Prospects for SUSY discovery based on inclusive searches with the ATLAS detector

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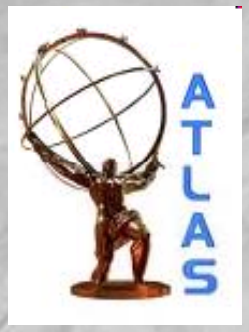
on behalf of the

ATLAS Collaboration



DISCRETE '08

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Introduction

- SUSY is expected to be one of the main topics of New Physics at the **ATLAS** experiment at the LHC
  - It is a promising extension of the Standard Model (**SM**)
  - Solves the Higgs mass hierarchy problem
  - If at TeV scale, it is to be discovered at the LHC
  - Can provide clear experimental evidence
- Topics discussed here:
  - **SUSY inclusive signatures** with jets, leptons (e/μ) and missing energy in R-parity conserving (RPC) scenarios
  - **Background** estimations and control samples
  - SUSY **discovery potential** with early data ($\sim$1 fb^{-1})

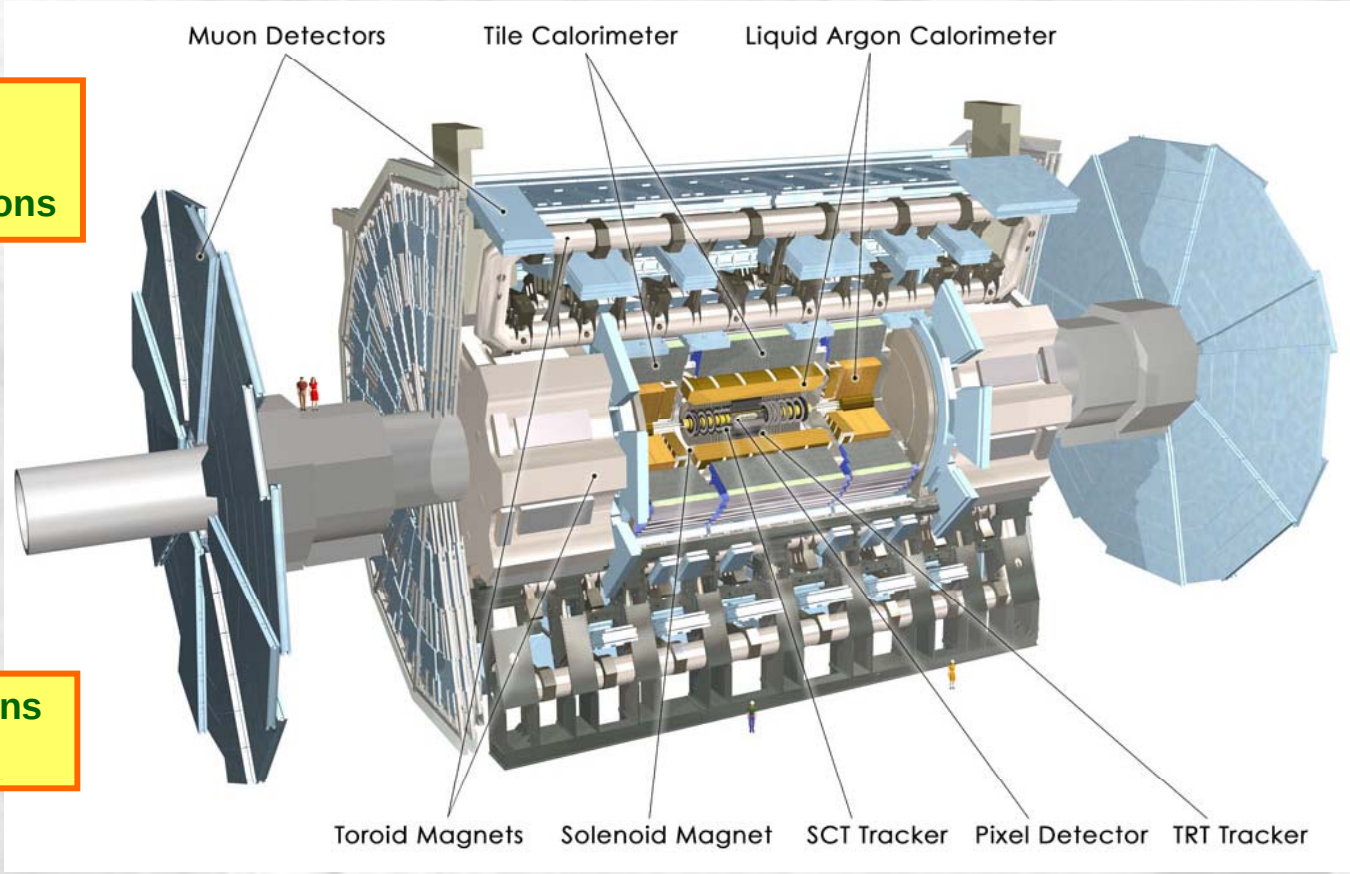
The ATLAS experiment

- One of the two general purpose experiments at CERN's Large Hadron Collider (LHC)

Length : ~45 m
Diameter : ~25 m
Weight : ~ 7000 tons

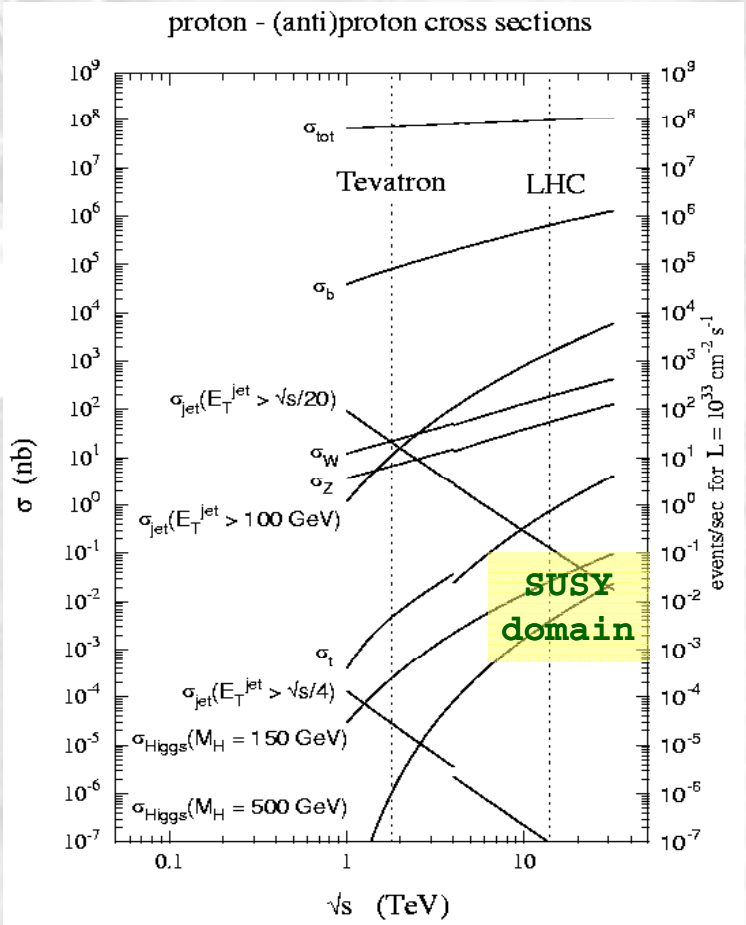
# of scientists : ~2000
# of institutes : ~170
# of countries : ~40

