Tommaso Lari
Università and INFN Milano
On Behalf of the ATLAS Collaboration

SUSY squark flavour studies with ATLAS

Outline

Introduction

- SUSY mass scale from inclusive searches
- Left-handed squark
- Sbottom and gluino
- Right-handed squark
- Stop

Conclusions

• Most of the ATLAS work since Physics TDR (1999) done on **mSUGRA** models.

A particularly extensive study is available for **SPS1a** point (**fast simulation**) – it will be used here to illustrate techniques to reconstruct the squark mass spectrum.

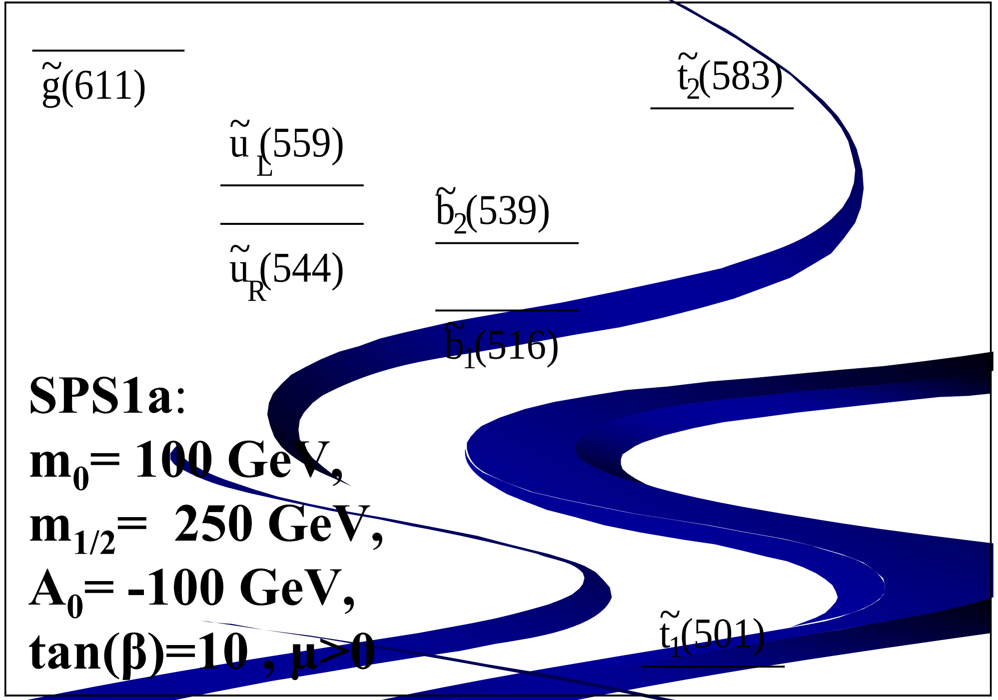
When available for a given signature, recent **full simulation** results will also be shown (obtained for other mSUGRA points)

Introduction

In mSUGRA:

- At the Unification scale, all scalars have the same mass.
- At the EW scale:
  - First two generation almost mass degenerate, but $m(\tilde{q}_L) \neq m(\tilde{q}_R)$
  - Large L-R mixing in 3° generation: $\tilde{b}_1, \tilde{b}_2, \tilde{t}_1, \tilde{t}_2$ mass eigenstates
  - Light $\tilde{b}_1$ and $\tilde{t}_1$

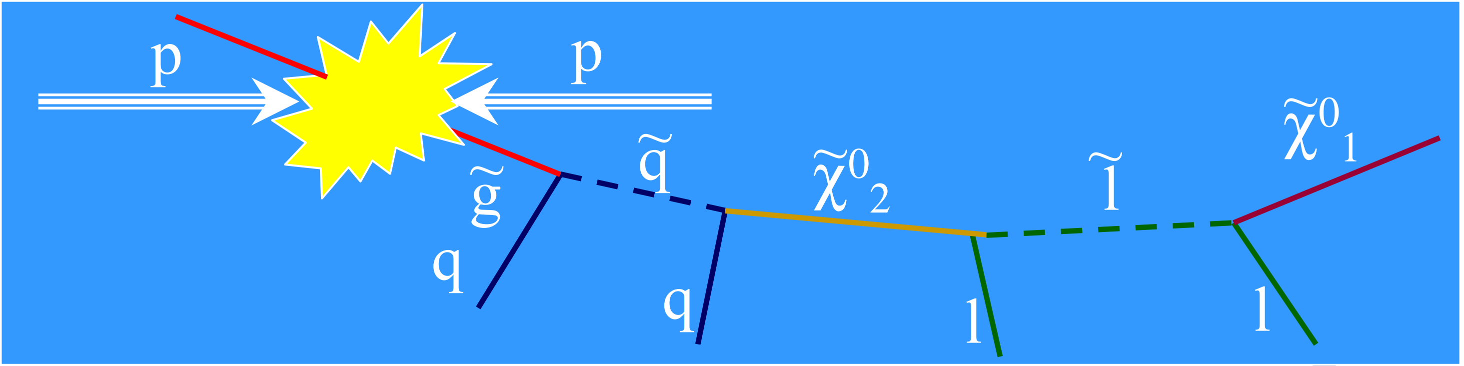
SPS1a mass spectrum (colored states)



SPS1a:
m_0= 100 GeV,
$m_{1/2}$= 250 GeV,
A_0= -100 GeV,
$\tan(\beta)$=10 , μ>0

mSUGRA free parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$, $\mathrm{sgn}(\mu)$

mSUGRA events topology



Strongly interacting sparticles (squarks, gluinos) dominate LHC production.

