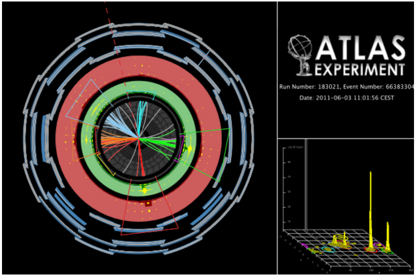
Searches for jets + E_T^{miss} + 0 leptons at ATLAS

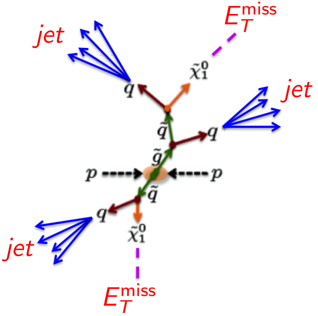
Tanya Sandoval
on behalf of the ATLAS Collaboration



UNIVERSITY OF CAMBRIDGE

Workshop on Searches for Supersymmetry at the LHC
LBNL, Oct 19-21 2011

- **LHC**'s high sensitivity to SUSY $\rightarrow$ squark & gluino factory
- Final-state of many SUSY models *e.g.* **R-parity conserving:**



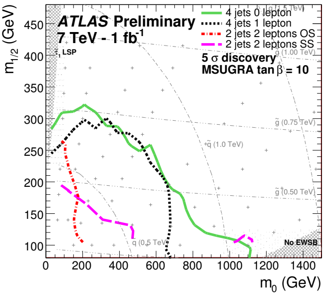
sparticles produced in pairs

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

decay chains and stable LSP

$$\left.\begin{array}{lcl} \tilde{g} & \rightarrow & q\bar{q}\tilde{\chi}_1^0 \\ \tilde{q} & \rightarrow & q\tilde{\chi}_1^0 \end{array}\right\} \begin{array}{l} \textit{high-}p_T \textit{ jets} + \\ \textit{moderate to large } E_T^{miss} \end{array}$$

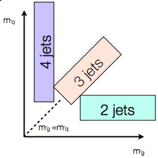
- **Simple & general signature**
- **High discovery reach**



ATL-PHYS-PUB-2010-010 [1]

Strategy - in a nutshell

- **Signal Regions (SRs) defined to maximise sensitivity to diff. models**

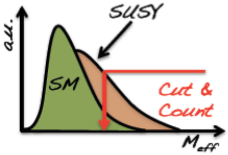


larger E_T^{miss} lower jet multiplicity	lower E_T^{miss} higher jet multiplicity
⬇	⬇
2-4 jet searches	6-8 jet searches
⬇	⬇
$m_{\text{eff}} = E_T^{\text{miss}} + H_T$	$E_T^{\text{miss}} / \sqrt{H_T'}$

- **Discriminating variables to maximise significance**

$$H_T, H_T' = \sum_{jets} p_T$$

- **Search for non-SM excess in m_{eff} and $E_T^{\text{miss}}/\sqrt{H_T'}$ tails $\rightarrow$ BG estimation crucial**
    - data-driven methods where possible
    - otherwise from MC



- **If no excess, set model-indep. limits**

$$\sigma_{\text{SUSY}} \times \varepsilon \times A$$

Inclusive 2-4 jet searches @ 1.04 fb^{-1}

2-4 jet search details :: SR Event Selection

- **5 different SRs** from $\geq n$-jets and m_{eff} cut
- After selecting good data-quality events with **no leptons**:

		$\tilde{q}\tilde{q}$	$\tilde{q}\tilde{g}$	$\tilde{g}\tilde{g}$	
	Signal Region	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet	High mass
Trigger requirements	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 130	> 130	> 130	> 130
	Leading jet p_{T}	> 130	> 130	> 130	> 130
Channel definition	Second jet p_{T}	> 40	> 40	> 40	> 80
	Third jet p_{T}	–	> 40	> 40	> 80
	Fourth jet p_{T}	–	–	> 40	> 80
QCD rejection	$\Delta\phi(\text{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\min}$	> 0.4	> 0.4	> 0.4	> 0.4
	$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	m_{eff}	> 1000	> 1000	> 500/1000	> 1100

arXiv:1109.6572[2]

