Search for Heavy, Long-Lived Particles Decaying to Lepton Pairs in *pp* Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector

K.K. Gan
The Ohio State University

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Outline

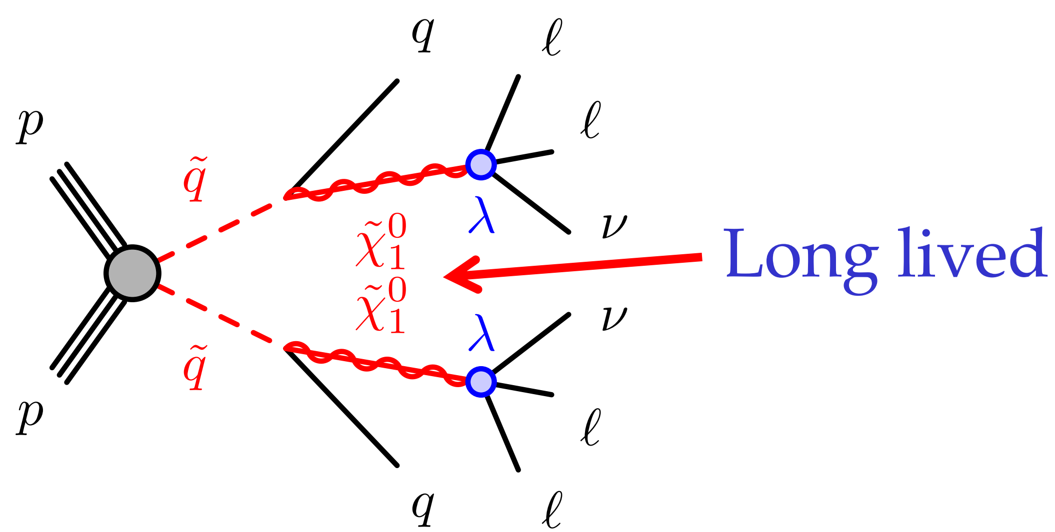
- Introduction
- Long-Lived Particles Reconstruction/Selection
- Background Estimates
- Systematic Uncertainties
- Summary

State of LHC

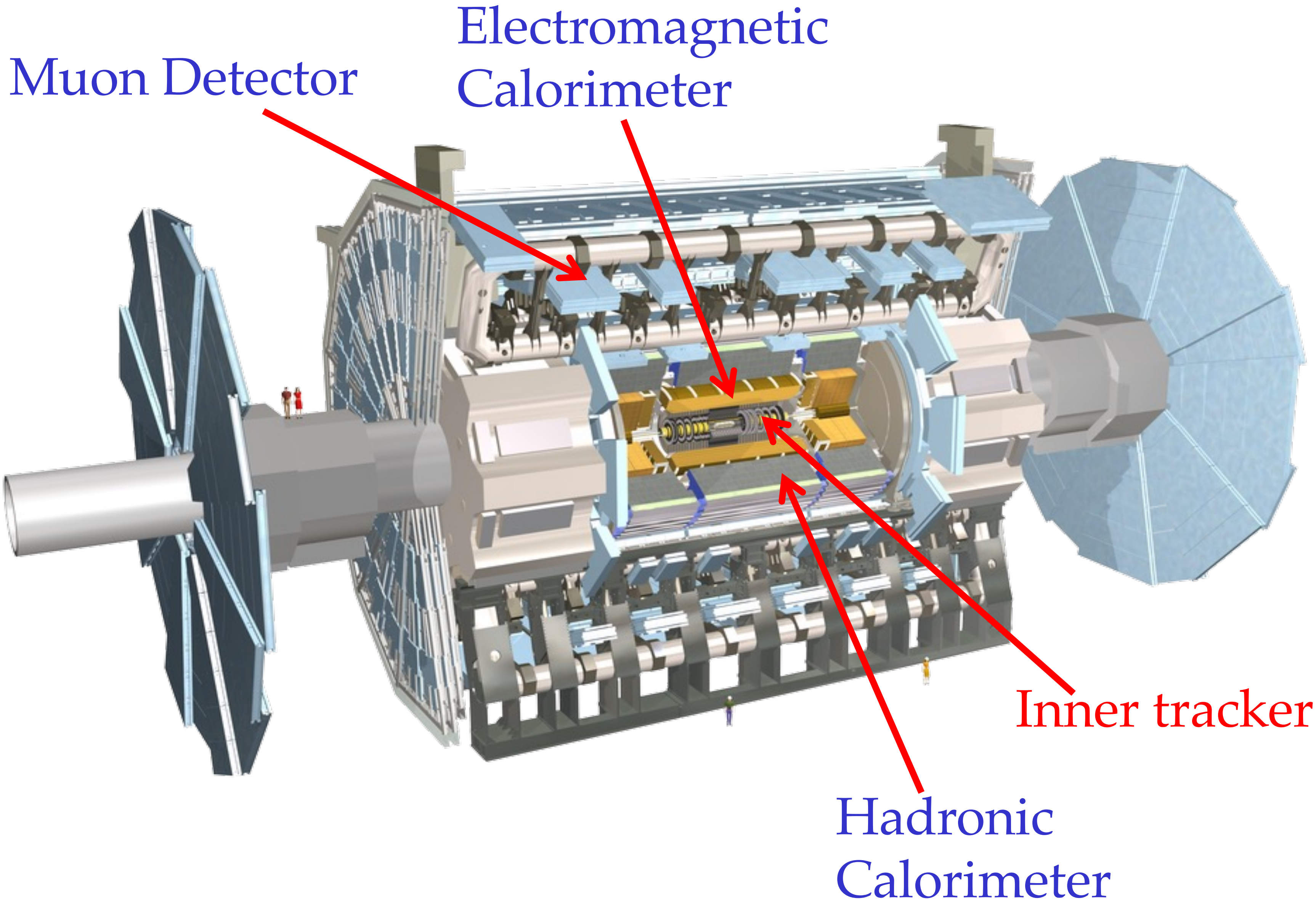
- LHC has been a spectacular success:
  - reliable operation
  - high luminosity
  - delivered large data sample (~100 fb^{-1}) at 13 TeV:
  - discovery of Higgs at 7/8 TeV
  - produced hundreds of papers on searches for physics beyond SM
    - no luck so far
    - most searches for particles decayed near *pp* collision region
    - ⇨ searches for long-lived particles are of particular interest

