SUSY Searches with ATLAS at LHC

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SUSY

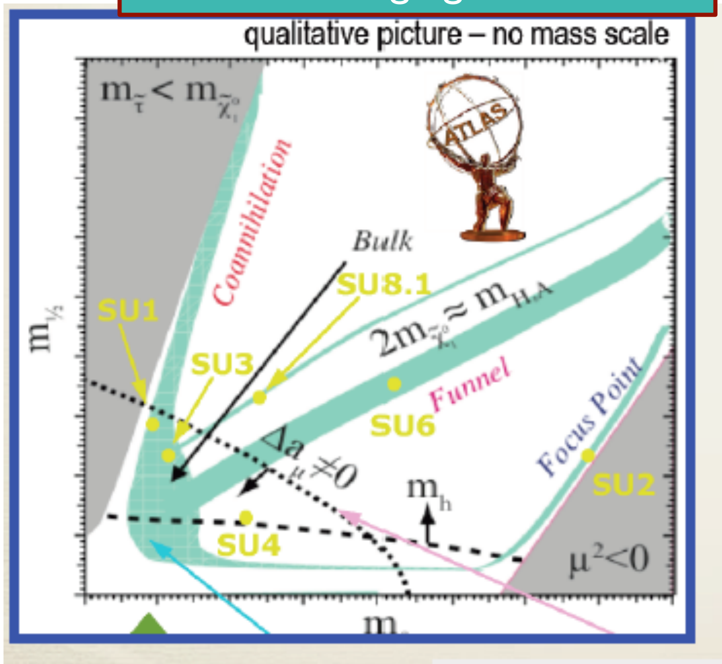
- Theoretically favored candidates for physics beyond the SM
  - Solution of the hierarchy problem
  - Stabilization of the Higgs mass against loop corrections
  - Allows for strong and electroweak forces unification
  - Provide a good candidate for dark matter
  - → SUSY mass scale expected to be @ TeV scale

- It is practically not possible to explore the 100-dimensional parameter space of MSSM. Adopt specific assumptions for the SUSY breaking
- R-Parity conserving mSUGRA model considered in the following
  - GMSB and scenarios with long-living particles or R-parity violation also studied by ATLAS
    - Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics, arXiv:0901.0512 [hep-ex]
- In the context of MSSM with R-parity conservation SUSY particles are produced in pairs and cascade down to undetected LSPs, with complex signatures

mSUGRA Benchmark Points

Dark matter constraints are taken as a rough guidance.

- Gravity mediated symmetry breaking
- it is determined by 5 free parameters defined at GUT scale and evolved down to electroweak scale using RGE:
  - 4 parameters: $m_0, m_{1/2}, A_0$, $\tan\beta$ *and a sign*
    - m_0, the universal sfermion mass at the GUT scale
    - $m_{1/2}$, the universal gaugino mass at the GUT scale
    - $\tan\beta$, the ratio of the Higgs vacuum expectation values
    - sgn μ , the Higgsino mass parameter sign
    - A_0, the universal trilinear coupling (higgs-sfermion-sfermion) at the GUT scale
  - m_0 and $m_{1/2}$ set sparticle masses at EW scale
- A set of benchmark points were chosen with the aim of exploring sensitivity to a wide class of signatures

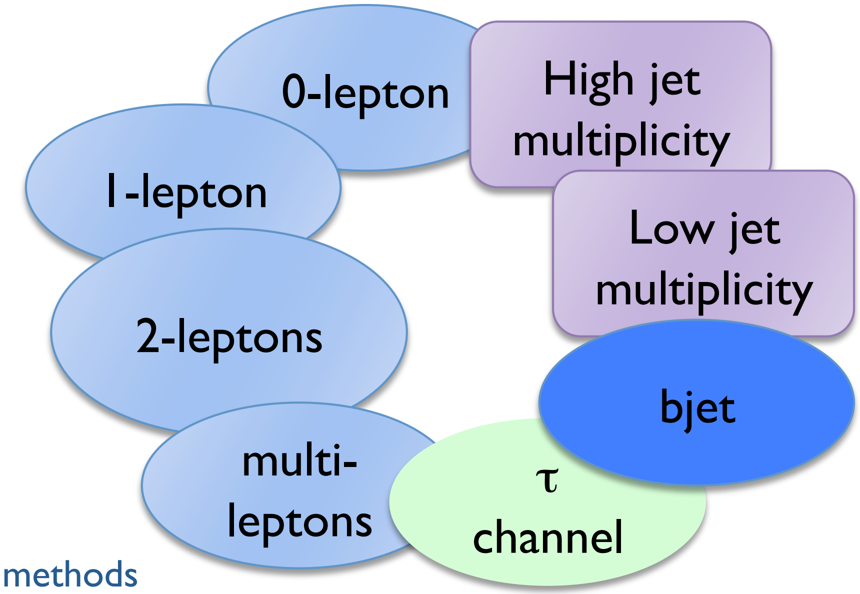


mSUGRA	σ(NLO) (pb)
SU1	10.86
SU2	7.18
SU3	27.68
SU4	402.19
SU6	6.07
SU8.1	8.7

$\sqrt{s}=14$ TeV

Studies at ATLAS

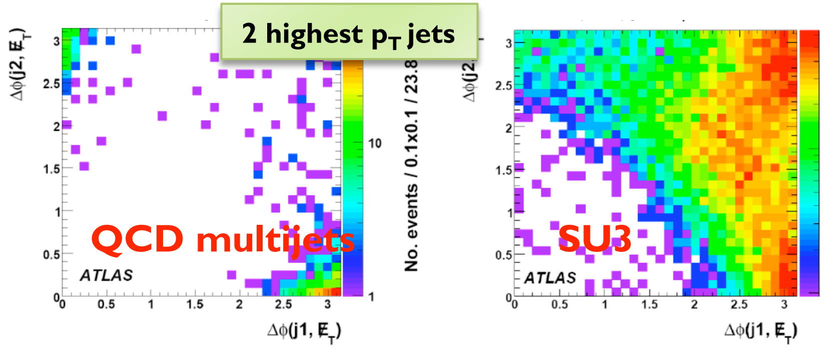
- Most of the studies are based on MC data for a total integrated luminosity of 1 fb^{-1}, $\sqrt{s}$= 14 TeV, simulation with realistic detector geometry with residual misalignments, all relevant SM bkg and trigger efficiencies taken into account
- Signatures involving jets, E_T^{miss}, leptons
- Different search channels
  - 0-lepton channel
  - 1-lepton channel
  - …

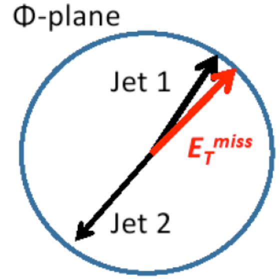


- Background: mainly from top pairs, W/Z+jets and QCD
  - New physics can only be claimed when the bkg under control
  - The prediction of bkg requires interplay of MC and data-driven methods
    - several independent data-driven methods in development for each search mode, some results shown later
    - Selection of control samples ideally free of SUSY events, unbiased, with enough statistics and small theoretical uncertainties
    - SUSY events may lead to an overestimation (20-30%) of the SM bkg that will be analysis and SUSY-model dependent
      - should be included in the systematics
- The uncertainties on the bkg are incorporated in the significances, for 1fb^{-1} estimated 50% for QCD, 20% for SM bkg