Cascade decays to the stable, weakly interacting lightest neutralino follows.

- **Event topology:**
  - **high p_T jets (from squark/gluino decay)**
  - **Large E_T^{miss} signature (from LSP)**
  - **High p_T leptons, b-jets, τ-jets (depending on model parameters)**

If sbottom or stop quarks in the decay chain: b-jets

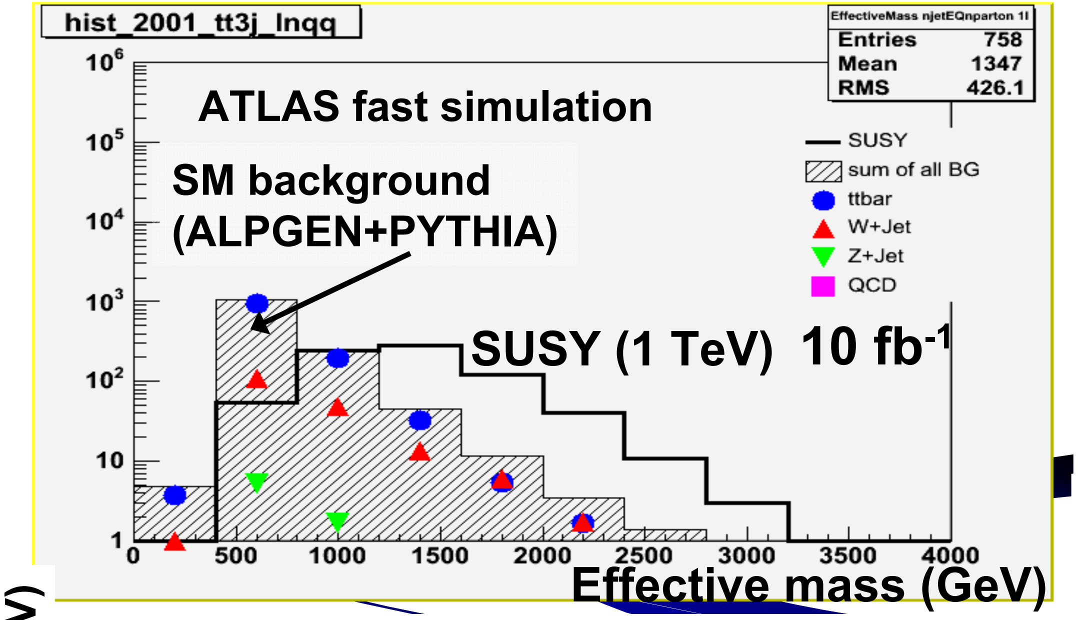
Charm tagging impossible?

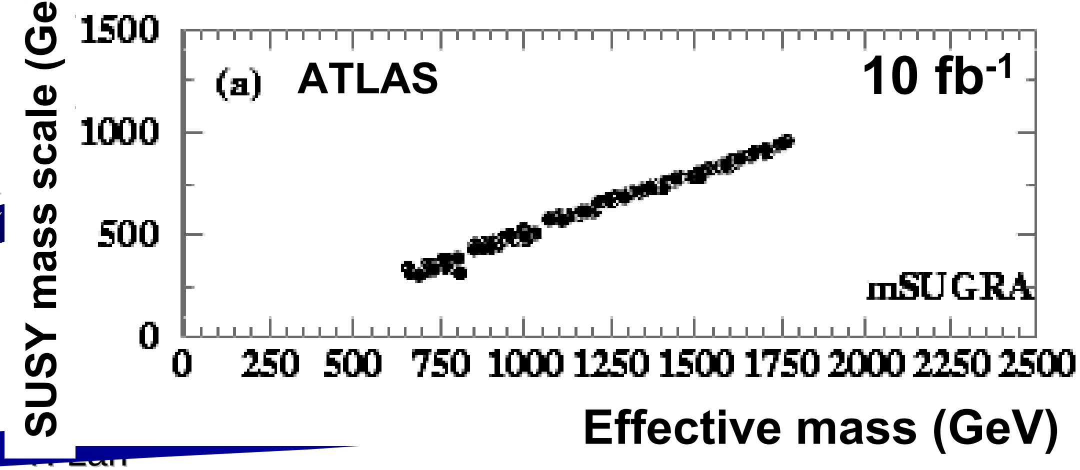
Inclusive signatures

- First hint of the existence of non-SM physics will probably be an excess of events with large missing energy and hard jets
- The peak of the distribution of the effective mass:

