Beyond the Standard Model

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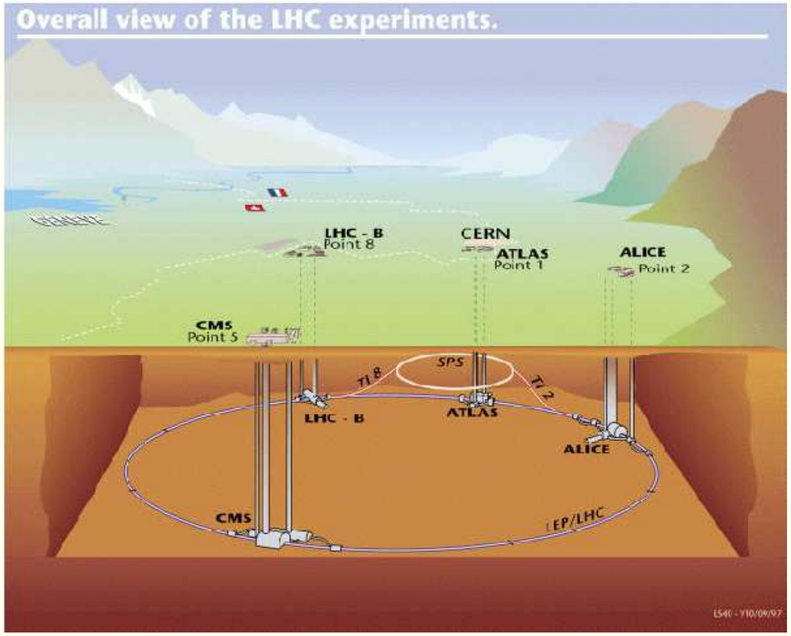
- ⋆ neutrinos
- ⋆ axions
- ⋆ GUTs
- ⋆ extra dimensions: LED, RS
- ⋆ little Higgs
- ⋆ supersymmetry



The Standard Model of Particle Physics

- ⋆ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow g$, $W^\pm$, Z^0, γ
- ⋆ matter content: 3 generations quarks and leptons

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

- ⋆ Higgs sector ⇒ spontaneous electroweak symmetry breaking:

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

- ⋆ ⇒ massive $W^\pm$, Z^0, 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!

Shortcomings of SM

Data

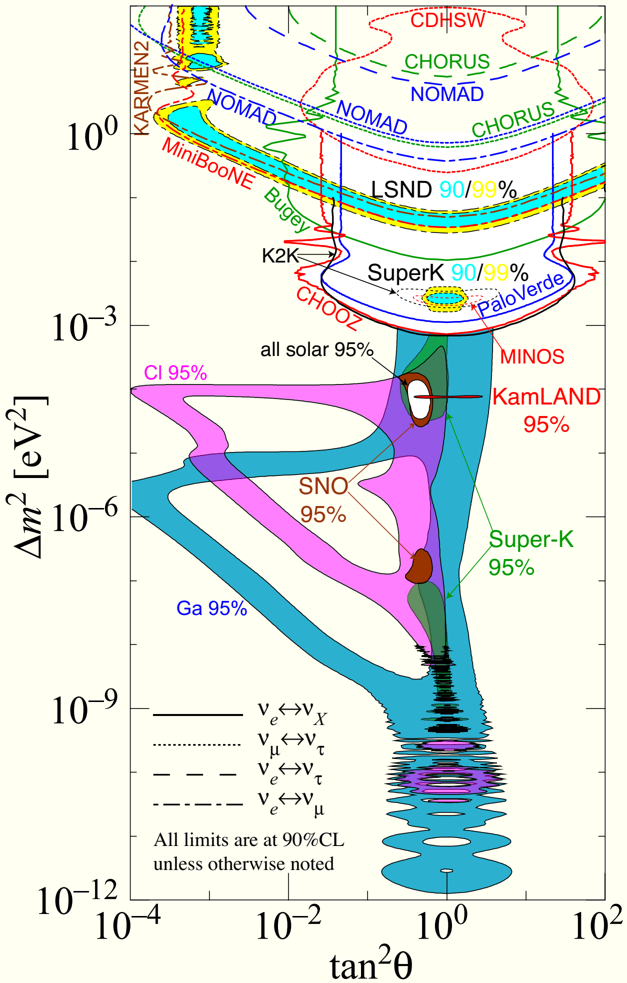
- ⋆ neutrino masses and mixing
- ⋆ baryogenesis (matter anti-matter asymmetry)
- ⋆ cold dark matter
- ⋆ dark energy

Theory

- ⋆ quadratic divergences in scalar sector $\Rightarrow$ fine-tuning
- ⋆ origin of generations
- ⋆ explanation of masses/ mixing angles
- ⋆ origin of gauge symmetry/ quantum numbers
- ⋆ unification with gravity

The neutrino revolution: 1999⇒ today

- ⋆ Solar ν problem: Davis-Bahcall
- ⋆ confirmed: Gallex, SAGE
- ⋆ SuperK atmos. oscillations
- ⋆ SNO ν NC observations
- ⋆ MINOS
- ⋆ KamLand
- ⋆ $K2K$



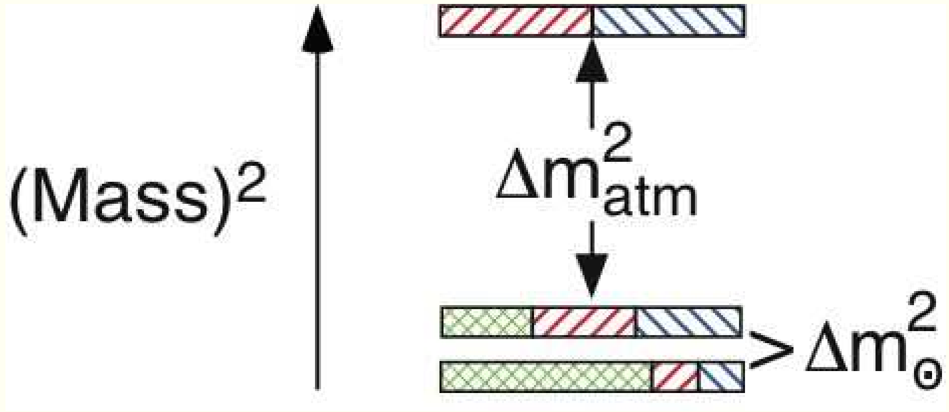
Interpretation: massive νs and oscillations

★ SuperK/$K2K$/Minos atm osc.:

- νs oscillate: are massive!
- $\Delta m^2_{atm.} \sim 0.003$ eV^2
- $\theta_{atm} \sim 45^\circ$

★ Solar ν problem

- MSW matter oscillations
- $\nu_e(r=0) \Rightarrow \nu_2(r=R_\odot)$
- measure ν_e content of ν_2
- $\Delta m^2_\odot \sim 5\times 10^{-5}$ eV^2
- $\theta_\odot \sim 30^\circ$

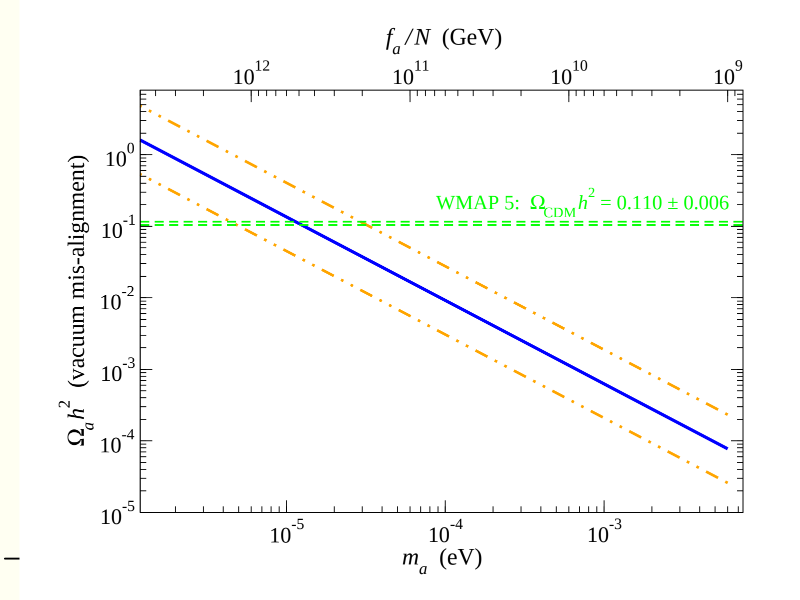


ν questions

- ⋆ what is absolute m_{ν_i}?
- ⋆ is ν spectra normal or inverted?
- ⋆ are νs Majorana or Dirac?
- ⋆ what is θ_{13}?
- ⋆ CP violation in PMNS mixing matrix?
- ⋆ interpretation in terms of see-saw:
  - $m_{\nu_i} \sim (f_{\nu_i} v)^2/M_N$
- ⋆ what is M_{N_i} scale?
- ⋆ implications for GUTs
  - disparate scales: m_{weak} and $M_{N_i} \sim M_{GUT}$?
- ⋆ implications for leptogenesis

