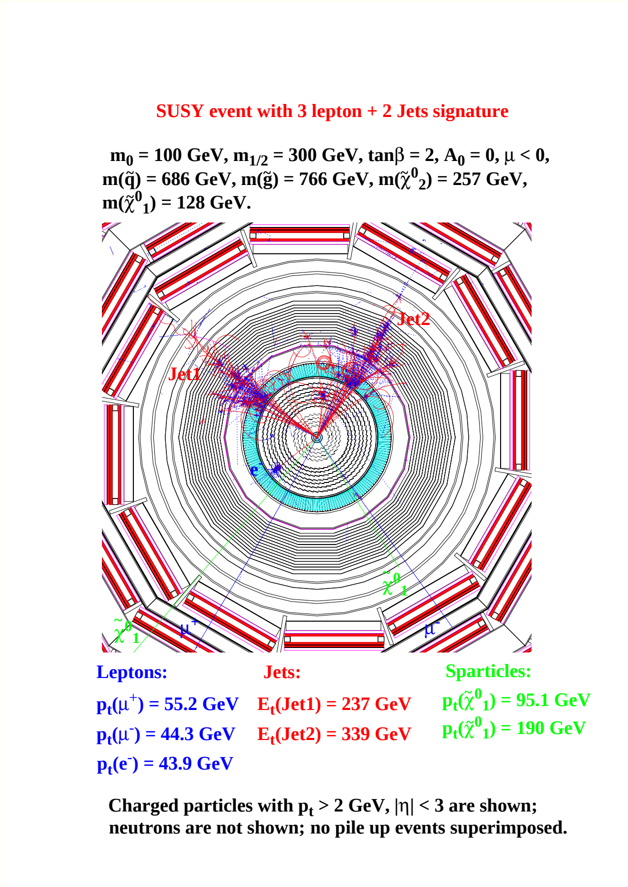
# LHC physics and supersymmetry

Howard Baer

Florida State University

- ★ Lecture 1:
  - Standard Model
  - SUSY overview
  - LHC overview
- ★ Lecture 2:
  - production
  - decay
  - event generation
- ★ Lecture 3:
  - LHC reach and precision measurements



# Relativistic Quantum Field Theory

⋆ Classical physics: two types of objects

- particles (Newtonian or relativistic mechanics)
- fields (Maxwell's electrodynamics with $\vec{E}$ and $\vec{B}$)

⋆ Elementary particle physics: the very small and very fast

- Need relativistic, quantum mechanical treatment

⋆ Relativistic QM: works on some levels, but ultimately non-causal

⋆ Quantize *relativistic fields*

- consistent merging of relativity/QM: causal, but need anti-particles!
- quantize fields- but end up with particle states: unify particles/fields!
- relate spin and statistics: bosons and fermions
- allow for particle creation/annihilation

⋆ RQFT: the right treatment for the laws of physics as we know them!

# Gauge theories

⋆ RQFT#1: Quantum Electrodynamics (QED)

- begin with RQFT of a Dirac electron: kinetic term
- assume Lagrangian invariant under *local* phase transf'n: $\psi(x) \to e^{i\alpha(x)}\psi(x)$
- then *must* introduce gauge field $A_\mu(x)$
- $\mathcal{L} = \bar{\psi}(i \not{D} - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ with $D_\mu = \partial_\mu + ieA_\mu(x)$

⋆ Phase invariance can be generalized to local non-Abelian gauge symmetry

- phase transf'n is matrix: $e^{i\alpha_A(x)t_A}$ where matrices $t_A$ obey commutation rel'ns of a Lie algebra *e.g.* $SU(N)$ and $A = 1 - N^2 - 1$
- for each generator $t_A$, must introduce $N^2 - 1$ gauge fields $A_{\mu A}$

⋆ *e.g.* QCD: based on $SU(3)$ (3 colored quarks) with eight generators $t_A$ and eight gluon fields $G_{\mu A}(x)$

# The Standard Model of Particle Physics

- ⋆ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow g_{\mu A}, W_{\mu i}, B_\mu$
- ⋆ matter content: 3 generations quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \; u_R,\; d_R; \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \; e_R \tag{1}$$

- ⋆ Higgs sector $\Rightarrow$ spontaneous electroweak symmetry breaking:

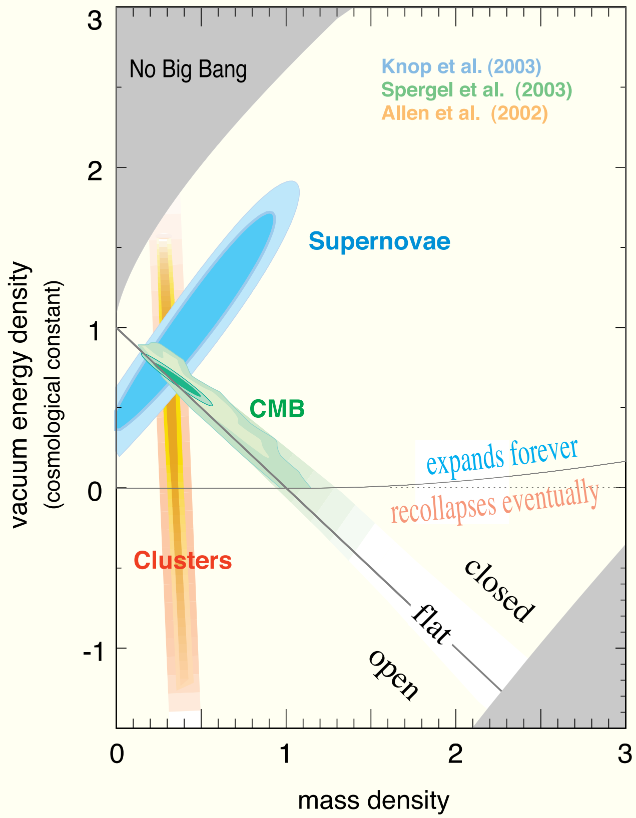
$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \tag{2}$$

- ⋆ $\Rightarrow$ massive $W^\pm$, $Z^0$, massless $\gamma$, massive quarks and leptons
- ⋆ $\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{matter} + \mathcal{L}_{Yuk.} + \mathcal{L}_{Higgs}$: 19 parameters
- ⋆ good-to-excellent description of (almost) *all* accelerator data!

# Data *not* described by the SM

- neutrino masses and mixing
- baryogenesis $n_B/n_\gamma \sim 10^{-10}$
  - (matter anti-matter asymmetry)
- cold dark matter
- dark energy

★ Note: astro/cosmo origin of all discrepancies!



