Physics at the TeV Scale

Discovery Prospects Using the ATLAS Detector at the LHC

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Physics Motivations

- **Experimental**
- **Theoretical**

New particles searches

- **Standard Model Higgs Boson**
- **Higgs Particles of Supersymmetric Extensions to the SM**
- **Supersymmetric Particles**

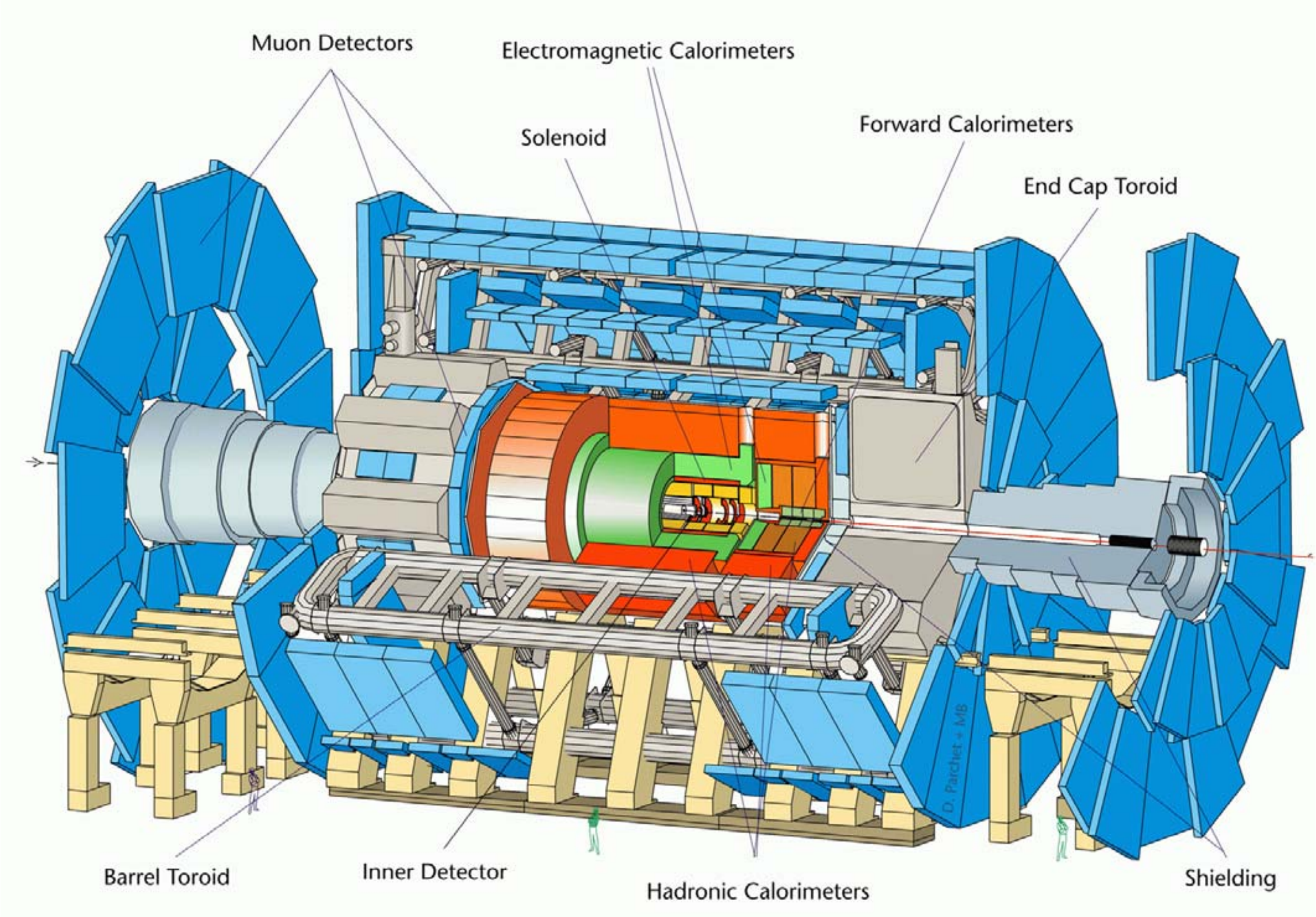
Other Scenarios

- **Large Extra Dimensions**

Summary

ATLAS and the LHC

Large Hadron Collider: proton proton collisions at $\sqrt{s} = 14\text{TeV}$



$L_{peak} = 10^{33}\ cm^{-2}s^{-1}$ 2005-2008 "Low luminosity running"

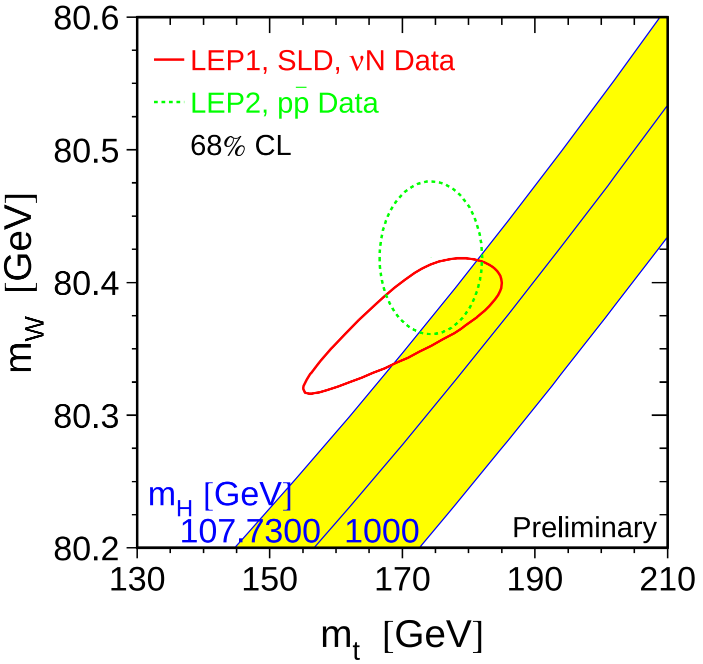
$L_{peak} = 10^{34}\ cm^{-2}s^{-1}$ 2009- ? "High luminosity running"

20 minimum bias events per crossing at high luminosity

Some physics quantities (e.g. b-tagging efficiency) degraded at high luminosity

The Standard Model

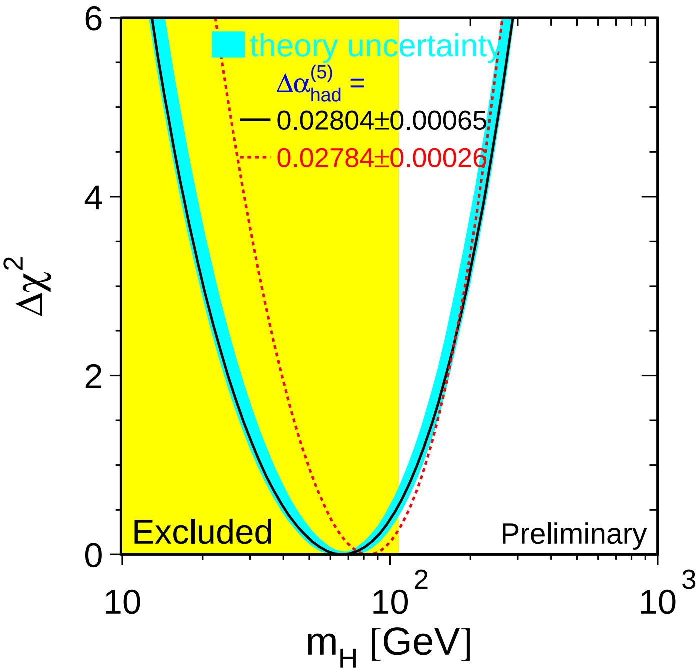
The SM healthy at energies $\leq$ 200 GeV



Direct measurements of M_w and M_{top} agree well with indirect constraints from LEP1

Predict low mass Higgs

Higgs boson remains experimentally unobserved



Direct limit from LEP2

M_H > 107.7 GeV @ 95% CL

Upper limit from LEP combined electroweak fit

M_H < 188 GeV @ 95% CL

Beyond the Standard Model

Hierarchy problem (2 fundamental energy scales)

$$\mathbf{M}_{\mathbf{EW}} / \mathbf{M}_{\mathbf{planck}} \approx 10^{-17}$$

Naturalness problem radiative corrections to Higgs mass squared $\propto \Lambda^2$ where Λ is the energy scale to which the theory remains valid → fine tuning problem with Higgs mass: can be resolved by

New physics at the TeV scale $\Lambda \approx 1\,\mathbf{TeV}$

OR

A symmetry protecting the Higgs mass against large radiative corrections (Supersymmetry)

If Higgs not discovered with mass < 800 GeV expect the dynamics of WW, ZZ scattering to reveal new structure energies $\approx$ 1 TeV

Must see something new at energies $\leq 1\,\mathbf{TeV}$

Supersymmetry (SUSY)

For each SM fermion (boson) there is a bosonic (fermionic) supersymmetric partner with identical mass and couplings

spin 0	spin ½	spin 1
sleptons $\tilde{\mathbf{l}}$	leptons $\mathbf{l}$	
squarks $\tilde{\mathbf{q}}$	quarks $\mathbf{q}$	
	gauginos $\tilde{\gamma}, \tilde{\mathbf{W}}, \tilde{\mathbf{Z}}$	gauge bosons $\gamma, \mathbf{W}, \mathbf{Z}$
	gluinos $\tilde{\mathbf{g}}$	gluons $\mathbf{g}$
Higgs bosons (5)	Higgsinos (5)	

SM (yellow)

SUSY (green)

Charged (neutral) gauginos and Higgsinos mix to form charginos (neutralinos)

$\tilde{\chi}^{\pm}_{\mathbf{i}=1,2}$ $\tilde{\chi}^{0}_{\mathbf{j}=1,2,3,4}$ **ordered by mass**

