# Searching for SUSY with ATLAS, and Beyond with MilliQan

University of Tokyo Seminar

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### How Do We Organize Searches at the LHC?





One of the great joys of working at a hadron collider: a nearly infinite possibility space of searches!

- Over 700 publications from ATLAS alone!
- How do we choose what to study?

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# 1. Consider the landscape: choose the "best" motivated signatures, search for these

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- 2. Search for these for a few years...
- 3. Update our priors from the experimental results. Are the "best" signatures still discoverable?
- 4. If you haven't found anything: are there signatures we could be missing entirely? Where are we still missing experimental input?



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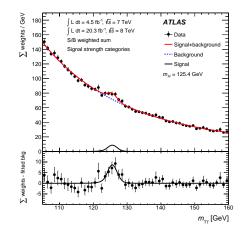
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#### Searching With the "Best" Theory Priors: SUSY With Many *b*-jets

ATLAS-SUSY-2016-10

## LHC Run 1 Legacy: The Higgs

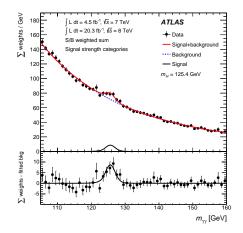




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## LHC Run 1 Legacy: The Higgs





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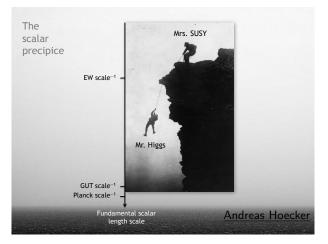


#### With the discovery of a 125 GeV Higgs, BSM physics is very well motivated!

Searches for (supersymmetric) top-partners are critical!



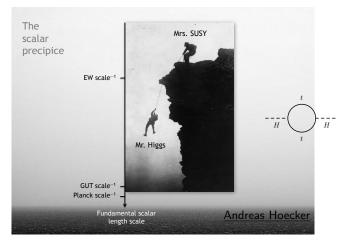
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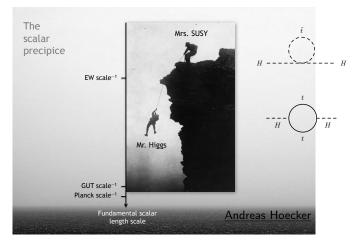
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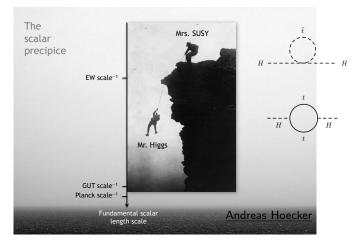
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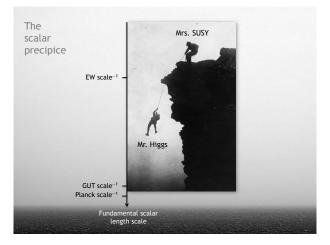


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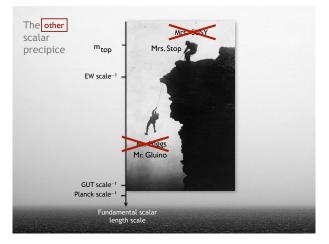


Stop is a scalar: natural mass value of *stop itself* set by gluino mass
 "Gluinos suck" (Savas Dimopolous)

Naturalness implies a light gluino as well as light stops

M. Swiatlowski (UC)



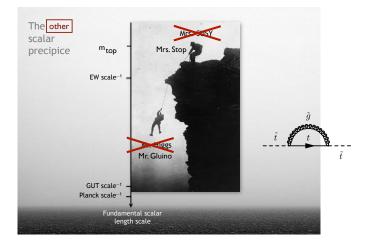


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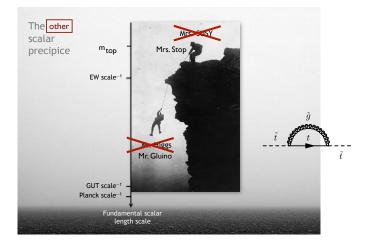


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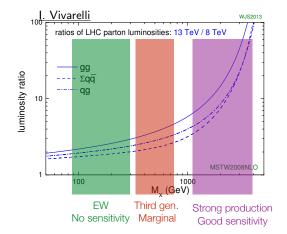


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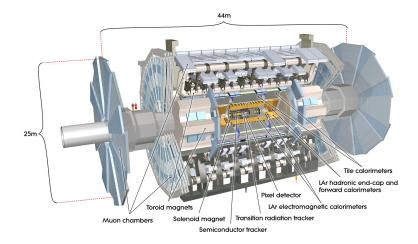
- ► New √s = 13 TeV data means exciting new prospects!
- Cross-section for higher-mass particles grows dramatically
  - Lighter particles, like third-gen squarks and electroweakinos, see a much smaller increase



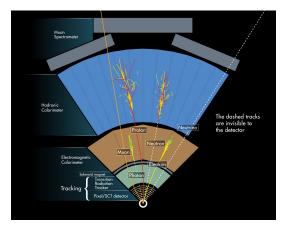
# Even though they are much more massive, lots of room for discovery for gluinos!

