Searches for Long-Lived Particles with ATLAS at the LHC

Antonio Policicchio

Università della Calabria & INFN Cosenza

Summary

Particles with macroscopic decay lengths are predicted by a large class of BSM models (SUSY, Hidden Sectors, R-parity violating MSSM, SUGRA..)

- SUSY searches
  - Stable Massive Particles (R-Hadrons, Sleptons)
  - Neutralino decays

- EXOTICS searches
  - Hidden Particles
  - Lepton-jets

In this talk

- overview of the results with 2011 data
- current activities on full 2011+2012 statistics

SUSY searches

Stable Massive Particles

- **Stable Massive Particles** (SMPs) predicted by many BSM scenarios, including several different SUSY models
- **sleptons** are massive, charged and metastable in GMSB
- **R-hadrons** are **colored** SMPs: bound states formed by **squarks and gluinos** hadronizing with a light SM quarks system, several **electric charges** (and the electric charge can change due to nuclear scattering in the detector)
- **Long-lived** for this search

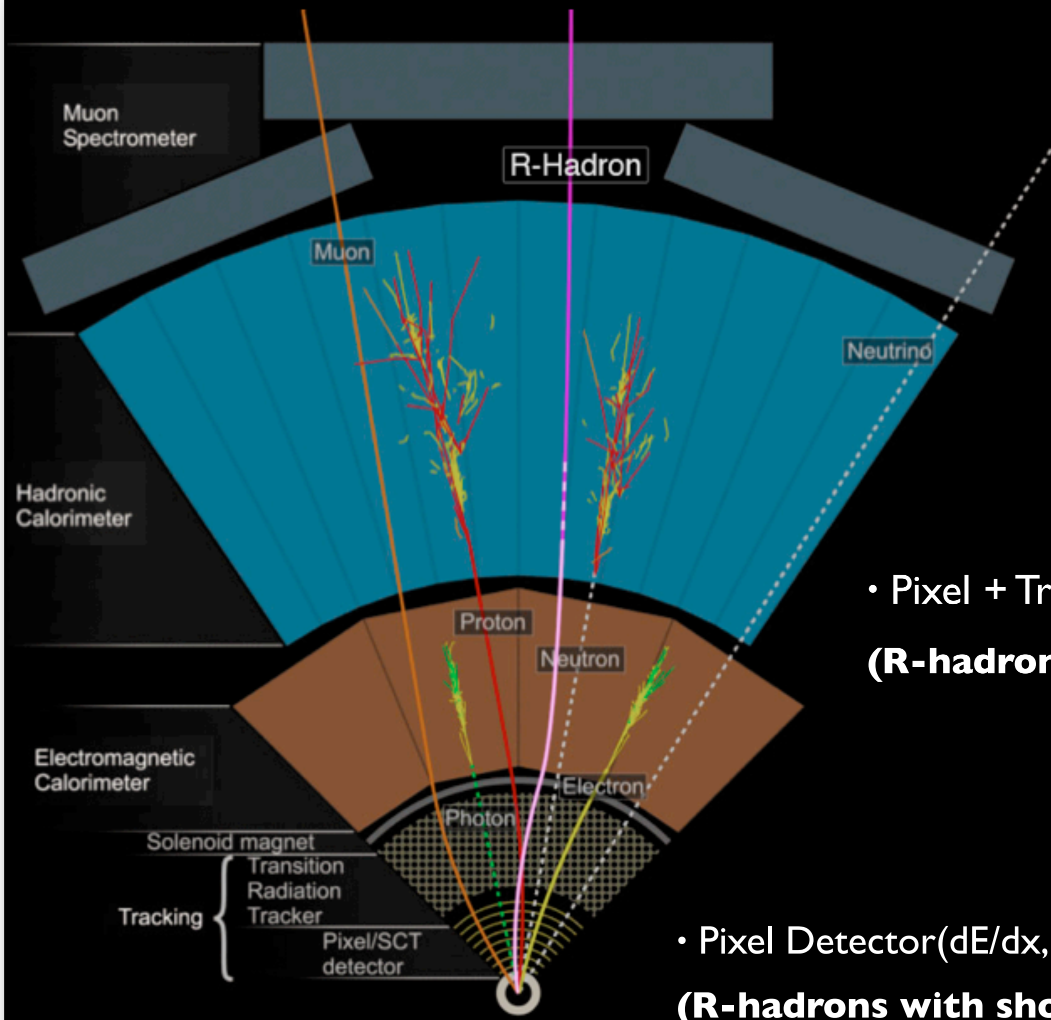
	composition	notation
R-mesons	$R = \tilde{g}q\bar{q}, (\tilde{q}\bar{q})$	R^+, R^-, R^0
R-baryons	$R = \tilde{g}qqq, (\tilde{q}qq)$	R^{++}, R^+, R^-, R^0
R-gluinoballs	$R = \tilde{g}g$	R^0

arXiv:hep-ph/0611040

SMP	LSP	Scenario	Conditions
$\tilde\tau_1$	$\tilde\chi_1^0$	MSSM	$\tilde\tau_1$ mass (determined by $m^2_{\tilde\tau_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde\chi_1^0$ mass.
	$\tilde G$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde g$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde\tau_1$	MSSM	Small $m_{\tilde\tau_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde g$MSB	Generic in minimal models.
$\tilde\ell_{i1}$	$\tilde G$	GMSB	$\tilde\tau_1$ NLSP (see above). $\tilde e_1$ and $\tilde\mu_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde\tau_1$	$\tilde g$MSB	$\tilde e_1$ and $\tilde\mu_1$ co-LSP and also SMP when stau mixing small.
$\tilde\chi_1^+$	$\tilde\chi_1^0$	MSSM	$m_{\tilde\chi_1^+} - m_{\tilde\chi_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg |\mu|$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll |\mu|$. Natural in O-II models, where simultaneously also the $\tilde g$ can be long-lived near $\delta_{GS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde g$	$\tilde\chi_1^0$	MSSM	Very large $m^2_{\tilde q} \gg M_3$, e.g. split SUSY.
	$\tilde G$	GMSB	SUSY GUT extensions [25–27].
	$\tilde g$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde t_1$	$\tilde\chi_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde q}$ and M_3, small $\tan\beta$, large A_t.
$\tilde b_1$			Small $m^2_{\tilde q}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

Experimental techniques

- Generic signature: **slow** (<u>β<1</u> and <u>highly ionizing</u>) and **high-p_T particles**, **μ-like**:
  - measurement done by different ATLAS sub-detectors



- Muon Spectrometer + ID (β,μ-like)

(<u>sleptons</u>)

- ID + Calo + Muon Spectrometer

(R-hadrons, <u>full-detector</u> analysis)

- Pixel + Tracker + Tile Calorimeter (β)

(R-hadrons, <u>μ-agnostic</u> analysis)