R-parity quantum number distinguishes SM and SUSY particles
Conventional to assume R-parity conservation

SUSY particles must be produced in pairs

Must be a lightest SUSY particle (LSP) which cannot decay

Usually the lightest neutralino $\tilde{\chi}^{0}_{1} \Longrightarrow$ **good CDM candidate**

Experimental signature: large missing transverse energy $\not{E}_{\mathbf{T}}$

Supersymmetry

Supersymmetry must be a broken symmetry

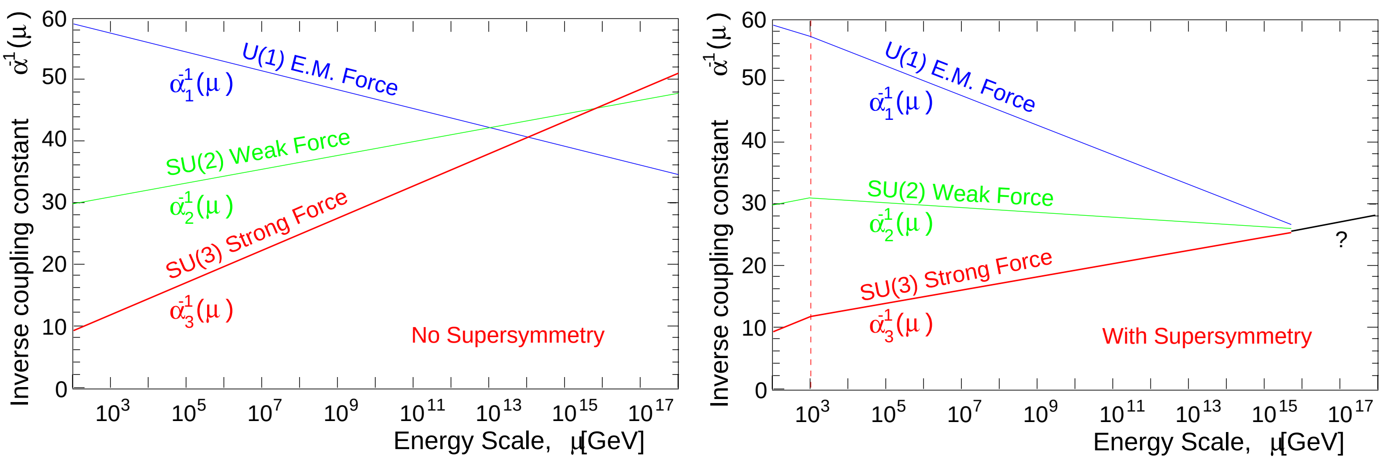
there is no $\tilde{e}$ with $M_{\tilde{e}} = M_e$

→ many model parameters (105 extra for MSSM)

SUSY solves the naturalness problem if $M_{susy} < 1$ TeV

Allows for gauge coupling unification if $M_{susy} < 1$ TeV

SUSY with $M_{SUSY} < 1$ TeV is called Weak-Scale SUSY



SUSY can provide dynamical EW symmetry breaking

SUSY may allow unification with gravity (all string theories are inherently supersymmetric)

MSSM Higgs Sector

Two Higgs doublets → 5 physical Higgs bosons

$$\mathbf{h^0, H^0, A^0, H^\pm}$$

Assume M_{SUSY} ~ 1 TeV so Higgs → SUSY kinematically forbidden

All masses and couplings then given as $\mathbf{f}(\tan\beta, \mathbf{M_A})$

$\mathbf{h^0}$

Lightest MSSM Higgs

$\mathbf{M_{h^0} < M_Z}$ **at tree level**

$\mathbf{M_{h^0} <}$ **140 GeV** **after loop corrections**

In limit of large $\mathbf{M_A}$ and/or $\tan\beta$, $\mathbf{h^0}$ behaves like $\mathbf{H^0_{SM}}$

$\mathbf{H^0 A^0}$

Heavy neutral CP-even, CP-odd Higgs respectively

Decays to $\tau^+\tau^-$, $\mu^+\mu^-$ enhanced for high $\tan\beta$

$\mathbf{H^\pm}$

Heavy charged Higgs

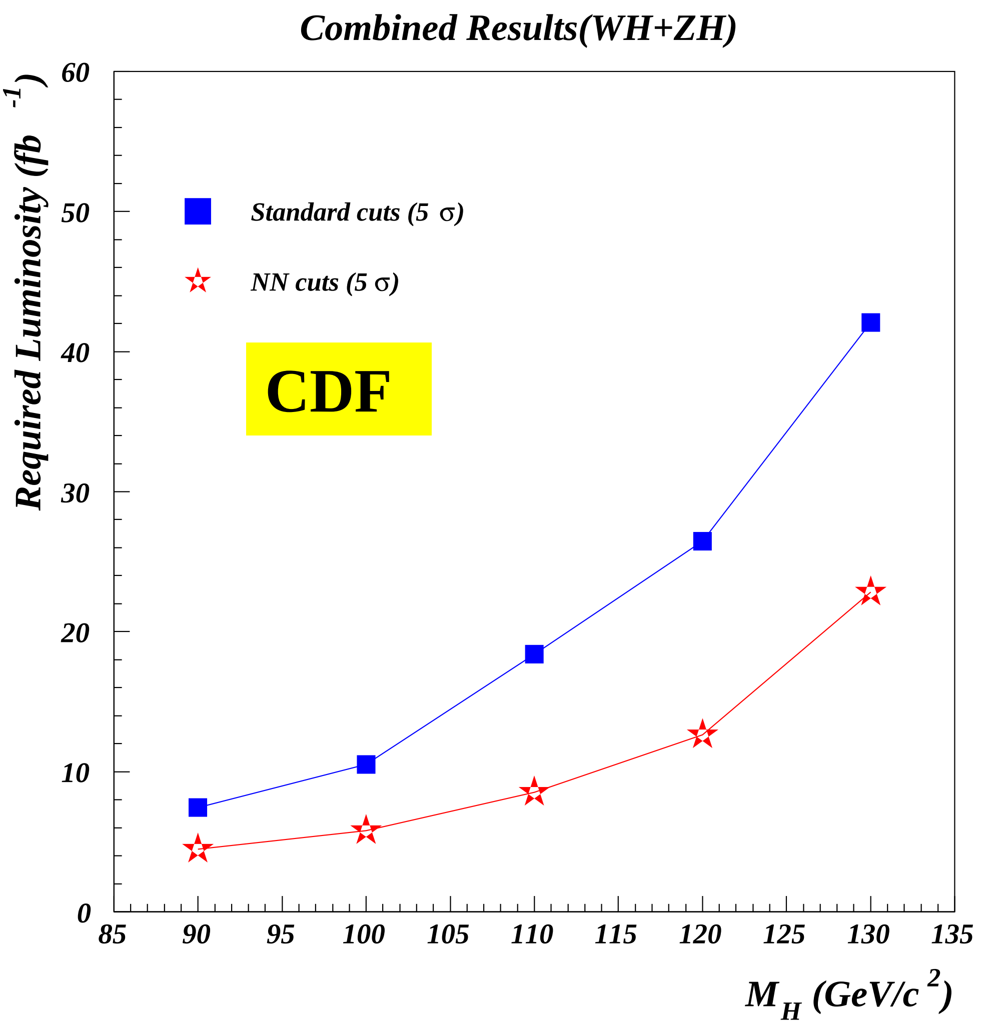
NB: for moderate ($\mathbf{M_A}$, $\tan\beta$) or $\mathbf{M_A}$ > 500 GeV
only $\mathbf{h^0}$ is observable

Higgs Discovery at Tevatron RUN II

$$p\bar{p} \rightarrow WH \rightarrow l\nu b\bar{b}$$

$$p\bar{p} \rightarrow ZH \rightarrow l^+l^- b\bar{b}$$

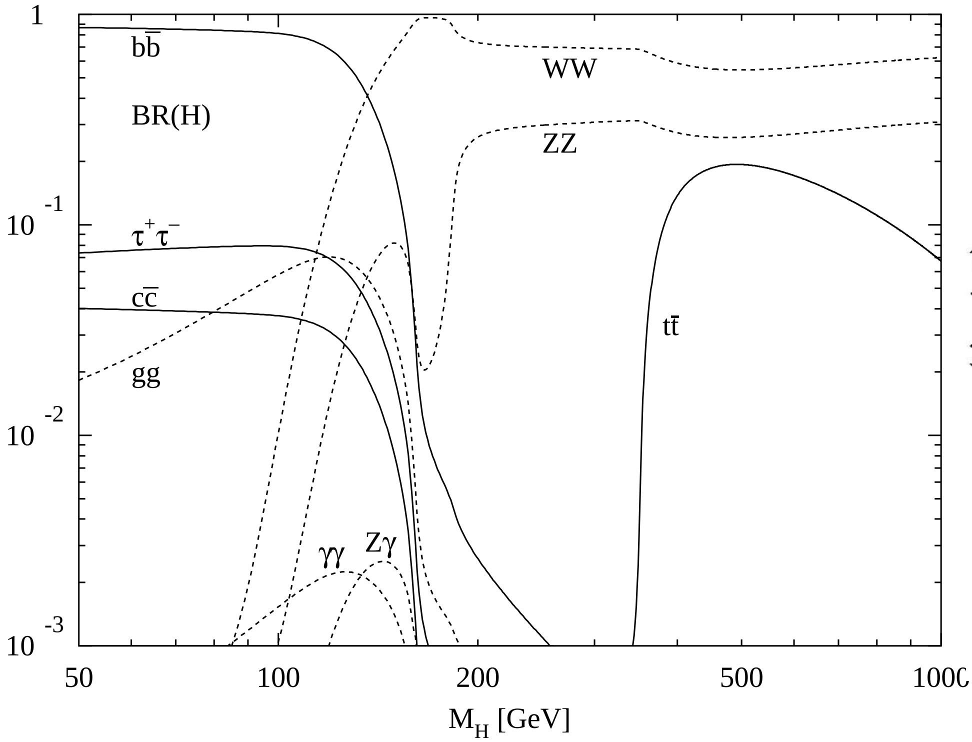
$$p\bar{p} \rightarrow ZH \rightarrow \nu\bar{\nu} b\bar{b}$$

