# Dark matter and the LHC connection

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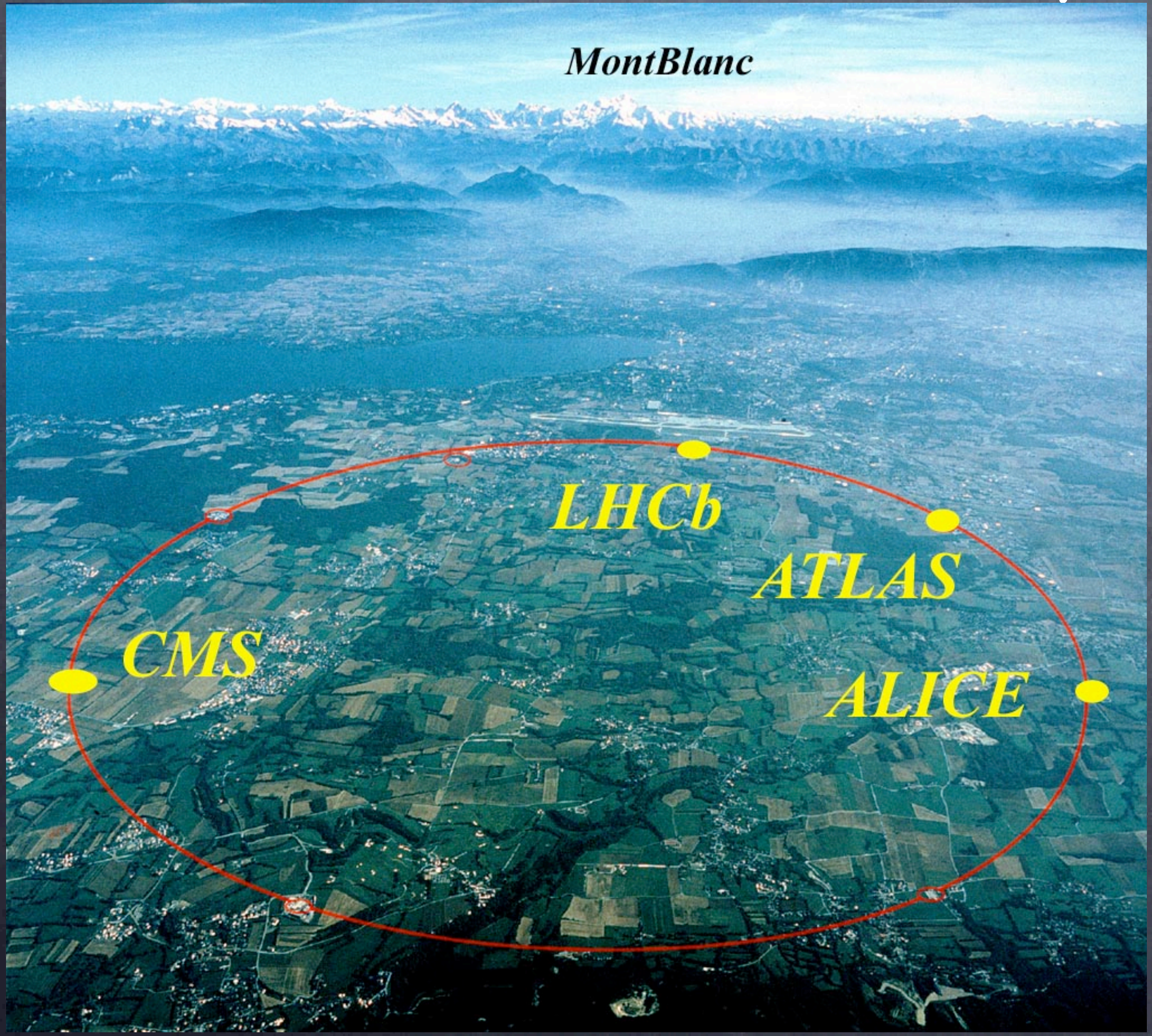
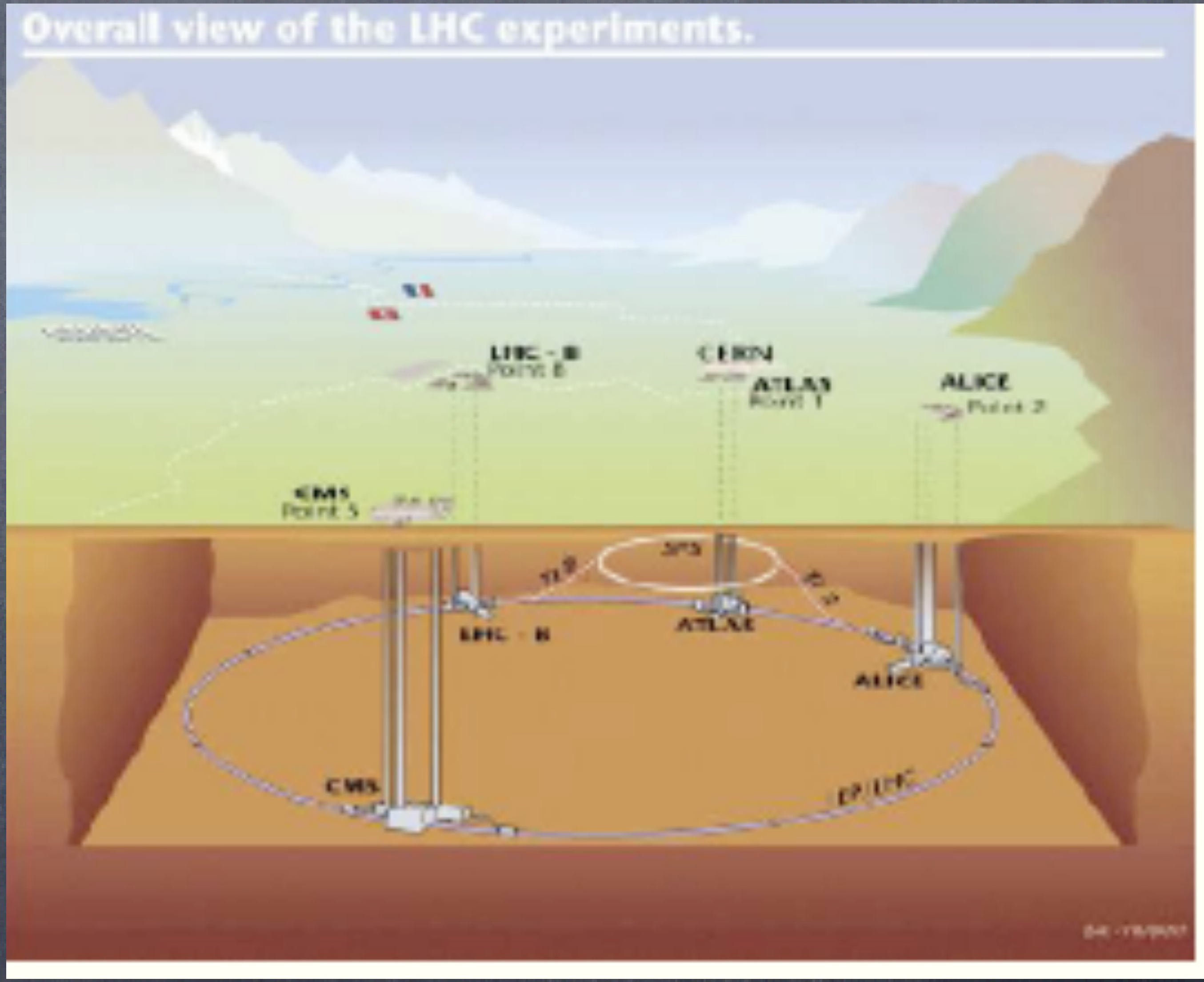


# Direct production of DM at LHC?

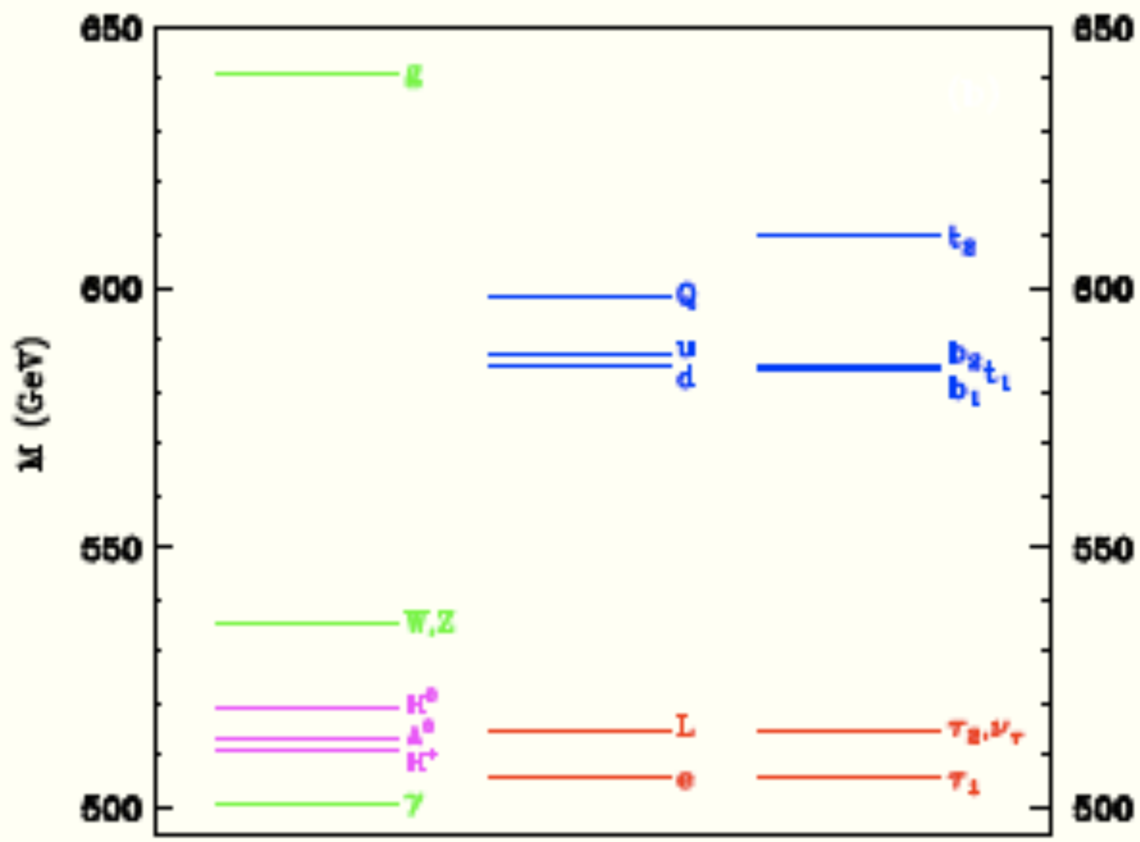
- $pp \to \chi\chi X$ , where X=assorted hadronic debris, not likely visible above BG due to lack of trigger
- An exception: early ASP search for sparticles at SLAC in early 1980s: $e^+e^- \to \chi\chi\gamma$ gave bounds in $m_{\tilde{e}}\ vs.\ m_\chi$ plane
- Similar search as ILC very difficult due to
- $e^+e^- \to \nu\bar{\nu}\gamma$ background

# Universal extra dimensions (UED)

- ⋆ Write down SM action in 5-d
- ⋆ expand SM fields in terms of $Z_2$ odd/even functions
- ⋆ Compactify on $S_1/Z_2$ orbifold with radius $R$
- ⋆ Orbifolding eliminates "wrong helicity" SM zero modes to give chiral SM as zero mode theory
- ⋆ $A_\mu$ has zero mode; $A_4$ does not
- ⋆ low energy theory is SM zero modes
- ⋆ also get KK excitations starting at $m \sim 1/R$
- ⋆ $KK$-parity conserved: get DM candidate LKP :Servant, Tait
- ⋆ spectrum: $Q^1$, $u^1, d^1$, $L^1$, $e^1$, $W^{1\pm}$, $Z^1$, $g^1$, $B^1$, $H^0$, $A^0$, $H^\pm$

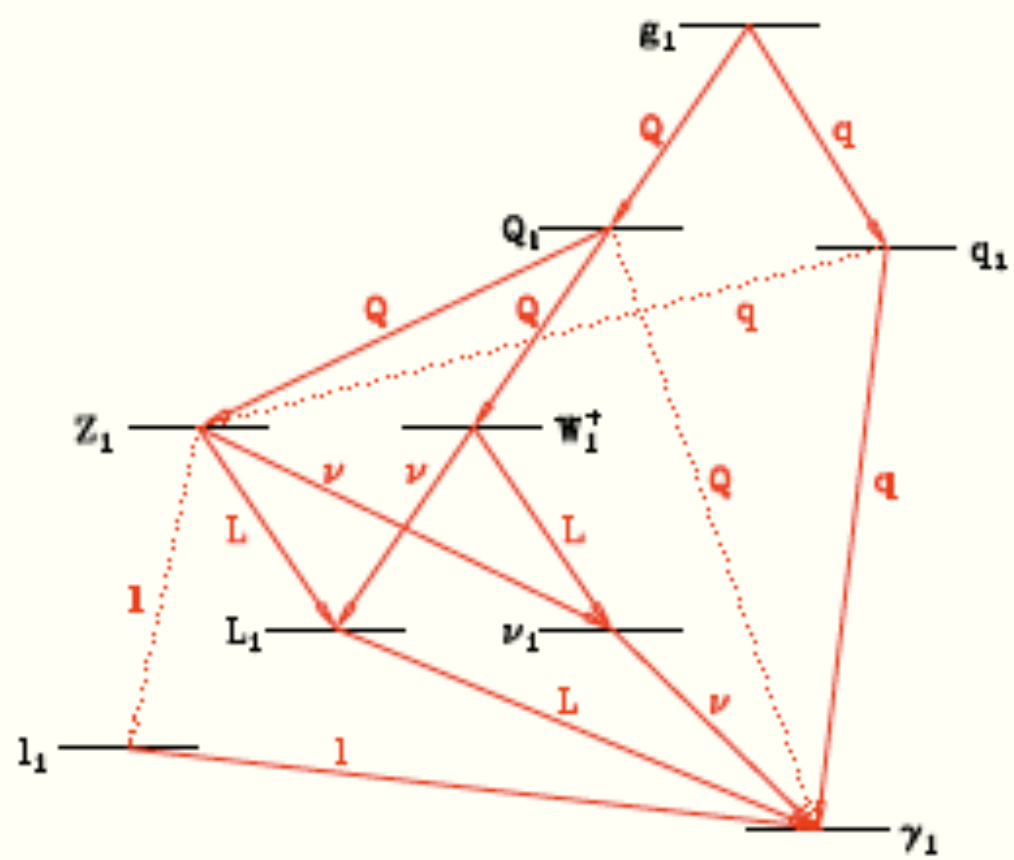
# Spectra of UED theories

- tree level mass spectra nearly degenerate:
- radiative corrections give some splitting (Cheng, Matchev, Schmaltz)



