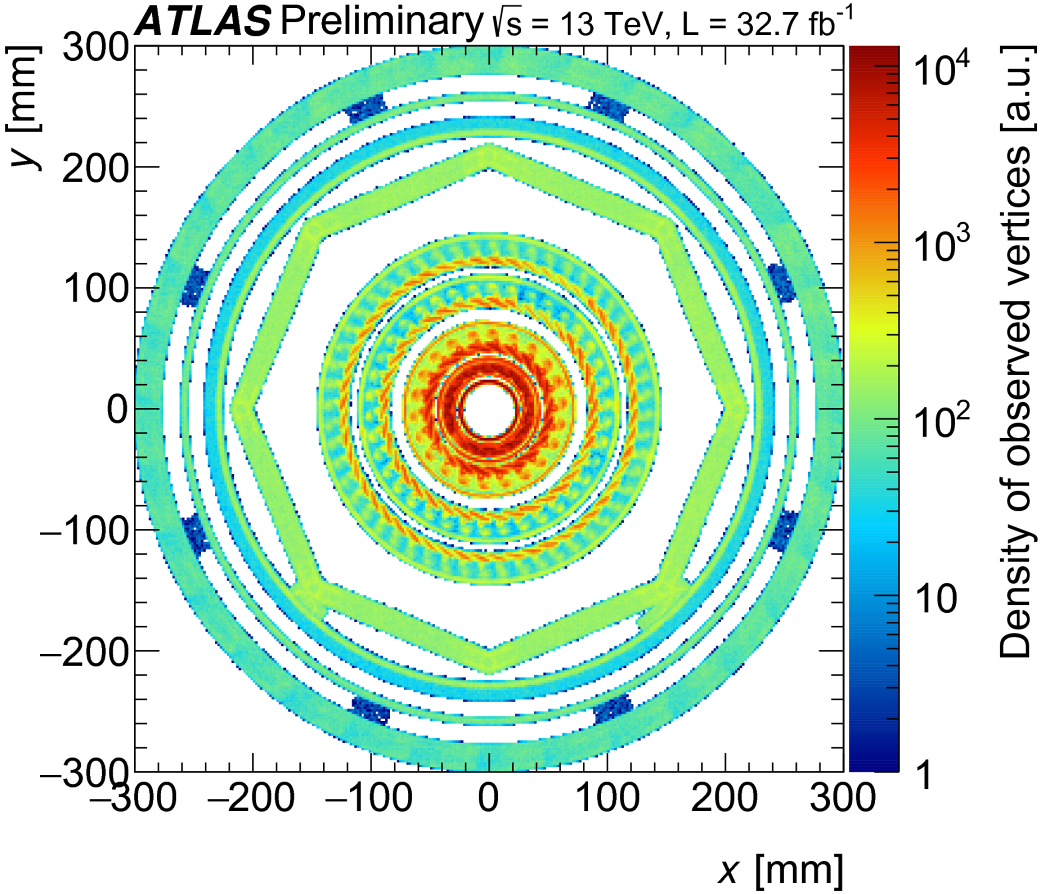


Simulation of Long-Lived Particles and their Decays

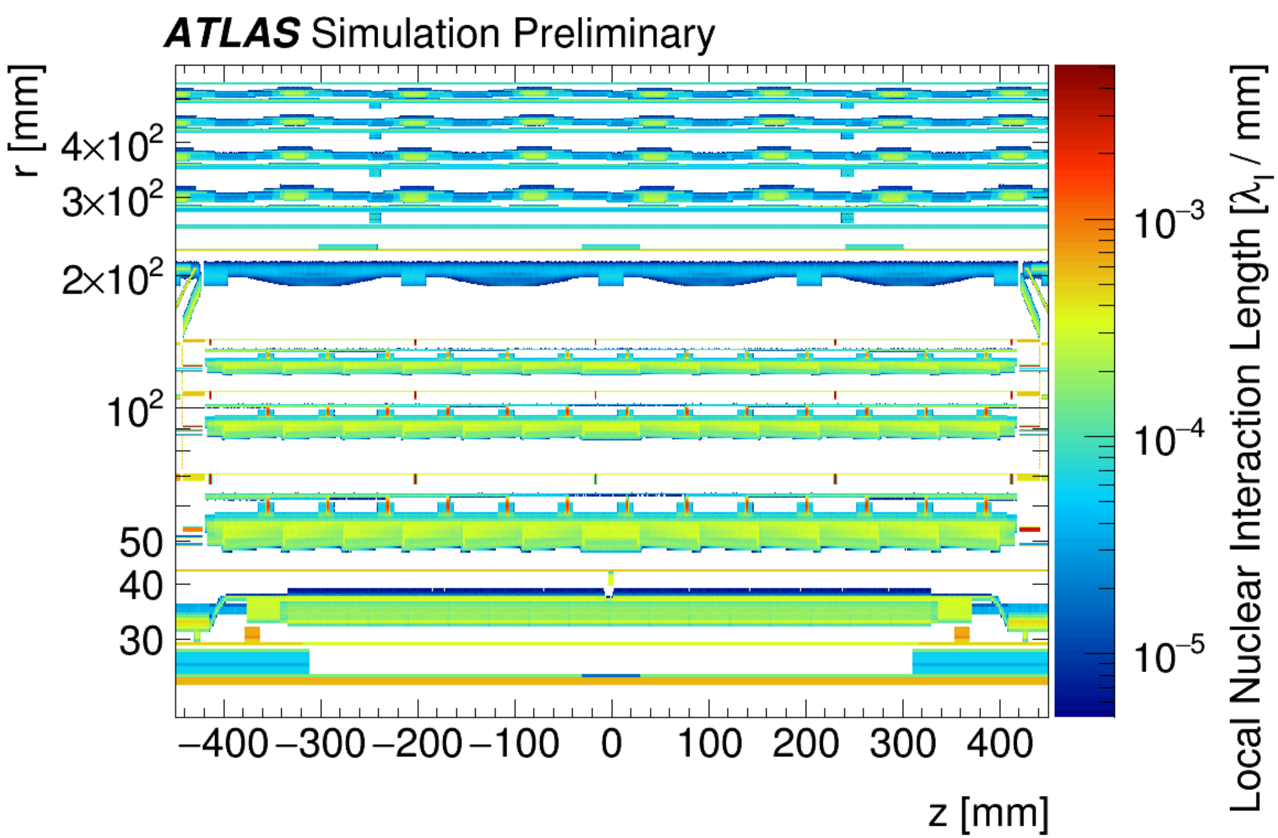
Zach Marshall (LBNL)

MC4BSM 2017

13 May 2017

What is Long Lived?

- ATLAS and CMS put detectors very close to collisions
  - 4.4cm→3.0cm for CMS, 3.35cm for ATLAS
- The detectors' beam pipes are inside of that
  - 2.2cm for CMS, 2.8cm for ATLAS



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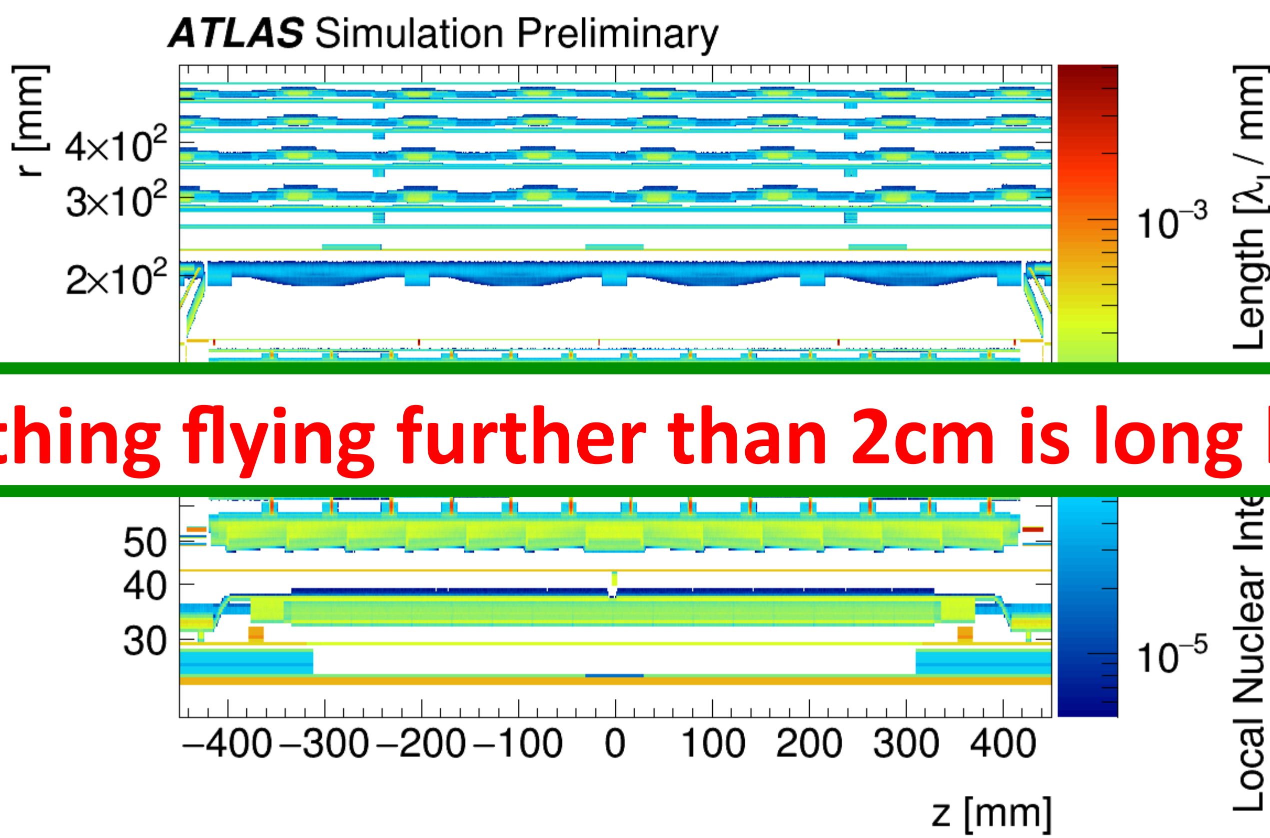