$\sqrt{s}$=7TeV, $\int Ldt$ = 5fb^{-1}

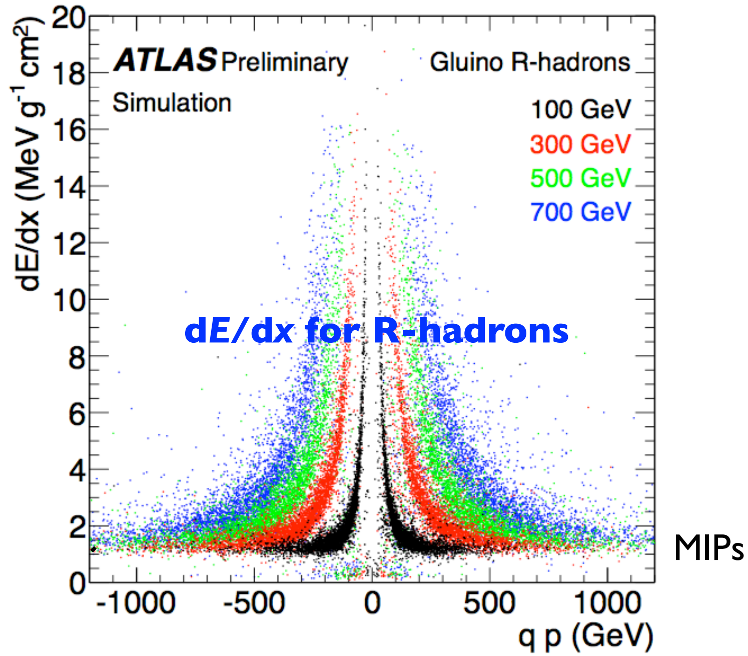
- Pixel Detector(dE/dx,p)+SCT(p)

(R-hadrons with short lifetimes, <u>ID-only</u> analysis)

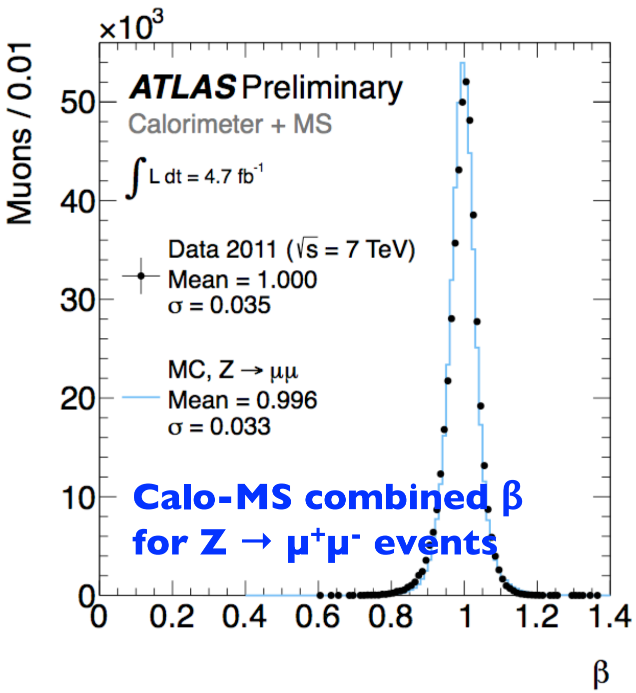
SMPs on 2011 Data (I)

http://arxiv.org/abs/1211.1597

- Mass measurement with the Pixel Detector
  - masses of slow charged particles measured using only ID information
  - dE/dx and p fitted to an empirical Bethe-Bloch function, to deduce mass



- β measurement with Calorimeters and MS
  - Tile and LAr Calorimeters: resolution ~2ns at 1 GeV → able to distinguish between highly relativistic particles and slow LLPs
  - MS: β measurement mainly by monitored drift-tube chambers (for slow LLPs combined track re-fit including ID and MS)

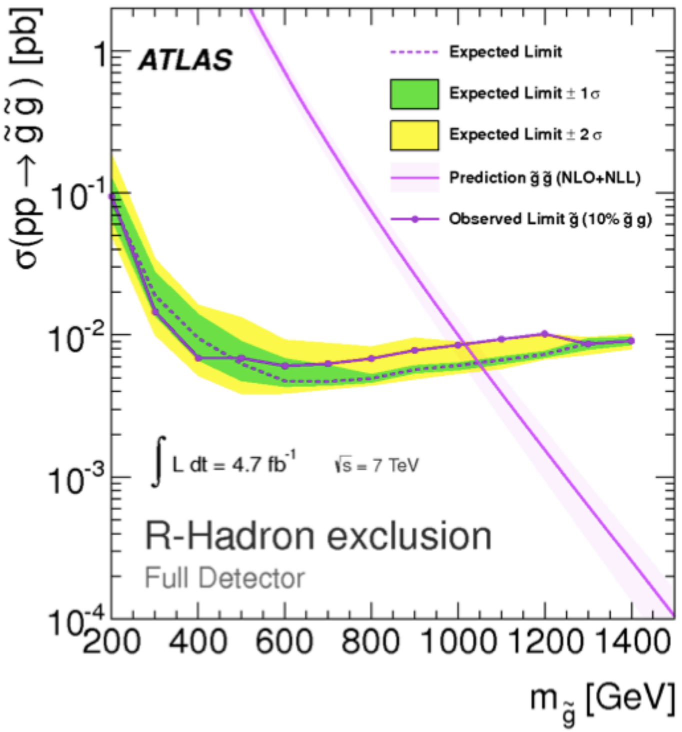


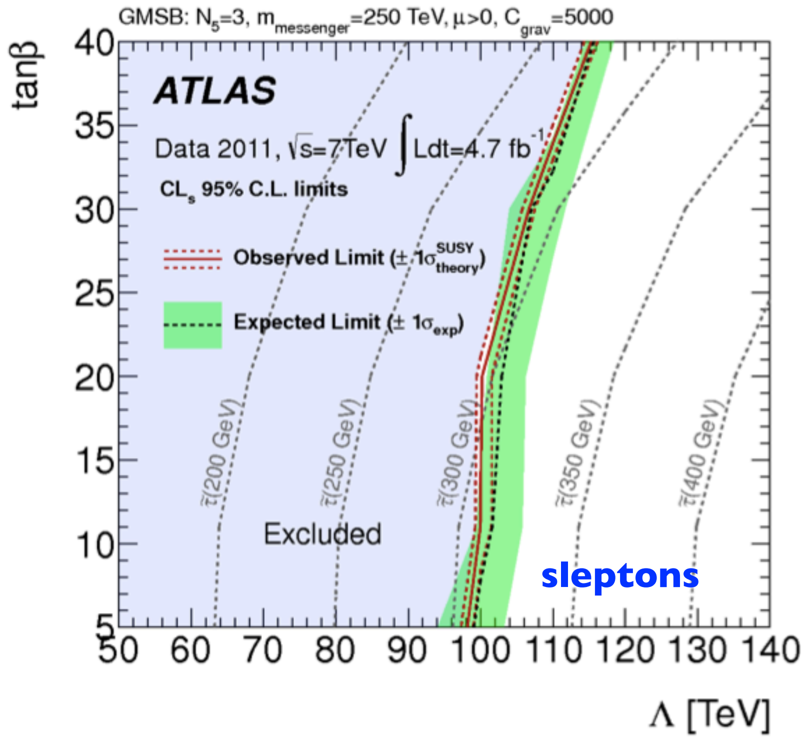
- Different selections for different searches:
  - <u>sleptons</u>: muon trigger, high p_T, β consistent from different sub-detectors
  - R-hadrons <u>full-detector and μ-agnostic</u>: MET trigger, high p, isolation from jets
  - R-hadrons <u>ID-only</u>: MET trigger, MET offline, high p and p_T, isolation from other tracks, veto for electrons, high ionization
- After selection, background is mainly due to high-p_T μ with mis-measured β
- Data-driven approach to build high-statistics random samples