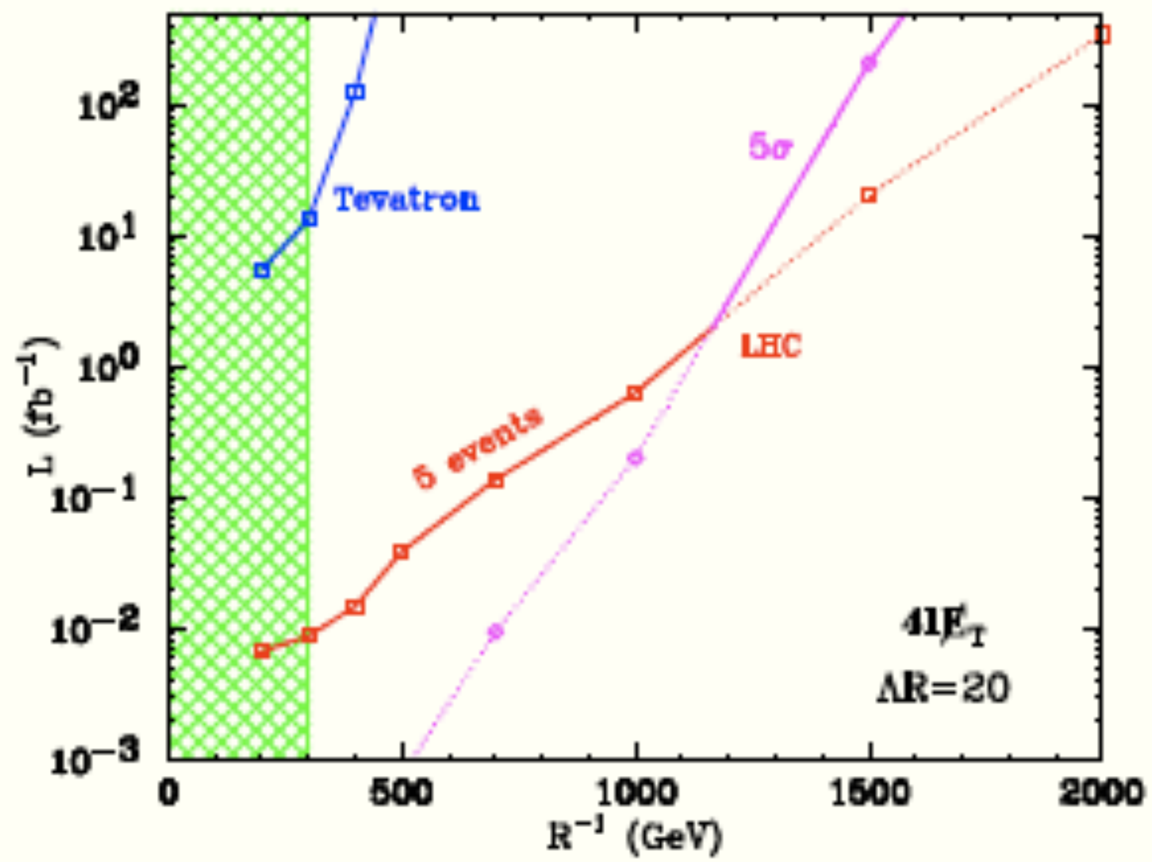
# Cascade decays in UED theories

- decay modes (CMS)



# LHC reach for UED in 4l +ETMISS channel

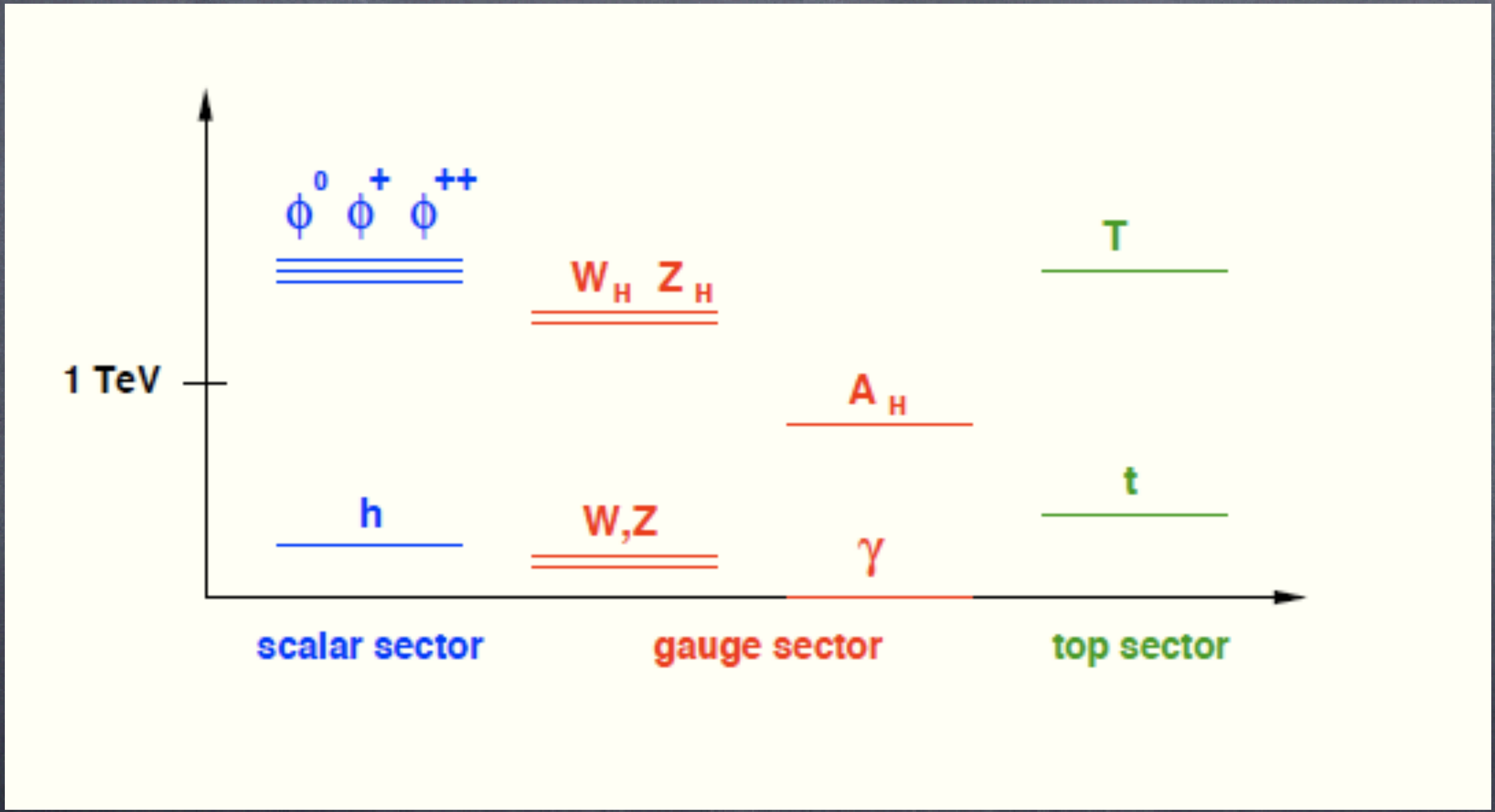
- $pp \to Z_1 Z_1 \to L_1 \bar{\ell} L_1 \bar{\ell} \to 4\ell + \not{E}_T$, etc.



# Little Higgs models

- New approach to EWSB: Arkani-Hamed, Cohen, Georgi, 2001
- Higgs field arises as pseudo-Nambu-Goldstone boson from "collective" symmetry breaking
- Symmetry ⇒ quadratic divergences to $m_H^2$ cancel at 1-loop (2-loop and higher quad. divergences remain)
- Natural cut-off of theory is $\sim 10$ 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 $SU(5)/SO(5)$

# Particle states in LHT theories



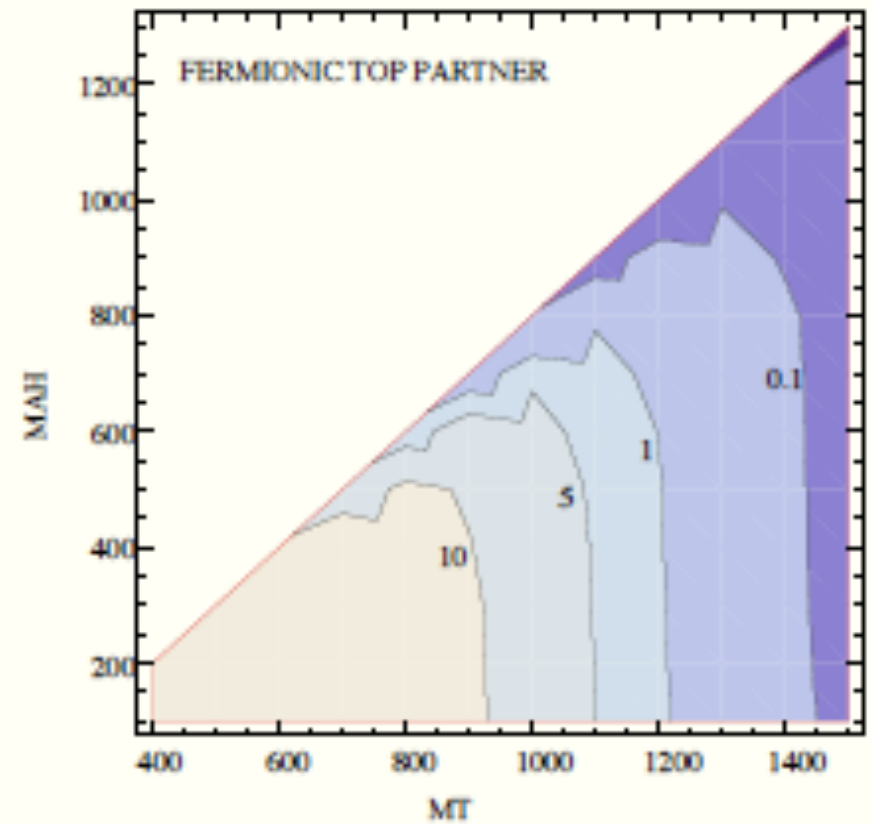
# T-party in LH models

- 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 discovery at LHC

$$pp \to T\bar{T} \to t\bar{t} + A_H + A_H$$

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



# Supersymmetric models

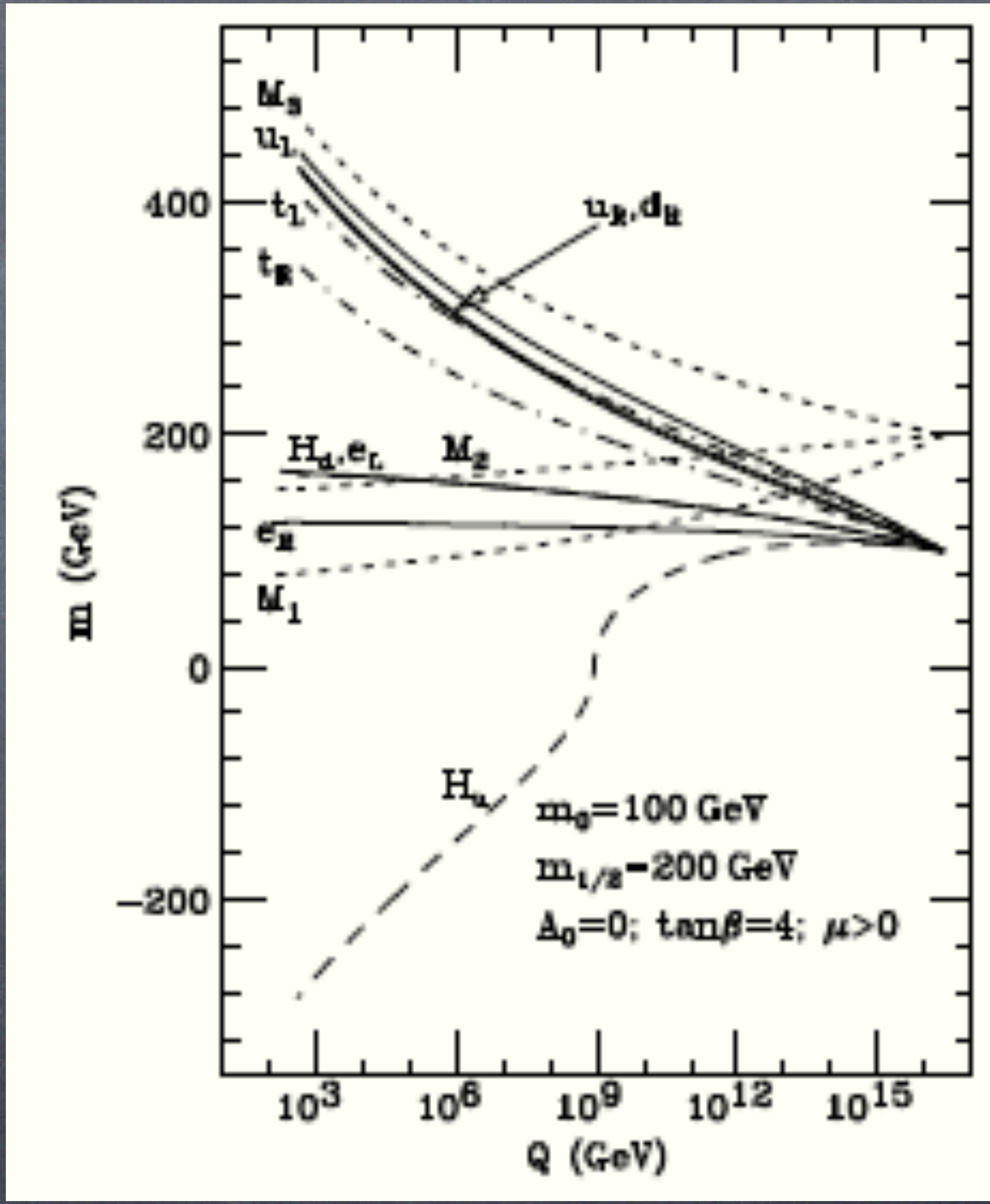
- GMSB: solves SUSY flavor problem, very light gravitino: does not naturally yield CDM
- AMSB: solves flavor problem, tachyonic sleptons; does not usually yield measured abundance of CDM
- AMSB $\longrightarrow$ Mixed-moduli AMSB $\longrightarrow$ CDM
- SUGRA: 3 candidate DM particles:

