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Searches for long-lived particles in Hidden Valley scenarios with the Atlas detector at the LHC

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Outline

- Why Long-Lived Particle searches
- The Hidden Valley scenario
- Run 1 strategy and results from the Atlas experiment:
  - ✓ Neutral LLP searches in the Hadronic Calorimeter
  - ✓ Neutral LLP searches in the Inner Detector and/or in the Muon Spectrometer
- Summary and Run 2 prospects

On the trail of particle longevity

The shortcomings of the Standard Model (SM) have motivated many attempts to develop intriguing, sometimes promethean, paradigm extensions.

Long-Lived Particles (LLPs) are indirect hints of new physics: their existence is predicted by many theories and models beyond the SM such as MSSM with R-Parity violation, gauge-mediated SUSY extensions of the MSSM, stealth SUSY models, Hidden Sectors.

Among others dark matter must be long-lived …

There is enough theory serving us guiding predictions for such out-of the-box searches → further incentive to develop LLP model independent search strategies.

These models can give rise to a broad range of specific unconventional signatures, depending on lifetime, charge, velocity and decay channels of LLP.

LLP searches: the experimental perspective
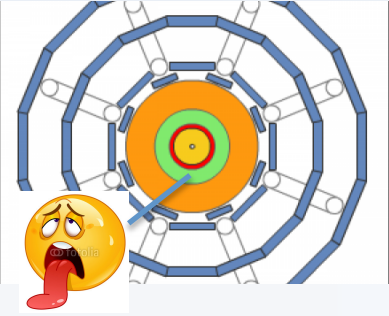
- **The detector:**
  Revealing displaced vertices in tracking detectors, disappearing tracks, decays in the calorimeter, displaced muonic jets is not the task the Atlas detector was designed for.

- **The trigger:**
  These particles provide unique experimental signature and would be discarded in collision events. The ATLAS Collaboration has developed dedicated algorithms for such unconventional searches.

- **Data analysis techniques:**
  Despite low background affecting LLPs analysis, instrumental effects could mimic some of the signatures and are poorly simulated by Monte Carlo. Sophisticated data-driven background estimation techniques implemented.

Huge efforts performed during RUN 1, inspired by some benchmark models

A premise

During this talk you'll be flooded with a plethora of :

HV -> Hidden Valley
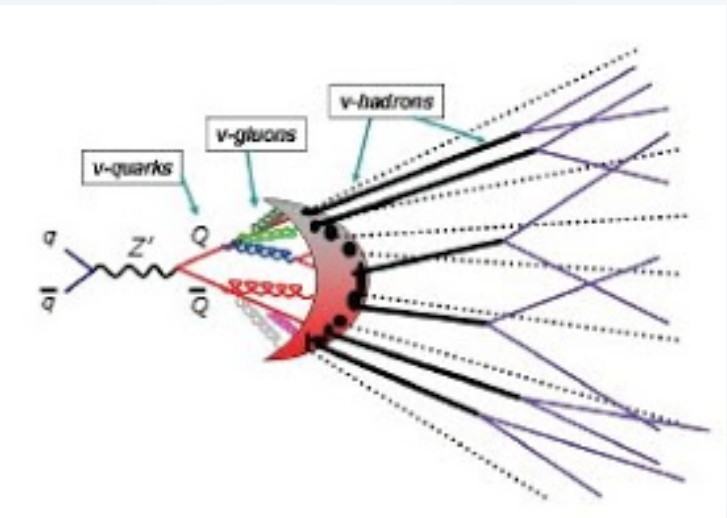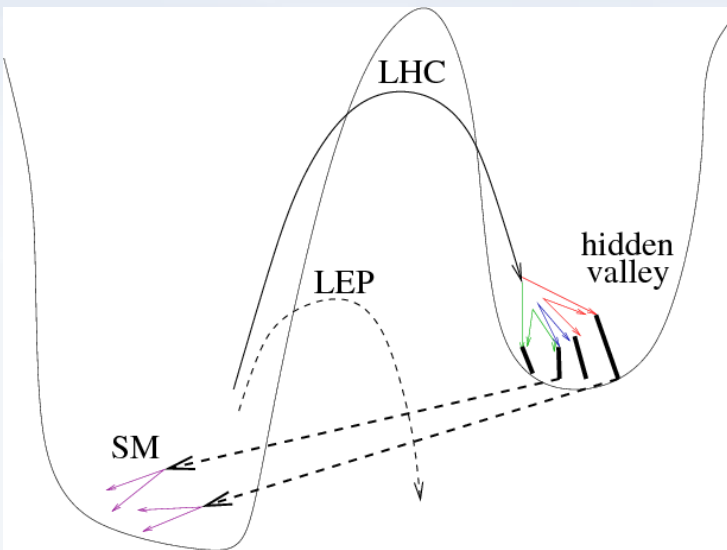LLP ->Long Lived Particle
DV -> Displaced Vertices
.
MS
ID
VRs
.
.
ID-MS-HV-LLP-DV … -> **apologize for the acronym abuse**

Hidden Valley Models ❖

- Hidden Valley (HV) refers to a large class of models with a new low mass scale physics sector, which might have evaded detection so far due to its weak coupling to the SM.

- The Higgs boson could be a mediator between the two sectors and the LHC is powerful enough to climb over the potential barrier produced by the mediator.

- In one such model, the new physics resembles QCD, and the primary production mechanism is that of v-quark pairs which v-hadronize.

- One crucial difference is the absence of stable particles at the end of the HV decay chain, so that v-hadrons decay back into SM particles.

- The signature of such models can be unusual and spectacular: states with a relatively long life-time lead to highly displaced vertices and large multiplicities of soft particles in jets.

❖ *Strassler, Zurek* (hep-ph:0604261,0605193,0607160)

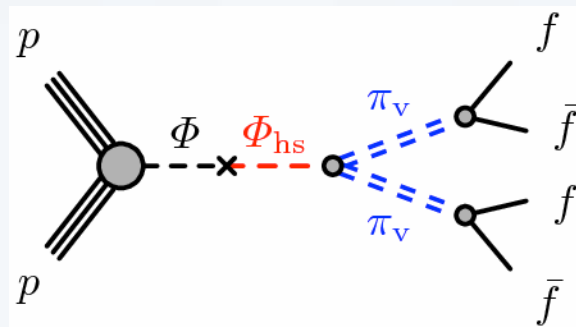# The benchmark model: Hidden Valley neutral LLPs

Hidden Valley is a very wide concept.
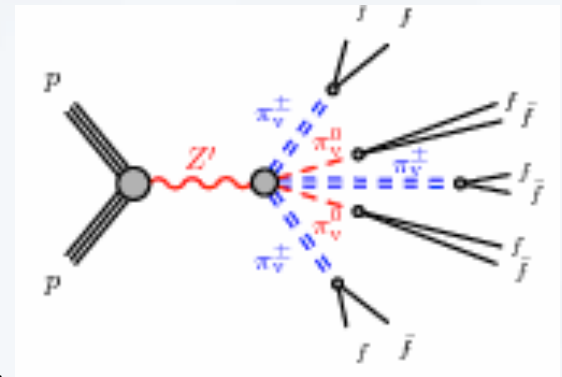This search is optimized for neutral LLPs produced in

- Hidden Valley models through Higgs or Z' decays

Phys. Lett. B 651, 374-379, 2007
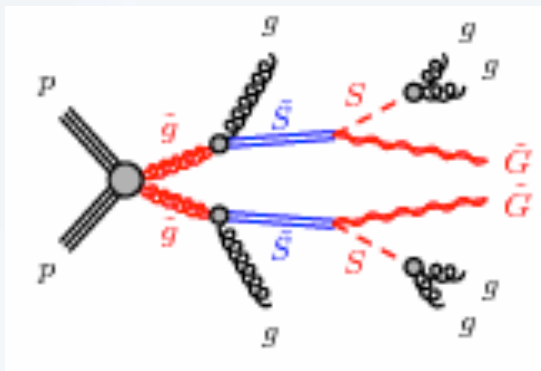*Phys. Lett. B 661, 263-268, 2008*

≥ two displaced hadronic jets

- Stealth SUSY models

JHEP 1111:012, 2011
JHEP 1207:196, 2012

... + 2 prompt hadronic jets

LLP search in the Hadronic Calorimeter

Phys. Lett. B, 743, 15-34 (2015)

Benchmarch process: $\phi \rightarrow \pi_V \pi_V$

- Scalar boson ϕ decays to a pair of v-particles which in turn decay to SM fermions (mostly b-quark).

