Displaced Decays

@

LHC HL-LHC FCC-ee FCC-hh

CERN FCC Brainstorming Session

25 Nov 2016

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University of Maryland

Outline

1. Motivation
2. LLP searches at the LHC
3. New Opportunities for the HL-LHC
4. LLP Searches at the FCC-hh
5. LLP Searches at the FCC-ee
6. Conclusion

Motivation

Motivation

No "conventional" BSM signals so far.
Maybe looking in wrong places?

Hidden Sectors and other theories with Long-lived particles (LLPs) are ubiquitous amongst BSM theories and can solve a lot of problems

including…

Hierarchy Problem — Baryogenesis — Dark Matter

LLPs are spectacular signals!
Relatively few events needed for discovery

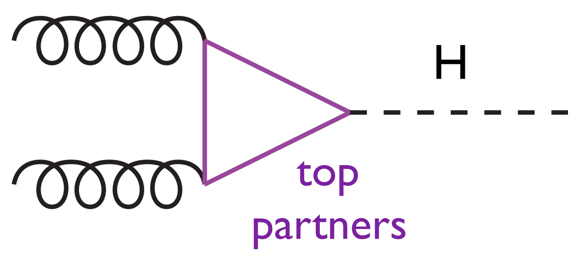
Theory Examples

— Neutral Naturalness —

Discrete symmetry could relate top to top partner

top partner charged under new copy of QCD
→ Hidden Valley Signatures

Higgs Portal allows for hidden hadron production in exotic Higgs decays. Even small Br gives many events!



HL-LHC will make 10^8 Higgses

Hidden hadrons can decay back to SM via Higgs (or other) portal → **LLP signatures!**

Theory Examples

— WIMP Baryogenesis —

Out-of-equilibrium decay of a metastable WIMP can produce baryon number.

Metastable WIMP is LLP, can be produced at colliders.

— FIMP DM —

New particle B has long-lived decay to SM + DM
In early universe, B in thermal equilibrium with SM and 'leaks' abundance into DM sector, where it accumulates.

DM abundance ↔ B lifetime (10^{-3}s ballpark)

LLP Searches at the LHC

Charged LLPs

They're not invisible!!!

muon triggers
anomalous dE/dX (high or low)
time-of-flight
track curvature
deposition and decay
kinked tracks
disappearing tracks

Searches get easier the longer they live.

Neutral LLP Searches

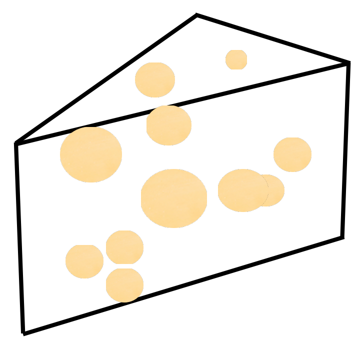
Neutral LLP searches are harder than charged LLP searches, but the signals can still be spectacular.

Distinctiveness of Signature in Detector:

Heavy charged track/ deposition > Displaced Decay > Missing Energy

not yet

more like



Rule of Thumb for Neutral LLP searches

DV	+	X	$\Rightarrow$	Very little background @ LHC
High quality very macroscopic **displaced vertex**		**Something else** that's kinda rare (leptons, high-mass, another DV…)		

X could be a property of the LLP itself

Limitation: With few exceptions, can't L1 trigger on DV

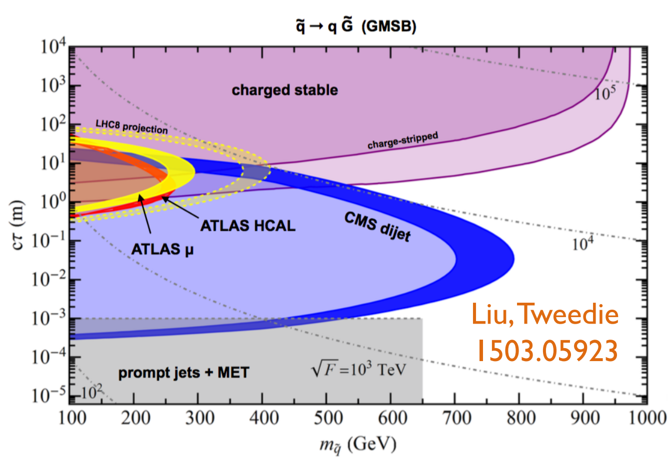
Performed Searches at ATLAS or CMS

DV + X ⇒ Very little background @ LHC

High quality very macroscopic **displaced vertex**

Something else that's kinda rare (leptons, high-mass, another DV…)

d ≳ cm **+** X = distinctive LLP decay products (leptons, lepton jets…)
X = 'hard' LLP: has high mass and decays in tracker
X = another DV, and first DV is in Muon System/HCAL *(longish lifetime)*



In combination, together with charged LLP and prompt searches, this already gives very significant reach for many theories!

Most important required searches

DV + X ⇒ Very little background @ LHC

High quality very macroscopic **displaced vertex**

Something else that's kinda rare (leptons, high-mass, another DV…)

1. Need sensitivity for "softer" LLPs, e.g. from **exotic Higgs decays, which is a highly motivated LLP production mode**
   ⇒ X = single lepton (Vh) or VBF jets *(events are on tape!)*

2. X = all of the above, **DV with d ~ 0.1mm - cm**
   (repurpose b-tagger? LHCb opportunity?)

3. LLP decay with **d >> detector size**
   (also relevant for testing if MET = DM)

Most important required searches

DV

High quality
very macroscopic
displaced vertex

Once implemented, this will allow us to probe

e.g. TeV-scale Neutral Naturalness

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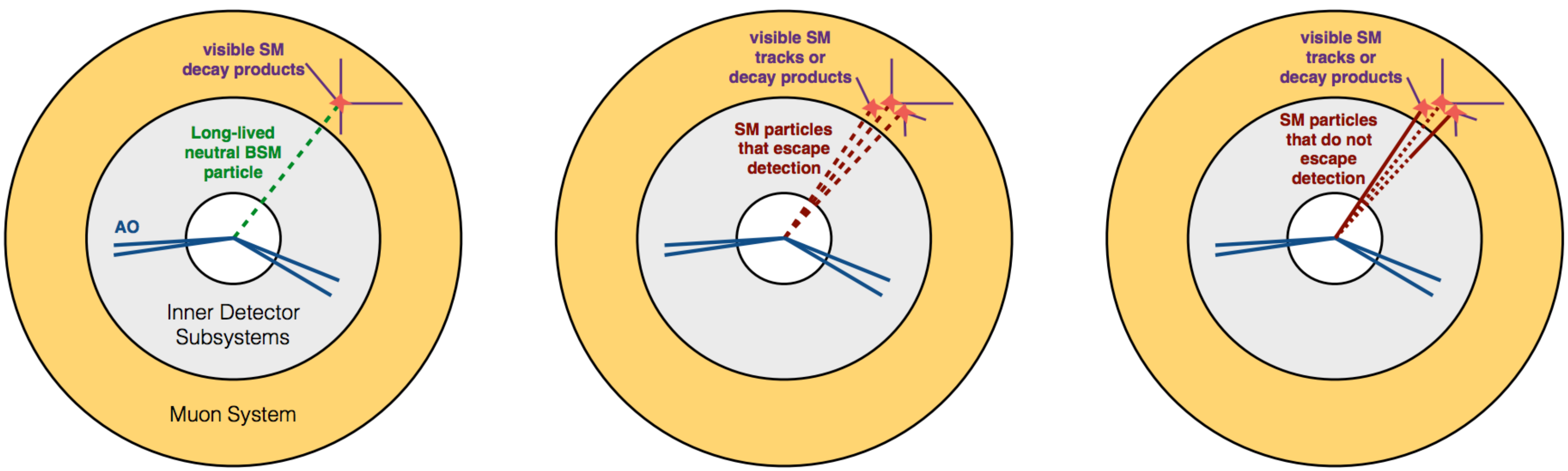
LLP Search for Long Lifetimes

Probably the best we can do at the LHC:
search for a single DV in the ATLAS Muon System.



Signal Trigger
iso event from BSM
(a)

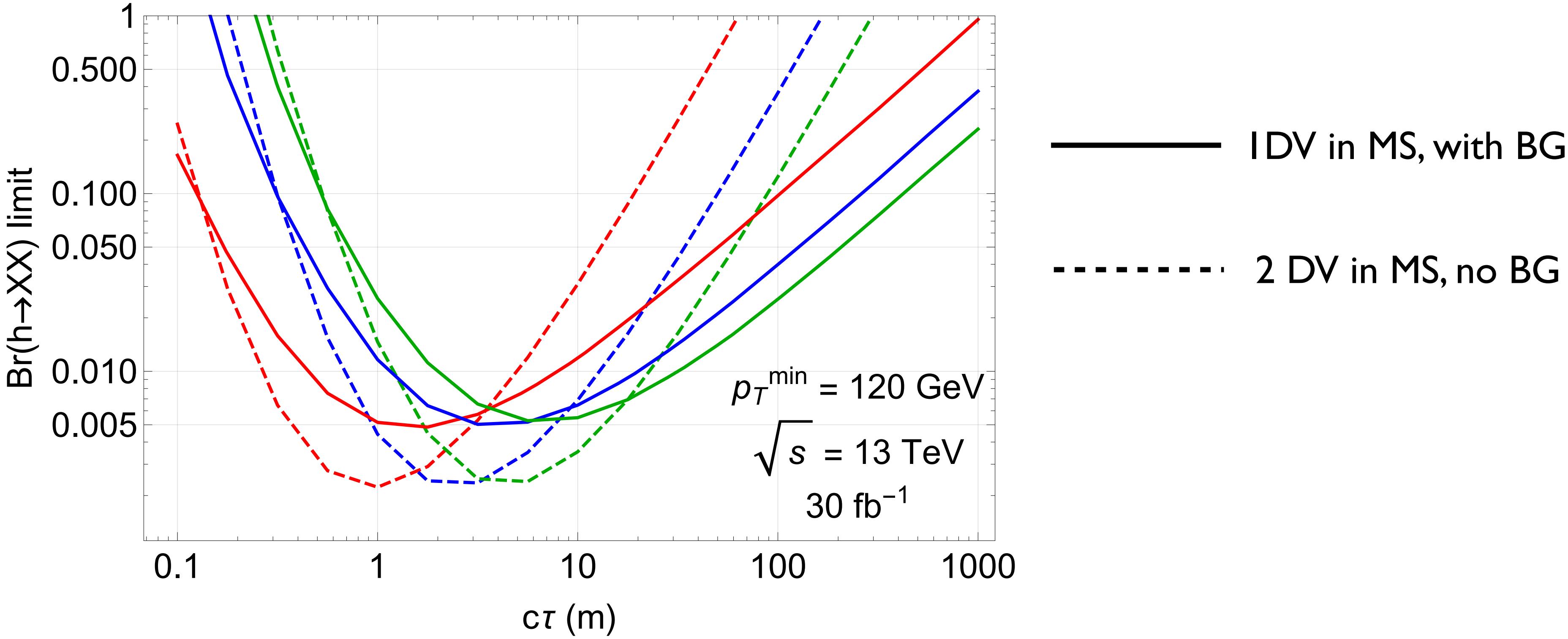
Signal Trigger
iso event from SM QCD
(b)

Orthogonal Trigger
non-iso event from SM QCD
(c)

Very challenging search! Have to obtain fully differential data-driven background estimates.

1605.02742 Andrea Coccaro, DC, Henry Lubatti, Heather Russell, Jessie Shelton

Projected Sensitivities: single DV in ATLAS MS



Hopefully will be implemented at run 2!

Projected limits of 1DV in MS search far superior at **long lifetimes** compared to existing 2DV search.

However, this inclusive search is severely background-limited!

New Opportunities for the HL-LHC

Going beyond the LHC

Of course, the LHC LLP search program will have to continue at the HL-LHC

Some techniques may take several years to mature and implement anyway.

HL-LHC is required to reach important projected sensitivities ~ lumi (for many important low BG searches)

Q: What are the qualitatively new possibilities @ HL-LHC?

A: we could scratch the BBN ceiling

$\tau \sim 0.1 - 1 s$

of LLP lifetime parameter space!

MATHUSLA

John-Paul Chou
David Curtin
Henry Lubatti
1606.06298

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

A dedicated, minimally instrumented displaced vertex detector.

