Simplified Models:

What have we learned so far?

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BNL Workshop

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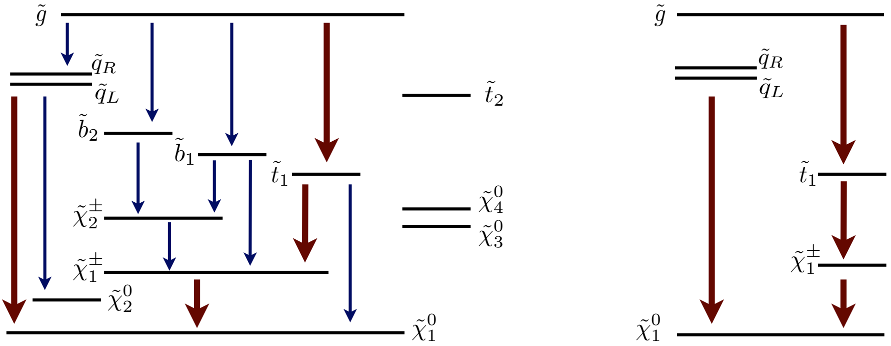
Simplified Models

Simplified Models are an intermediate step between a complete theory and experimental signature

Removes complications of model details and allows one to focus on kinematics when designing cuts

Complete Spectrum

Simplified Model



Simplified Models

Effective Field Theory for Collider Physics

Limits of Specific Theories

Keep only particles and couplings relevant for searches

Still a full Lagrangian description

Removes superfluous model parameters

Focus on masses, cross sections, branching ratios

Captures specific models

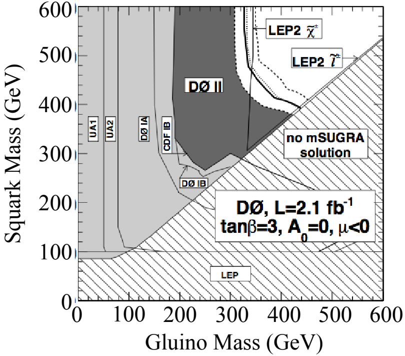
Including ones that aren't explicitly proposed

Easy to notice and explore kinematic limits

Tevatron Example

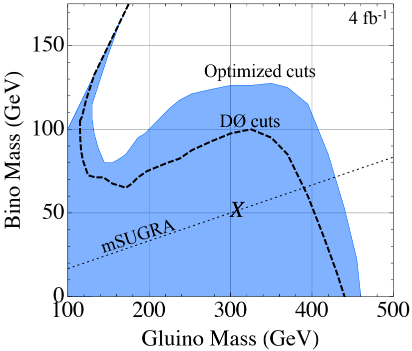
J. Alwall, M-P. Le, **ML**, J. Wacker [0803.0019, 0809.3264]

mSUGRA



Simplified Model

$$\tilde{g}\tilde{g} \rightarrow qqqq\chi\chi$$



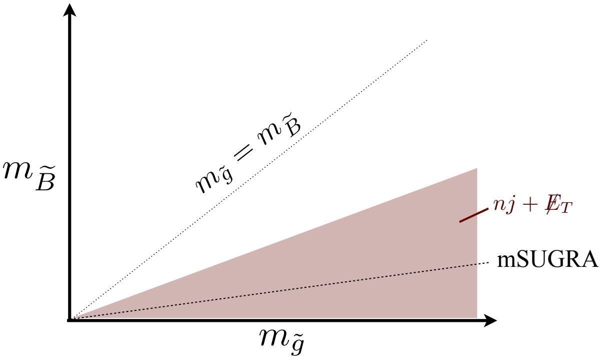
LHC New Physics Working Group [1105.2838]

Many SUSY searches at LHC now use simplified models

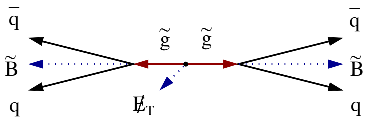
Kinematics

Mass difference between gluino and bino is relevant quantity

$m_{\tilde{g}} \gg m_{\tilde{B}}$	hard, well-separated jets
$m_{\tilde{g}} \sim m_{\tilde{B}}$	jets not as energetic



