapidities of opposite sign, separated in rapidity $|\eta_1 - \eta_2| > 5$; one jet has $E > 200$ GeV and the other $E > 100$ GeV



Summary of sensitivity

- T Observable in both $h(120)t$ (up to mass of 1.2 TeV) and Zt (up to mass 1.0 TeV): Wb is observable up to 1.3 TeV for $\lambda_1/\lambda_2 = 1$

- Z_H observable in e^+e^- to mass of 4.5 TeV for $\cot\theta = 0.5$
  $Z_H \to Zh(120) \to Zb\bar{b}$ observable for mass up to 2 TeV
  $Z_H \to Zh(120) \to Z\gamma\gamma$ observable for masses up to 1.1 TeV

- ϕ^{++} may be observable in W^+W^+ at 1.5 TeV

- More work needed for $m_h \gtrsim 150$ GeV

LHC finds it or motivation disappears

Hadron Production of Sparticles

LHC is likely to be above threshold for many sparticles

A consistent model must be used for simulation. Most popular is SUGRA

Unification all scalar masses (m_0) at GUT scale
Unification all gaugino masses ($m_{1/2}$) at GUT scale
Universal A and B
$\mid \mu \mid$ and B are traded off for M_Z and $\tan\beta = v_1/v_2$
So five parameters $\tan\beta = v_1/v_2$ $sign(\mu)$ A, $m_{1/2}$ and m_0 gives full mass spectrum and decays
Gluino mass strongly correlates with $m_{1/2}$, slepton mass with m_0.

Studies have also been done for Gauge, or Anomaly mediated models.

Enough cases have now been studied that given a complete set of masses and decay rates, we can usually estimate what can be done at LHC.

SUSY in hadron colliders

Inclusive signatures provide evidence up to $2.5\ \mathrm{TeV}$ 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.

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.

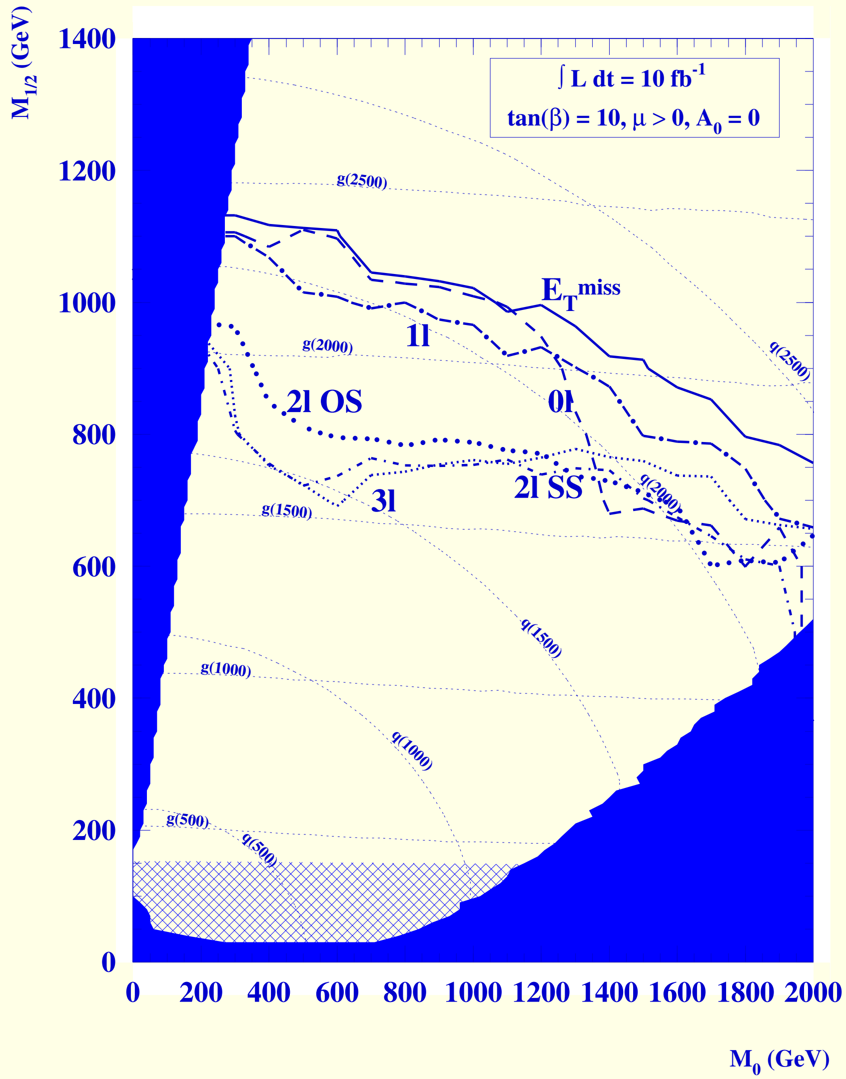
Studies shown here are not optimized; large event rates are exploited to cut hard to get rid of standard model background.

