Search for Supersymmetry Signatures at the LHC

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on behalf the ATLAS and CMS Collaborations

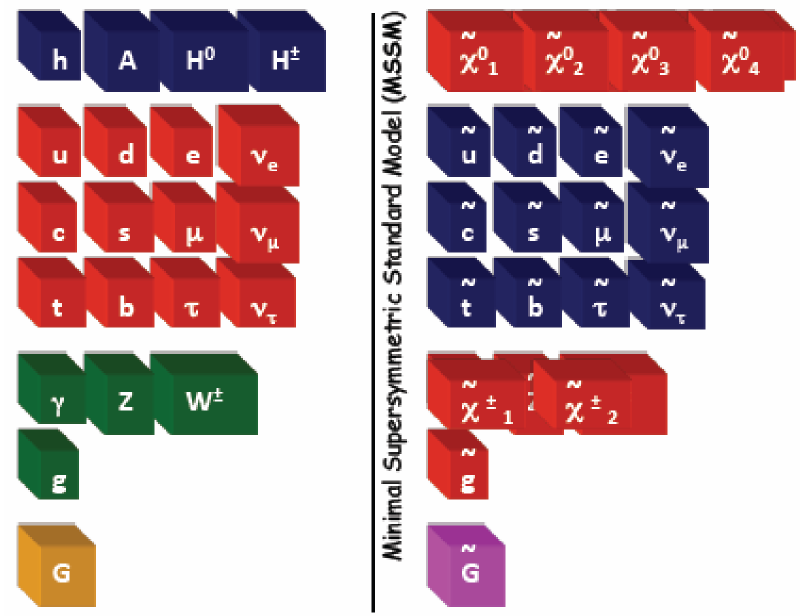
Outline

- Introduction to Supersymmetry
- Search Strategies at the LHC
- SUSY Studies in ATLAS and CMS
- Estimation of Backgrounds to SUSY
- Inclusive Searches
- Special SUSY signatures
- Discovery Reach
- SUSY Mass Measurements
- Determination of SUSY Model Parameters
- Conclusions

Introduction to Supersymmetry

- Supersymmetry (SUSY) is a fundamental global symmetry between fermions and bosons. SUSY is one of the most attractive extentions of the Standard Model (SM).
- Motivation for SUSY:
  - Higgs mass stabilization against loop correction (fine-tuning problem).
  - SUSY modifies running of SM gauge couplings just enough to give "Grand Unification" at single scale.
  - Offers a candidate for dark matter.
- All SM particles have SUSY partners with spin difference of ±1/2.
- SUSY partners of SM particles not observed at the same mass scale:
  - SUSY must be a broken symmetry at low energy.
  - Various possible SUSY symmetry breaking mechanisms proposed.

MSSM: Minimal Supersymmetric Standard Model (has >100 parameters)



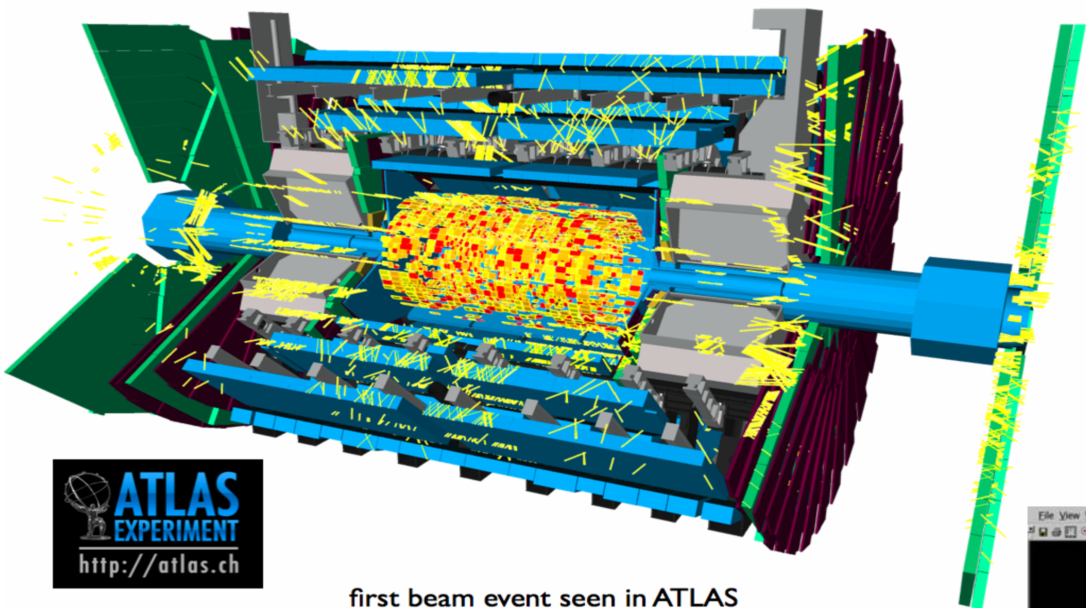
R-Parity: $R = (-1)^{3B+2S+L}$

- **R = +1 for SM particles**
- **R = -1 for SUSY partners**

If R-parity is conserved:

- **SUSY partners are pair produced. (R is a multiplicative quantum number)**
- **Lightest Supersymmetric Particle (LSP) is stable, candidate for dark matter.**

How to Discover SUSY



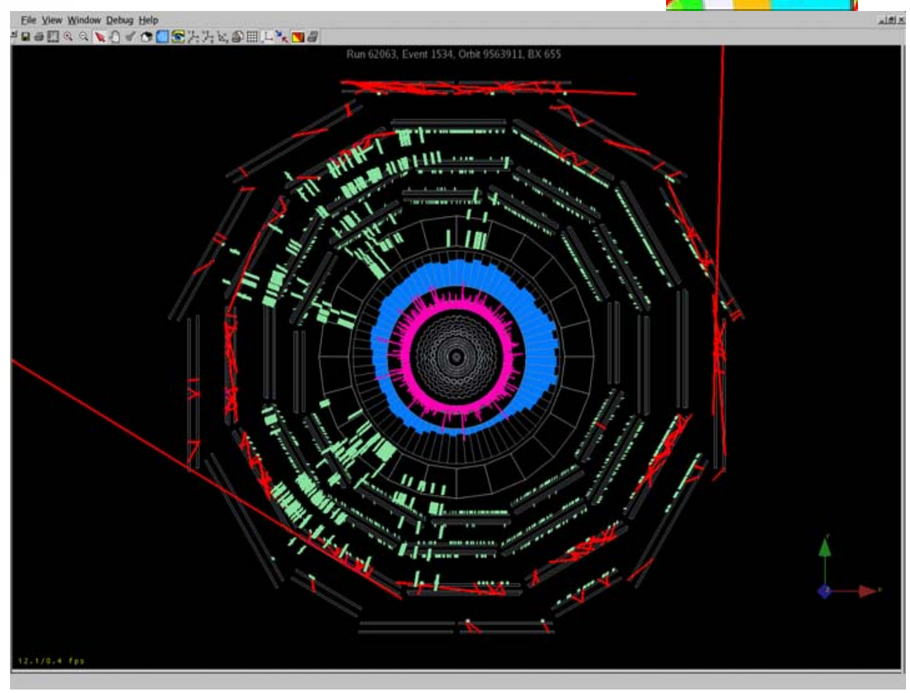
first beam event seen in ATLAS

ATLAS and CMS are two general purpose detectors at the LHC built for SUSY discovery as one of the main goals

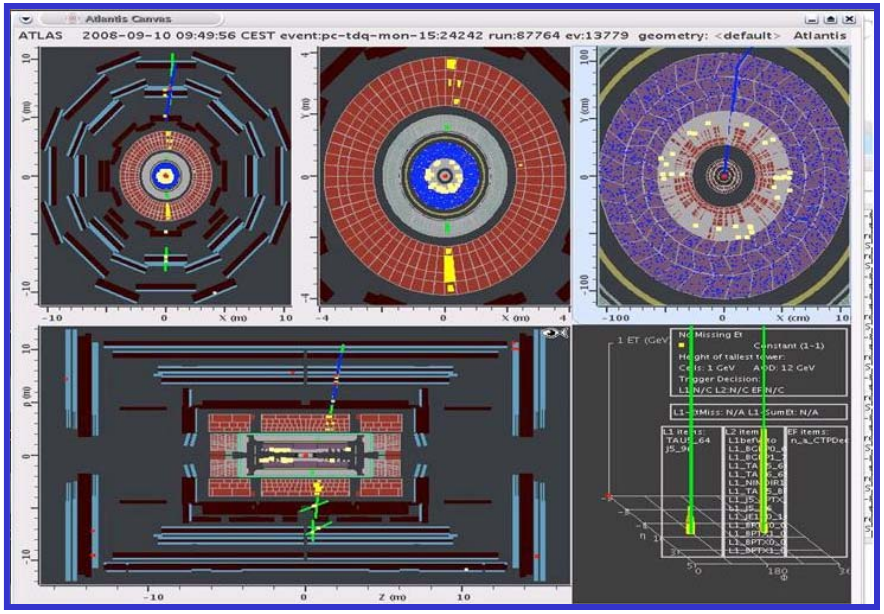
First beam event
September 10, 2008

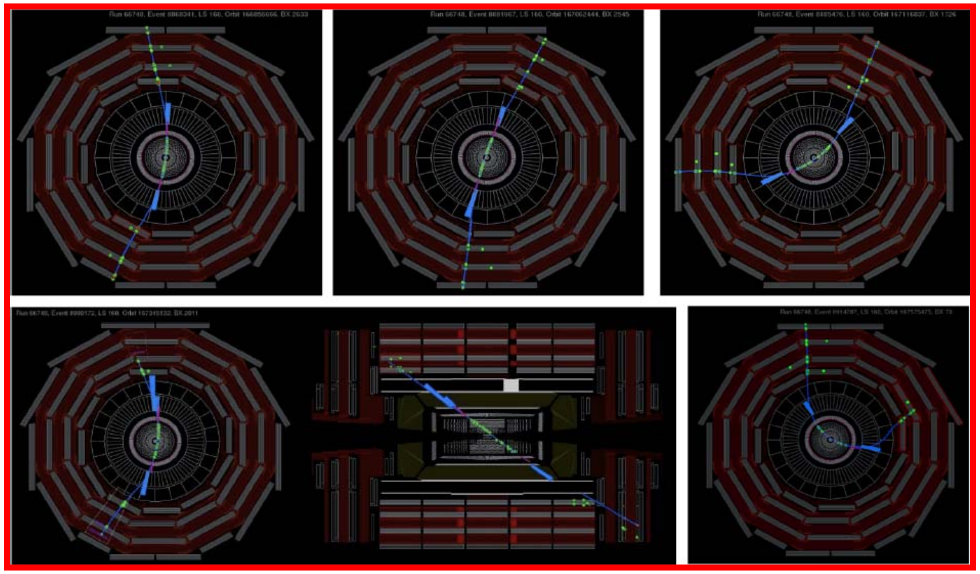
Energy deposits in:
- electromagnetic calorimeter
- hadronic calorimeter

