The MATHUSLA Surface Detector

CERN-EPFL-Korea Theory Institute
"New Physics at the Intensity Frontier"
28 February 2017

Marco Drewes
Technical University of Munich

Talk largely based on slides by
David Curtin
University of Maryland

MATHUSLA 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]

Soliciting contributions from the theory community…

Aim: release comprehensive report early 2017!

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MATHUSLA

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me

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MATHUSLA

Motivation

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

Hidden Sectors and other theories with Long-lived particles (LLPs) are common 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

How long lived can particles be?

HISTORY OF THE UNIVERSE

Dark energy accelerated expansion

Structure formation

Cosmic Microwave Background radiation is visible

Accelerators

RHIC & LHC heavy ions

LHC protons

High-energy cosmic rays

Size of visible universe

TODAY

Inflation

Big Bang

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

$t = 10^{-36}$ s
$E = 10^{16}$ GeV

$t = 10^{-10}$ s
$E = 10^{2}$ GeV

$t = 10^{-4}$ s
$E = 10^{-1}$ GeV

$t = 10^{2}$ s
$E = 10^{-4}$ GeV

$t = 3 \times 10^{5}$ y
$E = 3 \times 10^{-10}$ GeV

$t = 10^{9}$ y
$E = 10^{-12}$ GeV

$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

How long lived can particles be?

The concept for the above figure originated in a 1986 paper by Michael Turner.

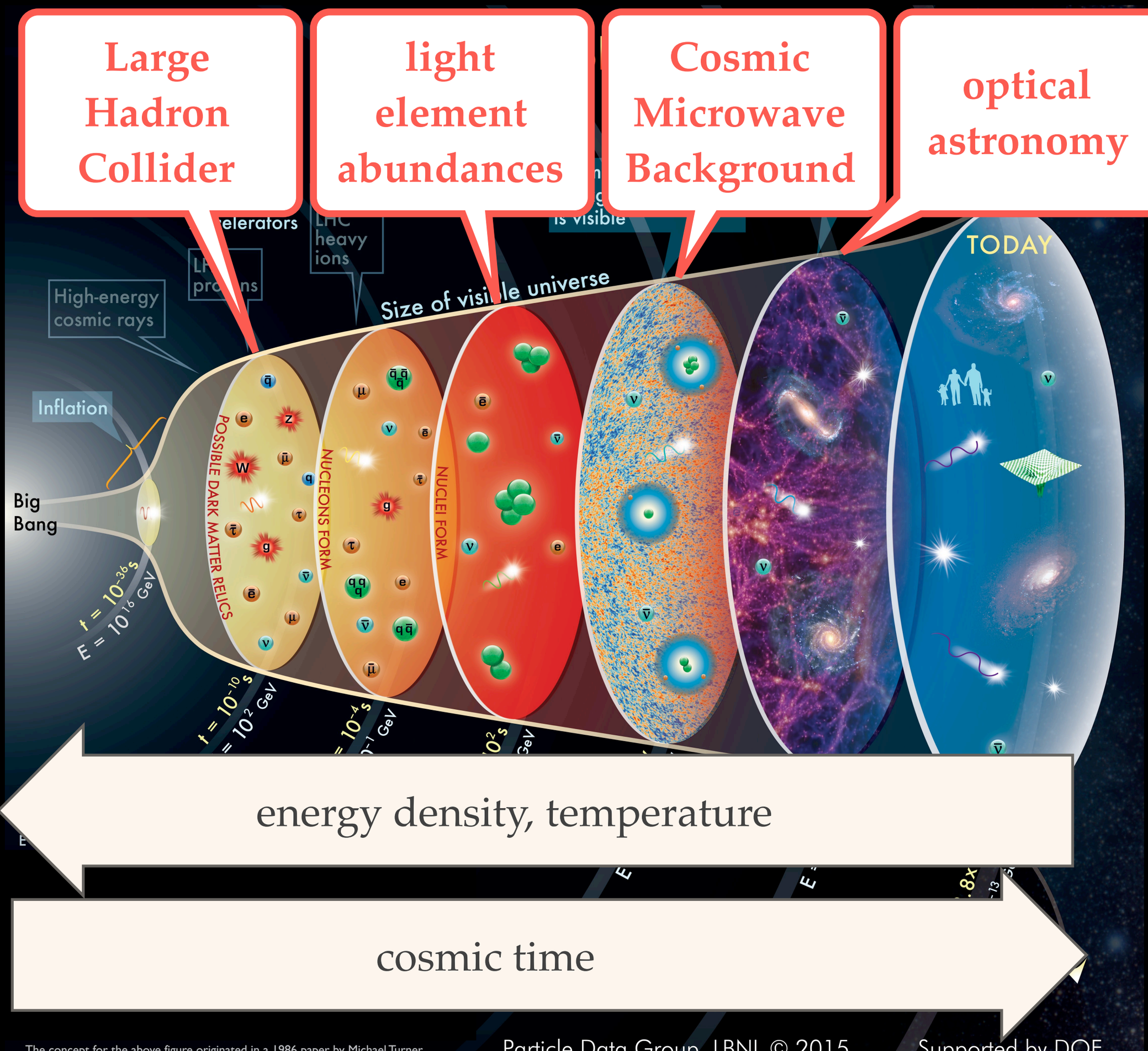
Supported by DOE

Large Hadron Collider

light element abundances

Cosmic Microwave Background

optical astronomy



energy density, temperature

cosmic time

The concept for the above figure originated in a 1986 paper by Michael Turner.

Supported by DOE

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.

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

Theory Examples

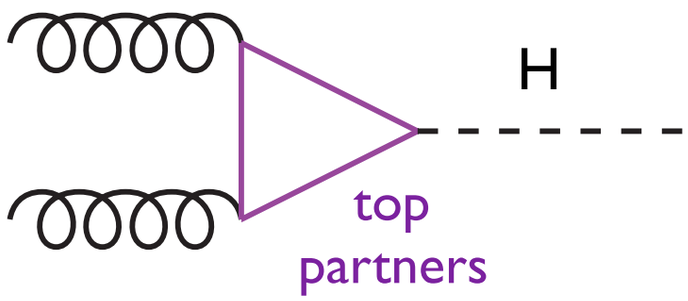
Chacko et al hep-ph/0506256
Craig et al 1501.05310
Curtin et al 1506.06141
…

— 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 (roughly 10^{-3}s)

