The reach of the ATLAS experiment in the SUSY parameter space

International Conference on Particle Physics
-in memoriam Engin Arik and her colleagues -
Istanbul, 28th of October 2008

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on behalf of the ATLAS Collaboration

Supersymmetry at LHC

Susy is one of the main topics at LHC:

- extension of SM: adds a boson ↔ fermion symmetry:
  - solves the **hierarchy** problem of the SM
  - can unify gauge coupling at GUT scale
- can provide **dark matter** candidate:
  - existence of a **lightest stable SUSY particle (LSP)**

This talk covers only direct SUSY searches (results for $1fb^{-1}$):

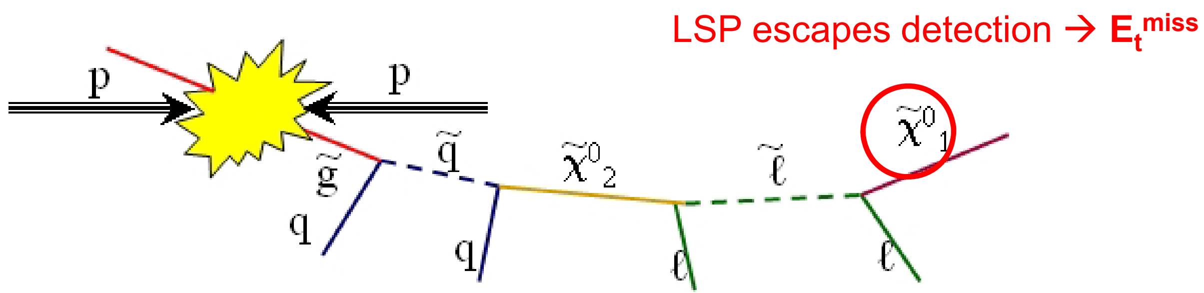
- R-parity conserving models
  - pair production of SUSY particles
  - cascade decay to lighter SUSY particles and finally to the LSP
  - LSP is stable → escapes detection: E_t^{miss}

Inclusive searches for new physics at TeV scale:

Look for deviations between 'data' and SM expectations in tails of M_{eff} distributions!

Characteristic SUSY signatures

example for SUSY signature :



- strongly interacting SUSY particles (squarks and gluinos) dominate SUSY production

→ many **high p_T objects** (model dependent): leptons, jets, b-jets, photons

- LSP is stable:

→ clear experimental signatures with **large E_t^{miss}**

generic signature = E_T^{miss} **+ multi-jets (+ multi-leptons + photons)**

→ build various channels depending on number/type of objects (inclusive channels)

signals studied at ATLAS (CSC note 2008):

2, 3, 4 jets + 0 ,1, 2, 3 leptons (e,μ) , tau or photon + E_t^{miss}

SUSY searches

SUSY signatures are quite model dependent:

mass scale of SUSY particles, SUSY breaking scenario,.. are unknown

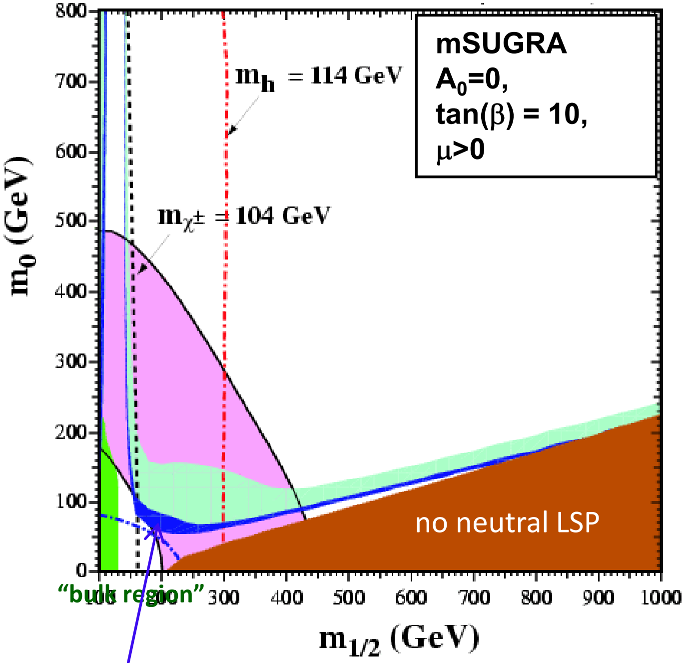
general "strategy":

- **define exclusive channels**
- **study selection cuts on benchmark points**

e.g.: SU3: m_0=100, $m_{1/2}$=300 , tanβ=6, A0=-300

- **test procedure with different scenarios**

- take **mSUGRA model** (5 parameter) as "baseline " paradigm for R-parity conserving SUSY model *:*
- use also other scenarios:
  NUHM, GMSB, AMSB



for a particular model the available parameter space is already limited from experimental results (Dark matter constraints)

Inclusive Searches

Example: 4jet + 0 lepton channel

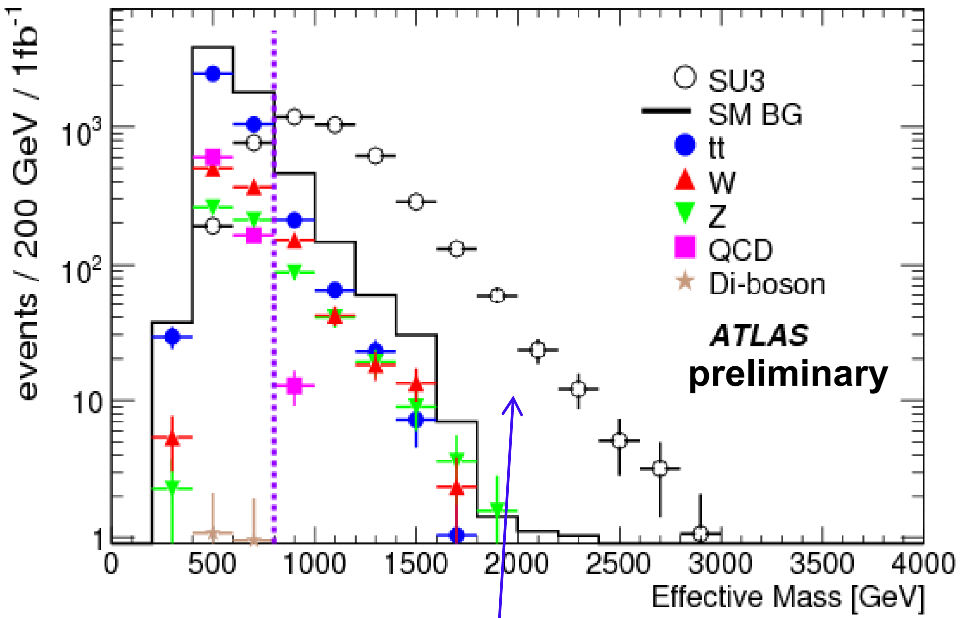
sensitive variable to detect SUSY: "effective Mass" $\mathbf{M_{eff} = \Sigma|p_T^i| + E_T^{miss}}$

0-lepton channel

event selection:

- Trigger: combined trigger
  jet - p_T >70 GeV/c + E_t^{miss} > 70 GeV/c
- 4 jets with p_T > 100, 50, 50, 50 GeV/c
- E_T^{miss} > 100 GeV/c and > 0.2 M_{eff}
- transverse Sphericity > 0.2
- veto isolated leptons
- min $\Delta\varphi(\text{jet}^i, E_t^{miss})$ > 0.2
  (QCD removal)

SU3: mSUGRA bulk region



excess at large M_{eff}

M_{eff} > 800 GeV:

S/B ≈ 6430 / 1210 for L=1fb^{-1}

Inclusive Searches

Example: 4jet + 0 lepton channel

0-lepton channel

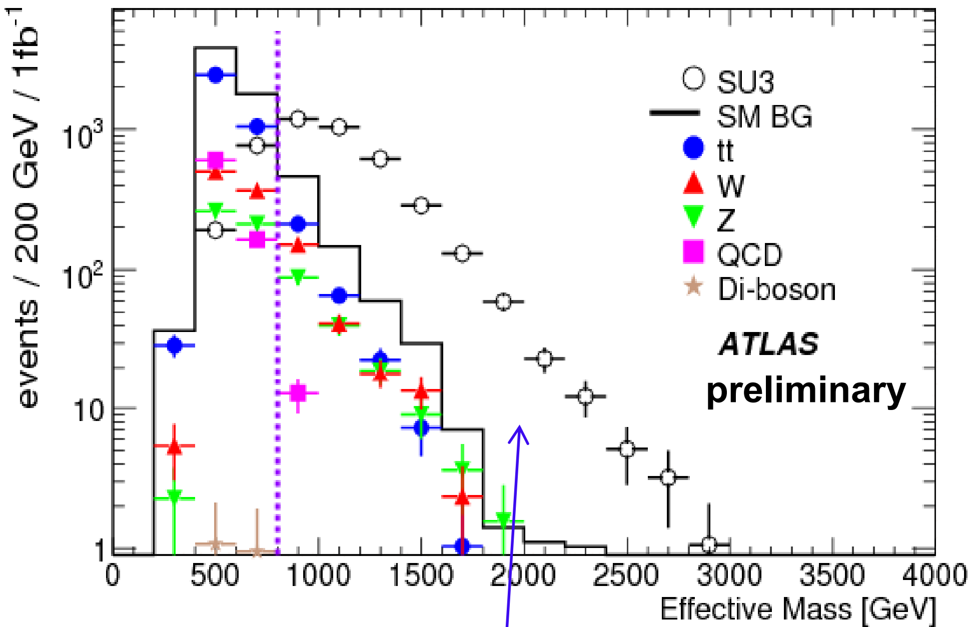
Main SM backgrounds :

• t-t bar, W(lv)+jets, Z(vv)+jets, QCD jets

• many (difficult) background contributions to control :
→ large theoretical uncertainties on backgrounds (multi-jet production)
→ try to rely on data-driven determination of backgrounds :

additional problem:

poor understanding of detector (E_t^{miss}, JES,…) with early data



excess at large M_{eff}

M_{eff} > 800 GeV:

S/B ≈ 6430 / 1210 for L=1fb^{-1}

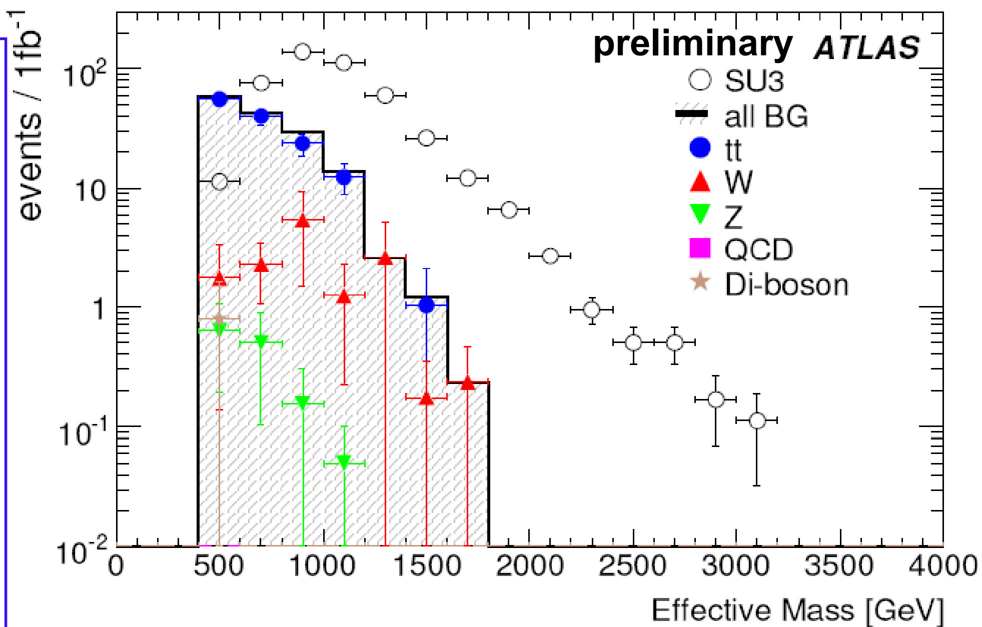
Inclusive Searches

1-lepton channel

$M_{eff} = \Sigma|p_T^i| + E_t^{miss} + |p_T\,(\text{lepton})|$

event selection:

- Trigger: combined trigger
  jet - p_T >70 GeV/c + E_t^{miss} >70GeV/c
- 4 jets with p_T > 100, 50, 50, 50 GeV/c
- E_T^{miss} > 100 GeV/c and > 0.2 M_{eff}
- transverse Sphericity > 0.2
- **exactly 1 isolated lepton (e or μ) with p_T> 20 GeV/c**
- **no other e or μ (p_T > 10 GeV/c)**
- **transverse Mass:**
  M_T (e/μ, E_T^{miss}) > 100 GeV/c



Main SM background:

- top pairs, W(lν)+jets

- lower, but more clear signal
- less QCD background

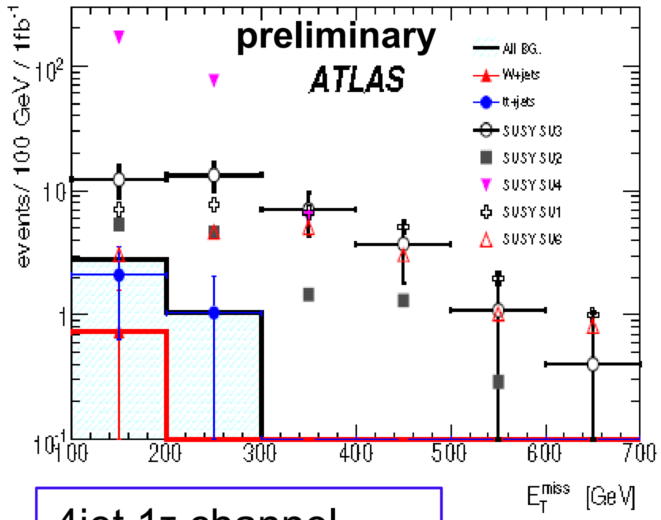
S/B ≈ 230 / 40 for L=1fb^{-1}

Inclusive Searches

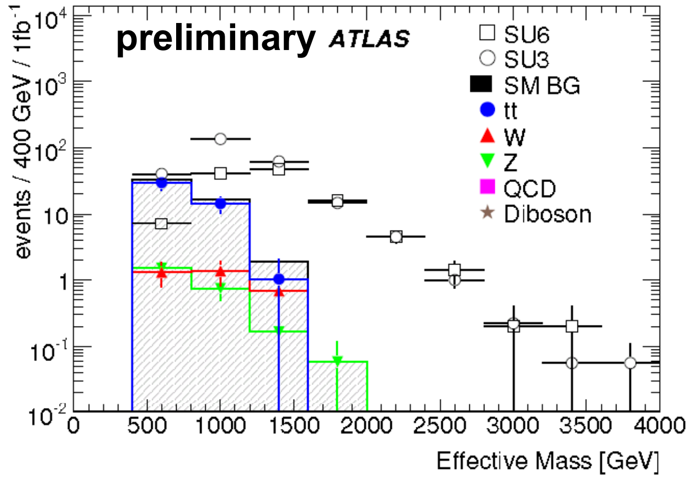
Other inclusive Search channels considered:

- relax N jets from 4 to 3 or 2 …
- 2 lepton same sign, opposite sign
- 3 leptons + jet (no E_T^{miss} !)
- 3 leptons + E_T^{miss} (no jets !)
- tau mode:
- e, μ replaced by hadronically decaying τ
- can dominate for high tanβ
- b-jet mode: exploit SUSY's richness in b-jets

4jet same sign 2 lepton channel



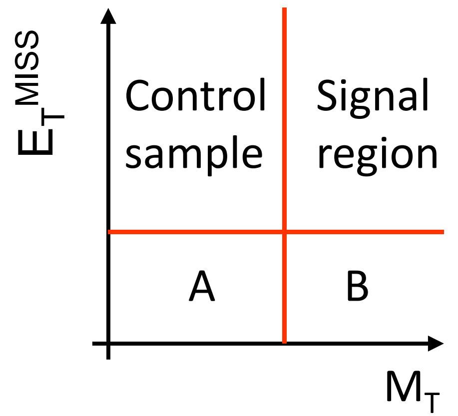
4jet 1τ channel

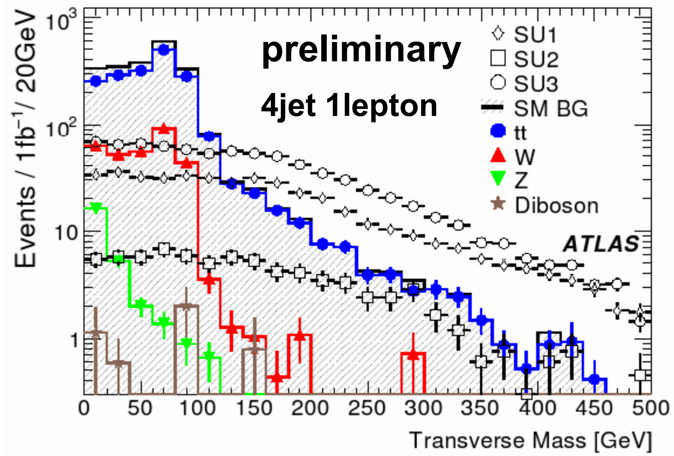


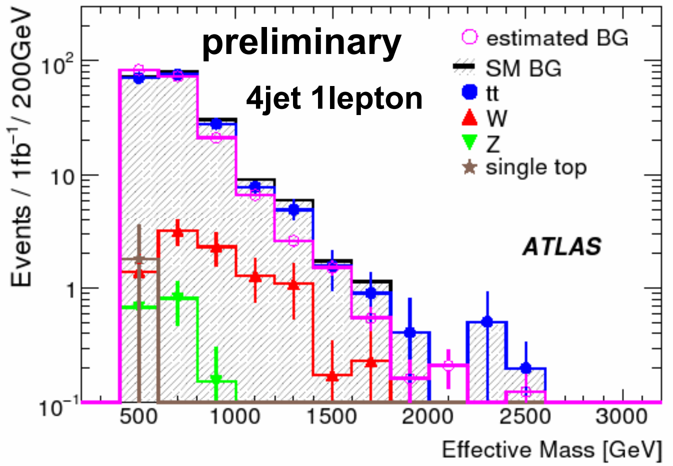
Background estimation

before claiming any discovery we need to understand our background expectations (MC, detector)
→ validate background estimation with data in defined control regions

estimate top / W background from data







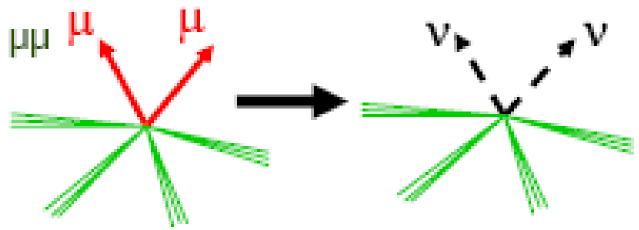
- Top background can be estimated with many methods
- use discriminating variable M_T < 100 GeV/c to select control sample region
- M_{eff} distribution in control region can be used to predict distribution in signal region (M_T > 100 GeV)

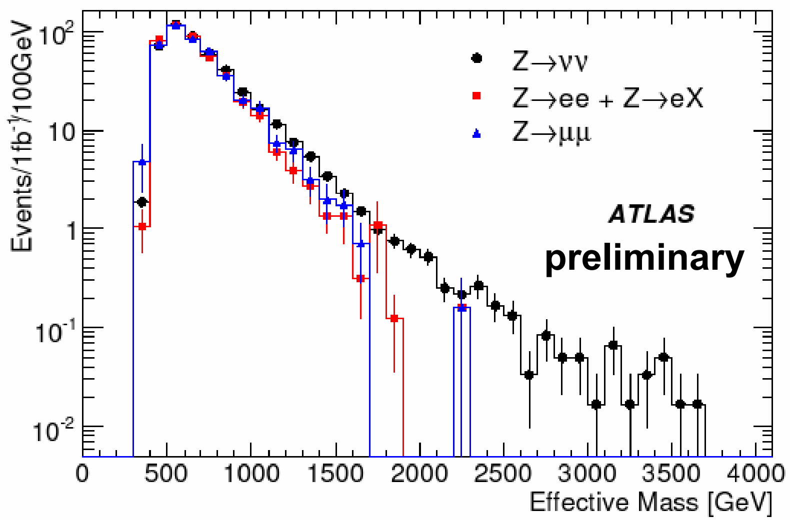
- **uncertainty for Top:** about 30 % (20 % for 1 lepton mode) for 1 fb^{-1}

Background estimation

estimate Z background from data

- $Z \to \nu\nu$ + jets is an irreducible background in 0-lepton channel
- estimate background fromdata with $Z \to l^+ l^-$ + jets

