Prospects for SUSY searches at the LHC

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Aspen Winter Conference

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Outline

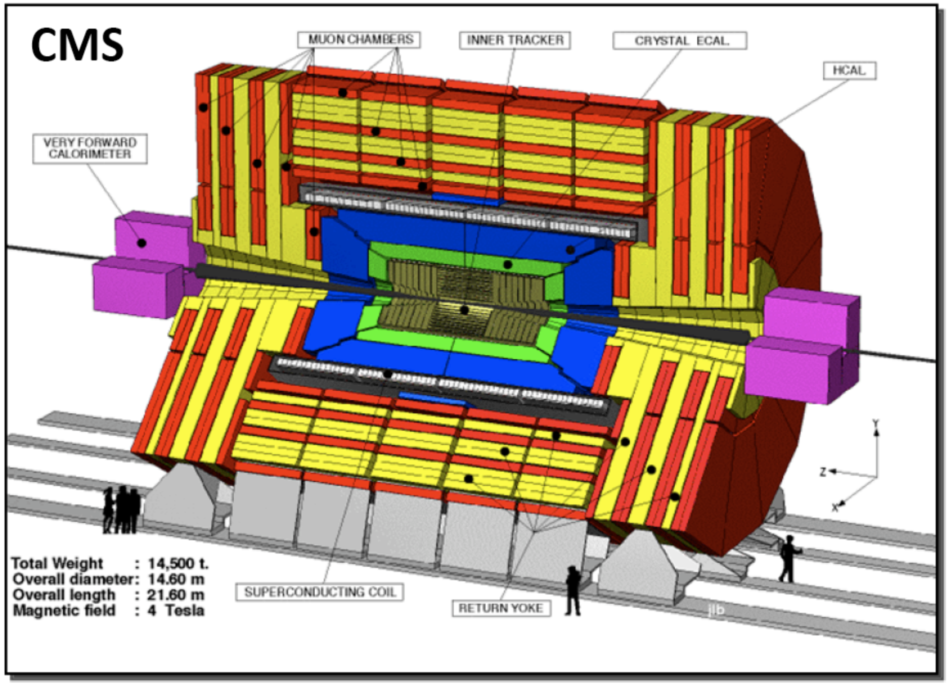
- Introduction
  - ATLAS / CMS detectors
  - Brief introduction to SUSY
  - SUSY models used
- Inclusive SUSY searches
  - 0-lepton searches
    - Including NEW CMS di-jet study
    - Background estimation for 0-leptons
  - 1-lepton searches
    - Background estimation techniques
  - 2-lepton searches
- Discovery reach
  - Effect of sqrt(s)<14 TeV
- Conclusions

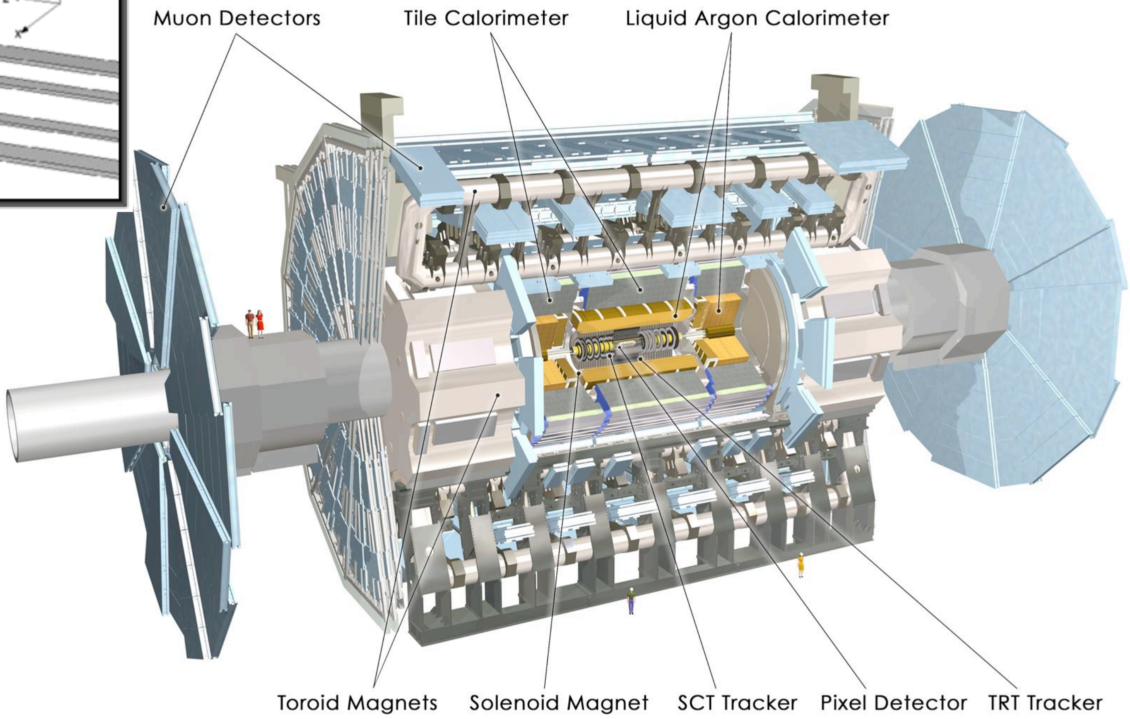
The Experiments

Both ATLAS and CMS detectors designed for SUSY discovery (amongst other things).

Hermeticity of detectors very important for SUSY discovery.

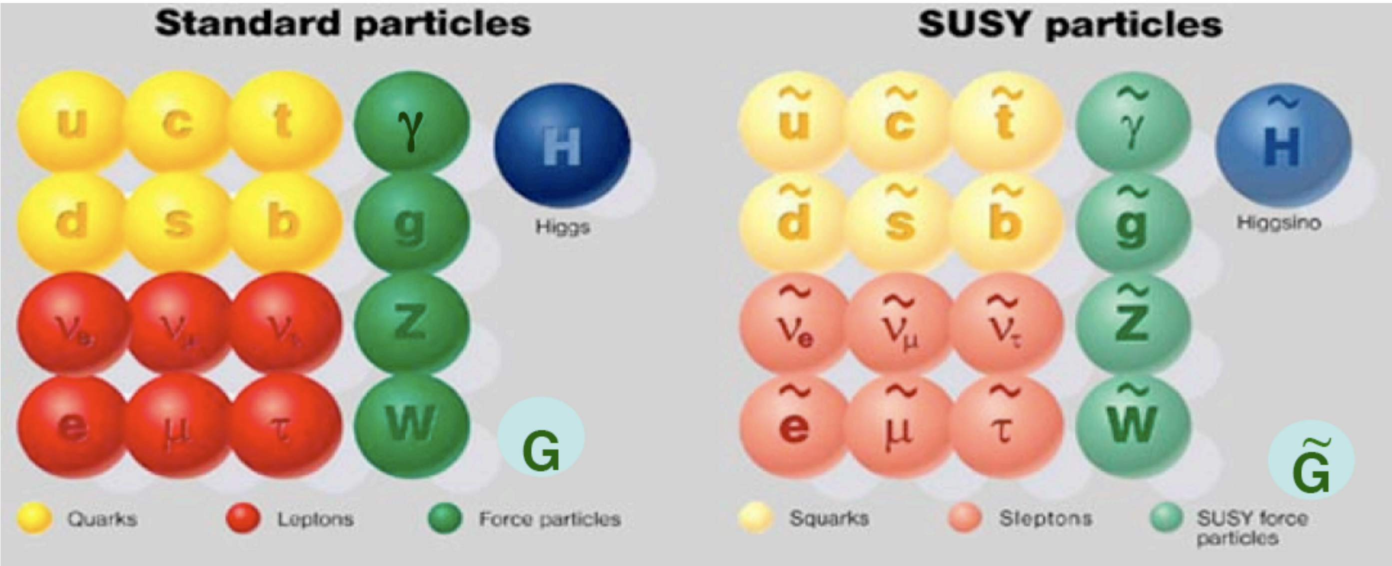
Both have excellent Jet, Electron, Muon and missing E_T performance, despite some very different design choices.



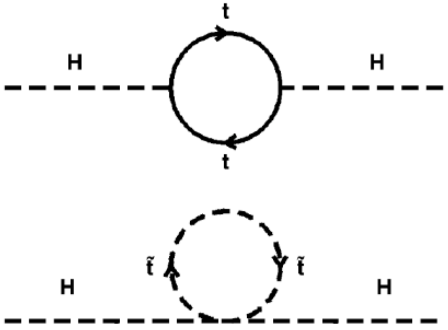


For more details on the experiments please see talks by:
J. Dubbert (ATLAS)
K. Maeshima (CMS)

Brief intro to SUSY



- SUSY partner for every SM particle (with ½ unit of spin different)
  - spin 0 Sfermions (squark, sleptons)
  - spin ½ Gauginos (chargino, neutralino)
- SUSY mass scale expected to be ~1TeV in order to:
  - Solve hierarchy problem (stabilize Higgs mass to radiative corrections)
  - Allow unification of strong and electroweak forces
  - Provide sensible dark matter candidate (R-parity)
  - Naturalises scalar (Higgs) sector of SM
- Downside of SUSY
  - Large parts of parameter space ruled out already
  - Many parameters



