Dark matter and the LHC

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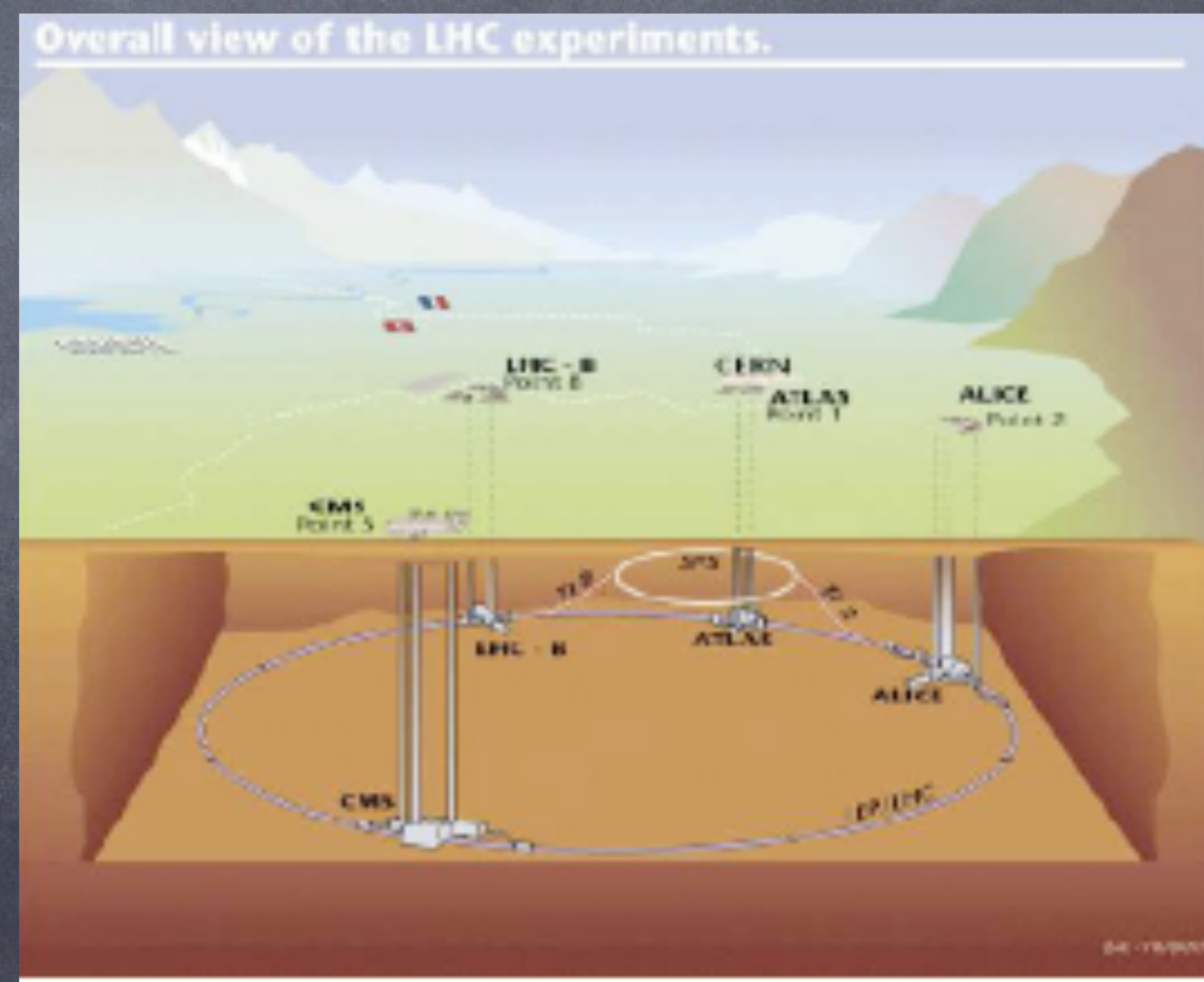
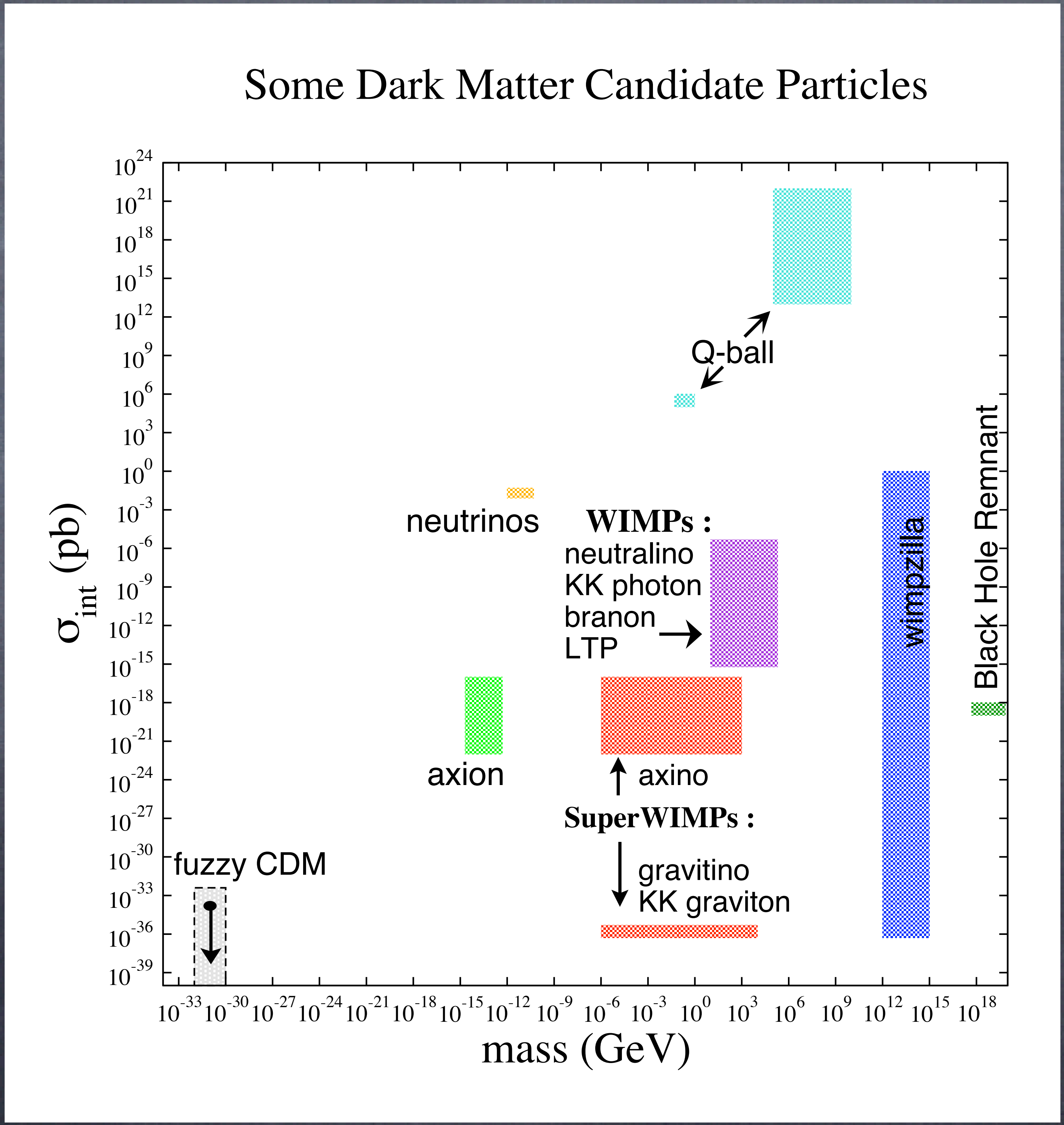


- Evidence for dark matter: overwhelming, and from numerous disparate sources!
- Properties: massive, neutral, cold (warm...)
- Of particles in the Standard Model (SM), only neutrinos have the right properties: but they constitute hot dark matter, and abundance is known
- Dark matter must be some particle state not contained in the SM: NEW PHYSICS NEEDED!

Some dark matter candidates: mass vs. interaction strength plane



- While some candidates are made up specifically to solve the DM problem, others emerge as part of solutions to long standing problems in particle physics:
- Peccei-Quinn solution to strong CP problem: axions
- Supersymmetry: at least 3 viable DM candidates: neutralino, gravitino, axino/(axion)

SUSY motivations:

- naturalness in quantum field theory (no quadratic divergences)
- means to unification with gravity (supergravity)
- gauge coupling unification provided superpartners at TeV scale
- precision EM corrections and Higgs mass
- radiative EWSB and the top mass
- accommodate baryogenesis: at least 3 ways

Supersymmetric models:

how SUSY breaking is communicated from hidden sector to visible sector

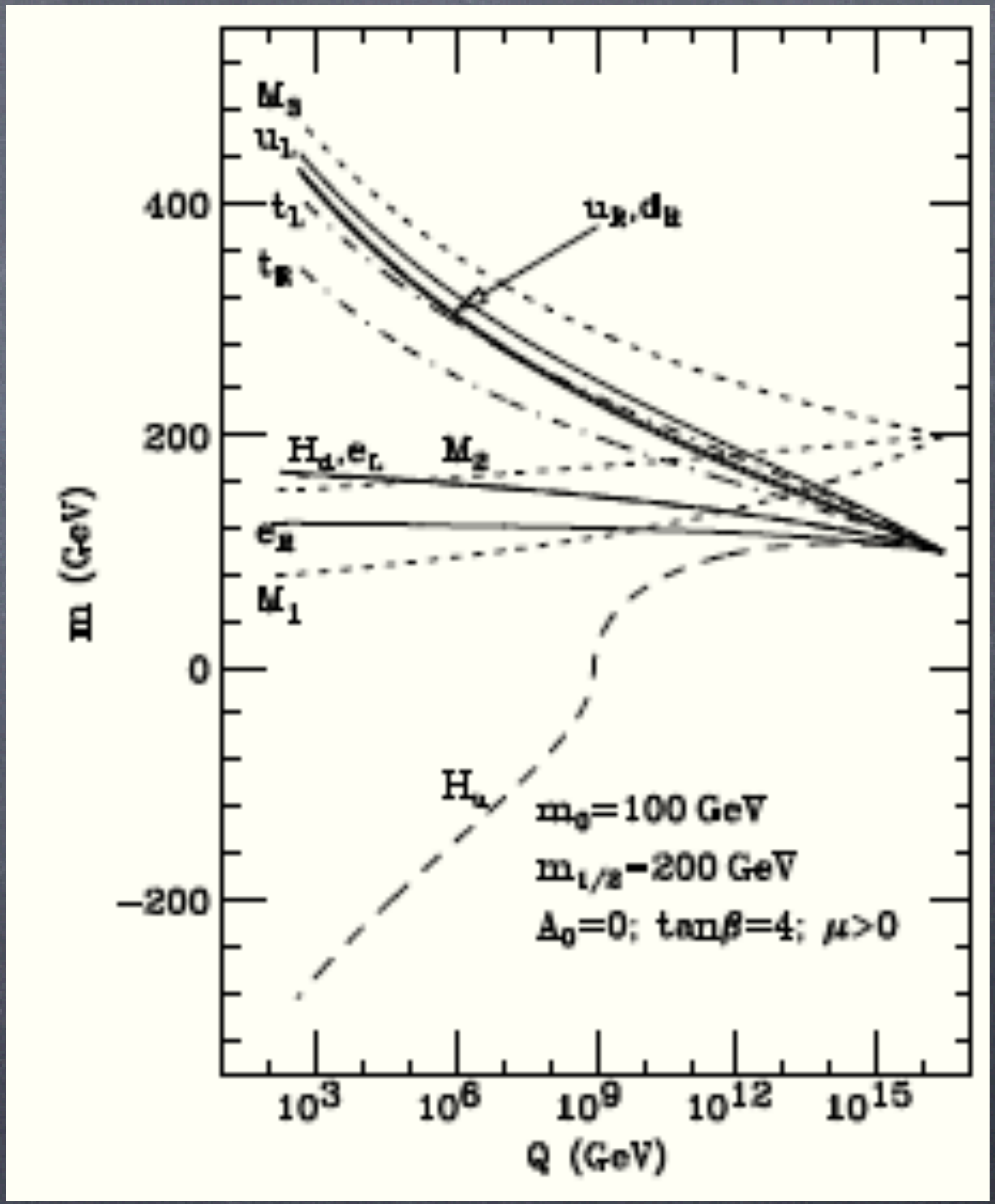
- GMSB:solves SUSY flavor problem, very light gravitino: does not naturally yield CDM
- AMSB: mAMSB, HCAMSB, inoAMSB: solves flavor problem; need additional sources of CDM since thermal abundance too low
- AMSB $\rightarrow$ Mixed-moduli AMSB $\longrightarrow$ CDM
- SUGRA: 4 candidate DM particles:

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

Simplest: mSUGRA or CMSSM

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

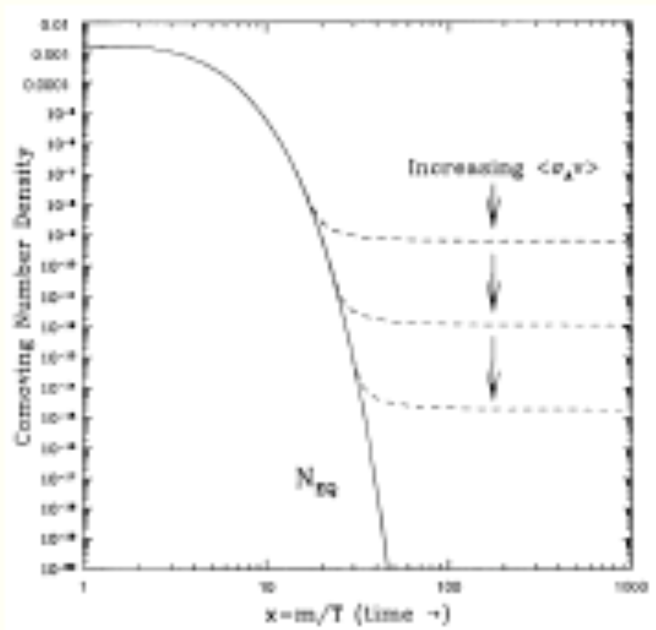
$m_0,\ m_{1/2},\ A_0\ \tan\beta,\ sign(\mu)$



The WIMP miracle

WIMPs: the WIMP miracle!

- Weakly Interacting Massive Particles
- assume in thermal equil'n in early universe
- Boltzman eq'n:
  - $dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
- $\Omega h^2 = \frac{s_0}{\rho_c/h^2} \left(\frac{45}{\pi g_*}\right)^{1/2} \frac{x_f}{M_{Pl}} \frac{1}{\langle \sigma v \rangle}$
- $\sim \frac{0.1\ pb}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{m_{wimp}}{100\ GeV}\right)^2$
- thermal relic $\Rightarrow$ new physics at M_{weak}!

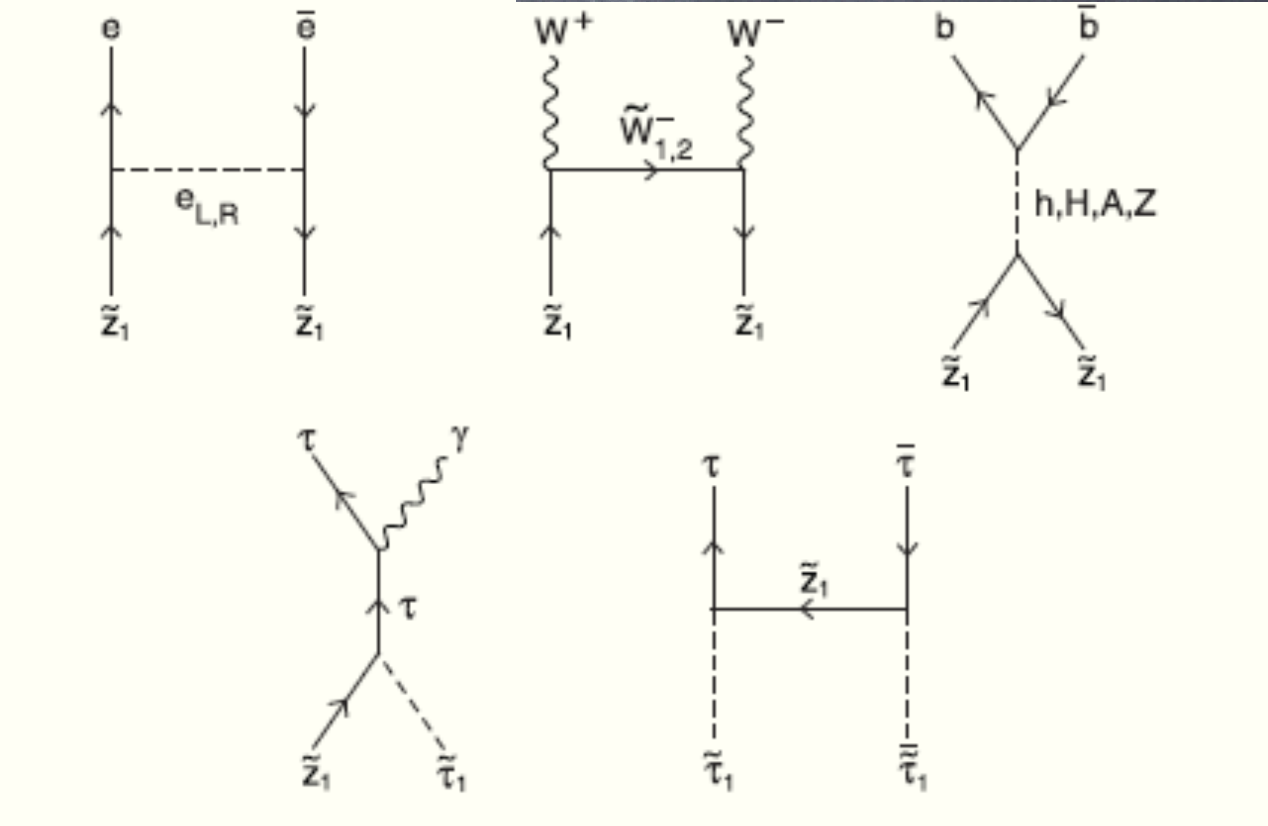


Neutralino an excellent WIMP candidate!?

