Experimental Exotics

John Paul Chou
Rutgers University

Saturday, February 25th, 2017

RUTGERS
THE STATE UNIVERSITY
OF NEW JERSEY

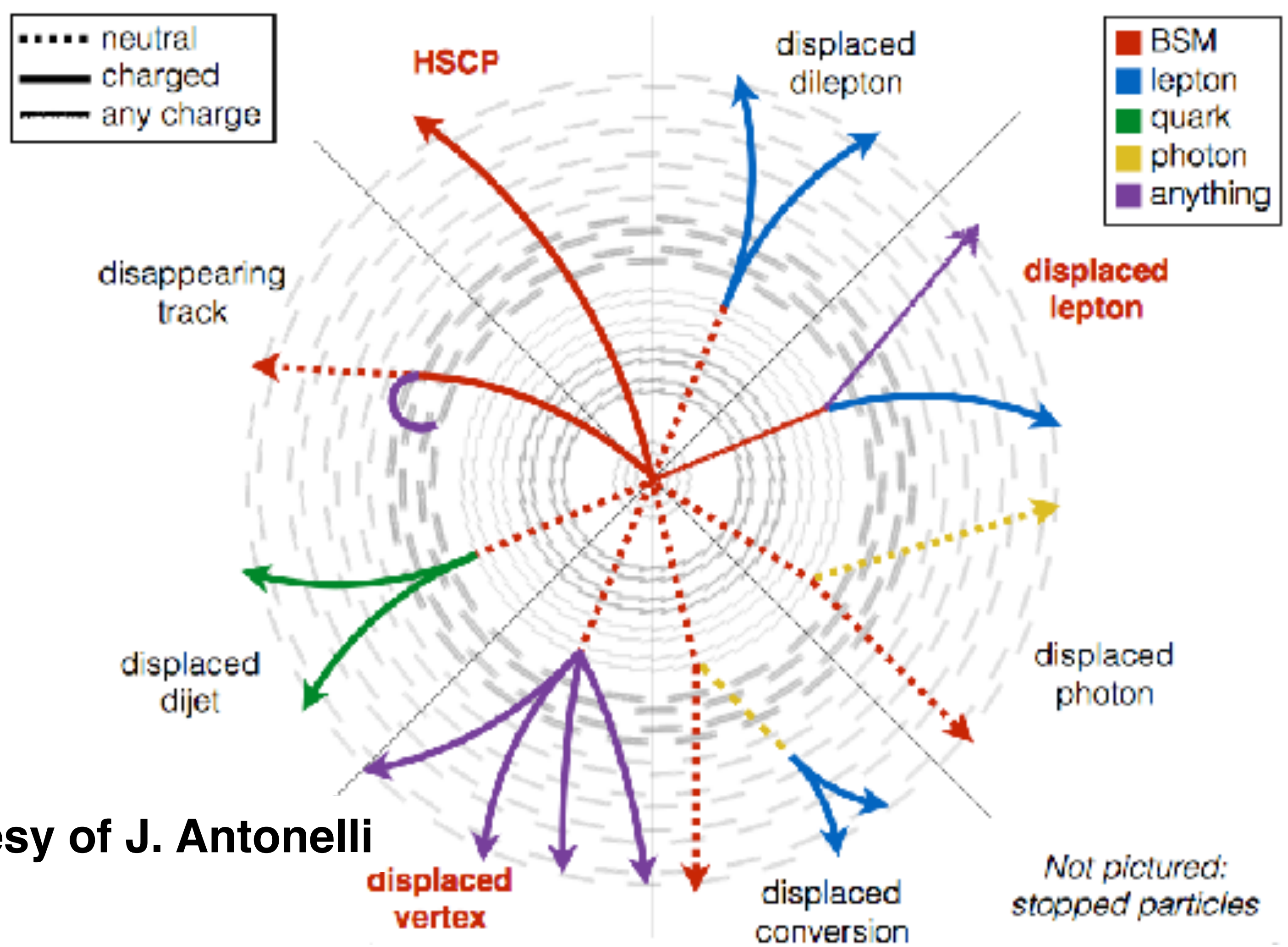
General Motivations

- An easy mistake to make is to assume that unconventional = unmotivated
  - long-lived particles arise naturally in a wide space of plausible models, supersymmetric and otherwise
    - gauge mediation, split, stealth, RPV SUSY, neutral naturalness, dark matter, hidden valleys, etc.
    - long-lived particles arise in solutions to all of the major questions in particle physics today (naturalness, dark matter, flavor, etc.)

- Paucity of evidence for new physics thus far suggests that unconventional signatures are **even more motivated** now than at the start of the LHC

Experimental Landscape

- Large landscape of experimental signatures
  - Not mentioned below: quirks, magnetic monopoles, soft bombs, etc.



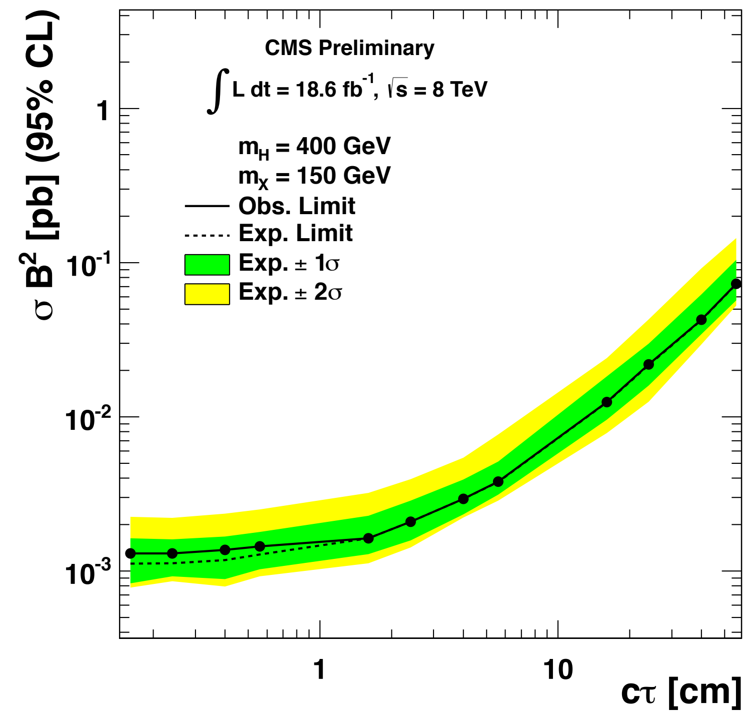
Courtesy of J. Antonelli

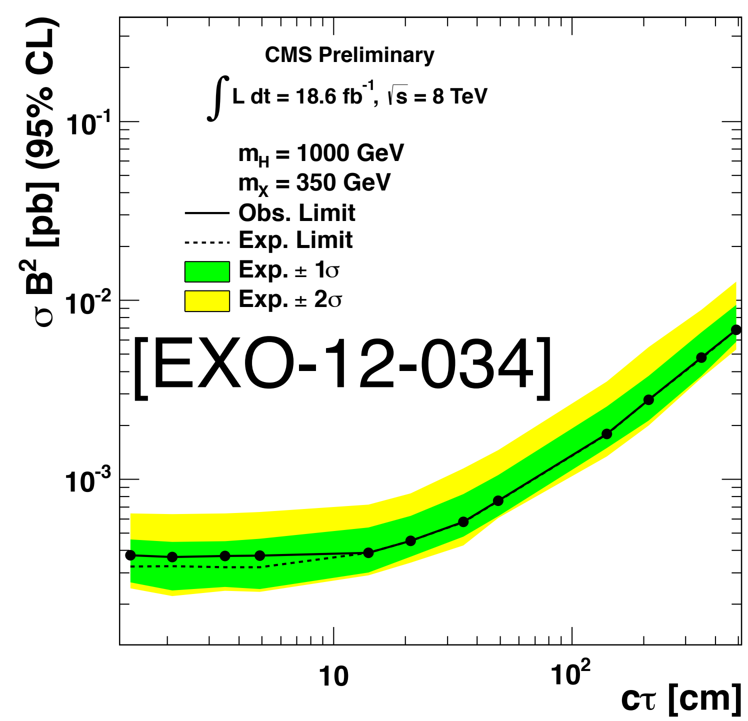
HIGGS PORTAL AS A TARGET

- Unconventional signatures produced through a Higgs boson are **an important target** for searches
  - Many LL searches have relatively low background rates, so going after Higgs production may be difficult but feasible
    - Low production rate (compared to QCD)
    - low p_T make things difficult to trigger
    - various production modes (associated W, Z, VBF, etc.)
- Requires serious thought about **triggers** and background rates
  - Can you trigger on direct production, or do you need to rely on associated production? Even L1 seeds can be constraining
  - Does your reconstruction have sensitivity to low mass, low p_T objects?

Run I Displaced Dijet Search

- Baseline signature
  - H→2X; X→dijets (udscb)
  - where X is long-lived, neutral, spin-0 particle decaying inside the tracker volume
- Selection
  - Scalar sum of the jets transverse momenta H_T > 300 GeV
  - **≥2** jets (p_T>60 GeV, |η| < 2) with small number of prompt tracks and prompt energy fraction
  - both jets reconstruct to a **single, displaced vertex**
    - likelihood discriminant determines quality of the vertex and promptness of the jets
    - cut-and-count strategy w/ ~0 background
- Final result: ~fb xs·BR limits for ~mm cτ





