Searches for Exotic Long-lived Particles using Early Data from the ATLAS Detector at the LHC

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on behalf of the ATLAS Collaboration

Outline

- Introduction
  - Long Lived Particles (LLP)
  - The ATLAS Detector
- Search strategies for LLPs in ATLAS
  - Initial Studies using Time-of-Flight techniques
    - Use TileCal, Pixel and Muon Spectrometer Detectors
  - Stopped gluino searches
- Summary & Conclusions

LLPs in SUSY Scenarios

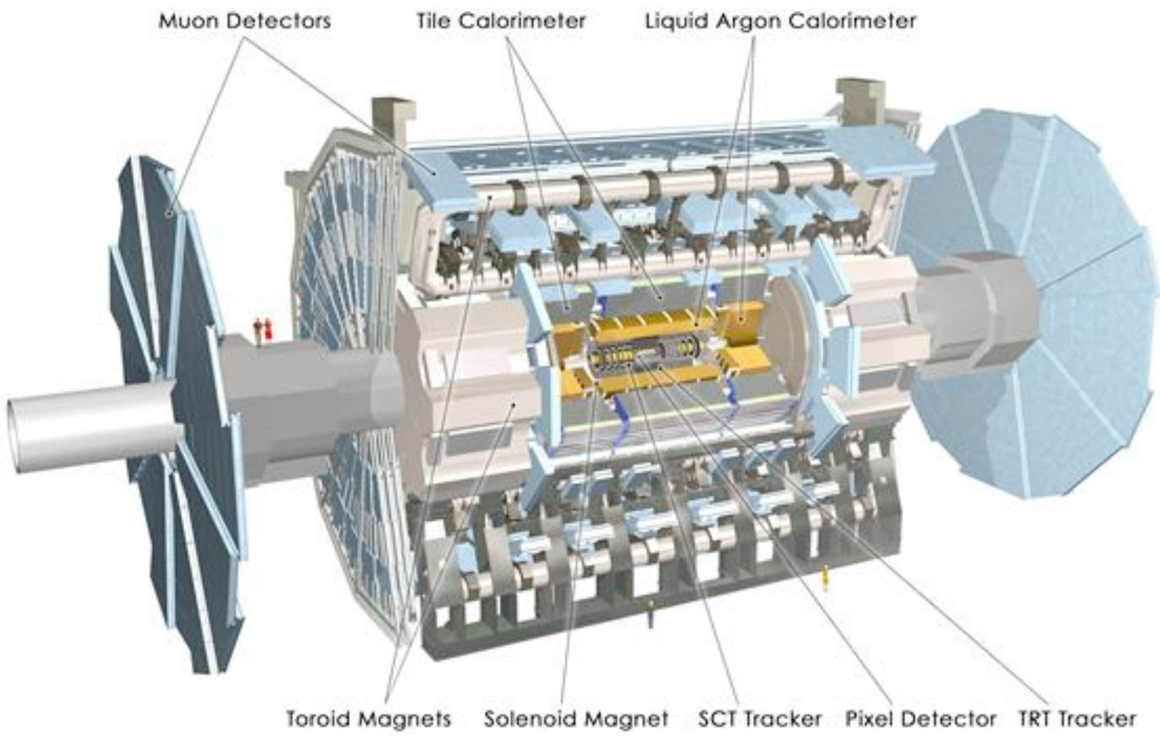
- LLPs are predicted in many SUSY and other BSM scenarios
- Within SUSY, LLPs can have different colour and electric charge
  - $\tilde{q}/\tilde{g}$ (bound states – R-Hadrons)
  - $\tilde{l}$ (or $\tilde{\chi}^{+}$)
- Typically $\beta < 1$
  - Use Time-of-Flight for measuring β
  - LLP Candidate mass = $p/\beta\gamma$
- In some case, R-Hadrons might stop in calorimeters and decay later
  - Large isolated energy deposit
  - Decay happens much later than production

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 $\gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{\mathrm{GS}} = -3$.
		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 $\delta_{\mathrm{GS}} = -3$.
		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 $A_b \gg A_t$.

Table 1
Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario.

arXiv: hep-ph/0611040v2

The ATLAS Detector



- Pixel Detector: high-resolution tracking in $|\eta| \leq 2.5$ region and dE/dx measurement
  - $r \sim 10\ \mu m$ in R-ϕ
  - $r \sim 115\ \mu m$ in z
- Liquid Argon Calorimeter (LAr)
  - e.m. calorimeter ($|\eta| < 3.2$)
- Tile Calorimeter: barrel part of Hadronic Calorimeter
  - Central Barrel: $|\eta| \leq 1$
  - Extended Barrel: $0.8 \leq |\eta| < 1.7$
  - use LAr technology for $|\eta| > 1.5$

- Muon Spectrometer: detects muons in range $|\eta| < 2.7$
  - Precision tracking chambers (Monitored Drift Tubes + Cathode-Strip Cambers)
  - Fast Trigger chambers (RPCs + Thin Gap Chambers) for $|\eta| < 2.4$

