Melting LHC Detectors

A novel search for stopped long-lived particles

Samuel Wong

University of Washington

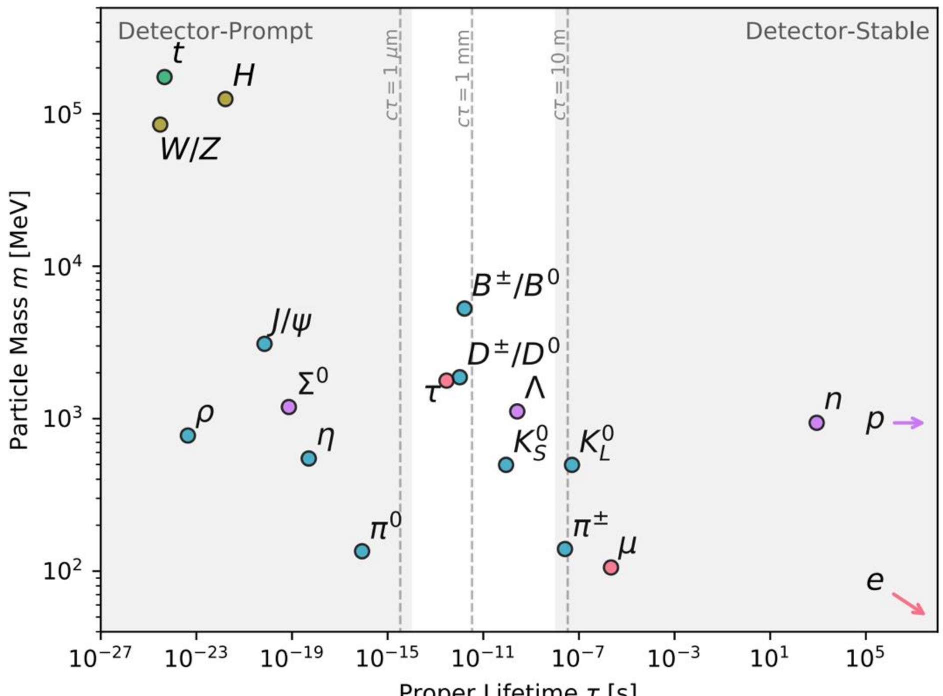
Collider Physics in the Northwest, TRIUMF

Feb 18, 2026

[2512.12023]: Julia Gonski, Peter Graham, Surjeet Rajendran, Harikrishnan Ramani, S. W.

Long-Lived Particles in SM

- SM particles have lifetimes that span many orders of magnitude.
- Long lifetimes (τ >> 1/M) due to heavy mediator (μ), small couplings (H), suppressed phase space (n), exact symmetry (e, p), etc.



[1810.12602]

Long-Lived Particles in BSM

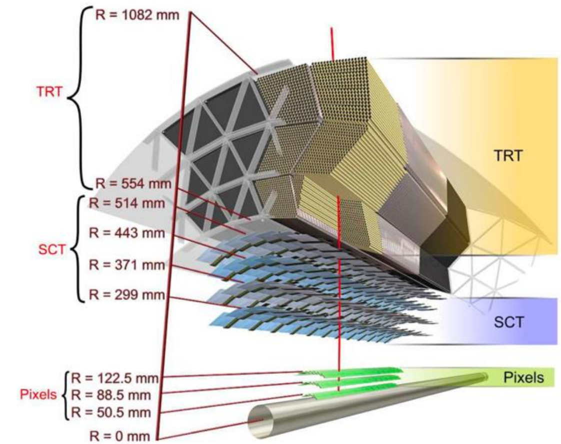
- Long-lived particles are ubiquitous in BSM physics.
- Potential "blind spot" of the LHC.
- For $\tau < 1\ \mathrm{ns} \sim 1\ \mathrm{m}$, can produce displaced vertices, decaying meters away from interaction point. Many dedicated analyses at the LHC, e.g. [1911.12575].

Long-Lived Particles in BSM

- Long-lived particles are ubiquitous in BSM physics.
- Potential "blind spot" of the LHC.
- For $\tau < 1~\mathrm{ns} \sim 1~\mathrm{m}$, can produce displaced vertices, decaying meters away from interaction point. Many dedicated analyses at the LHC, e.g. [1911.12575].
- But what if $\tau \gg 1~\mathrm{yr}$, or if the particle is stable?
- Decay signals are highly suppressed or entirely not available here.
- Currently, the most powerful technique:

  Ionization energy loss (dE/dx) for charged particles (electric/color).

dE/dx Searches



- Heavy particles are slower, depositing more ionization energy in the silicon detectors.

$$\frac{dE}{dx} = -\frac{4\pi\alpha^2}{m_p m_e}\frac{\rho Z}{A}\frac{z^2}{v^2}\left(\frac{1}{2}\log\frac{2m_e v^2}{I\,(1-v^2)} - v^2\right)$$

- But dE/dx search (e.g. ATLAS [2502.06694]) is background-limited.
- Pile-ups, particles from simultaneous pp-collisions, degrade track reconstruction.
- Pile-ups get worse by an order of magnitude at the High Luminosity-LHC (HL-LHC) (2030-2040).
- Unclear if dE/dx search improves at the HL-LHC.

Recovering Trapped Particles

- If charged particles are losing kinetic energy in the detector, some of them will also stop and remain trapped there.

We point out a **new class of background-free signal** for non-decaying particles:

recovery of trapped particles in (liquefied) detector material

- Background-free because there is no naturally occurring TeV-scale atoms.

- Turning the disadvantage of lack of decay signals into an advantage: non-decaying particles are still around!

Heavy Isotope Searches in 1980s

- In 1980s, a series of experiments searched for anomalously heavy particles in terrestrial material (e.g. sea water) [Smith et. al., Nucl. Phys. B 206, 333 (1982)].

- Production mechanism: relics from early universe.

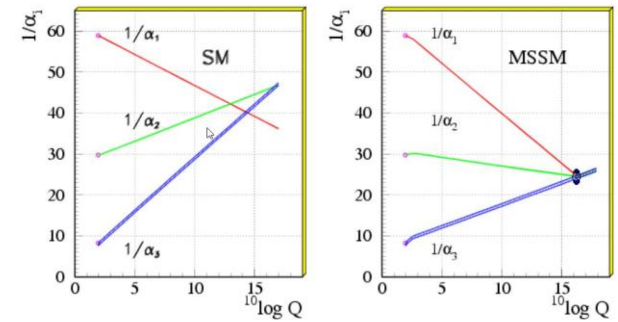
- Using centrifuge to "enrich" the water, followed by time-of-flight mass spectrometry, achieved concentration limit of 10^{-29}.

- We propose a similar experiment but the production mechanism is now proton-proton collisions at the LHC. Lower energy reach but occurrence is certain and localized.

Split Supersymmetry (SUSY)

- Traditional motivations for SUSY at the TeV scale:

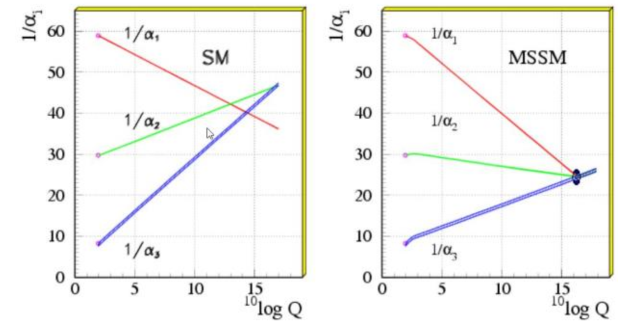
1) Higgs hierarchy
2) WIMP dark matter
3) Gauge coupling unification



Split Supersymmetry (SUSY)

- Traditional motivations for SUSY at the TeV scale:

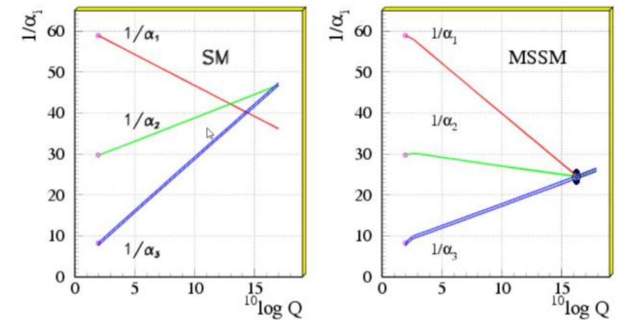
1) Higgs hierarchy (some tensions?)
2) WIMP dark matter
3) Gauge coupling unification



Split Supersymmetry (SUSY)

- Traditional motivations for SUSY at the TeV scale:

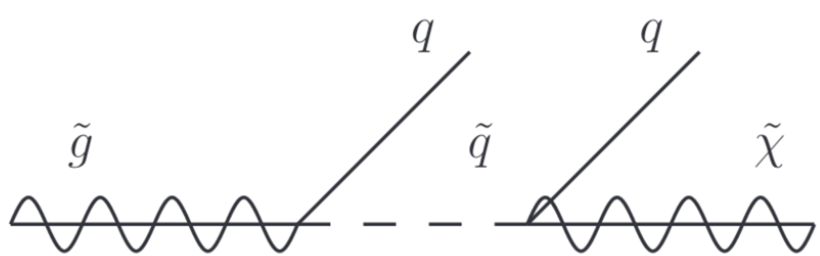
1) Higgs hierarchy (some tensions?)
2) WIMP dark matter
3) Gauge coupling unification



- Split SUSY gives up on (1), allowing weak scale to be fine-tuned [Arkani-Hamed and Dimopoulos, JHEP 0506 (2005) 073].
- SUSY breaking scale Λ_{SUSY} can be as large as the GUT scale, driving up masses of all scalar superpartners (squarks, sleptons).
- The fermions (gauginos, Higgsinos) can stay light, protected by chiral symmetry.
- Retaining motivations (2) and (3) still set them at the TeV scale.

