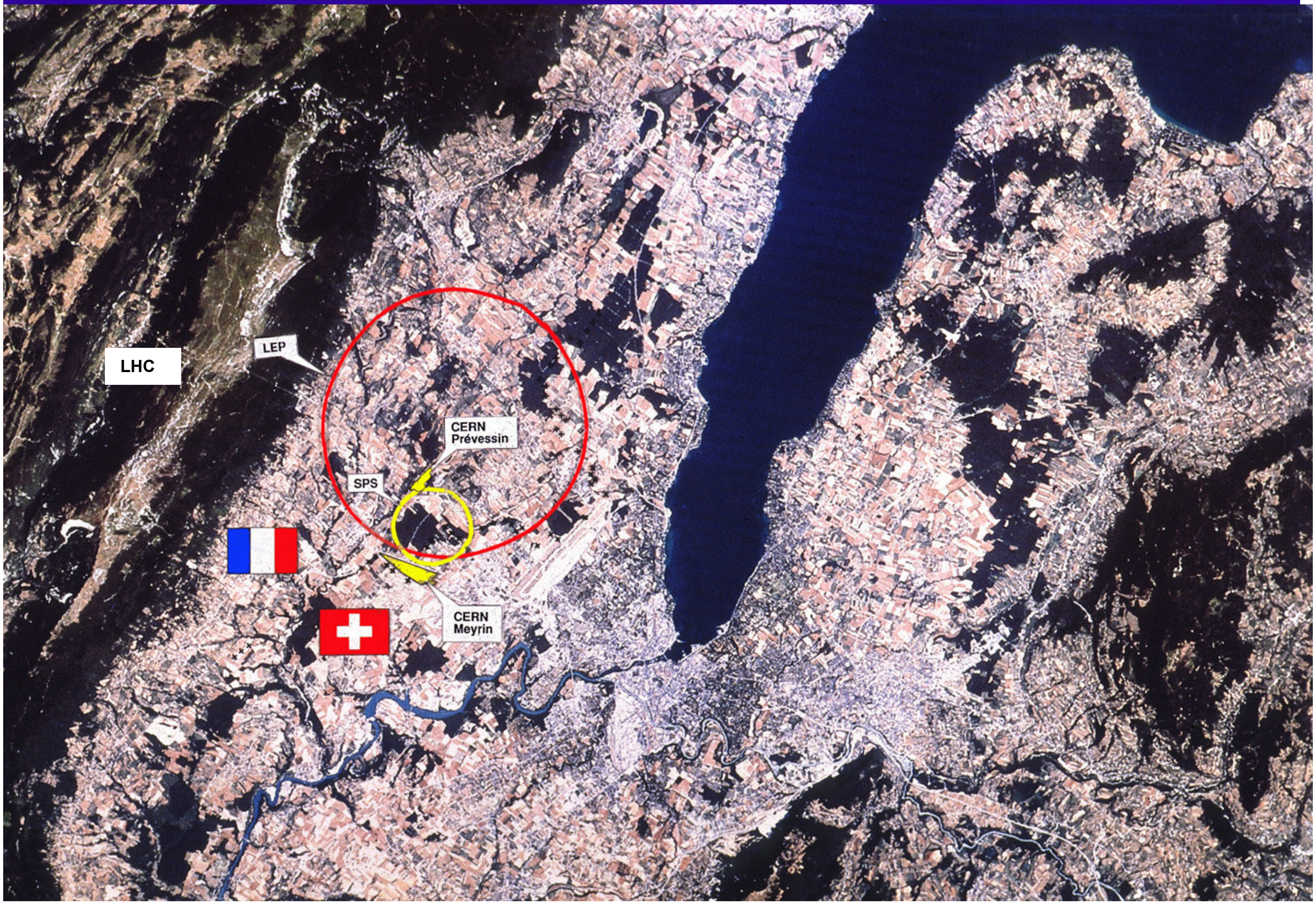
Dark Matter
Experiments and Searches

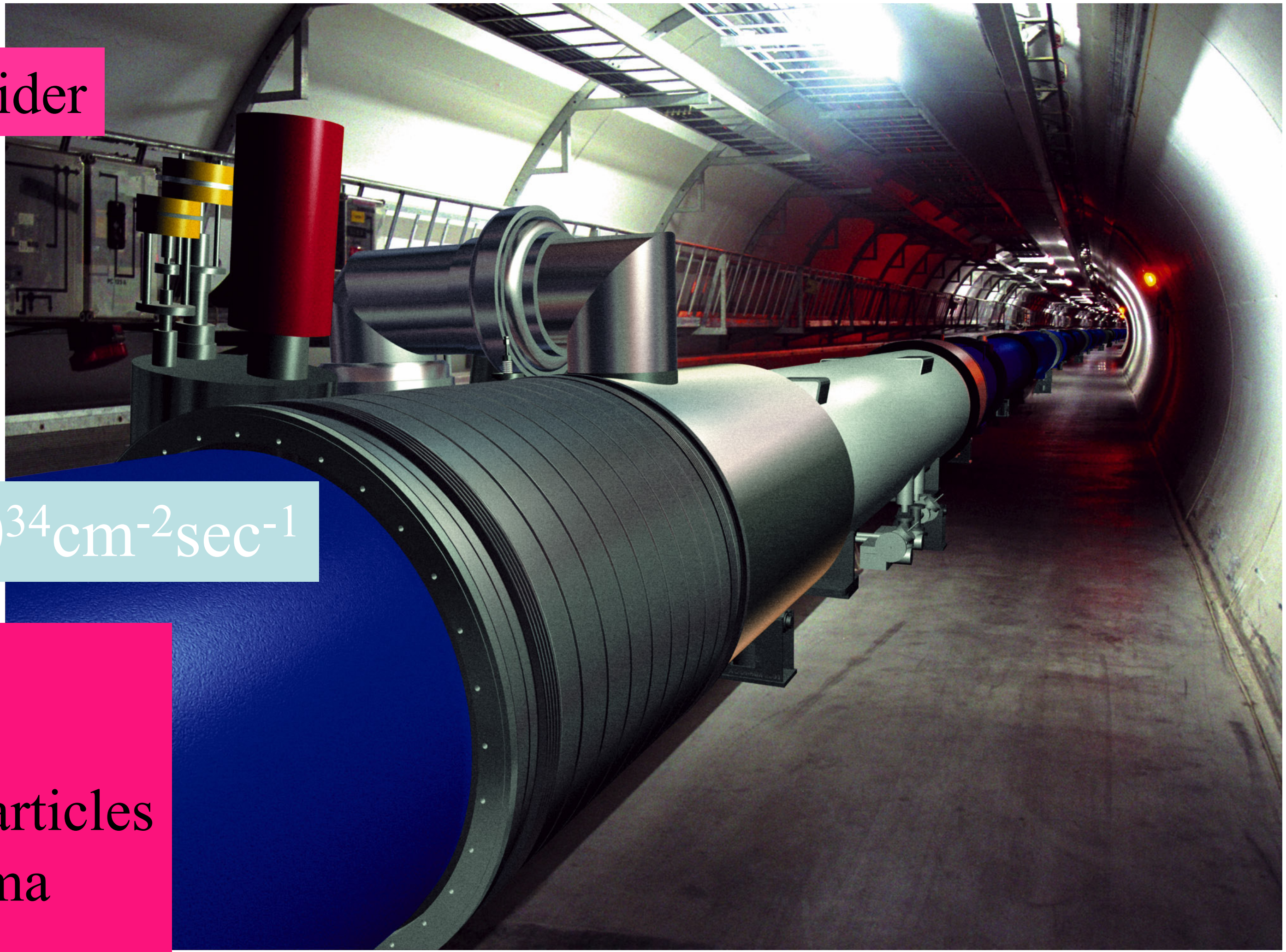
R.J.Cashmore
Principal Brasenose College,Oxford
and
Dept of Physics,Oxford

Dark Matter at LHC

Satellite view of Geneva and CERN site



The **L**arge **H**adron **C**ollider in the LEP Tunnel



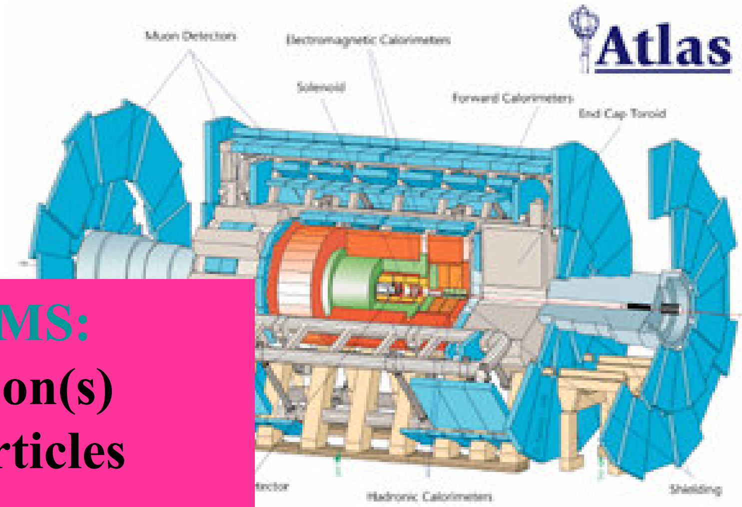
Proton- Proton Collider

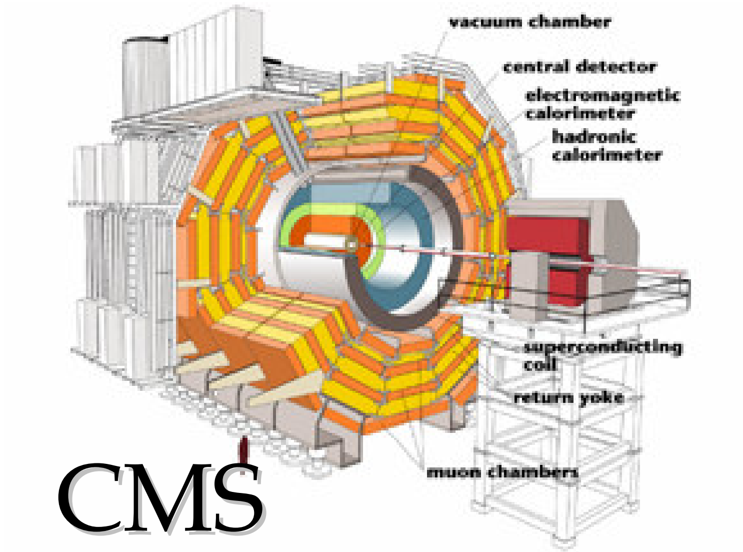
7 TeV + 7 TeV

Luminosity = $10^{34} cm^{-2} sec^{-1}$

The Physics:
- Higgs boson (s)
- Supersymmetric Particles
- Quark-Gluon Plasma
- CP violation in B

LHC Experiments

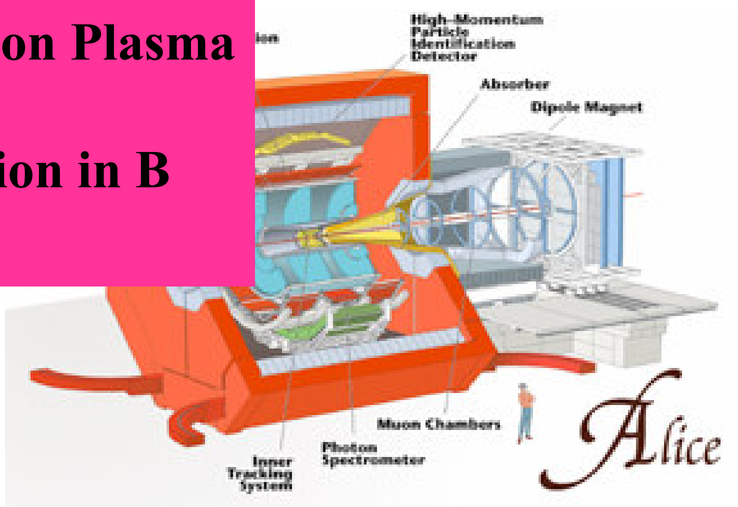


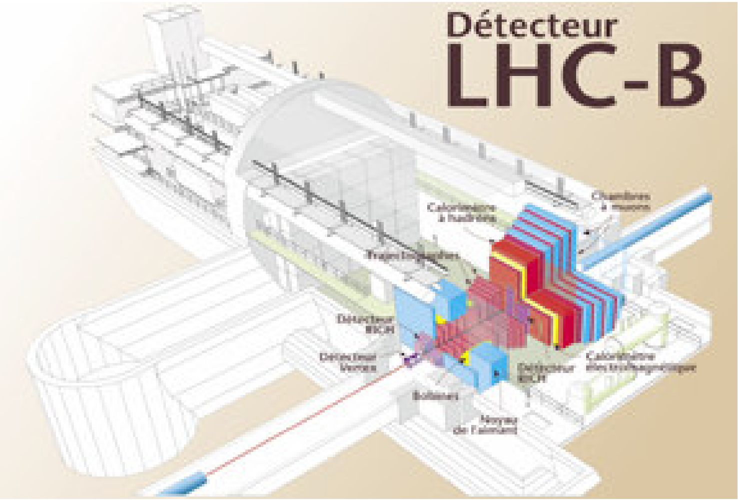


ATLAS, CMS:
- Higgs boson(s)
- SUSY particles
- …??

ALICE:
Quark Gluon Plasma

LHC-B:
- CP violation in B





Weakly Interacting Massive Particles

- The lightest of these new particles is an ideal candidate for dark matter
- Would have been created in the Big Bang
- A ***natural*** solution – makes it extremely attractive!

Now we need to detect these particles!

Particle type	Particle	Super partner
Fermion	Quark	Squark
	Neutrino	Sneutrino
	Electron	Selectron
	Muon	Smuon
	Tau	Stau
Boson	W	Wino
	Z	Zino
	Photon	Photino
	Gluon	Gluino
	Higgs	Higgsino

SUSY - sparticles

SUSYMSSM and mSUGRA parameter space
cross sections
decay BRs
SUSY event topology and mass reach
sparticle reconstruction
SUSY DM particles

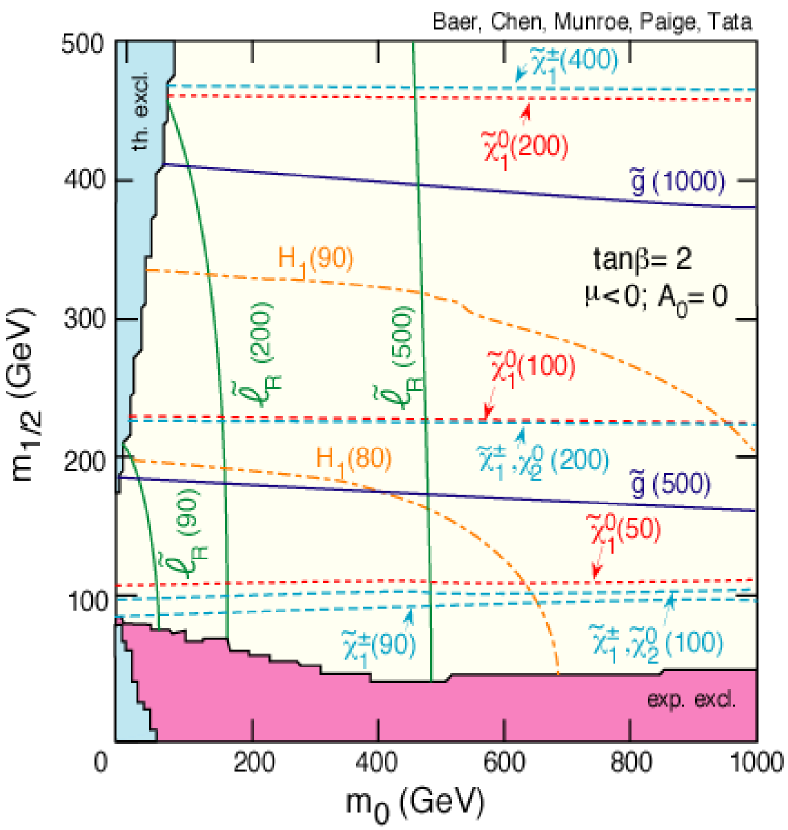
MSSM

- Two mass parameters: m_0, $m_{1/2}$, one sign: μ
- Region in parameter space restricted by
  - non-observation of SUSY signal at LEP and Tevatron
  - Cosmological parameters reflecting cold dark mass properties
- Two Higgs doublets, physical scalar bosons:
  - Neutral: h, H, A (m_A and $\tan\beta$ can be used as independent parameters)
  - Charged: $H^{\pm}$
- SUSY partners of known particles:
  - spin 0: squarks, sleptons,
  - spin 1/2: gluinos, gauginos, Higgsino
- R-parity conservations: decay chains contain several neutral, invisible particles $\rightarrow$ missing energy .

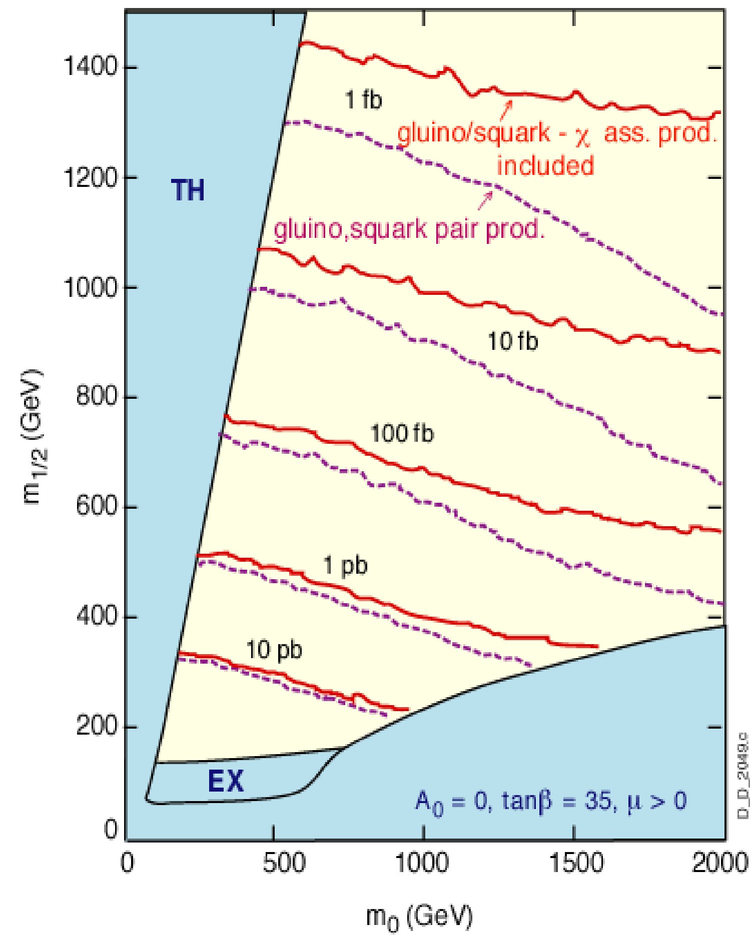
SUSY - parameter space, cross sections

Isomass contours in Minimal Supergravity, in m_0 vs $m_{1/2}$ plane

Parameters of theory: m_0, $m_{1/2}$, A_0, $tg\beta$, sign (μ)

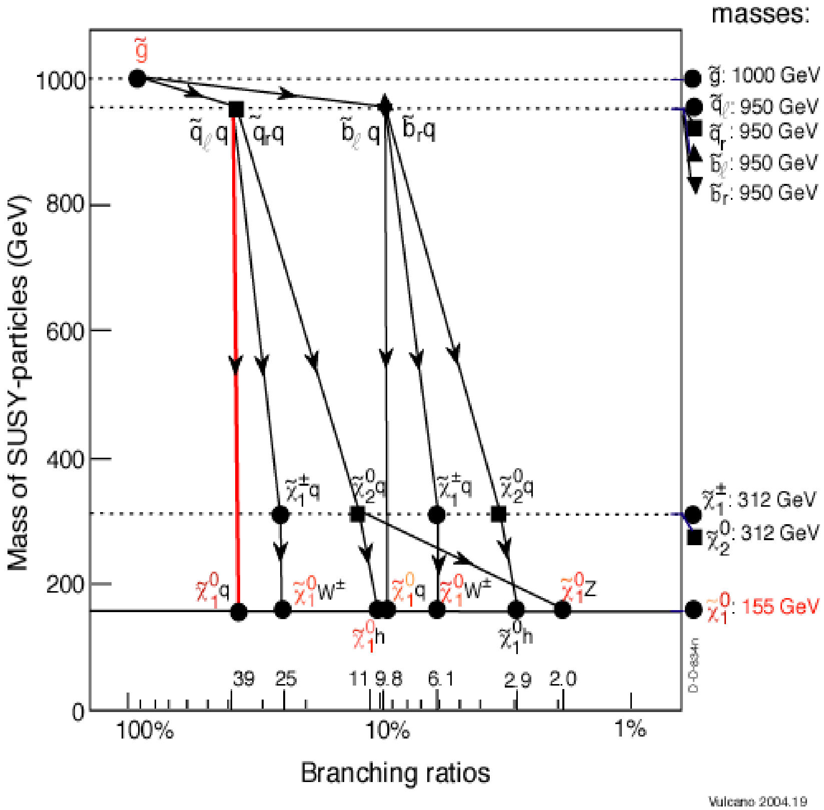


SUSY total cross sections (mSUGRA)

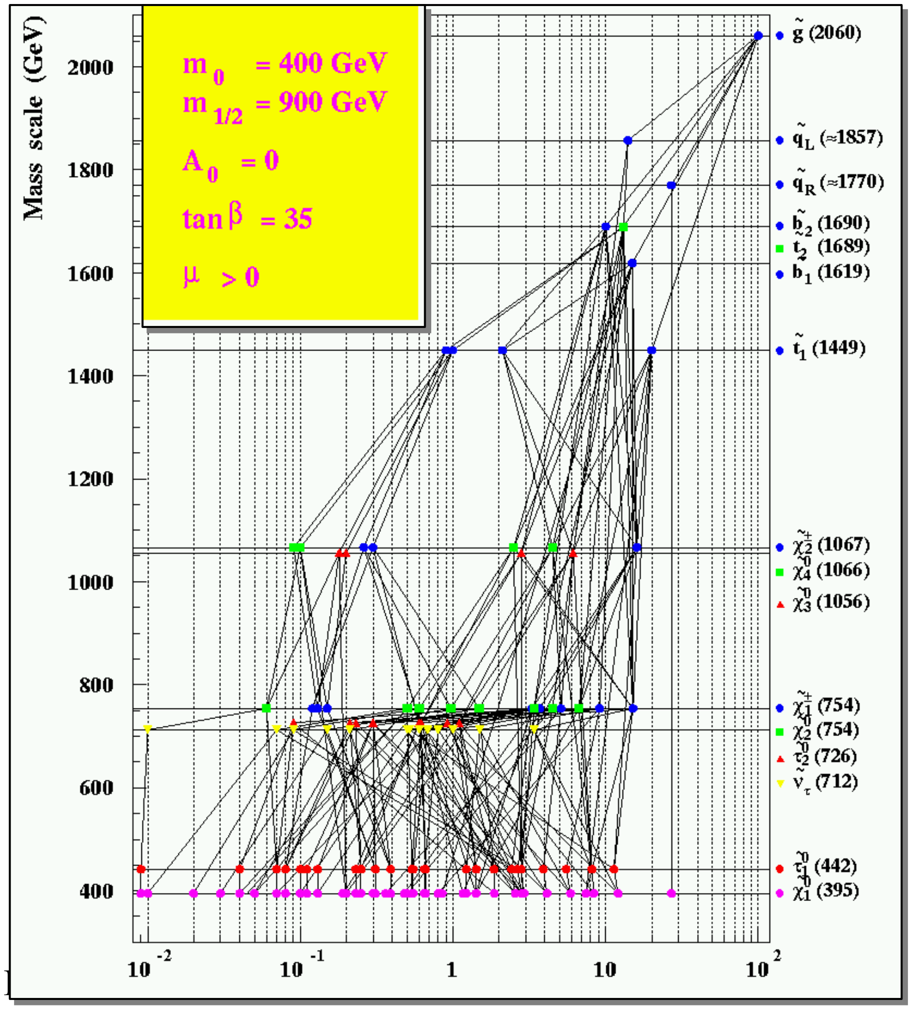


Gluino/squark decay chains

Decay chain for a light gluino or squark (MSSM)