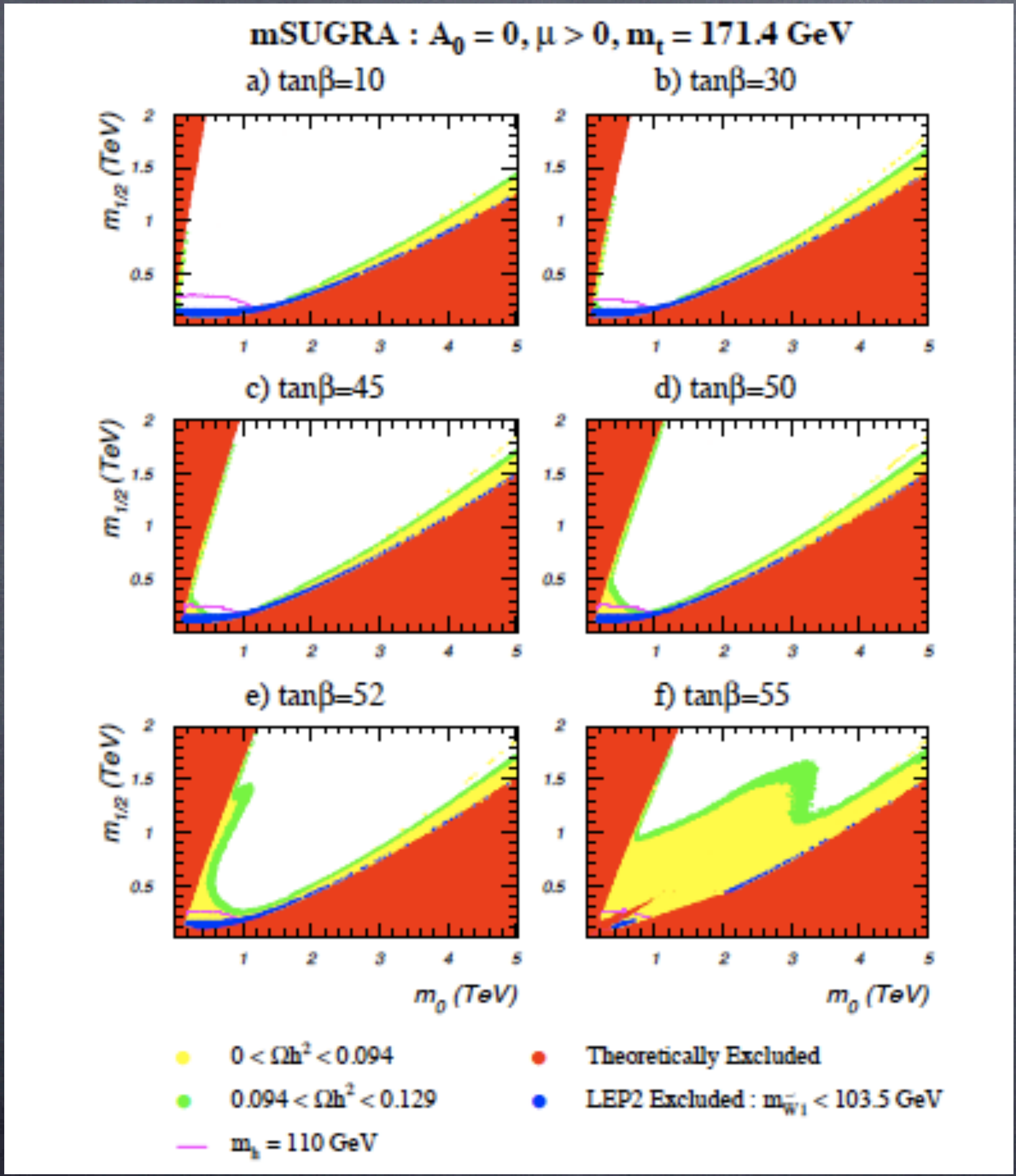
(more on this later)

Calculation of relic density

- ★ 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
- ★ several computer codes available
  - DarkSUSY, Micromegas, IsaReD (part of Isajet)



mSUGRA parameter space



HB, Mustafayev, Park, Tata

Beware non-standard cosmology!

*Scalar field decays:
-decays to inos
-inject add'l entropy

*gravitino production and decay

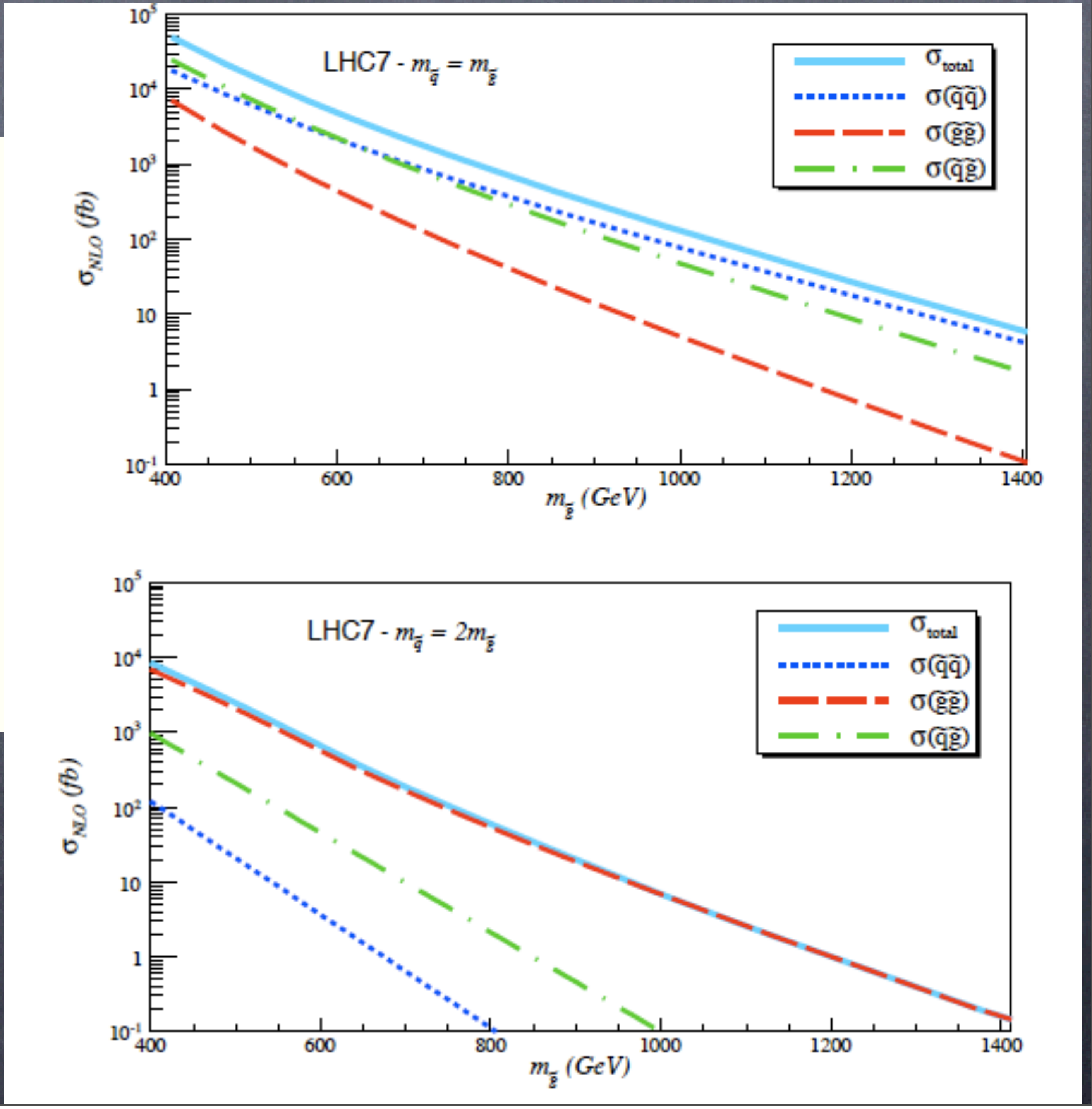
Direct production of DM at LHC?

- $pp \to \chi\chi X$, 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

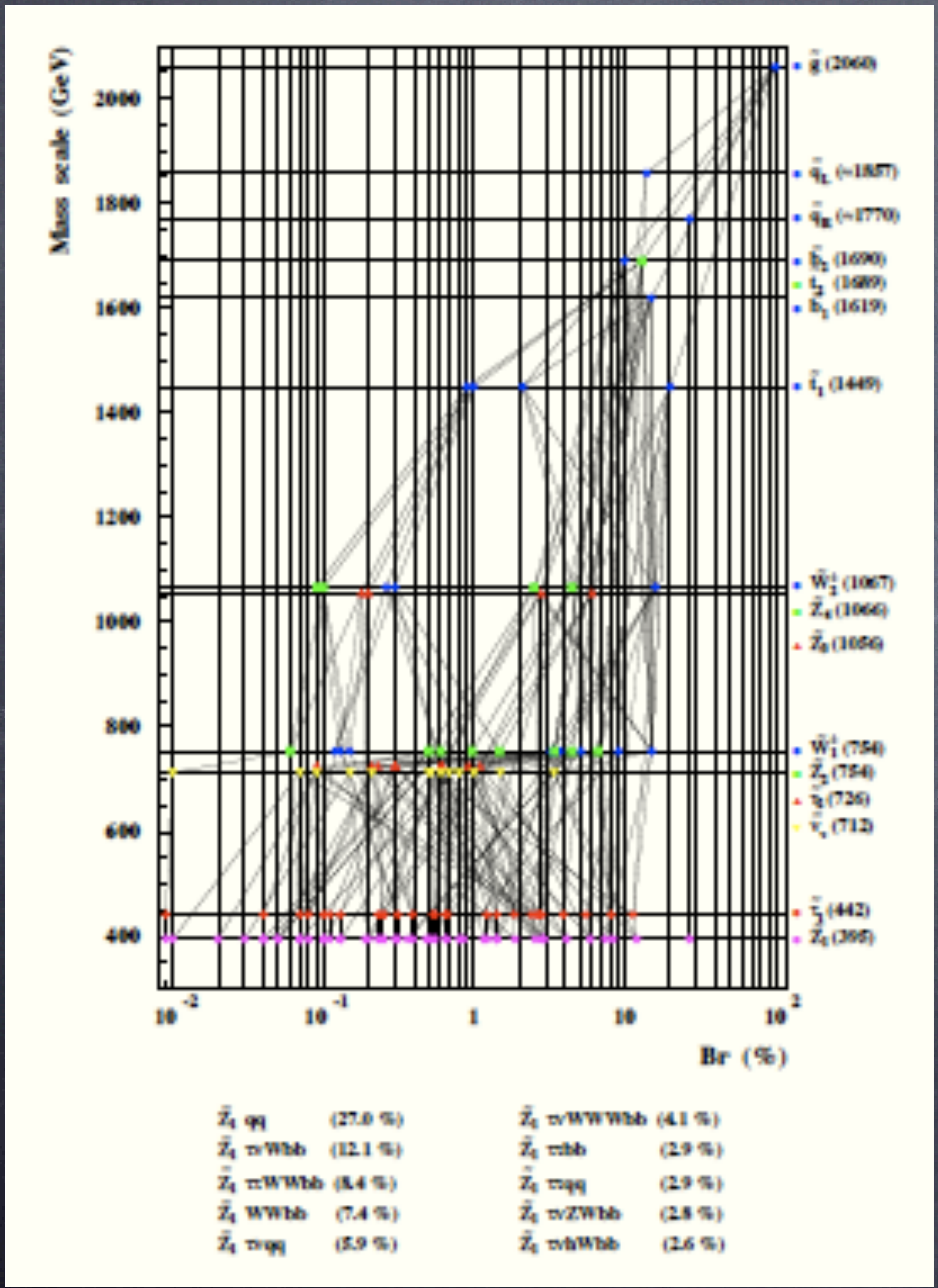
Production of SUSY matter at LHC7:

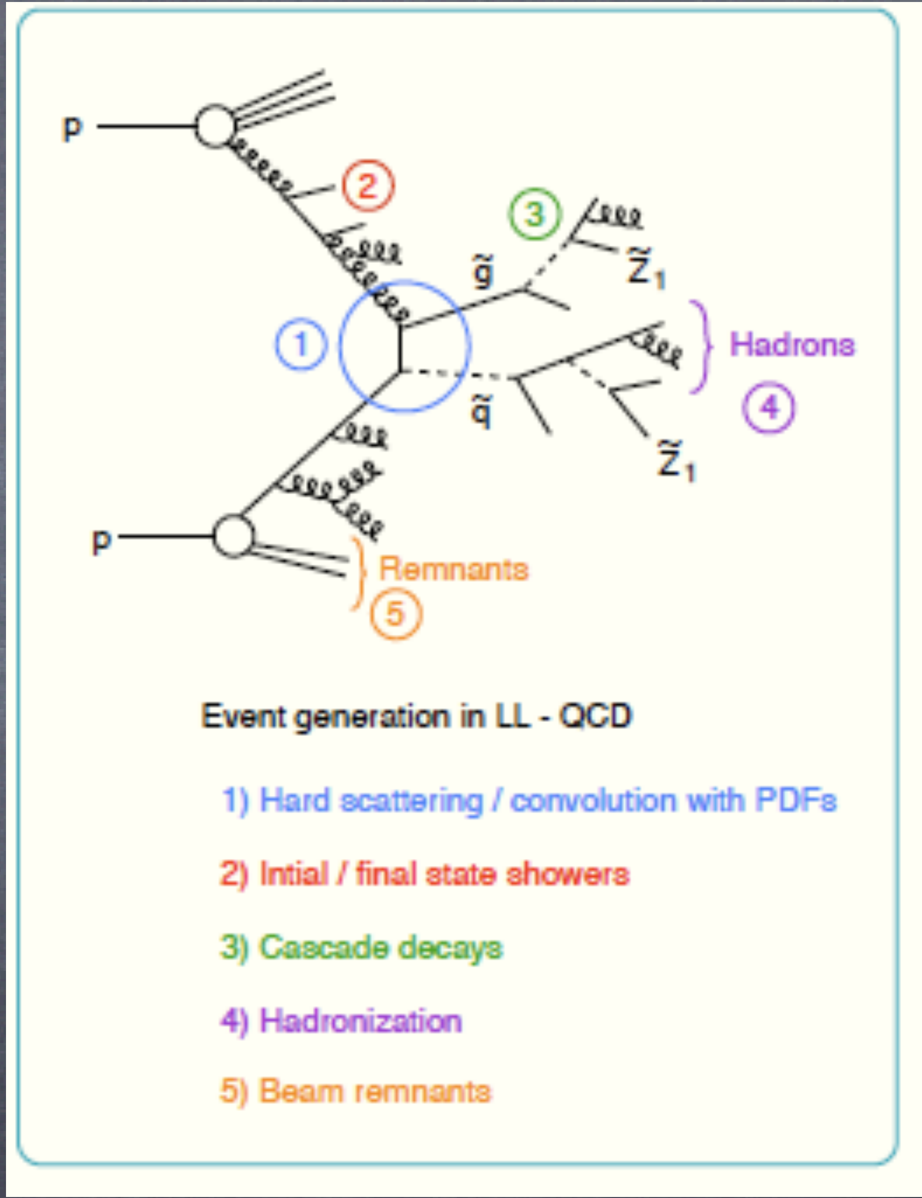
- usual SM gauge bosons, quarks and leptons
- gluino: $\tilde{g}$
- bino, wino, neutral higgsinos$\Rightarrow$ neutralinos: $\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{Z}_3, \widetilde{Z}_4$
- charged wino, higgsino $\Rightarrow$ charginos: $\widetilde{W}_1^{\pm}$, $\widetilde{W}_2^{\pm}$
- squarks: $\tilde{u}_L$, $\tilde{u}_R$, $\tilde{d}_L$, $\tilde{d}_R, \cdots$, $\tilde{t}_1$, $\tilde{t}_2$
- 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!

