



# Long-lived particle searches in ATLAS and CMS

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## Introduction

- Many models of new physics predict long-lived (LL) particles through small/suppressed couplings or high mass scales, e.g.
  - Split/RPV/stealth SUSY, and symmetry-breaking mechanisms
  - Exotic Higgs
  - Hidden valley
  - Dark sector
- Depending on model and lifetime, particles measured with different parts of the detector: analyses focused on signatures
- This talk: small sample of searches at ATLAS and CMS
  - Mostly 8 TeV results; corresponding 13 TeV analyses in progress

#### ATLAS Long-lived Particle Searches\* - 95% CL Exclusion

Status: July 2015



 $\int \mathcal{L} dt = (18.4 - 20.3) \text{ fb}^{-1}$   $\sqrt{s} = 8 \text{ TeV}$ 

		Model	Signature	∫£ dt[fb	-1]	Lifetime limit			Reference
		$RPV\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	$\chi_1^0$ lifetime	7-	740 mm	$m( ilde{g}) = 1.3  ext{ TeV},  m(\chi_1^0) = 1.0  ext{ TeV}$	1504.05162
	SUSY	$\operatorname{GGM} \chi^0_1 \to Z \tilde{G}$	displaced vtx + jets	20.3	$\chi_1^0$ lifetime	6-480 m	m	$m( ilde{g})=1.1$ TeV, $m(\chi_1^0)=1.0$ TeV	1504.05162
		AMSB $pp \rightarrow \chi_1^{\pm}\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^{\pm}$ lifetime		0.22-3.0 m	$m(\chi_1^{\pm})=$ 450 GeV	1310.3675
0.0		AMSB $pp \rightarrow \chi_1^{\pm}\chi_1^0, \chi_1^{\pm}\chi_1^{-}$	large pixel dE/dx	18.4	$\chi_1^{\pm}$ lifetime		1.31-9.0 m	$m(\chi_1^{\pm})=$ 450 GeV	1506.05332
		GMSB	non-pointing or delayed 3	20.3	$\chi_1^0$ lifetime		0.08-5.4 m	SPS8 with $\Lambda=200~\text{TeV}$	1409.5542
		Stealth SUSY	2 ID/MS vertices	19.5	<b>Š</b> lifetime			<b>0.12-90.6 m</b> $m(\tilde{g}) = 500 \text{ GeV}$	1504.03634
	= 10%	Hidden Valley $H \rightarrow \pi_{\rm v} \pi_{\rm v}$	2 low-EMF trackless jets	20.3	$\pi_v$ lifetime		0.41-7.57 m	$m(\pi_{ m v})=25~{ m GeV}$	1501.04020
0,		Hidden Valley $H \rightarrow \pi_{\rm v} \pi_{\rm v}$	2 ID/MS vertices	19.5	$\pi_v$ lifetime		0.31-	<b>25.4 m</b> $m(\pi_v) = 25 \text{ GeV}$	1504.03634
6	hd st	FRVZ $H \rightarrow 2\gamma_d + X$	2 e-, μ-, π-jets	20.3	$\gamma_{\rm d}$ lifetime	14-140 mm		$H  ightarrow 2\gamma_d + X, \ m(\gamma_d) = 400 \ { m MeV}$	1409.0746
	ы Дін	FRVZ $H  ightarrow 4\gamma_d + X$	2 <i>e</i> -, μ-, π-jets	20.3	$\gamma_{d}$ lifetime	15-260 mm		$H  ightarrow 4 \gamma_d + X, \ m(\gamma_d) = 400 \ { m MeV}$	1409.0746
Ì	%0	Hidden Valley $H \rightarrow \pi_{\rm v} \pi_{\rm v}$	2 low-EMF trackless jets	20.3	$\pi_v$ lifetime		0.6-5.0 m	$m(\pi_{ m v})=25~{ m GeV}$	1501.04020
6	BR =	Hidden Valley $H \rightarrow \pi_{\rm v} \pi_{\rm v}$	2 ID/MS vertices	19.5	$\pi_v$ lifetime		0.43-18.1	m $m(\pi_v) = 25 \text{ GeV}$	1504.03634
	HIGGS	FRVZ $H \rightarrow 4\gamma_d + X$	2 <i>e</i> -, μ-, π-jets	20.3	$\gamma_d$ lifetime	28-160 mm		$H  ightarrow 4 \gamma_d + X, \ m(\gamma_d) = 400 \ { m MeV}$	1409.0746
Vo.	ar	Hidden Valley $\Phi \rightarrow \pi_v \pi_v$	2 low-EMF trackless jets	20.3	$\pi_v$ lifetime		0.29-7.9 m	$\sigma  imes BR$ = 1 pb, $m(\pi_{ m v}) = 50~{ m GeV}$	1501.04020
300.6	scali	Hidden Valley $\Phi \to \pi_v \pi_v$	2 ID/MS vertices	19.5	$\pi_v$ lifetime		0.1	<b>9-31.9 m</b> σ×BR = 1 pb, m(π <sub>v</sub> ) = 50 GeV	1504.03634
Ve	ar	Hidden Valley $\Phi \rightarrow \pi_v \pi_v$	2 low-EMF trackless jets	20.3	$\pi_v$ lifetime		0.15-4.1 m	$\sigma  imes BR$ = 1 pb, $m(\pi_{ m v}) = 50~{ m GeV}$	1501.04020
o uuo	scali	Hidden Valley $\Phi \to \pi_v \pi_v$	2 ID/MS vertices	19.5	$\pi_{v}$ lifetime		0.11-18.3	<b>m</b> $\sigma \times BR = 1 \text{ pb, } m(\pi_v) = 50 \text{ GeV}$	1504.03634
	er	${\rm HV}\; Z'({\rm 1\;TeV}) \to q_{\rm v} q_{\rm v}$	2 ID/MS vertices	20.3	$\pi_v$ lifetime		0.1-4.9 m	$\sigma  imes BR$ = 1 pb, $m(\pi_{ ext{v}}) = 50 \; GeV$	1504.03634
ē	E C	HV Z'(2 TeV) $\rightarrow q_{\rm v} q_{\rm v}$	2 ID/MS vertices	20.3	$\pi_v$ lifetime		0.1-10.1 m	$\sigma  imes BR$ = 1 pb, $m(\pi_{ ext{v}}) = 50 \; GeV$	1504.03634
0.01 0.1 1							1 10	<sup>100</sup> cτ [m]	
√s = 8 TeV									