$\Delta\phi$ cut up to 3rd leading jet

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{\text{SR jets}} p_T \qquad m_{\text{eff}}^{\text{incl}} = E_T^{\text{miss}} + \sum_{\text{jets } p_T > 40} p_T$$

2-4 jet search details :: Background Estimation

Main backgrounds:

1. $Z/W+$jets — $Z \to \nu\nu$, $W \to l\nu$
2. TOP — $t\bar{t}/t \to$ jets
3. QCD — multijets, $b \to l\nu$

$\underbrace{\qquad\qquad\qquad\qquad}_{\text{true \& fake } E_T^{\text{miss}} \text{ from } \nu\text{'s \& mismeasured jets}}$

Method:

- ≥ 1 Control Region (CR) per background per SR, such that:

$$\text{CR} \xrightarrow{\text{Transfer Factor (TF)}} \text{SR}$$

$$\text{TF} = \frac{N(\text{SR,raw,proc})}{N(\text{CR,raw,proc})}$$

CR:

✔ Data-driven

✔ As close as possible to SR
to minimize extrapolation with reasonable stats.

✔ High purity ($> 50\%$) w.r.t calibration process

TF:

✔ from MC and/or data

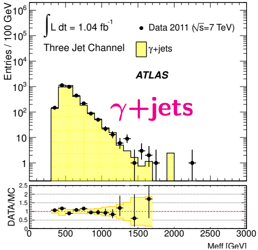
✔ ratio reduces uncert's

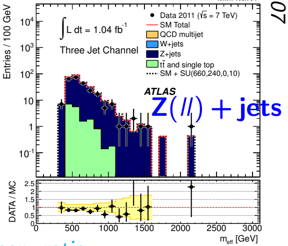
- Final result obtained from a **combined** likelihood **fit to all CRs**
  - handles mutual CR contamination & correlated uncert's

- **2 Control Regions:**

for $p_T > M_Z$, $p_T(\gamma) \propto p_T(Z)$ *arXiv:1107.2803[3]*

CR	γ+jets (high-purity)	$Z(ee, \mu\mu)$ +jets
Data-driven	✔	✔
Large stats	✔	✗
Small theory uncert's	✗	✔
Definition	· 1 iso. γ · $p_T(\gamma) \rightarrow E_T^{miss}$	· 2 iso. leptons · $p_T(Z) \rightarrow E_T^{miss}$ · looser m_{eff} cuts
TF	from MC & data	from MC
main uncert's	· acceptance · theory Z/γ	· stats · theory extrapol. · JES/JER





SUSY-2011-07

- **Example Transfer Function:**

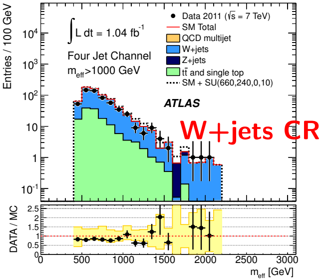
γ+jets

$$\mathrm{TF}(p_T) = \left[\frac{\overbrace{(1 - f_{bkg})}^{\text{photon purity}}}{\underbrace{A^{\gamma}(p_T) \cdot \varepsilon^{\gamma}(p_T)}_{\text{photon eff. and acceptance}}} \cdot \overbrace{R_{Z/\gamma}(p_T)}^{\text{theory ratio}} \cdot Br(Z \rightarrow \nu\nu) \right]$$

2-4 jet search details :: W and Top Backgrounds

W+jets

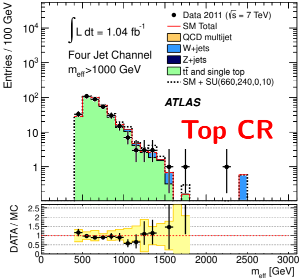
- **data-driven CR**
  - · 1 iso. lepton (e, μ), treated as jet
  - · $30 < m_T < 100$ GeV
  - · b-tag veto
  - · looser m_{eff} cuts
- **TF from MC**
  - · main uncert's: stats, theory extrapol, JES/JER, b-tagging



