# Stable Massive Particle Searches with the ATLAS Detector

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**LPCC workshop on BSM LHC physics**

**CERN**

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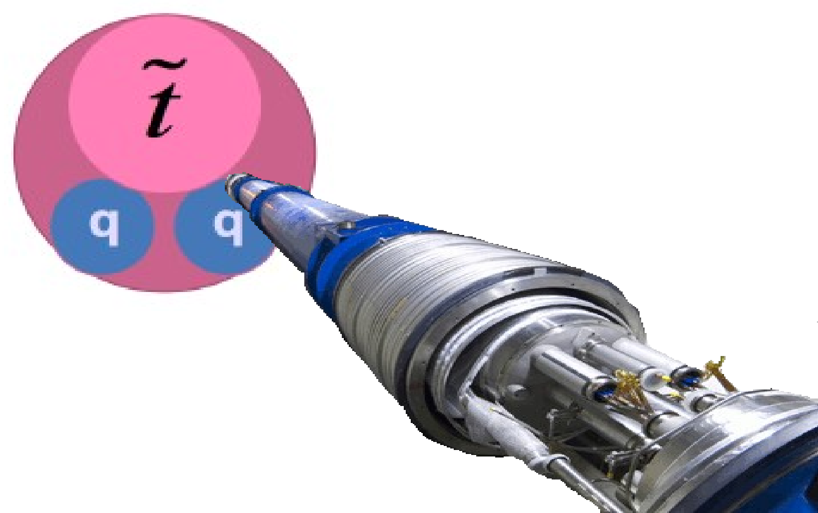


# Searches for Stable Massive Particles

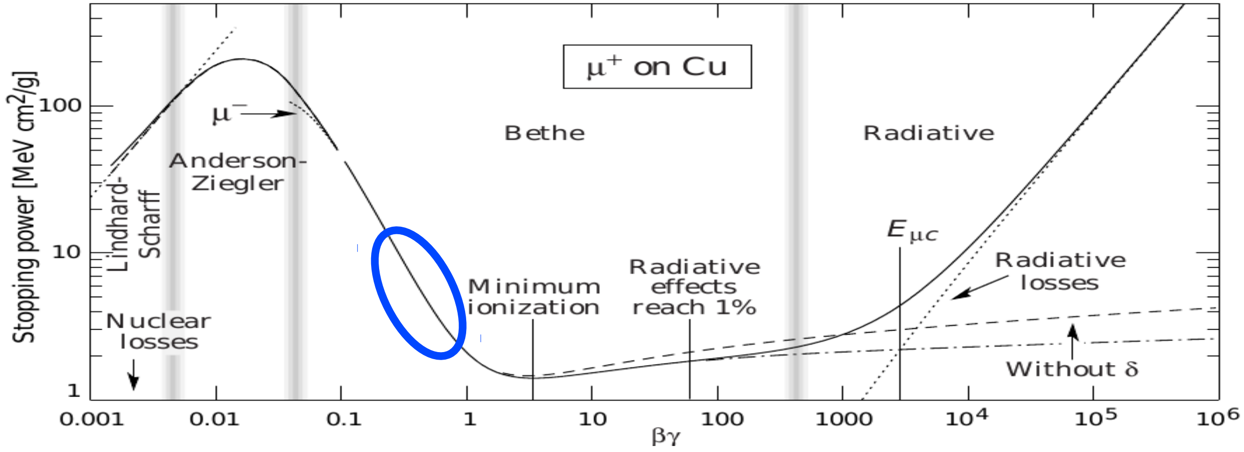
- Fine tuning problem
  - New TeV-scale physics
  - Type of "new physics" unknown
- Promising observables at LHC experiments:
  - Leptons
  - Jets
  - Missing energy
  - Long-lived particles with unknown quantum numbers

➔ High-electric/magnetic charge (HIPs)

➔ Color charge (giving rise to R-hadrons)

# A few comments about "highly ionising"

- R-hadrons ionise more than muons due to low speed
  - Up to 10 MIPs (β down to 0.4)
  - Generally penetrating through whole detector
- Monopoles/high-charges are very highly ionizing due to low speed *and* high charge ($dE/dx \propto q^2$)
  - ≫ 10 MIPs → highly ionising particle (HIP)
  - Generally stopping in detector
  - Specific detector effects e.g. saturation, anomalous bending, delta electrons, electron recombination...




PDG

# ArXiv:1102.0459 (accepted for publication in Phys. Lett. B)

3.1 $pb^{-1}$

*pp* @ 7 TeV

CERN-PH-EP-2011-010

## Search for Massive Long-lived Highly Ionising Particles with the ATLAS Detector at the LHC

The ATLAS Collaboration[1]



**Abstract**

A search is made for massive long-lived highly ionising particles with the ATLAS experiment at the Large Hadron Collider, using 3.1 $pb^{-1}$ of $pp$ collision data taken at $\sqrt{s}$ = 7 TeV. The signature of energy loss in the ATLAS inner detector and electromagnetic calorimeter is used. No such particles are found and limits on the production cross section for electric charges $6e \leq |q| \leq 17e$ and masses 200 GeV $\leq m \leq$ 1000 GeV are set in the range $1 - 12$ pb for different hypotheses on the production mechanism.

*Keywords:* high-energy collider experiment, long-lived particle, highly ionizing, new physics

### 1. Introduction

The observation of a massive long-lived highly ionising particle (HIP) possessing a large electric charge $|q| \gg e$, where $e$ is the elementary charge, would represent striking evidence for physics beyond the Standard Model. Examples of putative particles which can give rise to HIP signatures include $Q$-balls [1], stable micro black-hole remnants [2], magnetic monopoles [3] and dyons [4]. Searches for HIPs are made in cosmic rays [5] and at colliders [3]; recent collider searches were performed at LEP [6–8] and the Tevatron [9–12]. Cross sections and event topologies associated with HIP production cannot be reliably predicted due to the fact that the coupling between a HIP and the photon is so strong that perturbative calculations are not possible. Therefore, search results at colliders are usually quoted as cross section limits in a range of charge and mass for given kinematics [3]. Also, for the same reason, limits obtained at different collision energies or for different types of collisions cannot be directly compared; rather, they are complementary.

