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Beyond the Standard Model: Results with the 7 TeV LHC Collision Data

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Searches for Supersymmetry with the ATLAS Detector

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SUSY Searches at ATLAS

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On behalf of the ATLAS Collaboration

BSMLHC 2011 – ICTP, Trieste, Italy

University of Sussex

Celebrating 50 years of excellence

Outline

Introduction to SUSY

The LHC and ATLAS

Overview of R-parity conserving SUSY searches

(a.k.a. E_T^{miss} signals)

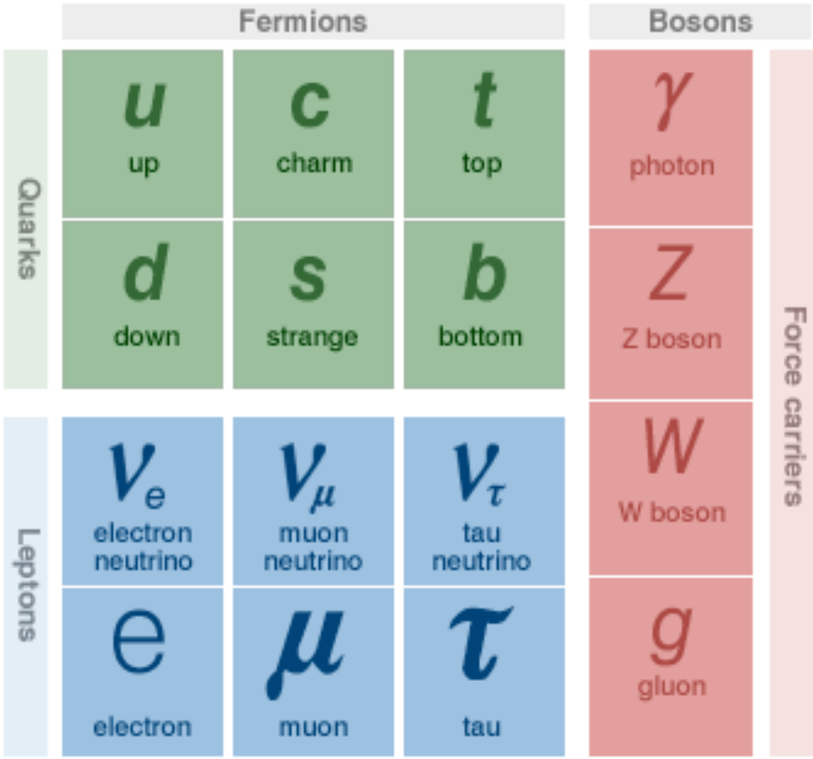
signals with lepton veto
leptonic signals
b-jet signals
di-photon signals

Summary of other searches

including R-parity violating signals

Conclusions

The (Very Resilient) Standard Model



Matter (Fermions)

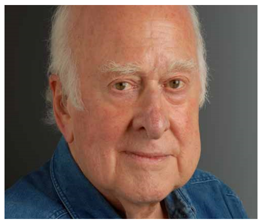
3 quark generations
3 lepton generations

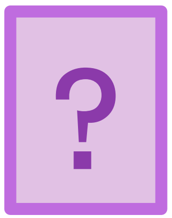
Forces (Bosons)

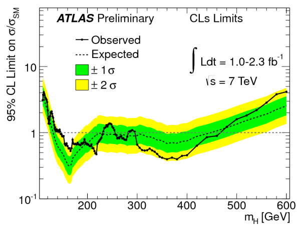
EWK – γ, Z, $W^{\pm}$
Strong – gluons

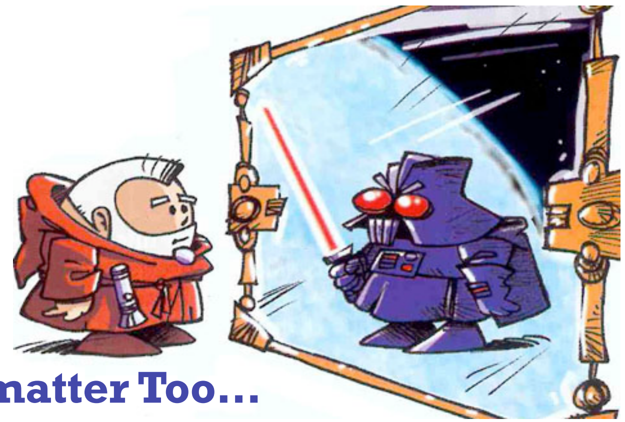
Mass

Higgs boson
(still elusive)



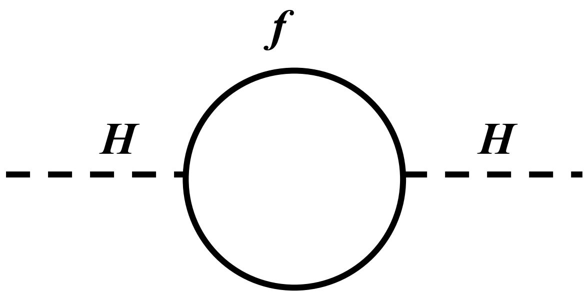






And Antimatter Too…

Some Outstanding Issues



Hierarchy problem

In absence of protective symmetries, Higgs mass can acquire radiative corrections from fermionic loops

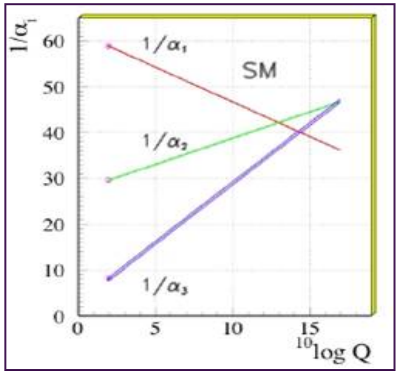
$$\delta m_H^2 \propto \Lambda_{cutoff}^2$$

If no new physics before Planck scale, need fine-tuning to keep Higgs mass relatively small

Weak Scale

The Desert ??

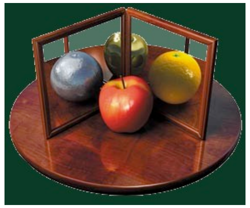
Planck scale



(Non-)Unification of forces

Dark Matter

Supersymmetry (SUSY)



New symmetry between bosons and fermions

Every SM particle has a supersymmetric partner with Δ(spin)=1/2

Extended Higgs sector: h, H, A, $H^{\pm}$

Natural solution to hierarchy problem
Exact cancellation of loop contributions

Gauge unification
Possible in SUSY theories

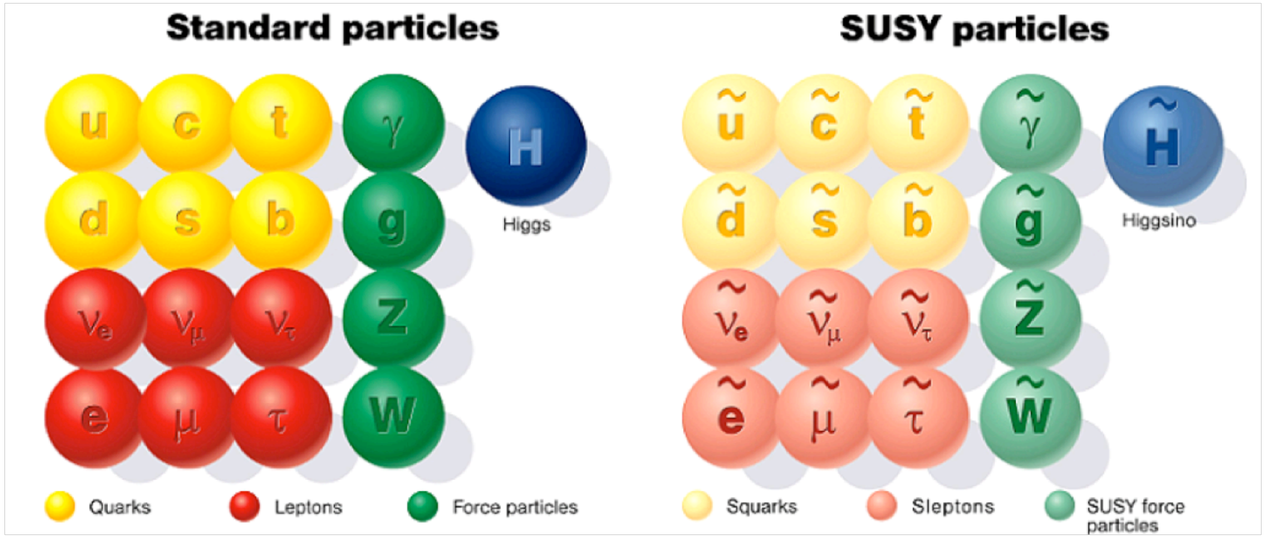
Dark Matter candidate
If R-parity is conserved, stable LSP
(More on R-parity later)

SUSY is a broken symmetry
No superpartners observed with same mass but different spin

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

$$R(SM) = +1$$
$$R(SUSY) = -1$$

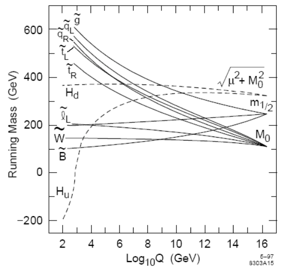
Mechanism for SUSY-breaking unknown

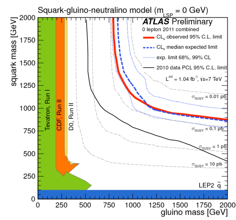


+ SUSY Models and Interpretation

The minimal SUSY extension of the SM (MSSM) has got 105+19 free parameters

Unmanageable!



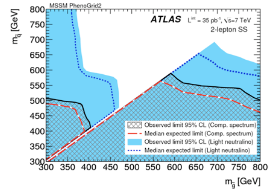


Top-down approach

Models of SUSY breaking – cMSSM/mSUGRA, GMSB, etc

Fix a limited number of parameters at some higher energy scale, then extrapolate back to to the EWK scale & predict phenomenology

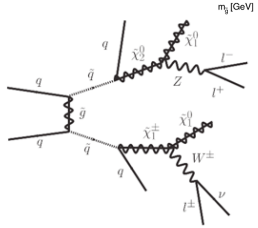
Search for a wide range of signatures – if null result, set limits in parameter space



Bottom-up approach

Phenomenological Models – Assume some sparticle mass hierarchy

Simplified Models – Consider individual decays as separate building blocks



Model-independent limits on "effective cross-section"

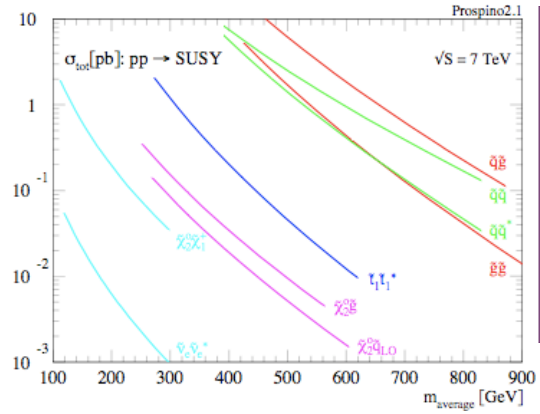
$$\boxed{\sigma \times \varepsilon \times A}$$

(A=acceptance, ε=efficiency)

(ie a limit on the number of events in the signal region – for a given luminosity)

+ Search Strategy

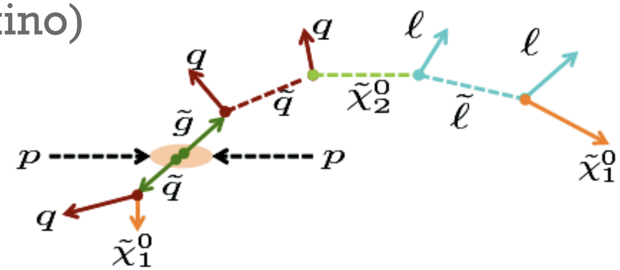
At the LHC, SUSY cross-sections dominated by production of coloured sparticles (squarks and gluinos)



R-parity Conserving (RPC) Models

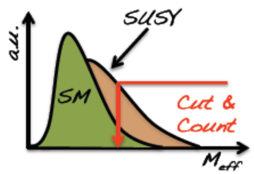
Sparticles produced in pairs

Decay chains (→ **jets**, **leptons, …**) terminating with a stable and neutral LSP (neutralino or gravitino)



LSP leaves the detector unseen
→ **Missing transverse energy** (E_T^{miss})

No mass peaks, signal in tails

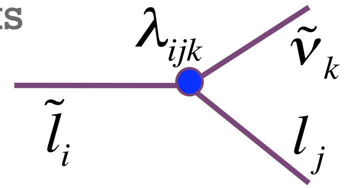


R-parity Violating (RPV) Models

LSP need not be stable or neutral

Can have mass peaks

Not-so-large E_T^{miss}



Other Scenarios

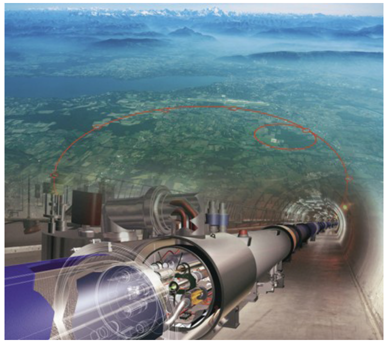
Displaced vertices

Slow highly hadronising particles

…

(see eg **P. Mermod's talk**)

+ The Large Hadron Collider



7 TeV pp collisions

2010 – gradual ramp-up of instantaneous luminosity
2011 – sustained delivery of integrated luminosity

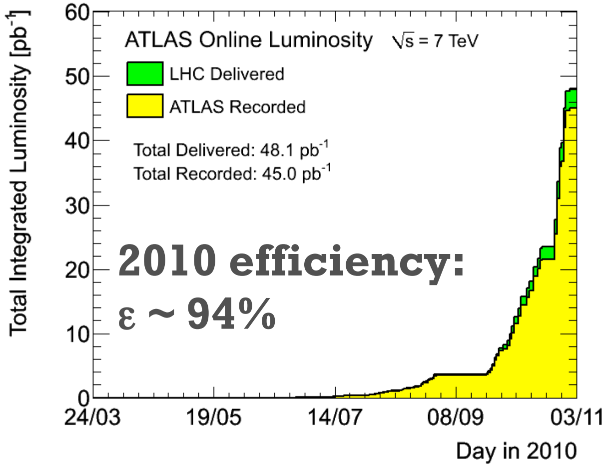
Status

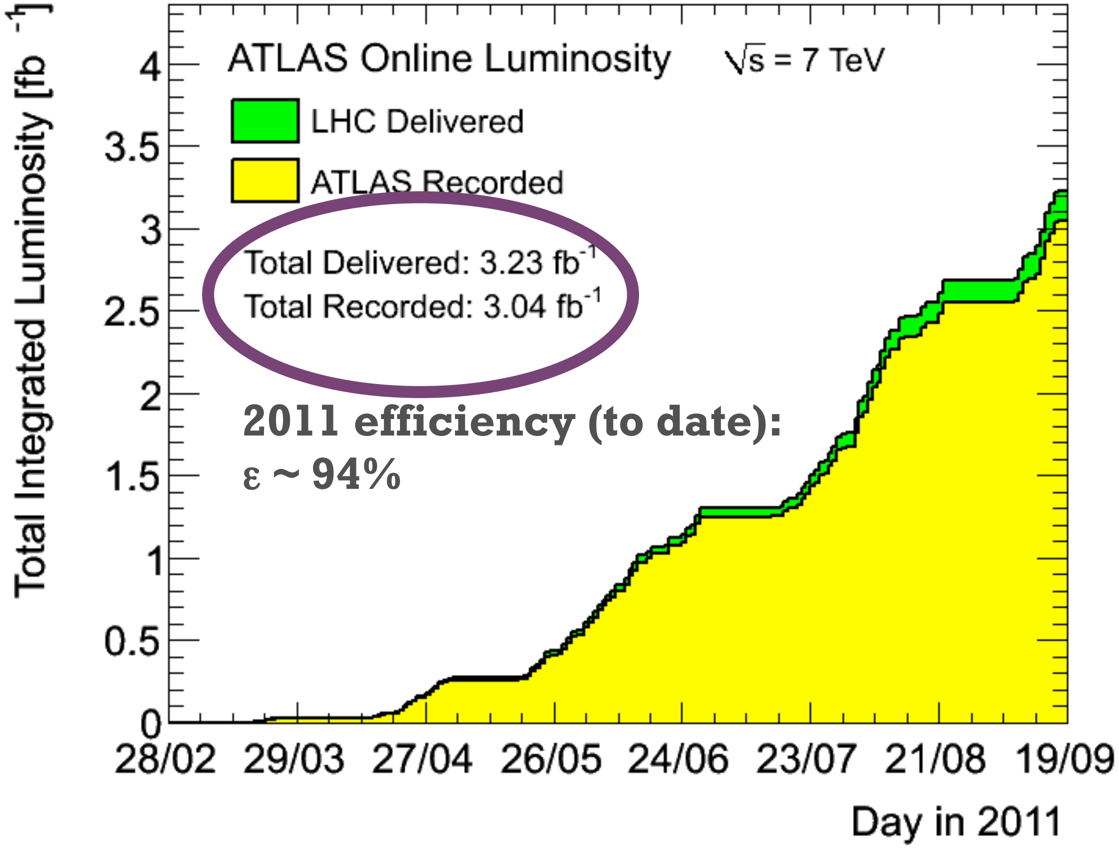
Peak luminosity – $3.3 \times 10^{33}\ cm^{-2}\ s^{-1}$