Hits in:
- resistive plate chamber (RPC) muon system
- drift-tube



Commissioning with Cosmics





Detectors are ready, see talks in the "First Results from LHC" session

Search Strategies at the LHC

- SUSY breaking mechanism determines phenomenology and search strategy in collider experiments.
  - mSUGRA, GMSB, AMSB, SO(10) SUSY GUTs, Split-SUSY, …
- Two classes of SUSY models:
  - Standard SUSY with R-parity conservation:
    - 0,1, 2 leptons + ≥ 2, 3, 4 jets + E_T^{miss}
    - photons, jets, E_T^{miss}
    - taus or b-jets + E_T^{miss}
    - Without E_T^{miss} ; namely multi-leptons, di-jets
  - Non-standard SUSY – special signatures:
    - Late NLSP → NLSP decays
    - R-parity violating LSP decays
    - Semi-stable gluinos and stops
    - Resonant sneutrino → eμ

  } Displaced vertices
  Stopped gluinos in the calorimeter
  Non-pointing photons
  Long-lived slow massive particles
  Multi-leptons
- Essential to SUSY searches:
  - Understanding fake E_T^{miss} , E_T^{miss} tails
  - Understanding SM backgrounds; data-driven bckg estimations, notably for QCD multi-jets
  - Reconstruction non-standard signatures

Main SM backgrounds:
- **top-antitop pairs**
- **W+jets**
- **Z+jets**
- **QCD jets**
- **diboson processes (ZZ,WW,WZ)**

SUSY Studies in ATLAS and CMS

Supersymmetry

- Supersymmetry Searches
- Data-Driven Determinations of W, Z and Top Backgrounds to Supersymmetry
- Estimation of QCD Backgrounds to Searches for Supersymmetry
- Prospects for Supersymmetry Discovery Based on Inclusive Searches
- Measurements from Supersymmetric Events
- Multi-Lepton Supersymmetry Searches
- Supersymmetry Signatures with High-p_T Photons or Long-Lived Heavy Particles

ATLAS CSC (Computer System Commissioning) Book (2008). arXiv:0901.0512

Recent/new studies

ATLAS Post-CSC Studies:

- ATL-PHYS-PUB-2009-084: SUSY and UED discovery based on inclusive searches, 200pb-1@10TeV
- ATL-PHYS-PUB-2009-083: Data-driven estimation of ttbar bckg, 200pb^{-1}@10TeV
- ATL-PHYS-PUB-2009-076: Discovering heavy particles with a RPV SUSY model, 1fb^{-1}@10 TeV
- ATL-PHYS-PUB-2009-075: Discovery with b-jets, 1fb^{-1}@14 TeV
- ATL-PHYS-PUB-2009-077: Bckg estimation using Tiles method, 1fb^{-1}@14 TeV

CMS Post-TDR Studies:

- SUS-09-001: Exclusive multi-jets, 100pb^{-1}@10TeV
- SUS-09-002: Dilepton study with 200pb^{-1}/1fb^{-1}@10TeV
- SUS-09-004: Data-driven bckg est. for di-photons, 100pb^{-1}@10TeV
- SUS-08-005: Search with dijets, 1fb^{-1}@14TeV
- SUS-08-001: Dilepton+jets+MET channel, 1fb^{-1}@14TeV
- SUS-08-002: Data-driven est. of Z->invs. bckg, 100pb^{-1}@14TeV
- EXO-09-001: Stopped-gluinos, 10^{32}cm^{-2}s^{-1}@10TeV

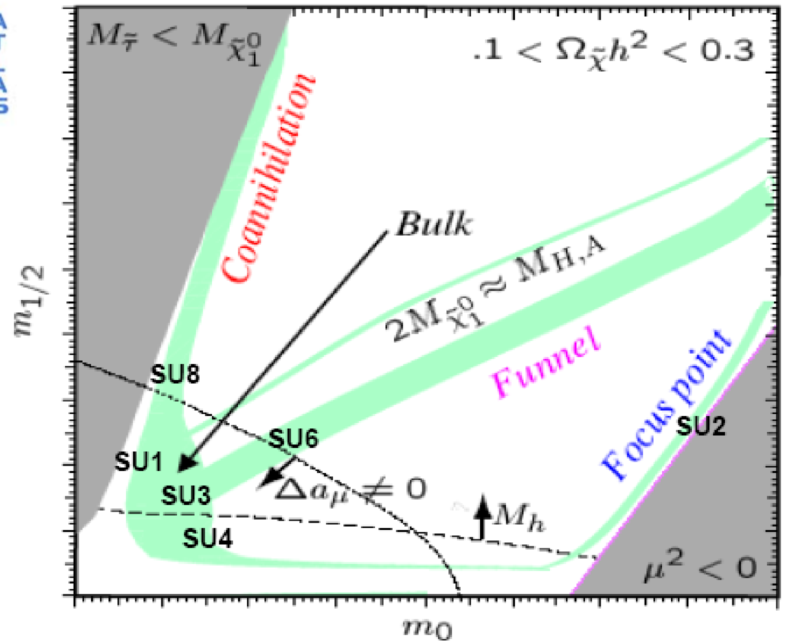
Supersymmetry

CMS TDR II
J. Phys. G, 34 (2007) 995

13.1 Introduction
13.2 Summary of supersymmetry
13.3 Scope of present searches
13.4 Hemisphere algorithm for separation of decay chains
13.5 Inclusive analysis with missing transverse energy and jets
13.6 Inclusive muons with jets and missing transverse energy
13.7 Inclusive analyses with same sign dimuons
13.8 Inclusive analyses with opposite sign dileptons
13.9 Inclusive analyses with ditaus
13.10 Inclusive analyses with Higgs
13.11 Inclusive SUSY search with Z
13.12 Inclusive analyses with top
13.13 Mass determination in final states with ditaus
13.14 Direct neutralino-chargino production in tri-leptons
13.15 Production of slepton pairs
13.16 Lepton flavour violation in neutralino decay
13.17 Summary of the reach with inclusive analyses
13.18 Look beyond mSUGRA

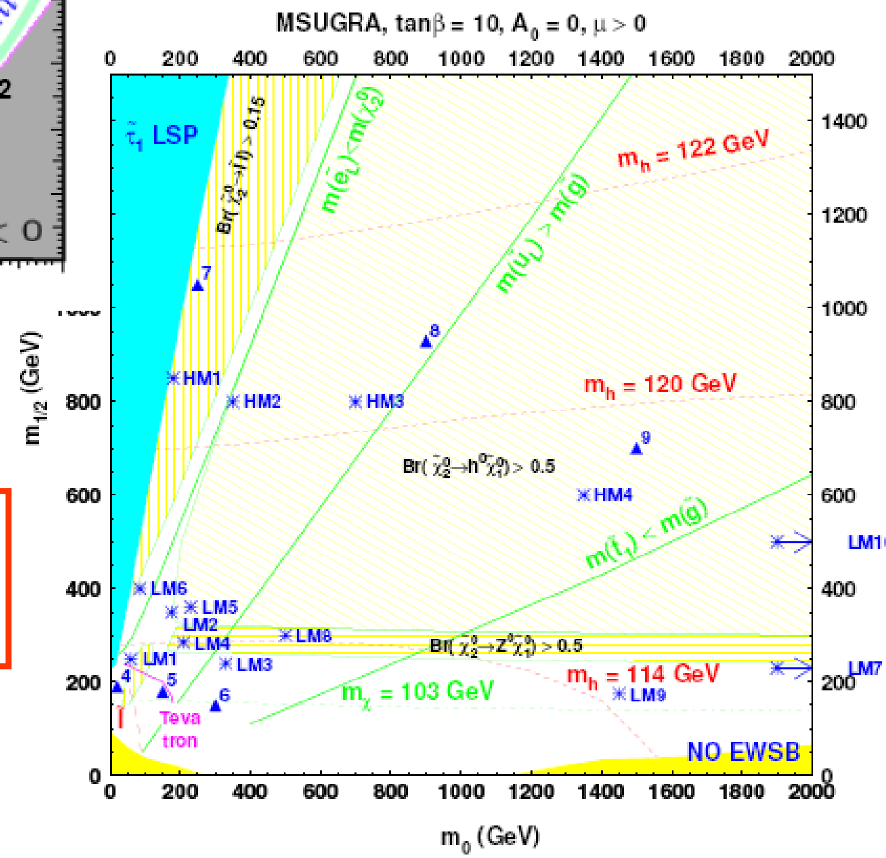
mSUGRA Benchmark Points

Label
SU1
SU2
SU3
SU4
SU6
SU8.1
SU9



mSUGRA framework: Assume SUSY is broken by gravitational interactions:

- unified masses and couplings at GUT scale.
- five free parameters: m_0, $m_{1/2}$, A_0, $\tan(\beta)$, $\mathrm{sgn}(\mu)$



Point
LM1
LM2
LM3
LM4
LM5
LM6
LM7
LM8
LM9
LM10
HM1
HM2
HM3
HM4

m(gluino) = 2.7 $m_{1/2}$

m^2(slepton) = $m_0^2 + 0.5m^2_{1/2}$, $m^2_0 + 0.15m^2_{1/2}$

m^2(squark) = $m_0^2 + 5m_{1/2}$

For each point see mSUGRA parameters in backup slides

Non-mSUGRA Benchmark Points

$N_5 = 1, \tan\beta = 5, \mathrm{sgn}(\mu) = +$

name	NLO (LO) σ [pb]	Λ [TeV]	M_m [TeV]	C_G	$c\tau$ [mm]	$M_{\tilde{\chi}_1^0}$ [GeV]
GMSB1	7.8 (5.1)	90	500	1.0	1.1	118.8
GMSB2	7.8 (5.1)	90	500	30.0	$9.5 \cdot 10^2$	118.8
GMSB3	7.8 (5.1)	90	500	55.0	$3.2 \cdot 10^3$	118.8

$N_5 = 3, \tan\beta = 5, \mathrm{sgn}(\mu) = +$

name	NLO (LO) σ [pb]	Λ [TeV]	M_m [TeV]	$M_{\tilde{\tau}_1}$ [GeV]
GMSB5	21.0 (15.5)	30	250	102.3

ATLAS CSC Book (2008)
arXiv:0901.0512

Points for GMSB model

name	NLO (LO) cross-section [pb]	sparticle	Mass [GeV]
R-Hadron1	567 (335)	$\tilde{g}$	300
R-Hadron2	12.2 (6.9)	$\tilde{g}$	600
R-Hadron3	0.43 (0.23)	$\tilde{g}$	1000
R-Hadron4	0.063 (0.033)	$\tilde{g}$	1300
R-Hadron5	0.011 (0.006)	$\tilde{g}$	1600
R-Hadron6	0.0014 (0.00075)	$\tilde{g}$	2000
R-Hadron7	11.4 (7.8)	$\tilde{t}$	300
R-Hadron8	0.27 (0.18)	$\tilde{t}$	600
R-Hadron9	0.010 (0.0064)	$\tilde{t}$	900

Points for:
- Split-SUSY model
- Stop NLSP/gravitino LSP models

Estimation of Backgrounds to SUSY

Several data-driven estimation techniques:

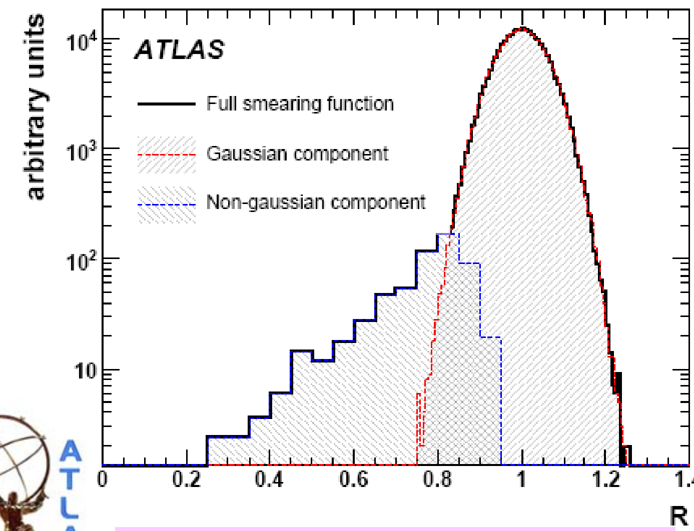
- **$Z \rightarrow \nu\nu$ bckg in 0-lepton mode SUSY search:**
  - **estimated from $Z \rightarrow ll$, $W \rightarrow \mu\nu$, γ+jets**
- **Combined bckg in 1-lepton mode SUSY search:**
  - **m_T method (further development: combined fit)**
  - **Tiles method**
- **t-tbar bckg: replacement technique**
- **QCD bckg in 0-lepton mode SUSY search: jet smearing**
- **QCD bckg in 1-lepton mode SUSY search: lepton isolation**
- **$tt \rightarrow bbl\nu qq$ in 1-lepton mode SUSY search: Topbox method**
- **Others**

Estimation of QCD Background - mSUGRA

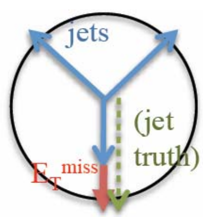
- **Biggest background estimation challenge for SUSY searches with jets+ E_T^{miss}**

- **QCD backgrounds include:**
  - **Fake E_T^{miss} : dead material, jet punch-through, pile-up, other effects. How to supress:**
    - **Detector fiducial regions**
    - **Jet - E_T^{miss} azimuthal angle correlations**
    - **Calorimeter and tracking cuts**
    - **Cosmic background and rejection cuts**
  - **Real E_T^{miss} : from non-interacting particles such as neutrinos or LSP**

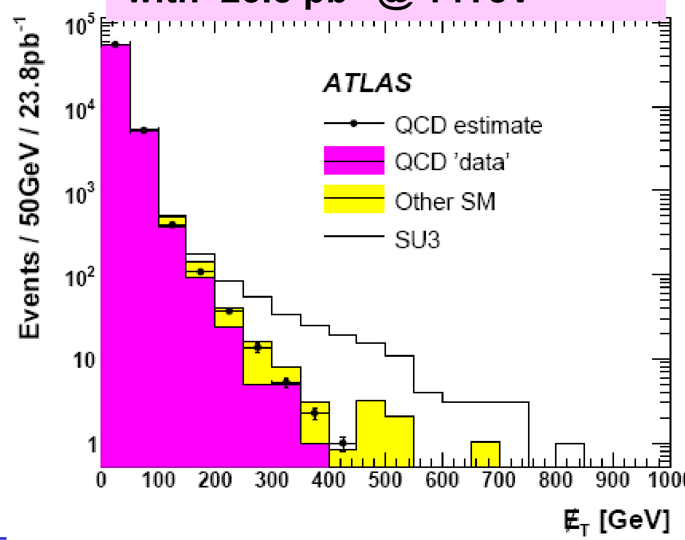
Detector jet response function



- **Two approaches to estimate remaining backgrounds:**
  - **Monte Carlo based estimates**
    - **Large systematic uncertainties**
  - **Data-driven estimates:**
    - **Method: Smear jet P_T in low E_T^{miss} QCD multi-jet data with a data-measured jet response function R (ratio of measured jet P_T to true jet P_T)**
    - **Measure the Gaussian part of jet response with balance of γ+jet events**
    - **Measure the non-Gaussian part of response based on 'Mercedes events'**
    - **Plot the jet response function R**
    - **Use R to smear jet P_T in multi-jet events with low E_T^{miss}**
    - **Systematic uncertainty in 0-lepton mode SUSY search : ~60% for 23.8pb^{-1} and assumed same for 1 fb^{-1}.**



0-lepton mode SUSY search with 23.8 pb^{-1} @ 14TeV

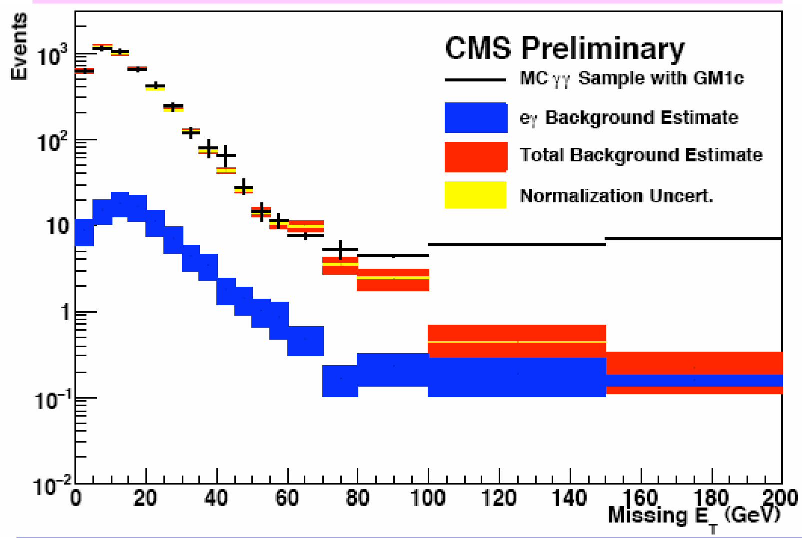


Background Estimates for SUSY Di-photon Search - GMSB

- **GMSB model signatures: two high P_T photons and large E_T^{miss}**
- **Predict E_T^{miss} distribution in a di-photon sample from the SM processes.**
- **SM contribution to final state is small:** $Z\gamma\gamma \rightarrow \nu\nu\gamma\gamma$ and $W\gamma\gamma \rightarrow \ell\nu\gamma\gamma$
- **Instrumental background:**
  - QCD events with no real E_T^{miss} (from γ-jet misidentification)
  - Events with real E_T^{miss} , from Wγ and Wjet production (γ-e misidentification)
  - High energy muons from cosmic rays and beam-halo (controlled bckg)
- **Signal: Snowmass Slope SP8 (GM1c) – used in Tevatron searches**
- **Compare closure test results for the γγ sample w/ and w/o SUSY signal.**
- **Good agreement between data-driven estimates and the predicted bckg.**

100 pb^{-1} @ 10TeV

Bckg closure test for Z→ee events used for QCD bckg estimation



Comparison with Monte Carlo truth

	no SUSY	with SUSY
$N_{\gamma\gamma}^{QCD}$	2.61 ± 0.23	2.61 ± 0.23
$N_{\gamma\gamma}^{EWK}$	0.17 ± 0.04	0.17 ± 0.04
N^{GM1c}		14.8 ± 0.1
$N_{\gamma\gamma}$	2.78 ± 0.24	17.5 ± 0.26
N_{BG}^{QCD}	2.34 ± 0.65	2.48 ± 0.67
N_{BG}^{EWK}	0.35 ± 0.10	0.50 ± 0.10
N^{BG}	2.69 ± 0.66	2.99 ± 0.68

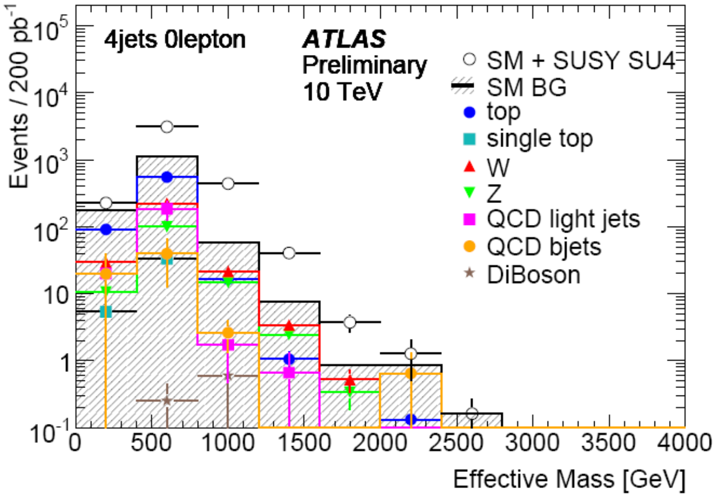
Monte Carlo

estimated

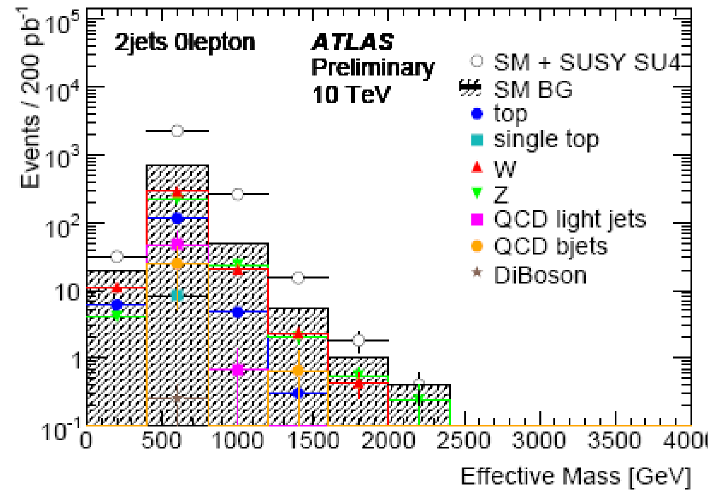
Inclusive Searches

Inclusive Searches - 0-lepton and 1-lepton modes

0-lepton mode: at least 4 jets, Etmiss



0-lepton mode: 2 jets, Etmiss



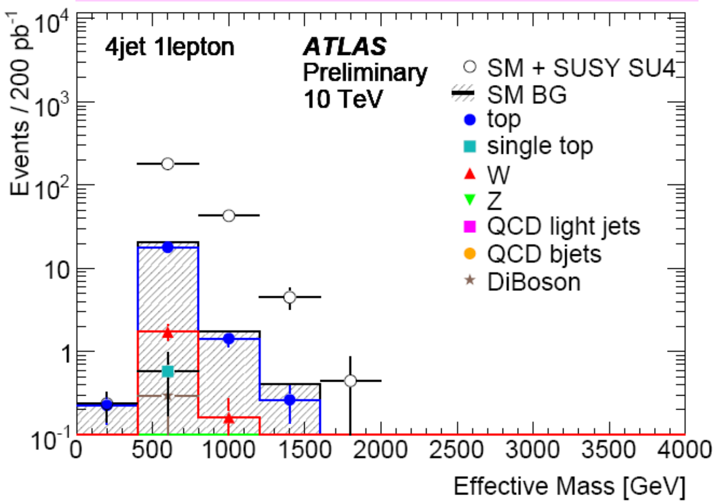
200 pb^{-1} @ 10TeV

Effective mass: measure of total activity in the event

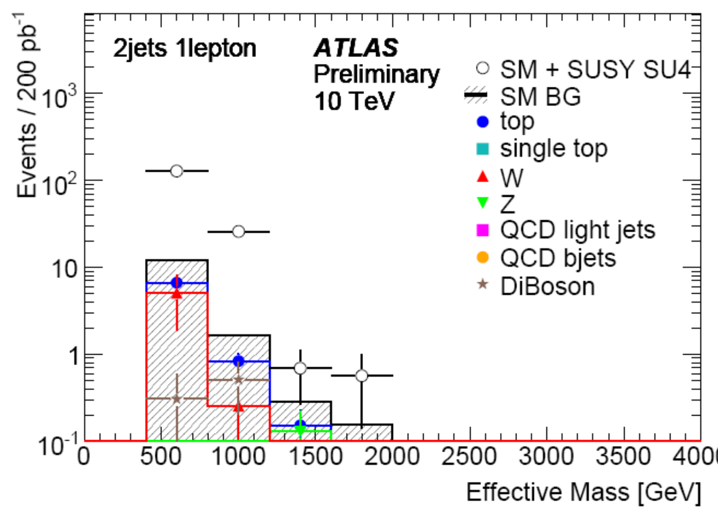
$$M_{\text{eff}} \equiv \sum_{i=1}^{4} p_T^{\text{jet},i} + \sum_{i=1} p_T^{\text{lep},i} + E_T^{\text{miss}}$$

