## RECONSTRUCTION **TECHNIQUES IN** SUPERSYMMETRY

SEARCHES WITH THE ATLAS EXPERIMENT





### THE ATLAS DETECTOR

- Main change for run 2 is the Insertable B-Layer (IBL)
- Improved vertexing capabilities



Reconstruction techniques in supersymmetry searches with the ATLAS experiment



### 80 60 40 20 Jan'<sup>15</sup> Jul'<sup>15</sup> Jan'<sup>16</sup> Jul'<sup>16</sup> Jan'<sup>17</sup> Jul'<sup>17</sup> Jan'<sup>18</sup> Jul'<sup>18</sup> Month in Year

25m

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### WHAT DO WE TARGET?



Reconstruction techniques in supersymmetry searches with the ATLAS experiment

- Low mass differences,  $\Delta m(\chi_2^0, \chi_1^0)$ can result in low P<sub>T</sub> jets or leptons
- Large mass differences,  $\Delta m(\tilde{g}, \chi_1^0)$ can result in a boosted system with multiple quarks, reconstructed with a large-R jet
- Neutralinos will cause





## LOW MASS RECONSTRUCTION



## **GOING LOWER IN LEPTON PT**

- dedicated Bremstrahlung correction
- Current published SUSY analyses use muons as far down as 4 GeV



Reconstruction techniques in supersymmetry searches with the ATLAS experiment

Electrons currently reconstructed down to 4.5 GeV, using topologically formed clusters and

Muons are reconstructed down to 3 GeV (average energy loss in the calorimeter is 3 GeV)





## HOWEVER.. CONSEQUENCES OF SOFT LEPTONS

- Further gains are possible with new lower P<sub>T</sub> thresholds
- However, lots of extra background is fake lepton from heavy flavour decays
- Key to improving the performance lies with lepton isolation and impact parameters 10<sup>°</sup> ATLAS
- New ideas could replace isolation algorithms, such as a BDTs



<u>ARXIV:1712.08119</u>

Reconstruction techniques in supersymmetry searches with the ATLAS experiment

 $\mathfrak{m}(\widetilde{\mathfrak{g}})$  -  $\mathfrak{m}(\widetilde{\chi}_1^0)$  [GeV]







## **A PROMPT LEPTON TAGGER**

- To replace isolation algorithms. A BDT could be trained which could potentially have better performance for rejection of heavy flavour decays
- Taking as input the energy deposits and charged-particle tracks in a cone around the lepton direction
- Example by the ttH group. Large SF's at low  $P_T$ , this could be improved with choosing a different working point ATLAS ATLAS



Reconstruction techniques in supersymmetry searches with the ATLAS experiment

### ARXIV:1712.08891



## HIGH MASS RECONSTRUCTION



### **RECLUSTERED JETS**

- "Standard" jet finding in ATLAS uses the Anti-Kt algorithm with a radius parameter of 0.4
- In boosted topologies the two jets could be close together
- Two strategies:
  - Use a larger radius parameter
  - Cluster existing calibrated 0.4 radius jets into a larger jet (reclustering)
- Reclustering can use the detailed calibrations and uncertainties from 0.4 jets - allows more flexibility in the parameters of large R jets because no dedicated calibration is needed



ATLAS-CONF-2017-062



### FLAVOUR TAGGING

- chain multi-vertex algorithms
- Significant b-tagging improvements can be seen with respect to run 1 (including IBL)



Reconstruction techniques in supersymmetry searches with the ATLAS experiment

Production of third generation squarks leads to decay signatures with charm or bottom quarks Boosted Decision Tree analyses output of impact parameter, secondary vertex finding and decay







### **CHARM TAGGING**

- Charm tagging algorithms use additional variables
- Such as invariant mass of secondary tracks, secondary track rapidities, distance from primary to secondary vertex, fraction of jet track energy carried by secondary tracks
- New result from run 2 on stop to charm decays recently released



Reconstruction techniques in supersymmetry searches with the ATLAS experiment

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## $E_T^{miss}$ WHICH IS FAKE

 $E_T^{miss}$  is an important variable in searches as it is indicative of neutralinos Fake  $E_T^{miss}$  can arise from interacting particles which escape the acceptance of the detector, are inaccurately (resolution) reconstructed, or fail to be reconstructed all together



0L suffer from QCD background, a process where real  $E_T^{miss} = 0$ 

Reconstruction techniques in supersymmetry searches with the ATLAS experiment

# Bad MC modelling, large cross-sections, and resolution effects result into large fake $E_T^{miss}$



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## T<sup>miss</sup> SIGNIFICANCE