New Particle Search Signatures

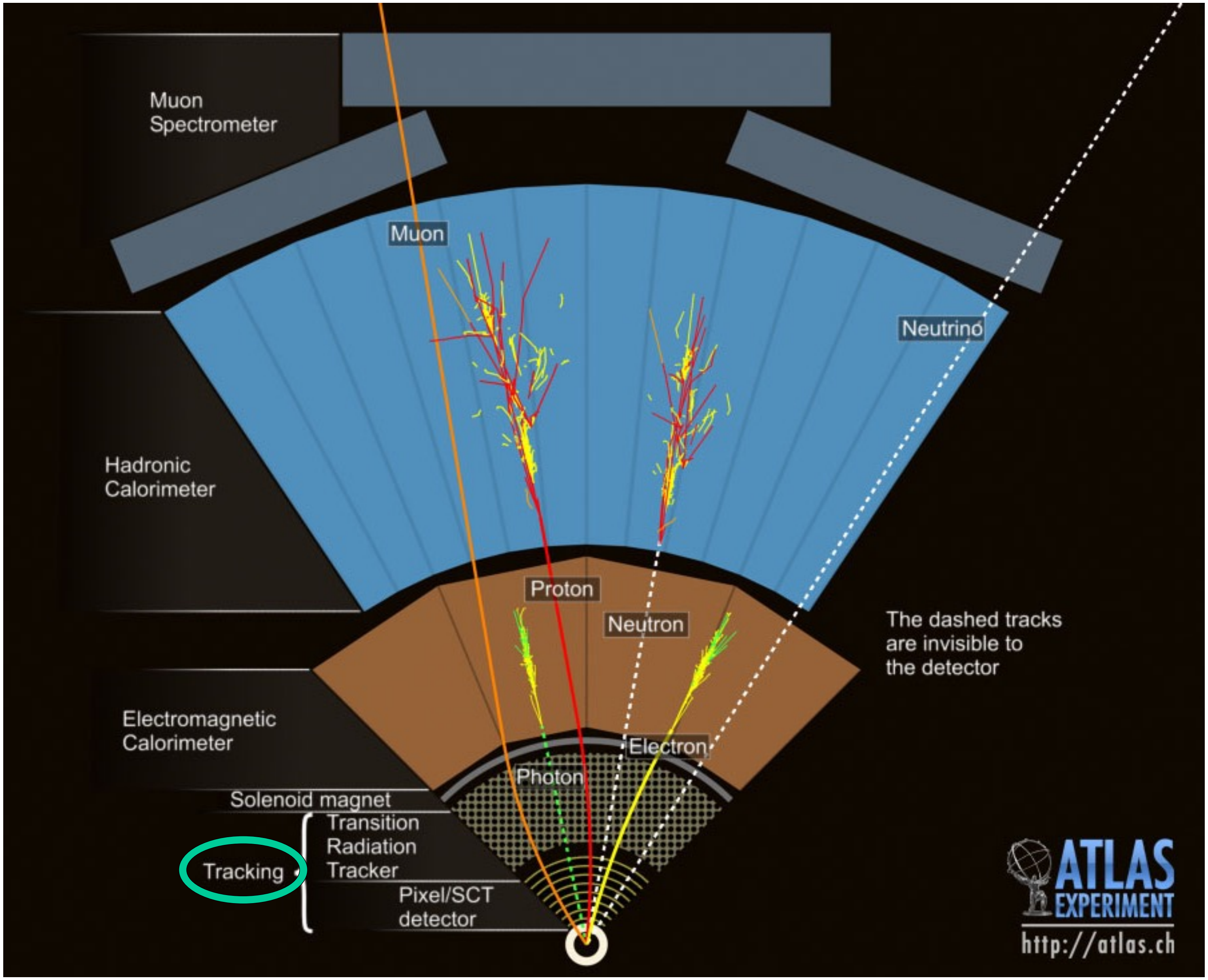
- Two long-lived particles decaying into two leptons are searched for
  - $Z' \rightarrow ee + \mu\mu + e\mu$
    - can be produced in pairs or from a decay
    - cannot be produced via $q\bar{q}$ or else would have been observed as displaced jets
  - SUSY RPV simplified model



