### SUSY Searches with the ATLAS Experiment

Epiphany 2016

#### Pawel Klimek on behalf of the ATLAS Collaboration

Stockholm University

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#### Supersymmetry

- Extends the Standard Model
- Each SM particle has at least one superpartner
- Superpartners have the same properties as their SM counterparts except for the spin that differs by 1/2
- SUSY is broken since superpartners have higher masses
- New quantum number: *R*-parity
- If *R*-parity conserved, LSP is stable



- Provides solution for hierarchy problem
- If *R*-parity is conserved, provides a dark matter candidate

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### Introduction



- SUSY has a very diverse phenomenology
- ATLAS search strategy is to cover a broad range of SUSY models to enhance discovery potential
- Increasing luminosity gives sensitivity to low cross section processes
- This talk will show a selection of few recent Run 1 results and new Run 2 results
- For other Run 2 results see Da Xu's talk

### SUSY Search Strategy

- Signal region (SR) targets a specific SUSY production/decay mode
- Background estimation
  - Irreducible background estimated using data in control region (CR) and extrapolated from CR to SR with Monte Carlo
  - Reducible background (fake/non isolated leptons, charge flip) estimated using data
  - Minor backgrounds estimated with pure Monte Carlo

#### The predictions are validated in validation regions (VR)



### Strong Production

- May be the dominant SUSY production process at the LHC due to high cross sections if squarks/gluinos are not too heavy
- Large yield even in small datasets
- Strong SUSY particle production: gluino, gluino-squark and squark pairs
- Typical signature: high-momentum jets, 0-1-2 leptons, large  $E_{\rm T}^{\rm miss}$  from LSP

New Run 2 SUSY strong produ	iction searches in ATLAS	
0 leptons + 2-6 jets + $E_{\rm T}^{\rm miss}$ 0 leptons + 7-10 jets + $E_{\rm T}^{\rm miss}$ 0 leptons + <i>b</i> -jets + boosted <i>t</i> 1 lepton + jets + $E_{\rm T}^{\rm miss}$	ATLAS-CONF-2015-062 ATLAS-CONF-2015-077 ATLAS-CONF-2015-067 ATLAS-CONF-2015-076	
2 leptons + Z boson + $E_{\rm T}^{\rm miss}$ 2 SS or 3 leptons + jets + $E_{\rm T}^{\rm miss}$	ATLAS-CONF-2015-082 See Da Xu s talk ATLAS-CONF-2015-078	h

## Inclusive Strong Production

New Run 2 results - simplified model interpretation

- 0 leptons
- 2-6 jets
- $E_{\mathrm{T}}^{\mathrm{miss}}$
- New limits exceed Run 1 results
- Gluino mass up to 1520 GeV and squark mass up to 980 GeV excluded for massless neutralino



ATLAS Prelin

oth Elko

5=13TeV, 3.2 fb

FW0 & sinnle ton

Signal Regi

## Inclusive Strong Production

#### New Run 2 results - simplified model interpretation



- The increase of the centre of mass energy provided increased sensitivity to higher mass sparticles
- Gluino mass up to 1400 GeV excluded for neutralino mass below 240 GeV



Events/ 50 GeV

5 = 13 TeV, 3.3 fb SR-Gbb-B b/t

otal backgroup

Single top tt + W/Z/h

Z+jets W+jets Diboson Gbb: m<sub>v</sub>, m<sub>v</sub> = 1700, 200 Gbb: m<sub>v</sub>, m<sup>2</sup><sub>v</sub> = 1400, 800

600 700

# Inclusive Strong Production

New Run 2 results - Gbb and Gtt models interpretation

- 0, 1 lepton (e,  $\mu$ )
- $\bullet$   $E_{\mathrm{T}}^{\mathrm{miss}}$
- $\blacksquare \ge 3 \ b$ -jets
- Boosted top for the selection targeting Gtt models with light neutralino
- New limits exceed Run 1 results



