ATLAS results on exotics searches with boosted objects

Boosted, semi-boosted, and "wish I were boosted" final states

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BOOST 2012 Workshop, Valencia, España

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New particles at the LHC

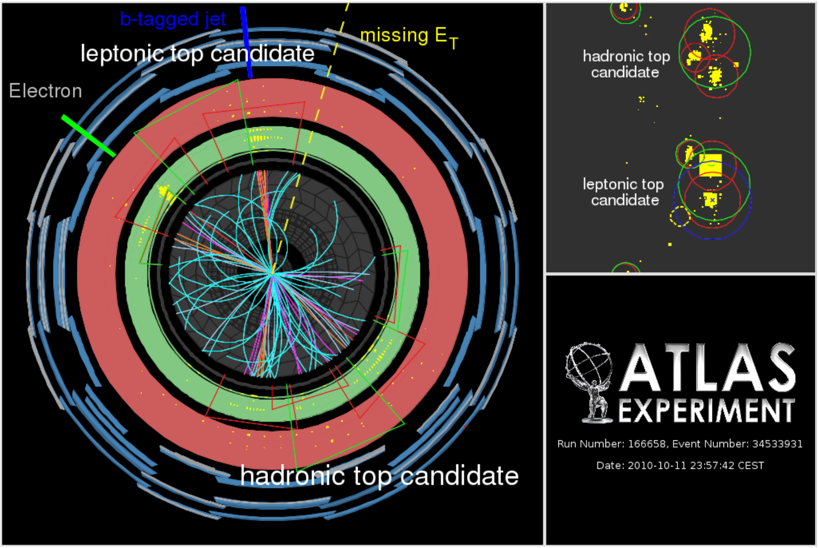
The LHC is now officially a discovery machine!

The question now is: *is that all there is?*

- **Composite boson resonances like W', Z'?**
- **Top partners in little Higgs models, t'?**
- **Vector-like quarks from GUTs?**
- **New particles with decays to bosons?**
- **Something totally different.....???**

Recent results constrain the range of possibilities, and the future looks bright for physics at the LHC.

A new era for nearly all final states

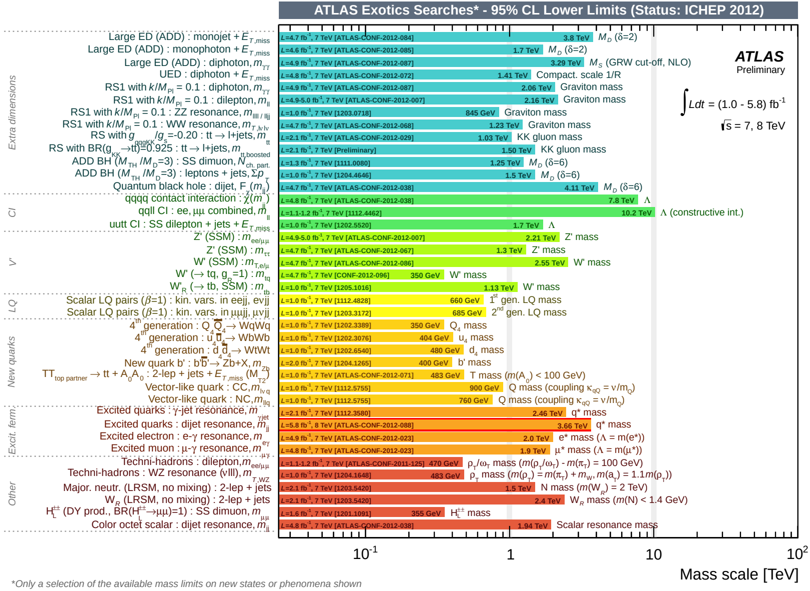


1000-fold increase in energy since the discovery of jets at SLAC 40 years ago. This opens a new energy regime; it also brings new challenges.