$$\tilde{G},\ \tilde{Z}_1\ or\ \chi,\ \tilde{a}/a$$

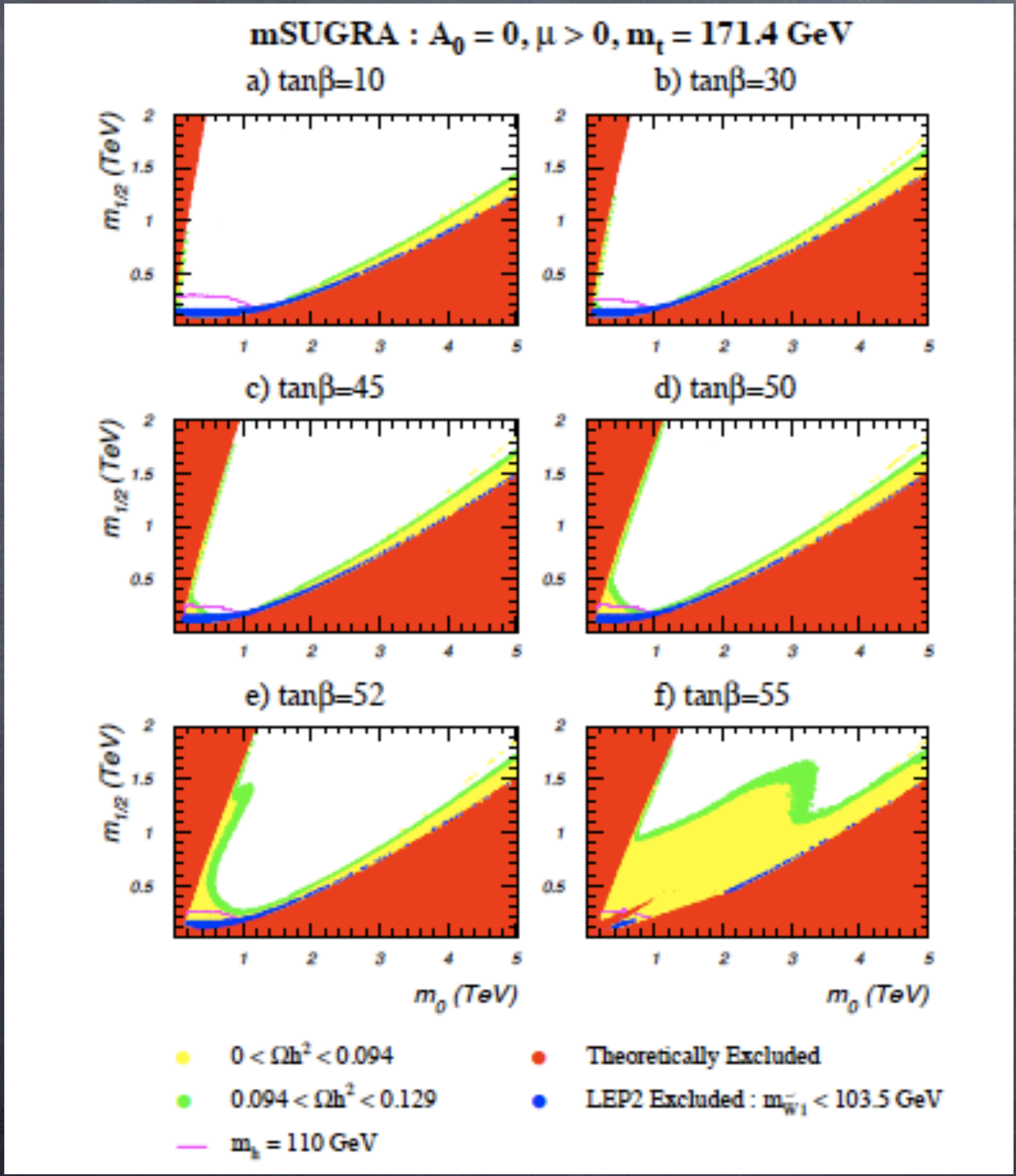
# Simplest: mSUGRA or CMSSM

- embed MSSM into SUGRA gauge theory
- SUSY breaking in simple hidden sector
- parameter space:

$$m_0,\ m_{1/2},\ A_0\ \tan\beta,\ sign(\mu)$$



# mSUGRA parameter space




HB, Mustafayev, Park, Tata

Beware non-standard cosmology!

Gelmini-Gondolo

# Search for mSUGRA at LHC

- ★ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ★ lengthy cascade decays of $\tilde{g}$ $\tilde{q}$ are likely
- ★ events characterized by multiple hard jets, isolated and non-isolated leptons $e$s and $\mu$s, and $\not{E}_T$ from $\widetilde{Z}_1$ or $\tilde{G}$ or $\nu$s escaping
- ★ many jets are $b$ (displaced vertices due to long $B$ lifetime) and $\tau$ (1 or 3 charged prongs) jets
- ★ one way to classify signatures is according to number of isolated leptons

- $\not{E}_T+$ jets
- $1\ell+$ $\not{E}_T+$ jets
- $opposite - sign\ (OS)\ 2\ell+$ $\not{E}_T+$ jets
- $same - sign\ (SS) 2\ell+$ $\not{E}_T+$ jets
- $3\ell+$ $\not{E}_T+$ jets
- $4\ell+$ $\not{E}_T+$ jets
- $5\ell+$ $\not{E}_T+$ jets

# SM backgrounds to SUSY

★ numerous SM processes give same signature as SUSY!

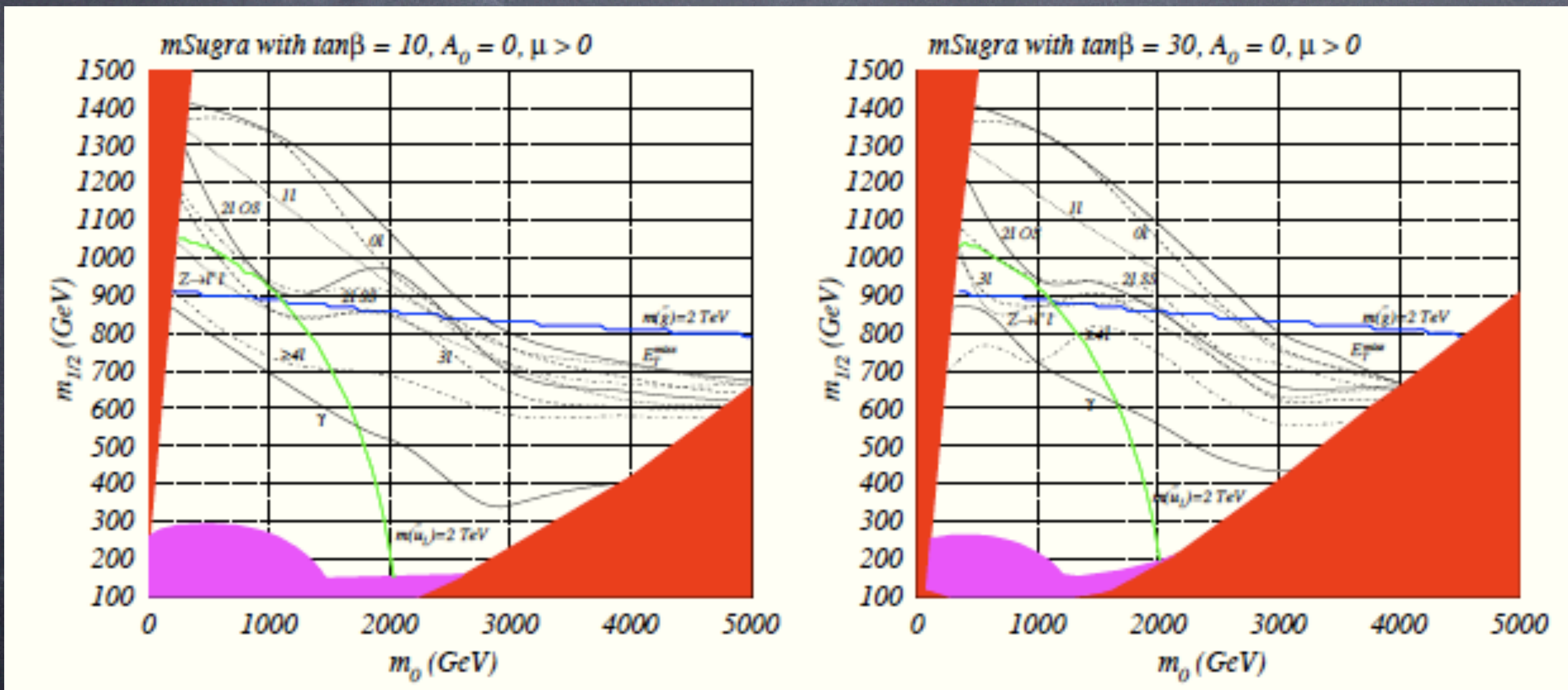
★ SM BGs include:

- QCD: multi-jet $qq$, $q\bar{q}$, $qg$, $gg$ production where $\not{E}_T$ comes from mis-measurement, cracks, etc.
  - $t\bar{t}$, $b\bar{b}$, $c\bar{c}$
  - $W$ or $Z+$ multi-jet production
  - $WW$, $WZ$, $ZZ$ production, where $Z \to \nu\bar{\nu}$ or $\tau\bar{\tau}$
    - ∗ all of above embedded in Isajet, Pythia, Herwig
  - four particle processes: $e.g.$ $t\bar{t}t\bar{t}$, $ttbb$, etc.
  - $WWW$, etc.
    - ∗ the $2 \to n$ for $n > 2$ processes usually need CalcHEP/Madgraph
  - overlapping events; fake $b$-jets; fake leptons, etc

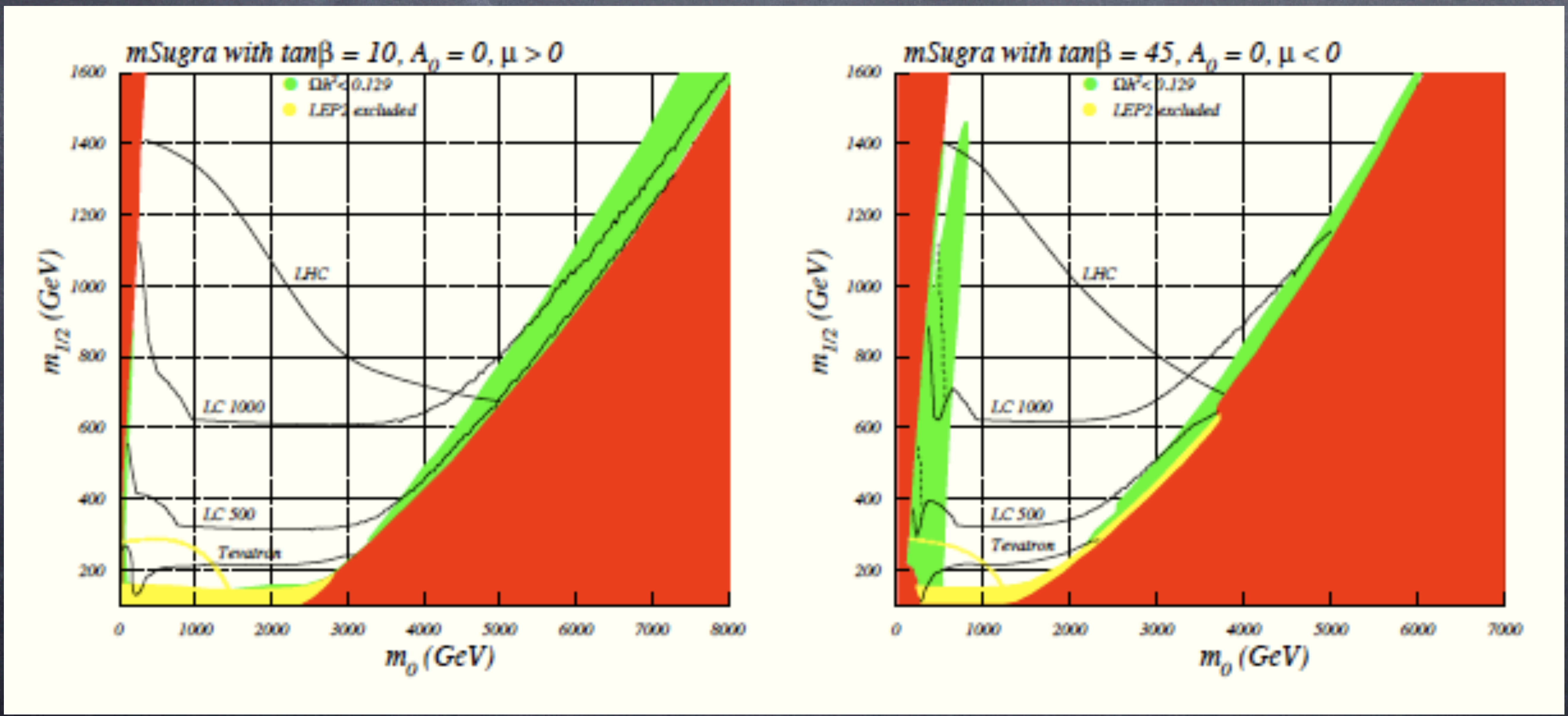
# Optimize cuts over parameter space

- ⋆ Cuts and pre-cuts:
- ⋆ $\not{E}_T > 200$ GeV
- ⋆ $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$
- ⋆ Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $\not{E}_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation
- ⋆ $S > 10$ events for 100 fb$^{-1}$
- ⋆ $S > 5\sqrt{B}$ for optimal set of cuts

