Difficult Signatures at the LHC

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The Successes of the LHC

Suppression

- Don't forget: HIGGS!
- Strong limits on the production of
	- massive colored states decaying with significant $\not\hspace{-1.2mm}E_{T}$
	- $\not\hspace{-.15cm}{\not\!\! E}_T$ + something
	- High- $p_T\,$ objects (*e.g.* RPV SUSY)

Degenerate Physics

• "SUSY-like" searches often rely on a massdifference variable to distinguish from background

$$
M_{\Delta} = \frac{m_P^2 - m_{\chi}^2}{m_P}
$$

• Difficult when signal point has $m_P \sim m_\chi$ or $M_\Delta \sim m_W$

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Super-Razor

- Attempt to reconstruct events of the form $pp \rightarrow S_1 S_2$, $S_i \rightarrow$ (visible) + χ
- Impossible event-by-event, what can we do statistically?

Super-Razor

- Build boost from lab frame to estimate of center of mass frame. This gives estimated CM mass.
	- Resulting mass variable $\sqrt{\hat{s}_R}$ estimator of M_Δ
	- Also get β_R , estimator of boost to CM frame $\overline{\overline{\beta}}$ *R*
- From this approximate CM frame, can build boost vector to approximate decay frames.

Super-

 $\int_{\mathbb{R}}^{\prime}$ / $2\gamma^{\mathrm{decay}}\mathrm{M}_{\Delta}$ 0 0.5 1 1.5 2 2.5 $\sum_{i=1}^{\infty}$ 0 0.2 versions of the original razor 0.8 • Mass variables are^{*} corrected" 1.2 10^{-5} -10^{-4} FIG. 7: Top Row: Distributions of ^p*s*ˆ*R/* variables. Sensitive to *M*

 $\rm M_{\Delta}^{R}$ / $\rm M_{\Delta}$

∆

s=8 TeV

0 0.2 0.4 0.6 0.8 1 1.2 1.4

MadGraph+PGS $\omega_{\text{DD}} \rightarrow \tilde{i} \tilde{j} \cdot \tilde{i} \rightarrow i \tilde{\infty}$

1.4 1.6 1.8 2

- Not good when $M_{\Delta} \rightarrow m_W$
- But we also have the approximations of the boosts.
- Notice that, as $m_{\tilde{\chi}_1^0}/m_{\tilde{\ell}} \rightarrow 1$, we overestimate the boost $\,\beta_R\,$
- Can define an $\Delta\phi_R^{\beta}$ angle between the boost direction and *R-*frame *q*¹ + *q*²

 $\overrightarrow{\beta_R}$ To trive the event, we more the more information about the mass variables all \mathbb{R} $\Delta \phi_R^{\scriptscriptstyle\wedge}$ and $\Delta \phi_R^{\scriptscriptstyle\wedge}$ between the azimuthal angle between the azimuthal angle between the razor boost $\Delta \phi_R^{\scriptscriptstyle\wedge}$ between the random values of $\Delta \phi_R^{\scriptscriptstyle\wedge}$ between the random values of $\Delta \phi_R^{\scriptscriptstyle$ between the lab and *R* frames and the sum of the visible momenta ~*q*¹ + ~*q*2, calculated in the razor frame *R*. An illustrative example of the relevant kinematics and angle definition is shown in Figure 8. We call this and angle \sim it is the di $\sum q_i$ and the visible system and the ratio q_i This angle is useful because it in heritage it information about ratio of \mathcal{L} indictionary $\downarrow q_2$ in conjunction with a variable such as $\downarrow q_2$

As can be seen from Figures 3 and 5, our estimators of CM and ˆ*s* (*^R* and ˆ*sR*), do not completely track the center

^R. The lab frame (seen here down the beam-line)

-4 10

-5 10

 $\frac{1}{2}$

-3 10

-3 10

MRB, J. Lykken, C. Rogan, M. Spiropulu 1310.4827Letter to the ratio of massession of massession of massession o actually comes from the previously discussed systematic shift of the variable previously discussed systematic o

 $\tilde{s}_{\rm R}$ / \sqrt{s} 0 0.5 1 1.5 2 2.5

> $\widetilde{\chi}^{\text{v}}_1$ \widetilde{l} ; \widetilde{l} → \widetilde{l} $\widetilde{\chi}$ *~ l* $pp \rightarrow \tilde{l}$

> > $= 0$ GeV 1 0 m
…∡

= 150 GeV *^l* m*[~]*

a.u.

