ATLAS Potential for Discovering and Measuring Supersymmetry at LHC



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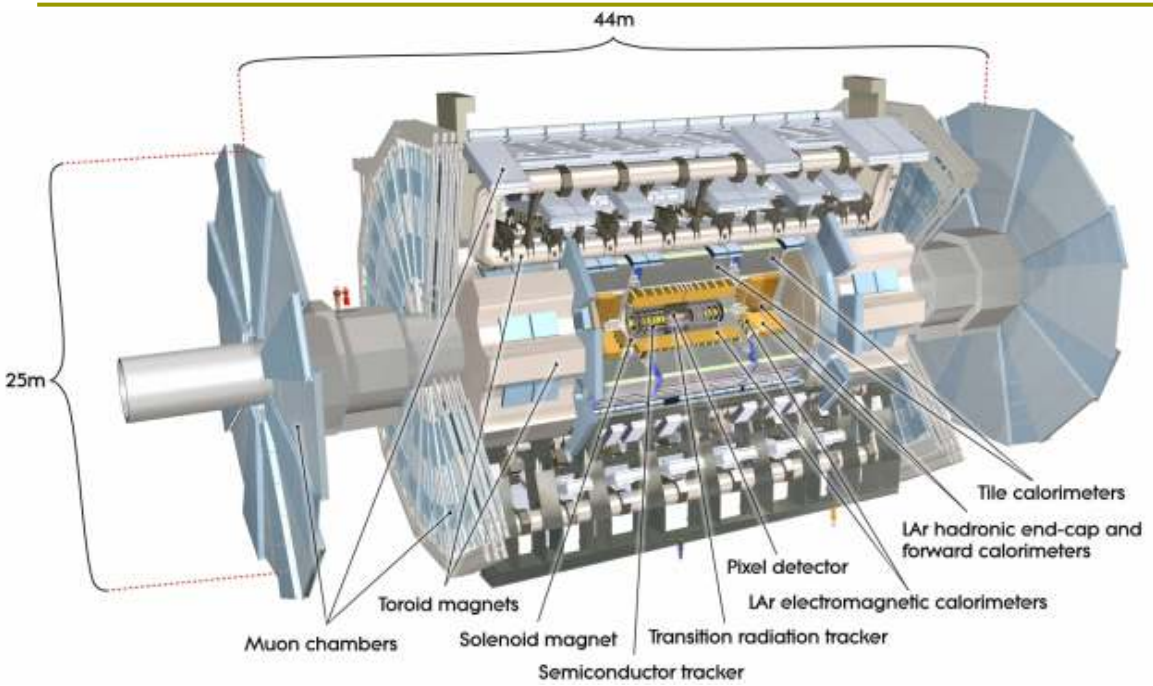
IFIC seminar

9 June 2008, Valencia, Spain

Outline

- Introduction
  - ATLAS/LHC status
  - Supersymmetry: motivation, framework, final states …
- ATLAS discovery potential - measurements
  - Background estimation from data
  - Inclusive signatures
    - discovery reach
  - Exclusive analyses
    - endpoint measurements
  - *R*-parity violation
  - MSSM Higgs bosons
- LHC versus Dark Matter evidence
  - Cosmology DM
  - Direct/indirect WIMP searches
  - Comparison with LHC, ILC
- Summary & outlook

The ATLAS detector



LHC luminosity

- **10^{31} – 10^{32} cm^{-2} s^{-1}**
  initial luminosity for which trigger menus have been defined in ATLAS
  ➔ useful for physics
  ➔ up to ~1 fb^{-1} collected
- **10^{33} cm^{-2} s^{-1}**
  low luminosity corresponding to 10 fb^{-1} per year
- **10^{34} cm^{-2} s^{-1}**
  high luminosity running corresponding to 100 fb^{-1} per year

LHC c.m.s. energy : $\sqrt{s} = 14$ TeV

Detector component	resolution	η coverage
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	$\lvert\eta\rvert < 2.5$
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$\lvert\eta\rvert < 3.2$
Hadronic calorimetry		
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$\lvert\eta\rvert < 3.2$
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1<\lvert\eta\rvert<4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%/p_T$ @ p_T=1 TeV	$\lvert\eta\rvert < 2.7$

LHC plans & ATLAS status

LHC

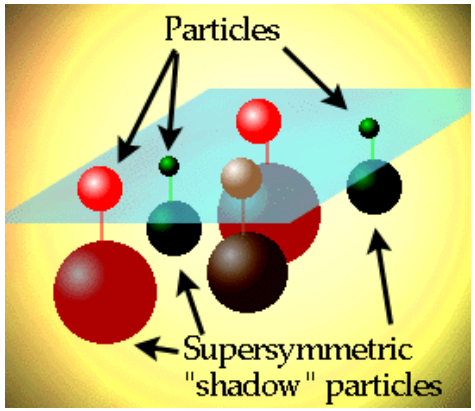
- End of June 2008
  - entire LHC cooled down
  - beam pipes of experiments baked out
- Middle of July
  - experimental caverns and tunnel closed
- End of July
  - first particles may be injected
  - commissioning with beams and collisions will start
- End of September
  - first collisions @ 10 TeV
  - safe setting to optimise up-time of the machine until winter shut-down
  - Few tens of pb^{-1} will be collected
- End of November: winter shut-down
  - commissioning and training of magnets up to full current
- 2009 run after winter shut-down will start at the **14 TeV** design energy

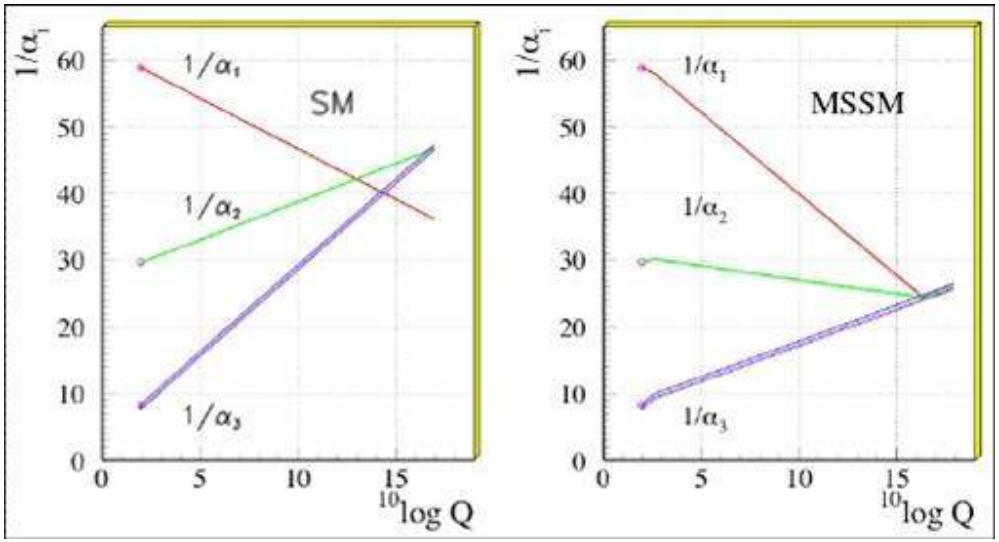
ATLAS

- Milestone weeks
  - detector timing and alignment
  - cosmics data taking
  - online software tests
- Full Dress Rehearsal (FDR)
  - data streaming
  - full data processing chain
- Computing System Commissioning (CSC) notes
  - assess sensitivity to early physics
    - realistic detector geometry
    - residual misalignments
    - trigger efficiency
  - exercise on current reconstruction and analysis software
- Simulations for 10 TeV c.m.e. have started

Supersymmetry (SUSY)

- Supersymmetry := fundamental global symmetry between fermions-bosons
  - all SM particles have SUSY-partners with spin difference of ±1/2
- Theoretical motivation
  - Higgs mass stabilisation against loop corrections (fine-tuning problem)
  - SUSY modifies running of SM gauge couplings 'just enough' to give Grand Unification at single scale
  - May explain Dark Matter
- Masses of SM states & SUSY partners cannot be degenerate in mass
  - Not observed
    → SUSY must be a broken symmetry at low energy
  - Various possible SUSY SB mechanisms proposed





SUSY particle spectrum

(□ = super-partners)

spin $\frac{1}{2}$	spin 0	spin 1	spin $\frac{1}{2}$
quark q_L, q_R	squark $\tilde{q}_L$, $\tilde{q}_R$	W_3, B	$\tilde{W}_3$, $\tilde{B}$
lepton ℓ_L, ℓ_R	slepton $\tilde{\ell}_L$, $\tilde{\ell}_R$	$W^\pm$	$\tilde{W}^\pm$
higgsino $\tilde{H}_1$, $\tilde{H}_2$	Higgs H_1, H_2	gluon g	gluino $\tilde{g}$

$\tilde{W}^\pm$, $\tilde{H}^\pm$ $\Longleftrightarrow$ charginos $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$

$\tilde{B}$, $\tilde{W}_3$, $\tilde{H}_1$, $\tilde{H}_2$ $\Longleftrightarrow$ neutralinos $\tilde{\chi}_1^0, \ldots, \tilde{\chi}_4^0$

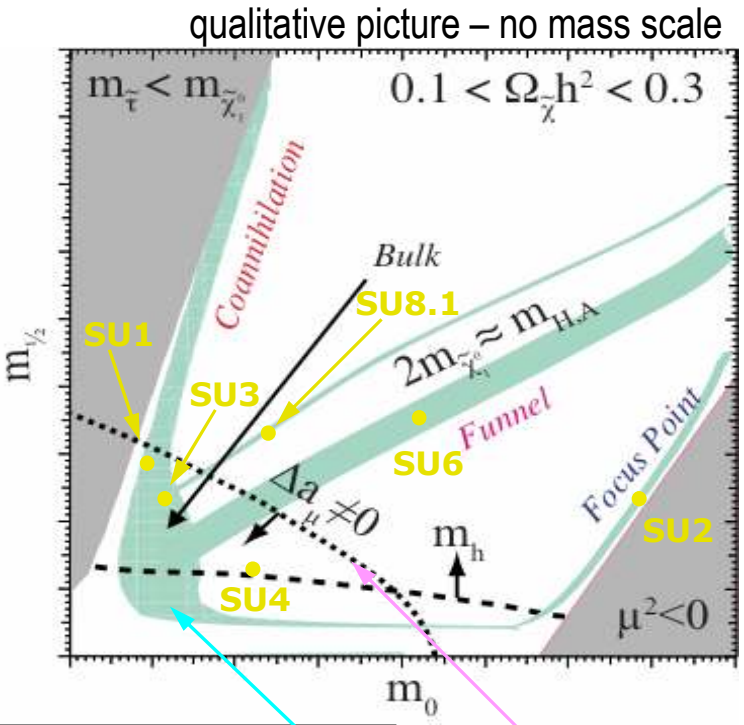
graviton (spin 2) $\leftrightarrow$ gravitino (spin 3/2)

- *R*-parity: $R = (-1)^{3(B-L)+2s}$ $\rightarrow$ $R = \begin{cases} +1, \text{ for SM particles} \\ -1, \text{ for superpartners} \end{cases}$
  - *R*-parity conservation hinted by *not required* by proton stability
  - Not a fundamental symmetry
- If *R*-parity is conserved:
  - SUSY-partners are always produced in pairs (*R* is a multiplicative quantum number)
  - Lightest SUSY-particle (LSP) is stable
    - should be colorless and neutral
    - dark matter candidate
    - weakly interacting → escapes the detector undetectable → *large missing energy*

