Physics at the TeV Scale: Discovery Potential of the ATLAS Detector at the LHC

Physics motivations

ATLAS and the LHC

Higgs searches

Beyond the Standard Model

Conclusions

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Abstract

The Standard Model (SM) of particle interactions spectacularly accounts for all experimental results to date. Only the Higgs sector of the theory, responsible for electroweak symmetry breaking and particle masses, remains to be confirmed. Despite this success, there are compelling theoretical reasons to believe that new physics beyond the SM must exist below or near 1 TeV. Supersymmetry (SUSY) is a particularly popular extension of the SM, as well as a critical ingredient in Grand Unified Theories, but its existence in nature awaits experimental confirmation. The LHC, currently under construction at CERN, Geneva, will produce proton-proton collisions at a centre of mass energy of 14 TeV, allowing the exploration of physics at the TeV scale. The ATLAS detector, also currently under construction, is designed to take full advantage of the LHC. This talk will review the physics discovery potential of the ATLAS detector, with emphasis on the SM and SUSY Higgs sectors .

Physics Motivation

The **Large Hadron Collider** will allow the exploration of the structure of matter at the **energy frontier** and, equivalently, at the **smallest scale**

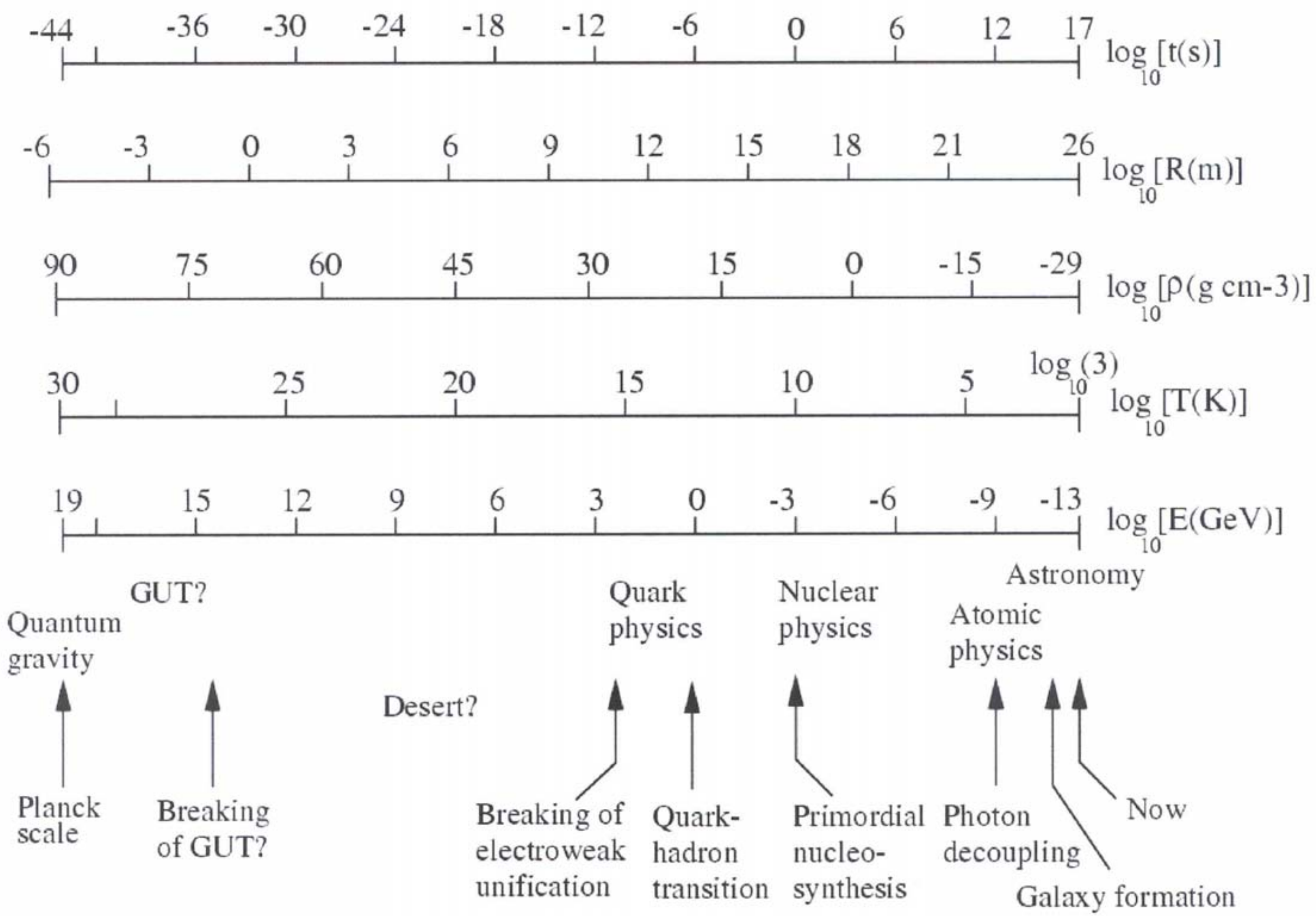
probe constituent energies in the 1-2 TeV region using

14 TeV pp collisions

- The physical origin of electroweak symmetry breaking and the origin of mass
  - The Higgs boson
- The physical origin of CP violation
  - Unitary triangle
- Searches beyond the Standard Model
  - Supersymmetry, extra dimensions, new gauge bosons, compositeness, ...
- Precision measurements of Standard Model parameters
  - top, bottom, tau, QCD, ...

Space, Time and the Energy Frontier

The "History" of the Universe from the Planck time to the present, showing how the size of the presently observable universe R, the average density ρ, the temperature T, and the energy per particle kT, have varied with time t according to the hot big bang model.



The Standard Model
of Electroweak and Strong Interactions

Gauge invariance
$U(1)_Y \times SU(2)_L \times SU(3)_C$

Glashow 1932-   Salam 1926-   Weinberg 1933-

Spontaneous symmetry hiding in the electroweak sector

Higgs mechanism: $U(1)_Y \times SU(2)_L \rightarrow U(1)_Q$

Residual (non-hidden) symmetry: $U(1)_Q \times SU(3)_C$

$U(1)_Q$ → **massless photons**

$SU(3)_C$ → **massless gluons**

The Standard Model

particle content

fermions (matter)

leptons	ν_e	ν_μ	ν	0
	e	μ	τ	-1
quarks	u	c	t	+2/3
	d	s	b	-1/3

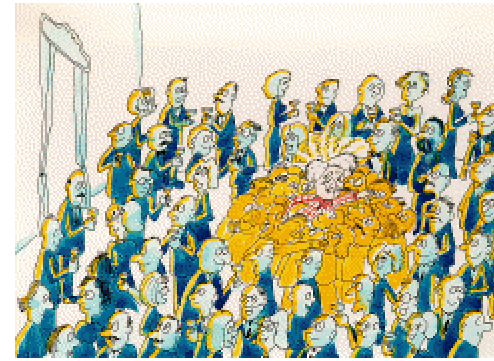
bosons (radiation)

$U(1)_Y$	B		γ	electro-weak
$SU(2)_L$	W_1, W_2, W_3	~~EW~~ →	W^+, W^-, Z^0	
$SU(3)_C$	$g_{1\text{-}8}$		$g_{1\text{-}8}$	strong
Higgs doublet	$\varphi_1 + i\varphi_2$, $\varphi_3 + i\varphi_4$		H^0	

Higgs Mechanism

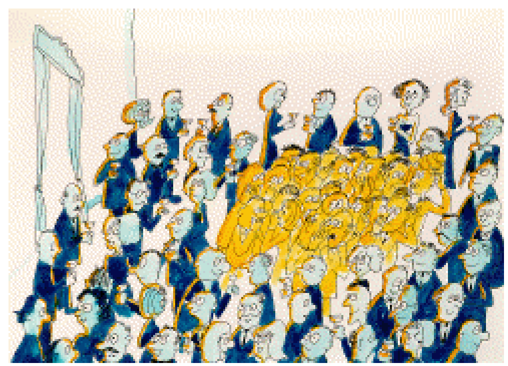
A room full of physicists chattering quietly is like space filled with the Higgs field...

… a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step...



…this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field...

…if a rumor crosses the room...



