Detecting Long-Lived Particles Trapped in Detector Material

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Jan Kieseler[1], **Juliette Alimena**[1], Jasmine Simms[1,2], Thea Aarrestad[1,3], Maurizio Pierini[1], Alexander Kish[4]
[1]CERN, [2]Oxford, [3]ETH Zurich, [4]Fermilab

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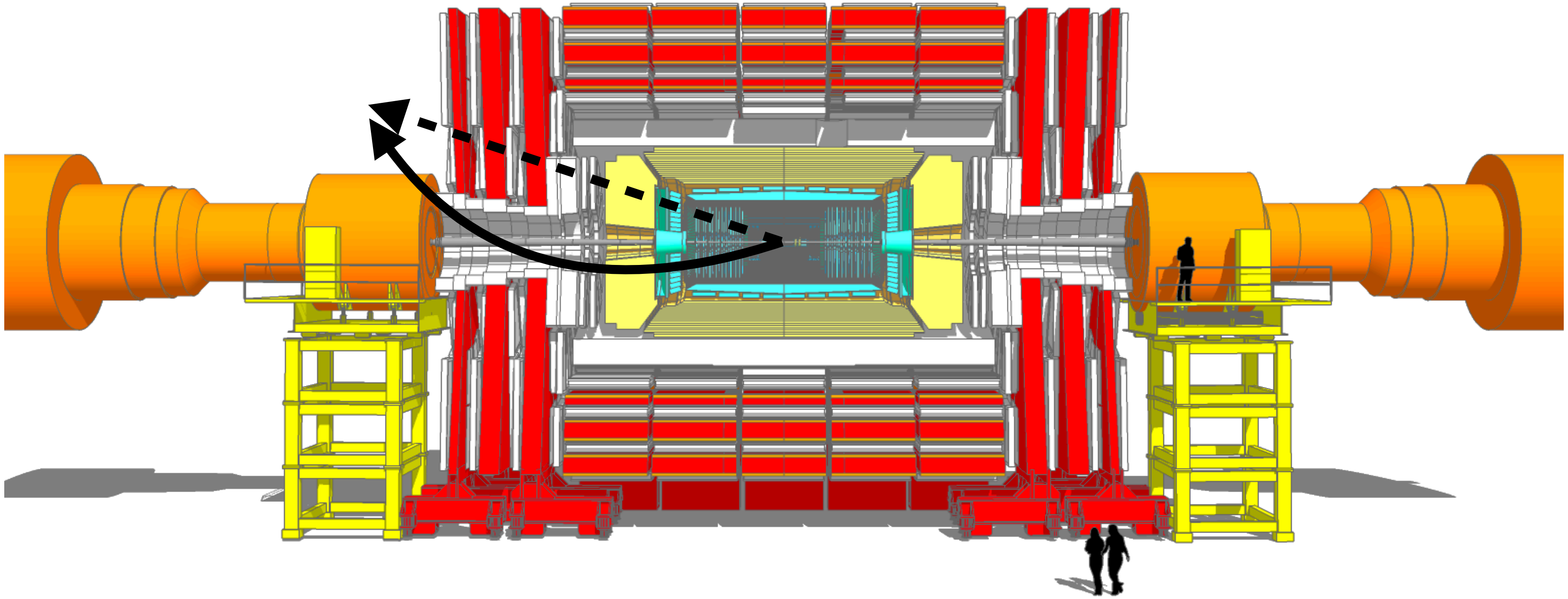
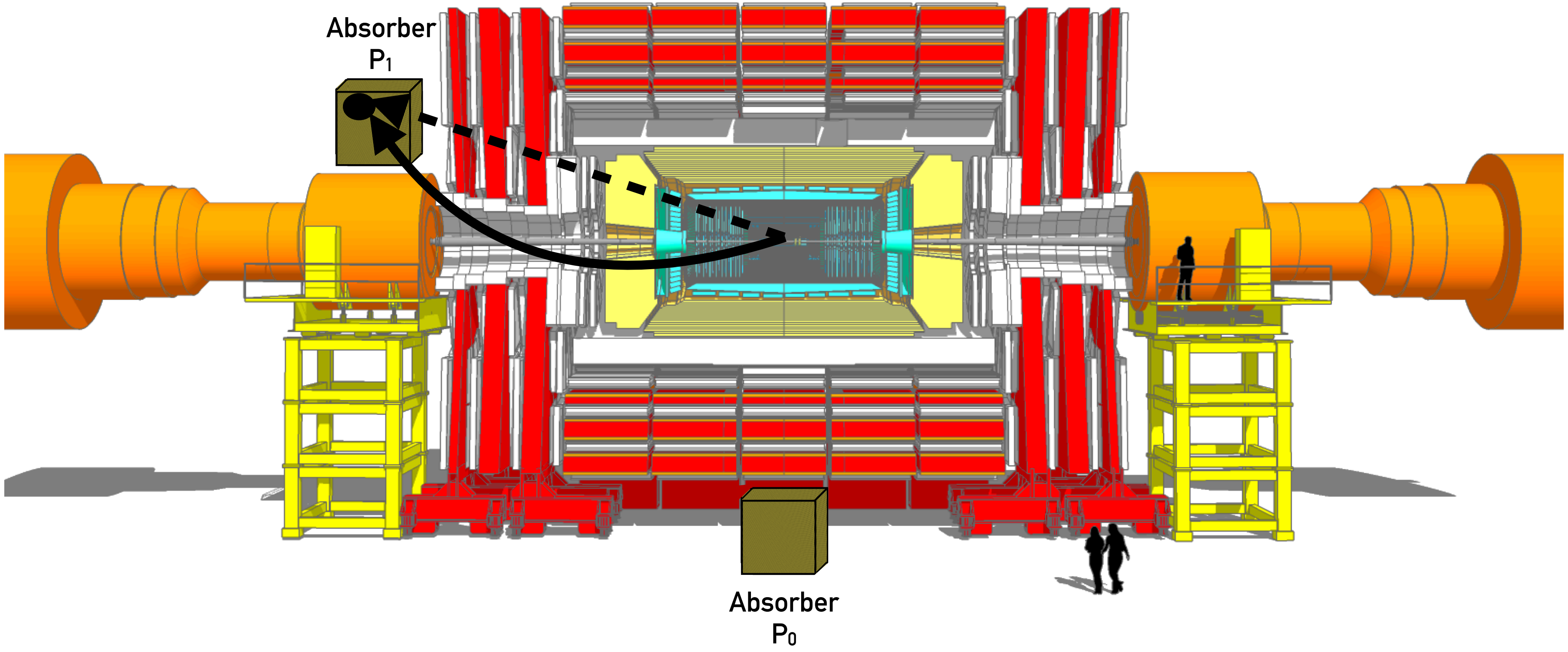
Looking for Long-Lived Particles at the LHC