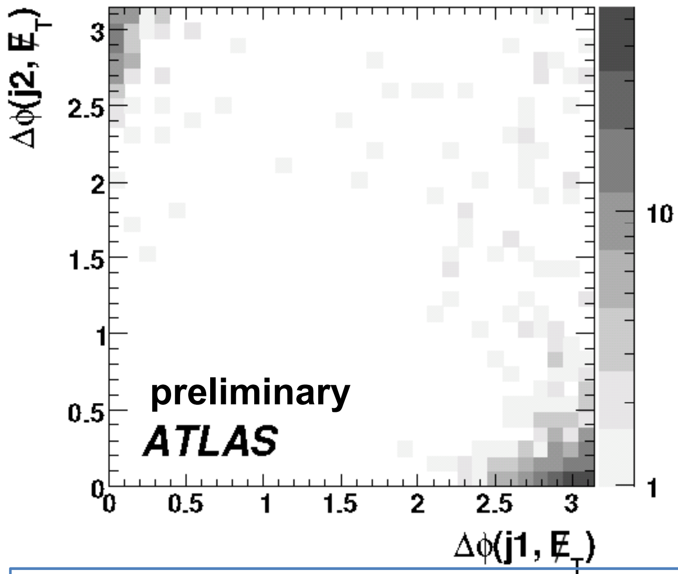




uncertainty for Z : about 20% (15 % for 0lepton mode) for 1fb^{-1}

estimate QCD background from data

- fake missing p_T due to jet mis-measurements and jet resolutions
- reducible with clean up cuts → $\Delta\varphi$ (jet- E_T^{MISS}) cut
- to estimate remaining QCD background after cleaning :
- measure smearing function in events with large MET associated to a single jet
- select seed events with low MET-significance and smear each jet

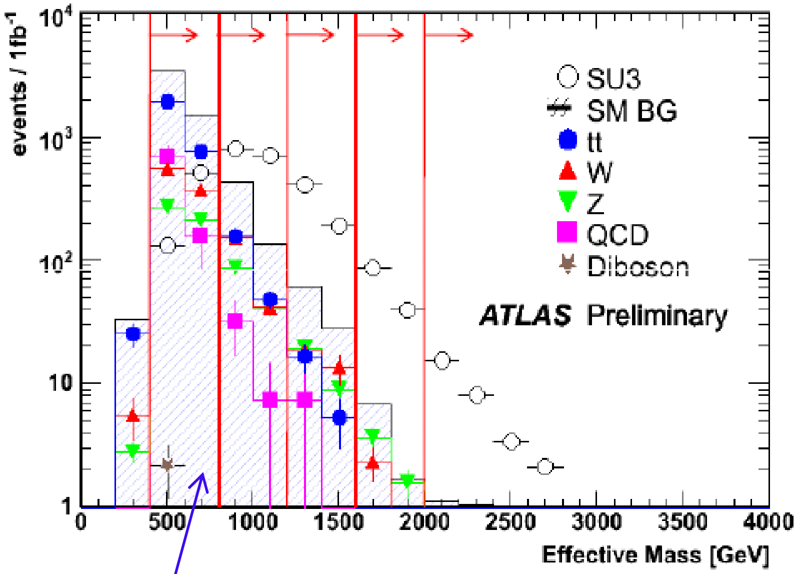


uncertainty for QCD: about 50% for 1fb^{-1}

Discovery reach - procedure

Scan in mSUGRA parameter space:

repeat searches using many different mSUGRA signals



Meff scan step size: 400 GeV/c

*prob: equation from Highland/Cousins
= convolution of the poisson probability with a Gaussian probability density function

Aim:
Scan M_{eff} distribution for deviation

Procedure:
- each point has a different M_{eff} distribution
- scan each distribution (try n cuts in M_{eff}): optimize M_{eff} cut to get best signal significance
- looking for M_{eff} cut with highest significance (lowest probability):

1. calculate probability prob*: to find D data events if B SM events are expected

2. choose region with lowest probability prob*

3. correct probability values for 'multiple testing' via a Monte Carlo method

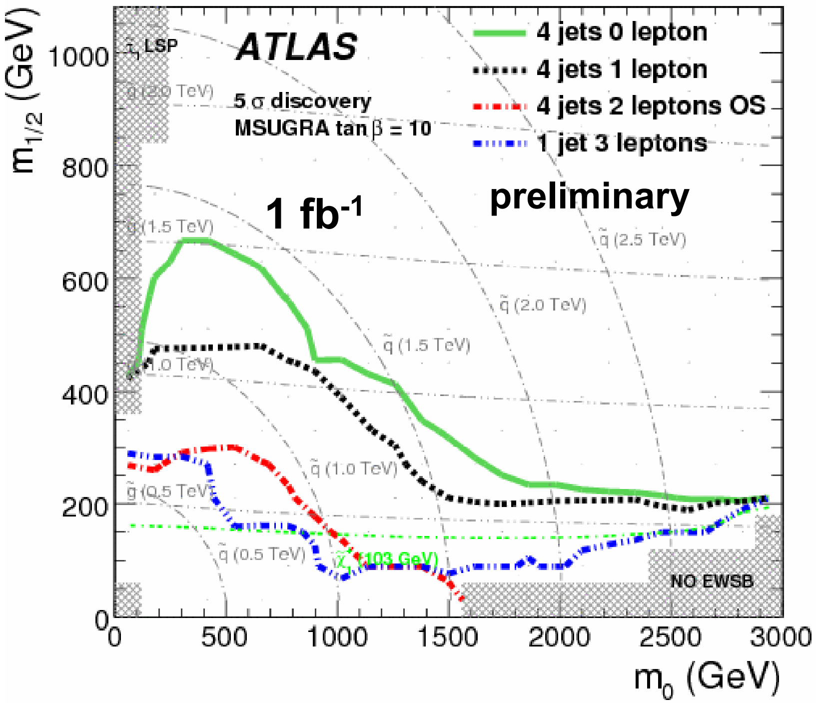
$$significance = erf^{-1}(1-2\cdot prob)\cdot\sqrt{2}$$

Discovery reach for mSUGRA

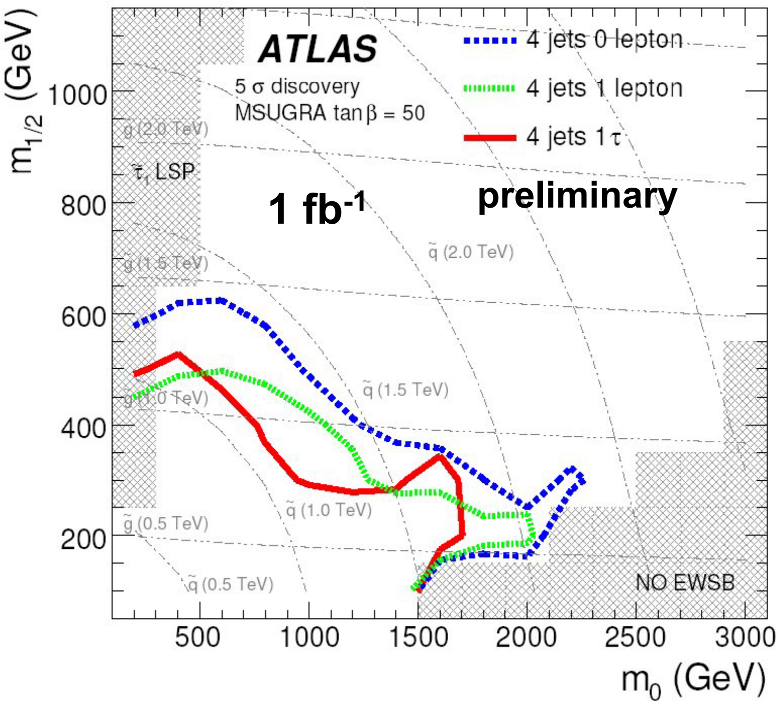
Scan in mSUGRA parameter space:

- LO signal cross sections were used
- significant (data-driven) uncertainties on background (QCD : 50%, other background 20 %)

tan β = 10



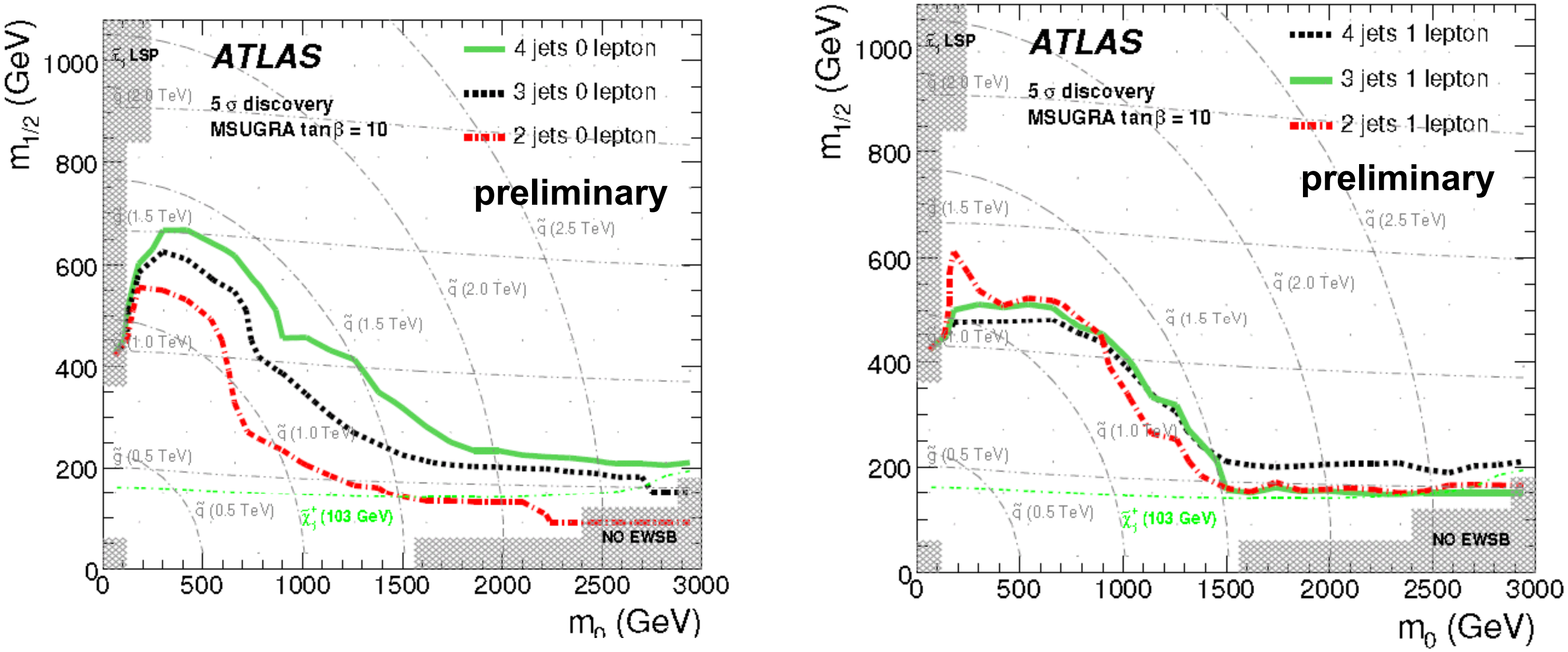
tan β = 50



- **for 1 fb^{-1} : cover a large part of mSUGRA phase space favored by electroweak, heavy-flavour physics and low energy precision data!**
- **tau channel can help for large tanβ**

