Searches for long-lived, massive particles with the ATLAS detector

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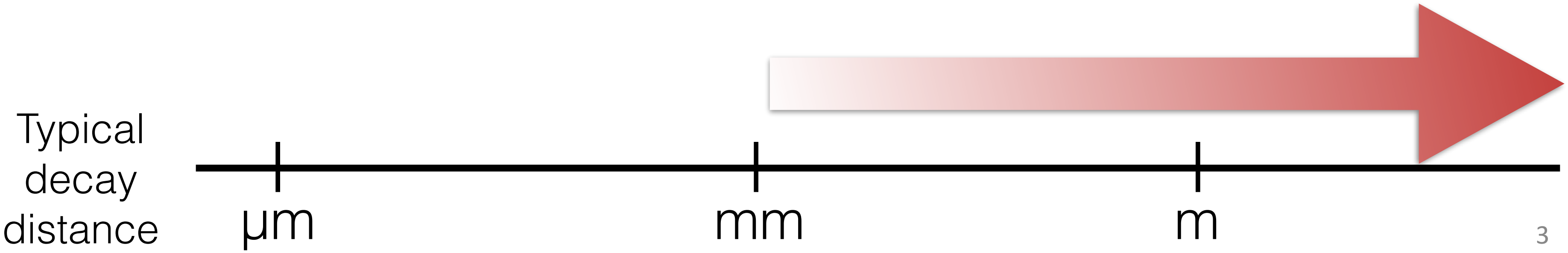
Contents

- Why should we look for long-lived particles, and what are we actually looking for?
- A very quick look at a couple of signal models.
- The ATLAS detector.
- SUSY-based searches:
  - Stable Massive Particles.
  - Stopped gluinos.
  - Disappearing tracks.
  - Displaced vertices in inner tracking detector.
  - Non-pointing photons.
- Other models:
  - Higgs to 2 long-lived pseudoscalars.
  - Multi-charged particles.
  - Magnetic monopoles.

What do I mean by “long-lived particles” (LLPs)?

- By “long-lived”, I mean that a particle travels far enough that its decay position is measurably displaced from the IP.

- In this talk I am talking about **new** (i.e. not-yet-discovered), **heavy** (i.e. mass > ≈10 GeV) particles with average decay distances in this range…



Typical decay distance

μm

mm

m

Why should we look for LLPs?

- Several New Physics models could give rise to new, massive particles, with (relatively) long lifetimes.
- Will give a very brief summary of a couple of examples, but there are also (infinitely) many possibilities that no-one has ever thought of!
- We should look for signatures of New Physics any way we can!

What are we actually looking for?

Charged or neutral?

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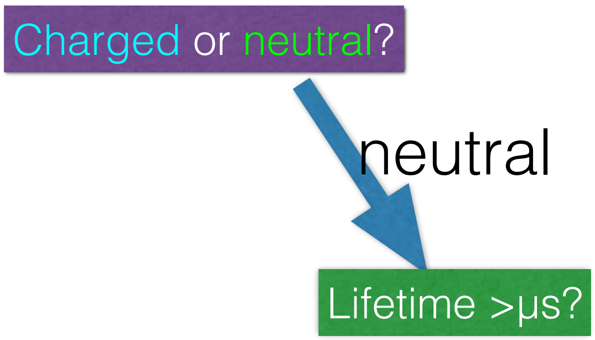
Charged or neutral?

neutral

What are we actually looking for?

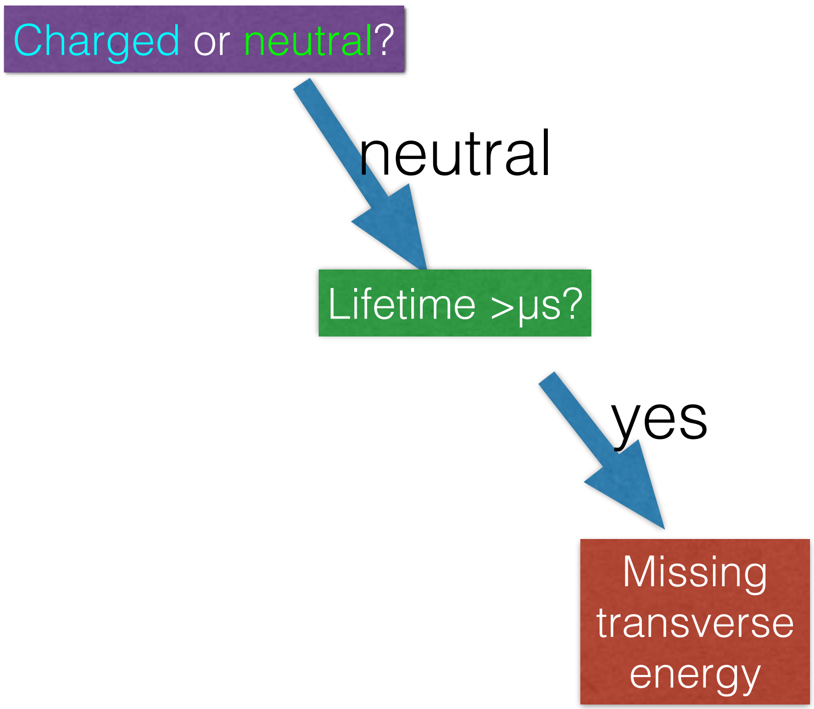


Charged or neutral?

neutral

Lifetime >μs?

What are we actually looking for?



Charged or neutral?

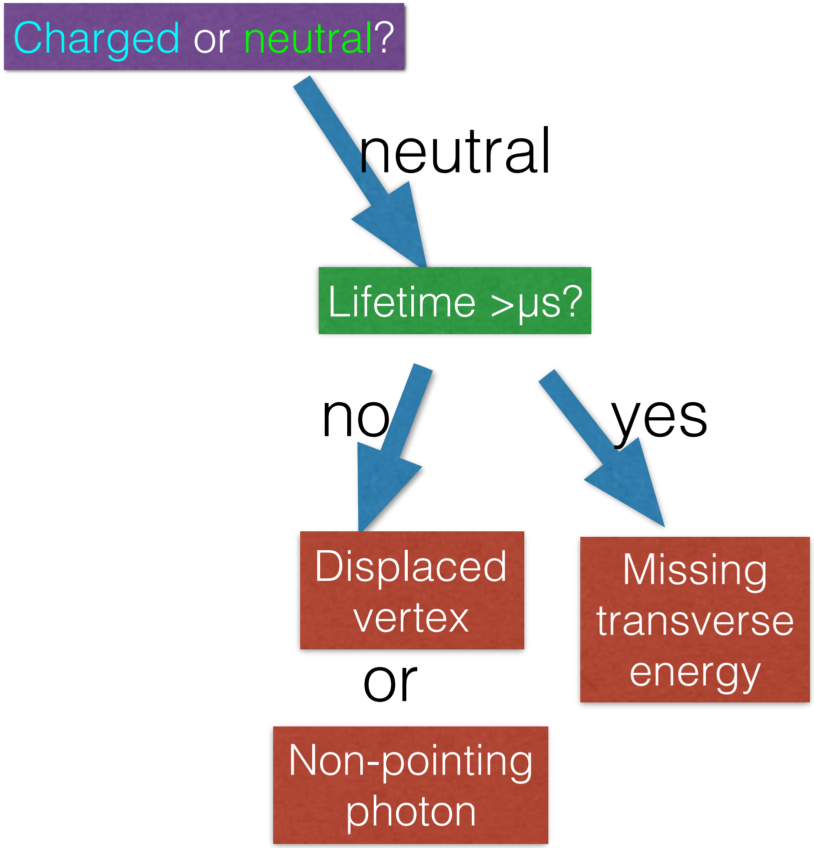
neutral

Lifetime >μs?

yes

Missing transverse energy

What are we actually looking for?



Charged or neutral?

neutral

Lifetime >µs?

no

yes

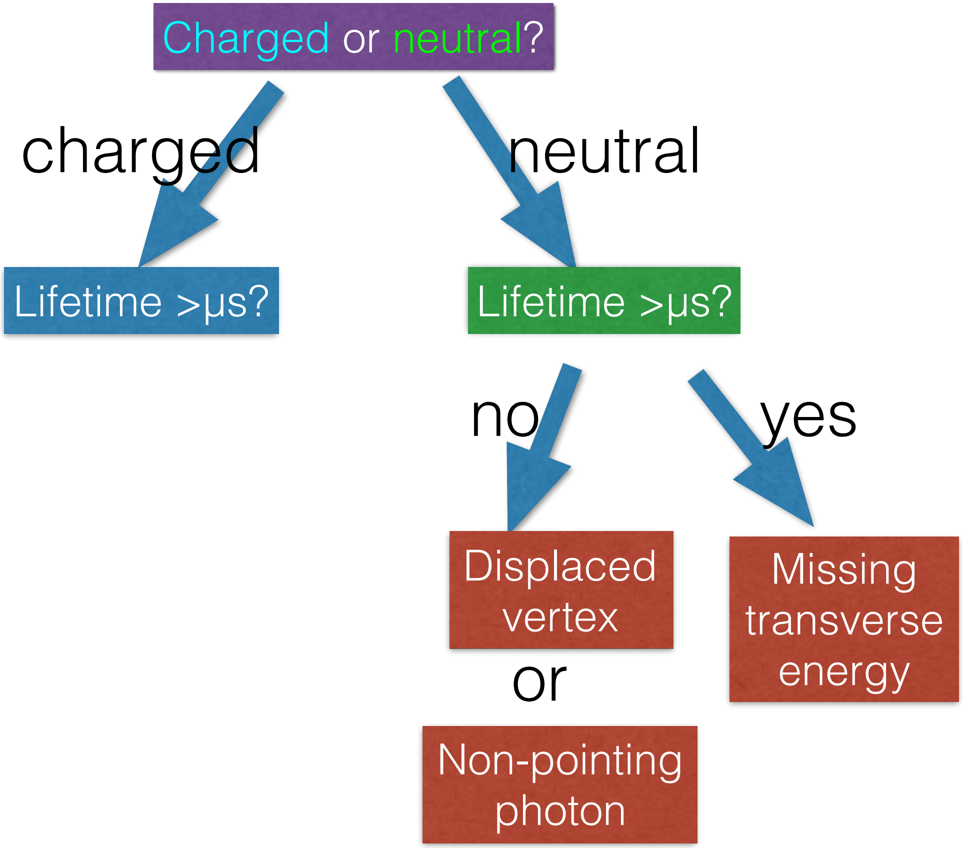
Displaced vertex

or

Non-pointing photon

Missing transverse energy

What are we actually looking for?



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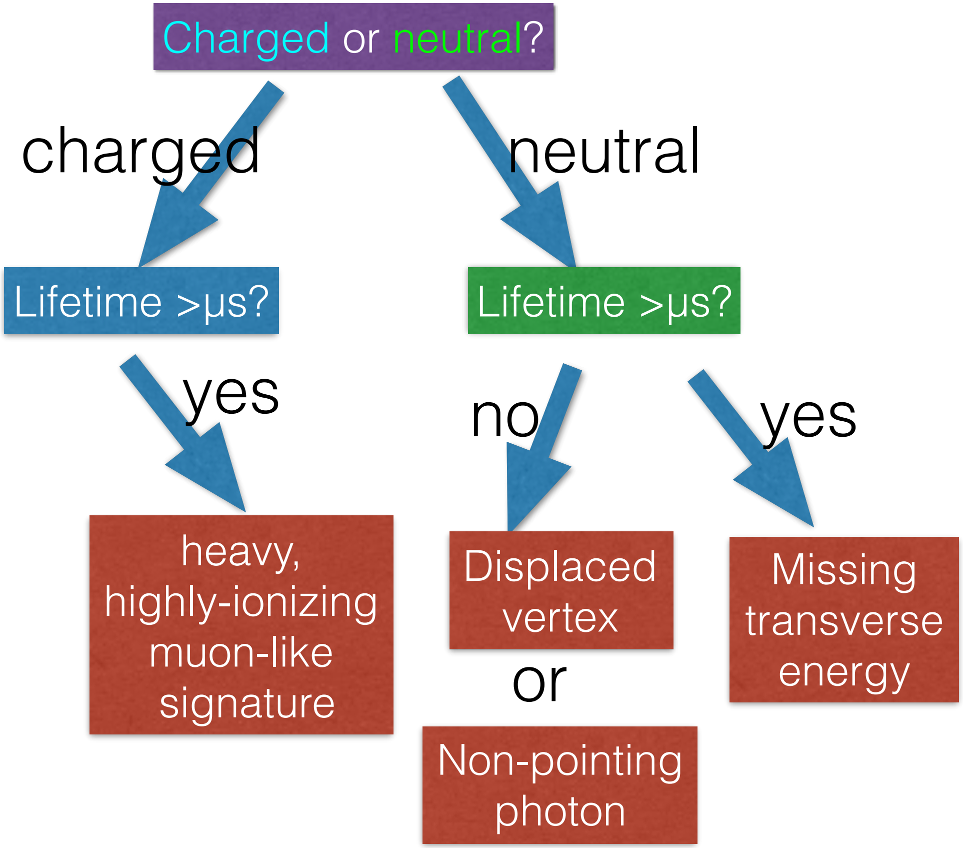

Charged or neutral?

charged

neutral

Lifetime >μs?

Lifetime >μs?

yes

no

yes

heavy, highly-ionizing muon-like signature

Displaced vertex

or

Non-pointing photon

Missing transverse energy

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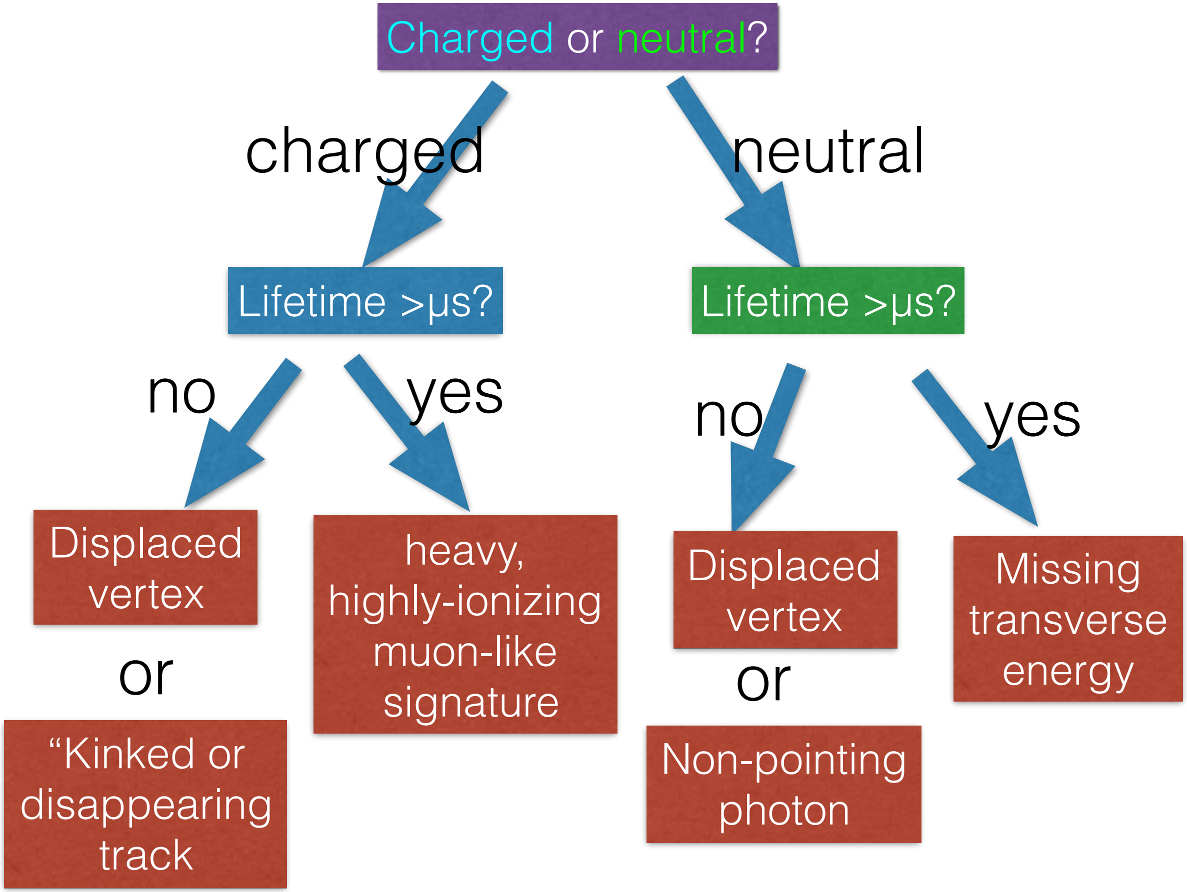

Charged or neutral?

charged

Lifetime >μs?

no

Displaced vertex

or

"Kinked or disappearing track

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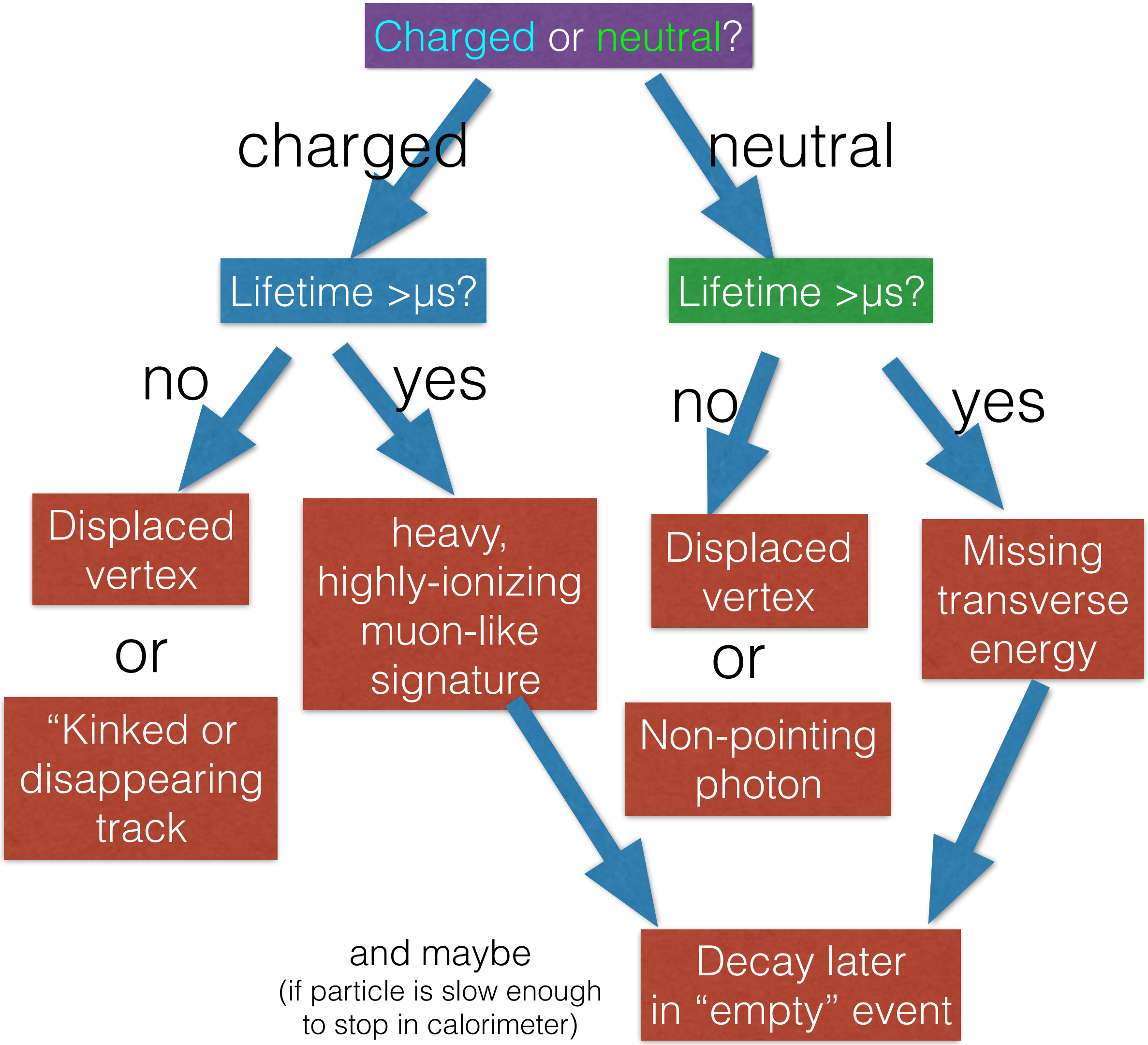


Charged or neutral?

charged

neutral

Lifetime >μs?

Lifetime >μs?

no

yes

no

yes

Displaced vertex

or

"Kinked or disappearing track"

heavy, highly-ionizing muon-like signature

Displaced vertex

or

Non-pointing photon

Missing transverse energy

and maybe
(if particle is slow enough to stop in calorimeter)

Decay later in "empty" event

What are we actually looking for?

“Standard” supersymmetry signature, studied by most analysis teams in ATLAS and CMS SUSY groups.

Displaced vertex

“Kinked or disappearing track

heavy, highly-ionizing muon-like signature

Displaced vertex

Non-pointing photon

Decay later in “empty” event

Missing transverse energy

What are we actually looking for?

All these signatures are covered by analyses in the ATLAS long-lived SUSY and exotics groups.

Displaced vertex

heavy, highly-ionizing muon-like signature

Displaced vertex

Missing transverse energy

“Kinked or disappearing track

Non-pointing photon

Decay later in “empty” event

Some physics models

(An extremely sketchy overview of a few possible examples of)

Some physics models

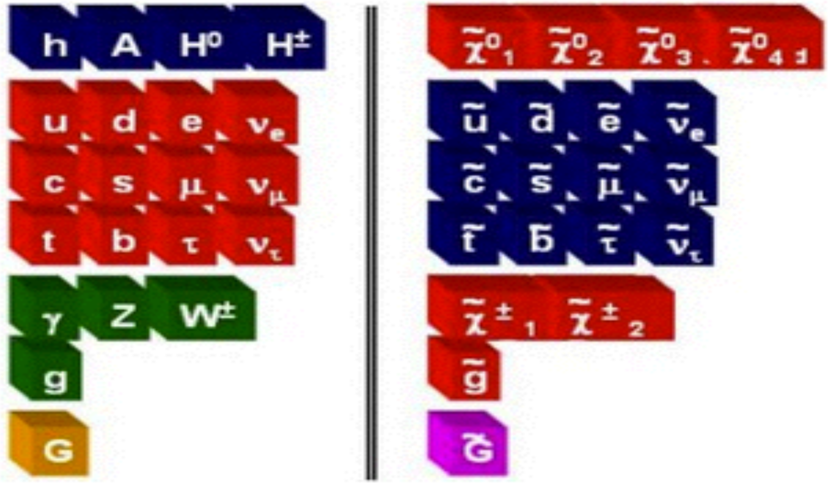
Why might we get LLPs?

- Long-lived particles can arise in a model if any of the following conditions are present:
  - Very small coupling in decay chain.
  - Strong virtuality due to decay via heavy particles.
  - Very small mass differences in decay chain (i.e. not much phase space for decay).
  - Pair production of particles with conserved quantum number.
- One or more of these cases are reasonably likely to come up when model-building.

→Searches for LLPs are an important part of the LHC physics program!

Supersymmetry

- Supersymmetry (SUSY) solves the Hierarchy Problem (sensible Higgs mass without fine-tuning) by introducing *superpartners* for SM particles.



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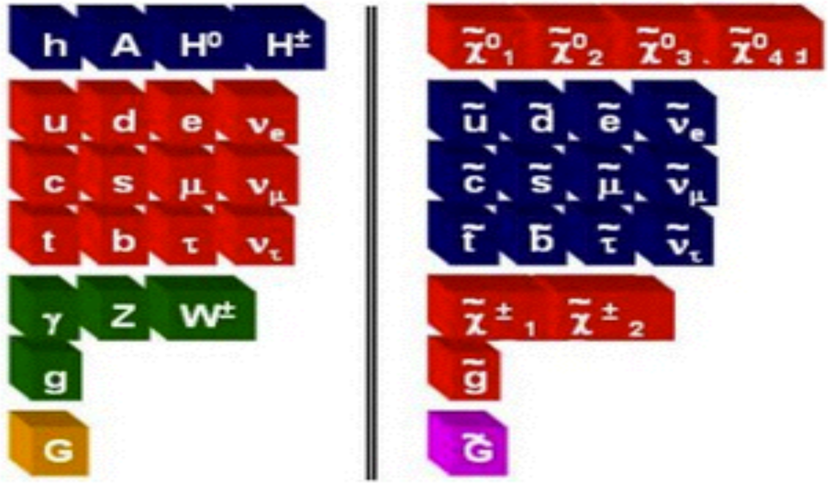

  - BUT, no SUSY particles (sparticles) have ever been seen..
  - ➔Supersymmetry is not a perfect symmetry – must be broken by some mechanism.

Some SUSY breaking mechanisms

- Gravity-mediated (e.g. mSUGRA).
- Gauge-mediated SUSY breaking (GMSB).
  - SUSY breaking communicated via SM gauge interactions.
  - Gravitino acquires mass (Lightest SupersymmetricParticle (LSP)).

    ➔Depending on SUSY-breaking scale, NLSP can be long-lived.
- Anomaly-mediated SUSY breaking (AMSB).
  - SUSY breaking is caused by loop effects, gives constrained mass spectrum:
  - Ratios of gaugino masses are approximately:

    $M_{bino} : M_{wino} : M_{gluino} \approx 3 : 1 : 7$
  - Masses of lightest chargino and lightest neutralino are nearly degenerate.

    ➔lightest chargino has long lifetime!
- Split SUSY.
  - New bosons are at very high mass scale, while new fermions at TeV-scale.

    ➔gluino has long lifetime!

    (will combine with SM quarks and gluons to form “R-hadrons”).

R-Parity Violating (RPV) SUSY

- Many SUSY models assume R-Parity conservation, i.e. Lightest Supersymmetric Particle (LSP) is stable.
  - (Excellent Dark Matter candidate!)
- BUT no reason to assume this *a priori*..
  - If we introduce R-Parity Violating terms into superpotential, LSP can decay to SM particles.

$$\lambda_{ijk} L^i L^j \overline{E}^k + \lambda'_{ijk} L^i Q^j \overline{D}^k + \lambda''_{ijk} \overline{U}^i \overline{D}^j \overline{D}^k + \epsilon_i L_i H_2$$

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$$\underbrace{\lambda_{ijk} L^i L^j \overline{E}^k + \lambda'_{ijk} L^i Q^j \overline{D}^k}_{\text{Lepton number violating}} + \lambda''_{ijk} \overline{U}^i \overline{D}^j \overline{D}^k + \epsilon_i L_i H_2$$

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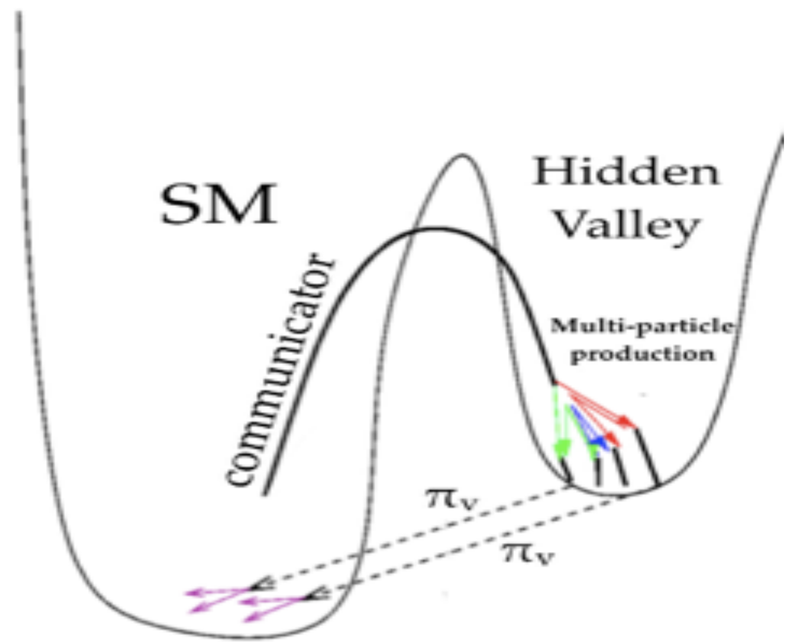
  - If these couplings are weak, LSP can have a long lifetime.

Hidden valley

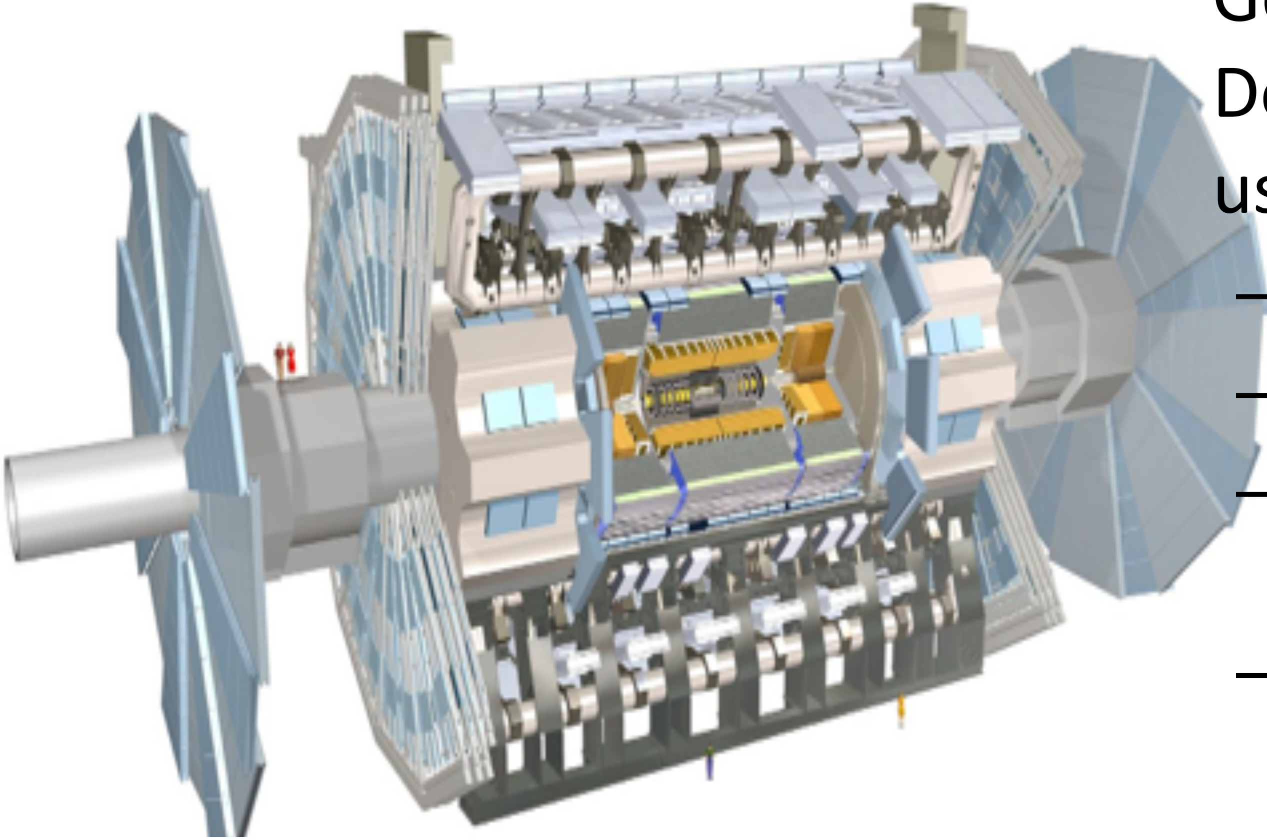
- Hidden sector interacts with SM via (heavy) Communicator particle(s).
  - Could be new Z’, Higgs boson or bosons, heavy sterile neutrinos, or something else..



Weak coupling between SM and hidden sectors can lead to particles in hidden sector having long lifetimes.

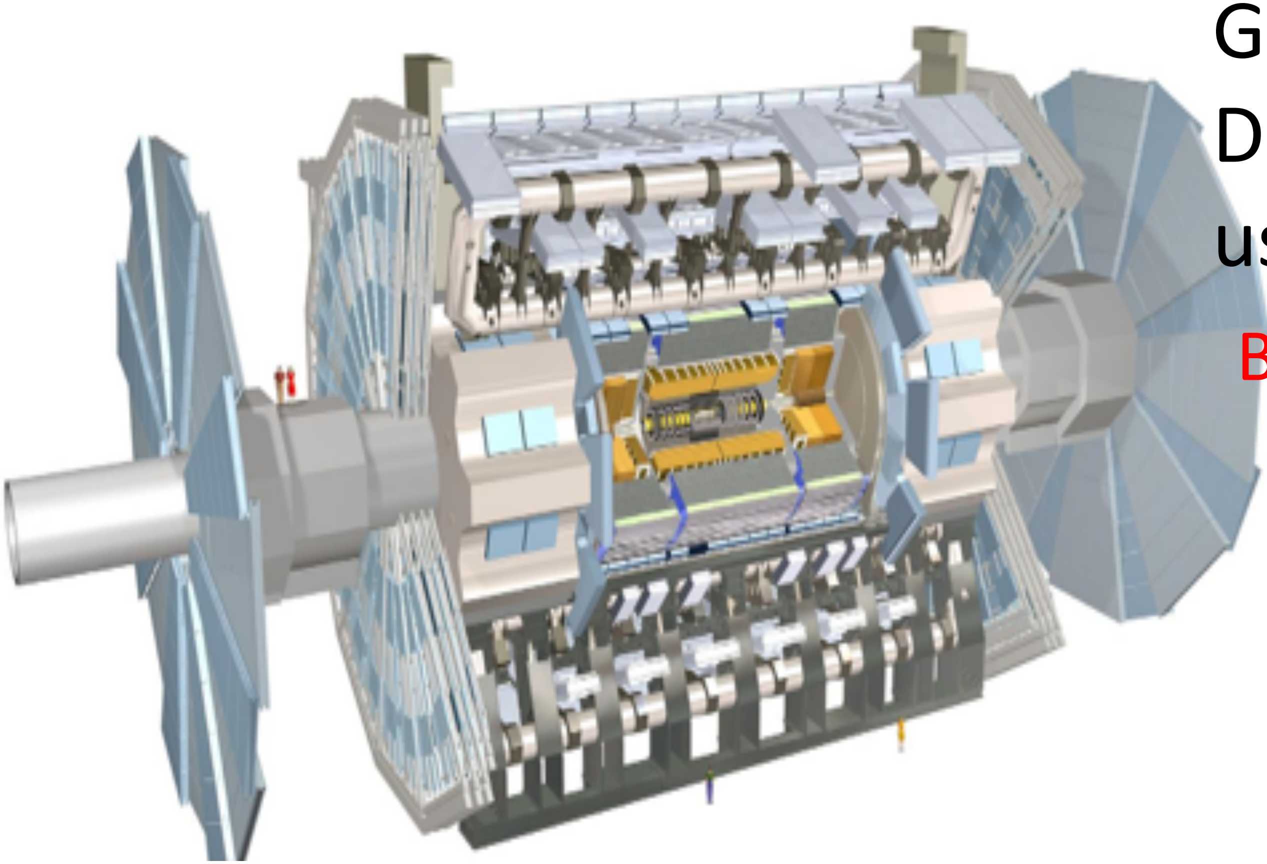
The Detector

The ATLAS detector



- ATLAS is a great General Purpose Detector for all the usual reasons..
  - Hermetic coverage.
  - Precise tracking.
  - Good calorimeter energy resolution.
  - Efficient muon reconstruction.
  - ….

The ATLAS detector



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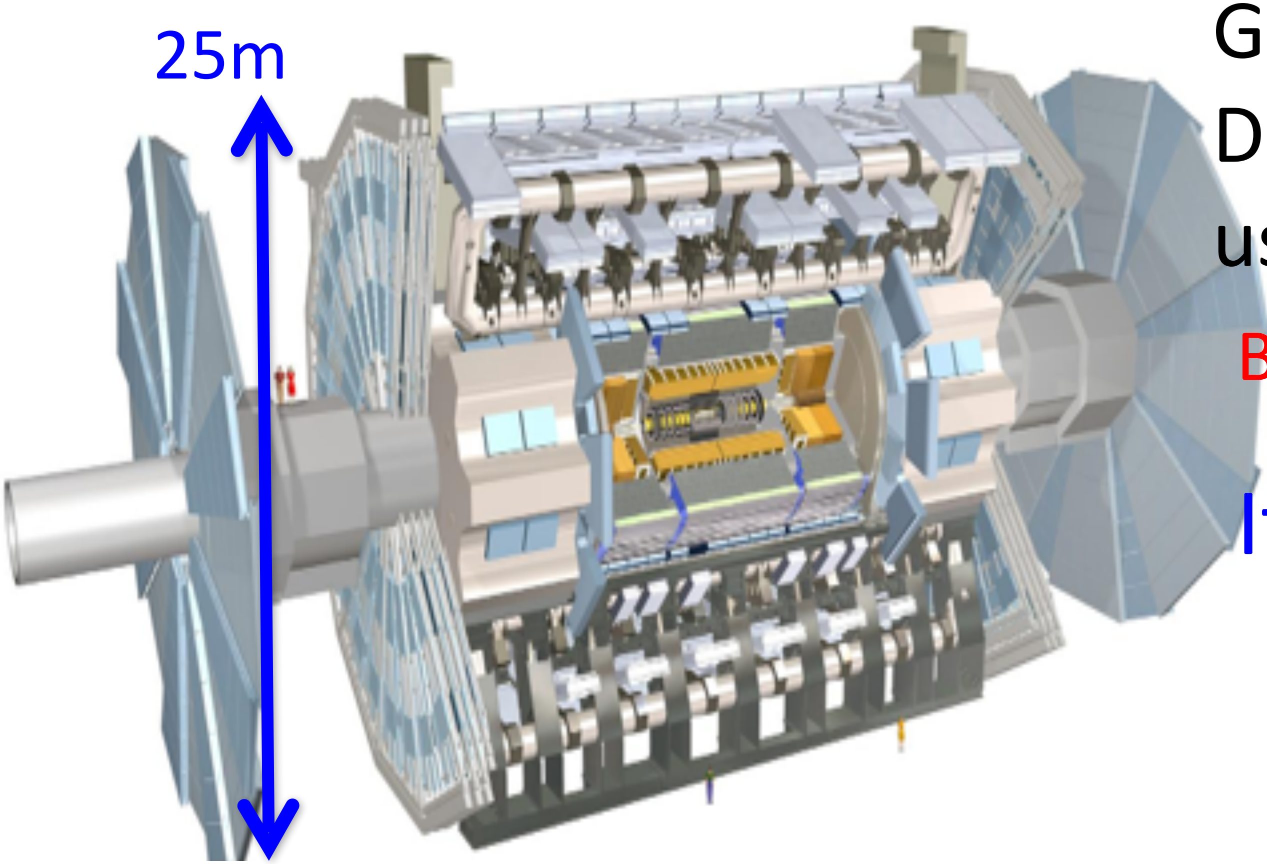
But also…..

The ATLAS detector

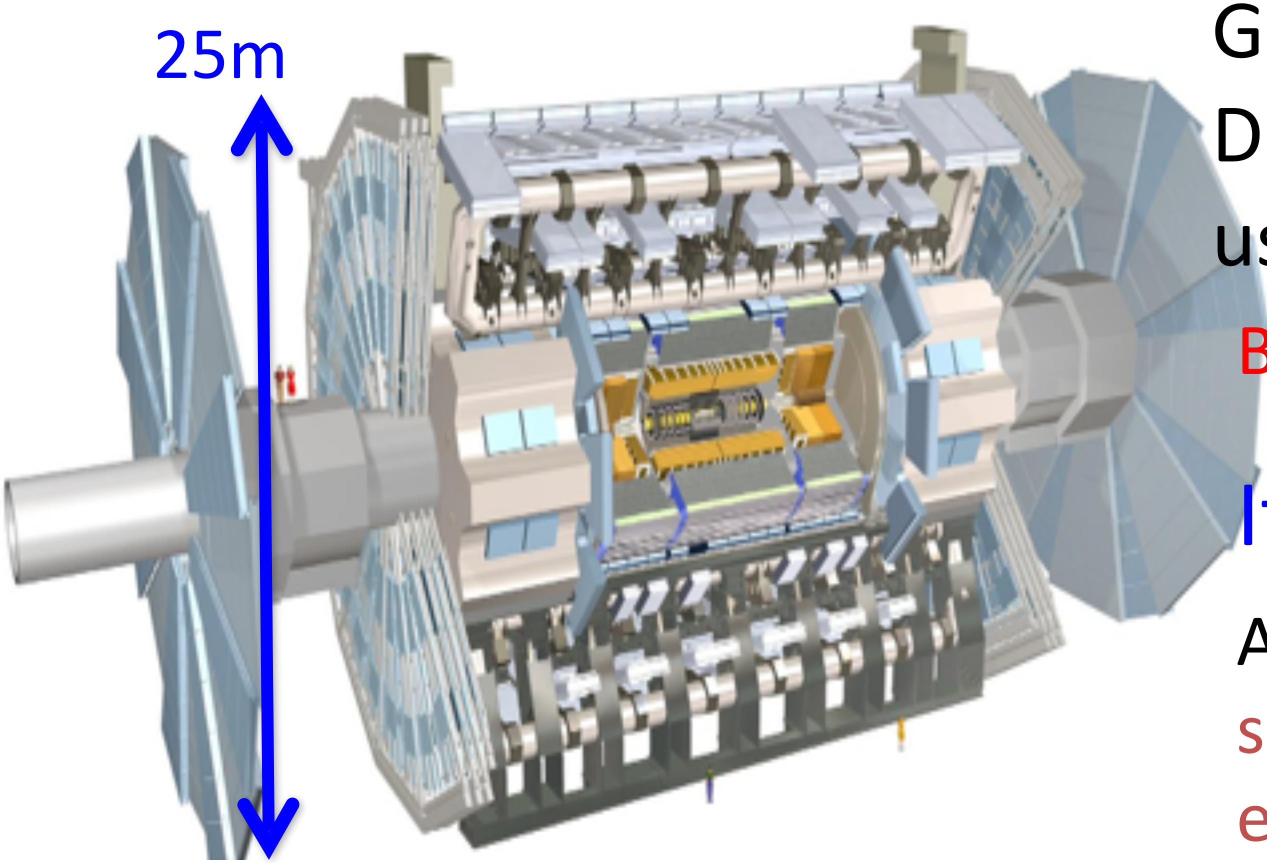


- ATLAS is a great General Purpose Detector for all the usual reasons..

