Multi-Jet Resonances and New Color-Flow Variables

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FSU Theory Seminar

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No New Physics Yet

- Higgs @ 125 GeV. Yay!
  - $\rightarrow$ Looks fairly SM-like . . . but there is hope.
- Limits on the production of strongly coupled particles + MET already pushed beyond TeV.
- If supersymmetry is realized in nature, then it is not the ‘vanilla’ scenario envisioned before the ~~*LEP*~~ LHC.
- What are the unexplored corners of NP parameter space?
  - Electroweak sector (e.g. charginos in WW?). LHC bounds weak but starting to bite.
  - Stealth SUSY, Compressed/Squeezed SUSY, . . . (reduce MET)
  - . . .
  - **RPV!!** Generically no MET signature, possibly no interesting leptonic final state either.

RPV MSSM

(Many reviews, e.g. Barbier et al. hep-ph/0406039)

Imposing discrete subset of R-symmetry $R = (-1)^{2S}(-1)^{3B+L}$ is an easy way to allow Majorana gaugino masses and

$$W_{MSSM} = \mu H_u H_d + \lambda^e_{ij} H_d L_i E^c_j + \lambda^d_{ij} H_d Q_i D_j - \lambda^u_{ij} H_u U^c_j$$

while forbidding dangerous L- and B-violating superpotential terms

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_k E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k .$$

Constraints can be severe. If $\mu_i \neq 0$, there is no unique way to separate lepton and higgs doublet.

Study the case with conserved lepton number: only $\lambda'' \neq 0$.

$\Longrightarrow$ $\tilde{q} \to qq$, $\tilde{g} \to qqq$ multijet signals.
No leptons, but large production cross sections.

RPV MSSM

Which simplified model to study?

- λ'' involving third generation is fairly unconstrained but provides handles for collider study.

  [e.g. in 2012: Allanach & Gripaios; Evans & Kats; Brust, Katz & Sundrum]

That only leaves $\lambda''_{112}$and λ''_{212}, since $\lambda''_{ikj} = -\lambda''_{ikj}$.

- λ''_{112} (uds) is constrained by nucleon-antinucleon oscillation through intermediate $\tilde{s}$ and $\tilde{g}$, but the bound depends on squark mixing. Tightest possible constraint is $|\lambda''_{112}| \lesssim 10^{-6}$ for $m_{\tilde{g}} \sim$ TeV and $m_{\tilde{s}_R} \sim 5$ TeV. The bound is greatly relaxed if the mixing is suppressed.

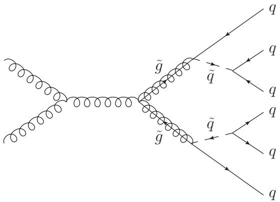
- λ_{212} (cds) is almost unconstrained and can be $\mathcal{O}(1)$.

Both of these possibilities can lead to gluinos promptly decaying to 6 light jets (maybe some charms) $\Rightarrow$ extremely difficult signature.

Our Signal

- Look for 2 gluinos $\rightarrow$ 6 jets.
- For simplicity assume squark is off-shell

$\rightarrow$ Interestingly, this automatically implies that $\tilde{g}$ forms an *R*-hadron before decaying. (More in this later.)



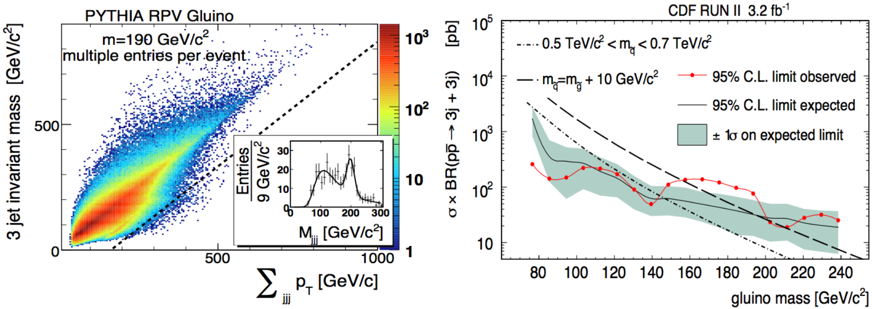
- Assume decay is prompt (displaced vertex would give additional handle on signal.
  [CMS 1011.5861; Graham, Kaplan, Rajendran, Saraswat 1204.6038]
- This signature can apply more broadly than RPV MSSM.

Existing Bounds on RPV Gluinos

- Event shape data excludes $m_{\tilde{g}} < 51.0\,\mathrm{GeV}$. [Kaplan, Schwartz 2008]
- Directly looking for $\tilde{g}\tilde{g} \to 6j$ is challenging:
  - no MET, so huge QCD background
  - Combinatorics
- Tevatron & CMS searches look for 6j resolved final state and attempt to reconstruct the resonance (shape analysis).
- ATLAS does a pure counting experiment.

$\Rightarrow$ $m_{\tilde{g}} \lesssim 650\,\mathrm{GeV}$ is excluded if $\mathrm{Br}(\tilde{g} \to 3j) = 100\%$.