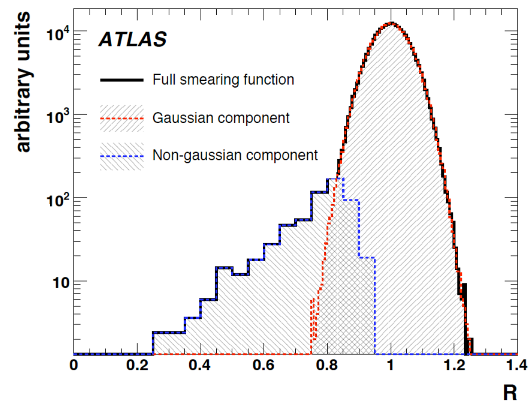
QCD Background

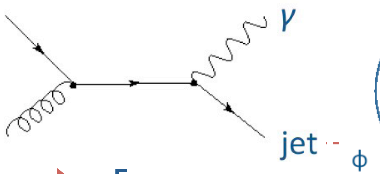
- Contributions
  - "Fake" E_T^{miss} events from mis-measurement of jet energies, cleaning procedure
    - Rejection of events in which E_T^{miss} is close to one of the leading jets
    - Jets pointing into non-fiducial regions of the detector rejected
    - Use of calorimeter and tracking cuts
    - Timing information to remove cosmic muons with hard Bremsstrahlung
  - "Real" E_T^{miss} events from non interacting particles
    - semi-leptonic heavy quark (b,c) decay dominant contribution to large E_T^{miss}

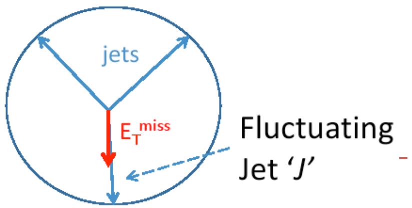




- Reduce the dependence on MC by smearing jet p_T in low E_T^{miss} QCD multijet with a data-measured jet response function R event by event
  1. Measure the Gaussian part of R with jet+γ events
  2. Non Gaussian response using multijet events with E_t^{miss} associated in ϕ to a jet
  3. Smear low E_T^{miss} multijet events with measured smearing function







for ~25 pb^{-1}
Statistic uncertainties ~1%
Systematic uncertainties ~60%.
Extrapolated to 1 fb^{-1} ~13%. Adopt a conservative approach.

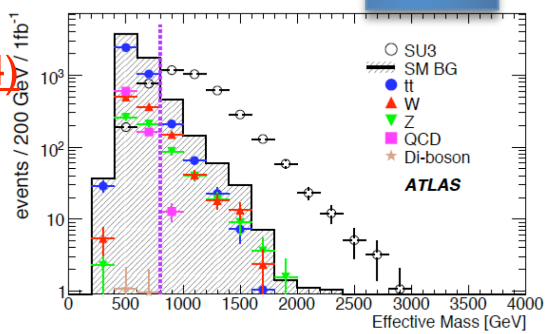
0-Lepton Selection

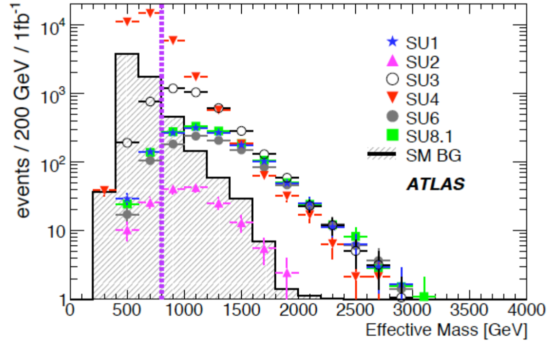
- Least model-dependent signature
- Search for events with multiple jets (at least 4)
- Selection
  - 4 jets (p_T thresholds: 100, 50, 50, 50 GeV)
  - E_T^{miss}>100 GeV, E_T^{miss}>0.2*M_{eff}
  - Transverse sphericity > 0.2
  - $\Delta\phi$ (jet1,2,3, E_T^{miss}) > 0.2
  - No e/mu (p_T > 20 GeV)
  - M_{eff}>800GeV

$$M_{\mathrm{eff}} \equiv \sum_{i=1}^{4} p_T^{\mathrm{jet},i} + \sum_{i=1} p_T^{\mathrm{lep},i} + E_T^{\mathrm{miss}}$$

- top pairs is the dominant bkg, W/Z+jets significant

1fb^{-1}



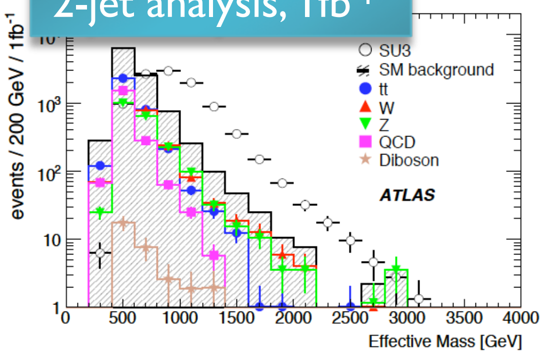


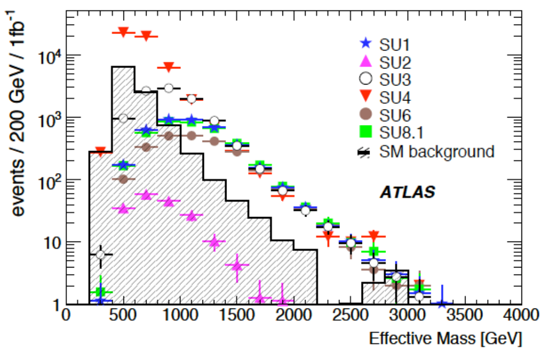
Indicative numbers
bkg x 2 : SU3 7.8, SU6 3.1

For SU2 larger M_{eff} cuts and greater luminosity needed

mSUGRA	Significance
SU1	6.3
SU2	0.9
SU3	13
SU4	25
SU6	6.3

2-jet analysis, 1fb^{-1}





- Lower jet multiplicities (2/3 jets)
- Harder cuts on jets and E_T^{miss}
  - 2 (3) jets (p_T thresholds: 150, 100 (100) GeV)
  - E_T^{miss}>100 GeV, E_T^{miss}>0.3 (0.25) * M_{eff}
  - $\Delta\phi$ (jet1,2,3, E_T^{miss}) > 0.2
- top pairs ,W/Z+jets and QCD give comparable contributions

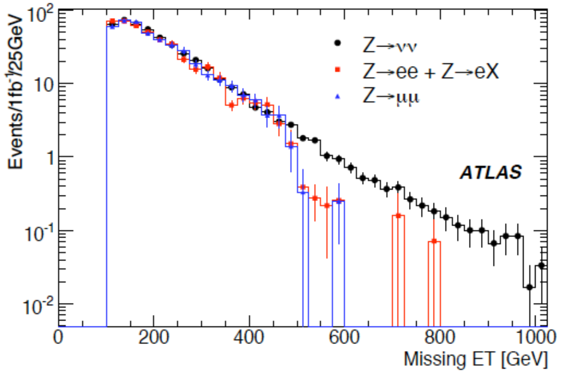
Background Estimation in 0-Lepton Mode Search

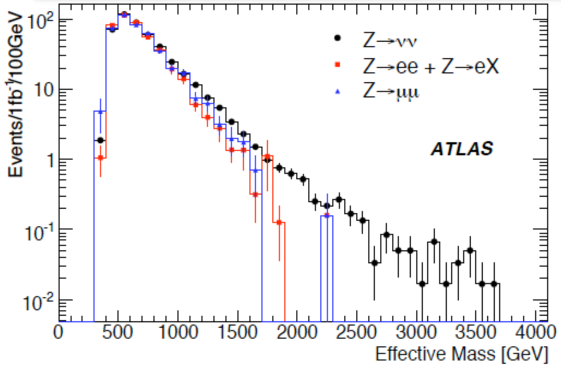
- $Z \rightarrow \nu\nu$ (+jets) one of the main bkg

- To estimate $Z \rightarrow \nu\nu$ use $Z \rightarrow \ell\ell$ replacing the leptons with the neutrinos
  - Corrections to derive $Z \rightarrow \nu\nu$ from $Z \rightarrow \ell\ell$
    - for the detected charged leptons that not cover the full phase space (η<2.5) of the neutrinos
    - kinematic for the additional cuts used to select $Z \rightarrow \ell\ell$
    - lepton identification efficiency
  - For high E_T^{miss} and M_{eff} statistics is low
    - BR(Z -> $\nu\nu$) / BR(Z->ll) ~ 6
  - SUSY contamination negligible