### A Few Words on the ATLAS Detector

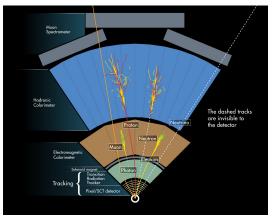








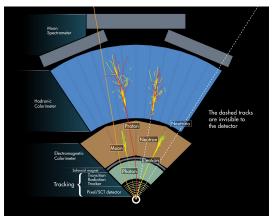




#### Electrons: inner detector track matched to EM calo deposit

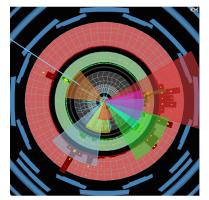
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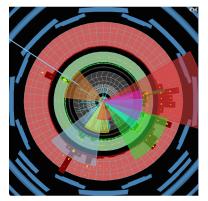
Muon: inner detector track matched to track in muon-spectrometer





Jet: Collimated spray of protons, neutrons, and more

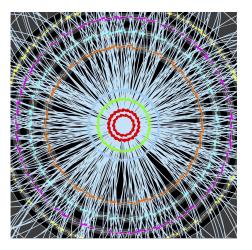


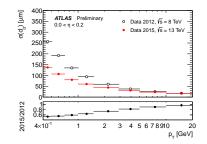


 $E_T^{miss}$ : Inferred missing energy, measured from energy misbalance

## New to ATLAS: The Inner-B-Layer





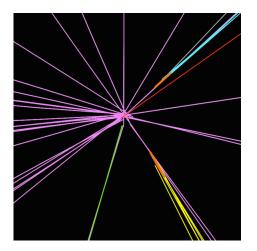


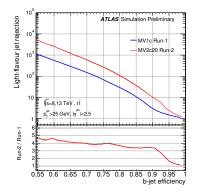
# Huge improvement in track $d_0$ resolution!

b-tagging (identification of displaced jets) benefits dramatically

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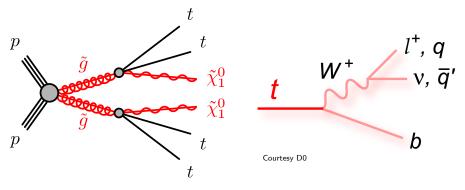


# Factor of $\approx$ 4 gain in light jet rejection!

b-tagging (identification of displaced jets) benefits dramatically

# Natural SUSY Signatures

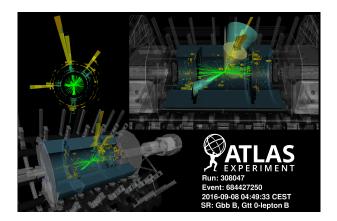




- Look for pair-production of gluinos
  - ▶ Highest cross-section particles, pair production guaranteed by *R*-parity
- Gluinos cascade decay to tops and LSP
  - Stops are assumed to be lightest squark for naturalness
- Use both  $0\ell$  and  $\geq 1\ell$  categories
  - Both have many b-jets in the final state!

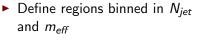
#### What Does This Look Like?



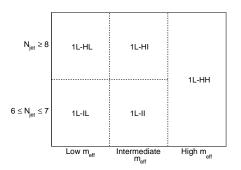


► Look for **spectacular** events: high  $n_{jet}$ , many *b*-tags, high  $E_T^{miss}$ , high  $m_{eff} = \sum p_T + E_T^{miss}$ 

Analysis Strategy



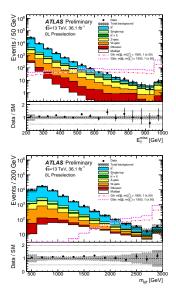
- Each region is orthogonal to the others
- Signal and background appears differently in each bin: combined fit has stronger sensitivity
- Carefully optimize these cuts, and other variables

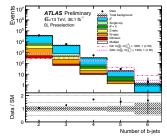




# Signal Discrimination



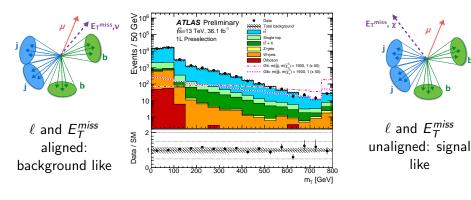




- Huge amount of power from  $E_T^{miss}$  and  $m_{eff}$ 
  - Especially in high mass-splitting regions, these provide great background rejection
- b-tagging clearly provides significant power as well

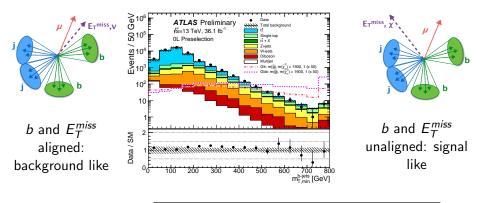
### More Variables: Transverse Mass $m_T$





$$m_T = \sqrt{2 p_T^\ell (1 - \cos(\Delta \phi(E_T^{miss}, \ell)))}$$

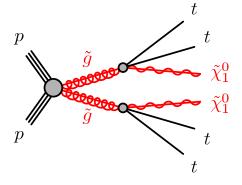
• Provides excellent discrimination in  $1\ell$  events



$$m_T^{b,min} = \min_{i \le 3} \sqrt{(E_T^{miss} + p_T^{j_i})^2 - (E_x^{miss} + p_x^{j_i})^2 - (E_y^{miss} + p_y^{j_i})^2}$$

• Provides excellent discrimination in both  $0\ell$  and  $1\ell$  channels

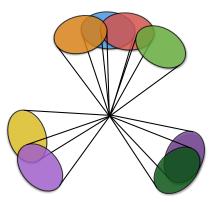
## Using Event (Sub)Structure



- ► Gtt signal has huge number of jets in the final state: 10 in 1ℓ, 12 in 0ℓ channels!
- These jets won't be isotropically distributed: g̃ will likely be produced at rest, but t will have significant p<sub>T</sub>
  - ▶ Depends on m<sub>g̃</sub> m<sub>χ̃1</sub><sup>0</sup>: high difference, more phase-space for large momentum
- $\rightarrow$  Jets will likely be grouped!
- How can we use this information?
  - NB: With so many jets in the final state, jets from other t can start to overlap as well!