- Several combinations of ϕ and π_V masses investigated.

ϕ Mass [GeV]	π_V Mass [GeV]
100	10, 25
126	10, 25, 40
140	10, 20, 40
300	50
600	50, 150
900	50, 150

The particle does not reach the muon system.
Challenging and spectacular signature: search for localized energy bursts in the Hadronic Calorimeter

Dedicated trigger: CalRatio trigger

Look for displaced jets final states in HCAL with:
- ✓ a narrow radius and no charged track match
- ✓ little or no energy deposit in ECAL

Background:
mainly multi-jet events
cosmic ray and beam-halo contributions negligible

→ estimated from data
require E_t^{miss} < 50 GeV

LLP search in HCal: the CalRatio trigger

For a long-lived particle decaying in the calorimeter a narrow jet is produced with

✓ the ratio of energy in HCAL to that in ECAL larger than from jets originated at the IP

✓ no nearby tracks pointing back to the IP
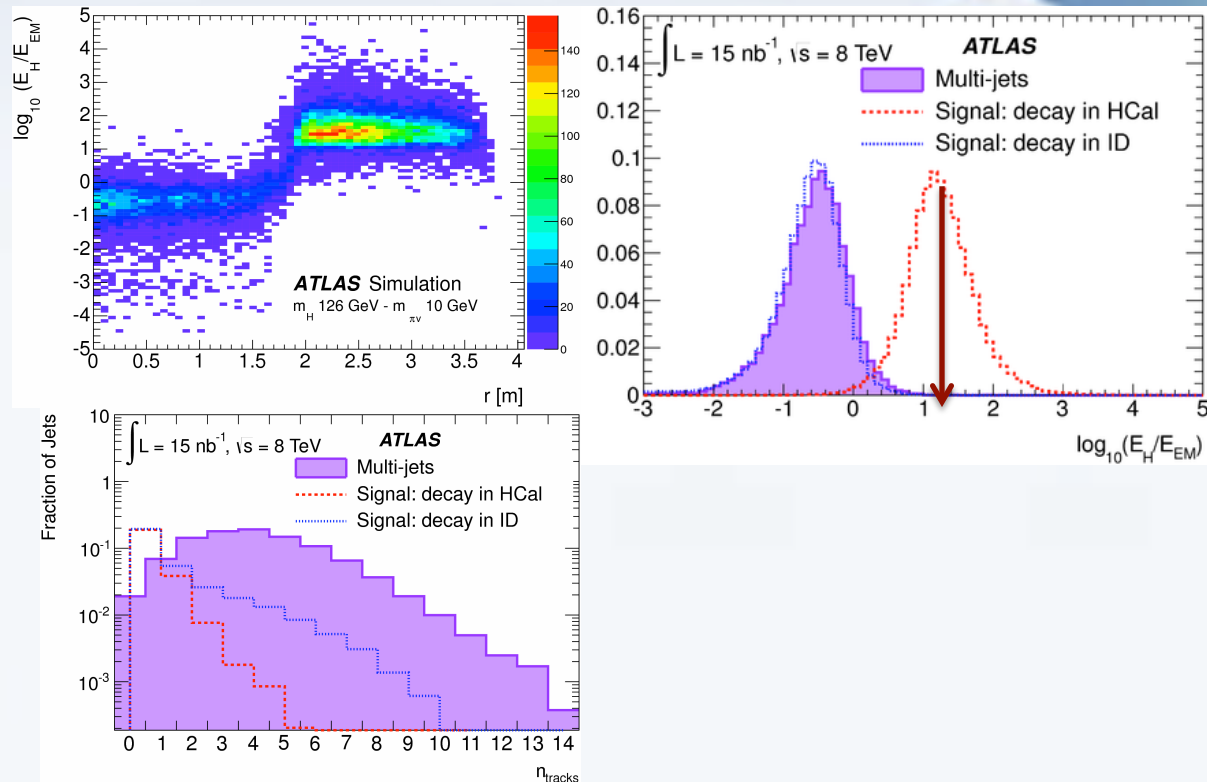
Developed a custom trigger (*JINST 8 (2013) P07015*) to select signal events:
- $\log(E_{HAD}/E_{EM}) > 1.2$
- $E_T > 35$ GeV
- no ID tracks in region around jet direction

Efficiency around 60% in barrel and 35% in endcap regions

HCal displaced decays: results

8 TeV Run 1 Data

No significant excess of events over the estimated background

Background	Expected events
SM Multi-jets	23.2 ± 8.0
Cosmic rays	0.3 ± 0.2
Total expected background	23.5 ± 8.0
Data	24

95% upper limits on σ×BR as a function of the π_V proper decay length for communicator masses ≠ 126 GeV
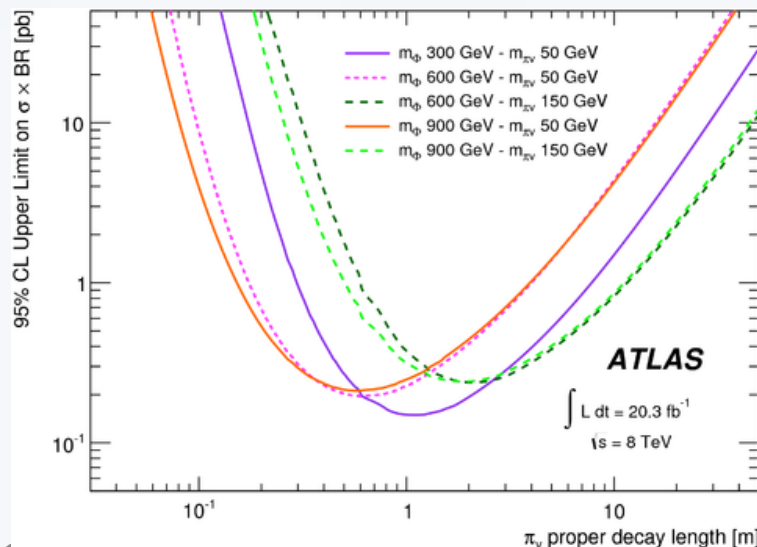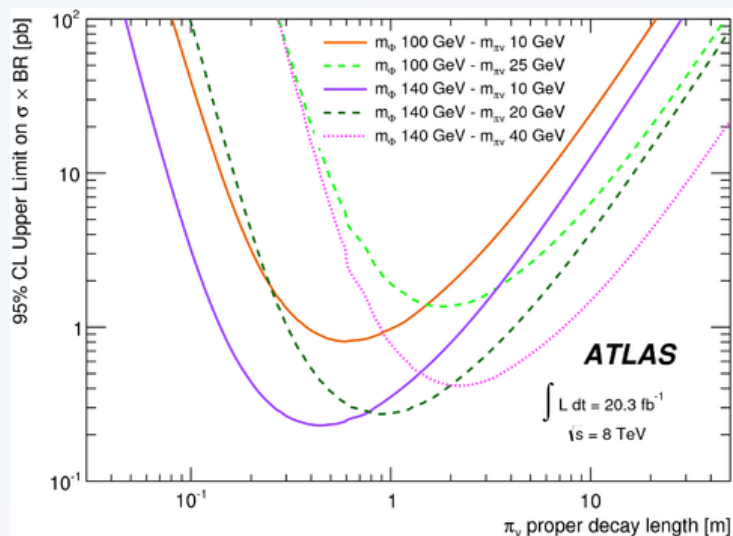
HCal displaced decays: results
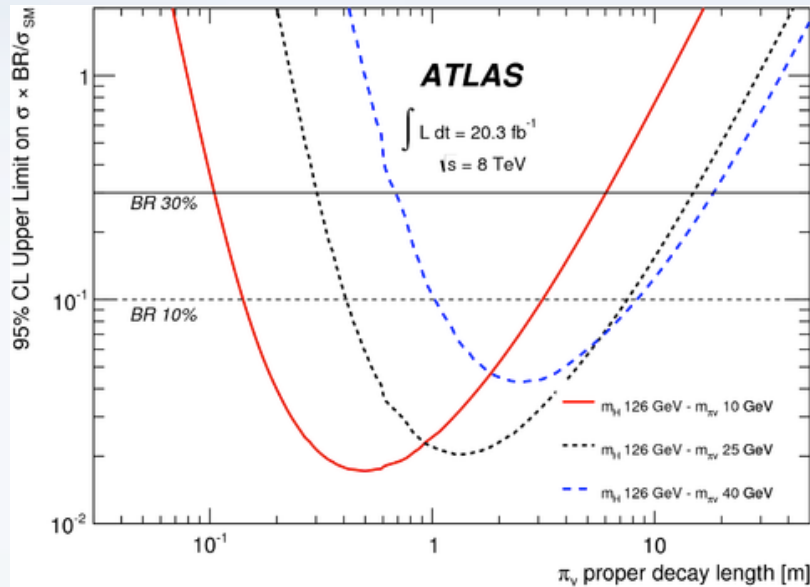
8 TeV Run 1 Data

m_H = 126 GeV

MC sample m_H, $m_{\pi v}$ [GeV]	Excluded range 30% BR $H \to \pi_V \pi_V$ [m]	Excluded range 10% BR $H \to \pi_V \pi_V$ [m]
126, 10	0.10 – 6.08	0.14 – 3.13
126, 25	0.30 – 14.99	0.41 – 7.57
126, 40	0.68 – 18.50	1.03 – 8.32

