ATLAS LLP Overview

Stefano Giagu (Sapienza U. di Roma and INFN Roma)
for the ATLAS Collaboration and Exotic/SUSY LLP Community

LHC Long-Lived Particle Mini-Workshop - CERN May 12th 2016

- Very quick overview of BSM LLP-related searches in ATLAS
  - not meant to be exhaustive, details and full lists available in the ATLAS web page:
    - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - meant as source of background informations to set the stage for the main discussion at the end of the workshop

- Succinctly covered topics:
  - ATLAS current and planned LLP searches
  - limitations in designing searches for LLPs and possible actions to do a better job in the future …

ATLAS strategy for LLP searches:

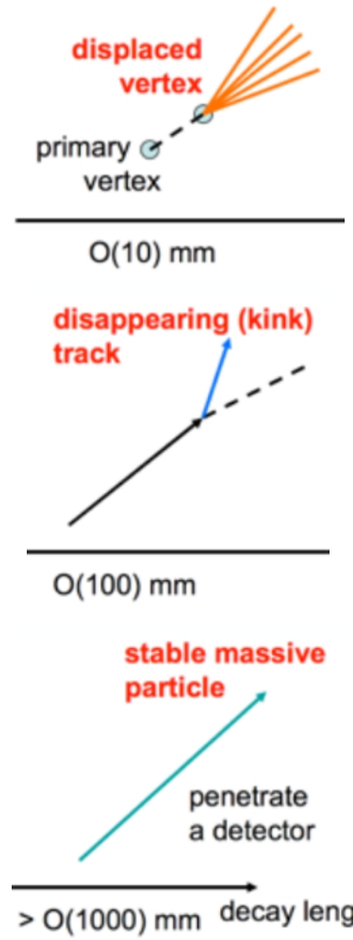
- wide diversity of decay topologies from LLP can be combined in a limited set of experimental signatures largely independent from the details of the underlying new physics models:
  - displaced vertices, non-pointing objects, lepton-jets, also outside the inner-tracker … ⬅ long lived neutral particles decaying in leptons and hadrons
  - anomalous (kinked, disappearing, …) tracks, particles sometime stopped in the detector that decays in different bunch crossing after a relatively long time … ⬅ (very) long-lived charged particles
  - long time-of-flight, large dE/dx ⬅ low-velocity massive charged particles with high p_T

- range of lifetimes explorable with the detectors maximised categorising the searches in broad groups of analyses, with significant overlap for some models and searches:
  - inner detector-based searches
  - calorimeter-based searches
  - muon spectrometer-based searches

- analysis design and interpretation :
  - first generation of searches designed and optimised in the context of specific benchmark models (SUSY, Hidden Valley / Dark Sectors, Exotic Higgs scenarios, etc. …)
  - second generation of analyses add sets of informations (efficiencies/acceptances per object as a function of the most significative kinematical observables, detailed trigger/selection criteria …) to facilitate to recast the results in the context of different models
  - very ambitious goal for current/next generation of analyses: to be as much as general as possible, with optimisation guided by simplified models able to capture the most relevant aspects of broader classes of theories, and providing extensive sets of tools/informations for (re)interpretation of the results
    - see as an example of an effort in this direction: arXiv:1605.02742 on proposal of a data-driven general search for LLP at LHC

- ATLAS LLP searches carried on in two different physics subgroups (planned to merge in the near future):

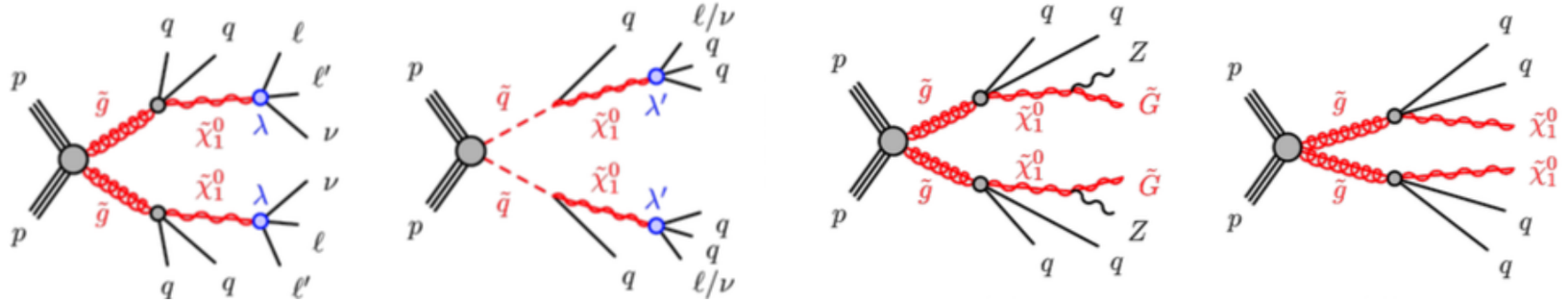
- SUSY RPV&Long-Lived signatures:
  - SUSY-based searches (RPV-SUSY, split-SUSY, GMSB, AMSB, etc..), but results sometime re-interpretable in a wider context
  - Organised according to the lifetime of the LLP:
    - displaced vertices (DV) or non pointing photons
    - unusual signatures: kinks, stopped particles in the detector material, …
    - slow particles or with anomalous specific ionisation



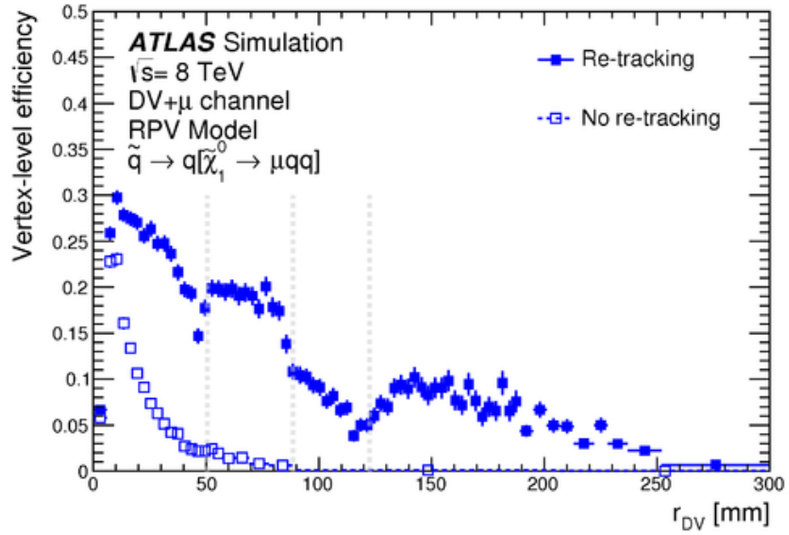
- EXOTIC Unconventional signatures and Exotic Higgs decays:
  - inspired by more exotic (SUSY and non-SUSY) scenarios: Hidden Valley, Dark sectors, HIP/Monopoles, fractional & multi-charged particles, Heavy Neutral Leptons
  - analyses designed mostly on signatures, often chosen exploiting ATLAS detector strengths