# Supersymmetry (SUSY)

- ⋆ This symmetry is similar to non-Abelian gauge symmetry except that:
  - transformation is $e^{i\bar{\alpha}Q}$, where $Q$ is a (Majorana) spinor generator, and $\alpha$ is a spinorial set of parameters with $\bar{\alpha} = \alpha^{\dagger}\gamma_0$
  - SUSY transforms bosons⇔ fermions
  - SUSY is a *spacetime* symmetry: the "square-root" of a translation
  - action is invariant under SUSY, but not Lagrangian (total derivative)
- ⋆ Can construct SUSY gauge theories
- ⋆ Can construct (softly broken) SUSY SM: MSSM
- ⋆ Solves problem of SM scalar fields: cancellation of quadratic divergences
- ⋆ allows for stable theories with vastly different mass scales: *e.g.* $M_{weak} \sim 10^3$ GeV and $M_{GUT} \sim 10^{16}$ GeV
- ⋆ *local* SUSY where $\alpha(x)$ spacetime dependent: supergravity and GR (but non-renormalizable; go to string theory?)

# Minimal Supersymmetric Standard Model (MSSM)

★ Adopt gauge symmetry of Standard Model: $SU(3)_C \times SU(2)_L \times U(1)_Y$

- gauge boson plus spin $\frac{1}{2}$ gaugino $\in$ gauge superfield

★ SM fermions $\in$ chiral scalar superfields: $\Rightarrow$ scalar partner for each SM fermion helicity state

- electron $\Leftrightarrow$ $\tilde{e}_L$ and $\tilde{e}_R$

★ *two* Higgs doublets to cancel triangle anomalies: $H_u$ and $H_d$

★ add all admissible soft SUSY breaking terms

★ resultant Lagrangian has 124 parameters!

★ Lagrangian yields mass eigenstates, mixings, Feynman rules for scattering and decay processes

★ predictive model!

# Physical states of MSSM:

- ⋆ usual SM gauge bosons, quarks and leptons
- ⋆ gluino: $\tilde{g}$
- ⋆ bino, wino, neutral higgsinos⇒ neutralinos: $\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{Z}_3, \widetilde{Z}_4$
- ⋆ charged wino, higgsino ⇒ charginos: $\widetilde{W}_1^{\pm}$, $\widetilde{W}_2^{\pm}$
- ⋆ squarks: $\tilde{u}_L$, $\tilde{u}_R$, $\tilde{d}_L$, $\tilde{d}_R, \cdots$, $\tilde{t}_1$, $\tilde{t}_2$
- ⋆ sleptons: $\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\nu}_e, \cdots$, $\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\nu}_\tau$
- ⋆ Higgs sector enlarged: $h$, $H$, $A$, $H^{\pm}$
- ⋆ a plethora of new states to be found at LHC/ILC?!

# Review: some SUSY successes

- ⋆ SUSY stabilizes particle physics models allowing vastly different mass hierarchies: $e.g.$ $M_{GUT}$ and $M_{weak}$ can co-exist
- ⋆ connection to gravity/superstring models
- ⋆ gauge coupling unification (grand unification)
- ⋆ EWSB radiatively due to large $m_t \sim 175$ GeV
- ⋆ MSSM predicts $m_h \lesssim 135$ GeV in accord with precision EW measurements
- ⋆ cold dark matter (CDM) candidate when $R$-parity is conserved

# some SUSY problems

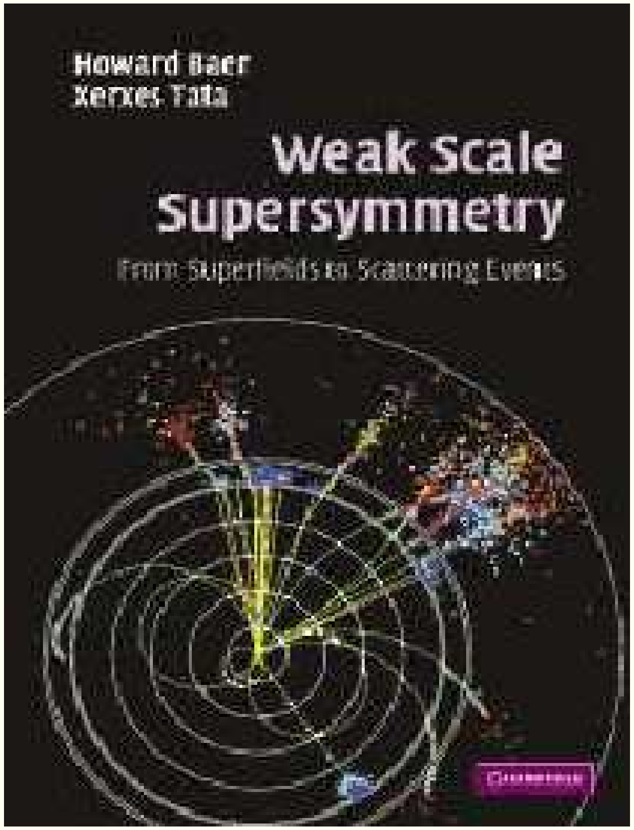
- flavor problem: universality; heavy scalars; alignment
- CP problem: complex phases small; heavy scalars

# Weak Scale Supersymmetry

HB and X. Tata

Spring, 2006; Cambridge University Press

- ⋆ Part 1: superfields/Lagrangians
  - 4-component spinor notation for exp'ts
  - master Lagrangian for SUSY gauge theories
- ⋆ Part 2: models/implications
  - MSSM, SUGRA, GMSB, AMSB, $\cdots$
- ⋆ Part 3: SUSY at colliders
  - production/decay/event generation
  - collider signatures
  - $R$-parity violation



## Connecting scales $M_{GUT} \sim 2 \times 10^{16}$ GeV to $M_{weak} \sim 10^3$ GeV

★ A major lesson from QFT: coupling constants are *not* constant!

- gives rise to QCD confinement at $Q \lesssim 1$ GeV, and asymptotic freedom at $Q \gg 1$ GeV: (Gross, Politzer, Wilczek)

★ in fact, all Lagrangian parameters "run" with mass/energy scale

★ the running is governed by "renormalization group equation": RGEs

★ RGEs come from computing quantities at higher order, and, after renormalization, taking derivatives.

