SUSY Studies with ATLAS

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Outline

- Introduction
- Search for a generic SUSY signal (excess of events over SM contribution)

  E^{T}_{miss}+jets search, background

- Reconstruction of the mass of SUSY particles using selected decays

  Basic techniques, some full simulation results

- Spin measurements

SUSY

SUSY at TeV mass scale most attractive extension of Standard Model. Provides **naturally light Higgs, grand unification, and cold dark matter**

For each Standard Model particle X, MSSM has partner $\tilde{X}$ with $\Delta J = \pm 1/2$:

Each gauge boson <=>
Massless spin-1/2 gaugino

- gluino
- fotino,wino, zino (mix with higgsinos =>netralinos, charginos)

Each chiral fermion <=> Massless spin-0 sfermion

- squark (stop, sbottom)
- slepton (selectron,smuon)

Also two Higgs doublets and corresponding
J=1/2 Higgsinos

Inexact symmetry – broken somehow

R-parity

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

$= +1$ (SM particles)

$= -1$ (SUSY particles)

Two main SUSY scenarios:

- R-parity conservation (RPC) or R-parity violation (RPV)

RPC implies:

- No proton decay
- SUSY particles produced in pairs and decay to stable Lightest SUSY Particle (LSP), usually $\tilde{\chi}^0_1$ which is stable, neutral and weakly interacting so escapes detector => large missing energy.
- WMAP results indicate cold dark matter. LSP is good candidate for cold dark matter

Would like to break SUSY dynamically. Not possible just with MSSM; must communicate breaking in hidden sector via some interactions

.

Many LHC studies use mSUGRA model.

Has simplest gravity mediated breaking with just 4 parameters:

- Common scalar mass $\mathbf{m_0}$ at GUT scale;
- Common gaugino mass $\mathbf{m_{1/2}}$ at GUT scale;
- Common trilinear coupling parameter $\mathbf{A_0}$;
- Common ratio **tan(β)** of Higgs VEV's at weak scale.

  Also sign **sgn(μ)=±1** of Higgs mass

Must solve RGEs' to connect GUT and weak scale masses

ATLAS activities in SUSY

Supersymmetry physics one of the priorities of on-going ATLAS studies

In the past (ATLAS Physics TDR 1998)

- Fast simulation studies (parametrized detector response), focus on discovery potential, reconstruction of s-particle masses for a few selected benchmarks

Now

- Full simulation studies (preliminary)
- Detector commissioning and systematic
- Background estimation (use/validate latest MC, techniques to measure background from data)
- New models and measurement techniques

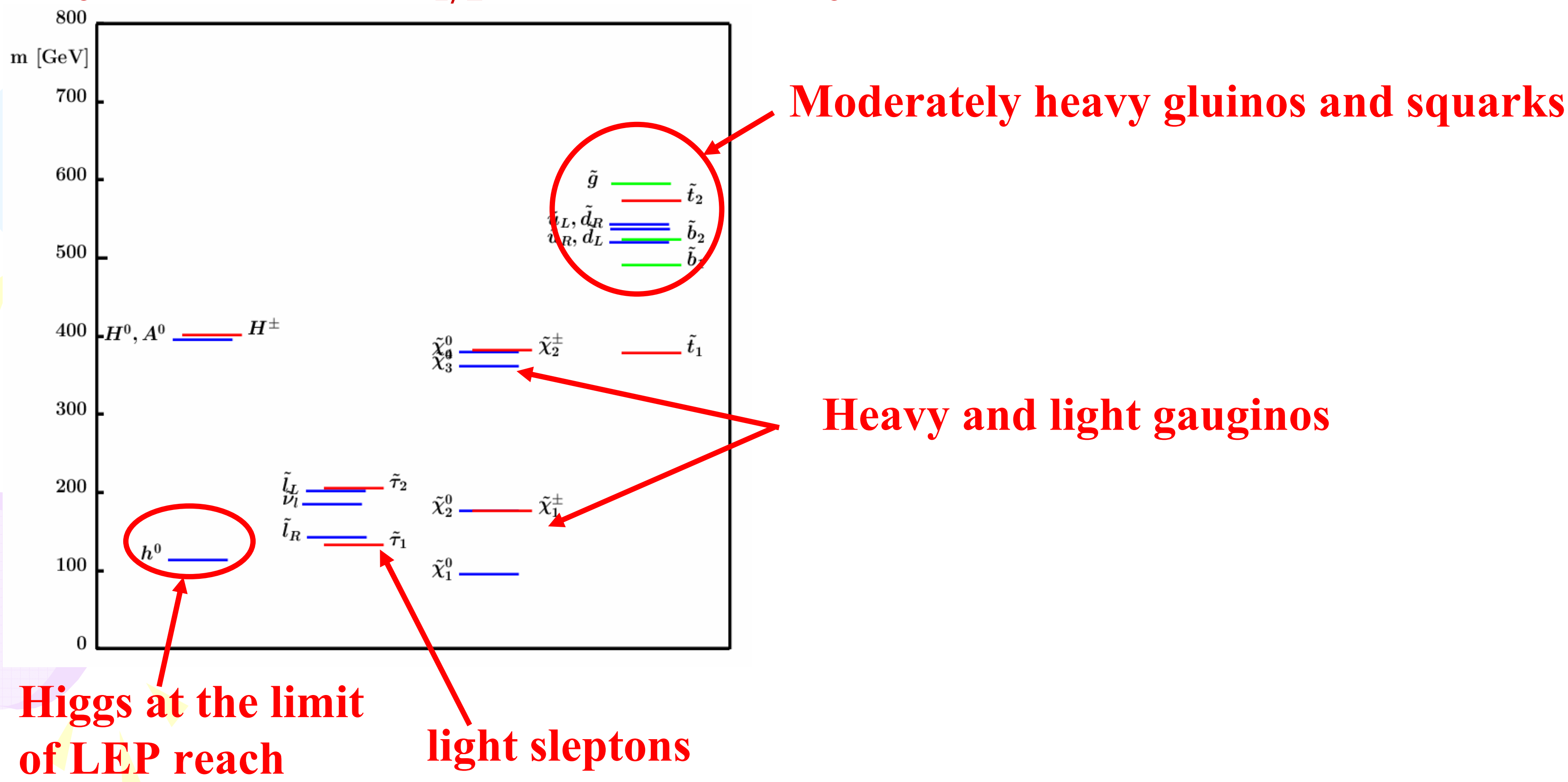
Huge variety of models being studied.

In this talk: mSUGRA

SPS1a point

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

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



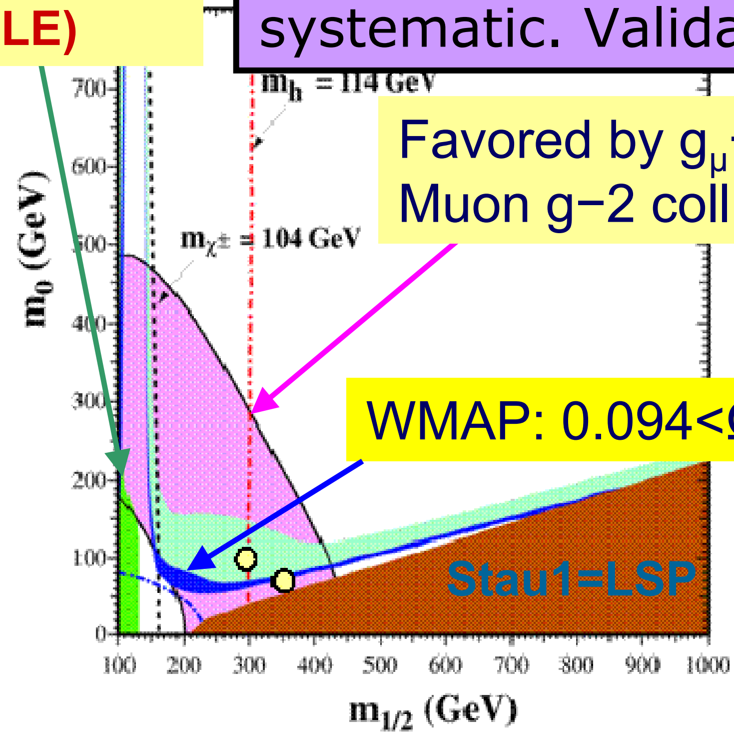
Coannihilation	70	350	0	10	+
Focus point	3550	300	0	10	+
Bulk	100	300	-300	6	+

Full detailed GEANT4 based simulation studies, when available will be also shown, for few recently selected set of benchmark points, in agreement with all the latest experimental and theoretical constraints [Ellis.] Goals: test software for data reconstruction and analysis, computing grid production. Study detector-related systematic. Validate fast simulation results.