$1\,fb^{-1}$

Statistical error: ~10%
Systematic uncertainties ~10%



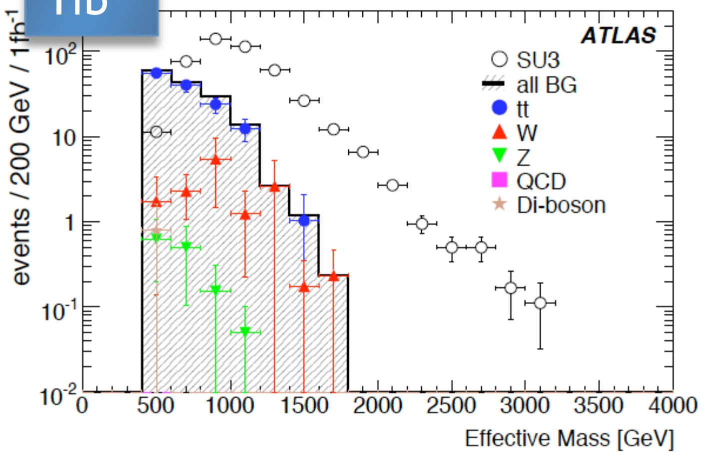


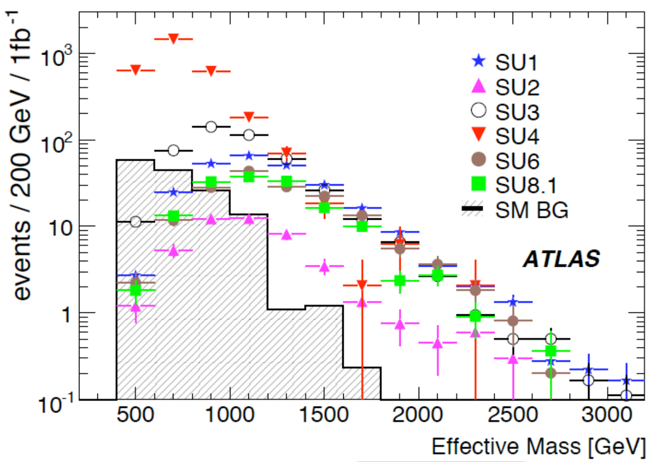
1-Lepton Selection

- Reduces the QCD multijet bkg → more robust against bkg uncertainties
  - Exactly 1 isolated lepton with p_T > 20 GeV and no other lepton with p_T >10 GeV
  - At least 4 jets with p_T > 50 GeV and p_T(J1) > 100 GeV
  - E_T^{miss} > max (100 GeV, $0.2M_{eff}$)
  - Transverse sphericity S_T > 0.2
  - Transverse mass M_T > 100 GeV (reduces W→lν)
  - M_{eff}>800GeV

$$M_T = \sqrt{2 p_T^{lepton} E_T^{miss} (1 - \cos\varphi(\vec{p}_T^{\,miss}, \vec{p}_T^{\,lepton}))}$$

1 fb^{-1}





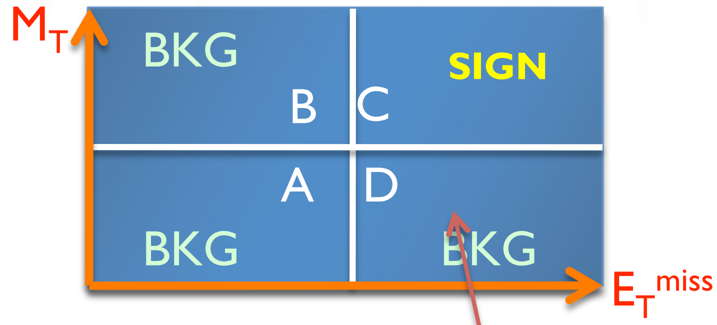
Bkg dominated by top pairs and W/Z+jets

All SUSY points except SU2 could be discovered with good significance with 1 fb^{-1}

Background Estimation in 1-lepton Search Mode

- M_T method for bkg estimation
  - M_T is only weakly dependent on E_T^{miss}

A,B,D regions don't contain signal
C = signal region obtained by application of selection cuts
D= control sample region is the one used to estimate bkg

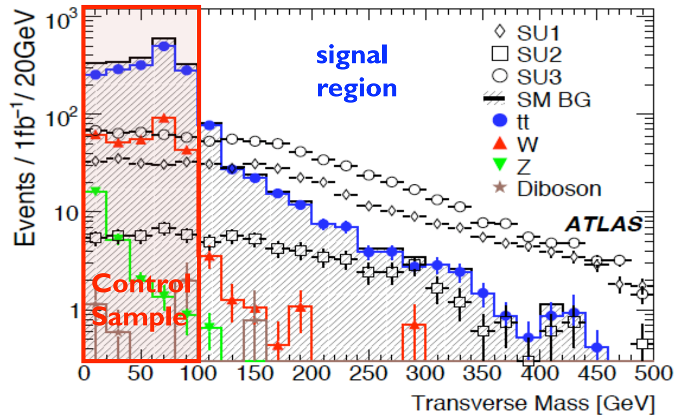


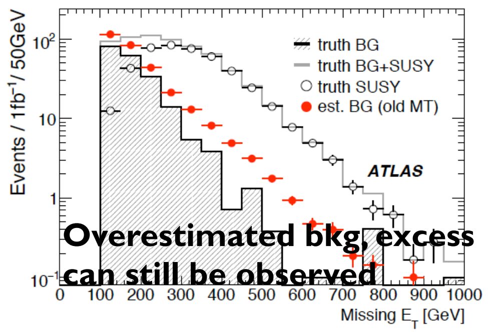
Background in C = D x B/A

Control region

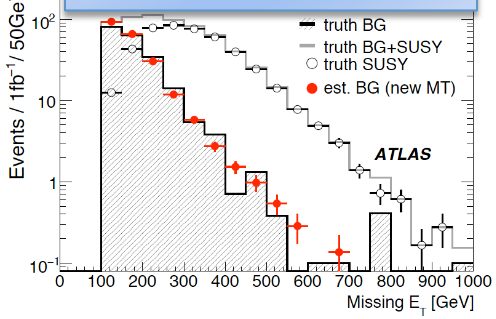
The normalization is obtained from the control samples in which SUSY is low

- M_T<100GeV : bkg (top &W) enhanced Sample [Control Sample]
- M_T>100GeV : SUSY signal enhanced Sample [Signal Region]
  - we need to estimate the bkg in this region





After SUSY subtraction



Neglecting to first order the SM bkg at high M_T SUSY in control sample can be estimated by Susy in M_T>100 GeV region: contamination can be subtracted

Remaining SM bkg in the high M_T region and variation in the shape for various SUSY model treated as systematics

1fb^{-1}

Stat error ~5%
Systematic error ~15%

2-Lepton Selection

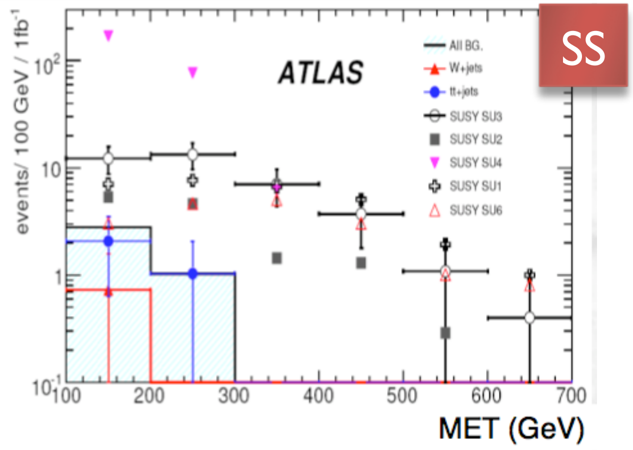
- Small rates expected (10-100 events/fb^{-1}) but higher S/B
- <u>2 Opposite Sign leptons with the Same Flavour (OSSF)</u>
  - Independent decays give OSSF or OSDF (Opposite Sign Different Flavour) leptons
  - Observing a non-resonant excess of OSSF over OSDF is a clear indication of new physics
  - Selection
    - 2 OS isolated lepton with p_T > 10 GeV
    - At least 4 jets with p_T > 50 GeV and p_T(J1) > 100 GeV
    - E_T^{miss} > max (100 GeV, 0.2M_{eff})
    - Transverse sphericity S_T > 0.2
  - Main background: top pairs
- <u>2 Same Sign leptons with the Same Flavour</u>
  - common in SUSY as gluino is a self-conjugate Majorana fermion
  - Same selection but 2 SS isolated lepton with p_T > 20 GeV
  - SM bkg very low (from top pairs)
    - top pairs : b jets can produce a second lepton of the same sign with a non negligible probability of being isolated

$$\chi_2^0 \rightarrow l^{\pm} l^{\mp} \chi_1^0$$

1 fb^{-1}

mSUGRA	Significance OS	Significance SS
SU1	1.65	7.2
SU2	0.43	1.9
SU3	3.55	7.7
SU4	22.5	19.9

