Searches for long-lived particles at the LHC

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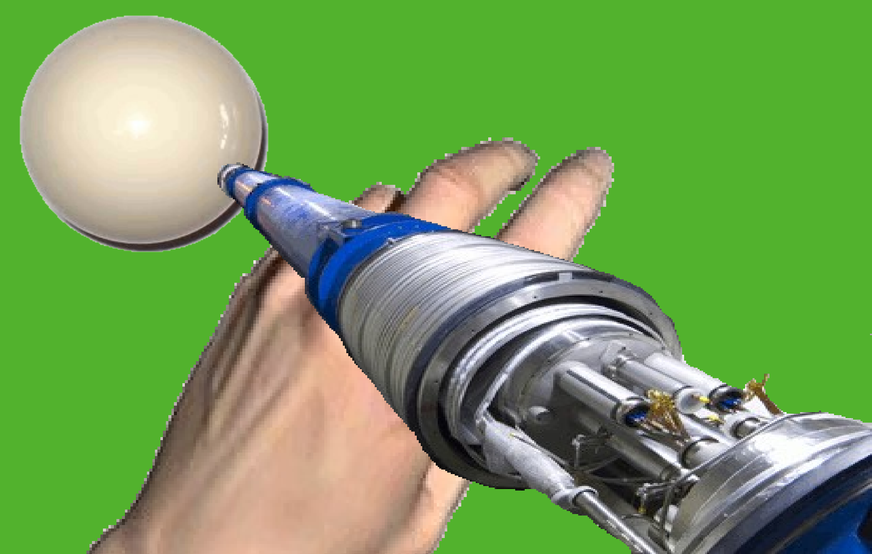


Long-lived particles

New physics can be expected at the TeV scale

- Type of ”new physics” unknown!

Reasons for long lifetimes (small couplings):

1) When the undelying dynamics are well described

- Constrained decay phase space
  - Examples: muon (W mass >> mass diff), neutron (idem)
  - Putative examples: split-SUSY gluino (squark mass), hidden photon (mediator mass)

2) When the underlying dynamics are unknown

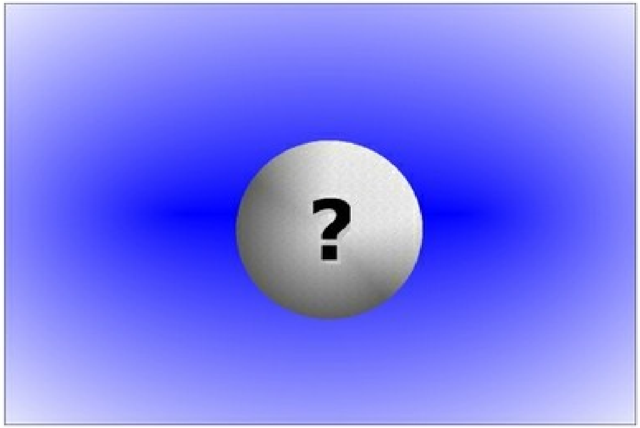
- Assume (approximatively) conserved quantum number
  - Examples: electron (electric charge), proton (baryon number), s quark (strangeness)
  - Putative examples: LSP (R-parity), monopole (magnetic charge)

Spin?

Couplings?

- Lifetime?
- Decay topologies?

Mass?



Colour charge?

(see next talks)

Electric and magnetic charges?

New interaction?

The LHC experiments should not miss a detectable signal! But: limited resources and limited imagination. Invest in which **signatures**? → **Generic (blue sky) vs. Specific (model-driven) dilemma**

Long-lived particle direct detection – what can we possibly do?

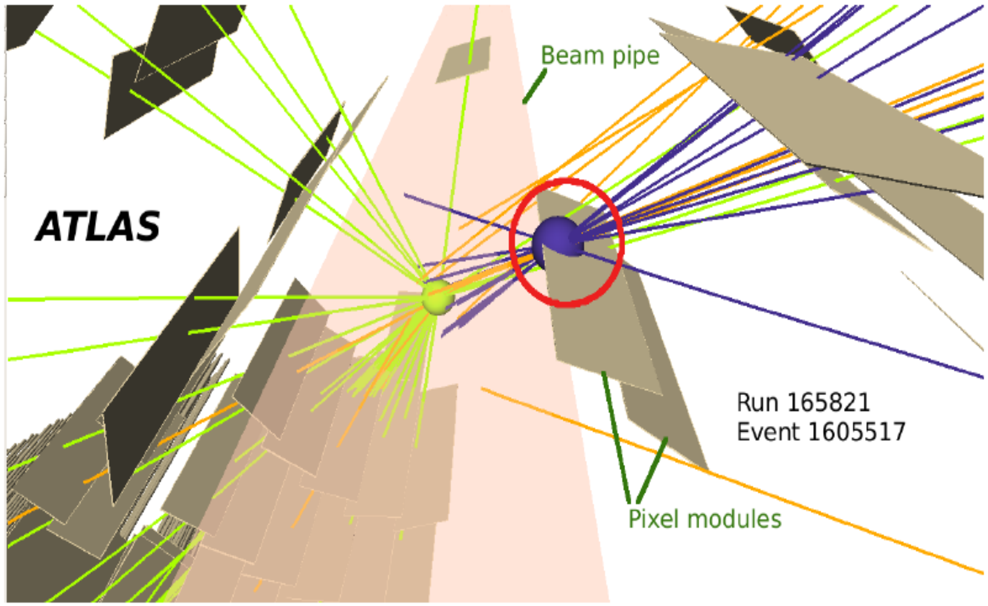
- Search for displaced decay vertices
- Search for out-of-time decays of particles which stopped in a detector
- Track stable charged particles through a detector
- Remove detector parts and look for trapped stable particles, in particular magnetic monopoles

Overview of LHC direct long-lived particle searches performed to date

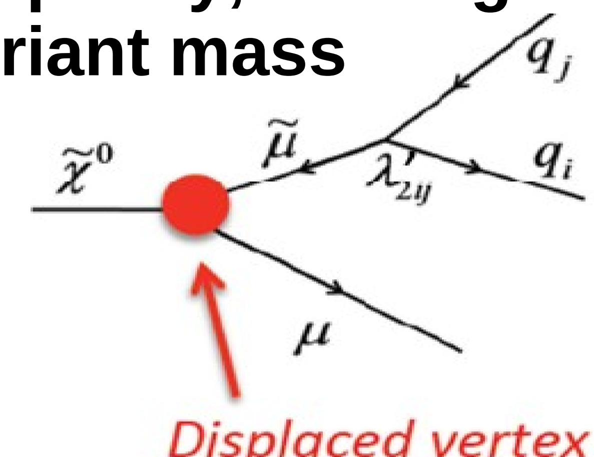
- ATLAS displaced jets in inner detector
- ATLAS displaced jets in muon system
- ATLAS disappearing tracks
- CMS displaced leptons → **later talk**
- CMS displaced photons → **later talk**
- ATLAS/CMS out-of-time decays → **later talks**
- ATLAS/CMS penetrating, charged, slow-moving particles → **later talks**
- ATLAS highly ionising

ATLAS displaced jets in inner detector (decay after up to 18 cm)

arXiv:1109.2242 [hep-ex]



Signature: muon and secondary vertex from tracks, with large impact parameter, high track multiplicity, and high invariant mass



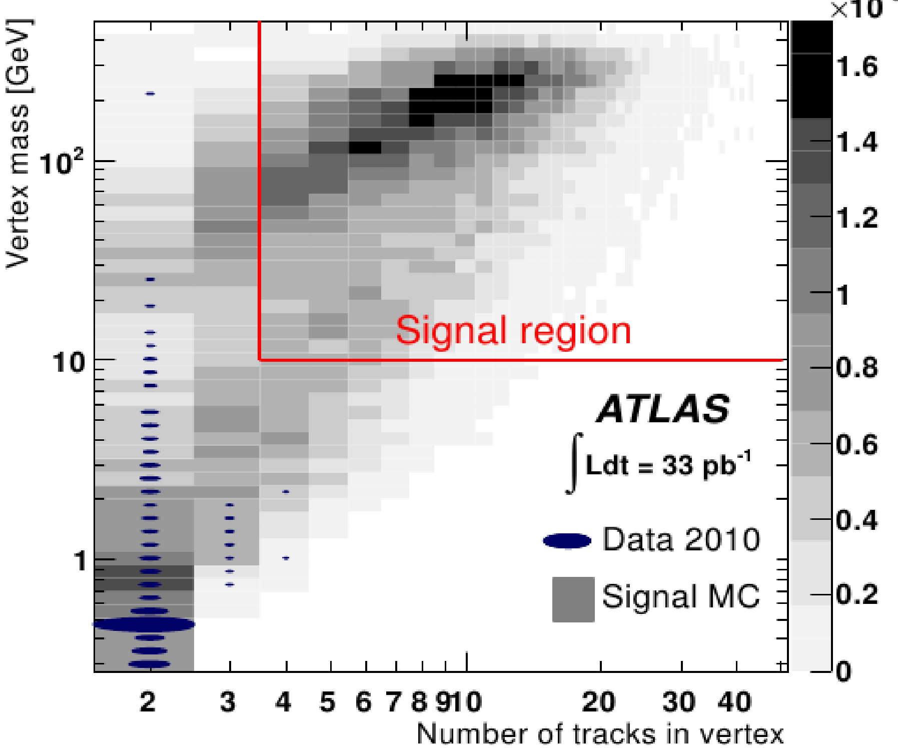
Intepreted in RPV SUSY scenario

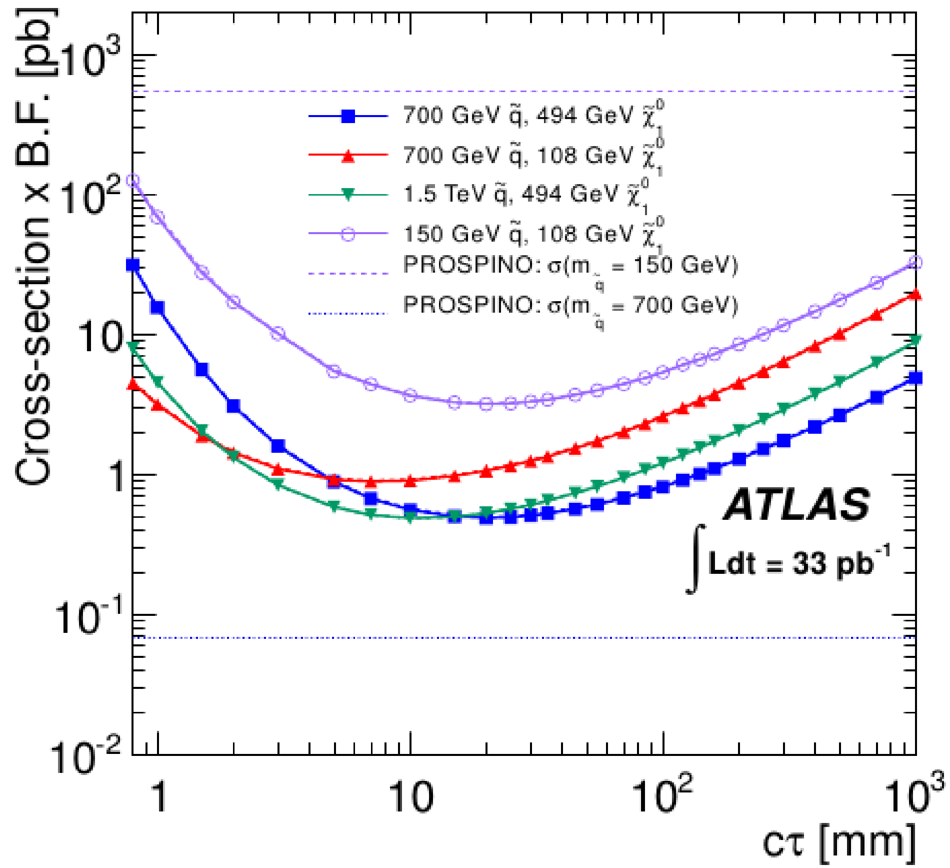
with non-zero λ' → L-violating

$$W_{\rm RPV} = \sum_i \mu_i L_i H_u + \sum_{i,j,k}\left(\frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k\right)$$

Displaced jets in inner detector – results

arXiv:1109.2242 [hep-ex]