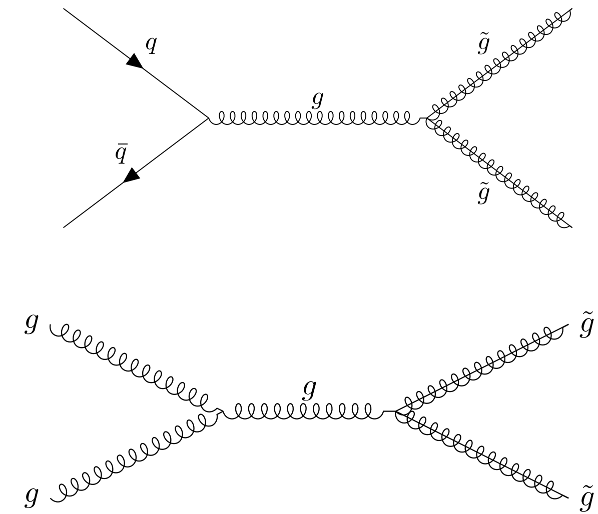
Long-Lived Gluinos

- In split SUSY, gluinos ($\tilde{g}$) are the only TeV sparticles abundantly produced at the LHC.
- Decay through a virtual squark, which are heavy, giving rise to long gluino lifetime: $\tau = 10^7 \mathrm{years} \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{\mathrm{m_s}}{10^{13}\mathrm{GeV}}\right)^4$
- Poster child of a large class of colored, long-lived particles.



Gluinos at the LHC

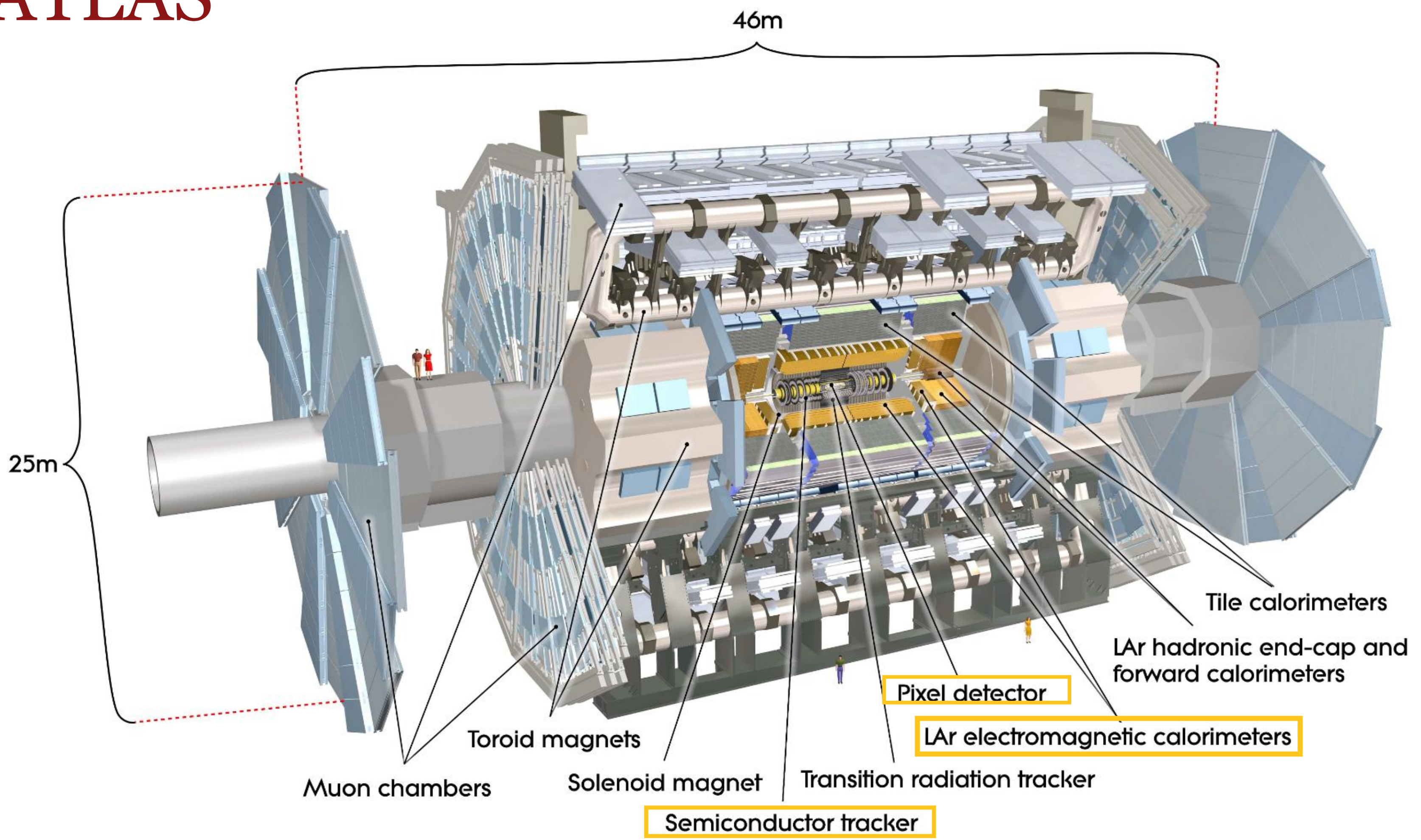
- Pair production: $pp \to \tilde{g}\tilde{g}$
- Binds with quarks to form R-hadrons, about 50% of them are charged.
- Every nuclear scattering can exchange quarks → charge oscillations [Dimopoulos et. al. PRD 76, 055007].
- While charged, lose energy via ionization (dE/dx).
- Final state: binds with a nucleus to form a TeV-scale **anomalously heavy atom**.



+

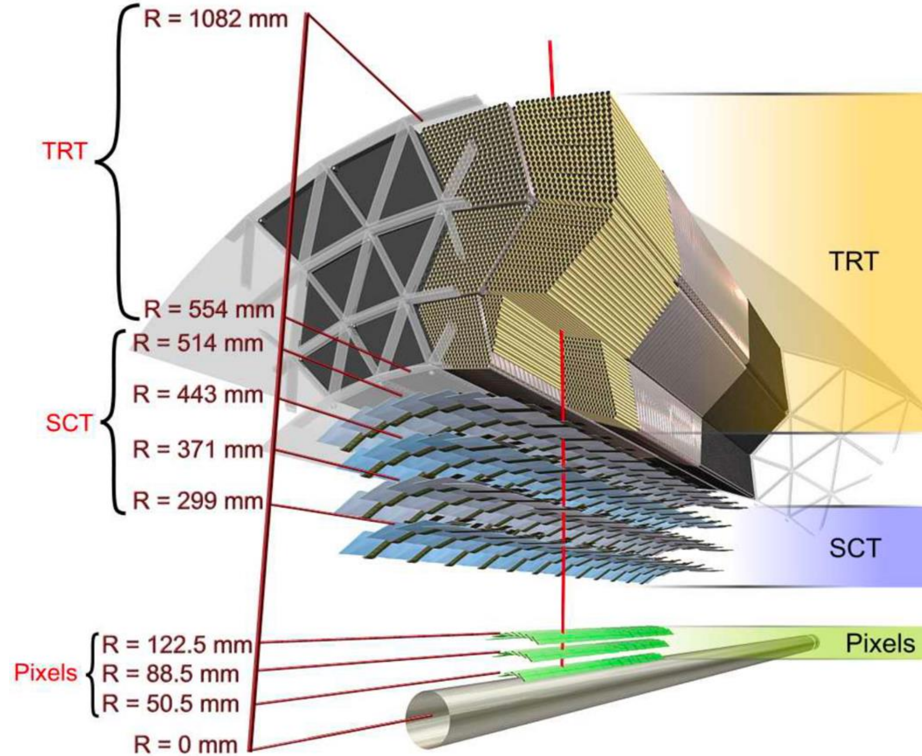
...