Axions

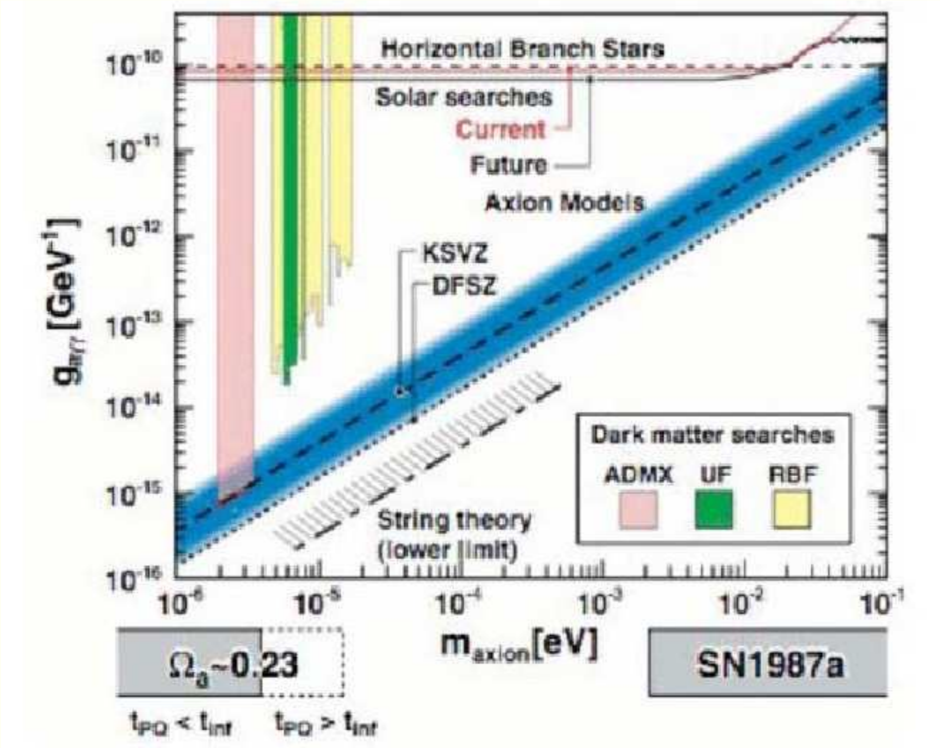
- ⋆ $\mathcal{L}_{QCD} \ni \frac{g_s^2 \bar{\theta}}{32\pi^2} F_A^{\mu\nu} \tilde{F}_{A\mu\nu}$: expect $\bar{\theta} \sim 1$ but $\bar{\theta} \lesssim 10^{-9}$
- ⋆ Peccei-Quinn solution to strong CP problem in QCD: $a(x)$
- ⋆ pseudo-Goldstone boson from
  PQ breaking at scale $f_a \sim 10^9 - 10^{12}$ GeV
- ⋆ non-thermally produced
  via vacuum mis-alignment as *cold* DM
  - $m_a \sim \Lambda_{QCD}^2 / f_a \sim 10^{-6} - 10^{-1} eV$
  - $\Omega_a h^2 \sim \frac{1}{2} \left[\frac{6 \times 10^{-6} eV}{m_a} \right]^{7/6} h^2$
  - astro bound: stellar cooling $\Rightarrow m_a < 10^{-}$
  - a couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)



Axion microwave cavity searches

⋆ ongoing searches: ADMX experiment

- Livermore⇒ U Wash.
- Phase I: probe KSVZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- Phase II: probe DFSZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- beyond Phase II:
  probe higher values m_a



Grand unified theories: $SU(5)$

- unify $SU(3)_C \times SU(2)_L \times U(1)_Y$ into $SU(5)$: single coupling constant: g_5
  - $SU(5) \to SU(3)_C \times SU(2)_L \times U(1)_Y$ at $Q = M_{GUT} \sim 10^{15}$ GeV
  - new $X_\mu,\ Y_\mu$ gauge bosons
  - predict p-decay: $\tau_p \sim 10^{30}$ years
  - experiment: $\tau_p \gtrsim 10^{33}$ years (rule out simplest models)
- partial matter unification
  - d_R^c, $\epsilon^{ab} L_b \ni \mathbf{5}^*$ of $SU(5)$
  - Q_a, u_R^c, $e_R^c \ni \mathbf{10}$ of $SU(5)$
    - Charge quantization: $Q(e^-) = 3Q(d_R)$!
- $m_b \sim 3m_\tau$ (true)
- doublet-triplet splitting: $\mathbf{5_H} \ni \phi_{SM},\ H_c$
- gauge hierarchy problem: $m_H \to M_{GUT}$ fine-tune $1:10^{28}$

Grand unified theories: $SO(10)$

- ⋆ unify $SU(3)_C \times SU(2)_L \times U(1)_Y$ into $S0(10)$
  - 45 gauge bosons
- ⋆ complete matter unification of each generation
  - conjugate spinor reps $\mathbf{16}$ and $\mathbf{16}^*$
  - $\mathbf{16} \ni \mathbf{10} + \mathbf{5}^* + 1$ of $SU(5)$
    - ∗ all matter unified!
    - ∗ $\mathbf{1}$ occupied by ν_R
    - ∗ $SO(10)$ breaking $\Rightarrow M_{N_i}$ (Majorana): see-saw m_ν
- ⋆ explain anomaly cancellation for SM and $SU(5)$
- ⋆ still suffers from gauge hierarchy problem
- ⋆ main idea probably right; implementation probably wrong

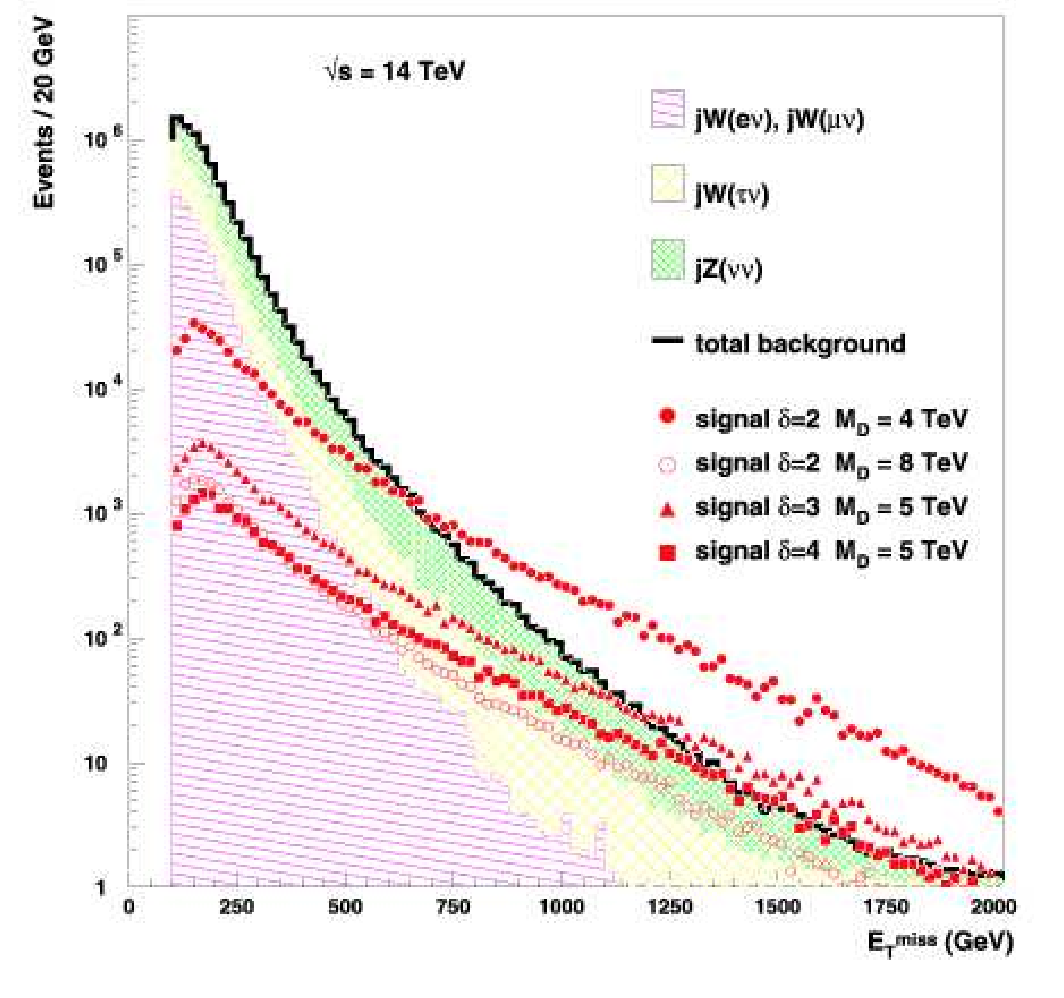
Large extra dimensions (LED or ADD)

- ⋆ assume SM lies on 3-brane surface embedded in $d=4+n$-dim'l bulk
- ⋆ fundamental scale in d-dim's: $M_* =?$
- ⋆ fundamental scale in 3-brane: $M_P = 2.4\times 10^{18}$ GeV
- ⋆ compactify n-dim's on $e.g.$ a torus
- ⋆ $M_P^2 = M_*^{n+2} V_n$ where V_n is volume of extra dim's
- ⋆ for $n>2$, then $M_*\sim m_{weak}$ allowed! Sol'n to hierarchy problem? But then why $r_{Pl}\ll r_c$?