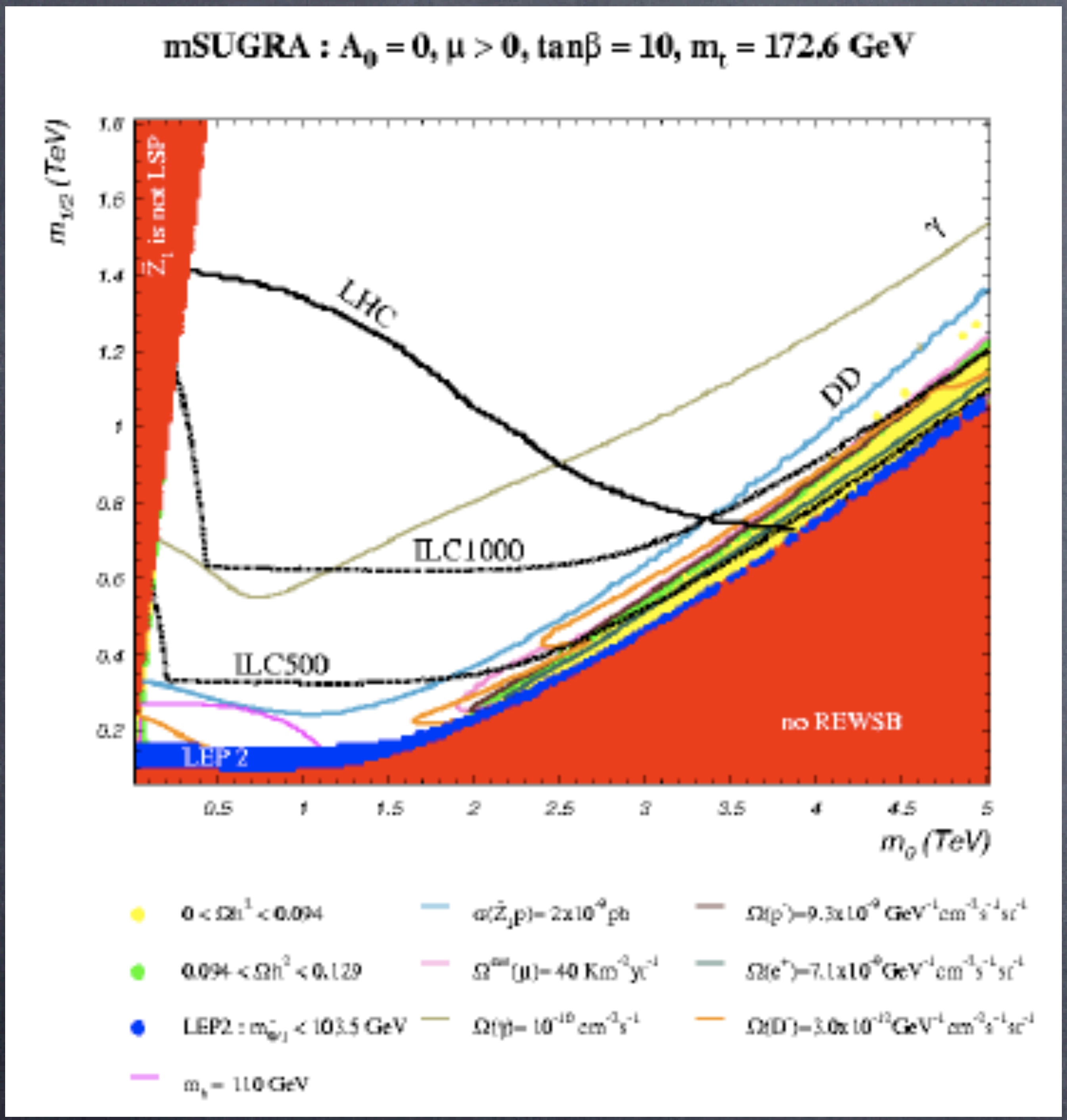
# Reach of LHC for various signals and 100 fb^-1

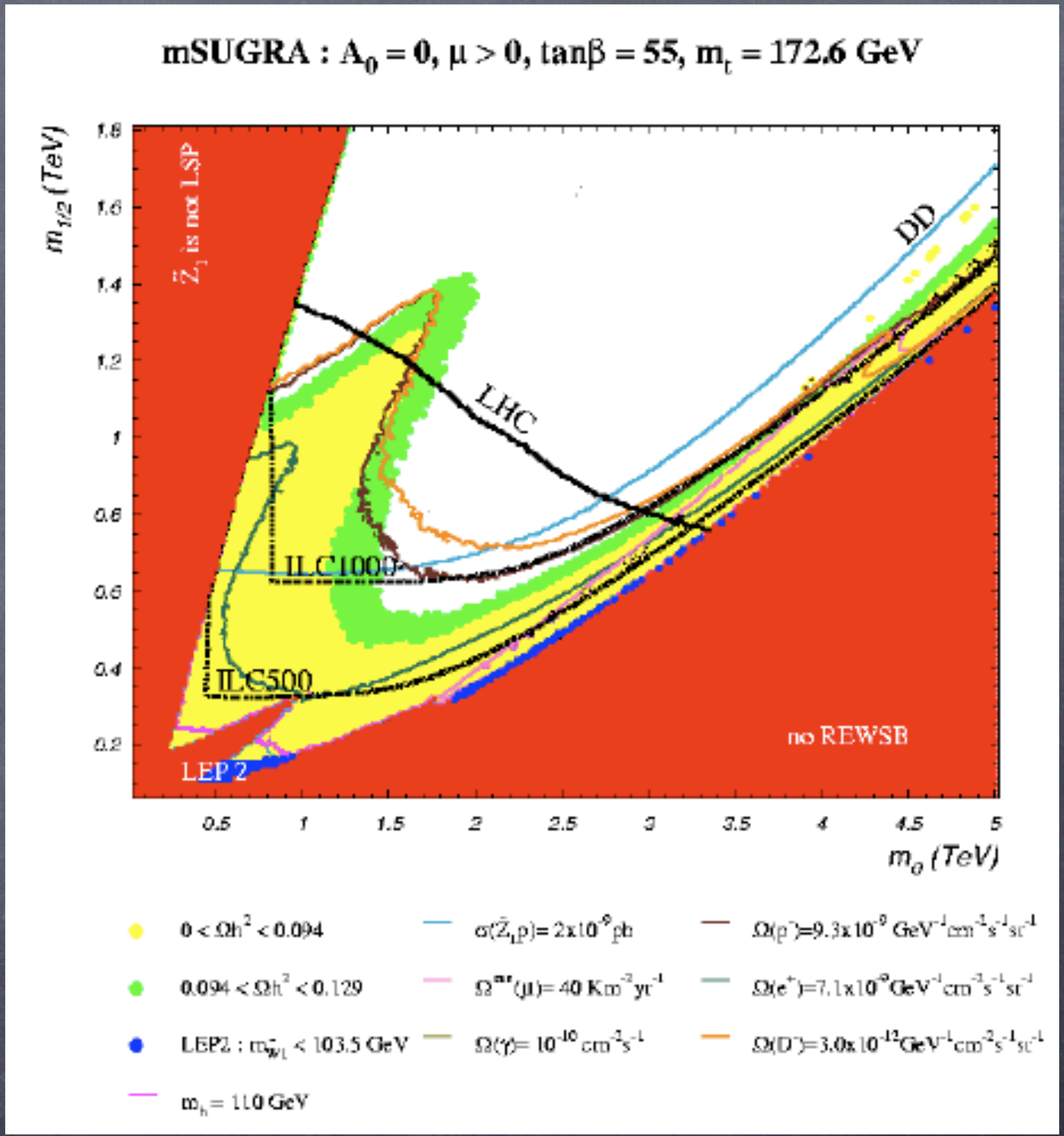


# Reach of LHC compared to Tevatron and ILC



# Reach of LHC, ILC compared to DD/ID WIMP search

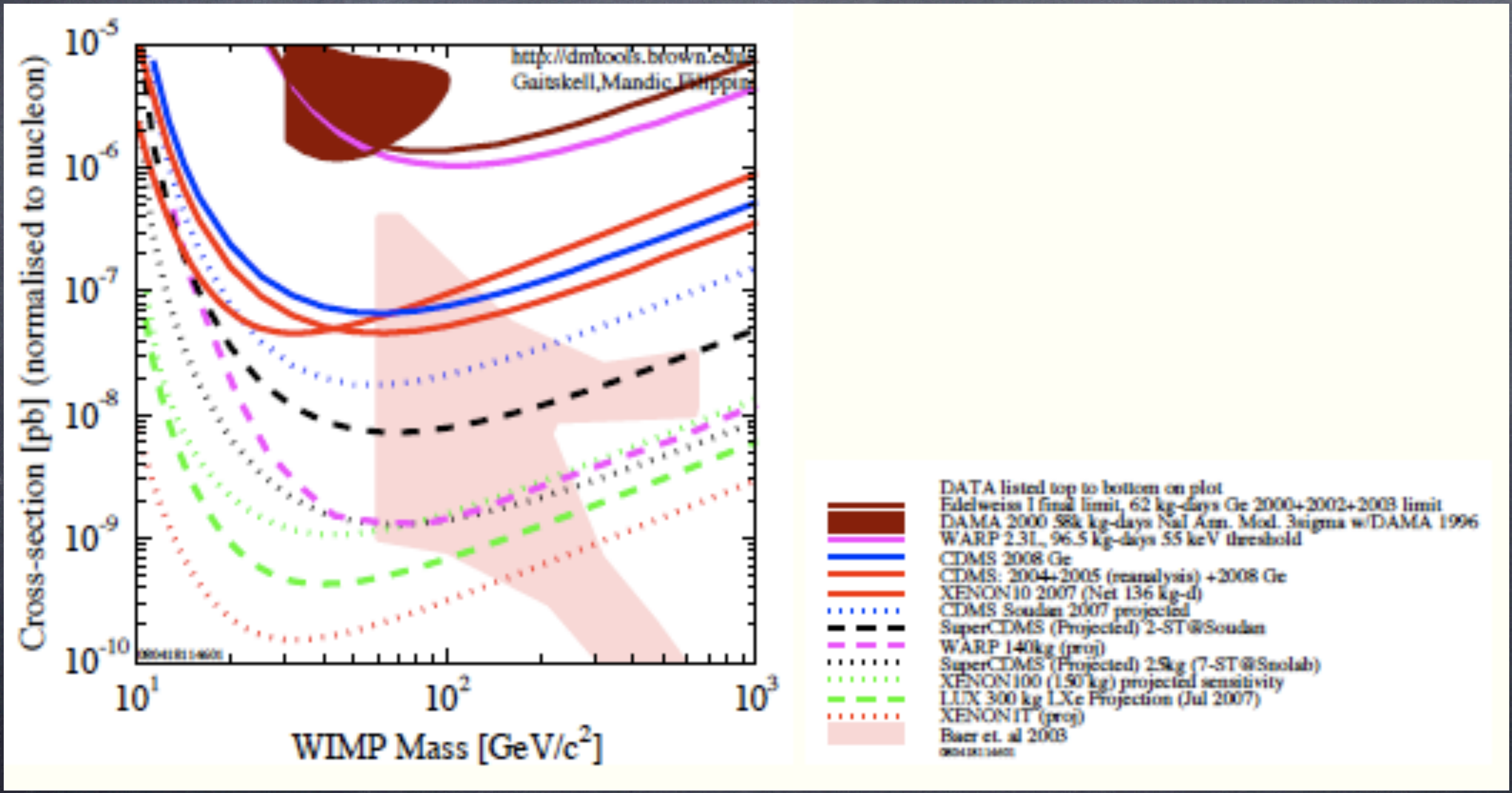



HB, Park, Tata

# DD vs. LHC in mSUGRA:

Xenon-100 should cover FP region!