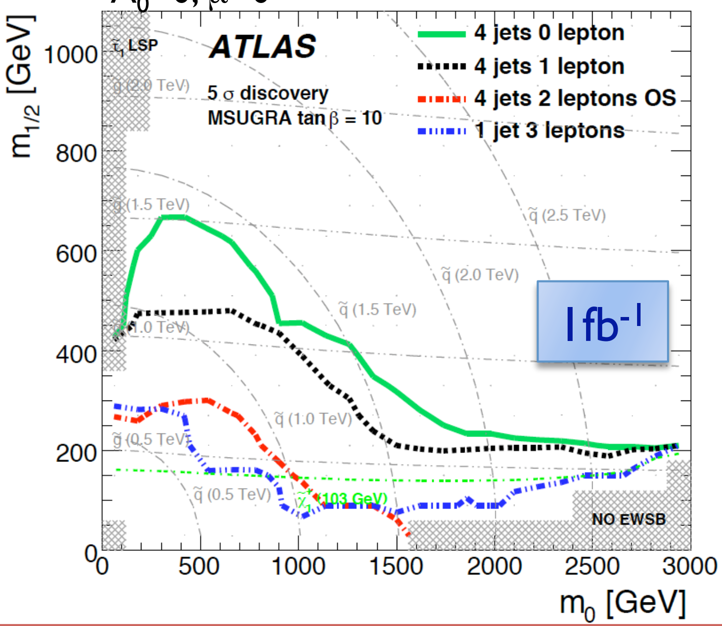
Can be improved optimizing cuts
For SU1 many leptons are soft because the small mass gaps between susy particles, improved analysis based on low p_T leptons would help



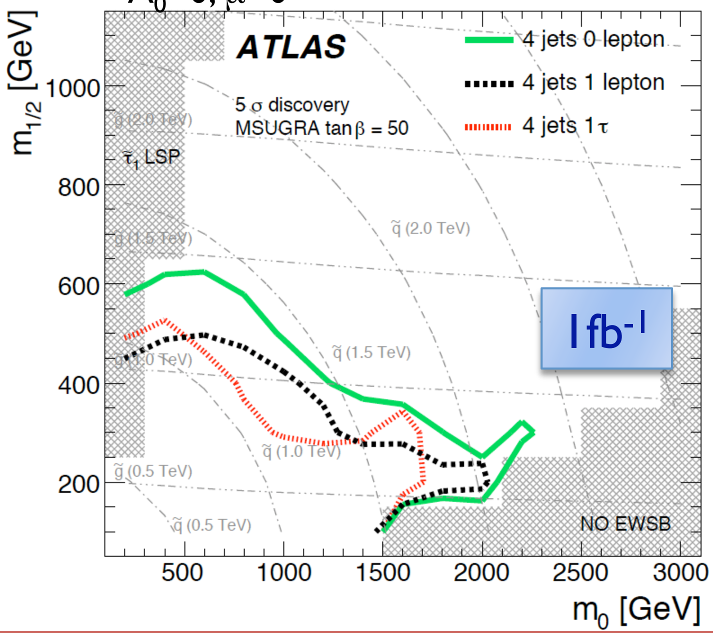
“Discovery” Parameter Scans (I)

- Scan over the parameters of models with R-parity conservation with fast simulation
- Test whether the previous approaches work for a wide range of models
  - Corrected to account for lepton reconstruction efficiency as a function of p_T and η
  - Reasonable agreement can be found with the full simulations with *Geant4*
- Optimal M_{eff} cut (steps of 400GeV) to maximize the significance

$A_0=0, \mu>0$



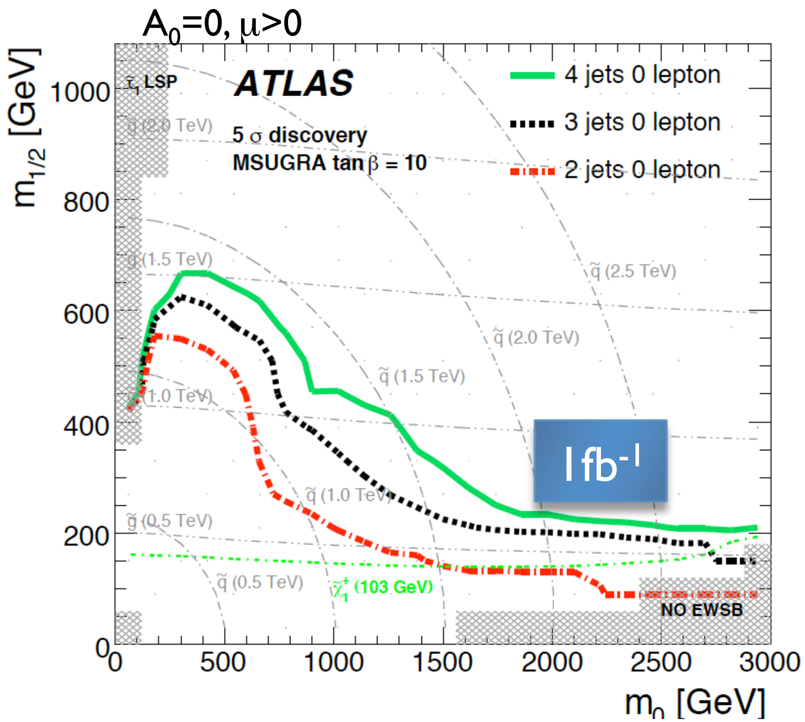
$A_0=0, \mu<0$

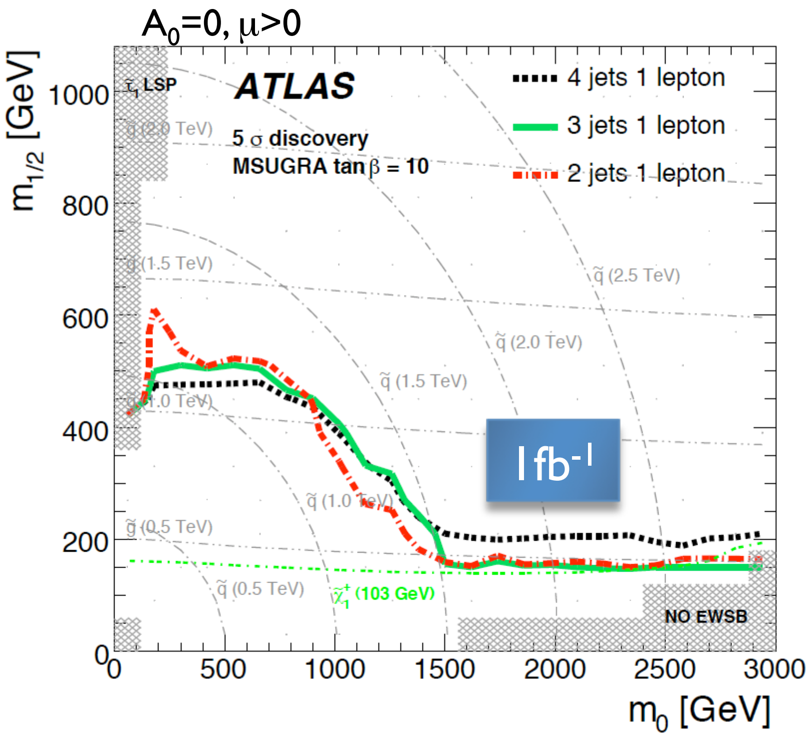


The 0-lepton mode has the best estimated 5σ reach (gluino and squark masses ~1.5TeV) The 1-lepton mode has worse reach, but better against QCD	Enhanced b and τ production 1-τ search slighly worse reflects the lower efficiency and purity for τ reconstruction (improvements expected)