Excluded by →
b- > sγ
(CLEO,BELLE)

Favored by $g_\mu-2$ at the 2σ level
Muon g−2 coll.

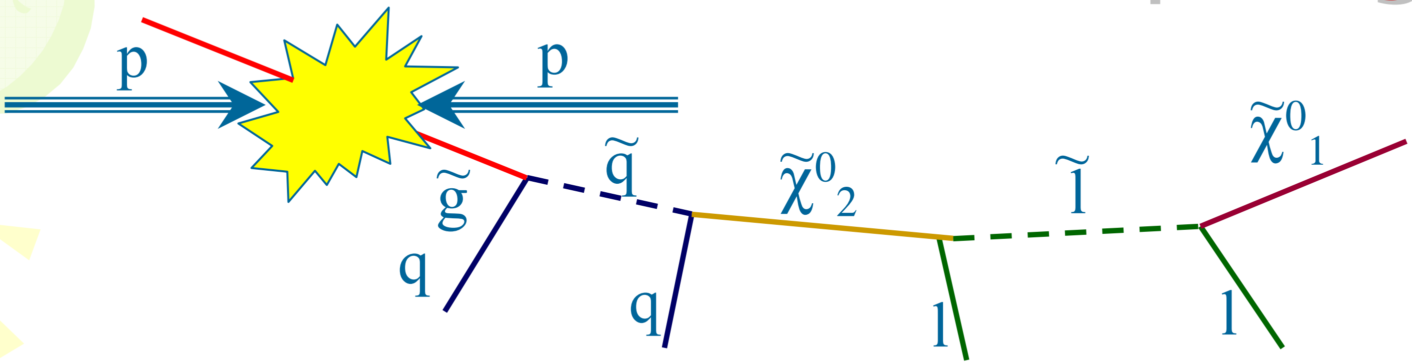
WMAP: $0.094<\Omega_\chi h^2<0.129$



tanβ=10, >0, A_0=0

SUSY discovery potential

mSUGRA events topology



Strongly interacting sparticles (squarks, gluinos) dominate LHC production.Cascade decays to the stable $\tilde{\chi}_1{}^0$

Event topology:

- High p_T jets (from squark/gluino decay)
- Large $E_T{}^{miss}$ signature (from LSP)
- High p_T leptons, b-jets, t-jets

(depending on model parameters)

Best strategy for mSUGRA is usually :

$E_T{}^{miss}$ + jets + n-leptons

Missing transverse energy

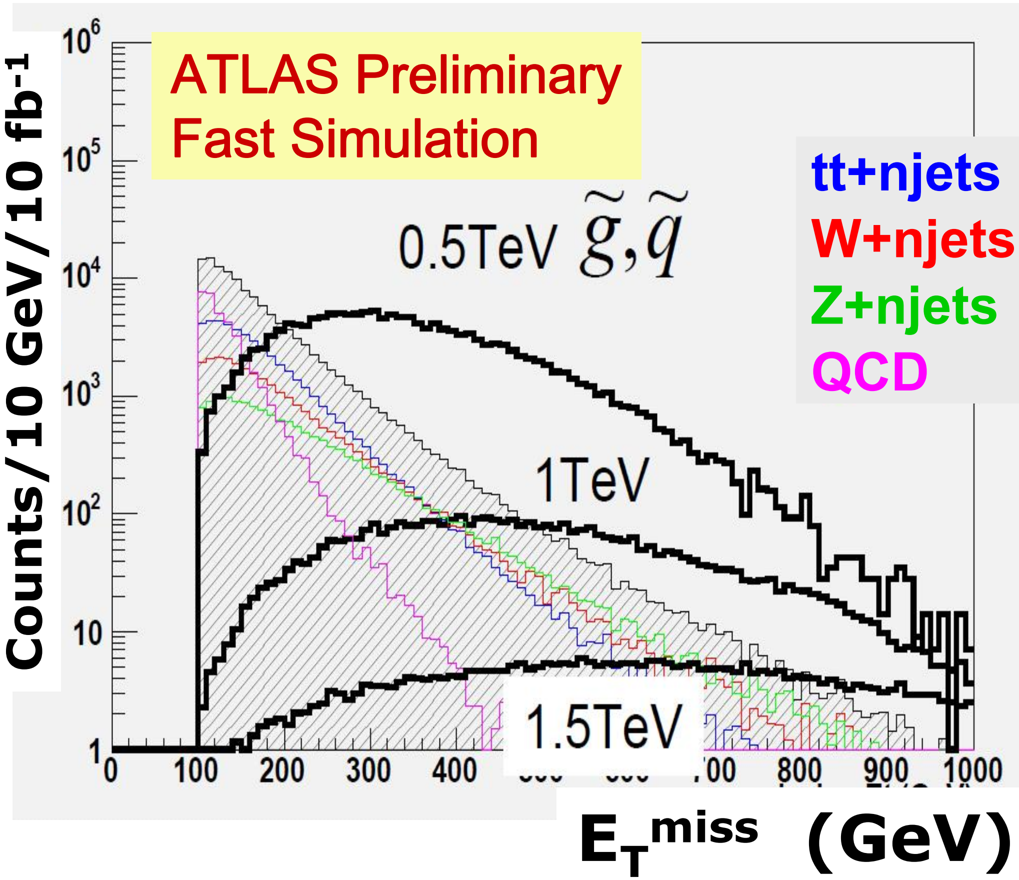
Missing E_T has an excellent discrimination power of signal from SM background

Standard SUSY cuts

- $E_T^{miss} > 100$ GeV
- $p_T^{1st} > 100$ GeV, $p_T^{4th} > 50$ GeV
- Transverse sphericity > 0.2

Better signal significance can be achieved by optimising missing E_T cut, depending on the SUSY mass scale

Background: ALPGEN



Effective mass

Jets $+E_T^{miss}$ events

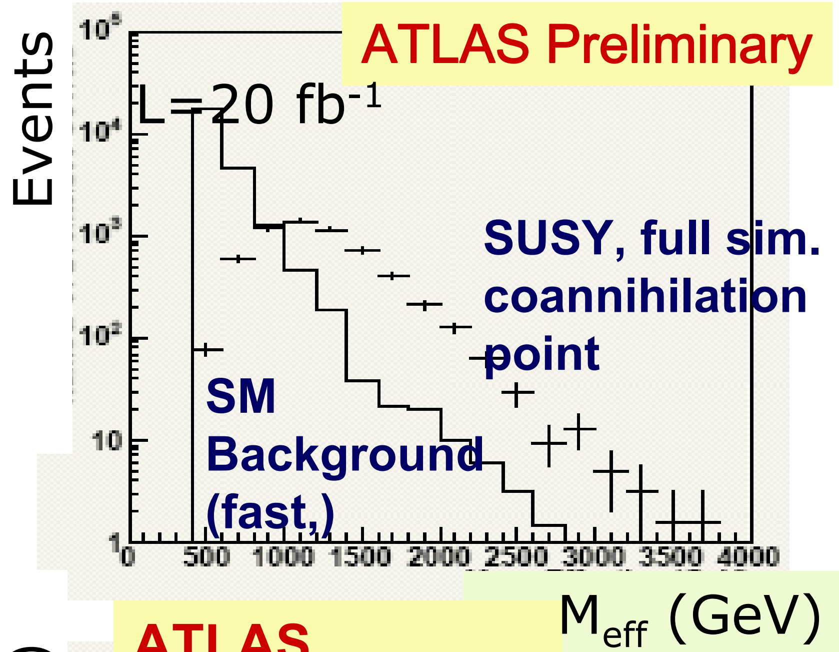
$$M_{eff} = E_T^{miss} + \Sigma p_T^{jets}$$