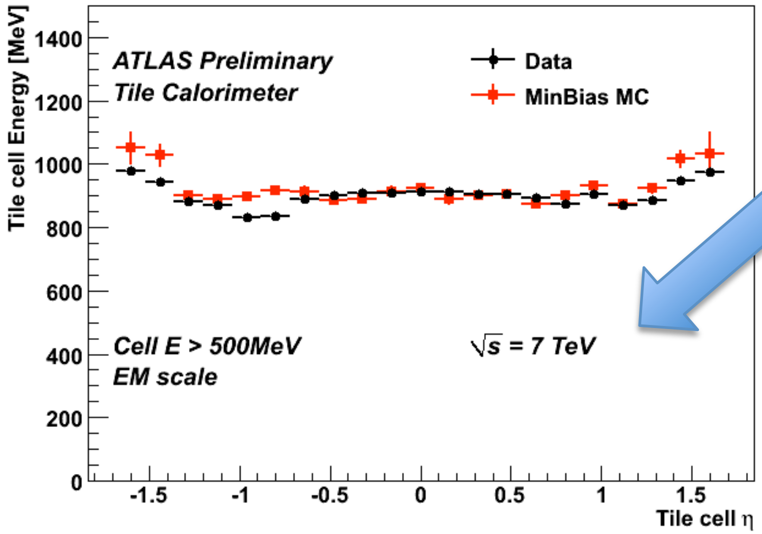
Strategies for LLP Searches using Time of flight Techniques

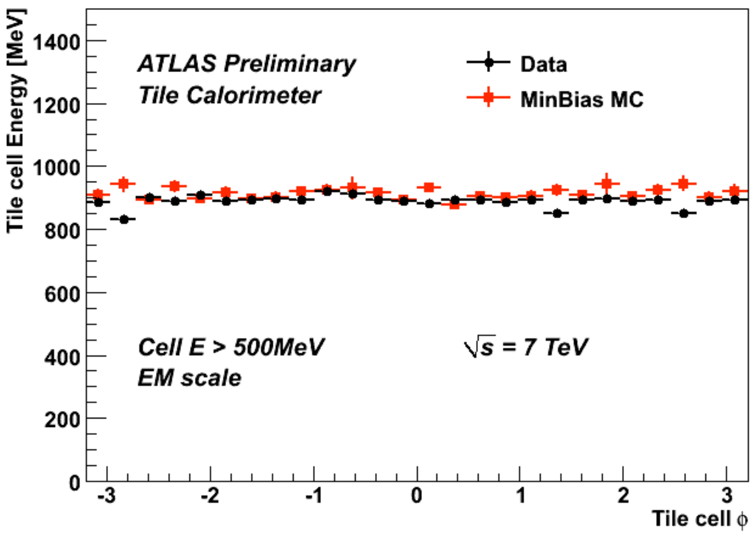
LLPs using ToF in TileCal

- Analysis strategy
  - Select events passing L1 Muon or Jet Triggers
  - LLP candidates: offline muons identified in the Muon Spectrometer as well as Inner Detector tracks tagged as muons by their energy deposit
  - Measure candidates velocity and momentum
    - $M(cand) = p/\beta\gamma$
- Use energy deposited in TileCal and Pixel to distinguish between signal and background
  - Need to check energy calibration in TileCal and dE/dx in Pixel
- Use timing info in TileCal to compute β of LLP candidates
  - Need to check TileCal timing calibration

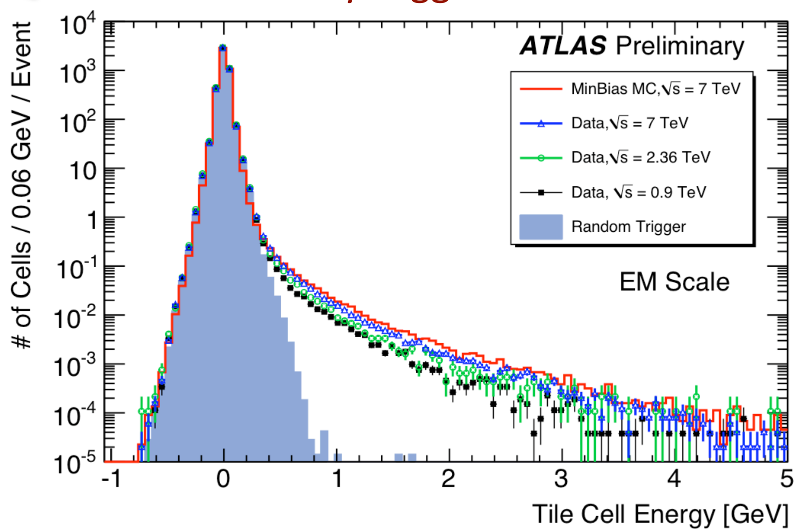
Energy in TileCal

- Average TileCal cell energy as a function of η/ϕ in collision candidate events at $\sqrt{s}$ = 7 TeV
  - Only cells energies above 500 MeV are considered.