Useful discriminating variable. Also used to quantify SUSY mass scale

1-lepton mode: 1 isolated lepton, at least 4 jets, Etmiss



1-lepton mode: 1 isolated lepton, 2 jets, Etmiss

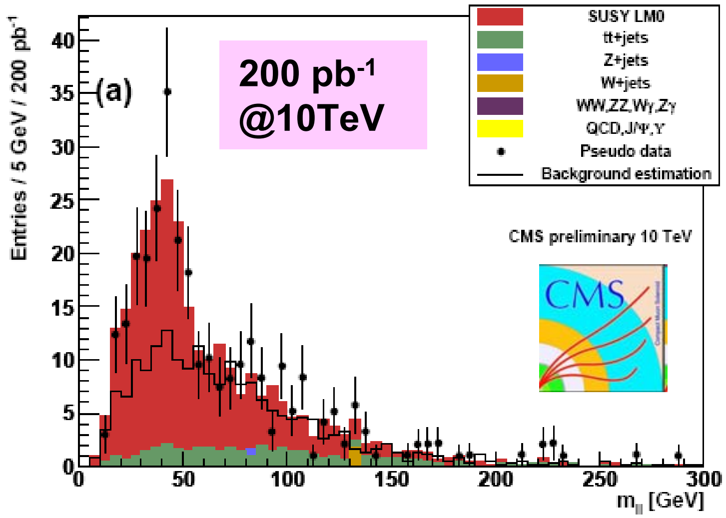


See more details in Tapas Sarangi's talk

Inclusive Searches – 2-lepton, tau and b-jet modes

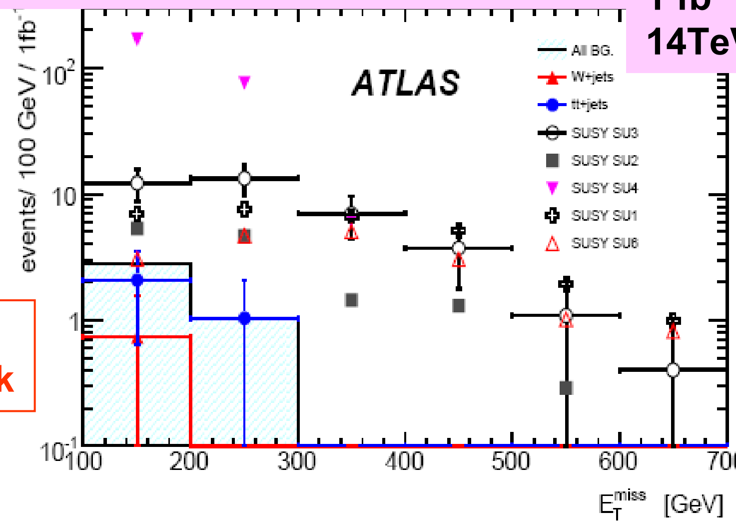
2-lepton mode: 2 opposite-sign leptons, at least 4 jets, Etmiss

200 pb^{-1} @10TeV



2-lepton mode: 2 same-sign leptons, at least 4 jets, Etmiss

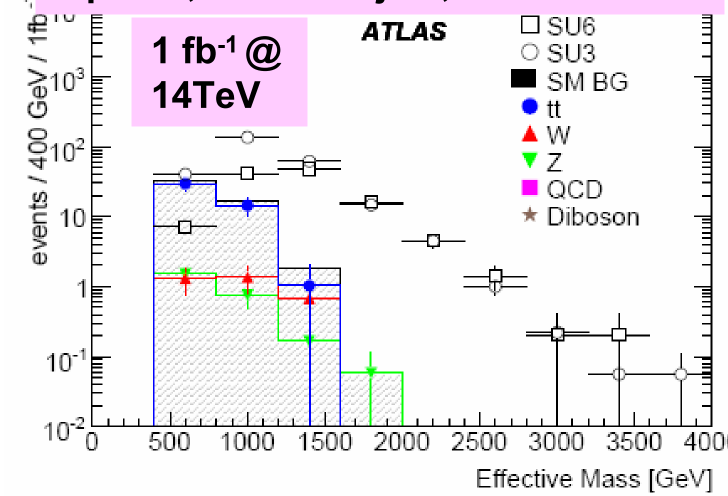
1 fb^{-1} @ 14TeV



See more details in Tapas Sarangi's talk

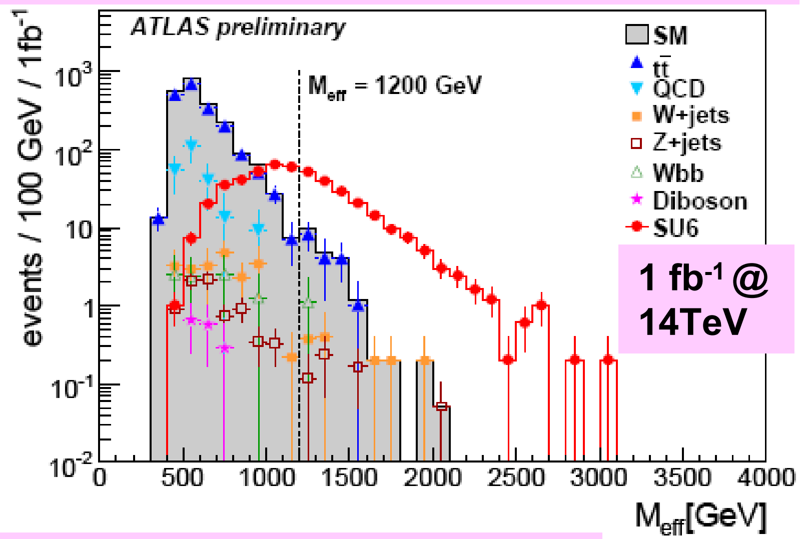
Tau mode: at least 1 tau, no isolated leptons, at least 4 jets, Etmiss

1 fb^{-1} @ 14TeV



b-jet mode: at least 2 b-jets, at least 4 jets, Etmiss

1 fb^{-1} @ 14TeV

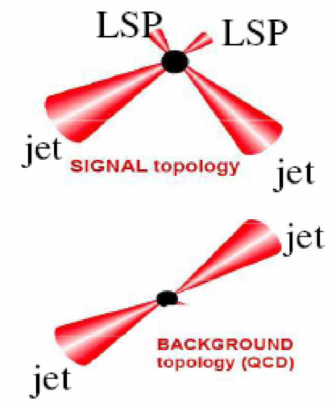


Three-lepton mode has also been studied with 1 fb^{-1}@14 TeV.

An Exclusive Search – all hadronic channel

See more details in Gheorghe Lungu's talk

- **Search without a cut on E_T^{miss} !**
- **Consider mSUGRA with R-parity conservation.**
- **Event topology: n (2…6) high P_T jets + two neutralinos.**
- **QCD multi-jet is dominant bckg where E_T^{miss} is introduced through jet mismeasurements.**
- **Use a kinematic variable to discriminate against QCD bckg:**



200 pb^{-1} @ 10TeV

$$\alpha_T = E_T^{j2} / M_T$$

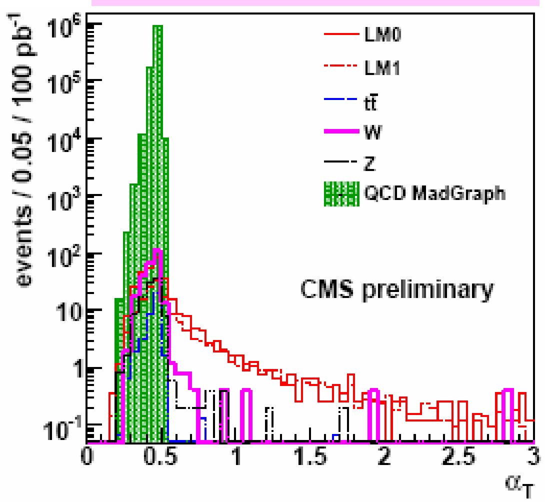
$$M_T = \sqrt{\left(\sum_{i=1}^{n} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{n} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{n} p_y^{j_i}\right)^2} = \sqrt{H_T^2 - (H_T^{miss})^2}$$

$$H_T = \sum_i p_T^{j_i}$$

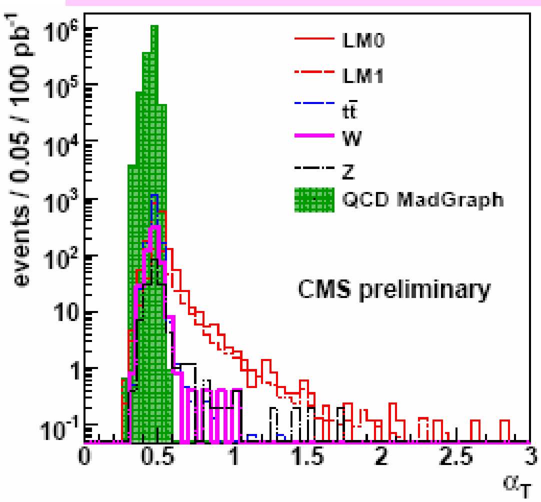
$$\vec{H}_T^{miss} = -\sum_i \vec{p}_T^{\,j_i}$$

- **α_T provides signal over bckg ratios of 4 to 8 (for favorable SUSY models).**

α_T for di-jet events

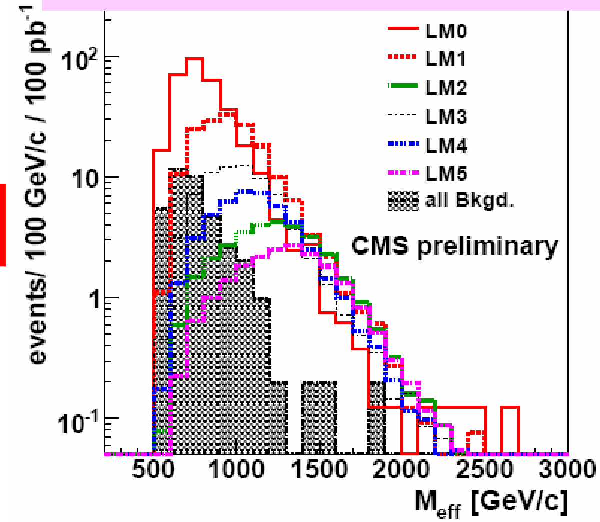


α_T for 3,4,5,6 jets events



$\alpha_T > 0.55$

Effective mass distribution



Special SUSY Signatures

Long-lived SUSY Particles

- Long-lived particle → they live long enough to pass through detector or decay in it.
- Predicted in many SUSY models →
  - stau, slepton, chargino, gluino, stop, neutralino
- Signatures:
  - slepton: ionization in detector, will look like muons except for higher energy deposition and longer time of flight.
  - gluino/stop: meta-stable, forms a bound state, called R-hadron: appearance of high P_T tracks in muon system with no matching track in inner-detector, or electric charge flipping between inner-detector and muon system. Signature similar to slepton.
  - neutralino: non-pointing photons. Decay vertex is somewhere in inner tracker volume.