Nearly degenerate regime



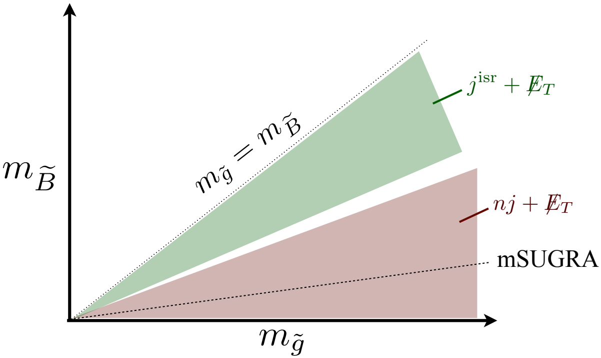
Kinematics

Mass difference between gluino and bino is relevant quantity

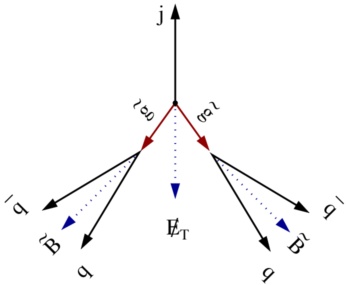
$m_{\tilde{g}} \gg m_{\tilde{B}}$ hard, well-separated jets

$m_{\tilde{g}} \sim m_{\tilde{B}}$ jets not as energetic

Simplified models help ensure that all kinematic possibilities are considered

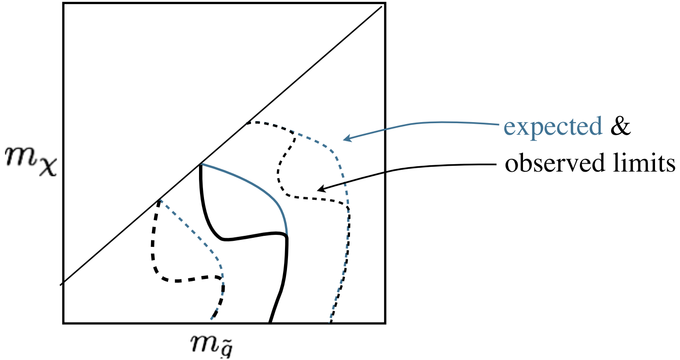


Nearly degenerate regime



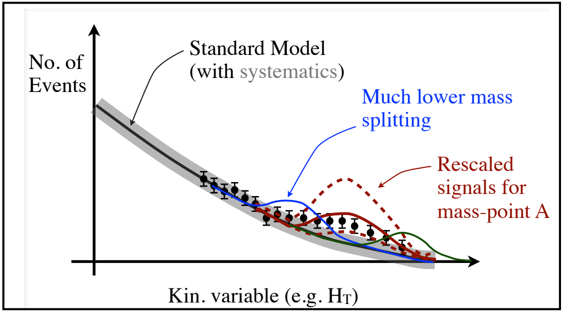
Discovery!

How are simplified models useful once there is a robust discovery claim?

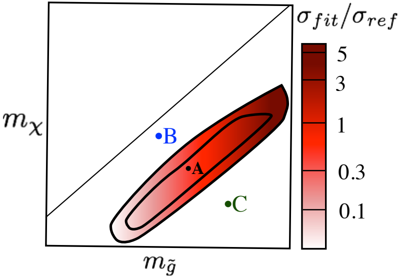


Characterize Signal

What are most consistent values for physical parameters?
(i.e., masses and cross sections)



χ^2 contours with rate chosen for best fit

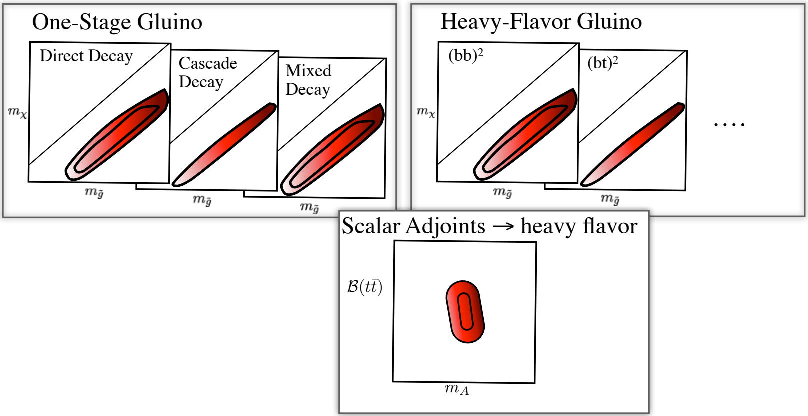


Figures from Natalia Toro

Multiple Searches

Similar plots for various simplified models with same final-state

Statistical comparison allows for model prioritization



Figures from Natalia Toro

Multiple Searches

Example

Excess in jets+MET, plus **search in 1-lepton mode**

Strong limit

Another excess

Constraint on what fraction of hadronic excess can contain W's

Consistent fits w/in same simplified model suggestive of unified interpretation

Also compatible with two distinct sources

Either way, further results get built into consistency requirements on new physics explanation for excesses

