Displaced Leptons and Other Exotic Objects at the LHC

Jared A. Evans

jaredaevans@gmail.com

Department of Physics

University of Illinois, Urbana-Champaign

Evans, Shelton – arXiv:1601.01326

Outline

Status of LHC Exotic Objects

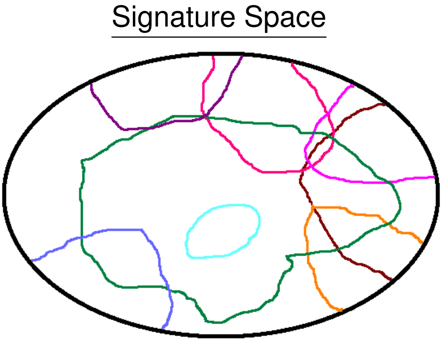
Displaced Leptons from $\tilde{\tau}_R$s in Gauge Mediation
- HSCP Searches (CMS)
- Disappearing Tracks Searches (ATLAS & CMS)
- CMS Displaced $e\mu$ Search
- Recast Limits
- Paths for Improvements

A Gap: Same-Flavor Displaced Leptons
- Models: co-NLSPs, EGMSB, RPV, freezein dark matter
- A Same-Flavor Displaced Lepton Search for 13 TeV

Comments and Perspectives

The LHC has constrained many new particles in many models

- MSSM
- t'/b'
- UED
- GMSB
- RPV
- Stealth
- 2HDM
- ...



These searches cast a wide net

The LHC Program

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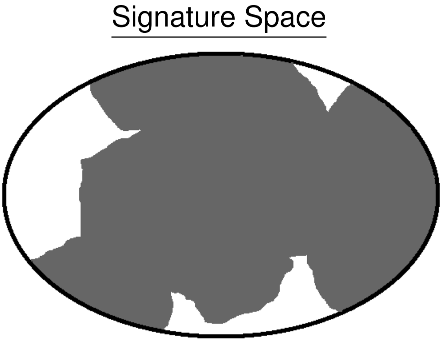

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Need comprehensive program that covers ALL new physics scenarios

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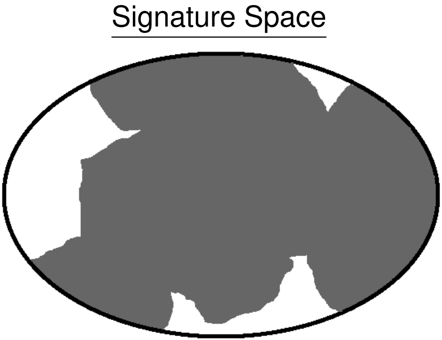

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An exotic object could be our FIRST pathway to BSM physics!

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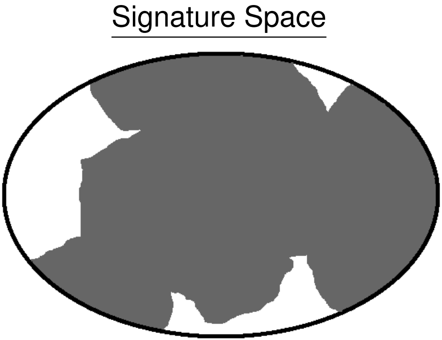


These searches cast a wide net – but there are gaps

Need comprehensive program that covers ALL new physics scenarios

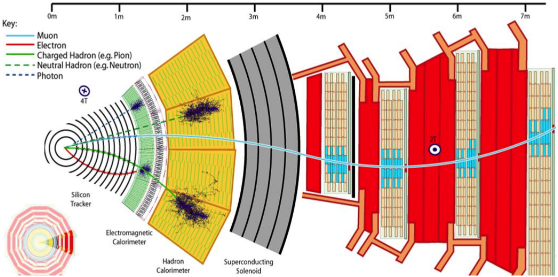
An exotic object could be our ONLY pathway to BSM physics!!!

What are Exotic Objects?

What are Standard Objects?

What are Standard Objects?

	Object	Very Rough Identification Criteria
1)	Photon	Hard, isolated EM calo deposit, $E_{tracks} \ll E_{calo}$
2)	Electron	Hard, isolated EM calo deposit, $E_{track} \sim E_{calo}$
3)	Muon	Hard, isolated track through muon chamber
4)	Jet	Other hard calo/track/particle clusters
a)	Tau	Single or 3-prong hard, isolated track(s)
b)	*b*-jet	Secondary vertex, looks *b*-ish
5)	$\not\vec{E}_T$	$-\sum \vec{p}_T$



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Loaded words: track, isolated, hard, cluster, vertex, *b*-ish ...

Exotic objects have properties that allow them to be distinguished from these standard objects

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Exotic objects have properties that allow them to be distinguished from these standard objects

Two basic classes: Direct & Indirect

What are Exotic Objects?

Direct vs Indirect

Direct	Indirect
Observe the object itself	Observe atypical SM decay products

What are Exotic Objects?

Direct vs Indirect

Direct

Observe the object itself

Examples:

Disappearing tracks

Heavy, stable, charged particles

Magnetic monopoles

R-hadrons

Quirks

. . .

Indirect

Observe atypical SM decay products

Direct

Observe the object itself

Examples:

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LHC searches exist

Indirect

Observe atypical SM decay products

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Examples:

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LHC searches exist

Indirect

Observe atypical SM decay products

Collimated particles fail isolation

Non-isolated leptons/photons

Photon or lepton jets

Direct

Observe the object itself

Examples:

Disappearing tracks

Heavy, stable, charged particles

Magnetic monopoles

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...

