Long-Lived Superparticles
After LHC Run 1

Brock Tweedie
PITT PACC, University of Pittsburgh
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LHC Searches for Long-Lived BSM Particles
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with Z Liu (1503.05923)
+ work by Yanou & Brian (1409.6729), Eric & collaborators (1505.00784)
SUSY and Displacement

- **R-Parity Violation**
  \[ c \tau_{\mathrm{RPV}} \approx 0.1 \text{mm} \left( \frac{100 \text{ GeV}}{\bar{m}} \right) \left( \frac{10^{-6}}{\lambda} \right)^2 \]
  - final-stage decay controlled by B/L-violating couplings, favored small by precision tests & cosmology (displaced when RPV Yukawas < O(10^{-7}))

- **Gauge mediation**
  \[ c \tau_{\mathrm{GMSB}} \approx 0.1 \text{mm} \left( \frac{100 \text{ GeV}}{\bar{m}} \right)^5 \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \]
  - final-stage decay controlled by Goldstino coupling (displaced when sqrt(F) > O(100 TeV))

- **Mini-split spectrum**
  \[ c \tau \approx 10^{-5} \ m \left( \frac{m_{\tilde{q}}}{\text{PeV}} \right)^4 \left( \frac{\text{TeV}}{m_{\tilde{q}}} \right)^5 \]
  - gluino forced to decay through very heavy off-shell squarks (displaced when m(\tilde{q}) > O(1000 TeV))

- **Wino co-LSP’s (e.g., anomaly mediation)**
  - \( m_{\pm} - m_0 \approx m(\pi) \)
  - O(10 cm) long “disappearing track”
  - well-covered experimentally!

* Plus many other non-minimal models (stealth SUSY, etc)
Long-Lived Searches at CMS

Displaced Dijets

- Background of displaced vertices from:
  - Standard Model

Displaced Dileptons

- Primary particles
- Materiale interaction vertex
- HSCP

Displaced Vertices

- Vertex
- Looking for
- No decaying inside the tracker volume.

- Final MC samples
- Tens of microns

- Vertex is greater than
  - Track is removed from the vertex

- Vertex is refitted
  - Track pairs
  - Vertex fit

- Graph approach
  - Similar to that used in Ref [in]
The Need to Recast

Displaced Dijets

- Background of displaced vertices from:
  - Standard Model background
  - Proton-proton randomly crossing tracks from different nuclear interaction vertices
  - Higgs interactions with material

- Vertices that are separated by less than 1 mm are combined if no tracks are shared among di-jets and refitted to a single vertex; otherwise, the track is assigned to the event selection criteria.

- To suppress background from tracks originating from the primary vertex, events containing at least one such displaced vertex are required to fit to a single vertex.

- The transverse distance to the primary vertex is required to be less than 2 mm, and the transverse range is less than 1 mm.

Displaced Dileptons

- Common displaced vertices from particle-material interactions near the interaction point.

- For vertices originating from the primary vertex, the tracks of the two vertices are combined if they have a vertex fit to the transverse position of the primary vertex.

- The sensitivity plateau of the 17 TeV level of the lh GeV level trigger is expected but not found and must satisfy an associated with the muon candidate identified by the trigger. The ID track associated with the muon candidate must satisfy the pseudorapidity of the reconstructed muon candidate and the muon candidate must satisfy the expected density dependent criteria.

- Vertex efficiency plateau of the lh GeV level of the lh GeV level trigger is expected but not found and must satisfy an associated with the muon candidate identified by the trigger. The ID track associated with the muon candidate must satisfy the pseudorapidity of the reconstructed muon candidate and the muon candidate must satisfy the expected density dependent criteria.

- Studies have shown in that the positions of pixel vertices reconstructed in data are well simulated in the detector model, while the simulated beam pipe position and associated material are well simulated in the detector model. The use of data events to construct the material map enables the use of data events to construct the material map.