Typical decay chain for a massive gluino or squar (mSUGRA)

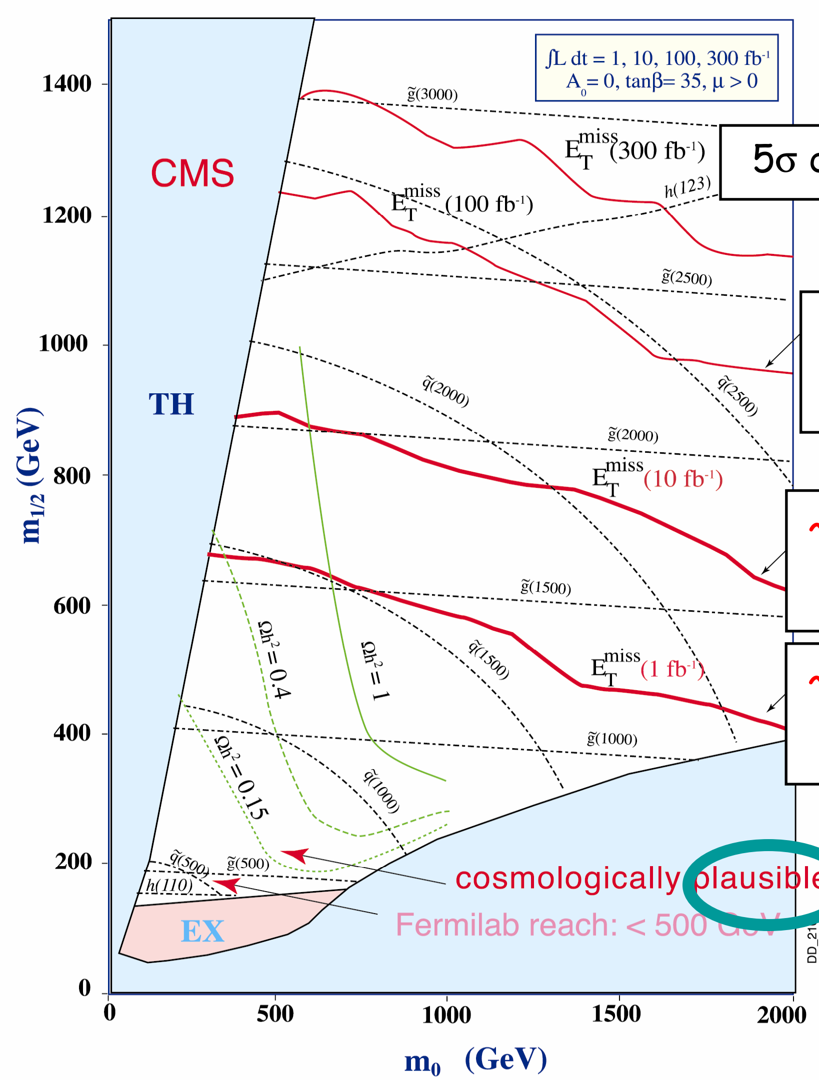


Vulcano 2004.6

SUPERSYMMETRY

Large $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ cross-section $\rightarrow \approx$ 100 events/day at 10^{33} for:

$m(\tilde{q}, \tilde{g}) \sim 1$ TeV



5σ discovery curves

Reach of Multijet + E_T^{miss} searches (most powerful and model-independent signature if R-parity conserved)

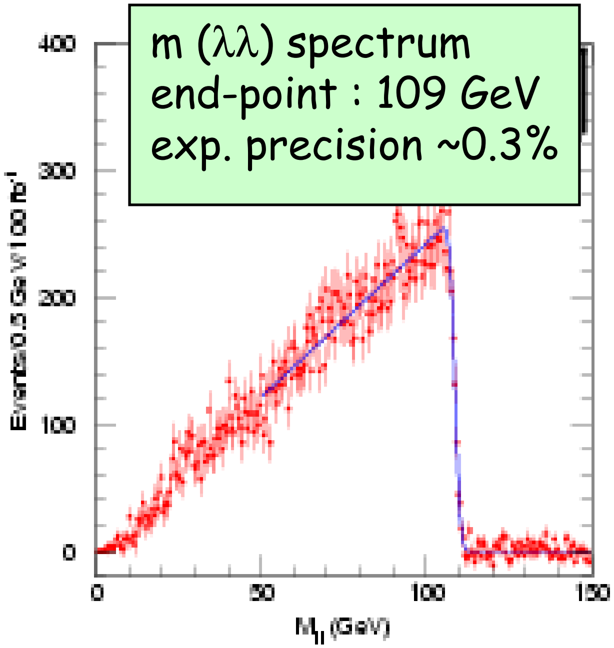
~ one year at 10^{34}: up to 2.8 TeV

~ one year at 10^{33} : up to 2.3 TeV

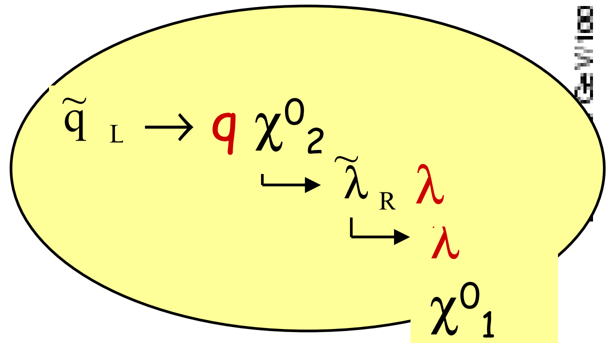
~ one month at 10^{33} : up to 2 TeV

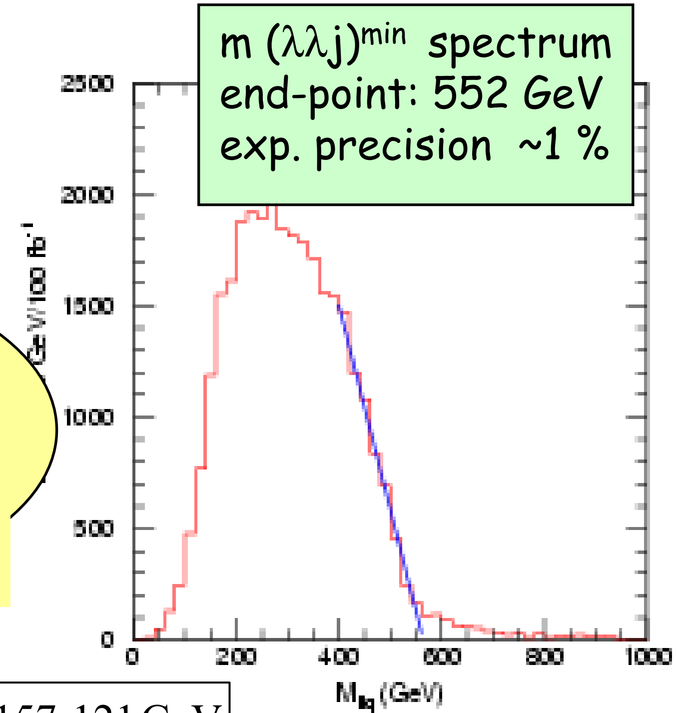
→ **SUSY could be found quickly**

… "plausible"= typical

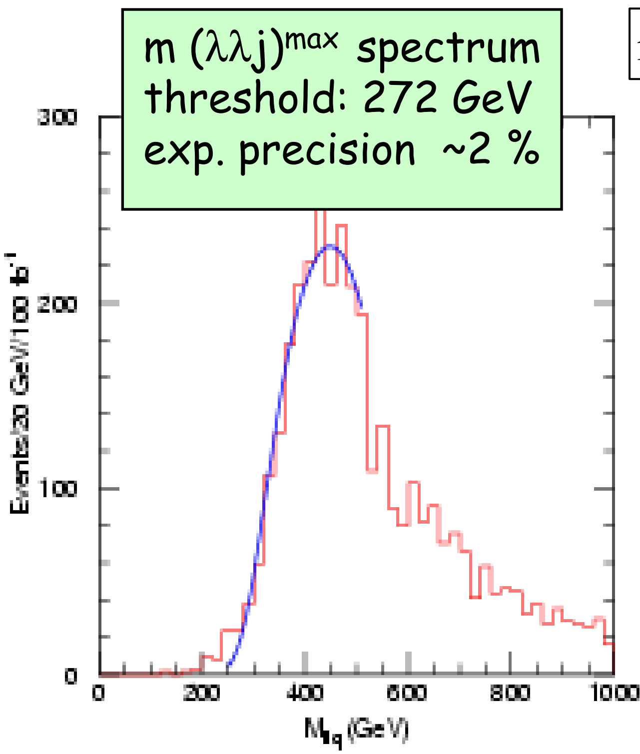


Example of
a typical chain:

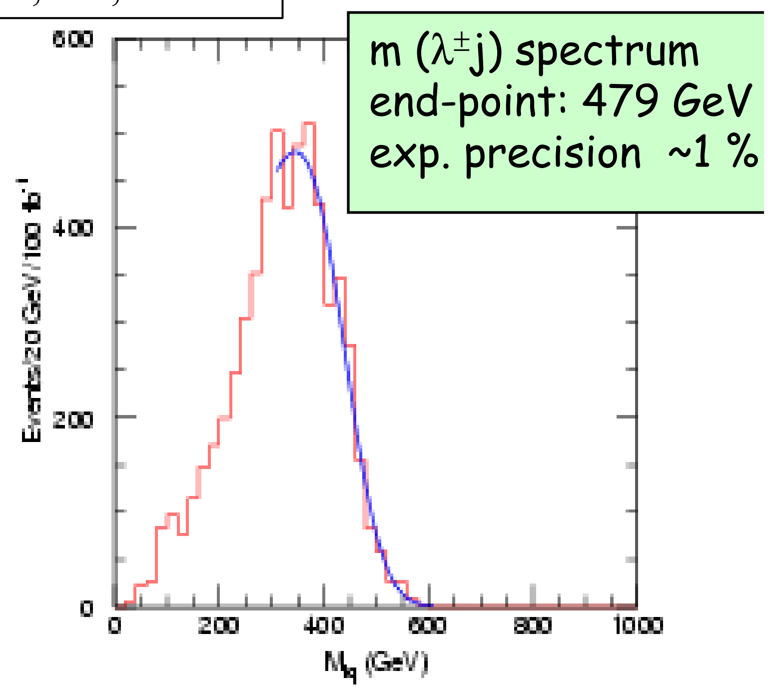


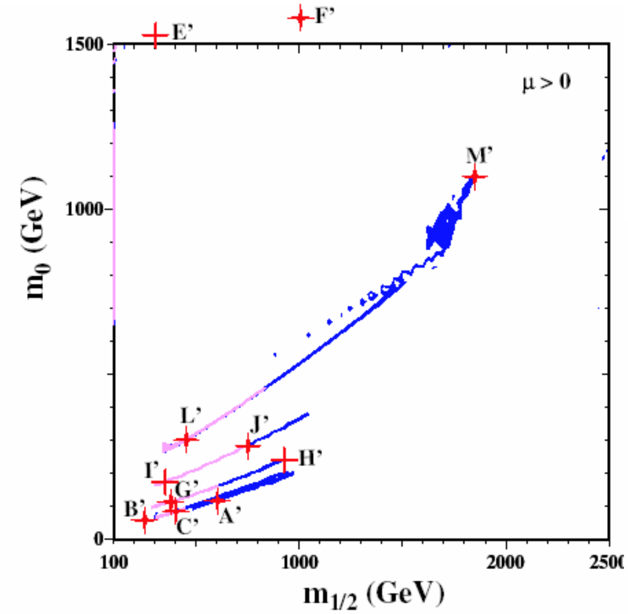


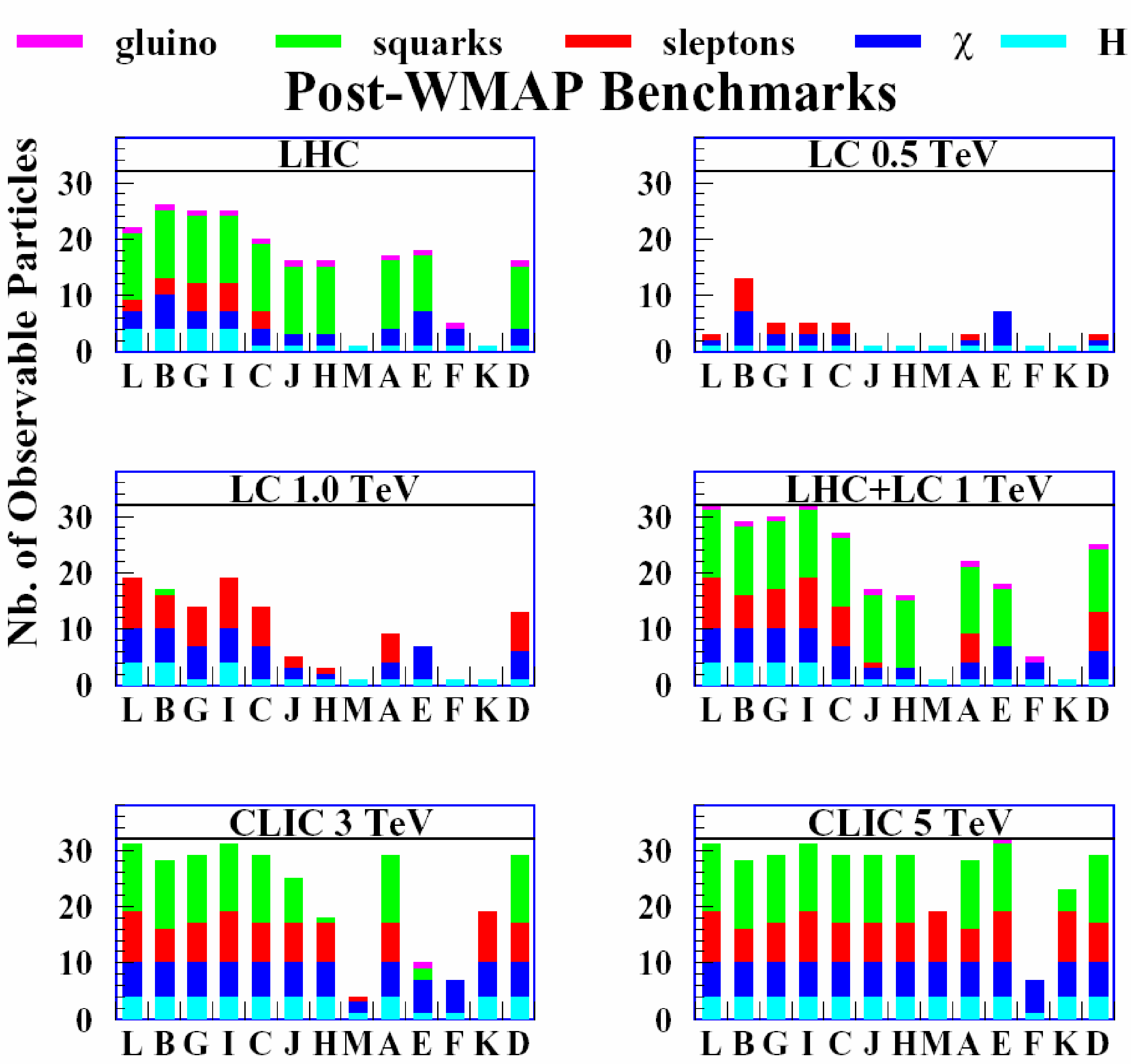
$$m(\tilde{q}_L, \chi^0_2, \tilde{\lambda}_R, \chi^0_1) = 690, 232, 157, 121\,\mathrm{GeV}$$



ATLAS
100 fb^{-1}
LHC Point 5







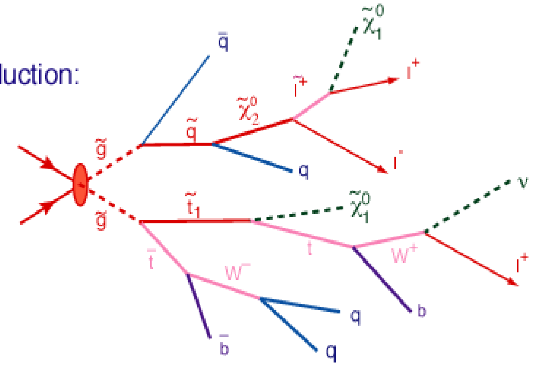
Benchmarking MSSMs restricted by Cosmological & Particle physics data

M. Battaglia et al.

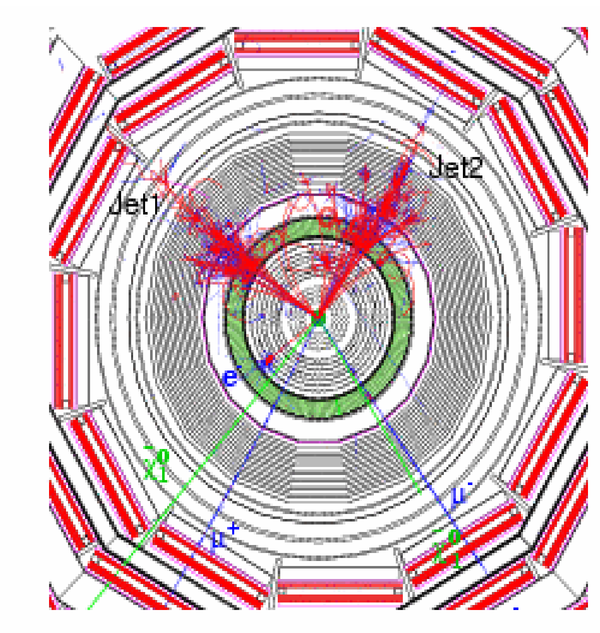
R.Cashmore

Squark and gluino searches, reach in various topologies

- Production:



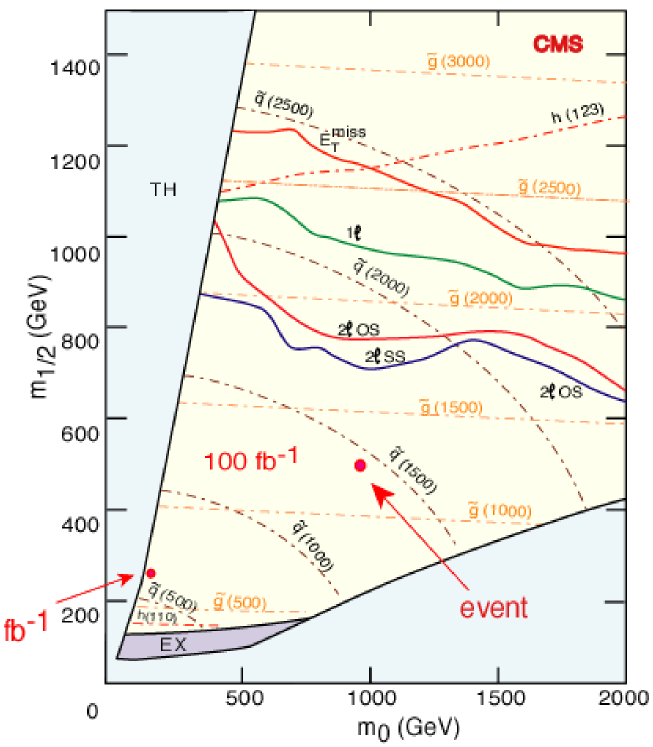
- More generally $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production leads to: lepton(s) + E_T^{miss} + jets final states
- Backgrounds: W + jets, Z+jets, $t\bar{t}$, Wtb, WW, WZ..



Explorable domain of m_0, $m_{1/2}$ parameter space in $\tilde{q}$, $\tilde{g}$ seaches in n leptons + E_t^{miss} + $\geq$ 2 jets

m SUGRA, $A_0 = 0$, tan β = 35, $\mu >$ 0

5 σ contours ; non - isolated muons

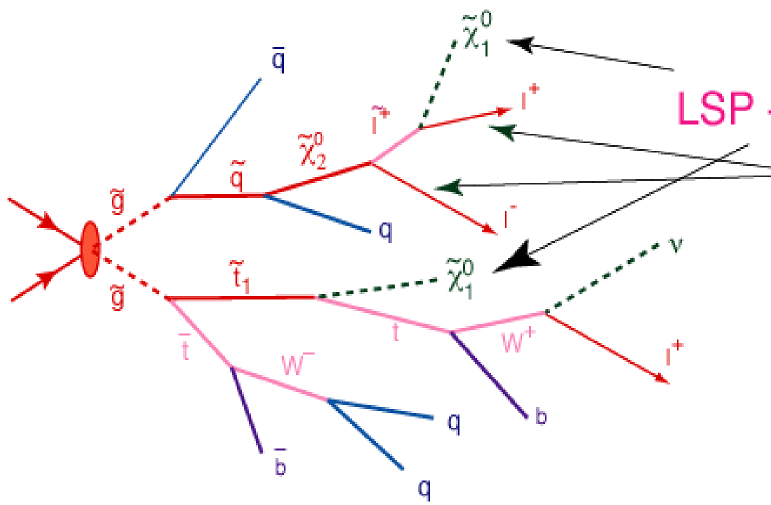


investigate sparticle reconstruction for 10 fb^{-1} (but tanβ = 10)

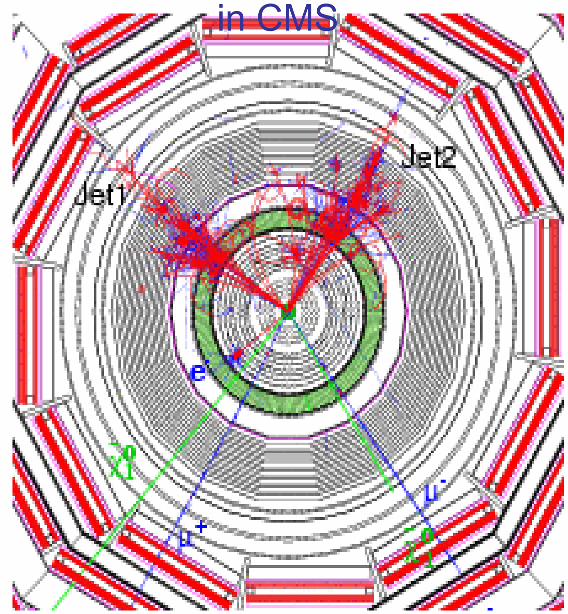
- Jets + E_t^{miss} has highest reach
- opposite-sign two-leptons are most usefull for sparticle reconstruction

Sparticle reconstruction

Gluino/squark production event topology
allowing sparticle mass reconstruction



Jets+leptons+neutralin
os
in CMS

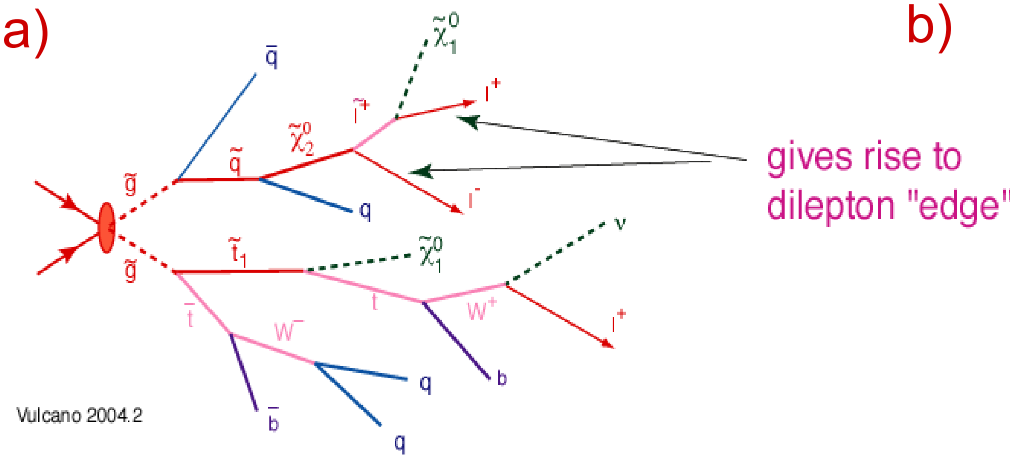


Such cascade decays allow to reconstruct sleptons, neutralinos, squarks, gluinos...in favorable cases with %level mass resolutions