Theory Examples

— Heavy Neutrinos—

Motivated by **neutrino mass / seesaw mechanism**

Usually assumed to be superheavy…

…but low scale seesaw with M > 100 eV is possible

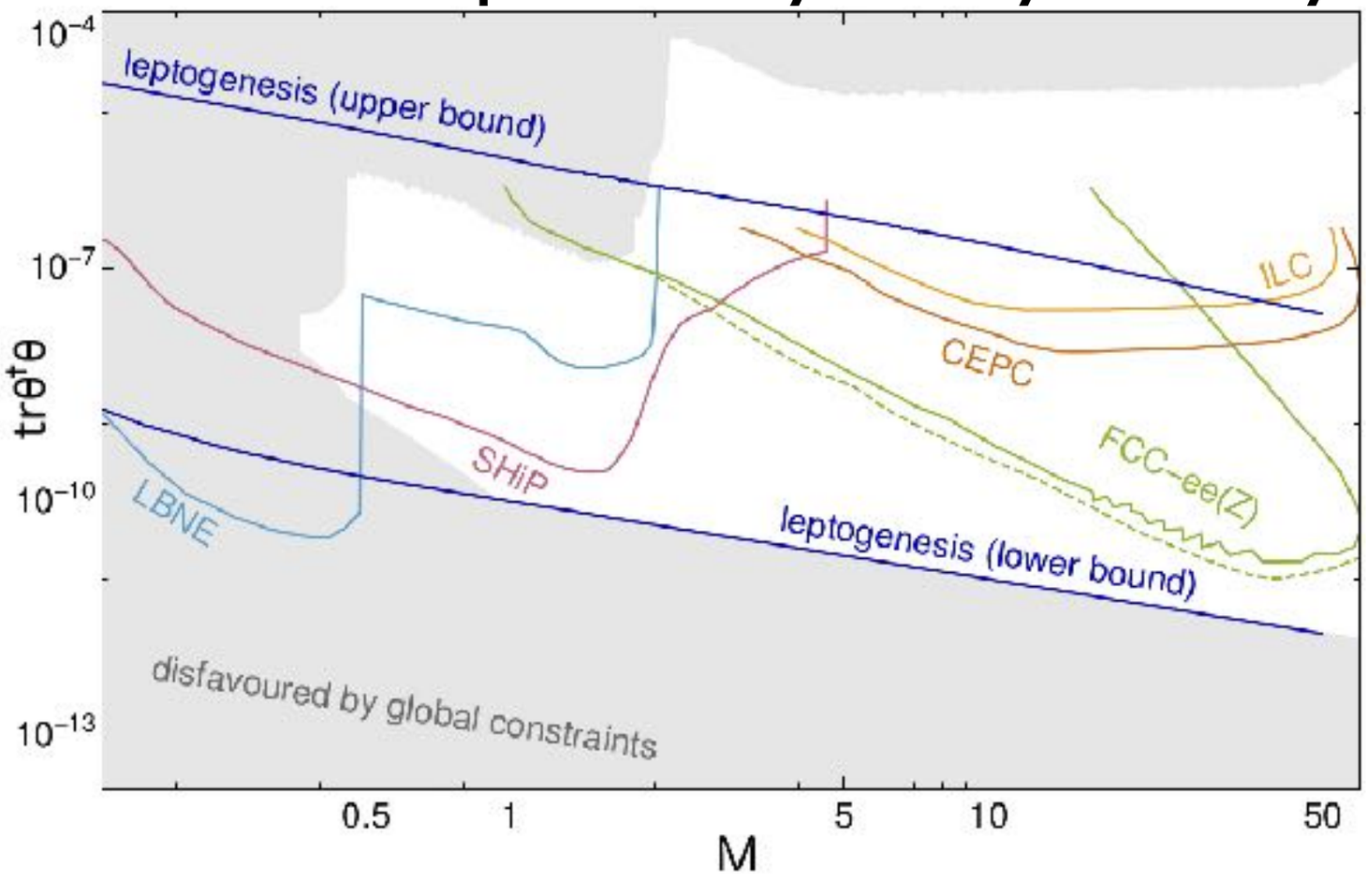
Asaka / Blanchet / Shaposhnikov 0503065

Asaka / Shaposhnikov 0505013

many follow-ups

…

Can explain baryon asymmetry via **leptogenesis**



MaD / Garbrecht / Gueter / Klaric 1609.09069

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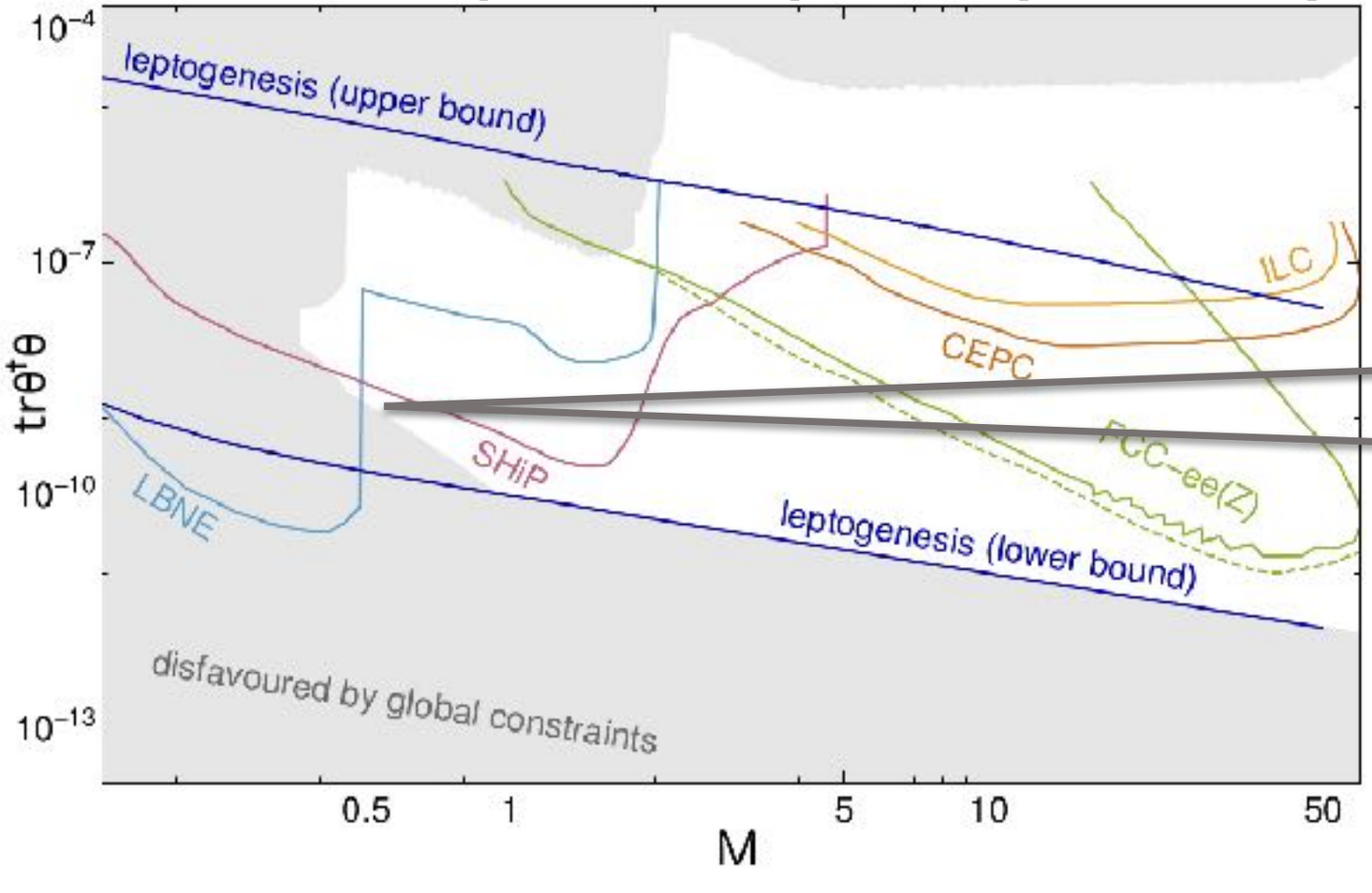

lifetime near BBN limit

MaD / Garbrech / Gueter / Klaric 1609.09069

Lessons from the LHC

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

Distinctiveness of Signature in Detector:

Missing Energy, **Displaced Decay**

… 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

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

→ **build 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

On track for

prototype mid 2017
letter of intent end 2017

theory physics case white paper mid 2017

th+exp Join us!