SUSY models

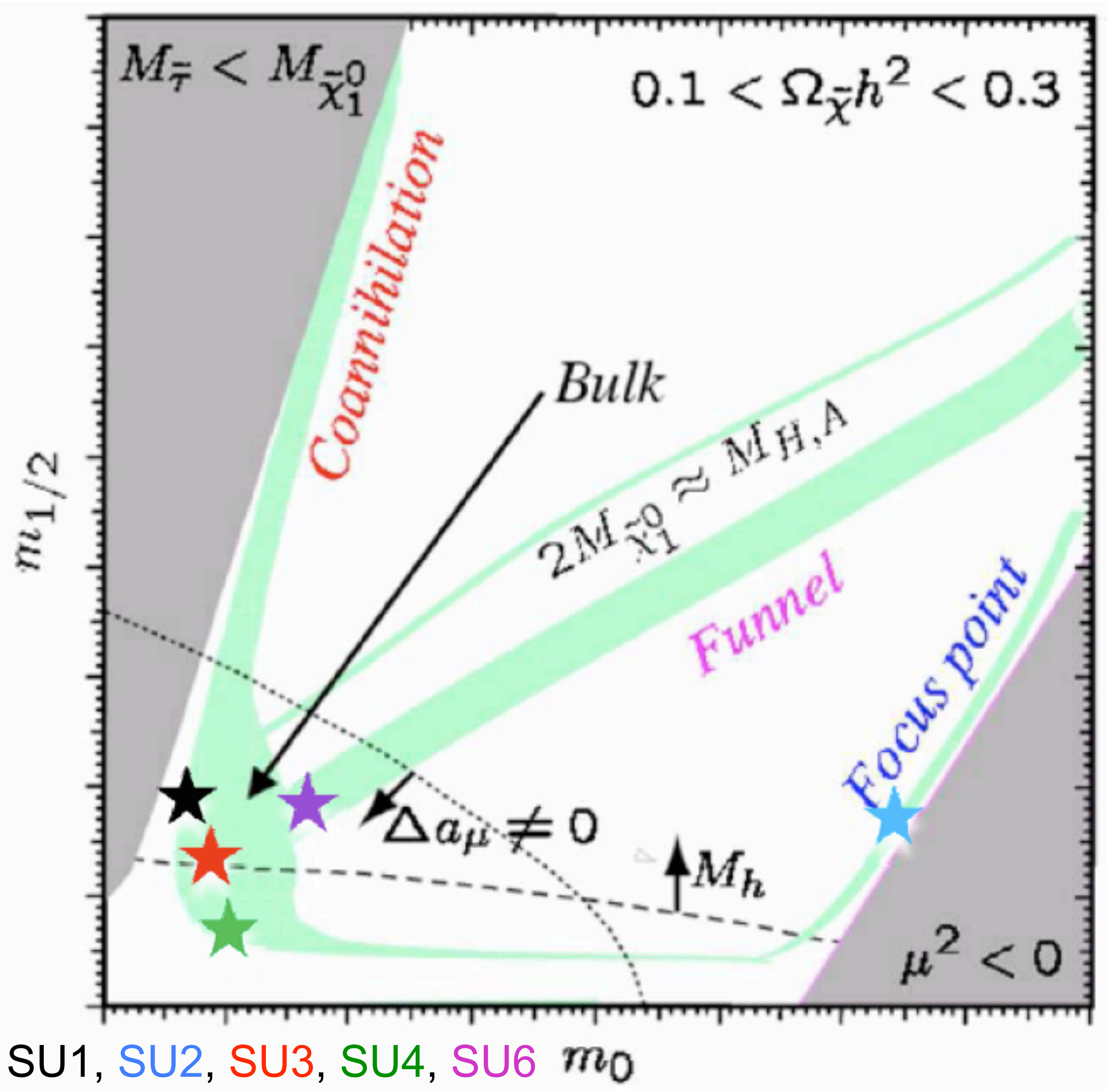
- Different models with different SUSY breaking mechanisms via interaction with hidden sectors
- Many models available, leading to very different phenomena
  - CMSSM / mSUGRA
    - SUSY breaking by gravity mediation in hidden sector
    - Model defined by 5 parameters at the GUT scale
    - Neutralino LSP
  - GMSB
    - SUSY breaking by gauge mediation in hidden sector
    - Can have long lived NLSP
    - Graviton LSP
  - Other
    - AMSB, Split SUSY (heavy sfermions), ...
- R-Parity conservation
  - Avoid proton decay
  - Sparticles produced in pairs
  - Lightest Supersymmetric Particle (LSP) undetected
    - Missing energy signature
- I will concentrate on R-Parity conserving models in this talk

mSUGRA parameters:

m_0 – common mass of squarks/sleptons
$m_{½}$ – common mass of Gauginos
A_0 – common trilinear coupling
tan β– ratio of Higgs expectation values
sign(μ) - value set by EWSB

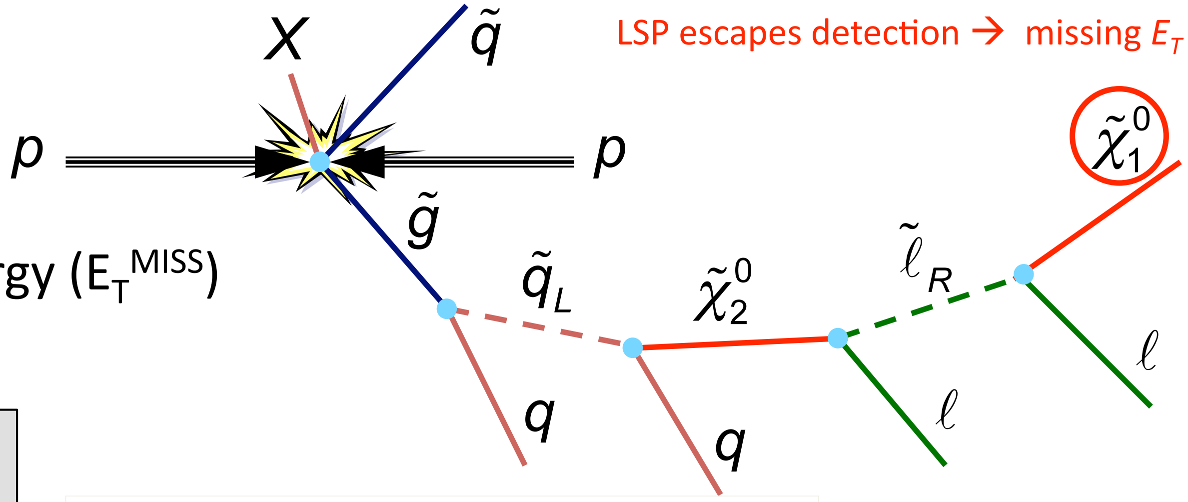
SUSY models – benchmark points

- ATLAS uses 5 mSUGRA benchmark points
  - ~Consistent with WMAP upper limit on cold dark matter
  - Chosen as they give different phenomenology
- Also have benchmarks for different models (eg. GMSB)
- CMS uses different points – but same idea
- Full list of points given in backup slides



SUSY @ the LHC

- SUSY production cross sections fairly independent of SUSY breaking model
  - Mostly driven by SUSY particle masses
  - For ~1 TeV SUSY, σ ~O(10) pb, ~ O(0.01) Events/s (for $L=10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Production cross section at LHC >> at Tevatron
  - eg. For M_{gluino}=400 GeV, $\sigma_{LHC}(\tilde{g}\tilde{g}) / \sigma_{Tevatron}(\tilde{g}\tilde{g})$ ~20,000
- SUSY signatures (model dependent)
  - Cascade decays
  - High P_T Jets
  - Isolated Lepton(s)
  - Missing Transverse Energy (E_T^{MISS})



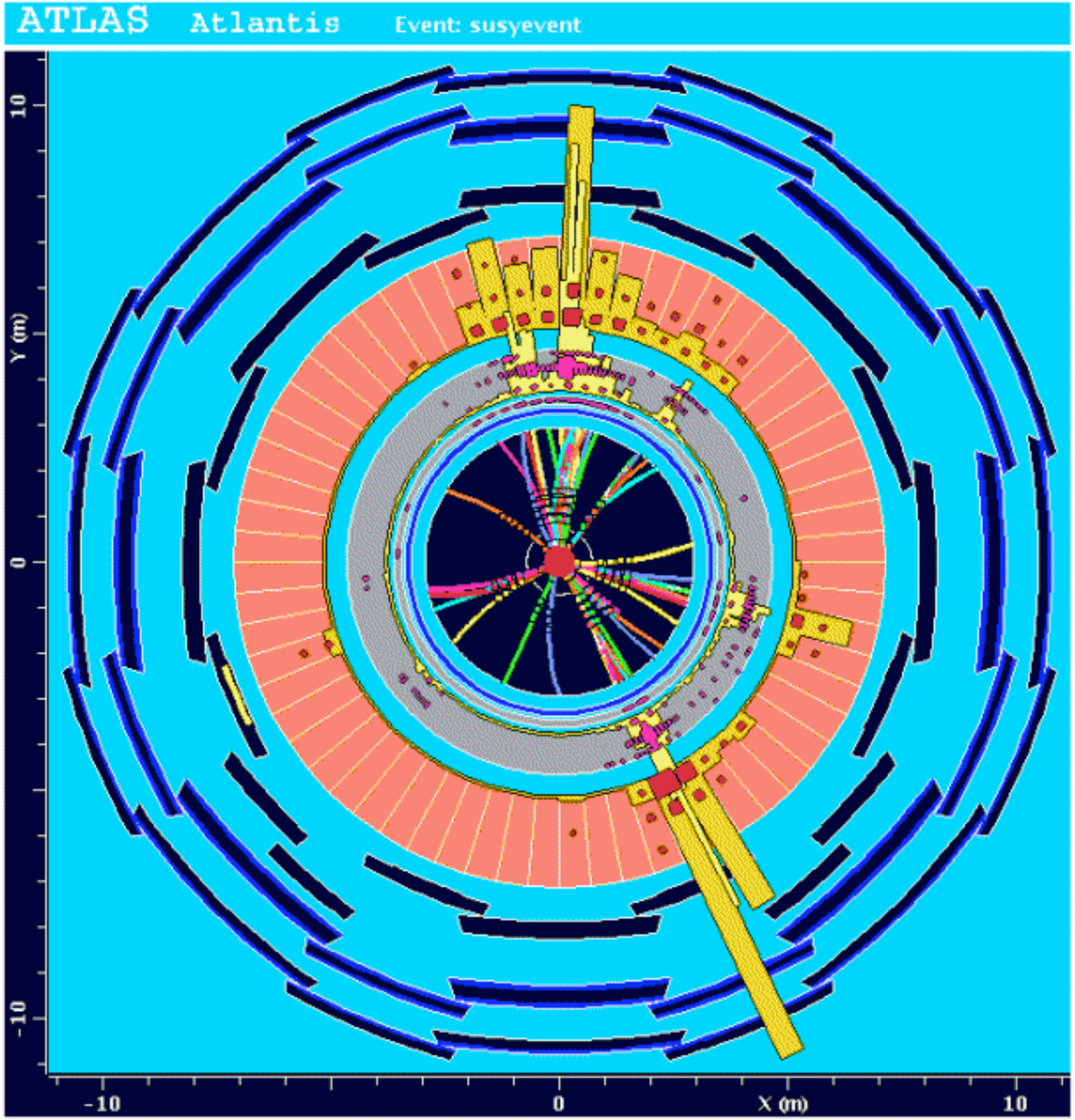
LSP escapes detection → missing E_T

"Typical" SUSY decay chain at the LHC

Look at transverse missing energy (and not overall missing energy) because hard scattering reaction usually has longitudinal boost