Selection cuts:

$E_T^{miss} > \min(100\ \text{GeV}, 0.2\ M_{eff})$

$p_T\ (j_1, j_2, j_3, j_4) > 100, 100, 50, 50$ GeV

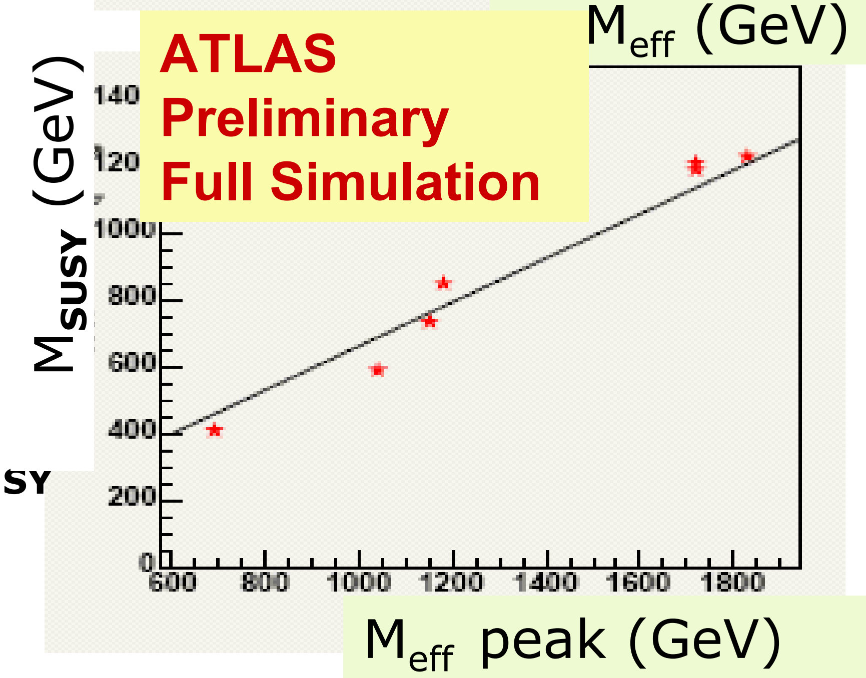
No leptons



The peak of the distribution of the effective mass: if visible above the background, is strongly correlated with the mass of the SUSY particle produced (squark/gluino):

$$\mathbf{M_{SUSY} = \min(M(\tilde{q}), M(\tilde{g})), M_{eff} \approx 2M_{SUSY}}$$

First estimate of SUSY mass scale [Tovey].



Background to SUSY searches

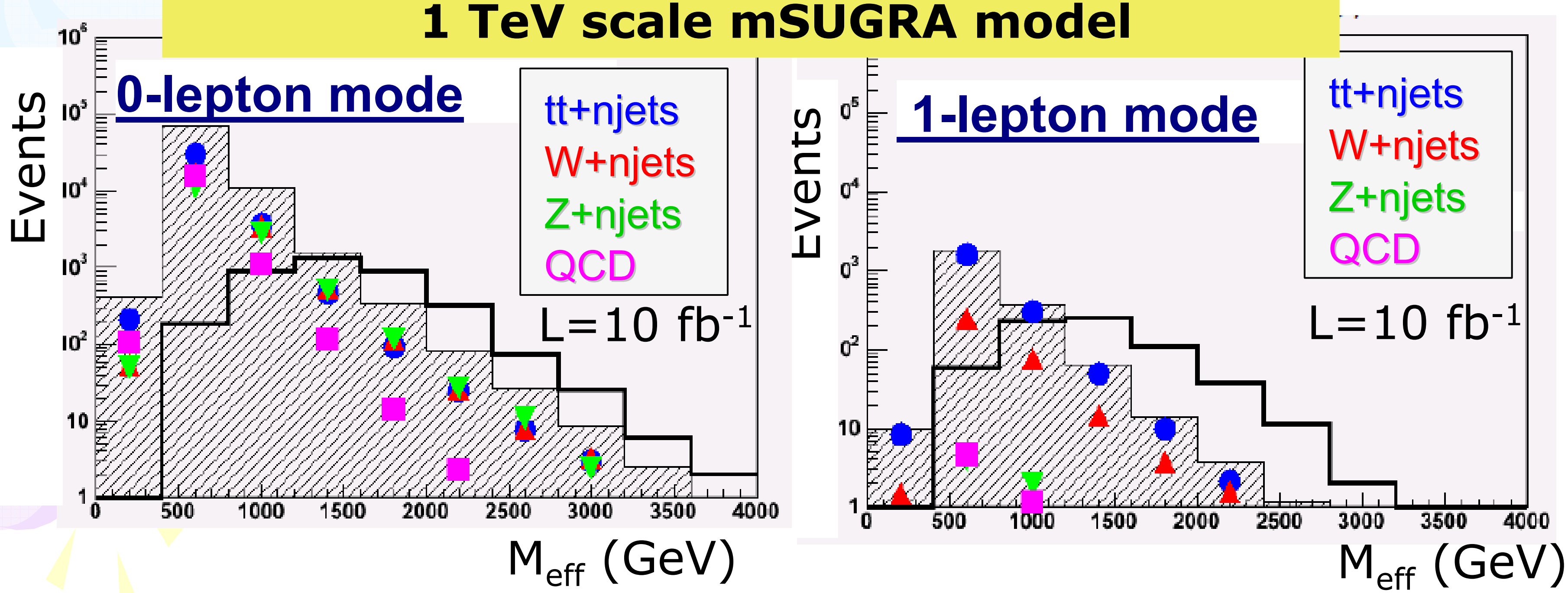
ATLAS Preliminary
Fast Simulation

- Recent (2005) study with AlpGen + Pythia (MLM match)
- Background increases

Discovery of 1 TeV SUSY still easy if systematic smaller than statistical errors

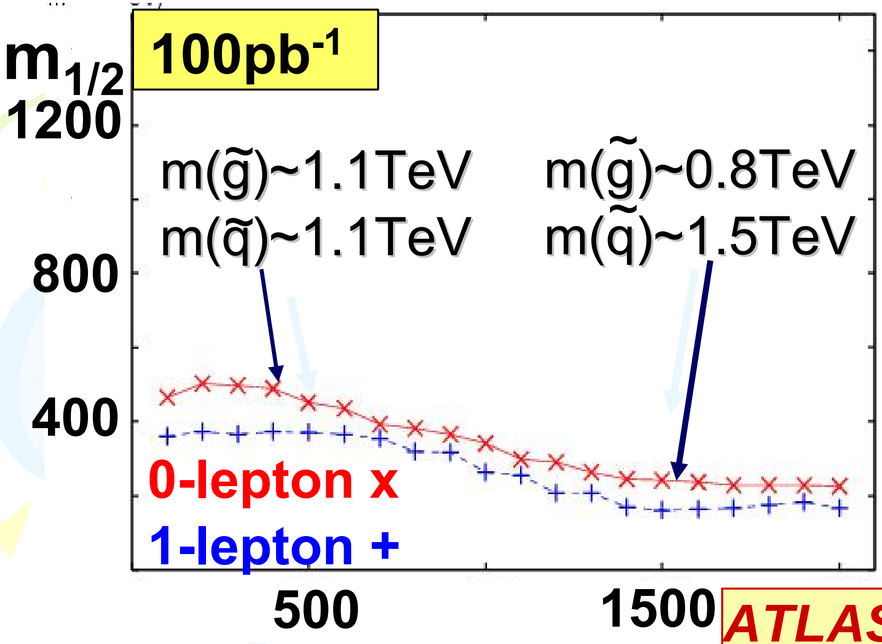
E_T^{miss} > max(100GeV, 0.2Meff), p_T(j1,j4) > 100, 50 GeV, S_T>0.2