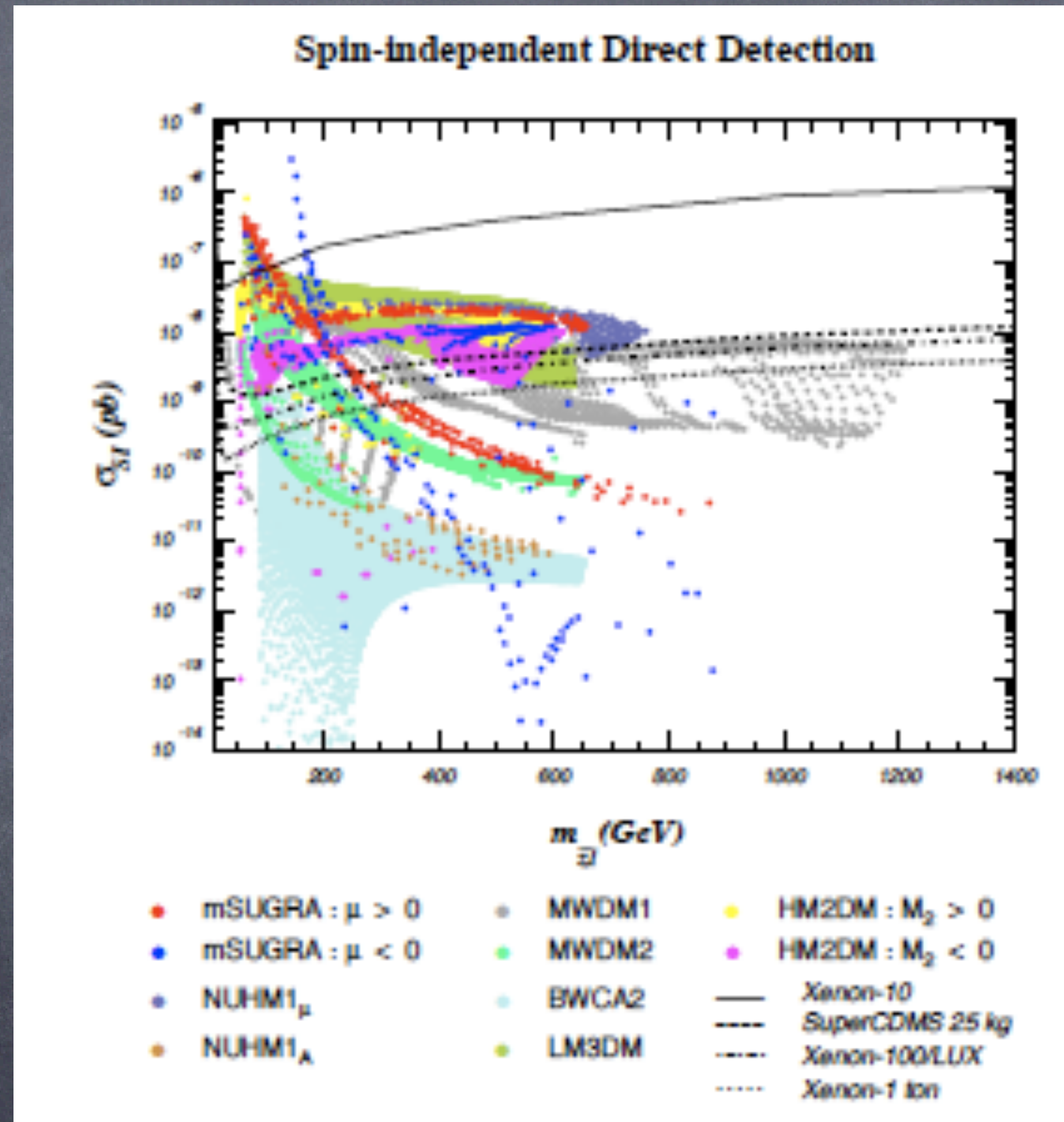


# Well-tempered neutralinos

Arkani-Hamed, Delgado, Giudice

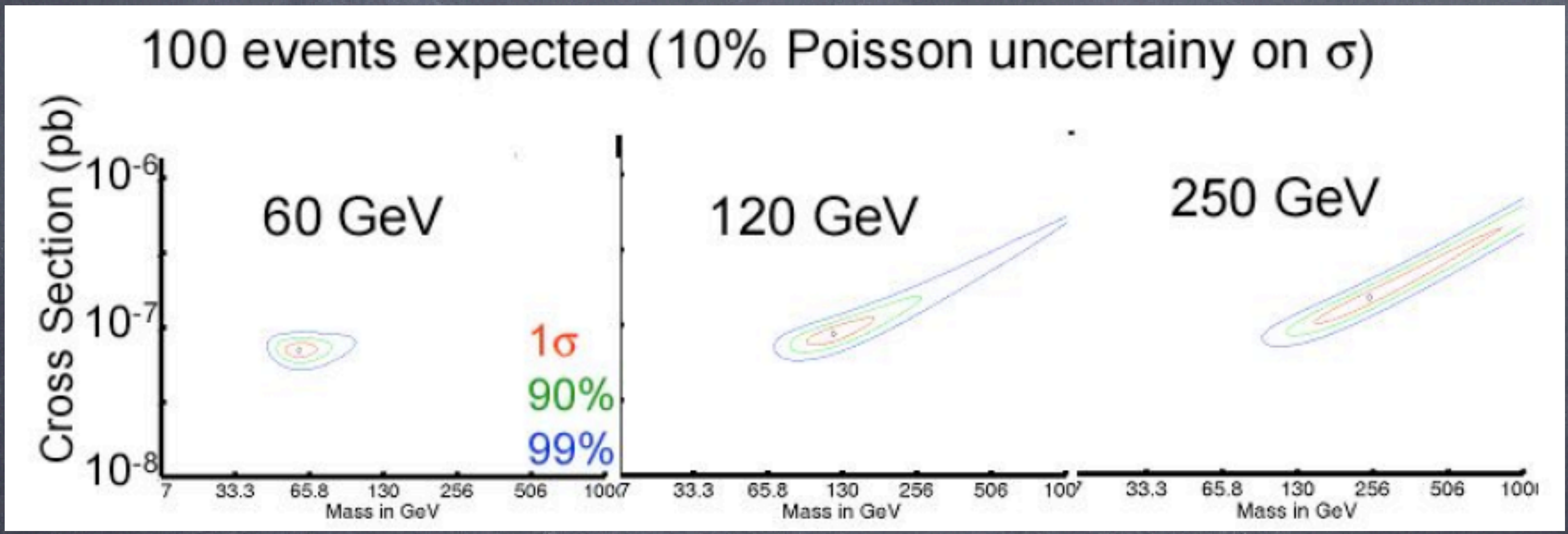
Scan over 10 models with and without universality; keep only models with correct relic abundance

Bulk of models asymptote at 10^-8 pb! Accessible to next Xenon-100 run!




HB, Mustafayev, Park, Tata

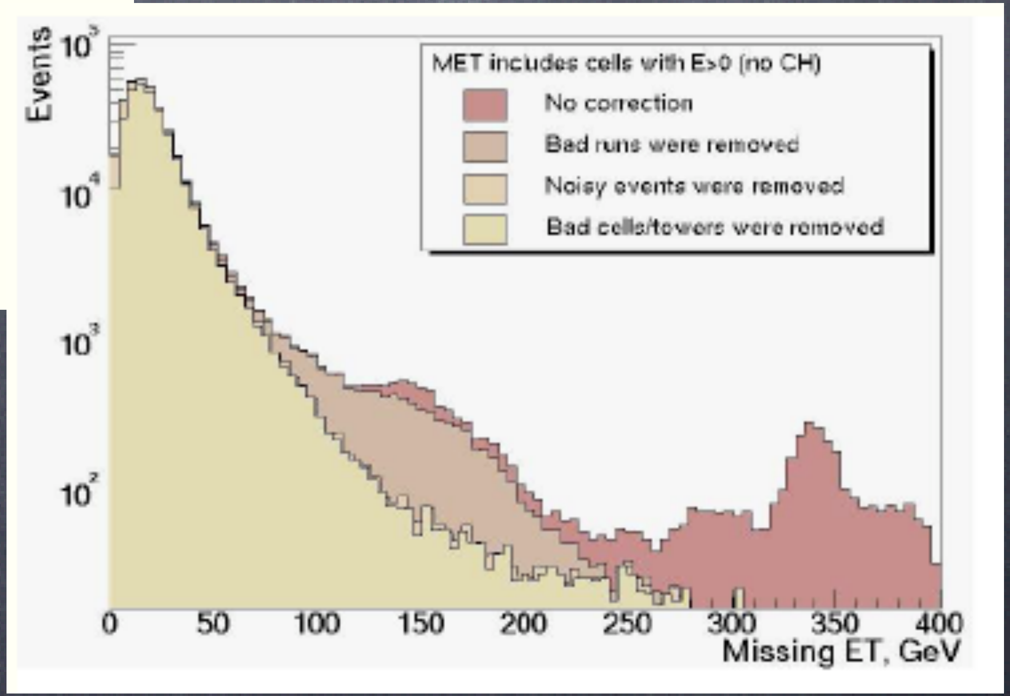
# If WIMP seen in DD, then mass measurement



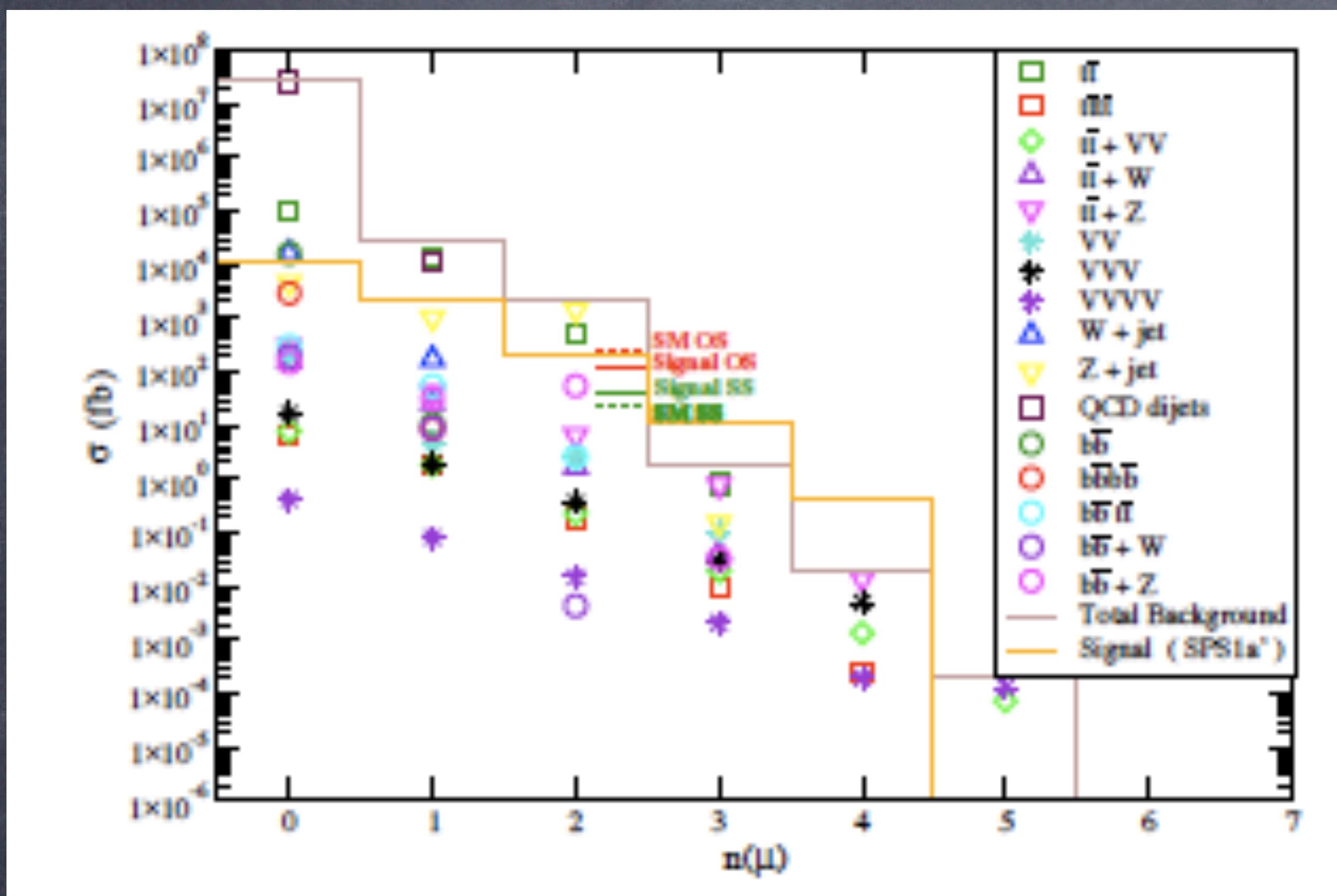

Study by Schnee; Green; Drees&Shan shows m(WMP) may be extracted from energy spectrum in DD experiments, for lower range of WIMP masses: crucial input for LHC?

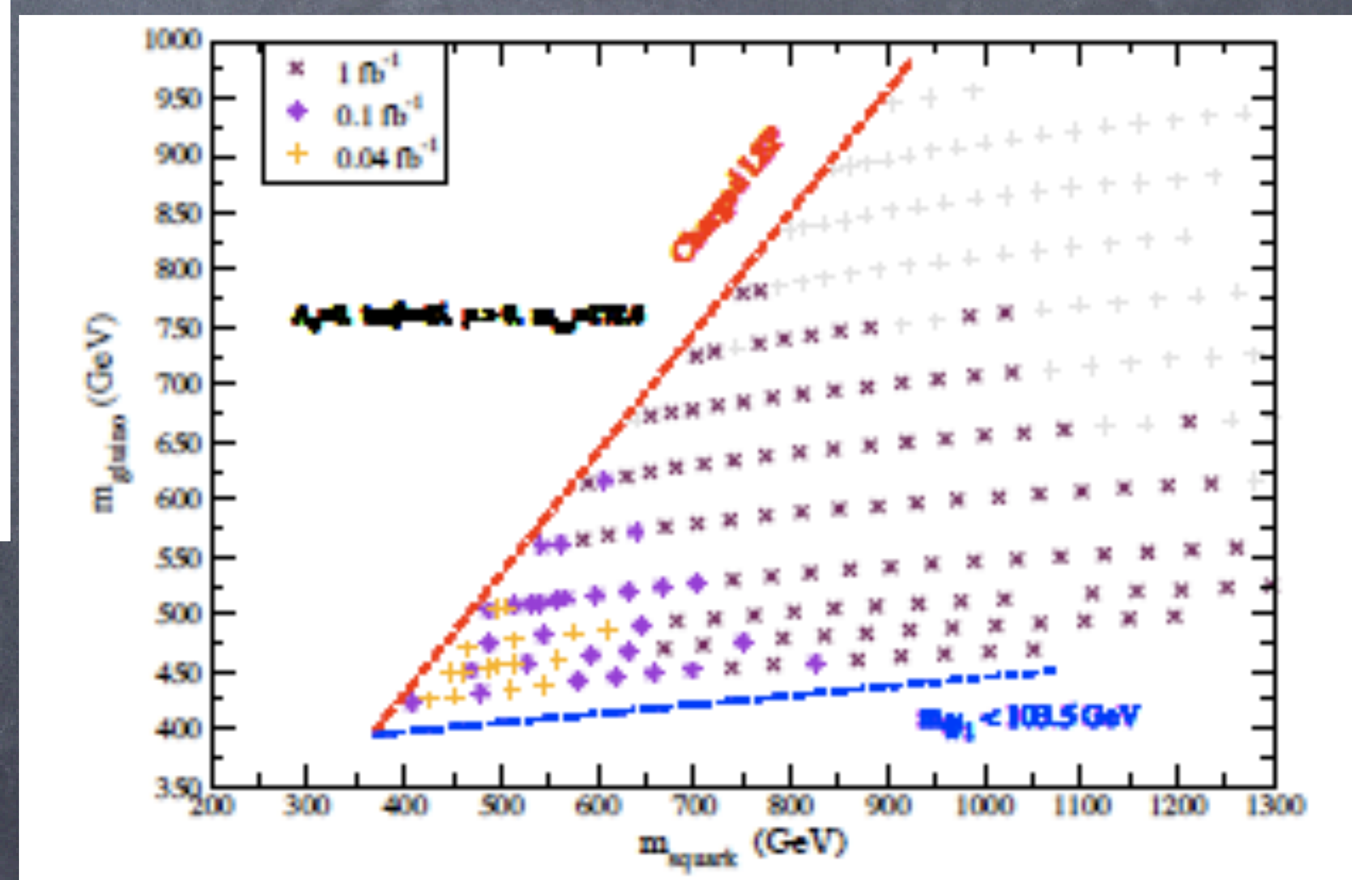
# Early search for SUSY at LHC: 0.04-0.1 fb^-1

- Can we make early discovery of SUSY at LHC *without* $\not\!\!E_T$?
- Expect $\tilde{g}\tilde{g}$ events to be rich in jets, $b$-jets, isolated $\ell$s, $\tau$-jets,....
- These are *detectable*, rather than inferred objects
- Inferred objects like $\not\!\!E_T$ require knowledge of complete detector performance
  - dead regions
  - "hot" cells
  - cosmic rays
  - calorimeter mis-measurement
- Answer: YES! See HB, Prosper, Summy, PRD77, 055017 (2008)
- electron ID problem? go with multi-muons: HB, Lessa, Summy, arXiv:0809.4719



# Reach of LHC for SUSY via SS dimuons and *no* ETMISS




HB, A. Lessa, H. Summy
arXiv:0809.4719

# Precision sparticle measurements at LHC

- $M_{eff} = \not{E}_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}},\ m_{\tilde{q}}$ scale
- $m(\ell\bar{\ell}) < m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ 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 $e.g.\ HB/FP$