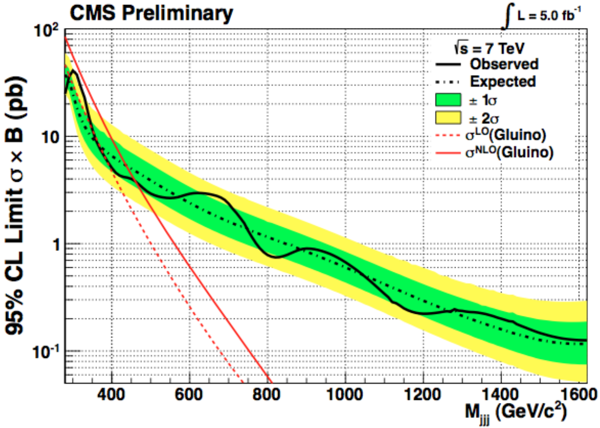
- 3.2/fb $\sqrt{s} = 1.96\,\mathrm{TeV}$ search: arxiv:1105.2815
- Search for 6 cone(0.4) jets from low-mass RPV gluino pairs.
- Main background is QCD multi-jet. Reduce QCD and combinatorics background with diagonal $p_{Tjjj} - M_{jjj}$ cut:



- **Exclude $m_{\tilde{g}} \sim 77 - 144\ \mathrm{GeV}$.**

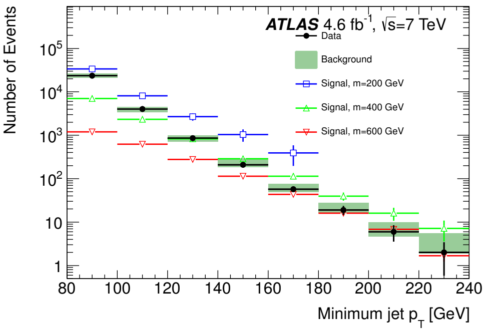
CMS Search for RPV gluinos

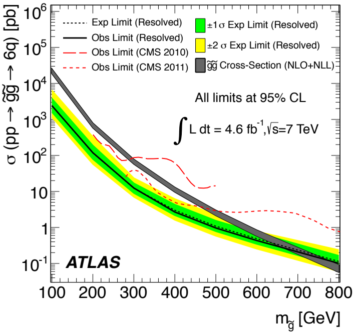
- arXiv:1107.3084 (36/pb), 1208.2931 (5/fb) @ LHC7
- Similar method to Tevatron search, now looking for 6 anti-k_T(0.5) jets. Excludes $m_{\tilde{g}} \in 200 - 450\,\mathrm{GeV}$:



ATLAS search for RPV gluinos

- arXiv:1210.4813. 5/fb @ LHC7
- Look for 6 anti-k_T(0.4) jets. Impose $p_T^{j_6} > 80 - 160\,\mathrm{GeV}$ cuts to reduce QCD BG. Pure counting experiment with data-driven background estimates.
- Excludes $m_{\tilde{g}} \lesssim 650\,\mathrm{GeV}$





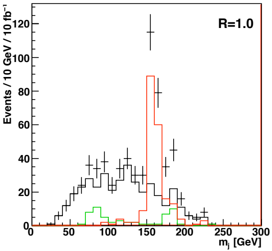
Boosted Gluino Search

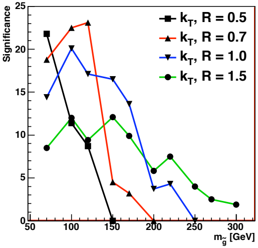
- If the gluinos are sufficiently **boosted**, all three daughter quarks can fall inside a single fat jet.
- Eliminates combinatorics problems and allows for reconstruction of resonance.
- Strongly reduces QCD Background.
- Allows application of **substructure** techniques for additional discriminating power.
- **The boosted search channel has independent systematic errors and much higher S/B than the other searches.**

ATLAS did some of this in a boosted search counting experiment, but the mass reach was very low, only $\sim 250\,\mathrm{GeV}$. Can do better!

Boosted Gluinos @ Tevatron

- Raklev, Salam, Wacker 2010: simple boosted gluino study for the Tevatron.
- Look for two fat jets with similar masses, each containing three similarly hard subjets.
- Could have increased reach of Tevatron RPV gluino search by $\sim 100\,\mathrm{GeV}$ to $\sim 250\,\mathrm{GeV}$ and closed the "top-mass window".





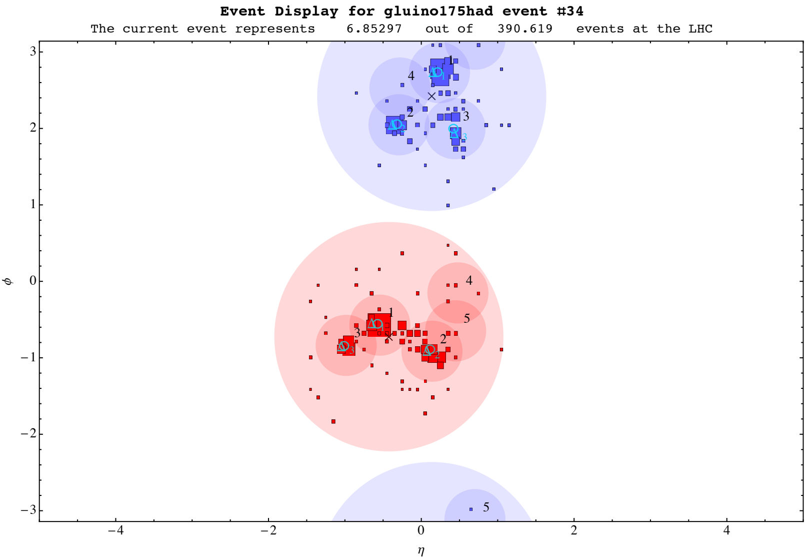
Boosted Gluinos @ LHC

- Not clear if Tevatron boosted reach scales to LHC: much lower cross section and boosted fraction (relatively speaking).
- Attempt to improve analysis techniques with full gamut of modern substructure tools.
- Define new color-flow variables to examine previously unexplored properties of *R*-hadron decay.
  - Axis Contraction explores sensitivity of *N*-subjettiness minimzing axes to the jet energy distribution.
  - Radial Pull is a generalization of pull-based color dipole taggers.

