Search for long-lived particles at ATLAS

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Outline

- Introduction
  - Long-lived particles
  - ATLAS detector
- Results - (at ATLAS SUSY Public Results page)
  - Disappearing/Stopping Track (4.7 fb^{-1})
  - Charged long-lived particle using dE/dx (2.06 fb^{-1})
  - Displaced vertices (33 pb^{-1})
- Summary

Long-lived particles

- 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…
- Stopping/Disappearing track signature
  - In AMSB models, charged & neutral winos are almost degenerate leading to a long lifetime for the former
- Anomalous dE/dx in Pixel detector
  - Sparticles that hadronize into long-lived, bound (colorless) hadronic states: ~g+g, ~g+qqbar, ~q+q, etc.
    - In R-parity conserving SUSY, Split SUSY, Universal Extra Dimensions

Long lived

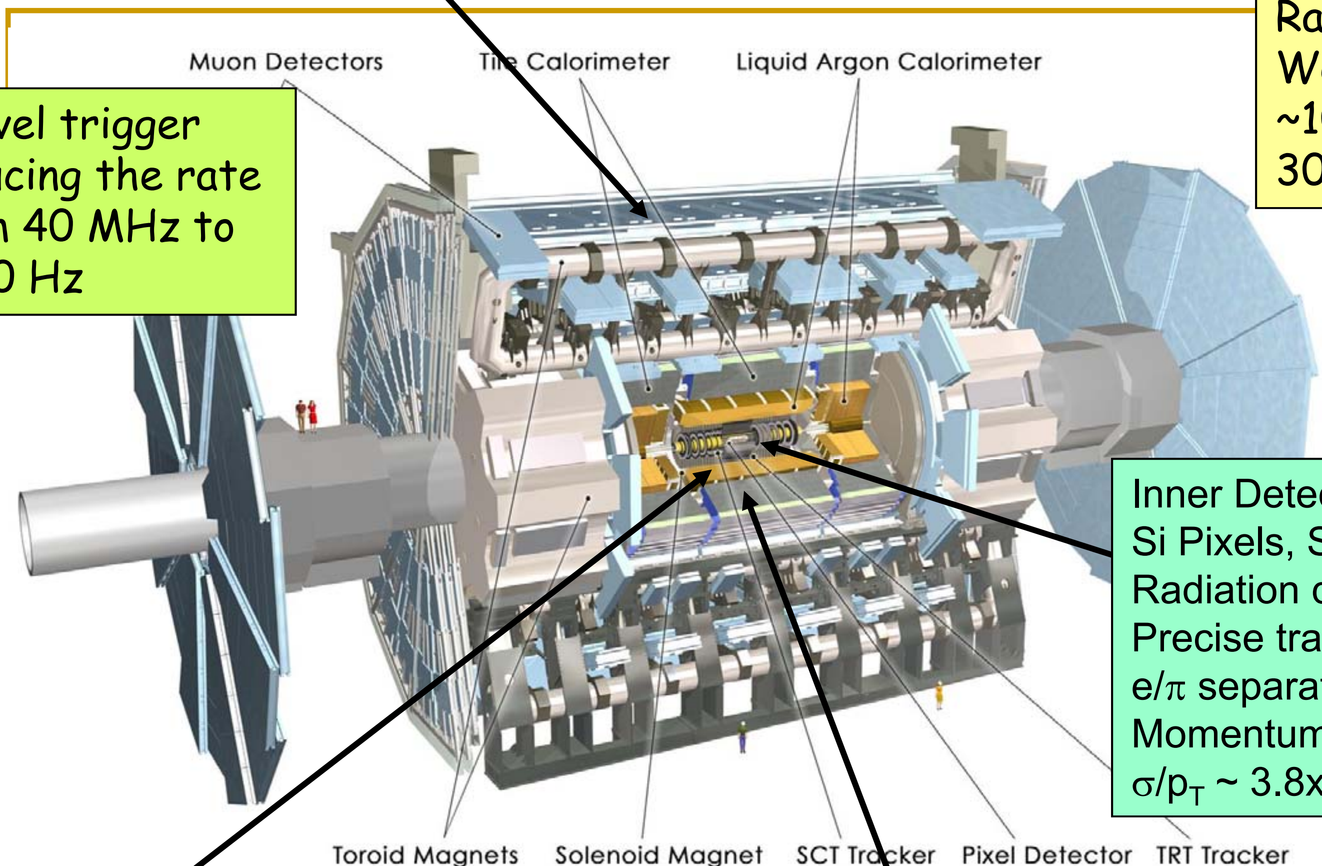
- Displaced vertices:
  - In R-parity violating SUSY ($\tilde{\chi}^0$ is LSP and decays), Split SUSY, Hidden valley models, Stealth SUSY…

- Many of these models may already be constrained by existing data, but the use of lifetime in search for Exotics is relatively unexplored territory

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: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

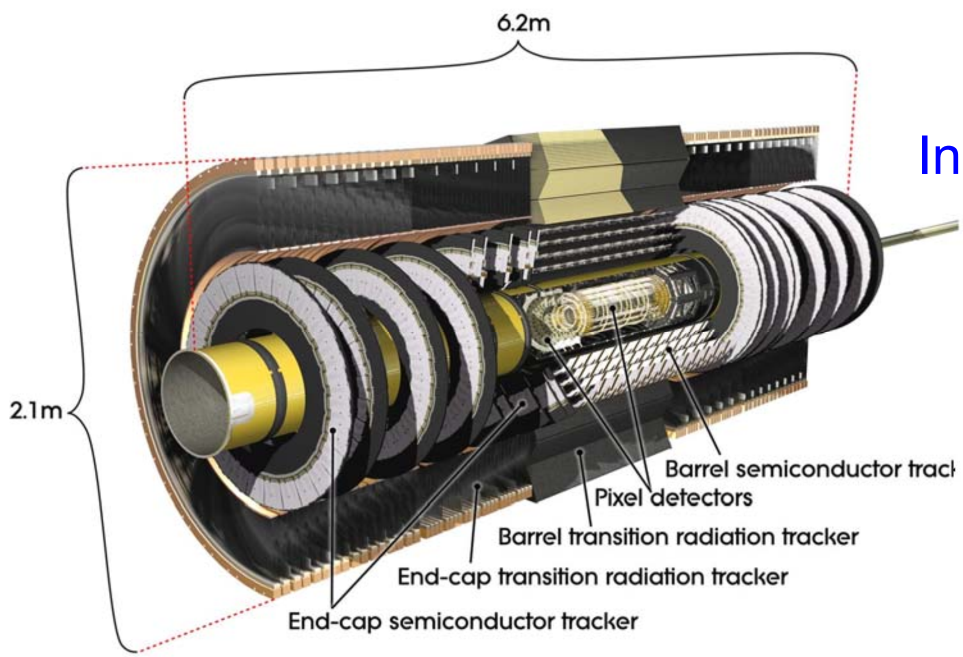
Analyses use a variety of triggers

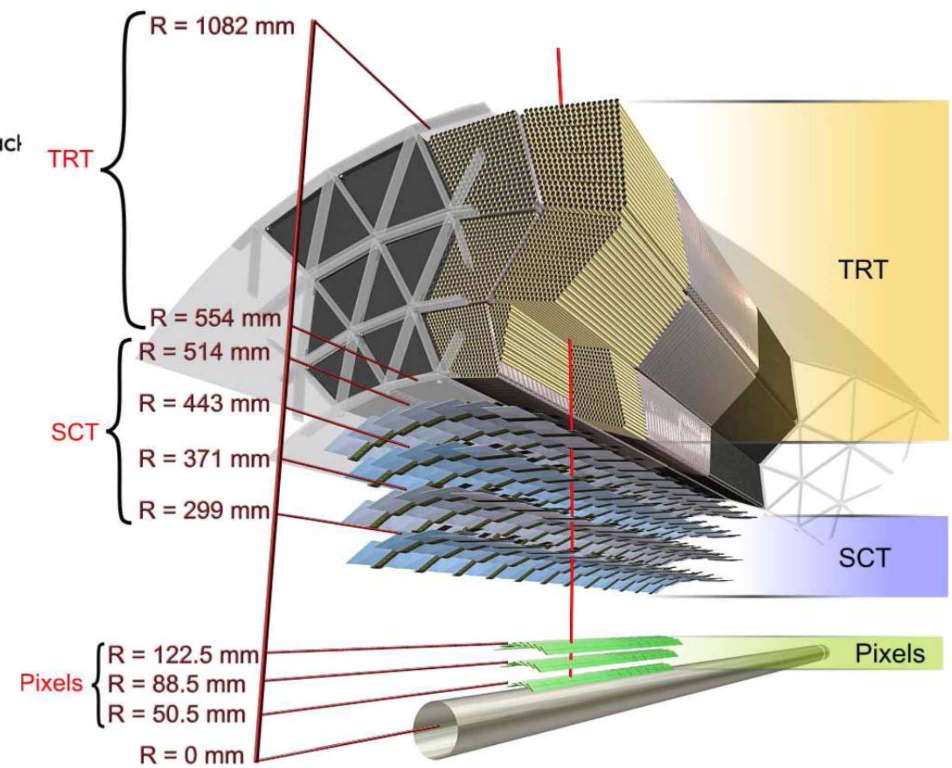
Inner Detector

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

Inside a 2 T solenoidal magnetic field





Coverage: |η| < 2.5 (2.0 for TRT)