But also…..

It is BIG!!

The ATLAS detector



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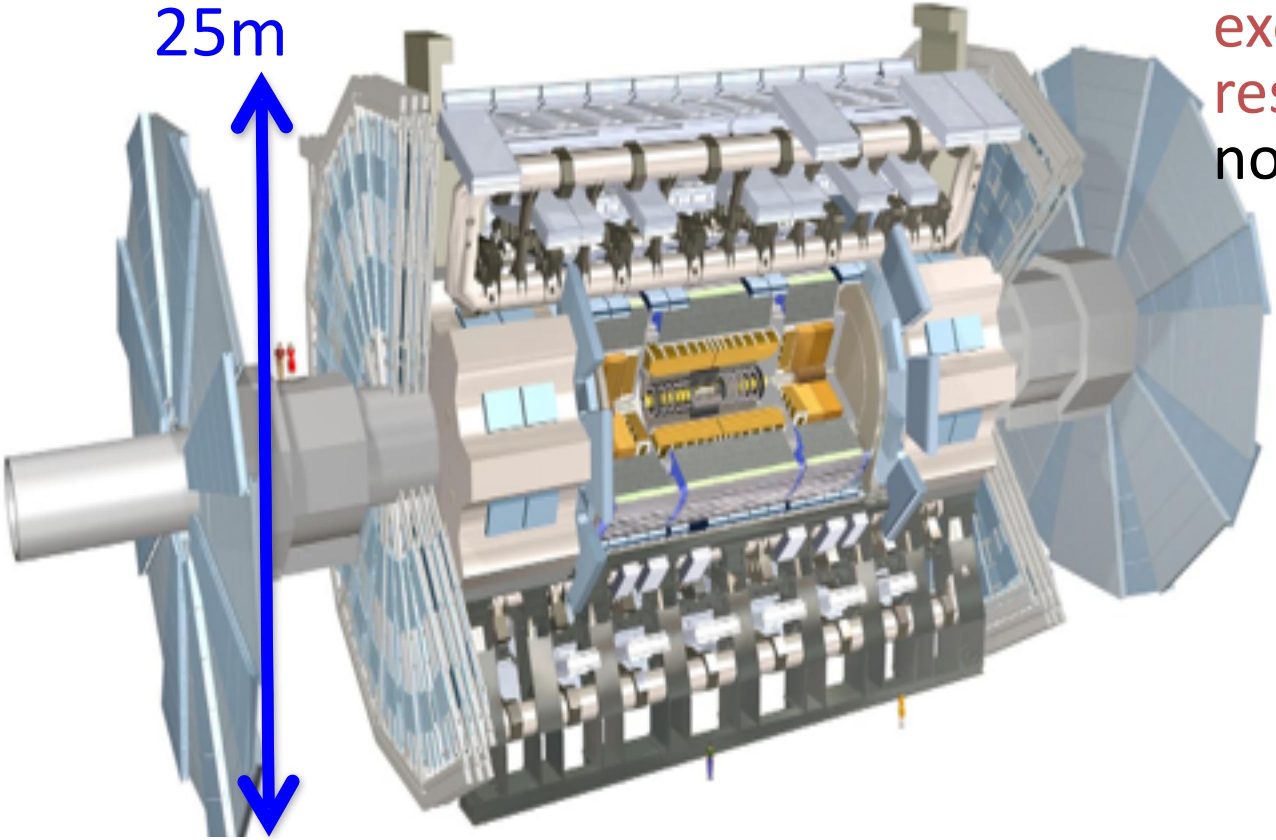
But also…..

It is BIG!!

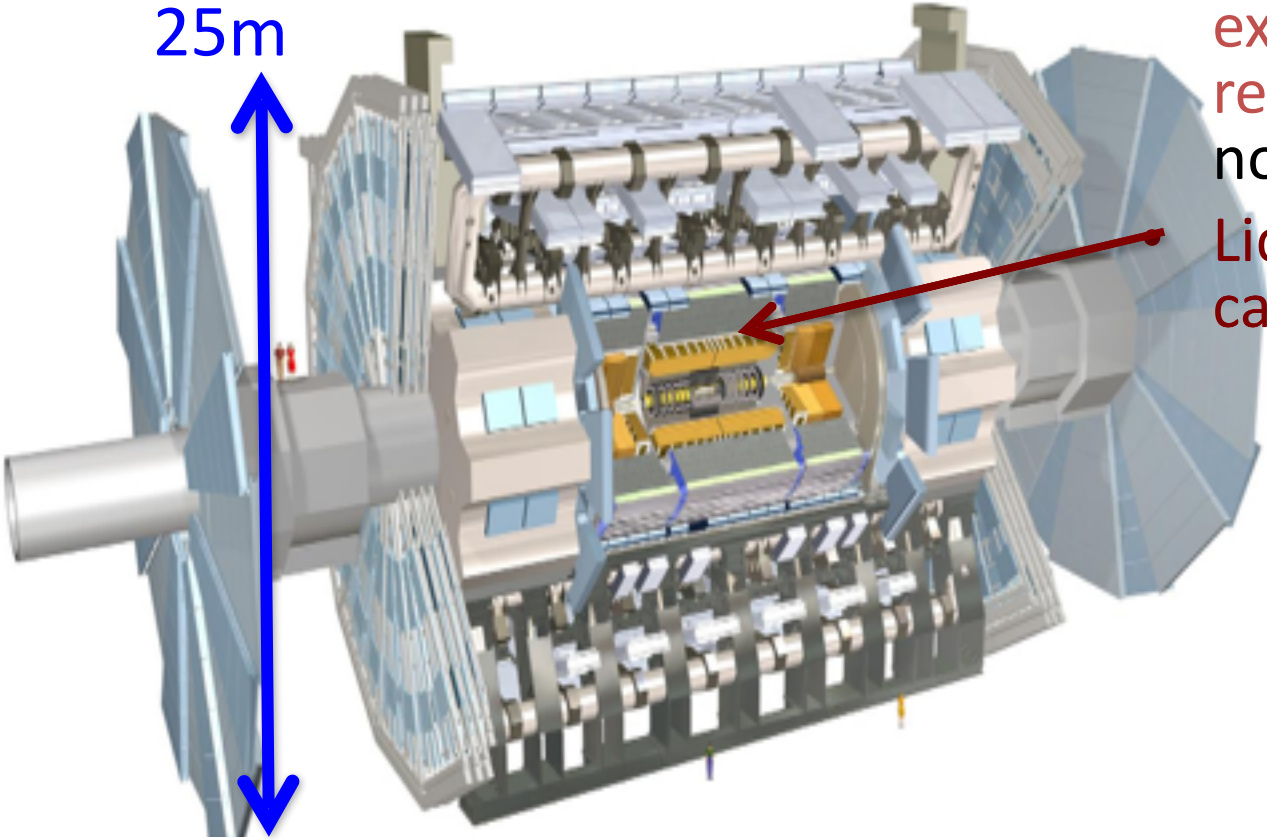
And has several subdetectors with excellent time resolution!

The ATLAS detector



- ATLAS has several subdetectors with excellent time resolution, including (but not only):

The ATLAS detector



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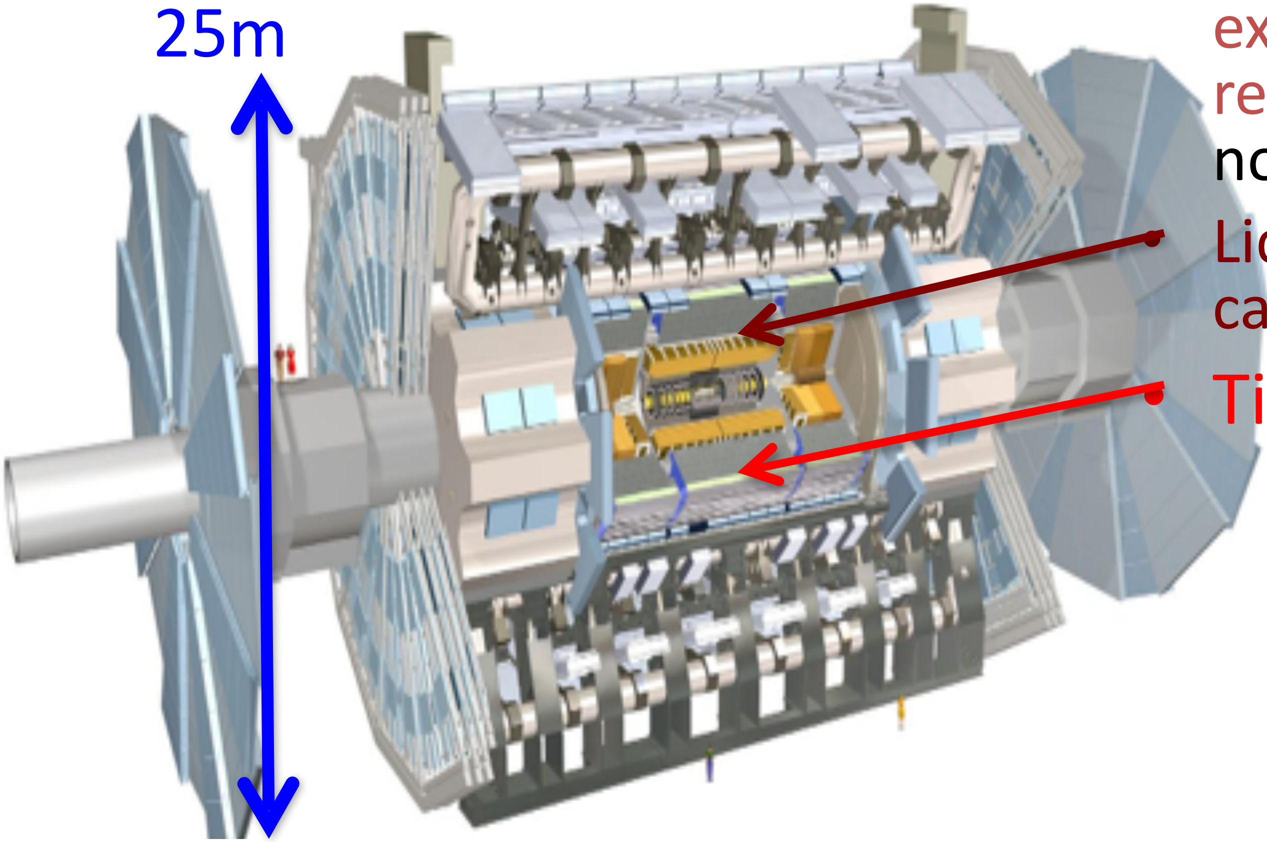
Liquid Argon (LAr) calorimeter.

The ATLAS detector

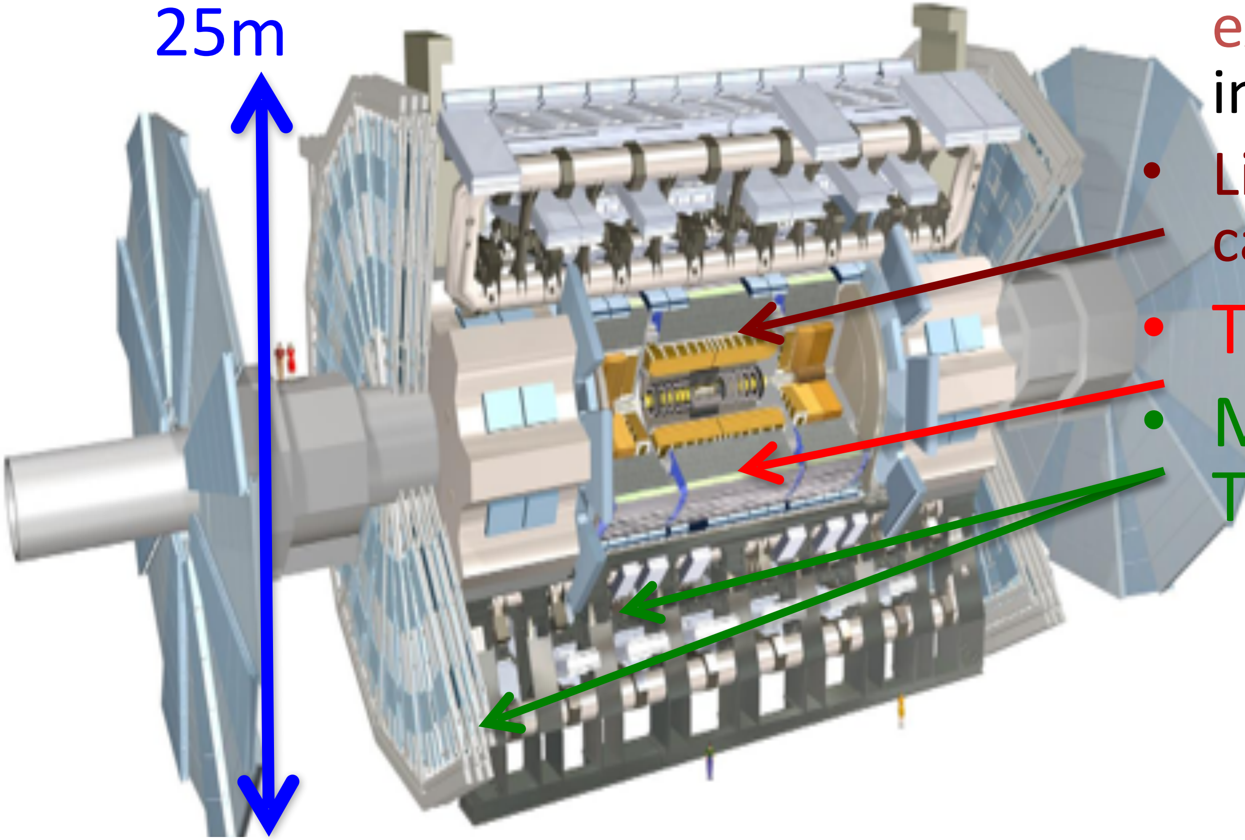


- ATLAS has several subdetectors with excellent time resolution, including (but not only):

Liquid Argon (LAr) calorimeter.

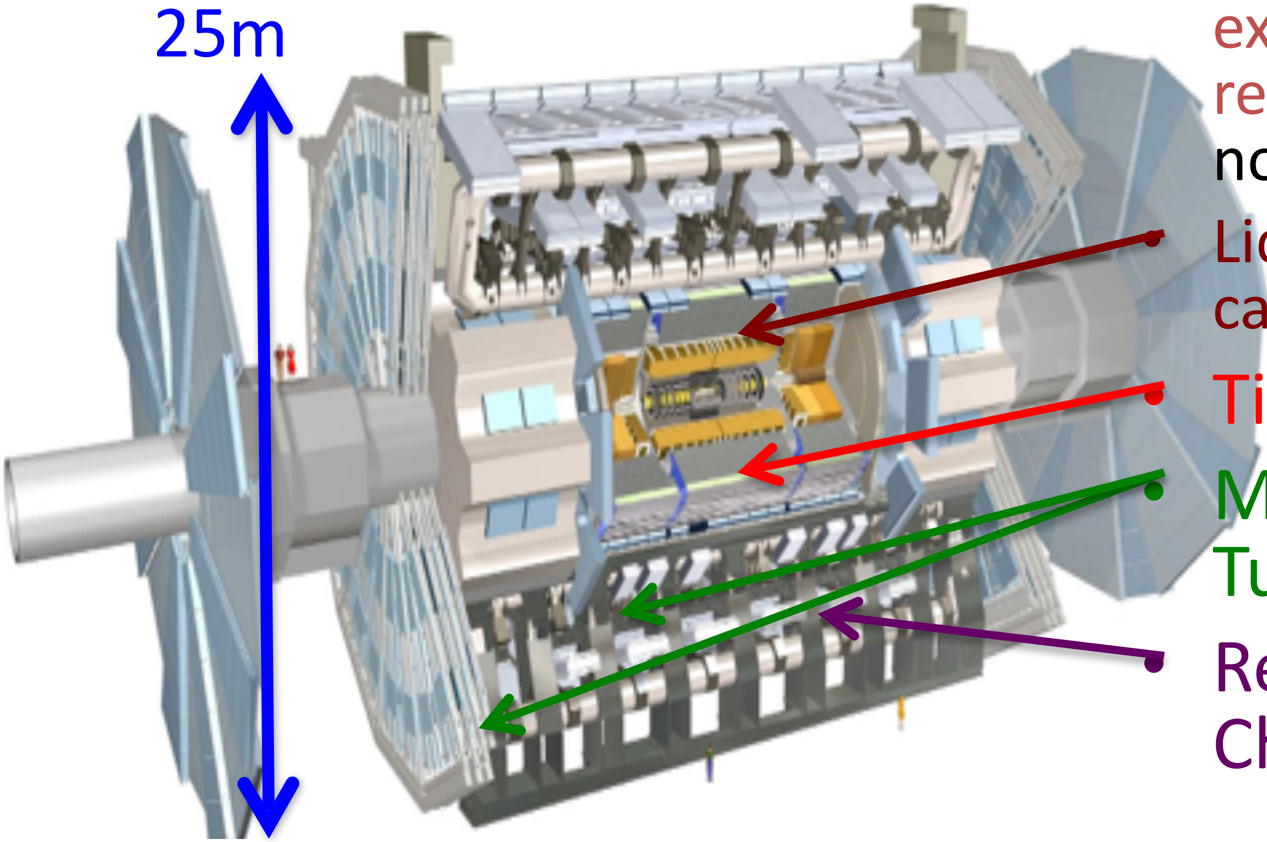
Tile calorimeter.

The ATLAS detector



- ATLAS has several subdetectors with excellent time resolution, including (but not only):
- Liquid Argon (LAr) calorimeter.
- Tile calorimeter.
- Monitored Drift Tubes (MDTs).

The ATLAS detector



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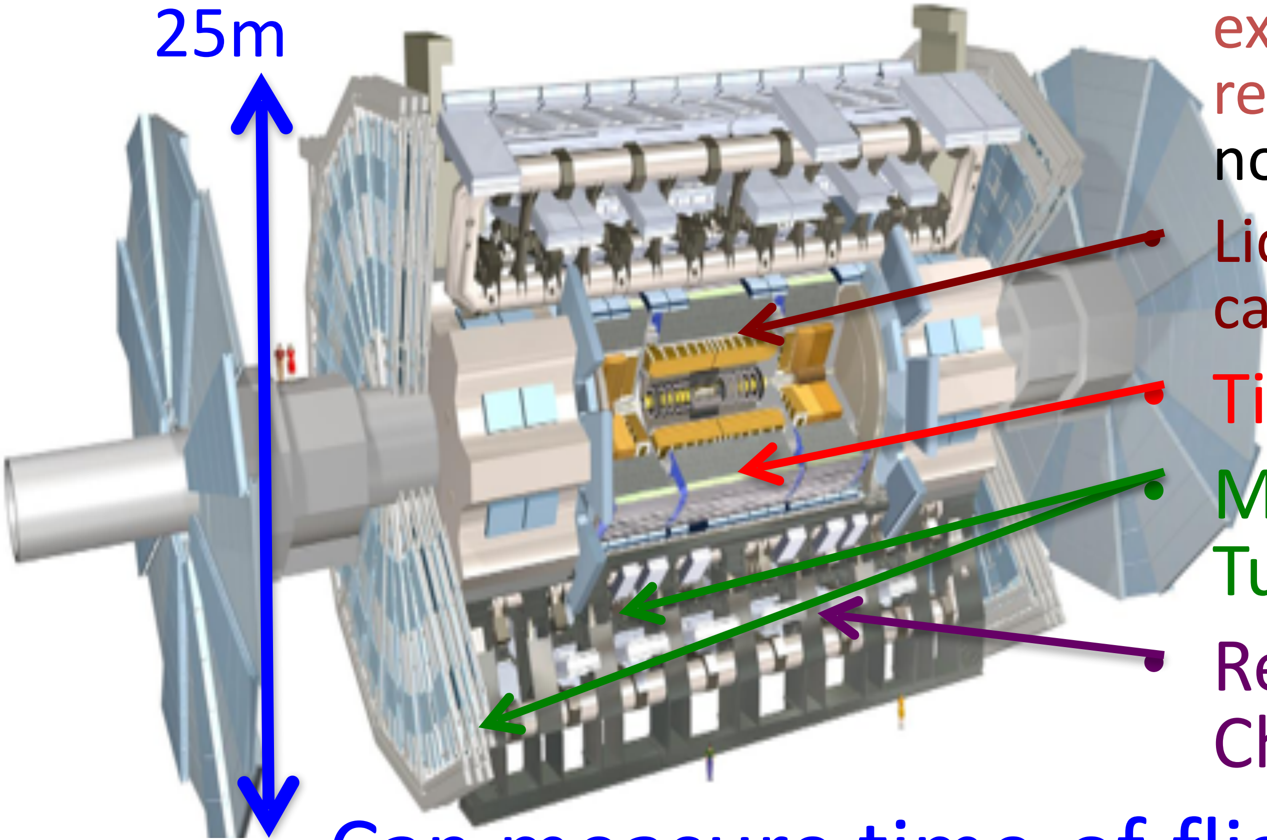
  - Monitored Drift Tubes (MDTs).
  - Resistive Plate Chambers (RPCs).

The ATLAS detector



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  - Liquid Argon (LAr) calorimeter.
  - Tile calorimeter.
  - Monitored Drift Tubes (MDTs).
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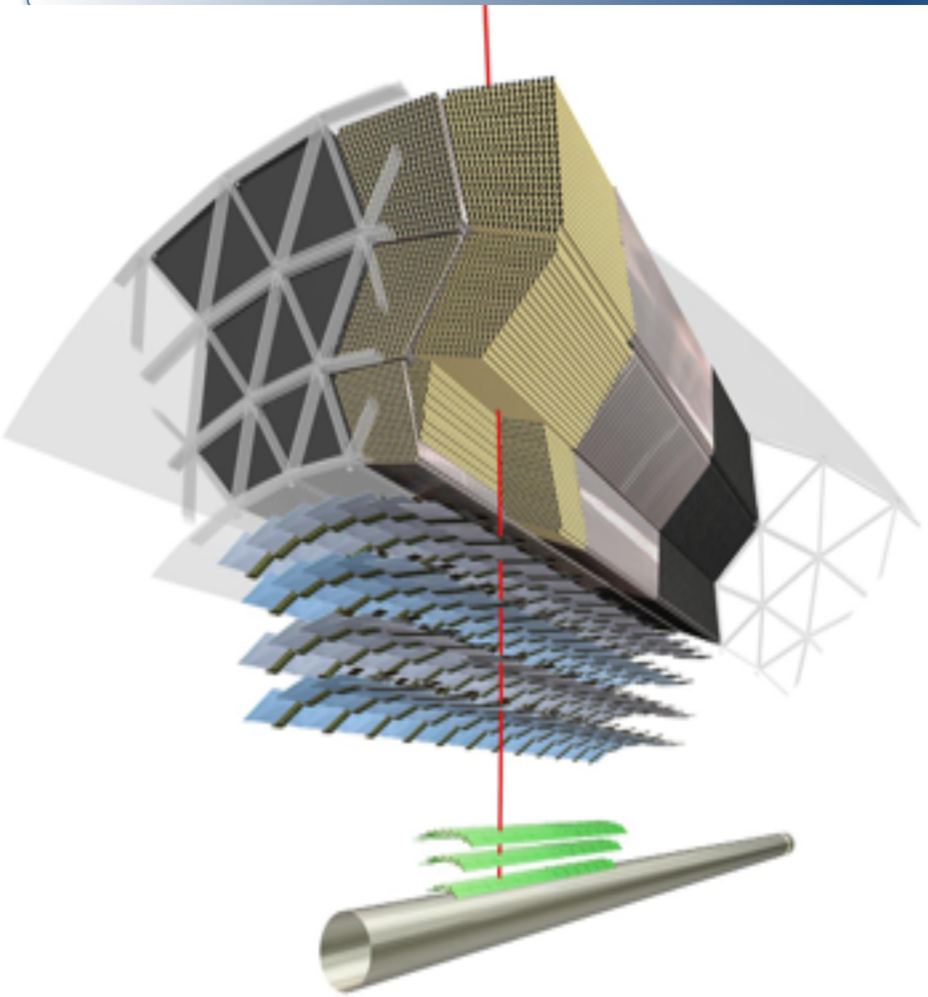
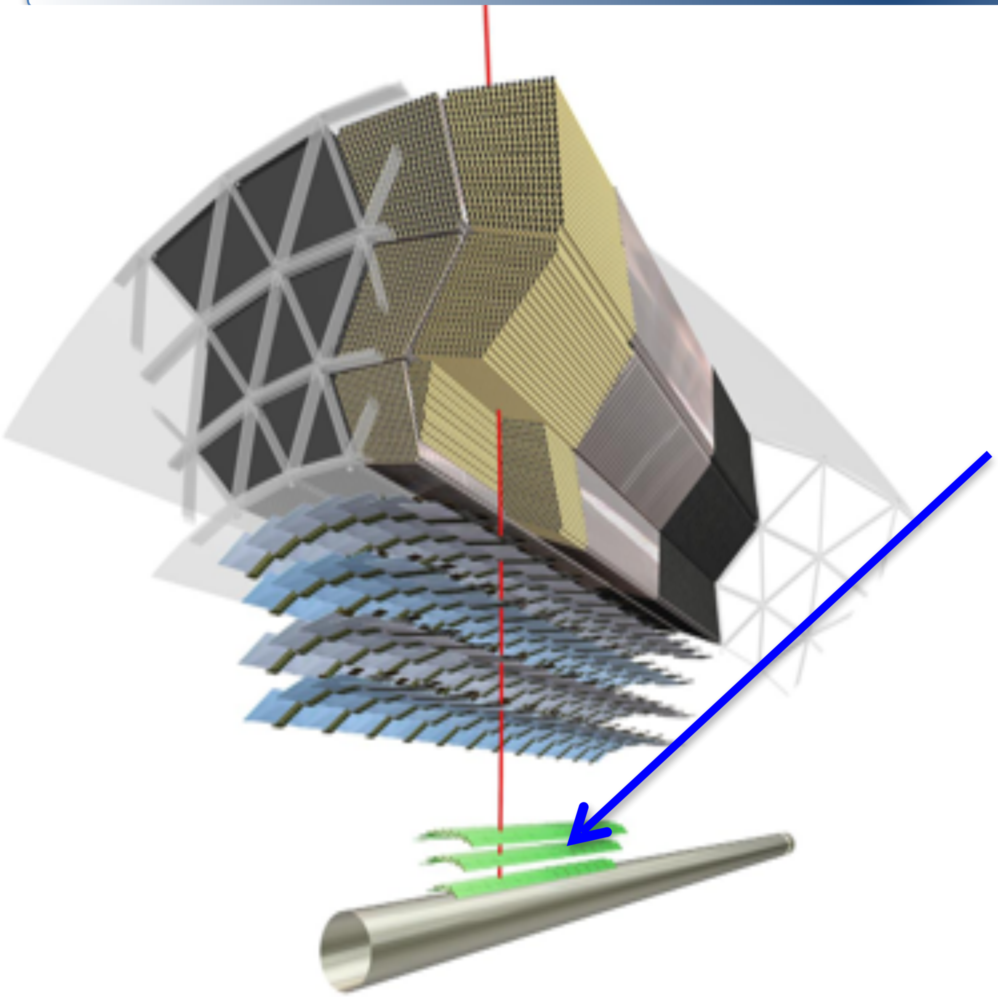
Can measure time-of-flight!

The ATLAS Inner Detector (ID)



ATLAS inner tracking system consists of:

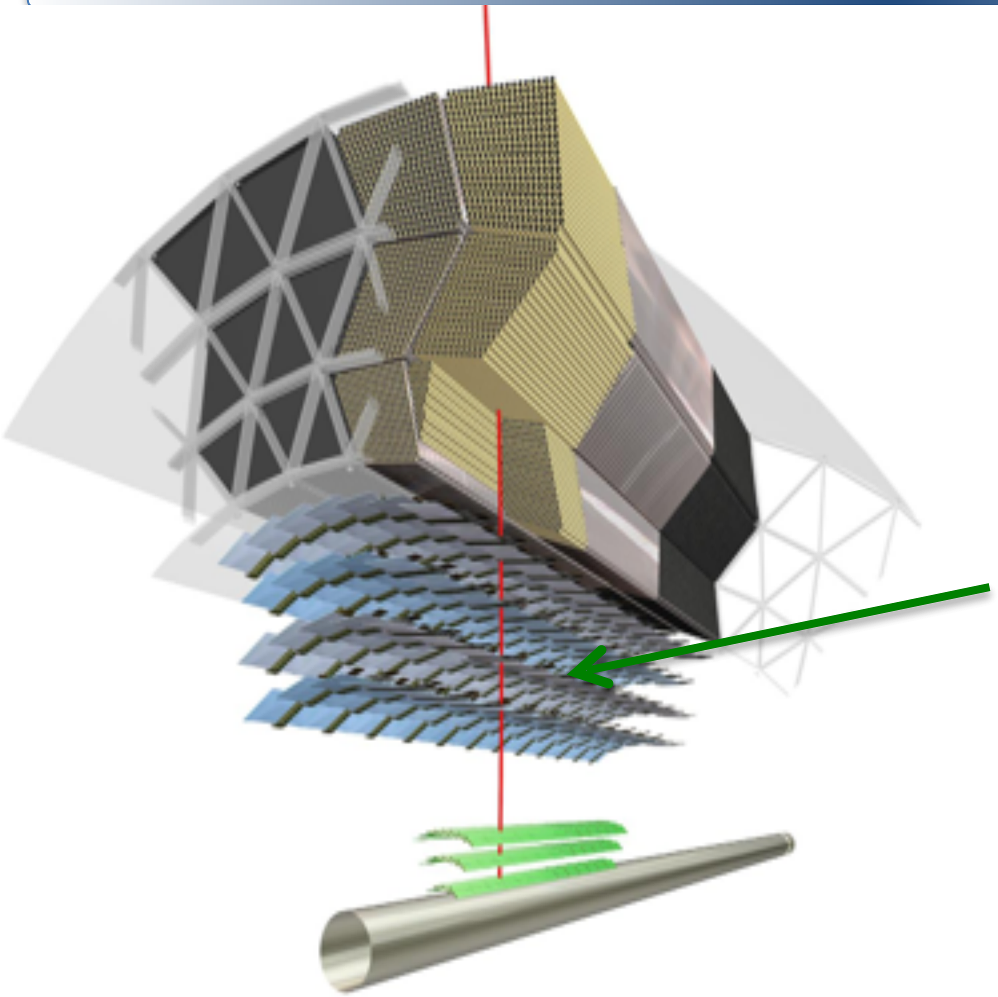
The ATLAS Inner Detector (ID)



ATLAS inner tracking system consists of:

Pixel detector.

The ATLAS Inner Detector (ID)



ATLAS inner tracking system consists of:

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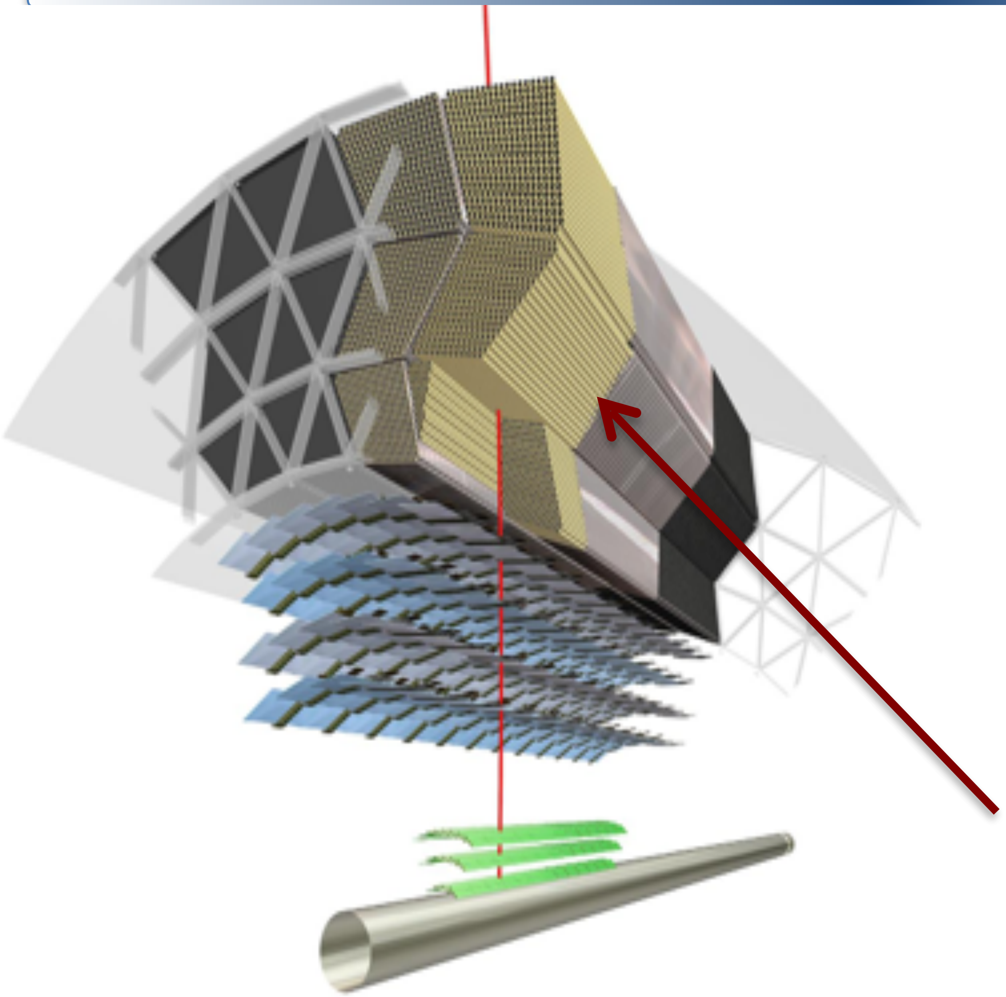
Semiconductor Tracker (SCT).

The ATLAS Inner Detector (ID)



ATLAS inner tracking system consists of:

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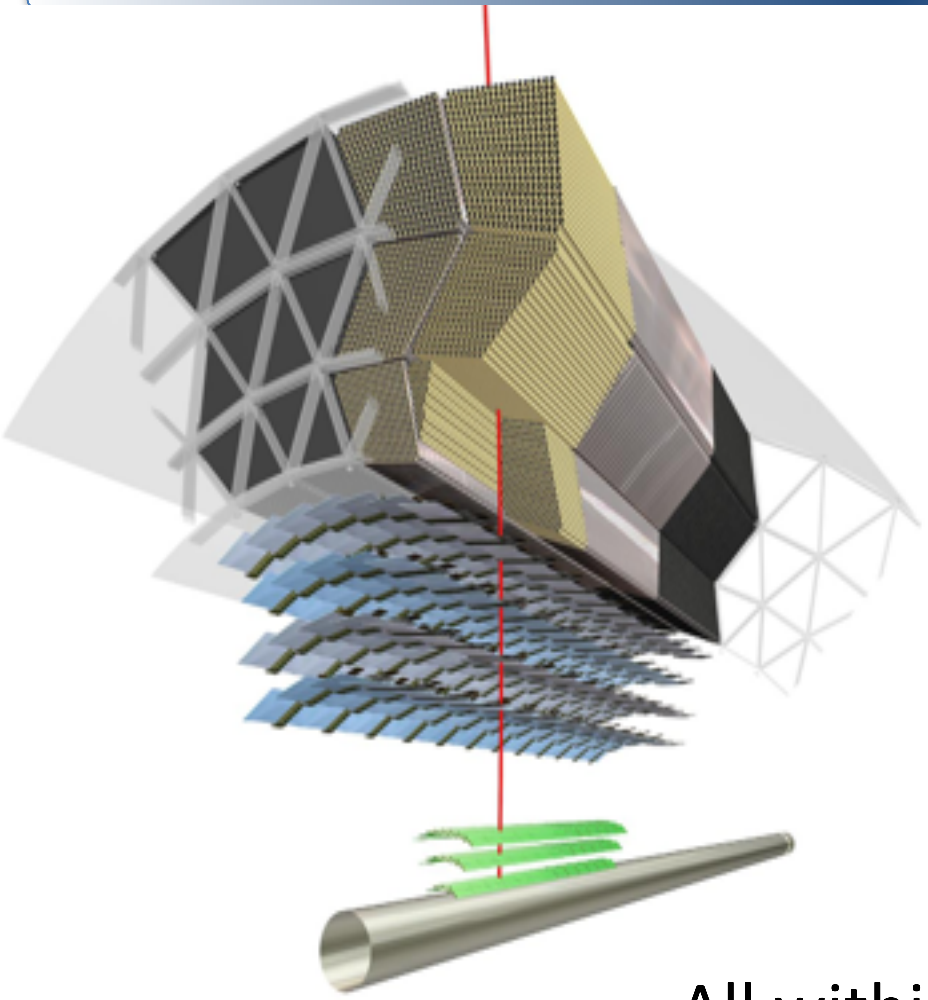
Semiconductor Tracker (SCT).

Transition Radiation Tracker (TRT).

The ATLAS Inner Detector (ID)



ATLAS inner tracking system consists of:

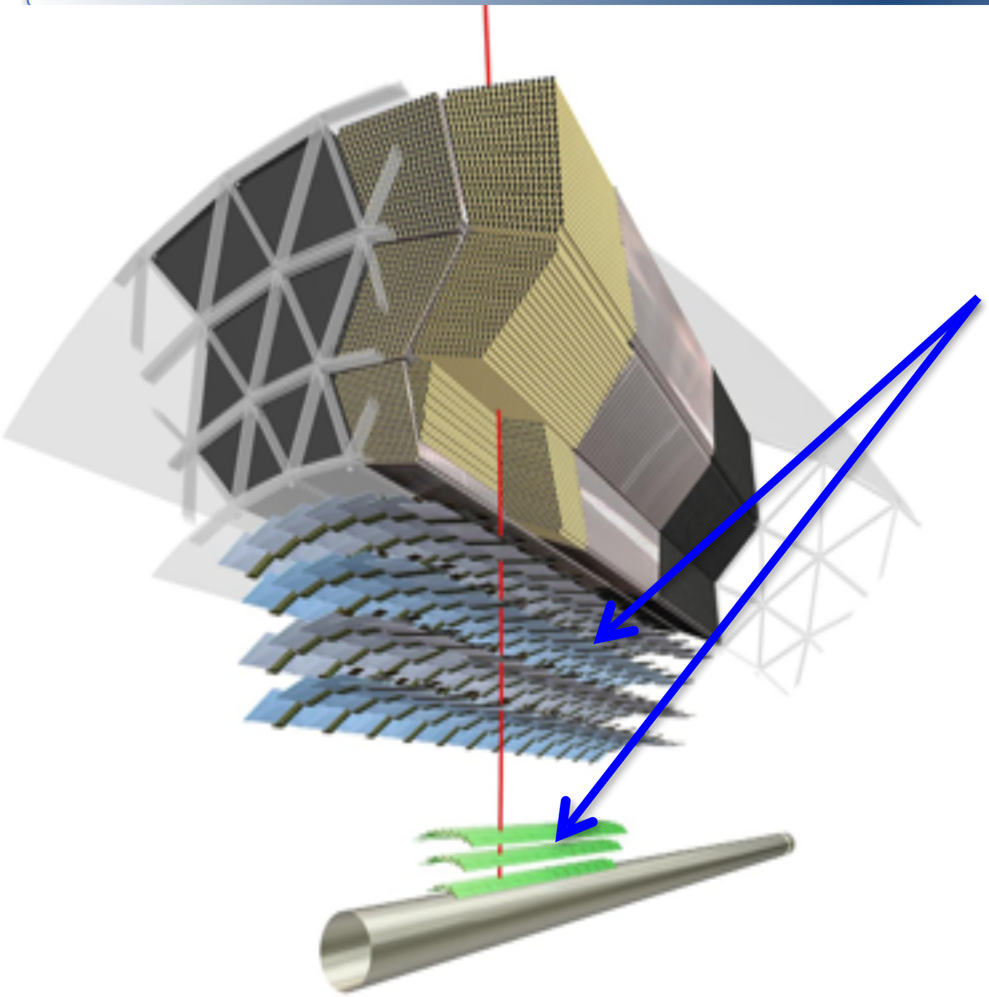
Pixel detector.

Semiconductor Tracker (SCT).

Transition Radiation Tracker (TRT).

All within a 2T solenoidal B-field.