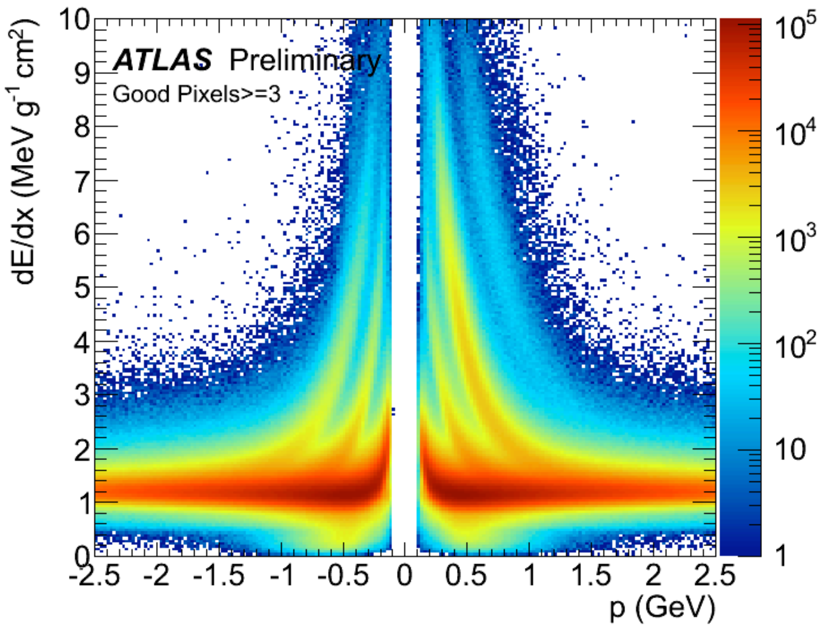


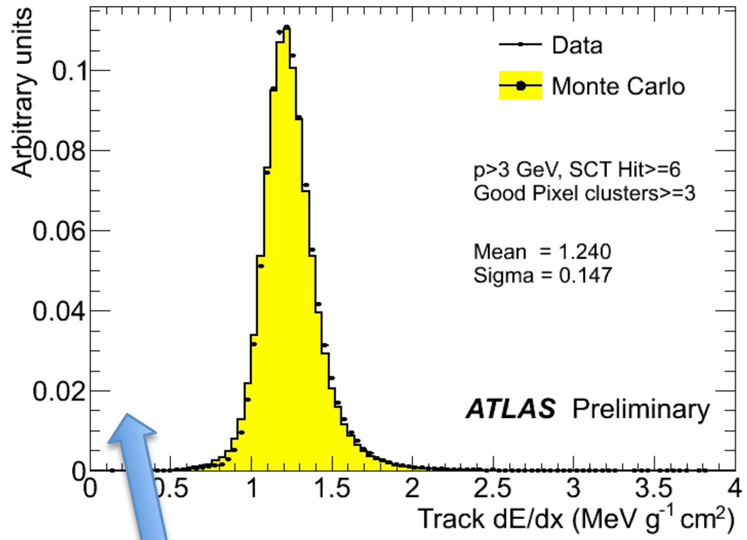
- Energy of the TileCal cells
  - 7, 2.36 and 0.9 TeV are superimposed with Pythia minimum bias Monte Carlo and randomly triggered events



dE/dx in Pixel Detector

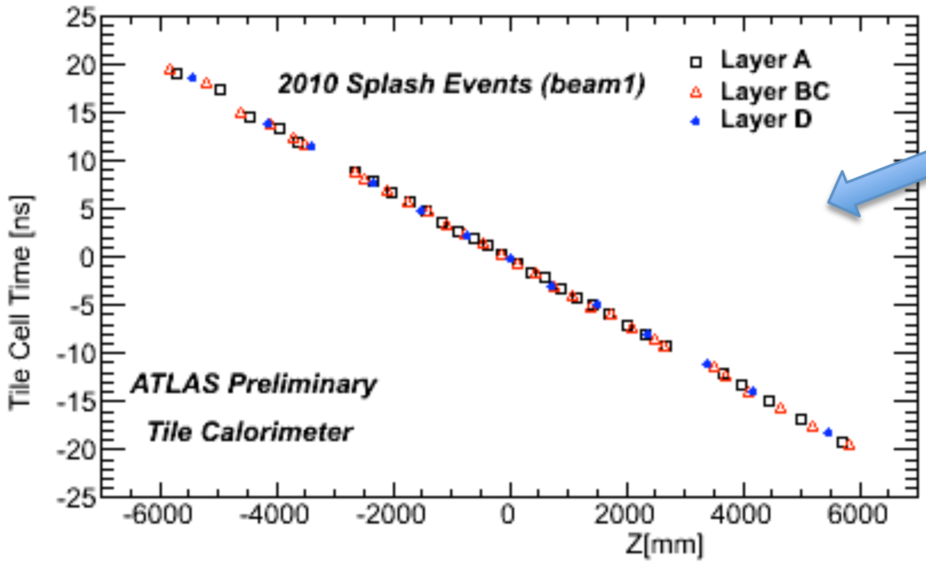
- Average of the individual dE/dx measurements for all the Good Pixel Clusters associated to a track
  - measure the time-over-threshold of the pixel signals and convert that to charge





