Long-lived Particles in SUSY(-like) Models

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What is a SUSY-like LLPs?

- Typically heavy particles (above LEP)
- Usually pair-produced
- No strong couplings
- Approximate symmetry ($\mathbf{Z}_2$) decouples production and decay

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LLP signature can be...

Direct: Observe the object itself ($c\tau \gtrsim 10$ cm)

Examples: disappearing tracks, HSCPs, R-hadrons

Indirect: Observe the decay products ($c\tau \lesssim 10$ m)

Examples: displaced dijets, displaced photons, displaced X(s)

Long-lived particles in SUSY-like theories

Candidate Particles

1) The NLSP in gauge mediated SUSY breaking (GMSB)

Particles couple to gravitino via higher-dimension operators sensitive to SUSY breaking scale $\mathcal{O} \sim F^{-1}\tilde{X}_\alpha \gamma^\mu \gamma^\nu \partial_\nu X \partial_\mu \tilde{G}_\alpha$

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

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2) The gauginos of mini-split SUSY

Mini-split: scalars heavy, gauginos light $\Rightarrow$ unification, but tuned

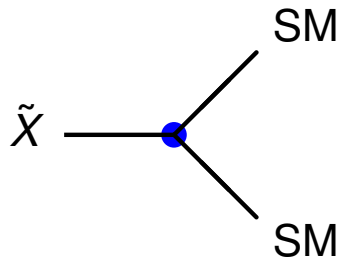
Integrating out heavy scalars gives higher-dimension operators

$$\mathcal{O} \sim \frac{c}{m_{\tilde{q}}^2}\tilde{g}\tilde{\chi}\bar{q}q \qquad c\tau\left(\tilde{g} \to \tilde{\chi}jj\right) \approx 100\,\mu\text{m}\left(\frac{m_{\tilde{q}}}{\text{PeV}}\right)^4\left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5$$

3) The LSP in R-parity violating (RPV) models

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

RPV could introduce very small couplings



$$c\tau\left(\tilde{X} \to SM_1 SM_2\right) \approx 1\ \text{cm}\left(\frac{10^{-7}}{\lambda}\right)^2\left(\frac{100\ \text{GeV}}{m_{\tilde{X}}}\right)$$

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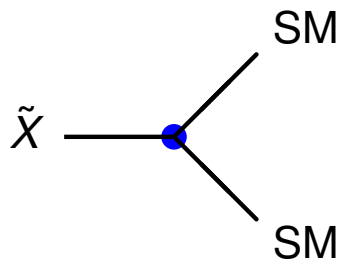