The ATLAS Inner Detector (ID)

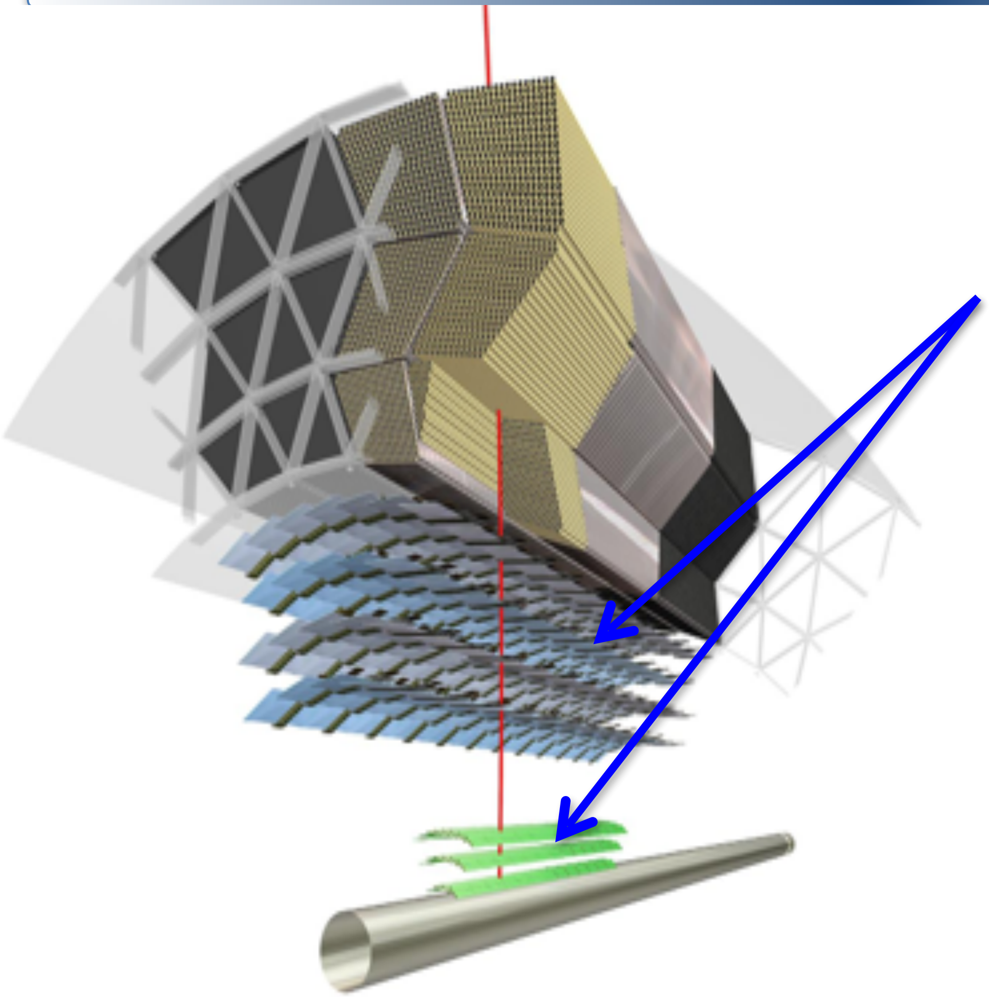


i.e. it has:

Precise Silicon detectors

- Good for finding vertices!

The ATLAS Inner Detector (ID)



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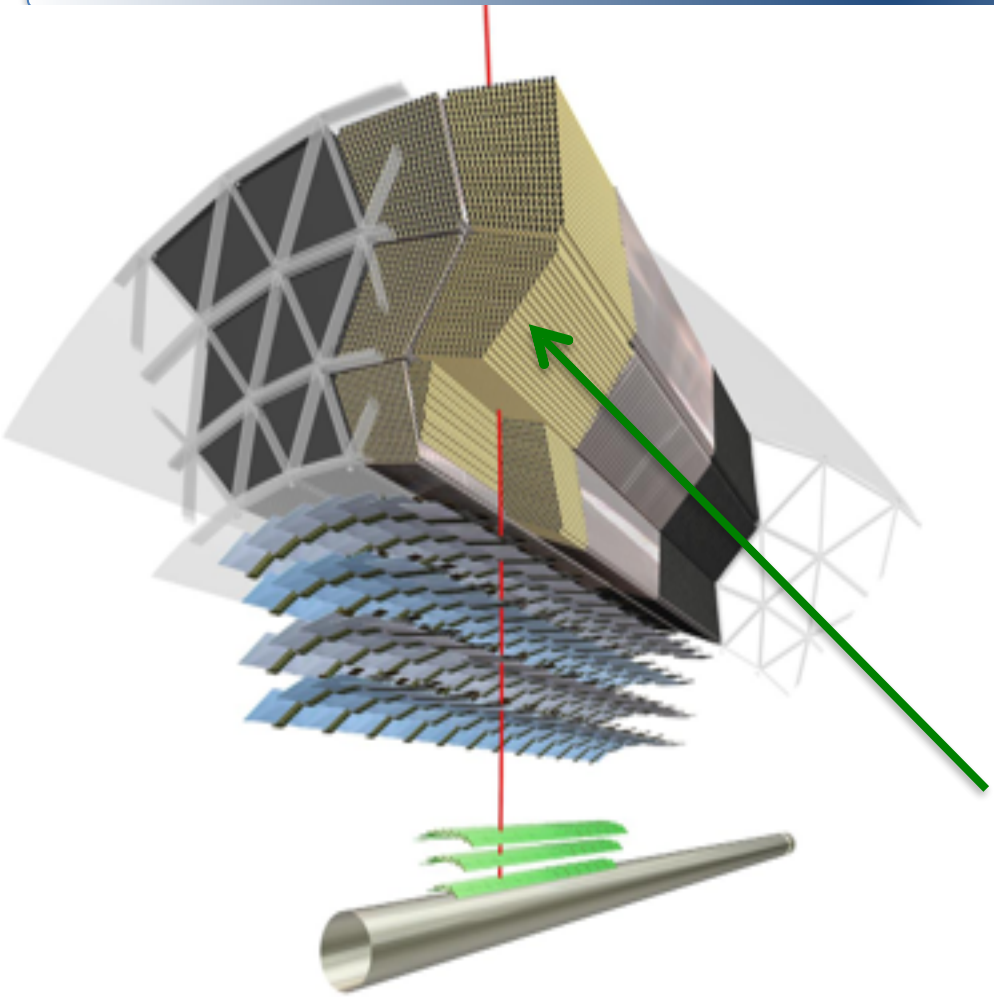
The ATLAS Inner Detector (ID)



i.e. it has:

Precise Silicon detectors

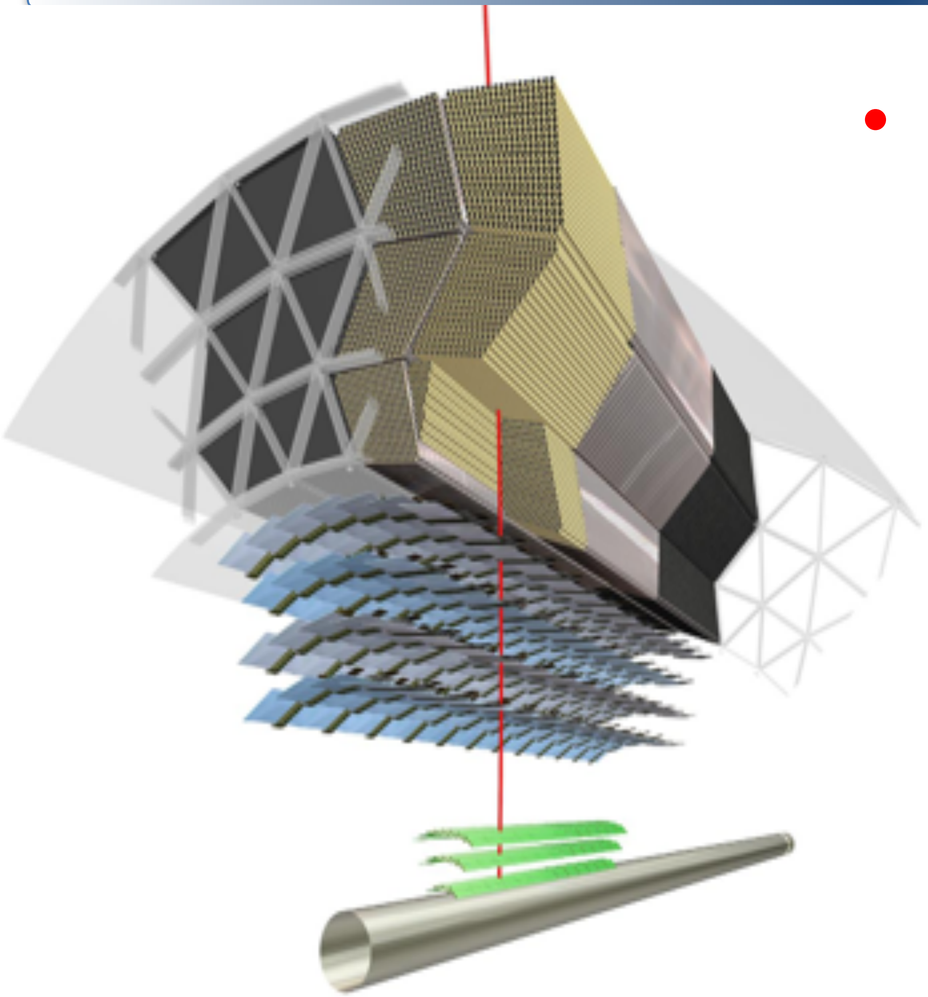
- Good for finding vertices!

and

a continuous tracker

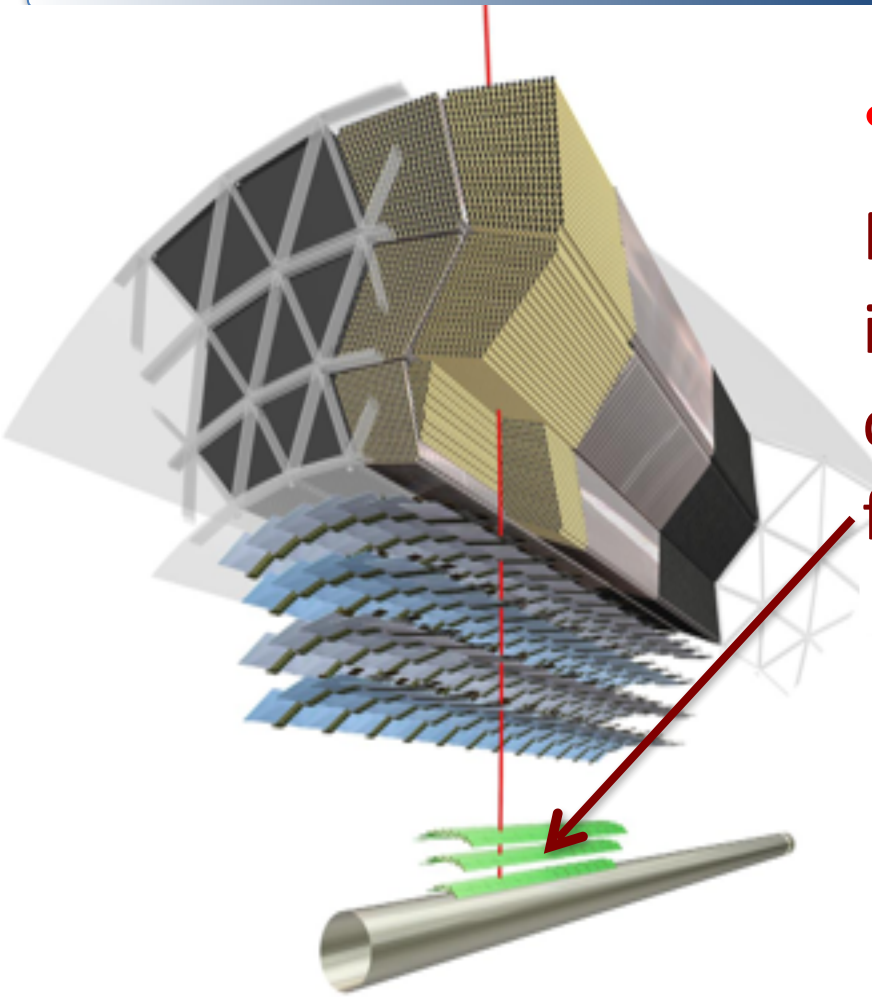
- Can detect kinked or disappearing tracks!

The ATLAS Inner Detector (ID)



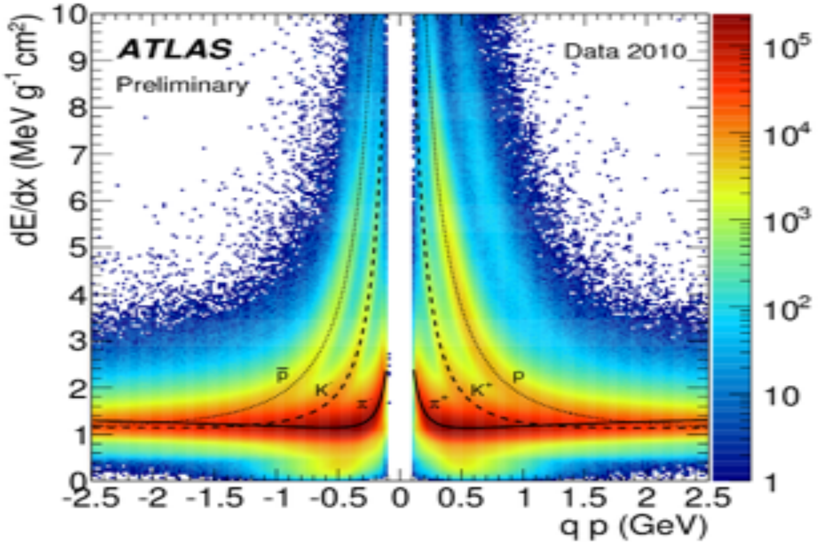
- And there's more!!

The ATLAS Inner Detector (ID)

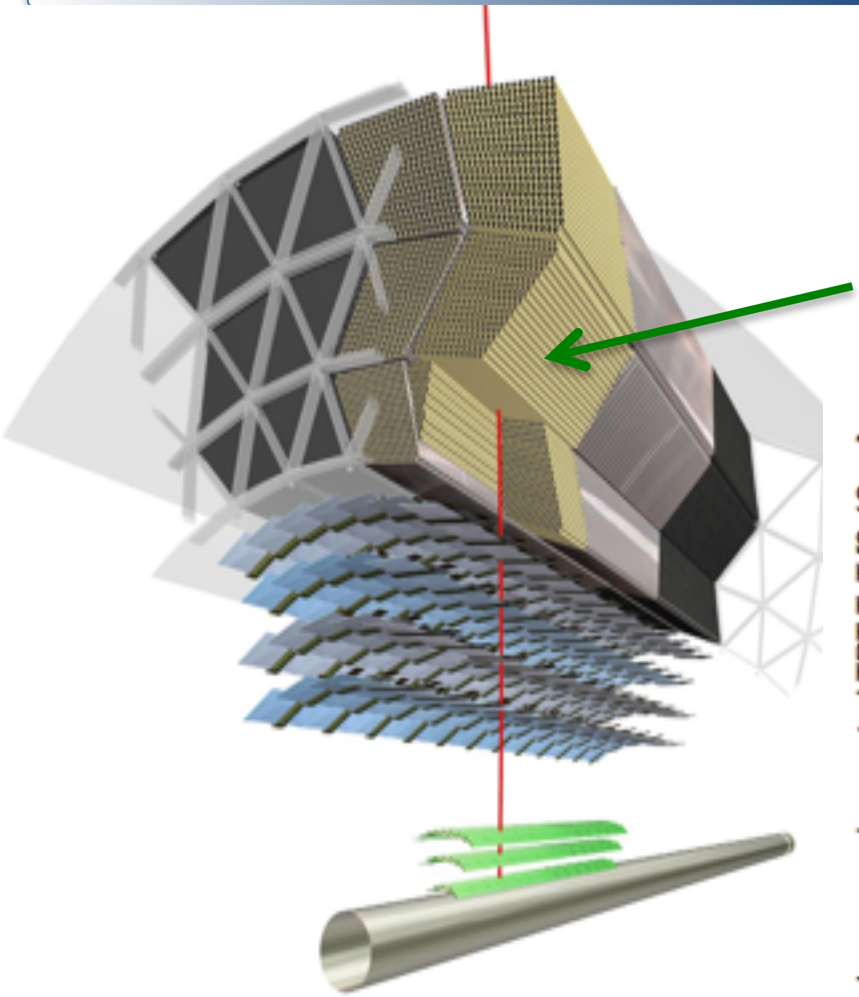


- And there's more!!

Pixel detector can measure ionization energy loss *dE/dx* via charge deposited (calculated from Time-over-Threshold).

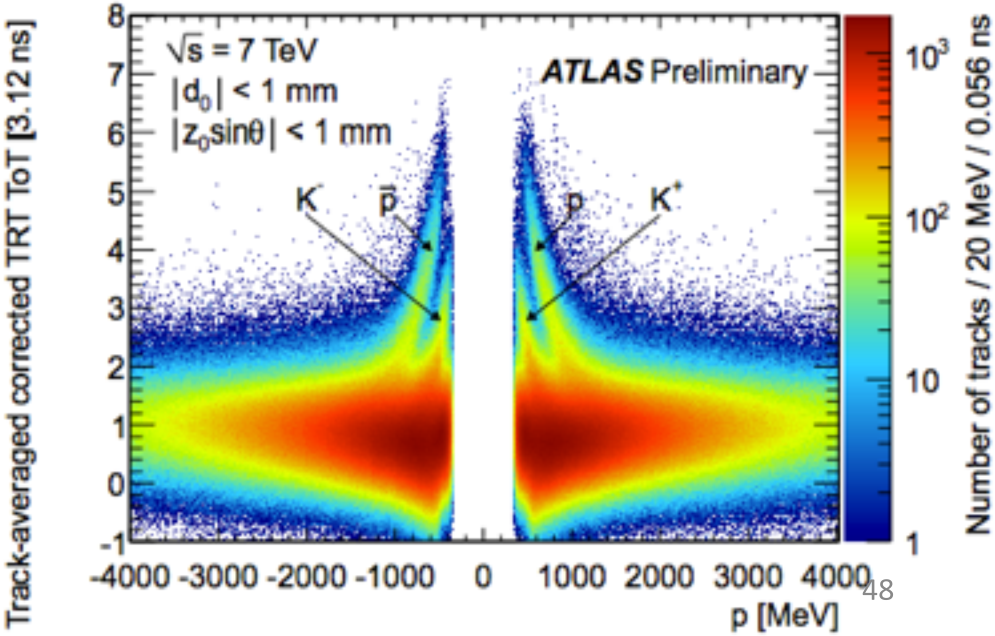


The ATLAS Inner Detector (ID)



- And there's more!!

TRT can also measure *dE/dx* via Time-over-Threshold.



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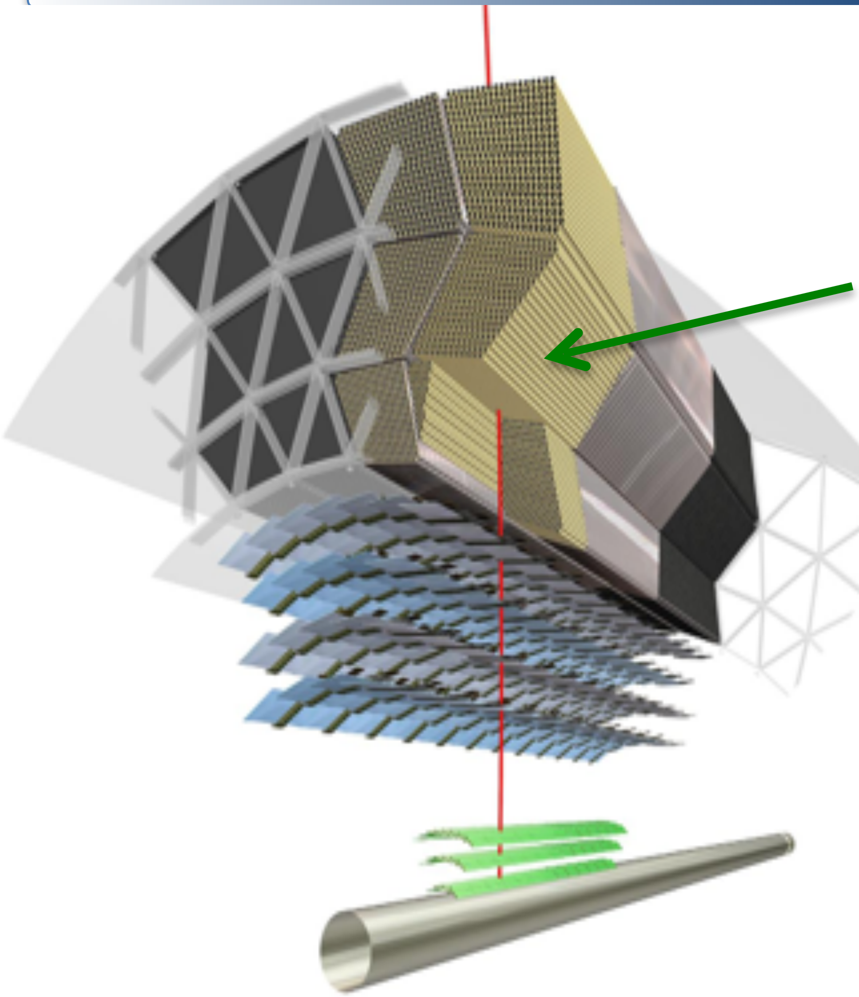


- And there's more!!

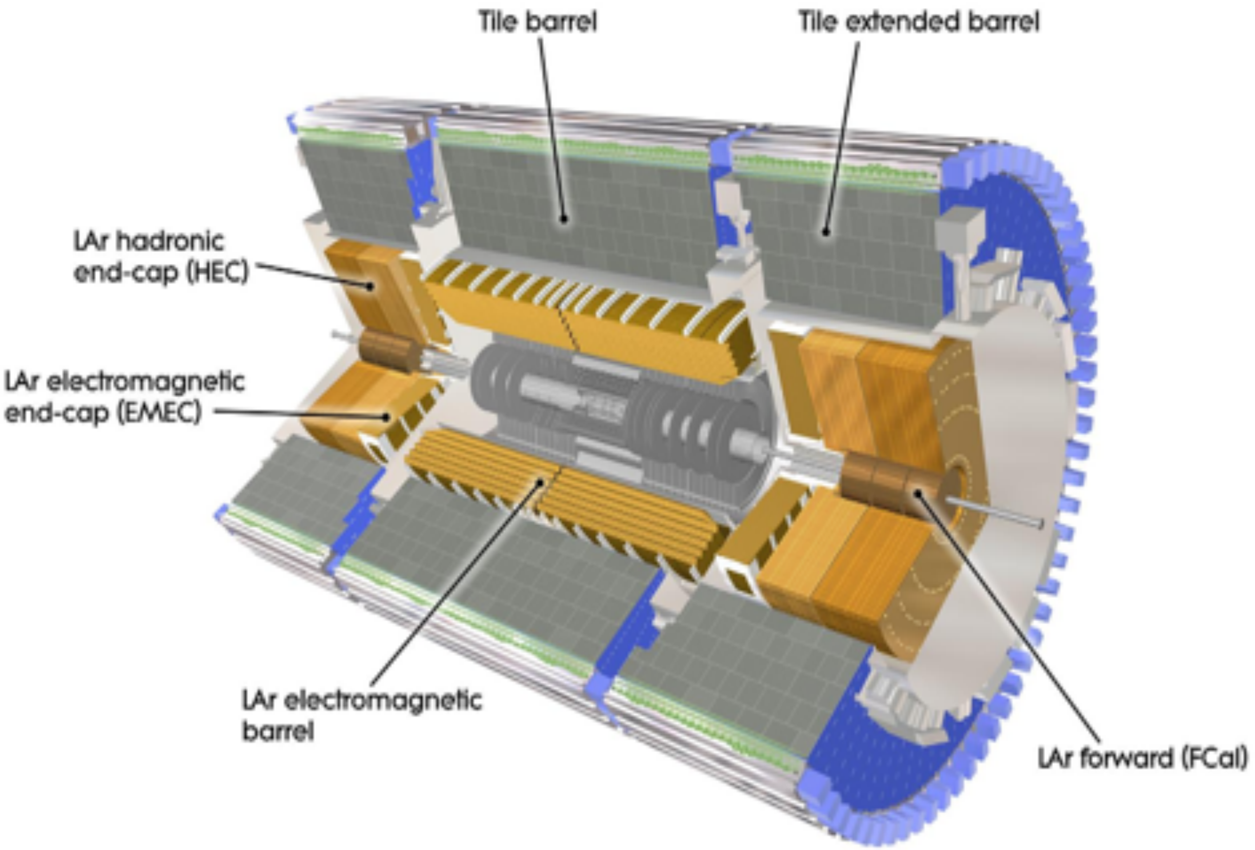
TRT can also measure *dE/dx* via Time-over-Threshold

and

"High Threshold" hit fraction (primarily intended for identifying electrons emitting transition radiation) is also a useful variable for identifying highly-ionizing particles.

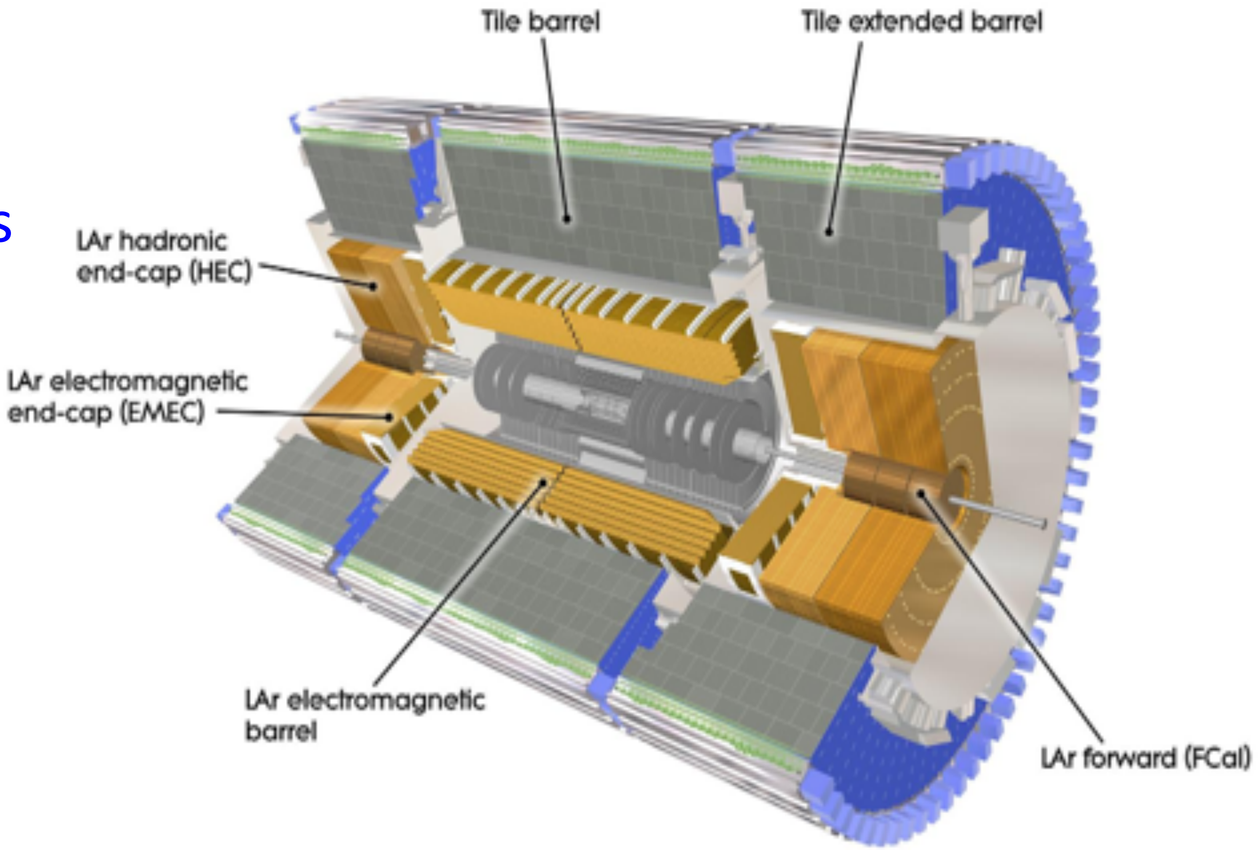
The ATLAS Calorimeters

- Liquid Argon (LAr) electromagnetic calorimeter has longitudinal as well as transverse segmentation.



The ATLAS Calorimeters

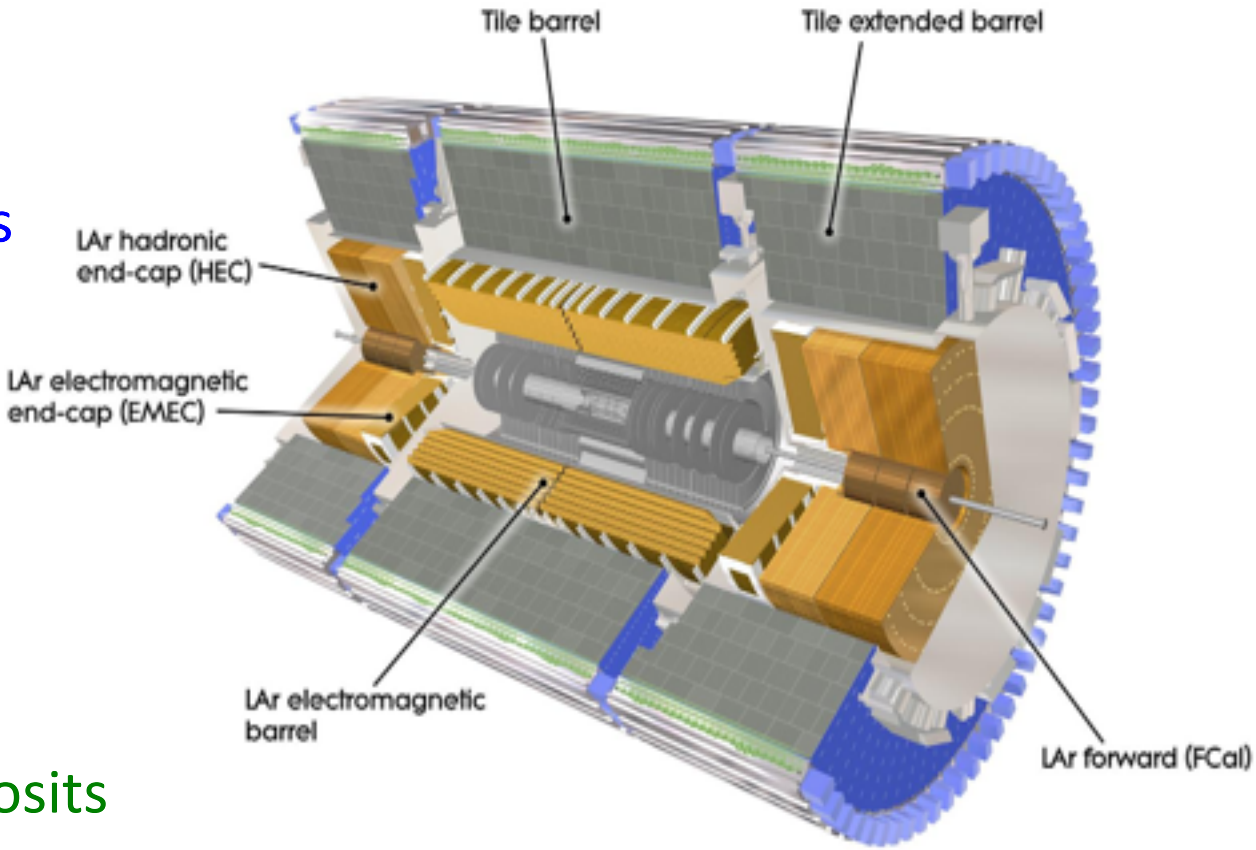
- Liquid Argon (LAr) electromagnetic calorimeter has longitudinal as well as transverse segmentation.
  - Can measure pointing direction of EM showers



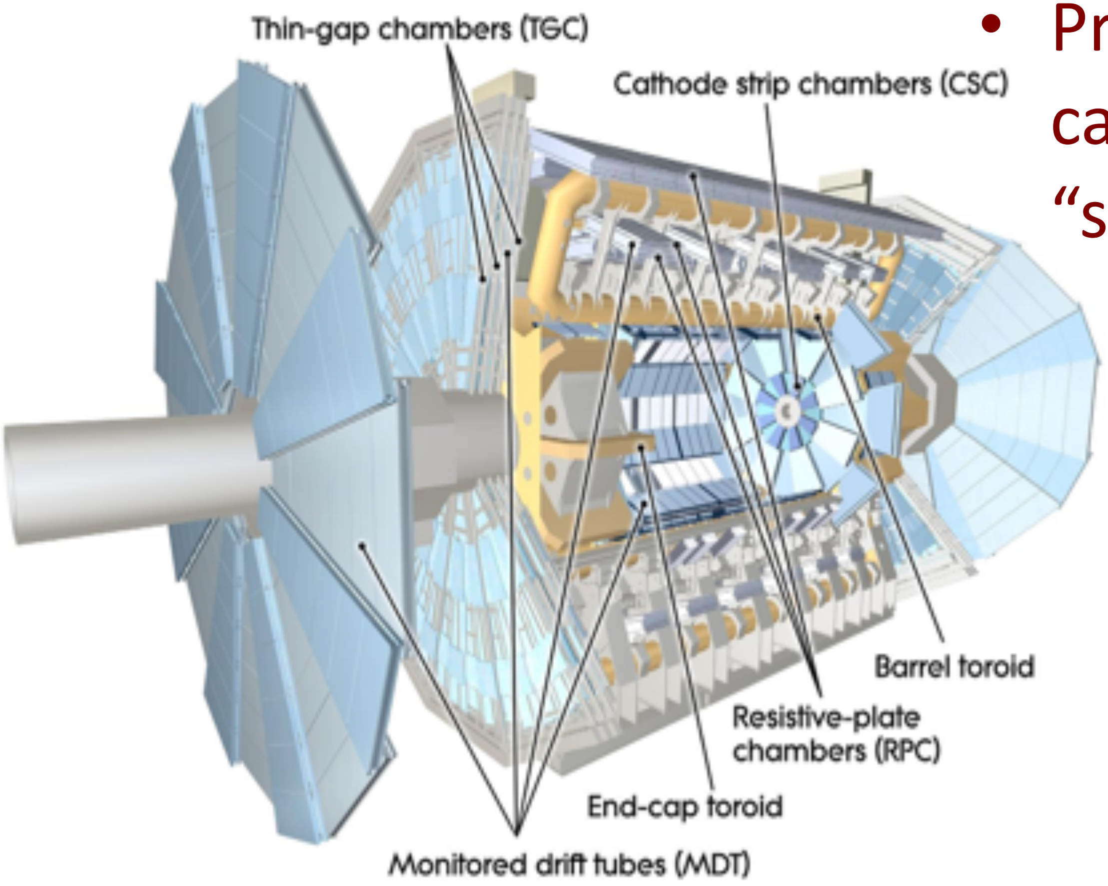
The ATLAS Calorimeters

- Liquid Argon (LAr) electromagnetic calorimeter has longitudinal as well as transverse segmentation.
  - Can measure pointing direction of EM showers

- Both LAr and Tile calorimeters can also measure *dE/dx* by summing energy deposits over path length.



The ATLAS Muon Spectrometer (MS)



- Precision muon chambers can reconstruct "standalone" tracks.

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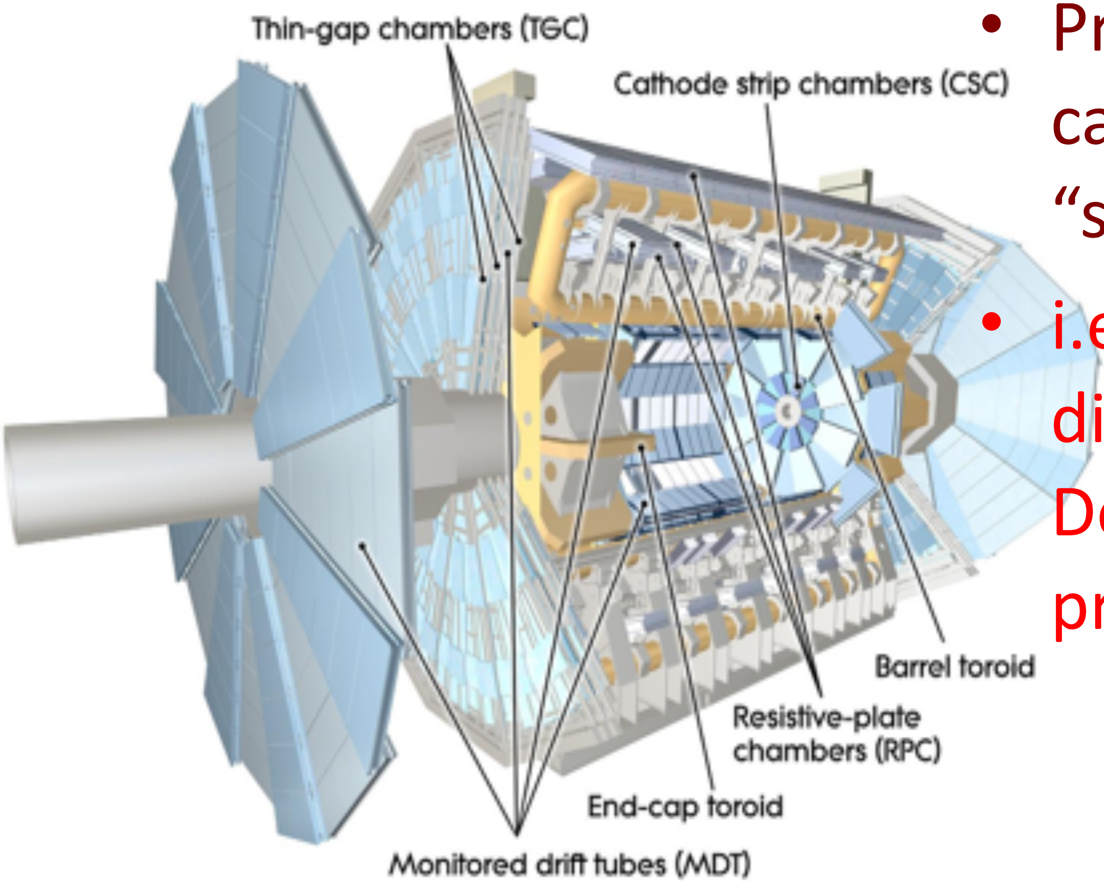

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- i.e. can find particles that did not leave tracks in Inner Detector (e.g. decay products of LLPs).

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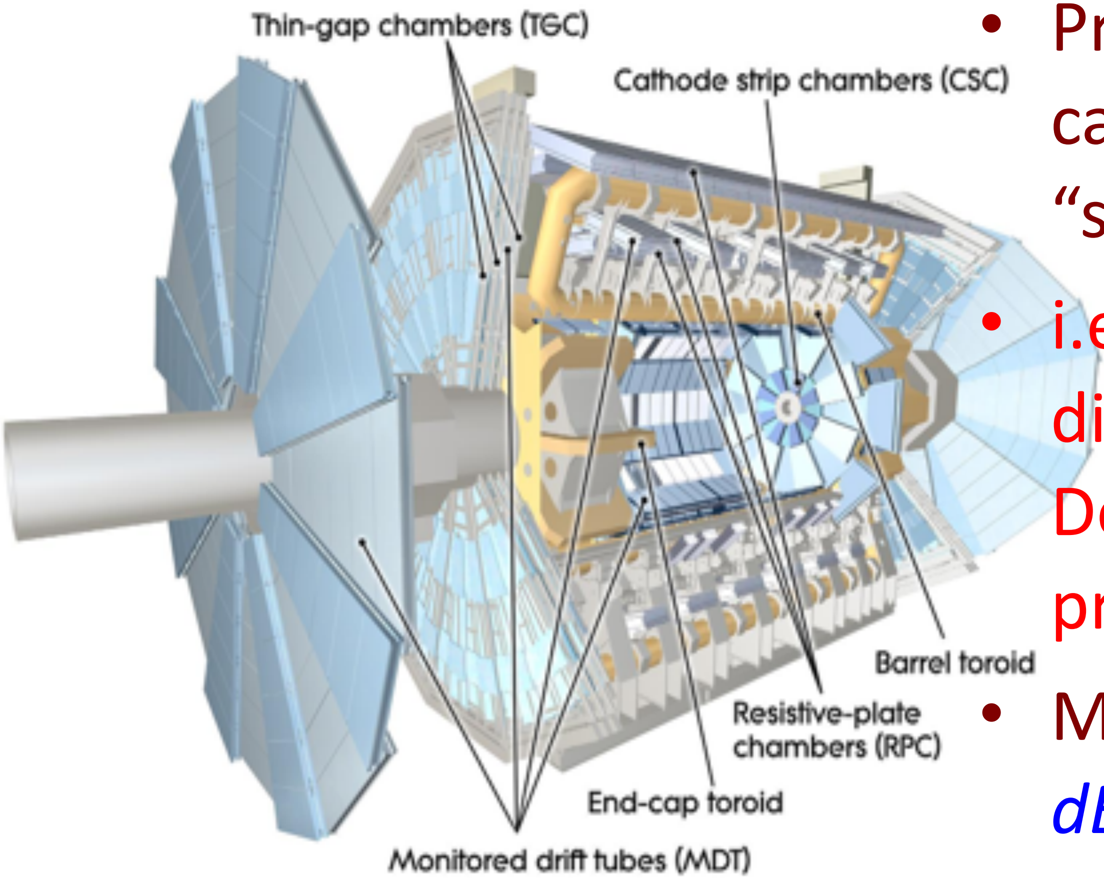

- Precision muon chambers can reconstruct "standalone" tracks.
- i.e. can find particles that did not leave tracks in Inner Detector (e.g. decay products of LLPs).
- MDTs can also measure *dE/dx* (similar principle to TRT).