LLP search in the Inner Detector and the Muon Spectrometer

Benchmarch processes:

Phys. Rev. D 92, 012010 (2015)

$$\phi \to \pi_V \pi_V$$

HV models

$$Z' \to \text{ showers of } \pi_V$$

Stealth SUSY model $\hat{g} \to \hat{S}$ (not prompt) g (one prompt jet)

$\searrow$ $S \ \hat{G}$

$\searrow$ gg (two displaced jets)

Several combinations of mass parameters investigated for each sample

Scalar boson mass [GeV]	π_v mass [GeV]
100	10, 25
125	10, 25, 40
140	10, 20, 40
300	50
600	50, 150
900	50, 150

Z' mass [TeV]	π_v mass [GeV]
1	50
2	50
2	120

$\tilde{g}$ mass [GeV]	$\tilde{S}, S$ mass [GeV]
110	100, 90
250	100, 90
500	100, 90
800	100, 90
1200	100, 90
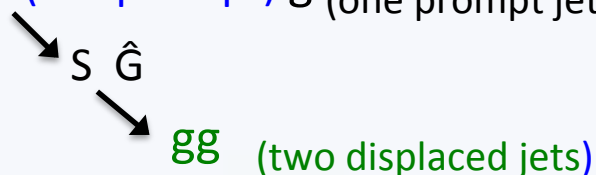
Dedicated triggers and standalone vertex reconstruction both in the ID and MS.

Look for a pair of displaced vertices in the ID, MS or one in each

Trigger	Applicable topologies	Benchmarks
Muon RoI Cluster	IDVx+MSVx, 2MSVx	Scalar boson, Stealth SUSY
Jet+E_T^{miss}	2IDVx, IDVx+MSVx, 2MSVx	Z'

Negligible background from fake vertices estimated from data

First search results for displaced decays in Z' and Stealth SUSY models

MS-ID displaced decays: the triggers
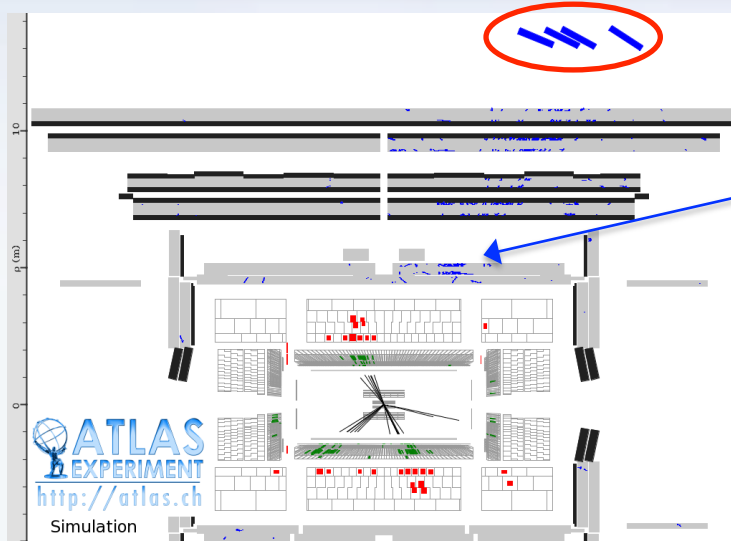
LLP decays in the MS are characterized by a large number of charged tracks and a cluster of Level 1 muon segments (ROIs)

Muon RoI Trigger

Custom MS cluster trigger (*JINST 8 (2013) P07015*) developed to select events with
- ✓ a cluster of muon ROIs in a $\Delta R = 0.4$ cone with little or no activity in the ID or calorimeters

Jet + E_T^{miss} dedicated trigger to select decays in the ID with large jet multiplicity (Z' -> many π_Vs)
- ✓ Leading jet $E_T > 110$ GeV
- ✓ $E_T^{miss} > 75$ GeV
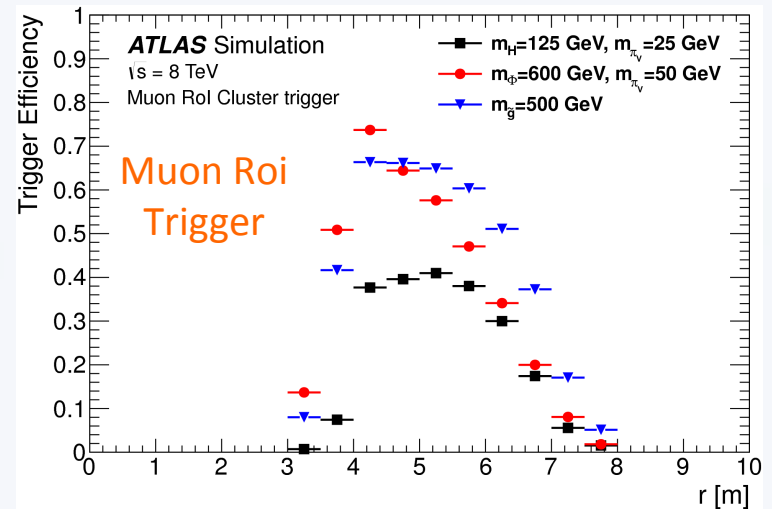
→ Trigger efficiency around 87% - 100%, depending on the MC simulated Z' sample

MS displaced decays: vertex reconstruction

MS vertex reconstruction (VR) (*JINST 9 P02001 (2014)*:
- construct track segments from hits in the two multilayers of an MDT chamber
- merge segments in tracklets according to specific criteria.

Detectable decay vertices between the outer edge of HCAL and the middle station of the muon chambers.
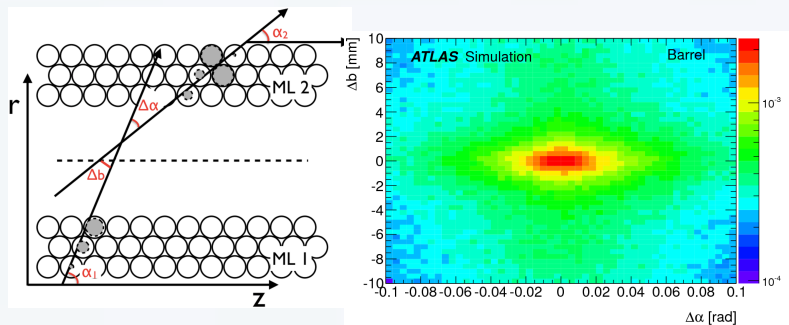
Requirement	Barrel	Endcap
MDT hits	$300 \leq n_{\mathrm{MDT}} < 3000$	$300 \leq n_{\mathrm{MDT}} < 3000$
RPC/TGC hits	$n_{\mathrm{RPC}} \geq 250$	$n_{\mathrm{TGC}} \geq 250$
Track isolation	$\Delta R < 0.3$	$\Delta R < 0.6$
Track Σp_{T}	$\Sigma p_{\mathrm{T}} < 10$ GeV	$\Sigma p_{\mathrm{T}} < 10$ GeV
Jet isolation	$\Delta R < 0.3$	$\Delta R < 0.6$

Run 2 data - NEW

MS VR algorithm tested on **Run 2 data** and **working**.
Sample cuts: Atlas data quality criteria + minimum track selection for background rejection.
Beam-halo contribution not quantified.