- Charged or neutral **long-lived particle (LLP)** is produced from an LHC collision, and then **travels all the way through**, say, the CMS detector
- Can have a **unique signature**:
  - Large energy loss (through ionization or nuclear interactions)
  - Slow-moving (large time-of-flight)
- If mass $\gtrsim$ 100 GeV, will be fairly central, but if mass is more like 10's of GeV, could be more forward



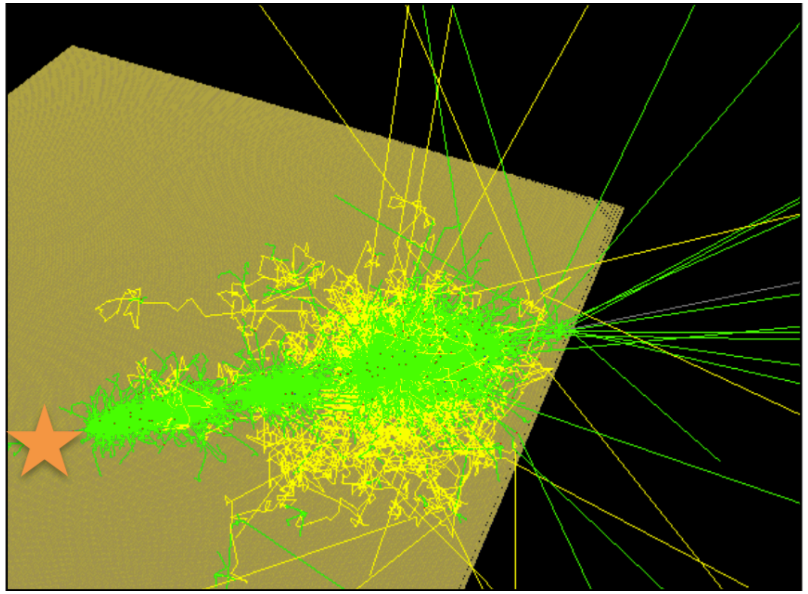
Stage 1: Trap the LLP

- LLP could come **to a stop in an absorber** made of a movable, dense material
- Could even move absorber to another position to target different LLP mass ranges
- Leave it in the LHC cavern for a few weeks or up to ~a year