LED phenomenology

- ⋆ compactification $\Rightarrow$ KK-excited gravitons $g^n_{\mu\nu}$: only $g^0_{\mu\nu}$ is massless
- ⋆ couple to matter $\sim 1/M_P$
- ⋆ KK-graviton mass splitting: tiny
- ⋆ tiny graviton emission cross-section compensated by vast number of graviton emissions possible: M_P factors cancel!
- ⋆ can see *e.g.* $pp \to g + g^n_{\mu\nu}$ at LHC!
- ⋆ can observe quantum gravity at colliders!
- ⋆ also, black hole production?

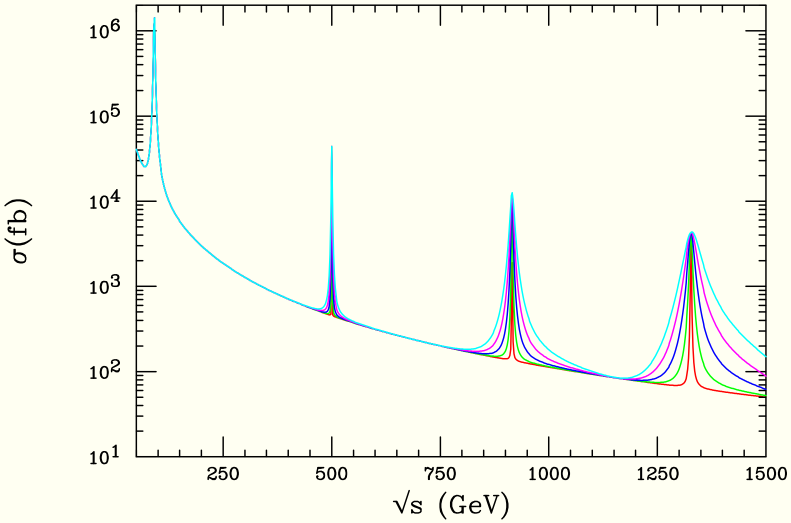
KK-graviton prod'n at LHC



Warped extra dimensions (Randall-Sundrum RS)

- ⋆ assume SM and hidden branes separated in warped (AdS_5) spacetime
- ⋆ warped metric: $ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$
- ⋆ solve Einstein eq'ns in 5-d; compactify 5th dim'n on an orbifold
- ⋆ find $m_{weak} = e^{-kr_c\pi}M_P$
- ⋆ weak scale emerges as exponential suppression of Planck scale
- ⋆ consequence: KK-excited gravitons with weak scale coupling and TeV-scale mass splitting!
- ⋆ can see excited graviton resonances at colliders!

RS phenomenology



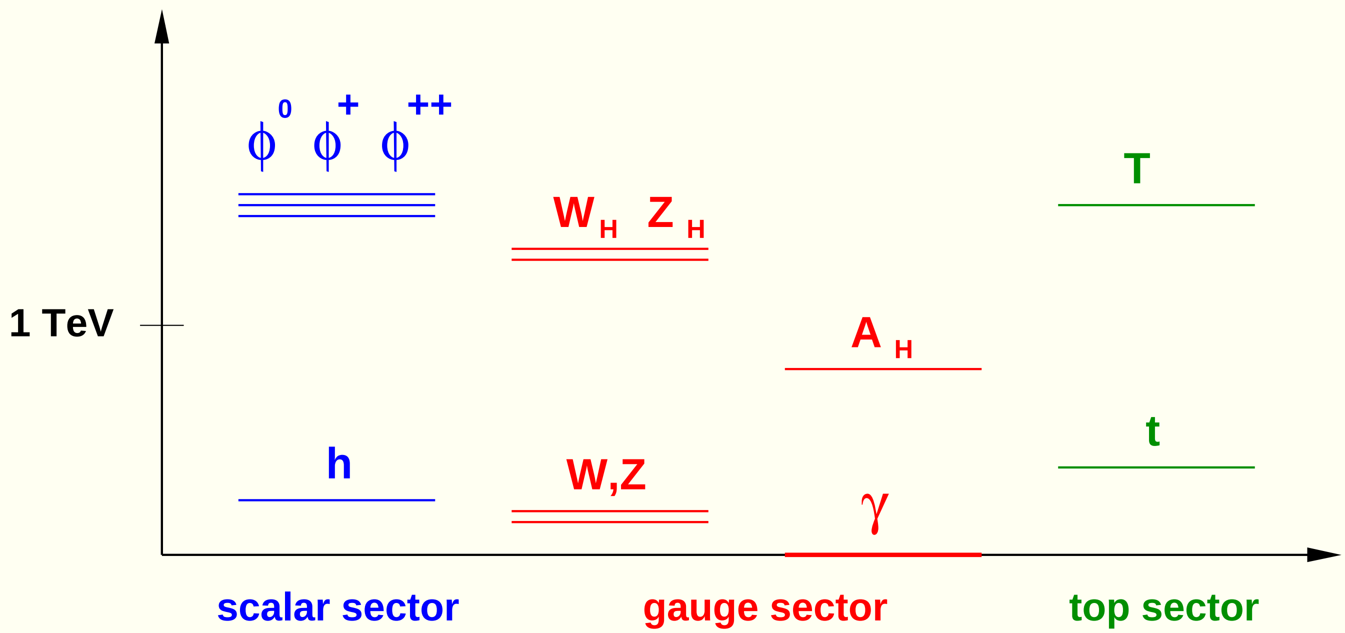
Davoudiasl, Hewett, Rizzo

- KK-excited gravitons: weak scale mass spacing via zeros of Bessel functions
- can produce RS gravitons at e^+e^- or hadron colliders
- massive graviton resonances couple to all matter pairs

Little Higgs theories

- New approach to EWSB: Arkani-Hamed, Cohen, Georgi, 2001
- Higgs field arises as pseudo-Nambu-Goldstone boson from "collective" symmetry breaking
- Symmetry $\Rightarrow$ quadratic divergences to m_H^2 cancel at 1-loop (2-loop and higher quad. divergences remain)
- Natural cut-off of theory is ~ 10 TeV to avoid "little hierarchy problem"
- All LH theories predict new particles at 1-10 TeV scale
  - new gauge bosons A_H, $W_H^\pm$, W_H^0 to cancel gauge boson loops in m_H^2
  - new top partner fermions T to cancel top loop in m_H^2
  - new scalars to cancel Higgs self coupling loops
- precise details model-dependent: most popular: littlest Higgs with $SU(5)/SO(5)$

Spectrum from Little Higgs theories



T-parity in Little Higgs theories (LHT)

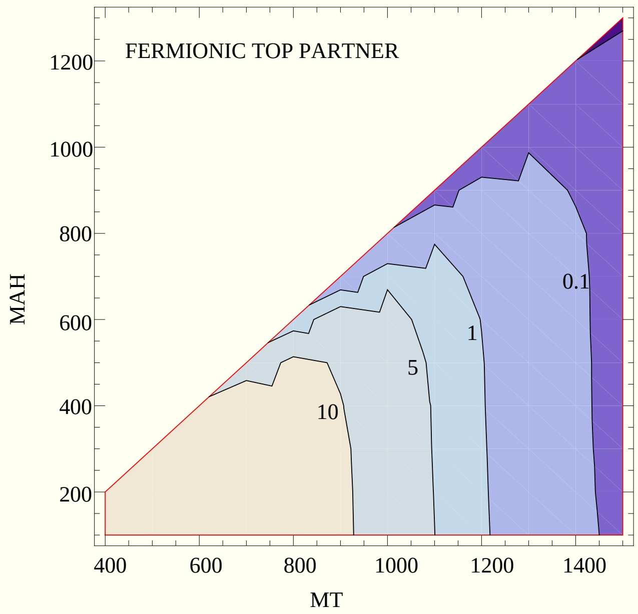
- It was found that LH models tend to give large corrections to precision EW observables unless $m_{LH} \to 10$ TeV
- This re-introduces fine-tunings in Higgs sector
- EWPOs can be saved by introducing T-parity (Cheng and Low)
  - SM particles: t-even
  - new GBs, scalars, some top-partners: t-odd
  - then contributions to EWPOs only occur at loop level
  - can allow much lighter new particle states
- t-odd particles produced in pairs
- $t$odd particles decay to other t-odd states
- Lightest t-odd particle absolutely stable: DM candidate, usually A_H (but see Hill+Hill anomalies paper)

LHT models at LHC

- main search channel: $pp \to T\bar{T}$ with $T \to tA_H$
- search for $t\bar{t}+ \not{E}_T$ states
- see Cheng, Low and Wang, PRD74, 055001 (2006)
- Matsumoto, Nojiri, Nomura, PRD75, 055006 (2007)
- Belyaev, Chen, Tobe and Yuan, PRD74, 115020 (2006)
- Carena, Hubisz, Perelstein, Verdier, PRD75, 091701 (2007)
- Han, Mahbubani, Walker, Wang, arXiv:0803.3820 (2008)

$T\bar{T}$ discovery at LHC

- Han, Mahbubani, Walker, Wang, arXiv:0803.3820 (2008)
- significance after cuts with 100 fb^{-1} at LHC



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 α 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!