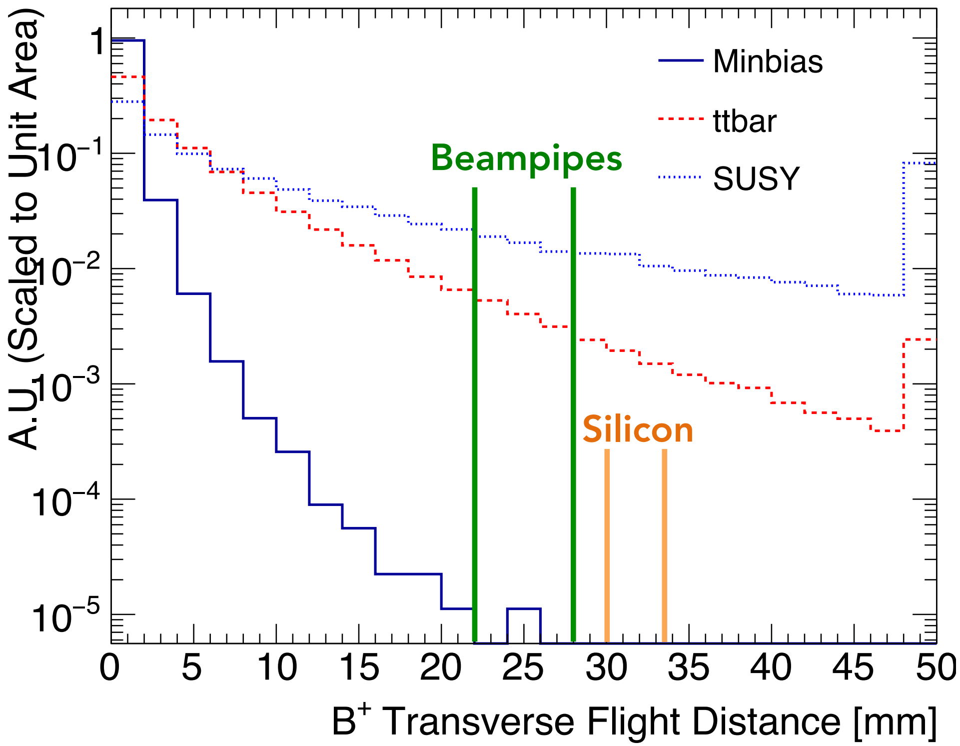
Anything flying further than 2cm is long lived

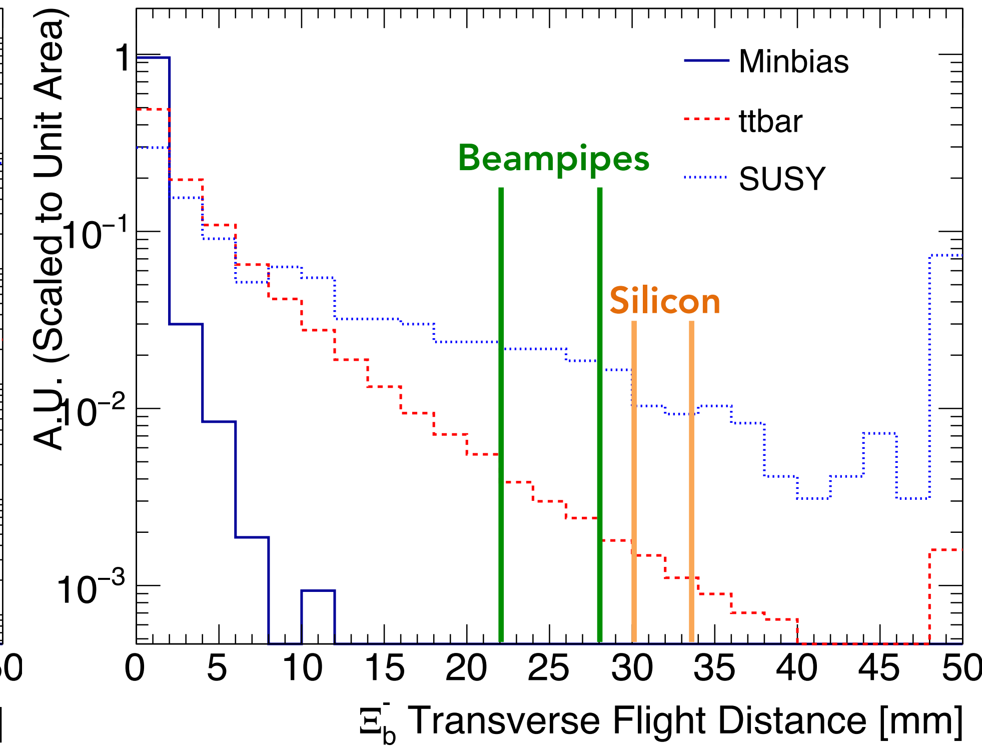
How We Define Long-Lived

- Any particle with τ_0**>10 ps** is "stable" to our generators
  - Note that this is τ_0 (lifetime), **not** flight distance
  - All particle-level definitions that we use (for acceptance, for unfolding, etc) use this requirement to define "particle level"
- Many Standard Model particles are "long-lived" (stable) by this definition
  - Λ, K_S, K_L, π, μ are long-lived and could decay in the detector
  - Most of these are "simple" decays, so programs like Geant4 can be (and are) trusted to perform the decay
- Short-lived particles are propagated and decayed by the event generators (B, D, τ…)
- The event generators do not know anything about our **detector material** or **magnetic field**!

How We Define Long-Lived (II)

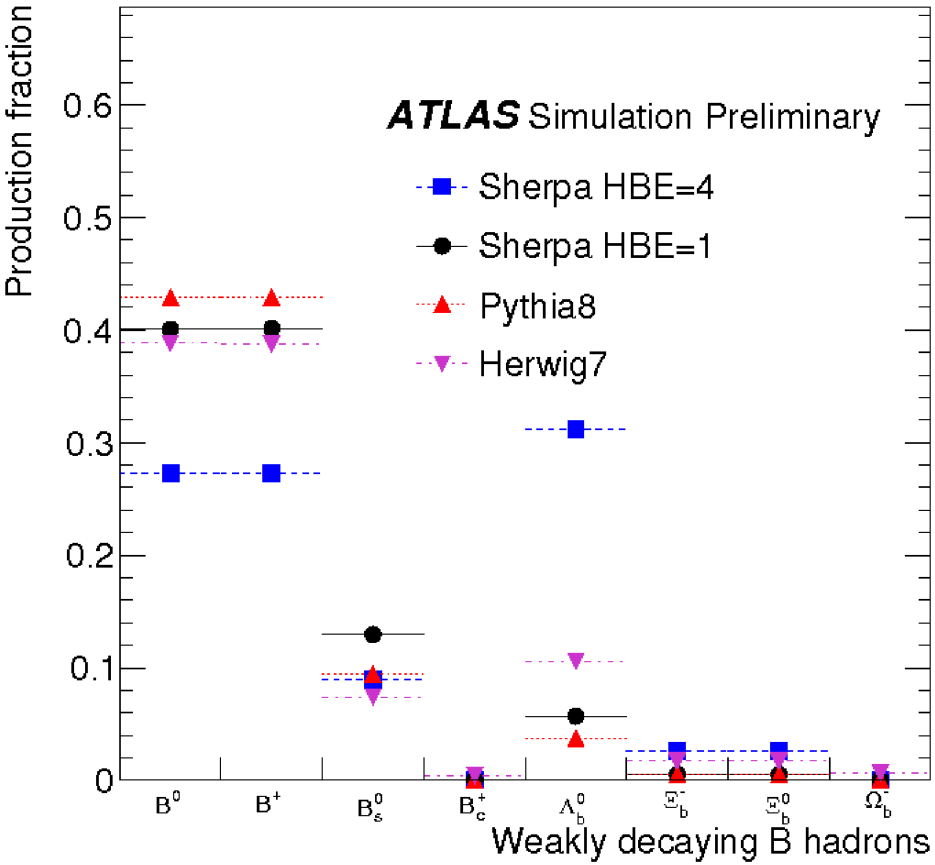
- Some particles with **τ_0<10 ps** would actually interact with our detector!
  - Potential for nuclear interactions with the beampipe and silicon
  - Potential for energy loss, which could give a signal in the silicon! Most older (and even some current) simulation misses these inner-layer hits!

