Neutral LLP Searches at Future Colliders

1st FCC Physics Workshop
CERN

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University of Maryland

Outline

1. Motivation

2. Lessons from the (HL-) LHC

3. Neural LLP Searches at the FCC-hh

4. Neutral LLP Searches at the FCC-ee

5. Conclusion

See also Sho Iwamoto's talk on Charged LLPs

See Oliver Fischer's talk for some FCC-ep possibilities..

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

Curtin et al, 1312.4992

— Exotic Higgs Decays —

The Higgs is an excellent source of new physics!

Any BSM sector can couple to Higgs with renormalizable or low-dimension effective operator.

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2 \qquad \Delta\mathcal{L} = \frac{\mu}{\Lambda^2} |H|^2 \bar{\psi}\psi$$

Light-ish BSM states can be produced in exotic Higgs decays. Only have to compete with small bottom yukawa ~0.02.

Even small Br gives many events!

Very motivated LLP production mode!

HL-LHC will make 10^8 Higgses	FCC-hh will make 10^{10} Higgses	FCC-ee will make 10^6 Higgses

See Chris Verhaaren's talk

Theory Examples

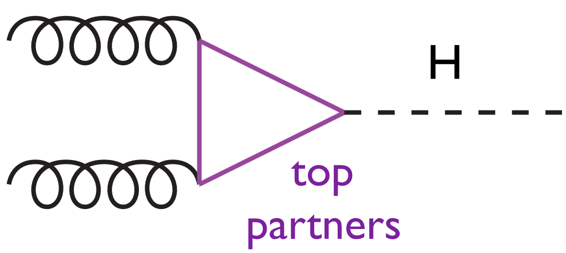
Chacko et al hep-ph/0506256
Craig et al 1501.05310
Curtin et al 1506.06141
...

— 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*.



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

Theory Examples

— WIMP Baryogenesis —

Cui et al 1212.2973
…

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

Metastable WIMP is LLP, can be produced at colliders.

— FIMP DM —

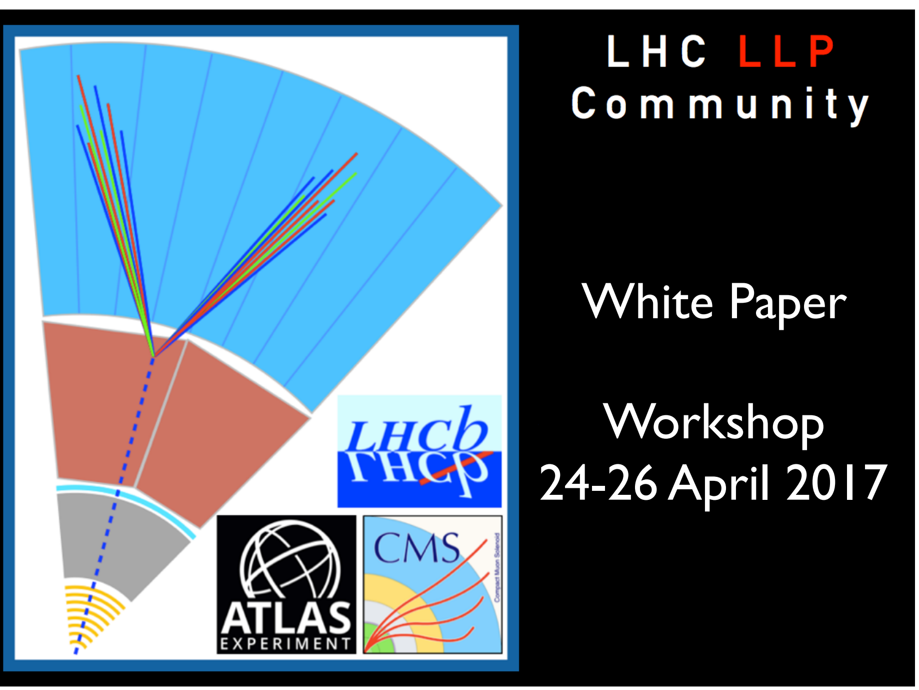
Hall et al 0911.1120
…

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)

Neutral LLP Searches:

"Lessons" from the (HL-) LHC



LLP searches are still very much a work in progress at the LHC.

Join us!!

Lessons from the LHC

A neutral LLP decaying in the detector
is a **spectacular** signature…

Distinctiveness of Signature in Detector:

Heavy charged track/deposition > **Displaced Decay** > Missing Energy

… but there can still be **some backgrounds**.

e.g. inclusive displaced vertex (DV) search in ATLAS Muon System at HL-LHC has ~O(100fb) equivalent backgrounds

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

Lessons from the LHC

1. Backgrounds

a) We don't know how to simulate most BG for LLP decays. Complicated mix of reducible and reducible (mostly QCD). **One aim for LHC: develop mix of MC & data-driven techniques for reliably estimating these backgrounds!**

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

b) Luckily, background is often very small:

DV + X ⇒ Very little background

High quality **displaced vertex** — **Something else** that's kinda rare

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)*

Lessons from the LHC

2. Triggering

A DV in the tracker, with no other handles (v. high energy, leptons..) cannot be L1 triggered on at LHC due to its geometrically complex nature.

Potential for great improvement at FCC.

Motivation for trigger-less operation, or at least low-level triggering with complete event reconstruction!

Lessons from the LHC

Lifetime Frontier

Short lifetimes < ~ mm

Long lifetimes > ~ 100m

Lessons from the LHC

3. Short lifetimes

< ~ mm.

Geometric acceptance of main detector is ~ 100%

Main challenge: backgrounds larger than for longer lifetimes and (not yet) carefully studied in this context.

Lessons from the LHC

3. Short lifetimes

< ~ mm.

Geometric acceptance of main detector is ~ 100%

Main challenge: backgrounds larger than for longer lifetimes and (not yet) carefully studied in this context.

Solution: clean environment

Can afford to produce less LLPs:

→ lepton colliders

Lessons from the LHC

4. Long lifetimes

> ~ 100 m

Geometric acceptance of main detector is low, ~ $L/c\tau$

For large production rates, still have signal, but swamped by backgrounds for inclusive searches!

Lessons from the LHC

4. Long lifetimes

> ~ 100 m

Geometric acceptance of main detector is low, ~ $L/c\tau$

For large production rates, still have signal, but swamped by backgrounds for inclusive searches!

Solution: clean environment + high production rate

Still need high LLP production rates

→ in analogy to neutrinos, we need an
EXTERNAL LLP DETECTOR
for HADRON COLLIDERS!

Example of external LLP detector:

MATHUSLA for the HL-LHC

(will serve as inspiration for FCC)

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 for HL-LHC.

UNIVERSITY of WASHINGTON
Henry Lubatti
Gordon Watts
Cristiano Alpigiani
Audrey Kvam

RUTGERS
John Paul Chou
Amit Lath
Steffie Thayil

TEL AVIV UNIVERSITY
Erez Etzion

UNIVERSITY OF MARYLAND
David Curtin
Sarah Eno

Fermilab
Sunanda Banerjee

Università di Roma Tor Vergata
Rinaldo Santonico
Roberto Cardarelli

SLAC NATIONAL ACCELERATOR LABORATORY
Charles Young
Robert Mina

UDLAP
Mario Rodriguez, Arturo Fernandez Tellez,
Guillermo Tejeda Muñoz, Mario Ivan Martinez,
Mario Rodríguez, Martin Alfonso Subieta,
Martin Hentschinski

+ more

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]

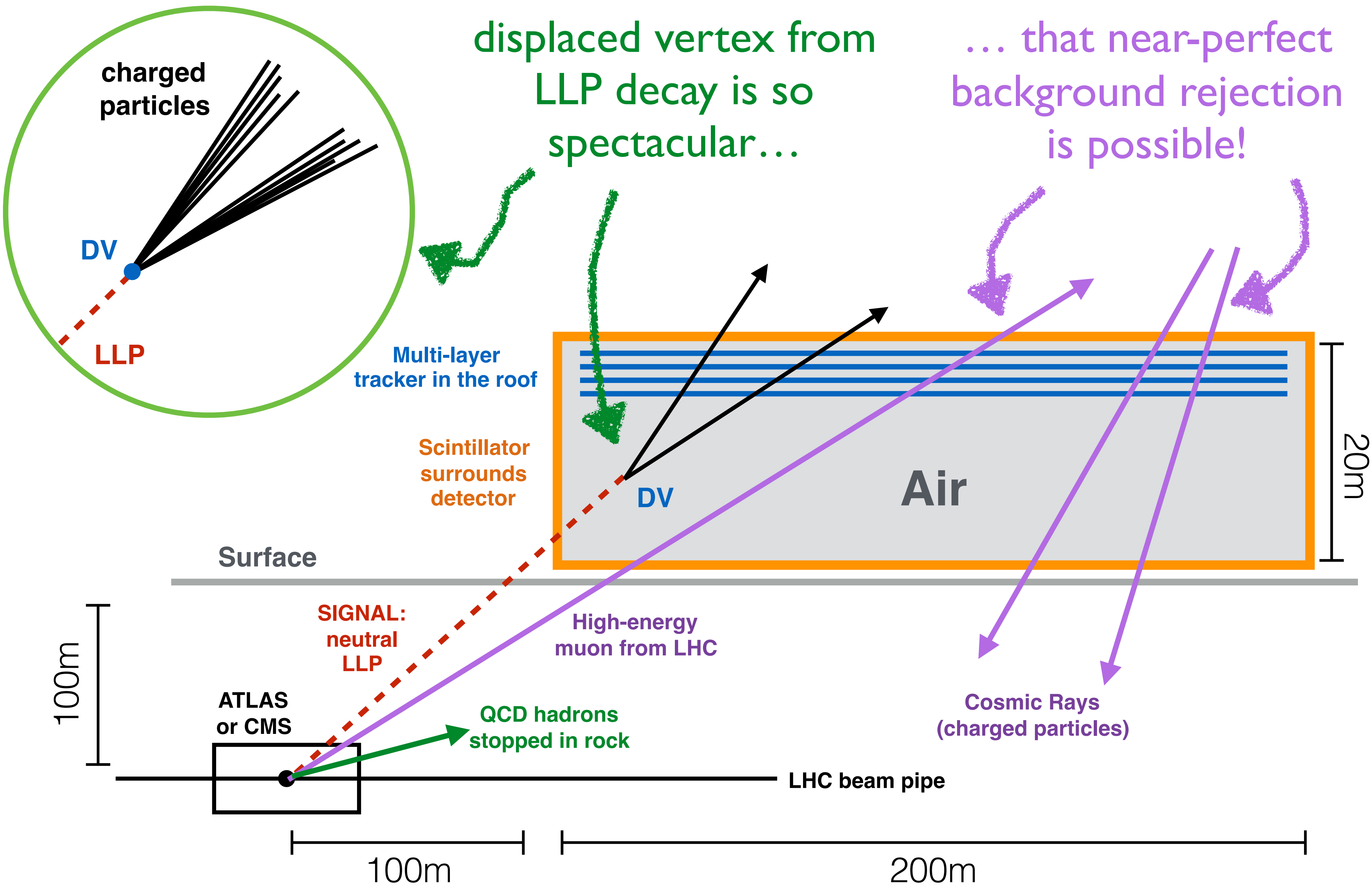
+ ~ 50

On track for

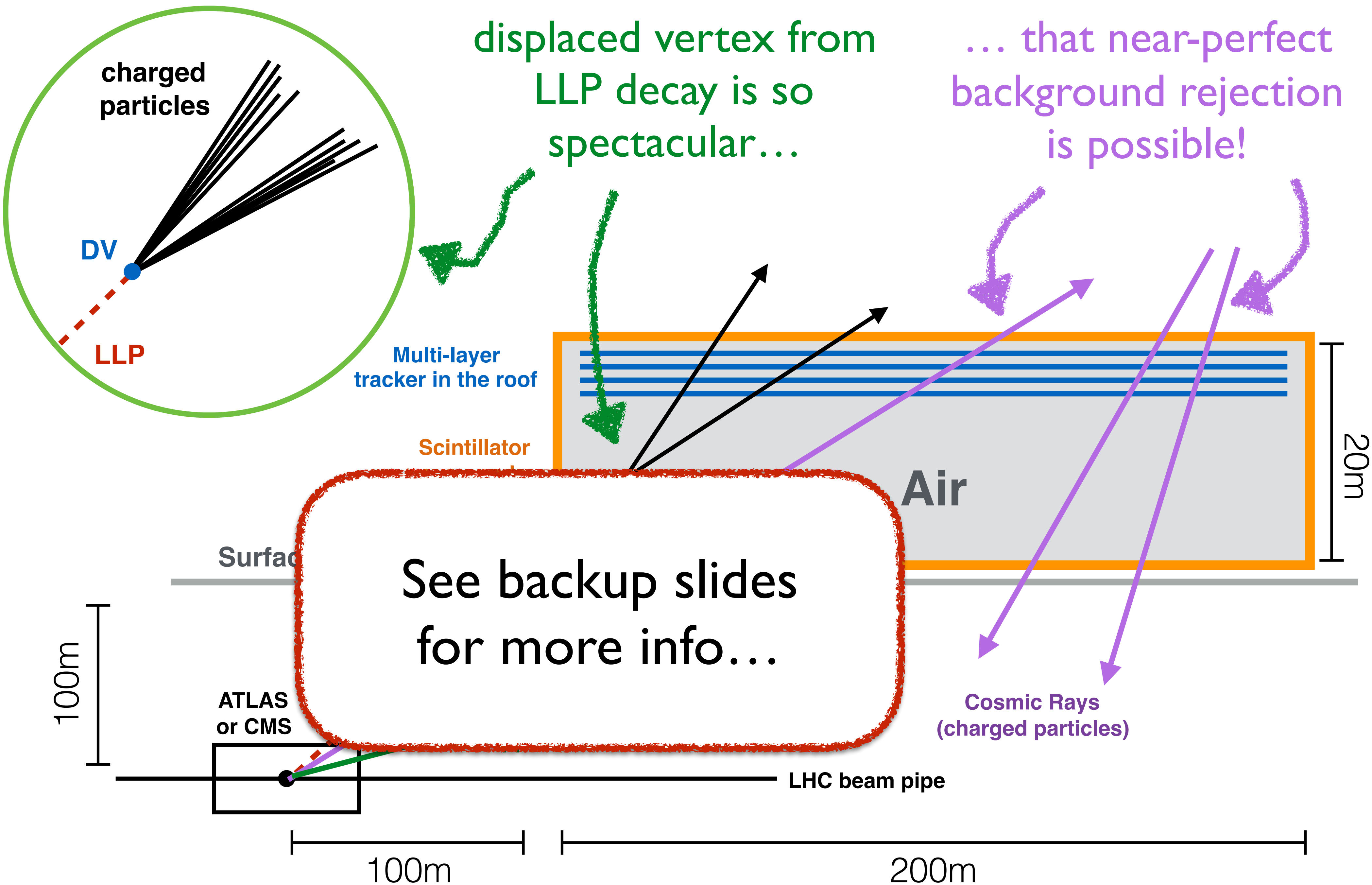
prototype mid 2017
letter of intent end 2017

theory physics case white paper mid 2017

th+exp Join us!