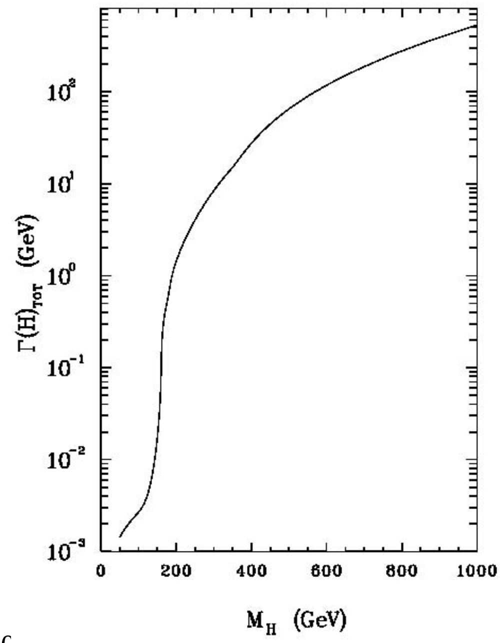


Int. luminosity target for Run II
15-20 fb^{-1} / expt.
Prior to start of LHC

5 year running → 3-5σ for $M_H \leq$ 130 GeV

SM Higgs Properties





Large QCD backgrounds: look for final states with high-p_T leptons and photons

Important channels:

low mass
$$\begin{cases} H \to \gamma\gamma \\ H \to b\bar{b} \end{cases}$$

intermediate mass
$$\begin{cases} H \to ZZ^{(*)} \to l^+l^-l^+l^- \\ H \to WW^{(*)} \to l^+\nu\ l^-\nu \end{cases}$$

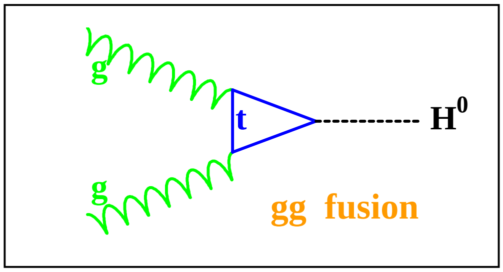
high mass
$$\begin{cases} H \to ZZ \to l^+l^-\nu\nu \\ H \to WW \to l\nu \text{ jet jet} \end{cases}$$

Higgs Production at LHC

Production cross-sections at the LHC

Process	σ	Events / sec	Event / year
$\mathbf{W} \to \mathbf{e}\,\nu$	15 nb	15	10^{8}
$\mathbf{Z} \to \mathbf{ee}$	1.5 nb	1.5	10^{7}
$\mathbf{t\bar{t}}$	800 pb	0.8	10^{7}
$\mathbf{b\bar{b}}$	500 μb	10^{5}	10^{12}
$\tilde{\mathbf{g}}\tilde{\mathbf{g}}\,(\mathbf{M}_{\tilde{g}} = 1\mathbf{TeV})$	1pb	10^{-3}	10^{4}
$\mathbf{H}_{SM}\,(\mathbf{M} = 0.8\mathbf{TeV})$	1pb	10^{-3}	10^{4}
QCDjets $\mathbf{p}_{T} > 200$ **GeV**	100 nb	10^{2}	10^{9}

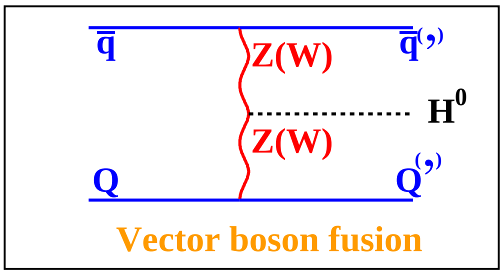
Direct Higgs production



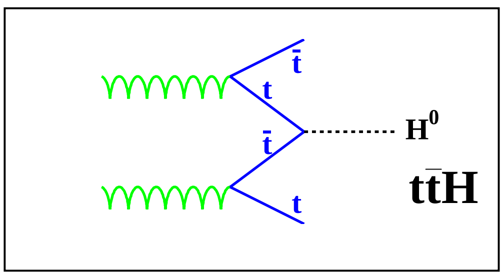
gg fusion or vector boson fusion:

Need high p_T leptons or photons from Higgs decay

Huge QCD background for channels with jets



Associated Higgs production



High p_T leptons from top decays used for triggering

Top reconstruction used for QCD

background suppression

$H \rightarrow \gamma\gamma$

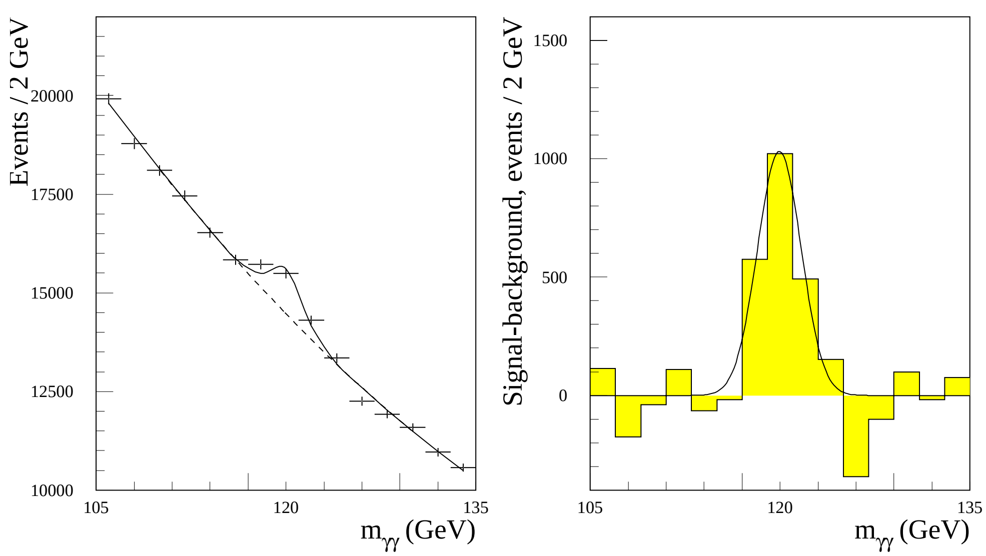
Useful for M_H < 140 GeV

low luminosity running: use direct production (utilize high p_T photons) → large signal, low S/B

high luminosity running: add contributions from associated production, $WH, ZH, t\bar{t}H$ (utilize reconstruction of associated particle(s)) → small signal, good S/B

Backgrounds

$\gamma\gamma$	**(irreducible)**	$\sigma_{\gamma\gamma} \sim 3\text{pb}$	→	**need** $\sigma_{M_H} \sim 1\%$
$\gamma j + jj$	**(reducible)**	$\sigma_j \sim 10^6 \sigma_{\gamma\gamma}$	→	**need** $R_j > 10^3$



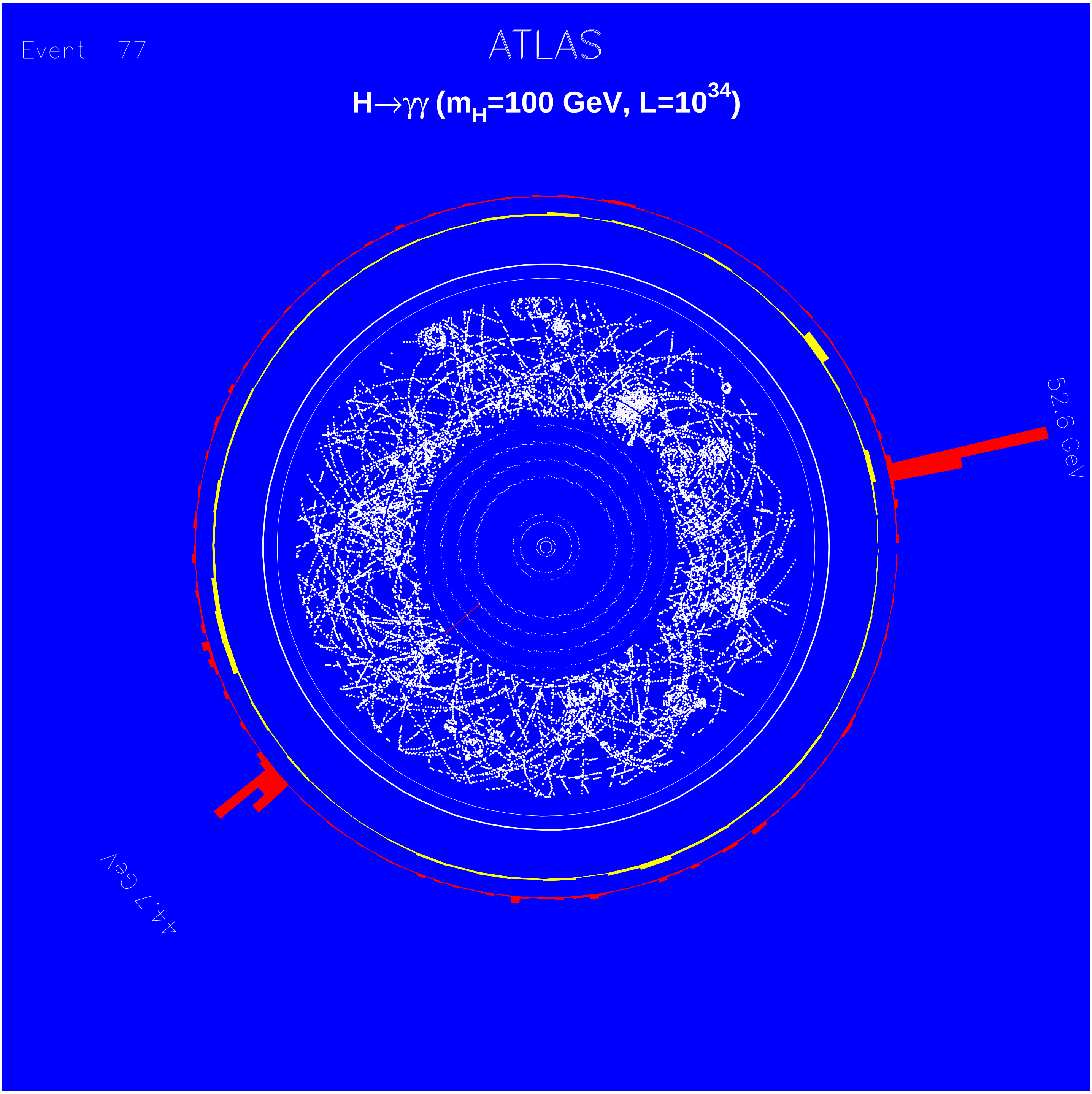
M_H = 120 GeV

100 fb^{-1}

signal

$\sigma \times BR \approx 50fb$

Sets severe requirements of the performance of the ATLAS electromagnetic calorimetry