★ In SUSY, the following running parameters are relevant:

– gauge couplings: $g_1\, g_2,\ g_3$

– Yukawa couplings: $f_t,\ f_b,\ f_\tau$

– soft SUSY breaking terms: many

# The MSSM: RGEs

- ⋆ If the MSSM is to be valid between vastly different mass scales, then it is important to relate parameters between these scales.
- ⋆ The gauge couplings, Yukawa couplings, $\mu$ term and soft breaking parameter evolution is governed by *renormalization group equations*, or RGEs
- ⋆ For gauge couplings, these have the form

$$\frac{dg_i}{dt} = \beta(g_i) \quad with \quad t = \log Q \tag{3}$$

- ⋆ In SM,

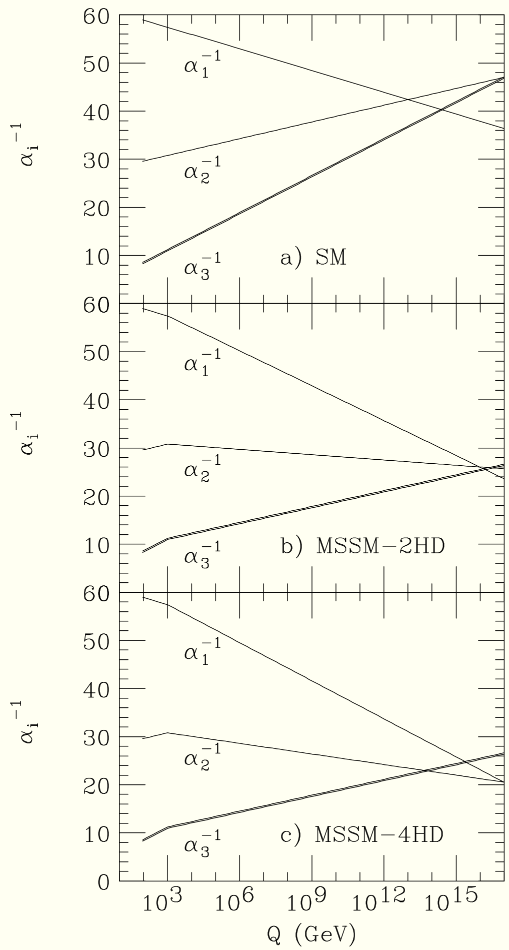
$$\beta(g) = -\frac{g^3}{16\pi^2}\left[\frac{11}{3}C(G) - \frac{2}{3}n_F S(R_F) - \frac{1}{3}n_H S(R_H)\right]. \tag{4}$$

- ⋆ In MSSM, the gauginos, matter and Higgs scalars also contribute:

$$\beta(g) = -\frac{g^3}{16\pi^2}\left[3C(G) - S(R)\right], \tag{5}$$

# Gauge coupling evolution

⋆ Can use the precision values of $g_1$, $g_2$ and $g_3$ measured at $Q = M_Z$ at LEP2 as boundary conditions, and extrapolate to high energy



# The MSSM: RGEs continued

$$\begin{aligned}
\frac{dM_i}{dt} &= \frac{2}{16\pi^2} b_i g_i^2 M_i, \\
\frac{dA_t}{dt} &= \frac{2}{16\pi^2}\left(-\sum_i c_i g_i^2 M_i + 6f_t^2 A_t + f_b^2 A_b\right), \\
\frac{dA_b}{dt} &= \frac{2}{16\pi^2}\left(-\sum_i c_i' g_i^2 M_i + 6f_b^2 A_b + f_t^2 A_t + f_\tau^2 A_\tau\right), \\
\frac{dA_\tau}{dt} &= \frac{2}{16\pi^2}\left(-\sum_i c_i'' g_i^2 M_i + 3f_b^2 A_b + 4f_\tau^2 A_\tau\right), \\
\frac{dB}{dt} &= \frac{2}{16\pi^2}\left(-\frac{3}{5} g_1^2 M_1 - 3g_2^2 M_2 + 3f_b^2 A_b + 3f_t^2 A_t + f_\tau^2 A_\tau\right), \\
\frac{d\mu}{dt} &= \frac{\mu}{16\pi^2}\left(-\frac{3}{5} g_1^2 - 3g_2^2 + 3f_t^2 + 3f_b^2 + f_\tau^2\right),
\end{aligned}$$

$$\frac{dm_{Q_3}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{1}{15}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{10}g_1^2S + f_t^2X_t + f_b^2X_b\right),$$

$$\frac{dm_{\tilde{t}_R}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{16}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 - \frac{2}{5}g_1^2S + 2f_t^2X_t\right),$$

$$\frac{dm_{\tilde{b}_R}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{4}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{5}g_1^2S + 2f_b^2X_b\right),$$

$$\frac{dm_{L_3}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + f_\tau^2X_\tau\right),$$

$$\frac{dm_{\tilde{\tau}_R}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{12}{5}g_1^2M_1^2 + \frac{3}{5}g_1^2S + 2f_\tau^2X_\tau\right),$$

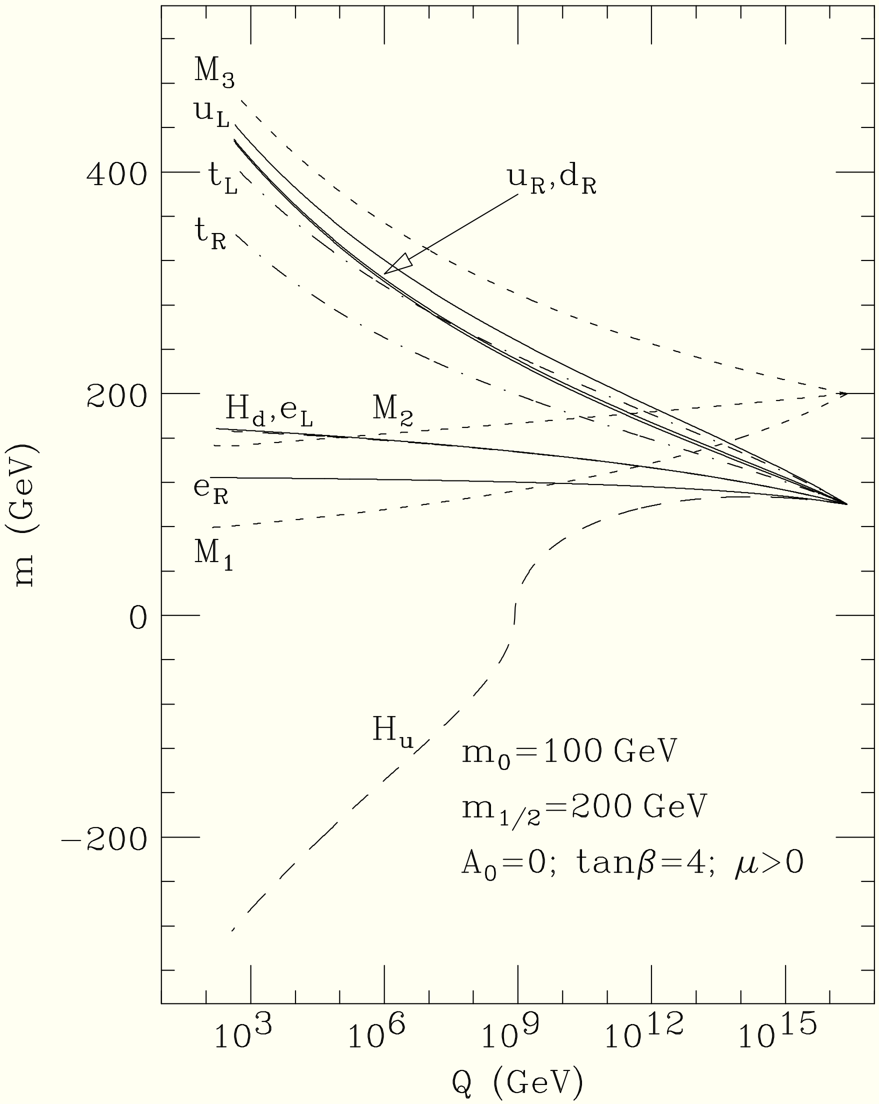
$$\frac{dm_{H_d}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + 3f_b^2X_b + f_\tau^2X_\tau\right),$$