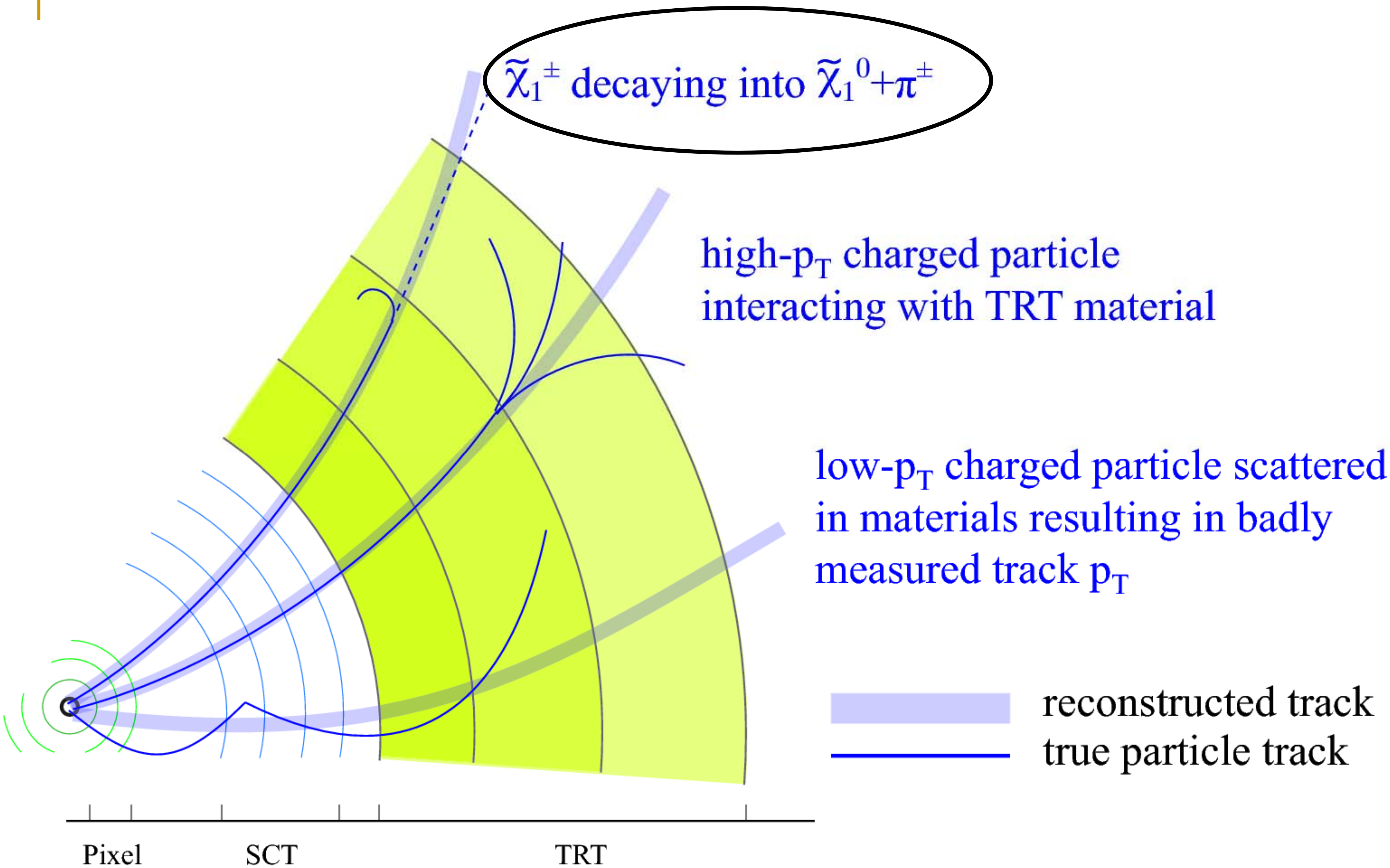
Accurate track & vertex reco.

Resolution is f(track pT, η)

(e.g., σ(pT)/pT ~ 1.5% for pT=5 GeV in central region

Stopping/Disappearing track in Inner Detector

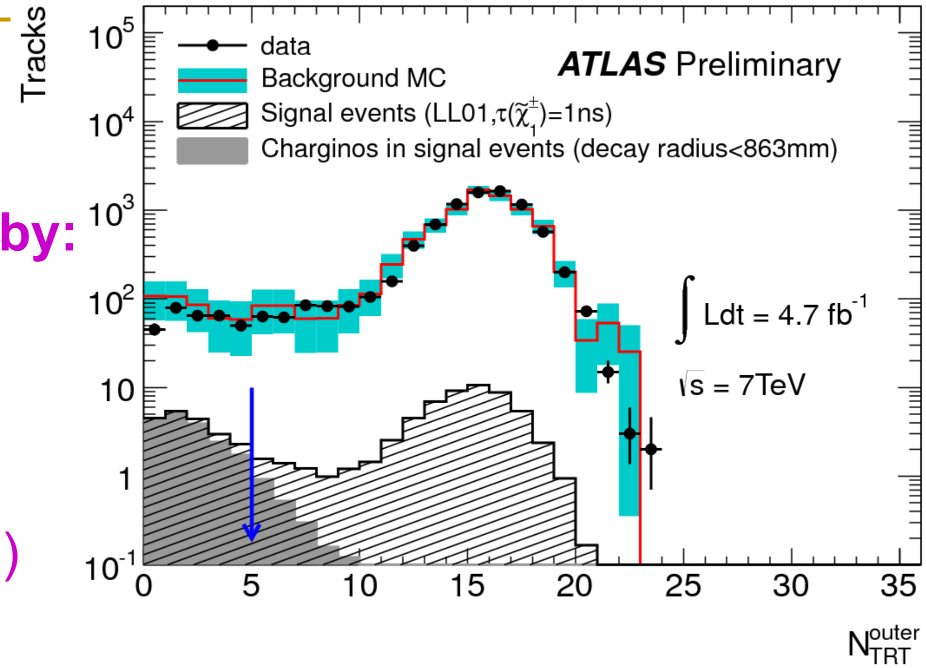
- In AMSB models, lightest gaugino is the wino, and lightest chargino ($\tilde{\chi}^{\pm}_1$) and neutralino ($\tilde{\chi}^{0}_1$) are the charged and neutral winos
  - Chargino is just slightly heavier due to radiative corrections involving EW gauge bosons, leading to a lifetime for the lightest chargino (can be large)
    - The chargino decays to a neutralino and a very soft pion, which go undetected. **Signature is a track that appears to stop/disappear in the detector**
  - Conference Note (ATLAS-CONF-2012-034): 4.7 fb-1.
  - Paper (accepted in EPJC, arXiv 1202.4847) :1.02 fb-1



$\tilde{\chi}_1^{\pm}$ decaying into $\tilde{\chi}_1^{0}+\pi^{\pm}$
high-p_T charged particle interacting with TRT material
low-p_T charged particle scattered in materials resulting in badly measured track p_T
reconstructed track
true particle track
Pixel
SCT
TRT

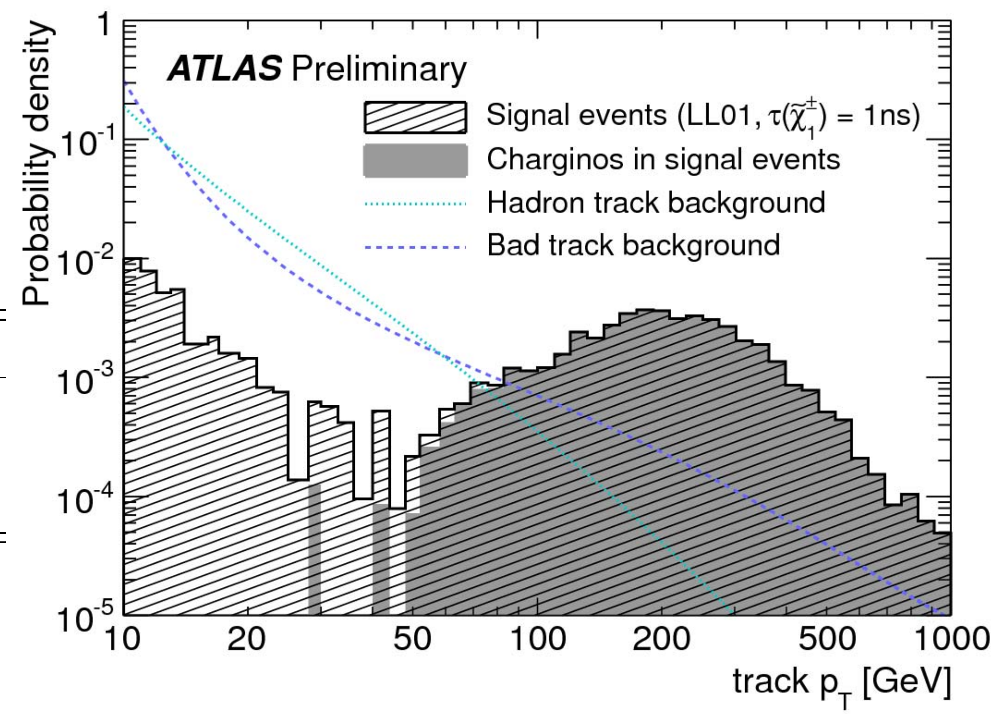
Minimal AMSB model characterized by:

Gravitino mass($m_{3/2}$)
Universal scalar mass (m_0)
Ratio of Higgs vev at EW scale (tan β)
Sign of the higgsino mass term (sgn(μ))



NLO+NLL

Sample	m_0[TeV]	$m_{3/2}$[TeV]	$m_{\tilde{\chi}_1^{\pm}}$[GeV]	Cross section[pb]
LL01	1.5	32	90.2	6.79×10^{-2}
LL02	1.8	41	117.8	8.66×10^{-3}
LL03	2.0	51	147.7	1.16×10^{-3}



tan β = 5, sgn(μ) = +1

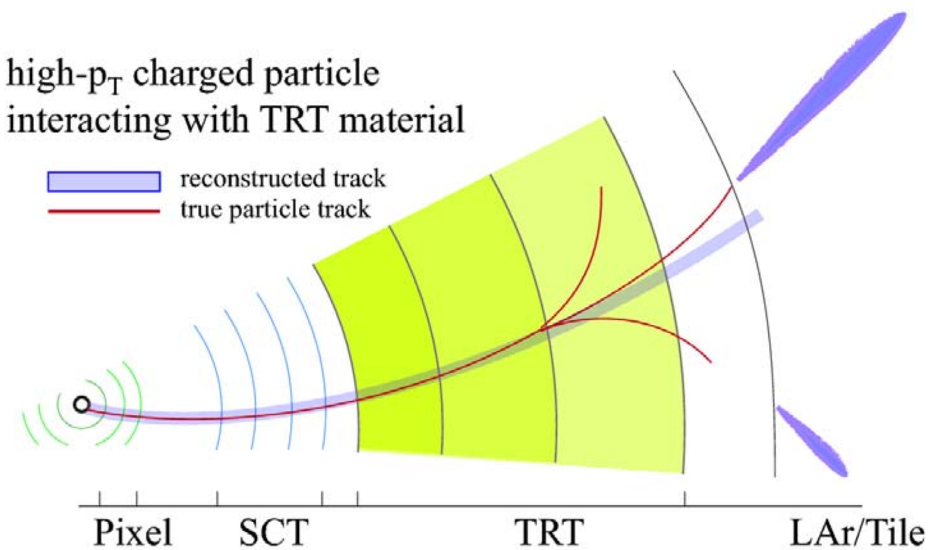
Selection criteria:

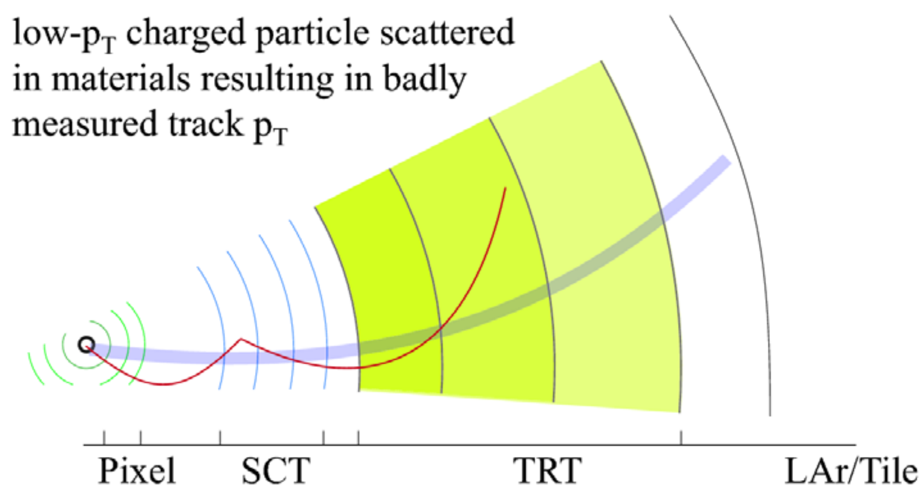
- Events are collected Jet/MET trigger
  - Trigger: ≥ 1 Jet with pT>75 GeV and Et Miss > 55 GeV
    Offline: Et Miss>130 GeV, three highest pt jets>130,60,60 GeV

- Good tracks:
  - ≥0 hits in the innermost pixel layer, ≥6 hits in SCT
  - Impact param. wrt PV: $|d_0|$ and $|z_0 \sin \theta| < 1.5$ mm
- Isolated tracks – no other track with pT>0.5 within ΔR<0.1. Lepton veto to reduce bkgd.
- Track with highest pT and above > 10 GeV
- Track should not point to inactive regions of the TRT around |η| ~ 0
- **#hits in the outer module of the TRT < 5**

Backgrounds:

- Two main sources of backgrounds:
  - Tracks that interact in the outer part of the inner detector (dominant source)
  - Some contribution from Low Pt tracks that scatter, and are badly measured

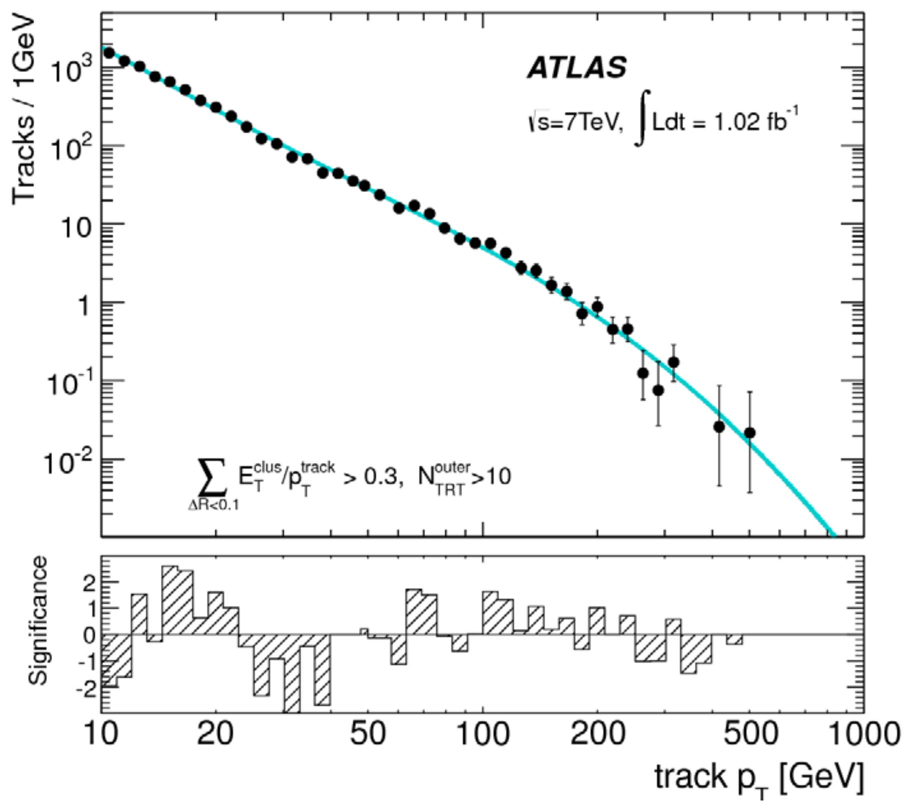




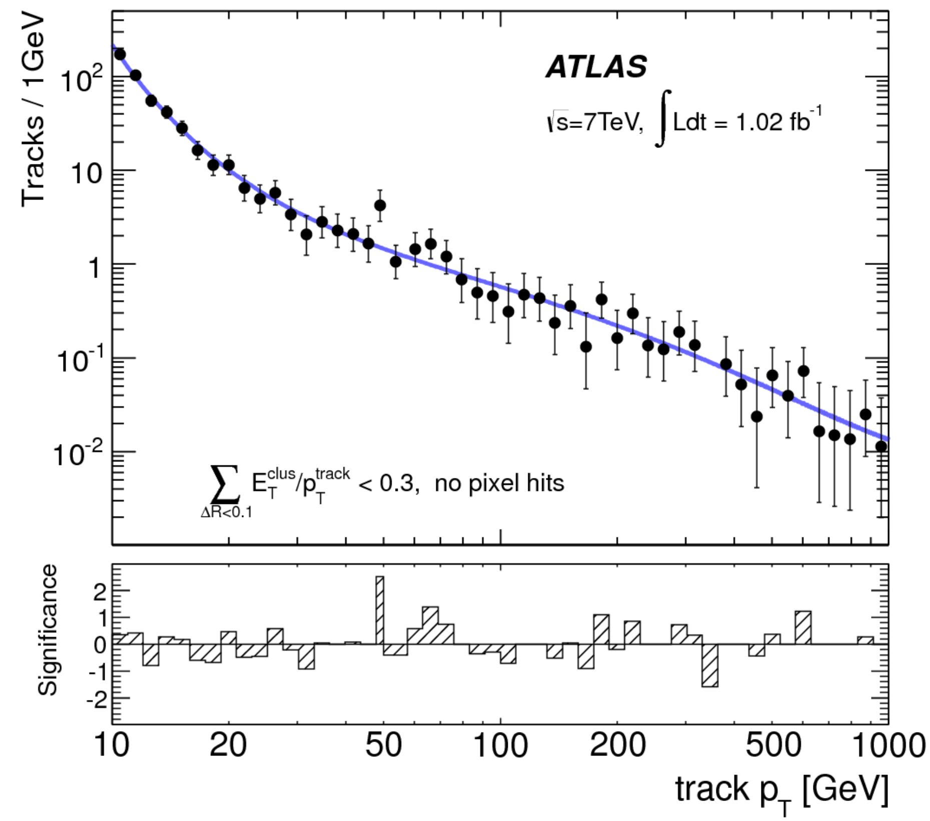
Backgrounds: data driven estimates

- Choose control samples to get *p*T spectrum of tracks that form background
  - Also make cuts on calorimeter activity around track to make the control samples orthogonal
- For interacting track background:
  - The *p*T spectrum of interacting hadron tracks is obtained from that of non-interacting tracks (require >10 hits in Outer TRT)
- For mis-measured track background:
  - Require 0 innermost pixel layer hits on track

Background – data driven estimates



pT spectrum of tracks from control sample to estimate the interacting track sample



pT spectrum of tracks from control sample To estimate the mis-measured track sample

$$\frac{(1+x)^{a_0}}{x^{a_1+a_2\ln(x)}}$$

Ansatz for background shape

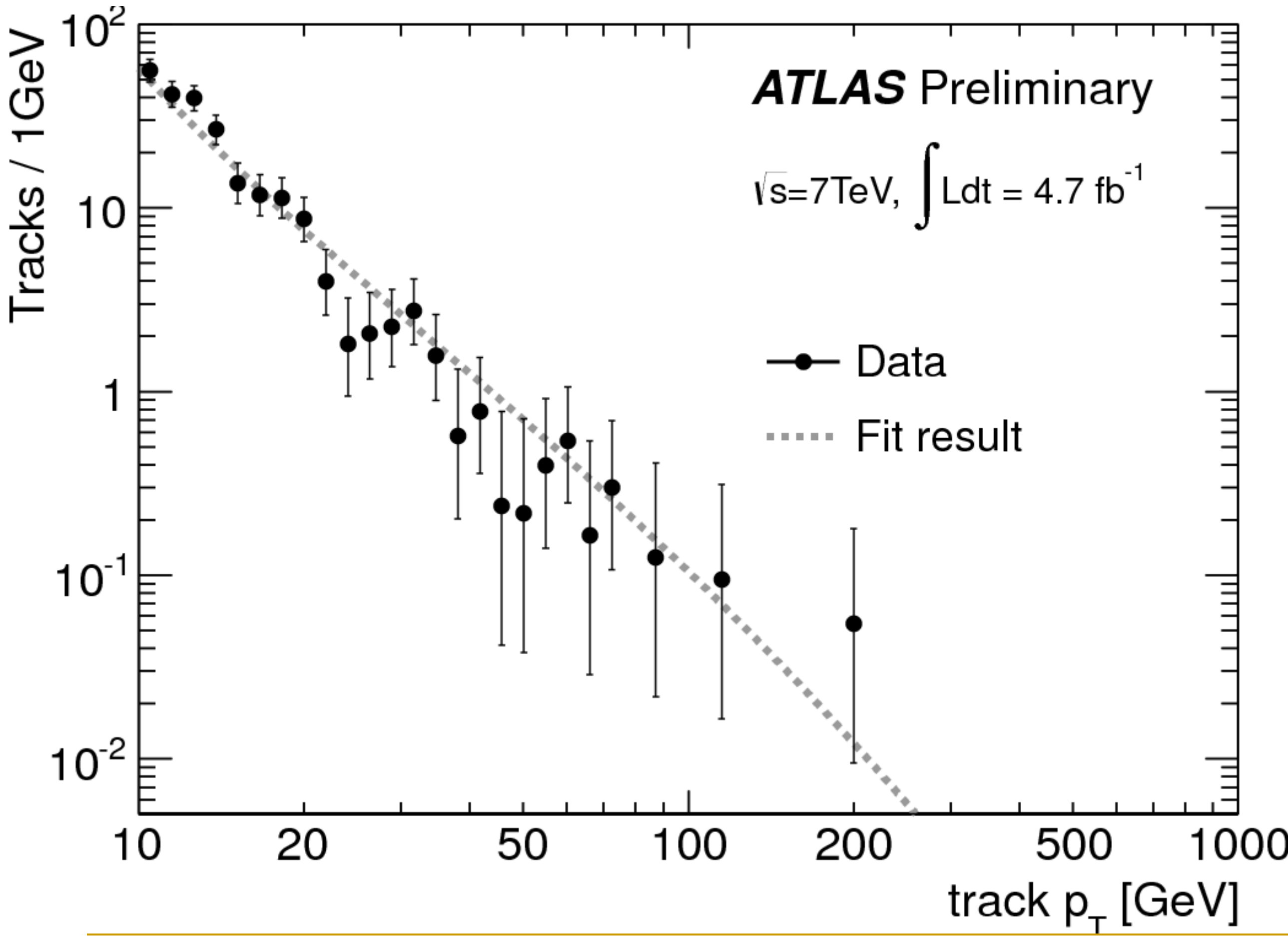
Use additional flat term for this source