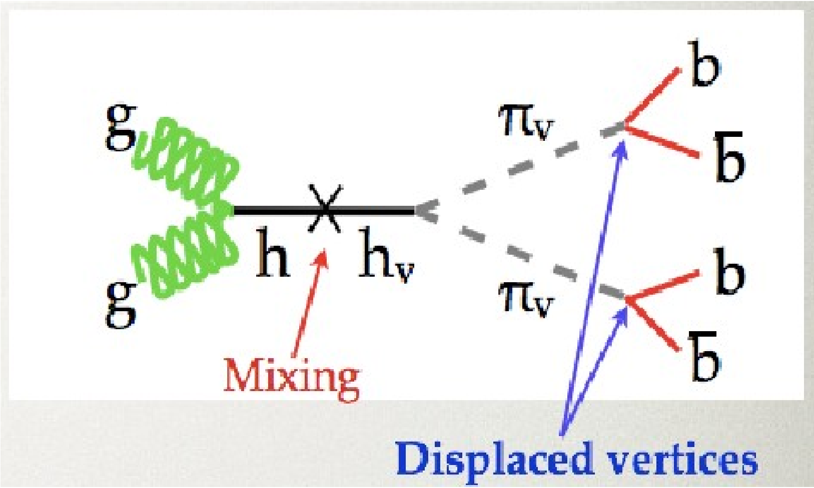
No events in signal region
(tiny backgrounds after vetoing on material interactions)

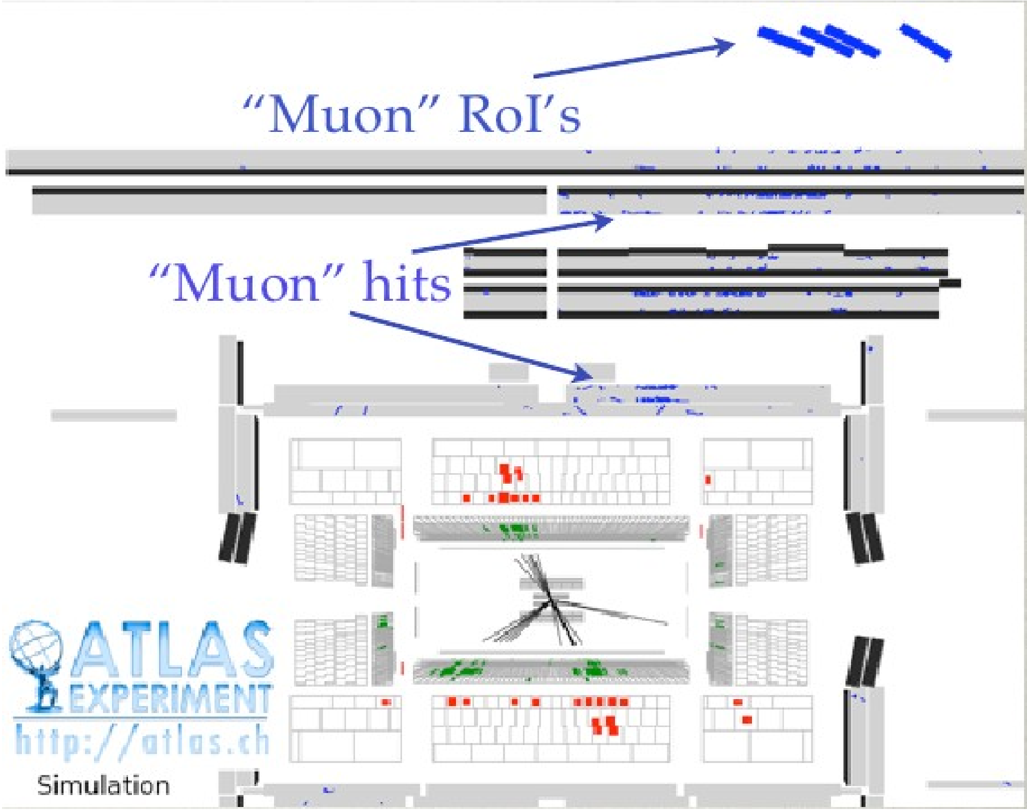
Upper limits at 95% c.l. as function of proper decay length for different SUSY mass splitting scenarios

ATLAS displaced jets in muon system (4 to 7 m)

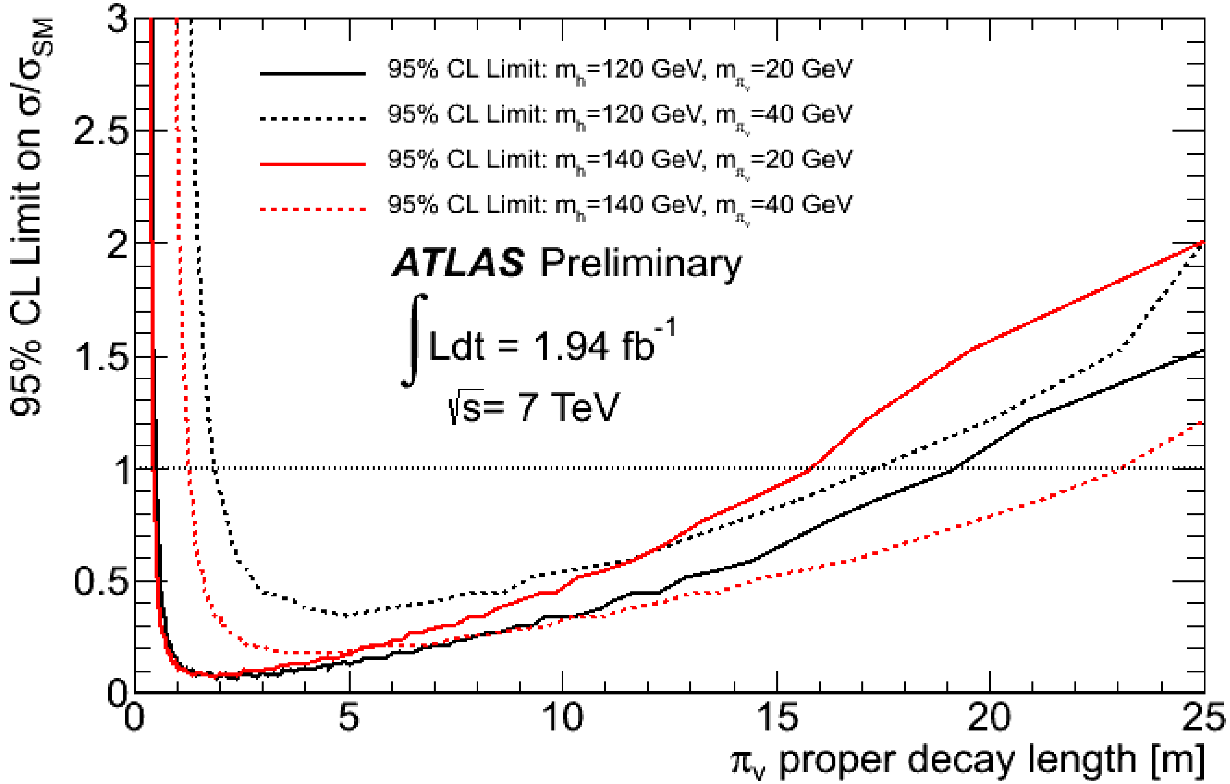
Signature: two highly-displaced vertices from muon hits, with calorimeter and inner track isolation

Interpreted in hidden valley scenario with long-lived v-pions





ATLAS displaced jets in muon system – preliminary results

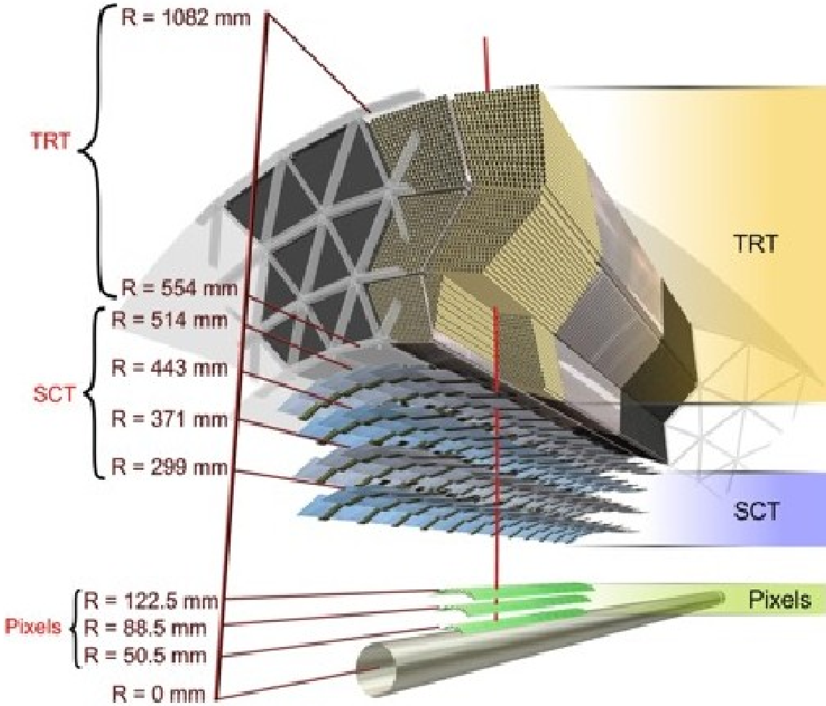


0 observed, 0 expected from backgrounds

Upper limits at 95% c.l. as function of proper decay length for different Higgs and hidden valley mass splitting scenarios

ATLAS disappearing tracks (70 to 90 cm)

Signature: events with jets and MET → search for tracks which leave no hits in the outer volume of the TRT



Intepreted in SUSY AMSB scenario with

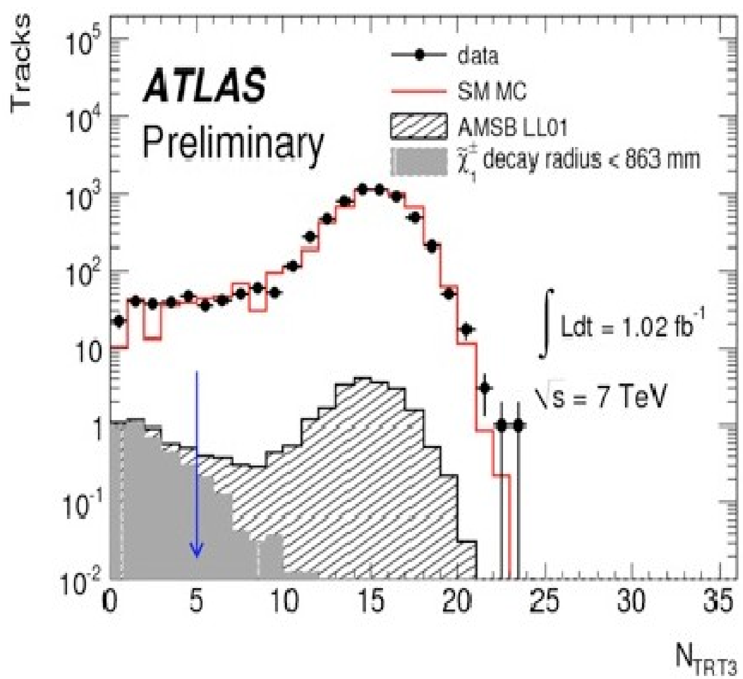
- near degenerate chargino and neutralino (long-lived chargino)
- Dominant decay:

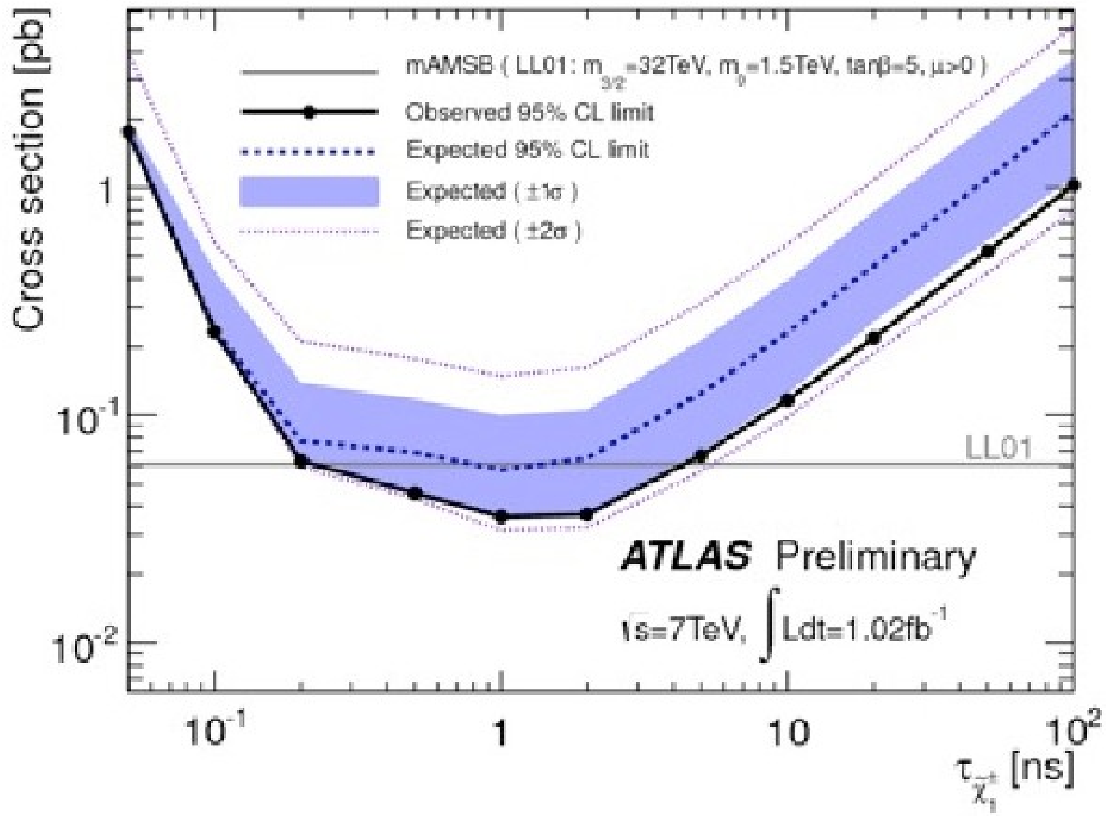
$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 + \pi^{\pm}$$