LHC searches exist

Indirect

Observe atypical SM decay products

Collimated particles fail isolation

Non-isolated leptons/photons

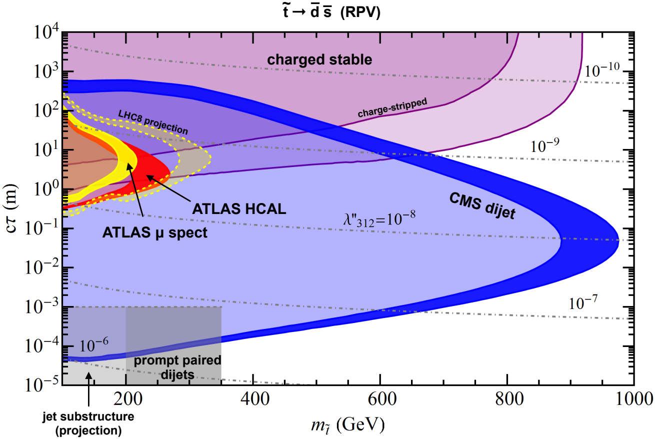
Photon or lepton jets

Particles that decay in flight

Long lifetime from an approximate symmetry in the low energy theory

High dimension operators
High mass scale
Small couplings

Long-lived / Displaced in SUSY

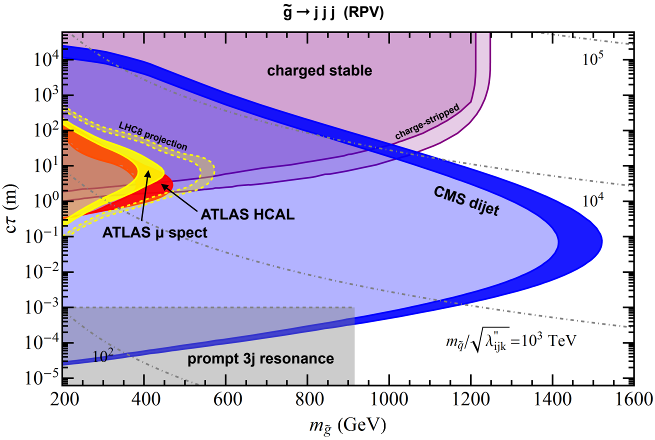


Liu, Tweedie – 2015

Many displaced decays are well-covered: Most RPV

Liu, Tweedie – 2015

Csaki, Kuflik, Lombardo, Slone, Volansky – 2015 Zwane – 2015



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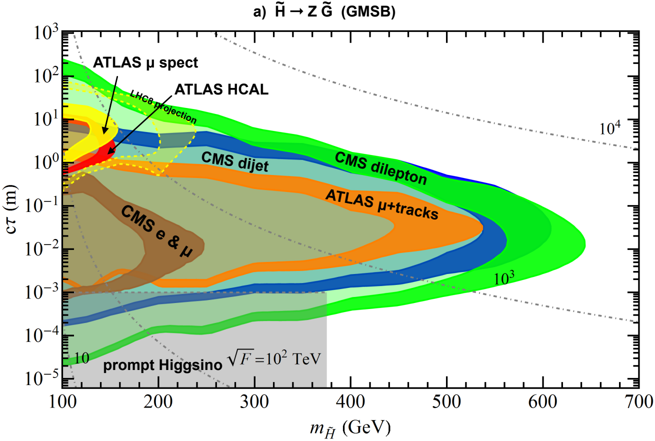
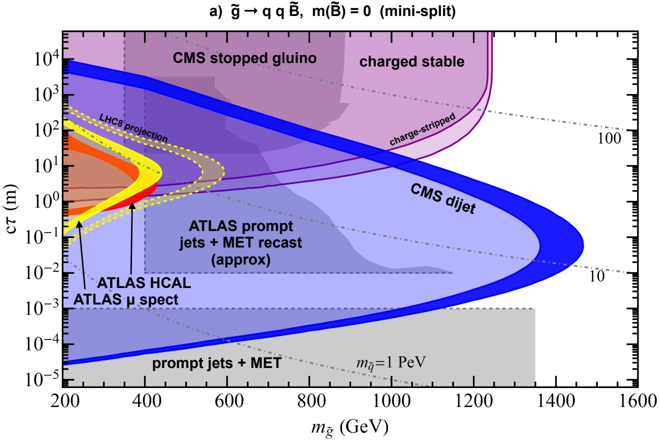


Liu, Tweedie – 2015

Many displaced decays are well-covered: Most GMSB

Liu, Tweedie – 2015

Long-lived / Displaced in SUSY



Liu, Tweedie – 2015

Many displaced decays are well-covered: Mini-Split

Liu, Tweedie – 2015

Coverage exceeds prompt signatures!

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Searches

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j							
b	X						
γ	X	X					
e	X	X	X				
μ	X	X	X	X			
τ	X	X	X	X	X		

Search	arXiv	Symbol	Comments

- Focused on pair produced, heavy decays inside the detector
- Only a selection of searches used, but fairly representative
- Cavalier about lifetime ranges and triggers; ignoring tops
- **Bold** is where searches are really optimized

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Searches

o_2 o_1	j	b	γ	e	μ	τ	$\not{E}_T$
j	**jj**	**jj**	jj	jj	jj	jj	jj
b	X	**jj**	jj	jj	jj	jj	jj
γ	X	X					
e	X	X	X				
μ	X	X	X	X			
τ	X	X	X	X	X		

Search	arXiv	Symbol	Comments
CMS Displaced Dijets	1411.6530	jj	$m_X > 50$ GeV

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Searches

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**jj**/**dv**	**jj**/**dv**	jj/dv	**jj**/**dv**	**jj**/**dv**	jj/dv	**jj**/**dv**
b	X	**jj**/**dv**	jj/dv	**jj**/**dv**	**jj**/**dv**	jj/dv	**jj**/**dv**
γ	X	X					
e	X	X	X	**dv**	**dv**	dv	
μ	X	X	X	X	**dv**	dv	
τ	X	X	X	X	X	dv	

Search	arXiv	Symbol	Comments
CMS Displaced Dijets	1411.6530	jj	$m_X > 50$ GeV
ATLAS Displaced Vertex	1504.05162	dv	$m_X > 10$ GeV

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Searches

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**jj**/**dv**	**jj**/**dv**	jj/dv	jj/**dv**	jj/**dv**	jj/dv	jj/**dv**
b	X	**jj**/**dv**	jj/dv	jj/**dv**	jj/**dv**	jj/dv	jj/**dv**
γ	X	X					
e	X	X	X	**dv**/**ll**	**dv**	dv/ll	
μ	X	X	X	X	**dv**/**ll**	dv/ll	
τ	X	X	X	X	X	dv/ll	

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Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Searches

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**jj**/**dv**	**jj**/**dv**	jj/dv/dA	jj/**dv**	jj/**dv**	jj/dv	jj/**dv**
b	X	**jj**/**dv**	jj/dv/dA	jj/**dv**	jj/**dv**	jj/dv	jj/**dv**
γ	X	X	dA	dA	dA	dA	**dA**
e	X	X	X	**dv**/**ll**	**dv**	dv/ll	
μ	X	X	X	X	**dv**/**ll**	dv/ll	
τ	X	X	X	X	X	dv/ll	

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ATLAS Delayed Photon	1409.5542	dA	$m_X \gtrsim 100$ GeV

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**jj/dv**	**jj/dv**	jj/dv/dA	jj/**dv**	jj/**dv**	jj/dv/em	jj/**dv**
b	X	**jj/dv**	jj/dv/dA	jj/**dv**	jj/**dv**	jj/dv/em	jj/**dv**
γ	X	X	dA	dA	dA	dA/em	**dA**
e	X	X	X	**dv**/**ll**	**dv**	dv/ll	
μ	X	X	X	X	**dv**/**ll**	dv/ll	
τ	X	X	X	X	X	dv/ll/em	em

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CMS Displaced $e\mu$	1409.4789	em	Best at LFU

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Searches

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**jj**/**dv**	**jj**/**dv**	jj/dv/dA	jj/**dv**	jj/**dv**	jj/dv/em	jj/**dv**
b	X	**jj**/**dv**	jj/dv/dA	jj/**dv**	jj/**dv**	jj/dv/em	jj/**dv**
γ	X	X	dA	dA	dA	dA/em	**dA**
e	X	X	X	**dv**/**ll**	**dv**	dv/ll	
μ	X	X	X	X	**dv**/**ll**	dv/ll	
τ	X	X	X	X	X	dv/ll/em	em

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Models

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j							
b	X						
γ	X	X					
e	X	X	X				
μ	X	X	X	X			
τ	X	X	X	X	X		

Models	Symbol

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Models

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not\!\!E_T$
j	**M**						**M**
b	X	M					M
γ	X	X					
e	X	X	X				
μ	X	X	X	X			
τ	X	X	X	X	X		

Models	Symbol
Mini-Split	M

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Models

$o_2 \, o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**M**G						**M**G
b	X	MG					MG
γ	X	X					**G**
e	X	X	X	G			G
μ	X	X	X	X	G		G
τ	X	X	X	X	X	G	**G**

Models	Symbol
Mini-Split	M
GMSB	G

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Models

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**M**GR	**R**		R	R	R	**M**GR
b	X	MGR		R	R	**R**	MGR
γ	X	X					**G**
e	X	X	X	GR	R	R	GR
μ	X	X	X	X	GR	R	GR
τ	X	X	X	X	X	GR	**G**R

Models	Symbol
Mini-Split	M
GMSB	G
RPV/dRPV	R

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	MGRS	R		R	R	R	MGR
b	X	MGRS		R	R	R	MGR
γ	X	X	S				G
e	X	X	X	GR	R	R	GR
μ	X	X	X	X	GR	R	GR
τ	X	X	X	X	X	GR	GR

Models	Symbol
Mini-Split	M
GMSB	G
RPV/dRPV	R
Stealth	S

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Models

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not\!\!E_T$
j	MGRS	R		R	R	R	MGR
b	X	MGRSH		R	R	R	MGR
γ	X	X	S				G
e	X	X	X	GR	R	R	GR
μ	X	X	X	X	GRH	R	GR
τ	X	X	X	X	X	GRH	GR

Models	Symbol
Mini-Split	M
GMSB	G
RPV/dRPV	R
Stealth	S
Higgs Mixed	H

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Models

$o_2 \, o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**MGRS**γ	**R**		R	R	R	**M**GR
b	X	MGR**SH**γ		R	R	**R**	MGR
γ	X	X	S				**G**
e	X	X	X	GRγ	R	R	GR
μ	X	X	X	X	GRHγ	R	GR
τ	X	X	X	X	X	GRHγ	**G**R

