# Searches for Long-Lived SUSY Particles

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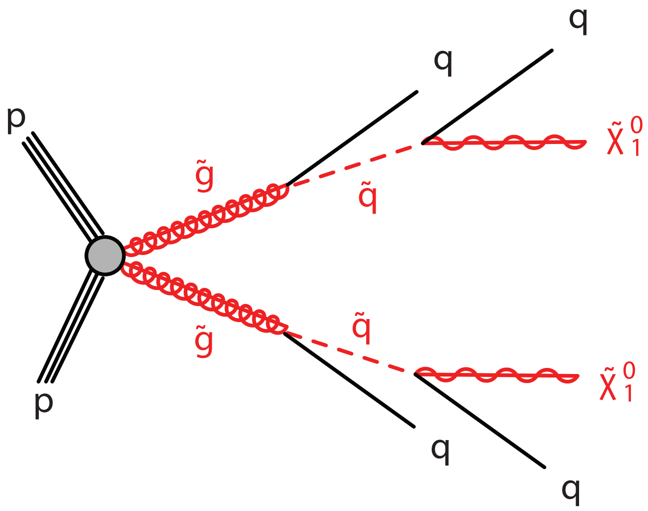
# Long-lived particles in supersymmetry

- Long-lived particles can arise from
  - Nearly conserved symmetries
  - Small coupling to final state
  - Phase-space suppression due to nearly degenerate masses

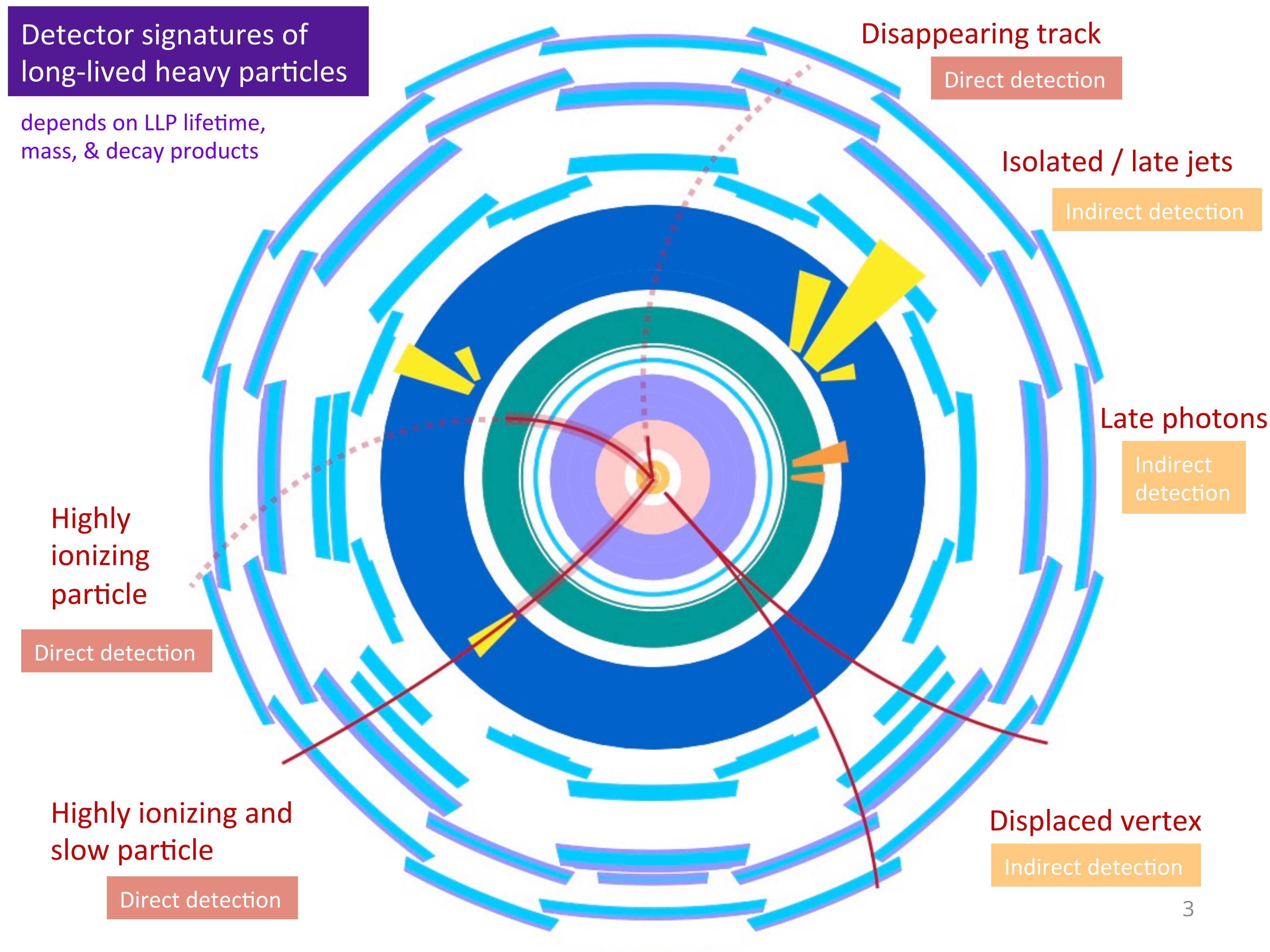



example: long-lived gluino if squark mass >> gluino mass

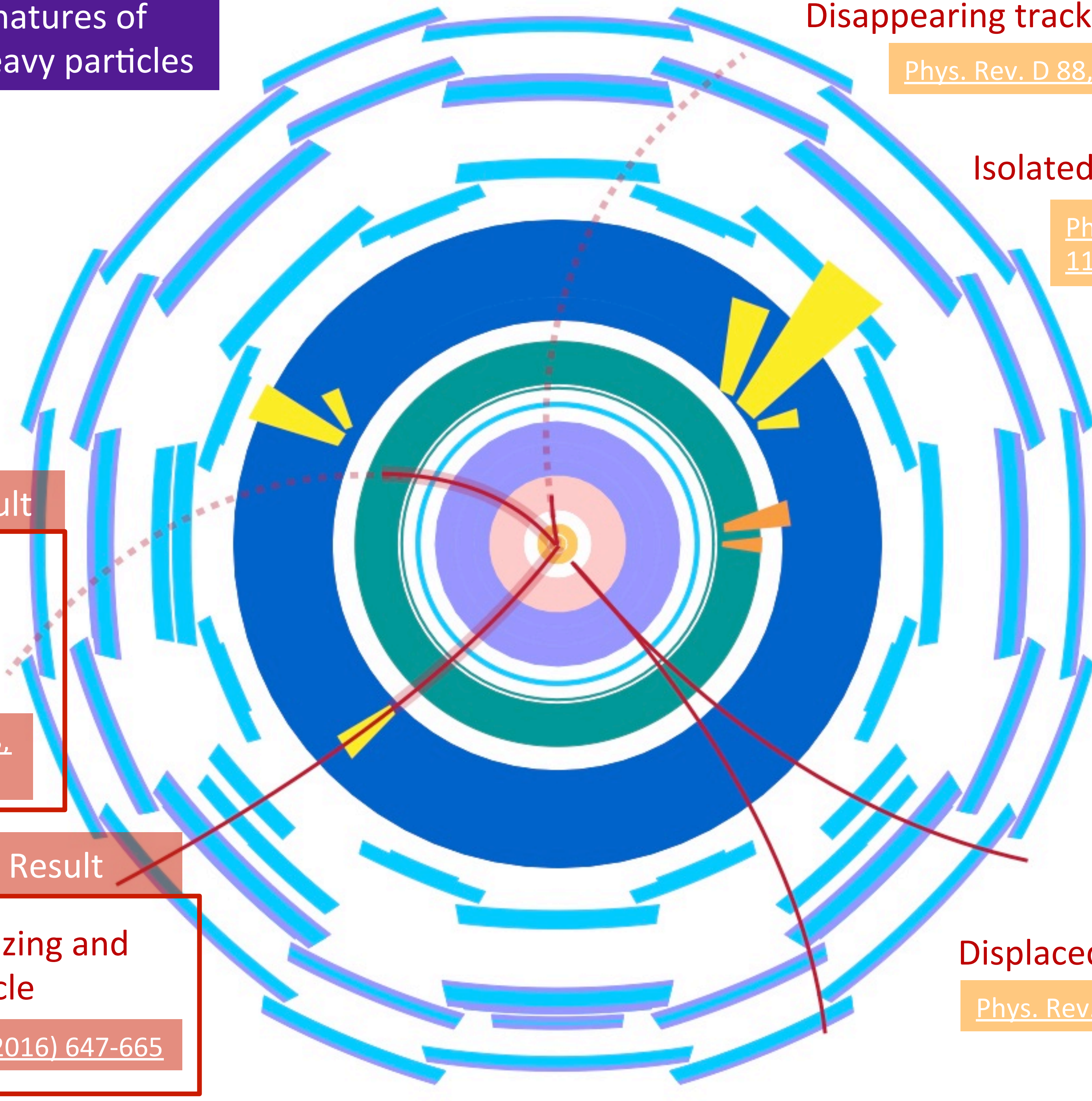
- Can arise in models including split SUSY, anomaly mediated SUSY breaking, and stealth SUSY