Starting point of reconstruction is the "dilepton edge" due to the neutralino-2 decays to dileptons + neutralino-1;
neutralino-2 decay to neutralino-1 + h($\rightarrow$ bb) can be used too

Dilepton edges, sparticle reconstruction

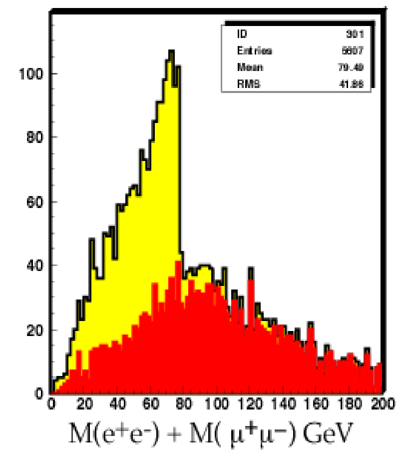
a)



Starting point of reconstruction is the "dilepton edge" due to the neutralino-2 decays to dileptons + neutralino-1

b) …m inclusive isolated dileptons + E_t^{miss} search

- $\tilde{q},\tilde{g} \rightarrow \tilde{\chi}_2^0 + X$ with large BR
- $\tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$ has significant BR



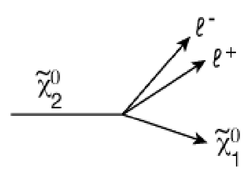
Dilepton edge

$E_t^{miss} > 100$ GeV

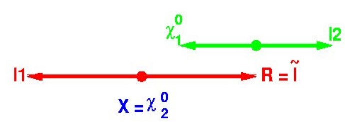
SUSY point B
$m_{1/2} = 250$ GeV,
$m_0 = 100$ GeV,
$\tan\beta = 10,\ \mu > 0$

c)

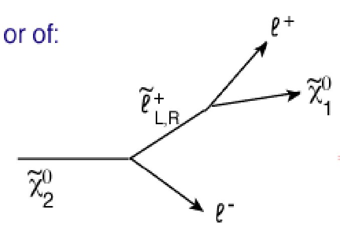
use kinematics of:



$\rightarrow$ $M_{\ell\ell}^{max} = m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$



or of:



$\rightarrow$ $M_{\ell\ell}^{max} = m(\tilde{\chi}_2^0)\sqrt{1-\frac{m^2(\tilde{\ell})}{m^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{m^2(\tilde{\chi}_1^0)}{m^2(\tilde{\ell})}}$

d)

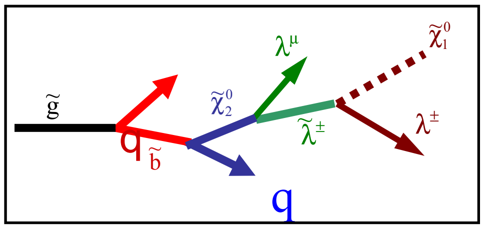
on the edge of $\tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$:

$\vec{P}_{\tilde{\chi}_2^0} = (1 + M_{\tilde{\chi}_1^0} / M_{\ell^+\ell^-})\ \vec{P}_{\ell^+\ell^-}$ in lab. frame

$\rightarrow$ reconstruct $\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q$ decay combining $\tilde{\chi}_2^0$ with q-jet and get $m(\tilde{q})$, assuming $m(\tilde{\chi}_1^0) = 0.5\, m(\tilde{\chi}_2^0)$ (for ex.)

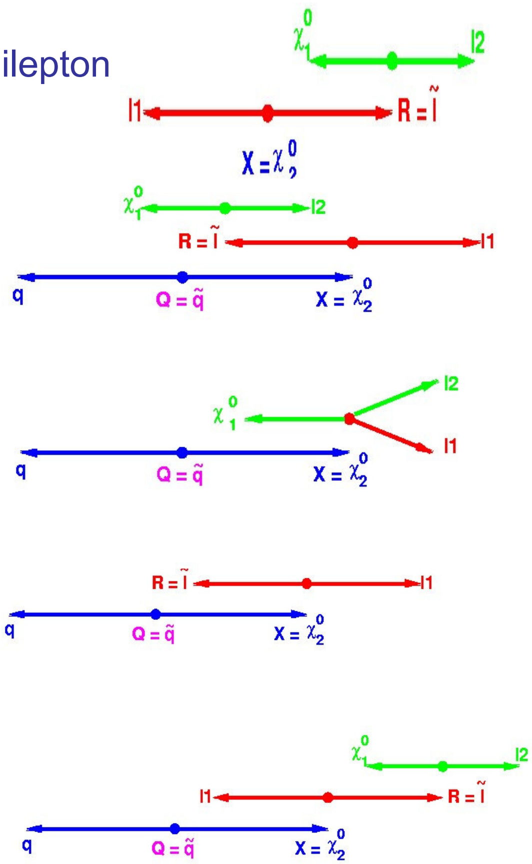
Sparticle reconstruction, end-points

In a long cascade of decays a number of particular kinematical configurations generate end-points depending on sparticle masses, fitting these end points allows to constrain or determine these masses



for ex.:
largest dilepton

mass:



$$M^{\max}_{\lambda\lambda} = \frac{\sqrt{\left(m^2_{\chi^0_2} - m^2_{\tilde{\lambda}}\right)\left(m^2_{\tilde{\lambda}} - m^2_{\chi^0_1}\right)}}{m_{\tilde{\lambda}}}$$

$$M^{\max}_{\lambda\lambda q} = \frac{\sqrt{\left(m^2_{\chi^0_2} - m^2_{\chi^0_1}\right)\left(m^2_{\tilde{q}} - m^2_{\chi^0_2}\right)}}{m_{\chi^0_2}}$$

$$M^{\max}_{\lambda\lambda q} = m_{\tilde{q}} - m_{\chi^0_1} \quad \text{if} \quad m^2_{\chi^0_2} > m_{\tilde{q}} m_{\chi^0_1}$$

$$M^{\max}_{\lambda_1 q} = \frac{\sqrt{\left(m^2_{\chi^0_2} - m^2_{\tilde{\lambda}}\right)\left(m^2_{\tilde{q}} - m^2_{\chi^0_2}\right)}}{m_{\chi^0_2}}$$

$$M^{\max}_{\lambda_2 q} = \frac{\sqrt{\left(m^2_{\tilde{\lambda}} - m^2_{\chi^0_1}\right)\left(m^2_{\tilde{q}} - m^2_{\chi^0_2}\right)}}{m_{\tilde{\lambda}}}$$

End-points depend on mass differences, thus strong correlations between masses;
A fit of mSUGRA predictions to the set of measured end-points can be performed, this yields model parameters and sparticle masses, neutralino mass and relic density, then check for consistency with terrestrial,CMB experiments…..

Sparticle reconstruction, full chain

Gluino and sbottom reconstruction

Post-LEP SUSY benchmark point B

($m_{1/2} = 250$ GeV, $m_0 = 100$ GeV, $\tan\beta = 10$, $\mu > 0$)

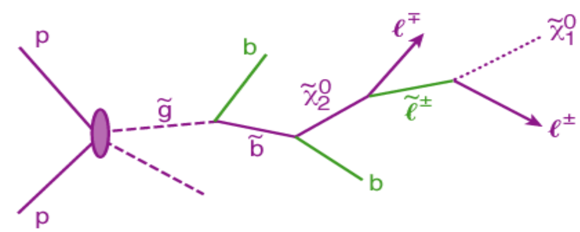
Decay chain and event topology:

$pp \to \tilde{g} \to \tilde{b}b$ (26%)

$\hookrightarrow \tilde{\chi}^0_2 b$ (35%)

$\hookrightarrow \tilde{\chi}^0_1 \ \ell^+\ell^-$ (0.2%)

$\hookrightarrow \tilde{\ell}^\pm\ell^\mp \to \tilde{\chi}^0_1 \ell^+\ell^-$ (60%)

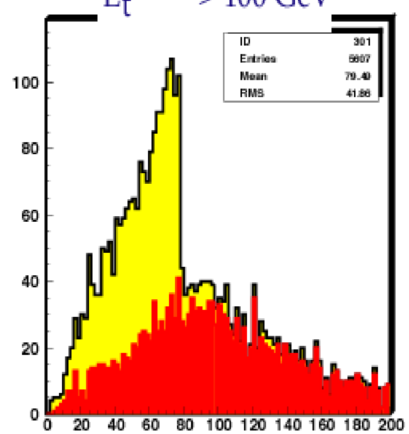


Event final state:

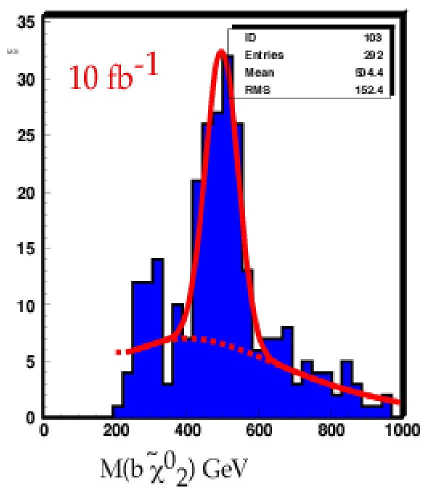
- $\geqslant$ 2 high p_t isolated leptons OS
- $\geqslant$ 2 high p_t b jets
- missing E_t

Dilepton edge

$E_t^{miss} > 100$ GeV



Sbottom reconstruction



fit:

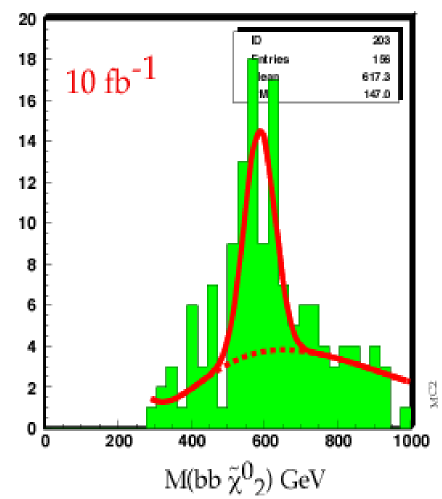
M(b $\tilde{\chi}^0_2$) GeV = 499 ± 7 GeV

σ = 48 GeV

generated: $M(\tilde{b}_L) = 496$ GeV

$M(\tilde{b}_R) = 524$ GeV

Gluino reconstruction



fit:

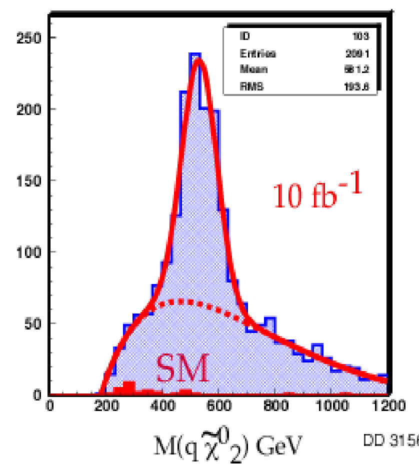
M(bb$\tilde{\chi}^0_2$) GeV = 587 ± 11 GeV

σ = 41GeV

generated mass: $M(\tilde{g}) = 595$ GeV

Squark reconstruction

anti-b-tag: σ < 2, b-veto



Vulcano 2004.10

fit:

M(q $\tilde{\chi}^0_2$) = 532 ± 4 GeV

σ = 62 GeV

$M(\tilde{d}_L) = M(\tilde{s}_L) = 543$ GeV

$M(\tilde{u}_L) = M(\tilde{c}_L) = 537$ GeV

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Sparticle reconstruction, full chain

Gluino and sbottom reconstruction

Post-LEP SUSY benchmark point B

$(m_{1/2} = 250\text{ GeV},\ m_0 = 100\text{ GeV},\ \tan\beta = 10,\ \mu > 0)$

Decay chain and event topology:

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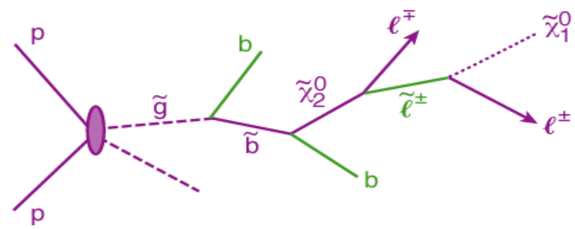
$\quad \hookrightarrow \tilde{\chi}^0_2 b$ (35%)

$\quad\quad \hookrightarrow \tilde{\chi}^0_1\ \ell^+\ell^-$ (0.2%)

$\quad\quad \hookrightarrow \tilde{\ell}^\pm\ell^\mp \rightarrow \tilde{\chi}^0_1\ell^+\ell^-$ (60%)



Event final state:

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- $\geqslant 2$ high p_t b jets
- missing E_t

Dilepton edge

$E_t^{miss} > 100$ GeV

fit:

$M(b\,\tilde{\chi}^0_2)$ GeV $= 499 \pm 7$ GeV
$\sigma = 48$ GeV

generated: $M(\tilde{b}_L) = 496$ GeV
$M(\tilde{b}_R) = 524$ GeV

fit:

$M(bb\tilde{\chi}^0_2)$ GeV $= 587 \pm 11$ GeV
$\sigma = 41$GeV

generated mass: $M(\tilde{g}) = 595$ GeV

fit:

$M(q\,\tilde{\chi}^0_2) = 532 \pm 4$ GeV
$\sigma = 62$ GeV

$M(\tilde{d}_L) = M(\tilde{s}_L) = 543$ GeV

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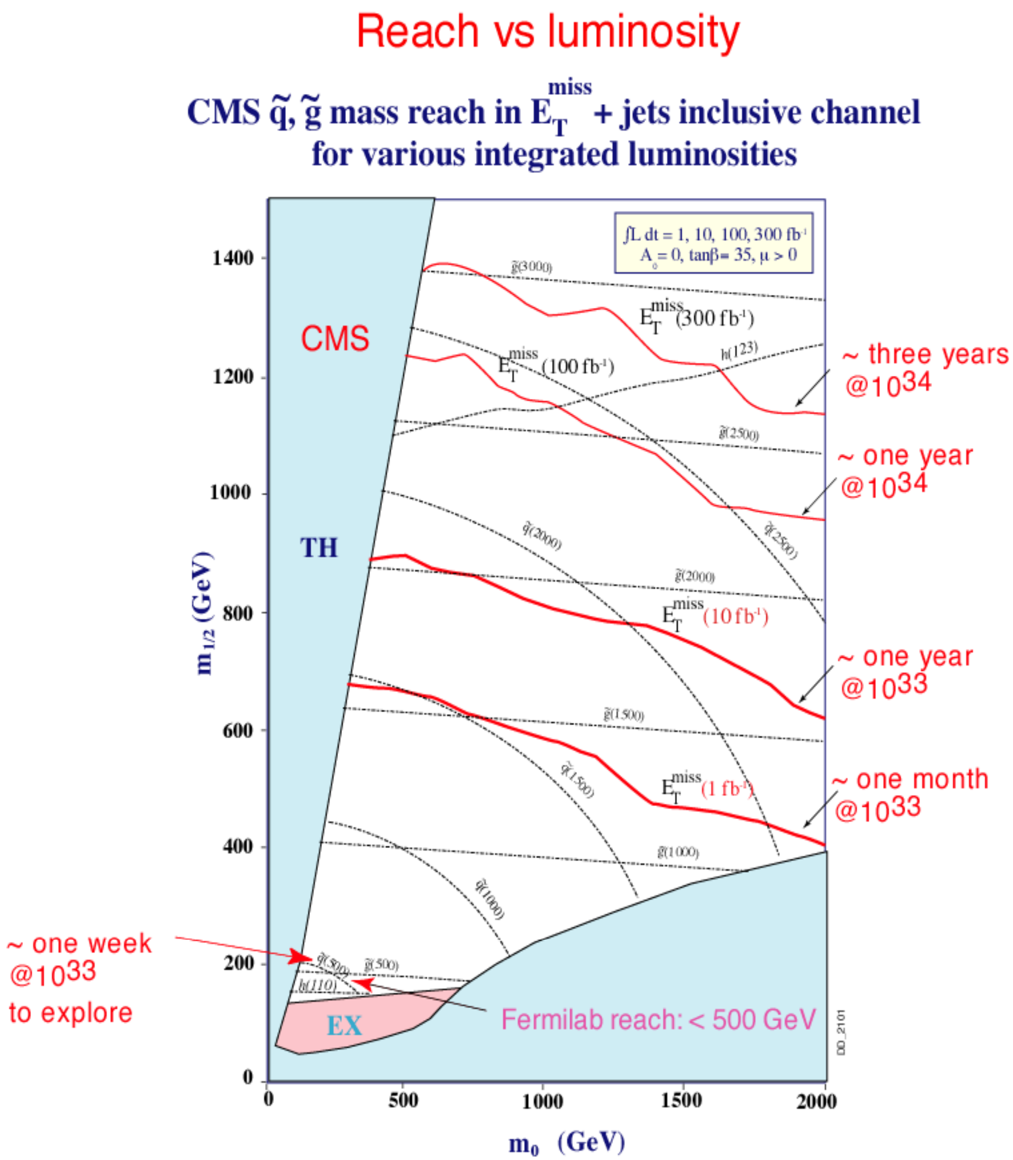
Squark/gluino mass reach vs luminosity

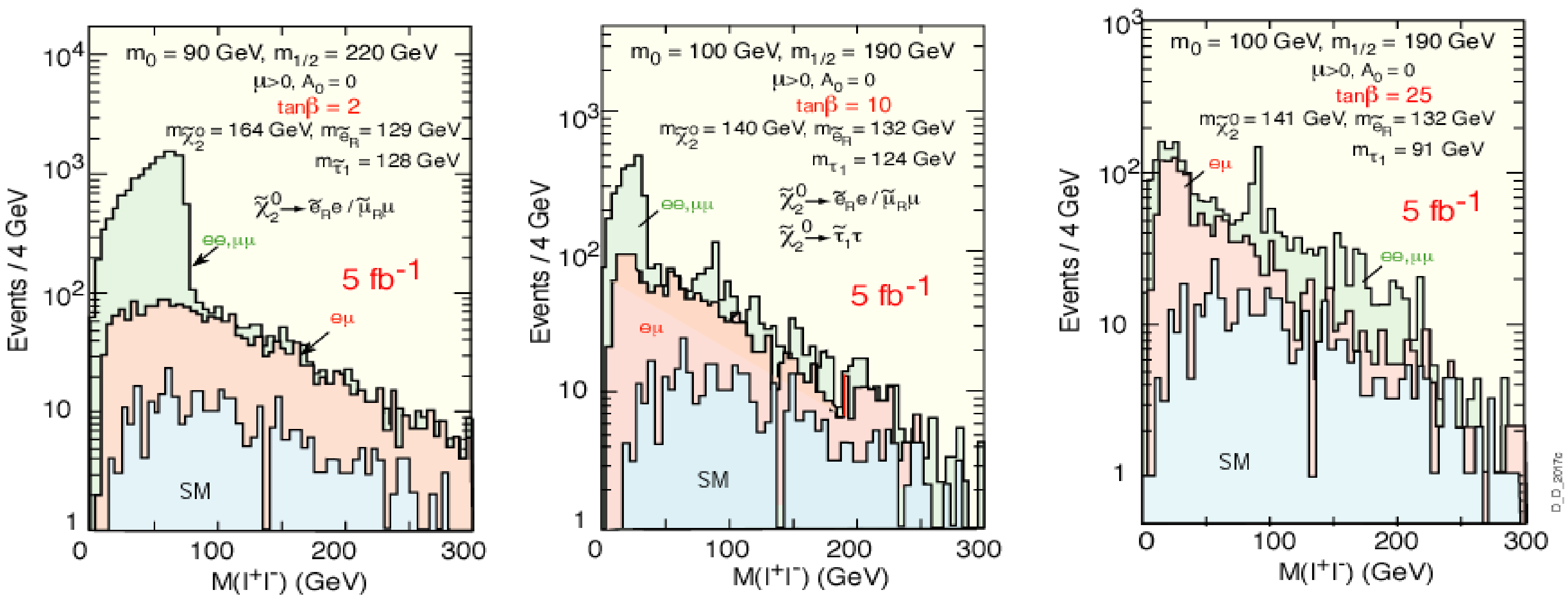


Dilepton edges at larger tanβ

Evolution of inclusive dilepton spectra with increasing tanβ

($m_0 \sim 100$ GeV, $m_{1/2} \sim 200$ GeV) 5 fb^{-1}

inclusive isolated opposite-sign dilepton spectra (ee, μμ, eμ)



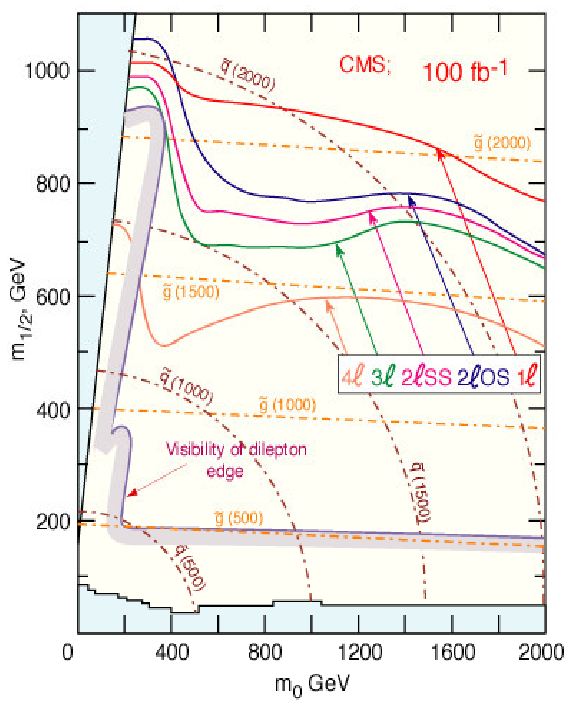
→ SUSY may reveal itself early through peculiarities in dilepton spectra, for example such "edges" or "collapsed edges"

Observability of dilepton structures

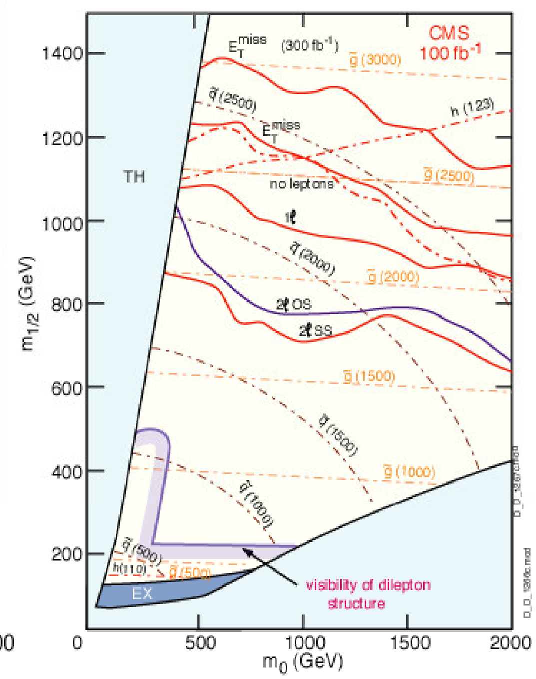
Observability of "$\ell^+\ell^-$ edge" or threshold structure in inclusive isolated two - leptons + E_t^{miss} final states

low tan β regime

m SUGRA; tg β = 2, A_0 = 0, μ < 0
all leptons isolated



m SUGRA, A_0 = 0, tan β = 35, μ > 0
5 σ contours ; non - isolated muons



high tan β regime

Structures tend to be less evident with increasing tanβ and are limited to smaller regions of parameter space