Models	Symbol
Mini-Split	M
GMSB	G
RPV/dRPV	R
Stealth	S
Higgs Mixed	H
Dark Photon	γ

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	MGRSγ	R		R	R	R	MGRD
b	X	MGRSHγ		R	R	R	MGRD
γ	X	X	S				G
e	X	X	X	GRγ	R	R	GRD
μ	X	X	X	X	GRHγ	R	GRD
τ	X	X	X	X	X	GRHγ	GRD

Models	Symbol
Mini-Split	M
GMSB	G
RPV/dRPV	R
Stealth	S
Higgs Mixed	H
Dark Photon	γ
MD Freezein Dark Matter	D

Displaced Objects: $pp \to XX$, $X \to o_1 o_2 (o_3)$

Models

$o_2 \backslash o_1$	j	b	γ	e	μ	τ	$\not{E}_T$
j	**M**GRSγ	**R**		R	R	R	**M**GRD
b	X	MGR**SH**γ		R	R	**R**	MGRD
γ	X	X	S				**G**
e	X	X	X	GRγ	R	R	GRD
μ	X	X	X	X	GRHγ	R	GRD
τ	X	X	X	X	X	GRHγ	**G**RD

Models	Symbol
Mini-Split	M
GMSB	G
RPV/dRPV	R
Stealth	S
Higgs Mixed	H
Dark Photon	γ
MD Freezein Dark Matter	D

Well-motivated Theoretically

Weak Coverage Experimentally

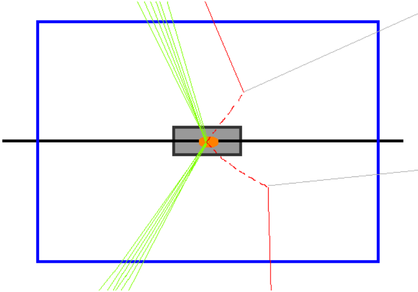
Displaced Leptons in Prompt Searches

Prompt lepton-based searches:

- Quality criteria drop displaced electrons
- Displaced muons veto events (cosmics)
- Vetoes range from 50 μm–1 mm

Prompt jets+$\not{E}_T$ searches:

- Veto events with leptons
- Definition not always transparent



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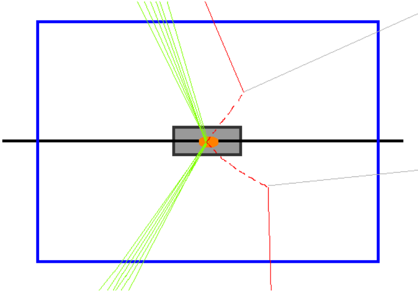


Prompt jets+$\not{E}_T$ searches:

- Veto events with leptons
- Definition not always transparent

Very dangerous region!

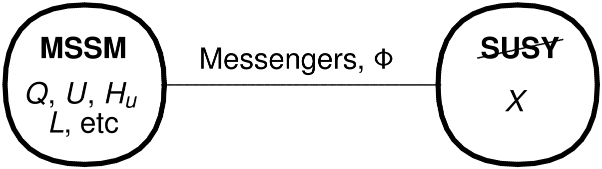
$$pp \to \tilde{\ell}^+\tilde{\ell}^- + X \to \{\text{displaced muons}\} + X$$

lives in a prompt search blind spot!

Displaced electrons and taus $\Rightarrow$ reduced efficiency

Gauge Mediation and $\tilde{\tau}_R$ NLSPs

Lightning Review of Minimal GMSB

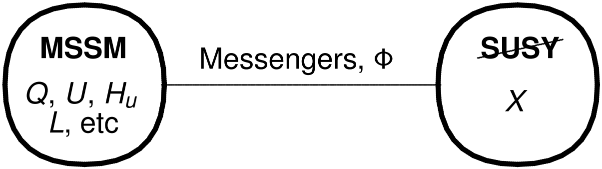


$$W \sim X\Phi\tilde{\Phi} + \{\text{MSSM yukawas}\}$$

$$\langle X \rangle = M + \theta^2 F, \qquad \Lambda \equiv F/M, \qquad \tilde{\Lambda} \equiv \frac{\Lambda}{16\pi^2}$$

Gauge Mediation and $\tilde{\tau}_R$ NLSPs

Lightning Review of Minimal GMSB



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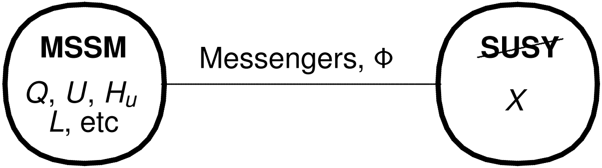
$$\langle X \rangle = M + \theta^2 F, \qquad \Lambda \equiv F/M, \qquad \tilde{\Lambda} \equiv \frac{\Lambda}{16\pi^2}$$

$$M_r \sim N_{eff} g_r^2 \tilde{\Lambda} \qquad A\text{-terms} = 0$$

$$m_{soft}^2 \sim 2N_{eff} C_r g_r^4 \tilde{\Lambda}^2 \qquad (C_r \text{ quadratic Casimirs } \mathcal{O}(1))$$

Gauge Mediation and $\tilde{\tau}_R$ NLSPs

Lightning Review of Minimal GMSB



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$$M_r \sim N_{eff}\, g_r^2 \tilde{\Lambda} \qquad\qquad A\text{-terms} = 0$$

$$m^2_{soft} \sim 2N_{eff}\, C_r\, g_r^4 \tilde{\Lambda}^2 \qquad (C_r \text{ quadratic Casimirs } \mathcal{O}(1))$$

Potential NLSP Masses: $\begin{cases} m_{\tilde{B}} = N_{eff}\, g_1^2 \tilde{\Lambda} \\ m_{\tilde{\ell}_R} = \sqrt{\frac{6N_{eff}}{5}}\, g_1^2 \tilde{\Lambda} \end{cases}$ $N_{eff} \geq 2 \Rightarrow \tilde{\tau}_R$ NLSP (or large running)

GMSB is a very well-motivated source of displaced particles

$$c\tau \approx 100\,\mu\text{m}\left(\frac{100\text{ GeV}}{m_{\tilde{\tau}}}\right)^5\left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^4$$

What is $\sqrt{F}$?

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$$c\tau \approx 100\,\mu\text{m}\left(\frac{100\text{ GeV}}{m_{\tilde{\tau}}}\right)^5\left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^4$$

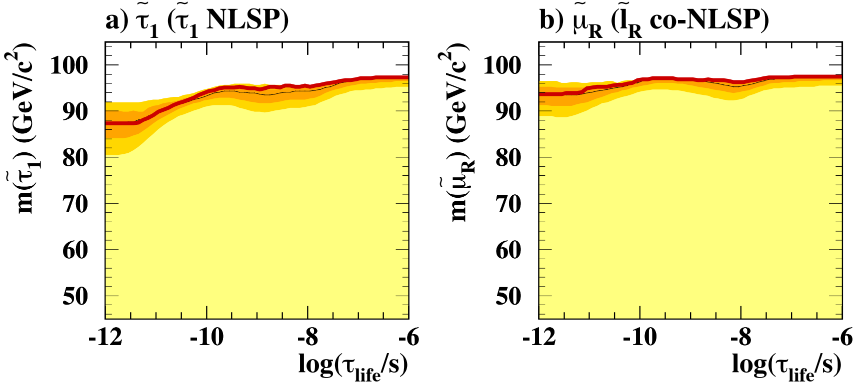
What is $\sqrt{F}$?

$F < M^2$; otherwise arbitrary

$$c\tau \sim 10\,\mu\text{m}\left(\frac{100\text{ GeV}}{m_{\tilde{\tau}}}\right)\left(\frac{M}{\sqrt{F}}\right)^4\frac{1}{N_{eff}^2} \qquad \text{(minimal GM only)}$$

LHC relevant range: $100\,\mu\text{m} \lesssim c\tau \lesssim 1\text{ m}$

Measuring $m_{\tilde{\tau}_R}$ & $c\tau_{\tilde{\tau}_R}$ probes SUSY breaking!