SMPs on 2011 Data (II)

http://arxiv.org/abs/1211.1597

- Systematics uncertainties from theoretical calculations, data-simulation discrepancies in signal efficiency, background estimation, luminosity
- No indication of signal above the expected background is observed
- Cross-section limits at 95% confidence level → translating into limits on the R-hadron/slepton mass





Limits on rhadron containing	95% CL limits on mass exclusion
gluino	985 GeV
stop	683 GeV
sbottom	612 GeV

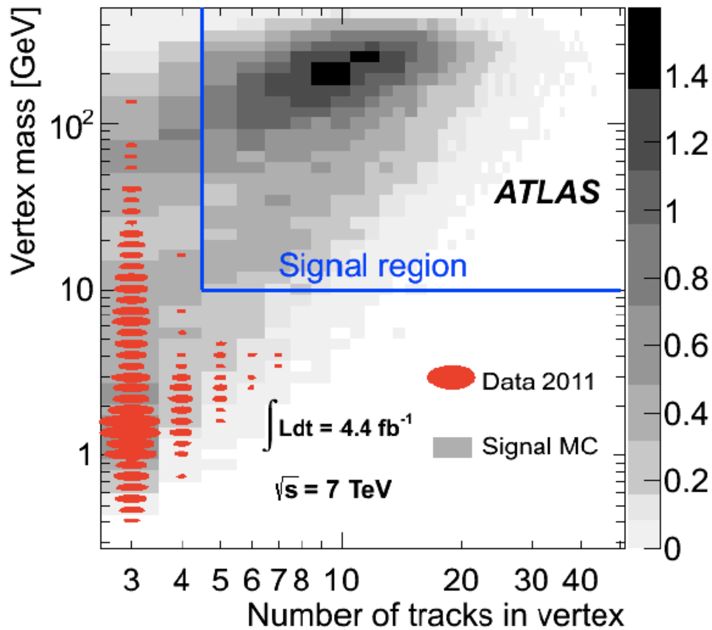
***m*(GMSB τ̃)**	> 300 - 268 GeV, 5<tanβ<40
***m*(directly produced sleptons)**	> 278 GeV, 5<tanβ<40

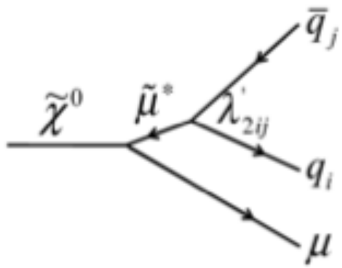
Displaced vertices with tracks + muons

http://arxiv.org/abs/1210.7451

- If particle has lifetime O(few ns), it can decay inside the tracking detector, producing a vertex at a distance away from the primary vertex

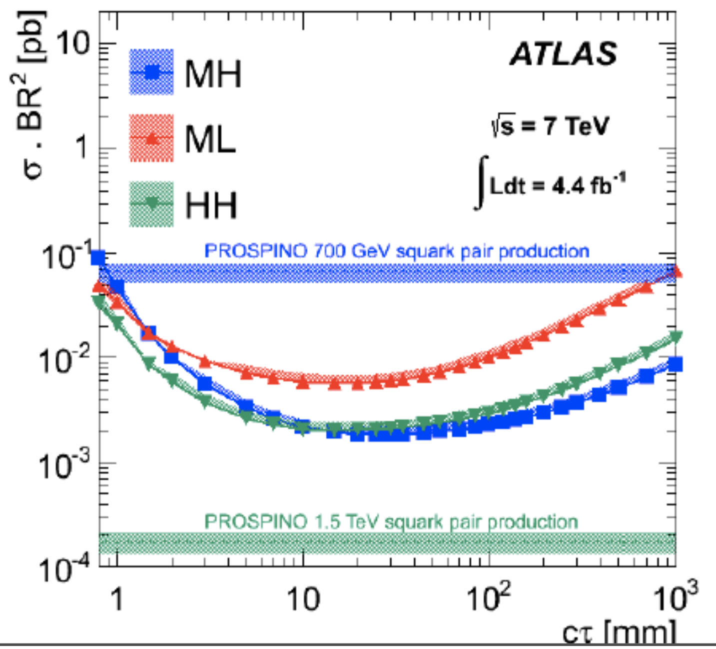
- E.g. RPV SUSY with non−zero but small λ_{211}
  - Neutralino decays to muon plus jets
  - Muon is useful for triggering and background rejection
  - High track multiplicity helps vertex reconstruction
  - Dedicated vertex reconstruction





- Background is random combinations of tracks inside the beampipe and high mass tail of distribution of real vertices from hadronic interactions with gas molecules

- No events in the signal region are observed and limits are set on the production cross section for supersymmetric particles



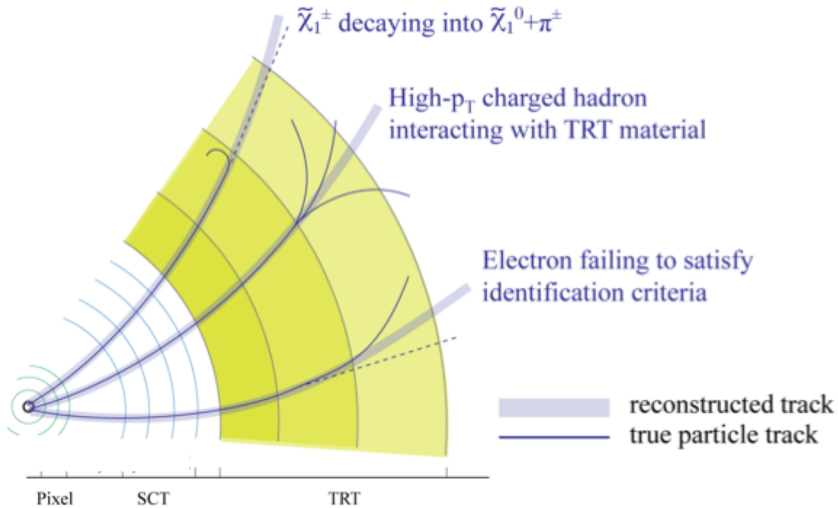
Disappearing track

http://arxiv.org/abs/1210.2852

- If the lowest gauginos are approximately mass-degenerate (predicted, eg, by AMSB),
- $\tilde{\chi}_1^{\pm}$ has lifetime $\mathcal{O}$(0.1ns) and decays to $\tilde{\chi}_1^0$ and a (~100 MeV) $\pi^{\pm}$
- Look for production processes:

$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 + jet \quad pp \to \tilde{\chi}_1^{+}\tilde{\chi}_1^{-} + jet$$

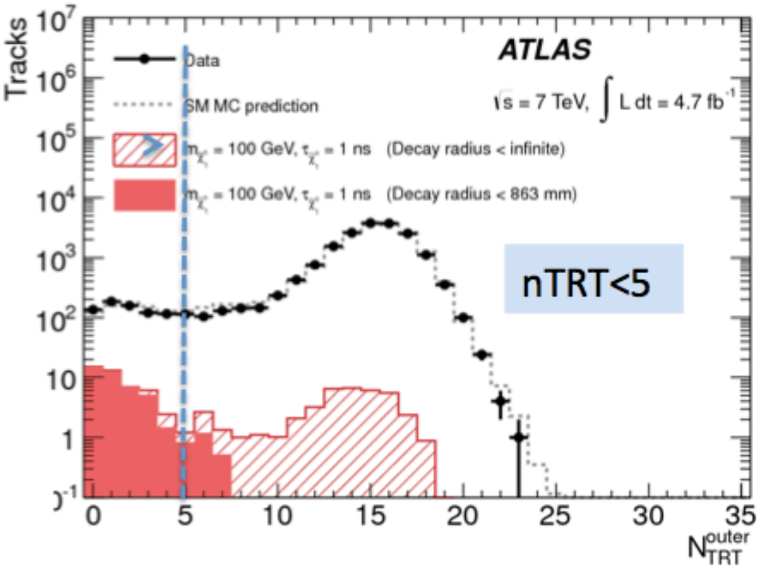
  – (jet from ISR, needed to trigger on event).

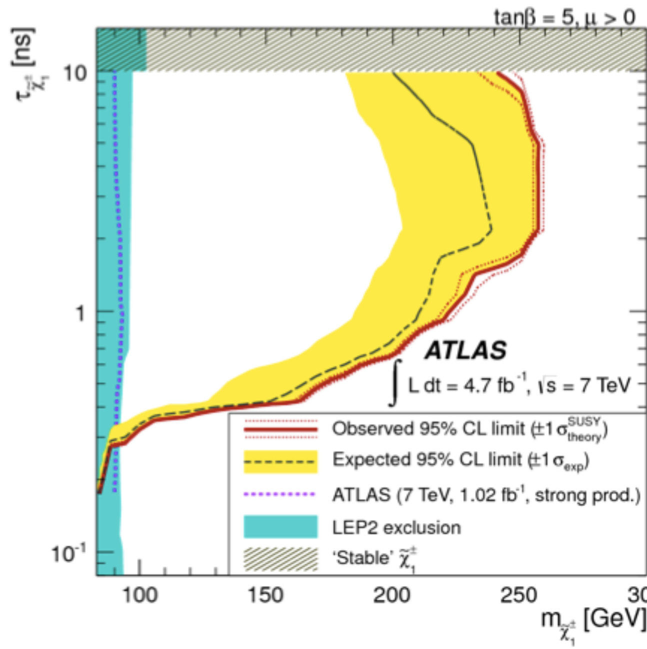


For Δm ~ 160 (170) MeV (most probable in AMSB), m(chargino) up to 103 (85) GeV is excluded

Main BG:

1. High p_T charged hadrons interacting in the TRT (80%)
2. Low p_T tracks performing large bremsstrahlung





Current activity

- Update of the analysis on the **8 TeV data** expected soon

- Interesting planned improvements:

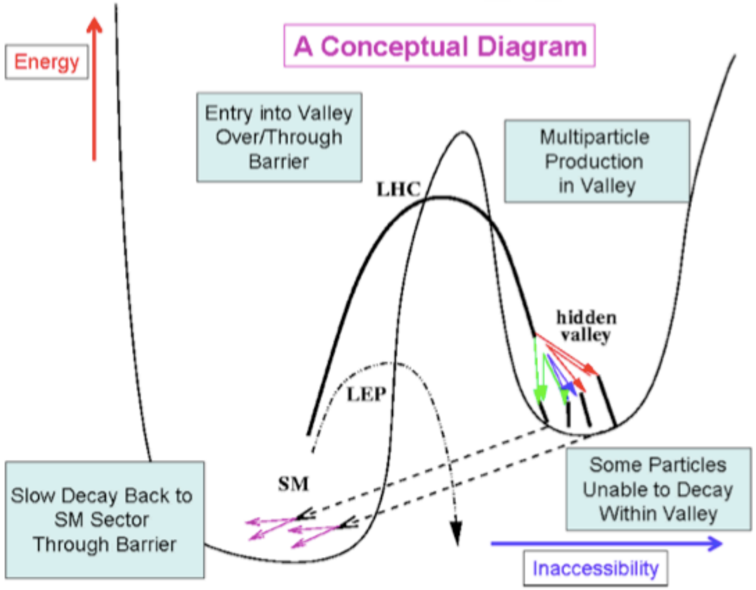
1. possibility for **R-hadrons** to **decay** or to interact with the detector material and to **change charge** (charged → neutral within a certain lifetime O(ns) only detected by ID; neutral → charged no track in the ID but detected by MS)
    - for the current analysis, only a simplified study of variation in efficiency with R-hadron lifetime → perform the new analysis as lifetime dependent (particularly sensible for ID-only approach)

2. investigating **different triggers**, both for muons and for R-hadrons

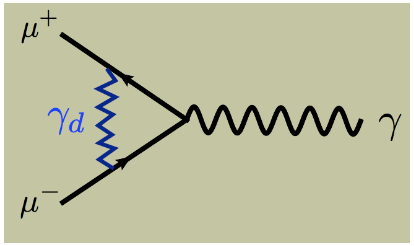
EXOTICS searches

Hidden Sector models (I)

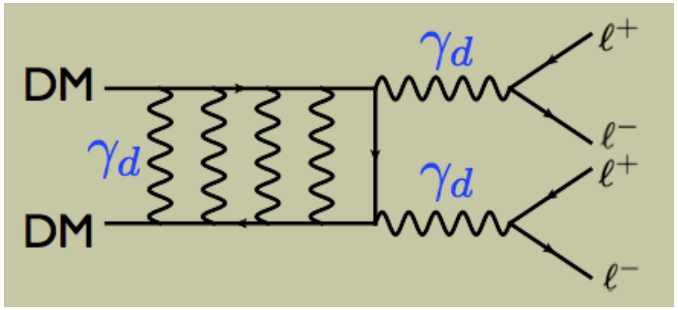
- Hidden Sector weakly coupled to SM
  - Hidden sectors and SM communicate through heavy mediator particles (Higgs, Z´, loop of SUSY particles)



- **(Some) motivations:**
  - $(g_s\text{-}2)_\mu$ anomaly: comparing theory to experiment there is a 3.2σ discrepancy → anomaly can be explained including corrections from an hidden photon