Borrowed from Natalia Toro

No excesses so far, unfortunately, but we have learned a lot about the character of BSM physics

For the remainder of this talk, I'll focus on one simplified model example...

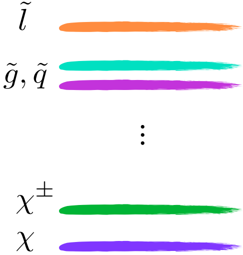
What have we learned so far?

What are the next steps?

Are new analysis tools necessary?

A Minimal Model

SUSY-inspired



Dark matter is a Majorana fermion and SM singlet

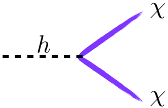
$$\chi = c_1 \widetilde{B} + c_2 \widetilde{W} + c_3 \widetilde{H}_u^0 + c_4 \widetilde{H}_d^0$$

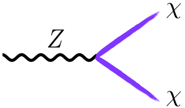
gauginos higgsinos

Also include an additional SM triplet

$$\chi^{\pm} = a_1 \widetilde{W}^{\pm} + a_2 \widetilde{H}^{\pm}$$

Dark matter couples to the SM through Higgs and Z bosons





LHC Tests

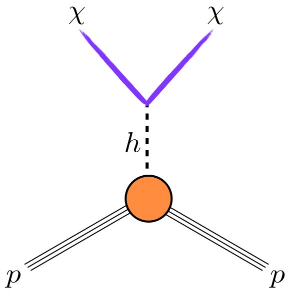
LHC is setting constraints on this minimal scenario

Three classes of searches are particularly relevant:

P. Fox, R. Harnik, J. Kopp, Y. Tsai [1109.4398]

A. Rajaraman, W. Shepherd, T. Tait, A. Wijangco [1108.1196]

ML and N. Weiner [1112.4834]



(1) Invisible branching fraction of the Higgs

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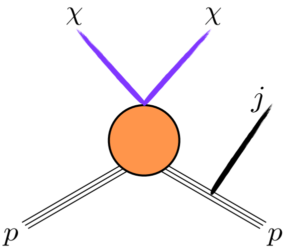

(1) Invisible branching fraction of the Higgs

(2) Direct production of electroweak states

(a) monojet searches

LHC Tests

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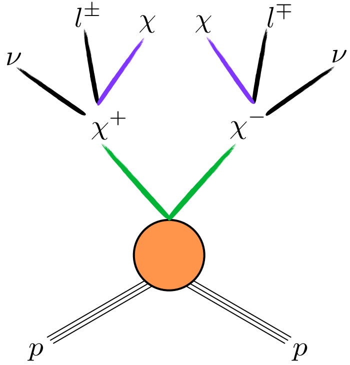


(1) Invisible branching fraction of the Higgs

(2) Direct production of electroweak states

(a) monojet searches

(b) multilepton searches

Multilepton Searches

Searches for 3+ leptons explore associated electroweakino production

$$pp \to \chi^{\pm}\chi' \to 3l + \not{E}_T$$

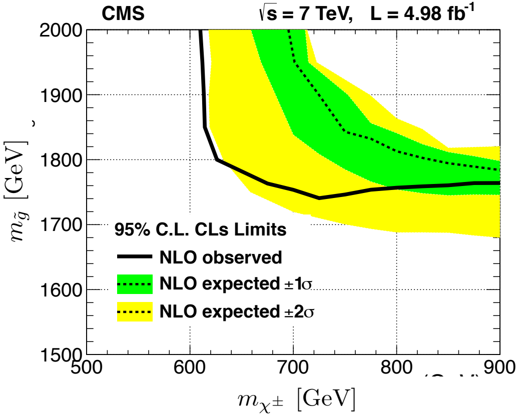
$$\tilde{g}, \tilde{q} \to \chi + X$$

$$\chi \to \tilde{l}^{\pm} l^{\mp}$$

$$\tilde{l} \to \tilde{G} l$$

$$m_{\tilde{l}_R} = 0.3 m_{\chi^{\pm}} \quad m_{\tilde{l}_L} = 0.8 m_{\tilde{\chi}^{\pm}}$$

$$m_{\tilde{\chi}} = 0.5 m_{\chi^{\pm}} \quad m_{\tilde{q}} = 0.8 m_{\tilde{g}}$$