Typical SUSY Event

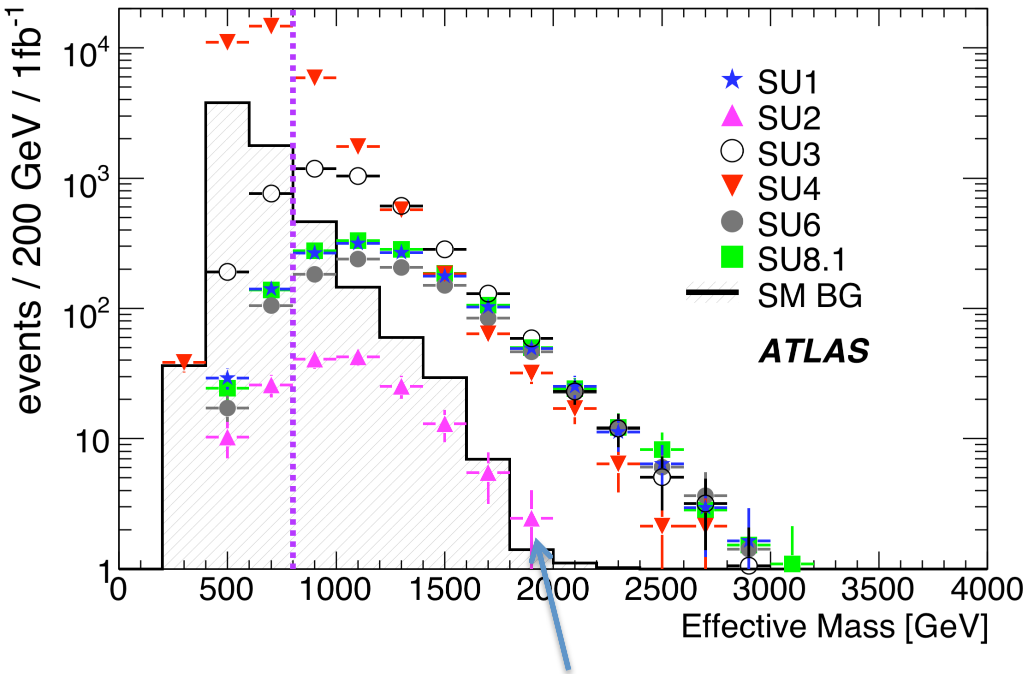
Example SUSY event in the ATLAS detector.
E_T^{MISS} clearly visible.



SUSY searches at LHC

- Look for excess of events in a region of phase space where SUSY is expected
  - Often use $M_{EFF} = E_T^{MISS} + \Sigma P_T$ (Sum over Jets and leptons in event)
  - We know SUSY particles are heavier than SM particles hence larger scalar mass in event
  - M_{EFF} gives an idea of SUSY mass scale
- Test analysis performance on:
  - Benchmark points (full simulation)
  - Fast simulation SUSY grids (eg. mSUGRA) to see model dependence and evaluate reach
  - Full simulation at LHC computationally expensive (eg. For ATLAS fullsim ~1000, fastsim <0.1 s/evt)
- Background determination crucial
  - Simulation alone can not be trusted at sqrt(s)=14 TeV
  - Need to develop data driven background estimation techniques
  - Complementary approaches to give confidence in understanding of the backgrounds
  - Main systematic from uncertainty of backgrounds normalization and shape
- Many complementary analyses so as not to miss anything
  - SUSY searches generally divided by lepton multiplicity
  - Need to correctly combine analyses to get correct overall significance

0-lepton searches



Not all models found. SU2 has low cross-section and so not found with 1fb^{-1}

For SU3 S/B ~6400 / 1200 for 1fb^{-1}

Atlas 4-Jet analysis:

Veto Isolated lepton (e,μ)
E_T^{MISS} >100 GeV
$N_{JETS} \geq 4$
$P_T(0)>100$ GeV, $P_T(3)>50$ GeV
$E_T^{MISS} > 0.2 M_{EFF}$
$\Delta\phi(\text{Jet}, E_T^{MISS}) > 0.2$ (for 3 hardest jets)
Trans. Sphericity > 0.2
M_{EFF}>800 GeV

0-lepton mode has best statistical significance. But QCD background needs to be well understood. (Tails of missing E_T in high energy Jet events).

ATLAS and CMS both have Analyses with <4 jets. Similar selection – but tighter Jet P_T and E_T^{MISS} requirements to keep backgrounds under control.

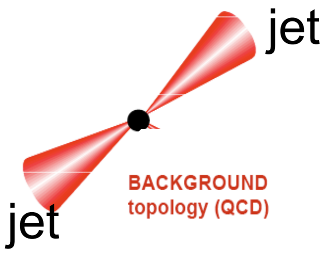
0-lepton Di-jet search

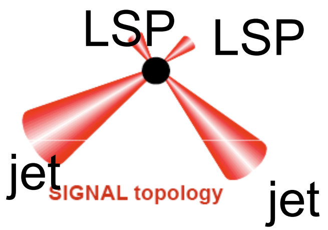
NEW!!

- CMS analysis with di-jet events
- Based on Phys.Rev.Lett.101:221803,2008 (L.Randall, D.Tucker-Smith)

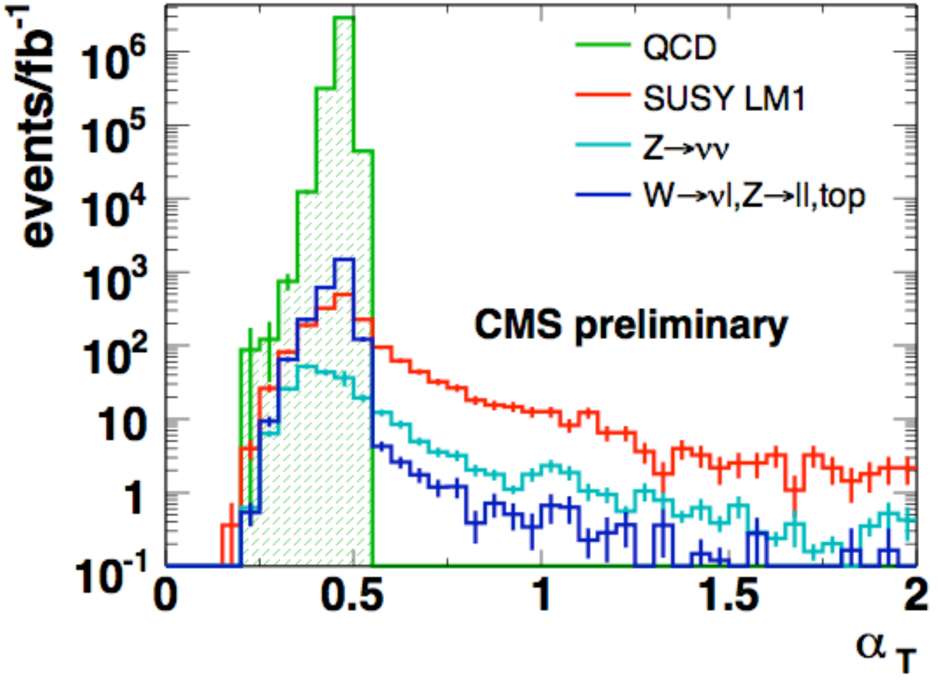
Event Selection:

- HT = $p_{Tj1} + p_{Tj2} > 500$ GeV
- $|\eta_{j1}| < 2.5$, $\Delta\phi(E_T^{MISS}, j_i) < 0.3$
- Veto additional jets and leptons
- $\alpha_T = E_{Tj2}/M_T^{j1,j2} > 0.55$