$m_{\tilde{\tau}} > 87$ GeV

$m_{\tilde{\mu}} > 94$ GeV

OPAL placed the best limits on sleptons of all lifetimes

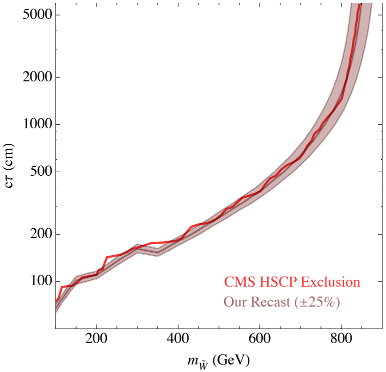
Relevant LHC search: HSCP

At long lifetime: $c\tau_{\tilde{\tau}} \gtrsim 1\text{m} \Rightarrow$ heavy, detector-stable, charged particle

CMS HSCP search 1305.0491 (expect similar from ATLAS 1411.6795)

Cuts

Central:	$\lvert\eta\rvert < 2.4$
Hard:	$p_T > 70$ GeV
Isolated:	$\sum p_{T,\Delta R<0.3}^{trks} < 50$ GeV $I_{\Delta R<0.3}^{calo,track} < 0.3$
Slow:	$1/\beta > 1.225$
Large dE/dx:	see 1305.0491



Efficiency maps provided: 1502.02522

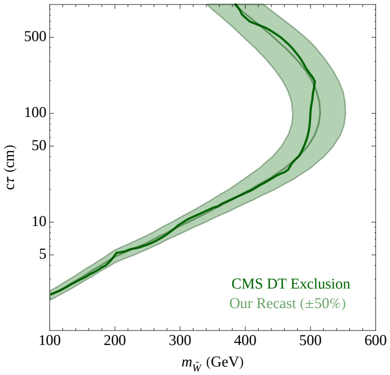
Relevant LHC search: Disappearing Tracks

CMS 1411.6006

At slightly shorter lifetimes: 30 cm $\lesssim c\tau_{\tilde{\tau}} \lesssim$ 3 m $\Rightarrow$ disappearing tracks

Cuts

A hard jet:	$p_T > 110$ GeV, $\lvert\eta\rvert < 2.4$
Missing energy:	$\not{E}_T > 100$ GeV
Hard track stub:	$p_T > 50$ GeV Few outer tracker hits
Particular eta:	$1.85 < \lvert\eta\rvert < 2.1$ $0.35 < \lvert\eta\rvert < 1.42$ or $\lvert\eta\rvert < 0.15$
Isolated:	$E^{calo}_{\Delta R<0.5} < 10$ GeV $I^{trks,track}_{\Delta R<0.3} < 0.05$



Simple efficiency map provided 1411.6006

Relevant LHC search: Disappearing Tracks

ATLAS 1310.3675

At slightly shorter lifetimes: 20 cm $\lesssim c\tau_{\tilde{\tau}} \lesssim$ 2 m $\Rightarrow$ disappearing tracks

Cuts

A hard jet: $p_T > 90$ GeV, $|\eta| < 2.5$

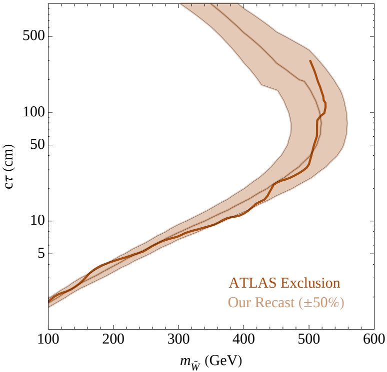
Missing energy: $\not{E}_T > 90$ GeV

Hard track stub: $p_T > 75$ GeV
highest p_T track in event
$<$ 5 hits in TRT

Eta: $0.1 < |\eta| < 1.9$

Isolated: $I^{trks,track}_{\Delta R<0.4} < 0.04$
$\Delta R_{jt} > 0.4 \forall p_{T,j} > 45$ GeV

Veto leptons: es, μs, &
μ calo tracks > 10 GeV



No efficiency map provided

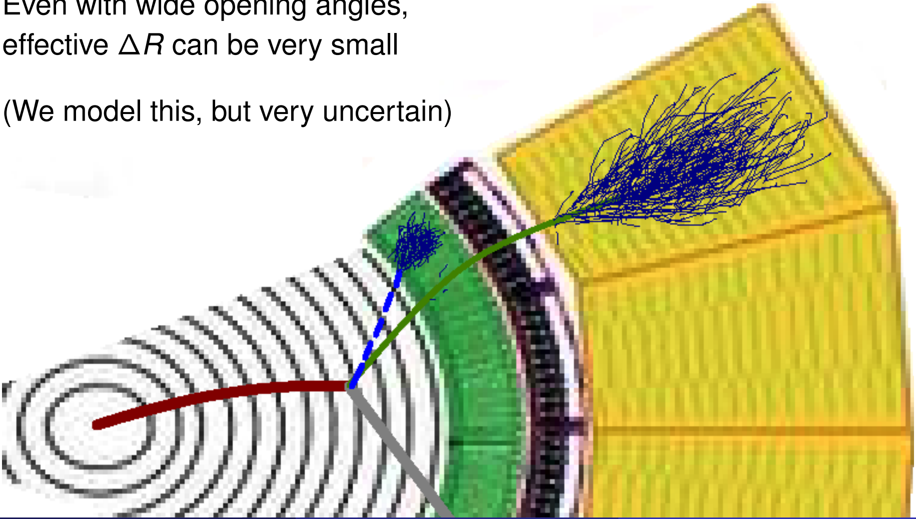
Relevant LHC search: Disappearing Tracks

Recast Caveats

Isolation requirements are hard on long-lived staus

Even with wide opening angles,
effective ΔR can be very small

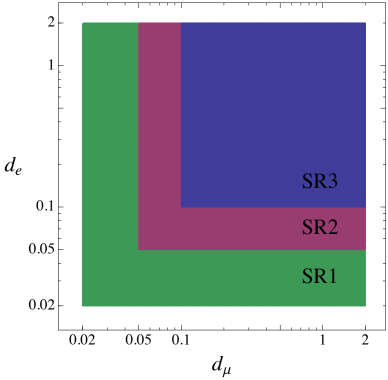
(We model this, but very uncertain)



Relevant LHC search: CMS Displaced $e\mu$ (1409.4789)

Cuts

Cut Summary of CMS $e\mu$
Preselection
1 OS $e^{\pm}\mu^{\mp}$ pair
→ $d_\ell > 100\ \mu$m
$p_{T,\ell} > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$
Reject $1.44 < \lvert\eta_e\rvert < 1.56$
$I^{calo,e}_{\Delta R<0.3} < 0.10$, $I^{calo,\mu}_{\Delta R<0.4} < 0.12$
$\Delta R_{\ell j} > 0.5\ \forall$ jets with $p_T > 10$ GeV
$\Delta R_{e\mu} > 0.5$
$v_{T,\tilde{\ell}} < 4$ cm, $v_{Z,\tilde{\ell}} < 30$ cm
Veto additional leptons



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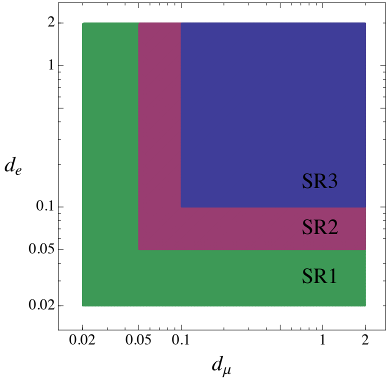

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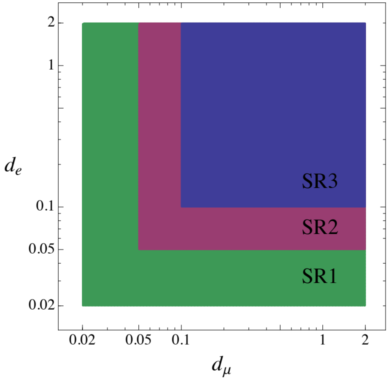