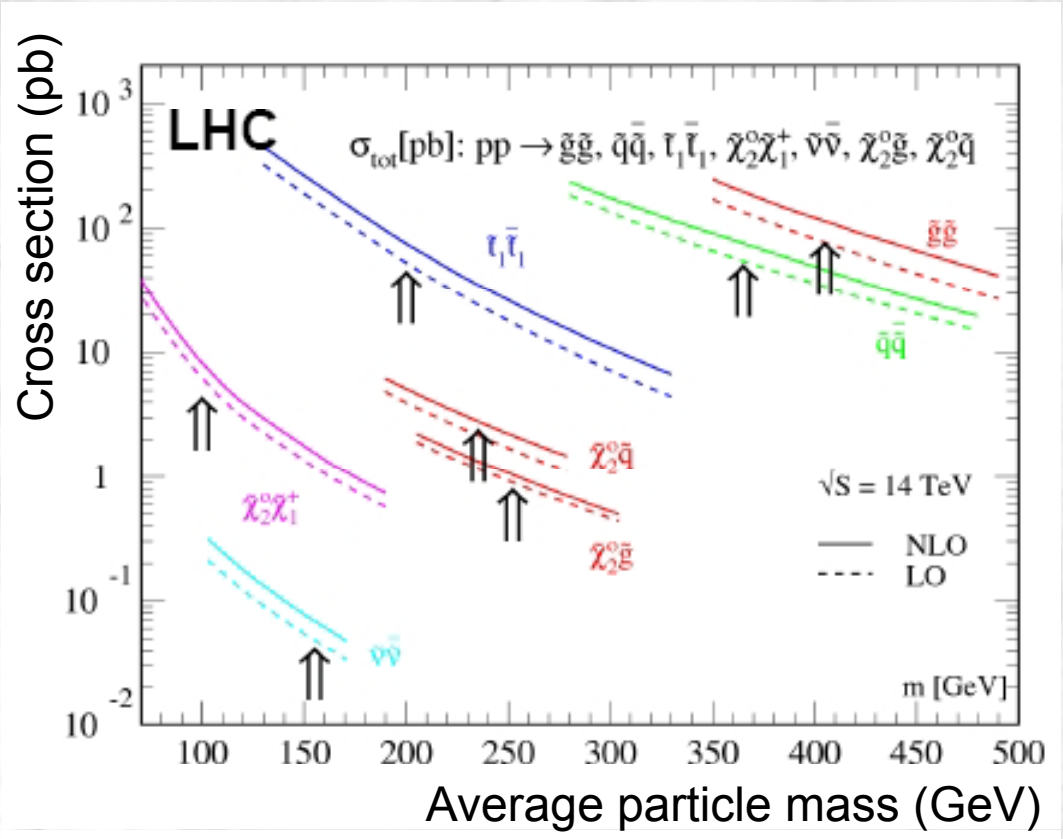
First collisions in 2009



SUSY production at the LHC

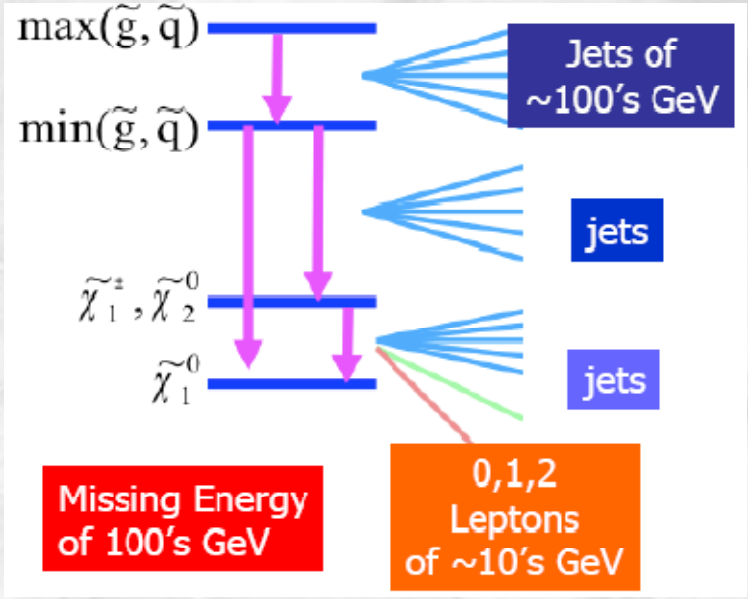
- At the LHC the MSSM cross sections are dominated by production of squark and gluino starting chains of SUSY states





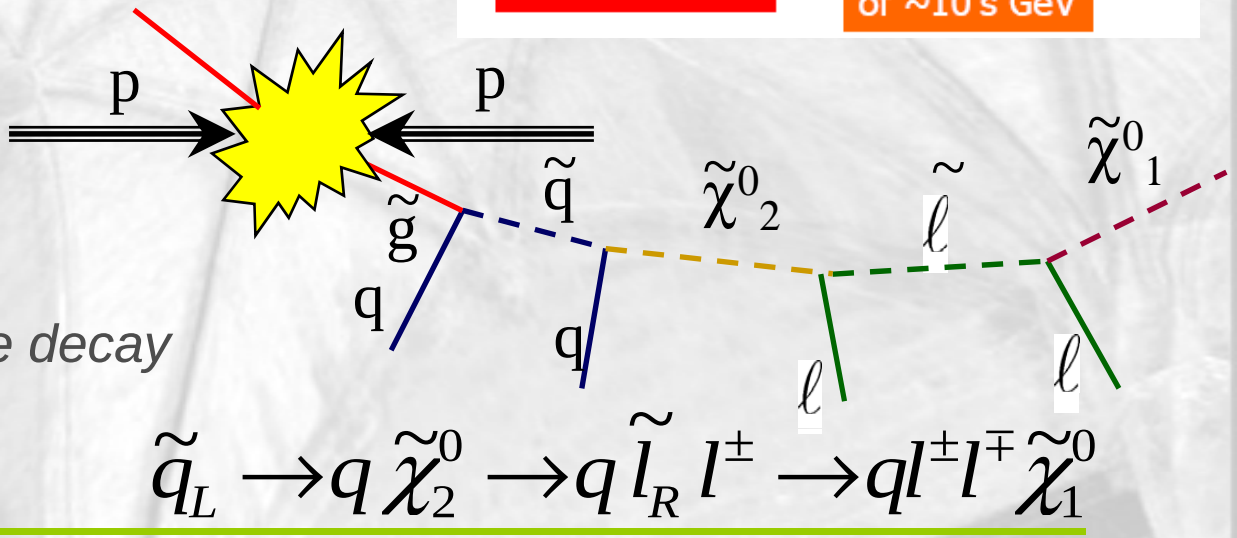
Typical SUSY event topology

- High-p_T **jets** from squark/gluino decays
- Large missing transverse energy **MET**
  from lightest SUSY particle (**LSP**)
- High-p_T **leptons** (e/μ) from gaugino/slepton
- High-p_T **b-jets/τ-jets**
  (depending on model)



The least model-dependent SUSY signature is the search for events with many jets and MET