…it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles

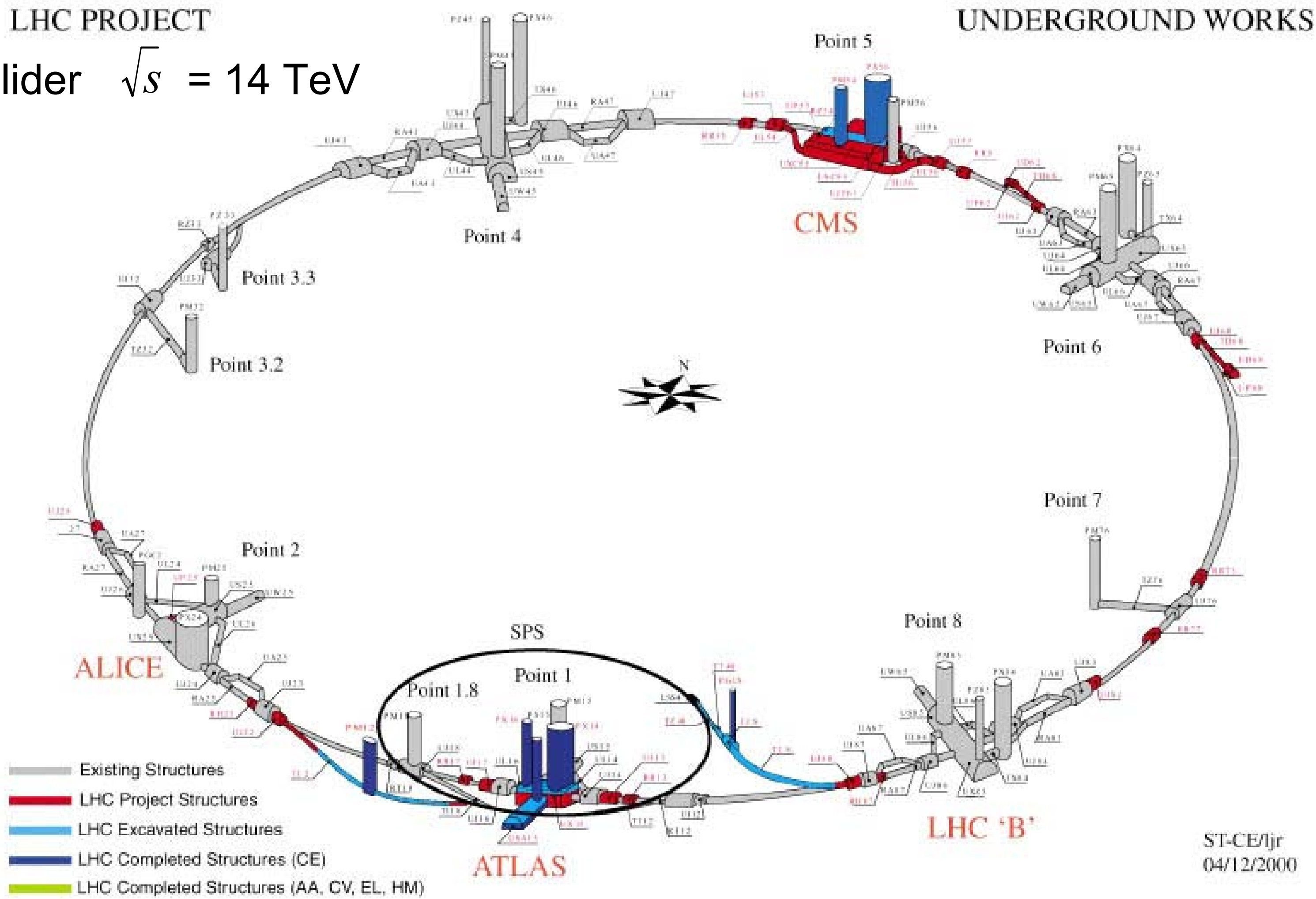
Higgs to be found below about 1 TeV and/or new physics beyond the Standard Model!!!

ATLAS educational web page, adapted from an idea from Dr D. J. Miller

Aerial View of CERN

Large Hadron Collider at CERN

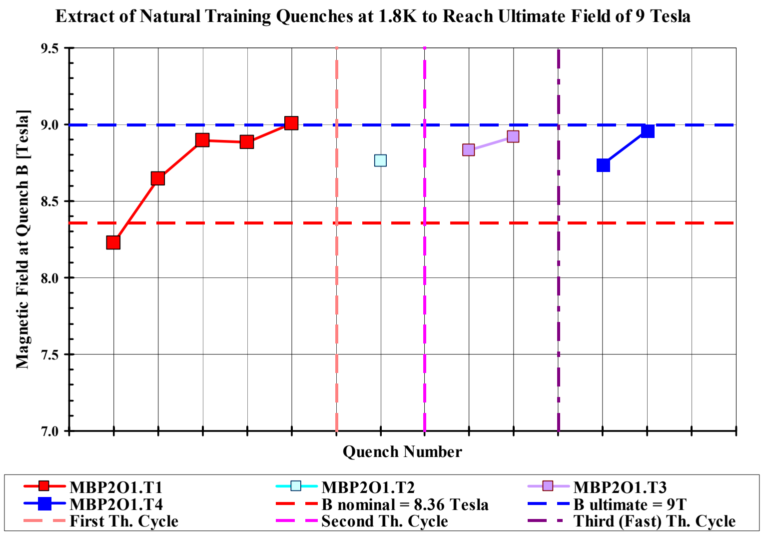
pp collider $\sqrt{s}$ = 14 TeV



Large Hadron Collider at CERN

pp collider $\sqrt{s}$ = 14 TeV

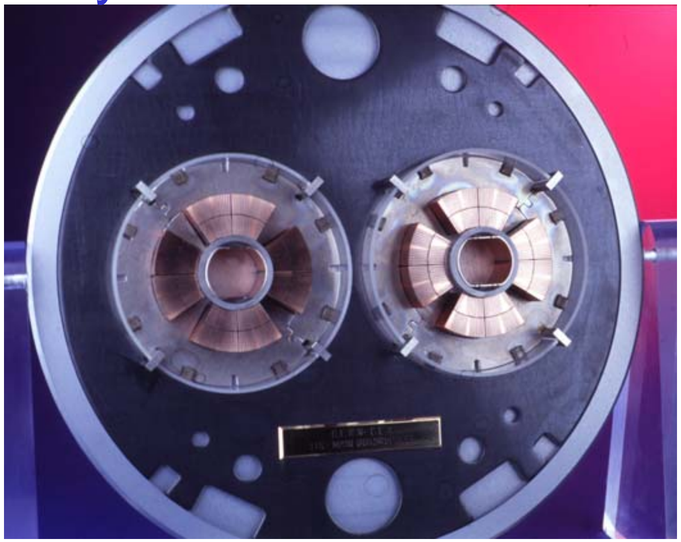
2835+2835 bunches, 25 ns
octan test in 2004
ring cooled by end 2005
beam for physics 2006
$\approx 2\times10^{33}$ $cm^{-2}s^{-1}$ after 7 months
latest: 10 fb^{-1} by March 2007
expect 10 fb^{-1}/y for first 3 years
design: 1×10^{34} $cm^{-2}s^{-1}$, 100 fb^{-1}/y



5000 superconducting magnets (1296 dipoles)
Cu-clad Nb-Ti cables
to operate at 1.9K with up to 15kA

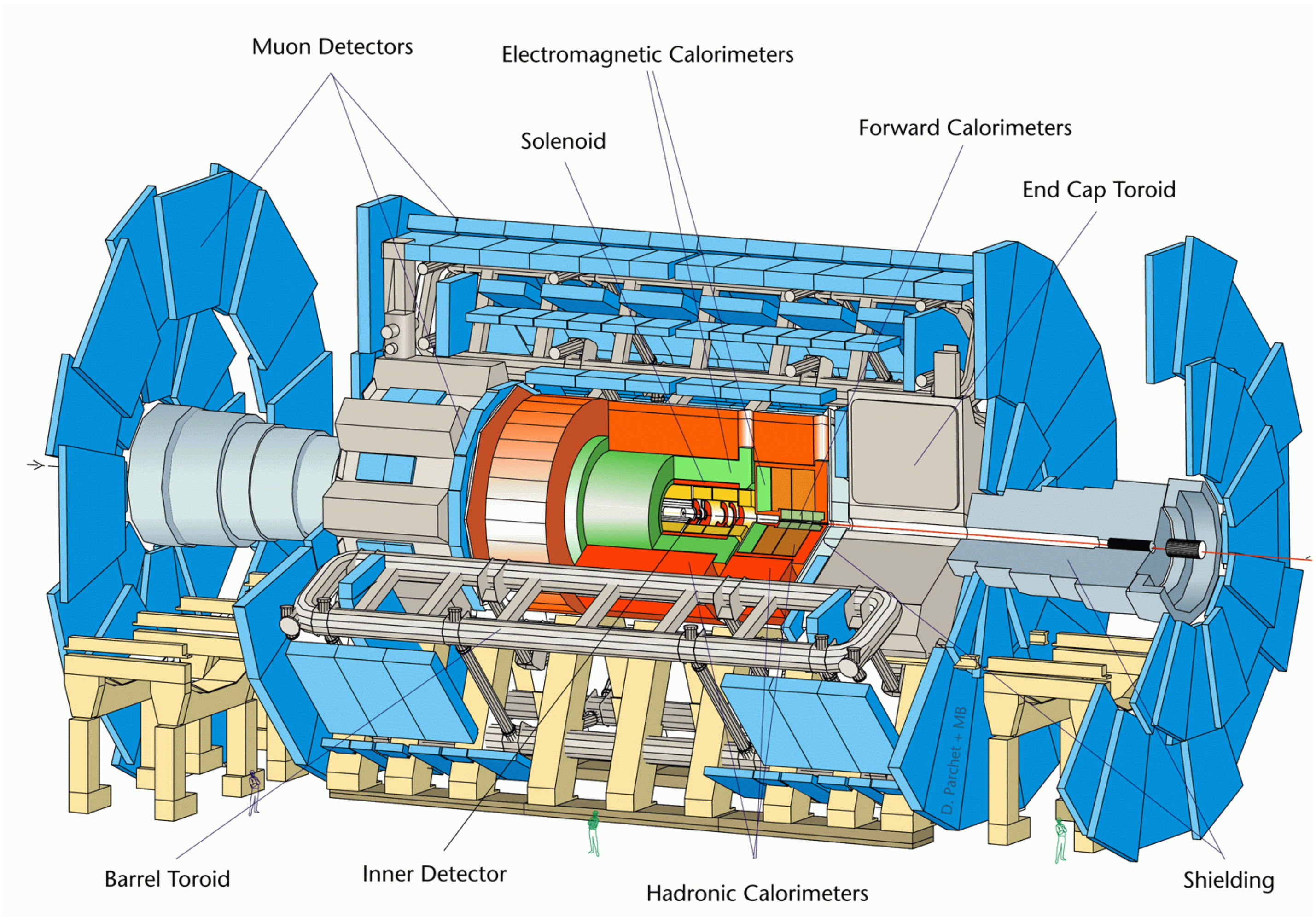
Dipole field of 8.36T
(Tevatron 4.5T, HERA, 5.5T)
"Contracts for all main components of dipoles are now placed and series production has started". L.R. Evans, Scientific Policy Comitte, CERN, 11/12/2000