program in ATLAS and CMS!

First:

rich

\*Only a selection of the available lifetime limits on new states is shown.



#### CMS long-lived particle searches, lifetime exclusions at 95% CL

RPV SUSY, t → bl, m(t) = 420 GeV 8 TeV, 19.7 fb<sup>-1</sup> (displaced leptons)

H → XX (10%), X → ee, m(H) = 125 GeV, m(X) = 20 GeV 8 TeV, 19.6 fb<sup>-1</sup> (displaced leptons)

 $H \rightarrow XX$  (10%),  $X \rightarrow \mu\mu$ , m(H) = 125 GeV, m(X) = 20 GeV 8 TeV, 20.5 fb<sup>-1</sup> (displaced leptons)

> GMSB SPS8,  $\tilde{\chi}_{i}^{0} \rightarrow \tilde{G} \gamma$ ,  $m(\tilde{\chi}_{i}^{0}) = 250 \text{ GeV}$ 8 TeV, 19.7 fb<sup>-1</sup> (disp. photon conv.)

GMSB SPS8,  $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$ , m( $\tilde{\chi}_2^0$ ) = 250 GeV 8 TeV, 19.1 fb<sup>-1</sup> (disp. photon timing)

RPV SUSY, m(q) = 1000 GeV, m(q2) = 150 GeV 8 TeV, 18.5 fb<sup>-1</sup> (displaced dijets)

RPV SUSY, m(q) = 1000 GeV, m(q2) = 500 GeV 8 TeV, 18.5 fb<sup>-1</sup> (displaced dijets)

> AMSB  $\tilde{\chi}_{1}^{*}, \tilde{\chi}_{1}^{*} \rightarrow \tilde{\chi}_{1}^{0} + \pi^{*}, m(\tilde{\chi}_{1}^{*}) = 200 \text{ GeV}$ 8 TeV, 19.5 fb<sup>-1</sup> (disappearing tracks)

cloud model R-hadron, m(g) = 1000 GeV 8 TeV, 18.6 fb<sup>-1</sup> (stopped particle)

AMSB  $\tilde{\chi}_{1}^{*}$ , tan( $\beta$ ) = 5,  $\mu$  > 0, m( $\tilde{\chi}_{2}^{*}$ ) = 800 GeV 8 TeV, 18.8 fb<sup>-1</sup> (tracker + TOF)

AMSB  $\tilde{\chi}_{,}^{*}$ , tan( $\beta$ ) = 5,  $\mu$  > 0, m( $\tilde{\chi}_{,}^{*}$ ) = 200 GeV 8 TeV, 18.8 fb<sup>-1</sup> (tracker + TOF)

First:

rich

program in ATLAS and CMS!