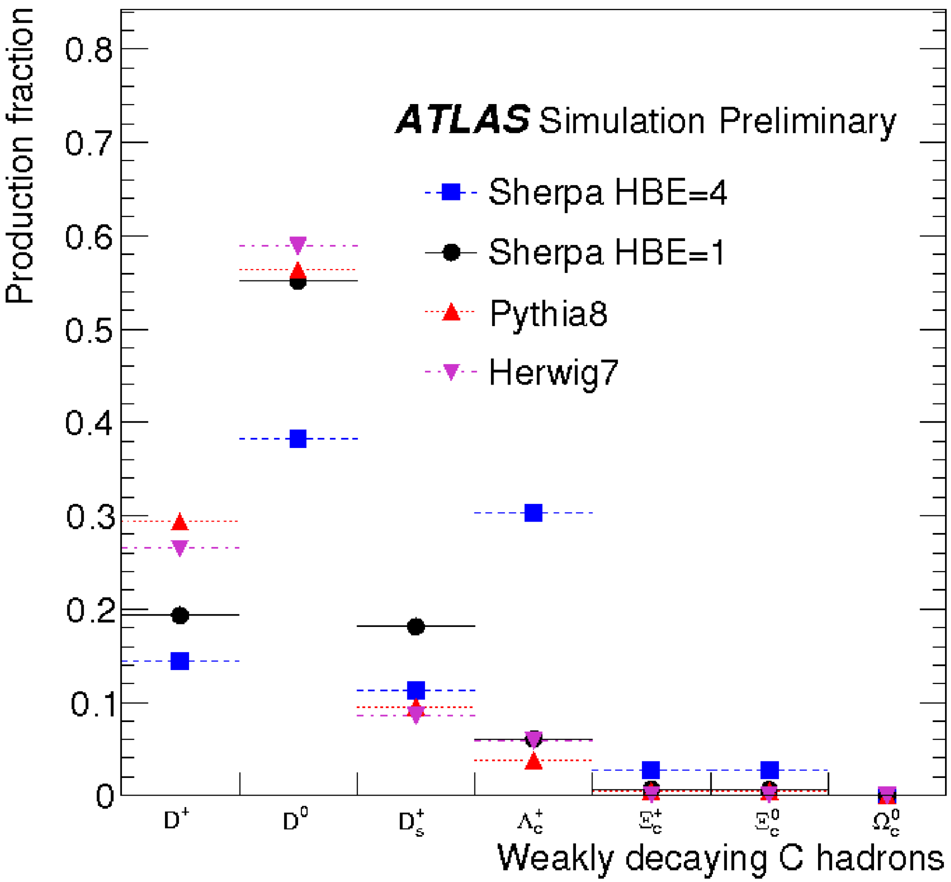




Side Note: Production Fractions

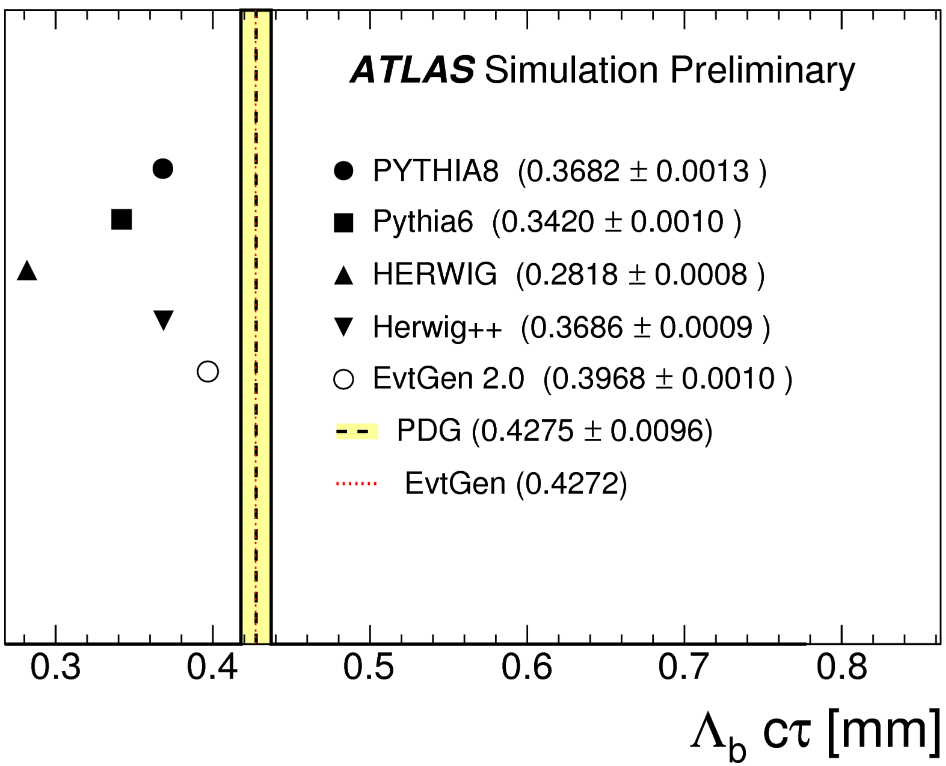
- Production fractions of B/C hadrons not well understood
  - Bottom baryon fraction also has large p_T/η dependence
- Currently dealt with in analyses with reweighting; could affect future analyses as an uncertainty. Time to measure something?

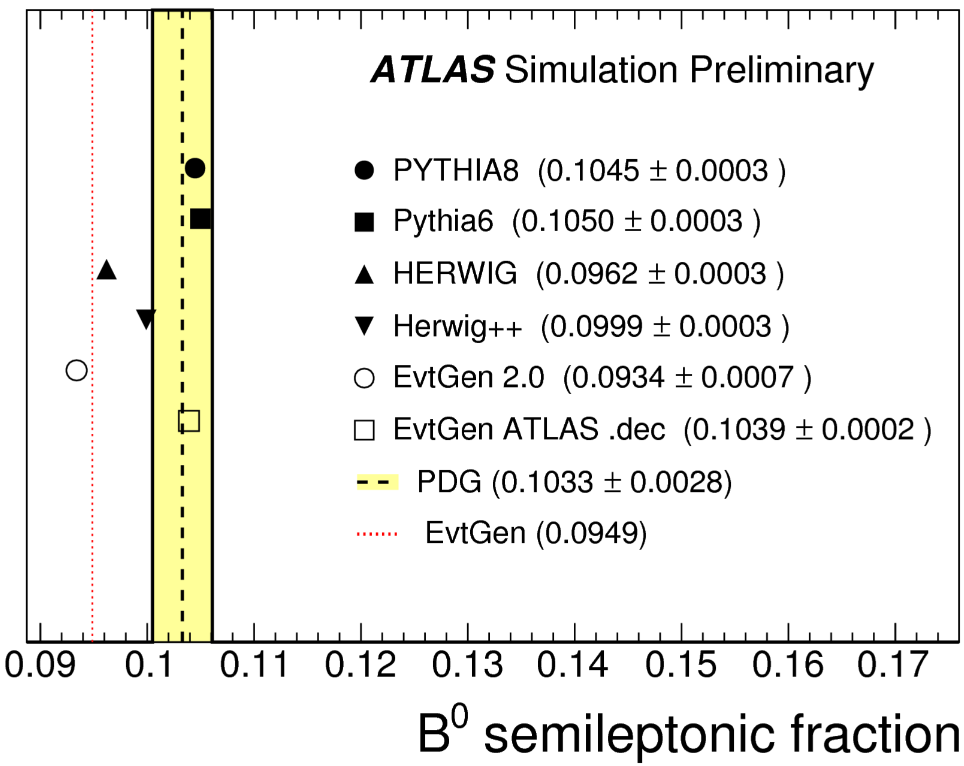




How We Define Long-Lived (III)

- We also know that these decays are complicated
- Even some generators have trouble getting them right!
  - Not a criticism – we know how complicated this is
- Shouldn't just add another tool that needs tuning and maintenance