→ **These variables should be useful for other searches as well.**

Color Flow
in
R-Hadron Decays

Event Display

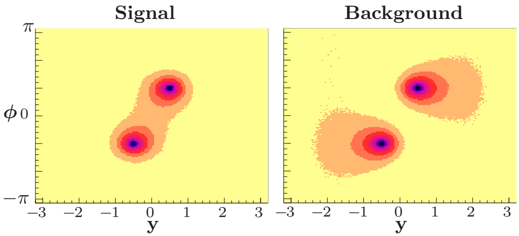


Exploiting Color Flow

One canonical example: Zh production, with $h \to b\bar{b}$:

- For boosted higgs ($p_T \gtrsim m_h$) the two b's will be $\sim$ collinear.
- The two b's form a color dipole, connected by a color string.
- Hadronization can be modeled as 'snapping' these color strings to make color singlets.

$\to$ This results in an excess of soft radiation between color-connected jets compared to QCD dijet background.

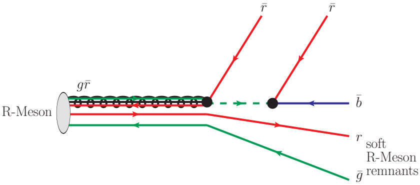


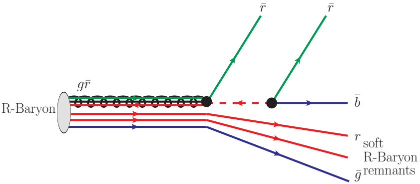
1001.5027 Gallicchio, Schwartz

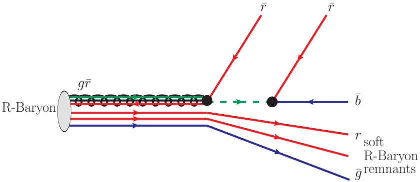
R-hadron decay

- The three hard jets from gluino decay form color singlets with the soft R-hadron remnants.

→ Two completely separate rounds of showering/hadronization.

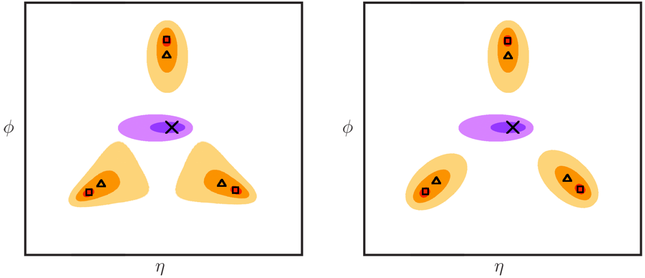






R-hadron decay

Exaggerated cartoon of expected energy deposition in calorimeter:



- Similar to $Z/W/h \to q\bar{q}$ color dipole taggers:
- Could this help eliminate QCD BG?
- Want to define new variables to quantify this.

Cui, Han, Schwartz 2011

Gallicchio, Huth, Kagan, Schwartz, Black, Tweedie, 2011

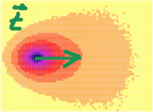
Hook, Jankowiak, Wacker 2011

Radial Pull

- Pull (Gallicchio, Schwartz '10) is a radial jet moment in the $(\eta - \phi)$ plane that is sensitive to the skew of the p_T distribution

$$\vec{t} = \sum_i \frac{p_T^i |r_i|}{p_T^{jet}} \vec{r}_i$$

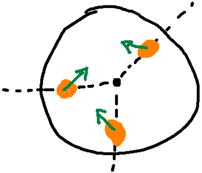
(r_i points from jet axis to i^{th} constituent)



- Radial Pull applies this to a 3-pronged fat jet and sums the inward components of the unit-pulls ($N = 3$):

$$t_r = \frac{1}{N} \sum_{j=1}^{N} \hat{t}_j \cdot \hat{n}_j$$

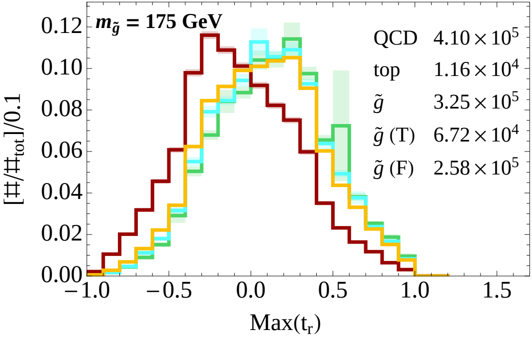
(unit $\hat{n}_i$ points from **fat** jet center to i^{th} **subjet** axis)



$t_r < 0$ if the subjets, on average, are 'pulled' inwards.

Radial Pull

Example distribution from our top-mass gluino analysis before performing the most drastic cuts:



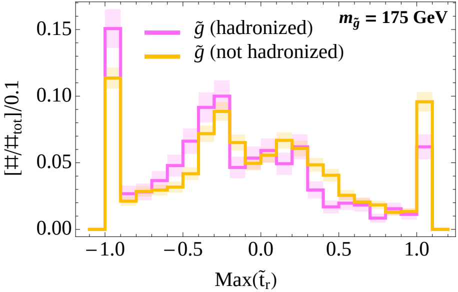
Very good distinguishing power if you can cut hard!