#### Accidental Substructure



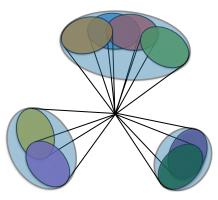


High multiplicity leads to significant "accidental" overlaps

→ We can use large jets to capture these overlaps: jets have mass
▶ We can use this structure to search for new physics!

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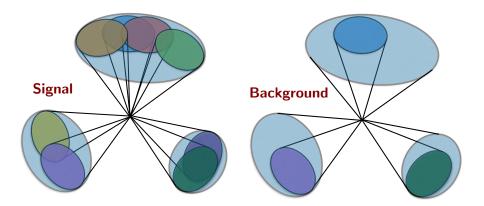


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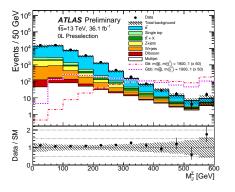


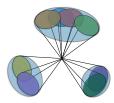
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## Total Jet Mass



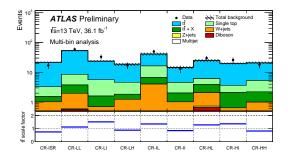




 Identify large-*R* jets with re-clustering approach

- Run a clustering algorithm on already-reconstructed jets, but with large size (R = 0.8)
- Naturally groups jets close to each other
- Form M<sup>Σ</sup><sub>J</sub> from sum of leading 4 large-R jet masses
  - In signal, many tops overlap, add mass to jets
  - ► Both 0ℓ and 1ℓ regions use this very effectively!

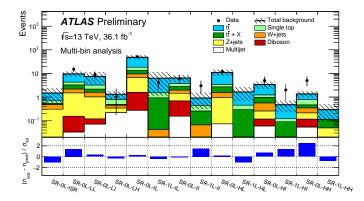




From MC, we know  $t\bar{t}$  will be the dominant background

- Use dedicated control regions with  $1\ell$  and inverted  $m_T$  cut
  - Allows for signal like region, but without signal
- Use these values to normalize  $t\bar{t}$  contribution in signal region





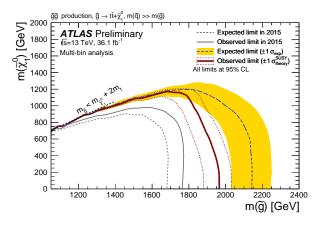
Signal region predictions both agree well with observation

- Slight excess in two regions targeting moderate and high mass
- Total size of excess is  $\approx 2\sigma$

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## Limits on Gluinos





- Limits significantly expand earlier Run 2 sensitivity: some of the strongest limits on gluinos from the LHC!
- No signal yet, but perhaps some interesting hints?
  - Will be following up with 2017 data: stay tuned!