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

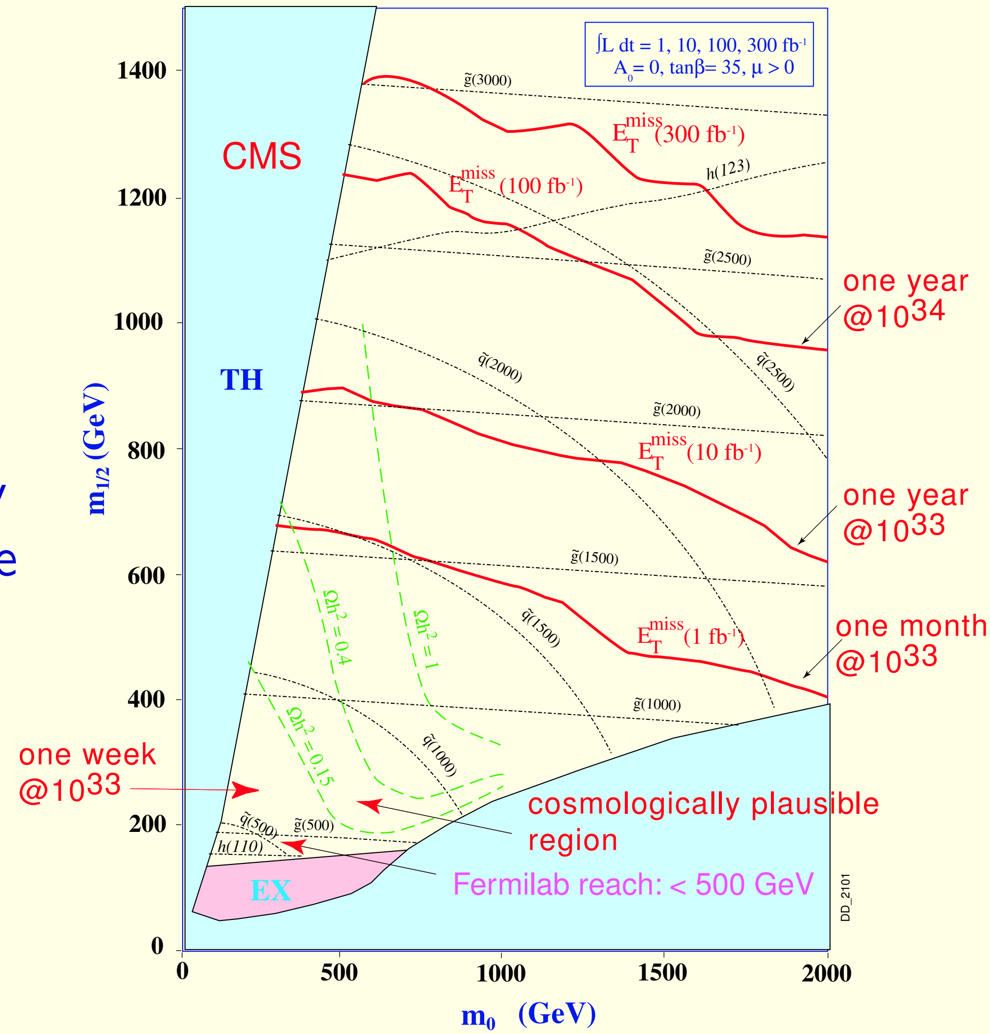
Inclusive analysis at LHC

These studies tend to be conservative

Reach is shown for various inclusive signals
Jets plus missing E_T
Multileptons of same and opposite sign
Shown for SUGRA
Shaded regions excluded by theory or LEP
Extends to gluino masses of over 2 TeV for $\mathbf{10}\mathrm{fb}^{-1}$

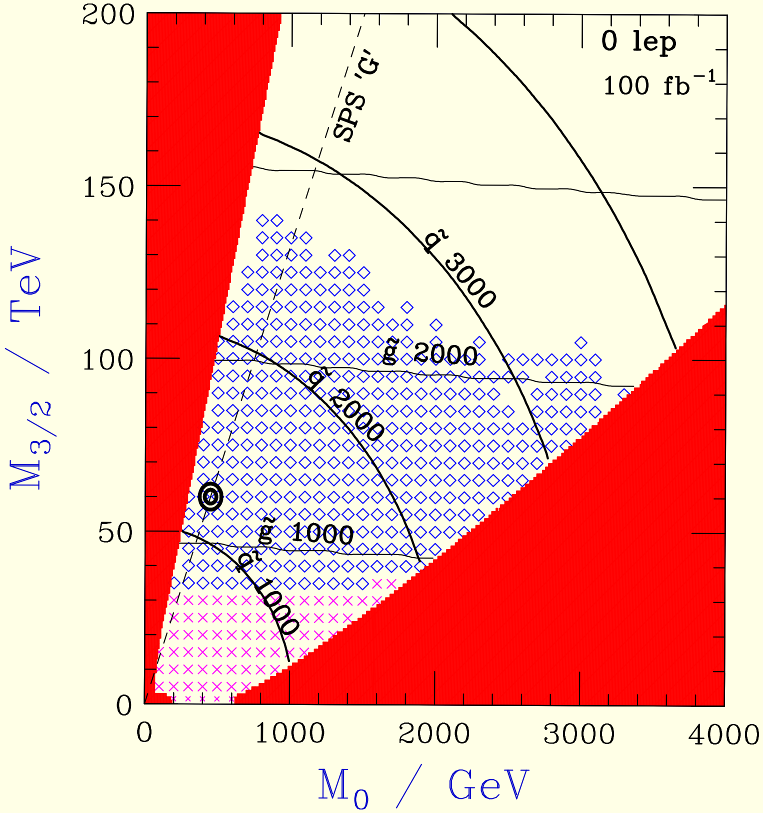


Plot shows evolution of reach with luminosity
Notice that a few $\mathbf{0.1}\mathrm{fb}^{-1}$ covers most of the region favored by fine tuning arguments



Catania 18

Reach is similar in other models
Example of anomaly mediated model
Shaded pink region is excluded by LEP



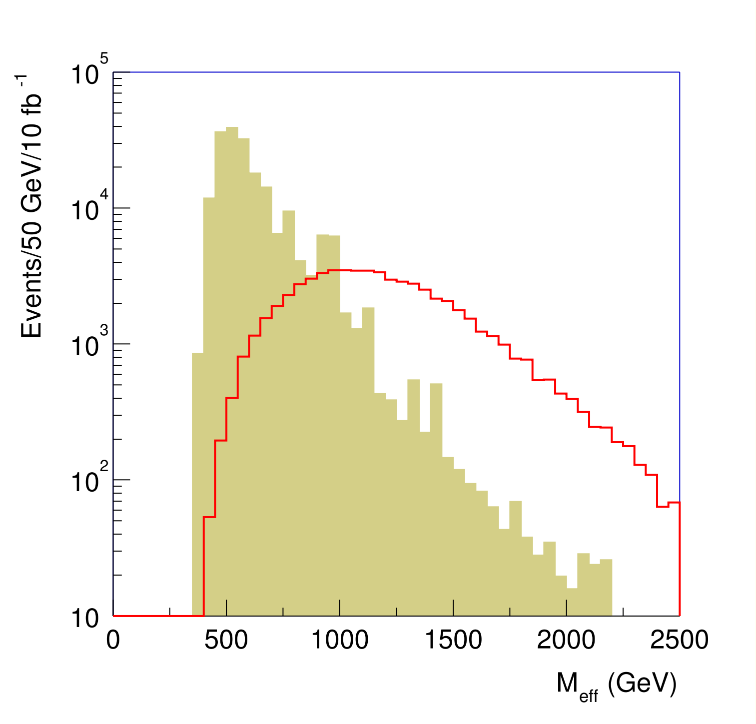
In general reach depends mainly on $M_{\tilde{g}}$ and $M_{\tilde{q}}$ provided $M_{\tilde{\chi}_1^0} \ll M_{\tilde{g}}, M_{\tilde{q}}$
rather model independent

Estimating the scale

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

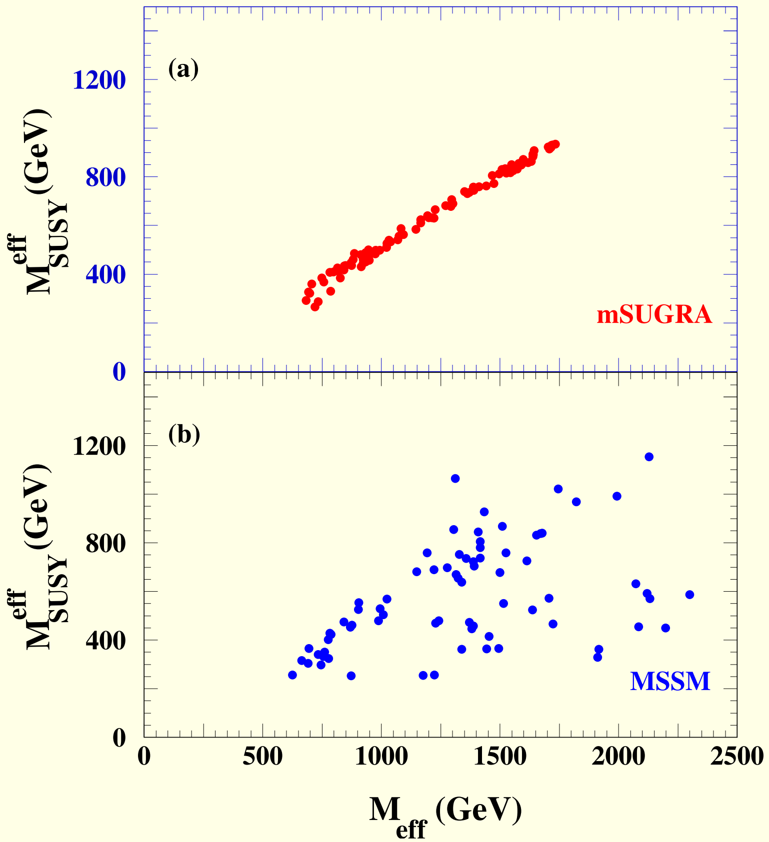


Peak in $M_{\rm eff}$ distribution correlates with SUSY mass scale

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

Will determine gluino/squark masses to $\sim 15\%$ in SUGRA, much poorer in a more general MSSM