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

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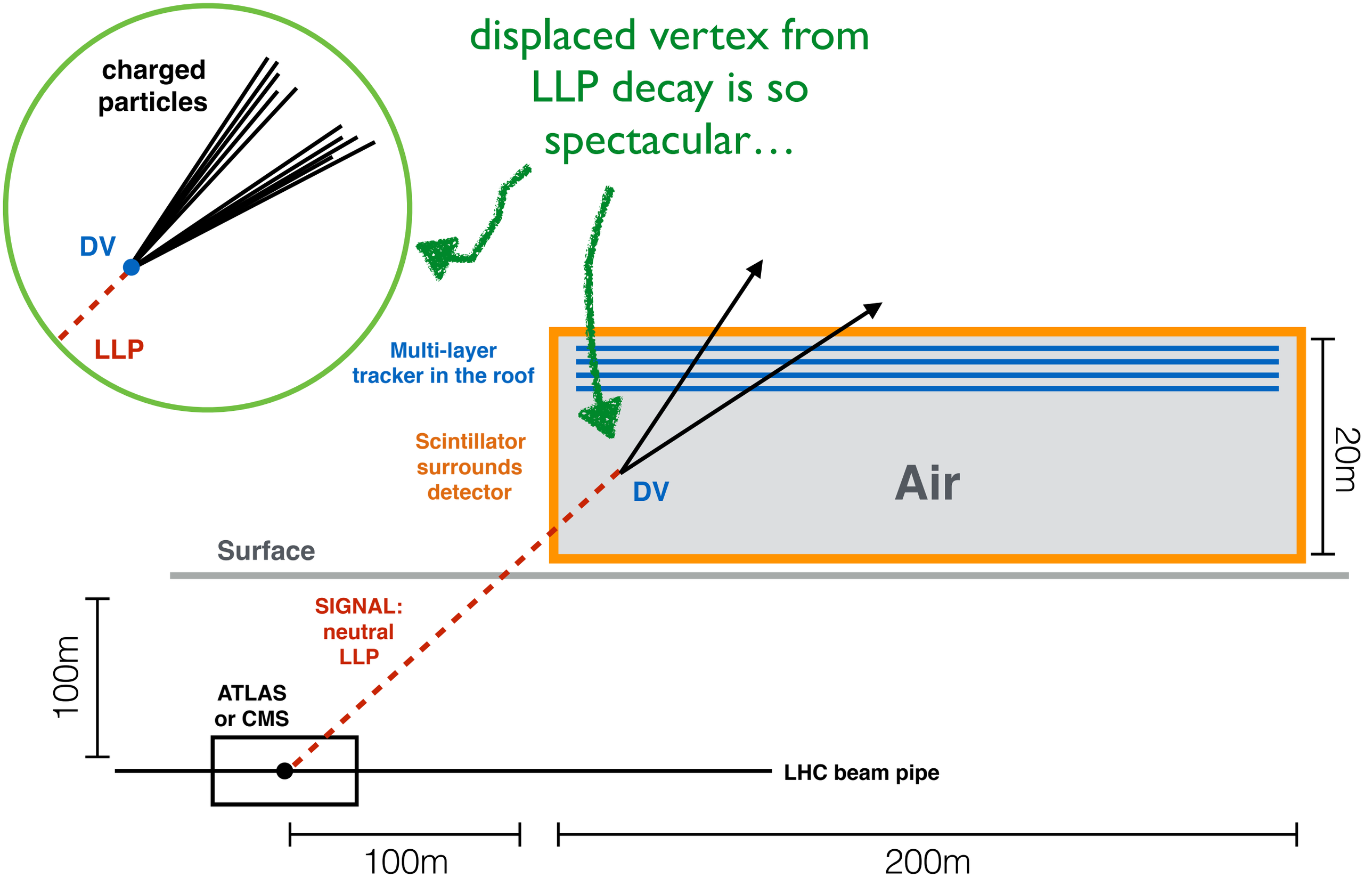
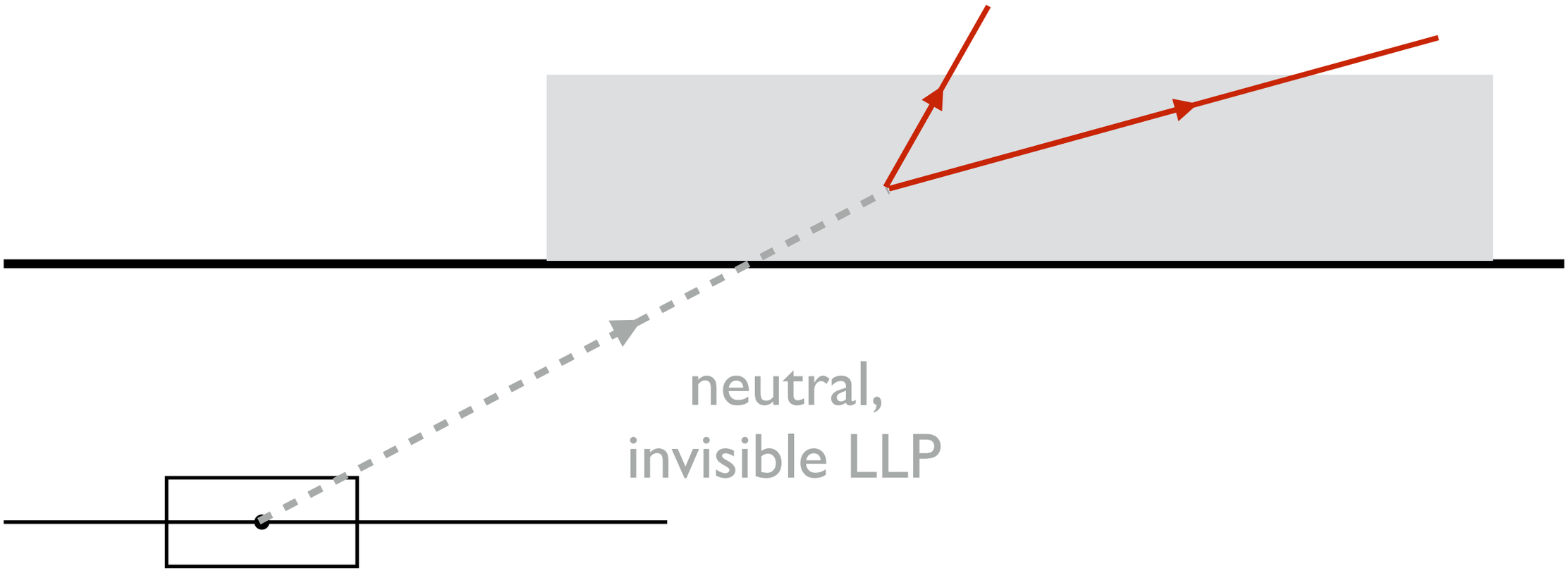
+ ~ 50