Soft pion (not reconstructed) → disappearing track

ATLAS disappearing tracks – preliminary results

Number of hits in TRT outer module





Upper limits at 95% c.l. as function of proper lifetime for given AMSB scenario

CMS displaced leptons (up to 50 cm)

(see later talk)

CMS-PAS-EXO-11-004

- **Signature: one or two displaced vertices from oppositely charged leptons (electrons or muons)**
- **Interpreted in a scenario with $H^0 \rightarrow 2X \rightarrow l^+l^-l^+l^-$ (X long lived)**

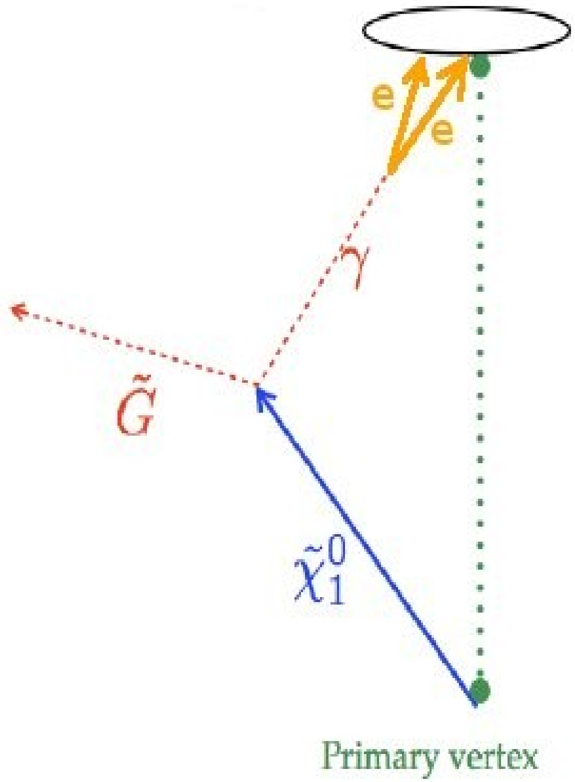
CMS displaced photons (up to 5 cm)

(see later talk)

CMS-PAS-EXO-11-067

Signature: two photons, among which one is identified as displaced converted photon; and MET

Interpreted in GMSB scenario with long-lived neutralino decaying into photon and gravitino



Displaced decay searches: things that can be improved

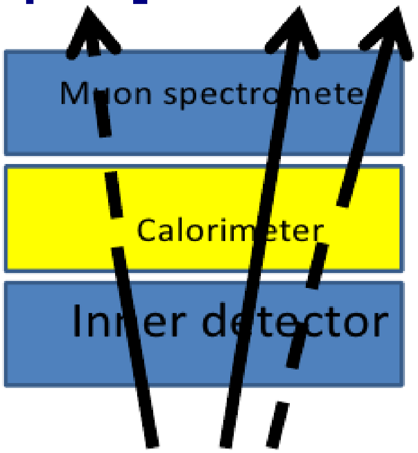
Difficult to be generic given the large number of possible scenarios, but we can try to cover as many as possible:

- Decay lengths ranging from mm to tens of meters
  - Use various detector component, specific triggers
- Minimise requirements on the rest of the events (additional muon, additional MET...)
  - If cannot trigger on displaced vertex itself, then use a combination of various triggers
- Systematic coverage of decay topologies
  - Hadrons, leptons, photons, invisible...
- Mass splittings range from hundreds of MeV to hundreds of GeV
  - e.g. need specific analyses for very collimated leptons or "lepton-jets" (high mediator mass, low long-lived particle mass)

Slow-moving particles

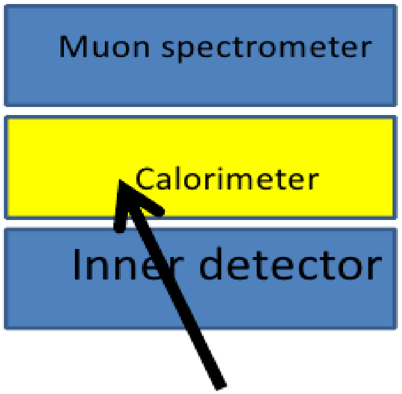
(CMS + ATLAS: see next talks)

arXiv:1101.1645 [hep-ex] arXiv:1103.1984 [hep-ex]
arXiv:1106.4495 [hep-ex] arXiv:1011.5861 [hep-ex]

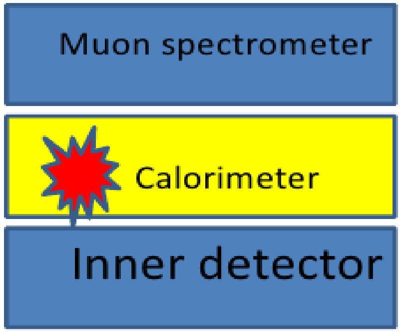


Penetrating signature: track with high p_T, time delay and anomalously large dE/dx

Decaying signature: energy deposition in calorimeter in events without collisions



Slow particle
stops in calorimeter



much later...

Penetrating signature: things that could also be covered

Searches are designed for |q| = 1e

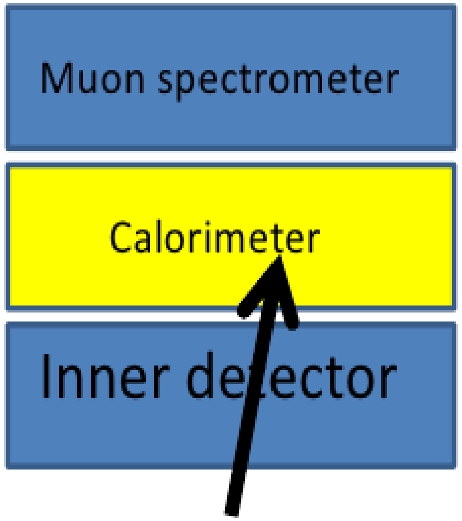
- **What about fractionally charged particles?**
  - Degraded hit efficiency affects trigger and reconstruction
  - Anomalously low dE/dx
  - Dedicated searches needed!
- **What about multiply charged particles?**
  - Lower apparent p_T affects selection efficiency
  - Detector effects of very high dE/dx need to be understood
  - Dedicated searches needed!
  - Above a certain charge, stop before or inside calorimeter
    → highly ionising particles (next slide)

ATLAS highly ionising

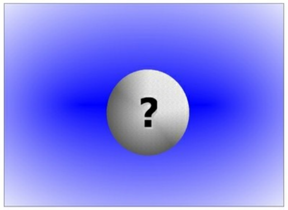
arXiv:1102.0459 [hep-ex]

Signature: electron candidate with very high-ionisation track and very narrow EM cluster

Intepreted as highly-charged long-lived particle ($6e < |q| < 17e$) stopping in EM calorimeter



- *Early search* (summer 2010, 3.1 pb^{-1})
- *Blue sky search,* motivated by detector capability rather than speculative theory

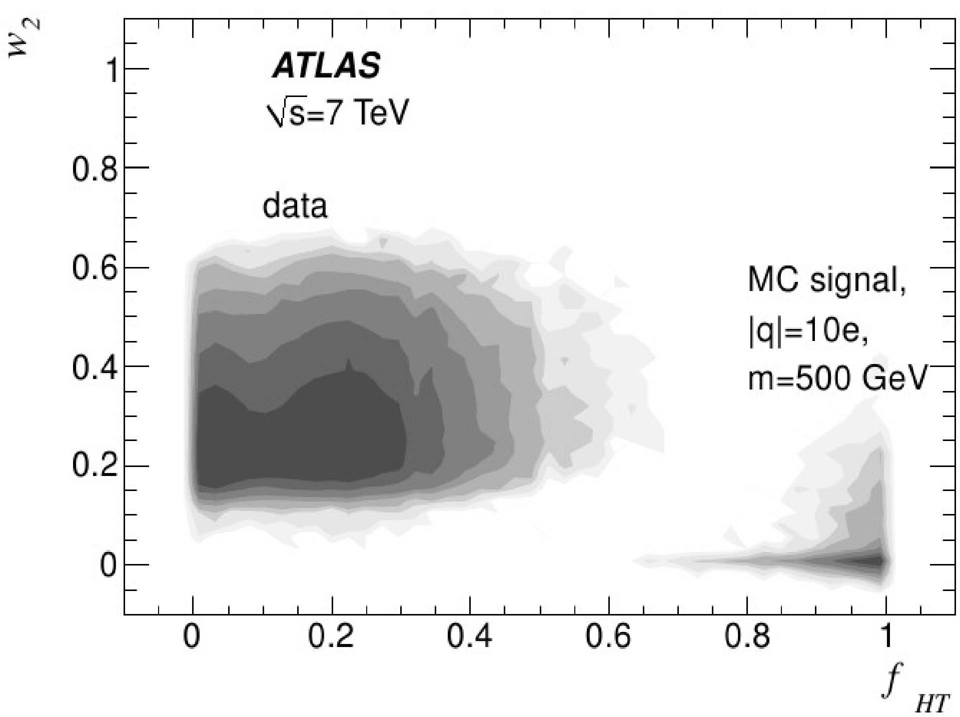


ATLAS highly ionising – results

arXiv:1102.0459 [hep-ex]

Independent variables:

- fraction of TRT high-threshold hits on track
- lateral extent of EM calorimeter energy deposition in first and second layers

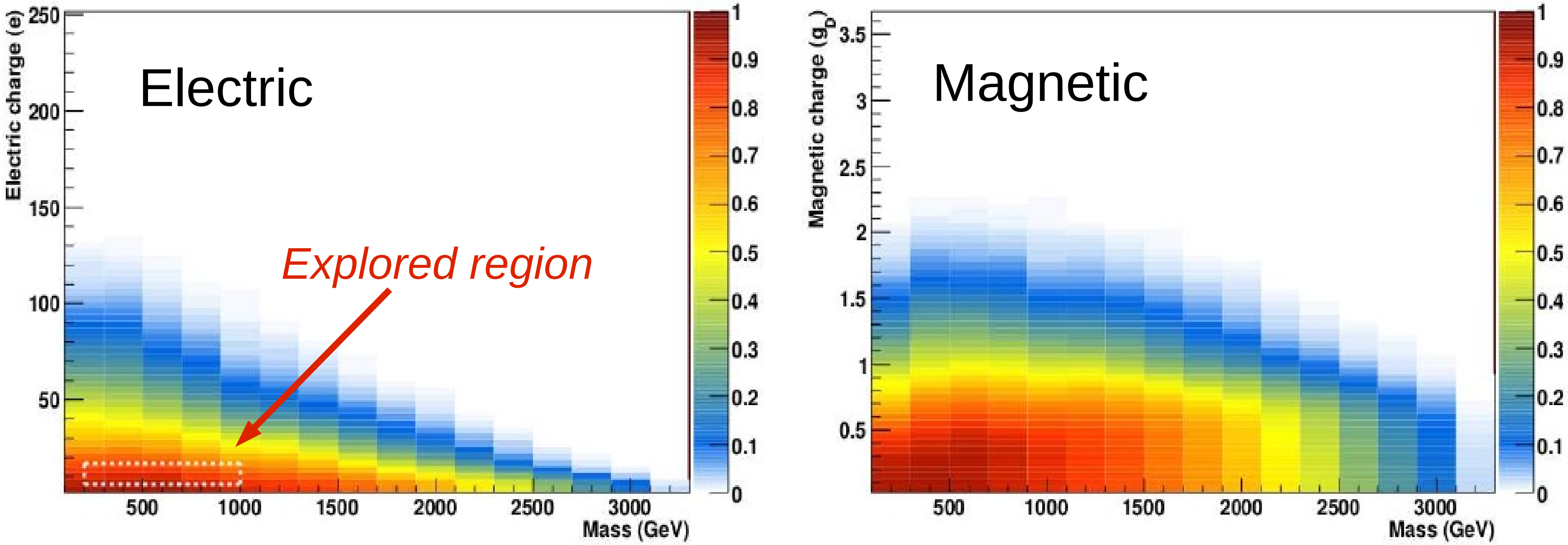


0 observed, 0 expected from backgrounds

- Cross section limits 6e ≤ |q| ≤ 17e and mass up to 1000 GeV
- Model-independent approach: fiducial kinematics

