Searching for SUSY with ATLAS, and Beyond with MilliQan

University of Tokyo Seminar

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11 April, 2018

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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A Bayesian(-ish) Search Strategy

1. Consider the landscape: choose the "best" motivated signatures, search for these
   - In the absence of experimental inputs (especially at a new energy scale), theory motivations can serve as effective priors
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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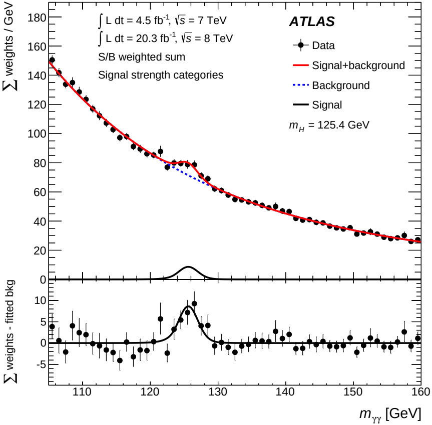
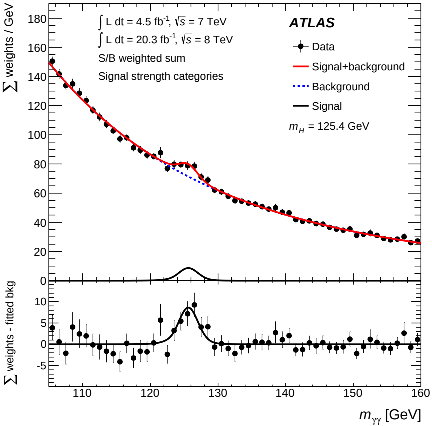
Searching With the “Best” Theory Priors: SUSY With Many b-jets

ATLAS-SUSY-2016-10

LHC Run 1 Legacy: The Higgs



What does the Higgs tell us about new physics around the corner?



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Naturalness with SUSY

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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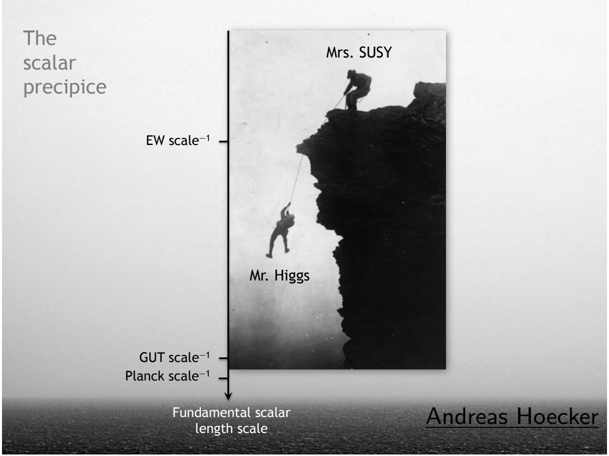

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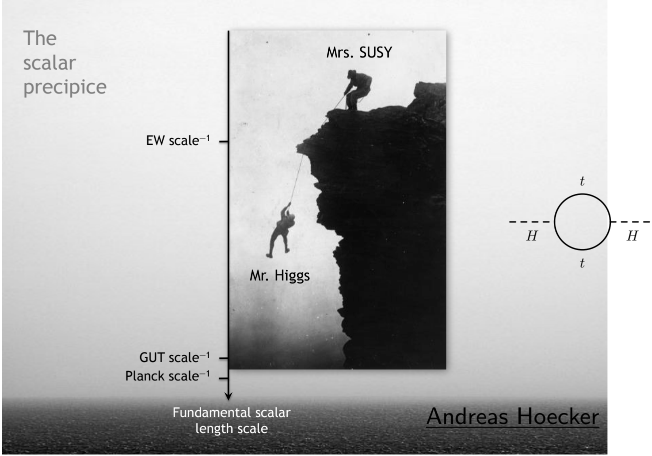

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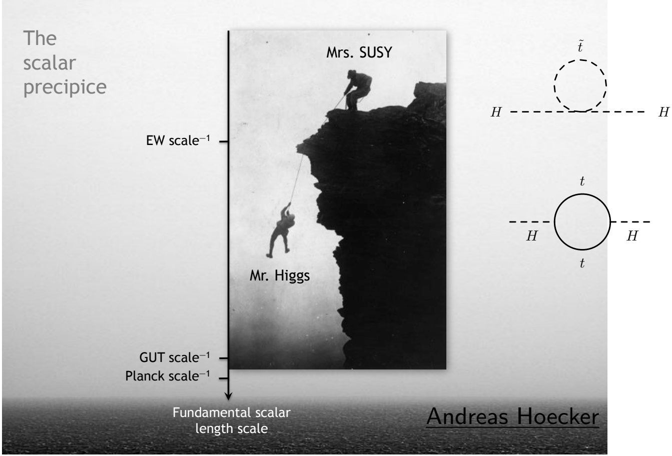

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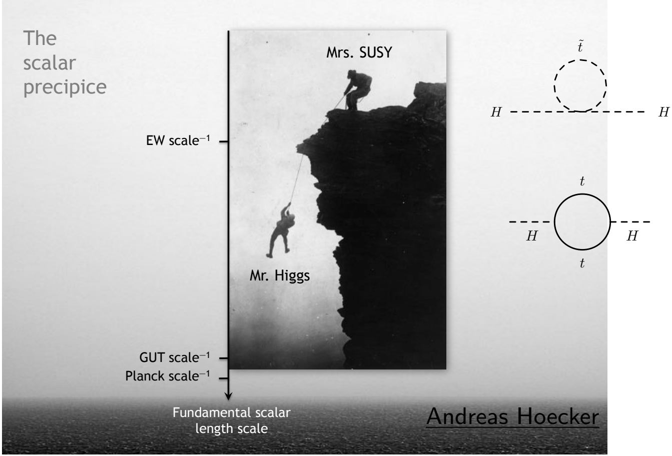
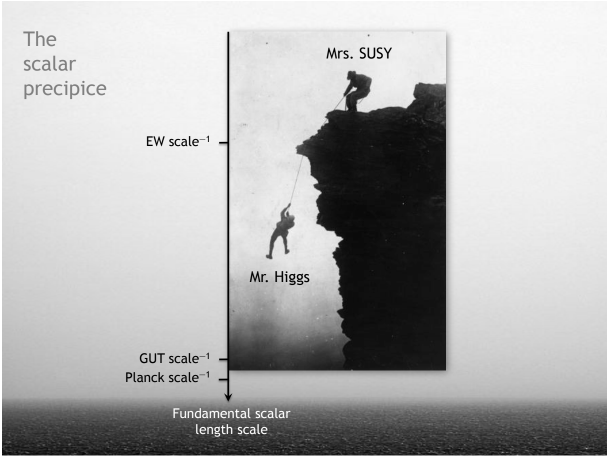
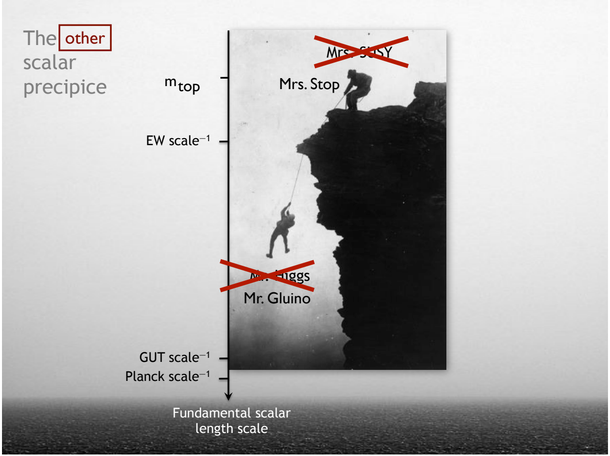