SUSY-2011-07

Top

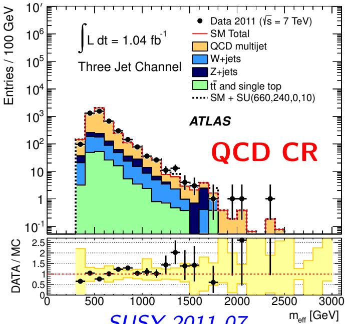
- **data-driven CR**
  - · as in $W+$jets except
    b-tag veto $\rightarrow$ b-tag required
- **TF from MC**
  - · main uncert's: as in $W+$jets



2-4 jet search details :: QCD background, Overall results

QCD

- **data-driven CR**
  - reversing $\Delta\phi(jet, E_T^{miss})_{min}$ cut
- **TF from Data**
  - pseudo-events with large E_T^{miss} obtained by jet-smearing low-E_T^{miss} events with 'jet response function'
  - main uncert's: jet response modelling



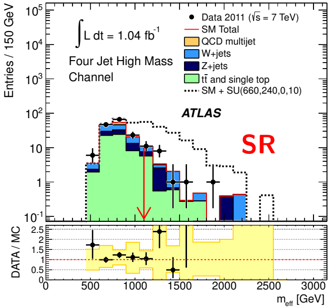
SUSY-2011-07

Overall Background results

✔ Validated: **data-driven** methods agree with the **MC** expectation

✔ For each SR, estimate taken from a **combined fit** (to the 5 CRs, TFs and uncert's)

- **No significant excess in SRs with respect to SM expectation:**

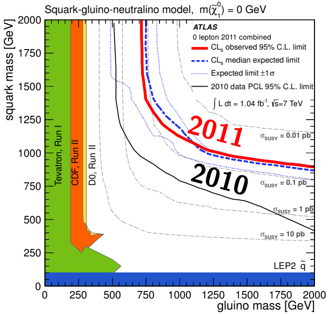


Process	arXiv:1109.6572[2] Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, m_{eff} > 500 GeV	$\geq$ 4-jet, m_{eff} > 1000 GeV	High mass
Z/γ+jets	32.3 ± 2.6 ± 6.9	25.5 ± 2.6 ± 4.9	209 ± 9 ± 38	16.2 ± 2.2 ± 3.7	3.3 ± 1.0 ± 1.3
W+jets	26.4 ± 4.0 ± 6.7	22.6 ± 3.5 ± 5.6	349 ± 30 ± 122	13.0 ± 2.2 ± 4.7	2.1 ± 0.8 ± 1.1
$t\bar{t}$+ single top	3.4 ± 1.6 ± 1.6	5.9 ± 2.0 ± 2.2	425 ± 39 ± 84	4.0 ± 1.3 ± 2.0	5.7 ± 1.8 ± 1.9
QCD multi-jet	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.73 ± 0.14 ± 0.50	2.10 ± 0.37 ± 0.82
Total	62.4 ± 4.4 ± 9.3	54.9 ± 3.9 ± 7.1	1015 ± 41 ± 144	33.9 ± 2.9 ± 6.2	13.1 ± 1.9 ± 2.5
Data	58	59	1118	40	18
Excluded σxAxε (fb)	**24**	**30**	**477**	**32**	**17**

- **Exclusion limits prescription:**
  - ✔ CL_s (95% CL) on $\sigma_{SUSY} \times A \times \varepsilon$ (model-indep)
  - ✔ statistic: Profile likelihood Ratio
  - ✔ SR with best expected limit chosen for each point
  - ✔ 2 different interpretations

1. Simplified Model

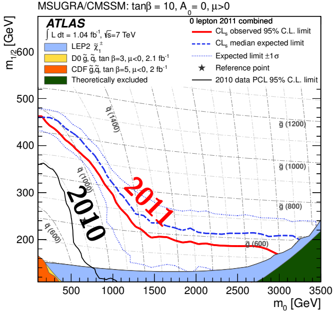
- **Pheno. MSSM**
  - · LSP ($m_{\mathrm{LSP}} = 0$)
  - · $\tilde{g}$ and $\tilde{q}$ (1st and 2nd gen.) $m = 100$ GeV - 2 TeV
  - · other sparticles $m = 5$ TeV
- **up to 1 TeV exclusion if $m_{\tilde{g}} = m_{\tilde{q}}$**
- **Limit stable up to $m_{\mathrm{LSP}} \sim 200$ GeV**



arXiv:1109.6572[2]