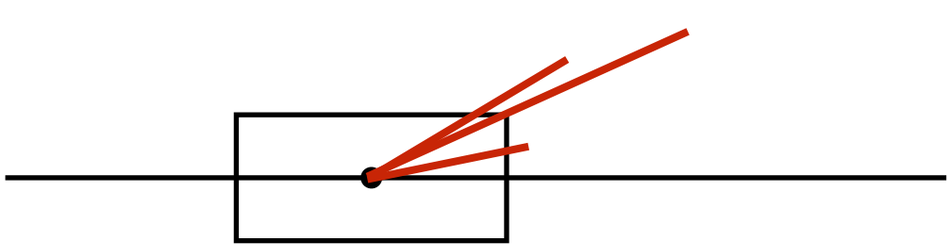

charged particles
DV
LLP
displaced vertex from LLP decay is so spectacular…
Multi-layer tracker in the roof
Scintillator surrounds detector
DV
Air
20m
Surface
SIGNAL: neutral LLP
ATLAS or CMS
100m
LHC beam pipe
100m
200m

Signal



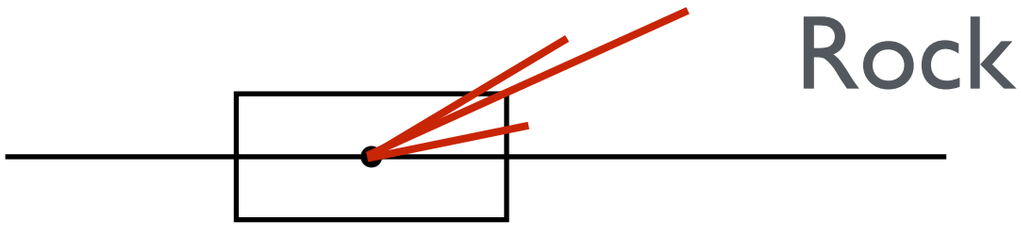
Need to detect this.
How exactly? Depends on backgrounds!

Backgrounds



QCD background from main collision?

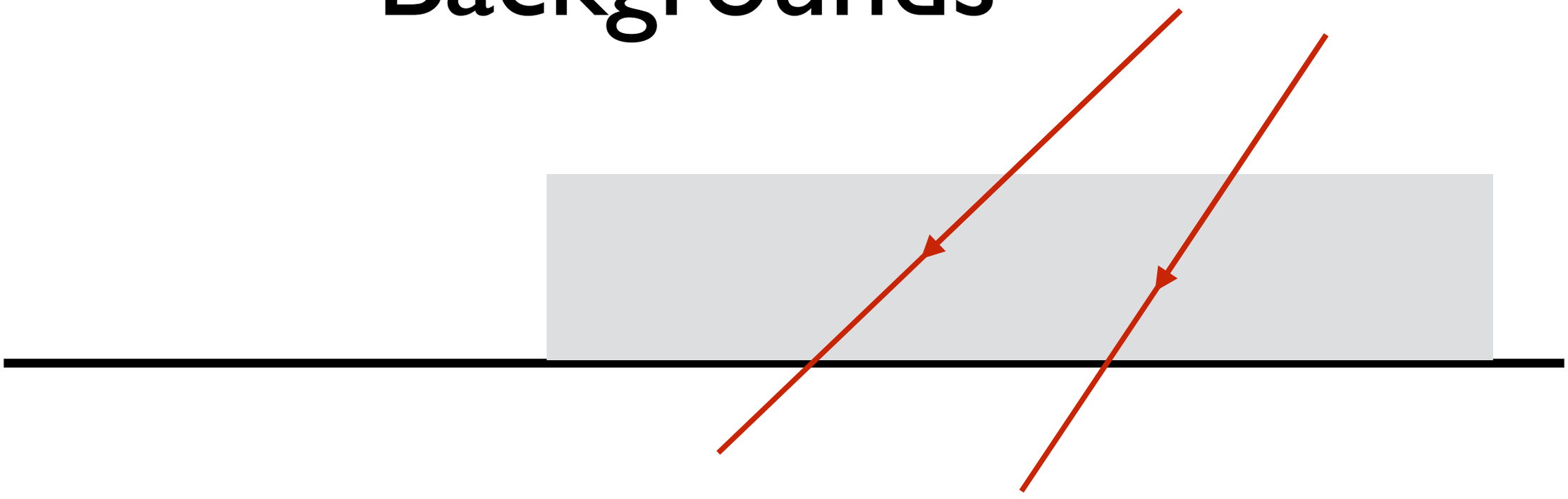
Backgrounds



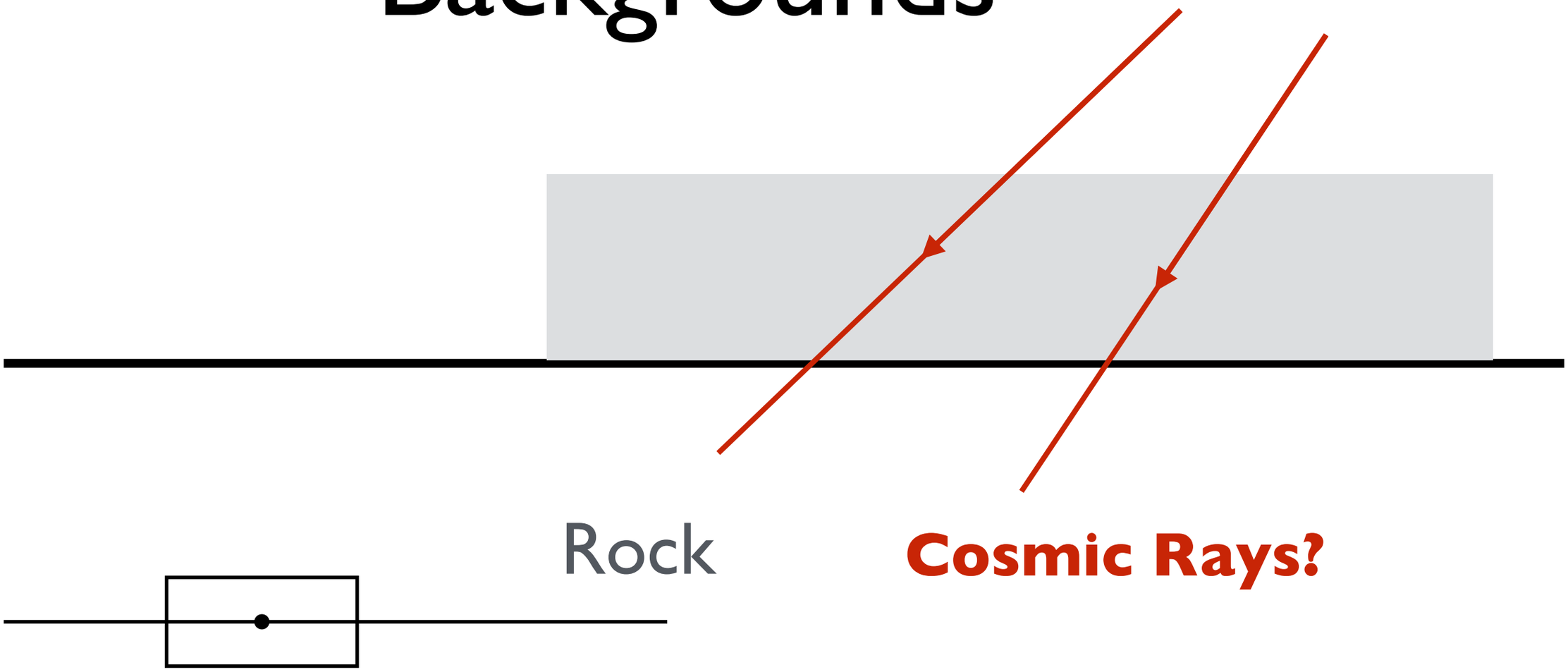
QCD background from main collision?