Searches for (supersymmetric) top-partners are critical!

The Role of Gluinos



- 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



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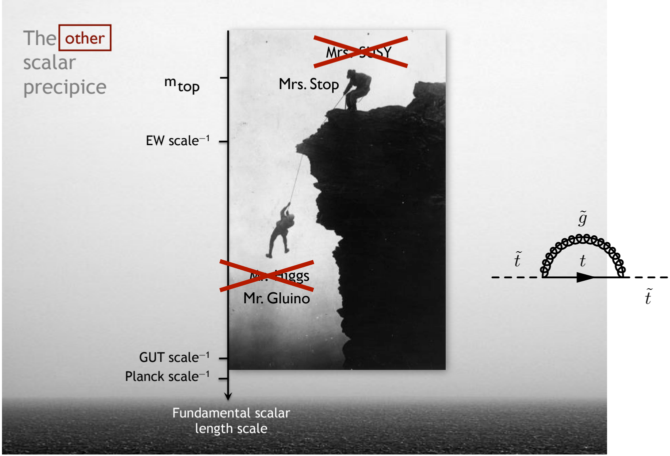

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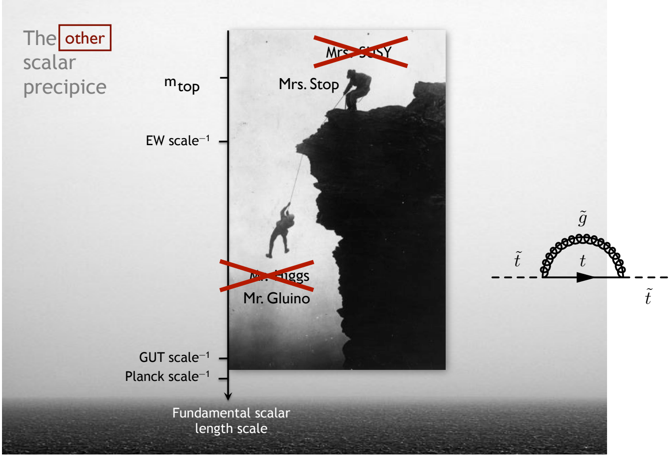

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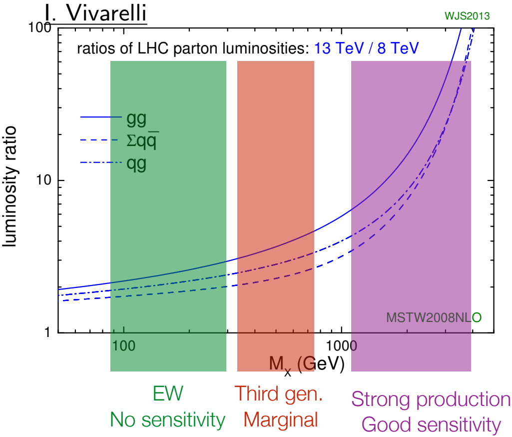
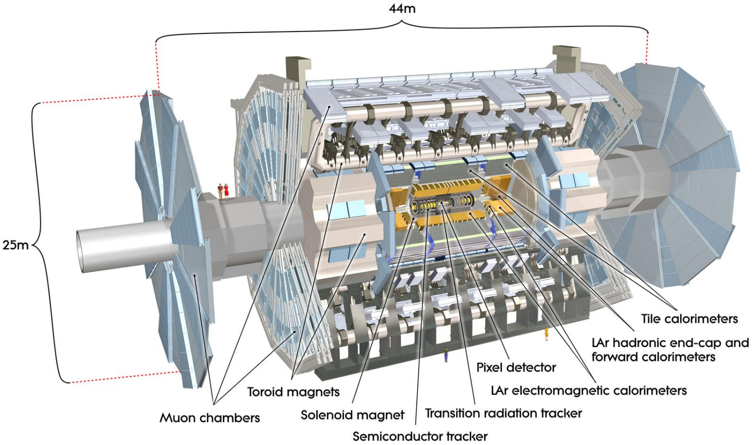
Gluinos and Cross-section

- New $\sqrt{s} = 13$ 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

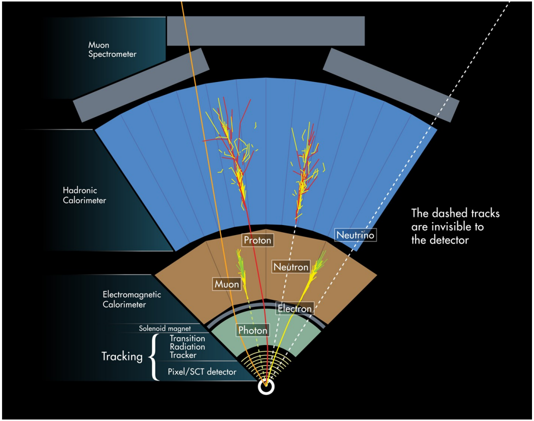


Even though they are much more massive, lots of room for discovery for gluinos!

