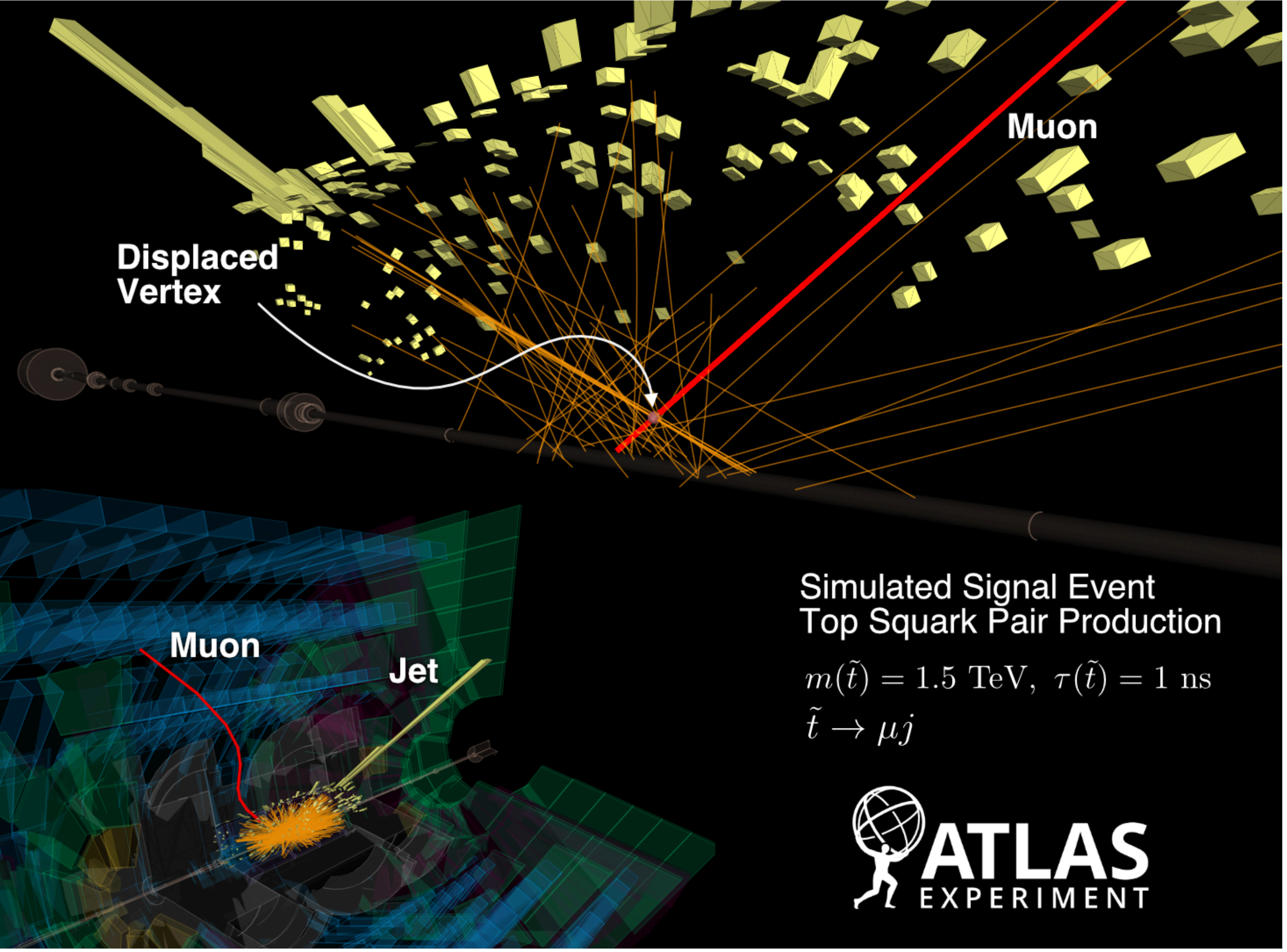
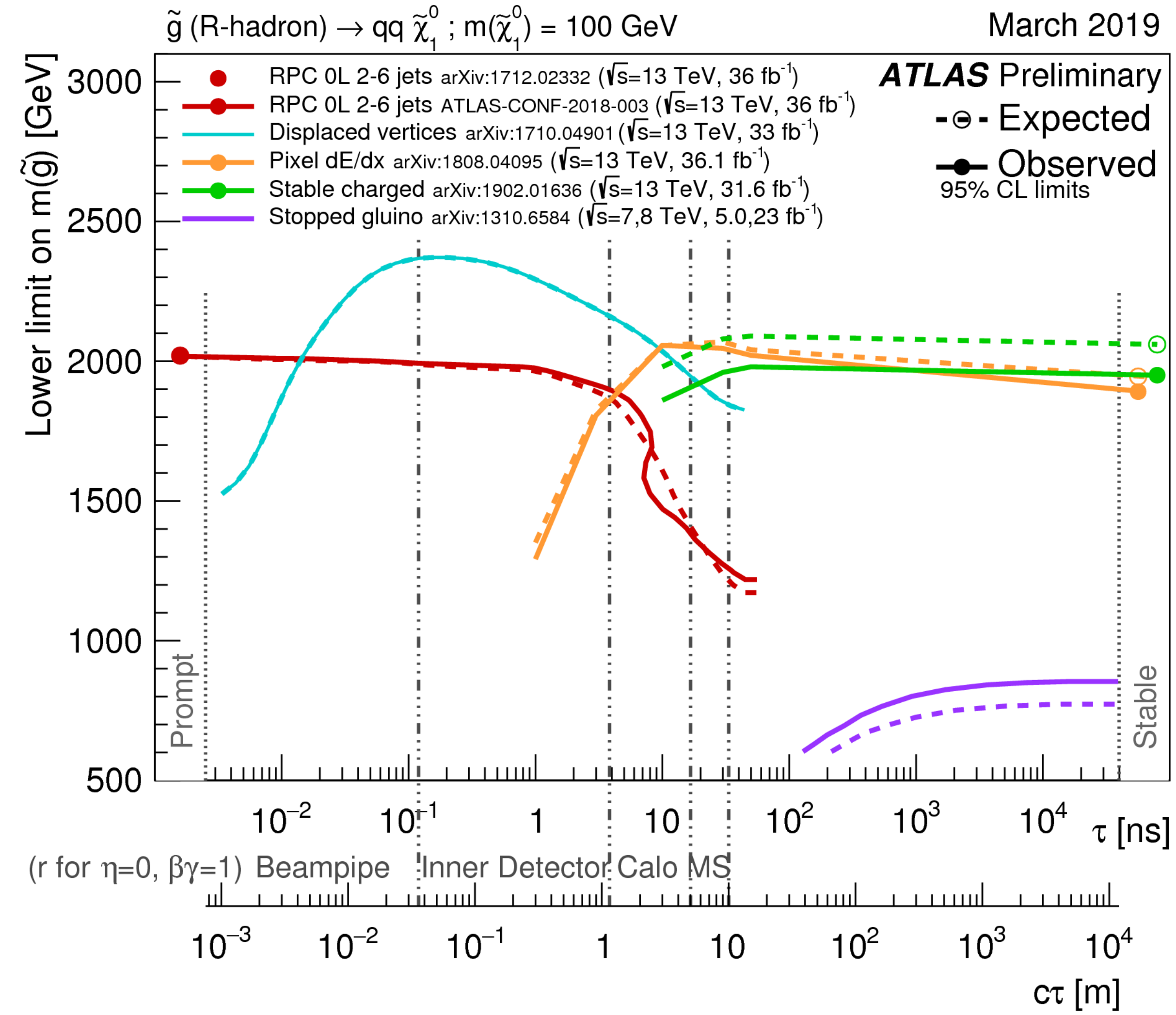




Generation and Simulation of R-Hadrons in the ATLAS Experiment

Zach Marshall (LBNL)
On behalf of the ATLAS Collaboration

SUSY 2019, Corpus Christi, Texas
21 May 2019

Introduction

- **R-Hadrons** are bound states of colored SUSY particles (squarks and gluinos) and SM partons (quarks and gluons)
- Many LLP searches in ATLAS (and CMS) use R-hadrons as a target signal or interpretation
- Many ways to motivate R-hadrons (split SUSY, GMSB, etc)
- ATLAS recently updated our R-hadron setup to use Pythia8
- In doing so, we took the chance to think carefully about the choices we've made in the generation and simulation of R-Hadrons, and to evaluate their impact
- Arguments apply to *any heavy, long-lived, color-charged state*.
- See our new public note for references for everything in this talk.

Which R-Hadrons?

- Pythia8 includes an explicit list of R-hadrons for generation
  - Much longer list than previously included
- PDG IDs look like: 1093214
  - Offset of 1M (usual SUSY thing)
  - 9=gluino; 109→gluino R-baryon, 1009→gluino R-meson
  - 6=stop, 5=sbottom; 1006/1005→stop/sbottom R-baryon, 10006/10005→stop/sbottom R-meson
  - Next numbers are light quark system (321=sud)
  - Then light quark system spin (J*2+1)
  - 1000993 is a gluinoball (gluino+gluon bound state)
- NB: In Pythia8, only J=1 gluino R-mesons are included, and only J=3/2 gluino R-baryons are included.

Masses: What do you Weigh?

- Three sources for masses in literature:
  - MIT Bag Model
  - Lattice QCD calculations (would be interesting to revisit this!)
  - Phenomenological models
- Pythia6 (ATLAS & CMS) used a phenomenological model
- Pythia8 by default uses a sum of constituent masses with a "cloud offset" of 200 MeV (to represent binding energy)

Masses: What do you Weigh?

- We started from the same phenomenological model as was used previously in Pythia6:

$$m_{\text{hadron}} = \sum_i m_i - k \sum_{i \neq j} \frac{(\mathbf{F}_i \cdot \mathbf{F}_j)(\mathbf{S}_i \cdot \mathbf{S}_j)}{m_i m_j}$$

Hyperfine splitting

- **F** and **S** are flavor and spin matrices. m_i are constituent masses. k is a constant.
  - Constituent masses and k value are typically derived from fits to SM hadrons. Different values come from different choices of hadrons to fit with this equation, and different methods for fitting.