Radial Pull

An alternative definition of radial pull

$$\tilde{t}_r = \left(\sum_{j=1}^{N} \vec{t}_j \cdot \hat{n}_j \right) \Big/ \left(\sum_{j=1}^{N} |\vec{t}_j \cdot \hat{n}_j| \right)$$

is great at distinguishing hadronized from un-hadronized gluino.



Could provide another handle on 2- vs 3-body decays.

N-subjettiness

- The pull variable works well, but it involves a reclustering step.
- An event-shape variable might be more suitable for some applications. (May also be more amenable to calculation.)
- We will be using *N*-subjettiness in both conventional and novel ways.

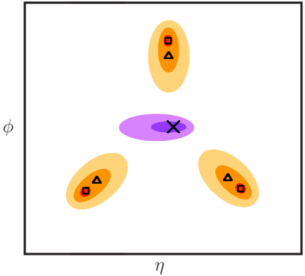
$$\tau_N^\beta \equiv \frac{1}{d_0}\sum_i p_{\mathrm{T}\,i} \min\left[(\Delta R_{1,i})^\beta, \ldots, (\Delta R_{N,i})^\beta\right]$$

$$d_0 = \sum_i p_{\mathrm{T}\,i} R_0^\beta,$$

[Stewart, Tackmann, Waalewijn '10; Thaler, Van Tilburg '11, '12]

N-subjettiness

Consider a three-pronged fat jet (like from our decaying R-hadrons).



- τ_3 is minimized when aligning the axes with the 'subjets'.
- $\tau_3 \ll \tau_2$ indicates a three-pronged jet. (Similarly for two-pronged.)

- Choice of distance measure (β) affects locations of axes which minimize τ_N^{β}:
  - $\beta = 1$ is sensitive to hard radiation centers: good for top tagging
  - $\beta = 2$ feels more of the overall fat jet structure

Axis Pull & Contraction

- Exploit the β-dependence of axes to measure color flow.
- Axis Pull: $\Delta \vec{R}^{\beta\beta'}_{a,N} \equiv \vec{R}^{\beta}_{a,N} - \vec{R}^{\beta'}_{a,N}$

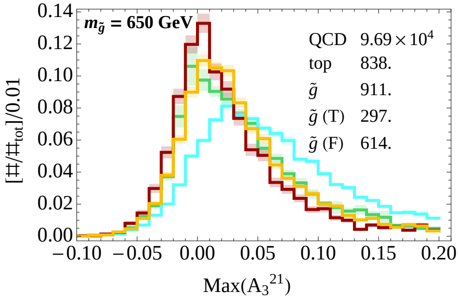
  Changing $\beta = 1$ to $\beta = 2$ shifts the axes and yields a variable that is similar to pull, but without reclustering.
- Combine axis pulls to form Axis Contraction that can find multi-pronged color-singlet fat jets.

$$A_N^{\beta\beta'} = \frac{\sum_{a=1}^{N} \left| \vec{R}^{\beta}_{a,N} - \vec{R}_{\mathrm{cen}} \right|}{\sum_{a=1}^{N} \left| \vec{R}^{\beta'}_{a,N} - \vec{R}_{\mathrm{cen}} \right|} - 1$$

We use $(\beta, \beta') = (2, 1)$. Just like t_r, $A_N^{21} < 0$ for ideal 'signal'.

Axis Contraction

Example distribution from our heavy gluino analysis before performing the most drastic cuts:



- Discrimination does not look as good as pull, but turns out to be better when having to cut conservatively.
- Likely very useful in scenarios with merged subjets.

- Note small variable values are not related to detector resolution.

These variables are general and should be useful elsewhere!

Monte Carlo Study:

Boosted RPV Gluino Search

LHC8 with 5 or 20 fb^{-1}

Simulation

Simulation of Signal

Problem: no event generator included RPV decay of R-hadrons.

$\rightarrow$ We thank Torbjörn Sjöstrand and Peter Skands for providing us with a developmental `Pythia` version to do this! (Changes now included in v 8.170)

- Even so, one has to be aware of possible modeling uncertainties!

Generated signal events for two different ranges of gluino masses:

- $m_{\tilde{g}} \sim m_t$:
  - Our shape analysis is complementary to ATLAS counting experiment
  - Show-pony for color-flow variables
- $m_{\tilde{g}} = 500 - 1000\,\mathrm{GeV}$:
  - Test mass reach of boosted analysis

In both cases generate many more events than expected at LHC8 for numerical precision. Renormalized cross sections with `Prospino`.

Simulation of Background

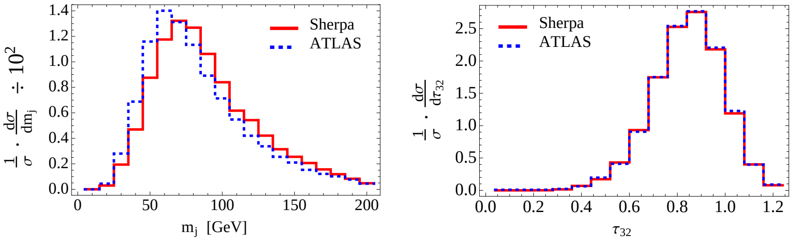
- Huge multi-jet QCD backgrounds in weird corners of phase-space.

⇒ Use `Sherpa` for fully matched 2-6 jet weighted QCD (and subdominant $t\bar{t}$) background generation.