LHCC 2002.62

Sparticle reconstruction, use several edges

Post-LEP SUSY benchmark point B, ATLAS/2004-007

A fit of mSUGRA predictions to the set of measured end-points can be performed

Edge	Nominal Value	Fit Value	Syst. Error Energy Scale	Statistical Error
$m(ll)^{edge}$	77.077	77.024	0.08	0.05
$m(qll)^{edge}$	431.1	431.3	4.3	2.4
$m(ql)^{edge}_{min}$	302.1	300.8	3.0	1.5
$m(ql)^{edge}_{max}$	380.3	379.4	3.8	1.8
$m(qll)^{thres}$	203.0	204.6	2.0	2.8
$m(bll)^{thres}$	183.1	181.1	1.8	6.3

+ eight other measurements

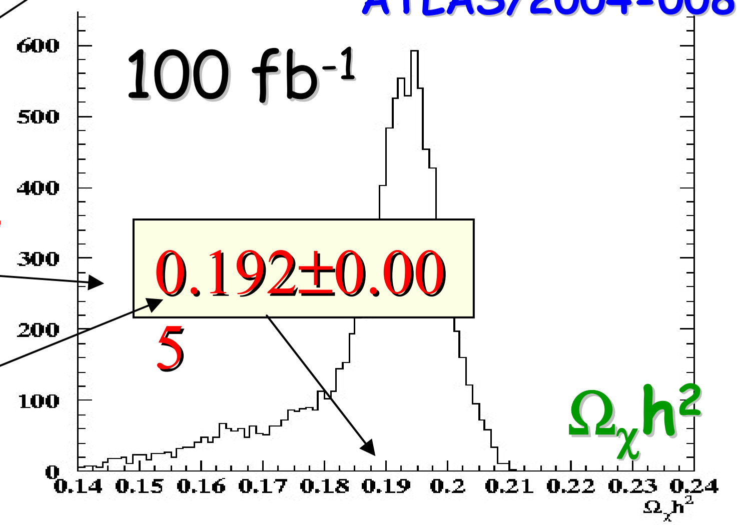
Parameter	Expected precision 30 fb^{-1}	300 fb^{-1}
m_0	± 3.2%	± 1.4%
$m_{1/2}$	± 0.9%	± 0.6%
$\tan(\beta)$	± 0.5%	± 0.5%

ATLAS/2004-008

Fit the best mSUGRA point by minimizing the overall χ^2

Deduce the LSP mass (with ~10% uncertair and relic density at the point

Determine $\Omega_\chi h^2$ and check for consistency with WMAP, terrestrial, astroparticle etc

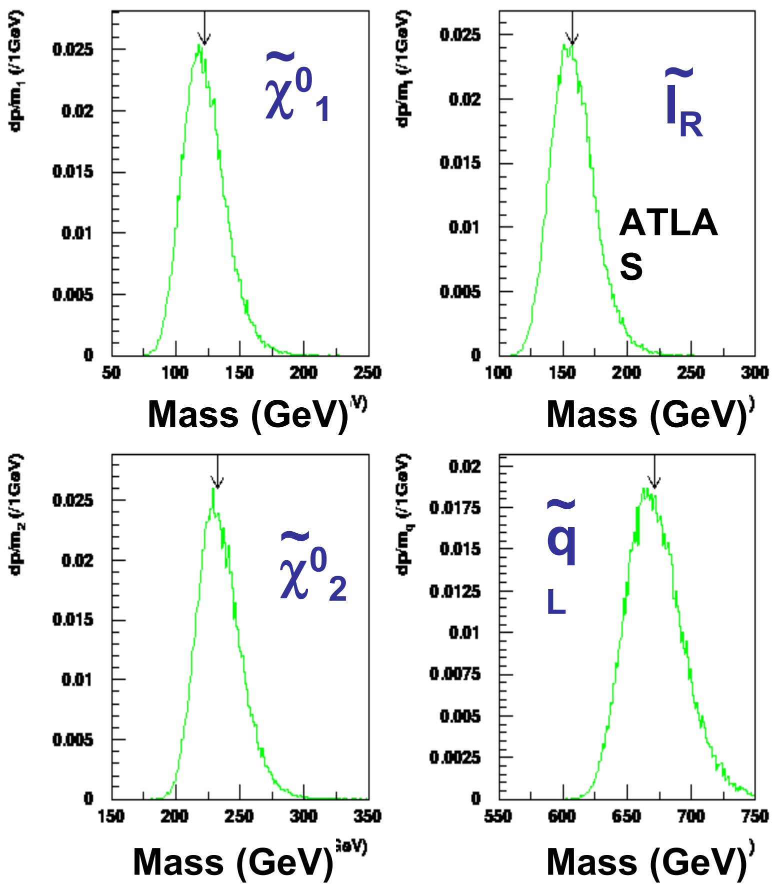


Model-independent predictions

Alternative approach to CMSSM fit to edge positions

numerical solution of simultaneous edge position equations

but interpretation of chain model dependent



ATLAS study results:

Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	$\pm$ 3%
$\tilde{\chi}^0_2$	$\pm$ 6%
$\tilde{l}_R$	$\pm$ 9%
$\tilde{\chi}^0_1$	$\pm$ 12%

Use approximations together with other measurements to obtain 'model-independent' estimates of $\Omega_\chi h^2$, $\sigma_{\chi p}$, ϕ_{sun} etc.

Dark Matter, SUSY, LHC (I)

Dark matter:

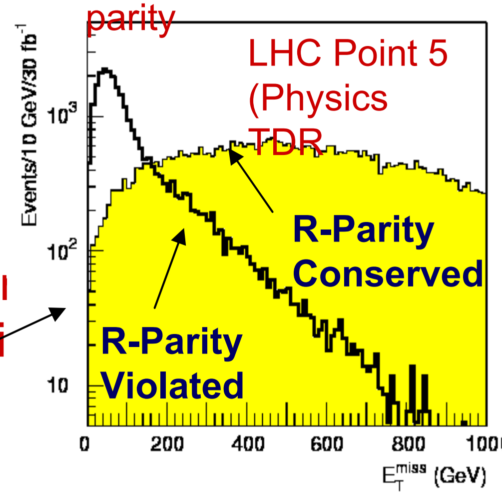
baryonic (machos, but represent no more than 20% of galactic halo DM),

elementary particles, particle physics candidates:

- axion,
- neutralino (CDM), χ^0_1
- neutrino (HDM), ν_τ, but too light, not more than few% of DM content

the neutralino-1 (χ^0_1) is a viable DM candidate only so fai is the Lightest Supersymmetric Particle (LSP) and R-pari is conserved i.e. is a stable particle

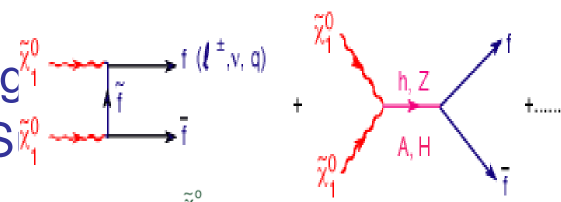
ATLAS, $E_t^{missing}$ and R-parity



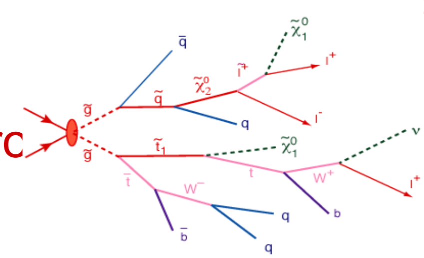
DM detection:

direct (ex.: relic neutralino (WIMP)-nucleon scatterinç

indirect (ex. relic neutralino annihilation in Earth or S giving, for example, two neutrinos:



neutralino production, as at LHC (or the Tevatrc



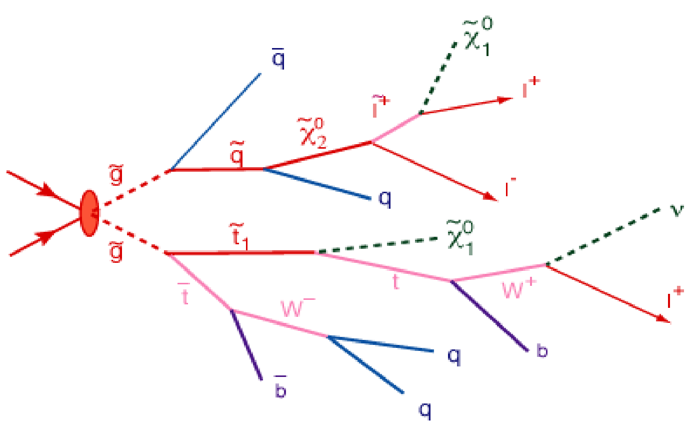
Dark Matter, SUSY, LHC (I)

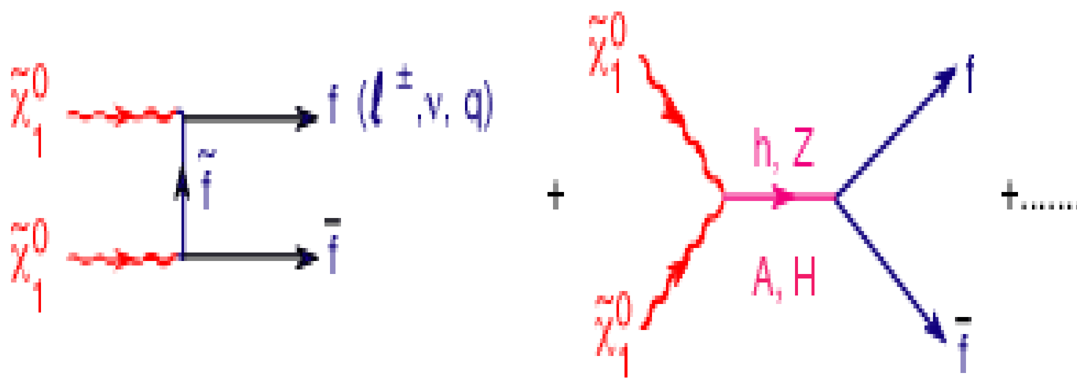
DM detection:

direct (ex.: relic neutralino (WIMP)-nucleon scattering)

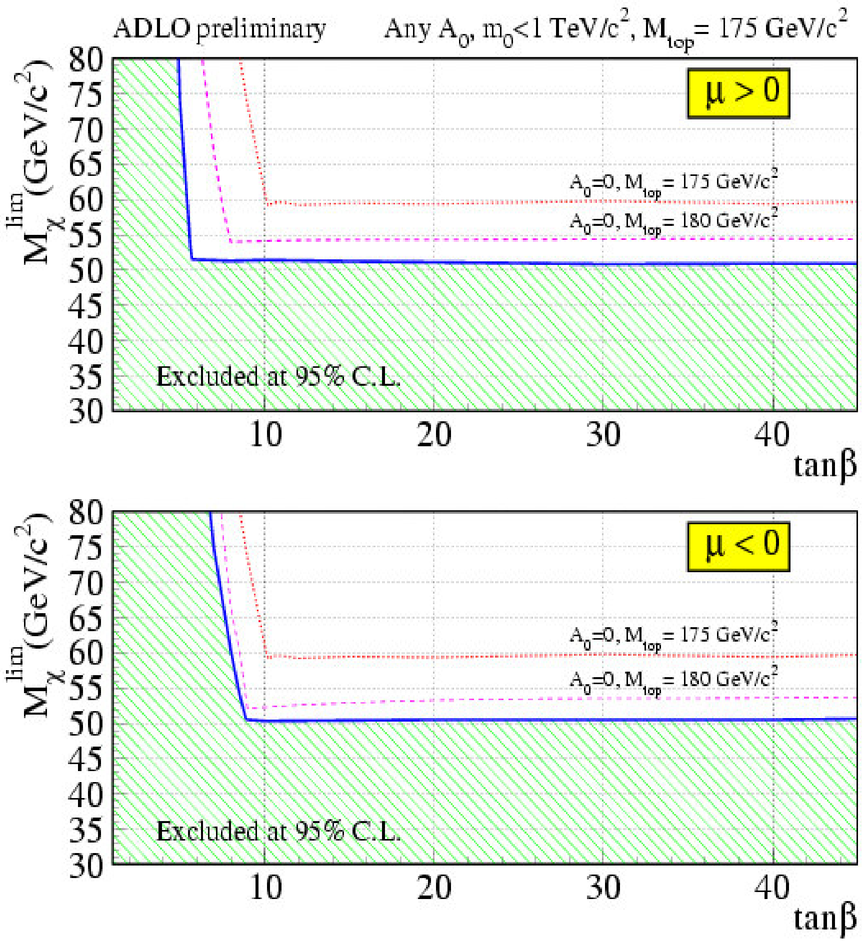
indirect (ex. relic neutralino annihilation in Earth or Sun giving, for example, two neutrinos:

neutralino production, as at LHC (or the Tevatron):





LEP neutralino limits



Dark Matter, SUSY, LHC (II)

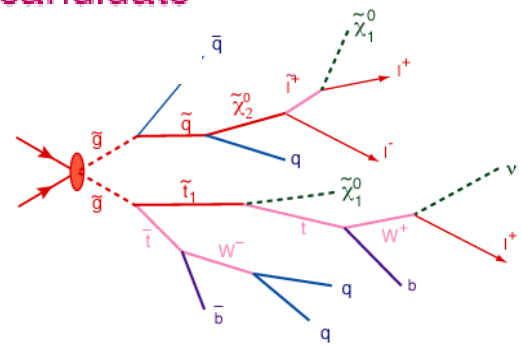
Two questions:

- do present (WMAP) constraints on DM assure SUSY detection at the LHC, and what limits do they imply on sparticle masses?

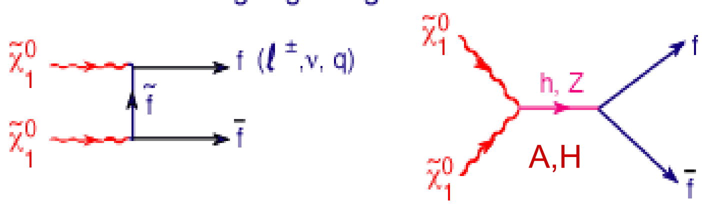
- can we measure the neutralino-1 mass?

Relic densities in LHC mSUGRA parameter space (pre-WMAP)

The lightest neutralino $\tilde{\chi}_1^0$ is an excellent cold dark matter candidate (provided it is the LSP and R-parity is conserved)



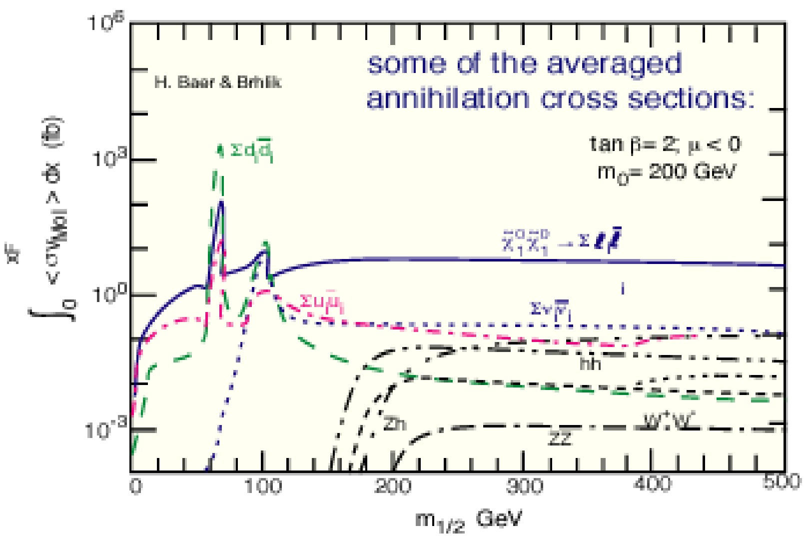
Typical $\tilde{\chi}_1^0$ annihilations during Big Bang cooldown:

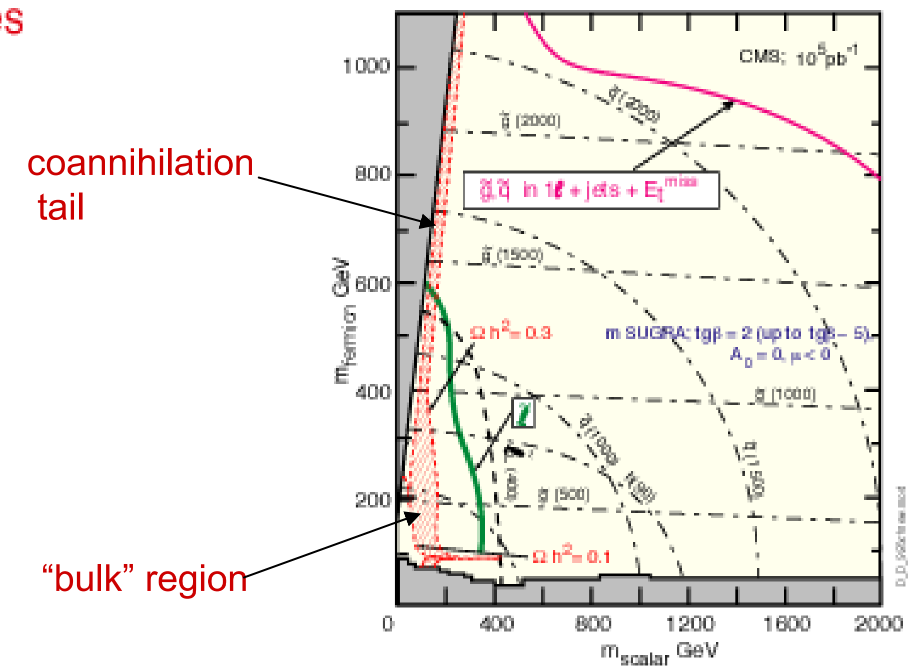


+ $\tilde{\tau}_R\,\tilde{\chi}_1^0$ + ...co-annihilation channels ($\tilde{\tau}_R\,\tilde{\chi}_1^0 \rightarrow \tau\gamma, \tau Z, \tau h$) +........

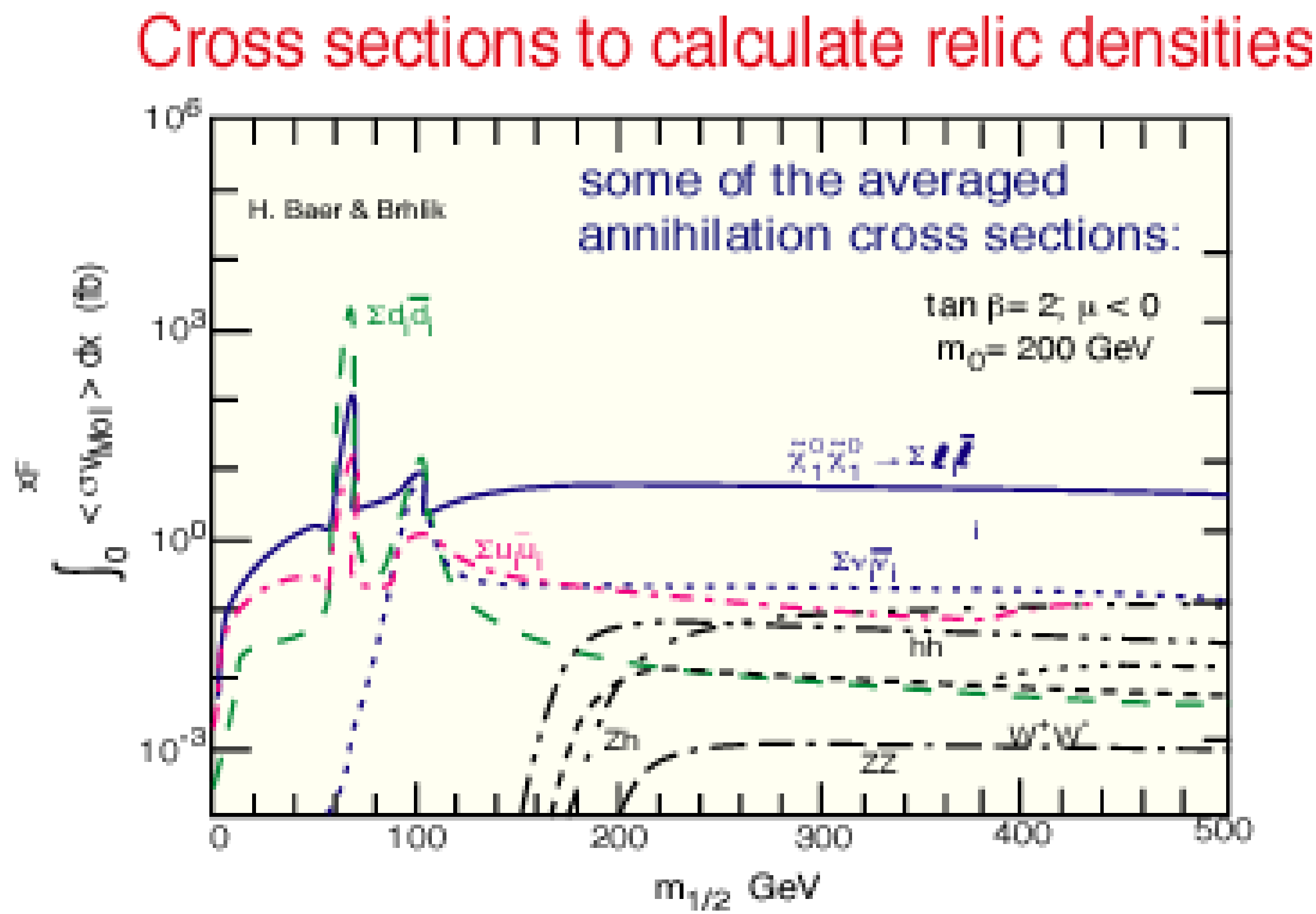
Newer Relic Densities and COBE limits in (mSUGRA) neutralino parameter space