ATLAS Detector



ATLAS Detector



Challenge in Long-Lived Particle Search

- Standard ATLAS trigger + track/vertex reconstruction are designed for particles originated near *pp* collision region
  - need special triggers without using inner tracker information
    - loose enough without producing too much data
  - need to recover tracks not originated near *pp* collision region
    - need special reprocessing

LLP Triggers

- search for LLP that decays into ee, $\mu\mu$, $e\mu$
- do not use inner tracker information
- muon:
  - identified using muon spectrum information only
  - $P_T > 60$ GeV + $|\eta| < 1.05$
- electron:
  - use photon trigger only
  - single photon: $P_T > 140$ GeV
  - di-photon: $P_T > 50$ GeV

Data and Global Event Selection

- 32.8 fb^{-1} at 13 TeV
- event primary vertex with z < 200 mm
- two leptons forming a detached vertex
- no other global event requirement to be model independent

Pre-Selection

- cuts on events passing special trigger to limit CPU/disk consumption
- muon:
  - $P_T > 62$ GeV + $|\eta| < 1.07$
  - χ^2/DoF < 5 if good match between tracks found with inner tracker and muon spectrometer
- electron:
  - single photon: $P_T > 150$ GeV + $|\eta| < 2.5$
    - photon: $P_T > 10$ GeV + $|\eta| < 2.5$
    - electron: $P_T > 10$ GeV + $|\eta| < 2.5$ + $|d_0| > 2.0$ mm
    - muon: $P_T > 10$ GeV + $|\eta| < 2.5$ + $|d_0| > 1.5$ mm
  - di-photon:
    - two photons: $P_T > 55$ GeV + $|\eta| < 2.5$
    - two electron: $P_T > 55$ GeV + $|\eta| < 2.5$ + $|d_0| > 2.0$ mm
    - photon + electron: $P_T > 55$ GeV + $|\eta| < 2.5$ + $|d_0| > 2.0$ mm

Large Radius Tracking

- special tracking program to recover tracks with large impact parameters not found by standard tracking program
  - use hits not used by the standard tracking

	Standard	Large radius
Maximum $\lvert d_0 \rvert$ [mm]	10	300
Maximum $\lvert z_0 \rvert$ [mm]	250	1500
Maximum $\lvert \eta \rvert$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7

Track Requirements

Parameter	Requirement
p_T (GeV)	> 1
χ^2/DoF	< 50
$\|d_0\|$ (mm)	$\boxed{2\text{–}300}$
$\|z_0\|$ (mm)	$\boxed{< 1500}$
SCT hits	≥ 2
Silicon shared hits	≤ 2
Pixel and TRT hits	TRT hits > 0 or pixel hits ≥ 2