- With some soft generator-level cuts still needed $\sim 50 - 100$ million events each for heavy and light gluino analysis.
- **We validated `Sherpa` background generation against ATLAS substructure data.**

Validation of BG Simulations

Compare `Sherpa` output to ATLAS 7 TeV 36 pb^{-1} data (1203.4606).



- Jet mass slightly shifted up $\rightarrow$ our simulations are conservative.
- τ_{32} shape agreement is spectacular!
- Extract *K*-factor of 2 for QCD background

Comments

- We neglect detector effects. They are unlikely to be a limiting factor:
  - hard, central jets
  - low statistics necessitate large jet mass bins
- Neglect pile-up, but should be OK (more on this later).
- If the truth-level gluinos in an event are more than $\Delta R = 0.3$ away from the fat jets, then mark the event as combinatorics background that we want to reduce in our analysis.

Analysis

Analysis Strategy

For both light and heavy boosted gluinos, we exploit the following properties of the signal to filter out background:

- Require two hard anti-k_T(1.5) fat jets with $p_T \gtrsim m_{\tilde{g}}$.
- $\tau_{32} < 0.5$ for $\beta = 1$.
- Both fat jets should have similar mass:

$$s_m = \frac{|m_1 - m_2|}{(m1 + m2)/2} < 0.1$$

- The subjets of each fat jet should not have hierarchical p_T's, i.e. $h_{31} = p_T^3 / p_T^1$ not too small.
- Select for color flow that is compatible with decaying R-hadron.

Also tried many other variables (e.g. girth, Planar Flow) but they were not useful.

Results for Heavy Gluinos

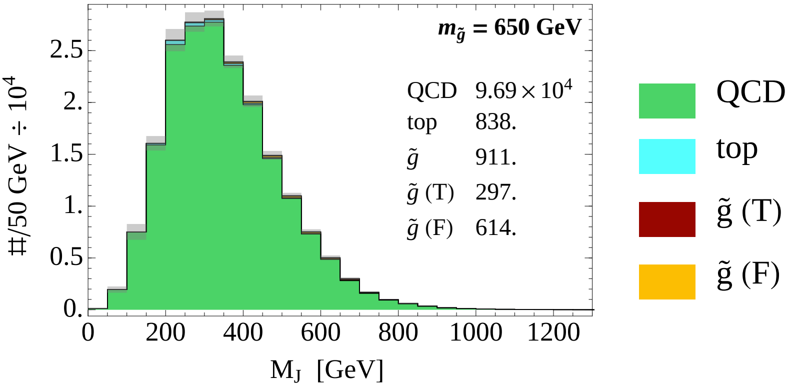
Cut Efficiencies for 650 GeV Gluinos:

	Analysis	Common Cuts							Optimized Cuts	
		generator level cuts	Trigger: $H_T > 850$ GeV, $p_T^{j1} > 250$ GeV	two fat jets with $p_T > 600$ GeV	$\max(\tau_{32}) < 0.7$	$\max(\tau_{32}) < 0.5$	$\max(s_{\rm m}) < 0.1$	$\min(h_{31}) > 0.2$	fat jet $\min(p_T) > p_T^{max}$	axis contraction cut $\max(A_3^{21}) < A^{max}$
$m_{\tilde{g}} = 650$ GeV	QCD	4.7×10^6 –	4.7×10^6 99.9%	1.6×10^6 34%	9.7×10^5 6.1%	2.1×10^3 2.2%	380 18%	88 23%	35 40%	21 ± 1 59%
	top	6.9×10^3 –	6.8×10^3 99%	2.4×10^3 35%	840 35%	50 6.0%	13 26%	0.56 4.3%	0.11 20%	0.049 ± 0.009 44%
	Gluinos [0.65pb]	1.3×10^4 –	1.2×10^4 89%	2.1×10^3 18%	910 43%	120 (43) 13 (15) %	33 (16) 27 (37) %	22 (9.8) 67 (62) %	13 (7.6) 58 (77) %	11 ± 1 (6.8 ± 0.7) 83 (90) % $S/B = 0.51$

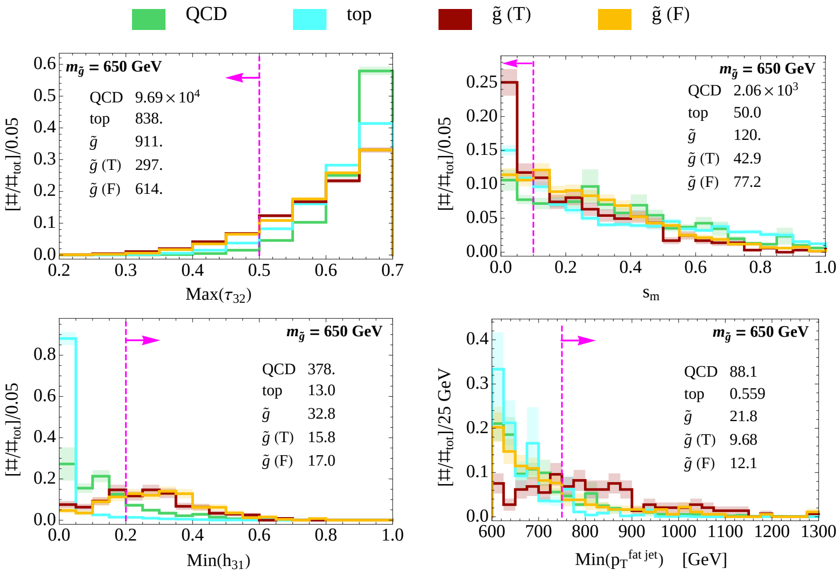
- Boosted fraction is a few % $\rightarrow$ small signal means we can't cut too harshly on color flow for heavy gluinos.
  - $\rightarrow$ Axis contraction performs better for soft cuts than radial pull.
- $\mathcal{O}(10\%)$ of boosted fraction survives cuts.
- $S/B \sim 1$ with a clearly resolved gluino mass peak.