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Multilepton Searches

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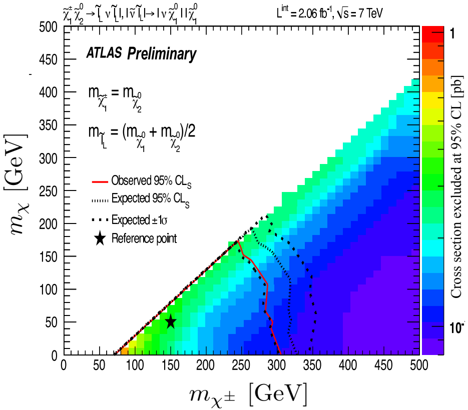
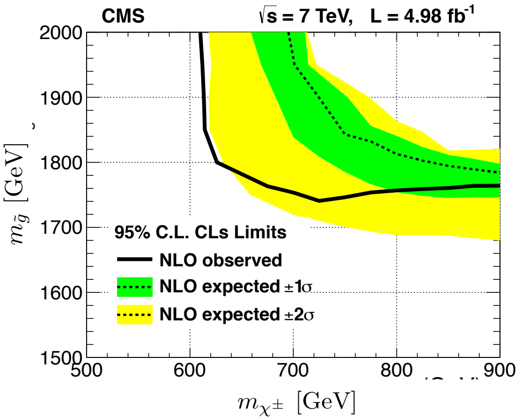
$$pp \to \chi^{\pm}\chi' \to 3l + \not{E}_T$$



ATLAS-CONF-2012-023



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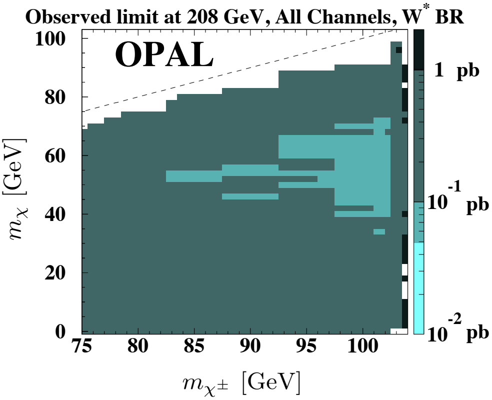
LEP Bounds

Ideally, set direct bounds on electroweakino pair production as well

LEP placed lower bound of ~100 GeV on chargino mass

Does the LHC extend this limit?

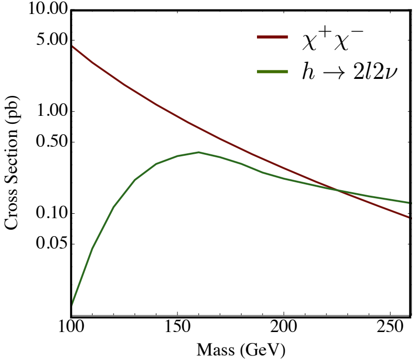


Direct Production at LHC

ML and N. Weiner [1112.4834]

Higgs searches are already sensitive to light electroweakino states

e.g., $pp \to h \to W^+W^- \to l^+\nu\ l^-\nu$



Higgs analyses are inclusive because they require minimal missing energy:

$$\not{E}_T \gtrsim 25\text{–}40\ \text{GeV}$$

*catches light electroweakinos

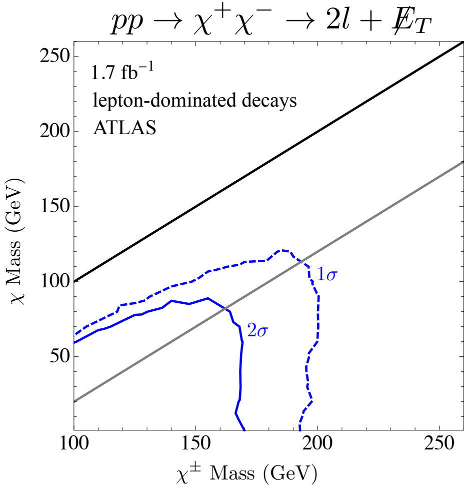
Many SUSY multilepton analyses require

$$\not{E}_T \gtrsim 80\text{–}100\ \text{GeV}$$

Direct Production at LHC

ML and N. Weiner [1112.4834]