ATLAS pit
3/11/2000



LHC: 25×E and 10k×L of SPS for same power

The ATLAS Detector



Alberta
Carleton
CRPP
Montréal
Toronto
TRIUMF
UBC
Victoria
York

over 1800 researchers from 150 institutions from 35 countries

See J.L Pinfold invited talk WE-P2-3

LHC PP Cross Section

ATLAS

Multi-purpose pp detector designed to exploit the full discovery potential of the LHC

Designed to operate at high luminosity

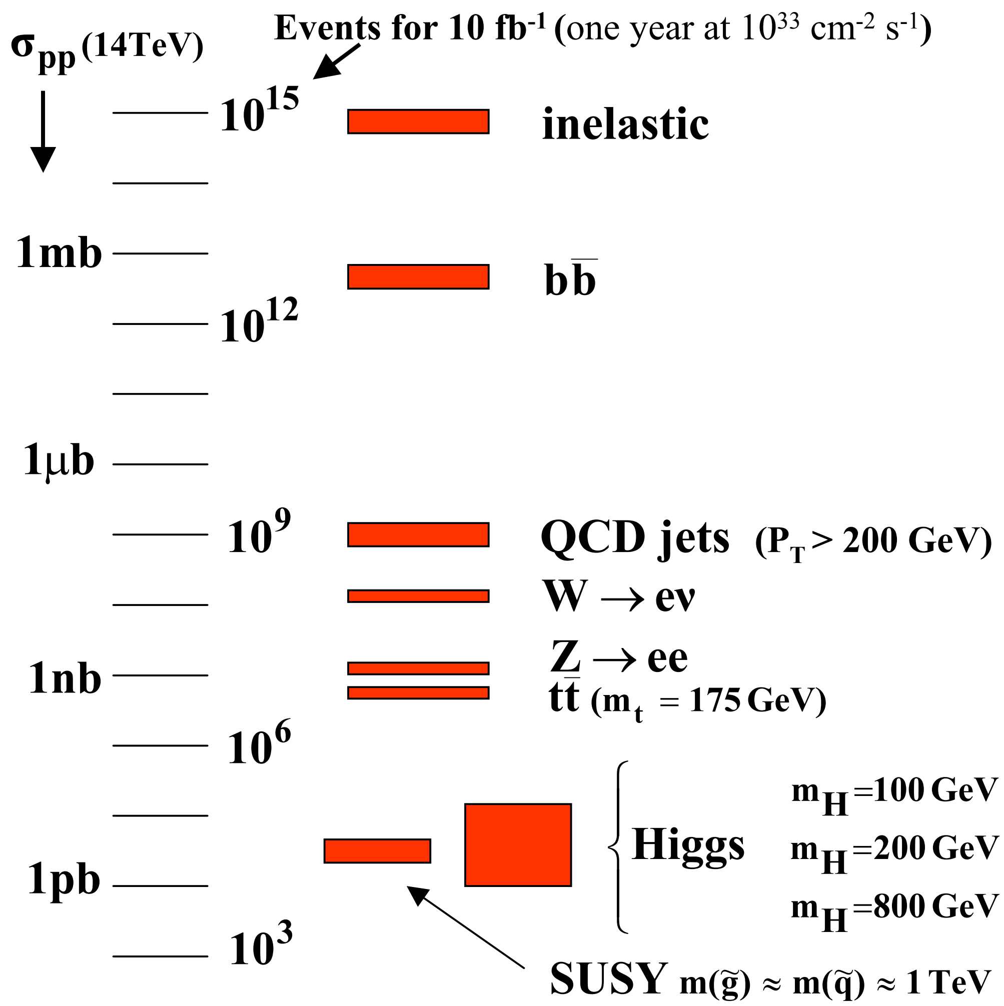
$$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

and at initial lower luminosities

Designed to be sensitive to many signatures

$$\mathrm{e}, \gamma, \mu, \mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{b\text{-}tagging}, \ldots$$

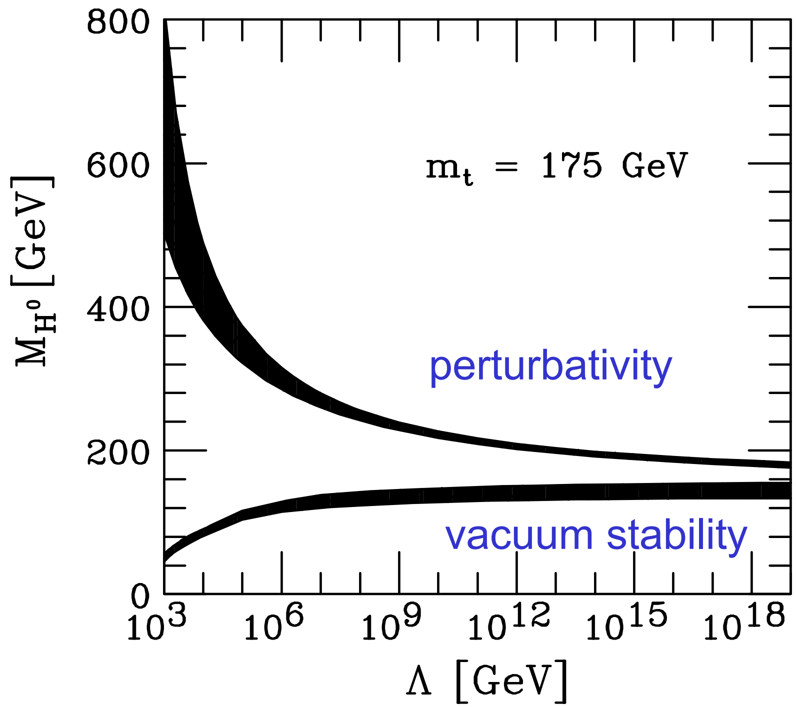
and to more complex signatures, like top and heavy flavour from secondary vertices



Theoretical Constraints on the Higgs Mass

M_H is a free parameter of SM

but it must lie in a limited region for electroweak symmetry hiding to work

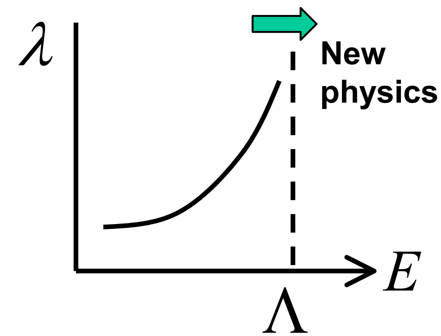


$130\ \text{GeV} \approx< M_H \approx< 180\ \text{GeV}$

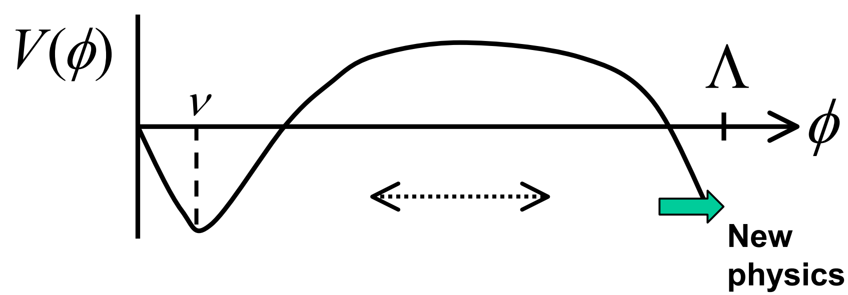
then, in principle consistent with $\Lambda = M_{PL}$