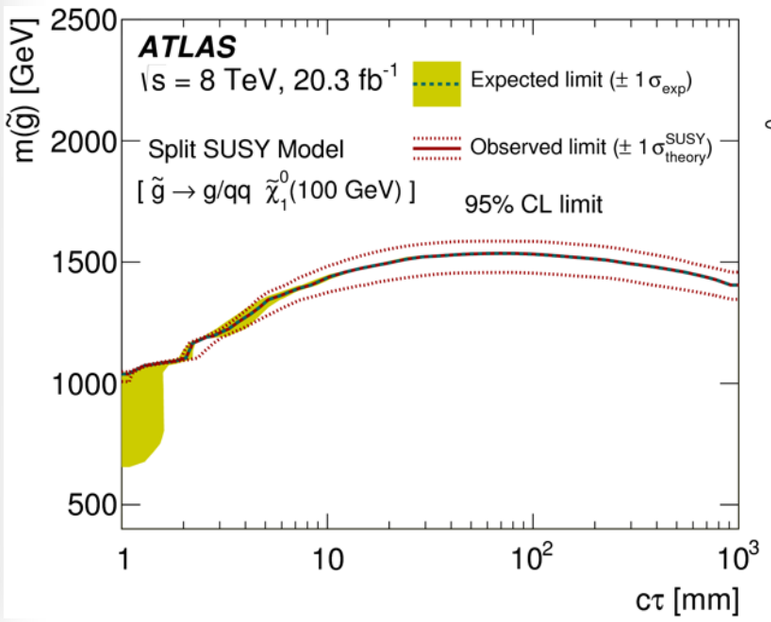
Phys. Rev. D 92, 072004 (2015)

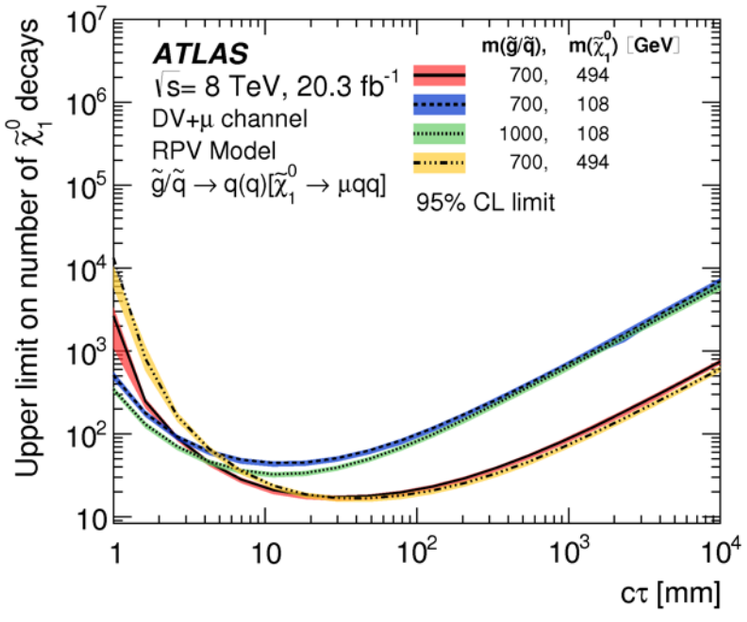
- SUSY Displaced Vertices
  - reconstruct secondary vertices for particles that decays after having traveled O(few cm)
  - generic search with multiple signal regions sensitive to different SUSY scenarios (RPV, GGM, Split-SUSY,…)

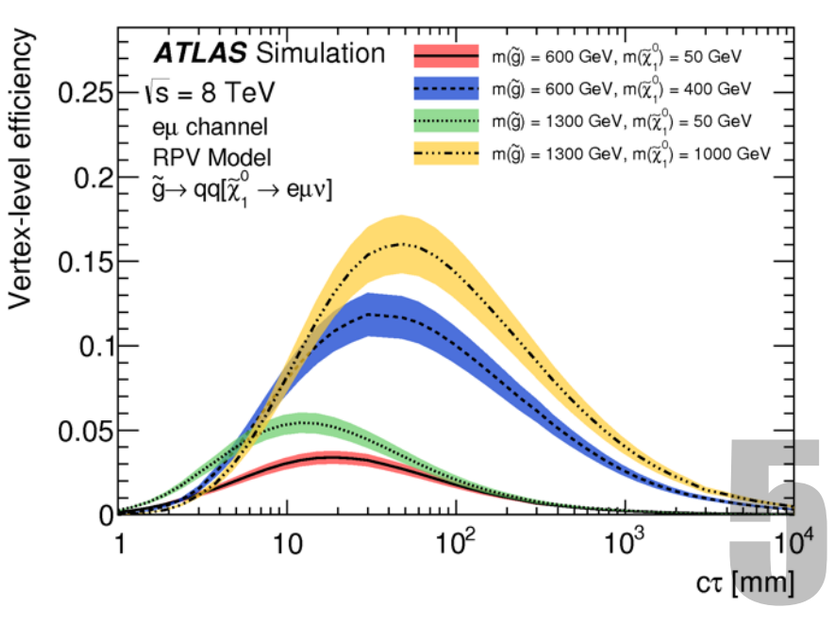


  - Multi-signature types considered: multitrack DV, dilepton DV
  - “Specialized” reconstruction of charged tracks non pointing to the PV
    - loose selection on tracks impact parameter and re-tracking using silicon hits non associated to standard ID tracks
    - improved secondary vertex efficiency up to decay lengths of ~30 cm wrt the PV ← strong effort to improve it in run2









Disappearing Tracks:

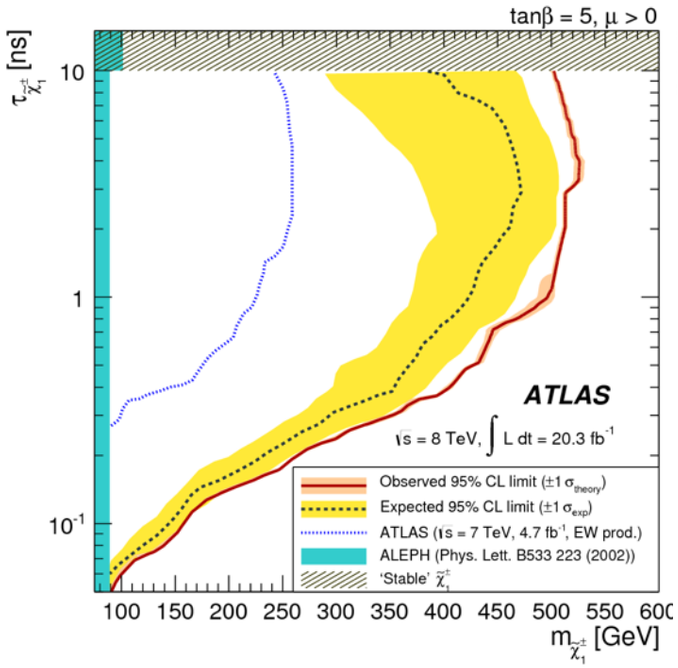
Phys. Rev. D 88 112006 (2013)

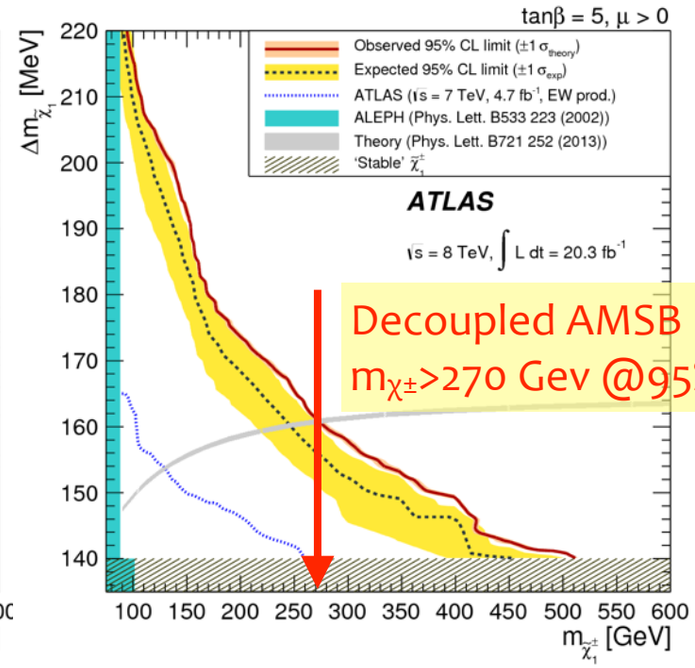
Carried on in the context of AMSB models, that predict lightest chargino nearly degenerate with lightest neutralino (LSP), resulting in long chargino lifetimes

Striking experimental signature: $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 \pi^{\pm}$
- with charged pion too soft (~100 MeV) to be reconstructed
- leads to charginos that "disappear"

Use a dedicate trigger (ISR jet) and modified ID tracking
Search for tracks with:
- inner silicon detector well measured
- outer TRT detector with low number of hits

Interpretation in the context of AMSB (tanβ=5, μ>0)

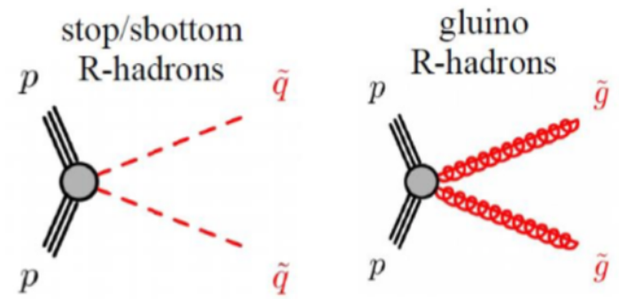




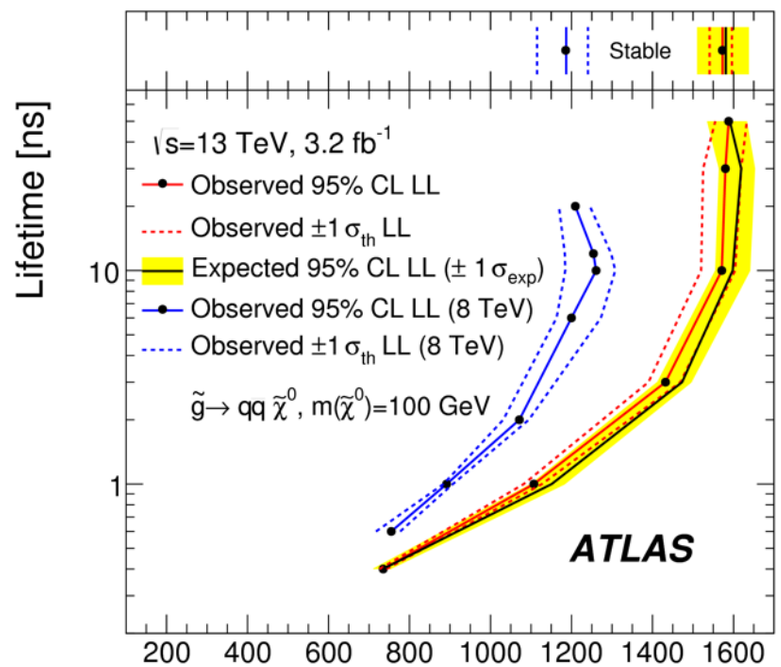
directly constrains the wino dark matter mass

dE/dx based massive LLP searches at 13 TeV:

Search for heavy (TeV scale) long-lived O(ns) charged particles: R-hadrons, meta-stable massive particles:



- heavy: β = v/c ≪ 1
- events triggered with missing energy and containing one high momentum, highly ionising isolated track
- dE/dx measured in inner pixel detector exploiting new insertable b-layer that improves truncated dE/dx
- final discriminant: reconstructed mass from βγ using dE/dx and momentum



arXiv:1604.04520 [hep-ex]

SUSY LLP: Summary

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit		Reference
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$ 495 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.54 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	*To appear*
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0 \to \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162