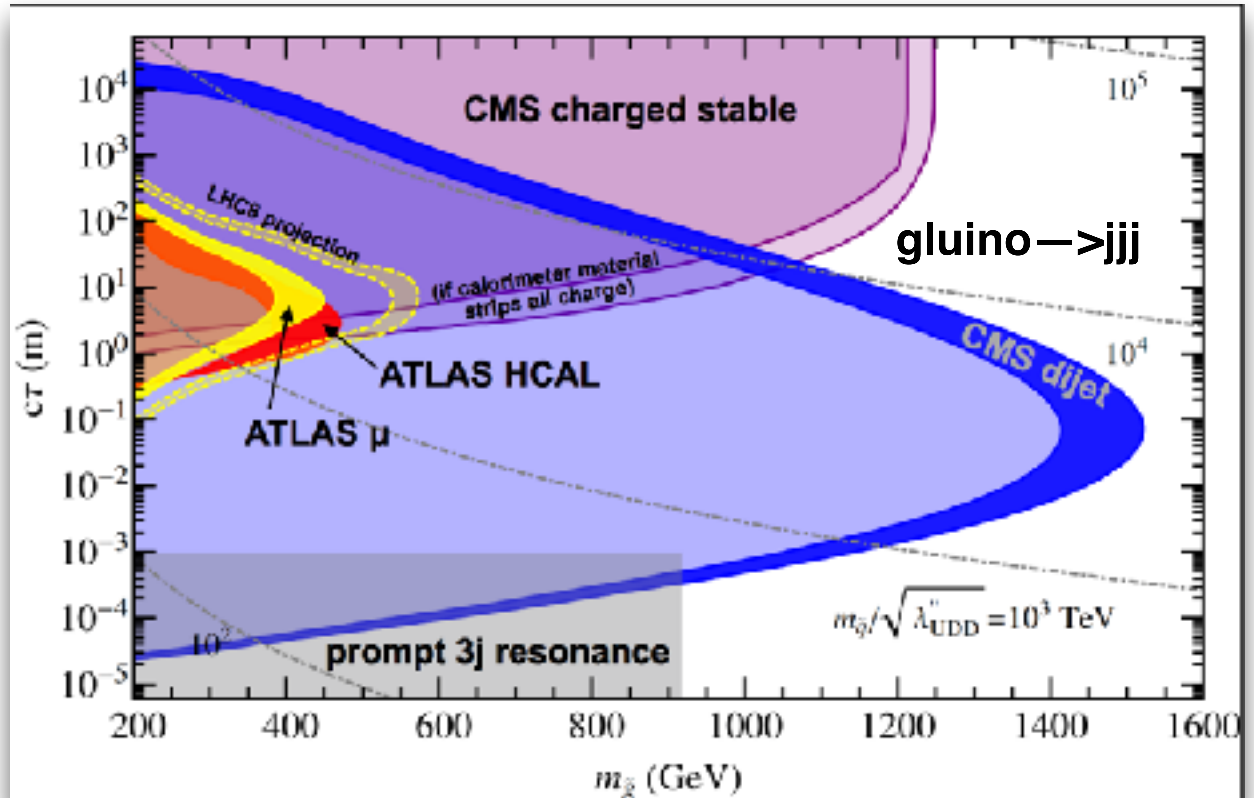
[EXO-12-034]

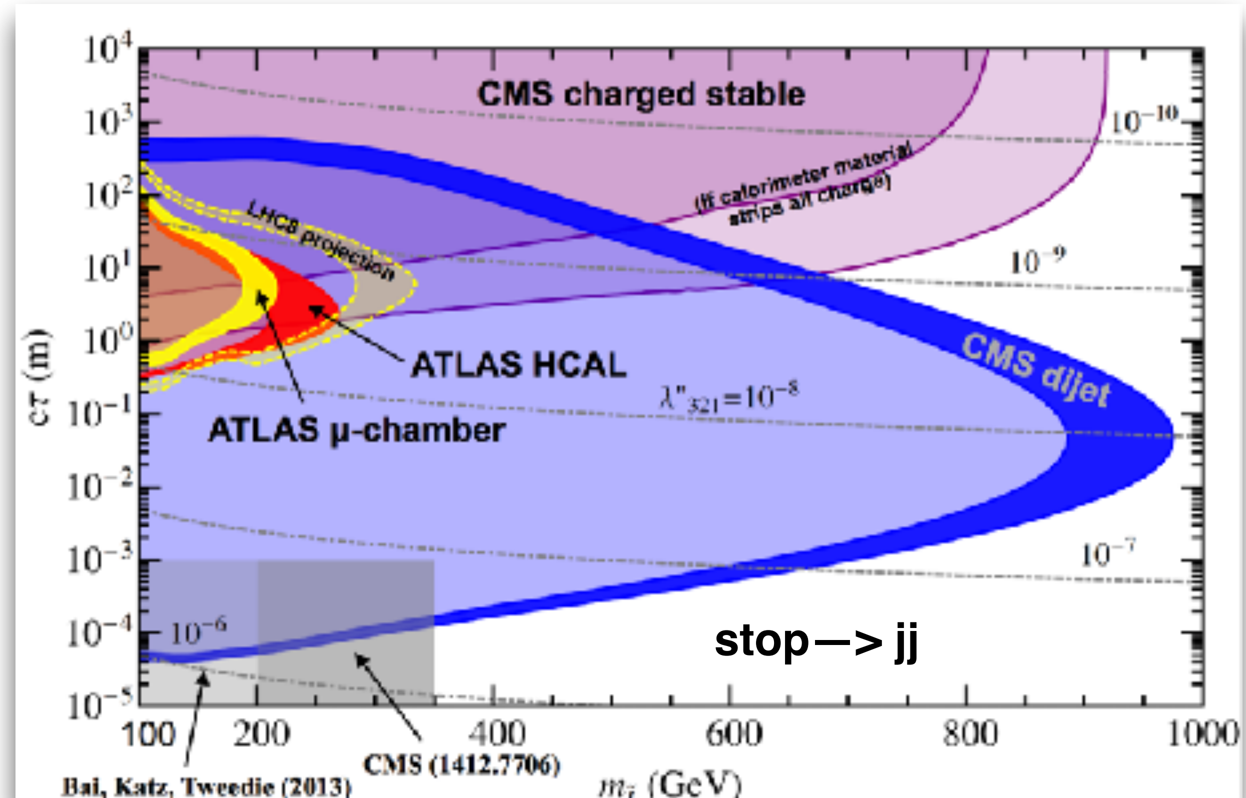
Run I Displaced Dijet Search

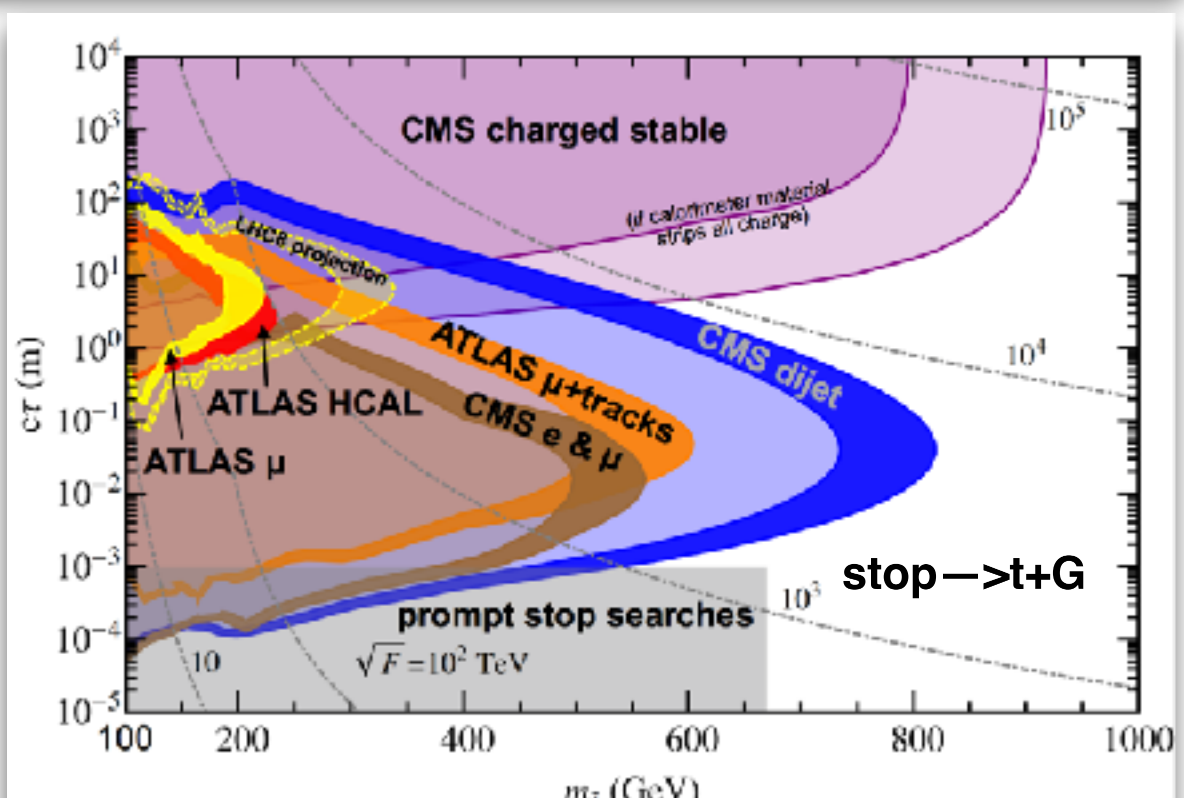
- Why focus on displaced dijet search?
  - It is a powerful search
    - covers many important models involving long-lived objects
    - It has sensitivity to a wide range of lifetimes ctau from 1mm to 1m
  - It takes a minimalistic approach
    - Two "jets" with a common displaced vertex and little prompt energy
    - H_T>300 GeV
  - ~0 backgrounds
    - Essentially a rate limited search: Improvements must be directed towards improving acceptance, not further reducing background