Cross sections to calculate relic densities





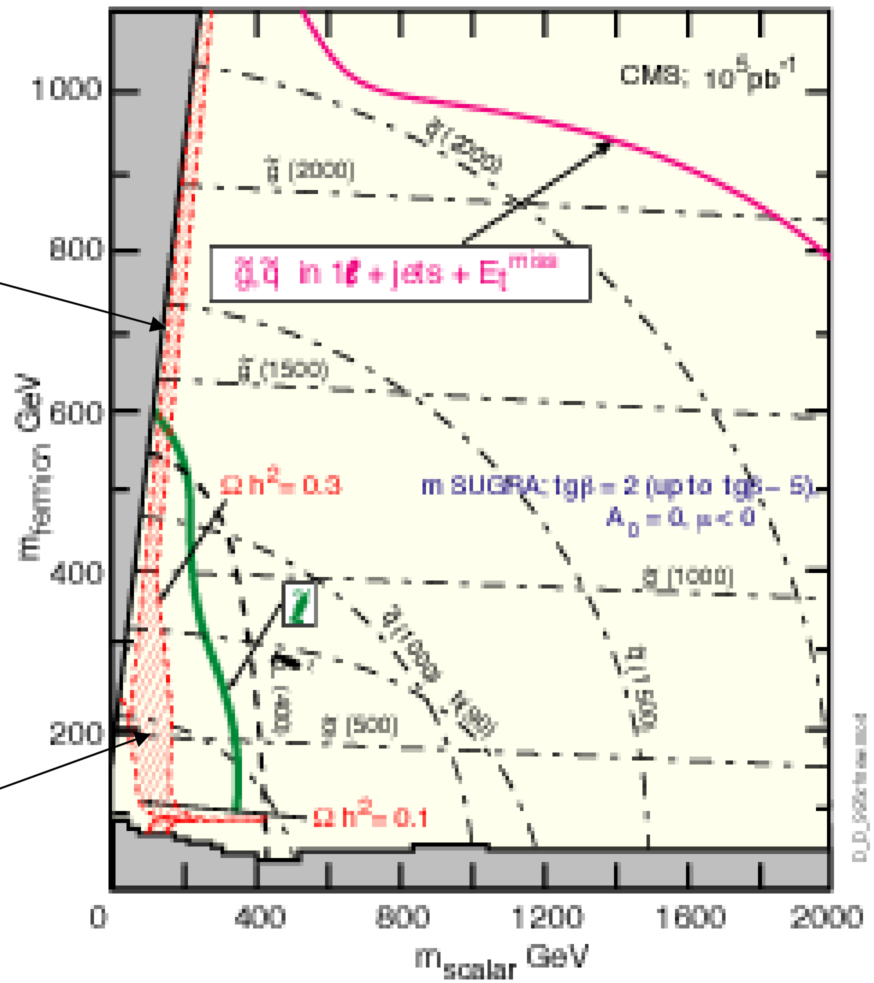
Relic densities in LHC mSUGRA parameter space (pre-WMAP)



Relic densities in LHC mSUGRA parameter space (pre-WMAP)

Newer Relic Densities and COBE limits in (mSUGRA) neutralino parameter space

coannihilation tail



"bulk" region

SUSY dark matter and present constraints from laboratory experiments and WMAP

Relic neutralino DM contours, including constraints from LEP, $b \to s\gamma$, g_μ-2 measurements and new WMAP cosmological DM constraints

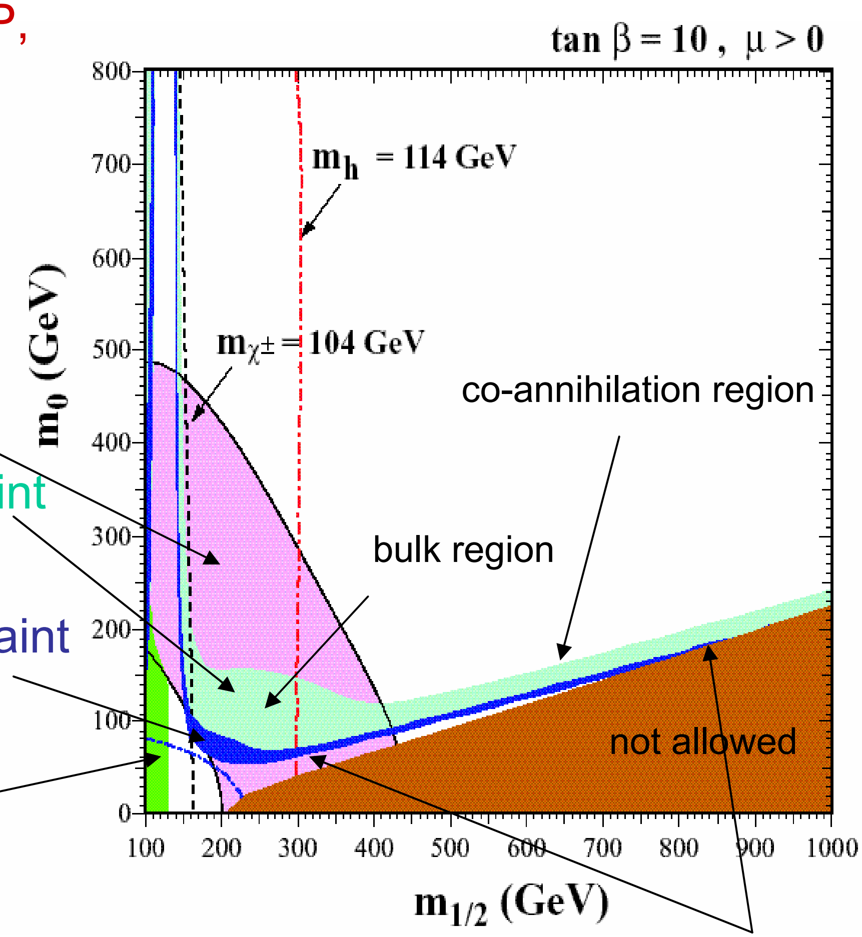
J. Ellis,K.A.Olive,Y.Santoso,V.C.Spanos,hep-ph/0303043

favored by g_μ-2 at 2σ level

older cosmological constraint $0.1 < \Omega\chi h^2 < 0.3$

newer cosmological constraint $0.094 < \Omega\chi h^2 < 0.129$

excluded by $b \to s\gamma$



example at $\tan\beta = 10$

only this tail is left!

SUSY dark matter and present

J. Ellis,K.A.Olive,Y.Santoso,V.C.Spanos,hep-ph/0303043

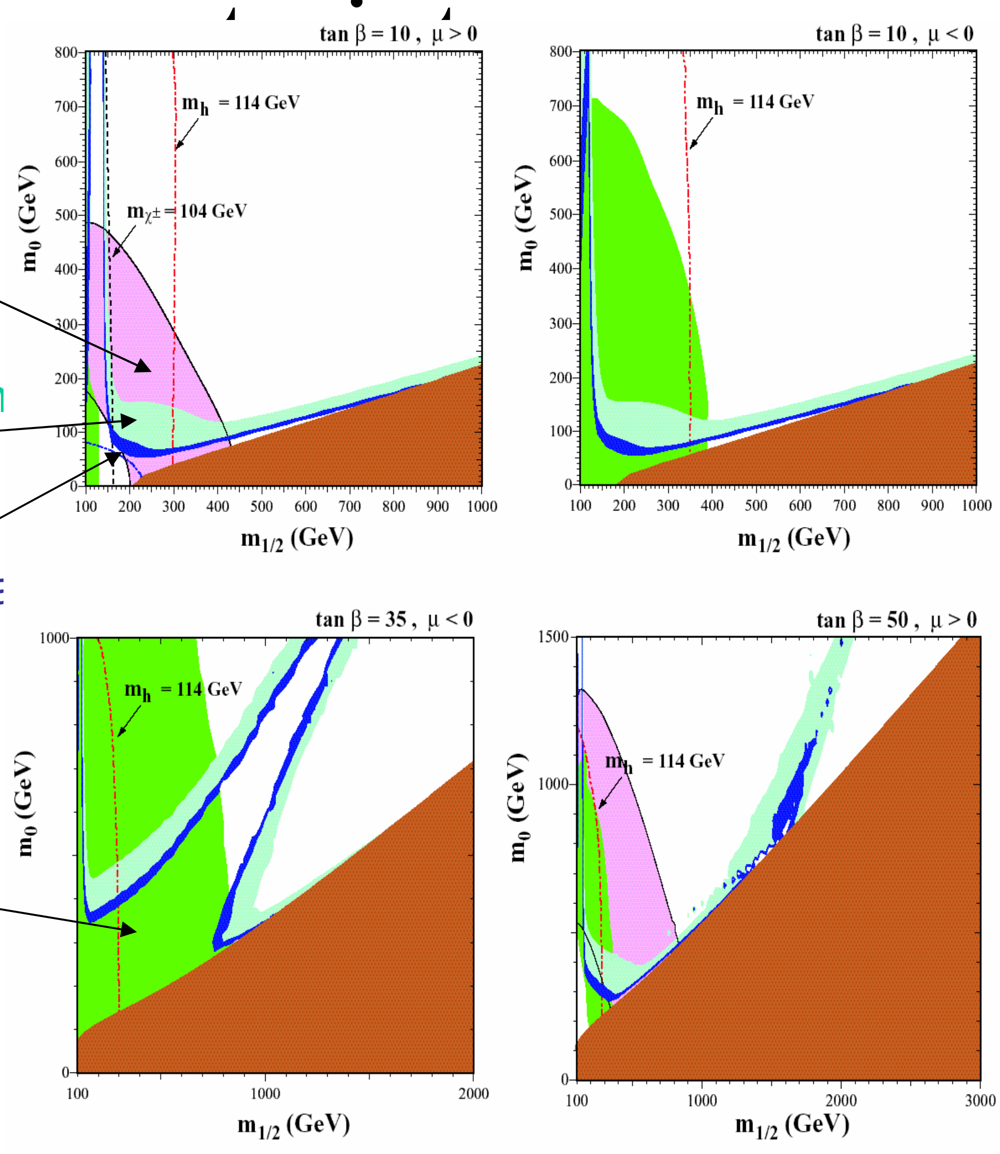
Full tanβ range

favored by g_μ-2
at 2σ level

older cosmological constrain
$0.1 < \Omega\chi h^2 < 0.3$

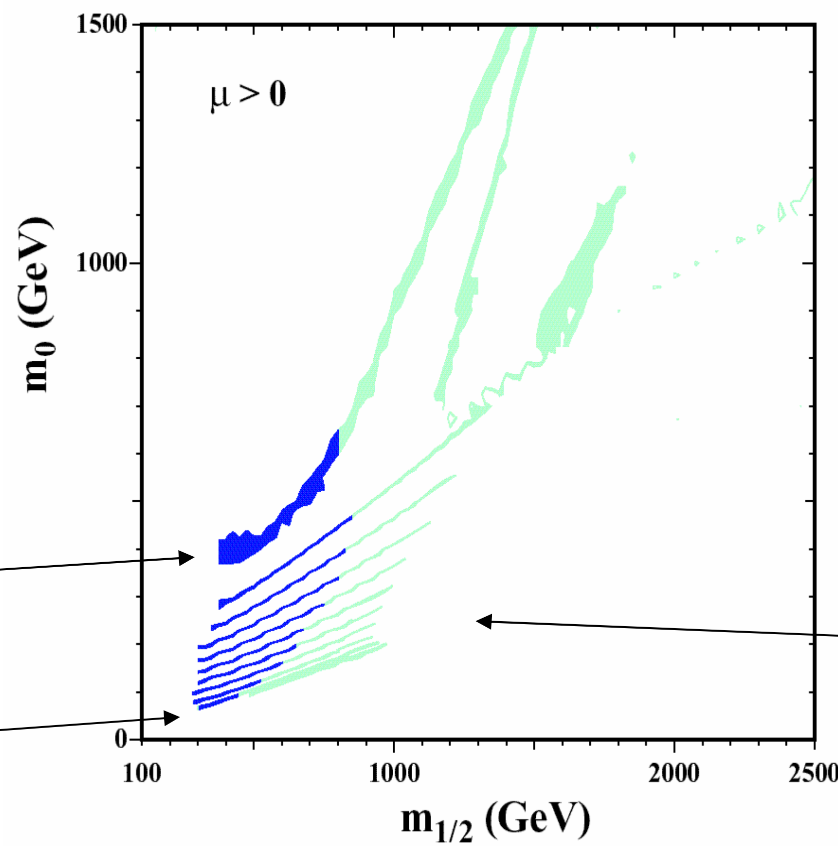
newest cosmological constra
$0.094 < \Omega\chi h^2 < 0.129$

excluded by b → sγ



WMAP results mapped onto m_0 vs $m_{1/2}$ plane

Compatibility between WMAP results and laboratory experiments - mapping of the WMAP constraint $0.094 < \Omega_\chi h^2 < 0.129$ onto the m_0 vs m 1/2 plane for tanβ from 5 to 55 (μ > 0)



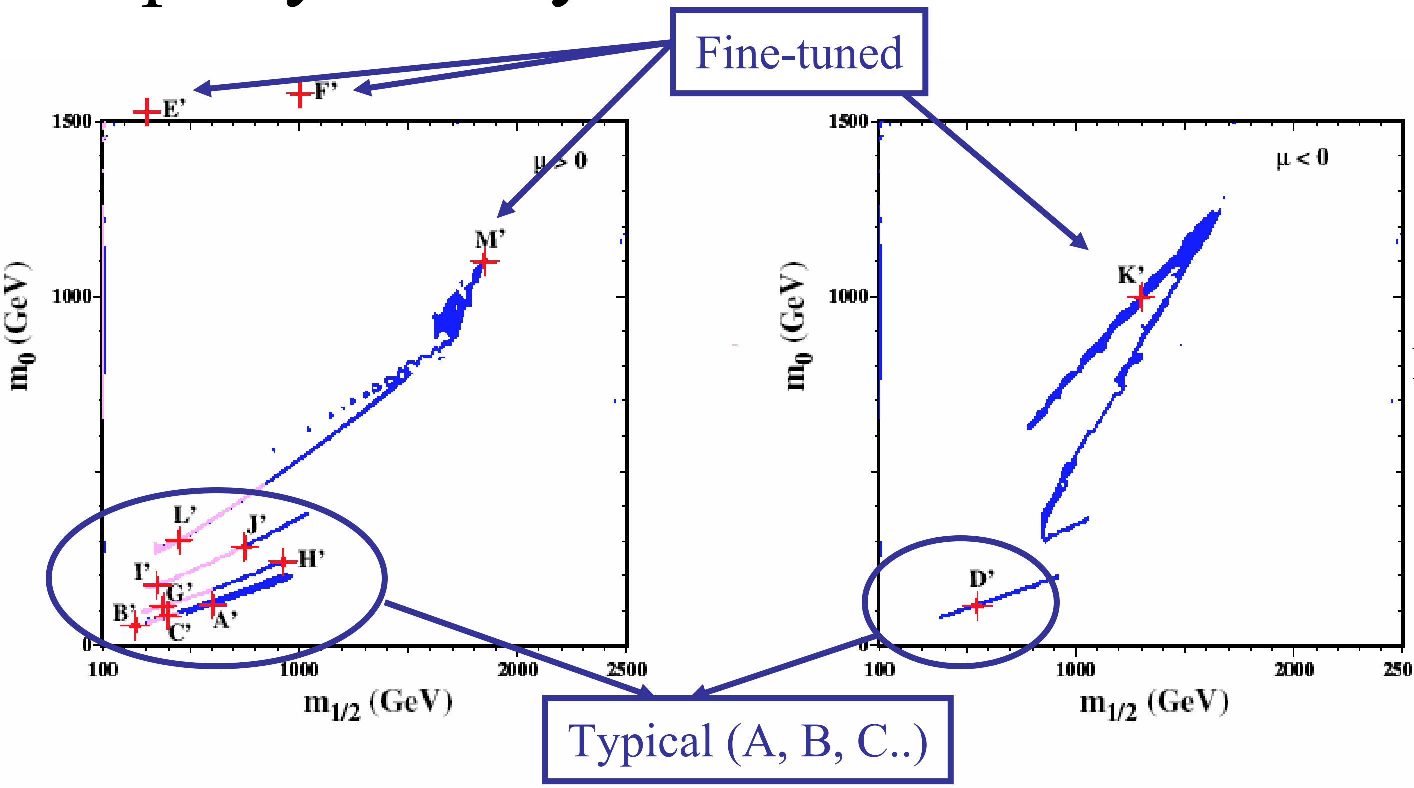
tanβ = 55

tanβ = 5

J. Ellis et al. hep-ph/0303043

blue region is favored by G_μ -2 (μ^+) at 2σ level

Updated Post-WMAP Benchmarks for Supersymmetry



M. Battaglia et al.
hep-ph/0306219
CERN–TH/2003-138

Figure 1: *The shaded strips display the regions of the* $(m_{1/2}, m_0)$ *plane that are compatible [15] with* $0.094 < \Omega_\chi h^2 < 0.129$ *in the 'bulk', coannihilation 'tail', and rapid-annihilation 'funnel' regions, as well as the laboratory constraints, for (a)* $\mu > 0$ *and* $\tan\beta = 5, 10, 20, 35$ *and 50, and (b) for* $\mu < 0$ *and* $\tan\beta = 10$ *and 35. The parts of these 'WMAP lines' for* $\mu > 0$ *compatible with* $g_\mu - 2$ *at the 2-*σ *level have lighter (pink) shading [7]. The updated post-WMAP benchmark scenarios are marked in red. Points (E',F') in the focus-point region have larger values of* m_0.

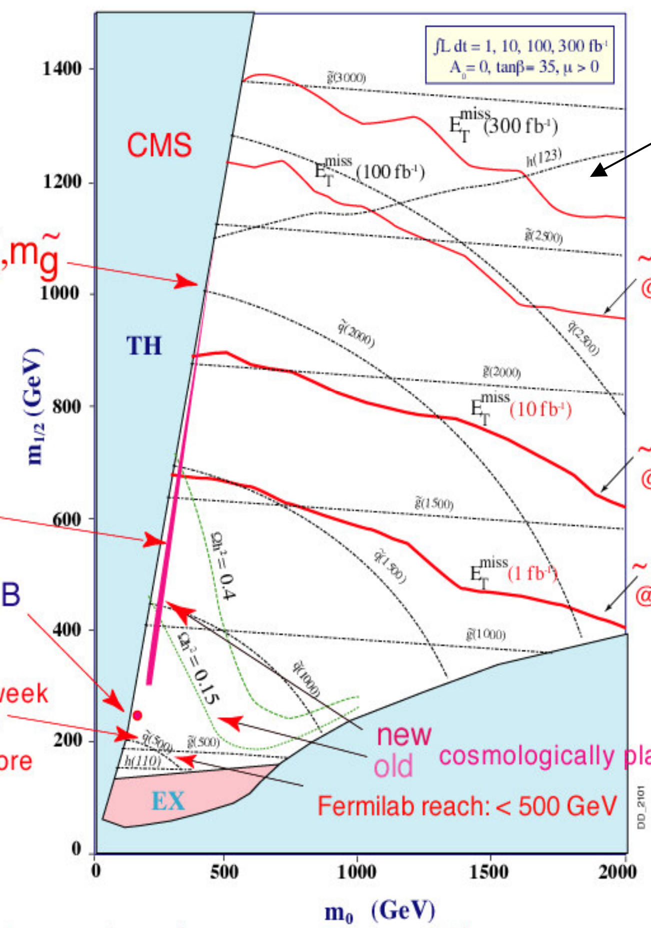
WMAP DM results and compatibility with LHC SUSY reach

Squark, Gluino reach at the LHC
- reach in jets + E_t^{miss}

LHC/CMS reach vs SUSY DM regions after WMAP results

Reach vs luminosity

CMS $\tilde{q}, \tilde{g}$ mass reach in E_T^{miss} + jets inclusive channel for various integrated luminosities



high tanβ = 35, μ > 0 regime

➜ limit $m_{\tilde{\chi}}, m_{\tilde{g}}$

$$m_\chi = 0.4 m_{1/2}$$

~ one year @10^{34}

~ one year @10^{33}

~ one month @10^{33}

new LEP, b → sγ, WMAP-compatible region $\Omega_{CDM}h^2 = 0.09\text{-}0.13$

point B

~ one week @10^{33} to explore

new

old

cosmologically plausible region

Fermilab reach: < 500 GeV

"old" Cold Dark Matter range: $\Omega_{CDM}h^2 = 0.1\text{-}0.3$

➜ neutralino mass < ~ 7-800 GeV

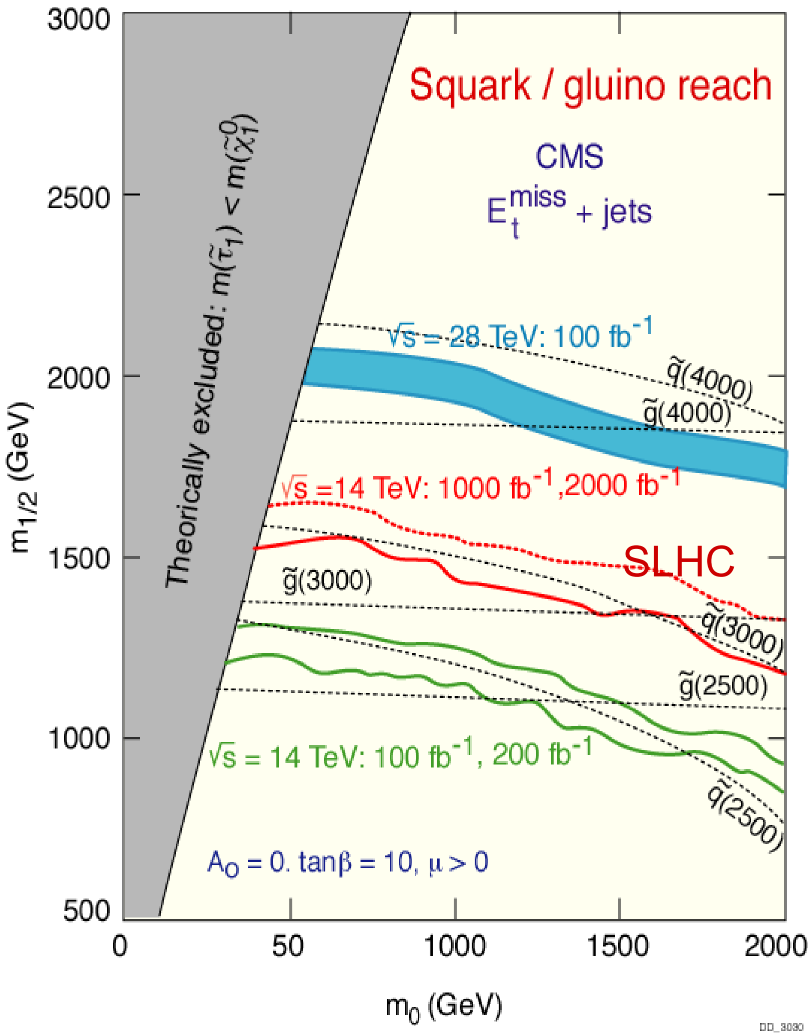
new WMAP range: $\Omega_{CDM}h^2 = 0.09\text{-}0.13$

➜ neutralino mass < ~ 4-500 GeV (for tgβ < 50, μ > 0 or for tgβ < 35, μ < 0)

Vulcano 2004.25

D. Denegri, CMS week June 2003.04

SUSY at SLHC (I)



Notice advantage of a 28 TeV machine

Higher integrated luminosity brings an obvious increase in mass reach in squark, gluino searches, i.e. in SUSY discovery potential; this is not too demanding on detectors as very high E_t jets, E_t^{miss} are involved, large pile-up not so detrimental

⇒ with SLHC the SUSY reach is increased by ~ 500 GeV, up to ~ 3 TeV in squark and gluino masses

but this is just "the reach", the main advantage of increased statistics should be in the sparticle spectrum reconstruction possibilities, larger fraction of spectrum, more precision, but this would require detectors of comparable performance to "present ones"

Model dependent tests, sparticle masses, neutralino mass

- If a viable DM candidate is found initially (events with large missing Et, stable) assume specific consistent model e.g. CMSSM / mSUGRA.

- Measure model parameters (m_0, $m_{1/2}$, $\tan(\beta)$, sign(μ), A_0 for mSUGRA).

- Check consistency with accelerator constraints (m_h, g_μ-2, $b \rightarrow s\gamma$ etc.)

- Estimate $\Omega_\chi h^2 \rightarrow$ consistency check with astrophysics (WMAP etc.)