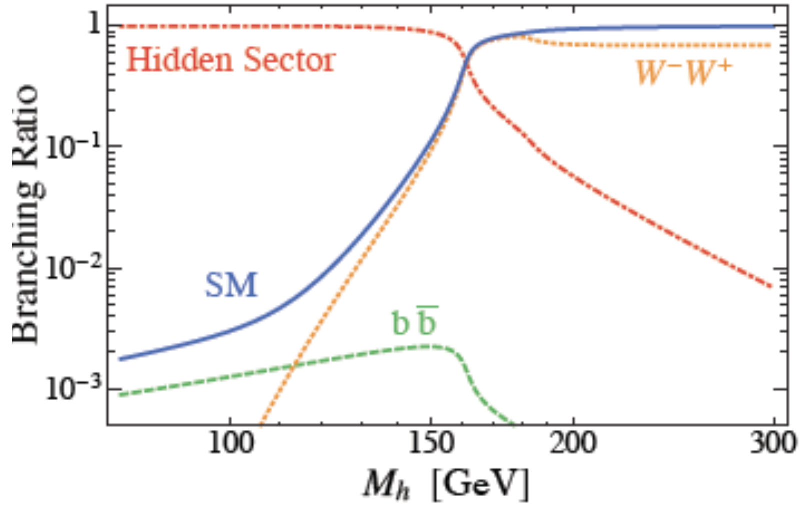


  - Cosmic ray excess: PAMELA and FERMI show an excess of positron flux (not anti-proton) → if DM annihilates to a hidden sector it would produce only leptons



Hidden Sector models (II)

- Exotics Higgs decay modes
  - Higgs sensitive to New Physics
  - still room for deviation from SM
  - important to continue exotics searches because additional resonances can arise (search for all masses!) as well as rare Higgs decays which may deviate from those predicted by the SM



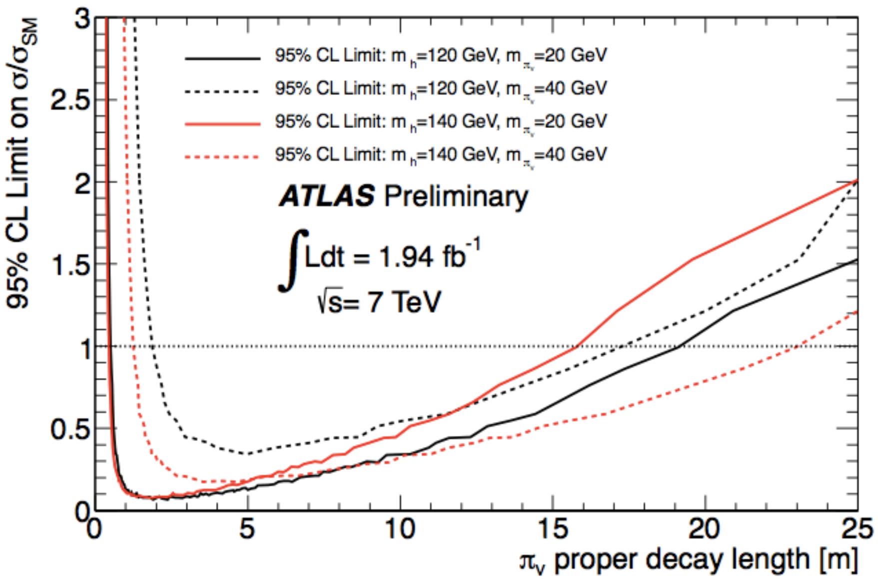
It is important to probe such new ideas

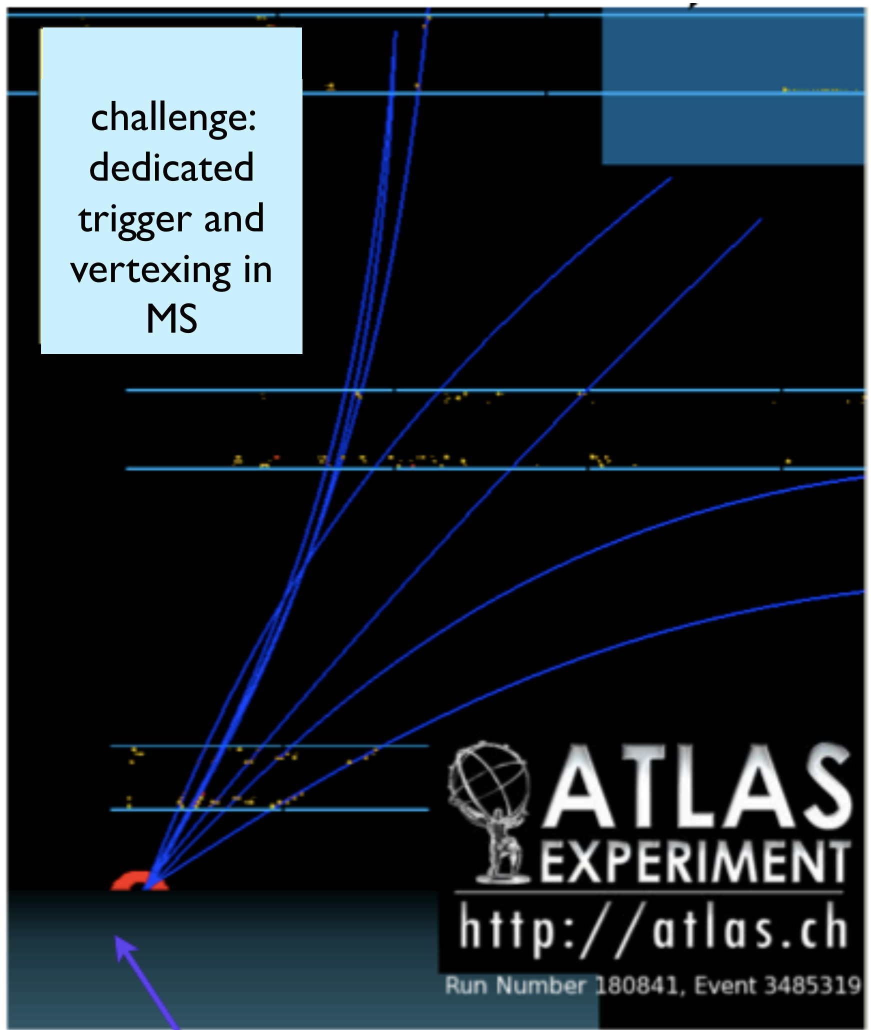
- Heavy particles (e.g. Higgs boson) decays to particles of the hidden sector that can decay back in the standard sector via:
  - hadronic jets
  - collimated jets of leptons: lepton-jets
  - hidden particles can be long-lived and neutral (LLNP) → displaced decays
- Displaced decays
  - dedicated triggers (**paper draft almost ready to be submitted to EPJ C**)
  - dedicated vertex reconstruction in Muon System (**ATL-PERF-2013-01 to be submitted to EPJ C**)