- MC sensitivity is the estimated uncertainty, where
  - $\Delta$ is the impact parameter of the track relative to the resulting DV
  - $\sigma_D$ is the estimated uncertainty
  - $\Delta p_T$ is the invariant mass of the dilepton system
  - $T$ is the transverse range of the vertex
  - $\eta$ is the pseudorapidity
  - $r$ is the distance between the vertices
  - $\phi$ is the angle between the vertices

- Studies have shown in that the positions of pixel vertices reconstructed in data are well simulated in the detector model, while the simulated beam pipe position and associated material are well simulated in the detector model.
An Example: BRPV Stop from $H \rightarrow aa \rightarrow$ Displaced Dijets

Motivated by Barry, Graham, Rajendran (1310.3853): “there are important factors that obfuscate the relative efficiency of this search”

- $m(\tilde{t}) = 150$ & $\sqrt{s} > 400 \Rightarrow \sigma \sim 30$ pb via direct QCD pair production
- $\sim50\%$ chance to get neutral stop-hadron
- $\sim50\%$ pass basic acceptance, $\sim5\%$ reco efficiency for $c\tau \sim 40$ cm
- $\times2$ stops per event
- Luminosity $\sim 20,000$ pb$^{-1}$
- TOTAL: $30 \times 0.5 \times 0.5 \times 0.05 \times 2 \times 20,000 = 15,000$ candidates
- 1 background event $\Rightarrow$ limit is $\sim4$ candidates
Loose Organizing Principles for Our First-Pass Survey

• **Hadronic final states**
  – can be difficult when decays are prompt
  – explicit displaced limits are limited (esp BRPV)
  – colored sparticles have big cross sections

• **Naturalness**
  – lightest sparticle tends to be stop or Higgsinos
  – gluino also can’t be too heavy

• **Simplified spectra**
  – only one or two new particles
  – no long decay chains
  – minimize # parameters
  – conservative total rates
Some of the Models We Studied

- BRPV stop
  \[ \tilde{t} \rightarrow q \tilde{q} \]

- BRPV gluino
  \[ \tilde{g} \rightarrow q \tilde{q}^* \]

- GMSB gluino
  \[ \tilde{g} \rightarrow g \tilde{G} \]

- GMSB Higgsino
  \[ \tilde{H}^\pm \rightarrow Z \tilde{G} \]
  \[ \tilde{H}^0_1 \rightarrow W^* \tilde{G} \]

- GMSB stop
  \[ \tilde{t} \rightarrow t^{(*)} \tilde{G} \]

- Mini-split gluino
  \[ \tilde{g} \rightarrow q \tilde{q}^* \tilde{\chi} \]
The Searches that We Recast

Applied to all models
- CMS displaced dijets (tracker)
- ATLAS low-EM jets (HCAL)
- ATLAS muon spectrometer vertices (7 TeV, 2 fb⁻¹)
- CMS charged stable particles

Applied to models with leptonic decays
- CMS displaced dileptons
- CMS displaced electron & muon
- ATLAS displaced muon + tracks

* For ATLAS displaced vertex+(l/j/MET) and lots more models, see Csaki, et al (1505.00784)
Detector Simulation
Methodology

• Minimalistic
  – basic geometry, no detector granularity or energy smearing
  – perfect absorptive calorimeters
  – tracking/vertexing efficiencies with simple linear falloff models in radius, z, impact parameter

• Try to reproduce all explicitly studied models
  – employ constant fudge factors where necessary to mock up unreproducible reconstruction efficiencies
  – a (by now well-known) lesson for experimentalists: the broader the kinematic range of benchmarks tested, the better

• Even O(1) modeling errors can be acceptable
  – rapid evolution of rates near limit boundaries
  – but we try to do better where we can!
E.g., Tracking Efficiency at “CMS”

![Graph showing efficiency vs radius with CMS simulation and data points.]

- Linearly-falling inefficiency vs Lz (to 55 cm)
CMS Dijets Validation

H(1000) \rightarrow X(350) X(350), c\tau = 35 \text{ cm}

H(200) \rightarrow X(50) X(50), c\tau = 20 \text{ cm}

H(400) \rightarrow X(150) X(150), c\tau = 40 \text{ cm}

QCD background
CMS Dijets Validation

H(1000) → X(350) X(350), cτ = 35 cm
H(200) → X(50) X(50), cτ = 20 cm
H(400) → X(150) X(150), cτ = 40 cm

QCD background
Perfect tracking & vertexing
Imperfect tracking, perfect vertexing
Imperfect tracking & vertexing