Constituent Masses

- Several sources for constituent masses in literature.
- Gluon constituent mass 700 MeV (glueball lattice calculations)

	Constituent Mass [GeV]				
Source	*u*	*d*	*s*	*c*	*b*
Pythia6 [35]	0.325	0.325	0.50	1.60	5.00
Meson fits [36]	0.314	0.314	0.466	1.63	–
Baryon fits [36]	**0.365**	**0.365**	**0.53**	**1.7**	–
Relativised quark model with QCD [37]	0.220	0.220	0.419	1.628	4.977
Feynman-Hellmann best fit [38]	0.3	0.3	0.475	1.640	4.990
Meson fits [39]	0.310	0.310	0.483	1.7	–
Meson spectroscopy [40]	0.290	0.290	0.460	1.65	4.80
Light/strange hadron fits [41]	0.360	0.360	0.540	1.71	5.50
Goldberger-Treiman relations [42]	0.3375	0.3375	0.486	1.550	**4.73**
Hadron fits [43]	0.311	0.311	0.487	1.592	–

Exceptions

- Gluino R-baryons are complicated spin and flavor states. Approximate that for most gluino R-baryons, the hyperfine splitting is small.
- Remember that the lightest states are most important
    - Things like to exist in the lightest states, decay to the lightest states, drop to the lightest states in hadronic interactions.
- The flavour singlet R-baryon (uds) is expected to be lightest and have the largest hyperfine splitting
- Literature yields $m(R_{\Delta})$-$m(R_{\Lambda})$=380 MeV , $m(R_{p})$-$m(R_{\Lambda})$=250 MeV

This Implies a Giant Table

PDG ID	R-hadron	Quark content	Pythia6 Mass [GeV]	Meson Fit Mass [GeV]	Baryon Fit Mass [GeV]	Min. Const. Mass [GeV]	Max. Const. Mass [GeV]
1000512	$\tilde{B}^0$	d	0.325	0.314	0.365	0.220	0.365
1000522	$\tilde{B}^-$	u	0.325	0.314	0.365	0.220	0.365
1000532	$\tilde{B}_s^0$	s	0.500	0.466	0.530	0.419	0.540
1000542	$\tilde{B}_c^-$	c	1.500	1.630	1.700	1.550	1.710
1000552	$\tilde{\eta}_b^0$	b	4.800	4.730	4.730	4.730	5.500
1005113	$\tilde{\Sigma}_b^-$	dd	0.650	0.672	0.763	0.530	0.763
1005211	$\tilde{\Sigma}_b^0$	ud	0.650	0.496	0.632	0.171	0.632
1005213	$\tilde{\Sigma}_b^{*0}$	ud	0.650	0.672	0.763	0.530	0.763
1005223	$\tilde{\Sigma}_b^+$	uu	0.650	0.672	0.763	0.530	0.763
1005311	$\tilde{\Xi}_b^-$	sd	0.825	0.691	0.828	0.498	0.833
1005313	$\tilde{\Xi}_b^{*-}$	sd	0.825	0.810	0.917	0.686	0.922
1005321	$\tilde{\Xi}_b^0$	su	0.825	0.691	0.828	0.498	0.833
1005323	$\tilde{\Xi}_b^{*0}$	su	0.825	0.810	0.917	0.686	0.922
1005333	$\tilde{\Omega}_b^-$	ss	1.000	0.952	1.075	0.863	1.095
1000612	$\tilde{T}^+$	d	0.325	0.314	0.365	0.220	0.365
1000622	$\tilde{T}^0$	u	0.325	0.314	0.365	0.220	0.365
1000632	$\tilde{T}s^+$	s	0.500	0.466	0.530	0.419	0.540
1000642	$\tilde{T}c^0$	c	1.500	1.630	1.700	1.550	1.710
1000652	$\tilde{\eta}_t^+$	b	4.800	4.730	4.730	4.730	5.500
1006113	$\tilde{\Sigma}_t^0$	dd	0.650	0.672	0.763	0.530	0.763
1006211	$\tilde{\Sigma}_t^+$	ud	0.650	0.496	0.632	0.171	0.632
1006213	$\tilde{\Sigma}_t^{*+}$	ud	0.650	0.672	0.763	0.530	0.763
1006223	$\tilde{\Sigma}_t^{++}$	uu	0.650	0.672	0.763	0.530	0.763
1006311	$\tilde{\Xi}_t^0$	sd	0.825	0.691	0.828	0.498	0.833
1006313	$\tilde{\Xi}_t^{*0}$	sd	0.825	0.810	0.917	0.686	0.922
1006321	$\tilde{\Xi}_t^+$	su	0.825	0.691	0.828	0.498	0.833
1006323	$\tilde{\Xi}_t^{*+}$	su	0.825	0.810	0.917	0.686	0.922
1006333	$\tilde{\Omega}_t^0$	ss	1.000	0.952	1.075	0.863	1.095

More Tables!

PDG ID	R-hadron	Quark content	Pythia6 Mass [GeV]	Meson Fit Mass [GeV]	Baryon Fit Mass [GeV]	Min. Const. Mass [GeV]	Max. Const. Mass [GeV]
1000993	$R^0_{\tilde{g}\text{gluinoball}}$	g	0.700	0.700	0.700	0.700	0.700
1009113	$R^0_{\tilde{g}\rho}$	$d\bar{d}$	0.650	0.610	0.717	0.403	0.717
1009223	$R^0_{\tilde{g}\omega}$	$u\bar{u}$	0.650	0.610	0.717	0.403	0.717
1009333	$R^0_{\tilde{g}\phi}$	$s\bar{s}$	1.800	0.924	1.054	0.828	1.074
1009443	$R^0_{\tilde{g}J/\Psi}$	$c\bar{c}$	3.400	3.259	3.399	3.099	3.419
1009553	$R^0_{\tilde{g}\Upsilon}$	$b\bar{b}$	9.460	9.460	9.460	9.460	11.000
1009213	$R^+_{\tilde{g}\rho}$	$u\bar{d}$	0.650	0.610	0.717	0.403	0.717
1009313	$R^0_{\tilde{g}K^*}$	$s\bar{d}$	0.825	0.768	0.886	0.620	0.891
1009323	$R^+_{\tilde{g}K^*}$	$s\bar{u}$	0.825	0.768	0.886	0.620	0.891
1009413	$R^+_{\tilde{g}D^*}$	$c\bar{d}$	2.000	1.940	2.062	1.843	2.067
1009423	$R^0_{\tilde{g}D^*}$	$c\bar{u}$	2.000	1.940	2.062	1.843	2.067
1009433	$R^+_{\tilde{g}D^*_s}$	$c\bar{s}$	2.200	2.094	2.228	2.034	2.248
1009513	$R^0_{\tilde{g}B^*}$	$b\bar{d}$	5.000	5.043	5.094	5.039	5.859
1009523	$R^+_{\tilde{g}B^*}$	$b\bar{d}$	5.000	5.043	5.094	5.039	5.859
1009533	$R^0_{\tilde{g}B^*_s}$	$b\bar{s}$	5.200	5.195	5.259	5.195	6.039
1009543	$R^+_{\tilde{g}B^*_c}$	$b\bar{c}$	7.000	6.360	6.430	6.280	7.210
1093214	$R^0_{\tilde{g}\Lambda}$	sud	1.150	0.562	0.715	0.280	0.715
1094214	$R^+_{\tilde{g}\Sigma^*_c}$	cud	2.300	1.726	1.885	1.489	1.885
1094314	$R^0_{\tilde{g}\Xi^*_c}$	csd	2.300	1.878	2.050	1.688	2.050
1094324	$R^+_{\tilde{g}\Xi^*_c}$	csu	2.300	1.878	2.050	1.688	2.050
1095214	$R^0_{\tilde{g}\Sigma^*_b}$	bud	5.600	4.826	4.915	4.796	5.660
1095314	$R^-_{\tilde{g}\Xi^*_b}$	bsd	5.750	4.978	5.080	4.970	5.840
1095324	$R^0_{\tilde{g}\Xi^*_b}$	bsu	5.750	4.978	5.080	4.970	5.840
1091114	$R^-_{\tilde{g}\Delta}$	ddd	0.975	0.812	0.965	0.530	0.965
1092114	$R^0_{\tilde{g}\Delta}$	udd	0.975	0.812	0.965	0.530	0.965
1092214	$R^+_{\tilde{g}\Delta}$	uud	0.975	0.812	0.965	0.530	0.965
1092224	$R^{++}_{\tilde{g}\Delta}$	uuu	0.975	0.812	0.965	0.530	0.965
1093114	$R^-_{\tilde{g}\Sigma^*}$	sdd	1.150	1.094	1.260	0.859	1.260
1093224	$R^+_{\tilde{g}\Sigma^*}$	suu	1.150	1.094	1.260	0.859	1.260
1093314	$R^-_{\tilde{g}\Xi^*}$	ssd	1.300	1.246	1.425	1.058	1.440
1093324	$R^0_{\tilde{g}\Xi^*}$	ssu	1.300	1.246	1.425	1.058	1.440
1093334	$R^-_{\tilde{g}\Omega}$	sss	1.600	1.398	1.590	1.257	1.620
1094114	$R^0_{\tilde{g}\Sigma^*_c}$	cdd	2.300	2.258	2.430	2.068	2.430
1094224	$R^{++}_{\tilde{g}\Sigma^*_c}$	cuu	2.300	2.258	2.430	2.068	2.430
1094334	$R^0_{\tilde{g}\Omega^*_c}$	css	2.300	2.562	2.760	2.466	2.790
1095114	$R^-_{\tilde{g}\Sigma^*_b}$	bdd	5.600	5.358	5.460	5.350	6.220
1095224	$R^+_{\tilde{g}\Sigma^*_b}$	buu	5.600	5.358	5.460	5.350	6.220
1095334	$R^-_{\tilde{g}\Omega^*_b}$	bss	5.900	5.662	5.790	5.662	6.580

More Tables!