- Indicates the degree to which the reconstructed  $E_T^{miss}$ is consistent with momentum resolution and particle identification efficiencies
- Event-based significance:  $\mathcal{S} = \frac{E_T^{miss}}{2}$  or  $\mathcal{S} = \frac{1}{2}$  $/H_{T}$
- Object-based definition: log-likelihood ratio that the reconstructed  $E_T^{miss}$  is consistent with the hypothesis of 0 real  $E_T^{miss}$ , based on full event composition



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# UNKNOWNS IN SUSY RECONSTRUCTION



### $M_{T2}$

We measure one variable  $E_T^{miss}$ , but this is actually two particles:

- Two massive particles have escaped undetected
- The masses of these particles are unknown
- The masses of their parent particles are unknown
- The center-of-mass energy of the collision is not known
- The boost along the beam axis is not known





$$\min_{E_{T1}^{miss(1)}+E_{T}^{miss(2)}=E_{T}^{miss}} \left[ \max\{m_{t}^{2}(p_{T}^{(1)}, E_{T}^{miss(1)}; \tilde{\chi_{1}^{0}}), m_{t}^{2}(p_{T}^{(2)}, E_{T}^{miss(2)}; \tilde{\chi_{1}^{0}}) \right]$$



- intermediate particles in a "decay tree"
- momenta of objects in these frames



Reconstruction techniques in supersymmetry searches with the ATLAS experiment



### CONCLUSIONS

- Reconstruction algorithms being used to push into more extreme parts of SUSY phase space
- Many new ideas lower P<sub>T</sub> leptons, BDT for isolation, object based  $E_T^{miss}$  significance, recursive jigsaw reconstruction
- Full run 2 results to come from ATLAS SUSY searches on challenging signatures

JL	ily 2018
	Model
(0	$\tilde{q}\tilde{q},\tilde{q}{ ightarrow}q\tilde{\chi}_1^0$
Irches	$\tilde{g}\tilde{g},\tilde{g}{\rightarrow}q\bar{q}\tilde{\chi}_{1}^{0}$
e Sea	$\tilde{g}\tilde{g},  \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$
clusiv	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$
Inc	$\tilde{g}\tilde{g},  \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$
ks on	$\tilde{b}_1\tilde{b}_1,\tilde{t}_1\tilde{t}_1,M_2=2\times M_1$
n. squal product	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1, \tilde{H} \text{ LSP}$
3 <sup>rd</sup> ge. direct	$\tilde{t}_1 \tilde{t}_1$ , Well-Tempered LSI $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}^0$
	$\tilde{t}_2\tilde{t}_2,  \tilde{t}_2 \rightarrow \tilde{t}_1 + h$
	$ ilde{\chi}_1^{\pm}  ilde{\chi}_2^0$ via $WZ$
V ect	$ \begin{split} \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0} \text{ via } Wh \\ \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} / \tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau} \nu(\tau \tilde{\nu}), \tilde{\chi} \end{split} $
EV	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$ , $\tilde{\ell}{\rightarrow}\ell\tilde{\chi}_1^0$
	$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$
p.	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-
icle:	Stable $\tilde{g}$ R-hadron
ong	Metastable $\tilde{g}$ R-hadron,
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow eev/e\mu v/\mu\mu v$
	$LFV pp \to \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \to e\mu$
	$ \begin{aligned} \tilde{\chi}_1^{\pm} \tilde{\chi}_1^+ / \tilde{\chi}_2^0 &\to WW/Z\ell\ell\ell\ell\nu \\ \tilde{g}\tilde{g},  \tilde{g} \to qq\tilde{\chi}_1^0,  \tilde{\chi}_1^0 \to qqq \end{aligned} $
RPV	$\tilde{g}\tilde{g}, \tilde{g} \to tbs / \tilde{g} \to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0$
	$u, \iota \to \iota \lambda_1, \lambda_1 \to tbs$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \to bs$
	$t_1t_1, t_1 \rightarrow bt$

\*Only a selection of the avai phenomena is shown. Man simplified models, c.f. refs. for the assumptions made