# $3^{\rm rd}$ generation squark direct production

- Natural (i.e. not fine-tuned) SUSY requires light stop and sbottom, gluino relatively light. 1<sup>st</sup> and 2<sup>nd</sup> generation squarks are allowed to be very heavy.
- 3<sup>rd</sup> generation squark production: stop, sbottom
- Typical signature: jets (usually including heavy-flavor, *b* or *c*-jets), 0-1-2 leptons, large  $E_{\rm T}^{\rm miss}$  from LSP
- Effort concentrated on simplified models with 100% branching ratios to chosen final state

New Run 2 SUSY  $3^{\rm rd}$  generation squark direct production searches in ATLAS

0 leptons + 2 *b*-jets +  $E_{\rm T}^{\rm miss}$ 2 SS or 3 leptons + jets +  $E_{\rm T}^{\rm miss}$  <code>ATLAS-CONF-2015-066</code> <code>ATLAS-CONF-2015-078</code> <code>} see Da Xu's talk</code>

Run 1 SUSY  $3^{\rm rd}$  generation squark direct production searches in ATLAS

3<sup>rd</sup> generation squark summary paper Eur. Phys. J. C (2015) 75:510

SUSY 3<sup>rd</sup> Generation Production

## $3^{\rm rd}$ generation squark direct production

New Run 2 results - simplified model interpretation



SUSY 3<sup>rd</sup> Generation Production Eur.

## 3<sup>rd</sup> generation squark direct production



#### Electroweak production

- May be the dominant SUSY production process at the LHC if squarks/gluinos are heavy and neutralinos/charginos are light
- Electroweak SUSY particle production: neutralinos, charginos, sleptons
- Typical signature: one or more leptons in the final state arising from the decay of sleptons or neutralinos/charginos decaying through intermediate sleptons, sneutrinos or gauge/Higgs bosons. Large E<sup>miss</sup> from LSP, often low hadronic activity.

Run 1 SUSY electroweak production searches in ATLAS

Electroweak production summary paper arXiv:1509.07152

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#### Electroweak production

Run 1 results - simplified model interpretation



Direct chargino production

# Electroweak production





- VBF production of SUSY particles investigated for the first time in ATLAS
- If observed it would prove that the exchanged neutralino is a Majorana particle

## pMSSM Interpretation

- Phenomenological MSSM (pMSSM)
  - no additional source of CP violation
  - quark and lepton flavour conservation in the SUSY sector
  - no additional source of flavour changing neutral currents
  - degenerate 1st and 2nd generation sfermions
- Interpretation of all ATLAS SUSY searches
- 22 Run 1 SUSY searches reinterpreted in pMSSM - 200 SR
- 500 milion pMSSM models randomly sampled
- 300 thousand models survive theory and non-LHC constraints (precision EW measurements, LEP, Tevatron Higgs, DM)
- Most comprehensive SUSY results from ATLAS

0-lepton + 2–6 jets +  $E_{\rm T}^{\rm miss}$ 0-lepton + 7–10 jets +  $E_{\rm T}^{\rm miss}$ nclusive 1-lepton + jets +  $E_T^{miss}$  $\tau(\tau/\ell)$  + jets +  $E_{\rm T}^{\rm miss}$ SS/3-leptons + jets +  $E_{T}^{miss}$ 0/1-lepton + 3b-jets +  $E_{T}^{miss}$ Monoiet 0-lepton stop generation 1-lepton stop 2-leptons stop Monojet stop Stop with Z boson a d 2b-jets +  $E_{T}^{miss}$  $tb+E_{T}^{miss}$ , stop ℓh Electroweak 2-leptons  $2-\tau$ 3-leptons 4-leptons Disappearing Track Other Long-lived particles  $H/A \rightarrow \tau^+ \tau^-$ 

# pMSSM Interpretation



## pMSSM Interpretation

- Highest sensitivity to strong processes
- Some differences observed between simplified models and pMSSM interpretaion
- Good complementarity between different searches and with direct detection experiments