Example:
the Left squark cascade decay

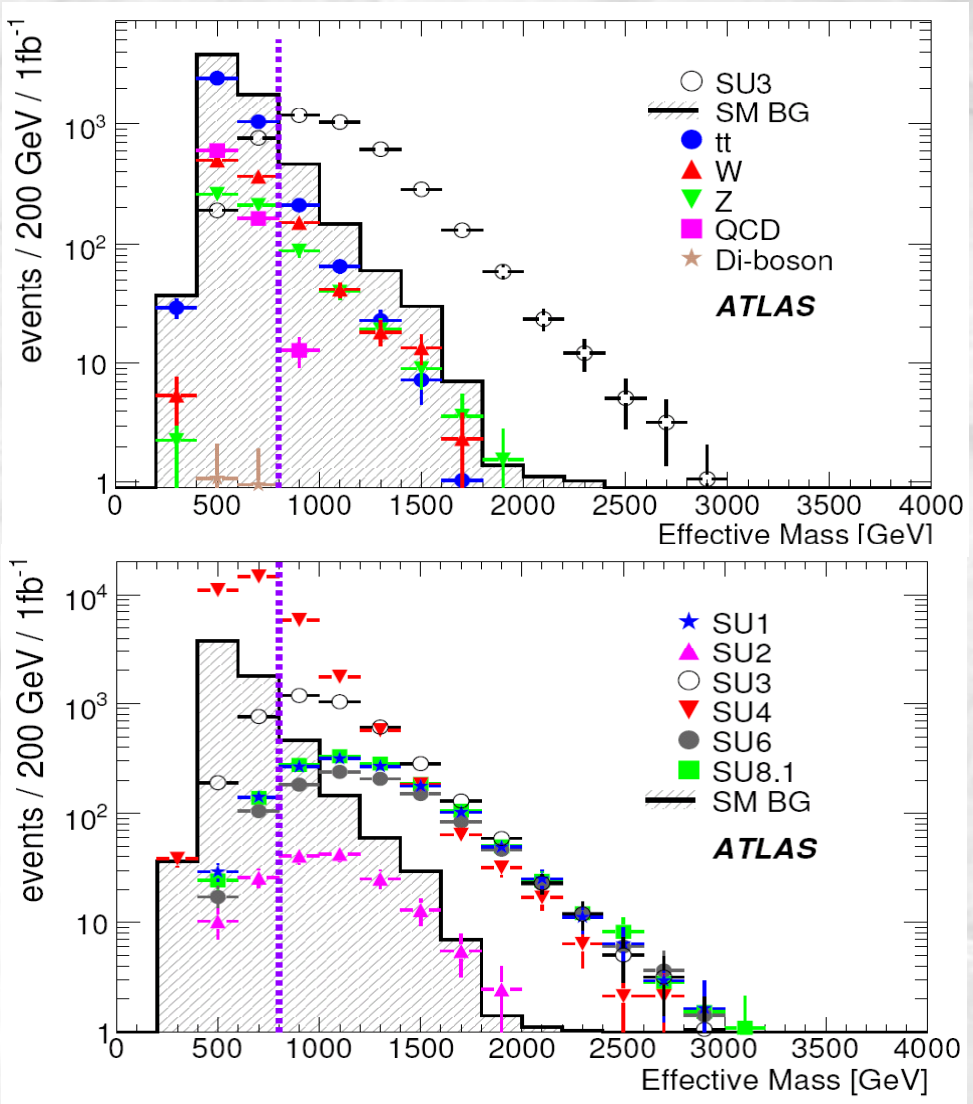


Zero-lepton mode searches (1)

- Basic selection criteria **[BSC]**:
  - At least 4 jets with p_T>50GeV
  - At least 1 jet with p_T>100GeV
  - Missing E_T : MET > 100 GeV, MET > 0.2 M_{eff}
  - Transverse sphericity S_T > 0.2
  - $\Delta\phi(jet_i - MET) > 0.2$, i=1,2,3
  - Effective mass: M_{eff} > 800 GeV

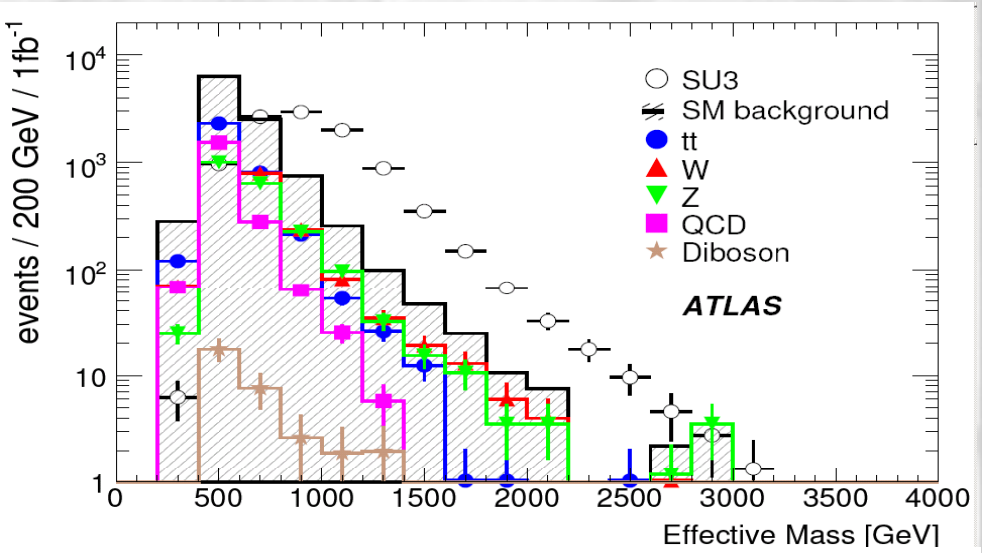
$$M_{eff} = MET + \Sigma\, p_T(jet)$$

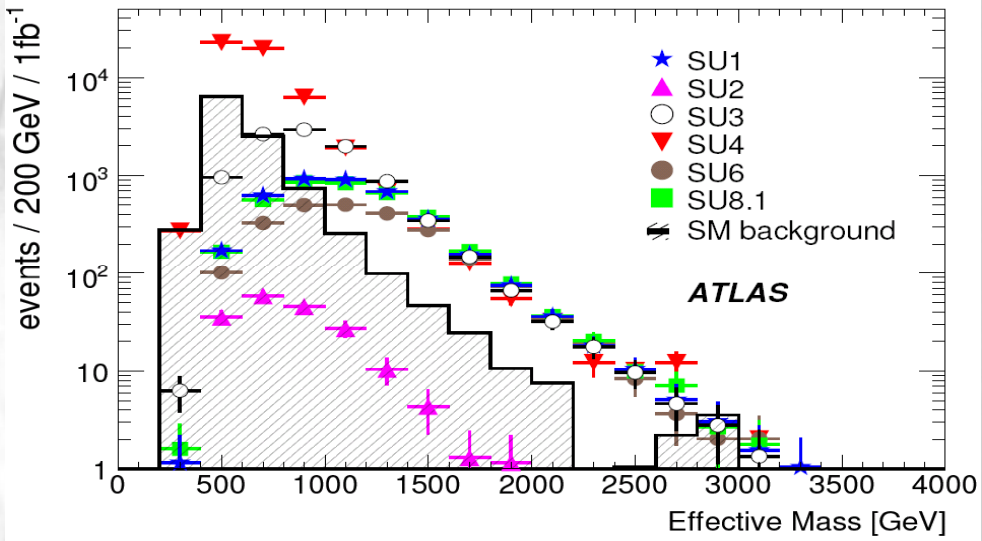
- Additional requirements:
  - No isolated *e* or μ with p_T>20GeV
- SM background sources vs. mSUGRA *SUn* benchmark points :
  - Multi-jet QCD, W+jets, Z(→νν)+jets, ttbar with lepton not identified or τ



Zero-lepton mode searches (2)

- **Inclusive 2-jet and 3-jet final states**: Selection criteria:
  - At least 2 (or 3) jets with p_T>100GeV
  - At least one jet with p_T>150GeV
  - MET > 0.3 (0.25) M_{eff}
  - $\Delta\phi(jet_i - MET) > 0.2$, i=1,2,3
  - M_{eff} > 800 GeV
  - No isolated *e* or μ with p_T>20GeV
- PYTHIA generated W+jets and Z+jets background samples
- SM background
  - QCD, W+jets, Z(→νν)+jets and ttbar backgrounds all give comparable contributions
- Number of events from both signal and background are doubled compared to 4-jet analysis (except low-mass *SU4*)