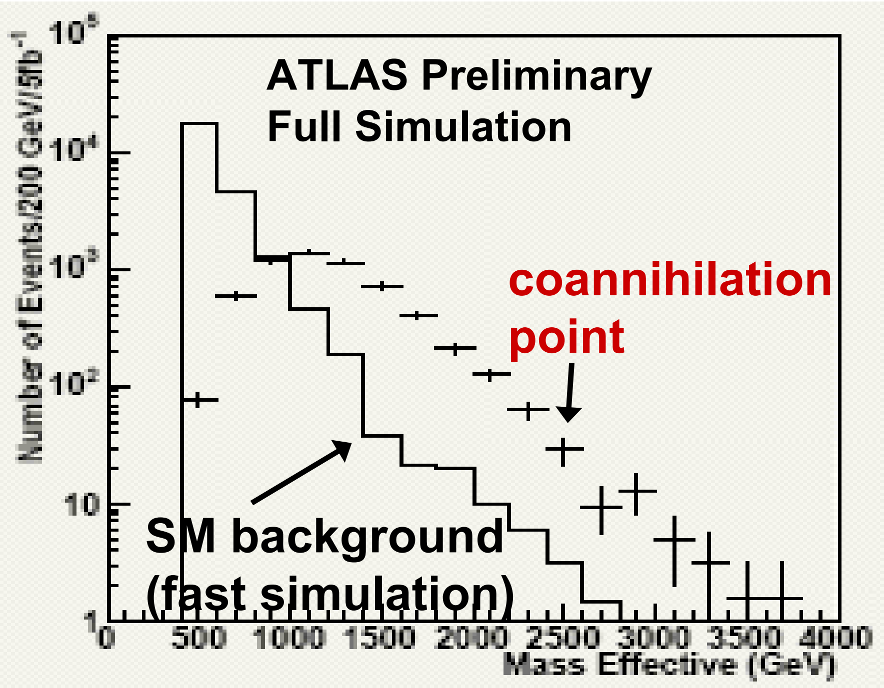
$$M_{eff} = E_T^{miss} + \sum_{jets} p_T^{jet}$$

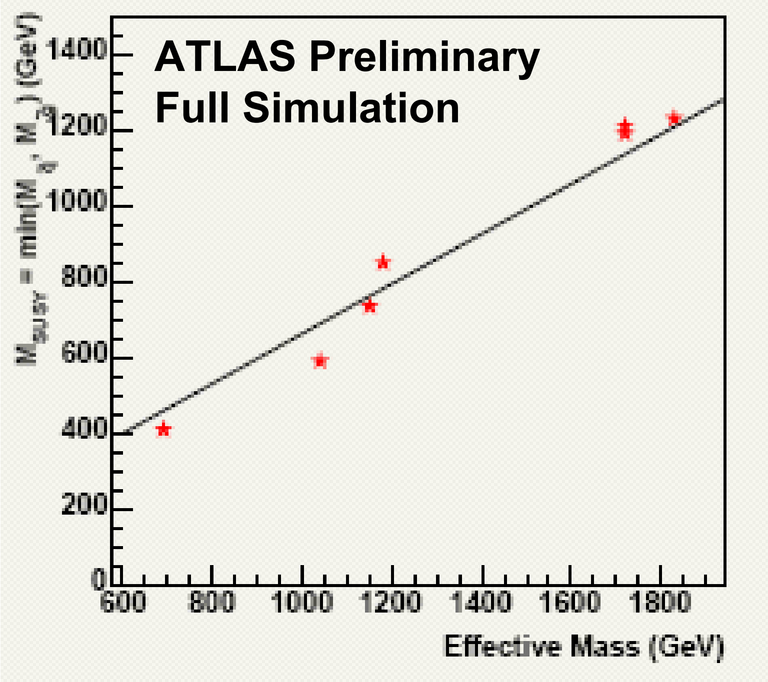
if visible above the background, is strongly correlated with the mass of the SUSY particle produced (gluino or squark): first estimate of SUSY mass scale





Inclusive searches (Full simulation)





- Full simulation data, produced for seven different mSUGRA points, confirms the good correlation between the Effective Mass peak and the SUSY mass scale

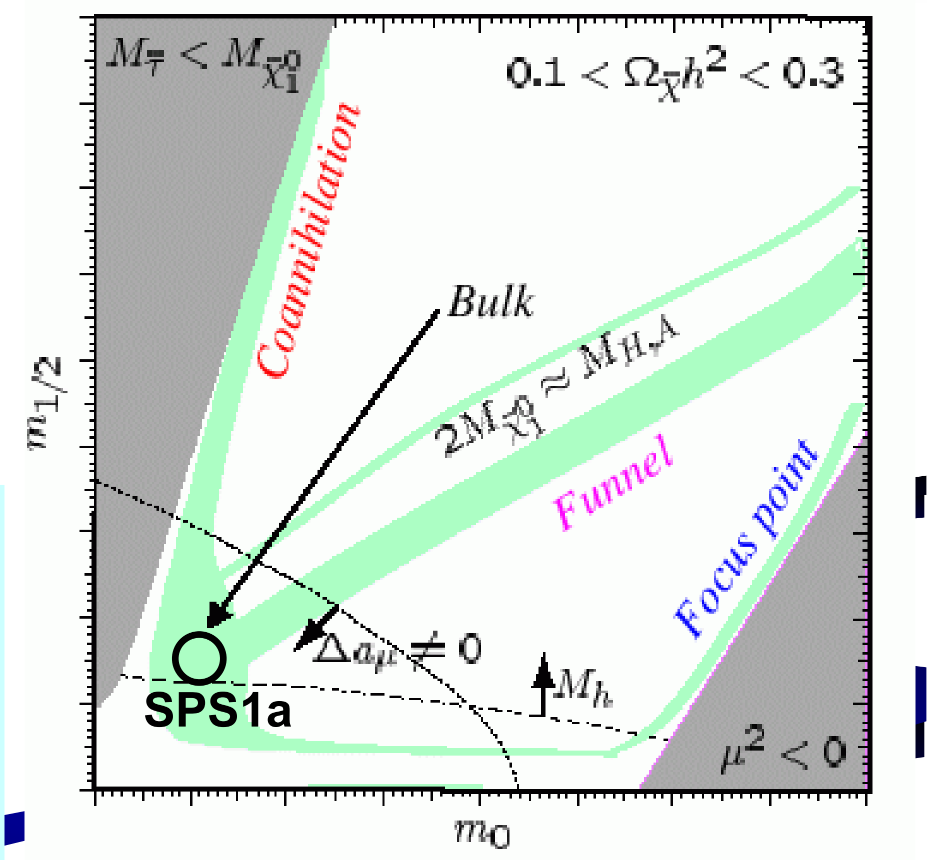
Stau coannihilation point: m_0 =70 GeV $m_{1/2}$ = 350 GeV A=0 $\tan\beta=10$ $\mu>0$