M_H is too large: the higgs self-coupling blows up at some scale Λ

$$m_H^2 = 2\lambda(m_H)v^2$$

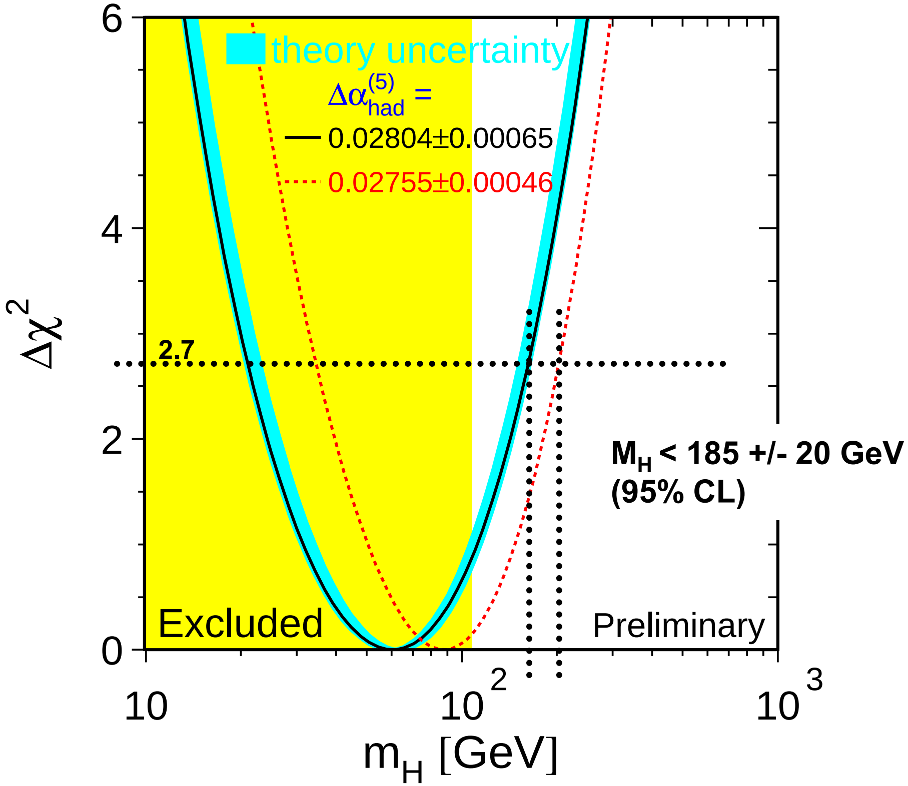


M_H is too small: the higgs potential develops a second (global!) minimum values of the scalar field of the order of Λ



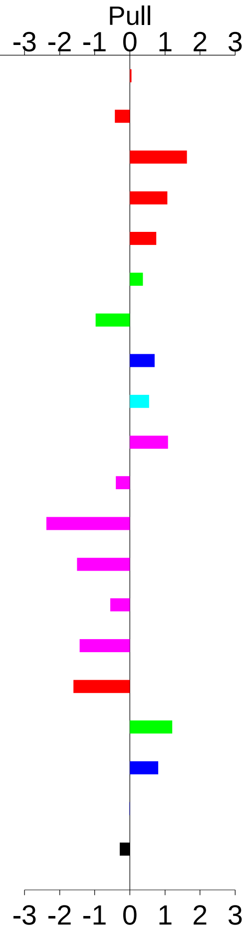
Experimental Constraints on M_H

H enters into loops… Global fits to precision EW data where M_H is the only unconstrained parameter

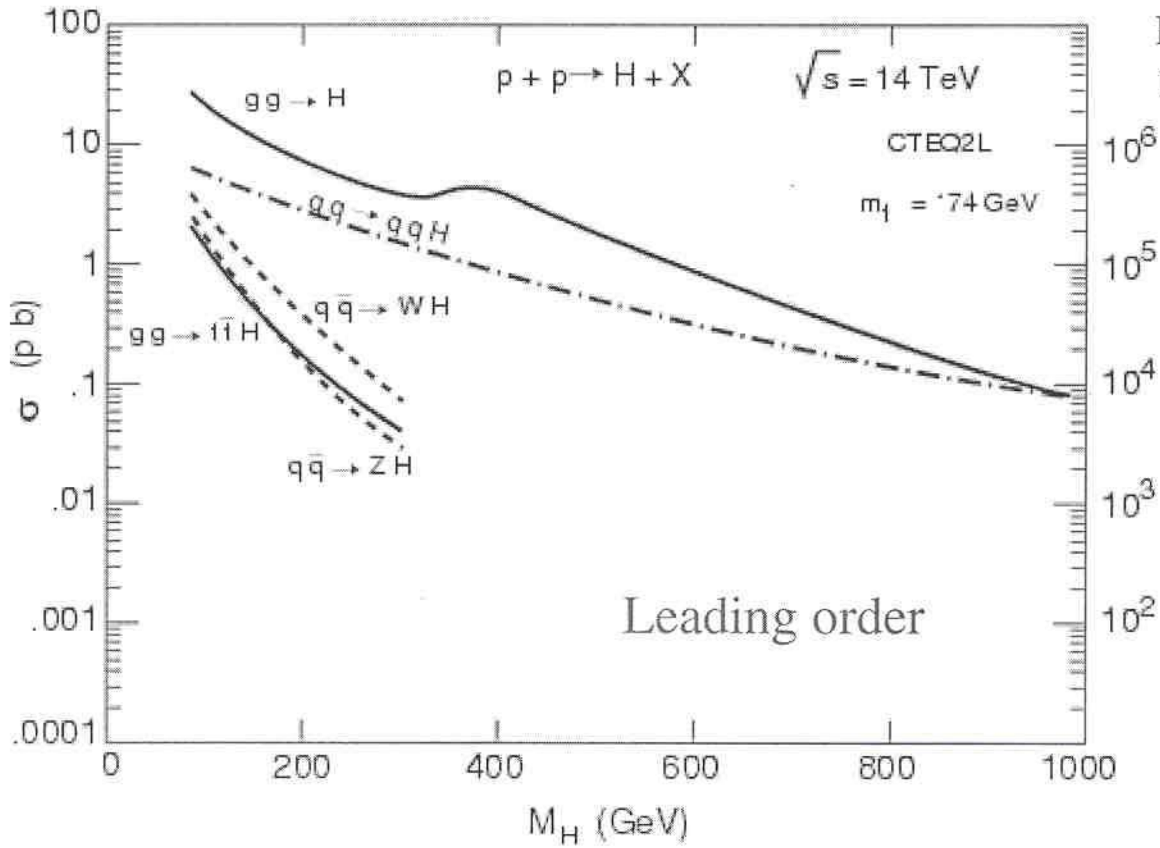


Osaka 2000

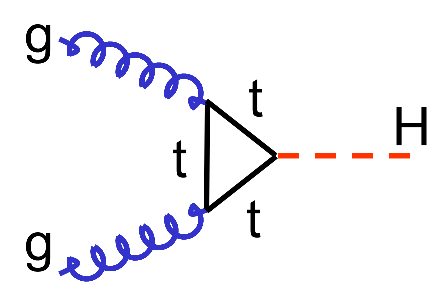
	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.07
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.75
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
R_b	0.21653 ± 0.00069	1.09
R_c	0.1709 ± 0.0034	-.40
$A^{0,b}_{fb}$	0.0990 ± 0.0020	-2.38
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.51
A_b	0.922 ± 0.023	-.55
A_c	0.631 ± 0.026	-1.43
$\sin^2\theta^{lept}_{eff}$	0.23098 ± 0.00026	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.81
m_t [GeV]	174.3 ± 5.1	-.01
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.29

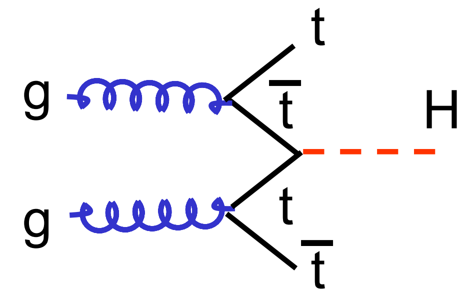


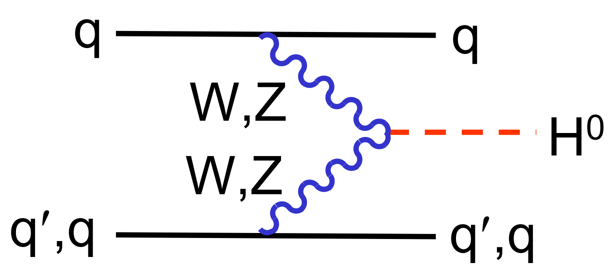
SM Higgs Production at the LHC

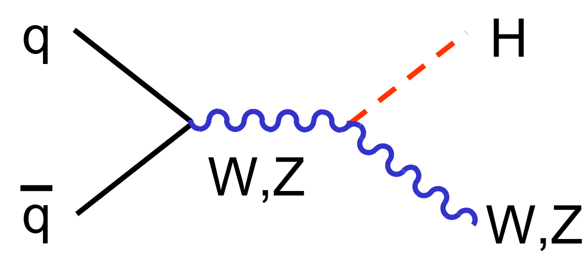


Events for 100 fb^{-1} (one year at 10^{34} cm^{-2} s^{-1})