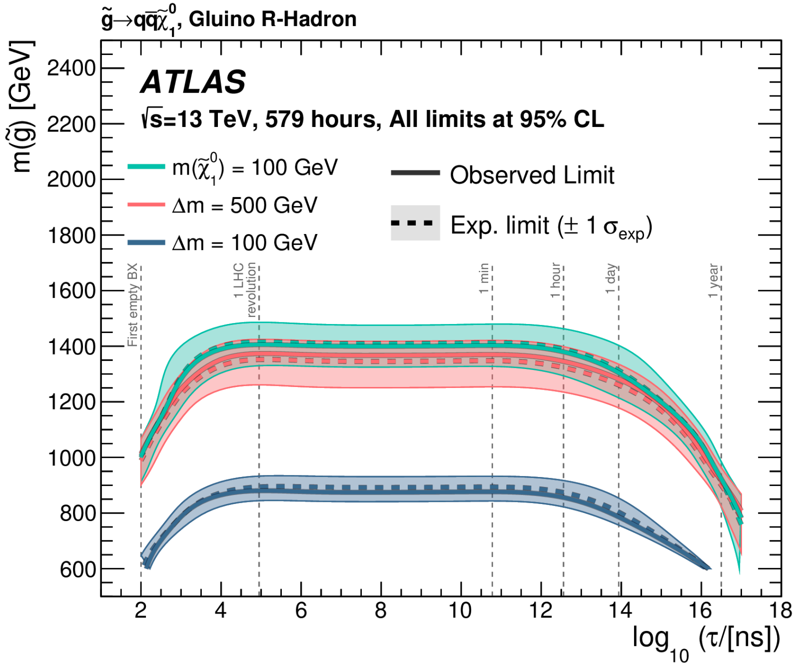
Stage 2: Detect LLP Decay

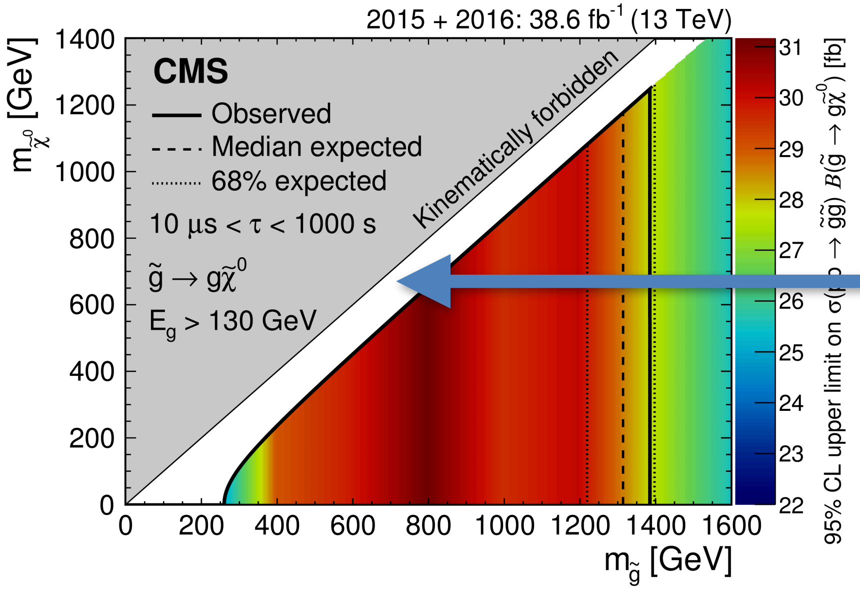
- Stopped LLP could decay to SM + BSM particles, leaving a **calorimeter signature**
- If stopped particle lifetime was long, decay could occur significantly after the stopped particle was absorbed
- Remove absorber from LHC cavern, then **detect decay in quiet environment**
  - Fewer sources of background
  - Avoids the need for a trigger - can target lower mass!
- **Target: long lifetimes (~days or longer), low energy (3-100 GeV) SM decay products (compressed spectra)**



Previous Searches at ATLAS and CMS

- Both CMS and ATLAS have performed several searches for particles that stop in the detectors and then decay later
  - Most recent CMS: 10.1007/JHEP05(2018)127
  - Most recent ATLAS: 10.1007/JHEP07(2021)173
- Benchmark model: **gluino R-hadrons in split SUSY**
- Both experiments set cross section and mass limits for lifetimes between **100 ns and ~days/1 year,** $\Delta m \gtrsim 100$ GeV





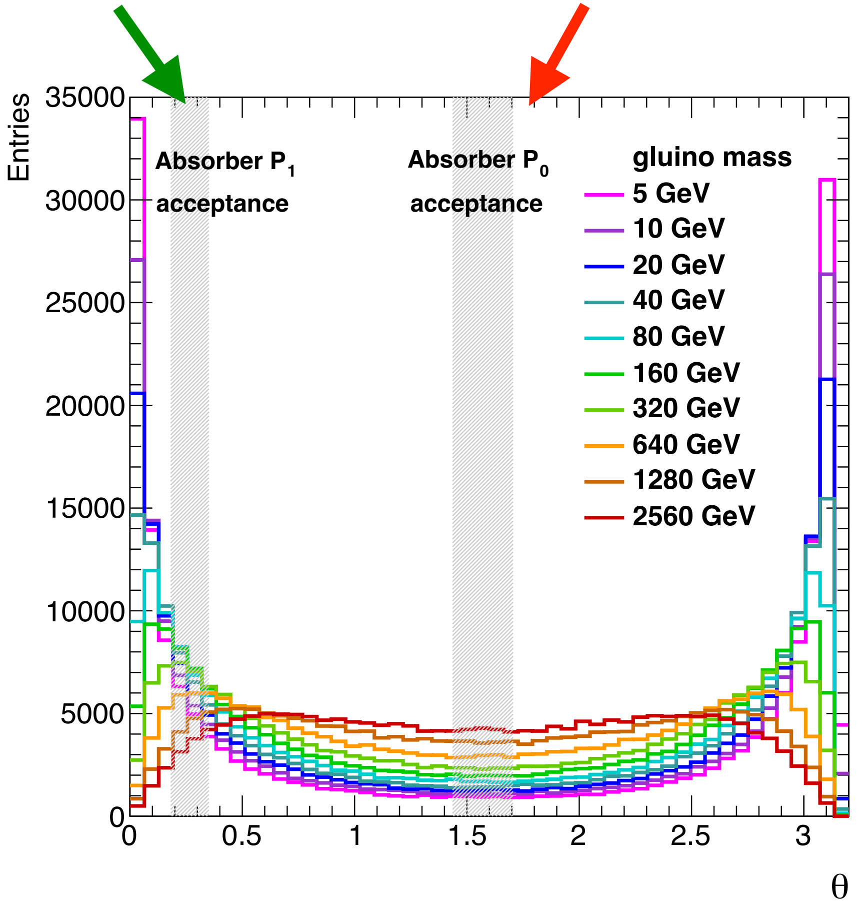
No trigger needed for new detection method, so could have **unique sensitivity in this white band**

Benchmark Model and Acceptance

- Benchmark case inspired by split SUSY: produce a pair of gluinos ($\tilde{g}$) with long lifetimes
- SUSY must be broken at a scale much higher than the weak scale
    - Squarks can be quite massive
    - Gluino becomes long-lived due to large mass difference between them and squarks, which mediate their decay
- Generate gluinos and their R-hadrons in PYTHIA8 to obtain the kinematic acceptance