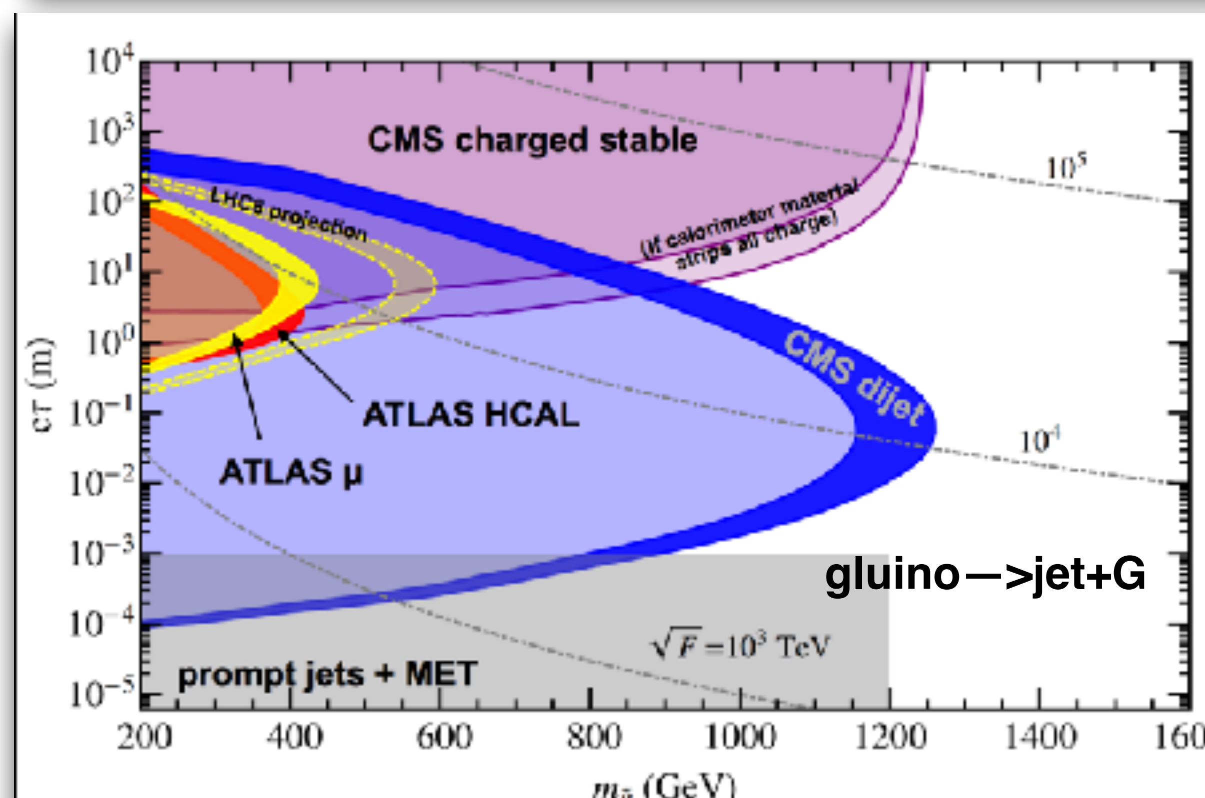
Sensitivity

c.f. Liu, Tweedie, JHEP06 (2015) 042







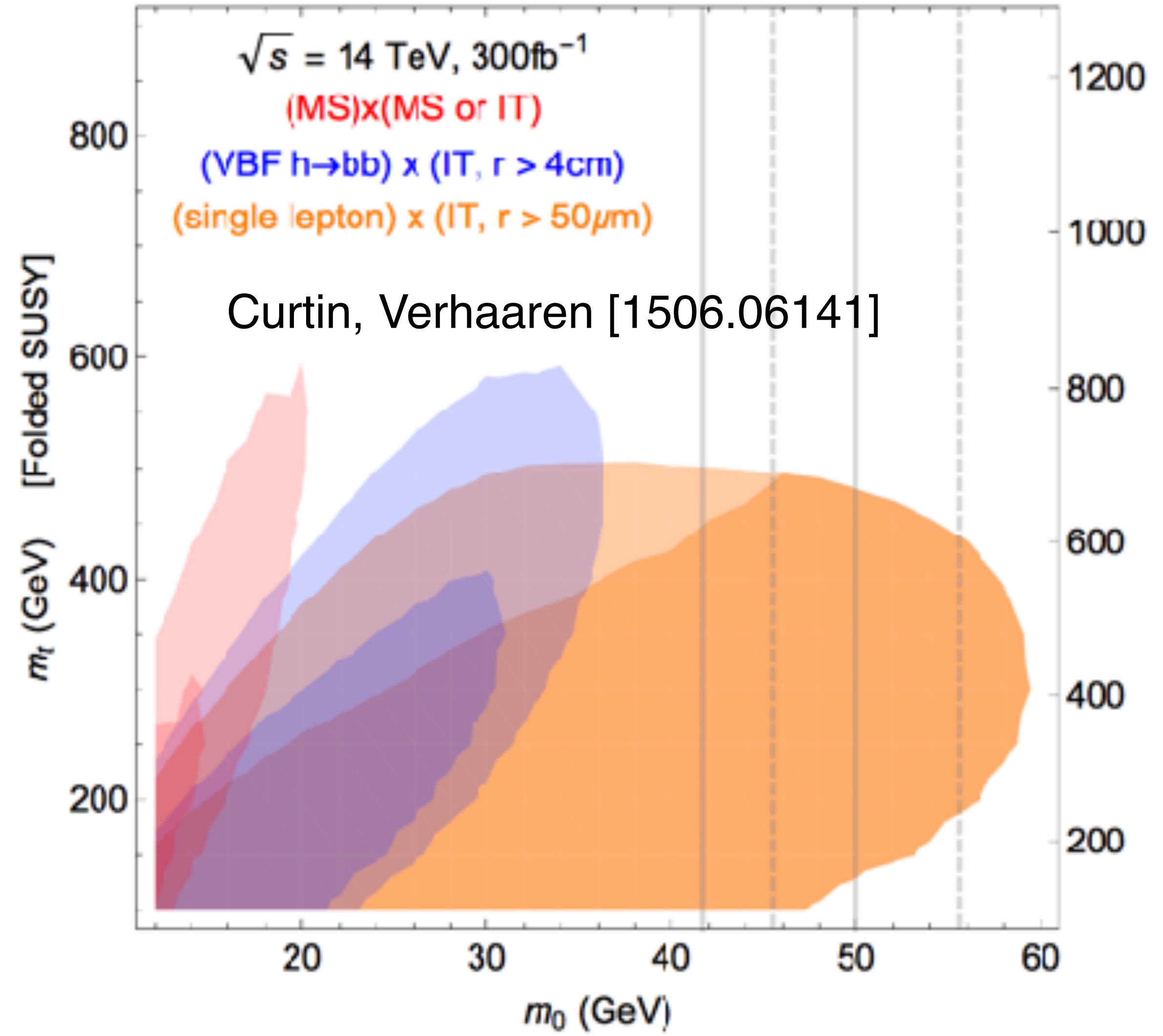


Displaced Dijet Coverage

- Again, this single analysis is transparently very powerful
  - Still, there are places that it lacks coverage
    - it requires two, separated jets from the same vertex
    - H_T>300 GeV
    - reduced sensitivity for lifetimes below 1 mm and above 1 m
- Model dependent improvements by considering different triggers targeting associated production
  - single lepton, dilepton, VBF, MET, etc.
  - LL analyses typically have data-driven methods for the backgrounds (ABCD, etc.) so adapting to different triggers is very easy

WHERE DISPLACED DIJETS FAIL

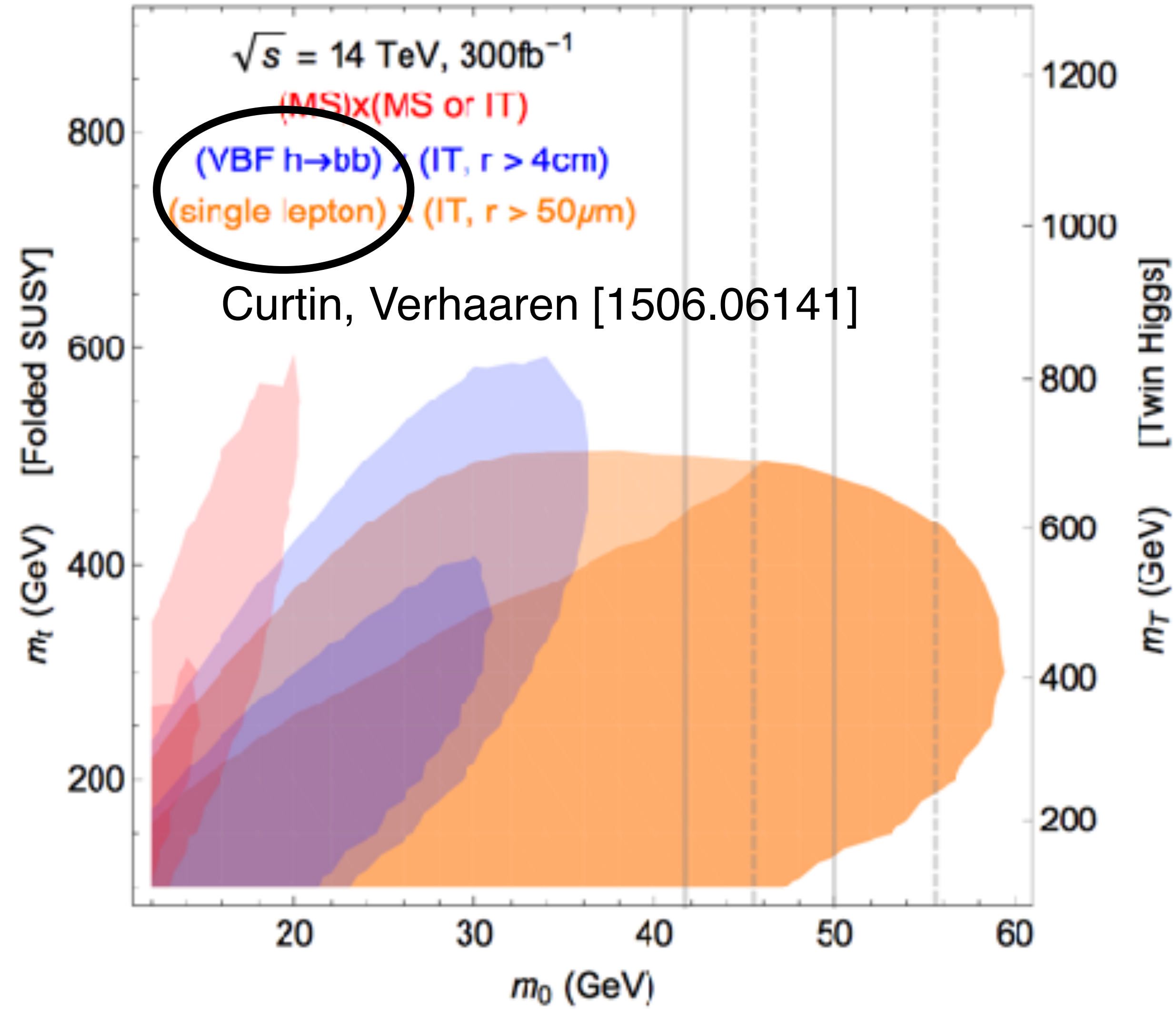
- Search for h(125)→XX→(ff)(ff)
  - X is a 0++ mirror glueball that decays through mixing with h(125)
    - **X preferentially decays to bb or ττ**
  - m_0 and m_T fully specify the X lifetime and h BR to mirror sector (lifetimes from μm on up)
- Shown are expected limits from ATLAS based on three sets of analyses combining various signatures to complete the coverage



- m_0 = mass of the 0^{++} mirror glueball
- m_T = mass of the mirror top partner
- different color regions correspond to the reach of potential ATLAS searches
- shading corresponds to uncertainties on the mirror gluon hadronization
- MS = muon station
- IT = inner tracker vertex