Vertex Requirements

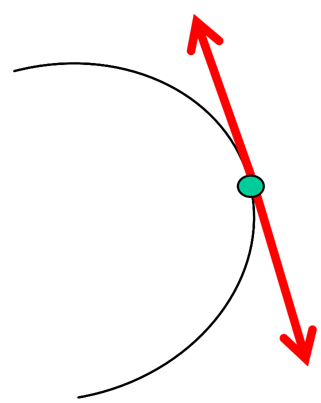
- track not allowed to have pixel hits smaller than the vertex radius
- must have nearby pixel or silicon strip hits at larger radius
- vertex cannot be inside disable pixel module
- electron cannot be in tracking layer or structure
- candidate tracks must match to trigger and pre-selection objects

Vertex fit $\chi^2/\mathrm{DoF} < 5$
$d_{xy} > 2$ mm
$r_{xy} < 300$ mm, $\lvert z \rvert < 300$ mm
$m_{\mathrm{DV}} > 12$ GeV
Opposite charge
Disabled module veto
Material veto (excluding $\mu\mu$)
Trigger matching (signal region only)
Preselection matching (signal region only)

Cosmic Ray Veto

- one segment of cosmic ray could be reconstructed in opposite direction
  - ⇨ two opposite signed track forming a detached vertex
    - ◆ two tracks separated in ϕ by π
    - ◆ two tracks of opposite η
      - ⇨ CR veto:

$$\Delta R_{\cos} = \sqrt{(\Delta\phi - \pi)^2 + (\Sigma\eta)^2} < 0.01$$



Lepton Identification

- use standard ATLAS electron and muon reconstruction/identification algorithm
  - no requirements on pixel hits
  - no requirements on impact parameter for electron

Muon	Overlap removal
	Combined ID + MS
	No requirement on pixel hits
	$\lvert\eta\rvert < 2.5$
	$p_T > 10.0$ GeV
Electron	Overlap removal
	Cluster quality criteria
	No requirements on d_0 or pixel hits
	$\lvert\eta\rvert < 2.47$
	$p_T > 10.0$ GeV

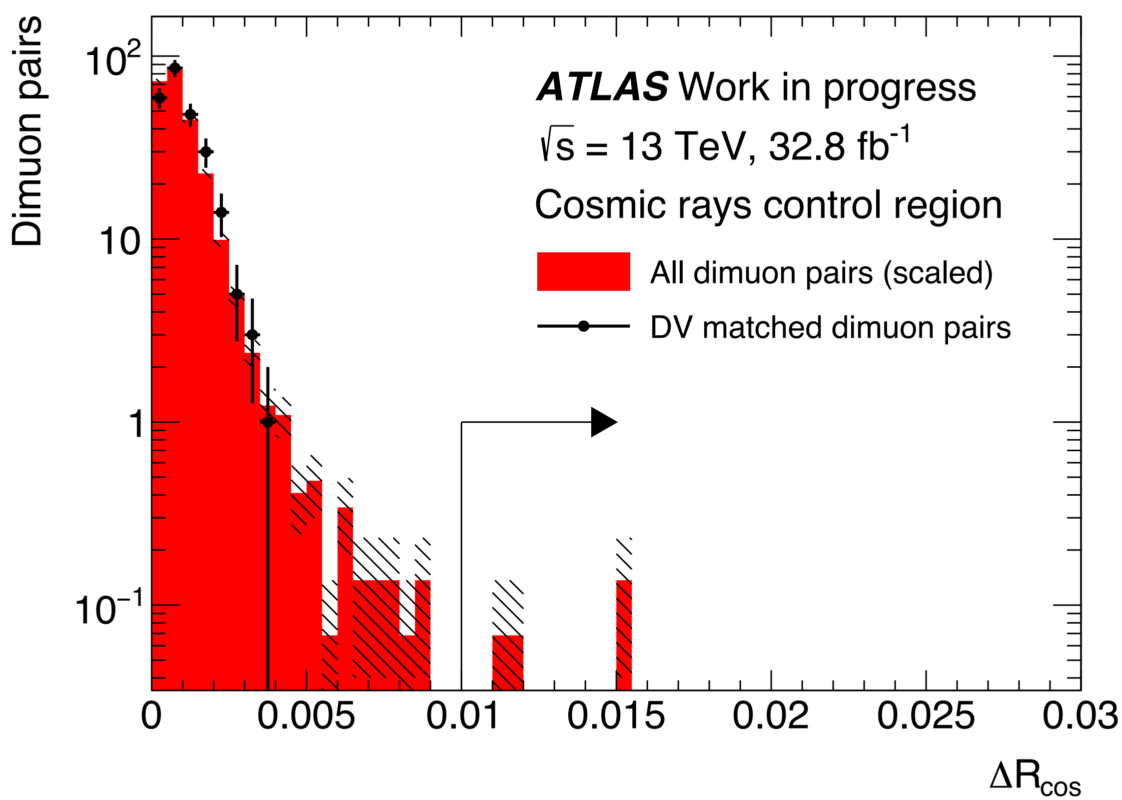
Background

- no standard model process can produce heavy lepton pair with detached vertex
- two potential backgrounds
  - cosmic ray
  - two random leptons forming a detached vertex