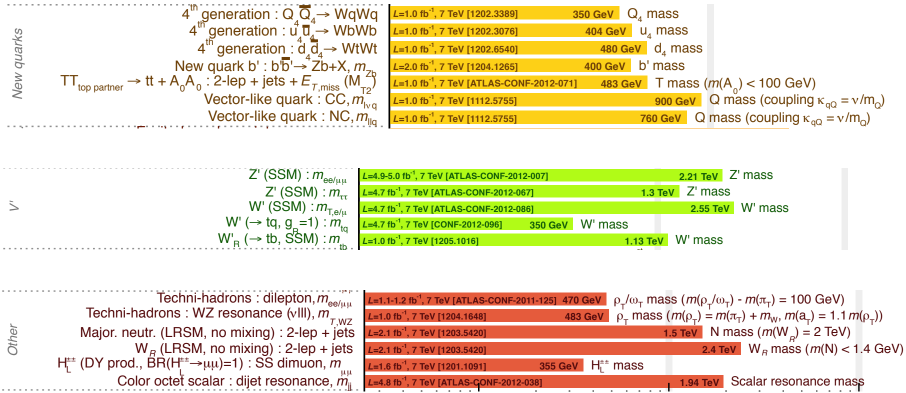
The advanced, precise detectors – the cameras used to take snapshots of the collisions – have fostered complex techniques for parsing and analyzing these complex final states.

I will review recent results on searches for exotic new states, many of which might offer alternative hypotheses to the “vanilla” SM Higgs boson, and comment on the era of boosted topologies.

Extensive program of exotics searches at the LHC



Extensive program of exotics searches at the LHC

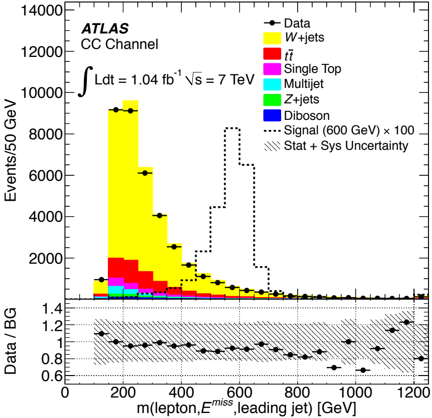


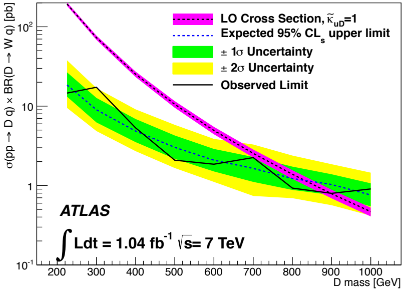
- 4^{th} Generation pushing the **1/2 TeV mark**
- VLQ (vector-like quarks) limits **nearing 1 TeV** (for some models, VLQ (w/ light decays))
- New heavy bosons (W' and Z') generally **well into the ∼TeV-scale**

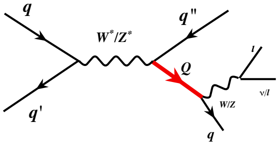
Vector-like quark searches (I)

Charged current channel: $Q \to W(\to l\nu) + q$

[arXiv:1112.5755], PLB 712 (2012) 22







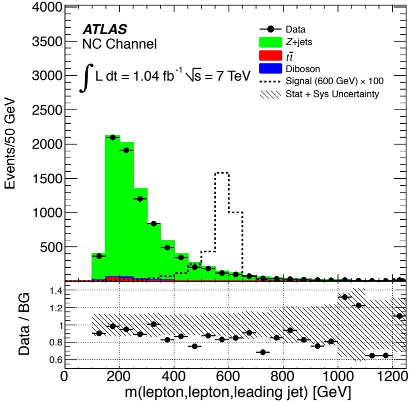
Search for $Q \to W(\to l\nu) + q$ in the mass of the system ($l + E_{\mathrm{T}}^{\mathrm{miss}} +$ jet)

Exclude masses up to $m_Q > 0.9$ TeV

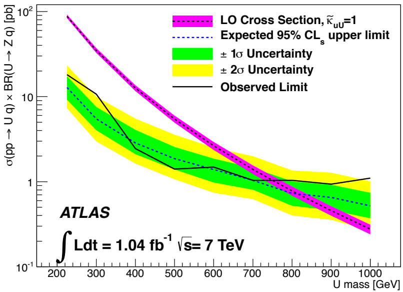
At higher m_Q, W significantly boosted

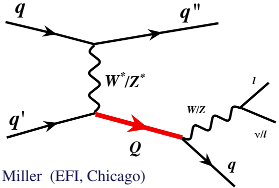
Vector-like quark searches (II)