15 parameters were varied



Note that rate information is difficult to use as BR are not known

Must reconstruct decays to get more information

Examples follow

Identifying typical decays

Assume $M_{\tilde{g}} > M_{\tilde{q}}$ (similar results in reverse case)
Then typically

$$B(\tilde{q}_L \to \tilde{\chi}_2^0 q) \sim 1/3, \quad B(\tilde{q}_L \to \tilde{\chi}_1^{\pm} q') \sim 2/3, \quad B(\tilde{q}_R \to \tilde{\chi}_1^0 q) \sim 1\,.$$

If channels are open, two body decays such as $\tilde{\chi}_2^0 \to \tilde{\ell}^+ \ell^-$, $\tilde{\chi}_2^0 \to Z \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to h \tilde{\chi}_1^0$ usually dominate
Otherwise $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ via virtual slepton

So a good idea to look for leptons

Leptonic final states

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

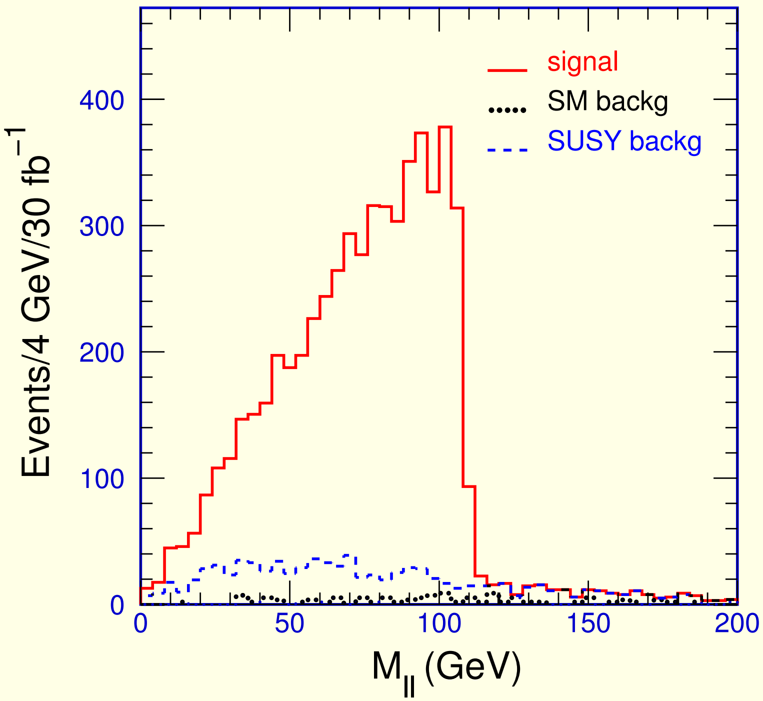
Straightforward case

Decay chain is $\tilde{\chi}_2 \longrightarrow \tilde{\ell}^+\ell^- \longrightarrow \tilde{\chi}_1\ell^+\ell^-$

- 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 opposite sign same flavor leptons is constrained by decay

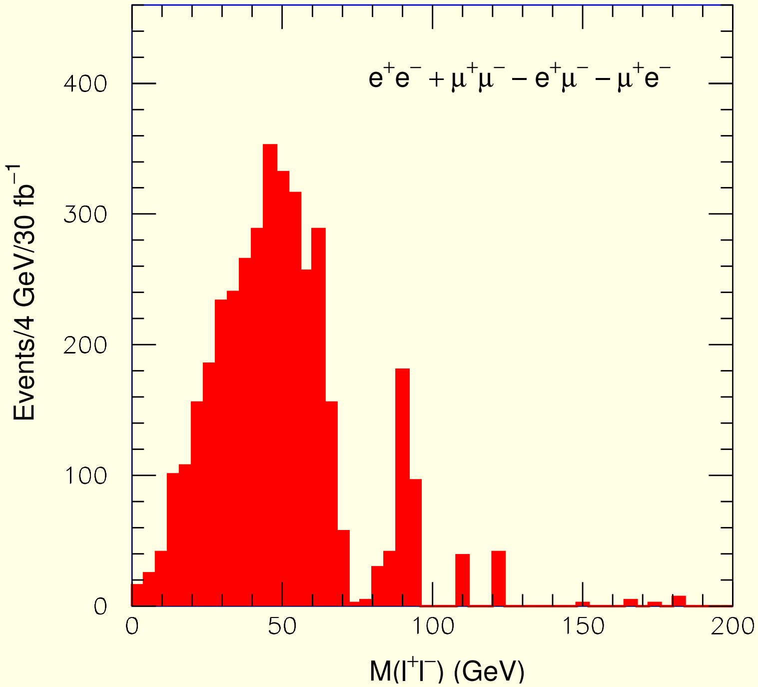
$$M_{\ell\ell} = \sqrt{(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}^0_1})}/M_{\tilde{\ell}}.$$



Standard Model background is dominated by $t\bar{t}$

Other SUSY events (mainly $\tilde{\chi}^{\pm}_1$ decays also contribute)

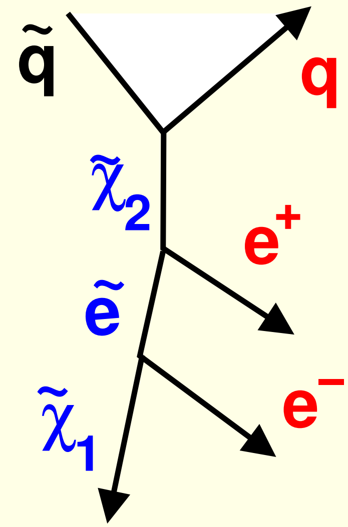
Flavor subtraction remove the SM background and cleans up signal
This example has both $\tilde{\chi}_2^0 \to \tilde{\ell}^+\ell^-$ and $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$,