2. CMSSM/mSUGRA

- $A_0 = 0, \mu > 0, \tan\beta = 10$
- **larger jet multiplicities SRs → larger m_0 reach**
- **up to 980 GeV exclusion if $m_{\tilde{g}} = m_{\tilde{q}}$**
- $m_{1/2} < 450$ **GeV excluded at low** m_0



Inclusive 6-8 jet searches ("multijet" analysis) @ 1.34 fb^{-1}

6-8 jet search details :: SR Event Selection

- **Extension of 2-4 jet analysis** to $\uparrow$ sensitivity to larger multiplicities with moderate E_T^{miss}
- **New challenge:** multi-jet events poorly modelled in MC
  - $\rightarrow$ want variable invariant under jet multiplicity to $\downarrow$ MC dependence

2-4 jet search

$\Delta\phi(E_T^{\text{miss}}, \text{jet})$

$E_T^{\text{miss}} / m_{\text{eff}}$

m_{eff}

6-8 jet search

$\mathbf{E_T^{miss}} / \sqrt{\mathbf{H_T}}$ $(H_T = \sum_{\text{jets}} p_T$

jet $p_T > 40$ GeV, $|\eta| < 2.8$)

since E_T^{miss} resolution $\sim \sqrt{H_T}$ for these events

- **Event Selection:**

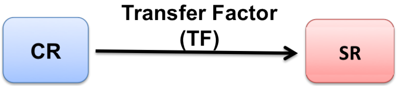
	Signal region	7j55	8j55	6j80	7j80
Trigger requirements	Jet p_T	> 55 GeV		> 80 GeV	
	Jet $\|\eta\|$	< 2.8			
	ΔR_{jj}	> 0.6 for any pair of jets			
SR definition	Number of jets	≥ 7	≥ 8	≥ 6	≥ 7
BG reduction and cotrol	$E_T^{\text{miss}} / \sqrt{H_T}$	> 3.5 GeV$^{1/2}$			

arXiv:1110.2299v1[4]

6-8 jet search details :: Background Estimation

Main backgrounds:

1. **multijet QCD + fully hadronic $t\bar{t}$** $(t\bar{t} \to qq)$
requires data-driven methods as MC not good enough

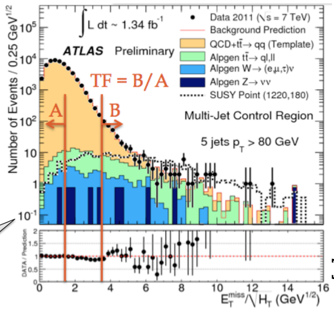


data-driven, using smaller jet mult. than in SRs

$$\text{TF} = \frac{N(\text{CR}_j | E_T^{\text{miss}}/\sqrt{H_T} > 3.5)}{N(\text{CR}_j | E_T^{\text{miss}}/\sqrt{H_T} < 1.5)}$$

data-driven from 5j/6j events

5j CR with 4j QCD template



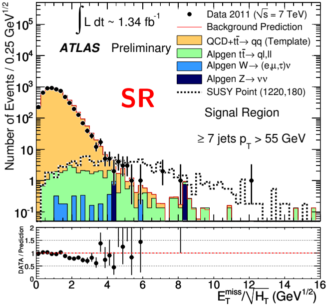
arXiv:1110.2299v1[4]

2. **Semi- and fully leptonic $t\bar{t}$** $(t\bar{t} \to ql, ll)$
data-driven CR: 1 μ (treated as jet), 1 b-jet
TF defined as above but from MC

3. **Z/W+jets** $(Z \to \nu\nu, W \to l\nu)$
data-driven CR (as in (2) but with b-jet veto),
TF from MC