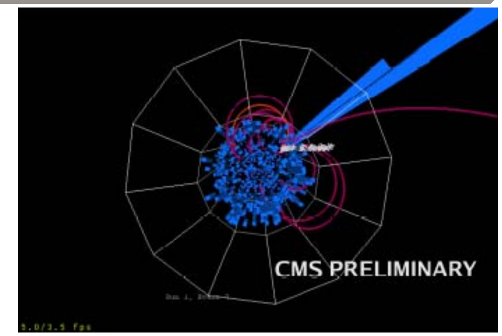
Some SUSY Models giving rise to Stable Massive Particles (SMP)

SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ mass.
	$\tilde{G}$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde{g}$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde{\tau}_1$	MSSM	Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde{g}$MSB	Generic in minimal models.
$\tilde{\ell}_{i1}$	$\tilde{G}$	GMSB	$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde{\tau}_1$	$\tilde{g}$MSB	$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}_1^+$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg |\mu|$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll |\mu|$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}_1^0$	MSSM	Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY.
	$\tilde{G}$	GMSB	SUSY GUT extensions [25–27].
	$\tilde{g}$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m^2_{\tilde{q}}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

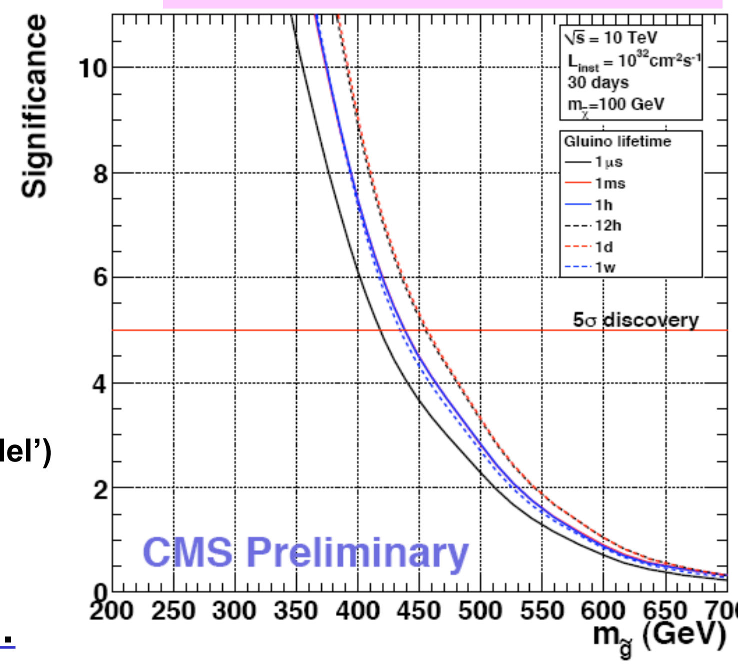
arXiv:hep-ph/0611040

Long-lived gluinos – Search for Split-SUSY

- **Split-SUSY:** very large mass differences between new scalars and new fermions:
  - gluinos can only decay through a virtual squark (assume R-parity conserved). Lifetime of gluino can be long.
- If long-lived gluinos produced they will hadronize into bound states, known as **R-hadrons**: $\tilde{g}g, \tilde{g}q\bar{q}, \tilde{g}qqq$
- Charged R-hadrons loose energy via ionization and significant fraction of them be stopped in detector volume.
- Stopped R-hadrons will decay inside the detector seconds, days or weeks later, this may occur at times:
  - when no collisions (beam-gap)
  - when no beam (interfill period)
- **Unambigous discovery for new physics!**
  - bckg only from cosmic rays and instrumental:
    - Use cosmic ray data from Fall-2008 to measure bckg.
  - syst uncert. is not from bckg estimation but from:
    - NLO calculation of gluino-gluino production cross section.
    - Simulated stopping effficiency (Geant4 employs 'cloud model')
    - Modelling exponential decay of instantenous luminosity
- **Potential to make a 5σ discovery in a matter of days!**
- Improved sensitivity over DØ results (arXiv: 0705.0306).



$10^{32}cm^{-2}s^{-1}$ @ 10TeV,
30 days of running,
cross sections: ~1 nb
neutralino mass=100GeV
gluino lifetimes: μs - week



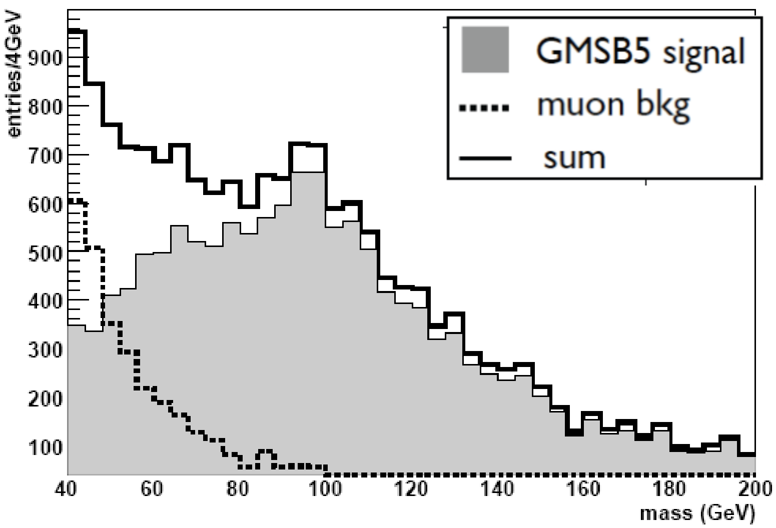
Long-lived slepton/neutralino – Search for GMSB

See more details in Devin Harper's talk

- **GMSB (Gauge Mediated SUSY Breaking) Model:**
  - **SUSY is broken by gauge interactions through messenger gauge fields.**
  - **Six model parameters**

Λ	SUSY Breaking Scale
M	Messenger Mass Scale
tanβ	Ratio of Higgs VEVs
N	Number of Higgs mass parameter
sign(μ)	Sign of Higgs mass parameter
C_{grav}	Scale factor of Gravitino coupling

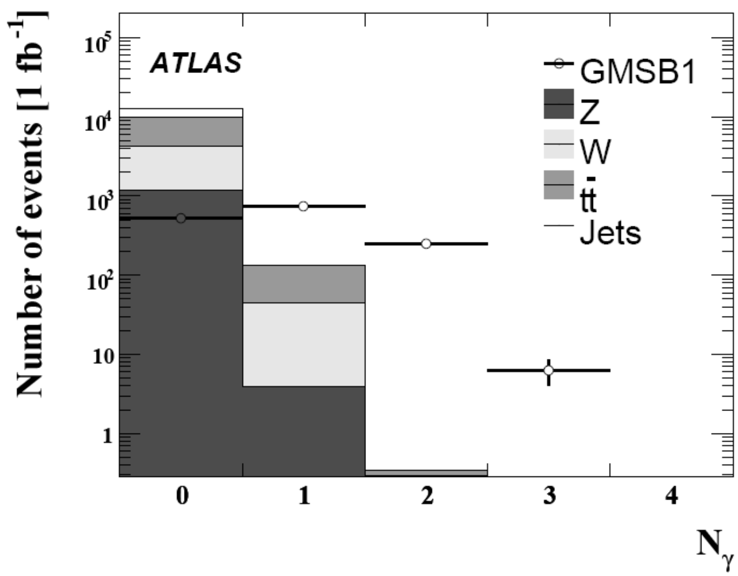
Long-lived slepton: $\tilde{l} \to l\tilde{G}$
- **couples weakly to gravitino**
- **detected as heavy, slow-moving muons**



ATLAS

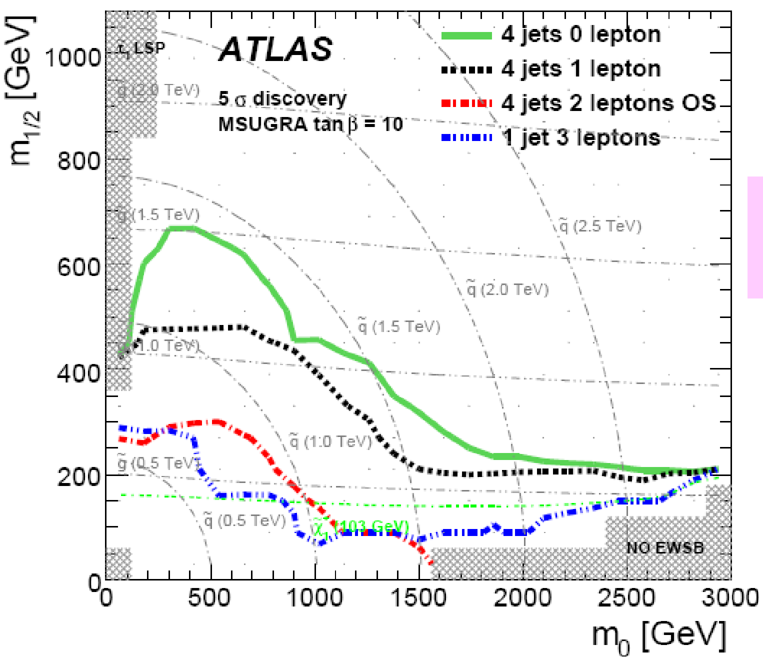
1 fb^{-1} @ 14TeV

Long-lived neutralino: $\tilde{\chi}_1^0 \to \gamma\tilde{G}$
- **non-pointing photons**
- **extracting lifetime of neutralino**