Neutral current channel: $Q \rightarrow Z(\rightarrow l\nu) + q$



[arXiv:1112.5755], PLB 712 (2012) 22





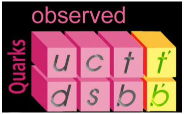
Search for $Q \rightarrow Z(\rightarrow ll) + q$ in the mass of the system $(l + l + \text{jet})$

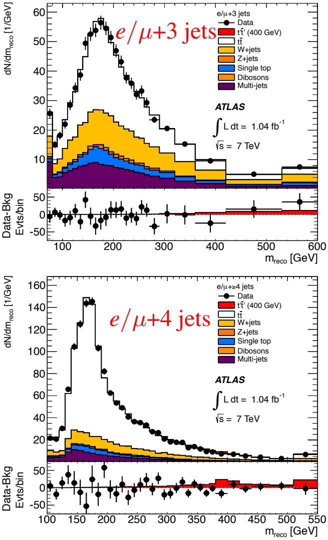
Exclude masses up to $m_Q > 0.76$ TeV

At higher m_Q*, Z significantly boosted*

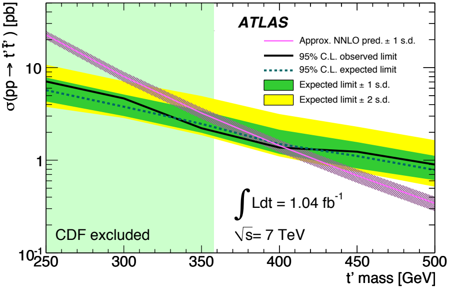
Searches for a 4^{th} Generation (I)

Up-type quark search: $t'\bar{t}' \xrightarrow{100\%} WbWb \rightarrow l\nu bqqb$





[arXiv:1202.3076], PRL 108 (2012) 261802

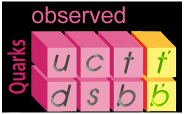


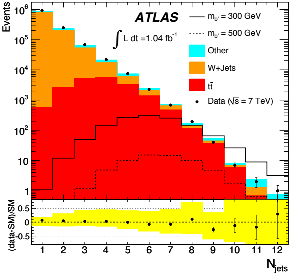
Search for $t' \rightarrow Wb$ in candidate mass of the quark (kinematic likelihood fit with constraints)

Exclude masses up to $m_{t'} > 0.4$ TeV

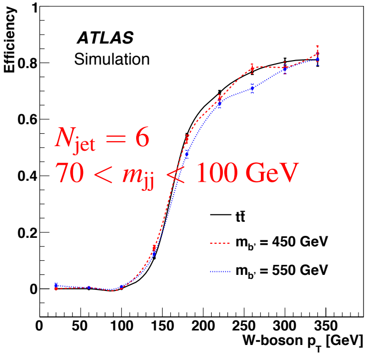
Searches for a 4^{th} Generation (II)

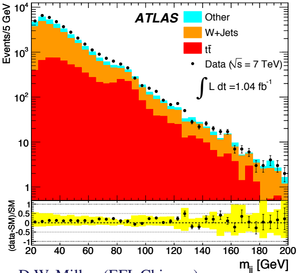
Down-type quark search: $b'\bar{b}' \xrightarrow{100\%} WtWt \rightarrow WWbWWb$ *Semi-Boosted*





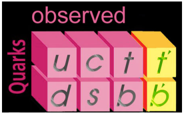
[arXiv:1202.6540], sub. to PRL





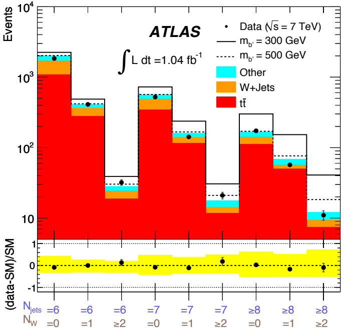
- **Approach:** $t\bar{t}$ (l+jets) selection
- **Add:** cut on m_{jj} iff $\Delta R(\mathrm{jet},\mathrm{jet}) < 1.0$
- Plateau at $\varepsilon = 80\%$

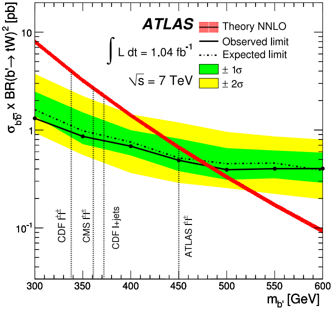
Searches for a 4^{th} Generation (III)