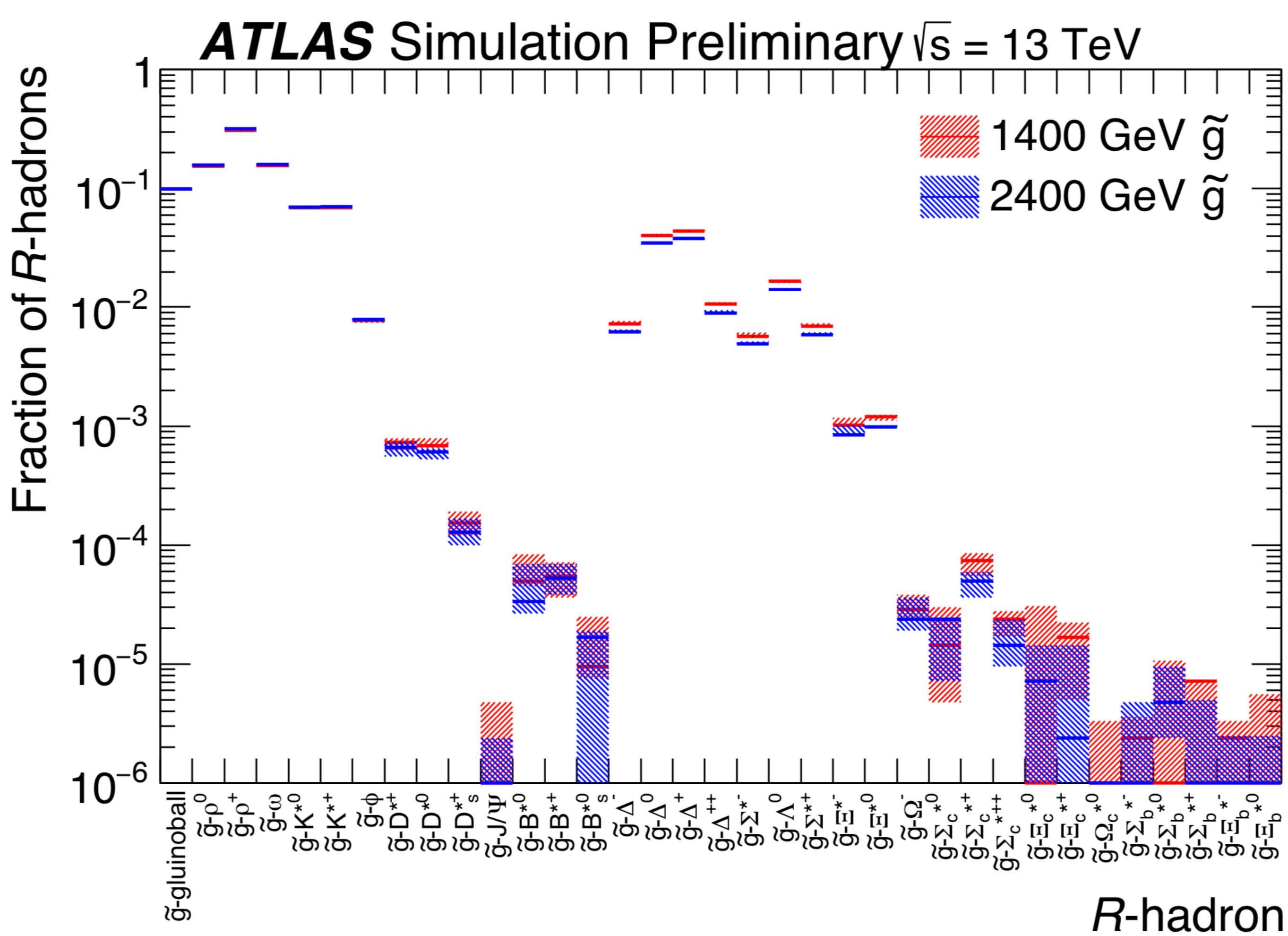
PDG ID	R-hadron	Quark content	Pythia6 Mass [GeV]	Meson Fit Mass [GeV]	Baryon Fit Mass [GeV]	Min. Const. Mass [GeV]	Max. Const. Mass [GeV]
1000993	$R^0_{\tilde{g}\text{gluinoball}}$	g	0.700	0.700	0.700	0.700	0.700
1009113	$R^0_{\tilde{g}\rho}$	$d\bar{d}$	0.650	0.610	0.717	0.403	0.717
1009223	$R^0_{\tilde{g}\omega}$	$u\bar{u}$	0.650	0.610	0.717	0.403	0.717
1009333	$R^0_{\tilde{g}\phi}$	$s\bar{s}$	1.800	0.924	1.054	0.828	1.074
1009443	$R^0_{\tilde{g}J/\Psi}$	$c\bar{c}$	3.400	3.259	3.399	3.099	3.419
1009553	$R^0_{\tilde{g}\Upsilon}$	$b\bar{b}$	9.460	9.460	9.460	9.460	11.000
1009213	$R^+_{\tilde{g}\rho}$	$u\bar{d}$	0.650	0.610	0.717	0.403	0.717
1009313	$R^0_{\tilde{g}K^*}$	$s\bar{d}$	0.825	0.768	0.886	0.620	0.891
1009323	$R^+_{\tilde{g}K^*}$	$s\bar{u}$	0.825	0.768	0.886	0.620	0.891
1009413	$R^+_{\tilde{g}D^*}$	$c\bar{d}$	2.000	1.940	2.062	1.843	2.067
1009423	$R^0_{\tilde{g}D^*}$	$c\bar{u}$	2.000	1.940	2.062	1.843	2.067
1009433	$R^+_{\tilde{g}D^*_s}$	$c\bar{s}$	2.200	2.094	2.228	2.034	2.248
1009513	$R^0_{\tilde{g}B^*}$	$b\bar{d}$	5.000	5.043	5.094	5.039	5.859
1009523	$R^+_{\tilde{g}B^*}$	$b\bar{d}$	5.000	5.043	5.094	5.039	5.859
1009533	$R^0_{\tilde{g}B^*_s}$	$b\bar{s}$	5.200	5.195	5.259	5.195	6.039
1009543	$R^+_{\tilde{g}B^*_c}$	$b\bar{c}$	7.000	6.360	6.430	6.280	7.210
1093214	$R^0_{\tilde{g}\Lambda}$	sud	1.150	0.562	0.715	0.280	0.715
1094214	$R^+_{\tilde{g}\Sigma^*_c}$	cud	2.300	1.726	1.885	1.489	1.885
1094314	$R^0_{\tilde{g}\Xi^*_c}$	csd	2.300	1.878	2.050	1.688	2.050
1094324	$R^+_{\tilde{g}\Xi^*_c}$	csu	2.300	1.878	2.050	1.688	2.050
1095214	$R^0_{\tilde{g}\Sigma^*_b}$	bud	5.600	4.826	4.915	4.796	5.660
1095314	$R^-_{\tilde{g}\Xi^*_b}$	bsd	5.750	4.978	5.080	4.970	5.840
1095324	$R^0_{\tilde{g}\Xi^*_b}$	bsu	5.750	4.978	5.080	4.970	5.840
1091114	$R^-_{\tilde{g}\Delta}$	ddd	0.975	0.812	0.965	0.530	0.965
1092114	$R^0_{\tilde{g}\Delta}$	udd	0.975	0.812	0.965	0.530	0.965
1092214	$R^+_{\tilde{g}\Delta}$	uud	0.975	0.812	0.965	0.530	0.965
1092224	$R^{++}_{\tilde{g}\Delta}$	uuu	0.975	0.812	0.965	0.530	0.965
1093114	$R^-_{\tilde{g}\Sigma^*}$	sdd	1.150	1.094	1.260	0.859	1.260
1093224	$R^+_{\tilde{g}\Sigma^*}$	suu	1.150	1.094	1.260	0.859	1.260
1093314	$R^-_{\tilde{g}\Xi^*}$	ssd	1.300	1.246	1.425	1.058	1.440
1093324	$R^0_{\tilde{g}\Xi^*}$	ssu	1.300	1.246	1.425	1.058	1.440
1093334	$R^-_{\tilde{g}\Omega}$	sss	1.600	1.398	1.590	1.257	1.620
1094114	$R^0_{\tilde{g}\Sigma^*_c}$	cdd	2.300	2.258	2.430	2.068	2.430
1094224	$R^{++}_{\tilde{g}\Sigma^*_c}$	cuu	2.300	2.258	2.430	2.068	2.430
1094334	$R^0_{\tilde{g}\Omega^*_c}$	css	2.300	2.562	2.760	2.466	2.790
1095114	$R^-_{\tilde{g}\Sigma^*_b}$	bdd	5.600	5.358	5.460	5.350	6.220
1095224	$R^+_{\tilde{g}\Sigma^*_b}$	buu	5.600	5.358	5.460	5.350	6.220
1095334	$R^-_{\tilde{g}\Omega^*_b}$	bss	5.900	5.662	5.790	5.662	6.580

