Simulation of Long-Lived Particles and their Decays

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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
What is Long Lived?

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Anything flying further than 2cm is long lived
How We Define Long-Lived

• Any particle with $\tau_0 > 10 \text{ ps}$ is "stable" to our generators
  – Note that this is $\tau_0$ (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
  – $\Lambda, K_S, K_L, \pi, \mu$ 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 ($B, D, \tau\ldots$)

• The event generators do not know anything about our detector material or magnetic field!
How We Define Long-Lived (II)

- Some particles with $\tau_0 < 10$ 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 $p_T/\eta$ dependence
- Currently dealt with in analyses with reweighting; could affect future analyses as an uncertainty. Time to measure something?

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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

\[ \Lambda_b \, c \tau \text{ [mm]} \]

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**ATLAS Simulation Preliminary**

- PYTHIA8 \((0.3682 \pm 0.0013)\)
- Pythia6 \((0.3420 \pm 0.0010)\)
- HERWIG \((0.2818 \pm 0.0008)\)
- Herwig++ \((0.3686 \pm 0.0009)\)
- EvtGen 2.0 \((0.3968 \pm 0.0010)\)
- PDG \((0.4275 \pm 0.0096)\)
- EvtGen \((0.4272)\)

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**ATLAS Simulation Preliminary**

- PYTHIA8 \((0.1045 \pm 0.0003)\)
- Pythia6 \((0.1050 \pm 0.0003)\)
- HERWIG \((0.0962 \pm 0.0003)\)
- Herwig++ \((0.0999 \pm 0.0003)\)
- EvtGen 2.0 \((0.0934 \pm 0.0007)\)
- EvtGen ATLAS .dec \((0.1039 \pm 0.0002)\)
- PDG \((0.1033 \pm 0.0028)\)
- EvtGen \((0.0949)\)

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Quasi-Stable Particle Simulation

- **Quasi-stable particle simulation** is the simulation of $b$-hadrons, $\tau$-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-$\beta$ or low-$\beta$ 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!

G4PhaseSpace Decay Channel : phase space decay
G4Dalitz Decay Channel : dalitz decay
G4Muon Decay Channel : muon decay
G4TauLeptonic Decay Channel : tau leptonic decay

Our Workhorse
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


![Graph showing energy loss and converted fraction vs. depth and kinetic energy](hep-ph/0612161)
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
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!

arXiv:1112.2999
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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**Noise burst**

**Mini-noise burst**
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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…