WHERE DISPLACED DIJETS FAIL

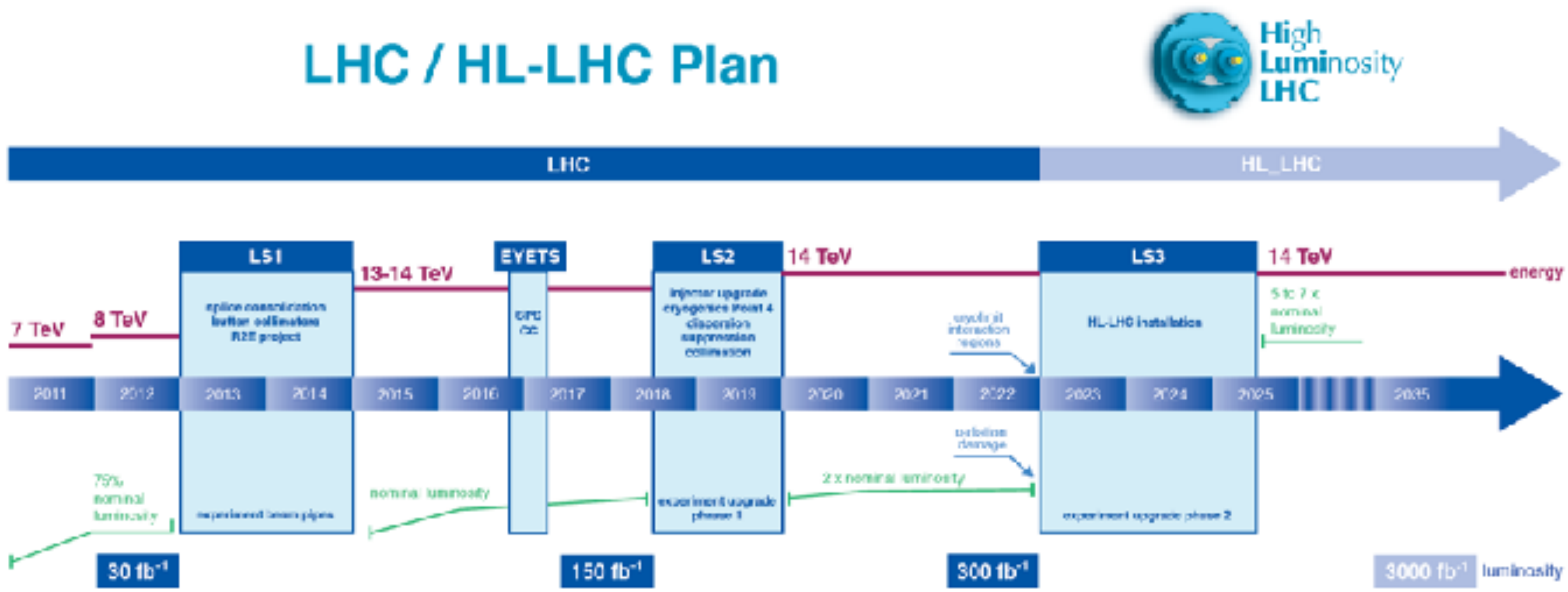
- Fantastic coverage of the meaningful/natural parameter space is possible
  - With 300/fb, LHC can place severe constraints the naturalness of these types of models
  - CMS could have much better sensitivity than ATLAS, but we're currently limited because of the HT>300 GeV threshold!
    - h(125) is accessible in this plot through single lepton and VBF triggers
- CMS has better offline track reconstruction than ATLAS
  - whereas ATLAS has better ECAL/HCAL pointing



- m_0 = mass of the 0^{++} mirror glueball
- m_T = mass of the mirror top partner
- different color regions correspond to the reach of potential ATLAS searches
- shading corresponds to uncertainties on the mirror gluon hadronization
- MS = muon station
- IT = inner tracker vertex

HIGH LUMINOSITY LHC

- CERN is the only lab in the world where you can produce Higgs bosons (and it will be that way for a long while)



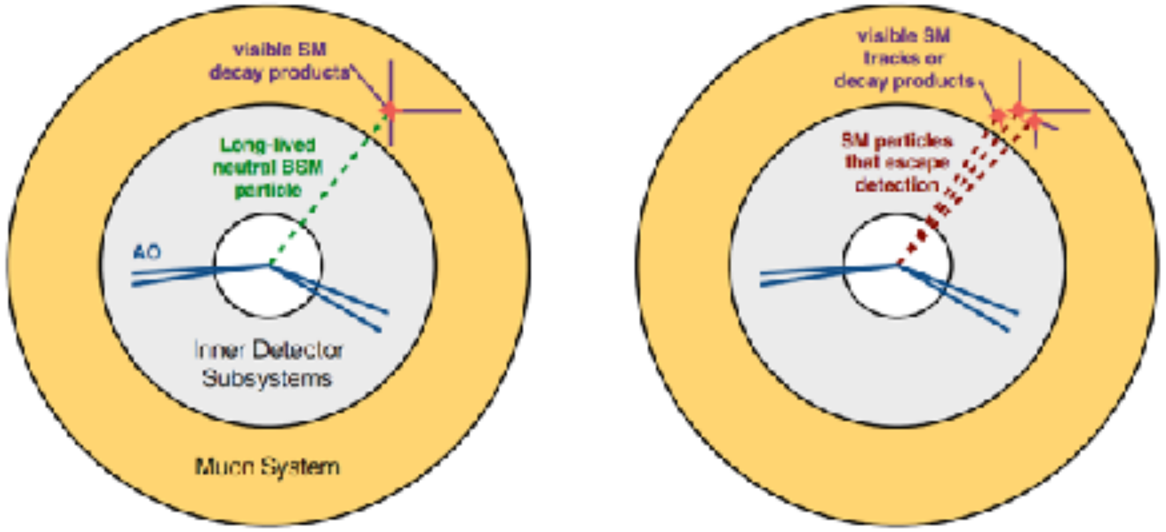
  - the HL-LHC plan is to run for 10 years (beginning in ~2025) and accumulate >3000/fb of data over that time
    - This will require significant effort and money to upgrade the accelerator and detectors to handle the challenging conditions
    - Over that time, ~1.5×10^8 Higgs bosons will be produced
      - FCC-ee may reach 10^6 Higgs boson/year

PRINCIPLES FOR ULLPS

- Two basic challenges for finding ultra-long-lived particles (ULLPs)
  - depth x geometrical acceptance

$$N_{\mathrm{obs}} \sim N_h \cdot \mathrm{Br}(h \to \mathrm{ULLP} \to \mathrm{SM}) \cdot \epsilon_{\mathrm{geometric}} \cdot \frac{L}{bc\tau}$$

    - CMS/ATLAS are large detectors with with considerable acceptance, but…
  - backgrounds
    - QCD induced fake backgrounds are a limiting factor



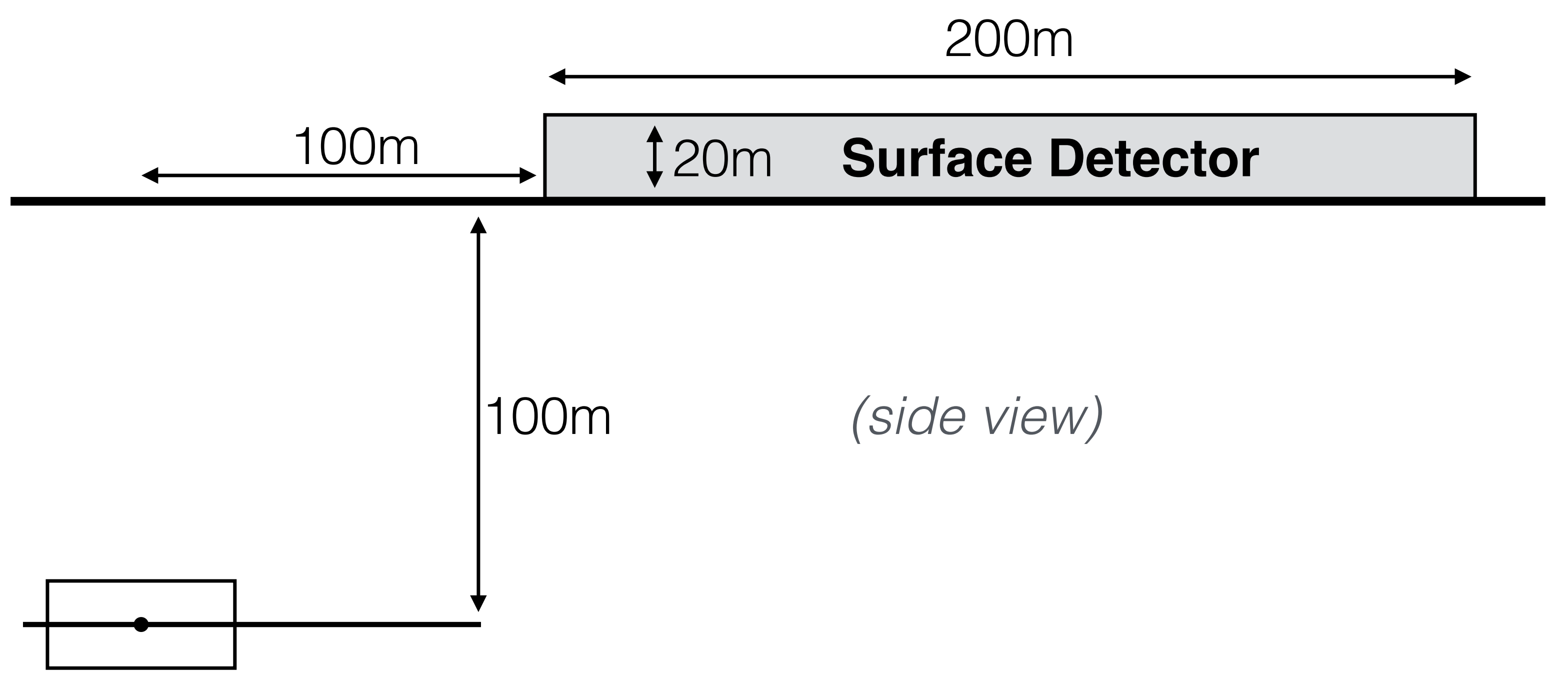
Signal Trigger iso event from BSM (a)

Signal Trigger iso event from SM QCD (b)

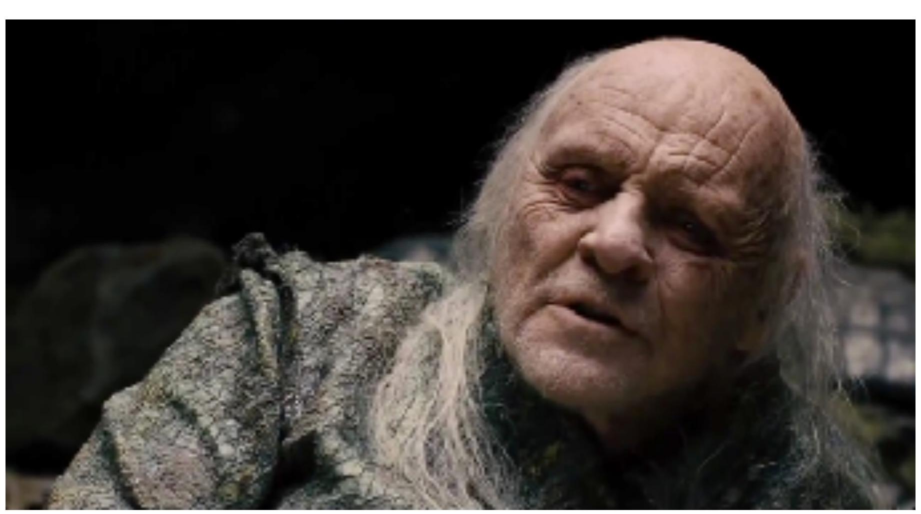
MATHUSLA

[JPC, D. Curtin, H. Lubatti arXiv:1606.06298]