Discovery reach for mSUGRA

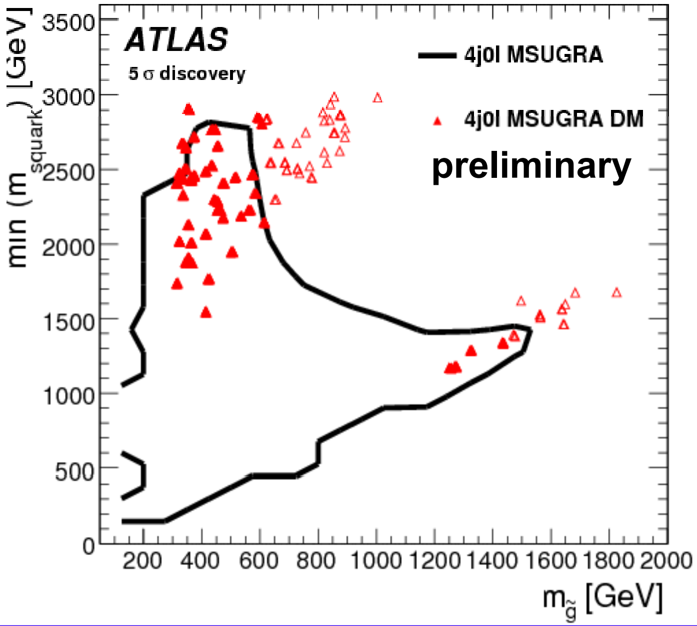
Comparison of 2,3,4 jets + 0,1 lepton

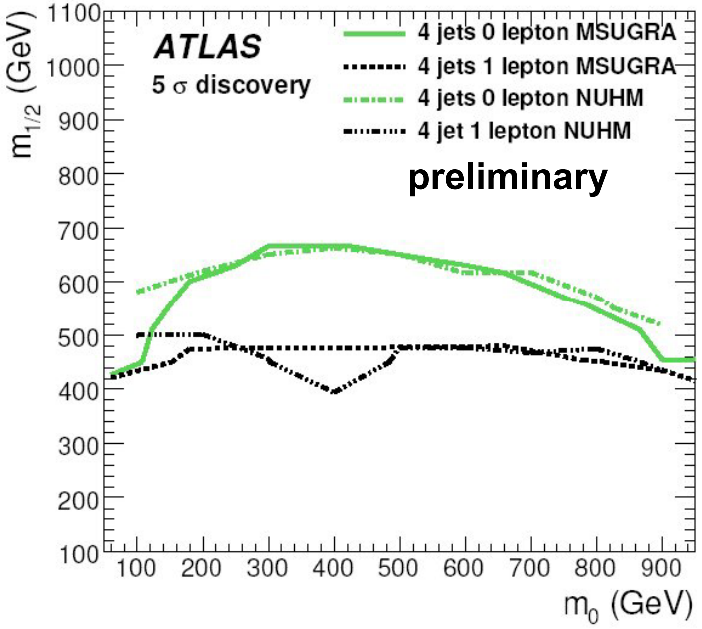


sometimes better discovery potential with lower jet multiplicities!

Discovery reach for other models

discovery reach for other models (1 fb^{-1}):





mSUGRA ↔ DM constraints (μ>0)

random mSUGRA points, but satisfying WMAP (dark matter constraints)
g_μ -2, M_h , b→sγ, B_s → μμ

(closed triangle : > 5σ discovery)

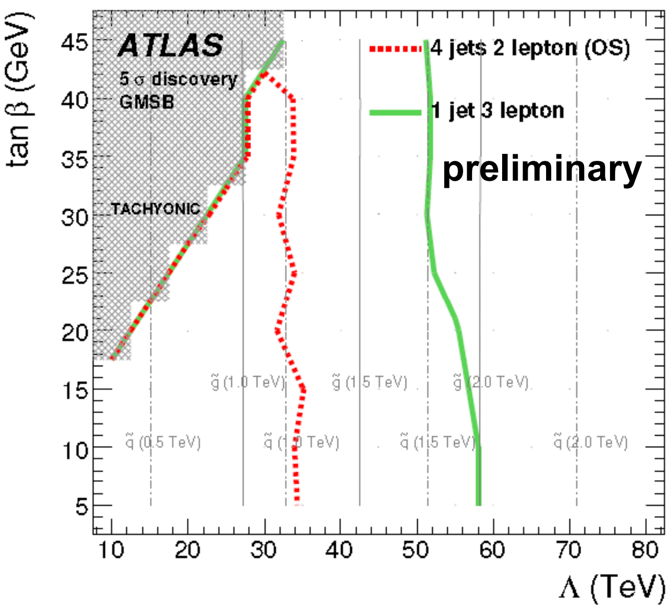
mSUGRA ↔ NUHM

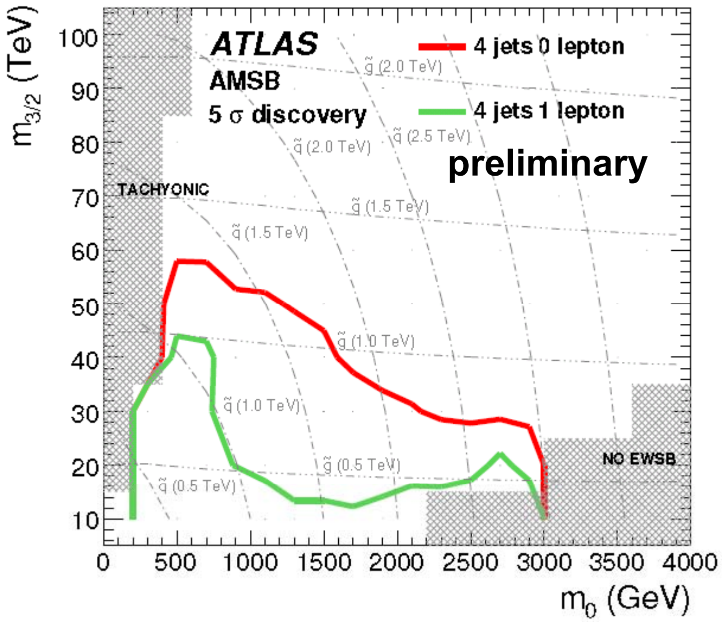
NUHM :
fix M_A and tan β to values compatible with WMAP constraints

similar results: discovery reach does not differ so much

Discovery reach for other models

discovery reach for other models (1 fb^{-1}):





GMSB :

- production: 2 leptons or τ on generator level
- 1 jet 3 lepton analysis shows highest discovery reach : less Standard Model background

AMSB:

- similar phenomenology as NUHM, but different masses and decay modes
- reach for 0 lepton channel similar to the reach for mSUGRA
- difference for 1 lepton channel: chargino decays in invisible leptons

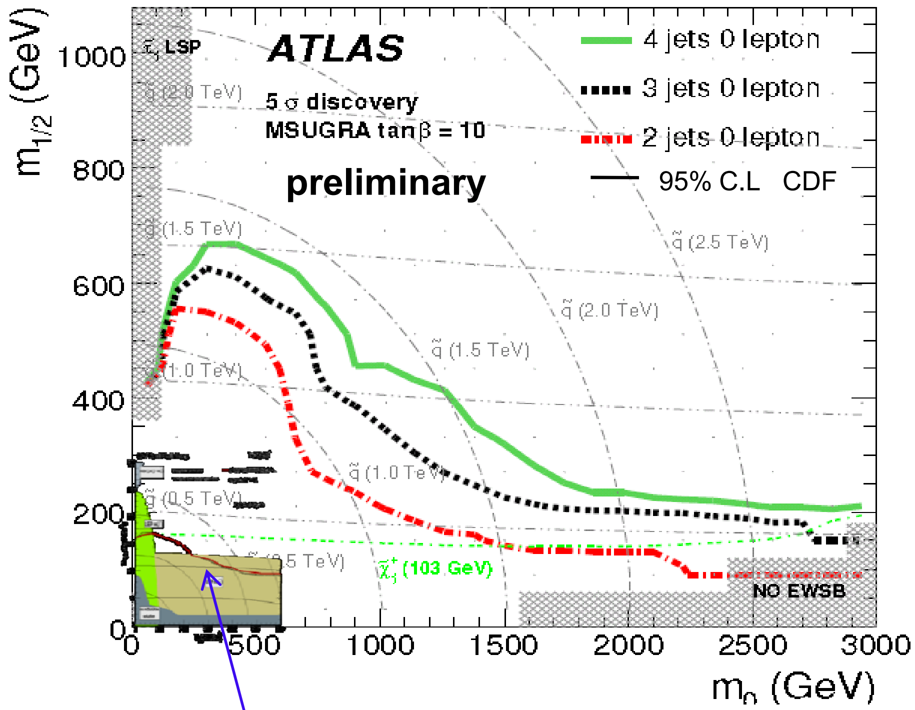
Comparison with Tevatron

for very early data taking:

discovery reach for L= 100 pb^{-1} higher than CDF 95% confidence level for L= 2fb^{-1} !