# Detector signatures of long-lived heavy particles

depends on LLP lifetime, mass, & decay products

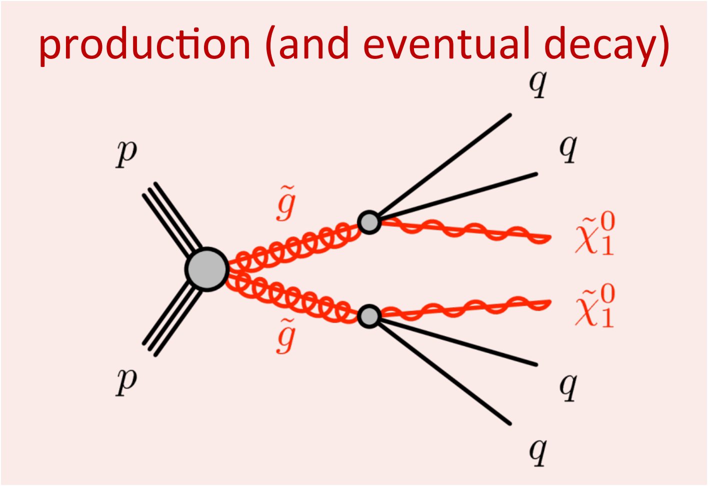


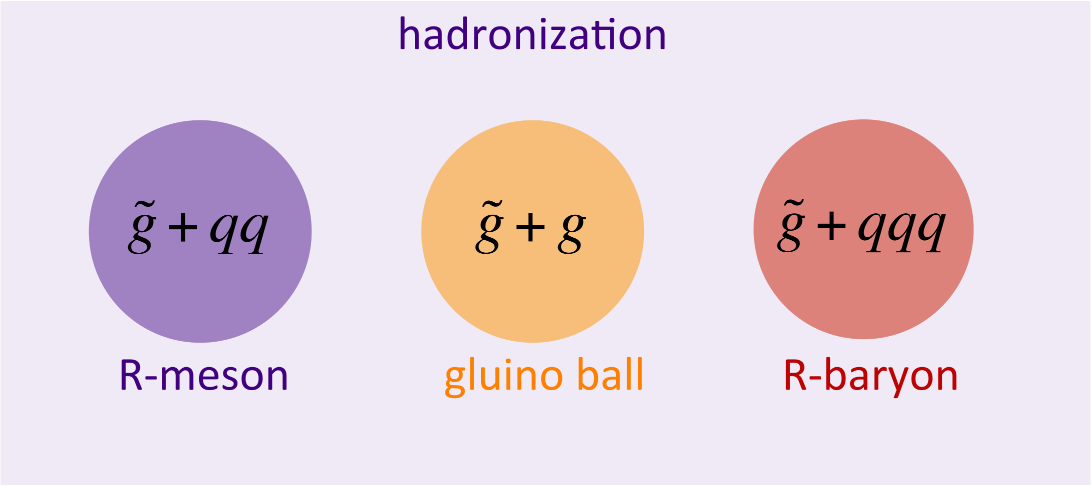
# Detector signatures of long-lived heavy particles



# What is an R-hadron?

- First 13 TeV results focus on strongly produced long-lived particles
- Long-lived gluinos or squarks hadronize into "R-hadrons"



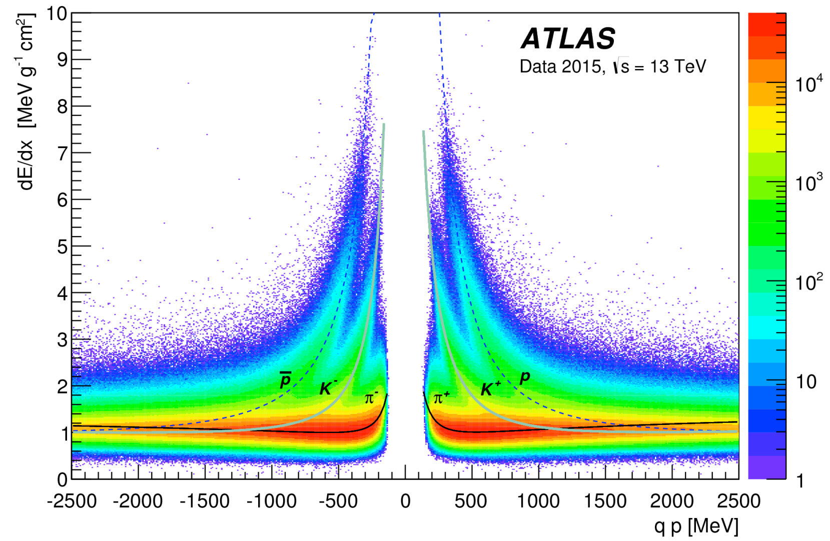

- Experimentally relevant properties
  - Slow, $\beta < 1$ → late time of arrival in calorimeters and muon system
  - Highly ionizing → dE/dx larger than minimum ionizing particle
  - Little energy lost in hadronic interactions → measured missing transverse momentum ($E_T^{miss}$), used for trigger

# Search for meta-stable R-hadrons

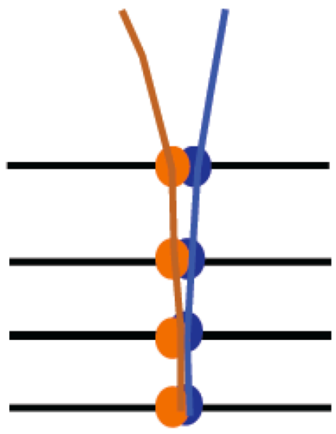
Search for metastable heavy charged particles

Phys. Rev. D 93, 112015

- Analysis overview
  - 3.2 $fb^{-1}$ of 2015 data
  - Use dE/dx to look for heavy charged particles with lifetimes >= 0.4 ns
  - Trigger using $E_T^{miss}$
  - Estimate particle mass using dE/dx and momentum
  - Background estimated from data
    - low $E_T^{miss}$ data region used to derive background dE/dx distribution
    - low dE/dx data region used to derive background momentum, η distributions




- 13 TeV analysis improvements
  - Higher production cross-section
  - Improve background rejection using clusters identified as merged by neural network used in tracking reconstruction
  - Use newly added pixel layer in ATLAS to improve dE/dx measurement