#### Where Next? Long-lived Particles With MilliQan

arXiv:1607.04669

## The Status of SUSY at the LHC



#### ATLAS SUSY Searches\* - 95% CL Lower Limits ATLAS Preliminary $\sqrt{s} = 7.8.13$ TeV $c, \mu, \tau, \gamma$ lets $E^{miss} \left( \mathcal{L} dt (b^{-1}) \right)$ Model Mass limit Vr - 7 8 TeV Reference 0-3 c, µ/1-2 r 2-10 jets/3 h Yes aa. a→ai Yes 36.1 m(1)-200 GeV m(1" ess. i)-m(2" es ATLAS-CONF-2017-022 mano-let 1-3 ints 33. 3-+o<sup>2</sup> (compressed 0 2-6 ints Yes 36.1 $\tilde{\chi}_{1}^{0}, \tilde{\chi} \rightarrow \phi q \tilde{\chi}_{1}^{0} \rightarrow \phi q W^{*} \tilde{\chi}_{1}^{0}$ Yes 36.1 m(f) (200 GeV; m(f) +0.5(m(f))+m(F) 88. 8-499(11/1v)<sup>3</sup> 88. 8-499(11/1v)<sup>3</sup> 88. 8-499(028<sup>2</sup>) 4 ints Yes 36.1 m(87) <400 Geb GMSB (( NLSP 1-2 r + 0-1 ( 0-2 jets Yes GGM (bino NLSP) 1606.09150 GGM (hippsino-bino NLSP) Yes 20.3 m(if)-siss Gel(, cr(NLSP)-0.1mm, p-0 GGM (higgsino-bino NLSP) 2 jets Yes m(C)>600Gel( criNLSP>:0.1mm, and ATLAS-CONF-2016-066 GGM (higgsino NLSP) 2 jets Yes mono-iei 20.3 miGo1.8 × 10<sup>-4</sup> el6 mi2-mi2-1.5 Tel 1502.01518 Yes 36.1 m(C)-600GeV Yes m<sup>(2</sup>)-200Get 20.1 Yes 21. 1 (55) Yes m(1)-200GeV m(1)- m(1)-100GeV 0.2 4.4 $m(\tilde{x}_{1}^{*}) = 2m(\tilde{x}_{1}^{*}), m(\tilde{x}_{1}^{*})=55 \text{ GeV}$ 1209 2102, ATLAS-CONF-2016-07 $\tilde{i}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow Wh\tilde{i}_1^0$ or $i\tilde{i}_1^0$ 0.2 .... 0-2 ints/1-2 /r Yes 20.3/36.1 90-195 GeV m(C)+1 GeV 1506.08616. ATLAS-CONF-2017-020 Yes mi1)-mi2)-5GeV 20.3 3 4. 4 (2) Yes 36.1 mill1+0 GeV ATLAS-CONE-2017-018 1-2 0.00 Yes 36.1 milli-sGeV m(il)+0, m(i, i)+0.5(m(il)+m(il)) Yes ATLAS-CONF-2017-025 $\hat{x}_1^{\dagger} \hat{x}_2^{\dagger} \rightarrow \hat{t}_L \sqrt{t}_L \hat{t}(\hat{v}_L), \hat{t} \hat{v} \hat{t}_L \hat{t}(\hat{v}_V)$ $\hat{x}_1^{\dagger} \hat{x}_2^{\dagger} \rightarrow W \hat{x}_1^{\dagger} Z \hat{t}_1^{\dagger}$ Yes $n(\hat{x}_{1}^{*}) = m(\hat{x}_{2}^{*}), m(\hat{x}_{1}^{*}) = 0, m(\hat{t}, \hat{v}) = 0.5(m(\hat{x}_{1}^{*}) = m(\hat{x}_{1}^{*}))$ 236.0 0-2 ints 36.1 $m(\tilde{t}_1^2) \rightarrow m(\tilde{t}_2^2), m(\tilde{t}_1^2) \rightarrow 0, \tilde{t}$ decoupled ATLAS-CONF-2017-029 $\begin{array}{c} x_1 x_2 \rightarrow W x_1 Z x_1 \\ \hat{x}_1^* \hat{x}_2^* \rightarrow W \hat{x}_1^* k \hat{x}_1^*, k \rightarrow b \hat{b} / W W / \tau \tau / \gamma \gamma \\ \hat{x}_1^* \hat{x}_1^*, \hat{x}_1^0, \dots \rightarrow b M \end{array}$ 0.24 Yes 20.3 1501.07110 $m(\vec{x}_1)=m(\vec{x}_2), m(\vec{x}_1)=0, m(\vec{x}, i)=0.5(m(\vec{x}_2)=m(\vec{x}_1))$ GGM (wino NLSP) weak prod., 21 115-370 Geb GGM (bino NLSP) weak prod. 1 Yes 20.3 Direct \$ \$ for prod., long-lived \$ m(1)-m(1)-160 MeV, r(1)-0.2 m Direct R1 R1 prod., long-lived R1 Stable, stopped 2 R-hadron m(x1)-m(x1)-160 MeV, r(x1)-:15 re 1506.05332 Yes m(2)1+100 GeV. 10 as-cri21-:1000 s Metastable 2 R-hadron m(x<sup>0</sup>)+100 GeV; r>10 ns GMSB, stable 7, $\hat{\chi}_1^0 \rightarrow f(\hat{x}, \hat{\mu}) + r(x, \mu)$ GMSB, $\hat{\chi}_1^0 \rightarrow rG$ , long-lyed $\hat{\chi}_1^0$ 1-2 µ 537 GeV 1411.6795 Yes 1<00<sup>10</sup>)-cline, SPSR model dapl. celeala 107 7 <uv(1) >: 740 mm, m(g)=1.3 TeV $\operatorname{GGM}_{\tilde{\mathcal{B}}^{0}_{1}},\tilde{\chi}^{d}_{1}{\rightarrow}ZG$ displ. yts + lets 20.3 6 surt () is 480 mm, mikh-1.1 TeV 1504.05162 Bilnear RPV CMSSM 21, (55) $\hat{X}_{1}^{*}\hat{X}_{1}^{-}, \hat{X}_{1}^{*} \rightarrow W\hat{X}_{1}^{0}, \hat{X}_{1}^{0} \rightarrow eev, epv., ppv.$ $\hat{X}_{1}^{*}\hat{X}_{1}^{-}, \hat{X}_{1}^{*} \rightarrow W\hat{X}_{1}^{0}, \hat{X}_{1}^{0} \rightarrow \tau\tau\tau_{r}, e\tau\tau_{r}$ Yes 13.3 m(KT)>400GeV, July #0 (k = 1, 2) ATLAS-CONF-2016-075 Yes 20.3 22. 2-4999 4-5 large-it jets 14.5 ATLAS-CONF-2016-057 $\begin{array}{c} & & & \\ & & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & &$ 4-5 large-& jets 14.8 m(1)+800 GeV ATLAS-CONF-2016-057 1 e.µ 8-10 jets/0-4 b 36.1 miller 1 Tell June ATLAS-CONF-2017-013 1 r. µ 8-10 jets/0-4 b 2 jets + 2 0 10 GeV 450-510 GeV KTLAS-CONF-2016-022, ATLAS-CONF-2016-084 $\tilde{h}\tilde{h}, \tilde{h} \rightarrow b\ell$ 36.1 0.4-1.45 TeV ATLAS-CONF-2017-026 Other Scalar charm. 2-+c8 m<sup>(2</sup>)-200GeV "Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on 10-1 Mass scale [TeV]

phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Lots of searches, but only limits coming out from these...