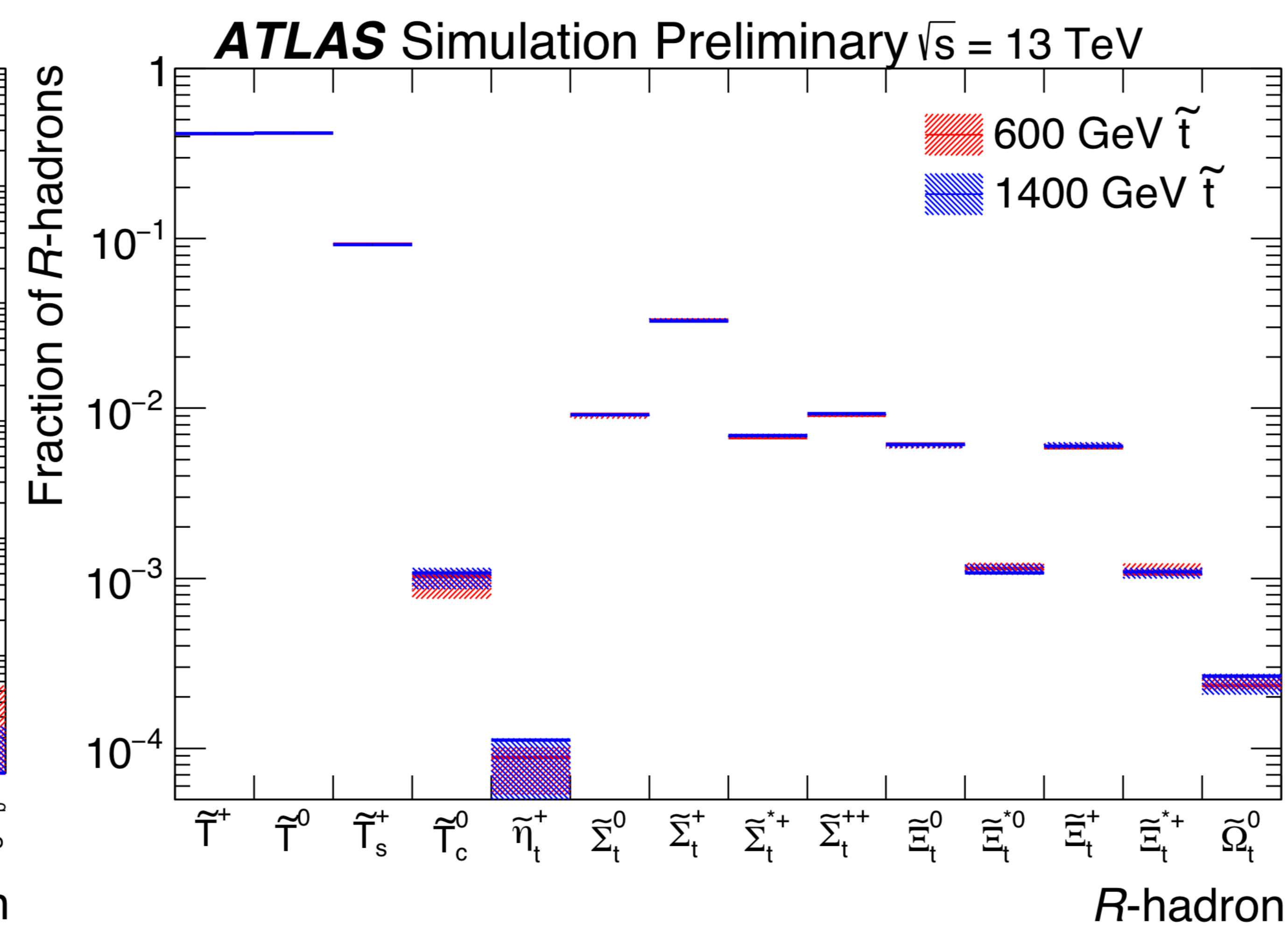
Nominal Mass and Variations

- We take the baryon-mass-fit constituent masses as nominal
- We test several variations:
  - Legacy Pythia6 mass setup (‘generic model’ masses)
  - Meson mass fits
  - Fits with largest constituent masses we found
  - Fits with smallest constituent masses we found
  - A modified setup where the gluinoball mass is kept constant, and all other masses are made heavier or lighter to move the gluinoball up or down in the spectrum.
- You will see these variations as uncertainty bands in the following plots

Event Generation

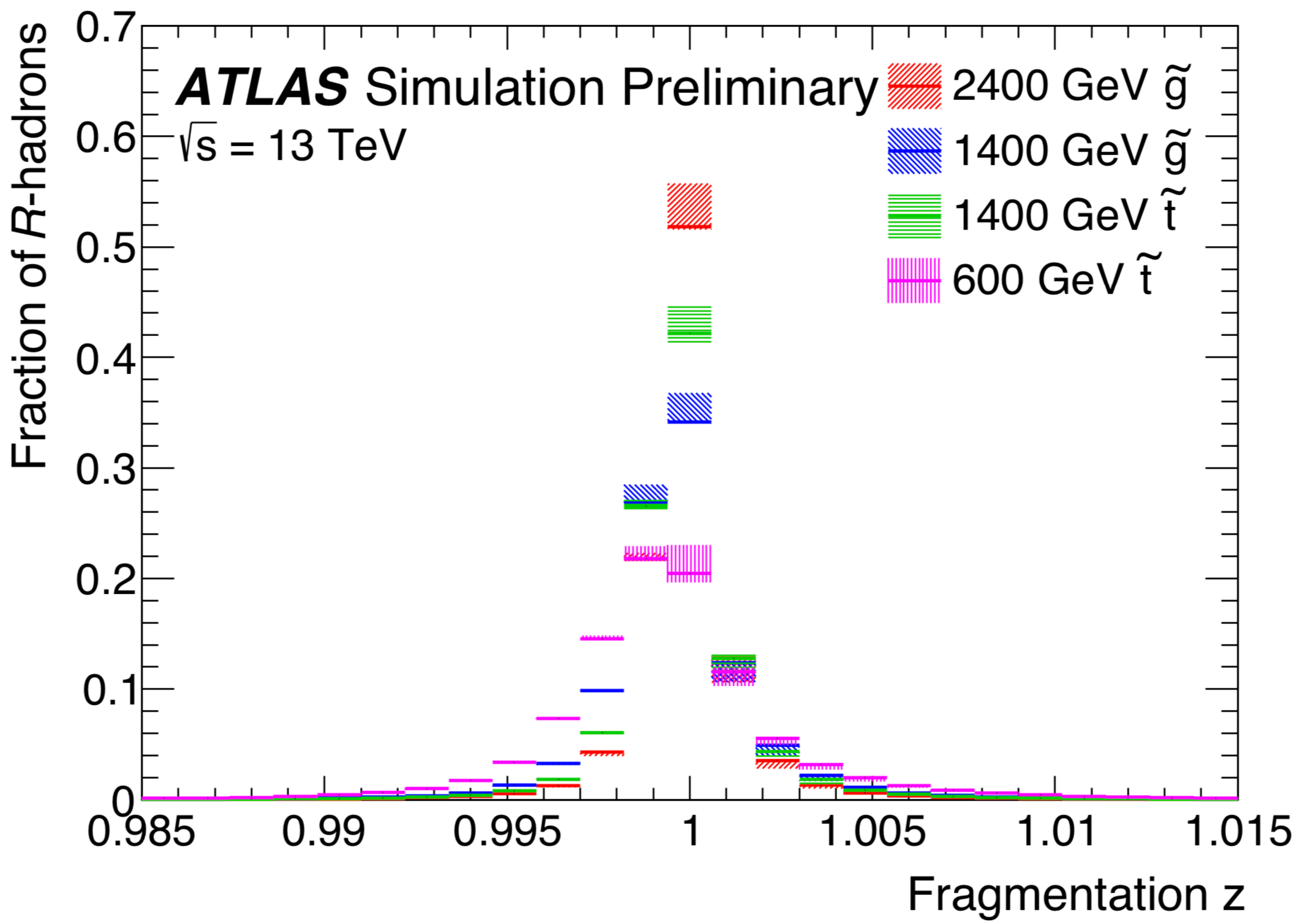
- We set the lifetimes of **all states** to be the same (more in a moment)
- Only one extra Pythia8 parameter to set: the gluinoball fraction
  - Set to 10%, but varied during event generation tests (more in a moment)
- Lightest states favored, heavy states rare (as expected)





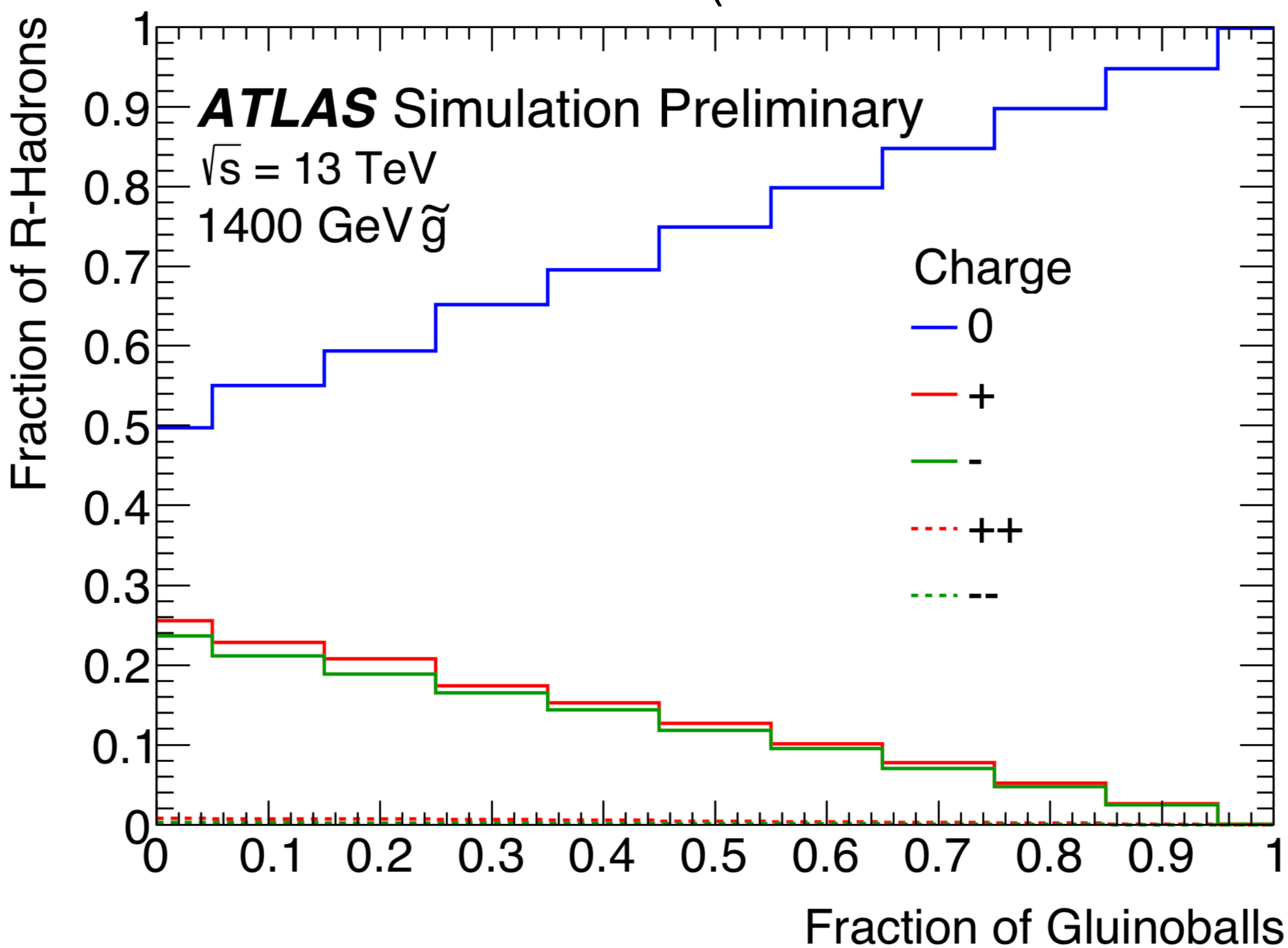
Fragmentation

- The heavier a particle gets, the more peaked at one its fragmentation function (this is why b-hadrons carry most of a b-quark's momentum)
  - Especially true for heavy BSM particles.
- Small difference between squarks and gluinos due to color charge.