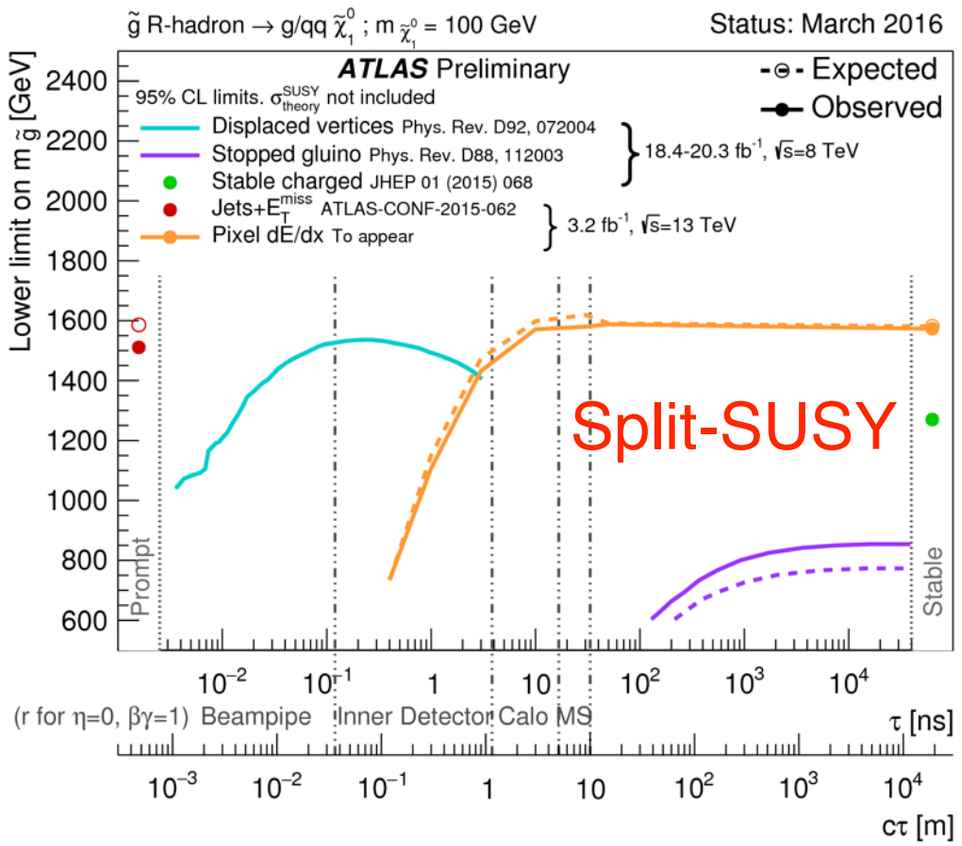
10^{-1} 1 Mass scale [TeV]

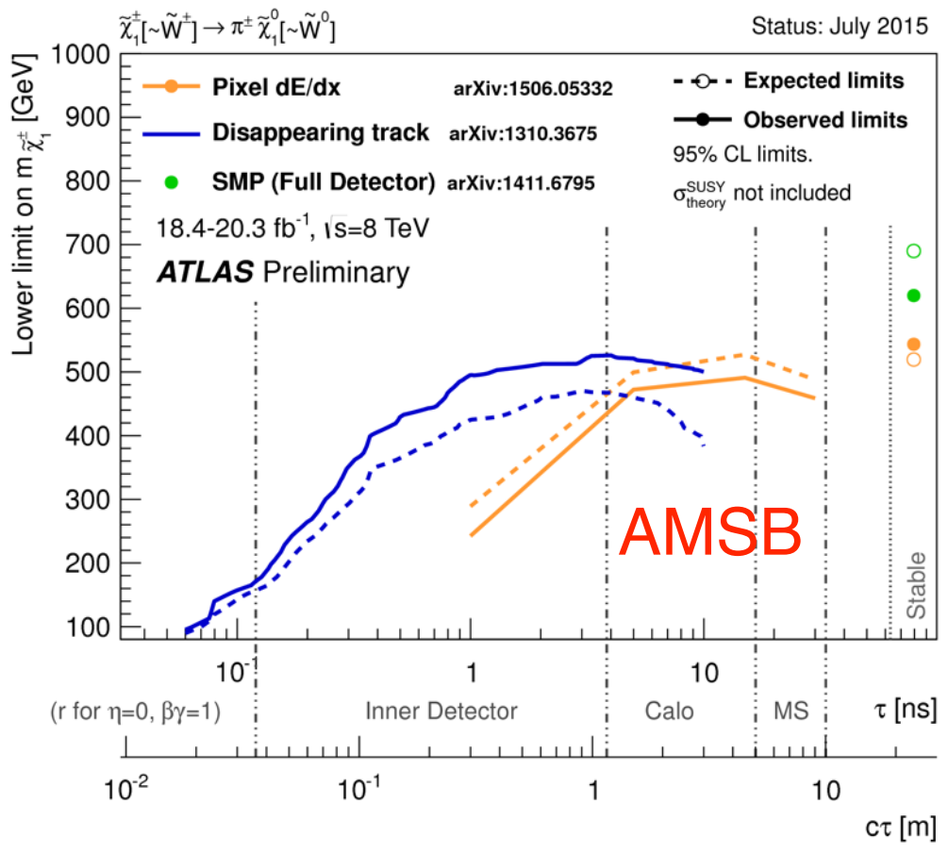
*Only a selection of the available mass limits on new states or phenomena is shown.

	Model	Signature	$\int \mathcal{L}\, dt$[fb^{-1}]	Lifetime limit		Reference
SUSY	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	χ_1^0 lifetime 7-740 mm	$m(\tilde{g}) = 1.3$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime 6-480 mm	$m(\tilde{g}) = 1.1$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^\pm$ lifetime 0.22-3.0 m	$m(\chi_1^\pm) = 450$ GeV	1310.3675
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	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 γ	20.3	χ_1^0 lifetime 0.08-5.4 m	SPS8 with $\Lambda = 200$ TeV	1409.5542
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime 0.12-90.6 m	$m(\tilde{g}) = 500$ GeV	1504.03634

0.01 0.1 1 10 100 $c\tau$ [m]