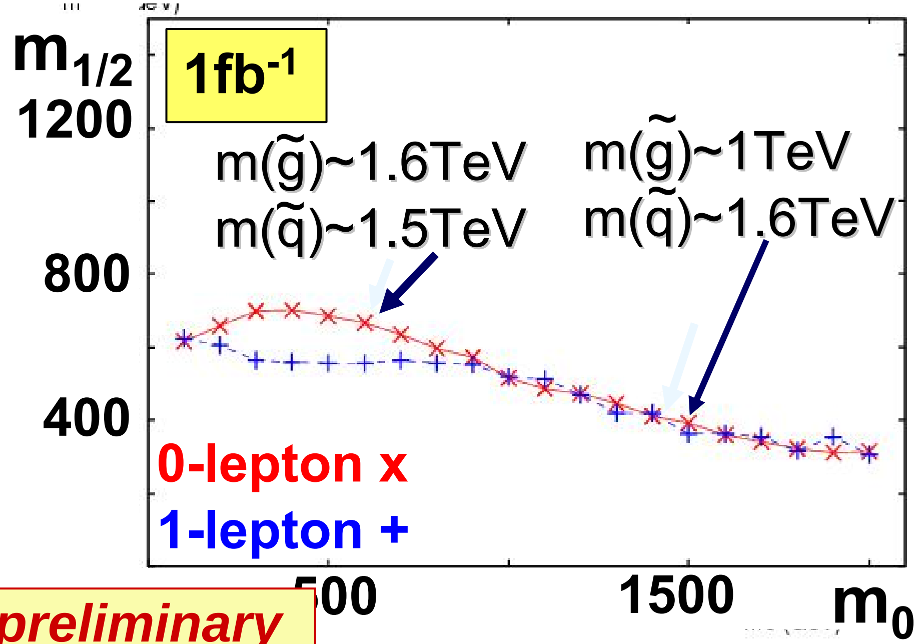
1 TeV scale mSUGRA model



Discovery potential

5-σ discovery potential on m_0-$m_{1/2}$ plane (**tanβ=10, >0, A_0=0)**
After scan of m0-m1/2 plane and optimisation of cuts for each point





ATLAS preliminary
Fast simulation

Background: ALPGEN

The discovery potential for the early data:

M_{SUSY}<1.1TeV at L=100 pb^{-1} (after one week)
M_{SUSY}<1.5TeV at L=1 fb^{-1} (after one month)

Mass measurements

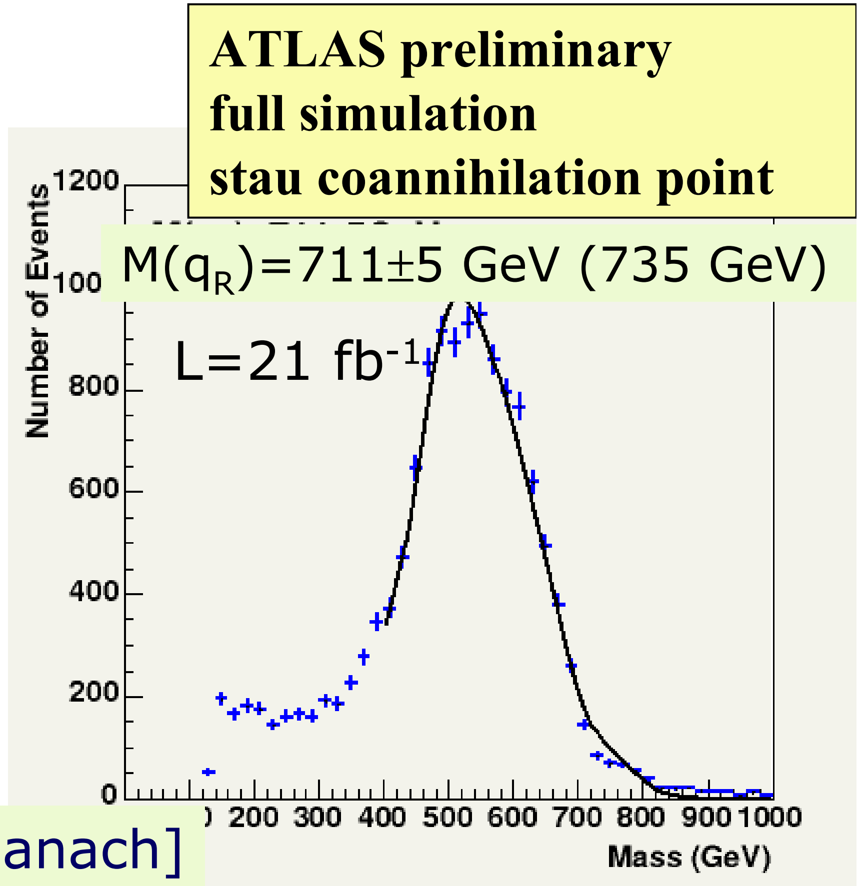
s-Transverse Mass

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

$E_{T\ miss}$ > 400 GeV

2 jets with p_T > 200 GeV

$\Delta R(j_1, j_2) > 1$



Partition in all possible ways

$\vec{\not{E}}_T = \vec{\not{E}}_{T1} + \vec{\not{E}}_{T2}$ and calculate M_{T2} [Allanach]

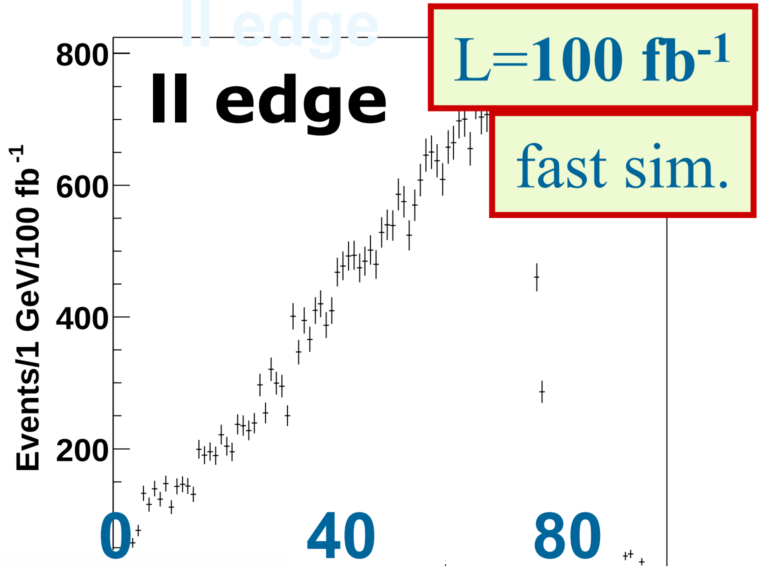
$$M_{T2}^2 = \min_{\not{E}_{T1},\ \not{E}_{T2}} \left[\max \left\{ m_T^2(p_{T,j1}, \not{E}_{T1}, M(\tilde{\chi}_1^0)),\ m_T^2(p_{T,j2}, \not{E}_{T2}, M(\tilde{\chi}_1^0)) \right\} \right]$$