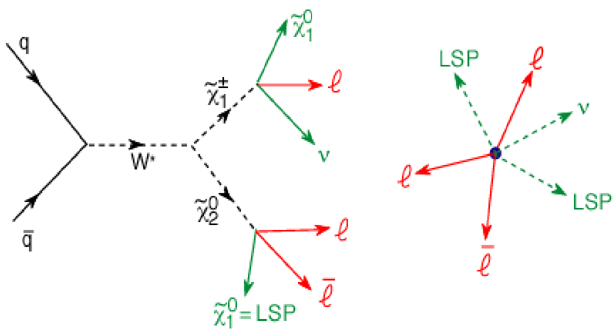
- Ultimate test of DM only possible in conjunction with astroparticle experiments

$\rightarrow$ measure m_χ , $\sigma_{\chi p}$, ϕ_{sun} etc.

neutralino mass in exclusive chargino-neutralino final states

How to look for charginos and neutralinos at LHC

- Production, for ex by Drell Yan:



➤ Search in: $3\ell^{\pm}$ and no jets + (E_T^{miss}) events

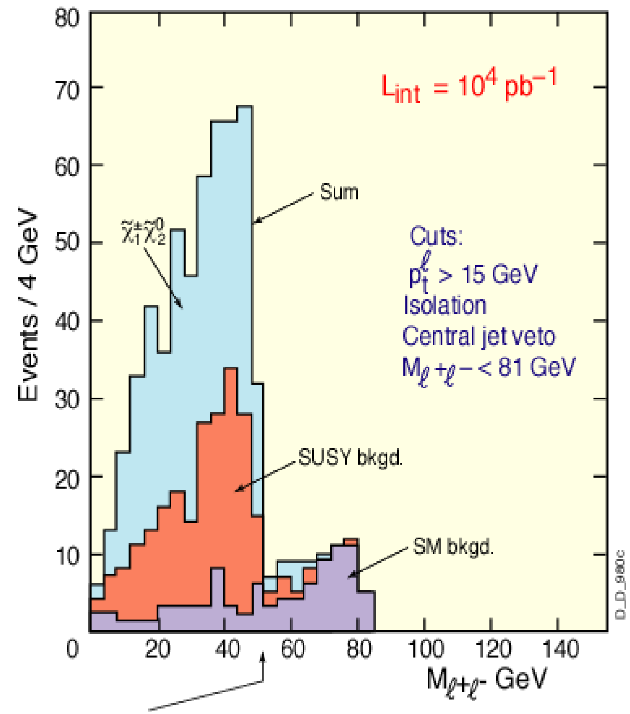
Require:

- Three isolated leptons: $p_t^{\ell} > 15$ GeV
- Veto central jets with $E_t > 25$ GeV in $|\eta^j| < 3.5$
- $m_{\ell\bar{\ell}} < 81$ GeV or $m_{\ell\bar{\ell}} \neq m_z \pm \delta m_z$
- E_t^{miss} < no cuts, shloud be significant

Backgrounds: $t\bar{t}$, WZ, ZZ, $Zb\bar{b}$, $b\bar{b}$ other SUSY channels ($\tilde{g}, \tilde{q}, \tilde{\ell}, \chi^0, \chi^{\pm}$)

$\tilde{\chi}_1^0$ mass determination in $3\ell^{\pm}$ + no jets + E_t^{miss} final state from $\tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0$ production

$m_0 = 200$ GeV, $m_{1/2} = 100$ GeV, $\tan\beta = 2$, $A_0 = 0$, $\mu < 0$
$M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0) \approx M(\tilde{\chi}_1^0) \approx 52$ GeV



$M_{\ell\ell}^{max} = M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0) \approx M(\tilde{\chi}_1^0) \rightarrow m_{1/2} \approx 2.5\, M(\tilde{\chi}_1^0)$

in m SUGRA

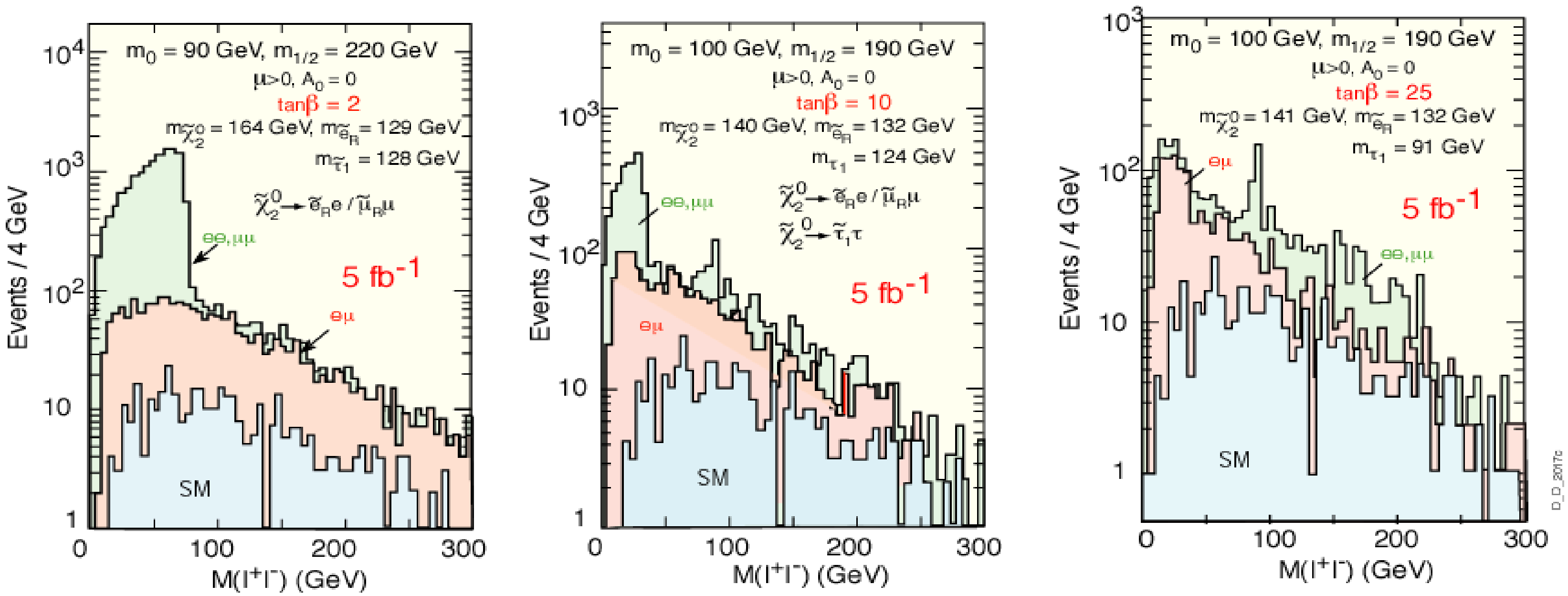
the “edge” can be measured with better than ~1 GeV precision and thus neutralino masses within this model - and where the edge is visible!

Evolution of inclusive dilepton spectra with increasing tanβ

Inclusive dilepton edges

($m_0 \sim 100$ GeV, $m_{1/2} \sim 200$ GeV) 5 fb^{-1}

inclusive isolated opposite-sign dilepton spectra (ee, μμ, eμ)



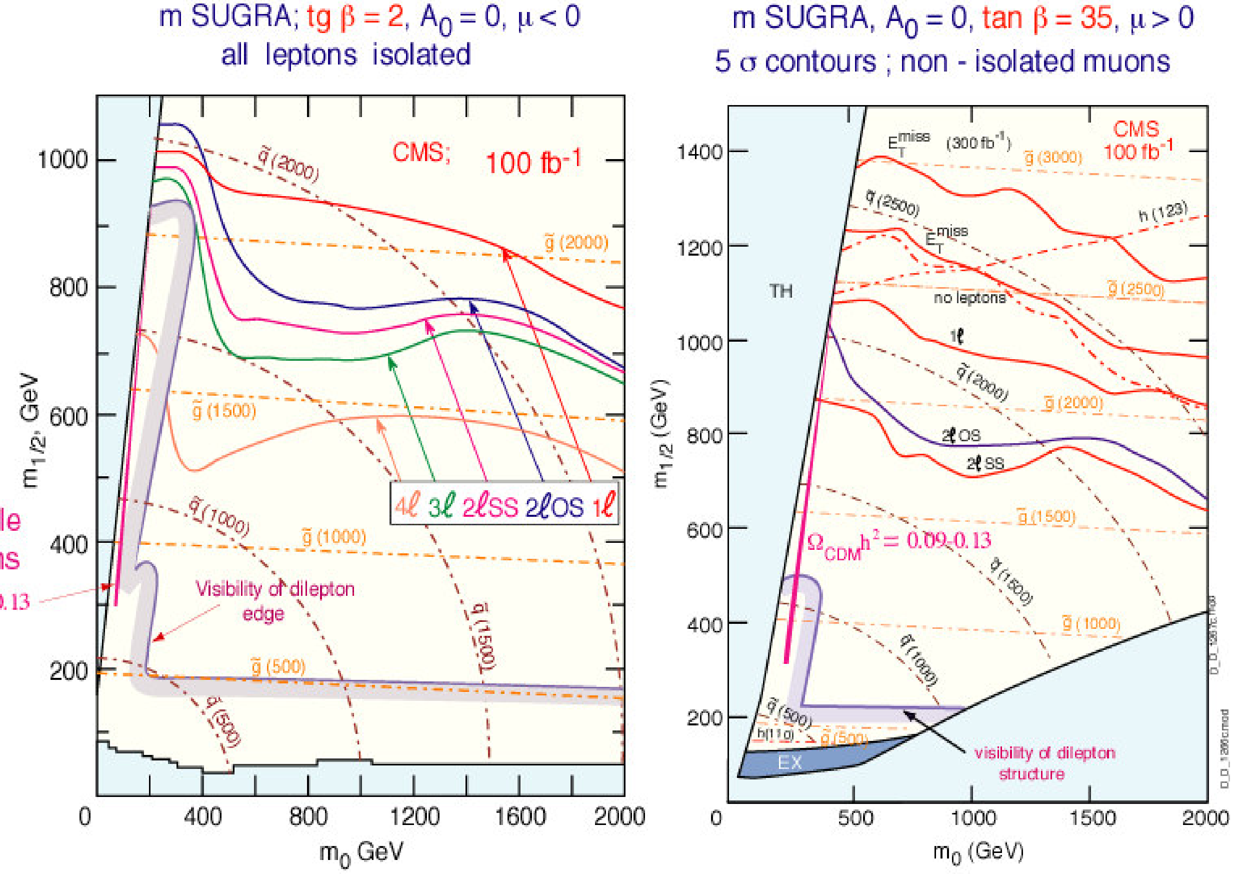
→ SUSY may reveal itself early through peculiarities in dilepton spectra, for example such "edges" or "collapsed edges"

WMAP- DM contours and dilepton structures

Observability of "ℓ+ℓ- edge" in inclusive isolated two - leptons + E_t^{miss} final states

WMAP compatible SUSY DM regions

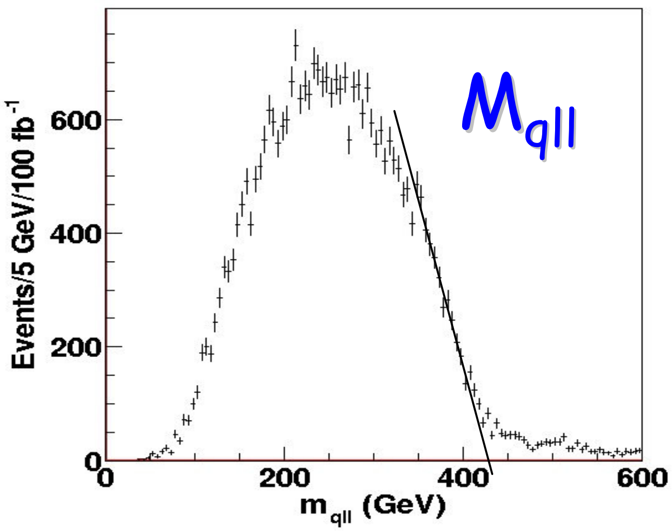
$\Omega_{CDM}h^2 = 0.09\text{-}0.13$

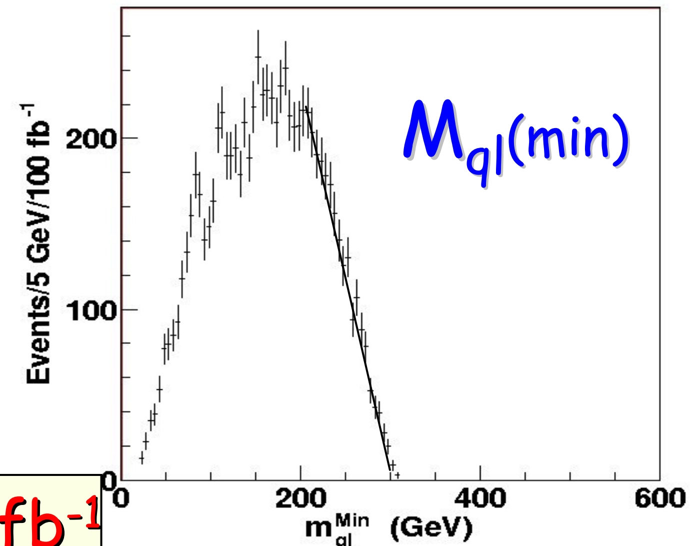


high tanβ regime

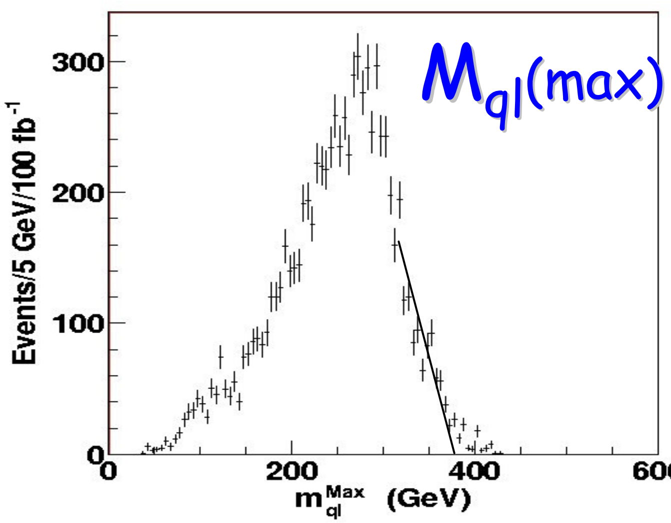
Sparticle reconstruction, use several edges

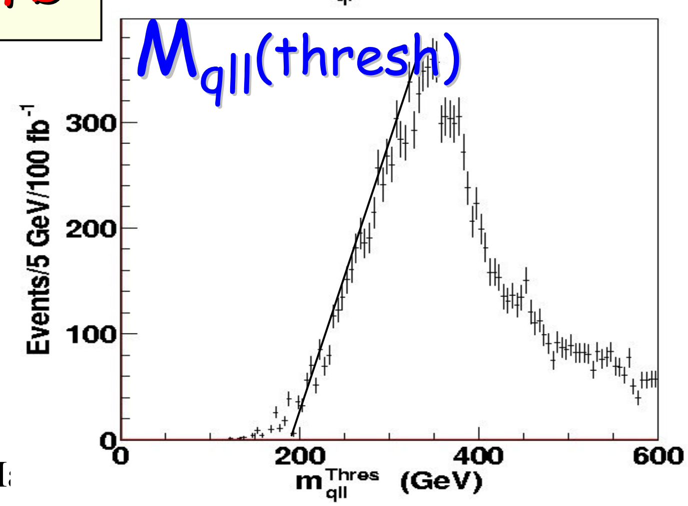
Post-LEP SUSY benchmark point B, ATLAS/2004-007





100 fb^{-1}





SUMMARY

- LHC and Direct Searches will allow an understanding of DM

The next 4 years should be an exciting time

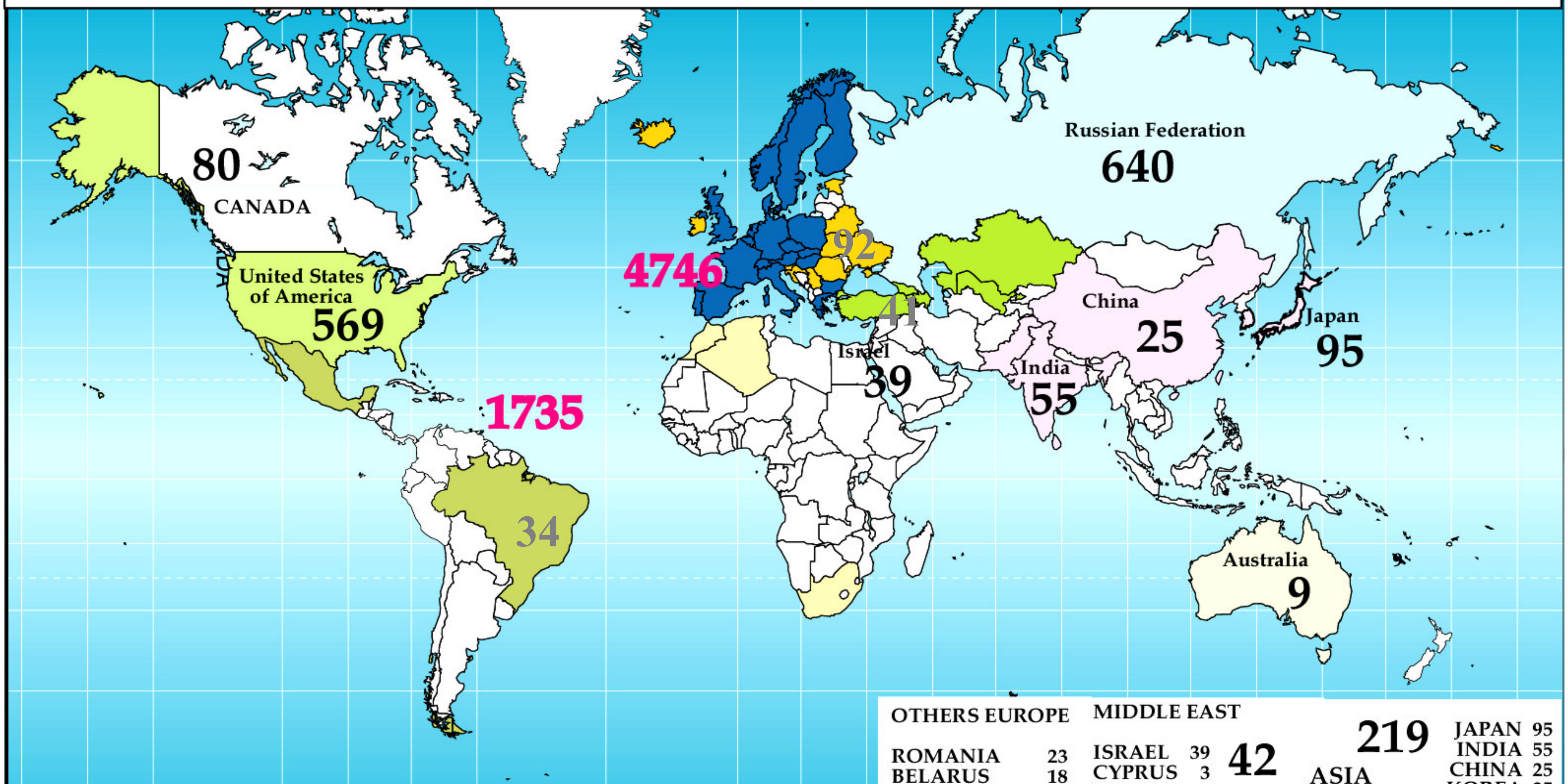
Particular Thanks

- Alex Murphy and Tim Sumner
- Colleagues at the Gran Sasso
- Daniel Denegri

and

- Numerous theorists

Worldwide Scientific Collaboration



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41

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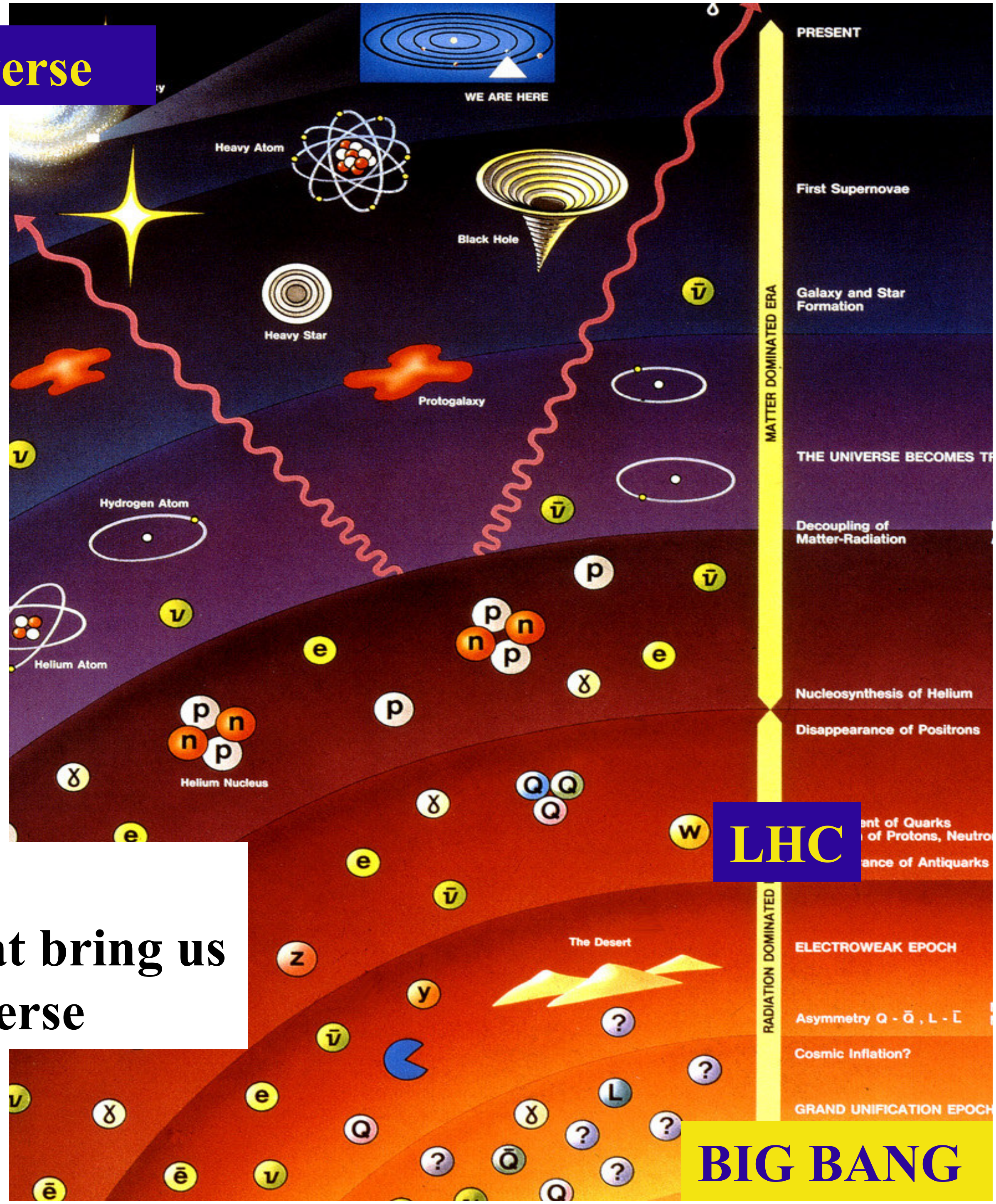
The History of the Universe

Time



Particle Accelerators are Time-Machines that bring us back to the Early Universe

R.Cashmore

Perspectives for Dark Matter Searches in ATLAS

Dan Tovey

University of Sheffield

Dark Matter Strategy

SUSY Dark Matter studies at ATLAS will proceed in four stages:

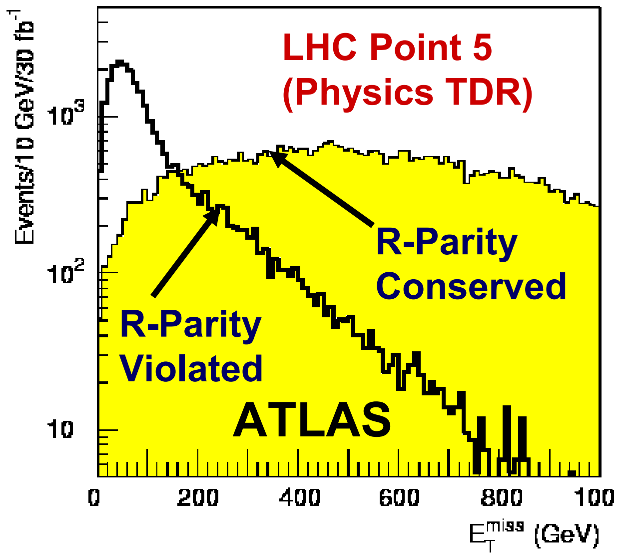
1) SUSY Discovery phase (discussed by Marco for CMS)
   - ➜ success assumed!
2) Inclusive Studies (measurement of SUSY Mass Scale, comparison of significance in inclusive channels).

