Search for long-lived massive particles at ATLAS

Vivek Jain, Indiana University

(for the ATLAS Collaboration)

DPF, Aug 9-13, 2011

Outline

- Introduction
  - Long-lived, massive particles
  - ATLAS detector
- Results - (available at this link)
  - Displaced vertices
  - R-hadrons
    - Bound states of coloured sparticles & SM partons
- Summary

Motivation

- Long-lived massive particles are in many BSM models with a variety of signatures.
  - Lifetimes range from microns to meters, β can be much less than 1, q>>e…
- Many of these models are already constrained by data, but the use of lifetime as a search parameter is uncharted territory
  - Displaced vertices, are in R-parity violating SUSY ($\tilde{\chi}^0$ is the LSP and decays), Split SUSY, Hidden valley models, Stealth SUSY…

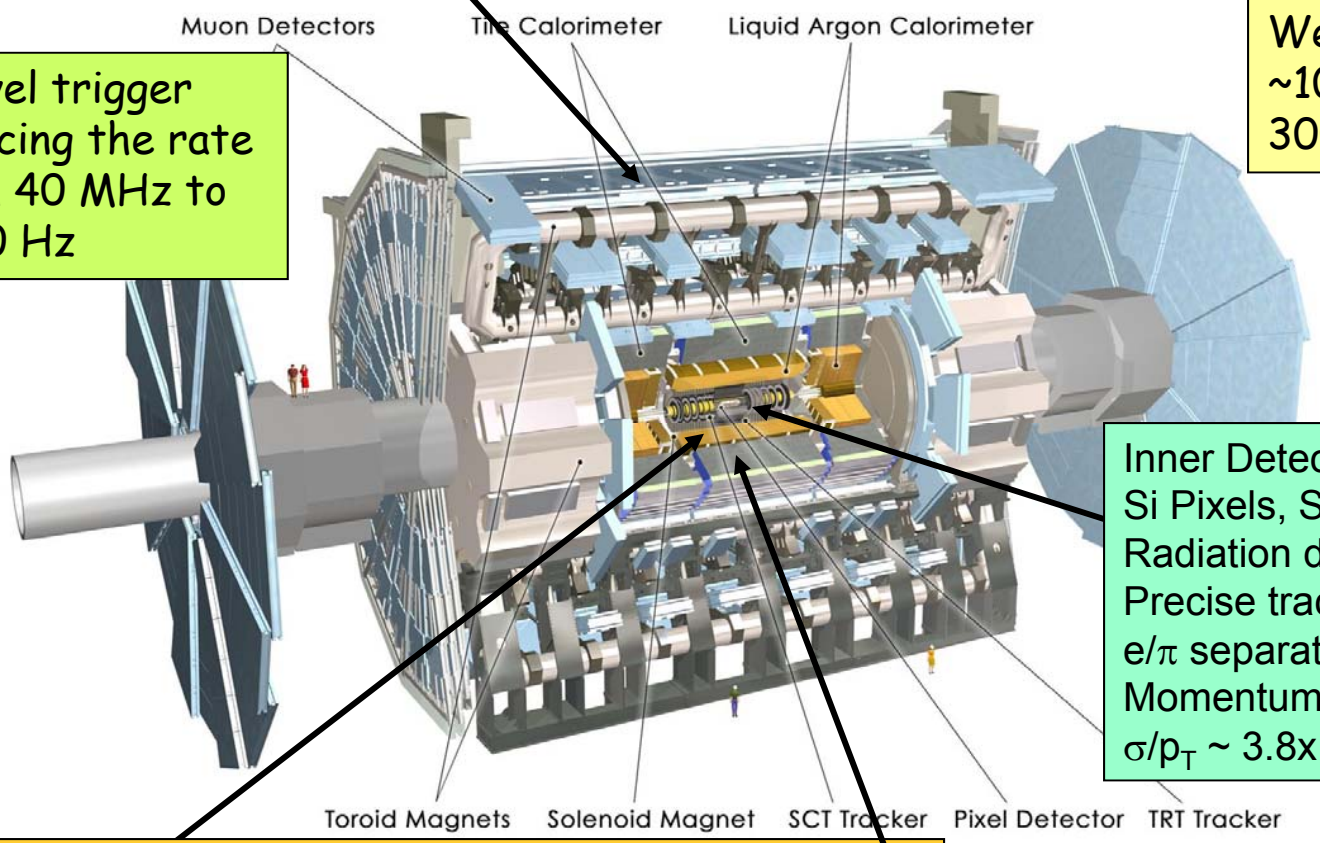
Search for long-lived massive particles

- R-hadrons: Coloured sparticles can hadronize into long-lived, bound hadronic states, e.g., ~g+g, ~g+qqbar, ~q+q, etc.
  - They are in R-parity conserving SUSY, Split SUSY, Universal Extra Dimensions
  - They can start out as neutral and due to interactions in the detector become charged and be detectable only further out in radius
  - They can also be Highly ionizing particles, q>>e, in models of Q-balls, micro black hole remnants, magnetic monopoles, dyons…
- Stau leptons, e.g., in GMSB models

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\ p_T\,(\mathrm{GeV}) \oplus 0.015$

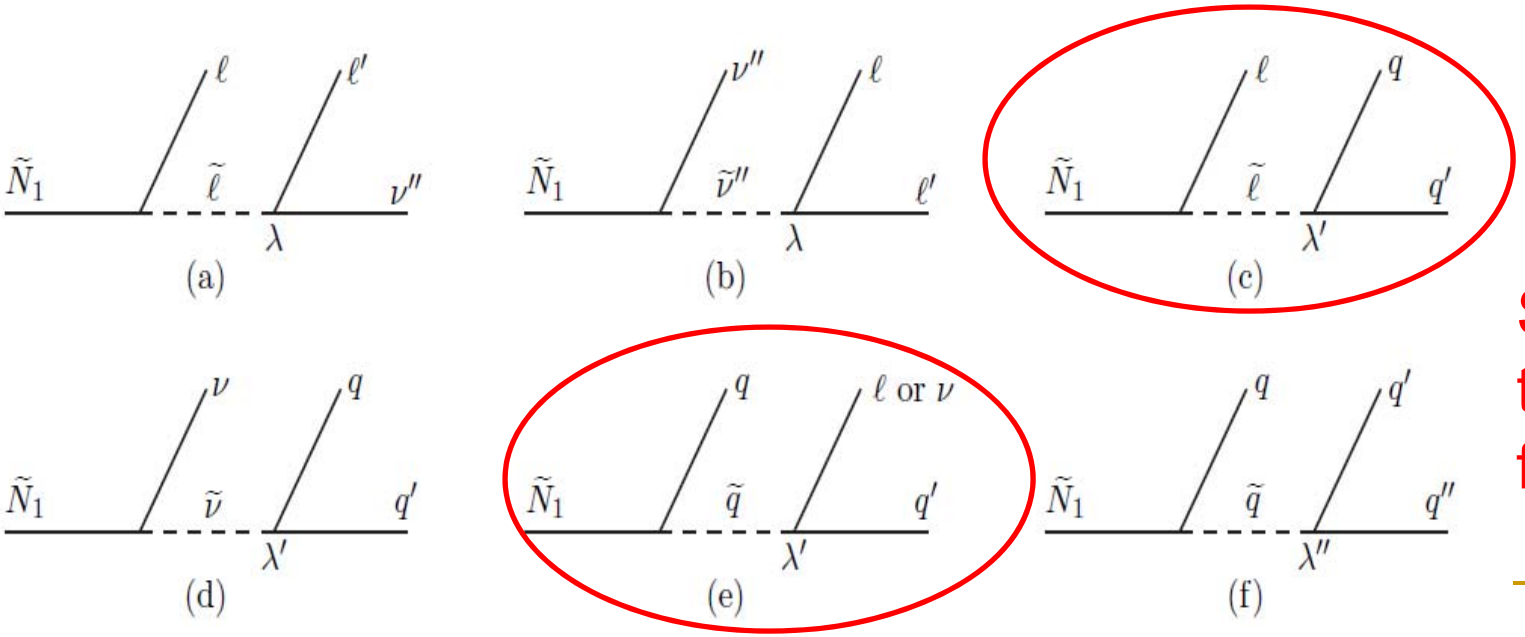
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

The analyses use a variety of triggers

Search for displaced vertices (I)

- Current analysis uses a R-parity violating framework to analyze the results
  - LSP, e.g., ~χ0, is produced via strongly produced squarks and gluinos, i.e., large production x-section. It is unstable, and can decay within the detector.