PART I
Supersymmetry with ATLAS/LHC

SUSY model framework

- Minimal SuperSymmetric Standard Model (MSSM) contains >100 free parameters
  → assume specific physically-motivated model (Э gravity) for systematic studies
- Simplest: minimal SuperGravity (mSUGRA)
  - local SUSY with soft breaking mediated by gravitational interactions
  - universal masses and couplings at the GUT scale
    → 5 free parameters: m_0, $m_{1/2}$, tanβ, A_0, sgn(μ)
  - other models also investigated
    - GMSB: gauge messengers; light gravitino (LSP)
    - AMSB: anomalies in SUGRA $\mathcal{L}$; no flavour problem
- Benchmark points for exclusive studies (R-parity conserved)



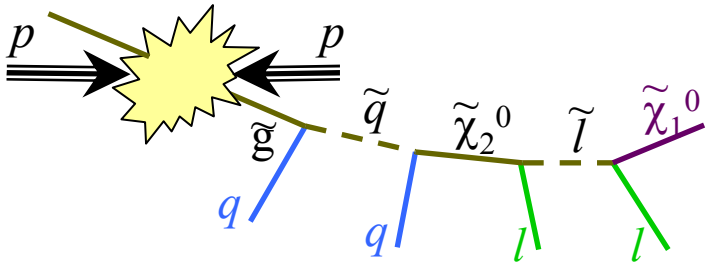
Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	tanβ	sgn(μ)	σ (pb)
Coannihilation - SU1	70	350	0	10	+	7.43
Focus Point - SU2	3550	300	0	10	+	4.86
Bulk - SU3	100	300	-300	6	+	18.6
Low Mass - SU4	200	160	-400	10	+	262
Funnel - SU6	320	375	0	50	+	4.48
Coannihilation - SU8.1	210	360	0	40	+	6.44

$(g-2)_\mu$ measurements

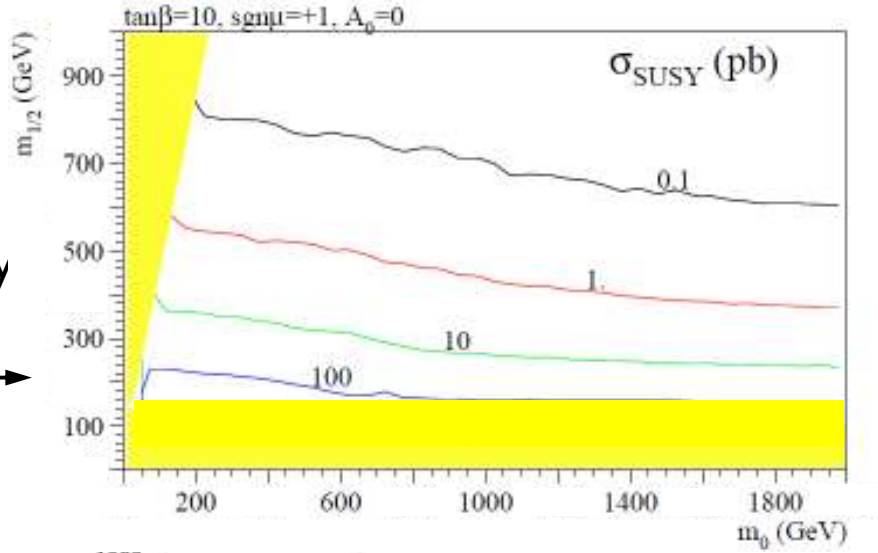
WMAP constraints on neutralino relic density

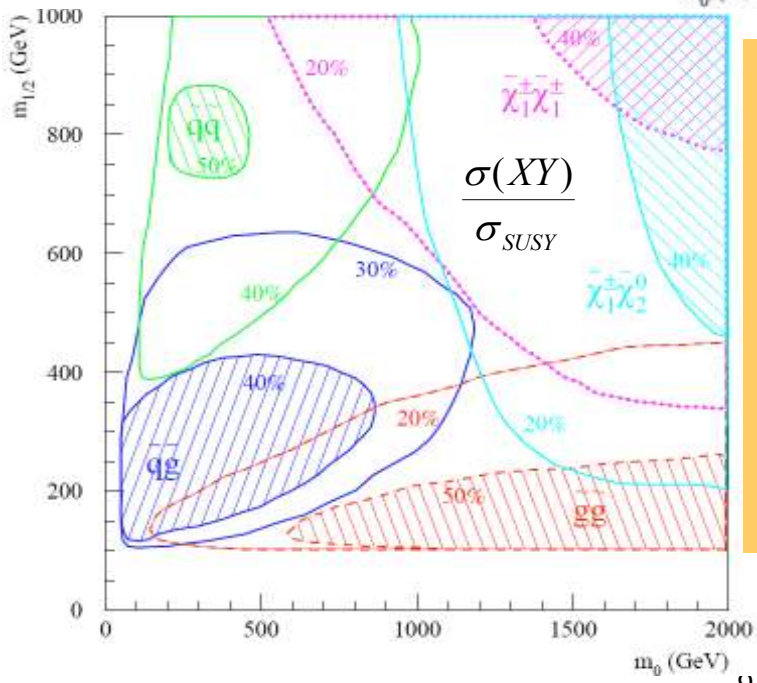
SUSY signature at LHC

- SUSY search is one of the major topics for LHC
- Focus on the early SUSY search at ATLAS
  → ~ 1 fb^{-1}: one year running at very low luminosity (10^{31}–10^{32} $cm^{-2}s^{-1}$)
- Relatively large cross sections
- Strongly interacting sparticles (squarks, gluinos) dominate production
- Long cascade decay into the LSP: e.g. lightest neutralino, $\tilde{\chi}_1^0$



- **'Golden discovery channel'**
  multi jets + missing E_T + (leptons)





V.A.M., PhD thesis (2002)

Strategy for SUSY searches @ LHC

- Model independent (as possible)
  - theoretically complicated
    - MSSM has > 100 parameters
    - many scenarios: mSUGRA, GMSB, AMSB, …
    - multi-dimensional parameter space: m_0, $m_{1/2}$, tanβ, …
  - experimentally rather simple
    - → search for multi-jets, large missing E_T and possibly high-p_T leptons
- Data-driven as possible
  - SUSY searches performed with early data at ATLAS
    - poor understanding of detector (jet energy scale, fake missing E_T, …)
    - large uncertainty of SM backgrounds, especially in signal region
  - → try to estimate dominant background sources using real data wherever possible, instead of believing Monte Carlo estimates

Main SM background

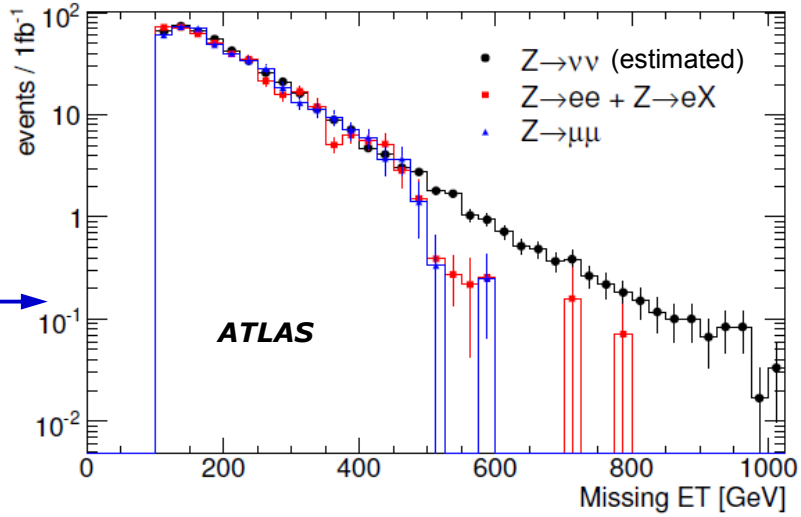
- top-antitop pairs
- W+jets
- Z+jets
- QCD jets
- diboson processes (ZZ, WW, WZ)

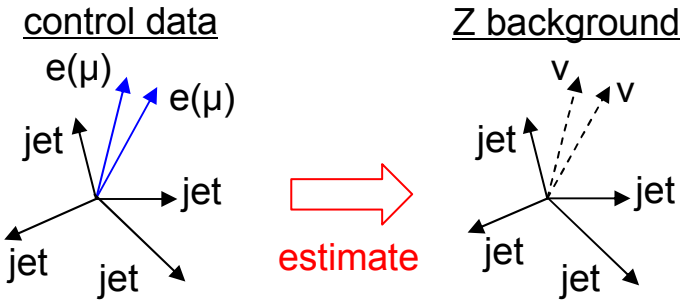
Baseline SUSY cuts

- at least 2 jets of p_T > 50 GeV
- leading jet of p_T > 100 GeV
- missing E_T > 100 GeV
- missing E_T > 0.2 M_{eff}
- transverse sphericity > 0.2
- leptons
  - either lepton veto
  - or exactly 1 or 2 leptons

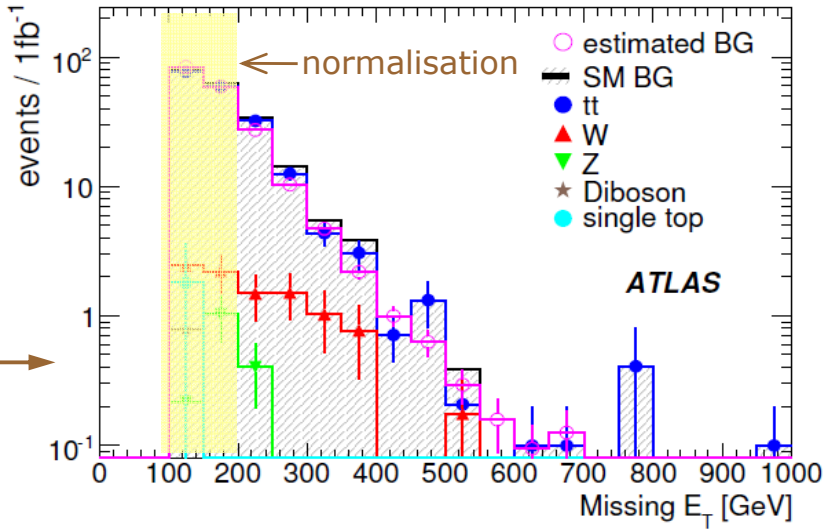
Background estimation from data

- **General aim: estimate bkg in a control sample and `propagate' this measurement to the signal sample**
  - Control region should be as close as possible to signal region
  - SUSY contamination should be as low as possible; if not, should be tackled by applying, e.g. an iterative technique
- Replace method in no-lepton mode
  - estimate E_T^{miss} distribution of $Z \rightarrow \nu\nu$ from $p_T(\ell^+\ell^-)$ distribution of $Z \rightarrow \ell^+\ell^-$
  - apply corrections for lepton reconstruction efficiency and coverage, additional cuts, …





- Reversing M_T cut in one-lepton mode
  - bkg to be measured: tt ($\ell\nu qq$)
  - signal region: M_T > 100 GeV
  - control region: M_T < 100 GeV
  - normalisation in 100 GeV < E_T^{miss} < 200 GeV