charged particles
DV
LLP
displaced vertex from LLP decay is so spectacular…
… that near-perfect background rejection is possible!
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



charged
particles
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displaced vertex from
LLP decay is so
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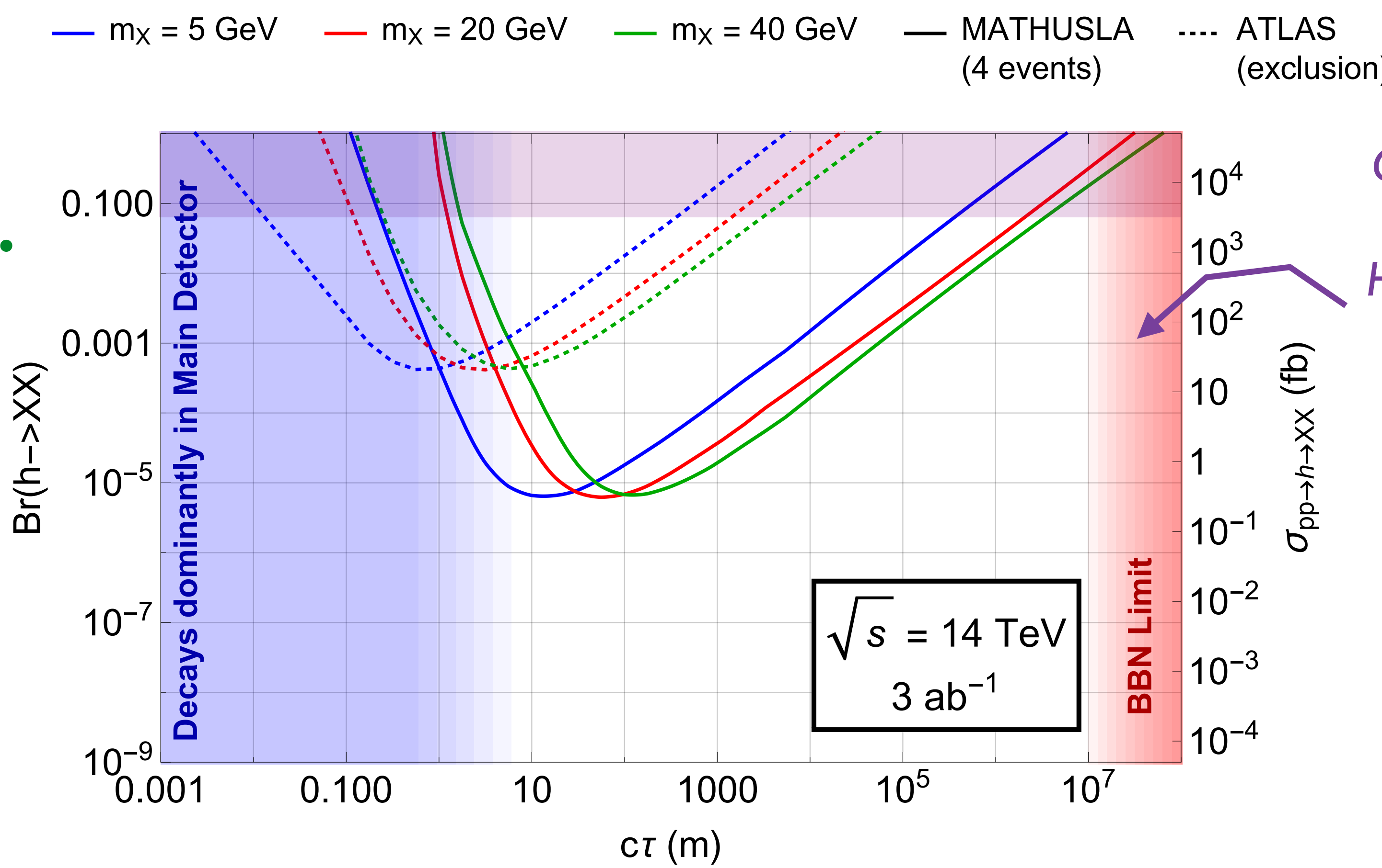
Multi-layer
tracker in the roof
Scintillator
Air
20m
Surfac
See backup slides
for more info…
Cosmic Rays
(charged particles)
100m
ATLAS
or CMS
LHC beam pipe
100m
200m

Example of Achievable Sensitivity

For LLP production in exotic Higgs decays:



Get close to BBN limit!

Comparison: h→invis HL-LHC limit

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

Neutral 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 → exotic H decays to 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?

Concrete theory examples:

- probe multi-TeV neutral top partners and exotic quarks in theories of **Neutral Naturalness** See Chris' talk!
- Probe displaced **dark photons** produced in exotic Higgs decays near the BBN lifetime limit Curtin et al 1412.0018
- Produce **WIMP-like parent particle of baryogenesis** Cui et al 1605.08736

LLPs @ FCC-hh

Many of these LLP searches will have very low background due to conspicuous LLP production or decay process (especially w/ trigger-free operation and good DV recon.)

For many other searches, hard to know what backgrounds would be.

Hopefully next 10 years of work at the LHC will generate significant progress in this regard.

LLPs @ FCC-hh

— Some new possibilities that need further study —

Could **high-p_T Higgs bosons** at the FCC-hh provide a clean environment for studying BSM exotic Higgs decays & LLP production? **Better than using VH production??**

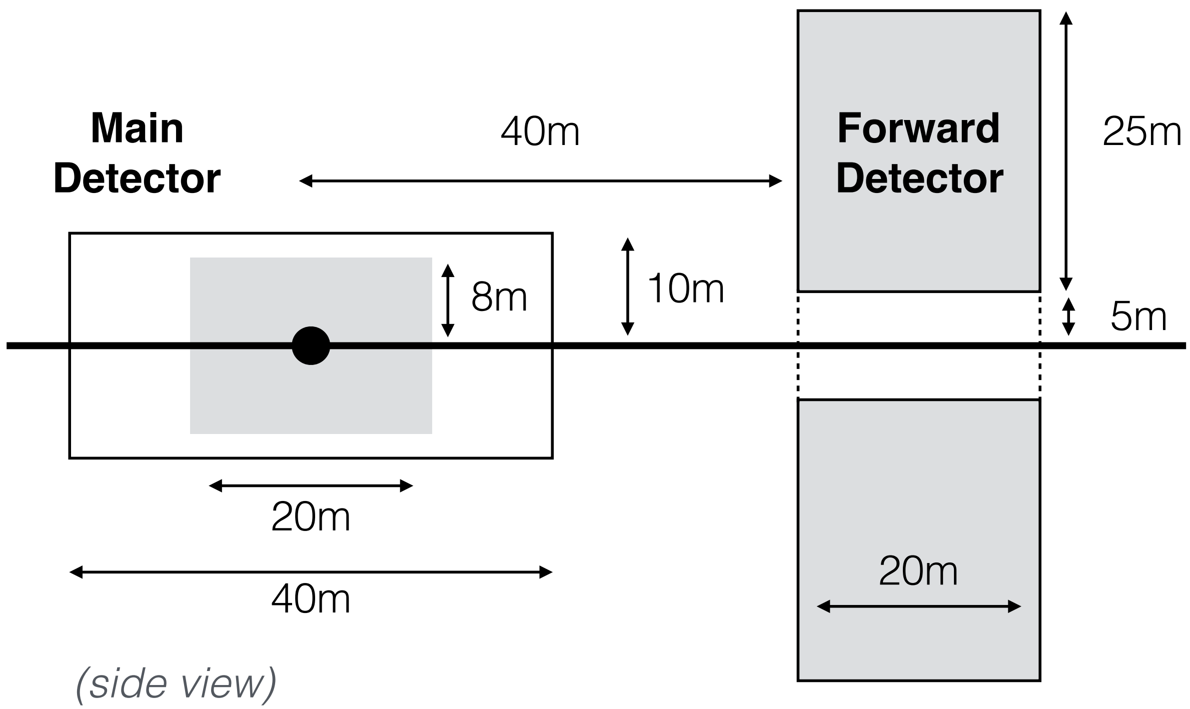
(see also Michelangelo's Talk!)

FCC-hh with 30/ab will produce ~ as many Higgs bosons with p_T > 500 GeV as entire HL-LHC inclusive production!

How do various backgrounds scale? Do you win at high p_T??

For longer lifetimes, a relatively cheap **part** of the program should be **an underground dedicated LLP detector!**

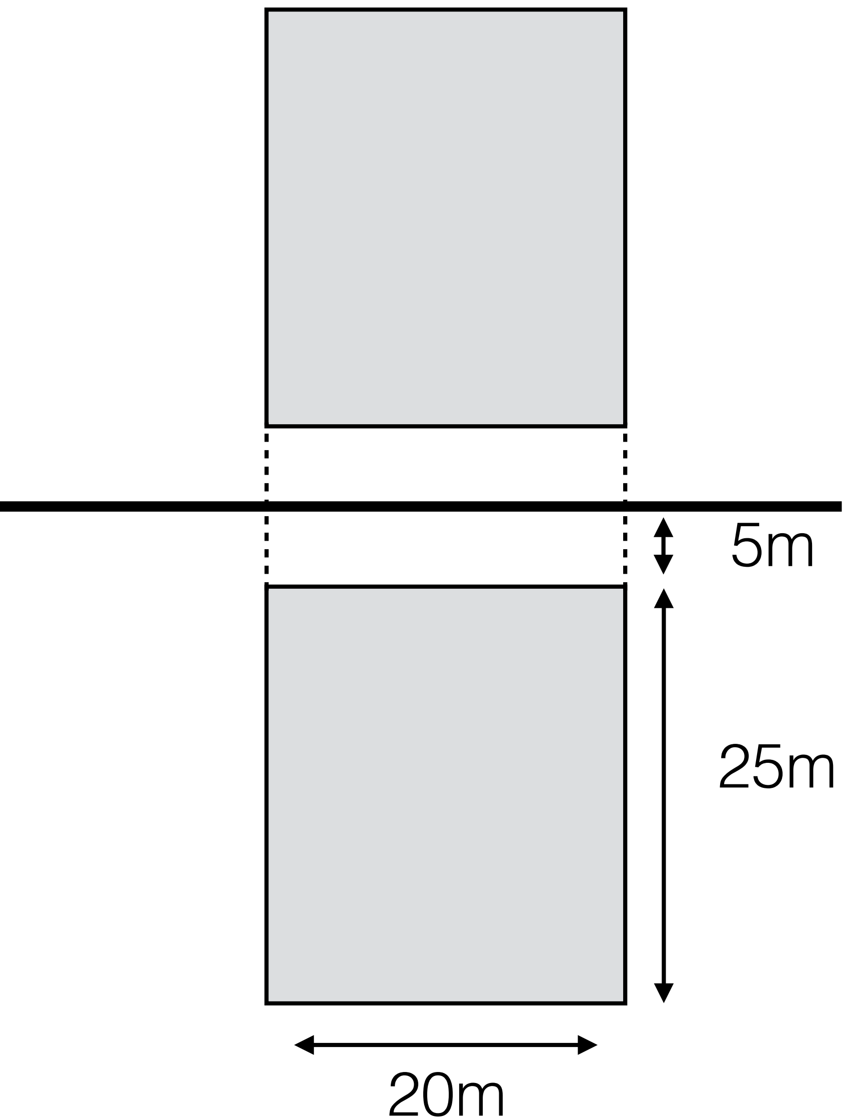
Incremental Add-On: LLP Detector!



Shielding from collision point eliminates hadronic backgrounds to LLP reconstruction.