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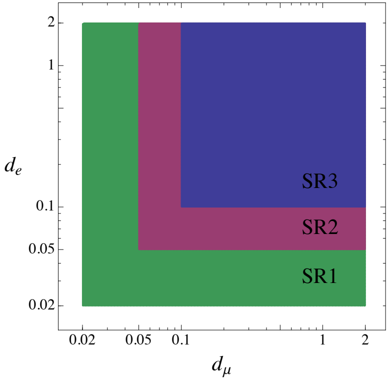

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Recast

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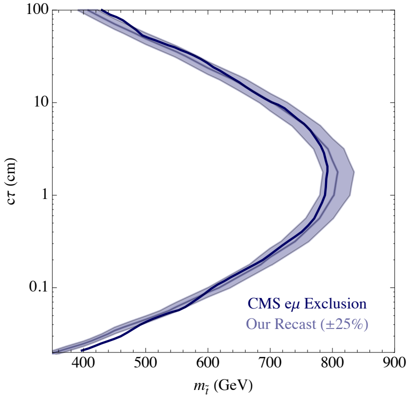
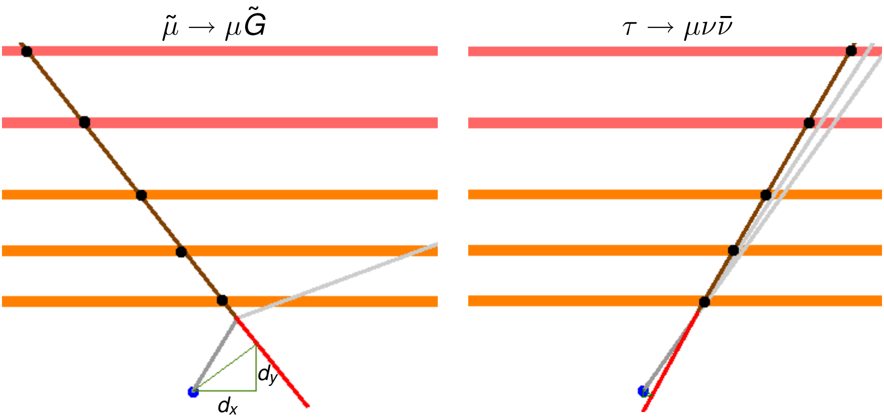


Extensive recasting details provided!

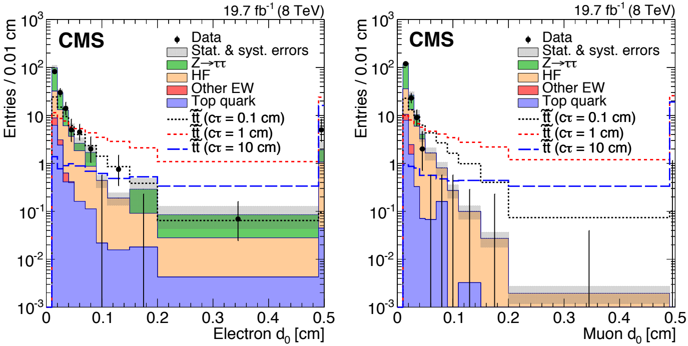


Impact Parameter is *not* the location of parent

b and τ decay products are more collimated

Relevant LHC search: CMS Displaced $e\mu$ (1409.4789)

Backgrounds & Data



Event source	SR1	SR2	SR3
Other EW	$0.65 \pm 0.13 \pm 0.09$	$(0.89 \pm 0.53 \pm 0.12) \times 10^{-2}$	$<(89 \pm 53 \pm 12) \times 10^{-4}$
Top quark	$0.77 \pm 0.04 \pm 0.08$	$(1.25 \pm 0.26 \pm 0.12) \times 10^{-2}$	$(2.4 \pm 1.3 \pm 0.2) \times 10^{-4}$
$Z \to \tau\tau$	$3.93 \pm 0.42 \pm 0.39$	$(0.73 \pm 0.73 \pm 0.07) \times 10^{-2}$	$<(73 \pm 73 \pm 7) \times 10^{-4}$
HF	$12.7 \pm 0.2 \pm 3.8$	$(98 \pm 6 \pm 30) \times 10^{-2}$	$(340 \pm 110 \pm 100) \times 10^{-4}$
Total expected background	$18.0 \pm 0.5 \pm 3.8$	$1.01 \pm 0.06 \pm 0.30$	$0.051 \pm 0.015 \pm 0.010$
Observed	19	0	0

Recast Limits on $\tilde{\tau}_R$

Only HSCP limits on direct $\tilde{\tau}_R$ production!

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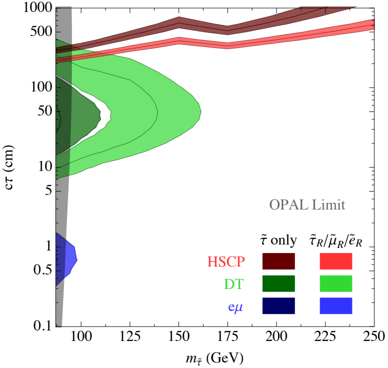
But . . . a $\tilde{\tau}_R$ is not expected in isolation

<u>Near degenerate slepton limits</u>

$$m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = m_{\tilde{\tau}_R} + 10\text{ GeV}$$

$$\tilde{\ell}_R \to \tilde{\tau}_R + \{\text{soft}\}$$



(Better limit from both disappearing track searches shown)

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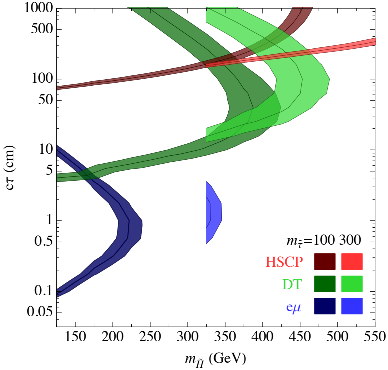
Higgsino production limits

$$m_{\tilde{\chi}_1^0} = m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^+}$$

$$\tilde{\chi}_{1,2}^0 \to \tilde{\tau}_R^{\pm} \tau^{\mp}, \;\; \tilde{\chi}_1^{\pm} \to \tilde{\tau}_R^{\pm} \nu$$



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Limits are very sensitive to $m_{\tilde{\tau}_R}$

Recast Limits on $\tilde{\tau}_R$

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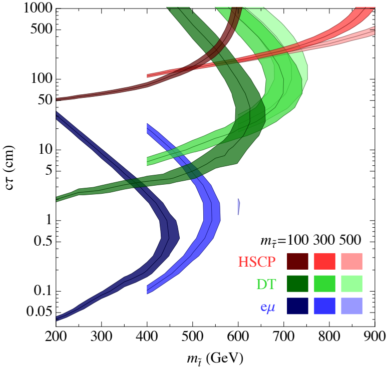
But . . . a $\tilde{\tau}_R$ is not expected in isolation

Stop production limits

$$m_{\tilde{H}} = m_{\tilde{t}} - 50 \text{ GeV}$$

$$\tilde{t} \to b\tilde{H}^+ \to b\nu\tilde{\tau}_R^+$$



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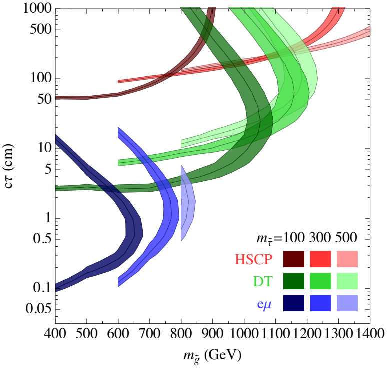
But . . . a $\tilde{\tau}_R$ is not expected in isolation

Gluino production limits

$$m_{\tilde{t}} = m_{\tilde{g}} - 200 \text{ GeV}$$
$$m_{\tilde{H}} = m_{\tilde{t}} - 50 \text{ GeV}$$

$$\tilde{g} \to \tilde{t}\bar{t} \to \bar{t}b\tilde{H}^+ \to \bar{t}b\nu\tilde{\tau}_R^+$$
$$\tilde{g} \to \tilde{t}^* t \to t\bar{b}\tilde{H}^- \to t\bar{b}\bar{\nu}\tilde{\tau}_R^-$$



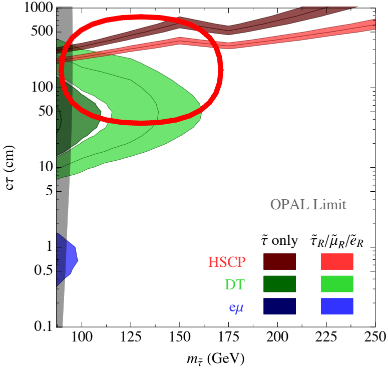
(Better limit from both disappearing track searches shown)

Limits are very sensitive to $m_{\tilde{\tau}_R}$

CMS heavy, stable, charged particle search does very well!