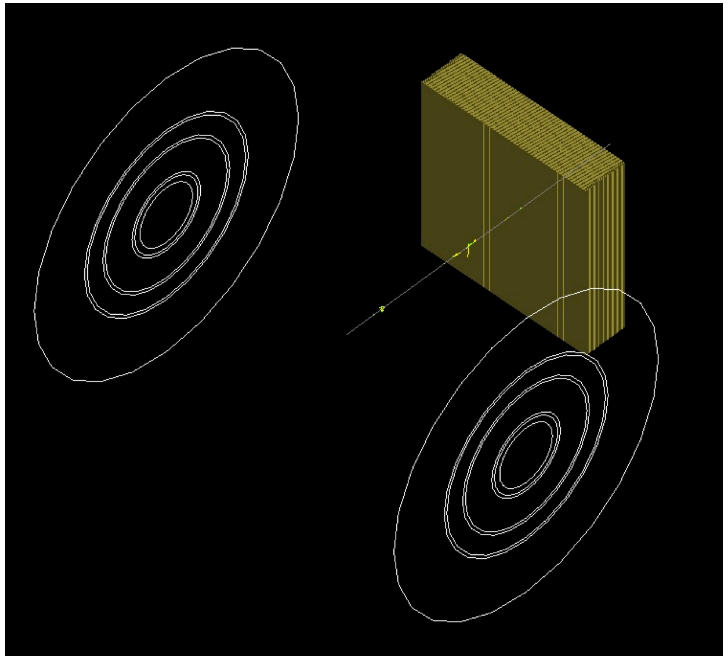
Best acceptance for **small mass** gluinos when the absorber is in a **forward** position

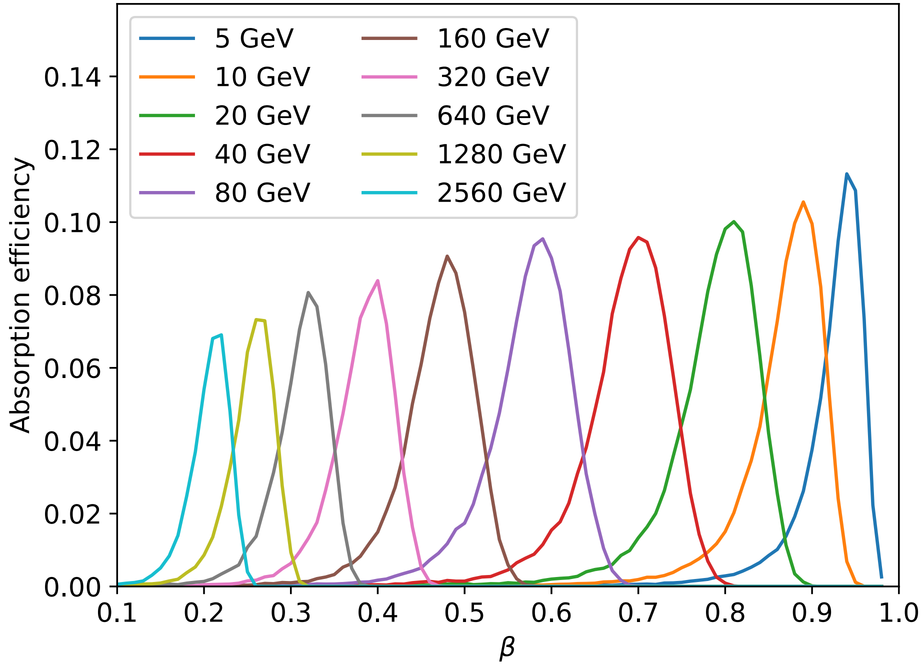
Best acceptance for **large mass** gluinos when the absorber is in a **central** position



Absorption

- We then simulate neutral R-hadrons that travel through an approximation of the CMS material and hit a brass absorber in GEANT4
- Choose absorber made of brass because high density, relatively cheap, reusable in/from (hadronic) calorimeters
- Choose 2 x 2 x 2 m absorber
- Absorption depends on velocity ($\beta = v/c$), mass, and depth