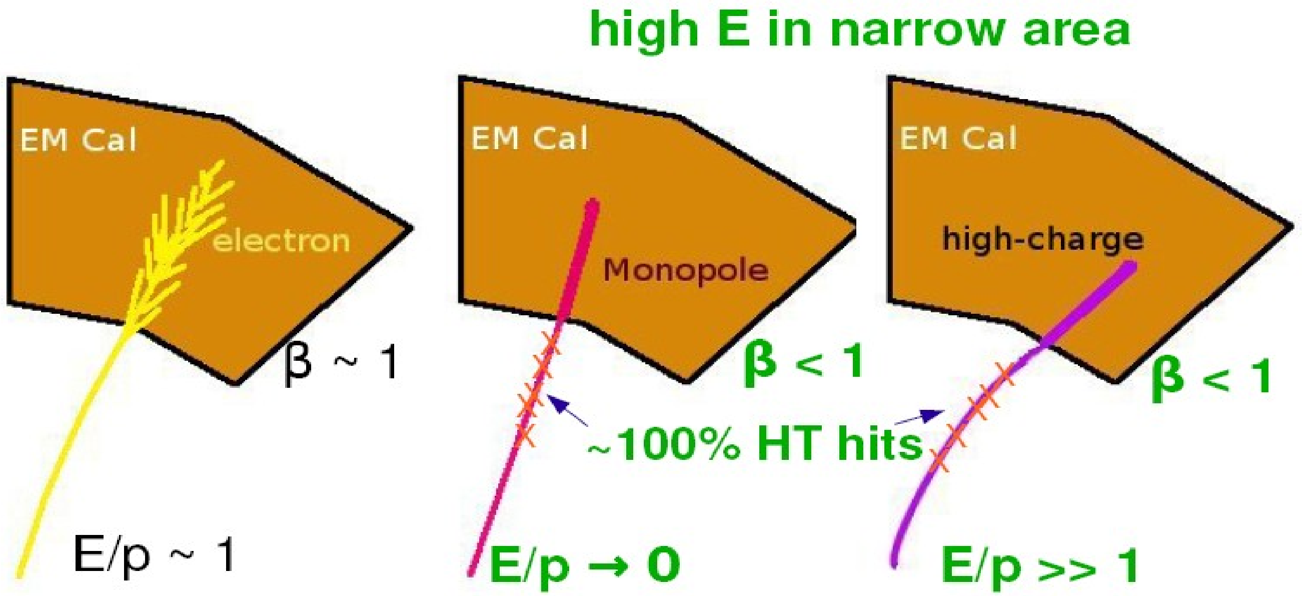
HIP searches are part of a program of searches at the CERN Large Hadron Collider (LHC) which explore the multi-TeV energy regime. Further motivation is provided by the gauge hierarchy problem, to which proposed solutions typically postulate the existence of hitherto unobserved particles with TeV-scale masses. HIPs at the LHC can be sought at the dedicated MoEDAL plastic-track experiment [13] or, as in this work, via their active detection at a multipurpose detector.

the electromagnetic calorimeter, giving rise to an electron-like signature. The presence of a HIP can be inferred from measurements of the proportion of high-ionisation hits in the inner detector. In addition, the lateral extent of the energy deposition in the calorimeter is a sensitive discriminant between HIPs and Standard Model particles.

The ranges of HIP charge, mass and lifetime for which unambiguous conclusions can be drawn are determined by the chosen trigger and event selections. The choice of an electromagnetic trigger limits the phase space to HIPs which stop in the electromagnetic calorimeter of ATLAS. The search is optimised for data collected at relatively low instantaneous luminosities (up to $10^{31}$ $cm^{-2}s^{-1}$), for which a low (10 GeV) trigger transverse energy threshold is available. In the barrel region of the calorimeter, this gives access to energy depositions corresponding to HIPs with electric charges down to $6e$. Standard electron reconstruction algorithms are used, which implies that tracks which bend like electrically charged particles are sought. Particles with magnetic charge, or electric charge above $17e$, are not addressed here due to the bending along the beam axis in the case of a monopole, and due to effects from delta electrons and electron recombination in the active detector at the corresponding values of energy loss ($dE/dx > 2 \cdot 10^3$ MeV/cm). For such types of HIPs, more detailed studies are needed to assess

# Highly Ionising Particles (HIPs)

- Monopoles, Qballs, black holes with $|q| \gg e$, etc.
  - We present a model-independent search
- Non-perturbative dynamics → no reliable model predictions for kinematics and cross sections
- High ionization energy loss in a detector
  - Possible signature in ATLAS:



# HIP parameter space: current limitations

**|q| ≥ 6e** bound determined by $E_T$ > 10 GeV trigger threshold

- electron trigger → **HIP must stop in EM Cal**

**|q| ≤ 17e** bound determined by delta electrons and electron recombination

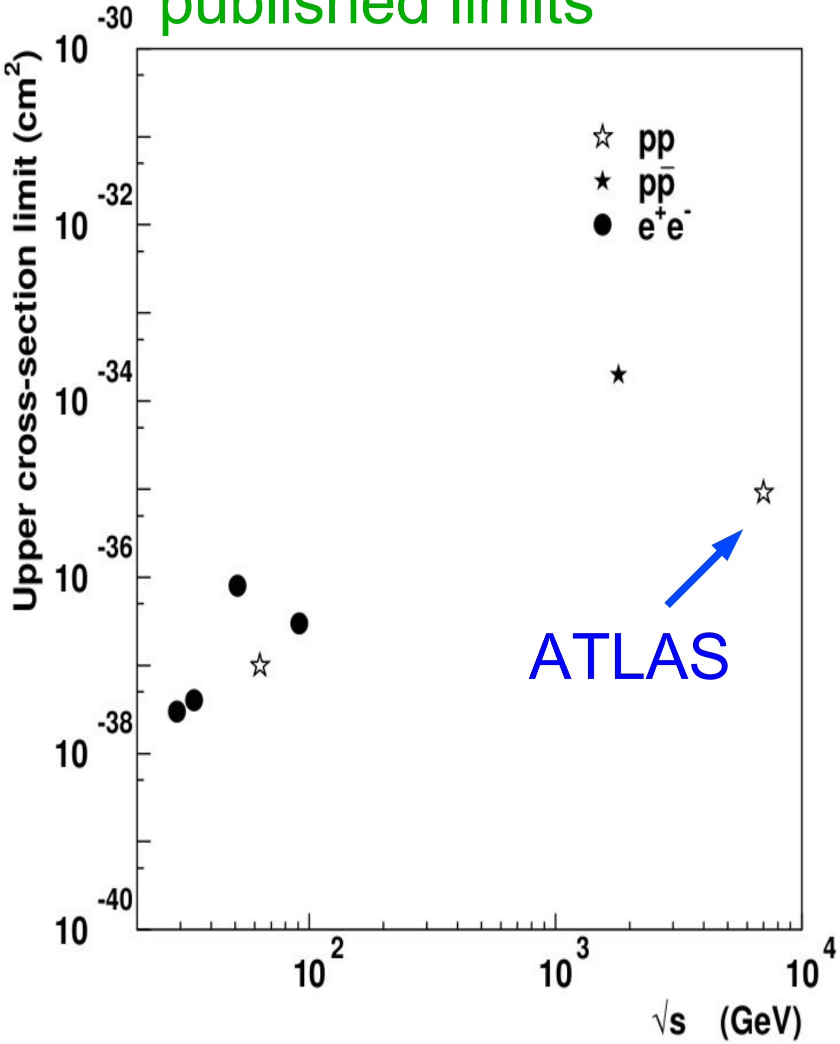
- **no interpretation yet for monopoles** for same reasons + bending