Using “tracker-only” signal region could improve sensitivity

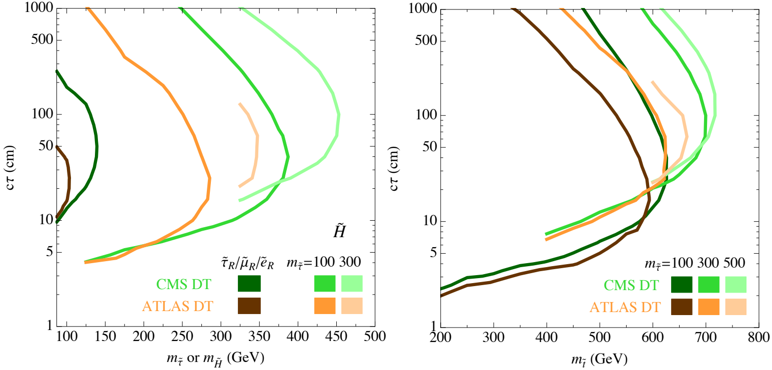
Currently no efficiency maps provided



Potential Improvements?

Disappearing Tracks

ATLAS hurt by lepton vetoes and hardest track requirement



Both disappearing tracks searches are hurt by isolation requirements

Could similar pre-selection capitalize on kinked track?

There are several lessons from GMSB $\tilde{\tau}_R$s to improve sensitivity

$$BR(\tilde{\tau}^+\tilde{\tau}^- \to e^\pm\mu^\mp + X) = 6\%$$
$$BR(\tilde{\tau}^+\tilde{\tau}^- \to e^+e^- + X) = 3\%$$
$$BR(\tilde{\tau}^+\tilde{\tau}^- \to \mu^+\mu^- + X) = 3\%$$

1) Add same-flavor lepton channels

Potential Improvements?

CMS Displaced Lepton Search

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1) Add same-flavor lepton channels

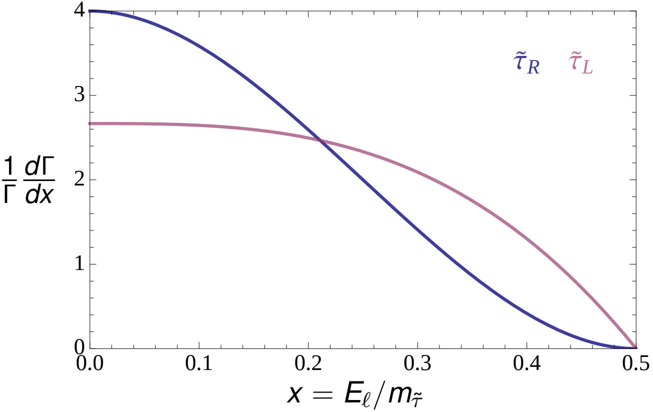
$$BR(\tilde{\tau}^+\tilde{\tau}^- \to e^\pm\tau_h^\mp + X) = 23\%$$
$$BR\tilde{\tau}^+\tilde{\tau}^- \to \mu^\pm\tau_h^\mp + X) = 23\%$$
$$BR(\tilde{\tau}^+\tilde{\tau}^- \to \tau_h^\pm\tau_h^\mp + X) = 42\%$$

2) Include hadronic τ_hs

Experimental feasibility of displaced τ_hs?

Potential Improvements?

CMS Displaced Lepton Search



Right-handed polarized τs from $\tilde{\tau}_R$ decays give softer leptons

3) Lower p_T thresholds can capture a lot more signal

Additional triggers – $\not{E}_T + \ell\ell$, $\not{E}_T$, $\ell\ell\ell$, etc

Potential Improvements?

CMS Displaced Lepton Search

Search vetoes additional leptons.
Why?

Displaced multilepton background should be very small

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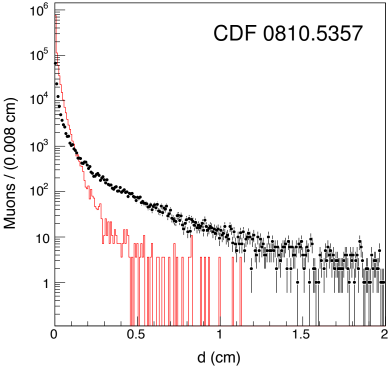
(CDF ghost muons???)



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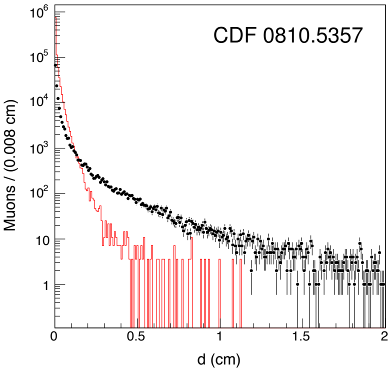

Gluino & Higgsino model have additional leptons often $\sim$(45%, 30%)

If pair-produced object is not charged under lepton number, additional leptons are generic

4) Don't veto additional leptons

Potential Improvements?
CMS Displaced Lepton Search

Gluino & Higgsino models have Majorana particles in chain

$\Rightarrow$ same-sign displaced leptons

5) Include same-sign displaced lepton signal regions

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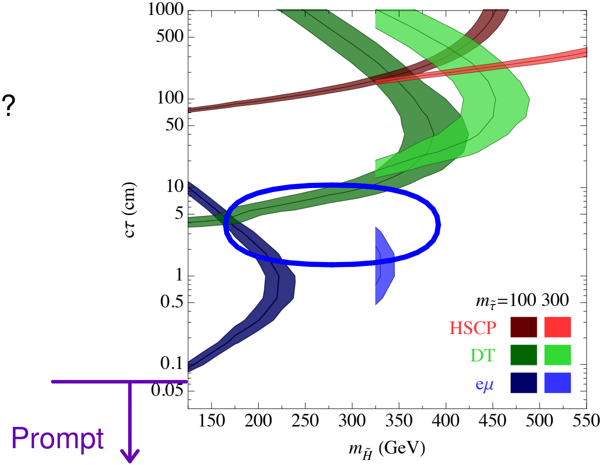
5) Include same-sign displaced lepton signal regions

5') Same-sign possibility fairly generic, be wary of CR contamination

SSℓ can appear in the $\tilde{t} \to \ell^+ b$ benchmark of CMS 1409.4789

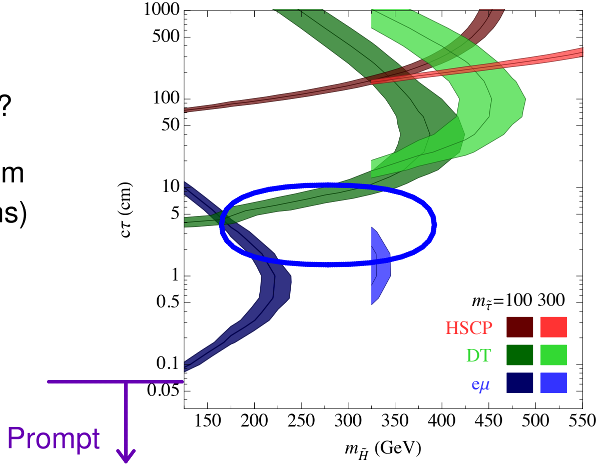
Mesino oscillation allows up to 3/8 of events as SSℓ Sarid, Thomas – 9909349

Extend reach in $c\tau$?