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

Backgrounds

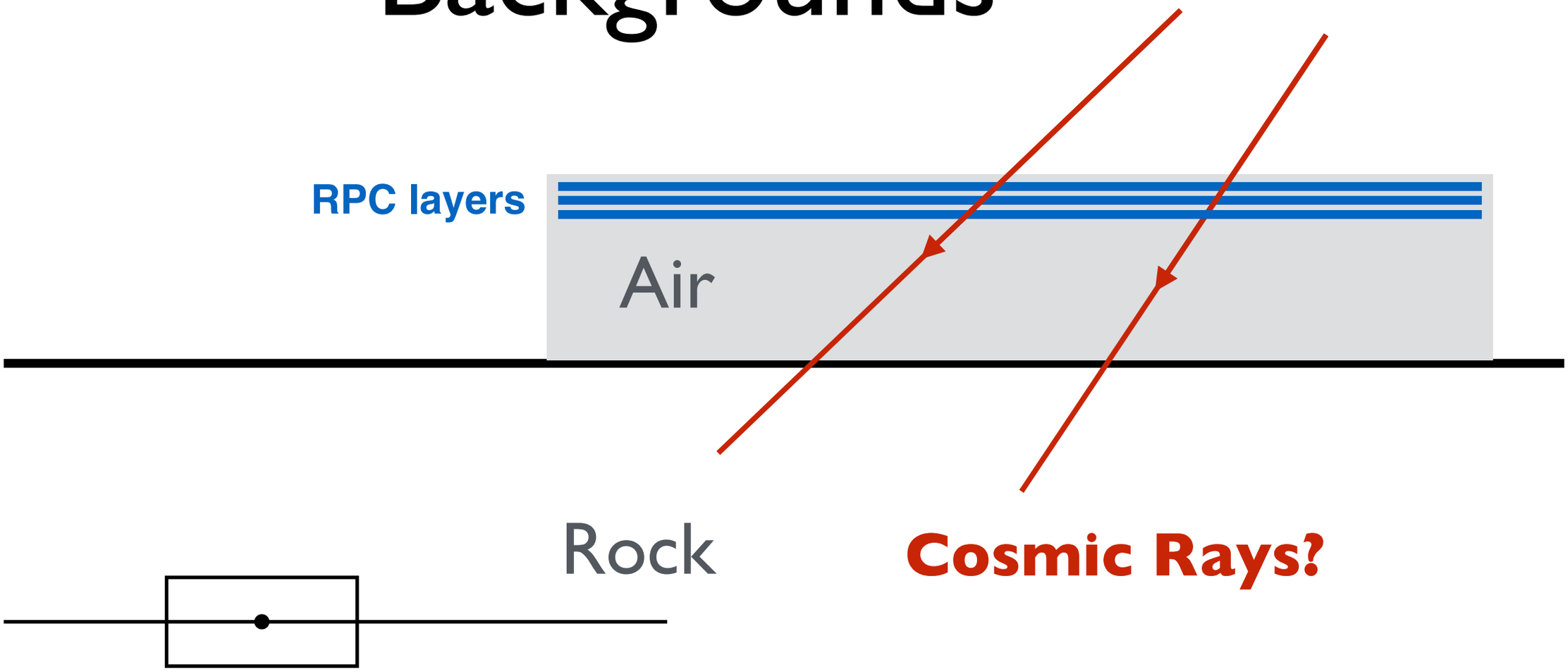


Backgrounds



Do not reconstruct a displaced vertex.
Travel downwards.

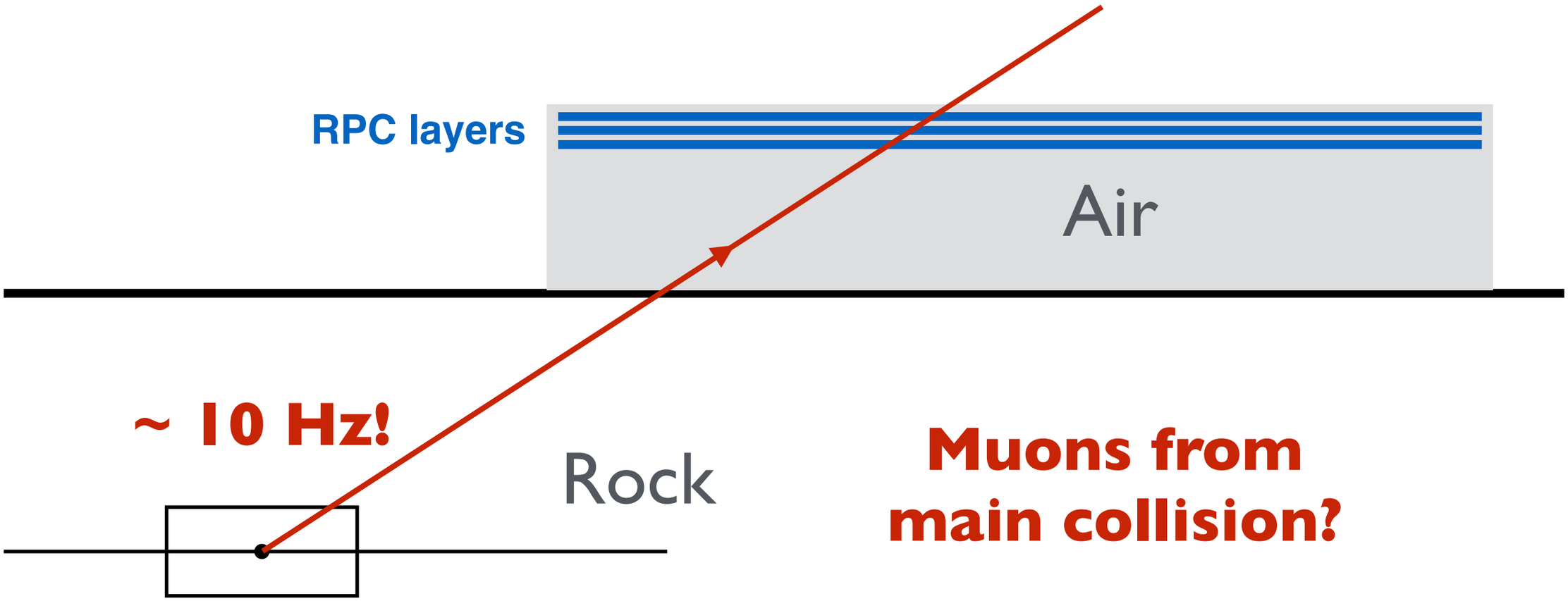
Backgrounds



Do not reconstruct a displaced vertex.
Travel downwards.