In this talk focus on Stages 2, 3 and 4

3) Exclusive studies and interpretation within specific model framework (e.g. Constrained

Inclusive St…

- Following any discovery of SUSY next task will be to test broad features of potential Dark Matter candidate.



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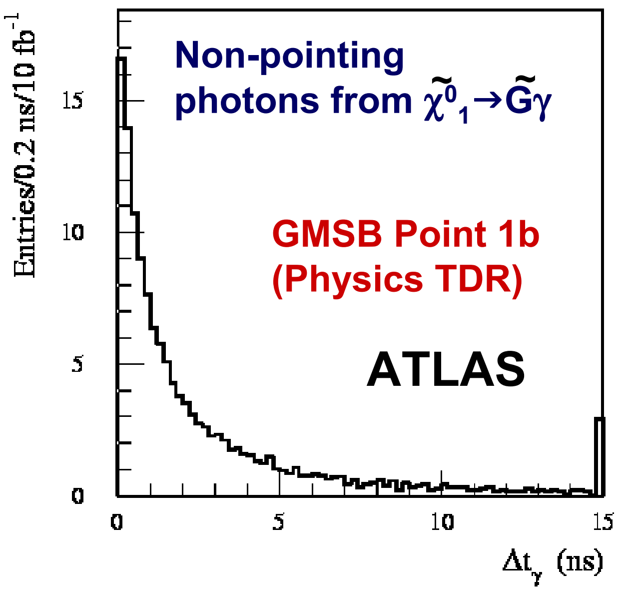
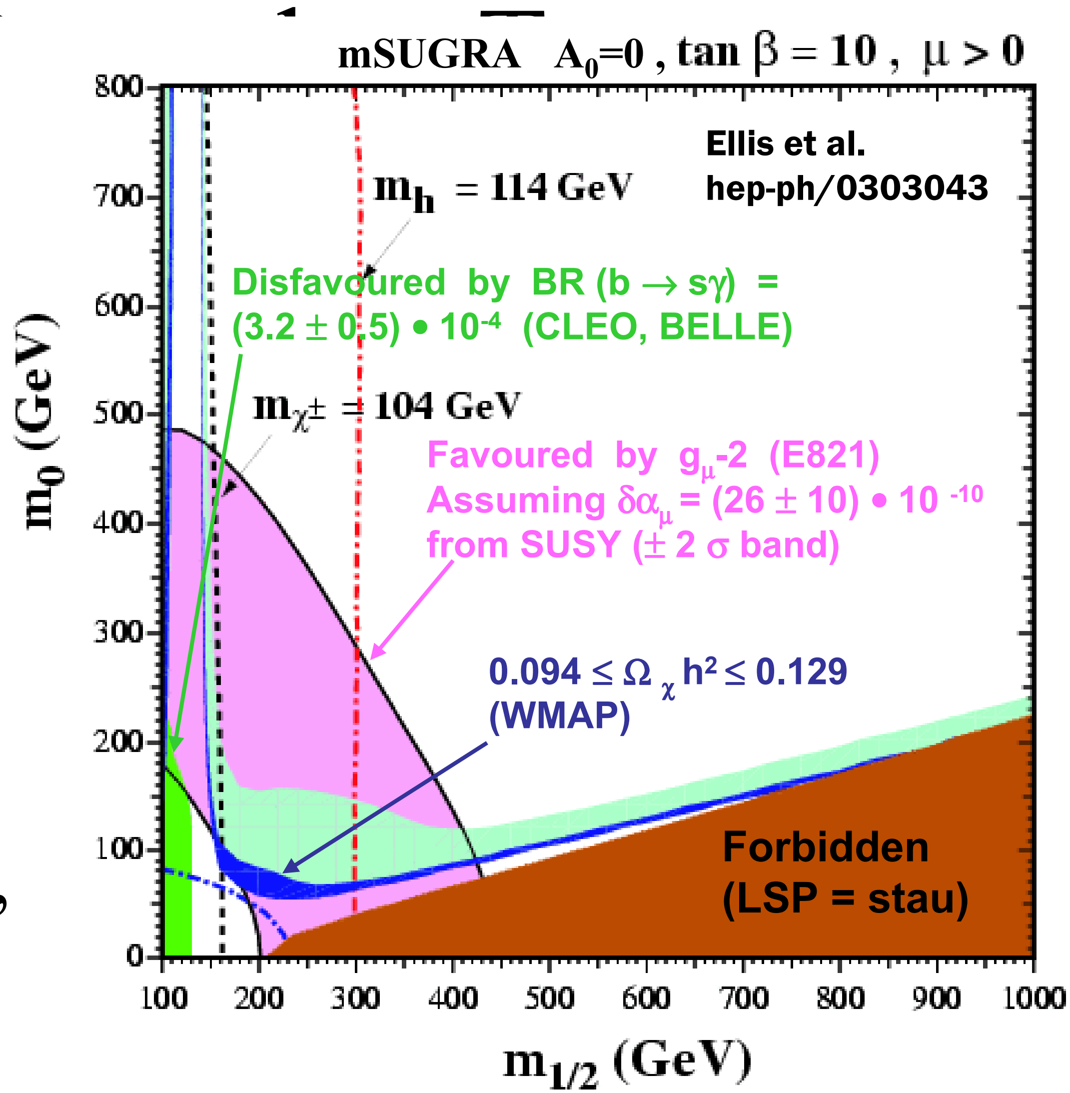
    (… < 1 ms
    (… 13.7 Gyr)



- **Question 2: Is the LSP the lightest neutralino?**
  - **Natural in many MSSM models**
  - **If YES then test for consistency with astrophysics**
  - **If NO then what is it?**
    e.g. Light Gravitino DM from GMSB models (not considered here)

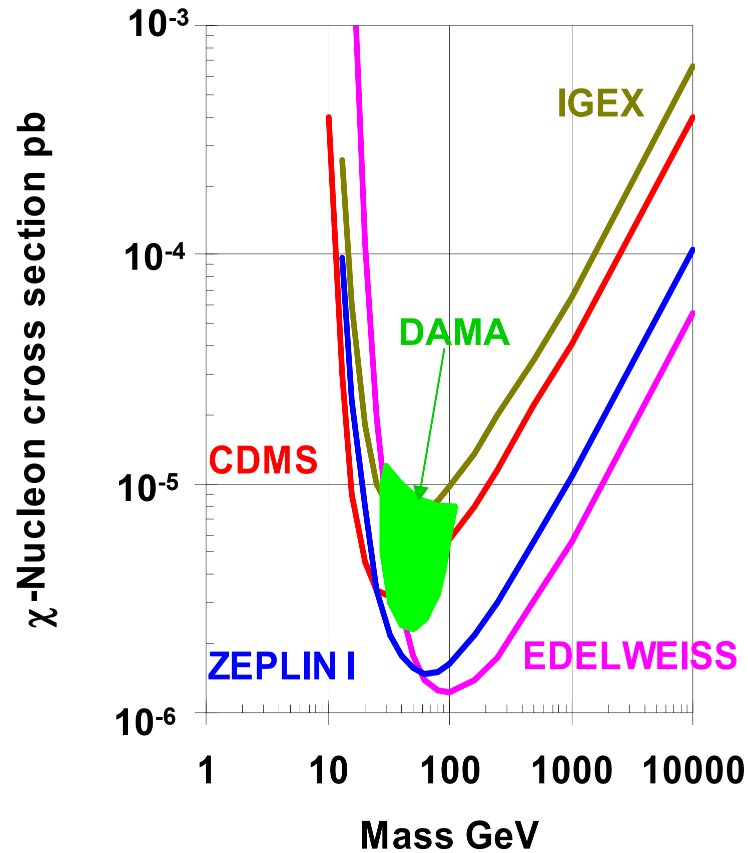
Model-D

- If a viable DM candidate is found initially assume specific consistent model
  - e.g. CMSSM / mSUGRA.
- Measure model parameters (m_0, $m_{1/2}$, $\tan(\beta)$, sign(μ), A_0 for CMSSM).
- Check consistency



Terrestrial Dark Matter Experim

- Terrestrial Dark Matter experiments:
  - Direct searches for elastic scattering of Dark Matter particles from atomic nuclei ($\sigma_{\chi p}$)
  - Indirect searches via self-annihilation products from e.g. centre of sun (e.g. high energy neutrino flux ϕ_{sun})
- Direct search experiments can measure neutralino



Current world-best limits (ZEPLIN-I, EDELWEISS): $\sigma_{\chi p} \lesssim 10^{-6}$ pb ($m_\chi \sim 100$ GeV)

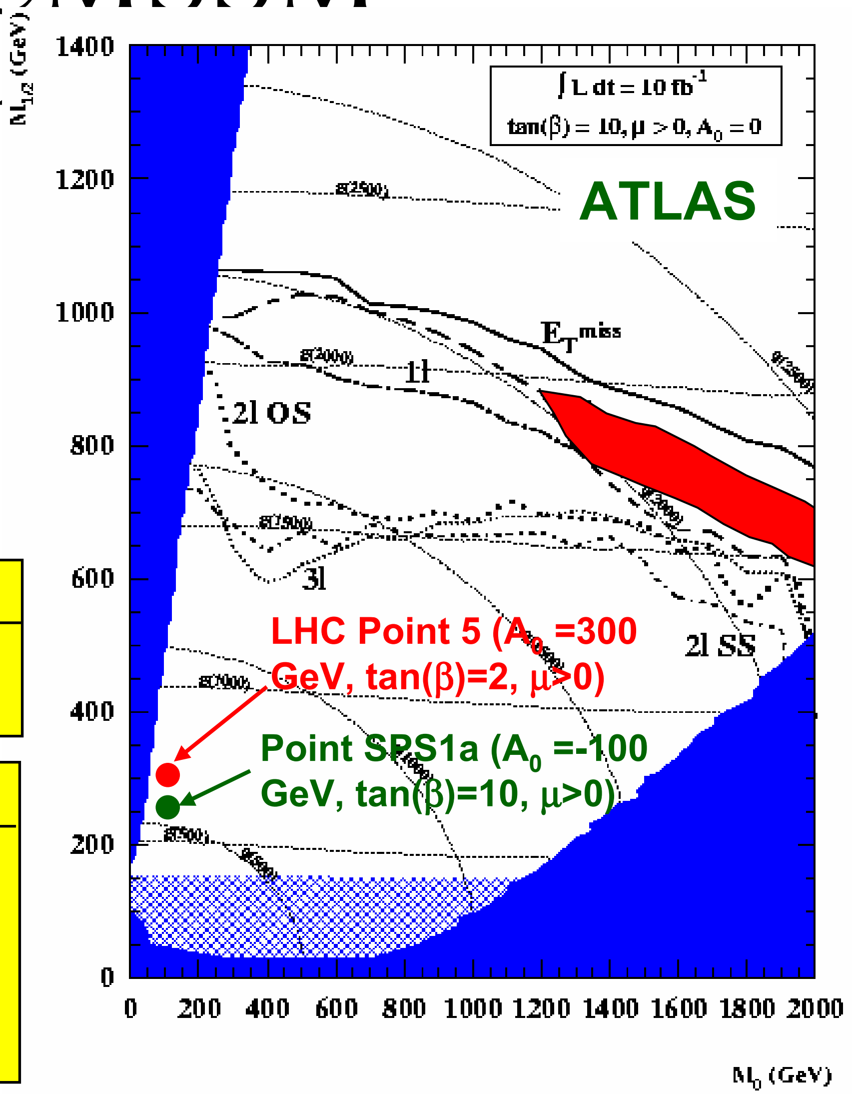
Measuring CMSSM Parame

- First indication of CMSSM parameters from inclusive channels
  - Compare significance in jets + E_T^{miss} + n leptons channels
-

Point	m_0	$m_{1/2}$	A_0	tan(β)	sign(μ)
LHC Point 5	100	300	300	2	+1
SPS1a	100	250	-100	10	+1

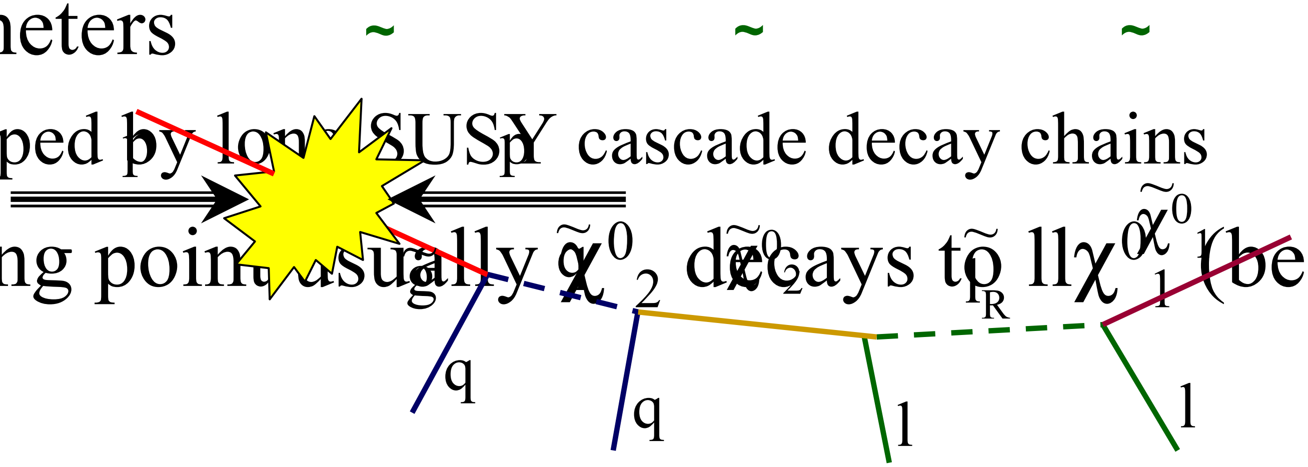
Sparticle	Mass (LHC Point 5)	Mass (SPS1a)
$\tilde{q}_L$	~690 GeV	~530 GeV
$\tilde{\chi}^0_2$	233 GeV	177 GeV
$\tilde{l}_R$	157 GeV	143 GeV
$\tilde{\chi}^0_1$	122 GeV	96 GeV

- previously:



Mass Measurements

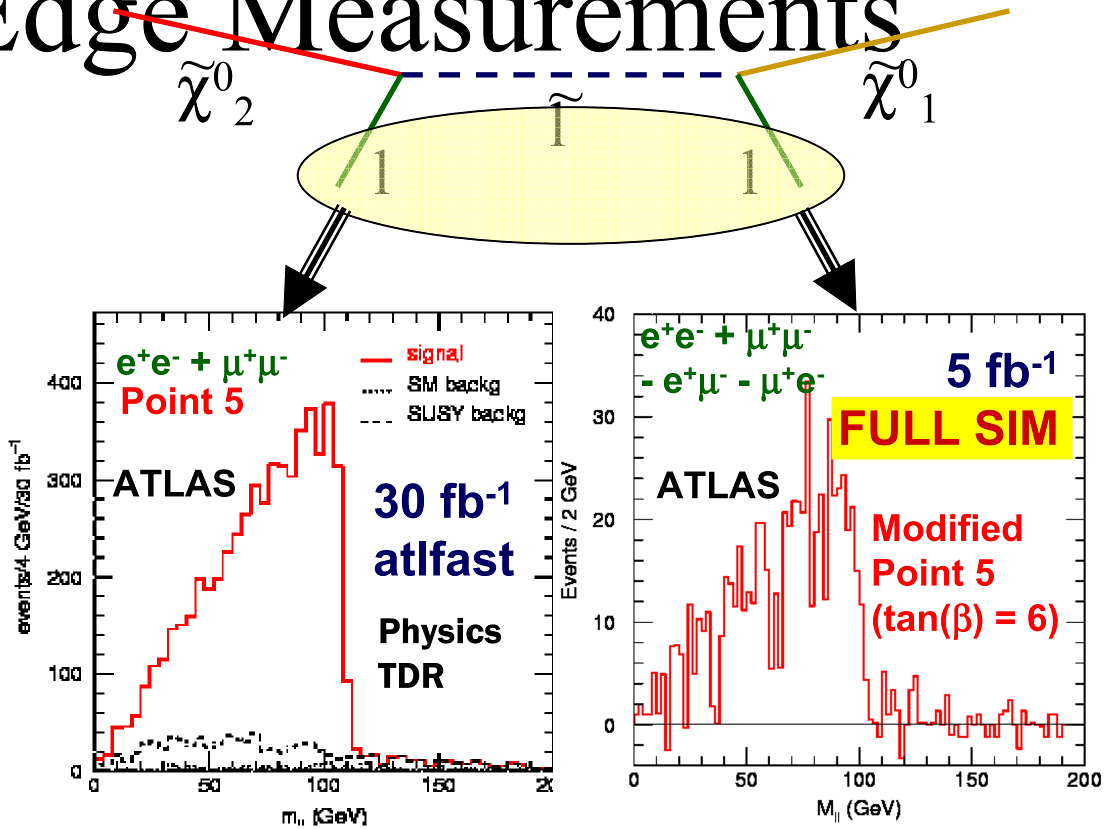
- Fit reconstructed mass combinations to obtain parameters
  - Helped by long SUSY cascade decay chains



- Starting point usually $\tilde{\chi}^0_2$ decays to $ll\chi^0_1$ (below) or $h\chi^0_1$
- Two neutral LSPs escape from each event

Dilepton Edge Measurements

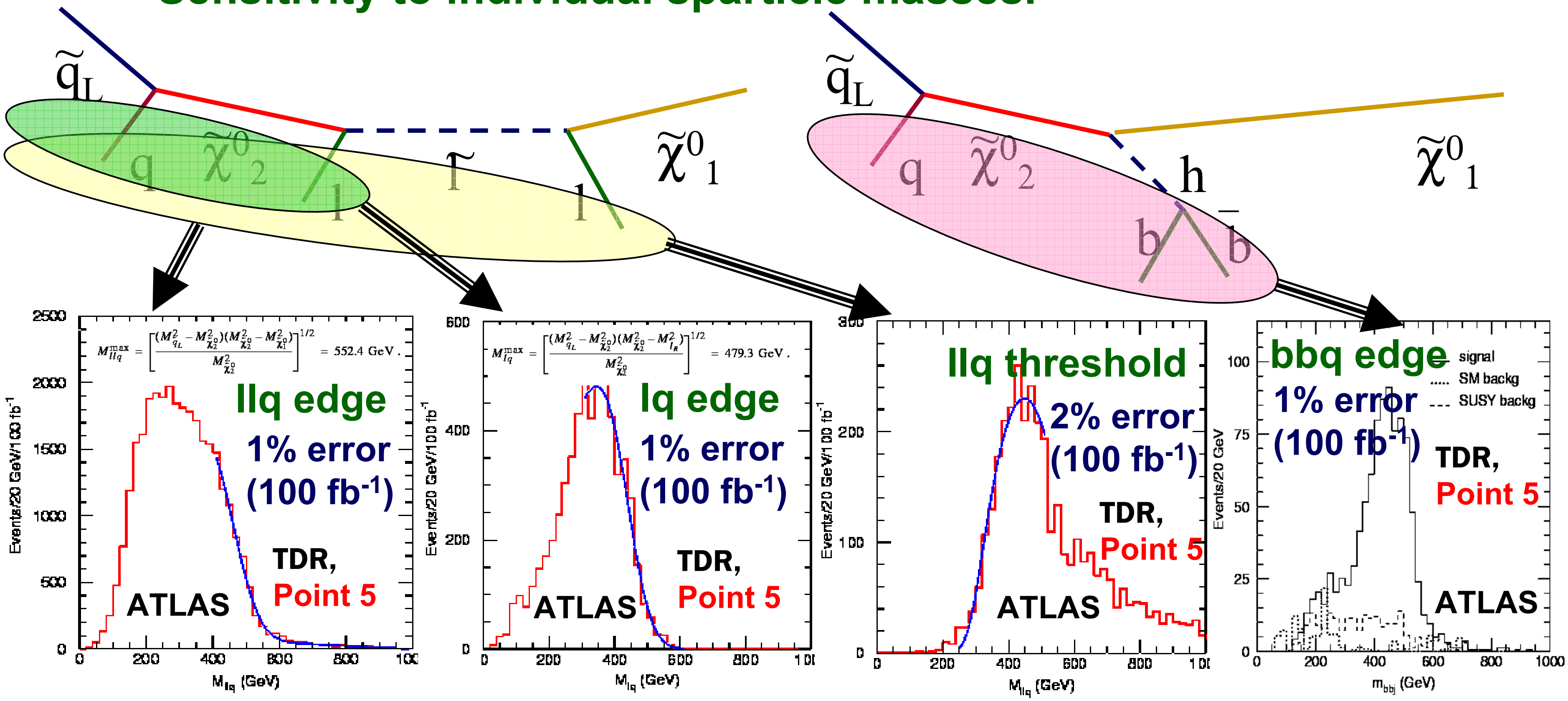
- When kinematically accessible χ^0_2 can undergo sequential two-body decay to χ^0_1 via a right-slepton (e.g. LHC Point 5).
- Results in sharp OS SF dilepton invariant mass edge sensitive to



$$M_{ll}^{max} = M(\tilde{\chi}^0_2)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}^0_2)}}\sqrt{1-\frac{M^2(\tilde{\chi}^0_1)}{M^2(\tilde{l}_R)}} = 108.93 \text{ GeV}$$

Measurements Involving Squarks

- **Dilepton edge starting point for reconstruction of decay chain.**
- **Make invariant mass combinations of leptons and jets.**
- **Gives multiple constraints on combinations of four masses.**
- **Sensitivity to individual sparticle masses.**



Measuring CMSSM Parameters

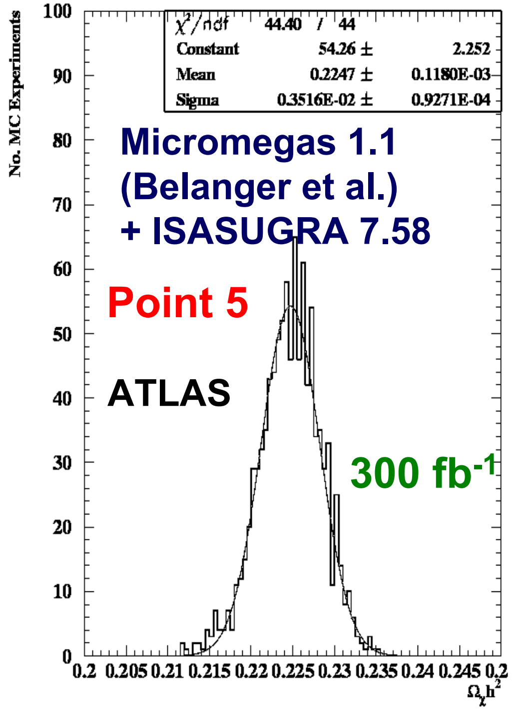
- Within CMSSM most direct approach is to calculate edge positions using sparticle masses and formulae (us[illegible] a [illegible]