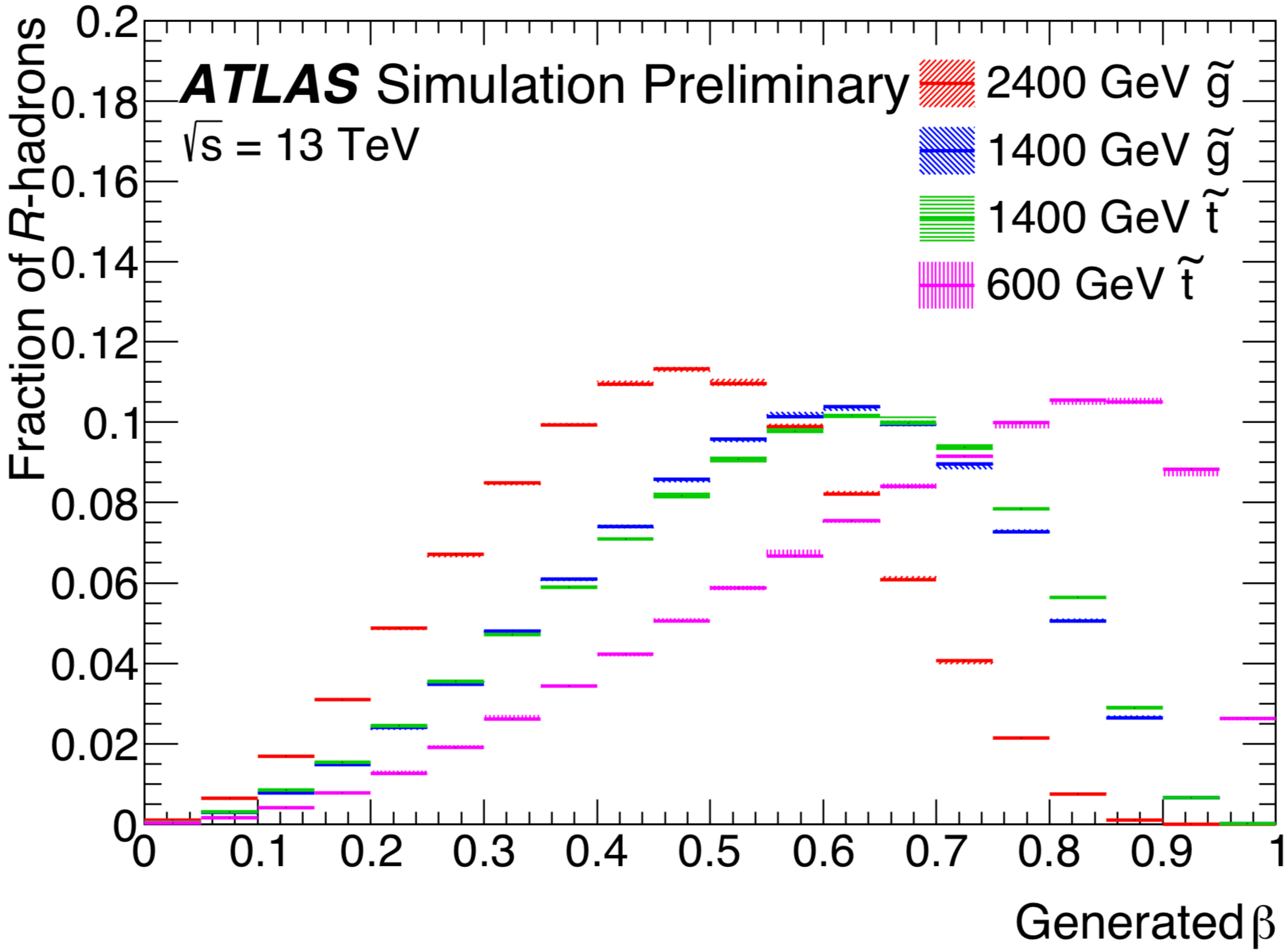
Charge Fraction

- Experimentally, we care a lot about the fraction of charged R-hadrons
- Just driven by the fraction of gluinoballs that we produce
- Slightly more + and ++ than - and -- (LHC has a ++ initial state!)



Initial Velocity

- For many of our searches, we care about the beta distribution
- dE/dX, time of flight, stopped particles all depend on this

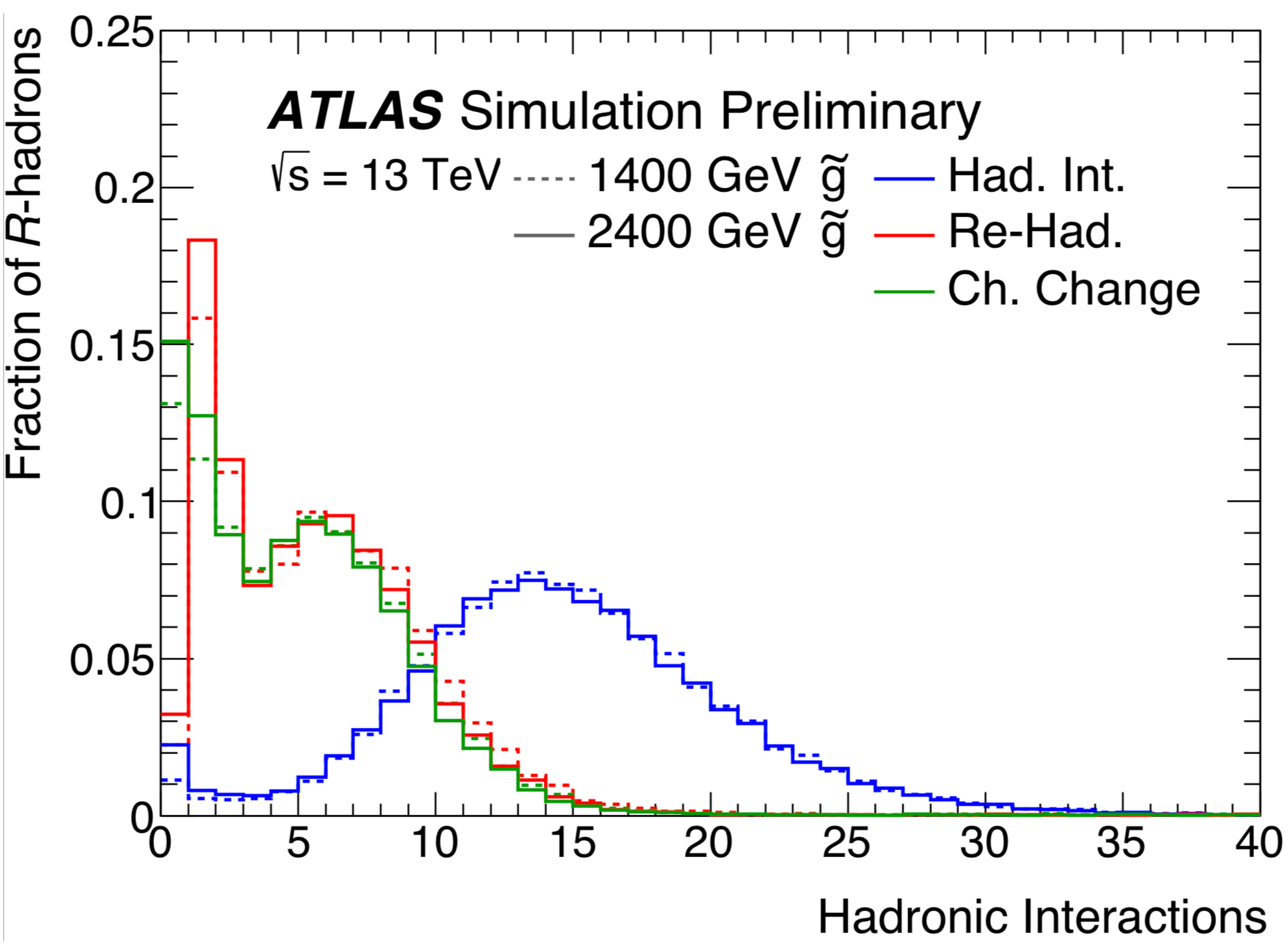


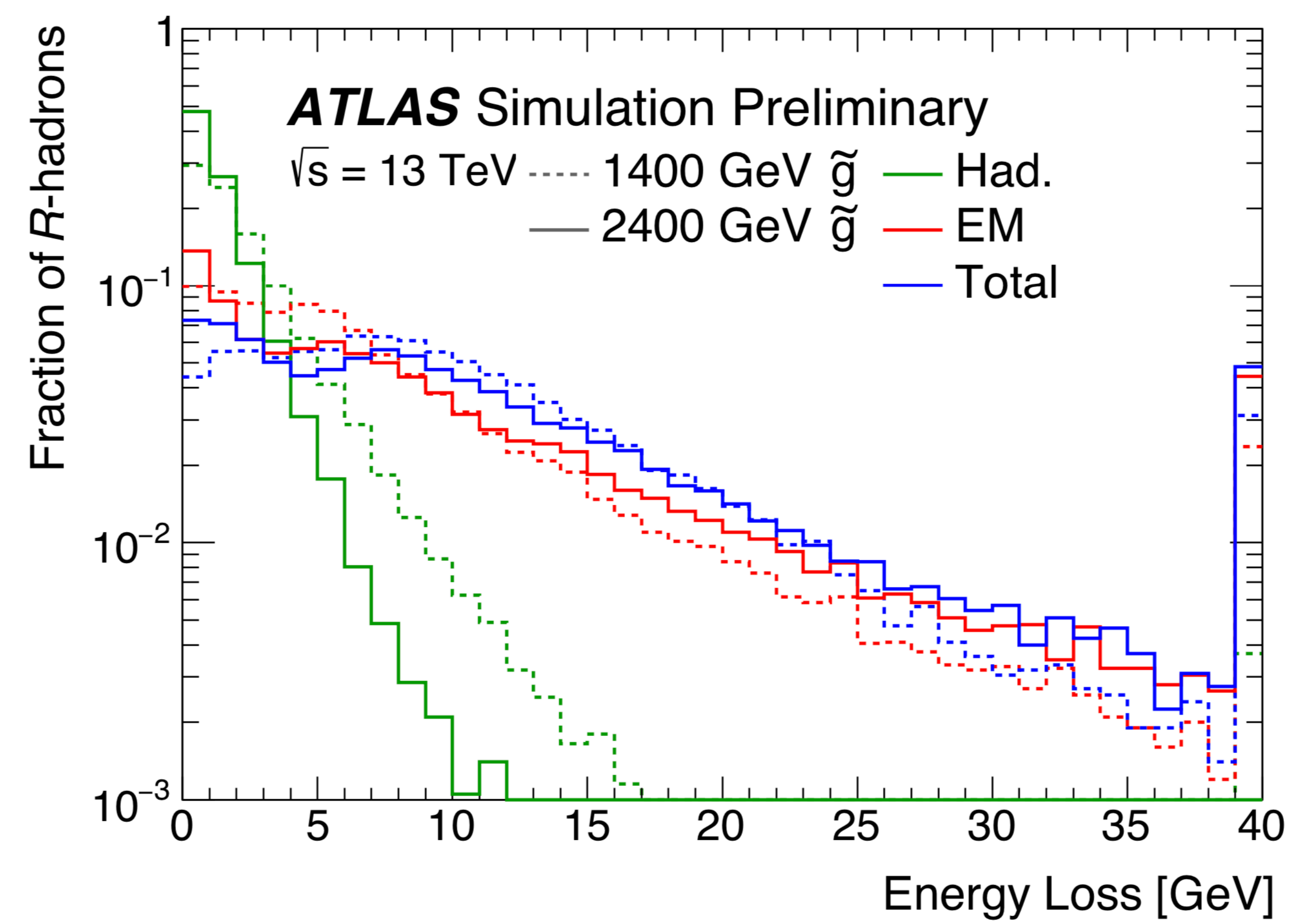
Simulation (It’s Tricky)