ATLAS


46m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Transition radiation tracker
Semiconductor tracker
Solenoid magnet
Toroid magnets
Muon chambers

Target 1: Silicon Detectors

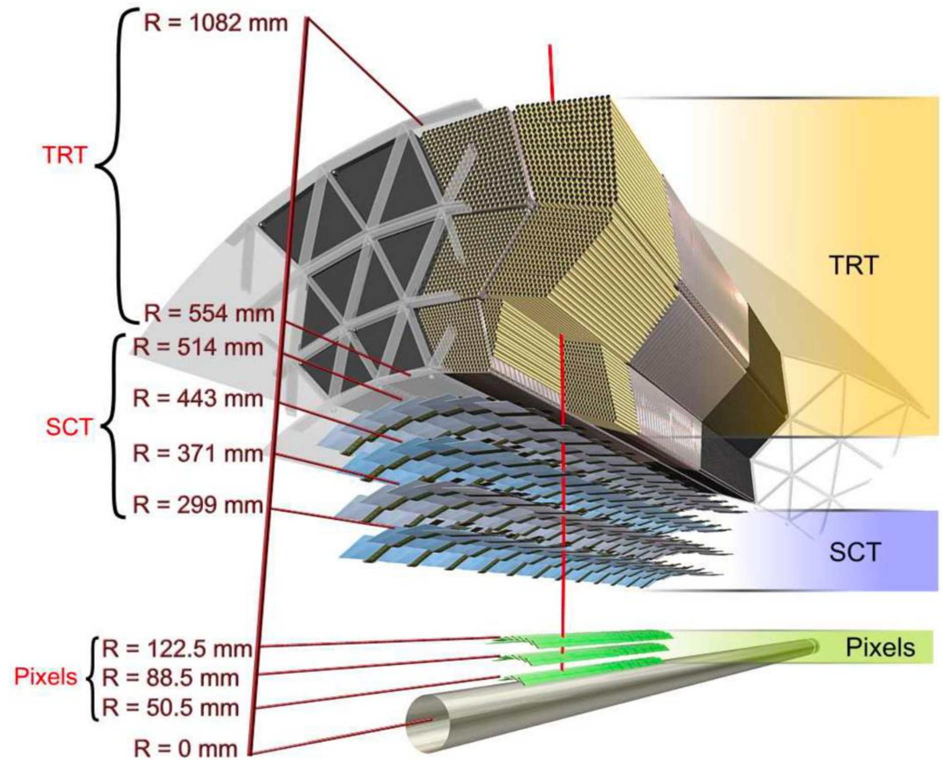
- Silicon detectors: pixels and semiconductor trackers.
- Closest to collision point, large exposure.
- Periodically taken out due to radiation damage.



volume of silicon = 230 L

Target 1: Silicon Detectors

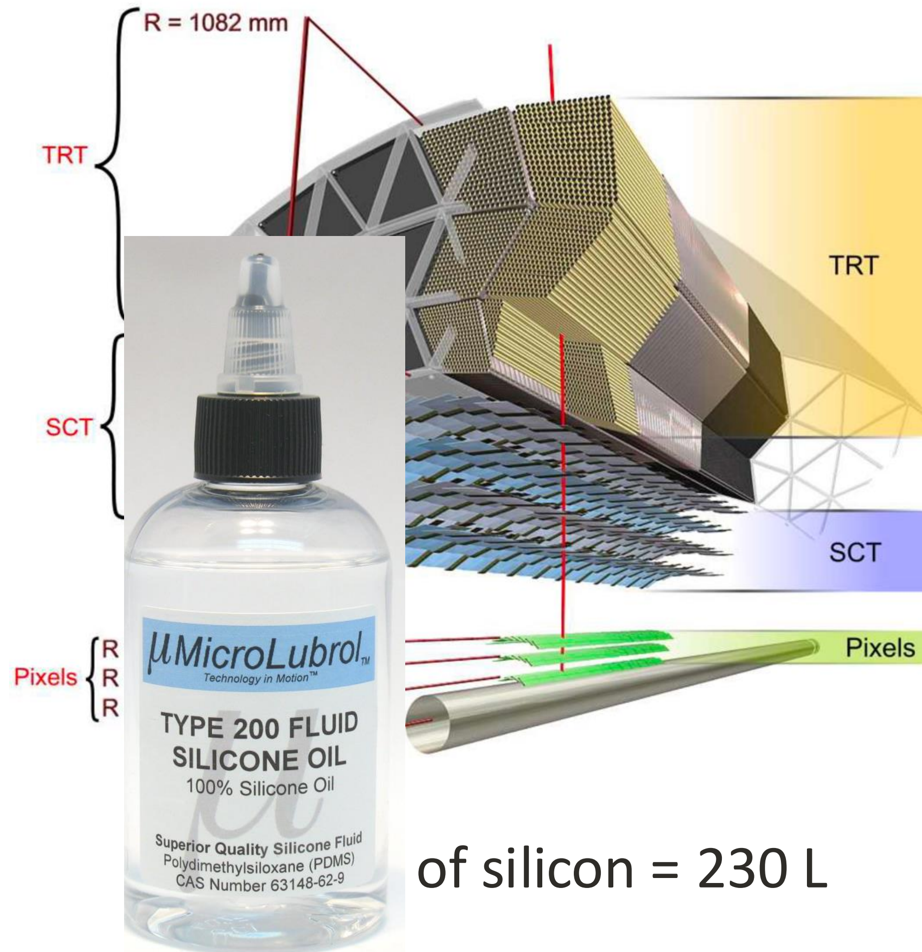
- Silicon detectors: pixels and semiconductor trackers.
- Closest to collision point, large exposure.
- Periodically taken out due to radiation damage.
- **Drawback**: our detection method requires liquid.
- **Solution**: melt and chemically convert silicon to a liquid compound, e.g. silicone oil.



volume of silicon = 230 L

Target 1: Silicon Detectors

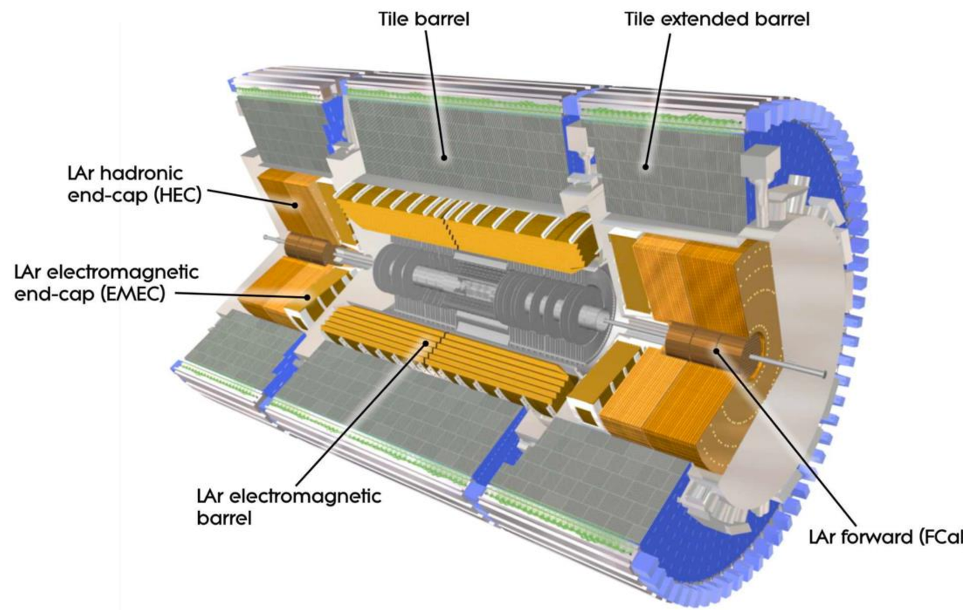
- Silicon detectors: pixels and semiconductor trackers.
- Closest to collision point, large exposure.
- Periodically taken out due to radiation damage.
- **Drawback**: our detection method requires liquid.
- **Solution**: melt and chemically convert silicon to a liquid compound, e.g. silicone oil.



of silicon = 230 L

Target 2: Liquid Argon

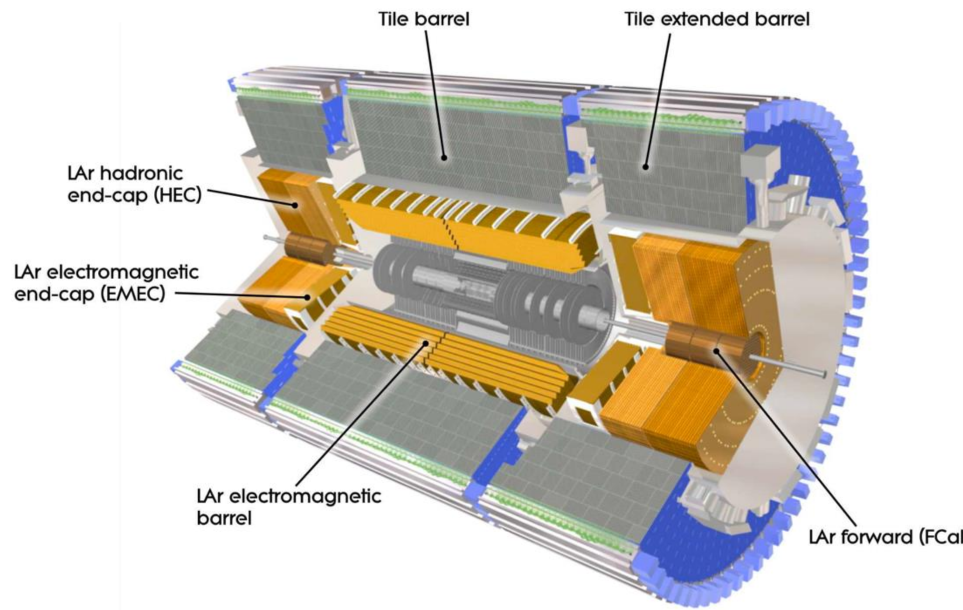
- The liquid argon in EM calorimeter is *already* liquid.
- Second closest to collision point.