ATLAS collab, ATL-COM-PHYS-2008-063

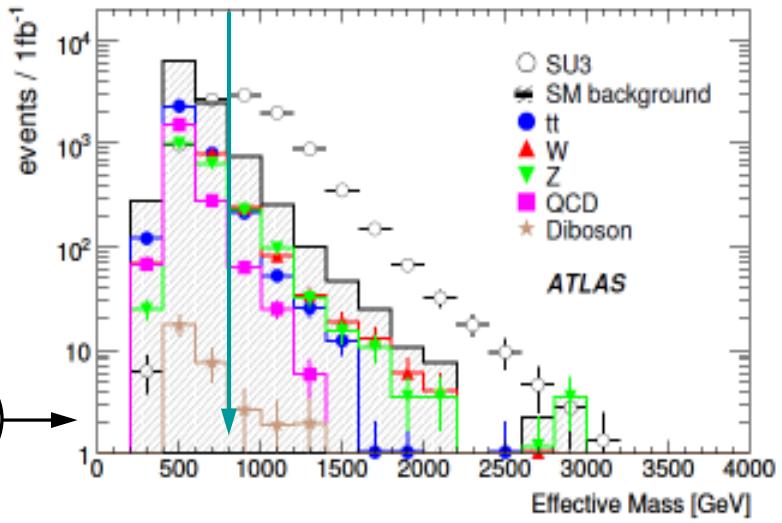
Discriminating variables

- Effective mass, M_{eff}

$$M_{\text{eff}} = \sum_{4\text{ jets}} p_{\text{T}} + \sum_{\text{leptons}} p_{\text{T}} + E_{\text{T}}^{miss}$$

  - correlates with SUSY mass scale
  - example: no-lepton mode @ 1 fb^{-1}
    - lepton veto (no e or μ)
    - $p_T^{j1} > 150$ GeV
    - $p_T^{j2} > 100$ GeV
    - $E_T^{miss} > 0.3\ M_{eff}$
    - $\delta\varphi(\text{jet}_i, E_T^{miss}) > 0.2$
    - **$M_{eff} > 800$ GeV**

0-lepton plus 2 jets analysis after all cuts have been applied



ATLAS collab, CSC note, ATL-COM-PHYS-2008-063

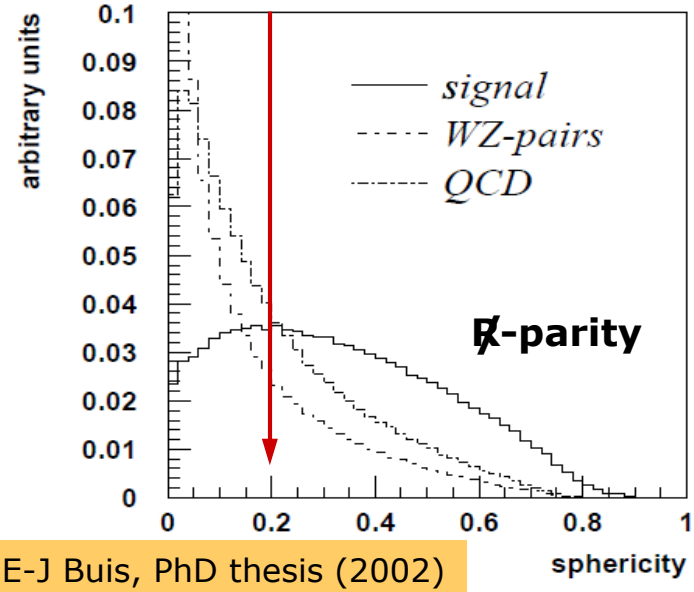
- Transverse sphericity, S_T

$$S_T = 2\min(\lambda_1, \lambda_2)/(\lambda_1 + \lambda_2)$$

  - λ_1, λ_2 eigenvalues of the 2×2 sphericity tensor

$$S_{ij} = \sum_k p_{ki} p^{kj}$$

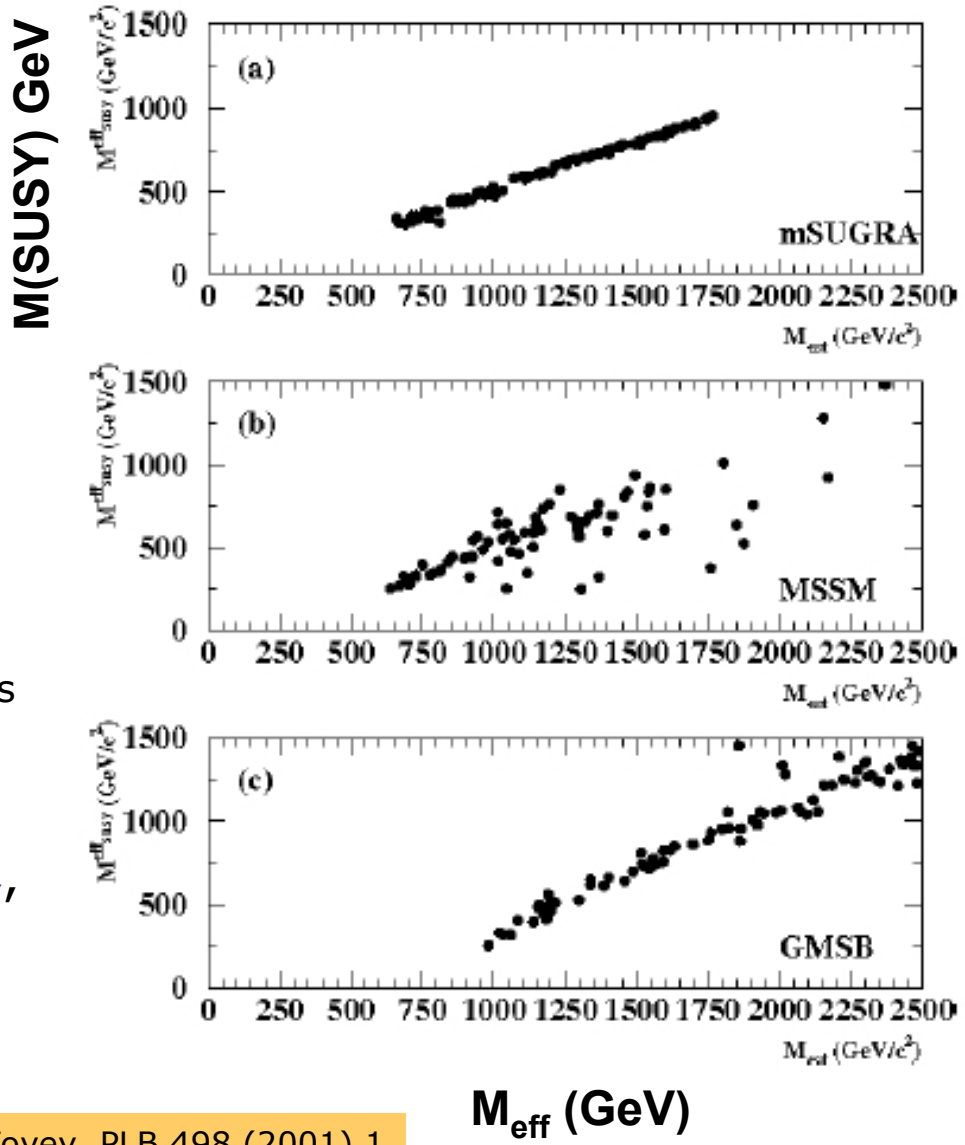
    calculated over all jets ($p_T^{jet} > 20$ GeV) and leptons
  - SUSY events are more `spherical'
  - Common cuts in SUSY analyses: **$S_T > 0.2$**



E-J Buis, PhD thesis (2002)

SUSY mass scale versus M_{eff}

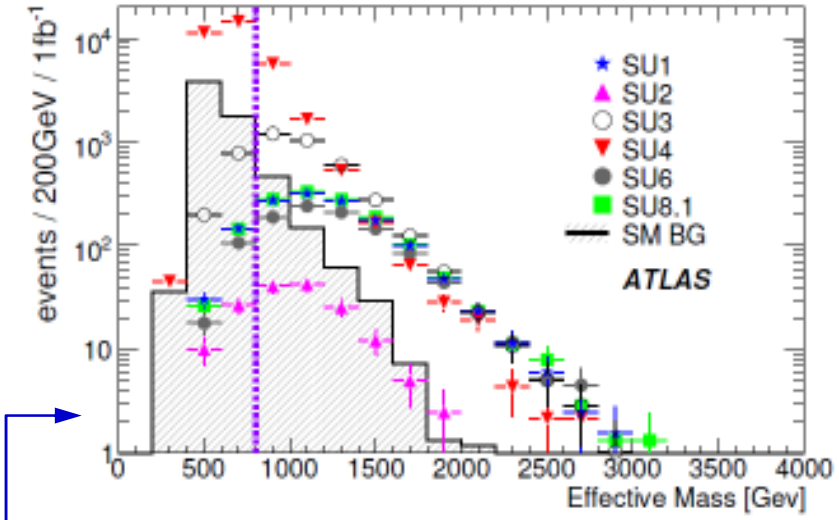
- SUSY mass scale, M_{SUSY}, is defined as the average of squark and gluino masses
- The M_{eff} peak is strongly correlated to the SUSY mass scale
- Measurement of M_{SUSY} is feasible with 10 fb^{-1}
  - 15% precision for mSUGRA
  - 40% precision for MSSM
  - also possible for GMSB with rapid decays to gravitino LSP
    - significantly increased statistics needed
    - or variables using photon or lepton p_T
- Total SUSY cross section, σ_{SUSY}, can be estimated in a similar way with 10 fb^{-1} with a precision of
  - 15% in mSUGRA
  - 50% in MSSM



D R Tovey, PLB 498 (2001) 1

Inclusive signatures

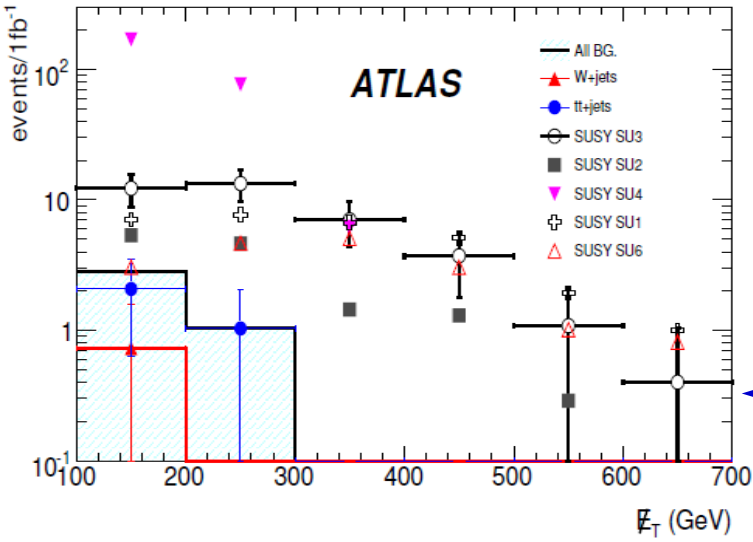
4 jets + E_T^{miss} + 0 leptons



- **Veto on electrons & muons**
- $\Delta\varphi(E_T^{miss}, jet_{1\text{-}3}) > 0.2$ against mismeasured jets (QCD bkg)

4 jets + E_T^{miss} + 2 leptons

ATLAS collab, CSC note, ATL-COM-PHYS-2008-063



Exactly two isolated **opposite-sign leptons** (e, μ) with $p_T > 20$ GeV

Exactly two isolated **same-sign leptons** (e, μ) with $p_T > 20$ GeV

Common cuts

- at least 4 jets with $p_T > 50$ GeV
- $p_T(jet_1) > 100$ GeV
- $E_T^{miss} > \max(100\text{ GeV}, 0.2M_{eff})$
- transverse sphericity $S_T > 0.2$