A Few Words on the ATLAS Detector



Raw detector measurements are reconstructed to particles/objects for analysis



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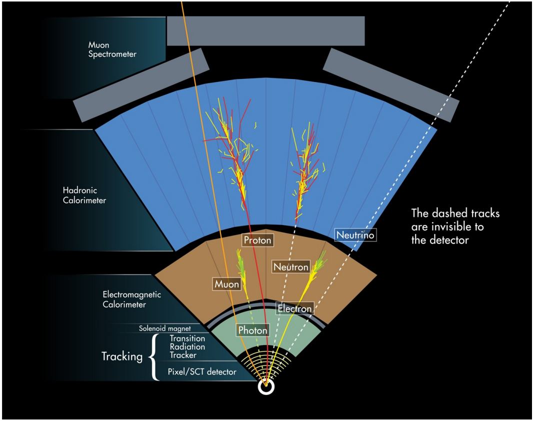

Electrons: inner detector track matched to EM calo deposit

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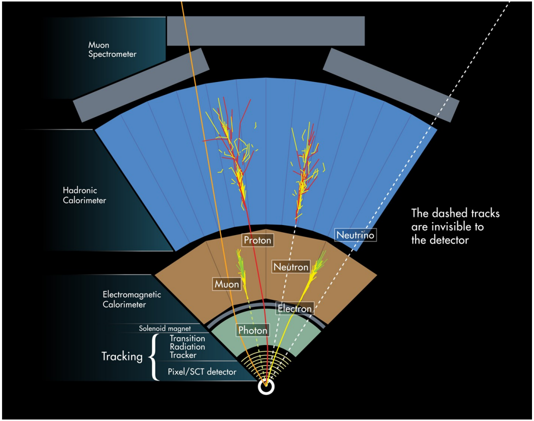

Muon: inner detector track matched to track in muon-spectrometer

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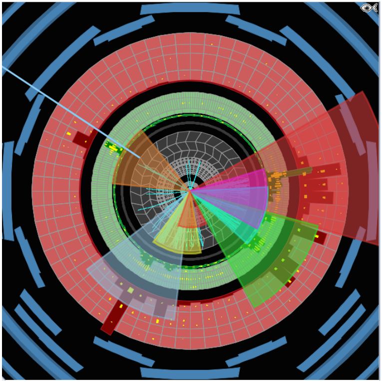

Jet: Collimated spray of protons, neutrons, and more

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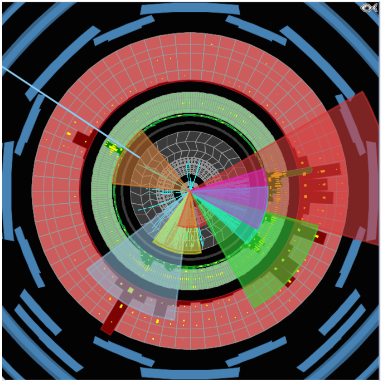
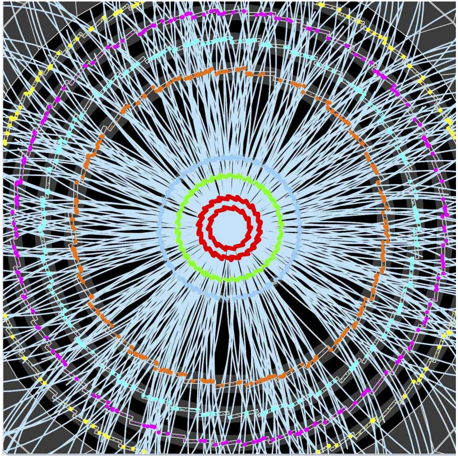
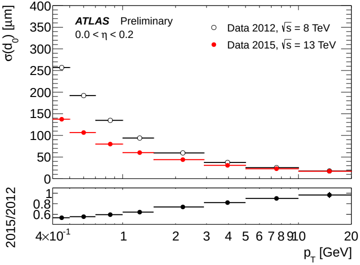


E_T^{miss}: Inferred missing energy, measured from energy misbalance

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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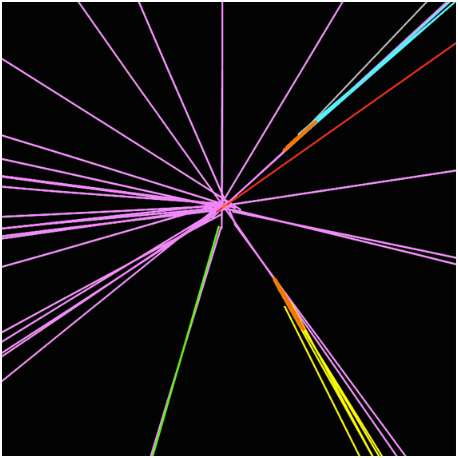
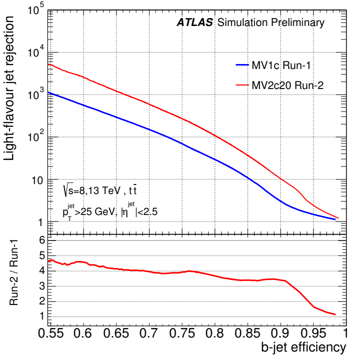
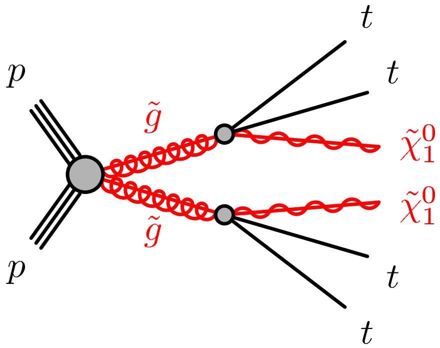
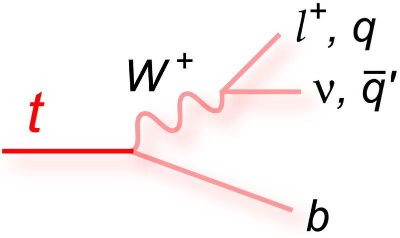




Factor of ≈ 4 gain in light jet rejection!

- *b*-tagging (identification of displaced jets) benefits dramatically

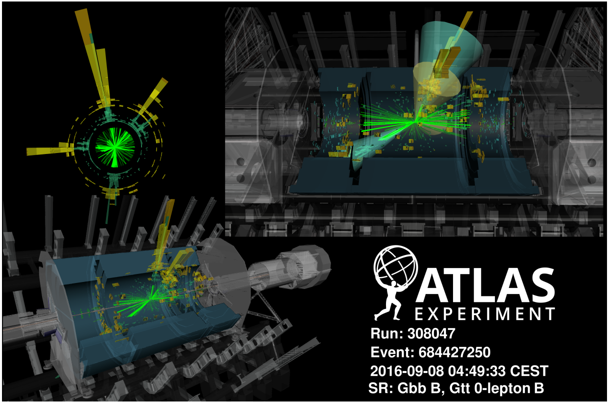




Courtesy D0

- 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 0ℓ and $\geq 1\ell$ categories
  - Both have many *b*-jets in the final state!

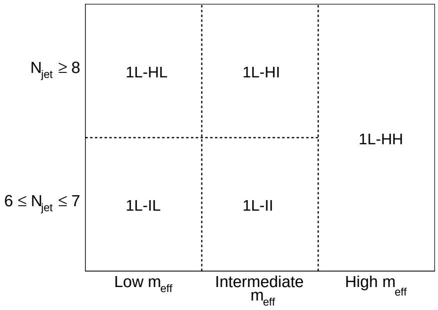
What Does This Look Like?