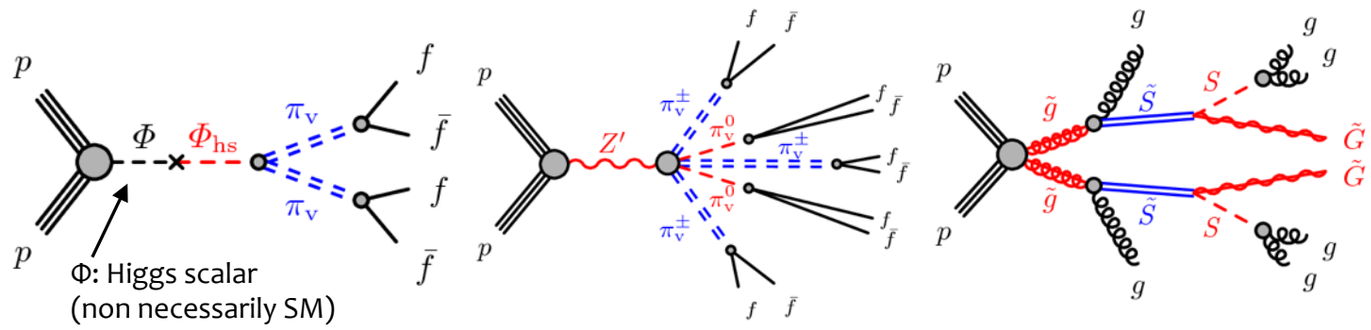
$\sqrt{s}$ = 8 TeV





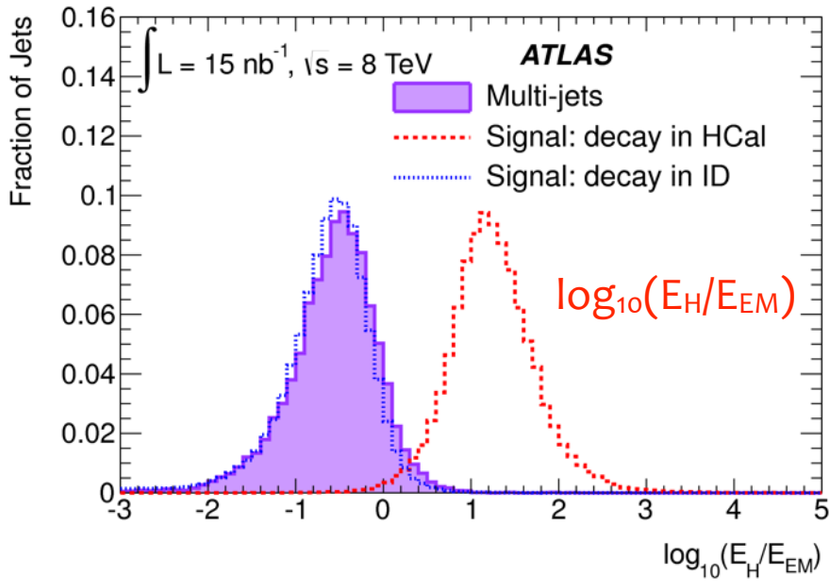
Search for displaced jets topologies predicted by models with Hidden sectors:

- benchmark models used for optimisation and interpretation: Hidden Valley with Higgs and Z' communicators, stealth-SUSY models

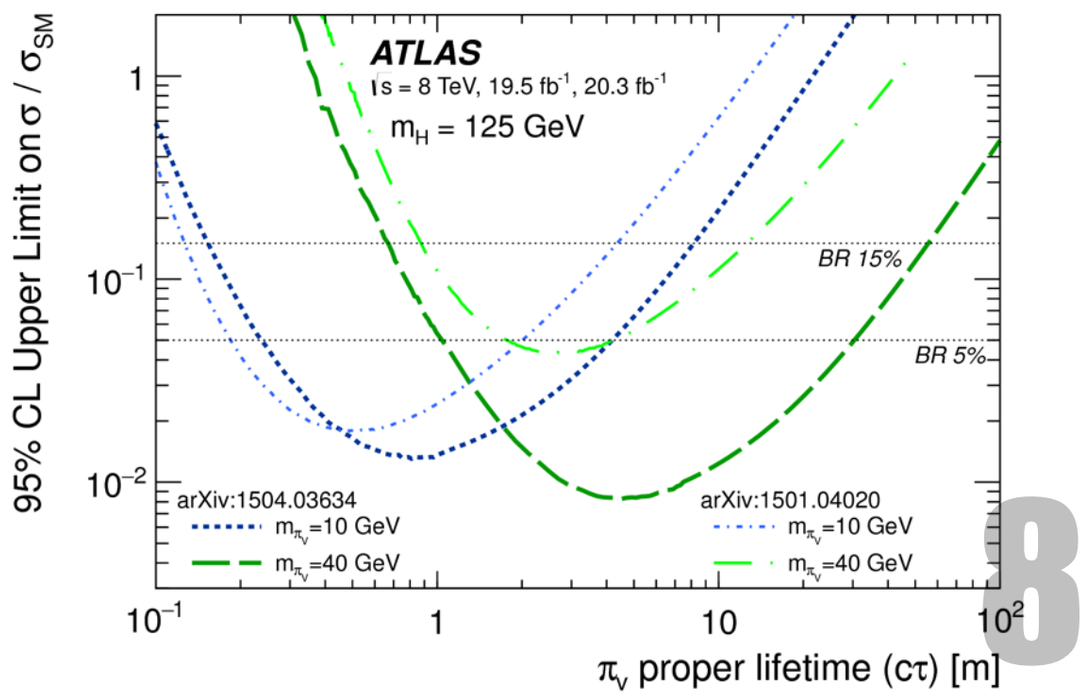


Two different searches:

- Trackless Jets analysis: aim at decays of LLP inside calorimeters
  - specialised calorimeter trigger to select decays into the hadron calorimeter
    - select narrow jets with an anomalous HAD/EM energy ratio ($\log_{10}(E_{HAD}/E_{EM})>1.2$) and $E_T>60$ GeV
    - no inner detector activity pointing toward the jets (track-less jets): no charged tracks with $p_T>1$ GeV in $\Delta R<0.2$



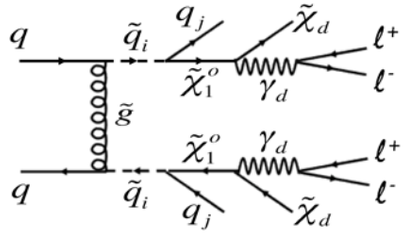
- Displaced Vertices in MS and ID analysis: aim at decays in the inner-tracker or in muon spectrometer
  - two specialised triggers:
    - MS: Muon RoI → cluster of standalone muons reconstructed by L1 trigger in a cone of $\Delta R<0.4$, isolated in the calorimeters and inner-tracker
    - ID: jet + MET → optimised for events with large jet multiplicity (Hidden Valley with Z' mediator)
  - custom algorithms developed to reconstruct standalone vertices in the muon spectrometer and very displaced vertices in the inner-tracker (in synergy with the SUSY-LLP DV analysis)