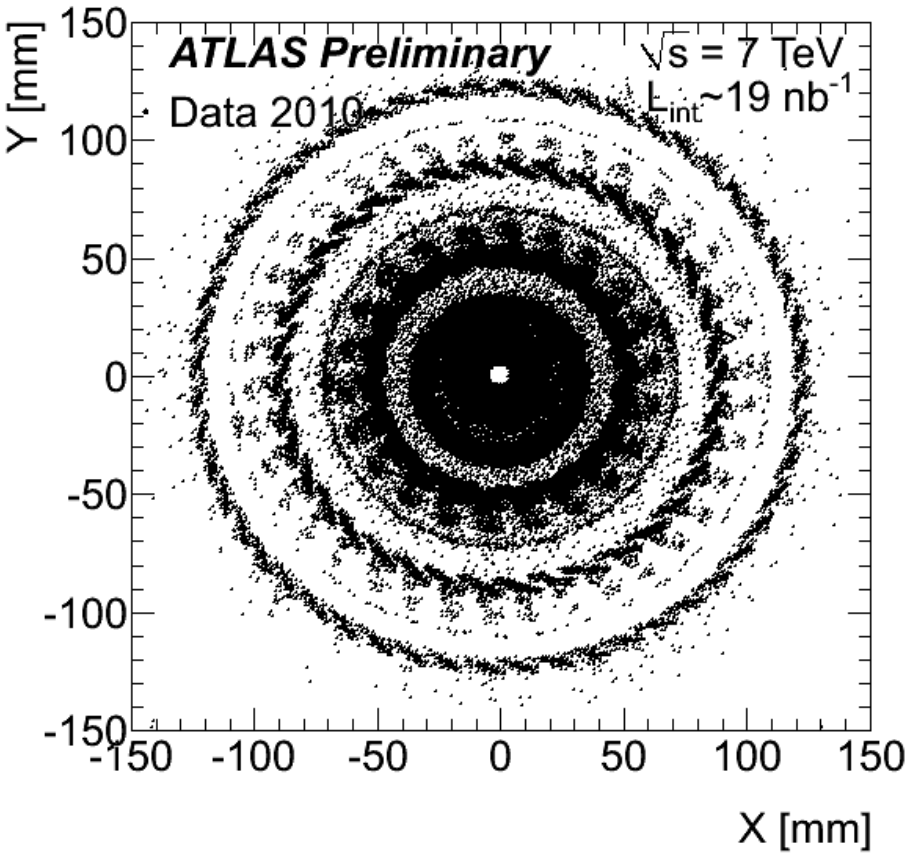


Search in the qq'μ final state

- Final state contains many charged tracks and a muon that come from a displaced vertex
  - Muon trigger, pT>40 GeV, in 2010 data (33 pb^{-1})
  - Vertex charged tracks, with $|d_0|$>2 mm
    - Muon not required to be in vertex (improvement for future)
  - Remove contamination from material interactions, (material veto map), Ks…

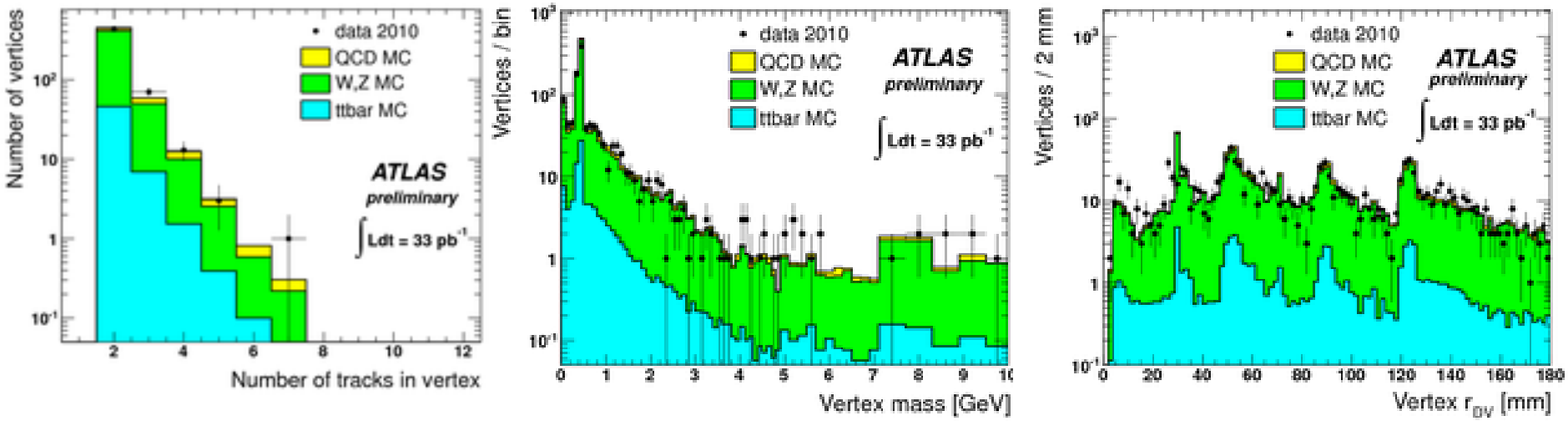
Require Vertex to have $N_{trk} \geq 3$, Mass > 10 GeV