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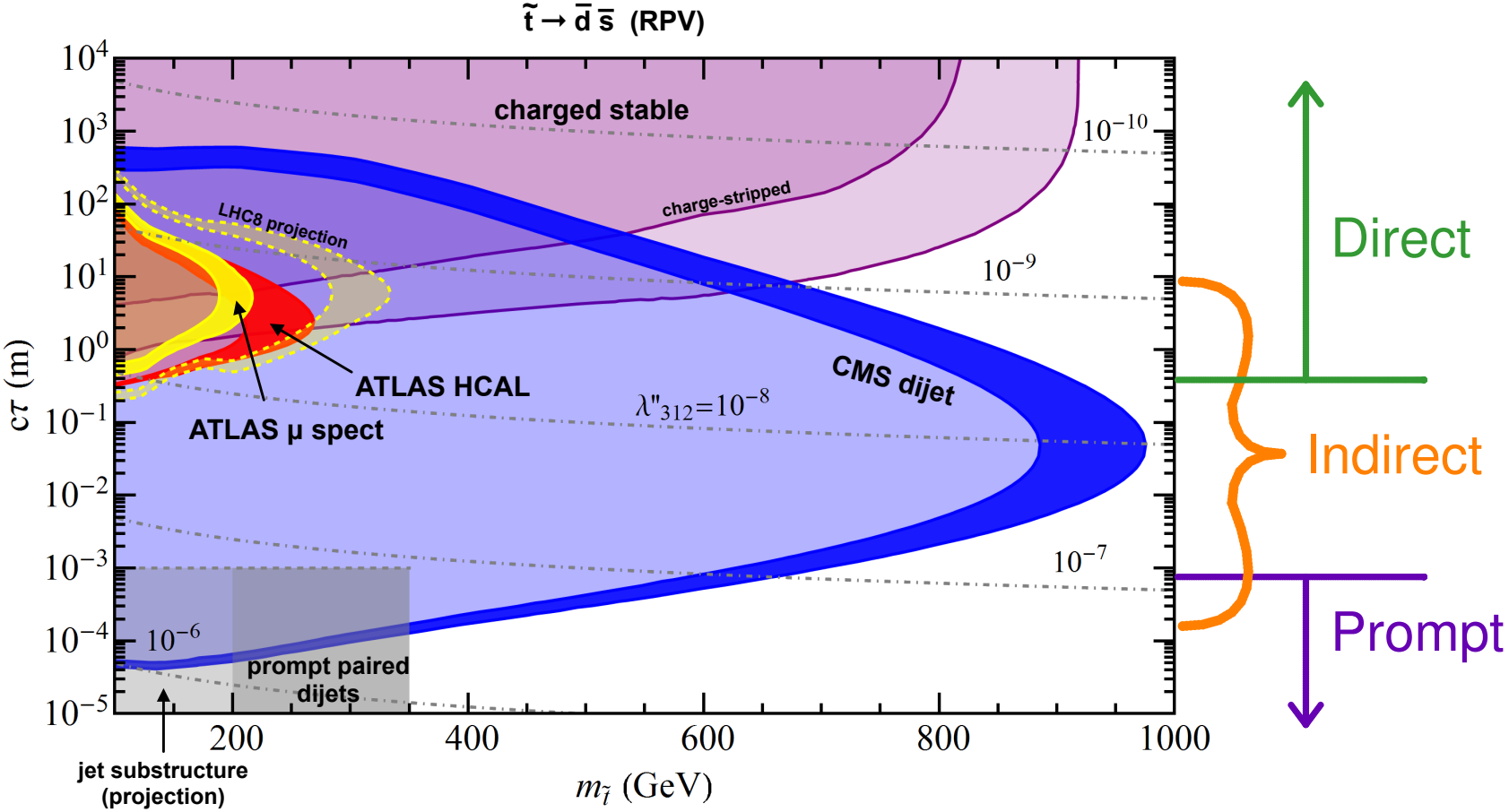
4) Charginos in anomaly mediated SUSY breaking (AMSB)

LSP Wino can have $\Delta m \sim m_{\tilde{\chi}^+} - m_{\tilde{\chi}^0} \sim \mathcal{O}(m_\pi)$