Toroidal structure of the Atlas magnetic coil is visible
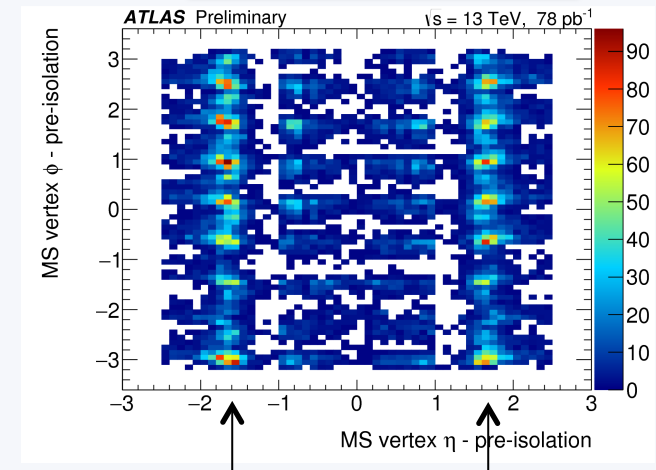
Gap between barrel and end-cap calorimeters

ID displaced decays: track and vertex reconstruction

ID track reconstruction
For a displaced decay in the Inner Detector the impact parameters of tracks are generally larger than those allowed by the default reconstruction algorithm: many unassociated (to any tracks) hits are produced.
Use a dedicated algorithm developed for a SUSY LLP DV analysis.

ID vertex reconstruction algorithm identifies secondary vertices in the ID based on the Atlas primary reconstruction algorithm.
✓ Background removed through **Good vertex criteria**❖
✓ Efficiency from 15 to 30% for different benchmarks.

❖

Requirement	Muon Cluster channel	Jet+E_T^{miss} channel
d/σ from material	≥ 6	≥ 6
Vertex χ^2 prob.	> 0.001	> 0.001
ΔR(vtx,jet)	< 0.4	< 0.6
Number of tracks	≥ 5	≥ 7

Track reconstruction		
Parameter	Default value	Modified value
Max. d_0	$10\,\mathrm{mm}$	$500\,\mathrm{mm}$
Max. $|z_0|$	$320\,\mathrm{mm}$	$1000\,\mathrm{mm}$
Min. number of silicon hits	6	2
Max. number of shared hits	1	2
Tracks for vertex reconstruction		
Parameter	Default value	Modified value
Min. d_0	–	$10\,\mathrm{mm}$
Max. $d_0/\sigma(d_0)$	5	–
Max. $|z_0|/\sigma(z_0)$	10	–
Min. number of silicon hits	6	4
Min. number of pixel hits	1	0
Min. number of SCT hits	4	2
Max. track $\chi^2/\mathrm{d.\,o.\,f.}$	3.5	5

Parameters used for ID track and vertex reconstruction

MS-ID displaced decays: results

95% CL limits as a function of the LLP proper decay length for the three benchmark models
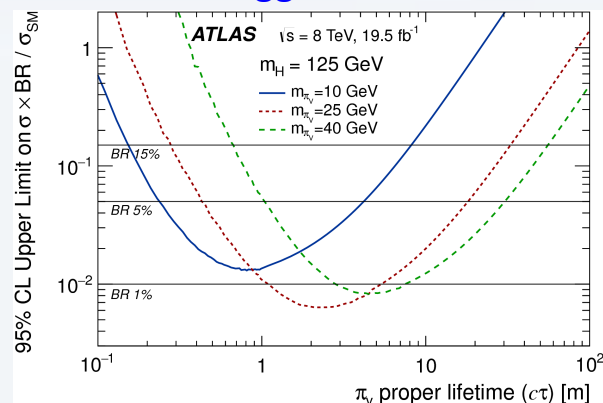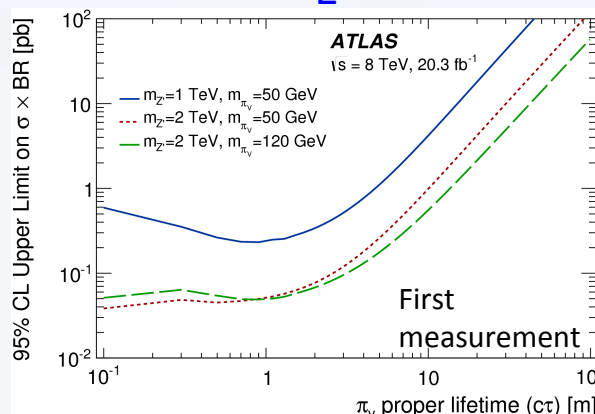
Higgs boson   **Z'**   **Stealth SUSY**
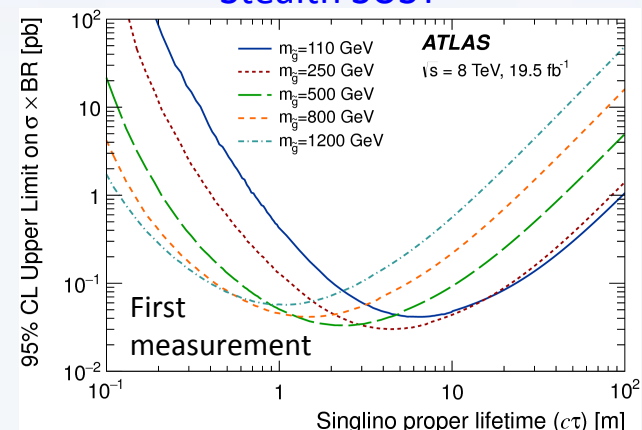
No significant excess of events above the background expectation is observed

Topology	m_{π_v} [GeV]	Expected events		Observed events
		Signal	Background	
IDVx+MSVx	10	1.9 ± 1.4		
	25	62 ± 8	2.0 ± 0.4	0
	40	41 ± 6		
2 MSVx	10	234 ± 15		
	25	690 ± 26	$0.4^{+0.3}_{-0.2}$	2
	40	313 ± 18		

Scalar boson benchmark model with m_H = 125 GeV

Status of HV-LLP searches in Atlas after LHC Run 1

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

Status: July 2015

ATLAS Preliminary

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

Stealth SUSY

Hidden Valley

Z'

	Model	Signature	$\int \mathcal{L}\, dt\,[\text{fb}^{-1}]$	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	$m(\tilde{g}) = 1.3\ \text{TeV}, m(\chi_1^0) = 1.0\ \text{TeV}$	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime 6-480 mm	$m(\tilde{g}) = 1.1\ \text{TeV}, m(\chi_1^0) = 1.0\ \text{TeV}$	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	$m(\chi_1^{\pm}) = 450\ \text{GeV}$	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	$m(\chi_1^{\pm}) = 450\ \text{GeV}$	1506.05332
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime 0.08-5.4 m	SPS8 with $\Lambda = 200\ \text{TeV}$	1409.5542
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime 0.12-90.6 m	$m(\tilde{g}) = 500\ \text{GeV}$	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	$m(\pi_v) = 25\ \text{GeV}$	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.31-25.4 m	$m(\pi_v) = 25\ \text{GeV}$	1504.03634
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 14-140 mm	$H \to 2\gamma_d + X, m(\gamma_d) = 400\ \text{MeV}$	1409.0746
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 15-260 mm	$H \to 4\gamma_d + X, m(\gamma_d) = 400\ \text{MeV}$	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	$m(\pi_v) = 25\ \text{GeV}$	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.43-18.1 m	$m(\pi_v) = 25\ \text{GeV}$	1504.03634
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime 28-160 mm	$H \to 4\gamma_d + X, m(\gamma_d) = 400\ \text{MeV}$	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	$\sigma \times BR = 1\ \text{pb}, m(\pi_v) = 50\ \text{GeV}$	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.19-31.9 m	$\sigma \times BR = 1\ \text{pb}, m(\pi_v) = 50\ \text{GeV}$	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	$\sigma \times BR = 1\ \text{pb}, m(\pi_v) = 50\ \text{GeV}$	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime 0.11-18.3 m	$\sigma \times BR = 1\ \text{pb}, m(\pi_v) = 50\ \text{GeV}$	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	$\sigma \times BR = 1\ \text{pb}, m(\pi_v) = 50\ \text{GeV}$	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	$\sigma \times BR = 1\ \text{pb}, m(\pi_v) = 50\ \text{GeV}$	1504.03634

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

$\sqrt{s} = 8\ \text{TeV}$

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

Summary

- Neutral LLP searches have been performed by the Atlas Collaboration within Hidden Valley model specific assumptions.

- Regardless of the theoretical frame, LLP searches have a strong motivation as a unique window to access new physics beyond the Standard Model.

- The extensive Atlas search program of Run 1 resulted in non-trivial limits on LLP effects at the LHC along with a remarkable experience in terms of approaches, methods and analysis techniques.

- Searches of new physics have come up empty.

- The 13-TeV collisions scenario under way at the LHC will be exceptionally accomodating for such studies.