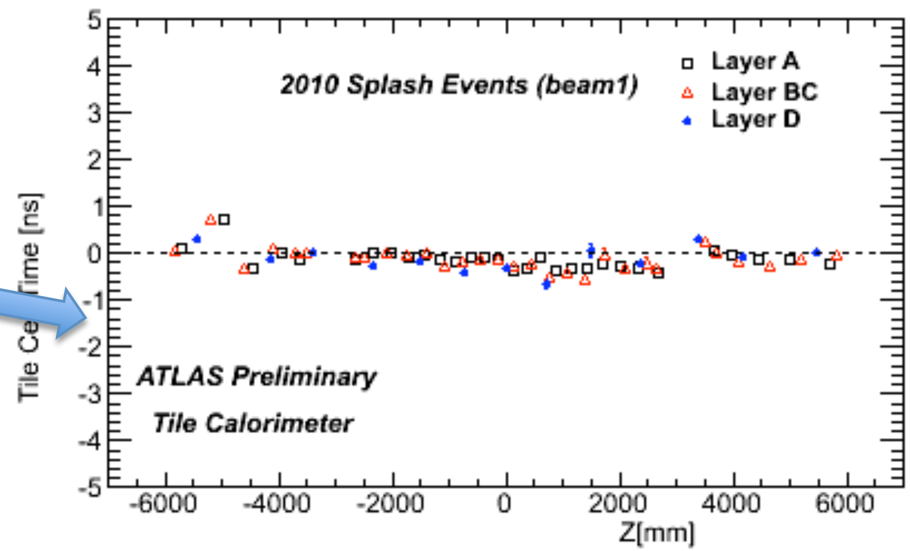
- dE/dx resolution of ~12% is measured using particles with p > 3 GeV
  - Mean and sigma are obtained from a gaussian fit of the data

Timing of TileCal Signal



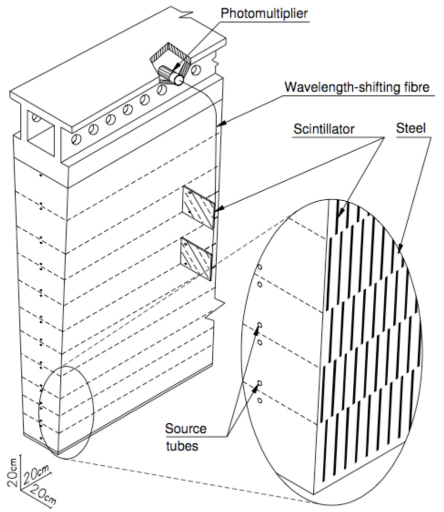
- Average time over all cells with the same phi coordinate
- The observed slopes match the time the muons take to cross the calorimeter along the Z direction

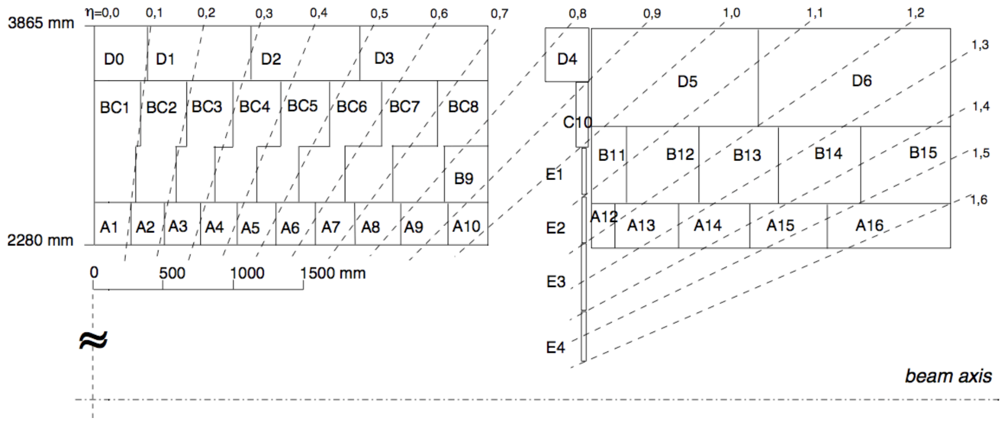
- Same distribution after applying the time of flight correction that assumed a track parallel to the Z-axis
- Flat distribution demonstrates the very good time equalization



Measuring β using TileCal

- Use timing info from calorimeter





- 64 modules in ϕ
- each module is divided in cells
  - 23 cells for LB
  - 18 cells for EB

- Each cell gives a measurement of beta: $\beta = \dfrac{d_{cell}}{t_{reco}c + d_{cell}}$

