Long-lived Particles Decaying to Taus

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Outline

A Brief Motivation

LLP to τ:Topologies and Models

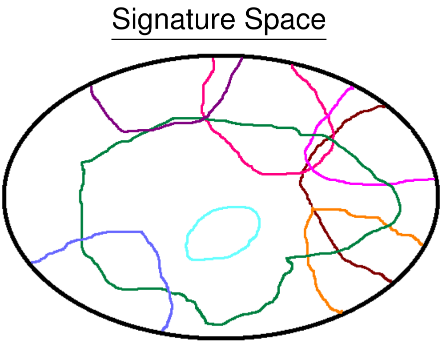
LLP to τ: Experimental Considerations
- (Brief) Example in $h \rightarrow aa \rightarrow (\tau^+\tau^-)(\tau^+\tau^-)$
- Example in GMSB $\tilde{\tau}$s

Summary

The LHC Program

The LHC has constrained many new particles in many models

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



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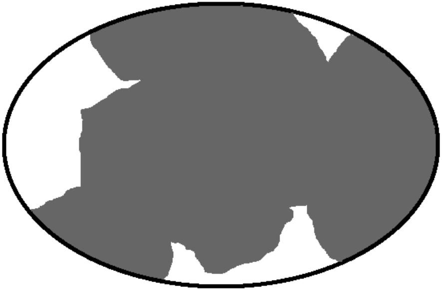
<u>Signature Space</u>



These searches cast a wide net – but there are gaps

Need comprehensive program that covers ALL new physics scenarios

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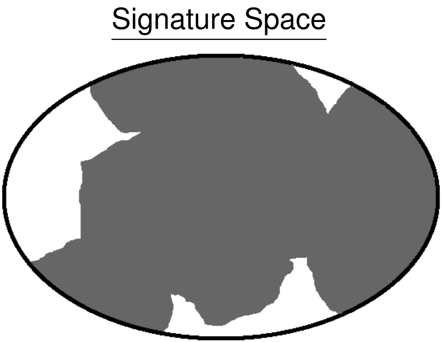

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An exotic object could be our FIRST pathway to BSM physics!

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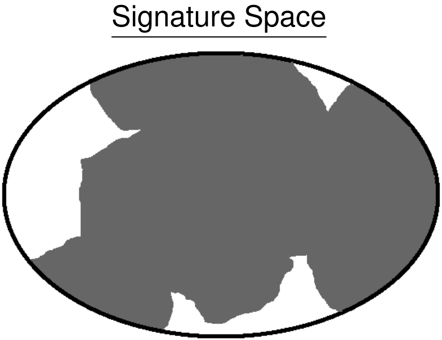

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An exotic object could be our ONLY pathway to BSM physics!!!

What are Exotic Objects?

What are Standard Objects?

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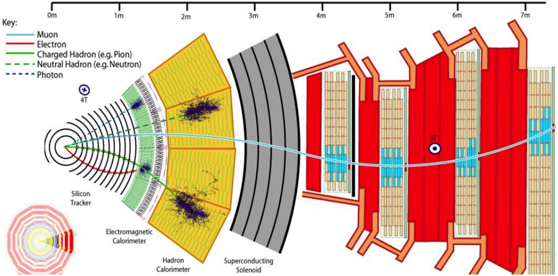
	Object	**Very Rough Identification Criteria**
1)	Photon	Hard, isolated EM calo deposit, $E_{tracks} \ll E_{calo}$
2)	Electron	Hard, isolated EM calo deposit, $E_{track} \sim E_{calo}$
3)	Muon	Hard, isolated track through muon chamber
4)	Jet	Other hard calo/track/particle clusters
a)	Tau	Single or 3-prong 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 ...

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Two basic classes: Direct & Indirect

What are Exotic Objects?

Direct vs Indirect

Direct	Indirect
Observe the object itself	Observe atypical SM decay products

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Direct vs Indirect

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Examples:

Disappearing tracks

Heavy, stable, charged particles

Magnetic monopoles

R-hadrons

Quirks

...

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Particles that decay in flight

Long lifetime from an approximate symmetry in the low energy theory

High dimension operators
High mass scale
Small couplings

Prompt τs are tough

LLP to Tau

Why?

Prompt τs are tough

- High background (QCD / heavy flavor)
- Irreducible $\not{E}_T$ (foils mass construction)
- Lower overall energy (triggering can be harder)
- BR (soft leptons, hadrons) $\sim (1/3, 2/3)$

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Displaced τs can find motivation in several models – some challenges remain, but the QCD backgrounds are greatly reduced

May be a promising place to find new physics!

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- $X^{\pm} \to \tau^{\pm} + \not{E}_T$

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Simple models	Complicated models
High motivation	Pretty ad hoc

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Easy to get 100% BR Simple models High motivation	Hard to get 100% BR Complicated models Pretty ad hoc	Require baroque UV Very complicated Completely made up

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cRaZy DeCaYs

- $X^0 \to \tau^\pm \ell^\mp \nu (\cancel{W^\mp})$
- $X^{\pm\pm} \to \tau^\pm W^\pm$
- $X^\pm \to \tau^\pm \gamma$
- $X^{\cdots} \to \tau^\pm ab...$

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Let's discuss in roughly reverse order (craziest to most motivated)...
(Next few slides are fast and theory heavy, will get easier)

$X^{\cdots} \to \tau^{\pm} ab...$

Barring examples later, $X^{\cdots} \to \tau^{\pm} + 2$ or more SM particles is typically:

- poorly motivated (e.g., no good models)
- requires high dimension operators
- a UV completion would likely generate other (better) operators
- some make flavor problems
- usually not qualitatively different than other signals

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For example: $\mathcal{L} \ni \frac{y}{\Lambda^3} X^+ \tau_R^- G_{\mu\nu} G^{\mu\nu}$ can be written....