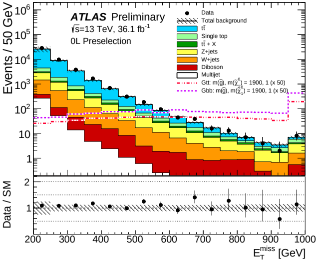
- Look for **spectacular** events: high n_{jet}, many b-tags, high E_T^{miss}, high $m_{eff} = \sum p_T + E_T^{miss}$

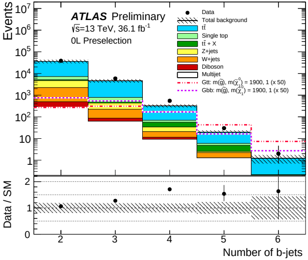
Analysis Strategy

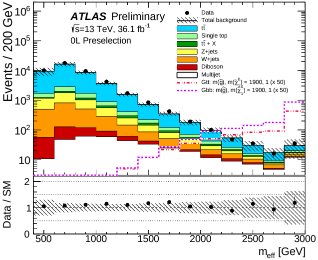
- Define regions binned in N_{jet} and m_{eff}
- Each region is orthogonal to the others
- Signal and background appears differently in each bin: combined fit has stronger sensitivity
- Carefully optimize these cuts, and other variables



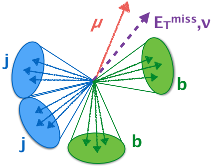
Signal Discrimination



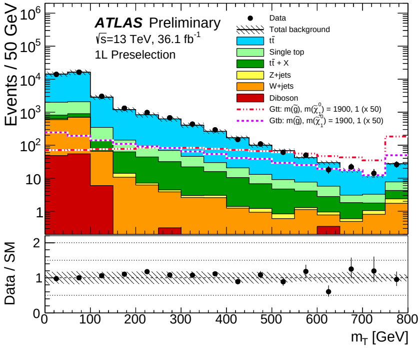


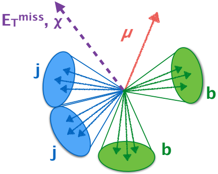


- Huge amount of power from E_T^{miss} and m_{eff}
  - Especially in high mass-splitting regions, these provide great background rejection
- *b*-tagging clearly provides significant power as well



ℓ and E_T^{miss} aligned: background like



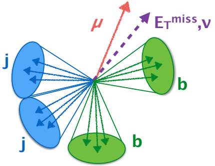


ℓ and E_T^{miss} unaligned: signal like

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

- Provides excellent discrimination in 1ℓ events

More Variables: Minimum Tranverse b-jet Mass $m_T^{b,min}$



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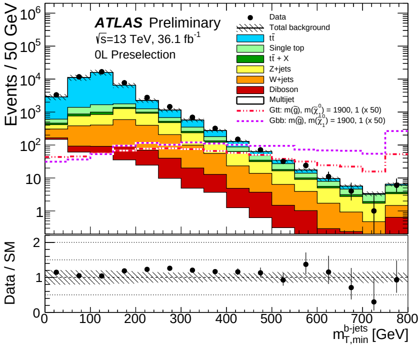
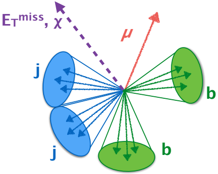
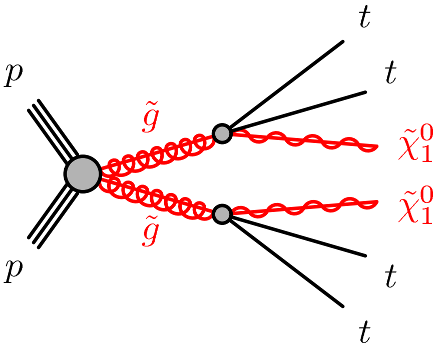




b and E_T^{miss} unaligned: signal like

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

- Provides excellent discrimination in both 0ℓ and 1ℓ channels

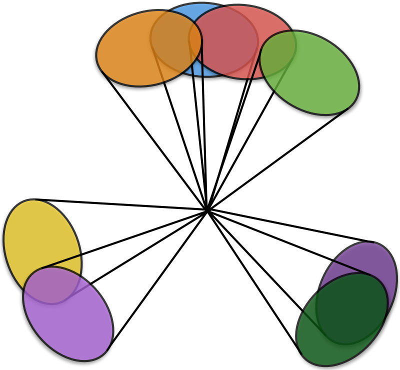


- Gtt signal has *huge number of jets* in the final state: 10 in 1ℓ, 12 in 0ℓ channels!
- These jets won't be isotropically distributed: $\tilde{g}$ will likely be produced at rest, but t will have significant p_T
  - Depends on $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$: high difference, more phase-space 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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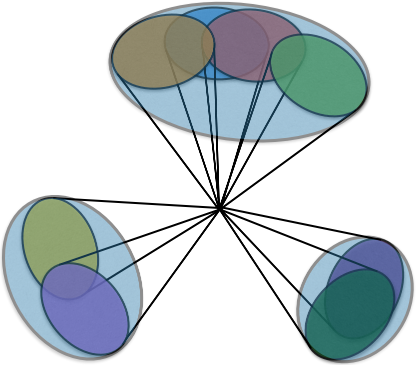

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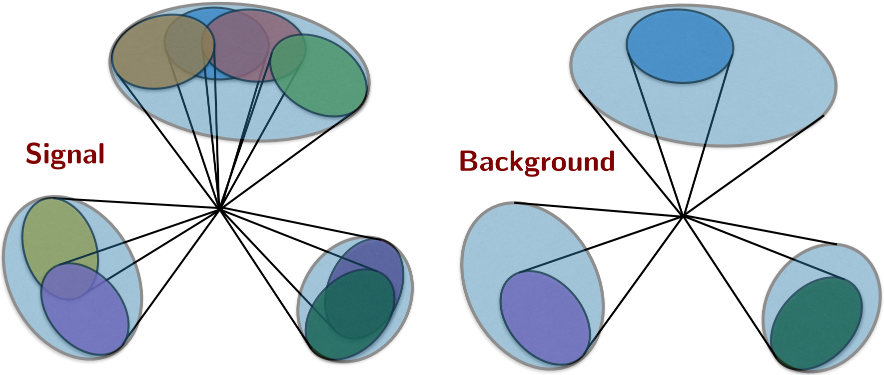