LLNP decaying to displaced heavy fermion pairs

Phys.Rev.Lett. 108 (2012) 251801

- Search in 1.94 fb^{-1} of 2011 data for pairs of back-to-back neutral particles decaying in the muon system (2 vertices in MS, isolation in calorimeter and ID)
- Signature of $h \rightarrow \pi_v \pi_v$ where π_v is a long-lived pseudoscalar from Hidden Sector decaying to heavy fermion pair (mainly b-bbar)
- 95% CL limits as a function of the proper decay length of the π_v assuming 100% BR of $h \rightarrow \pi_v \pi_v$



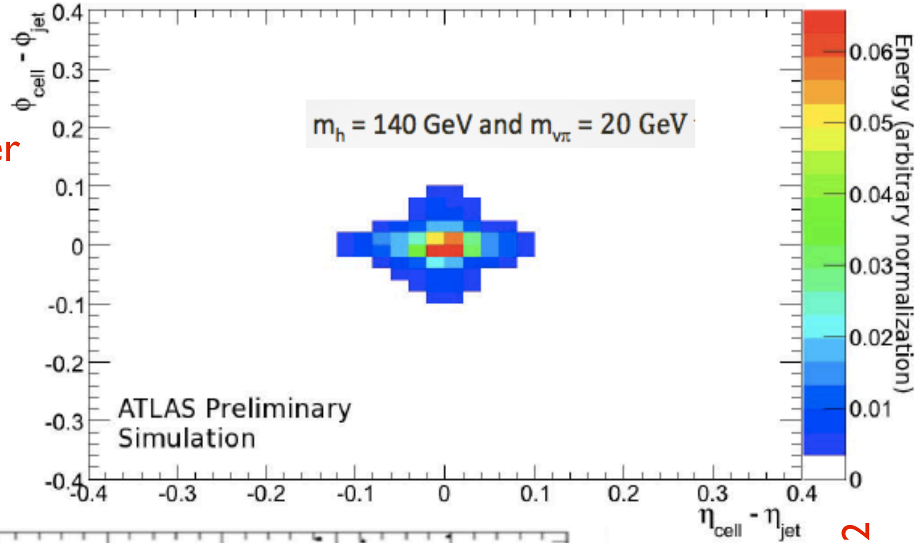


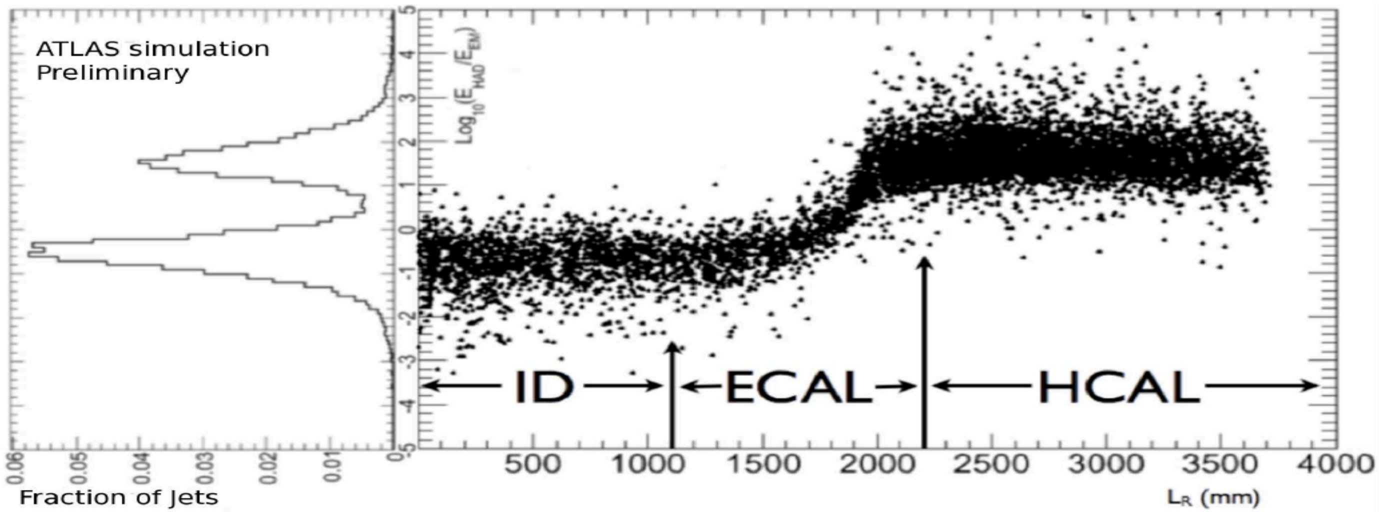
reconstructed MS vertex

data event with one vertex in the MS

Current activity: 2011+2012 full dataset

- Extend previous analysis to the entire collected statistics
- Search for displaced vertices in Inner Tracker
- Search for two π_v's decaying both in the Hadronic Calorimeter (well advanced)
  - Signature of a π_v decaying in the HAD calorimeter:
    - narrow energy deposition in HAD calorimeter
    - anomalous $\log(E_{HAD}/E_{EM})$
    - isolation (no tracks) in ID

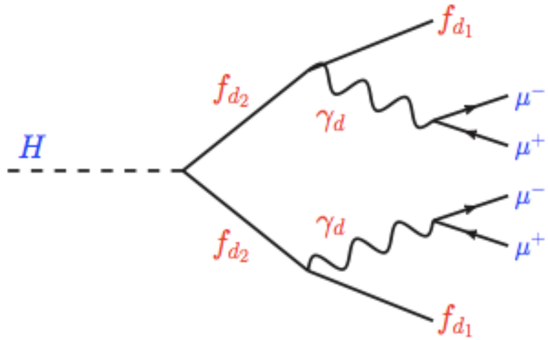




ATLAS-PHYS-PUB-2009-082

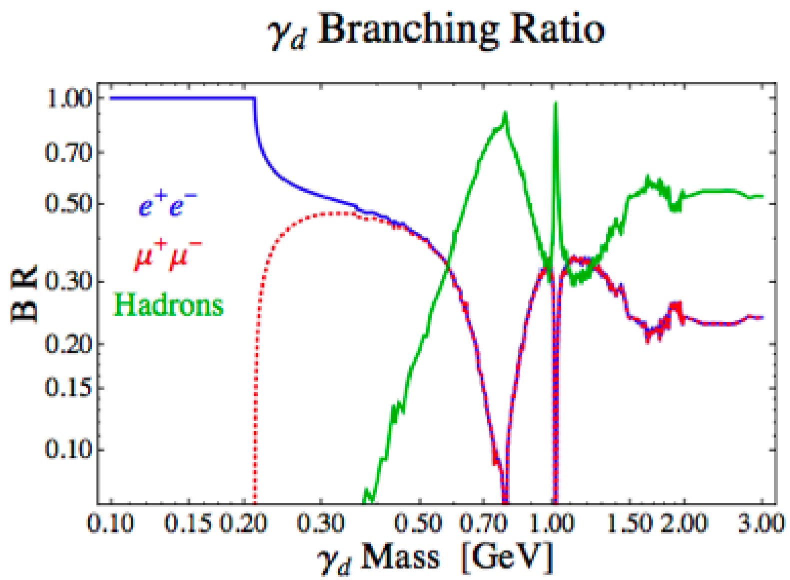
Displaced muon-jet search with 1.94 fb^{-1} of 2011 data (I)