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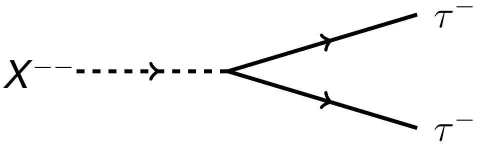
What UV completion makes this happen?

Loops of charged and neutral color octets that talk to only X and τ_R^c?
$\Rightarrow$ induces a mass term between X and τ_R^c $\Rightarrow$ simpler decay to $\tau^{\pm} Z/h$
AND phenomenologically equivalent to $X \to \tau q\bar{q}$

$X^{\pm\pm} \to \tau^{\pm}\tau^{\pm}\,(\tau^{\pm}\ell^{\pm})\,[\tau^{\pm}W^{\pm}]$

Can easily add an operator $\mathcal{L} \ni y_{ij}X^{--}\ell_i^c\ell_j^c + \text{h.c.}$ with y_{ij} symmetric

for singlet X^{--} with vector-like mass $m_X^2 X^{++}X^{--}$, tiny $y_{ij} \Rightarrow$ long-life



Charge 2 object a bit strange, but operator is dim-4, could be easily embedded in SUSY, other UV structures are reasonable

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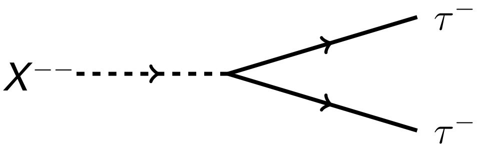

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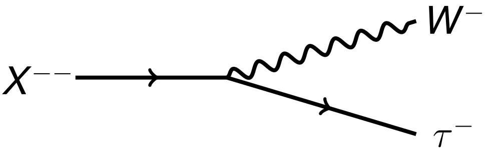
$X^{\pm\pm} \to \tau^\pm W^\pm$ is much stranger...

Need fermion $X^{\pm\pm}$ that talks to W, e.g., from vector-like $SU(2)_L$ doublet with $3/2$ hypercharge



$$M \sim \begin{pmatrix} m_\tau & \kappa v \\ \kappa v & M_X \end{pmatrix}$$

Adding a term $\mathcal{L} \ni \kappa X H \tau_R^c \Rightarrow \lambda v X^- \tau^+$ with small λ in addition to vector-like $\bar{X}X$ mass term generates small-mixing between X^+ and τ

Now have $X^{--} \to X^{-*} W^- \to \tau^- W^-$ decay

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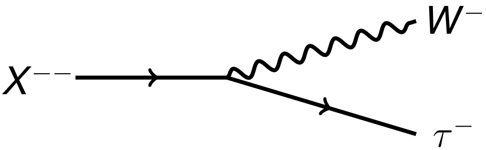

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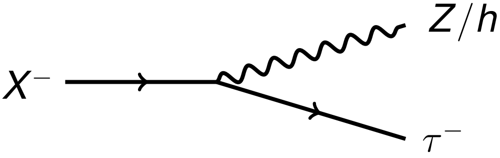
Also, have $X^{--} \to X^- W^{-*}$ decay $\Rightarrow$ difficult to make very long-lived

Also, pretty ad hoc

$X^\pm \to \tau^\pm Z/h$

Same basic idea can produce $X^\pm \to \tau^\pm Z/h$

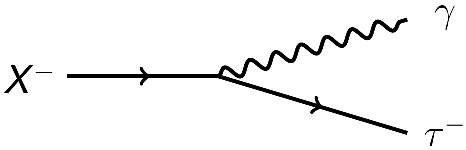


Same basic mechanism as 4th-generation top partners

$T \to bW$, $T \to tZ$, $T \to th$ are all good decay paths

4th-gen τ partner $X^\pm$ has $X \to \nu W$, $X \to \tau Z$, $X \to \tau h$ as decay paths

$X^\pm \to \tau^\pm\gamma$



However, $X^\pm \to \tau^\pm\gamma$ is not so easy as E&M is a good symmetry

Need (for instance) to induce a loop-level magnetic dipole operator

$$\mathcal{L} \ni X\sigma^{\mu\nu}\tau_R^c F_{\mu\nu}$$

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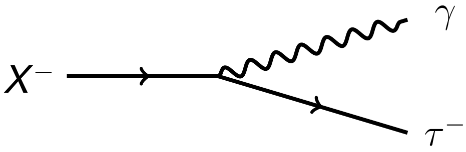

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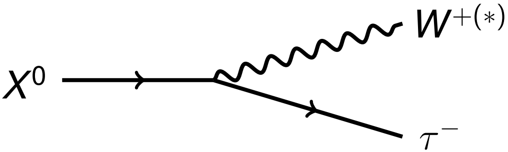
Hard to do with out also generating less suppressed $X \to \tau Z$ decay

Also, dangerous for well-measured LFV processes ($\mu \to e\gamma$)

$X^0 \to \tau^\pm W^\mp$

Arguably, the most highly motivated LLP to τ is $X^0 \to \tau^\pm W^\mp$



$X^0 \to \tau^\pm W^\mp$ is very well-motivated from sterile ν!