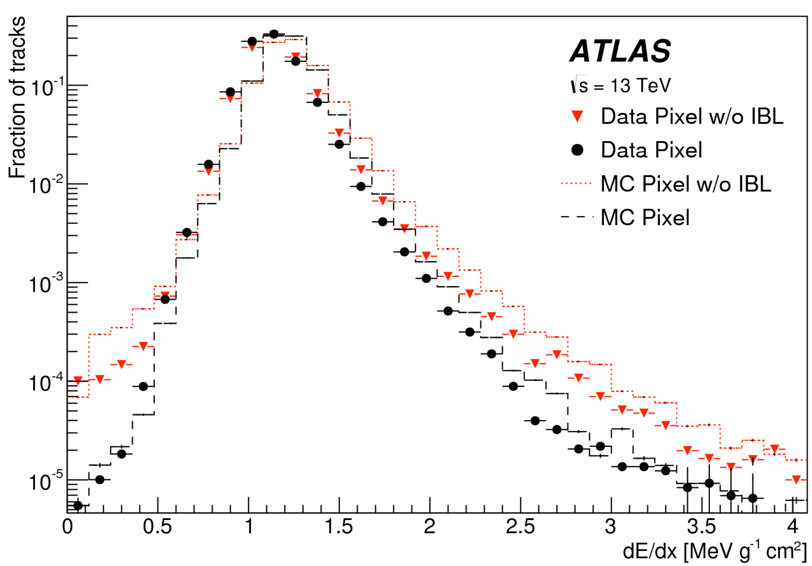
merged clusters identify energy deposits consistent w/ multiple particles

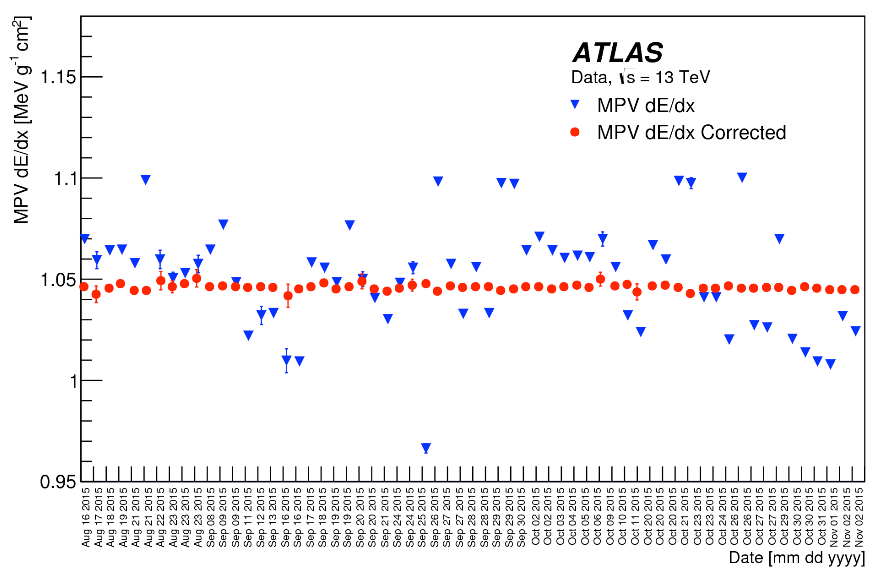
# Measuring dE/dx and Mass Calculation

Search for metastable heavy charged particles

Phys. Rev. D 93, 112015

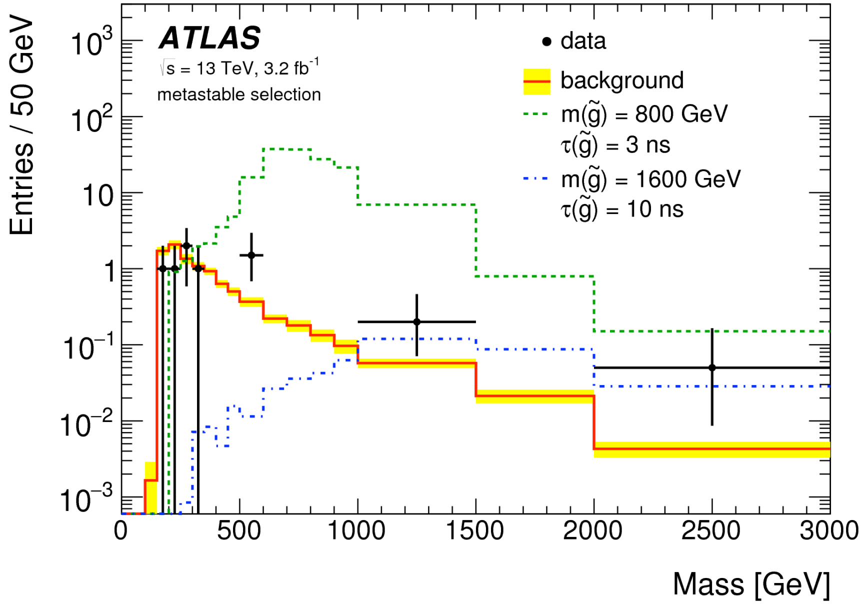
- Estimate particle mass from energy loss dE/dx and momentum
- Calibrate mass in data and simulation using protons, pions, and kaons
- dE/dx measured in Pixel detector in ATLAS
  - new Insertable B-Layer (IBL) adds a fourth measurement point to track dE/dx, improves resolution and reduces Landau tails by 50%
  - … and requires run-by-run dE/dx correction due to radiation-induced effects in IBL front-ends

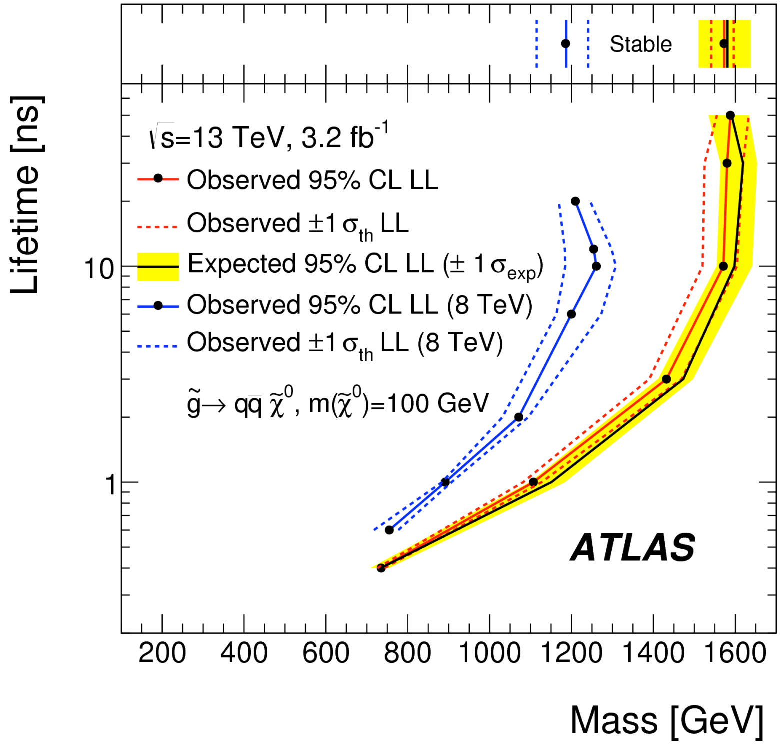


# Results

- Good agreement between background expectation and data
- Mass distribution used to set limits on production cross-section
- Results interpreted for gluino R-hadrons with varying lifetimes, assuming gluino decays to 100 GeV neutralino
  - all other SUSY particles are decoupled