volume of argon = 10^4 L

Target 2: Liquid Argon

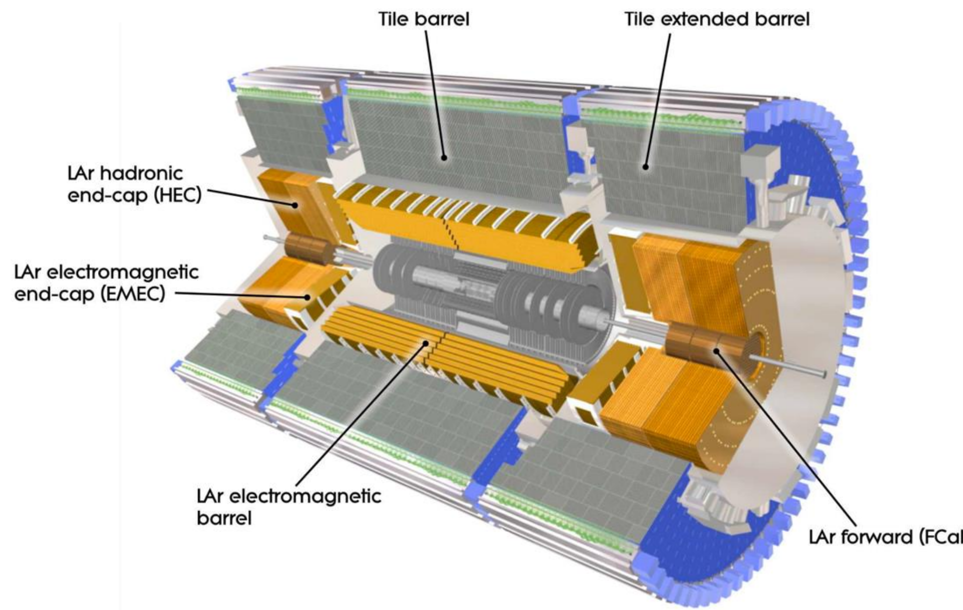
- The liquid argon in EM calorimeter is *already* liquid.
- Second closest to collision point.
- **Drawback**: need to maintain below argon boiling point of -186 °C.
- **Solution**: biologists already use cryogenic centrifuge at this temperature.



volume of argon = 10^4 L

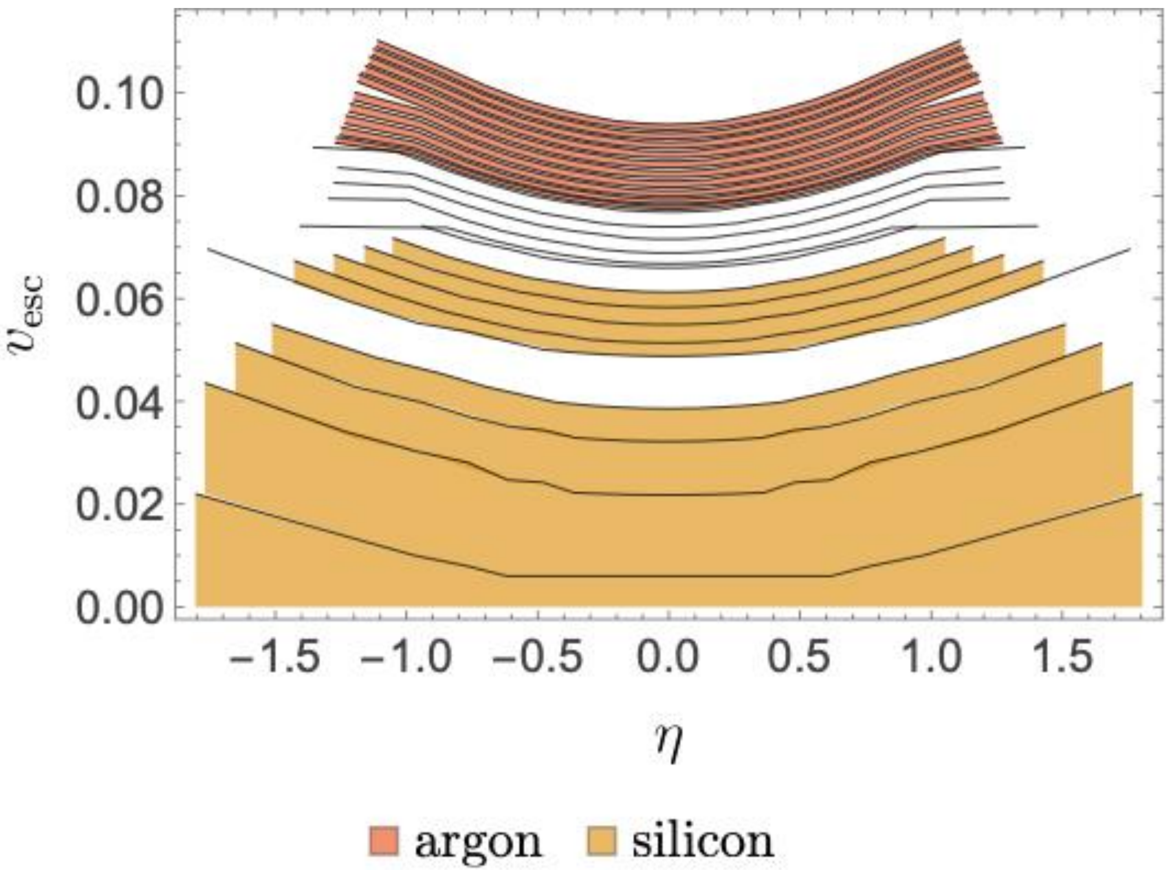
Target 2: Liquid Argon

- The liquid argon in EM calorimeter is *already* liquid.
- Second closest to collision point.
- **Drawback**: need to maintain below argon boiling point of -186 °C.
- **Solution**: biologists already use cryogenic centrifuge at this temperature.
- **Drawback**: rarely removed.