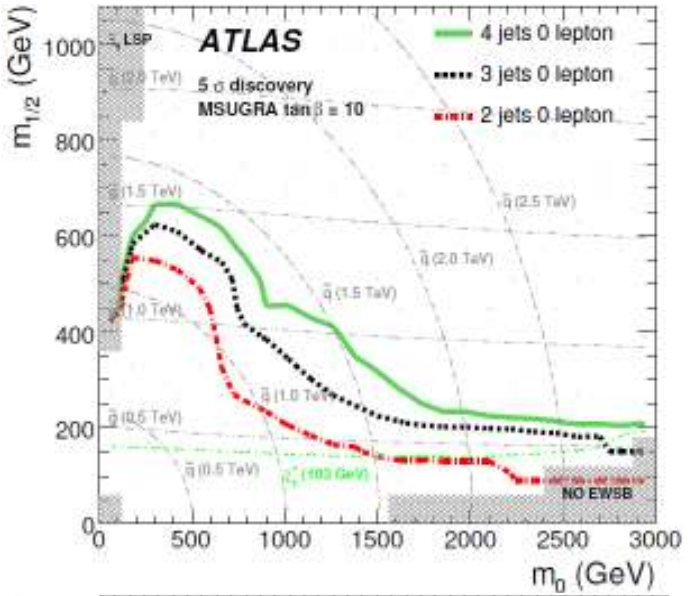
Point	S/B	Z_n
SU3	1.88	7.3
SU1	0.86	3.5
SU2	0.22	0.9
SU4	9.56	19.7

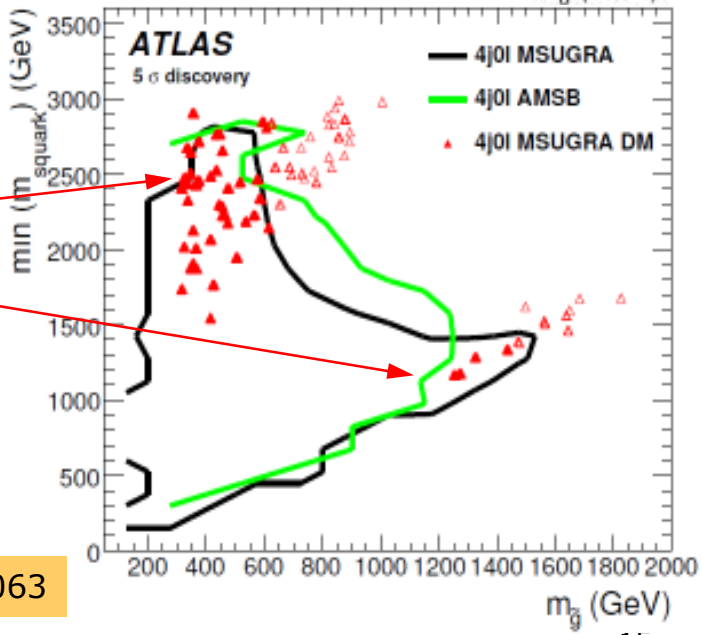
measure of significance

Clear excess of events is visible with 1 fb^{-1}

Inclusive search: discovery reach @ 1fb^{-1}

- **Search for: *m* jets + E_T^{miss} (+ *n* leptons)**
- Sensitivity only weakly dependent on tanβ, A_0 & sgn(μ)
- M_{eff} cut optimised to maximise significance $Z_n^{(*)}$
- Best reach achieved with 0-lepton mode
- 1-lepton mode more robust against QCD bkg
- **SUSY @ 2 TeV is accesible with 1 fb^{-1} (1 year of data taking)**
  - **also true for GMSM** (not shown)
  - **result independent of chosen model (mSUGRA, AMSB, …)**
- Caveat: excess of events is not enough
  - possibly other physics beyond the Standard Model
  - further precision measurements required



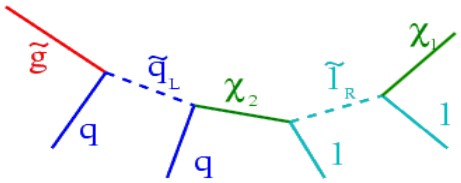


Random mSUGRA points compatible with various constraints (dark matter, $(g-2)_\mu$, …)

(*) **Z_n**: measure of significance which takes into account systematic uncertainties on bkg estimation
- 50% on QCD bkg
- 20% on tt-bar, W+jets, Z+jets, di-bosons

ATLAS collab, CSC note, ATL-COM-PHYS-2008-063

Exclusive studies



- SUSY events contain two LSPs which escape the detector
  - reconstruction of mass peaks impossible
- Mass measurement strategy
  - apply kinematics on long decay chains to link endpoints with combinations of masses
  - measure endpoints (edges, thresholds) in invariant mass distributions
- $\tilde{g}, \tilde{b}_1, \tilde{b}_2$ masses: near di-lepton endpoint
- $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{q}_L, \tilde{q}_R$ masses: kinematic endpoints and stransverse mass M_{T2} (variant of M_T for two-body decays)
- Comments:
  - cuts applied depend on the SUSY mass scale; has to be known from M_{eff} distribution
  - method does not depend on underlying model (pure kinematics)

Related edge	Kinematic endpoint
l^+l^- edge	$(m_{ll}^{\max})^2 = (\tilde{\xi}-\tilde{l})(\tilde{l}-\tilde{\chi})/\tilde{l}$
l^+l^-q edge	$(m_{llq}^{\max})^2 = \begin{cases} \max\left[\frac{(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi})}{\tilde{\xi}}, \frac{(\tilde{q}-\tilde{l})(\tilde{l}-\tilde{\chi})}{\tilde{l}}, \frac{(\tilde{q}\tilde{l}-\tilde{\xi}\tilde{\chi})(\tilde{\xi}-\tilde{l})}{\tilde{\xi}\tilde{l}}\right] \\ \text{except for the special case in which } \tilde{l}^2 < \tilde{q}\tilde{\chi} < \tilde{\xi}^2 \\ \text{and } \tilde{\xi}^2\tilde{\chi} < \tilde{q}\tilde{l}^2 \text{ where one must use } (m_{\tilde{q}} - m_{\tilde{\chi}_1^0})^2. \end{cases}$
Xq edge	$(m_{Xq}^{\max})^2 = X + (\tilde{q}-\tilde{\xi})\left[\tilde{\xi} + X - \tilde{\chi} + \sqrt{(\tilde{\xi}-X-\tilde{\chi})^2 - 4X\tilde{\chi}}\right]/(2\tilde{\xi})$
l^+l^-q threshold	$(m_{llq}^{\min})^2 = \begin{cases} [2\tilde{l}(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi}) + (\tilde{q}+\tilde{\xi})(\tilde{\xi}-\tilde{l})(\tilde{l}-\tilde{\chi}) \\ -(\tilde{q}-\tilde{\xi})\sqrt{(\tilde{\xi}+\tilde{l})^2(\tilde{l}+\tilde{\chi})^2 - 16\tilde{\xi}\tilde{l}^2\tilde{\chi}}]/(4\tilde{l}\tilde{\xi}) \end{cases}$
$l^{\pm}_{\text{near}}\, q$ edge	$(m_{l^{\pm}_{\text{near}}\, q}^{\max})^2 = (\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{l})/\tilde{\xi}$
$l^{\pm}_{\text{far}}\, q$ edge	$(m_{l^{\pm}_{\text{far}}\, q}^{\max})^2 = (\tilde{q}-\tilde{\xi})(\tilde{l}-\tilde{\chi})/\tilde{l}$
$l^{\pm}q$ high-edge	$(m_{lq(\text{high})}^{\max})^2 = \max\left[(m_{l^{\pm}_{\text{near}}\, q}^{\max})^2, (m_{l^{\pm}_{\text{far}}\, q}^{\max})^2\right]$
$l^{\pm}q$ low-edge	$(m_{lq(\text{low})}^{\max})^2 = \min\left[(m_{l^{\pm}_{\text{near}}\, q}^{\max})^2, (\tilde{q}-\tilde{\xi})(\tilde{l}-\tilde{\chi})/(2\tilde{l}-\tilde{\chi})\right]$
M_{T2} edge	$\Delta M = m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$

$$\tilde{\chi} = m^2_{\tilde{\chi}_1^0}, \tilde{l} = m^2_{\tilde{l}_R}, \tilde{\xi} = m^2_{\tilde{\chi}_2^0}, \tilde{q} = m^2_{\tilde{q}} \text{ and } X \text{ is } m_h^2 \text{ or } m_Z^2$$

Allanach *et al.*, JHEP 09 (2000) 004

Di-lepton endpoint

$$\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^{\pm} l^{\mp}$$

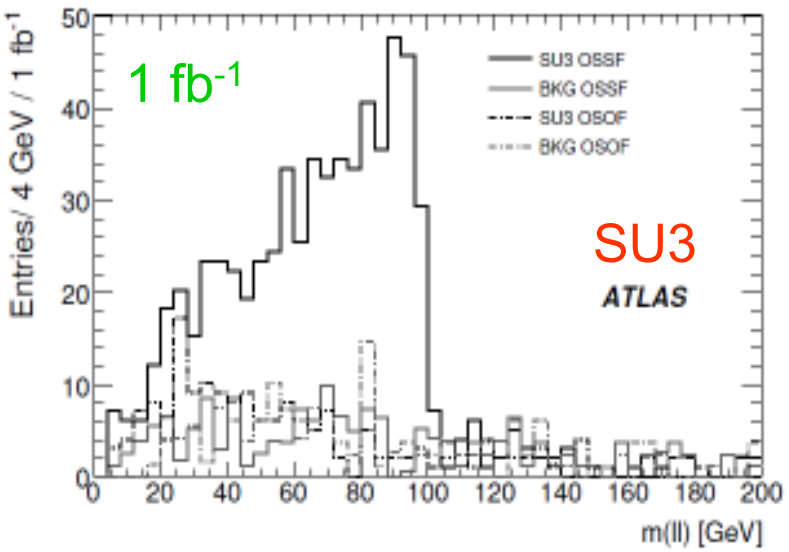
$$M_{ll}^{\max} = \sqrt{\frac{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{l}}^2)(M_{\tilde{l}}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{l}}^2}}$$

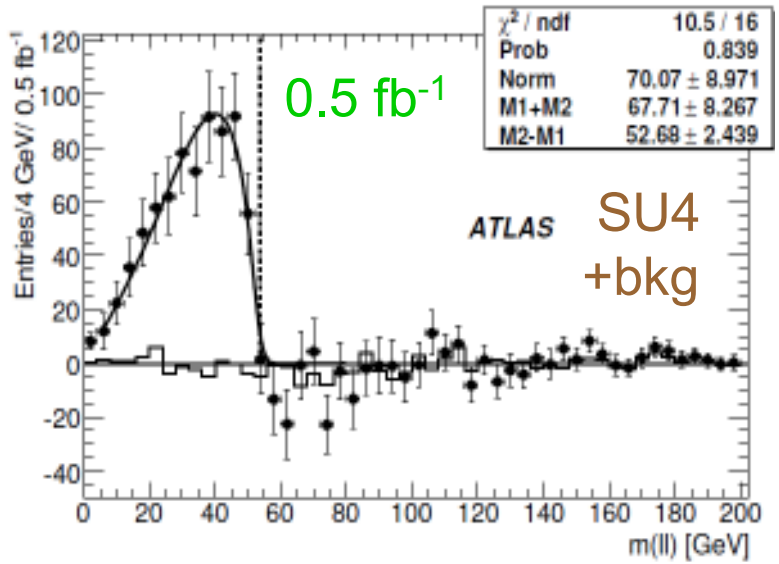
- Event selection:
  - 2 or 3 leptons with p_T > 10 GeV, |η| < 2.5
  - at least 2 jets: $p_T(j_1)$ > 180 (100) GeV, $p_T(j_2)$ > 100 (50) GeV for SU3 (SU4)
  - E_T^{miss} > 120 GeV
  - ($M_{\ell\ell} < M_{\ell\ell}^{max}$ + 10 GeV)
- **Flavour subtraction** is applied (OSSF-OSOF) to remove SUSY/SM background

$$N(e^{\pm}e^{\mp})/\beta + \beta N(\mu^{\pm}\mu^{\mp}) - N(e^{\pm}\mu^{\mp}), \quad \beta = \varepsilon_e/\varepsilon_\mu$$