Did we have a bad prior? Are more generic signatures showing any

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### The Status of Searches at the LHC



	Model	ί,γ	Jets†	Erniss	∫£ dt[fb	Limit			Reference
Extra dimensions	$\begin{array}{l} \text{ADD } \mathcal{G}_{\text{DC}} + g/q \\ \text{ADD non-resonant } \gamma\gamma \\ \text{ADD OBH} \\ \text{ADD BH high } \sum_{PT} \\ \text{ADD BH multiplet} \\ \text{PS1} \int_{G_{\text{AC}}} \rightarrow \gamma\gamma \\ \text{Bulk PS } \mathcal{G}_{\text{RC}} \rightarrow WW \rightarrow qq/r \\ \text{Bulk PS } \mathcal{G}_{\text{RC}} \rightarrow WW \rightarrow qq/r \\ \text{Bulk PS } \mathcal{G}_{\text{RC}} \rightarrow WW \rightarrow qq/r \\ \end{array}$	0 e,μ 2 γ - ≥ 1 e,μ - 2 γ 1 e,μ 1 e,μ	1-4j - 2j $\geq 2j$ $\geq 3j$ - 1J $\geq 2b, \geq 3j$	Yes - - - - - - - - - - - - - - - - - - -	36.1 36.7 37.0 3.2 3.6 36.7 36.1 13.2	An Andrew State St	7.75 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV 4.1 TeV	$\begin{array}{l} a=2\\ a=3\rm{HLZNLO}\\ a=6\\ a=6,M_{\odot}=3\rm{TeV},\rm{getBH}\\ a=6,M_{\odot}=3\rm{TeV},\rm{getBH}\\ k/M_{\rm{FV}}=0.1\\ k/M_{\rm{FV}}=1.0\\ \rm{Tors}(r,5,\rm{d}\rm{d}\rm{d}^{1,1})\to\rm{rr})=1 \end{array}$	ATLAS-CONF-2011 CERN-EP-2017- 1702.02015 1512.02085 1512.02086 CERN-EP-2017- ATLAS-CONF-2011 ATLAS-CONF-2011
Gaugebosons	$\begin{array}{l} \text{SSM } Z' \to t t \\ \text{SSM } Z' \to \tau \tau \\ \text{Leptophobic } Z' \to bb \\ \text{Leptophobic } Z' \to t t \\ \text{SSM } W' \to t r \\ \text{HYT } V' \to WV \to qqpq \mbox{ model } B \\ \text{HYT } V' \to WH/2H \mbox{ model } B \\ \text{LRSM } W_R' \to t b \\ \text{LRSM } W_R' \to b \end{array}$	1.4.4	- 2b 21b, 21J2 - 2J 2b, 0-1j 21b, 1J	- - Ves - Ves -	36.1 36.1 3.2 36.1 36.7 36.1 20.3 20.3	cmit         2.4 TeV           cmit         2.4 TeV           cmit         1.5 TeV           cmit         2.8 TeV           finance         2.8 TeV           finance         2.1 TeV           finance         2.1 TeV           finance         2.1 TeV           finance         1.2 TeV           finance         1.2 TeV	4.5 TeV S.1 TeV STeV IV	$\Gamma/m = 25_0$ $g_V = 3$ $g_V = 3$	ATLAS-CONF-281 ATLAS-CONF-281 1622.08791 ATLAS-CONF-281 1706.04786 CERN-EP-2017 ATLAS-CONF-281 1415.4102 1408.0886
õ	Ci qqqq Ci //qq Ci autt	- 2 e,µ 2(55)/≥3 e,	2j - v >1 b, >1 j	- - Yes	37.0 36.1 20.3		4.9 TeV	21.0 TeV q <sub>1</sub> 40.1 TeV q <sub>2</sub>  Cer  = 1	1703.09217 ATLAS-CONF-201 1504.04605
M	Axial-vector mediator (Dirac DN Vector mediator (Dirac DM) VV222 EFT (Dirac DM)	η Ο σ,μ Ο σ,μ, 1 γ Ο σ,μ	1-4j $\le 1j$ $1J, \le 1j$	Yes Yes Yes	36.1 36.1 3.2	Auar 1.5 TeV Auar 1.2 TeV A, 700 GeV		$\begin{array}{l} g_{q^{0}}0.25,g_{q}=1.0,m(\chi)<400~{\rm GeV}\\ g_{q^{0}}0.25,g_{q}=1.0,m(\chi)<400~{\rm GeV}\\ m(\chi)<150~{\rm GeV} \end{array}$	ATLAS-CONF-201 1704.03948 1608.02372
9	Scalar LQ 1 <sup>st</sup> gen Scalar LQ 2 <sup>st</sup> gen Scalar LQ 3 <sup>st</sup> gen	2 e 2 µ 1 e,µ	$\begin{array}{c} \geq 2 j \\ \geq 2 j \\ \geq 1 b, \geq 3 j \end{array}$	- - Yes	3.2 3.2 20.3	Q mass 1.1 TeV Q mass 1.05 TeV Q mass 640 GeV		$\begin{array}{c} \rho = 1 \\ \rho = 1 \\ \rho = 0 \end{array}$	1605.06035 1605.06035 1508.04735
Heary quarks	$\begin{array}{l} \text{VLQ } TT \rightarrow ltt + X \\ \text{VLQ } TT \rightarrow 2t + X \\ \text{VLQ } TT \rightarrow Wb + X \\ \text{VLQ } BB \rightarrow Hb + X \\ \text{VLQ } BB \rightarrow Hb + X \\ \text{VLQ } BB \rightarrow Wb + X \\ \text{VLQ } BB \rightarrow Wt + X \\ \text{VLQ } QQ \rightarrow WqWq \end{array}$	1 σ.μ 1 σ.μ 1 σ.μ 2/23 σ.μ	$\geq 2b, \geq 3j$ $\geq 1b, \geq 3j$ $\geq 1b, \geq 1JQ$ $\geq 2b, \geq 3j$ $\geq 2/\geq 1b$ $\geq 1b, \geq 1JQ$ $\geq 2/\geq 1b$ $\geq 1b, \geq 1JQ$ $\geq 2/\geq 1b$	Yes Yes	13.2 36.1 20.3 20.3 20.3 36.1 20.3	Insur         1.2 TeV           Insur         1.16 TeV           Insur         1.25 TeV           Insur         700 GeV           Insur         7.00 GeV		$\begin{split} & S(T \to Ht) = 1 \\ & S(T \to 2t) = 1 \\ & S(T \to Hb) = 1 \\ & S(R \to Hb) = 1 \\ & S(R \to Hb) = 1 \\ & S(R \to 2b) = 1 \\ & S(R \to Wt) = 1 \end{split}$	ATLAS-CONF-201 1705.10751 CERN-EP-0017- 1505.04006 1409.5500 CERN-EP-0017- 1509.04001
Excited fermions	Eacted quark $q^2 \rightarrow qg$ Eacted quark $q^2 \rightarrow q\gamma$ Eacted quark $b^2 \rightarrow bg$ Eacted quark $b^2 \rightarrow We$ Eacted quark $b^2 \rightarrow We$ Eacted lepton $t^2$ Eacted lepton $v^2$	- 1 γ - 1 or 2 e, μ 3 e, μ 3 e, μ, τ	2j 1j 1b,1j 1b,20j -	- - Yes -	37.0 36.7 13.3 20.3 20.3 20.3 20.3	" Plats Plats 2.3 TeV " Plats 2.3 TeV " Plats 1.5 TeV 2.0 TeV 3.0 TeV 1.5 TeV	6.0 TeV 5.3 TeV	$\begin{array}{l} \cos(ya^{*}\mathrm{and}a^{*},A=m(q^{*})\\ \cos(ya^{*}\mathrm{and}a^{*},A=m(q^{*})\\ \end{array}\\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ $	1703.09127 CERN-EP-0017- ATLAS-CONF-001 1510.00664 1411.0821 1411.0821
Other	LTSM Majorana $v$ Higgs triplet $H^{*+} \rightarrow \ell \ell$ Higgs triplet $H^{*+} \rightarrow \ell \tau$ Monotop (non-res prod) Multi-charged particles Magnetic monopoles	2 e, µ 2,3,4 e, µ (52 3 e, µ, 7 1 e, µ - -	2) - 16 - -	Yes 	20.3 36.1 20.3 20.3 20.3 7.0	2 лини 10 лини до Сон 11 лини далкая вер Сон 10		$\begin{split} & e(W_R) = 2.4 \text{ TeV}, \text{no mixing} \\ & \text{DY production} \\ & \text{DY production}, \text{S}(H_L^{++} \rightarrow \ell r) = 1 \\ & a_{\min \to \infty} = 0.2 \\ & \text{DY production},  q  = 5e \\ & \text{DY production},  q  = 1g_D, \text{spin } 1/2 \end{split}$	1506.06020 ATLAS-CONF-201 1411.2921 1410.5454 1504.04188 1509.08059