Inverse seesaw $\Rightarrow$ m_X and mixing angle U_τ are free parameters

Small U_τ and/or $m_X < m_W$ provide long lifetime

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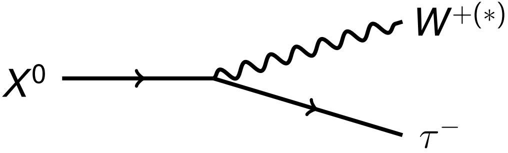

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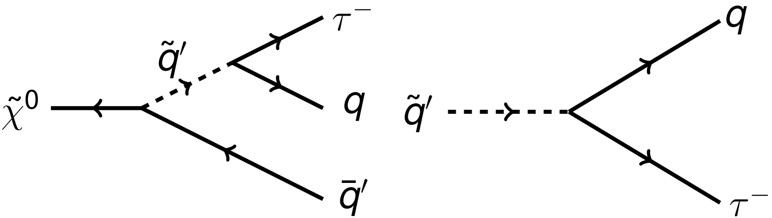
Could also emerge from slightly more complicated structures with more accessible LHC production (e.g. 4th-gen L)

Production of X^0 through W/Z

$\tilde{\chi}^0 \to \tau^- q\bar{q}'$ & $\tilde{q}' \to \tau q$



$\tilde{\chi}^0 \to \tau^- q\bar{q}'$ & $\tilde{q}' \to \tau q$ motivated from *R*-parity violating SUSY and leptoquark extensions to the SM

RPV (LQD) couplings $\lambda'_{ijk} \ll 1$ due to flavor, hierarchical expected

$X^0 \to \tau^+\tau^-$

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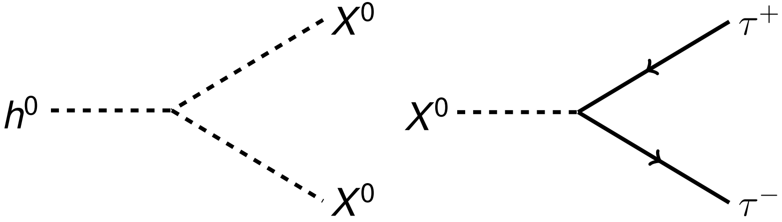

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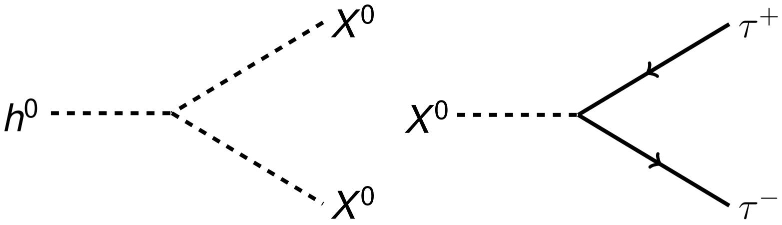

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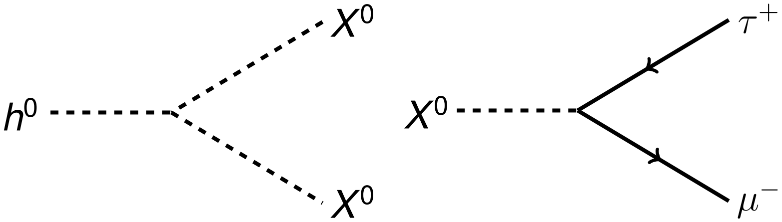
$\mathrm{BR}(h \to X^0 X^0) \lesssim 0.1$ within current constraints

Higgs mixing in the $m_X \in \{3.5, 10.5\}$ GeV range has large $\tau\tau$ BR

Leptophilic scalars can extend above this range easily

Less motivated, but still easy to do is $X^0 \to \tau^+ \ell^-$



Introduce operator $\frac{a_{ij}}{\Lambda} X L_i H E_j^c$

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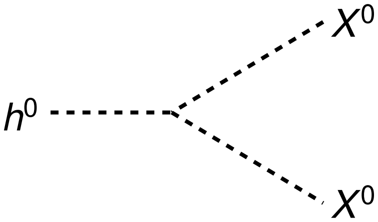
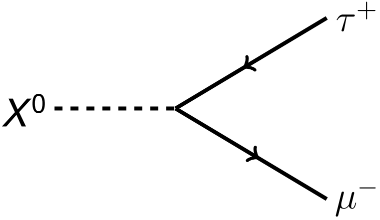




Introduce operator $\frac{a_{ij}}{\Lambda} X L_i H E_j^c$

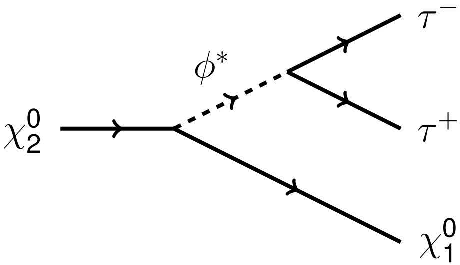
a_{ij} flavor structure can be altered by UV content JAE, Tanedo, Zakeri – 1910.07533

UV models aren't elegant, but it is straight forward to attain a ~ 1 BR to flavor violating path

$X^0 \to \tau^+\tau^- + \not{E}_T$ ($X^0 \to \tau^+\ell^- + \not{E}_T$)

Without a W, $X^0 \to \tau^+\ell^- + \not{E}_T$ is pretty contrived...