Systematic Uncertainties:

- Theoretical cross-section uncertainty – 27%
- Jet Energy Scale – 3%
- Track reconstruction efficiency – 2%
- Luminosity – 3.9%
- Pile-up modelling – 0.5%
- Trigger efficiency – 2%

Result:

Background shapes for pT>10 GeV
Signal contribution for pT>50
in a likelihood fit.



Best fit is consistent with 0 signal events

p-value of consistency with background hypothesis is 0.5

304 candidates with pT>10 GeV

Limits:

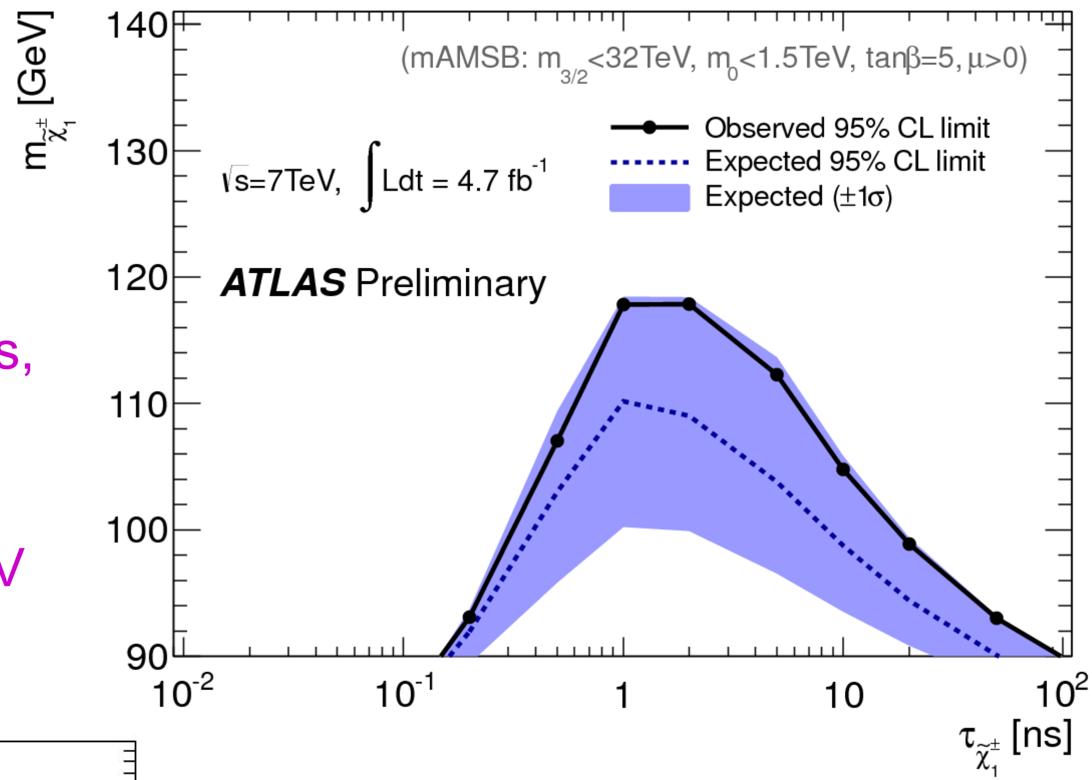
In one AMSB model:

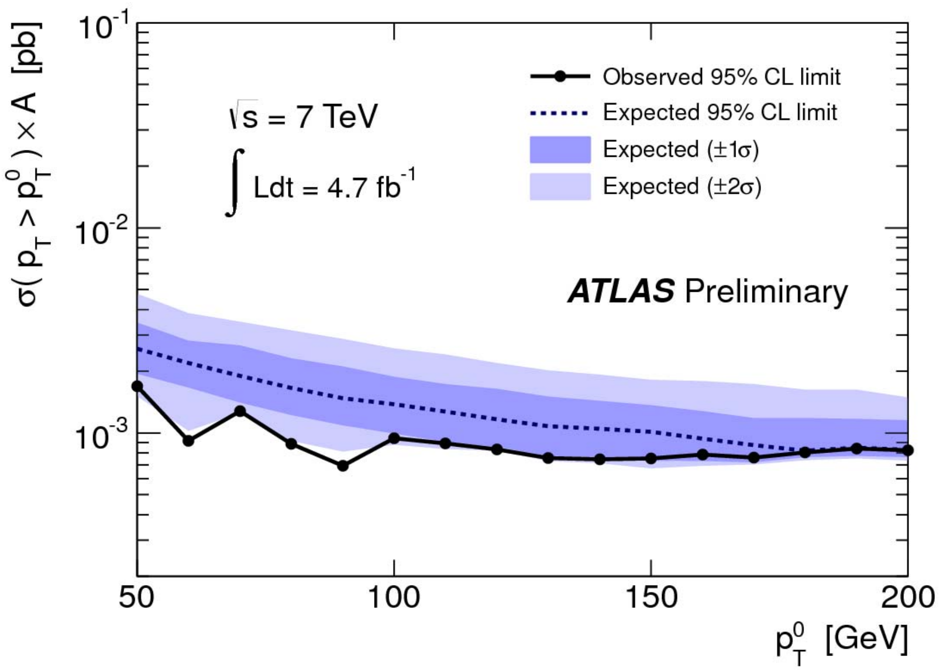
For chargino mass of 90.2 mass,

0.2 ns < τ < 90 ns is excluded

For chargino mass of 117.8 GeV

1 ns < τ < 2 ns is excluded



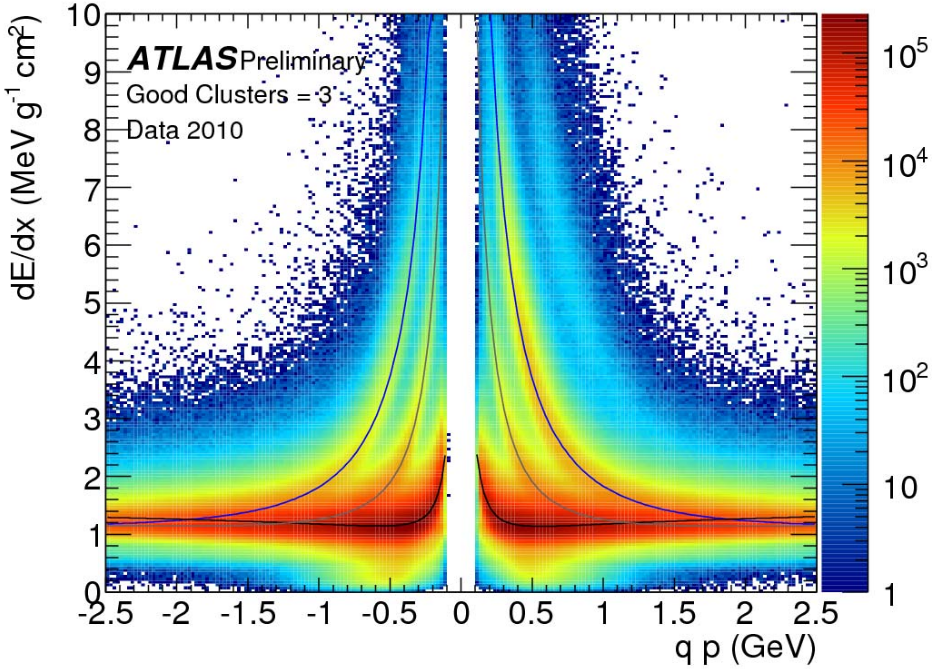


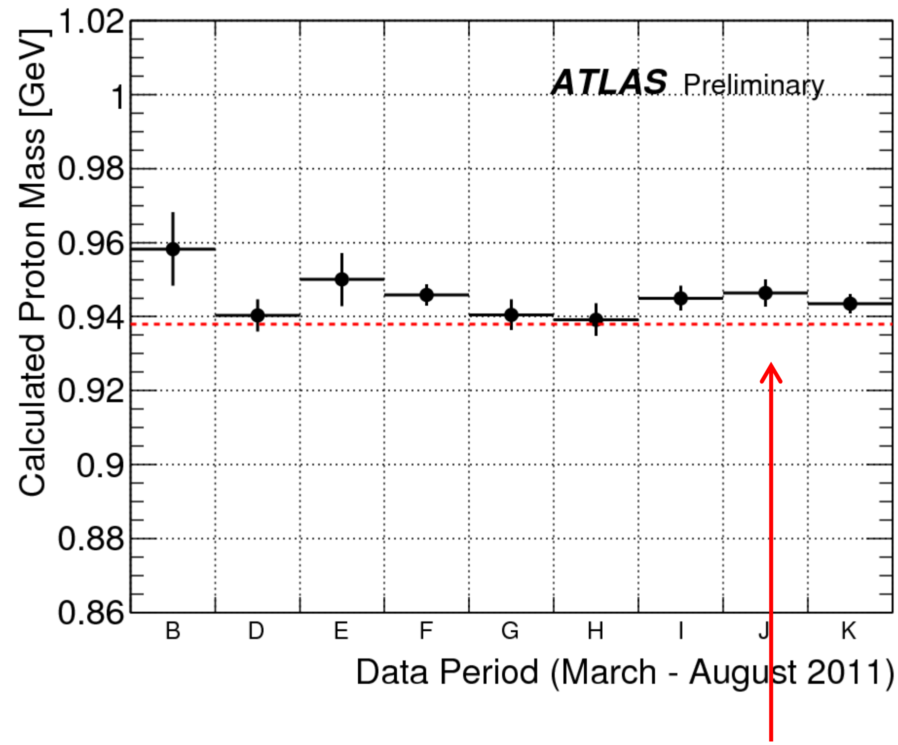
Model independent limits on
Cross-section times acceptance for non-SM production of disappearing tracks with $pT > pT^0$ (as a function of pT^0)
Background estimate is from the bkgd. only fit in the region 10<pT<50 GeV