\$ Small-radius (large-radius) jets are denoted by the letter j (J).

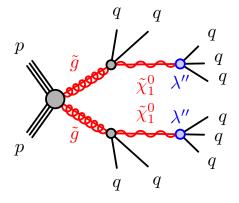
Even with less theory "bias", still only limits
Where is new physics?

M. Swiatlowski (UC)



## Where Could the Signal Be Hiding?

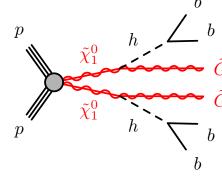
- 1. It's in an (accessible) signature we haven't searched yet
  - Keep broadening the search program!
  - RPV multijets, diplaced vertices, displaced leptons...
- 2. The cross-section is too small to have been observed
  - Keep doing existing searches, push down systematics
  - Study electroweak SUSY production, explore differing branching ratios of decays...
- 3. The signal is something our detector cannot observe
  - ▶ Uhoh...





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???





- ▶ What if new physics (Dark Matter, etc.) is in a "hidden" sector?
  - Lots of attention to this in the BSM program at the LHC: hidden valleys, Higgs portals, etc.
  - Another generic possibility for coupling this hidden sector to the SM are vector portals:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\text{extra-sector}}$$
  
=  $\mathcal{L}_{SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i \bar{\psi} \left( \partial + i e' A' + i M \right) \psi - \frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$ 

- $\frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$  is the kinetic mixing term: the vector portal.  $\kappa$  assumed small: otherwise would be observed already.
  - ▶ Can diagonalize kinetic terms by defining  $A'_{\mu} o A'_{\mu} + \kappa B_{\mu}$

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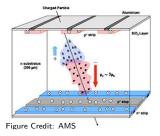
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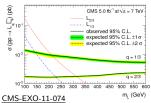
Can be produced at LHC via Drell-Yan processes

## What About Existing Searches?



- Can the LHC see this?
- Silicon detectors work via *ionization*: creating electron/hole pairs as particle traverses detector
- But if Q if our particle is very low: very low ionization signal
- Our detectors have high "charge over threshold" cuts to reduce noise, data volume
- ▶ In practice, cannot set limits lower than Q = 1/3 (or so) very easily
- Essentially the same issue for calorimeters: tiny signals because of low ionization/scintillation

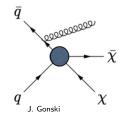




 NB: beam dump experiment at SLAC set limits, but only at very low mass because of low beam energy