- ATLAS and CMS use the same EM and <u>hadronic</u> physics models
- Based on the work of Mackeprang and Milstead from ~8-10 years ago
- It’s configurable:
  - “Generic” model (default): 12 mb cross section per light quark, optional suppression of interactions that change the charge of the light quark system
  - “Regge” model (based on triple-Regge theory): more complex cross section, optional mixing of neutral mesons, optional cross section multiplier
- In either case we have to *specify all possible interactions*.
  - New for this setup: List all possible 2->2 and 2->3 interactions that conserve charge, baryon number, and strangeness.
  - Bottom (charm) counts as +1 (-1) strange in the initial state. Not allowed in the final state of a hadronic interaction.
  - Gluinoballs not allowed in the final state of a hadronic interaction.

Energy Loss and Interactions

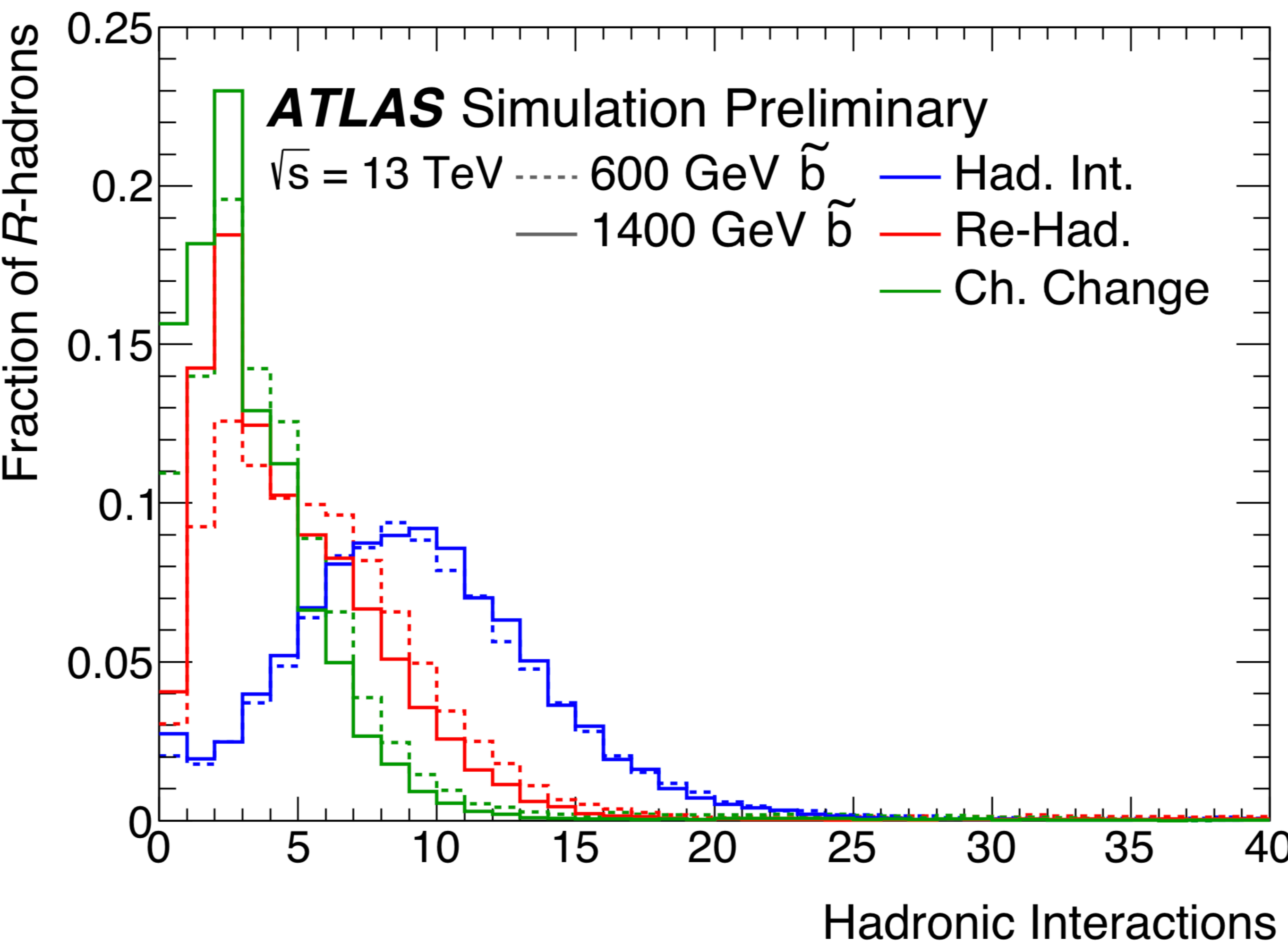
- Most energy loss is electromagnetic.
- Many hadronic interactions do not the change light quark system