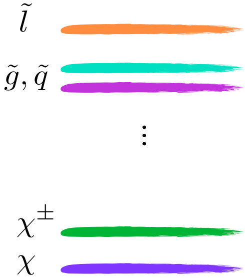
Higgs searches provide the tightest limits, extending LEP bound



New Colored States

Introduce colored states such as squarks or gluinos in the spectrum

Takes advantage of large colored production cross section



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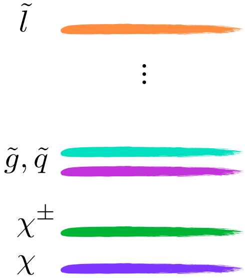
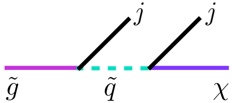
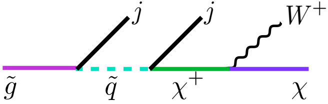


Example: Gluino Pair Production



4 jets



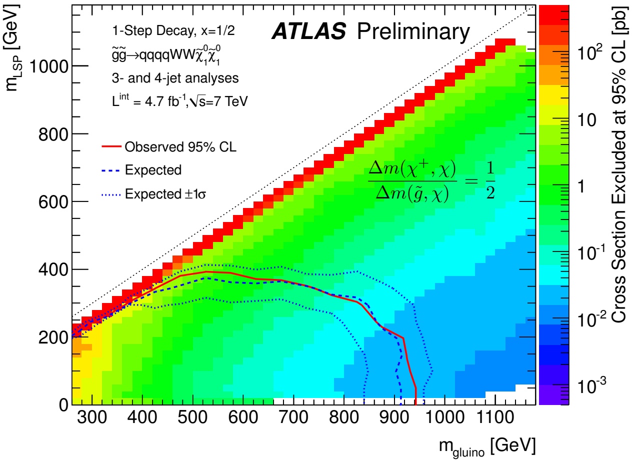
4-8 jets, 0-2 leptons

Jets + MET Searches

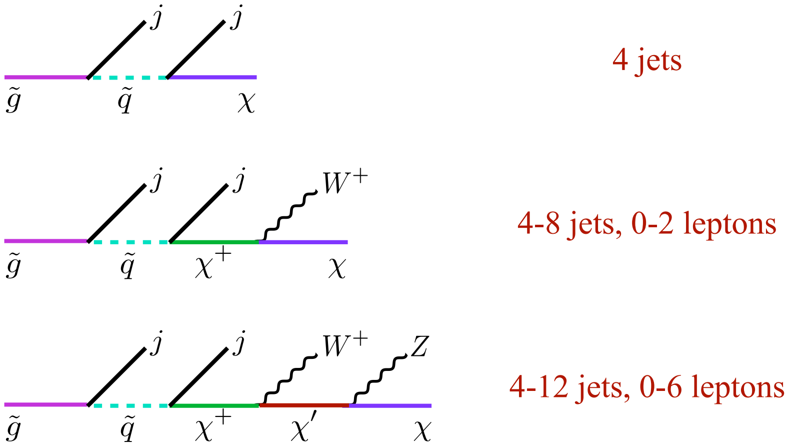
Current searches probe gluino masses up to ~1 TeV for direct decay of gluino to (massless) bino

Limits are weaker for cascade decays

$$\tilde{g}\tilde{g} \to qqqqWW\chi\chi$$



Cascade Decays



For longer cascades, more energy goes into visible final states

Momentum of LSP is reduced $\Rightarrow$ less missing energy

High Multiplicity Final States

Many examples in BSM physics

Multi-top final states (4 tops $\rightarrow$ 12 jets)

Long cascades (2-step cascade $\rightarrow$ 12 jets)

UDD R-Parity Violation ($\sim$ 10 jets)