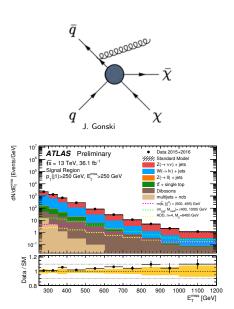
- Traditionally monojet is used to set limits on non-interacting (or weakly-interacting) particles
- Unfortunately SM backgrounds are huge and irreducible
- Drell Yan signals produced with Q<sup>2</sup> coupling: millicharge means that signal has low cross-section
- ► Sufficient S/√B challenging to reach, and quickly become systemically limited



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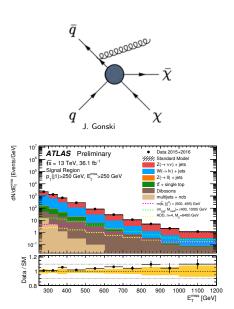
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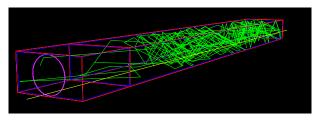
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## What Kind of Detector Would We Need?



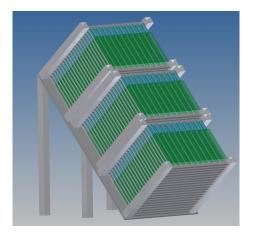
- Scintillators are a good material to build a millicharge detector with:
  - Plastic scintillator yields 10<sup>4</sup> photons/MeV
  - Q = 1 MIP deposits 2 MeV/cm
  - 80 cm long bar gets  $1.6 \times 10^6$  photons
  - For  $Q = 10^{-3}$ , lower yield by  $Q^2$ : O(1) photons
  - Even if not all photons are detected, still will have some sensitivity with enough data
- Rough estimates confirmed with GEANT simulation



► NB: same basic design as MilliQ experiment at SLAC

### The Full Detector: MilliQan





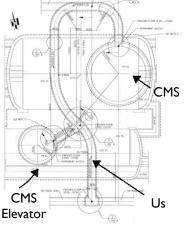
- Full detector would be 1 m  $\times$  1 m  $\times$  3 m
- Three layers allow for triple coincidence to reduce backgrounds
  - $\blacktriangleright$  Our signature: three low photon pulses within 15 ns in adjacent PMTs

# backgrounds from hadrons

Where Should It Go?

Need rock barrier to remove

- Backgrounds would be too large if we kept these!
- ► Need to not be too far: acceptance falls as R<sup>2</sup>
- Needs to be at P1 or P5: maximum luminosity
- No suitable site at ATLAS :(
- PX56 drainage gallery is in the Goldilocks zone:
  - > 2.78 m in height, 2.73 m in width
  - ▶ 33 m from IP, 17 m through rock
  - $43.1^{\circ}$  from IP: not too forward
  - ► Acceptance is ≈ 10<sup>-5</sup>: sufficient for observations!

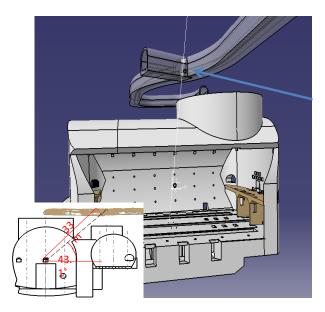




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#### Another View of the Location







- Muons: not actually a large background, since they leave large signals
  - Can put maximum cut on  $N(\gamma)$ , remove these nearly completely
  - Afterpulses would be removed by detector deadtime when reading out main pulse
- Radiation (radon, etc.) also expected to be low for similar reasons
- Main background comes from dark current: false flashes from PMT
  - ▶ Measured on surface to be O(1 kHz)
  - Triple coincidence in 15 ns window reduces rate to 10<sup>-6</sup> Hz
  - Can potentially reduce this further with timing information from CMS
- NB: main sources of noise scale with *time*, not *luminosity*: higher pileup is good for us!
- Testing these assumptions now with a demonstrator system: 1% of the detector installed during TS2



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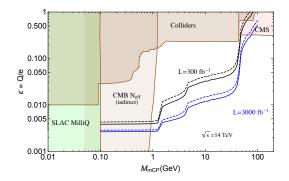


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- Strong unique sensitivity to a wide range of phase space: no other detector can reach these signals!
- Fairly conservative cuts applied for these estimates: continued optimization can improve reach further

- To test our detector strategy, we have built and installed a demonstrator at P5
- Approximately 1% of the detector: 2x3 bars of scintillator, in 3 layers
- ► Goals are to:

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- Prove that we can install a large device in this area
- Show that we can align to IP
- Demonstrate remote operation and readout
- Measure backgrounds in-situ

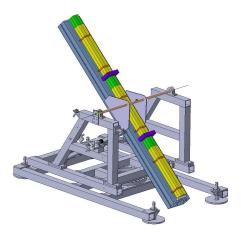




## The Demonstrator System

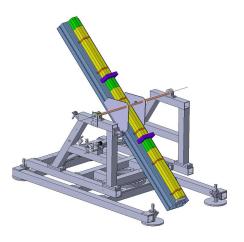
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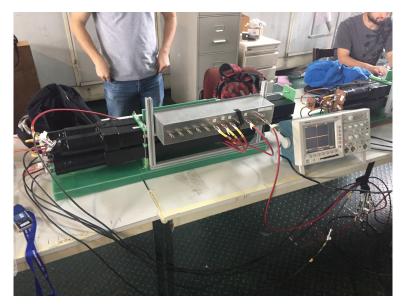
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# Surface Assembly