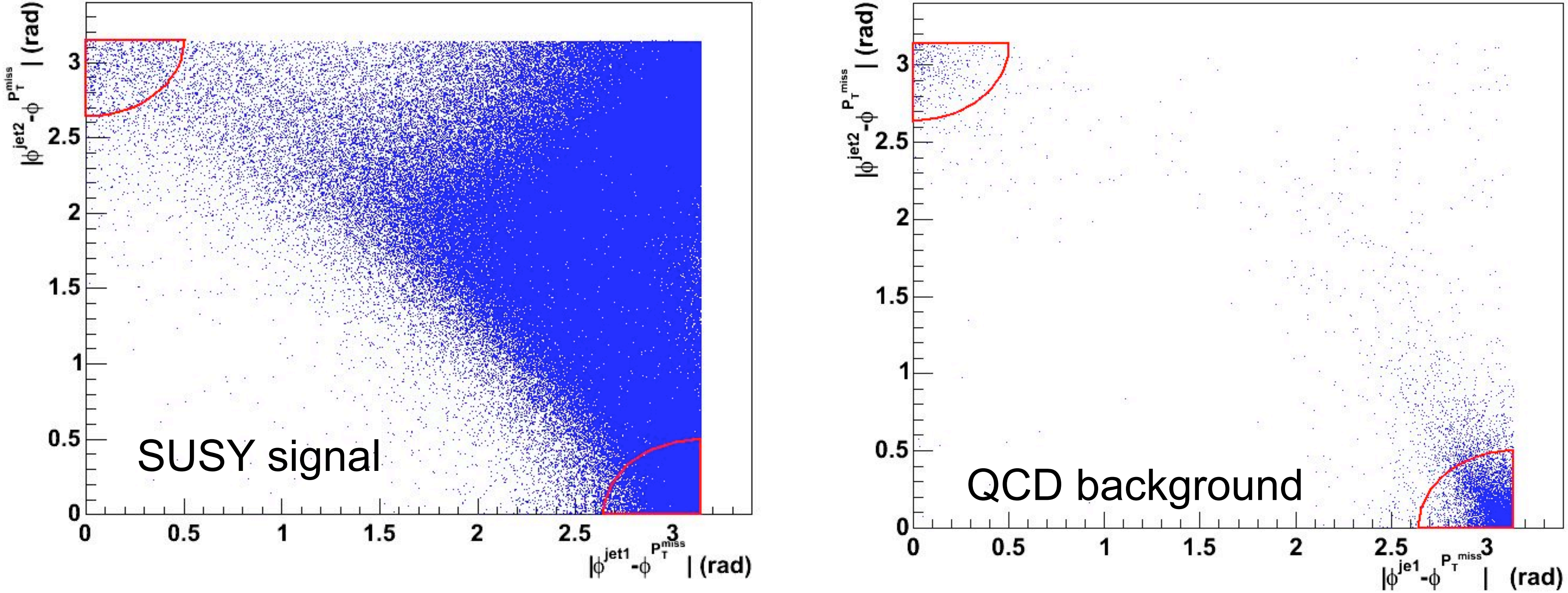
- Does not rely on calorimetric E_T^{MISS}
  - Well suited for early data
- Main backgrounds
  - Di-jets (α_T cut very effective)
  - Z->νν̄ irreducible background



QCD Bkgd in 0-lepton searches

- QCD background
  - Contains fake and real E_T^{MISS} (from heavy flavor)
    - Fake E_T^{MISS} from detector problems and from resolution effects
  - Huge cross section – need to worry about tails of distributions
  - Large theoretical uncertainty on QCD background rates / distributions
  - Fake E_T^{MISS} correlated with Jet direction

CMS plots – showing cleanup cuts against QCD background

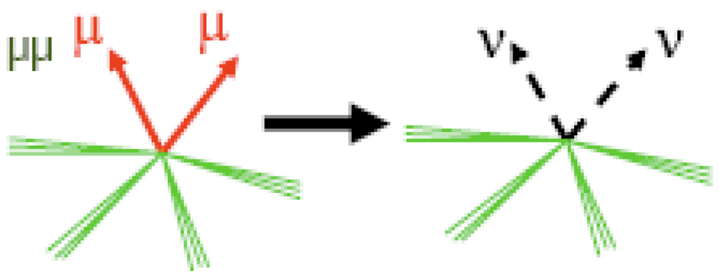


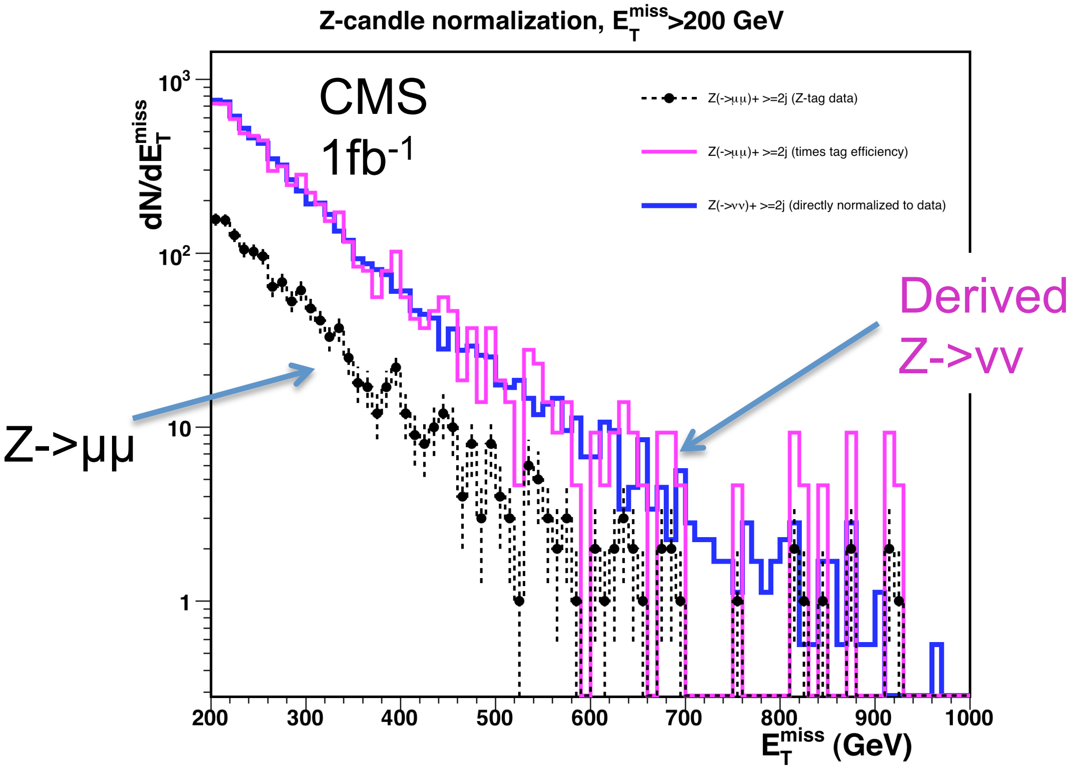
Bkgd estimation for 0-lepton searches

- Irreducible background from Z->νν̄ + Jets
- Can estimate background using Z->l^+l^- + Jets
  - $E_T^{MISS} \sim P_T(Z)$
  - Correct for branching fraction differences, efficiencies

$$N_{Z\to\nu\bar{\nu}}(E_T^{\rm miss}) = N_{Z\to\ell^+\ell^-}(p_T(\ell^+\ell^-)) \times c_{\rm Kin}(p_T(Z)) \times c_{\rm Fidu}(p_T(Z)) \times \frac{{\rm Br}(Z\to\nu\bar{\nu})}{{\rm Br}(Z\to\ell^+\ell^-)},$$

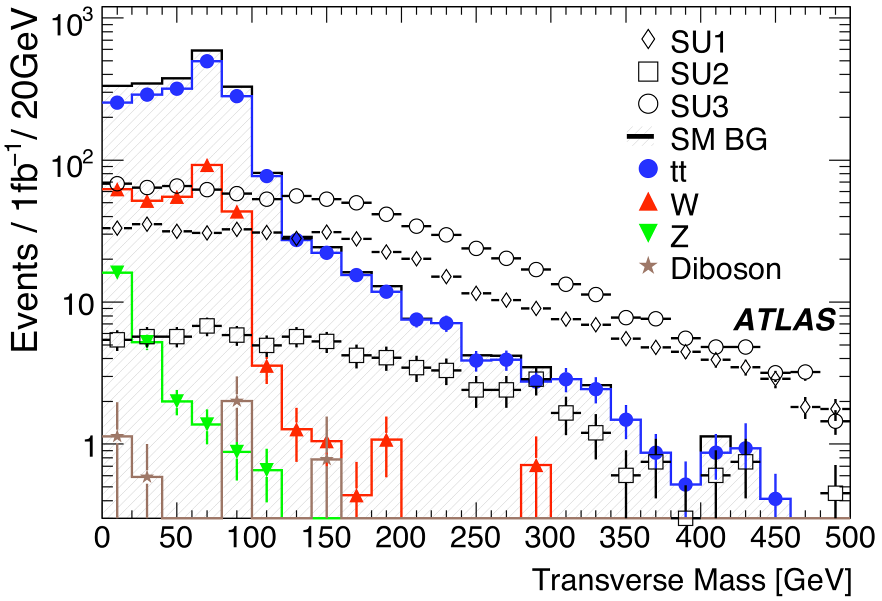
- Uncertainty ~20% for 1 fb^{-1}





Can also use photon+Jets and W + Jets to estimate Z->νν bkgd
– higher statistics
– but normalization more difficult

1-lepton search



ATLAS Selection (very similar to 0-lepton mode):