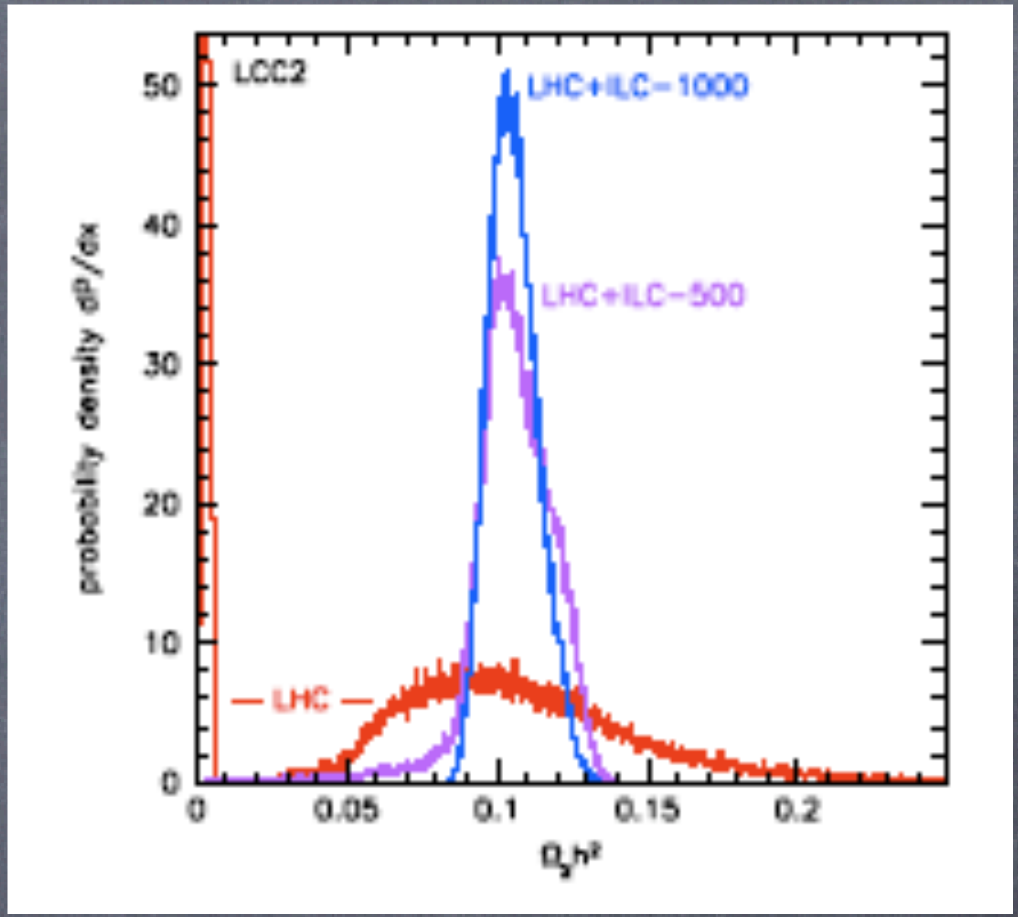
# Paige, Hinchliffe et al. studies

- examined many model case studies in mSUGRA, GMSB, high $\tan\beta$...
- classic study: pt.5 of PRD**55**, 5520 (1997) and PRD**62**, 015009 (2000)
- $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu) = (100, 300, 0, 2, 1)$ in GeV
- dominant $\tilde{g}\tilde{g}$ production with $\tilde{g} \to q\tilde{q}_L \to qq\widetilde{Z}_2 \to q_1q_2\ell_1\tilde{\ell} \to q_1q_2\ell_1\ell_2\widetilde{Z}_1$ (string of 2-body decays)
- can reconstruct 4 mass edges; allows one to fit four masses: $m_{\tilde{q}_L},\ m_{\widetilde{Z}_2},\ m_{\tilde{\ell}},\ m_{\widetilde{Z}_1}$ to $3-12\%$
- can also find Higgs $h$ in the SUSY cascade decay events
- if enough sparticle masses measured, can fit to MSSM/SUGRA parameters

# Precision SUSY measurements and cosmology

- Find which parameter space choices lead to precision measurements
- Map parameters onto e.g. relic density, DD cross section, ID <sigma.v>
- -> Collider measurement of

$$\Omega_\chi h^2,\ \sigma(\chi p),\ \langle\sigma \cdot v\rangle, \cdots$$

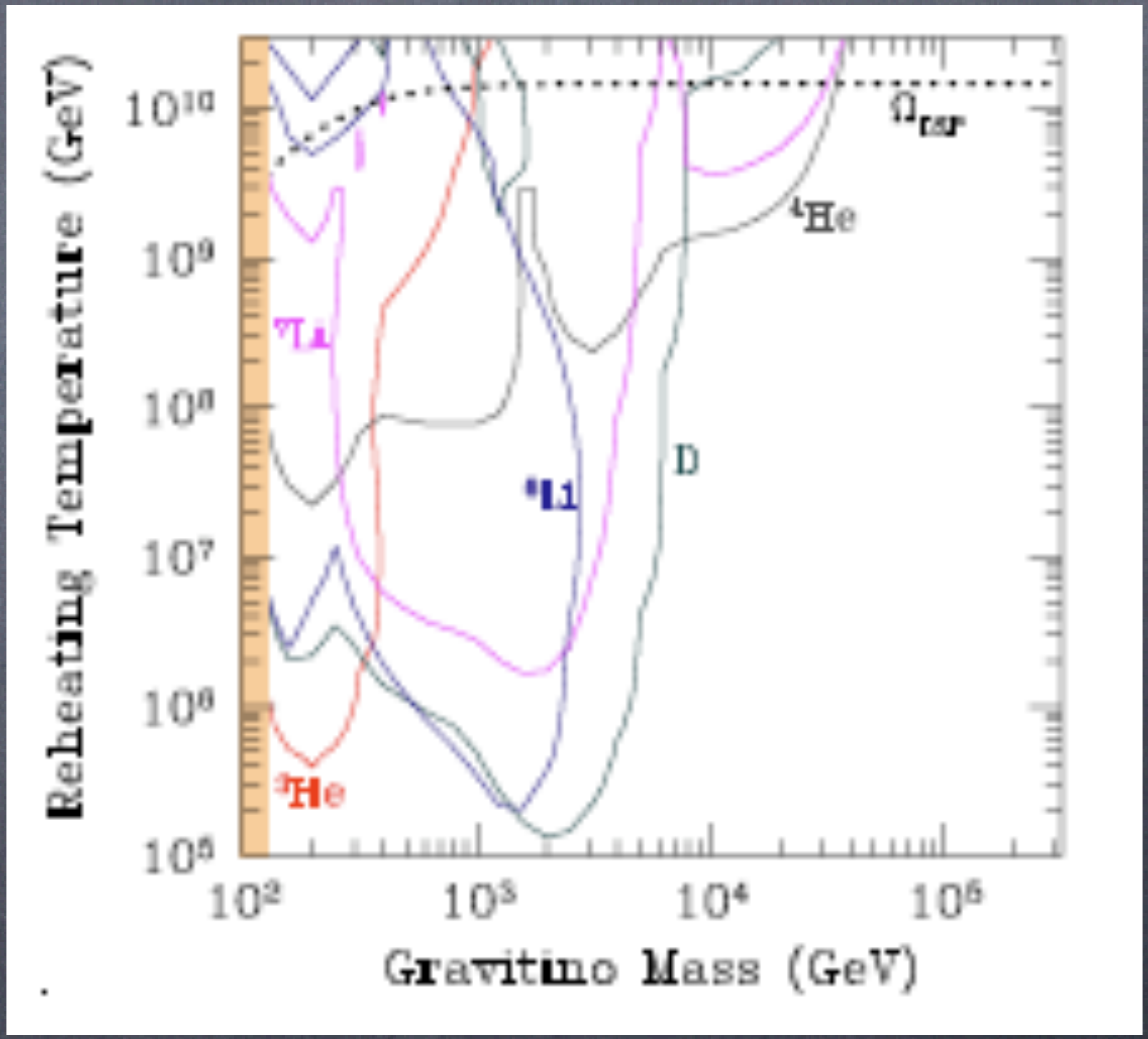



Allanach, Belanger, Boudjema, Pukhov
Nojiri, Polesello, Tovey
Baltz, Battaglia, Peskin, Wisansky
Arnowitt, Dutta, Kamon, ..

Beware: points chosen are SPS1a or accessible to ILC500

# The gravitino problem in SUGRA models

- Gravitinos can be produced thermally in early universe
- Gravitino lifetime suppressed by M_Pl^-2
- Late decays disrupt successful BBN predictions
- Need either m_grav > 5 TeV or T_R<10^5 GeV (but then problems with baryogenesis)




Kawasaki et al; Ellis et al.

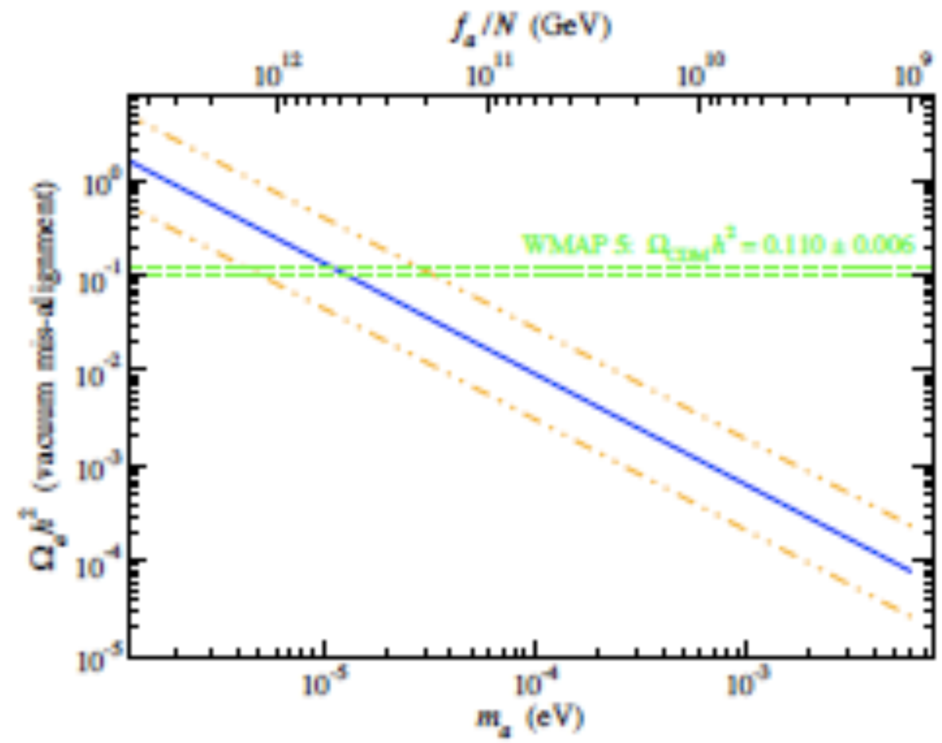
# Gravitino DM

★ $m_{\tilde{G}} = F/\sqrt{3}M_* \sim$ TeV in Supergravity models

- usually $\tilde{G}$ decouples (but see Moroi et al. for BBN constraints)
- if $\tilde{G}$ is LSP, then calculate NLSP abundance as a thermal relic: $\Omega_{NLSP}h^2$
- $\widetilde{Z}_1 \to h\tilde{G},\ Z\tilde{G},\ \gamma\tilde{G}$ or $\tilde{\tau}_1 \to \tau\tilde{G}$ possible
  - lifetime $\tau_{NLSP} \sim 10^4 - 10^8$ sec
  - constraints from BBN, CMB not too severe
  - DM relic density is then $\Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{NLSP}}\Omega_{NLSP} + \Omega_{\tilde{G}}^{TP}(T_R)$
  - Feng, Rajaraman, Su, Takayama; Ellis et al; Buchmuller et al.
- $\tilde{G}$ undetectable via direct/indirect DM searches
- unique collider signatures:
  - $\tilde{\tau}_1$=NLSP: stable charged tracks
  - can collect NLSPs in e.g. water (slepton trapping)
  - monitor for $NLSP \to \tilde{G}$ decays

# Axion dark matter

- ★ PQ solution to strong CP problem in QCD
- ★ 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 $\Rightarrow m_a < 10^{-1} eV$
  - $a$ couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)
  - axion microwave cavity searches



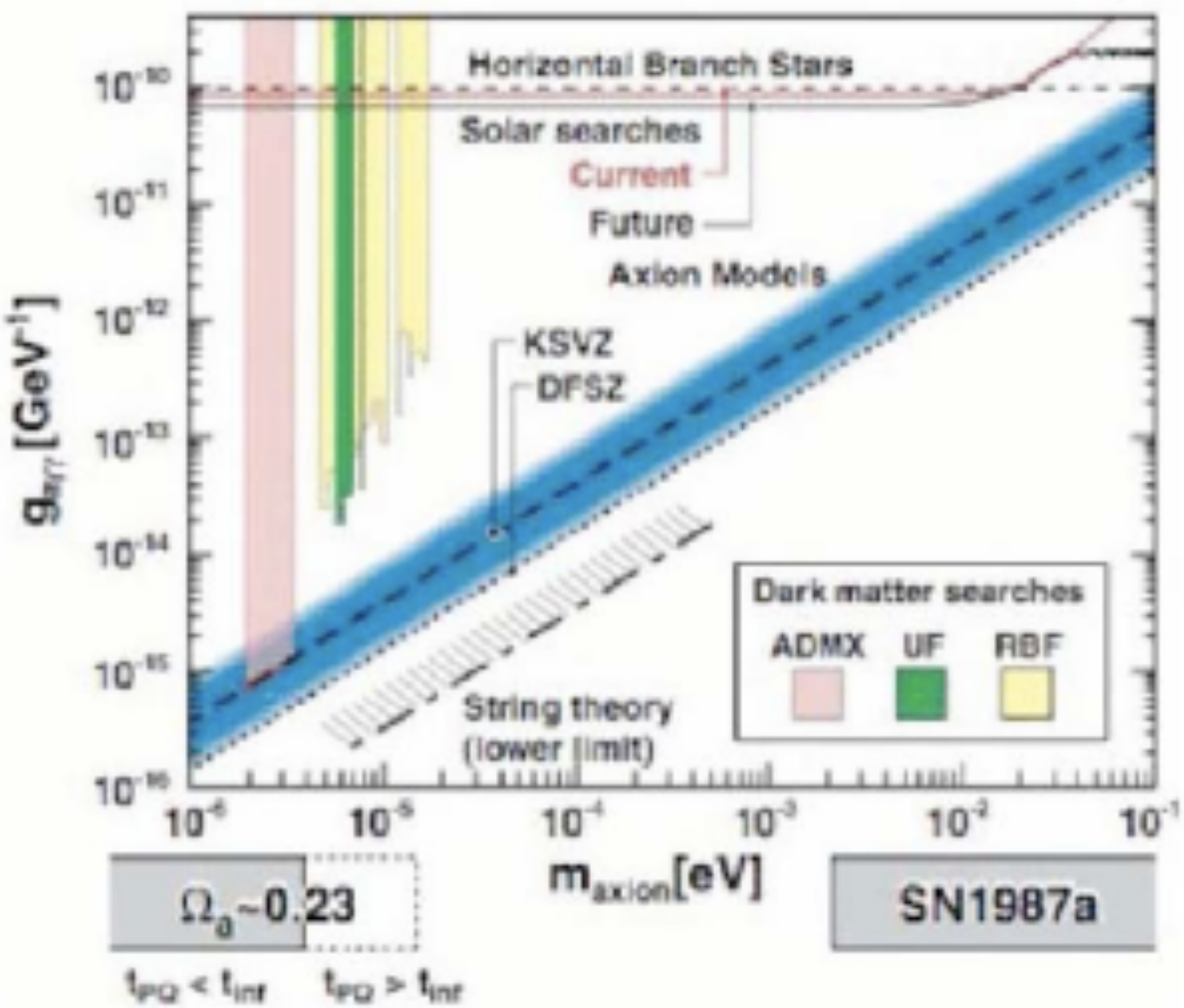

Axion DM: forms BEC, suppresses small scale structure, gives mechanism for galactic rotation