6-8 jet search details :: Results

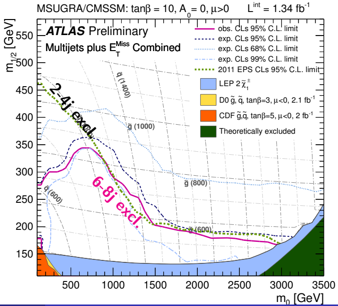
- **No significant excess in SRs with respect to SM expectation:**



Signal region	7j55	8j55	6j80	7j80
Multi-jets	26 ± 5.2	2.3 ± 0.7	19 ± 4	1.3 ± 0.4
$t\bar{t} \to q\ell, \ell\ell$	10.8 ± 6.7	$0^{+4.3}$	6.0 ± 4.6	$0^{+0.13}$
W + jets	0.95 ± 0.45	$0^{+0.13}$	0.34 ± 0.24	$0^{+0.13}$
Z + jets	$1.5^{+1.8}_{-1.5}$	$0^{+0.75}$	$0^{+0.75}$	$0^{+0.75}$
Total Standard Model	$39.3^{+8.7}_{-8.5}$	$2.3^{+4.4}_{-0.7}$	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
$\sigma^{95\%}_{\mathrm{BSM,max}} \times \epsilon/\mathrm{fb}$	19.4	8.4	12.2	4.5
p_{SM}	0.30	0.36	0.49	0.16

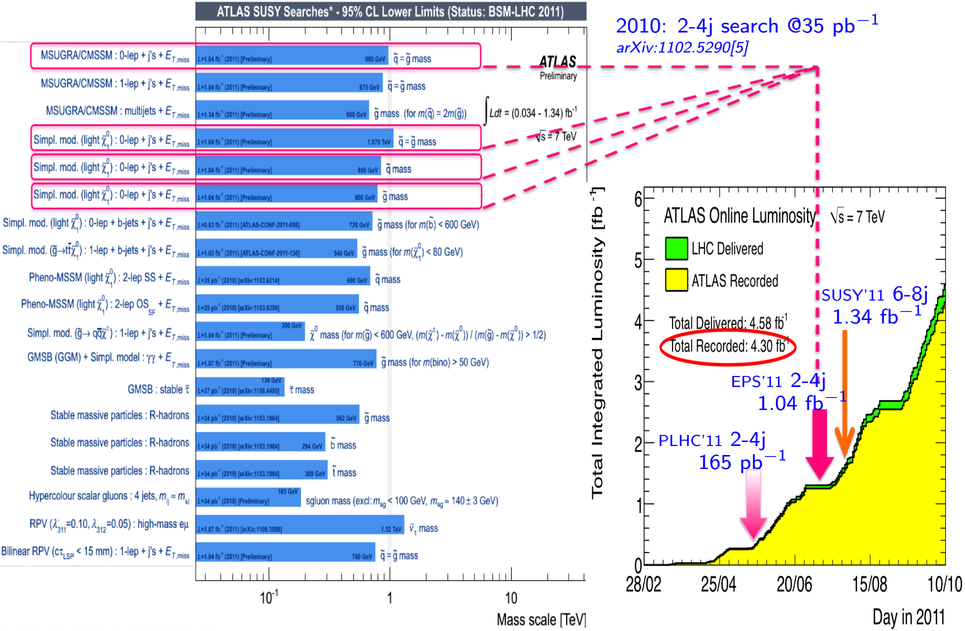
arXiv:1110.2299v1[4]

- **Limit prescription as in 2-4j analysis**
  - Exclusion less than predicted due to upward fluctuations in two channels
  - $m_{\tilde{g}} > 520$ GeV