Lowers missing energy

Can't calculate backgrounds

$$d\sigma(12j) \sim (\alpha_s(\mu))^{12}$$

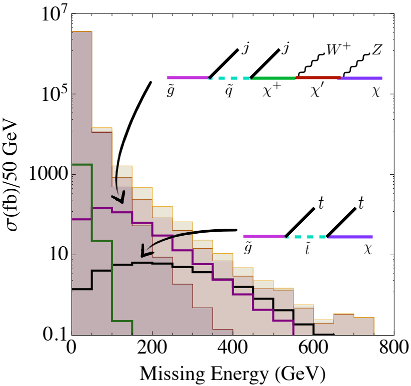
Data-driven backgrounds have large errors

Standard Observables

Neither $\not\!\!E_T$ nor H_T provide great discriminating power against background for high-multiplicity final states

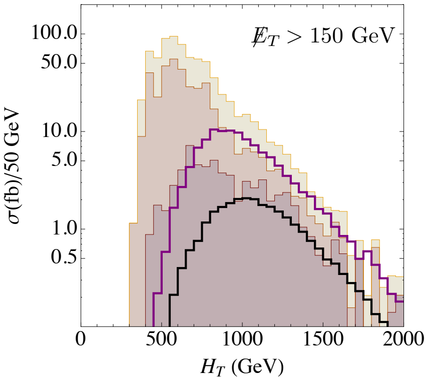
Missing Energy

$\not\!\!E_T$



Total Visible Energy

$$H_T = \sum p_{T,i}$$



QCD $\quad W/Z + \text{jets} \quad t\bar{t}$

$\{m_{\tilde{g}}, m_{\chi^+}, m_{\chi'}, m_{\chi}\} = \{600, 300, 150, 1\}$ GeV $\qquad \{m_{\tilde{g}}, m_{\chi}\} = \{800, 1\}$ GeV

Fat Jets and Jet Mass

E. Izaguirre, A. Hook, **ML**, and J. Wacker [1202.0558]

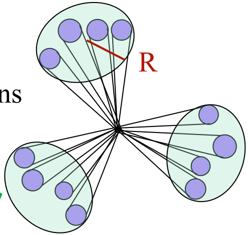
Cluster events into large-radius jets

Require that each event has multiple massive jets

Jet mass discriminates between signal and background:

independent partons

$\langle m_j^2 \rangle \propto p_T^2 R^2$

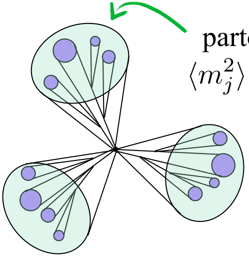


Signal-like

e.g., $\tilde{g}\tilde{g} \to 12j$

parton shower

$\langle m_j^2 \rangle \propto \alpha_s p_T^2 R^2$



QCD, W/Z Backgrounds

Jet Mass Observable

Define the total jet mass of an event to be

$$M_J = \sum m_{j_i}$$

M_J is a more efficient background discriminator than H_T

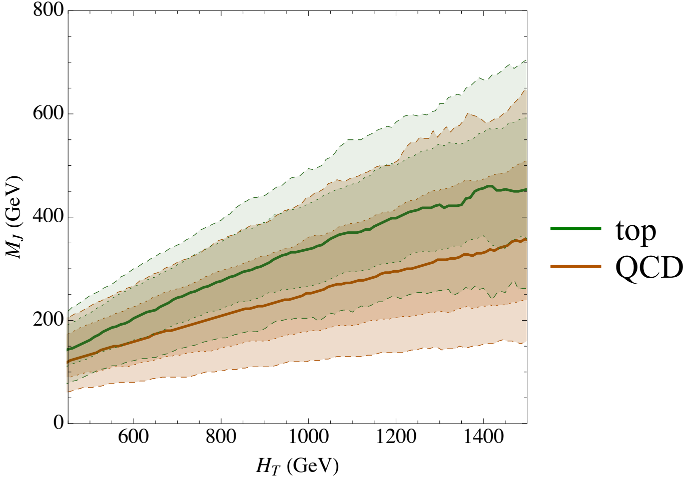
$$H_T \sim \sum_{i=1}^{n_J} p_{T,i} \propto \sum_{i=1}^{n_J} \sqrt{\frac{\langle m_{j_i}^2 \rangle}{\kappa^2 R^2}} \simeq \frac{M_J}{\kappa R}$$

$$\kappa = \begin{cases} 1 & \text{signal-like} \\ \sqrt{\alpha_s} & \text{background} \end{cases}$$

Background and signal-like events with similar H_T distributions will differ in M_J