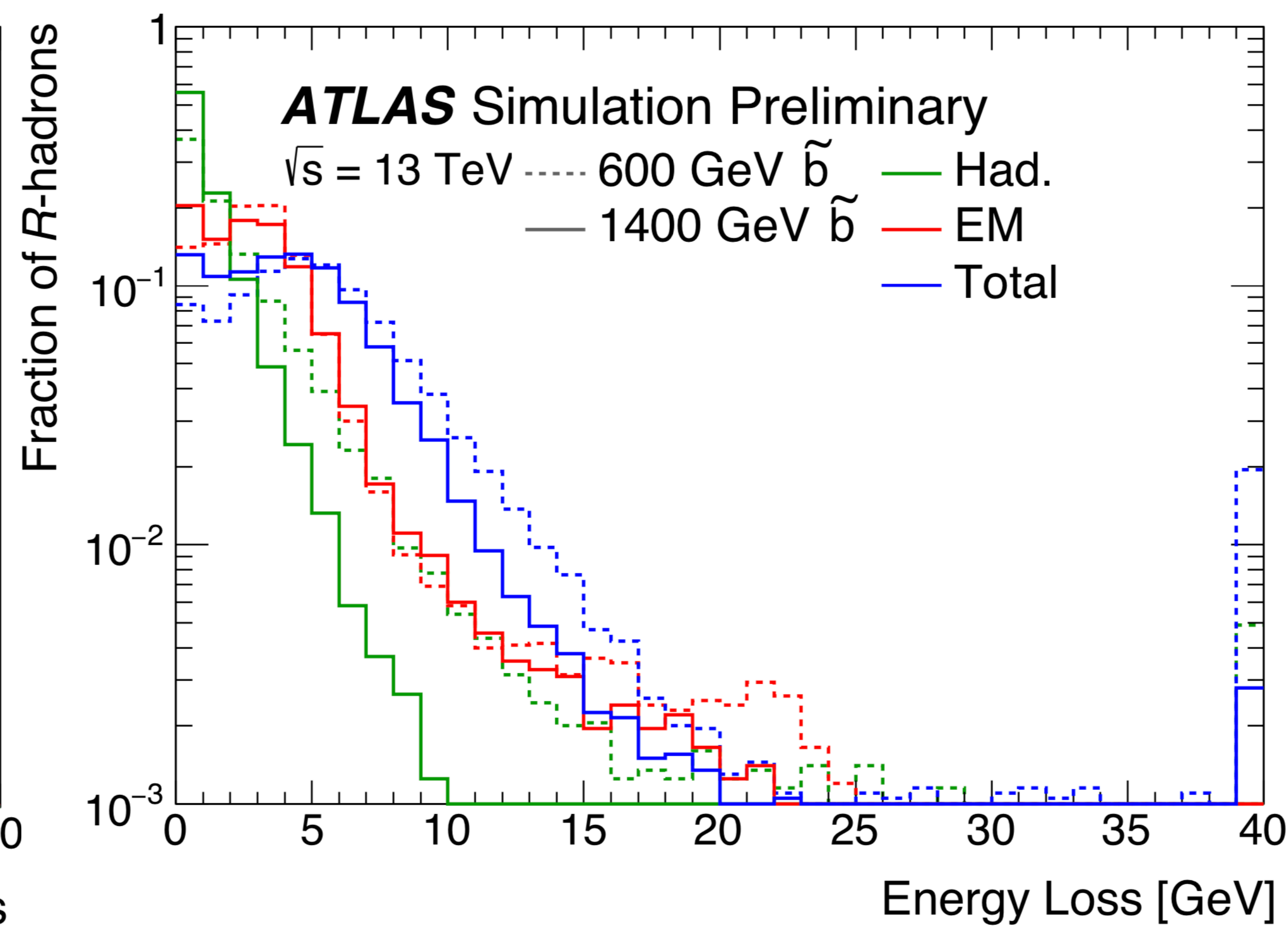




Energy Loss and Interactions

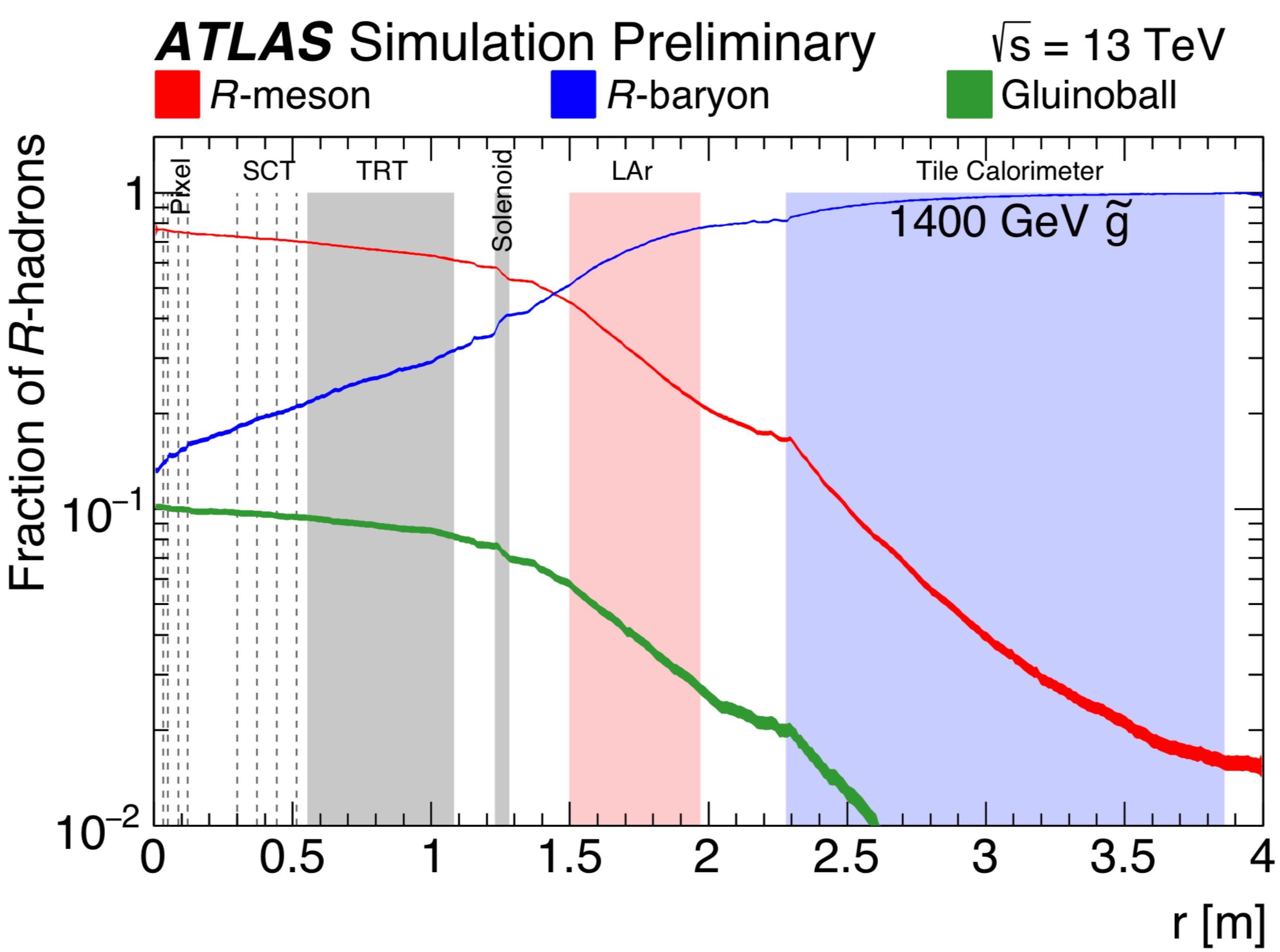
- Most energy loss is electromagnetic.
- Many hadronic interactions do not the change light quark system
- For stop/sbottom R-hadrons, fewer interactions (fewer SM partons)
- For sbottom R-hadrons, lower energy loss (fewer charged states)

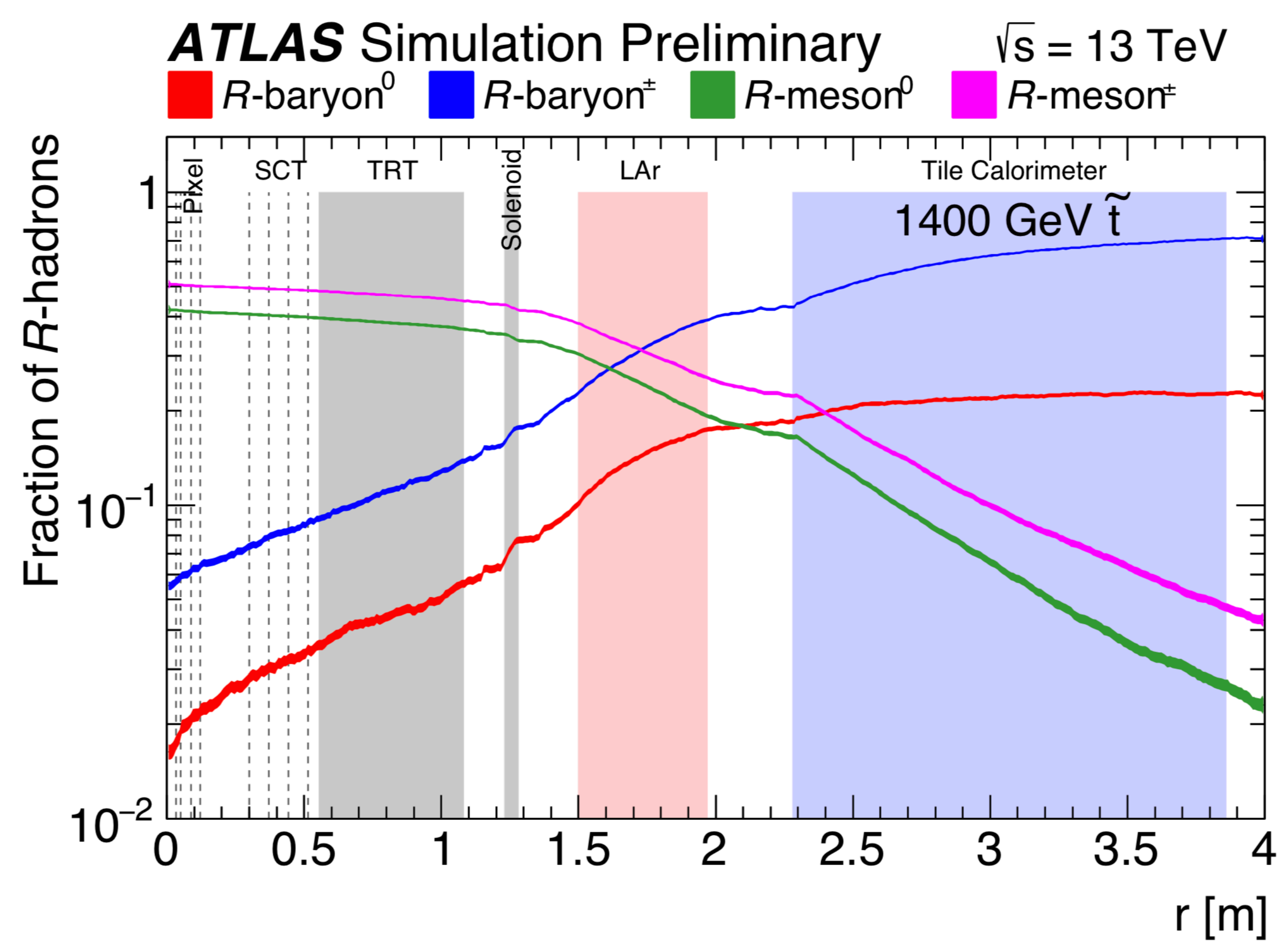




Conversion Via Interactions

- Because of conservation of baryon number and kinematics, conversion from mesons into baryons is favored
  - More rapid conversion than in Pythia6 configuration
- Charge fraction dependent on lightest state configuration
  - Sbottoms are upside-down compared to stops in terms of charge
  - Important for searches using muon system tracks (if R-hadrons are neutral…)





Stopping

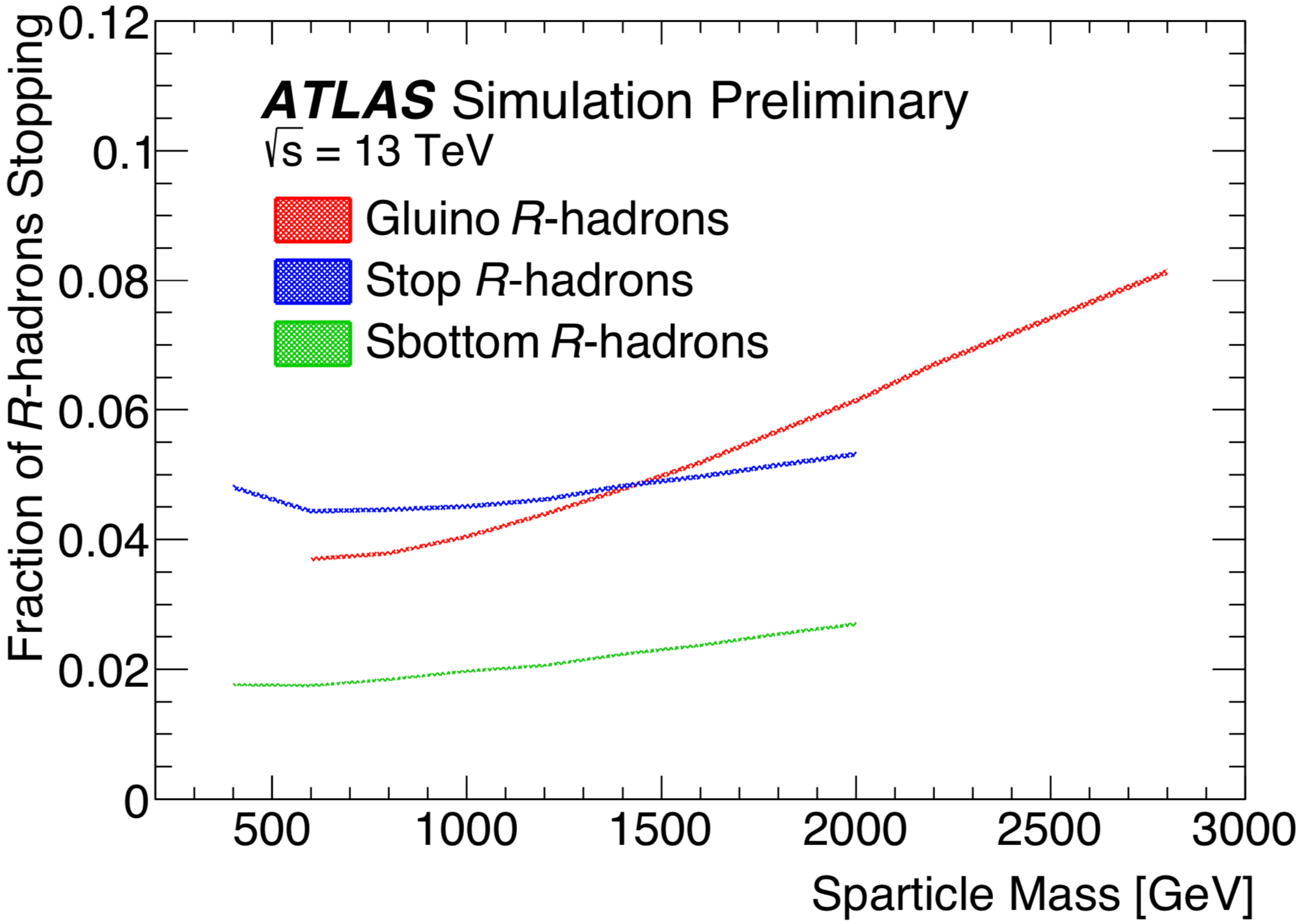
- Long-lived R-hadrons may also stop in the detector. The stopping condition in our simulation is (v_F the Fermi velocity = 0.15c, A an atomic number):