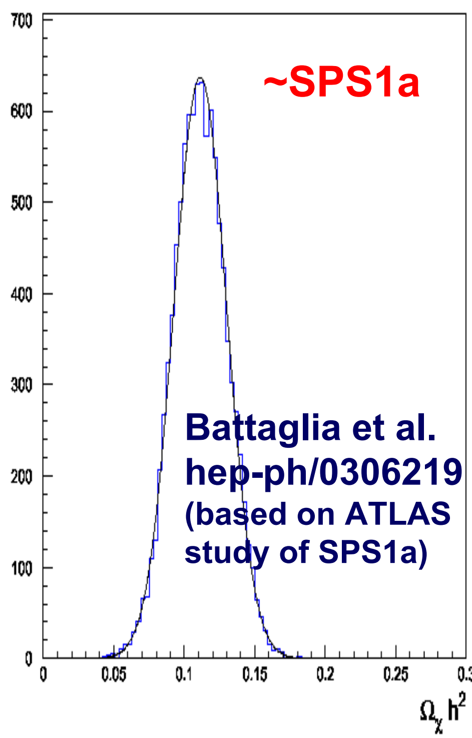
Point	m_0	$m_{1/2}$	A_0	tan(β)	sign(μ)
LHC Point 5	100	300	300	2	+1
SPS1a	100	250	-100	10	+1

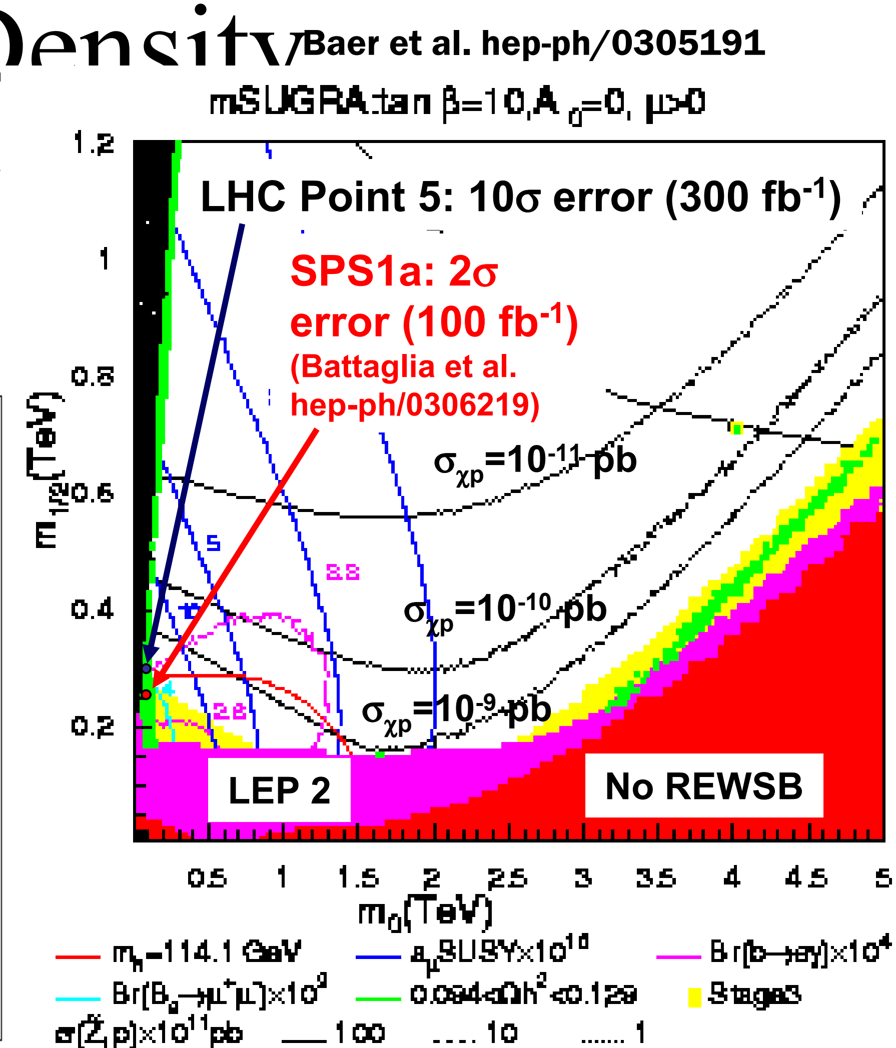
Parameter	Expected precision	
	30 fb^{-1}	300 fb^{-1}
m_0	± 3.2%	± 1.4%
$m_{1/2}$	± 0.9%	± 0.6%
tan(β)	± 0.5%	± 0.5%

Relic Density

- Measurement precision for $\Omega_\chi h^2$ depends strongly on region of parameter space

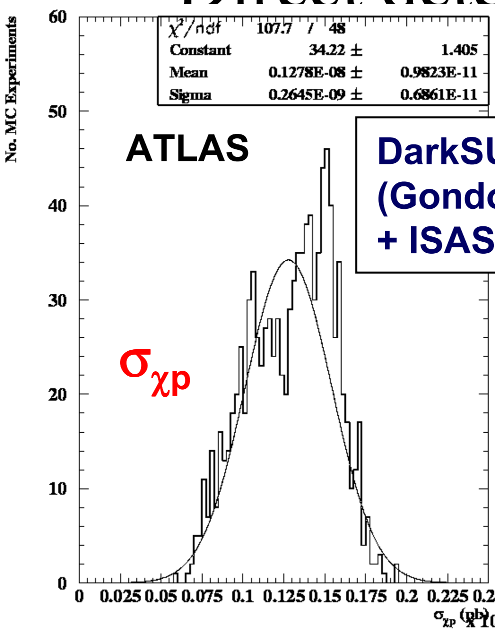


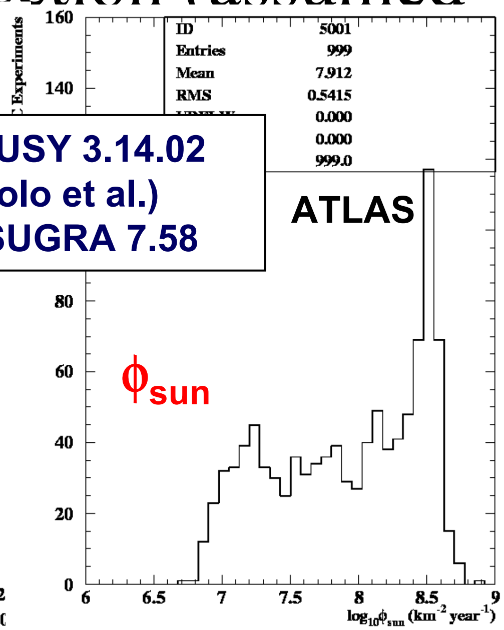


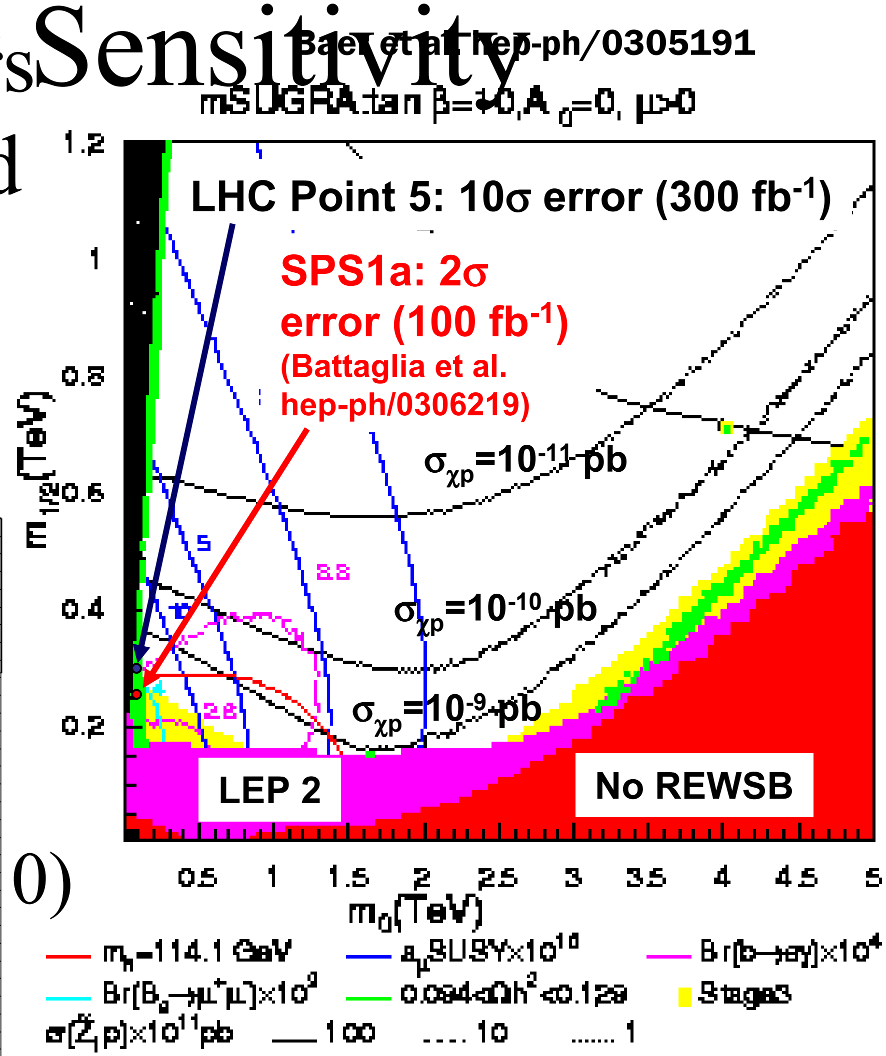


Dark Matter Sensitivity

- Also use model parameters to predict signals observed in terrestrial dark matter searches (Point 5)
  - Direct detection (assumed … 0)







Model-Independent Predictions

- Alternative approach to CMSSM fit to edge positions.

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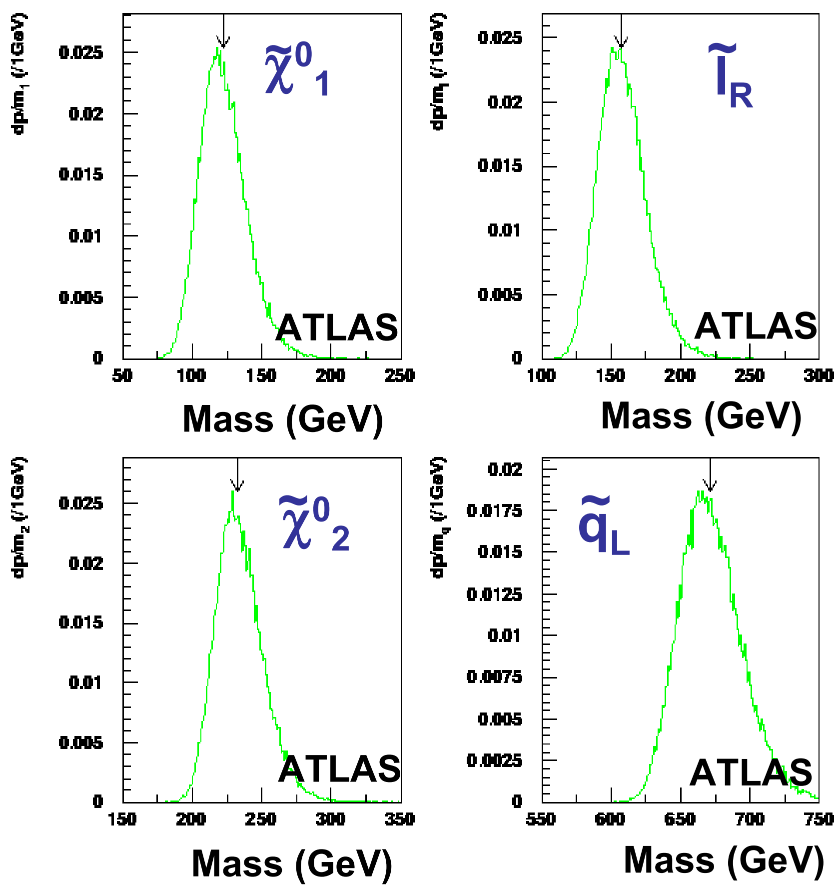
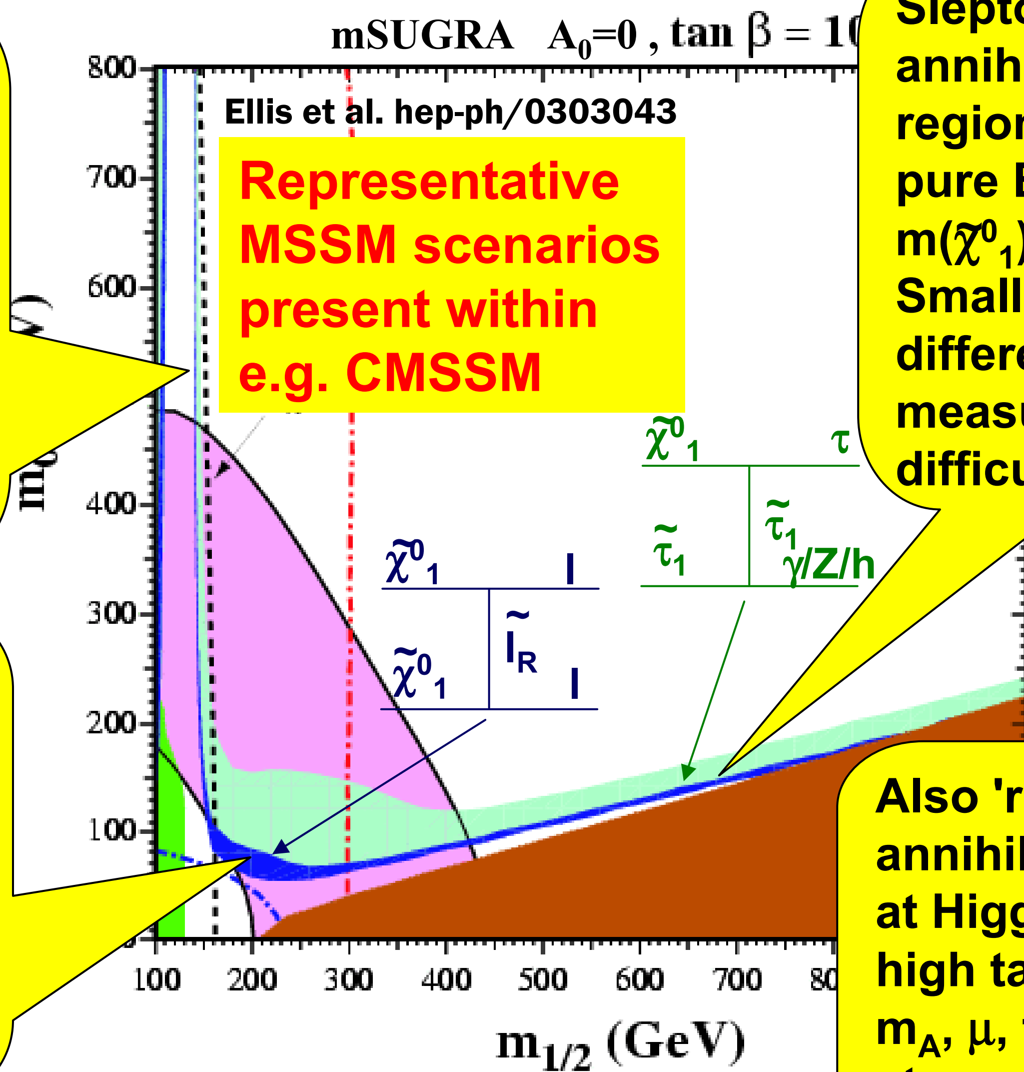


Similar process for $\tilde\tau_1$ mass at high tan(β)

Sparticle	Expected precision (100 fb^{-1})
$\tilde q_L$	$\pm$ 3%
$\tilde\chi^0_2$	$\pm$ 6%
$\tilde l_R$	$\pm$ 9%
$\tilde\chi^0_1$	$\pm$ 12%

- **Use approximations together with other measurements to obtain 'model-independent' estimates of $\Omega_\chi h^2$, $\sigma_{\chi p}$, ϕ_{sun} etc.**

'Focus point' region (significant $\tilde{h}$ component to LSP): v. difficult, need $m(\tilde{\chi}^0_1)$, μ, m_A $\tan(\beta)$ etc. + m(t) to high precision. More study needed



Slepton Co-annihilation region (LSP ~ pure Bino): need $m(\tilde{\chi}^0_1)$, $m(\tilde{\tau}_1)$. Small mass difference makes measurement difficult however.

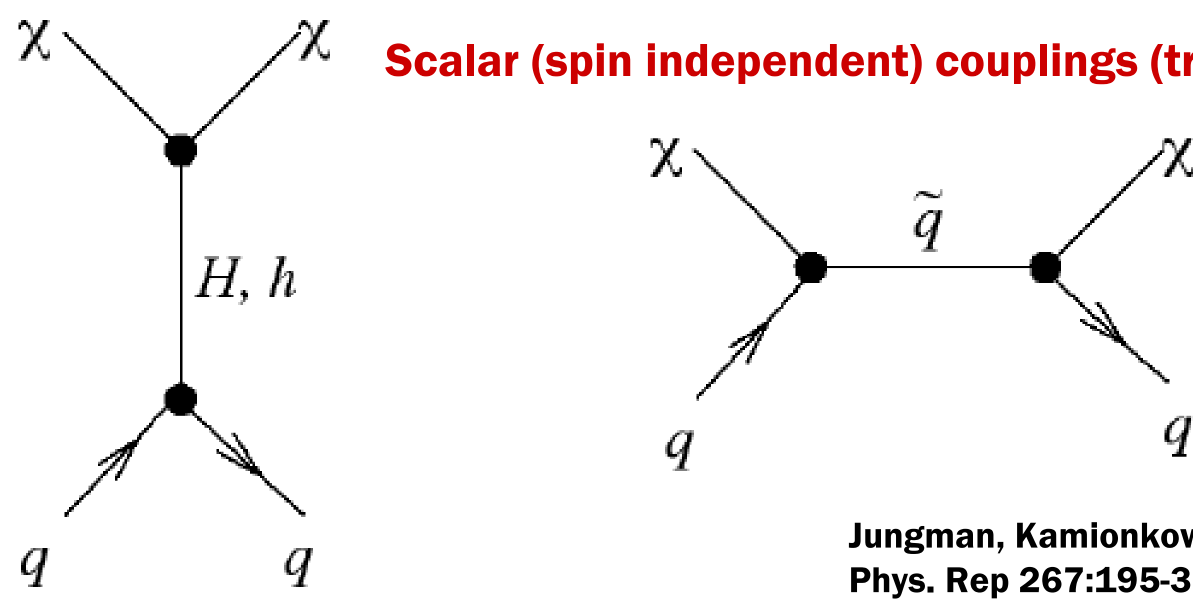
'Bulk' region (t-channel slepton exchange - LSP mostly Bino): need $m(\tilde{\chi}^0_1)$, $m(\tilde{l}_R)$, $m(\tilde{\tau}_1)$. 'Bread and Butter' region for LHC Expts.

Also 'rapid annihilation funnel' at Higgs pole at high $\tan(\beta)$: $m(\tilde{\chi}^0_1)$, m_A, μ, $\tan(\beta)$, m(t) etc. needed.

Dark Matter Searches

- Scalar elastic neutralino-nucleon scattering (DM direct detection) dominated by Higgs and squark exc… M(χ … n).

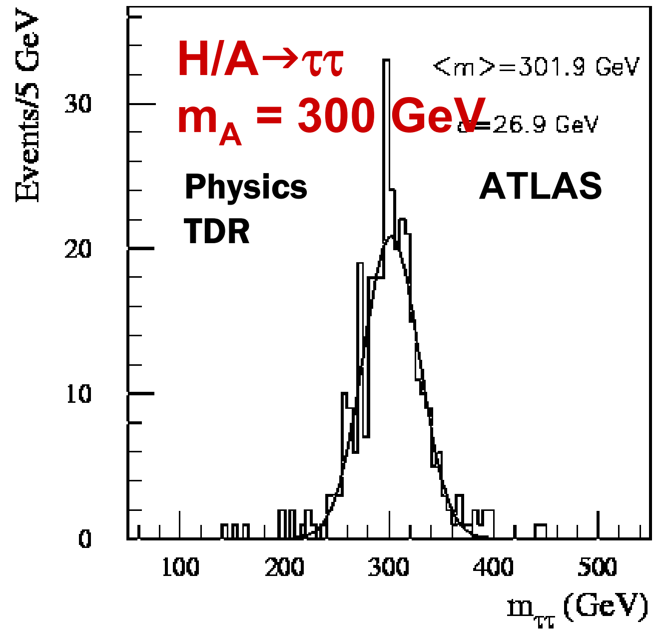
Scalar (spin independent) couplings (tree-level)

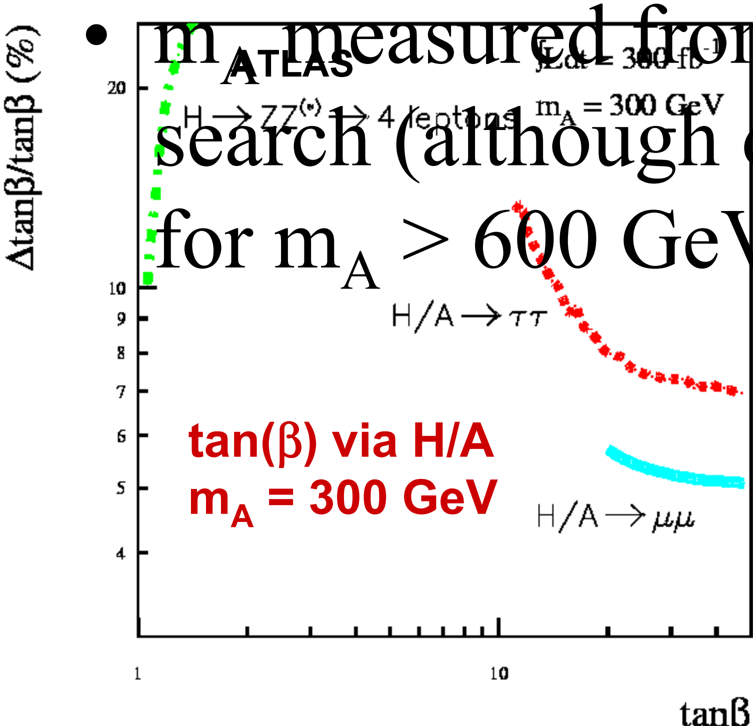


Jungman, Kamionkowski and Griest, Phys. Rep 267:195-373 (1996)

Other Measurements

- Further input regarding the weak scale SUSY parameters needed.
- m_A measured from direct search (although difficult for m_A > 600 GeV).





- Higgsino mass parameter μ (governs higgsino content of $\tilde{\chi}^0_1$) measurable from heavy neutralino edges.
- tan(β) accessible from σ.BR(H/A→ττ,μμ) or BR($\tilde{\chi}^0_2 \to \tau\tilde{\tau}_1$)/BR($\chi^0_2 \to l\tilde{l}_R$).
- More work needed.

Summary

- Following a SUSY discovery ATLAS will aim to test the SUSY Dark Matter hypothesis.
- Conclusive result only possible in conjunction with astroparticle experiments (constraints on LSP life-time).
- Estimation of relic density and direct / indirect DM detection cross-sections in model-dependent scenario will be first goal.
- Less model-dependent measurements will follow.
- Ultimate goal: observation of neutralinos at

This would be major triumph for both Particle Physics and Cosmology!

Earth from Apollo 17 (NASA)

The Fundamental Particles

Leptons

ν_e	ν_μ	ν_τ
~0.0 MeV 0 e	~0.0 MeV 0 e	~0.0 MeV 0 e
0.5 MeV -1 e	0.1 GeV -1 e	1.8 GeV -1 e
e	μ	τ

Quarks

uuu	ccc	ttt
5.0 MeV +2/3 e	1.3 GeV +2/3 e	175 GeV +2/3 e
10.5 MeV -1/3 e	0.2 GeV -1/3 e	4.3 GeV -1/3 e
ddd	sss	bbb