Cut Flow for 650 GeV Gluinos

After applying fat jet $p_T > 600\,\mathrm{GeV}$ $\tau_{32} < 0.7$ cut, get the following jet mass distribution:

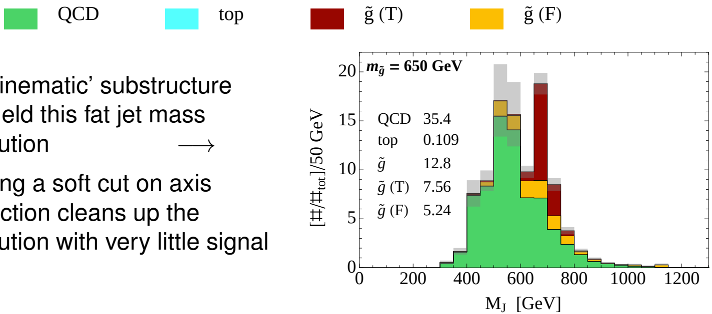


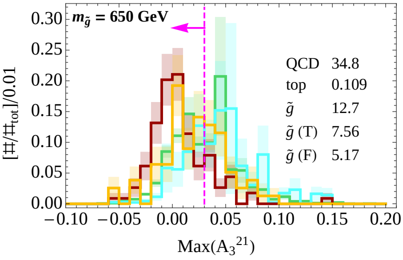
Cut Flow for 650 GeV Gluinos

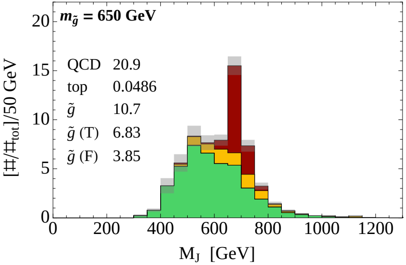


Cut Flow for 650 GeV Gluinos

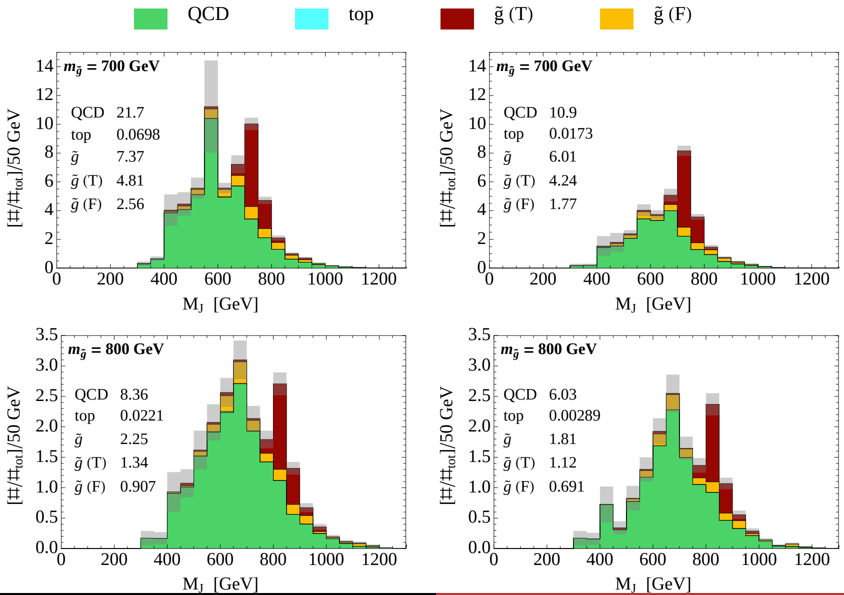
- The 'kinematic' substructure cuts yield this fat jet mass distribution →
- Applying a soft cut on axis contraction cleans up the distribution with very little signal loss ↓





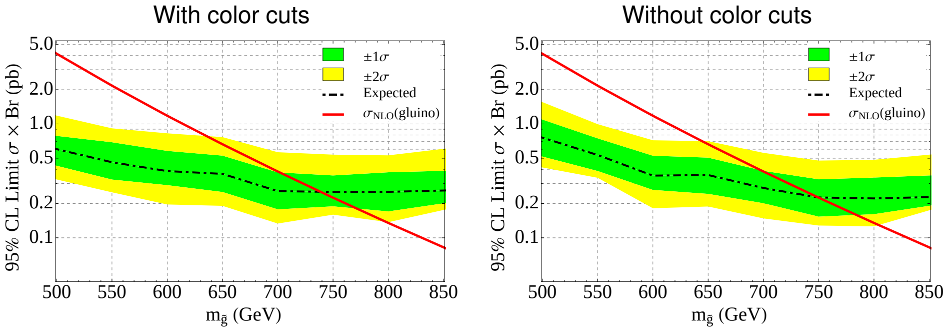


Resolving very heavy gluinos



Mass Reach of Boosted Analysis

For 20 fb^{-1} @ LHC8:



- Mass Exclusion Reach is $\sim$ 750 GeV (650 GeV) with 20 fb^{-1} (5 fb^{-1}).
- 5 fb^{-1} reach is comparable to ATLAS counting experiment (5 fb^{-1} @ LHC7).
- Color flow cuts do not increase mass reach due to low statistics but could reduce systematics. Also improve cross section exclusion at lower masses.