  - Search for displaced vertices for R < 180 mm

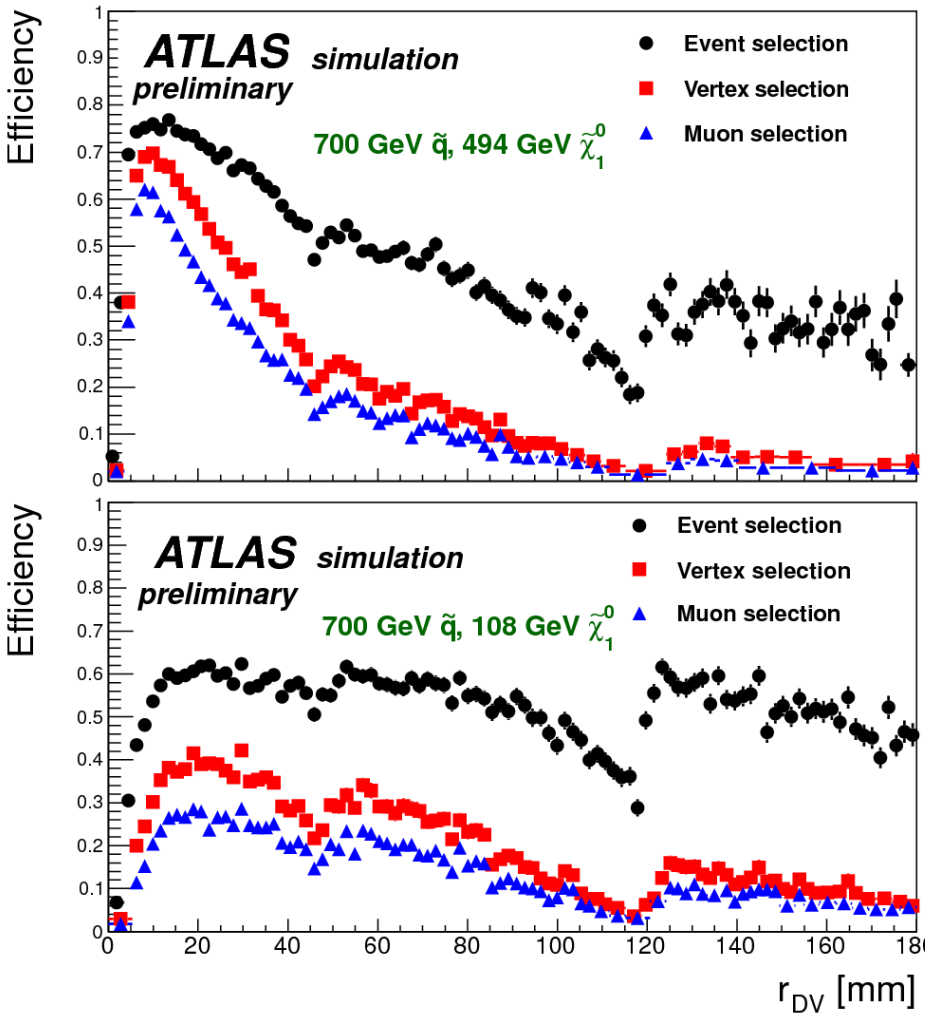


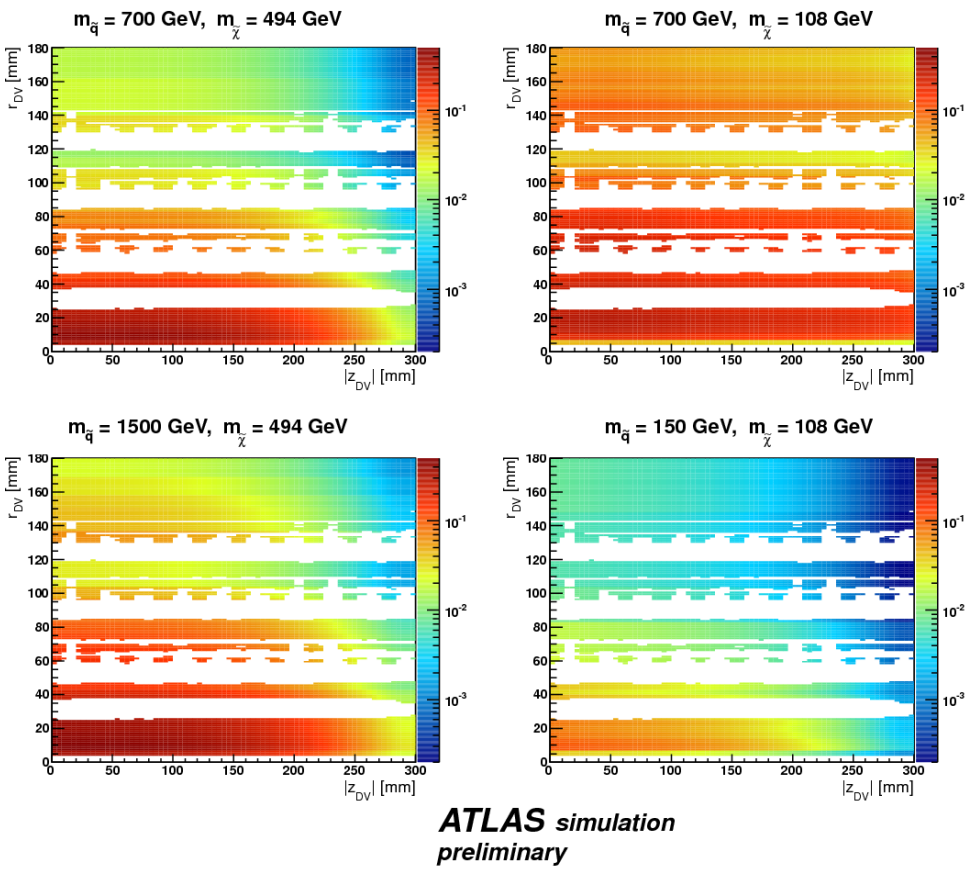
Comparing Data with Monte Carlo

- Loosen selection, i.e., mass (<10 GeV), # trks ≥ 2 to stay away from signal region



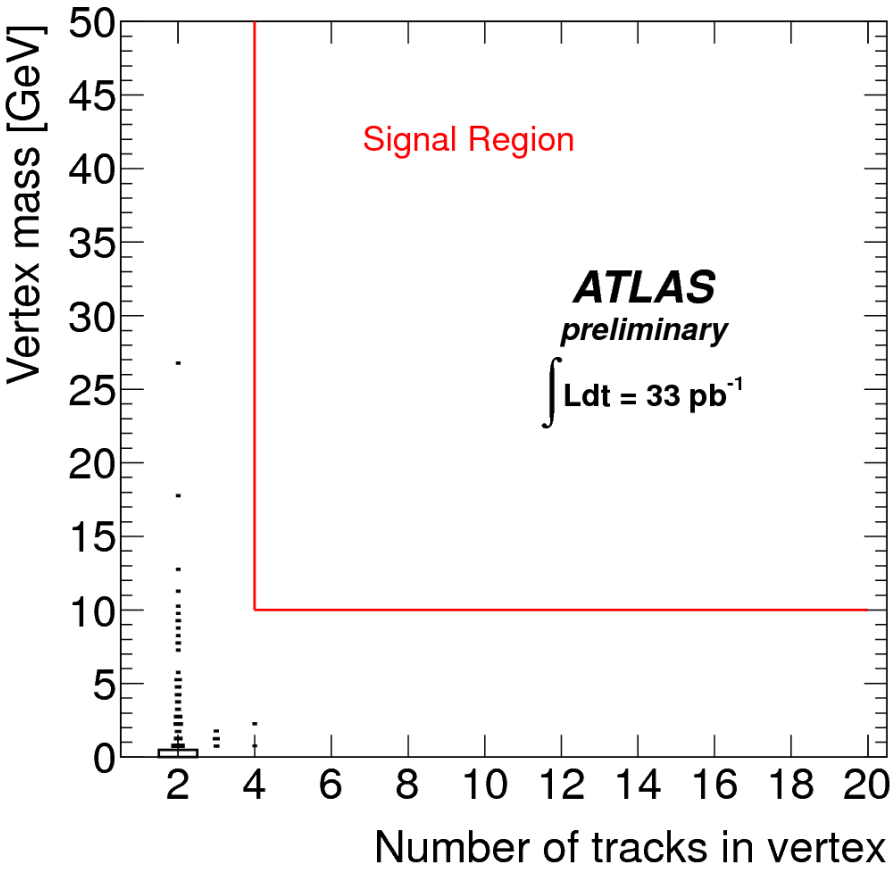
- Good agreement





Signal Efficiency as a function of R for
700 GeV squarks &
(top) 494 GeV neutralinos
(bottom) 108 GeV neutralinos

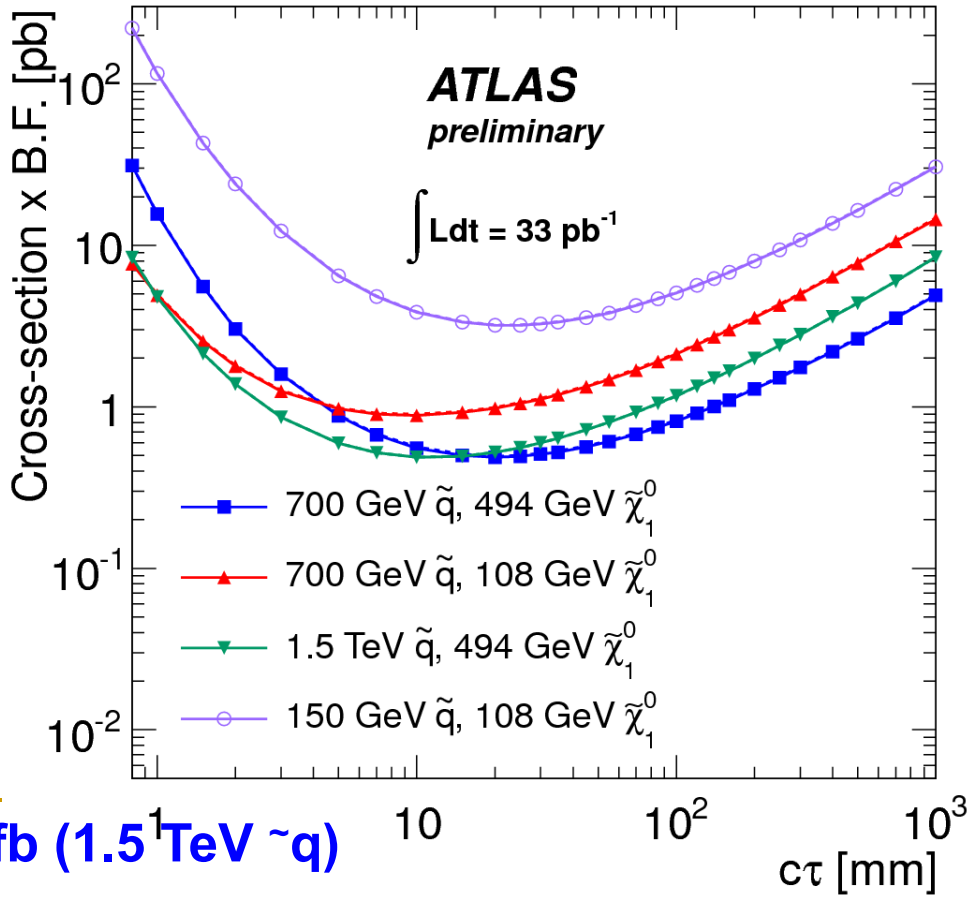
Signal Efficiencies as R vs. Z
(red ~ 10%, blue < 1%
White spaces are vetos using material map)



Results:

 # observed events in signal region: 0

Background estimate (MC and a data driven cross-check): **< 0.03 @ 90%CL**



- Use CLs w/ one-sided profile likelihood as test statistic.
- Each cτ treated as number counting experiment with errors on ε, lumi and background as nuisance parameters
- **σ * detector acceptance * ε < 0.09 pb @ 95% CL for any signal**