$X^0 \to \tau^+\tau^- + \not{E}_T$ has some dark matter motivations...



Inelastic DM could allow for displaced decay to $\tau\tau + \not{E}_T$

Typically involves small $\chi_2^0 - \chi_1^0$ splitting and thus soft τs

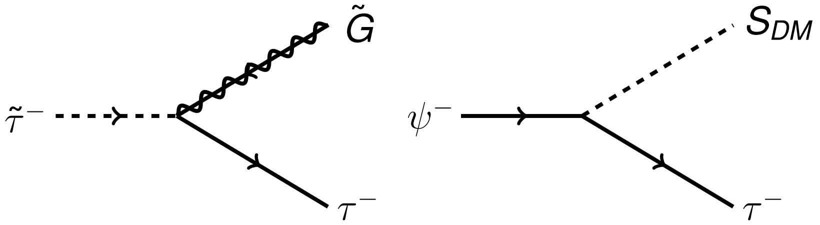
$X^\pm \to \tau^\pm + \not{E}_T$

JAE, Shelton – 1601.01326; Khoze et al – 1702.00750; Bélanger et al – 1811.05478

Arguably, the most highly motivated LLP to τ is $X^\pm \to \tau^\pm + \not{E}_T$

Classic signal of gauge mediated SUSY breaking (GMSB) is LLP $\tilde{\tau}$

Dark matter motivations, RPV SUSY with LLE operators (not shown)



In GMSB, $m_{\tilde{G}}$ is tiny, but DM models could have it heavy

Lastly, $\chi^- \to \tau^- \nu \chi_0$ is possible, but a bit contrived

That model building blitz in brief

To summarize, there are a lot of ways to get an LLP decaying to τ

$$X^0 \to W^\pm \tau^\mp \text{ and } X^0 \to \tau^+ \tau^- \text{ and } X^\pm \to \tau^\pm + \not{E}_T$$

are the most motivated and pretty good benchmark examples

Questions before moving to experimental considerations?

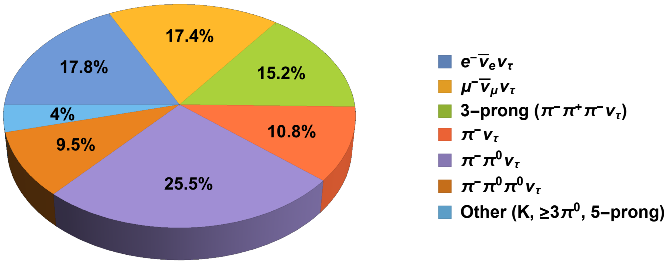
Tau

The Recalcitrant Charged Lepton

Tau facts:

- $M_\tau = 1776.82$ MeV
- $c\tau_\tau = 87.11\mu$m $\Rightarrow$ 100 GeV τ has $\gamma c\tau_\tau = 5$mm

τ branching ratios:



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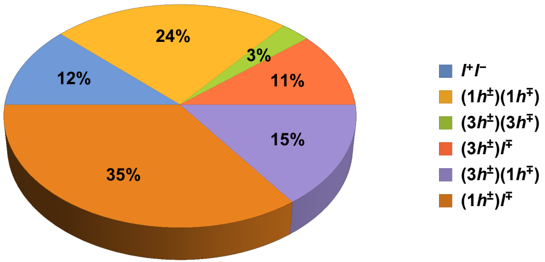

$h \to aa \to (\tau^+\tau^-)(\tau^+\tau^-)$

Some naïve theorist math...

- $m_h = 125$ GeV
- $\Rightarrow E_a \sim 60$ GeV
- $\Rightarrow E_\tau \sim 30$ GeV
- $\Rightarrow E_{\tau_h} \sim 20$ GeV
- $\Rightarrow E_{\tau_\ell} \sim 10$ GeV

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Signal $\sim 2\tau_h$ & 2 soft ℓ

Triggering

How possible is it to pick up these events?

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Signal $\sim 2\tau_h$ & 2 soft ℓ

Triggering

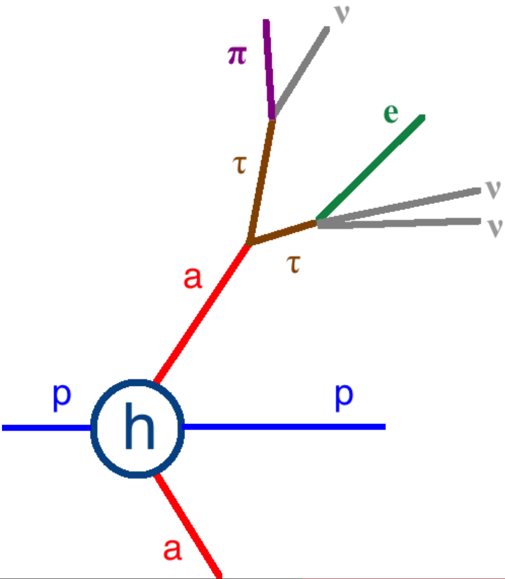
How possible is it to pick up these events?

Is 2 10 GeV ℓ + 2 τ_h possible?

Can it work with VBF triggers?

Or need Z/W triggers?