Highly ionising particles: things that can be improved

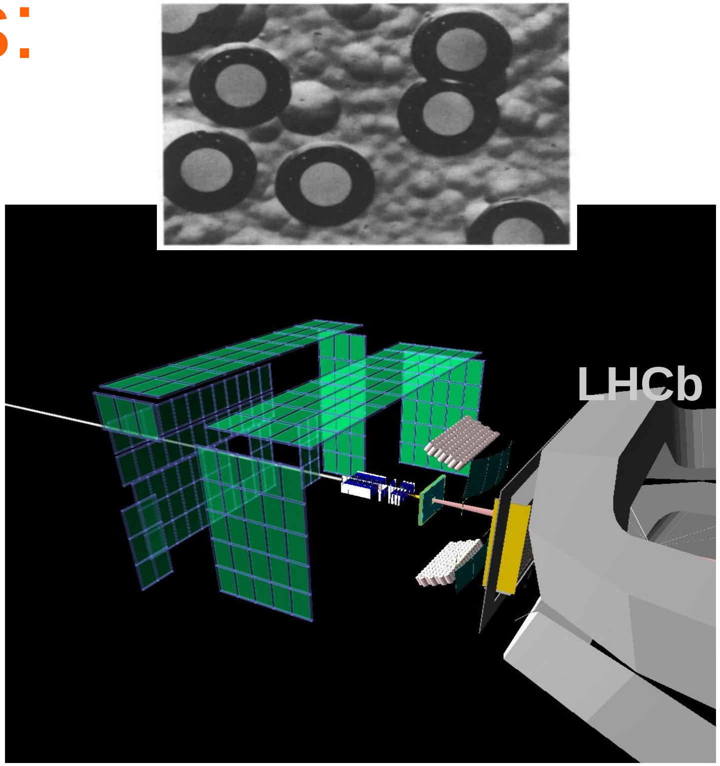
arXiv:1112.2999 [hep-ph]



– Theoretical ATLAS acceptance for 7 TeV Drell-Yan pair production

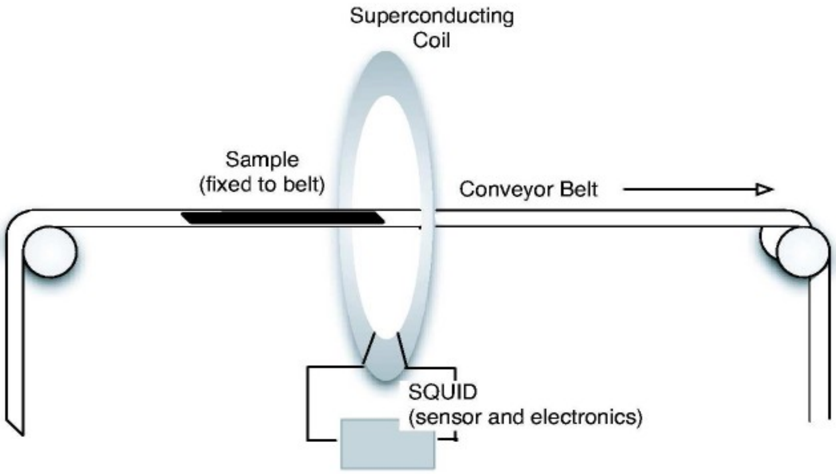
- Magnetic monopoles are not covered yet at the LHC!
- A well-designed analysis can in principle cover a wide range of charges and masses

Highly ionising particles: other approaches

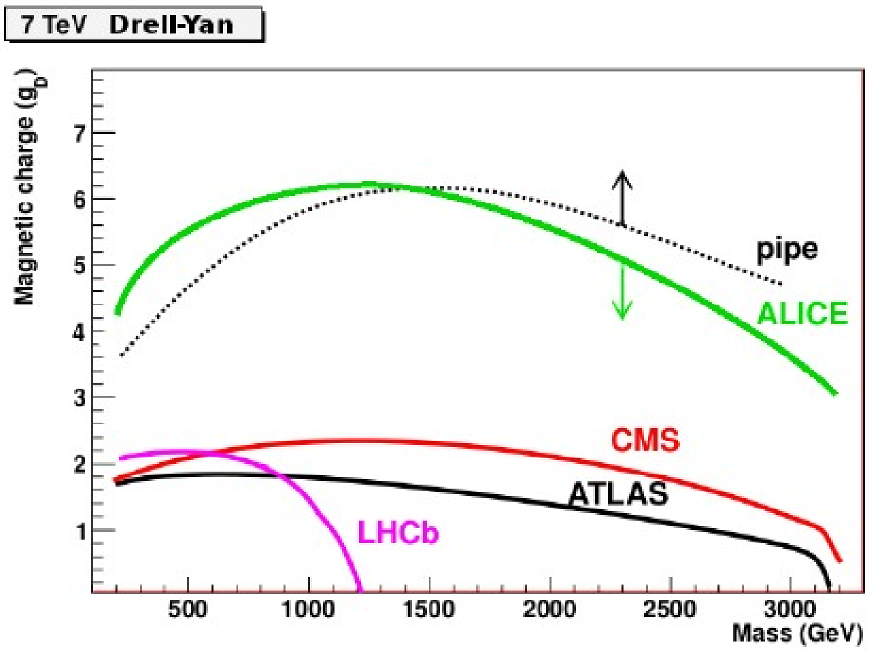


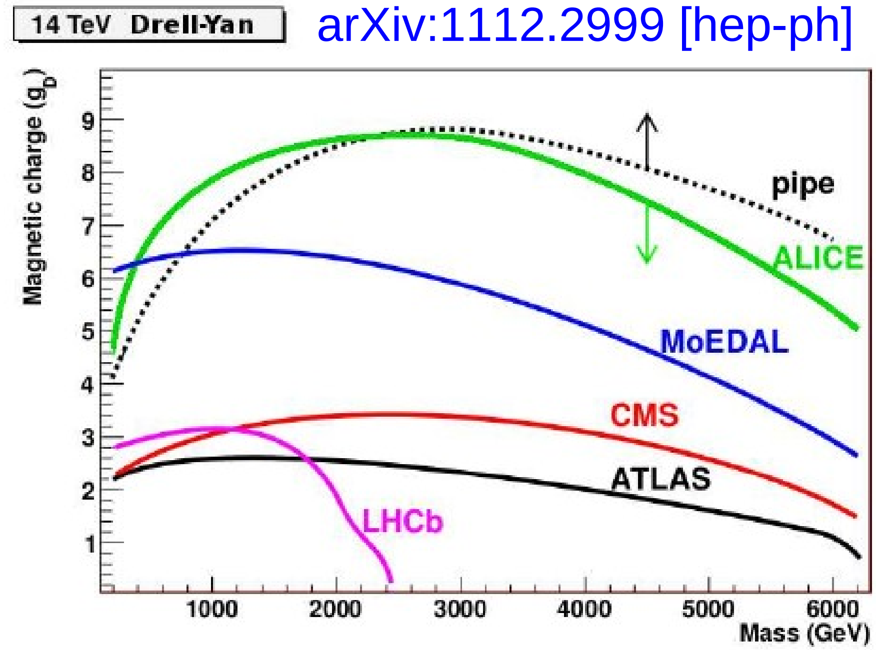
- **Track-etch technique: MoEDAL experiment**
  - Look for etch-pit cones in plastic foils deployed around LHCb interaction point

- **SQUID technique**
  - Look for persistent current induced by monopoles in detector and accelerator material, **e.g. ATLAS and CMS beam pipes**



Monopoles: potential reach





arXiv:1112.2999 [hep-ph]

Contours for >5% acceptance

- Assuming Drell-Yan pair production
- Not taking detector efficiency into account
- Not weighted with luminosity

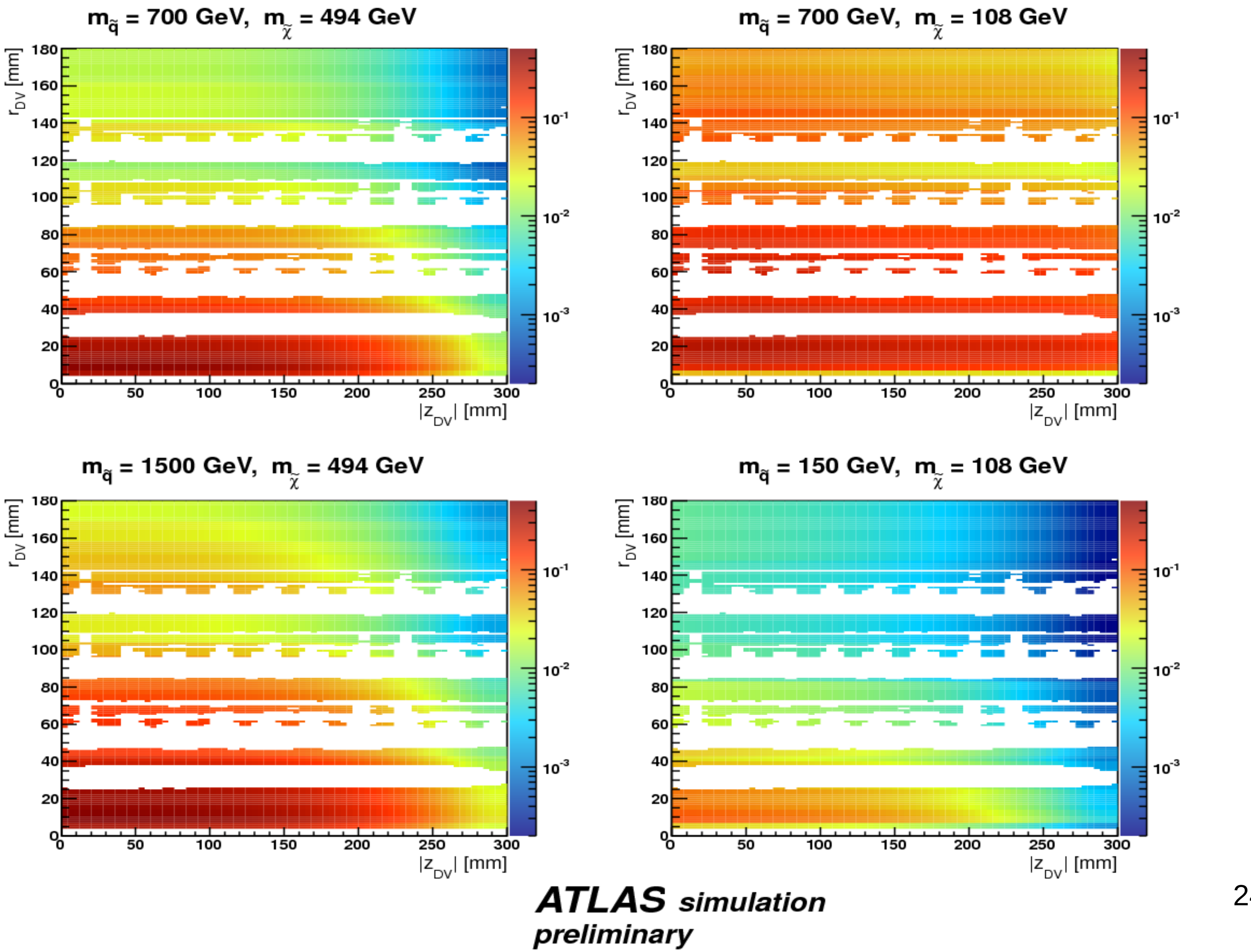
The different techniques are complementary!