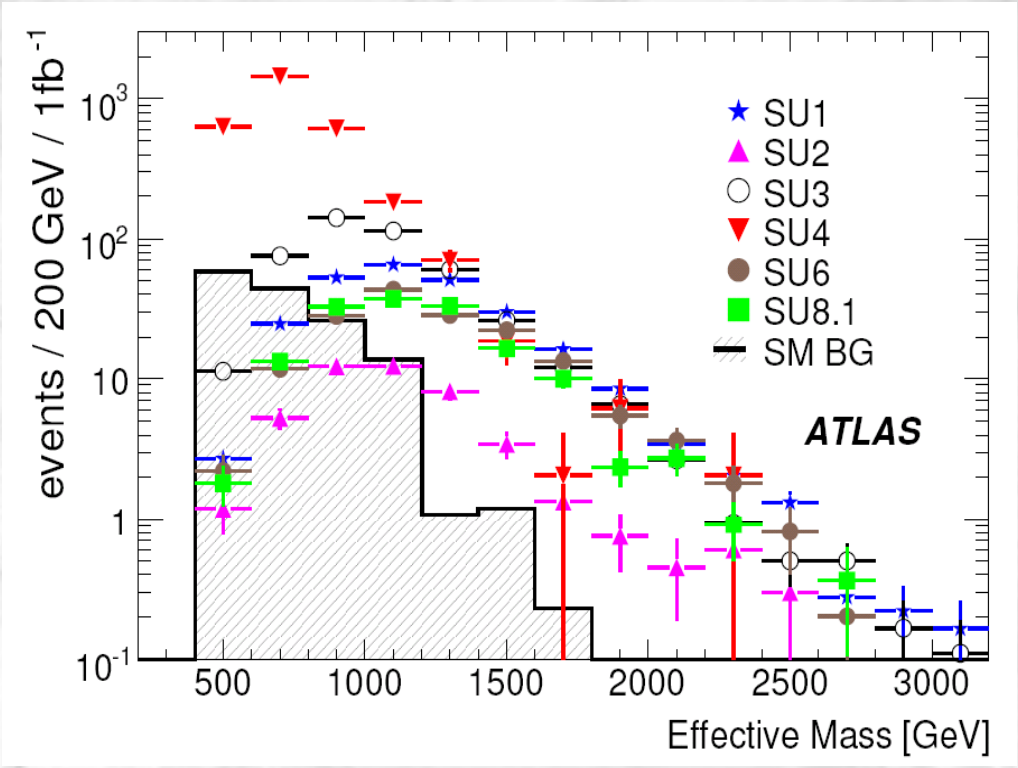




One-lepton mode searches

- **1-lepton** rate similar to 0-lepton (leptons can also come from τ decays of gauginos)
- Additional cuts to [BSC]:
  - Exactly one isolated *e* or μ with p_T>20GeV
  - No other leptons with p_T>10GeV
  - Transverse mass: M_T>100 GeV
- Main background:
  - W+jets
  - ttbar semileptonic (or dileptonic with lepton missed or τ)

No requirements on M_{eff}

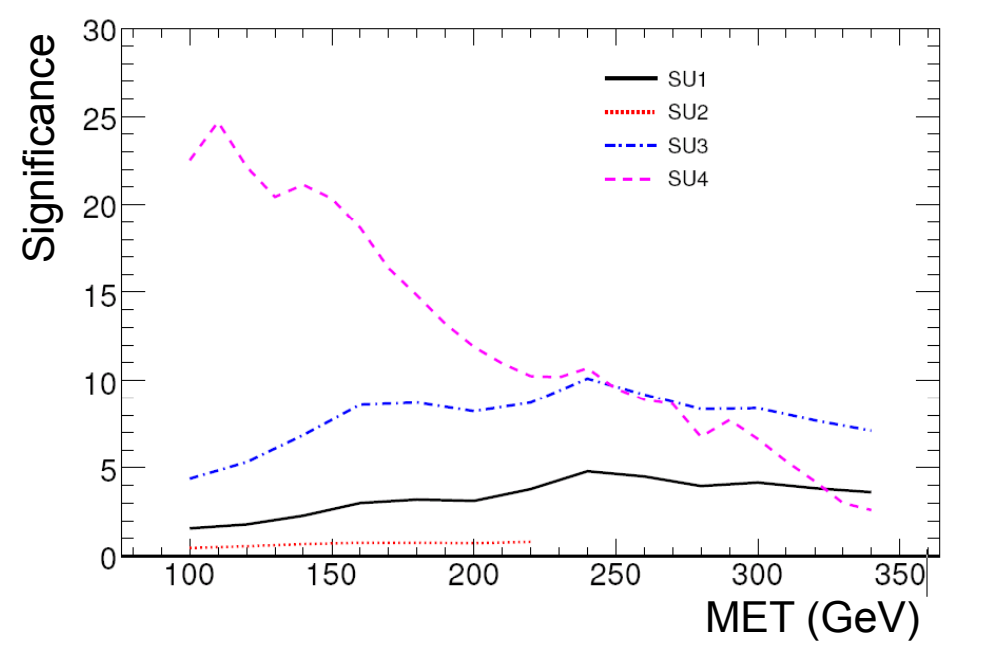


- Significance with 1 fb^{-1} is Z_n > 5 for all mSUGRA *SUn* points (except *SU2*)

Di-lepton mode search (1)

- **Opposite sign leptons**
  - In SUSY can arise from neutralino decays, e.g.:

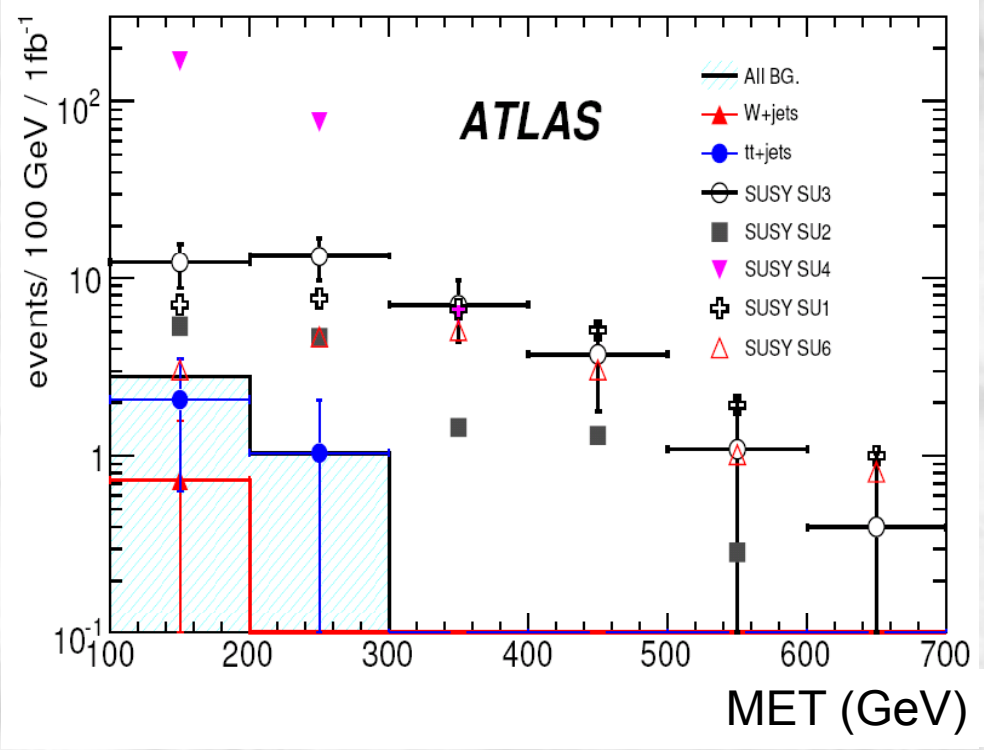
$$\tilde{\chi}_2^0 \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$$



- Same cuts of [BSC] (except those on S_T and M_{eff}) plus:
  - Exactly two isolated *e* or μ having opposite sign, with p_T>10GeV and |η|<2.5 ,
- Clean event signature
- Crucial for exclusive studies (or measuring SUSY parameters)
- Smaller yield than 0, 1 lepton modes
- Largest background: $t\bar{t} \rightarrow b\bar{b}\ell\nu\ell\nu$
  but also SUSY chains with leptonic decays of **W** or **top**.

Di-lepton mode search (2)

- **Same sign leptons**
  - Common in SUSY as gluino is a self-conjugate Majorana sfermion
  - Expected small rate in SM



- Same cuts of [BSC] (except those on S_T and M_{eff}) plus:
  - Exactly two isolated *e* or μ having same sign, with p_T>10GeV and |η|<2.5

- Very clean event signature
- Small rates expected (10÷100 events/fb^{-1}) but high S/B ratio
- Cuts strongly suppress SM background
- Main background: ttbar. A possible control sample: $t\bar{t}, t \to \ell^+ X, \bar{b} \to \mu^+ X$