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

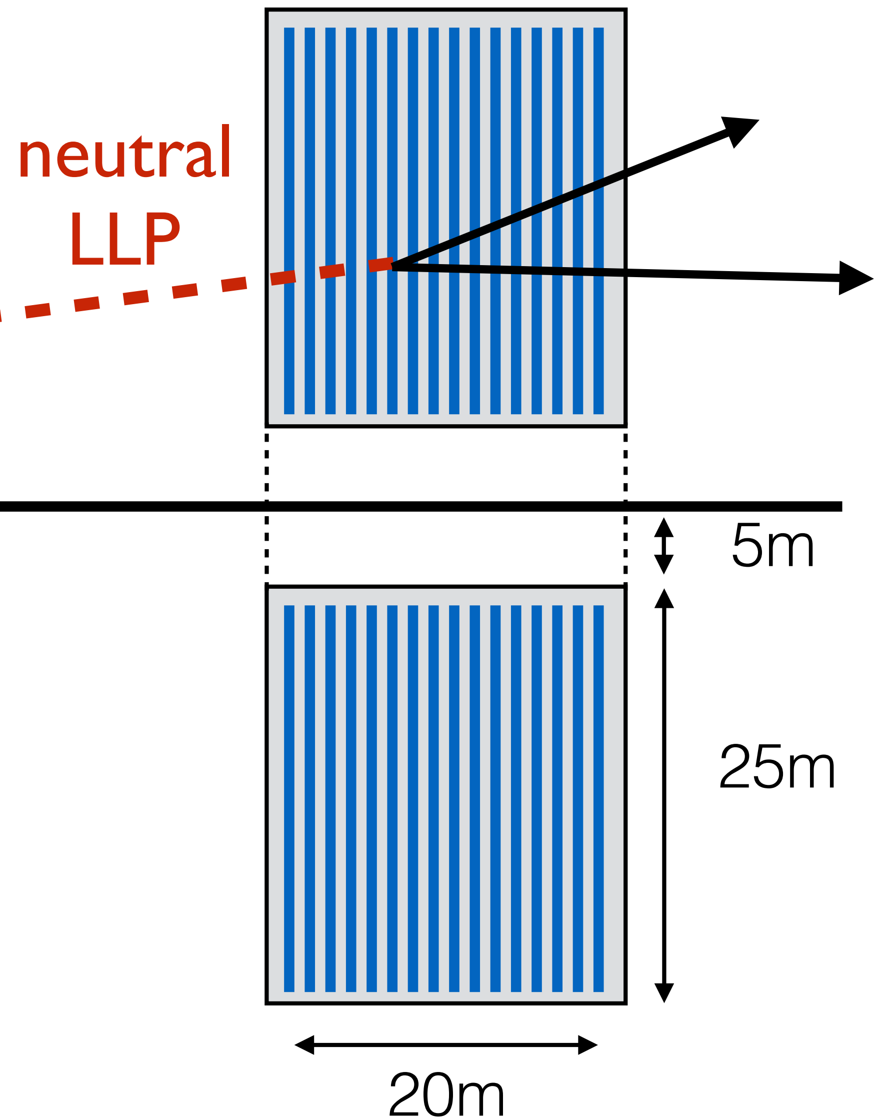
Instrumentation & Backgrounds



Many possibilities for instrumentation…

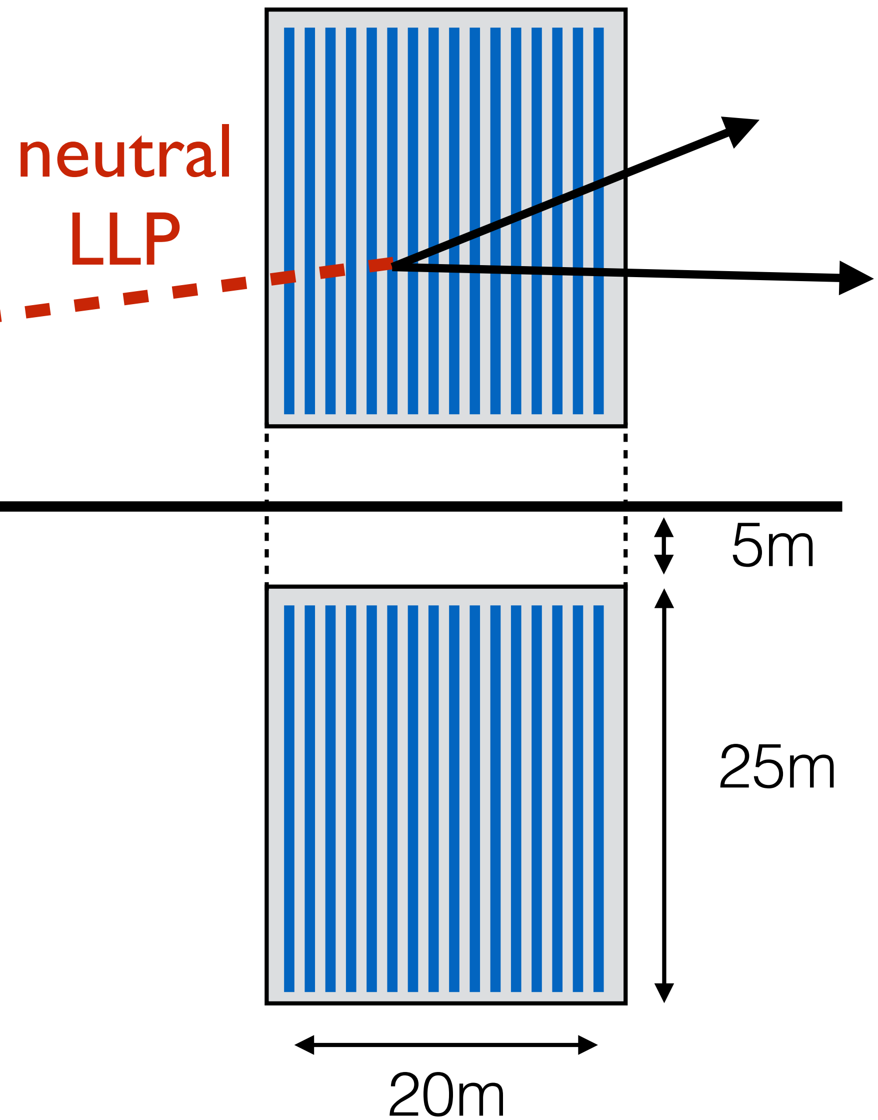
Point is: requirements of near-perfect background veto are easy to satisfy

Instrumentation & Backgrounds



Could fill with tracker planes every 0.5m for < ~1/3 sensor cost of MATHUSLA

Instrumentation & Backgrounds



Could fill with tracker planes every 0.5m for < ~1/3 sensor cost of MATHUSLA

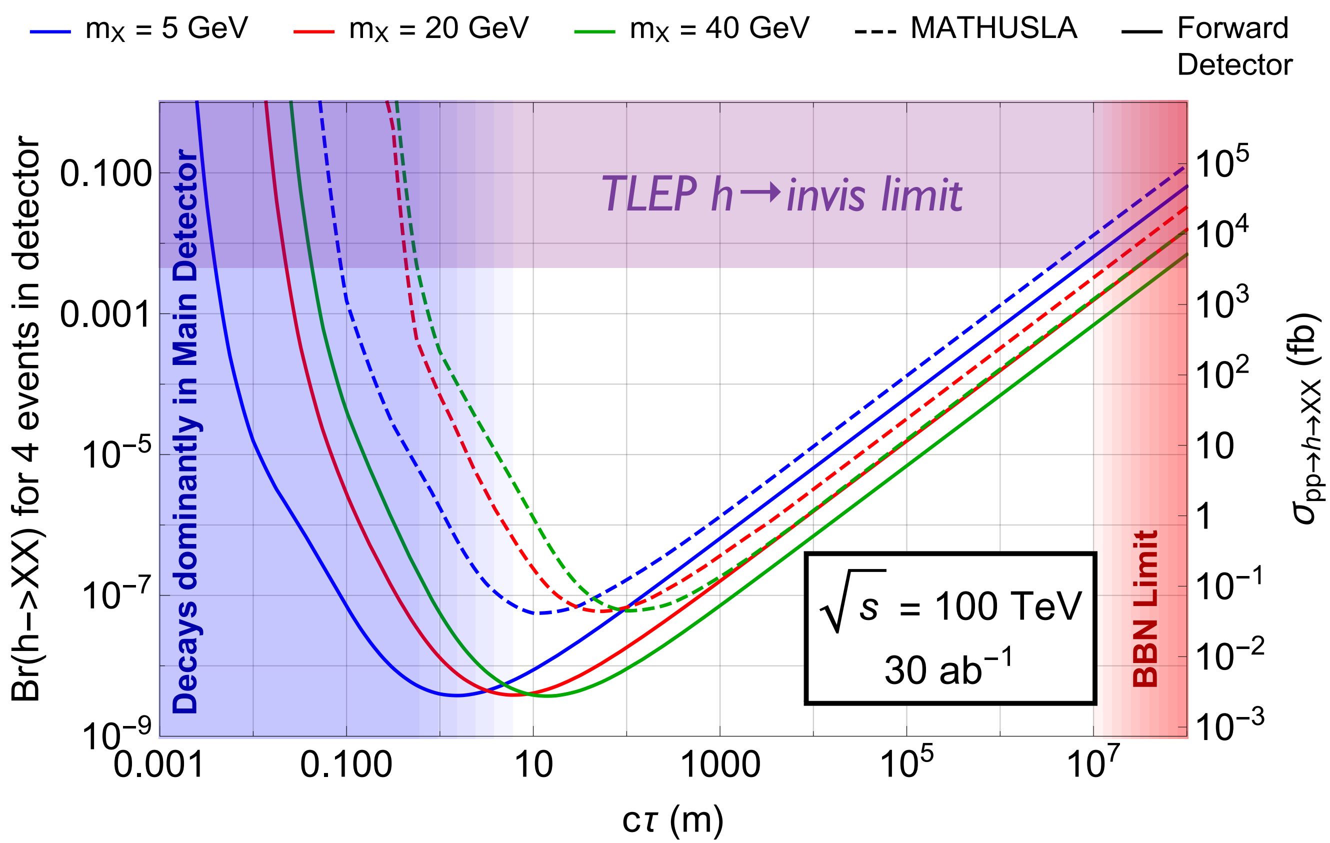
Hugely redundant tracking & rejection of prompt muons/ neutrinos from collision

All cosmic backgrounds < 5% of MATHUSLA (~volume). Also easily rejected.

Background-free LLP search plausible! *(needs study)*

Incremental Add-On: LLP Detector!

Sensitivity assuming zero BG:



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

Neutral LLP Searches at the FCC-ee

LLPs @ FCC-ee

Studied mostly for sterile neutrinos, see talk by Eros Cazzato, but there are general lessons we can anticipate:

Superpowers:

ultra-clean events

full center-of-mass reconstruction

much 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! (10 μm!?)**

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!

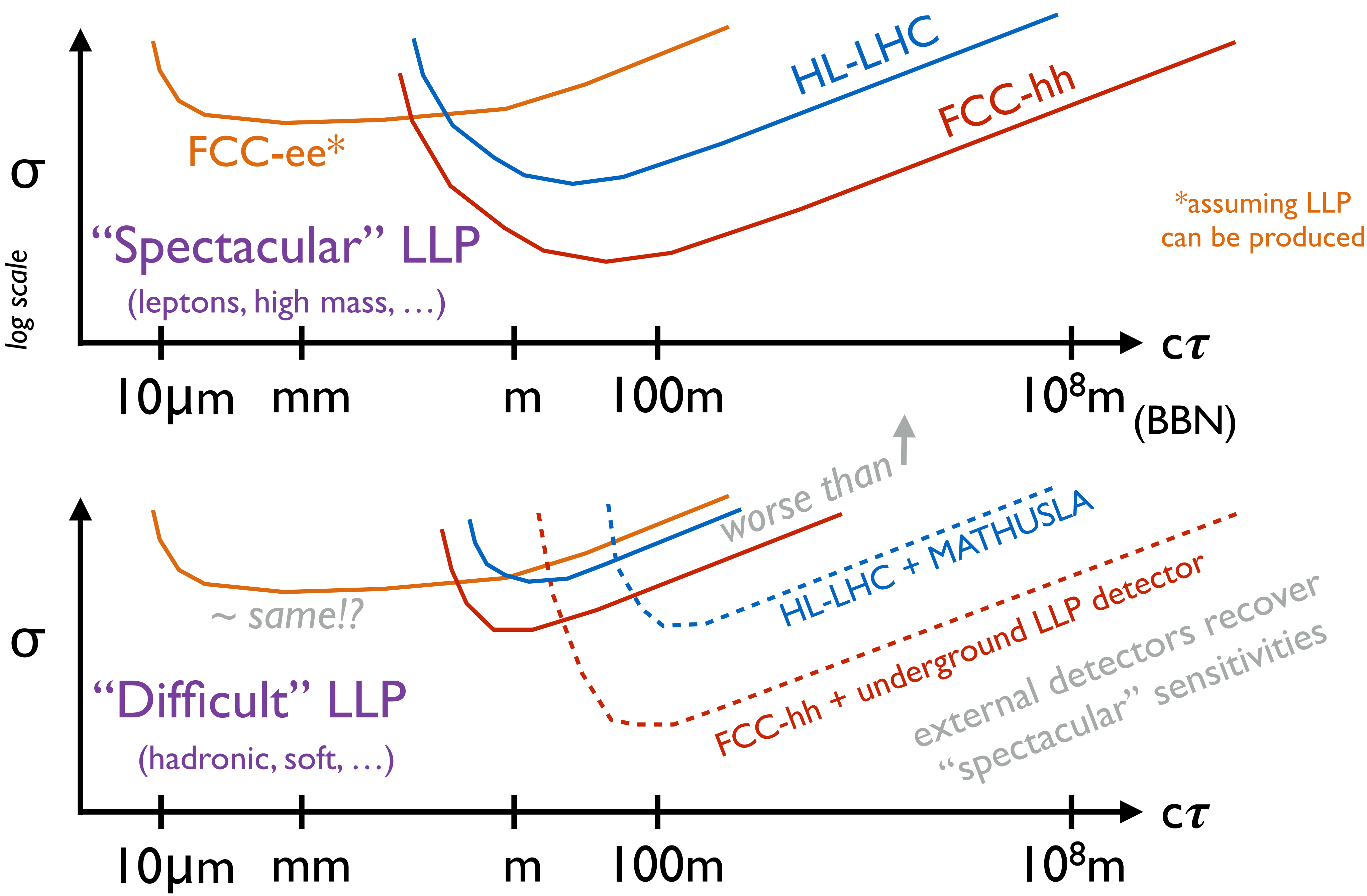
Qualitatively new opportunity at HL-LHC: MATHUSLA can extend LLP sensitivity by factor of 10^3!!

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

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

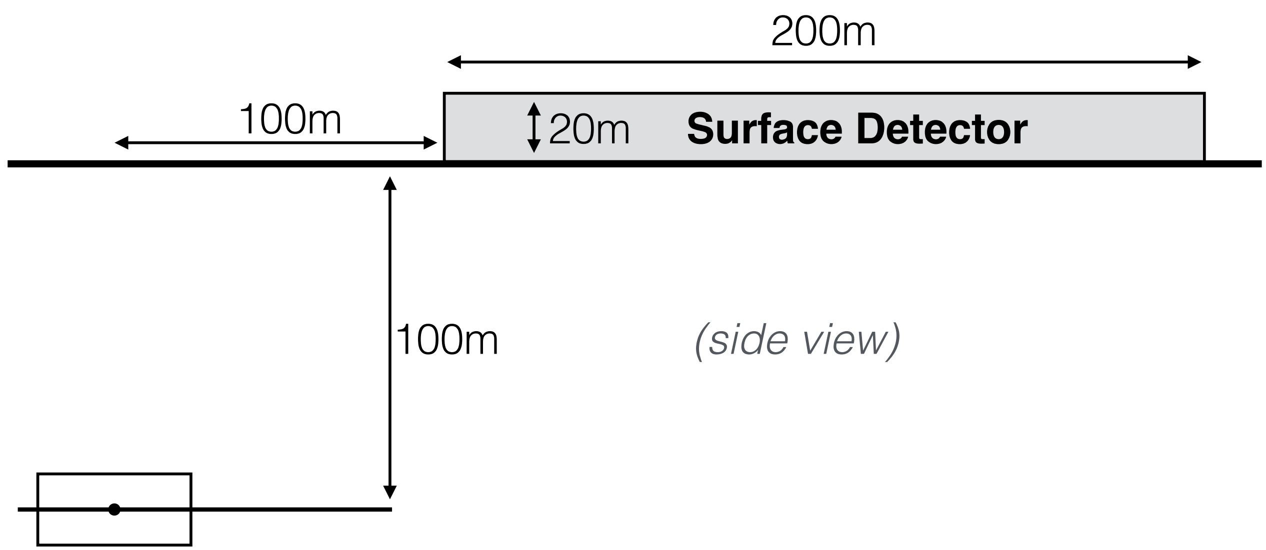
What are the FCC-ep possibilities???

★Cartoon★ of relative LLP sensitivities



Extra Material

MATHUSLA Surface Detector



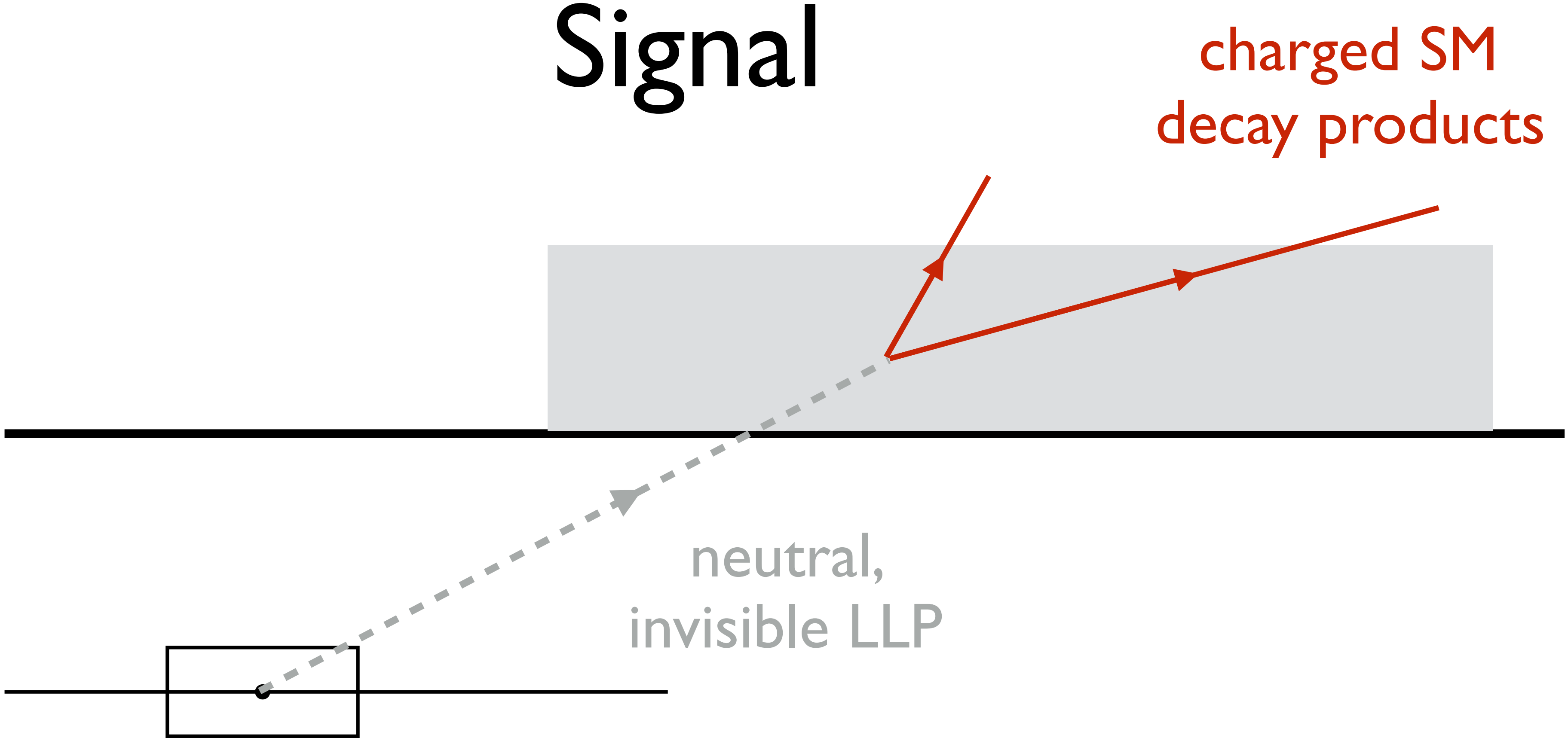
Dedicated detector for ultra-long-lived particle (ULLP) decays.