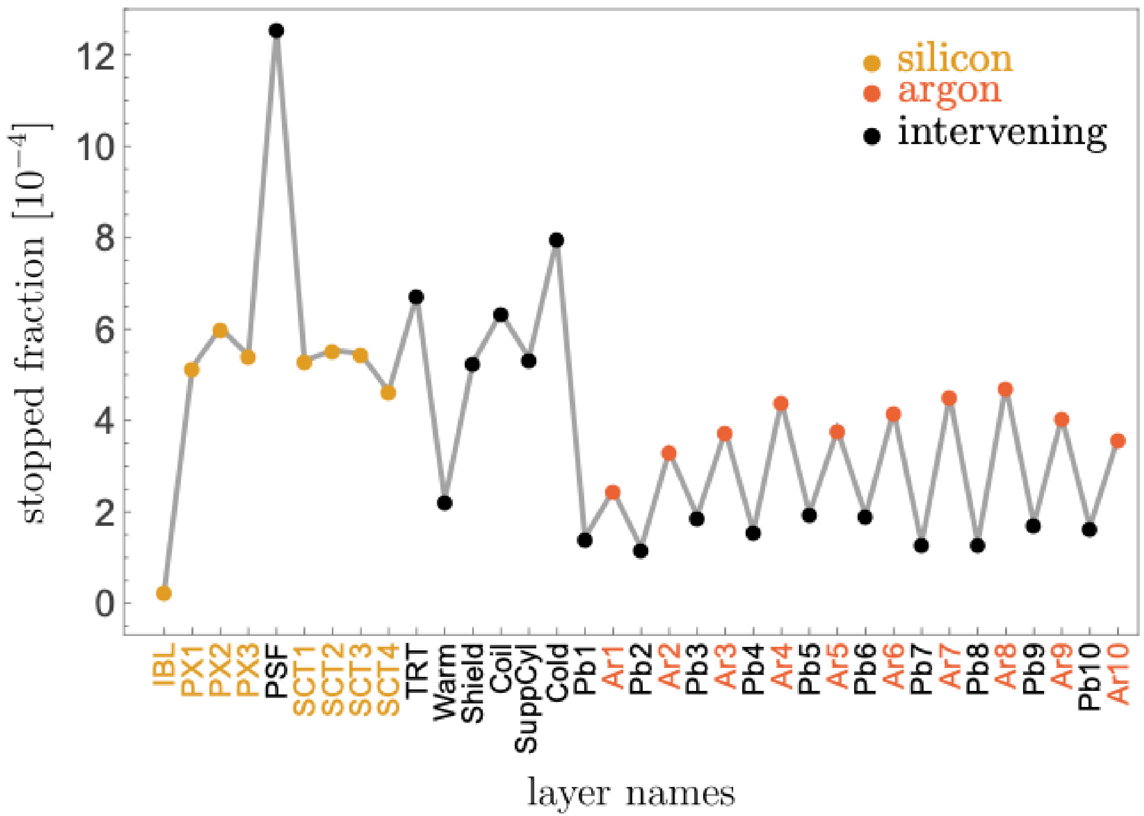


volume of argon = 10^4 L

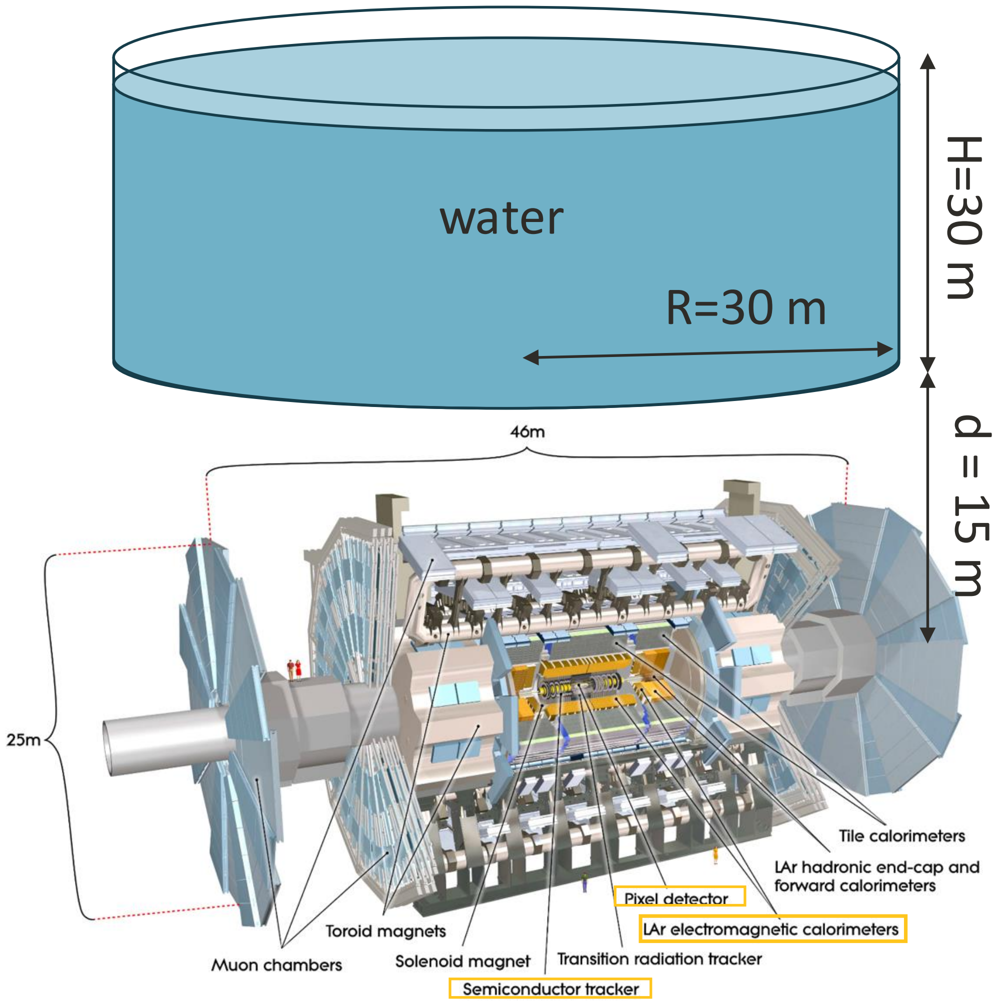
Stopping Velocity



Stopped Fraction



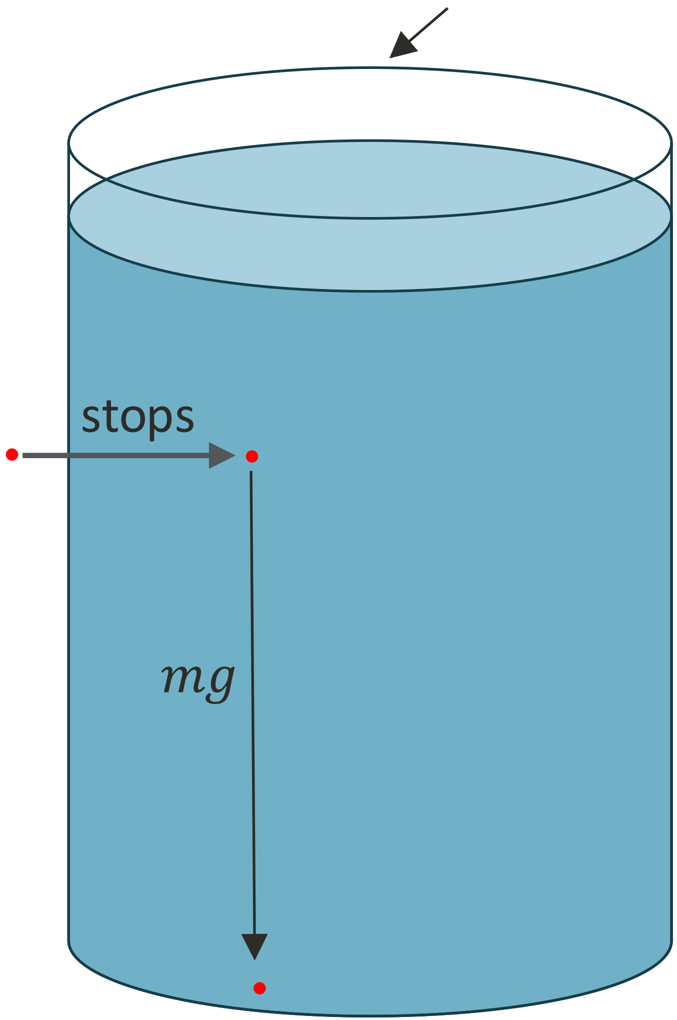
Target 3: Custom-Built Water Pool



- Build a large-volume (10^8 L) water pool directly above ATLAS.
- The large volume makes up for the large distance from collision point.
- No need to disrupt regular collider operation.
- Room temperature.

Thermal Suspension

If gluinos sink, just collect the liquid at the bottom of container.

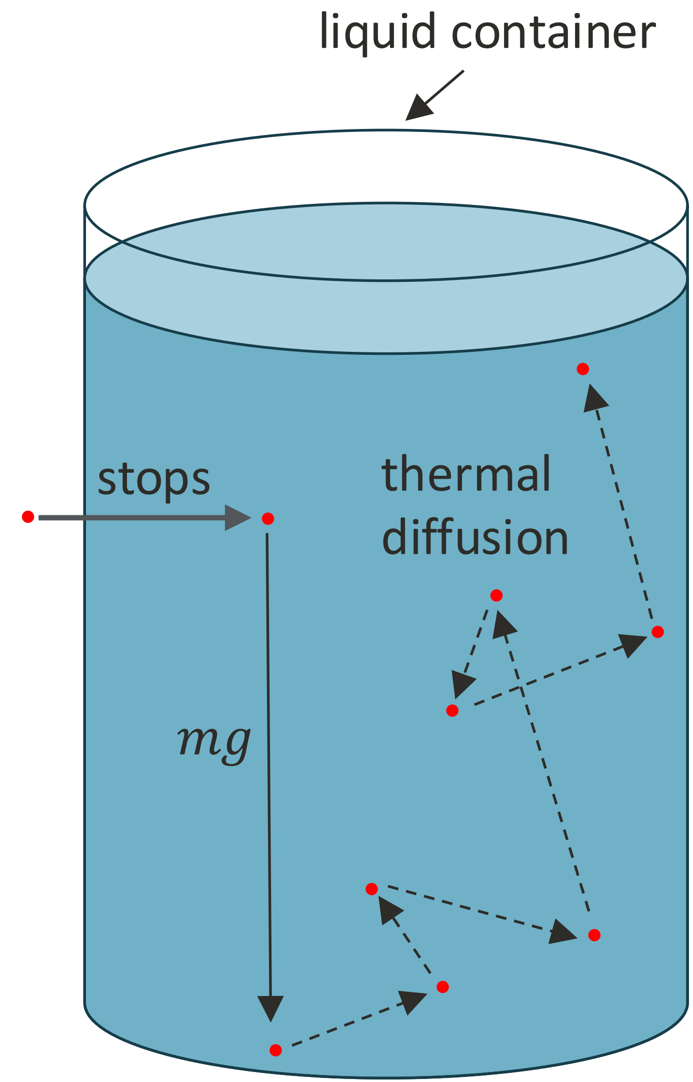


Thermal Suspension

If gluinos sink, just collect the liquid at the bottom of container.

But thermal diffusion kicks it back up.

Boltzmann: $\rho(h) \propto e^{-mgh/T} \equiv e^{-h/h_0}$



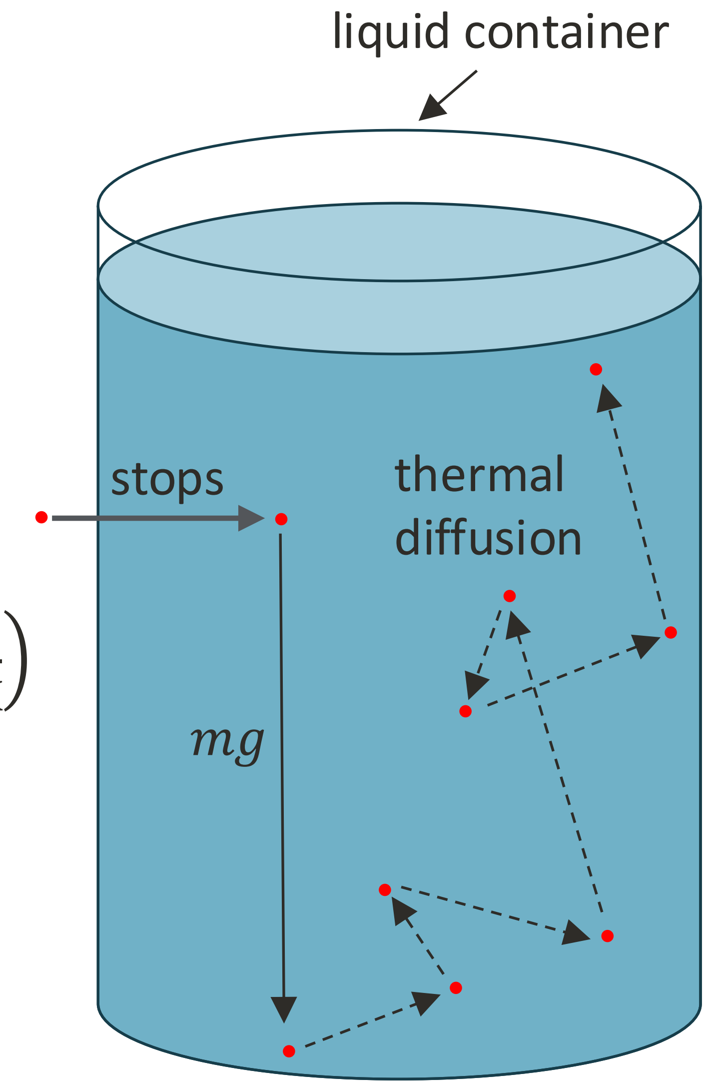
Thermal Suspension

If gluinos sink, just collect the liquid at the bottom of container.