Suppressed phase-space leads to long lifetimes

Just EW 1-loop splitting can give the disappearing track signature

Long-lived / Displaced in SUSY

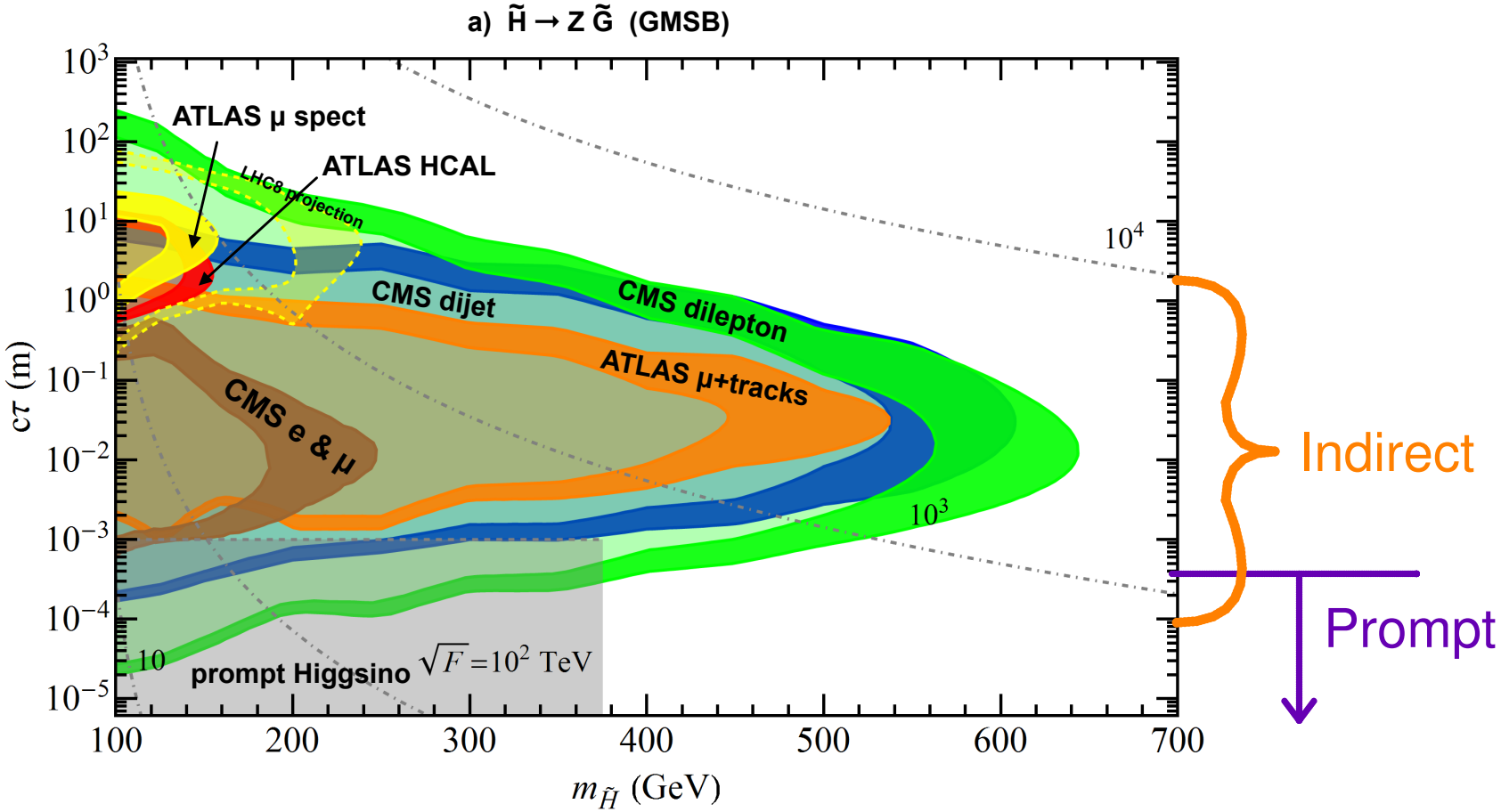


Liu, Tweedie – 2015

Many displaced decays are well-covered: Most RPV

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

Long-lived / Displaced in SUSY



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Many displaced decays are well-covered: Most GMSB