Datasets for SUSY analyses

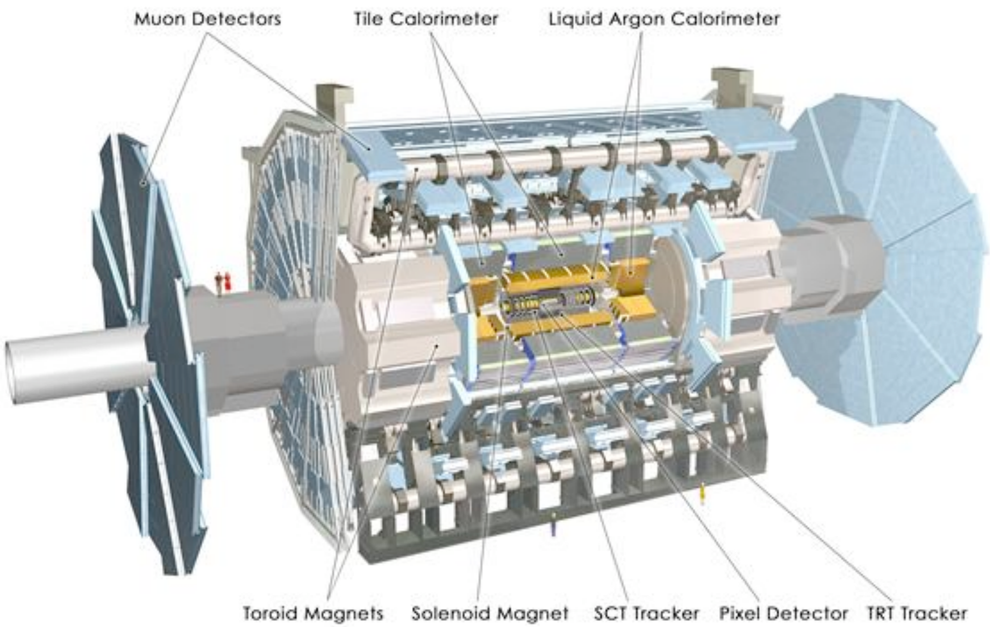
2010 : ~35 pb^{-1}
2011 : up to 1.34 fb^{-1}

(to date)





+ ATLAS Detector



Multi-purpose detector

Large acceptance (~4π coverage) and hermeticity

Excellent particle identification and reconstruction

Excellent E_T^{miss} and jet reconstruction

Excellent vertex reconstruction

Inner Detector (|η|<2.5,B=2T)
Si pixels and strips, TRT straws
Tracking and vertexing, e/π separation

$$\sigma_{p_T}/p_T \sim 3.8\times10^{-4}\, p_T(GeV)\oplus 0.015$$

EM Calorimeter (|η|<4.9)
Pb-Lar Accordion
e/γ trigger, id and measurement

$$\sigma_E/E \sim 10\%/\sqrt{E(GeV)}$$

Hadron Calorimeter (|η|<4.9)
Fe-scintillator tiles (barrel)

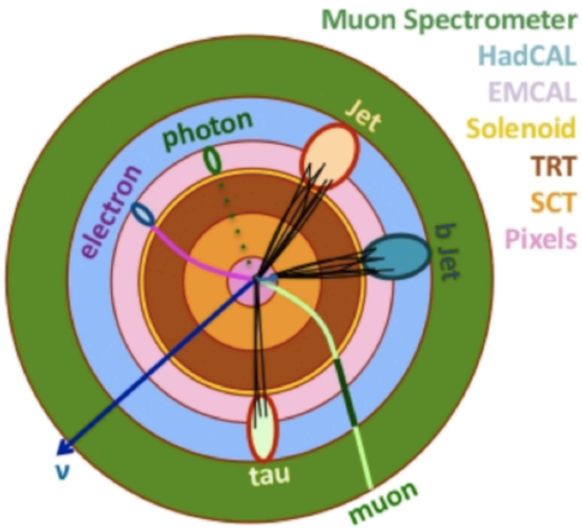
$$\sigma_E/E \sim 50\%/\sqrt{E(GeV)}\oplus 0.03$$

Cu/W-Lar (endcap)

$$\sigma_E/E \sim 90\%/\sqrt{E(GeV)}\oplus 0.07$$

Trigger and measurement of jets and E_T^{miss}

Muon Spectrometer (|η|<2.7)
Air-core toroids with gas-based muon chambers
Muon trigger and measurement
p_T resolution <10% up to ~1TeV



+ A Collaborative Effort

SUSY Searches at ATLAS

E_T^{miss} signatures

ATLAS SUSY Analysis	Publications
E_T^{miss} + jets + 0-lep	arXiv:1102.5290 (35 pb^{-1}) [PLB]; ATL-CONF-2011-086 (163 pb^{-1}); preliminary (1.04 fb^{-1})
E_T^{miss} + multi-jets + 0-lep	Preliminary (1.34fb^{-1})
E_T^{miss} + jets + 1-lep	arXiv:1102.2357 (35 pb^{-1}) [PRL]; ATL-CONF-2011-906 (163 pb^{-1}); preliminary (1.04 fb^{-1})
E_T^{miss} + b-jets + 0/1-lep	arXiv:1103.4344 (35 pb^{-1}) [PLB]; ATL-CONF-2011-098 (0.83 fb^{-1}); ATL-CONF-2011-130 (1.03 fb^{-1})
E_T^{miss} + jets + 2-lep (SS, OS, SF sub.)	arXiv:1103.6214 (35 pb^{-1}) [EPJC]; arXiv:1103.6208 (35 pb^{-1}) [EPJC]; ATL-CONF-2011-091; preliminary (1.04 fb^{-1})
E_T^{miss} + jets + >=3-lep	ATL-CONF-2011-039 (34 pb^{-1})
E_T^{miss} + 2γ	arXiv:1107.0561 (35 pb^{-1}) [EPJCL]; preliminary (1.04 fb^{-1})
Coloured scalars	Preliminary (34 pb^{-1})
eμ resonance (RPV)	arXiV:1103.5559 (35 pb^{-1}) [PRL]; ATL-CONF-2011-109 (0.87 fb^{-1}); ArXiV:1109.3089 (1.07 fb^{-1})
Stable hadronising squarks and gluinos	arXiV:1103.1984 (34 pb^{-1}) [PLB]
Heavy long-lived charged particles	arXiV:1106.4495 (34 pb^{-1}) [PLB]
Heavy medium-lived particles	Preliminary (33 pb^{-1})

SUSY Searches at ATLAS

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Other signatures

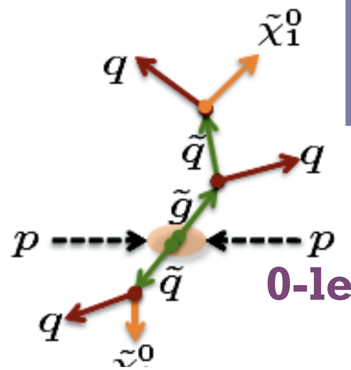
Signals with E_T^{miss}

RPC Signals with E_T^{miss}

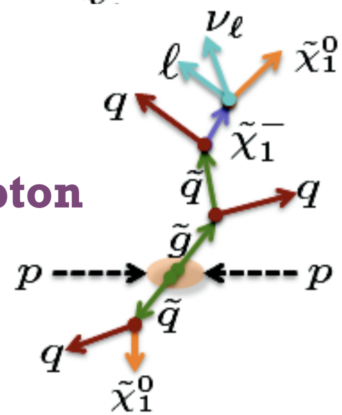
Broad searches

To cover as many signatures as possible from a broad range of scenarios

- short / long cascades
- high-pT jets (including b-jets)
- possibly (multi-)leptons (of different flavours)
- possibly photons
- moderate-to-large E_T^{miss}



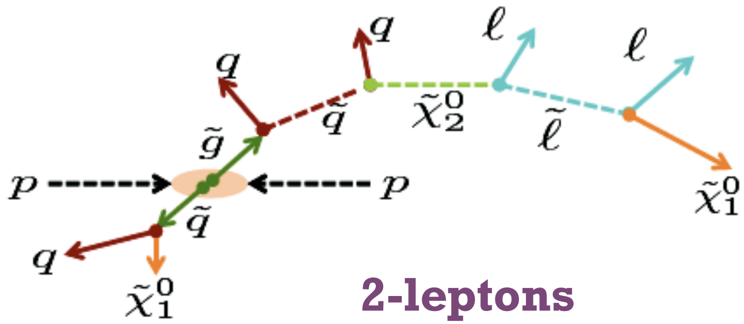
0-lepton



1-lepton

Understanding of SM backgrounds crucial

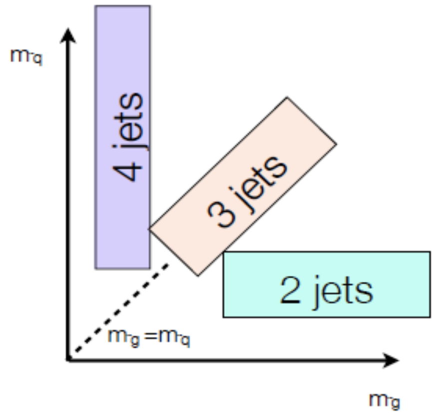
- QCD, W/Z+jets, ttbar, …
- From (or verified in) control regions



2-leptons

0-lepton + jets + E_T^{miss}

+ 0-lepton + jets + E_T^{miss} – Strategy



Squarks and/or gluinos are produced in pairs

$$\tilde{g}\tilde{g},\ \tilde{q}\tilde{g},\ \tilde{q}\tilde{q}$$

Dominant mechanism depends on mass hierarchy

Typically

$$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 \quad \text{(2 jets)}$$

$$\tilde{q} \rightarrow q\tilde{\chi}_1^0 \quad \text{(1 jet)}$$

Signal regions optimised to maximise sensitivity to different production mechanisms

Select events with 2-4 jets and large E_t^{miss}

Veto events with isolated e or μ of p_T>20 GeV

Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

anti-QCD cuts

small/large mass splittings

$$\boxed{m_{eff} = \sum_{i=1}^{n} p_T^{jet,i} + E_t^{miss}}$$

n= all signal jets
(High mass: all jets with p_T>40 GeV)

+ 0-lepton + jets + E_T^{miss} – Background Estimation

Background Sources	
W+jets	W→τν (had τ), W->eν,μν (e,μ not seen)
Z+jets	Z→νν (irreducible)
ttbar, single top	Hadronic top decays
QCD	Misreconstruction of jets, ν from heavy flavour

Five **control regions** (**CR**) are defined for each of the five signal regions (SR) – 25 CRs in total

Background estimation performed by means of a combined likelihood fit to all CRs

Contributions from all CRs to each SR (and to the CRs themselves) and their correlations are all taken into account simultaneously

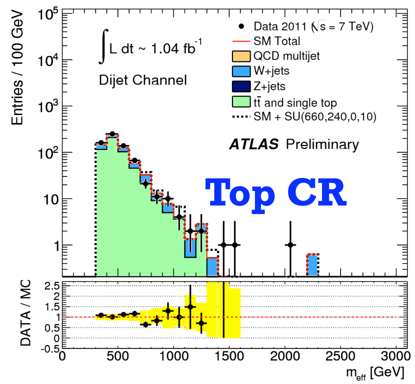
Transfer Factors (TF) relate CR measurement to SR background estimate

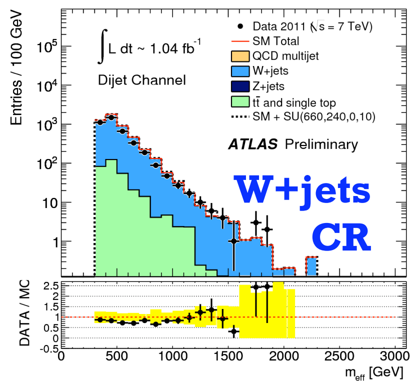
$$N(SR,est,proc) = N(CR,obs,proc) * \left[\frac{N(SR,raw,proc)}{N(CR,raw,proc)}\right]$$

TFs computed using a mix of data-driven and MC based techniques

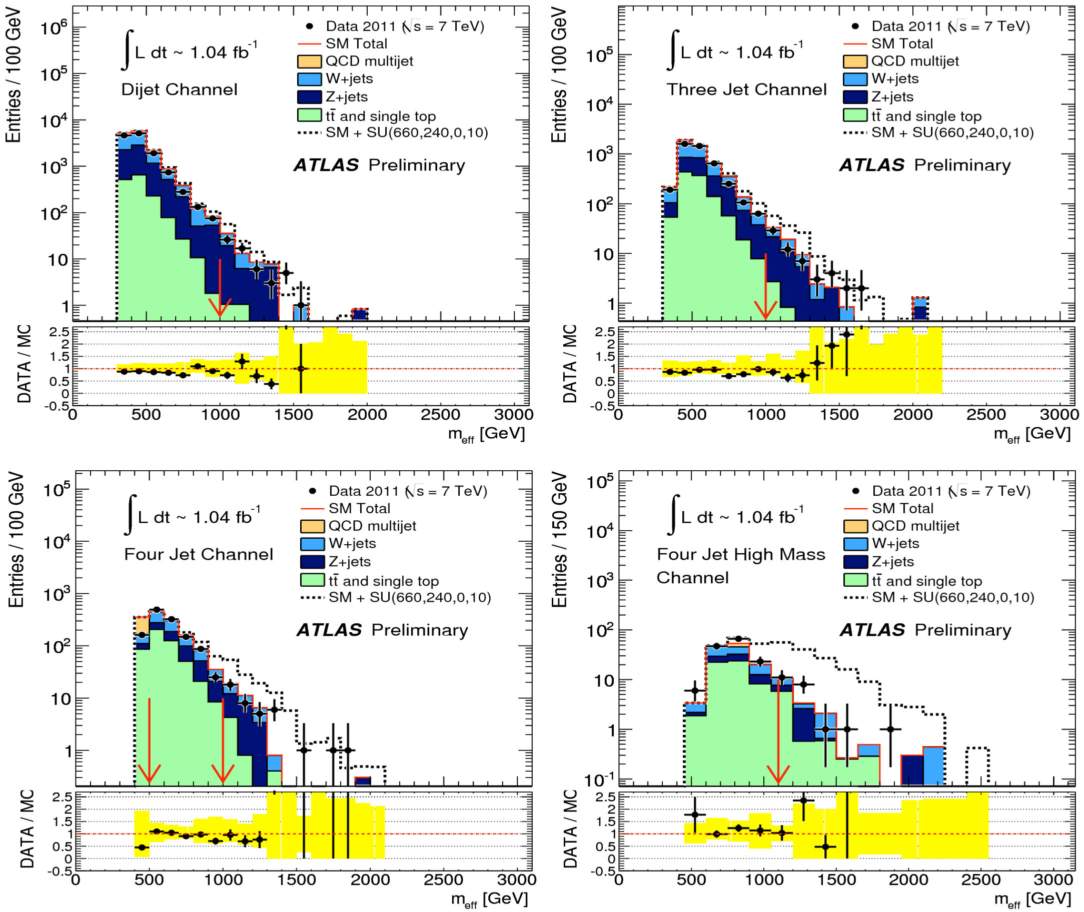
eg: **W(→lν)+jets CR –**
30 GeV < $m_T(l,E_T^{miss})$<100 GeV,
b-jet veto

Top (ttbar, single top) CR –
30 GeV < $m_T(l,E_T^{miss})$<100 GeV
b-jet tag





0-lepton + jets + E_T^{miss} – Results



1.04 fb^{-1}

Observations agree with SM expectations in all SRs

Result are interpreted as a 95% CL exclusion limit on the effective cross section σ×ε×A

Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, $m_{\rm eff} > 500$ GeV	$\geq$ 4-jet, $m_{\rm eff} > 1000$ GeV	High mass
Excluded $\sigma\times$ Acc $\times\varepsilon$ (fb)	24	30	477	32	17