Sikivie, Wang arXiv:0901.1106

# Axion microwave cavity seach

★ 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 $m_a$



# Axions+ SUSY=> axinos

- axino is spin-1/2, R-odd spartner of axion
- axino mass is model dependent: keV-> GeV
- axino is an EWIMP; coupling suppressed by Peccei-Quinn scale $f_a : 10^9 - 10^{12}$ GeV
- good candidate for cold DM
- for review, see Covi, Kim, Kim, Roszkowski JHEP 0105 (2001) 033

Non-thermal axino production via NLSP decay

- If $\tilde{a}$ is LSP, then it can be produced via decay of NLSP
- e.g. $\tilde{Z}_1 \to \tilde{a}\gamma \; or \; \tilde{\tau}_a \to \tilde{a}\tau$
- NLSP lifetime: $10^{-3} - 10^{1}$ sec: (BBN safe)
- axinos inherit NLSP number density
- $$\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2$$
- NTP axino is warm DM for $m_{\tilde{a}} < 1 - 10$ GeV

# Thermal production of axinos

- Axinos likely never in thermal equilibrium
- Can be produced thermally via bremsstrahlung off particles in thermal equilibrium
- TP axinos are cold DM for $m_{\tilde{a}} > 100$ keV

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_s^6 \ln\left(\frac{1.108}{g_s}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2 \left(\frac{m_{\tilde{a}}}{0.1\ \mathrm{GeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right)$$

- CKKR; Brandenberg, Steffen

# SO(10) SUSY GUTs

- gauge coupling unification
- matter unification into 16-dim. spinor rep.
- 16th element contains RHN: see-saw
- explain anomaly cancellation in MSSM and SU(5)
- explain R-parity conservation
- allow for t-b-tau Yukawa unification

# SO(10) model parameter space

- $m_{16},\ m_{10},\ M_D^2,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- Here, $M_D^2$ parametrizes splitting of Higgs soft terms at $M_{GUT}$:

$$m_{H_{u,d}}^2 = m_{10}^2 \mp 2M_D^2$$

★ The Higgs splitting only (HS) method gives better Yukawa unification than full $D$-term splitting (DT) model for $\mu > 0$ and $m_{16} \gtrsim 2$ TeV

HB, Kraml, Sekmen, Summy

- Scan over p-space using Isasugra to check for Yukawa unified solutions:
- $R = max(f_t, f_b, f_\tau)/min(f_t, f_b, f_\tau)$

Related work: Blazek, Dermisek, Raby;
Wells, Tobe; Dermisek, Raby, Roszkowski, Ruiz; Altmannshofer, Guadagnoli, Raby,Straub

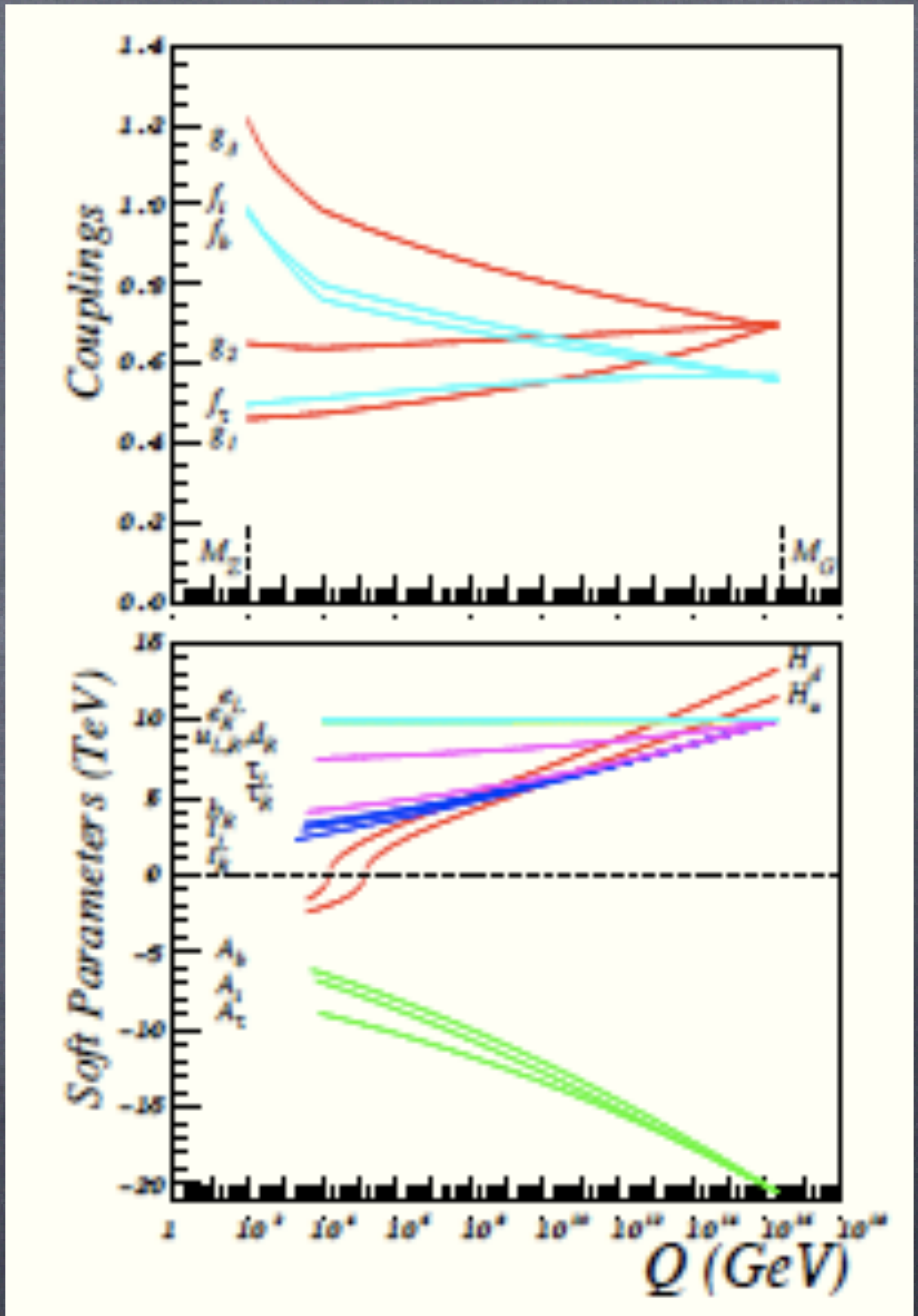
# t-b-tau unified solutions

$m_{16} \sim 10\ TeV$

$m_{1/2}\ small$

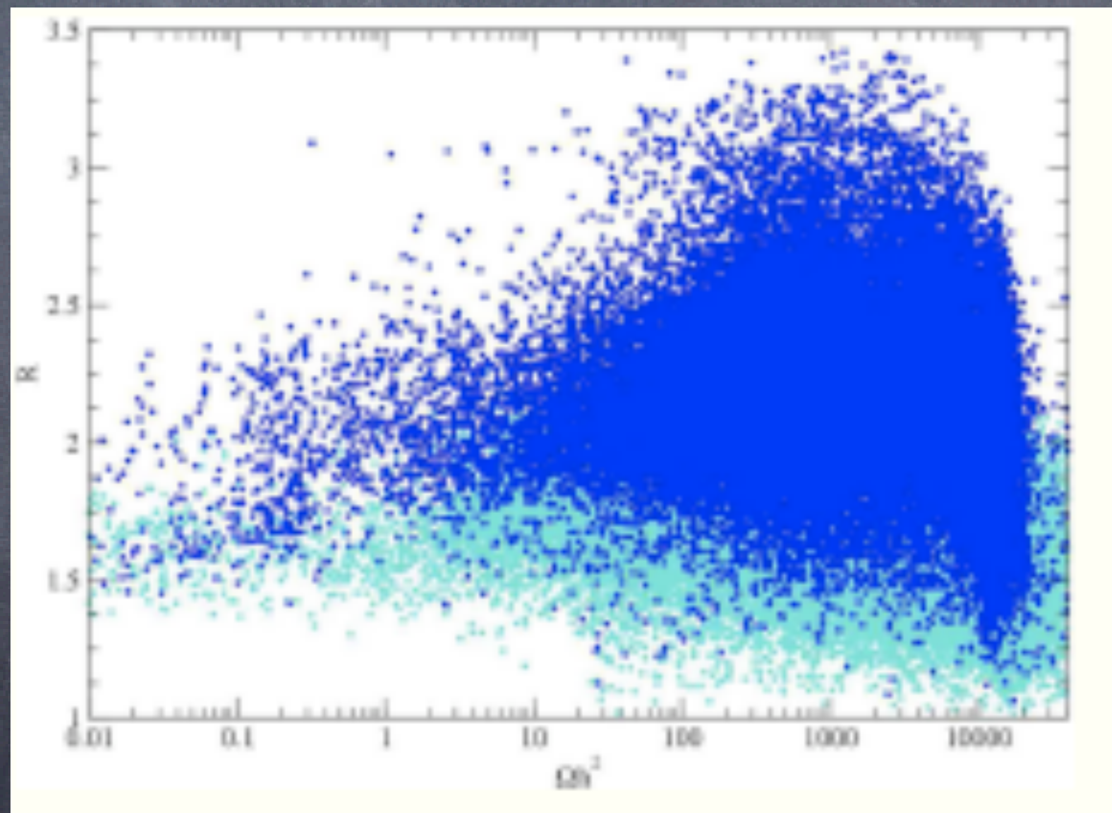
- need $m_{10} \simeq \sqrt{2} m_{16}$
- $A_0 \simeq -2 m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m^2_{H_u} < m^2_{H_d}$

- $m_{\tilde{q},\tilde{\ell}}(1,2) \sim 10$ TeV
- $m_{\tilde{t}_1},\ m_A,\ \mu \sim 1-2$ TeV
- $m_{\tilde{g}} \sim 300-500$ GeV



# Dark matter problem in Yukawa-unified models

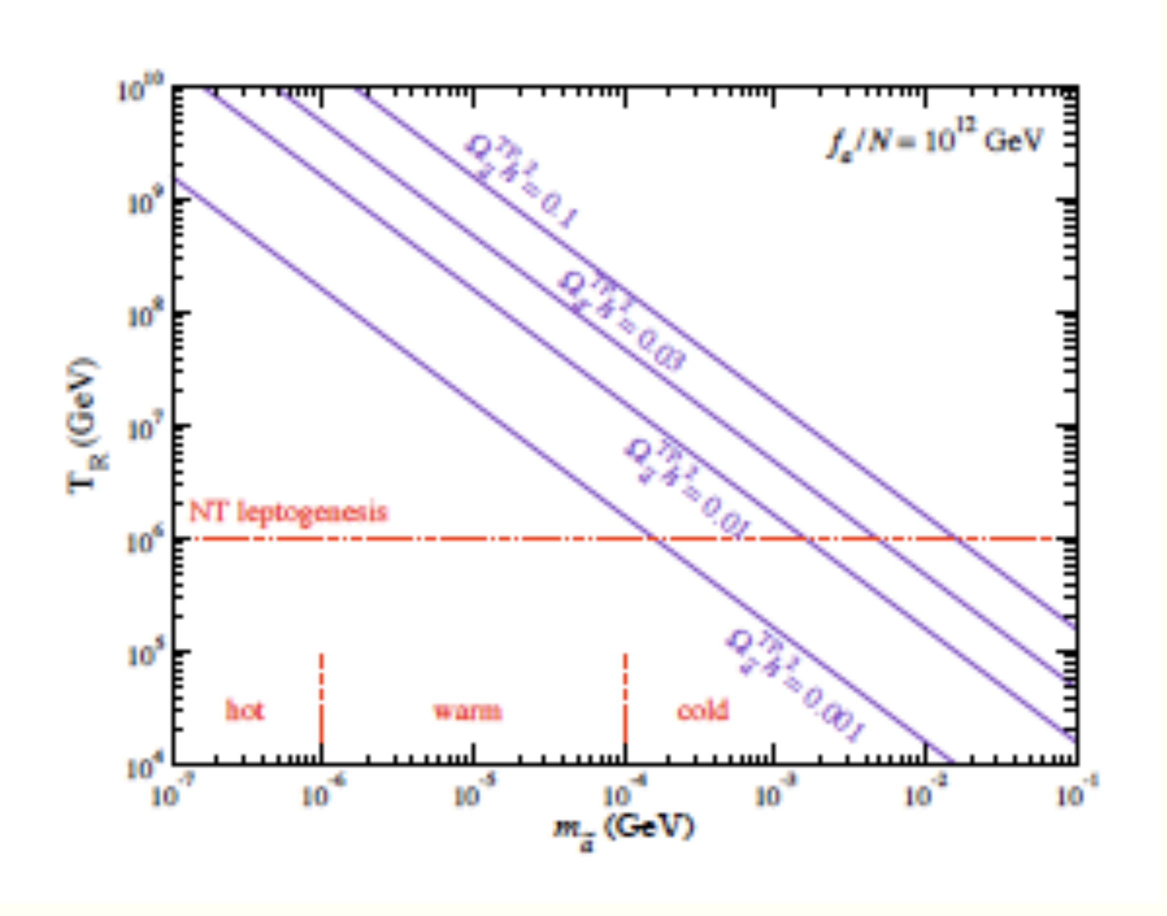
- m(16)~10 TeV with m_1/2 small
- neutralino is pure bino-like




relic density too high by factor 10^3-10^5!