$$\sqrt{s} = 7\ TeV$$



Sparticles decay via a cascade until LSP state is reached

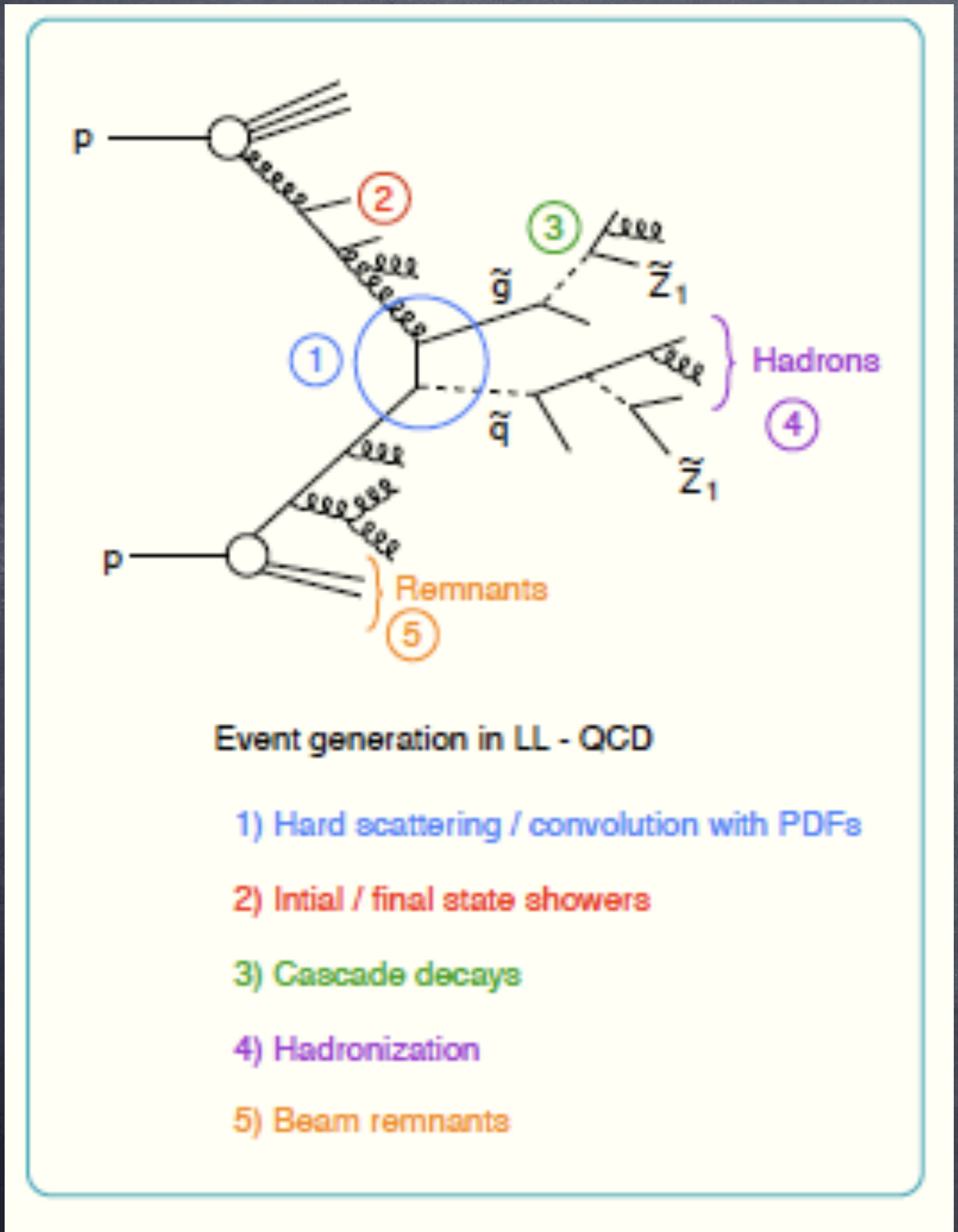


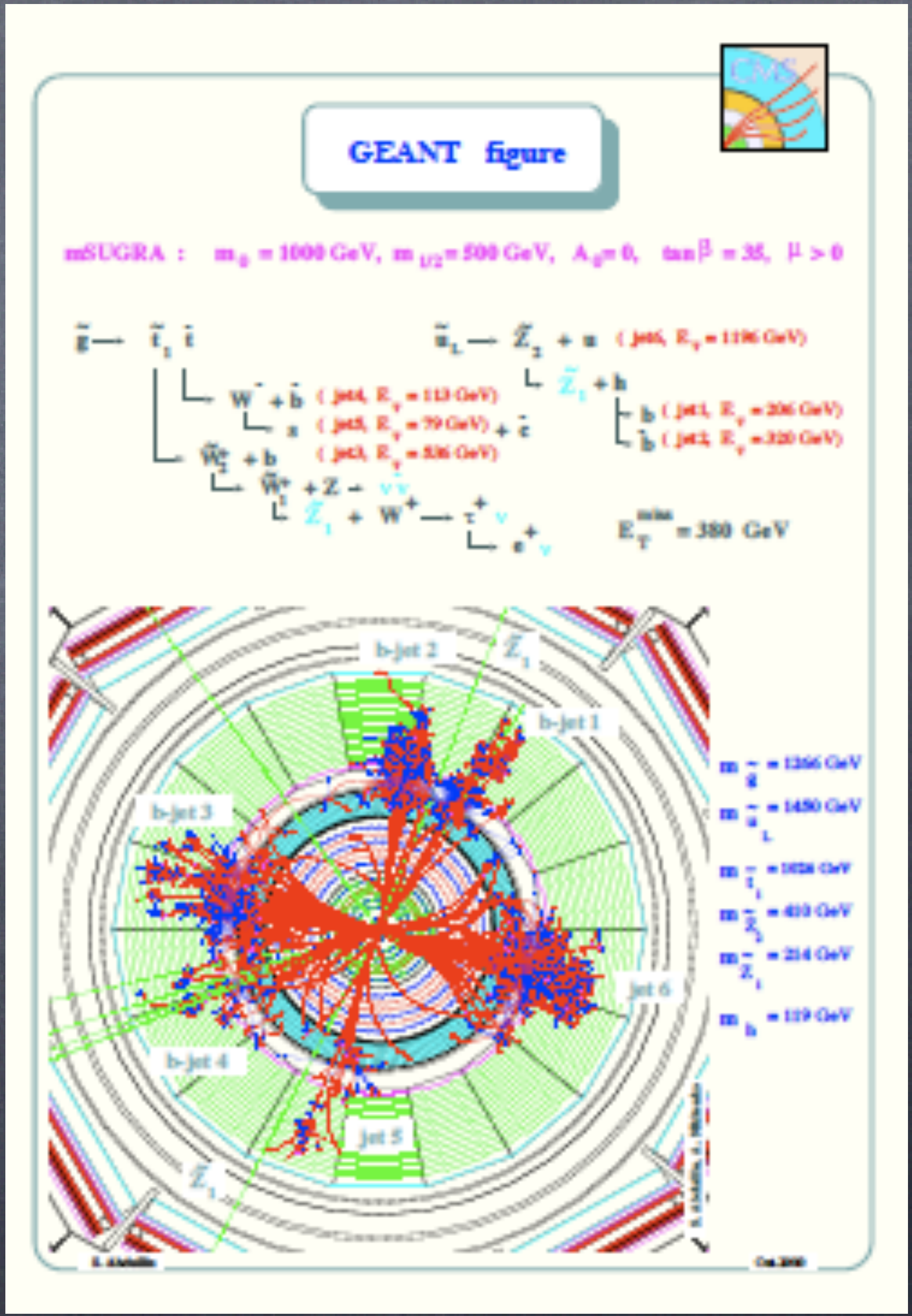


Event generation

Simulated production of neutralino

DM from SUSY at LHC





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 es and μs, and $\not{E}_T$ from $\widetilde{Z}_1$ or $\tilde{G}$ or νs escaping
- ⋆ many jets are b (displaced vertices due to long B lifetime) and τ (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

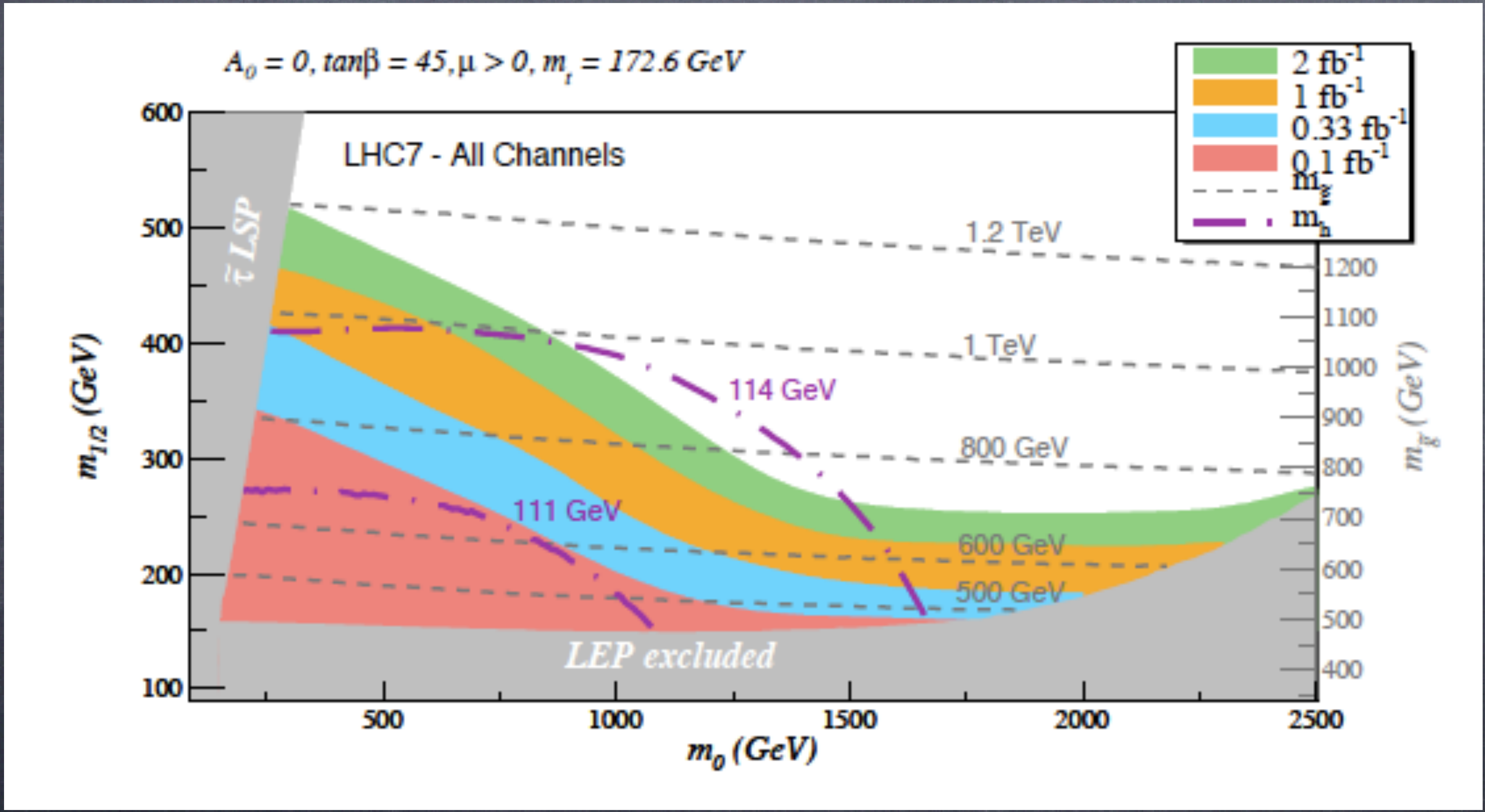
Optimize cuts over parameter space

- $E_T^{\text{miss}} >$ 100 - 1000 GeV (in steps of 100 GeV),
- $n(jets) \geq 2, 3, 4, 5$ or 6,
- $n(b - jets) \geq 0, 1, 2$ or 3,
- $E_T(j_1) >$ 50 - 300 GeV (in steps of 50 GeV) and 400-1000 GeV (in steps of 100 GeV) (jets are ordered $j_1 - j_n$, from highest to lowest E_T),
- $E_T(j_2) >$ 50 - 200 GeV (in steps of 30 GeV) and 300, 400, 500 GeV,
- $n(\ell) = 0, 1, 2, 3$, OS, SS and inclusive channel: $n(\ell) \geq 0$. (Here, $\ell = e,\ \mu$).
- 10 GeV$\leq m(\ell^+\ell^-) \leq$ 75 GeV or $m(\ell^+\ell^-) \geq$ 105 GeV (for the OS, same flavor (SF) dileptons only),
- transverse sphericity $S_T > 0.2$.

Then require, for some set of cuts and integrated luminosity:

$$S \geq max\left[5\sqrt{B},\ 5,\ 0.2B\right]$$

Reach of LHC7 for various integrated luminosities:

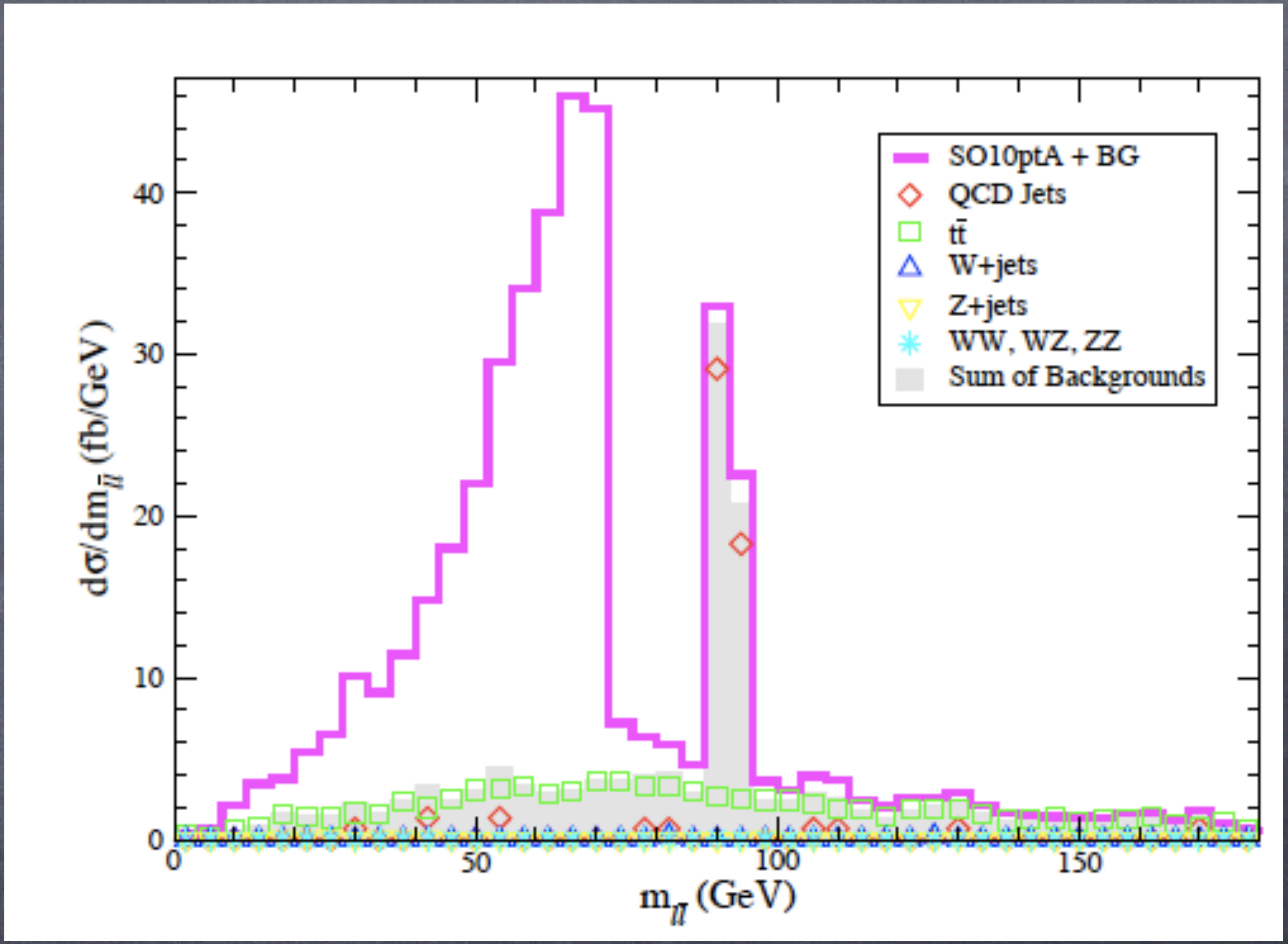


HB, Barger, Lessa, Tata: JHEP

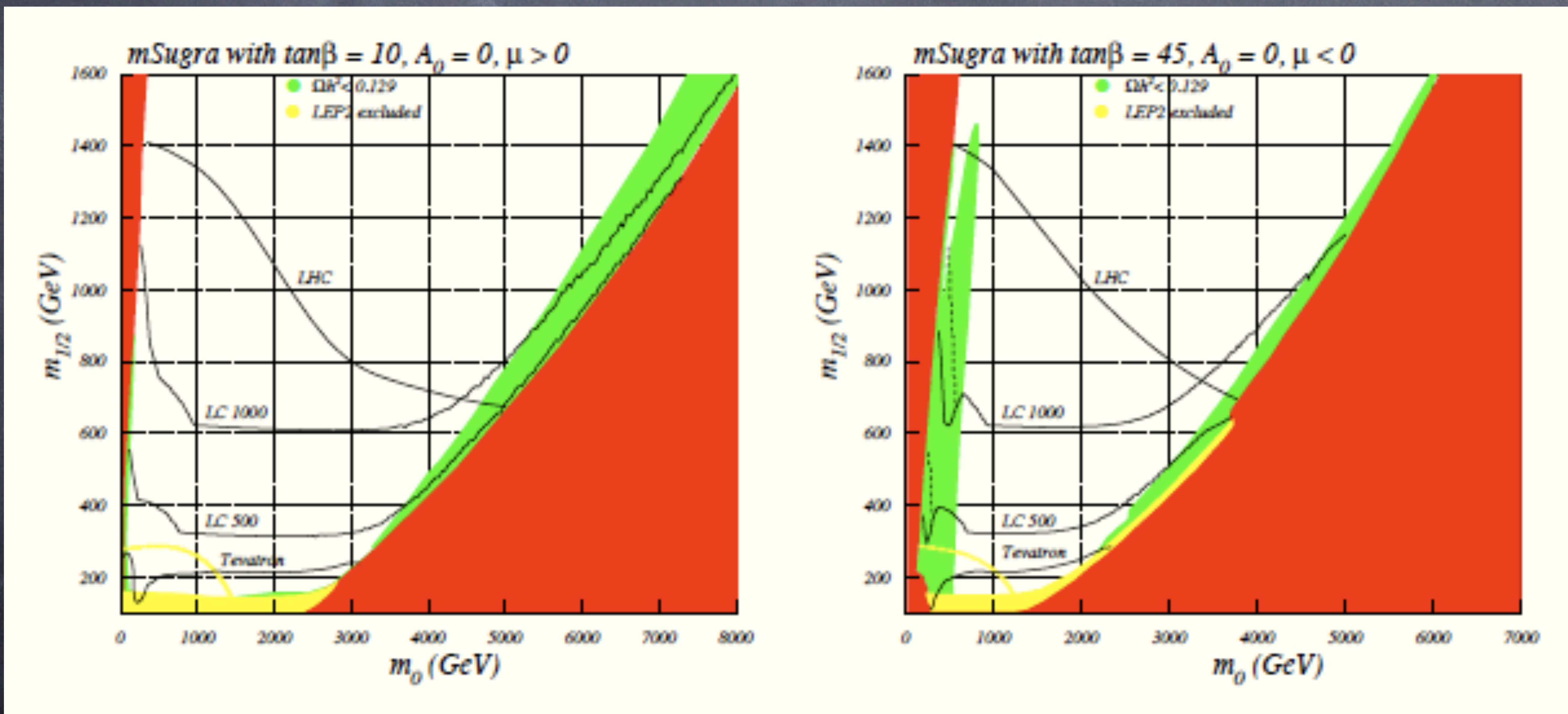
Smoking gun signature for LHC7: OS/SF dileptons

- Models with gaugino mass unification
- $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} < M_Z$
- i.e.