Must add jets to this to try to get full decay chains

Squark masses

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



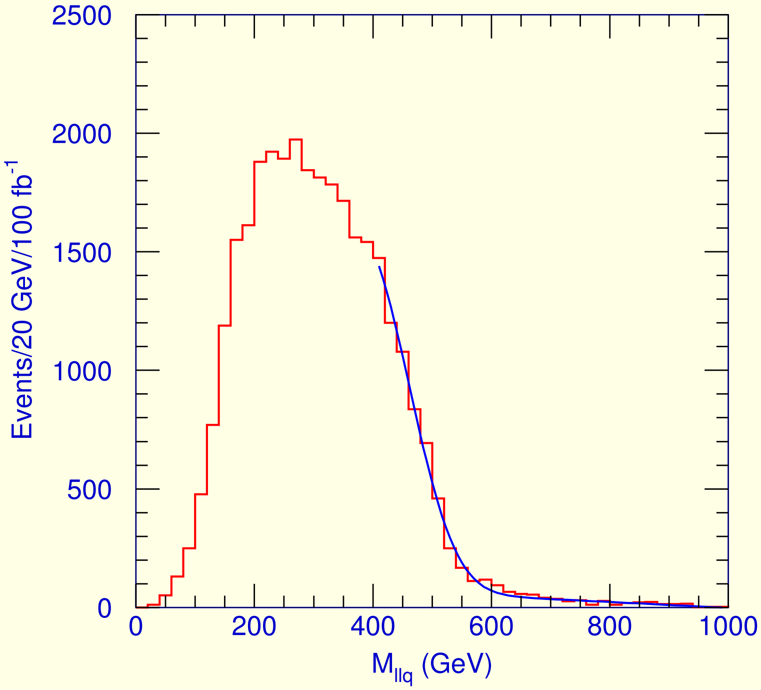
Identify and measure decay chain

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

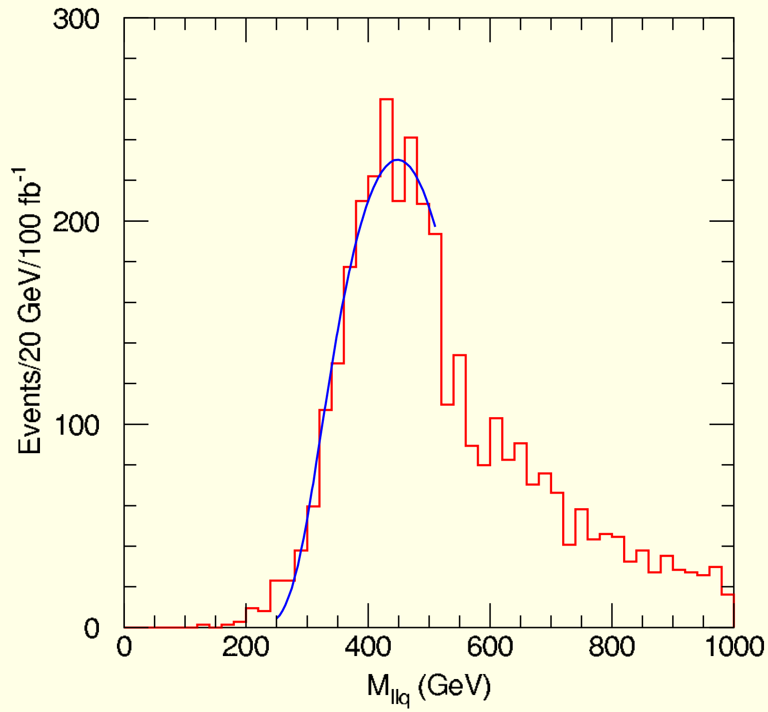
Mass of $q\ell\ell$ system has max at

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

and min at 271 GeV (in the example shown)