Require 1 isolated lepton (e, mu) P_T> 20 GeV

E_T^{MISS} > 100 GeV

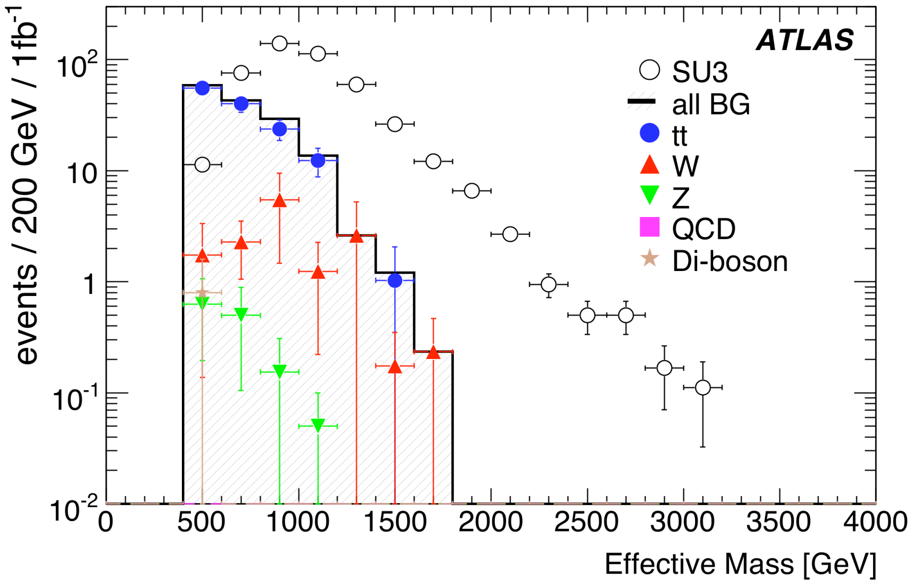
$N_{JETS} \geq 4$

$P_T(0)$> 100 GeV, $P_T(3)$> 50 GeV

E_T^{MISS} > 0.2 M_{EFF}

Transverse mass (lepton, E_T^{MISS}) M_T >100 GeV (top and W veto)

M_{EFF}> 800 GeV



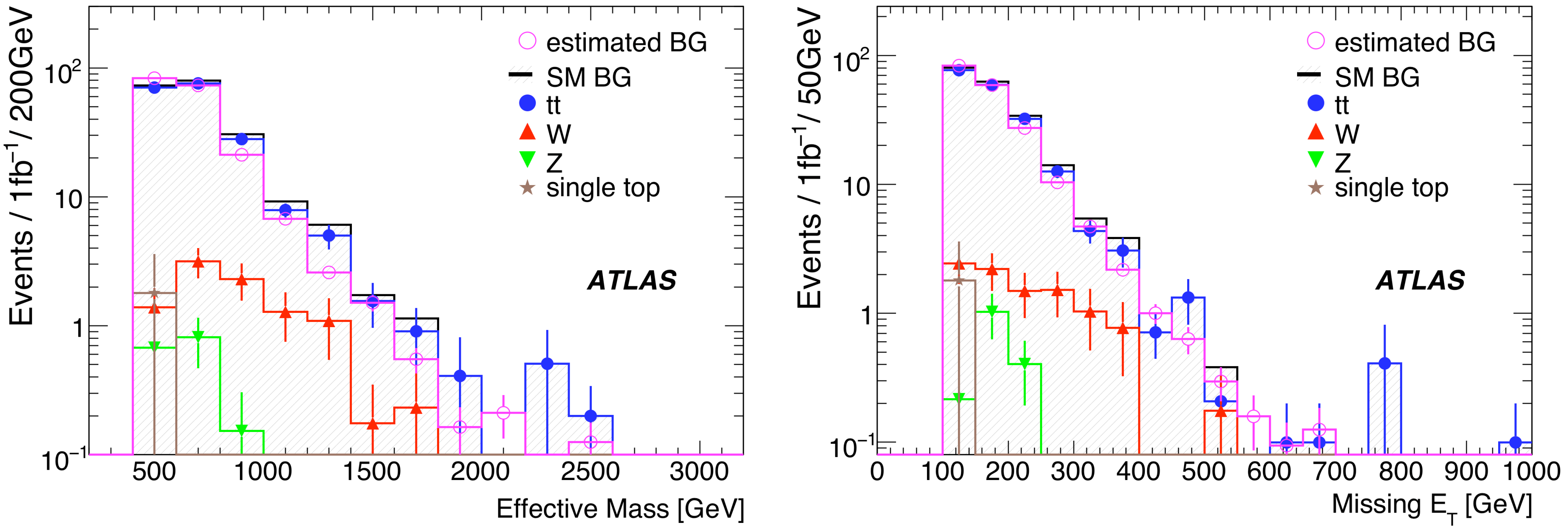
Remaining background mostly fully leptonic $t\bar{t}$ decays.

Less statistical power than 0-lepton analysis but more robust as much reduced QCD background.

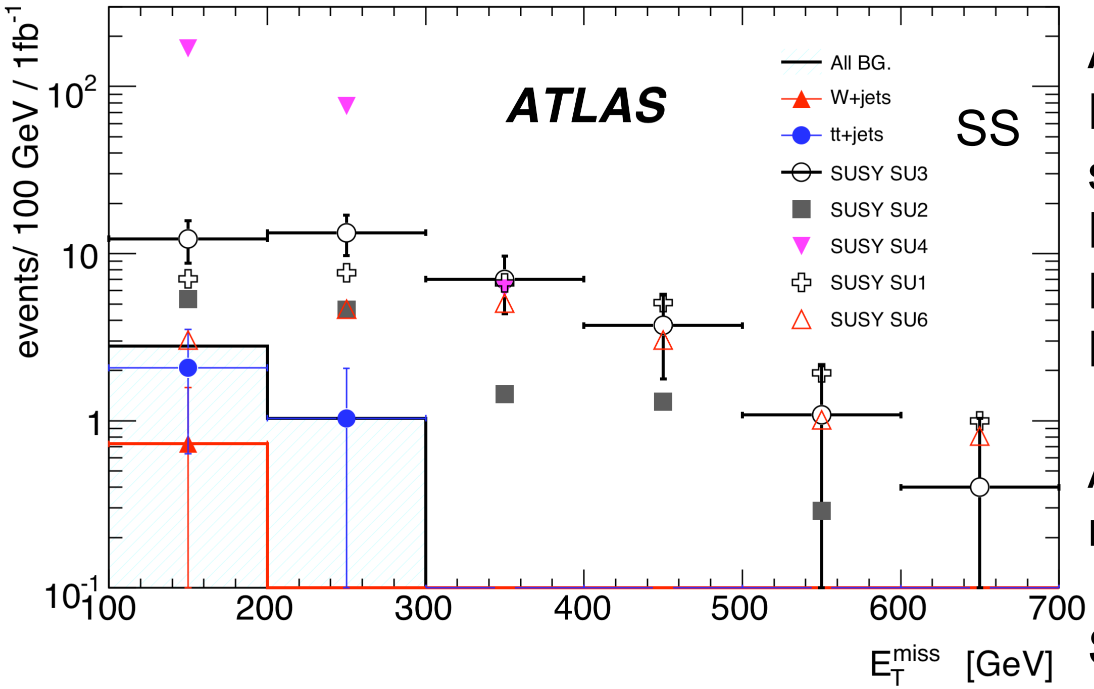
For SU3 S/B ~ 230 / 40 for $1fb^{-1}$

Bkgd estimate for 1-lepton search

- Can estimate background from tt̄ and W+Jets by using control sample with M_T<100 GeV
- Normalize distribution from control sample at low E_T^{MISS}
  - Potential problem from contamination of SUSY events in normalization region (over-estimates background) – model dependent
  - Also need to worry about correlations between M_T, E_T^{MISS}
  - Background composition changes with M_T
- Many other background estimation methods



Di-lepton searches



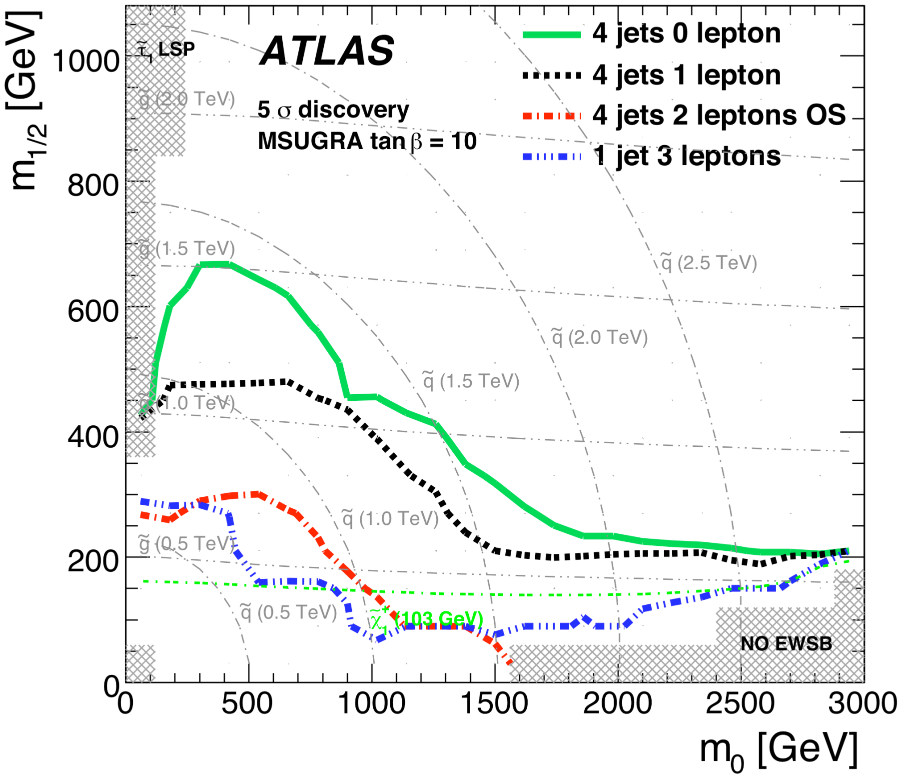
For SU3 S/B ~ 25 / 2 (SS)
S/B ~ 160 / 85 (OS)

ATLAS Same Sign (SS) Selection:
Require 2 isolated lepton (e, mu) with same charge
E_T^{MISS} > 100 GeV
$N_{JETS} \geq 4$
$P_T(0)$> 100 GeV, $P_T(3)$> 50 GeV

Also opposite sign (OS) analysis but more background.