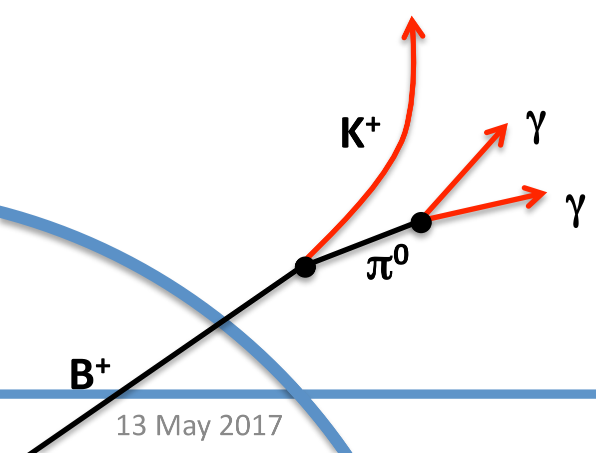




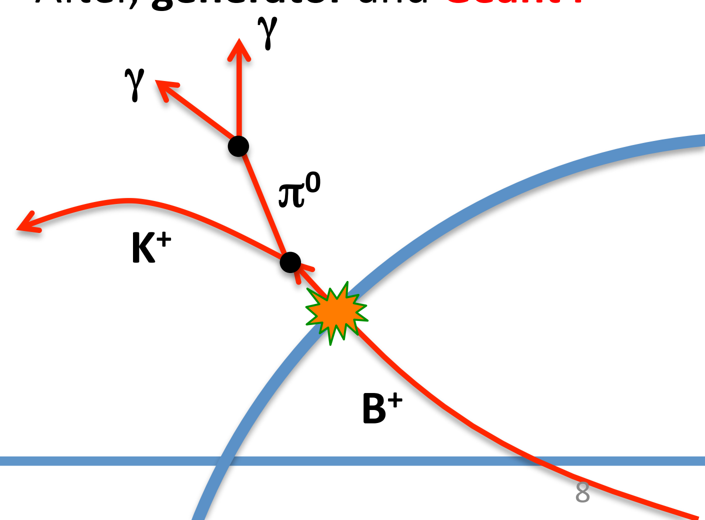
Quasi-Stable Particle Simulation

- **Quasi-stable particle simulation** is the simulation of b-hadrons, τ-leptons, and other particles that may ***bend in the magnetic field***, or may ***interact with the IBL*** (or beampipe)
  - **EM interactions only** for most of these particles (no data!)
- Decide who gets simulated based on a **white list**
  - List of particles that Geant4 might know how to propagate
  - We simulate *all* particles that (1) are themselves on the white list, and (2) have daughters who are all on the white list
- Use the **generator decay** in Geant4
  - We don't trust Geant4 to be able to do this decay itself

Before, **generator** and **Geant4**



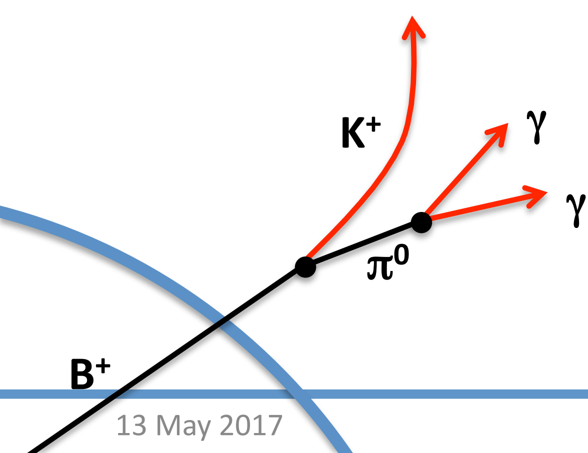
After, **generator** and **Geant4**



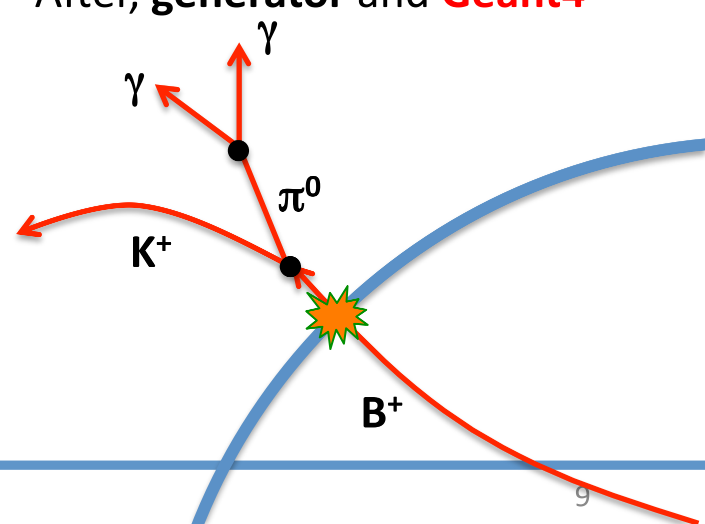
Quasi-Stable Particle Simulation

- Once hadronic interaction models are available, they will come 'free' with this approach
  - Ideas for how heavy flavor particles interact with material welcome!
- One major problem: the handling of particle-level information
  - Particularly in a disk-space efficient way
  - We need the original generator record, because that is what we will unfold to and what we use for acceptance definitions (for you all!)
  - A modified truth record contains what *actually* happened in the detector; have to somehow link these so that we know which particles are the same!
  - Have to turn your brain on to know what tools and studies should use which!

Before, **generator** and **Geant4**

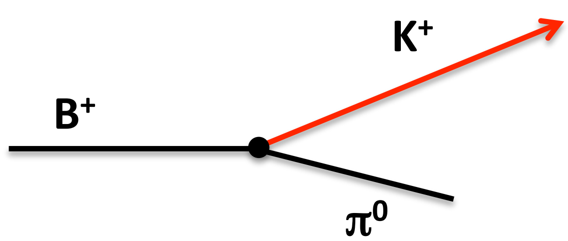


After, **generator** and **Geant4**



You Can Help!

- Might be interesting to extend the formal HepMC standard to handle these cases
- Also notice the white list being used
  - Particles not on the white list include quarks and W bosons…
- Means we can handle these sorts of interactions:



- **If** there is **no quark or W boson** in the truth record!
  - The simpler the better, really – this is a rare case where documentation makes our lives more difficult
  - Once we reach hadrons, we should only have hadrons
  - Loops are also a big pain in this sort of thing
- **NB**: ATLAS and CMS shouldn't have separate implementations of this… add common code in Geant4?

WHAT ABOUT EXOTIC PARTICLES?

Easiest: Weakly Interacting Neutrals

- For anything **neutral** and **weakly interacting**, we do not need a detector simulation!!
- Neutralinos, sneutrinos, dark photons, etc can all be propagated by the event generator safely
  - No material interactions, no magnetic field issues
  - Decay happens where it happens, and **from there** we have to pick up the particle history
  - In principle, quasi-stable particle simulation should be used on top of these decays (important for e.g. decay in calorimeters)
- Hardest and most interesting part of long-lived particle simulation is **detector interactions**