"Discovery" Parameter Scans (II)

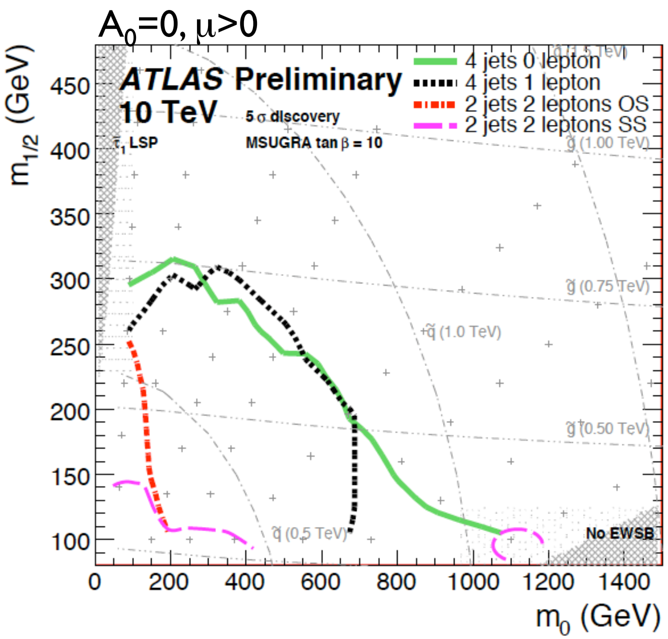
- Requiring 4 jets is not necessary the best choice.
- For 0-lepton mode the choice of 4 jets seems best while for the 1-lepton mode the 2-jet 3-jet and 4-jet reaches are comparable

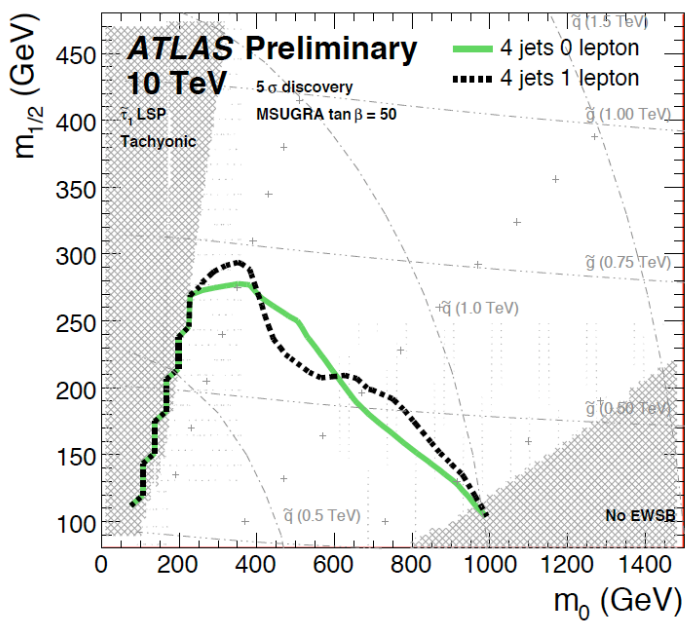




Discovery Reach at √s = 10 TeV, L=200 pb^{-1}

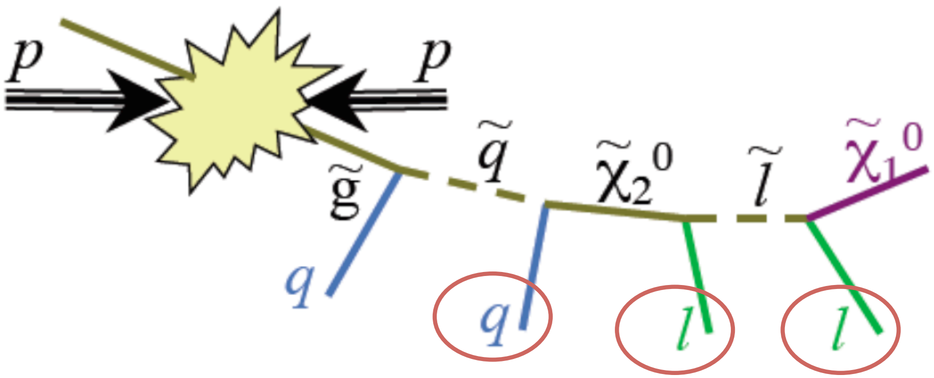
- Analysis performed in the same channels but looser selection criteria on jet energies and E_T^{miss}
- Optimal M_{eff} cuts to maximize the significance
- Can discovery signals with squark and gluino masses less then 600-700 GeV





Measurements from SUSY Particles

- Once (and if) SUSY is discovered concentrate on the measurements that can be performed with early data
  - To derive relations between the masses of the s-particles
  - Measure the spin of the SUSY particles
  - …
- Error on measurements limited by statistics
  - with early data measurements possible only for models with moderate (<1TeV) SUSY mass scale
- Studies based on MC data corresponding to L=0.5 – 1 fb^{-1} for SU4 (Low Mass region) and SU3 (Bulk Region)



Due to the LSPs, the decay chain cannot be completely reconstructed
Edges, rather than mass peaks, are measured in the invariant mass distribution of the decay products (e.g. m_{ll}, m_{llq}, m_{lq})
Give indications on the SUSY mass spectrum

Edge Reconstruction

- Selection of event with 2 OS or 3 leptons (e/μ) with p_T>10GeV, η<2.5
- Cut on jets and E_T^{miss} optimized to maximize the ratio

$$S \equiv (N_{\mathrm{OSSF}} - N_{\mathrm{OSDF}})/\sqrt{N_{\mathrm{OSSF}} + N_{\mathrm{OSDF}}}$$

that can be computed from data

- Estimation of the SUSY and SM combinatorials from data with flavour subtraction
  - signal: OSSF leptons
  - bkg: OSSF+OSDF
  - the bkg can be removed with the subtraction of OSDF leptons
    - taking into account the different reconstruction efficiencies of e/μ
- Needed statistics depend on mSUGRA point
  - for SU1 (Co-annihilation) edges visible with ~20fb^{-1}