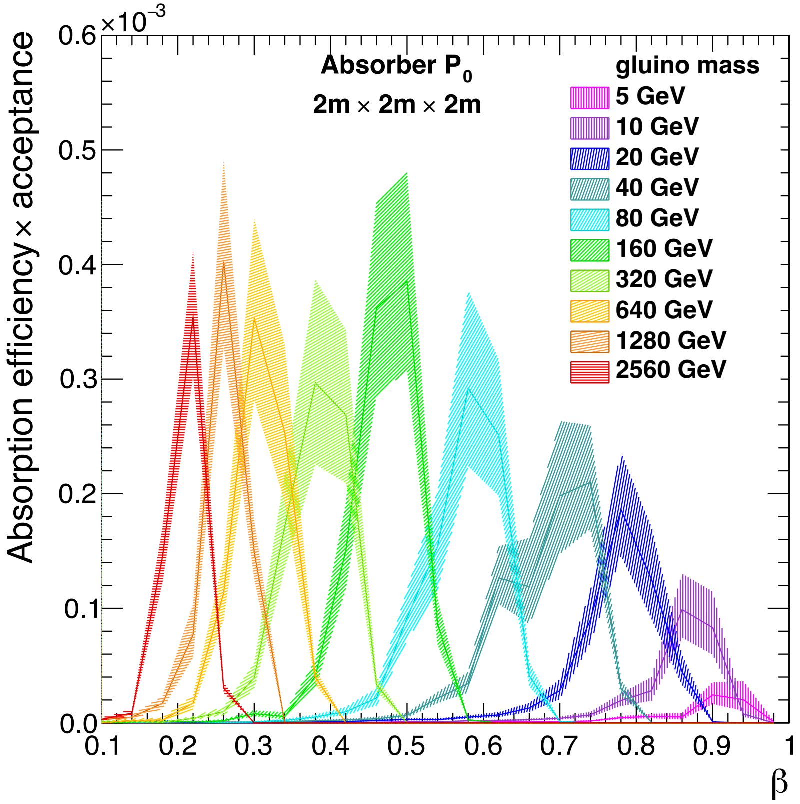




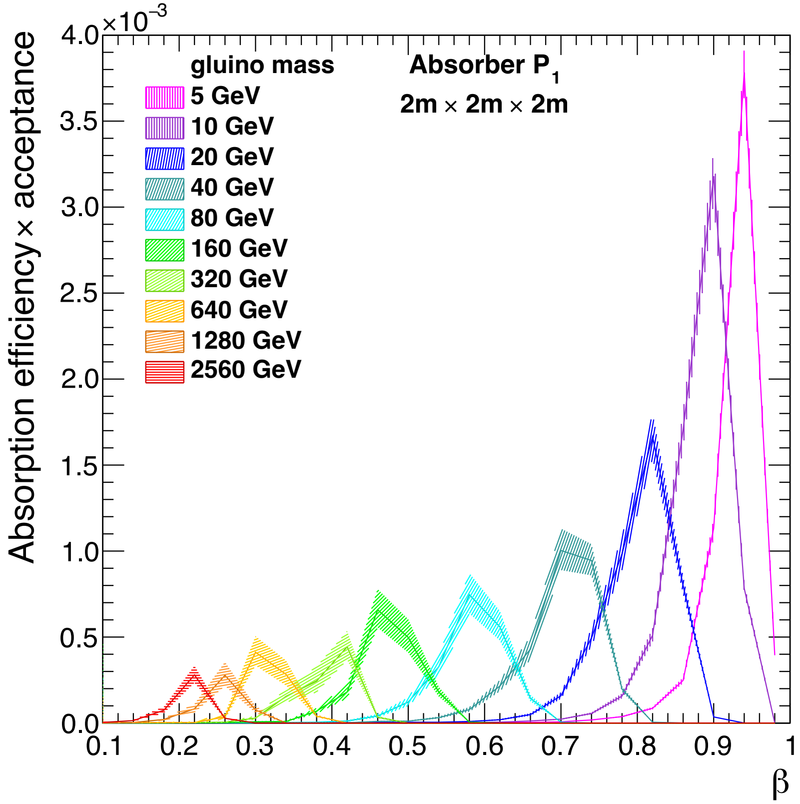
Total Trapping Efficiency

- Convolve R-hadron angular acceptance with the absorption efficiency to get the total efficiency times acceptance
- Total trapping efficiency between 0.1 and 1%, depending on particle mass and absorber position