+ 0-lepton Analysis – Interpretation

Phenomenological MSSM

LSP mass = 0
(results ~unchanged for LSP mass up to 200 GeV)

gluino and (1st and 2nd generation) squark mass varied from 100 GeV to 2 TeV

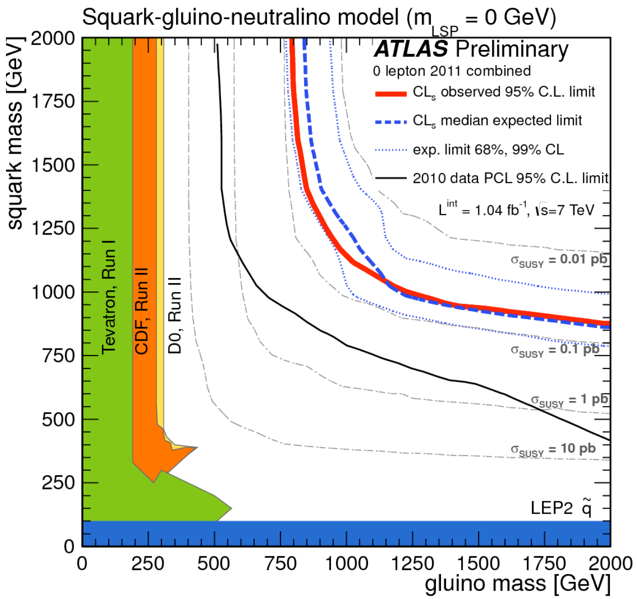
all other masses at 5 TeV

mSUGRA/CMSSM

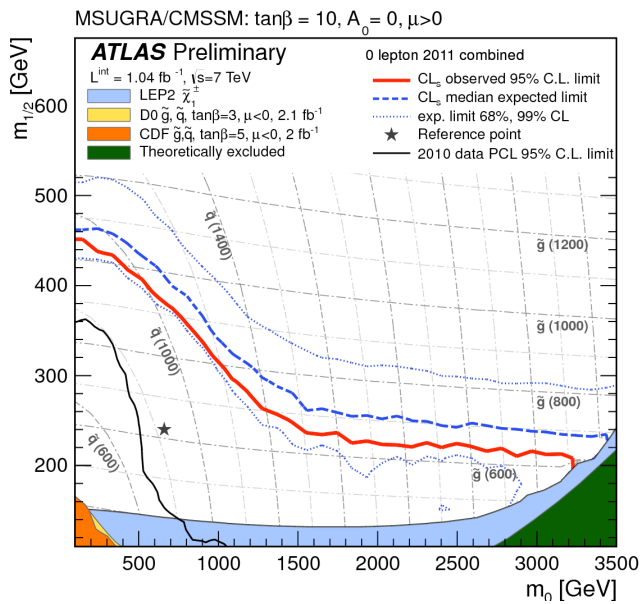
(A_0=0, tanβ=10, μ>0)

Huge improvement on 2010 result

Limit at large m_0 benefits from the introduction of SRs with larger jet multiplicities



1.04 fb^{-1}

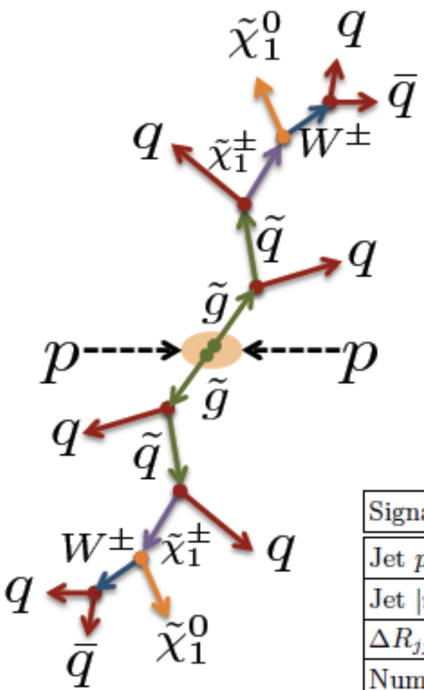


Equal squark-gluino masses up to ~1 TeV are excluded

At low m_0, $m_{1/2}$ values below ~450 GeV are excluded

0-lepton + Multi-jet + E_T^{miss}

+ 0-lepton + Multi-jets + E_t^{miss} – Strategy



Signal region	7j55	8j55	6j80	7j80
Jet p_T	> 55 GeV		> 80 GeV	
Jet $\|\eta\|$	< 2.8			
ΔR_{jj}	> 0.6 for any pair of jets			
Number of jets	≥ 7	≥ 8	≥ 6	≥ 7
$E_T^{miss}/\sqrt{H_T}$	> 3.5 GeV$^{1/2}$			

E_T^{miss} resolution dominated by stochastic fluctuations

$$\boxed{\sigma^2\left(E_T^{miss}\right) \sim H_T \equiv \sum_{jets} p_T}$$

(sum over jets with: p_T>40 GeV, $|\eta|$<2.8)

Extension of (2-4)-jet analysis

Provides increased sensitivity to models with many-body decays or sequential cascade decays to coloured particles

such as SUSY models with TeV-scale gluinos and heavy squarks

eg high-m0 mSUGRA/CMSSM

Signal regions with (≥6, ≥7, ≥8) high-p_T jets, plus E_T^{miss} and lepton veto

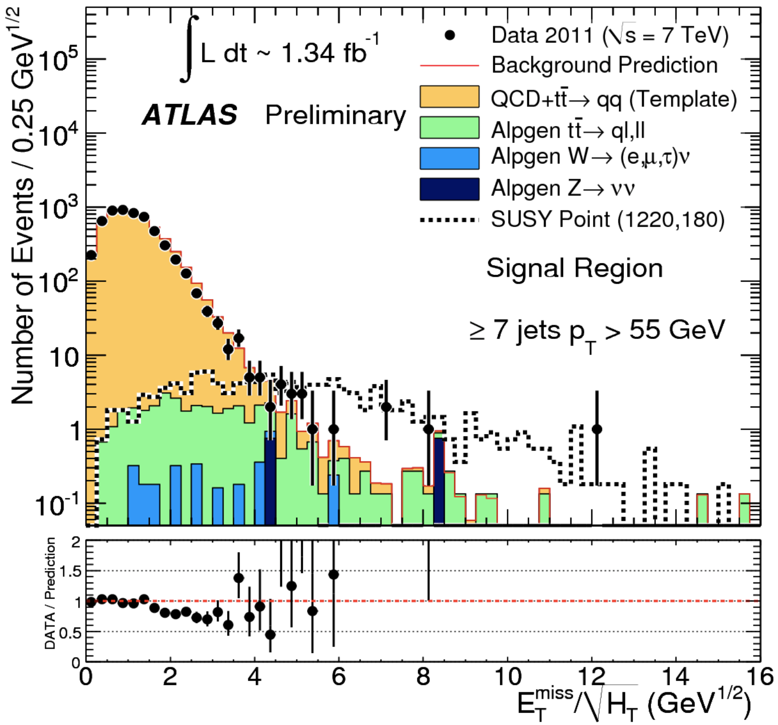
jet multiplicities and pT thresholds chosen to guarantee high trigger efficiencies and good signal acceptance

Data-driven approach

Cannot expect a good modelling of QCD from MC predictions only

$E_T^{miss}/\sqrt{H_T}$ variable (nearly independent of jet multiplicity and pileup) used to remove MC dependence (transfer factors from lower jet multiplicities)

+ 0-lepton + Multi-jets + E_t^{miss} – Results



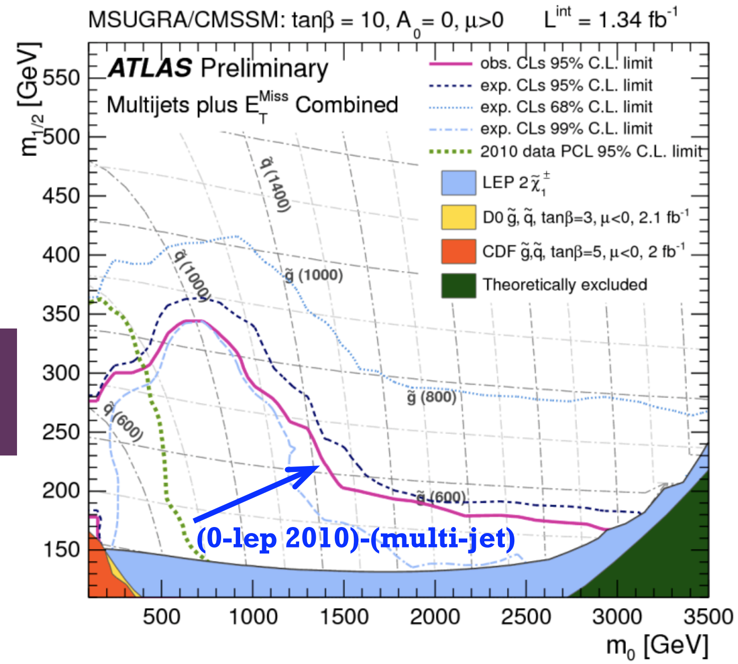
Background Sources	
Multi-jet QCD + Fully hadronic ttbar	Dominant
Semi- and fully leptonic ttbar	Significant
W/Z+jets	Small

Signal region	7j55	8j55	6j80	7j80
Multi-jets	26 ± 5.2	2.3 ± 0.7	19 ± 4	1.3 ± 0.4
$t\bar{t} \rightarrow \ell(\ell)X$	10.8 ± 6.7	$0^{+4.3}$	6.0 ± 4.6	$0^{+0.13}$
W + jets	0.95 ± 0.80	$0^{+0.13}$	0.34 ± 0.34	$0^{+0.13}$
Z + jets	$1.5^{+1.8}_{-1.5}$	$0^{+0.75}$	$0^{+0.75}$	$0^{+0.75}$
Total SM	$39.3^{+8.7}_{-8.5}$	$2.3^{+4.4}_{-0.7}$	25.8 ± 6.1	$1.3^{+0.9}_{-0.4}$
Data	45	4	26	3
$N^{95\%}_{\mathrm{BSM,max}}$	26.0	11.2	16.3	6.0
$(\sigma^{95\%}_{\mathrm{BSM,max}} \times \epsilon)$/fb	19.4	8.4	12.2	4.5
p_{SM}	0.30	0.36	0.49	0.16

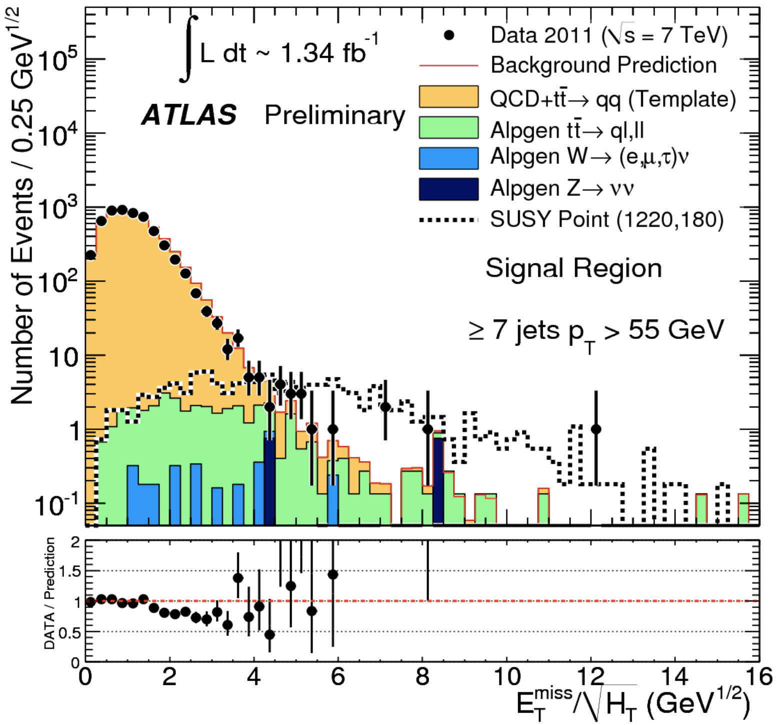
1.34 fb^{-1}

mSUGRA/CMSSM

(A_0=0, tanβ=10, μ>0)



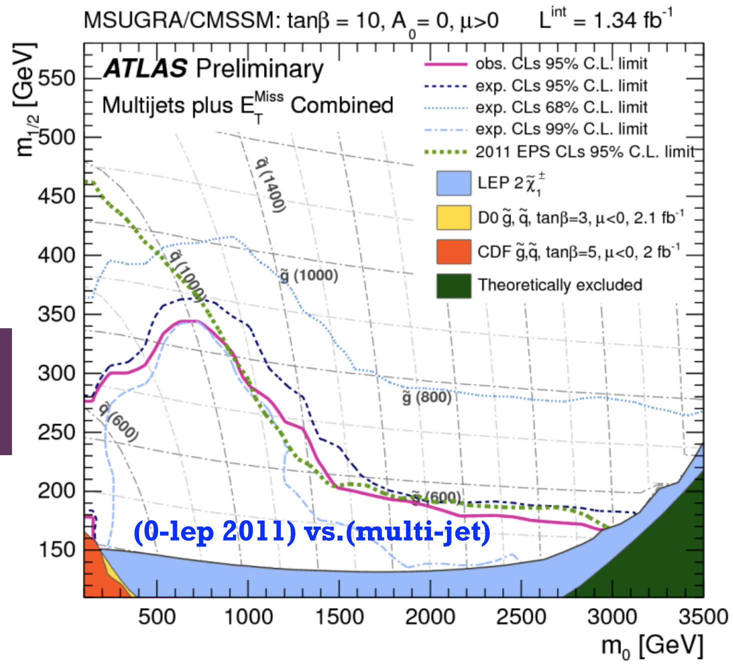
+ 0-lepton + Multi-jets + E_t^{miss} – Results



Background Sources	
Multi-jet QCD + Fully hadronic ttbar	Dominant
Semi- and fully leptonic ttbar	Significant
W/Z+jets	Small

mSUGRA/CMSSM

(A_0=0, tanβ=10, μ>0)

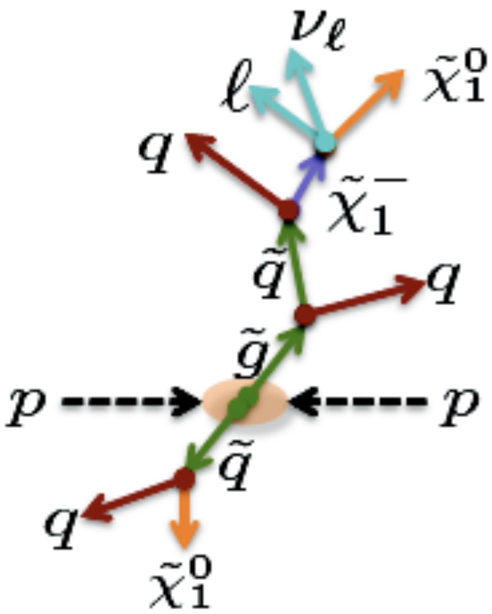


Signal region	7j55	8j55	6j80	7j80
Multi-jets	26 ± 5.2	2.3 ± 0.7	19 ± 4	1.3 ± 0.4
$t\bar{t} \rightarrow \ell(\ell)X$	10.8 ± 6.7	$0^{+4.3}$	6.0 ± 4.6	$0^{+0.13}$
W + jets	0.95 ± 0.80	$0^{+0.13}$	0.34 ± 0.34	$0^{+0.13}$
Z + jets	$1.5^{+1.8}_{-1.5}$	$0^{+0.75}$	$0^{+0.75}$	$0^{+0.75}$
Total SM	$39.3^{+8.7}_{-8.5}$	$2.3^{+4.4}_{-0.7}$	25.8 ± 6.1	$1.3^{+0.9}_{-0.4}$
Data	45	4	26	3
$N^{95\%}_{\mathrm{BSM,max}}$	26.0	11.2	16.3	6.0
$(\sigma^{95\%}_{\mathrm{BSM,max}} \times \epsilon)$/fb	19.4	8.4	12.2	4.5
p_{SM}	0.30	0.36	0.49	0.16

1.34 fb^{-1}

1-lepton + jets + E_T^{miss}

+ 1-lepton + jets + E_t^{miss} – Strategy



Presence of lepton provides extra advantages compared to purely hadronic searches

- **Triggering**
  - efficient single lepton triggers
- **Background suppression**
  - QCD background greatly reduced by lepton requirement
- **Background modelling**
  - using data-driven techniques

Additional variables used in the event selection:

$$\boxed{m_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss}\left(1-\cos\left(\Delta\phi(\vec{\ell},\vec{E}_T^{miss})\right)\right)}}$$