Event 77
ATLAS
H→γγ (m_H=100 GeV, L=10^34)
52.6 GeV
44.7 GeV

$t\bar{t}H, H \rightarrow b\bar{b}$

Largest BR for low mass Higgs, but huge QCD background

Use associated production with full reconstruction of both top quarks (allows triggering and background suppression)

Backgrounds from ttZ, Wjjjjjj ttjj etc., (see below)

Dominant – can be measured in tt production

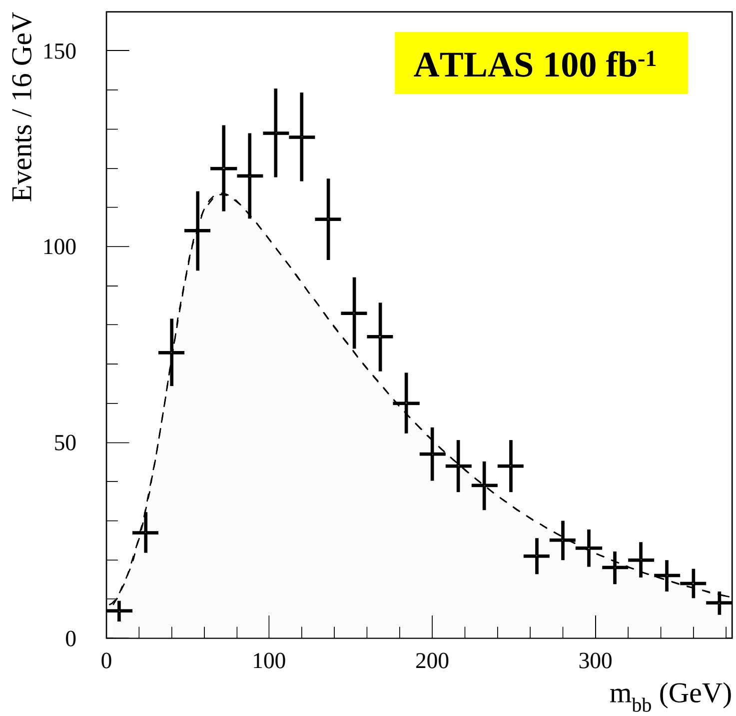
Both top quarks reconstructed

$$H \rightarrow b\bar{b}$$
$$t \rightarrow bjj$$
$$\bar{t} \rightarrow \bar{b}l\nu$$

$$\varepsilon \approx 1\%$$

ATLAS 30 fb^{-1}

Higgs mass (GeV)	80	100	120
Signal S	81	61	40
$t\bar{t}Z$	7	8	2
Wjjjjjj	17	12	5
$t\bar{t}jj$	121	130	120
Total background B	145	150	127
S/B	0.56	0.41	0.32
$S/\sqrt{B}$	6.7	5.0	3.6
$S_{H\rightarrow b\bar{b}}/S_{total}$	0.67	0.64	0.59