Cosmic Background Estimate

- use cosmic veto distribution to estimate background
- use distribution without vertex requirement to increase statistics in predicting number of cosmic events in signal region (> 0.01)

$0.27 \pm 50\%$ (stat.) $\pm$ 36% (syst.) events



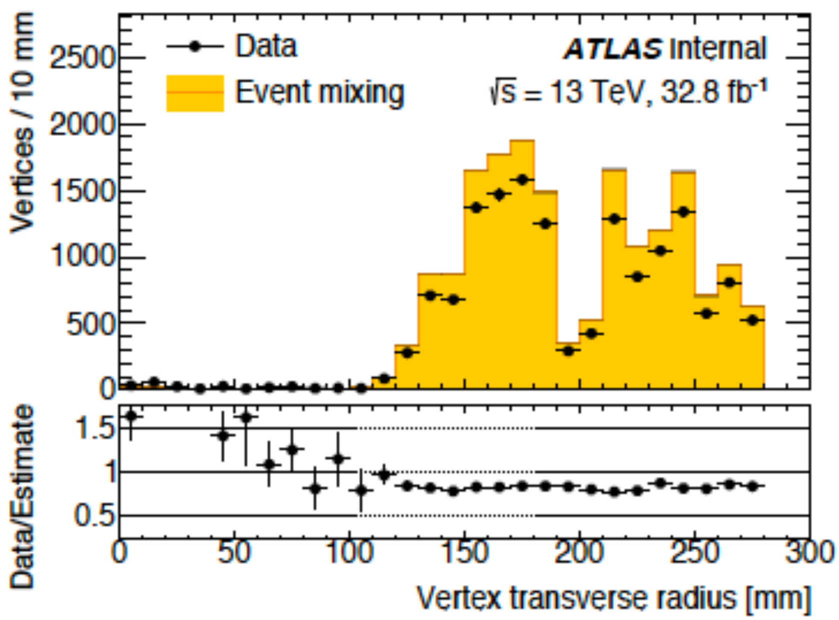
Random Crossing Background

- estimated using two techniques
- no assumption on lepton origin or fake rate
  - event mixing
    - calculate probability for forming detached vertex using leptons from different events
    - multiple this by number of lepton pairs in data to yield number of vertices from random crossing
  - track flipping
    - randomly flip one track in a lepton pair with respect to beam spot
      ⇨ try to reconstruct the vertex
    - number of successfully reconstructed vertex is then the estimated background

Random Crossing Background Test

- use xx, *e*x, μx samples to test reliability of estimates
  - measure number of xx, *e*x, μx pairs in data
  - calculate expected number of xx, *e*x, μx pairs
  - both methods reproduce the structures observed in data
  - both methods overestimate number of xx pairs by ~20%

Vertex Type	Track Flipping	Event Mixing	MC
μx	3	4	5
*e*x	5	2	4
xx	1154	1125	989



Random Crossing Background Estimate

Channel	$N_{\text{pairs}}^{\text{obs}}$	$p_{\text{xing}}\ (10^{-5})$	$N_{vx}^{est}\ (10^{-4})$
ee	21 ± 4.6	1.2	2.6 ± 0.6
$e\mu$	10 ± 3.2	7.0	7.0 ± 2.2
$\mu\mu$	9 ± 3.0	15.9	14.3 ± 4.8
SR			23.9 ± 5.3

- track flipping estimates background of 39.2 x 10^{-4} vertices
  - difference of 63% is assigned as systematic uncertainty
- dilepton vertex can be misidentified as xx, ex, μx vertex
  - estimated systematic uncertainty to be less than 40%
- total systematic uncertainty: 75%

Summary of Background

Source	Yield [Events]	Stat. uncertainty (%)	Syst. uncertainty (%)
Cosmic-ray muons	0.27	± 50	± 36
Random crossings	24×10^{-4}	± 21	± 75