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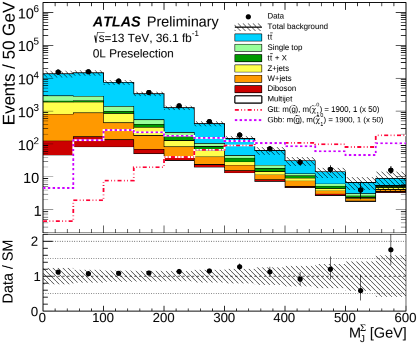
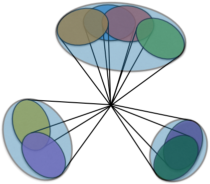
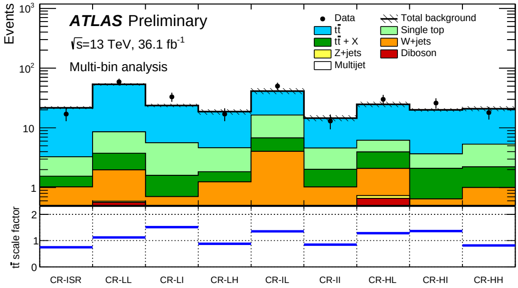
Total Jet Mass





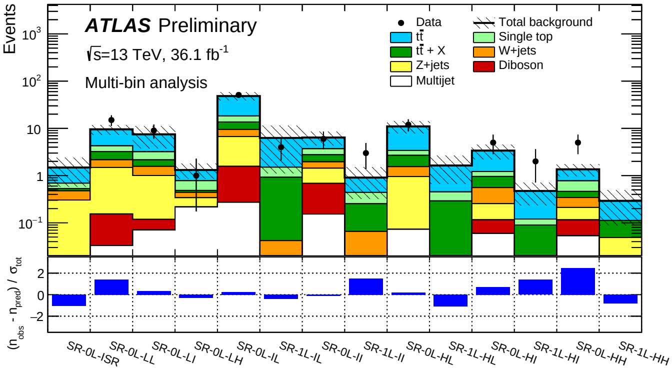
- Identify large-R jets with *re-clustering* approach
  - Run a clustering algorithm on already-reconstructed jets, but with large size ($R = 0.8$)
  - Naturally groups jets close to each other
- Form M_J^Σ from sum of leading 4 large-R jet masses
  - In signal, many tops overlap, *add mass* to jets
  - Both 0ℓ and 1ℓ regions use this very effectively!

Background Estimation



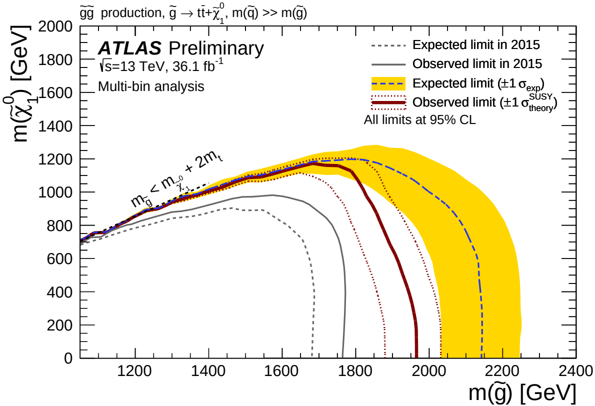
- From MC, we know $t\bar{t}$ will be the dominant background
- Use *dedicated control regions* with 1ℓ and *inverted* m_T cut
  - Allows for signal like region, but without signal
- Use these values to normalize $t\bar{t}$ contribution in signal region

Results: Signal Region Yields



- Signal region predictions both agree well with observation
  - Slight excess in two regions targeting moderate and high mass
  - Total size of excess is $\approx 2\sigma$

Limits on Gluinos

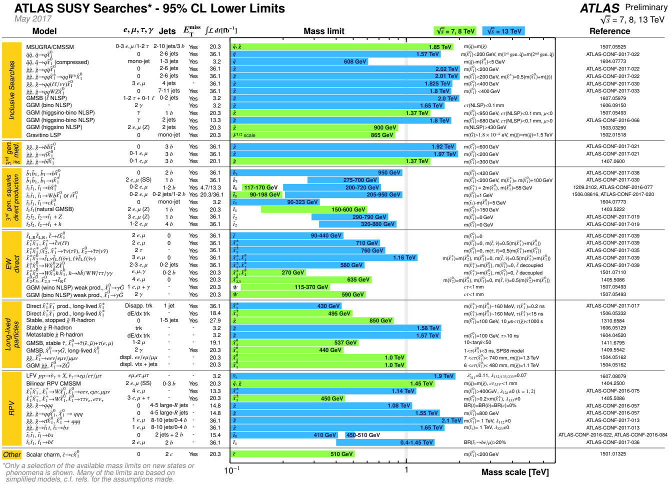


- Limits significantly expand earlier Run 2 sensitivity: some of the strongest limits on gluinos from the LHC!
- No signal yet, but perhaps some interesting hints?
  - Will be following up with 2017 data: stay tuned!

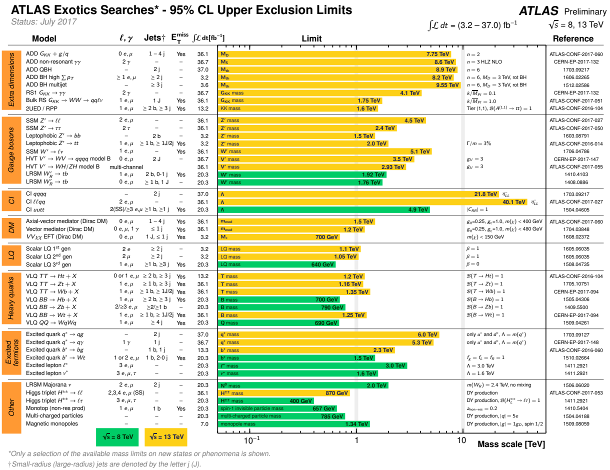
Where Next? Long-lived Particles With MilliQan

arXiv:1607.04669

The Status of SUSY at the LHC



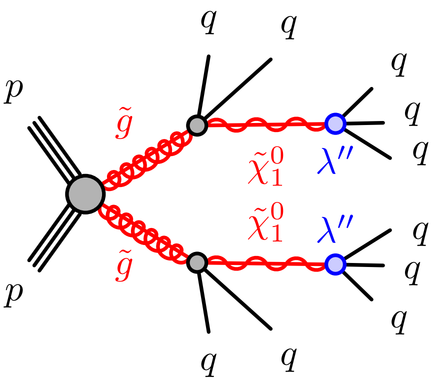
- Lots of searches, but only limits coming out from these...
- Did we have a bad prior? Are more generic signatures showing any hints?



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

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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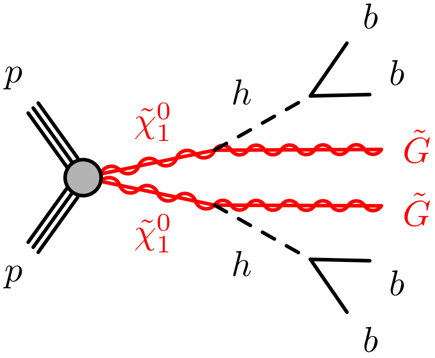

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???