Results for Top-Mass Gluinos

Cut Efficiencies for 175 GeV Gluinos:

Analysis		generator level cuts	Trigger: 6 thin jets with $p_T > 60$ GeV	two fat jets with $p_T > 200$ GeV	$\max(\tau_{32}) < 0.7$	$\max(\tau_{32}) < 0.5$	$\max(s_\mathrm{m}) < 0.1$	$\min(h_{31}) > 0.2$	radial pull cut $\max(t_\mathrm{r}) < -0.6$	b-veto
$m_{\tilde{g}} = 175$ GeV	QCD	2.5×10^8 –	1.9×10^6 0.78%	1.7×10^6 88%	4.1×10^5 24%	2.0×10^4 4.8%	4.5×10^3 24%	488 11%	0.86 0.18%	0.81 ± 0.24 94%
	top	1.1×10^6 –	2.6×10^4 2.4%	2.3×10^4 88%	1.2×10^4 51%	2.2×10^3 19%	771 36%	253 33%	5.6 2.2%	0.48 ± 0.25 8.6%
	Gluinos [1.9nb]	3.7×10^7 –	1.1×10^6 2.9%	9.5×10^5 90%	3.3×10^5 34%	2.0×10^4 (6.6×10^3) 6.1% (9.9%)	6.1×10^3 (3.2×10^3) 30% (49%)	1.5×10^3 (1.0×10^3) 24% (31%)	128 (118) 8.7% (12%)	120 ± 17 (111 ± 15) 94% (94%) $S/B = 93$

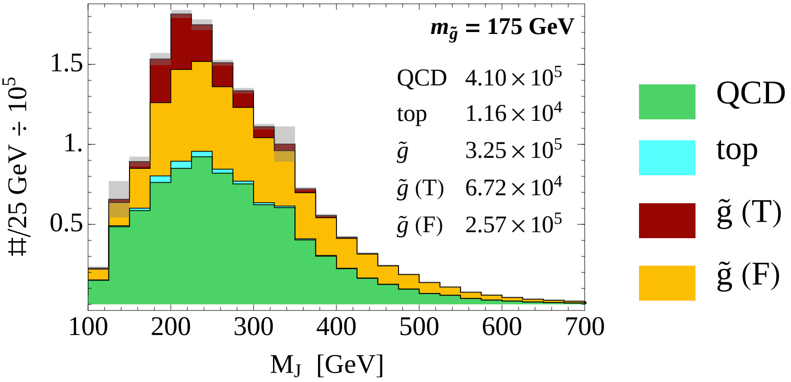
- Larger signal means we can cut harshly on color flow.

→ Spectacular signal vs background discrimination: 12% of signal survives **radial pull** cut, but only 2% of combinatorics background and 0.2% of QCD.

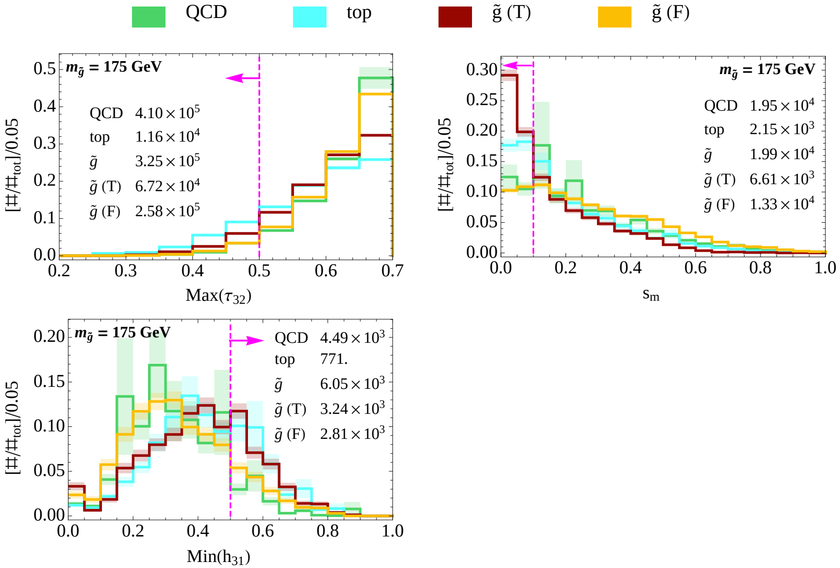
- $S/B \sim 3 \rightarrow 100$ before and after radial pull cut.

Cut Flow for 175 GeV Gluinos

After applying fat jet $p_T > 200\,\mathrm{GeV}$ $\tau_{32} < 0.7$ cut, get the following jet mass distribution:



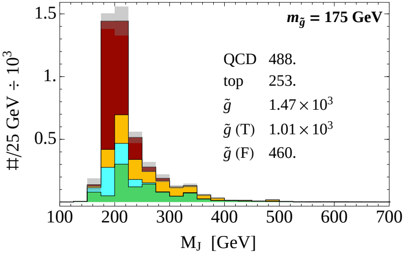
Cut Flow for 175 GeV Gluinos

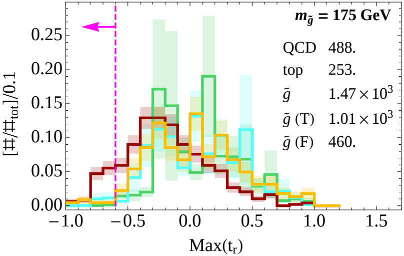


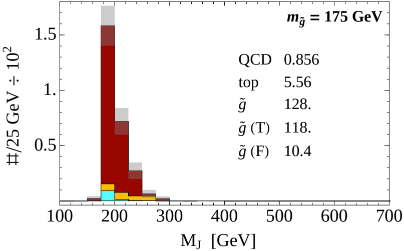
Cut Flow for 175 GeV Gluinos

QCD   top $\tilde{g}$ (T) $\tilde{g}$ (F)

- The 'kinematic' substructure cuts yield this fat jet mass distribution →
- Applying a hard cut on radial pull eliminates all the backgrounds and cleans up the resonance at 175 GeV ↓







Results for Top-Mass Gluinos

Can compare our study to the recent ATLAS analysis.