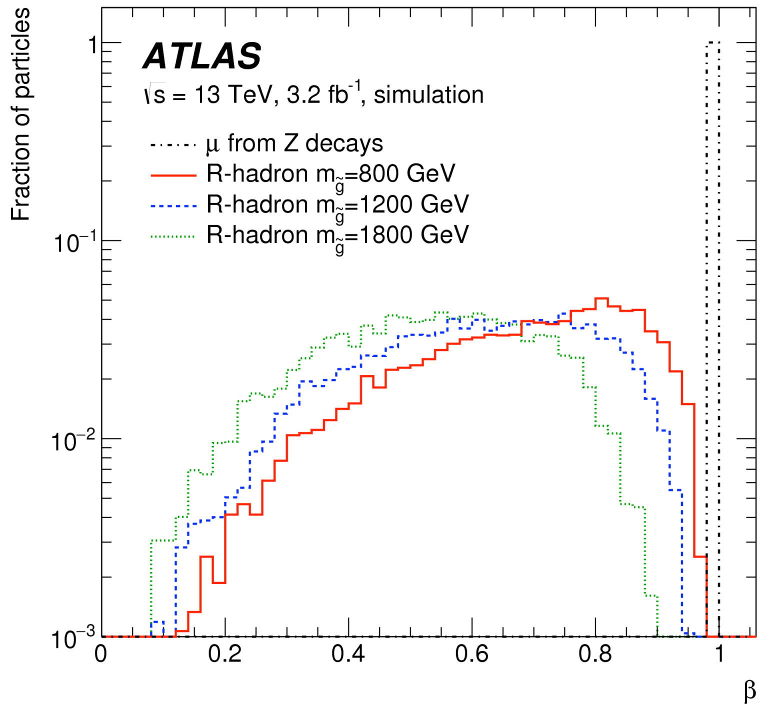

→ Exclude R-hadrons at 95% CL with masses up to 740 - 1590 GeV, depending on lifetime

Search for metastable heavy charged particles
Phys. Rev. D 93, 112015

# Search for stable R-hadrons

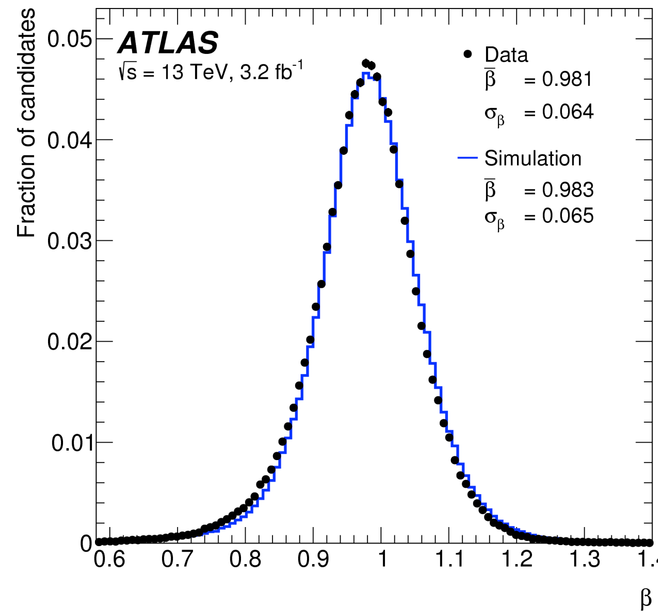


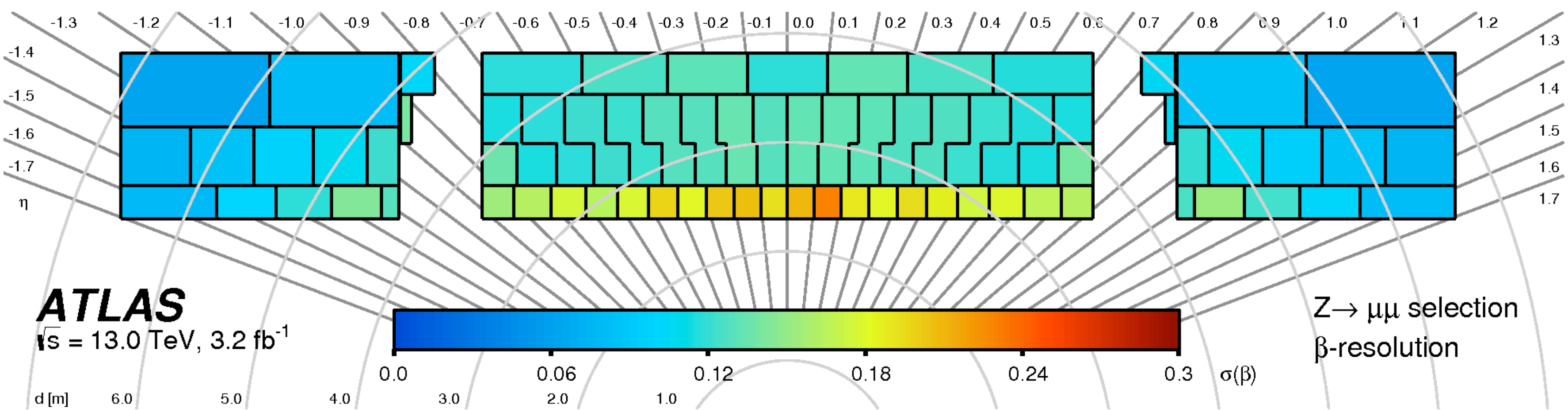
- Analysis overview
  - 3.2 $fb^{-1}$ of 2015 data
  - Use dE/dx to estimate mass from track βγ
  - Use calorimeter time-of-flight measurement to estimate mass from track β
  - Trigger using missing transverse momentum
  - Background estimated from data
    - sidebands of track momentum, β, and βγ distributions in data used to generate background probability distribution functions
    - randomly drawn values are used to estimate background mass distribution



# Measuring β

- Time-of-flight measurement made in tile calorimeter
  - Calibrate timing measurement using Z→ μμ sample in data and simulation
  - 1.3 - 2.5 ns single calorimeter cell timing resolution
  - → 0.06 - 0.23 resolution on β



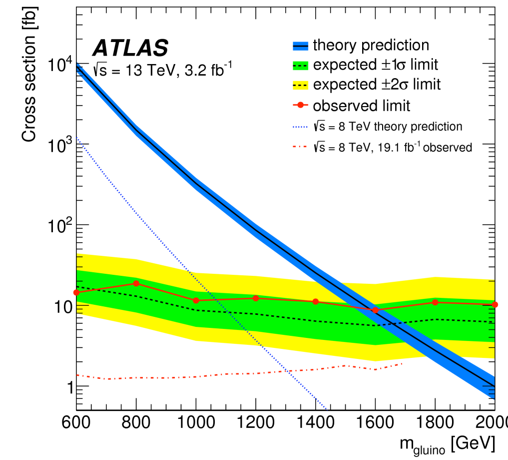

Search for heavy long-lived charged R-hadrons

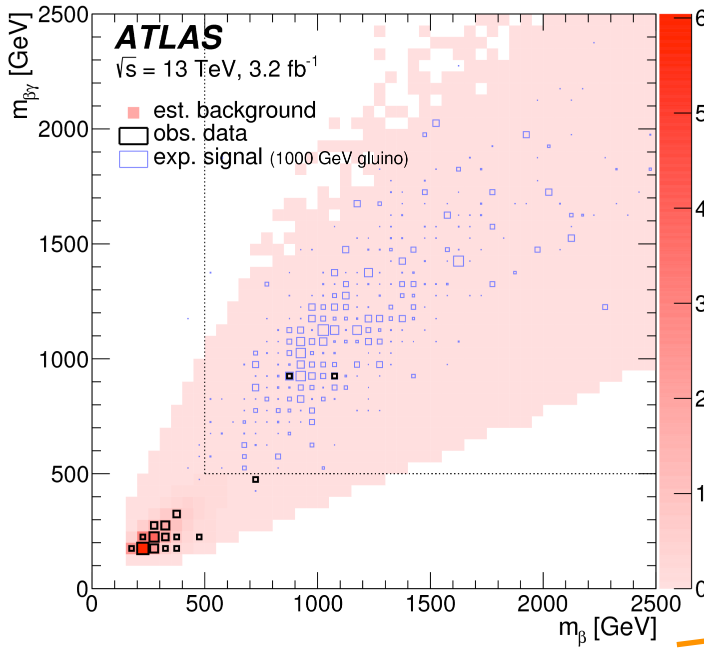
Phys. Let B (2016) 647-665

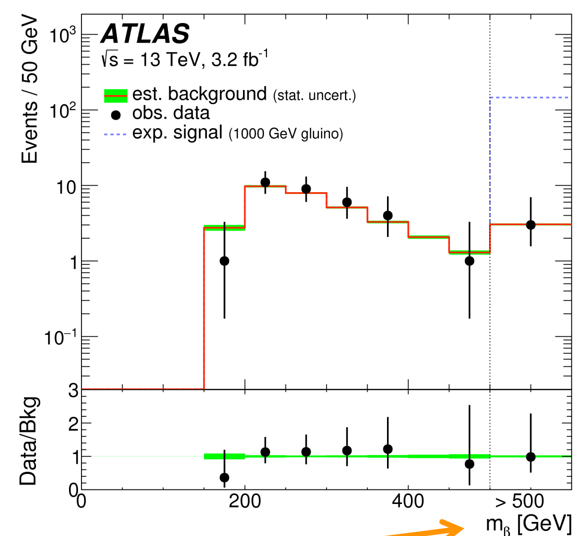
# Results



- Good agreement between background expectation and data
- Limits on production cross-section set based on # events w/ mass above a value dependent on hypothetical R-hadron mass
- Results for gluino, stop, sbottom R-hadrons
  - all other SUSY particles are decoupled