X → bb / X → qq
Efficiency

CMS Displaced Dijet
per vertex efficiency for
RPV stop

$mt = 100 \text{ GeV}$

$mt = 1200 \text{ GeV}$

$\text{RPV Stop Efficiencies}$
**ATLAS HCAL & Muon Spectrometer Validations**

**ATLAS low-EM jets**

- $H(126) \rightarrow X(10) \times X(10)$
- $H(126) \rightarrow X(25) \times X(25)$
- $H(140) \rightarrow X(40) \times X(40)$

**ATLAS muon spectrometer**

- $H(120) \rightarrow X(20) \times X(20)$ solid
- $H(120) \rightarrow X(40) \times X(40)$ dashed
- $H(140) \rightarrow X(20) \times X(20)$ solid
- $H(140) \rightarrow X(40) \times X(40)$ dashed

Analyses specialized for low-mass scenarios...We must blindly extrapolate to higher-mass SUSY models

* explicit max delay cut 5 ns
* calibrated max delay 7 ns
**Lepton Validations**

### CMS dilepton

- $H(1000) \rightarrow X(20) \ X(150) \ X(50) \ X(350)$

### ATLAS muon + tracks

- $\tilde{q}(700) \rightarrow \tilde{X}(494)$
- $\tilde{q}(700) \rightarrow \tilde{X}(108)$
- $\tilde{q}(1000) \rightarrow \tilde{X}(108)$

### CMS electron & muon

- $t(500) \rightarrow \text{lepton} + \text{b}$

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*Note: The plots show comparisons to CMS limits and simulation results for different SUSY models, with a focus on leptonic decays and the calculation of reconstruction rates. The plots illustrate the ratio of event reconstruction rates to CMS for various stop masses and lifetimes.*
RPV Stop $\rightarrow 2q$ (Light Flavors)
Figure 1

w 95. CL exclusion curves for fully hadronic stop decays to two down-type quarks. In the upper left plot we show \( \tilde{t} \rightarrow \bar{d}\bar{d} \) in the upper right plot \( \tilde{t} \rightarrow \bar{d}\bar{b} \) and in the bottom plot \( \tilde{t} \rightarrow \bar{b}\bar{b} \) is presented. While all displaced searches of ATLAS and CMS have been recast we only display the curves yielding the strongest constraints. Stable searches for HSCPs were recast for an unstable RHadron. The prompt searches here correspond to the CMS dijet resonance search.

4.1 Stop LSP

For the case of a stop LSP, we have considered the three final state topologies, as given in Table 1. Only direct production of the stop has been simulated and the gluino was assumed to be decoupled for the determination of production cross section. Despite the change in kinematics, we expect the gluino production to mostly affect the overall stop production rate, and therefore the limits presented here can be used to estimate the limits for the non-decoupled gluino case.

For the \( \tilde{t} \rightarrow \bar{d}\bar{d} \) final state we have considered all combinations of final state bottom and light down quarks. For the \( \tilde{t} \rightarrow d_l + \) final state, we have considered bottom quarks with all three lepton generations. For the \( \tilde{t} \rightarrow u\nu \) final state, we studied top and charm quarks. For this final state, we have also considered the case where the LSP stop is lighter than the top in which case the stop decays to \( W^+b\nu \) via an off-shell top.

The results are presented in Figs. 1-3. One can see that the whole region of natural stop masses \( m_{\tilde{t}} < 800 \) GeV is excluded, except for purely hadronic prompt decay, \( \tilde{t} \rightarrow \bar{d}\bar{d} \). There is also some allowed parameter space by these searches for prompt decays with neutrinos, however we expect that prompt missing energy searches will further constrain some of the.
RPV Gluino $\rightarrow 3q$ (Light Flavors)
Figure 1: Cross section limits for our simulation of winos decaying to three displaced jets each at $\sqrt{s} = 8$ TeV. The solid red curve shows the NLO production cross section. The kinks in this and subsequent plots are due to the finite resolution of our parameter scan. State topologies beyond the intended displaced dijet analysis; in particular, long-lived particles decaying to three or more quarks are constrained.