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

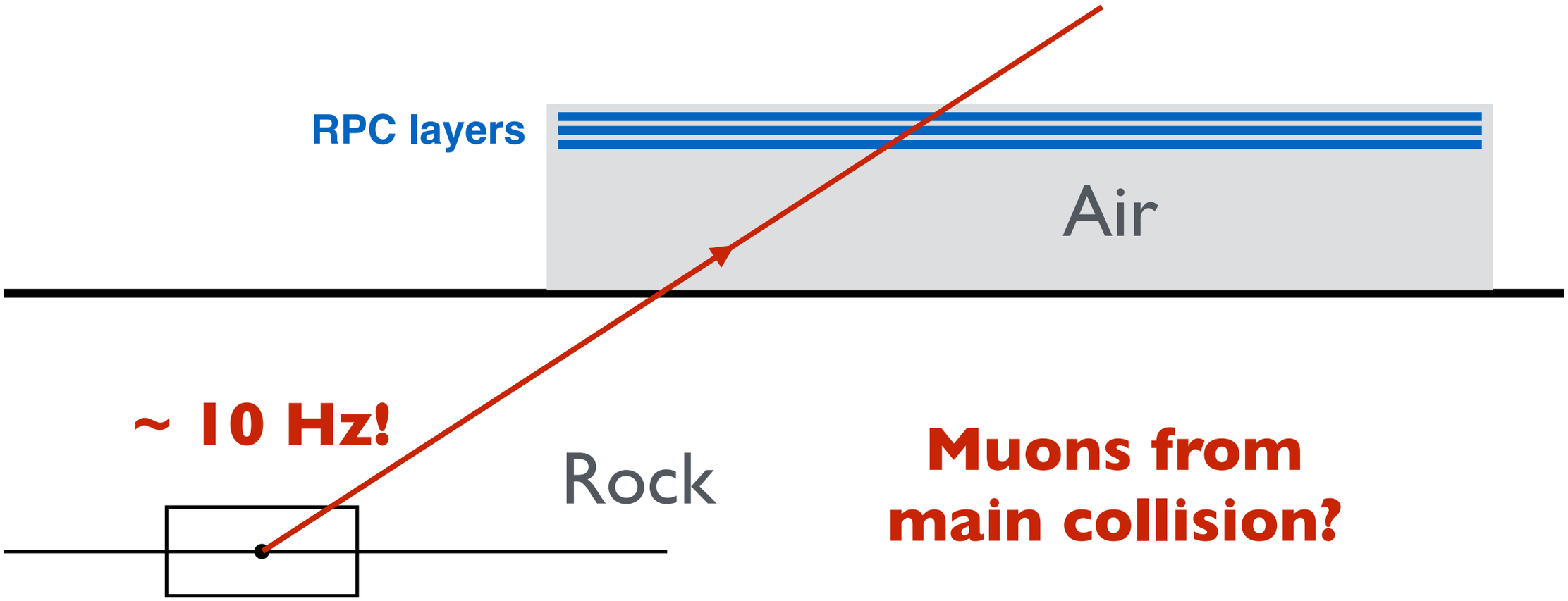
Backgrounds



~ 10 Hz!

Muons from main collision?

Backgrounds

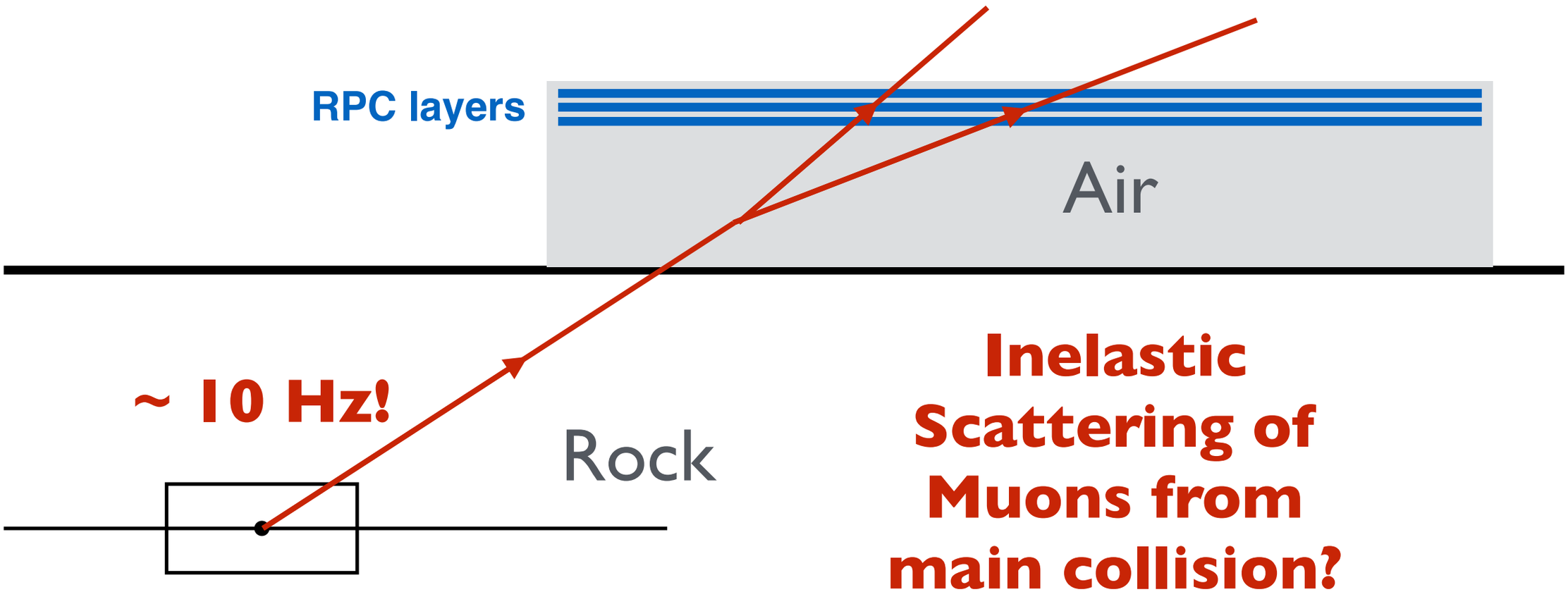


~ 10 Hz!

Muons from main collision?

Do not reconstruct a displaced vertex.

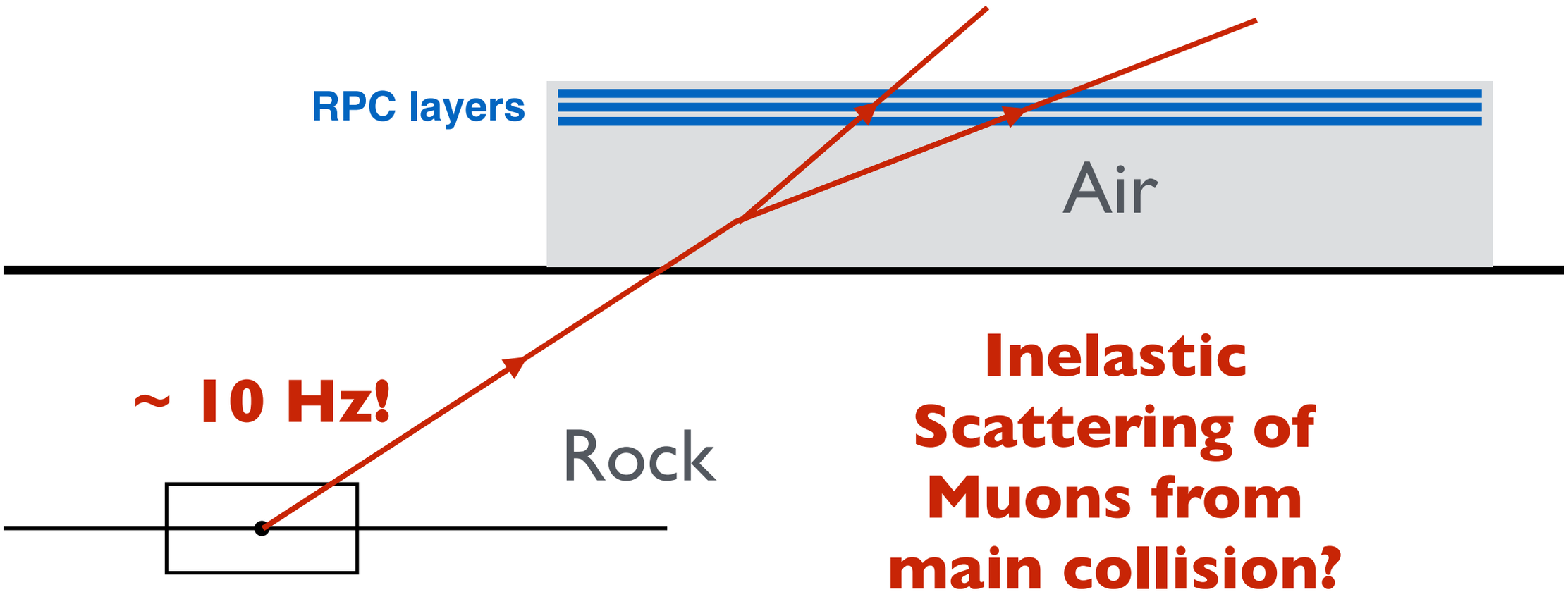
Backgrounds



~ 10 Hz!