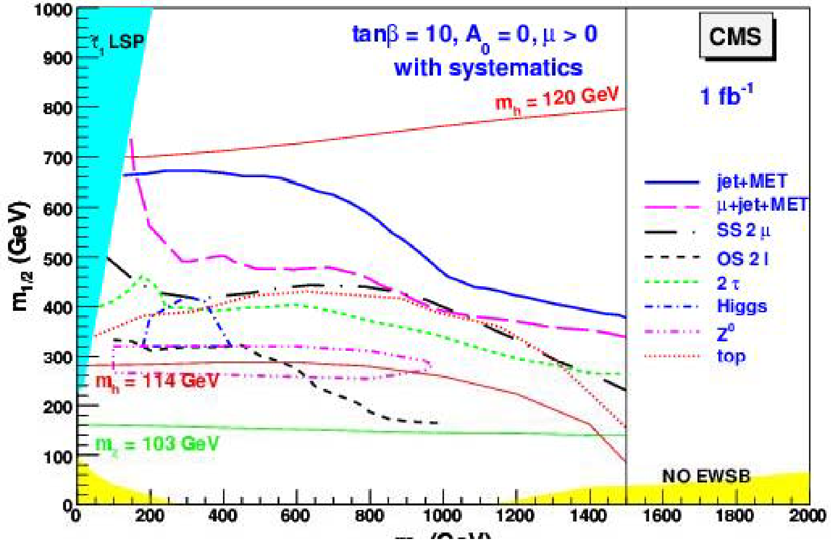
- ATLAS is sensitive mainly to a region of squark and gluino masses up to 600 GeV for 10 TeV with 20 pb^{-1}
- D0/CDF 2-σ limits are at m_{squark} / m_{gluino} of 350-400 GeV now

plots for 14 TeV (≅ 1fb^{-1})



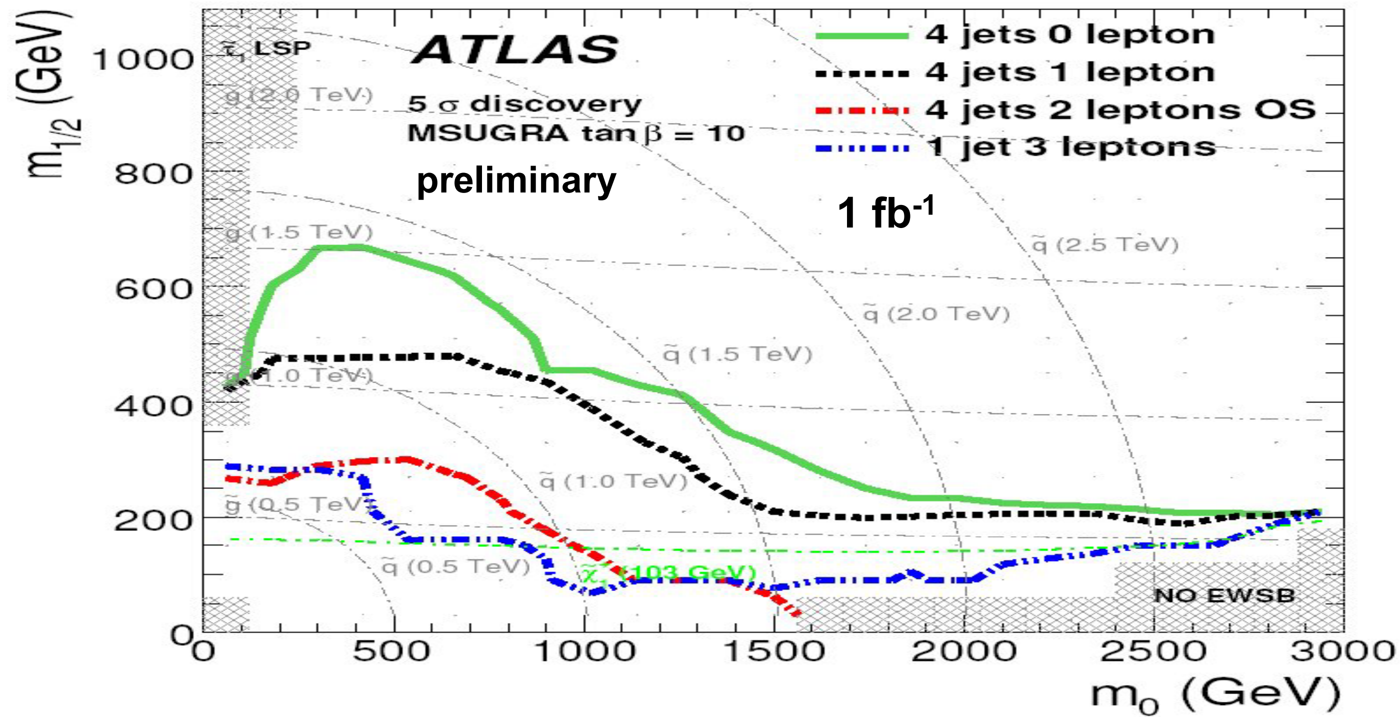
95 % confidence level : D0/CDF

Comparison ATLAS ←→CMS



The potentials of CMS and ATLAS are very similar.

Largely determined by signal and background cross sections!



Conclusion

• recent studies for various SUSY channels and various background estimation strategies have been presented

• ATLAS shows a high potential to discover R-parity conserving SUSY signatures with gluino and squark masses up to 1 TeV for 1 fb^{-1}…

….but :

we have to estimate all backgrounds and understand our detectors, triggers,etc … first!

What we need NOW is real data! (hopefully spring 2009)

We are at the threshold of very exciting times!

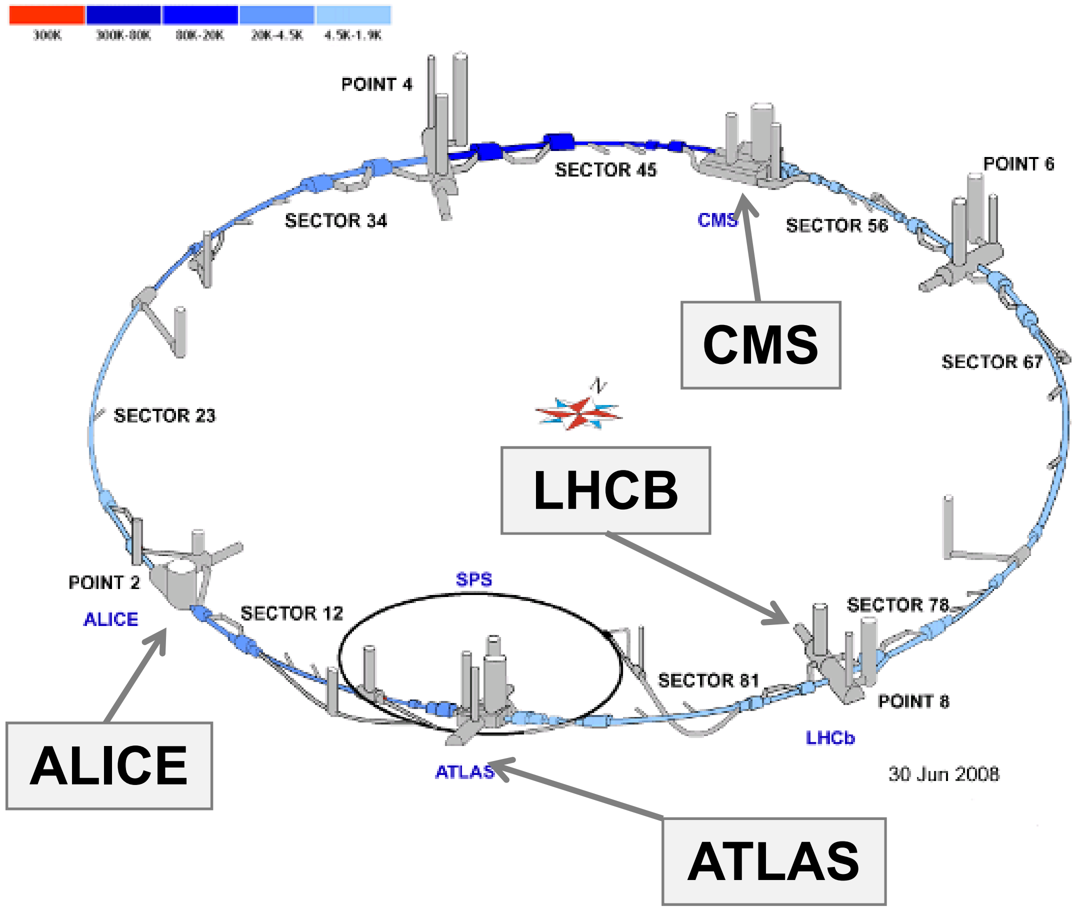
THANKS!

Many thanks to the organizers!

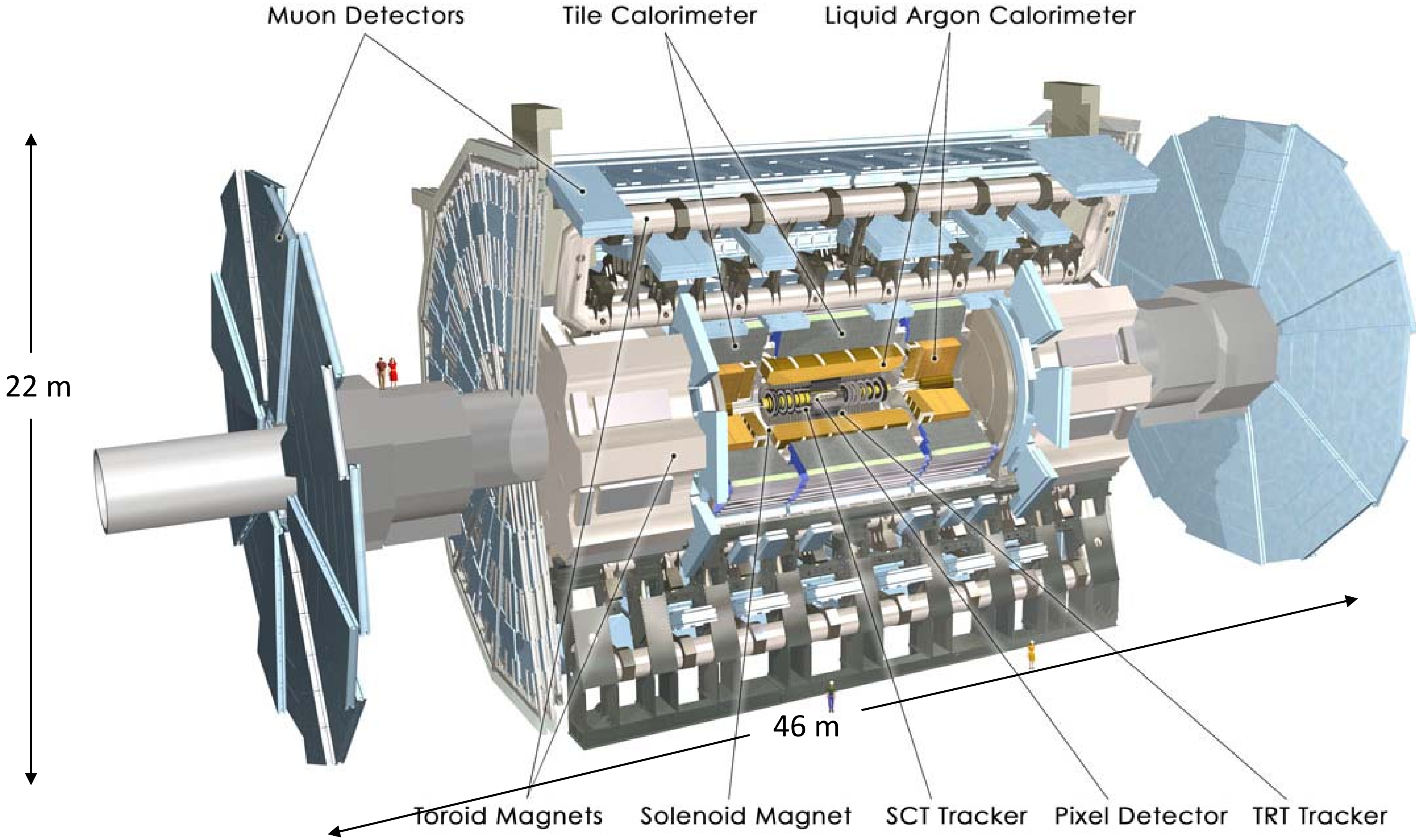
BackUps

Large Hadron Collider @ CERN

- LHC collides protons –protons (or Pb ions)
- √s=14 TeV (10 TeV early next year?)
- Design Luminosity $10^{34}cm^{-2}s^{-1}$
- Bunch crossing rate 40 MHz
- Events per bunch crossing ~20 ("pile-up")
- 4 main experiments
    - CMS, ATLAS (multi purpose)
    - ALICE (heavy ion physics)
    - LHCB (low-p_T B physics)