~5% geometric coverage.

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

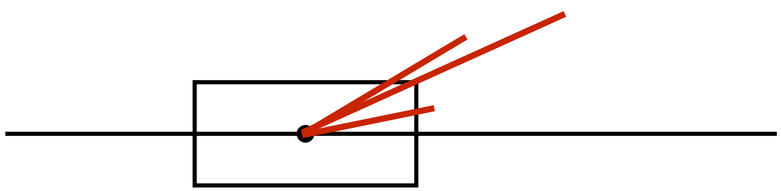
How to design the detector?

Signal



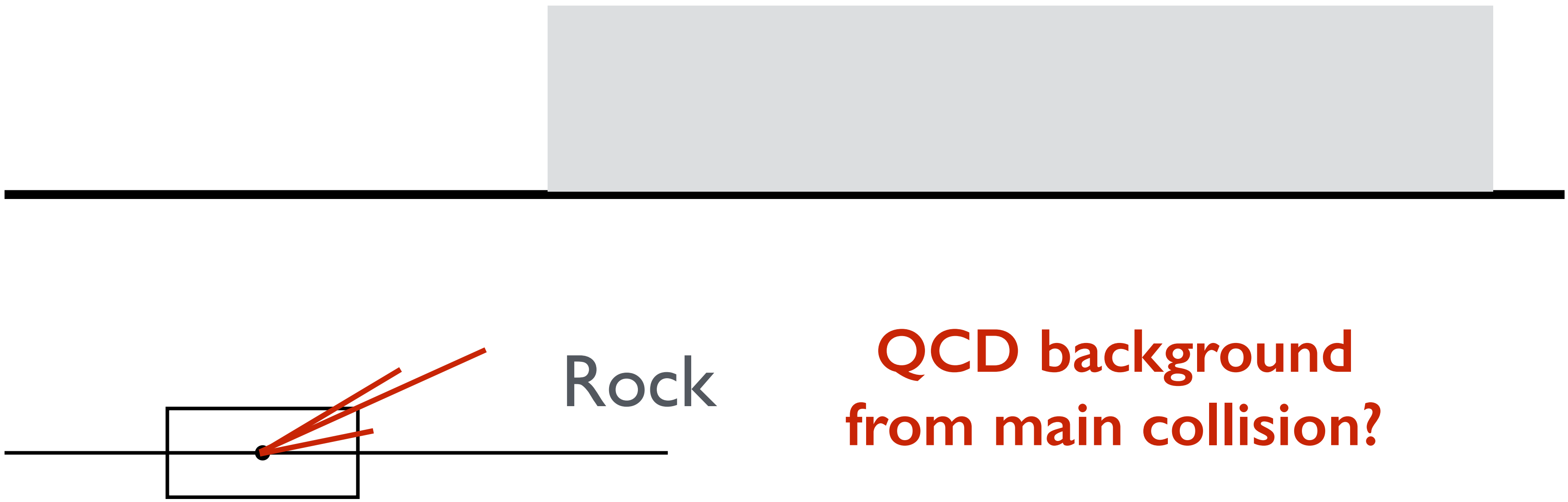
Need to detect this.
How exactly? Depends on backgrounds!

Backgrounds



QCD background from main collision?

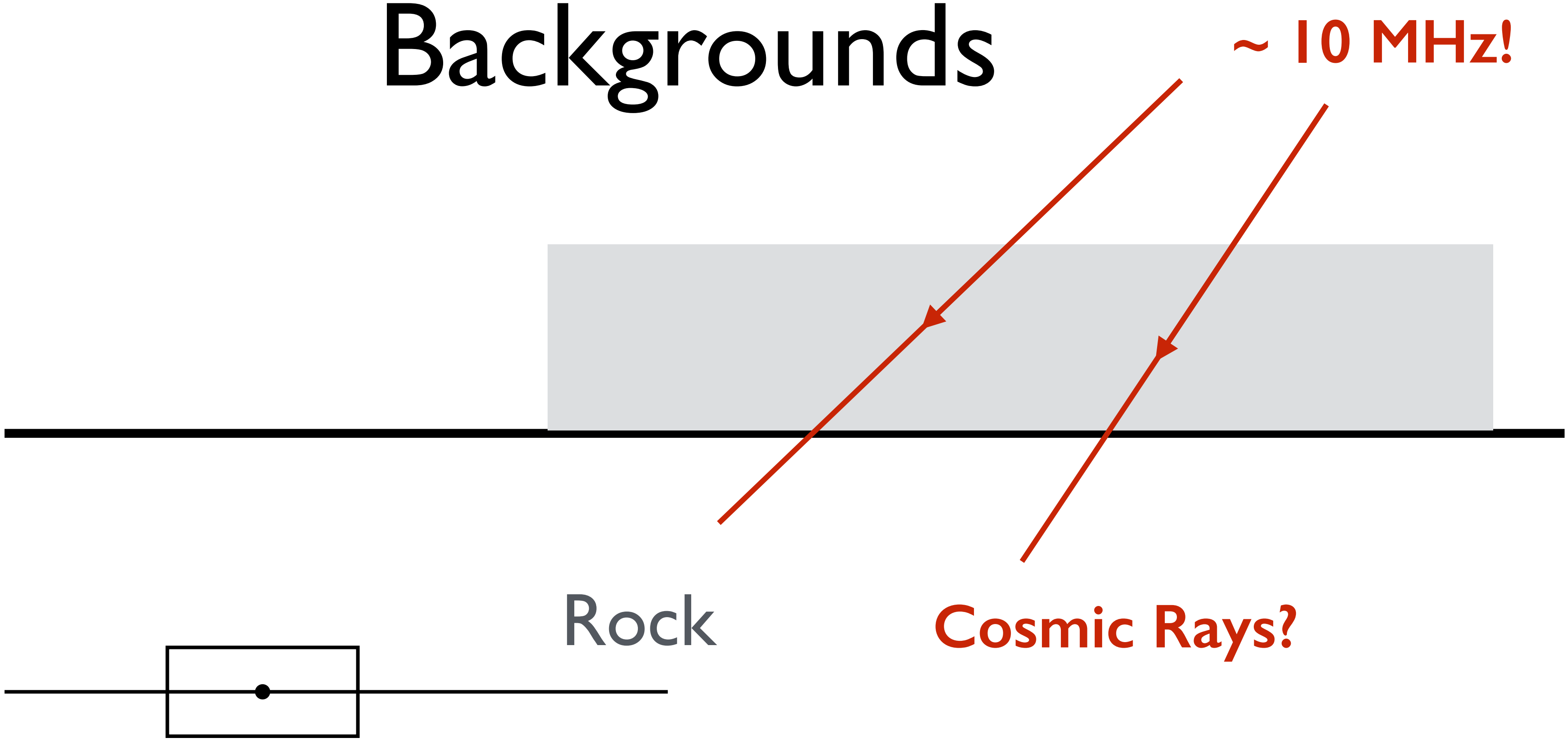
Backgrounds



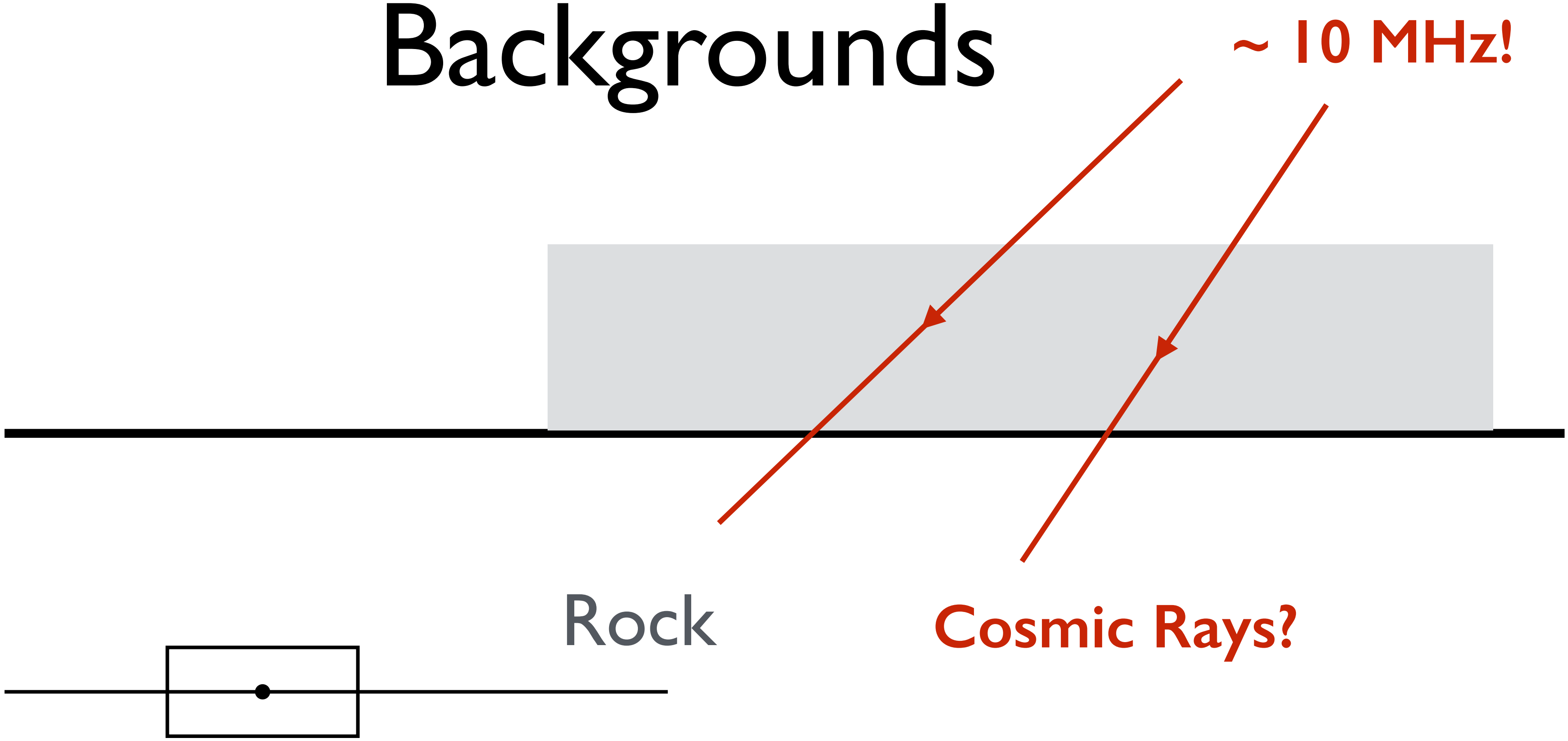
QCD background
from main collision?

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

Backgrounds

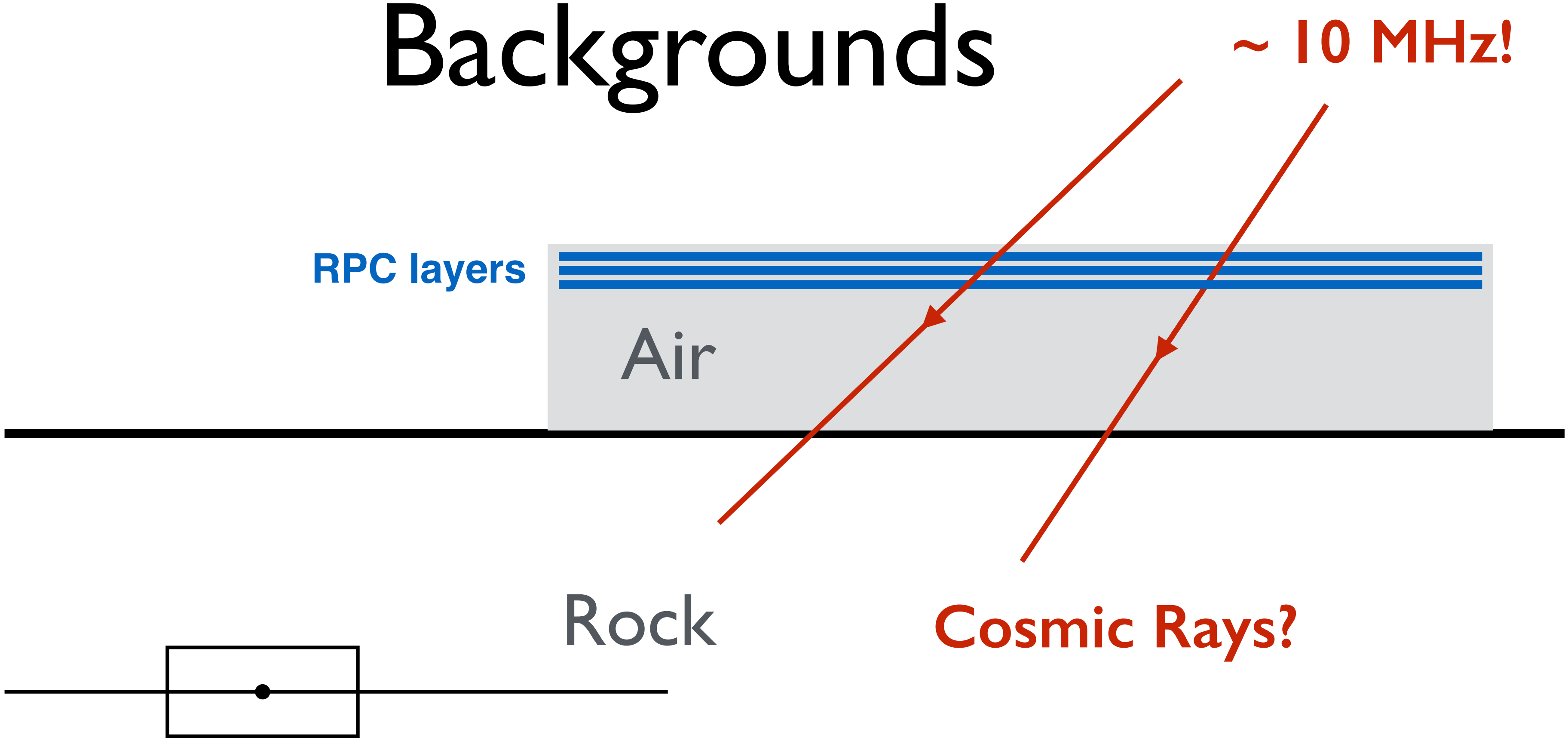


Backgrounds



Do not reconstruct a displaced vertex.
Travel downwards.