### **ATLAS** Preliminary

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

	$e, \mu,  au, \gamma$	′ Jets	$E_{ m T}^{ m miss}$	$\int \mathcal{L} dt [\mathbf{fb}^{T}]$	<sup>-1</sup> ] Ma	ss limit		$\sqrt{s}$	<u>s</u> = 7, 8 TeV	$\sqrt{s}$ = 13 TeV	Reference
	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	$ ilde{q}$ [2x, 8x Degen.] $ ilde{q}$ [1x, 8x Degen.]	0.43	0.9 0.71	1.55	I	$m( ilde{\chi}_1^0){<}100GeV\ m( ilde{q}){=}5GeV$	1712.02332 1711.03301
	0	2-6 jets	Yes	36.1	ĩc ĩc		Forbidden	0.95-1.6	2.0	m $(\tilde{\chi}_1^0)$ <200 GeV m $(\tilde{\chi}_1^0)$ =900 GeV	1712.02332 1712.02332
	3 e,μ ee,μμ	4 jets 2 jets	- Yes	36.1 36.1	ές δ			1 1.2	1.85	$m( ilde{\chi}_1^0){<}800\mathrm{GeV}\ m( ilde{g}){=}m( ilde{\chi}_1^0){=}50\mathrm{GeV}$	1706.03731 1805.11381
	0 3 <i>e</i> , µ	7-11 jets 4 jets	Yes -	36.1 36.1	ĩco ĩco		0.98		1.8	$m( ilde{\mathcal{X}}_1^0)\!<\!\!400\mathrm{GeV}\ m( ilde{g})\!=\!\!200\mathrm{GeV}$	1708.02794 1706.03731
	0-1 e,μ 3 e,μ	3 <i>b</i> 4 jets	Yes -	36.1 36.1	ξ δ δ			1.25	2.0	$m(\tilde{\chi}^0_1){<}200\mathrm{GeV}$ $m(\tilde{g}){-}m(\tilde{\chi}^0_1){=}300\mathrm{GeV}$	1711.01901 1706.03731
		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{ccc}  ilde{b}_1 & Forbidden \  ilde{b}_1 &  ilde{b}_1 & egin{array}{ccc}  ilde{b}_1 &  ilde{b}_1 &  ilde{b}_1 & egin{array}{cccc}  ilde{b}_1 &  ilde{b}_1 & $	Forbidden Forbidden	0.9 0.58-0.82 0.7		$m( ilde{\chi}_1^0)=3$ $m( ilde{\chi}_1^0)=200Ge$	$m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=1$ $300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=BR(t\tilde{\chi}_{1}^{\pm})=0.5$ $eV, m(\tilde{\chi}_{1}^{\pm})=300 \text{ GeV}, BR(t\tilde{\chi}_{1}^{\pm})=1$	1708.09266, 1711.03301 1708.09266 1706.03731
		Multiple Multiple		36.1 36.1	$\tilde{t}_1$ $\tilde{t}_1$ Forbidden		0.7 0.9			$m(\widetilde{\chi}^0_1){=}60\mathrm{GeV}\ m(\widetilde{\chi}^0_1){=}200\mathrm{GeV}$	1709.04183, 1711.11520, 1708.032 1709.04183, 1711.11520, 1708.032
	0-2 <i>e</i> , <i>µ</i>	0-2 jets/1-2 Multiple Multiple	b Yes	36.1 36.1 36.1	<ul> <li><i>t</i><sub>1</sub></li> <li><i>t</i><sub>1</sub></li> <li><i>t</i><sub>1</sub></li> <li><i>Forbidden</i></li> </ul>		1.0 0.4-0.9 0.6-0.8		$m(\widetilde{\chi}_{1}^{0}) = 150Gr$ $m(\widetilde{\chi}_{1}^{0}) = 300Gr$	$\begin{split} m(\tilde{\chi}_1^0) =& 1 \text{ GeV} \\ eV, m(\tilde{\chi}_1^{\pm}) \cdot m(\tilde{\chi}_1^0) =& 5 \text{ GeV}, \ \tilde{t}_1 \approx \tilde{t}_L \\ eV, m(\tilde{\chi}_1^{\pm}) \cdot m(\tilde{\chi}_1^0) =& 5 \text{ GeV}, \ \tilde{t}_1 \approx \tilde{t}_L \end{split}$	1506.08616, 1709.04183, 1711.115 1709.04183, 1711.11520 1709.04183, 1711.11520
		Multiple		36.1	$\tilde{t}_1$		0.48-0.84		$m(\tilde{\chi}_1^0)=150  Ge$	eV, m( $\tilde{\chi}_1^{\pm}$ )-m( $\tilde{\chi}_1^0$ )=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	0	2 <i>c</i>	Yes	36.1 26.1	$\tilde{\ell}_1$ $\tilde{\ell}_1$ $\tilde{\epsilon}$	0.46	0.85				1805.01649 1805.01649 1711.02201
	1-2 e u	1 h	Voc	36.1	ř.	0.45	0 32-0 88		$m(\tilde{v}^0)$	$-0 \operatorname{Col}(m(\tilde{t}), m(\tilde{t}^{0}) - 180 \operatorname{Col})$	1706.03986
	22 c, µ	40	165 	30.1	$\tilde{r}_2$		0.32-0.66		m(x 1)	=0 GeV, $m(r_1) - m(x_1) = 180$ GeV	1402 5204, 1806 02002