**mass ≤ 1000 GeV** (β ≥ 0.4) bound determined by L1 trigger timing constraints

**lifetime ≥ 100 ns** to maintain narrow energy deposit

**Highly-charged particles**

published limits

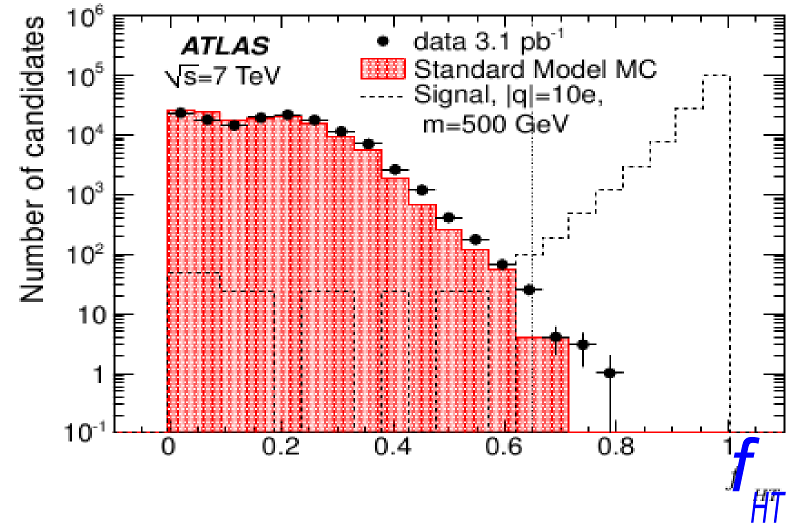


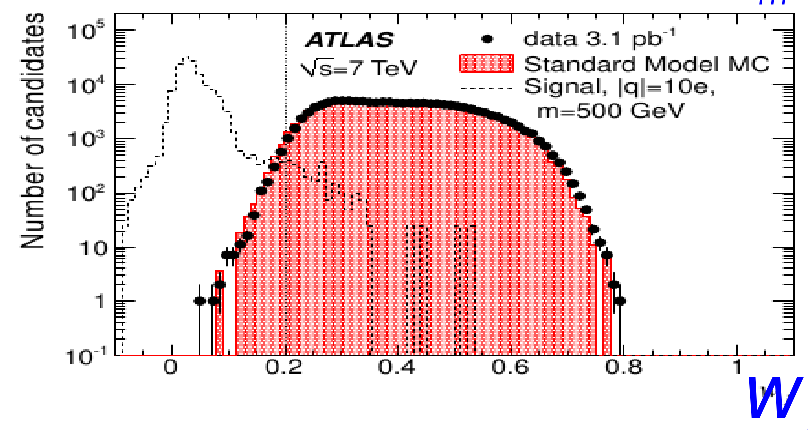
# HIP selection variables

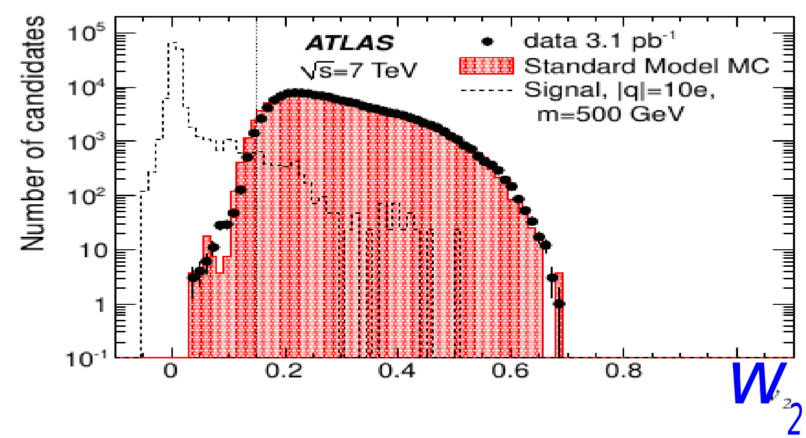
(applied to electron candidates with $|\eta| < 1.35$, $E_T > 15$ GeV)

$f_{HT}$ – fraction of TRT hits on the track which pass high threshold

$w_1, w_2$ – fraction of cluster energy outside three most energetic cells in first and second layers of EM calorimeter

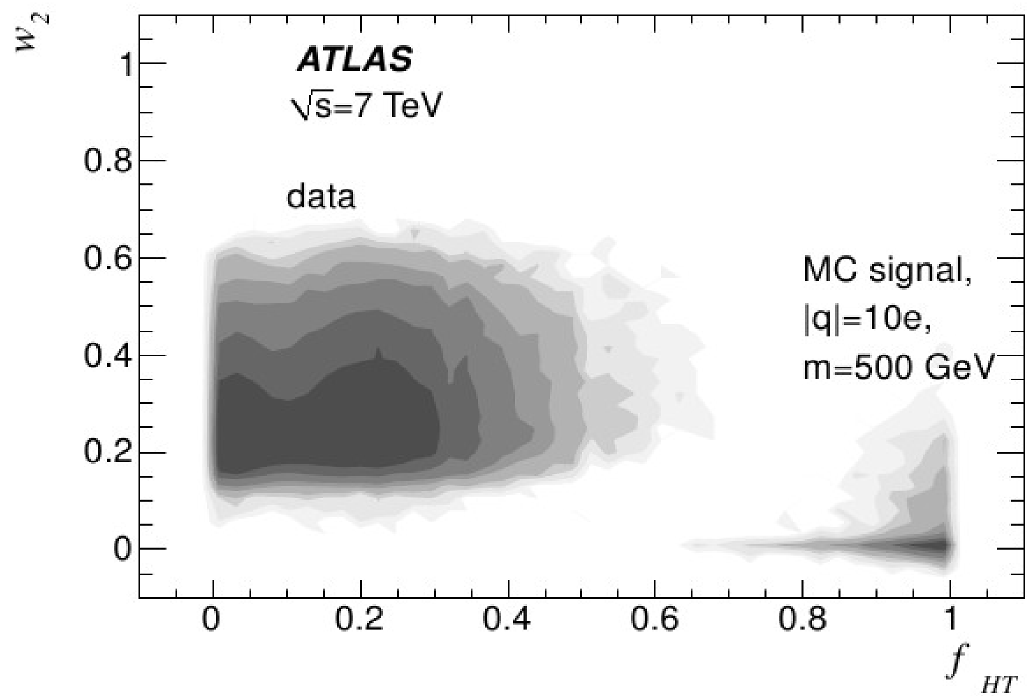


# Data-driven background estimation

- **ABCD method**: exploits approximate lack of correlation between $f_{HT}$ and $(w_1, w_2)$