SPS1a

A detailed study for SPS1a (**bulk** region of parameter space) was done in fast simulation

Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007

- $\tilde{q}_L$ mass from
  $\tilde{q}_L \rightarrow q\chi^0_2 \rightarrow q\, l\, \tilde{l} \rightarrow q\, l\, l\, \chi^0_1$
- $\tilde{q}_R$ mass from
  $\tilde{q}_R \rightarrow q\, \chi^0_1$
- $\tilde{b}$, $\tilde{g}$ mass from
  $\tilde{g} \rightarrow b\tilde{b} \rightarrow bb\, \chi^0_2 \rightarrow bb\, l\tilde{l} \rightarrow bb\, ll\, \chi^0_1$

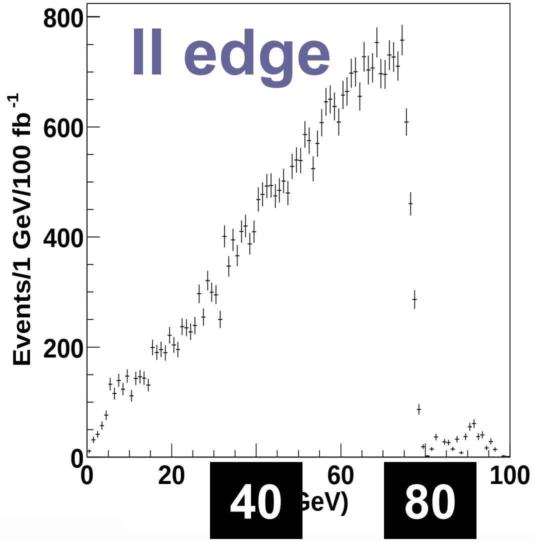


Left squark cascade decay

The decay chain (note the two isolated leptons)

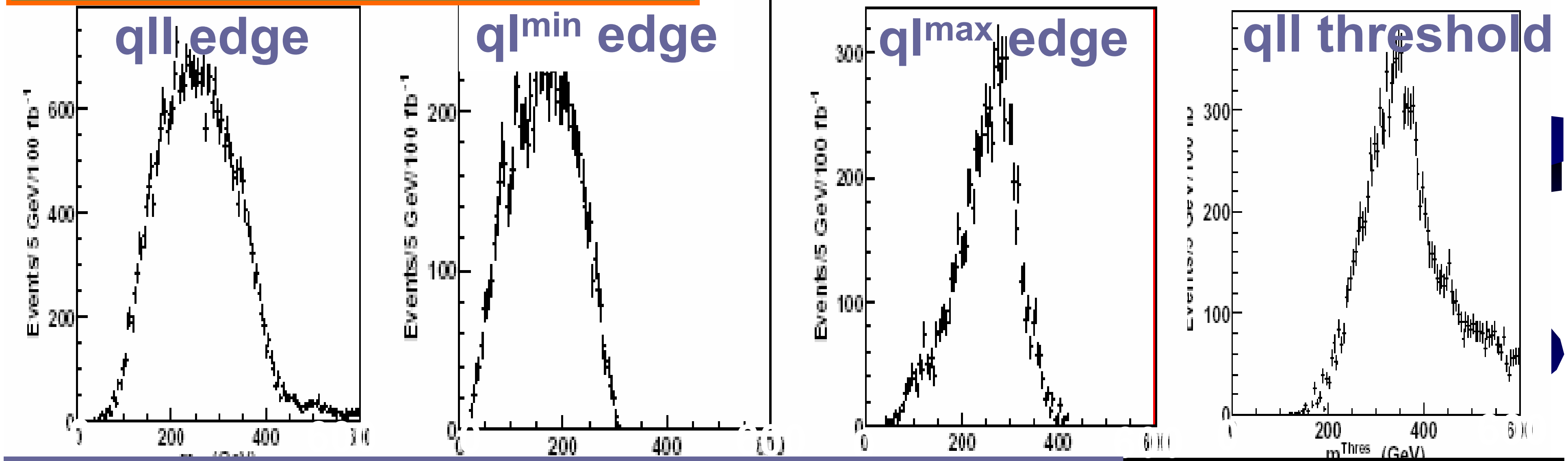
$$\tilde{q}_L \to \tilde{\chi}_2^0\, q \to \tilde{l}_R\, l\, q \to llq\, \tilde{\chi}_1^0$$

Allows to measure several **kinematical endpoints**, each providing one mass relation between the SUSY particles.