$h \to aa \to (\tau^+\tau^-)(\tau^+\tau^-)$



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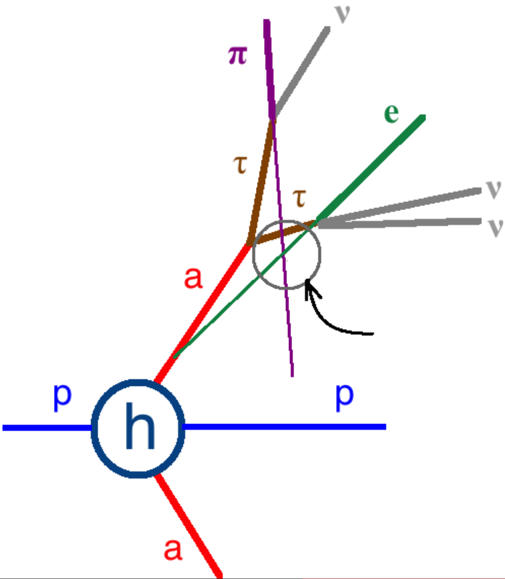

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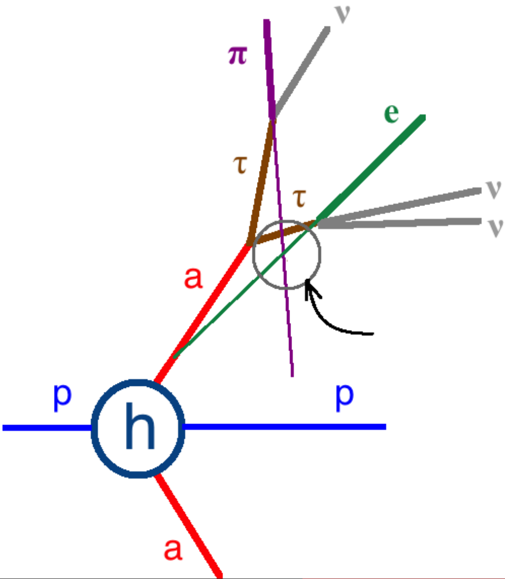


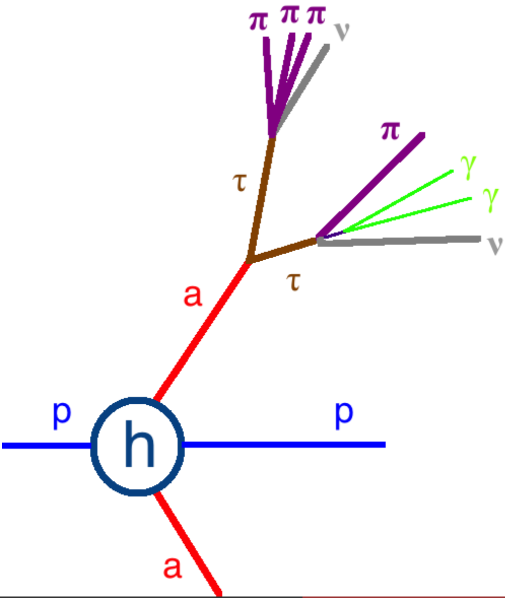
Vertexing resolution at the LHC is very good

τs have $\gamma c\tau \sim 2$ mm

How reliably can the vertexing identify these very low multiplicity objects?

How reliably can the vertexing reject coincident crossings?

$h \to aa \to (\tau^+\tau^-)(\tau^+\tau^-)$



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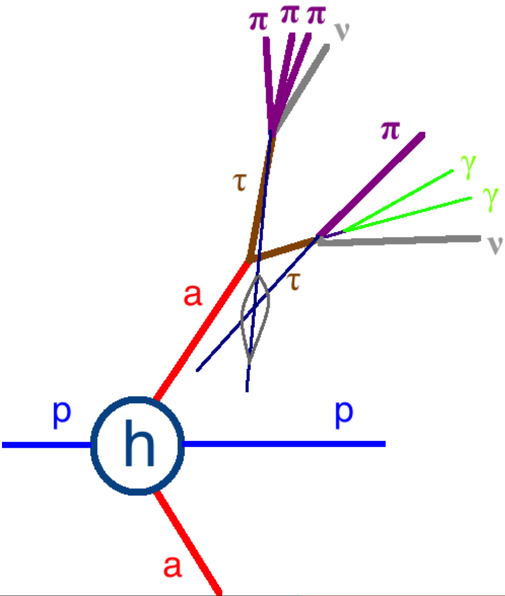
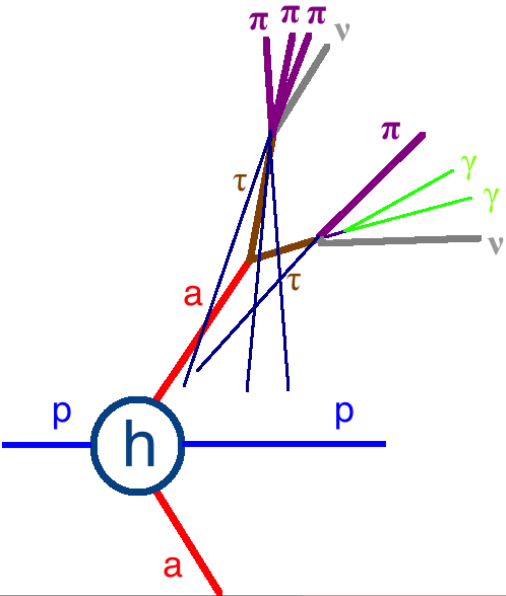


Can π^0s be used in vertexing at all?