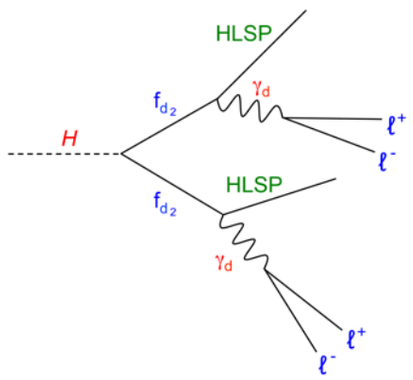


Physics Letters B 743 (2015) 15-34, Phys. Rev. D 92 (2015) 012010

EXOTIC LLP: LeptonJets

Search for light hidden particles from heavy mediators decays that very boosted in the lab frame producing collimated decay products, called LeptonJets (LJ)





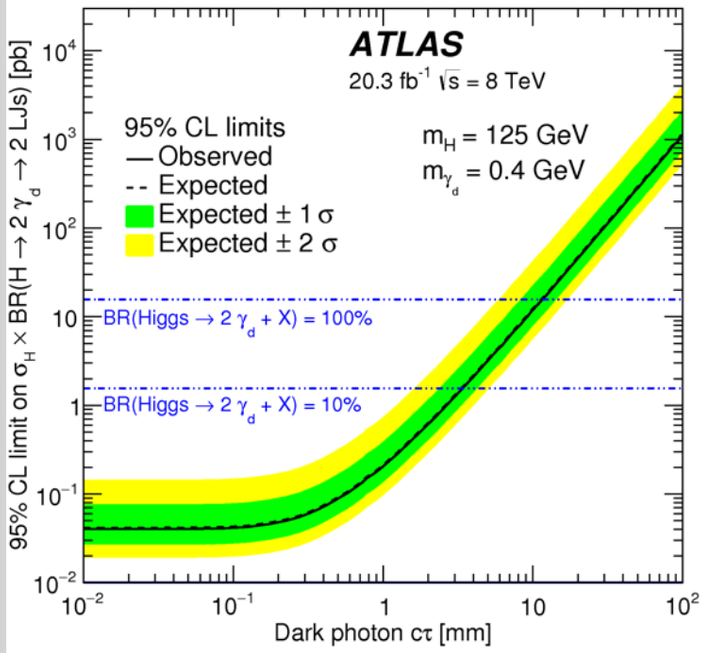
- Expected in different extensions of the SM:
  - Dark sectors: dark-SUSY, higgs-portal based models (FVRZ), …
    - connection to the hidden sector via kinetic mixing (ε), ε determines lifetime of dark photons
    - predict low mass dark photons decays to very collimated pair of electrons/muons/hadrons
    - BR($\gamma_d \rightarrow 2\mu$) sizeable O(40%) for $m_{\gamma d} > 2m_\mu$
  - also NMSSM: $h \rightarrow 2a + X \rightarrow 4\mu + X$ with light CP-odd scalar

Two independent search for prompt and displaced LJ:

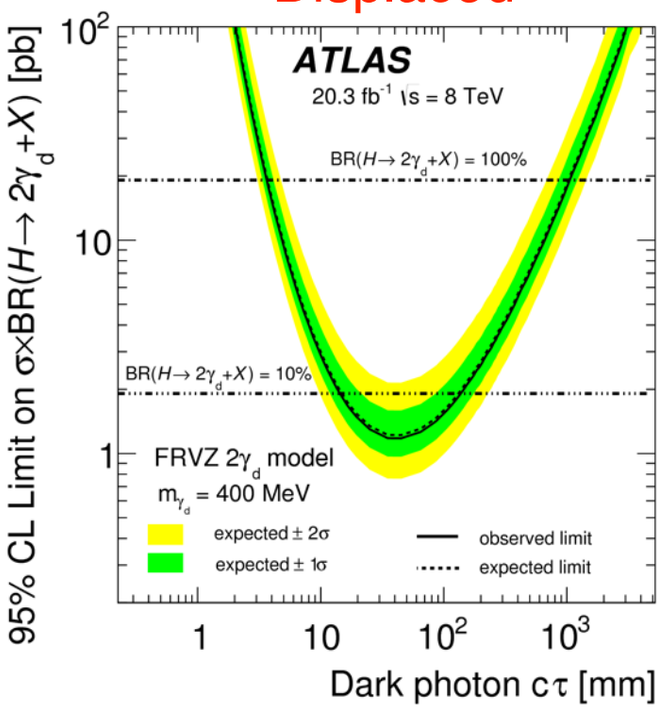
- model independent strategy starting from topological definition of LJ
- efficient also for LJ produced by multiple dark-photons collimated decays in ee/μμ/hadrons

- Triggers:
  - muon-LJ: 3MU6 standalone: low p_T, based only on muon spectrometer
    - implicitly select two-LJ topologies
  - e/had-LJ: jet with low E_T threshold (35 GeV) + unbalanced E_{HAD}/E_{EM} ratio → efficient for decays inside the hadron calorimeter