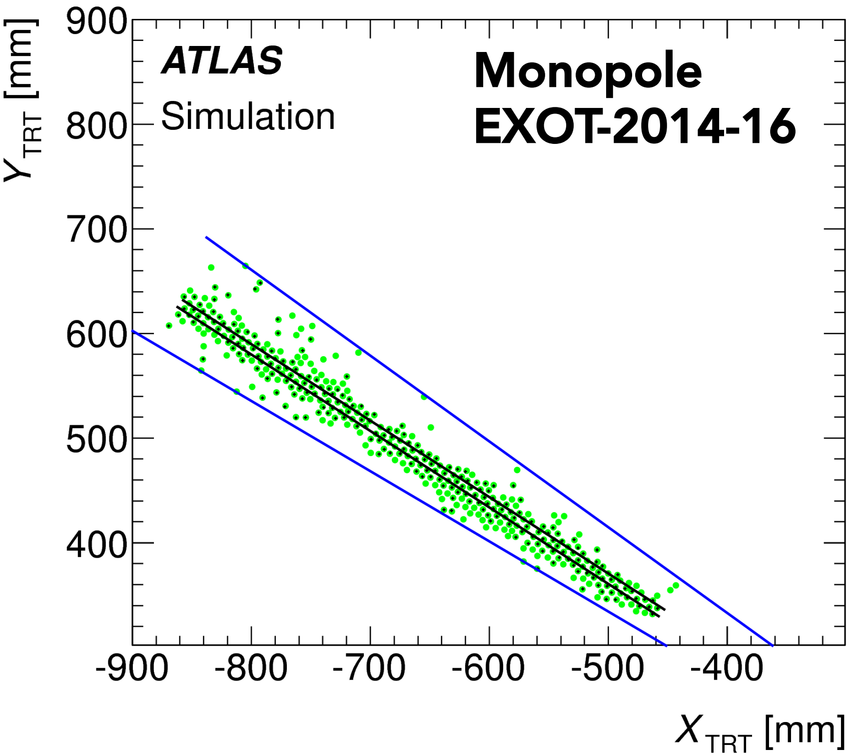
Pretty Easy: Sleptons, Charginos

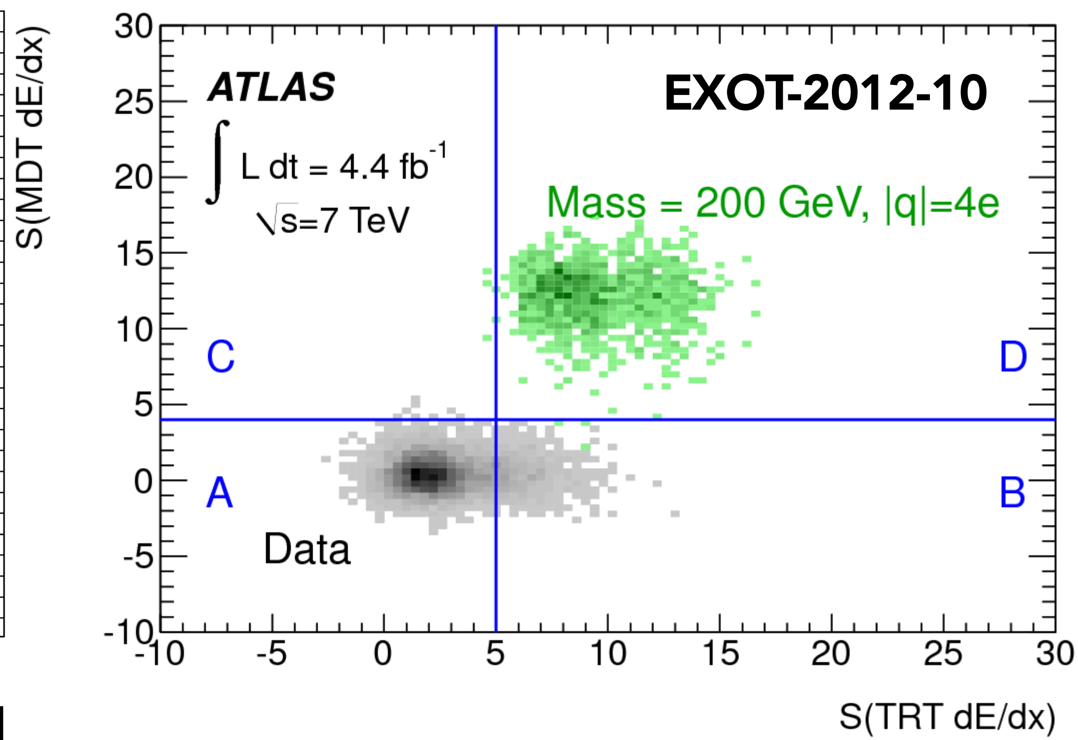
- Simply heavy charged particles
- Only have to get their propagation, ionization, and multiple scattering right
  - Geant4 has modules for heavy particles; have to decide whether to use a high-β or low-β model based on search phase space
- If they decay in the detector, decays can be complicated
  - Geant4 has some methods to deal with "simple" decays
  - As long as we have fairly **simple final states** with no more than four outgoing particles, **no polarization**, and **no spin correlations**, we can treat the decays this way
  - For leptonic sleptons and chargino decays, that's good enough!

G4PhaseSpaceDecayChannel	: phase space decay	← **Our Workhorse**
G4DalitzDecayChannel	: dalitz decay	
G4MuonDecayChannel	: muon decay	
G4TauLeptonicDecayChannel	: tau leptonic decay	

Pretty Easy: Monopoles, Q-balls

- Big lumps of charge in the detector ionize at a higher rate, but that's not terribly difficult to model
  - Some detectors are sensitive to the amount of ionization
- Monopoles need a different equation of motion
  - This is a surprisingly easy change (see later for a harder one)

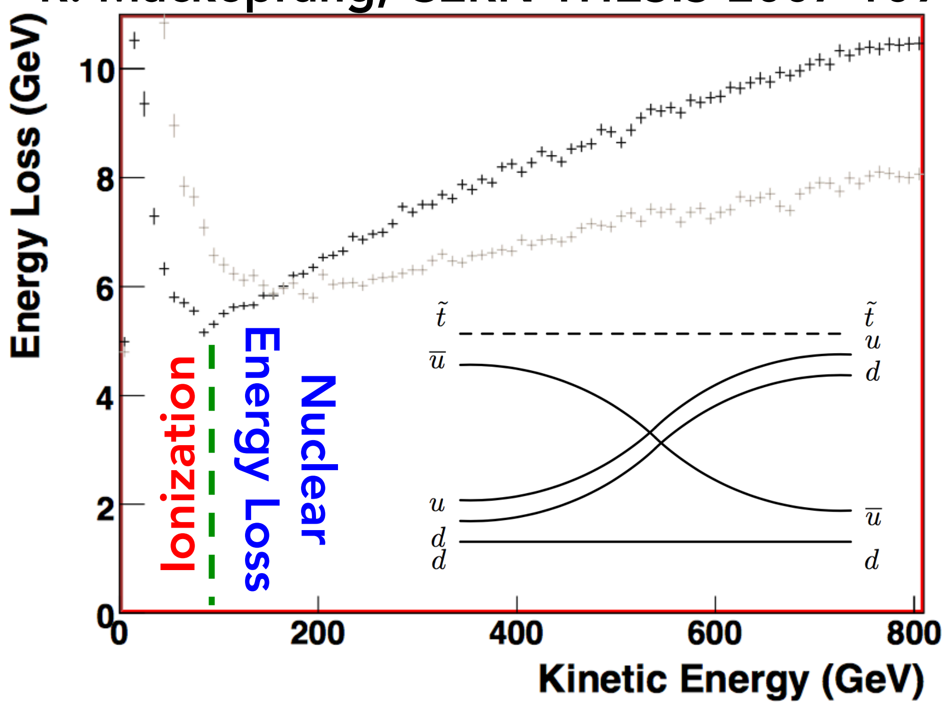


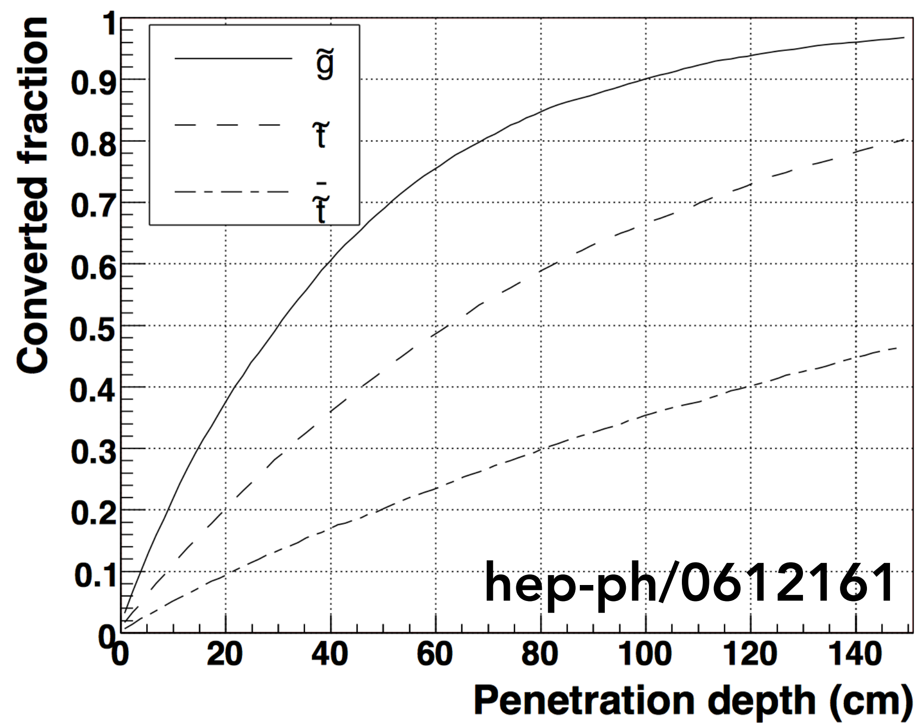


Medium: R-Hadrons

- Color-charged particles can re-hadronize in the detector
  - Main source of **energy loss** at high energy is re-hadronization
- Need hadronic interaction models (Regge, generic)
  - Probability for **baryon number** to be gained in the detector
  - Don't really have **uncertainties** on these models at the moment.
  - Three models: Regge, generic, "intermediate"; currently we pick