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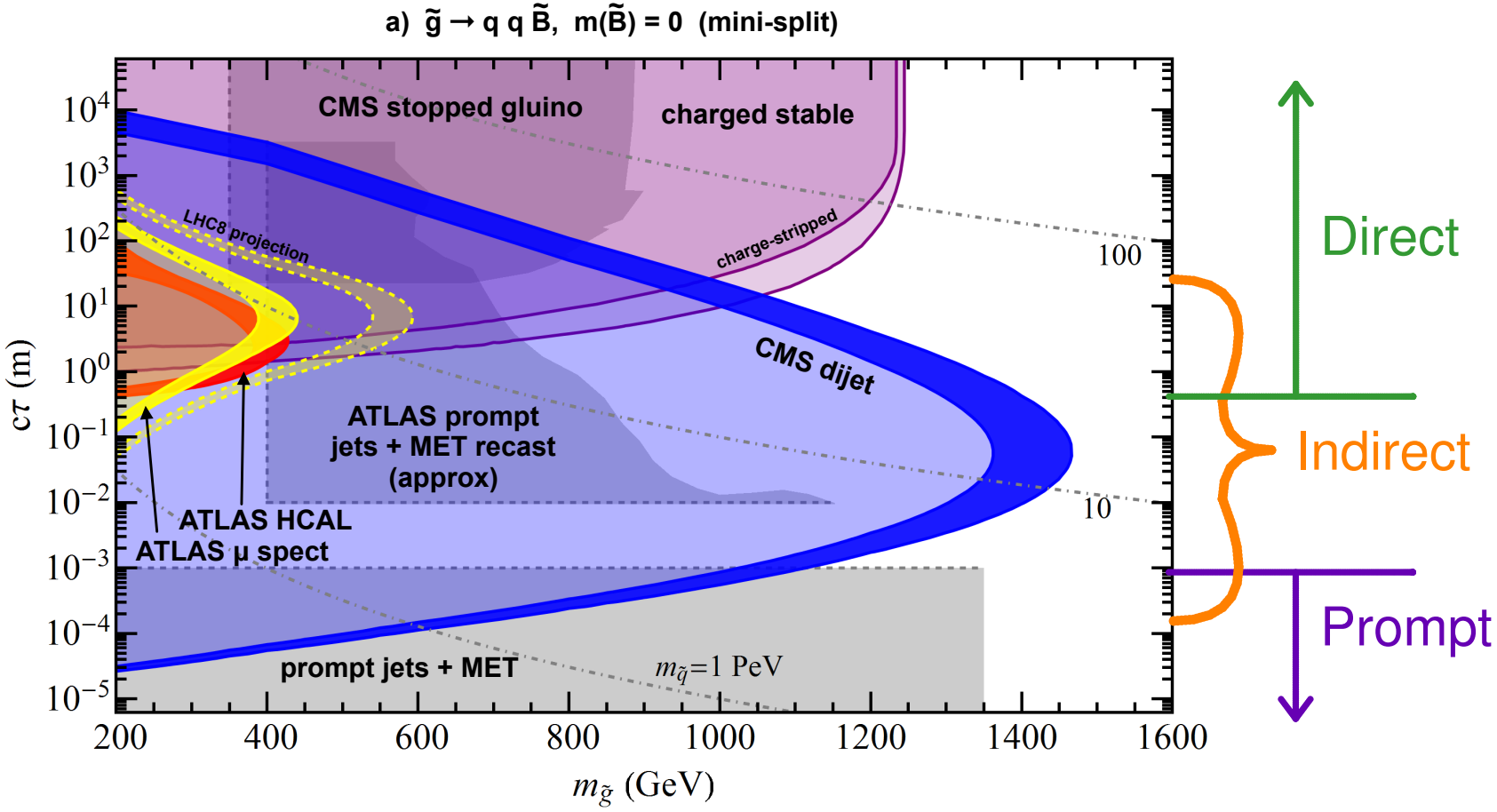
Long-lived / Displaced in SUSY



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

$o_2 o_1$	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	

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**/**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	

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CMS Displaced Dijets	1411.6530	jj	
ATLAS Displaced Vertex	1504.05162	dv	$m_X > 10$ GeV

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

Searches

$o_2 o_1$	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

$o_2 o_1$	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

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**/**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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ATLAS Delayed Photon	1409.5542	dA	$m_X \gtrsim 100$ GeV
CMS Displaced $e\mu$	1409.4789	em	Best at LFU

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

Searches

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

Models

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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

$o_2 o_1$	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	**MG**						**MG**
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

$o_2 o_1$	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

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**GRS	**R**		R	R	R	**M**GR
b	X	MGR**S**		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	**G**R

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

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

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	**M**GRSγ	**R**		R	R	R	**M**GR
b	X	MGR**S**Hγ		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

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**GRSγ	**R**		R	R	R	**M**GR**D**
b	X	MGR**SH**γ		R	R	**R**	MGR**D**
γ	X	X	S				**G**
e	X	X	X	GRγ	R	R	GR**D**
μ	X	X	X	X	GRHγ	R	GR**D**
τ	X	X	X	X	X	GRHγ	**G**R**D**