2 SFOS lep., p_T>20, 10 GeV
≥ 4 jets, p_T>150,100,50,50 GeV
M_{eff} > 600 GeV
E_{Tmiss} >max(100, 0.2 M_{eff})

SPS1a
100 fb^{-1}
Fast simulation



Gjelsten, Lytken, Miller, Osland, Polesello,ATL-PHYS-2004-007

Invariant mass (GeV)

Left squark mass fit

Fit results (L = 100 fb^{-1})

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

5 relations for 4 masses!

Can compare qll and bll thresholds, and measure $m(\tilde{b})$-$m(\tilde{u}_L)$

Precision limited by systematics: error on jet energy scale (1% expected)

Mass reconstruction

$$\chi^2 = \sum_j \chi_j^2 = \sum_j \left[\frac{E_j^{\text{theory}}(\vec{m}) - E_j^{\text{exp}}}{\sigma_j^{\text{exp}}}\right]^2$$

$$E_j^i = E_j^{\text{nom}} + a_j^i \sigma_j^{\text{fit}} + b^i \sigma_j^{Escale}$$

$m(\chi_1^0)$ = 96 GeV

$m(\chi_2^0)$ = 177 GeV

$m(\tilde{l}_R)$ = 143 GeV

$m(\tilde{q}_L)$ = 540 GeV

$\Delta m(\chi_1^0)$= 4.8 GeV, $\Delta m(\chi_2^0)$= 4.7 GeV,

$\Delta m(\tilde{l}_R)$ = 4.8 GeV, **$\Delta m(\tilde{q}_L)$= 8.7 GeV**

Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007

Going up the decay chain

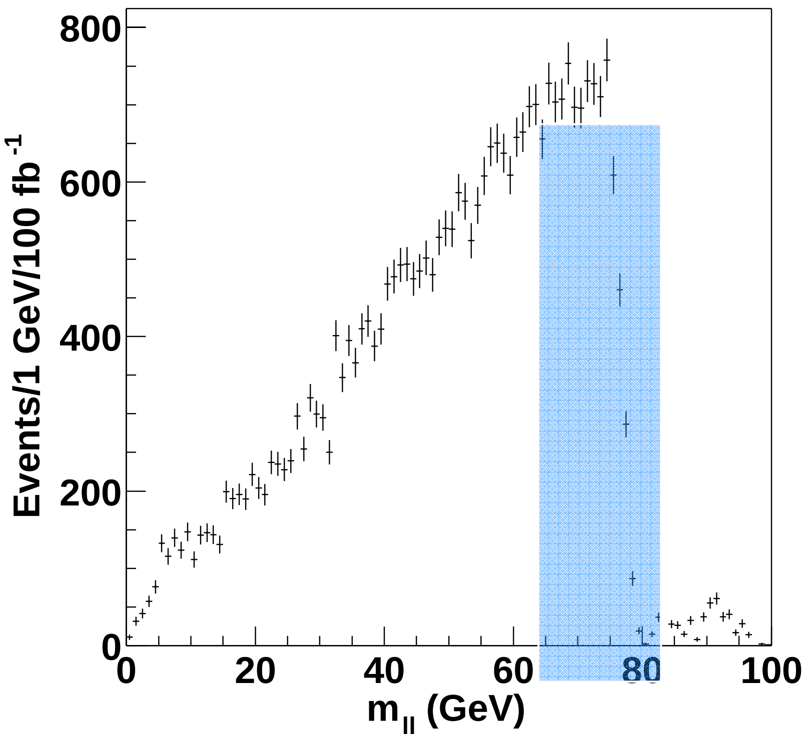
- Once the mass of the χ^0_1 is known, it is possible to get the momentum of the χ^0_2 using the approximate relation

  $$p(\chi^0_2) = (1-m(\chi^0_1)/m(ll))\ p_{ll}$$

  valid for lepton pairs with invariant mass near the edge.
- The χ^0_2 can be combined with b-jets to reconstruct the **gluino and sbottom mass peaks**:

  $$\tilde{g} \to b\tilde{b} \to bb\chi^0_2$$

b-tagging used to separate light and bottom squark decay chains



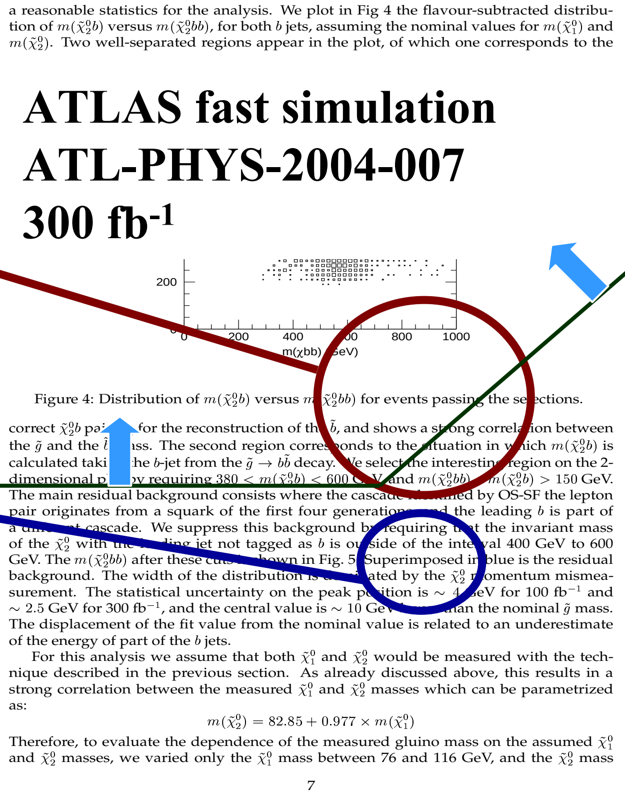
ATLAS fast sim.
ATL-PHYS-2004-007

Dilepton invariant mass

Gluino and sbottom reconstruction

Good combinations.
m($\tilde{g}$) and m($\tilde{b}$) correlated
(Dominant error from
$\tilde{\chi}^0_2$ Momentum affects both)

Bad $\tilde{\chi}^0_2$ b combinations (b-jet
is from gluino decay)



a reasonable statistics for the analysis. We plot in Fig 4 the flavour-subtracted distribution of $m(\tilde{\chi}^0_2 b)$ versus $m(\tilde{\chi}^0_2 bb)$, for both b jets, assuming the nominal values for $m(\tilde{\chi}^0_1)$ and $m(\tilde{\chi}^0_2)$. Two well-separated regions appear in the plot, of which one corresponds to the

ATLAS fast simulation
ATL-PHYS-2004-007
300 fb^{-1}

Figure 4: Distribution of $m(\tilde{\chi}^0_2 b)$ versus $m(\tilde{\chi}^0_2 bb)$ for events passing the selections.

correct $\tilde{\chi}^0_2 b$ pa[illegible] for the reconstruction of the $\tilde{b}$, and shows a strong correlation between the $\tilde{g}$ and the $\tilde{b}$ [illegible]ass. The second region corresponds to the situation in which $m(\tilde{\chi}^0_2 b)$ is calculated taki[illegible] the b-jet from the $\tilde{g} \to b\tilde{b}$ decay. We select the interesting region on the 2-dimensional p[illegible] by requiring $380 < m(\tilde{\chi}^0_2 b) < 600$ GeV and $m(\tilde{\chi}^0_2 bb)$ [illegible] $m(\tilde{\chi}^0_2 b) > 150$ GeV. The main residual background consists where the cascade [illegible] by OS-SF the lepton pair originates from a squark of the first four generations [illegible] the leading b is part of a [illegible] cascade. We suppress this background by requiring that the invariant mass of the $\tilde{\chi}^0_2$ with the [illegible] jet not tagged as b is outside of the interval 400 GeV to 600 GeV. The $m(\tilde{\chi}^0_2 bb)$ after these cuts [illegible] shown in Fig. 5. Superimposed in blue is the residual background. The width of the distribution is [illegible]ated by the $\tilde{\chi}^0_2$ momentum mismeasurement. The statistical uncertainty on the peak position is ~ 4 GeV for 100 fb^{-1} and ~ 2.5 GeV for 300 fb^{-1}, and the central value is ~ 10 GeV [illegible] than the nominal $\tilde{g}$ mass. The displacement of the fit value from the nominal value is related to an underestimate of the energy of part of the b jets.

For this analysis we assume that both $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ would be measured with the technique described in the previous section. As already discussed above, this results in a strong correlation between the measured $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ masses which can be parametrized as:

$$m(\tilde{\chi}^0_2) = 82.85 + 0.977 \times m(\tilde{\chi}^0_1)$$

Therefore, to evaluate the dependence of the measured gluino mass on the assumed $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ masses, we varied only the $\tilde{\chi}^0_1$ mass between 76 and 116 GeV, and the $\tilde{\chi}^0_2$ mass

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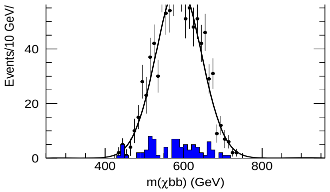
Gluino mass reconstruction

ATLAS fast simulation
ATL-PHYS-2004-007
300 fb^{-1}



M(χbb) (GeV)

ATLAS fast simulation
ATL-PHYS-2004-007
300 fb^{-1}

M(χbb) (GeV)