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



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

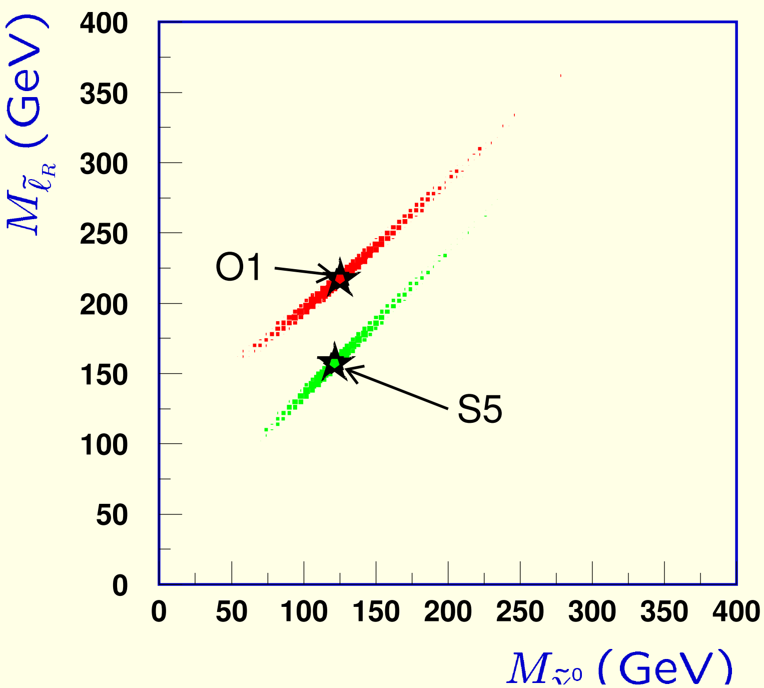
Kinematic structure clearly seen

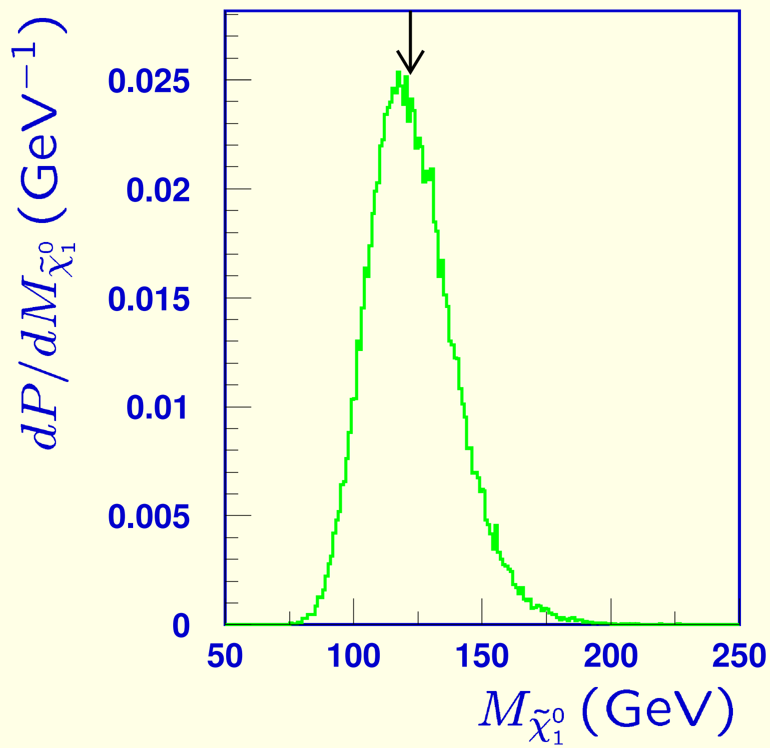
Can also exploit ℓjet mass

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

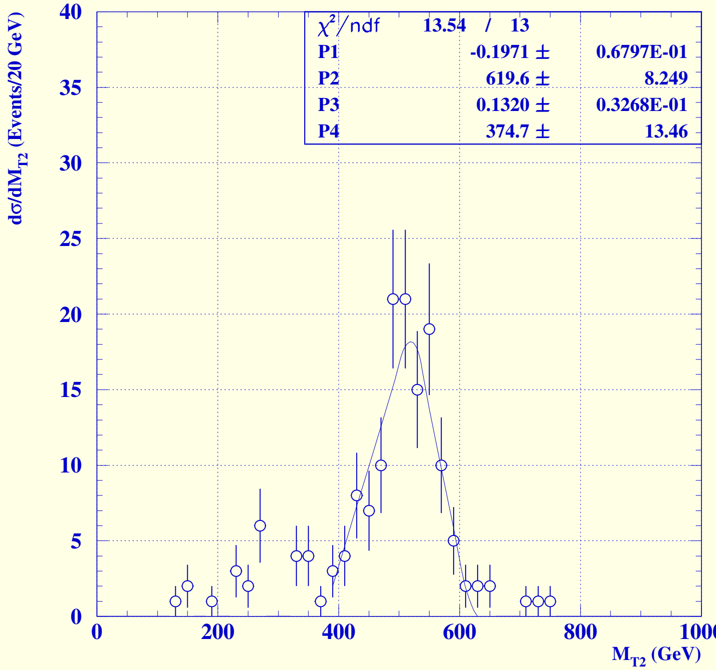
Errors are strongly correlated and a precise independent determination of one mass reduces the errors on the rest.

What about $\tilde{q}_R$?

$\tilde{q}_r\tilde{q}_r \to qq\tilde{\chi}_1^0\tilde{\chi}_1^0$ produces clean events

$$m_{T2}^2(\chi) \equiv \min_{\not{q}_T^{(1)}+\not{q}_T^{(2)}=\not{E}_T} \left[\max\left\{m_T^2(\mathrm{p}_T^{j^{(1)}},\not{q}_T^{(1)};\chi),\ m_T^2(\mathrm{p}_T^{j^{(2)}},\not{q}_T^{(2)};\chi)\right\}\right]$$

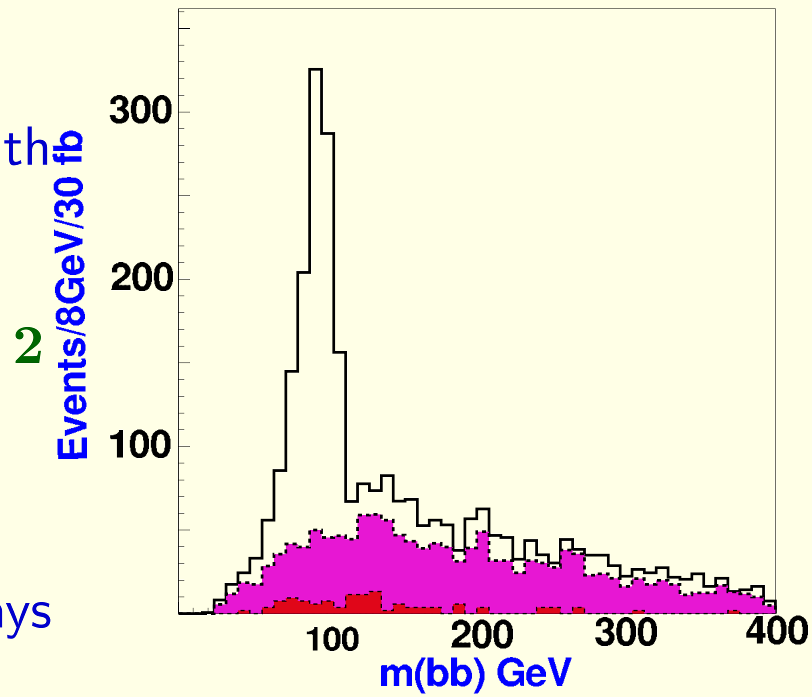
Event selection
Two jets with $P_T > 150$ GeV
$\not{E}_T > 200$ GeV
No other jets with $P_T > 40$ GeV
Clear structure
Determines a combination of M_{q_r} and $M_{\tilde{\chi}_1^0}$



Decays to Higgs

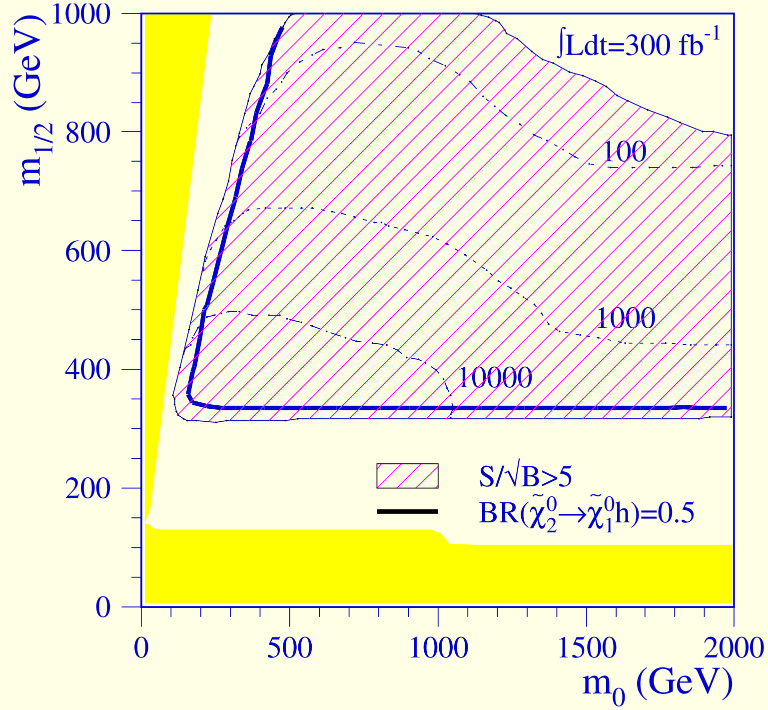
If $\chi_2^0 \to \chi_1^0 h$ exists then this final state followed by $h \to b\bar{b}$ results in discovery of Higgs at LHC.
In these cases $\sim 20\%$ of SUSY events contain $h \to b\bar{b}$

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

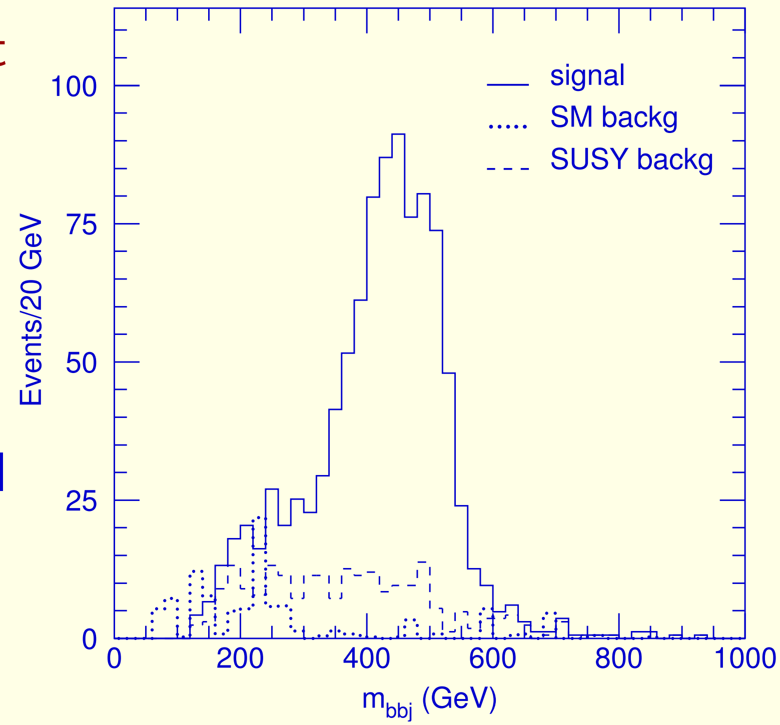


Generally applicable

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 $m_{1/2}$



Combine with a jet to attempt to get $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\chi}_1^0$