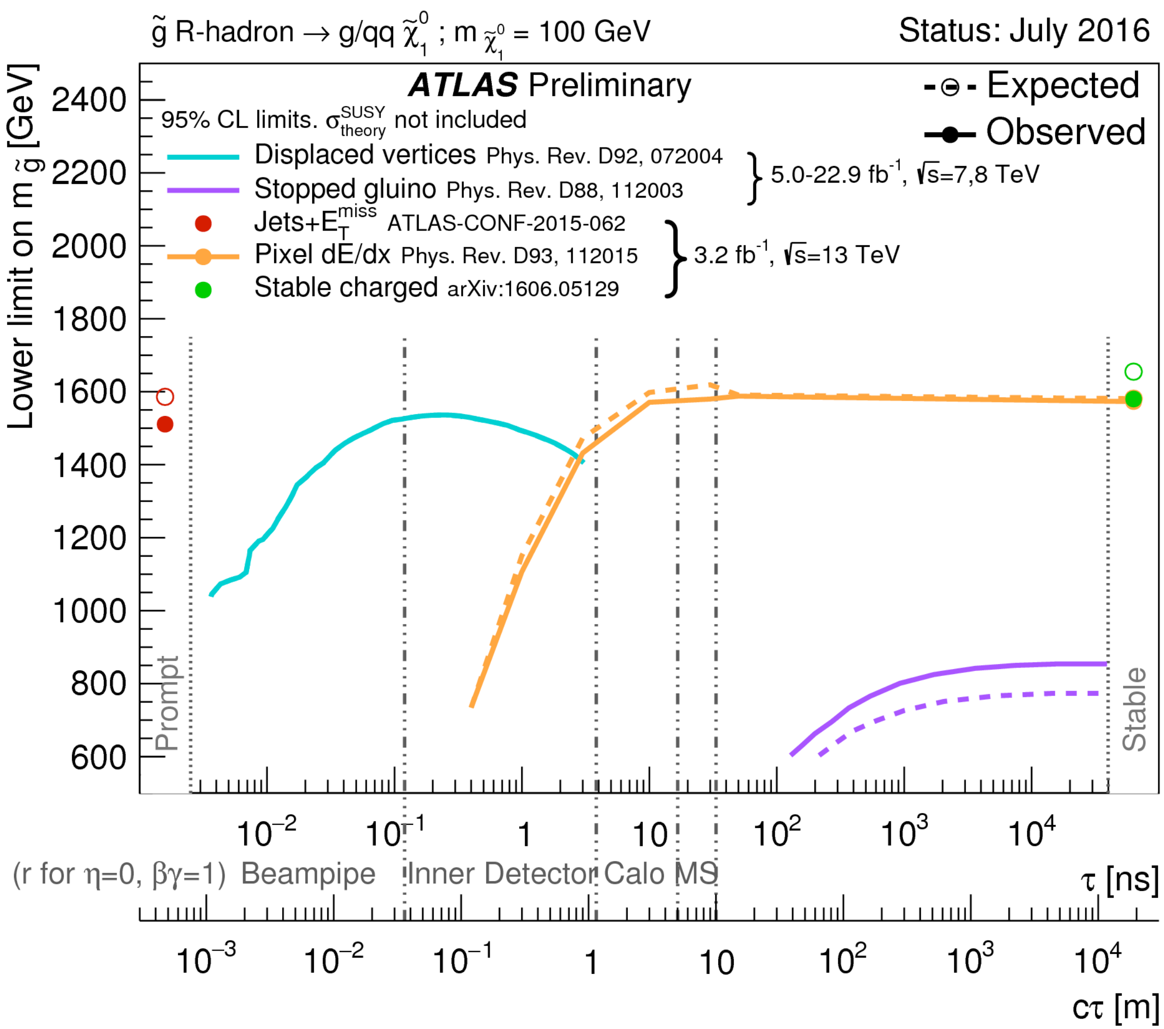




→ Exclude R-hadrons at 95% CL with masses up to:

1580 GeV (gluino R-hadrons) 805 GeV (sbottoms) 890 GeV (stops)

# Outlook

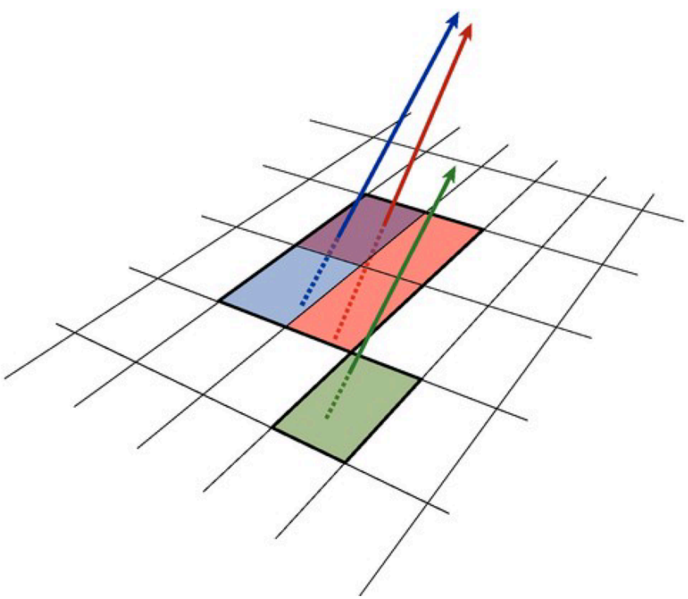
- Early 13 TeV results exclude R-hadrons up to 1590 GeV
- Many more production and decay topologies under study now, expect significant improvement over results from 8 TeV