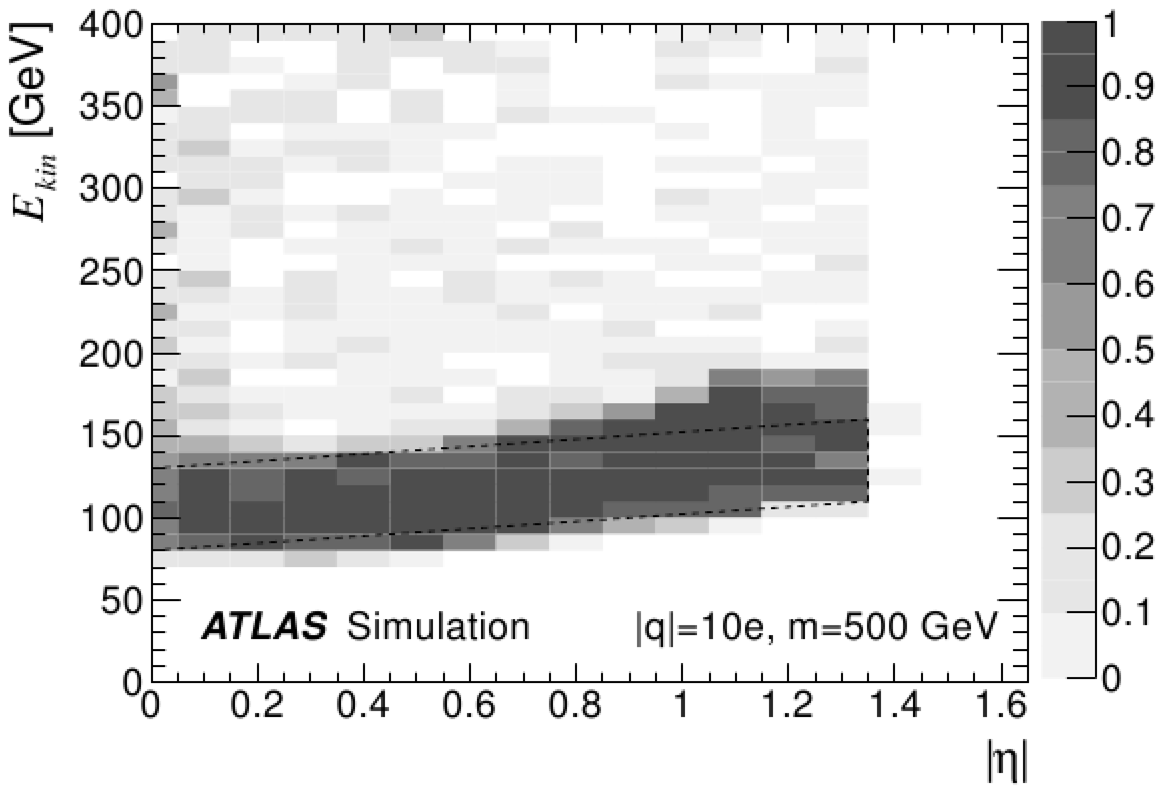



- Estimated background after selection: 0.019 ± 0.005 events
- Number of events in data: 0
  - Data match Standard Model Monte Carlo

# HIP efficiencies

Major source of inefficiency comes from acceptance (probability to stop in second layer of EM barrel)

– Depends on model of kinematics




In specific kinematic ranges, signal selection efficiency estimated from MC is flat, around 80%

→ Model-independent approach

# HIP cross section upper limits

- Bayesian cross section limits including systematic uncertainties in efficiency and integrated luminosity
- Limits on HIPs in fiducial ranges of $(\eta, E_{kin})$ (pb, 95% c.l.)

| $m$ [GeV] | $\|q\| = 6e$ | $\|q\| = 10e$ | $\|q\| = 17e$ |
|---|---|---|---|
| 200 | 1.4 | 1.2 | 2.1 |
| 500 | 1.2 | 1.2 | 1.6 |
| 1000 | 2.2 | 1.2 | 1.5 |

- Limits for Drell-Yan fermion pair production (pb, 95% c.l.)

| $m$ [GeV] | $\|q\| = 6e$ | $\|q\| = 10e$ | $\|q\| = 17e$ |
|---|---|---|---|
| 200 | 11.5 | 5.9 | 9.1 |
| 500 | 7.2 | 4.3 | 5.3 |
| 1000 | 9.3 | 3.4 | 4.3 |

# arXiv:1103.1984 (submitted to Phys. Lett. B)

34 $pb^{-1}$

*pp* @ 7 TeV

Search for stable hadronising squarks and gluinos with the ATLAS experiment at the LHC

CERN-PH-EP-2011-026

The ATLAS Collaboration



**Abstract**

Hitherto unobserved long-lived massive particles with electric and/or colour charge are predicted by a range of theories which extend the Standard Model. In this paper a search is performed at the ATLAS experiment for slow-moving charged particles produced in proton-proton collisions at 7 TeV centre-of-mass energy at the LHC, using a data-set corresponding to an integrated luminosity of 34 $pb^{-1}$. No deviations from Standard Model expectations are found. This result is interpreted in a framework of supersymmetry models in which coloured sparticles can hadronise into long-lived bound hadronic states, termed $R$-hadrons, and 95% CL limits are set on the production cross-sections of squarks and gluinos. The influence of $R$-hadron interactions in matter was studied using a number of different models, and lower mass limits for stable sbottoms and stops are found to be 294 and 309 GeV respectively. The lower mass limit for a stable gluino lies in the range from 562 to 586 GeV depending on the model assumed. Each of these constraints is the most stringent to date.