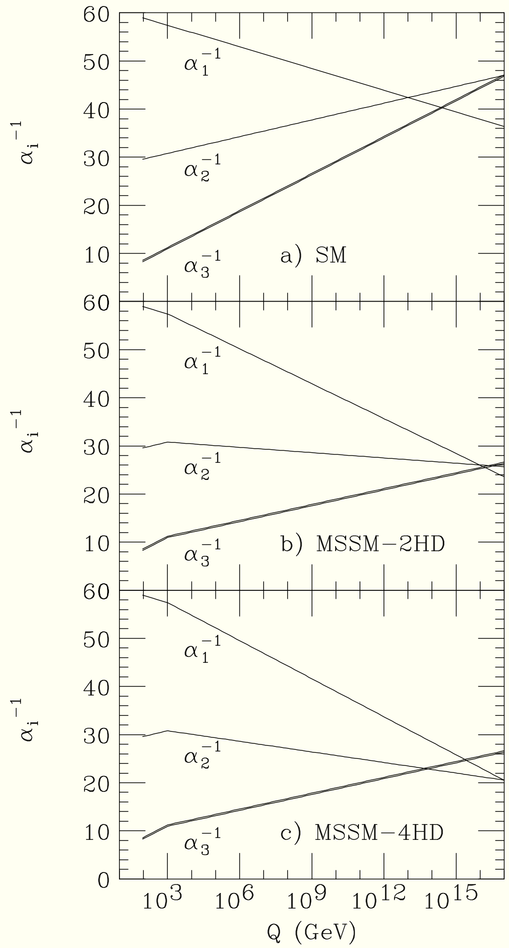
Supergravity (SUGRA)

- ⋆ $e^{i\bar{\alpha}Q}$ with $\alpha(x)$: *local* SUSY transformation
  - forces introduction of spin 2 graviton and spin $\frac{3}{2}$ gravitino
  - resultant theory $\Rightarrow$ General Relativity in classical limit!
- ⋆ rules for Lagrangian in supergravity gauge theory: Cremmer et al. (1983)
- ⋆ fertile ground: supergravity $\cup$ grand unification: LE limit of superstring?
- ⋆ minimal supergravity model (mSUGRA)
- ⋆ $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
  - $m_0 =$ mass of all scalars at $Q = M_{GUT}$
  - $m_{1/2} =$ mass of all gauginos at $Q = M_{GUT}$
  - $A_0 =$ trilinear soft breaking parameter at $Q = M_{GUT}$
  - $\tan\beta =$ ratio of Higgs vevs
  - $\mu =$ SUSY Higgs mass term; magnitude determined by REWSB!

Some successes of SUSY GUT theories

- ⋆ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- ⋆ gauge coupling unification!

Gauge coupling evolution



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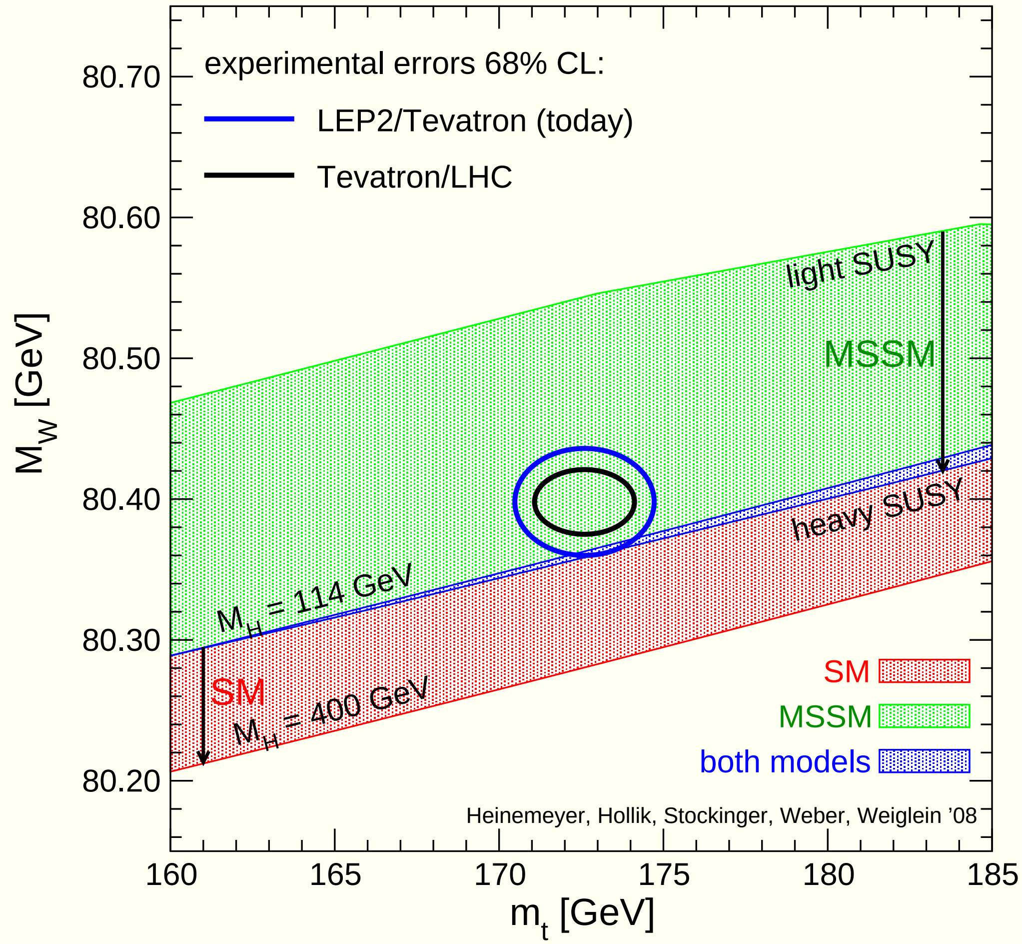
- ⋆ gauge coupling unification!
- ⋆ Lightest Higgs mass $m_h \lesssim 135$ GeV as indicated by radiative corrections!

Precision electroweak data and the Higgs mass:



S. Heinemeyer et al.

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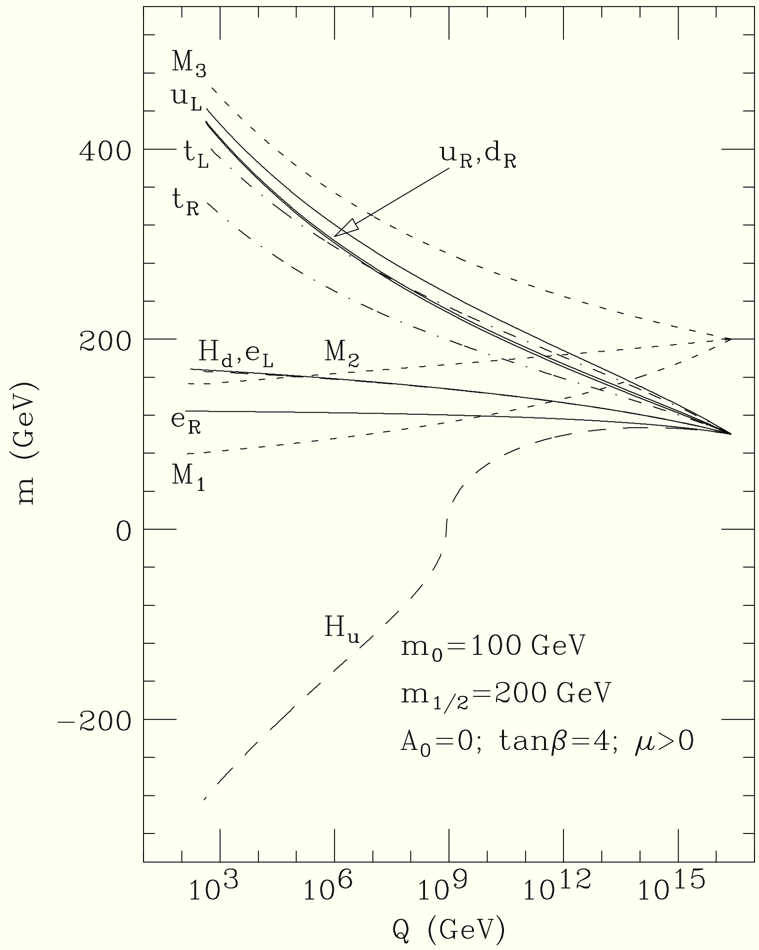
- ⋆ gauge coupling unification!
- ⋆ Lightest Higgs mass $m_h \lesssim 130$ GeV as indicated by radiative corrections!
- ⋆ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!