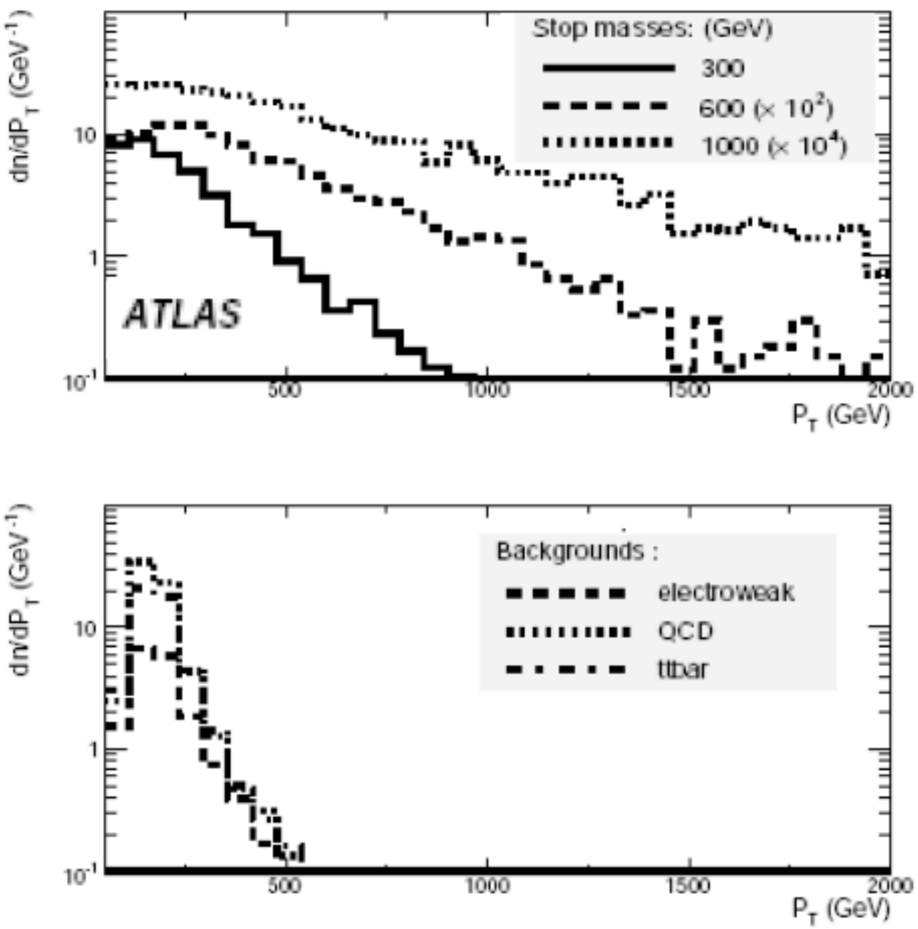
- Combine cells along extrapolated path of LLP candidate

$$\beta = \frac{\sum \omega_i \beta_i}{\sum \omega_i} \quad \text{where} \quad \omega_i(E_{cell}) = E_{cell}$$

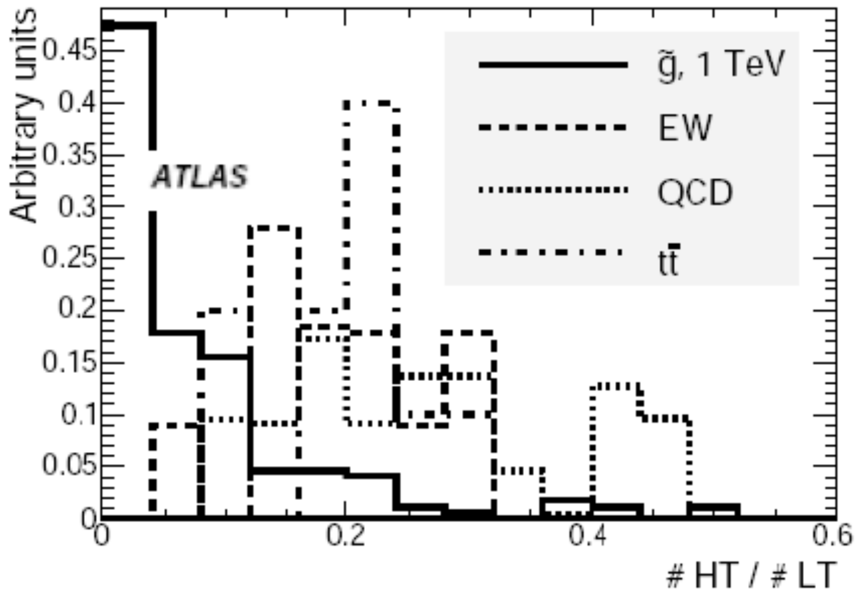
~ 5% resolution and 95% efficiency for signal LLPs on MC events (E_{cell} > 500 MeV)

More Final State Observables

p_T of muon tracks
(normalized to $1fb^{-1}$)