The ATLAS experiment,   1900 scientists, 165 institutes, 35 countries



Supersymmetry MSUGRA - tan(β) = 10

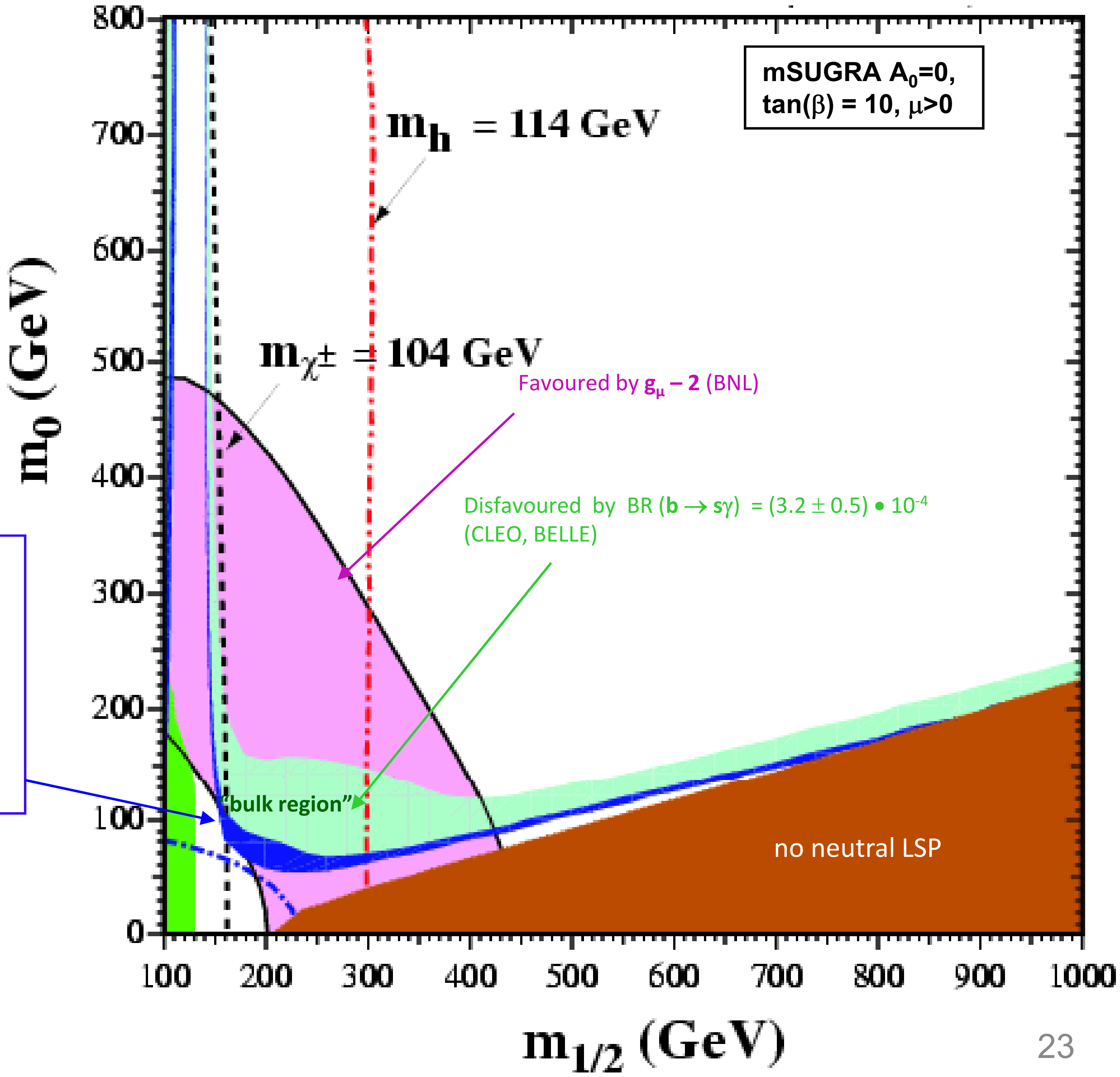
mSUGRA model:

- minimal gravity mediated SUSY breaking
- 5 parameters (m_0, $m_{1/2}$, …)
- LSP = lightest neutralino

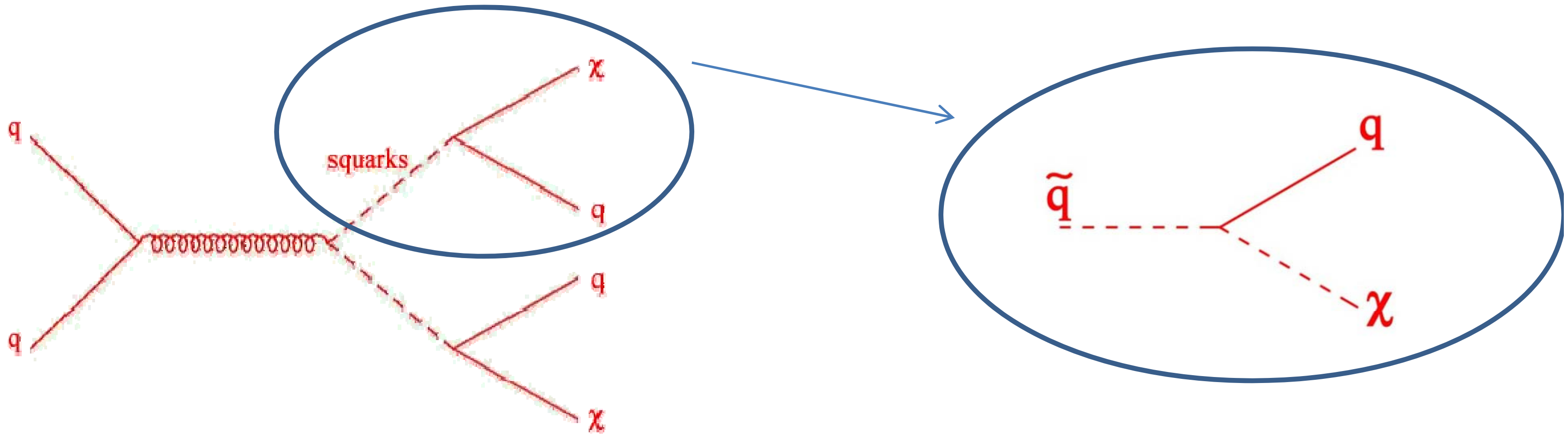
Large LSP annihilation cross-section required by WMAP data:

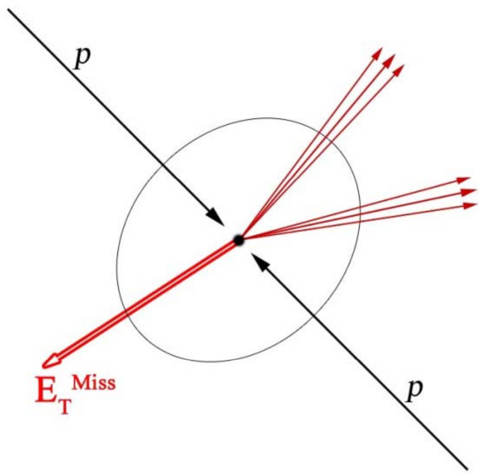
CMB measurement:

$0.094 < \Omega_{DM} h^2 < 0.129$ strongly bounds SUSY parameter space

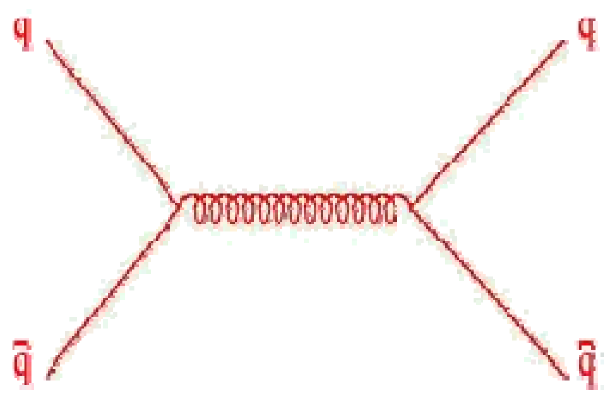


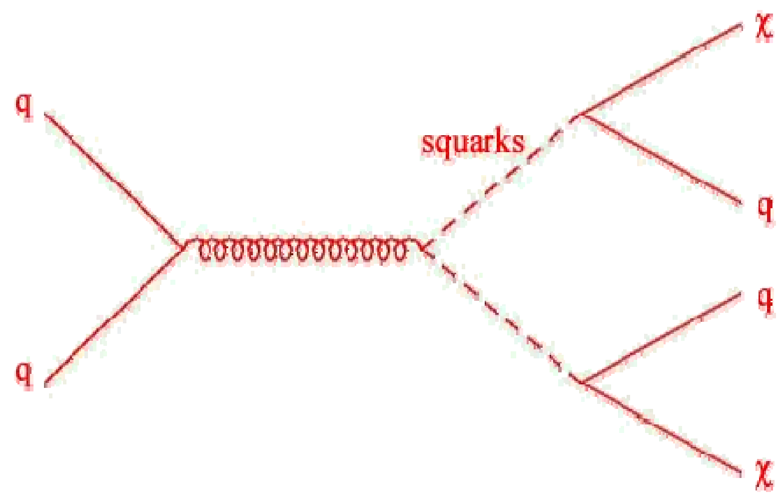
SUSY signatures - an example





QCD background ←→SUSY signature





SUSY searches

- ‘baseline model’ paradigm: **RP-conserving mSUGRA**

→ gluino/squark production and cascade decay

→ energetic jets, missing E_T , (leptons)