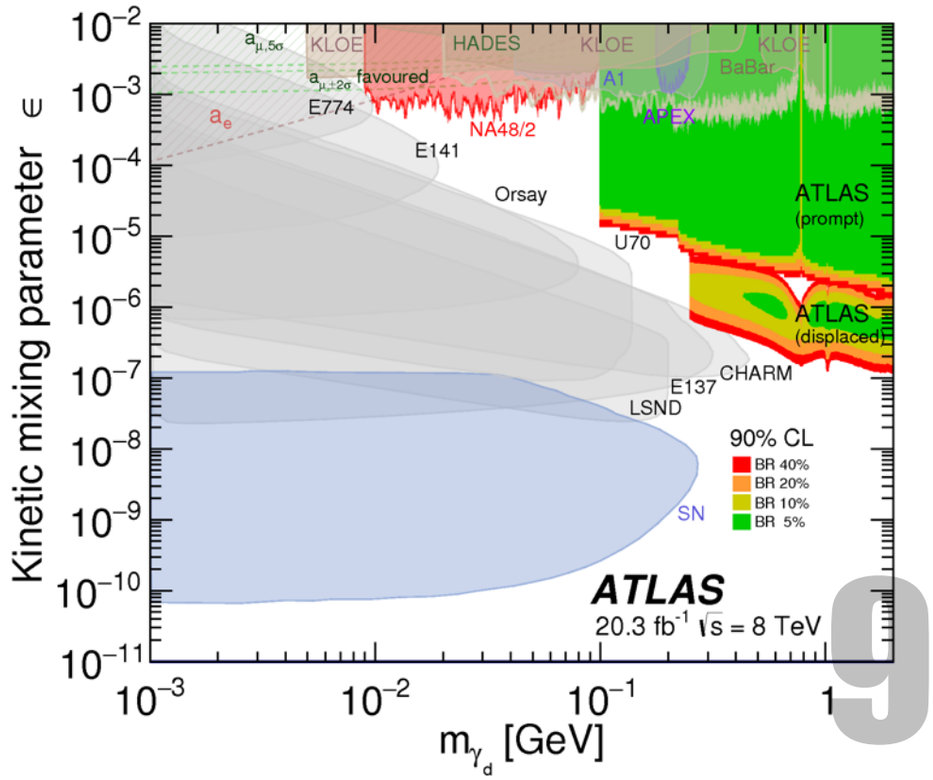
Prompt



Displaced



σ×BR limits interpreted as exclusion regions in the (ε,$m_{\gamma d}$) plane in the context of the Vector portal model as a function of the BR (h→ dark sector)

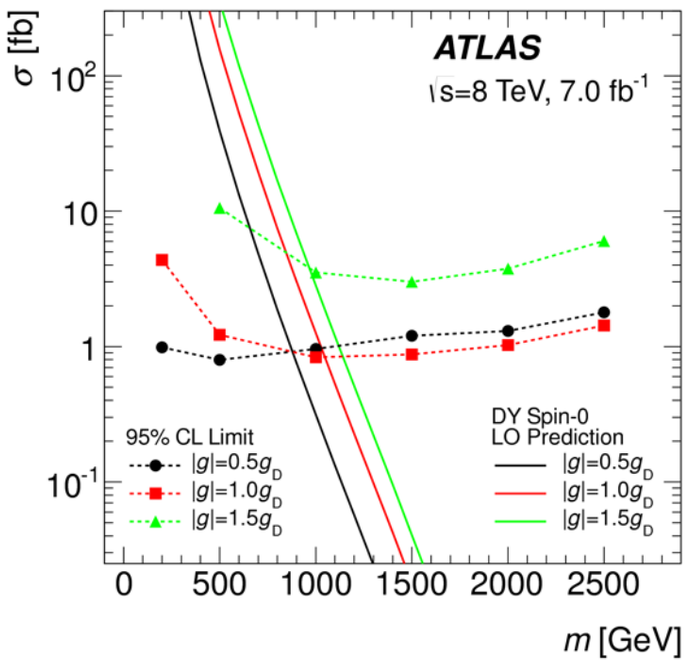


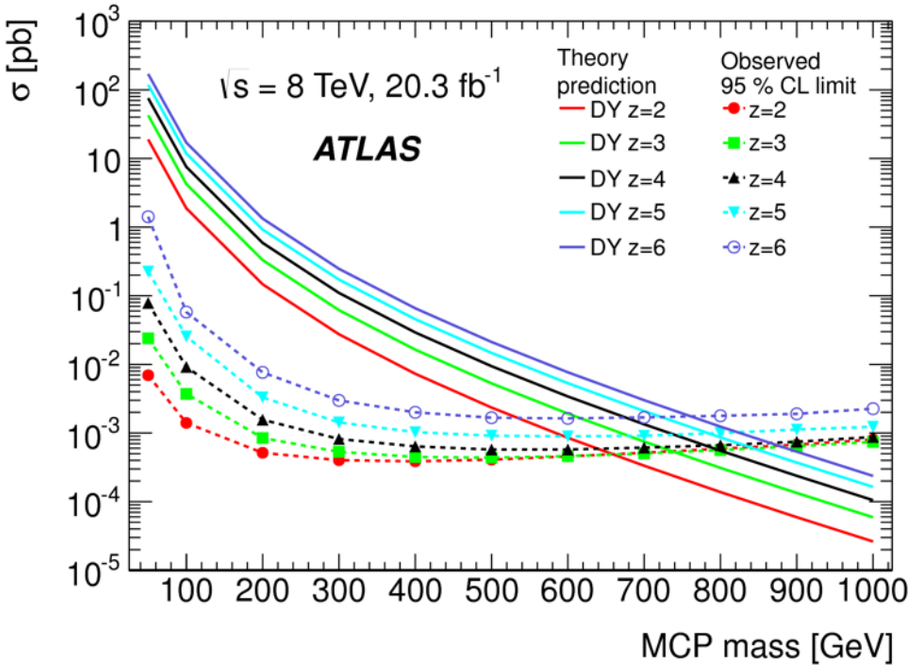
arXiv:1511.05542 [hep-ex], JHEP11(2014)088

Additional ATLAS Exotic LLP searches: performed or in progress:

- Magnetic Monopoles
- Multi-charged particles

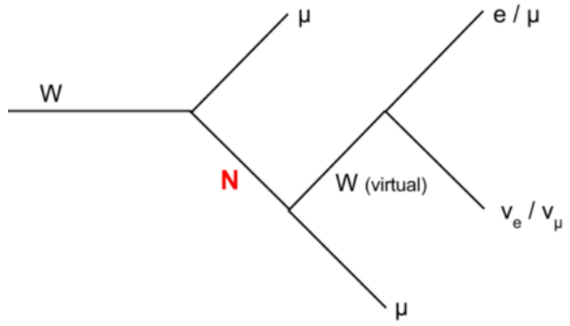
Eur. Phys. J. C (2015) 75:362, Phys. Rev. D 93, 052009 (2016)