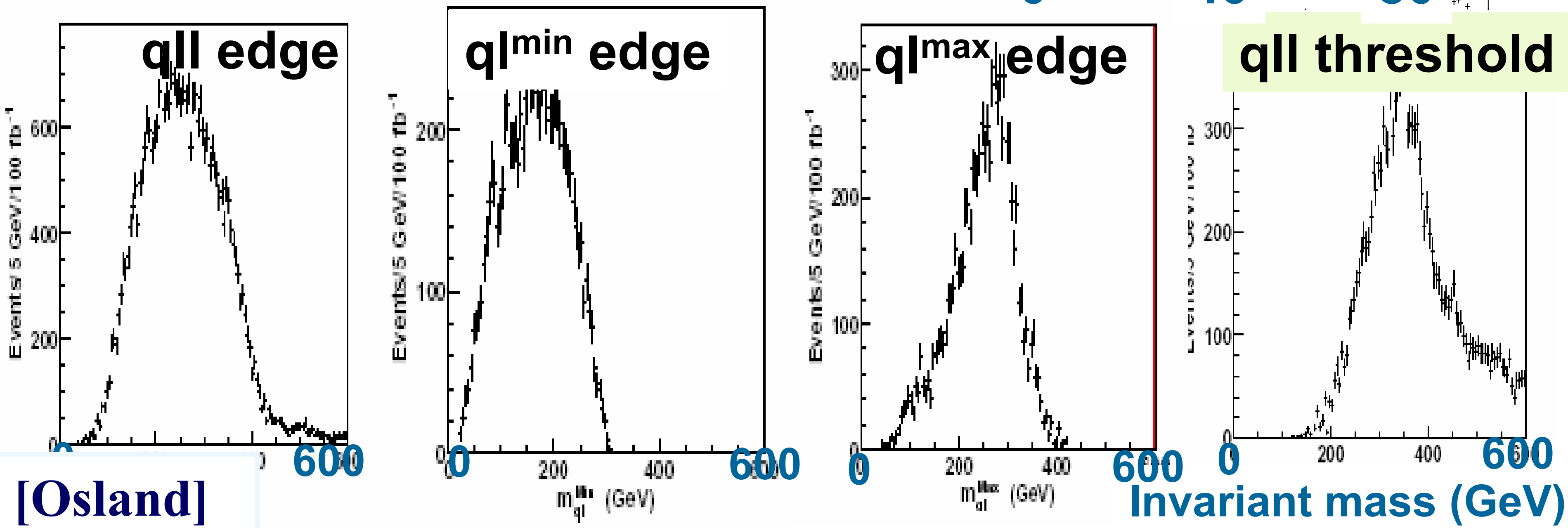
Left squark cascade decay

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

SPS1a

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})





[Osland]

Endpoint formulas

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	$(m_{l_{\text{near}}q}^{\max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{\xi} - \tilde{l})/\tilde{\xi}$
$l^{\pm}_{\text{far}}q$ edge	$(m_{l_{\text{far}}q}^{\max})^2 = (\tilde{q} - \tilde{\xi})(\tilde{l} - \tilde{\chi})/\tilde{l}$
$l^{\pm}q$ high-edge	$(m_{lq(\text{high})}^{\max})^2 = \max\left[(m_{l_{\text{near}}q}^{\max})^2, (m_{l_{\text{far}}q}^{\max})^2\right]$
$l^{\pm}q$ low-edge	$(m_{lq(\text{low})}^{\max})^2 = \min\left[(m_{l_{\text{near}}q}^{\max})^2, (\tilde{q} - \tilde{\xi})(\tilde{l} - \tilde{\chi})/(2\tilde{l} - \tilde{\chi})\right]$
M_{T2} edge	$\Delta M = m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$

Table 4: The absolute kinematic endpoints of invariant mass quantities formed from decay chains of the types mentioned in the text for known particle masses. The following shorthand notation has been used: $\tilde{\chi} = m^2_{\tilde{\chi}_1^0}, \tilde{l} = m^2_{\tilde{l}_R}, \tilde{\xi} = m^2_{\tilde{\chi}_2^0}, \tilde{q} = m^2_{\tilde{q}}$ and X is m^2_h or m^2_Z depending on which particle participates in the "branched" decay.

L=100 fb^{-1}

Fit results

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

Mass reconstruction

5 endpoints measurements, 4 unknown masses

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

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

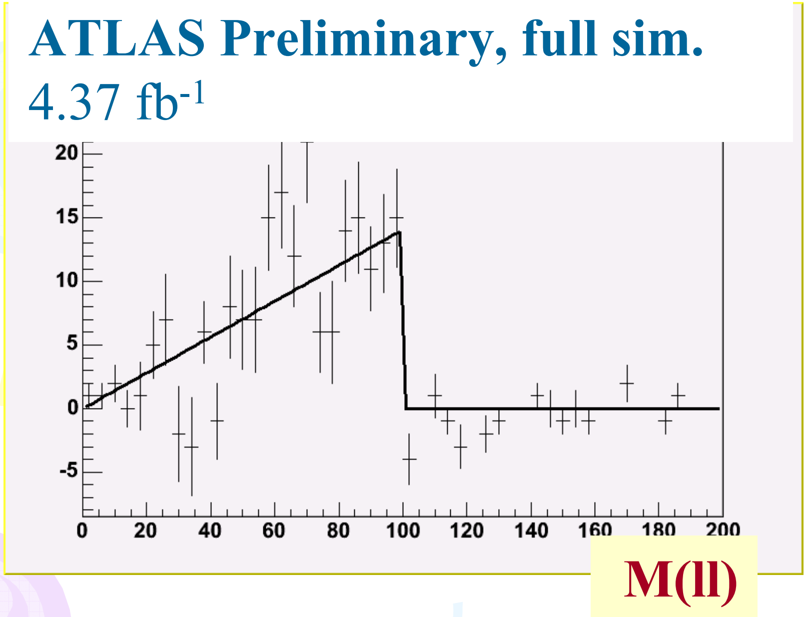
$m(\chi_1^0)$ = 96 GeV
$m(l_R)$ = 143 GeV
$m(\chi_2^0)$ = 177 GeV
$m(q_L)$ = 540 GeV

$\Delta m(\tilde{\chi}_1^0)$= 4.8 GeV, $\Delta m(\tilde{\chi}_2^0)$= 4.7 GeV,
$\Delta m(\tilde{l}_R)$ = 4.8 GeV, $\Delta m(\tilde{q}_L)$= 8.7 GeV

[Osland]