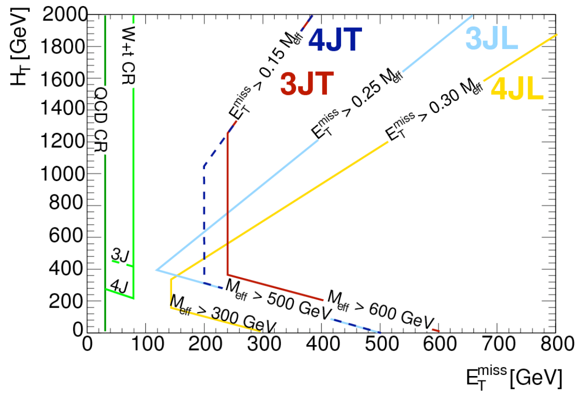
Transverse mass between selected lepton and E_T^{miss} vector

$$\boxed{m_{eff} = \underbrace{p_T^\ell + \sum_{i=1}^{3(4)} p_T^{jet(i)}}_{} + E_T^{miss}}$$

Effective mass (using leading 3 (4) jets)

H_T

+ 1-lepton + jets + E_t^{miss}



Four Signal Regions

1 lepton
$p_T(e)>25$ GeV, $p_T(\mu)>20$ GeV
different thresholds due to trigger

No extra leptons
Veto e/μ with $p_T(e)>20$ GeV, $p_T(\mu)>10$ GeV

At least 3 or 4 jets with p_T above threshold
"loose" (L) or "tight" (T) jets

Jets not aligned with E_t^{miss} vector
$\Delta\Phi(\text{jet}, E_T^{miss})>0.2$, all 3 (4) jets

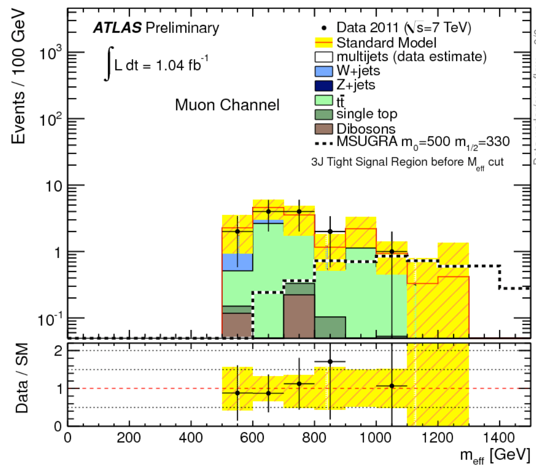
$m_T>100$ GeV
suppress W+jets

Cuts on E_T^{miss}, E_t^{miss}/m_{eff}, m_{eff}
for further signal enrichment

Selection	Signal Regions 3JL	3JT	4JL	4JT	Control Regions 3J	4J
Number of Leptons	= 1					
Lepton p_T (GeV)	> 25(20) for electrons (muons)					
Veto lepton p_T (GeV)	> 20(10) for electrons (muons)					
Number of jets	≥ 3		≥ 4		≥ 3	≥ 4
Leading jet p_T (GeV)	60	80	60	60	60	60
Subsequent jets p_T (GeV)	25	25	25	40	25	25
$\Delta\phi(\vec{\text{jet}}_i, \vec{E}_T^{miss})$	[> 0.2 (mod.π)] for all 3 (4) jets					
m_T (GeV)	> 100				$40 < m_T < 80$	
E_T^{miss} (GeV)	> 125	> 240	> 140	> 200	$30 < E_T^{miss} < 80$	
E_T^{miss}/m_{eff}	> 0.25	> 0.15	> 0.30	> 0.15	–	–
m_{eff} (GeV)	> 500	> 600	> 300	> 500	> 500	> 300

QCD background using "loose-tight" Matrix Method
use data with "loose" lepton to estimate data with "tight" lepton

Non-QCD background dominated by top and W+jets
do MC-data normalisation in CRs
extrapolate to SR relying on MC shapes
perform simultaneous likelihood fit of different CRs



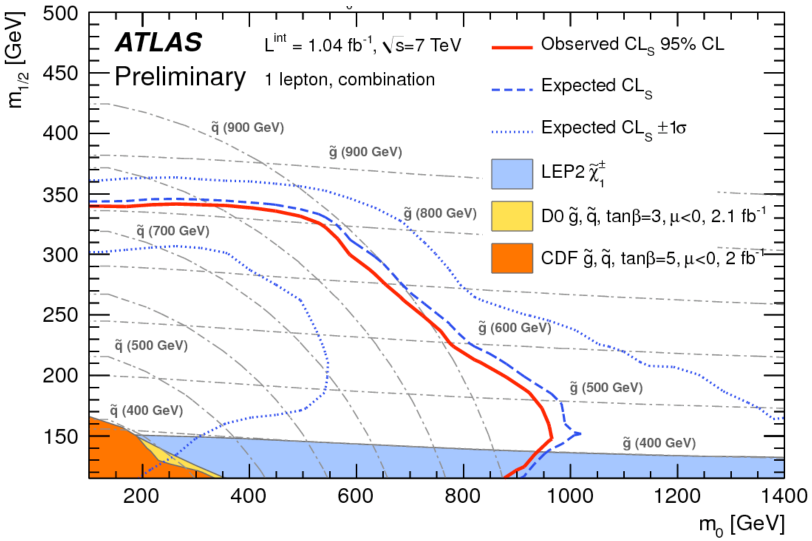
1-lepton + jets + E_t^{miss} – Results

Observed number of events in data consistent with SM

uncertainties dominated by jet energy scale and resolution, theory, MC modeling and statistics

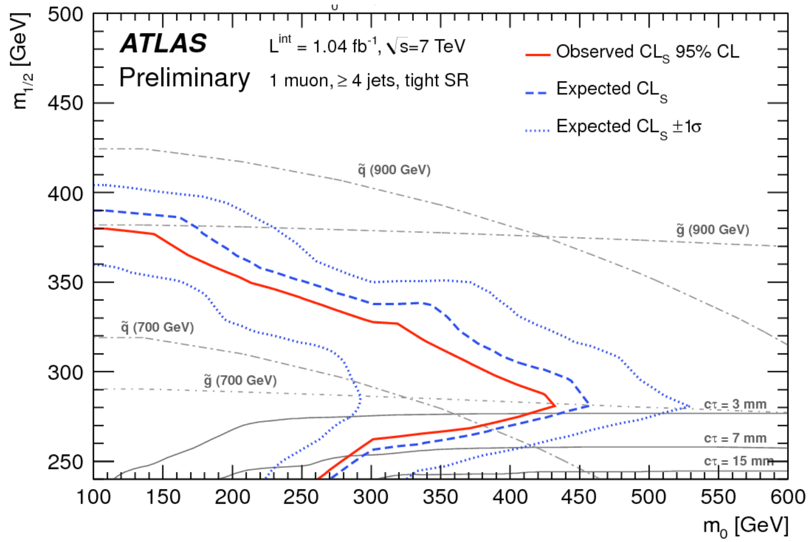
Interpretation in mSUGRA/MSSM, bilinear RPV, simplified models (next page)

mSUGRA/MSSM ($\tan\beta$=10, A_0=0, μ>0)



1.04 fb^{-1}

Bilinear RPV ($\tan\beta$=10, A_0=0, μ>0)



At low m_0, $m_{1/2}$ values below ~350 GeV are excluded

Model tested for cτ up to ~15 mm (prompt muons)

[Grossman &Rakshit,PRD.D69,093002 (20004)]

+ 1-lepton + jets + E_t^{miss} – Simplified Models

95% CL upper limit on visible cross-section for new physics, as a function of $\boxed{x = \left(m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}^{0}}\right) / \left(m_{\tilde{g}(\tilde{q})} - m_{\tilde{\chi}^{0}}\right)}$ **for the gluino (squark) model**

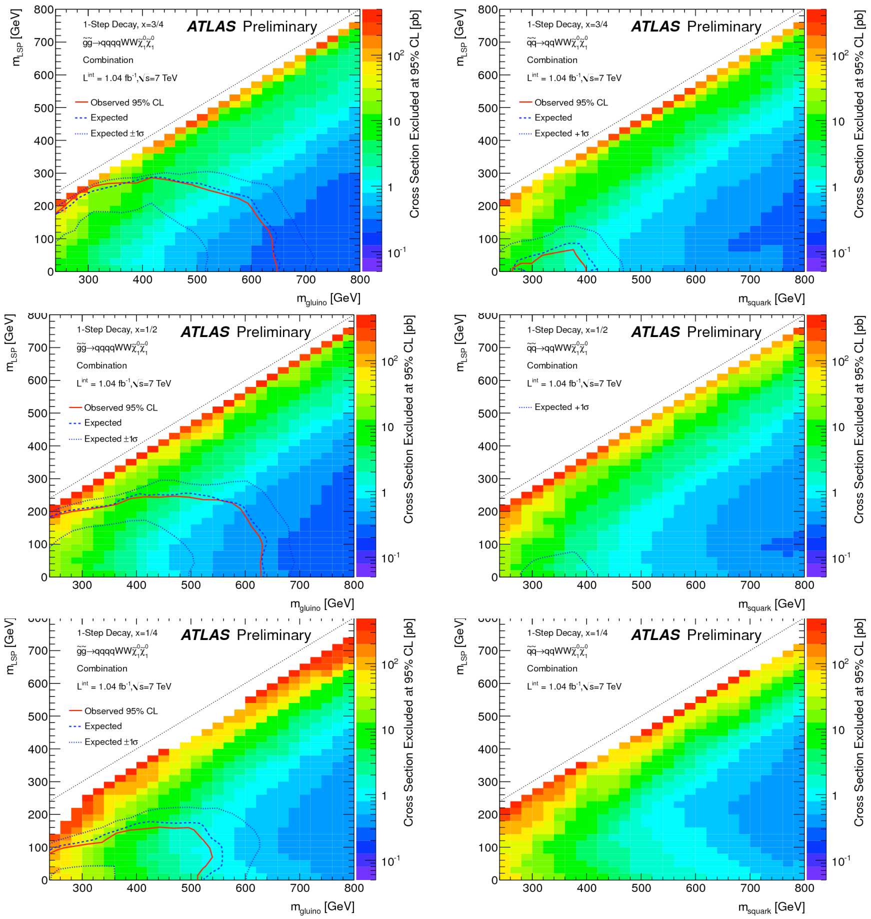
1.04 fb^{-1}

$\boxed{\tilde{g} \rightarrow \tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^{0}}$ $\boxed{\tilde{q} \rightarrow \tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^{0}}$

$\boxed{x = 3/4}$

$\boxed{x = 1/2}$

$\boxed{x = 1/4}$



Identical cross-sections assumed for the electron and muon channels

Colour coding → Model-independent cross-section limit

Exclusion lines → Production cross-sections as calculated with PROSPINO for MSSM

Assuming 100% branching fractions to the assumed decay modes

Gluino model has better sensitivity, including for small x values, due to the inclusion of a 4-jet SR

b-jets + 0/1-lep + E_T^{miss}

SUSY Searches with b-jets

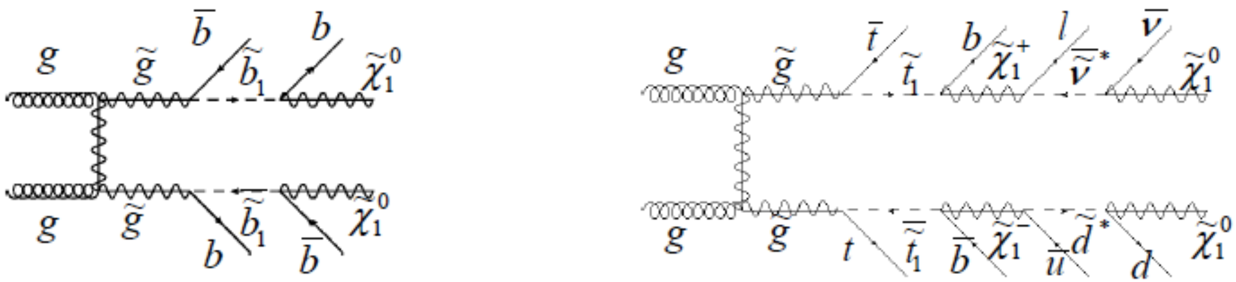
Mixing effects for squarks are proportional to the mass of the fermion partners and become important for 3rd generation squarks

$$m^2(\tilde{t}_{1,2}) = \frac{1}{2}\left[m^2(\tilde{t}_R) + m^2(\tilde{t}_L)\right] \mp \frac{1}{2}\sqrt{\left[m^2(\tilde{t}_R) + m^2(\tilde{t}_L)\right]^2 + 4m^2(t)\left[A_t - \mu\tan\beta\right]^2}$$

Large mixing can yield light sbottom ($\tilde{b}_1$) and stop ($\tilde{t}_1$) squarks

possibly large production cross-sections for sbottom and stop at the LHC

light stop also motivated by naturalness (stop mass <~500 GeV to avoid fine tuning)



Final states with b-jets, 0/1-leptons, light jets and E_T^{miss}

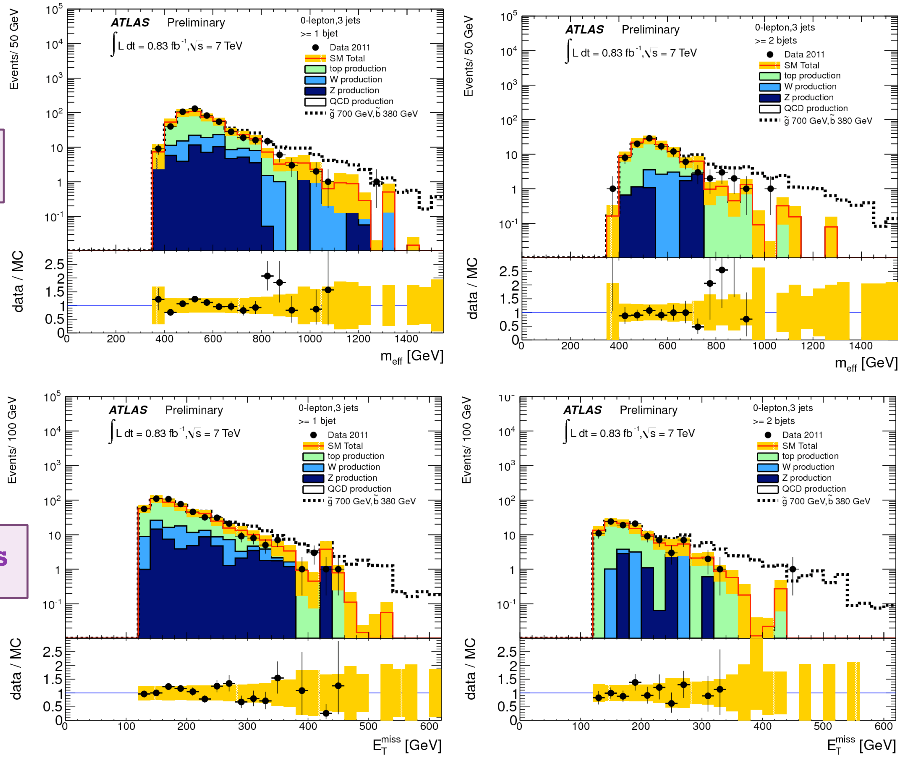
+ b-jets + 0-lepton + E_T^{miss} – Results

0.83 fb^{-1}

>=1 b-jet **>=2 b-jet**

m_{eff}

E_T^{miss}



Good agreement between data and MC before final cut on m_{eff}

Four Signal Regions

(best selection chosen for each signal point)

Signal Region	# b-jets	m_{eff} cut (GeV)
3JA	≥1	500
3JB	≥1	700
3JC	≥2	500
3JD	≥2	700