Backup

The Atlas Detector

- Segmented ECAL/HCAL -
  Low energy hadronic jets from IP deposit most of the energy in ECAL -> use this feature to search for LLPs decaying in HCAL.

- Air-core and segmented tracking in a large muon system -> excellent performance for very highly displaced vertices reconstructed with the muon system.
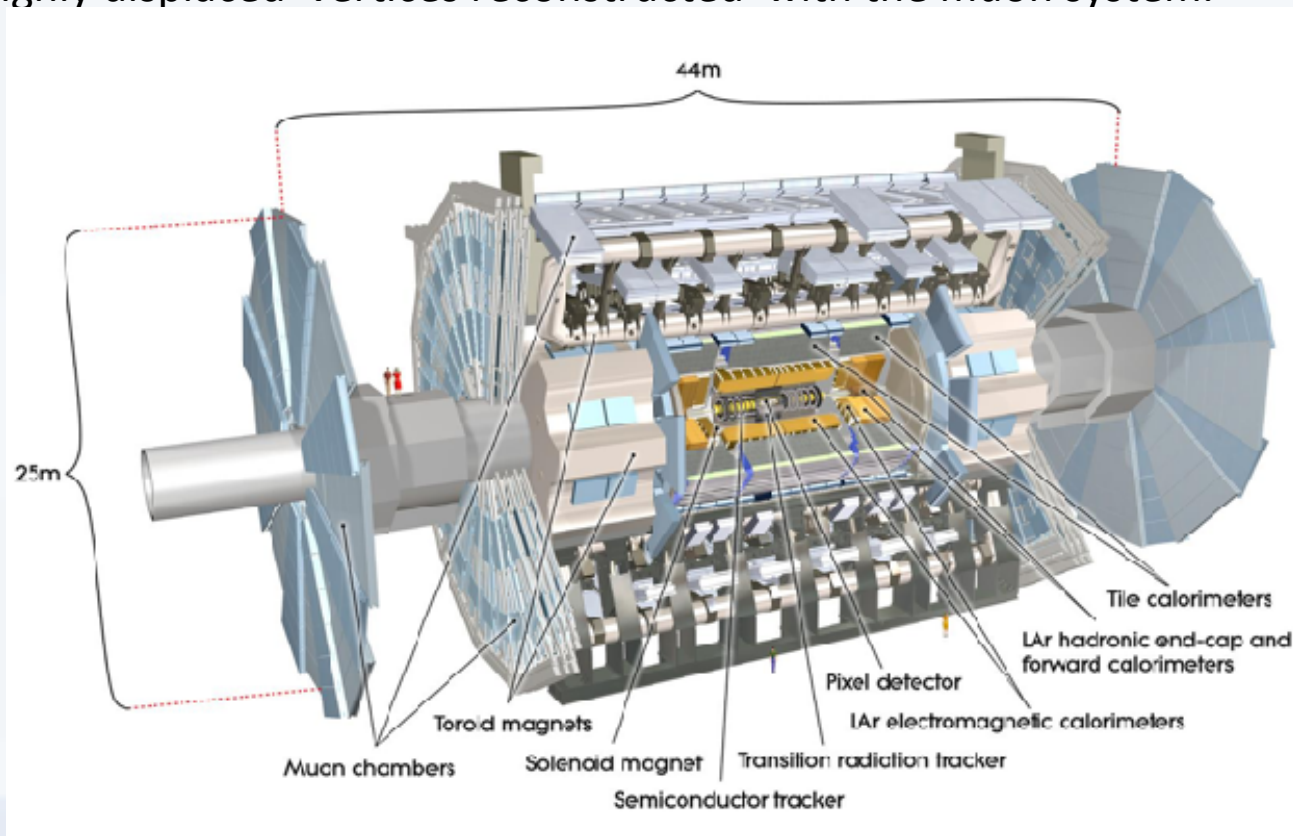
LLP searches: the scenario

✓ In principle, searches for LLPs are entirely detector driven, no model of associated production is really needed (if we can trust measured observables …).

✓ Despite being a daunting task, the choice of input parameters serves nevertheless as a guidance to navigate through this explosion of new particles, and improve a limit.

✓ Hidden Valley in one of the scenarios that may produce visible signals within the reach of the LHC.

✓ Most of those scenarios feature a common signature. So requiring a great level of fine tuning in trackless jets, missing energy and displaced vertices based-searches enables testing a broad variety of models.

✓ Developing LLPs model independent search strategies is an asset for future searches.

Where are LLPs hiding

Decay probability for π_V from gg fusion vs cτ
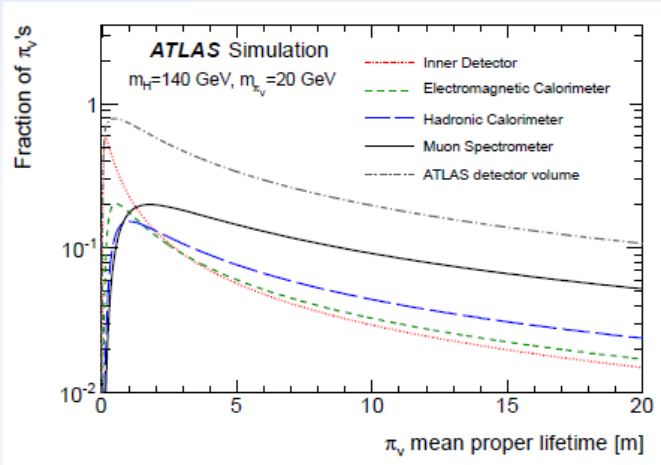
All parts of the detector are sensitive to displaced vertices

Neutral particles decaying to b-jets.
Different signatures are visible

Include all possible detector signatures:

- Inner-detector based searches
  → **displaced vertices in ID**
- Calorimeter-based searches
  → **trackless jets**
- Muon Spectrometer-based searches
  → **displaced vertices in MS**
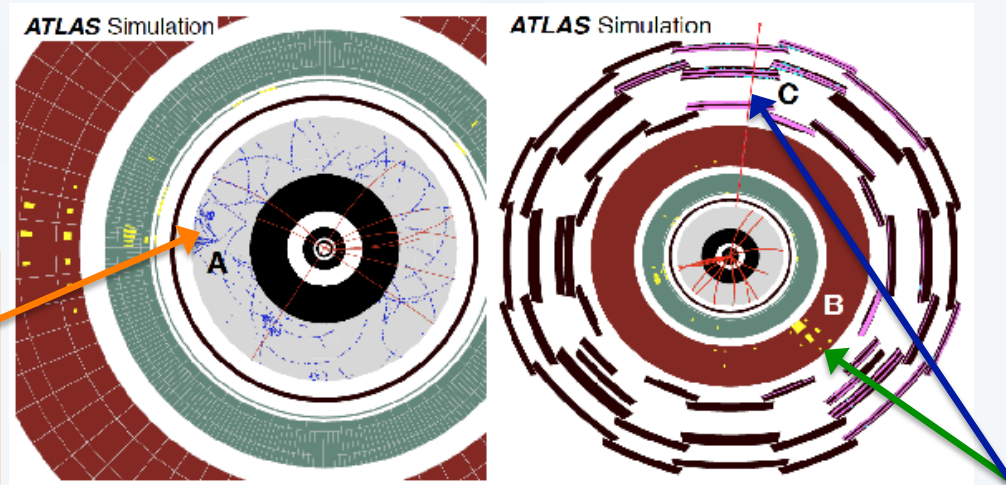
Left: π_V decays in the Inner Detector (A).
Right: one displaced decay in the hadronic calorimeter (B) and a second in the muon spectrometer (C).