4.1.1 MSSM wino with RPV couplings

In the RPV wino scenario, the new particles form an electroweak triplet $\tilde{\chi}^\pm$ and charginos $\tilde{\chi}^\pm$. They are produced through the SM electroweak interaction and subsequently decay at a mean transverse distance $L_{xy}$. As discussed in Section 4, we assume that the charginos quickly decay into neutralinos so that DVs arise only from neutralino decays. We impose all of the cuts of the CMS analysis including an event-level $H_T > n_k$ GeV requirement, two $p_T > q_k$ GeV displaced jets at a vertex, and several other vertex selection criteria. We correct our particle-level Monte Carlo according to the prescription in Section 4 in order to take detector effects into account. Because the winos are pair-produced with low boost, we correct our MC at $L_{xy} = x$ cm using CMS/average over the two lowest boost mass benchmark points (namely $m_{H_X} = 300$ GeV and $m_{H_X} = 800$ GeV). This procedure allows us to approximately recast the CMS results for the hadronic RPV wino signal. We assume that the winos each decay into three light-flavour jets. We show our results for the bounds on the wino pair production cross section as a function of mass in Figure 1. For winos decaying in the most sensitive part of the detector ($L_{xy} \approx 3$ cm), winos are excluded up to about 50 GeV while the bounds weaken to 80 GeV for very long lifetimes. Nevertheless, this excludes winos over much of the electroweak scale and we see that the sensitivity of the CMS cuts is as high for displaced vertices with $n$ jets as it is for $m_{h_J}$ vertices. Therefore, the CMS analysis places strong bounds on WIMP baryogenesis through winos via hadronic RPV operators below the TeV scale.

Using all three mass benchmarks at 3 and 30 cm changes the cross section limit by $\sim 30\%$. Cui & Shuve (1409.6729)
RPV Higgsino $\rightarrow$ 3q (Light Flavors)

\[
\tilde{H} \rightarrow jjj \text{ (RPV)}
\]

* No prompt limits

\[
m_{\tilde{q}}/\sqrt{Y_q \lambda_{ijk}} = 10^2 \text{ TeV}
\]
GMSB Gluino $\rightarrow g + \text{Gravitino}$

Needs to be re-evaluated with ATLAS DV+X!
GMSB Higgsino → Z + Gravitino

a) \( \tilde{H} \rightarrow Z \tilde{G} \) (GMSB)

(Insert traditional X+MET searches here)
GMSB Higgsino → H + Gravitino

b) $\tilde{H} \rightarrow h \tilde{G}$ (GMSB)

* No prompt limits

[Diagram with various search techniques and projections]
GMSB Stop $\rightarrow$ Top$(*)$ + Gravitino

$\tilde{t} \rightarrow t^{(*)} \tilde{G}$ (GMSB)

charged stable

charge-stripped

LHC8 projection

ATLAS HCAL

ATLAS $\mu$+tracks

CMS e & $\mu$

ATLAS $\mu$ spect

CMS dijet

$\sqrt{s} = 10^2$ TeV

prompt stop

$m_t$ (GeV)

cr (m)
GMSB Stop $\rightarrow$ Top(*) + Gravitino

Figure 2

$v$ 95% CL exclusion curves for stop decays to a bottom quark and a charged lepton. In the upper left plot we show $\tilde{t} \rightarrow b e$ + 2 int. In the upper right plot $\tilde{t} \rightarrow b \mu$ + 2 int. In the bottom plot we have $\tilde{t} \rightarrow b \tau$ + v. While all displaced searches of ATLAS [08] and CMS [09] have been recast two only display the curves yielding the strongest constraints. Stable searches for HSCPs [33] were recast for an unstable Ruhadron. The prompt searches here correspond to leptoquark searches at the Tevatron and LHC [35–43].