Down-type quark search: $b'\overline{b}' \xrightarrow{100\%} WtWt \rightarrow WWbWWb$ *Semi-Boosted*

[arXiv:1202.6540], sub. to PRL





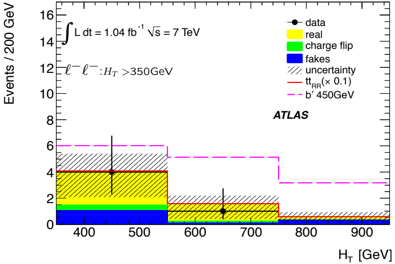
- Discriminant from N_{jet} and N_W (semi-boosted selection)
- Uncertainty dominated by JES and ISR/FSR in $t\bar{t}$

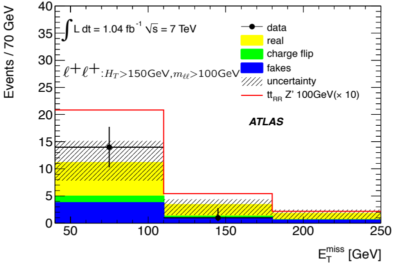
Search for $b' \rightarrow Wt \rightarrow WWb$ in candidate mass of the quark

Exclude masses up to $m_{t'} > 0.48$ TeV

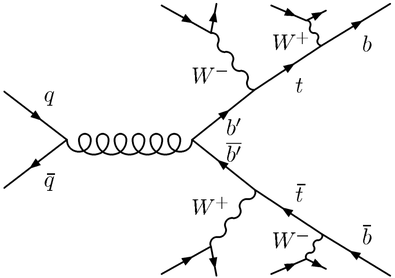
Searches for a 4^{th} Generation (IV)

Same-sign (SS) top and down-type quark search ($b'\overline{b}' \xrightarrow{100\%} WtWt \rightarrow WWbWWb$) *Non-Boosted*





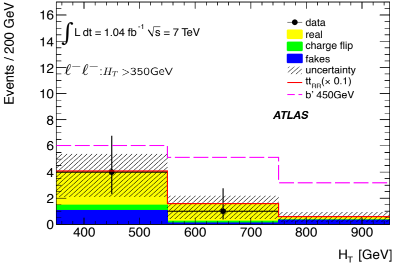
[arXiv:1202.5520], JHEP 1204 (2012) 069

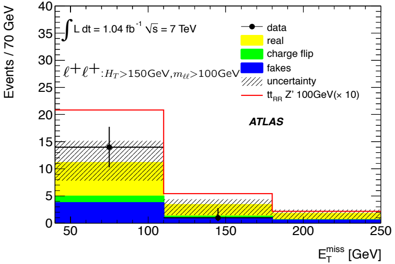


- Two same-sign leptons + 2 jets + H_T+ E_T^{miss}

Searches for a 4^{th} Generation (V)

Same-sign (SS) top and down-type quark search ($b'\bar{b}' \xrightarrow{100\%} WtWt \rightarrow WWbWWb$) *Non-Boosted*





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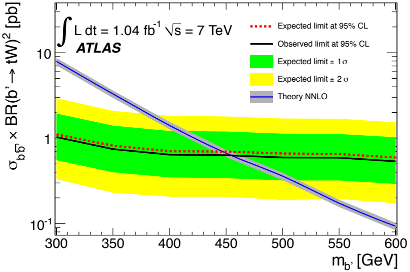


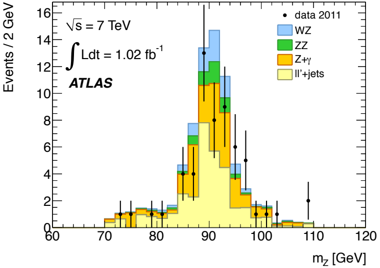
Search for $b' \rightarrow Wt \rightarrow WWb$ in event yields using both (+) and (-) leptons

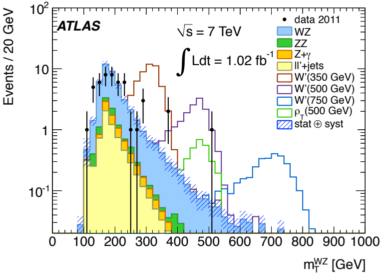
Exclude masses up to $m_{t'} > 0.45$ TeV