Take $b\bar{b}$ around the peak and combine with all jets

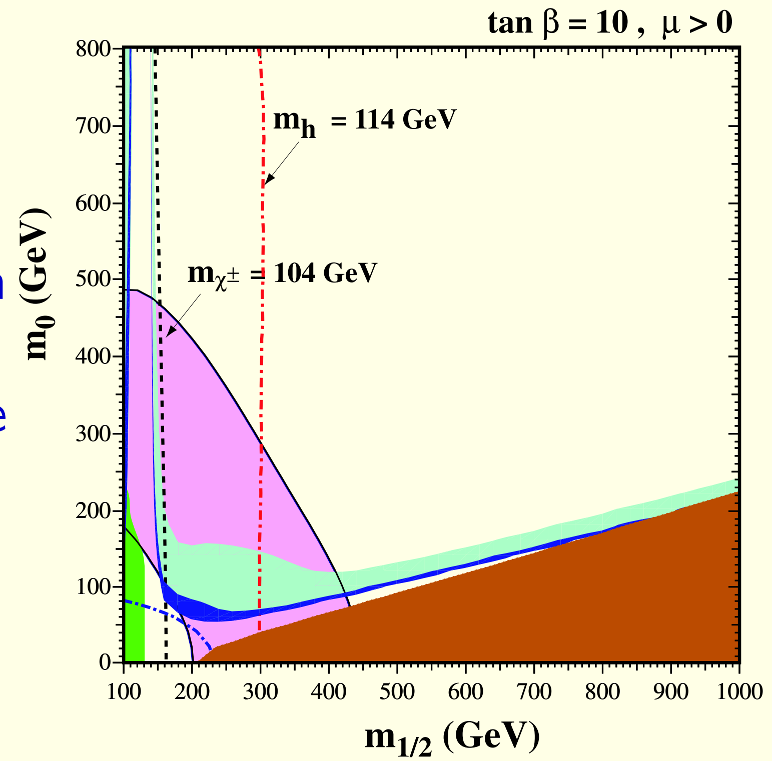
Plot the combination with the smallest mass

Again we see upper kinematic limit

Preferred regions?

It would be nice to know where to look

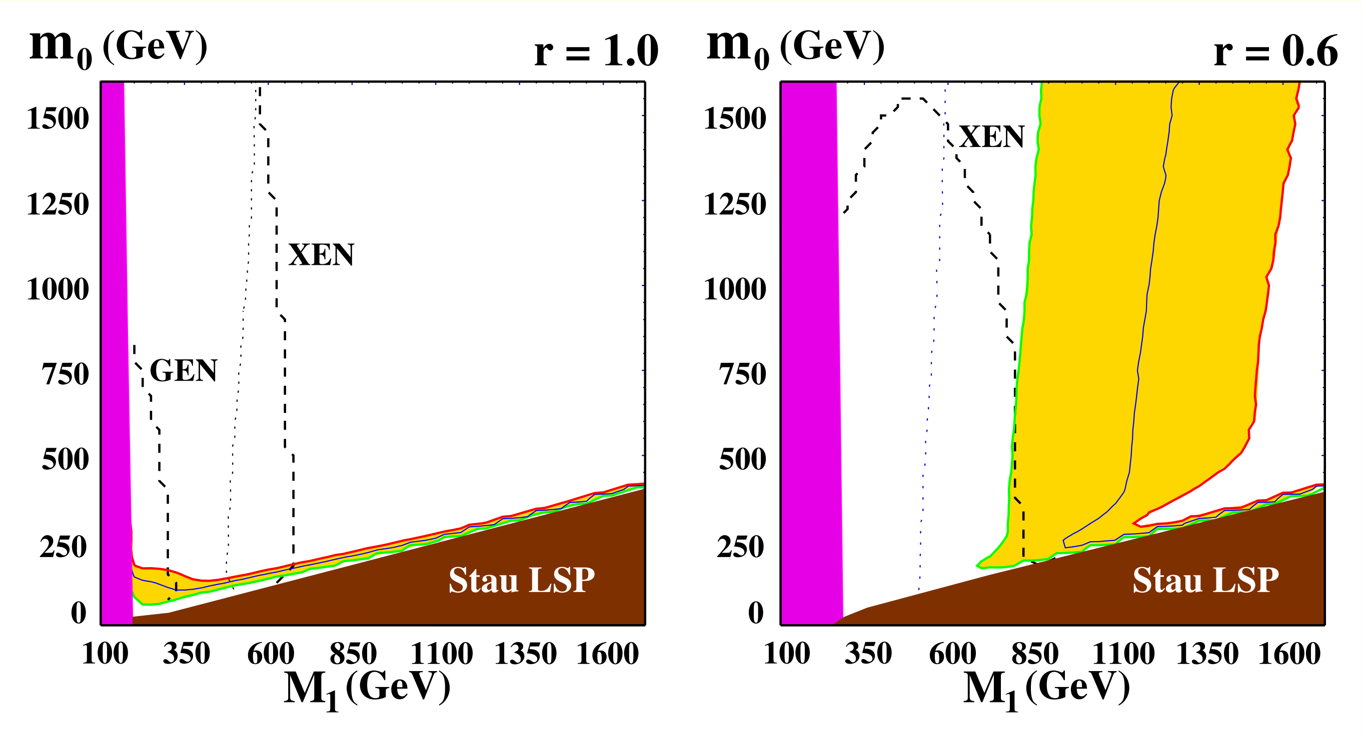
If we really believe in minimal SUGRA then WMAP provides strong constraints
Even stronger if $g-2$ is included (with one value of $R(e^+e^-)$ at low energy)



Plot from Ellis, Olive

But constraints weaken outside minimal SUGRA

$R = M_2/M_3$ at GUT scale.



Plot from Birkdahl-Hansen etal

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 $\Delta m \sim 1/R$

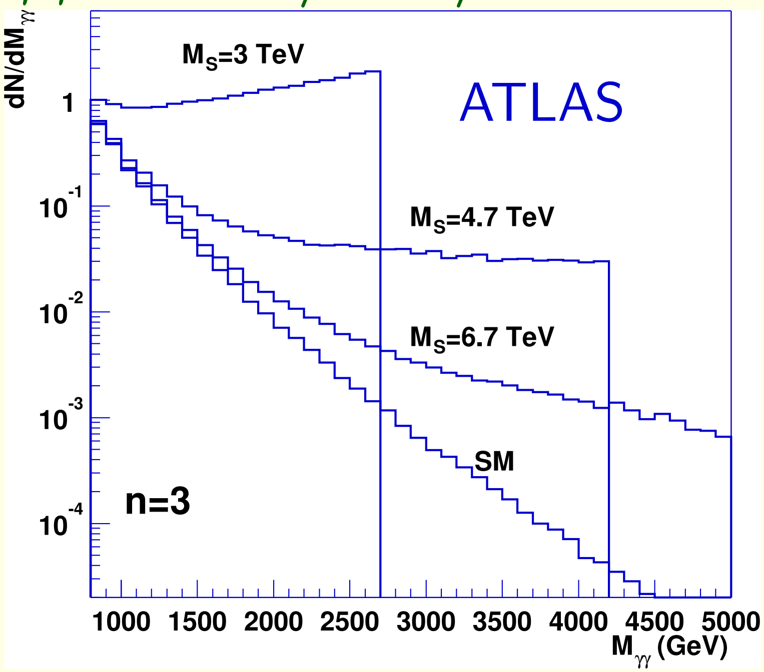
$\Rightarrow$ Standard Model fields must be stuck in $d = 4$ But many graviton (G) excitations can exist.