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Henry Lubatti
Gordon Watts
Cristiano Alpigiani
Audrey Kvam

RUTGERS
John Paul Chou
Amit Lath
Steffie Thayil

SLAC NATIONAL ACCELERATOR LABORATORY
Charles Young
Robert Mina

Fermilab
Sunanda Banerjee

Università di Roma Tor Vergata
Rinaldo Santonico
Roberto Cardarelli

University of Maryland
David Curtin

TEL AVIV UNIVERSITY
Erez Etzion

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]

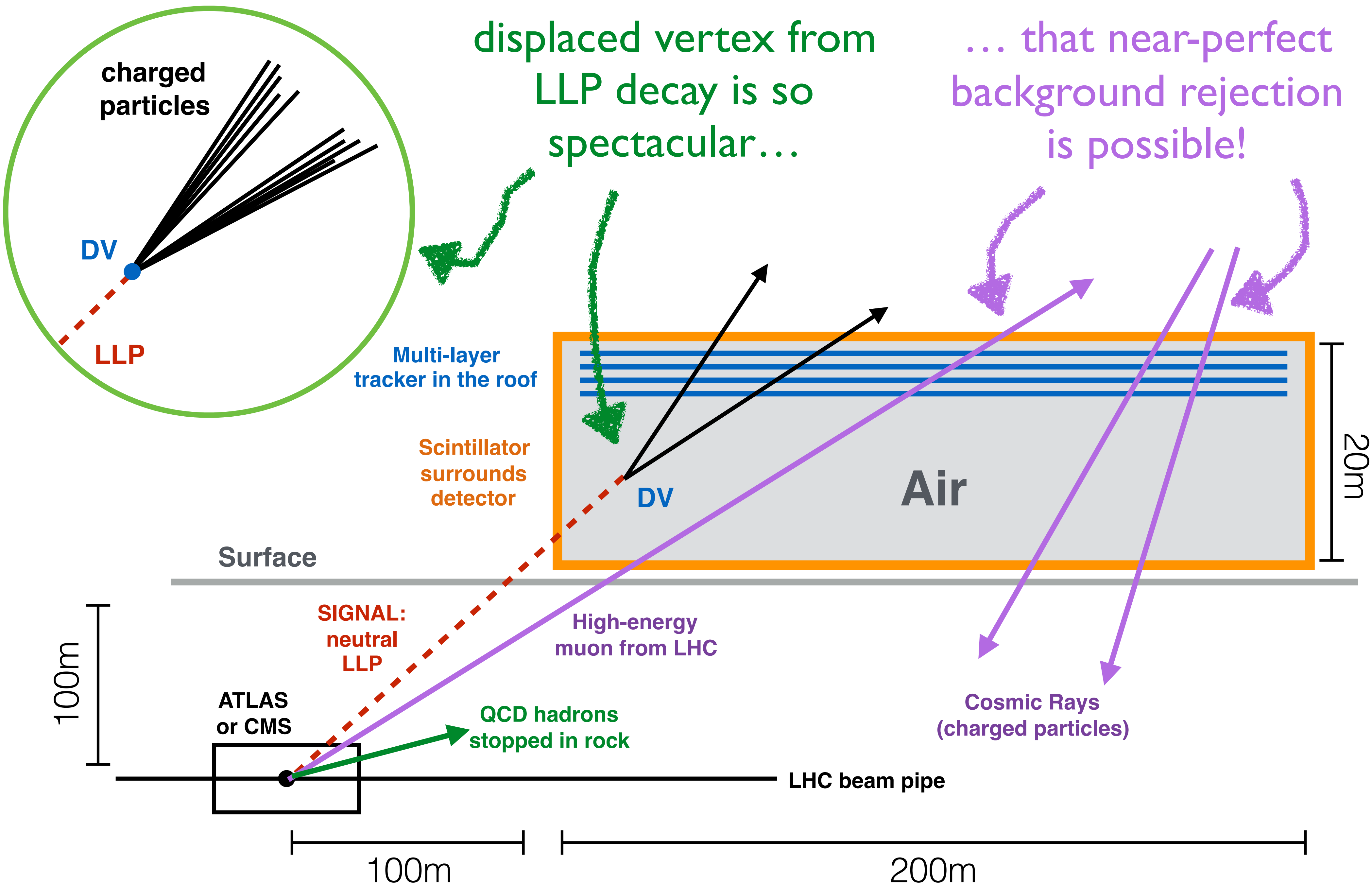
+ ~ 50

On track for

prototype mid 2017
letter of intent end 2017

theory physics case white paper mid 2017

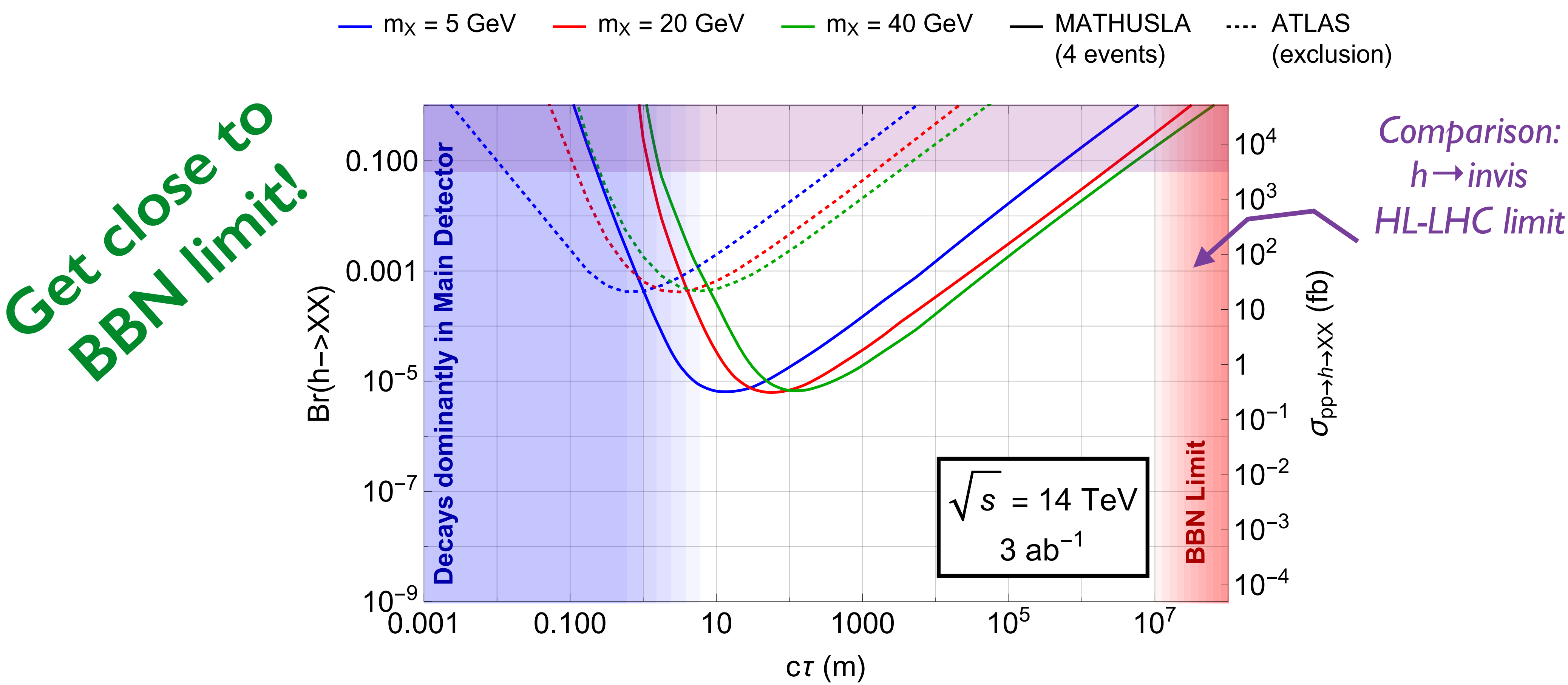
th+exp Join us!
We're growing fast…



displaced vertex from LLP decay is so spectacular…
… that near-perfect background rejection is possible!
charged particles
DV
LLP
Multi-layer tracker in the roof
Scintillator surrounds detector
DV
Air
20m
Surface
SIGNAL: neutral LLP
High-energy muon from LHC
Cosmic Rays (charged particles)
100m
ATLAS or CMS
QCD hadrons stopped in rock
LHC beam pipe
100m
200m

Example of Achievable Sensitivity

For LLP production in exotic Higgs decays:



3 orders of magnitude better than ATLAS search for single DV in MS due to much lower (or ~ zero) backgrounds

LLP Searches at the FCC-hh

LLPs @ FCC-hh

LLP searches should be part of design process NOW!
(Trigger issues??)

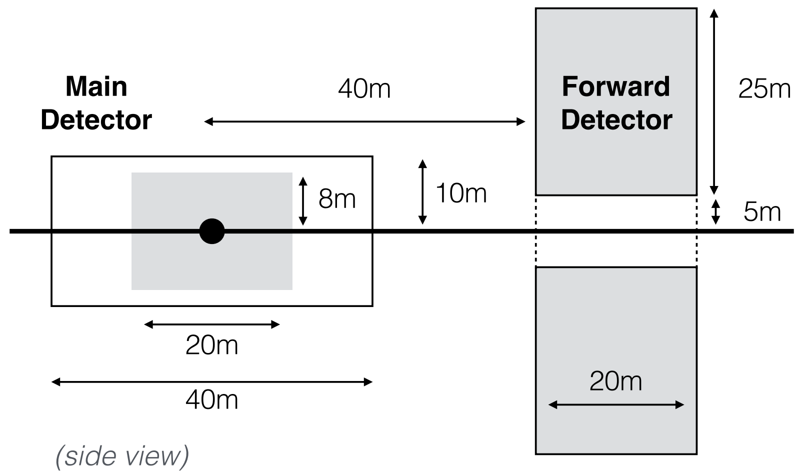
Hugely motivated:

- makes 10^{10} Higgs bosons → LLPs?
- other "light" states like Higgsinos, where only high production rate allows us to see their displaced signatures?
- *directly* produce heavy states that decay to hidden sectors?

Hard to know now e.g. what backgrounds for these searches would be, but is likely to be an issue just as for LHC…

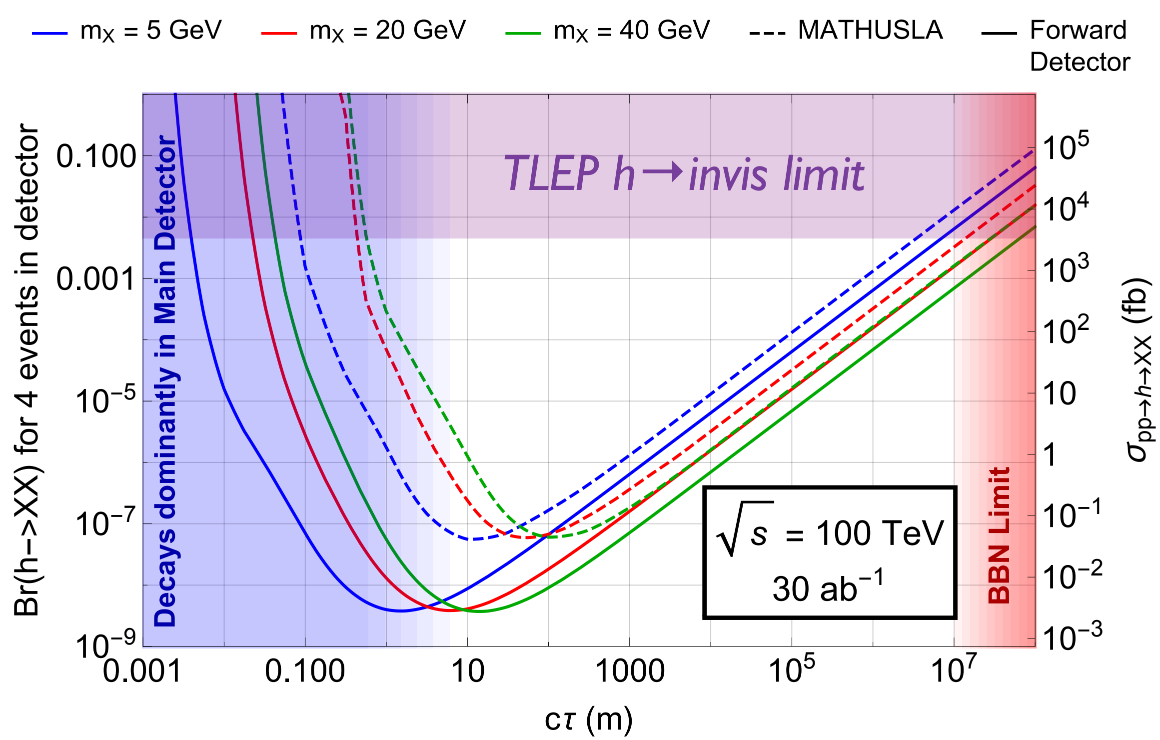
Relatively cheap **part of the solution:**
An underground dedicated LLP detector!

Incremental Add-On: LLP Detector!



When digging a new tunnel, cavity for dedicated LLP detector carries very little additional cost!

Compact sub-surface design can achieve much better sensitivity than TLEP for any ULLPs from exotic Higgs decays



LLP Searches at the FCC-ee

LLPs @ FCC-ee

Superpowers:
ultra-clean events
full center-of-mass reconstruction
muuuuuch less QCD background
no triggering issues?

not Superpowers:
lower energy and
production rates, e.g.
10^6 Higgs bosons
~ 1/100 of HL-LHC

LLPs:

Geometrical acceptances similar to LHC or FCC-hh

might be able to beat HL-LHC (w/o MATHUSLA) for EW-scale **LLP with ultra long lifetimes** by factor of 10 in sensitivity

possible killer app: **LLPs with very short lifetimes!**

LLPs with very short decay lengths

Think about exotic Higgs decays as example: relatively low-mass LLP source that FCC-ee could probe. (Also: Higgsinos etc…)

Make 1/100 as many Higgses as HL-LHC, but no triggering issues. So for **Higgs → short-decay-length LLPs** might end up with similar number of decays "on tape"

At these short lifetimes, LHC might be good at reconstruction (b-tag regime) but even after trigger requirements (VBF, lepton) there might be QCD backgrounds which limit sensitivity.

FCC-ee is so clean, it might do *much* better finding LLPs with such short lifetimes!

Conclusions

Conclusions

LLP searches highly motivated in many theories & scenarios

LHC LLP search program is getting underway
Lots of work left to be done to cover all accessible scenarios.
We might actually get lucky and find something!