Lepton veto

Veto e/μ with $p_T(e)>20$ GeV, $p_T(\mu)>10$ GeV

At least 3 jets with p_T > 130, 50, 50 GeV
E_T^{miss}>130 GeV

jet and E_T^{miss} cuts dictated by trigger

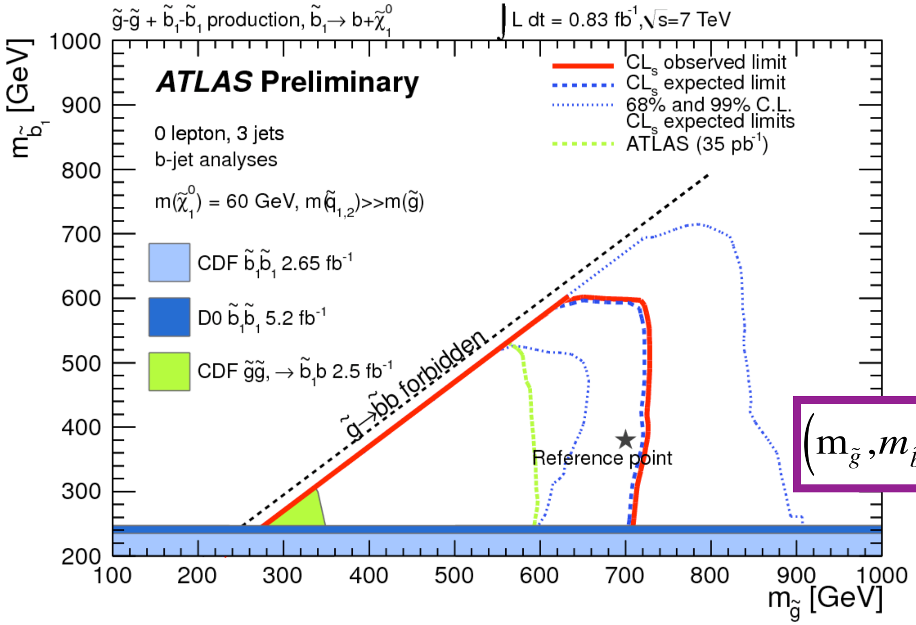
Jets not aligned with E_t^{miss} vector

$\Delta\Phi_{min}(\text{jet}, E_T^{miss})>0.4$

$E_t^{miss}/m_{eff}>0.25$

for further signal enrichment

+ b-jets + 0-lepton + E_T^{miss} – Interpretation



$\left(m_{\tilde{g}}, m_{\tilde{b}_1}\right)$ plane

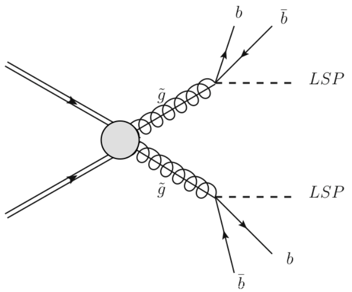
MSSM scenario with 1st/2nd generation squarks at 2 TeV

$$m_{\tilde{g}} > m_{\tilde{b}_1} > m_{\tilde{\chi}_1^0}$$
$$\tilde{b}_1 = \text{lightest squark}$$
$$m_{\tilde{\chi}_1^0} = 60\ GeV$$
$$BR(\tilde{g} \rightarrow b\tilde{b}_1) = 100\%$$

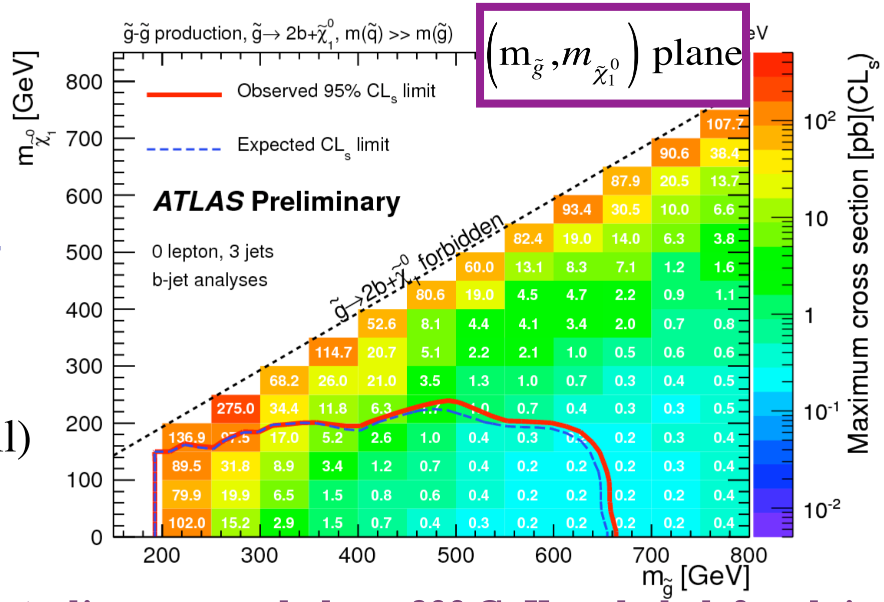
0.83 fb^{-1}

Gluino masses below ~720 GeV excluded for sbottom masses up to ~600 GeV

Simplified Models MSSM-like scenario where all squarks (including light sbottom) are heavy



$$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0 \quad \text{(off - mass - shell)}$$



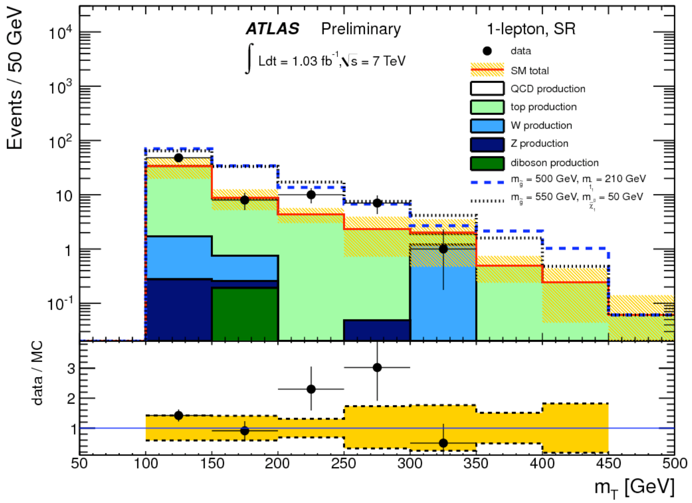
$\left(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}\right)$ plane

Neutralino masses below ~200 GeV excluded for gluino masses of 200-660 GeV **(for m_gluino-m_neutralino)>100 GeV)**

+ b-jets + 1-lepton + E_T^{miss} – Results

1.03 fb^{-1}

m_{eff} , e+μ channels



Selection similar to 1-lep+jets+E_t^{miss}, with b-jets

Exactly 1 lepton

Veto e/μ with p_T(e)>25 GeV, p_T(μ)>20 GeV

Track isolation applied to leptons

>=4 jets with p_T > 50 GeV

>=1 b-jets

E_T^{miss} > 80GeV

m_T > 100 GeV

m_{eff} > 600 GeV

Backgrounds –

QCD – Data-driven

Non-QCD – normalisation from low-mT using MC-based transfer functions

Searching for:

$\tilde{g} \rightarrow \tilde{t}t$, with :

$\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$

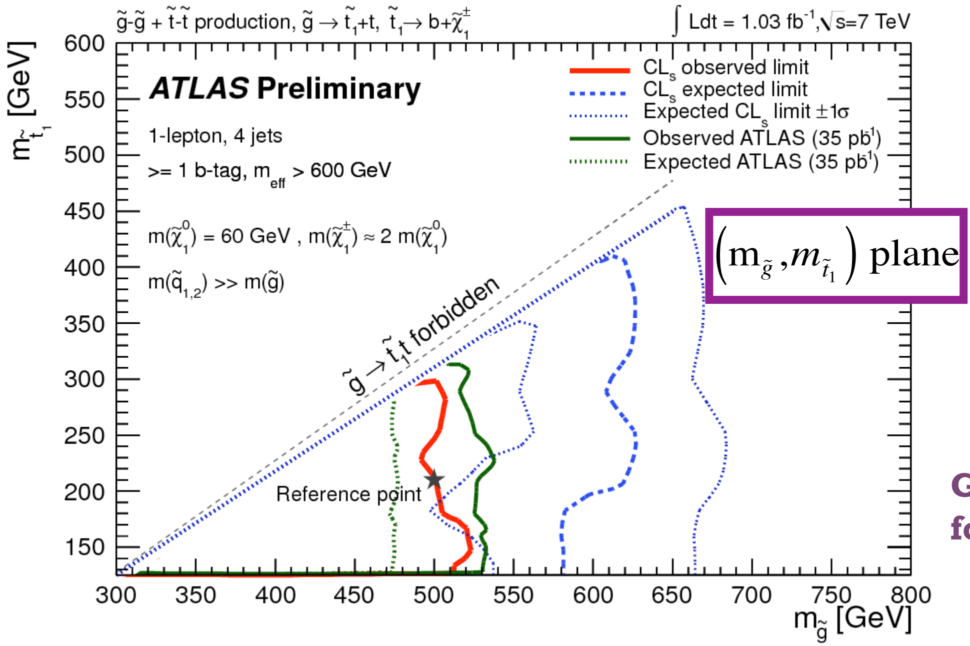
$\tilde{t} \rightarrow t\tilde{\chi}_1^0$

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$

SM (expected): 54.9 ±13.6
Data (seen) : 74

(1.2 σ upward fluctuation)

+ b-jets + 1-lepton + E_T^{miss} – Interpretation



MSSM scenario with 1st/2nd generation squarks, sleptons and sbottom at TeV-scale

$$m_{\tilde{g}} > m_{\tilde{t}_1} > m_{\tilde{\chi}_1^0}$$
$$m_{\tilde{\chi}_1^0} = 60\ GeV$$
$$BR(\tilde{g} \rightarrow \tilde{t}_1 t) = 100\%$$
$$BR(\tilde{t}_1 \rightarrow b\chi_1^{\pm}) = 100\%$$

1.03 fb^{-1}

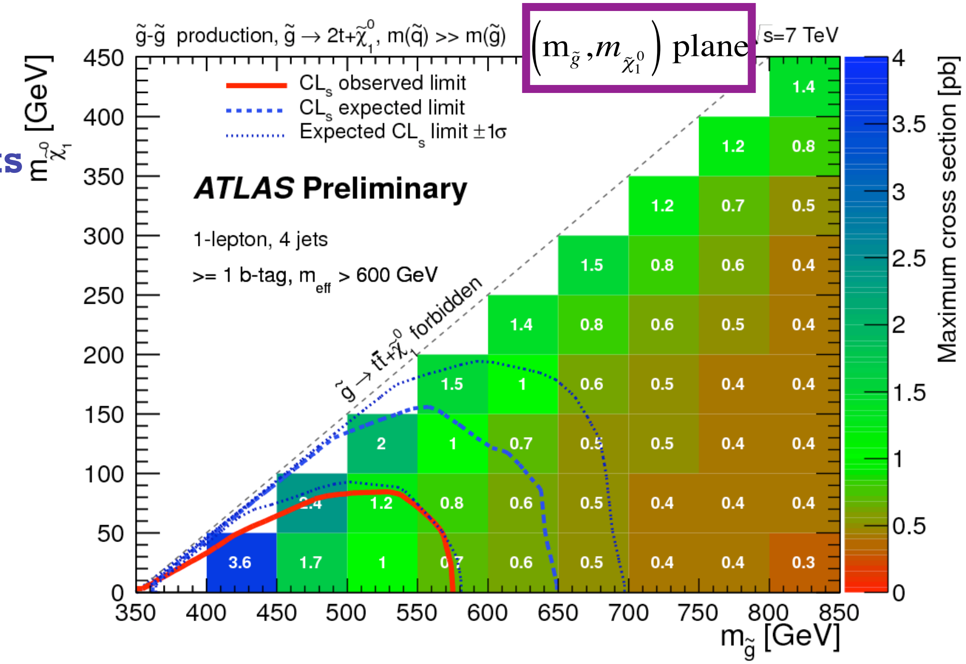
Gluino masses below ~500-520 GeV excluded for stop masses between 125-300 GeV

Simplified models MSSM-like, with all squarks (including 3rd generation) heavy and

$$m_{\tilde{q}_{1,2}} \cong m_{\tilde{b}_1} >> m_{\tilde{t}_1}$$

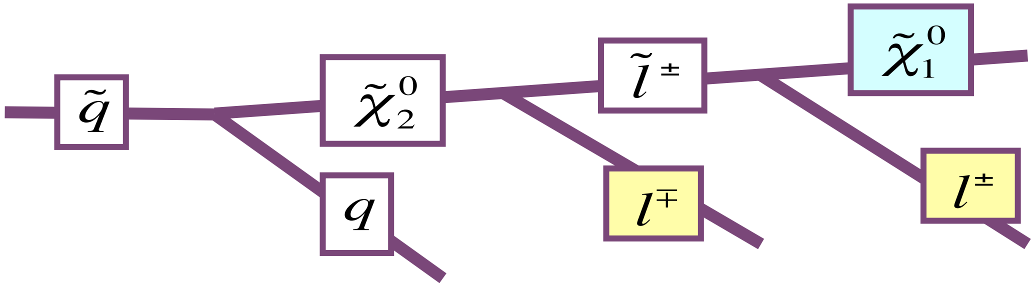
Gluino pair-production the only allowed process, with gluinos decaying off-mass-shell to $\bar{t}t\chi_1^0$

Gluino masses below 570 (540) GeV excluded for neutralino masses below 40 (80) GeV



>= 2-leptons + E_T^{miss}

+ "Multilepton" + E_T^{miss} Signatures



"Lepton" = e, μ

Different combinations of decay modes (a)-(d) on the two legs can give rise to >=2-lepton signatures in the final state:

eg: (a) or (b) on either leg → **Same-Sign (SS) 2-lep**

(c) or (d) on single leg → **Opposite-Sign (OS) or SS 2-lep**

$$
\begin{array}{ll}
(a) & \tilde{\chi}_i^0 \rightarrow l^\pm \nu \tilde{\chi}_i^\mp \\
(b) & \tilde{\chi}_i^\pm \rightarrow l^\pm \nu \tilde{\chi}_j^0 \\
(c) & \tilde{\chi}_i^0 \rightarrow l^\pm l^\mp \tilde{\chi}_j^0 \\
(d) & \tilde{\chi}_i^\pm \rightarrow l^\pm l^\mp \tilde{\chi}_j^\pm
\end{array}
$$

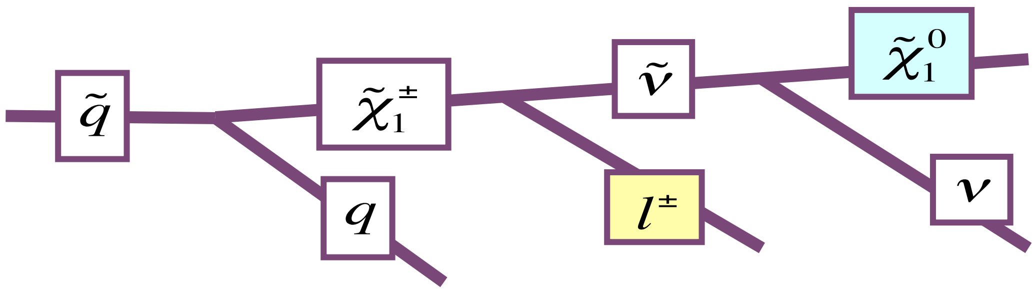
If production of leptons is correlated →

Same-Flavour Opposite-Sign (SFOS) 2-lep

(dilepton mass endpoint → SUSY masses)

Other combinations can also give rise to **>=3-lep**

Background composition different for different flavour and sign combinations



+ SS 2-leptons (+ Jets) + E_T^{miss}

1.04 fb^{-1}

Exactly 2 leptons

$p_T(e) > 20$ GeV (25 GeV if leading)
$p_T(\mu) > 10$ GeV (20 GeV if leading)
$m_{ll} > 12$ GeV

Two control regions

SR	E_t^{miss} cut (GeV)	Leading jets p_T cut (GeV)
SS-SR1	100	--
SS-SR2	80	50, 50

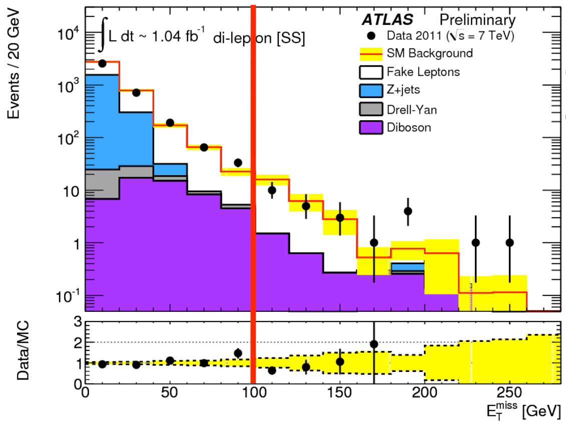
Main backgrounds:

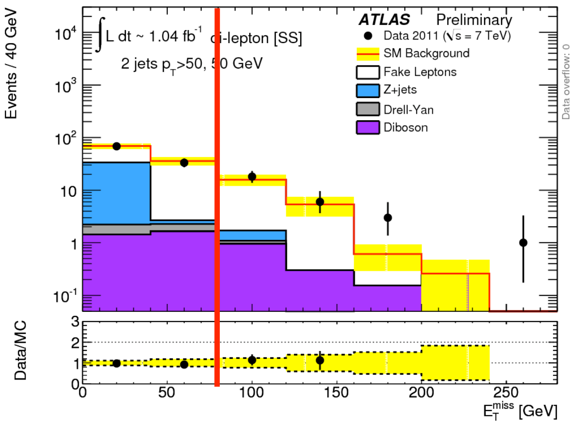
fake leptons

dominant, estimate using "matrix method"

charge misidentification

dibosons





SR	Background	Data	$\sigma\times\varepsilon\times A$ (95% CL)
SS-SR1	32.6±4.4±4.4	25	10.2 fb
SS-SR2	24.9±4.1±6.6	28	20.3 fb