decay chain

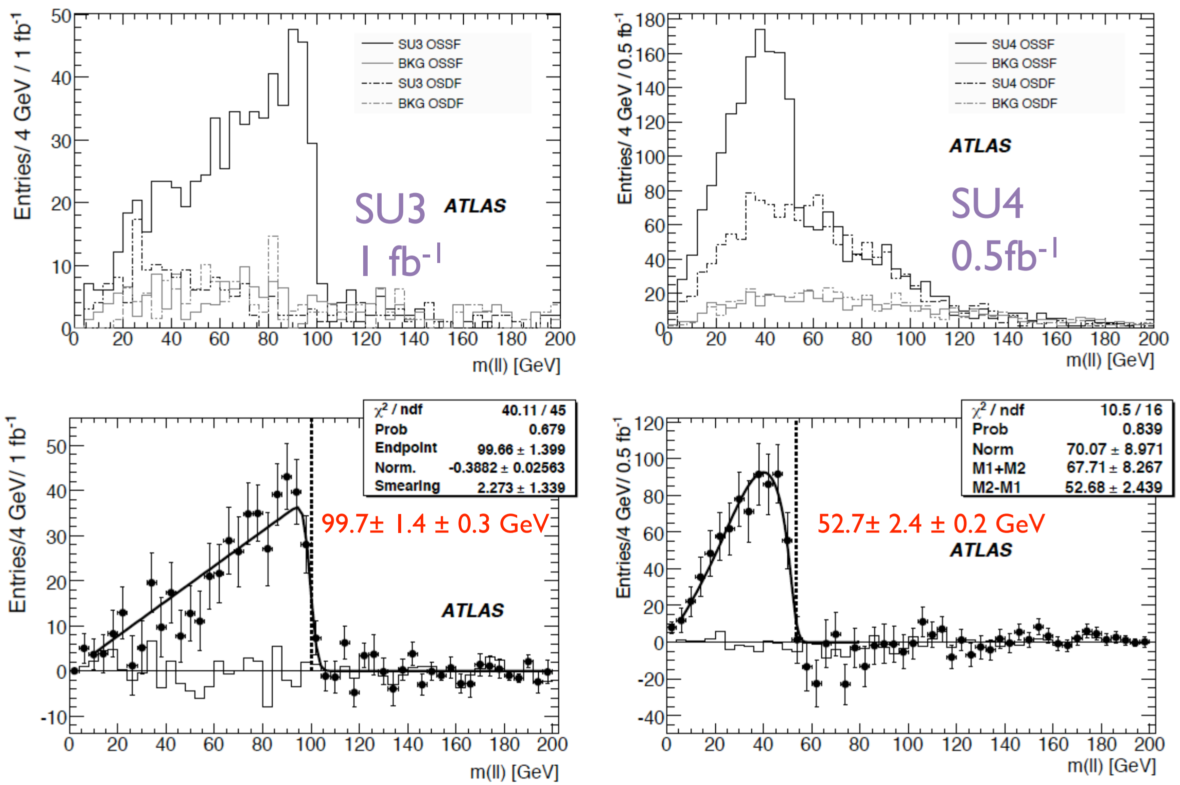
$$\tilde{q}_L \to \tilde{\chi}_2^0 q (\to \tilde{\ell}^{\pm}\ell^{\mp} q) \to \tilde{\chi}_1^0 \ell^+ \ell^- q$$

$$m_{\ell\ell}^{\mathrm{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}.$$

3-body decay

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$$

$$m_{\ell\ell}^{\mathrm{edge}} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$



Conclusions

- Inclusive searches are the first step towards finding SUSY at the LHC
  - Cuts need to be simple and powerful against backgrounds
  - Backgrounds and detector need to be understood
- Optimisation for different topologies/channels
  - Significant excesses in particular channels may be the first hint towards the understanding of the new physics.
- Should be able to observe squarks and gluinos with a mass up to 1-1.5 TeV (if systematics are as expected for 1 fb^{-1})
  - SUSY at higher mass scales could still show up but would make detailed study quite difficult
- if SUSY-like signal is found, work to confirm and determine models
  - exclusive studies to determine model parameters

Backup

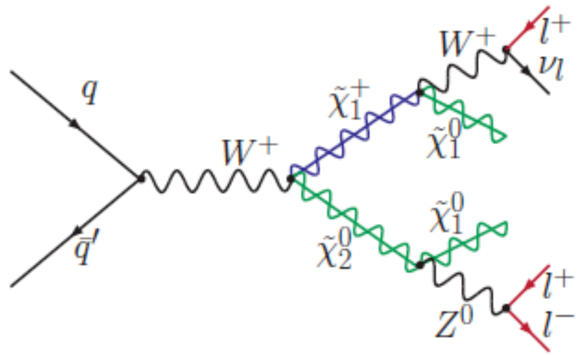
Trigger Efficiencies

- Trigger threshold defined for $2x10^{33}cm^{-2}s^{-1}$ menu
- E_T^{miss} + jet trigger highly efficient
- Jet triggers alone is in a range 30-70% → provide useful redundancy in the early phases when E_t^{miss} may require longer time to be understood
- For topologies involving leptons both single lepton trigger and E_T^{miss} + jet trigger have efficiencies >80%

Trigger	SU1	SU2	SU3	SU4	SU6	SU8.1
	0-lepton, 4-jet selection [Section 2.1]					
JETS	44.6	51.0	33.8	7.7	51.7	48.2
j70_xE70	99.7	98.7	99.5	97.2	99.6	99.7
	0-lepton, 3-jet selection [Section 2.2]					
JETS	64.9	71.1	54.9	34.3	71.8	66.8
j70_xE70	100.	99.8	100.	99.9	100.	100.
	0-lepton, 2-jet selection [Section 2.2]					
JETS	44.1	39.9	30.1	8.8	53.6	47.6
j70_xE70	100.	100.	100.	99.9	100.	100.
	1-lepton, selection [Section 3]					
JETS	41.8	50.5	31.7	8.1	48.4	45.6
j70_xE70	99.6	99.0	98.9	95.6	98.9	99.1
1LEP (mu20 OR e22i)	81.2	81.0	79.9	80.3	80.4	79.5
	OS 2-lepton, selection [Section 4.1]					
JETS	36.7	47.3	34.0	6.7	47.2	40.8
j70_xE70	99.2	100.0	98.9	94.3	99.6	100.0
1LEP (mu20 OR e22i)	87.0	90.0	87.5	84.8	79.6	86.4
2LEP (2mu10 OR 2e15i)	20.5	35.5	27.0	18.0	26.0	14.6
	SS 2-lepton, selection [Section 4.2]					
JETS	39.9	48.8	29.2	1.6	46.6	34.5
j70_xE70	99.3	100.0	98.9	84.1	98.3	100.0
1LEP (mu20 OR e22i)	94.2	92.7	95.9	95.2	89.7	96.6
2LEP (2mu10 OR 2e15i)	32.6	41.5	32.2	25.4	25.9	31.0
	3-lepton, selection [Section 5]					
JETS	43.7	60.2	40.1	17.6	46.4	48.3
j70_xE70	95.6	85.4	93.5	79.8	96.4	98.3
1LEP (mu20 OR e22i)	95.2	94.2	95.8	94.7	94.6	96.7
2LEP (2mu10 OR 2e15i)	49.1	60.2	51.0	44.7	47.3	53.3

SU2 (I)

- If squarks, sleptons and possibly also gluinos are heavy – direct gaugino production becomes important
  - Gauginos may decay leptonically through real or virtual $W^{\pm}$, Z^0 (or sleptons, if these are not too heavy)
    - Low jet activity
    - Relatively low $\not{E}_T$ – the gauginos are produced back to back



- The so-called "Focus point region" of the SUSY parameter space (SU2) is particularly interesting
- Characterised by very heavy squarks and sleptons
- The gauginos are light and dominate the production cross-section
- Trilepton signal mainly from the pair production of $\chi_1^{\pm}\chi_2^0$

- The trilepton requirement gives strong SM background suppression

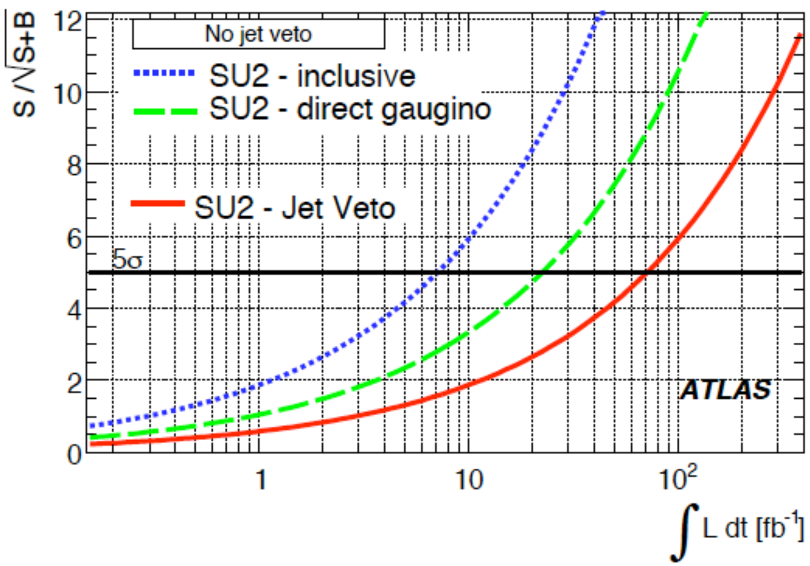
The main SM backgrounds

- $t\bar{t}$ – additional lepton from semileptonic b-decay
- Zb – additional lepton from semileptonic b-decay
- SM counterpart: diboson production, WZ, ZZ, WW, $Z\gamma$ – additional leptons from photon conversion