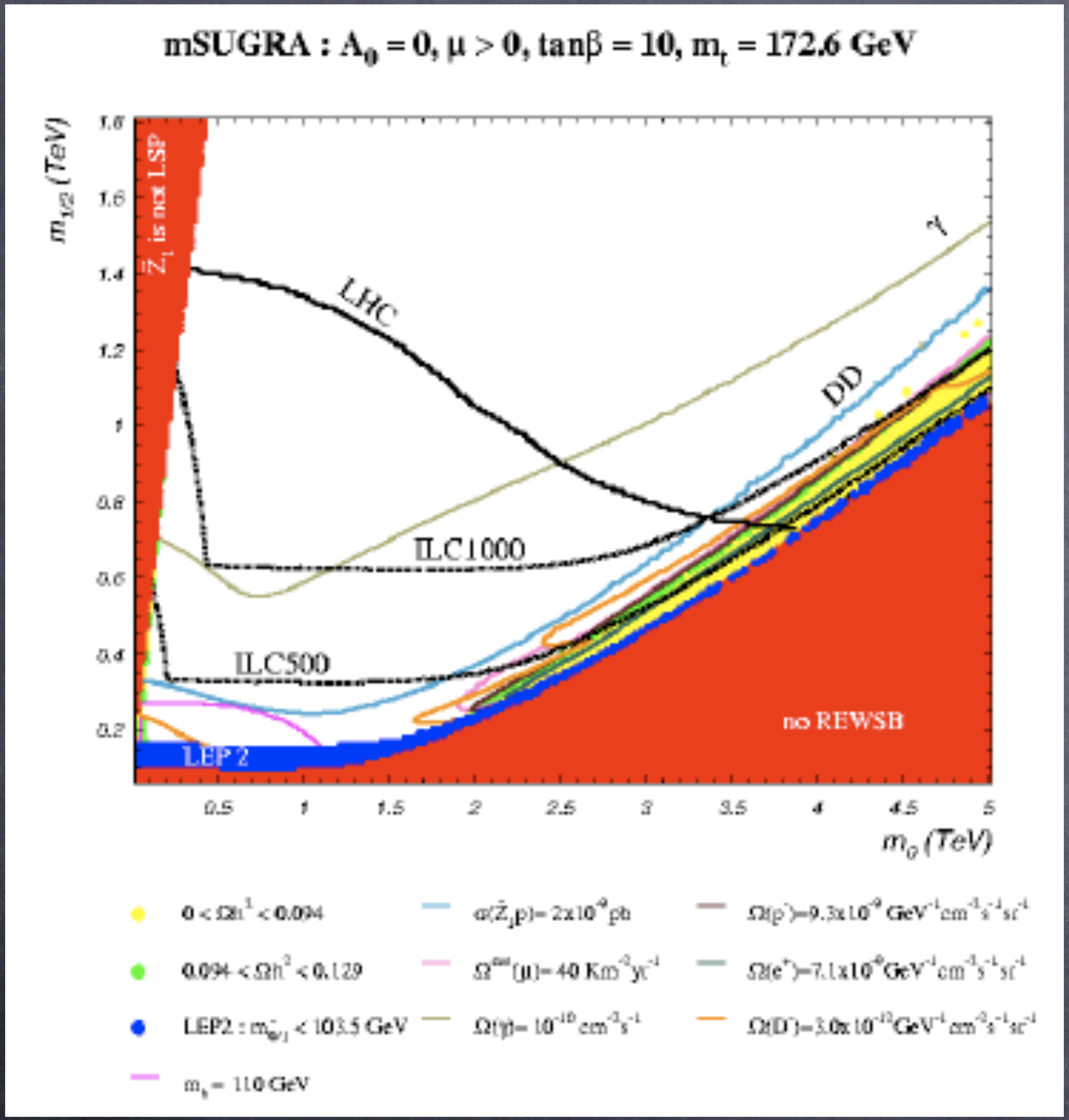
  $m_{\tilde{g}} < 630\ GeV$
- dilepton mass edge below MZ!

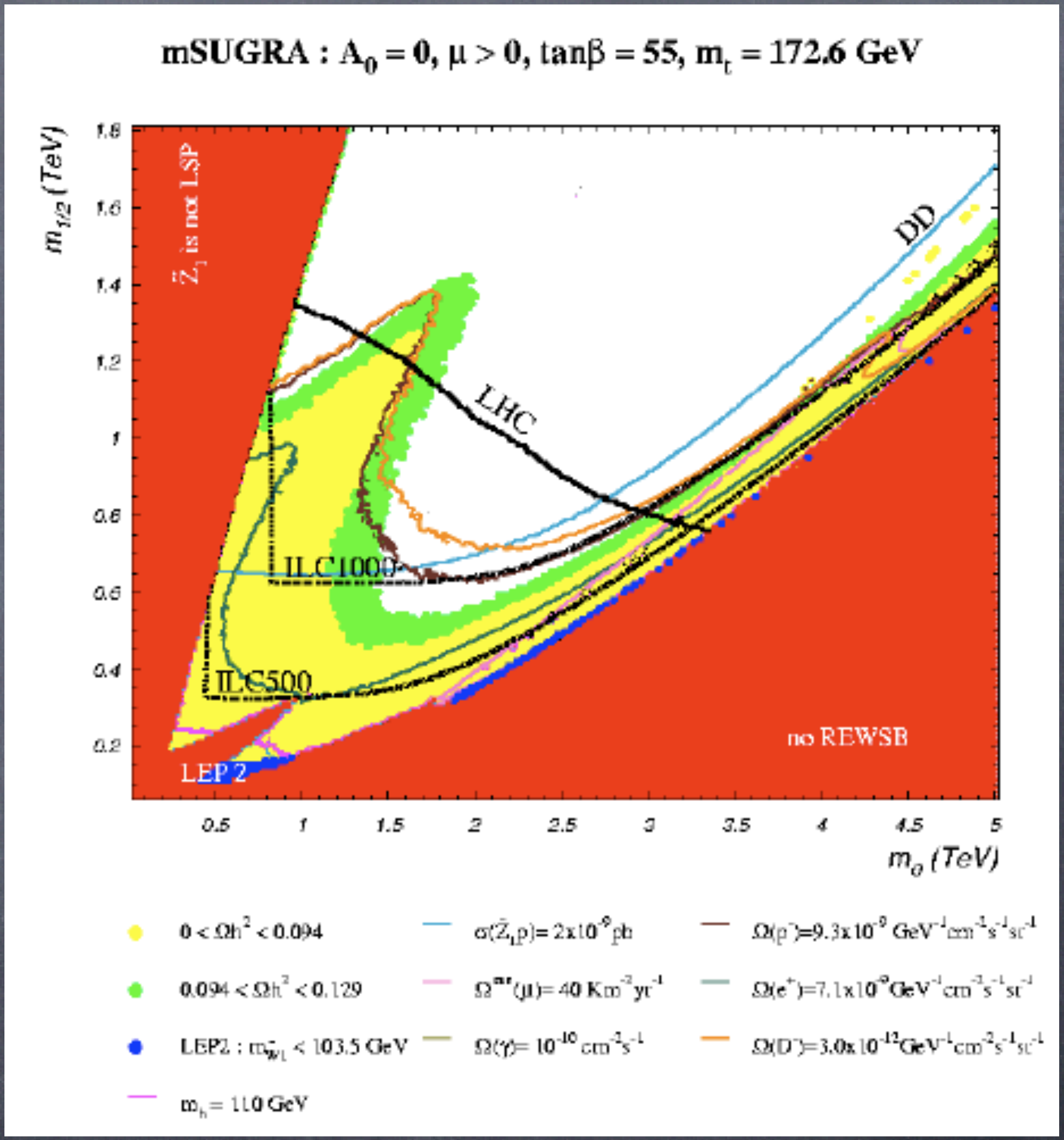


Reach of LHC14 compared to Tevatron and ILC



Reach of LHC14, ILC compared to DD/ID WIMP search

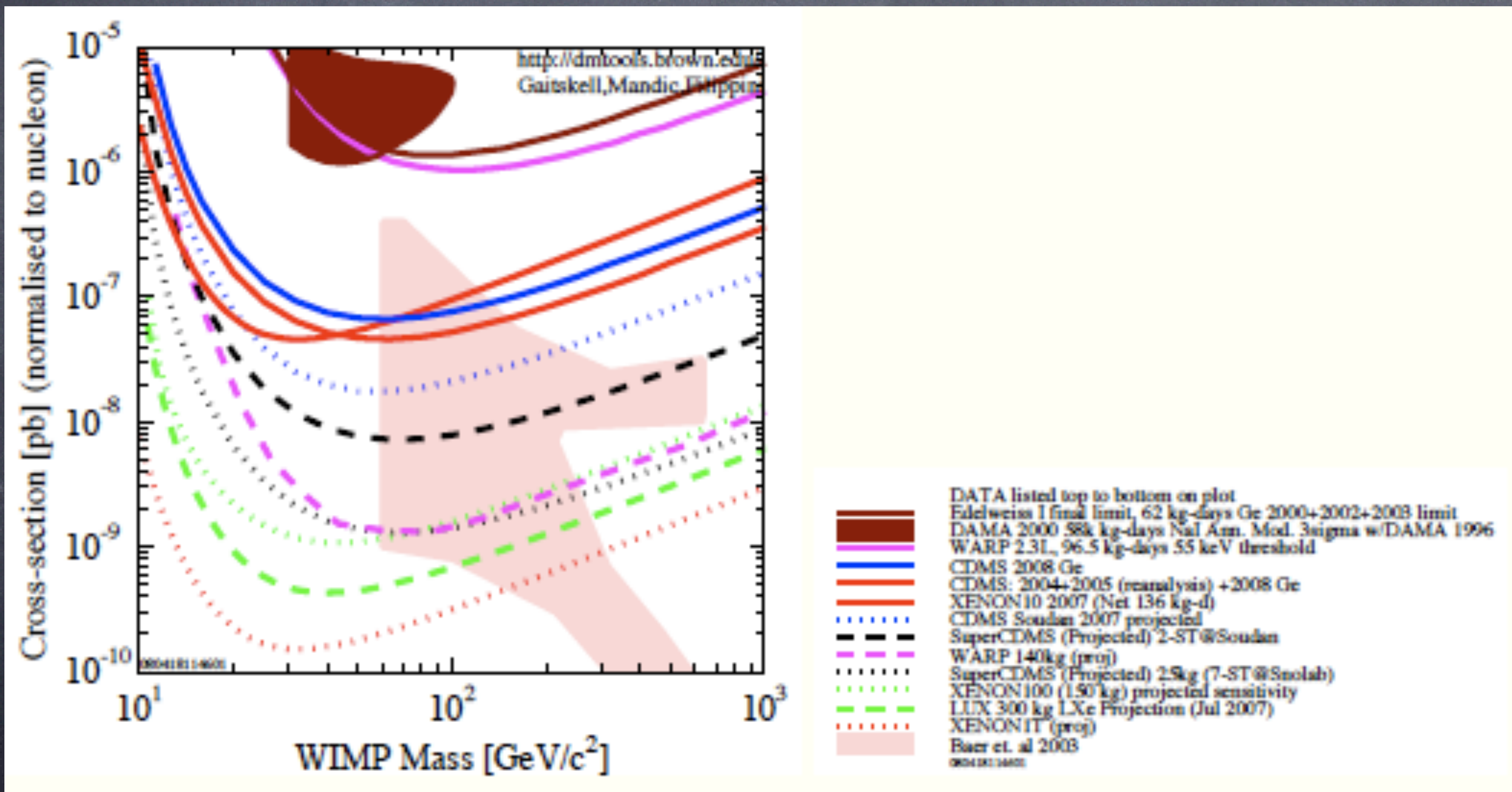




HB, Park, Tata

DD vs. LHC in mSUGRA:

Xenon-100 should cover FP region!

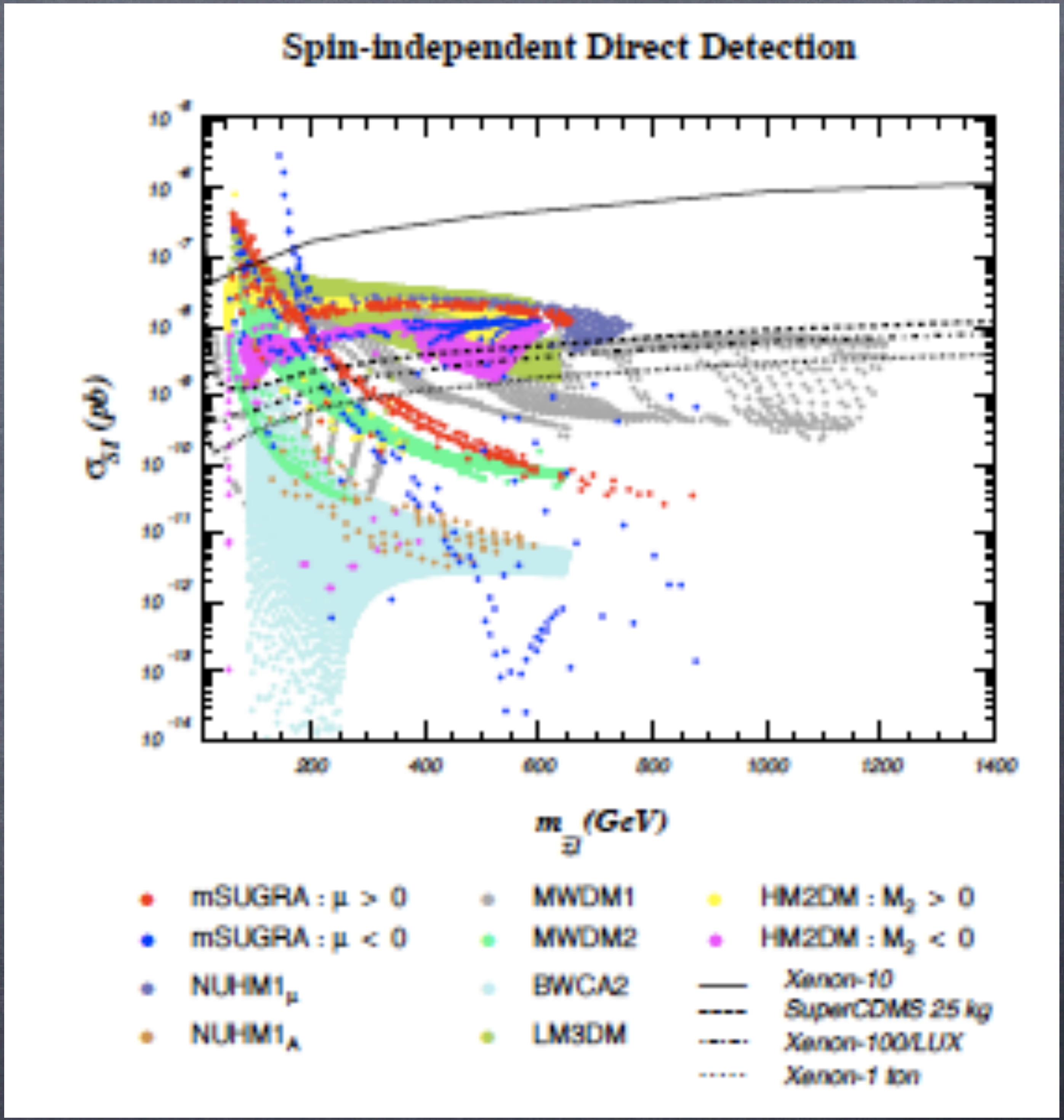


Well-tempered neutralinos

Arkani-Hamed, Delgado, Giudice

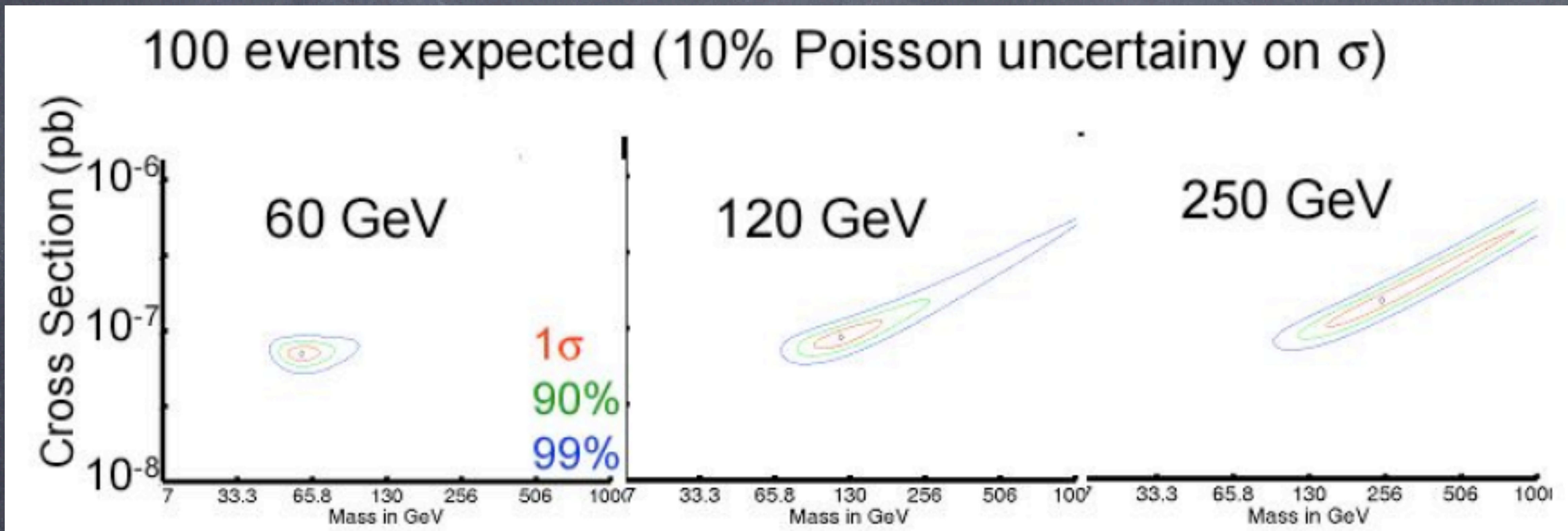
Scan over 10 models with and without universality; keep only models with correct relic abundance

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(WIMP) may be extracted from energy spectrum in DD experiments, for lower range of WIMP masses: crucial input for LHC?