- **MA**ssive **T**iming **H**odoscope for **U**ltra-**S**table **N**eutra**L** P**A**rticles



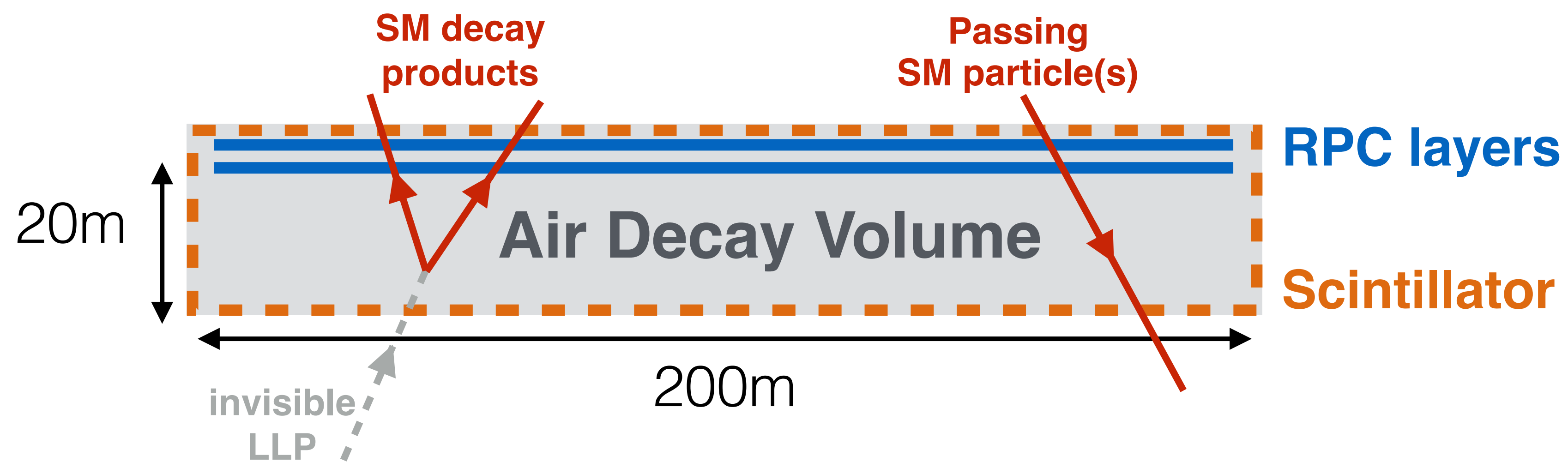
- a dedicated **surface detector** for ultra-long-lived particle (ULLP) decays
  - ~5% geometric coverage
  - minimal RPC/scintillator instrumentation required
  - can be virtually background free



Hypothetical Locations

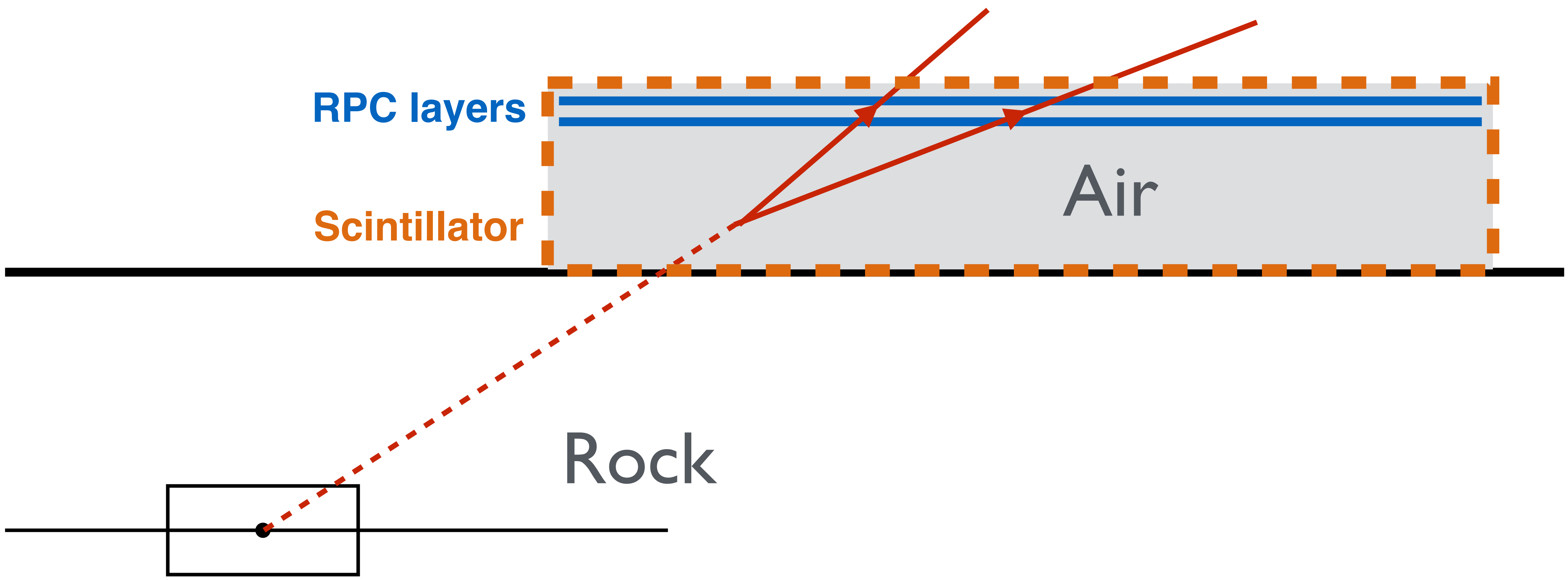
Design Sketch

- Layers of RPCs in the roof act as a directional tracker
- Scintillators give additional veto:
  - ~ns timing, ~10 cm position resolution
  - Reconstructed vertex and time-of-flight measurement of final states distinguishes LLP decay from passing cosmic rays, neutrino scattering
- Need to minimize instrumentation to bring down costs
  - Sensitivity grows with volume, cost with surface area



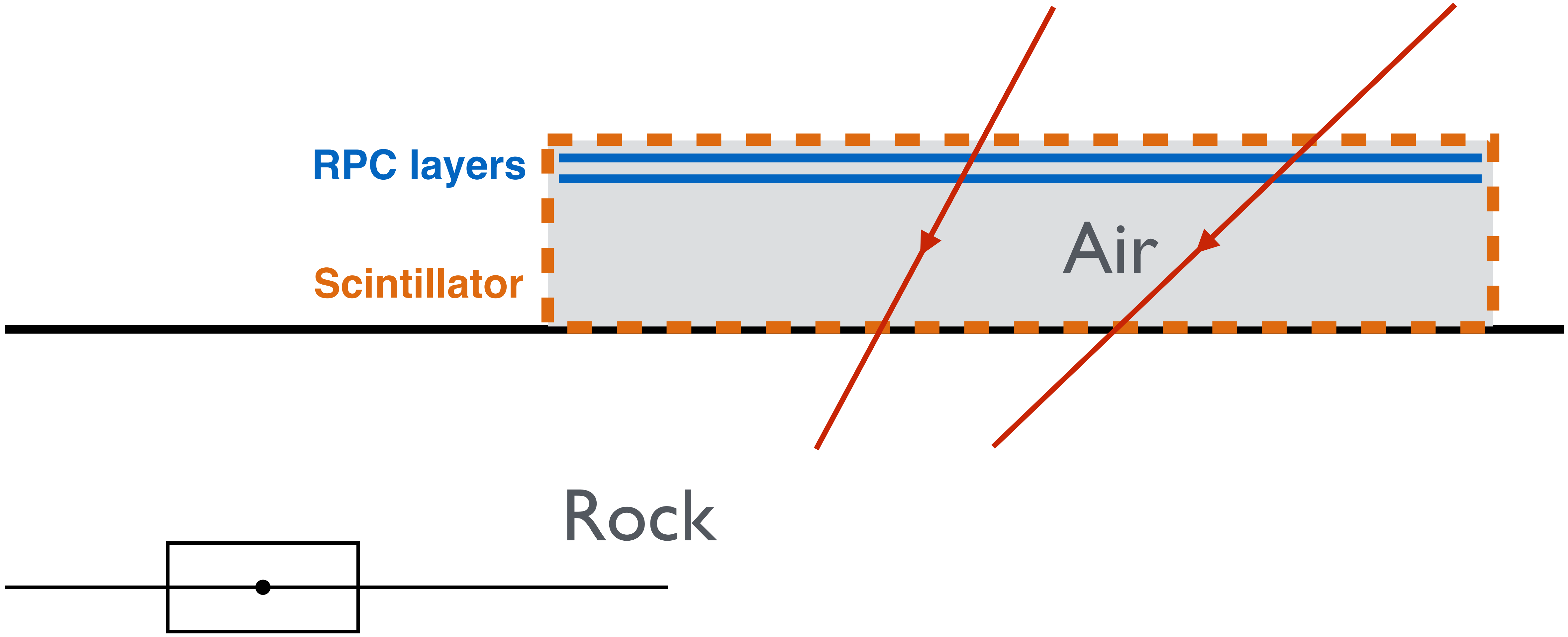
SIGNAL V. BACKGROUNDS

- Signal induces an upward going vertex in the detector
  - possible decay to many charged particles, but should have at least 2
  - particles should typically be relativistically boosted
    - No magnetic field complicates pointing
    - Material could help with particle ID (but induce other backgrounds)