Three-lepton mode search

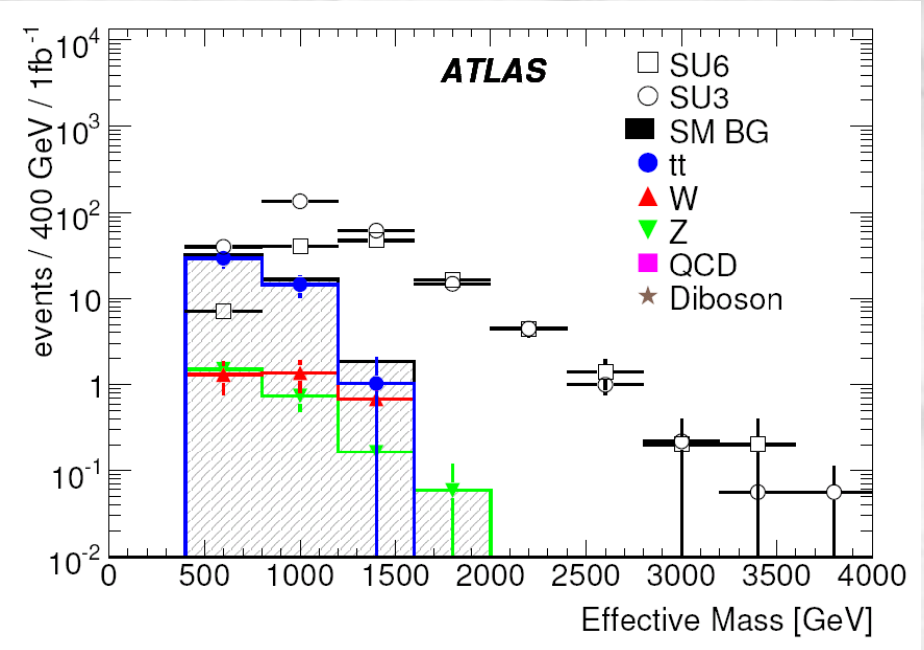
- 3 leptons + jet
  - (1) ≥ 3 isolated leptons p_T>10GeV
  - (2) ≥ 1 jet with p_T>200GeV
- 3 leptons + MET
  - (1) ≥ 3 isolated leptons with p_T>10GeV
  - (2) ≥ 1 dilepton pair with M>20GeV
  - (3) Lepton isolation: p_T < 1 (2) GeV for μ (e) in a cone R=0.2 around
  - (4) MET > 30 GeV
  - (5) Any dilepton pair with M<M_Z – 10GeV
- Main background: WZ, Wγ* (suppressed requiring jet), γ*,J/ψ, conversion, b/c and Z decays (reduced by cuts on M and MET)
- S/√B with 1 fb^{-1} from ~3 to ~100

Sample	Cut 1	Cut 2	S/B	$S/\sqrt{B}$	Z_n
SU2	35	13	1.1	3.7	2.7
SU3	139	94	7.8	27.1	11.5
SU4	1284	312	26.0	90.0	24.4
$t\bar{t}$	455	11	–	–	–
ZZ	59	0	–	–	–
ZW	193	1	–	–	–
WW	3	0	–	–	–
$Z+\gamma$	9	0	–	–	–
Zb	656	0	–	–	–

Process	Cuts 1-2	Cut 3	Cut 4	Cut 5
SU1	42.2	33.0	32.6	24.1
SU2	29.8	24.1	21.1	17.6
SU3	130.1	101.2	98.6	63.9
SU4	968.1	691.5	654.3	544.9
SU8.1	10.2	8.0	8.0	5.3
WZ	188.3	166.2	122.5	22.8
ZZ	55.9	46.4	10.3	1.6
Zb	582.5	221	1.3	0
$t\bar{t}$	283.2	59.9	56.6	47.9

Tau mode search

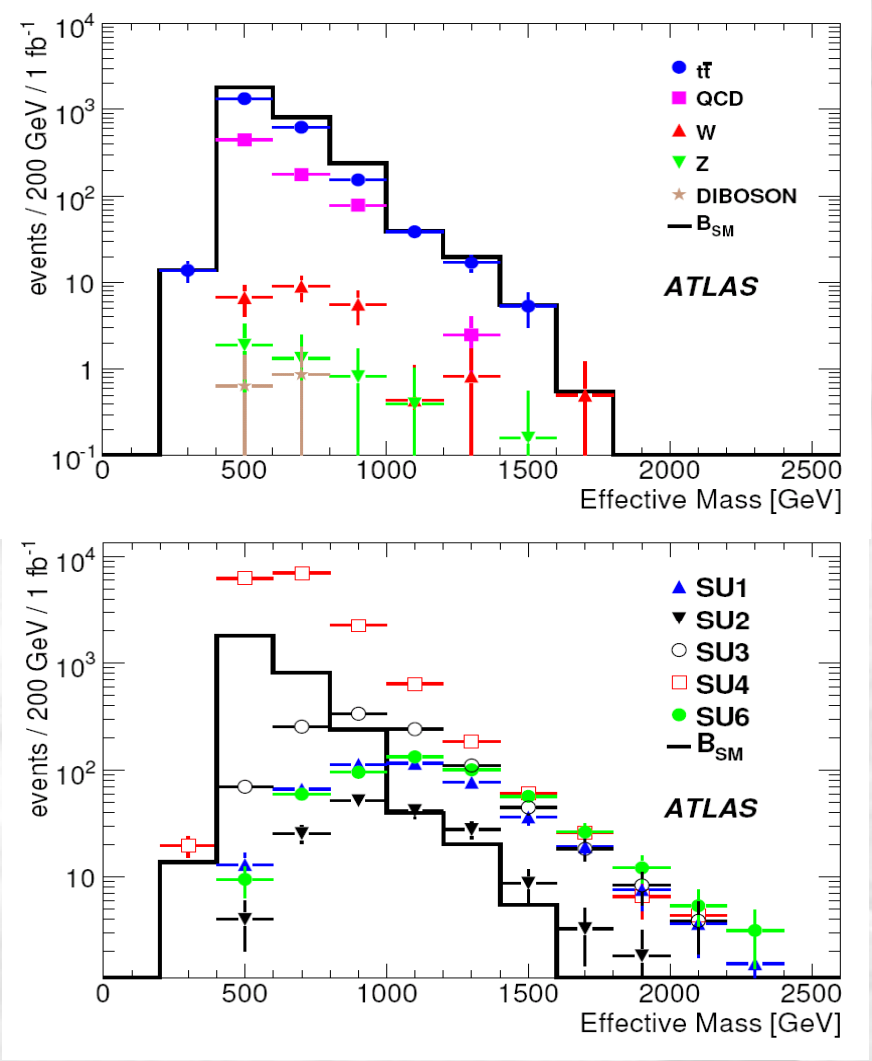
- **Signatures with τ's**
  - τ decays may be dominating in SUSY at tanβ>>1 (e/μ/τ universality violated)
  - Large fake rate expected from jets
- Same cuts of [BSC] (except those on S_T and M_{eff}) plus:
  - No isolated *e* or μ with p_T>10GeV
  - At least one τ with p_T>40GeV and |η|<2.5 *["high p_T" algorithm]*
  - M_T>100GeV (using visible momentum of hardest τ and MET)



- Most favoured points: ***SU3*** and ***SU6***
- Purity of selected samples: ~80%
- Main background: ttbar, W+jets, QCD. S/B ratio between 2 and 5.
- Systematics estimated around 20%

b-jet mode search

- **Signatures with b's**
  - Depending on SUSY parameters, signals can be rich of jets from b quarks (since $\tilde{b}$ and $\tilde{t}$ are lighter than the other squarks)
- Same cuts of [BSC] (except those on M_{eff}) plus:
  - At least two jets tagged as *b-jets*: p_T>20GeV plus b-tagging cuts on vertex and impact parameter
  - M_{eff}>600, 800 or 1000 GeV
- Background is mostly ttbar and QCD
- Light-jet rejection in b-tagging *O*(100)
- Some overlap wrt previous analyses
- Significance with 1 fb^{-1} is Z_n>10 for (syst. of 50% for QCD, 20% for W, Z, t)