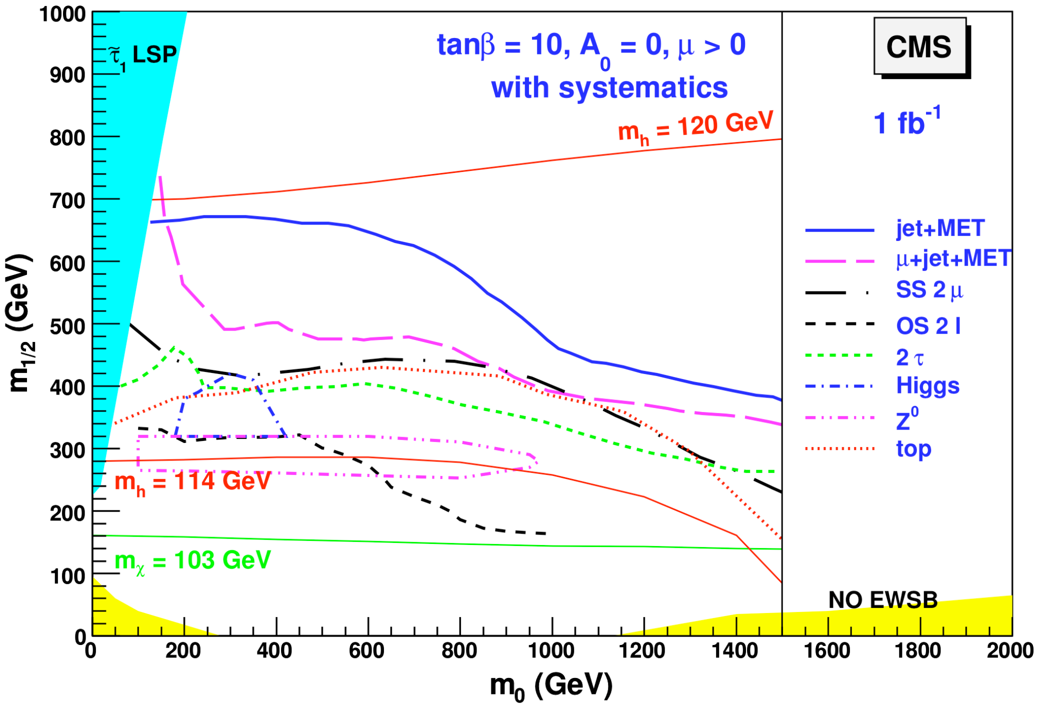
SS mode very clean.
OS mode has background from $t\bar{t}$ & Z.
Signal much reduced by di-lepton requirement.

Discovery Reach



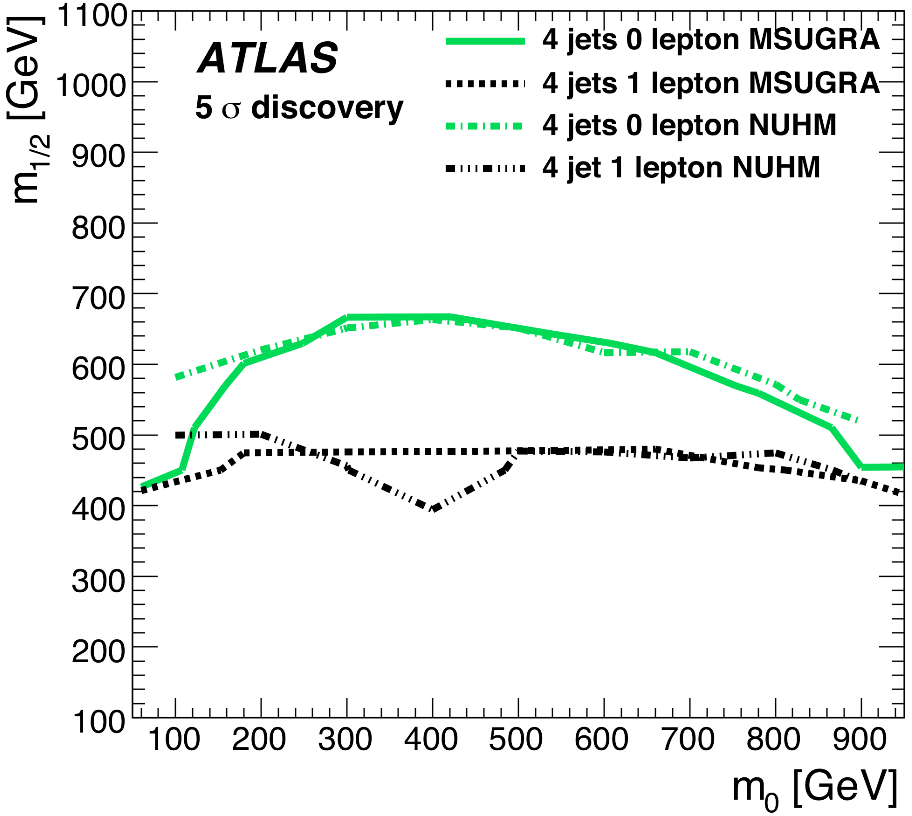
Discovery reach very similar between ATLAS and CMS

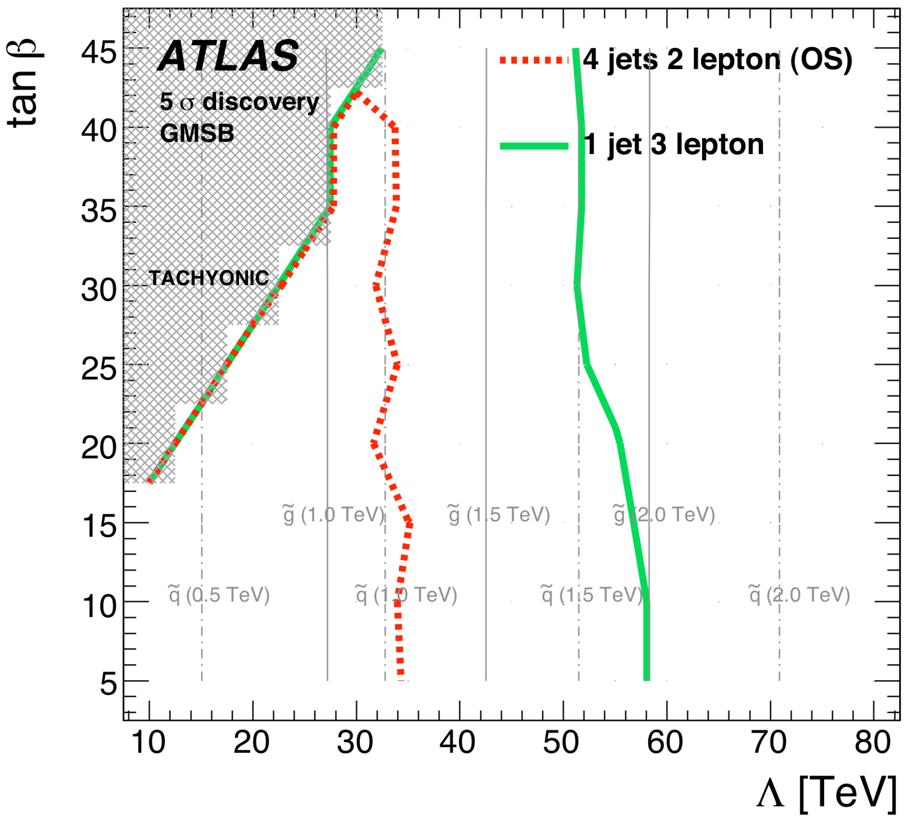
For 1fb^{-1} of understood data we should be able to discover sparticles with masses of ~1 TeV



Systematics are included in these plots – eg. For ATLAS assume QCD background known to 50% and W,Z,top to 20%

Different SUSY Models





Non Universal Higgs Model (NUHM). Here fix M_A and tanβ to values compatible with WMAP constraints.

Shows very similar discovery reach to mSUGRA

For GMSB SUSY particles with similar masses (1TeV) can be discovered with 1fb^{-1}.

Here 1 Jet, 3 lepton analysis is important.

SUSY discovery at sqrt(s)<14 TeV

- All results presented here are for sqrt(s) = 14 TeV
- LHC will start running at reduced energy
  - What that energy will be is not decided yet
- Estimates of discovery reach at lower energies by ATLAS show:
  - Discovery of SUSY just above the Tevatron limits, needs 2-2.5 times as much luminosity going from 14 to 10 TeV
  - A similar factor in luminosity is needed going from 10 to 8 TeV
  - 4 - 5 times as much luminosity is needed going from 8 to 6 TeV
  - Running below 6 TeV is not useful as we need as much luminosity as the Tevatron

Not Covered in this talk

- R-Parity violating SUSY
- Long lived SUSY particles
  - Non-pointing photons
  - R hadrons
- Searches with τ and b-jets
  - Good for models with high tan β
- SUSY Higgs searches
- Extracting SUSY model parameters from data
  - Kinematic endpoints (eg. Di-lepton edges)

Conclusions

- R-Parity conserving SUSY well motivated extension to the Standard Model
- ATLAS and CMS both designed for SUSY discovery
- Have very similar discovery reach
  - SUSY particles of mass ~1 TeV with $1fb^{-1}$ of understood data
  - Discovery reach reduced when running at lower energies
- Critical to understand detector performance
  - Especially E_T^{MISS}
- Backgrounds estimation also crucial
  - Interplay between data-driven estimates and simulations

Backup slides

- References
  - ATLAS:

    CERN-OPEN-2008-020

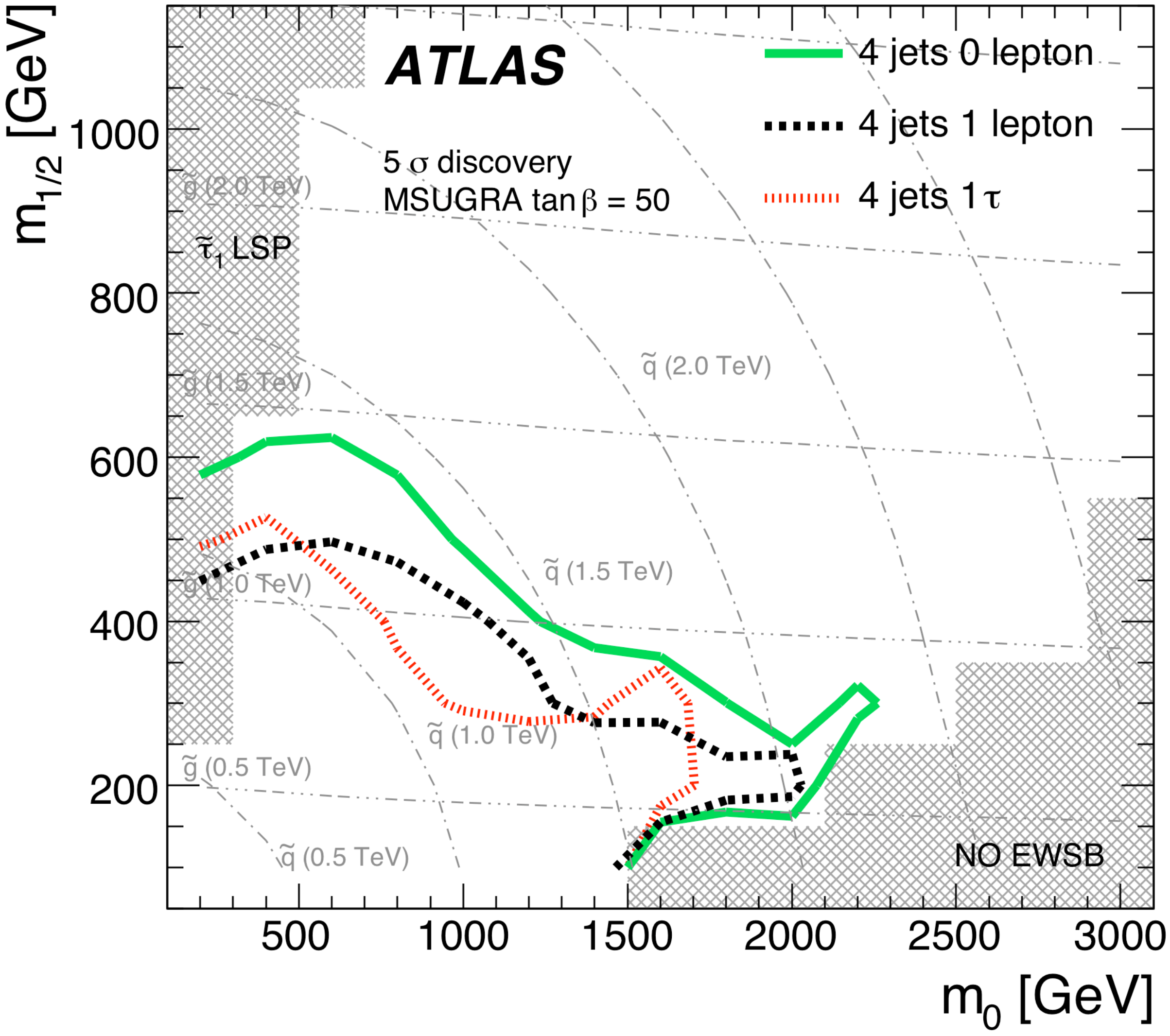
    http://cdsweb.cern.ch/record/1125884?ln=en
  - CMS:

    CERN-LHCC-2006-021

    http://cdsweb.cern.ch/record/942733

    http://cms-physics.web.cern.ch/cms-physics/public/SUS-08-005-pas.pdf

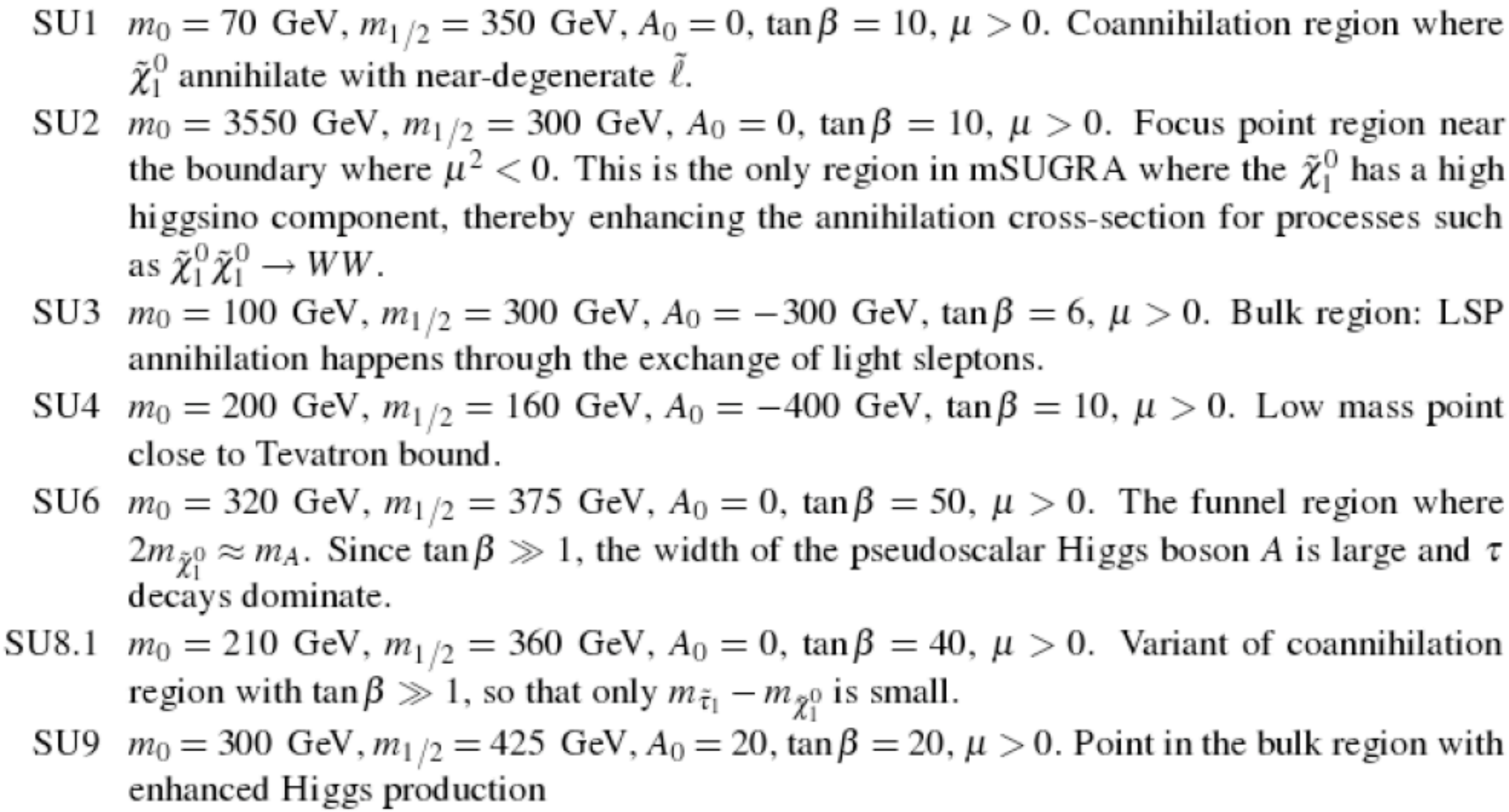
Effect of tan β on discovery reach



Discovery reach for tan β = 50 very similar to that for tan β = 10

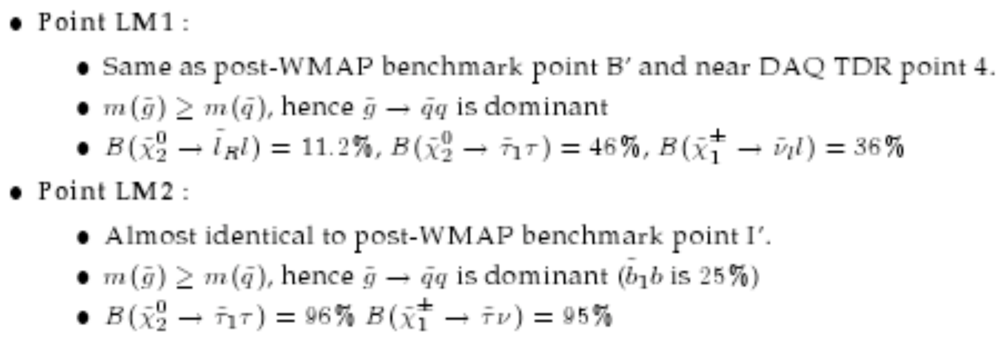
Analysis with τ now important.