The CalRatio trigger

Dedicated CalRatio trigger to select at least one jet π_V in the HCAL:

- $\text{Log}_{10}(E_{HAD}/E_{EM}) > 1.2$

- $|eta!| < 2.5$

- no ID tracks with $p_T > 1$ GeV in $\Delta R = 0.2$

- $E_T > 35$ GeV

- Line of Fire jets removal: fake jets by beam-halo muon emitting bremmstrahlung radiation in the HCAL
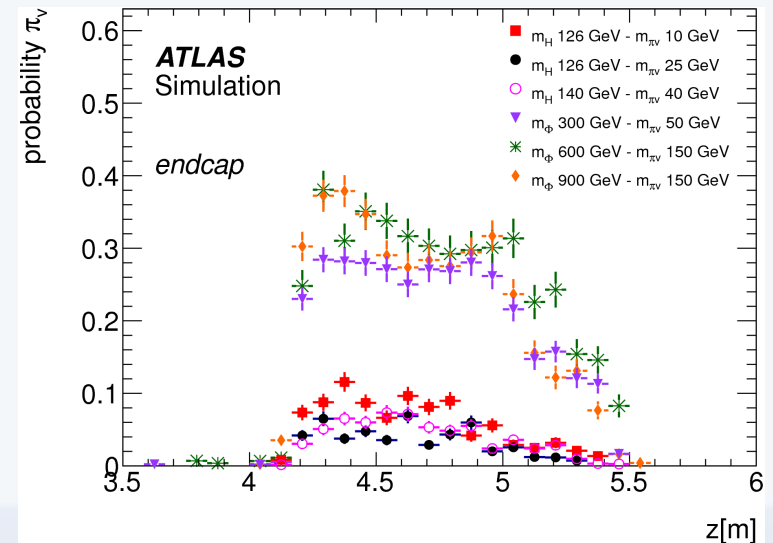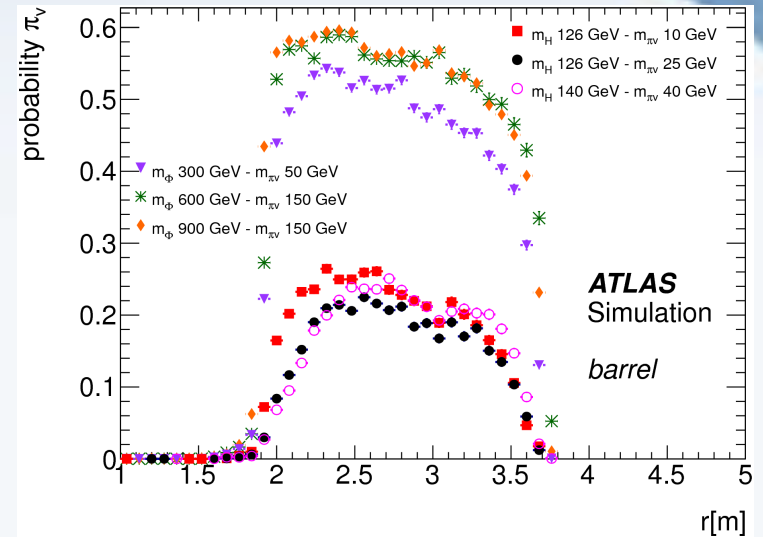
# HCal displaced decays: analysis cut flow

Considering all ϕ and π_V masses.
The same cut-flow has been applied to all the signal samples. Requiring two jets passing all analysis cuts

- Event Level Cuts
- Event triggered by dedicated CalRatio trigger
- Data Quality criteria
- Missing Energy (E_t^{miss}) < 50 GeV

- Require two jets passing:
  - ✓ $\log(E_{HAD}/E_{EM})$ > 1.2
  - ✓ no tracks p_T > 1.0 GeV in a 0.2 cone around the jet
  - ✓ |eta| < 2.5 and -1 ns < t < 5 ns
  - ✓ one of the two jets must have fired the trigger and satisfy E_t > 60 GeV, the other must have E_t > 40 GeV
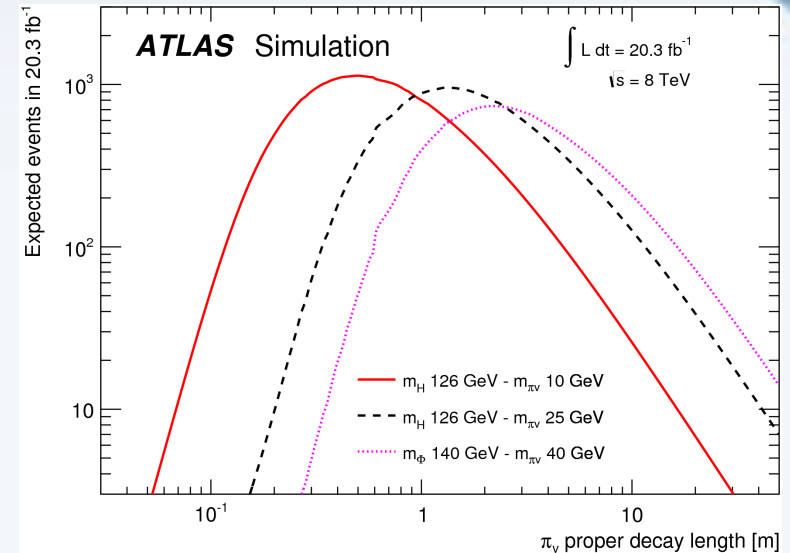
HCal displaced decays: background modelling
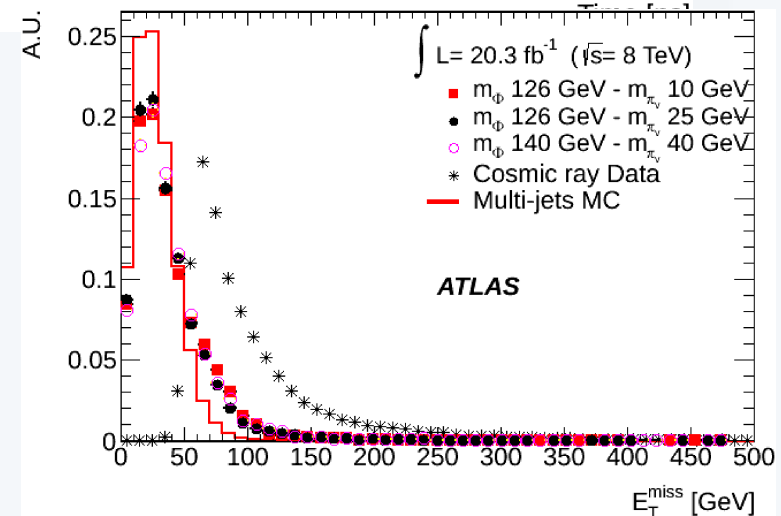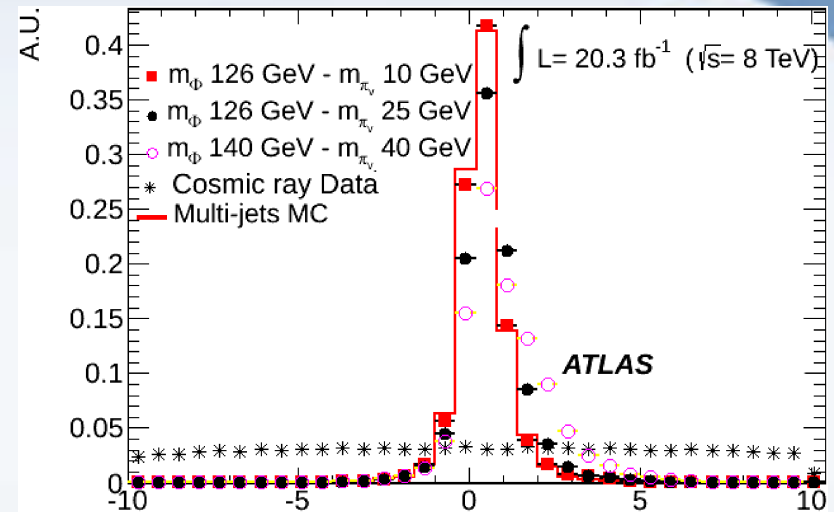
Three sources of background considered:

SM multijet events
- Dominant background
- Studied with a tag-and-probe method of an independently triggered dataset

Cosmic ray events
- Small contribution
- Reduced by cuts on Etmiss and jet timing

Beam halo events
- Very small
- Reduced by same cuts as in cosmic ray events as well as by dedicated trigger and analysis DQ cuts

Line of Fire selection: ATL-COM-PHYS-2011-844

Uses 3 parameters of MS segments:

- $\delta\phi$, the difference in phi between the trigger jet and Moore segment.