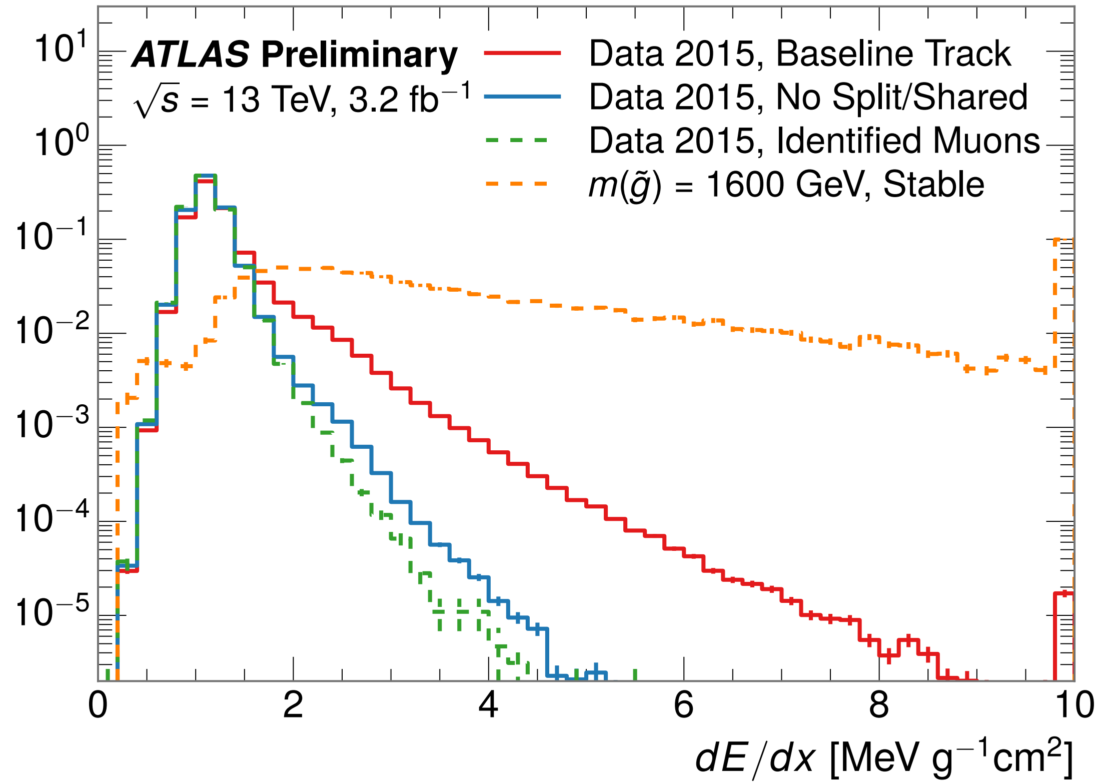
# Backup

# Tracks w/ merged clusters

- Removing tracks which are identified as having at least one cluster which is shared or split with another track significantly reduces the long dE/dx tail from overlapping SM particles

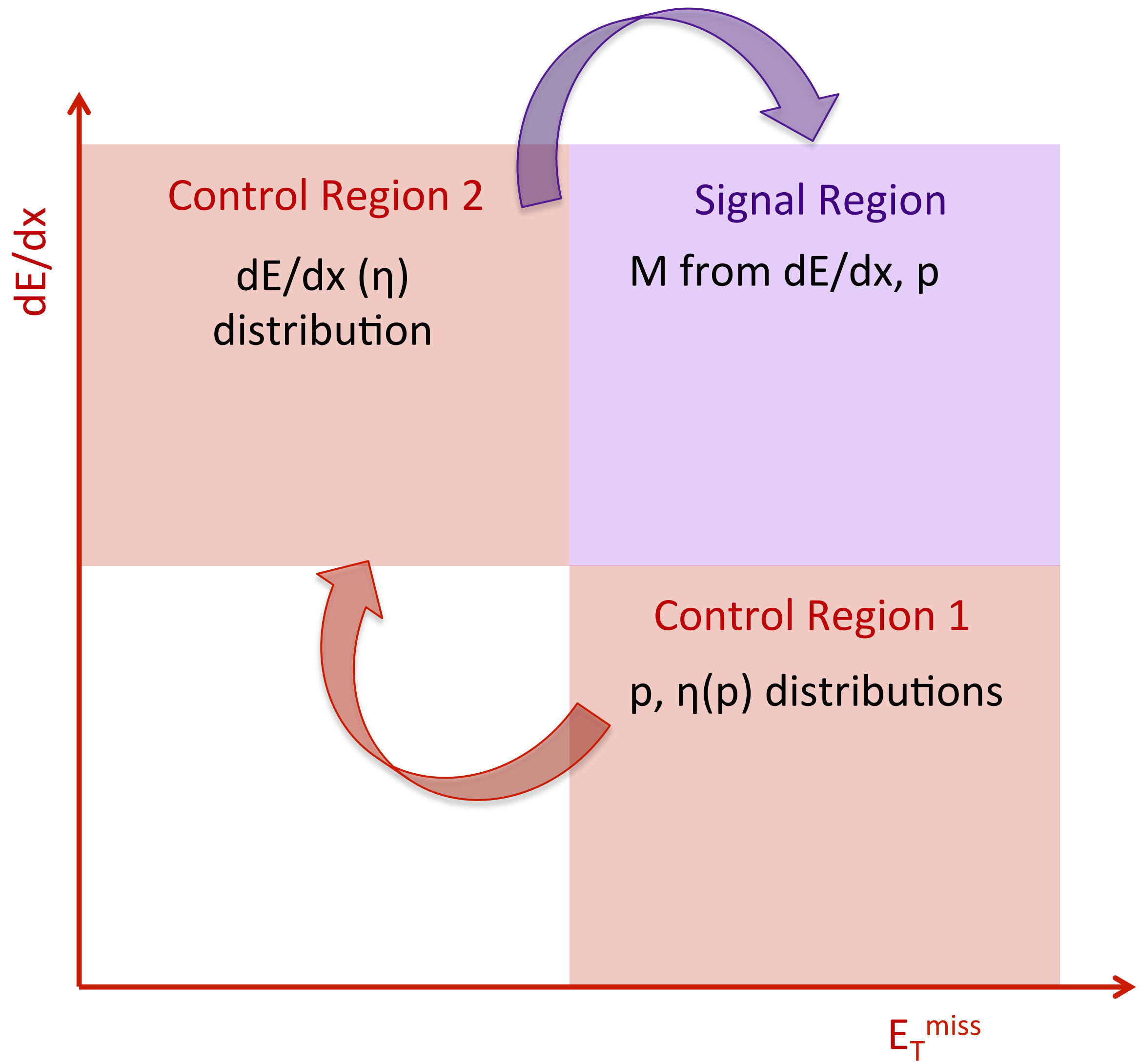


merged clusters can be identified by the neural network in part based on the shape of the shape of the pixel hits forming the cluster



# Meta-stable search: Background estimation

- Background PDFs sampled from two control regions in data
  - dE/dx and $E_T^{miss}$ uncorrelated
  - dE/dx, η, and p distributions take from CR to maintain correlation
- Estimated background mass calculated from randomly sampled p, and η(p) and dE/dx (η) from CR
- Normalized in low mass region before ionization
- Validated in momentum region outside signal