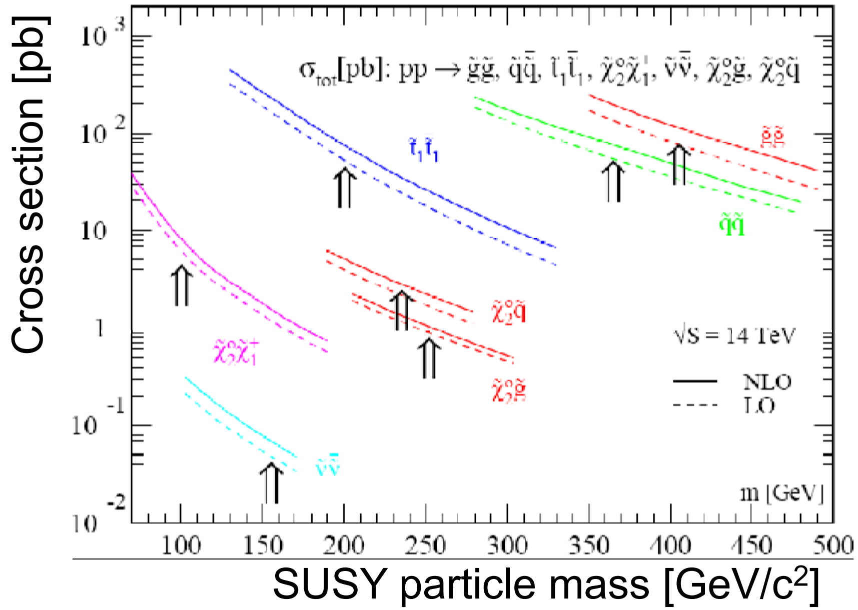
- also using :

NUHM: non-universal Higgs masses

GMSB: gravitino LSP

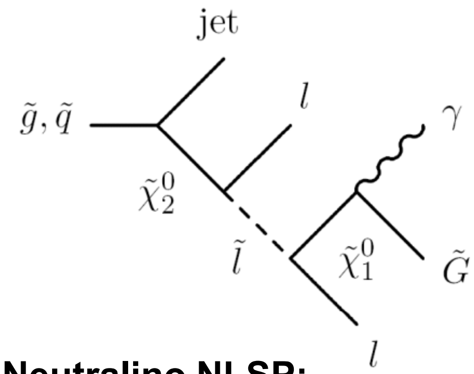
NLSP: neutralino → gravitino + γ
NLSP: slepton (stau) → gravitino + lepton (tau)

AMSB



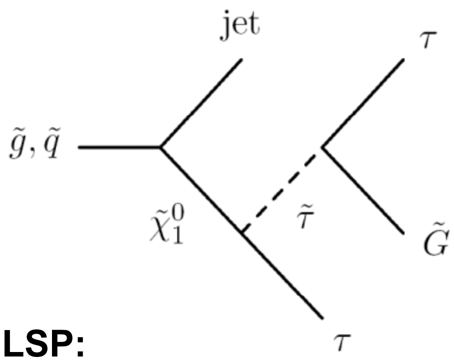
- cross-sections mainly depend on SUSY masses (masses are model dependent)

GMSB Model



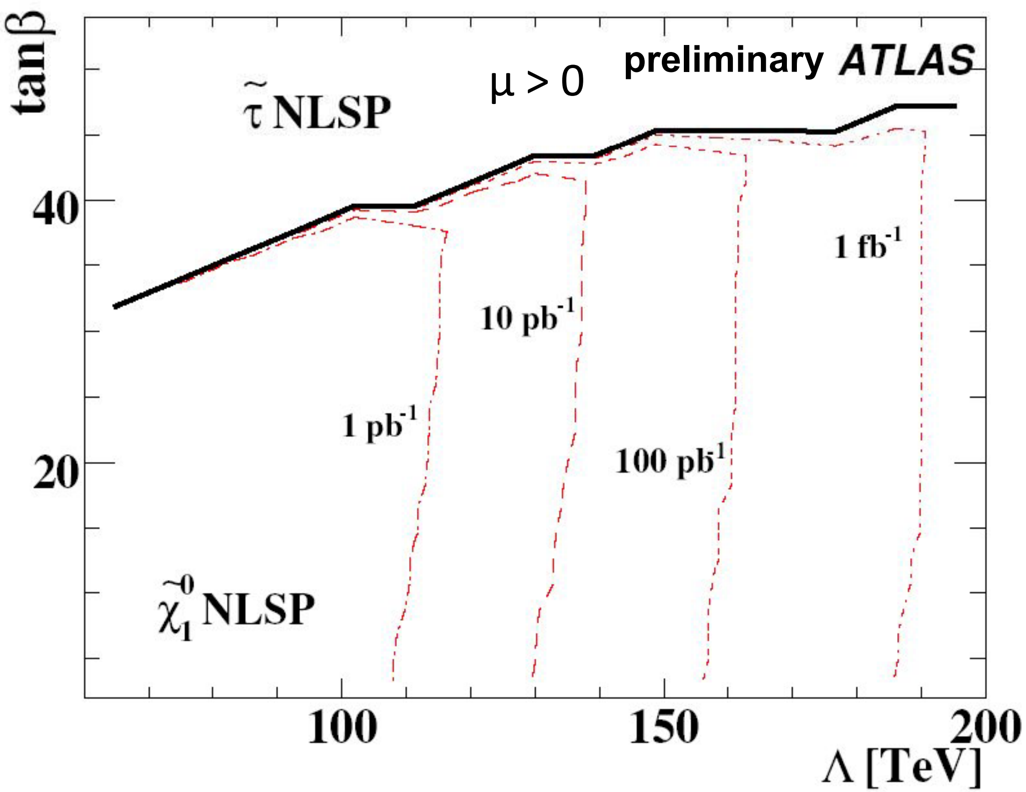
Neutralino NLSP:

prompt photons
non-pointing photons



Slepton NLSP:
prompt leptons
long living sleptons:
semi-stable massive particle.

reach in Λ and tan β (N_5 = 1, M_m = 500 TeV)



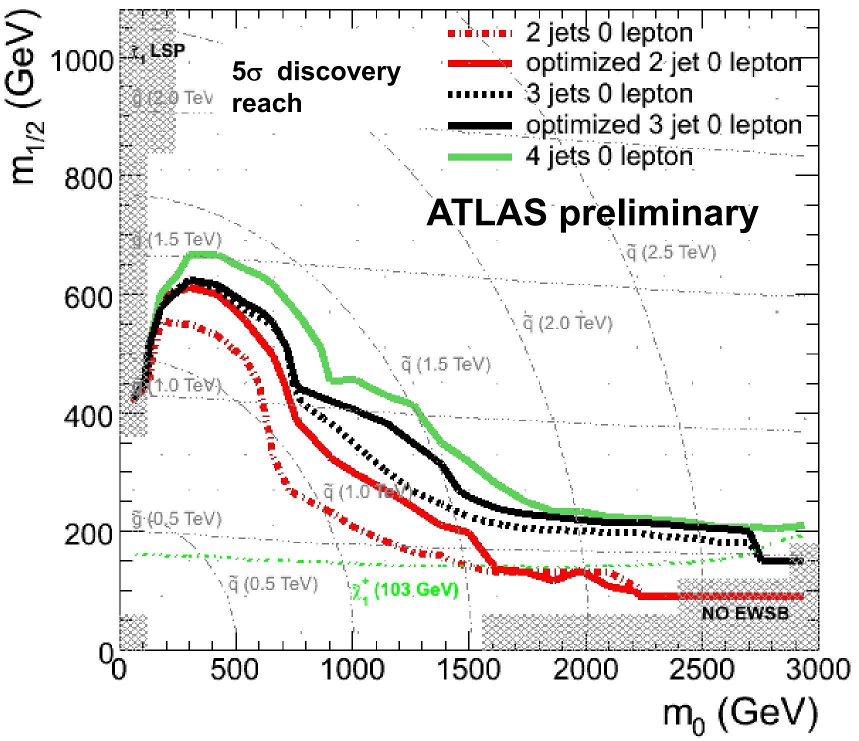
Results of Optimization

5 σ contour line plots with optimum selection for 1 fb^{-1}

systematic errors:

QCD	= 50 %
other bg	= 20 %

The cut optimization could significantly improve the discovery reach !



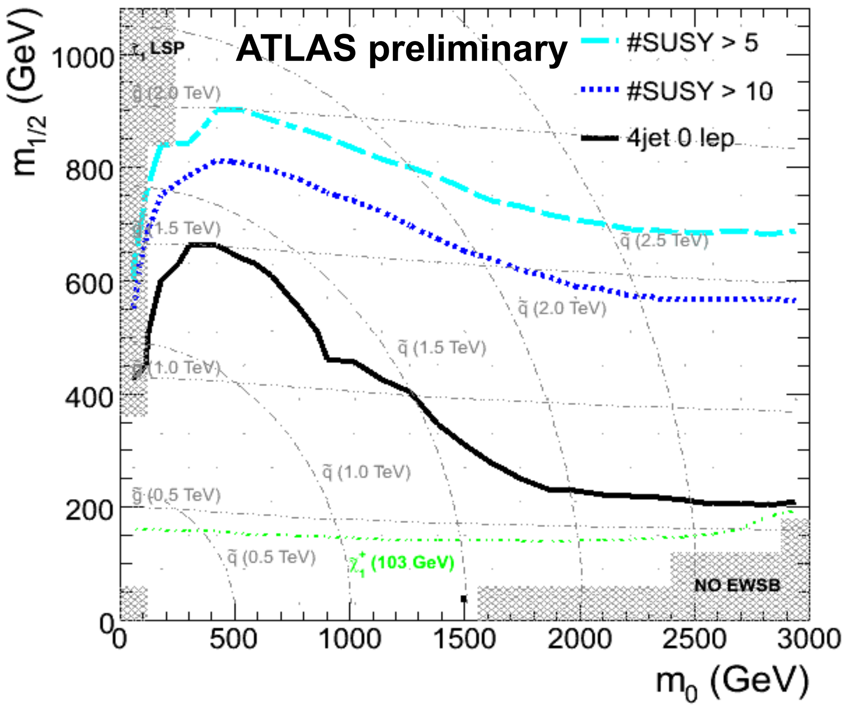
How can we improve the discovery reach?