Dark $U(1)$ and Millicharged Particles

- 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*:

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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

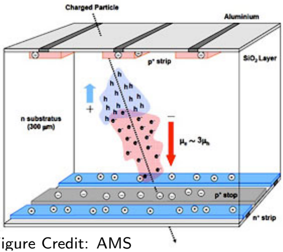
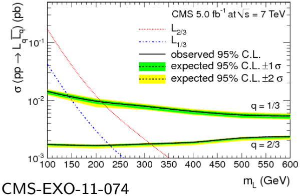


Figure Credit: AMS

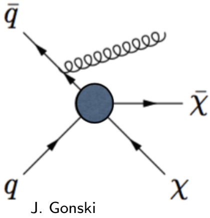


CMS-EXO-11-074

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

What About Monojet?

- 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^2 coupling: millicharge means that signal has low cross-section
- Sufficient $S/\sqrt{B}$ challenging to reach, and quickly become systemically limited



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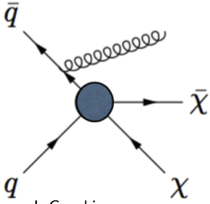
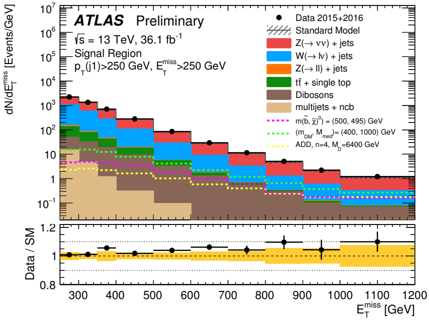


J. Gonski



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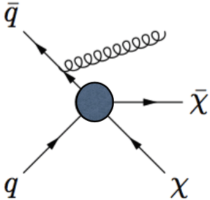

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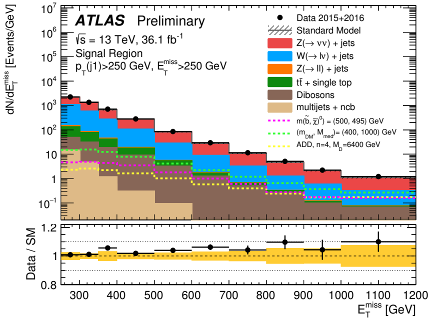
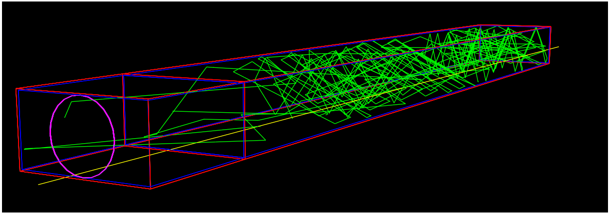


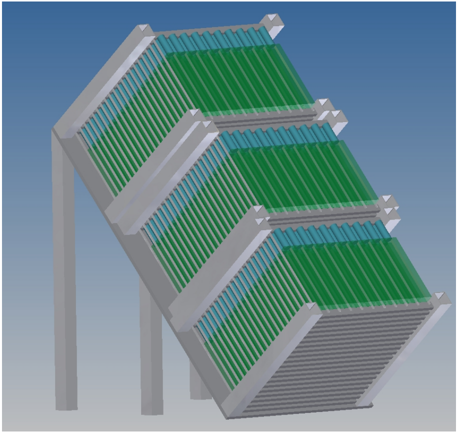
What Kind of Detector Would We Need?

- Scintillators are a good material to build a millicharge detector with:
  - Plastic scintillator yields 10^4 photons/MeV
  - $Q = 1$ MIP deposits 2 MeV/cm
  - 80 cm long bar gets 1.6×10^6 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

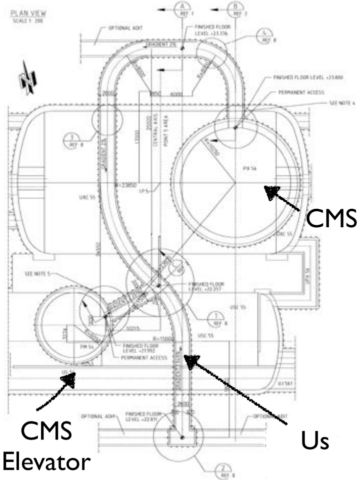
The Full Detector: MilliQan



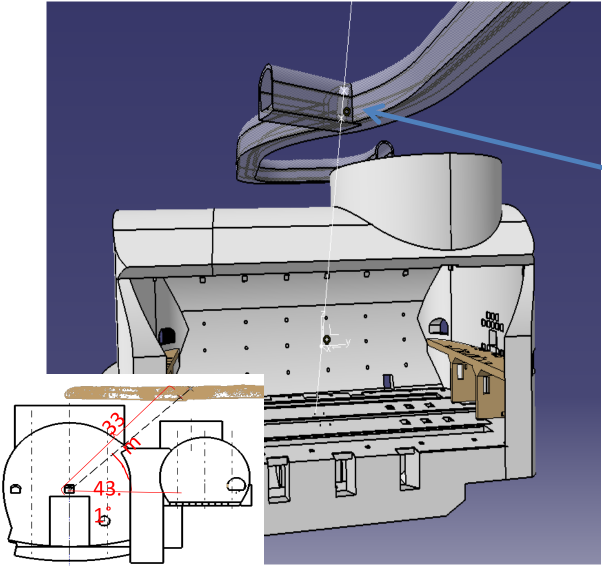
- Full detector would be 1 m $\times$ 1 m $\times$ 3 m
- Three layers allow for triple coincidence to reduce backgrounds
  - Our signature: three low photon pulses within 15 ns in adjacent PMTs

Where Should It Go?

- Need rock barrier to remove backgrounds from hadrons
  - Backgrounds would be too large if we kept these!
- Need to not be too far: acceptance falls as R^2
- 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° from IP: not too forward
  - Acceptance is $\approx 10^{-5}$: sufficient for observations!