Summary and outlook

- Decaying signatures:
  - Searched only a fraction of all possible scenarios, still a lot to be done
- Penetrating signatures:
  - Fractional and multiple charge particles still uncovered
- Highly ionising signatures:
  - Monopoles still uncovered, large potential at the LHC using various techniques

Extra slides

Displaced vertices – efficiencies

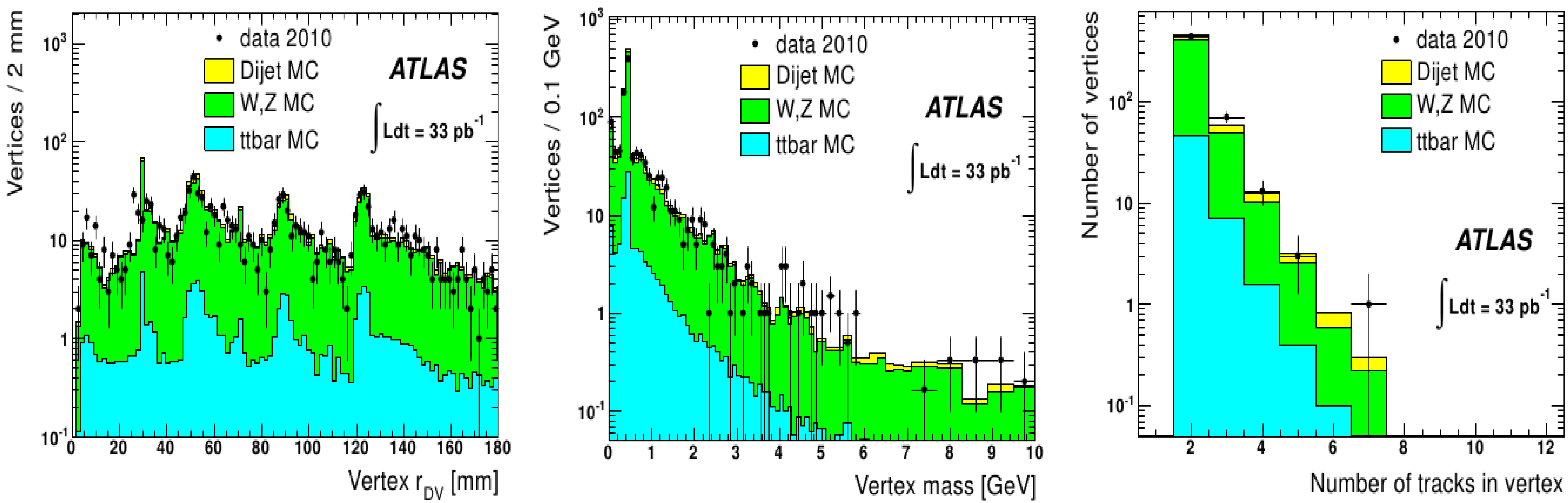


Displaced vertices – simulation vs. data

Loose selection for data/MC comparison

- Allow vertices with two tracks
- Low vertex mass (< 10 GeV)
- No material veto

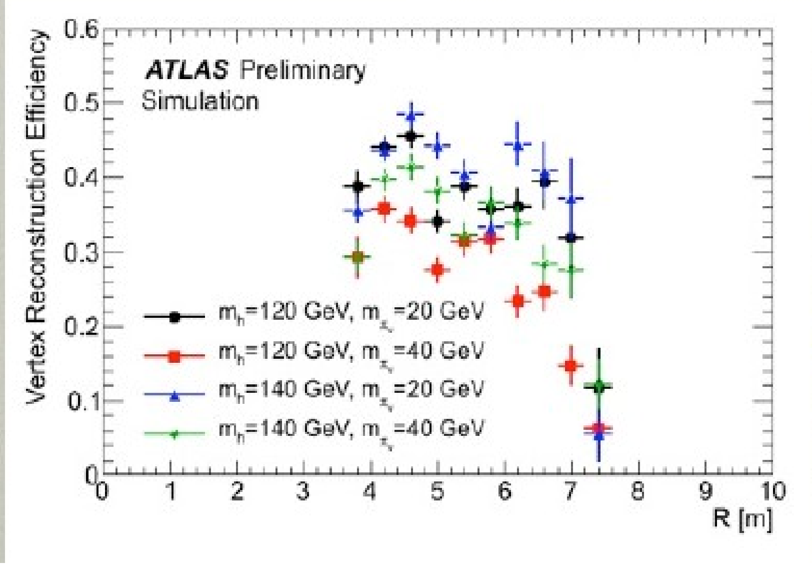
arXiv:1109.2242 [hep-ex]

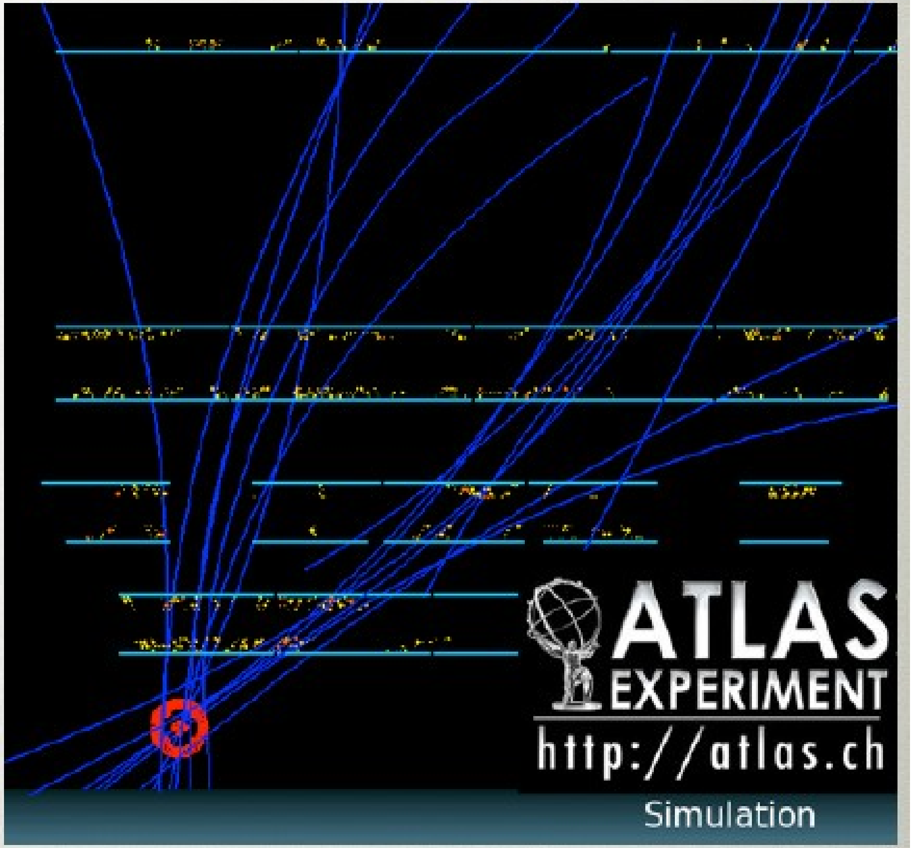


→ excellent agreement in shape and yield

Displaced jets in MS – vertex reconstruction

- A dedicated tracking and vertex reconstruction routine has been developed to identify displaced vertices in the MS
- Resolution of ~20 cm in z and ~32 cm is achieved

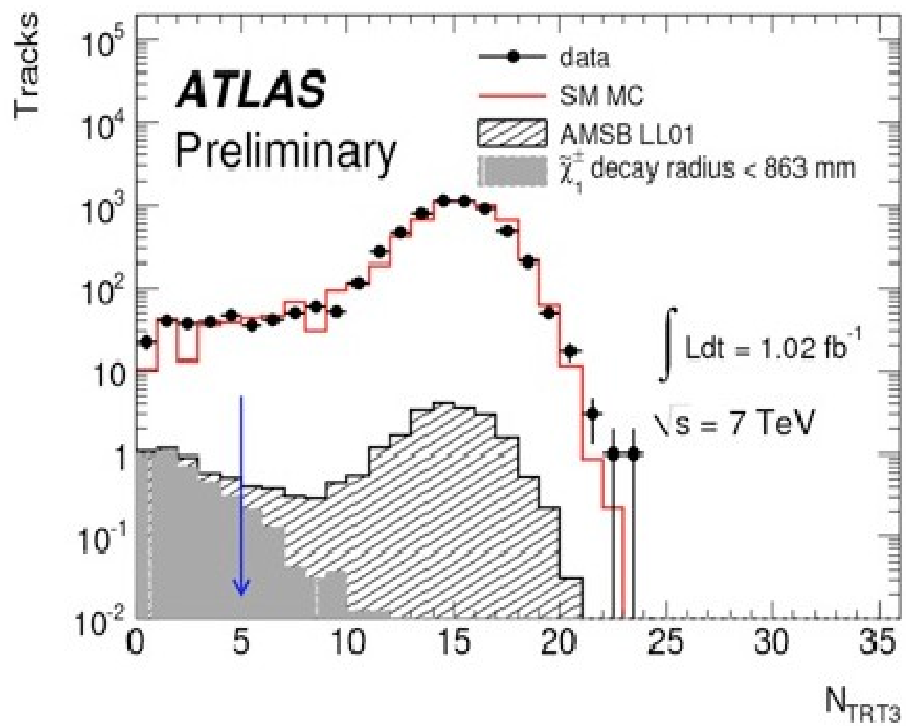




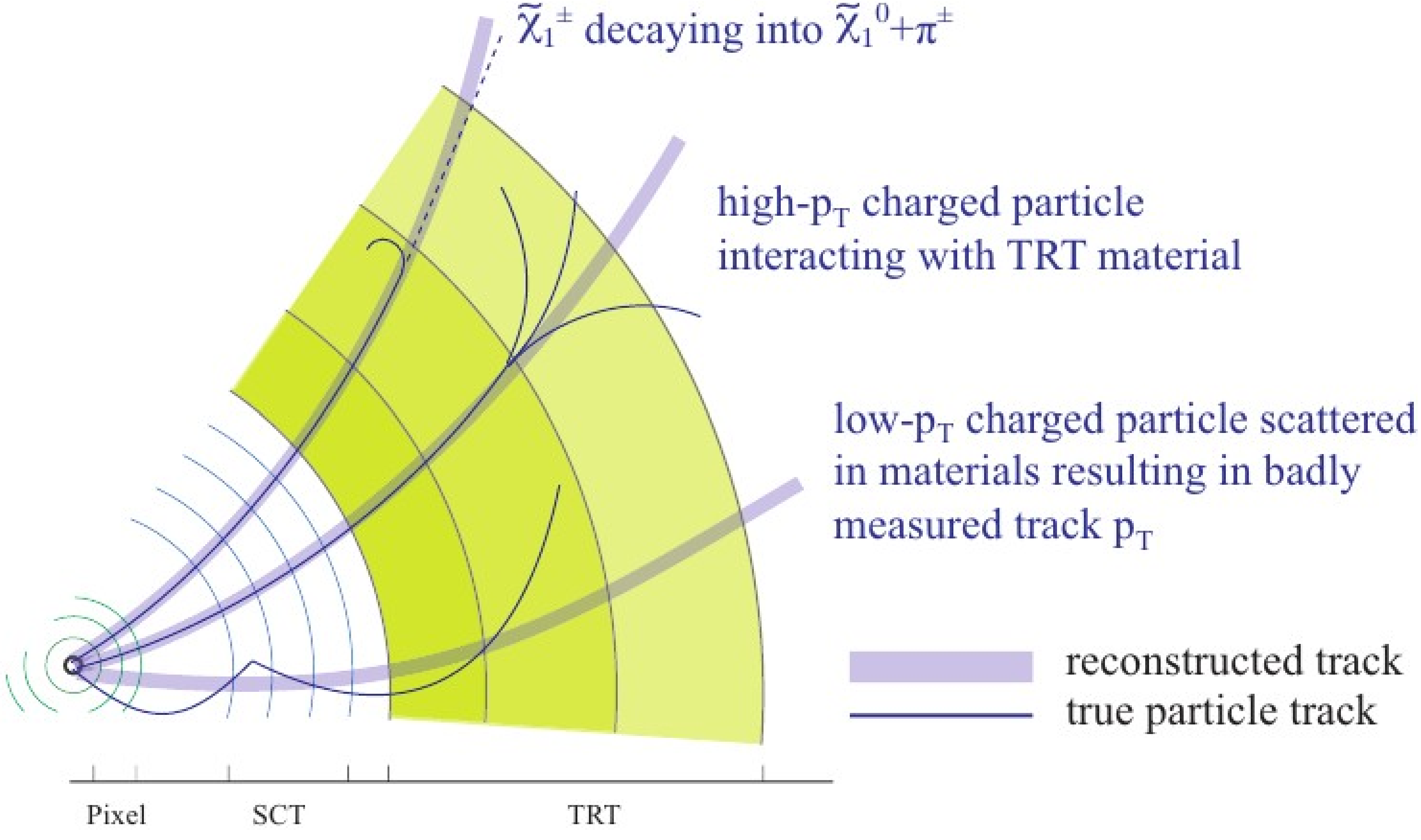
Disappearing tracks – selection

- Jet+MET trigger
- MET > 130 GeV
- 3 jets with p_T > 130, 60, 60 GeV and $|\eta| < 3.2$
- Track with:
  - p_T > 10 GeV (highest)
  - Isolated
  - $|\eta| < 0.63$
  - N(PIX) ≥ 1
  - N(SCT) ≥ 6
  - N(TRT3) < 5