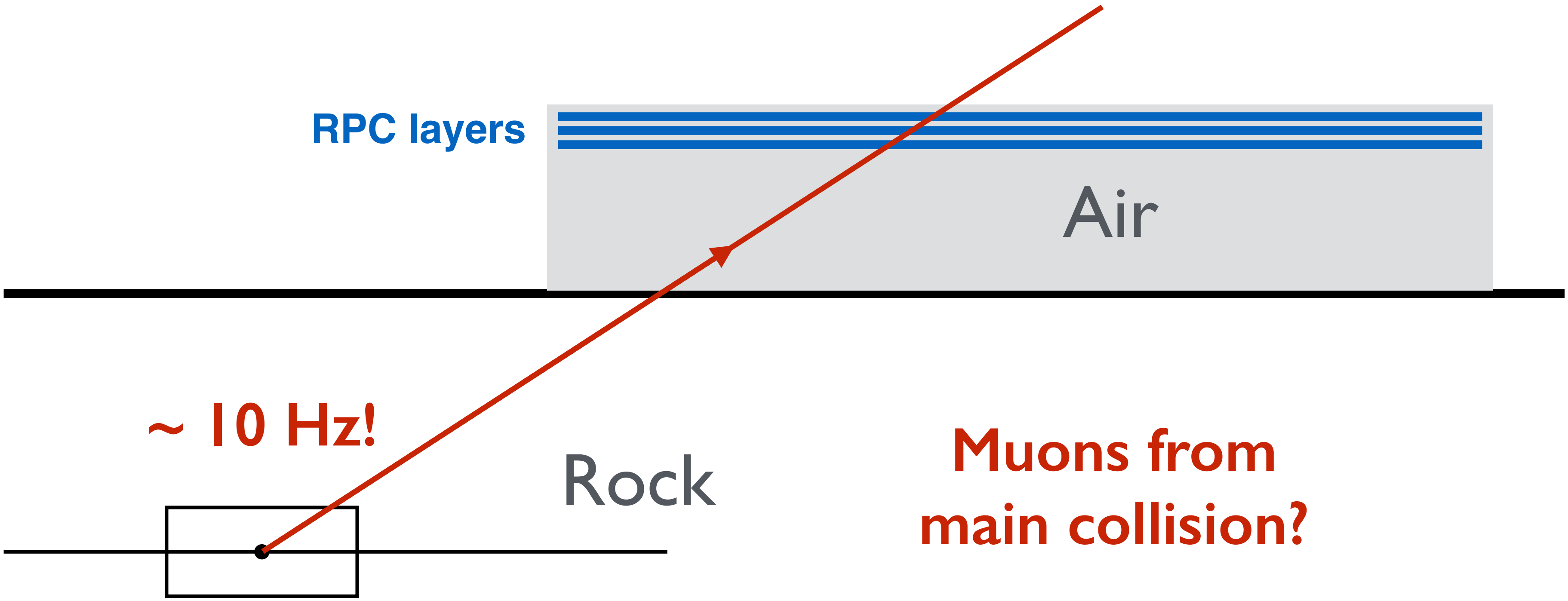
Backgrounds



Do not reconstruct a displaced vertex.
Travel downwards.

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

Backgrounds



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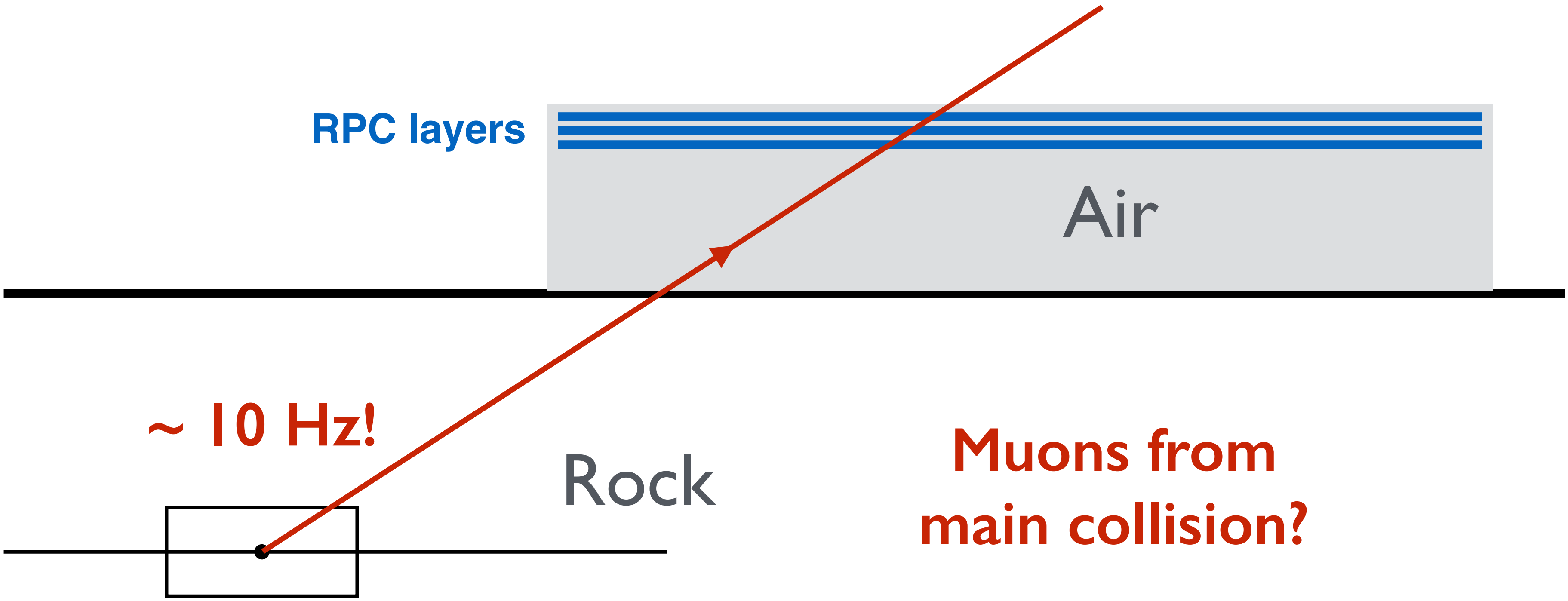

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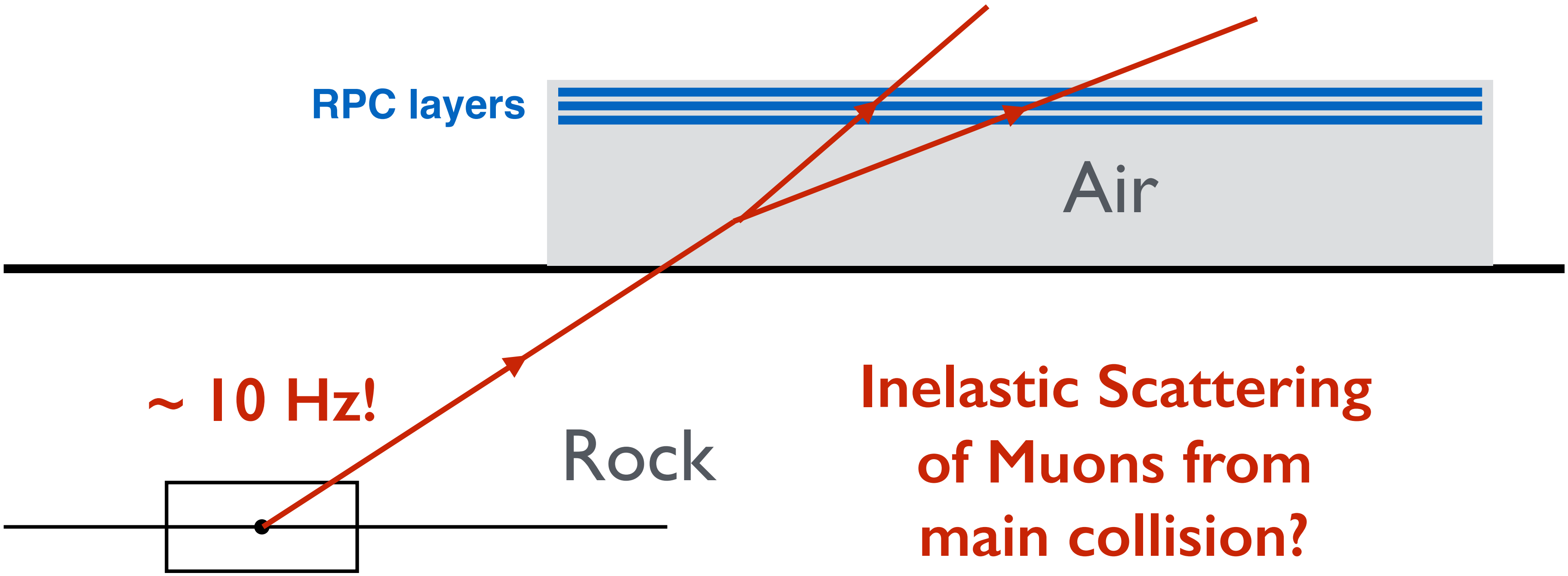
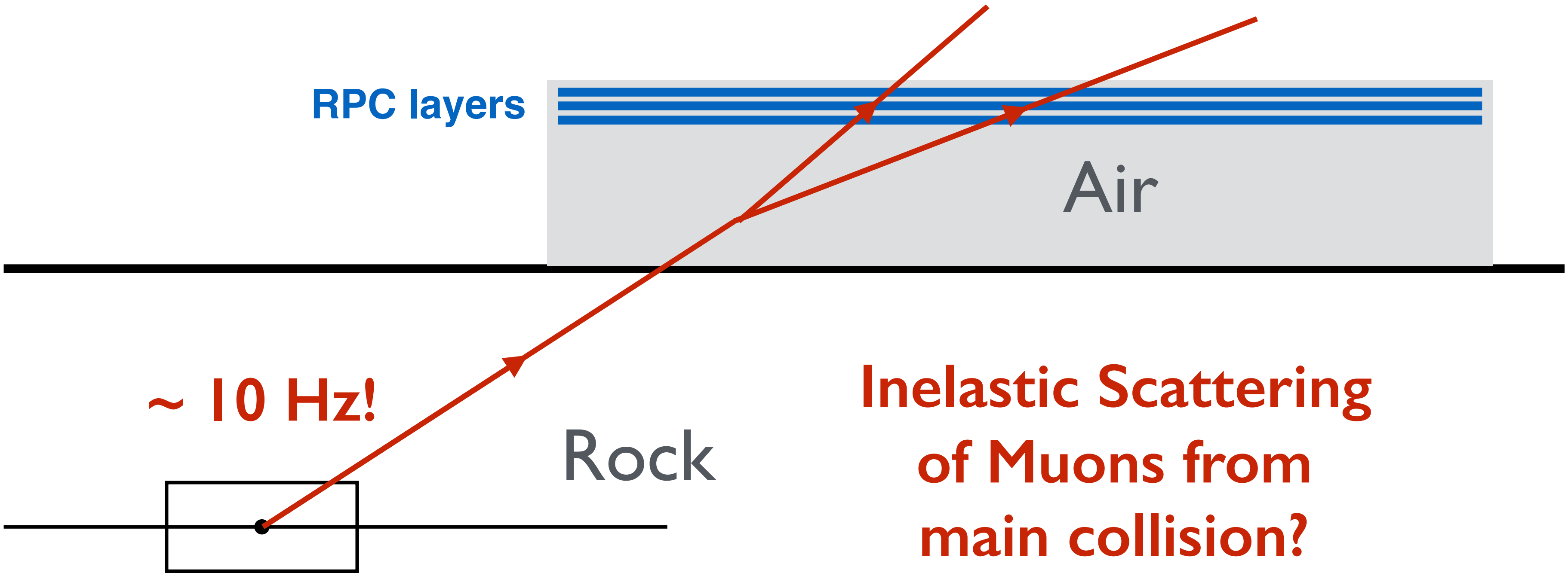


Inelastic Scattering of Muons from main collision?

Backgrounds

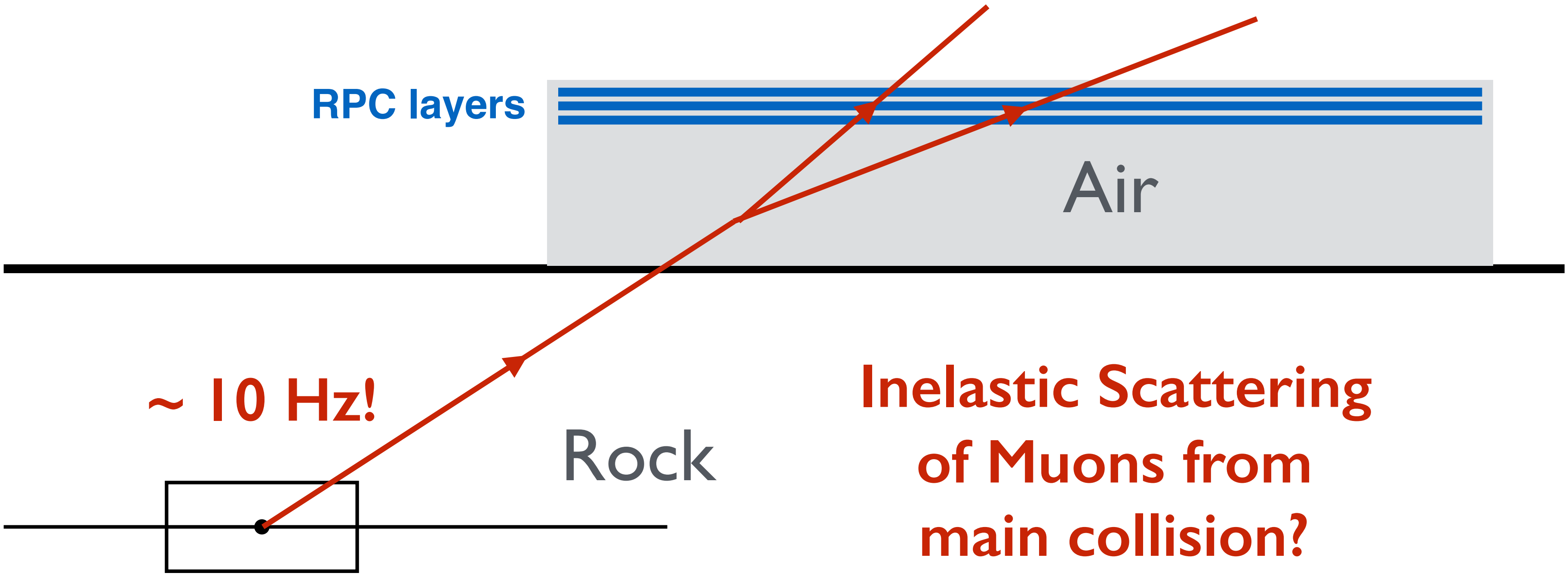


Inelastic Scattering of Muons from main collision?