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
- $m(\ell\bar{\ell}) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ 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

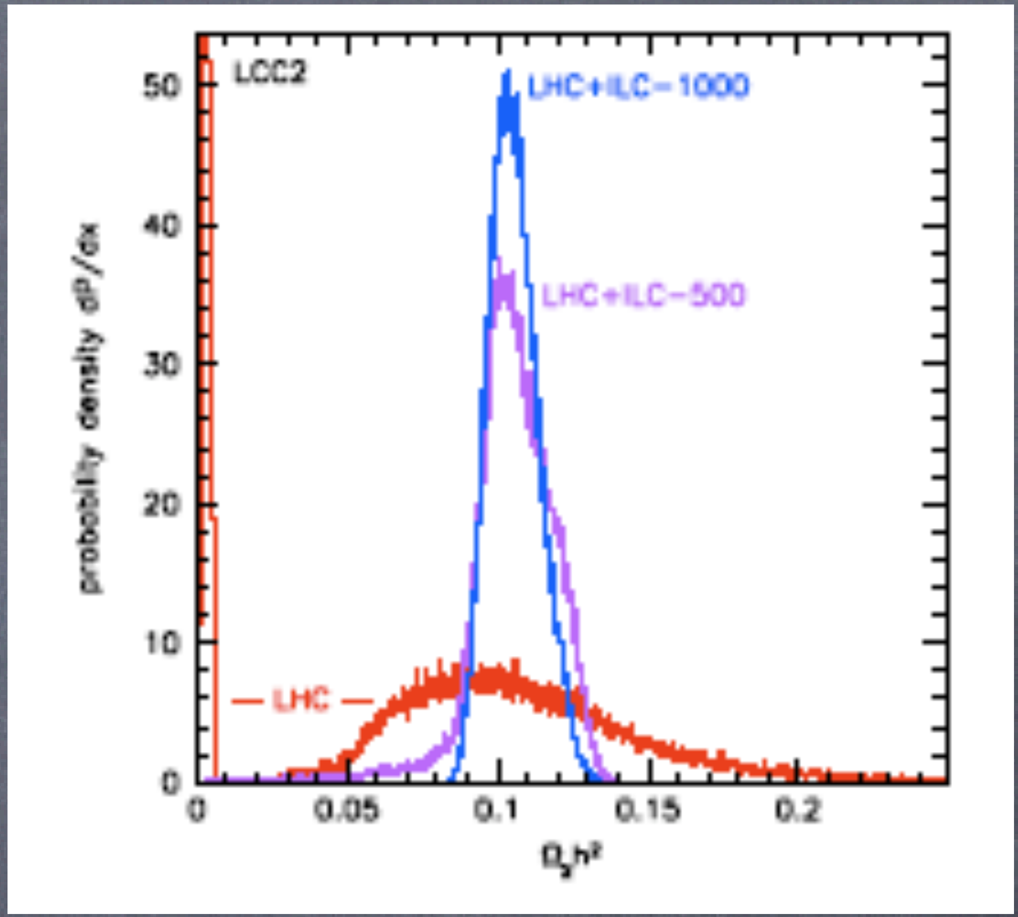
Paige, Hinchliffe et al. studies

- 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

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

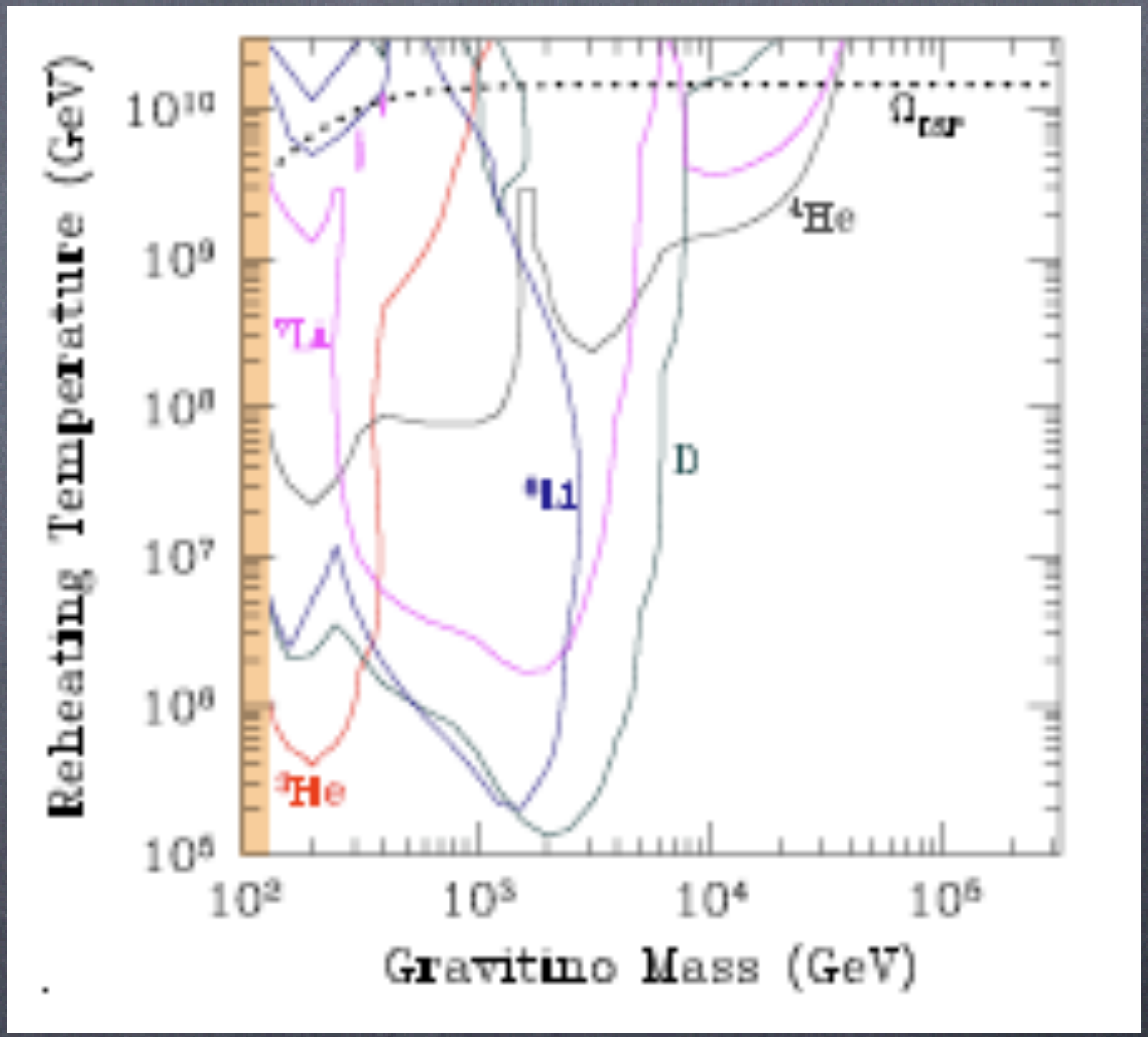


Allanach, Belanger, Boudjema, Pukhov
Nojiri, Polesello, Tovey
Baltz, Battaglia, Peskin, Wisansky
Arnowitt, Dutta, Kamon, ..

Beware: points chosen are SPS1a or accessible to ILC500

Problem#1: gravitino production in early universe (gravitino problem)

- 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)



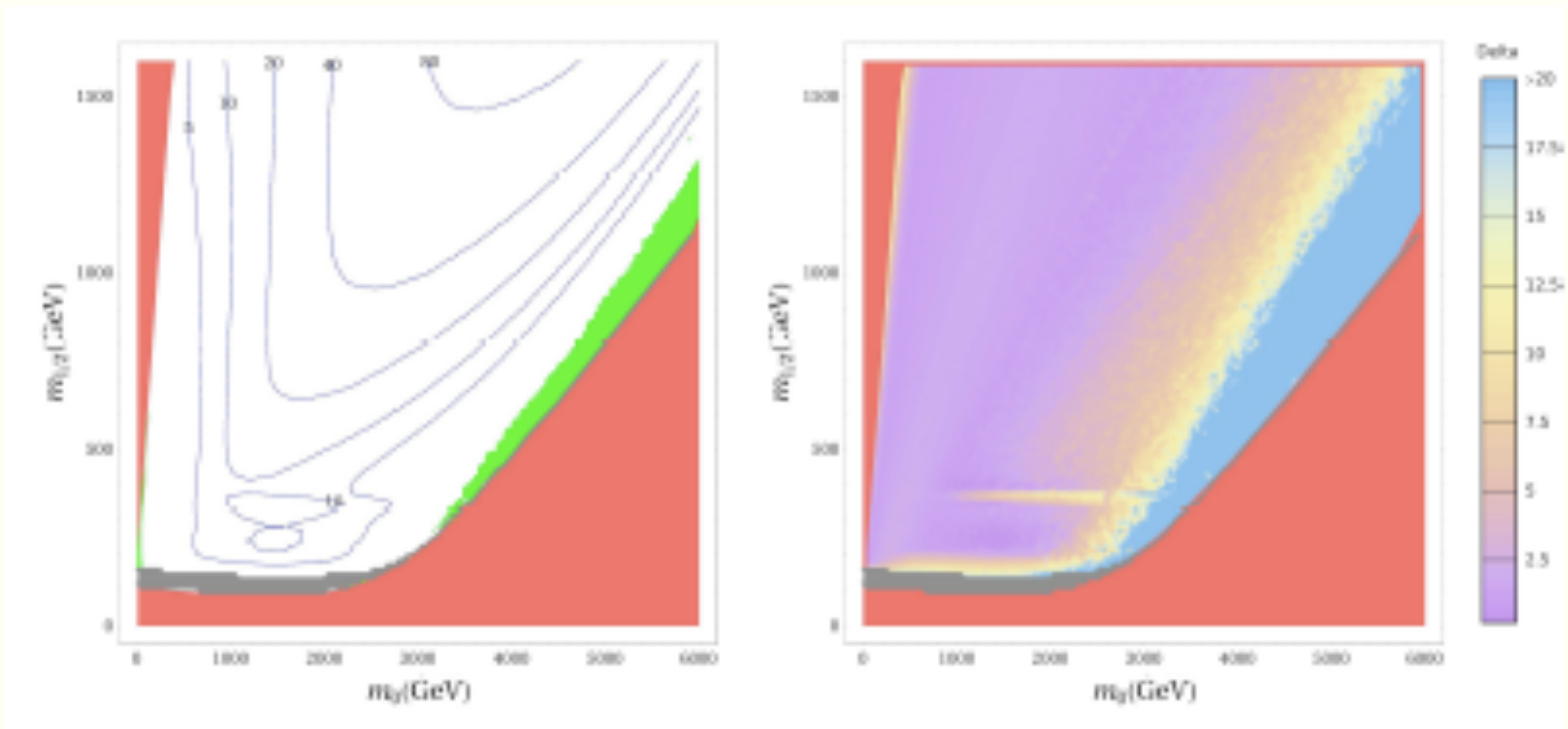
Kawasaki et al; Ellis et al.

Baryogenesis and gravitino problem

- EW baryogenesis in MSSM: mt1<125 GeV
- Leptogenesis: need T(reheat)>10^9 GeV (conflicts with gravitino problem)
- Non-thermal leptogenesis: TR>10^6 GeV
- Affleck-Dine leptogenesis: can have TR~10^6 GeV
- ....

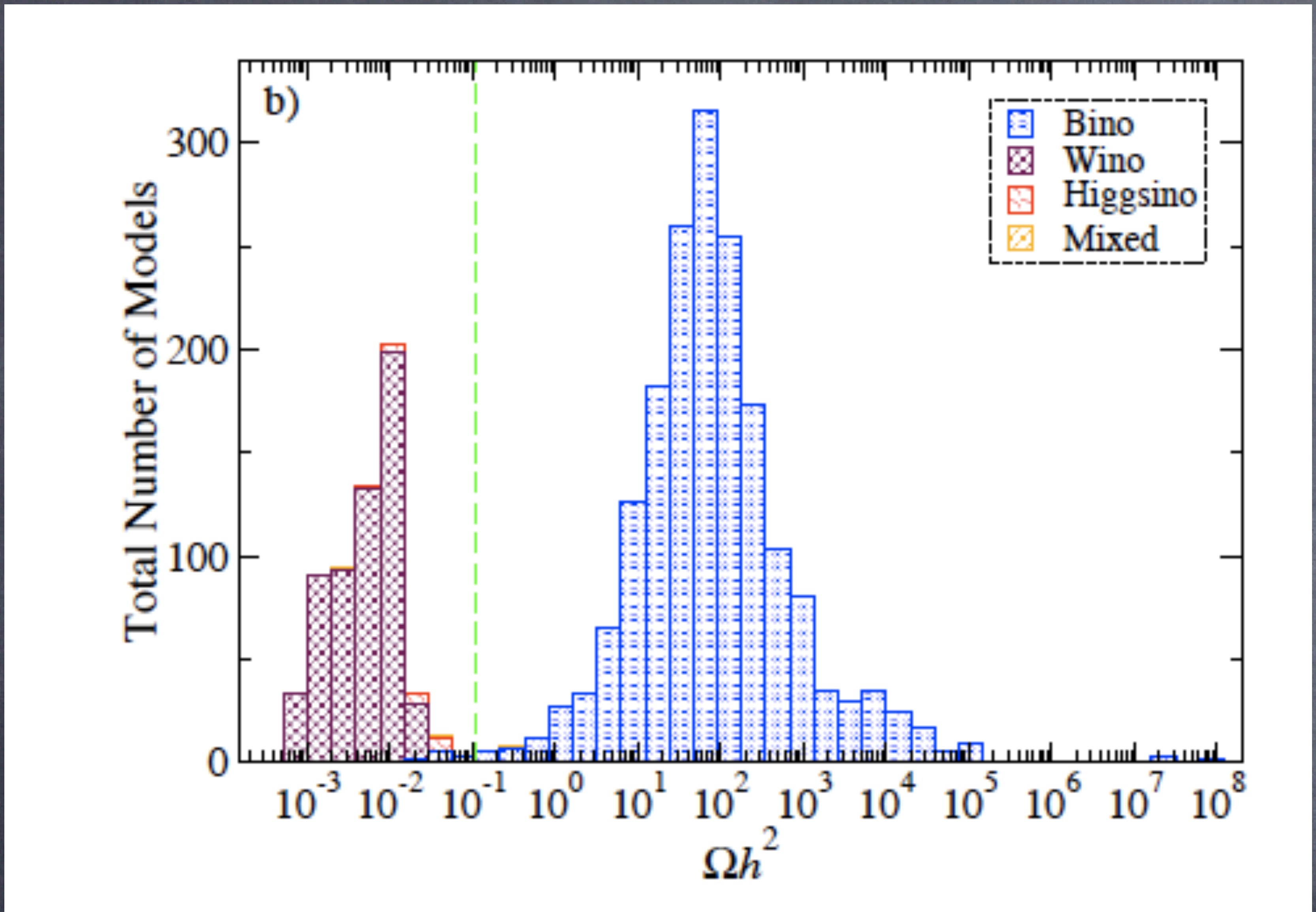
Problem #2: Relic density in mSUGRA almost always too big, unless fine-tuned!