Prospino signal x-sections from 0.2 fb (1.5 TeV ~q) to 540 pb (150 GeV ~q)

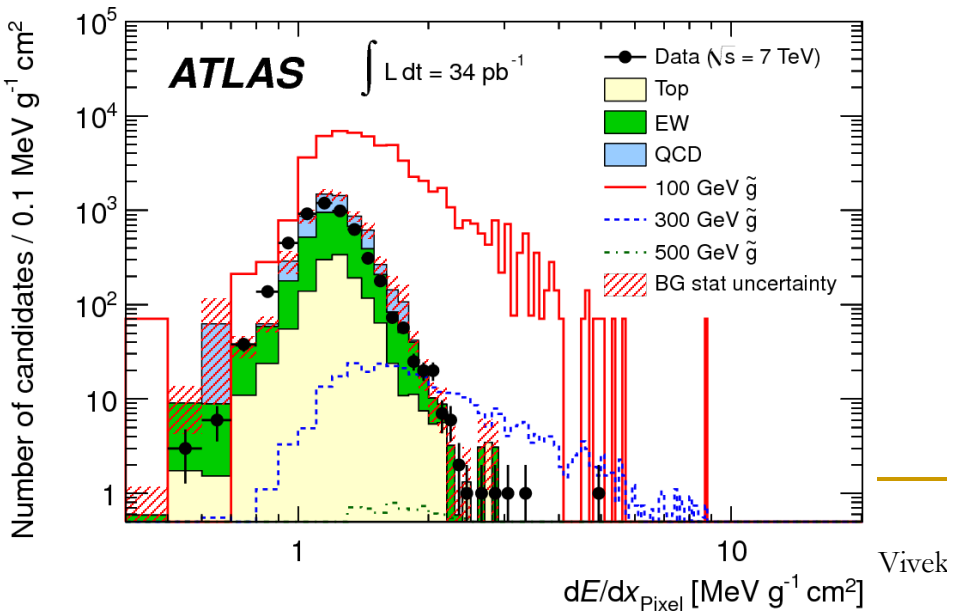
R-hadrons

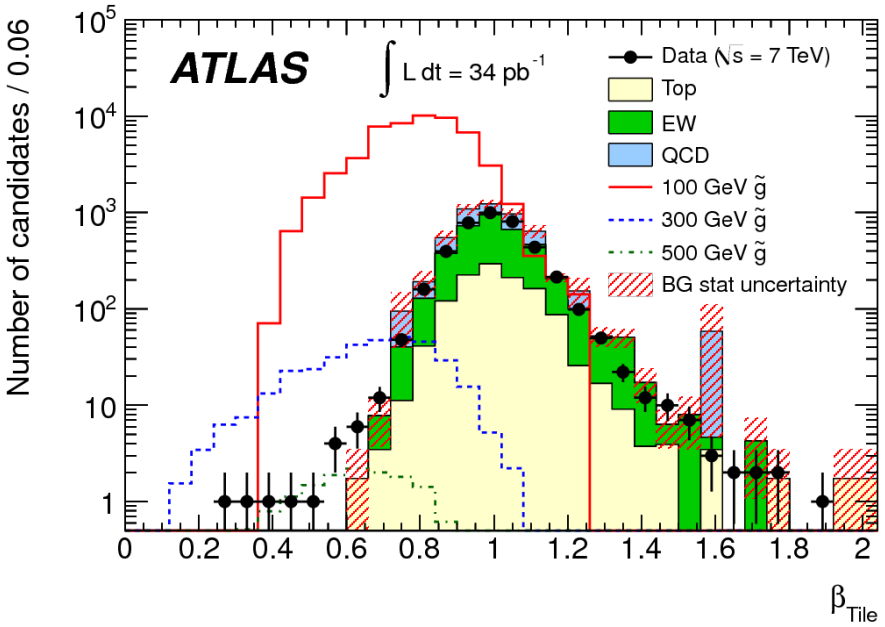
- Bound states of Sparticles and SM partons.
  - Slow-moving, Lifetime long enough to traverse detector
  - Can be neutral at production, and become charged later
- Possibility of direct pair production via strong force implies large production cross-sections.
  - MC uses specialized routines to create R-hadrons and handle their interactions in detector
- Complementary analyses – both use 2010 data
  - One uses Inner Detector & Calorimeter
    - Uses Missing Energy trigger (34 pb^{-1})
  - Other uses Muon Spectrometer
    - Uses Muon trigger (37 pb^{-1})

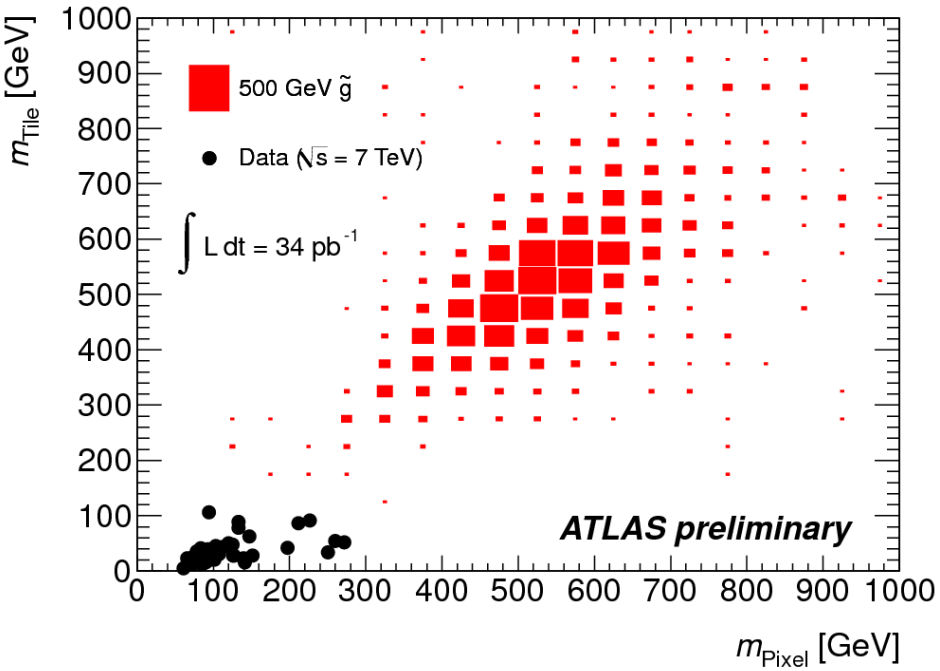
R hadrons in ID and Calorimeter

- Use dE/dx in Pixels & Time from Tile Cal.
  - Get independent measurements of β
- Combine β with momentum and get two estimates of mass.
  - MIP compatible deposits in CAL
  - Track pT > 50 GeV