- $\gamma_{MS} = p_{\hat{Moore}} \cdot \hat{z}/|p_{Moore}|$, the directional cosine between the Moore segment and z-ax

- δr, the difference between the radius of the leading HEC cell in the jet and CSC segment.
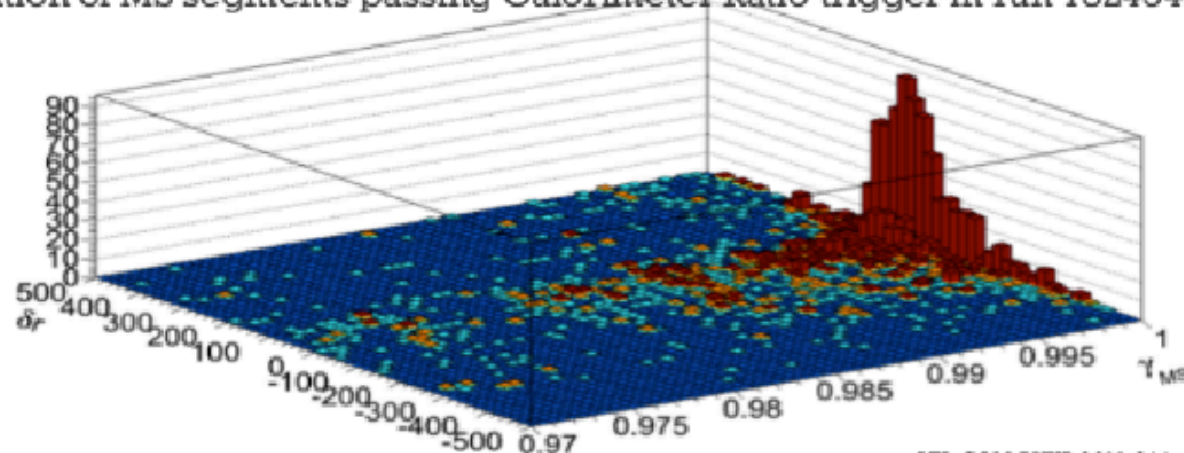
Criteria
End-cap
1 MS segment with: $|\delta r| < 120$ mm, $|\delta\phi| < 0.2$, $|\gamma_{MS}| > 0.98$.

Distribution of MS segments passing Calorimeter Ratio trigger in run 182454.

ATL-COM-PHYS-2011-844

Uses 6 parameters of HCAL cells:

Criteria	
≥ 3 cells in the HCAL such that:	$\|\delta\phi\| < .2,$ $E > 240$ MeV, each lie outside of the triggering jet cone of ΔR of .3, $t < 2.0$ ns, $\|t - \delta t\| < 5.0$ ns, where $\delta t = \dfrac{\pm z - \sqrt{z^2 + R^2}}{c}$

- $\delta\phi$, the difference in phi between the trigger jet and HCAL cell.

- Based on the early arrival of beam halo muons.

Distribution of HCAL cells in events passing Calorimeter Ratio trigger in run 182454.
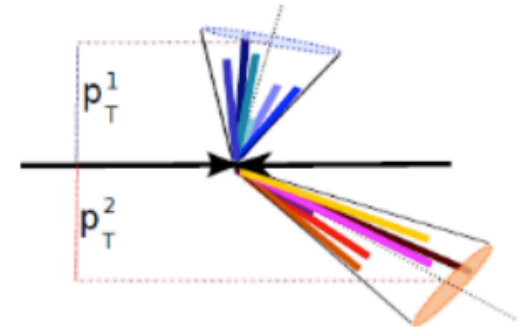

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Peach arrow: Difference in time
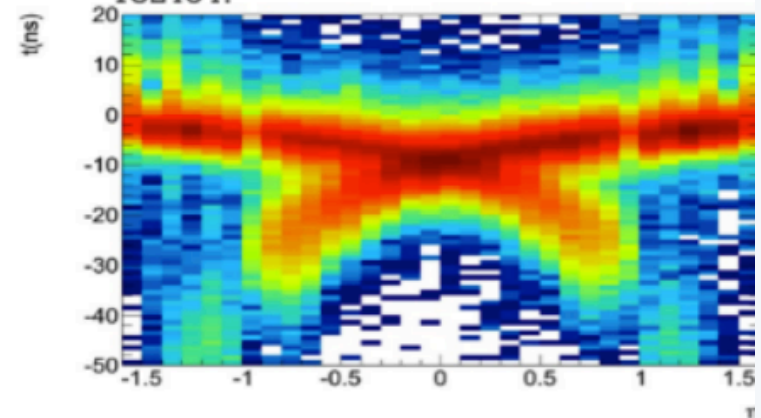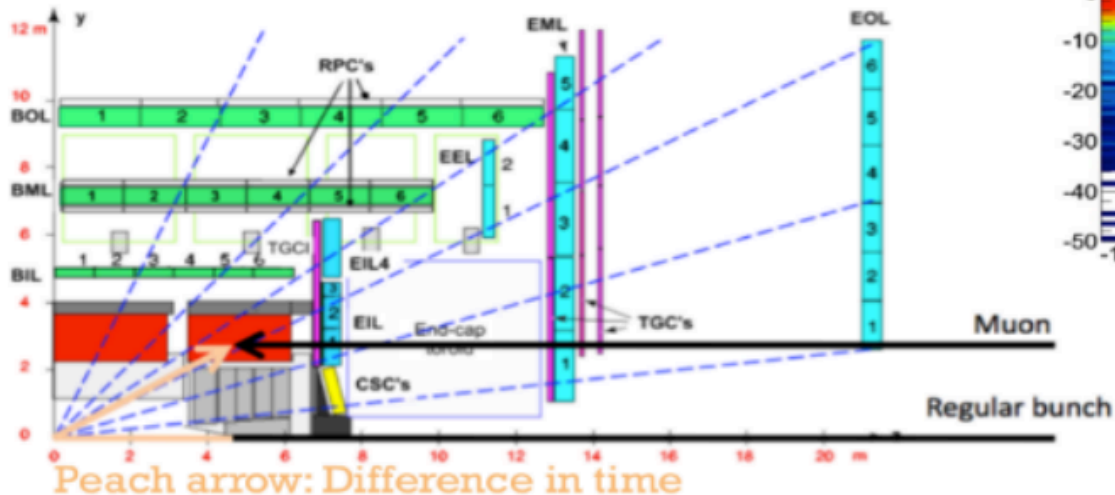
JES uncertainty

- We use the **Dijet Pt Balance Method** (In-situ technique D0: hep-ex/0012046v2)
- This technique uses two jets:
    - a **Reference jet**
    - and a **Probe jet,** back-to-back
- We study the **di-jet pT balance** of the jet energy response in pseudo-rapidity (we added even EMF dependency)

- We study the **Asymmetry** of dijets pt:

$$A = \frac{p_T^{Probe} - p_T^{Ref}}{p_T^{average}}$$

- and the **Response** of the probe jet wrt the reference jet:

$$R = \frac{2+A}{2-A} = \frac{p_T^{Probe}}{p_T^{Ref}}$$

The inverse of the Response is proportional to the average JES correction

- **The final uncertainty is obtained by comparing DATA / MC Response**

HCal displaced decays: systematics

Dominant systematic uncertainty comes from the Higgs cross section.

Pile-up and trigger uncertainty evaluated using a direct data vs MC comparison with multijet samples for relevant variables.

JES uncertainty calculated as a function of EMF and η for low EMF by comparing balance in data and MC.

(*) Systematic errors that have common values across samples are not listed (pile-up at 10%, ISR at 2.9 – 1.2 %, and PDF at 2.1%). The last column reports the overall systematic uncertainty (including the luminosity and common systematic errors).

Sample m_H, m_{π_v} [GeV]	H σ [%]	JES [%]	Trigger [%]	E_T^{miss} [%]	Time Cut [%]	Total [%]
126, 10	+10.4 −10.4	+2.2 −2.7	±1.1	+5.5 −2.4	+1.6 −6.6	+16.4 −16.7
126, 25	+10.4 −10.4	+1.5 −1.6	±1.3	+3.1 −1.8	+0.8 −3.3	+15.6 −15.5
126, 40	+10.4 −10.4	+2.6 −6.2	±1.1	+7.7 −4.6	+1.9 −5.9	+18.2 −16.9

Sample m_Φ, m_{π_v} [GeV]	Φ σ [%]	JES [%]	Trigger [%]	E_T^{miss} [%]	Time Cut [%]	Total [%]
100, 10	+11.1 −10.6	+2.3 −4.0	±0.1	+4.6 −3.4	+2.7 −9.5	+16.7 −18.5
100, 25	+11.1 −10.6	+5.5 −3.7	±1.2	+3.4 −2.5	+1.7 −0.7	+17.0 −15.8
140, 10	+10.1 −10.3	+0.6 −1.1	±0.5	+4.0 −5.6	+1.9 −6.6	+15.6 −17.2
140, 20	+10.1 −10.3	+1.2 −1.6	±1.0	+4.0 −3.9	+0.4 −5.0	+15.5 −16.2
140, 40	+10.1 −10.3	+1.3 −1.6	±1.5	+6.3 −4.6	+1.8 −2.4	+16.5 −15.8
300, 50	+9.6 −10.0	+0.1 −0.3	±0.3	+9.0 −7.4	+0.5 −3.0	+13.9 −13.3
600, 50	+11.2 −10.1	+0.0 −0.1	±0.2	+11.7 −11.3	+2.2 −4.4	+17.0 −16.2
600, 150	+11.2 −10.1	+0.2 −0.2	±0.3	+11.5 −10.2	+2.7 −5.3	+17.5 −15.1
900, 50	+12.8 −11.5	+0.0 −0.1	±0.1	+12.6 −9.7	+1.0 −3.7	+18.5 −15.9
900, 150	+12.8 −11.5	+0.2 −0.3	±0.2	+11.8 −10.9	+0.9 −2.5	+18.1 −16.3

MS-ID displaced decays: background

Negligible background from fake vertices estimated from data control regions

ID vertex fake rate

Main contribution from jets with high track multiplicity.