#### Loading the Crane





#### Lowering the Crane





#### Lowering the Crane





#### Lowering the Crane





#### Standing Above CMS









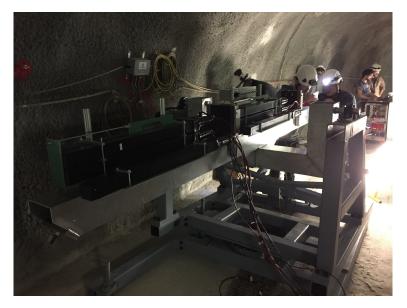
#### Installation





#### Progress...





#### **Final Product**





## Commissioning



- Installation was a success!
- ▶ Everything done in < 3 days: hugely compressed schedule
- Passed safety examinations, etc.
- Operating smoothly now
  - Able to see muons from collisions at P5!
- ► Super small team, but lots of great help from CMS technical staff



## Demonstrator Program



- Lots more to go for the demonstrator:
  - Upgrade with new cosmic veto panels installed during shutdown
  - 2. Measure dark current rates: are they similar to surface?
  - 3. Commision timing information from CMS, establish how tight can we cut on timing
  - 4. Examine both low charge and high charge events
  - 5. Prove to funding agencies that our experiment is possible :)



#### Conclusion

## Conclusions



- Substantial  $\sqrt{s} = 13$  TeV dataset is here, but SUSY is not (yet!)
- First searches optimized for discovery have not yet observed any significant deviation from the SM
- ▶ Run 2 has just begun, though: full dataset promises ≈5x the data!
  - These searches are important to continue: lots of potential for discovery to go
- Given the null results, though, it is time to ask whether our detector assumptions can be hiding new physics
- MilliQan is a small, affordable new detector proposed to cover a hole in ATLAS's sensitivity
- Looking forward to installation for Run 3 and 4!

#### Thank you for your attention!

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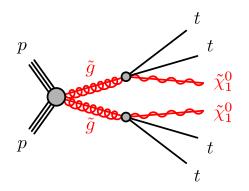
#### Thank you for your attention!

#### Backup

**RPV** Multijets

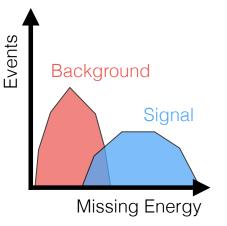
ATLAS-CONF-2016-057





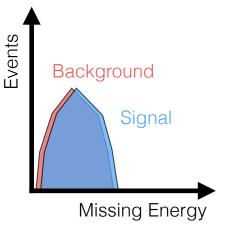
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  - ► These models assume *R*-parity, which means the Lightest Supersymmetric Particle (X<sup>0</sup><sub>1</sub>) is stable
  - This neutralino does not interact: escapes detection, appears as E<sub>T</sub><sup>miss</sup>
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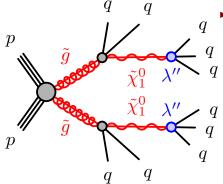




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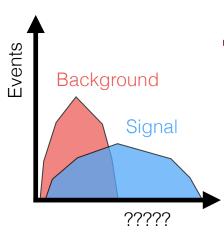
• Consider  $\tilde{g}$  pair production, decaying with  $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$ ,  $\tilde{\chi}_1^0 \rightarrow 3q$ : *R*-parity violating!



- Final state has huge number of quarks!
  - Between 10 (light quarks only) and 22 (top decays) partons
  - Extremely difficult background estimation: high-mass extremes of QCD are difficult to model
  - ► No source of  $E_T^{miss}$ : need other discrimination handles

# High Multiplicity RPV Signatures

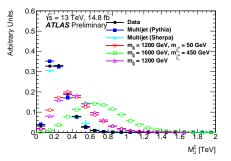
- Consider ğ̃ pair production, decaying with ğ̃ → qq X̃<sup>0</sup><sub>1</sub>, X̃<sup>0</sup><sub>1</sub> → 3q: *R*-parity violating!



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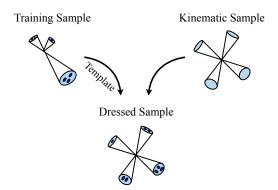
- As used in the multi-B analysis and previous 8 TeV analyses, M<sup>T</sup><sub>1</sub> can come to the rescue
- Mass comes when combining widely spaced particles
  - $\rightarrow \;$  Jets with substructure have high mass!
    - ▶ No individual jet corresponds to  $\tilde{\chi}_0^1$  or  $\tilde{g}$
- Many different signals look very different from background



NB: use trimmed R = 1.0 jets with  $p_T > 100~{
m GeV},~|\eta| < 2.5$ 

# Background Estimation Strategy



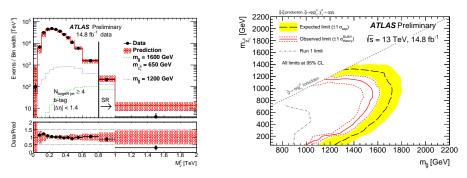


- Use 3-jet region to build jet mass templates:  $m(p_T, \eta)$
- ▶ Use kinematics of events from 4/5-jet region to build background
  - ► Even if signal is present, p<sub>T</sub> distributions are very similar, but mass distributions would be very different

M. Swiatlowski (UC)

## **Results and Limits**





- Several regions also require the presence of a *b*-tagged jet to increase sensitivity to heavy flavor
- No significant signal observed (1.5 $\sigma$  excess)
- Significant improvement over Run 1 analysis!