Another View of the Location



Backgrounds, and How to Avoid Them

- 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^{-6} 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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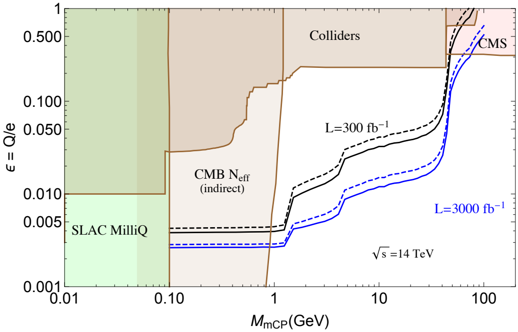
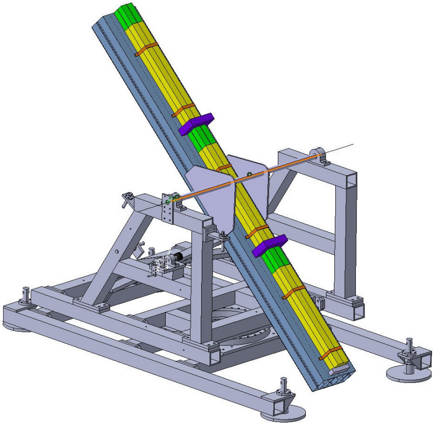
Physics Reach



- 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

The Demonstrator System

- 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:
  - 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



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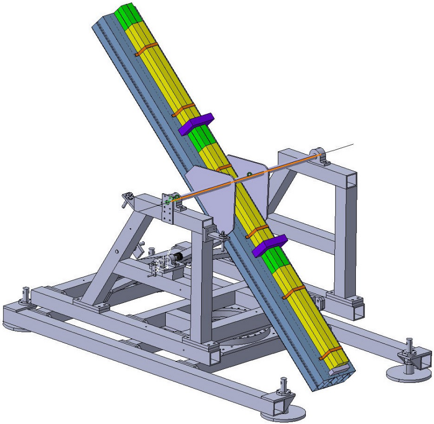

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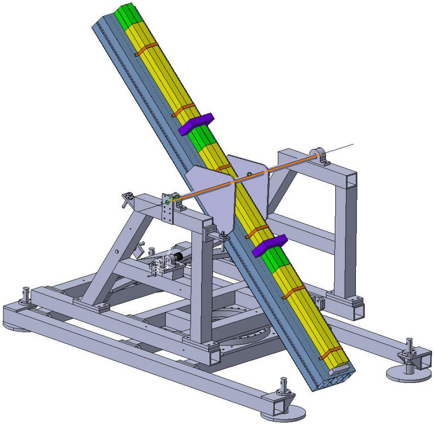
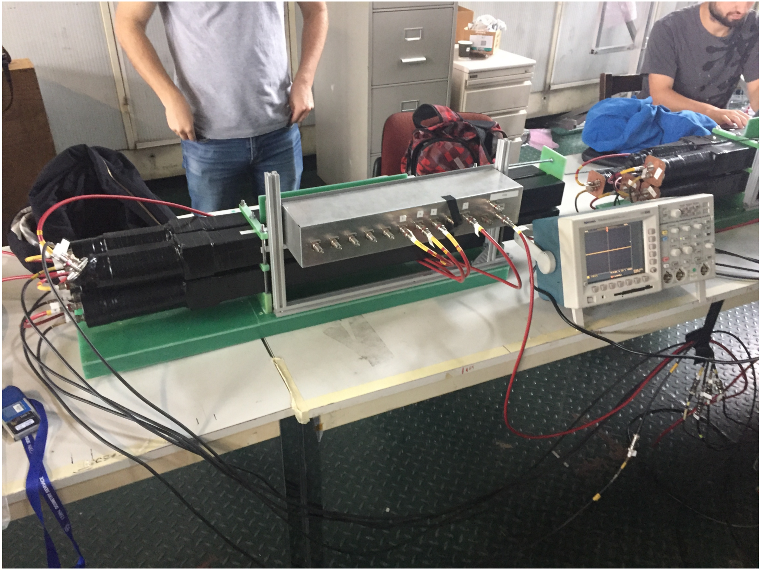


Surface Assembly



Loading the Crane

Lowering the Crane

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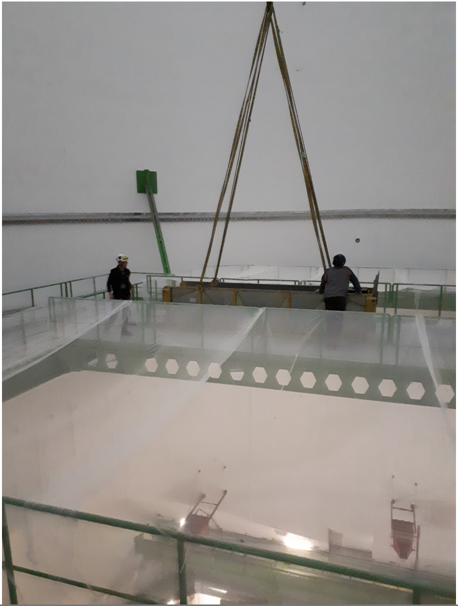
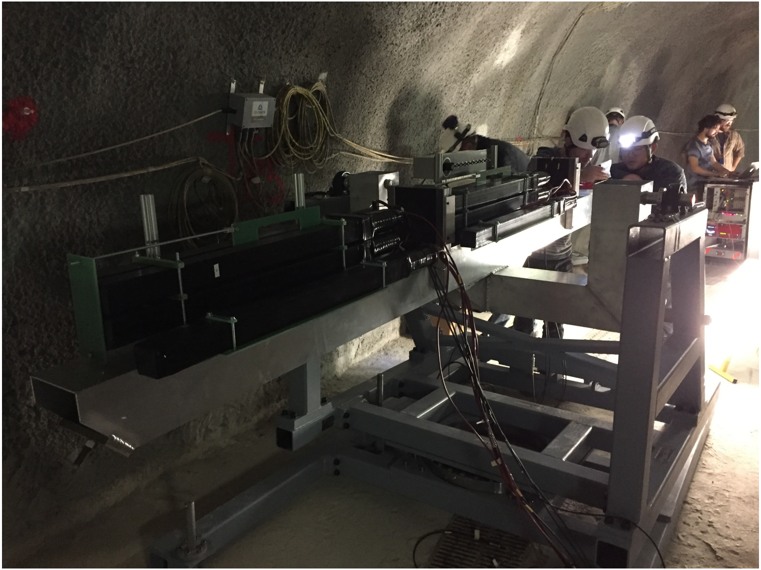


Standing Above CMS

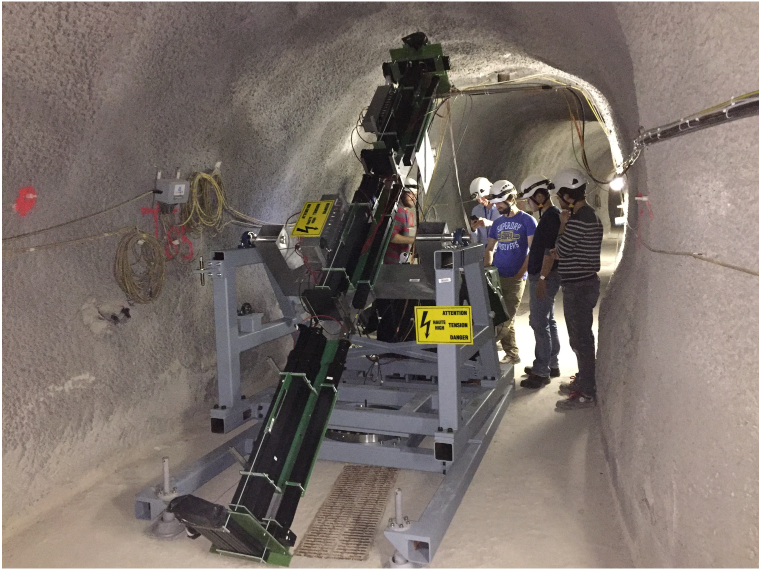
Trying to Connect to WiFi...