	2-3 e,μ ee,μμ	≥ 1	Yes	36.1 36.1			0.6			$m({\mathcal{X}}_1)=0$ $m({\widetilde{\mathcal{X}}}_1^\pm)$ - $m({\widetilde{\mathcal{X}}}_1^0)=$ 10 GeV	1712.08119
	<i>ℓℓ/ℓγγ/ℓbb</i>	-	Yes	20.3	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ 0.26					$m(\tilde{\chi}_{1}^{0})=0$	1501.07110
$\rightarrow \tilde{\tau} \tau(\nu \tilde{\nu})$	2 τ	-	Yes	36.1	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} \\ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}  $ 0.22		0.76	r	$m(\tilde{\chi}_1^{\pm})$ - $m(\tilde{\chi}_1^{0})$ =100	$ \begin{array}{l} \overset{0}{}_{1}) = 0, \ m(\tilde{\tau},\tilde{\nu}) = 0.5(m(\tilde{\chi}_{1}^{\pm}) + m(\tilde{\chi}_{1}^{0})) \\ \mathrm{GeV}, \ m(\tilde{\tau},\tilde{\nu}) = 0.5(m(\tilde{\chi}_{1}^{\pm}) + m(\tilde{\chi}_{1}^{0})) \end{array} $	1708.07875 1708.07875
	2 e,μ 2 e,μ	0 ≥ 1	Yes Yes	36.1 36.1	ℓ̃ ℓ̃ 0.18	0.5				$m( ilde{\chi}_1^0){=}0\ m( ilde{\chi}_1^0){=}5\ GeV$	1803.02762 1712.08119
	0 4 <i>e</i> , µ	$\geq 3b$ 0	Yes Yes	36.1 36.1	$ ilde{H}$ 0.13-0.23 $ ilde{H}$ 0.3		0.29-0.88			$ \begin{array}{l} BR(\tilde{\chi}^0_1 \to h\tilde{G}) = 1 \\ BR(\tilde{\chi}^0_1 \to Z\tilde{G}) = 1 \end{array} $	1806.04030 1804.03602
/ed $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\begin{array}{cc}  ilde{\chi}_1^{\pm} & \  ilde{\chi}_1^{\pm} & 0.15 \end{array}$	0.46				Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
0	SMP	-	-	3.2	Ĩ			1.6			1606.05129
$\rightarrow qq\tilde{\chi}_1^0$	2	Multiple		32.8	$\tilde{g} [\tau(\tilde{g}) = 100 \text{ ns}, 0.2 \text{ ns}]$			1.6	2.4	$m(\tilde{\chi}_1^0)=100 \text{ GeV}$	1710.04901, 1604.04520
$d \chi_1^o$	2γ displ. ee/eμ/μ	- 1µ -	Yes -	20.3 20.3	$\frac{\chi_1^*}{\tilde{g}}$	0.44	_	1.3	6 <	$1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model $c\tau(\tilde{\chi}_1^0) < 1000$ mm, $m(\tilde{\chi}_1^0) = 1$ TeV	1409.5542 1504.05162
	ец.ет.ит	-	_	3.2	ν <sub>-</sub>		_		10	$\lambda'_{212} = 0.11. \lambda_{132} / 133 = 0.07$	1607.08079
.,	4 e, μ	0	Yes	36.1	$\tilde{\chi}_{\pm}^{\dagger}/\tilde{\chi}_{2}^{0}  [\lambda_{122} \neq 0, \lambda_{124} \neq 0]$		0.82	1.33	1.5	$m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$	1804.03602
	0 4	-5 large-R je	ets -	36.1	$\tilde{g} = [m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 1100 \text{ GeV}]$			1.3	1.9	Large $\lambda_{112}''$	1804.03568
		Multiple		36.1	$\tilde{g}$ [ $\lambda_{112}''$ =2e-4, 2e-5]		1.05	5	2.0	m $({ ilde{\mathcal{X}}}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003
$\rightarrow tbs$		Multiple		36.1	$\tilde{g}$ [ $\lambda''_{323}$ =1, 1e-2]				1.8 2.1	m $(\tilde{\chi}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003
	~	Multiple		36.1	$g [\mathcal{X}'_{323}=2e-4, 1e-2]$	0.55	1.05	5		m $(\tilde{\chi}_1^{\prime})$ =200 GeV, bino-like	ATLAS-CONF-2018-003
	0	2  jets + 2 t	, -	36.7 26.1	[qq, bs]	0.42 (	0.61	0/11/5		$BB(\tilde{t} \rightarrow h_a/h_a) > 200/$	1710.07171
	<b>ε</b> ε,μ	20		30.1	<i>v</i> <sub>1</sub>			0.4-1.40		υτι(1]-συε/υμ)>20 %	1710.00044
					I I						
lable ma v of the	ass limits on limits are ba	new state ised on	s or	10	$D^{-1}$		1			Mass scale [TeV]	