The Analyses

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Stable Massive Particles (SMPs)

- Particles with lifetimes of order nanoseconds or greater are likely to traverse the whole detector.
  - If they are neutral, and weakly interacting, they will show up as missing E_T.
  - If they are charged (at any point!) or strongly interacting, we have a chance to detect them directly!
- Several candidate particles, including:
  - Long-lived sleptons in GMSB models.
  - Charginos in AMSB models.
  - R-hadrons.

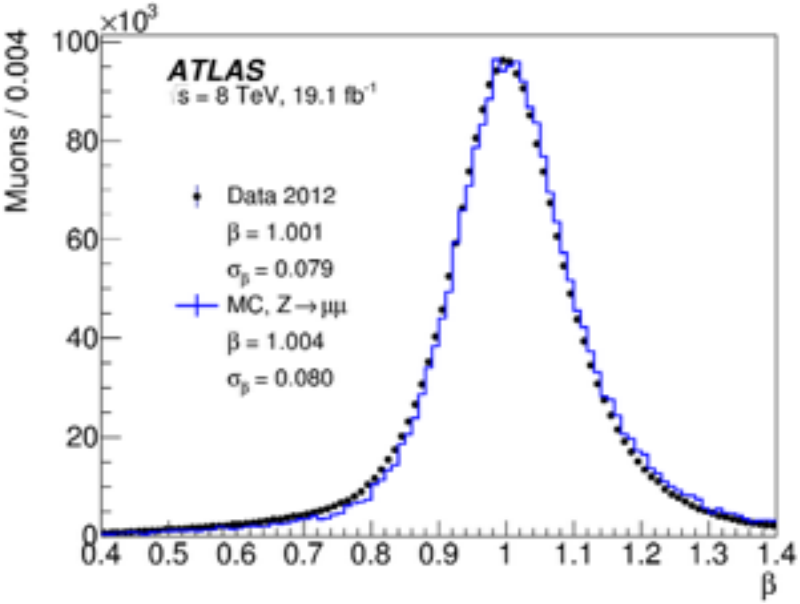
ATLAS-CONF-2012-075

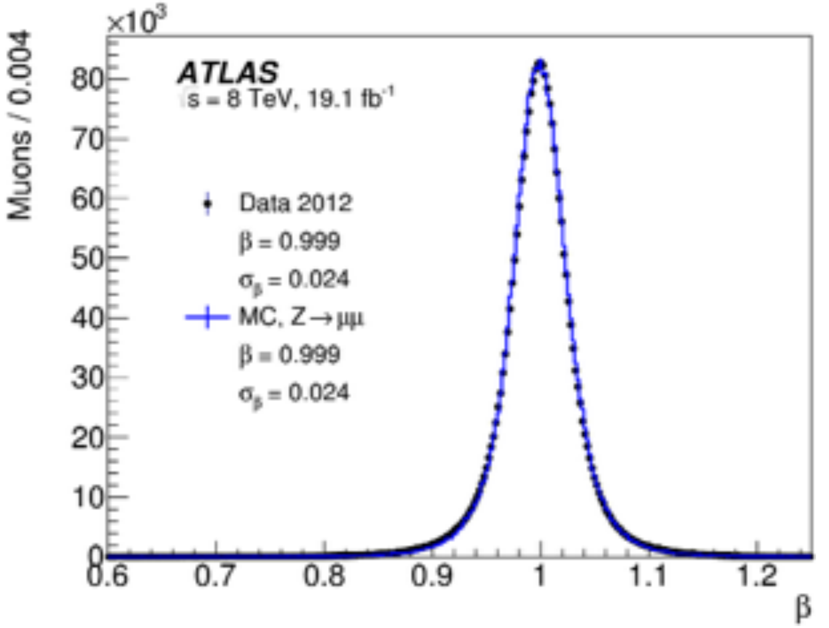
Stable Massive Particles (SMPs)

- Particles with lifetimes of order nanoseconds or greater are likely to traverse the whole detector.
  - If they are neutral, and weakly interacting, they will show up as missing E_T.
  - If they are charged (at any point!) or strongly interacting, we have a chance to detect them directly!
- Several candidate particles, including:
  - Long-lived sleptons in GMSB models.
  - Charginos in AMSB models.
  - R-hadrons.
  - Common feature: if they are massive, they will be produced with low velocities: $\beta < 1$.

SMPs - Combining β measurements

- Use Z to μμ events to calibrate β measurements.
- If β measurements from different systems are > 0.2 and internally consistent, they are combined in a weighted average.





Measuring the mass of SMPs

- Can measure time-of-flight in several subdetectors.
  - For these analyses, use Tile+LAr Calorimeters, RPC, MDT.
  - Can therefore measure velocity β.
- Can measure charged particle momentum p in Inner Detector and Muon Spectrometer.
- Can measure energy loss dE/dx in several subdetectors.
  - For these analyses, use Pixel detector.
  - dE/dX is related to relativistic boost factor $\beta\gamma$.

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$$p=\beta\gamma m$$

SMP Selection

- **Sleptons** would behave like “heavy muons”, releasing energy throughout detector.
- Likely to be 2 produced per event - look for events with 2 offline muons.
- Define “2 candidate” signal region (both candidates passing loose pT and β cuts) and “1 candidate” signal region (one candidate passes tighter selection, the other just passes muon selections.

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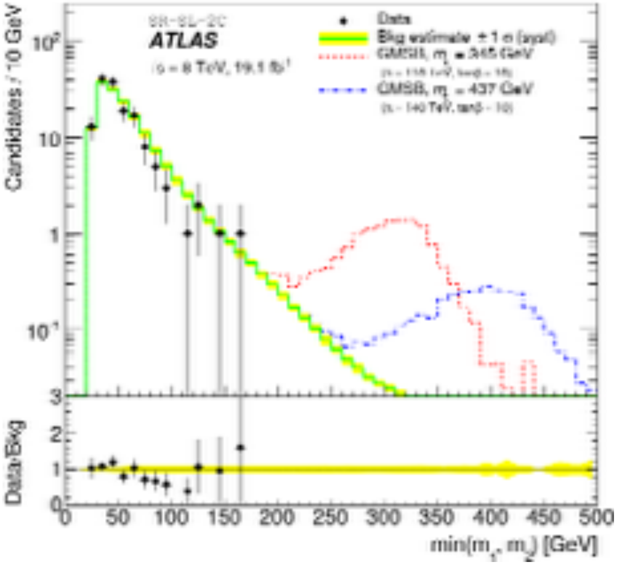
- Also define “1 candidate” and “2 candidate” signal regions, but don’t require a second muon candidate for the former..

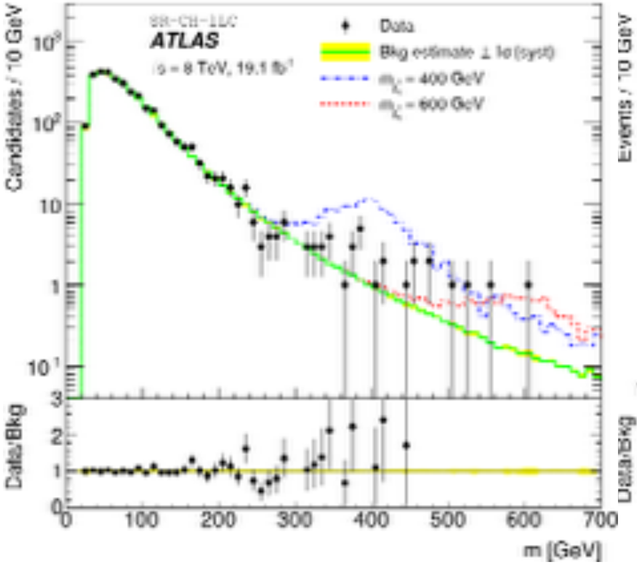
- **R-hadrons** would interact with detector material - could stop, or change charge.
- Only require 1 candidate per event.
- Define “muon agnostic” and “full-detector” searches using information from different sub-detectors.

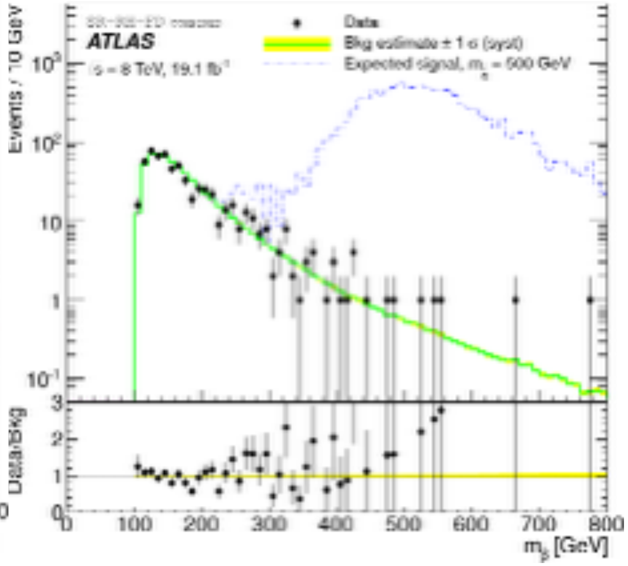
Stable Massive Particles - backgrounds

- Main background is high-p_T muons with mis-measured β.
  - Exploit fact that mis-measurements of β or $\beta\gamma$ in different subdetectors are uncorrelated.
- Use data-driven method, based on randomly sampling β or $\beta\gamma$ values from control sample distributions and combining with measured p for each candidate.
  - Sample many times for each p measurement to reduce statistical uncertainty.

SMPs - Results



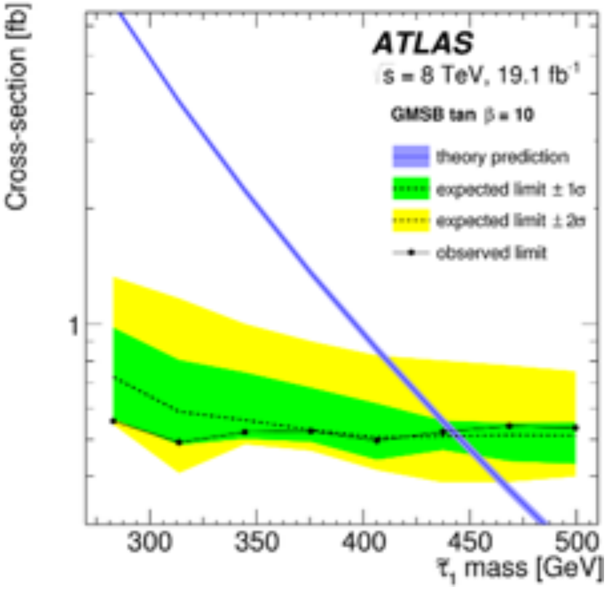


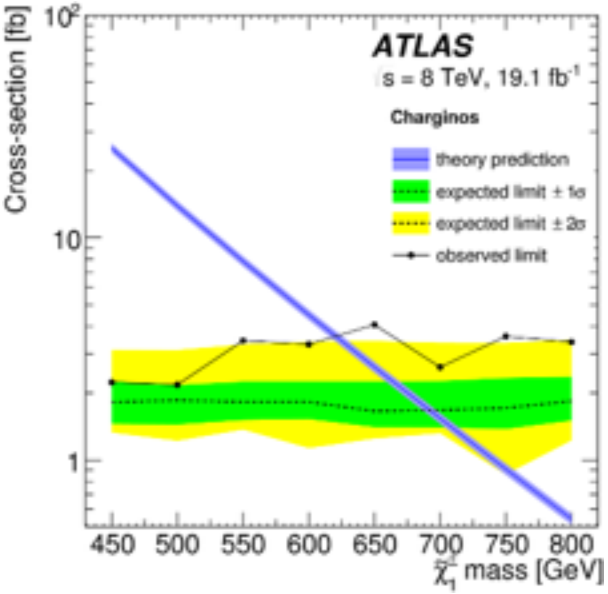


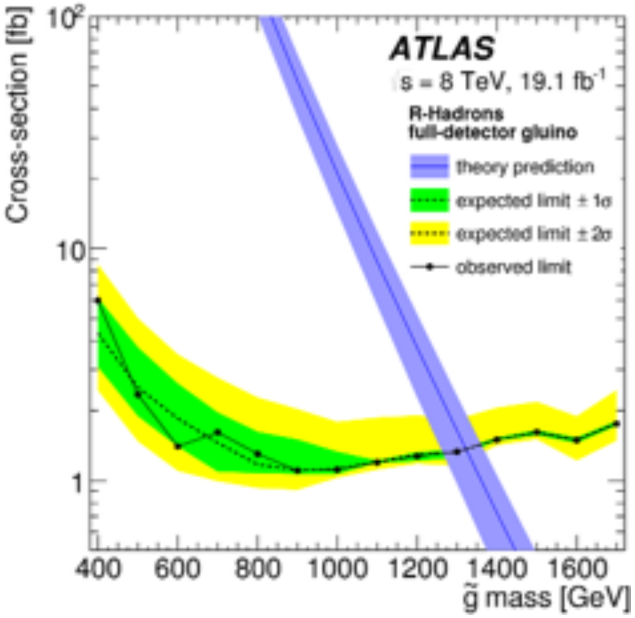
- No excess above background expectation is seen.

Stable Massive Particles - limits

- Set limits on stau mass in GMSB scenario, chargino mass in AMSB scenario, and R-hadron mass for gluino, sbottom, and stop R-hadrons.







arXiv:1310.6584 [hep-ex]

Stopped R-hadrons

- Particles with very long lifetimes, produced with low β, could potentially stop in dense region of detector material.
  - i.e. calorimeters.
- Look for significant calorimeter activity during empty bunch crossings.
- Potential backgrounds are:
  - Cosmics
  - Beam halo
  - Detector noise

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Veto events containing reconstructed muon segments

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Veto events containing reconstructed muon segments

Use event cleaning and jet shape variable cuts

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Rate is proportional to live-time (not lumi), measure during “cosmics period” in early 2011, and scale to “data period” from mid-2011 to end of 2012.

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Estimate using data from unpaired bunches.

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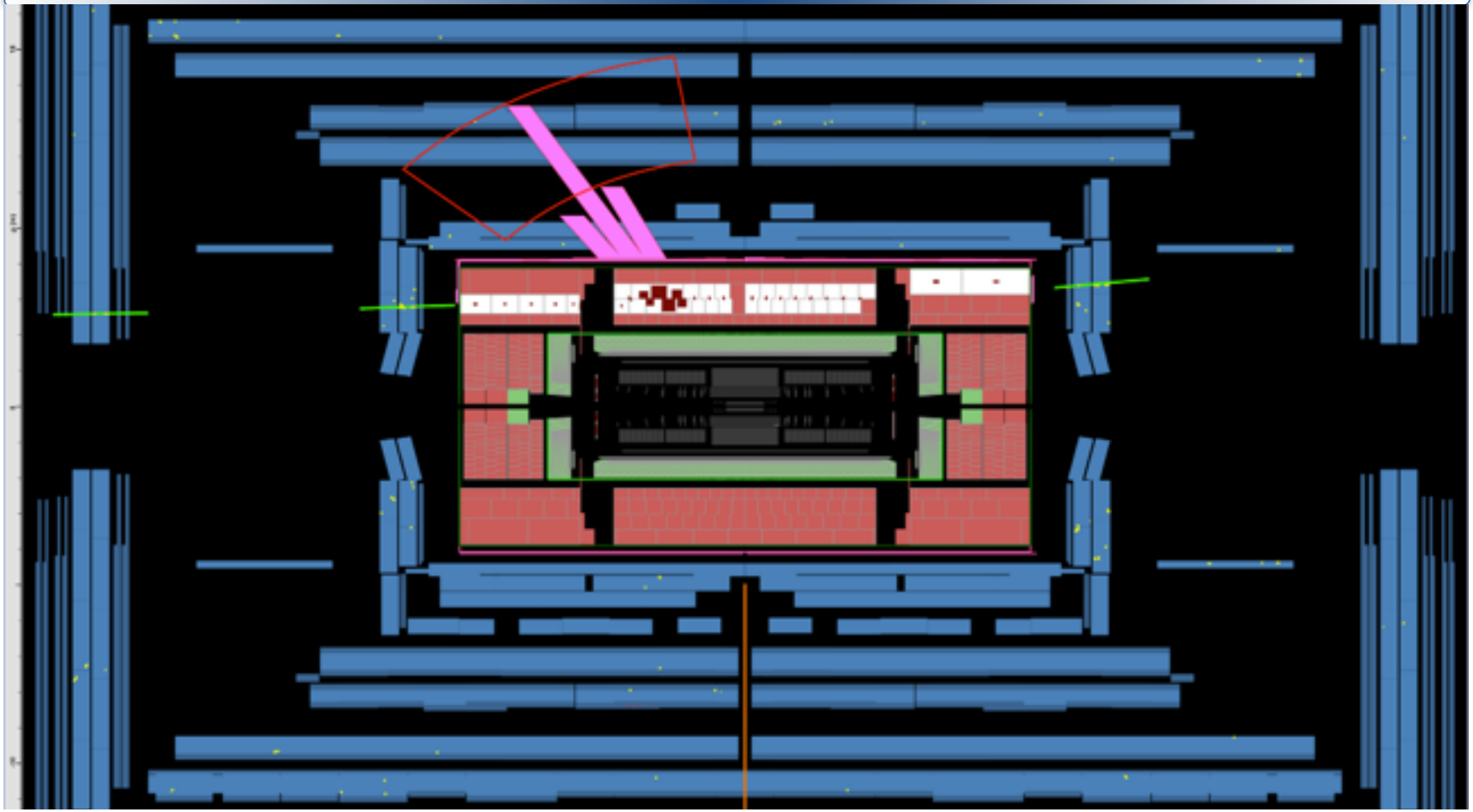
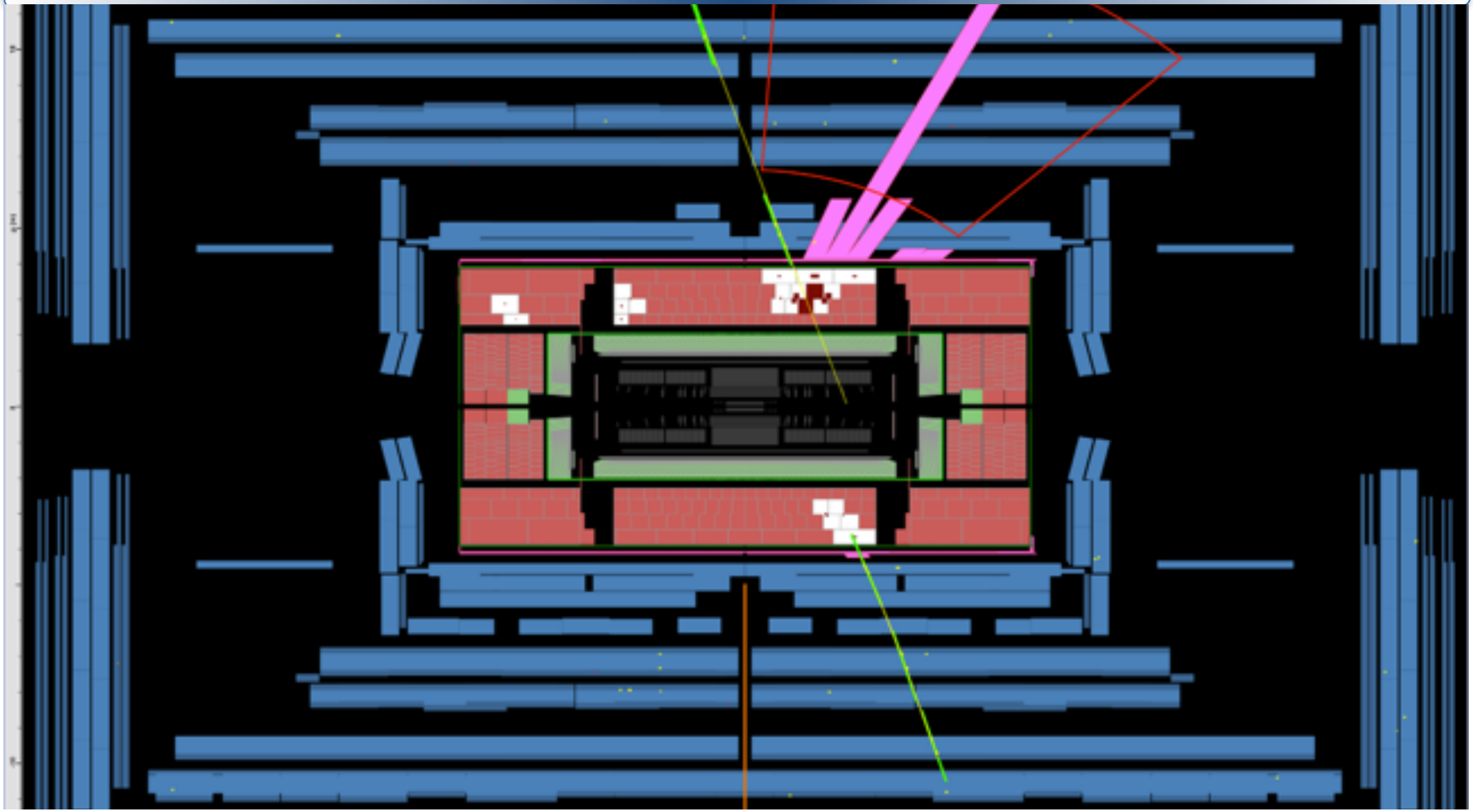
  - Detector noise

Negligible after event cleaning.

Stopped R-hadrons – beam halo



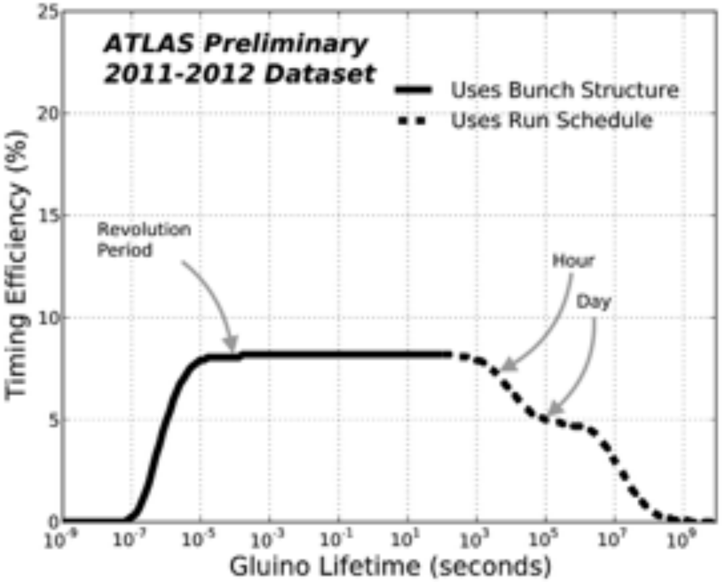
Stopped R-hadrons – cosmic muon



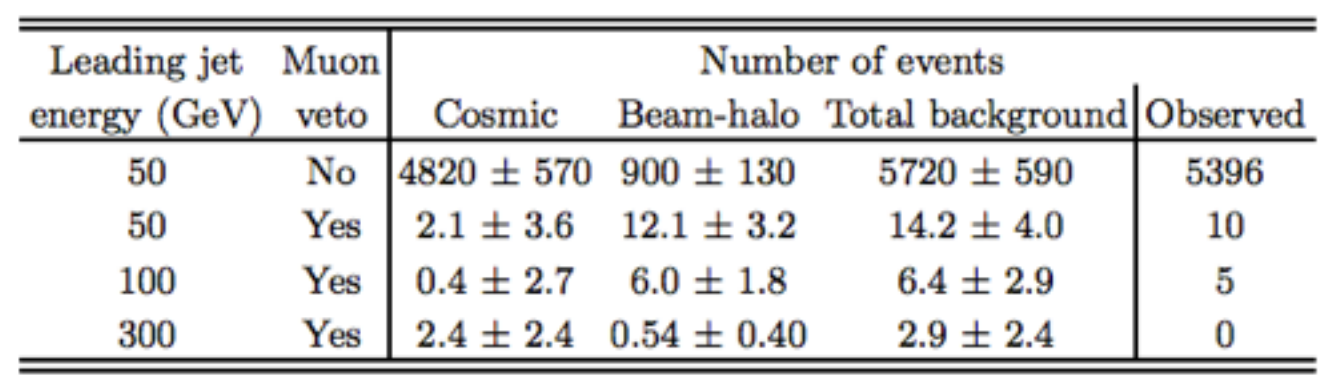
Stopped R-hadrons – acceptance and efficiency

- Simulation of stopped R-hadrons was significant technical challenge:
  - Sparticle pair-production and hadronization in PYTHIA
  - Propagate through GEANT4 detector simulation, and store stopping locations.
    - “Generic”, “Regge”, “Intermediate” models for R-hadron nuclear interactions and spectrum of R-hadron states
  - Decay R-hadrons in PYTHIA, translate to stopping location and add random rotation.

- To get timing acceptance for decays in the same LHC fill, need bunch structure within that fill
- To get acceptance for longer lifetimes, need whole luminosity history of LHC.

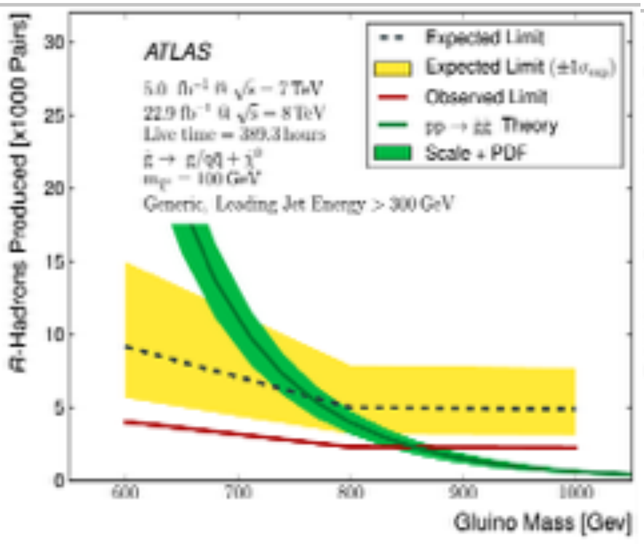


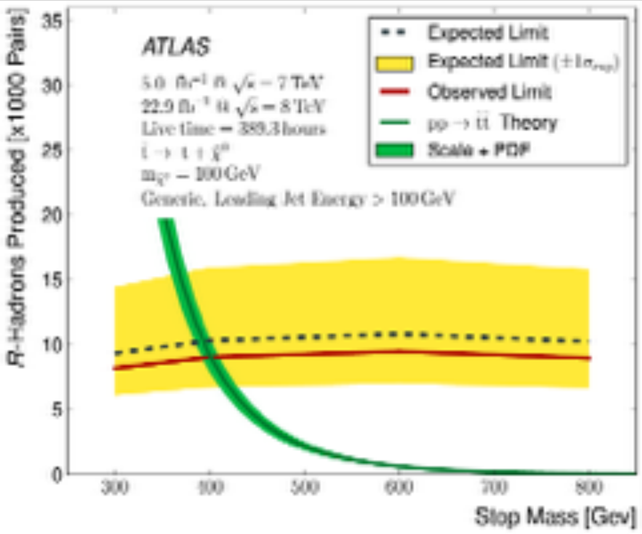
Stopped R-hadrons – results.

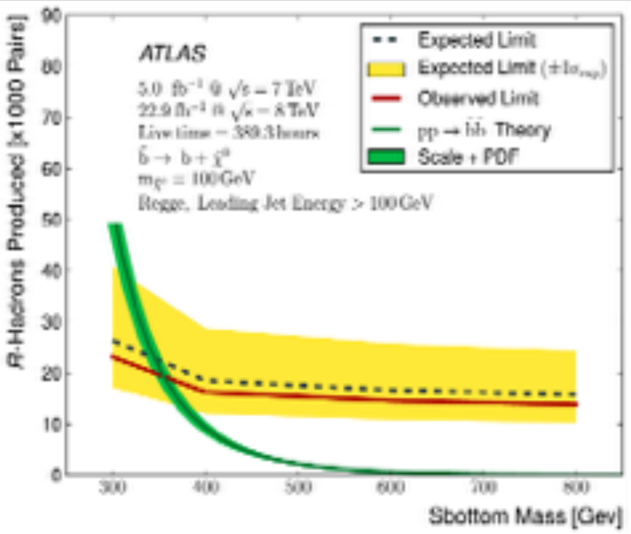


Leading jet energy (GeV)	Muon veto	Number of events Cosmic	 Beam-halo	 Total background	 Observed
50	No	4820 ± 570	900 ± 130	5720 ± 590	5396
50	Yes	2.1 ± 3.6	12.1 ± 3.2	14.2 ± 4.0	10
100	Yes	0.4 ± 2.7	6.0 ± 1.8	6.4 ± 2.9	5
300	Yes	2.4 ± 2.4	0.54 ± 0.40	2.9 ± 2.4	0

- No excess observed – set limits for various signal models:





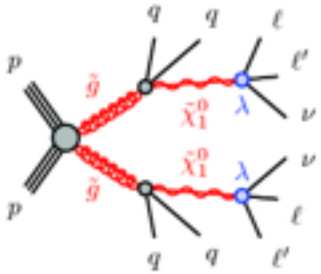


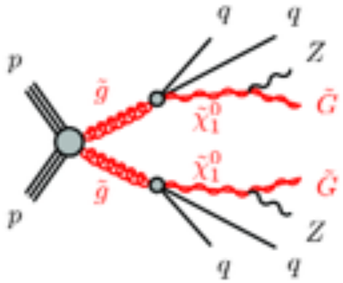
Brand new!!!

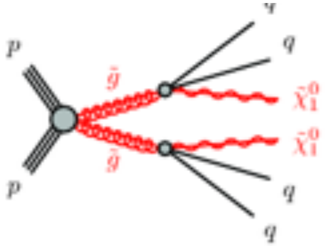
Displaced vertices in the Inner Detector

- Particles with average lifetimes up to a few nanoseconds could decay within the ID, giving rise to displaced vertices (DVs).

- Previous iterations of this analysis looked at DV+muon, interpreting in RPV SUSY scenario.
- Major expansion for final Run 1 paper:
  - Now look at DV+electron, DV+MET, DV+jets, displaced dileptons.
  - Interpret in RPV, GGM, and split SUSY models.

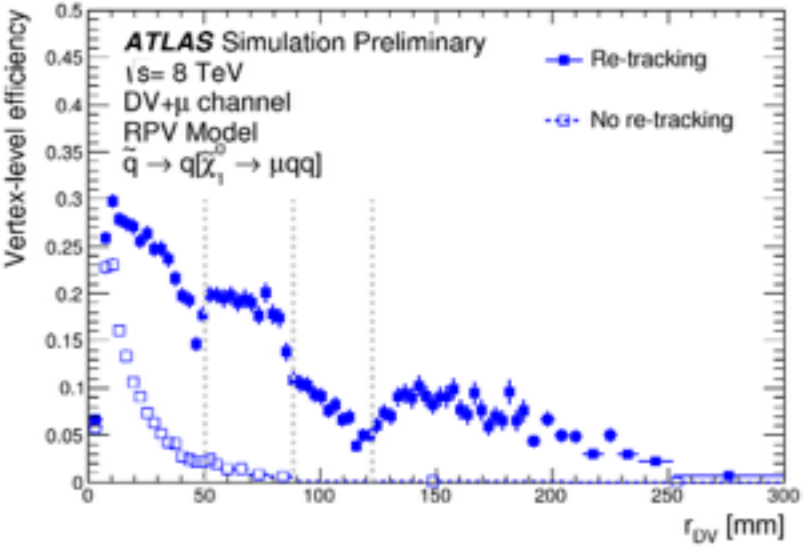






Displaced vertices – track and vertex reconstruction

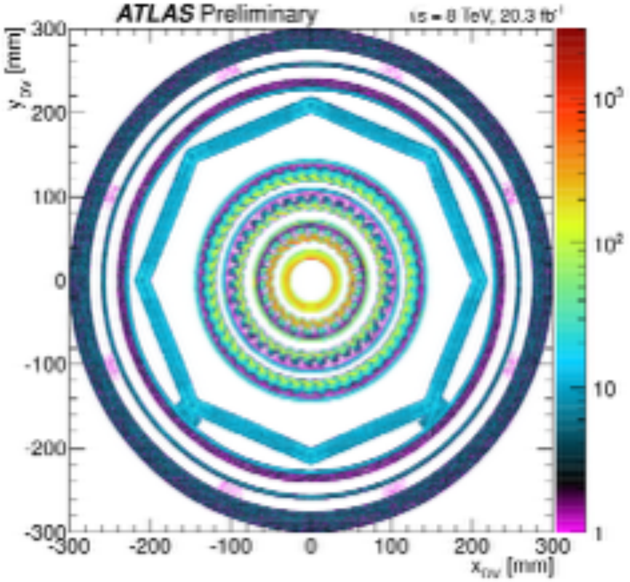
- Standard ATLAS tracking is highly optimized for tracks coming from the primary interaction point (IP).
- To increase efficiency for secondary tracks, we re-run Silicon-seeded tracking algorithm, with looser cuts on transverse impact parameter, using “left-over” hits from Standard tracking.



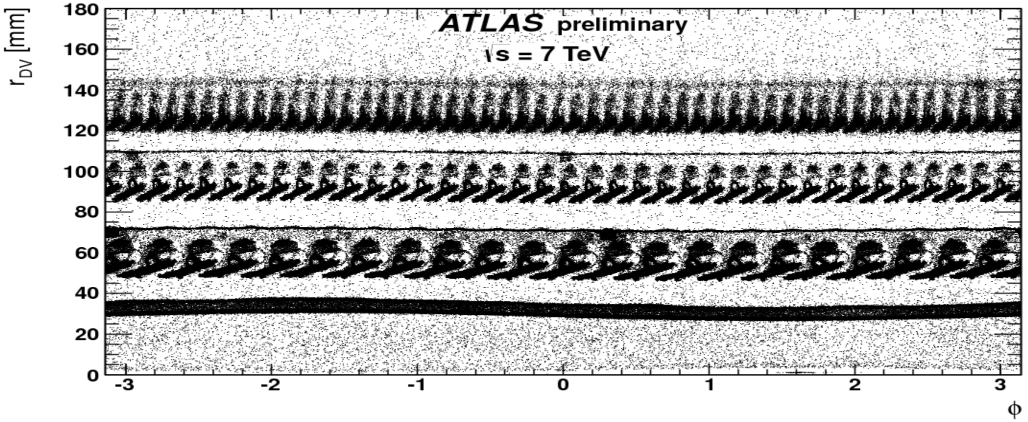
- Vertex-finding algorithm based on *incompatibility graph* method.
- Iterative disambiguation process then splits/merges/refits vertices until no tracks are shared between vertices.

Displaced vertices – selection

- Use tracks with $|d_0|>2\text{mm}$, $p_T>1$ GeV as input to vertexing.
- Look in fiducial volume roughly corresponding to Pixel barrel.
- Require vertex mass > 10 GeV.
- For multi-track searches, require at least 5 tracks in vertex.
- For dilepton searches, require two oppositely charged leptons (ee, mumu, or emu).

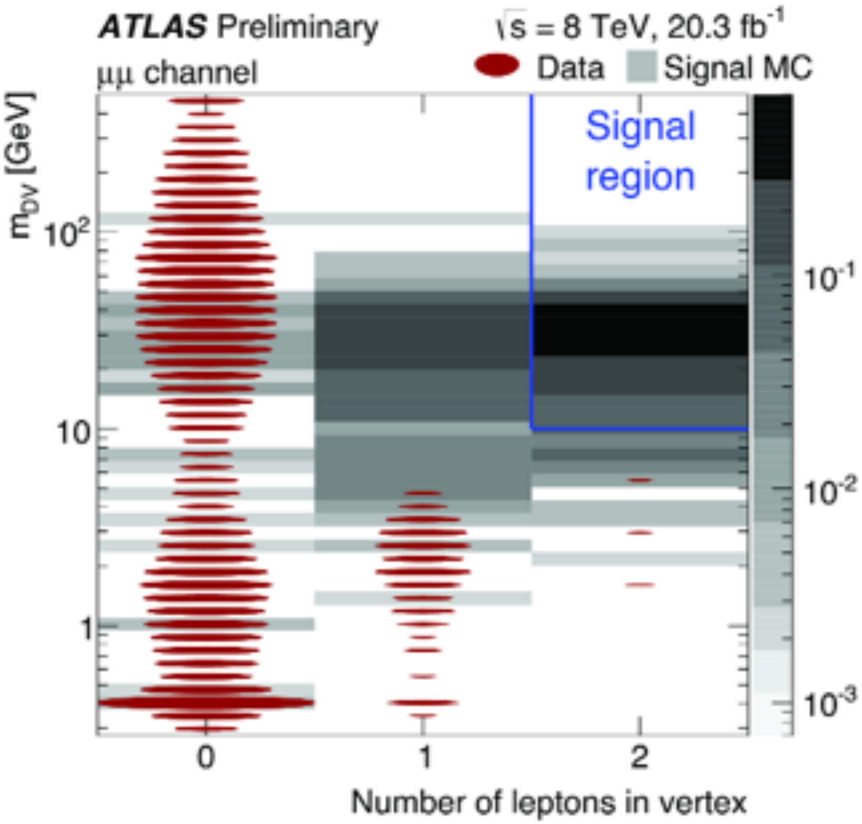


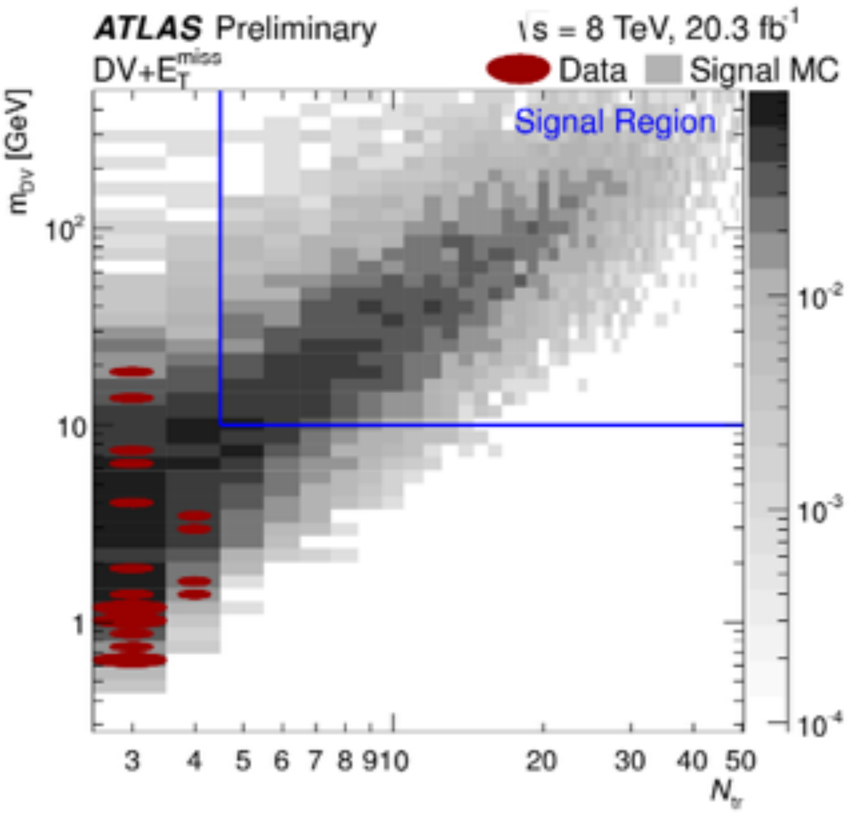
- Veto vertices reconstructed in regions with high material density.



Displaced vertices – results

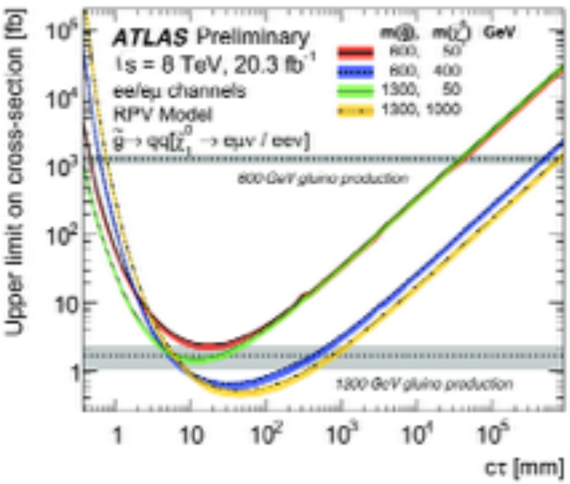
- <<1 background vertex expected in all channels.
- Zero vertices pass selection requirements observed in 20.3 fb^{-1}

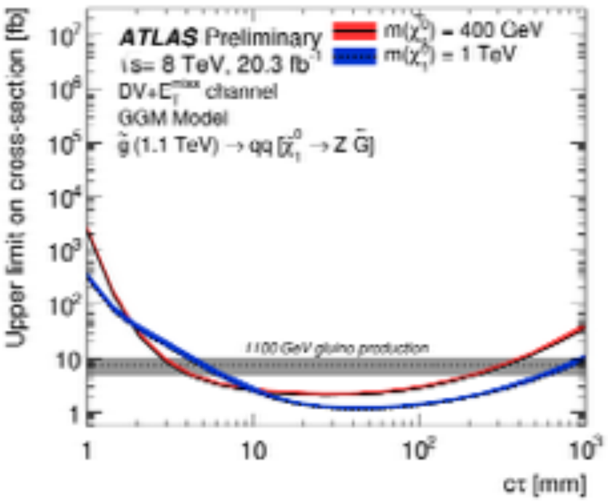




Displaced vertices – interpretation

- Reweight events in signal MC to set limits over a large range of cτ.