Figure 3

$v$ 95% CL exclusion curves for stop decays to an up type quark and a neutrino. In the left plot we have $\tilde{t} \rightarrow t^\nu$ and in the right plot $\tilde{t} \rightarrow c^\nu$. While all displaced searches of ATLAS [08] and CMS [09] have been recast two only display the curves yielding the strongest constraints. Stable searches for HSCPs [33] were recast for an unstable Ruhadron. The prompt searches here correspond to the Ruparity conserving supersymmetric searches [3244] overlayed.
Mini-Split Gluino $\rightarrow 2j + \text{LSP}$

- $\tilde{g} \rightarrow q \bar{q} \tilde{B}, \ m(\tilde{B}) = 0$ (mini-split)

* $m(\text{LSP}) = 0$ (Also: Comparable limits from decays with tops)
Some Lessons

• Displaced SUSY is difficult to hide
  – non-dedicated displaced searches usually beat dedicated prompt searches in mass reach
  – strong complementarity across prompt/displaced/stable searches
  – “zero to infinity” lifetime coverage in many cases
  – when hadronic decays are active, CMS displaced dijets and ATLAS DV+X usually win

• Weak points at $c\tau \sim m$ and $c\tau \sim mm$
  – ATLAS CAL/muon searches suffer multiple penalties: coincidence requirement, timing issues, strict isolation criteria, MET veto
  – more b-tag recasts might cover some space at low lifetime
  – prompt search reach is probably broader than we show

• Inner tracker seems to be the most sensitive instrument
  – small volume, but tons of detailed information for crafting cuts
  – still, more aggressive searches with CALs & MS seem possible
Comments on Model Space

• It’s big
  – as elsewhere, facilitating recasting seems mandatory
  – RPV in particular has $O(b’gillion)$ parameters even in simplified spectra
  – we’ve just scratched the surface here (with lots of personal bias)

• Natural+displaced options generally in bad shape
  – possible escape hatches: prompt-ish BRPV stop at $> 350$ GeV, really short/long-lived Higgsinos (could still be seen in heavier sparticle prompt decays), decay modes very different from what we’ve shown, not-so-simplified spectra, .....  

• Mini-split gluino is probably above a TeV

• GMSB simplified models have finite options
  – sleptons (staus): amenable to track-stub searches, di- displaced leptons; need/benefit from explicit “kinked track” search? displaced $\tau$-jets?
  – Wino: neutral NLSP gives displaced $Z/\gamma$, charged NLSP (non-generic) gives displaced W’s; both easy to see
Recaster’s Wishlist

• More varied test models for calibration
  – higher/lower masses
  – different topologies
  – neutral & charged

• More details on detector efficiencies over broad ranges of kinematics, esp. tracking/vertexing
  – isolated tracks vs (\(\eta, r, z, \text{IP}\))
  – transparent/parametrized vertexing criteria
  – fate of “exploding tracks”?

• Some “standard” detector/analysis emulation strategy?
  – but effective # of dials grows rapidly, often several new ones for each new analysis
  – is one experimentally-vetted toy detector per analysis too labor-intensive? (e.g., CMS HSCP recast map: PAS EXO-13-006)
More...
CMS dijet

ATLAS µ spect

LHC8 projection

charged stable

charge-stripped

charged stable

charge-stripped

ATLAS HCAL

ATLAS µ tracks

dRPV Stop ➞ 2b

** Now covered by CMS
GMSB Higgsino $\rightarrow Z/h + \text{Gravitino}$

Large $\tan\beta$ Limit

$c) \, \tilde{H} \rightarrow Z/h \, \tilde{G}, \, \text{large} \, \tan\beta \, (\text{GMSB})$
Mini-Split Gluino → 2j + LSP

b) $\tilde{g} \rightarrow q \bar{q} \tilde{B}, \ m(\tilde{B}) = m(\tilde{g}) - 100 \text{ GeV} \ (\text{mini-split})$

$LHC8 \text{ projection}$

$\text{charged stable}$

$\text{charge-stripped}$

$\tilde{g}\rightarrow 2j + LSP$

$\text{ATLAS prompt jets + MET recast (approx)}$

$\text{ATLAS HCAL}$

$\text{ATLAS } \mu \text{ spect}$

$\text{prompt jets + MET}$

$m_{\tilde{g}} = 1 \text{ PeV}$
A Few SUSY Limits

detector-stable charged

stop → lepton + bottom (LRPV)

disappearing track (Wino co-LSPs)

1305.0491

1409.4789

1310.3675
A Few More

**displaced “dijet”**: neutralino → μ + jets (LRPV)

**DV + jets/leptons/MET**: gluino → tt + neutralino (Mini-split)

**non-pointing photons** (GMSB)

1411.6530

1504.05162

1409.5542