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

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

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

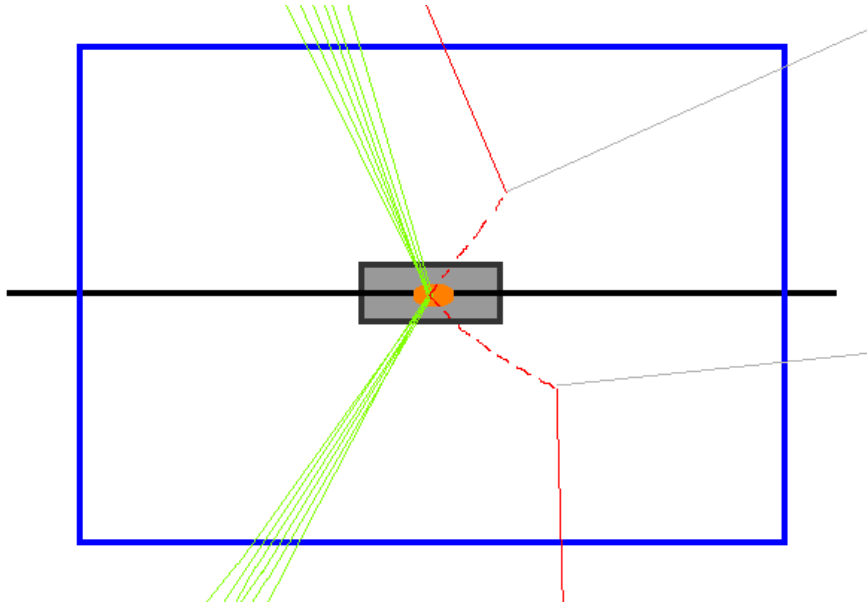
Well-motivated Theoretically

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



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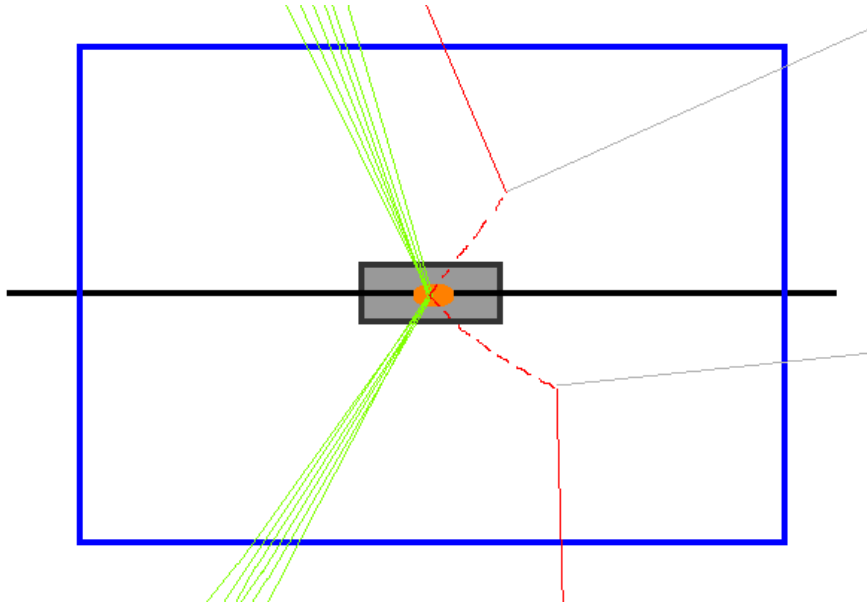

Prompt jets+$\not{E}_T$ searches:

- 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

Displaced Leptons in Exotic Searches

Recast Limits on $\tilde{\tau}_R$ (JAE, Shelton – 2016)

Displaced leptons constrained by:

- Heavy stable charged particle searches (HSCP) – CMS recast
- Disappearing tracks (DT) at ATLAS and CMS – best limit shown
- CMS displaced $e^{\pm}$ and $\mu^{\mp}$ search ($e\mu$) – constrain $\tilde{\tau}$s only