Due to collimation are $3\pi^\pm$ much more useful than $1\pi^\pm$?

Do $3\pi^\pm$ make vertexing worse?

$h \to aa \to (\tau^+\tau^-)(\tau^+\tau^-)$



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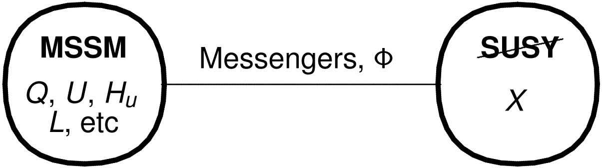
Gauge Mediation and $\tilde{\tau}_R$ NLSPs

Lightning Review of Minimal GMSB



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

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

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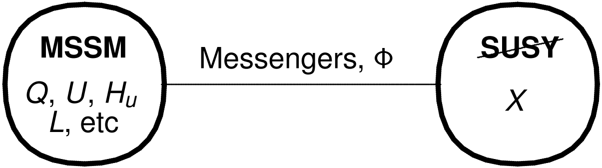

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$$M_r \sim N_{eff} g_r^2 \tilde{\Lambda} \qquad A\text{-terms} = 0$$

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

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

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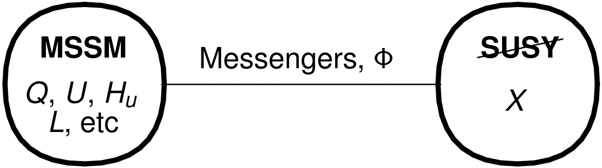

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$$m_{soft}^2 \sim 2N_{eff} C_r g_r^4 \tilde{\Lambda}^2 \qquad (C_r \text{ quadratic Casimirs } \mathcal{O}(1))$$

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)

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

Lifetimes

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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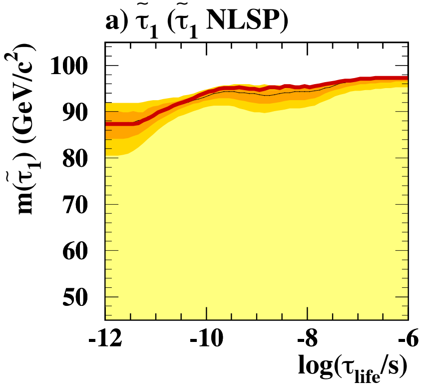
What is $\sqrt{F}$?

$F < M^2$; 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: $100\,\mu\text{m} \lesssim c\tau \lesssim 1$ m

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



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

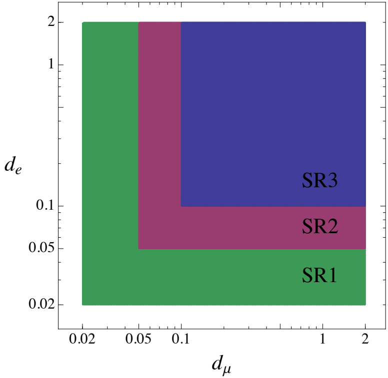
$m_{\tilde{\mu}} > 94$ GeV

OPAL placed the best limits on sleptons of all lifetimes

Relevant LHC search: 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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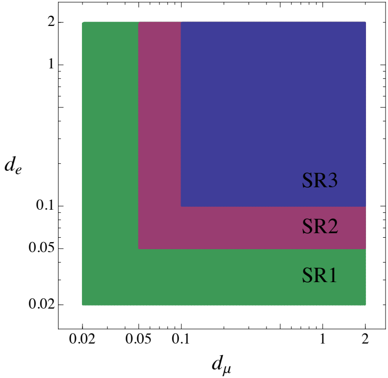

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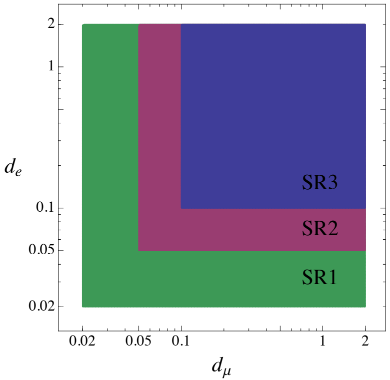

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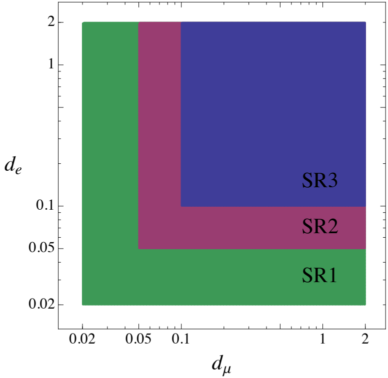