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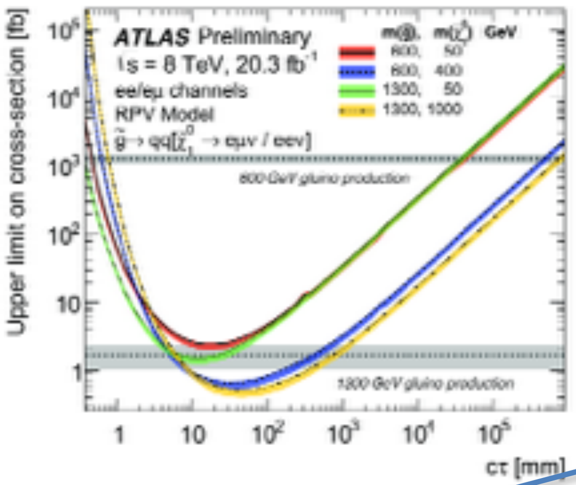
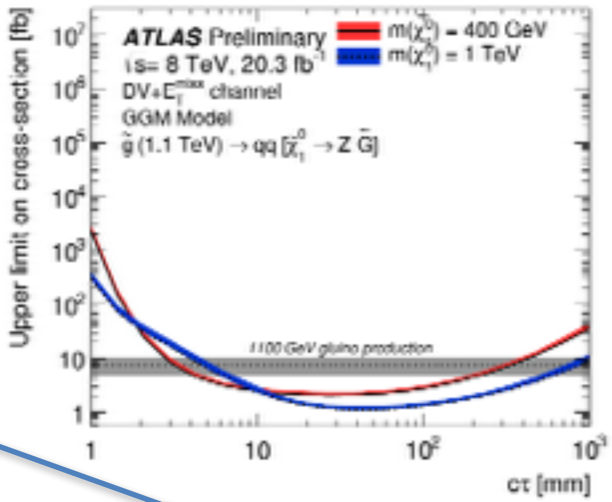
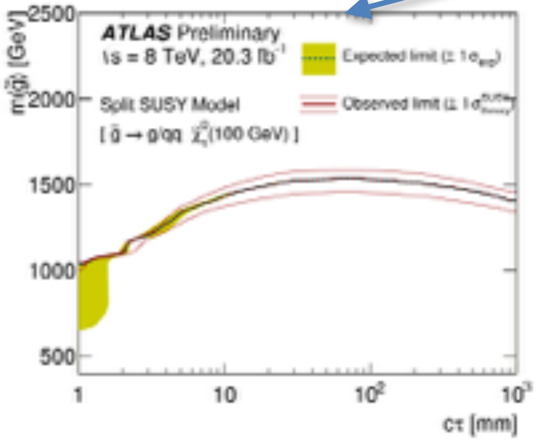
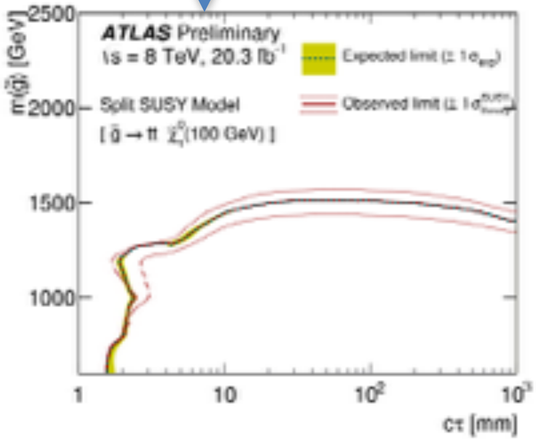
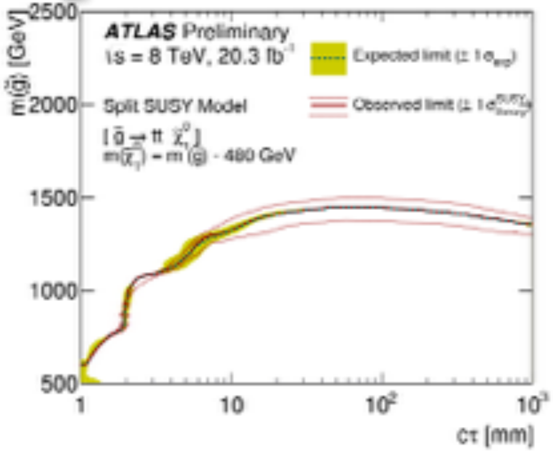


For split SUSY / R-hadron samples, scan over different gluino masses.

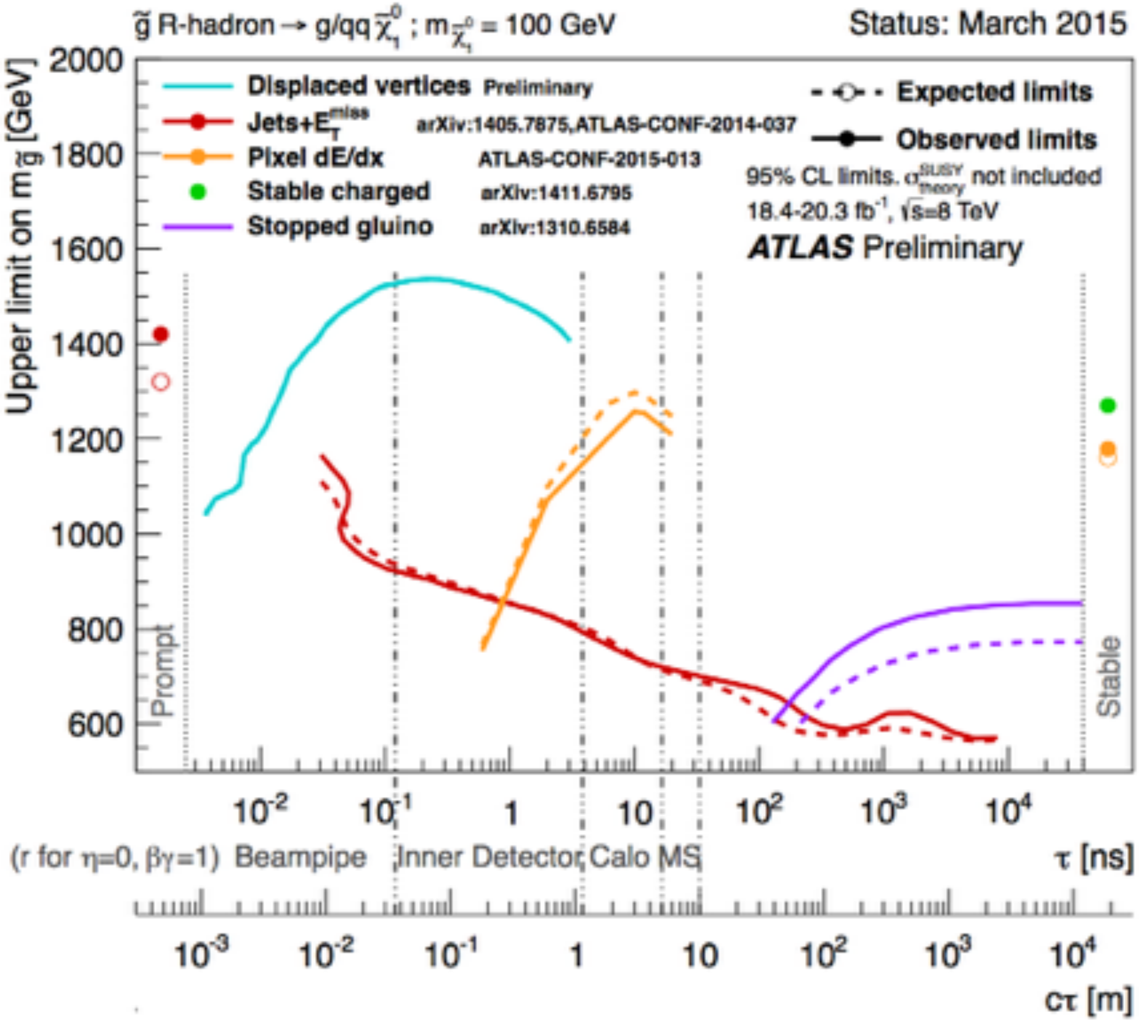








Summary of ATLAS R-hadron searches



arXiv:1310.3675 [hep-ex]

Disappearing tracks - introduction

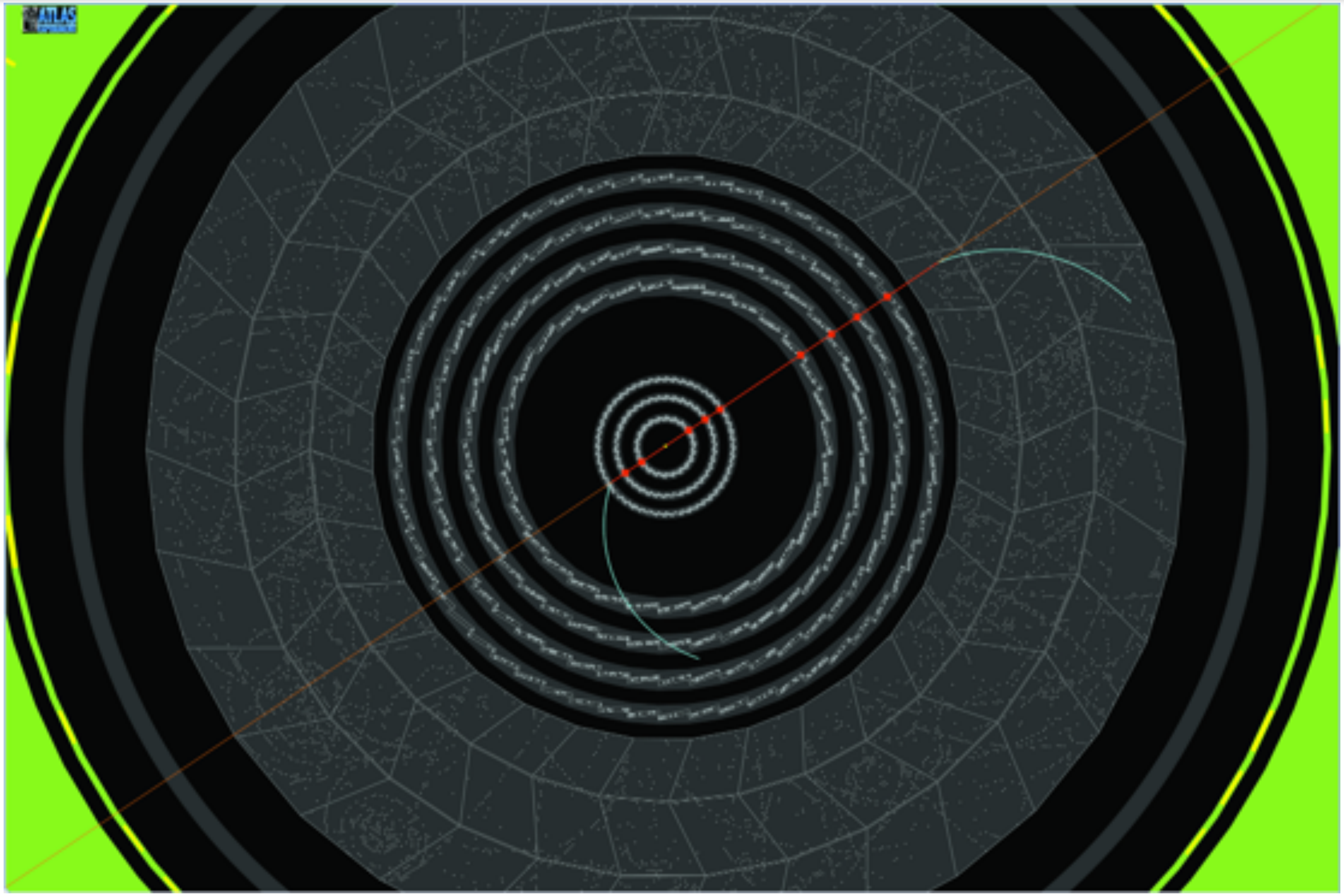
- SUSY breaking could leave the lowest gauginos approximately mass-degenerate (predicted, eg, by AMSB), giving rise to LL chargino decaying to neutralino and soft pion.
- Look for production processes:

$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{0} + \mathrm{jet}\ ,\ pp \to \tilde{\chi}_1^{+}\tilde{\chi}_1^{-} + \mathrm{jet}$$

(jet from ISR, needed to trigger on event).

- Resulting final state will include:
  - High p_T jet
  - Large missing transverse momentum.
  - High-p_T disappearing track (or "kinked" track, but reconstruction efficiency for soft pion is not so good..)

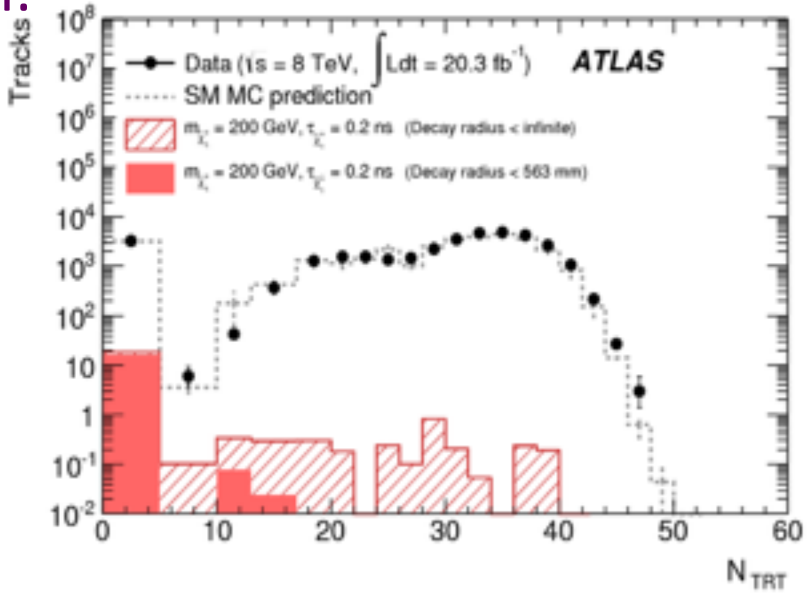
Disappearing tracks – simulated signal event.



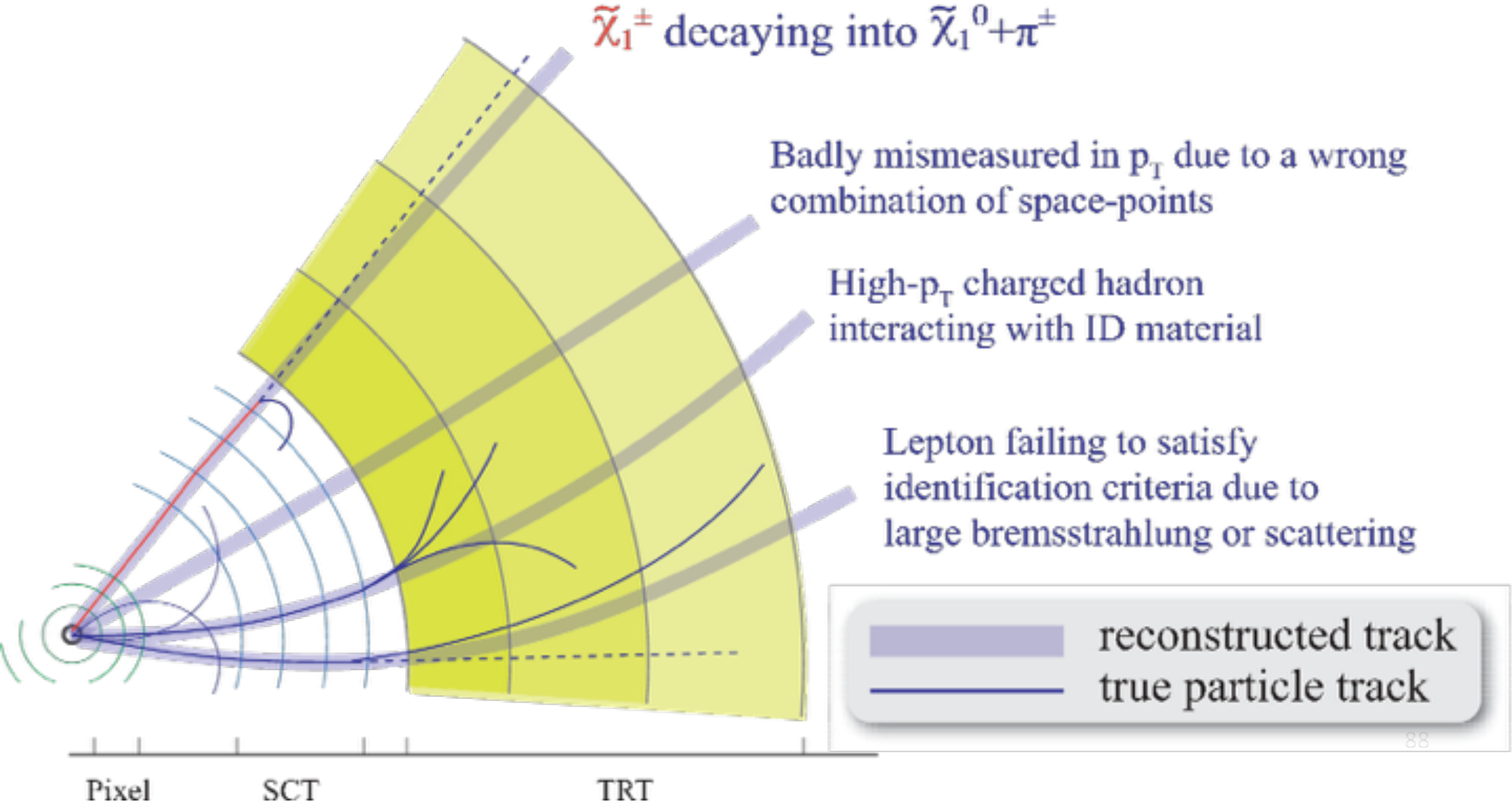
Disappearing tracks - selection

- Event selection:
  - Trigger on jet + missing $E_{T.}$
  - In offline selection, require missing E_T > 90GeV and at least one jet with p_T > 90GeV, well separated from missing E_T direction in ϕ.
  - Lepton veto – no reconstructed electron or muon candidates.
- Disappearing track candidate selection:
  - Track must be isolated,
  - have p_T > 15 GeV,
  - at least 3 Pixel, 1 b-layer and 2 SCT hits,
  - originate from primary vertex,

  and point to TRT barrel (but not region around $|\eta|$=0).
  - Fewer than 5 hits in TRT.



Disappearing tracks - backgrounds



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

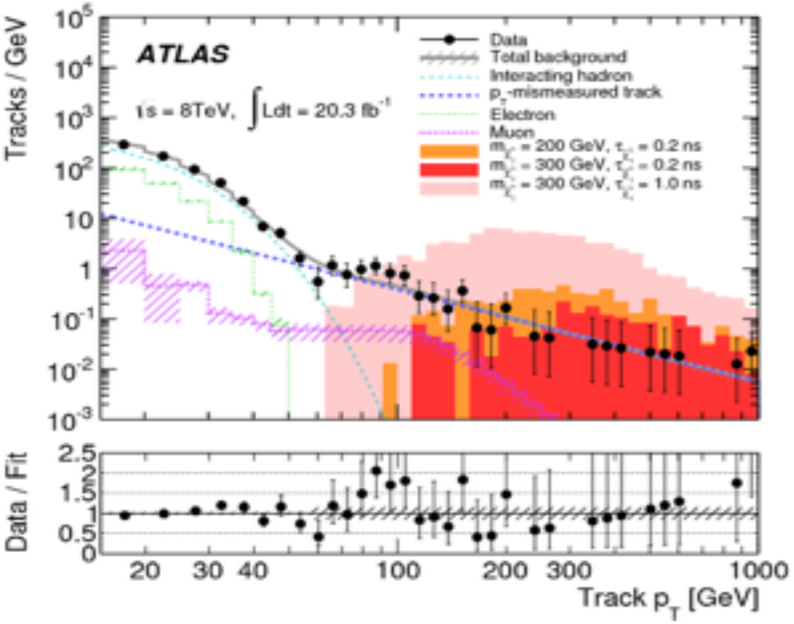
Badly mismeasured in p_T due to a wrong combination of space-points

High-p_T charged hadron interacting with ID material

Lepton failing to satisfy identification criteria due to large bremsstrahlung or scattering

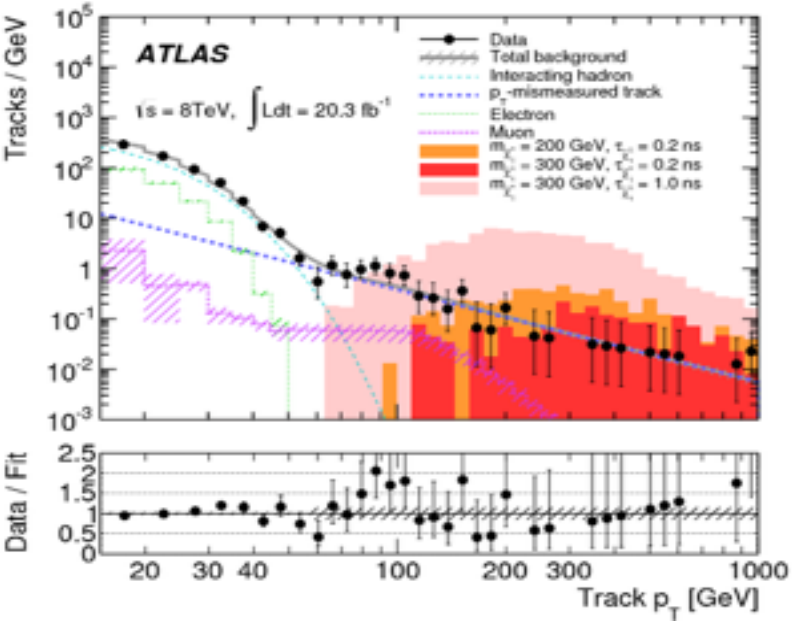
Disappearing tracks - results

- Use signal+background likelihood fit to track p_T spectrum, to test different signal hypotheses.



Disappearing tracks - results

- Use signal+background likelihood fit to track p_T spectrum, to test different signal hypotheses.
- No significant excess found.



Disappearing tracks - results

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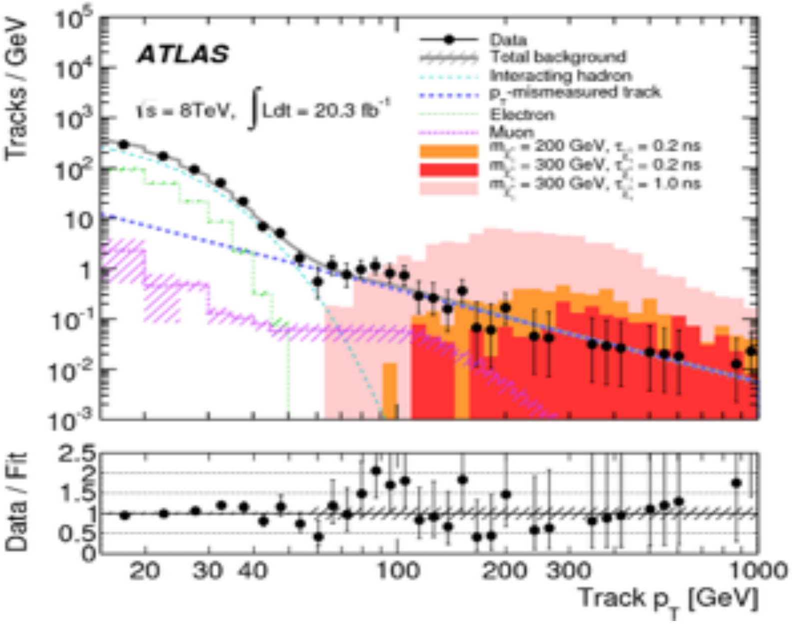
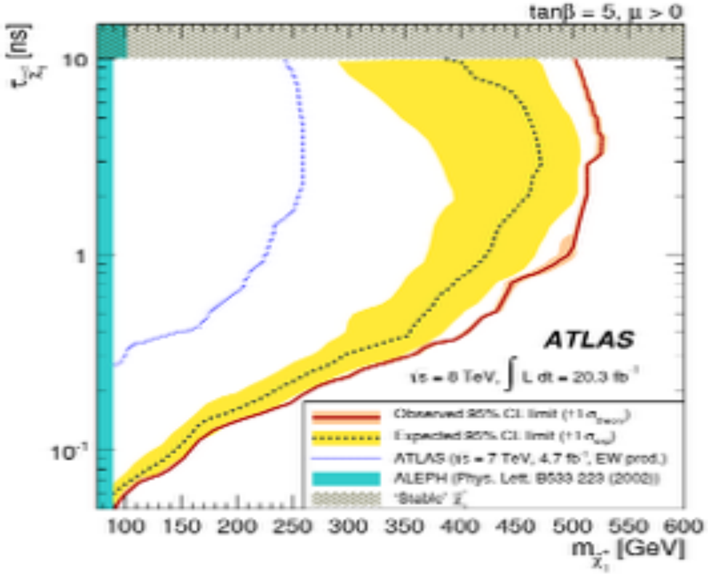
- Set limits on chargino mass and lifetime:





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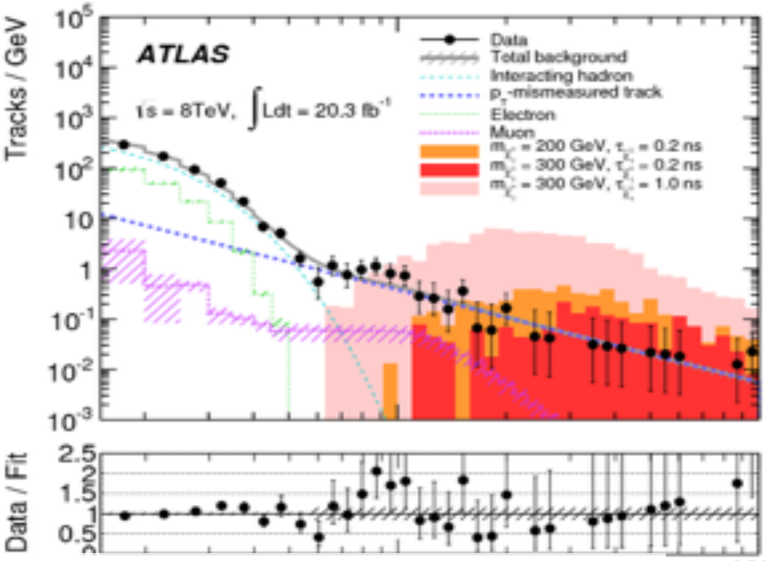
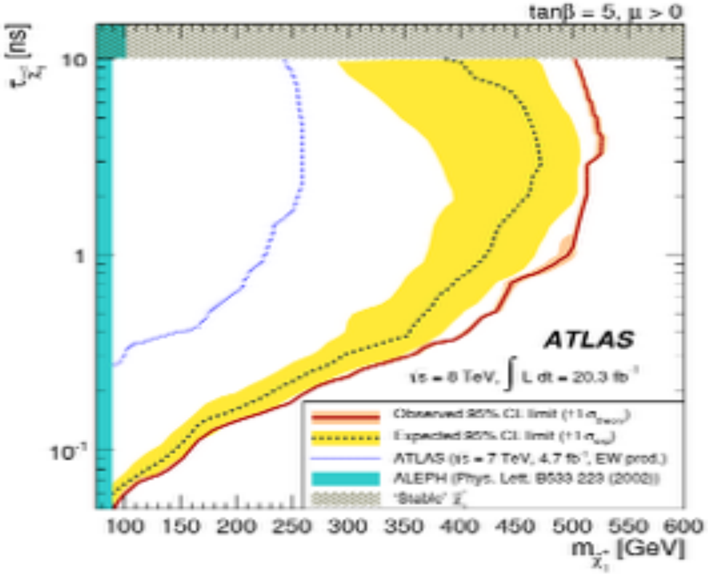
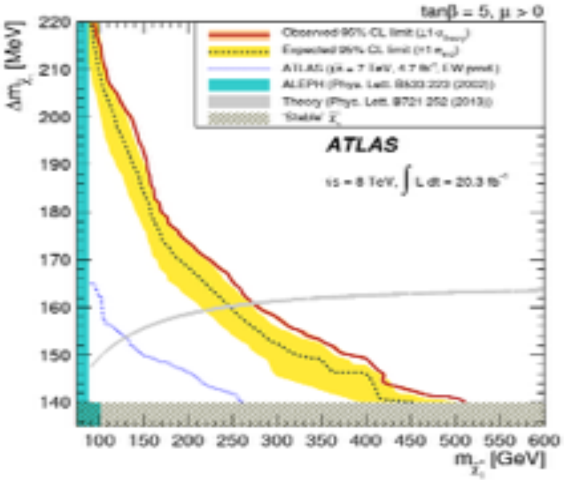


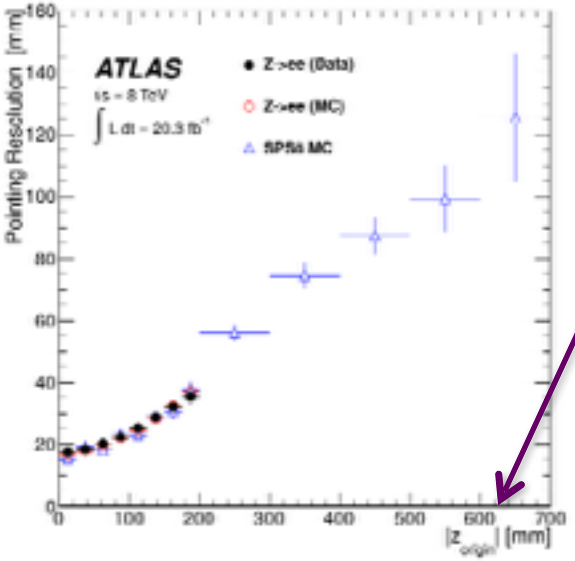


- And on chargino – neutralino mass difference:

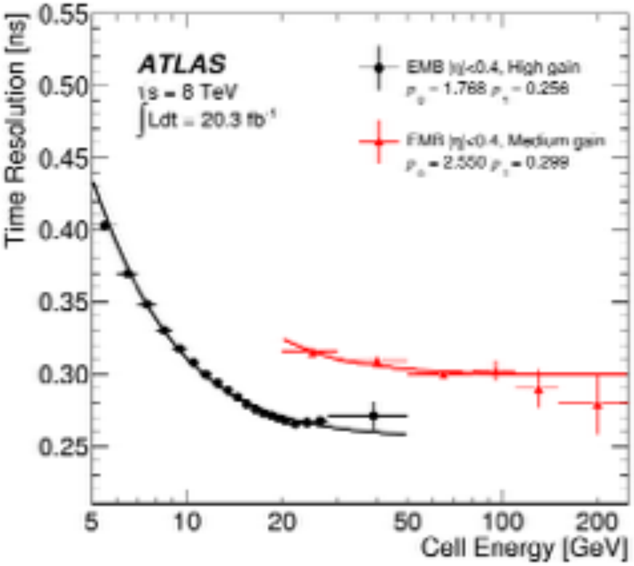


Non-pointing photons

- If NLSP is a photino-rich neutralino, then GMSB models can have long-lived neutralinos decaying to photon+gravitino.
    - Use longitudinal segmentation, and timing, of EM calorimeter to search for non-pointing photons.

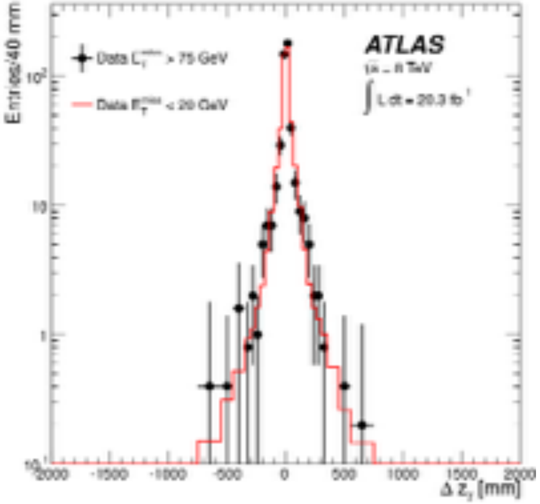


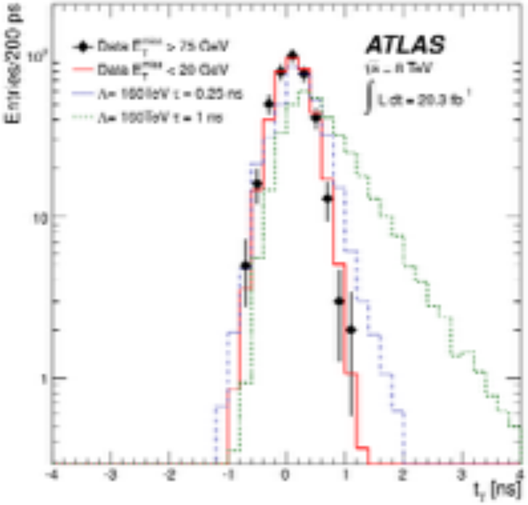
Z_{DCA} is a measure of "non-pointing-ness".

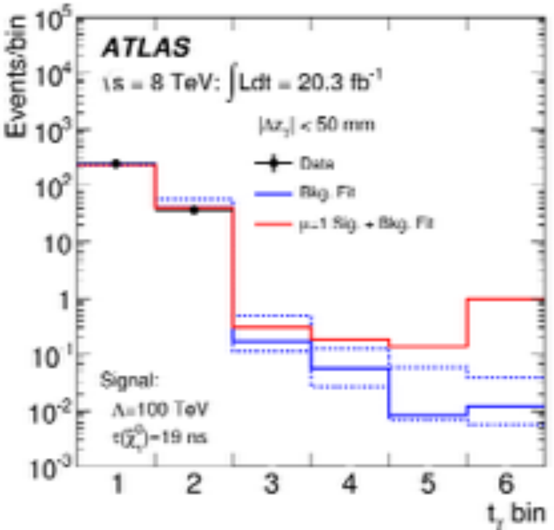


Non-pointing photons – selection and background estimation.

- We expect 2 photons per event.
- Require missing $E_T > 75$ GeV for signal region
  - Transverse energy carried off by Gravitinos.
  - Use lower missing-E_T regions as control regions.
- Divide Z_{DCA} distribution into slices, and fit Δt distribution in each slice.

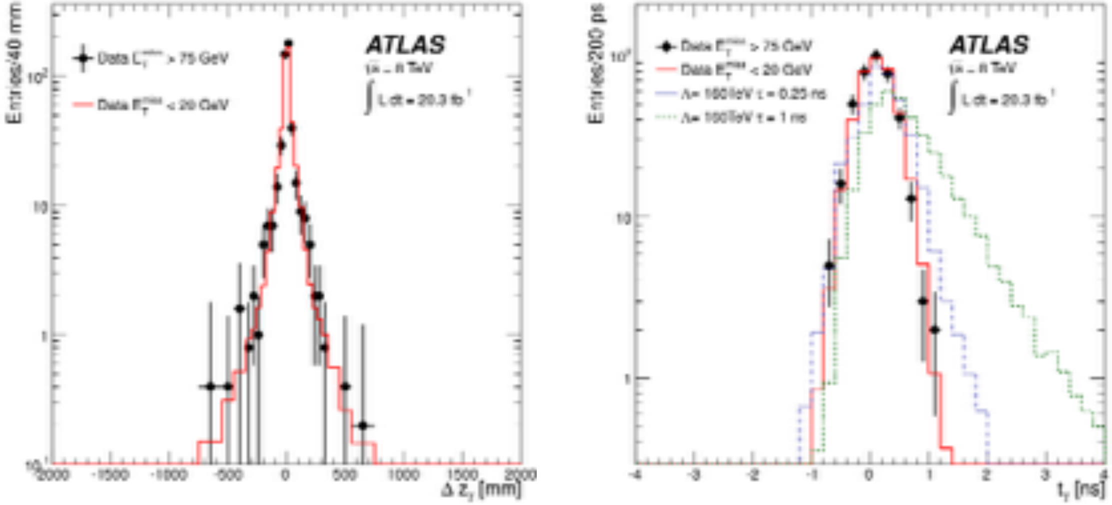






Non-pointing photons – selection and background estimation.

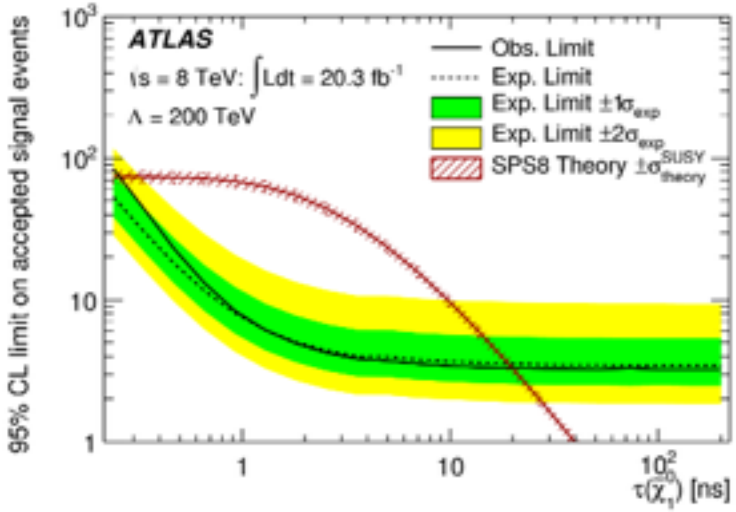
- We expect 2 photons per event.
- Require missing $E_T > 75$ GeV for signal region
  - Transverse energy carried off by Gravitinos.
  - Use lower missing-E_T regions as control regions.
- Divide Z_{DCA} distribution into slices, and fit Δt distribution in each slice.

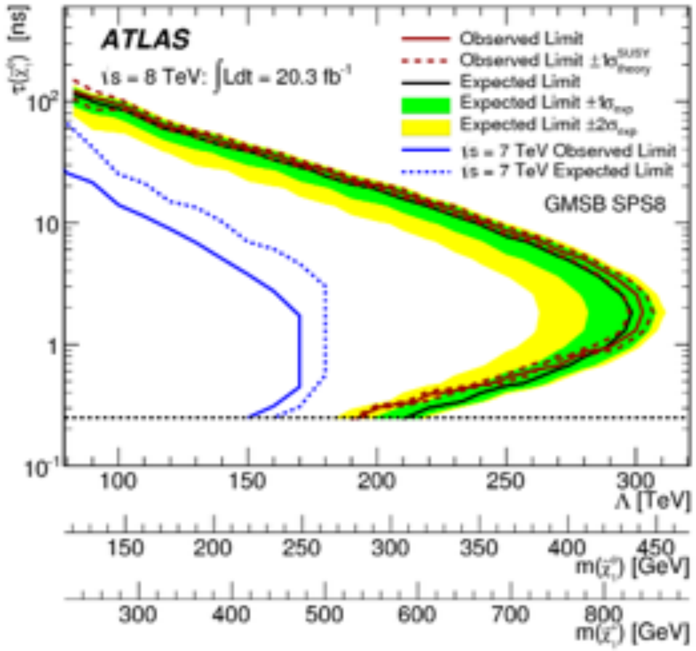


No excess seen..

Non-pointing photons - interpretation

- Set limits on cross-section vs neutralino lifetime.

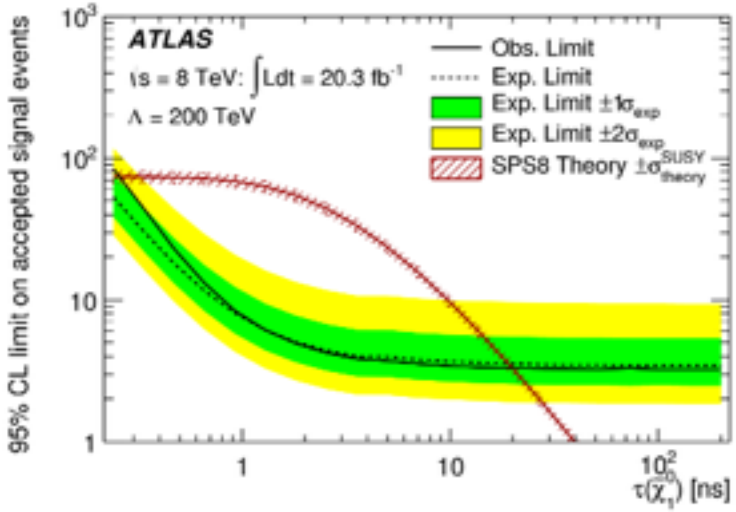


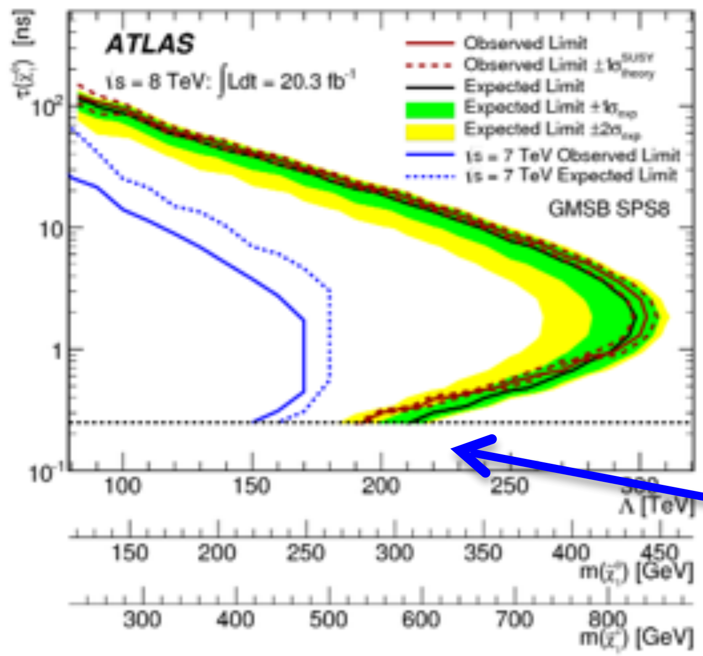


- Also set limits on parameter space for this particular GMSB SUSY model (SPS8).