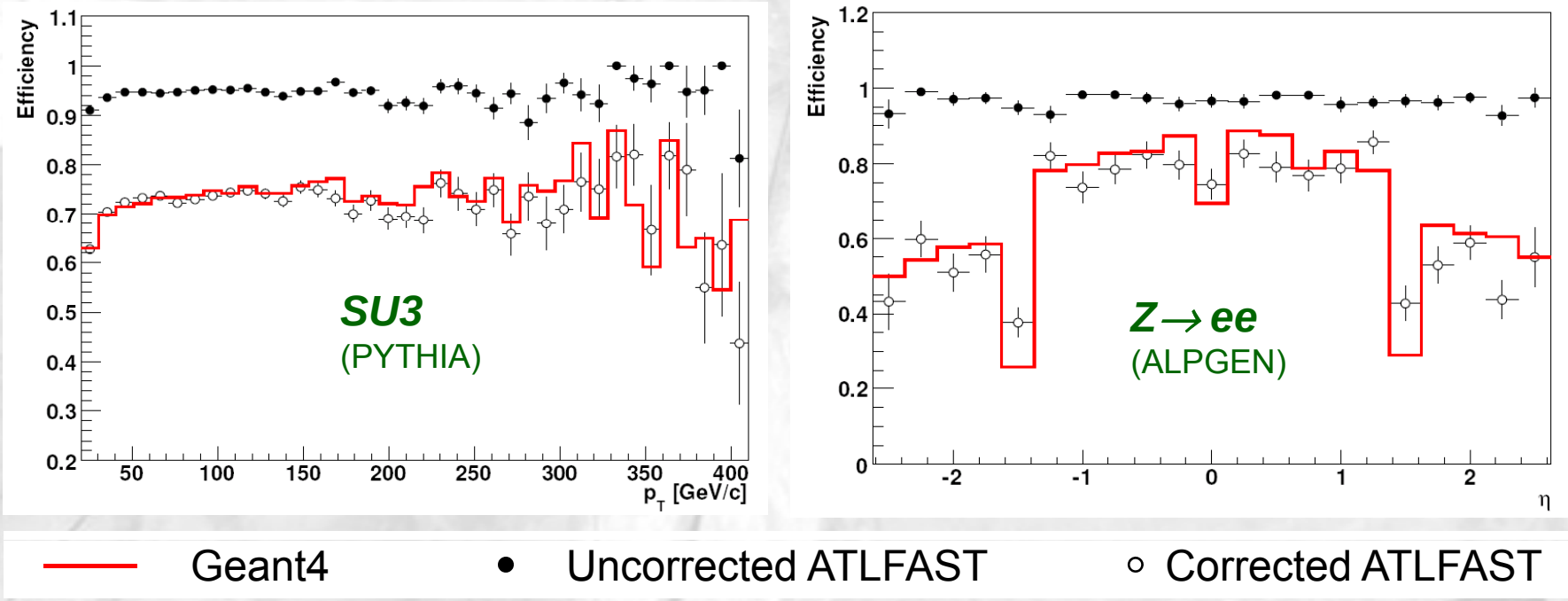


Scans and optimizations

- The *SUn* points chosen for ATLAS are not representative of all possible RPC SUSY-breaking models
- A fast parameterized simulation (**ATLFAST**) of the detector has been used to scan the allowed parameter space
  - Cross sections: LO for signals, NLO for background (conservative)
- Grids under study (m_t = 175 GeV):
  - **mSUGRA** with fixed grid, tanβ=10, A_0=0, μ>0: a grid of 25×25 points with m_0 from 60 to 2940 GeV, $m_{1/2}$ from 30 to 1470 GeV
  - **mSUGRA** with fixed grid, tanβ=50, A_0=0, μ<0: similar to above
  - **mSUGRA** random grid with constraints: points chosen in $\{0<m_0<2\text{TeV}, 0.5<m_{1/2}<1.3\text{TeV}, -0.34<A_0<2.4\text{TeV}, 39<\tan\beta<55\} \cup \{1<m_0<3\text{TeV}, m_{1/2}<0.5\text{TeV}, -2<A_0<2\text{TeV}, 20<\tan\beta<55\}$, μ>0
  - **NUHM** grid (Non-Universal Higgs Model): like mSUGRA but more relaxed dark matter constraints (more gaugino/Higgsino mixing); (m_0,$m_{1/2}$) scan with adjusted values of M_A and μ
  - **GMSB** grid (Gauge Mediated Symmetry Breaking): M_{mess}=500 TeV, N_{mess}=5, C_{grav}=1; Λ from 10 to 80 TeV, tanβ from 5 to 40

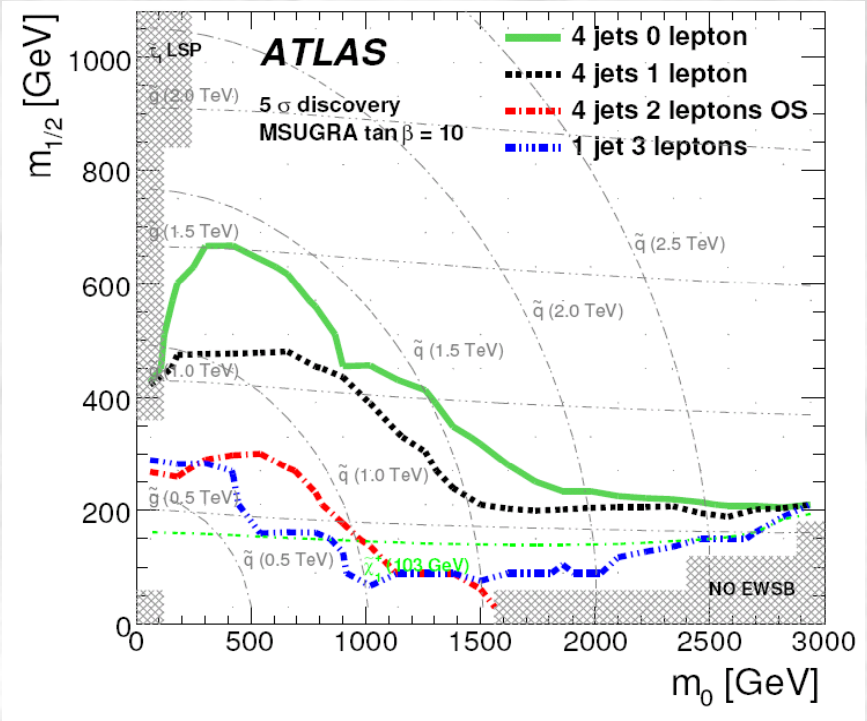
Simulation corrections

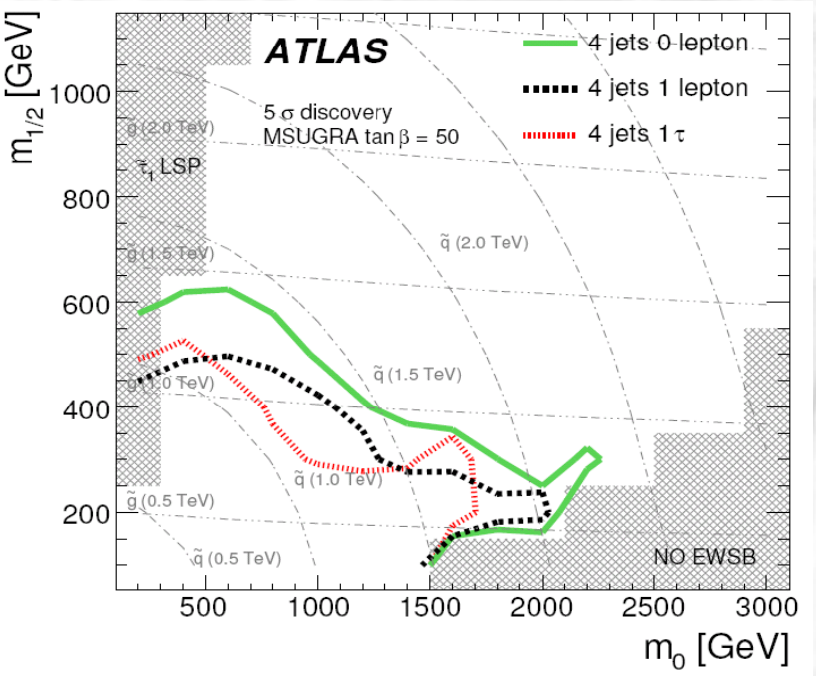
- **ATLFAST** simulation has been corrected to account for lepton reconstruction efficiency as a function of p_T and η
- Reasonable agreement can be found between ATLFAST and the **full simulations** with *Geant4*



Discovery reach with 1 fb^{-1} (1)

- The **0-lepton mode** has the best estimated 5σ reach (~1.5TeV for smaller of $m_{\tilde{g}}$ and $m_{\tilde{q}}$)
- The **1-lepton mode** has worse reach, but better against QCD