Long-lived Particle search using dE/dx

- Several theories (R-parity conserving SUSY, Split SUSY, Universal Extra Dimensions) predict charged and heavy long-lived particles (LLP), which can be slow, thus identifiable through anomalous d*E*/d*x* energy loss in the ATLAS Pixel detector
- One potential class is bound states of Sparticles and SM partons (R-hadrons) - ˜g+g, ˜g+$q\bar{q}$, ˜q+q,
  - 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

Use dE/dx in Pixels (previous paper ($34\ pb^{-1}$) also used the time from Tile Calorimeter, smaller |η| coverage)





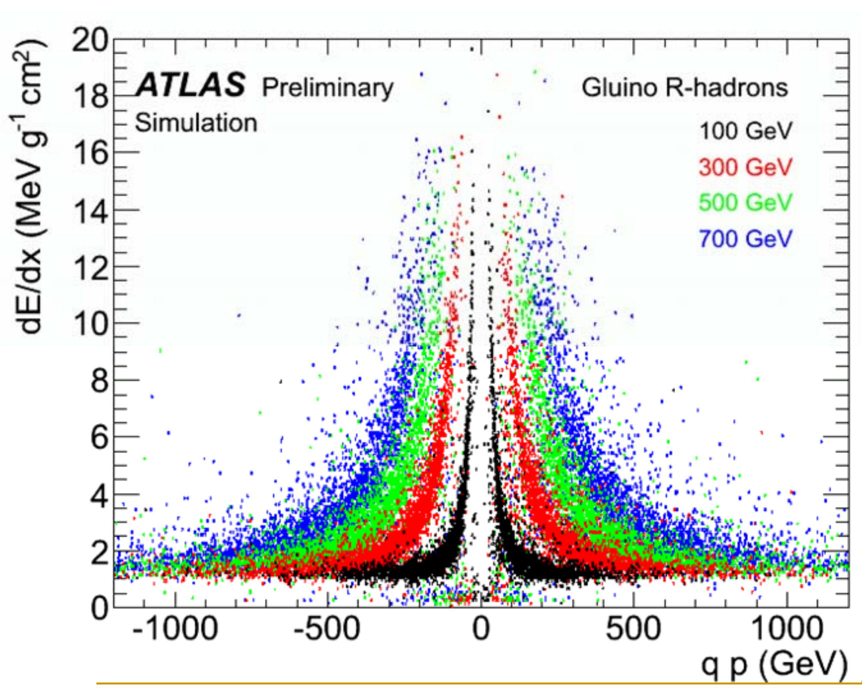
- β from dE/dx, combine with momentum, estimate mass
- Track pT > 50 GeV

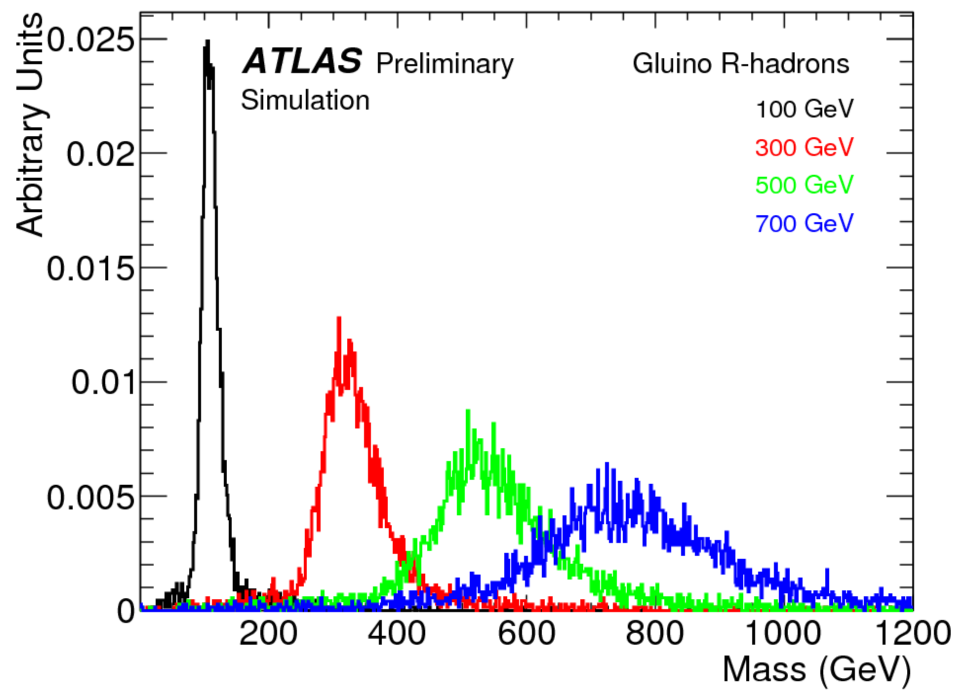
Mass estimate after selection:
dE/dx > (1.8 + f(|η|)) MeV g $^{-1}$cm^2

$$\mathscr{M}_{\frac{dE}{dx}}(\beta) = \frac{p_1}{\beta^{p_3}} \ln(1+(p_2\beta\gamma)^{p_5}) - p_4$$

Simulations of R-hadrons

- Pythia for ~g production
- Specialized hadronization routines within string hadronization to produce R-hadrons
- Simulation of R-hadron interactions with matter are handled using 3 different models





X-sections of individual samples done with PROSPINO NLO

Selection criteria:

- ISR from gg fusion, and low energy deposits of R-hadrons in CALO lead to the use of a missing Et trigger (>70 GeV). Offline MET>85 GeV
- Good tracks (as in previous analysis)
- Track pT>50 GeV and p>100 GeV
  - No other track with pT>5 GeV within $\Delta R<0.1$
- dE/dx > $p_0^{cut} + p_1|\eta| + p_2\eta^2 + p_3|\eta|^3$
  - Values of various p_N stable between 2010/2011, and are 1.8, -0.045, 0.115, -0.033 respectively
- In event with multiple tracks, choose one with highest momentum

Cut flow in data & MC

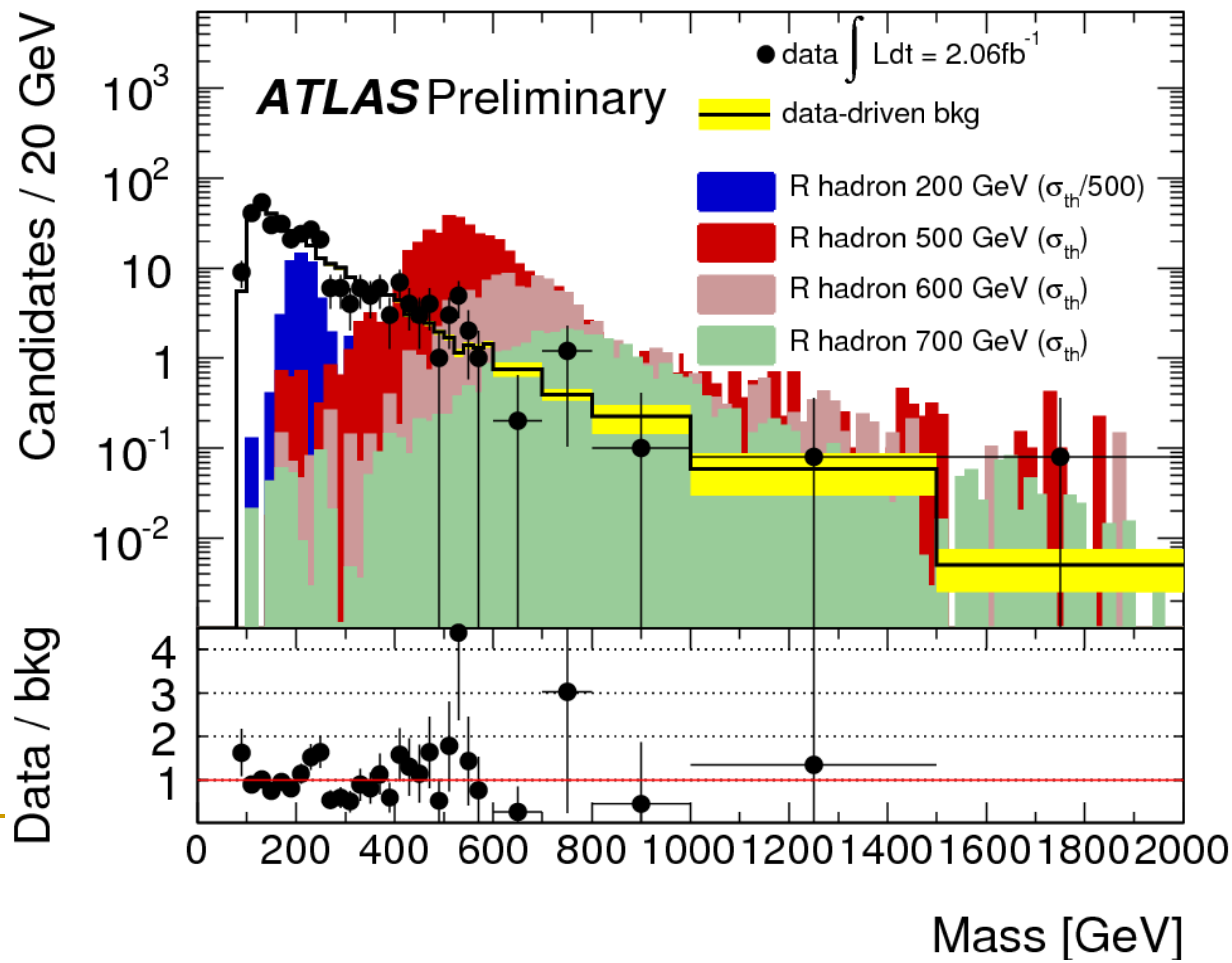
Cut level	# Events	Cut Eff.	Total Eff.
Trigger	2,413,863		
Offline E_{T}^{miss}	1,421,497	0.589	0.589
Primary vtx	1,368,821	0.963	0.567
High-p_T	212,464	0.155	0.0880
Isolation	32,188	0.151	0.0133
High-p	21,040	0.654	8.7E-03
ionization	333	0.016	1.4E-04