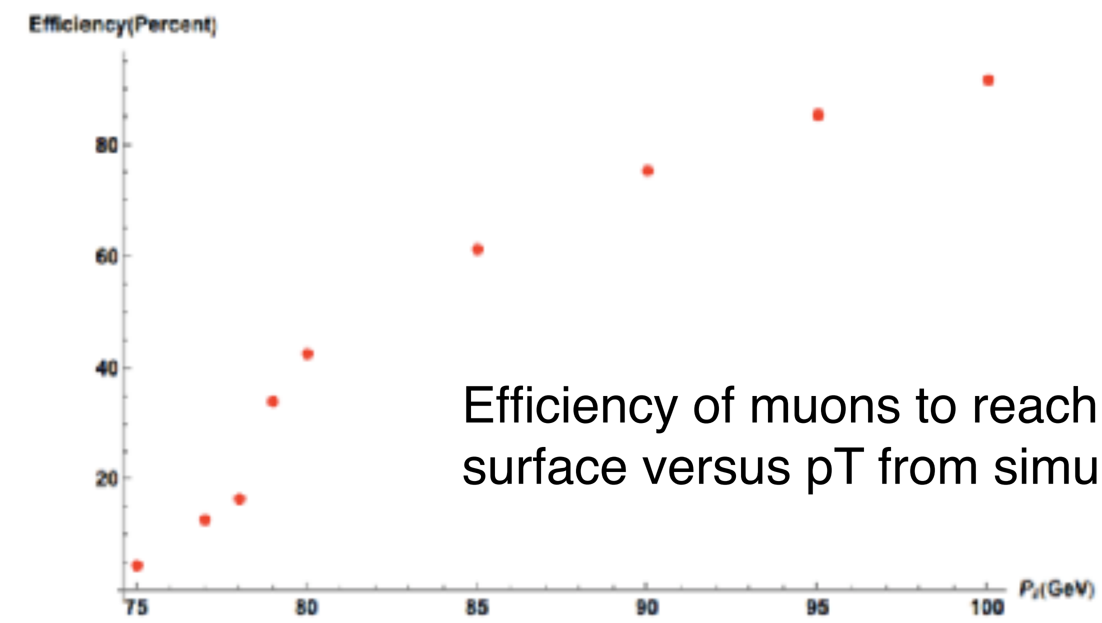
Signal v. Backgrounds

- Cosmic Muons
  - ~10 MHz rate, but many handles to reject
    - downward going, so can be rejected with timing
    - also reject if track punches through the floor
    - no vertex

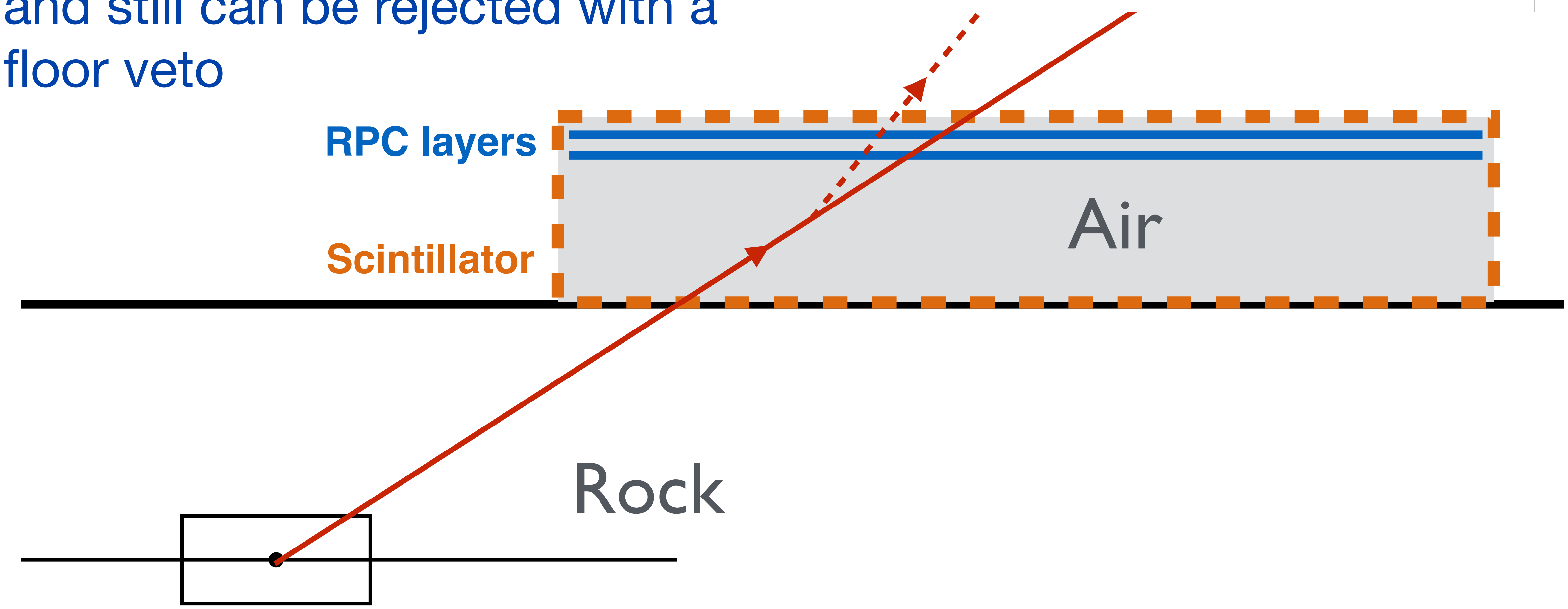


SIGNAL V. BACKGROUNDS

- Muons from the collision
  - ~1 Hz rate
    - veto tracks that pass through floor
    - no vertex
  - inelastic scatter rate is small, and still can be rejected with a floor veto