*Keywords:* Supersymmetry, Long-lived particle, R-hadron, Limit

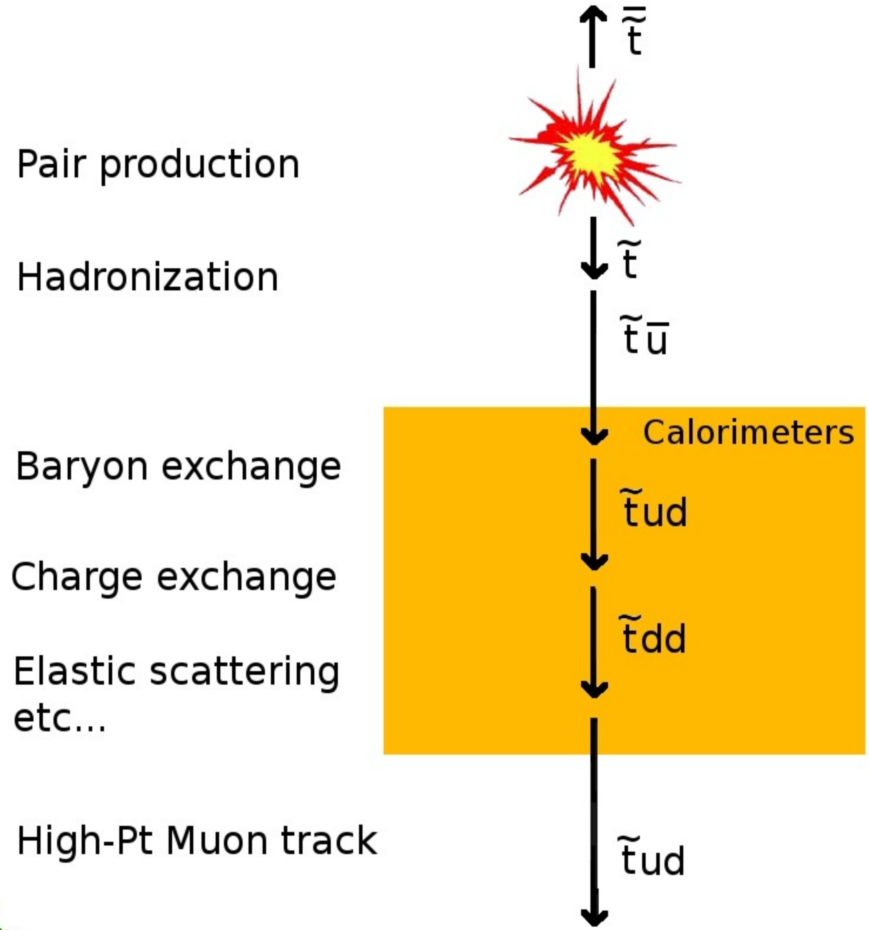
## 1. Introduction

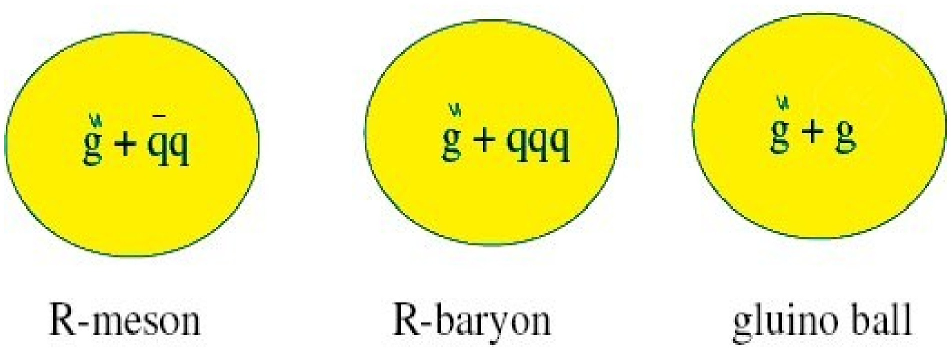
The discovery of exotic stable massive particles (SMPs)[1] at the LHC would be of fundamental significance. The motivation for SMP searches at ATLAS arises, for example, from proposed solutions to the gauge hierarchy problem, which involve previously unseen particles with TeV-scale masses [1, 2]. The ATLAS experiment has recently searched for SMPs with large electric charge [3]. SMPs possessing colour charge represent another class of exotic particle which can be sought. Hadronising SMPs are anticipated in a wide range of exotic physics models [1] that extend the Standard Model (SM). For example, these particles appear in both $R$-parity conserving supersymmetry (SUSY) and universal extra dimensions. The possibility of direct pair production through the strong nuclear force implies large production cross-sections. Searches for these particles are thus an important component of the early data exploitation programs of the LHC experiments [4]. In this paper, the first limits from the ATLAS experiment are presented on the production of coloured, hadronising SMPs in proton-proton collisions at 7 TeV centre-of-mass energy at the LHC. Results are presented in the context of SUSY models predicting the existence of $R$-hadrons [5], which are heavy objects formed from a coloured sparticle (squark or gluino) and light SM partons.

# R-hadrons

New particle properties:

- Colored
  (high cross sections at hadron colliders, hadronising)
- *Long-lived* > 50 ns
  (size of detector)
- **Heavy** > 100 GeV

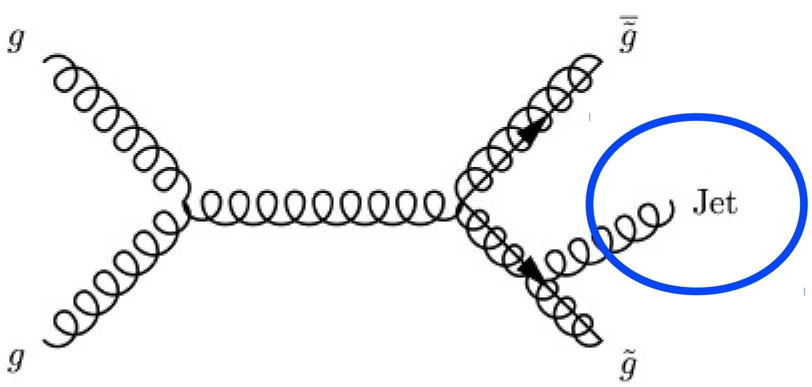



Generic signature:
slow and high momentum

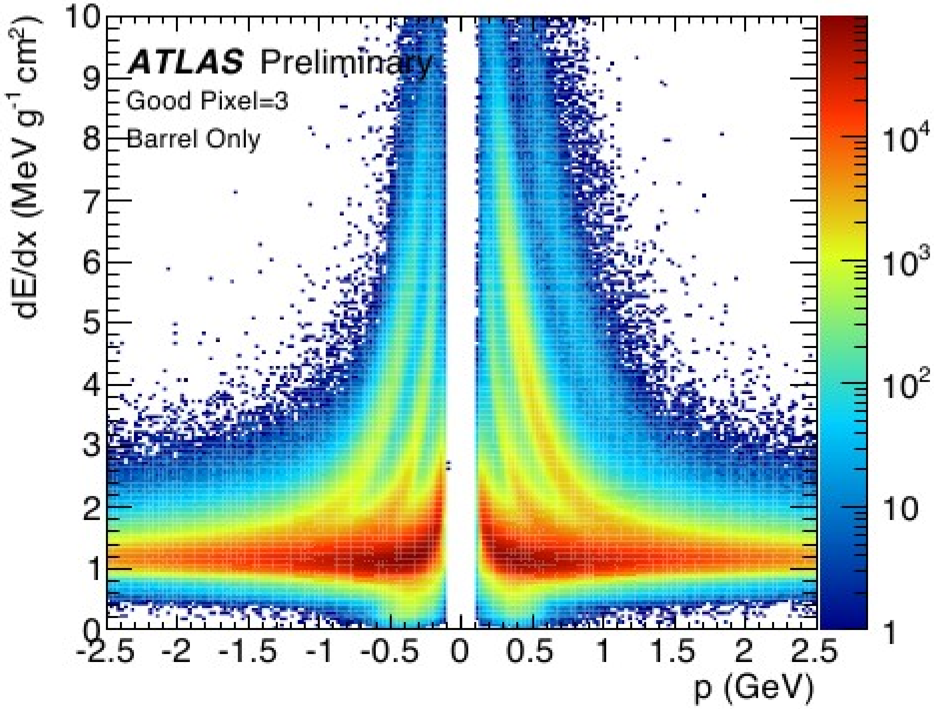
# R-hadron search strategy

- Target: generic R-hadrons comprising a stable *g*-like, *t*-like or *b*-like heavy parton
  - *b*-like (perhaps also g-like) lowest baryonic state likely neutral → cannot rely on muon system
  - Motivates "muon-agnostic" approach (use "calomuons")
- Preselection:
  - $E_T^{miss} > 40$ GeV for triggering
  - ID track with $p_T > 50$ GeV
- Three complementary observables:
  - Pixel detector dE/dx
  - Tile calorimeter β
  - TRT dE/dx as a cross-check