- ★ contours of $\Omega_{\tilde{Z}_1} h^2$
- ★ regions of fine-tune: $\Delta \equiv \frac{\partial \log \Omega_{\tilde{Z}_1} h^2}{\partial \log a_i}$: (HB, A. Box)



HB, A. Box, arXiv:0910.0333

More general: scan over SUGRA-19 model



$m_\chi < 500\ GeV$

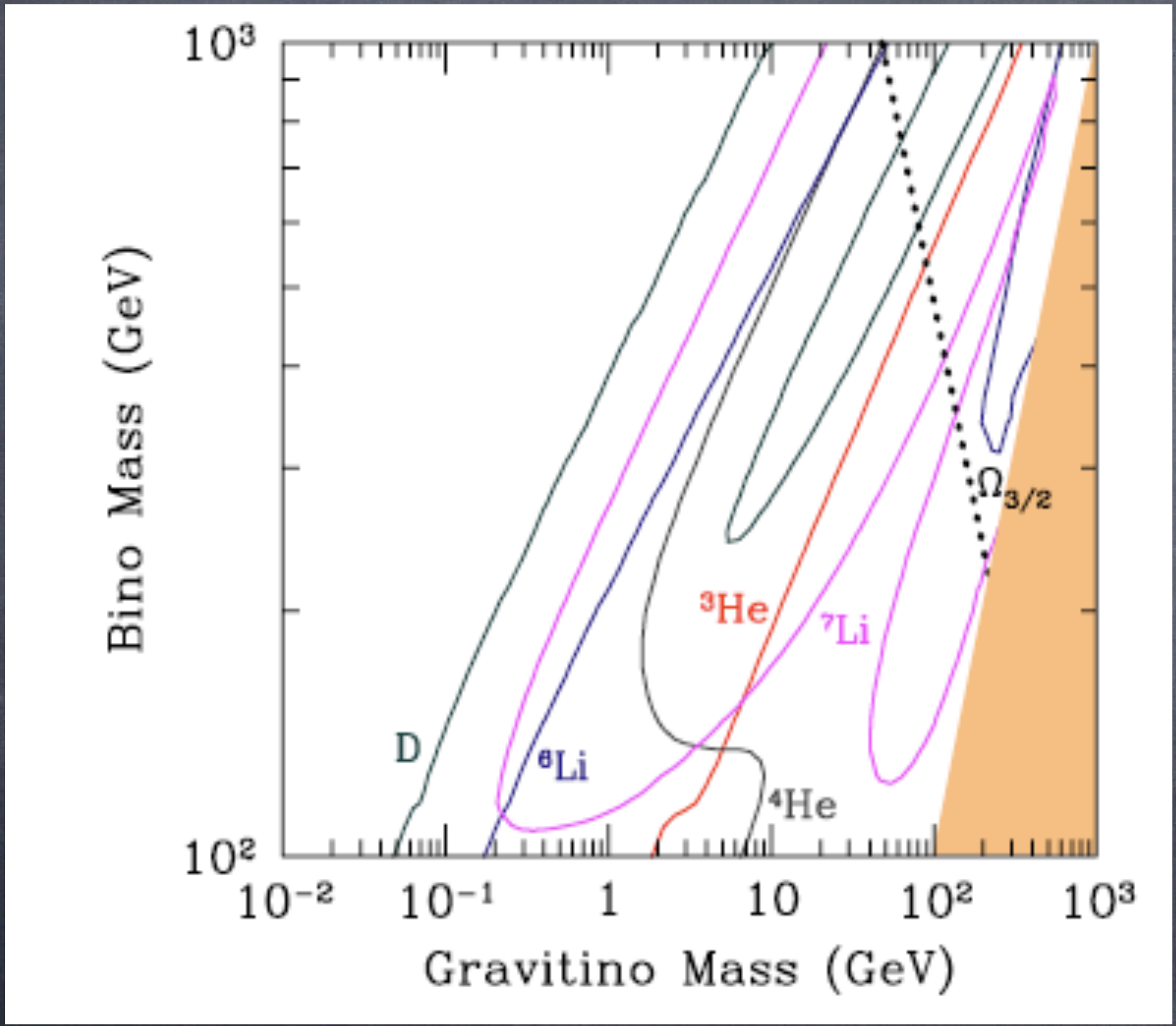
HB, Box,Summy, arXiv:1005.2215

$\Omega_\chi h^2 \sim 0.11$ is most unlikely value!

SUSY neutralino is not a very good DM candidate

Gravitino (superWIMP) dark matter:

BBN constraints on gravitino as LSP are severe unless it is very light, as in GMSB

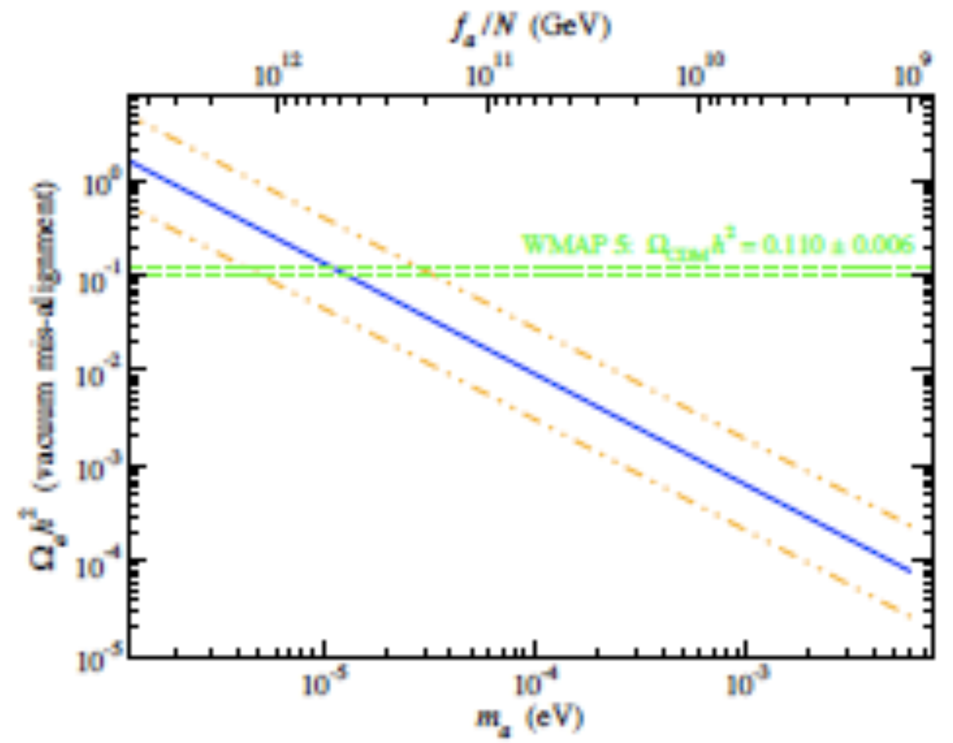


(Case of bino NLSP)

Kawasaki, Kohri, Moroi, Yatsuyanagi, PRD78, 065011(2008)

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



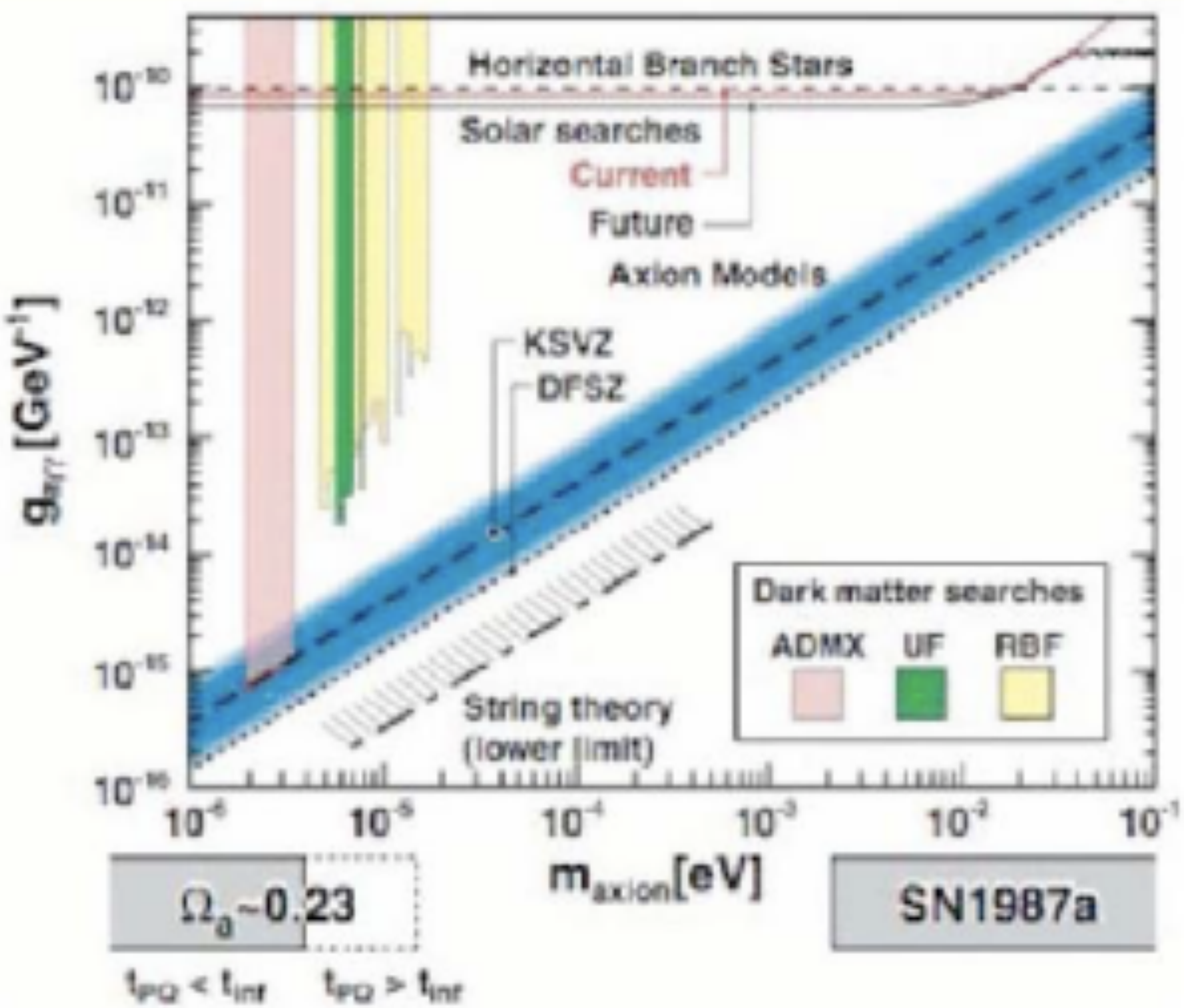
Axion DM: forms BEC, suppresses small scale structure, gives mechanism for galactic rotation

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

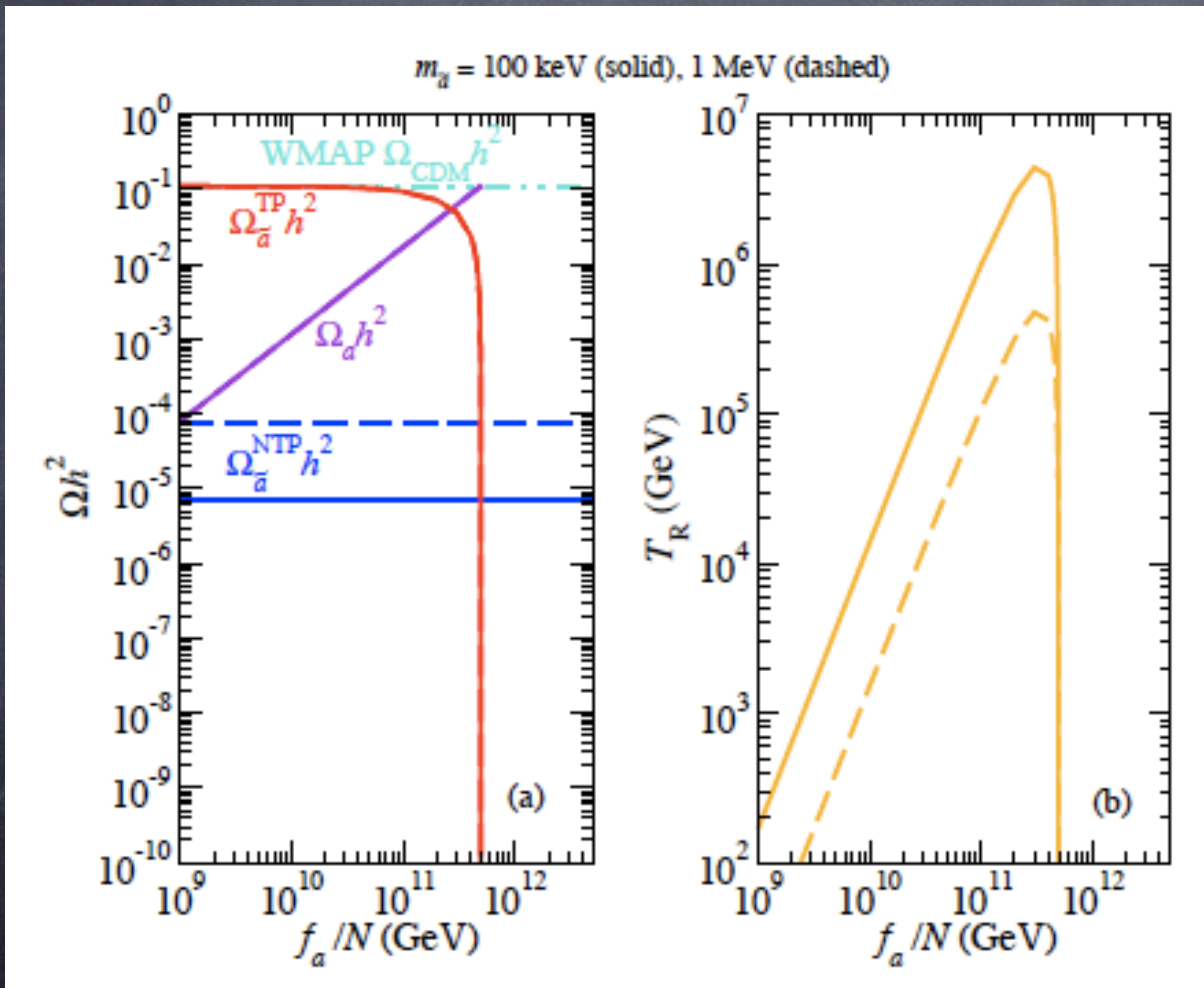
Thermal production of axinos

- 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; Strumia

Mixed axion/axino DM in mSUGRA model



Asking for high T_R requires large f_a: get mainly axion CDM!

HB, Box and Summy, JHEP0908,080 (2009)

Mainly axion CDM in mSUGRA model

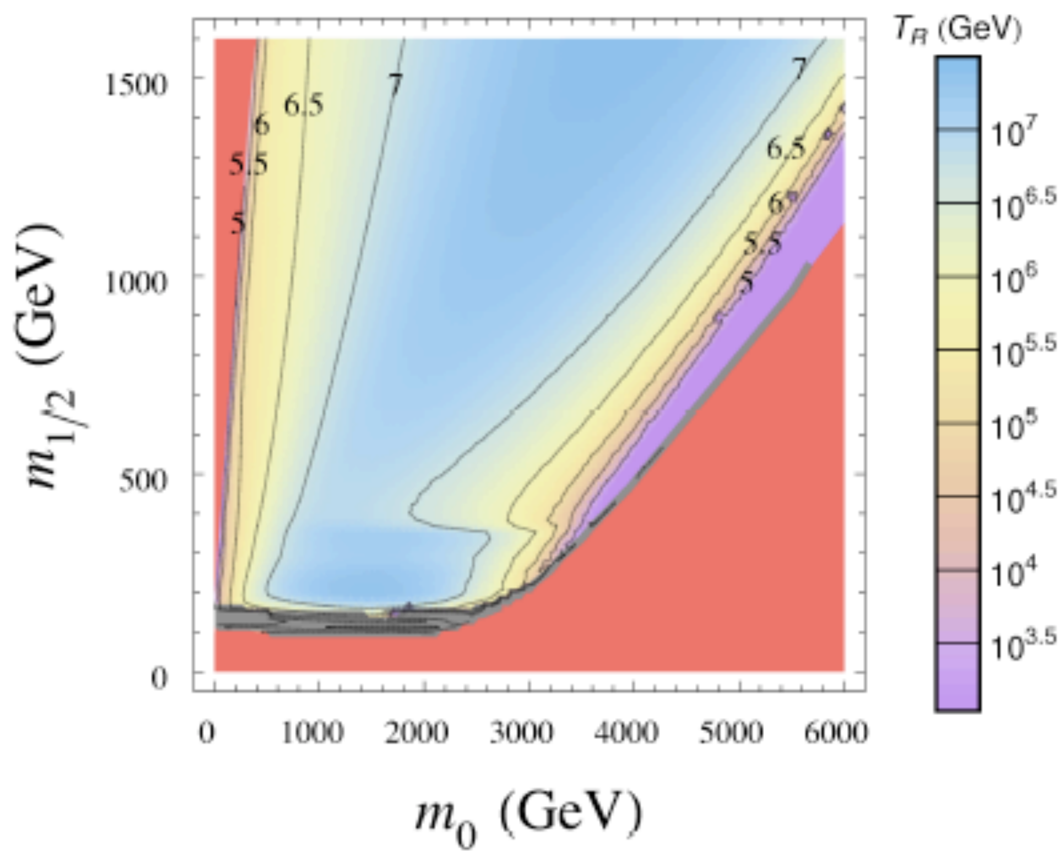


Figure 6: Contours of constant T_R in the m_0 *vs.* $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and $\Omega_{\tilde{a}}^{TP} h^2 = 0.006$ and $\Omega_{\tilde{a}}^{NTP} = 6 \times 10^{-6}$.

Most dis-favored regions with neutralino DM are most favored with mainly axion CDM!