Resolution ~ 10%



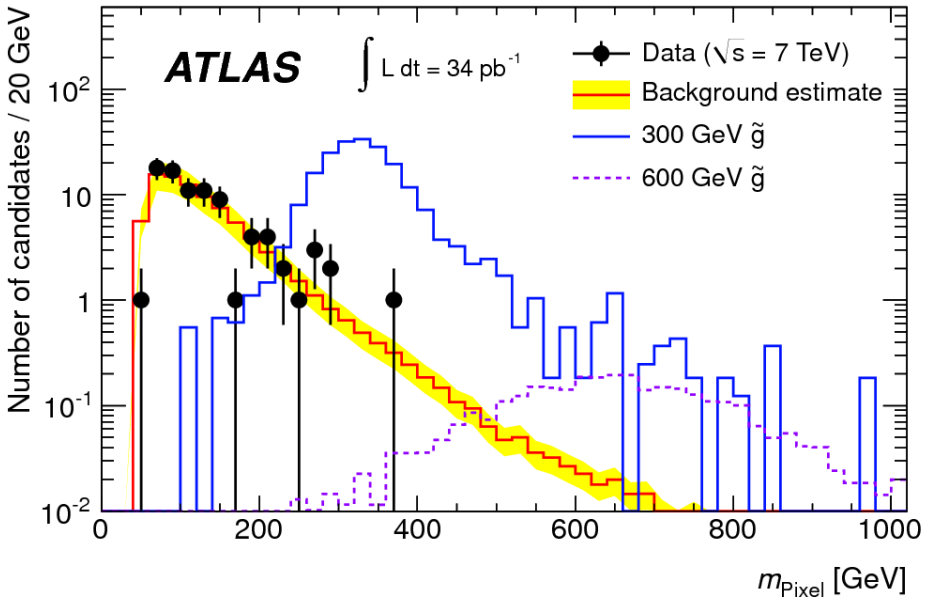


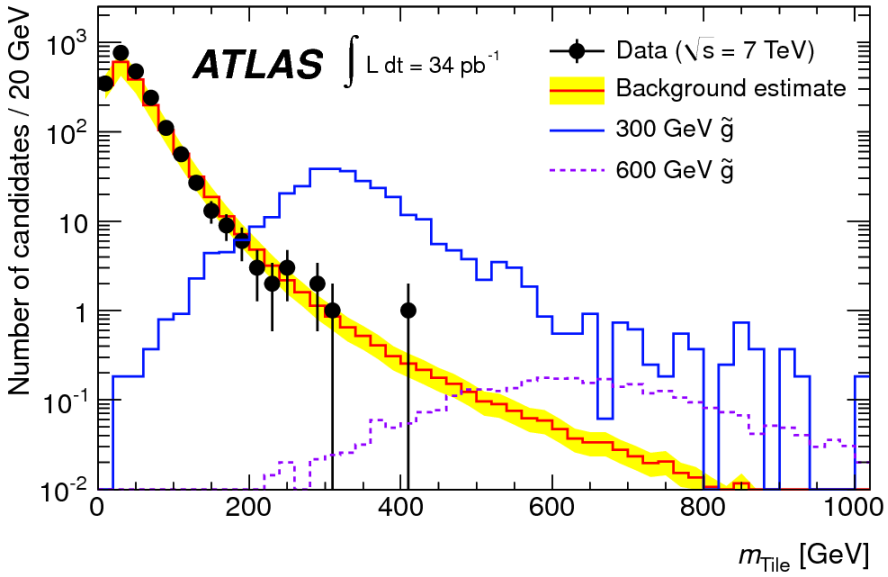


Distributions after selection cuts:

dE/dx > 1.8 MeV g^{-1} cm^2 (pixel),
β < 1 (tile),
pT > 50 GeV

2-D plot of mass estimates in Tile calorimeter vs pixels.





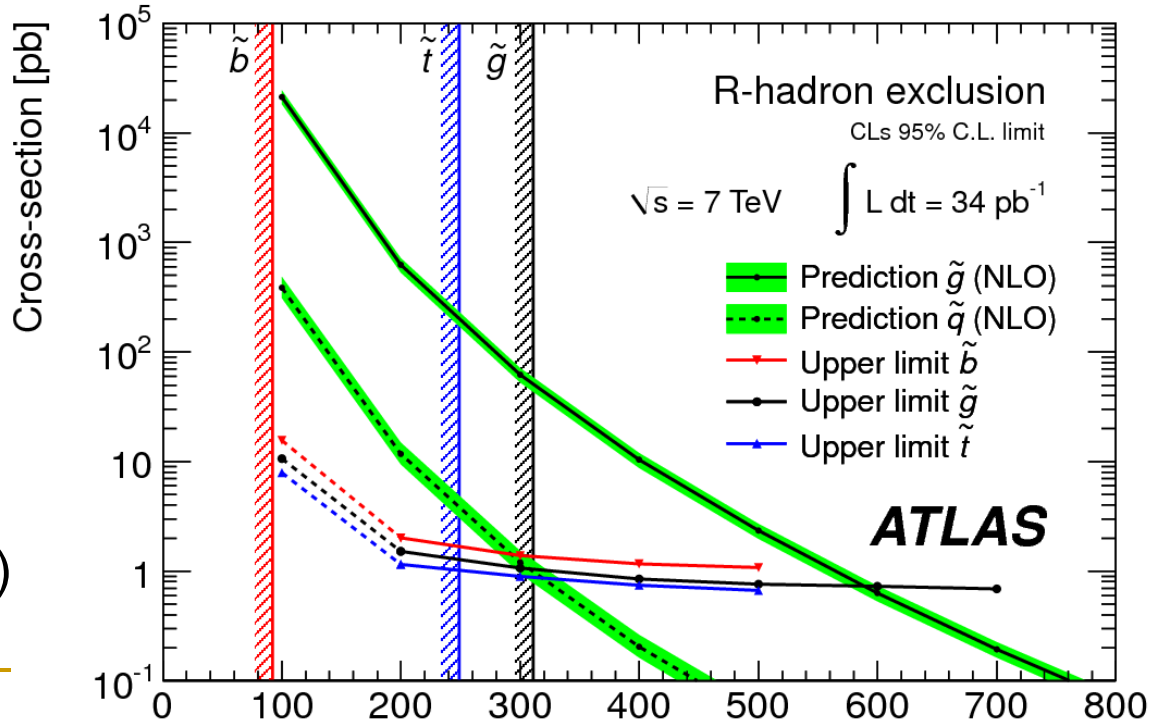
Background estimates use random combinations of track pT & dE/dx and β to construct a mass distribution

- Combine the two mass estimates to reduce background
  $m_{Pixel} > \mu_{Pixel} - 2*\sigma_{Pixel}$ & $m_{Tile} > \mu_{Tile} - 2*\sigma_{Tile}$
  - σ ~ 10-20% for Pixels, ~ 20% for Tile
- Background estimate < 1 event for M>100 GeV
- No events in data with M>100 GeV
- Limits: Use cross-sections from PROSPINO, signal ε and CLs method

- ATLAS limits:

M(sbottom) > 294 GeV
M(stop) > 309 GeV
M(gluino) > 586 GeV

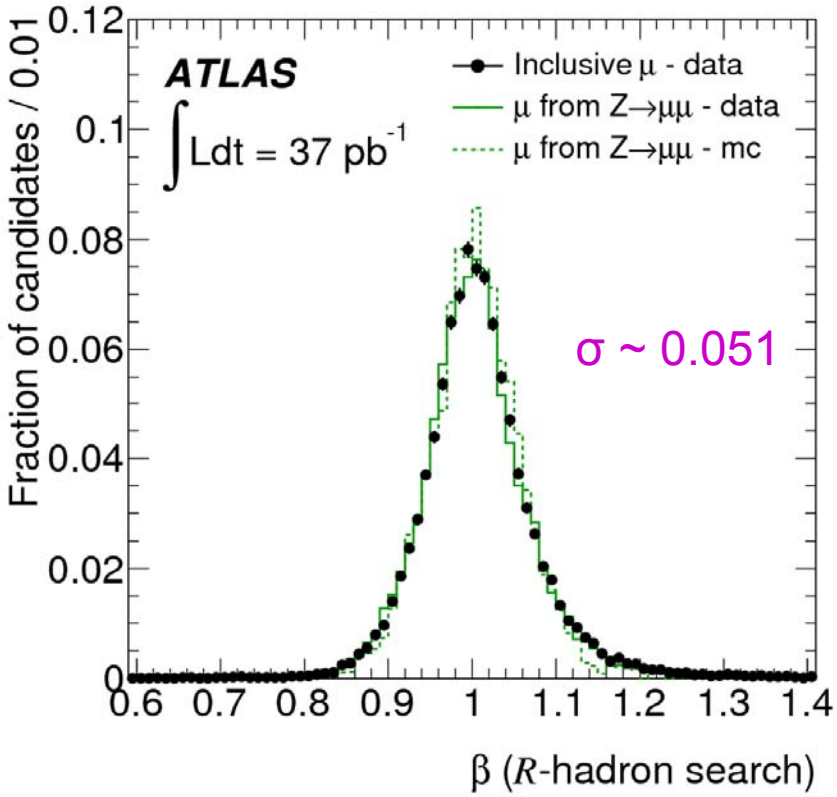
- Previous limits are from ALEPH(sbottom), CDF (stop) CMS (gluino w/ 3.1 pb^{-1})