(Phys. Lett. B 721 (2013) 32)



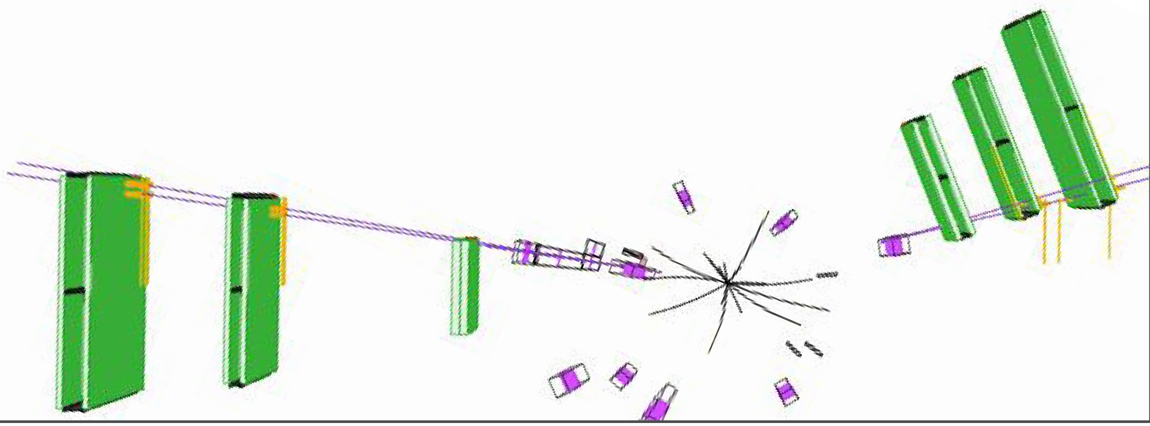
MODEL PARAMETERS

- m_h = 100/140 GeV
- m_{fd2} = 5 GeV
- $m_{fd1/LSP}$ = 2 GeV
- $m_{\gamma d}$ = 400 MeV
- BR($\gamma_d \rightarrow$ ee) = 45%
- BR($\gamma_d \rightarrow \mu\mu$) = 45%
- BR($\gamma_d \rightarrow \pi\pi$) = 10%
- cτ(γ_d) = 47 / 36 mm



- simple topology: H → 2 f_{d2}, f_{d2} → LSP + γ_d
- Dark photon (γ_d) lifetime chosen to get enough decays in each detector region → derive exclusion limit as a function of proper lifetime

- Signature: two isolated pairs of 'standalone' muons (reconstructed only in the Muon System and no match with Inner Detector tracks)
- High p_T and large boost of the γ_d → small opening angle between muons in the pair ($\Delta R<0.1$)
- Small muon p_T (peak @ 7GeV)

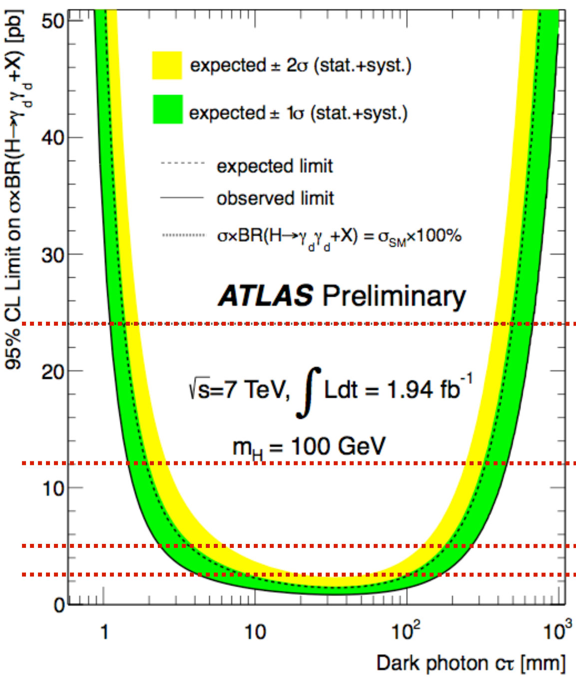


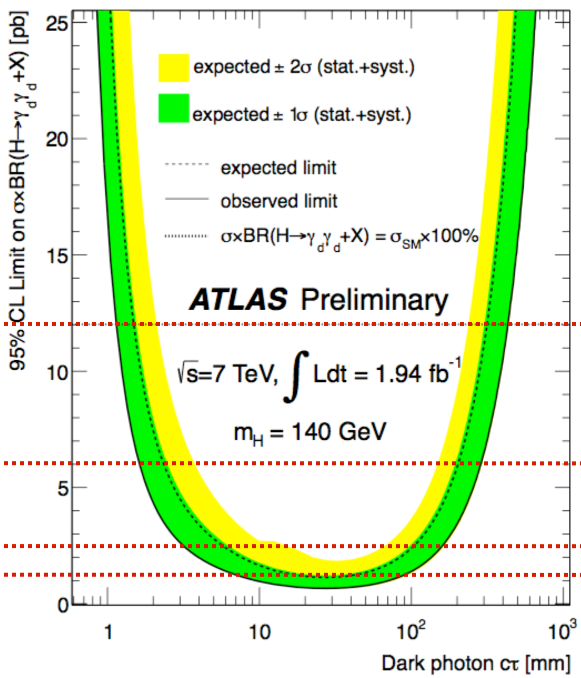
Displaced muon-jet search with 1.94 fb^{-1} of 2011 data (II)

(Phys. Lett. B 721 (2013) 32)

- No events found in data after cut flow
- **Limits at 95% CL as a function of the proper decay length of the γ_d**

cut	cosmic-rays	multi-jet	total background	m_H =100 GeV	m_H =140 GeV	DATA
$N_{MJ} = 2$	3.0 ± 2.1	N/A	N/A	$135\pm11^{+29}_{-21}$	$90\pm9^{+17}_{-13}$	871
$E_T^{isol} \le 5$ GeV	3.0 ± 2.1	N/A	N/A	$132\pm11^{+28}_{-21}$	$88\pm9^{+17}_{-13}$	219
$\lvert\Delta(\phi)\rvert > 2$	3.0 ± 2.1	153 ± 18 ± 9	154.5 ± 18.1 ± 9	$123\pm11^{+26}_{-19}$	$81\pm9^{+15}_{-12}$	104
$Q_{MJ} = 0$	1.5 ± 1.5	57 ±15±22	58.5 ± 15.5 ± 22	$121\pm11^{+26}_{-19}$	$79\pm8^{+15}_{-12}$	80
$\lvert d_0^\mu\rvert, \lvert z_0^\mu\rvert$	$0^{+1.64}_{-0}$	111±39±63	111±39±63	$105\pm10^{+22}_{-16}$	$66\pm8^{+12}_{-10}$	70
$\Sigma p_T^{ID} < 3$ GeV	$0^{+1.64}_{-0}$	$0.06\pm0.02^{+0.66}_{-0.06}$	$0.06^{+1.64+0.66}_{-0.02-0.06}$	$75\pm9^{+16}_{-12}$	$48\pm7^{+9}_{-7}$	0