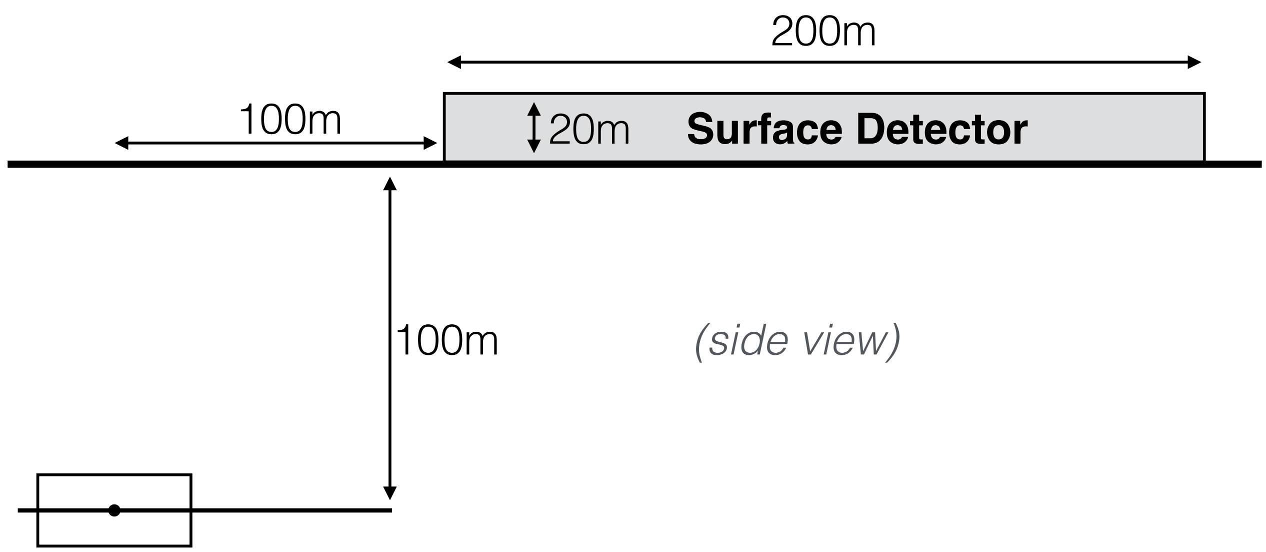
Qualitatively new opportunity at HL-LHC: MATHUSLA can extend LLP sensitivity by factor of 10^3!!

Make sure that FCC-hh and FCC-ee detectors can do LLP searches!

Plan an extra cavern at FCC-hh for dedicated LLP detector!

Extra Material

MATHUSLA Surface Detector



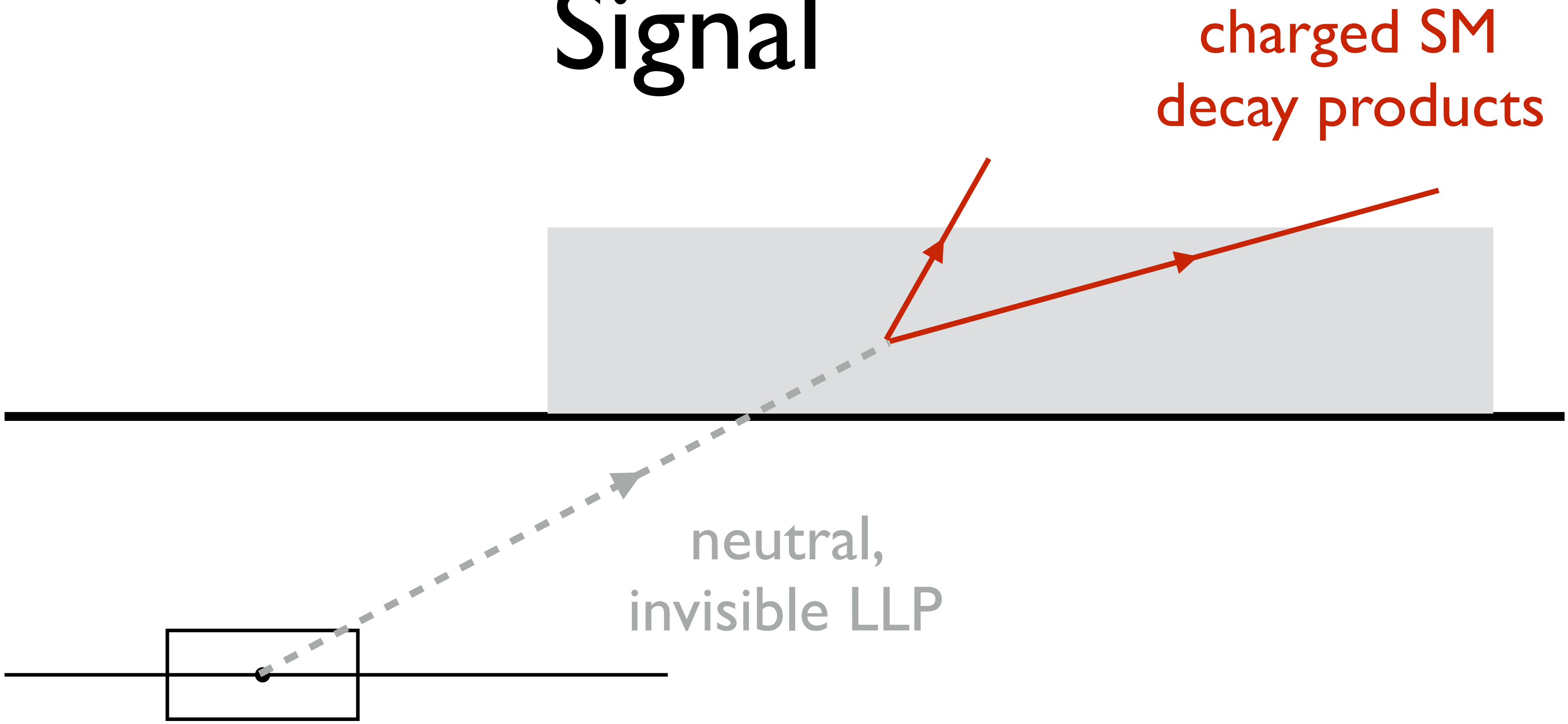
Dedicated detector for ultra-long-lived particle (ULLP) decays.

~5% geometric coverage.

Can we operate in the near-background-free regime?

How to design the detector?

Signal

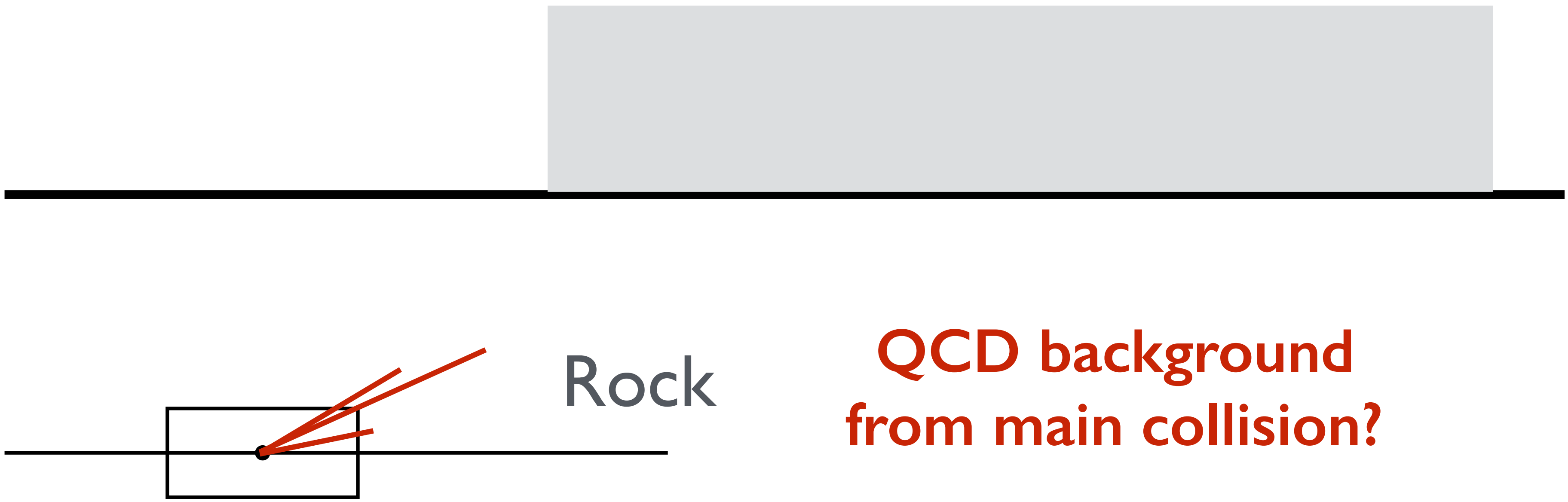


Need to detect this.
How exactly? Depends on backgrounds!

Backgrounds

QCD background from main collision?

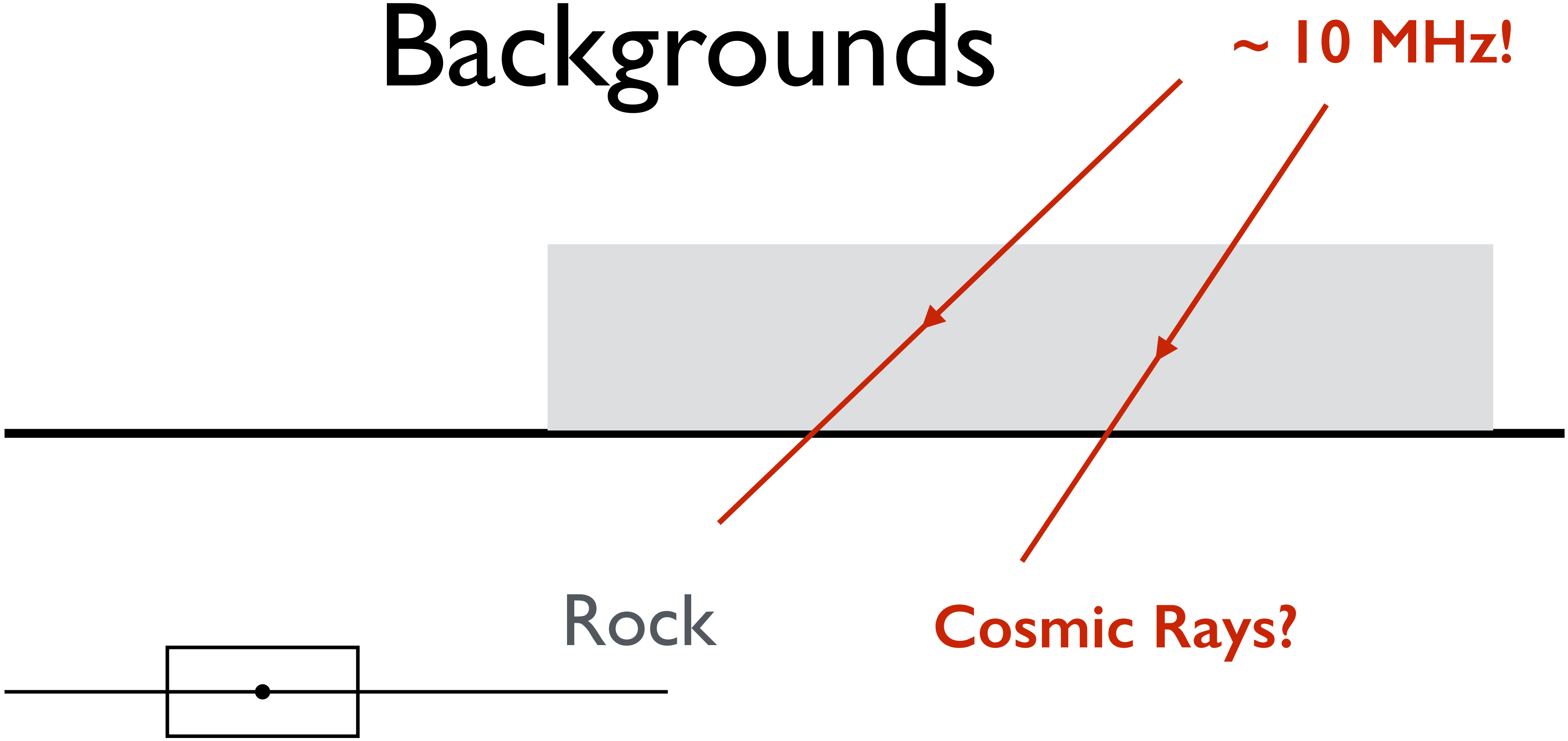
Backgrounds



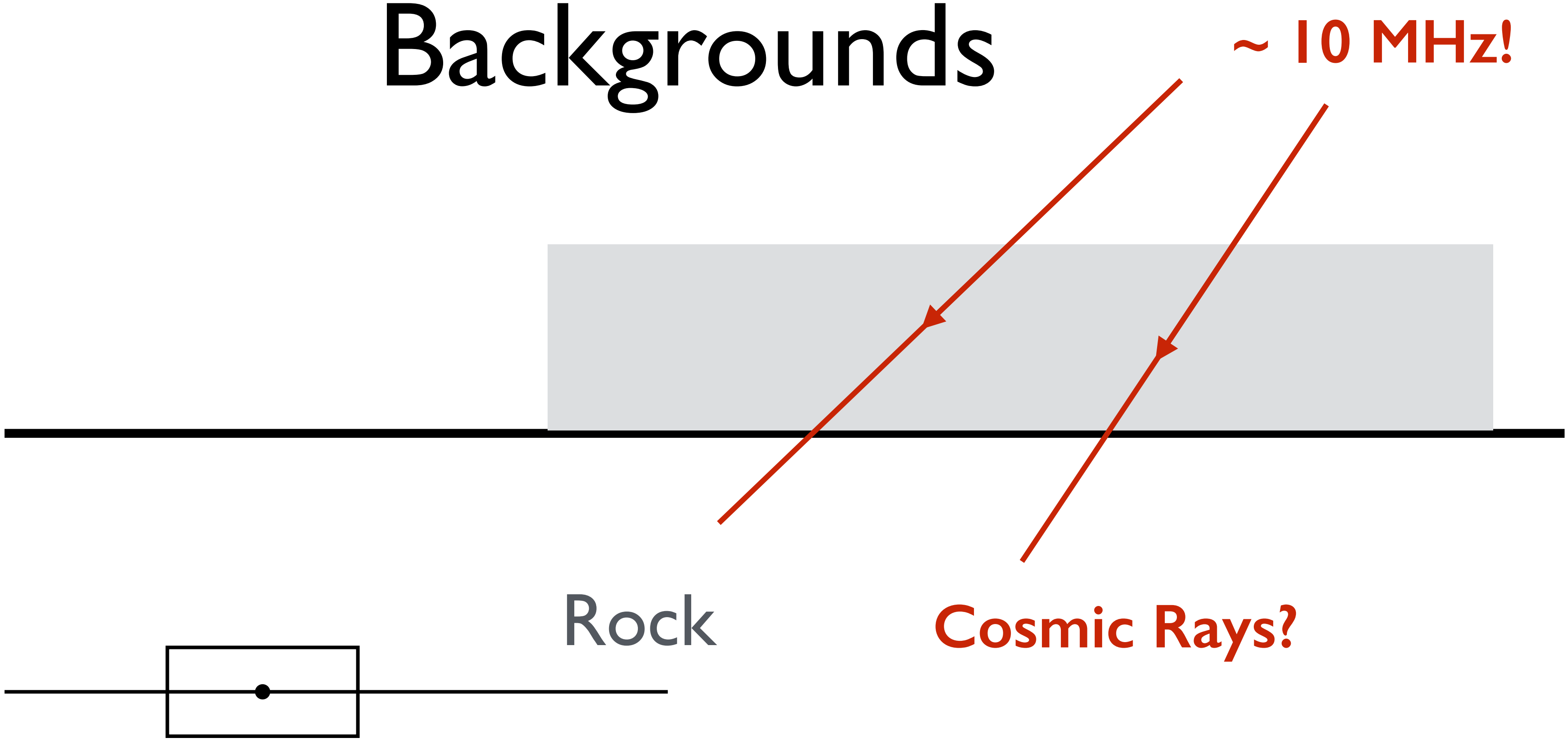
QCD background from main collision?