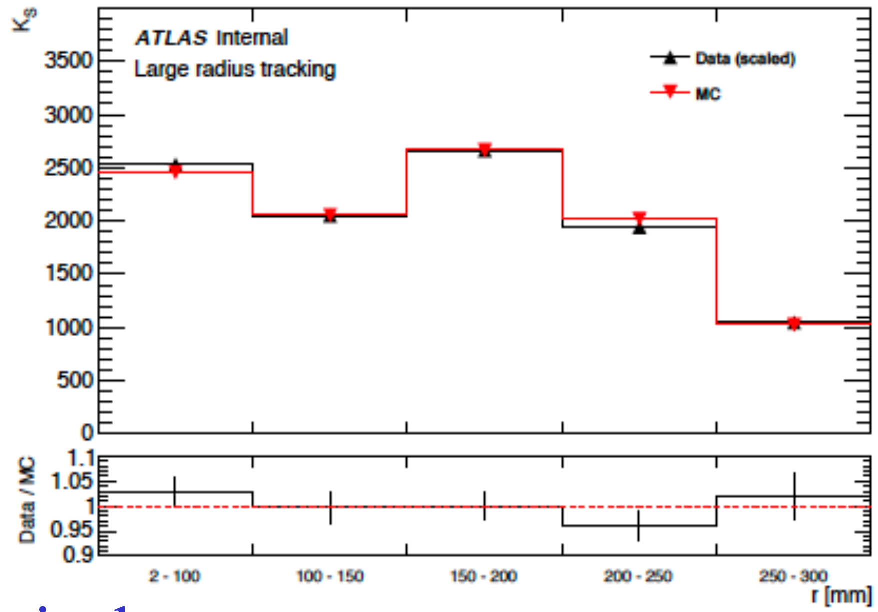
Systematic Uncertainty

- SUSY production cross section:
  - 8.7% for 700 GeV squark
  - 17.8% for 1600 GeV squark
- luminosity: 2.2%
- pile-up reweighting: ~10%
  - reweighted MC events to reproduce observed number of primary vertices
- trigger: few %
  - using Z boson with tag-and-probe technique
    - tag lepton satisfies stringent identification/isolation criteria
    - probe lepton satisfies same identification criteria as signal
    - comparing the trigger efficiencies measured in the data to those of Z+jets MC sample.

Systematic Uncertainty

- tracking and vertexing efficiency for LLP
  - use $K_s \rightarrow \pi\pi$
  - K_s can be reconstructed using standard or large radius tracking
  - number of K_s is not well known simulated by MC
    - ⇨ normalize number of K_s found in data with standard tracking to MC
    - ⇨ compare number of K_s found in data with large radius tracking to MC as a function of transverse decay radius