# R-hadrons: pixel dE/dx

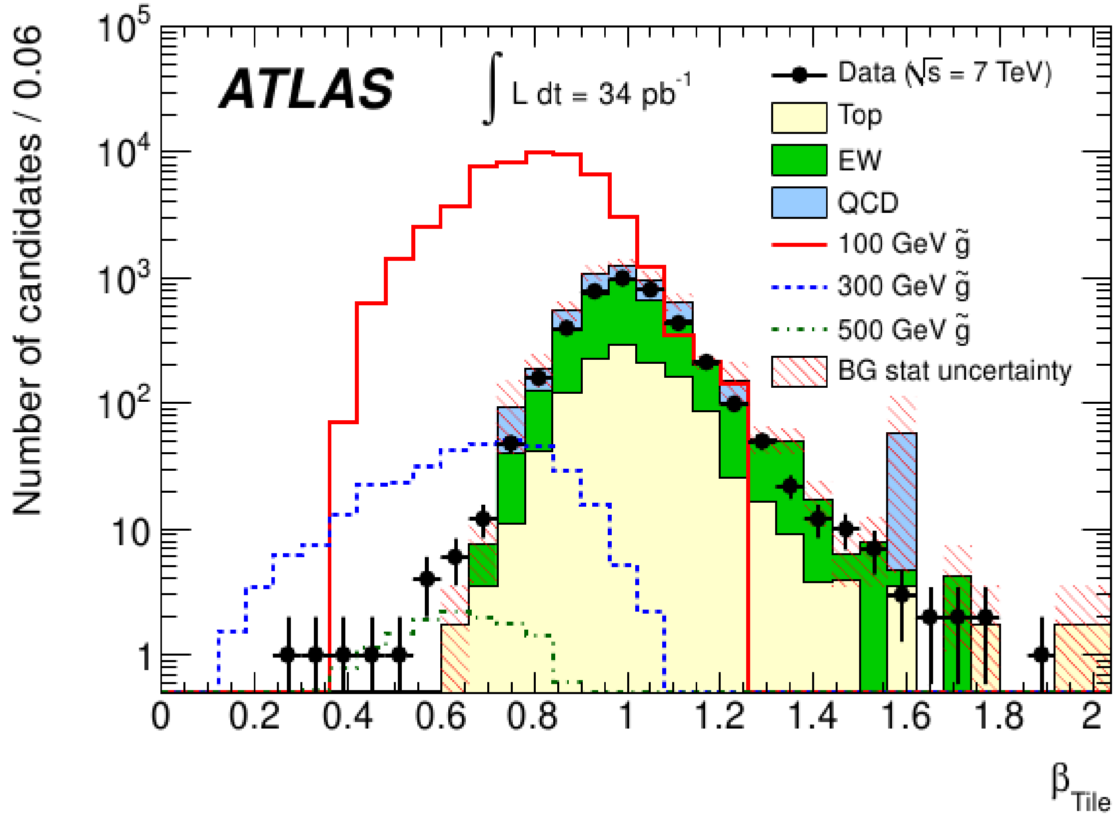
- Plot shows dE/dx vs. measured momentum in low-momentum region ⇒ can separate deuteron, p, K and π!
- Analog read-out provides accurate time-over-threshold → deposited energy
- Mass estimator available when dE/dx value is outside MIP band



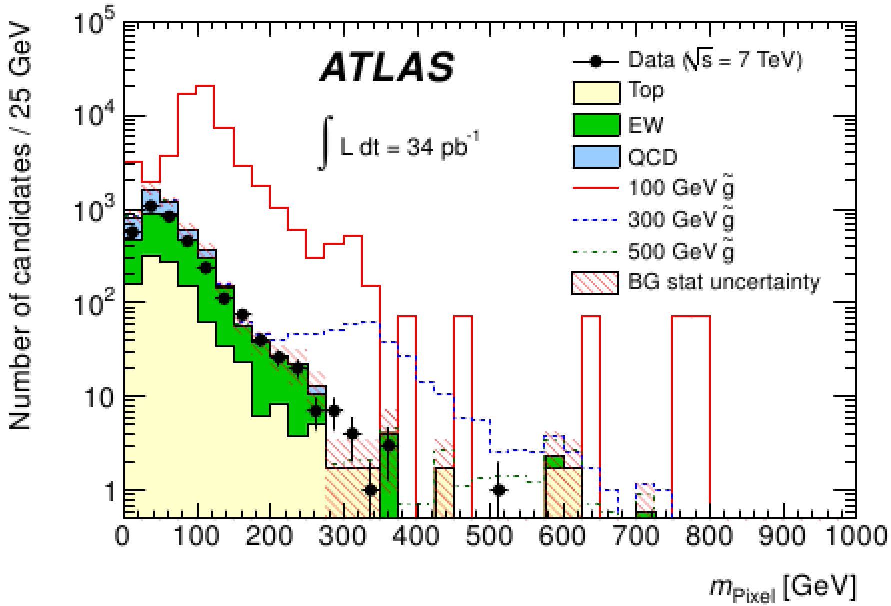
# R-hadrons: βTile

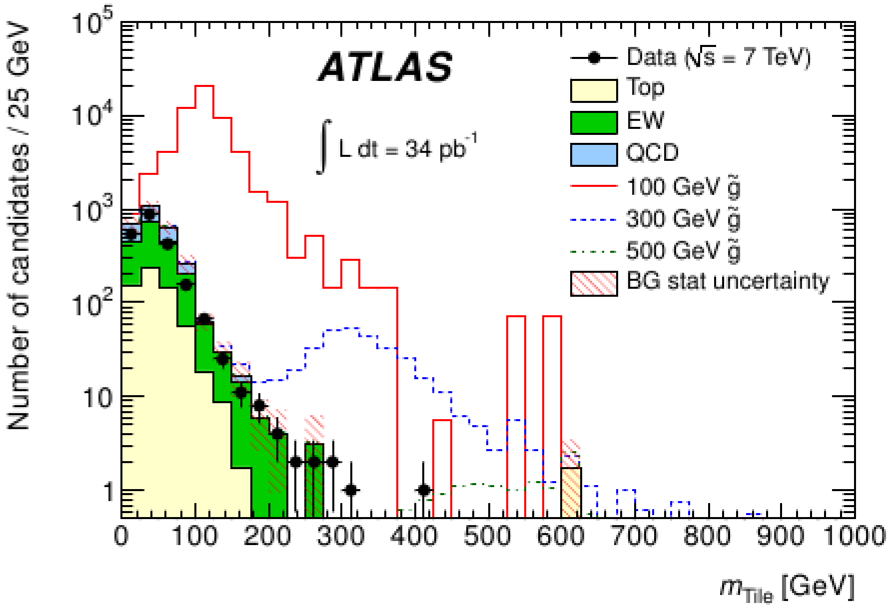
- Particle speed measured from time-of-flight
  - Each cell gives a β measurement

- Resolution of 1 ns achieved by combining cells along trajectory
- Calibrated with muons from *Z* decays
- Mass estimator: $m = p/(\beta\gamma)$