Number of hits in TRT outer module

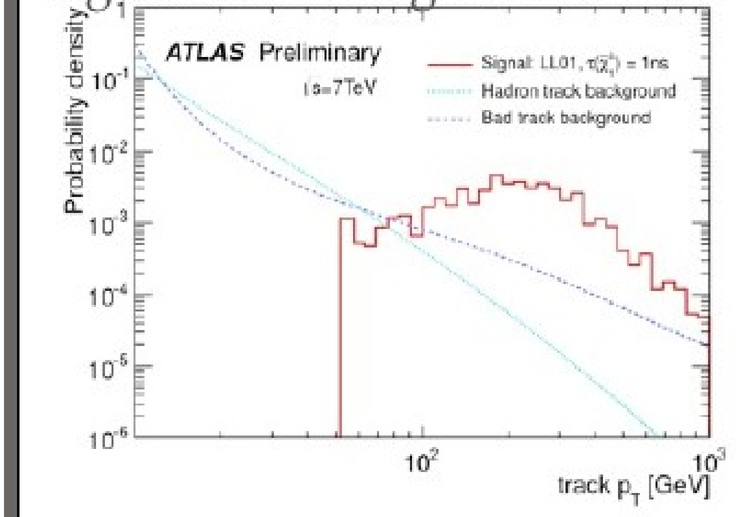


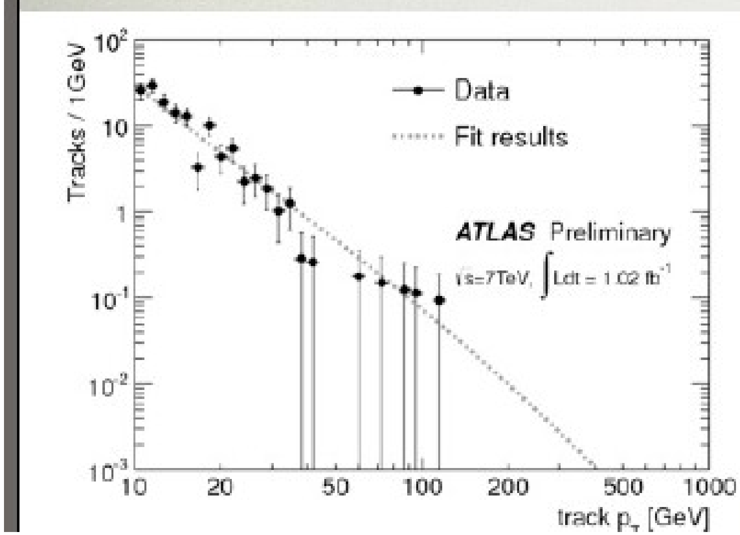
Disappearing tracks – backgrounds



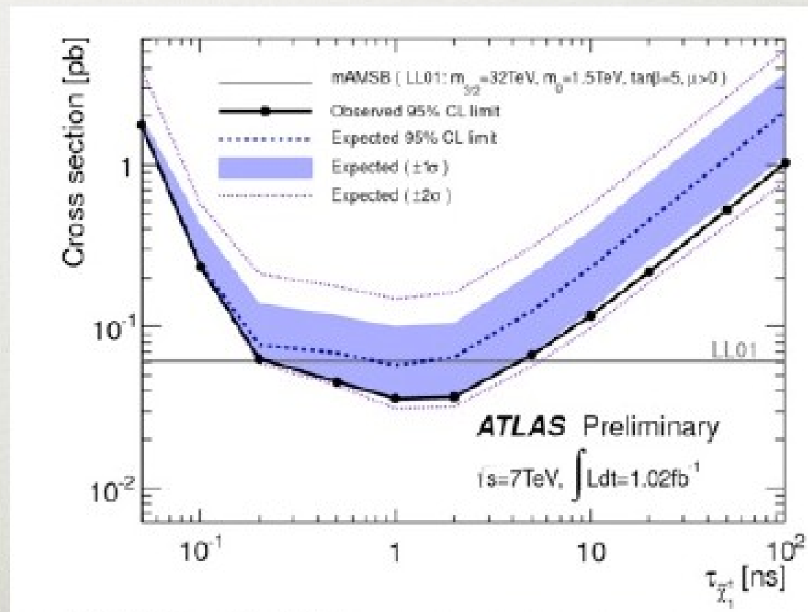
Disappearing tracks – results

Signal and background PDFs



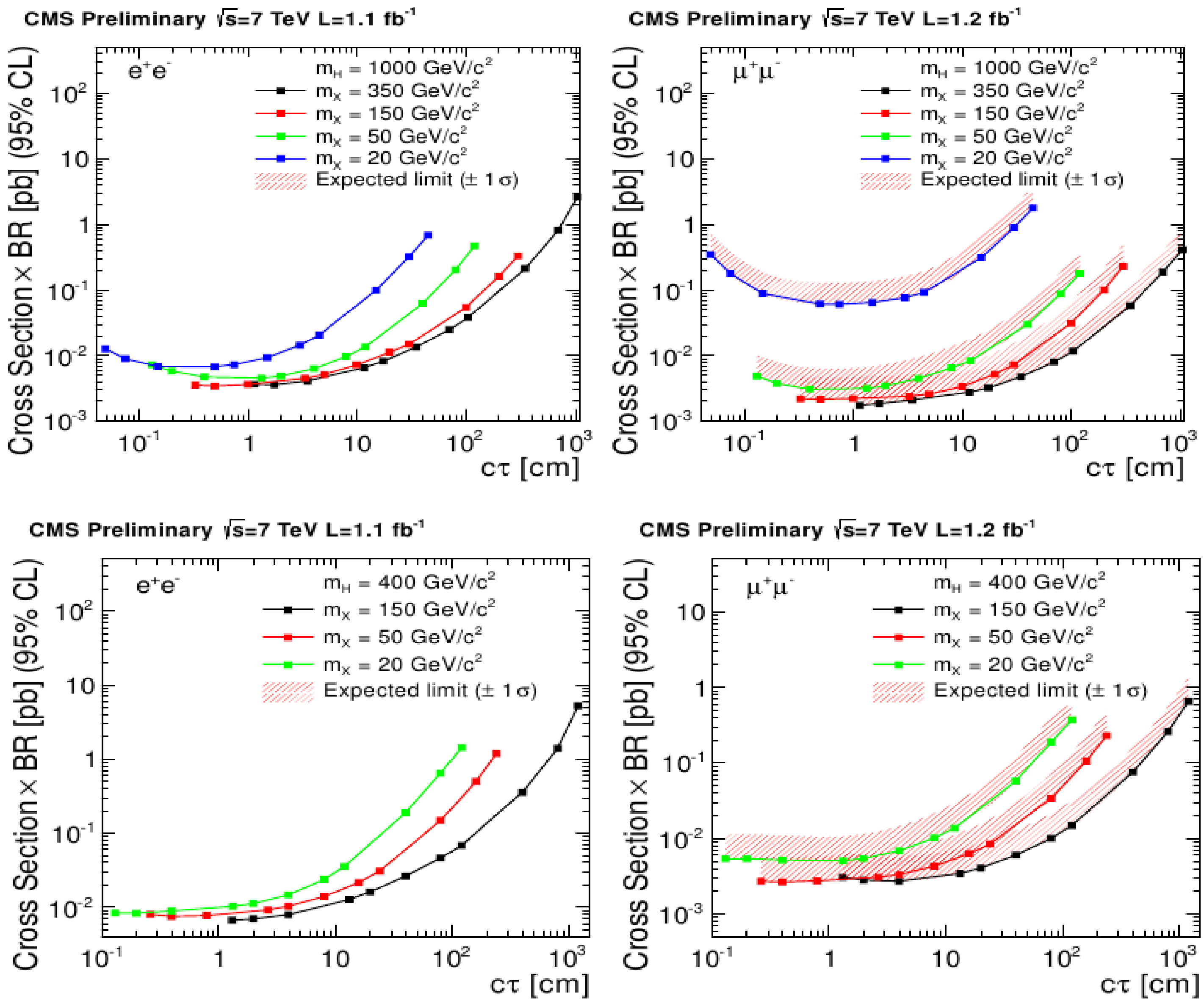


- Background is estimated by fitting the region $10 < p_T < 50$ GeV with the background PDFs
  - Expected background with $p_T > 50$ GeV is 13 ± 1
  - Observed 5 events with $p_T > 50$ GeV
- For the mAMSB point LL01 (m_0 =1.5 TeV, $m_{3/2}$ =32 TeV, $m_{\chi^\pm}$ = 90.2 GeV), $\chi^\pm$ lifetimes of $0.5 < \tau_{\chi^\pm} < 2$ ns are excluded at 95% CL



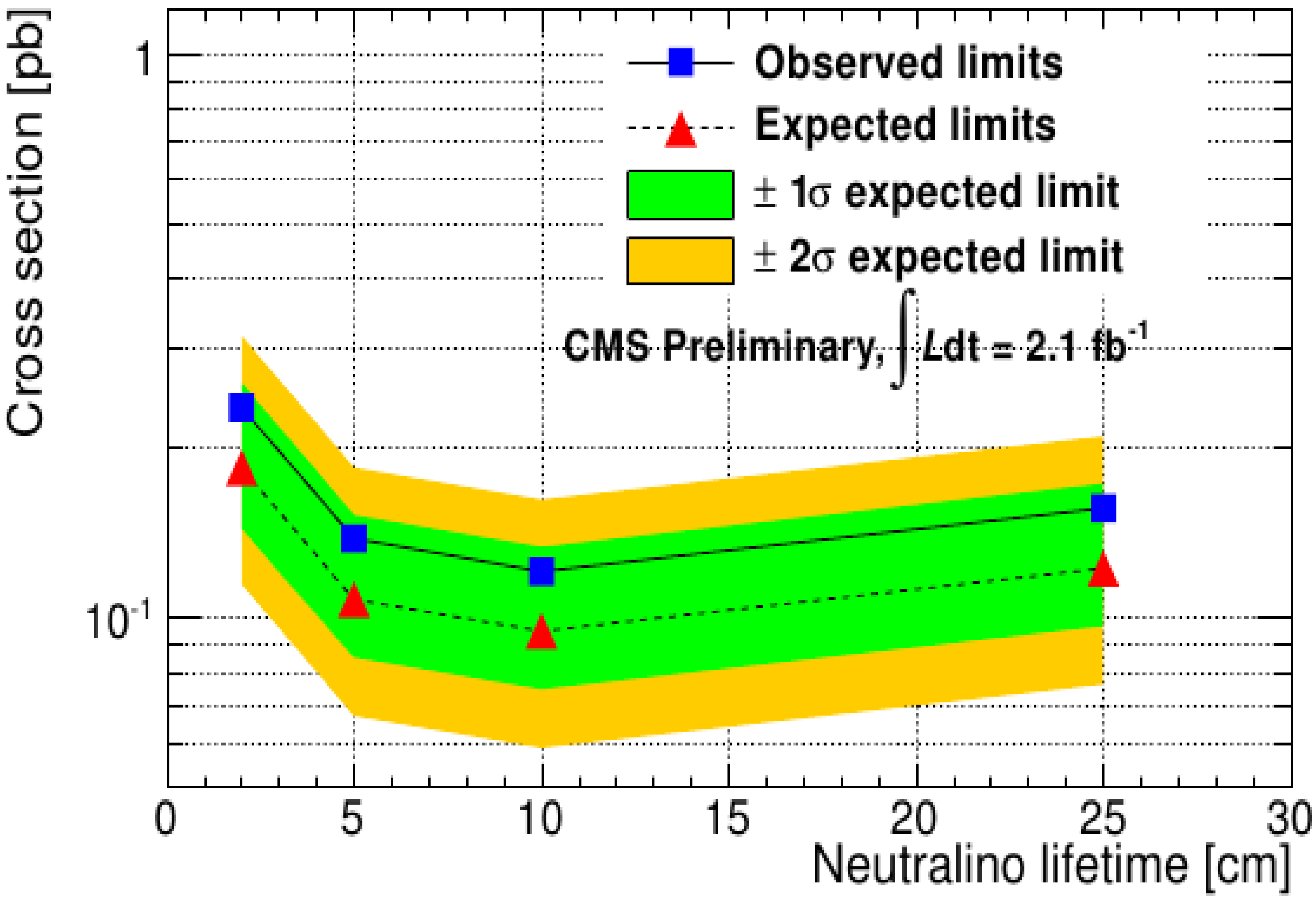
CMS displaced leptons – results

CMS-PAS-EXO-11-004



CMS displaced photons – results

CMS-PAS-EXO-11-067

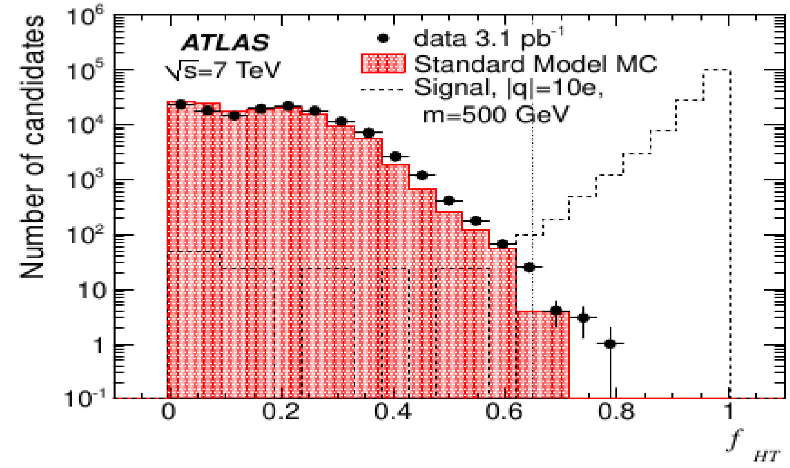


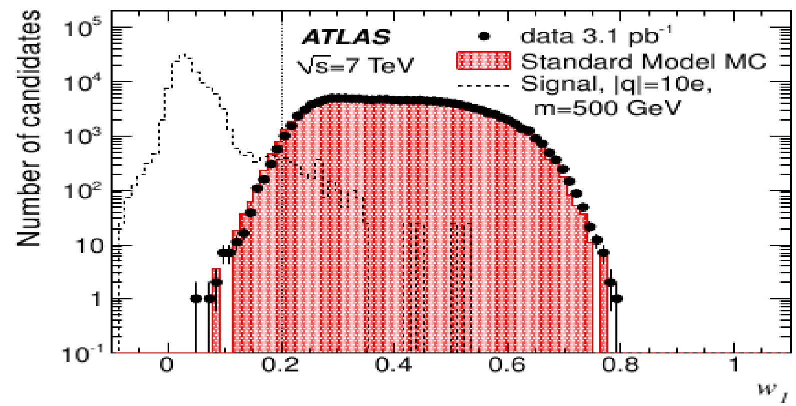
arXiv:1102.0459 [hep-ex]