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right),$$

where $m_{Q_3}$ and $m_{L_3}$ denote the mass term for the third generation $SU(2)$ squark and slepton doublet respectively, and

$$\begin{aligned}
X_t &= m_{Q_3}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 + A_t^2, \\
X_b &= m_{Q_3}^2 + m_{\tilde{b}_R}^2 + m_{H_d}^2 + A_b^2, \\
X_\tau &= m_{L_3}^2 + m_{\tilde{\tau}_R}^2 + m_{H_d}^2 + A_\tau^2, \text{ and} \\
S &= m_{H_u}^2 - m_{H_d}^2 + Tr\left[\mathbf{m}_Q^2 - \mathbf{m}_L^2 - 2\mathbf{m}_U^2 + \mathbf{m}_D^2 + \mathbf{m}_E^2\right].
\end{aligned}$$

# Soft term evolution and radiative EWSB for $m_t \sim 175$ GeV



## Calculating sparticle mass at $M_{weak}$ based on $M_{GUT}$ inputs

⋆ We expect physics to be more simple (more symmetry) at high energy scales such as $M_{GUT}$

- *e.g.* in "minimal supergravity" grand unified models, it is common to assume all scalars masses at $M_{GUT}$ equal $m_0$
- gaugino masses $= m_{1/2}$
- trilinear SSB terms $= A_0$
- given these, how do we find weak scale spectrum expected to show up at LHC?

1. Begin with measured gauge, Yukawa couplings at $Q = M_Z$: $g_1,\ g_2,\ g_3,\ f_t,\ f_b,\ f_\tau$
2. run these up to $Q = M_{GUT}$ to see what their value is there (their running does not depend on soft terms at 1-loop)
3. At $Q = M_{GUT}$, run the soft breaking parameters along with gauge and

Yukawas down to $M_{weak}$

4. At $M_{weak}$, minimize scalar potential $V(\phi_i)$ to see if electroweak symmetry is properly broken by Higgs mechanism

5. Usually, the large top Yukawa coupling pushes the Lagrangian parameter $m_{H_u}^2$ to negative values, which is just what is needed for proper EWSB:

$$B = \frac{(m_{H_u}^2 + m_{H_d}^2 + 2\mu^2)\sin 2\beta}{2\mu} \quad \text{and}$$

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{(\tan^2\beta - 1)} - \frac{M_Z^2}{2}.$$

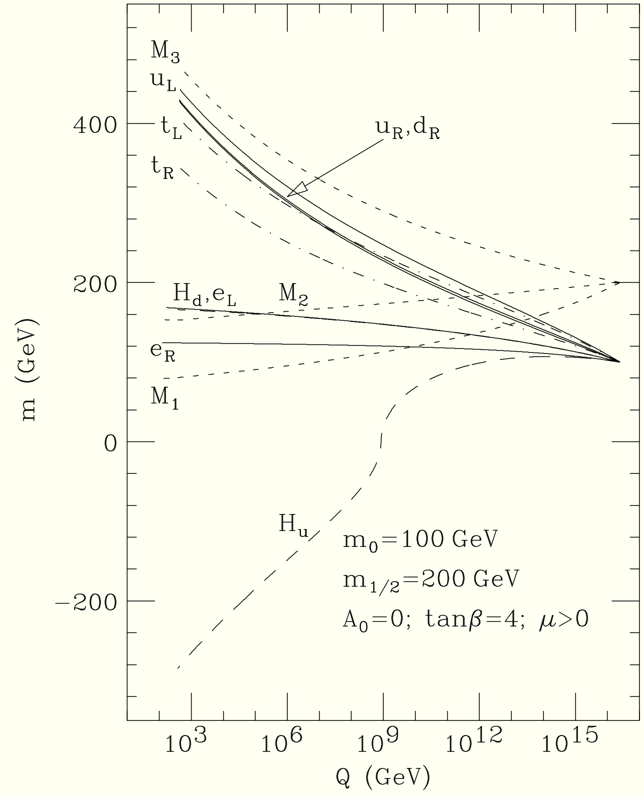
- If EWSB occurs, then calculate all physical mass eigenstates as functions of the Lagrangian parameters
- In practice, an iterative approach is used (running up-down-up-down...) until a stable solution is found
- State of art: include 2-loop running, radiative corrections, etc.

# Sparticle mass spectra

★ Mass spectra codes

★ RGE running: $M_{GUT} \to M_{weak}$

- Isajet 7.75 (HB, Paige, Protopopescu, Tata)
  - $\geq$7.72: Isatools
- SuSpect (Djouadi, Kneur, Moultaka)
- SoftSUSY (Allanach)
- Spheno (Porod)




★ Comparison (Belanger, Kraml, Pukhov)

★ Website: `http://kraml.home.cern.ch/kraml/comparison/`

# SUSY model #1: minimal supergravity (mSUGRA or CMSSM)

- ⋆ Assume nature described by $N = 1$ supergravity gauge theory Lagrangian:
- ⋆ To accomodate SUSY breaking, must introduce a "hidden sector", consisting of a field or fields which are SM singlets (hence hidden)
- ⋆ Arrange superpotential of hidden sector such that supergravity breaks at mass scale $m \sim 10^{11}$ GeV via *superHiggs* mechanism
- ⋆ Gravitational interactions *induce* exactly the right form of soft SUSY breaking masses, with $m_{SUSY} \sim m_{3/2} \sim m^2/M_P \sim (10^{11}\ GeV)^2/10^{19}\ GeV \sim 10^3\ GeV$
- • gravitino decouples? $\widetilde{Z}_1 = LSP$ or $\tilde{G}$ (see papers by Feng/Ellis)
- ⋆ simplest models ($e.g.$ Polonyi superpotential) give:
  - single scalar mass $m_0$,
  - gaugino mass $m_{1/2}$,
  - trilinear term $A_0$, bilinear term $B$

- ⋆ EWSB radiatively due to large $m_t$
- ⋆ EWSB condition: $B \to \tan\beta$; $\mu^2$ fixed by $M_Z$
- ⋆ parameter space: $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- ⋆ this is simplest choice and a baseline model, but **many** other possibilities depending on high scale physics
  - non-universal matter scalars: $m_{Q_i}^2$, $m_{U_i}^2$, $m_{D_i}^2$, $m_{L_i}^2$, $M_{E_i}^2$
  - non-universal Higgs scalars: $m_{H_u}^2$, $M_{H_d}^2$
  - non-universal gaugino masses: $M_1$, $M_2$, $M_3$
  - non-universal $A$ terms: $A_t$, $A_b$, $A_\tau$
  - FC soft SUSY breaking terms
  - large $CP$ violating phases
  - additional fields beyond MSSM below $M_{GUT}$?
  - $R$-parity violating couplings
  - $\cdots$