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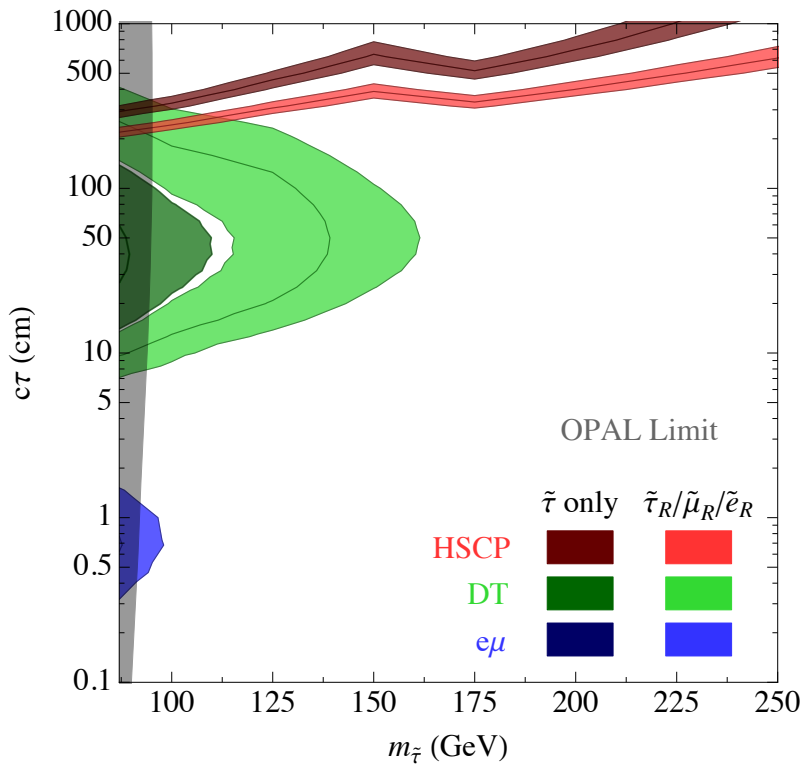

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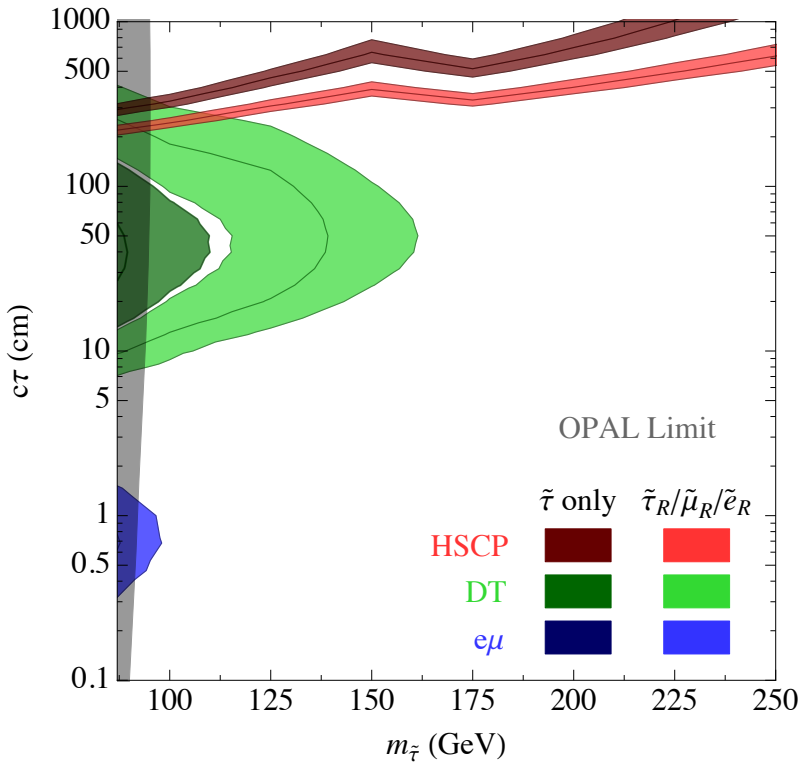
But. . . $\tilde{\tau}_R$ is not expected in isolation