ATLAS Benchmark points

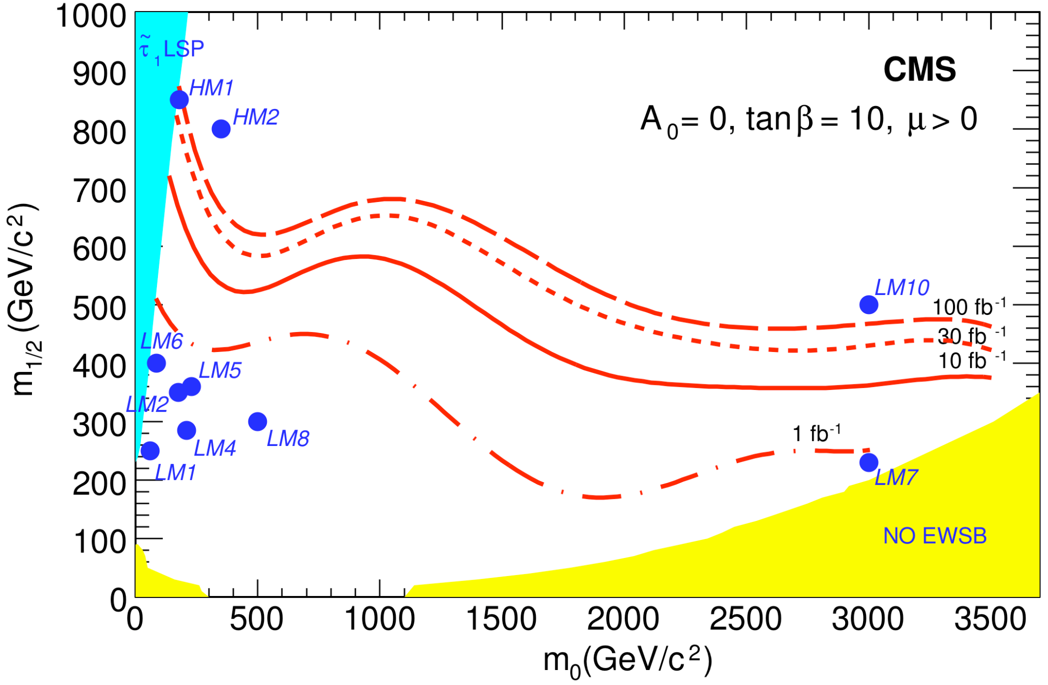


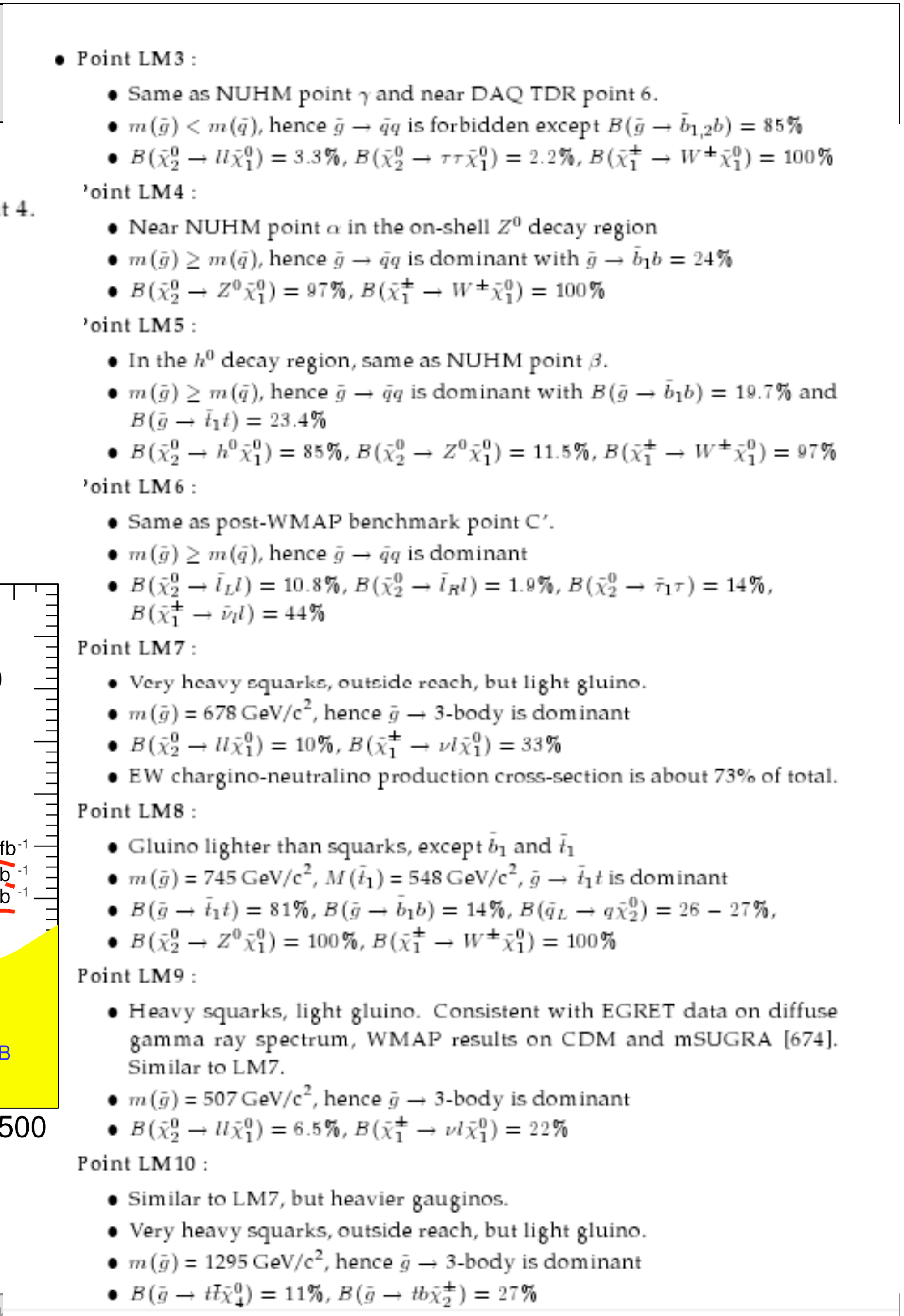
SU1	$m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.
SU2	$m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Focus point region near the boundary where $\mu^2 < 0$. 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

CMS benchmarks



- Point LM1 :
  - Same as post-WMAP benchmark point B′ and near DAQ TDR point 4.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant
  - $B(\tilde{\chi}_2^0 \to \tilde{l}_R l) = 11.2\%$, $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) = 46\%$, $B(\tilde{\chi}_1^{\pm} \to \tilde{\nu}_l l) = 36\%$
- Point LM2 :
  - Almost identical to post-WMAP benchmark point I′.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant ($\tilde{b}_1 b$ is 25%)
  - $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) = 96\%$ $B(\tilde{\chi}_1^{\pm} \to \tilde{\tau}\nu) = 95\%$





- Point LM3 :
  - Same as NUHM point γ and near DAQ TDR point 6.
  - $m(\tilde{g}) < m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is forbidden except $B(\tilde{g} \to \tilde{b}_{1,2} b) = 85\%$
  - $B(\tilde{\chi}_2^0 \to ll\tilde{\chi}_1^0) = 3.3\%$, $B(\tilde{\chi}_2^0 \to \tau\tau\tilde{\chi}_1^0) = 2.2\%$, $B(\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0) = 100\%$
- Point LM4 :
  - Near NUHM point α in the on-shell Z^0 decay region
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant with $\tilde{g} \to \tilde{b}_1 b = 24\%$
  - $B(\tilde{\chi}_2^0 \to Z^0\tilde{\chi}_1^0) = 97\%$, $B(\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0) = 100\%$
- Point LM5 :
  - In the h^0 decay region, same as NUHM point β.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant with $B(\tilde{g} \to \tilde{b}_1 b) = 19.7\%$ and $B(\tilde{g} \to \tilde{t}_1 t) = 23.4\%$
  - $B(\tilde{\chi}_2^0 \to h^0\tilde{\chi}_1^0) = 85\%$, $B(\tilde{\chi}_2^0 \to Z^0\tilde{\chi}_1^0) = 11.5\%$, $B(\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0) = 97\%$
- Point LM6 :
  - Same as post-WMAP benchmark point C′.
  - $m(\tilde{g}) \geq m(\tilde{q})$, hence $\tilde{g} \to \tilde{q}q$ is dominant
  - $B(\tilde{\chi}_2^0 \to \tilde{l}_L l) = 10.8\%$, $B(\tilde{\chi}_2^0 \to \tilde{l}_R l) = 1.9\%$, $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) = 14\%$, $B(\tilde{\chi}_1^{\pm} \to \tilde{\nu}_l l) = 44\%$
- Point LM7 :
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g}) = 678$ GeV/c^2, hence $\tilde{g} \to$ 3-body is dominant
  - $B(\tilde{\chi}_2^0 \to ll\tilde{\chi}_1^0) = 10\%$, $B(\tilde{\chi}_1^{\pm} \to \nu l\tilde{\chi}_1^0) = 33\%$
  - EW chargino-neutralino production cross-section is about 73% of total.
- Point LM8 :
  - Gluino lighter than squarks, except $\tilde{b}_1$ and $\tilde{t}_1$
  - $m(\tilde{g}) = 745$ GeV/c^2, $M(\tilde{t}_1) = 548$ GeV/c^2, $\tilde{g} \to \tilde{t}_1 t$ is dominant
  - $B(\tilde{g} \to \tilde{t}_1 t) = 81\%$, $B(\tilde{g} \to \tilde{b}_1 b) = 14\%$, $B(\tilde{q}_L \to q\tilde{\chi}_2^0) = 26 - 27\%$,
  - $B(\tilde{\chi}_2^0 \to Z^0\tilde{\chi}_1^0) = 100\%$, $B(\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0) = 100\%$
- Point LM9 :
  - Heavy squarks, light gluino. Consistent with EGRET data on diffuse gamma ray spectrum, WMAP results on CDM and mSUGRA [674]. Similar to LM7.
  - $m(\tilde{g}) = 507$ GeV/c^2, hence $\tilde{g} \to$ 3-body is dominant
  - $B(\tilde{\chi}_2^0 \to ll\tilde{\chi}_1^0) = 6.5\%$, $B(\tilde{\chi}_1^{\pm} \to \nu l\tilde{\chi}_1^0) = 22\%$
- Point LM10 :
  - Similar to LM7, but heavier gauginos.
  - Very heavy squarks, outside reach, but light gluino.
  - $m(\tilde{g}) = 1295$ GeV/c^2, hence $\tilde{g} \to$ 3-body is dominant
  - $B(\tilde{g} \to t\bar{t}\tilde{\chi}_4^0) = 11\%$, $B(\tilde{g} \to tb\tilde{\chi}_2^{\pm}) = 27\%$