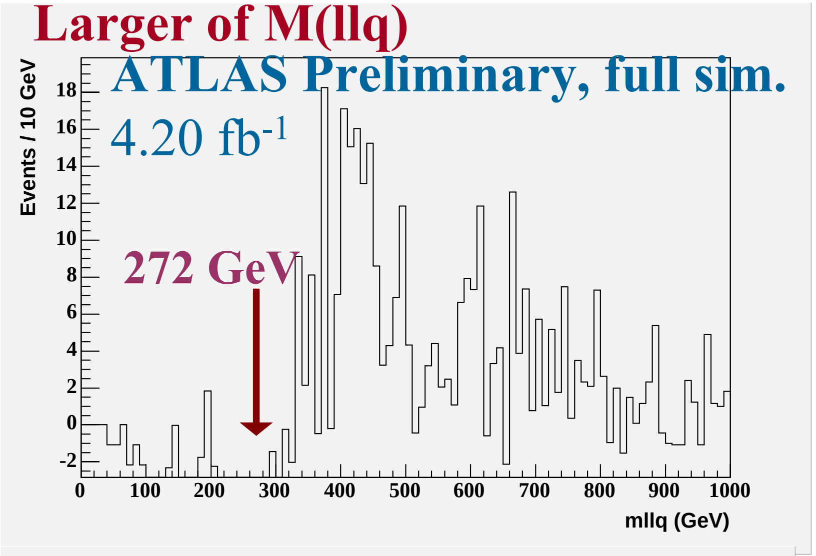
Bulk point

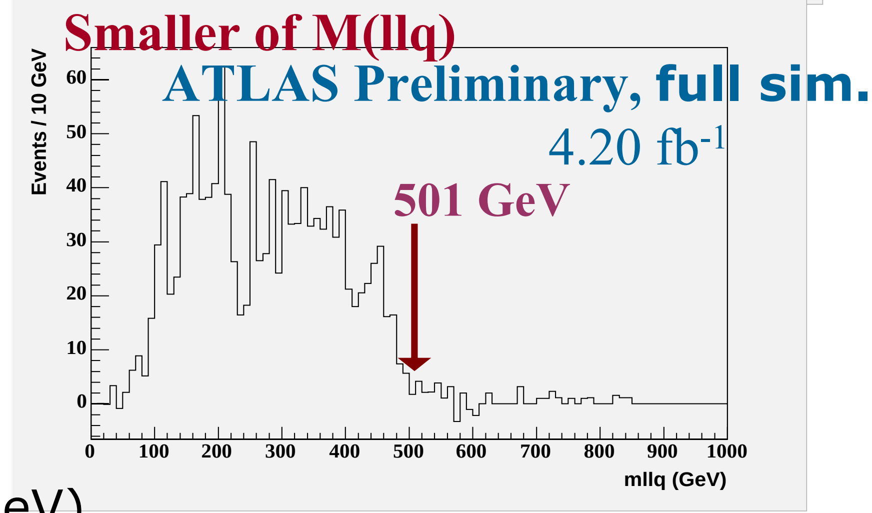
After SM BG cuts + 2 leptons,
Loose stats but still triangular
shape visible.



(e+e-) + β²(η) (μ+μ-) – β(η) (e+μ-)

Edge at: 99.8 ± 1.2 GeV (100.17 GeV)





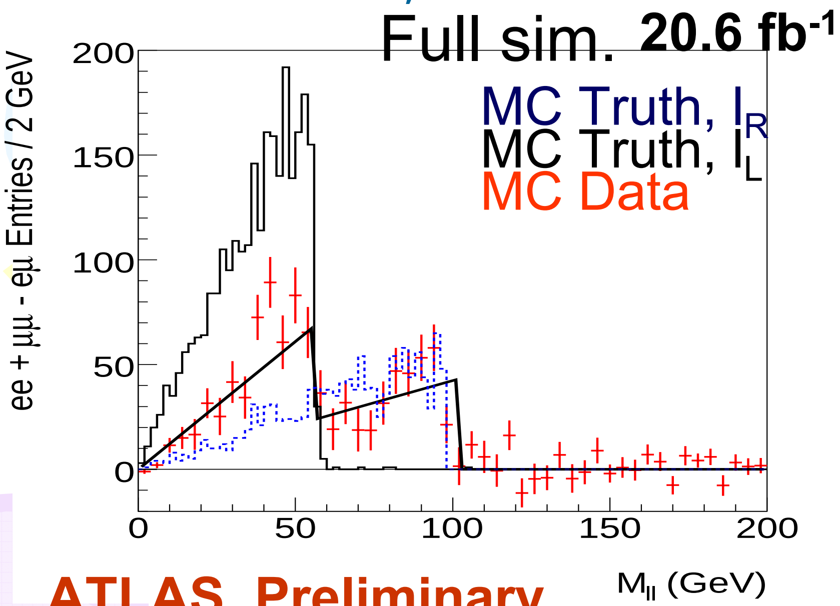
More complicated case: **coannihilation point**

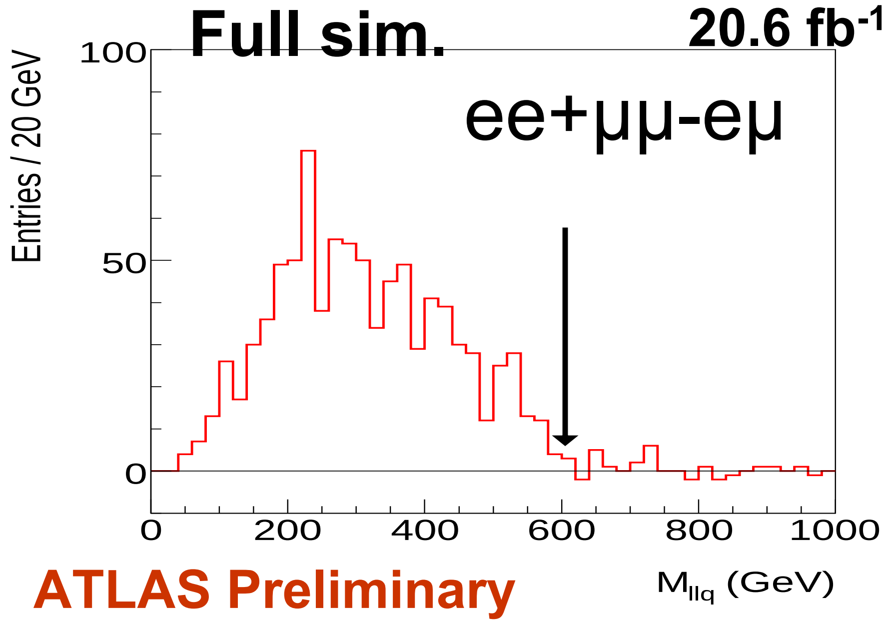
Main feature: small mass difference between sleptons and neutralinos, soft leptons in the final state.

$$\tilde{\chi}_2^0 \rightarrow l\tilde{l}_{R,L} \rightarrow ll\tilde{\chi}_1^0$$

264   154 , 255   137

Selection: e^+e^- , $\mu^+\mu^-$ pair, SFOS-OFOS subtraction applied





ATLAS Preliminary   **ATLAS Preliminary**

$M(ll)^{max}$=58.19 / 100.9 GeV (L/R)

$M(llq)^{max}$=603 GeV

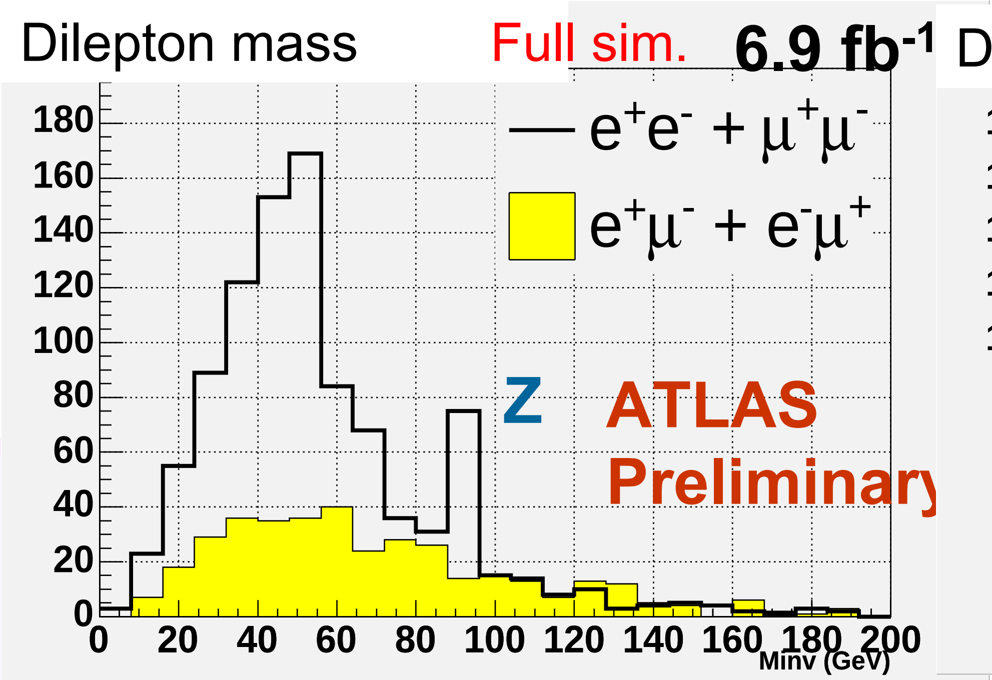
optimisation of cuts against SM backg., fit to distributions to be done