# SUSY model #2: gauge-mediated SUSY breaking (GMSB)

- ⋆ Assume 3 sectors: MSSM, messenger sector, hidden sector
- ⋆ SUSY breaking in HS
- ⋆ SUSY breaking communicated to MSSM via gauge interactions from messenger sector
- ⋆ $m_{SUSY} \sim \frac{g_i^2}{16\pi^2}\frac{\langle F_S\rangle}{M} \sim 1$ TeV, where $M =$messenger mass and $\langle F_S\rangle$ is SUSY breaking scale
- ⋆ gravitino $m_{\tilde{G}} = \frac{\langle F\rangle}{\sqrt{3}M_P}$ can be very light $\sim keV$ so $\tilde{G} = LSP$ and $e.g.$ $\widetilde{Z}_1 \to \gamma\tilde{G}$
- ⋆ EWSB radiatively due to large $m_t$ as usual

# GMSB parameter space

⋆ parameter space:

- $\Lambda,\ M,\ n_5,\ \tan\beta,\ sign(\mu), C_{grav}$
- $\Lambda \sim 10 - 150$ TeV sets sparticle mass scale $m_{SUSY} = \frac{\alpha_i}{4\pi} n_5 \Lambda$
- $M$ =messenger scale $> \Lambda$
- $n_5 = \#$ of messenger fields
- $C_{grav}$ just affects how long lived the NLSP is
- at colliders: get isolated photons from $\widetilde{Z}_1 \to \gamma \tilde{G}$ or long-lived charged tracks if $\tilde{\tau}_1 \to \tau \tilde{G}$ is NLSP

⋆ model solves SUSY flavor problem at price of introducing non-minimal messenger sector

# SUSY model #3: anomaly-mediated SUSY breaking (AMSB)

- ⋆ supergravity theories always have 1-loop contributions to soft breaking terms of order $m_{SUSY} \sim m_{3/2}/16\pi^2$ coming from superconformal anomaly: usually suppressed compared to tree level SUGRA contribution
- ⋆ suppose hidden sector is "sequestered" in extra dimensions
- ⋆ then if $m_{3/2} \sim 10 - 100$ TeV, AMSB contribution to sparticle masses is dominant
- ⋆ gauginos: $M_i = \frac{\beta_i}{g_i} m_{3/2}$
- ⋆ scalars: $m_{\tilde{f}}^2 = -\frac{1}{4}\left\{\frac{d\gamma}{dg}\beta_g + \frac{d\gamma}{df}\beta_f\right\} m_{3/2}^2$
- ⋆ EWSB radiatively due to large $m_t$
- ⋆ slepton masses tachyonic $m_{\tilde{\ell}}^2 < 0$ so add by hand universal contribution $m_0^2$ (or other solutions)

# AMSB parameter space

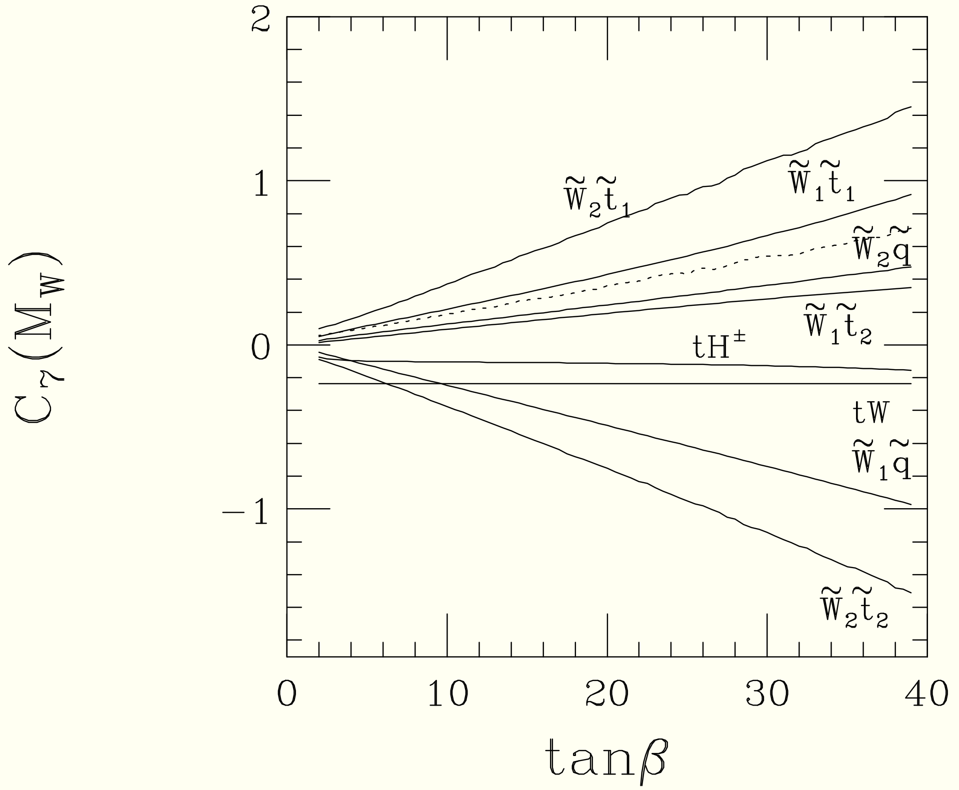
- parameter space:
  - $m_0$, $m_{3/2}$ $\tan\beta$, $sign(\mu)$
- $LSP$ =lightest $\widetilde{Z}_1$ which is *wino-like*
- $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1} \sim 200$ MeV so $\widetilde{W}_1 \to \widetilde{Z}_1 \pi^+$ and may give an observable track of few cm length: possibly observable
- wino-like $\widetilde{Z}_1$ gives very low relic density: hard to explain dark matter
- solves SUSY flavor problem but tachyonic masses...