Top Background

Signals with heavier parent particles than the top give even larger M_J

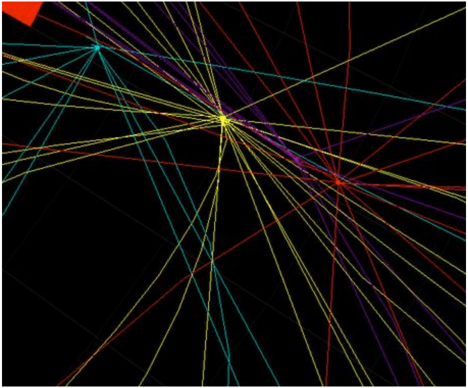


Jet Filtering at ATLAS

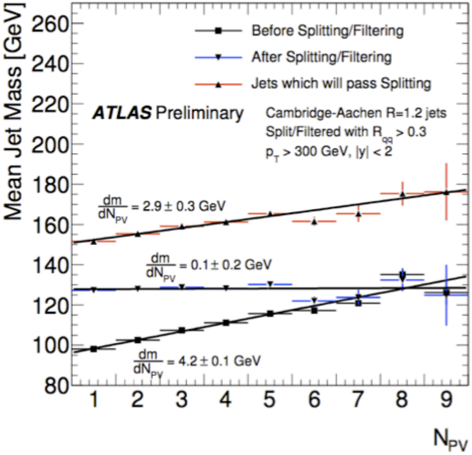
Different methods for removing stray radiation

Jet filtering/pruning/trimming solves problem

CMS Event Display

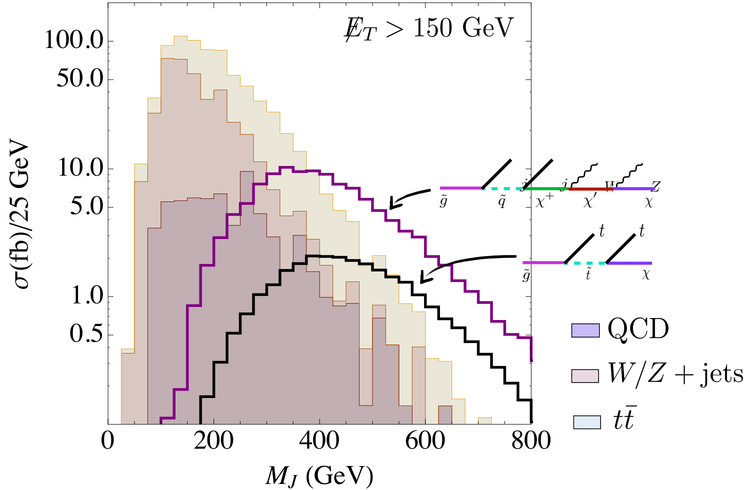


4 pileup vertices



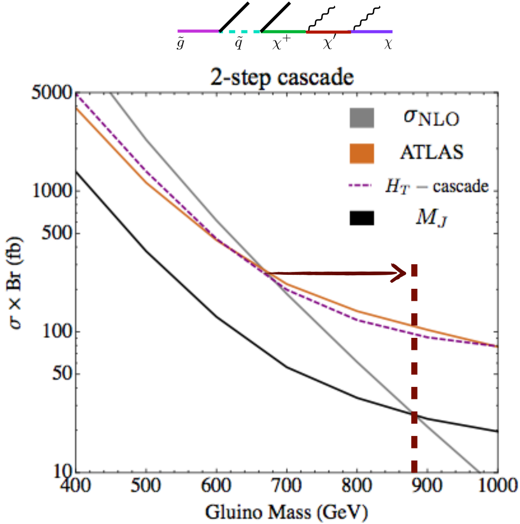
Jet Mass Observable

A jet mass discriminant distinguishes between signal and background



Jet Mass Search

E. Izaguirre, A. Hook, **ML**, and J. Wacker [1202.0558]



Search	N_j	R	Leptons	N_b	$\not{E}_T$ [GeV]	H_T [GeV]	M_J [GeV]
ATLAS	6-8$^+$	0.4	0	0$^+$	$3.5\sqrt{H_T}$	$\emptyset$	$\emptyset$
H_T+SSDL-top	3$^+$	1.2	SSDL	1$^+$	$\emptyset$	300	$\emptyset$
H_T-top	4$^+$	1.2	0$^+$	1$^+$	250	800	$\emptyset$
H_T-cascade	4$^+$	1.2	0$^+$	0$^+$	150	1000	$\emptyset$
M_J search	4$^+$	1.2	0$^+$	0$^+$	150	$\emptyset$	450

~200 GeV increase in limits!