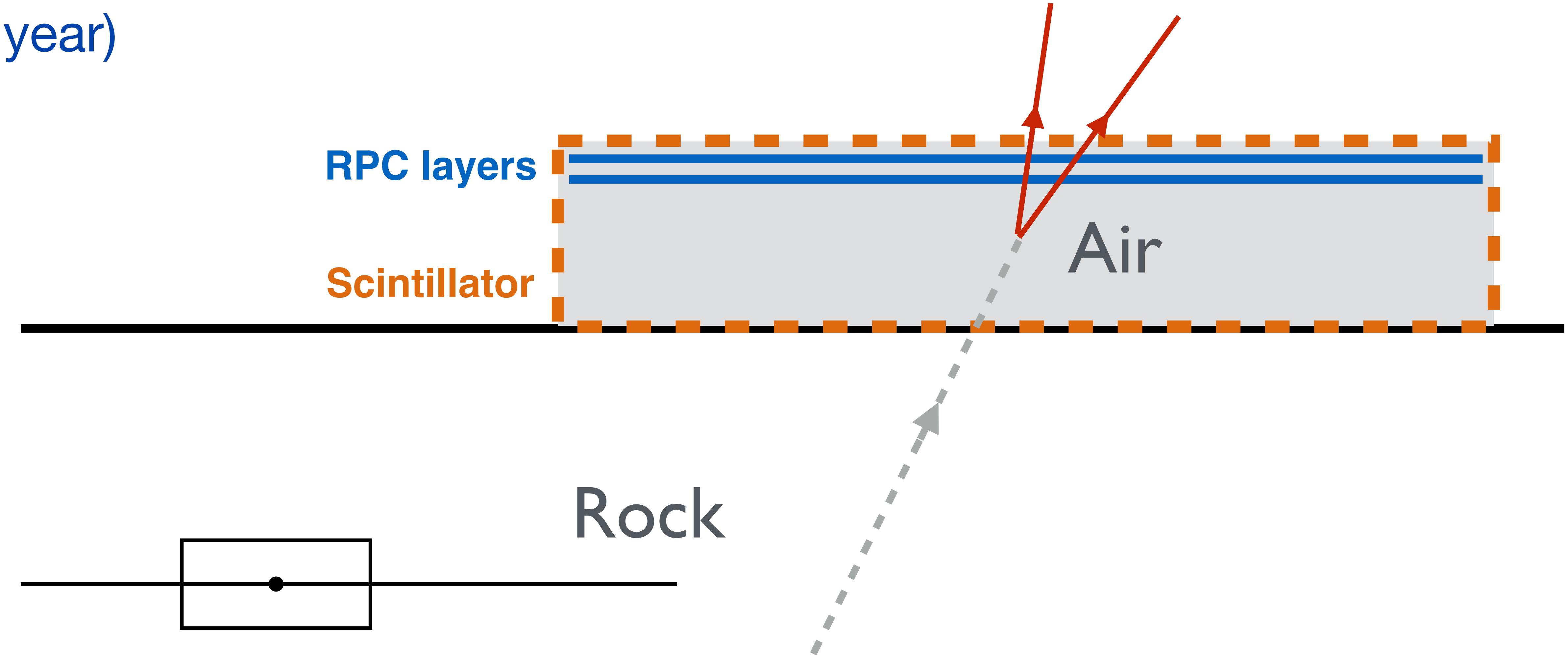


Efficiency of muons to reach surface versus pT from simulation



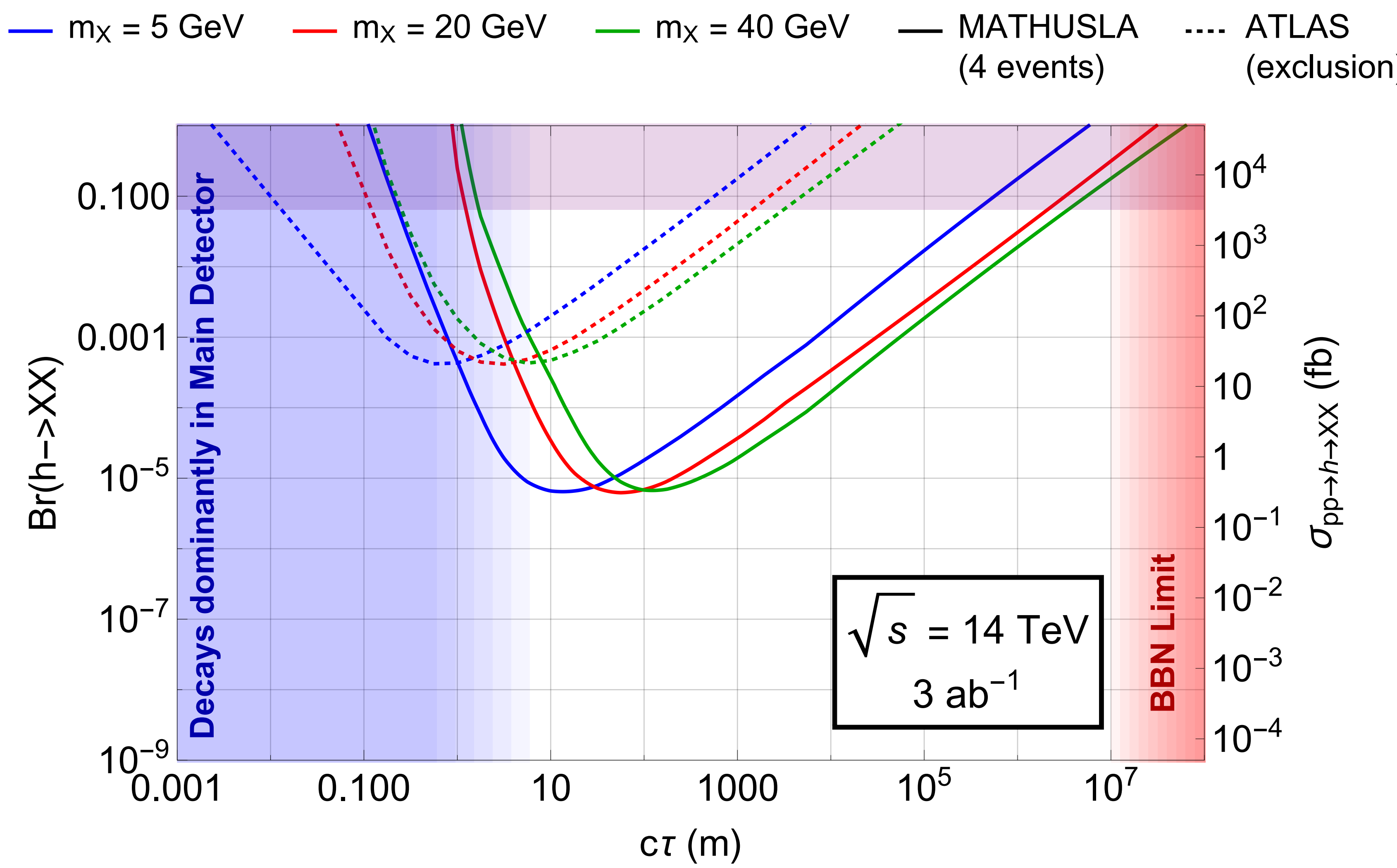
SIGNAL V. BACKGROUNDS

- Neutrino backgrounds
  - Low rate from cosmic neutrinos (10-100 interactions per year above 300 MeV)
    - final state proton is **slow**: reject with time-of-flight
    - also non-pointing; study during beam down-time
  - Very low rate of neutrinos from LHC secondaries (<1 event per year)



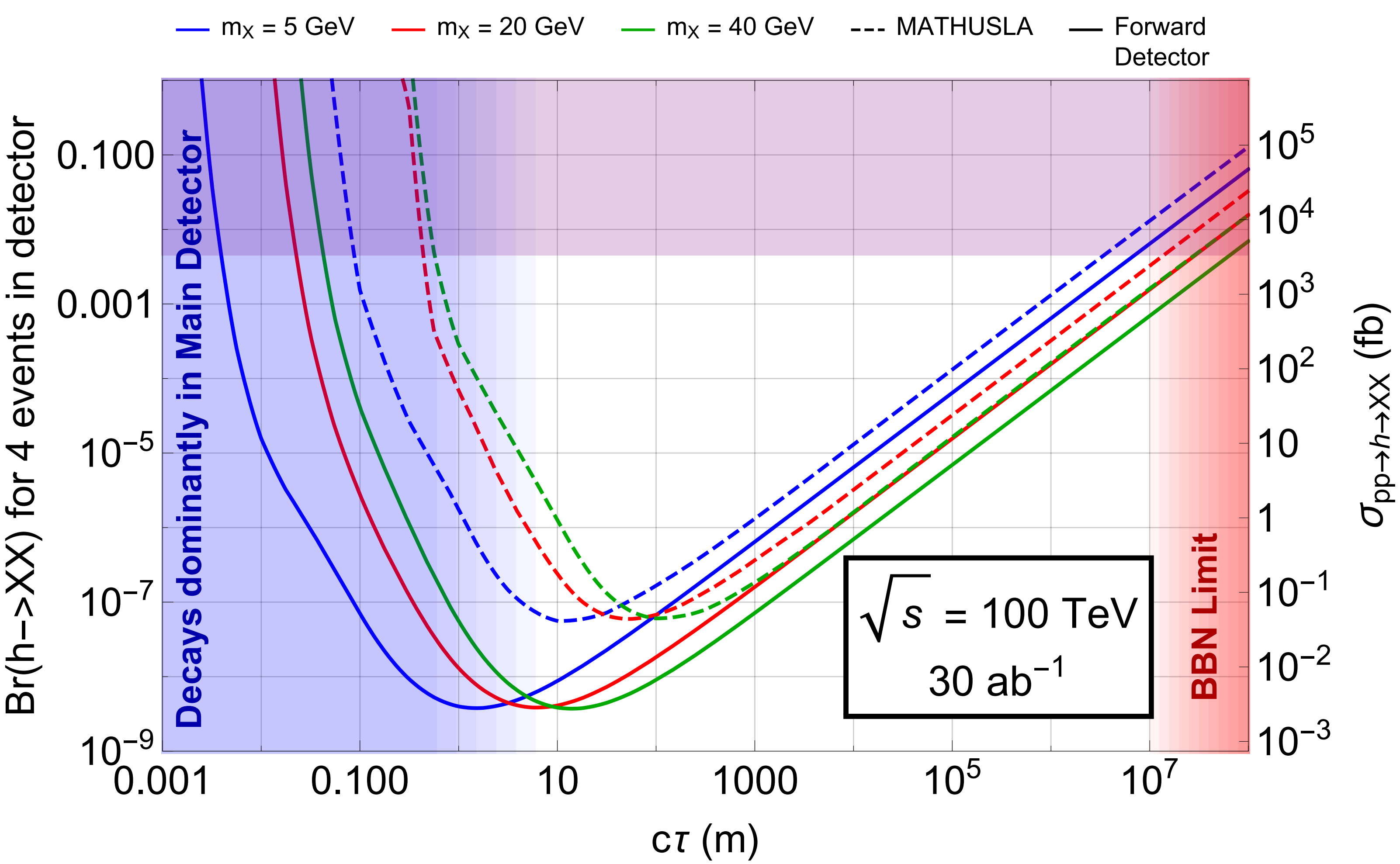
Possible Reach

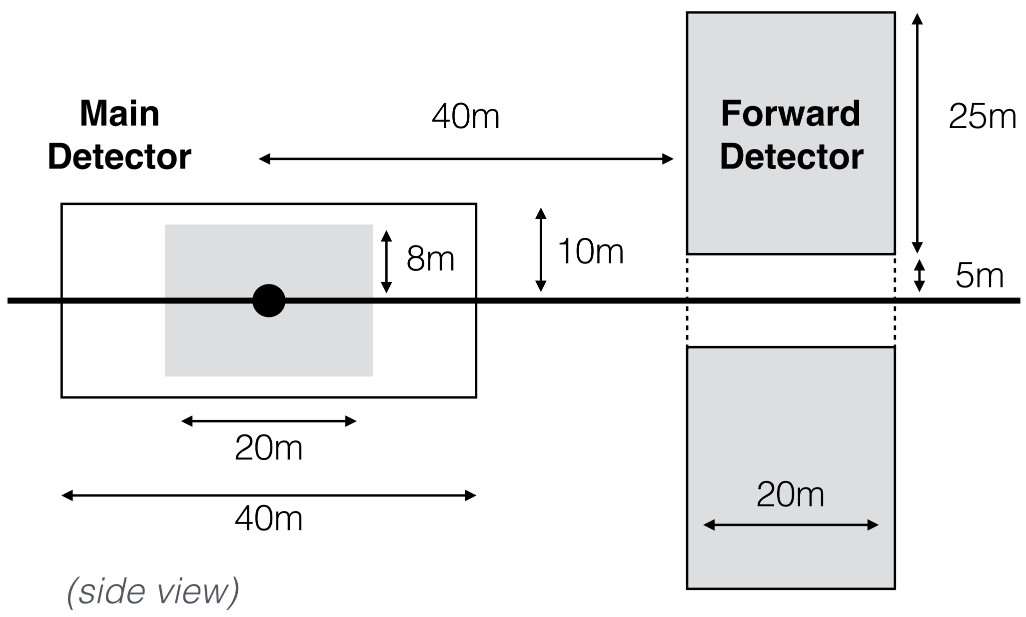
- Such a detector could get close to the BBN limit for **a very large class of models** (not just Higgs portal)
  - ~3 orders of magnitude better than projected ATLAS search over the HL-LHC (assuming zero background)



100 TeV Machine

- Reach for 100 TeV machine is naturally even greater
  - Possibility of dedicated ULLP *underground* detector
    - optimize cost/acceptance/backgrounds





Other Motivations

- Many different models produced neutral, long-lived particles
  - ~pb sensitivity at BBN limit to pair-produced neutral ULLPs
- Complementary approach for DM searches
  - How do we verify that a MET+X signature is really DM and not ULLP?
  - Observation of MET+X further motivates detector

NEXT STEPS

- Experiment: build a small prototype
  - 20 m^2 of scintillators and phototubes from spares of the D0 experiment at Fermilab
  - RPCs and electronics provided by Rome Tor Vergara group (gas provided in the construction hall by ATLAS)
    - RPC and readout come from ARGO experiment
  - Main goal is to ground the simulation of background rates in experimental measurements
    - should have discernible rate of events from LHC