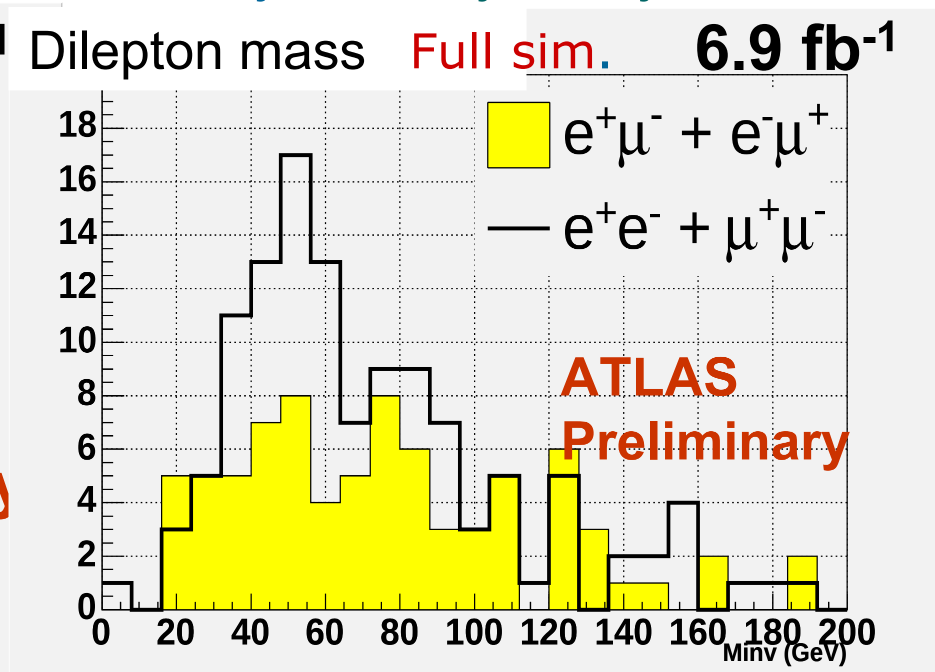
More complicated case: **focus point**

Very heavy squarks and sleptons (masses > 2TeV) , relatively light gauginos (masses < 200 GeV)

$\tilde{\chi}_2^0 \rightarrow ll\tilde{\chi}_1^0 \quad \tilde{\chi}_3^0 \rightarrow ll\tilde{\chi}_1^0$ $\Delta m = m(\tilde{\chi}_n^0) - m(\tilde{\chi}_1^0) = 76,\ 57$GeV

Cuts to reject SM:2j100+4j50+xE100





More integrated luminosity needed

M(ll) GeV

Model parameters

From a given set of measurements one scans the parameter space and finds the points compatible with data. These points are fed to relic density calculators to get constraints on relic density.

SPS1a point, 300 fb^{-1}

Variable	Value (GeV)	Errors Stat. (GeV)	Errors Scale (GeV)	Errors Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde\chi_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde\chi_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde g) - 0.99 \times m(\tilde\chi_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde q_R) - m(\tilde\chi_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde g) - m(\tilde b_1)$	103.3	1.5	1.0	1.8
$m(\tilde g) - m(\tilde b_2)$	70.6	2.5	0.7	2.6

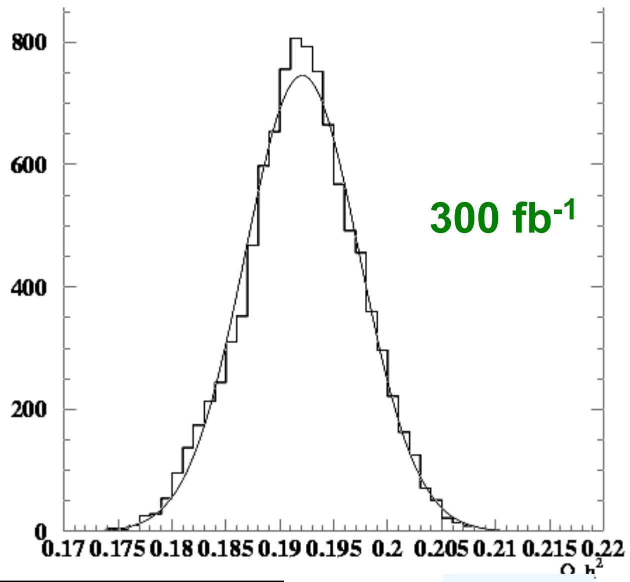
Fit by using SFITTER, [Zerwas]

Parameter	Expected precision (300 fb^{-1})
m_0	± 1.2%
$m_{1/2}$	± 1.0%
tan(β)	± 0.9%
A_0	± 20%

sign(μ) fixed

Micromegas 1.1 + ISASUGRA 7.69

$\Omega_\chi h^2 = 0.1921 \pm 0.0053$



[Polesello]

$\Omega_\chi h^2$

Spin measurement

It is vital to measure the spins of the new particles to demonstrate that they are indeed the predicted super-partners

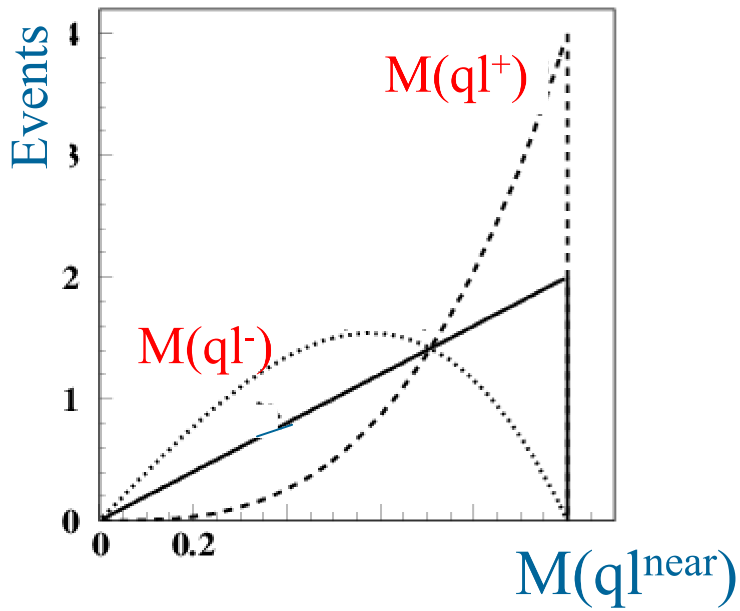
$$\overset{0}{\tilde{q}_L} \to q\, \overset{1/2}{\tilde{\chi}_2^0} \to q\, \overset{0}{\tilde{l}_R}\, l^{near} \to q\, l^+ l^- + \tilde{\chi}_1^0$$

First emitted lepton ("near")

l = e, μ

Due to neutralino spin 1/2, angular distrib. of slepton is not spherically symmetric, invariant mass $M(ql^{near})$ is charge asymmetric. [Barr]