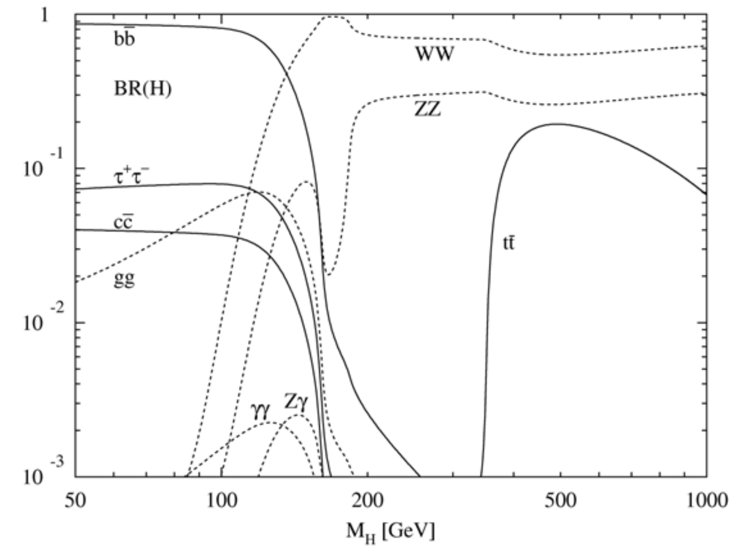








Main SM Higgs Search Channels



Large QCD backgrounds:

$$\sigma(H \to b\bar{b}) \approx 20\ \mathrm{pb}$$

$$\sigma(b\bar{b}) \approx 500\ \mu\mathrm{b}$$

M_H=120 GeV, direct production

No hope to trigger on or extract fully hadronic final states

Look for final states with photons and leptons

Detector performance is crucial: b-tag, γ/l E-resolution, γ/j separation, missing energy resolution, forward jet tag,...

$M_H < 2M_Z$

- $t\bar{t}H \to l\, b\bar{b} + X$ — **large backgrounds**
- $H \to \gamma\gamma$ — **low branching ratio**
- $H \to ZZ^* \to 4l$
- $H \to WW^* \to l\,\nu\, l\,\nu$

$M_H > 2M_Z$

- $H \to ZZ \to 4l$ — **Gold-plated channel!**
- $H \to ZZ \to l\,l\,\nu\,\nu$
- $H \to ZZ \to l\,l\,j\,j$
- $H \to WW \to l\,\nu\,j\,j$

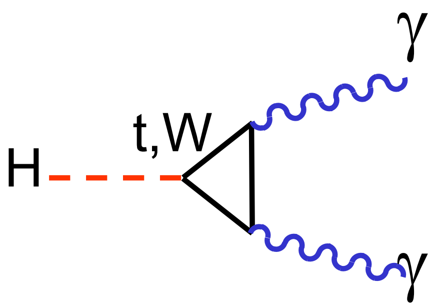
(last three:) **M_H > 300 GeV forward jet tag**

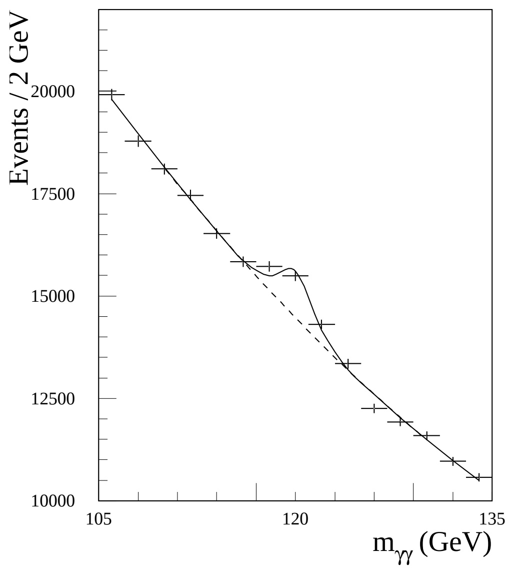
$H \rightarrow \gamma\gamma$ at ATLAS

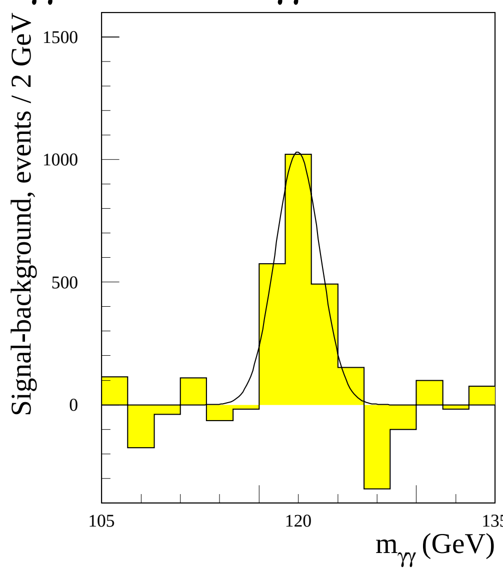
Signal $\sigma \times BR = 43\ \text{fb}\ (m_H = 100\ \text{GeV})$

$\gamma\gamma$ background (irreducible) $\frac{d\sigma}{dm_{\gamma\gamma}} \sim 1200\ \text{fb/GeV}\ (m_{\gamma\gamma} = 100\ \text{GeV})$

QCD jet background $\frac{\sigma_{\gamma,j}}{\sigma_{\gamma\gamma}} \sim 1000,\quad \frac{\sigma_{j,j}}{\sigma_{\gamma\gamma}} \sim 2\times10^6$ **(reducible)**







m_H (GeV)	100	120	140
signal events	960	1200	930
$\gamma\gamma$ background	44700	30300	20800
γ - jet, jet - jet background	6700	4400	3900
Statistical significance	4.7σ	6.9σ	6.3σ

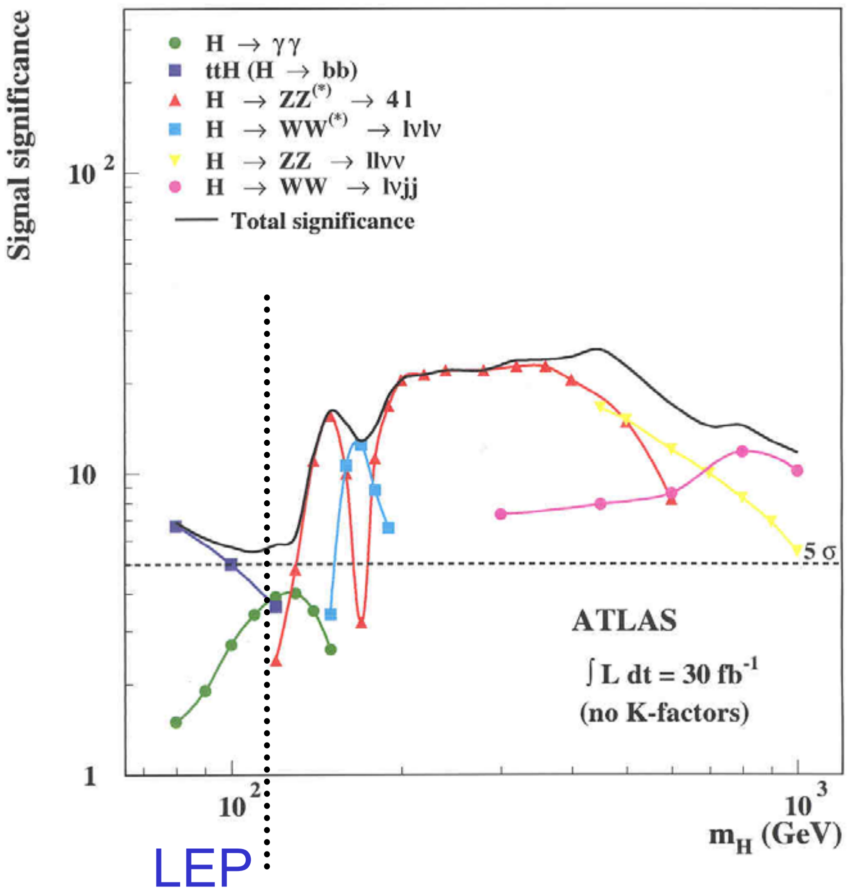
Analysis:

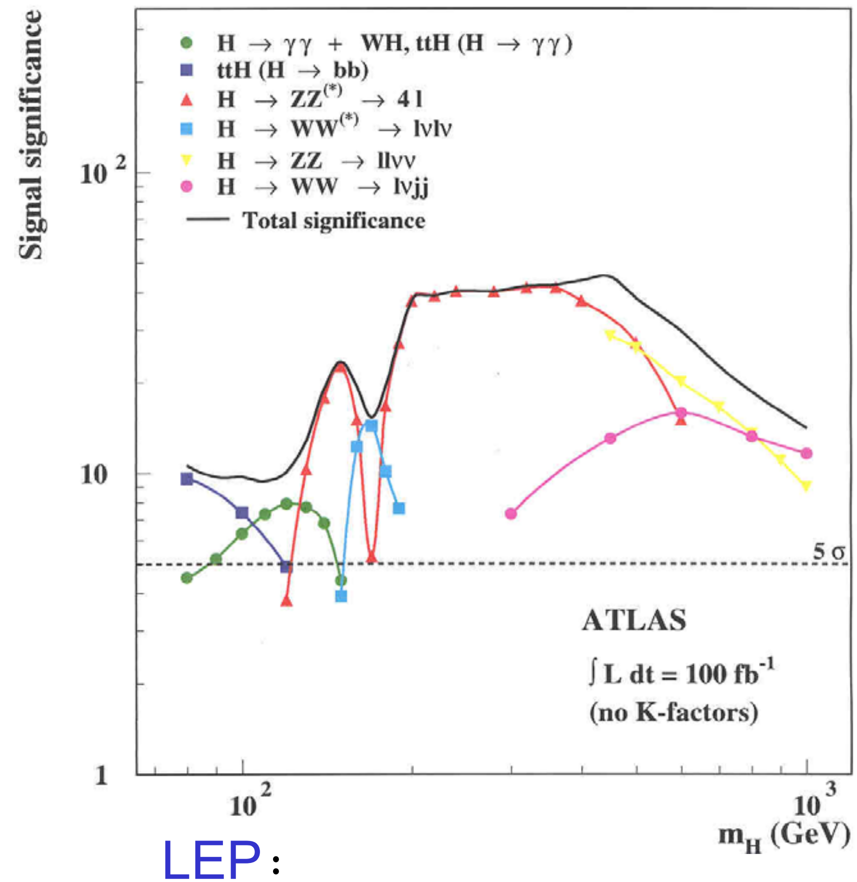
Two isolated γ's: $p_T^1 > 40$ GeV, $p_T^2 > 25$ GeV, $|\eta| < 2.5$

Good γ/jet separation: QCD jet background at the level of 10 to 20% of the irreducible $\gamma\gamma$ background

Good mass resolution: $\sigma_m = 1.3$ GeV for $m_H = 100$ GeV

ATLAS SM Higgs Discovery Potential



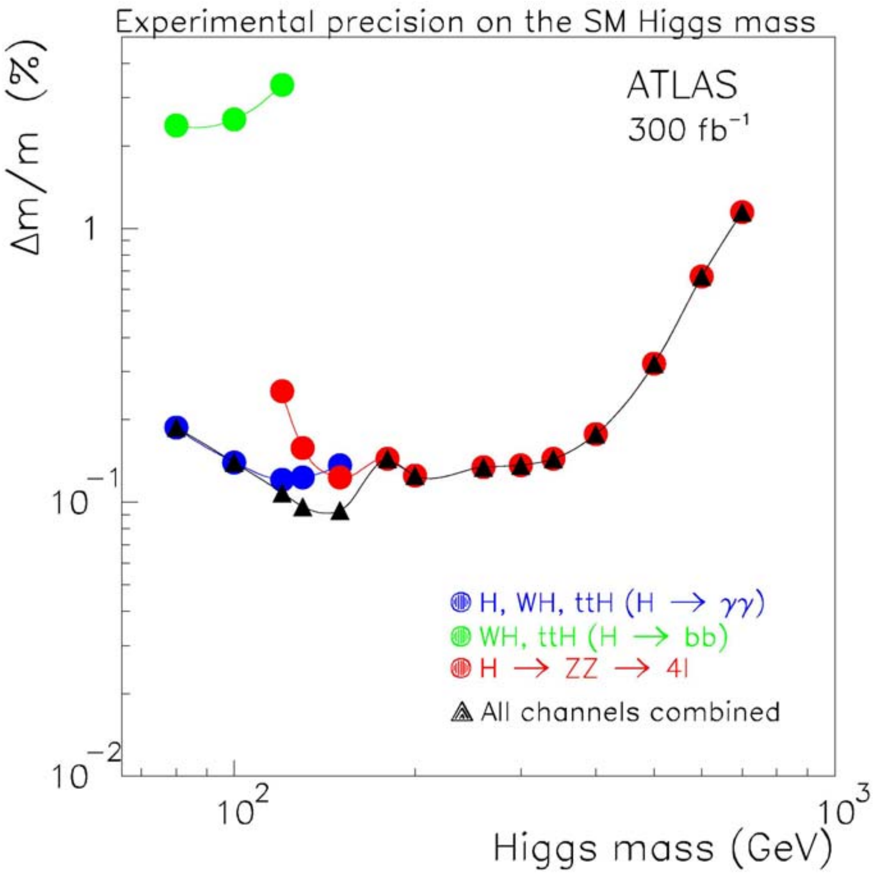


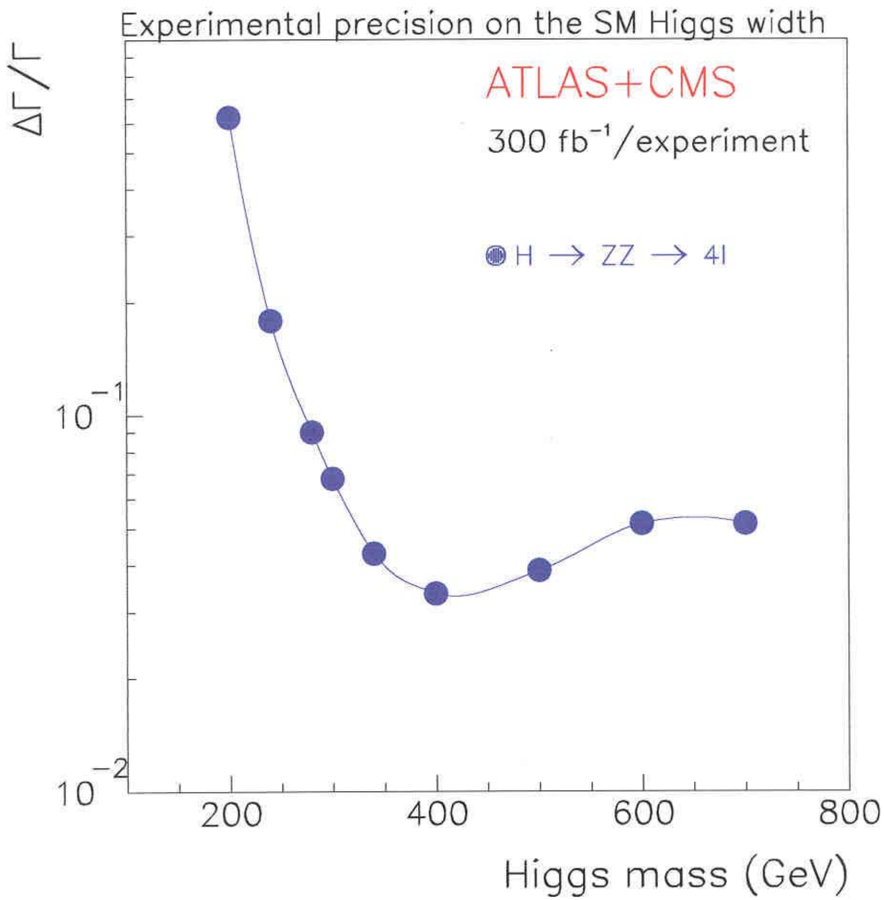
SM Higgs can be discovered over full mass range with 30 fb^{-1}

In most cases, more than one channel is available.

Signal significance is $S/B^{1/2}$ or using Poisson statistics

SM Higgs Mass and Width





Beyond the Standard Model

In principle, if $130\,\mathrm{GeV} \approx< M_{\mathrm{H}} \approx< 180\,\mathrm{GeV}$ then the SM is viable to M_{PL}

But, SM one loop corrections

$$M_{\mathrm{H}}^2 = \left(M_{\mathrm{H}}^2\right)_0 + bg^2\Lambda^2 \qquad b \sim O(1) \qquad \left(M_{\mathrm{H}}\right)_0 \text{ is parameter of fundamental theory}$$

The "natural" value for M_{H} is $g\Lambda$, which leads to the expectation

$$\Lambda \sim \frac{M_{\mathrm{H}}}{g} \sim O(1\,\mathrm{TeV})$$

If Λ >> 1 TeV, need "unnatural" tuning

Beware… what seems unnatural today...

$$\frac{\left(M_{\mathrm{H}}^2\right)_0}{\Lambda^2} = \frac{M_{\mathrm{H}}^2}{\Lambda^2} - g^2$$

If $\Lambda = M_{\mathrm{PL}}$, need adjustment to the 38th decimal place!!!