High-threshold (HT) hits
in the Inner Tracker

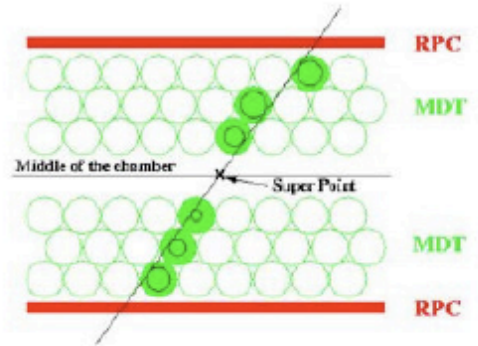


SUSY Chapter in CERN-OPEN-2008-020
arXiv:0901.0512

LLP using ToF in Muon Spectrometer

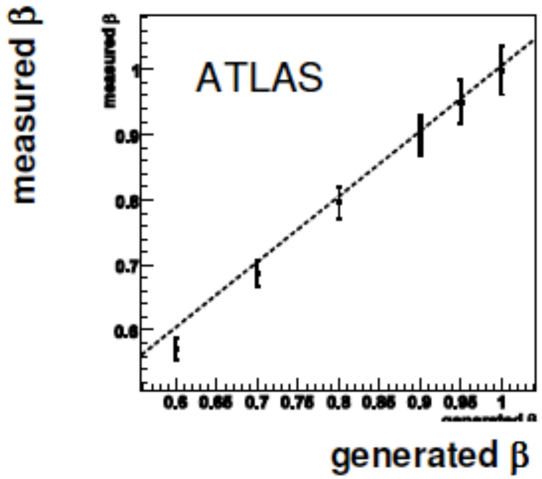
- Analysis strategy
  - LLP candidates: offline muons in Muon Spectrometer
- Muons are reconstructed using the precision muon chambers (MDTs), in combination with RPC, TGC and CSC sub-detectors
  - Use MS to measure momentum and velocity of LLP candidates
- Slow particles are reconstructed looking at Muon Spectrometer hits matched to Inner Detector tracks
  - recover trigger detector hits from the next bunch-crossing
  - estimate particle velocity from the RPC hit time
  - select the β that gives the best MDT segment fit
  - Efficiency > 90% for $\beta \geq 0.4$ (on signal MC events)

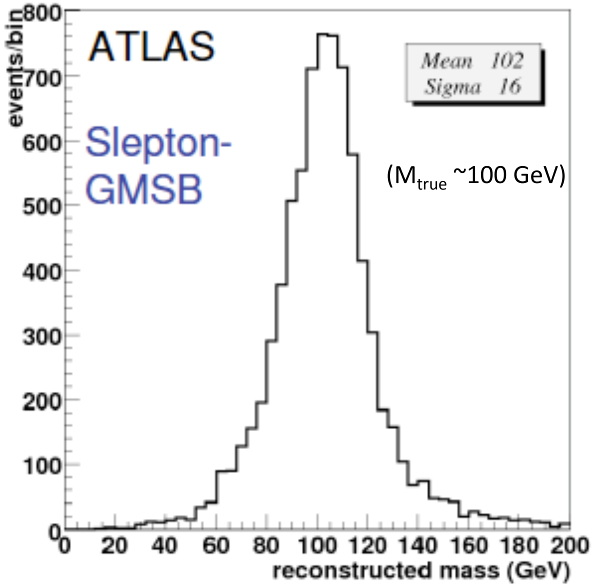
Reconstructing LLP Mass

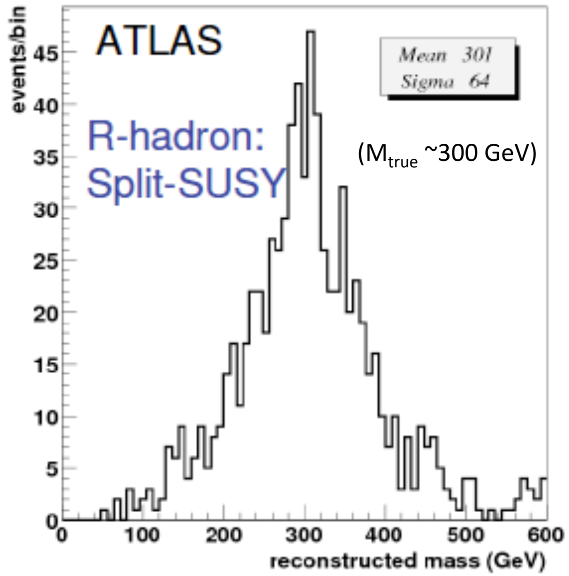


β from RPC, and MDT track fit

EPJC62 (2009), 281







Stopped-gluino Searches

Event Signature

- In split-SUSY gluino R-Hadrons will be produced approximately back to back in transverse plane
- Some of these may loose enough energy and stop in the calorimeters
  - Decay later to gluon+LSP or qq+LSP
- Signature:
  - large isolated energy deposit in calorimeters
  - rest of the event is “empty”
- Need to devise a search strategy to reduce background processes as efficiently as possible
  - Trigger in empty bunch crossings of LHC to remove background from collision processes
  - only background left from cosmic ray events and beam background
- Compare cosmic ray data to out of bunch collision data