Central absorber



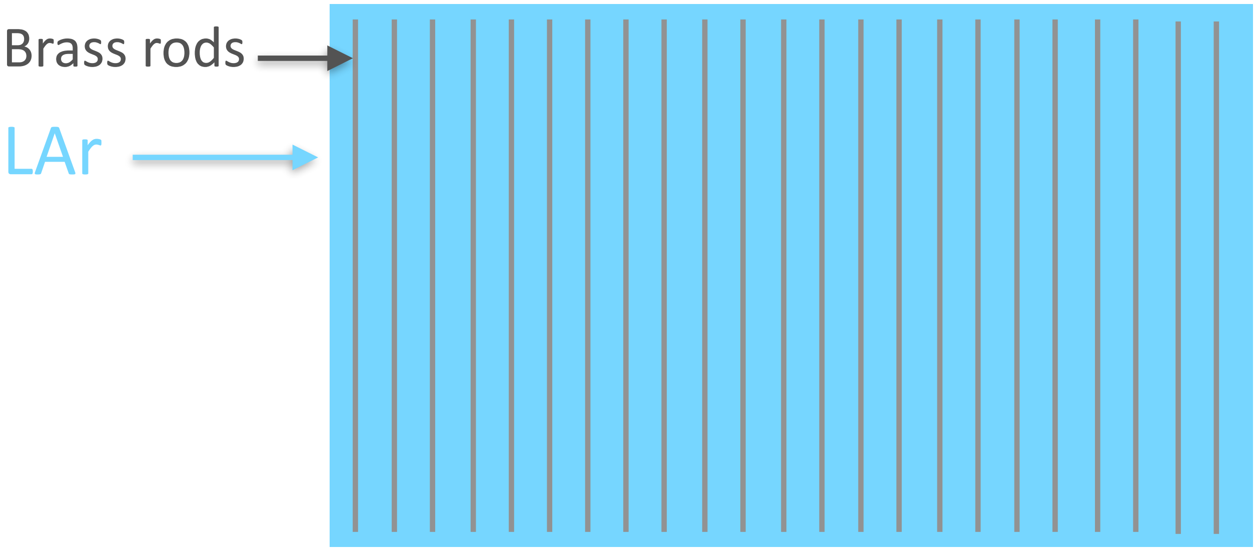
Forward absorber



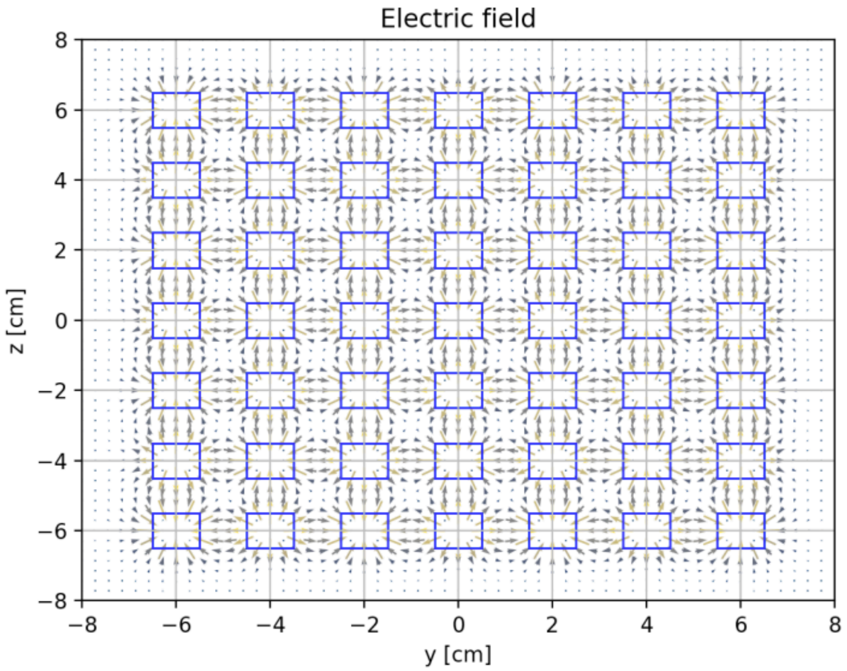
Detection Setup

1. Take the absorber apart
   - Separate the 1 cm x 1 cm x 2m brass rods
2. Submerge rods into liquid argon (LAr), leave 1 cm space between them
3. Apply voltage to each rod and attach readout electronics

Creates LAr calorimeter!



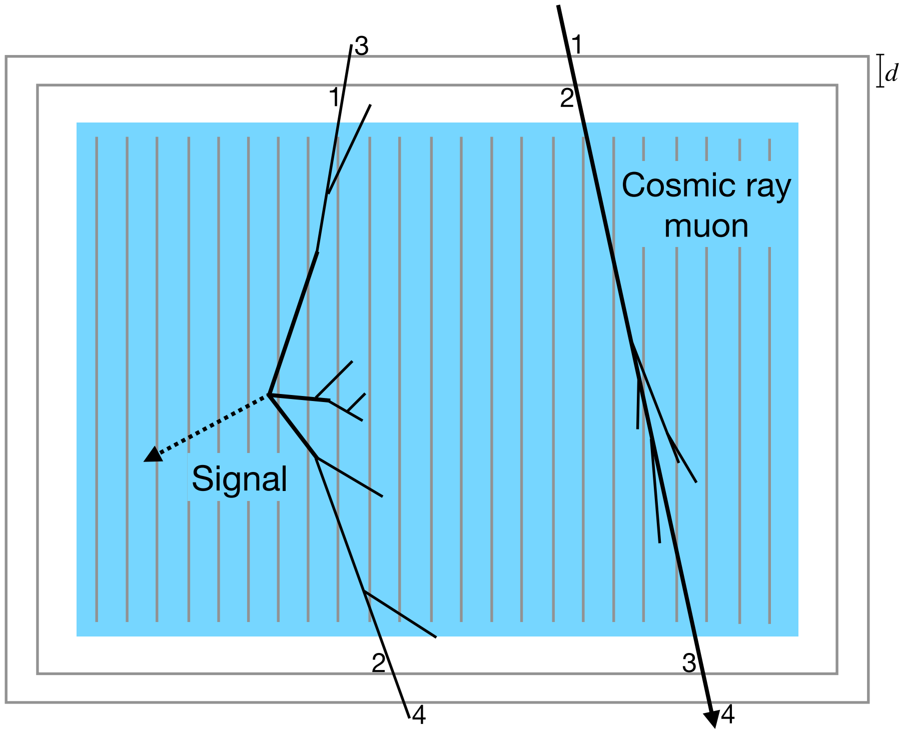
- GEANT4 simulation shows that particles with energy > 100 MeV escape the rods
- Therefore, SM decay products with **energy > 3 GeV can easily be detected** by this setup



Cosmic Muon Background

- If we put this LAr calorimeter detector in a quiet environment, most relevant background will be from cosmic rays
- Shielding can reject everything but **muons from cosmic rays**
- Cosmic ray muons can mimic the signal
- To reject this cosmic background, will add a muon veto system with a fast response, e.g. restive plate chambers (RPCs)

Two layers of RPCs, above and below LAr



Background Estimation

- **To estimate background from cosmic muons:**
  - Take the spectrum of vertical cosmic ray muons at sea level as an upper limit
  - Convolve it with the fraction of energy muons can leave in LAr (from simulation)
  - Integrate the convolved muon spectrum over the momentum, starting from a threshold of $\frac{\Delta m}{2}$
  - **Expected background** = assume RPC efficiency * integral
- In the future, background estimation can also be measured from data with unexposed rods (e.g. from twin detector)