	Gluino 400 GeV		Gluino 700 GeV		Gluino 1000 GeV	
Cut level	**Cut Eff.**	**Total Eff.**	**Cut Eff.**	**Total Eff.**	**Cut Eff.**	**Total Eff.**
Trigger	0.205 ± 0.013	0.205 ± 0.013	0.219 ± 0.009	0.219 ± 0.009	0.177 ± 0.009	0.177 ± 0.009
Offline E_{T}^{miss}	0.98 ± 0.08	0.200 ± 0.013	0.99 ± 0.05	0.216 ± 0.009	0.98 ± 0.07	0.175 ± 0.009
Primary vtx	1.00 ± 0.09	0.200 ± 0.013	1.00 ± 0.05	0.216 ± 0.009	1.00 ± 0.07	0.175 ± 0.009
High-p_T	0.59 ± 0.06	0.120 ± 0.010	0.58 ± 0.04	0.129 ± 0.007	0.59 ± 0.05	0.108 ± 0.008
Isolation	0.84 ± 0.10	0.100 ± 0.009	0.84 ± 0.06	0.105 ± 0.006	0.88 ± 0.09	0.091 ± 0.007
High-p	0.99 ± 0.12	0.099 ± 0.009	0.99 ± 0.08	0.104 ± 0.006	1.00 ± 0.10	0.091 ± 0.007
Ionization	0.66 ± 0.09	0.067 ± 0.008	0.80 ± 0.07	0.085 ± 0.005	0.92 ± 0.09	0.084 ± 0.006

- Data driven approach to estimate background. Use control samples to get templates for track pT, η (use dE/dx < 1.8) and dE/dx (use pT>10 and 20 <p< 100 GeV)

Combine random combinations of track parameters to generate bkgd. distribution in mass

Normalize bkgd. to data in region of mass<140 GeV and before cut on high dE/dx

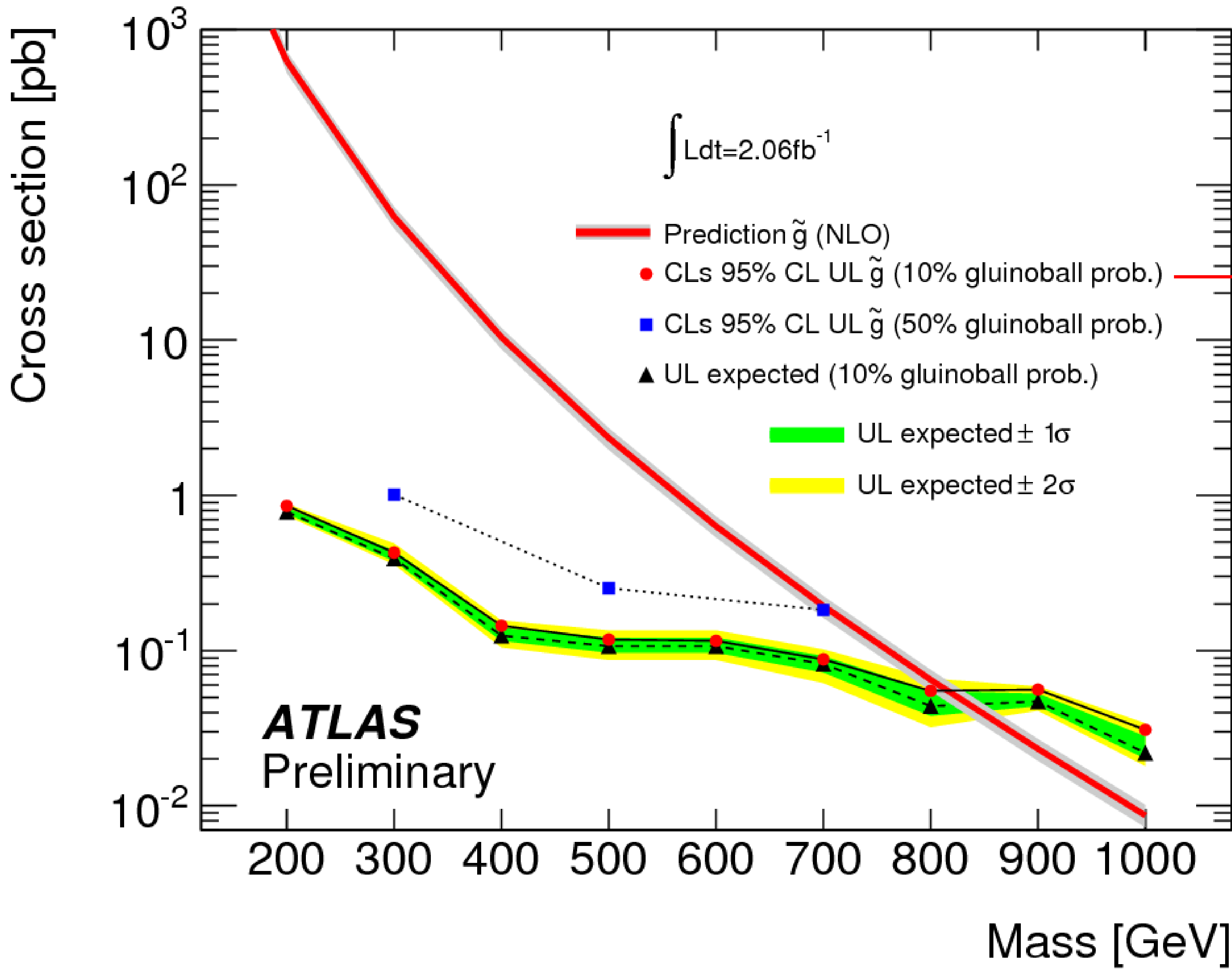


Systematic Uncertainties

- Uncertainties on signal yield – ***14-19%***
  - Theoretical (14%): QCD accuracy, R-hadron scattering,
  - Experimental: Trigger, Et miss and Jet Energy scale, Pile-up, dE/dx in data vs. MC, Lar ineff., track momentum in data/MC.

- Uncertainties on background estimate: ***1-10%***
- Overall normalization uncertainties: ***16%***
  - Luminosity, Prospino NLO, PDFs

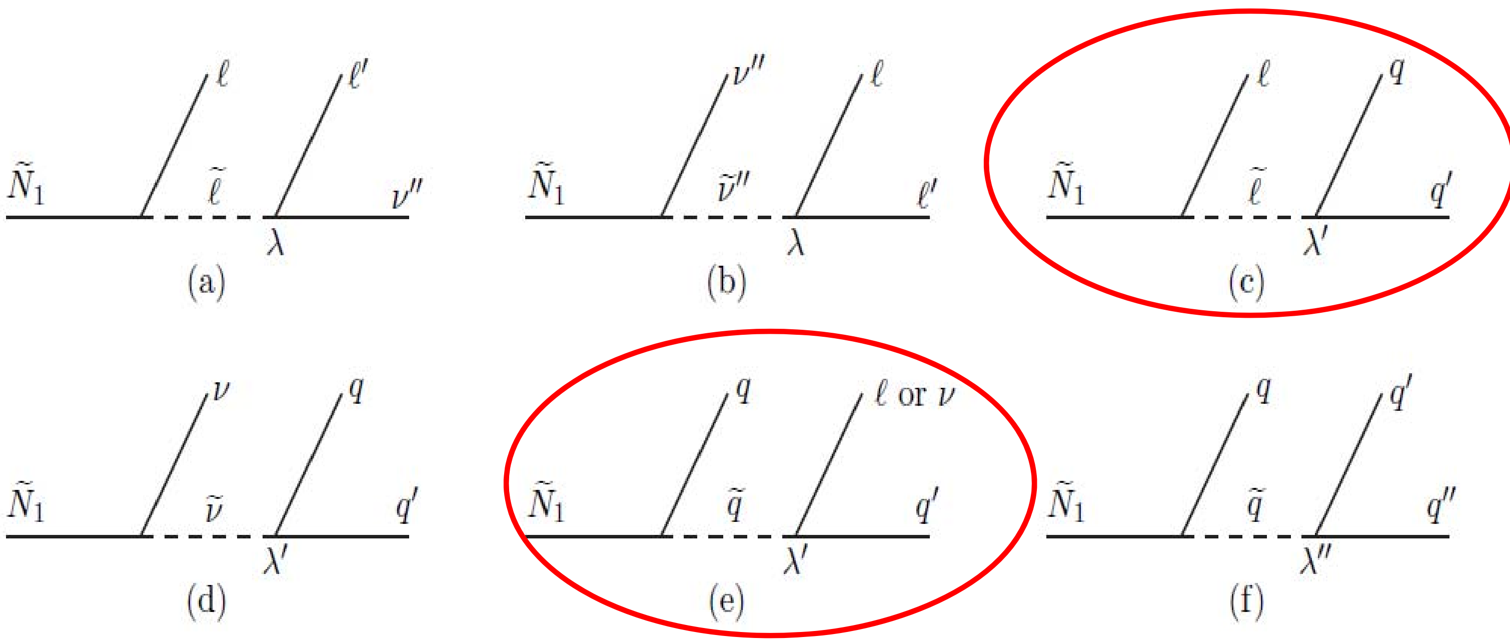
Results:



~g R-hadron masses below 810 GeV are ruled out at the 95% CL

Search for displaced vertices

- 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.