Complementary to the semi-boosted analysis, sensitivity is similar

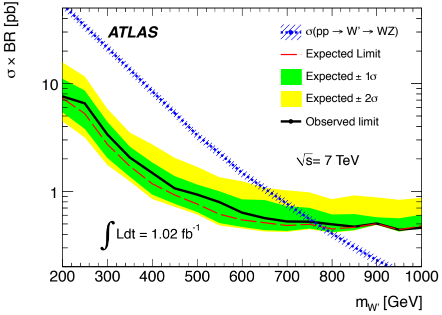
Resonant W/Z from W'_{SSM}

$W'_{\mathrm{SSM}} \to WZ \to l\nu ll$





[arXiv:1204.1648], PRD 85 (2012) 112012



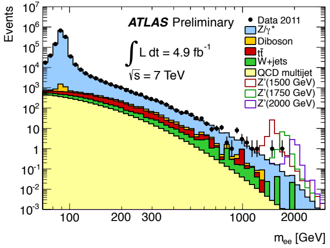
Search for $W' \to WZ$ in $m_T^{WZ} = \sqrt{(E_T^Z + E_T^W)^2 - (p_x^Z + p_x^W)^2 - (p_y^Z + p_y^W)^2}$

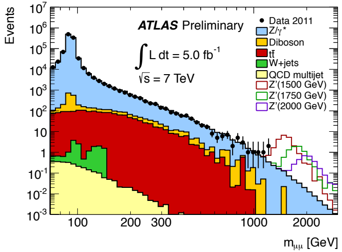
Exclude masses up to $m_{W'} > 0.76$ TeV

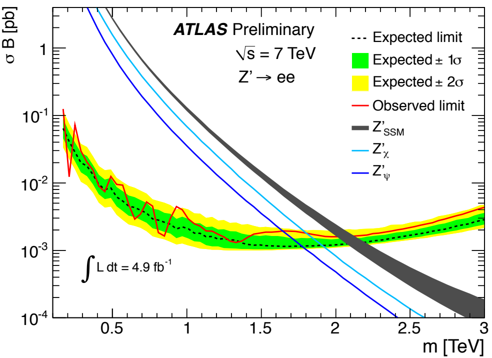
Search for Z'_{SSM} in high-mass dilepton events

$Z'_{SSM} \to ll$

ATLAS-CONF-2012-007







Search for anomalous events in tail of $m_{\ell\ell}$

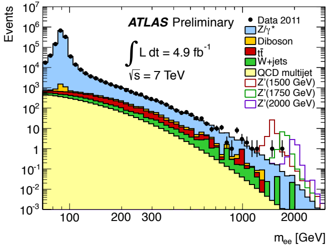
Resolution for $Z \to ee$ better than for $Z \to \mu\mu$

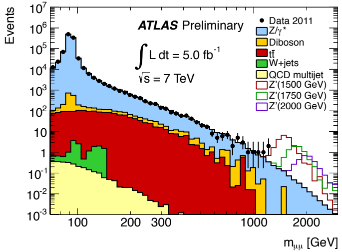
Exclude masses up to $m_{Z'} > 2.21$ TeV

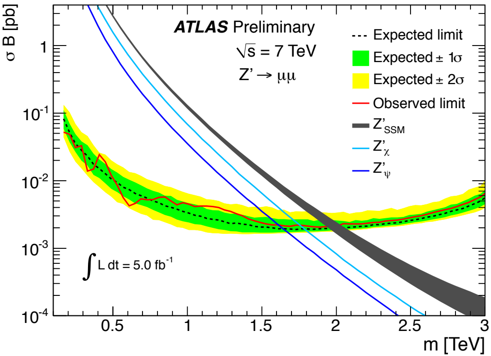
Search for Z'_{SSM} in high-mass dilepton events