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

Has to pass through floor.

Backgrounds



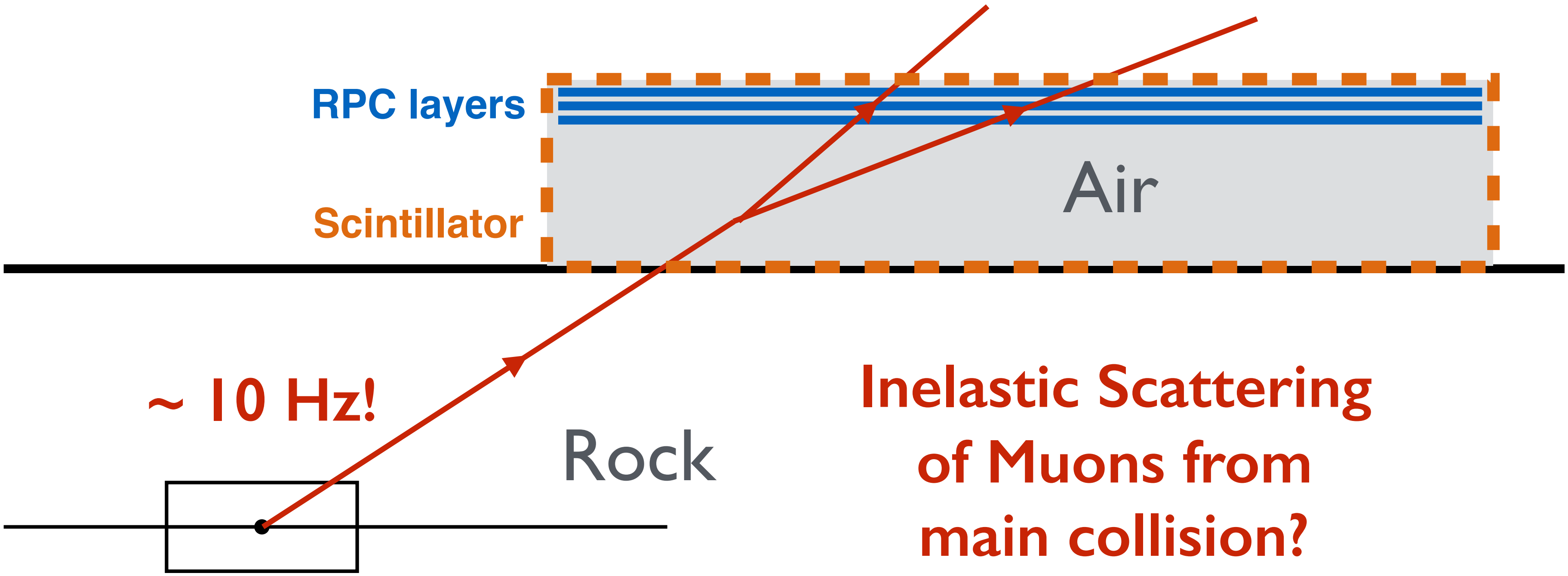
Inelastic Scattering of Muons from main collision?

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



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

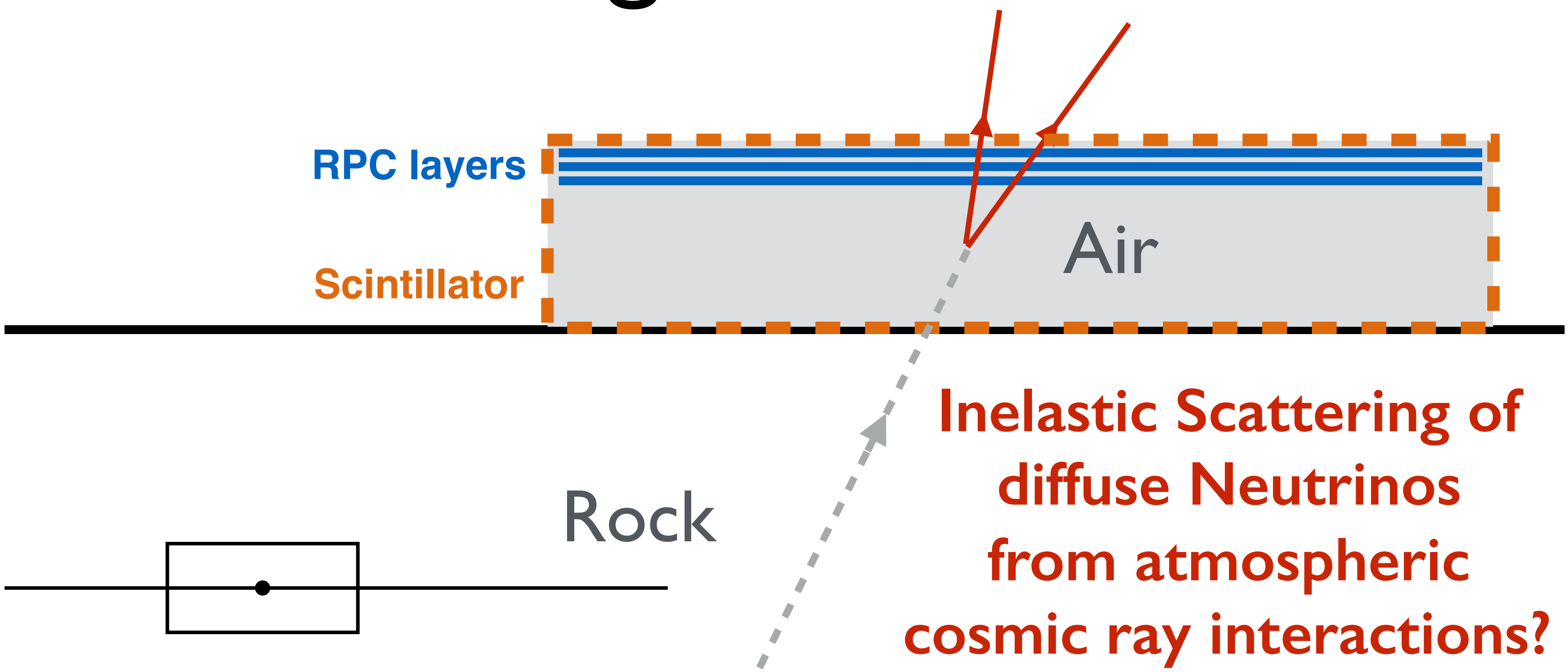
Has to pass through floor.

Surround volume with Scintillator Veto!

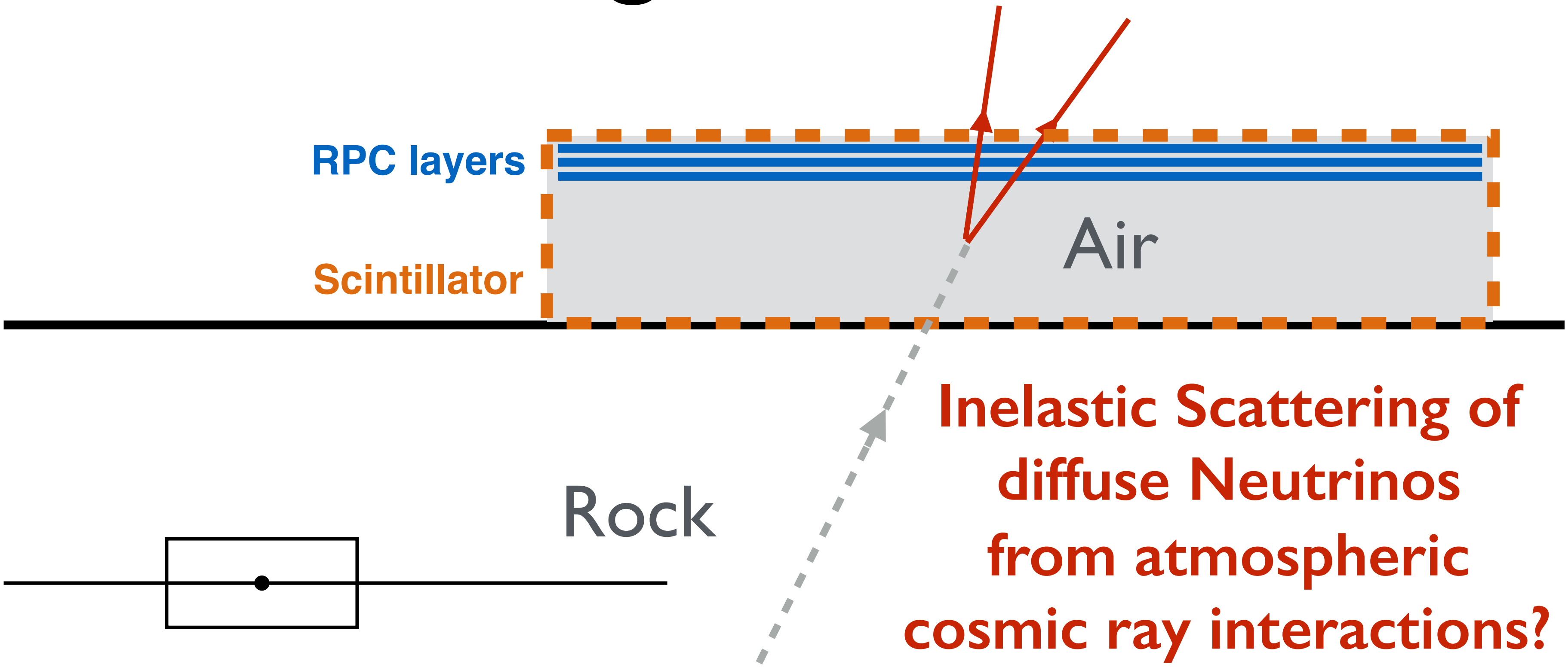
Also gives additional rejection power for stray cosmics

Would allow search for one-pronged LLP decays!

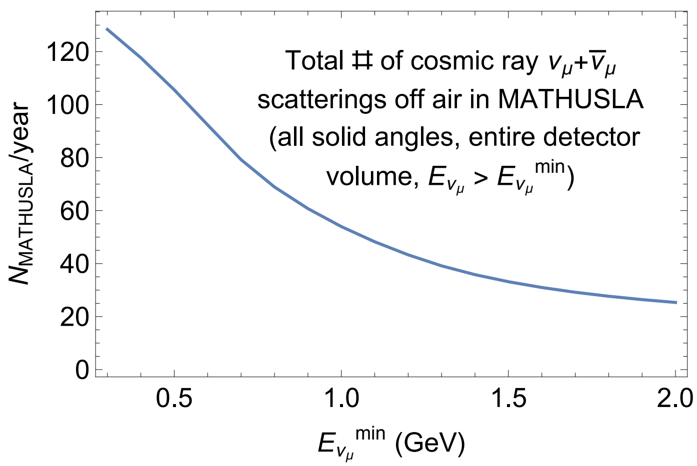
Backgrounds



Backgrounds



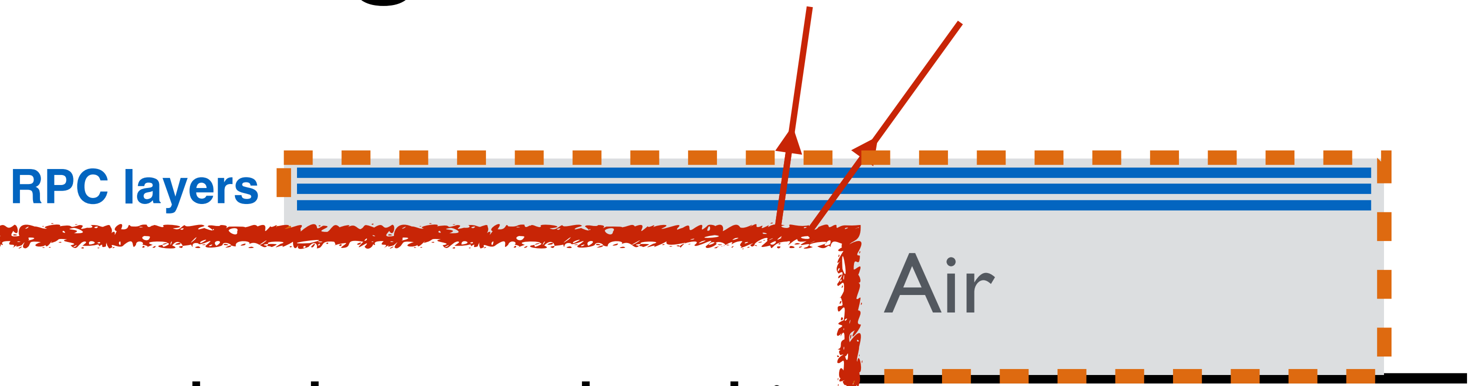
Inelastic Scattering of diffuse Neutrinos from atmospheric cosmic ray interactions?



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

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

Backgrounds

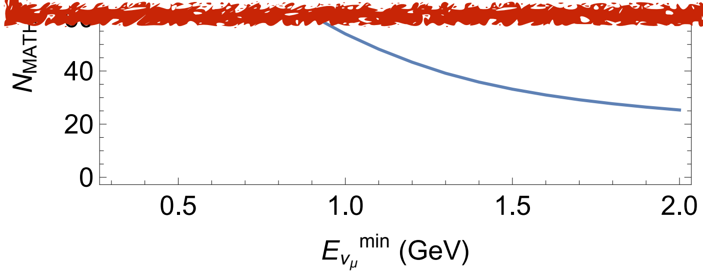


This is the biggest background and it can be rejected with cuts.

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

...astic Scattering of
...ffuse Neutrinos
...om atmospheric
...ic ray interactions?

...-100 per year
...00 MeV.