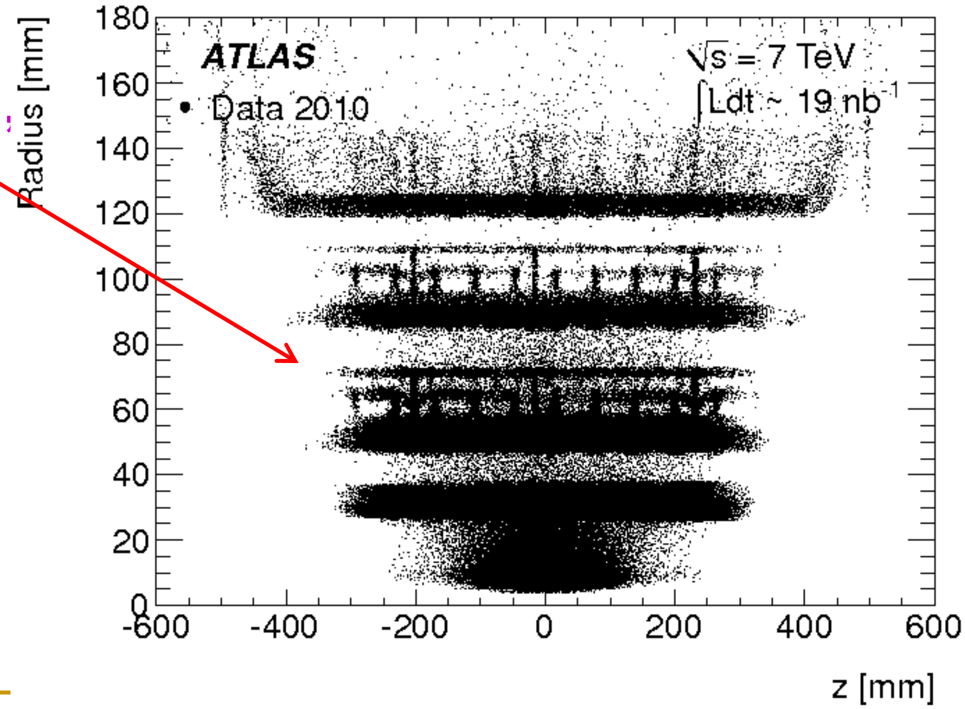


Search in the qq'μ final state

- 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), Ks…

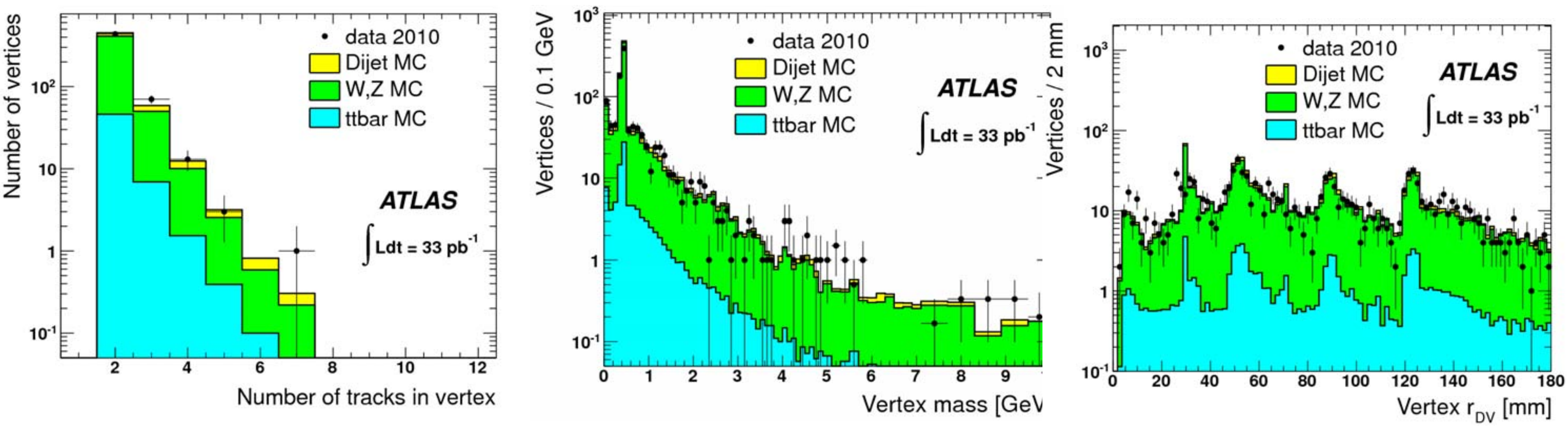
Require Vertex to have $N_{trk} \geq 4$, Mass > 10 GeV

  - Search for displaced vertices for R < 180 mm

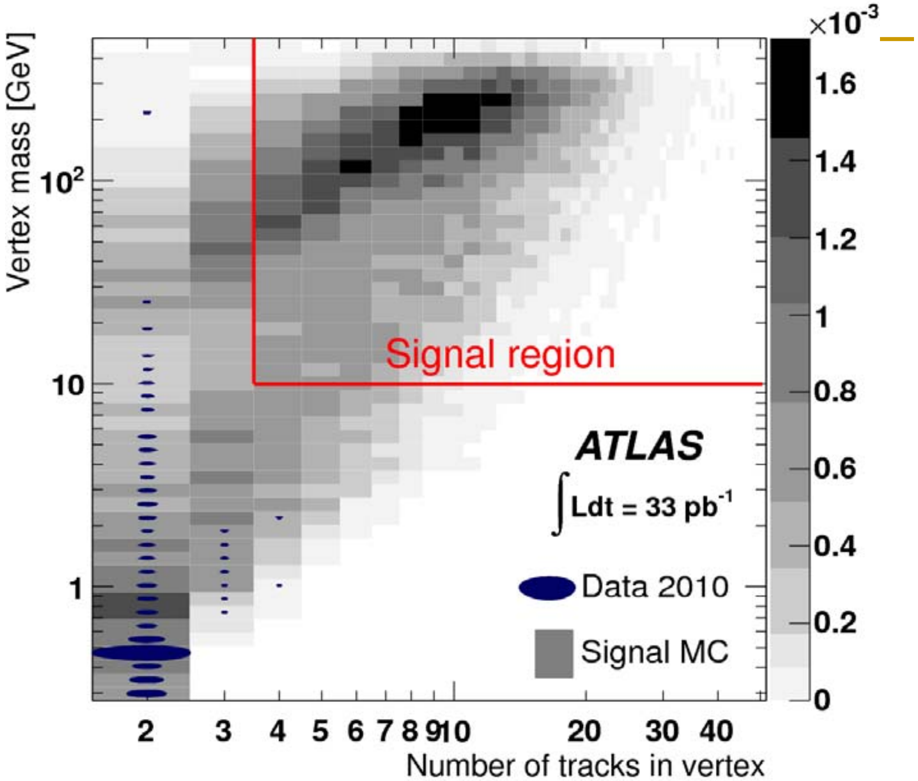


Comparing Data with Monte Carlo

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



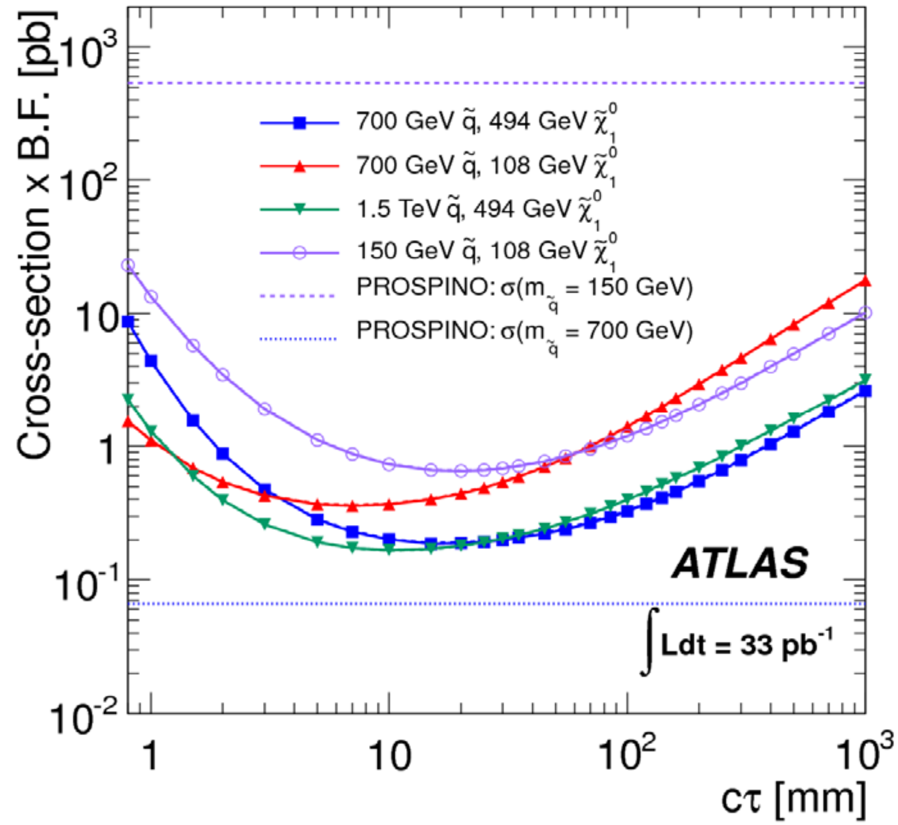
- Good agreement



Results:

 # observed events in signal region: 0

Background estimate (MC with data driven cross-checks): **< 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)

Future improvements:

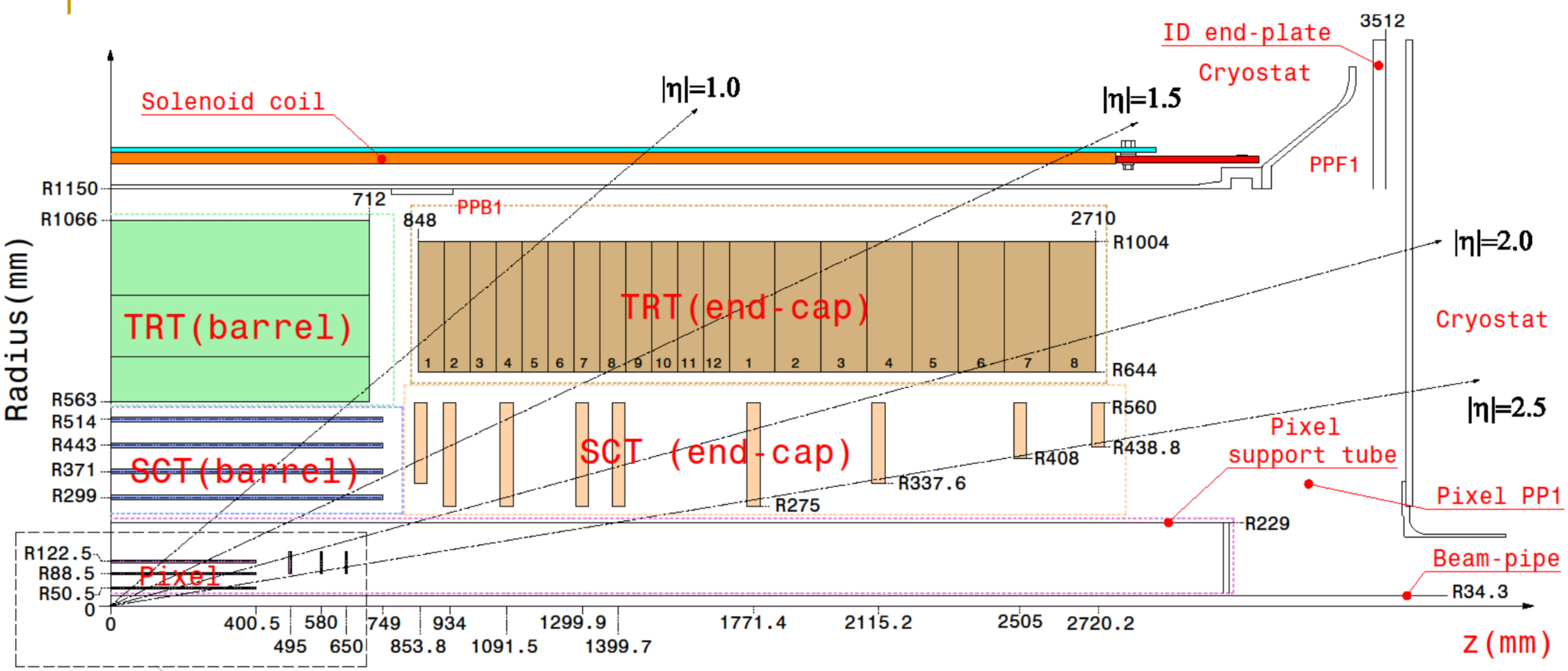
- Displaced vertex analysis is being updated with analysis improvements and more data:
  - Redo track reconstruction to pick up tracks with large impact parameters, and re-run muon reconstruction to use these new Inner Det. tracks
  - Improve vertexing for tracks and muons
  - Data driven approach to estimate background