Soft term evolution and radiative EWSB



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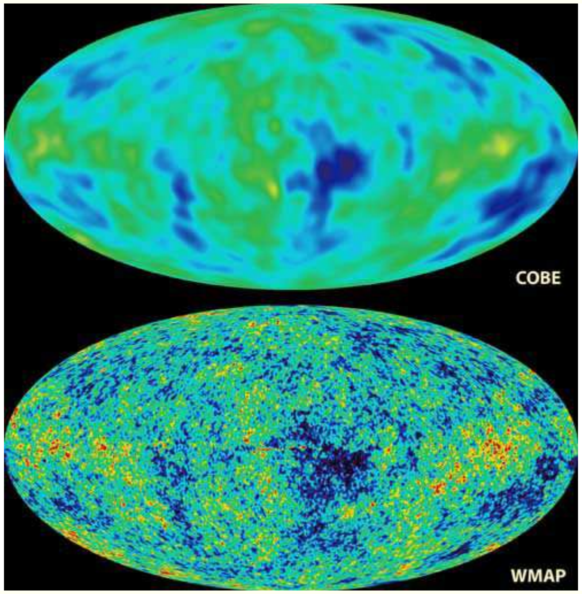
- ⋆ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
- ⋆ dark matter candidate: lightest neutralino $\tilde{Z}_1$
- ⋆ stablize neutrino see-saw scale vs. weak scale
- ⋆ $SO(10)$ SUSY GUT: baryogenesis via leptogenesis
- ⋆ can give dark energy via CC Λ (but need huge fine-tuning...)
  - SUGRA = low energy limit of superstring?
  - stringy multiverse: anthropic selection of small CC?

Evidence for dark matter in the universe

- ⋆ binding of galactic clusters (Zwicky, 1930s)
- ⋆ galactic rotation curves
- ⋆ large scale structure formation
- ⋆ inflation $\Rightarrow \Omega = \rho/\rho_c = 1$
- ⋆ gravitational lensing
- ⋆ anisotropies in cosmic MB (WMAP)
- ⋆ surveys of distant galaxies via SN (DE)
- ⋆ Big Bang nucleosynthesis
  - $\Omega_\Lambda \simeq 0.7$
  - $\Omega_{CDM} \simeq 0.25$
  - $\Omega_{baryons} \simeq 0.045$ (dark baryons ~ 0.040
  - $\Omega_\nu \sim 0.005$



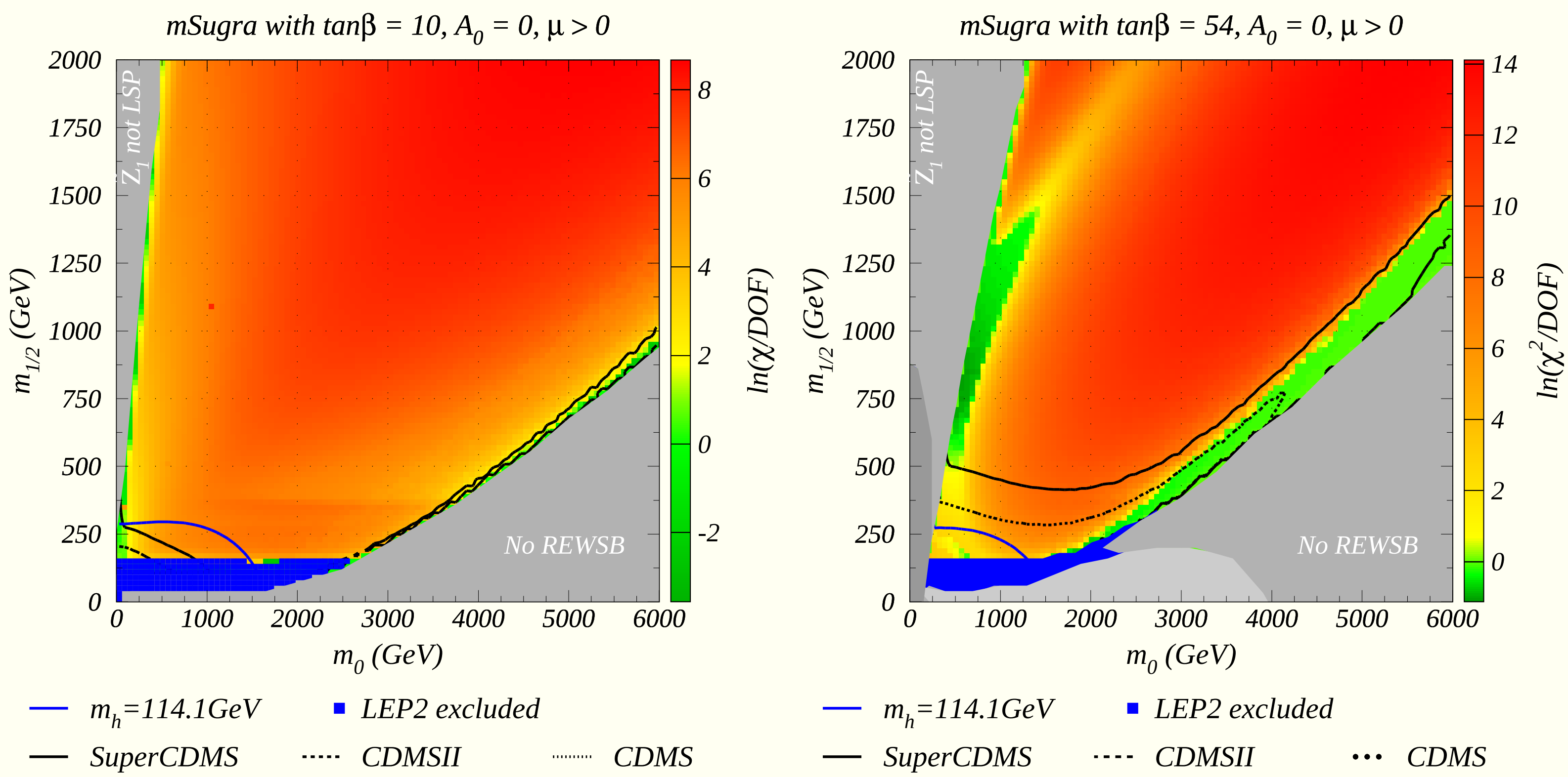
SUSY dark matter

- ⋆ R-parity conservation⇒ conserved B and L ⇒ proton stability
  - $R(particle) = 1$; $R(sparticle) = -1$
- ⋆ Naturally occurs in $SO(10)$ SUSY GUT theories
- ⋆ Some consequences:
  - Sparticles are produced in pairs
  - Sparticles decay to other sparticles
  - Lightest SUSY particle (LSP) is absolutely stable (good candidate for dark matter)
- ⋆ LSP must be charge, color neutral (bound on cosmological relics)
  - lightest neutralino $\tilde{Z}_1$ is WIMP candidate
  - axion/axino multiplet
  - gravitino

Calculating the relic density of neutralinos

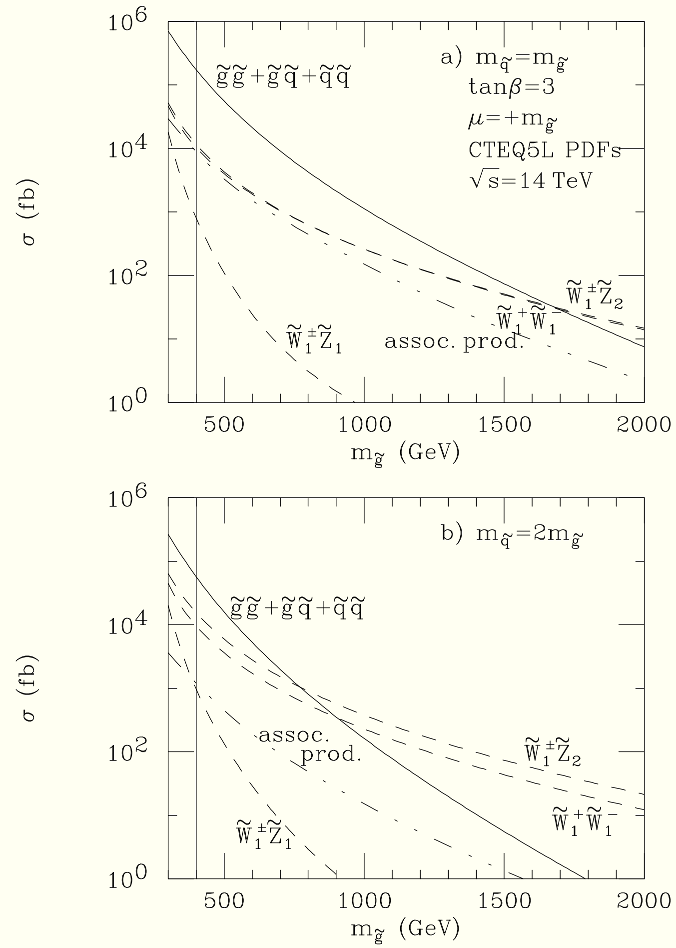
- ⋆ At very high T, neutralinos in thermal equilibrium with cosmic soup
- ⋆ As universe expands and cools, expansion rate exceeds interaction rate (freeze-out)
- ⋆ number density is governed by Boltzmann eq. for FRW universe
  - $dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
  - $\Omega_{\widetilde{Z}_1} h^2 = \frac{s_0}{\rho_c/h^2} \left(\frac{45}{\pi g_*}\right)^{1/2} \frac{x_f}{m_{Pl}} \frac{1}{\langle \sigma v \rangle}$
  - $\Omega_{CDM} h^2 \sim 0.1 \Rightarrow \langle \sigma v \rangle \sim 0.9$ pb!
  - $\langle \sigma v \rangle = \pi \alpha^2 / 8m^2 \Rightarrow m \sim 100$ GeV
  - "The WIMP miracle!": cosmic motivation for new physics at weak scale
- ⋆ SUSY: 1722 annihilation/co-annihilation reactions; 7618 Feynman diagrams
- ⋆ IsaReD program (HB, A. Belyaev , C. Balazs)