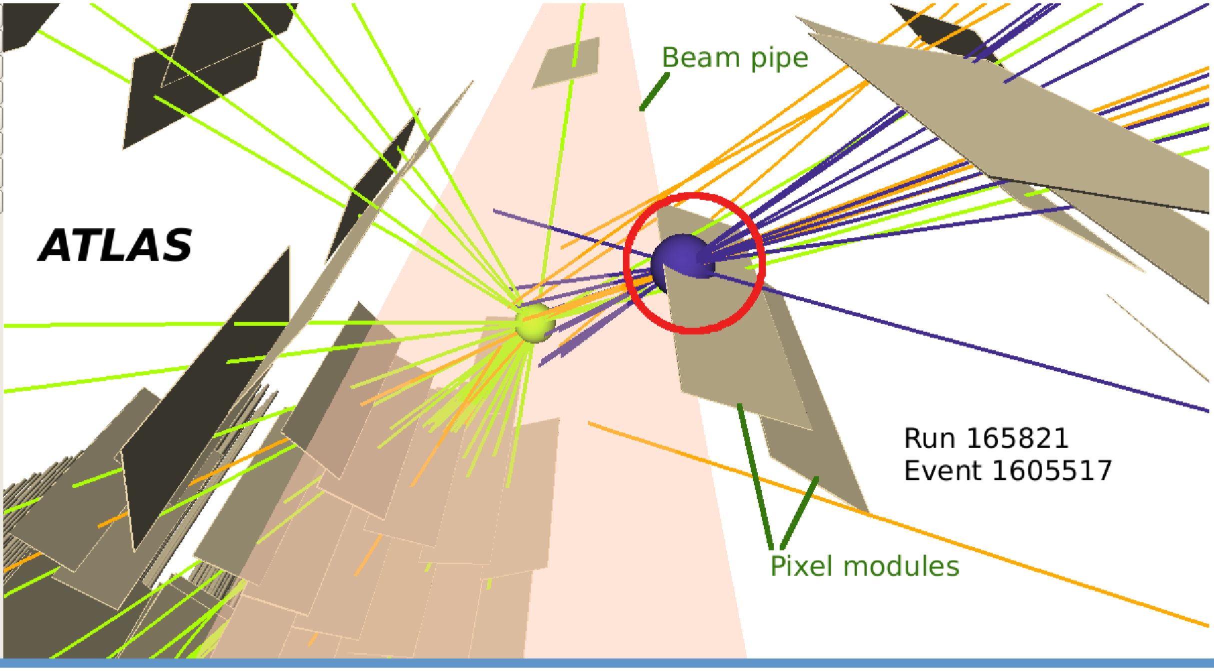
R. Mackeprang, CERN-THESIS-2007-109

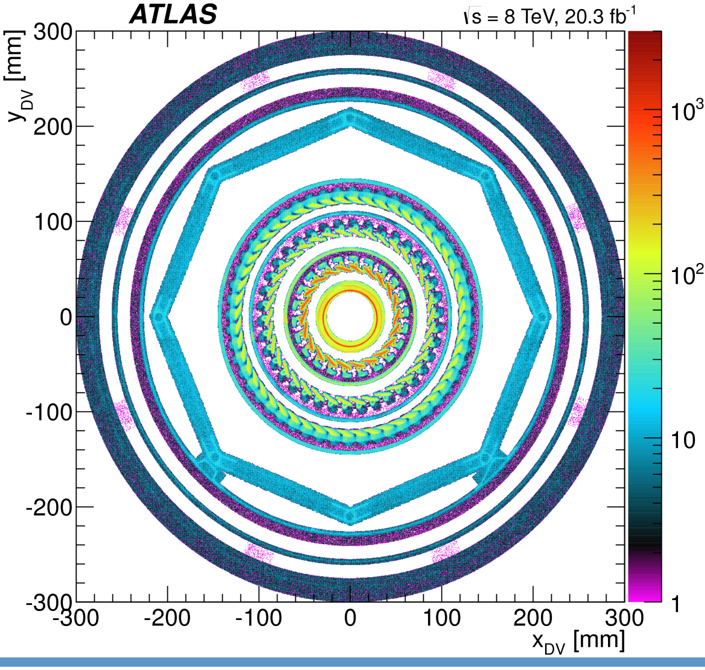




R-Hadron Decays in Flight

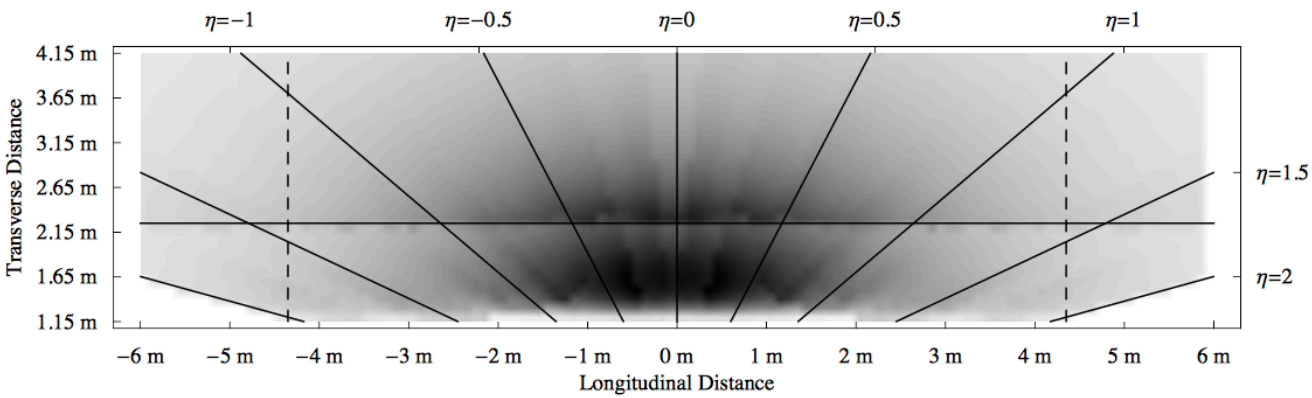
- Strong decay with hadronization is tough to get right!
- Take the R-hadrons *out* of Geant4, hand them to Pythia(8), decay them, and re-insert the decay products
  - Can add on the quasi-stable particle simulation from earlier to get all the charged particles right in the detector
  - Requires correct configuration of Pythia(8) during simulation
- Searches require **detailed understanding of detector material**

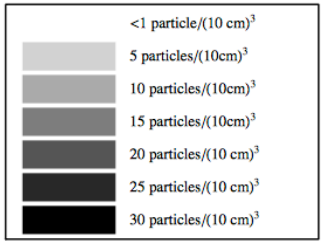




Or Stopped R-Hadrons

- R-hadrons can also **stop** in the detector
- Have to simulate in two separate steps
  - Simulate the initial events and track the R-hadrons until they stop
  - Simulate the R-hadron decays, out of time (**only** decay products)
- Have to make sure we emulate the right bunch crossing
  - Decays can be at *any* time, not just between two filled crossings!

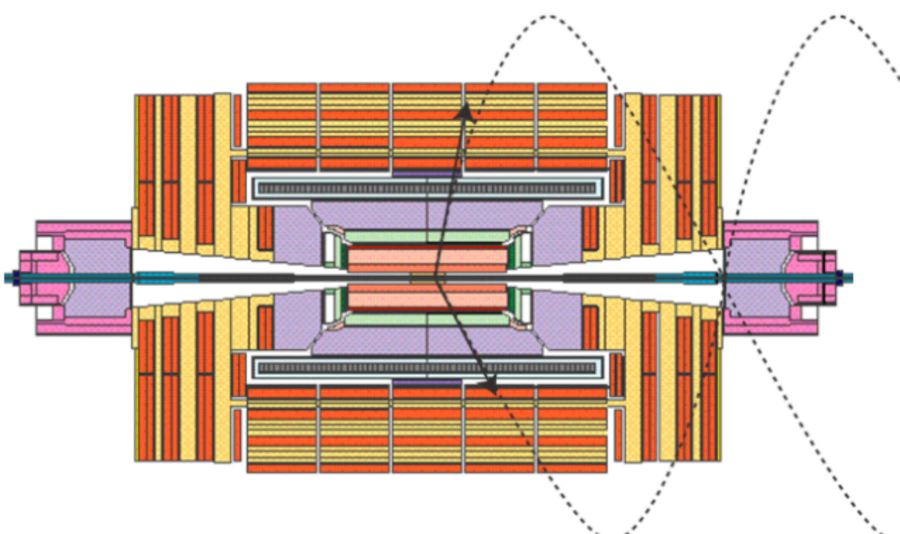


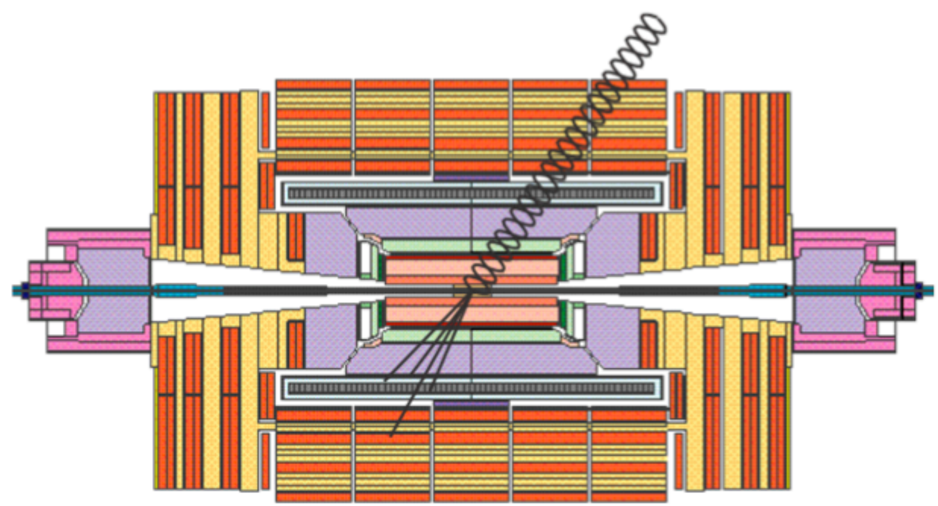


300 GeV Gluino, 100 fb^{-1}
hep-ph/0506242

Hard: Quirks

- Quirks are macroscopic charged-particle bound states
- Requires custom transport inside the Geant4 simulation
  - Normally we assume that the propagation of all particles is independent, and it is not in this case!
- Otherwise, in simple models these things behave like fairly straightforward stable, heavy charged particles
  - Can interact when crossing, which could make things trickier