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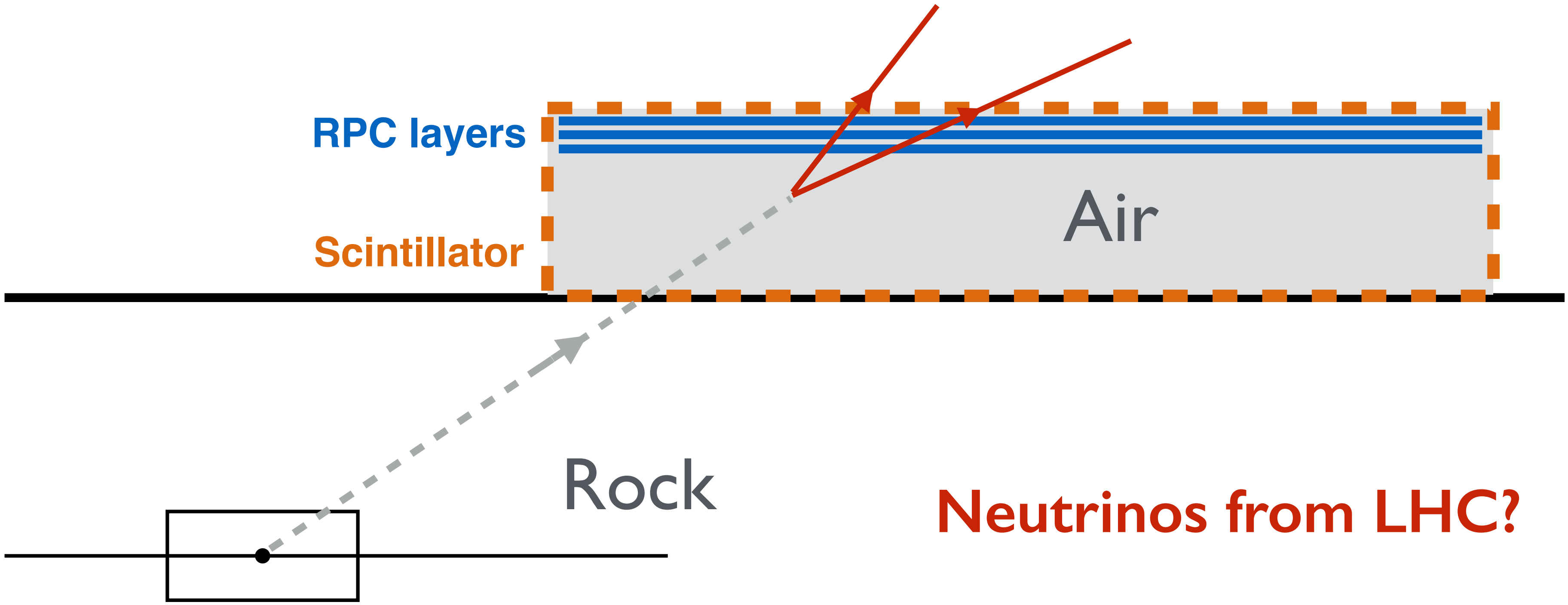
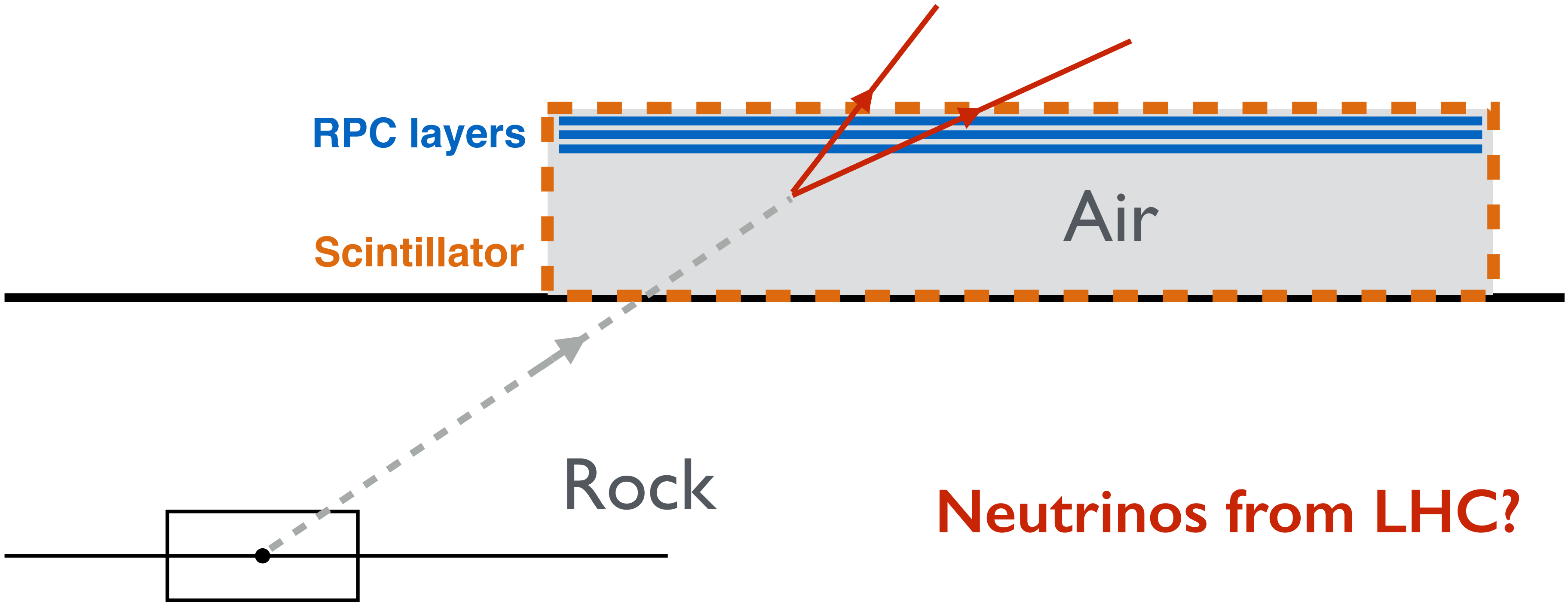
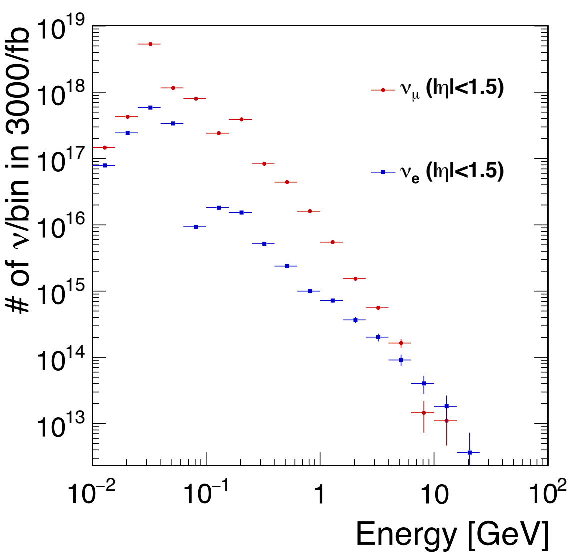


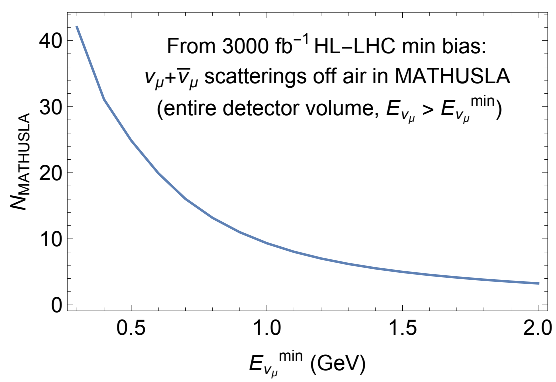
Neutrinos from LHC?

Backgrounds



Neutrinos from LHC?

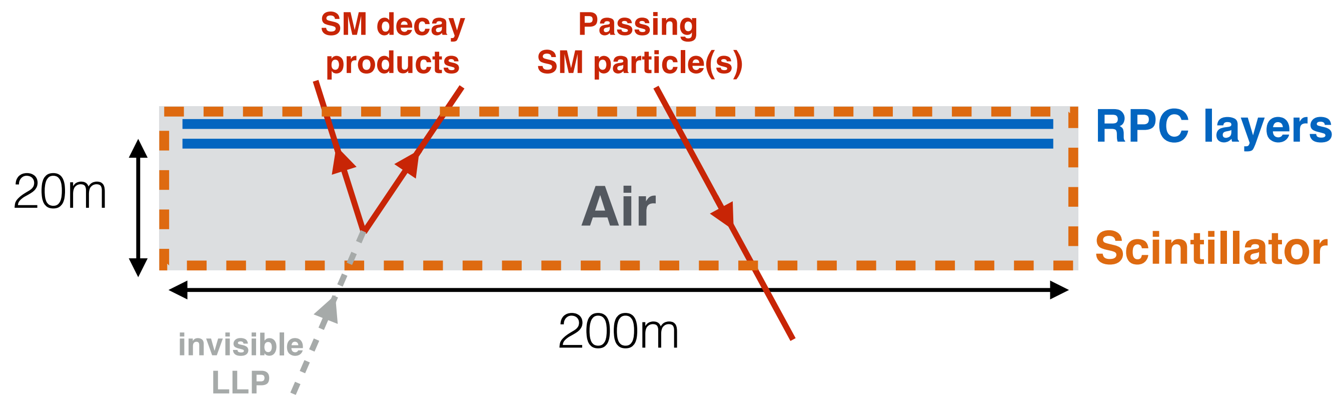




Same as cosmic neutrinos but they point back at IP. Same cuts can reject!

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.

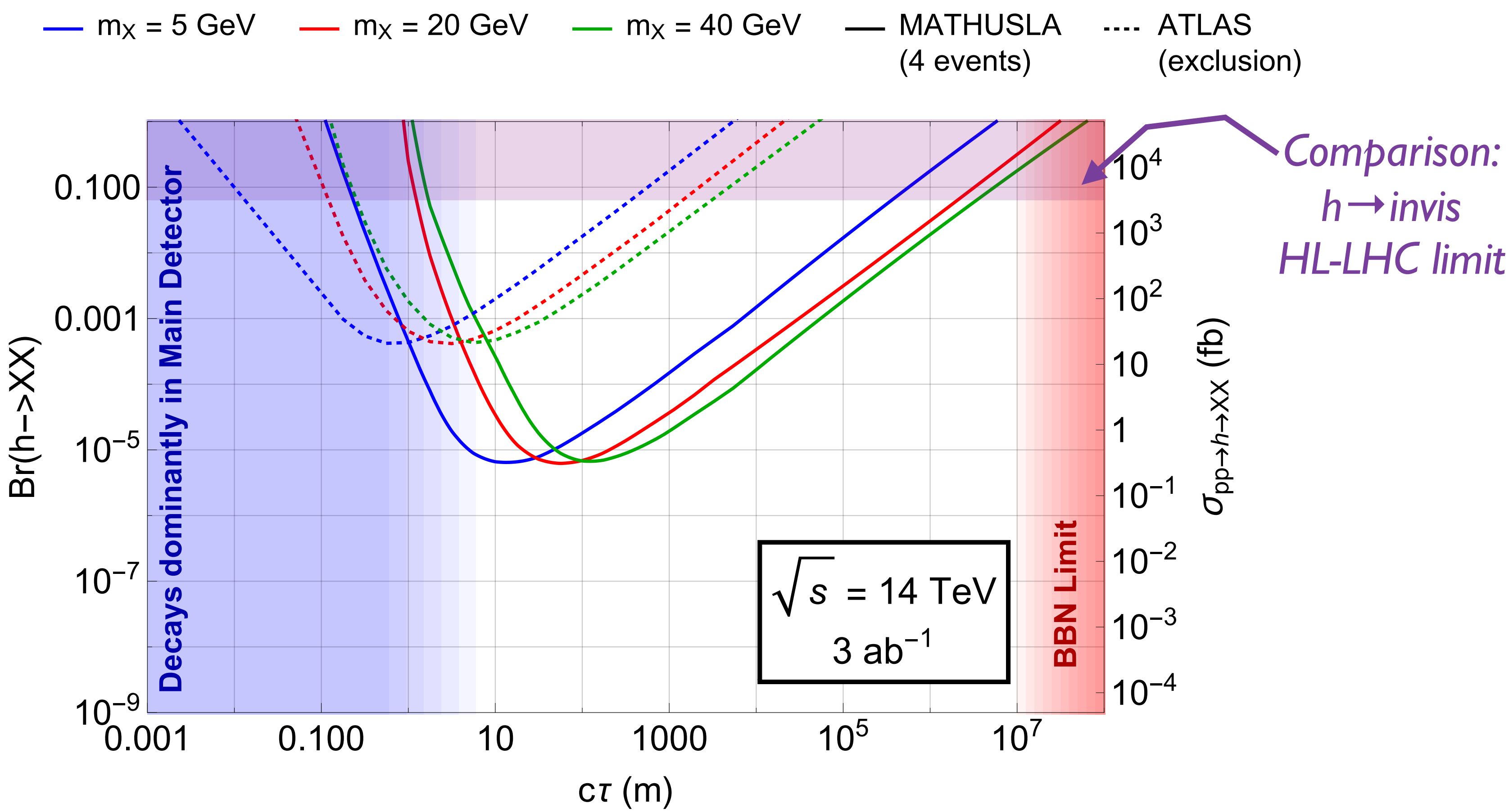
Reconstructed vertex and **time-of-flight measurement** of final states allows for **near-background-free LLP search**

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]

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Can we learn anything about a discovered LLP?

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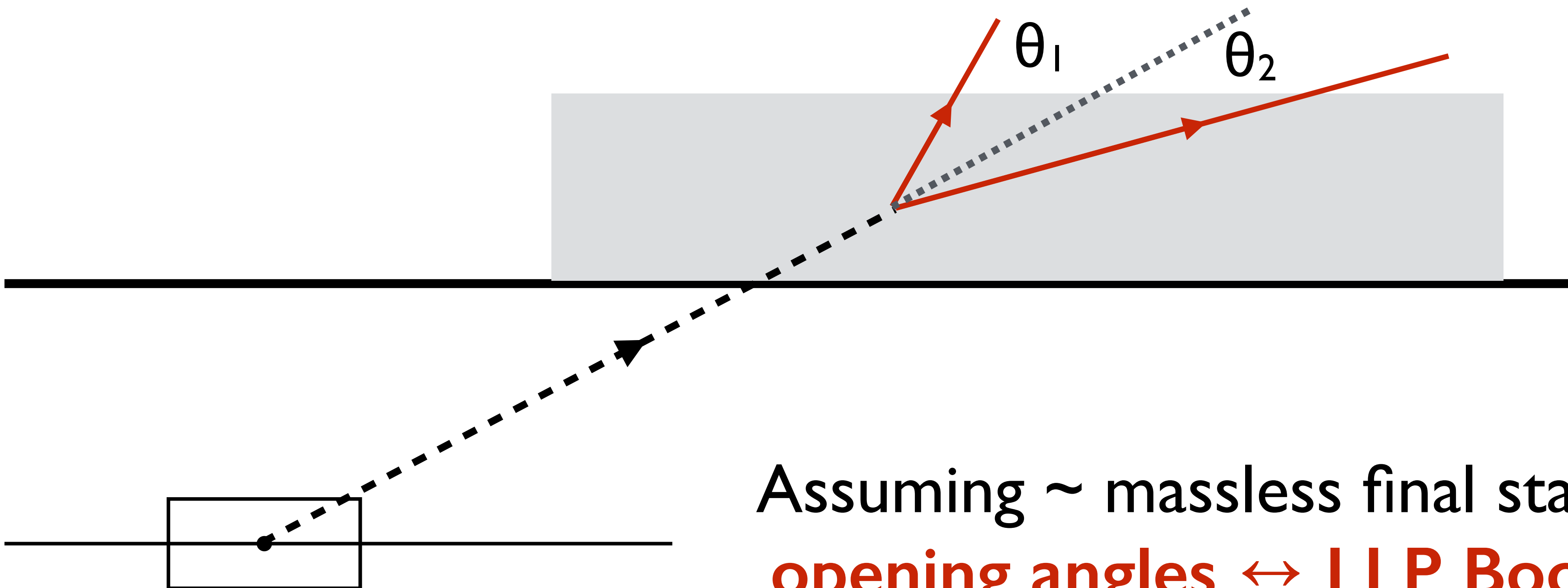


Assuming ~ massless final states:
opening angles ↔ LLP Boost!