More than 100m of rock is a *very* effective shield.

Backgrounds

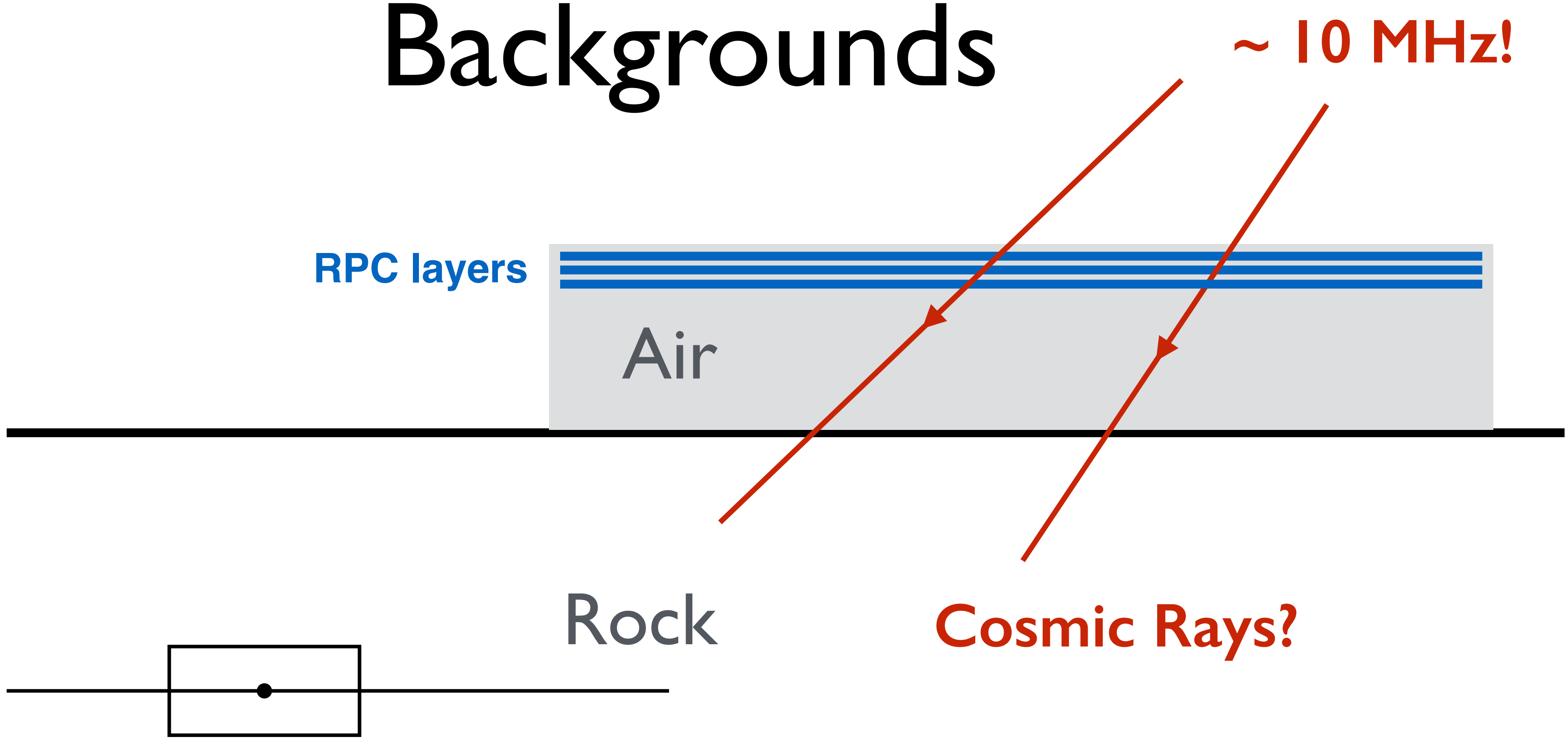


Backgrounds



Do not reconstruct a displaced vertex.
Travel downwards.

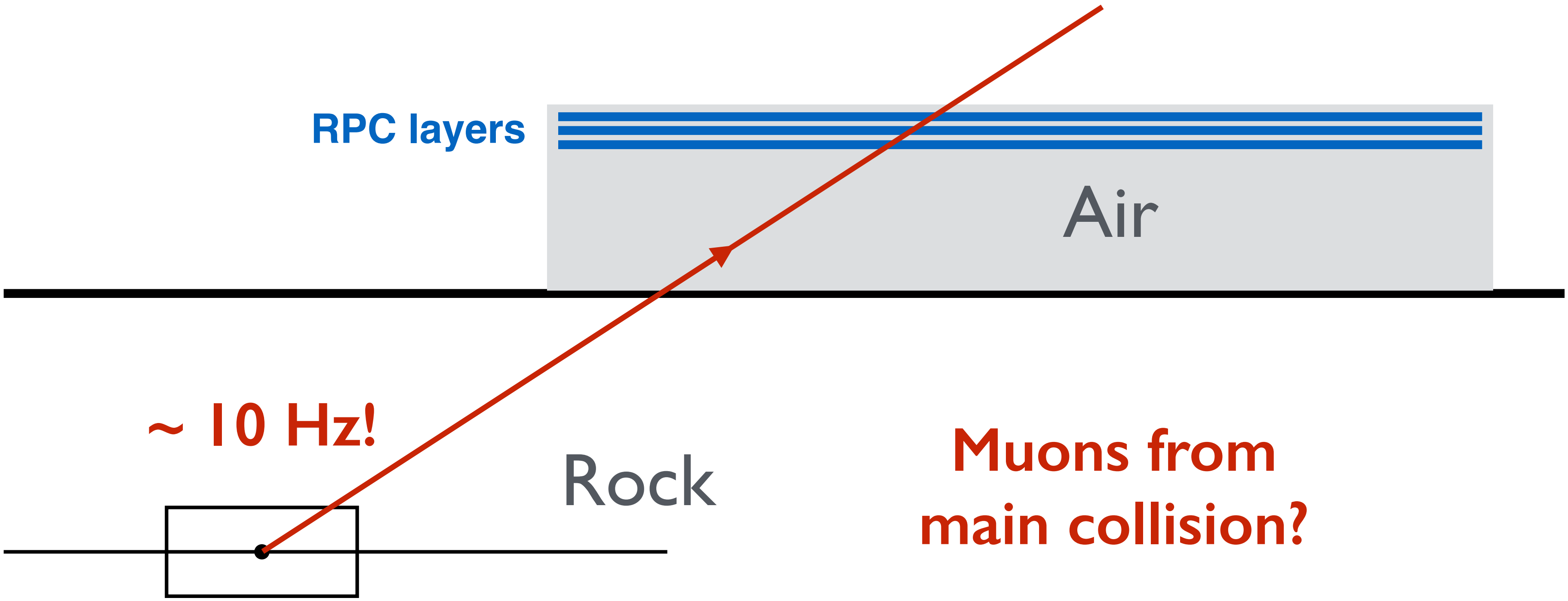
Backgrounds



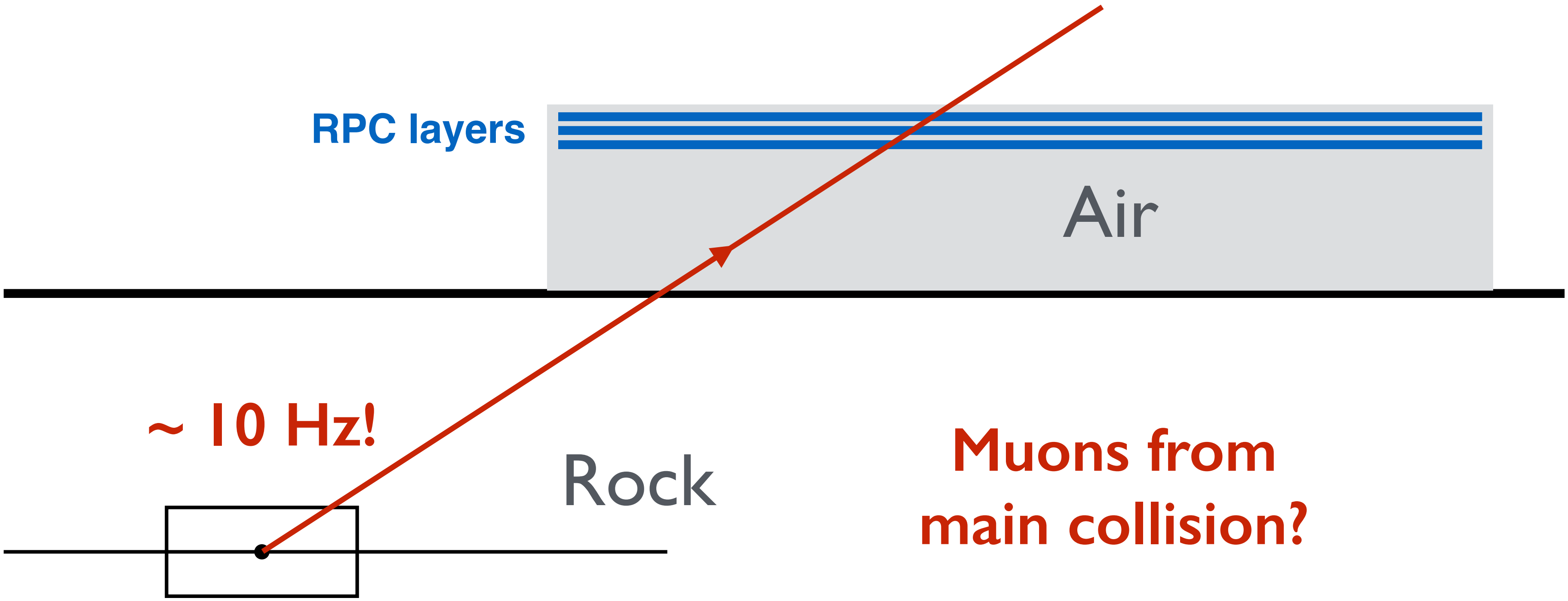
Do not reconstruct a displaced vertex.
Travel downwards.

Can reject with tracking and time-of-flight measurement in ceiling!