But thermal diffusion kicks it back up.

Boltzmann: $\rho(h) \propto e^{-mgh/T} \equiv e^{-h/h_0}$

Scale height: $h_0 = \frac{T}{mg} = 80\ \mathrm{m}\left(\frac{3\ \mathrm{TeV}}{m}\right)\left(\frac{T}{300\ \mathrm{K}}\right)$



Thermal Suspension

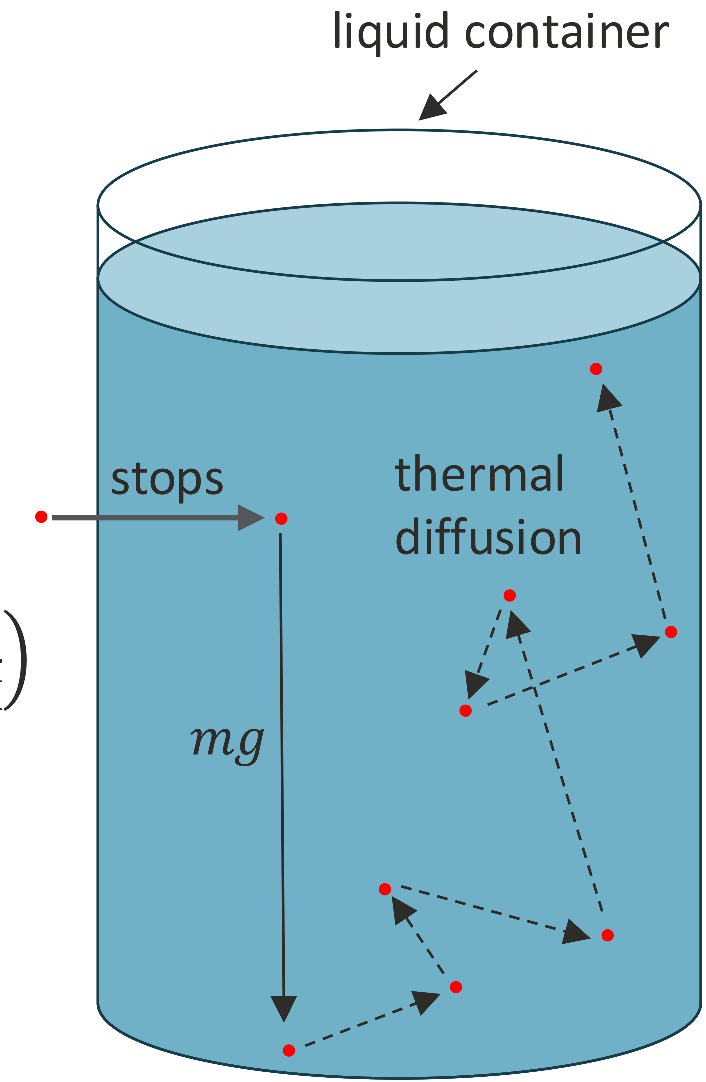
If gluinos sink, just collect the liquid at the bottom of container.

But thermal diffusion kicks it back up.

Boltzmann: $\rho(h) \propto e^{-mgh/T} \equiv e^{-h/h_0}$

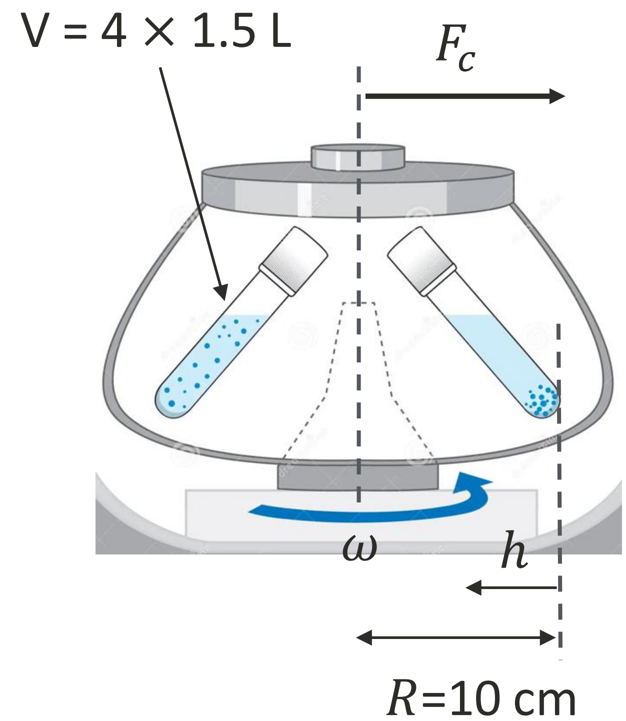
Scale height: $h_0 = \frac{T}{mg} = 80\ \mathrm{m} \left(\frac{3\ \mathrm{TeV}}{m}\right)\left(\frac{T}{300\ \mathrm{K}}\right)$

Bad news: we need to process the entire liquid volume, up to 10^8 L!



Centrifuge

Centrifugal acceleration drives heavier particles outward in a centrifuge.



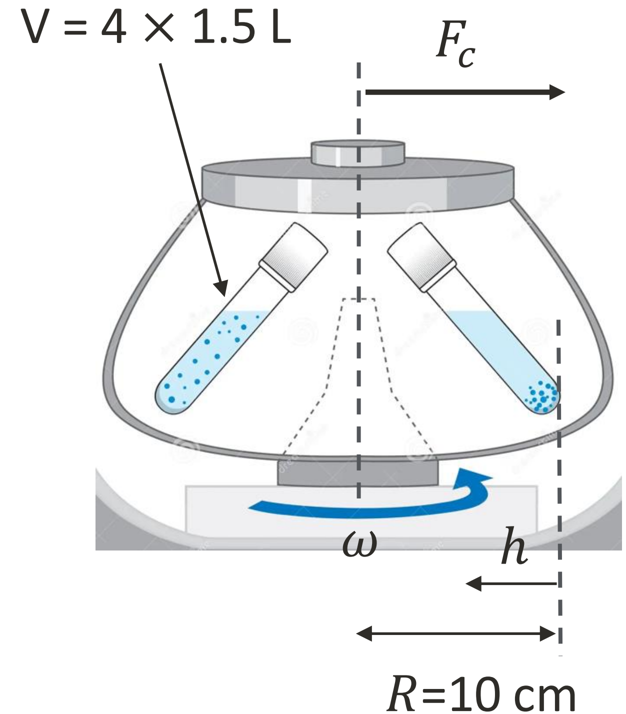
[Reference model: Eppendorf CR30NX]

Centrifuge

Centrifugal acceleration drives heavier particles outward in a centrifuge.

Takes 40 s to reach maximum acceleration:

$$g_{\mathrm{eff}} = \omega^2 R = 10^5 g.$$



[Reference model: Eppendorf CR30NX]

Centrifuge

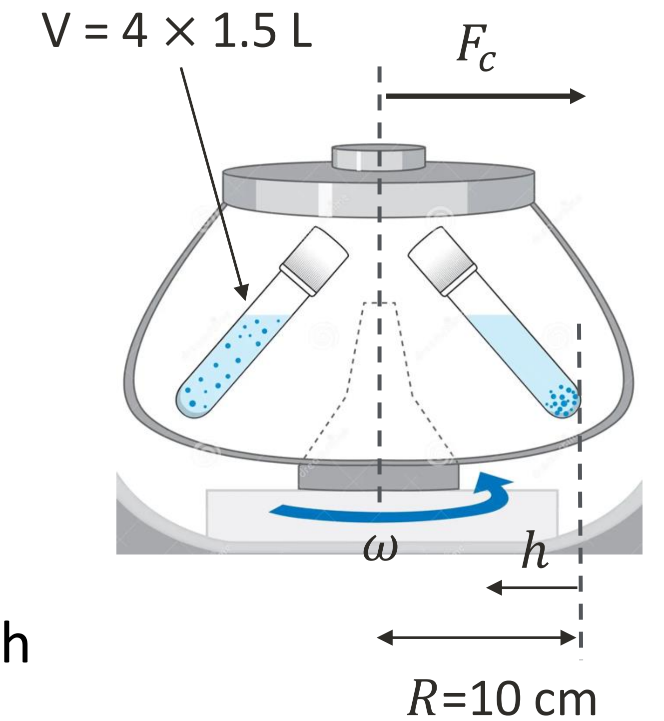
Centrifugal acceleration drives heavier particles outward in a centrifuge.