Event Selection

- Use 7 TeV data triggered during gaps between beam crossings in the LHC
- Select events where ≥ 1 Jets are present and no tracks or segments are reconstructed in the muon system
  - Jets are central in the detector: $|\eta| < 1.2$
  - Energy of leading jet > 50 GeV
- Allow up to 3 additional jets
  - to retain sensitivity to $\tilde{g} \rightarrow q\bar{q}\chi^0$ channel
- Additional cuts on Jet energy to clean sample are applied
- Event yield and shape of variable distribution is compared between 2010 collision data and 2009 Cosmic Ray data

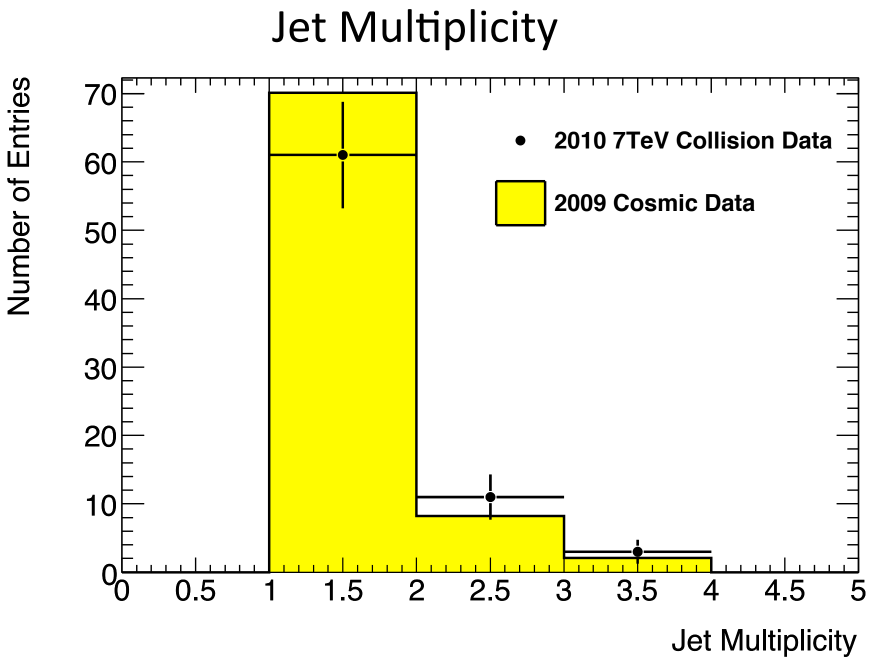
Event Yield

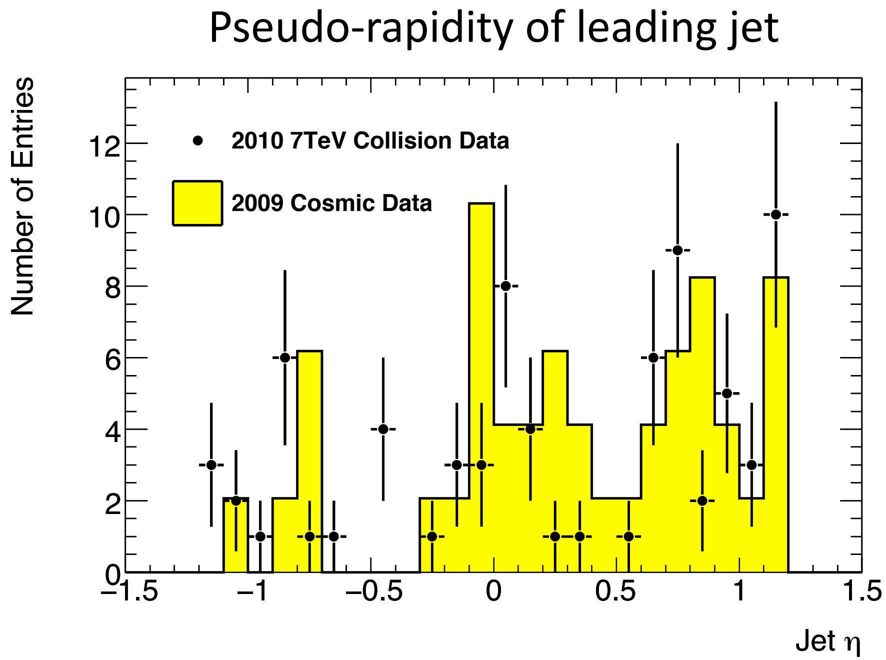
- Reduce possible bias from different detector conditions between 2009 and 2010 run by using additional data quality requirements in the analysis
  - remove "bad" runs from Cosmic data, LAr noise, etc…