Non-pointing photons - interpretation

- Set limits on cross-section vs neutralino lifetime.





- Also set limits on parameter space for this particular GMSB SUSY model (SPS8).

Gap can potentially be filled by re-interpretation of SUSY prompt di-photon analysis.

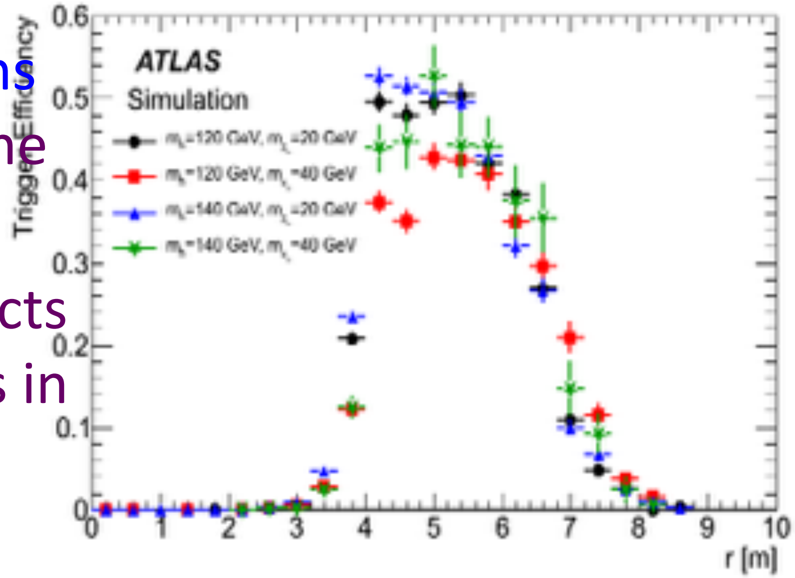
Phys.Rev.Lett. 108 (2012) 251801

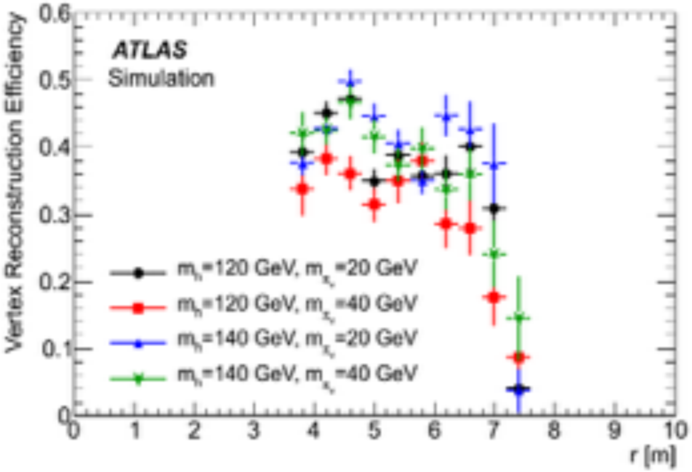
Hidden Valley: light Higgs-to-LLP search

- We can also look for displaced vertices at larger radii, near outer radius of hadronic calorimeter, or in the MS.
- As benchmark, take a Hidden Valley model, where hidden sector includes pseudoscalar π_v.
- Higgs could decay to pair of π_v.
  - Due to weak coupling with SM, π_v is long-lived.
  - Will decay to fermion-antifermion pair, predominantly bb,cc,$\tau^+\tau^-$ (due to helicity suppression).
- Signature will be two back-to-back (η,Φ) clusters of charged and neutral hadrons in the MS, (one for each π_v decay).
  - Use specially developed trigger algorithm, and specialized tracking and vertexing, to reconstruct vertices in MS.

Hidden Valley: light Higgs-to-LLP search

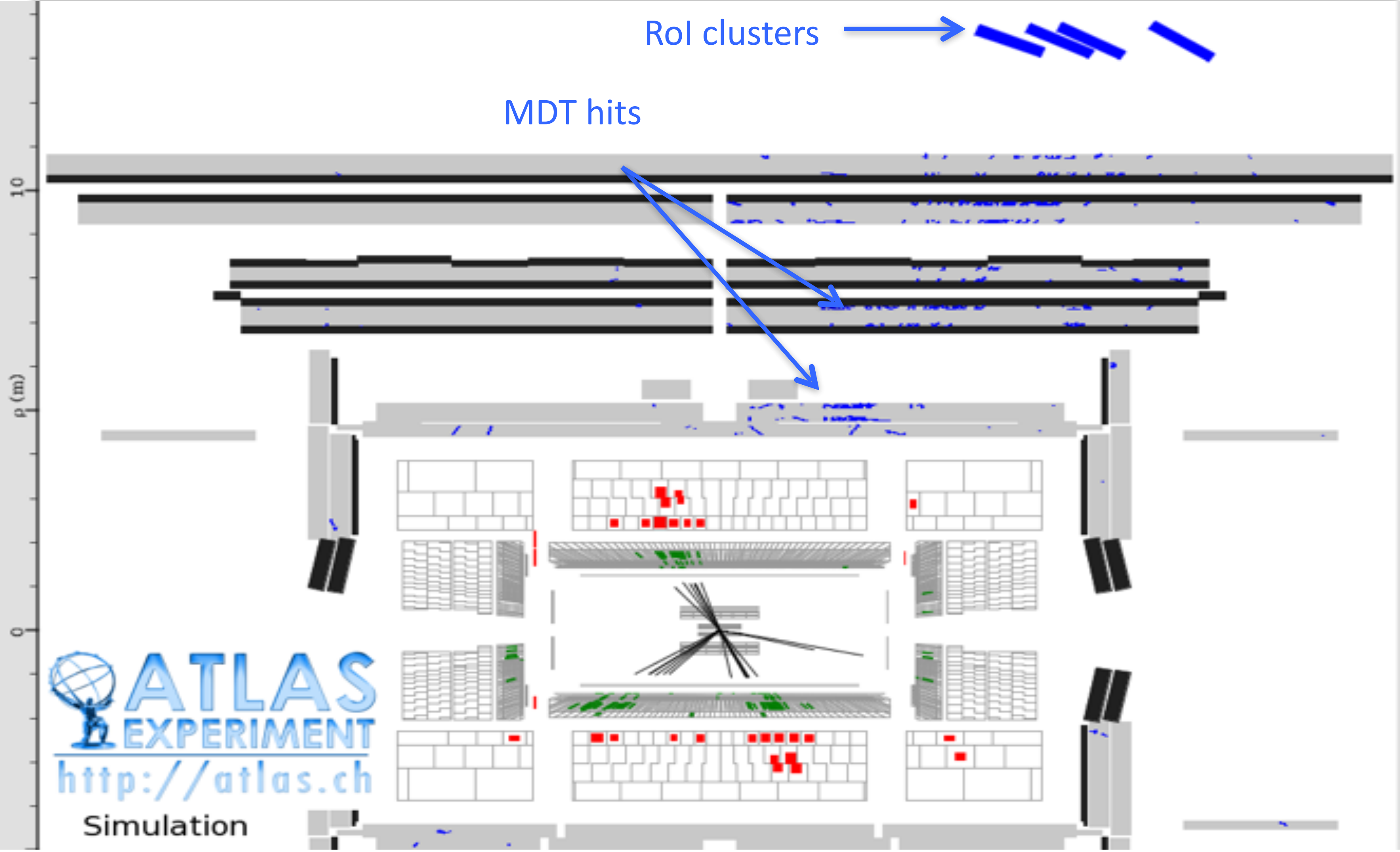
- Level 1 muon trigger creates "Regions Of Interest" (RoIs) based on hits in the MS trigger chambers.
- "Muon RoI cluster trigger" then selects events with cluster of 3 or more RoIs in ΔR=0.4 cone in MS barrel.



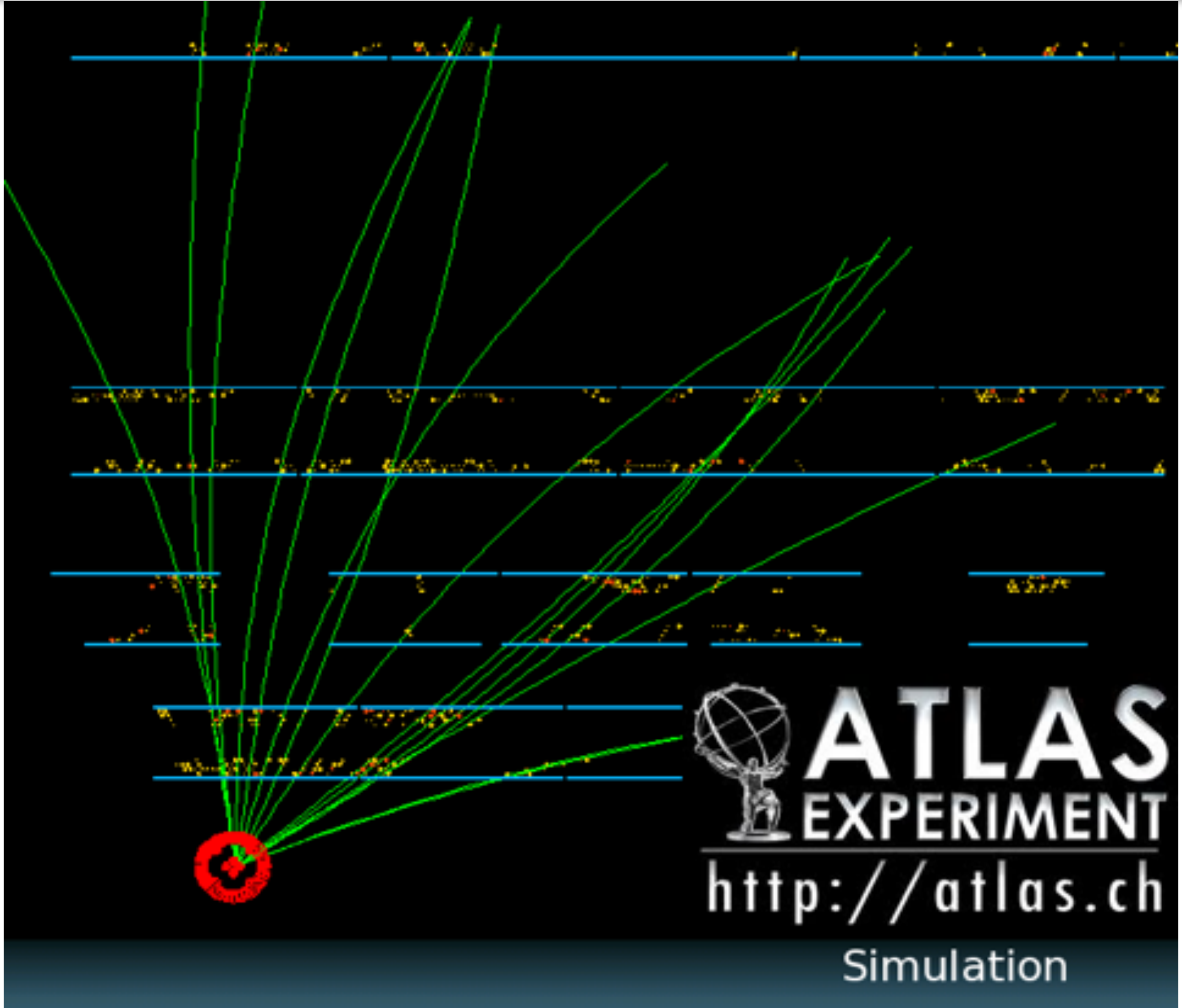


- Reconstruct "tracklets" from MDT hits.
- Extrapolate back through B-field, and reconstruct vertex position as point in (*r*,*z*) that uses highest number of tracklets to make vertex with χ^2 probability > 5%.

Hidden Valley: light Higgs-to-LLP search

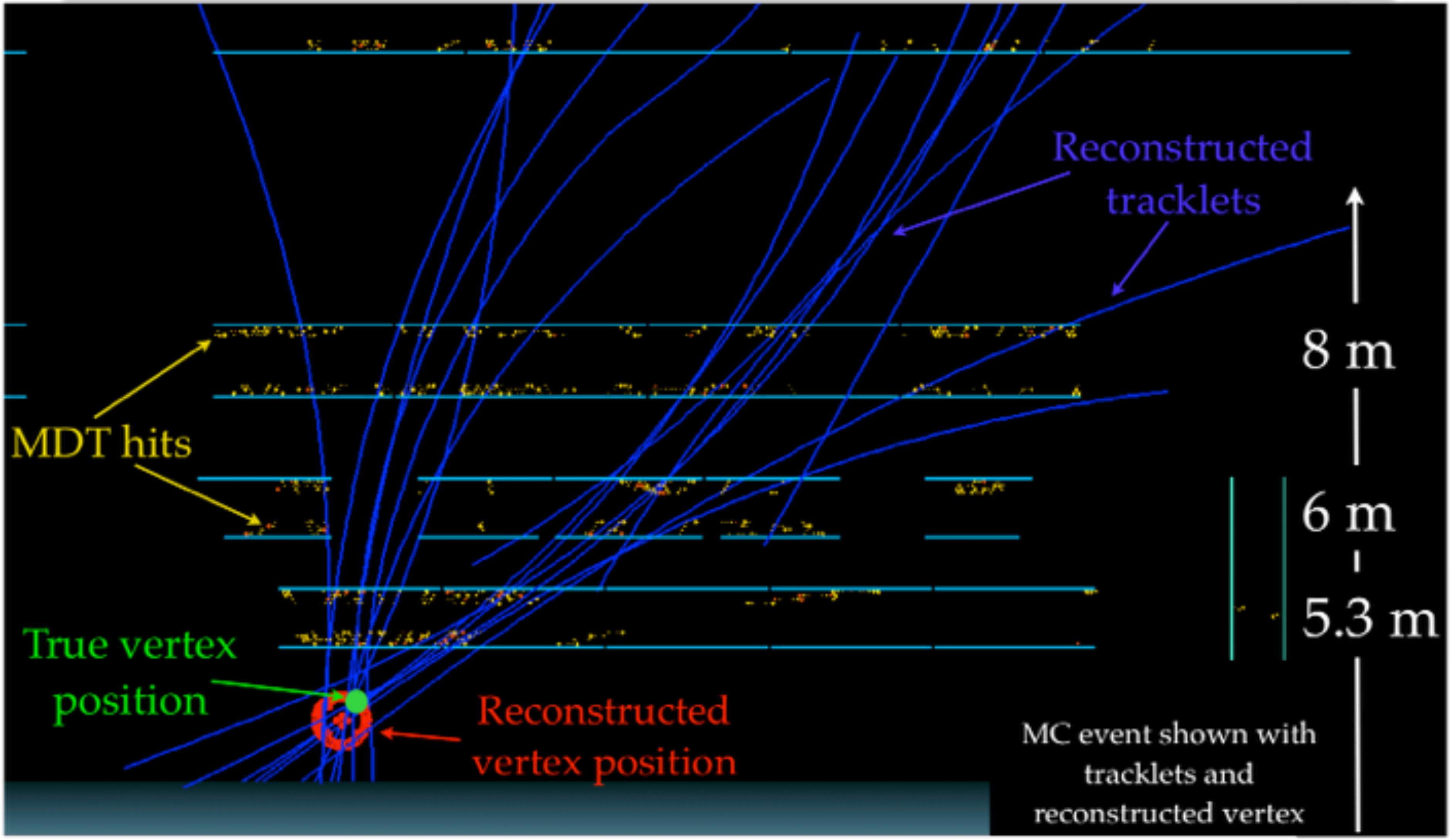


Hidden Valley: light Higgs-to-LLP search



Truth tracks

Hidden Valley: light Higgs-to-LLP search



MC event shown with tracklets and reconstructed vertex

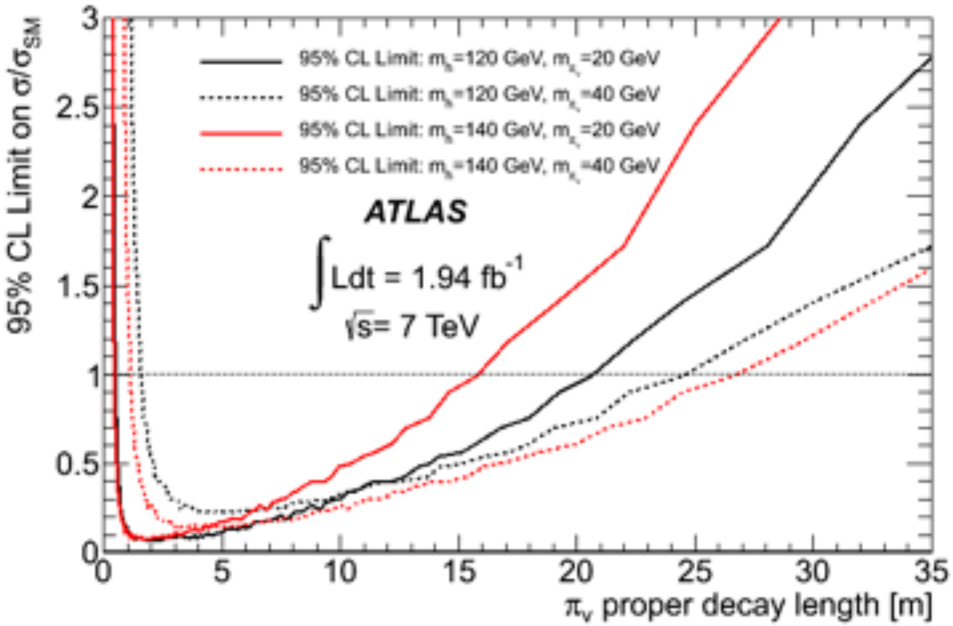
Hidden Valley: light Higgs-to-LLP search

- Reconstructed vertices are required to:
  - have at least three "tracklets",
  - point back to IP,
  - be in range $|\eta|<2.2$,
  - be separated from high-p_T tracks and jets.
- 2 vertices per event are required, separated by $\Delta R>2$.
- Calculate background using data-driven method, exploiting the fact that the two vertices can be triggered on and reconstructed independently.
  - Estimate: 0.03±0.02 events.

Hidden Valley: light Higgs-to-LLP search results

No events seen passing all selection requirements, in 1.9 fb^{-1} data.

- Set limits on h^0 to $\pi_v\ \pi_v$ cross-section as a function of π_v proper decay length, in multiples of SM Higgs production cross-section (assume 100% branching ratio).

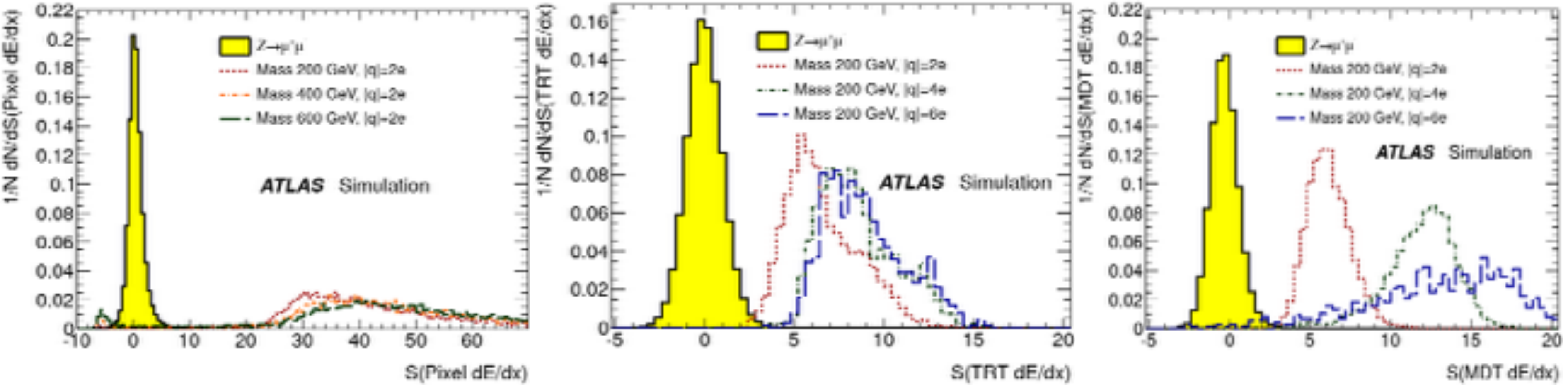


arXiv:1301.5272 [hep-ex]

Multi-charged particles

- Some SUSY theories allow for stable, non-topological solitons, “Q-balls”. [arXiv:hep-ph/9749492]
    - Could be copiously produced in early Universe, contribute to dark matter today.
- Long-lived, multi-charged particles will be highly ionizing, should leave distinctive dE/dx signature.
    - Use measurements from Pixel, TRT, and MDT.
    - Define *dE/dx significance*:

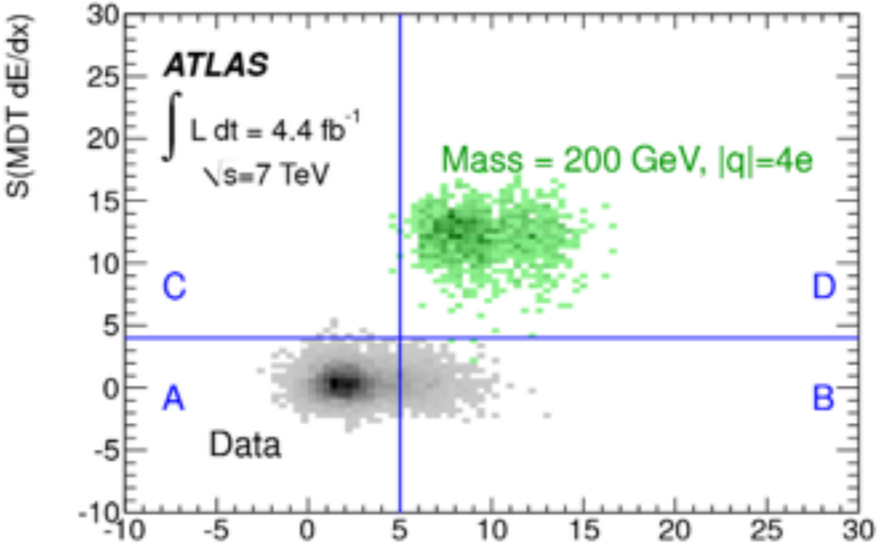
$$S(\mathrm{d}E/\mathrm{d}x) = \frac{\mathrm{d}E/\mathrm{d}x_{\mathrm{track}} - \langle \mathrm{d}E/\mathrm{d}x_{\mu} \rangle}{\sigma(\mathrm{d}E/\mathrm{d}x_{\mu})}$$



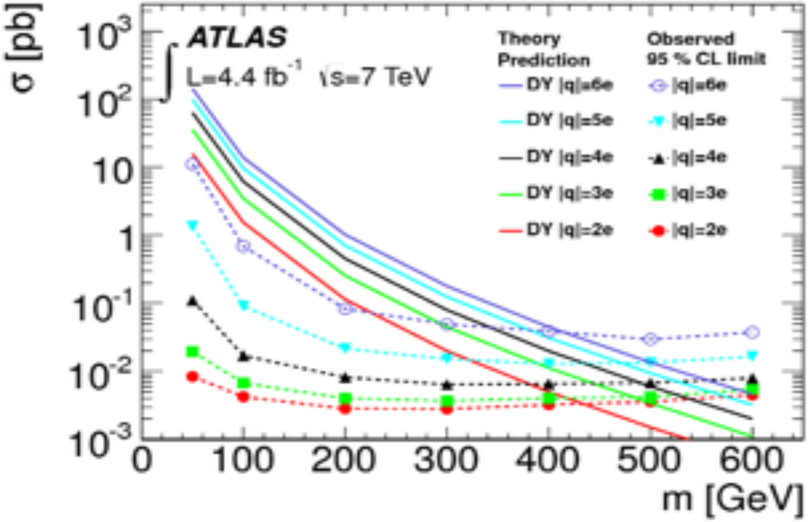
Multi-charged particles

- Consider Drell-Yan production.
- Select events using high-pT single muon trigger.

No events observed in signal region.



Set limits on DY production cross section vs mass, for different charges.



arXiv:1207.6411 [hep-ex]

Magnetic monopoles

- Magnetic monopoles appear in many Grand Unified Theories.
- Their existence would explain quantisation of electric charge.
- Dirac quantization condition:

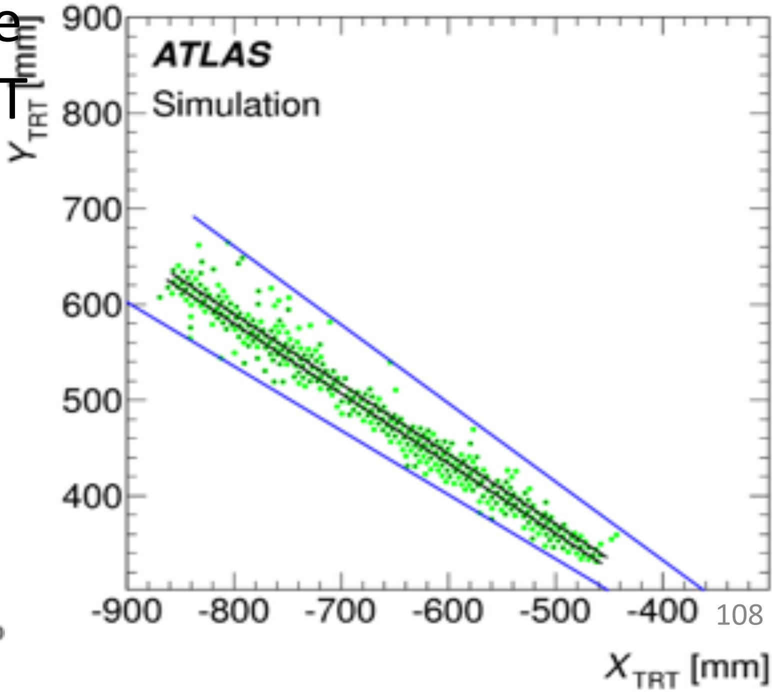
$$\frac{ge}{\hbar c} = \frac{1}{2} \Rightarrow \frac{g}{e} = \frac{1}{2\alpha_e} \approx 68.5$$

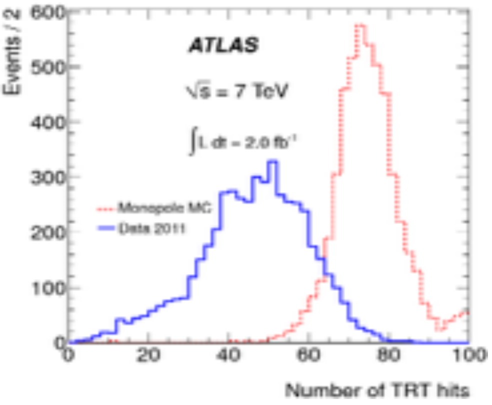
- i.e. would interact with matter like an ion with electric charge 68.5*e*… very highly ionizing!!
  - Even more so due to “knock-on” δ-rays.
- Electrically neutral magnetic monopole traversing ID would be straight in (r,Φ) plane and curved in (r,z).

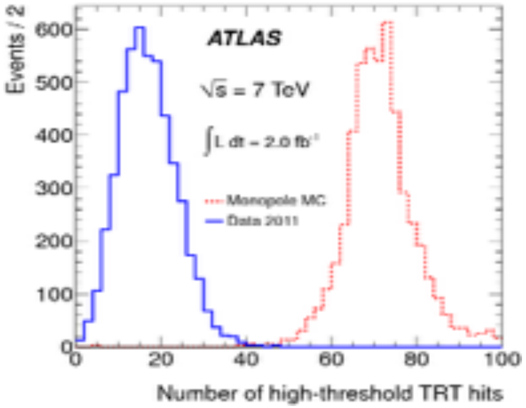
Magnetic monopoles

- Experimental signature would be large, localized energy deposit in EM calorimeter, associated with region of high ionization in TRT.
- Use high-p_T single electron trigger to select events.

- Use Φ position of EM cluster to define "roads" from beamline, and count TRT High Threshold hits.

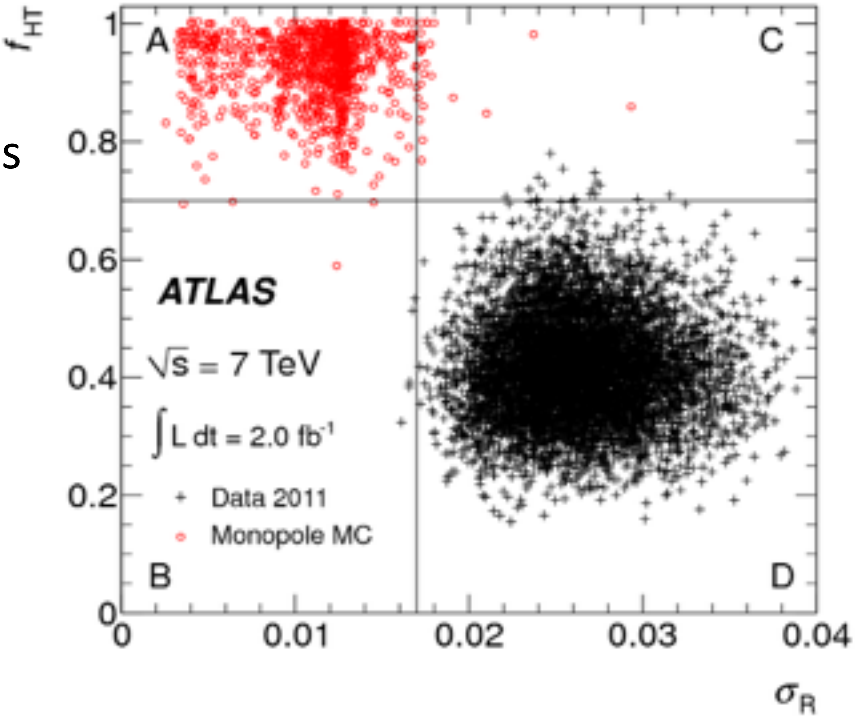






Magnetic monopoles

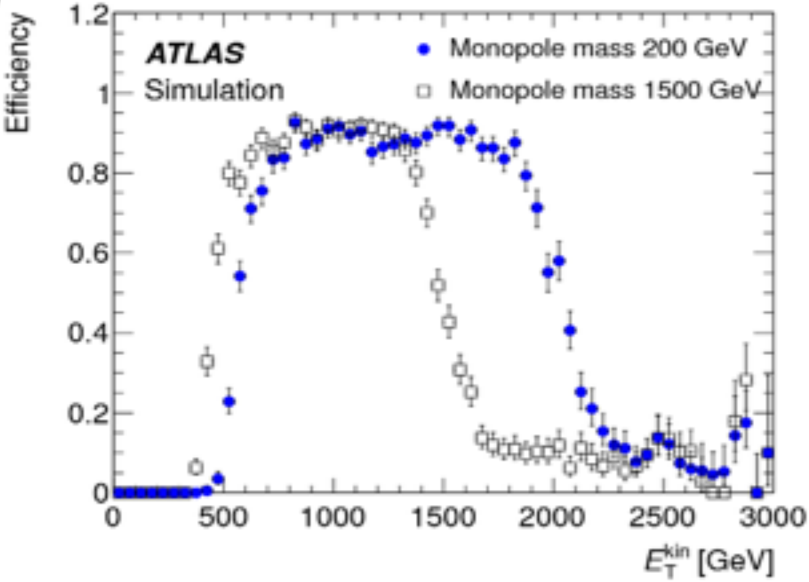
- Final Discriminating variables are:
  - Fraction f_{HT} of High Threshold TRT hits in narrow road from beamline to cluster.
  - Energy-weighted η-Φ cluster dispersion σ_R in second layer of EM calorimeter.
- Main backgrounds are high-p_T electrons, photons, jets, which have no correlation in these variables.
  - Expected background in signal region is 0.011±0.007 events.

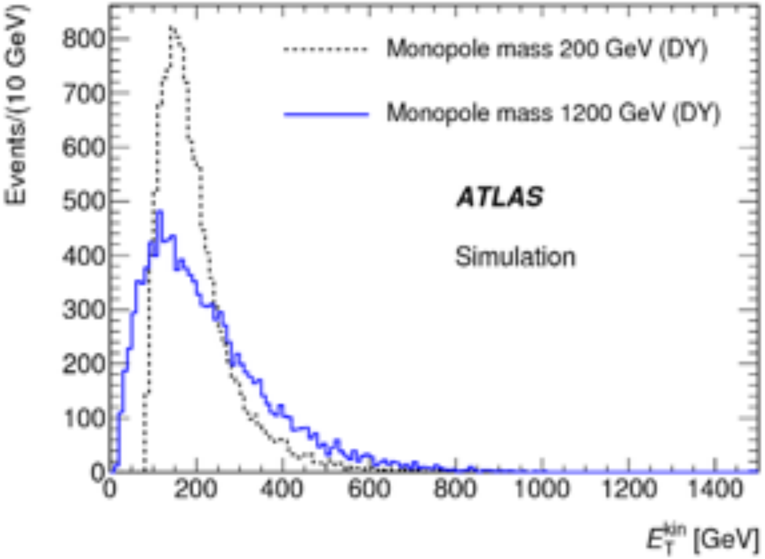


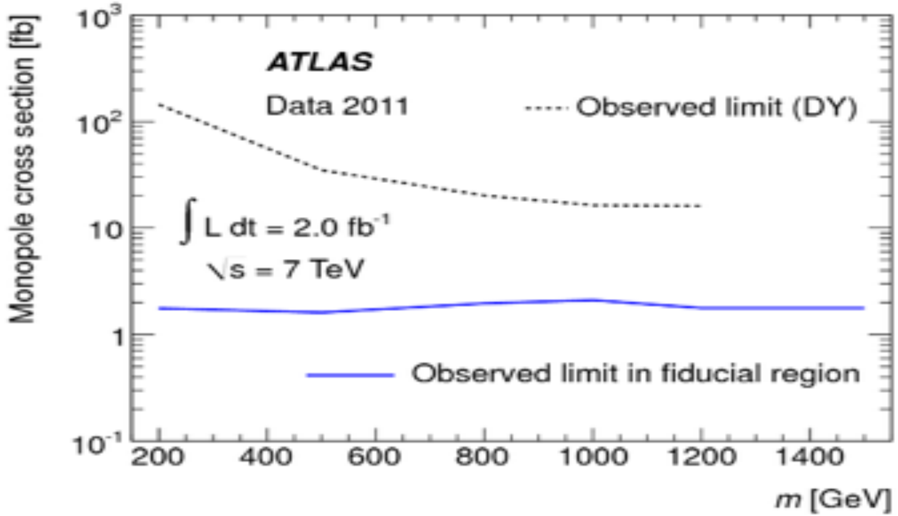
In 2 fb^{-1} dataset, no events observed in signal region.

Magnetic monopoles - limits

- From MC signal, reconstruction efficiency is high and uniform for large range in E_T^{Kin}.
- Set upper limits on production cross-section for both single monopoles in fiducial region, and Drell-Yan production.







Conclusions

- Wide range of analyses, looking for many different signatures, and often using the detector in interesting and "non-standard" ways.
  - Provide a fun challenge for ambitious experimentalists!
- No sign of New Physics so far….
- BUT:
  - Run 2 is starting, higher CM energy, higher mass reach for searches.
- We are doing our best to cover as much parameter space as we can..
  - And also to get maximum possible value out of our fantastic detector!

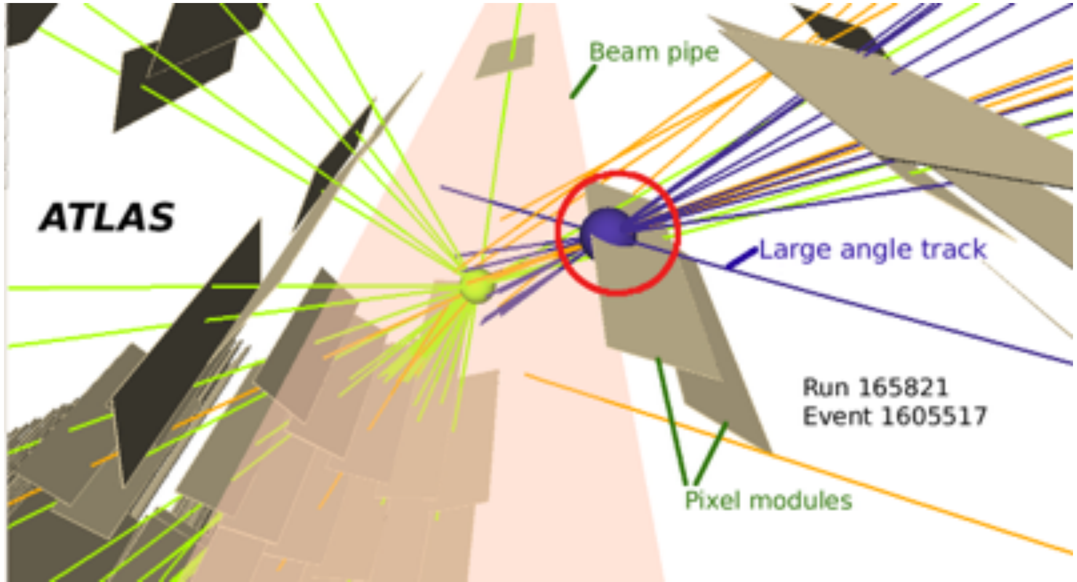
References:

- Stable Massive Particles: JHEP 01 (2015) 068.
- Stopped gluinos: Phys. Rev. D 88, 112003 (2013)
- Disappearing tracks: Phys. Rev. D 88, 112006 (2013).
- Displaced vertices with muon: coming very soon!
- Non-pointing photons: Phys. Rev. D. 90, 112005 (2014)
- Light Higgs decay to LLPs: Phys.Rev.Lett. 108 (2012) 251801.
- Multi-charged particles: PLB 722 (2013) 305.
- Magnetic monopoles: PRL 109 (2012) 261803.

Backup

Displaced vertices – backgrounds

- Two sources of background vertices considered for multi-track search:
  - Purely random combinations of tracks inside the beampipe (where vacuum is good, but track density is high).
  - High-mass tail of distribution of real vertices from hadronic interactions with gas molecules.
    - Particularly if vertex is crossed by random (real or fake) track at large angle.



- Add random tracks from different events to (n-1)-track DVs to estimate mass distribution.
- Similarly, background for dilepton search is evaluated looking at uncorrelated leptons in different events - see how often they would form a DV.

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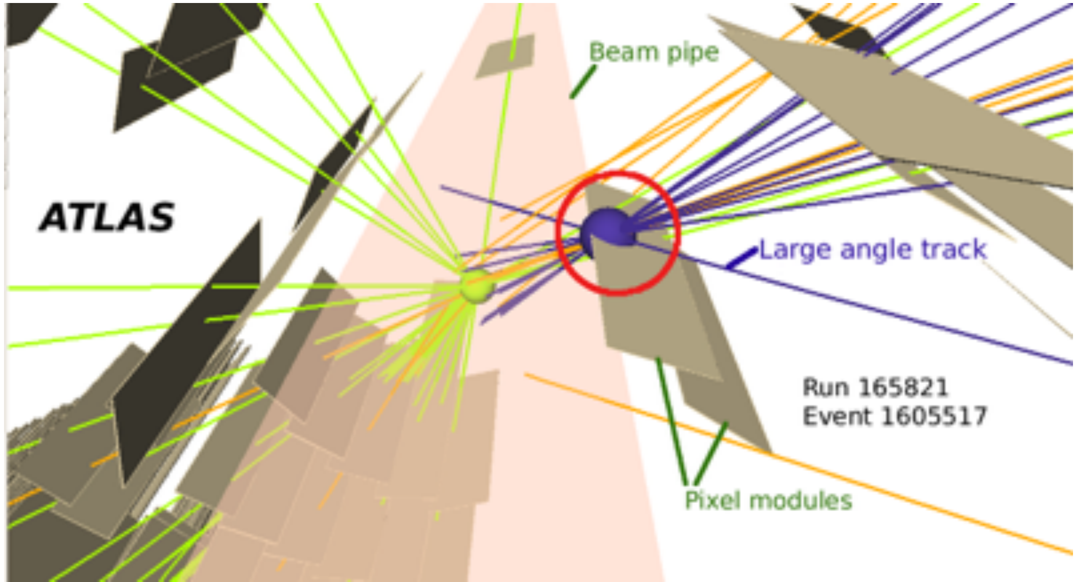


- Add random tracks from different events to (n-1)-track DVs to estimate mass distribution.
- Similarly, background for dilepton search is evaluated looking at uncorrelated leptons in different events - see how often they would form a DV.