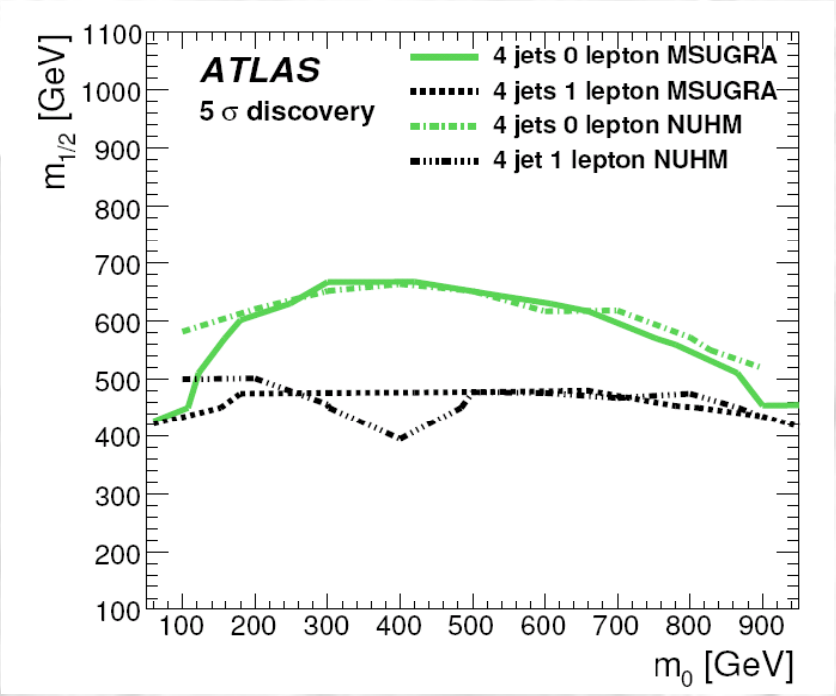


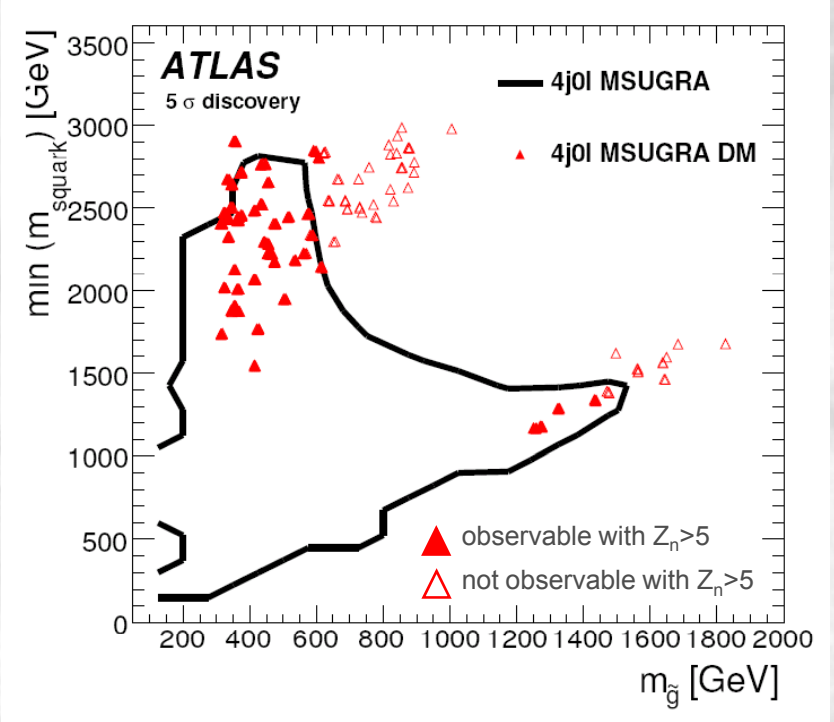


- At very high tanβ, 0- and 1-lepton mode are still better than **τ-mode** (because of lower efficiency and purity of τ reconstruction)

Discovery reach with 1 fb^{-1} (2)

- The approach of **random grid with constraints** is comparable with mSUGRA scans (SUSY cross sections are controlled by the gluino and squark masses)

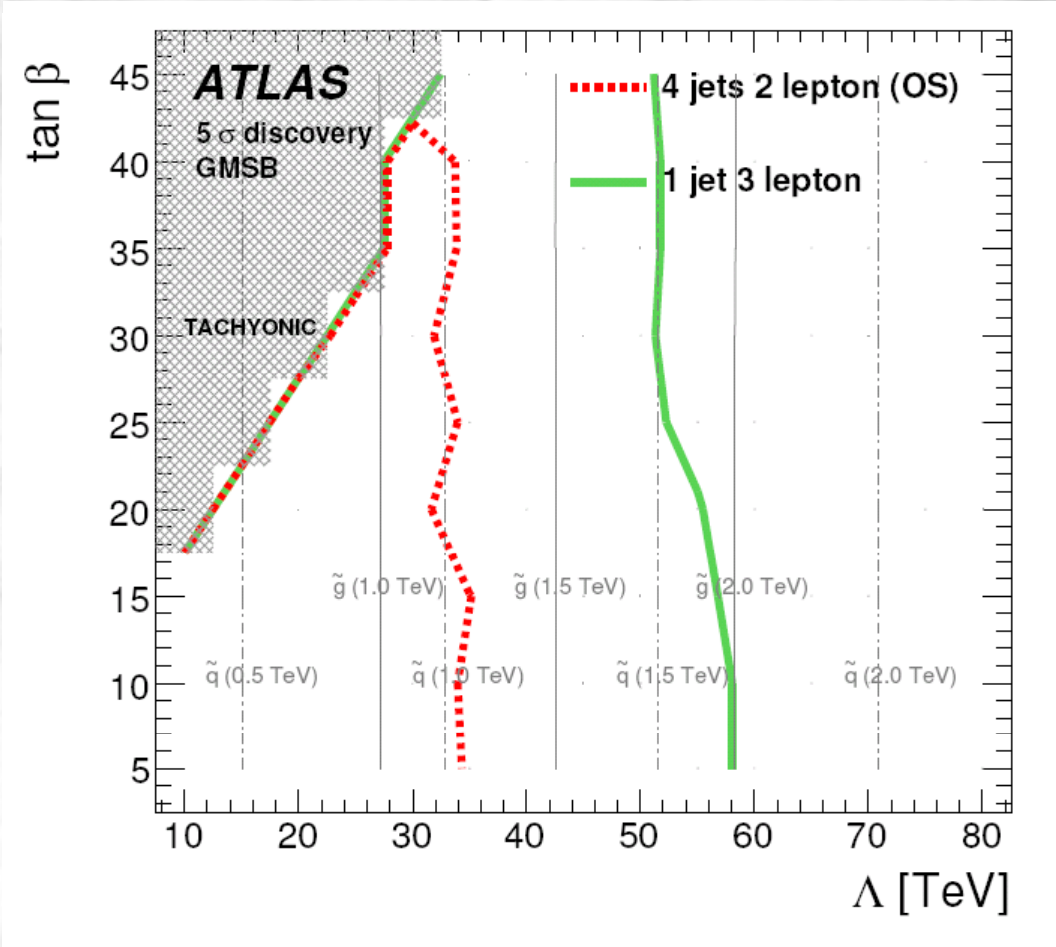




- The **NUHM 0-lepton** and **1-lepton** reach plots are virtually identical to mSUGRA with similar assumptions

Discovery reach with 1 fb^{-1} (3)

- Models considered here for the **GMSB scan** are easier to distinguish from SM backgrounds
- The **3-lepton** search is much better than that for 2 opposite sign leptons:
  - well beyond 2 TeV for gluinos for large tanβ
  - close to 2 TeV for all values tanβ



Conclusions

- **ATLAS** is ready to probe SUSY at 1 TeV mass scale with the first **LHC** data
  - In favorable cases the mass reach could be greater
- All studies shown here were made with realistic simulations, accounting for uncertainties in the various SM background sources
- **SUSY** discovery in RPC models (e.g. mSUGRA, NUHM, GMSB) will be possible with little integrated luminosity (~**1 fb^{-1}** of understood collected data)
  - SUSY at higher mass scales could still show up but would make detailed study quite difficult

Backup slides

Supersymmetry reminder

Adds to each SM **fermion (boson)** a **bosonic (fermionic)** partner.