# DM solution: three components: warm axinos, cold axinos, cold axions!

- ★ best solution: axion/axino DM instead of neutralino
- each $\widetilde{Z}_1 \to \tilde{a}\gamma$ so $\Omega_{\tilde{a}} h^2 \sim \frac{m_{\tilde{a}}}{m_{\widetilde{Z}_1}} \Omega_{\widetilde{Z}_1} h^2$: $\Rightarrow$ warm DM
- also thermal component depending on $T_R$: $\Rightarrow$ CDM
- also axion DM via vacuum mis-alignment




HB, Kraml, Sekmen, Summy
JHEP 0803 (2008) 056

HB,Summy
PLB666 (2008) 5

HB, Haider, Kraml, Sekmen, Summy
arXiv:0812.2693

# Can we find Yukawa-unified models with dominant CDM?

- Given $\Omega_{\widetilde{Z}_1} h^2$ and $m_{\widetilde{Z}_1}$ and $\Omega_{\tilde{a}}^{NTP} h^2$ can calculate $m_{\tilde{a}}$.
- Given $\Omega_{\tilde{a}}^{TP} h^2$, $m_{\tilde{a}}$ and $f_a/N$, can calculate re-heat temperature of universe

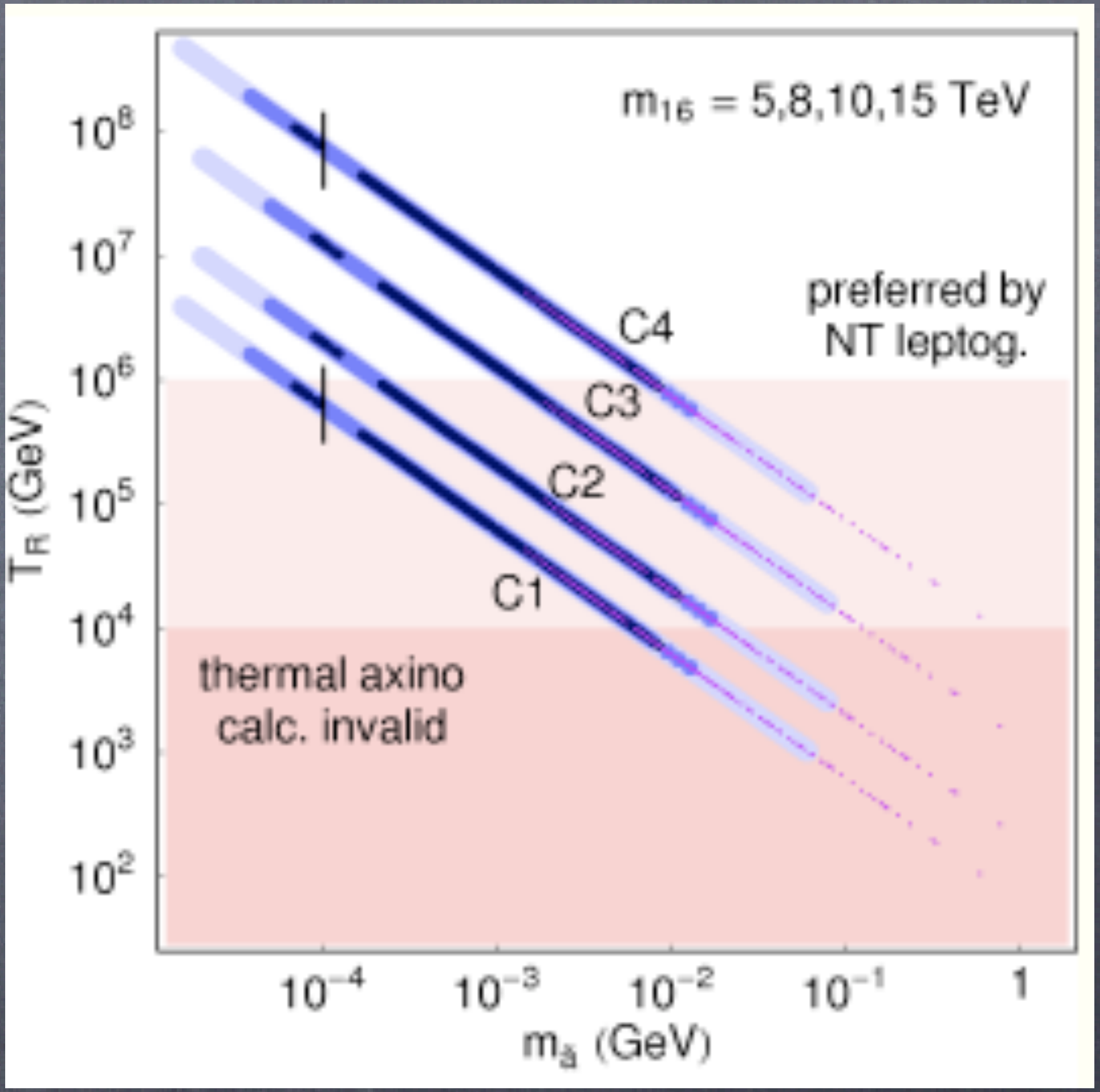
★ Four cases:

1. Take $f_a/N = 10^{11}$ GeV so $\Omega_a h^2 = 0.017$. Bulk of DM must be thermally produced $\tilde{a}$. Take $\Omega_{\tilde{a}}^{TP} = 0.083$ and $\Omega_{\tilde{a}}^{NTP} = 0.01$
2. Take $f_a/N = 4 \times 10^{11}$ GeV so $\Omega_a h^2 = 0.084$. (Bulk of DM is cold axions.) Take $\Omega_{\tilde{a}}^{TP} = \Omega_{\tilde{a}}^{NTP} = 0.013$
3. Take $f_a/N = 10^{12}$ GeV and lower mis-align error bar so $\Omega_a h^2 = 0.084$. (Bulk of DM is cold axions.) Take $\Omega_{\tilde{a}}^{TP} = \Omega_{\tilde{a}}^{NTP} = 0.013$
4. Take $f_a/N = 10^{12}$ GeV but allow accidental near vacuum alignment so $\Omega_a h^2 \sim 0$. Bulk of DM must be thermally produced axinos. Take $\Omega_{\tilde{a}}^{TP} = 0.1$ and $\Omega_{\tilde{a}}^{NTP} = 0.01$

# Mixed axion/axino cold and warm DM in Yukawa-unified models

Need:

1. large f_a~10^12 GeV
2. solutions C2, C3 with dominant axion CDM
3. solution C4 has accidental vacuum alignment and dominant TP axino CDM

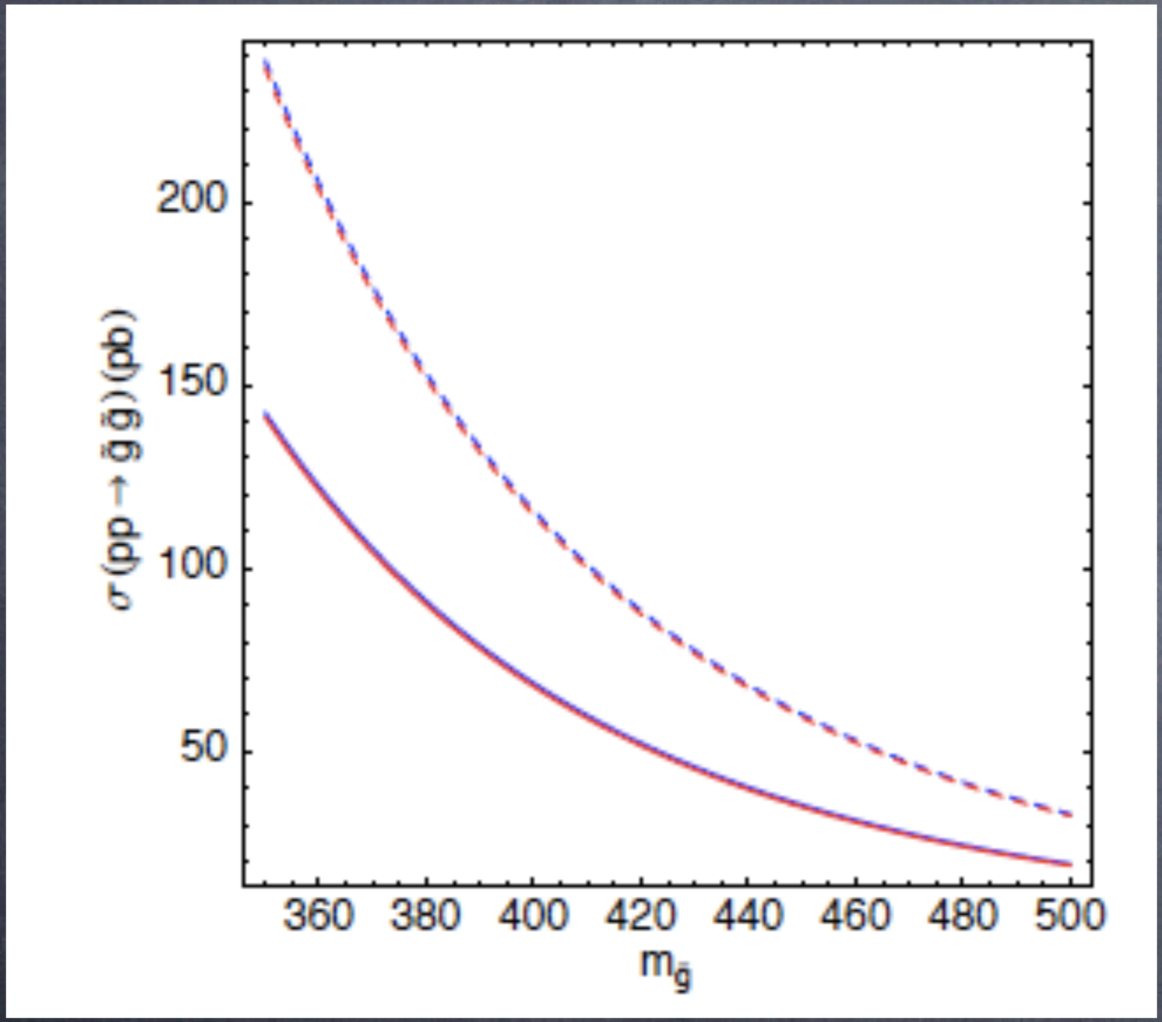


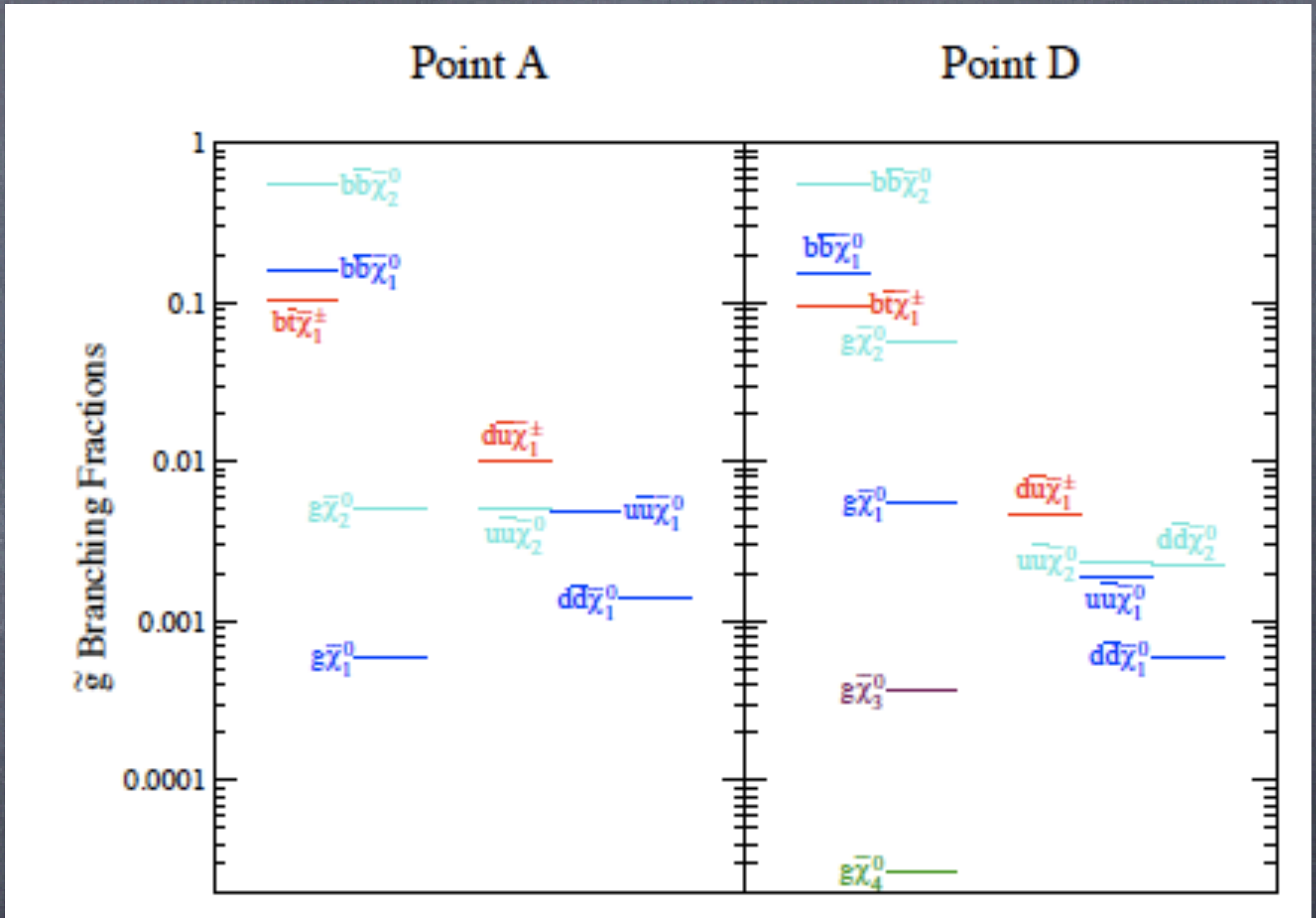

4. Solutions with m16>8 TeV have TR>10^6 GeV

# Many pieces of puzzle fit:

- PQ solution to strong CP problem
- Solve gravitino problem: m(Grav'ino)~10 TeV
- CDM: dominated by axions, but also cold/warm axinos
- Allow high enough re-heat 10^6-10^9 GeV for e.g. non-thermal leptogenesis
- Large m16~10 TeV suppresses FCNC, CPV, p-decay
- All within framework of simple SO(10) SUSY GUT

# Cross sections/BFs, LHC signatures




HB, Kraml, Sekmen, Summy: JHEP 0810 (2008) 079

# Testable consequences:

- m(gluino)~350-500 GeV:  abundant LHC signatures: early discovery via isolated multi-leptons plus jets (ETMISS not needed)
- LHC dilepton mass edge: 50-90 GeV; no second edge implies bino-like neutralino
- high b-jet multiplicity
- reconstruct m(gluino) via m(lljj)
- possible axion signal at ADMX
- no direct/indirect WIMP signals

# Conclusions:

- Role of LHC: produce matter states associated with dark matter; decay to stable DM candidate (LHT, UED, SUSY, etc) usually gives ETMISS signature (charged stable NLSP counter-example)
- In case of WIMP dark matter, additional signals from DD/ID of DM will provide complementary information (e.g. WIMP mass?)
- Xenon-100/LUX will soon test FP region of mSUGRA and well-tempered neutralino models
- precision measurements may allow collider measurment of relic density, associated quantities
- SuperWIMP, EWIMP DM possible (gravitino, axino/axion)
- SO(10) Yukawa-unified SUSY with axion/axino DM very compelling!