Ideal distribution

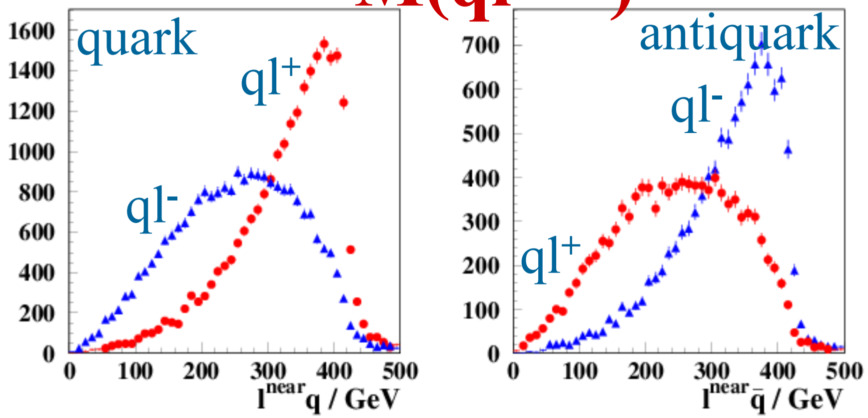


Example

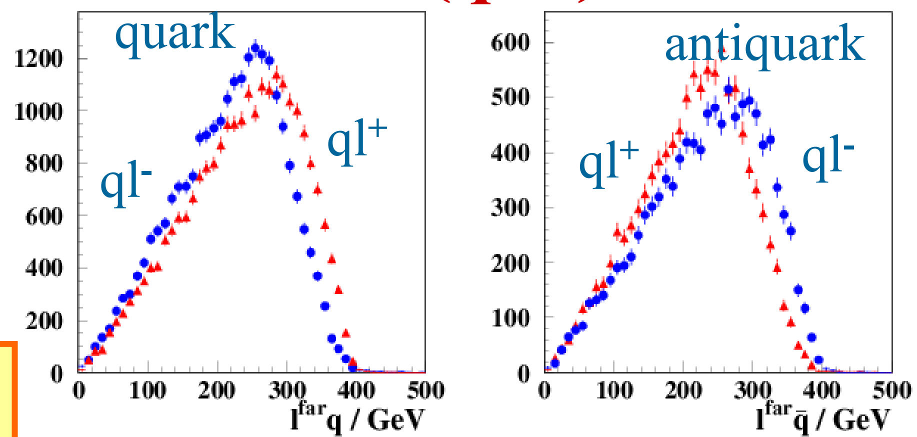
LHCC5: m_0 =100 GeV
$m_{1/2}$ =300 GeV
A_0 =-300 GeV
tan(β) =2.1
sign(μ)=+

Parton distributions

$M(ql^{near})$

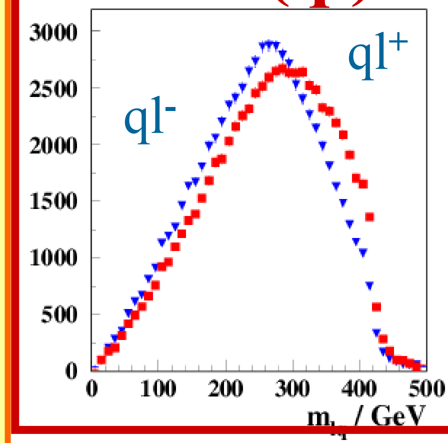


$M(ql^{far})$

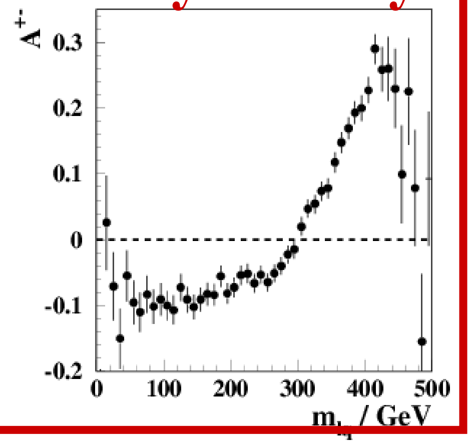


l^{near} and l^{far} are experimentally indistinguishable. Instead, study of $M(l^-q)$ and $M(l^+q)$ distributions. Each distribution contain contribution from both near and far lepton and contribution from both quark and antiquark.
Quark and antiquarks have opposite asymmetries and are experimentally indistinguishable. LHC is pp collider → more quarks then antiquarks will be produced

M(ql)



asymmetry



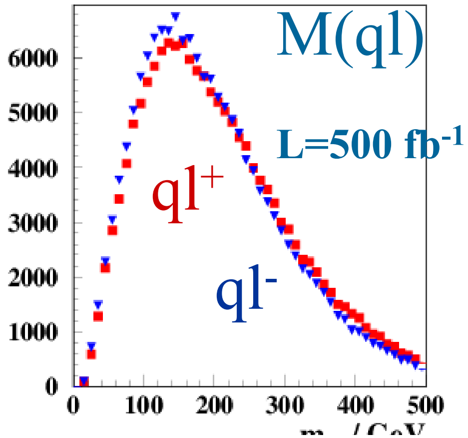
[Barr]

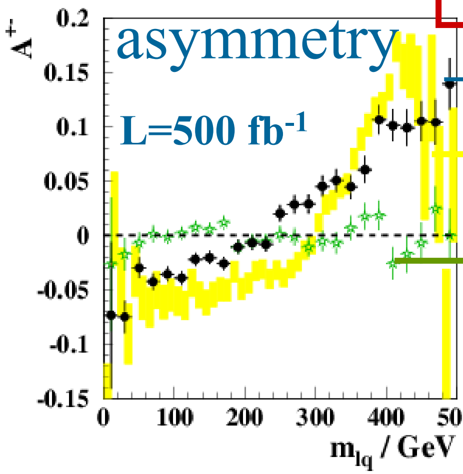
Asymmetry

LHCC5

$$A = \frac{s^+ - s^-}{s^+ + s^-}$$

$$s^{\pm} = \frac{d\sigma}{d(m_{l^{\pm}q})}$$





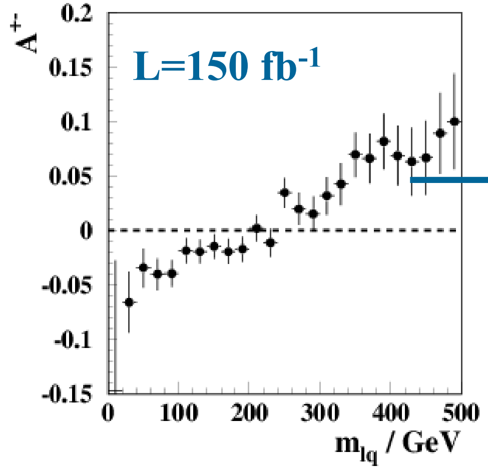
Fast simulation

After selection

Parton level x 0.6

No spin correlations, no asymmetry

asymmetry



Asymmetry is negative for low values of M(lq) and positive for large values. This is consistent with spin ½ neutralino and spin 0 slepton

[Barr]

SPS1a Non-zero M(ql) asymmetry may be observed with $30 fb^{-1}$ **[Nojiri]**

Summary

- Supersymmetry is one of the priorities of ATLAS studies.
- Large scale productions on the grid of full simulation data are used to study detector systematic. Knowledge of the Standard Model background is crucial for discovery. Lot of work is being done on SM background computation and measurement from data.
- Still on-going studies of new models and new techniques to measure the properties of SUSY particles.
- In most models, a few fb-1 of data will allow ATLAS to measure a clear excess over the SM contribution and reconstruct several mass relations.
- Looking eagerly forward to the first data!

References

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