$Z'_{\text{SSM}} \to ll$

ATLAS-CONF-2012-007





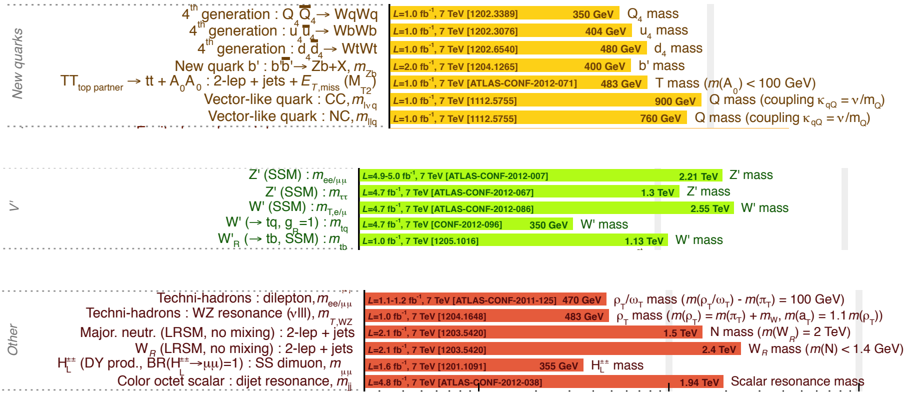


Search for anomalous events in tail of $m_{\ell\ell}$

Resolution for $Z \to ee$ better than for $Z \to \mu\mu$

Exclude masses up to $m_{Z'} > 2.21$ TeV

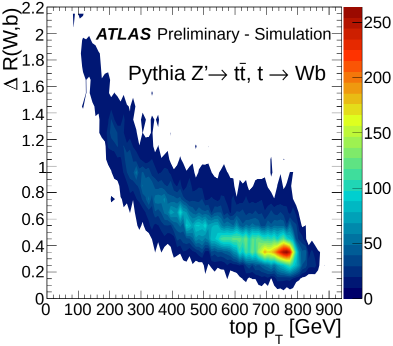
Recall the current status of the exclusion limits ∼today



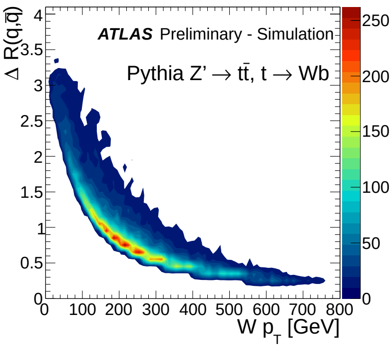
- 4^{th} Generation pushing the **<u>1/2 TeV mark</u>**
- VLQ (vector-like quarks) limits **<u>nearing 1 TeV</u>** (for some models, VLQ w/ light decays)
- New heavy bosons (W' and Z') generally **<u>well into the ∼TeV-scale</u>**

Implications for identifying these final states

As the mass scale increases → so does the boost of the final state particles



$t \rightarrow Wb$

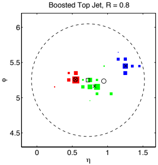


$W \rightarrow q\bar{q}$

It is becoming increasingly important to provide tools for reconstructing these special topologies with new approaches to old analyses.

Applying the tools to exotic all hadronic final states (I)

High-mass resonances decaying to *WW/WZ/ZZ* presents challenges to for standard reconstruction → crucial use-case for the boosted techniques

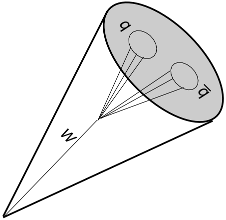


$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min_A \{\Delta R_{A,k}\}$$

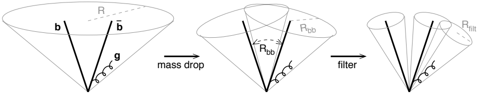
Sum over constituents

Minimize distance to candidate subjet axes

Later: Minimize τ_N over all possible subjet axes, becomes a true jet shape



→ Jet shapes from **unfiltered** jet for baseline discrimination

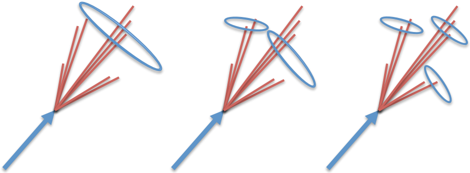


→ Splitting and Filtering for the 2-body decay

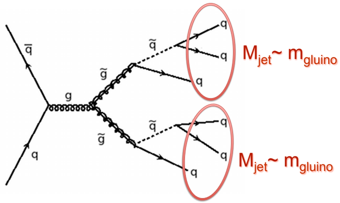
- ☑ Subjet energy scales validation
- ☑ Splitting/filtering performance
- ☑ Mass scale calibration
- ☑ High-p_T shapes & internal scales
- ☑ Pile-up resilience
- ☑ Multi-variate tagging