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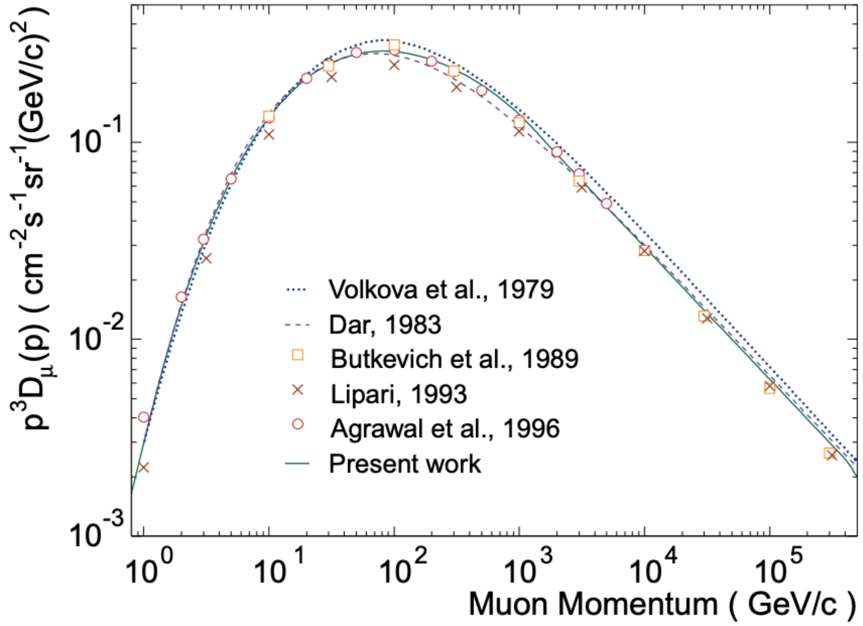
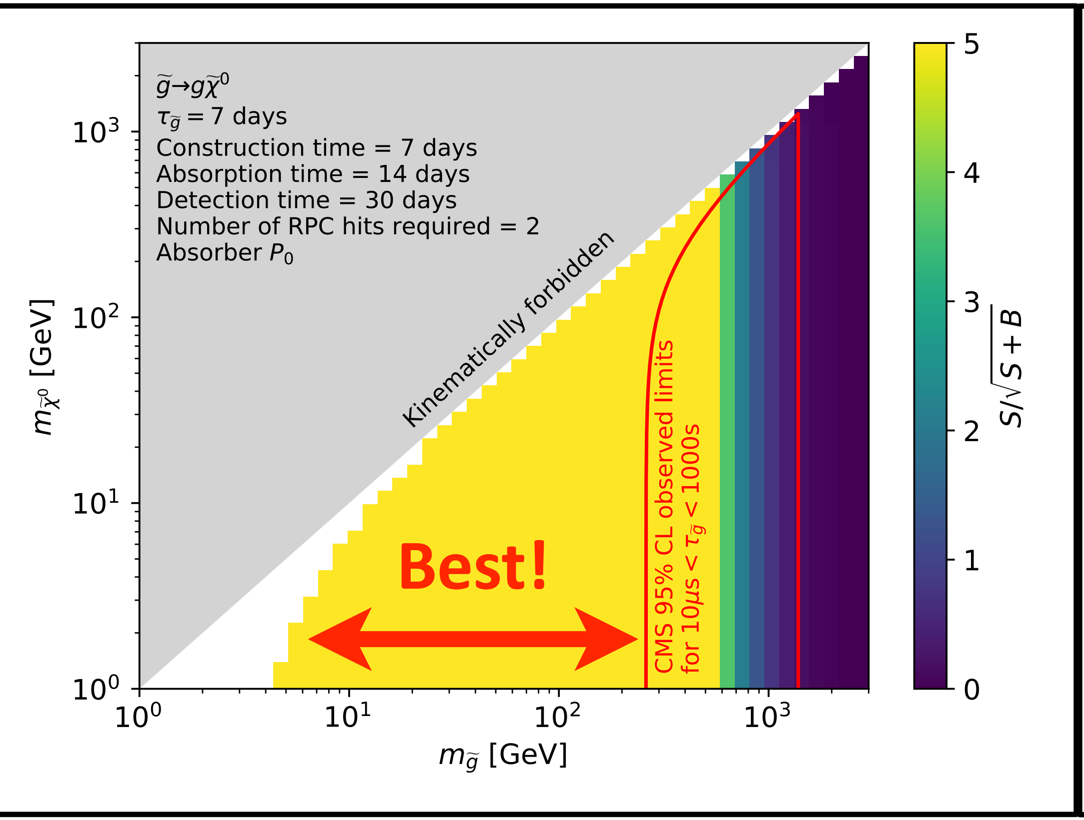
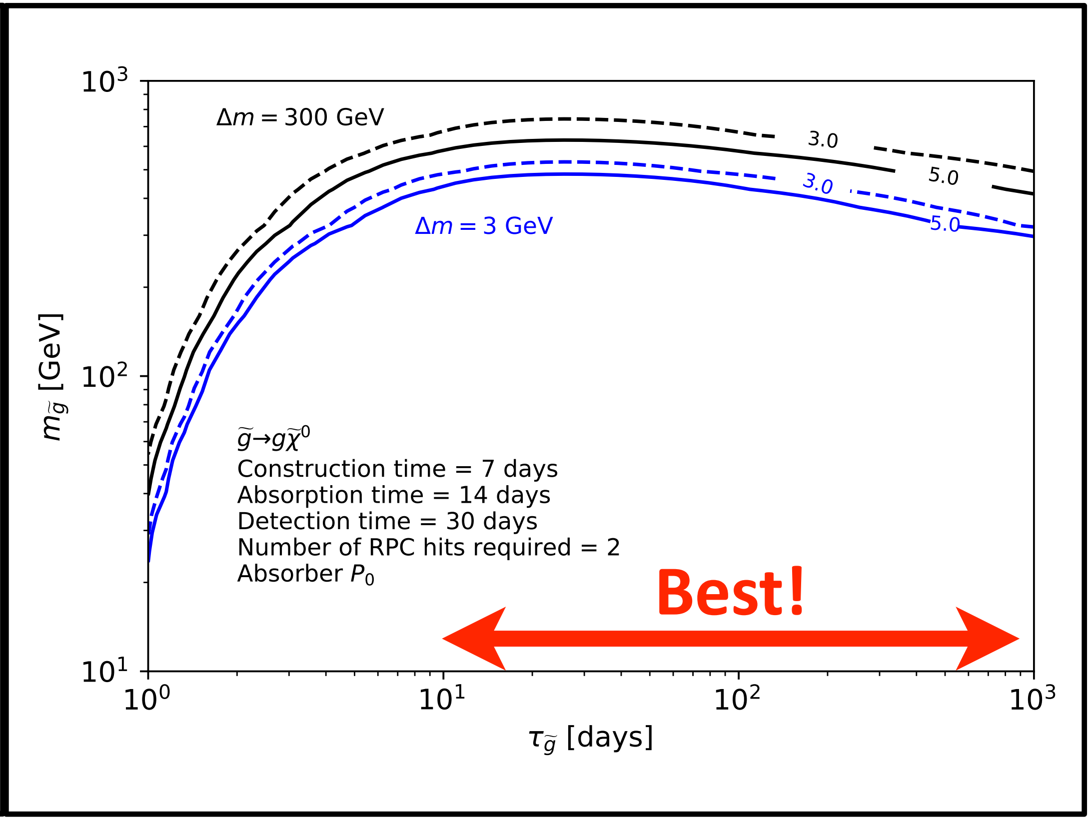
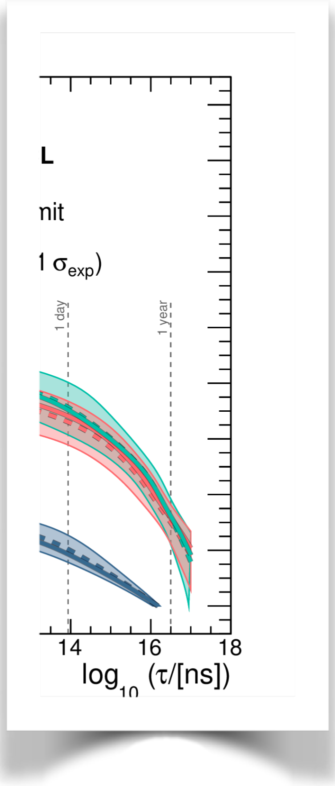