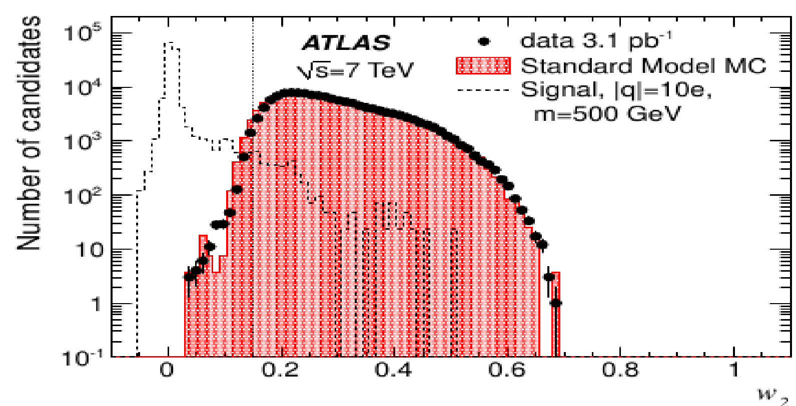
ATLAS HIPs – selection

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

- Independent variables:
  - fraction of TRT high-threshold hits on track
  - lateral extent of EM calorimeter energy deposition in first and second layers
- Number of selected events in data: 0
- Data-driven background estimate: 0.019 ± 0.005



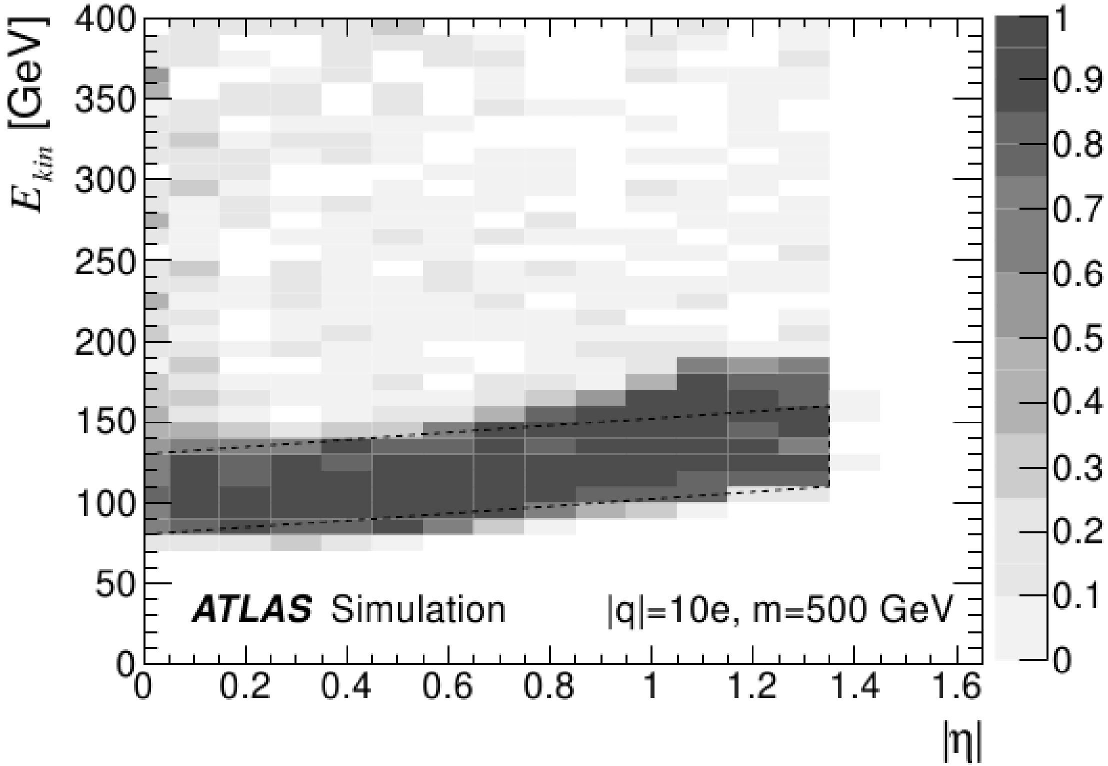




ATLAS highly ionising – model-independent approach arXiv:1102.0459 [hep-ex]

Major source of inefficiency comes from acceptance (probability to punch through inner detector)

- Depends on mass, charge, and model of kinematics



→ limits are set in well-defined kinematic ranges with high and flat signal selection efficiency (estimated from MC)

ATLAS highly ionising – limits

arXiv:1102.0459 [hep-ex]

- In fiducial ranges of (η, E_{kin}) (pb, 95% c.l.)

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

Model-independent!

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

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

- First HIP search at LHC energies

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

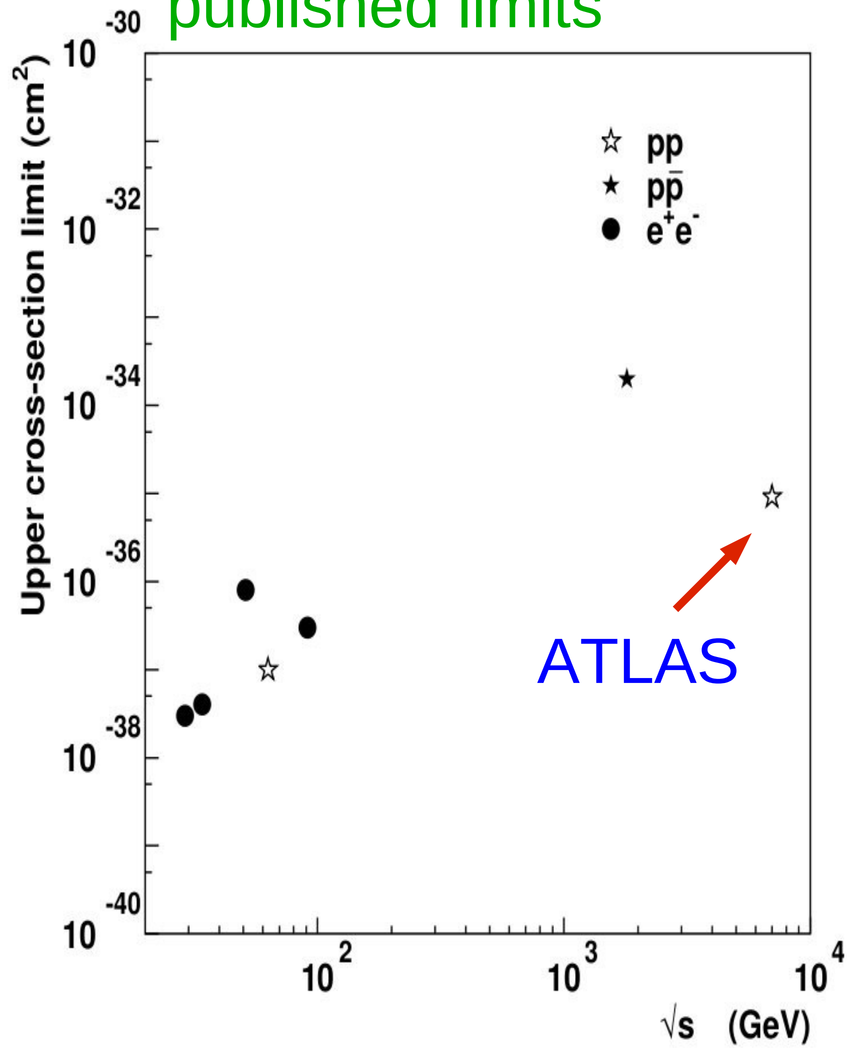
- **no interpretation yet for monopoles** for same reasons + bending

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

lifetime ≥ 100 ns to maintain narrow energy deposit

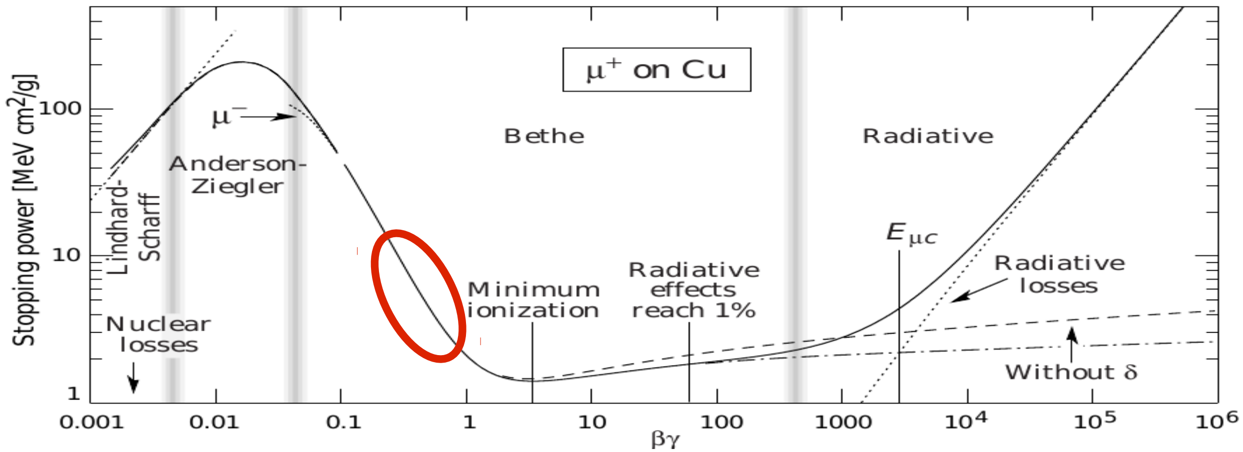
Highly-charged particles

published limits



A few comments about "highly ionizing"

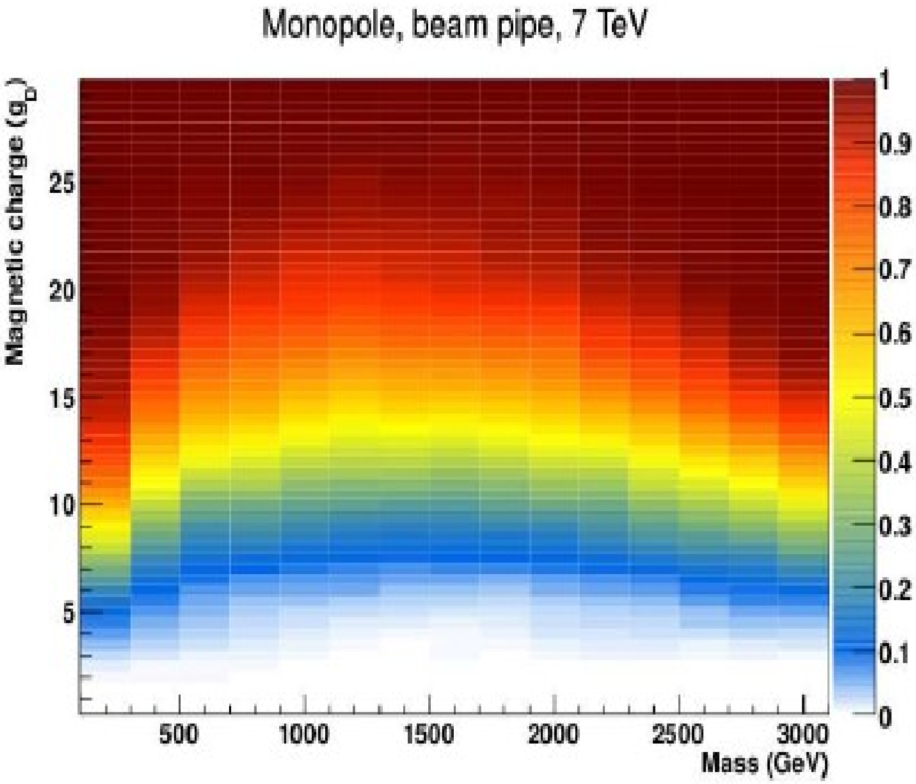
- R-hadrons ionize more than muons due to low speed
  - Up to 10 MIPs (β down to 0.4)
  - Generally penetrating through whole detector
- Monopoles/high-charges are very highly ionizing due to low speed *and* high charge ($dE/dx \propto q^2$)
  - >> 10 MIPs → highly ionizing particle (HIP)
  - Generally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