Results of χ^2 fit using τ data for a_μ:

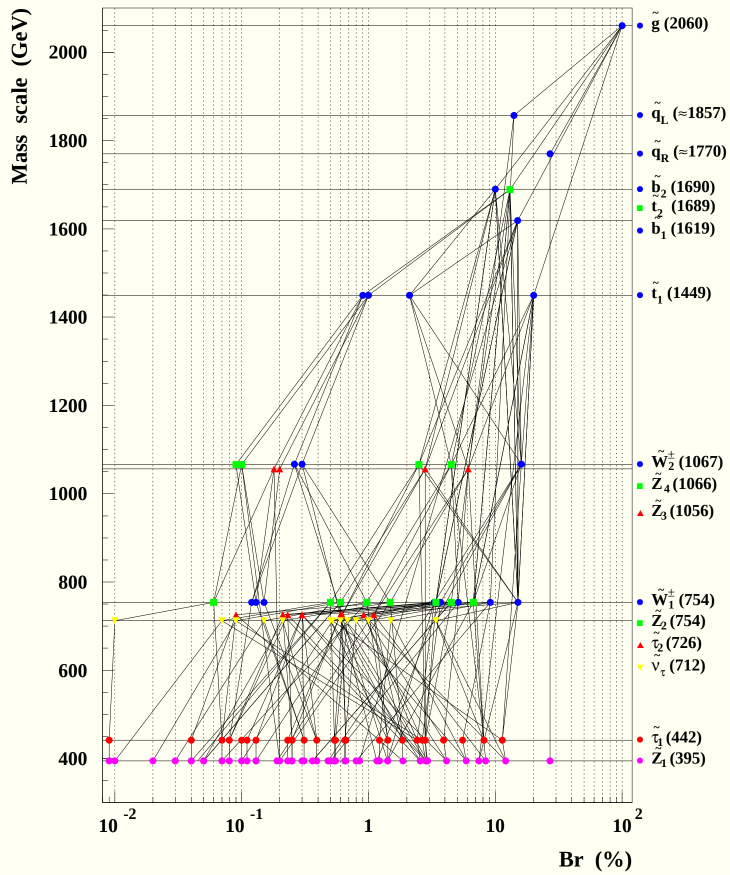


HB, C. Balazs: JCAP 0305, 006 (2003)

Production of sparticles at CERN LHC

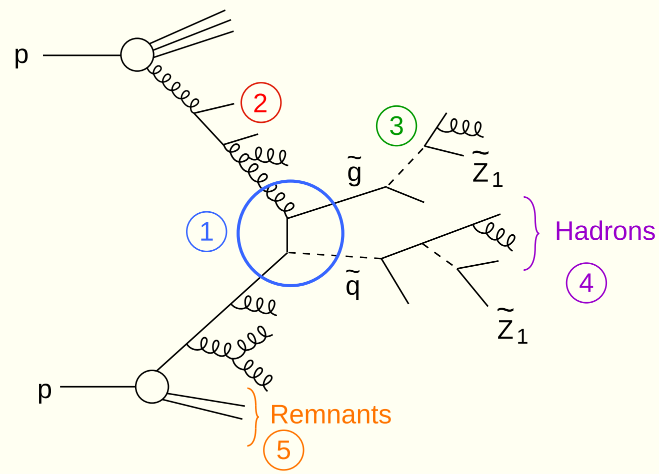


Sparticle cascade decays



$\tilde{Z}_1$ qq (27.0 %)
$\tilde{Z}_1$ $\tau\nu$Wbb (12.1 %)
$\tilde{Z}_1$ $\tau\tau$WWbb (8.4 %)
$\tilde{Z}_1$ WWbb (7.4 %)
$\tilde{Z}_1$ $\tau\nu$qq (5.9 %)
$\tilde{Z}_1$ $\tau\nu$WWWbb (4.1 %)
$\tilde{Z}_1$ $\tau\tau$bb (2.9 %)
$\tilde{Z}_1$ $\tau\tau$qq (2.9 %)
$\tilde{Z}_1$ $\tau\nu$ZWbb (2.8 %)
$\tilde{Z}_1$ $\tau\nu$hWbb (2.6 %)

Event generation for sparticles



Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

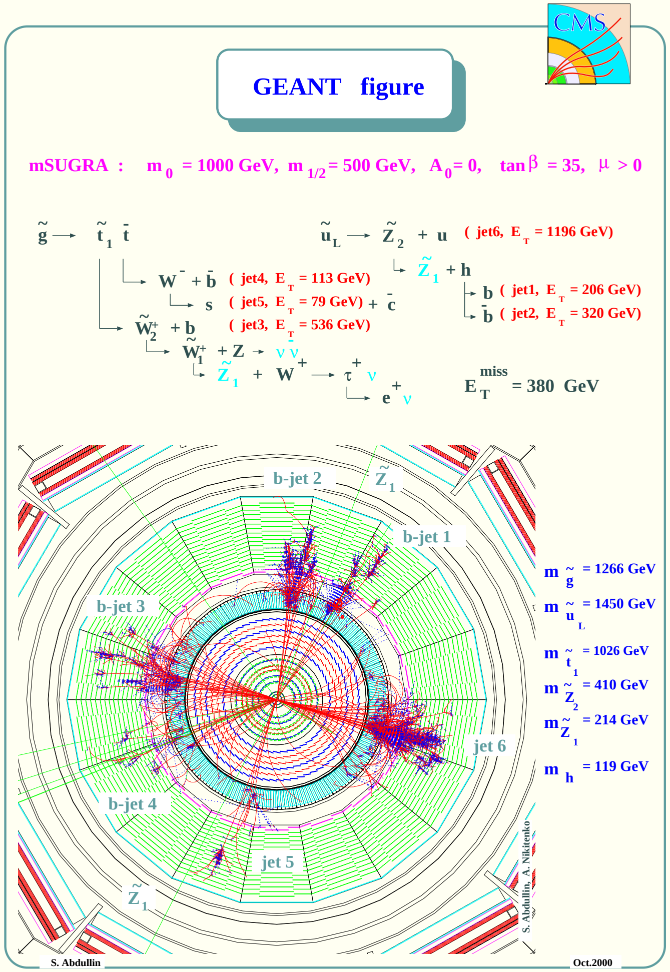
2) Intial / final state showers

3) Cascade decays

4) Hadronization

5) Beam remnants

Simulated sparticle production event at LHC



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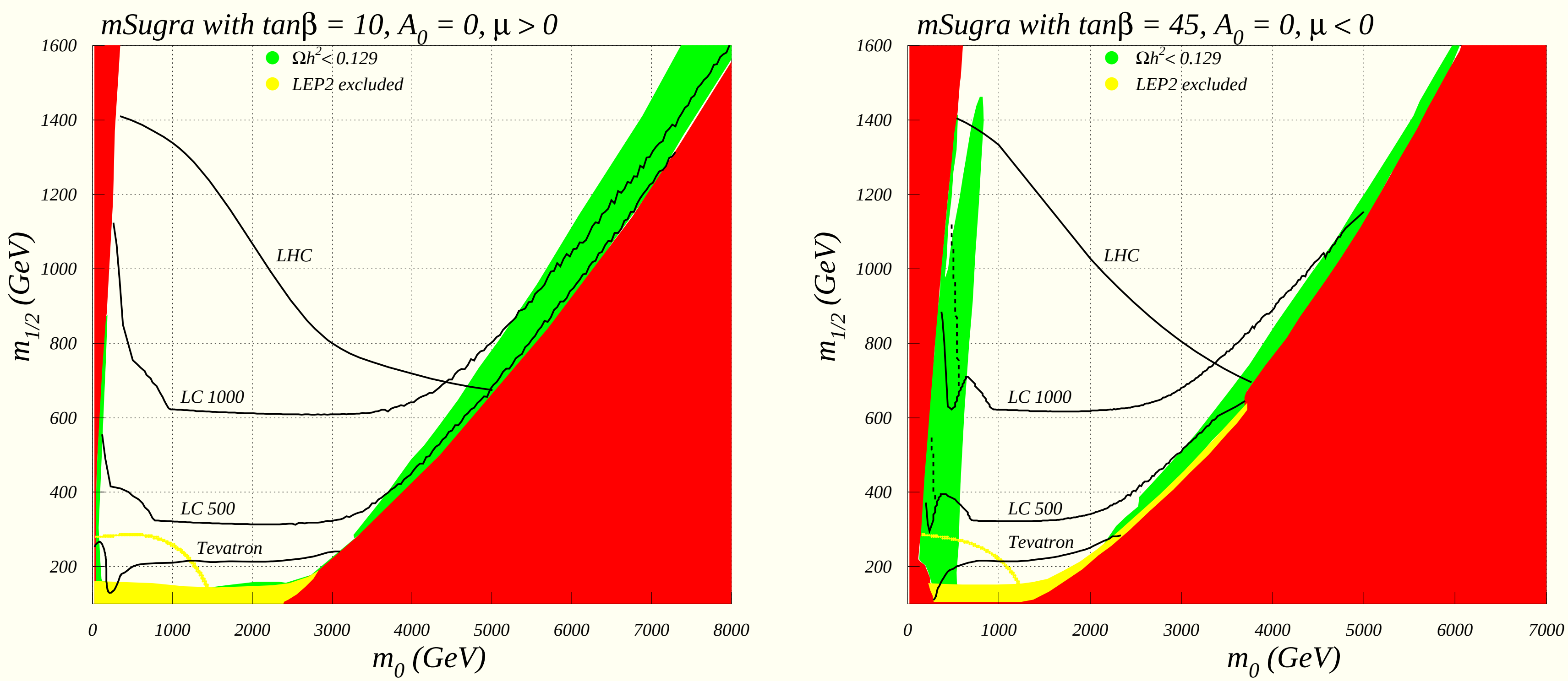
Sparticle reach of all colliders with relic density



HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)

Precision measurements at LHC: Atlas and CMS

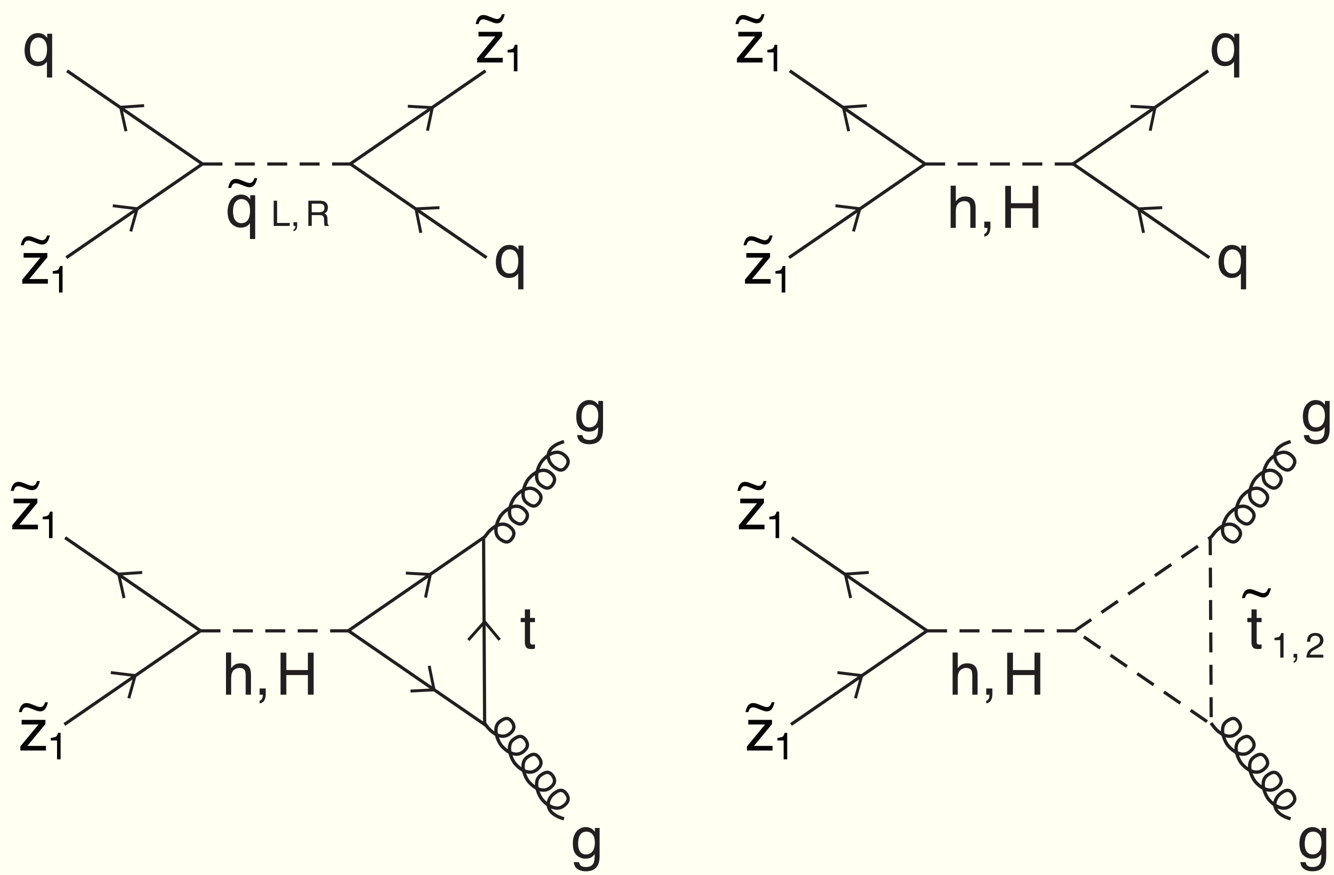
- $M_{eff} = \not{E}_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}},\ m_{\tilde{q}}$ scale
- $m(\ell\bar{\ell}) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ mass edge
- $m(\ell\bar{\ell})$ distribution shape
- combine $m(\ell\bar{\ell})$ with jets to gain $m(\ell\bar{\ell}j)$ mass edge: info on $m_{\tilde{q}}$
- further mass edges possible $e.g.$ $m(\ell\bar{\ell}jj)$
- Higgs mass bump $h \to b\bar{b}$ likely visible in $\not{E}_T + jets$ events
- in favorable cases, may overconstrain system for a given model

⋆ methodology very p-space dependent

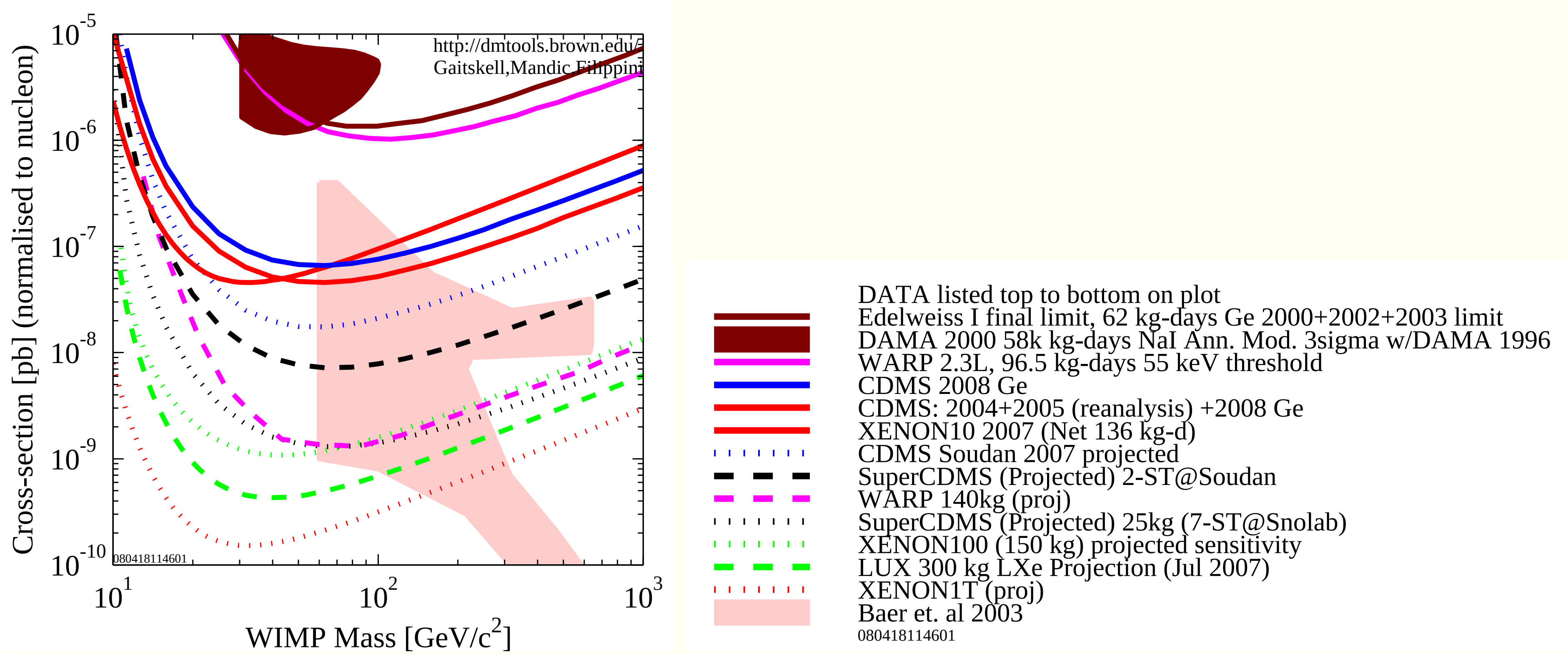
⋆ some regions are very difficult $e.g.$ HB/FP