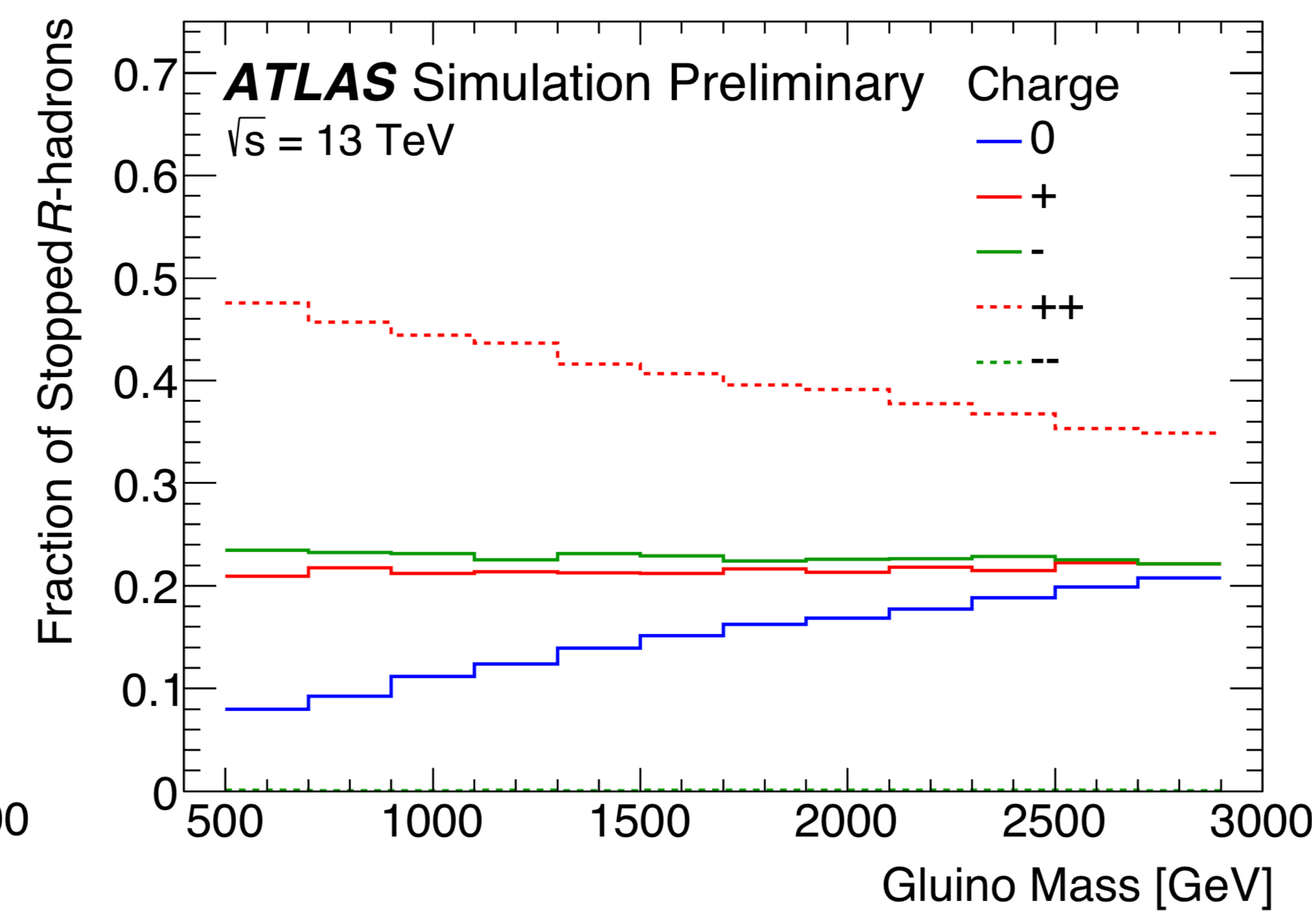
$$v \leq \frac{v_F}{A^{2/3}}$$

- Things worth pointing out here:
  - It depends on all the atoms in a material (use the smallest)
  - It is independent of density (veto stopping in a gas)
  - It is independent of charge (test stopping for negative R-hadrons)
  - Does not account for R-hadron energy (no stopping in the tracker)
  - Some fraction of R-hadrons stop as soon as they encounter material

Who Stops?

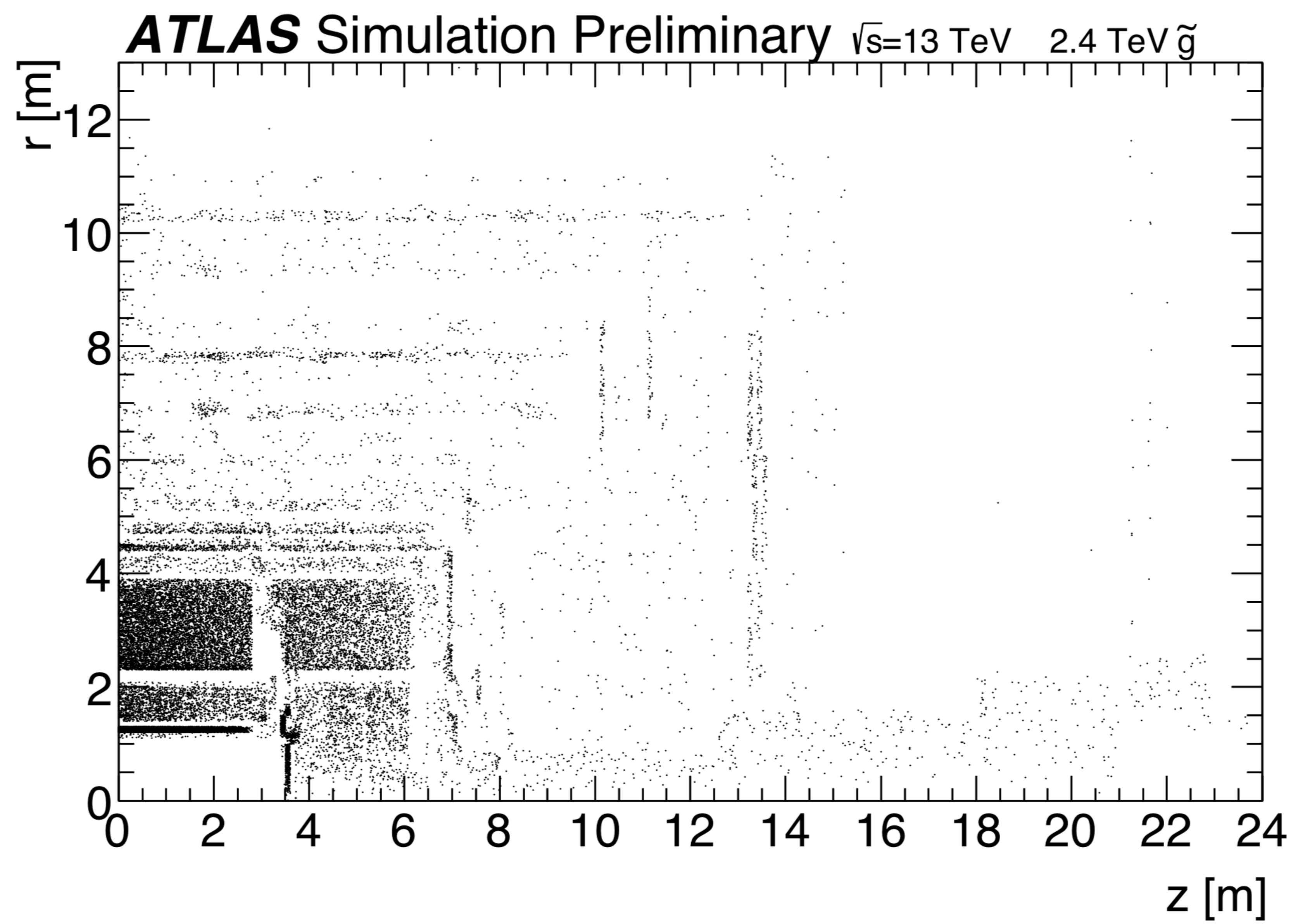
- Gluinos R-hadrons are somewhat easier to stop
- Sbottoms R-hadrons are harder to stop (more neutrals)
- Doubly-charged R-hadrons are easier to stop





Where Do They Stop?

- Many particle stop as soon as they encounter thick material
- Some particles stop in shielding throughout the detector



Summary

- We've prepared a little public note on R-hadron event generation and simulation in ATLAS
- All the details and explanation of what we're really doing for event generation and simulation
- Took the opportunity to test variations and assumptions in the models
- Hoping that this can serve as a starting point for harmonization of configurations in the community
- Look forward to a bunch of ATLAS search results using all this new software soon!