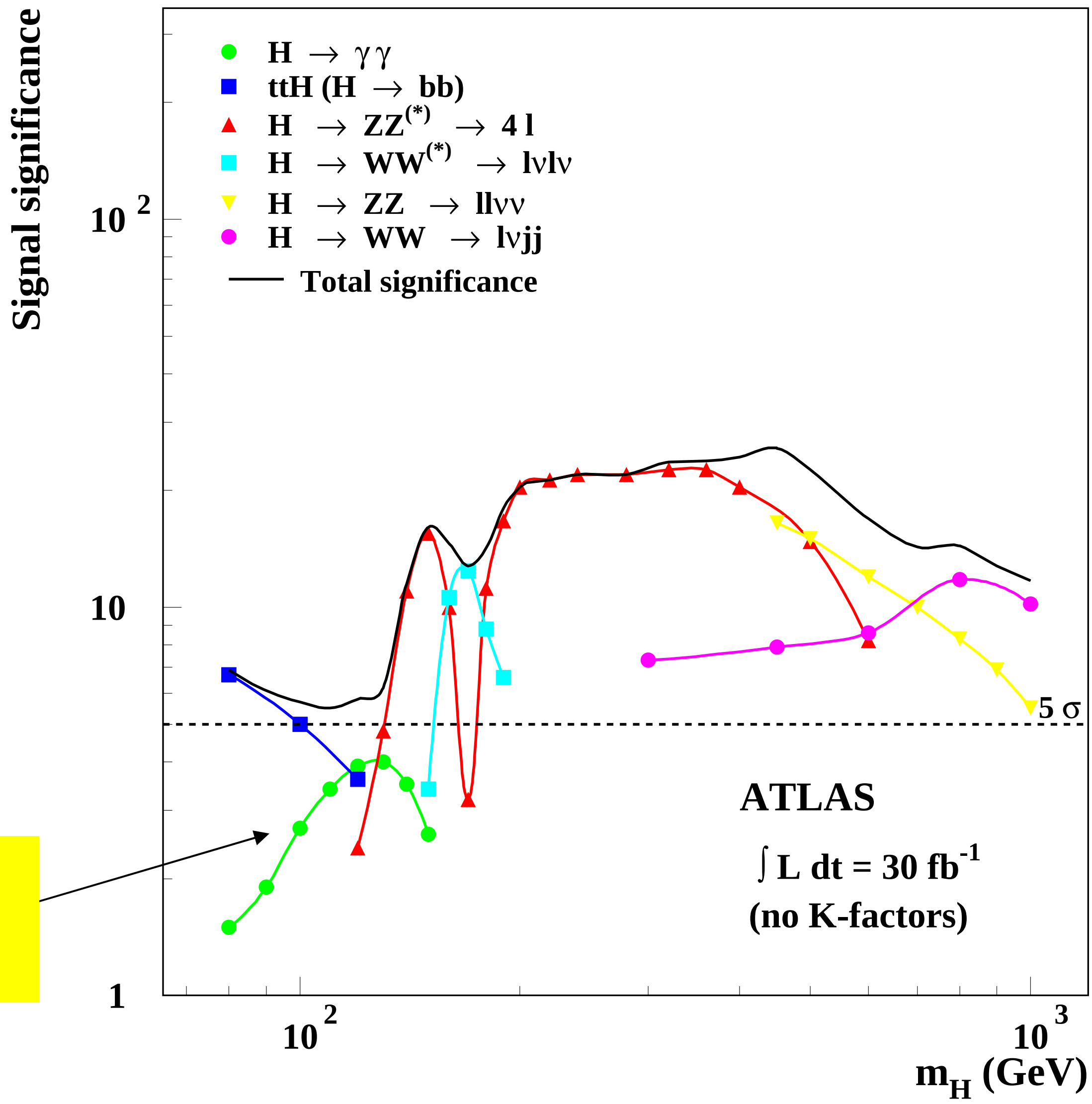


$$S/B \approx 0.25$$
$$S/\sqrt{B} \approx 4$$

Sets stringent requirements on b-tagging performance at high luminosity

SM Higgs Sensitivity 30 fb^{-1}

3 years of running at low luminosity



No single channel discovery for M_H=100-130 GeV

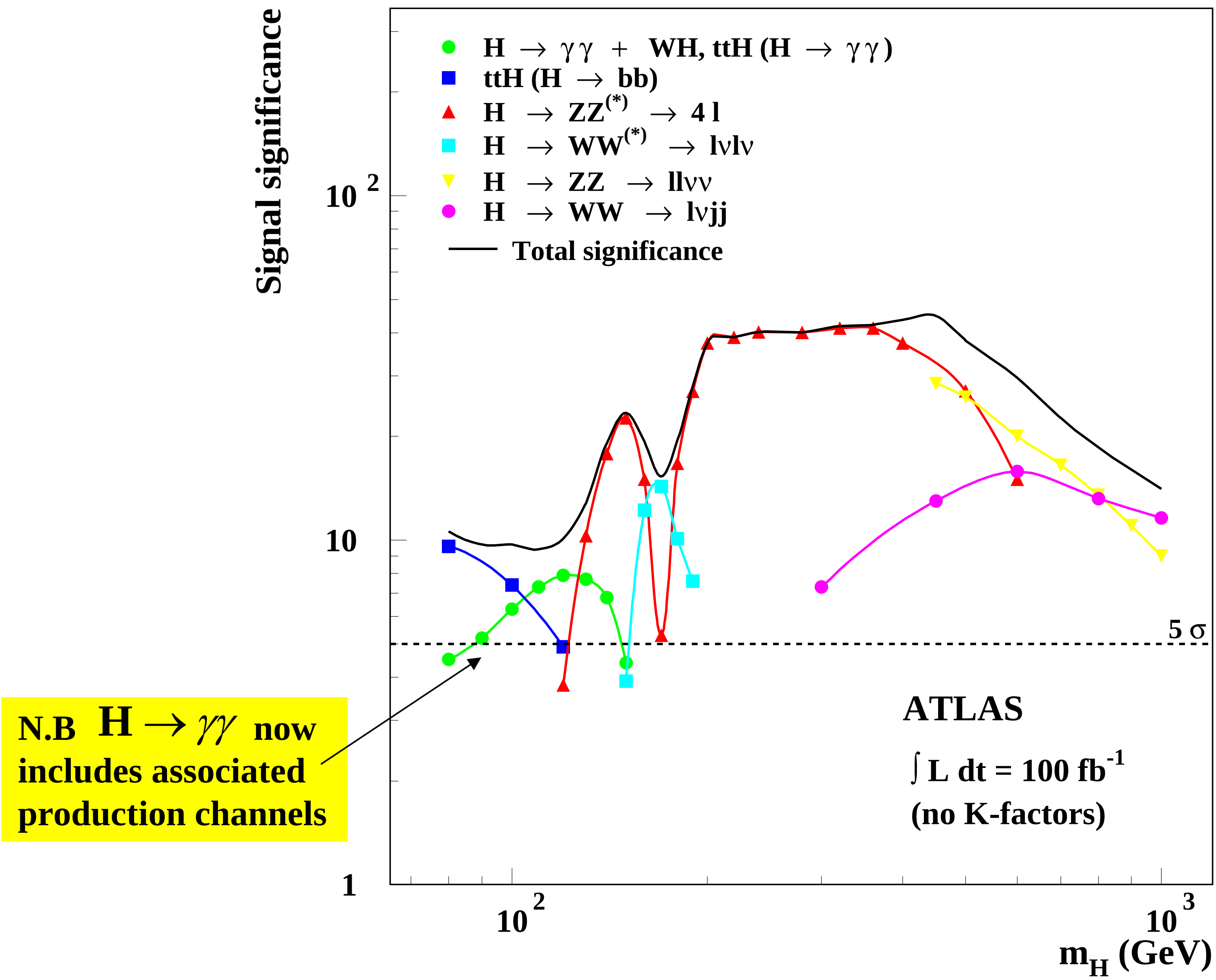
Full coverage of mass region with significance > 5 σ

Needs combined channels for discovery at low M_H

Multiple discovery channels for M_H > 300 GeV

SM Higgs Sensitivity 100 fb^{-1}

1 year running at high luminosity

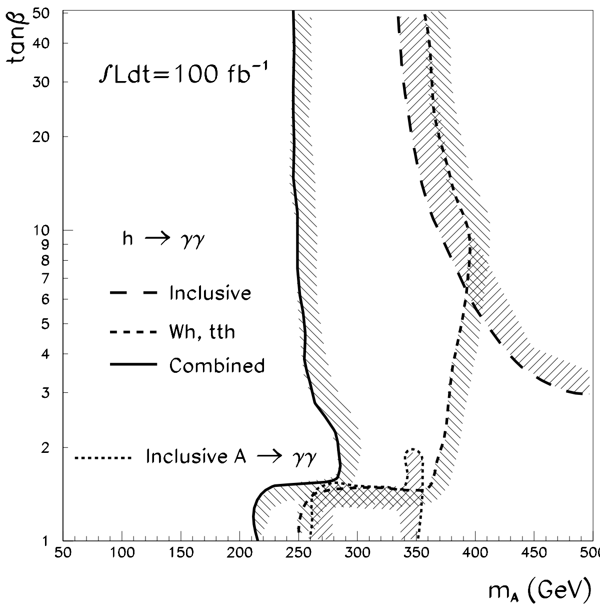


Multiple discovery channels for all M_H

Search for MSSM Higgs Bosons

$\mathbf{h \to \gamma\gamma}$ **and** $\mathbf{t\bar{t}h, h \to b\bar{b}}$ **very important in search for lightest MSSM Higgs (as they are for** $\mathbf{H_{SM}}$**)**

$\mathbf{h \to \gamma\gamma}$

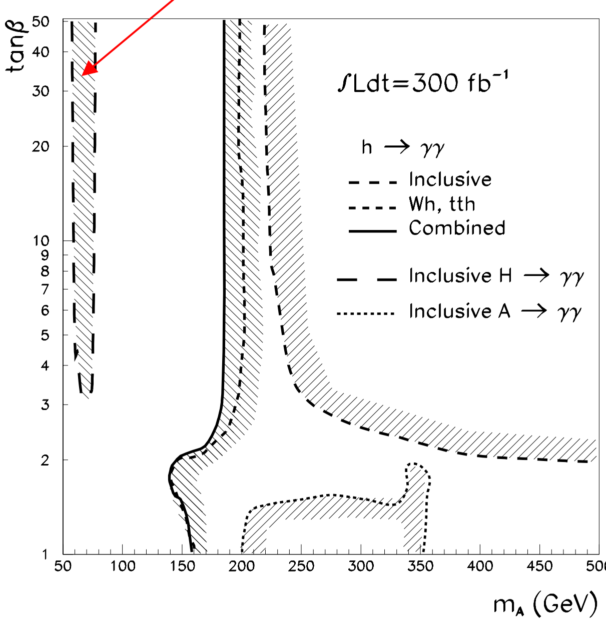


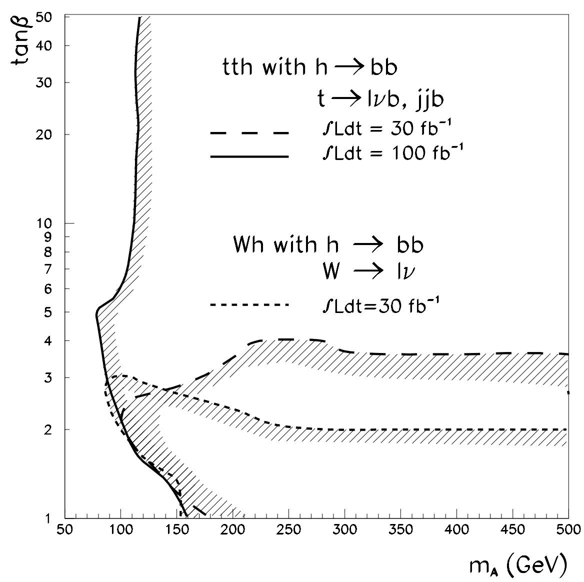
$\mathbf{M_{SUSY}}$ ~ 1 TeV
Higgs properties are function of ($\mathbf{M_A}$, $\tan\beta$) only