Direct detection of SUSY DM

★ Direct search via neutralino-nucleon scattering



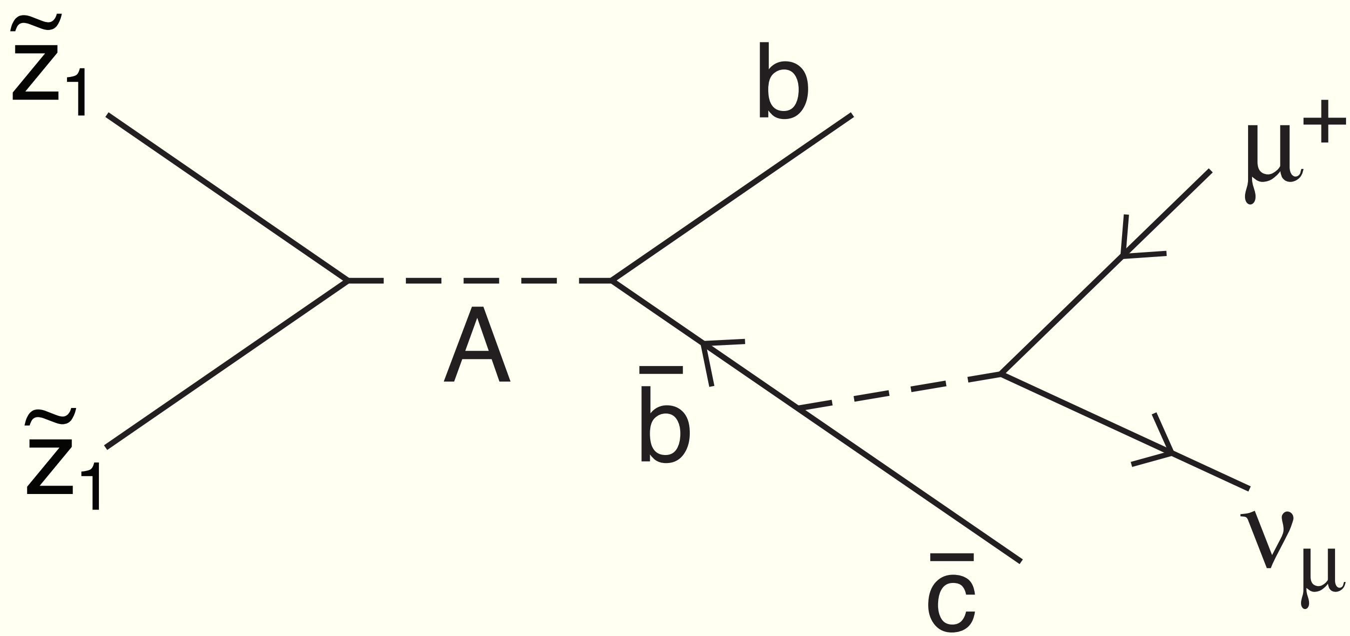
Direct detection of neutralino DM: the race is on!



Indirect detection (ID) of SUSY DM: ν-telescopes

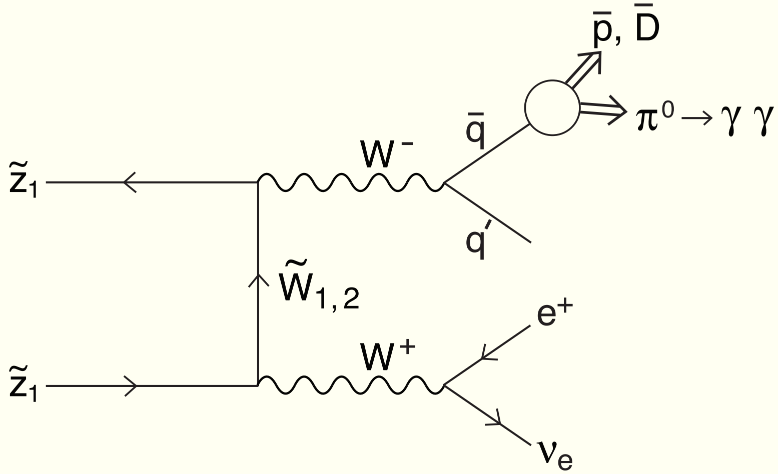
★ $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in ν telescopes

- Amanda, Icecube, Antares

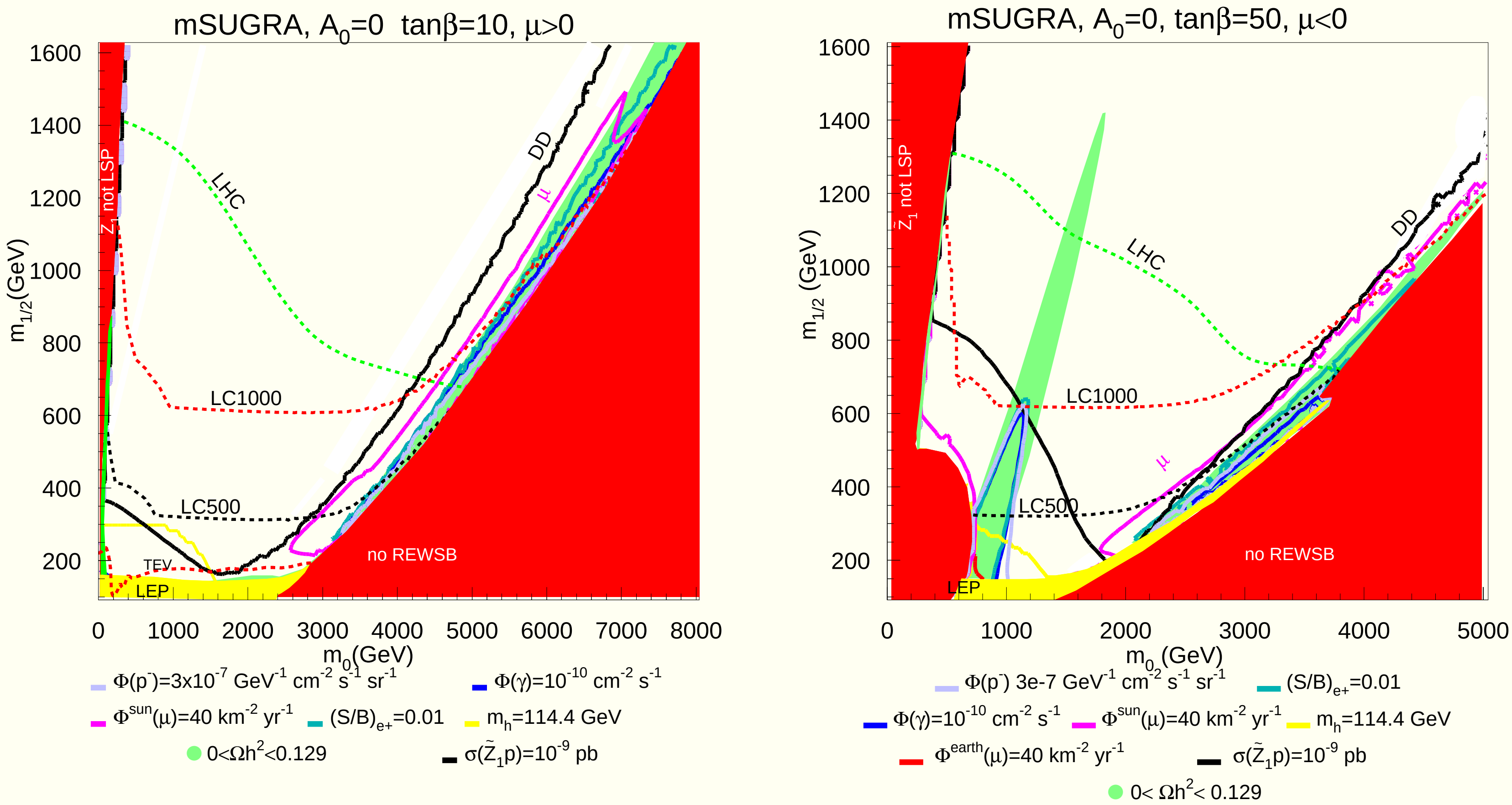


ID of SUSY DM: γ and anti-matter searches

- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ in galactic core or halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to e^+$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{p}$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{D}$ in galactic halo



Direct and indirect detection of neutralino DM



HB, Belyaev, Krupovnickas, O'Farrill: JCAP 0408, 005 (2004)

Impact of DM direct/indirect detection on LHC program

- Extend reach in $\sigma_{SI} \sim 10^{-9} - 10^{-10}$ pb
  - explore thoroughly region of MHDM, possibly MWDM
- after discovery, extract m_{wimp}?
  - $m_{\widetilde{Z}_1}$ sets absolute mass scale for SUSY particles-
  - combine with LHC mass edges to gain LHC absolute sparticle masses
  - learn if $\widetilde{Z}_1$ is absolutely stable: R-conservation
- IceCube turn-on can discover/verify especially MHDM
- knowledge of LHC spectra, σ_{SI}, σ_{SD} combined with possible gamma ray signals may allow map of dark matter distribution in the galaxy
- role of $\bar{p}$, e^+, $\bar{D}$ signals

Conclusion: We are entering a revolutionary period!

- ⋆ I covered just a *few* of the new physics possibilities
  - neutrino physics
  - axions and strong CP problem
  - extra dimensions
  - little Higgs models
  - supersymmetry in many guises: neutralino, axion/axino, gravitino as DM
- ⋆ new facilities (LHC, ν exp'ts, DM searches, ...) should lead, in the next few years, to a new paradigm– beyond the Standard Model– for the laws of physics as we know them!