# dE/dx in pixels

- Search for charged (meta)stable R-hadrons ( $\tilde{g}$ ) decaying via  $\tilde{g} \rightarrow q \bar{q} \tilde{\chi}^0$
- Trigger on calorimeter MET from  $\tilde{\chi}^0$  or unbalanced ISR
- Look for high-p, high dE/dx track
- Reconstruct most probable value of dE/dx from pixel cluster charge info (now with IBL)
- Use parameterized Bethe-Bloch to estimate  $\beta\gamma \rightarrow$  mass of particle







See talk from T. Lenz on Friday for

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# dE/dx in pixels

- Background estimated using control regions with tracks failing dE/dx, MET cuts
- Set improved limits as function of  $\tilde{g}$  lifetime and mass







# Displaced e + $\mu$

- Pair-produced  $\tilde{t} \rightarrow bl$  with small RPV coupling
- Select events with isolated, oppositely-charged e + μ
- Three exclusive signal regions in 2D plane of leptons' transverse impact parameter: 0.02 < d<sub>0</sub> < 2 cm
- Main SM background is heavy flavor (HF), estimated from data using non-isolated, same-sign samples (ABCD)

#### **CMS, 8 TeV** Phys. Rev. Lett. 114, 061801 (2015) 19.7 fb<sup>-1</sup> (8 TeV)



# Displaced $e + \mu$

- In tightest signal region:
  - background prediction  $0.05 \pm 0.01$  events; >1 event expected for  $\tilde{t}$  with M =  $\frac{1}{50}$
  - 500 GeV and  $c\tau = 1$  mm;
  - 0 events observed.
- 95% CL limits set as function of cτ and M of  $\tilde{t}$
- Inclusive requirements  $\rightarrow$ sensitive to other models with oppositely-charged  $e + \mu$



# Displaced vertices + X

- X = e, μ, jets, or MET; X used to trigger
- "Re-tracking" to recover tracks with large d<sub>0</sub>
- Reconstruct vertices starting from pairs of tracks, merge iteratively
- Veto vertices in detector material
- Discriminant: vertex mass and number of tracks
- Background from accidental track crossings and merged vertices: estimate from data

#### ATLAS, 8 TeV Phys. Rev. D 92, 072004 (2015)



## Displaced vertices + X

ATLAS, 8 TeV Phys. Rev. D 92, 072004 (2015)

- Signal region: background prediction <1 event in all channels; 0 observed
- Interpreted in the context of many models: example RPV  $ilde{\chi}^0$  model



# CMS-PAS-SUS-14-020

- Pair-prod.  $\tilde{g} \rightarrow tbs$  : 2 displaced multi-jet vertices
- Focus on intermediate lifetimes down to 300 μm
- Background from mis-reconstruction, b quark jets
- Discriminant d<sub>vv</sub>: x-y distance between vertices
- Estimate background using distances, angles in one-vertex sideband





#### CMS, 8 TeV CMS-PAS-SUS-14-020

- Fit with signal template from MC, background from data
- Set 95% CL upper limits as function of lifetime and mass



## Summary

- Searches for long-lived particles are an active, rich program both w. theorists and at ATLAS + CMS
- Different decays and mass + lifetime ranges lend to different experimental techniques
  - Many analyses using different objects and targeting different models not described here!
- 8 TeV program set the stage for Run 2; many 13 TeV analyses underway!

### Supplementary material

### dE/dx in pixels

ATLAS, 13 TeV SUSY-2016-03 arXiv:1604.04520





## Displaced e + $\mu$

#### CMS, 8 TeV Phys. Rev. Lett. 114, 061801 (2015)



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#### Displaced vertices + X

ATLAS, 8 TeV Phys. Rev. D 92, 072004 (2015)



#### CMS, 8 TeV CMS-PAS-SUS-14-020



#### CMS, 8 TeV CMS-PAS-SUS-14-020



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