New CMS results w/ 1 fb^{-1}: ~t > 620 GeV, ~g > 899 GeV

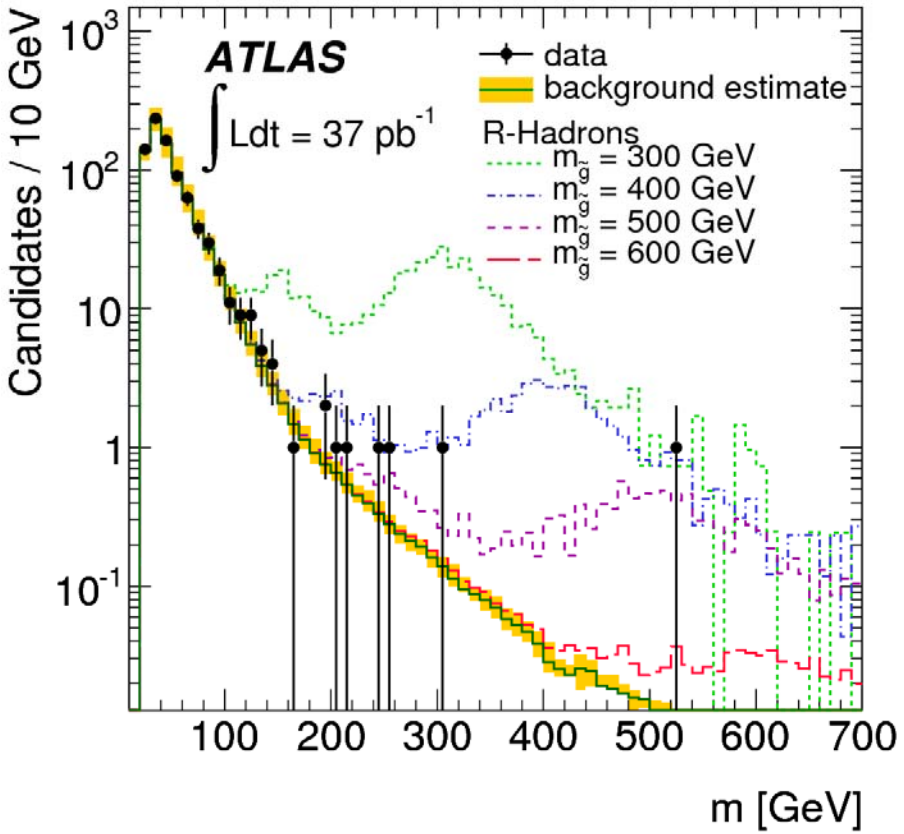
R hadrons in Muon Spectrometer

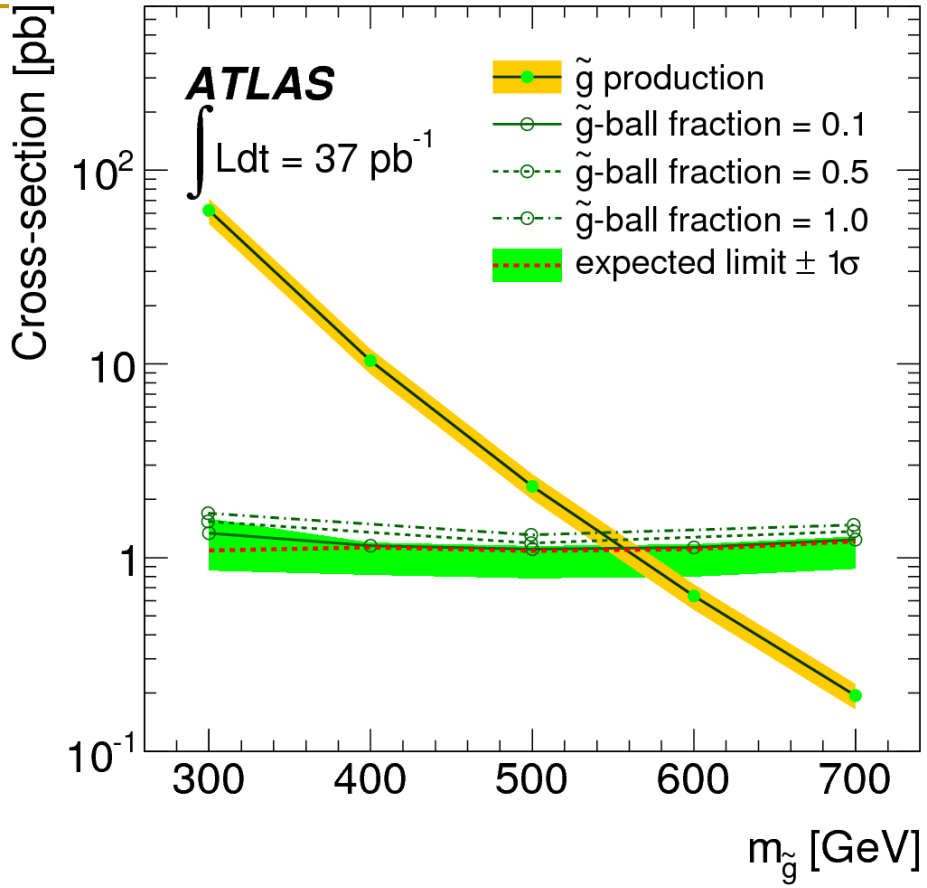
- Can be electrically neutral at production, and get a charge from interactions in Calorimeter
- Reconstruct candidates using only the Muon Spectrometer
  - Determine β by minimizing χ^2 between available timing measurements and timing expected from hypothesized value
  - β values in various layers have to be consistent



Analysis details

- Trigger requires MS only pT>40 GeV
  - Offline selection: pT >60 GeV & pT < 1 TeV (latter to remove bad reconstructions)
- Reject cosmic muons by requiring tracks to point back toward Primary Vertex. No back-to-back μ
  - Estimate < 1 cosmic μ background in signal region
- Remove $Z \rightarrow \mu\mu$
- Determine Mass of candidate using momentum and β information. Reject muons with $\beta < 0.95$
- Background mainly due to high pT muons with mismeasured β. Data-driven technique as for previous analysis





$m_{\tilde{g}}$[GeV]	mass cut [GeV]	expected signal	expected background	data
300	250	254.4	2.3	3
400	350	36.2	0.7	1
500	350	8.7	0.7	1
600	350	2.2	0.7	1
700	350	0.6	0.7	1

95% CL Limits on R-hadron masses:

˜g-ball fraction of 0.1, M > 544 GeV

˜g-ball fractions of 0.5 and 1.0, M> 537 GeV and 530 GeV

The systematic uncertainties on the signal yield (based on Split SUSY) & background estimate are 6% and 20% respectively.

Summary

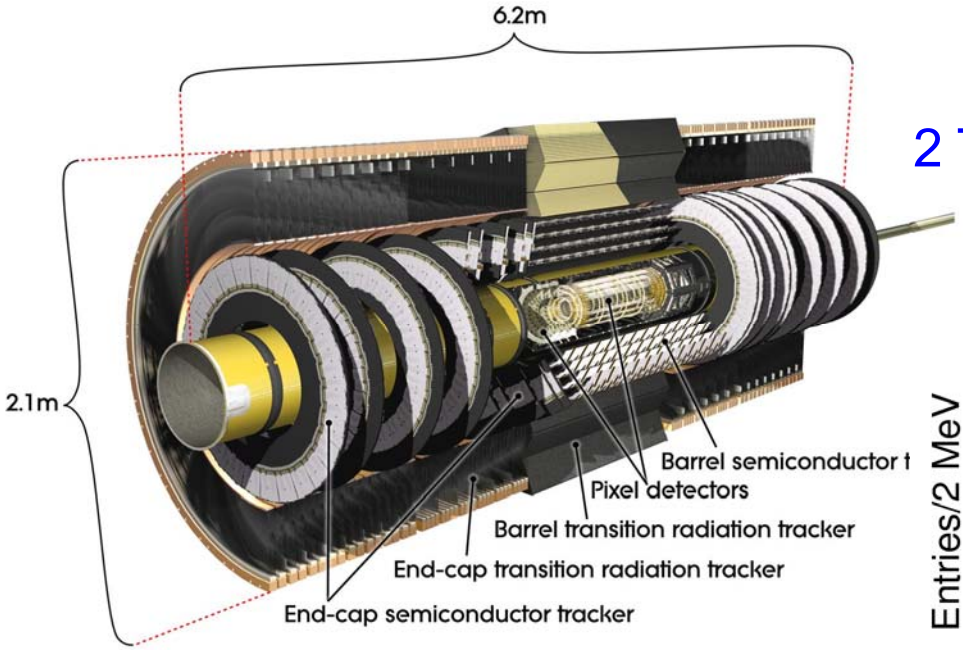
- Many exciting results using lifetime as a search parameter
  - Not mentioned here: Results on stable stau search, and R-hadron search with large q (6-17 e)
- Improvements in analysis techniques and more data in the pipeline
- LHC performing very well. Already have 1.7 fb^{-1} and more coming. Stay tuned!