SO(10) SUSY GUTs

- gauge coupling (force) 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
- Higgs unification into 10

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}:

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

★ 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

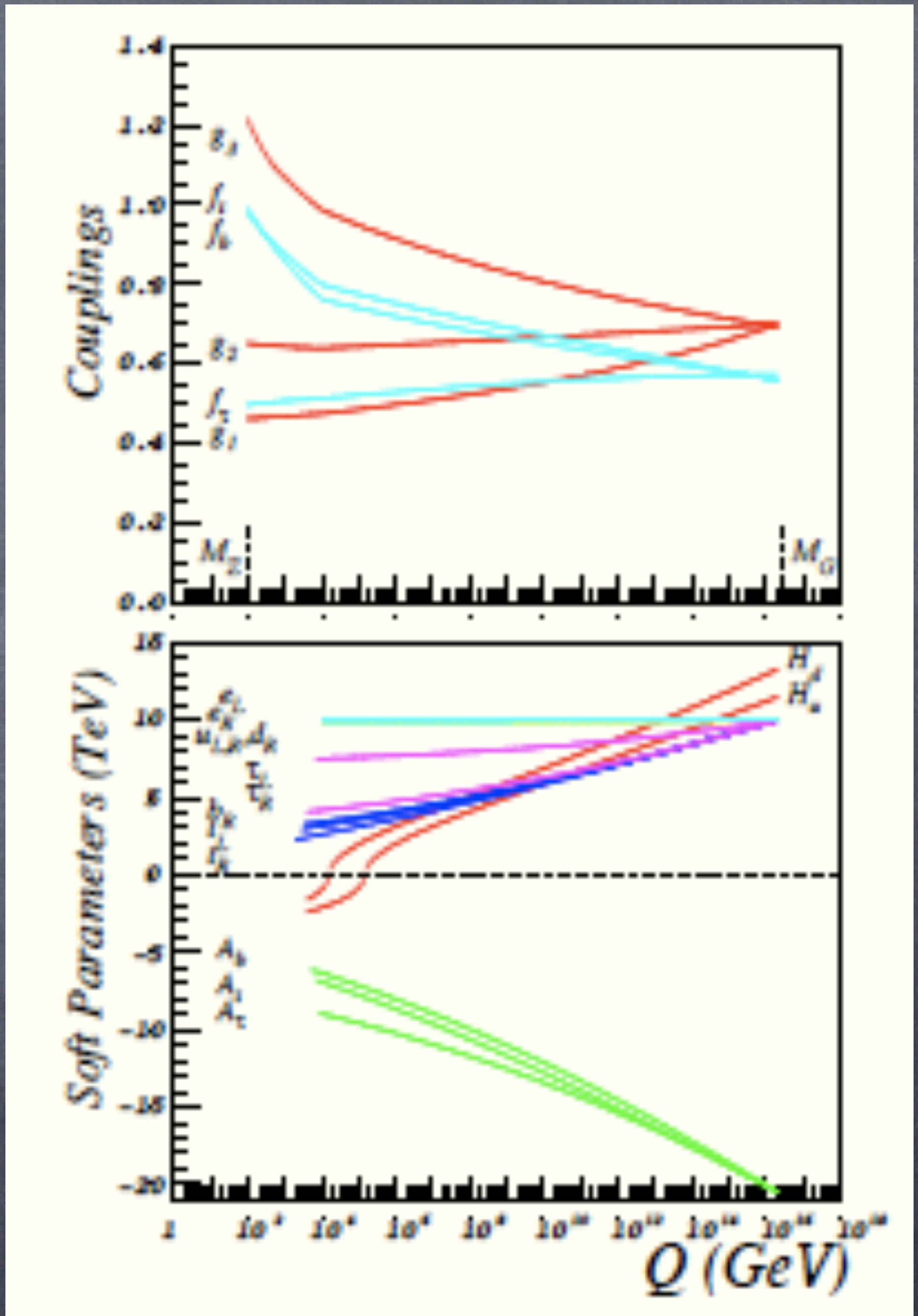
t-b-tau unified solutions

$$m_{16} \sim 10\ TeV$$

$$m_{1/2}\ small$$

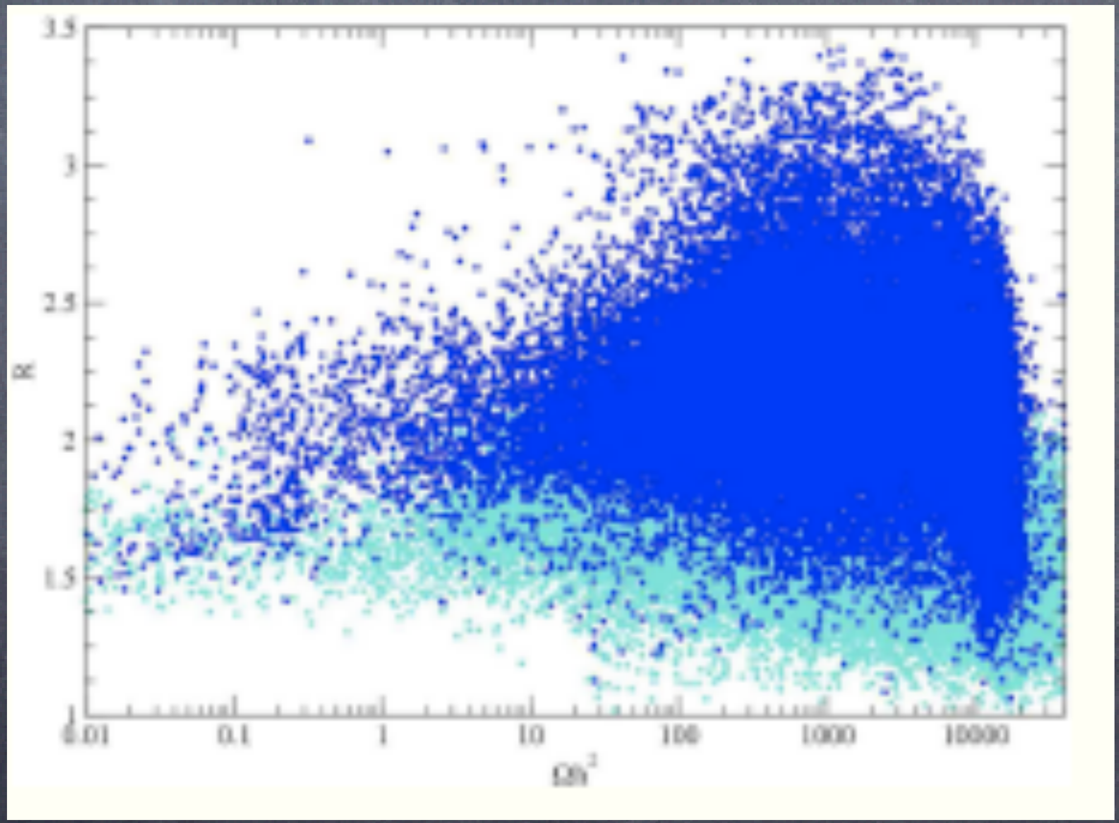
- need $m_{10} \simeq \sqrt{2} m_{16}$
- $A_0 \simeq -2m_{16}$
- inverted scalar mass hierarchy: Bagger et al.
- split Higgs: $m^2_{H_u} < m^2_{H_d}$

– $m_{\tilde{q},\tilde{\ell}}(1,2) \sim 10$ 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

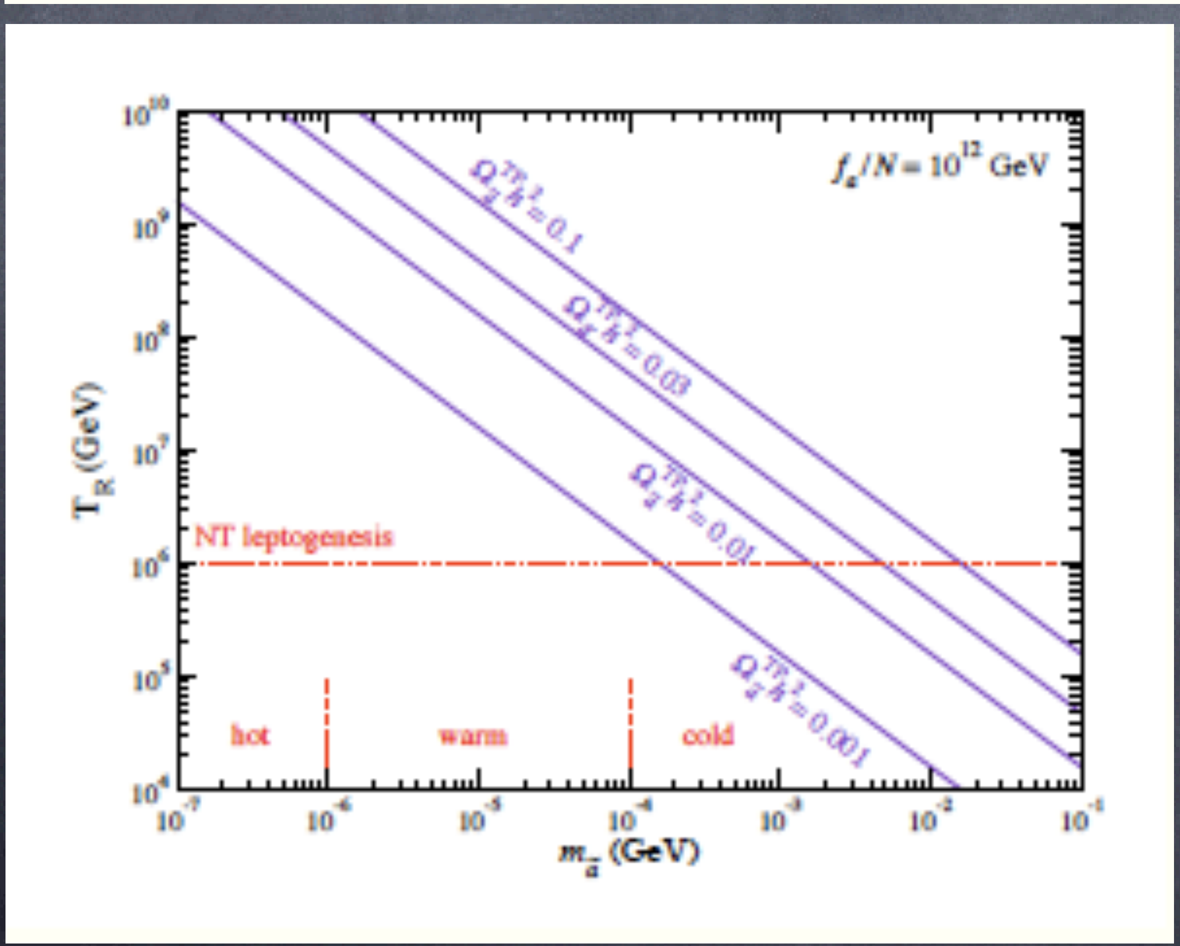


relic density too high by factor 10^3-10^5!

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 $\Omega_{\tilde{Z}_1} h^2$ and $m_{\tilde{Z}_1}$ 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

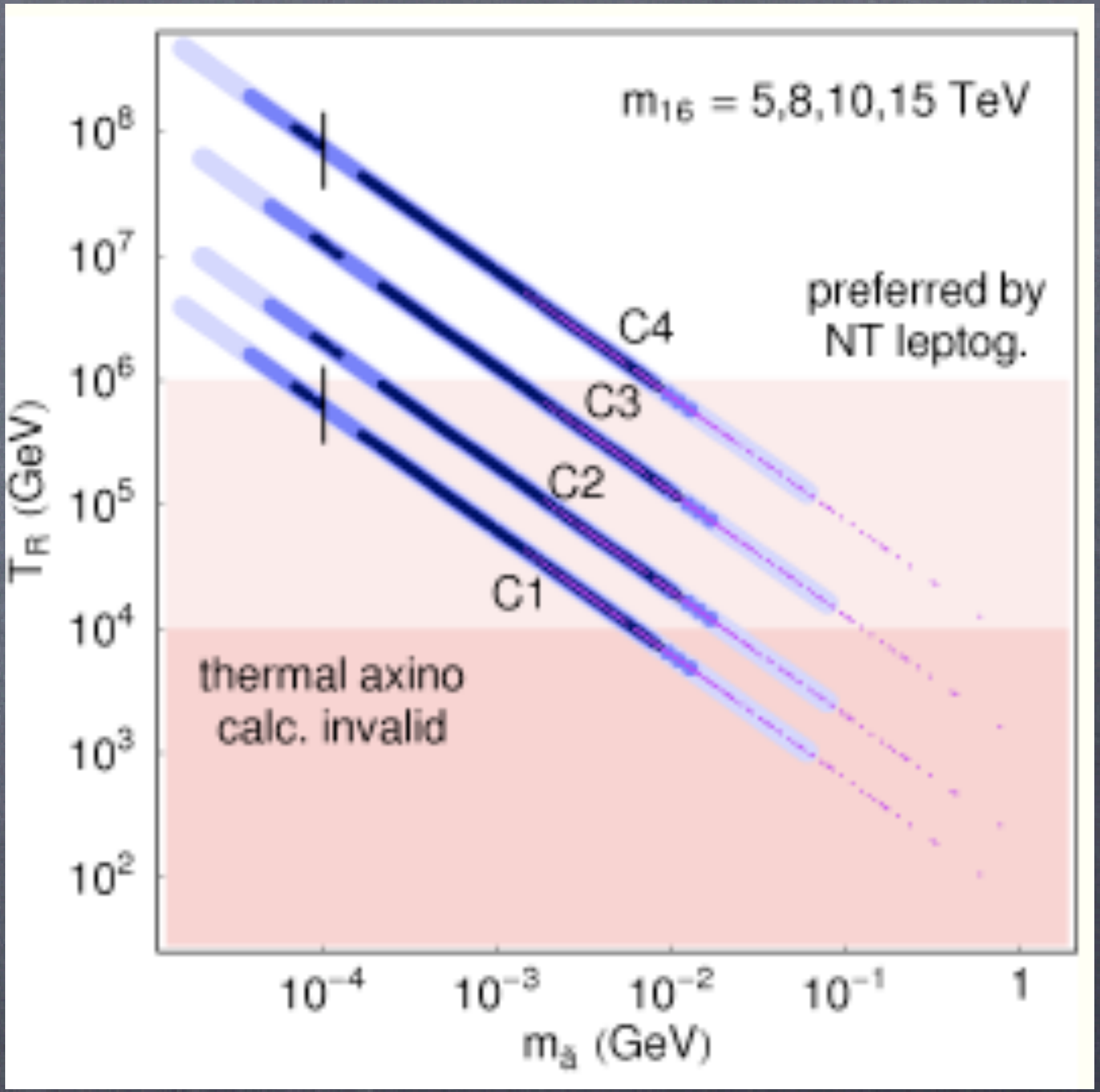
★ Four cases:

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

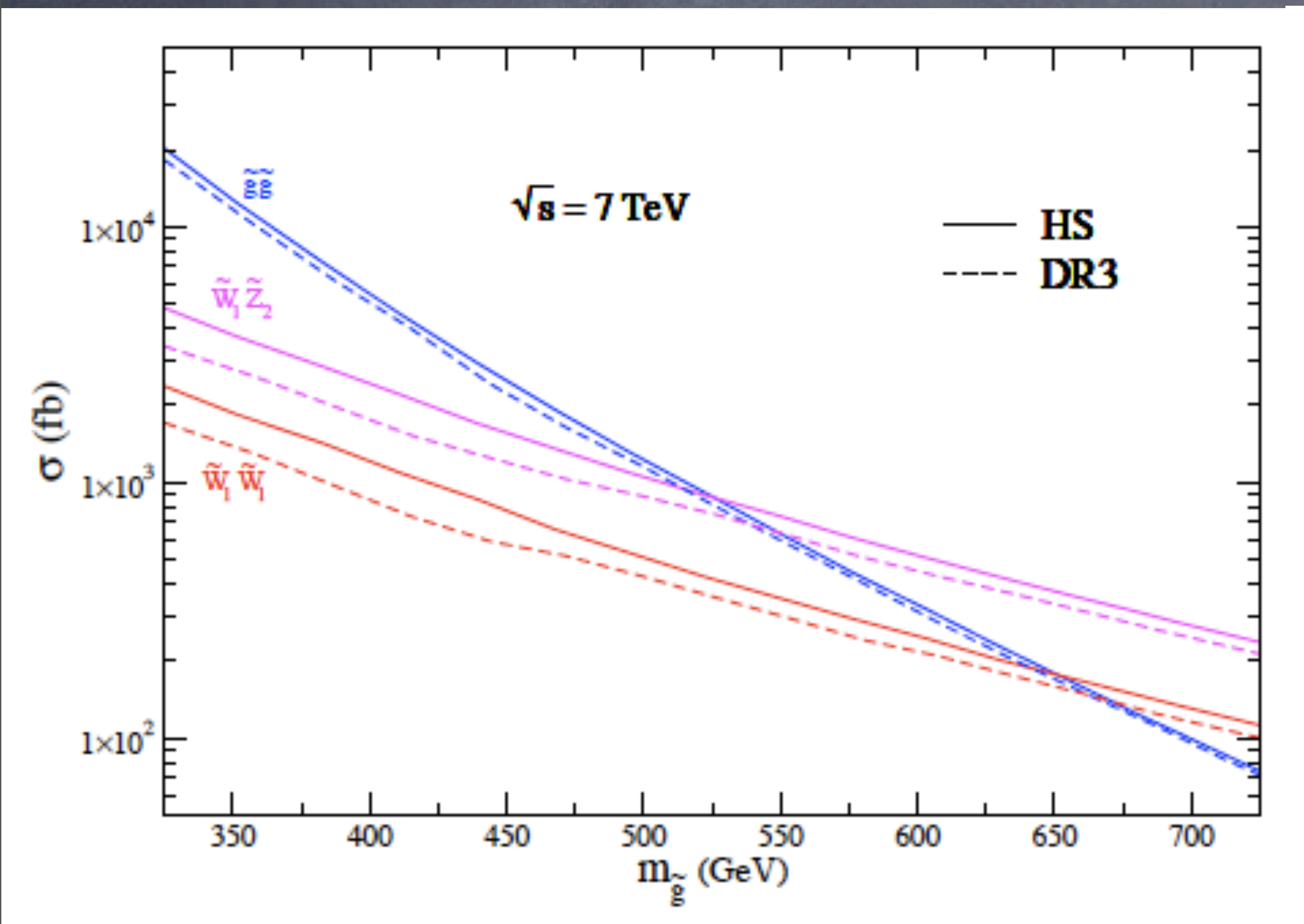


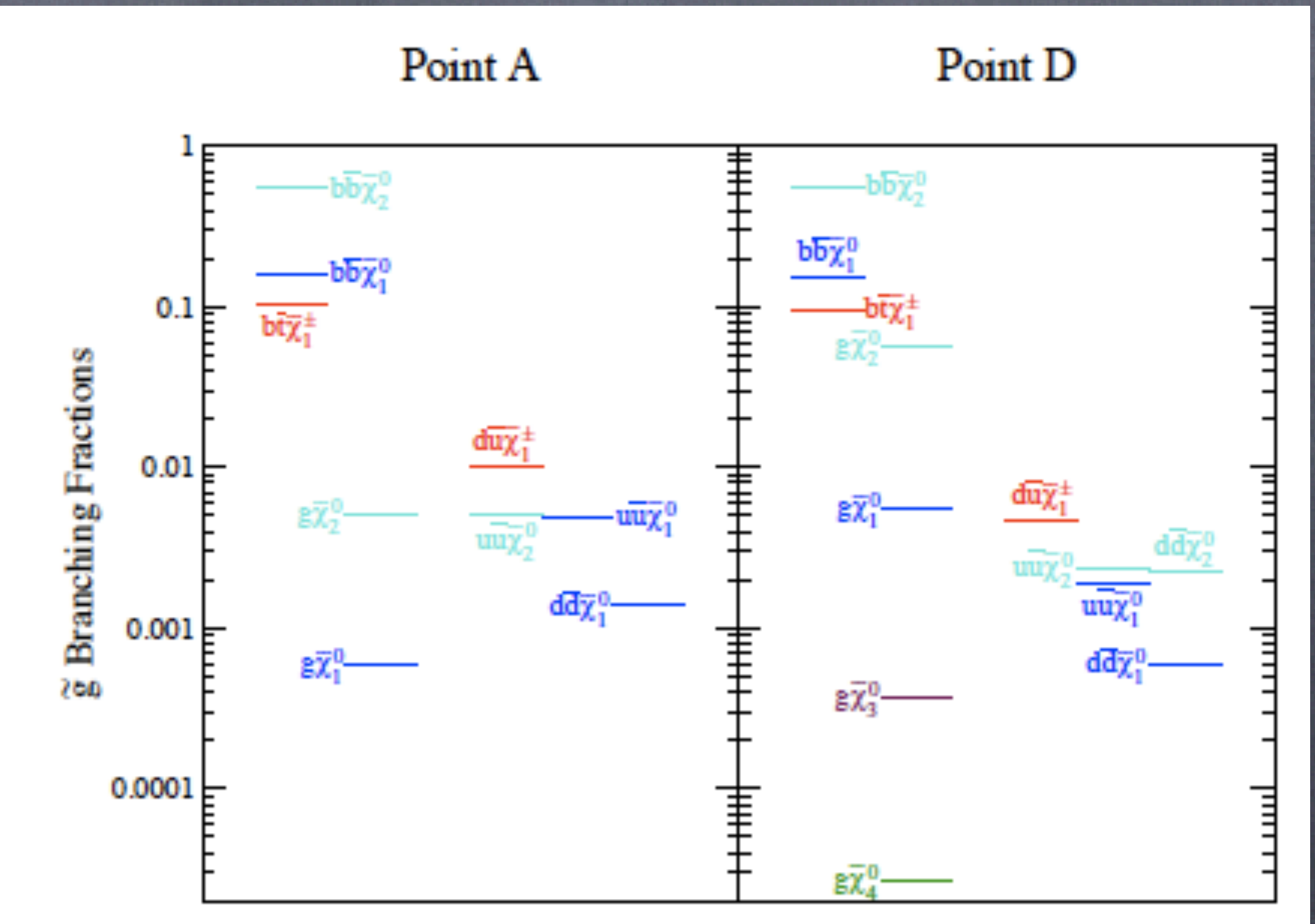
2. solutions C2, C3 with dominant axion CDM
3. solution C4 has accidental vacuum alignment and dominant TP axino CDM
4. Solutions with m16>8 TeV have TR>10^6 GeV