SU2 (II)

Event selection

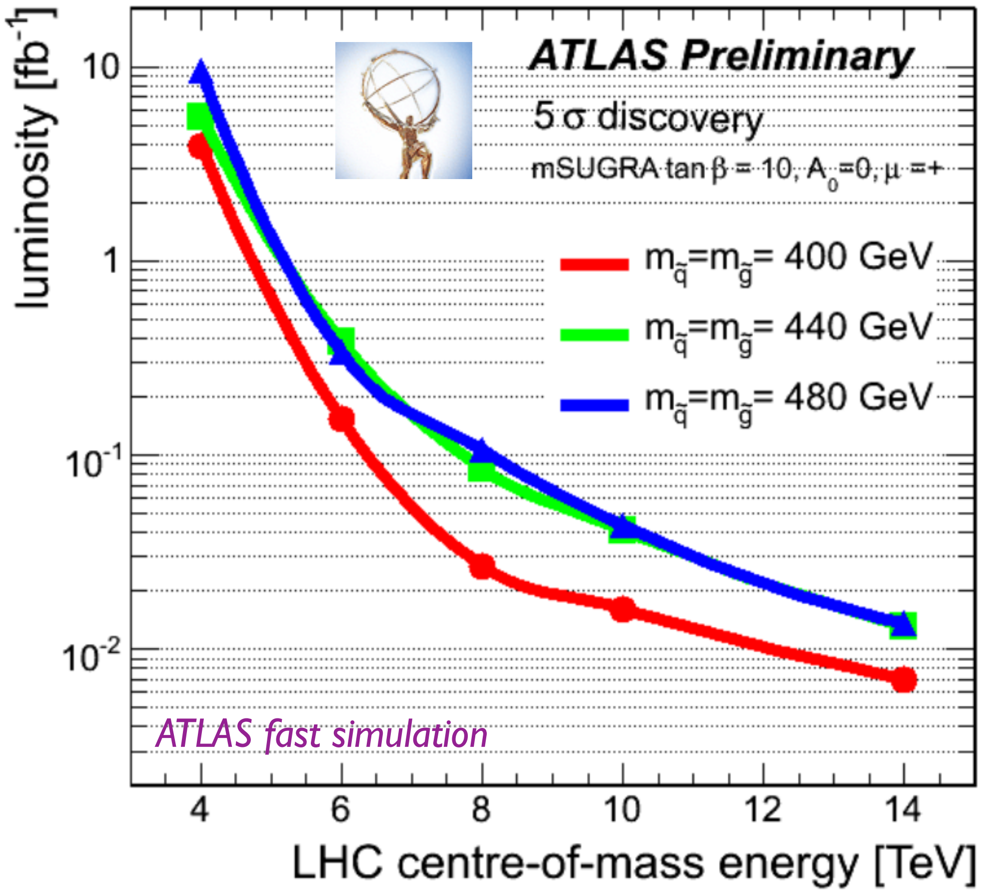
1. At least one pair of opposite sign, same flavour leptons (SFOS) (e^+e^- or $\mu^+\mu^-$) with $M_{l^+l^-} > 20$ GeV
2. $N_\ell >= 3$ ($\ell \in \{\mathrm{e}, \mu\}$)
3. $p_{T\,\mathrm{track,max}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T\,\mathrm{track,max}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T\,\mathrm{track,max}}^{\Delta R=0.2}(\ell)$ is the maximum p_T of any track in a $\Delta R = 0.2$ cone around the lepton
4. No SFOS dilepton pair with invariant mass in the Z^0-mass window $|M_{SFOS} - M_Z| > 10$ GeV
5. $\not{E}_T > 30$ GeV – a moderate $\not{E}_T$ cut
6. Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto



SUSY, an example

LHC Performance Workshop - Chamonix 2009

- ℓ+jets+missing-E_T channel
  - Not most sensitive, but will be usable before inclusive jets+missing-E_T analysis
- Tevatron limit currently is 380 GeV in this model ($m_{\tilde{q}} = m_{\tilde{g}}$)
  - plot shows 3 masses above this
- We will be sensitive to a region overlapping with ultimate Tevatron reach
- Below $E_{cm} \approx 8$ TeV, the sensitivity collapses



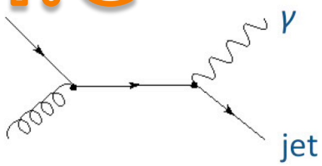
5σ discovery beyond current Tevatron limits is possible with **$s^{1/2}$ = 8-10 TeV** and **~30-15 pb^{-1} g.d.**

Data Driven QCD Background

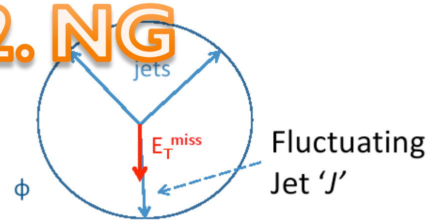
- The systematic and statistical uncertainties in MC based QCD bkg estimate will limit their use until sufficient data have been acquired to understand both the detector and underlying physics.
  - Reduce the dependence on MC by smearing jet p_T in low E_T^{miss} QCD multijet with data-measured jet response function R event by event
- 1. Measure the Gaussian part of R with jet+γ events
  - event with 1 γ passing the γ60 trigger and 1 and only 1 jet
  - limited statistics prevent the measurement of non-Gaussian tail
  - Jet response measured with R_1
- 2. Non Gaussian response using events in which E_T^{miss} is associated in ϕ to a single jet
  - events required to pass a high p_T or E_T^{miss} trigger
  - at least 3 jet with pT>250, 50, 25 GeV
  - ETmiss > 60GeV, parallel or antiparallel to the p_T of one of the jets
- 3. Smear low E_T^{miss} multijet events with measured smearing function
  - The estimate is normalized to data with E_T^{miss} <50 GeV

Statistic uncertainties ~1%
Systematic uncertainties ~60% from biased event selection, statistics in non-gaussian tail and jet response function measurement
low SUSY contamination

1. G



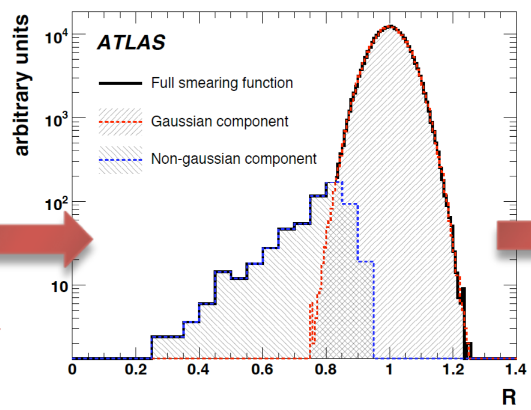
2. NG



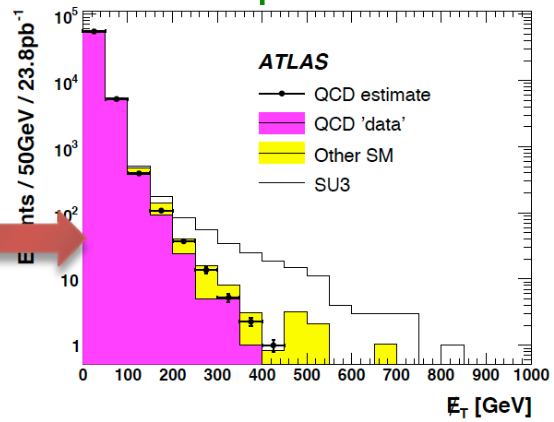
$$R_1 = 1 + \frac{\mathbf{p}_T^{\mathrm{miss}} \cdot \mathbf{p}_T(\gamma)}{|\mathbf{p}_T(\gamma)|^2},$$

$$R_2 = \frac{\mathbf{p}_T(J) \cdot \mathbf{p}_T(J,\mathrm{true})}{|\mathbf{p}_T(J,\mathrm{true})|^2}$$

$$\mathbf{p}_T(J,\mathrm{true}) \simeq \mathbf{p}_T(J) + \mathbf{p}_T^{\mathrm{miss}}$$