#### SUSY Searches Summary

#### Not including yet Run 2 results

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

ATLAS Preliminary

	Model	$e, \mu, \tau, \gamma$	Jets	$E_{\rm T}^{\rm miss}$	∫£ dt[fb	<sup>1</sup> ] Mass limit $\sqrt{s} = 7 \text{ TeV}$ $\sqrt{s} = 8 \text{ TeV}$	Reference
Inclusive Searches	$\begin{array}{l} \text{MSUGRACMSSM} \\ \tilde{q}\bar{v}_{s}^{1} \tilde{q}_{s}^{-1} q_{s}^{(2)} \\ \tilde{q}\bar{v}_{s}^{1} \tilde{q}_{s}^{-1} q_{s}^{(2)} \\ \tilde{q}\bar{v}_{s}^{1} \tilde{q}_{s}^{-1} q_{s}^{(2)} \\ \tilde{q}\bar{v}_{s}^{1} \tilde{q}_{s}^{-1} q_{s}^{(2)} q_{s}^{(2)} \\ \tilde{g}\bar{v}_{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} q_{s}^{(2)} \\ \tilde{g}\bar{s}_{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} (r_{r})\bar{v}_{s}^{(1)} \\ \tilde{g}\bar{s}_{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} (r_{r})\bar{v}_{s}^{(1)} \\ \tilde{g}\bar{s}_{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} (r_{r})\bar{v}_{s}^{(1)} \\ \tilde{g}\bar{s}\bar{s}_{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} (r_{r})\bar{v}_{s}^{(1)} \\ \tilde{g}\bar{s}\bar{s}_{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} \tilde{s}\bar{s}_{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} \\ \tilde{g}\bar{s}\bar{s}\bar{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} \tilde{s}\bar{s}\bar{s}^{1} \tilde{s}_{s}^{-1} q_{s}q\bar{v}^{(1)} \\ \tilde{g}\bar{s}\bar{s}\bar{s}\bar{s}^{-1} q_{s}q\bar{s}\bar{s}\bar{s}\bar{s}\bar{s}\bar{s}\bar{s}\bar{s}\bar{s}\bar{s}$	$\begin{array}{c} 0.3 \ e, \mu/1 \cdot 2 \ r \\ 0 \\ mono-jet \\ 2 \ e, \mu \ (otto) \\ 0 \\ 0 \\ 1 \cdot 1 \ e, \mu \\ 2 \ e, \mu \\ 1 \cdot 2 \ r + 0 \cdot 1 \ i \\ 2 \ \gamma \\ \gamma \\ 2 \ e, \mu \ (Z) \\ 0 \end{array}$	2-10 jets/3 2-6 jets 1-3 jets 2-6 jets 2-6 jets 2-6 jets 0-3 jets 0-2 jets 2 jets 2 jets 1 b 2 jets 2 jets 1 b 2 jets	6 Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	4.1 51 Yet (1994) 51 Set (1994) 5	1507.05525 1405.7875 1507.05625 1507.05625 1405.7875 1507.05625 1407.7860 1507.05483 1507.25483 1507.25483 1507.25483 1507.25483
3 <sup>rd</sup> gen. <u>8</u> med.	$\begin{array}{l} \hat{g} \hat{g}, \hat{g} \rightarrow \delta \hat{g} \hat{\chi}_{1}^{0} \\ \hat{g} \hat{g}, \hat{g} \rightarrow \delta \hat{\chi}_{1}^{0} \\ \hat{g} \hat{g}, \hat{g} \rightarrow \delta \hat{\chi}_{1}^{0} \\ \hat{g} \hat{g}, \hat{g} \rightarrow \delta \delta \hat{\chi}_{1}^{0} \end{array}$	0 0-1 e,µ 0-1 e,µ	3 b 7-10 jets 3 b 3 b	Yes Yes Yes	20.1 20.3 20.1 20.1	8         1.25 TeV         m(1)-480 GeV           8         1.1 TeV         m(1)-480 GeV           8         1.34 TeV         m(1)-480 GeV           8         1.34 TeV         m(1)-580 GeV	1407.0500 1308.1841 1407.0500 1407.0500