<<1 expected background DV in all search channels.

How to get βγ from dE/dx

- Get most probable value of dE/dx from 5-parameter simplified version of Bethe-Bloch:

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

- Most probable value for MIPS is about 1.2MeV$g^{-1}cm^{2}$.

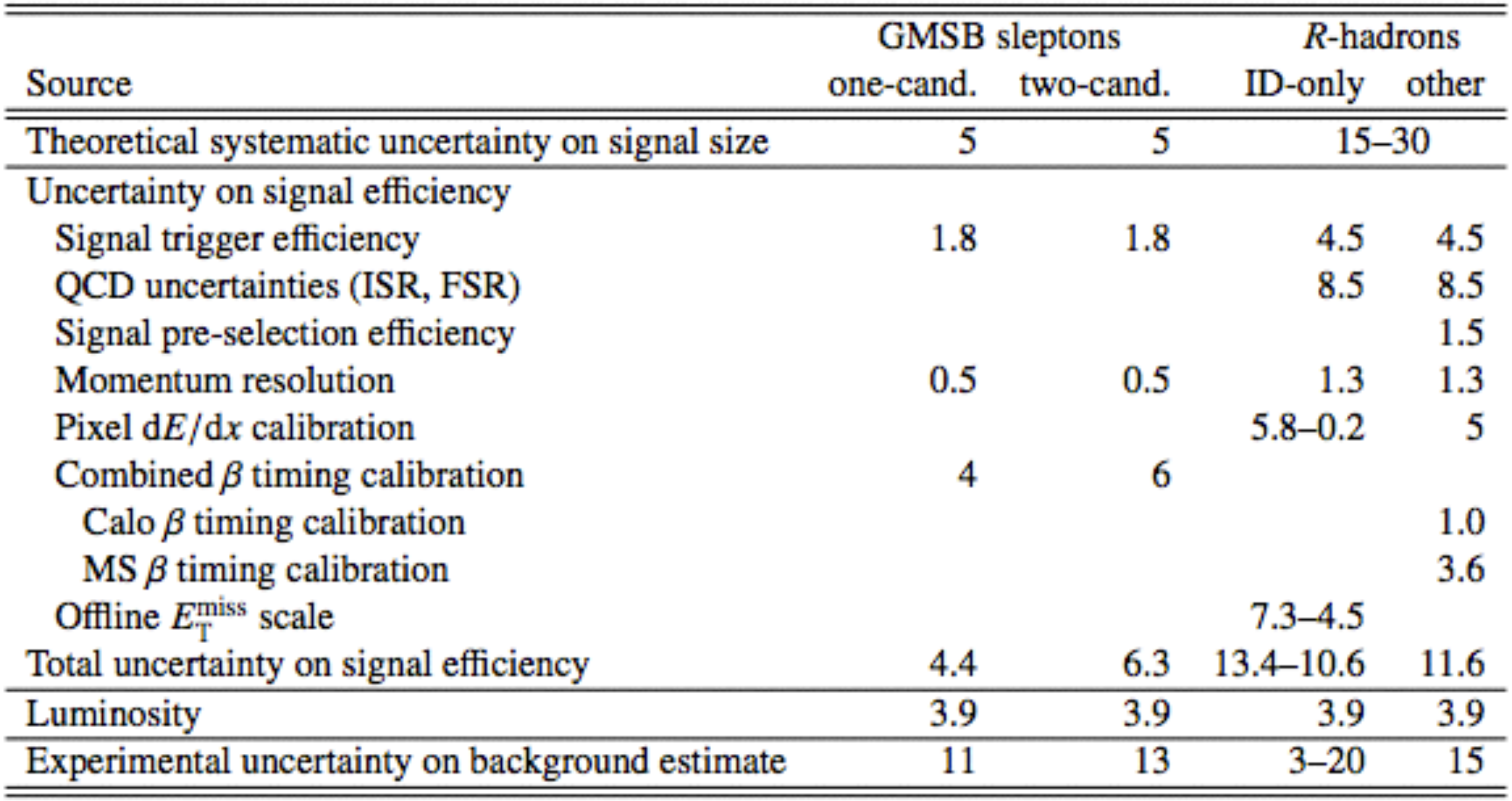
Long-lived sleptons - selection

- Use single muon trigger.
- In offline selection, require 2 muon candidates per event.
- Loose SMP selection:
  - p_T > 50 GeV (and consistent between MS and ID measurements)
  - Z-veto.
  - Consistent β and βγ measurements in different systems, with combined β <0.95.
- If one of the muon candidates in an event fails this loose SMP selection, the other one is then required to pass tight selection:
  - p_T > 70 GeV.
  - Tighter requirements on consistency between β measurements.
- Final requirements on beta and betagamma optimized for each hypothesis.

R-hadrons – selection

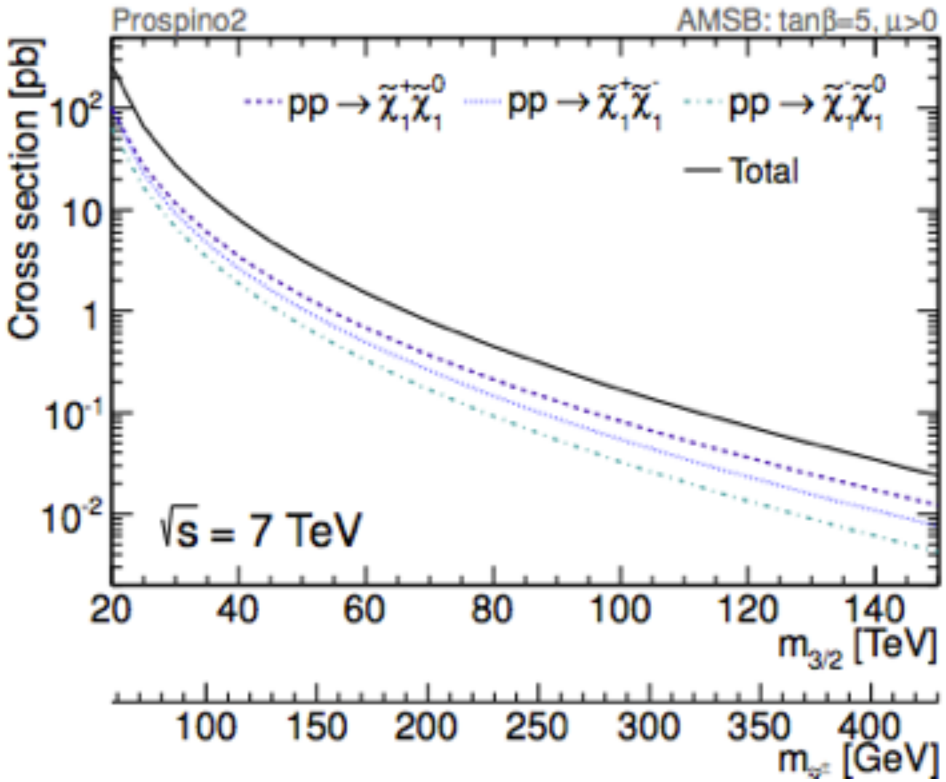
- Full detector and MS-agnostic:
  - ID track with p>140 GeV and |eta|<2.5.
  - No jet with $p_T > 40$ GeV within 0.3 cone, no track with $p_T > 10$ GeV within 0.25 cone.
  - Good dE/dx measurement.
  - Uncertainty on beta less than 10% for calo only, or 4% for combination.
- ID only:
  - PV must have more than 4 tracks.
  - Offline missing E_T cut of 85 GeV.
  - 2 pixel and 6 SCT hits, $p_T > 50$ GeV and $p > 100$ GeV.
  - No tracks with $p_T > 1$ GeV within 0.25 cone.
- Final requirements on beta and betagamma optimized for each hypothesis.

SMPs - systematics



	GMSB sleptons		*R*-hadrons	
Source	one-cand.	two-cand.	ID-only	other
Theoretical systematic uncertainty on signal size	5	5	15–30	
Uncertainty on signal efficiency				
Signal trigger efficiency	1.8	1.8	4.5	4.5
QCD uncertainties (ISR, FSR)			8.5	8.5
Signal pre-selection efficiency				1.5
Momentum resolution	0.5	0.5	1.3	1.3
Pixel $\mathrm{d}E/\mathrm{d}x$ calibration			5.8–0.2	5
Combined β timing calibration	4	6		
Calo β timing calibration				1.0
MS β timing calibration				3.6
Offline $E_{\mathrm{T}}^{\mathrm{miss}}$ scale			7.3–4.5	
Total uncertainty on signal efficiency	4.4	6.3	13.4–10.6	11.6
Luminosity	3.9	3.9	3.9	3.9
Experimental uncertainty on background estimate	11	13	3–20	15

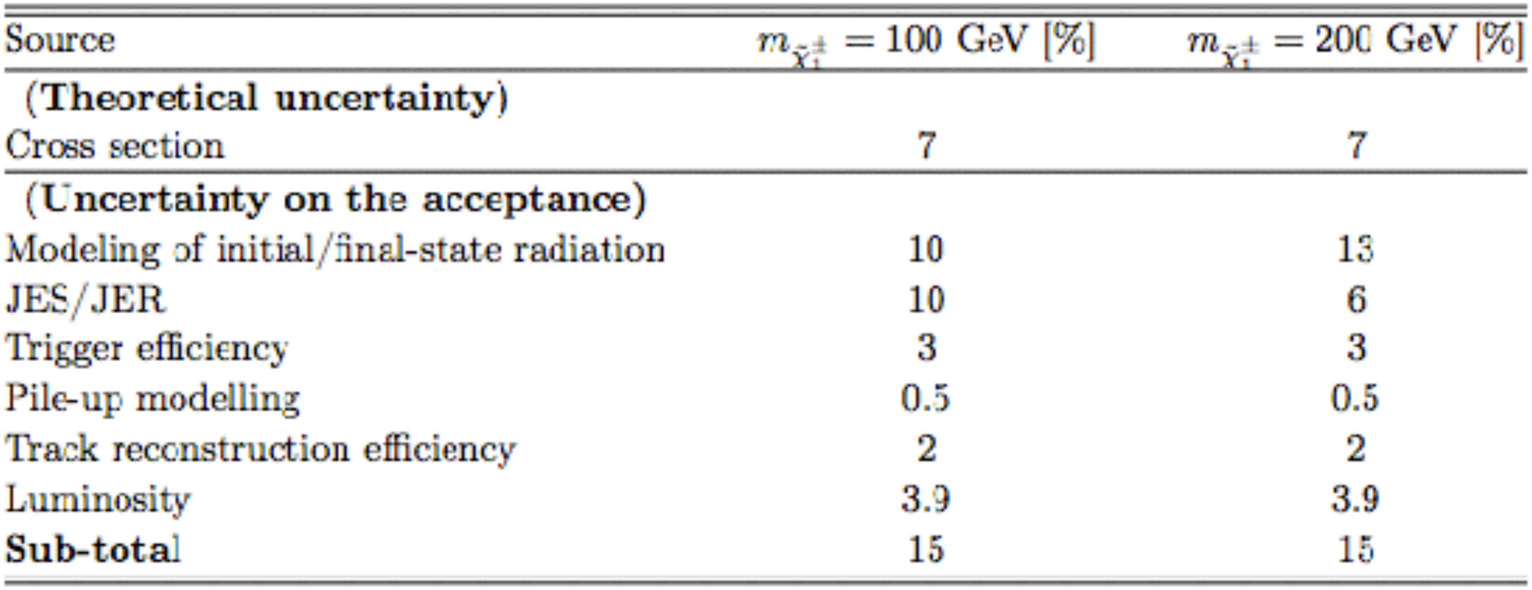
Disappearing tracks



Cross-section for direct chargino production.

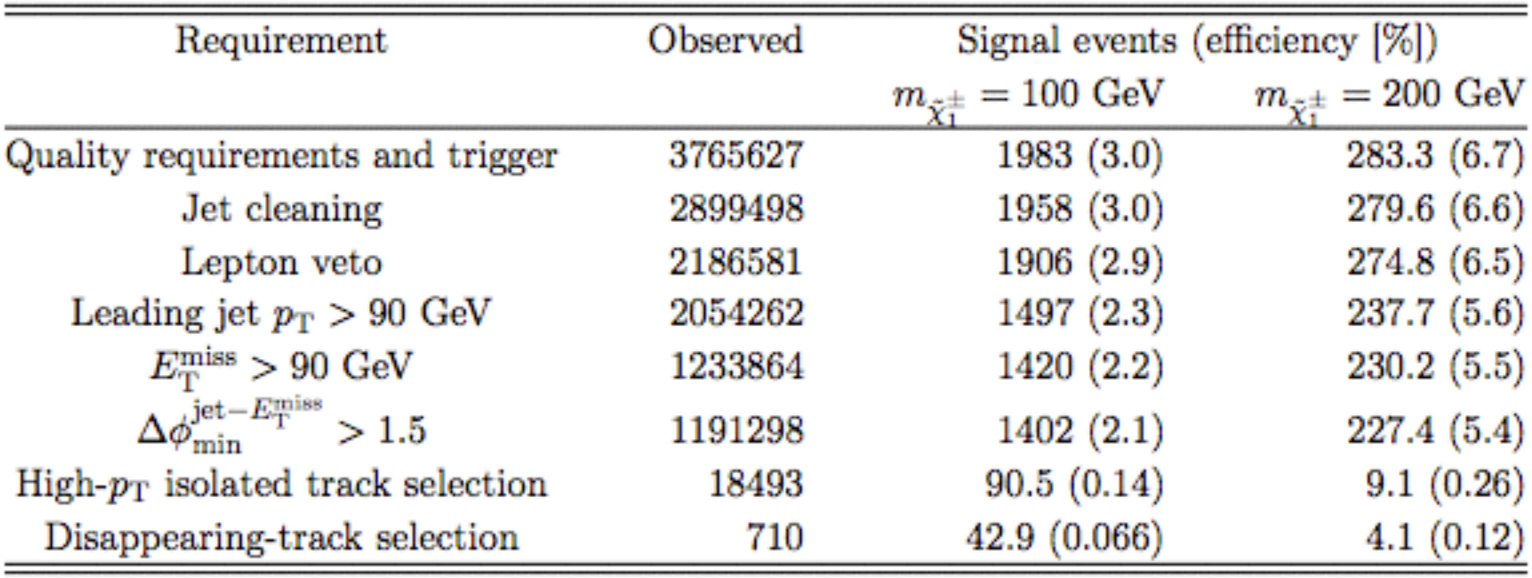
Disappearing tracks – background and systematics

- Main background after high-pT isolated track selection is from W->tau nu events.
- Data-driven method uses control samples to get pT distribution
  - Non interacting hadron tracks by requiring >10 hits in TRT outer barrel.
  - Electrons, by requiring normal selection apart from lepton veto, and applying “medium” electron ID.
- Systematics:



Source	$m_{\tilde{\chi}_1^\pm} = 100$ GeV [%]	$m_{\tilde{\chi}_1^\pm} = 200$ GeV [%]
(Theoretical uncertainty)		
Cross section	7	7
(Uncertainty on the acceptance)		
Modeling of initial/final-state radiation	10	13
JES/JER	10	6
Trigger efficiency	3	3
Pile-up modelling	0.5	0.5
Track reconstruction efficiency	2	2
Luminosity	3.9	3.9
Sub-total	15	15

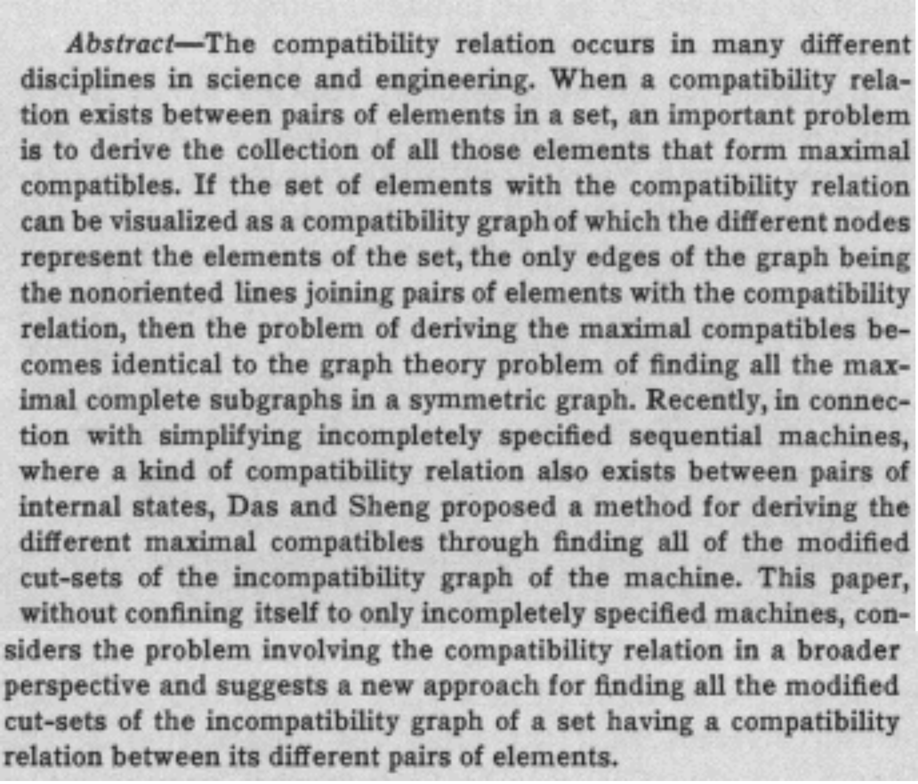
Disappearing tracks - cutflow



Requirement	Observed	Signal events (efficiency [%])	
		$m_{\tilde{\chi}_1^\pm} = 100$ GeV	$m_{\tilde{\chi}_1^\pm} = 200$ GeV
Quality requirements and trigger	3765627	1983 (3.0)	283.3 (6.7)
Jet cleaning	2899498	1958 (3.0)	279.6 (6.6)
Lepton veto	2186581	1906 (2.9)	274.8 (6.5)
Leading jet $p_{\mathrm{T}} > 90$ GeV	2054262	1497 (2.3)	237.7 (5.6)
$E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV	1233864	1420 (2.2)	230.2 (5.5)
$\Delta\phi_{\mathrm{min}}^{\mathrm{jet}-E_{\mathrm{T}}^{\mathrm{miss}}} > 1.5$	1191298	1402 (2.1)	227.4 (5.4)
High-p_{T} isolated track selection	18493	90.5 (0.14)	9.1 (0.26)
Disappearing-track selection	710	42.9 (0.066)	4.1 (0.12)

Incompatibility graph

- S. R. Das, "On a new approach for finding all the modified cut-sets in an incompatibility graph", IEEE Transactions on Computers v22(2) (1973) 187.



Abstract—The compatibility relation occurs in many different disciplines in science and engineering. When a compatibility relation exists between pairs of elements in a set, an important problem is to derive the collection of all those elements that form maximal compatibles. If the set of elements with the compatibility relation can be visualized as a compatibility graph of which the different nodes represent the elements of the set, the only edges of the graph being the nonoriented lines joining pairs of elements with the compatibility relation, then the problem of deriving the maximal compatibles becomes identical to the graph theory problem of finding all the maximal complete subgraphs in a symmetric graph. Recently, in connection with simplifying incompletely specified sequential machines, where a kind of compatibility relation also exists between pairs of internal states, Das and Sheng proposed a method for deriving the different maximal compatibles through finding all of the modified cut-sets of the incompatibility graph of the machine. This paper, without confining itself to only incompletely specified machines, considers the problem involving the compatibility relation in a broader perspective and suggests a new approach for finding all the modified cut-sets of the incompatibility graph of a set having a compatibility relation between its different pairs of elements.

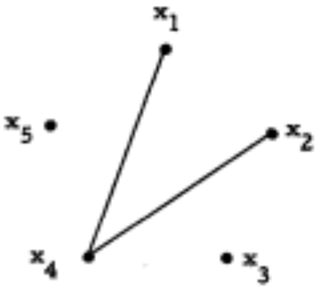


Fig. 1. Compatibility graph of five elements.

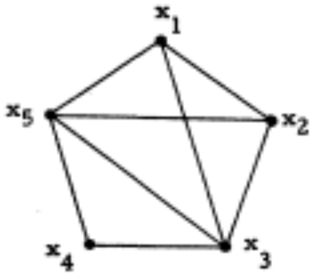
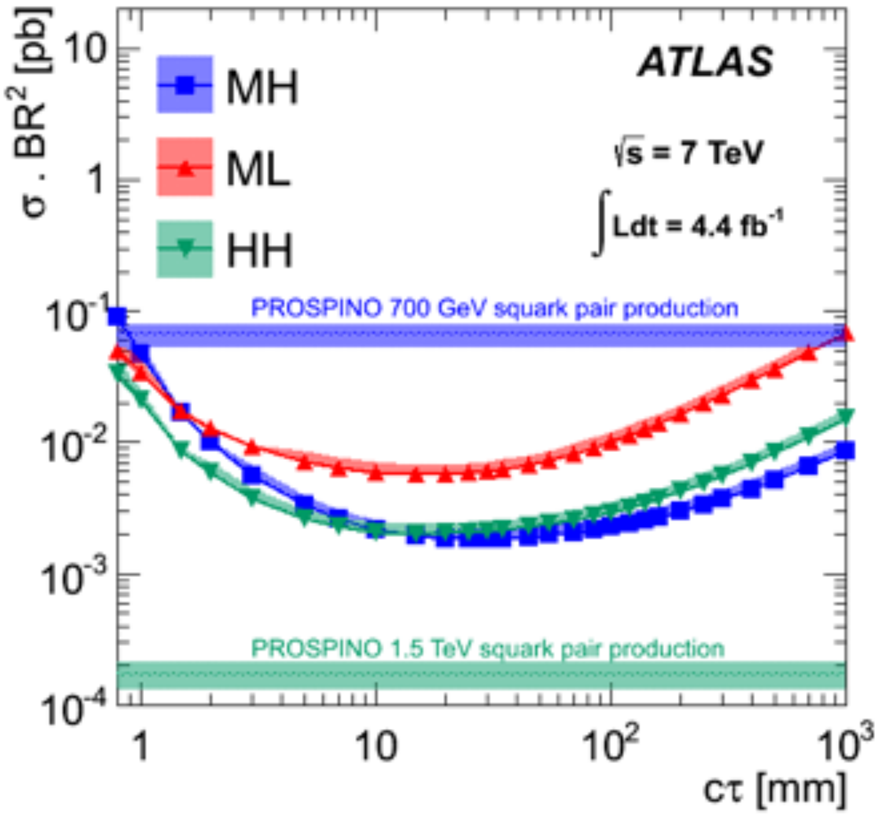


Fig. 2. Incompatibility graph of five elements.

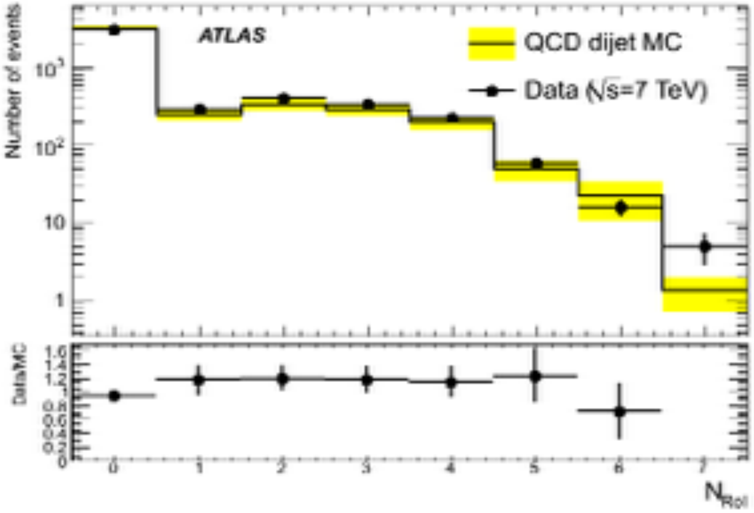
Displaced vertices – interpretation

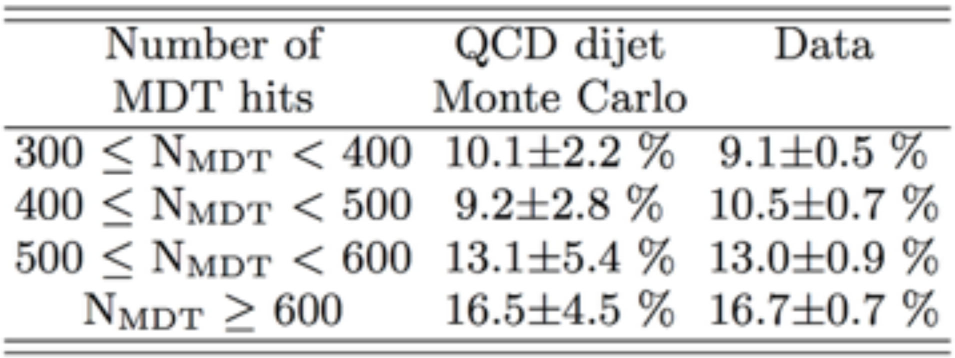


Use CL_s method to set 95%C.L. upper limit on σ-vs-*cτ* for each mass combination.

Limit shown here is for two neutralinos per event, but efficiency factorizes, so limit for single vertex can be easily calculated: $(eff_{evt}=2*eff_{vtx}-eff_{vtx}^{2})$.

Higgs to LLPs – systematics



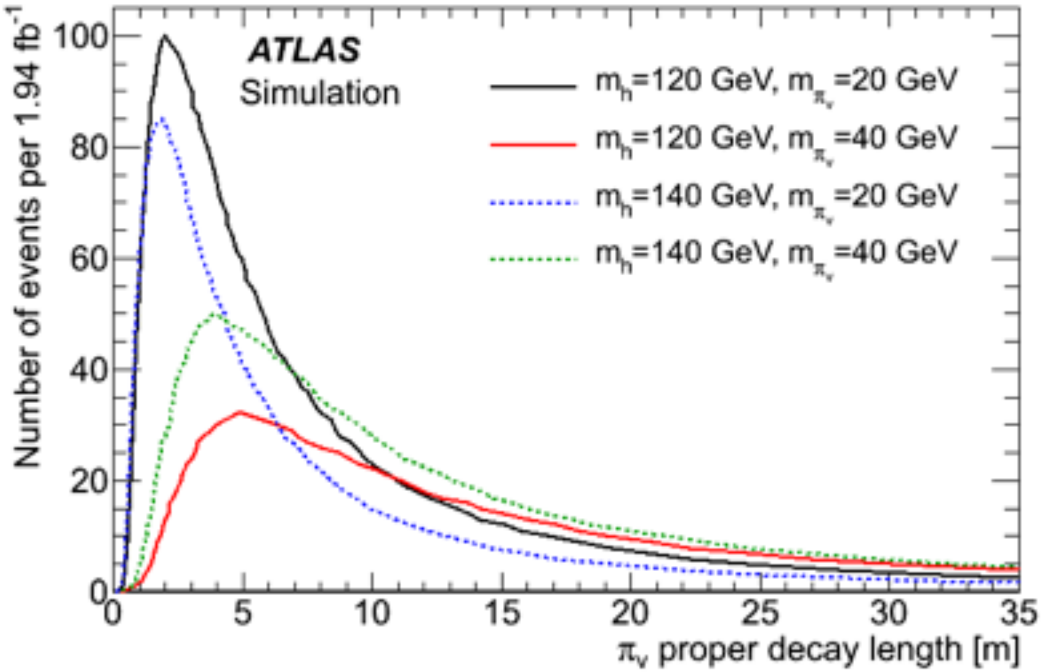


Number of MDT hits	QCD dijet Monte Carlo	Data
$300 \leq N_{MDT} < 400$	10.1±2.2 %	9.1±0.5 %
$400 \leq N_{MDT} < 500$	9.2±2.8 %	10.5±0.7 %
$500 \leq N_{MDT} < 600$	13.1±5.4 %	13.0±0.9 %
$N_{MDT} \geq 600$	16.5±4.5 %	16.7±0.7 %

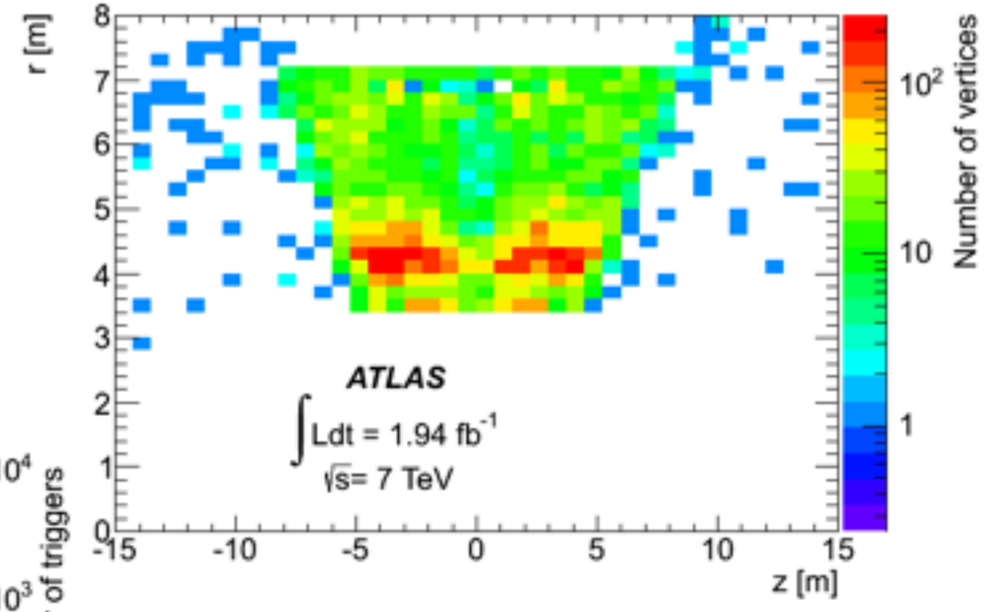
Look at data/MC difference in numbers of RoIs and in vertex reconstruction efficiency for punch-through jets.

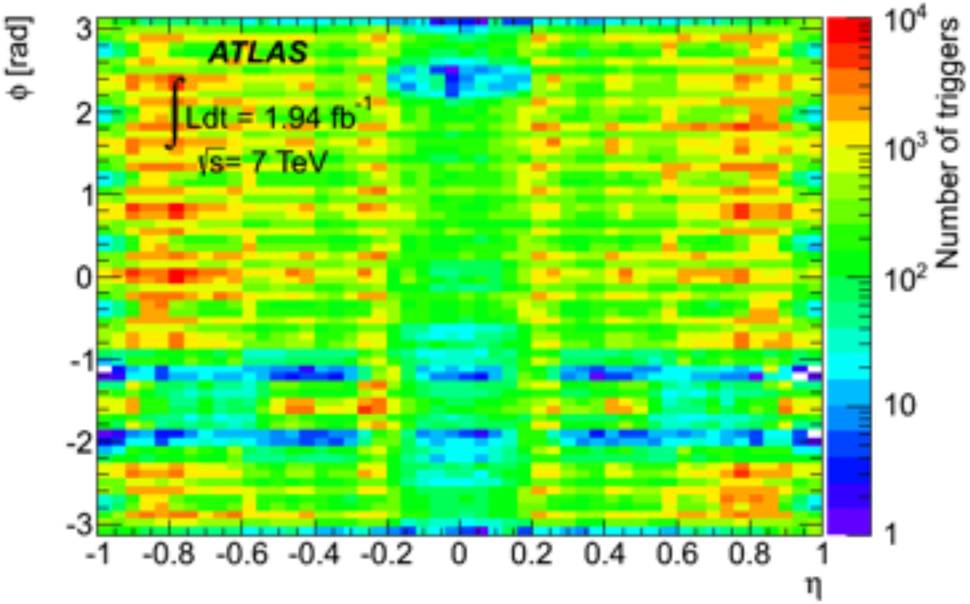
Total systematic uncertainty on efficiency for reconstructing a vertex is 16%.

Higgs to LLP – ctau vs mass



Higgs to LLP – RoI positions in data





Higgs to LLP – Background estimate

Number of events with single muon RoI trigger object, and isolated MS vertex.

Probability for random event to contain an MS vertex.

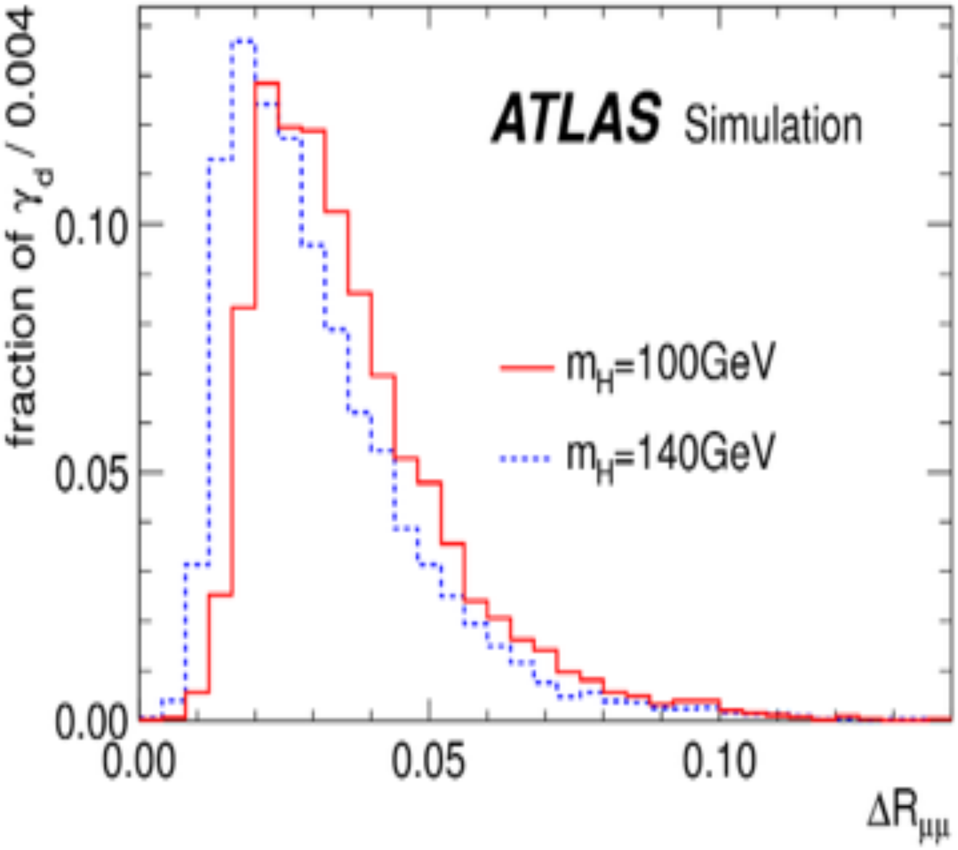
$$N_{\text{fake}}(2\ \text{MS vertex}) = N(\text{MS vertex, 1trig})*P_{\text{vertex}}$$
$$+\ N(\text{MS vertex,2trig})*P_{\text{reco}}$$

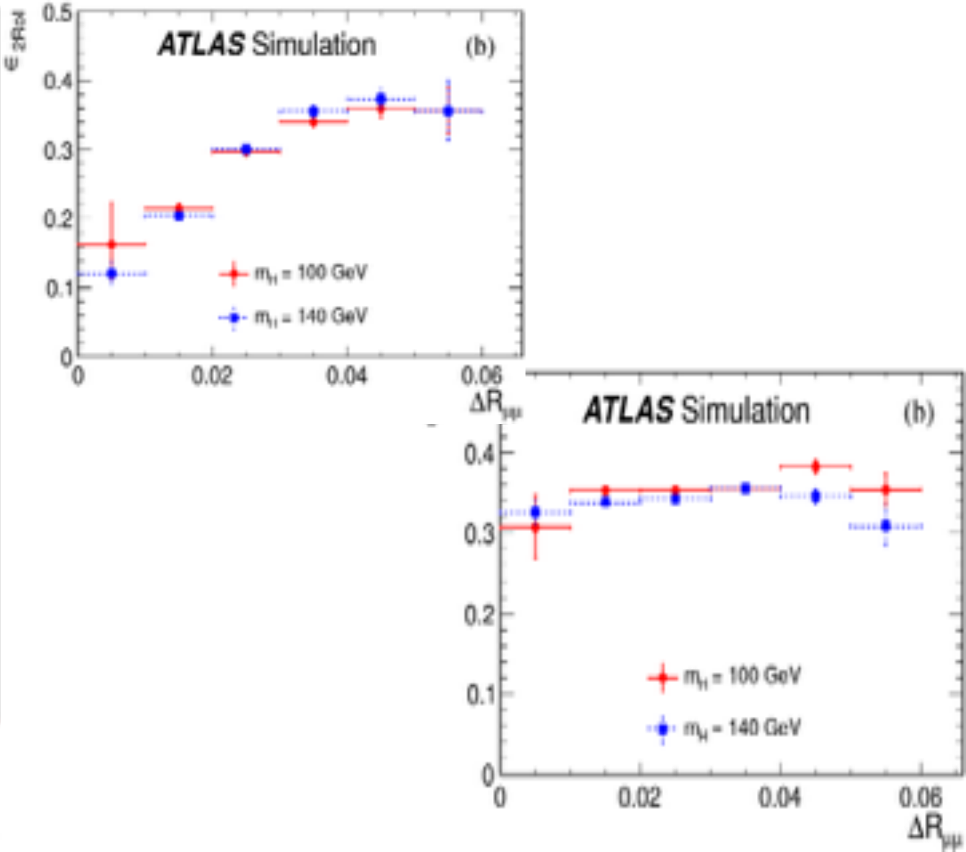
Number of events with isolated vertex and 2 trigger muon RoI cluster objects.

Probability to reconstruct a vertex given that there was an RoI cluster.

Displaced muonic lepton jets

- Challenge is getting separate RoIs from two very collimated muons, separated by DeltaR.

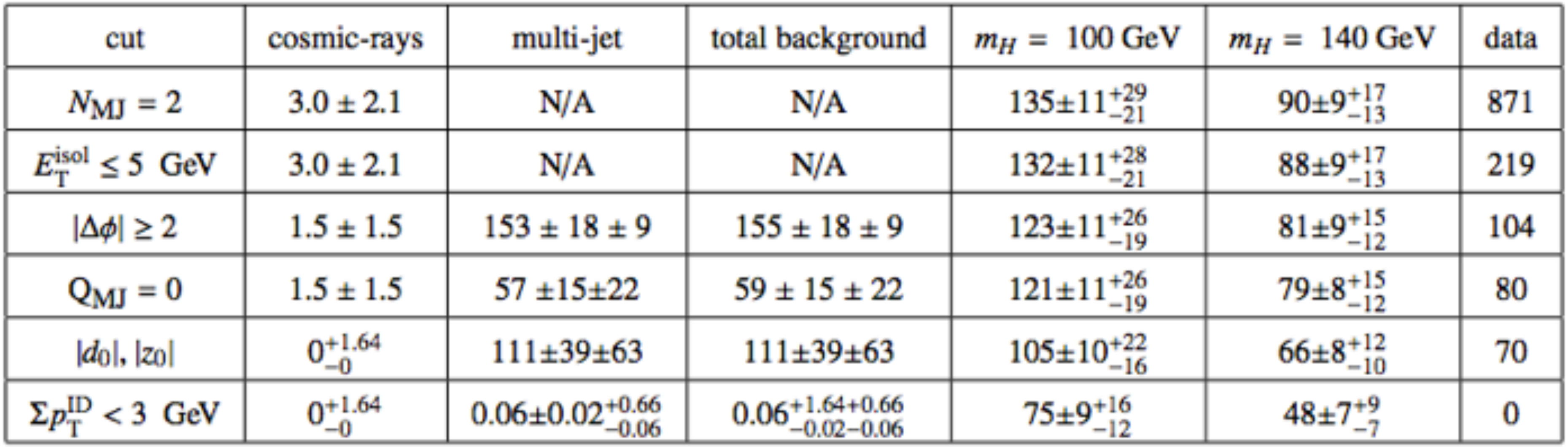




Displaced muonic lepton jets - selection

- Exactly 2 MJs, each of which have exactly 2 oppositely charged muons.
- Difference E_t^{isol} between calorimeter energy in R=0.4 cone around highest pT muon and in 0.2 cone must be < 5 GeV for both MJs.
- Sum of pT of all ID tracks in 0.4 cone around MJ must be < 4 GeV.
- abs(Delta phi) between two MJs must be >2.