Backgrounds



Backgrounds



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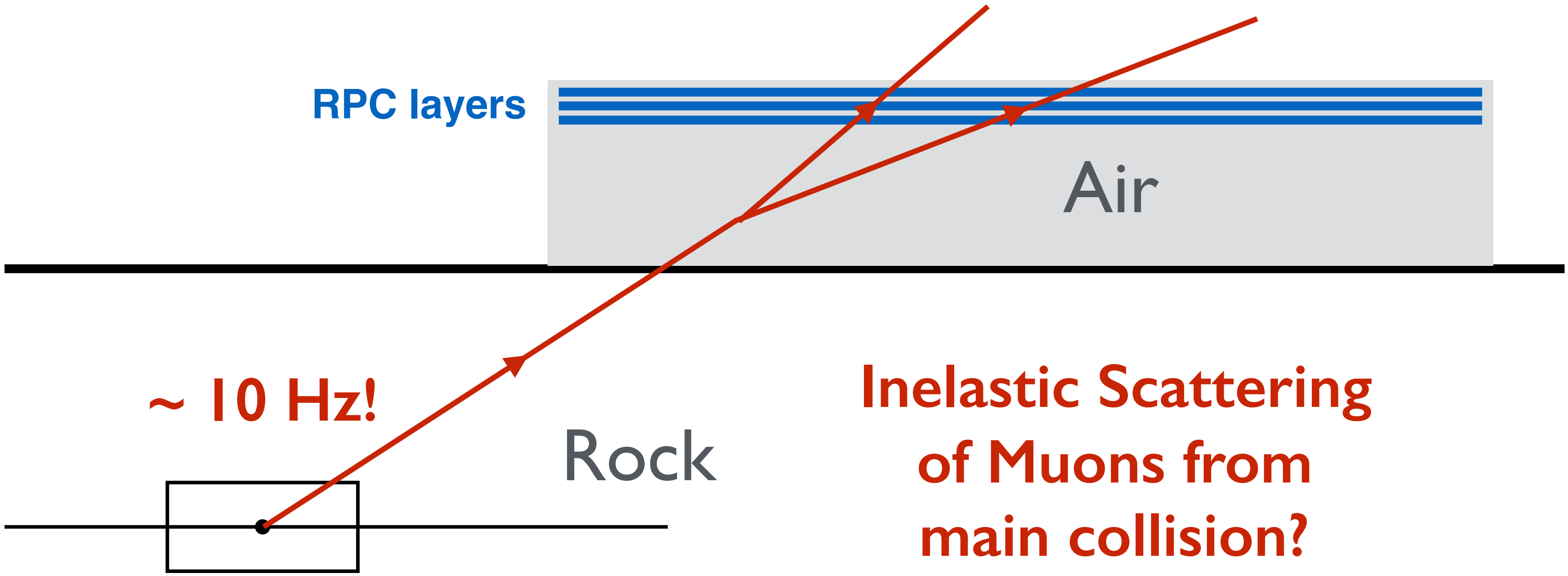
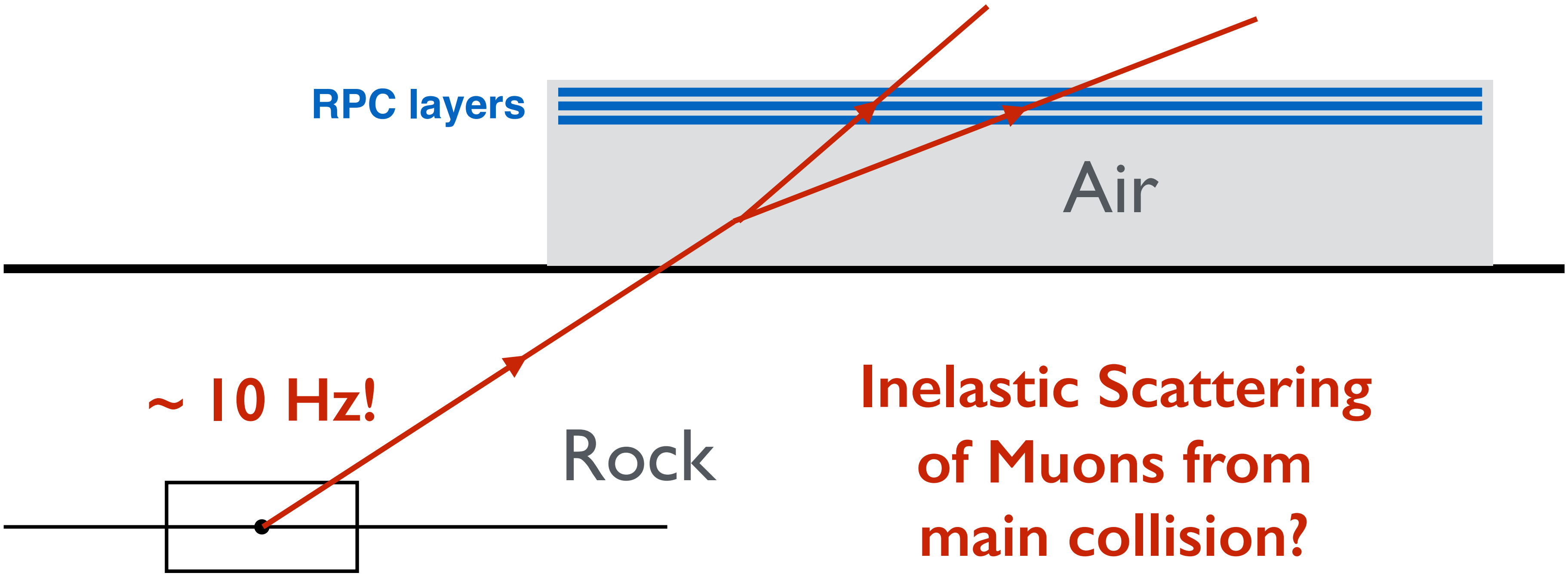


Inelastic Scattering of Muons from main collision?

Backgrounds

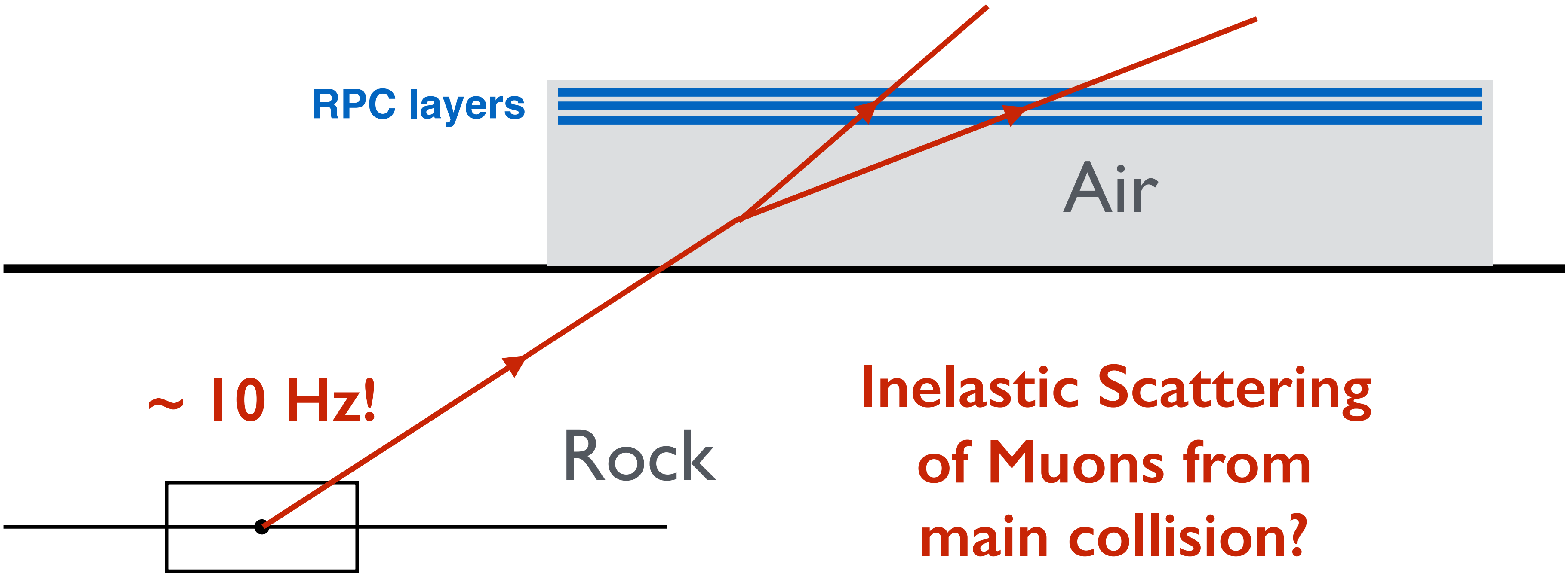


Inelastic Scattering of Muons from main collision?

Only O(10) such events over HL-LHC run.

Has to pass through floor.

Backgrounds

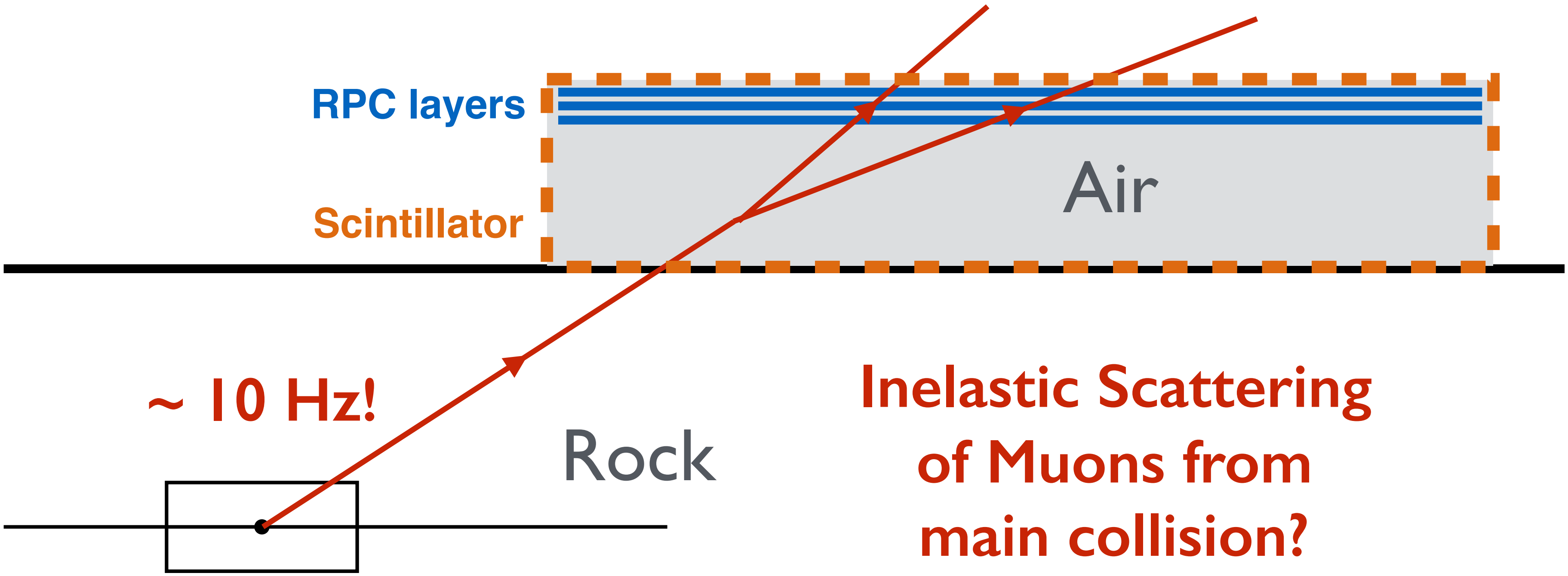


Only O(10) such events over HL-LHC run.

Has to pass through floor.

We could veto these events with main detector muon trigger.

Backgrounds



Inelastic Scattering of Muons from main collision?

Only O(10) such events over HL-LHC run.

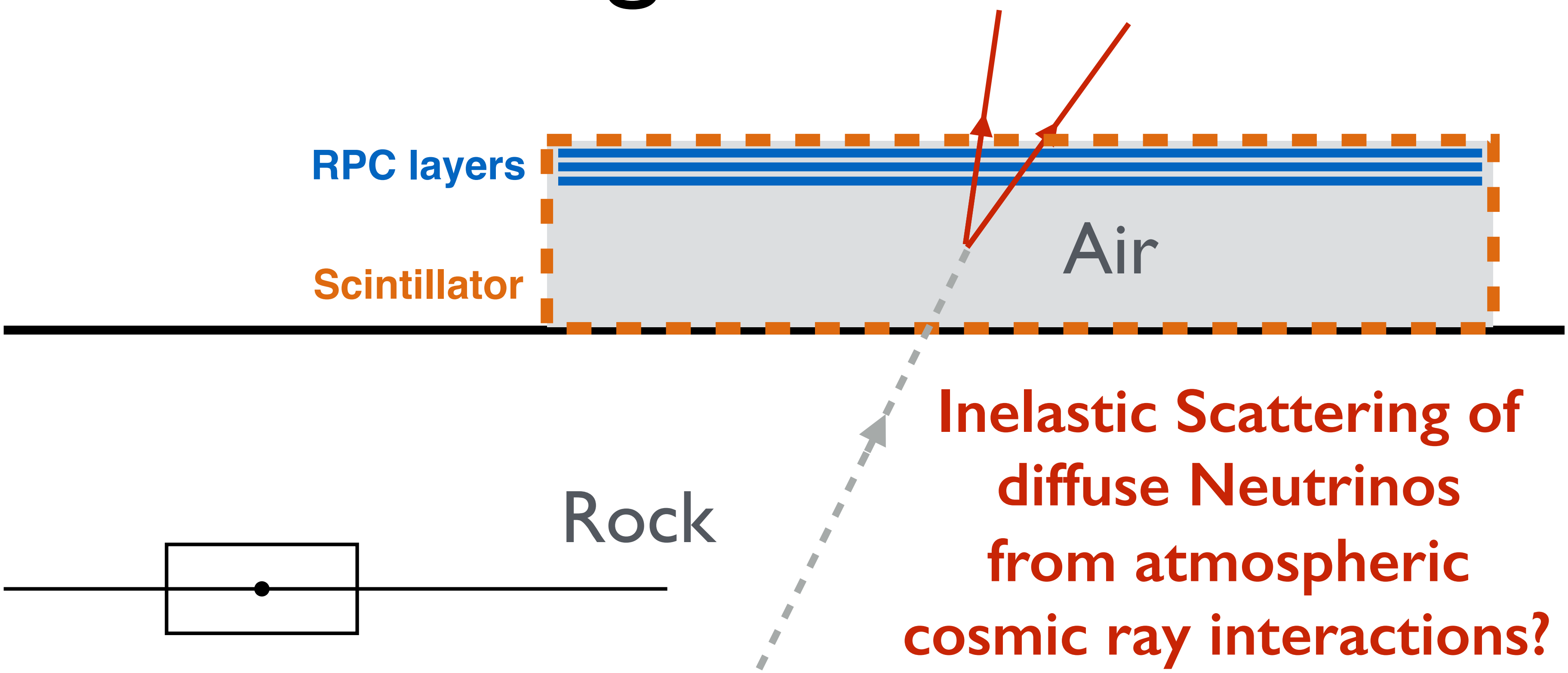
Has to pass through floor.

Surround volume with Scintillator Veto!