3 <sup>rd</sup> gen. squarks direct production	$ \begin{array}{l} b_1 b_1, b_1 \rightarrow b \tilde{t}_1^0 \\ b_1 b_1, b_1 \rightarrow b \tilde{t}_1^0 \\ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b \tilde{t}_1^0 \\ \tilde{t}_1 \tilde{t}_1 (natural (MSB)) \\ \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z \end{array} $	0 2 ε, μ (SS) 1-2 ε, μ 0-2 ε, μ 2 ε, μ (Z) 3 ε, μ (Z)	2 b 0-3 b 1-2 b 0-2 jets/1-2 nono-jet/c-1 1 b 1 b	Yes Yes Yes Yes tag Yes Yes Yes	20.1 20.3 4.7/20.3 20.3 20.3 20.3 20.3 20.3	Ν         199-832 GeV         μ( <sup>2</sup> / <sub>1</sub> ), social           β         275-440 GeV         μ( <sup>2</sup> / <sub>1</sub> ), social         μ( <sup>2</sup> / <sub>1</sub> ), social           β         110-100 M         230-900 GeV         μ( <sup>2</sup> / <sub>1</sub> ), social, μ( <sup>2</sup> / <sub>1</sub> ), social           β         110-100 M         210-900 GeV         μ( <sup>2</sup> / <sub>1</sub> ), social, μ( <sup>2</sup> / <sub>1</sub> ), social           β         110-100 M         210-900 GeV         μ( <sup>2</sup> / <sub>1</sub> ), social           β         110-100 M         100-900 GeV         μ( <sup>2</sup> / <sub>1</sub> ), social           β         100-900 GeV         μ( <sup>2</sup> / <sub>1</sub> ), social         μ( <sup>2</sup> / <sub>1</sub> ), social           β         100-900 GeV         μ( <sup>2</sup> / <sub>1</sub> ), social         μ( <sup>2</sup> / <sub>1</sub> ), social	1308.2631 1404.2500 1209.2102, 1407.0583 1506.08515 1407.0508 1403.5222 1403.5222
EW direct	$ \begin{array}{l} \tilde{l}_{\pm k} \tilde{l}_{\pm k}, \tilde{t} \! \! - \! \! + \! \! t \tilde{\mathcal{K}}_{1}^{0} \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k}, \tilde{r}_{\pm -} \! \! - \! \! \bar{t} \tilde{r}(\tilde{r}) \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k}, \tilde{r}_{\pm -} \! \! - \! \! \bar{r}(\tilde{r}) \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k}^{*} \! - \! \! t \tilde{r}(\tilde{r}) \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k}^{*} \! - \! \! t \tilde{r}_{\pm k} \tilde{r}(\tilde{r}) \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k}^{*} \! - \! \! W \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k} \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k}^{*} \! - \! W \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k} \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k}^{*} \! - \! W \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k} \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k} \! - \! W \tilde{r}_{\pm k} \\ \tilde{r}_{\pm k}^{*} \tilde{r}_{\pm k} \\ \tilde{r}_{\pm k} \\$	2 e, µ 2 e, µ 2 τ 3 e, µ 2 3 e, µ r/yy e, µ, y 4 e, µ 1 e, µ + y	0 0 0-2 jets 0-2 b 0 0	Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3		1403.5294 1403.5294 1403.5294 1402.7025 1402.7029 Ied 1403.5294,1402.7029 Ied 1501.07110 1403.5296 1507.05483