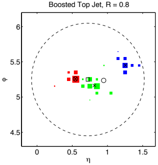
Applying the tools to exotic all hadronic final states (II)

Direct decay of SUSY particles to SM particles can occur via in the R-parity violation (RPV) superpotential, $W_{\not R_p}$, via $\frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$ (generally poorly constrained at colliders)



Y-scale 1-2 (y_1)   Y-scale 2-3 (y_2)





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Sum over constituents

Minimize distance to candidate subjet axes

Later: Minimize τ_N over all possible subjet axes, becomes a true jet shape

- $\tilde{g}\tilde{g} \rightarrow (qqq)(qqq) \rightarrow JJ$
- $\tilde{\chi}^0_1\,\tilde{\chi}^0_1 \rightarrow (qqq)(qqq) \rightarrow JJ$
- Use jet masses and substructure observables to discriminate against background

Status and future of exotic boosted object physics at ATLAS

The physics program is well underway at ATLAS, with the discovery of the Higgs boson and many new phenomena models already excluded up to the TeV scale.

To understand whether we have a "Standard Model-only" universe, we will need to work hard to rule out other mechanisms for EWSB near the TeV scale.

- New heavy SSM bosons need to be above $m \sim 1 - 2$ TeV
- New vector-like quarks (light decays) be above $m \sim 0.7 - 0.9$ TeV
- 4^{th} Generation quarks must be above $m \sim 0.5$ TeV

(with some caveats, of course!)

Most 2011 analyses are now incorporating fully boosted channels using all the techniques you've heard about in the workshop for "re-analysis" in 2012.

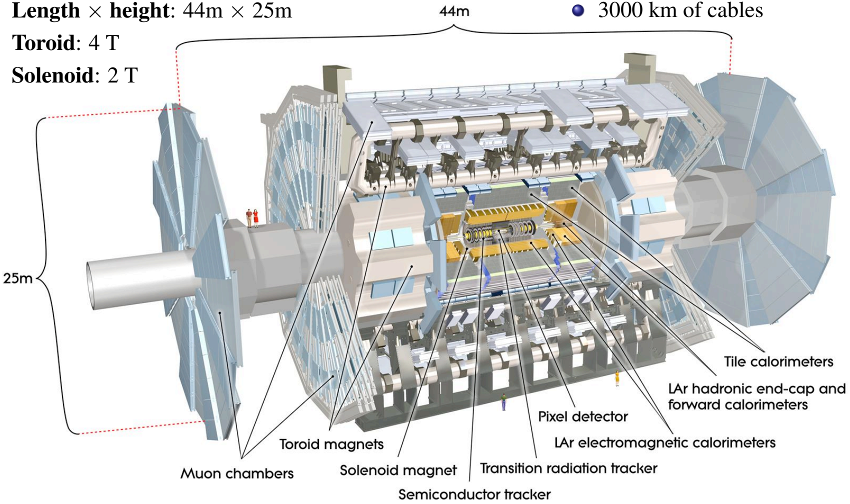
$\rightarrow$ **Trimming, pruning, splitting/filtering, *N*-subjettiness, splitting scales, subjets, and large-*R* jets are all becoming a standard part of the ATLAS analysis toolbox.**

Additional Material

The ATLAS detector at the LHC

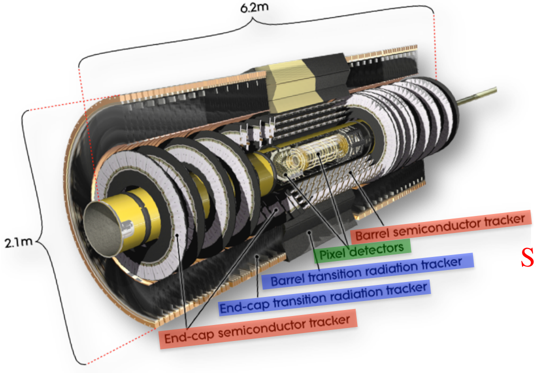
- **Weight**: 7000 tons
- **Length** × **height**: 44m × 25m
- **Toroid**: 4 T
- **Solenoid**: 2 T

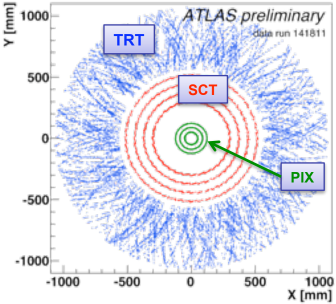
- 100,000,000 electronic channels
- 3000 km of cables



But the whole is more than just the sum of its parts...