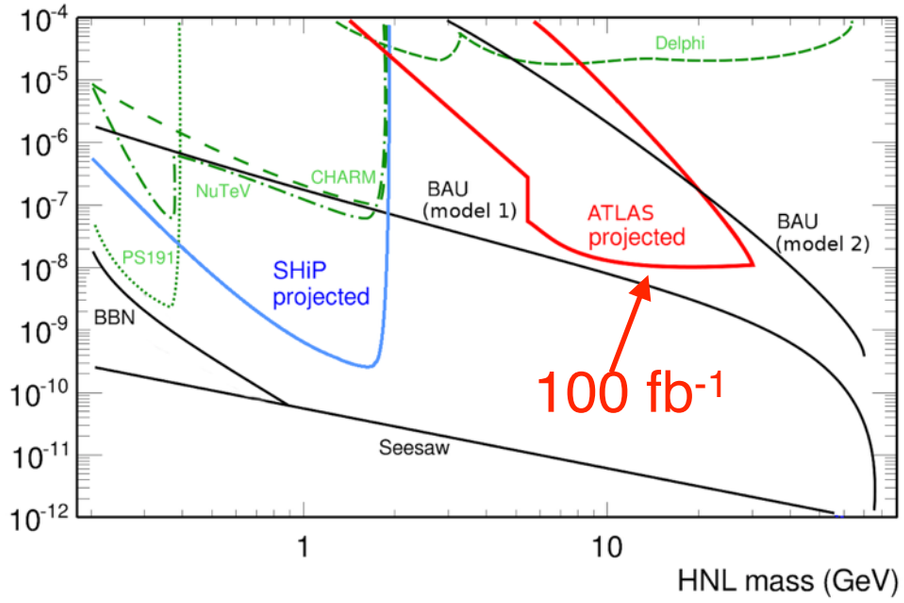


- Non collimated muons:
  - studied in the context of VLQ, GGM SUSY, HiddenSectors
  - also extend LeptonJets analysis to higher Z_d masses

- Heavy Neutral Leptons:
  - ex heavy LL right-handed neutrinos in vMSM



private extrapolation by P. Mermod



- Emerging jets:
  - dark or hidden sector quarks decay to the visible sector via multiple displaced vertices with different displacements within the same jet object
  - need specialised trigger and reconstruction to cope with SM BG

- Model-independent general search for final state of two stable particles, one electrically charged and the other neutral

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

Status: July 2015

ATLAS Preliminary

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

	Model	Signature	$\int \mathcal{L}\, dt$[fb^{-1}]	Lifetime limit		Reference
SUSY	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	χ_1^0 lifetime 7-740 mm	$m(\tilde{g}) = 1.3$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime 6-480 mm	$m(\tilde{g}) = 1.1$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^\pm$ lifetime 0.22-3.0 m	$m(\chi_1^\pm) = 450$ GeV	1310.3675
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	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 γ	20.3	χ_1^0 lifetime 0.08-5.4 m	SPS8 with $\Lambda = 200$ TeV	1409.5542
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime 0.12-90.6 m	$m(\tilde{g}) = 500$ GeV	1504.03634
Higgs BR = 10%	Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.41-7.57 m	$m(\pi_v) = 25$ GeV	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.31-25.4 m	$m(\pi_v) = 25$ GeV	1504.03634
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 14-140 mm	$H \to 2\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 15-260 mm	$H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
Higgs BR = 5%	Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.6-5.0 m	$m(\pi_v) = 25$ GeV	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.43-18.1 m	$m(\pi_v) = 25$ GeV	1504.03634
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 28-160 mm	$H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
300 GeV scalar	Hidden Valley $\Phi \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.29-7.9 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.19-31.9 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
900 GeV scalar	Hidden Valley $\Phi \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime 0.15-4.1 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.11-18.3 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
Other	HV Z'(1 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	π_v lifetime 0.1-4.9 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
	HV Z'(2 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	π_v lifetime 0.1-10.1 m	σ×BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634

0.01 0.1 1 10 100 $c\tau$ [m]

$\sqrt{s}$ = 8 TeV

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

Limitations in the LLP searches performed in ATLAS, and ongoing work & wish list of things useful to cope with it …

- experimental:
  - triggers:
    - need to develop custom algorithms and fight for bandwidth and resources
    - this has strongly constrained the number of triggers that have been developed for LLP searches in ATLAS in Run-1, limiting the development of more general / broader acceptance ones in favour of very specialised ones optimised for specific theory benchmarks
    - ongoing developments: new triggers able to extend explorable topologies (i.e. single LLP decays in contrast to the typical pair production explored in run-1), wider lifetime range, more efficient, and robust against pileup
      - ID:
        - exploiting new fast tracking (FTK) to implement b-jet like triggers tailored for very displaced decays
        - explicit reconstruction of displaced secondary vertices in triggers at HLT
        - exploit anomalies in hit multiplicities in the vicinity of jet tracks due to decays of the LLP
      - CaloRatio trigger:
        - improved Run-2 algorithm with new L1 topo trigger that requires no EM activity, is pileup safe and more clean wrt LAr noise and beam-related BG
      - Muon triggers:
        - new narrow-scan muon trigger, allow to reconstruct collimated muons with low p_T
        - a factor 3 more efficient of Run-1 trigger used for displaced decays (3MU6_SA), and allows to trigger on a single LeptonJet (single LeptonJets searches, etc..)

Comments and initial thoughts

- experimental:
  - custom reconstruction / simulation: re-tracking, high displaced vertices, vertices in the muon spectrometer, simulation of energy loss and propagation of very exotic particles …
    - some of these tasks require in ATLAS a very high level of technical skills to be performed → either slow down the analysis and/or accept compromises in terms of performances / discovery potential
    - also standard quality definitions for physics objects, performance assessment, validation, procedure for evaluation of systematic uncertainties etc., from detector/reconstruction performance groups cannot be applied to LLP analyses
    - ongoing developments:
      - increased effort on large-radius tracking and DV reconstruction spanning different physics and performance groups
      - optimisation of muon reconstruction parameters / definition for standalone muons / and muons non pointing at the PV to be used in LLP analyses
    - would also be certainly beneficial for some of these tasks (like inclusion in G4 of propagation and interaction of non standard particles (monopoles, multi/fractional-charged particles, quirks, …)) to coordinate the work among experiments

- theory related:
  - a complete survey of the interesting LLP topologies to be studied + a set of simplified models agreed among the theory community that can be used to setup/design the different searches
    - will prevent to design searches optimised for specific theory models
    - specific benchmarks will be useful to compare results from different experiments
  - a more coherent and complete view of what theorists need to recast/reinterpret our results in different contexts would be certainly beneficial
  - a set of common tools to calculate and plot exclusions regions in the different simplified models (and benchmark models) parameter space

- sociological:
  - manpower:
    - LLP searches not considered mainstream in ATLAS → important to convey the message that LLP searches is a very important tool to exploit the discovery potential of LHC
    - analyses takes often longer time to get to publication level due to the issues listed above …