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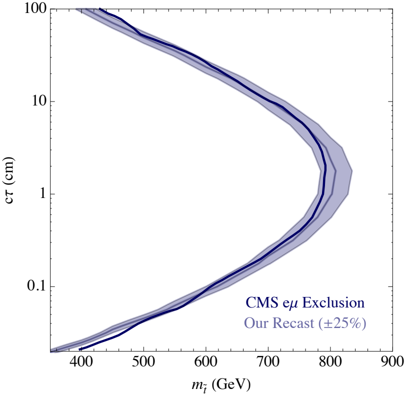
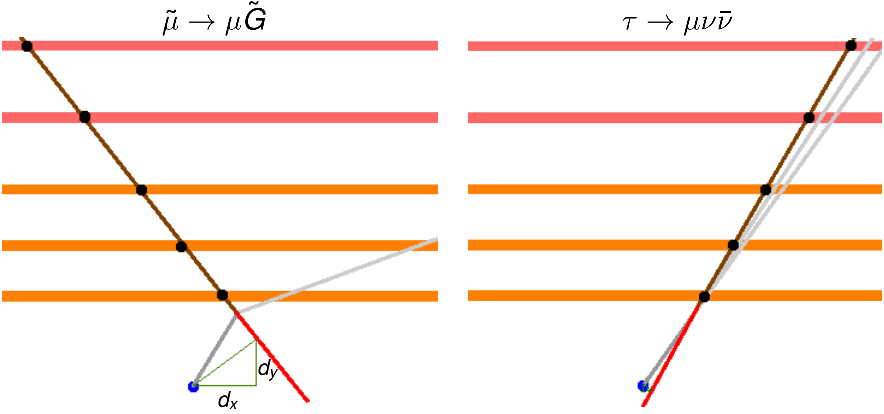


Extensive recasting details! (Signal model: $\mathrm{BR}(\tilde{t} \to j\ell_i) = \{\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\}$)

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

Impact Parameter

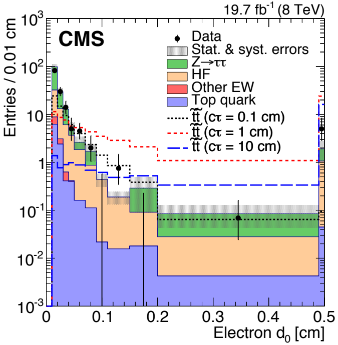


Impact Parameter is *not* the location of parent

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 $\tilde{\tau}_R$

(Note: updated searches exist)

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

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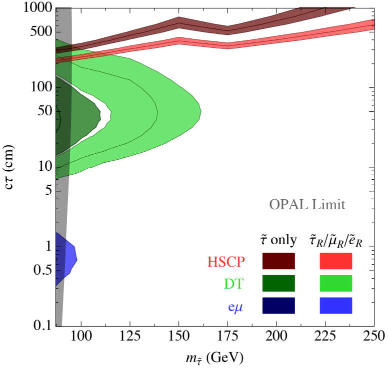
But . . . a $\tilde{\tau}_R$ is not expected in isolation

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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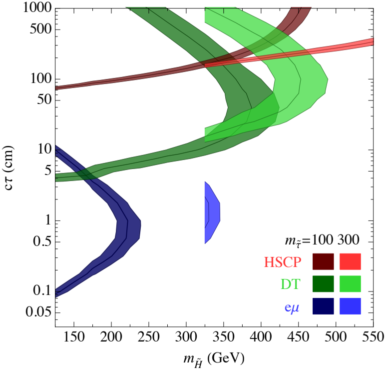
Higgsino production limits

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

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



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

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

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

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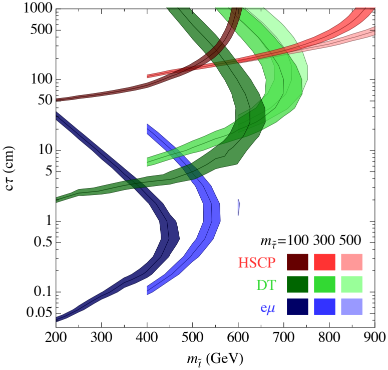
Stop production limits

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

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



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

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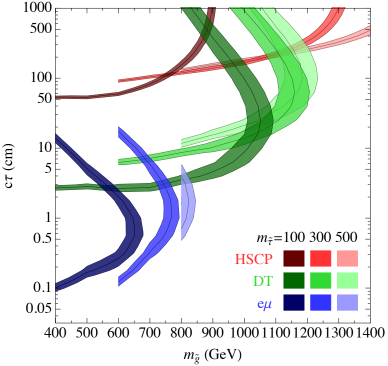
But . . . a $\tilde{\tau}_R$ is not expected in isolation

<u>Gluino production limits</u>

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

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



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

Potential Improvements?

CMS Displaced Lepton Search

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

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1) Add same-flavor lepton channels

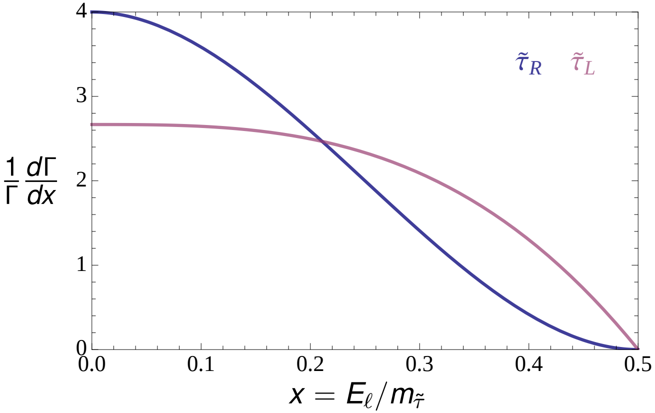
$$BR(\tilde{\tau}^+\tilde{\tau}^- \rightarrow e^\pm\tau_h^\mp + X) = 23\%$$
$$BR\tilde{\tau}^+\tilde{\tau}^- \rightarrow \mu^\pm\tau_h^\mp + X) = 23\%$$
$$BR(\tilde{\tau}^+\tilde{\tau}^- \rightarrow \tau_h^\pm\tau_h^\mp + X) = 42\%$$