The ATLAS tracking system





Silicon Strips (SCT)

- 4 barrel layers, 2x9 end-cap disks
- $\sigma_{r\phi} \sim 17\mu$m, $\sigma_z \sim 580\mu$m
- 6.3M channels

Transition Radiation Drift Tubes (TRT)

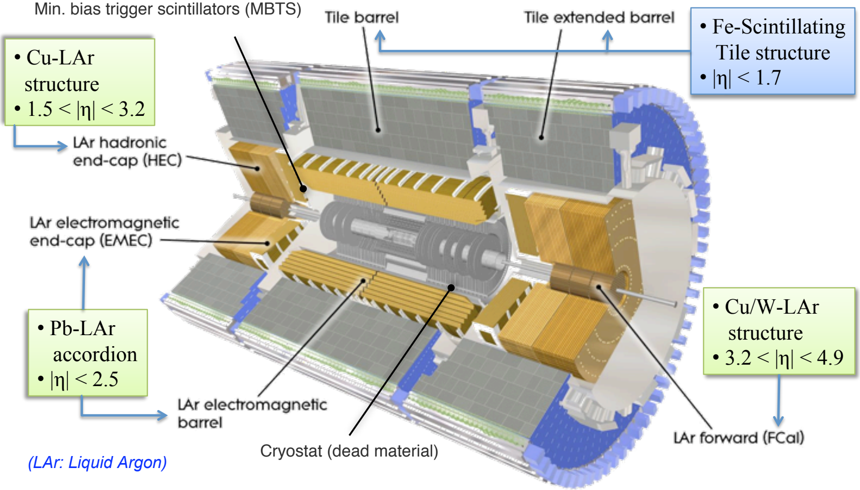
- 73 barrel straws, 2x160 end-cap disks
- $\sigma_r \sim 130\mu$m, particle ID
- 350k channels

Silicon Pixels (PIX)

- 3 barrel layers, 2x3 end-cap disks
- $\sigma_{r\phi} \sim 10\mu$m, $\sigma_z \sim 115\mu$m
- 80M channels

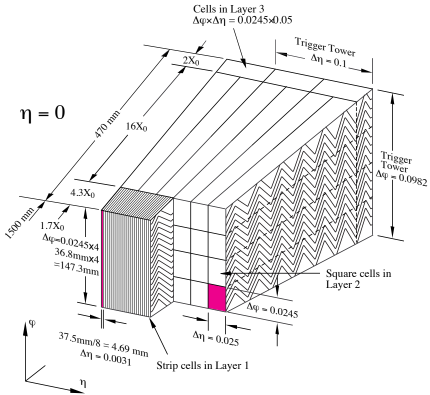
Excellent position resolution, tracking efficiency, vertexing performance.

The ATLAS calorimeter system (I)



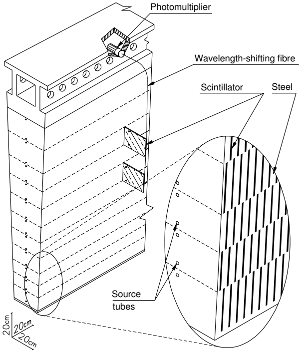
Well known technologies with fast readout and high granularity.

The ATLAS calorimeter system (II)



- Highly granular EM calorimeter with longitudinal segmentation
- $\Delta\eta \times \Delta\phi \approx 0.025 \times 0.025$ for the central compartment
- $22X_0 - 33X_0$ in the barrel

- Excellent energy resolution overall ($\approx 60\%/\sqrt{E}$)
- $7 - 8\lambda_0$ in the hadronic calorimeter alone



Boosted particle signatures measured in inclusive jets

Published measurements: arXiv:1203.4606, JHEP

We have established a thorough understanding the accuracy and precision of the predictions from various MCs of these complex substructure observables.
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