Inelastic Scattering of Muons from main collision?

Backgrounds



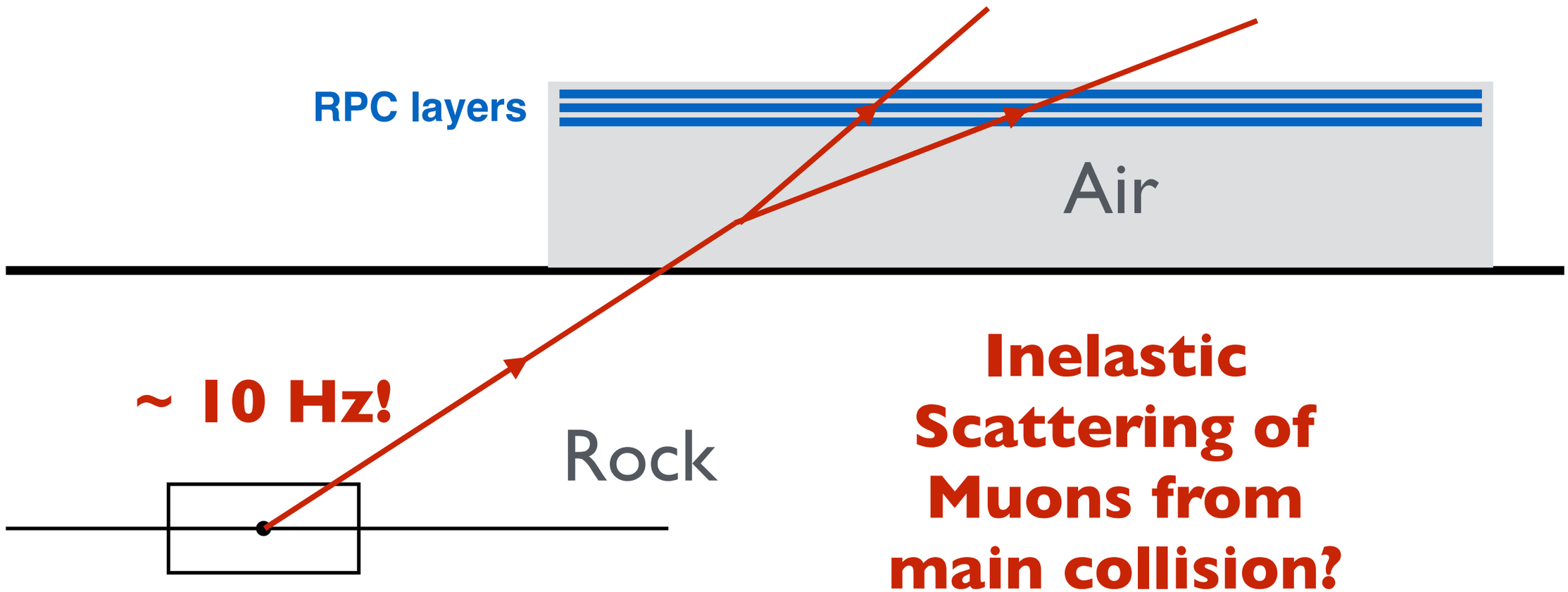
~ 10 Hz!

Inelastic Scattering of Muons from main collision?

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

Has to pass through floor.

Backgrounds



~ 10 Hz!

Inelastic Scattering of Muons from main collision?

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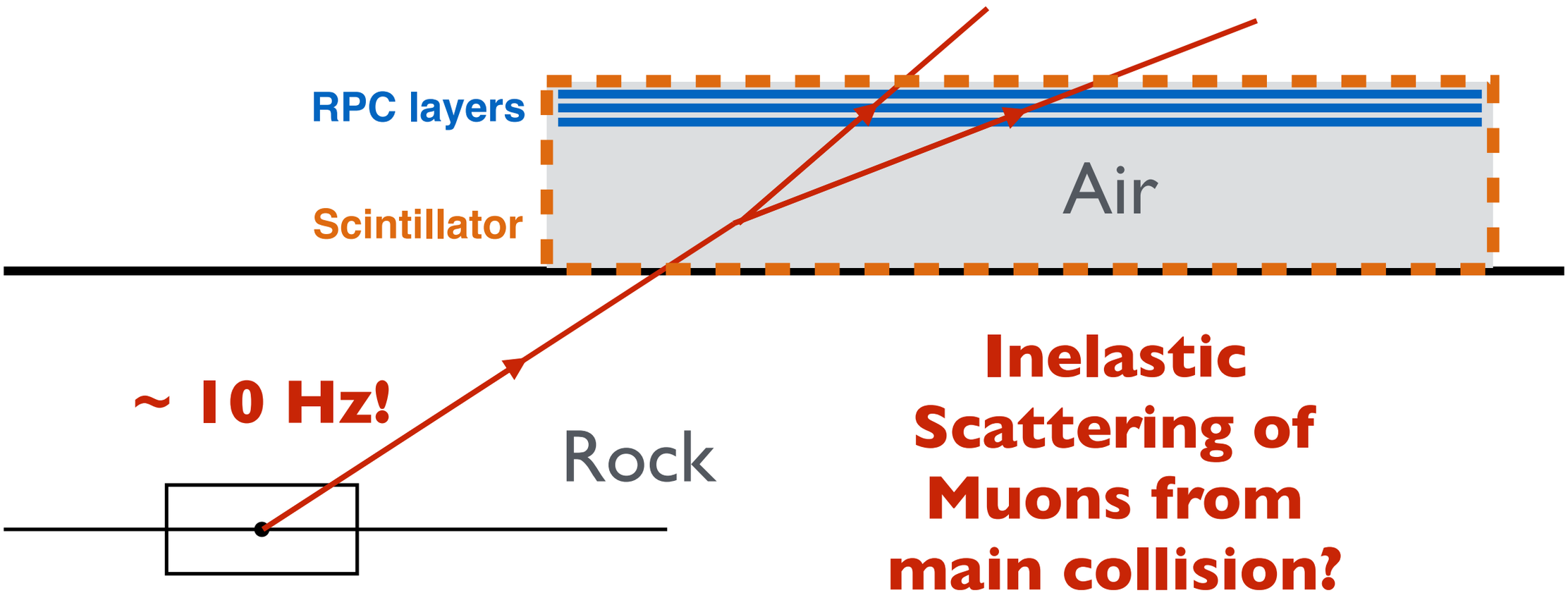
We could veto these events with main detector muon trigger.