Jet Mass Search

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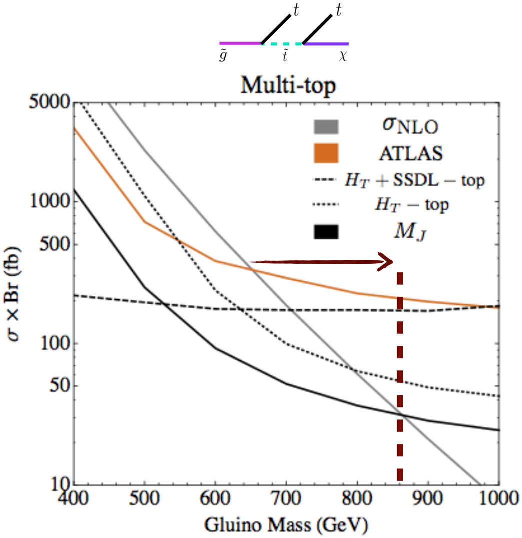

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ATLAS	6-8$^+$	0.4	0	0^+	$3.5\sqrt{H_T}$	∅	∅
H_T+SSDL-top	3^+	1.2	SSDL	1^+	∅	300	∅
H_T-top	4^+	1.2	0^+	1^+	250	800	∅
H_T-cascade	4^+	1.2	0^+	0^+	150	1000	∅
M_J search	4^+	1.2	0^+	0^+	150	∅	450

Conclusions

LHC analyses setting bounds on new colored states and starting to constrain light electroweak states

Higgs diboson analyses complementary to standard trilepton searches; extend limits on electroweakinos beyond LEP

Cascade decays can lead to final states with 10+ jets at the LHC

Jet mass variables improve sensitivity to high-multiplicity events

Limits improve by 20-50% over standard searches

Questions?

Jet Mass

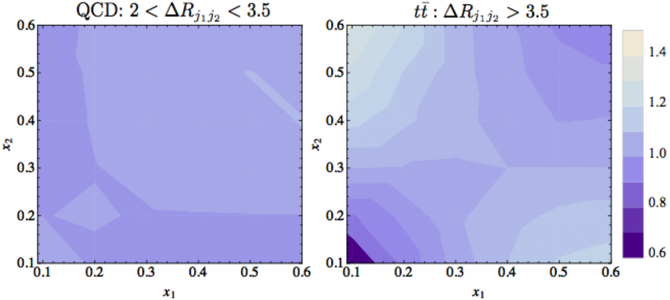

FIG. 2: The jet mass correlation, $H(x_1, x_2)$, for the hardest two jets in QCD (left) and $t\bar{t}$ (right) events that are clustered into three fat jets, where $x_i = m_{j_i}/p_{T,i}$. A mild positive correlation is shown for QCD events, while a sizable anti-correlation is shown for $t\bar{t}$ events.

$$H(x_1, x_2) = \frac{h(x_1, x_2) \int h(x_1, x_2) dx_1 dx_2}{\int h(x_1, x_2) dx_1 \int h(x_1, x_2) dx_2}$$

Jet Mass

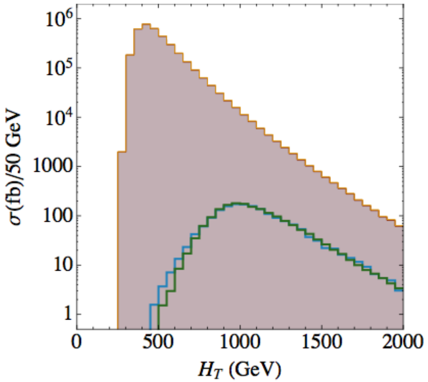

FIG. 6: (Left) H_T and (right) M_J distributions, after requiring four or more fat jets for backgrounds and 500 GeV gluinos decaying via RPV (blue) and stealth SUSY with $m_{\tilde{S}} = 250\,\text{GeV}$ and $m_S = 220\,\text{GeV}$ (green). The backgrounds are shown stacked as in Fig. 3, but are dominated by QCD.

Stealth SUSY: $\tilde{g} \to g\tilde{S} \to g\tilde{G}S \to g\tilde{G}gg$