Extend reach in $c\tau$?

6) Allow d_0 above 2 cm
(Even just for muons)

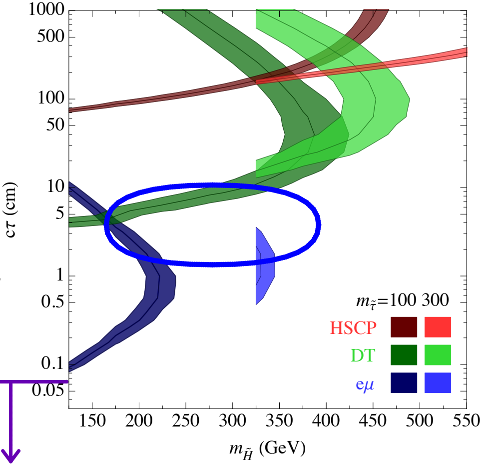


Extend reach in $c\tau$?

6) Allow d_0 above 2 cm
(Even just for muons)

7) Relax isolation in high d_0 bins
(Backgrounds are small there)

Prompt



Same-flavor Displaced Lepton Models

Slepton Co-NLSP in GGM

If $m_{\tilde{\ell}_R} - m_{\tilde{\tau}_R} \ll 10$ GeV **or** $m_{\tilde{B}} \gg m_{\tilde{\tau}_R}$,

then $\Gamma(\tilde{\ell}_R \to \ell\tau\tilde{\tau}_R) \ll \Gamma(\tilde{\ell}_R \to \ell\tilde{G}) \;\Rightarrow$ Slepton Co-NLSP

Events have displaced e^+e^-, $\mu^+\mu^-$, or $\tau^+\tau^-$

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Small splitting can happen for low $\tan\beta$

In GGM, M_1 and $m^2_{\tilde{E}_R}$ are independent

$\mu^+\mu^-$ and e^+e^- searches would be more sensitive to this model

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Can one get 100% e^+e^- or $\mu^+\mu^-$ without $\tau^+\tau^-$?

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$\tilde{\tau}_1$ with *LLE* RPV

RPV can do almost anything

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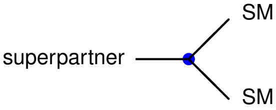
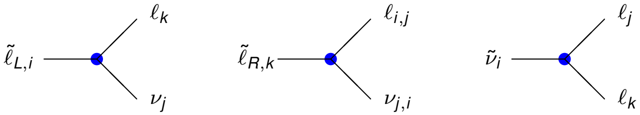


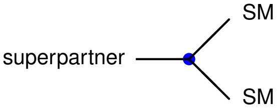
$$W = \tfrac{1}{2}\lambda_{ijk}\, L_i L_j E^c_k + \lambda'_{ijk}\, L_i Q_j D^c_k + \tfrac{1}{2}\lambda''_{ijk}\, U^c_i D^c_j D^c_k + \mu_i L_i H_u$$

i, j, k = generation indices

LLE



RPV can do almost anything



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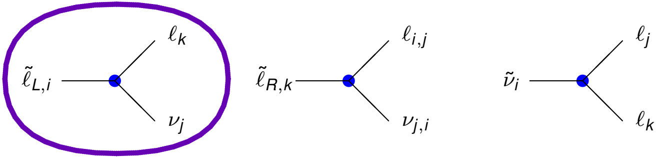
LLE



$$c\tau \approx 1\text{ cm}\left(\frac{10^{-7}}{\lambda_{232}}\right)^2\left(\frac{100\text{ GeV}}{m_{\tilde{\tau}}}\right)\sec^2\theta_{\tilde{\tau}} \qquad (\theta_{\tilde{\tau}} = 0 \Rightarrow \tilde{\tau}_1 = \tilde{\tau}_L)$$

$$\lambda_{232}\cos\theta_{\tilde{\tau}} \gg \text{other RPV} \quad \Rightarrow \quad \text{BR}(\tilde{\tau}_1 \to \mu\nu) \approx 100\%$$

Same-flavor Displaced Lepton Models
EGMSB

Extended GMSB (EGMSB) models can generate large A_t

for maximal $\tilde{t}$ mixing and decreased tuning of the MSSM Higgs

Craig, Knapen, Shih, Zhao – 1206.4086; Evans, Shih – 1303.0228; others

EGMSB can *also* give a 1st- or 2nd-gen slepton NLSP Shadmi, Szabo – 1103.0292

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Add EGMSB MSSM-Messenger coupling: $W \supset \kappa_i E_i^c \Phi_U \Phi_{\bar{D}}$

$\vec{\kappa} = (0, \kappa_2, 0)$ gives $\Delta m_{\tilde{\mu}} \sim -25\kappa_2^2 m_{\tilde{\ell}}$

$\kappa_2 \sim 0.1 \Rightarrow \tilde{\mu}_R$ NLSP

$\frac{\kappa_1}{\kappa_2} \ll 0.1$ & $\frac{\kappa_3}{\kappa_2} \lesssim 0.3$ no CMS $e\mu$ sensitivity and safe from flavor

Minimal models of lepton-flavored DM

Model	Mediator	DM	Lagrangian
1	Scalar	Fermion	$y_{ij}^{LDM}\ell_i^c\zeta^-\chi_i + m_\zeta^2\zeta^+\zeta^- + m_{\chi,ij}\chi_i\bar{\chi}_j$
2	Fermion	Scalar	$y_{ij}^{LDM}\ell_i^c\psi S_j + m_\psi\psi\bar{\psi} + m_{S,ij}^2 S_i^\dagger S_j$

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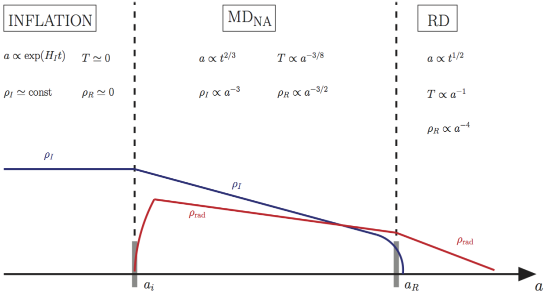
Inflaton decay

$\Downarrow$

early matter-dominated era

$T_{RH} < m_{\psi/\zeta} \Rightarrow$ less Ω_{DM}
due to entropy injection



Co, D'Eramo, Hall, Pappadopulo - 1506.07532

Same-flavor Displaced Lepton Models

Freezein of Dark Matter During a Matter-Dominated Era

Minimal models of lepton-flavored DM

Model	Mediator	DM	Lagrangian
1	Scalar	Fermion	$y^{LDM}_{ij}\ell^c_i\zeta^-\chi_i + m^2_\zeta\zeta^+\zeta^- + m_{\chi,ij}\chi_i\bar{\chi}_j$
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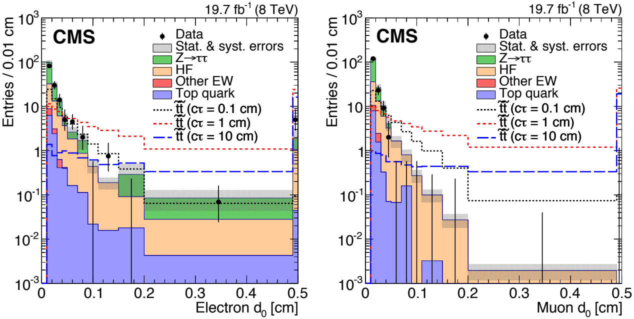
For Model 2:

$$\frac{\Omega_{DM}}{\Omega_{DM,obs}} \approx \left(\frac{20}{m_\psi/T_{RH}}\right)^7 \left(\frac{500\text{ GeV}}{m_\psi}\right)^2 \left(\frac{m_S}{1\text{ MeV}}\right) \left(\frac{1\text{ cm}}{c\tau_\psi}\right)$$

For $100\text{ GeV} < m_\psi \lesssim 1\text{ TeV}$ and $100\ \mu\text{m} \lesssim c\tau \lesssim 1\text{ m}$

$m_S \ll m_\psi$ and T_{RH} can be chosen to give $\Omega_{DM} = \Omega_{DM,obs}$!