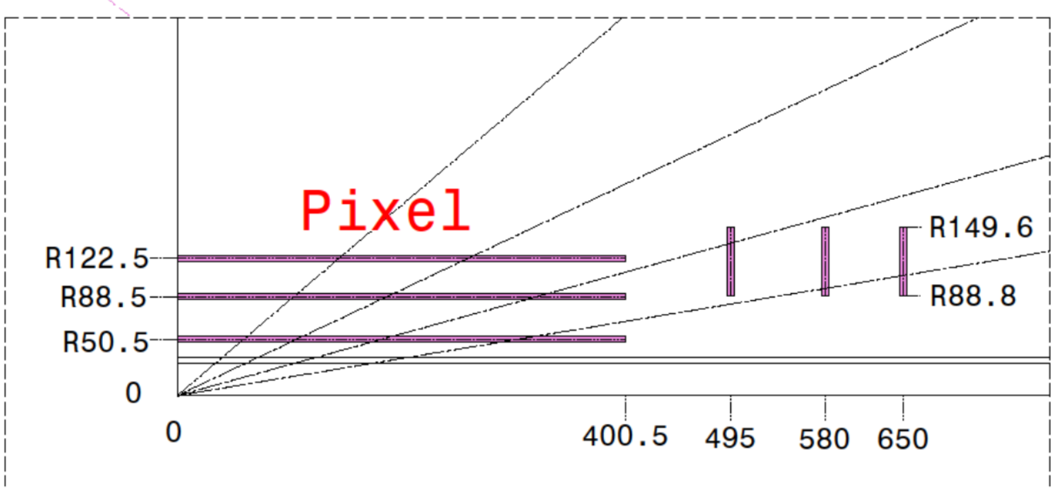
Summary

- Many exciting results using lifetime as a search parameter
  - Disappearing/stopping track
  - Massive, slow moving particles
  - Displaced vertices

- Improvements in analysis techniques and more data in the pipeline

Extra stuff





Envelopes

Pixel		45.5<R<242mm |Z|<3092mm
SCT barrel		255<R<549mm |Z|<805mm
SCT end-cap		251<R<610mm 810<|Z|<2797mm
TRT barrel		554<R<1082mm |Z|<780mm
TRT end-cap		617<R<1106mm 827<|Z|<2744mm

Details of Disappearing track analysis

Requirement	Observed events	Signal efficiency (purity) [%]		
		LL01	LL02	LL03
Trigger selection and non-collision rejection	7141026	87.3	89.1	90.1
Lepton veto	6644394	72.8	72.5	72.6
$E_T^{miss} > 130$ GeV	321412	66.5	68.2	69.6
Jet requirements	73433	64.9	67.4	69.0
High-p_T isolated track selection	8458	24.8 (67.6)	26.2 (66.8)	27.2 (66.7)
Disappearing track selection	304	6.1 (94.6)	6.6 (94.5)	7.3 (94.7)

Table 2: Summary of selection cuts, the data reduction and the selection efficiencies for the AMSB signals. The purities of chargino tracks, i.e. the fraction of selected tracks in signal events originating from charginos, are also shown in parentheses.

R-hadron search using Pixels

3.2 Mass reconstruction

Particles can then be identified by fitting each $\mathrm{d}E/\mathrm{d}x$ and momentum measurement to an empirical Bethe-Bloch function and deducing their mass value. This particle identification method, described in detail in [38], uses a 5-parameter function to describe how the Most Probable Value of the specific energy loss ($\mathscr{M}_{\frac{\mathrm{d}E}{\mathrm{d}x}}$) depends on β:

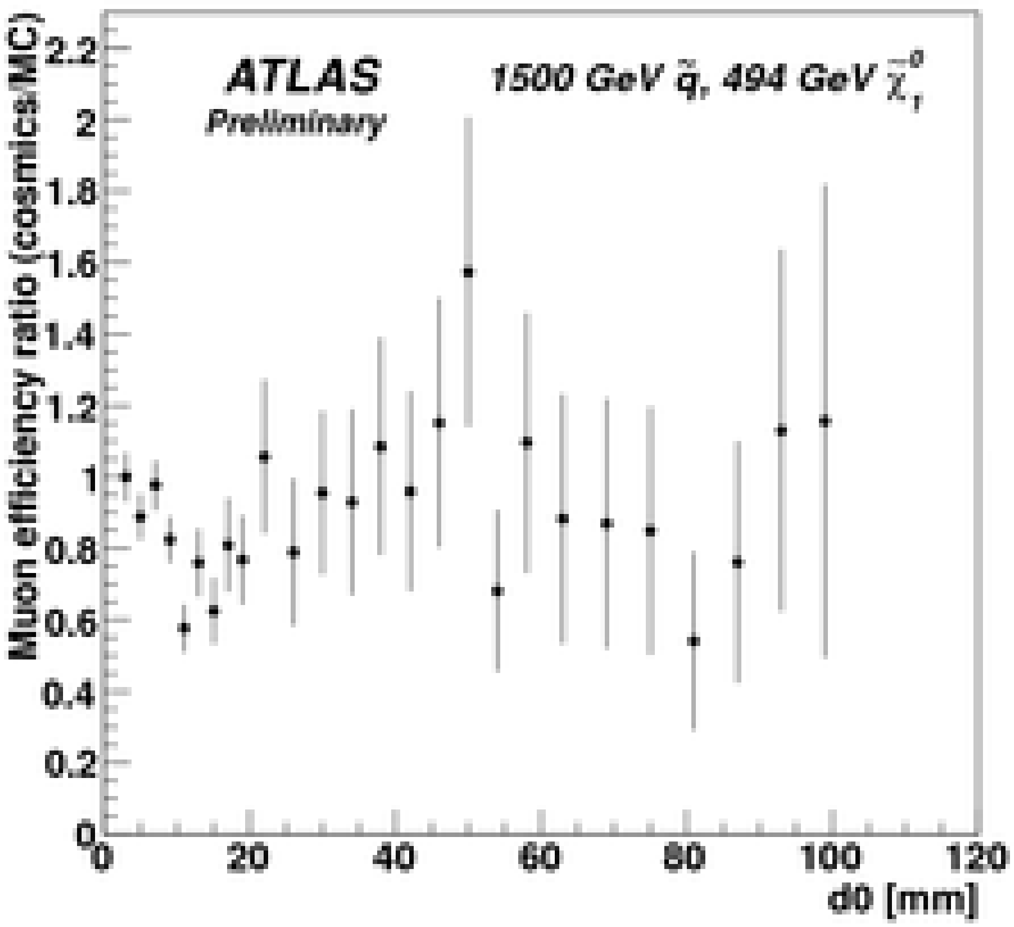
$$\mathscr{M}_{\frac{\mathrm{d}E}{\mathrm{d}x}}(\beta) = \frac{p_1}{\beta^{p_3}} \ln(1 + (p_2 \beta \gamma)^{p_5}) - p_4 \tag{1}$$

[2)] The single highest $\mathrm{d}E/\mathrm{d}x$ cluster is removed for tracks with 3 or 4 associated clusters, while for tracks having 5 or more clusters, the two highest $\mathrm{d}E/\mathrm{d}x$ clusters are disregarded.

4

Systematic Uncertainties on Efficiency	[%]
QCD Accuracy	$\pm$ 8.5
Ratio of charged R-hadrons	$\pm$ 0.2
Scattering models	$\pm$ 11
Trigger turn-on	$\pm 4 \div \pm 3$
MET scale	$-8.6 \div -3.4; +1$
Pile-up	$\pm$ 2
Ionization Parametrization	$-9 \div -2$
Momentum Parametrization	$\pm$ 1
LAr Inefficiency	$\pm$ 1
Total uncertainty on Efficiency	$19 \div 14$
Systematic Uncertainties on Background	[%]
Binning p,η and $\eta\,(p)$	$-2 \div +4$
Smoothing	$-2 \div +3$
dE/dx CB	$-1 \div +3$
dE/dx CB+exp	$-1 \div +3$
Pile-up	$-2 \div +2$
Total uncertainty on Background	$1 \div 10$
Other uncertainties	
Luminosity	$\pm$ 3.7
Prospino NLO	$\pm$ 15
PDFs	$\pm$ 5

Check efficiency using cosmics (muons)



Sample	$m_{\tilde{q}}$ [GeV]	σ [fb]	$m_{\tilde{\chi}_1^0}$ [GeV]	$\langle\gamma\beta\rangle_{\tilde{\chi}_1^0}$	$c\tau_{MC}$ [mm]
MH	700	66.4	494	1.0	78
ML	700	66.4	108	3.1	101
LL	150	539×10^3	108	1.5	196
HH	1500	0.2	494	1.9	82

Table 1: Parameters of the four signal MC samples used in the analysis: the squark mass, production cross-section from PROSPINO [13], neutralino mass, average neutralino boost factor from PYTHIA [11], and average proper flight distance.

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