Contributions to exclusion regions from H/A are small

$\mathbf{t\bar{t}h, h \to b\bar{b}}$

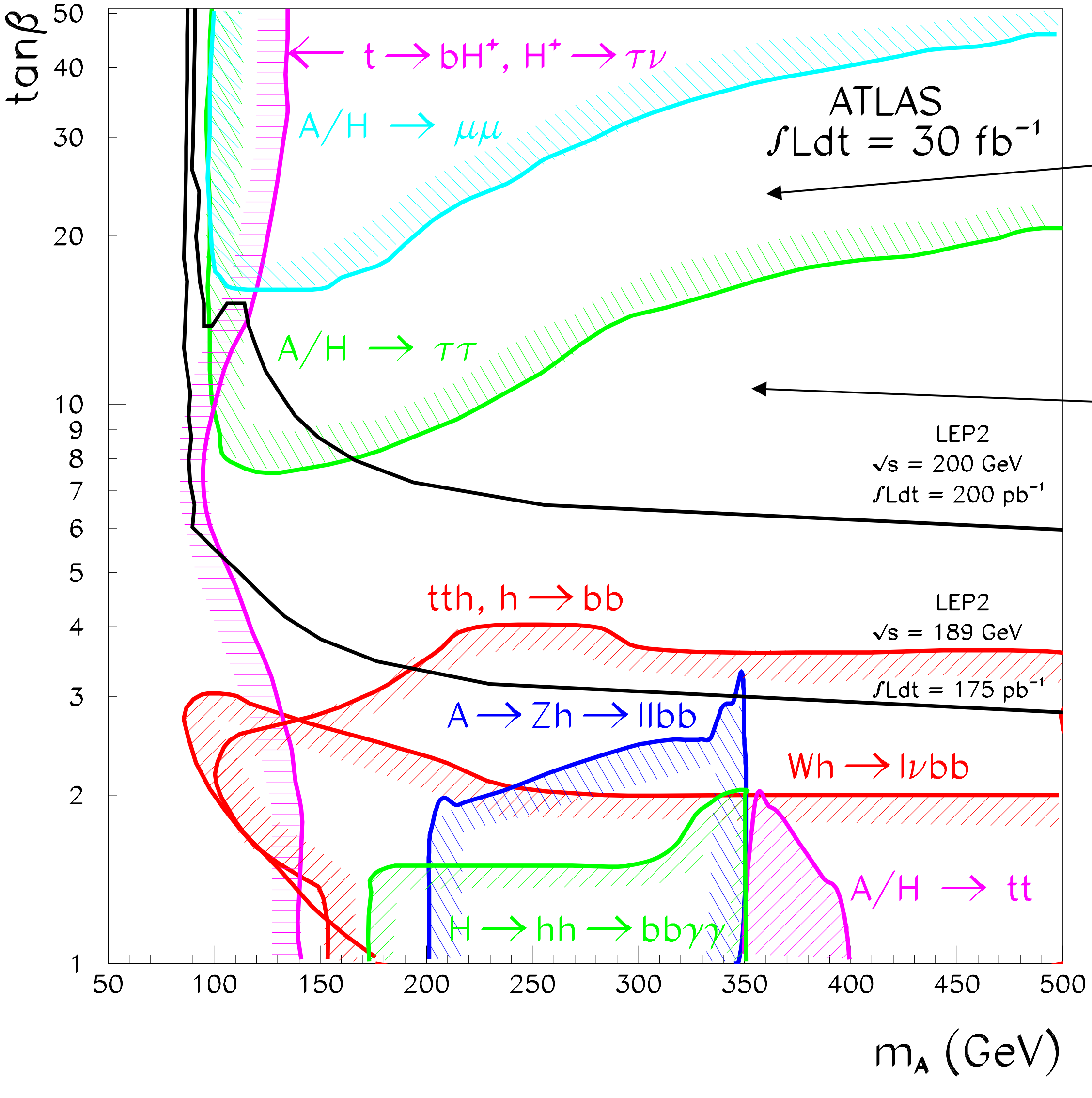
Almost excluded by LEP





MSSM Higgs Sensitivity 30fb^{-1}

Three years of running at low luminosity



H/A important for high $\tan\beta$

Unexcluded region with moderate $(M_A, \tan\beta)$

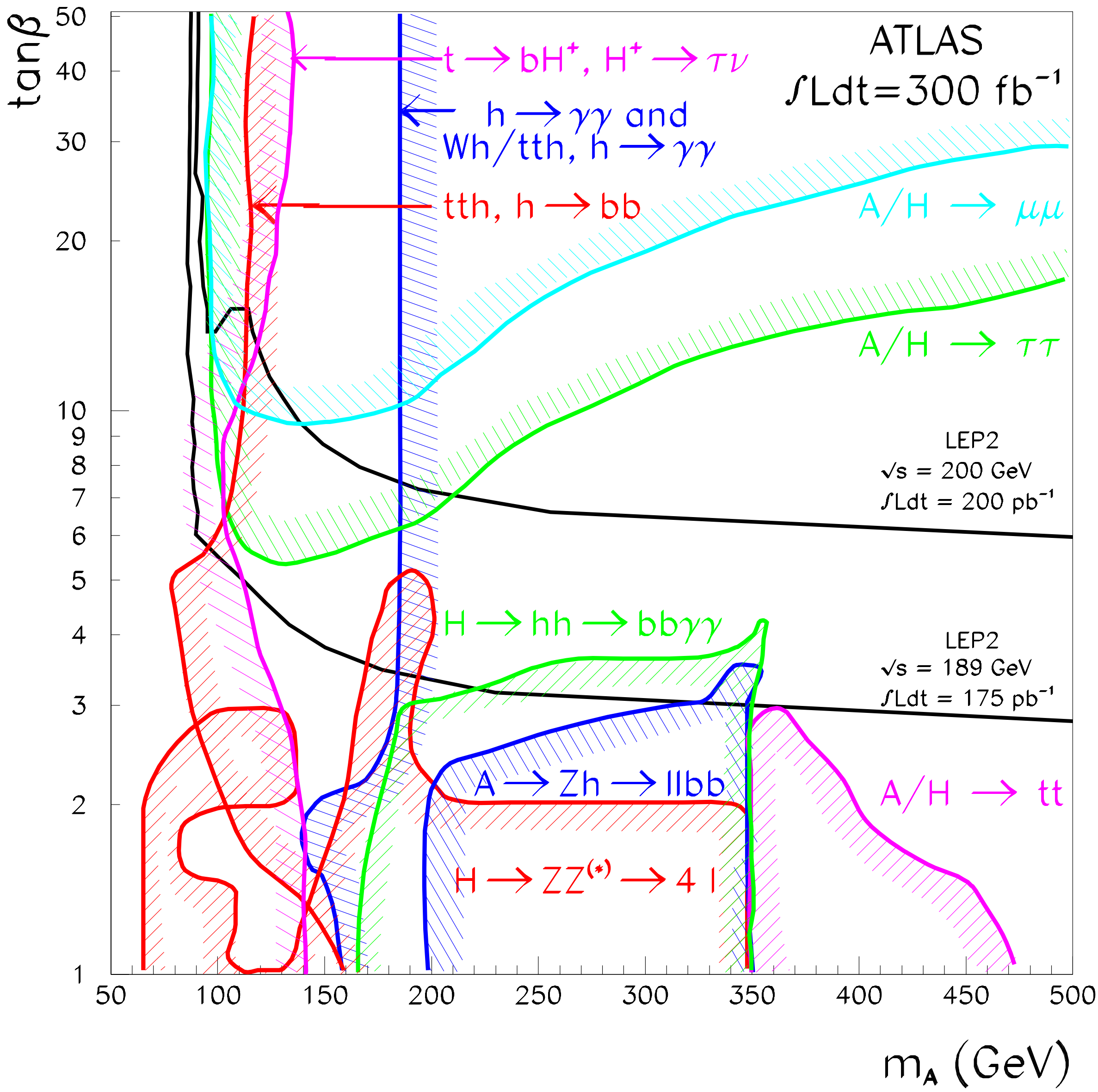
Combined ATLAS/LEP2 exclusion for most of the $(M_A, \tan\beta)$ plane

Region with moderate $(M_A, \tan\beta)$ remains unexcluded

N.B. LEP2 exclusion for 200 pb^{-1} / expt at 200 GeV so should be conservative

MSSM Higgs Sensitivity 300 fb^{-1}

Three years running at high luminosity



Full coverage of the $(\mathrm{M_A}, \tan\beta)$ plane

Multiple channel coverage for most the plane

Most important channels $\mathbf{h \to \gamma\gamma}$ and $\mathbf{t\bar{t}h, h \to b\bar{b}}$

Supersymmetric Particle Searches

Reduce number of SUSY free parameters

Assume SUSY broken in some hidden sector at high energy
SUSY breaking "mediated" to visible sector via some interaction

Two popular scenarios with different phenomenologies:

Gravity-mediated **Phenomenology dictated LSP**

Gravitino $\tilde{G}$ very heavy, phenomenologically unimportant

MSUGRA: 5 parameter model, assumes parameter unifications at GUT scale

$\mathbf{m}_0$	**Common scalar mass at unification scale**
$\mathbf{m}_{1/2}$	**Common gaugino mass at unification scale**
$\tan\beta$	**Ratio of Higgs vevs**
$\mathbf{A}_0$	
$\mathbf{sign}(\mu)$	

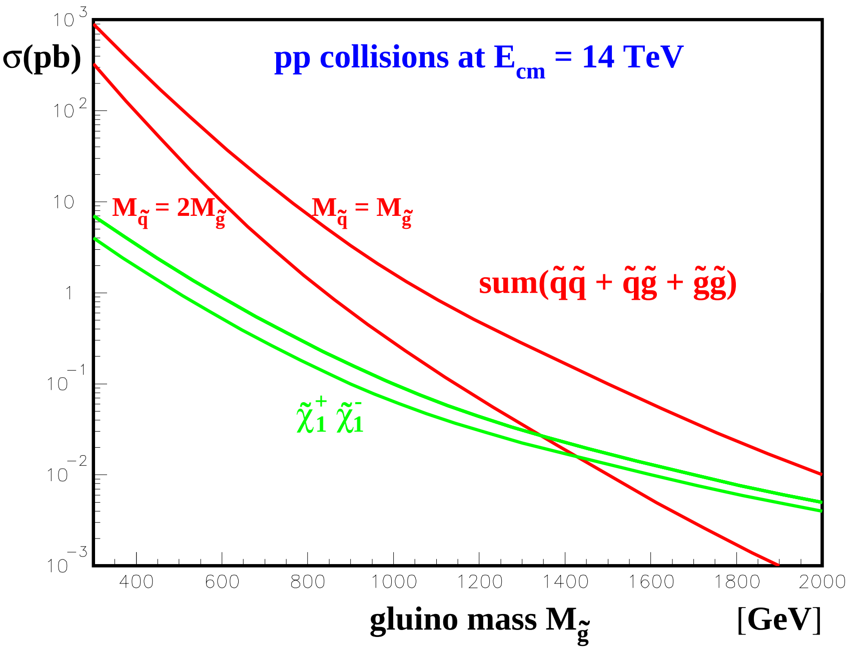
Gauge-mediated **Phenomenology dictated NLSP**

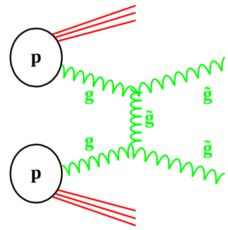
Gravitino is the LSP ! $\mathbf{M}_{\tilde{G}} << 1\mathbf{MeV}$ **Next to lightest SUSY particle**

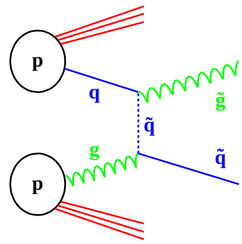
NLSP can have short or long decay length

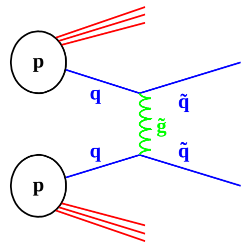
Minimal model studied by ATLAS has 6 parameters