Discovery Reach

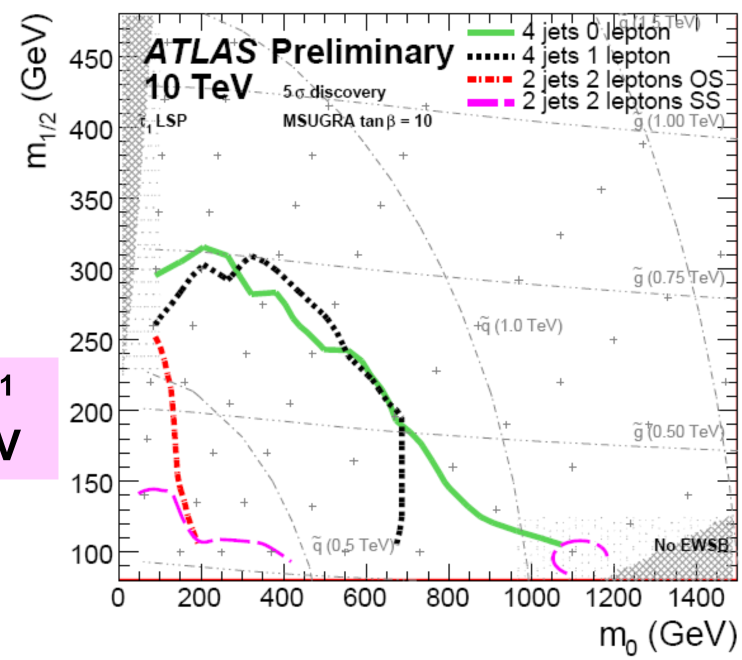
SUSY Discovery Reach – mSUGRA



1 fb^{-1} @ 14TeV

→

200 pb^{-1} @10TeV

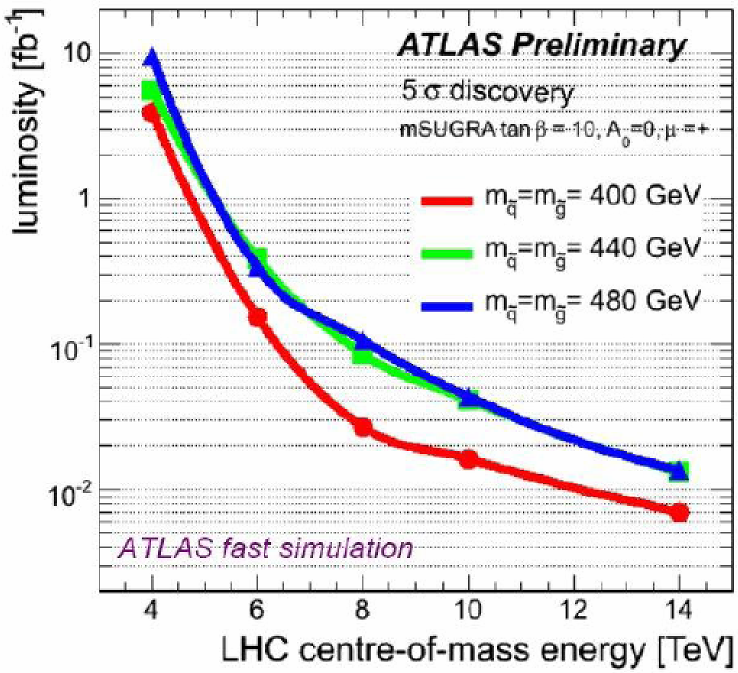


- Squark and gluino masses up to 1.5 TeV.
- Plot includes systematic uncertainty on bckg estimation:
  ±50% for QCD bckg
  ±20% for W, Z, top bckg

0-lepton is best channel, 1-lepton is robust against QCD bckg.

- Squark and gluino masses up to 750 GeV.
- Plot includes systematic uncertainty on bckg estimation:
  ±50% for overall backg

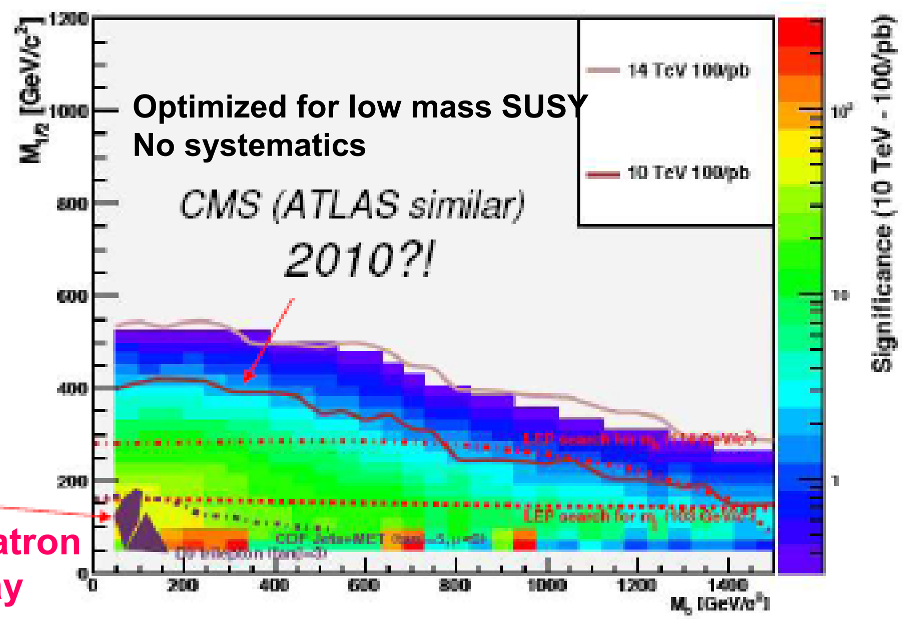
SUSY Discovery Reach – mSUGRA



- Current Tevatron limits: ~400 GeV on squark and gluino masses (mSUGRA)

- At LHC: ≥ 50pb^{-1} @ 10 TeV will give sensitivity to new regions, provided that data are sufficiently understood.

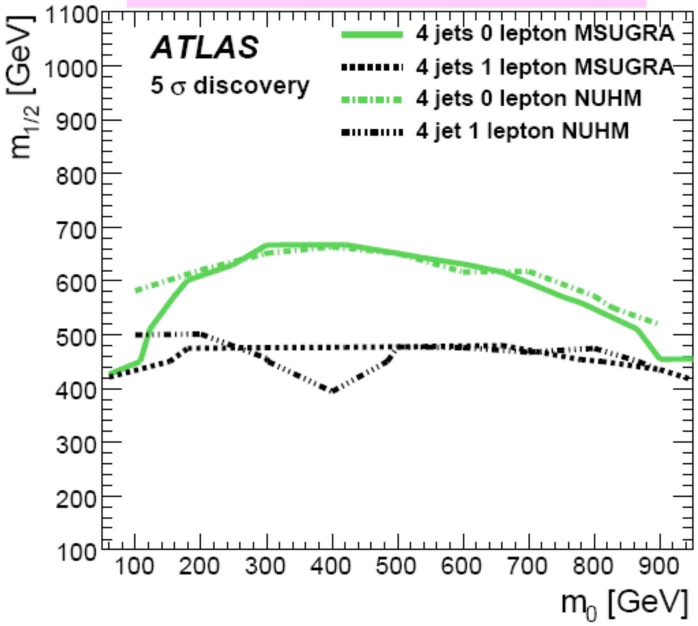
14 TeV ⟶ 10 TeV (100 pb^{-1})



Tevatron today

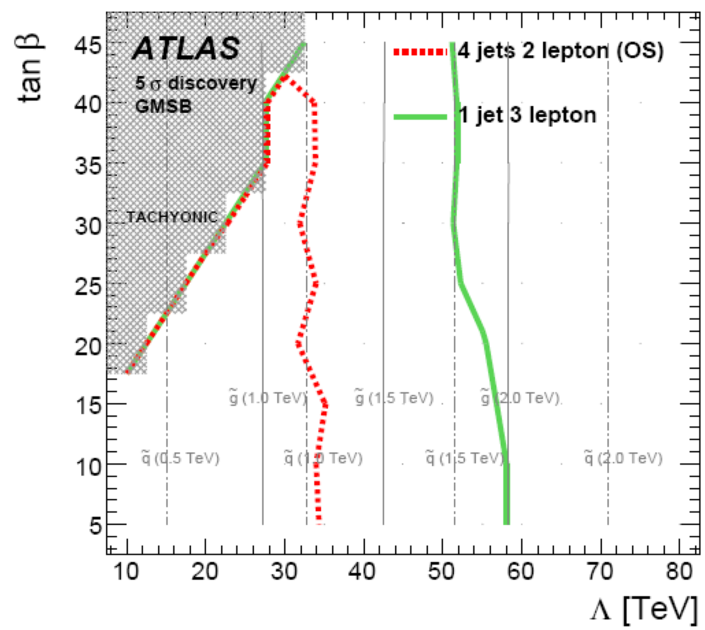
SUSY Discovery Reach – NUHM, GMSB

mSUGRA versus NUHM



1 fb^{-1} @ 14TeV

GMSB



- **The non-universal-Higgs model (NUHM) is similar to mSUGRA, but does not assume that the Higgs masses unify with the squark and sleptons ones at GUT scale.**

- **NUHM parameters: m_0, $m_{1/2}$, A_0, tan(β), sign(μ), m_A, |μ|**

- **Adjust values of m_A, |μ| at weak scale to give compatible WMAP constraints.**

- **Reach with 0- and 1-lepton is virtually identical to that for mSUGRA.**

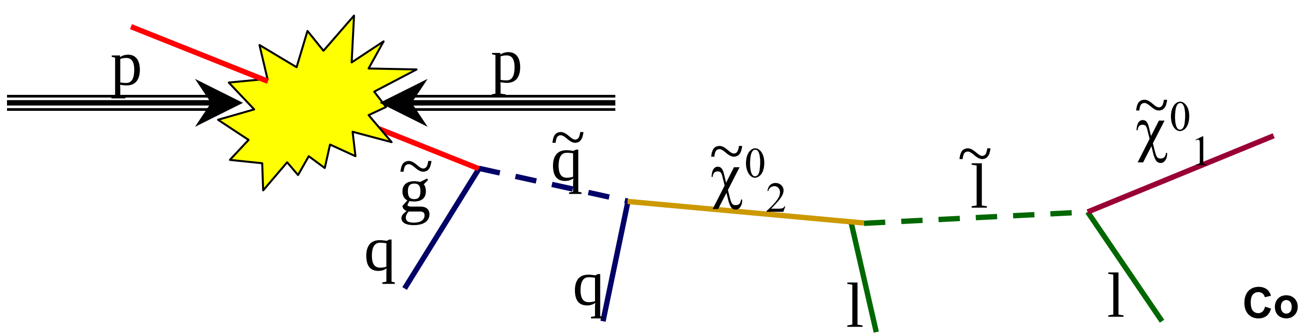
- **GMSB grid:**
  - **M_{mess}=500 TeV, N_{mess}=5, C_{grav}=1.**
  - **NLSP is slepton, decays promptly to leptons or tau's.**
  - **Vary Λ, vary tan(β).**

- **Reach for 3-leptons is better than for 2-leptons and extends well beyond 2 TeV for gluinos for large tan(β), and is close to 2 TeV for all tan(β).**

SUSY Mass Measurements

Is it SUSY?

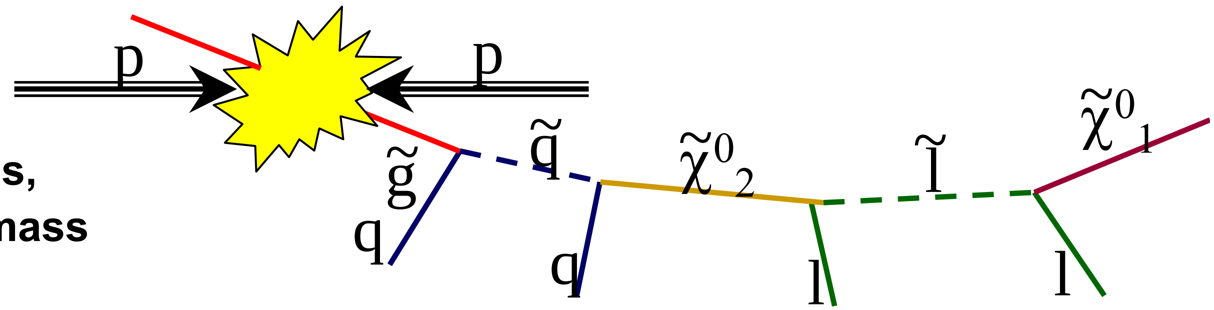
- As soon as a SUSY discovery can be made by inclusive searches → make measurements to confirm that it is SUSY and of which type:
  - describe the model; open decay channels, masses, branching ratios
  - obtain the underlying model parameters
  - measure the spin of new particles (not in this talk)
- A complete coverage of all allowed SUSY models is impossible → limit the study to mSUGRA models. Develop measurement techniques and fit methods.
- The mass measurement strategy is to exploit kinematics of long decay chains.
- The first decay chain likely to be reconstructed:



Consider mass hierarchy:

$$\tilde{g} > \tilde{q} > \tilde{\chi}_2^0 > \tilde{l} > \tilde{\chi}_1^0$$

Mass Measurement Techniques



- LSP's are undetected ⟶ measure kinematic endpoints in invariant mass of visible particles, m_{ll} , m_{llq} , m_{lq} , etc. rather than mass peaks.