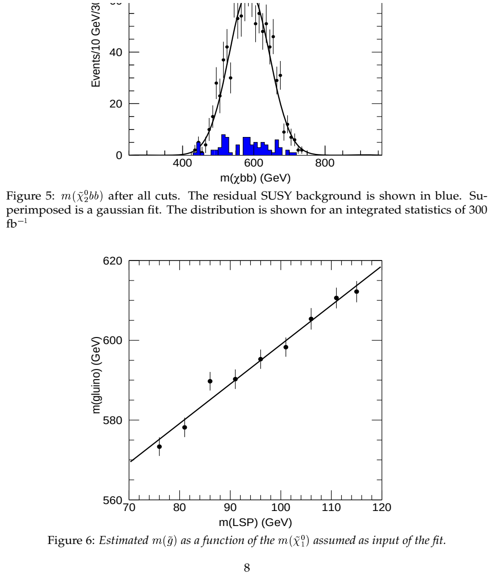


Figure 5: $m(\tilde{\chi}_2^0 bb)$ after all cuts. The residual SUSY background is shown in blue. Superimposed is a gaussian fit. The distribution is shown for an integrated statistics of 300 fb^{-1}

Figure 6: *Estimated $m(\tilde{g})$ as a function of the $m(\tilde{\chi}_1^0)$ assumed as input of the fit.*

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M(LSP) (GeV)

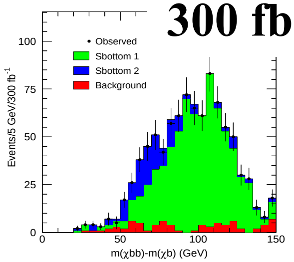
$m(\tilde{g})-0.99m(\tilde{\chi}^0_1) = (500.0 \pm 6.4)$ GeV with 300 fb^{-1}

Error is statistical plus (dominant) 1% uncertainty on jet energy scale

Central value 10 GeV lower than nominal because no dedicated calibration for b-jet energy scale used in this (fast sim) study

sbottom mass

ATLAS fast simulation
ATL-PHYS-2004-007
300 fb^{-1}



$\tilde{b}_2$

$\tilde{b}_1$

m(χbb)-m(χb) (GeV)

ATLAS fast simulation
ATL-PHYS-2004-007
300 fb^{-1}

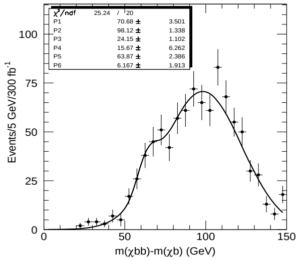


Figure 8: Distribution of $m(\tilde{\chi}_2^0 bb) - m(\tilde{\chi}_2^0 b)$ for an integrated luminosity of 300 fb^{-1}. Superimposed is the fit performed assuming the sum of two gaussian distributions.

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m(χbb)-m(χb) (GeV)

With 300 fb^{-1} it should be possible to separate the $\tilde{b}_1$ and $\tilde{b}_2$ peaks

m($\tilde{g}$)-m($\tilde{b}_1$) = (103.3 ± 1.8) GeV   m($\tilde{g}$)-m($\tilde{b}_2$) = (70.6 ± 2.6) GeV

With lower statistics only measure the average

Right-handed squark

$\tilde{q}_R$ does not couple to Wino
χ^0_1 is nearly a Bino
χ^0_2 is nearly a Wino

⇒ $\tilde{q}_R \rightarrow q\, \chi^0_1$

ATLAS fast simulation
ATL-PHYS-2004-007
SPS1a 30 fb^{-1}

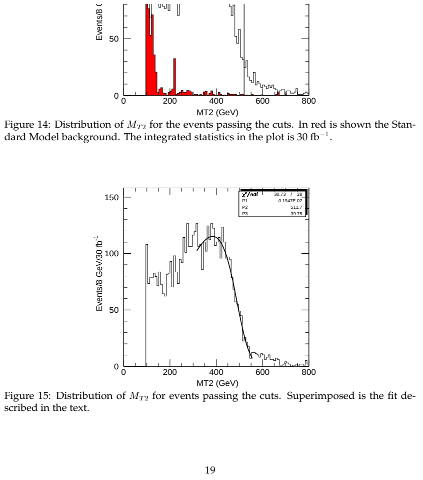

Figure 14: Distribution of M_{T2} for the events passing the cuts. In red is shown the Standard Model background. The integrated statistics in the plot is 30 fb^{-1}.

Figure 15: Distribution of M_{T2} for events passing the cuts. Superimposed is the fit described in the text.

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$\tilde{q}_R\,\tilde{q}_R$ production: two high p_T jets and missing energy

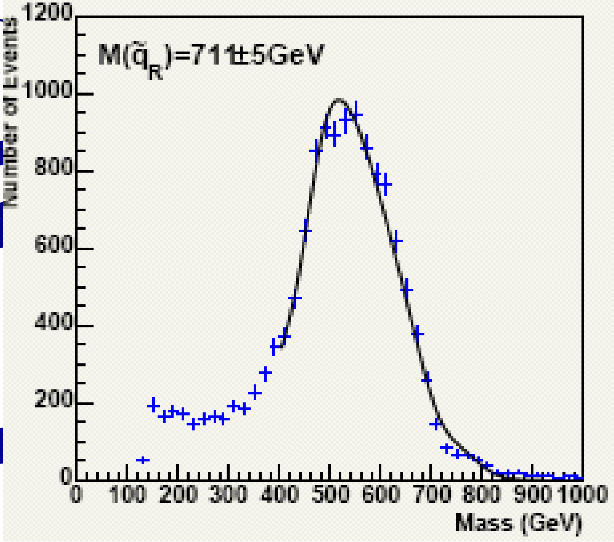
The different decay chains allow separation from q_L (veto additional jets and b-tagged jets)