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

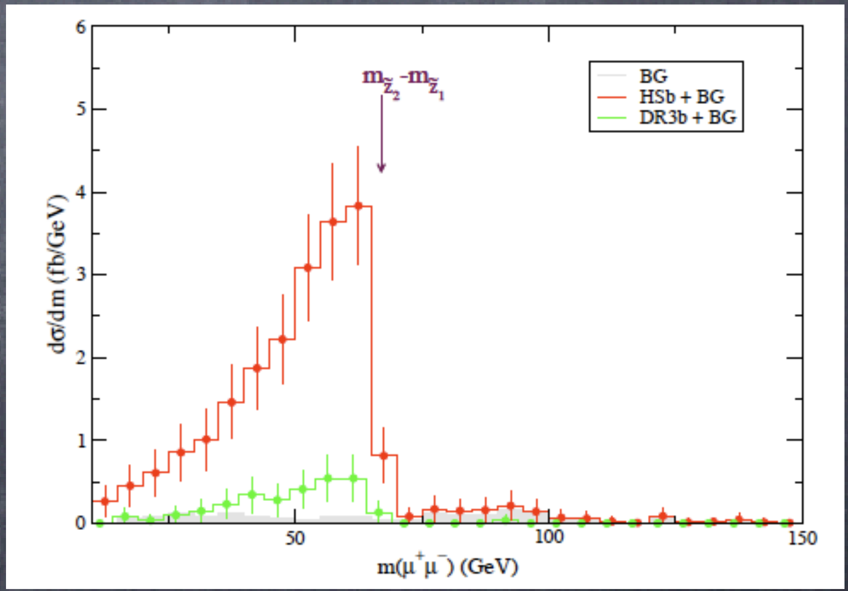




HB, Kraml, Sekmen, Summy: JHEP 0810 (2008) 079

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:

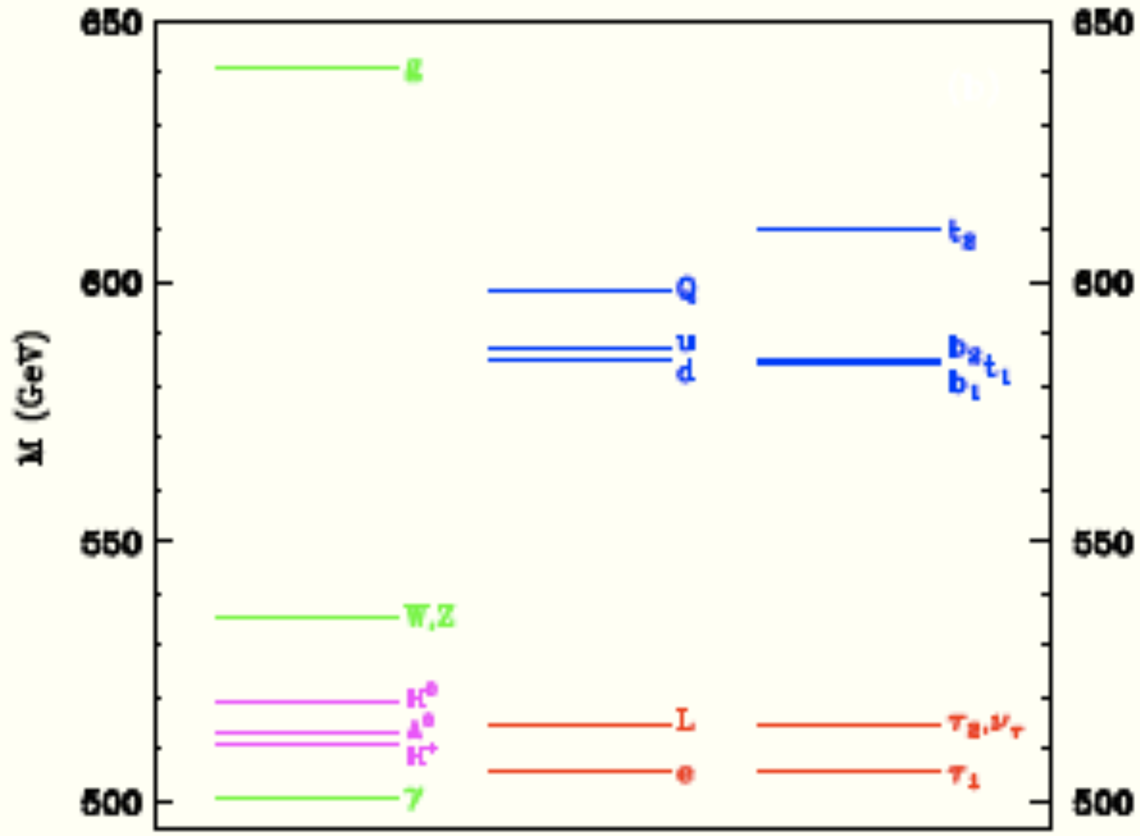
- Role of LHC: produce matter states associated with dark matter; decay to stable DM candidate (LHT, UED, SUSY, etc) usually gives ETMISS signature (charged stable NLSP counter-example)
- In case of WIMP dark matter, additional signals from DD/ID of DM will provide complementary information (e.g. WIMP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

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_μ 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: $Q^1,\ u^1, d^1,\ L^1,\ e^1,\ W^{1\pm},\ Z^1,\ g^1,\ B^1,\ H^0,\ A^0,\ H^\pm$

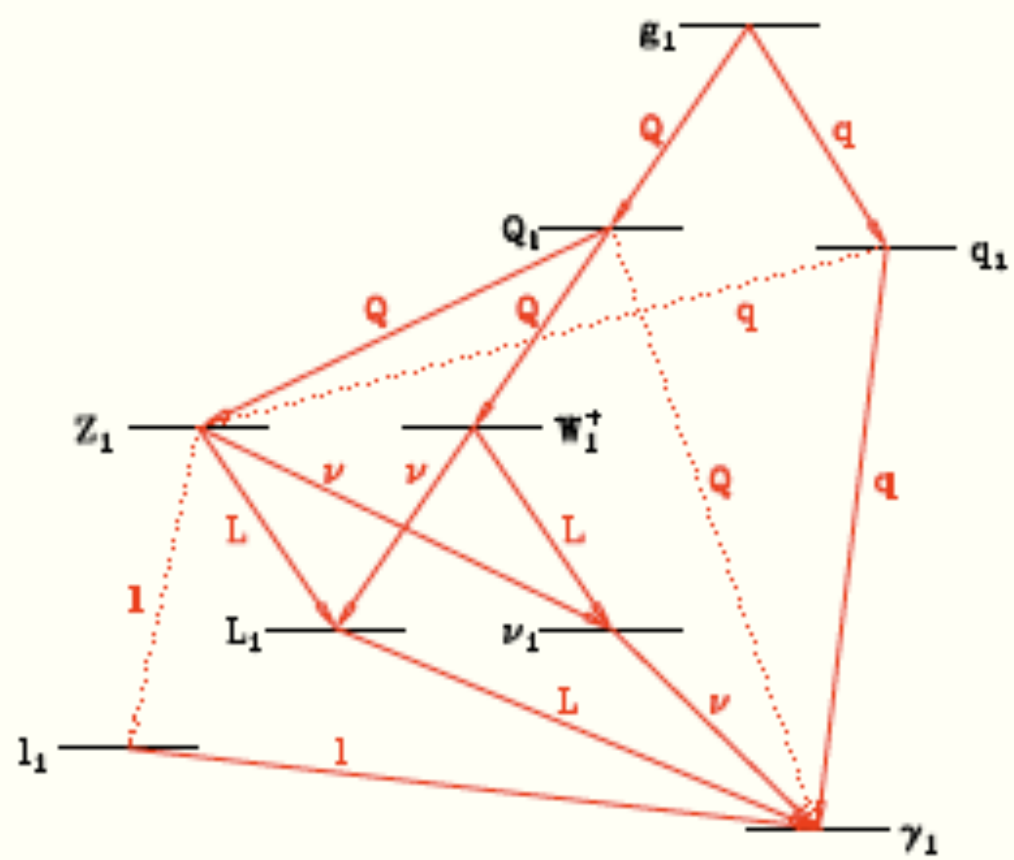
Spectra of UED theories

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



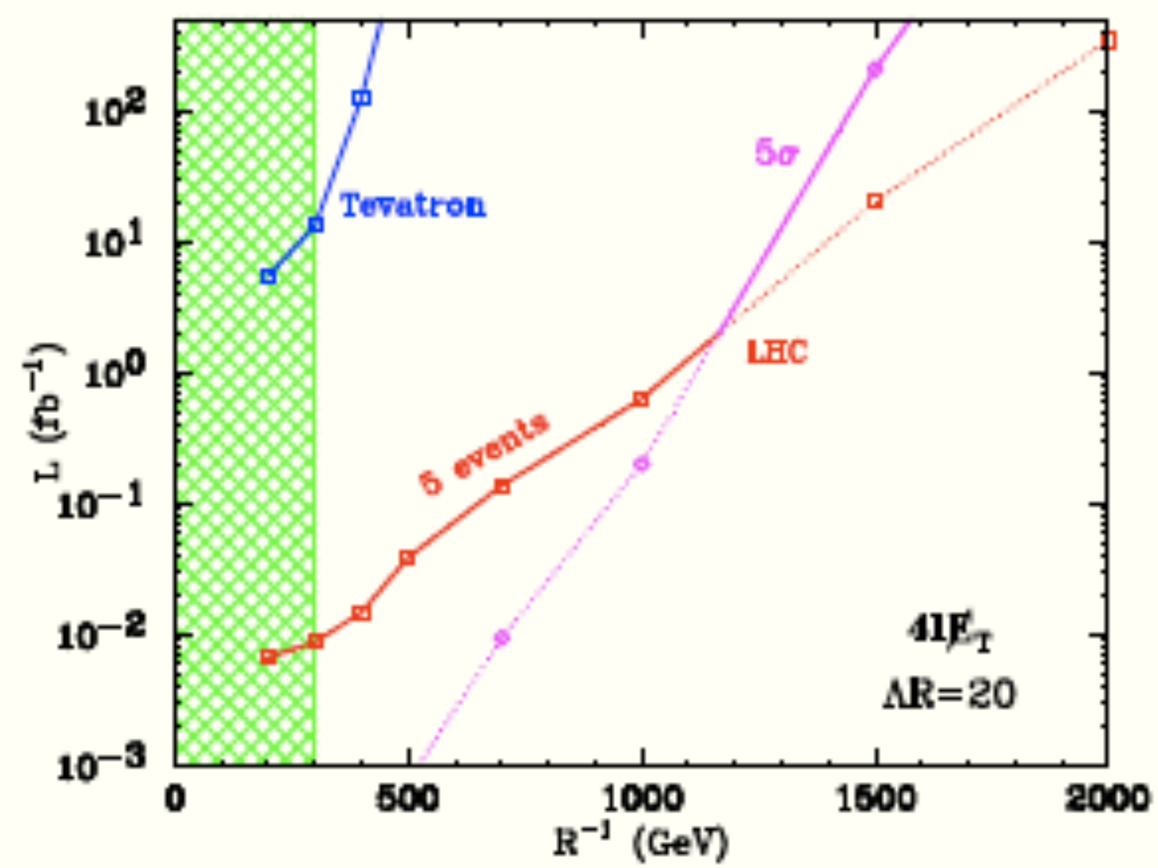
Cascade decays in UED theories

- decay modes (CMS)



LHC reach for UED in 4l +ETMISS channel

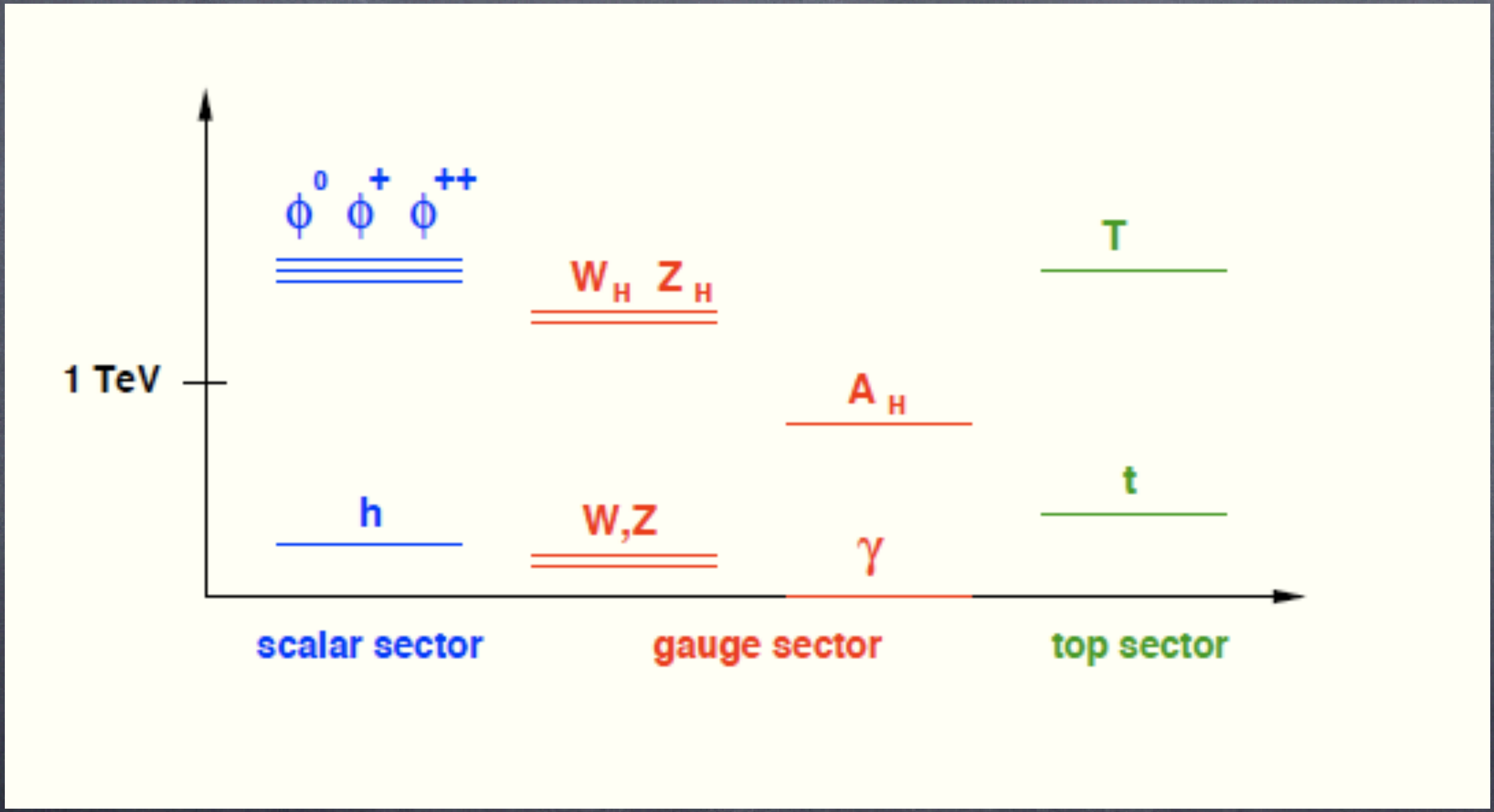
- $pp \to Z_1 Z_1 \to L_1 \bar{\ell} L_1 \bar{\ell} \to 4\ell + \not{E}_T$, etc.



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 $\Rightarrow$ 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 $SU(5)/SO(5)$

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 fb^{-1} at LHC