Near degenerate slepton limits

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

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



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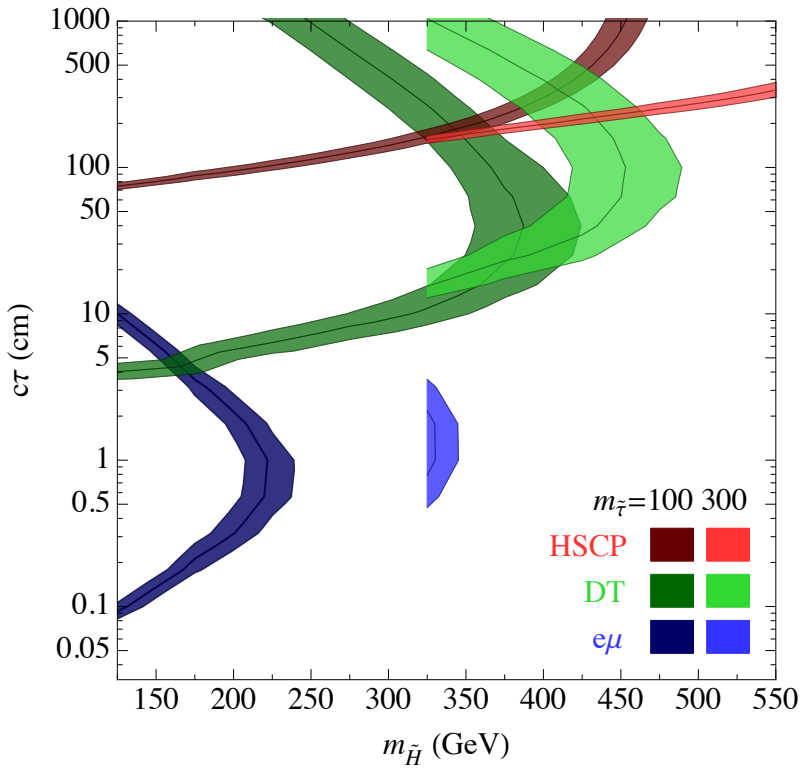
Higgsino production limits

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

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



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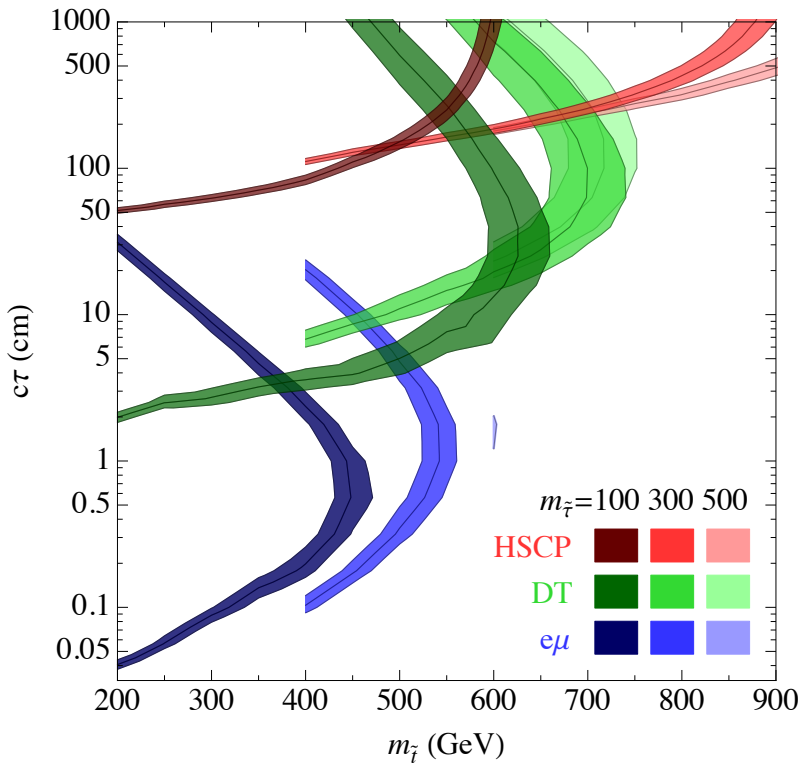
But. . . $\tilde{\tau}_R$ is not expected in isolation

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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Lots of ways to improve region $c\tau \lesssim 5$ cm!

- 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

Displaced Leptons in Exotic Searches

Hypothetical 13 TeV Same-Flavor Displaced Lepton Search (JAE, Shelton – 2016)

NLSP $\tilde{e}$ or $\tilde{\mu}$ are unconstrained!!!