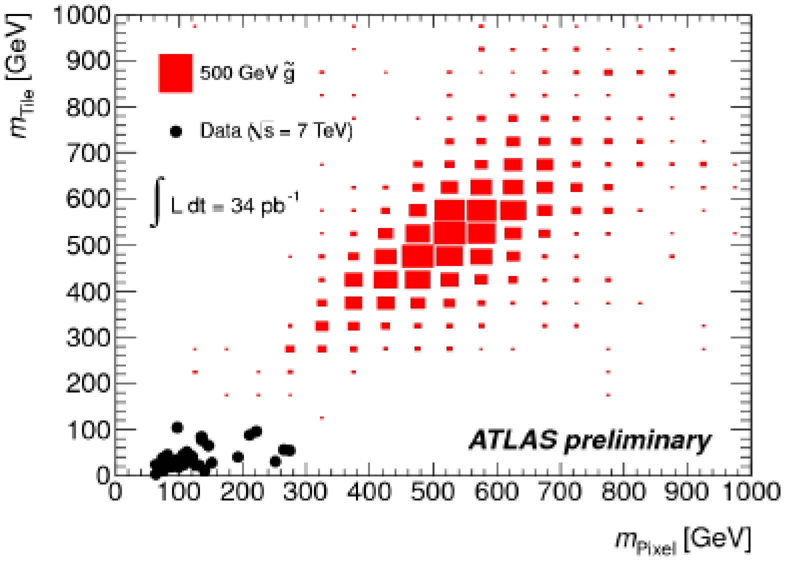


# Two independent R-hadron mass estimators



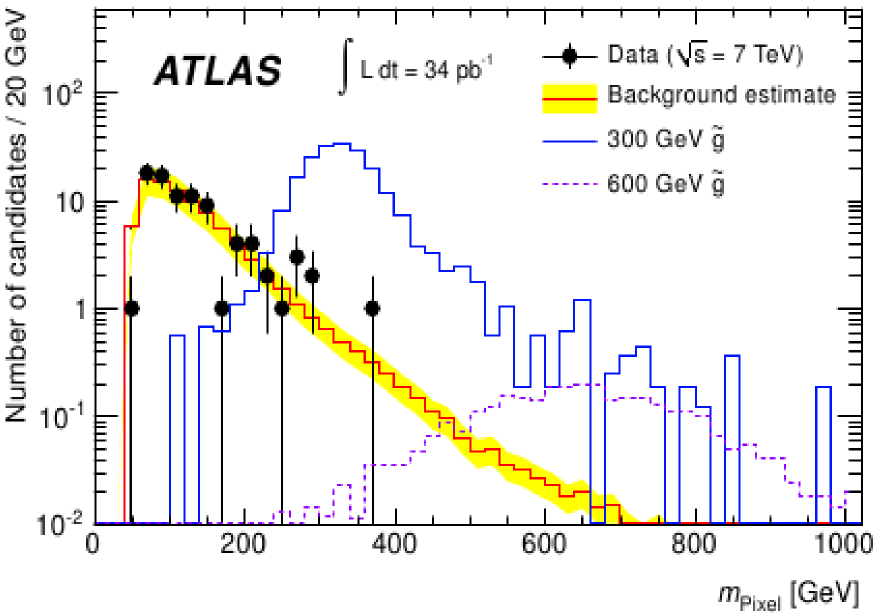



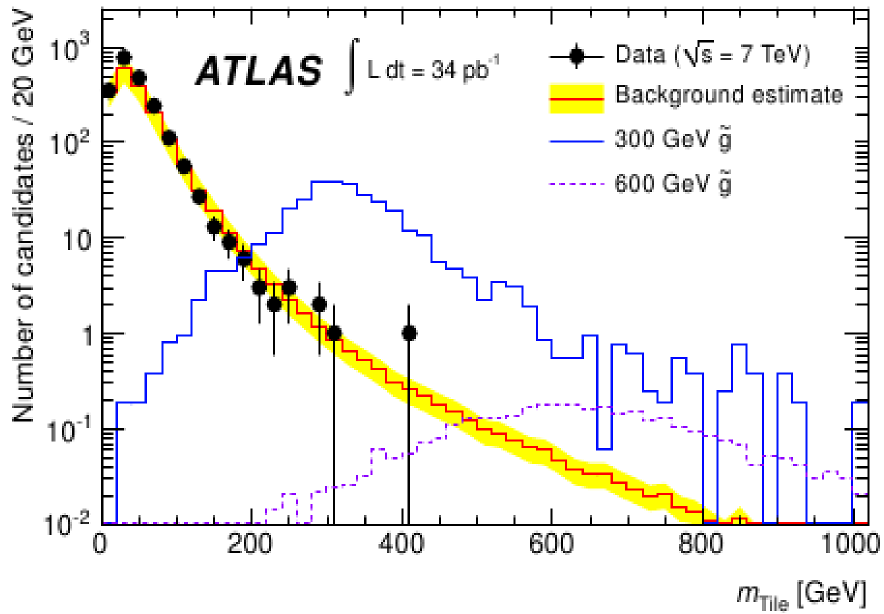

- Data are consistent with SM expectation
- Correlation in mass variables for signal is an effect of using the same momentum measurement



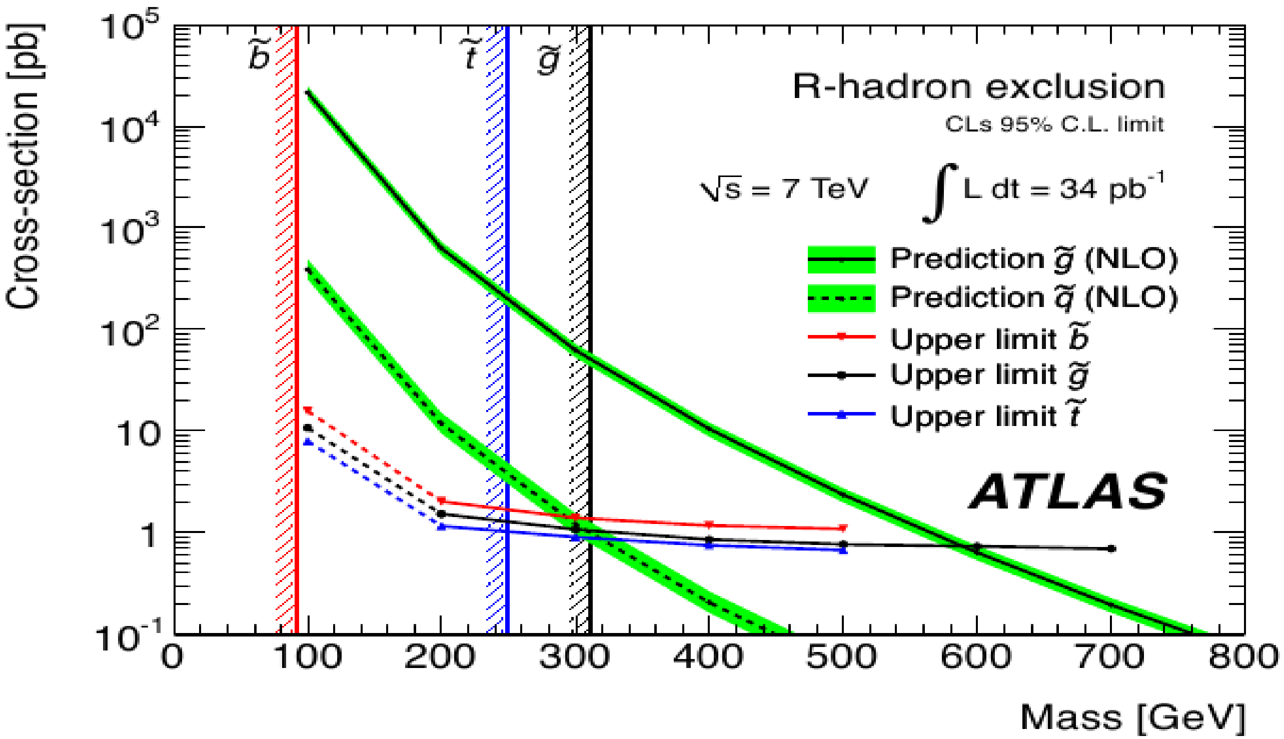
# Data-driven background estimation

- Relies on approximate lack of correlation between momentum, pixel dE/dx and βTile in background
  - Build up distributions from data for pixel dE/dx and βTile
- Generate candidates:
  - Draw random momentum
  - Pair with values from pixel dE/dx and βTile