Summary & Outlook

Status



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: BSM-LHC 2011)
ATLAS Preliminary
$\int Ldt = (0.034 - 1.34)\ \mathrm{fb}^{-1}$
$\sqrt{s} = 7$ TeV
MSUGRA/CMSSM : 0-lep + j's + $E_{T,miss}$ — 980 GeV — $\tilde{q} = \tilde{g}$ mass
MSUGRA/CMSSM : 1-lep + j's + $E_{T,miss}$ — 875 GeV — $\tilde{q} = \tilde{g}$ mass
MSUGRA/CMSSM : multijets + $E_{T,miss}$ — 680 GeV — $\tilde{g}$ mass (for $m(\tilde{q}) = 2m(\tilde{g})$)
Simpl. mod. (light $\tilde{\chi}_1^0$) : 0-lep + j's + $E_{T,miss}$ — 1.075 TeV — $\tilde{q} = \tilde{g}$ mass
Simpl. mod. (light $\tilde{\chi}_1^0$) : 0-lep + j's + $E_{T,miss}$ — 850 GeV — $\tilde{g}$ mass
Simpl. mod. (light $\tilde{\chi}_1^0$) : 0-lep + j's + $E_{T,miss}$ — 800 GeV — $\tilde{q}$ mass
Simpl. mod. (light $\tilde{\chi}_1^0$) : 0-lep + b-jets + j's + $E_{T,miss}$ — 720 GeV — $\tilde{g}$ mass (for $m(\tilde{b}) < 600$ GeV)
Simpl. mod. ($\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$) : 1-lep + b-jets + j's + $E_{T,miss}$ — 540 GeV — $\tilde{g}$ mass (for $m(\tilde{\chi}_1^0) < 80$ GeV)
Pheno-MSSM (light $\tilde{\chi}_1^0$) : 2-lep SS + $E_{T,miss}$ — 690 GeV — $\tilde{q}$ mass
Pheno-MSSM (light $\tilde{\chi}_1^0$) : 2-lep OS_{SF} + $E_{T,miss}$ — 558 GeV — $\tilde{g}$ mass
Simpl. mod. ($\tilde{g} \to q\bar{q}\tilde{\chi}_1^{\pm}$) : 1-lep + j's + $E_{T,miss}$ — 200 GeV — $\tilde{\chi}_1^0$ mass (for $m(\tilde{g}) < 600$ GeV, $(m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0)) / (m(\tilde{g}) - m(\tilde{\chi}_1^0)) > 1/2$)
GMSB (GGM) + Simpl. model : $\gamma\gamma$ + $E_{T,miss}$ — 776 GeV — $\tilde{g}$ mass (for m(bino) > 50 GeV)
GMSB : stable $\tilde{\tau}$ — 136 GeV — $\tilde{\tau}$ mass
Stable massive particles : R-hadrons — 562 GeV — $\tilde{g}$ mass
Stable massive particles : R-hadrons — 294 GeV — $\tilde{b}$ mass
Stable massive particles : R-hadrons — 309 GeV — $\tilde{t}$ mass
Hypercolour scalar gluons : 4 jets, $m_{ij} \approx m_{kl}$ — 185 GeV — sgluon mass (excl: $m_{sg} < 100$ GeV, $m_{sg} \approx 140 \pm 3$ GeV)
RPV (λ'_{311}=0.10, λ_{312}=0.05) : high-mass eμ — 1.32 TeV — $\tilde{\nu}_\tau$ mass
Bilinear RPV ($c\tau_{LSP}$ < 15 mm) : 1-lep + j's + $E_{T,miss}$ — 760 GeV — $\tilde{q} = \tilde{g}$ mass
10^{-1}
1
10
Mass scale [TeV]
2010: 2-4j search @35 pb^{-1}
arXiv:1102.5290[5]
ATLAS Online Luminosity $\sqrt{s} = 7$ TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 4.58 fb^{-1}
Total Recorded: 4.30 fb^{-1}
SUSY'11 6-8j
1.34 fb^{-1}
EPS'11 2-4j
1.04 fb^{-1}
PLHC'11 2-4j
165 pb^{-1}
Total Integrated Luminosity [fb^{-1}]
0
1
2
3
4
5
6
28/02
25/04
20/06
15/08
10/10
Day in 2011

Outlook

Next update planned for Moriond'12 with further improvements:

- More data (recorded lumi $> 4\ \mathrm{fb}^{-1}$!)
- Extended m_{eff}-based reach with minimal changes:
  - re-optimise cuts for higher lumi *e.g.* harder m_{eff}
  - include 5j and 6j channels
  - optimise $\Delta\phi(E_T^{\mathrm{miss}}, m_{\mathrm{eff}})$
- Use of signal-shape info
  - $\downarrow$ dependence on cut optimisation
  - constrain better backgrounds and uncert's
- Refined background estimation
  - treatment of low background rates
  - decrease MC dependence *e.g.* in TFs
  - decrease uncertainties (stat. + syst.)