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

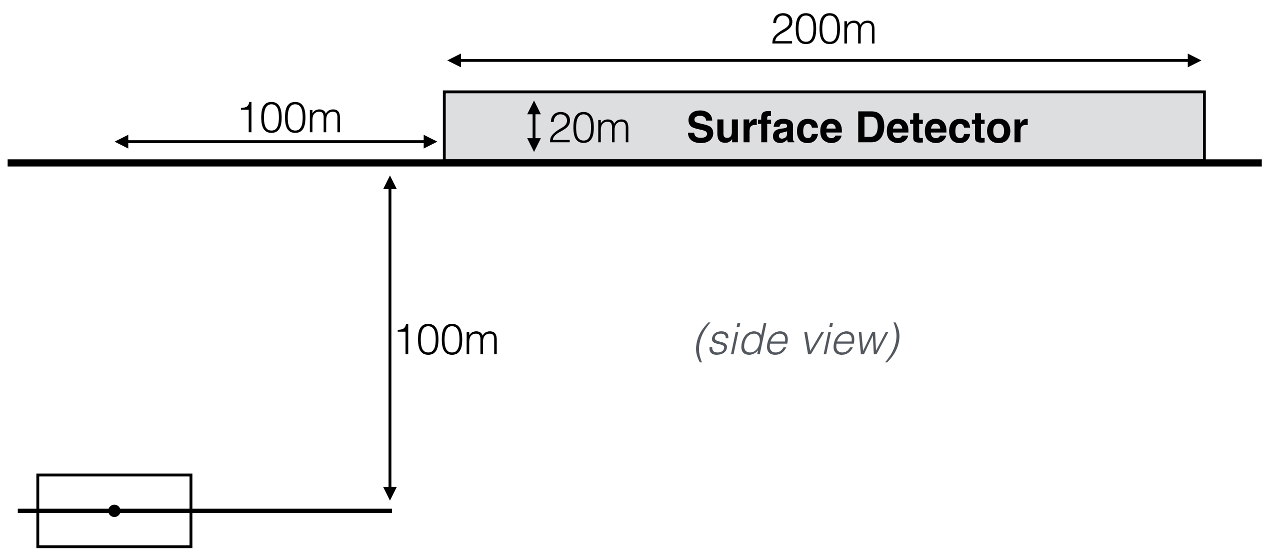
with a bit of showering material: e vs μ?

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.

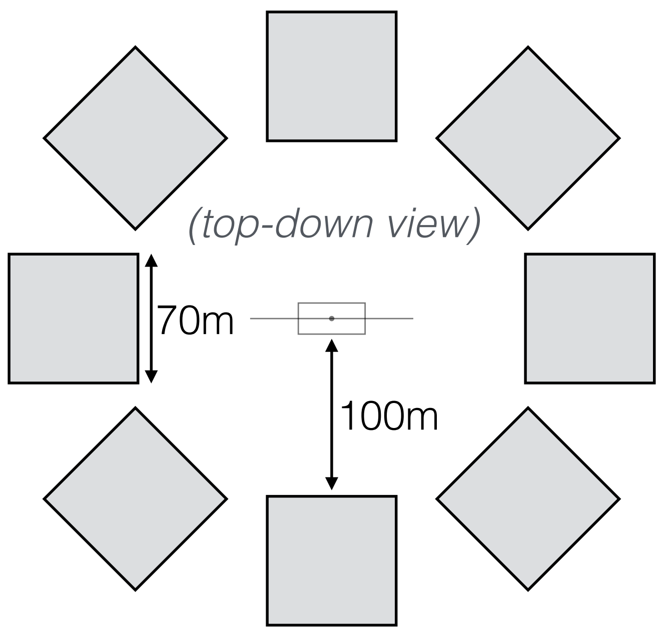
Available Space

need ~ one
nearby farm plot

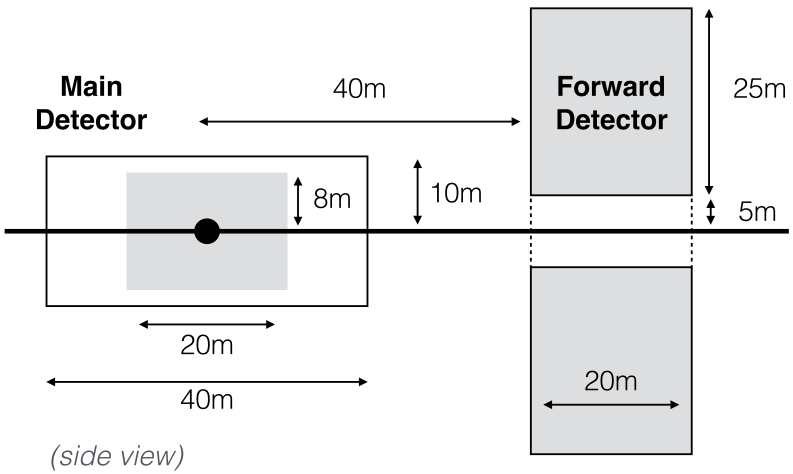
Available Space

Geometry is very flexible!

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

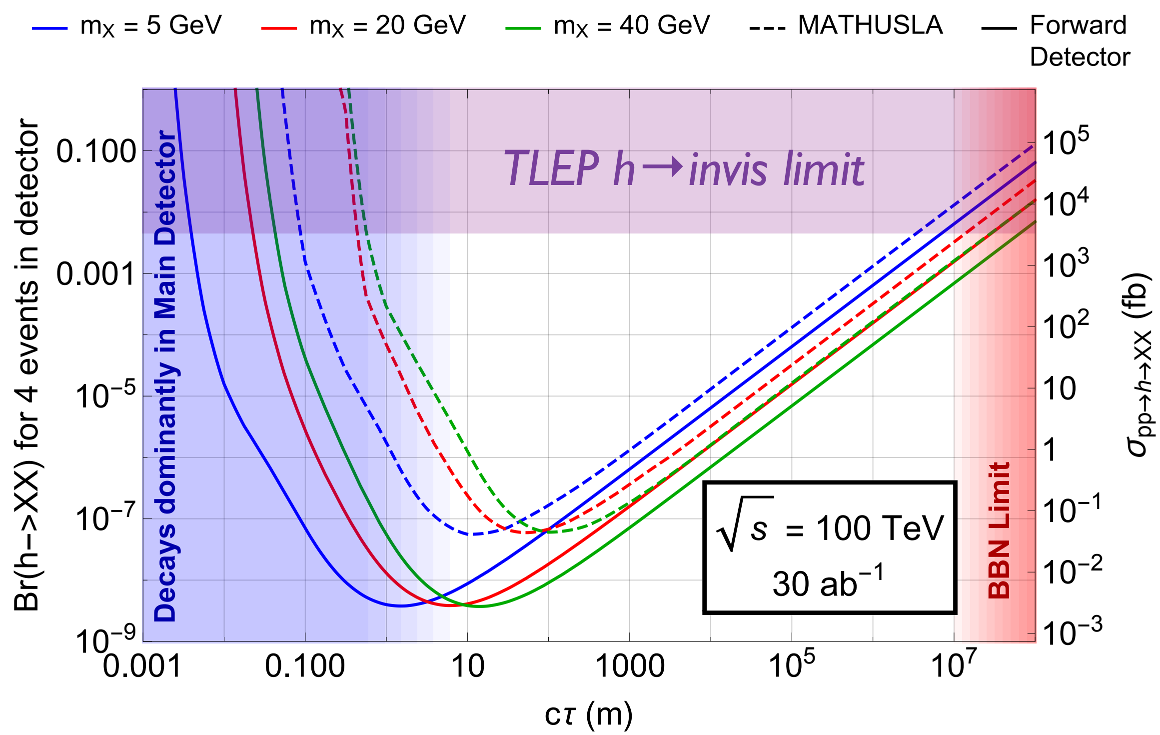


Aside: Start Planning for 100 TeV!



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

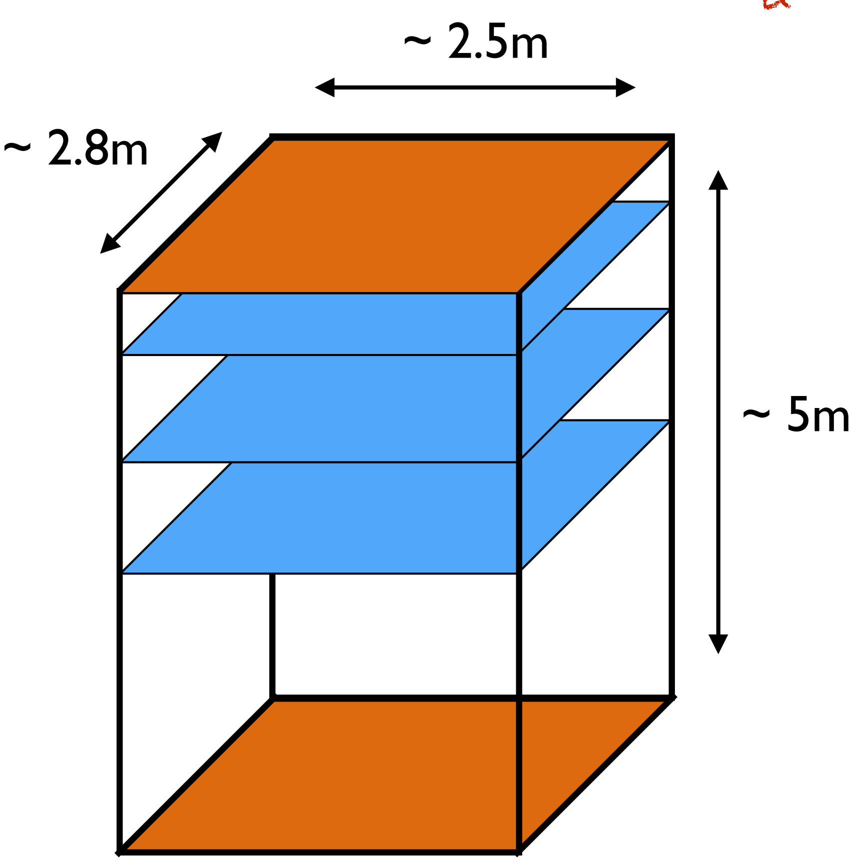
Theory:

White-paper describing the physics case

MATHUSLA Prototype

Required to validate design, background estimates, etc..

Sketch of possible geometry:



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!*

RPCs

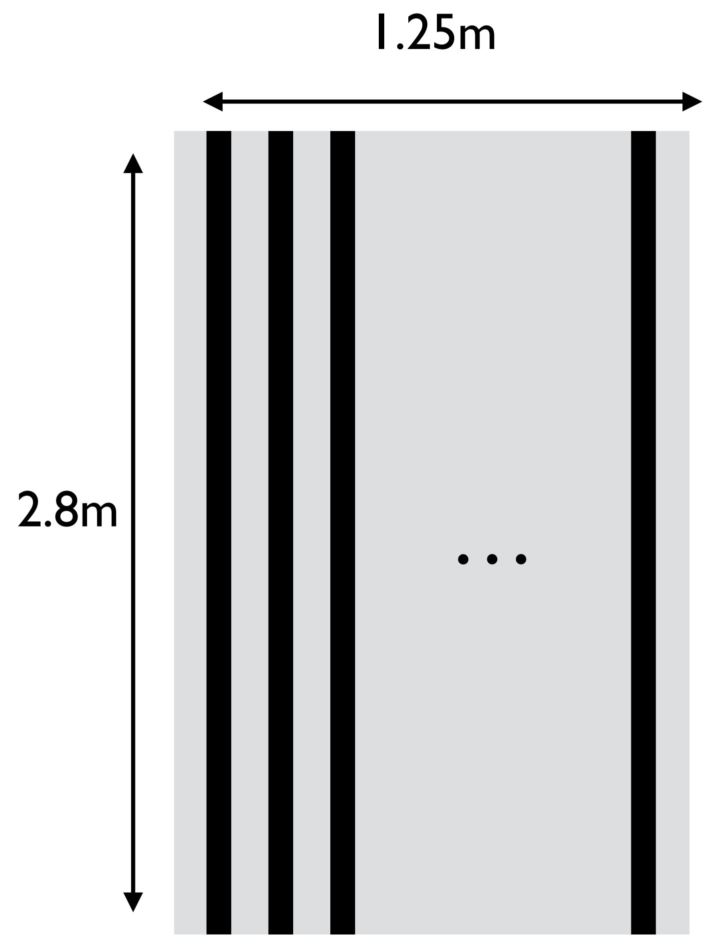
Supplied by University of Rome Tor Vergata, chambers + DAQ systems from prototype of ARGO cosmic shower experiment in Tibet

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.

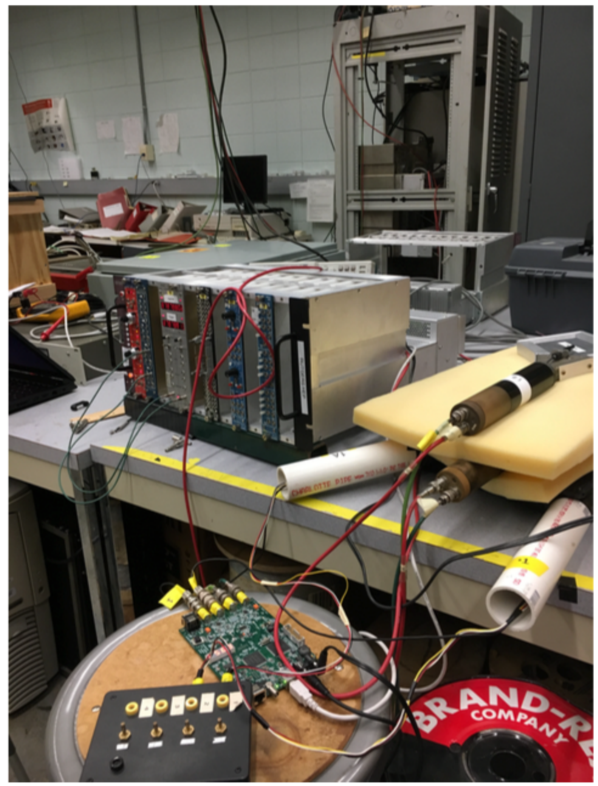
Use gas supply in ATLAS instrument hall

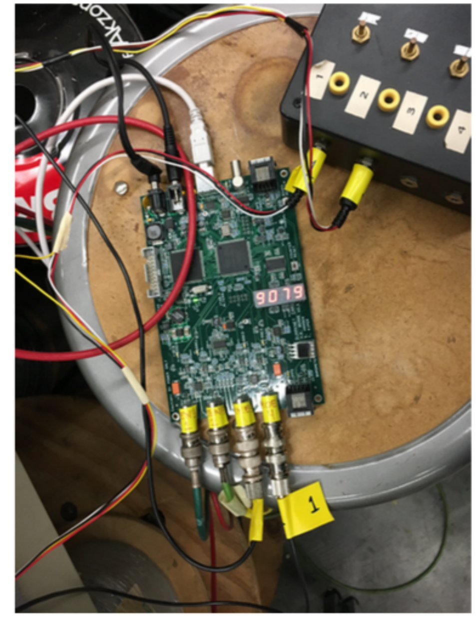


Strips 3cm wide, 2cm spacing

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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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

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Soliciting contributions from the theory community…

Aim: release comprehensive report early 2017!