# Constraints on SUSY models

- ⋆ LEP2:
  - $m_h > 114.4$ GeV for SM-like $h$
  - $m_{\widetilde{W}_1} > 103.5$ GeV
  - $m_{\tilde{e}_{L,R}} > 99$ GeV for $m_{\tilde{\ell}} - m_{\widetilde{Z}_1} > 10$ GeV
- ⋆ $BF(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ (BELLE, CLEO, ALEPH)
  - SM theory: $BF(b \to s\gamma) \simeq 3.3 \pm 0.3 \times 10^{-4}$
- ⋆ $a_\mu = (g-2)_\mu/2$ (Muon $g-2$ collaboration)
  - $\Delta a_\mu = (22 \pm 10) \times 10^{-10}$ (PDG $e^+e^-$)
  - $\Delta a_\mu^{SUSY} \propto \frac{m_\mu^2 \mu M_i \tan\beta}{M_{SUSY}^4}$
- ⋆ $BF(B_s \to \mu^+\mu^-) < 1 \times 10^{-7}$ (CDF-new!)
  - constrains at very large $\tan\beta \gtrsim 50$
- ⋆ $\Omega_{CDM}h^2 = 0.113 \pm 0.009$ (8% WMAP compilation)

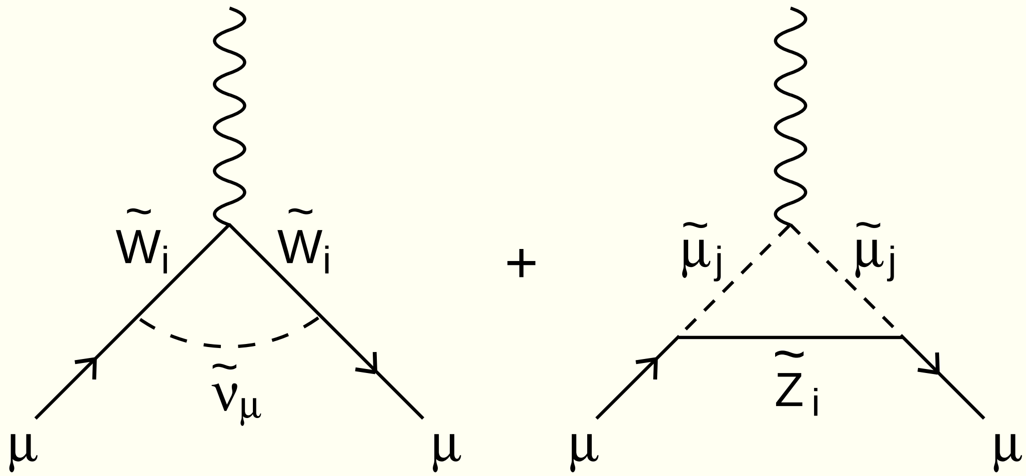
# Branching fraction $BG(b \to s\gamma)$

- occurs in SM via $tW$ loops
- in SUSY, $\tilde{t}_i \widetilde{W}_j$, $tH^-$ loops large, comparable to SM
- calculate "Wilson co-efficients" at $Q = M_W$; rate proportional to sum of contributions.



## $g-2$ of the muon

- $\Delta a_\mu \equiv (g-2)_\mu/2 \sim \frac{m_\mu^2 \mu M_i \tan\beta}{M_{SUSY}^4}$




- large if $M_{SUSY}$ is small and/or $\tan\beta$ is large

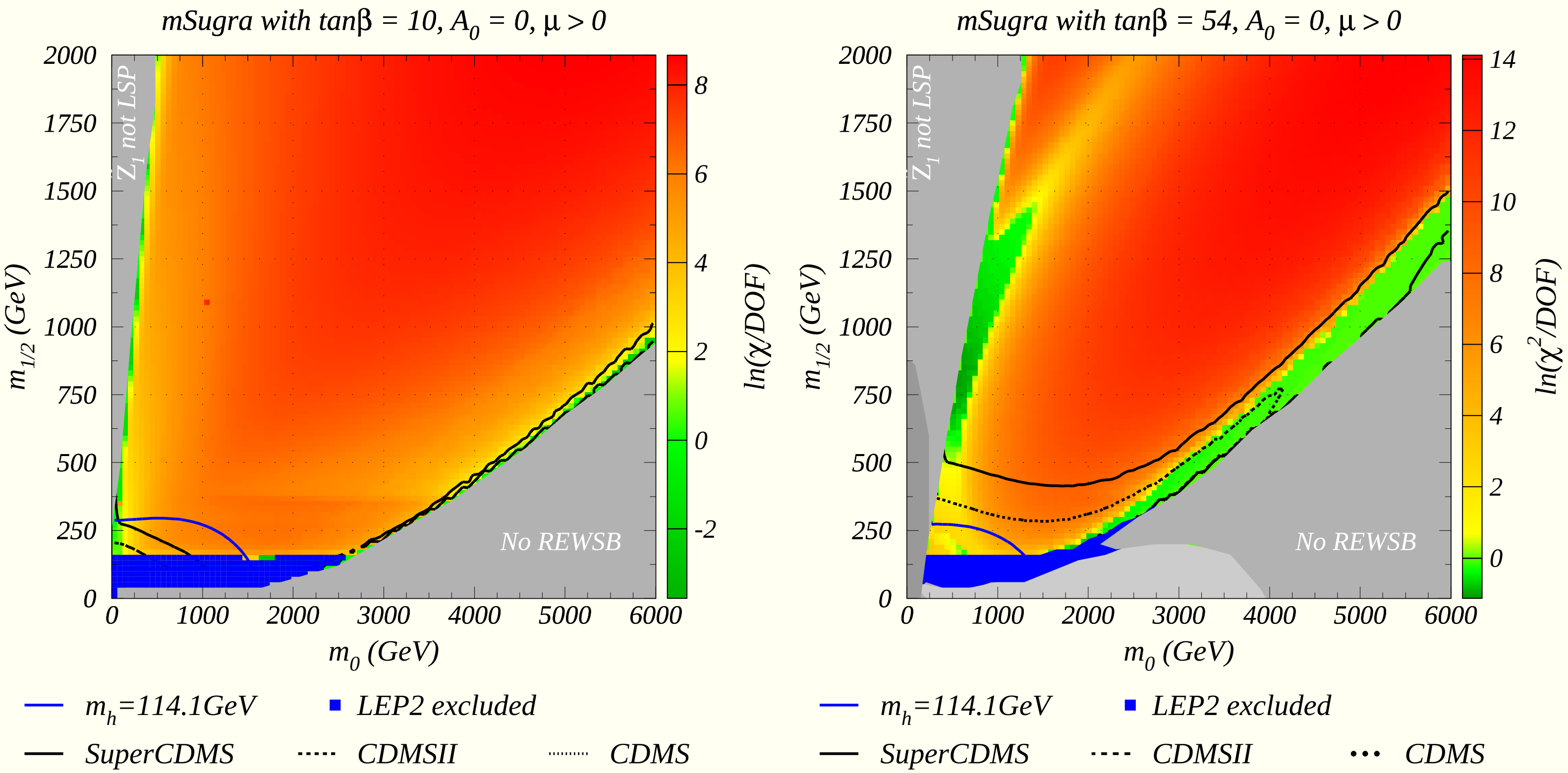
# Neutralino dark matter

- ⋆ Why $R$-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin, Kawamura, $\cdots$)
- ⋆ In thermal equilibrium in early universe
- ⋆ As universe expands and cools, freeze out
- ⋆ Number density obtained from Boltzmann eq'n
  - $dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
  - depends critically on thermally averaged annihilation cross section times velocity
- ⋆ many thousands of annihilation/co-annihilation diagrams
- ⋆ equally many computer codes
  - DarkSUSY, Micromegas, IsaReD, $\cdots$