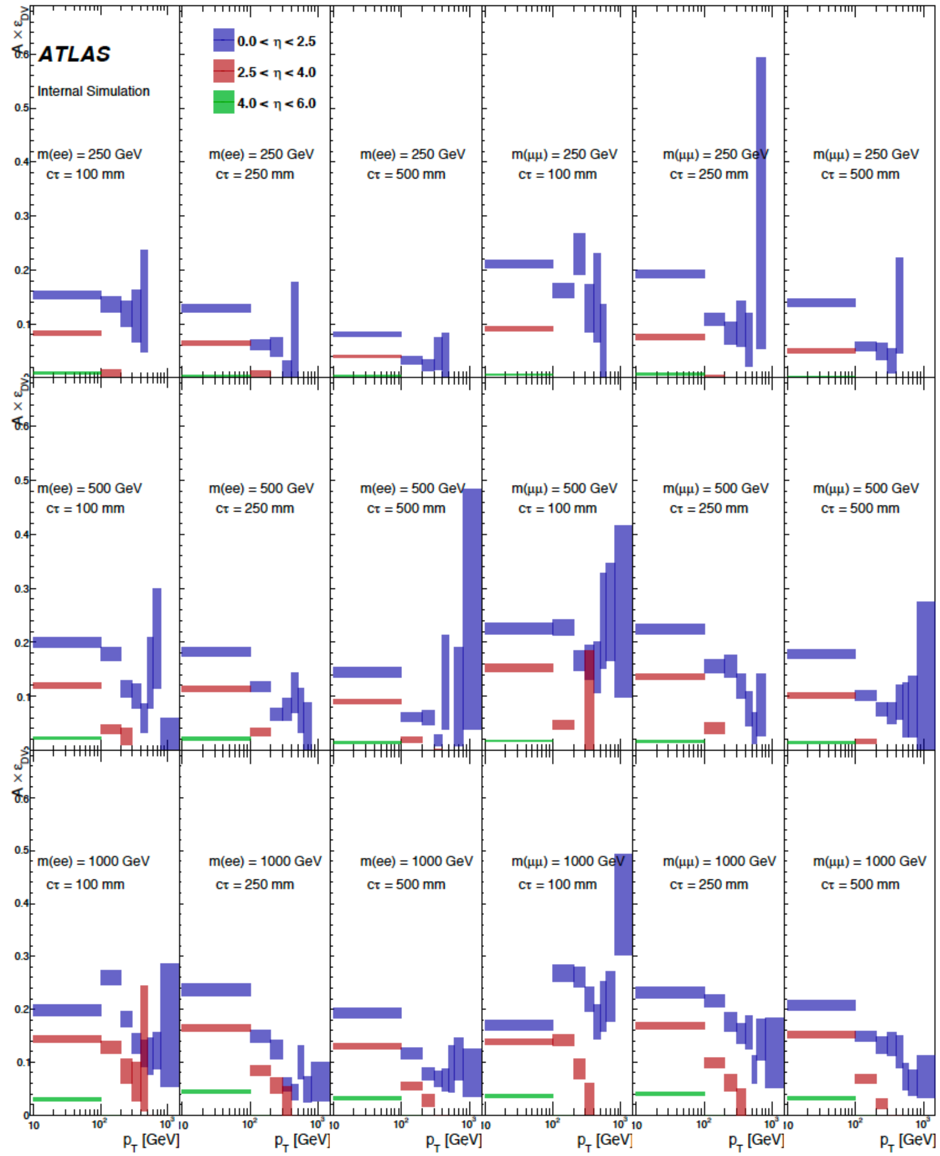
Systematic Uncertainty



- Largest discrepancy between data and MC is 6%, including statistical error
  - 2% systematic uncertainty in standard tracking
  - 1% systematic uncertainty in standard secondary vertexing
  - in principle the above two standard tracking/vertexing systematic uncertainties have been normalized out but…
  - add three systematic uncertainties linearly to yield conservative 10% systematic uncertainty