Summary

ATLAS searches for $E_T^{\text{miss}} + jets + $ 0-leptons **have been updated to** ~ 1 **fb**$^{-1}$

- 2-4 jet channels
- 6-8 jet channels

Data agrees with SM prediction in all SRs

No indication of SUSY yet

- in R-parity conserving models and CMSSM

Exclusion limits have been set for above models

- Now approaching ~ 1 TeV

R&D is ongoing for next analysis round

- Aimed to extend reach

References

[1] ATLAS, 2010. SUSY CSC Note
http://cdsweb.cern.ch/record/1278474?ln=en.

[2] ATLAS, 2011. 0-lepton EPS results (paper submitted to PLB),
http://arxiv.org/abs/1109.6572.

[3] S. Ask, M.A. Parker, T. Sandoval, M.E. Shea, and W.J. Stirling. Using γ+jets Production to Calibrate the Standard Model $Z_{\nu\nu}$+jets Background to New Physics Processes at the LHC, 2011.
http://arxiv.org/abs/1107.2803.

[4] ATLAS, 2011. 0-lepton Multijet search,
http://arxiv.org/abs/1110.2299v1.

[5] ATLAS, 2010. 0-lepton December results,
http://arxiv.org/abs/1102.5290.

– *Backup* –

Object Definitions

JET PRESELECTION:
- Anti-k_T - $\Delta R = 0.4$
- $P_T > 20$ GeV, $|\eta| < 2.8$

Missing E_T (MET):
- Reconstructed from the vectorial sum of all jets and leptons. Clusters not belonging to any jets are added to the MET

LEPTON VETO:
- **Electrons** Identified using shower shape and track matching criteria; $P_T > 20$ GeV, $|\eta| < 2.47$
- **Muons** identified with a track matching between the ID and muon spectrometer; $P_T > 20$ GeV, $|\eta| < 2.4$

Statistical Methods

- Simultaneous likelihood fit to Signal Region + 5 Control Regions in each channel
  - Six Poisson-distributed variables and PDF to constrain systematic uncertainties

$$L(n \mid \mu, b, \theta) = P_{\mathrm{SR}} \times P_{\mathrm{WR}} \times P_{\mathrm{TR}} \times P_{\mathrm{ZRa}} \times P_{\mathrm{ZRb}} \times P_{\mathrm{QR}} \times C_{\mathrm{syst}}$$

- Correlations between Control Regions taken into account
  - eg jet energy scale and b-tagging efficiency

Highest m_{eff} event in EPS'11 dataset

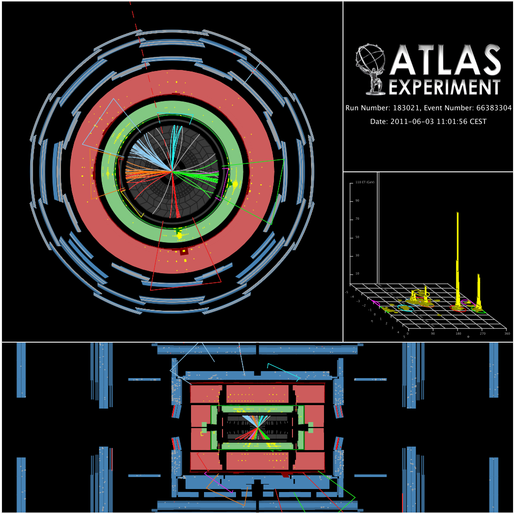


Figure: This event possesses five jets with $p_T > 40$ GeV ($p_T = 528$, 418, 233, 171 and 42 GeV respectively), $E_T^{\mathrm{miss}} = 460$ GeV and $m_{\mathrm{eff}} = 1810$ GeV (calculated using the leading four jets).