 $\rm M_{\Delta}^{R}$ / $\rm M_{\Delta}$

 $\bf M^R_\Delta$ / $\bf M_\Delta$

s=8 TeV

 10^{-5}

 10^{-3}

 $\mathcal{F}_\mathbf{S} = \mathcal{F}_\mathbf{S} = \mathcal{F}_\mathbf{S} = \mathcal{F}_\mathbf{S}$

contains two visible objects, *q*¹ and *q*2. The direction of the boost ~*^R* (defined in Eq. (10)), in the lab frame is also shown.

 10^{-4}

 10^{-3}

Super-Razor Angles 1.91 \cup \cup $\sqrt{ }$

- So far, these are "jet-corrected" versions of the original razor variables. Sensitive to
	- Not good when $M_\Delta \to m_W$
- But we also have the approximations of the boosts.
- Notice that, as $m_{\tilde{\chi}_1^0}/m_{\tilde{\ell}} \rightarrow 1$, we overestimate the boost $\,\beta_R\,$

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• Can define an $\Delta \phi_R^{\beta}$ angle between the $\frac{1}{4}$ $\frac{1}{4}$ $\frac{2\pi U(t)}{2(U(t))t}$ $\frac{1}{8}$ boost direction and *R-*frame *q*¹ + *q*² a.u.

are the distributions of the *WW*⁺ and Drell-Yan *Z* backgrounds.

FIG. 9: Distributions of

 $s = 8$ Mad

 $\overline{s}=\xi$ Mad

As can be seen from Figures 3 and 5, our estimators of CM and ˆ*s* (*^R* and ˆ*sR*), do not completely track the center

^R for a 150 GeV slepton (left) or chargino (right) and a range of neutralino masses. Also shown

1 χ W(*l*ν)W(*l*ν)

Predicted Reach at 8 TeV 50 100 **150** 2 ∼ χ m 50 \blacksquare 150au
150au 1510au 1520au 1530au 1540au 1550au 1550a

350 400

 \sim CMS selection \sim

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350 400

 \sim CMS selection \sim

CMS (upper left) and ATLAS (lower left) selection cuts, and directly compared to our expected exclusions using our simulated

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FIG. 29: Expected exclusion limits (in units of) for charginos decaying to neutralinos and leptonic *W* bosons using 20 fb¹ of 8 TeV data, as a function of both selectron and neutralino masses. Expected limits are shown for our 1D *M^R* analysis using FIG. 31: Expected exclusion limits (in units of) for left-handed selectrons (upper left) right-handed selectrons (upper right), and charging to neutralinos and leptonic content of 8 TeV data, and 8 TeV data, and 8 TeV data, as a function o $F = 1100$ $F = 1000$ for leaders (in upper left-handed selectrons (upper right), right-handed selectrons (upper right), regions (u MRB, J. Lykken, C. Rogan, M. Spiropulu 1310.4827 **Katalinos (bottom center)** selectron/chargino and neutralino masses. Expected limits are derived using our multi-dimensional *M^R*

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analysis super-razor analyses with the razor selection cuts described in the previous section.

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 \Box

N

N

χ

Predicted Reach at 8 TeV

- Moderate increases in the dilepton channels. $pp \to \tilde{\ell}^- \tilde{\ell}^+ \to \ell$ $-\ell^+ \tilde{\chi}^0_1 \tilde{\chi}^0_1$ $pp \to \tilde{\chi}_1^- \tilde{\chi}_1^+ \to \ell^- \ell^+ \nu \bar{\nu} \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- Major problem is lack of events passing trigger.

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• New triggers based on super-razor variables?