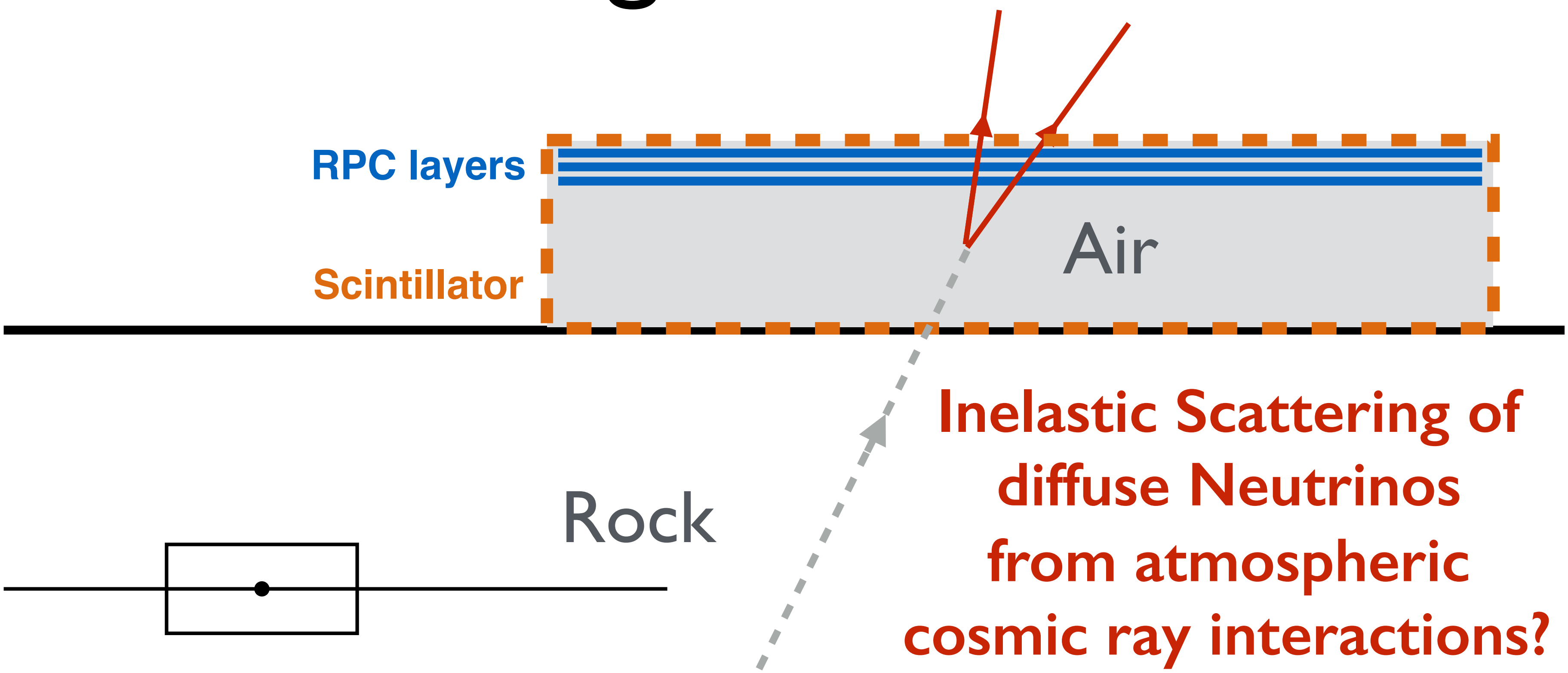
Also gives additional rejection power for stray cosmics

Would allow search for one-pronged LLP decays!

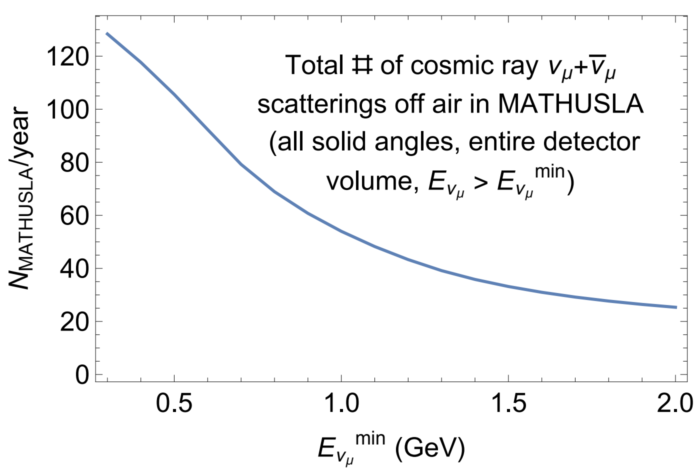
Backgrounds



Backgrounds



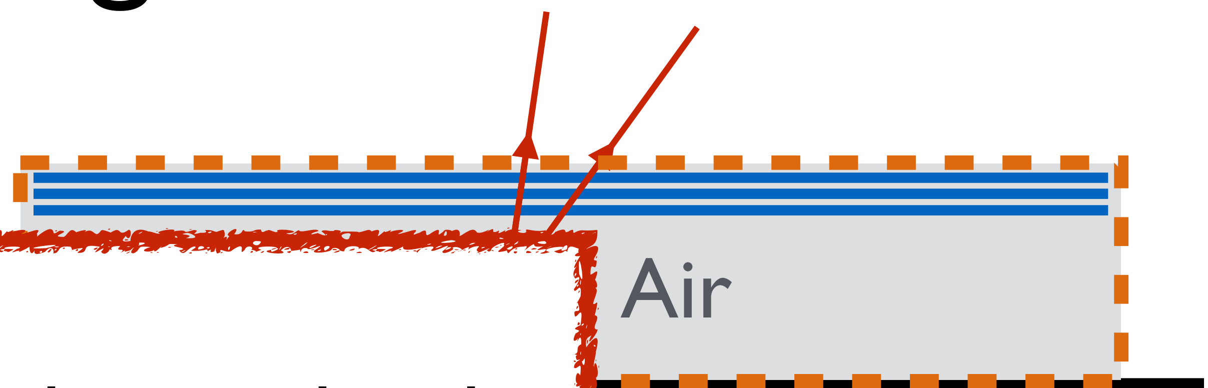
Inelastic Scattering of diffuse Neutrinos from atmospheric cosmic ray interactions?



Low rate ~ 10-100 per year above 300 MeV.

Final state proton is SLOW: can reject 99+% with time-of-flight measurement!

Backgrounds



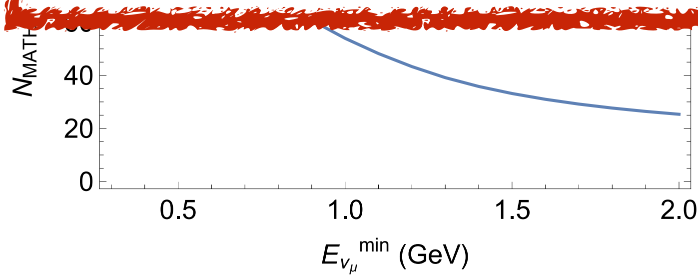
This is the biggest background and it can be rejected with cuts.

Furthermore, it can be thoroughly MEASURED and STUDIED during beam downtime!

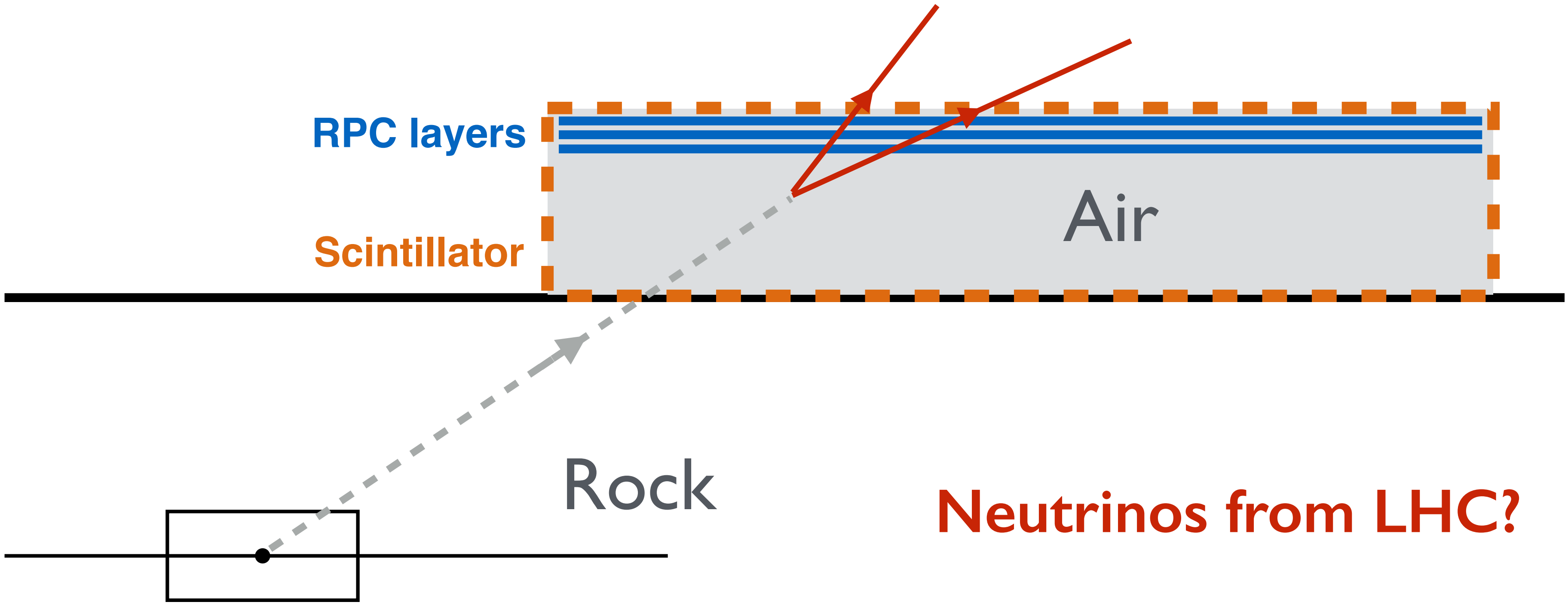
astic Scattering of
ffuse Neutrinos
om atmospheric
ic ray interactions?

100 per year
0 MeV.

Final state proton is SLOW: can reject 99+% with time-of-flight measurement!



Backgrounds



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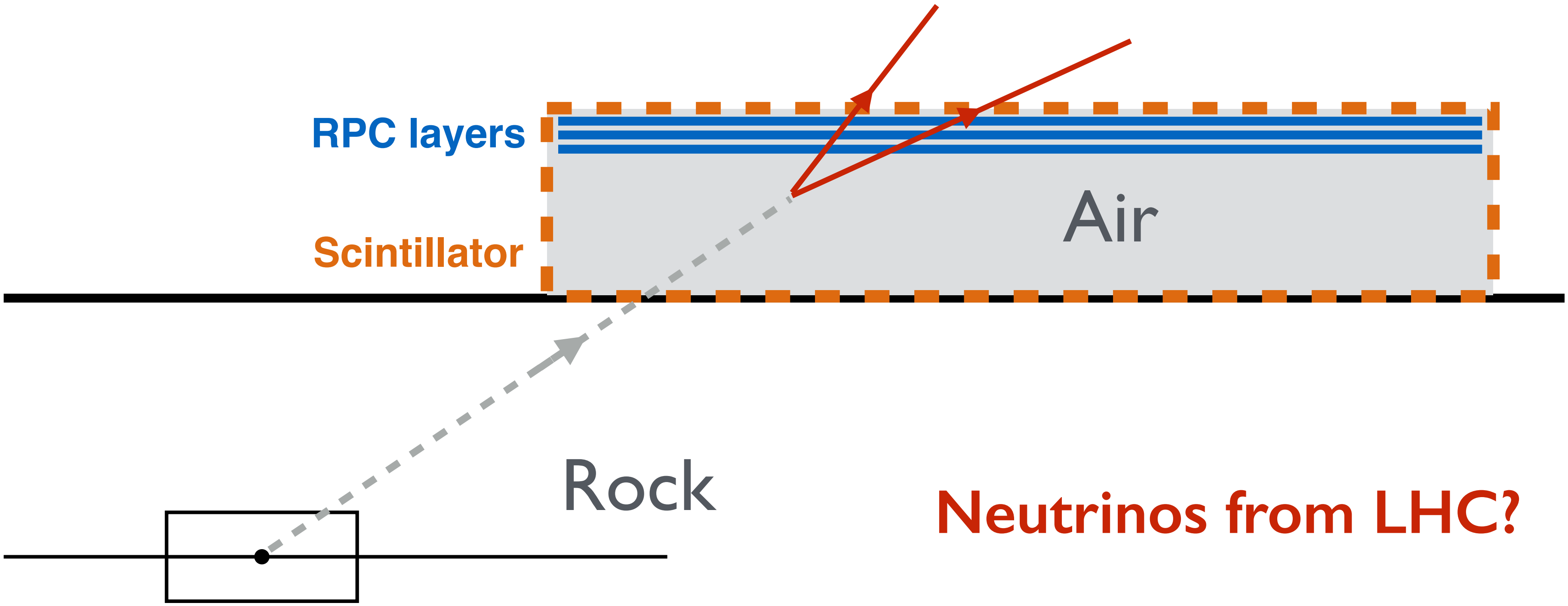
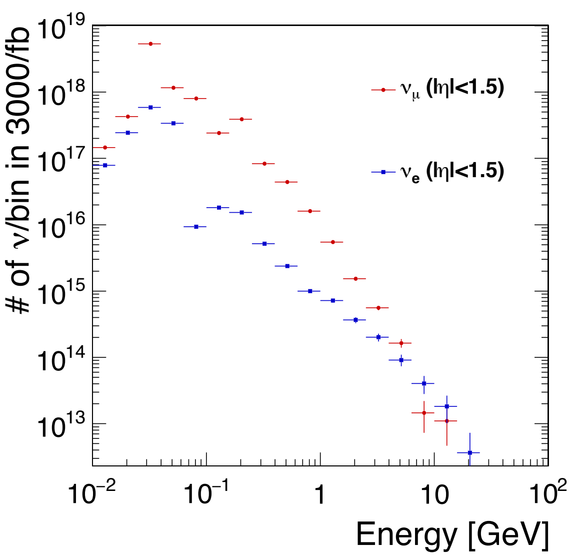
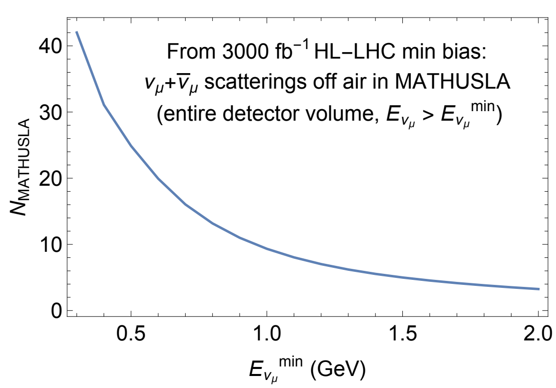




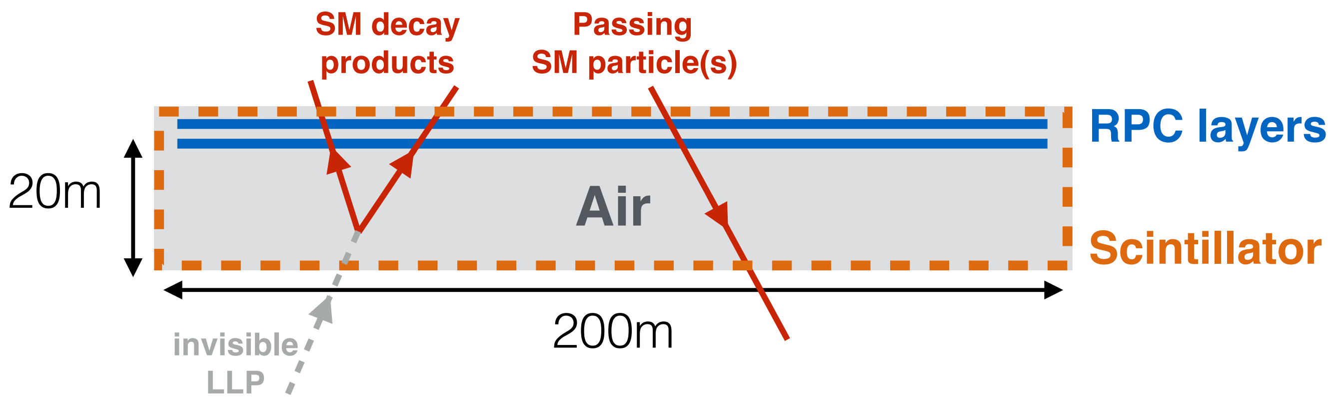


Neutrinos from LHC?