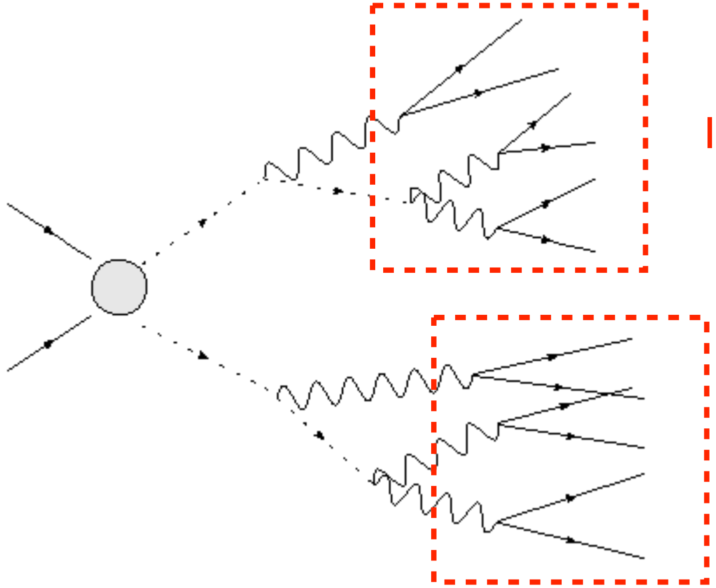


Ranges of γ_d proper decay lengths excluded at 95% CL for both Higgs masses

BR (%)	cτ (mm) m_H=100GeV	cτ (mm) m_H=140GeV
100	1.1÷674	1.2÷431
50	1.5÷455	1.6÷286
20	2.4÷260	3.3÷156
10	4.5÷159	7.3÷87

Current activity: 2011+2012 full dataset

- Investigate more complex decay modes → higher particle multiplicity in the final state and final states with electrons, muons and pions
- Extend search to be as more model independent as possible → constrain many theoretical models



LJ 1 / LJ 2	electrons	muons	electrons +muons	light hadrons	leptons +light hadrons
electrons					
muons		only 2 μ + 2 μ in 2011			
electrons +muons					
light hadrons					
leptons +light hadrons					

= work in progress

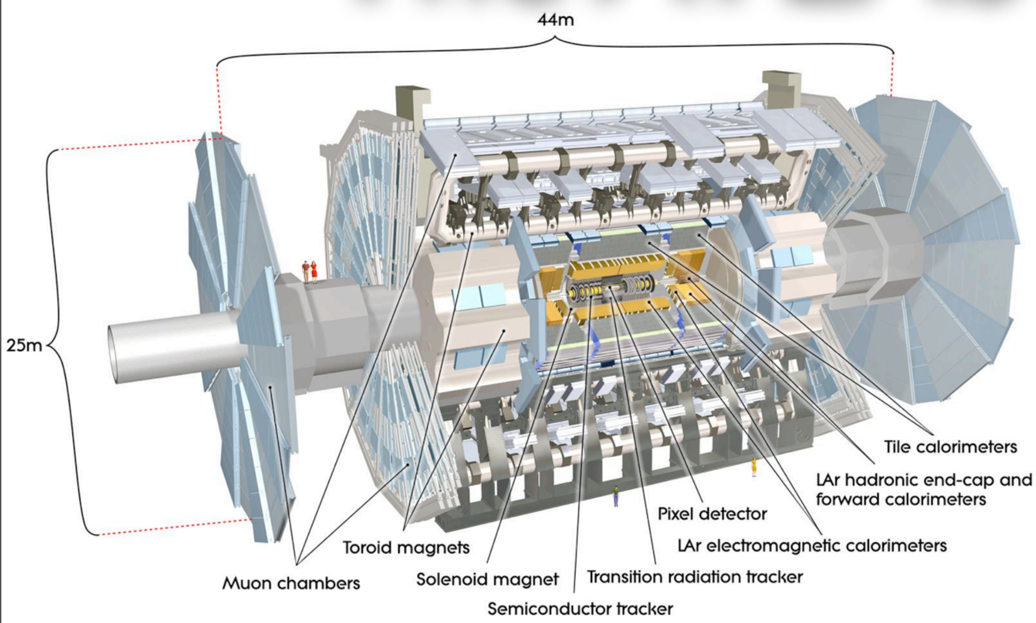
Very challenging search!

Conclusions

- Several SUSY and Exotics Models predict interesting signatures with long-lived particles
- Searches for LLP are really challenging → need a full understanding of the detectors and "non-standard" analysis techniques
- So far, there is no evidence of new physics
- Most of the analysis are being updated and improved with full statistics: we still have 20 fb^{-1} 2012 data to look at
- Expect updates soon!

Spares

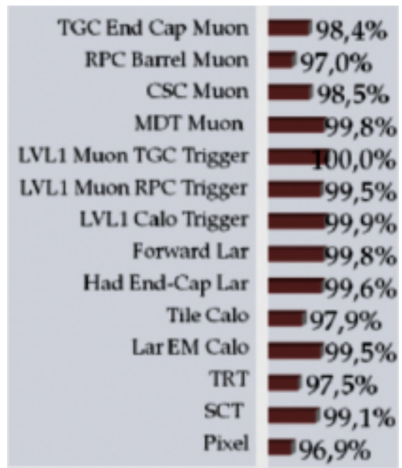
The ATLAS detector



- Inner Detector (ID) tracking: semiconductors (pixel and SCT) and transition radiation tracker (TRT)
- Sampling-based calorimetry: lead+liquid argon for EM energy (ECAL), steel+scintillator for Hadronic energy (HCAL), copper/tungsten+liquid argon in the forward calorimeter (FCAL)
- 2 T magnetic field by a solenoid just enclosing the ID
- One barrel and 2 end-cap toroids in the air-core muon spectrometer provide fields to bend muon tracks in η
- **~99% of channels working in 2011**

PERFORMANCE (E, p_T in GeV)

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4



LJ 2011+2012 data analysis

- Search for lepton jets containing electrons, muons and pions
- Use dedicated triggers for displaced decays
  - 3mu6_MSonly: selects decays to muons
  - 2mu10_MSonly_g10_loose: selects decays to muons and electrons
  - calorimeter ratio trigger: selects decays to electrons/pions in the HAD calo
- Lepton-jet definition
  - $\geq$2 clustered μ's, isolation in calorimeter and ID
  - $\geq$2μ + EM cluster (photon-like), isolation in ID
  - $\geq$2μ + jet with $\log(E_{HAD}/E_{EM})>1$, narrow energy deposition, isolation in ID
  - a jet with $\log(E_{HAD}/E_{EM})>1$, narrow energy deposition, isolation in ID
  - an EM cluster (photon-like), isolation in ID

- Lepton-jet gun developed in collaboration with the prompt lepton-jet group
  - validated and available in release
  - help in defining analysis strategies and in making less model-dependent searches