FIG. 32: Expected exclusion limits (in units of) for left-handed selectrons decaying to leptons and neutralinos using 20 fb¹

Stau Search • Current bounds on have 1^{250} impro **•** ATLAS-UUINF-2U IS-UZO. the confidence level for the background-only hypothesis (*CLB*) and the compatibility of the data with the background-only expectation (*p*(*s* = 0)). ${\sf m}_{\widetilde{\sf \chi}_1^*,\widetilde{\sf \chi}_2^0}$ [GeV] 100 150 200 250 300 350 400 450 500 m_{μο} [GeV] 0 50 100 150 200 250 300 350 400 0 1 $\tilde{\chi}^0_2$ → $\tilde{\tau}_L$ ν (τ $\tilde{\nu}$) $\tilde{\tau}_L$ τ $(\tilde{\nu} \nu)$ → τν $\tilde{\chi}^0_1$ ττ $(\nu \nu)$ $\tilde{\chi}$ ±∼ $\widetilde{\chi}^{\scriptscriptstyle \pm}_1$ ∼ $= 0.5$ 1 0 χ ∘ + m $\frac{1}{\sqrt{2}}$ 2 χ ∼ , ± 1 χ $\overline{\mathsf{m}_z}$ ν ${\sf m}_{\!\scriptscriptstyle \tilde\tau,\tilde\mathrm{v}}$ $_{\rm theory}^{\rm top}$) Observed limit ($\pm1\sigma^{\rm SUSY}_{\rm theory}$ Expected limit ($\pm 1 \sigma_{\text{ext}}$ L dt \equiv 20.7 **j**b⁻¹, √s § TeV SR combined χ r_{ϕ} χ \curvearrowright All limits at 95% CL *ATLAS* Preliminary \overline{a} $\mathsf{m}_{\widetilde{\mathsf{x}}_1^\ast}$ [GeV] 100 150 200 250 300 350 400 [GeV] 0 1 ∼ χ m 250 0^{0}_{100} 50 100 150 200 300 $\widetilde{\chi}_1^{\pm} \widetilde{\chi}_1^{\mp} \rightarrow 2 \times \widetilde{\tau} \nu (\widetilde{\nu} \tau) \rightarrow 2 \times \tau \nu \widetilde{\chi}_1^0$ $= 0.5$ 1 0 χ $_∗$ + m^{$\frac{1}{2}$} 1 $\overline{m_{\overline{\chi}}}$ ν ${\sf m}_{\!\scriptscriptstyle \widetilde{\tau},\widetilde{\sf v}}$ Observed limit (±1 $\sigma_{\text{theory}}^{\text{SUSY}}$) Expected limit $(\pm 1 \sigma_{\text{evn}})$. dt = 20.7 fb⁻¹, \sqrt{s} =8 TeV SR combined χ r_{ψ} χ \curvearrowright All limits at 95% CL *ATLAS* Preliminary $\overbrace{\prod_{\text{decombined}}^{\text{L}}$ L dt = 20.7 pd¹, \sqrt{s} Te χ + $\overbrace{\prod_{\text{decomodor}}^{\text{SUSY}}}$ $\frac{1}{4}$

- "The best upper limit on the production cross*section is found for a stau mass of 140 GeV and a* $\tilde{\chi}_1^0$ mass of 10 GeV." chargino production. The SR with the SR with the best expected limit at each point is used. The dashed lines shows best expected lines shows best expected lines shows best expected lines shows best expected lines shows be ction is found for a stau mass of 140 GeV and \pm a_n^0 mose of the signal considerations, and α $\tilde{\chi}^0_1$ mass of 10 GeV."
	- (no plot) $\mathbf{t} = 1$ theoretical SUSY signal uncertainty.

Stau Search

- Using Super-Razor variables should be able to improve the reach.
- Working on theorist-level analysis at 14 TeV.
	- Use super-razor variables for both shape analysis and event selection.

Conclusions

- Impressive bounds from the LHC from 7/8 TeV.
	- Can expect this to continue at 13/14 TeV
- However: "low" energy physics could remain undiscovered even in existing data.
	- Especially when signal lives inside background distributions
	- Higher energy may make these channels more difficult, as trigger thresholds rise
	- We still need new ways to search.

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• Super-Razor is one way, but not the only new way.