2) Include hadronic τ_hs

Experimental feasibility of displaced τ_hs? (Part of why we are here)

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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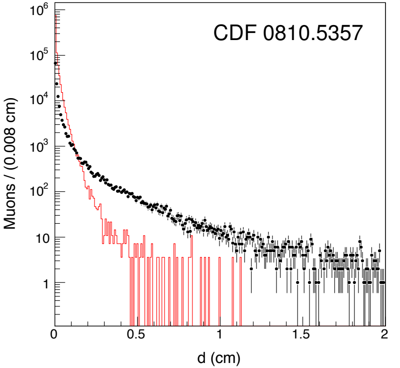
(CDF ghost muons???)



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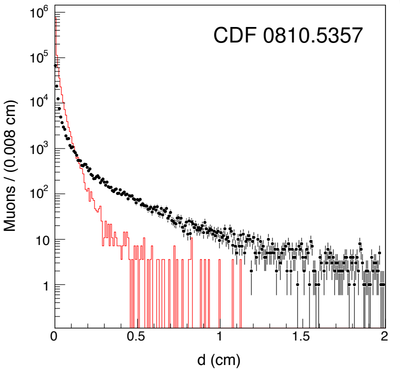

Gluino & Higgsino model have additional leptons often $\sim$(45%, 30%)

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

Potential Improvements?

CMS Displaced Lepton Search

Gluino & Higgsino models have Majorana particles in chain

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5) Include same-sign displaced lepton signal regions

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

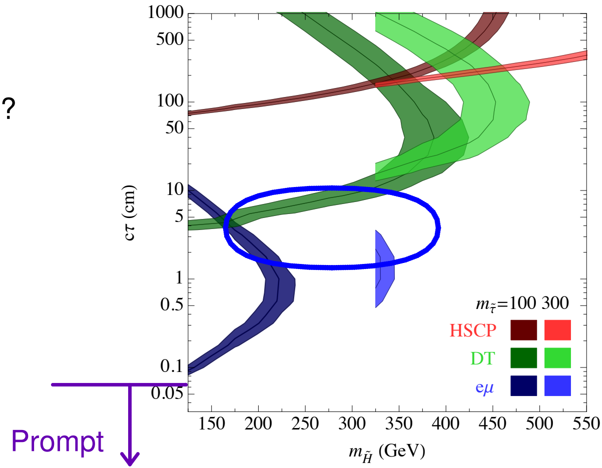
SSℓ can appear in the $\tilde{t} \to \ell^+ b$ benchmark of CMS 1409.4789

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

Potential Improvements?

CMS Displaced Lepton Search

Extend reach in $c\tau$?

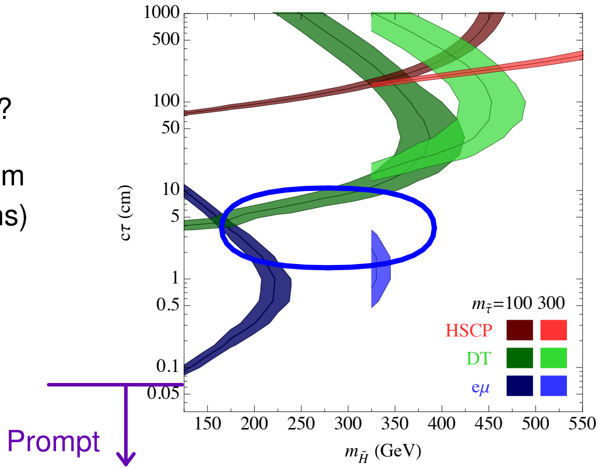


Potential Improvements?

CMS Displaced Lepton Search

Extend reach in $c\tau$?

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



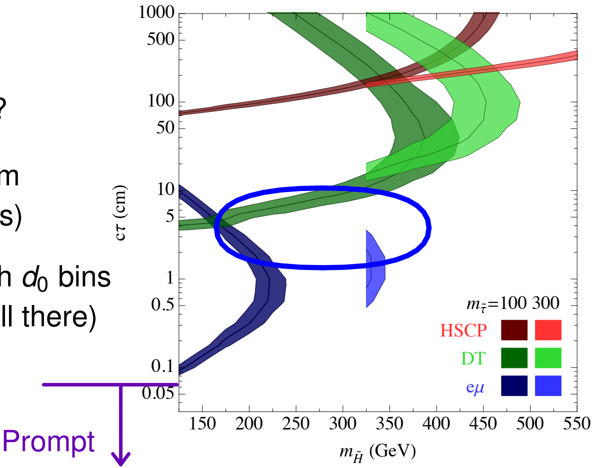
Potential Improvements?

CMS Displaced Lepton Search

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)



Summary

- Displaced τs are a challenging (but necessary place) to find BSM
- $X^0 \to W^\pm \tau^\mp$, $X^0 \to \tau^+\tau^-$, and $X^\pm \to \tau^\pm + \not{E}_T$ are well motivated
- Other models (of varying quality) exist
- 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 (didn't discuss)
- These highlight the value of considering multiple benchmarks
- Motivated $h \to aa \to (\tau^+\tau^-)(\tau^+\tau^-)$ is a big gap at LHC
- A lot of work still needs to be done on displaced τs!