The ID vertex fake rate is calculated from jets passing single jet triggers.

Per-jet fake rate for the <u>Muon Cluster channel</u>: $2 \times 10^{-5} \div 3 \times 10^{-4}$

Per-jet fake rate for the <u>Jet + E_t^{miss} channel</u>: $\quad 6 \times 10^{-6} \div 3 \times 10^{-5}$ for non-leading jets

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad 4 \times 10^{-6} \div 2 \times 10^{-5}$ for leading jets

MS vertex fake rate

The MS vertex fake rate is calculated from events with a single MS vertex that passes either the Muon Roi Cluster trigger or a set of minimum-bias triggers.
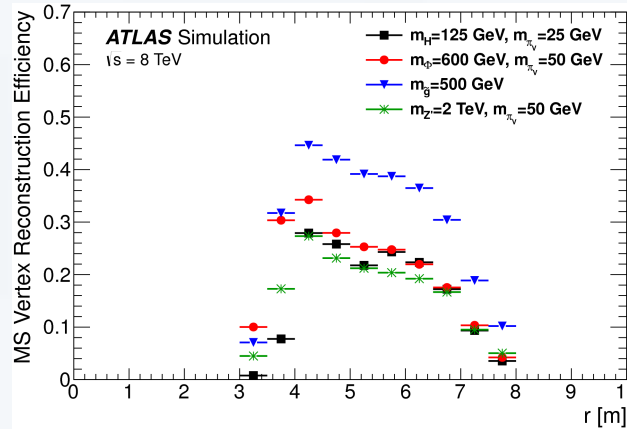
Total number of good MS vertices/total number of events = $(0^{+5}_{0}) \times 10^{-7}$

Background events

Trigger	Topology	Predicted
Jet+E_T^{miss}	2IDVx	$(1.8 \pm 0.4) \times 10^{-4}$
Jet+E_T^{miss}	IDVx+MSVx	$(5.5 \pm 1.4) \times 10^{-4}$
Jet+E_T^{miss}	2MSVx	$(0.0^{+1.4}_{-0.0}) \times 10^{-5}$
Muon RoI Cluster	IDVx+MSVx	2.0 ± 0.4
Muon RoI Cluster	2MSVx	$0.4^{+0.3}_{-0.2}$

MS-ID displaced decays: trigger and vertexing efficiency
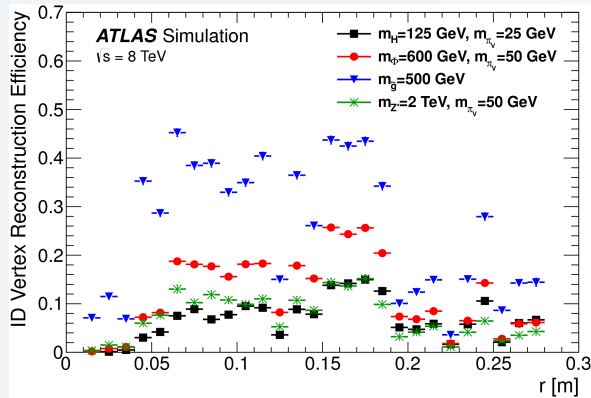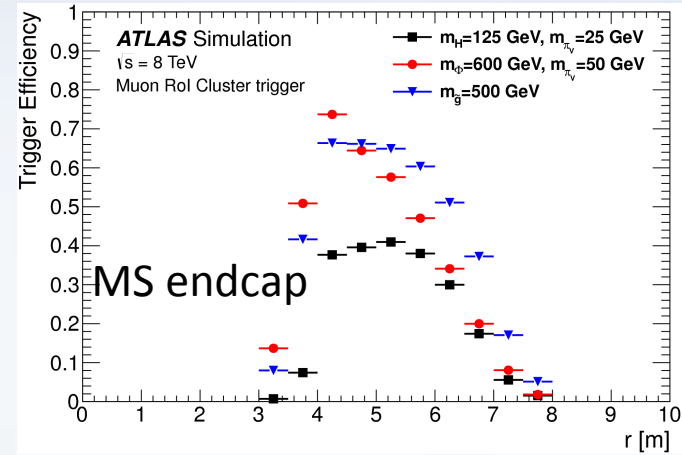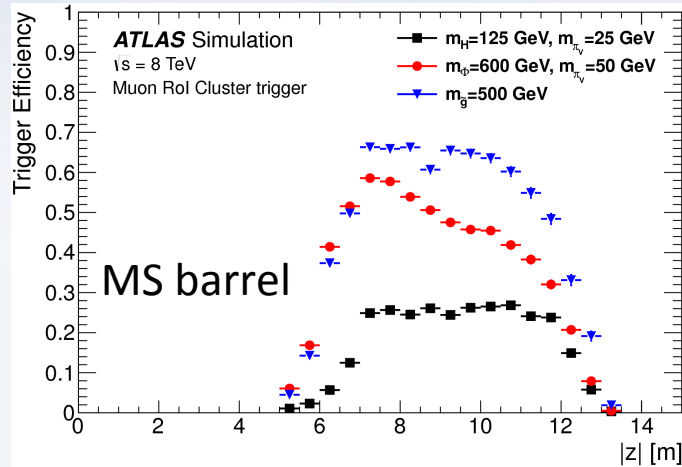
MS barrel

MS endcap
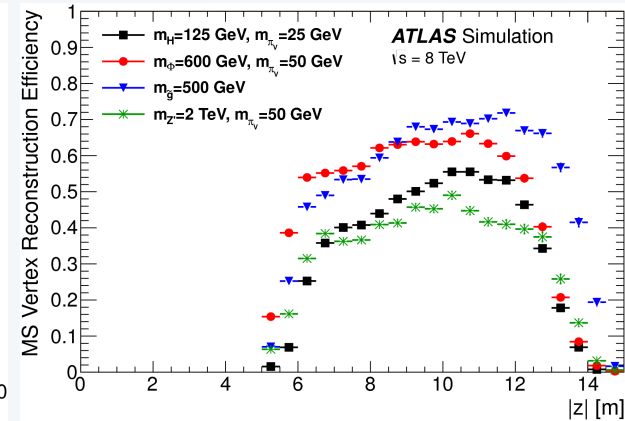
MS barrel

MS endcap

ID

MS-ID displaced decays: systematics

m_Φ [GeV]	m_{π_v} [GeV]	IDVx [%]	MSVx [%] barrel	MSVx [%] endcaps
100	10	2.7	6.8	11.2
100	25	2.1	6.4	10.4
125	10	2.5	7.0	9.9
125	25	2.5	6.8	9.7
125	40	2.4	6.5	8.0
140	10	2.7	7.0	9.6
140	20	2.7	6.6	9.6
140	40	1.6	6.6	7.9
300	50	2.7	6.9	6.3
600	50	2.9	6.8	5.4
600	150	3.1	6.6	4.0
900	50	3.5	6.6	5.7
900	150	3.0	5.9	3.8

$m_{\tilde{g}}$ [GeV]	IDVx [%]	MSVx [%] barrel	MSVx [%] endcaps
110	3.8	5.6	4.0
250	2.3	5.8	3.8
500	2.4	6.3	3.8
800	2.7	6.5	3.5
1200	1.5	6.6	3.8

$m_{Z'}$ [TeV]	m_{π_v} [GeV]	IDVx [%]	MSVx [%] barrel	MSVx [%] endcaps
1	50	2.5	6.8	6.3
2	50	2.6	7.0	6.6
2	120	2.2	6.6	5.2

ID: systematic uncertainty due to differences in track reconstruction in data and simulation estimated by studying K_S^0 decays in multi-jet control samples.

MS: systematic uncertainty due to data-simulation discrepancies studied using jets that punch through the calorimeter and showers in the MS. Both for trigger and reconstruction.