- Kinematic endpoint formulae ⟶ Allanach *et al*., JHEP 0009 (2000) 004, Gjelsten *et al*., JHEP 0506 (2005) 015.

- If sufficiently long decay chains can be isolated and enough endpoints are measured ⟶ the masses of the individual particles can be obtained.

- What can be done with ≤ 1 fb^{-1}:

Measurements: m_{ll} , m_{llq} , m_{llq}^{thres}, m_{lq}^{low}, m_{lq}^{high}, $m_{\tau\tau}$, $m_{T2}(\tilde{q}_R)$, m_{tb}

Constrains (or determines) mass of:

$$\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{l}_R\ ,\ \tilde{q}_L\ ,\ \tilde{q}_R,\ \tilde{\tau}_1,\ \tilde{t}_1$$

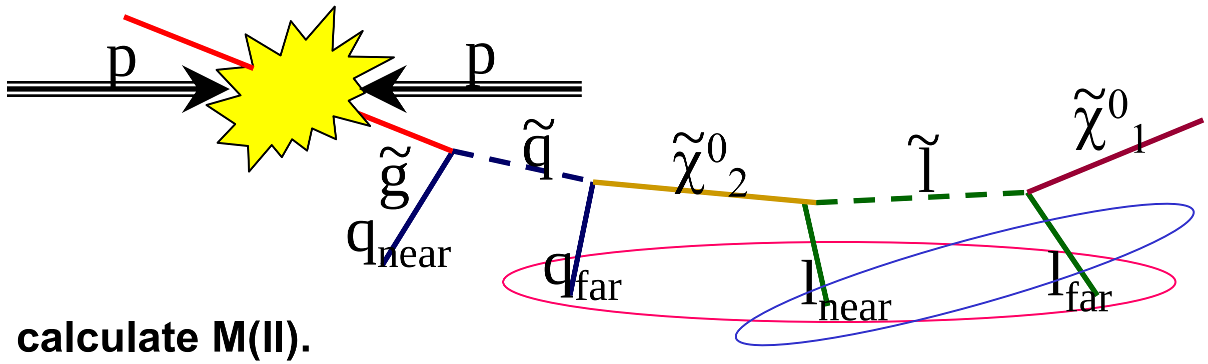
Advantage of this decay chain:

- large signal to background ratio.

- technique, known as flavor subtraction, removes both SUSY combinatorial and Standard Model background.

Mass determination is model-independent, but relies on interpretation of the decay chain.

Kinematic Endpoints



- m_{ll}^{edge} : calculate M(ll).

- Combine the jet with leptons: Not possible to identify the quark from the squark decay → assume it generates one of the two highest p_T jets in the event. Then:

- m_{llq}^{edge} : calculate $M(llq_1)$, $M(llq_2)$, choose the smallest.

- m_{llq}^{thres} : calculate $M(llq_1)$, $M(llq_2)$, choose the largest.

- m_{lq}^{low} and m_{lq}^{high} edges: not possible to distinguish the near lepton from the far lepton → define masses which are observable (use the jet selected for m_{llq}^{edge}):

$$M(lq)^{low} = \min(M_{l^+q}, M_{l^-q}) \equiv \min(M_{l_{near}q}, M_{l_{far}q}) \quad and \quad M(lq)^{high} = \max(M_{l^+q}, M_{l^-q}) \equiv \max(M_{l_{near}q}, M_{l_{far}q})$$

- Total 5 constraints on 4 unknown SUSY masses → solvable.

Dilepton Endpoint

- **Plot invariant mass of dileptons after flavor subtraction and efficiency correction applied:**

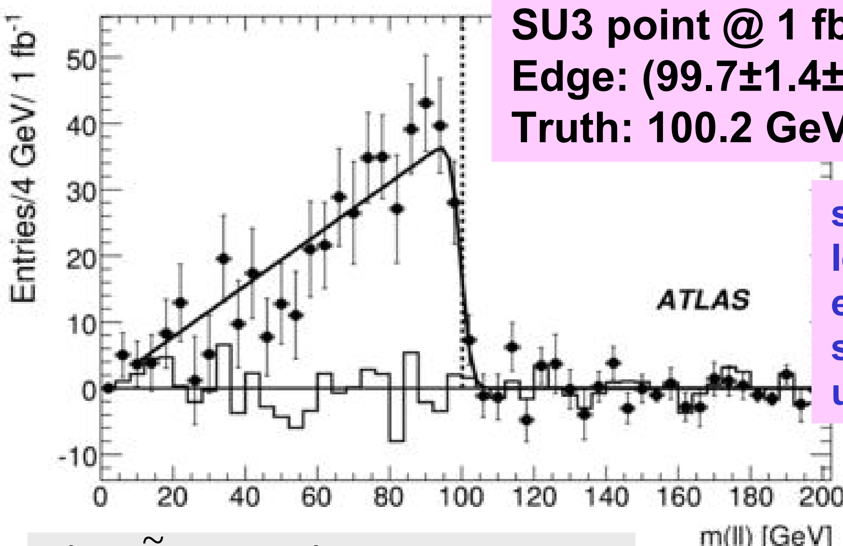
$$\frac{M(e^+e^-)}{\beta} + \beta M(\mu^+\mu^-) - M(e^\pm\mu^\mp)$$

beta=ratio of electron and muon reconstruction efficiencies=0.86

14TeV

SU3 point @ 1 fb^{-1}
Edge: (99.7±1.4±0.3) GeV
Truth: 100.2 GeV

syst error: lepton energy scale uncertainty



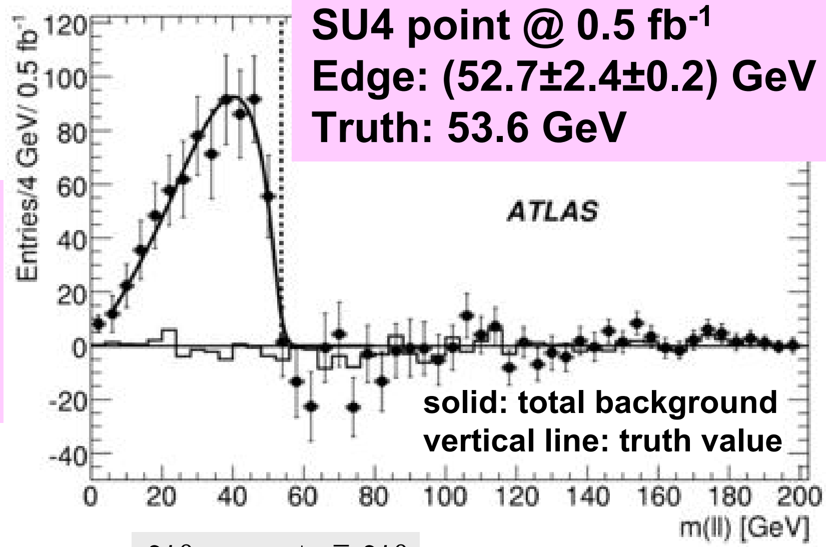
$$\tilde{\chi}_2^0 \rightarrow \tilde{l}^\pm l^\mp \rightarrow \tilde{\chi}_1^0 l^\pm l^\mp$$

$$M_{ll}^{\max} = \sqrt{\frac{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{l}}^2)(M_{\tilde{l}}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{l}}^2}}$$

Fit function: triangular function smeared with a Gaussian.

Edge can be measured with a precision of a few percent already.

SU4 point @ 0.5 fb^{-1}
Edge: (52.7±2.4±0.2) GeV
Truth: 53.6 GeV

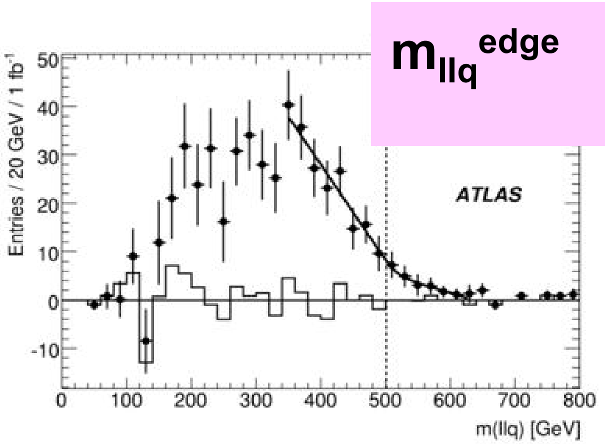


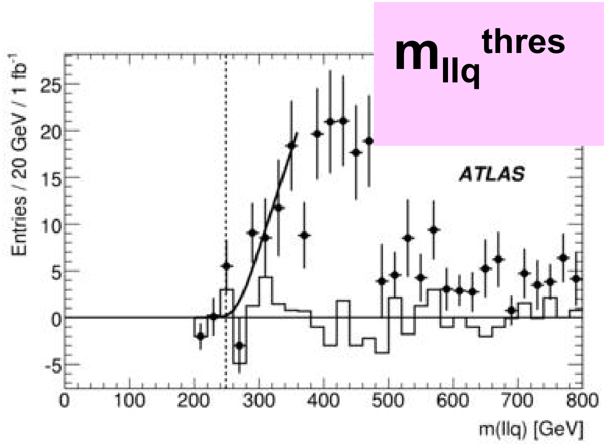
$$\tilde{\chi}_2^0 \rightarrow l^\pm l^\mp \tilde{\chi}_1^0$$ **3-body decay.**

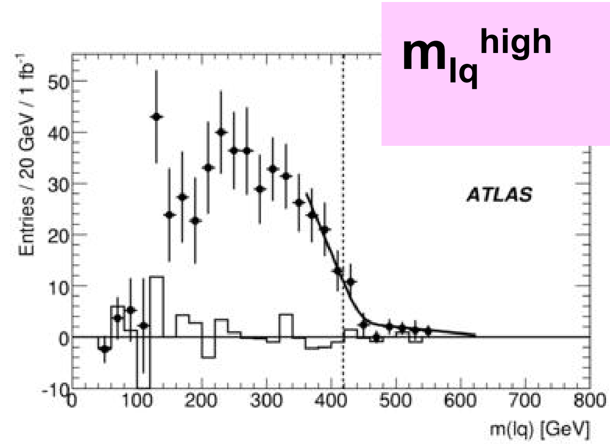
Fit function: theoretical three-body decay shape with Gaussian smearing.