	2009 Cosmic Data		2010 Collision Data
Selection Criteria	Yield of cosmics	Cosmics (scaled)	Yield of data
Good runs and data quality cuts	9.43×10^5	–	1.58×10^6
Leading Jet $\|\eta\| < 1.2$	6.26×10^5	1.29×10^6	1.29×10^6
Jet n90>3	3.83×10^5	7.89×10^5	7.90×10^5
number of Jets<4	3.82×10^5	7.87×10^5	7.83×10^5
Muon Segment Veto	530 ± 23.0	1092 ± 47.4	1170
Leading Jet Energy > 50 GeV	39 ± 6.2	80 ± 12.8	75
Leading Jet Width > 0.05	6 ± 2.4	12 ± 4.9	8
Jet n50<6	3 ± 1.7	6 ± 3.5	4
Leading Jet EMF<0.95	2 ± 1.4	4 ± 2.9	4

Yield in collision data in agreement with expectations from Cosmic run

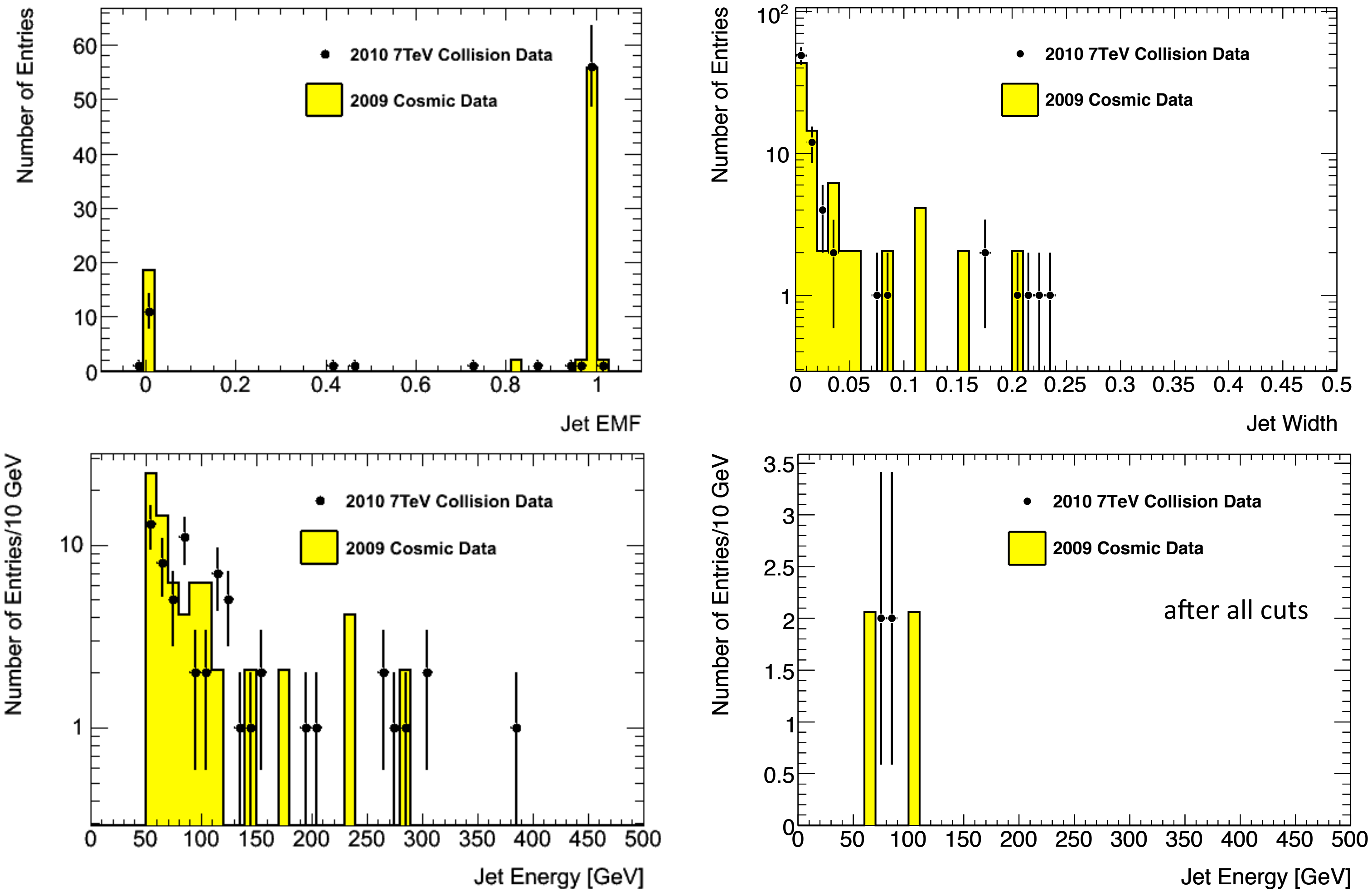
Jet Multiplicity and η Distribution





- Majority of events have only single jet
- Leading jet should be central in detector

Jet Energy/Shape Distributions



Overall, good agreement in the shape of the distributions between collision data and Cosmic ray events

Summary & Outlook

- New exotic long-lived particles are predicted in most Beyond the Standard Model theories and could be the first signal of new physics at the LHC
- Several studies under way in ATLAS to look for LLP signatures using various techniques
- Various observables have been studied that can be used to discriminate between signal and Standard Model background

Looking forward more exciting results with increasing LHC data !