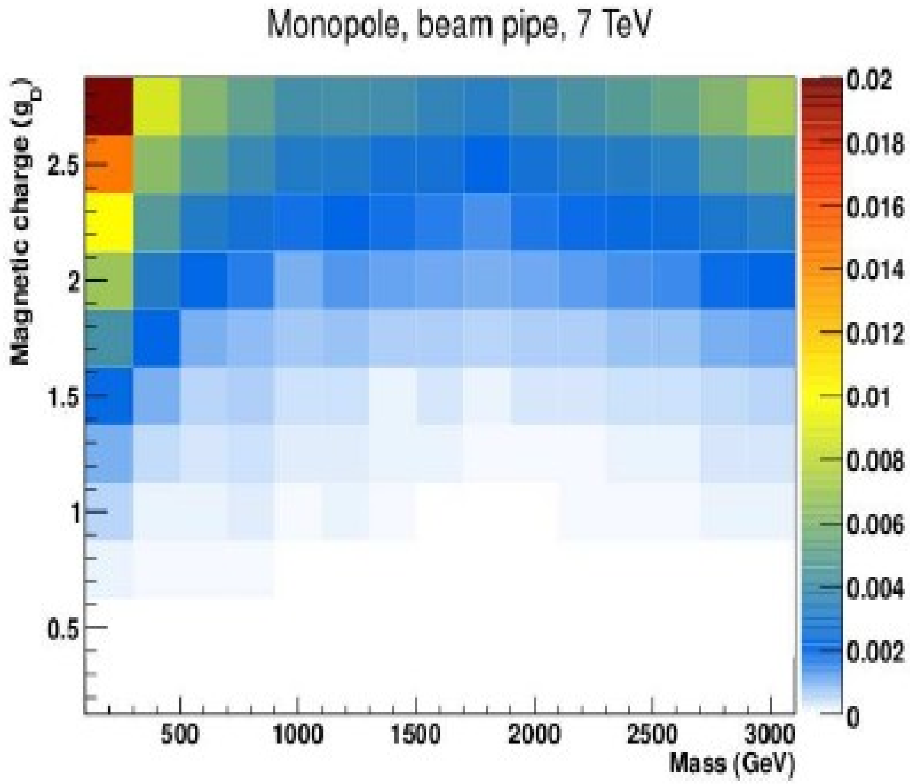


PDG

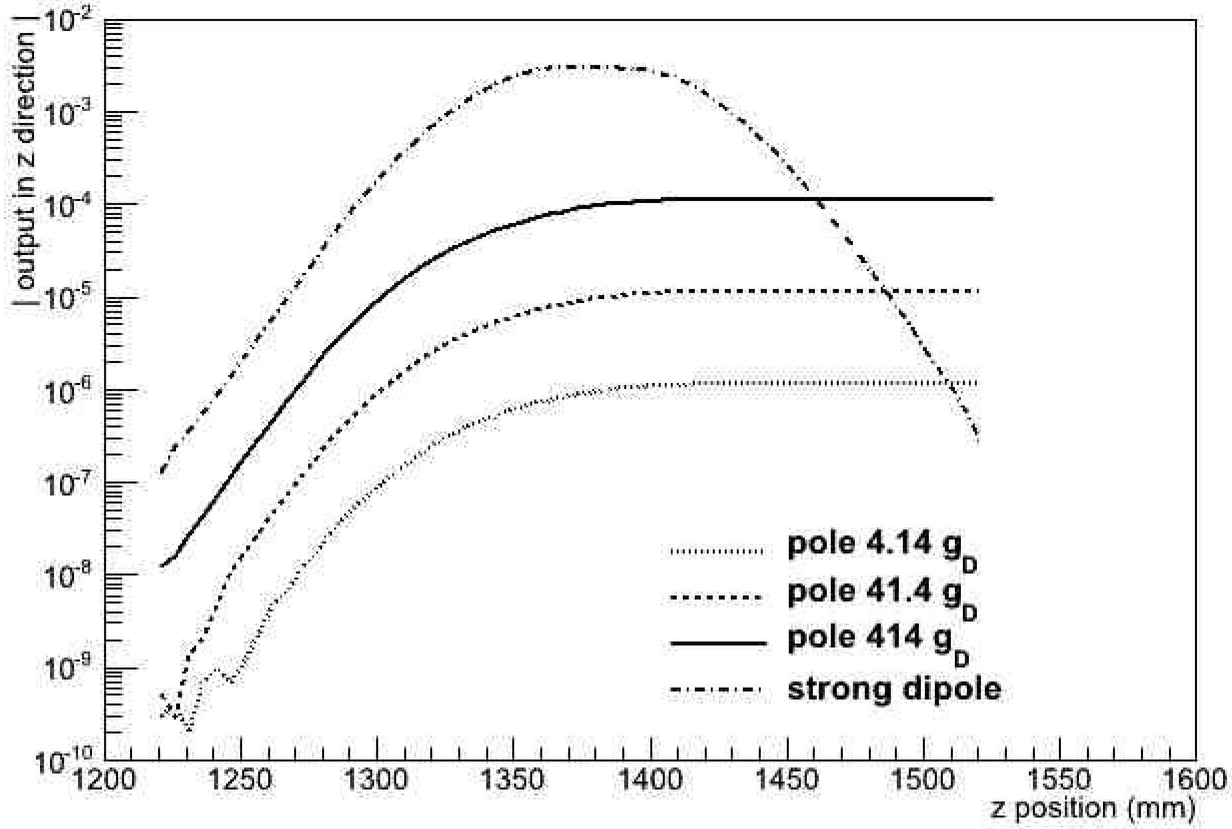
Highly ionising particles: beam pipe stopping acceptance (SQUID analysis)

arXiv:1112.2999 [hep-ph]





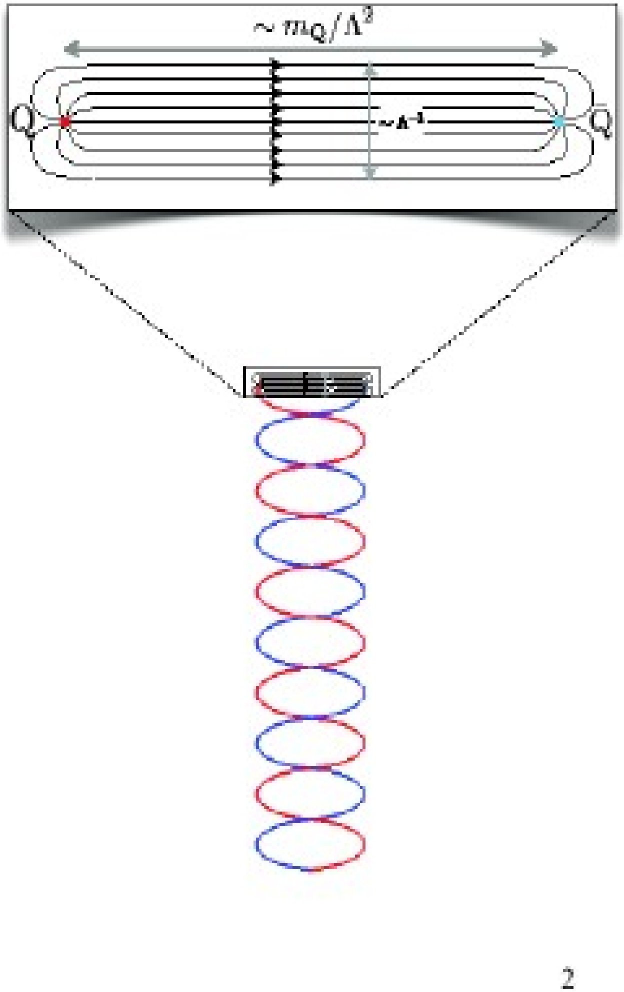
SQUID tests at ETH Zurich



Quirks?!

[Kang & Luty, arxiv:0805.4642]

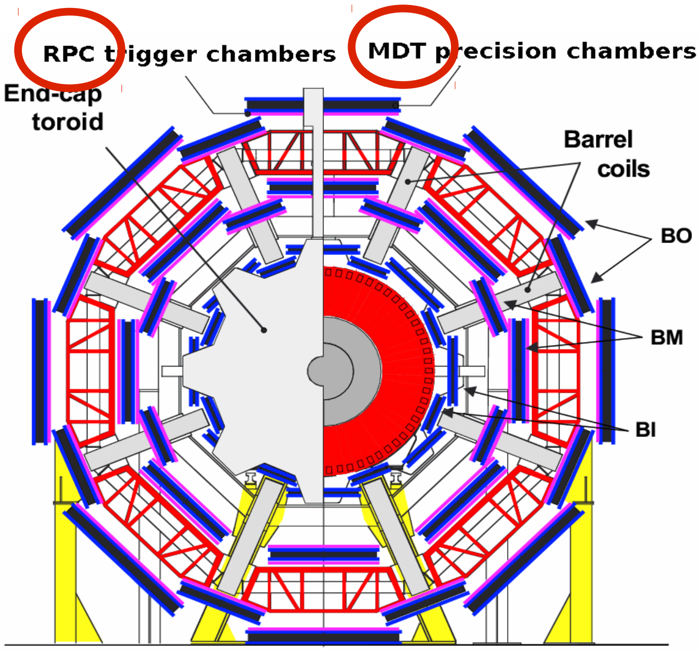
- New confining gauge field, "**infracolor**," forms strings between massive stable particles, "**quirks.**"
- Quirk mass larger than confinement scale prevents string from fragmenting as in QCD.
- String force of ~ Λ_{IC}^2 causes quirks to *oscillate* around center of mass, forming bizarre tracks
- Two important parameters:
  - Quirk mass m_Q: considering 100 GeV – 1 TeV range where discovery possible
  - Confinement scale Λ_{IC}: smaller than m_Q; possible values range over many orders of magnitude
- Very long strings possible. Depends on Λ_{IC}, so strings could be subatomic or larger than detector.
- Assume quirks have electrical charge – otherwise we can't see the tracks.



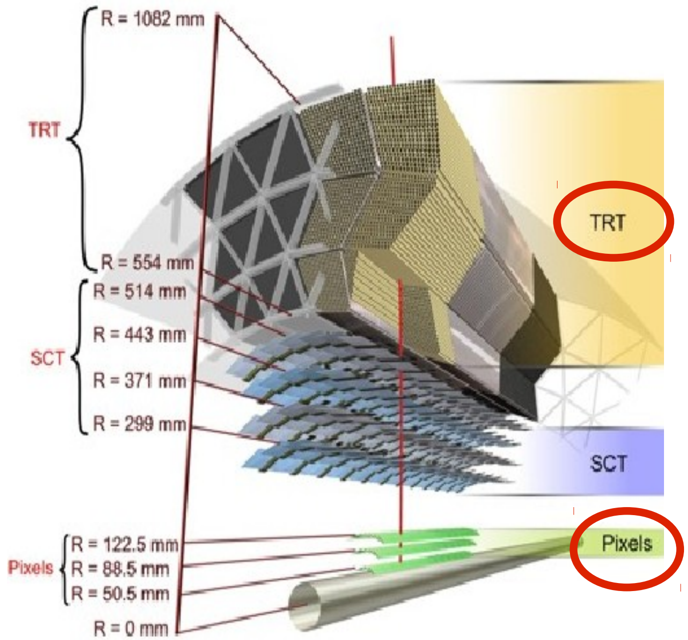
ATLAS subdetectors

- Long-lived particles often require non-standard reconstruction
- Timing is often an issue

Muon Spectrometer (MuSp)



Inner Detector (ID)



Calorimeters