Violation of naturalness = hierachy problem

Low-energy **supersymmetry** is a way out...

Not the only way out… extra dimensions!

Supersymmetry

3D rotations, pure boosts } Lorentz
Lorentz, 4D translations } Poincare′
Poincare′, SUSY translations } superPoincare′

Maximal extension of the Poincaré group

SUSY actions are invariant under superPoincaré

they are composed of an equal number of bosonic and fermionic degrees of freedom

SUSY mixes fermions and bosons

exact SUSY ⟹ there should exist fermions and bosons of the same mass
clearly NOT the case ⟹ SUSY IS BROKEN ⟹ WHY BOTHER WITH SUSY??

A solution to the hierarchy problem

If the Higgs is to be light without unnatural fine tuning, then (softly broken) SUSY particles should have M_{SUSY}<~ 1 TeV. SUSY can be viable up to M_{PL} AND be natural!

GUT acceptable coupling constant evolution

The precision data at the Z mass (LEP and SLC) are inconsistent with GUT's using SM evolution, but are consistent with GUT's using SUSY evolution, if $M_{SUSY} \approx$ 1 TeV

A natural way to break EW symmetry

The large top Yukawa coupling can naturally drive the Higgs quadratic coupling negative in SUSY

Lightest SUSY particle is a cold dark matter candidate

Local SUSY is SUperGRAvity

Minimal SUSY Particle Spectrum

MSSM: SM + an extra Higgs doublet + SUSY partners

SUSY breaking

0	H_d^-	H_d^0	H_u^0	H_u^+						$\tilde{q}_R^d$	$\tilde{q}_L^d$	$\tilde{q}_R^u$	$\tilde{q}_L^u$	$\tilde{\nu}_L$	$\tilde{l}_R$	$\tilde{l}_L$
$\frac{1}{2}$	$\tilde{H}_d^-$	$\tilde{H}_d^0$	$\tilde{H}_u^0$	$\tilde{H}_u^+$	$\tilde{B}^0$	$\tilde{W}^0$	$\tilde{W}^-$	$\tilde{W}^+$	$\tilde{g}$	q_R^d	q_L^d	q_R^u	q_L^u	ν_L	l_R	l_L
1					B^0	W^0	W^-	W^+	g							

EW symmetry breaking

0	A	H	h	H^-	H^+					$\tilde{q}_2^d$	$\tilde{q}_1^d$	$\tilde{q}_2^u$	$\tilde{q}_1^u$	$\tilde{\nu}_l$	$\tilde{l}_2$	$\tilde{l}_1$
$\frac{1}{2}$	χ_4^0	χ_3^0	χ_2^0	χ_1^0	χ_2^-	χ_1^-	χ_2^+	χ_1^+	$\tilde{g}$	q_R^d	q_L^d	q_R^u	q_L^u	ν_l	l_R	l_L
1					Z^0	γ	W^-	W^+	g							

→ **5 massive Higgs particles, with M_h < 130 GeV**

At tree level, all Higgs boson masses and couplings can be expressed in terms of two paramerets only (in "constrained MSSM")

$$m_A \quad \text{and} \quad \tan\beta = \frac{\text{vev } H_u}{\text{vev } H_d}$$

Note that we also have the following mixings

$$B^0, W^0 \rightarrow \gamma, Z^0$$

$$\tilde{W}^\pm, \tilde{H}^\pm \rightarrow \chi_{1,2}^\pm$$

$$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0 \rightarrow \chi_{1,2,3,4}^0$$

$$\tilde{l}_L, \tilde{l}_R \rightarrow \tilde{l}_1, \tilde{l}_2$$

$$\tilde{q}_L, \tilde{q}_R \rightarrow \tilde{q}_1, \tilde{q}_2$$

with off-diagonal elements proportional to fermion masses

Discovering Supersymmetry

If SUSY exists at the electroweak scale, finding it at ATLAS should be easy

- Gluinos and squarks are strongly produced, with cross sections as high as a few pb for masses as high as 1 TeV
- They decay through cascades to the Lightest SUSY Particle (LSP)
- Combination of jets, leptons, missing energy

Look for deviation from the SM

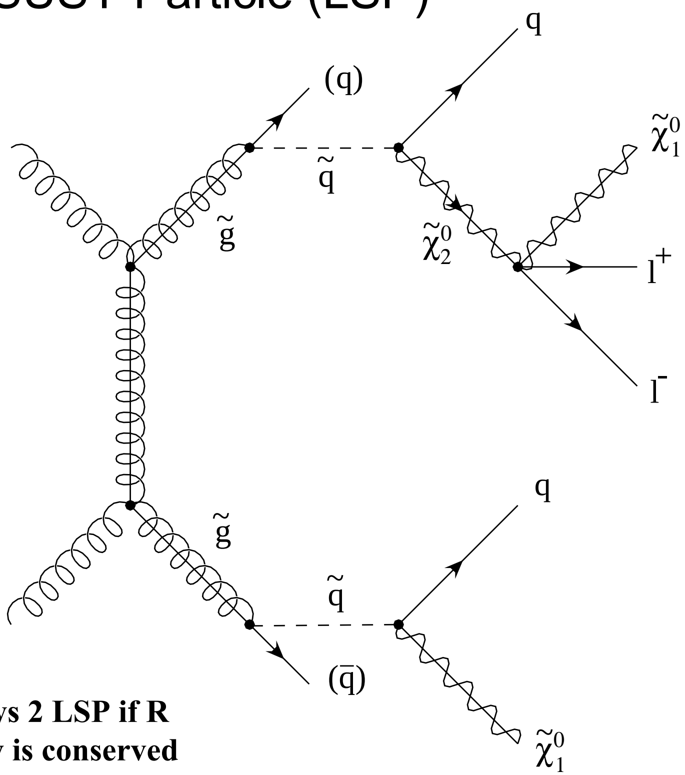
- Multijets and missing energy

Establish SUSY scale

- Effective mass distribution

Determine SUSY model parameters

- A challenge!



Always 2 LSP if R parity is conserved

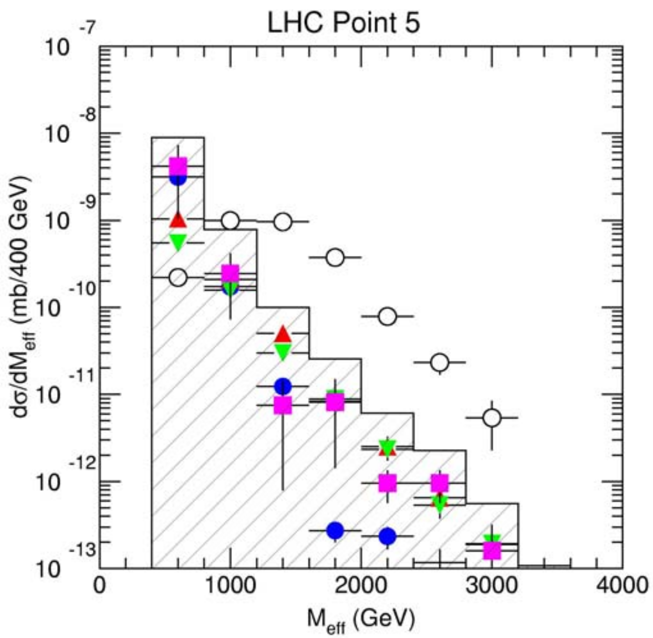
Squarks and Gluinos

Experimental signature: Several jets with large P_T and E_T^{miss}

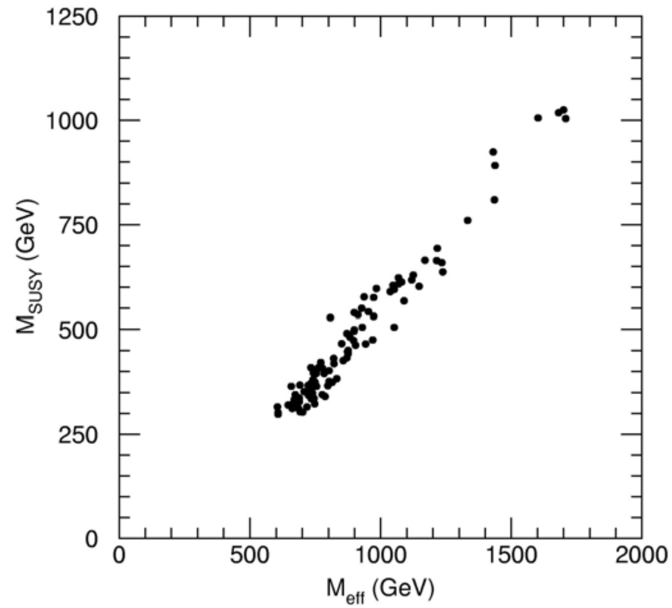
Define an effective mass:

$$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$

$$M_{SUSY} = \min\left(M_{\tilde{g}}, M_{\tilde{u}_R}\right)$$



M_{eff} for SUSY (open circles) and for SM background (histo)