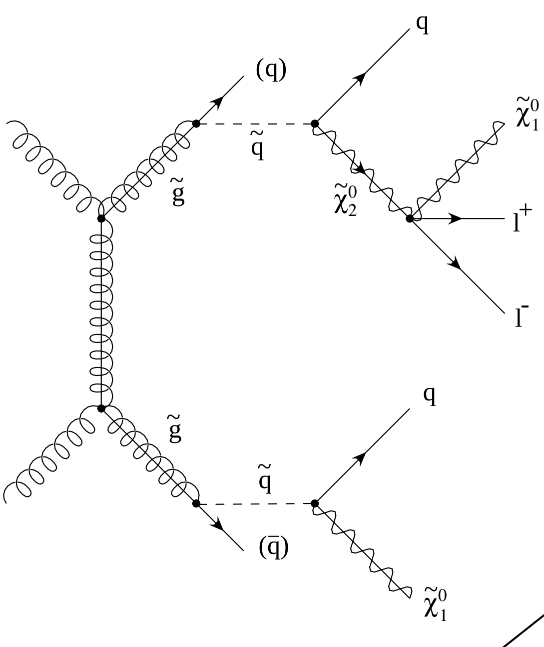
Supersymmetric Particle Searches











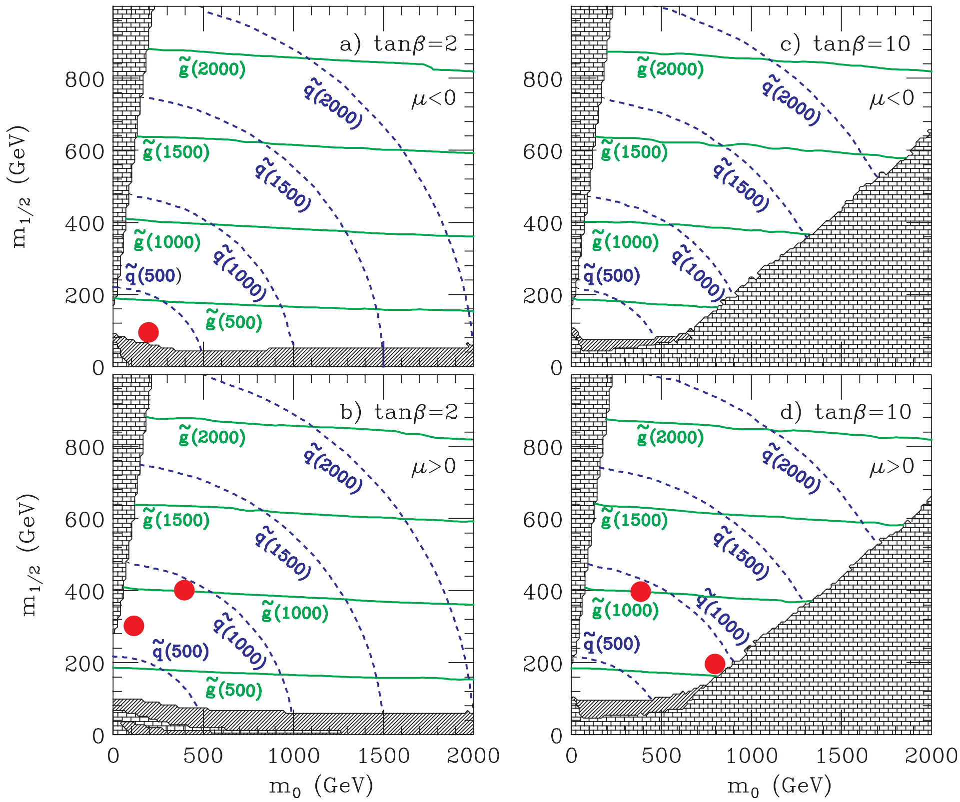
Signature channels

0 l	Jets + missing E_T
1 l	1 lepton + jets + missing E_T
2 l	2 leptons + jets + missing energy SS, OS
3 l	3 leptons + jets + missing energy
2 (3) l,0j	2 or 3 leptons with jet veto + missing E_T

$l^+ l^-$ jet jet + missing E_T final state

Search channels for direct gaugino or slepton production

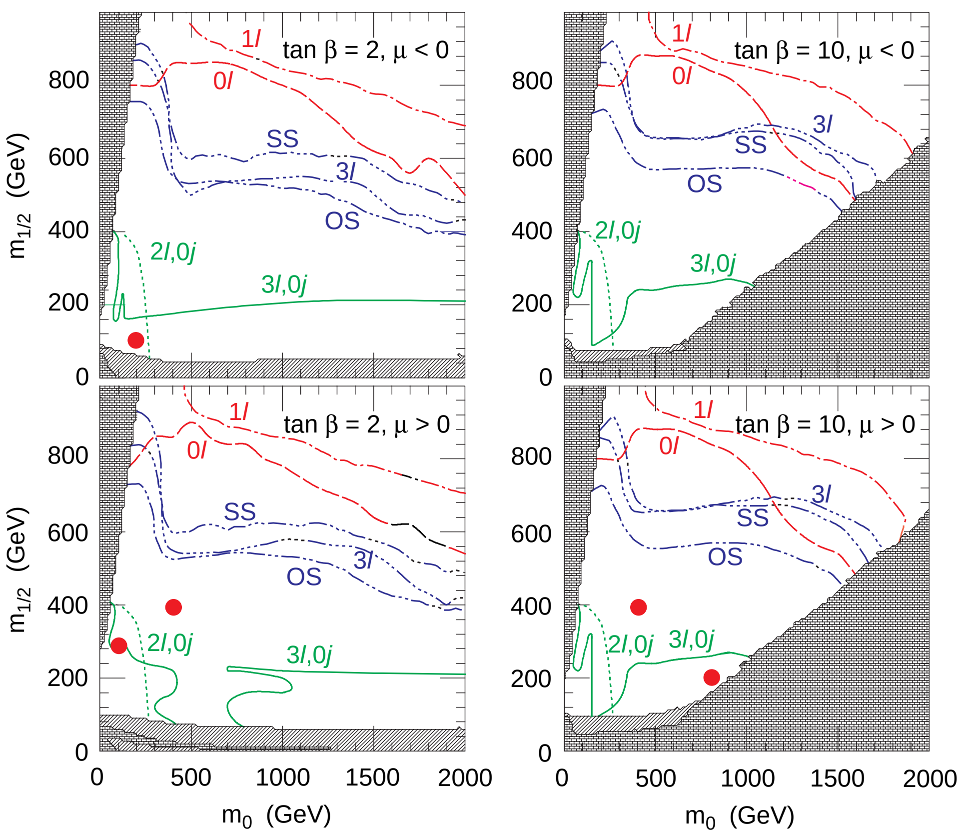
Supersymmetric Particle Searches



SUGRA

5 points in MSUGRA parameter space chosen for study

Mass points shown in red

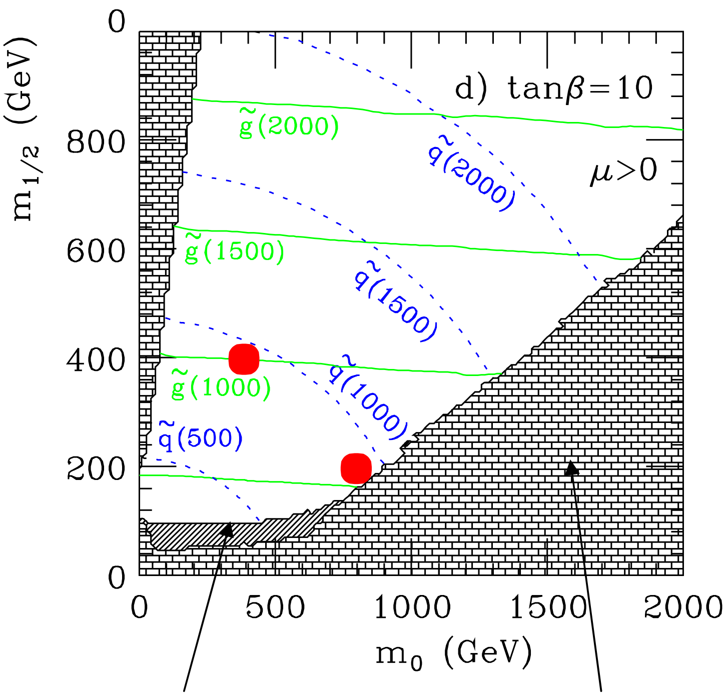


Coverage shown for various lepton and/or jet + missing energy signals

SUSY Searches (SUGRA)

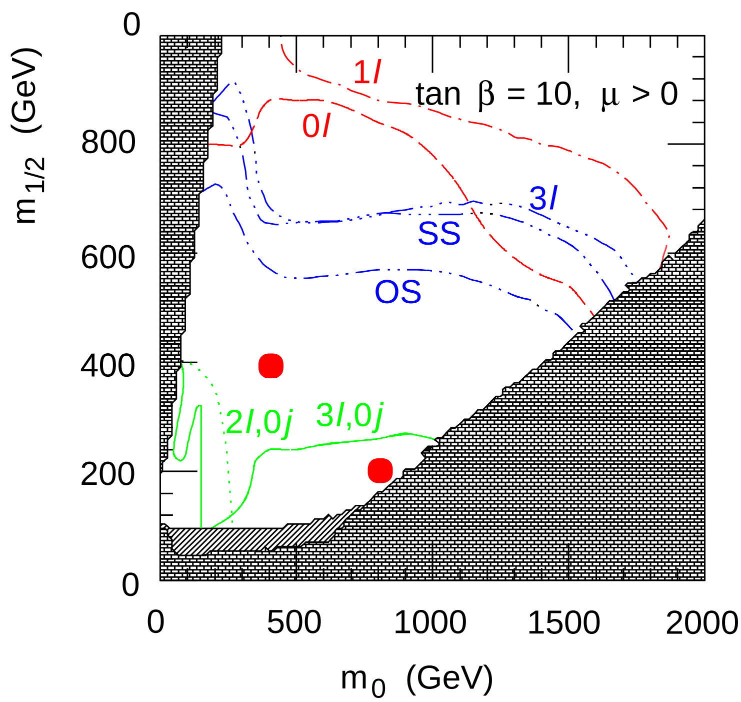
LHC studies choose 5 representative points in parameter space

Two shown here in red



Experimentally excluded

No EW symmetry breaking



$$\int L = 10\,\mathrm{fb}^{-1}$$

Mass reach defined by ≥ 10 signal events with $S/\sqrt{B} > 5$

For jets + missing energy, mass reach for squarks and gluinos extends to > 2 TeV

In multilepton channels reach extends to > 1 TeV

Weak scale SUSY easily discovered. Dominant background to a given process is from other SUSY processes

SUSY Searches (GMSB)

Most significant difference phenomenlogically is ~ massless LSP

Phenomenology dictated by:

NLSP (usually either $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ or $\tilde{l}^{\pm} \rightarrow \tilde{G} l^{\pm}$)

Scale of SUSY breaking (one of model parameters) dictates the gravitino mass and the NLSP lifetime

NLSP lifetime →

NLSP	**short**	**intermediate**	**long**
$\tilde{\chi}_1^0$	**photons + $\not{E}_T$**	**non-pointing photons + $\not{E}_T$**	**As in SUGRA**
$\tilde{l}$	**leptons + $\not{E}_T$**	**kinked charged tracks + $\not{E}_T$**	**Long lived heavy charged particles**