Combine the transverse momentum of two leading jets with missing transverse momentum as follows:

$$M_{T2}^2 = \min_{\not p_1 + \not p_2 = \not p_T} \left[\max\left\{ m_T^2(p_T^{\ell_1}, \not p_1), m_T^2(p_T^{\ell_2}, \not p_2) \right\} \right]$$

$$m(\tilde{q}_R) - m(\chi^0_1) = (424.2 \pm 10.9)\ \text{GeV}$$

ATLAS full simulation
stau coannihilation point



SPS1a: summary

The following masses would be measured by ATLAS for SPS1a:

$m(\tilde{q}_R)-m(\chi^0_1) = (424.2 \pm 10.9)$ GeV   30 fb^{-1}

$m(\tilde{q}_L) = (444.0 \pm 4.9)$ GeV   300 fb^{-1}

$m(\tilde{g})-m(\chi^0_1) = (500.0 \pm 6.4)$ GeV   300 fb^{-1}

$m(\tilde{g})-m(\tilde{b}_1) = (103.3 \pm 1.8)$ GeV   300 fb^{-1}

$m(\tilde{g})-m(\tilde{b}_2) = (70.6 \pm 2.6)$ GeV   300 fb^{-1}

After a few years at LHC design luminosity, precision would be **limited by systematic** error on jet energy scale

The analysis works in a **large fraction of parameter space** (when relevant decay chains exist) but results depend on specific point

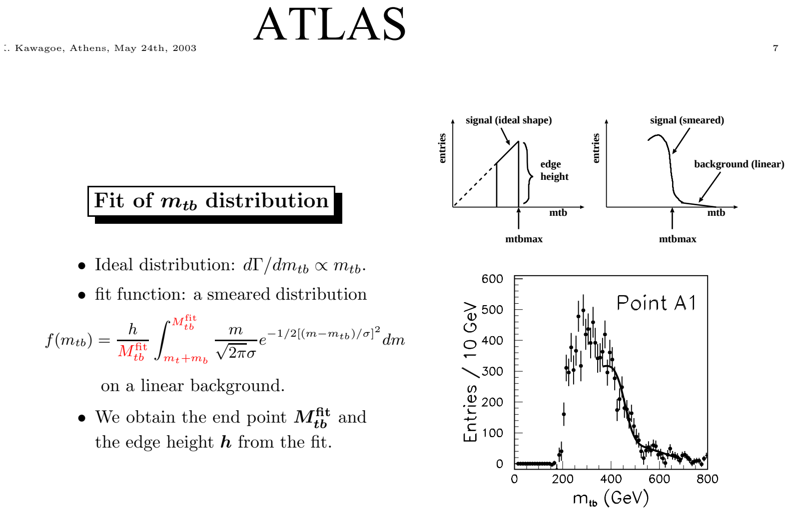
Stop edges

$\tilde{g} \rightarrow t\tilde{t}_1 \rightarrow tb\chi^{\pm}_1$ or $\tilde{g} \rightarrow b\tilde{b} \rightarrow bt\ \chi^{\pm}_1$

tb invariant mass has a maximum function of the masses of $\tilde{g}$, $\tilde{b}$(or $\tilde{t}$) and $\chi^{\pm}_1$
Two closely spaced edges from the two decays: can measure a weighed average.

Selections:
- total jet energy and missing energy
- 2 b-jets
- lepton veto
- 4 to 6 non-b jets

Reconstruction:
- m(jj) close to m(W)
- m(jjb) close to m(t)
- W-sidebands to estimate and subtract combinatorial background



ATLAS

:. Kawagoe, Athens, May 24th, 2003 7

Fit of m_{tb} distribution

- Ideal distribution: $d\Gamma/dm_{tb} \propto m_{tb}$.
- fit function: a smeared distribution

$$f(m_{tb}) = \frac{h}{M_{tb}^{\rm fit}} \int_{m_t+m_b}^{M_{tb}^{\rm fit}} \frac{m}{\sqrt{2\pi}\sigma} e^{-1/2[(m-m_{tb})/\sigma]^2} dm$$

on a linear background.

- We obtain the end point $\boldsymbol{M_{tb}^{\rm fit}}$ and the edge height $\boldsymbol{h}$ from the fit.

See J. Hisano et al., Phys. Rev. D68, 035007 for details

Conclusions

On a significant fraction of mSUGRA parameter space, the LHC would be able to measure the mass of $\boldsymbol{\tilde{q}_R,\tilde{q}_L,\tilde{b}_1,\tilde{b}_2}$

Many measurements studied also with **Full Simulation** data for a variety of points – they confirm that fast simulation results are realistic.

A model-independent measurement of the **stop mass** is **more challenging** (but kinematical decays related to stop decays would be observed for most parameter values)

Measurement of mixing angles needs more study

CPV, FV, mixing and non-degenerate masses in first two generations also poorly covered

- availability in HERWIG/PYTHIA/ISAJET ?
- criteria to choose parameters? flavour benchmarks?