Same as cosmic neutrinos but they point back at IP. Same cuts can reject!

Significant rate uncertainty, but only O(10) over entire HL-LHC lifetime!

Design Sketch



Layers of RPCs in the roof act as a directional **tracker**.
Scintillators give additional **veto**.
~ns timing, ~cm position resolution.

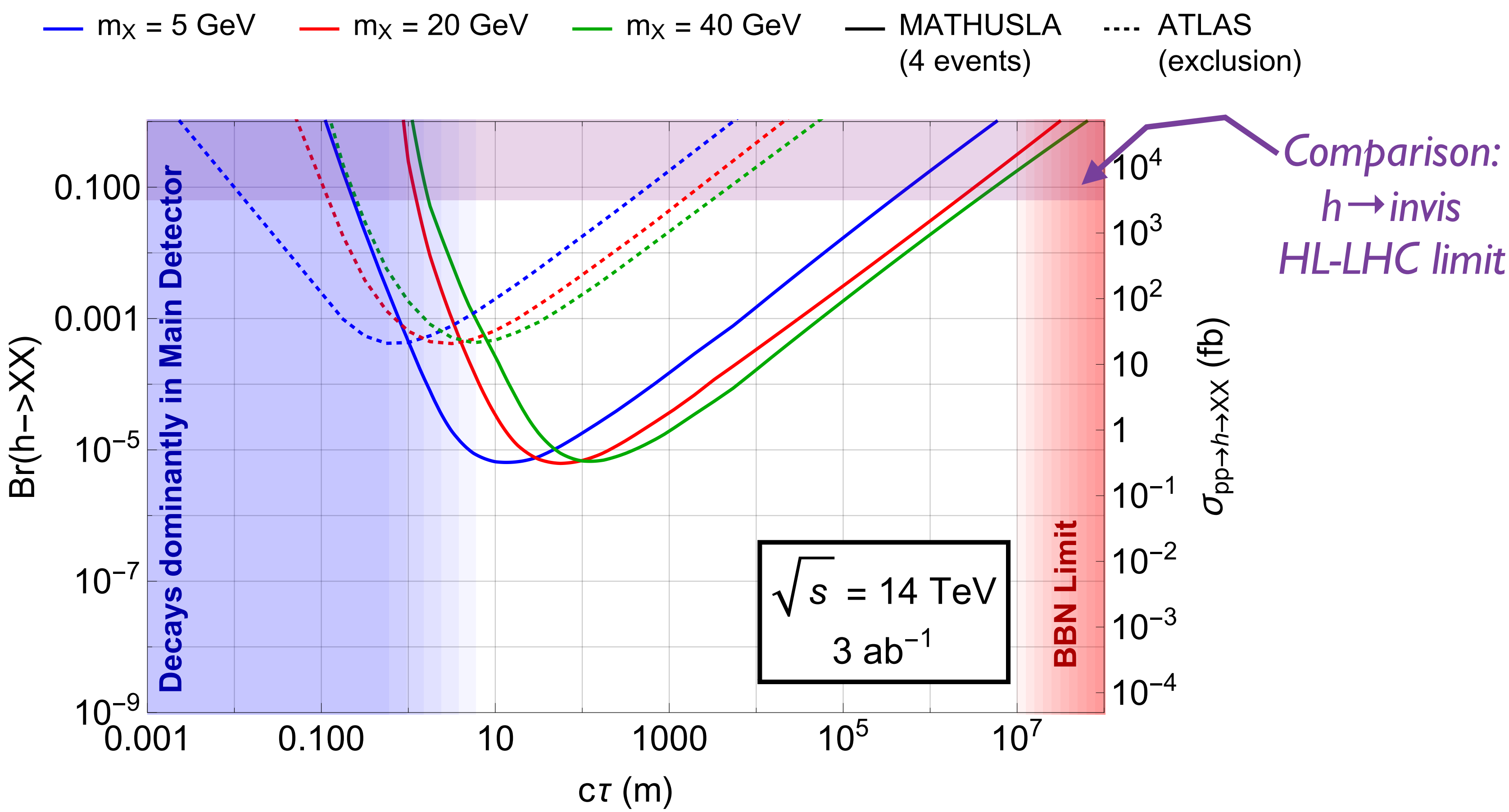
Reconstructed vertex and **time-of-flight measurement** of final states allows for **near-background-free LLP search**

Preliminary estimates: sensor cost of O(20 million USD)

Example of Achievable Sensitivity

For LLP production in exotic Higgs decays:

Get close to BBN limit!



3 orders of magnitude better than ATLAS search for single DV in MS

General Purpose LLP Detector

MATHUSLA is sensitive to any produced neutral LLPs!

How to nail down production mode?

Inclusive VBF/Vh trigger at LHC could "tag" MATHUSLA events as "invisible" Higgs decays.

Could check whether signals in MET searches really are dark matter!

LLP Diagnosis

DC, Peskin
[in preparation]

Let's be greedy:
Can we learn anything about a discovered LLP?

MATHUSLA is a precise 3D tracker and nothing else.

LLP Diagnosis

DC, Peskin
[in preparation]

Let's be greedy:
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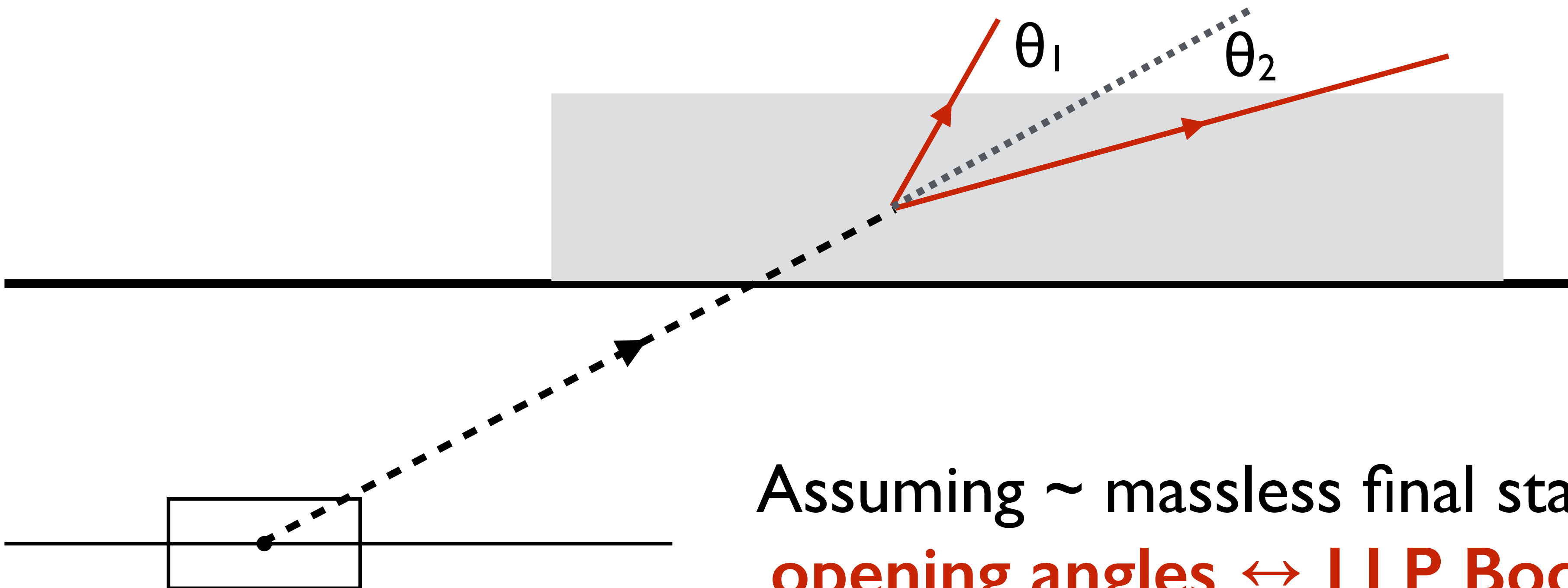


Assuming ~ massless final states:
opening angles ↔ LLP Boost!

LLP Diagnosis

DC, Peskin
[in preparation]

If LLP is discovered (and we have some statistics),
we can measure its boost distribution!

For given production mode …
(correlate with main detector events?)
… this reveals LLP mass!

Could we diagnose the LLP decay products?

LLP Diagnosis

DC, Peskin
[in preparation]

Its huge size gives MATHUSLA excellent spatial resolution, as well as speed measurement of NR particles.

track multiplicity can distinguish jets vs leptons

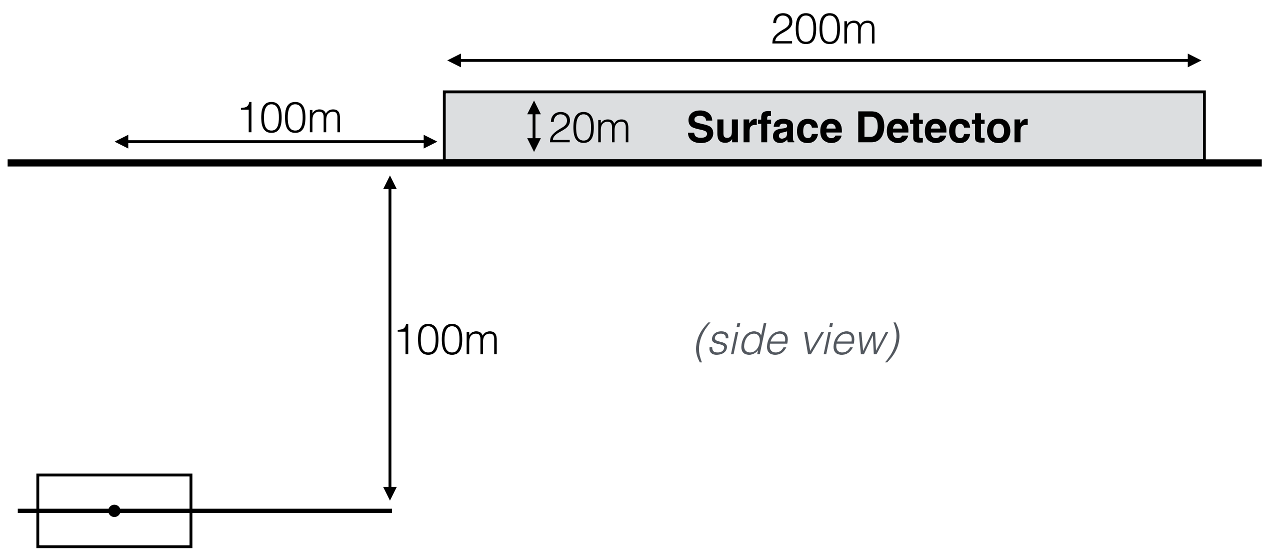
with a bit of showering material: e vs μ?

heavy flavor vs light flavor jet???
is there some information in hadron speed distribution?

Interesting MacGyver Physics Challenge!

OK so what's the plan…

Build this for the HL-LHC Upgrade!



Crazy Expensive? Nope!

Hallow! Air-filled! Room-Temperature!

Low-rate high-threshold environment.

Only the **outside area** of the detector volume needs to be instrumented with relatively simple detectors.