4 jet 0 lepton channel at $1 fb^{-1}$

CSC 5: we only claim a discovery with
$\geq$ 6 data events (Susy+ bg)

blue line shows max. discovery reach we could have at all

→ improvement possible at high m_0

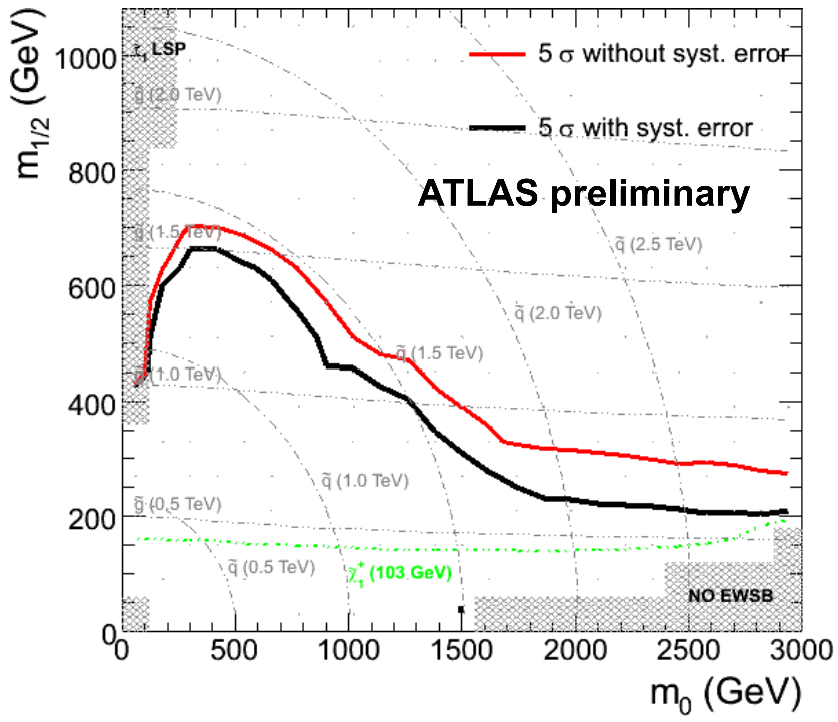


plot: M. Rammensee

How big is the effect of systematic uncertainties?

5 σ contour lines for 4 jet 0 lepton channel at 1fb^{-1} with and without uncertainties

uncertainties have less influence on discovery reach than expected!



plot: M. Rammensee

Systematic uncertainties

Assuming uncertainties for different samples are gaussian distributed and uncorrelated

total systematic uncertainty for SM background:

for each bin in the M_{eff} distribution:

$$\delta SM = \sqrt{\delta W_{e\nu}^2 + \delta W_{\mu\nu}^2 + \ldots + \delta Z_{ee}^2 + \ldots + \delta QCD^2}$$

and:

$$\delta \text{ sample} = \sqrt{(\text{systematic error})^2 + (\text{statistical error})^2}$$

Note:
the statistical error gives the const. systematic error a bin dependence in the M_{eff} distribution

Uncertainties for backgrounds

	method	stat. unc.	syst. unc.
QCD	combine MC and data-driven jet smearing	1 %	50 %
$Z \rightarrow \nu\nu$	data (or MC) from $Z \rightarrow ll$ ($Z \rightarrow ee$ / $Z \rightarrow \mu\mu$)	8-13 %	10-15 %
top+W	reverse cut on M_T	4-8 %	15 %
top $\rightarrow \tau$	select sl τ decay	6 %	15 %
tt $\rightarrow l\nu bbjj$	top sample using top mass	5 %	22 %
tt $\rightarrow l\nu l\nu bb$	control sample using H_{T2} kinematic reconstruction top MC redecay method	10 %	20 %

Calculation of the probability

- the background can never be known exactly
- uncertainties on the background are incorporated in the significance by convoluting the Poisson probability that the background fluctuates to the observed signal with a Gaussian background probability density function with mean N_b and standard deviation δN_b
- given these assumptions, the probability p that the background fluctuates by chance to the measured value N_{data} or above is given by:

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

- where $G(b;N_b,\delta N_b)$ is a Gaussian and the factor A ensures that the function is normalized to unity:

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

Correction of probability

looking at many different data selections :
•statistical fluctuations can be misinterpreted as new phenomena if the number of selections is not considered : 'multiple comparisons'.

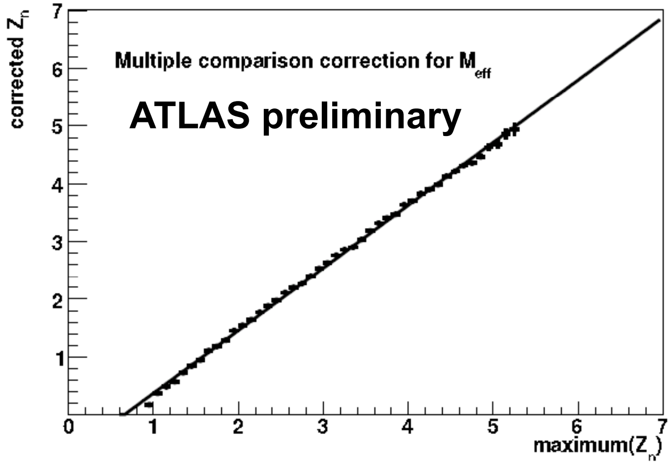
→ **correct probability values for 'multiple comparisons' via a Monte Carlo method (‚toy experiment')**

1. generate 50 Mio. Meff histograms by dicing in each bin a random number of events (poisson distributions)

• each histogram =possible outcome of measurement
• no SUSY signal is involved in this procedure

2. for each histogram apply M_{eff} scan algorithm

•.select cut with largest significance Z_n



3. fraction F of histograms with a larger significance than Z_n is calculated

F= corrected probability for finding a deviation with significance max(Z_n) in data
F is comparable to the probability observed in a single counting experiment!
4. convert F into corrected Z_n

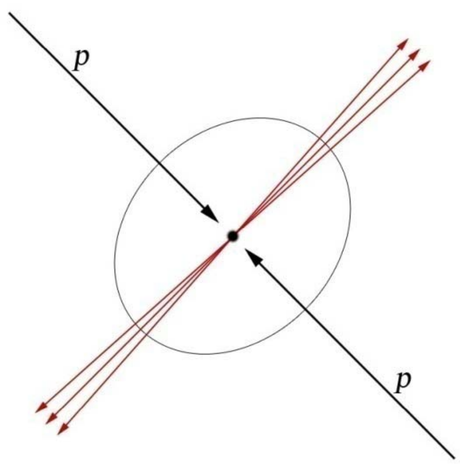
Files

studies are for Susy discovery potential at 1fb^{-1}

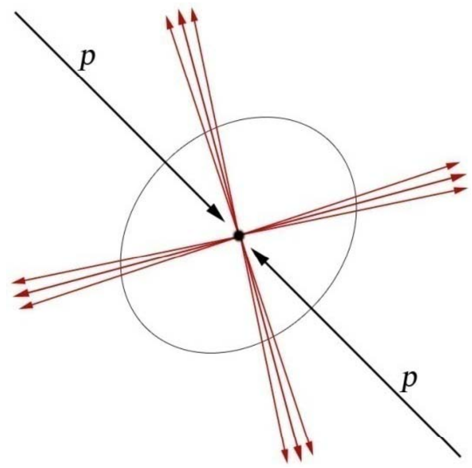
background files:	full simulation for 4jet studies: W/Z : Alpgen QCD: : Pythia DiBoson : Alpgen top: : MCNLO for 2/3 jet studies: W/Z Phythia samples
Susy signals:	
benchmark points:	Isajet 7.74 + herwig/Jimmy + full simulation
grids:	Isajet 7.75 + Herwig/Jimmy 6.5.10 + fast simulation + correction

Transverse sphericity

- measure of the isotropy of the event perpendicular to beam axis.
- $0 \leq S_T \leq 1$



$S_T = 0$



$S_T = 1$

Files

Grids:

Msugra grid:

tanβ =10

- 600 points a 20000 events
- $\tan\beta=10$, sgn $\mu=+1$, $A=0$, m_t = 175 GeV/c^2

m_0 = {60,180,....,2940}
$m_{1/2}$ = {30, 90,.....,1470}

tanβ = 50

- 625 points with 1000/2000 events
- $\tan\beta=50$, sgn $\mu=-1$, $A=0$, m_t = 175 GeV/c^2

m_0 = {200,400,....,3000}
$m_{1/2}$ = {100, 200,.....,1500}

random DM constraints grid

- about 25 points with sgn $\mu=1$

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Grids:

NUHM:

step size of 100 GeV in both m_0 and $m_{1/2}$
for each point the values of μ and MA at the weak scale are adjusted to give acceptable cold dark matter

GMSB

described by 5+1 parameters:

M_{mess} ; Λ ; Nmess ; ;C_{grav} ; tan β ; sign μ:
M_{mess} is a mass scale of the messenger fields
Λ is the scale of SUSY breaking
N_{mess} is the number of SU(5) messenger multiplets

tan β is the usual ratio of vacuum expectation values C_{grav} is the gravitino mass factor in $m_{3/2}$

Files

Grids:

GMSB

Λ	tanβ	M_{mess}	N_{mess}	C_{grav}	sign μ
10-80 by step 5TeV	5-40 by step 5 TeV	500 TeV	5	1	>0

AMSB

- expressed by 3+1 parameters:

  m_0, $m_{3/2}$, tanβ,sign μ

- $m_{3/2}$={10, 20,…,150 } TeV
- m0 = {100,300,…, 3700} GeV

ATLAS benchmark points

SU1 $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.

SU2 $m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Focus point region near the boundary where $\mu^2 < 0$. This is the only region in mSUGRA where the $\tilde{\chi}_1^0$ has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to WW$.

SU3 $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan\beta = 6$, $\mu > 0$. Bulk region: LSP annihilation happens through the exchange of light sleptons.

SU4 $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan\beta = 10$, $\mu > 0$. Low mass point close to Tevatron bound.

SU6 $m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$, $\tan\beta = 50$, $\mu > 0$. The funnel region where $2m_{\tilde{\chi}_1^0} \approx m_A$. Since $\tan\beta \gg 1$, the width of the pseudoscalar Higgs boson A is large and τ decays dominate.

SU8.1 $m_0 = 210$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan\beta = 40$, $\mu > 0$. Variant of coannihilation region with $\tan\beta \gg 1$, so that only $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ is small.

SU9 $m_0 = 300$ GeV, $m_{1/2} = 425$ GeV, $A_0 = 20$, $\tan\beta = 20$, $\mu > 0$. Point in the bulk region with enhanced Higgs production

→ SU3: m(gluino)=720 GeV/c^2 , m(squark)=630 GeV/c^2, σ=28 pb for 1fb^{-1}