Takes 40 s to reach maximum acceleration:

$$g_{\mathrm{eff}} = \omega^2 R = 10^5 g.$$

Calculated bias random walk (Drude model) with ballistic motion

→ 100 s for gluinos to reach equilibrium



[Reference model: Eppendorf CR30NX]

Centrifuge

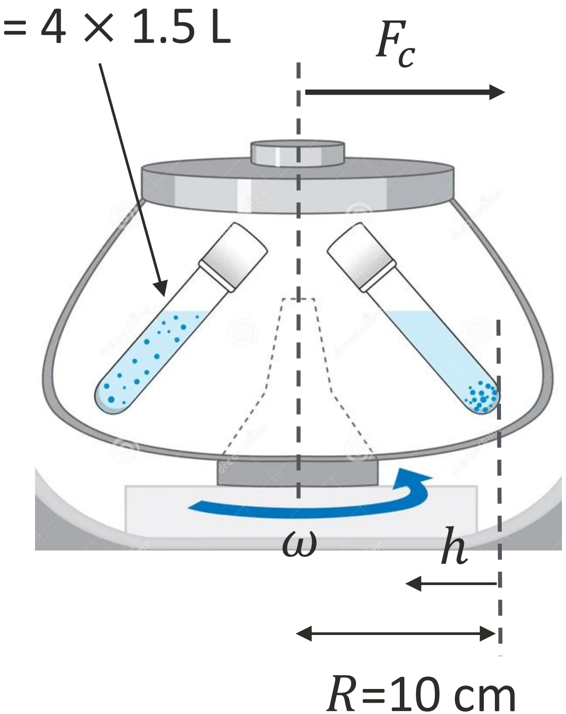
Centrifugal acceleration drives heavier particles outward in a centrifuge.

Takes 40 s to reach maximum acceleration:

$$g_{\text{eff}} = \omega^2 R = 10^5 g.$$

Calculated bias random walk (Drude model) with ballistic motion

→ 100 s for gluinos to reach equilibrium



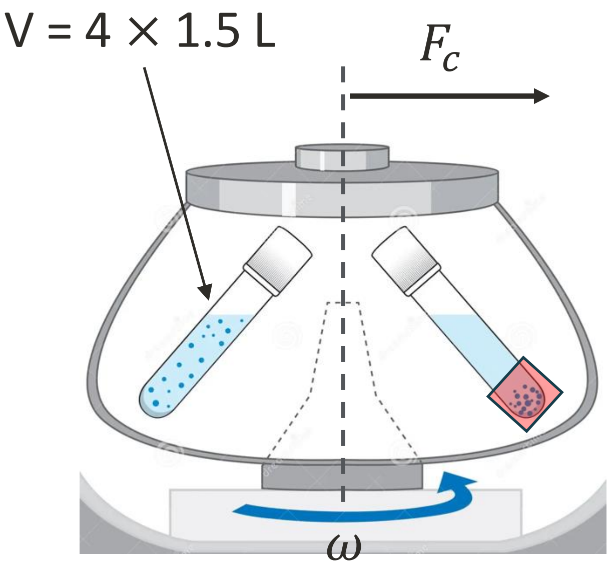
[Reference model: Eppendorf CR30NX]

Boltzmann: $\rho(h) \propto e^{-m g_{\text{eff}} h/T} \equiv e^{-h/h_0}$

Scale height: $h_0 = \frac{T}{m g_{\text{eff}}} = 0.8\,\text{mm}\left(\frac{3\,\text{TeV}}{m}\right)\left(\frac{T}{300\,\text{K}}\right)$

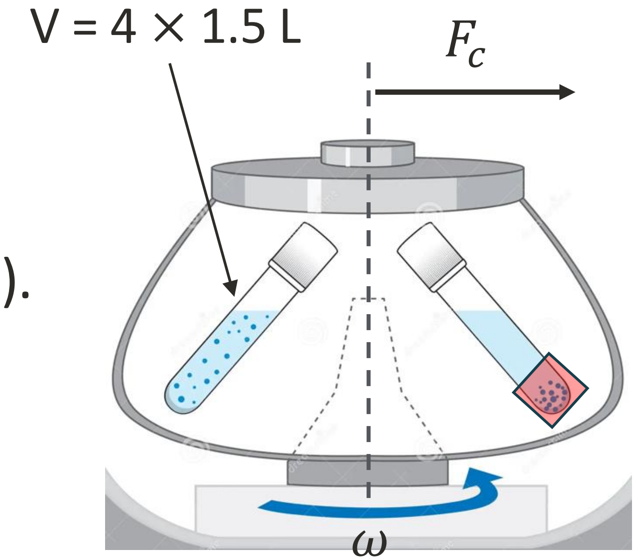
Iterative Centrifugation

- Retain only heaviest 10% of test tube; repeat.

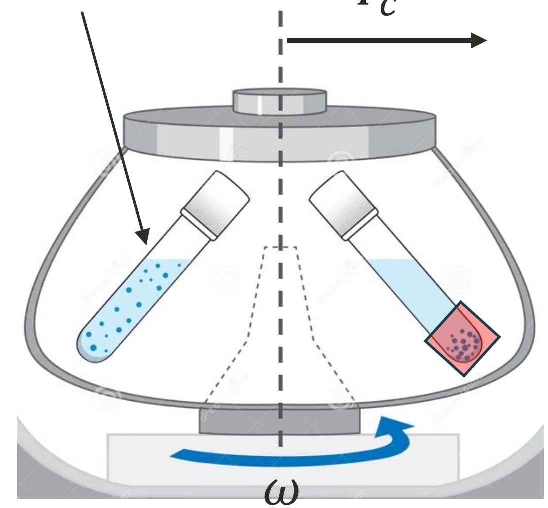


Iterative Centrifugation

- Retain only heaviest 10% of test tube; repeat.
- Most aggressive proposal: 50 centrifuges ($2.5M).



Iterative Centrifugation



- Retain only heaviest 10% of test tube; repeat.
- Most aggressive proposal: 50 centrifuges ($2.5M).

- About a year for first cycle:

$$t = 430 \text{ days} \left(\frac{50}{N_{\text{cen}}}\right)\left(\frac{6\text{ L}}{V_{\text{cen}}}\right)\left(\frac{V_{\text{sample}}}{0.8\times 10^{8}\text{L}}\right)\left(\frac{t_a+t_{eq}}{140\text{ s}}\right)$$

Iterative Centrifugation

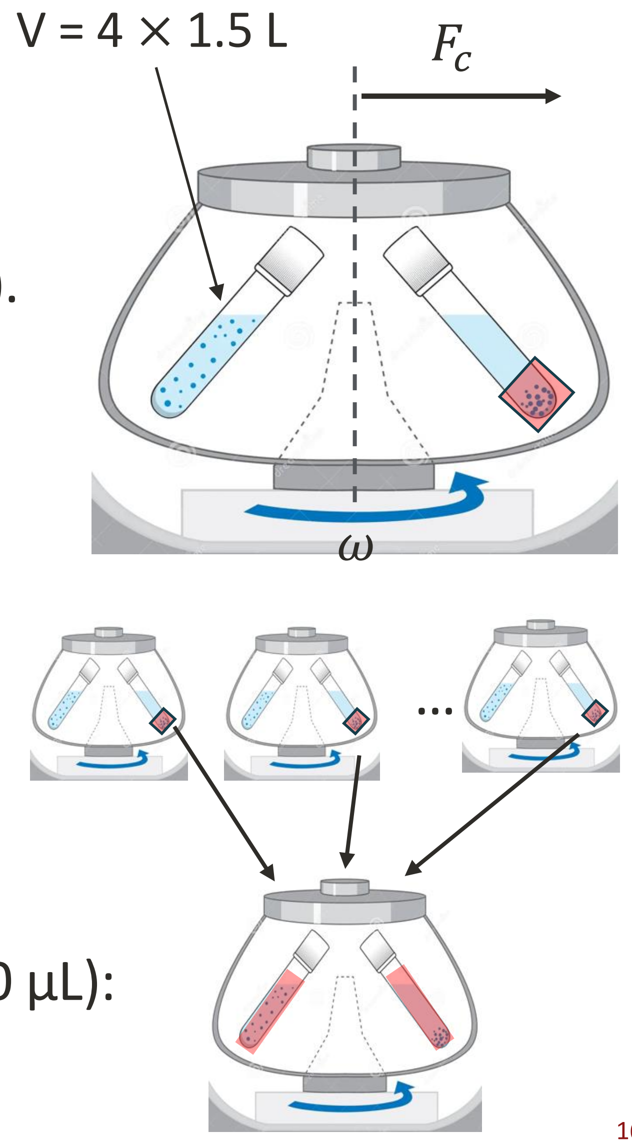
- Retain only heaviest 10% of test tube; repeat.
- Most aggressive proposal: 50 centrifuges ($2.5M).