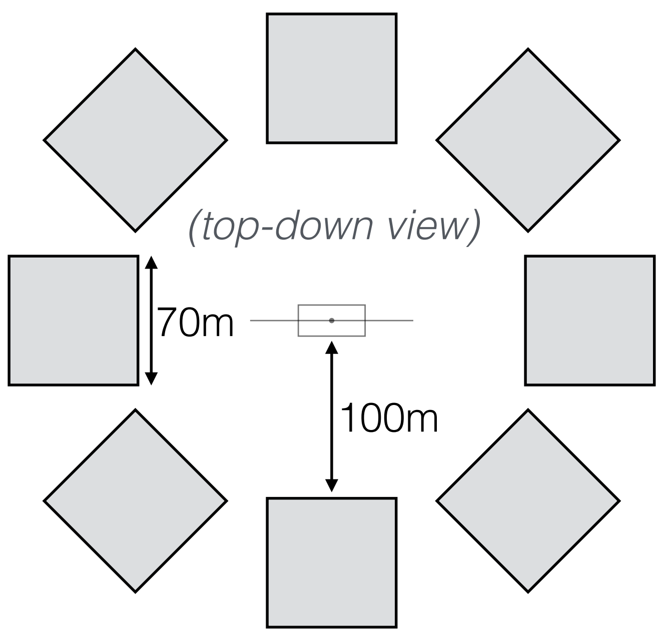
Available Space

need ~ one
nearby farm plot

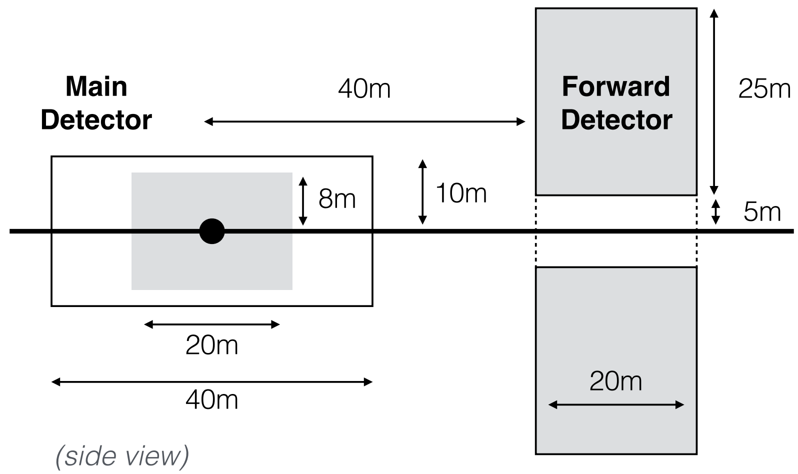
Available Space

Geometry is very flexible!

Could have distributed design,
even split between ATLAS and CMS sites!

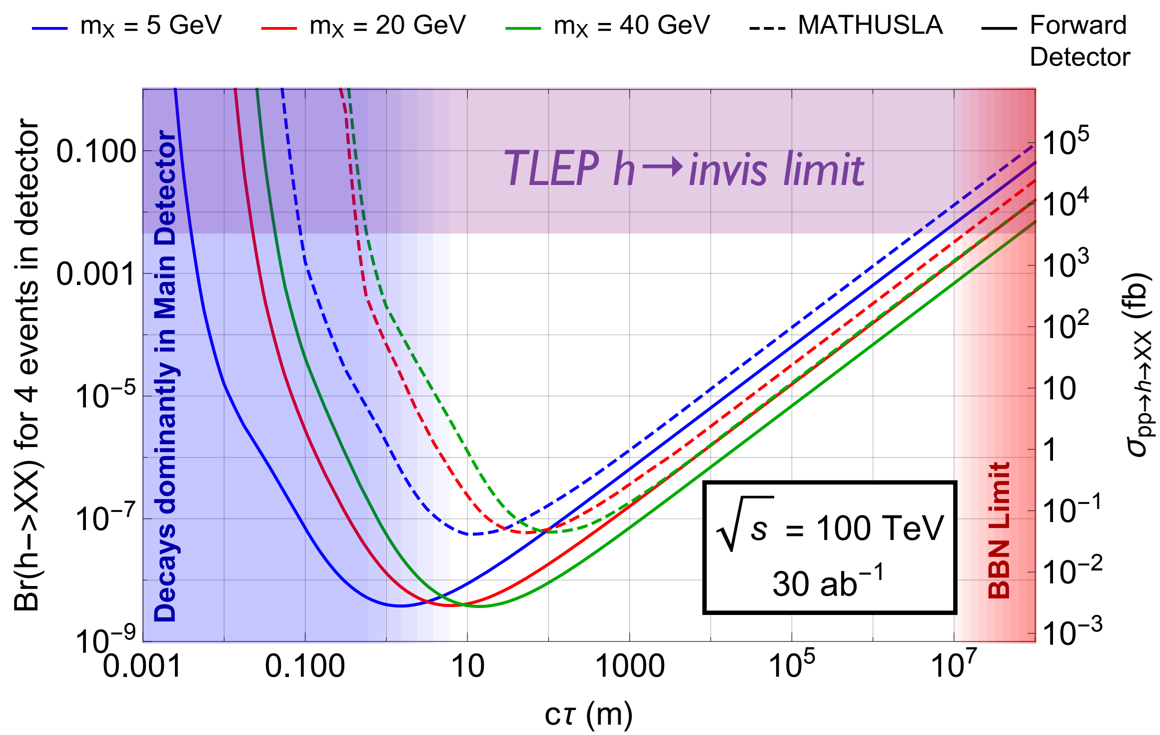


Aside: Start Planning for 100 TeV!



When digging a new tunnel, cavity for dedicated ULLP detector carries very little additional cost!

Compact sub-surface design can achieve much better sensitivity than TLEP for any ULLPs from exotic Higgs decays



To Do

Experiment:

Build Prototype

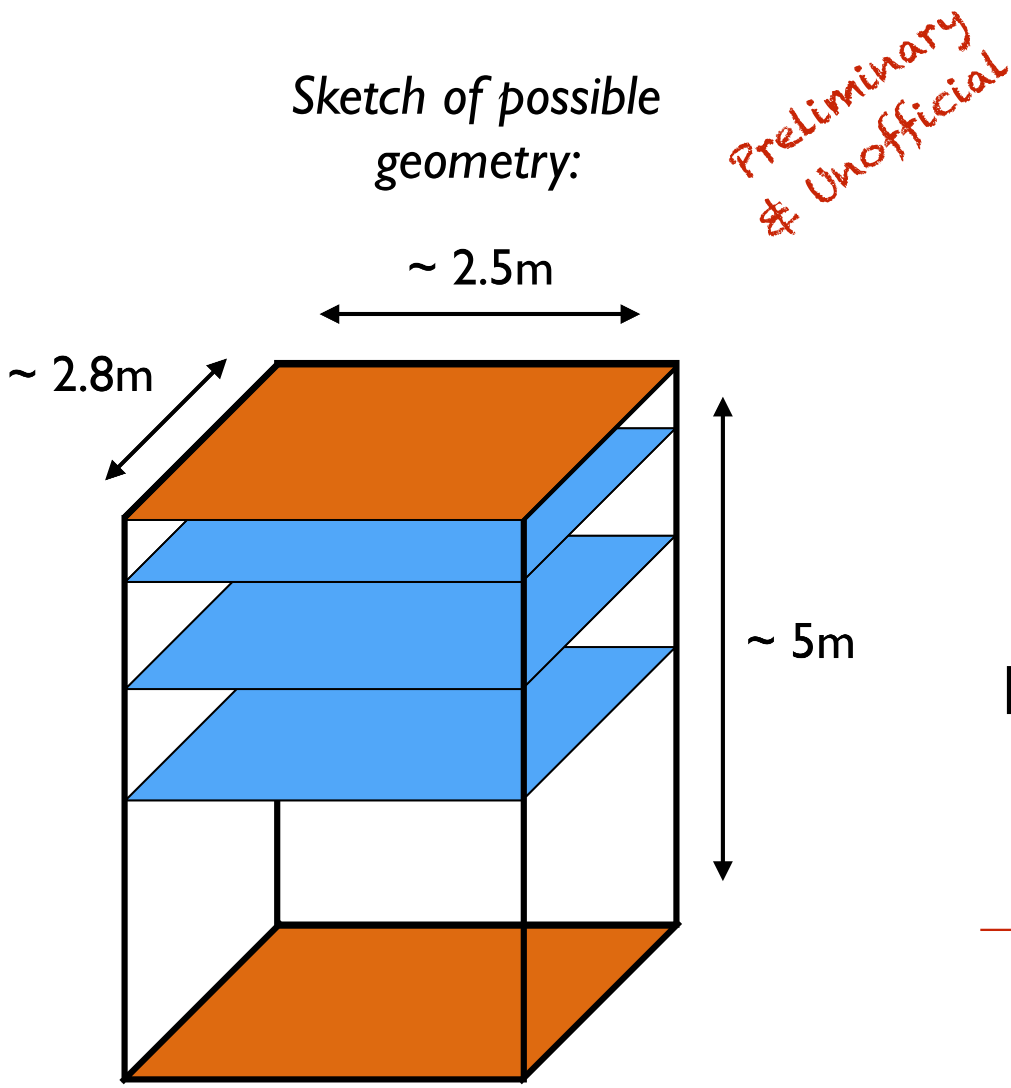
Theory:

White-paper describing the physics case

MATHUSLA Prototype

Required to validate design, background estimates, etc..

Sketch of possible geometry:



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!*

RPCs

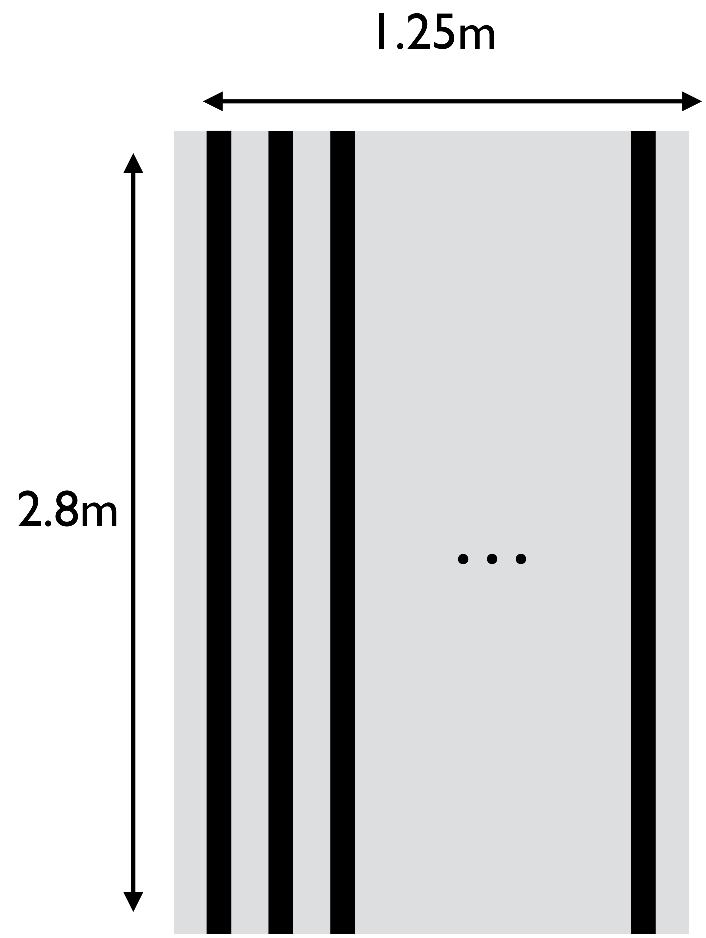
Supplied by University of Rome Tor Vergata, chambers + DAQ systems from prototype of ARGO cosmic shower experiment in Tibet

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

These old chambers run in streamer mode, final MATHUSLA RPCs will run in avalanche mode and possibly have better resolution.

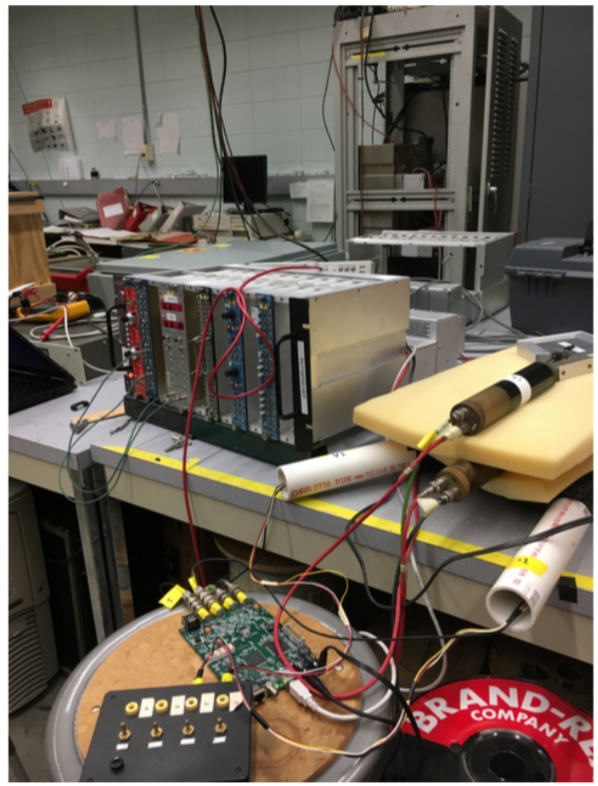
Use gas supply in ATLAS instrument hall

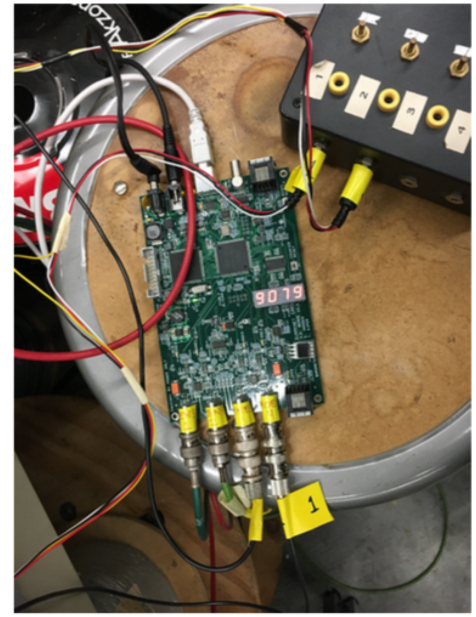


Strips 3cm wide, 2cm spacing

Scintillator

- Use D0 muon tiles + PMTs with Quarknet DAQ board
  - good timing resolution (~1.5 ns) and noise characteristics
  - DAQ has four channel input, provides digitized time and time-above-threshold
  - working out issues with DAQ
    - reflections?
    - how to distribute clock?





Building a MATHUSLA collaboration

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University of Maryland 1856

David Curtin

TEL AVIV UNIVERSITY

Erez Etzion

Aim: take test data & write letter of intent 2017!

Join us! We're growing fast…

MATHUSLA Theory White Paper

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

Editors:
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Soliciting contributions from the theory community…

Aim: release comprehensive report early 2017!