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

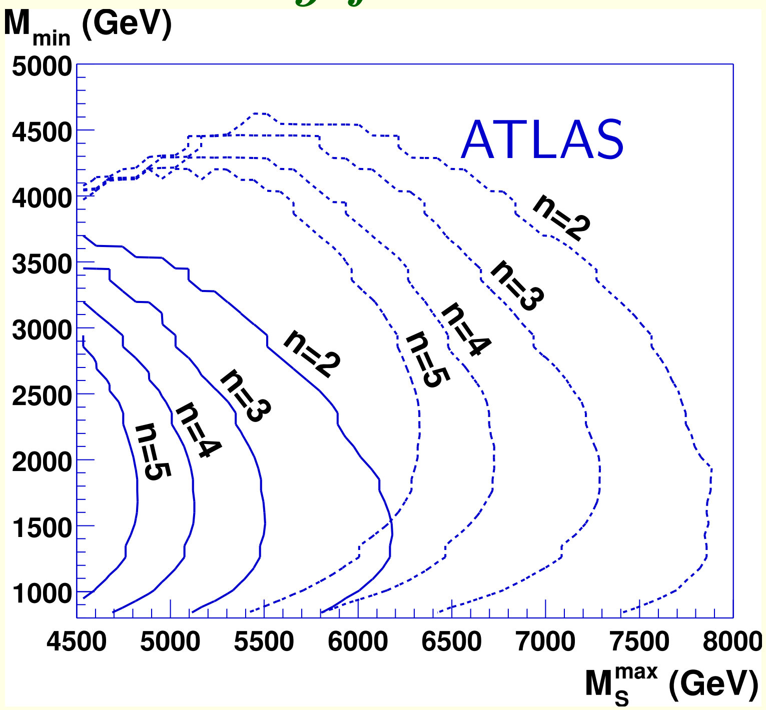
Studies have focused on jets $+ \not\!\!E_T$, $\gamma + \not\!\!E_T$, $\gamma\gamma$, and $\ell\ell$ final states.

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

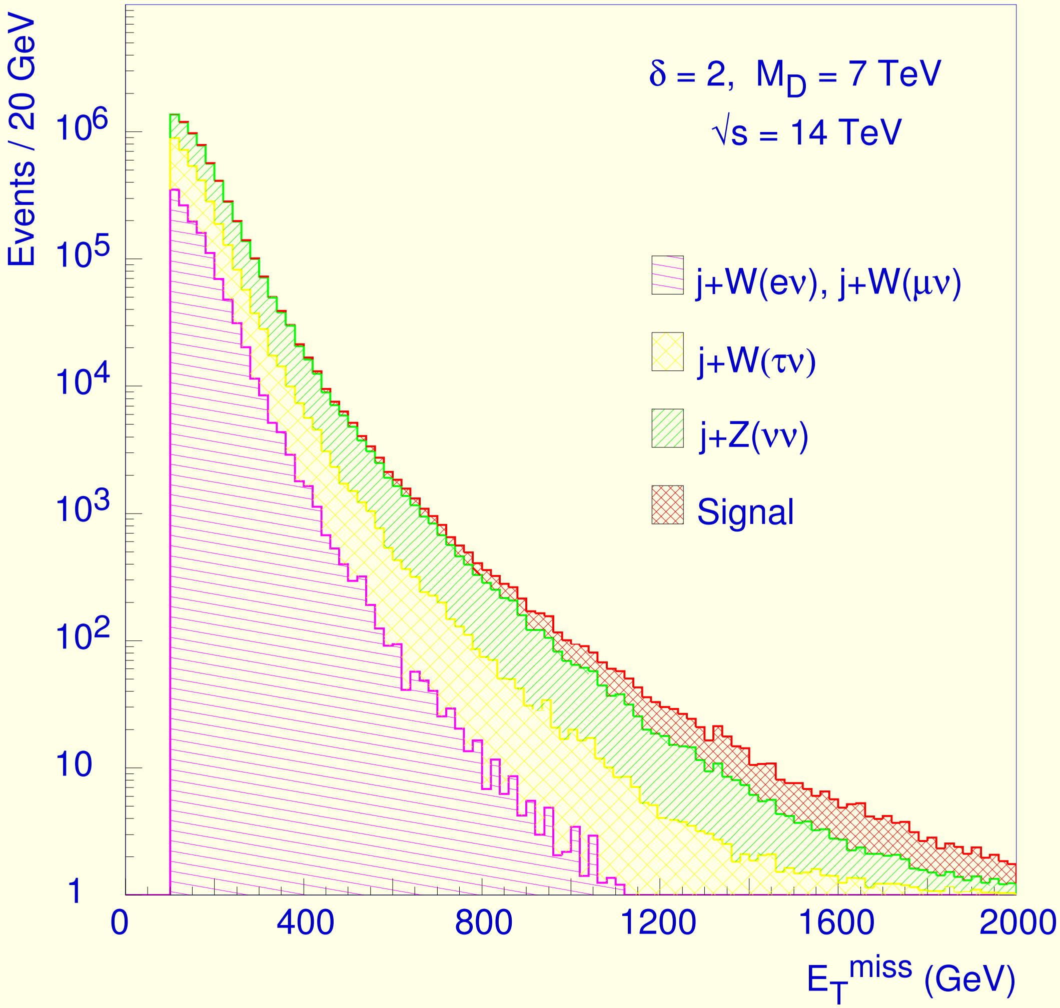
$\gamma\gamma$ ***Events/GeV/10*** fb^{-1}



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

δ	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"