# R-hadrons – Results




New strongest limits

– Interpreted here for stable gluino, stop and sbottom

**Exclude**

$m_{\tilde{g}} < 562 - 586\,\mathrm{GeV}$

$m_{\tilde{t}} < 309\,\mathrm{GeV}$

$m_{\tilde{b}} < 294\,\mathrm{GeV}$

# Summary and outlook – R-hadrons

- We presented a muon-agnostic search, relying on characteristic low speed of R-hadrons
  - Two independent mass estimates
- Most stringent mass limits to date for generic gluon-, top- and bottom-type R-hadrons
- Mature tools for time-of-flight and dE/dx measurements allow to extend the analysis with:
  - More data
  - Specific signatures (e.g. using muon system)
  - Lepton-like SMPs
  - Doubly-charged leptons and R-hadrons

# Summary and outlook – HIPs

- We presented a powerful event selection based on a striking highly-ionising signature
  - Model-independent approach: eliminate acceptance dependence
- First limits on HIPs at LHC energies
  - Cover electric charges 6e **≤ |q| ≤ 17e**
  - HIP masses above 800 GeV probed for the first time at a particle collider
- Monopoles are not covered yet at the LHC
  - ATLAS and CMS have the potential for initial searches
  - MoEDAL and ALICE, despite lower luminosity, have better sensitivity to e.g. lower β ranges
  - Search for monopoles trapped in beam pipe → access very high charges

# Extra slides

# Birks' correction

- Due to electron recombination effects, the energy deposited in LAr is not entirely recorded
- Visible energy fraction parametrized as a function of d*E*/d*x* with Birks' law:

$$\frac{E}{E_0} = \frac{A}{1 + dE/dx \cdot k/(E_D \cdot \rho)}$$

**Birks' parameter, depends on**

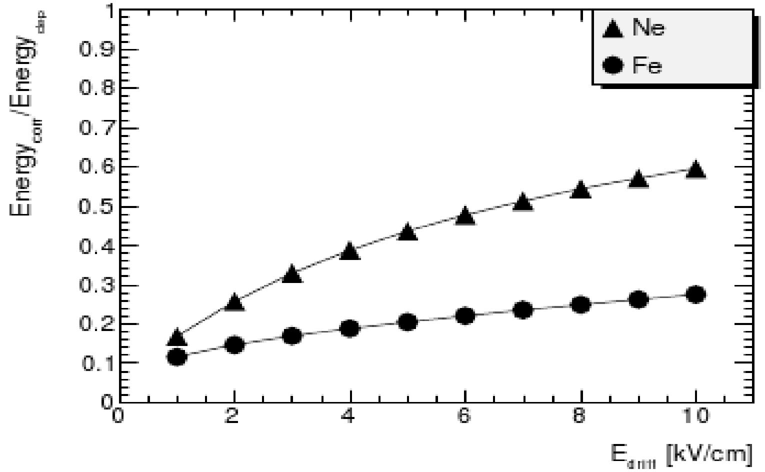
**the regime in d*E*/d*x***

- Description uncertain for large d*E*/d*x* regime
  - Large systematic uncertainty

# Birks' correction systematics

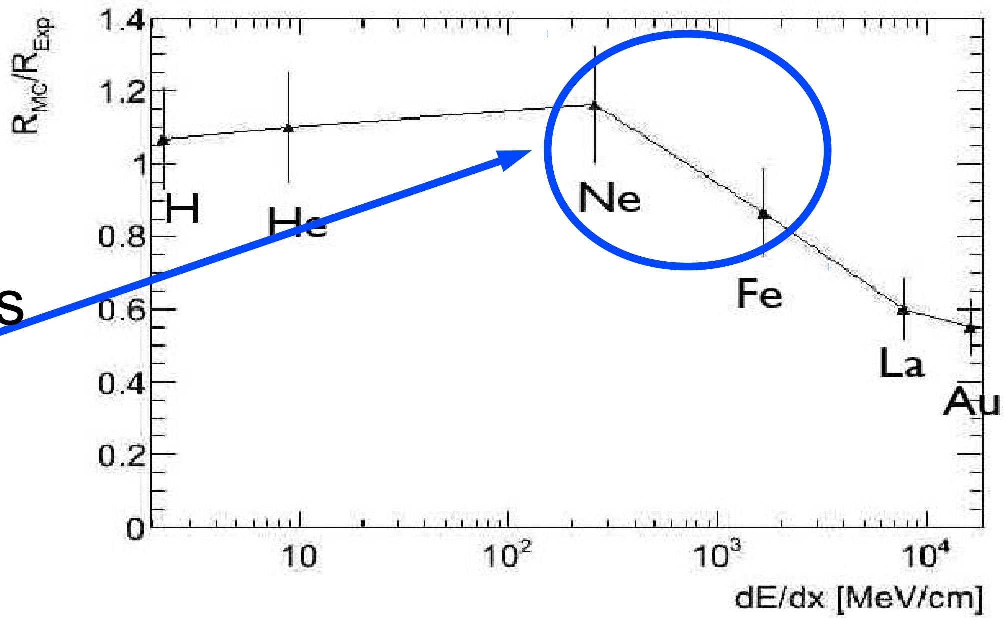
Birks parameter used in ATLAS LAr simulation fitted from muon/proton data

- Lower electric field
- Not expected to apply to the higher d*E*/d*x* regimes of HIPs




Simulation of punch-through ions in LAr compared to data

Signal of stopping HIPs lies in this region
→ fraction of visible energy is precise within +-15%



# HIP systematics – summary

- Signal efficiency:
  - Birks' correction 4–23%
  - Material budget 6%
  - Delta electron cut-off parameter 3%
  - PDF uncertainty 3%
  - Statistics, inactive detectors, cross-talk, timing all at 1–2% level

| $m$ [GeV] | $\|q\| = 6e$ | $\|q\| = 10e$ | $\|q\| = 17e$ |
|---|---|---|---|
| 200 | 25% | 11% | 9% |
| 500 | 17% | 10% | 9% |
| 1000 | 28% | 10% | 9% |

- Integrated luminosity 11%

# R-hadron systematics – summary

- Signal efficiency
  - Trigger: 7-13% MET scale uncertainty, 3-5% turn-on curve
  - Pile-up, ID momentum uncertainty, track reco, scale and resolution of pixel dE/dx and βTile all at 1% level
- Theoretical
  - ISR 10%
  - Renormalization scale 15%
  - PDF choice 5%
- Background estimate 30%
- Integrated luminosity 11%