Good agreement with SM expectations

Result interpreted as a limit on the effective cross-section

$\sigma\times\varepsilon\times A$

+ OS 2-leptons (+ Jets) + E_T^{miss}

1.04 fb^{-1}

Exactly 2 leptons

$p_T(e)$ > 20 GeV (25 GeV if leading)
$p_T(\mu)$ > 10 GeV (20 GeV if leading)
m_{ll} > 12 GeV

Backgrounds –

fully leptonic ttbar (dominant), Z+jets (sub-dominant)

normalise data to MC using suitable control regions

dibosons, single top

event yields from MC

fake leptons

"matrix method"

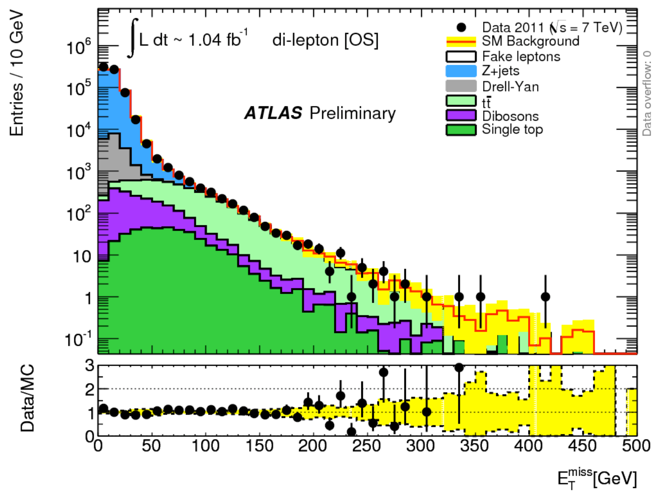
Three control regions

SR	E_T^{miss} cut (GeV)	Leading jets p_T cut (GeV)
OS-SR1	250	--
OS-SR2	220	80, 40, 40
OS-SR3	100	100, 70, 70, 70

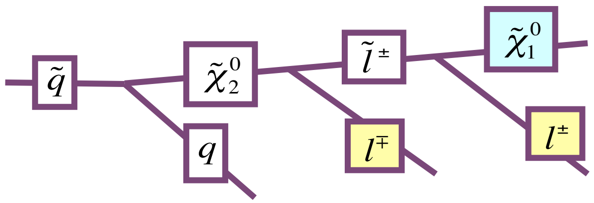
Good agreement with SM expectations

Result interpreted as a limit on the effective cross-section $\sigma \times \varepsilon \times A$ (CLs prescription)

SR	Background	Data	$\sigma\times \varepsilon \times A$ (95% CL)
OS-SR1	15.5±1.2±4.4	13	9.5 fb
OS-SR2	13.0±1.8±4.1	17	15.2 fb
OS-SR3	5.7±1.1±3.5	8	5.0 fb



+ OS "Flavour Subtraction" 2-leptons



Search for excess of SFOS 2-leptons over Different-Flavour (DF) OS 2-leptons

In the presence of SUSY, measure sparticle masses via edges in flavour-subtracted m_{ll} (2-lep invariant mass) distribution

1.04 fb^{-1}

Define quantity S to quantify the excess of SF vs DF 2-leptons

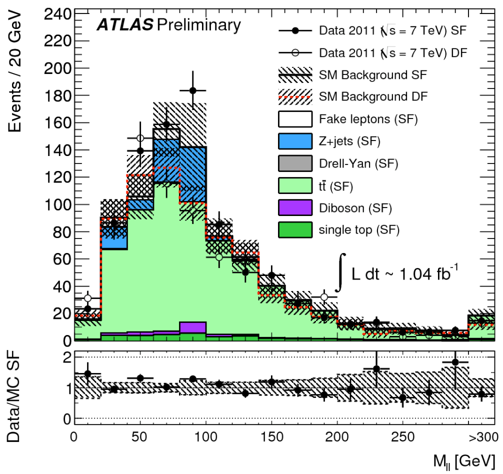
$$S = \frac{N(e^{\pm}e^{\mp})}{\beta\left(1-(1-\tau_e)^2\right)} - \frac{N(e^{\pm}\mu^{\mp})}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^{\pm}\mu^{\mp})}{1-(1-\tau_\mu)^2}$$

β = ratio of e/μ efficiencies

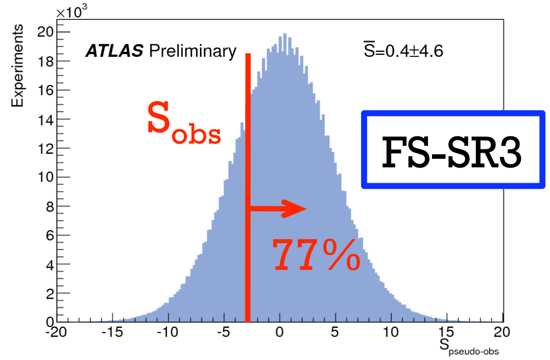
$\tau_{e,\mu}$ = e/μ trigger efficiency

SR	E_t^{miss} cut (GeV)	# Jets	m_{ll} veto (GeV)
FS-SR1	80	2	--
FS-SR2	80	--	80-100
FS-SR3	250	--	--

	S_{obs}	$\bar{S}_b$	RMS
FS-SR1	131.6±0.6(sys)	126.5±23.5±17.2	49.9
FS-SR2	142.2±0.6(sys)	70.0±23.2±16.8	49.1
FS-SR3	-3.1±0.0(03)(sys)	0.4±1.2±1.2	4.6

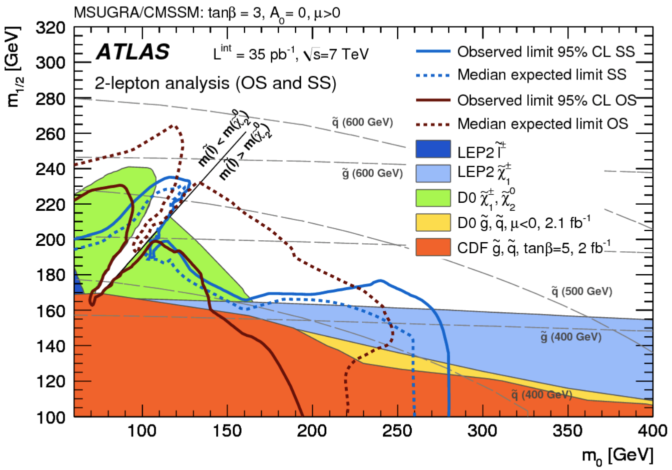


No deviations from SM observed of SF vs DF, in all signal regions



Background-only hypothesis for S (S_b) calculated using pseudo-experiments

+ 2010 Searches with >=2 Leptons



Summary of 2010 2-leptons (SS and OS), mSUGRA/CMSSM

35 pb^{-1}

Signal regions: E_T^{miss}>150 (100) GeV for OS (SS)

95% CL limits on effective cross-section $\sigma \times \varepsilon \times A$:

OS – ee: 0.09 pb; eμ: 0.22 pb; μμ: 0.21 pb

SS – 0.07 pb

"Multilepton" 2010 SR –

≥3 leptons

p_T(lep1,2,3)>20, 20, 20 (10) GeV for e (μ)

M_{ll}>20 GeV and Z-mass veto

≥2 jets with p_T>50 GeV

E_T^{miss} > 50 GeV

Backgrounds is virtually all ttbar

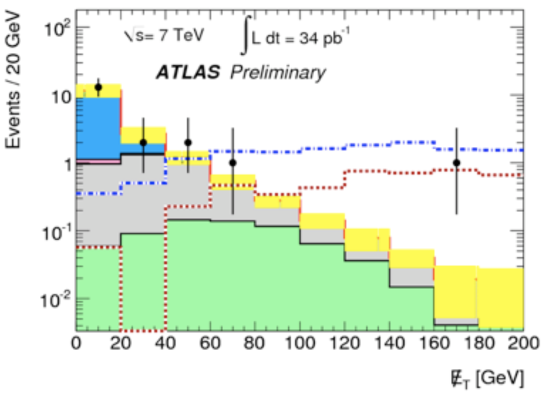
Expect $0.109 \pm 0.023^{+0.036}_{-0.025}$

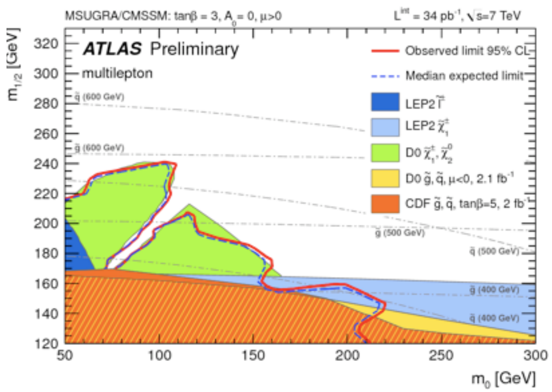
No event survives the selection

Limit on $\sigma \times \varepsilon \times A$: 62 pb

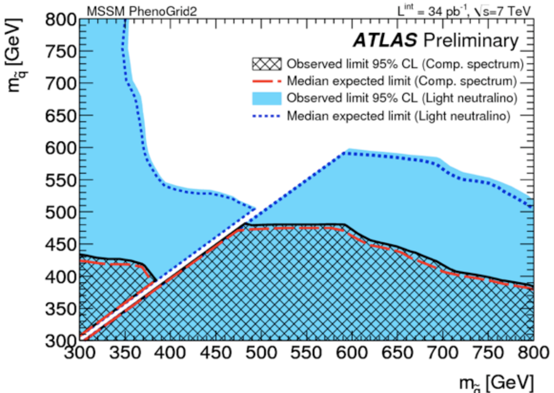
High-E_T^{miss} event removed by the Z-mass veto

34 pb^{-1}





mSUGRA/CMSSM exclusion similar to Tevatron



Also MSSM-24 interpretation, "compressed spectrum"/"light LSP"

$2\gamma + E_T^{miss}$

+ $2\,\gamma + E_T^{miss}$ – Motivations

Gauge Mediated SUSY Breaking (GMSB)

gravitino $\tilde{G}$ is LSP

NLSP (often $\tilde{\chi}_1^0$) dictates phenomenology

di-photon + E_T^{miss} signature from NLSP decays:

$$\boxed{\tilde{\chi}_1^0 \rightarrow \tilde{G}\,\gamma \rightarrow \gamma + E_T^{miss}} \quad (\times 2)$$

$$\boxed{\Rightarrow \quad 2\gamma + E_T^{miss}}$$

Minimal Gauge Mediation (MGM)

one mass scale Λ for the symmetry breaking and
messengers of mass M_{mess}
gluino much heavier than neutralinos

e.g. **SPS8** – assumes unification of gaugino masses at GUT scale
(gaugino pair production dominant)

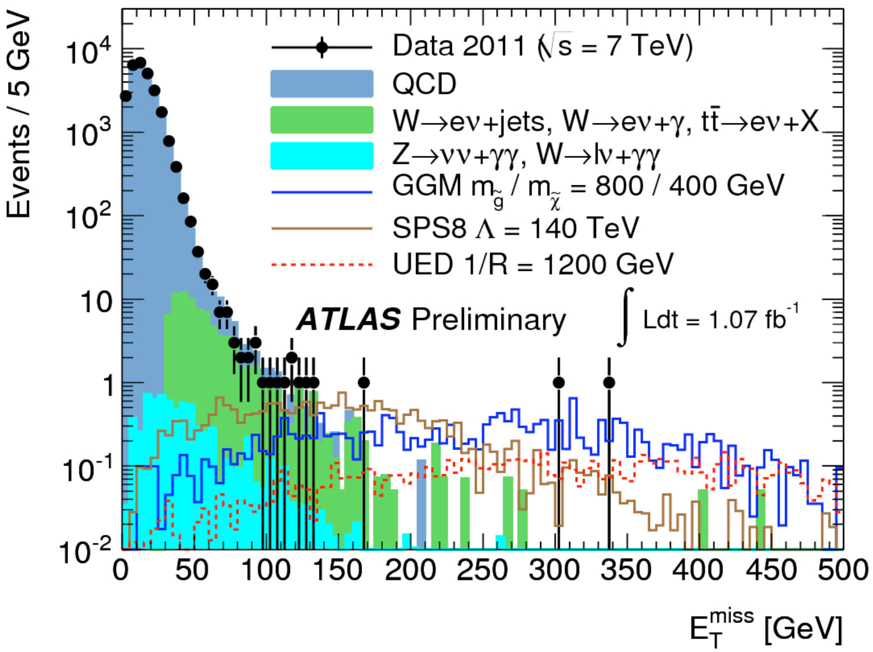
General Gauge Mediation (GGM)

no hierarchy assumed for gluino/squark and gaugino masses

UED models can also give $2\gamma+E_T^{miss}$ signatures

2 γ + E_T^{miss} – Results

1.07 fb^{-1}



Backgrounds

Instrumental effects –
QCD: γγ, γ-jet, -jet-jet
jets faking photons

Genuine –
W+γ, W+jets, and ttbar
electron faking photon
final-state ν → sizable E_T^{miss}

data-driven

Irreducible –
Z→νν+γγ and W→lν+γγ

MC

Signal selection

2 photons, p_T>25 GeV

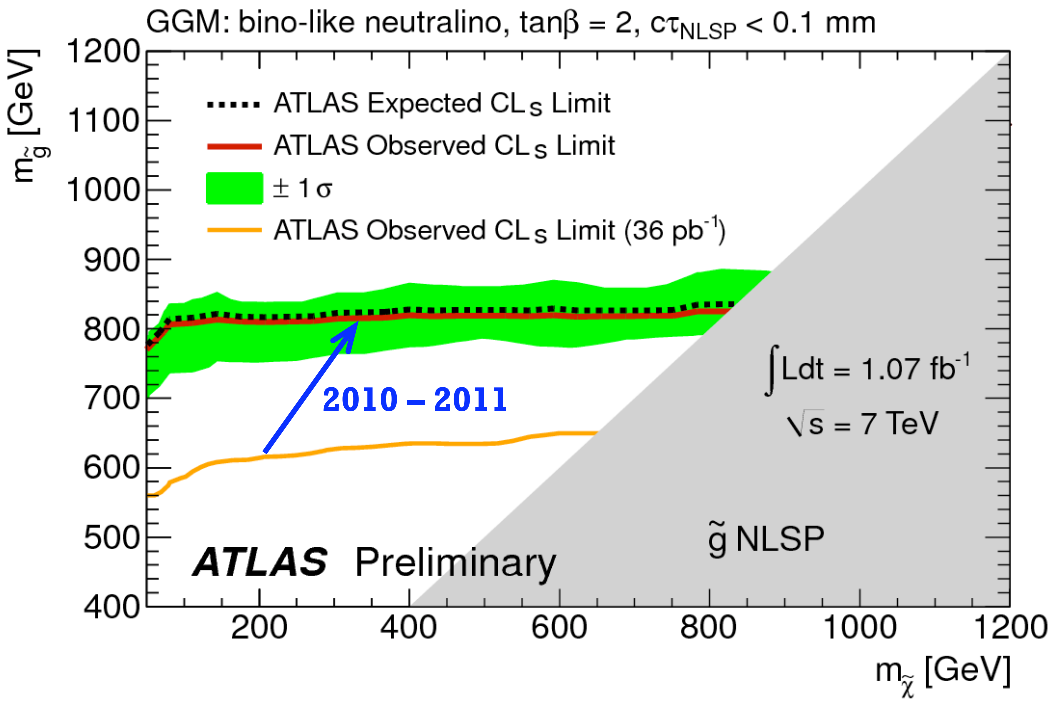
E_T^{miss} > 125 GeV

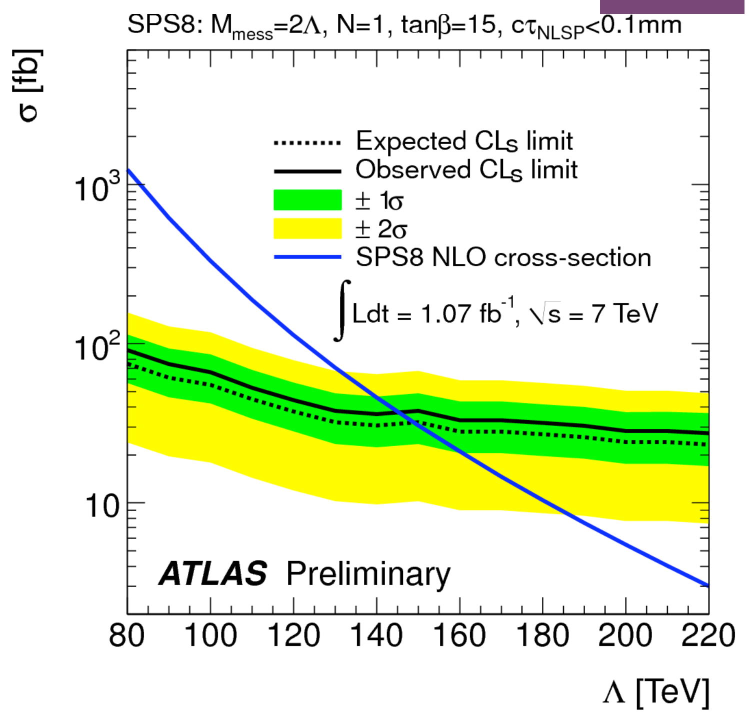
E_T^{miss} range [GeV]	Data events	Predicted background events Total	QCD	$W/t\bar{t}(\to e\nu)+X$	Irreducible
0 - 20	20881	-	-	-	-
20 - 50	6304	5968 ± 29	5951 ± 28	13.3 ± 8.1	3.6 ± 0.3
50 - 75	86	87.1 ± 3.3	60.9 ± 2.8	25.2 ± 1.7	1.0 ± 0.2
75 - 100	11	14.7 ± 1.2	6.7 ± 0.9	7.4 ± 0.8	0.52 ± 0.10
100 - 125	6	4.9 ± 0.7	1.6 ± 0.4	3.0 ± 0.5	0.32 ± 0.08
> 125	5	4.1 ± 0.6	0.8 ± 0.3	3.1 ± 0.5	0.23 ± 0.05