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

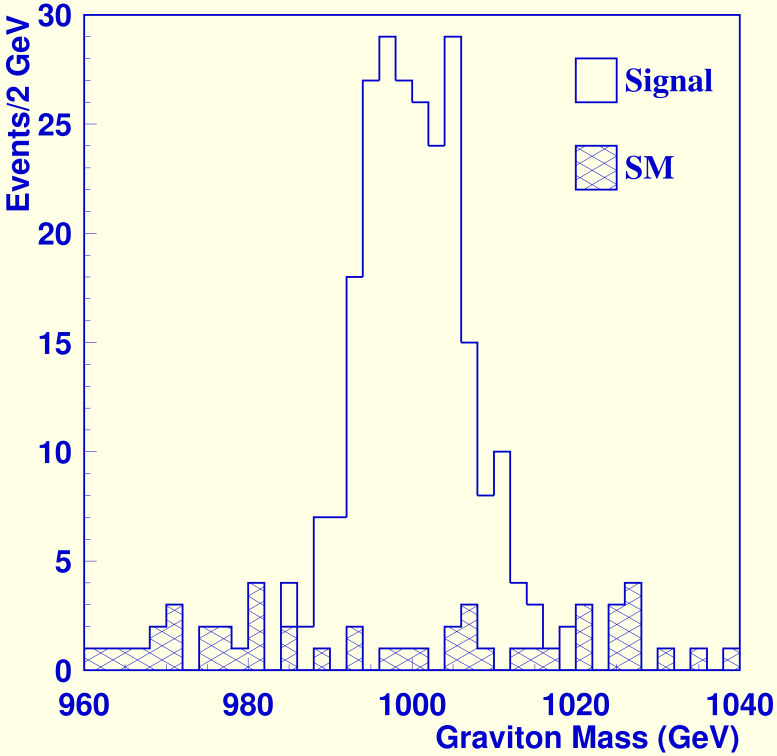
Scale $\Lambda = ke^{-kR\pi}$ in 4-D world

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

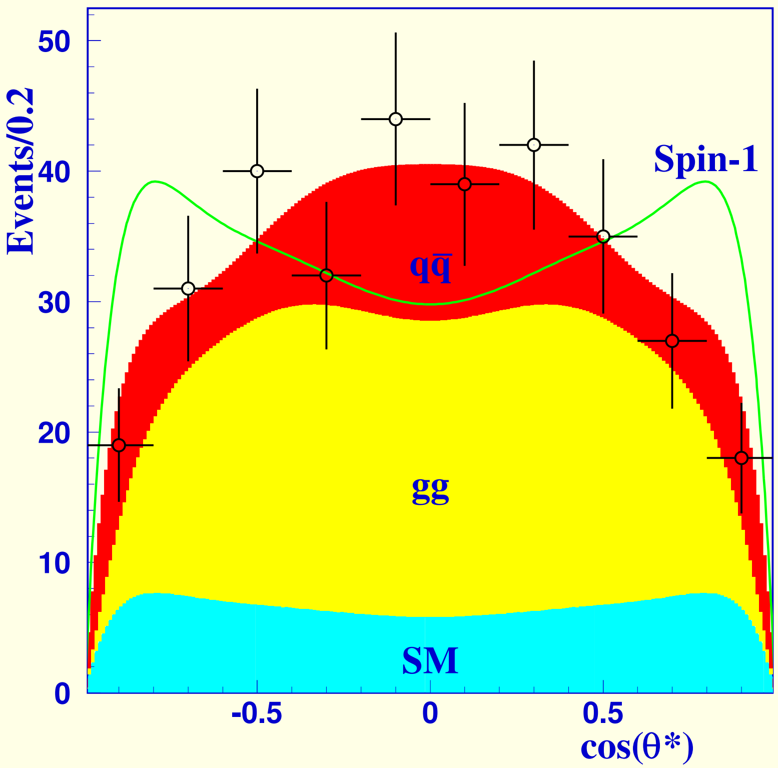
Graviton excited states have mass gaps of order Λ

Properties are determined by k/M_P.

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



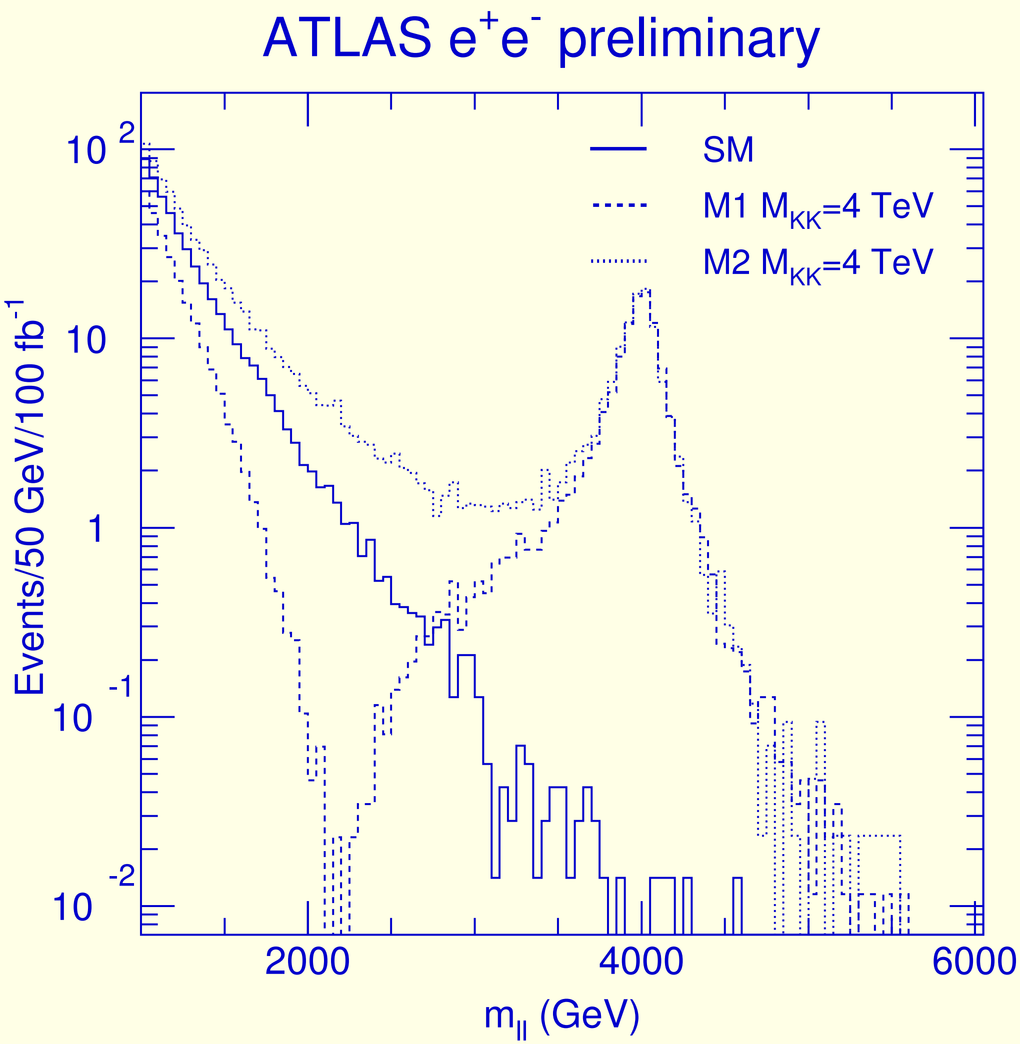
Look for a resonance in dilepton final states *e.g.* $gg \to e^+e^-$ Discovery limit is $\sim$ $1.8 TeV$ for 100 fb^{-1}



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}

Can also have standard model fields in extra dim.
Excitations of SM particles



Insufficient reach to see second resonance

Conclusions

- We are 42 Months from first data
- Much work remains in completing and commissioning hardware and software
- Set of ongoing data challenges to test out software, Physics readiness document in 2006 – updates to Physics TDR (1999).
- Full capability of defector requires restoring staged components – vital for full luminosity operation and some physics (*b-physics*
- Serious thinking has started about what might be done at $\mathbf{10^{35}}$ and what machine and detector upgrades are needed.