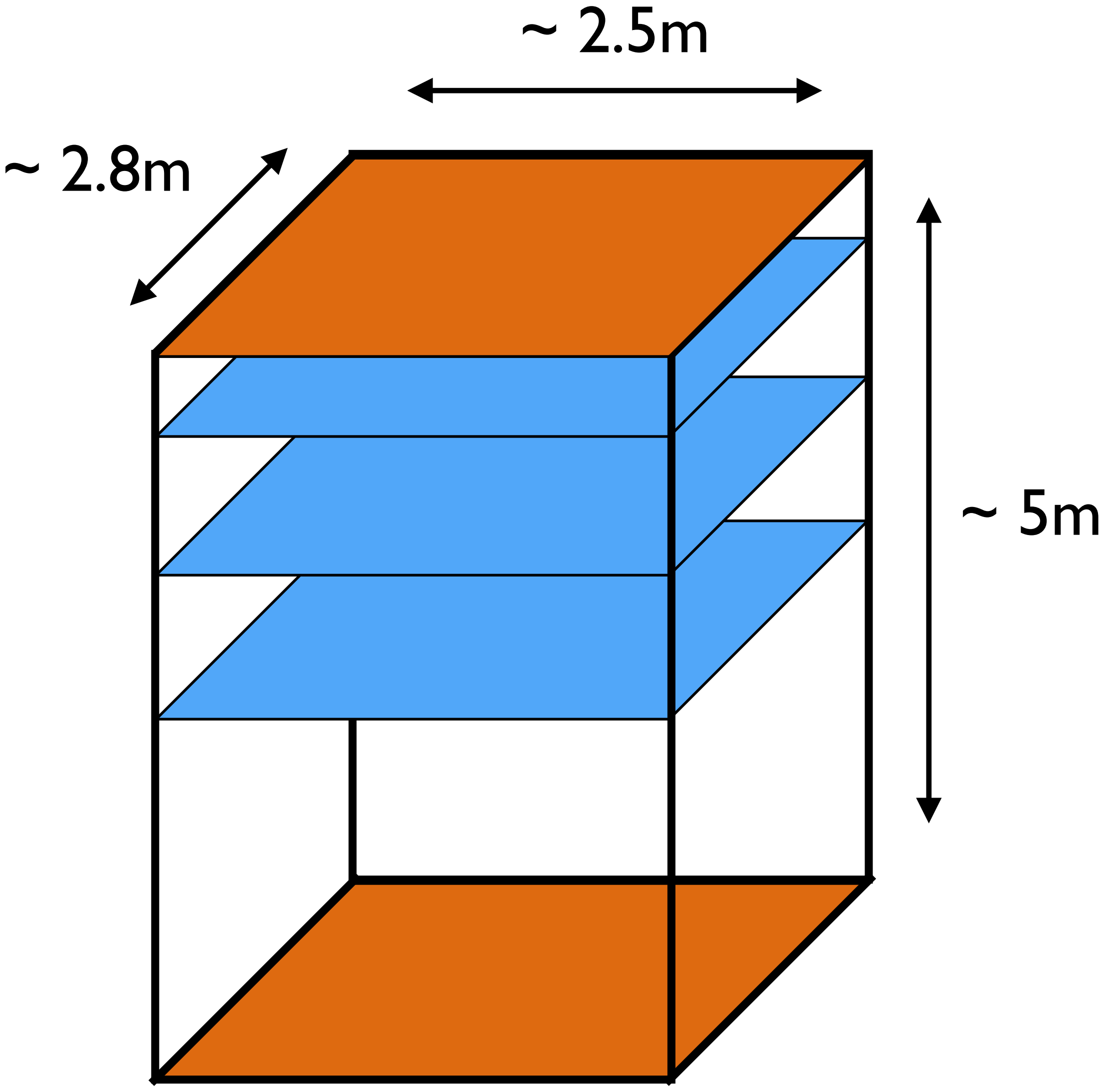
- Theory: Make a more detailed physics case
  - a comprehensive report making a detailed physics case is aiming for early 2017

MATHUSLA PROTOTYPE

Required to validate design, background estimates, etc..

Sketch of possible geometry:

Preliminary & Unofficial



Few-meter-scale test stand:

A few layers of RPCs…

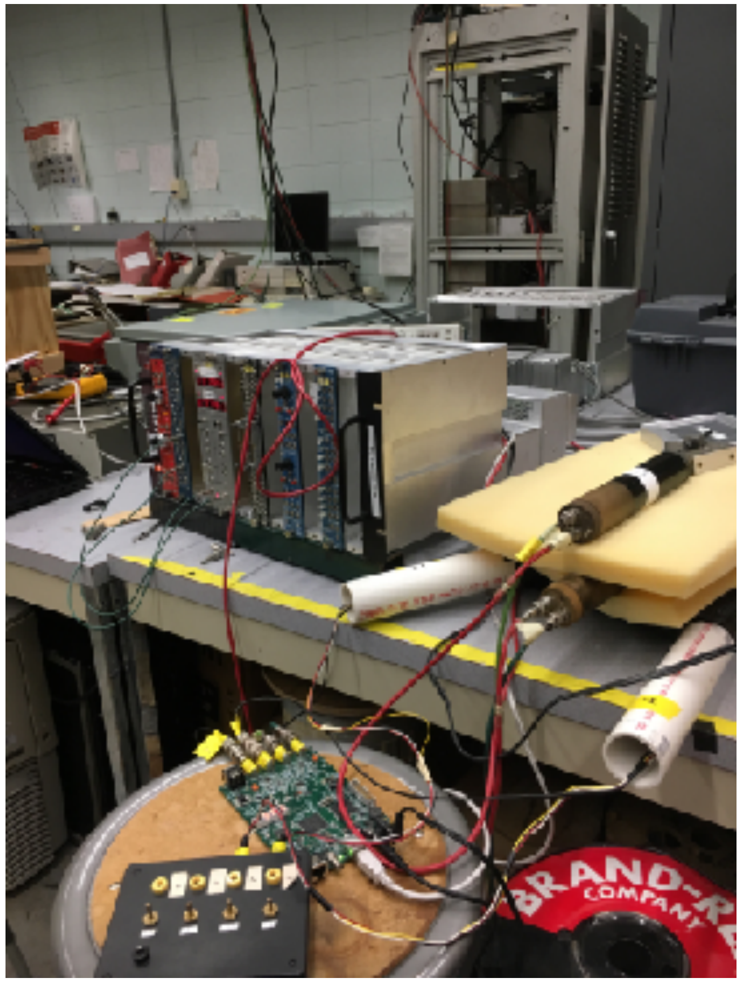
… some scintillator

Place in ATLAS installation pit to get data with and without LHC collisions.

→ *approved by Technical coordinator, get access to gas for RPCs!*

TESTING SCINTILLATOR TILES

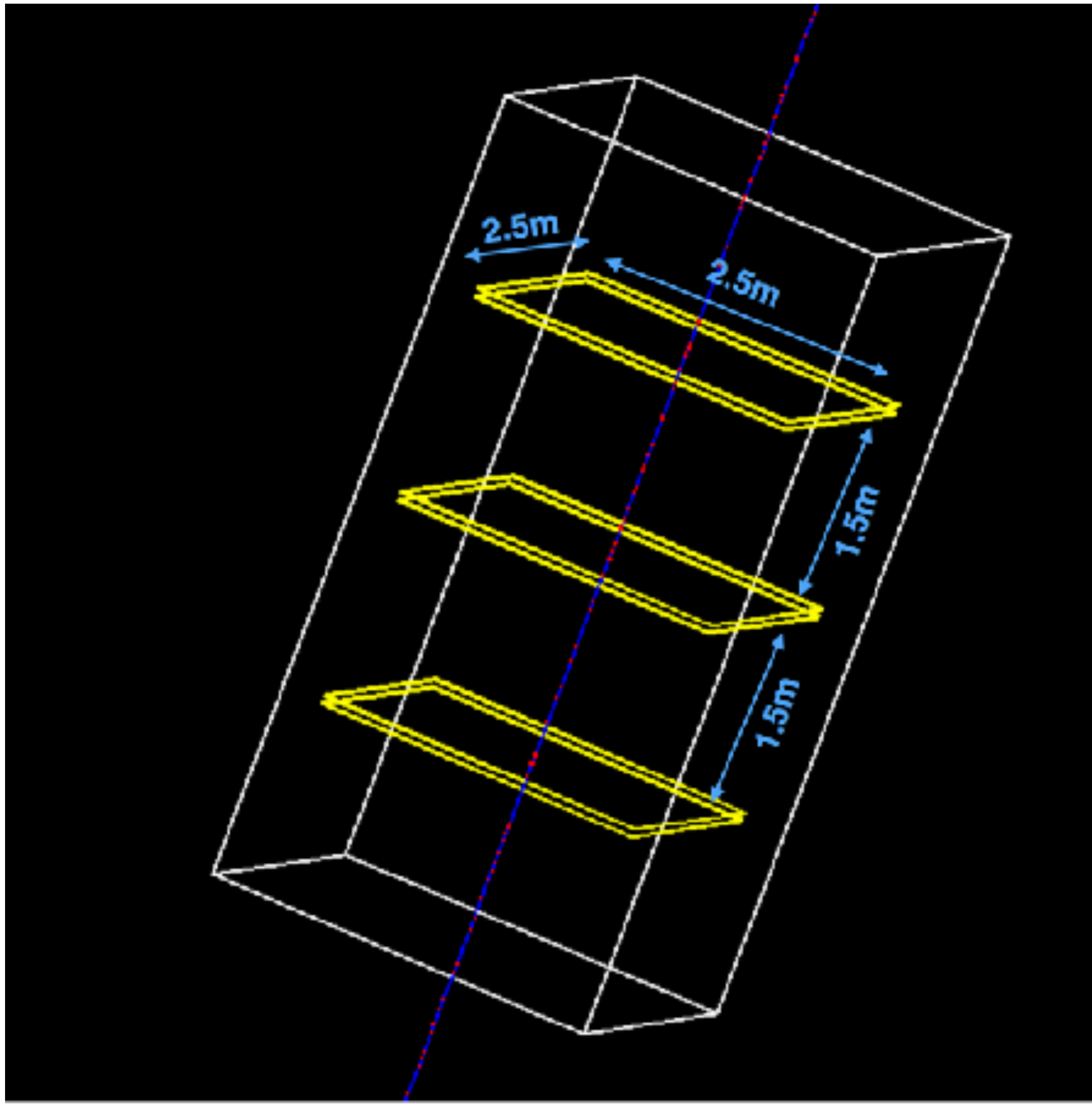
- Use D0 muon tiles + PMTs with Quarknet DAQ board
  - good timing resolution (~1.25 ns) and noise characteristics
  - DAQ has four channel input, provides digitized time and time-above-threshold
  - working out issues with DAQ, clock distribution



RPCs

- Supplied by University of Rome Tor Vergata, chambers + DAQ systems from prototype of ARGO cosmic shower experiment in Tibet
  - 12 chambers → can use 4 to make an RPC layer of 2.5x2.8 with ~cm tracking resolution in x-y plane
  - 3 layers, O(1m) apart, will give 3D tracking
  - run in avalanche mode
  - gas supplied by collision hall

GEANT4 Geometry



BUILDING A COLLABORATION

- ~12 institutes
- ~40 collaborators

THEORY WHITE PAPER

Detecting Ultra-Long-Lived Particles: The MATHUSLA Physics Case

Editors:
David Curtin[1], *Matthew McCullough*[2], *Patrick Meade*[3], *Michele Papucci*[4], *Jessie Shelton*[5]

BUDGET JUSTIFICATION

- What are total costs?
  - critical: prototype will help inform us if more (or less) instrumentation needed to reduce backgrounds
- Can such a project be justified?
  - The HL-LHC is the **obvious** place to perform such an experiment
    - FCC-ee would need ~100 times more acceptance to be competitive
  - Physics motivation is very strong
    - an exhaustive statement about naturalness at the TeV scale cannot be made without consideration of ULLPs
  - Cost is small compared to total cost of LHC project
    - global investment in LHC program exceeds 10 billion USD; the marginal cost is small to exploit fully a once-in-a-generation machine

CONCLUSIONS: DIGGING DEEPER

- Large space of motivated searches for unconventional signatures
  - Take advantage of x-triggers (MET, VBF, etc.) to enhance sensitivity in a model dependent way
- Having a dedicated detector to look for ultra-long-lived particles will greatly enhance the new physics reach of the HL-LHC
  - Approaching the BBN limit is possible, in principle
  - A prototype detector will help us determine if this concept works in practice