Expected : 4.1±0.6 (stat)±1.4(syst)
Observed: 5

No significant deviation from SM expectations

+ $2\gamma + E_T^{miss}$ – Interpretation





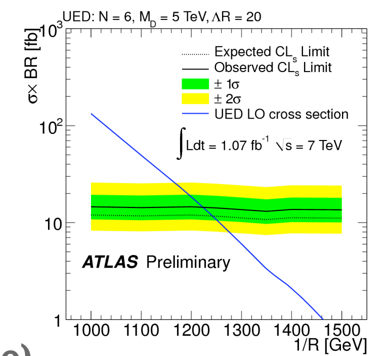
GGM: $m_{\tilde{g}} < 776$ GeV $(m_{\tilde{\chi}} = 50$ GeV$)$

SPS8: $\Lambda < 145$ TeV excluded

1.07 fb^{-1}

Search is generic enough also for **UED models**

1/R <1224 GeV excluded



(See also talk by Sourabh Dube)

Other SUSY Searches

+ Massive Coloured Scalar

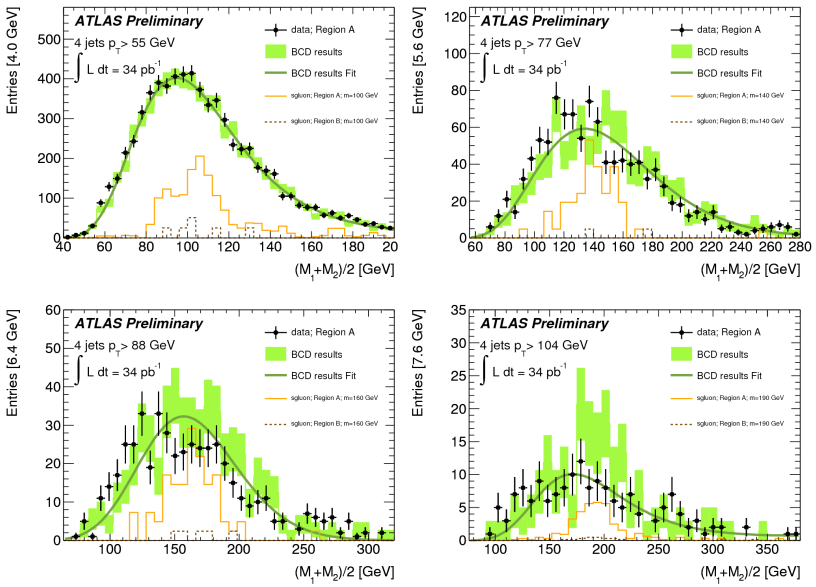
Search for pair-produced scalar particles, each decaying to 2 jets

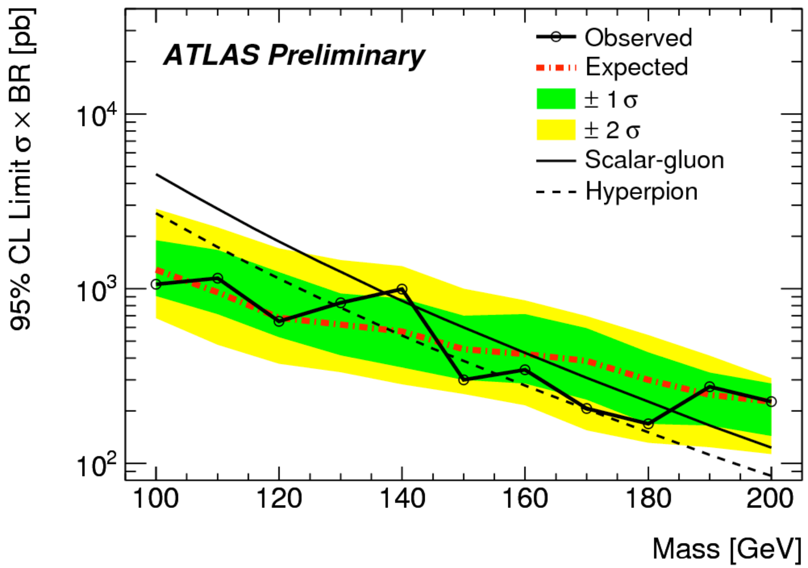
Motivated for example by SUSY models with an extended QCD sector (sgluon)

Signature: 4 jets (2 jet-jet resonances) and no E_T^{miss}

Probe sgluon mass >100 GeV
Pair jet pairs based on proximity of jets (ΔR_{jj})
Require consistency of M_{jj} values from both jet pairs in event ($\Delta M_{jj}/(M_{jj,1}+M_{jj,2})$ <7.5%)
Select central signal (scattering angle of candidate sgluons in 4-jet rest frame |cosθ*|<0.5)

Result based on 2010 data due to availability of low-p_T 4-jet trigger

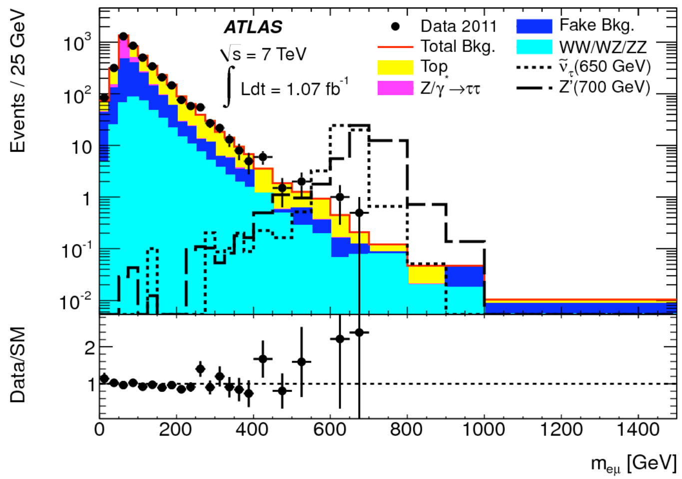


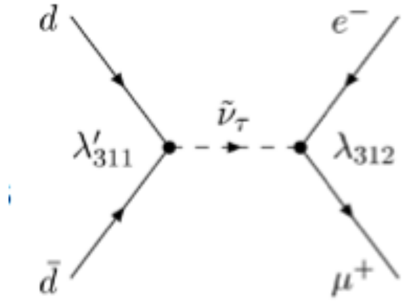


A De Santo, SUSY at ATLAS, BSMLHC 2011

Sgluons with masses between 100-185 GeV (except ~5 GeV window around 140 GeV) excluded at 95% CL

RPV Scalar Tau Neutrino

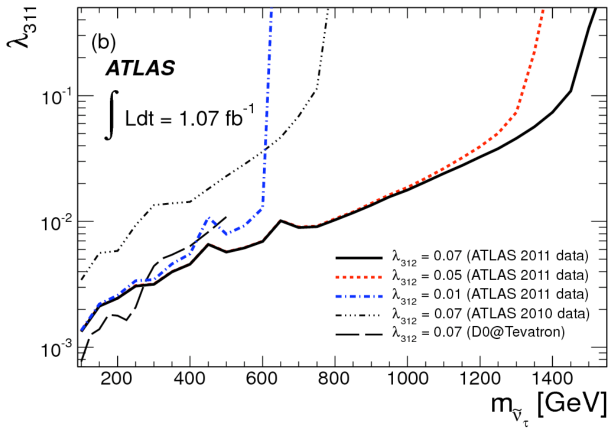


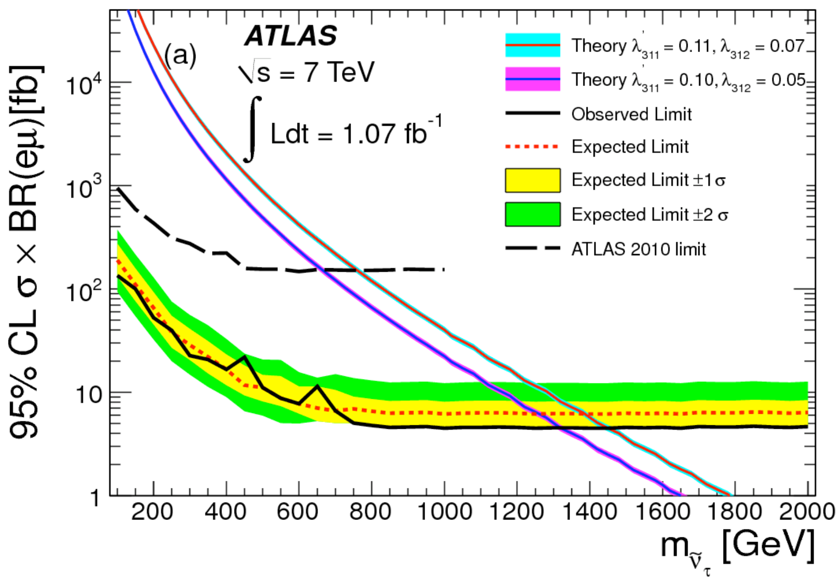


Search for an excess at high values of the opposite-charge eμ invariant mass spectrum

Signal possibly originating from resonant decays of neutral sparticles in RPV SUSY

1.07 fb^{-1}

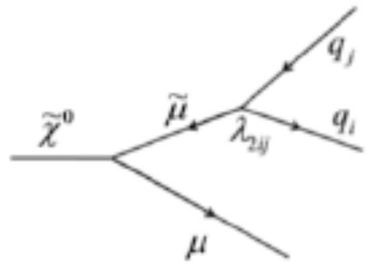


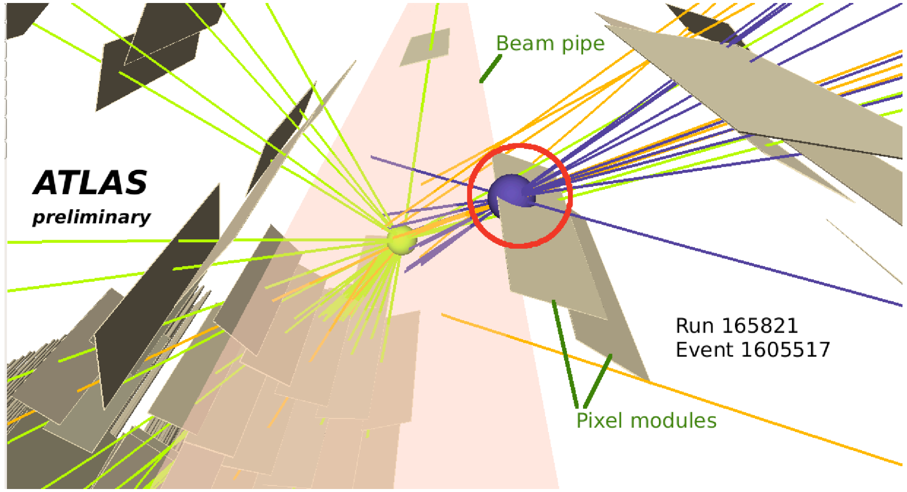


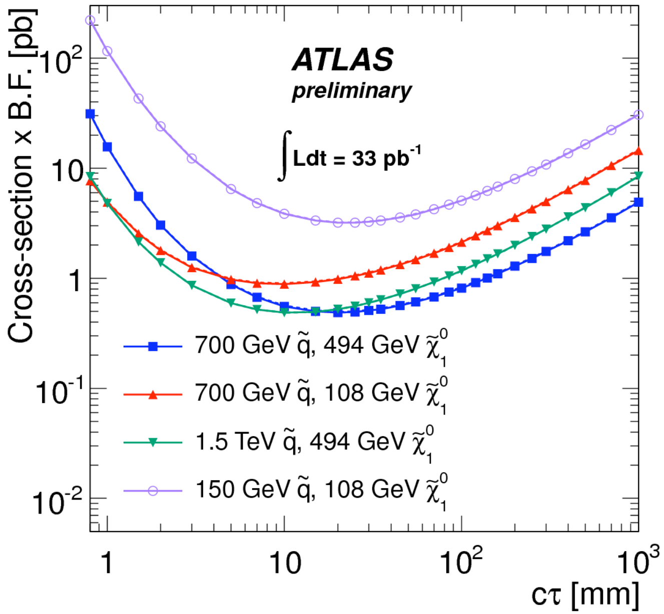
Null result translates into limit on σ × BR and on the coupling constants as a function of the mass of the scalar neutrino

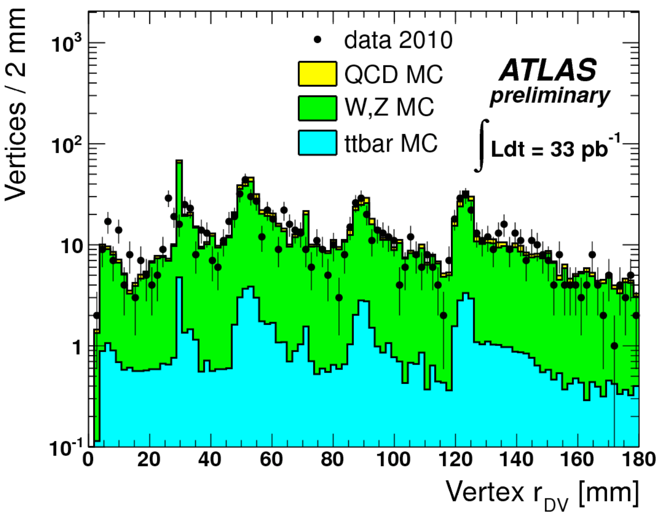
See Dongliang Zhang's talk

+ RPV SUSY – Displaced Vertices









33 pb^{-1}

Search for heavy medium-lived particles in the inner detector

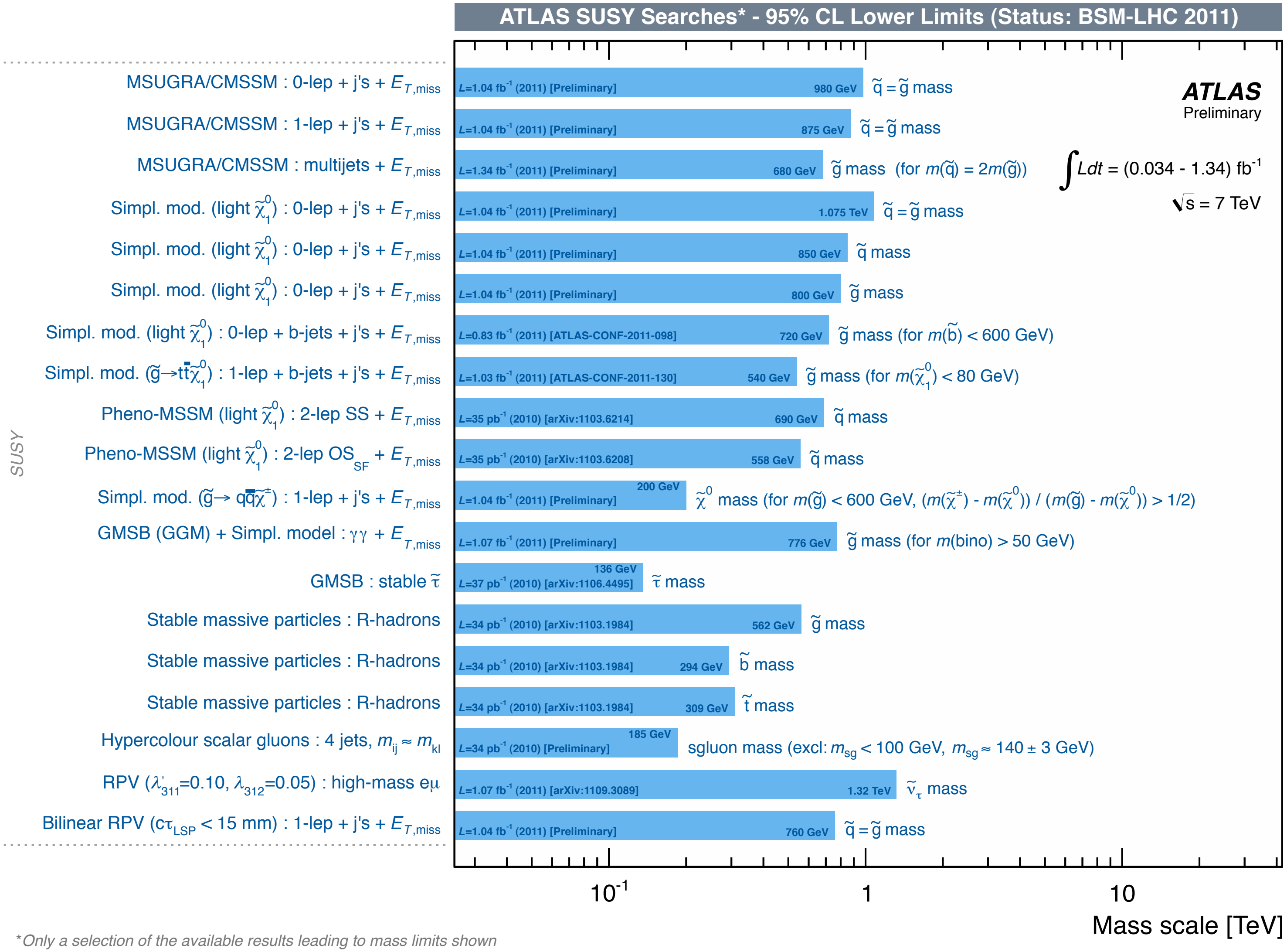
Signature: displaced vertex + high-pT muon

Crucial to have a very good understanding of tracking and of the spatial distribution of passive material

See Philippe Mermod's talk
also for more results on long-lived particles

Summary and Conclusions

Summary of SUSY Searches at ATLAS



Conclusions

ATLAS has produced an impressive range of results from SUSY searches in 2010 and 2011 collision data

Sadly, no SUSY just yet ☹

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It was not around the corner!!