## Main mSUGRA regions consistent with WMAP

- ⋆ bulk region (low $m_0$, low $m_{1/2}$)
- ⋆ stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\widetilde{Z}_1}$)
- ⋆ HB/FP region (large $m_0$ where $|\mu| \to small$)
- ⋆ $A$-funnel ($2m_{\widetilde{Z}_1} \simeq m_A,\ m_H$)
- ⋆ $h$ corridor ($2m_{\widetilde{Z}_1} \simeq m_h$)
- ⋆ stop co-annihilation region (particular $A_0$ values $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$)

# Results of $\chi^2$ fit using $\tau$ data for $a_\mu$:

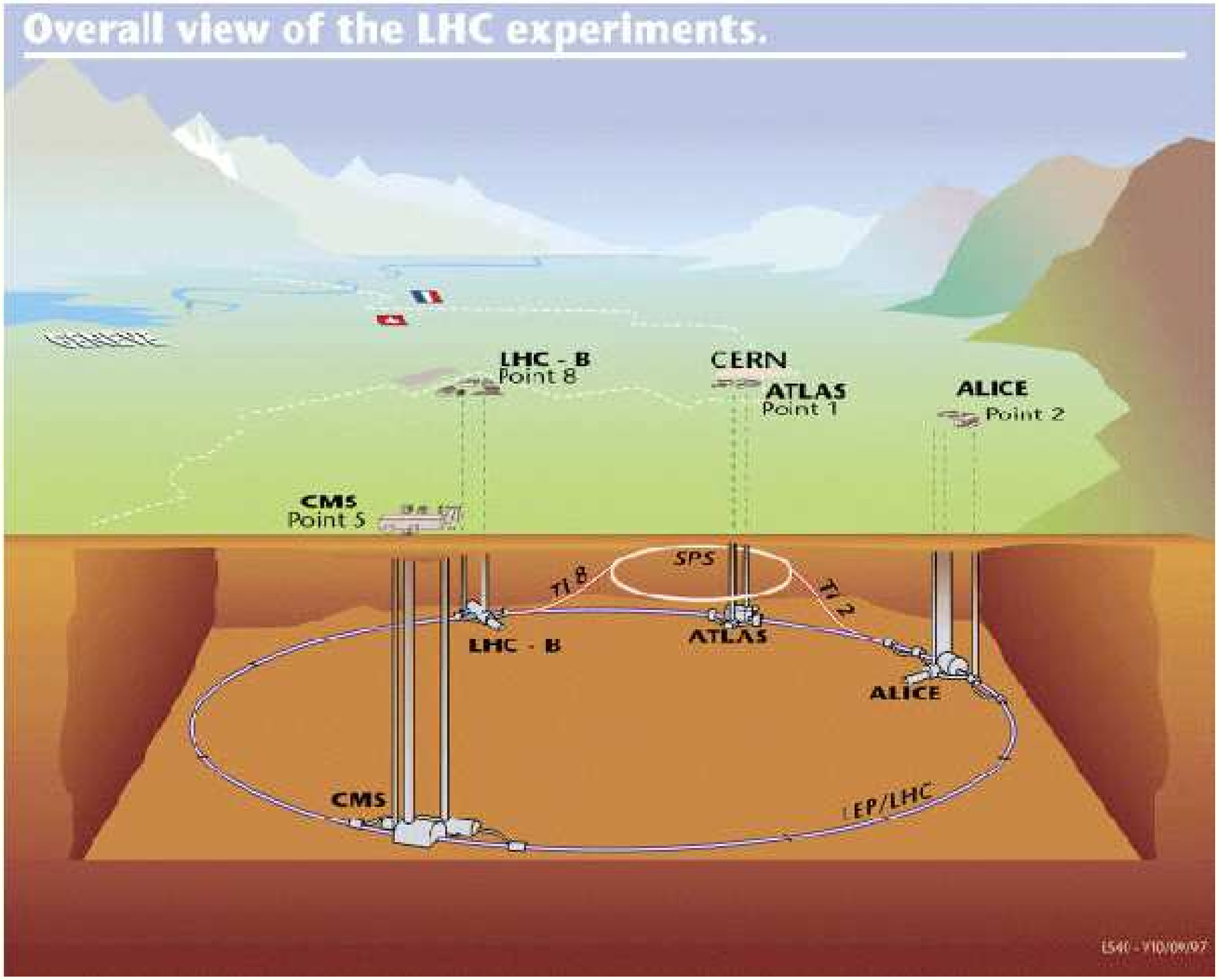



HB, C. Balazs: JCAP 0305, 006 (2003)

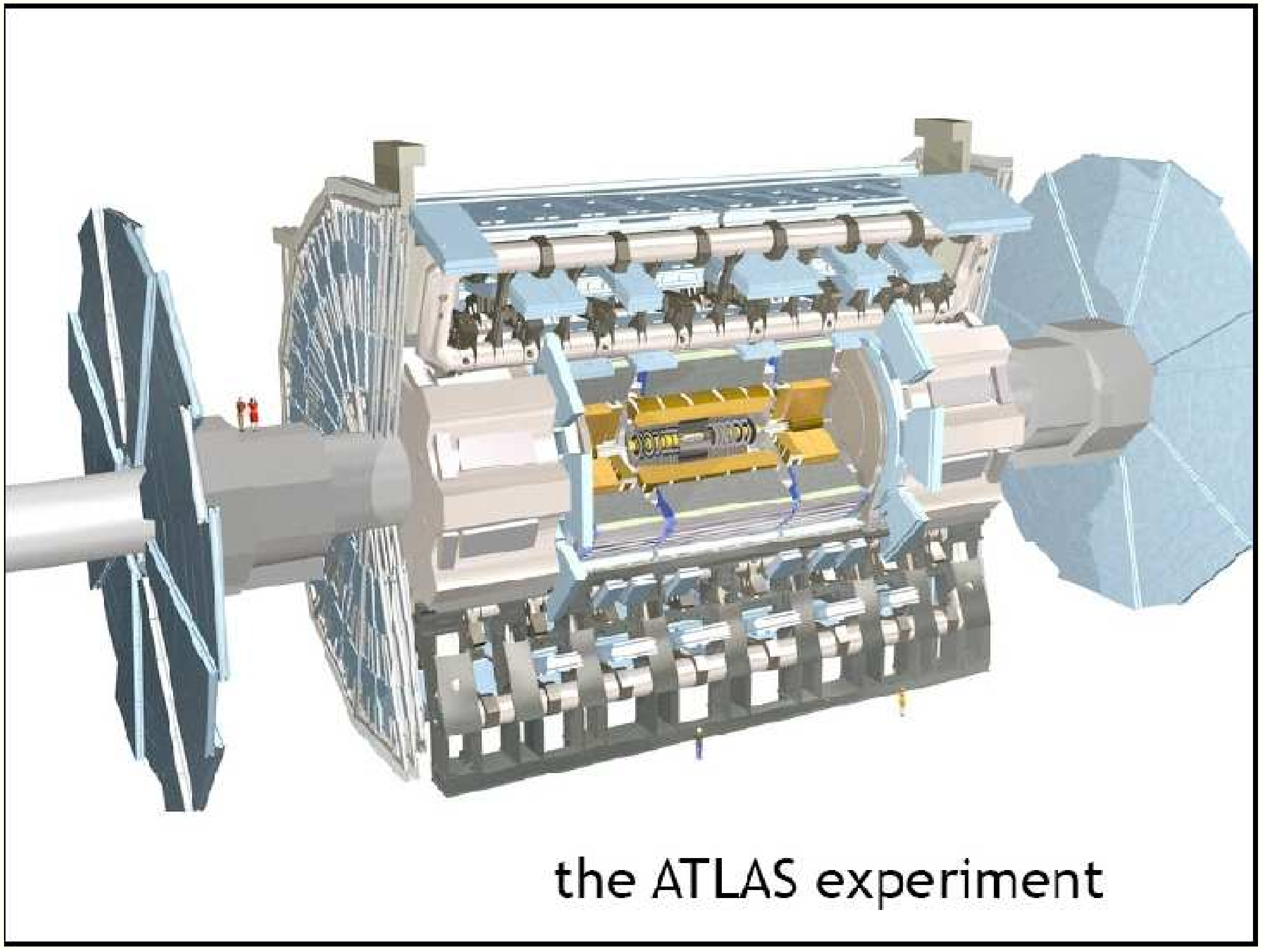
# The role of the CERN Large Hadron Collider (LHC)