- The 95% CL exclusion of the ATLAS resolved gluino search (**counting** experiment) at $m_{\tilde{g}} = 175\,\mathrm{GeV}$ is $\mathrm{Br}(\tilde{g} \to qqq) \lesssim 0.25$ with 5 fb^{-1} @ LHC7.
- Our nearly background-free **shape** analysis would exclude (treating it as a counting experiment) $\mathrm{Br} \lesssim 0.15$ @ LHC8 with 5 fb^{-1} and $\mathrm{Br} \lesssim 0.05$ with 20 fb^{-1}.

→ Boosted analysis can provide an 'orthogonal cross-check' on the ATLAS counting experiment with data-driven error estimates.

The light gluino case also demonstrated the potential power of these color flow variables to reject QCD background!

Pile-Up

Pile-Up Considerations

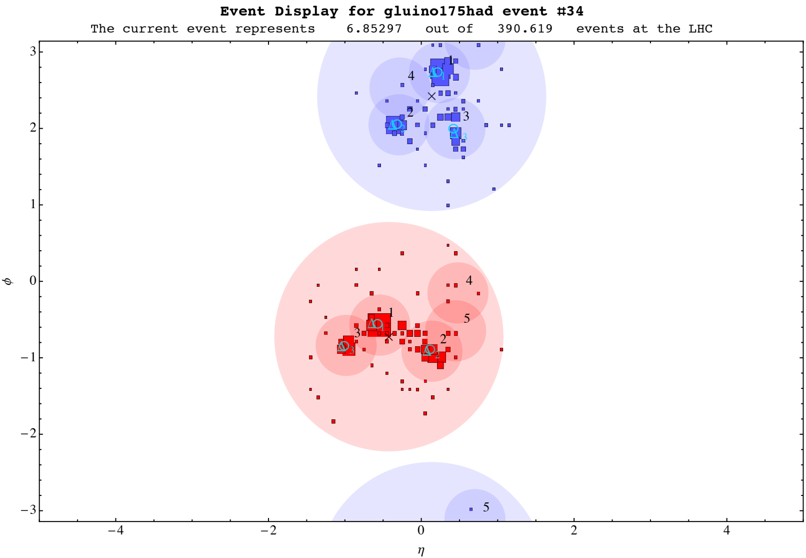
- Our measurements look susceptible to Pile-Up, since our fat jets are very large ($\Delta R = 1.5$).
- PU is a well-understood problem that can be addressed with various grooming techniques (filtering, trimming, pruning, ...).

  $\rightarrow$ **Would these techniques destroy our variables?**

- We did not do a full study with PU, but there are reasons to be optimistic:
  - We performed *kinematic* cuts with **filtering**. The τ_{32} threshold had to be lowered, but then the efficiencies stayed the same or better.
  - The color flow variables should be OK since their values are almost always determined by soft radiation close to subjet centers.

  $\rightarrow$ Keeping soft radiation within $\Delta R = 0.4$ of subjet centers should reduce PU contamination (c.f. Hook, Jankowiak, Wacker '12).

Event Display



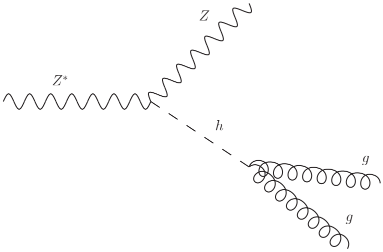
Future Directions

Future Directions

- Experimentalists need to study color flow variables!
  - MC/data agreement?
  - PU dependence/compensation?
- Axis Contraction and Radial Pull could find application in other searches (possibly along with existing dipole taggers like dipolarity or pull).
- Tantalizing Application: detecting $h \to gg$ decay!

PRELIMINARY: Detecting $h \to gg$ decay

- Similar to boosted $h \to b\bar{b}$ search in association with W/Z, but replace b-tag by a color-dipole tag.
- Could work very well for gluons ('double-dipole'). Measurement of the hgg vertex might be possible with a few years of LHC14 data?



- Important closure test of higgs physics & more independent information for higgs coupling fits.
- Opportunity to learn more about gluon physics.

$\rightarrow$ **We are investigating this now.**

Conclusions

Conclusions

- A shape-based search for boosted colored multi-jet resonances can be competitive in mass reach to resolved searches that are conducted as counting experiments.
  - $\rightarrow$ Much lower S/B
  - $\rightarrow$ Orthogonal set of systematic errors
- First study of color flow in R-hadron decays. Explores important intermediate regime not covered by displaced vertex and stable R-hadron searches.
- Demonstrated the power of new color flow variables to improve RPV gluino searches
  - Axis Shift/Contraction is event-shape based and does not require reclustering. N-subjettiness contains lots of information!
  - Radial Pull generalizes pull-based dipole taggers.
- These variables are widely applicable. Stay tuned for $h \rightarrow gg$!

Thank You!