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:
  1. 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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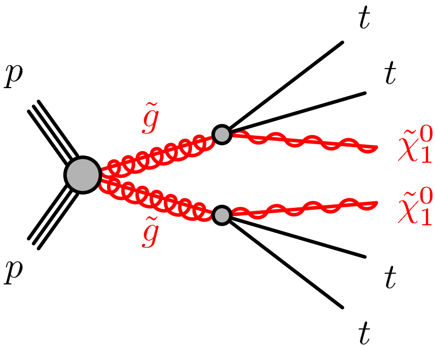
Backup

RPV Multijets

ATLAS-CONF-2016-057

SUSY Signatures



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  - These models assume R-parity, which means the Lightest Supersymmetric Particle ($\tilde{\chi}_1^0$) **is stable**
  - This neutralino **does not interact**: escapes detection, appears as E_T^{miss}
- But what if the LSP decays? Existing searches will not work!

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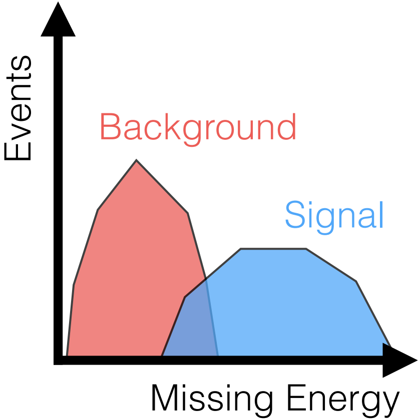

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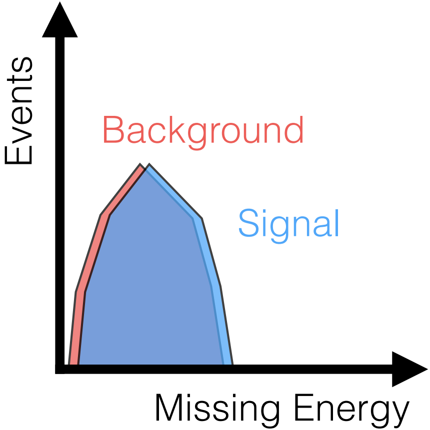

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High Multiplicity RPV Signatures

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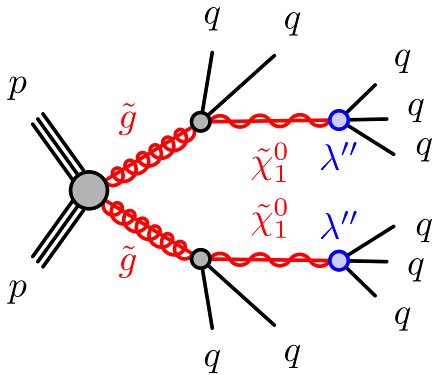

- Final state has huge number of quarks!
  - Between **10** (light quarks only) and **22** (top decays) partons
  - **Extremely difficult background estimation:** high-mass extremes of QCD are difficult to model
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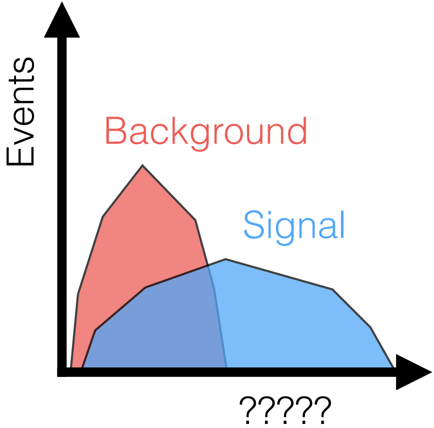

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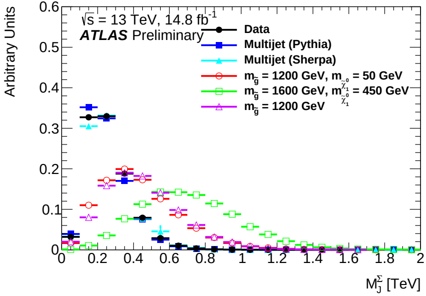
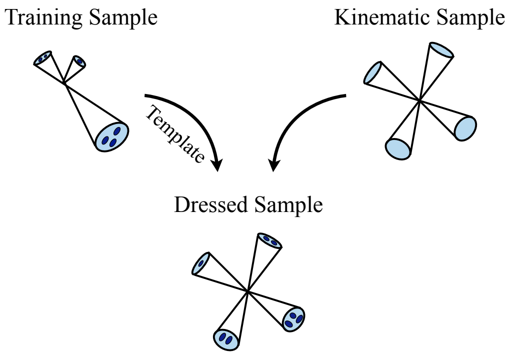
Total Jet Mass

- As used in the multi-B analysis and previous 8 TeV analyses, M_J^{Σ} 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**



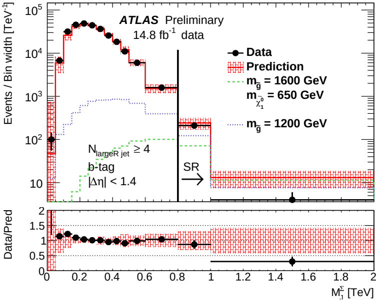
NB: use *trimmed* $R = 1.0$ jets with $p_T > 100$ GeV, $|\eta| < 2.5$

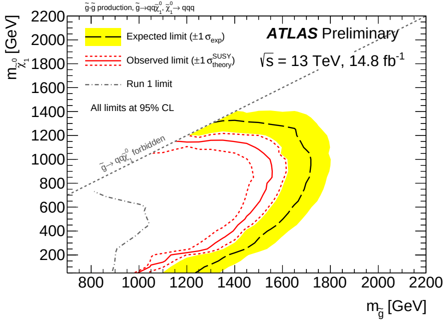
Background Estimation Strategy



- 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_T distributions are very similar, but mass distributions would be very different

Results and Limits





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