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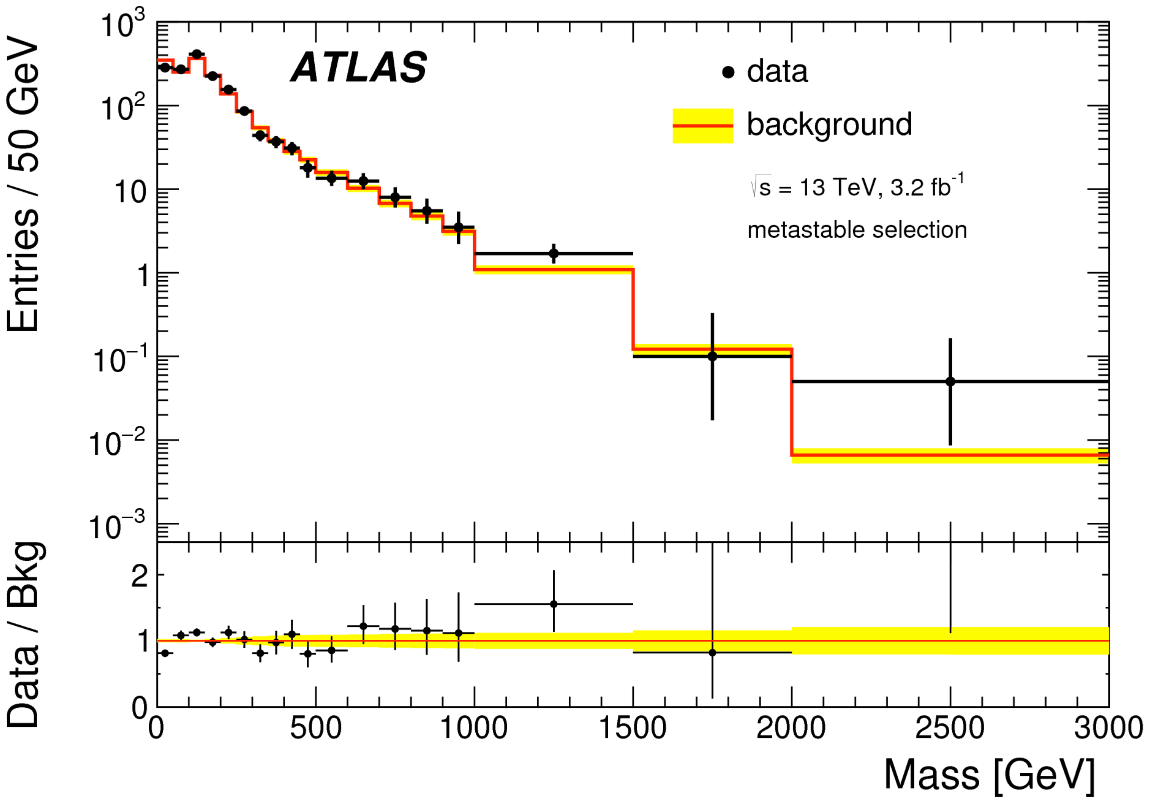
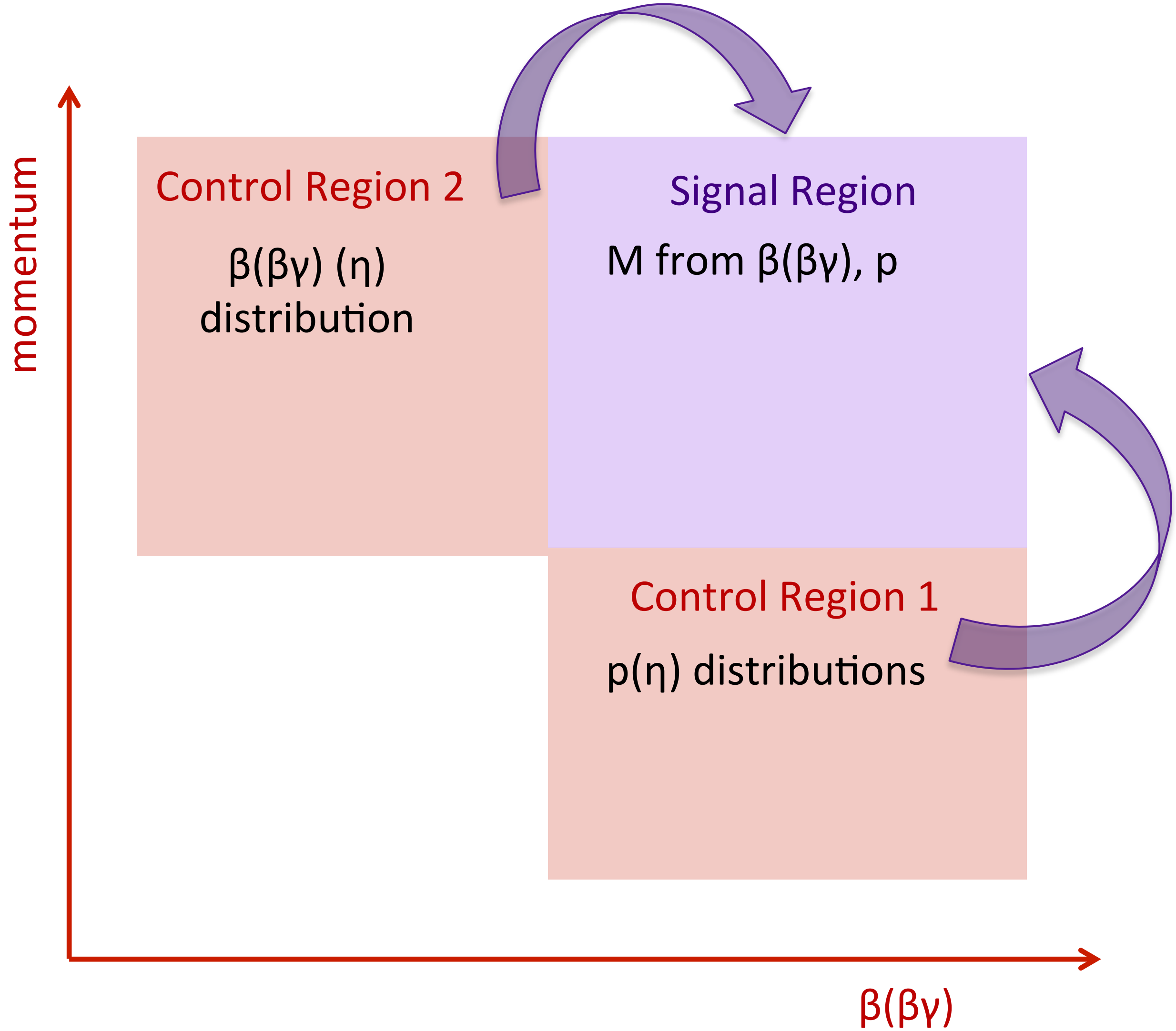
Background & data before ionization requirement



# Stable search: Background estimation

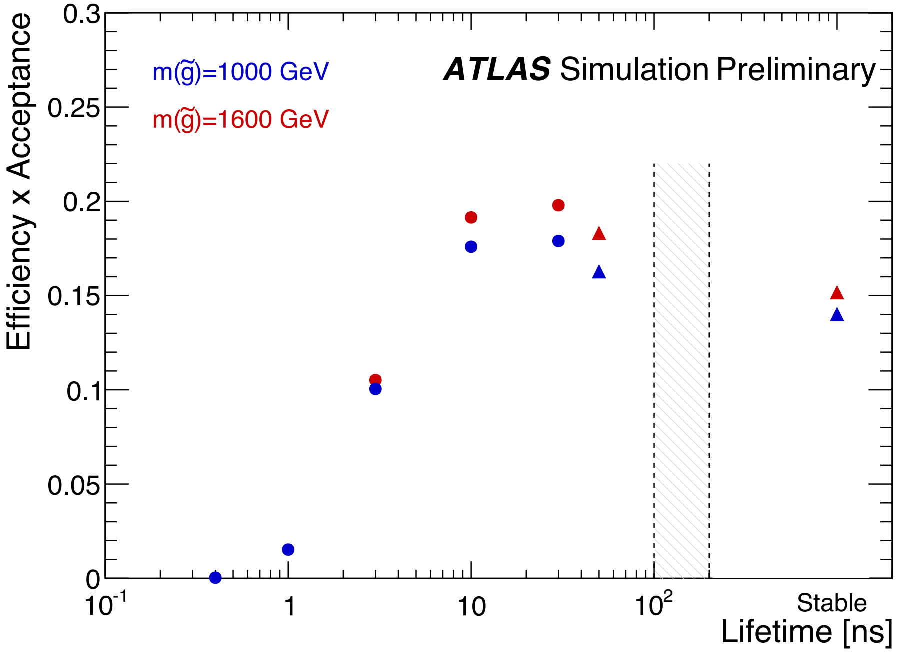
- Background PDFs constructed from control regions in data
  - sidebands of track momentum and β(βγ) region used in several η bins
- Random sampling from background PDFs
- Mass constructed from sampled p and β(βγ) values
- Normalized in events that are below $M_{\beta(\beta\gamma)}$ requirement for signal