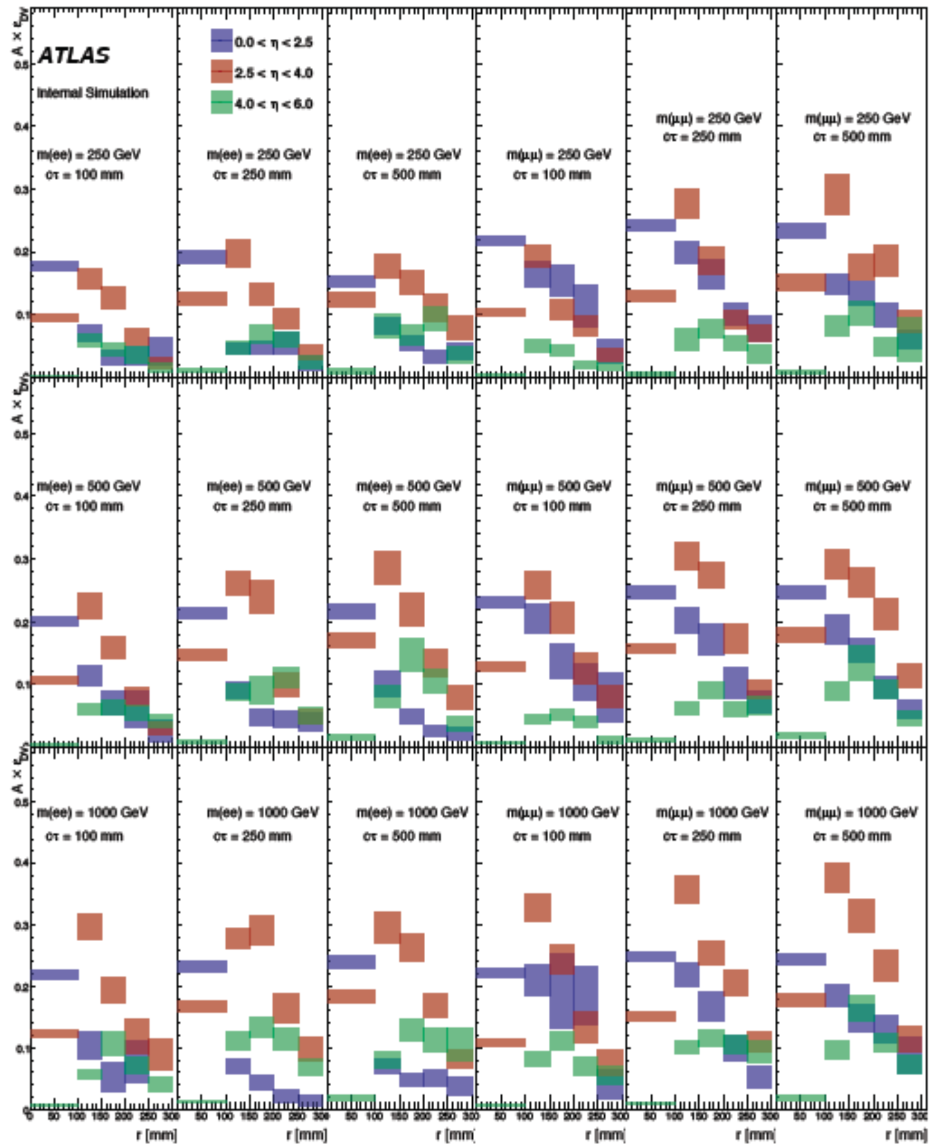
Sensitivity for Z' vs. P_T

- efficiency ~20% in central region of ATLAS



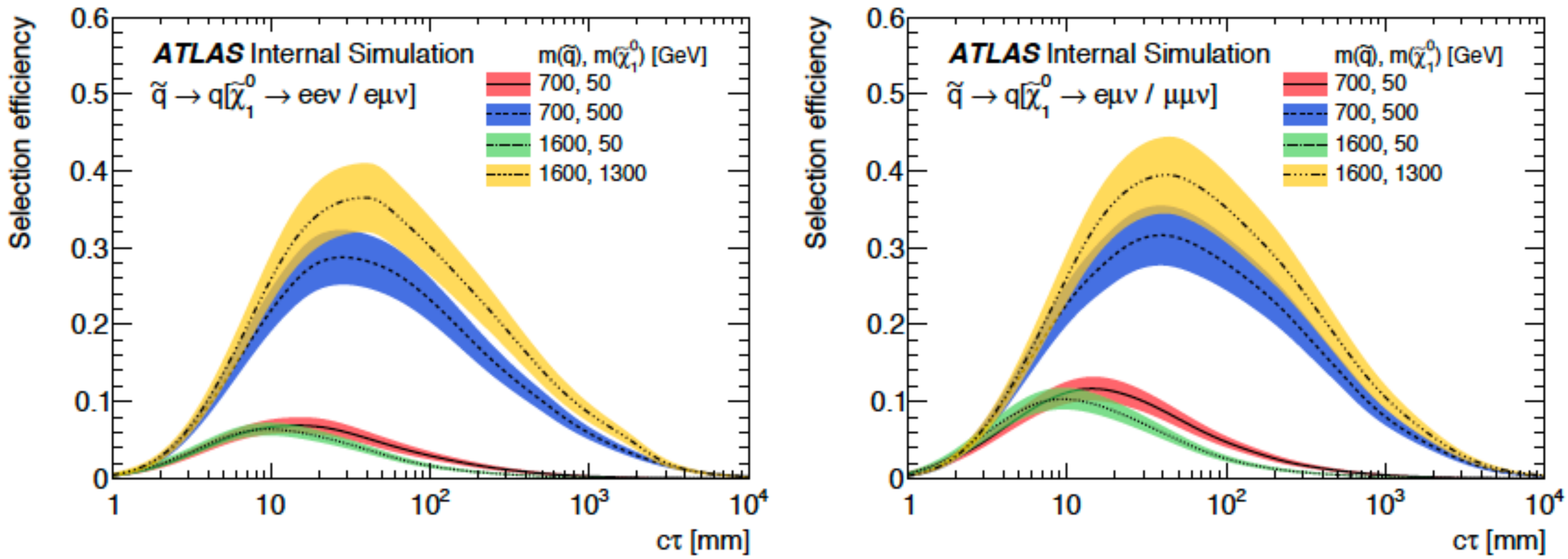
Sensitivity for *Z'* vs. Decay Radius

- efficiency ~20% in central region of ATLAS out to r ~ 100 mm



Sensitivity for RPV SUSY

- two independent scenarios:
  - LSP decay is mediated by single dominant RPV coupling λ_{121} or λ_{122}
    - 1.3 TeV neutralino: 40%
    - 50 GeV neutralino: 12%



(a) λ_{121}

(b) λ_{122}

Summary

- Search for heavy, long-lived particles with two lepton final states in two search scenarios
  - $Z' \rightarrow ee + \mu\mu + e\mu$
  - SUSY RPV simplified model
  - efficiency is ~20% per vertex in the ATLAS central tracker
  - results will be submitted for publication shortly