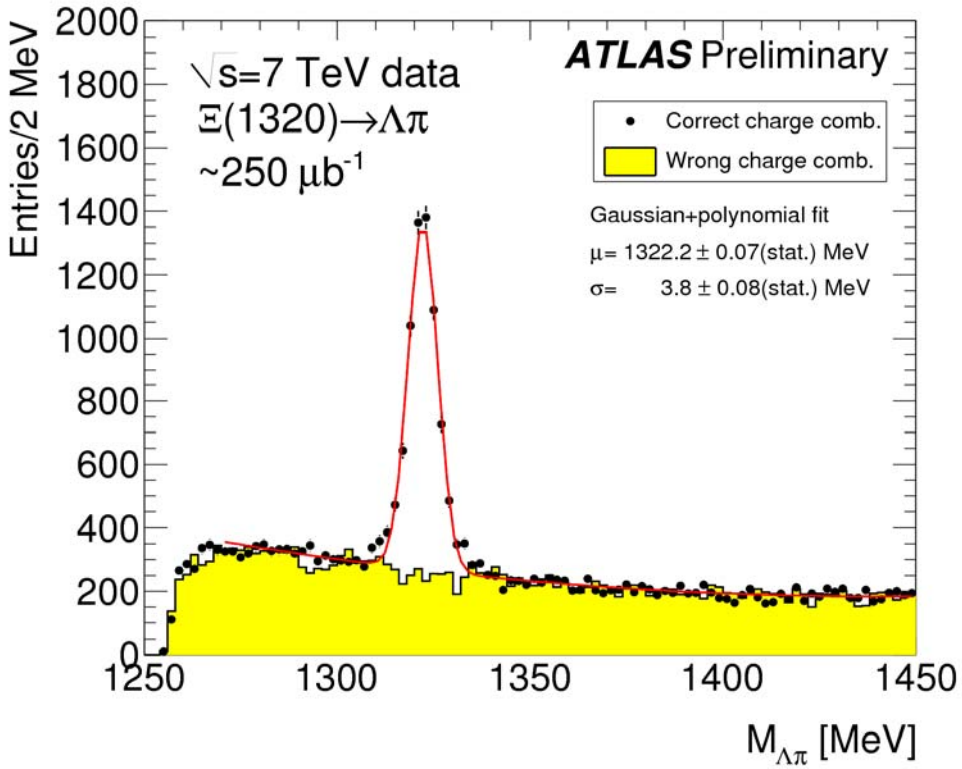
Extra stuff

Inner Detector

ID contains 3 sub-detectors (resolutions)
- Pixel detector: 10/115 μm in Rϕ/z
- Silicon strip detector: 17/580 μm
- Transition radiation tracker: 130μm Rϕ

2 T solenoidal magnetic field





Coverage: $|\eta| < 2.5$ (2.0 for TRT)

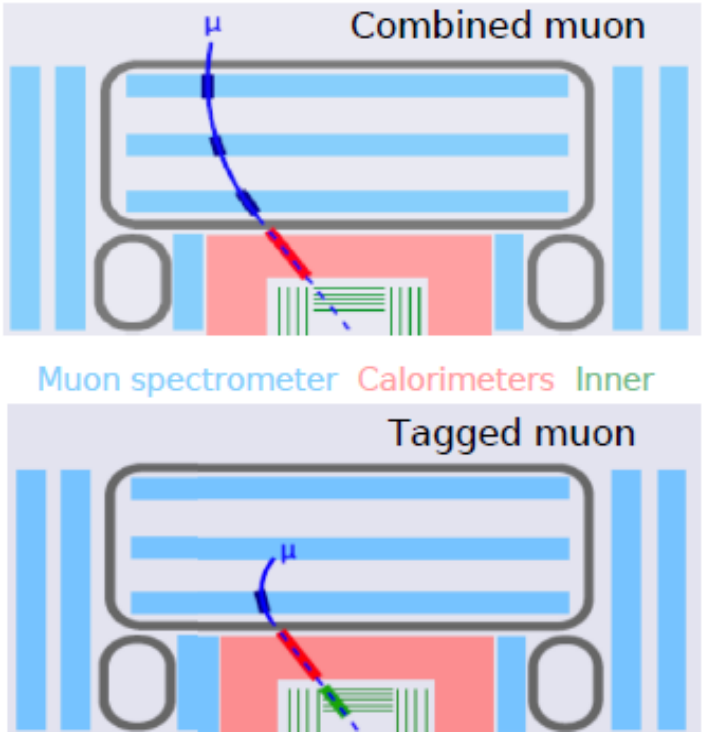
Accurate track & vertex reco.

Resolution goal:

$\sigma_{pT}/p_T = 0.05\%\ p_T \oplus 1\%$

Muon Reconstruction

In selection of J/ψ candidates we consider two types of muon:



Combined muons have an ID track matched to a MS track and refitted through the detector to give the best measurement. At least one muon in a pair must be combined.

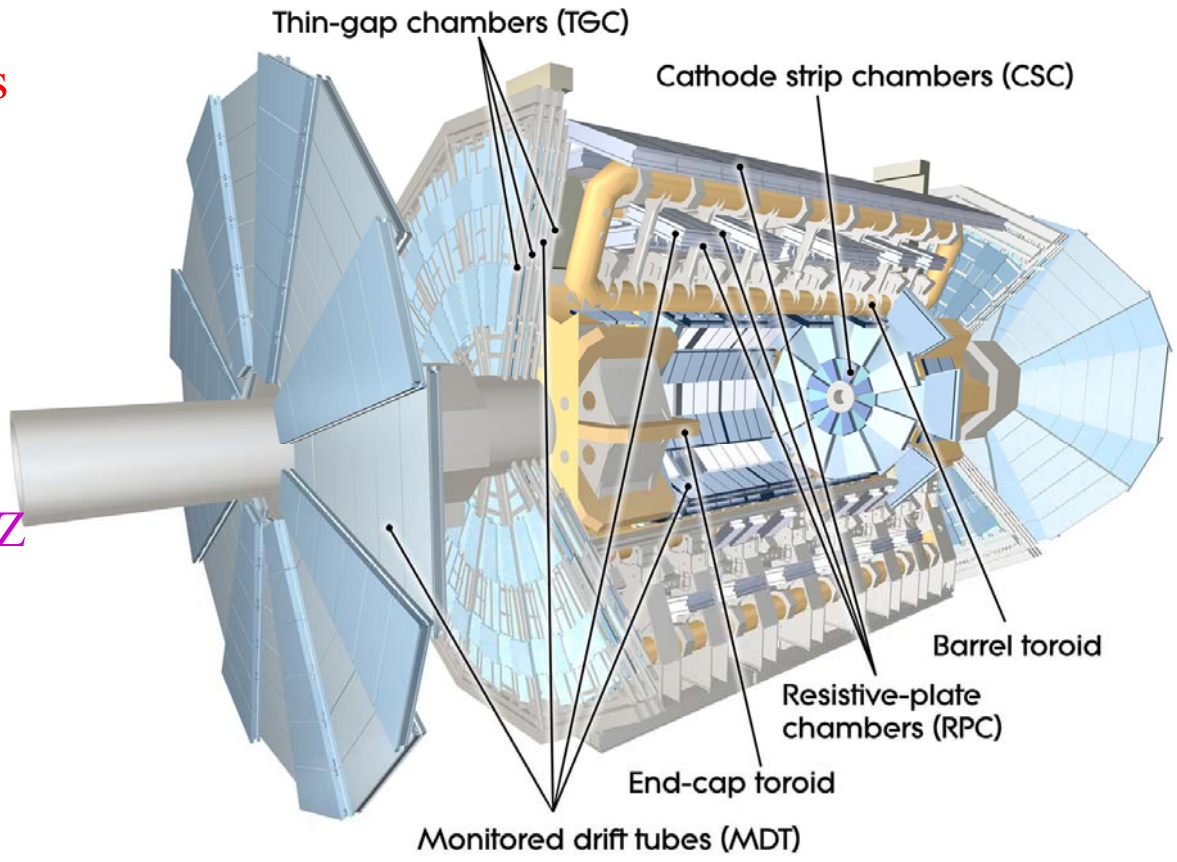
Tagged muons are ID tracks matched to muon segments when extrapolated to the MS. Such muons generally have low momentum.