0-lepton search



ttbar: Reconstruction of the Top Mass

- Estimation of the "semileptonic" ttbar bkg
  - Reconstruct leptonic W assuming neutrino from W responsible for all MET
  - Reconstruct "best" (mass closest to top mass) leptonic top with one of the leading jets
  - Reconstruct best hadronic W with the three remaining leading jets
  - Reconstruct best hadronic top
  - Top box cuts (define control sample)

Cuts to define control sample
+ $M_T < M_W$

$$\begin{aligned} M_{Top-lep} - M_{Top}\ | &< 25\ \mathrm{GeV} \\ M_{W-had} - M_W\ | &< 15\ \mathrm{GeV} \\ M_{Top-had} - M_{Top}\ | &< 25\ \mathrm{GeV} \end{aligned}$$

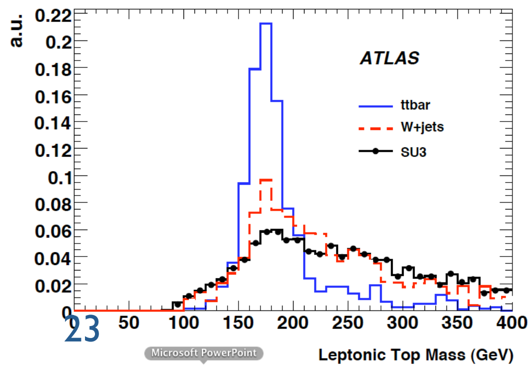
SUSY contamination small (<2%) with exception of low mass points (SU4) since low spectrum makes it rather similar to ttbar

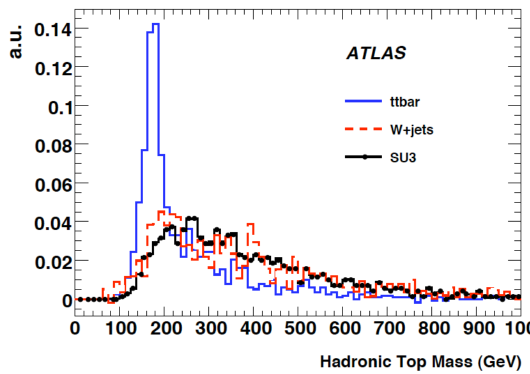
Normalization
Model dependence (MC) on R_{tt} treated as systematic uncertainties (around 8%)

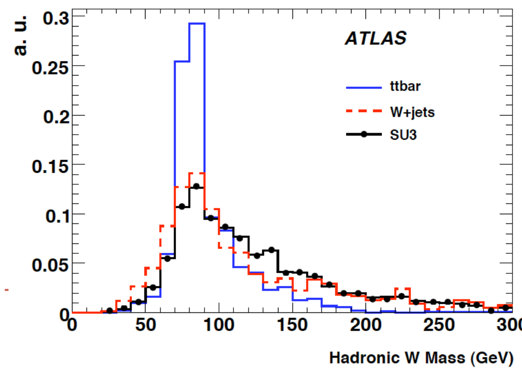
$$N_{t\bar{t}}^{\text{signal-region}}(\text{data}) = N_{t\bar{t}}^{\text{topbox}}(\text{data}) \cdot R_{tt}$$

$$R_{tt} \equiv N_{t\bar{t}}^{\text{signal-region}}(\text{MC}) / N_{t\bar{t}}^{\text{topbox}}(\text{MC})$$

Statistical error ~5%
Systematic error ~20% (largest from JES)

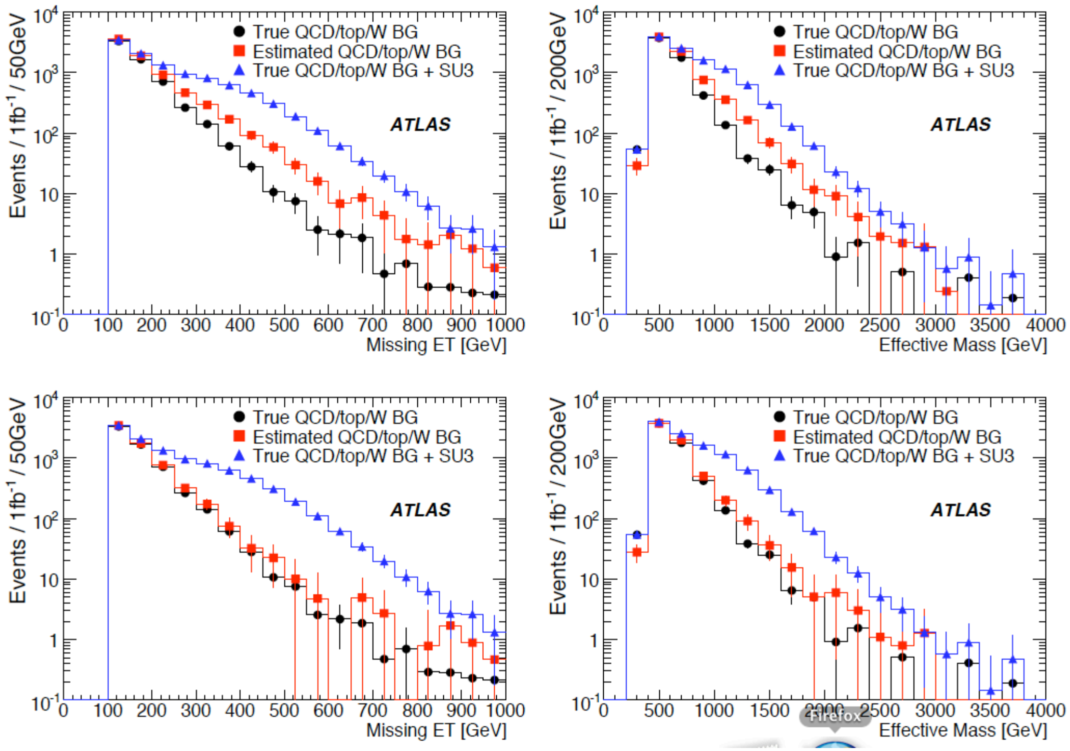






0-Lepton Mode Search (II)

- ttbar and W+jets contribute to the bkg when the lepton emitted by the W is not identified:
  - $W \rightarrow \tau \rightarrow$ hadrons (~40%)
  - out of acceptance (~40%)
  - isolation (close to jets) (~20%)
- Control samples : ttbar and $W \rightarrow l\nu$ where the lepton is identified
  - similar kinematic distribution except for the presence of the lepton
  - Selection
    - same as for the signal 0-lepton sample
    - 1 isolated lepton (e/μ p_T>20GeV)
    - M_T<100 GeV to enhance ttbar and W processes (M_T=mass between leptons and E_T^{miss})
    - the identified lepton is treated as if had been missed and all the kinematic variables are recalculated



  - Normalization with data 100 GeV < E_T^{miss} < 200 GeV where the contribution from SUSY is expected to be small
- QCD semi-leptonic heavy quarks contributing to large E_T^{miss} included
- SUSY contamination causes a decreases of event excess
  - but it is still obeservable with 1 fb^{-1}
  - contamination estimated from control sample (new M_T method)

Stat error ~5%
Systematic error ~15%