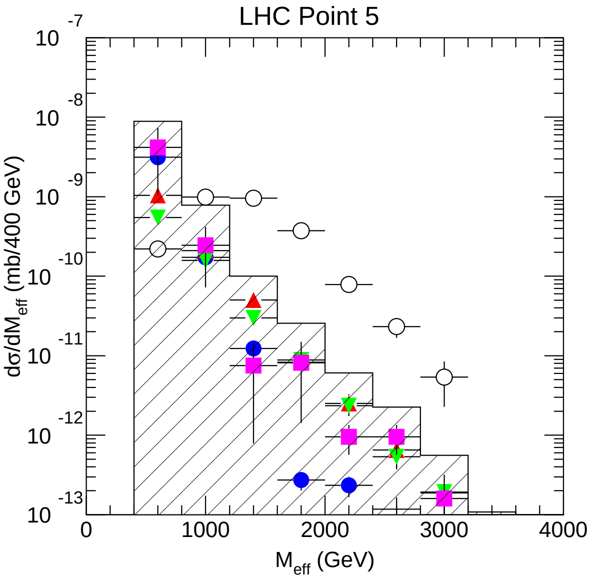
Unusual signatures in case of intermediate τ_{NLSP}

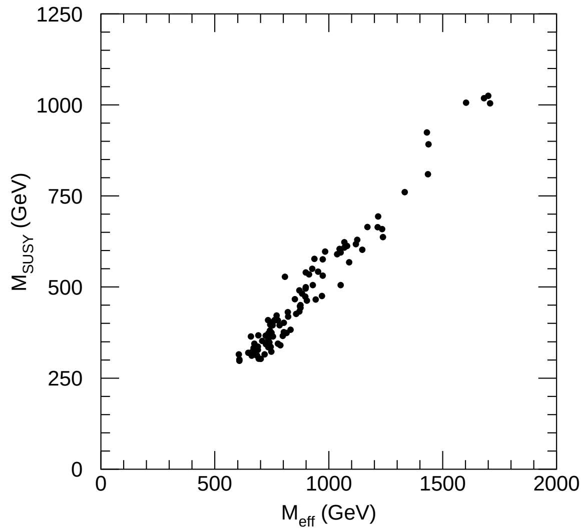
Scenarios have especially low standard model backgrounds

Discovery generally straightforward

Parameter determination trickier (as for SUGRA)

Supersymmetric Particle Searches





Estimate of M_{SUSY} in jets + missing energy channel

$$\mathbf{M_{eff} = E_T^{miss} + p_T^1 + p_T^2 + p_T^3 + p_T^4}$$

Heavy Higgs

H_{SM} coupling to gauge bosons increases with increasing mass

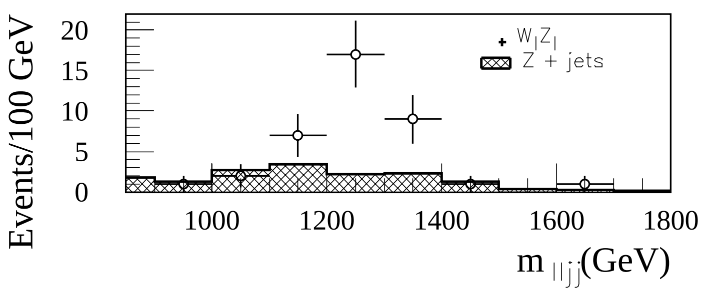
- **Resonance wider**
- **interaction stronger → eventual violation of unitarity limit**

No fundamental scalar ?

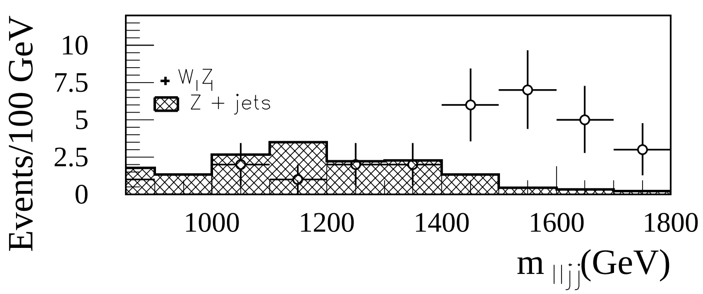
- **Need new physics to EW symmetry breaking, regularization of vector boson couplings and fermion mass generation**

Study $V_L V_L \rightarrow V_L V_L$ scattering (longitudinal gauge bosons are goldstone bosons of symmetry breaking process)

Forward-jet tagging important



Sensitivity to WZ resonance shown for M_{WZ} = 1.2, 1.5 TeV for 300 fb^{-1}



Non-resonant $V_L V_L$ searches more challenging

Many Other Searches

- **Technicolour**
- **Additional gauge bosons**
- **Compositeness, leptoquarks, excited quarks**
- **Monopoles**
- **R-parity violating SUSY (baryon, lepton number violating decays)**

Large Compact Extra Dimensions

Recall hierarchy problem $M_{EW} / M_{planck} \sim 10^{-17}$

Postulate M_{planck} effective energy scale, not fundamental

Assume existence of n compact spatial dimensions of (compactified) radius R

$$V(r) = \frac{m_1 m_2}{M_{pl(4+n)}^{2+n}} \bullet \frac{1}{r^{n+1}} \quad (r << R) \qquad V(r) = \left\{ \frac{m_1 m_2}{M_{pl(4+n)}^{n+2}} \bullet \frac{1}{R^n} \right\} \frac{1}{r} \quad (r >> R)$$

Effective 4-dim planck M_{planck} is then given by $M_{planck}^2 = M_{pl(4+n)}^{n+2} R^n$

Requiring $M_{pl(4+n)} \sim M_{EW}$ → $R \sim 10^{(30/n)-17}$ cm

Various constraints on models with compactification

n = 1 → R = 10^{13} cm (cosmologically excluded)

n = 2 → R ~ 0.1 – 1.0 mm (unexcluded by tests of $1/r^2$ nature of gravitation, but excluded by SN1987)

Collider limits from missing energy searches (next slide)

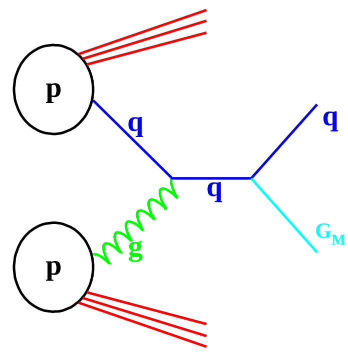
Large Compact Extra Dimensions

Model of Arkani-Hamed, Dimopoulos and Dvali: only gravitons propogate freely in the "bulk"

Massless gravitons in 4+n dim → massive KK gravitons G_M in 4D ⇒ Missing energy signature

Possible signatures at LHC

$$pp \rightarrow G_M + \text{jet}$$ **monojet** →



$$pp \rightarrow G_M + \gamma$$

$$pp \rightarrow G_M + Z$$

Non-kinematic high p_T cutoff

Other particles localized within $1/M_{EW}$ in the extra n dimensions

In sufficiently hard collisions $E_{esc} > M_{EW}$ particles can acquire momentum in the extra dimensions and disappear from the 4D world → upper limit for p_T distributions at

$$p_T = E_{esc}$$

Such particles may or may not periodically return to and deposit energy in the 4D world

Constraint Evasion !

Keith Meyers/The New York Times

Dr. Lisa Randall and Dr. Raman Sundrum, superstring theorists who portray the universe as one of many bubbles floating inside a four-dimensional megaverse.

Physicists Finally Find a Way To Test Superstring Theory

The idea, if correct, explains the universe.

By GEORGE JOHNSON

For a quarter of a century, superstring theory has promised that the universe could be understood more deeply than ever before, with all the forces unified into one, if it were seen in a startling new light — as a kind of mathematical music played by an orchestra of tiny vibrating strings. Each note in this cosmic symphony would represent one of the many different kinds of particles that make up matter and energy.

But despite heroic efforts to keep this strange vision alive, with one mathematical embellishment after another, a seemingly fatal credibility problem has remained: no one has been able to figure out how to test the idea with experiments.

To give the strings enough wiggle room to carry out their virtuoso performance, theorists have had to supplement the familiar three dimensions of space with six more — curled up so tiny that they would be explorable only with absurdly high-powered particle accelerators the size of an entire galaxy. It's a fact of life on the subatomic realm that smaller and smaller distances take higher and higher energies to probe.

In the last few months, however, new ideas emerging from the theoretical workshops offer some hope of connecting the airy speculations to reality. Physicists are proposing a revised view in which at least one of the extra dimensions is vastly larger — large enough perhaps to be indirectly detected with existing accelerators.

"This is a field day for the experimenters," said Dr. Joseph Lykken, a theoretical physicist at Fermi National Accelerator Laboratory in Batavia, Ill. "Now there are all these things they can look for." In fact, he ventured, it is conceivable that experimenters have already found subtle hints of other dimensions. They just have had no way of appreciating what they were seeing.

Though human brains are not wired to picture a world beyond the familiar three dimensions of space, one can begin to overcome this myopia by pretending to be antlike creatures in a two-dimensional fantasy world like the one in Edwin A. Abbott's story "Flatland." Confined to the surface of a plane, the Flatlanders can move left and right or forward or backward, but the idea of up and down is inconceivable to them.

Now suppose this two-dimensional world were rolled into a long tube. The Flatlanders could still move in only two directions — along or around the outside surface of their soda

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Randall and Sundrum: can derive the same relationship between a higher dimensional planck mass and the one of our 4-dim world WITHOUT compactification. Evades some astrophysical constraints on compactified models.

Summary

Exciting times ahead !

LEP provided

Promise of precision tests of the SM

Hope for new physics discoveries

LHC will provide

Promise of discovery

Initial parameter determination

$\Rightarrow$ **precision tests will be done at NLC**

Provided they exist, we will observe

SM Higgs or MSSM Higgs (h^0)

Weak Scale Supersymmetry

Sensitivity also to other anticipated new physics not discussed here

Possibly (or even probably ?) we may discover something entirely unexpected