Can reconstruct muons with Pt>1 GeV

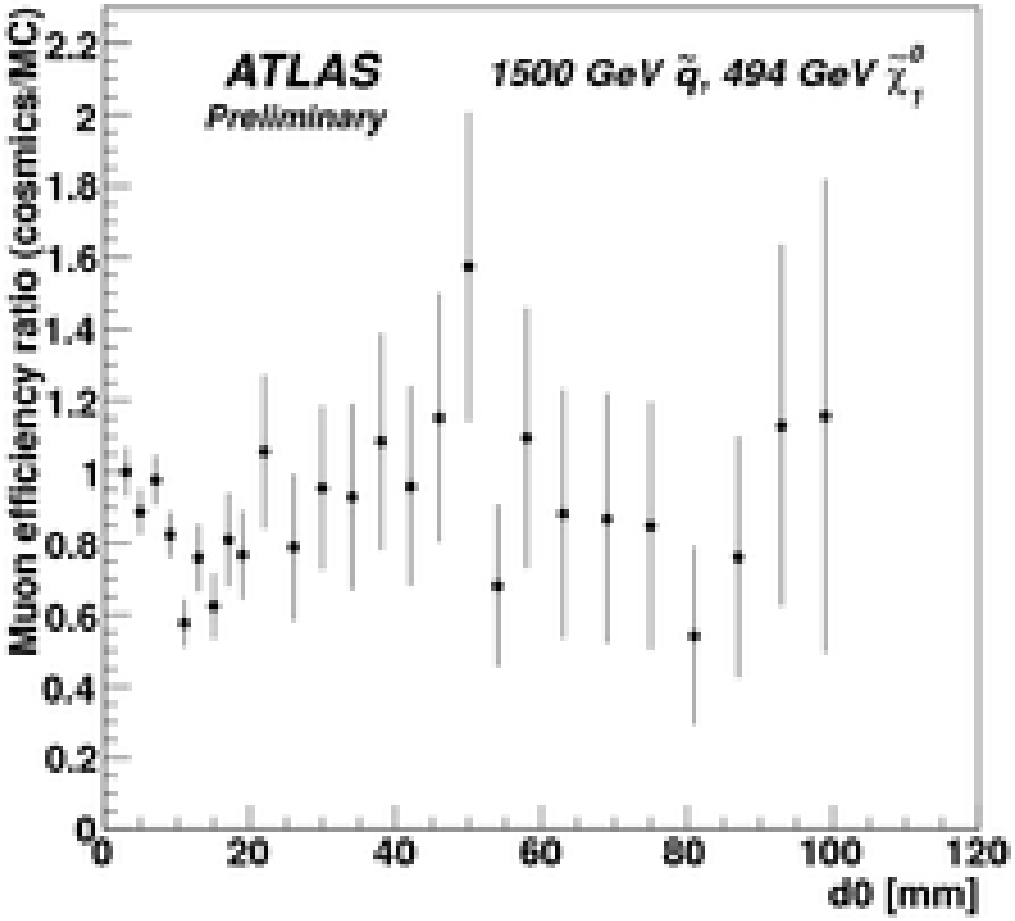
Muon Spectrometer

- Precision tracking chambers and trigger chambers
  - Monitored drift tubes
  - Cathode drift chambers
  - Thin-gap chambers
  - Resistive plate chambers
- $|\eta|$ coverage up to 2.7
- Magnetic field produced by 3x8 air-core toroids
  - Barrel/End Cap toroids
  - Complex field map
  - B ~ 0.5T, but varies in R/Z
  - Bend in barrel is in Z
  - Bend in ECap is along R

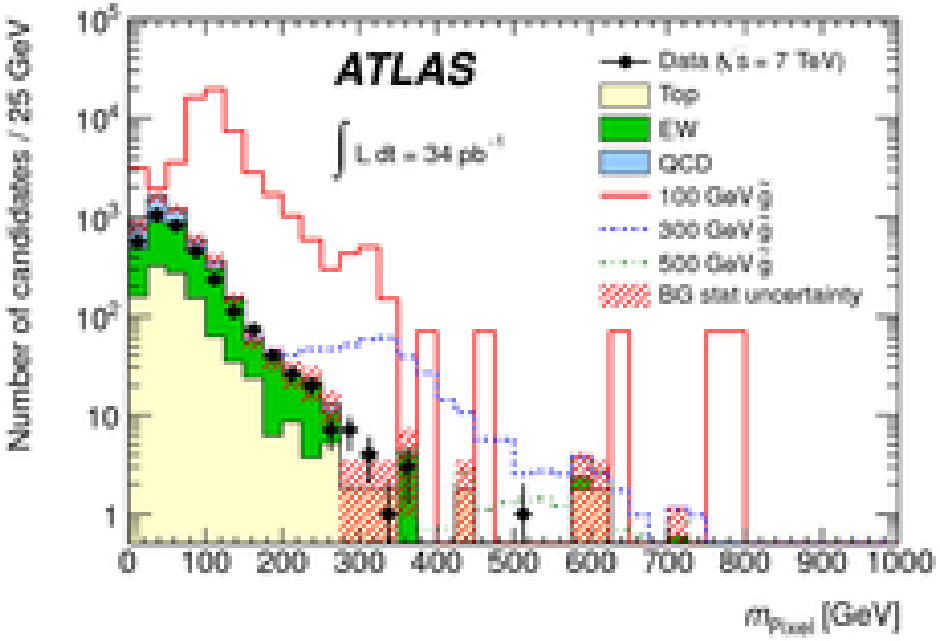
σ_{p_T}/p_T=10% at p_T = 1 TeV



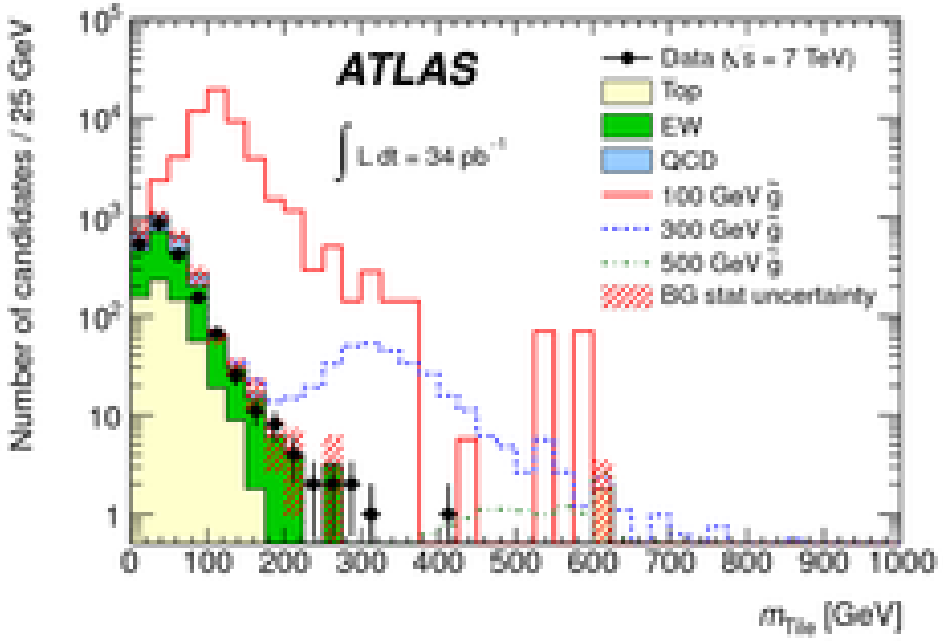
Check efficiency using cosmics (muons)



Ratio between the d0 of cosmic-muons and the d0-dependence of the signal-MC muon reconstruction efficiency given the selection cuts



R-hadron search using Pixels and Tile Cal.



R-hadron search using ID & CALO

Table 2: Expected number of signal and background events for the pixel detector and the tile calorimeter separately and combined for gluino mass hypotheses between 100 and 700 GeV. The fitted means and widths of the estimated mass distributions are shown on the left. To the right of the vertical line, the number of signal and estimated background events are shown in the relevant signal regions, along with the number of events observed in data. Systematic uncertainties are discussed in Section 7.

Nominal mass (GeV)	μ_{Pixel} (GeV)	σ_{Pixel} (GeV)	μ_{Tile} (GeV)	σ_{Tile} (GeV)	No. of signal cand. ($\tilde{g}$) Pixel	Tile	Comb.	Est. no. of bkg. cand. Pixel	Tile	Comb.	N_{Data} Comb.
100	107	10	109	19	15898	49300	13912	61	330	5.4	5
200	214	24	211	36	1417	2471	1235	19	61	0.87	0
300	324	40	315	56	202	304	173	6.5	17	0.22	0
400	425	67	415	75	43	57	37	3.4	7.2	0.082	0
500	533	94	513	106	11	13	9.2	1.82	4.4	0.044	0
600	641	125	624	145	3.1	3.5	2.6	1.08	3.2	0.028	0
700	727	149	714	168	0.99	1.07	0.84	0.74	2.1	0.018	0

Background estimation technique

- The background is mainly composed of high pT muons with mis-measured β.
- Data-driven estimate relies on two premises:
  - (1) S/B ratio before applying requirements on β is small (2) pdf for μ resolution is independent of μ source and its P.
- For each μ candidate a random β is drawn from the muon β pdf. If $\beta < 0.95$, mass is calculated using reconstructed P of and the random β.
- Similar technique for analysis using ID & Cal