Long-lived particles	Direct $\hat{x}_1^+ \hat{x}_1^-$ prod., long-lived $\hat{x}$ Direct $\hat{x}_1^+ \hat{x}_1^-$ prod., long-lived $\hat{x}$ Stable, stopped $g$ R-hadron Stable $\tilde{g}$ -R-hadron GMSB, stable $\tilde{\tau}$ , $\hat{x}_1^0 \rightarrow \tilde{\tau}(x, \tilde{\mu}) \ast \tau$ GMSB, $\hat{\chi}_1^0 \rightarrow \gamma G$ , long-lived $\hat{\chi}_1^0$ $\hat{g}g$ , $\hat{x}_1^0 \rightarrow erg/qw/qw/qw/qw/qw/qw/qw/qw/qw/qw/qw/qw/qw/$	$ \begin{array}{c} \stackrel{*}{\underset{1}{\overset{1}{\overset{1}{\overset{1}{\overset{1}{\overset{1}{\overset{1}{1$	1 jet 	Yes Yes · · Yes ·	20.3 18.4 27.9 19.1 19.1 20.3 20.3 20.3		1310.3675 1506.05332 1310.6584 1411.6726 1403.5542 1504.05162
NdB	$ \begin{array}{l} {\rm LFV} \ pp {\rightarrow} \bar{v}_t + X, \bar{v}_t {\rightarrow} e\mu/e\tau/\mu\tau\\ {\rm Bilnear} \ {\rm RPV} \ {\rm CMSSM} \\ \bar{\chi}_1^{+} \tilde{\chi}_1^{-}, \bar{\chi}_1^{+} {\rightarrow} W \tilde{\chi}_1^{+} \tilde{\chi}_1^{0} {\rightarrow} ee\bar{v}_{\mu}, ep\bar{v}\\ \bar{\chi}_1^{+} \tilde{\chi}_1^{-}, \bar{\chi}_1^{+} {\rightarrow} W \tilde{\chi}_1^{+} \tilde{\chi}_1^{0} {\rightarrow} ee\bar{v}_{\mu}, er\bar{v}\\ \bar{\chi}_2^{+} \tilde{\chi}_1^{-} {\rightarrow} W \tilde{\chi}_1^{+} \tilde{\chi}_1^{0} {\rightarrow} eqq \\ \bar{\chi}_2^{+} \tilde{\chi}_2^{-} {\rightarrow} e^{i f_{1}} \tilde{\chi}_1^{-} {\rightarrow} bs\\ \bar{\chi}_1^{+} \tilde{\chi}_1^{-} {\rightarrow} bs\\ \bar{\chi}_1^{+} \tilde{\chi}_1^{-} {\rightarrow} bd \end{array}$	$e^{\mu,e\tau,\mu\tau}_{2e,\mu}$ $2e,\mu$ (SS) $4e,\mu$ $3e,\mu+\tau$ 0 $2e,\mu$ (SS) 0 $2e,\mu$ (SS) 0 $2e,\mu$	0.3 b 6.7 jets 6.7 jets 0.3 b 2 jets + 2 2 b	- Yes Yes Yes - - Yes b -	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	5 5 5 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7	1503.04430 1404.2300 1405.5085 1502.05885 1502.05885 1404.250 ATLAS-CONF-2015-025 ATLAS-CONF-2015-015
Other	Scalar charm, $\hat{c} \rightarrow c \hat{t}_1^0$	0	2 c	Yes	20.3	2 490 GaV m(r) <200 GeV	1501.01325
					1	1 Mass scale [Te	/]

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1\0007 theoretical signal cross section uncertainty.

#### https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Pawel Klimek (Stockholm University)

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#### Conclusions & summary

- ATLAS SUSY searches cover broad range of signatures.
   Effort to cover maximum area of the SUSY parameter space.
- The 8 TeV LHC data have been investigated extensively.
- First results have been obtained using the entire dataset collected in 2015 at 13 TeV.
- No sign of SUSY in the LHC data yet. Therefore, exclusion limits are set.
- High energy running and higher luminosity will significantly increase the sensitivity to many SUSY scenarios in Run 2.

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