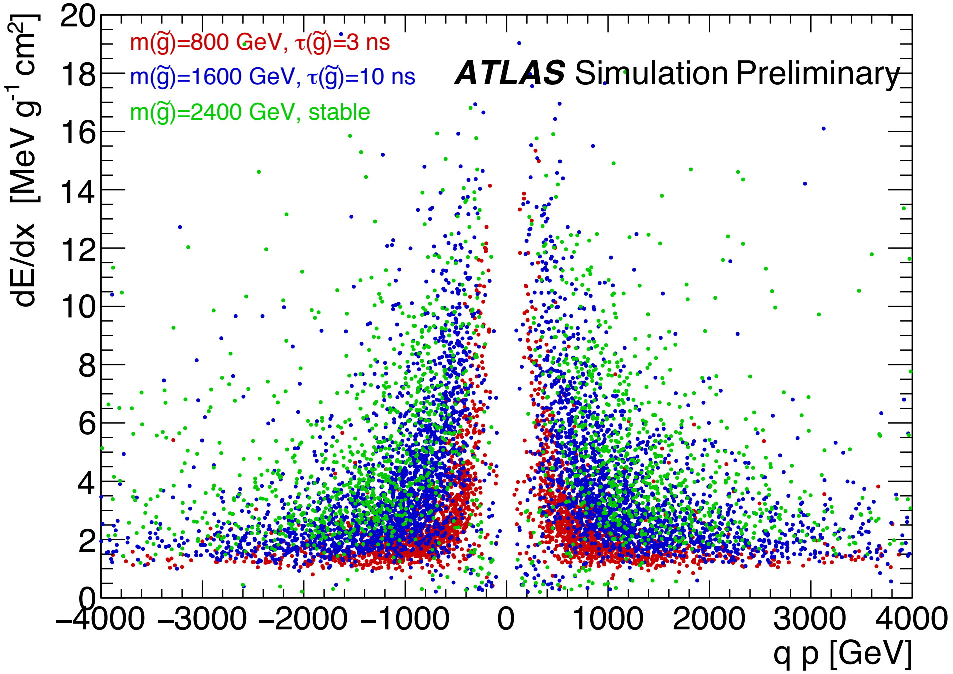
# R-hadron signal

- meta-stable R-hadron search

Efficiency x Acceptance




Signal dE/dx v. qp



# Event selection

- Meta-stable analysis, shown for 1600 GeV R-hadron with lifetime of 10 ns

| Selection level | Expected signal events | Observed events in 3.2 $fb^{-1}$ |
|---|---|---|
| Generated | $26.0 \pm 0.3$ | |
| $E_T^{miss}$ trigger & preselection | $24.8 \pm 0.3$ (95%) | |
| $E_T^{miss} > 130$ GeV | $23.9 \pm 0.3$ (92%) | |
| Track $p_T > 50$ and cluster requirements | $10.7 \pm 0.2$ (41%) | 368324 |
| Isolation requirement | $9.0 \pm 0.2$ (35%) | 108079 |
| Track $p > 150$ GeV | $6.6 \pm 0.2$ (25%) | 47463 |
| $m_T > 130$ GeV | $5.8 \pm 0.2$ (22%) | 18746 |
| Electron & hadron veto | $5.5 \pm 0.2$ (21%) | 3612 |
| Muon veto | $5.5 \pm 0.2$ (21%) | 1668 |
| Ionization requirement | $5.0 \pm 0.1$ (19%) | 11 |

# Event selection

- Stable gluino R-hadron search

| | data | 800 GeV | | 1400 GeV | | 1600 GeV | | 1800 GeV | |
|---|---|---|---|---|---|---|---|---|---|
| | observed | expected | eff. | expected | eff. | expected | eff. | expected | eff. |
| initial | | 4781.48 | | 81.19 | | 25.96 | | 8.86 | |
| trigger | 35931856 | 2037.58 | 0.43 | 37.05 | 0.46 | 11.36 | 0.44 | 3.54 | 0.40 |
| event-quality | 34055804 | 2037.58 | 0.43 | 37.05 | 0.46 | 11.36 | 0.44 | 3.54 | 0.40 |
| $N_{\mathrm{trk}}^{\mathrm{PV}} > 1$ | 34048524 | 2037.58 | 0.43 | 37.05 | 0.46 | 11.36 | 0.44 | 3.54 | 0.40 |
| $p_{\mathrm{T}} > 50$ GeV | 10185277 | 1404.41 | 0.29 | 26.51 | 0.33 | 8.01 | 0.31 | 2.60 | 0.29 |
| $0 < p < 6.5$ TeV | 10165453 | 1404.05 | 0.29 | 26.28 | 0.32 | 7.89 | 0.30 | 2.55 | 0.29 |
| $\Delta R_{\mathrm{jet},p_{\mathrm{T}}>50\ \mathrm{GeV}} > 0.3$ | 1218562 | 1049.18 | 0.22 | 20.93 | 0.26 | 6.42 | 0.25 | 2.02 | 0.23 |
| $\Delta R_{\mathrm{track},p_{\mathrm{T}}>10\ \mathrm{GeV}} > 0.2$ | 938051 | 1049.18 | 0.22 | 20.93 | 0.26 | 6.42 | 0.25 | 2.02 | 0.23 |
| $N_{\mathrm{hits}}^{\mathrm{silicon}} >= 7$ | 905670 | 1049.18 | 0.22 | 20.93 | 0.26 | 6.42 | 0.25 | 2.01 | 0.23 |
| $\|d_0\| < 2.0$ mm | 787592 | 1047.96 | 0.22 | 20.90 | 0.26 | 6.42 | 0.25 | 1.99 | 0.22 |
| $\|z_0^{\mathrm{PV}} \sin(\theta)\| < 0.5$ mm | 720747 | 1044.40 | 0.22 | 20.90 | 0.26 | 6.42 | 0.25 | 1.98 | 0.22 |
| $\|\eta\| < 1.65$ | 532568 | 884.31 | 0.18 | 18.08 | 0.22 | 5.62 | 0.22 | 1.77 | 0.20 |
| cosmic-muons veto | 532521 | 884.31 | 0.18 | 18.08 | 0.22 | 5.62 | 0.22 | 1.77 | 0.20 |
| $Z$ veto | 485366 | 868.18 | 0.18 | 17.64 | 0.22 | 5.38 | 0.21 | 1.67 | 0.19 |
| $N_{\mathrm{pixel}}^{\mathrm{shared+split\ hits}} = 0$ | 472548 | 868.00 | 0.18 | 17.55 | 0.22 | 5.36 | 0.21 | 1.65 | 0.19 |
| $N_{\mathrm{d}E/\mathrm{d}x}^{\mathrm{used\ hits}} > 1$ | 445853 | 779.90 | 0.16 | 15.76 | 0.19 | 4.59 | 0.18 | 1.43 | 0.16 |
| $0.0 < \mathrm{d}E/\mathrm{d}x < 20.0$ | 445853 | 779.90 | 0.16 | 15.76 | 0.19 | 4.59 | 0.18 | 1.43 | 0.16 |
| $0.204 < \beta\gamma < 10.0$ | 304271 | 769.00 | 0.16 | 15.47 | 0.19 | 4.50 | 0.17 | 1.39 | 0.16 |
| $0.2 < \beta_{\mathrm{calo}} < 2.0$ | 271827 | 672.10 | 0.14 | 13.40 | 0.17 | 4.05 | 0.16 | 1.13 | 0.13 |
| $\sigma_\beta < 0.12$ | 226107 | 667.84 | 0.14 | 13.40 | 0.17 | 4.05 | 0.16 | 1.13 | 0.13 |

# Systematics on signal

stable search

| Source | Relative uncertainty [±%] |
|---|---|
| Theoretical uncertainty on signal | 14–57 |
| Uncertainty on signal efficiency | 20–16 |
| ˪ Trigger efficiency | 2 |
| ˪ QCD uncertainty (ISR, FSR) | 14 |
| ˪ Pile-up | 7–1 |
| ˪ Pixel $\beta\gamma$ measurement | 1–3 |
| ˪ Calorimeter $\beta$ measurement | 10–2 |
| Luminosity | 5 |
| Uncertainties on background estimate | 30–43 |

meta-stable search

| Source of uncertainty | −[%] | +[%] |
|---|---|---|
| ISR modeling ($R$-hadron stable) | 14 | 14 |
| ISR modeling ($R$-hadron metastable) | 1.5 | 1.5 |
| Trigger turn-on | 0.9 | 0.9 |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ scale | 1.1 | 2.2 |
| Pileup | 1.1 | 1.1 |
| Ionization parameterization | 7.1 | 0 |
| Momentum parameterization | 0.3 | 0.3 |
| $\mu$ identification (metastable only) | 3.2 | 3.2 |
| Total systematic uncertainty in acceptance × efficiency | | |
| Stable $R$-hadron | 16 | 14 |
| Metastable $R$-hadron | 9 | 5 |
| Luminosity | 5 | 5 |
| Signal cross section | 28 | 28 |