How can we estimate 13 TeV backgrounds?



1. Use 8 TeV backgrounds to estimate 8 TeV SF backgrounds
2. Rescale backgrounds by $\frac{\sigma(13)}{\sigma(8)}$ (supported by HF MC)
3. Assume displaced $Z \to e^+e^-/\mu^+\mu^-$ is small or can be controlled
4. Artificially low trigger, but have a background we can estimate

How can we estimate 13 TeV backgrounds?

Sample	SR1	SR2	SR3
$e^\pm\mu^\mp$ 8 TeV (CMS actual)	18.0 ± 3.8	1.01 ± 0.31	0.051 ± 0.018
$e^\pm\mu^\mp$ 8 TeV (estimate)	19.8 ± 4.1	0.92 ± 0.28	0.055 ± 0.024
$e^\pm\mu^\mp$ 13 TeV (20 fb^{-1})	34.1 ± 6.5	1.49 ± 0.44	0.086 ± 0.038
e^+e^- 13 TeV (20 fb^{-1})	25.2 ± 3.6	1.43 ± 0.33	0.31 ± 0.06
$\mu^+\mu^-$ 13 TeV (20 fb^{-1})	13.0 ± 3.1	0.50 ± 0.15	0.012 ± 0.006

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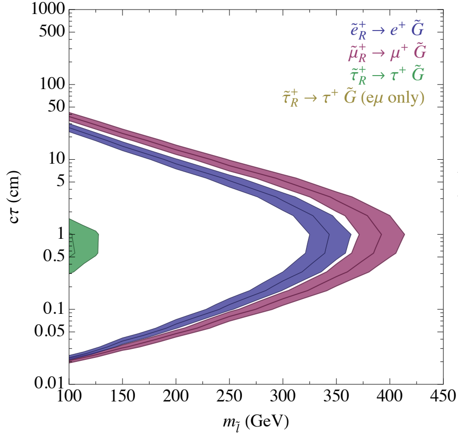
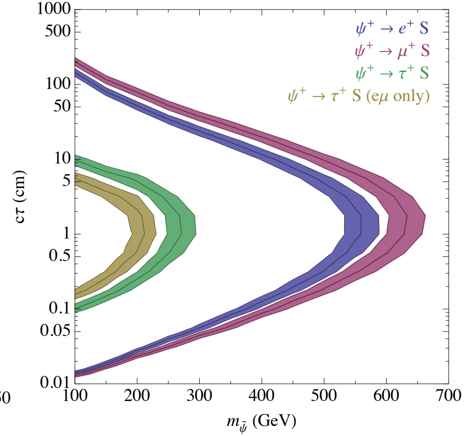
Same-Flavor Displaced Lepton Search

13 TeV Same-Flavor Search





Same-Flavor Displaced Lepton Search

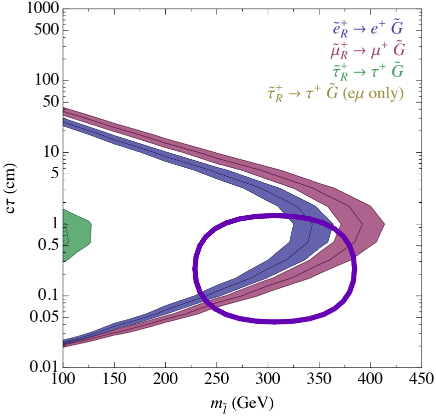
Improving a 13 TeV Same-Flavor Search

$\tilde{e}^+ \to e^+ \tilde{G} \Rightarrow$ hard leptons

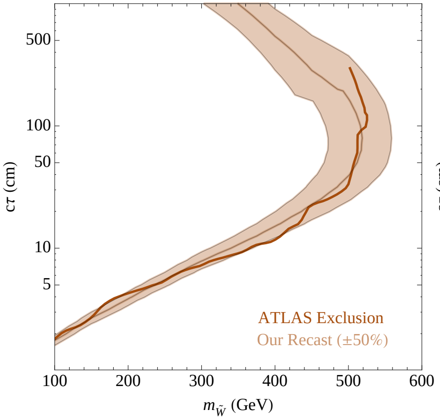
$\tilde{\mu}^+ \to \mu^+ \tilde{G} \Rightarrow$ hard leptons

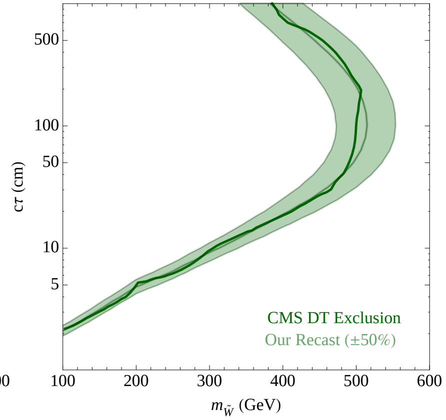
$\tilde{\tau}^+ \to \tau^+ \tilde{G} \Rightarrow$ soft leptons

8) SF search can be improved with higher $p_{T,\ell}$, lower background bins



Efficiency maps and recasting instructions are an *essential* facet to all searches for exotic objects

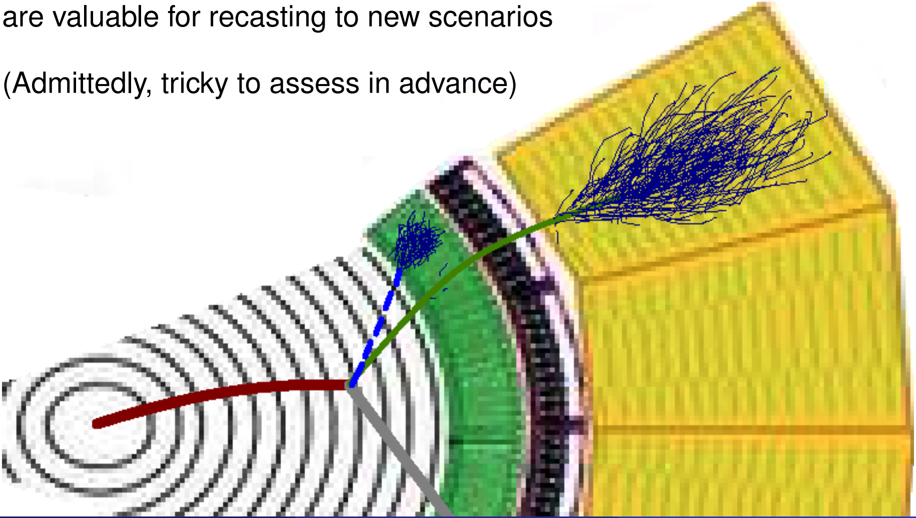




Clear information about applying the search beyond the benchmark

are valuable for recasting to new scenarios

(Admittedly, tricky to assess in advance)



Comments and Perspectives

Known unknowns. . .

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  Is there a gap at ATLAS? Does CMS fill it?

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- Hidden valleys (high mass and Higgs portal)

  What classes of models are constrained by existing searches?

  Can model-specific details be distilled to a simplified framework?

  Minimal set of searches to cover all observable possibilities?

Comments and Perspectives

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- Unknown unknowns — {insert your paper here}

Conclusions

- Many exotic objects are covered, but there are gaps
- Displaced $\tilde{\tau}$s from GMSB: well-motivated and weakly constrained
- Sensitivity to $\tilde{\tau}_R$ can be improved in the CMS $e^{\pm}\mu^{\mp}$ search
  - Add SFℓ bins
  - Add τ_h bins
  - Lowered p_T thresholds
  - Extend $d_0 > 2$ cm
  - Add SSℓ bins (CR contamination)
  - Allow extra ℓs
  - Relax isolation in high d_0 bins
  - Add high $p_{T,\ell}$ bins
- Disappearing track searches should consider this benchmark
  - Kinked tracks?
- Several models with displaced $ee/\mu\mu$ uncovered at LHC
- A lot of exciting work needs to be done on exotic objects!