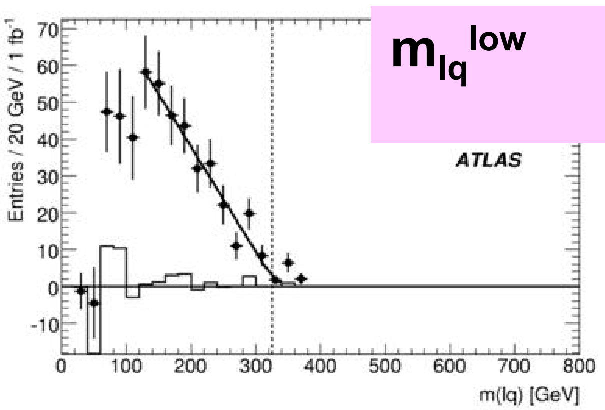
Also CMS study @ 10 TeV

Leptons+jets Endpoints









solid: total background
vertical line: truth value

Good consistency with Truth values.

Plots: SU3 point @ 1 fb^{-1} SU4 point @ 0.5 fb^{-1}

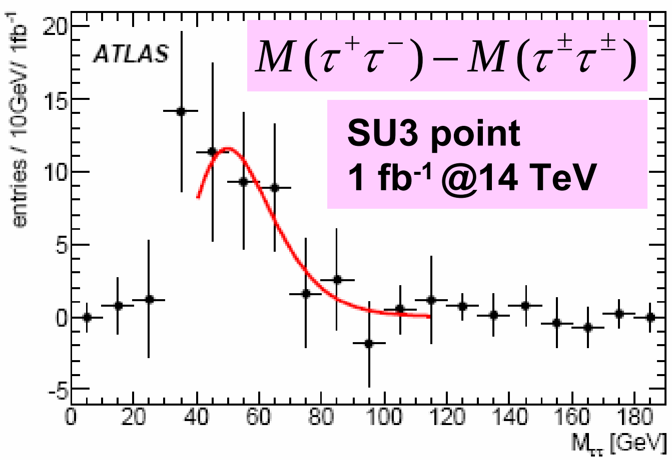
Edge & Threshold	SU3 Truth	SU3 Measured	SU4 Truth	SU4 Measured
m_{llq}^{edge}	501	517 ± 30 ± 10 ± 13	340	343 ± 12 ± 3 ± 9
m_{llq}^{thres}	249	265 ± 17 ± 15 ± 7	168	161 ± 36 ± 20 ± 4
m_{lq}^{low}	325	333 ± 6 ± 6 ± 8	240	201 ± 9 ± 3 ± 5
m_{lq}^{high}	418	445 ± 11 ± 11 ± 11	340	320 ± 8 ± 3 ± 8

Measured = fit ± stat ± (lepton energy scale uncertainty) ± (jet energy scale uncertainty)

Some Other Endpoint Measurements

Di-tau endpoint

$$\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1^{\pm}\tau^{\mp} \rightarrow \tilde{\chi}_1^0\tau^{\pm}\tau^{\mp}$$

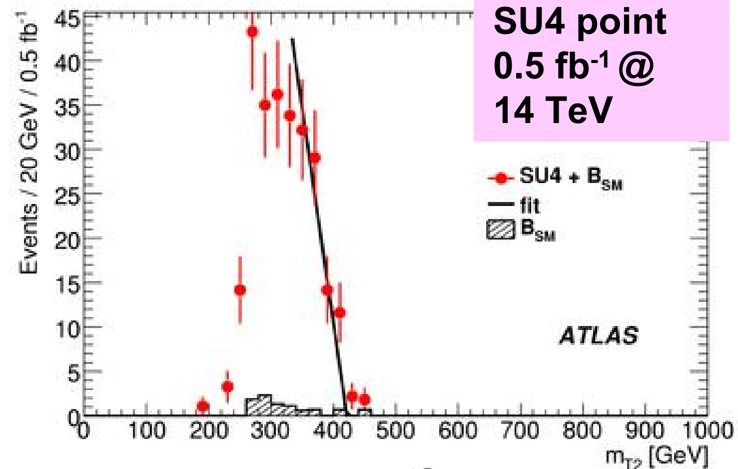


Edge: ($102 \pm 17^{stat} \pm 5.5^{syst} \pm 7^{pol}$) GeV

Truth: 98.3 GeV

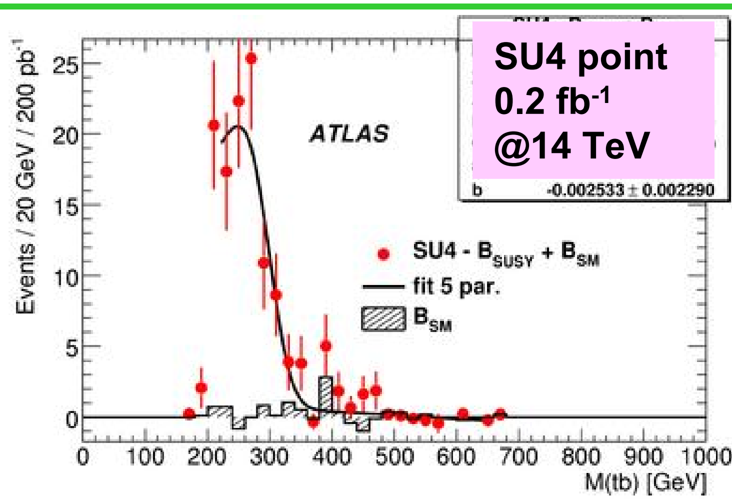
Right handed squark mass

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



Edge: $421 \pm 17(\text{stat})^{+10}_{-3}(\text{sys})$ GeV

Truth: 406 GeV



Light stop mass

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

Edge: $298 \pm 6(\text{stat})^{+16}_{-41}(\text{sys})$ GeV

Truth: 300 GeV

From Endpoints to SUSY Masses

14TeV

- Measured endpoints → extract involved SUSY particle masses.
- Use a numerical χ^2 minimization based on the MINUIT package:

$$\chi^2 = \sum_{k=1}^{n} \frac{(m_k^{\max} - t_k^{\max}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_R}, m_{\tilde{q}_L}))^2}{\sigma_k^2}$$

- Use only the endpoints involving leptons and jets → five measurements:
  m_{ll} , m_{llq} , m_{llq}^{thres}, m_{lq}^{low}, m_{lq}^{high}
- For SU3, five endpoint measurements for four masses → solvable.
- Large statistical error at 1 fb^{-1}.
- Mass of LSP is not well determined.
- Mass differences are better measured than absolute masses → endpoints most sensitive to mass differences.

SU3 point @ 1 fb^{-1}

Observable	Measured: SU3 m_{meas} [GeV]	Truth: SU3 m_{MC} [GeV]
$m_{\tilde{\chi}_1^0}$	$88 \pm 60 \mp 2$	118
$m_{\tilde{\chi}_2^0}$	$189 \pm 60 \mp 2$	219
$m_{\tilde{q}}$	$614 \pm 91 \pm 11$	634
$m_{\tilde{\ell}}$	$122 \pm 61 \mp 2$	155
Observable	**SU3 Δm_{meas} [GeV]**	**SU3 Δm_{MC} [GeV]**
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	$100.6 \pm 1.9 \mp 0.0$	100.7
$m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$	$526 \pm 34 \pm 13$	516.0
$m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$	$34.2 \pm 3.8 \mp 0.1$	37.6

first error is from MIGRAD, second error is from jet energy scale uncertainty.

From Endpoints to mSUGRA Parameters

- Ultimate goal → determine SUSY model parameters from endpoint measurements.

14TeV

- Markov chain analysis → obtain a first glimpse of the possible parameter space.
- Use all the endpoints measured : m_{ll} , m_{llq} , m_{llq}^{thres}, m_{lq}^{low}, m_{lq}^{high}, $m_{T2}(q_R)$, $m_{\tau\tau}$
- Preferred parameters are found around the true parameter points. No further preferrred regions occur. Please see at backup slides.
- Fittino package → determine the mSUGRA parameters. Parameter uncertainties and their correlations are obtained from 500 toy fits.

Fit results:

- sign(μ)=+1 is favored, but sign(μ)=-1 is not ruled out: χ^2=12.6 versus χ^2=15.4 with N_{dof}=11.
- M_0 and $M_{1/2}$ are well constrained.
- Determination of A_0 and tanβ are more problematic as no information from Higgs sector at low luminosity.

Fit results: SU3 point @ 1 fb^{-1}
Truth Mean RMS

Parameter	SU3 value	fitted value	exp. unc.
		$\text{sign}(\mu) = +1$	
$\tan\beta$	6	7.4	4.6
M_0	100 GeV	98.5 GeV	±9.3 GeV
$M_{1/2}$	300 GeV	317.7 GeV	±6.9 GeV
A_0	−300 GeV	445 GeV	±408 GeV
		$\text{sign}(\mu) = -1$	
$\tan\beta$		13.9	±2.8
M_0		104 GeV	±18 GeV
$M_{1/2}$		309.6 GeV	±5.9 GeV
A_0		489 GeV	±189 GeV

Conclusions

- If SUSY exists in nature ATLAS and CMS should discover it (SUSY particles at sub-TeV range).
- With ~50 pb^{-1} @ 10 TeV of data we should be able to go significantly beyond the reach of Tevatron (provided that data sufficiently understood).
- What is expected with the first data:
  - 2 pb^{-1} ⟶ reconstruction and object ID (E_T^{miss}, jets, leptons)
  - 20 pb^{-1} ⟶ data-driven background understanding
  - 200 pb^{-1} ⟶ a real shot at new physics (first 200 days of operation)
- SUSY search strategies:
  - by inclusive searches: establish SUSY discovery, deviation from SM in events like jets + E_T^{miss} (+leptons)
  - by exclusive measurements: select specific SUSY decay chains to measure SUSY masses and rough determination of model parameters
  - by spin measurements: is it SUSY?
- How can we distinguish among various SUSY models:
  - E_T^{miss} spectrum ⟶ R-parity
  - hard photons, NLSP's, long-lived gluinos ⟶ GMSB, split-SUSY
  - tau leptons ⟶ large tan(β)
- Lots of techniques have been developed to search for SUSY.
- An exciting time ahead of us with the upcoming LHC collisions in few months!

Backup Slides

mSUGRA Parameters

mSUGRA Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	tan(β)	sign(μ)	σ (pb) (NLO)
Coannihilation - SU1	70	350	0	10	+	10.86
Focus Point - SU2	3550	300	0	10	+	7.18
Bulk - SU3	100	300	-300	6	+	27.68
Low Mass - SU4	200	160	-400	10	+	402.19
Funnel - SU6	320	375	0	50	+	6.07
Coannihilation - SU8.1	210	360	0	40	+	8.70
Bulk, with enhanced Higgs prod – SU9	300	425	20	20	+	3.28

ATLAS CSC Book (2008)
arXiv:0901.0512

Point	m_0	$m_{1/2}$	$\tan\beta$	$\mathrm{sgn}(\mu)$	A_0
LM1	60	250	10	+	0
LM2	185	350	35	+	0
LM3	330	240	20	+	0
LM4	210	285	10	+	0
LM5	230	360	10	+	0
LM6	85	400	10	+	0
LM7	3000	230	10	+	0
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0
LM10	3000	500	10	+	0
HM1	180	850	10	+	0
HM2	350	800	35	+	0
HM3	700	800	10	+	0
HM4	1350	600	10	+	0

CMS TDR II
J. Phys. G, 34 (2007) 995

Markov Chain Likelihood Maps