Displaced Leptons in Exotic Searches

Hypothetical 13 TeV Same-Flavor Displaced Lepton Search (JAE, Shelton – 2016)

NLSP $\tilde{e}$ or $\tilde{\mu}$ are unconstrained!!!

Displaced $\tilde{\tau} \rightarrow \tau + \not{E}_T$ more common

$\tilde{\ell} \rightarrow e + \not{E}_T$ & $\tilde{\ell} \rightarrow \mu + \not{E}_T$ can arise:

- Extended GMSB – $\tilde{\ell}_R$ NLSP
- LLE RPV – $\tilde{\tau}_L^+ \rightarrow \mu^+ \nu_\ell$
- Lepton Flavored Dark Matter

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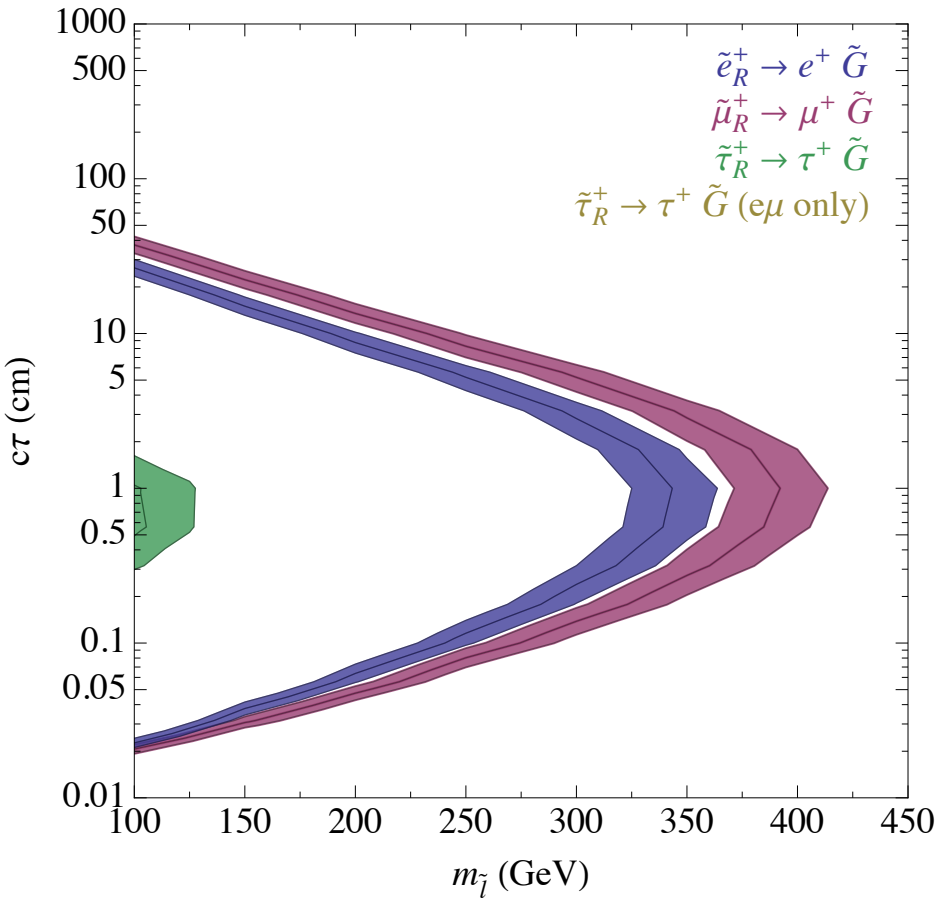

NLSP $\tilde{e}$ or $\tilde{\mu}$ are unconstrained!!!

Displaced $\tilde{\tau} \to \tau + \not{E}_T$ more common

$\tilde{\ell} \to e + \not{E}_T$ & $\tilde{\ell} \to \mu + \not{E}_T$ can arise:

- Extended GMSB – $\tilde{\ell}_R$ NLSP
- LLE RPV – $\tilde{\tau}_L^+ \to \mu^+ \nu_\ell$
- Lepton Flavored Dark Matter

Simple estimate at 13 TeV (20 fb^{-1})

Comments and Perspectives

Known unknowns. . .

What more is wanted from **theory**?

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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?

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- Unknown unknowns {insert your paper here}