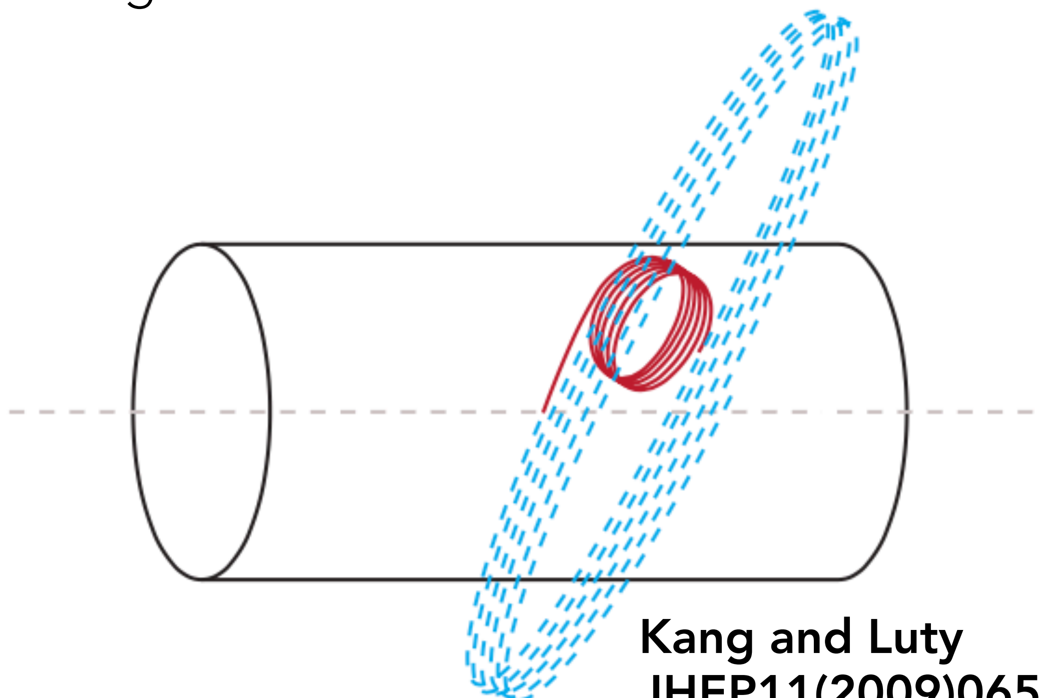


Z. Chacko

Kang, Luty, Nasri

Very Hard: Colored Quirks

- Quirks *could* have **color charge**
- Now we have the pain of **simultaneous propagation** *as well* as R-hadron-like **hadronic interactions**
- Bound state can change from +/- to +/0 to +/+ to 0/+…
  - Can induce angular momentum in the bound state, among other weird-looking features



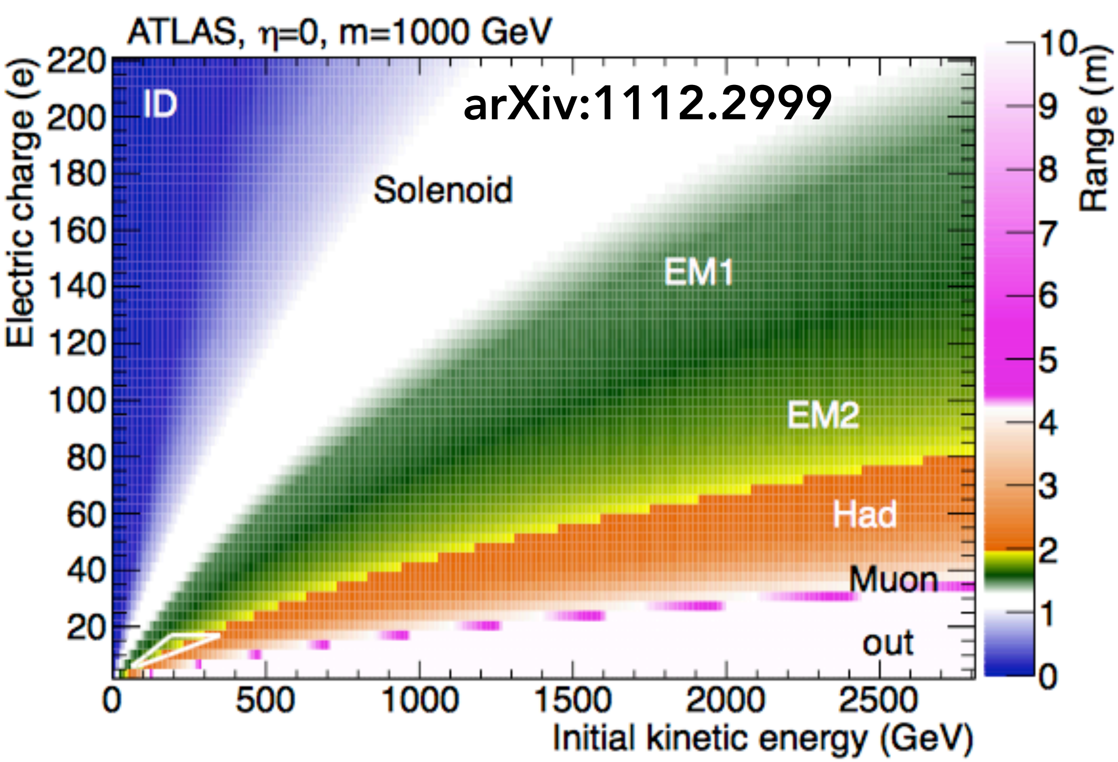
Kang and Luty JHEP11(2009)065

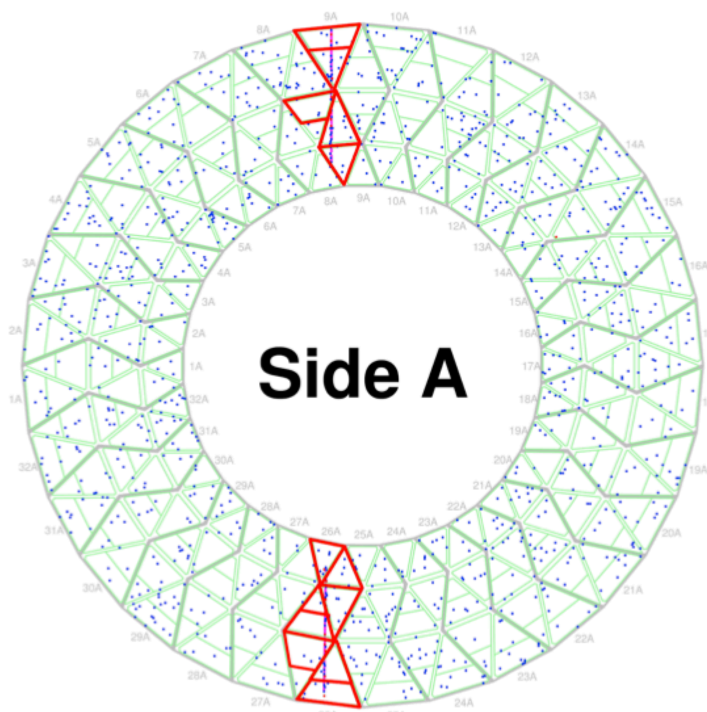
Model Difficulties

- **EM physics** can be tuned on ions, to some degree
- **Hadronic interaction** models are tricky beasts!
  - Similar problem for heavy flavor hadronic interactions
  - How large a variation we introduce in the parameters of these models matters to what we are doing!
- For very long-lived particles, event generator **hadronization models** matter as well
  - EM shower fraction directly relates to detector response when particles decay inside the calorimeter
- Need handles on uncertainties
  - Where can we **test** these simulation models against data?
  - Are there ways to **tune** the free parameters?
  - What **extrapolation** is safe, and what is not?
- Deep thoughts and clever ideas are welcome here!