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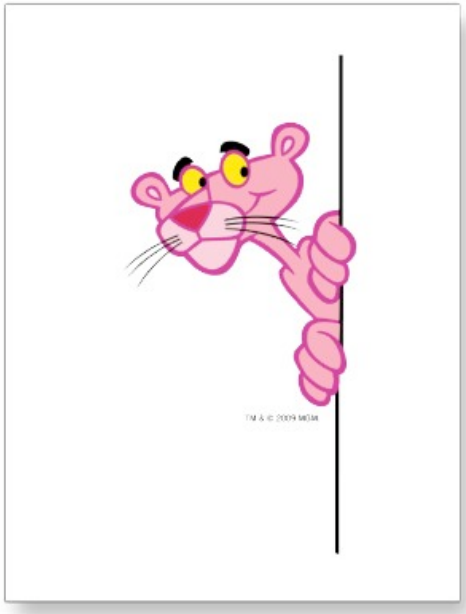
But a lot more results still to come…



Conclusions

ATLAS has produced an impressive range of results from SUSY searches in 2010 and 2011 collision data

Sadly, no SUSY just yet ☹

It was not around the corner

But a lot more data still to come…
… and plenty of data too!

Can’t We See the Wood for the Trees ??

Backup Slides

+ 0-lepton Analysis – Results

1.04 fb^{-1}

Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, $m_{\mathrm{eff}} > 500$ GeV	$\geq$ 4-jet, $m_{\mathrm{eff}} > 1000$ GeV	High mass
Z/γ+jets	32.5 ± 2.6 ± 6.8	25.8 ± 2.6 ± 4.9	208 ± 9 ± 37	16.2 ± 2.1 ± 3.6	3.3 ± 1.0 ± 1.3
W+jets	26.2 ± 3.9 ± 6.7	22.7 ± 3.5 ± 5.8	367 ± 30 ± 126	12.7 ± 2.1 ± 4.7	2.2 ± 0.9 ± 1.2
$t\bar{t}$+ Single Top	3.4 ± 1.5 ± 1.6	5.6 ± 2.0 ± 2.2	375 ± 37 ± 74	3.7 ± 1.2 ± 2.0	5.6 ± 1.7 ± 2.1
QCD jets	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.74 ± 0.14 ± 0.51	2.10 ± 0.37 ± 0.83
Total	62.3 ± 4.3 ± 9.2	55 ± 3.8 ± 7.3	984 ± 39 ± 145	33.4 ± 2.9 ± 6.3	13.2 ± 1.9 ± 2.6
Data	58	59	1118	40	18

Backgrounds partially correlated → uncertainties on total background estimates not quadrature sum of individual components

Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, $m_{\mathrm{eff}} > 500$ GeV	$\geq$ 4-jet, $m_{\mathrm{eff}} > 1000$ GeV	High mass
Excluded $\sigma\times$ Acc $\times\varepsilon$ (fb)	24	30	477	32	17

Result are interpreted as a 95% CL exclusion limit on the effective cross section $\sigma\times\varepsilon\times A$

(profile likelihood ratio approach, CLs prescriptions)

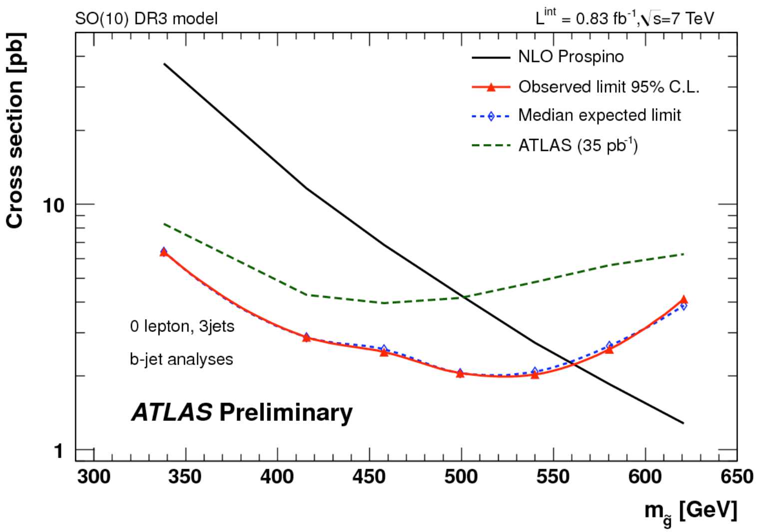
b-jets + 0-lepton + E_T^{miss} – Interpretation

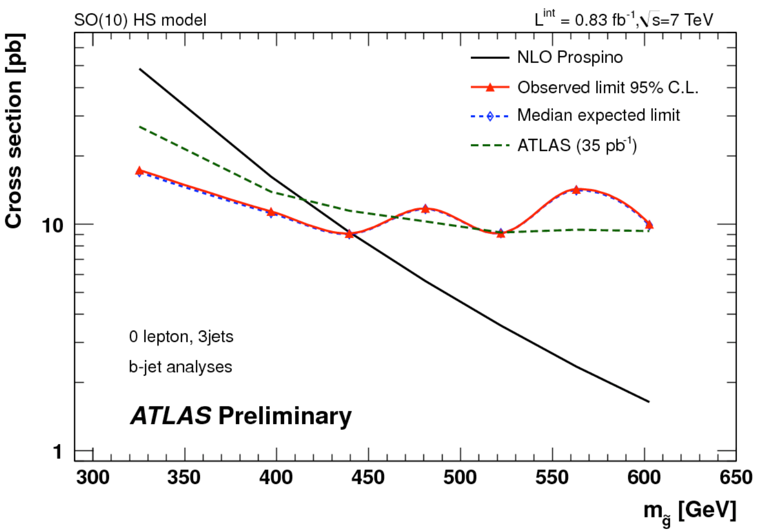
Interpretation in terms of SO(10) GUTs

gluino mass ~300-600 GeV
chargino mass 100-180 GeV
LSP neutralino mass 50-90 GeV, m(chi20)~2m(chi10)
$1^{st}/2^{nd}$ generation scalars: m~10 TeV
3^{rd} generation squarks: m~1-3 TeV
gluino→bbar chi10 or gluino→bbbar chi20

0.83 fb^{-1}

Two specific models – D-term splitting model (DR3) and Higgs splitting model (HS)





2-lepton SS analysis

1.04 fb^{-1}

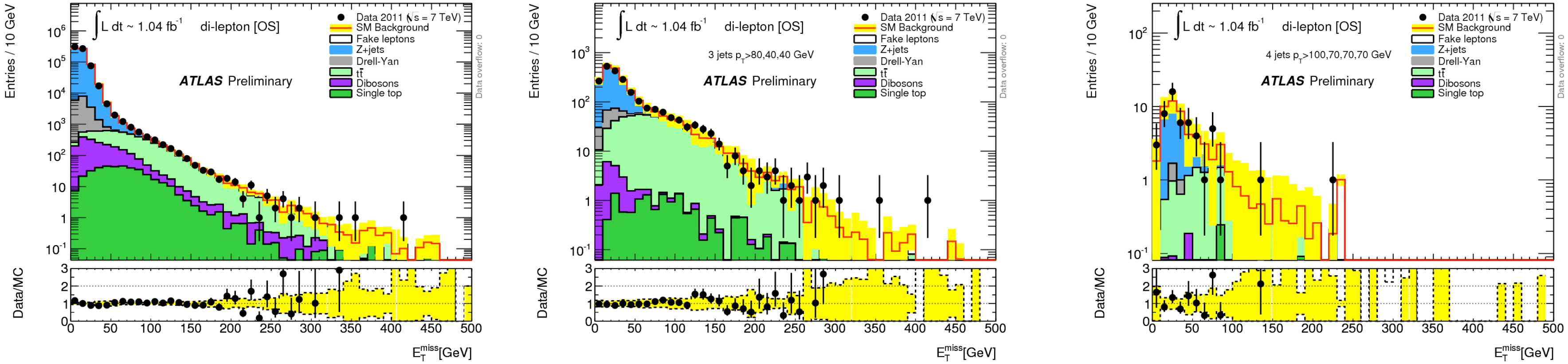
Same Sign [SS-SR1]	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Fake	3.5±0.7±2.0	14.4±3.2±0.6	9.2±4.0±1.8
Charge flip	0.73±0.05±0.06	1.10±0.07 ±0.08	*neg.*
Dibosons	0.79±0.27±0.05	1.7±0.4±0.3	1.1±0.2±0.1
Standard Model	5.0±0.8±2.0	17.2±3.2±0.6	10.3±3.0±1.8
Cosmics	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
Observed	6	14	5

Same Sign [SS-SR2]	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Fake	1.5±0.5±2.0	13.4±3.2±2.7	6.7±2.5±1.8
Charge flip	0.59±0.04±0.04	1.36±0.05±0.06	*neg.*
Dibosons	0.25±0.06±0.13	0.9±0.2±0.2	0.64±0.05±0.02
Standard Model	2.4±0.5±2.0	15.6±3.2±2.7	6.9±2.5±1.8
Cosmics	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
Observed	4	14	10

For 2010 Results, see:
EPJC 71 (2011) 1682

2-lepton OS analysis

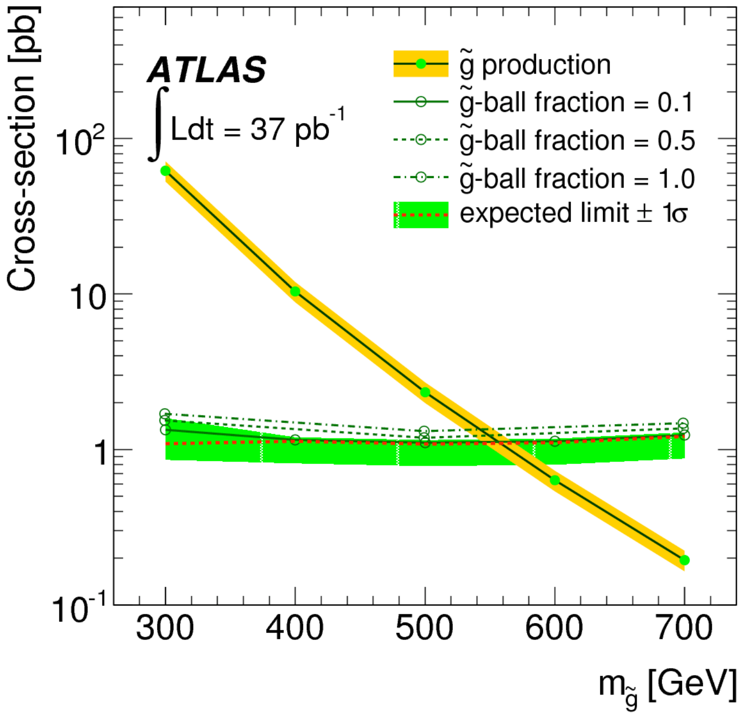
1.04 fb^{-1}

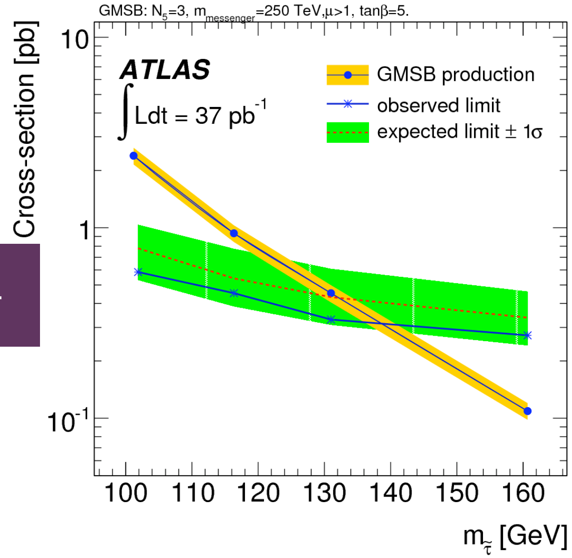


Signal Region	OS-SR1	OS-SR2	OS-SR3	SS-SR1	SS-SR2	FS-SR1	FS-SR2	FS-SR3
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	250	220	100	100	80	80	80	250
Leading jet p_{T} [GeV]	-	80	100	-	50	-	-	-
Second jet p_{T} [GeV]	-	40	70	-	50	-	-	-
Third jet p_{T} [GeV]	-	40	70	-	-	-	-	-
Fourth jet p_{T} [GeV]	-	-	70	-	-	-	-	-
Number of jets	-	-	-	-	-	-	≥ 2	-
m_{ll} veto [GeV]	-	-	-	-	-	80-100	-	-

For 2010 Results, see:
EPJC 71 (2011) 1682

Long-lived Particles

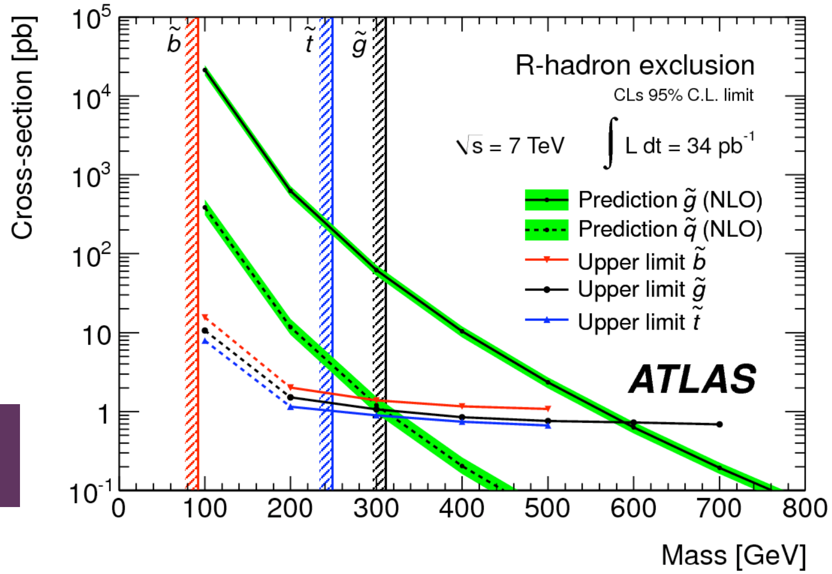




37 pb^{-1}

(see **P. Mermod's talk)**

34 pb^{-1}



Some SUSY Scenarios

- mSUGRA/CMSSM:
  - **m_0:** common scalar mass
  - **$m_{1/2}$:** common gaugino mass
  - **A_0:** common trilinear coupling
  - **tan β:** ratio of Higgs vacuum expectation values
  - **sign(μ):** sign of SUSY Higgs potential parameter

- GMSB:
  - **Λ:** SUSY breaking scale
  - **M:** messenger mass scale
  - **N:** number of messenger fields
  - **tan β:** ratio of Higgs vacuum expectation values
  - **sign(μ):** sign of SUSY Higgs potential parameter
  - C_{grav}: ratio of the gravitino mass to its value at the breaking scale Λ