- Fit triangular distribution with a Gaussian smearing

mSUGRA point	Expected endpoint (GeV)	Fitted endpoint with σ_{stat}, σ_{sys} (GeV)
SU3	100.2	(99.7±1.4±0.3)
SU4	53.6	(52.7±2.4±0.2)

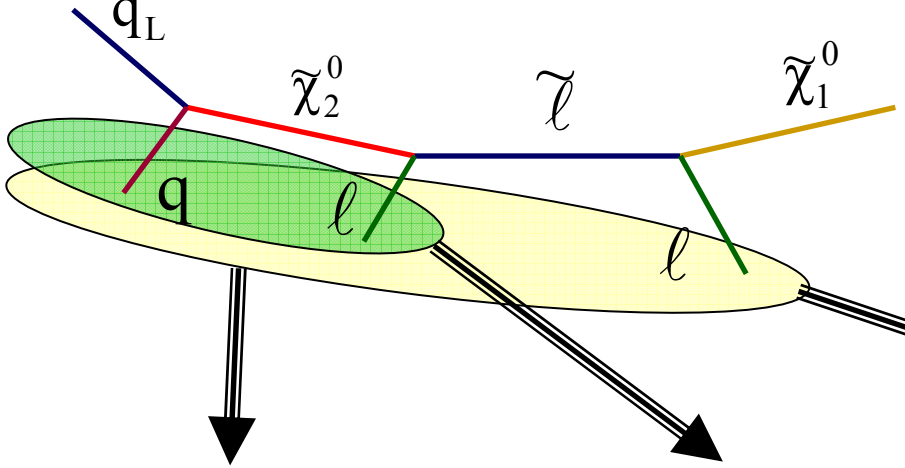




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Leptons+jet edges

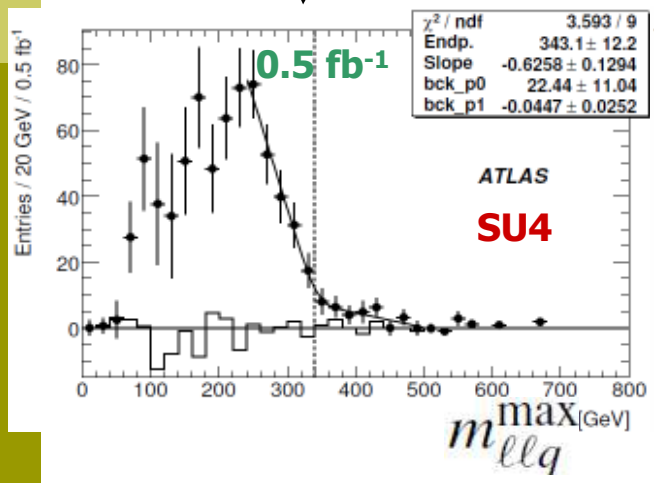
- Di-lepton edge starting point for reconstruction of decay chain
- Make invariant mass combinations of leptons and jets
- Gives multiple constraints on combinations of four masses
- Sensitivity to individual sparticle masses

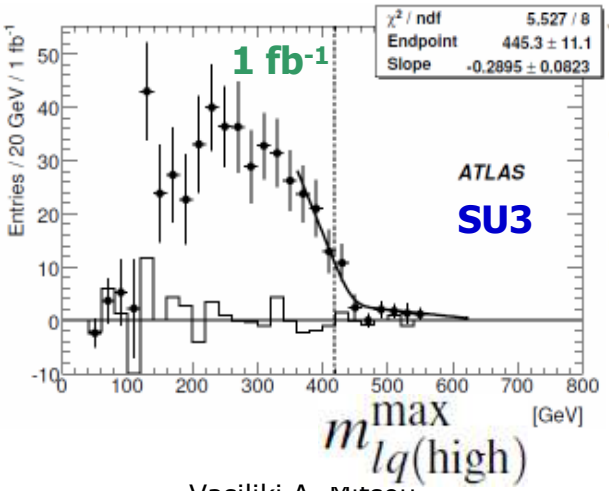


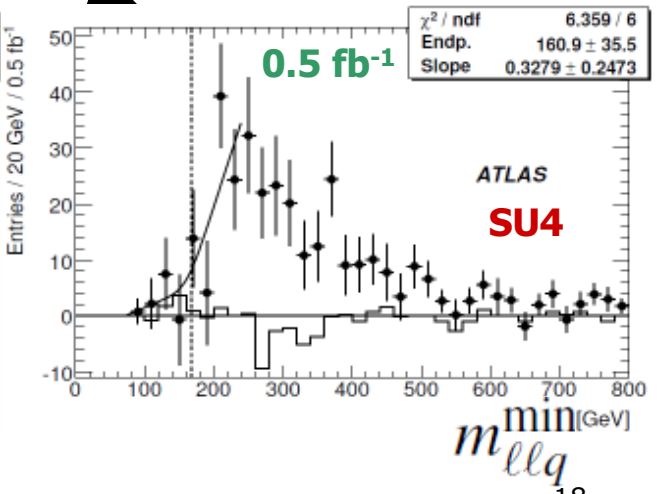
with 1 fb^{-1}

Endpoint	SU3 truth	SU3 measured
$m_{\ell\ell q}^{\max}$	501	$517 \pm 30 \pm 10 \pm 13$
$m_{\ell\ell q}^{\min}$	249	$265 \pm 17 \pm 15 \pm 7$
$m_{lq(\mathrm{low})}^{\max}$	325	$333 \pm 6 \pm 6 \pm 8$
$m_{lq(\mathrm{high})}^{\max}$	418	$445 \pm 11 \pm 11 \pm 11$

ATLAS collab, CSC note, ATL-COM-PHYS-2008-063







mSUGRA masses/parameters determination

ATLAS collab, CSC note, ATL-COM-PHYS-2008-063

Measurement of mass combinations - `endpoints'

$m_{\ell\ell q}^{\max}$ $m_{lq(\text{high})}^{\max}$ $m_{\ell\ell q}^{\min}$ ...

Sparticles masses determination with high uncertainty even for SU3 (optimum case)

1 fb^{-1}

$\delta m(\tilde{\chi}_1^0) = 70\%$ $\delta m(\tilde{q}) = 15\%$

$\delta m(\tilde{\chi}_2^0) = 30\%$ $\delta m(\tilde{\ell}) = 50\%$

mSUGRA parameters determination:

1 fb^{-1}

- m_0, $m_{1/2}$ at 1–3%
- tanβ, A_0 only order of magnitude
- *BUT:* Higgs width measurement ➔ tanβ determination

Fitting mass combinations with Sfitter program

	SPS1a	error
m_0	100	**1.2 (1%)**
$m_{1/2}$	250	**1.0 (0.4%)**
tanβ	10	**0.9 (9%)**
A_0	-100	**20 (20%)**

If sgn(μ) fixed

300 fb^{-1}

Determination of mSUGRA parameters with a precision at the percent level

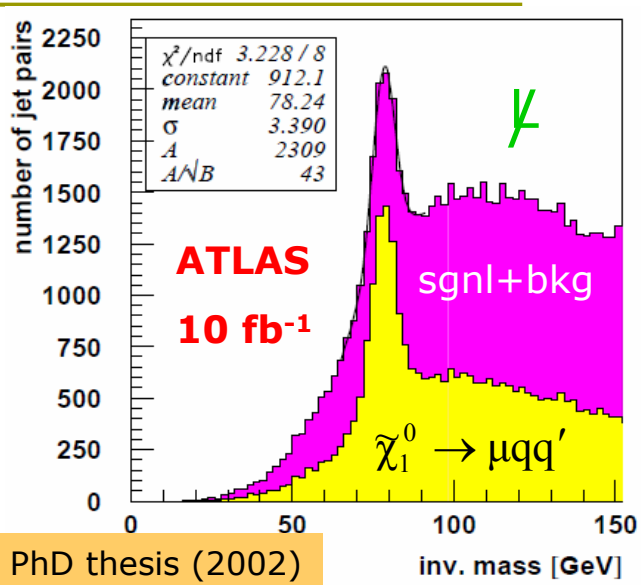
Lafaye *et al,* hep-ph/0512028

For a more precise parameter determination, SLHC, ILC is needed

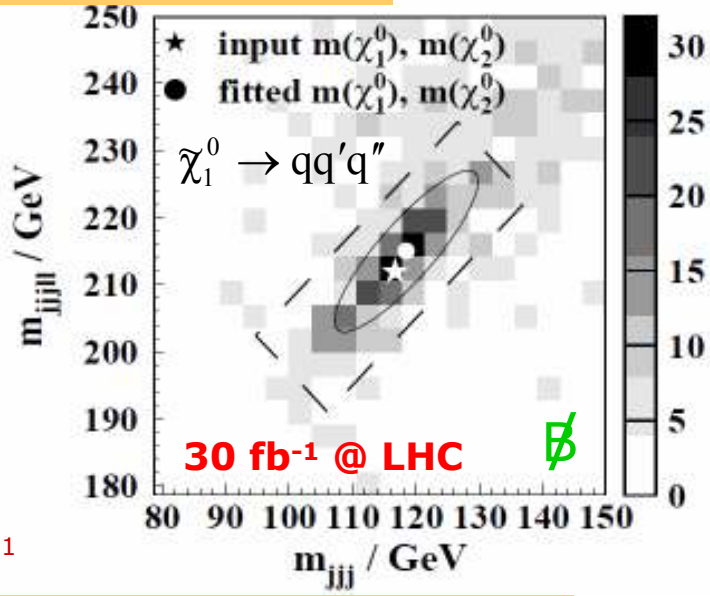
R-parity violation (RPV)

$R = (-1)^{3(B-L)+2s}$

- Proton stability → either baryon or lepton number can be violated (not both!)
- Phenomenological consequences
  - single sparticle production is allowed
  - LSP may be charged (e.g. stau, sleptons)
  - LSP is not stable!
  - no missing energy! (if LSP decays in the detector)
- What about dark matter (DM)?
  - constraints on neuralino relic densities do *not* apply, if LSP lifetime < age of Universe
  - other non-SUSY particles may account for DM *(axions, wimpzillas, KK gravitons, …)*
  - possible DM candidates in SUSY with RPV:
    - gravitino NLSP with lifetime much longer than the age of the Universe
    - cosmologically long-lived axino LSP or neutralino LSP (split SUSY)
- RPV @ ATLAS/LHC
  - various cases have been studied: B or L violating; dilepton production; in top decays; stau LSP; sneutrino LSP; …
  - RPV SUSY can be discovered and studied with 10 fb^{-1}



E-J Buis, PhD thesis (2002)



Allanach *et al*, JHEP 0103 (2001) 048

Bilinear RPV studies

- R-parity violating terms in superpotential:

L-number violating terms

bilinear terms

$$W_{\not R_P} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

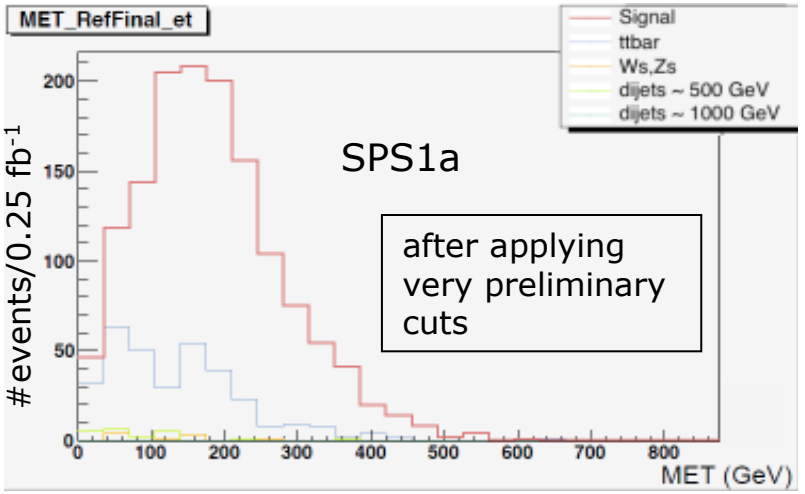
B-number violating term

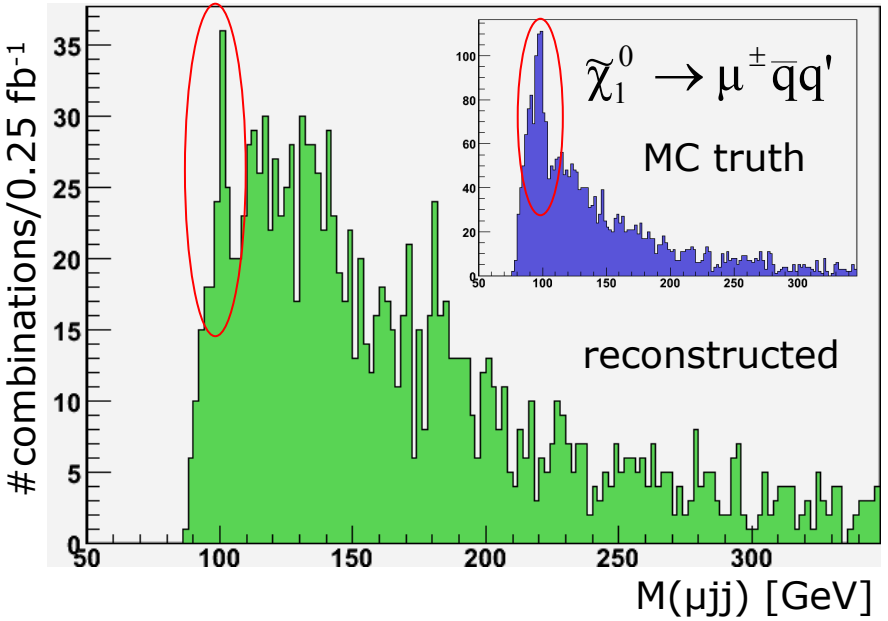
- Specific model under study [Hirsch, Diaz, Porod, Romao, Valle, PRD 62 (2000) 113008]:
  - relevant for neutrino masses and mixing
  - BRs of LSP sensitive to neutrino mixing parameters,

$$\text{e.g.: } \tan^2\theta_{atm} \approx \frac{BR(\tilde{\chi}_1^0 \to \mu^{\pm}W^{\mp})}{BR(\tilde{\chi}_1^0 \to \tau^{\pm}W^{\mp})}$$

- Very preliminary selection criteria
  - missing E_T (MET) *not* a discriminating variable against SM bkg
  - high transverse sphericity and M_{eff}
  - multi-jets & high-p_T leptons
  - $|M(jj)-M_W| < 5$ GeV
  - key point: reconstruct displaced vertex from LSP decay

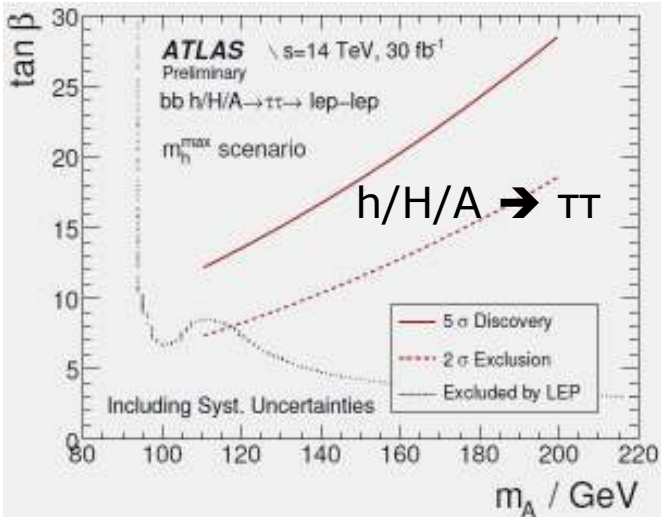
E. Torró, V.A.M., C. García, ongoing analysis

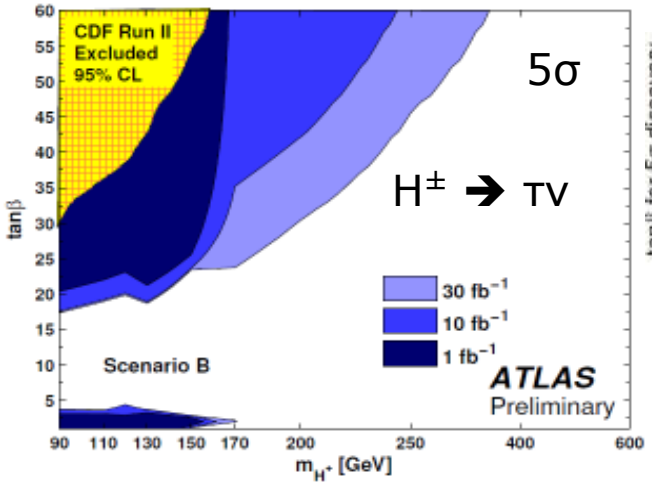


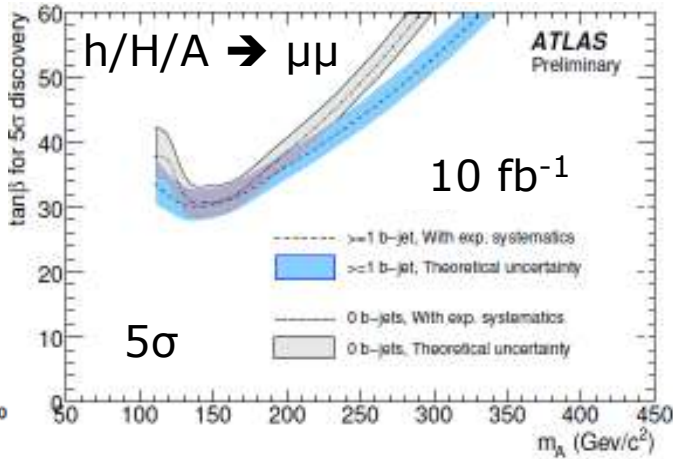


What about the (SUSY) Higgs bosons?

- Supersymmetry requires two Higgs doublets ➔ five physical states
  - three neutral: two CP-even (h and H) and one CP-odd (A)
  - two charged: H^+, H^-
- The lightest Higgs, h, can be discovered in the whole (m_A, tanβ) plane
  - however, indistinguishable from a light SM Higgs
  - discovery of other (heavy) Higgs bosons (➔SUSY) should be necessary
- Searches for MSSM Higgs boson
  - analysis for neutral Higgs focused on:
    - inclusive (gg fusion and VBF), applying b-jet veto
    - associated with a b-jet pair, requiring ≥ 1 b-jet
  - decay modes: h/H/A ➔ ττ, h/H/A ➔ μμ
  - charged Higgs: $H^\pm$ ➔ τν
- Measurement of Higgs properties with 300 fb^{-1}:
  - mass (~0.1%)
  - width / tanβ (5–10%)
  - couplings (~20%)
  - spin / **CP**







Higgs properties – CP violation

- In principle, supersymmetric Higgs bosons are CP eigenstates
- However, from electroweak baryogenesis:
  - baryon asymmetry: $\eta_b = (n_b - n_{\bar{b}})/n_\gamma = (6.3 \pm 0.3) \times 10^{-10}$ from large scale structure & cosmic microwave background measurements
  - CKM quark mixing cannot account for observed asymmetry
  - ➔ more CP violation required
- Possible sources of additional CP violation
  - leptogenesis
  - SUSY squarks
  - SUSY Higgs sector
- If CP-violation appears in the SUSY Higgs sector ➔ H/A mixing
  [e.g. Bernabeu, Binosi, Papavassiliou, JHEP09 (2006) 023]
- Study decay H/A ➔ ττ and exploit τ polarisation
  [Ellis, Lee, Pilaftsis, PRD 70 (2004) 075010]
  - Possibly testable with ATLAS/LHC, through the energy and angular distributions of the decay products of the tau leptons
  - **under study!** (Bernabeu, V.A.M., Papavassiliou, Pilaftsis)

Recap: What LHC can(not) tell us about SUSY?

- SUSY discovery potential
  - SUSY @ 1 TeV with 0.1 fb^{-1} – could be first discovery
  - SUSY @ 2 TeV with 1-10 fb^{-1} – within 1 year of data taking
  - SUSY @ 5 TeV – may need SLHC
- Measurement of effective mass
  - mass scale
  - total SUSY x-section
- Endpoint measurements
  - sparticle masses at 10% level
  - model parameters at 1 – 10% level (assuming specific model!)
- Higgs sector
  - discovery of SM Higgs: observable for the whole allowed mass range
  - additional Higgs bosons from the MSSM can be discovered on a large fraction of the parameter space
  - measurement of Higgs bosons properties is possible with 300 fb^{-1}
    - masses, total width, ratios of couplings, spin / CP properties
- *And what it cannot tell us ...*
  - *observe and measure the full gaugino spectrum (in particular charginos)*
  - *constrain model parameters to < 1%*
  - *define directly the nature of neutralino & chargino (higgsino / bino / wino -like?)*

PART II
Supersymmetry: LHC vs Dark Matter Studies

Dark matter: cosmological evidence

- Astrophysical evidence (purely gravitational)
  - Galactic rotation curves
  - Velocity dispersions of galaxies
  - Gravitational lensing
  - Structure formation
- The case for Cold DM
  - Large structure formation disfavour:
    - Ulta-relativistic (Hot DM): neutrinos …
    - Relativistic (Warm DM): sterile neutrinos …
  - ➔ CDM: non-relativistic matter
- CDM candidates
  - Weakly Interacting Massive Particles (WIMPs)
    - 3 GeV < m_X < 50 TeV
    - thermal relics from Big Bang
    - possible WIMPs
      - supersymmetric neutralino (R-Parity Cons)
      - Kaluza-Klein states
      - axino, gravitino (SuperWIMPS)
      - heavy neutrino-like particles
      - T-odd states in "Little Higgs"
  - Axions (introduced to solve strong CP problem)
  - Non-thermal (maybe superheavy) relics
    - wimpzillas, cryptons, …

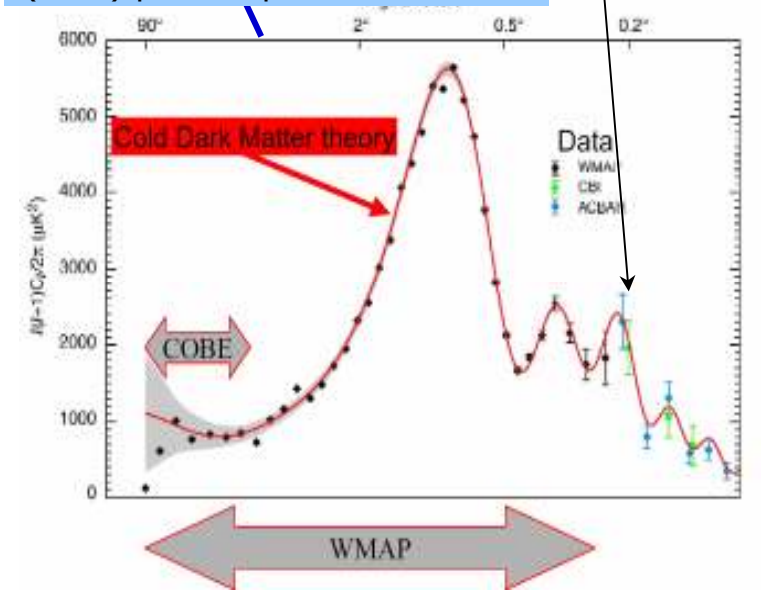
~23% dark matter
~5% ordinary matter (baryonic mostly)
~72% dark energy