- The LHC is a proton-proton collider ($pp$)
- Each beam will have $E = 7$ TeV (trillion electron volts)
- Center-of-mass energy $E \equiv \sqrt{s} = 14$ TeV
- The collider is on a circular tunnel 27 km in circumference
- It is nearly completed: turn-on expected in May 2008!
- Protons are not fundamental particles: made of quarks $q$ and gluons $g$
- The quark and gluon collisions should have enough energy to produce TeV-scale superparticles at a large enough rate that they should be detectable above SM background processes
- LHC should be able to discover SUSY or other new physics: but probably can't rule SUSY out if just a Higgs or nothing new is found

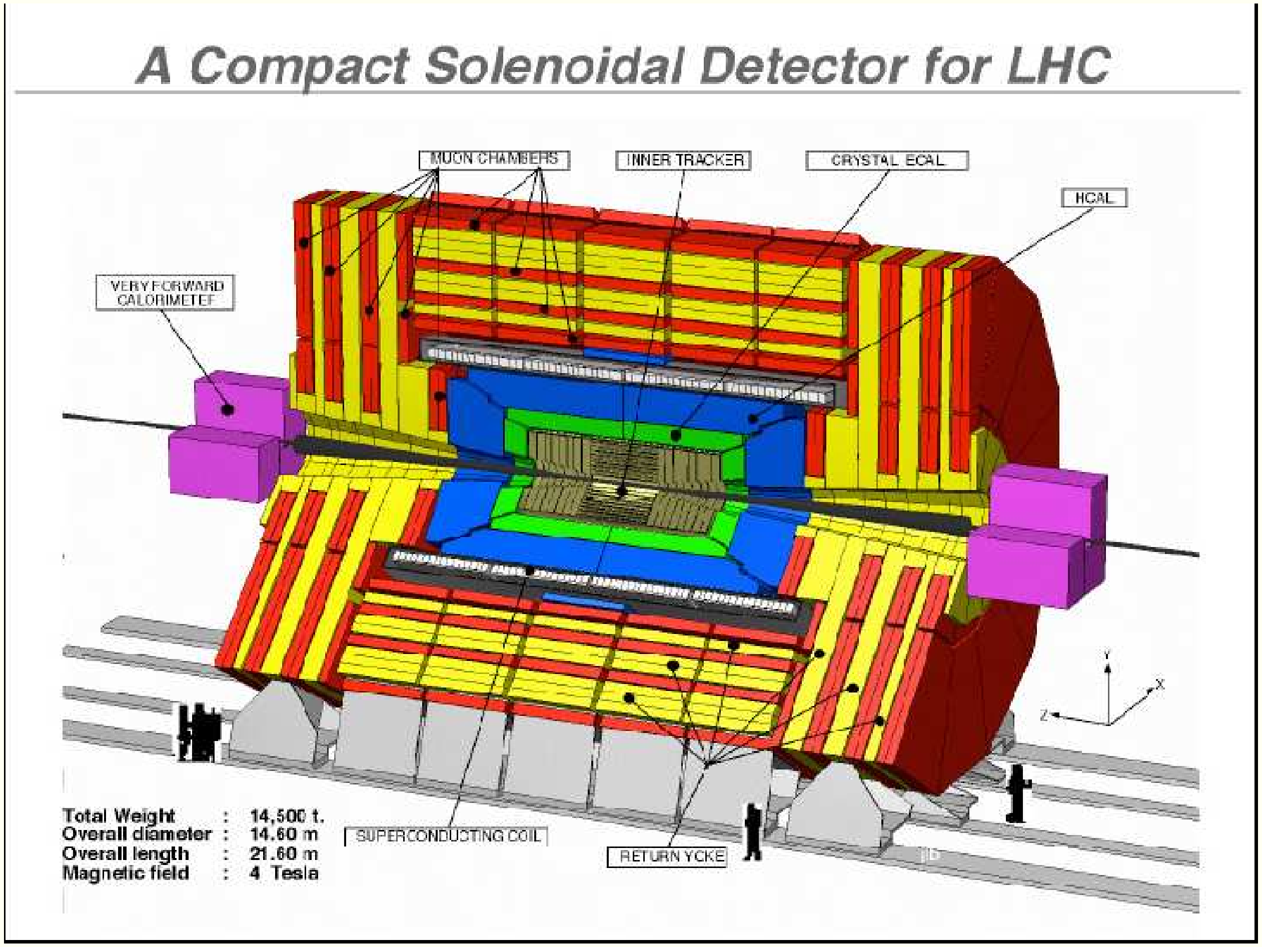
## Layout of the LHC:two main detectors: Atlas and CMS



# The Atlas detector



# The CMS (Compact Muon Solenoid) detector



## End with a quote:

"if we consider the main classes of new physics that are currently being contemplated···, it is clear that (supersymmetry) is the most directly related to GUTs. SUSY offers a well defined model computable up to the GUT scale and is actually supported by the quantitative success of coupling unification in SUSY GUTs. For the other examples···, all contact with GUTs is lost or at least is much more remote. ··· the SUSY picture··· remains the standard way beyond the Standard Model"

G. Altarelli and F. Feruglio, hep-ph/0306265