- About a year for first cycle:

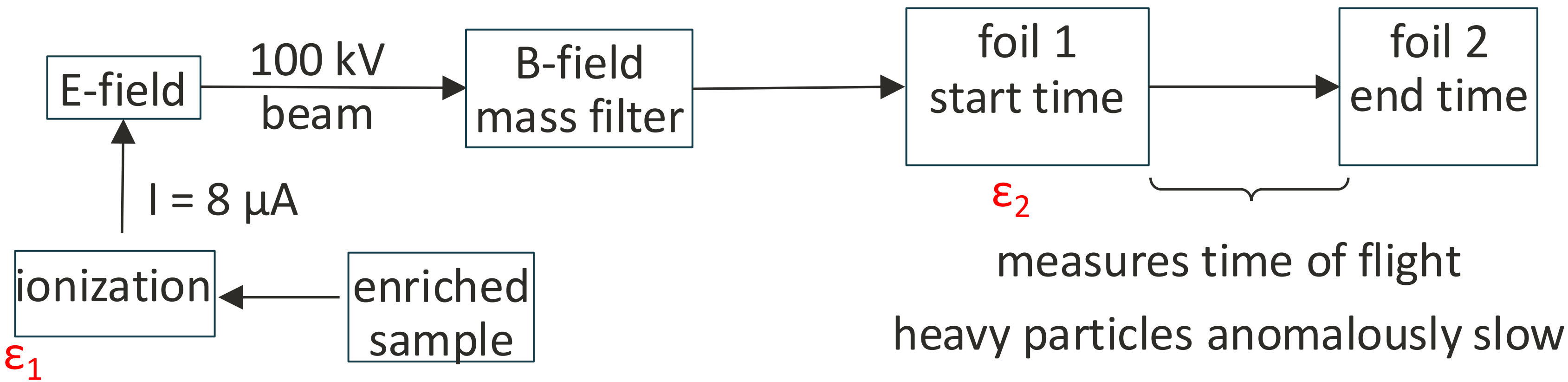
$$t = 430 \text{ days} \left(\frac{50}{N_{\text{cen}}}\right)\left(\frac{6\text{ L}}{V_{\text{cen}}}\right)\left(\frac{V_{\text{sample}}}{0.8\times10^{8}\text{L}}\right)\left(\frac{t_a+t_{eq}}{140\text{ s}}\right)$$

- Geometric series: time for subsequent cycles negligible (1 + 0.1 + 0.01 + …).
- Limited by smallest cut on smallest test tube (100 μL):

1 mm → 1 μL

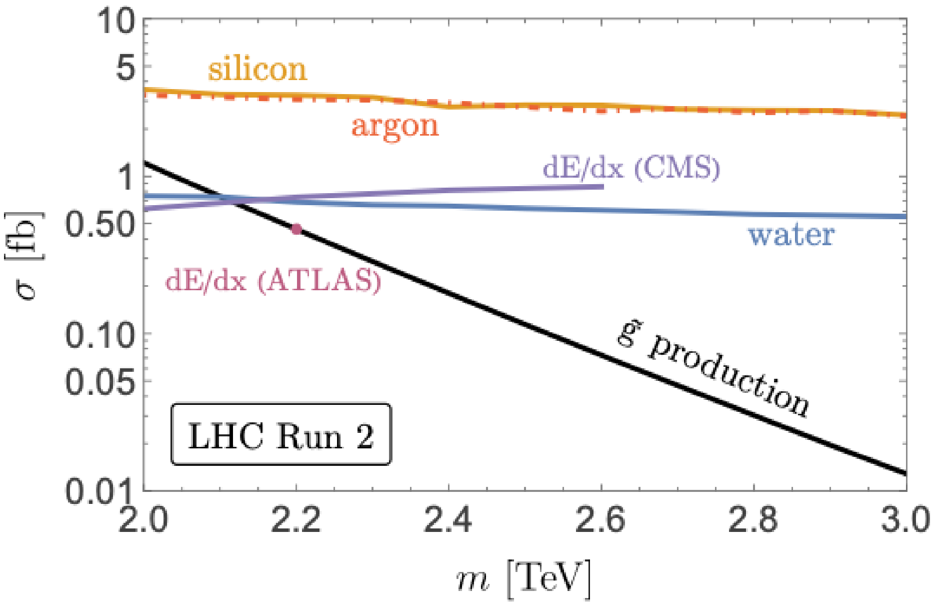


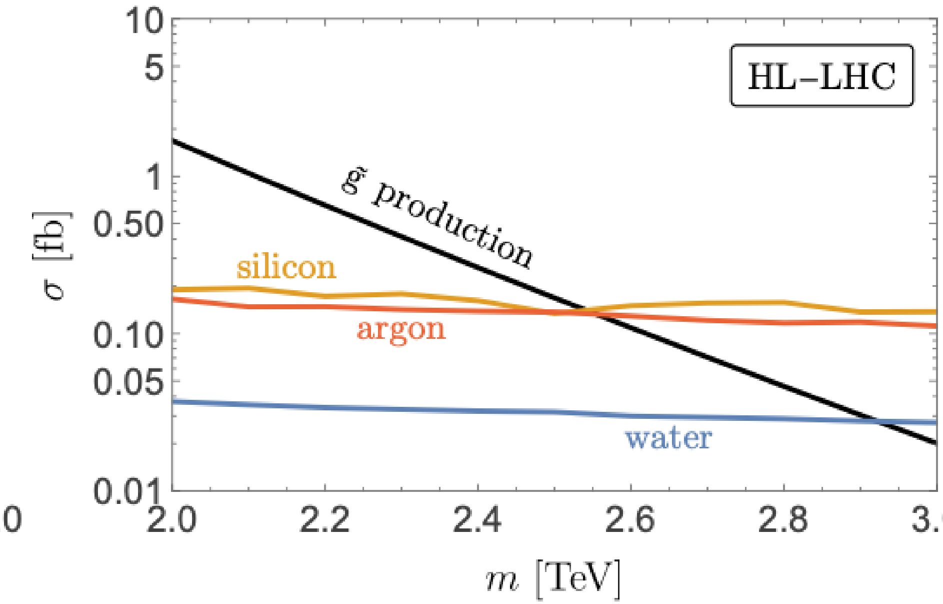
Time-of-Flight Mass Spectrometry



- Performed on natural water in 1980s [Smith et. al., Nucl. Phys. B 206, 333 (1982)].
- Efficiency limited by ionization $\varepsilon_1 = 10^{-2}$ and detection $\varepsilon_2 = 10^{-3}$, various ways to improve these (e.g. recycling unionized gas, microchannel plate).
- Takes about 1 week to process a 1 μL volume.

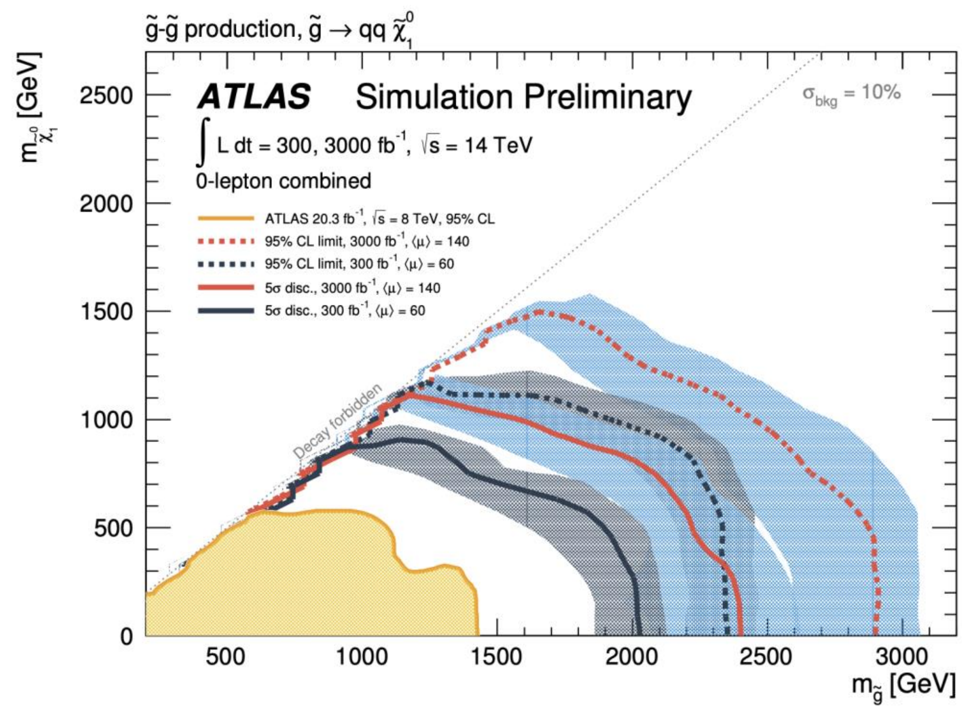
Projected Limits (95% CL)





5σ Discovery Reach

- Discovery threshold of 5σ usually trails 95% (≈ 2σ) exclusion limit by a lot.
- But if we find even a single heavy ion, we can isolate the heavy particle and run further tests, arbitrarily increasing statistical significance!
- Our exclusion limit rivals those of prompt decay searches, and have the best discovery reach in gluino mass.



[ATLAS, ATL-PHYS-PUB-2014-010]

Summary

- Long-lived particles with lifetimes of years or longer could stop in detector materials and be recovered.
- Proposed a background-free experiment that fully benefits from the higher luminosity of HL-LHC.
- Competitive with existing dE/dx searches and potentially world leading, especially discovery reach.
- Motivates further study of this method as well as improving background discrimination of dE/dx searches.

Thank You