Detector Issues

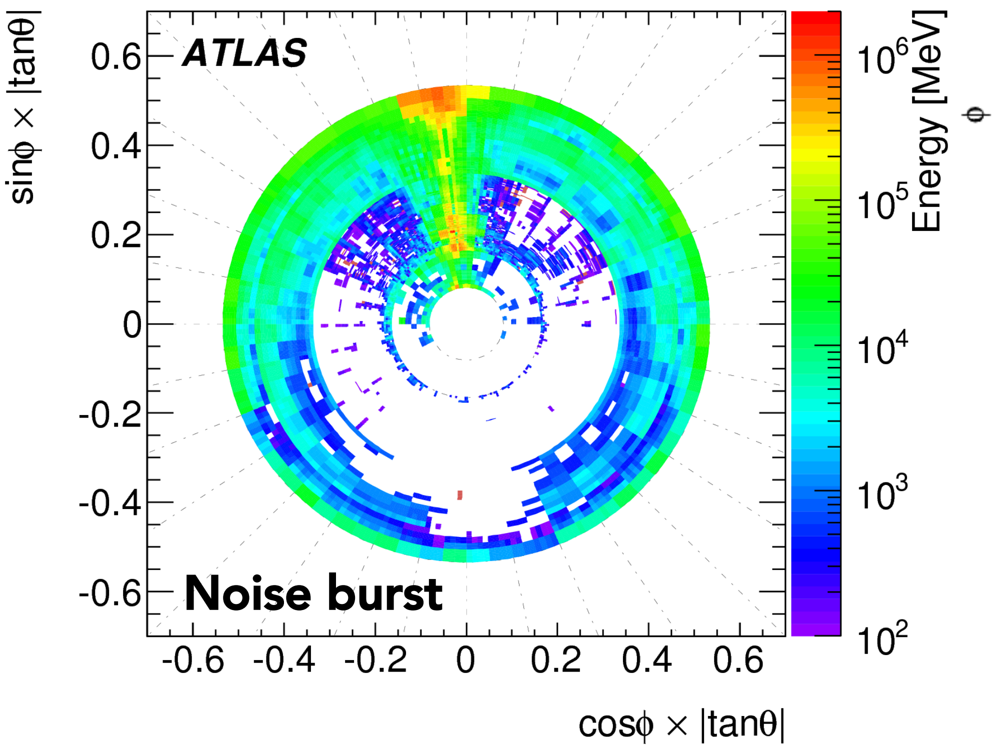
- Detector response is **very tricky** to get right
- Detector electronics have many little effects hiding in their circuits that few people know about
  - Exotic particles are more likely to trigger these issues
  - Some of them can be exploited to make searches easier!

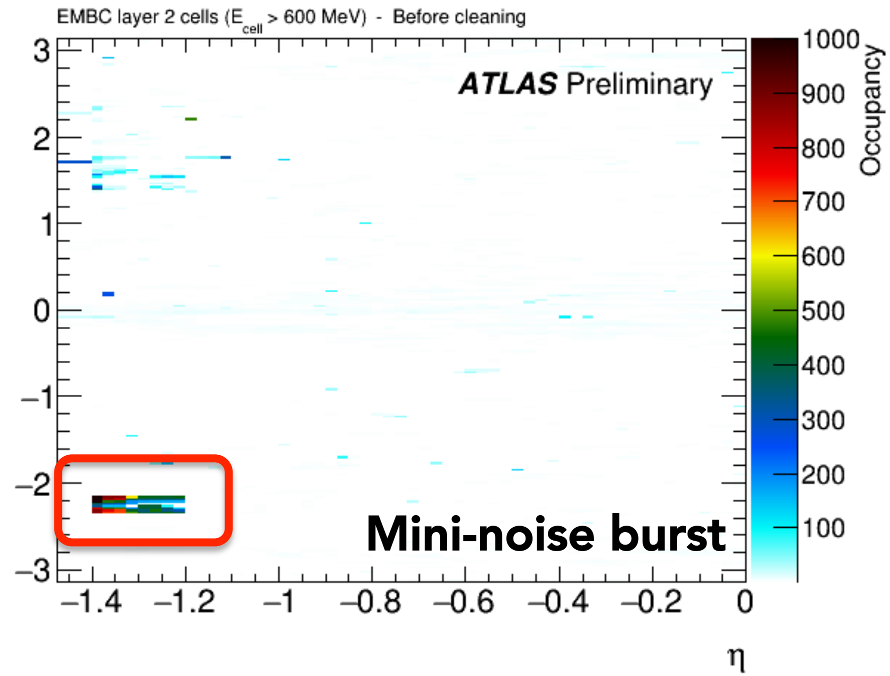




Data Quality Matters

- Most analyses include **data quality** requirements
- Does our signal create an effect that would be flagged as a detector failure / data quality issue?
- If we want to be sure, we **need to model data quality issues**, which is very difficult!!





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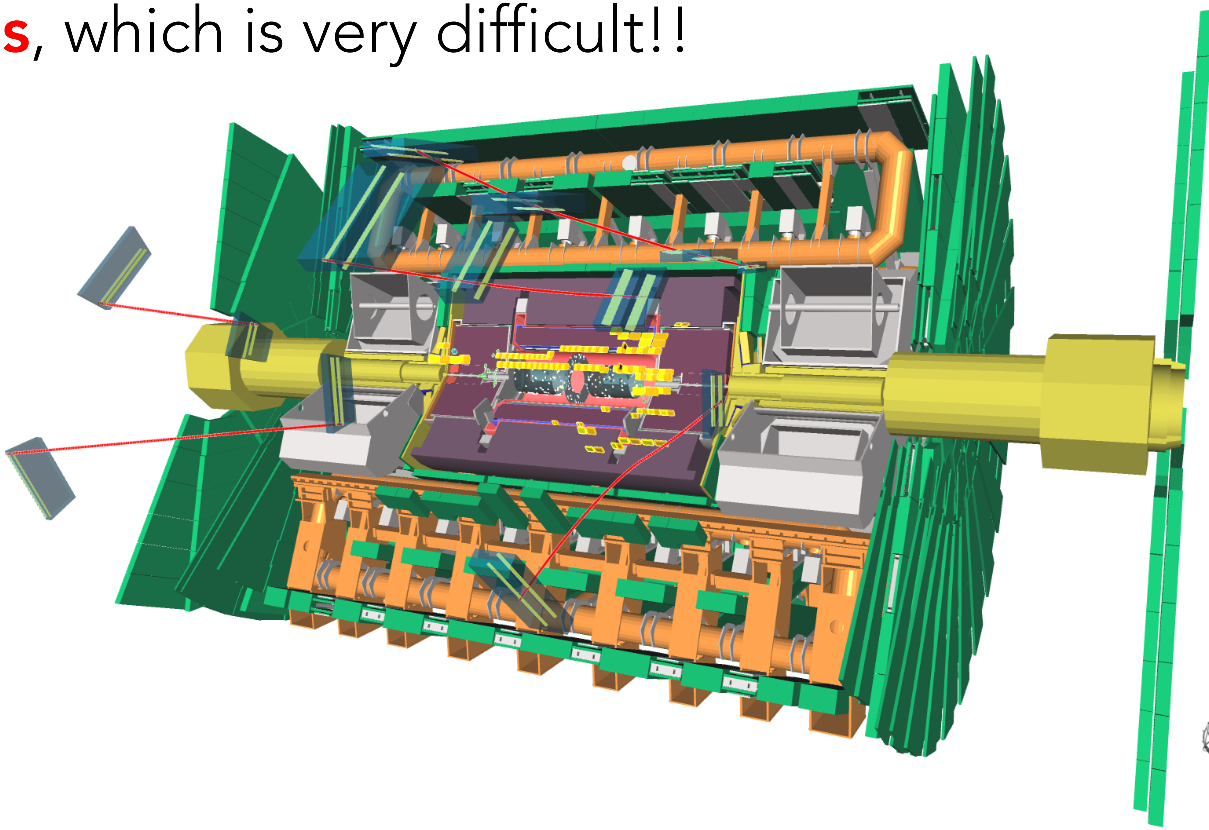

ATLAS EXPERIMENT
http://atlas.ch

Summary

- Lots of technology built up to simulate long-lived particles at the LHC
- Challenges both for Standard Model and Exotic particles
  - Standard Model challenges will only be worse in future colliders
- Models have been constructed for the interaction of exotic particles with matter
  - It would be great to share these models among experiments
  - Need to understand the uncertainties in these models – can we use any data to constrain them?
- Need to be careful that all the relevant detector effects are included in the full simulation model
  - Often not obvious!! May only be known by a few people…
  - This is one of the reasons that it's so hard to reinterpret LLP results. We are working on improving this, but it is a long row to hoe! Stay tuned!