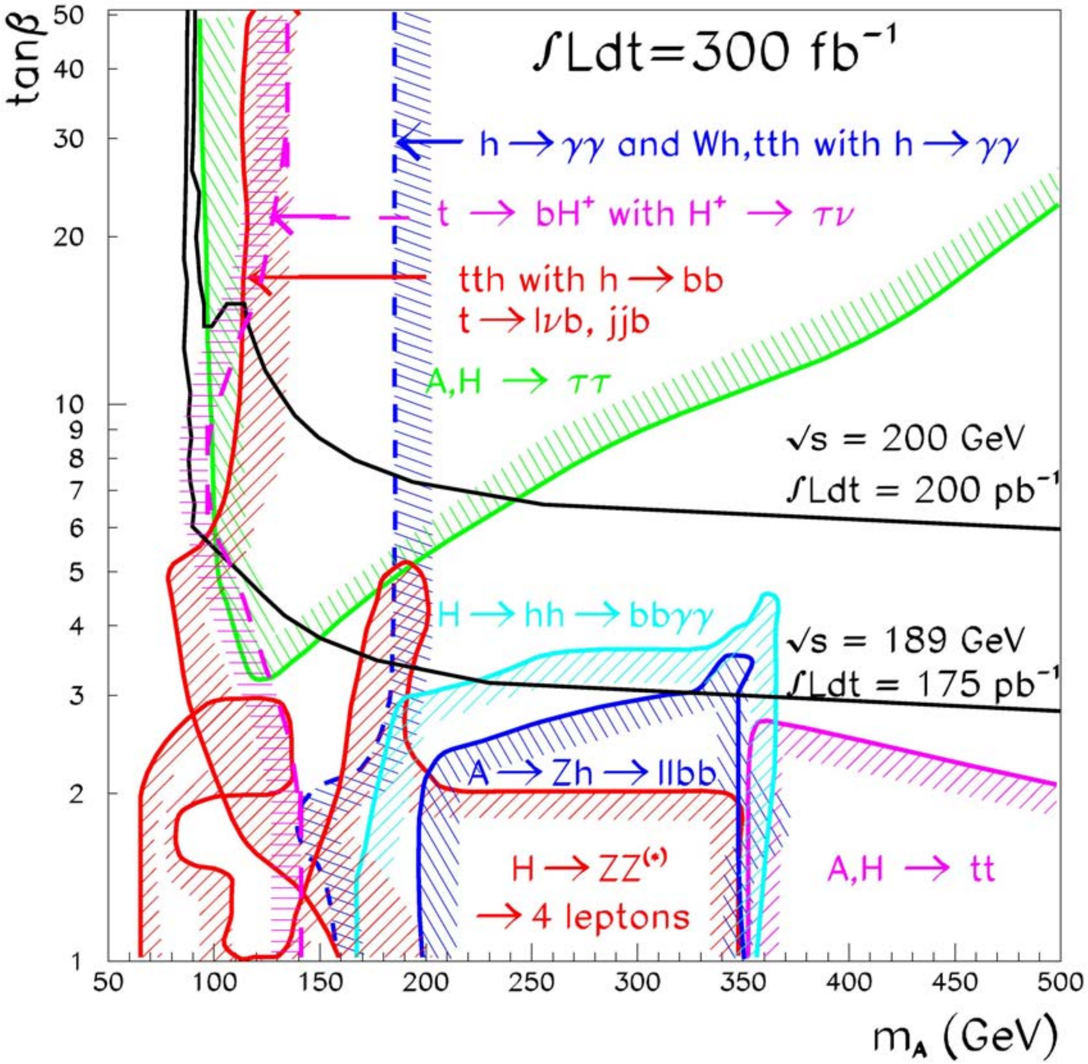


Peak of M_{eff} vs M_{SUSY} for various models

gluinos mass limits

	$1\ fb^{-1}$	$100\ fb^{-1}$
$m_{\tilde{q}} = 2m_{\tilde{g}}$	1050	1600
$m_{\tilde{q}} \approx m_{\tilde{g}}$	1800	2300
$2m_{\tilde{q}} = m_{\tilde{g}}$	2600	3600

ATLAS MSSM Higgs Search



Full parameter space covered, SM and MSSM can be distinguished for almost all cases

Most part of the parameter space covered by at least two channels, except low m_A region (covered by LEP200)

Discovery of heavy Higgses (m_A > 500 GeV) seem to be difficult (top modes)

Large Compact Extra Dimensions

Many models attempt to solve the hierarchy problem by postulating the existence of extra dimensions

e.g. Arkani-Hamed, Dimopoulos, Dvali model **(see Scientific American Aug 2000)**

SM in 3+1 dimensions (the wall), gravitons free to propagate in 3+1+n dimensions (the bulk), where the n dimensions are compactified. The fundamental scale of gravity M_D is related to the observed Newton constant G_N by $G_N = 8\pi R^n M_D^{-(2+n)}$ **Weakness of gravity is only apparent in 3+1**

where R is the size of the compactified dimensions.

Assuming M_D ~ 1 TeV, then

$\mathbf{n = 1 \Rightarrow R} \sim 10^{13}\,\mathrm{cm}$ cosmologically excluded

$\mathbf{n \geq 2 \Rightarrow R} \sim 0.1\ \mathrm{to}\ 1.0\,\mathrm{mm}$ Not excluded by tests of $1/r^2$ nature of gravitation, but excluded by SN1987

Massless graviton G in 3+1+n dimensions becomes Massive KK gravitons GM in 3+1 dimensions

→ Missing energy signature

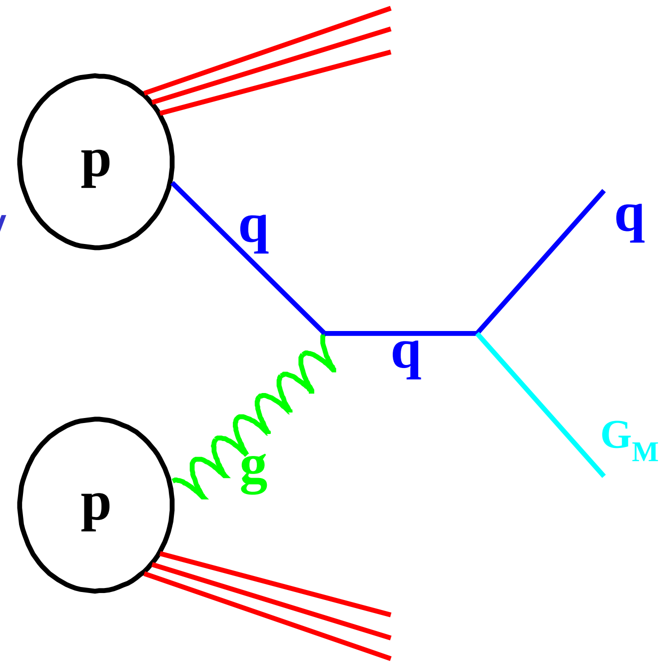
Large Compact Extra Dimensions

Possible signature in ATLAS at LHC:

$pp \rightarrow G_M + j$ ⟶ Jet + missing energy

$pp \rightarrow G_M + \gamma$ ⟶ single photon

$pp \rightarrow G_M + Z$



Jet + missing energy

n	$M_D^{min}(\text{TeV})$	$M_D^{max}(\text{TeV})$	R
2	~ 4	7.5	10 μm
3	~ 4.5	5.9	300 pm
4	~ 5	5.3	1 pm

Graviton escape into the bulk!!

single photon

n	$M_D^{min}(\text{TeV})$	$M_D^{max}(\text{TeV})$	R
2	~ 3.5	3.7	30 μm

ATL-PHYS-2000-016

More Searches!

Technicolour

Additional gauge bosons

Compositeness, leptoquarks, excited quarks or leptons

R-Parity violating SUSY (baryon and/or lepton number violating decays)

Monopoles (up to masses of 20 TeV)

Other ATLAS talks

J.L. Pinfold	WE-P2-3	Invited Talk
M. Dobbs	WE-P2-5	
R. Mazini	WE-P2-6	

Conclusions

The ATLAS detector at the LHC has a huge potential for physics discoveries...

- SM Higgs: full mass range
- MSSM Higgs: cover $\mathbf{m_A \times \tan\beta}$ plane
- SUSY: squarks and gluinos up to m ~ 2 TeV
- Many other searches!!

… and for precision measurements

- W, top, Higgs, SUSY parameters, QCD, B-physics

To fully take advantage of the LHC is a big experimental challenge

- ATLAS under construction, many Canadians involved!

We also need to be as ready as possible for the unexpected!