Displaced lepton jets - cutflow



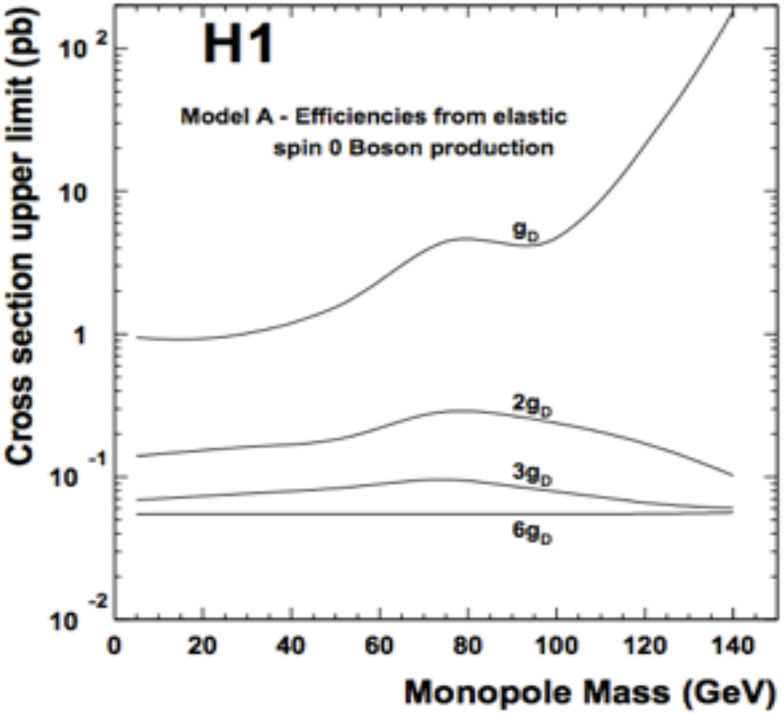
cut	cosmic-rays	multi-jet	total background	m_H = 100 GeV	m_H = 140 GeV	data
$N_{\mathrm{MJ}} = 2$	3.0 ± 2.1	N/A	N/A	$135{\pm}11^{+29}_{-21}$	$90{\pm}9^{+17}_{-13}$	871
$E_{\mathrm{T}}^{\mathrm{isol}} \leq 5$ GeV	3.0 ± 2.1	N/A	N/A	$132{\pm}11^{+28}_{-21}$	$88{\pm}9^{+17}_{-13}$	219
$\lvert\Delta\phi\rvert \geq 2$	1.5 ± 1.5	$153 \pm 18 \pm 9$	$155 \pm 18 \pm 9$	$123{\pm}11^{+26}_{-19}$	$81{\pm}9^{+15}_{-12}$	104
$\mathrm{Q}_{\mathrm{MJ}} = 0$	1.5 ± 1.5	$57 \pm 15 \pm 22$	$59 \pm 15 \pm 22$	$121{\pm}11^{+26}_{-19}$	$79{\pm}8^{+15}_{-12}$	80
$\lvert d_0\rvert, \lvert z_0\rvert$	$0^{+1.64}_{-0}$	$111{\pm}39{\pm}63$	$111{\pm}39{\pm}63$	$105{\pm}10^{+22}_{-16}$	$66{\pm}8^{+12}_{-10}$	70
$\Sigma p_{\mathrm{T}}^{\mathrm{ID}} < 3$ GeV	$0^{+1.64}_{-0}$	$0.06{\pm}0.02^{+0.66}_{-0.06}$	$0.06^{+1.64+0.66}_{-0.02-0.06}$	$75{\pm}9^{+16}_{-12}$	$48{\pm}7^{+9}_{-7}$	0

Displaced lepton jets - systematics

- Luminosity: 3.7%.
- Muon momentum resolution: negligible.
- Trigger (evaluated using T&P on Jpsi->mumu): 17%.
- Reco efficieny (evaluated using T&P on Jpsi->mumu): 13%.
- Pile-up: negligible.

H1 monopole search

- H1 removed beampipe, used magnetometer to look for stable monopoles.
  - Eur.Phys.J. C41 (2005) 133-141.

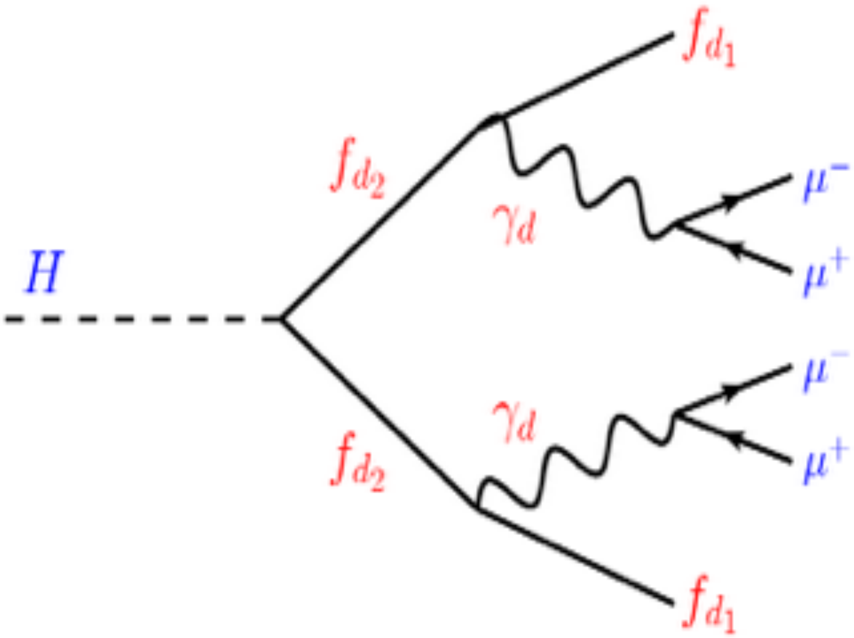


arXiv:1210.0435 [hep-ex]

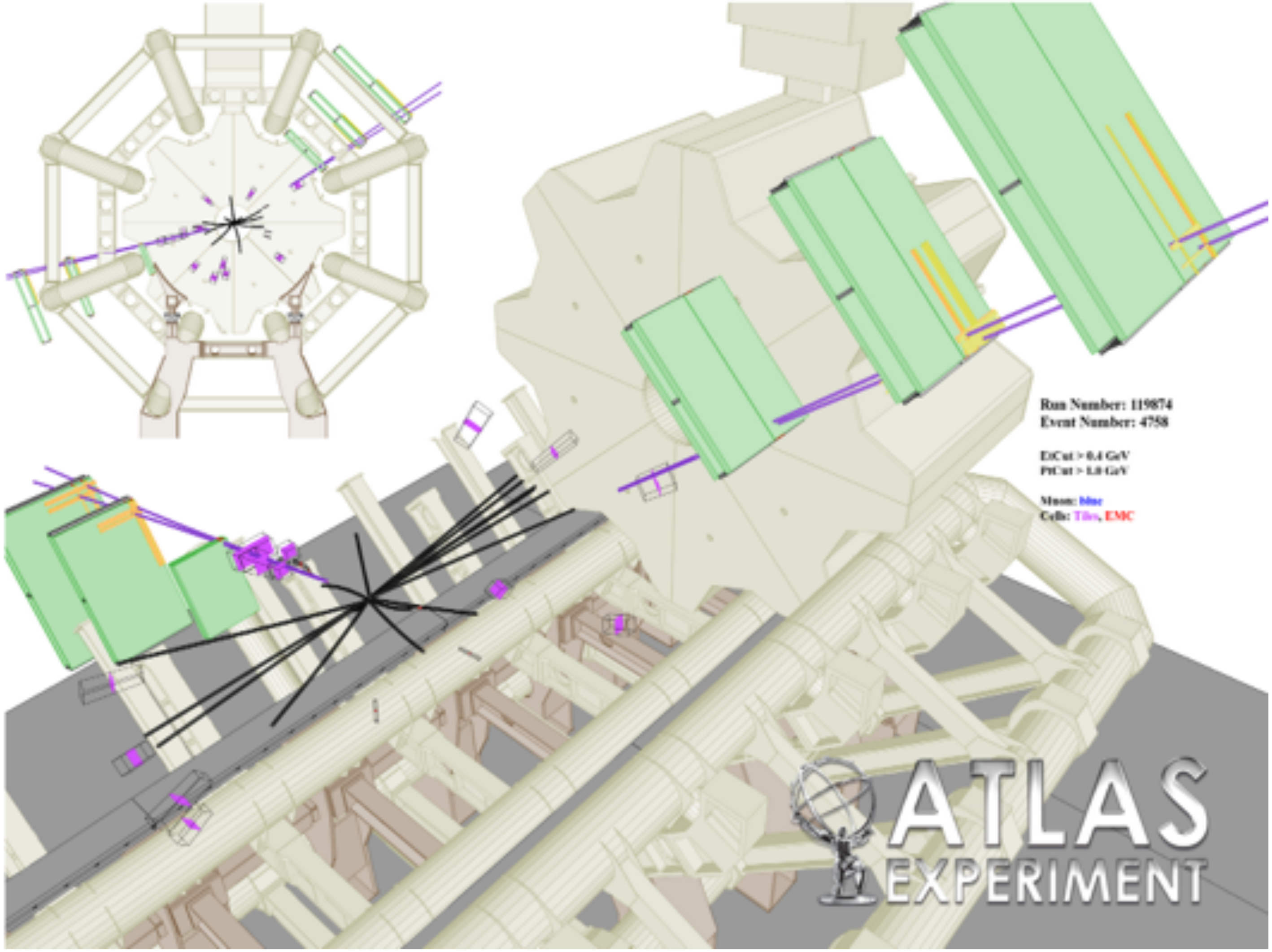
Displaced muonic lepton jets

- At the LHC, hidden sector particles could be produced with large boosts, such that their decay products form jet-like structures.

- If the Higgs can decay to hidden-sector fermions, these could in turn decay to a (potentially long-lived) neutral hidden-sector particle γ_d and a stable hidden sector fermion that escapes detection.
- Decay of γ_d could give rise to collimated pairs of leptons.

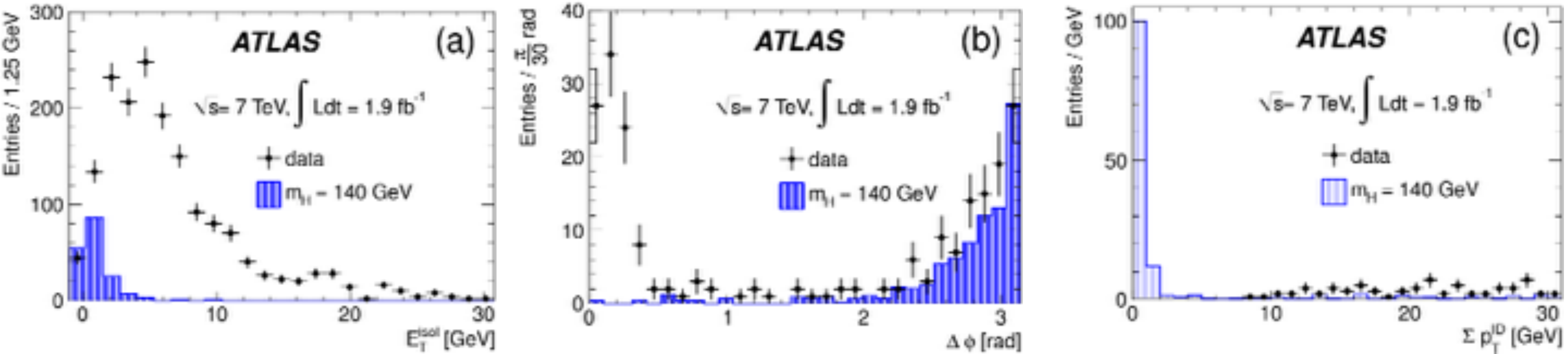


Displaced muonic lepton jets



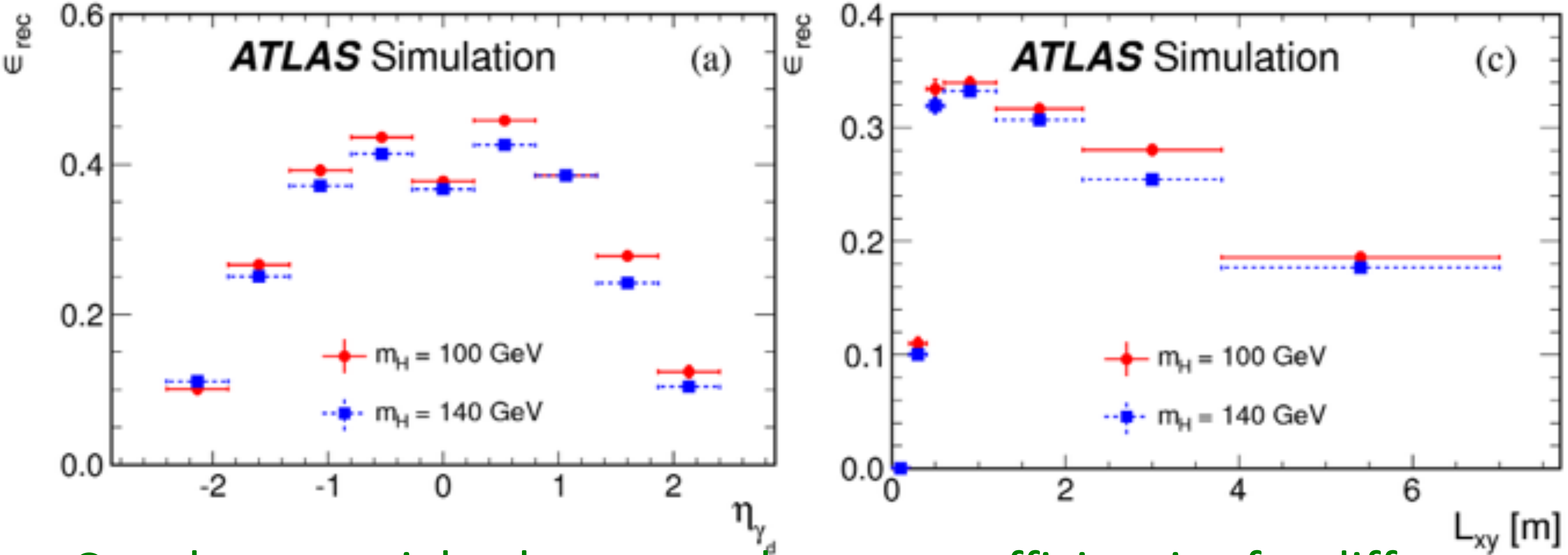
Displaced muonic lepton jets – reconstruction and selection

- Muon jets (MJs) from displaced γ_d decays will have pair of muons in narrow cone.
- Use low-p_T multi-muon trigger without any ID track requirement.
- Reconstruct tracks in MS, and use clustering algorithm to gather muons within a cone.
- Require MJs to have 2 oppositely charged muons, and 2 MJs per event.
- Reject background using cuts on track and calorimeter isolation, $\Delta\Phi$ between MJs.
- Use data collected in empty bunch crossings to estimate potential background from cosmic ray showers – estimate fewer than 2 events.



Displaced muonic lepton jets – signal efficiency

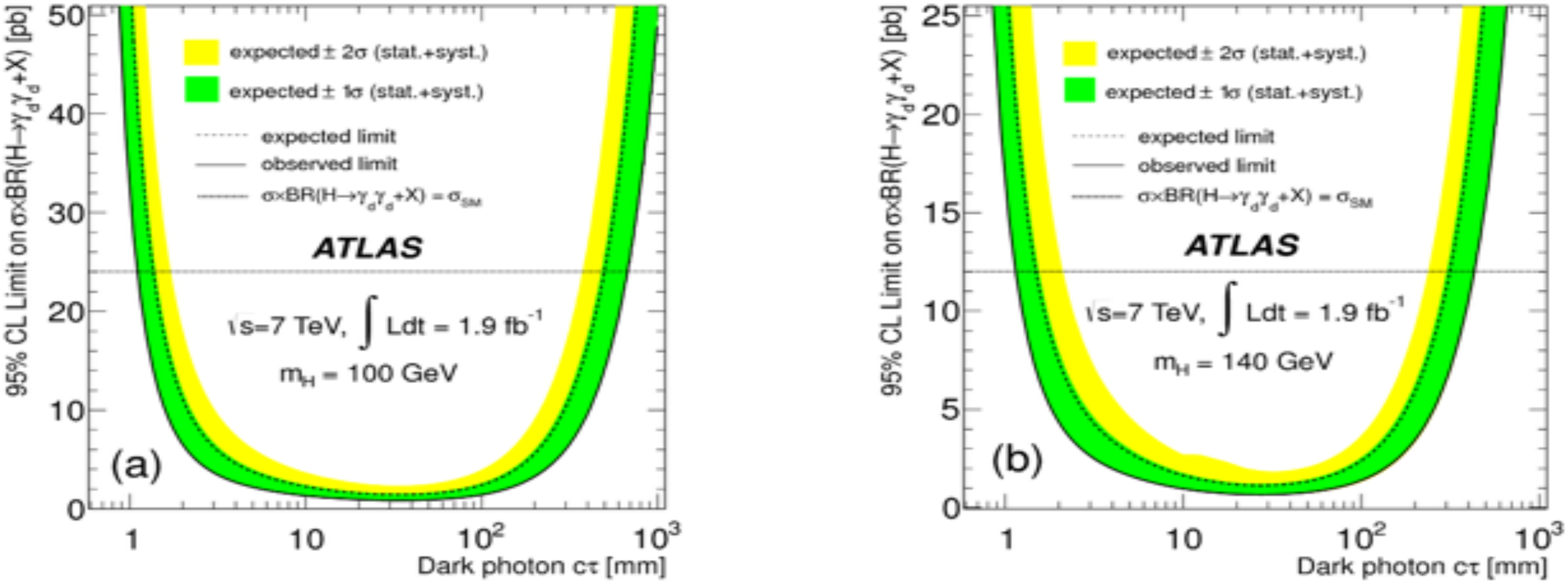
- Use signal Monte Carlo samples with Higgs masses of 100 GeV and 140 GeV, γ_d mass of 0.4 GeV, and proper decay length cτ of a few cm.



- Can then reweight these samples to get efficiencies for different values of cτ.

Displaced muonic lepton jets – results

- No candidate events survive all selection requirements in 1.9 fb^{-1} data sample.
- Set limits on σ.BR(H to $\gamma_d\ \gamma_d$ +X) vs *cτ.*
  - Assuming BR(γ_d to μμ)=45% and mass(γ_d)=0.4 GeV.



Definition of R-parity

$$P_R = (-1)^{3(B-L)+2s}$$

SM particles have R-parity = +1

SUSY particles have R-parity = -1

R-hadrons - selection

- Can undergo interactions with detector material.

  ➔can even change charge as it moves through detector!
- If β is too low, particle might be associated with following bunch crossing by the time it gets to MS.
- Due to both these effects, efficiency for single muon trigger can be quite low.

  ➔also use missing E_T trigger (due to strong production, events often contain high p_T jets, while R-hadron itself will only deposit a small amount of energy in calorimeters).

- Three different analyses:
  - "Full Detector",
  - "MS agnostic",
  - "ID only".

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Uses the most information – best sensitivity for SMPs that are charged all the way through.

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- Three different analyses:
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  - “ID only”.

Can detect R-hadrons even if they become neutral before traversing Muon Spectrometer.

R-hadrons - selection

- Can undergo interactions with detector material.

  →can even change charge as it moves through detector!
- If β is too low, particle might be associated with following bunch crossing by the time it gets to MS.
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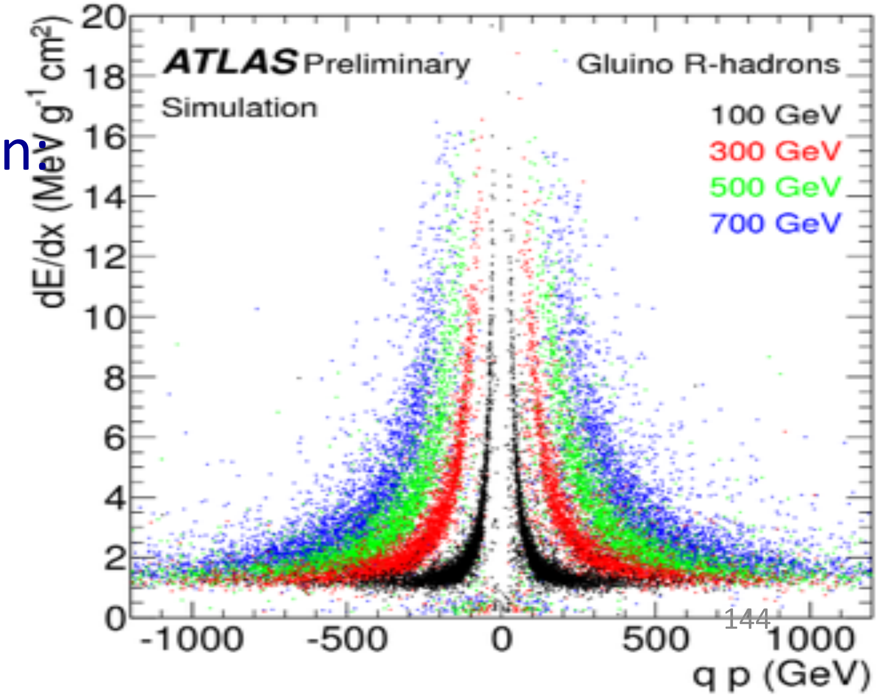
- Three different analyses:
  - "Full Detector",
  - "MS agnostic",
  - "ID only".

Can also detect R-hadrons that decay with few ns average lifetime.

R-hadrons - selection

- All three analyses require good quality, isolated, high-momentum ID track.
- "MS agnostic" uses missing E_T triggers, and calorimeter-only timing measurement.
- "ID only" analysis has tighter selection:
  - Offline missing E_T cut.
  - Tighter cuts on isolation and number of silicon hits.



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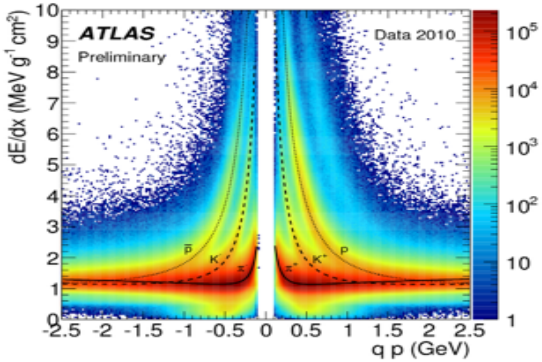

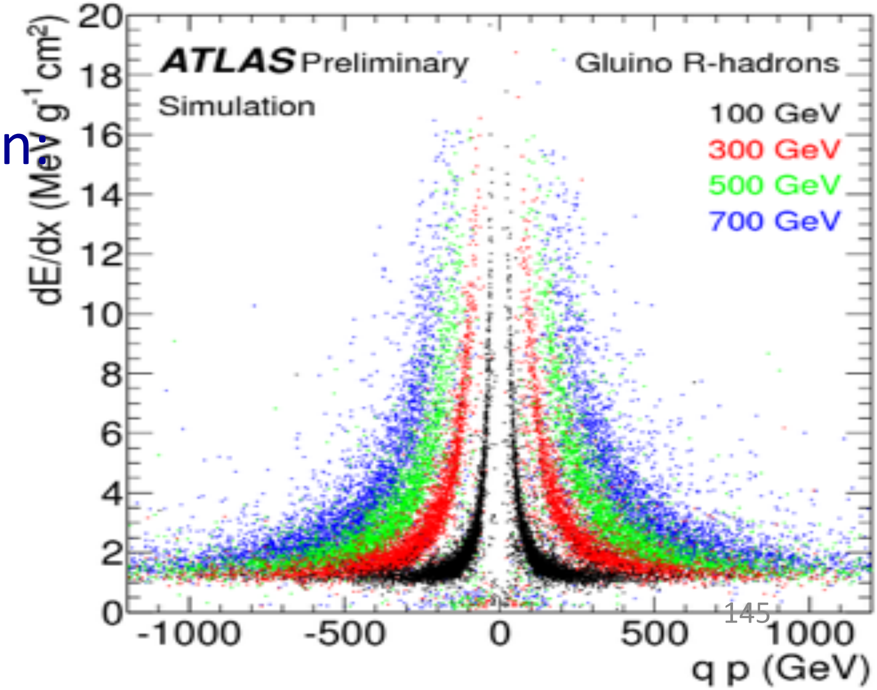

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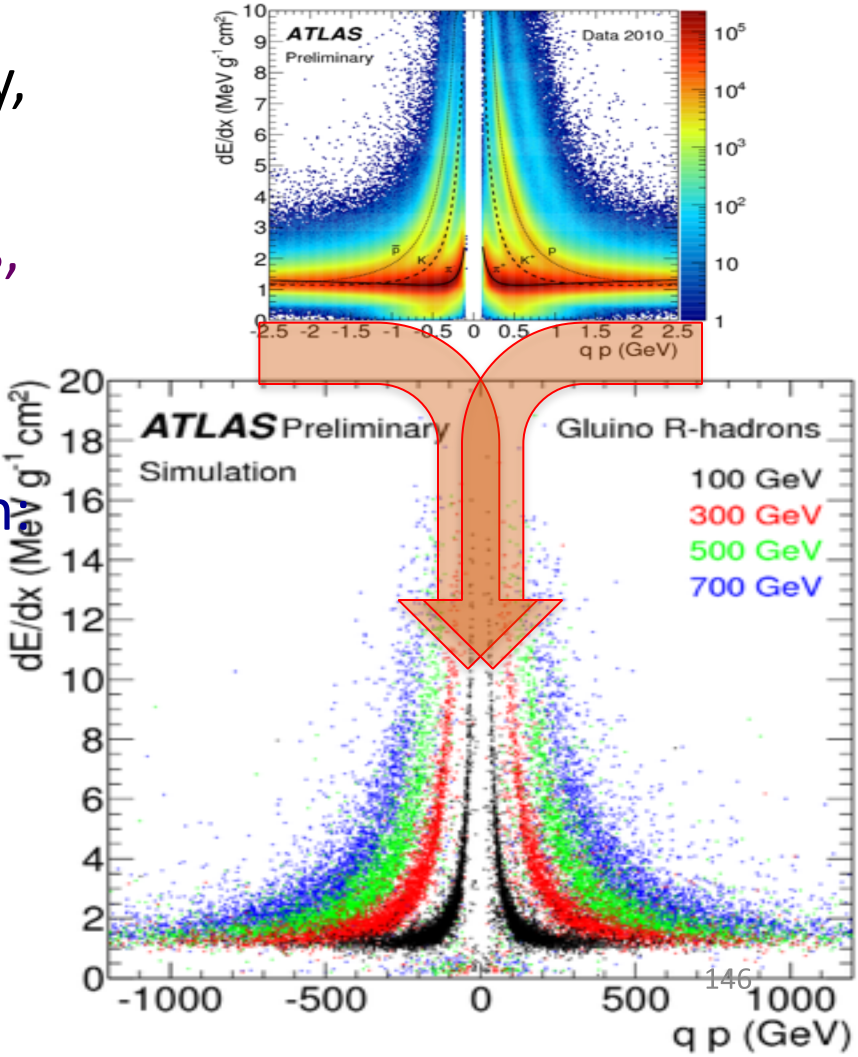
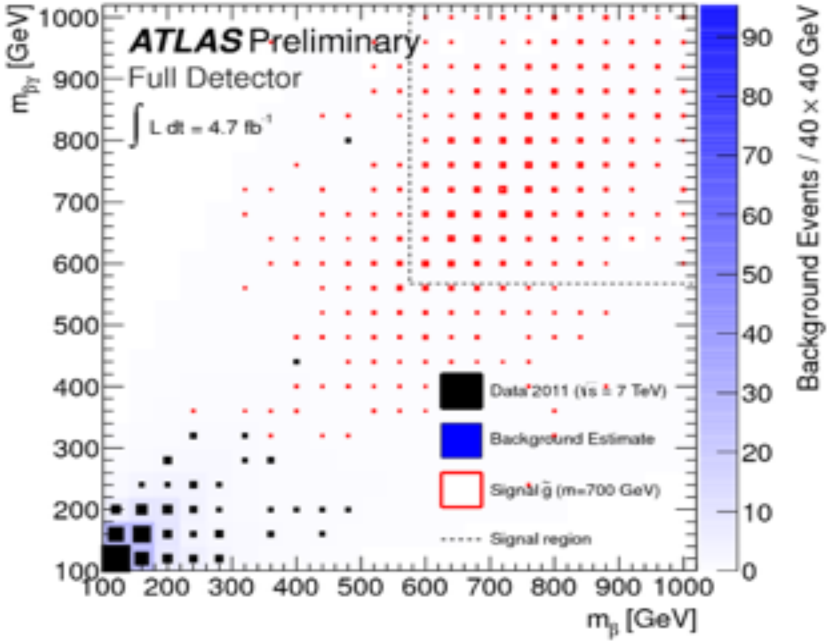
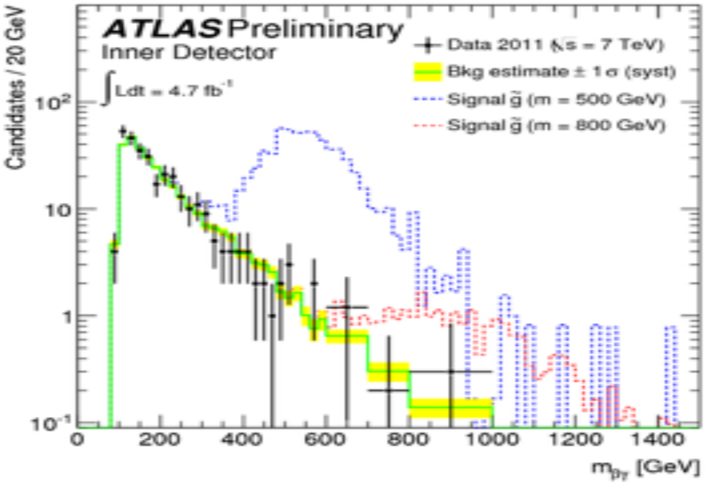
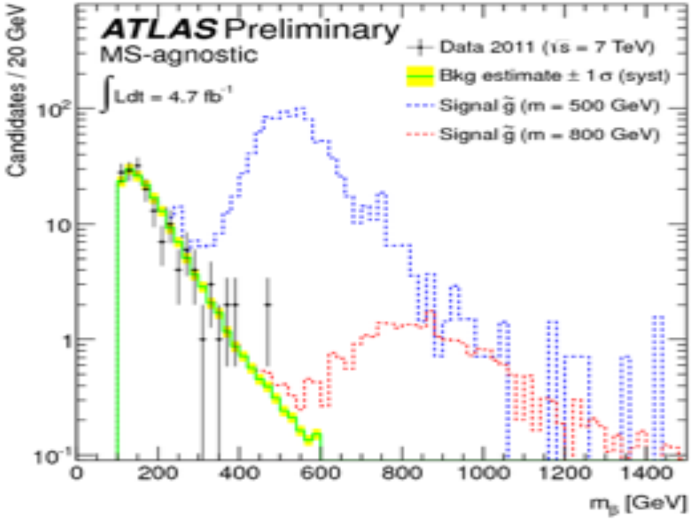


R-hadron searches - results







- No excess above background expectation seen in any of the three analyses.

R-hadron searches - results

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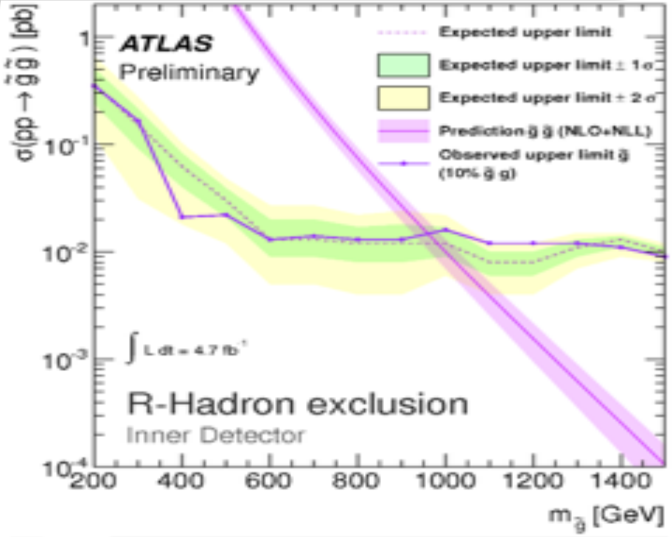
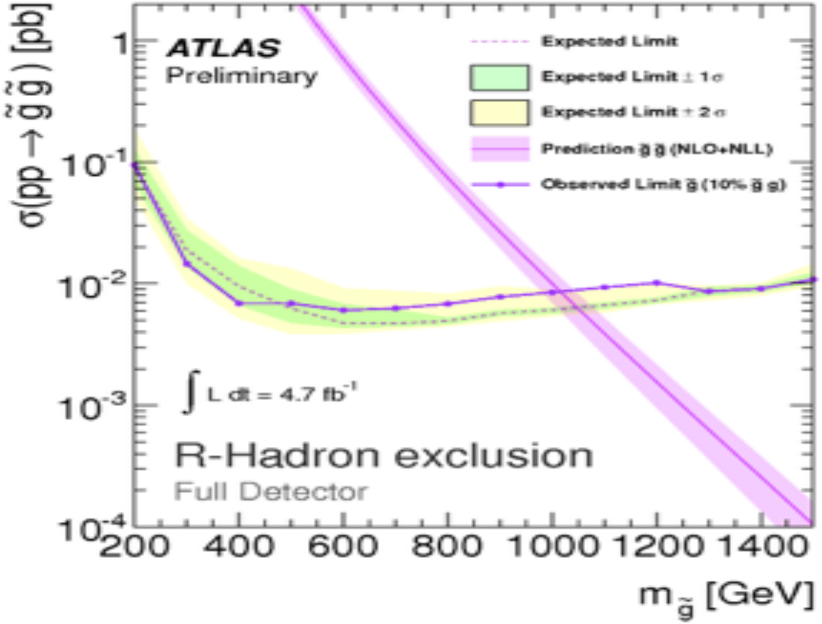
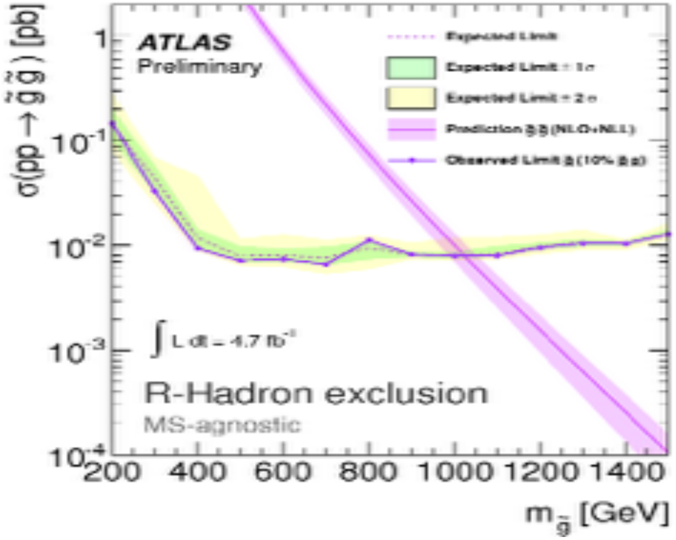
- Set limits on gluino R-hadrons:

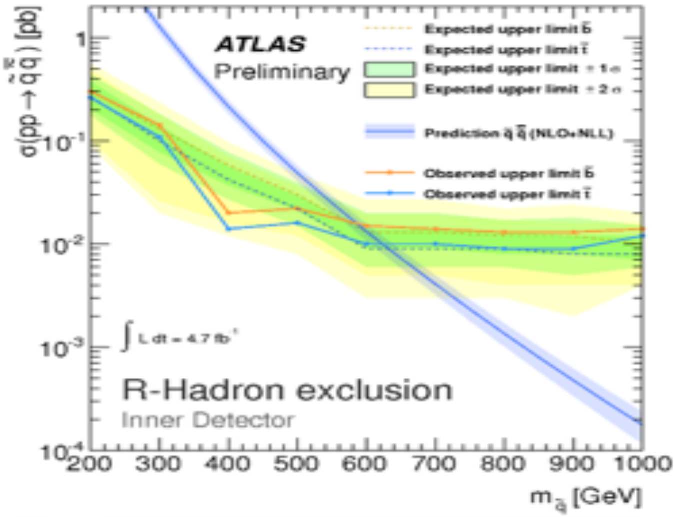


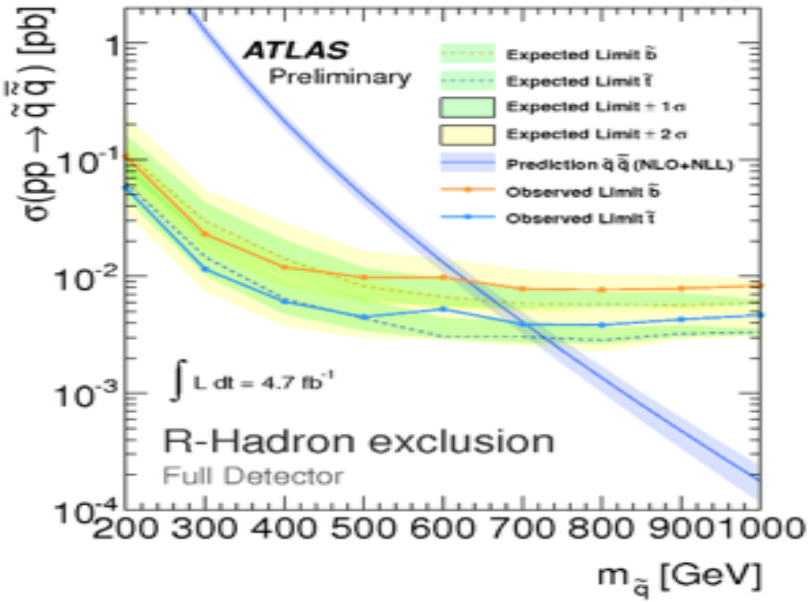


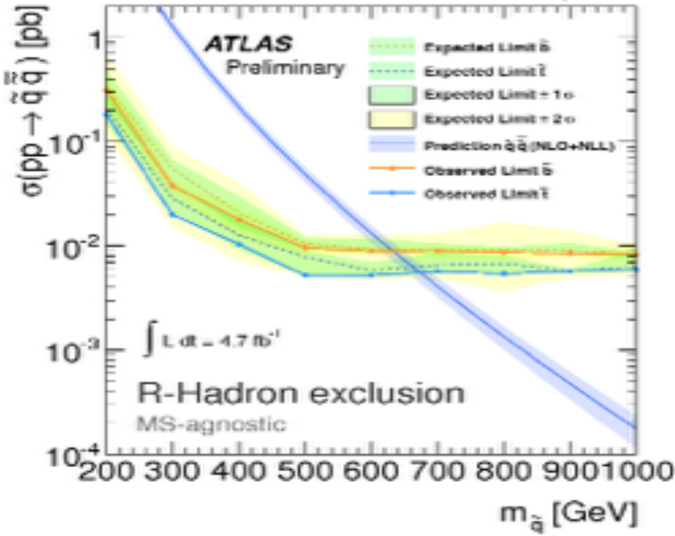


R-hadron searches - results

- No excess above background expectation seen in any of the three analyses.
- Set limits on squark R-hadrons (using triple-Regge model):

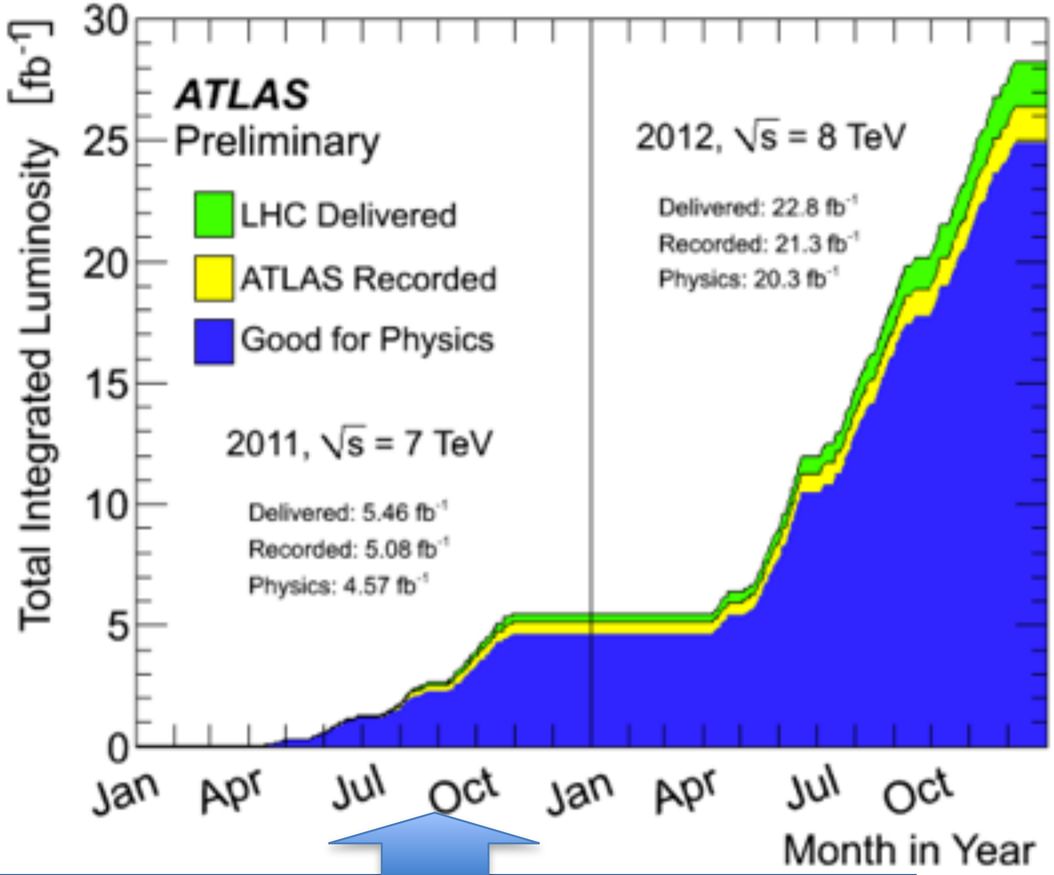






The Data

ATLAS data-taking in 2011 and 2012



2012 data: 20.3 fb^{-1} good for physics.
Much higher pileup.
Relatively constant conditions throughout year.

2011 data: 4.3-4.6 fb^{-1} good for physics.
Conditions varied during run.