Bradac et al, ApJ 652 (2006) 937

sensitive to DM

Cosmic Microwave Background (CMB) power spectum



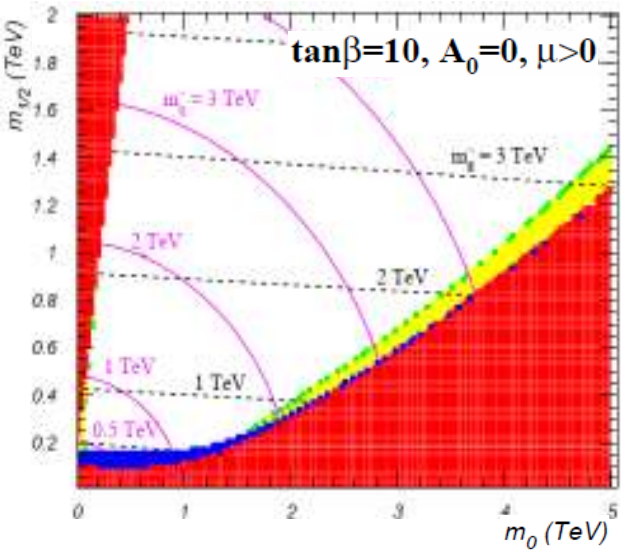
Spergel *et al,* ApJ 170 (2007) 377

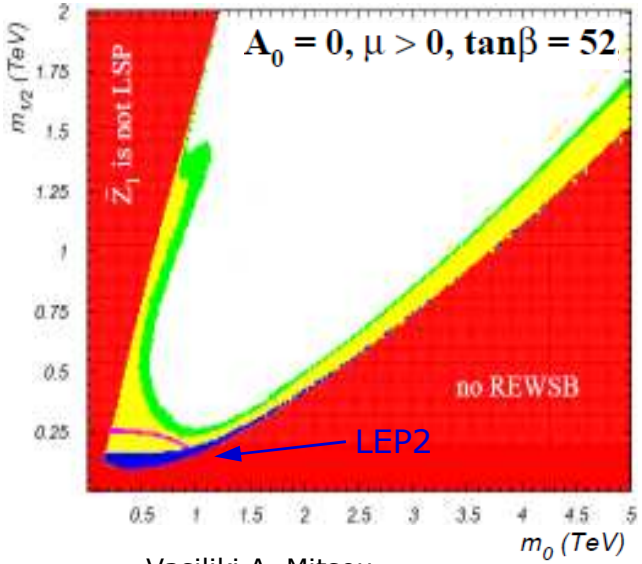
If neutralino is the WIMP

- CMB (WMAP5) + type-Ia supernovae + baryon acoustic oscillations (BAO) in galaxies
  ➔ measurement of the relic density of dark matter:
  $\Omega_X h^2 = 0.1143 \pm 0.0034$ [arXiv:0803.0547v1 [astro-ph]]
  assuming model for Big Bang Nucleosynthesis (BBN)
- Severe constraints on models of WIMPs, in particular SUSY models
- Available parameter space, e.g. in mSUGRA, limited
- Caveat 1: WMAP data interpretation depends on assumptions made on cosmological model & BBN
- Caveat 2: this precision depends on assuming very constrained SUSY breaking scenario; in more general scenario: much looser constraints
- ➔ LHC's role decisive in determining supersymmetry

``The WIMP miracle''
- thermally-averaged WIMP annihilation cross section
- EW cross section for annihilation of non-relativistic particles

For a specific SUSY model, predicted neutralino relic density is calculated by taking into account all possible neutralino annihilation processes





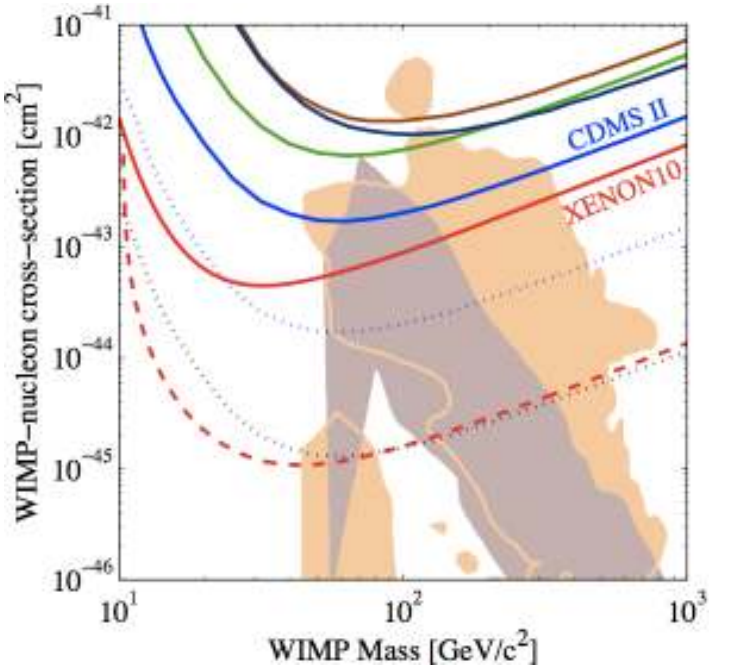
$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

- $0 < \Omega h^2 < 0.094$
- $0.094 < \Omega h^2 < 0.129$

Baer & Tata, arXiv:0805.1905 [hep-ph]

Dark matter: (in)direct WIMP searches

- Direct detection
  - look for **elastic scattering** of WIMP on nuclei
  - sensitive to WIMP mass m_X and cross section $\sigma_{X\text{-nucleon}}$
  - various techniques applied to observe the recoil: scintillator NaI, cryogenic, noble liquids (Ar, Xe), bubble chamber (superheated liquid) ➔ uncorrelated systematics
  - annual modulation observed by DAMA/LIBRA (?)
    - not confirmed by other experiments
- Indirect detection
  - look for **annihilation** products in galactic halo
  - sensitive to DM particle annihilation processes
  - telescopes
    - neutrinos: ANTARES, Amanda, Icecube, SuperK
    - γ-rays: MAGIC, HESS, Veritas, Cangaroo
    - γ-rays, antiprotons, e^+: Glast, Pamela, AMS, HEAT
  - can distinguish different WIMPs: neutralinos, KK states, ...
  - hints of DM annihilation seen by EGRET & HESS
- **Important for checking compatibility of cosmological and particle physics (LHC) results with SUSY (or other) scenario**



http://dmtools.brown.edu

Outlook: SUSY / Dark Matter @ LHC

- Discovery: search for deviation from SM in inclusive signatures like **missing energy + jets (+leptons)**
  - Inclusive studies: establish SUSY discovery
  - Exclusive studies: rough determination of model parameters
- Scheme developed for SUSY, but applicable to other BSM scenarios, e.g. UED, T-parity Little Higgs, ...
- LHC should discover general WIMP dark matter, but it is non-trivial to prove that it has the right properties
  ➔ SLHC, ILC: extend discovery potential of LHC
    - improve on LHC capability of identifying DM model
    - more precise determination of model parameters
- LHC, SLHC, ILC will put bounds on relic density, direct detection rate, WIMP annihilation processes, etc.
- Complementarity between LHC and cosmo/astroparticle experiments
  - uncorrelated systematics
  - measure different parameters
- In the following years we expect a continuous interplay between particle physics experiments (LHC, SLHC, ILC) and astrophysical/cosmological observations
  - either for model exclusion or discovery of New Physics

SUSY&DM: the complete (?) picture

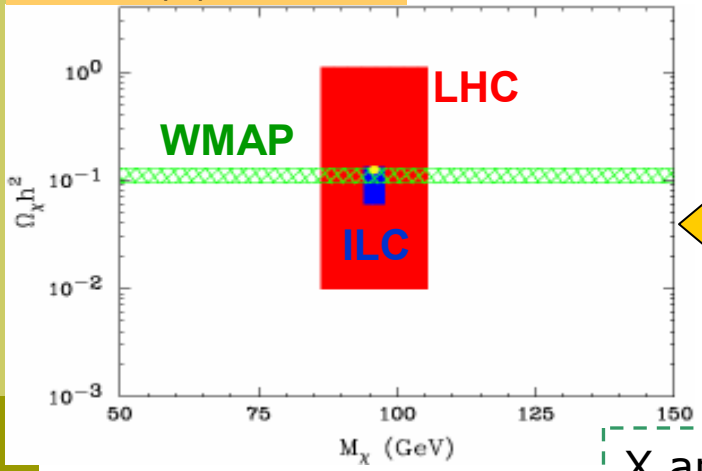
Direct WIMP detection (through nuclear recoil)

Collider experiments (LHC, SLHC, ILC, ...)

X + A → X + A
coherent x-section, m_X

SUSY production @ EW scale
"WIMP disappearance exps"

Birkedal *et al*,
arXiv:hep-ph/0507214



SUPERSYMMETRY AS DARK MATTER

CP violation in Higgs sector

X annihilation properties

X relic density

Indirect WIMP detection (neutrinos, γ-rays, ...)

Cosmological/astrophysical evidence (galaxy clusters, CMB, ...)

Backup…



SUSY @ 10 TeV: SU3 & bkg's

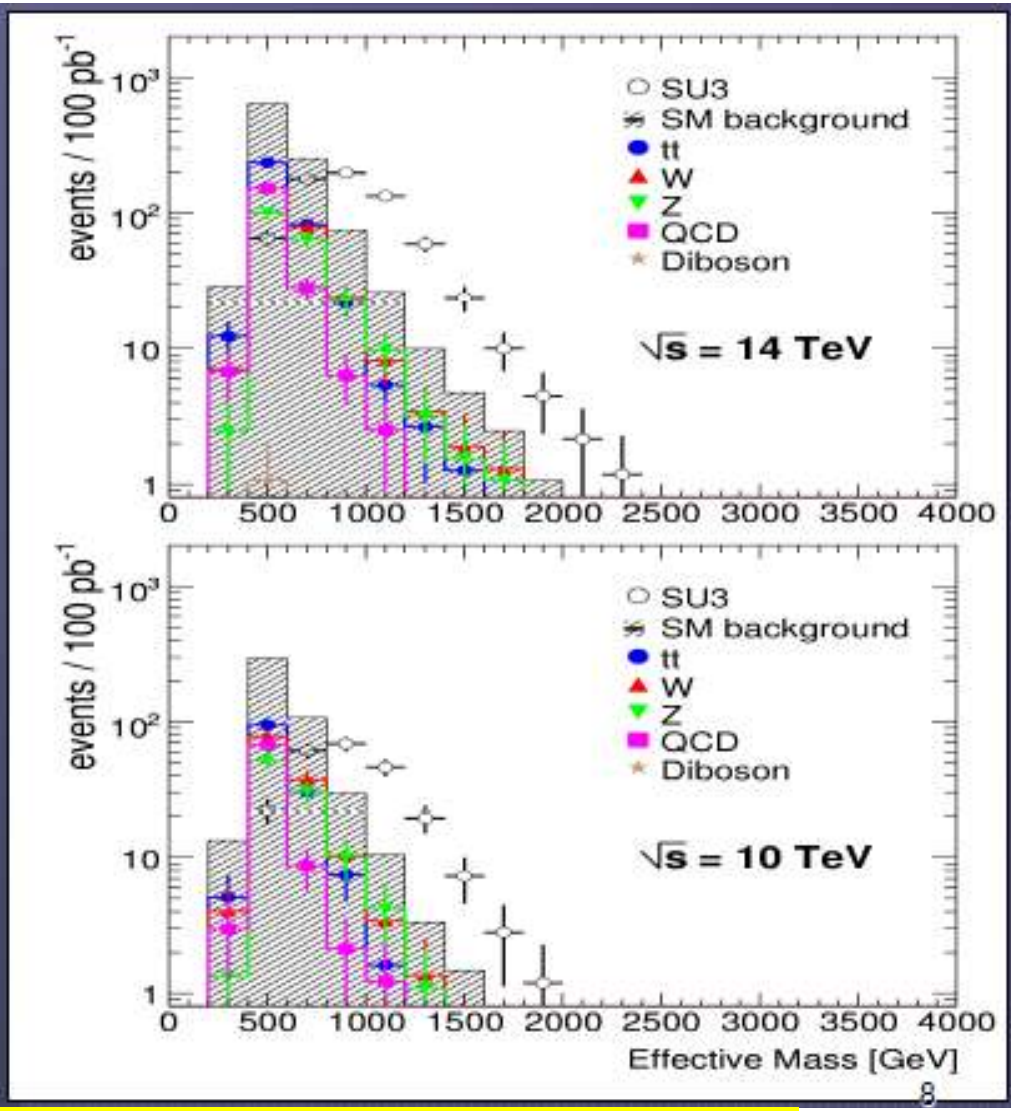
EG: CSC5 2–Jet + MET + 0–lepton SUSY analysis:

- Integrated L = 100 pb^{-1}
- **BEFORE** reweighting ➔
- **AFTER** reweighting ➘

14 TeV ➔ 10 TeV:

- SU3 signal reduced by ~ 2.9
- SM bkg reduced by ~ 2.3
  - QCD reduced by ~ 2.4
  - tt reduced by ~ 2.6
  - W/Z reduced by ~ 2
  - diboson reduced by ~ 1.9

NOTE: all MC predictions shown at LO (i.e. no k-factors applied)



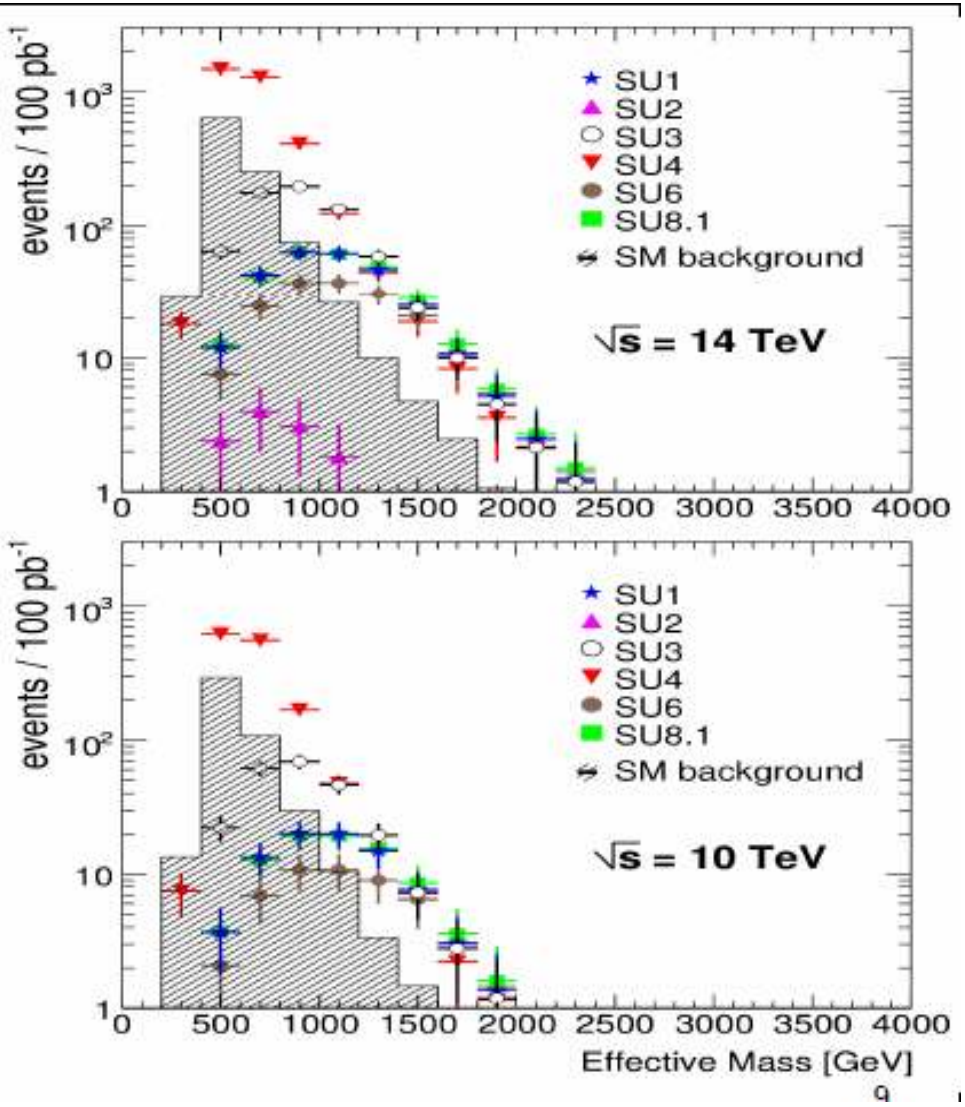
Claire Gwenlan (UCL), SUSY WG meeting, 21.05.2008

SUSY @ 10 TeV: various mSUGRA points

EG: CSC5 2–Jet + MET + 0–lepton SUSY analysis:

- Integrated L = 100 pb^{-1}
- Comparison of some other SUSY benchmark points (SUX)
  - all are mSUGRA, but cover quite a wide range of phenomenologies

SU1	coannihilation region
SU2	focus point region
SU3	bulk region
SU4	low mass point
SU6	funnel region
SU8.1	coannihilation region



Claire Gwenlan (UCL), SUSY WG meeting, 21.05.2008

SUSY @ 10 TeV: discovery significance

100 pb^{-1}

Discovery Significance (Z_n) *		
	14 TeV	10 TeV
SU1	9.1	5.9
SU2	<1	<1
SU3	11.2	8.3
SU4	12.5	12.5
SU6	7.5	4.8
SU8	9.7	6.2

- Numbers are maximum significances (taken above some M_{eff} threshold)
  (don't take too much notice of the actual values – it's just to get a (very) rough feeling)

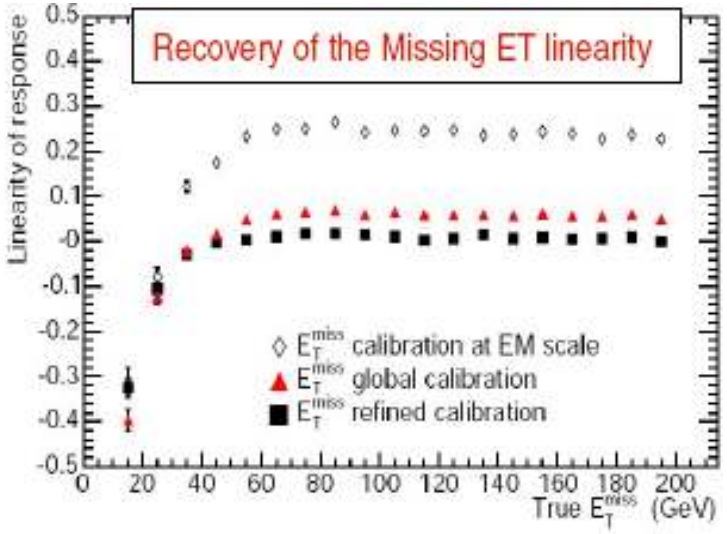
* Z_n is a measure of the significance (as used in CSC5) which tries to take into account systematic uncertainties on the bkg measurements. Numbers in the table are calculated assuming 50% uncertainty on QCD and 20% on all other bkgs – these are not the "right" numbers – dedicated bkg studies needed for those!

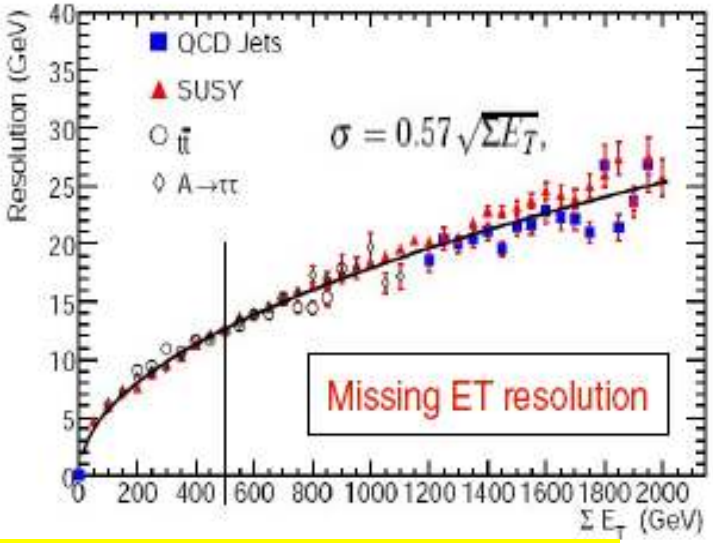
Claire Gwenlan (UCL), SUSY WG meeting, 21.05.2008

Missing transverse energy resolution

- **Missing ET calculation:**
  - Raw Missing ET
    - Default: Cell-based
    - Alternate: Cluster-based
  - Noise suppression
    - Use only cells within topo clusters
  - Refinement:
    - Cell associated with electrons, muons, taus and jets are calibrated according to the energy scale of the respective object
    - Correct for dead material





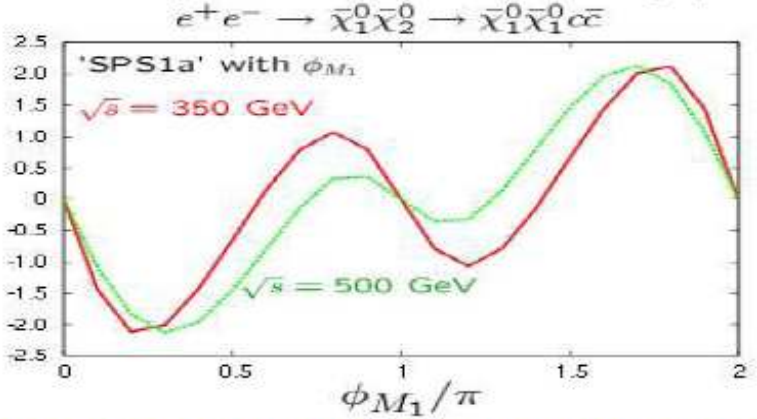


Ulla Blumenschein (IFAE), QCD Moriond, 18.03.2008

CP violation in supersymmetry

- **SUSY provides new sources for CP-violation** (explain baryon asymmetry...
  - many phases available in SUSY, but strong experimental constraints from measurements of the e, n, Hg, Tl dipole moments
  - sensitive observables needed to detect even small phases: very sensitive are asymmetries constructed via three momenta 'triple products'
  - use transversely polarized beams: effects ~ $P^T(e^-)\, P^T(e^+)$
  - or use SUSY decays into τ's and exploit τ polarization
  - or use SUSY leptonic or hadronic decays, often b- and c-tagging needed:

A_{CP}/%



→ c and $\bar{c}$ distinction needed!

- **Challenging, good statistics needed, but not hopeless!!!**

Gudrid Moortgat-Pick, LC Physics School, Ambleside, 09.2006