Sensitivity

- We consider gluinos that decay to a jet and a neutralino: $\tilde{g} \rightarrow g\tilde{\chi}^0$
- **Complimentary to ATLAS and CMS, in both mass and lifetime coverage**



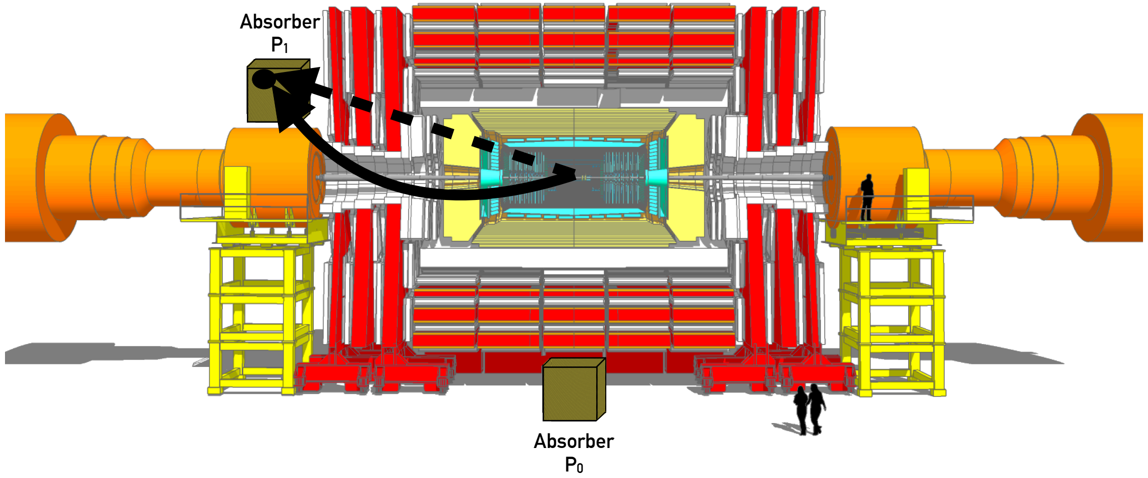




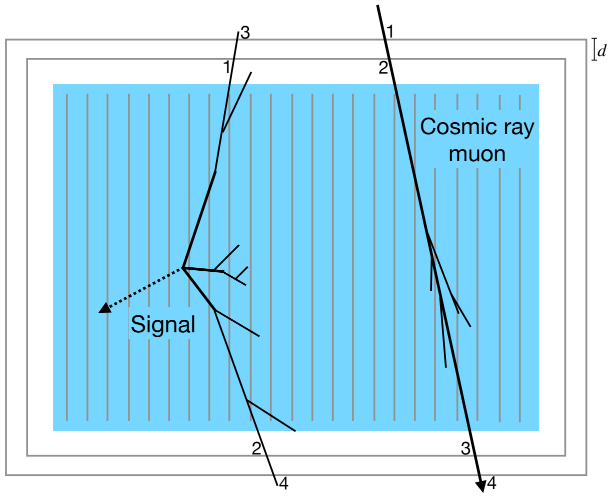
Summary: Why new experiment to search for stopped LLPs?

- **Striking signature** of new physics!
- **Unique sensitivity** with this new 2 stage detection strategy
  - To small mass splitting regime (~3-100 GeV)
  - To lifetimes on the order of days to years
- Possibility of **discovery reach within a few months** of operation
- Relatively low cost (~1M CHF) with opportunities to reuse existing components (e.g. cryostat)

Stage 1: Trap



Stage 2: Detect



Next Steps

- Prospects in discussion with Physics Beyond Colliders group
- R&D has started at Fermilab ("Fermilab Detector R&D New Initiative")
  - Goal: small-scale demonstrator of the detection strategy
  - Optimize electrodes, readout electronics, measure calorimeter response, study energy threshold

Want to build a new detector? Let us know if you want to get involved!