SM Particles	SUSY Particles		
quarks: q	q	squarks: $\tilde{q}$	
leptons: l	l	sleptons: $\tilde{l}$	
gluons: g	g	gluino: $\tilde{g}$	
charged weak boson: $W^{\pm}$	$W^{\pm}$	Wino: $\widetilde{W}^{\pm}$	$\tilde{\chi}^{\pm}_{1,2}$ chargino
Higgs: H^0	$H^{\pm}$	charged higgsino: $\widetilde{H}^{\pm}$	
	h^0, A^0, H^0	neutral higgsino: $\tilde{h}^0, \tilde{A}^0,$	$\widetilde{H}^0$ higgsino
neutral weak boson: Z^0	Z^0	Zino: $\widetilde{Z}^0$	$\tilde{\chi}^0_{1,2,3,4}$ neutralino
photon: γ	γ	photino: $\tilde{\gamma}$	

- **R-parity** $R=(-1)^{3(B-L)+2s}$ can be conserved (RPC) or violated (RPV)
- RPC implies:
  - SUSY particles produced in pairs
  - stable and neutral lightest SUSY particle (**LSP**)
  - no proton decay
- **LSP** is a good candidate for cold **Dark Matter**

MSSM Lagrangian depends on 105 parameters
mSUGRA requires only 5 parameters
- Also other SUSY models exist: **GMSB**, **AMSB**, …

Par.	Description
m_0	Common scalar mass
$m_{1/2}$	Common gaugino mass
A_0	Common trilinear term
tanβ	Ratio of Higgs vev
sign(μ)	μ from Higgs sector

Benchmark points in mSUGRA

ATLAS Point	m_0	$m_{1/2}$	tanβ	sgn(μ)	A0	x-sec (pb)
Coannihilation (**SU1**)	70	350	10	+	0	7.43
Focus Point (**SU2**)	3550	300	10	+	0	4.86
Bulk (**SU3**)	100	300	6	+	-300	18.59
Low Mass (**SU4**)	200	160	10	+	-400	262
Scan (**SU5.1**)	130	600	10	+	0	0.44
Scan (**SU5.2**)	250	600	10	+	0	0.40
Scan (**SU5.3**)	500	600	10	+	0	0.31
Funnel (**SU6**)	320	375	50	+	0	
Coannihil. (**SU8.1**)	210	360	40	+	0	6.44
Coannihil. (**SU8.2**)	215	360	40	+	0	6.40
Coannihil. (**SU8.3**)	225	360	40	+	0	6.32

Significance Z_n

Given these assumptions, the probability p that the background fluctuates by chance to the measured value N_{data} or above is given by

$$p = A \int_0^\infty db\, G(b; N_b, \delta N_b) \sum_{i=N_{\text{data}}}^{\infty} \frac{e^{-b} b^i}{i!},$$

where $G(b; N_b, \delta N_b)$ is a Gaussian and the factor

$$A = \left[\int_0^\infty db\, G(b; N_b, \delta N_b) \sum_{i=0}^{\infty} e^{-b} b^i / i! \right]^{-1}$$

ensures that the function is normalised to unity. If the Gaussian probability density function G is replaced by a Dirac delta function $\delta(b - N_b)$, the estimator p results in a usual Poisson probability.

The probability p is transformed into "standard-deviations", denoted in this note by the symbol Z_n, using the formula

$$Z_n = \sqrt{2}\, \text{erf}^{-1}(1 - 2\text{p})$$

Dilepton mode searches

- Number of collected events in 1 fb^{-1}

Sample	Cuts 1-3	Cut 4	S/B	Z_n
SU3	200.8	159.8	1.88	3.55
SU1	91.0	72.6	0.86	1.65
SU2	22.5	18.8	0.22	0.43
SU4	948.0	809.5	9.56	22.5
$t\bar{t}$	111.1	81.5		
$W+$jets	2.47	1.97		
$Z+$jets	1.77	1.20		
QCD (J3-J7)	0	0		
Total Standard Model	115.34	84.67		

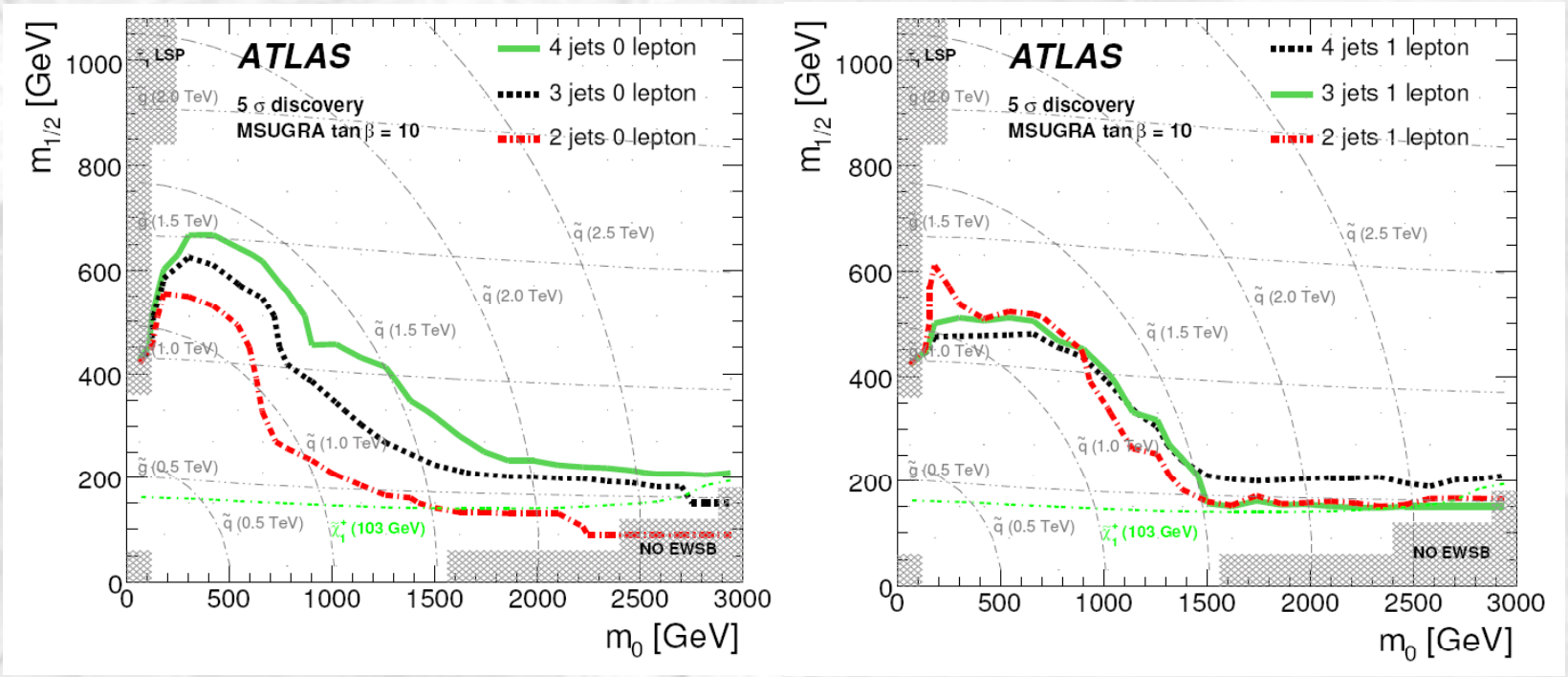
Two opposite sign leptons

Process	Cuts 1–3	Cut 4	Z_n
SU1	30.1	21.9	7.2
SU2	13.0	6.6	1.9
SU3	37.9	24.9	7.7
SU4	251.8	138.8	19.9
SU6	18.0	13.9	4.5
$t\bar{t}$	2.1	< 2.3	
$W+$jets	0.7	0.0	
$Z+$jets	0.0	0.0	

Two same sign leptons

Discovery reach (with <4 jets)

- 1 fb^{-1} 5σ contours for search modes: 0-lepton and 1-lepton + MET



On mSUGRA scans

- For **0-lepton** mode search in mSUGRA, the best choice for discovery is asking for 4 jets, while for **1-lepton** mode the 2-jet, 3-jet and 4-jet reaches are comparable.