Backgrounds



~ 10 Hz!

Inelastic Scattering of Muons from main collision?

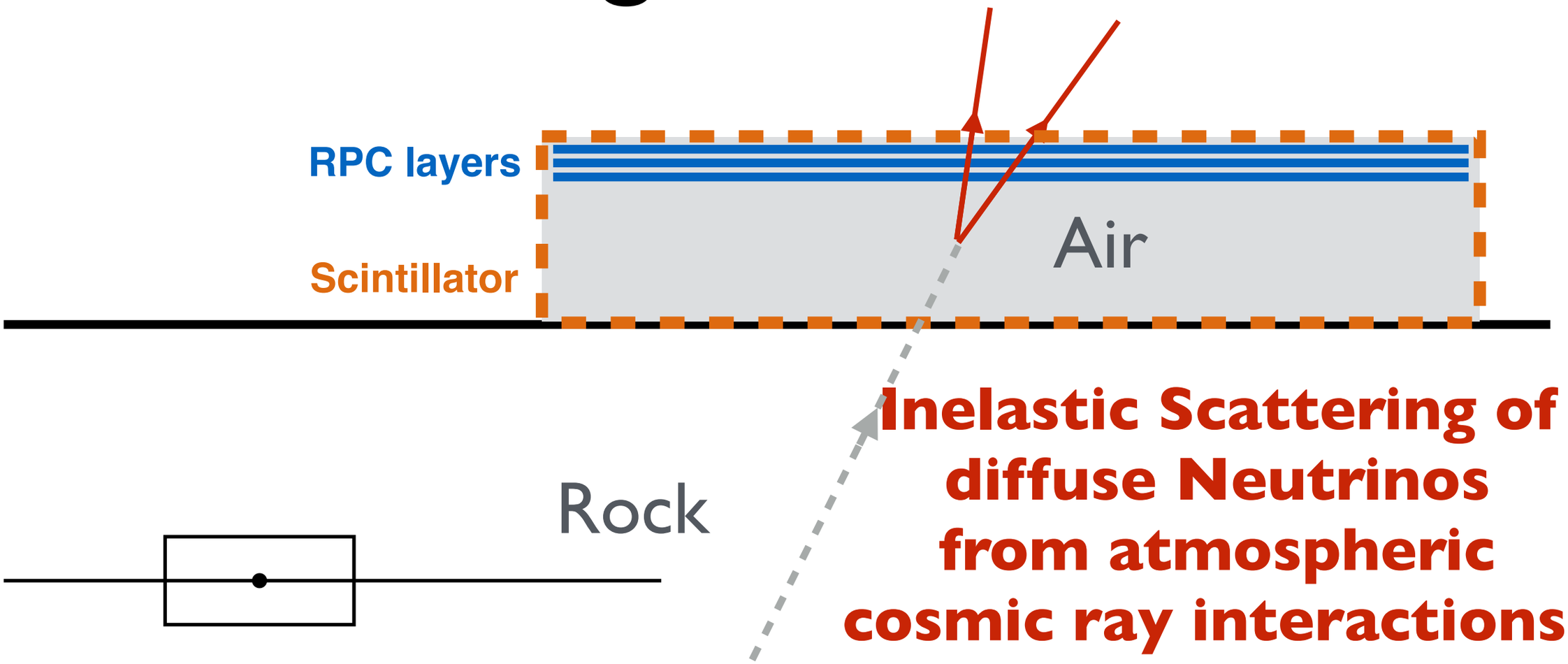
Only O(10) such events over HL-LHC run.
Has to pass through floor.

Surround volume with Scintillator Veto!

Also gives additional rejection power for stray cosmics

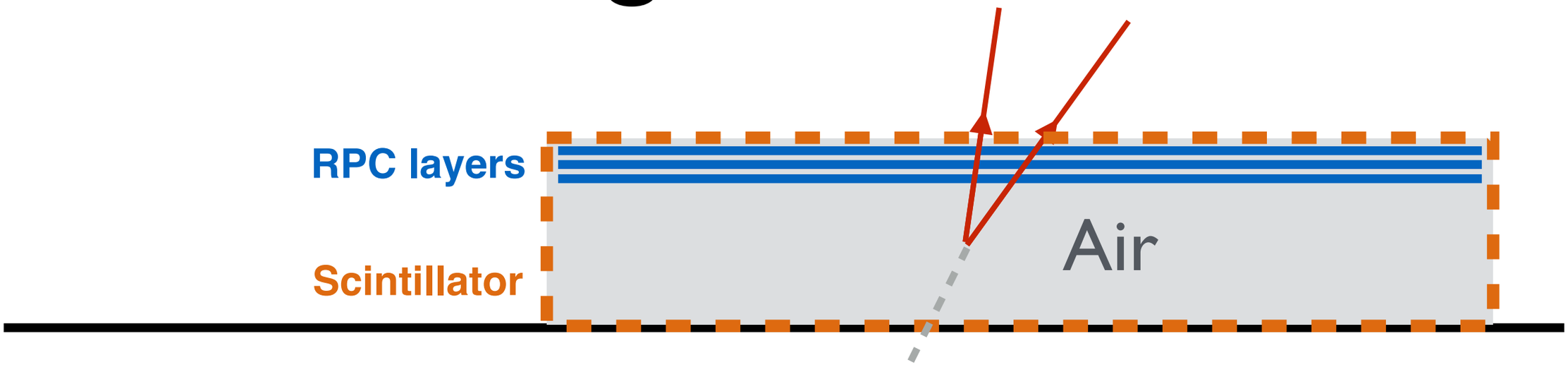
Would allow search for one-pronged LLP decays!

Backgrounds



Inelastic Scattering of diffuse Neutrinos from atmospheric cosmic ray interactions?

Backgrounds



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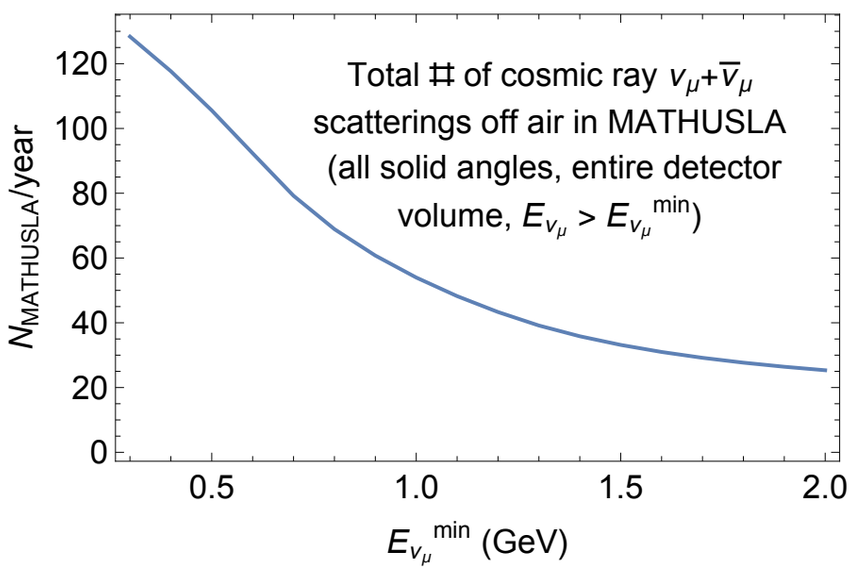
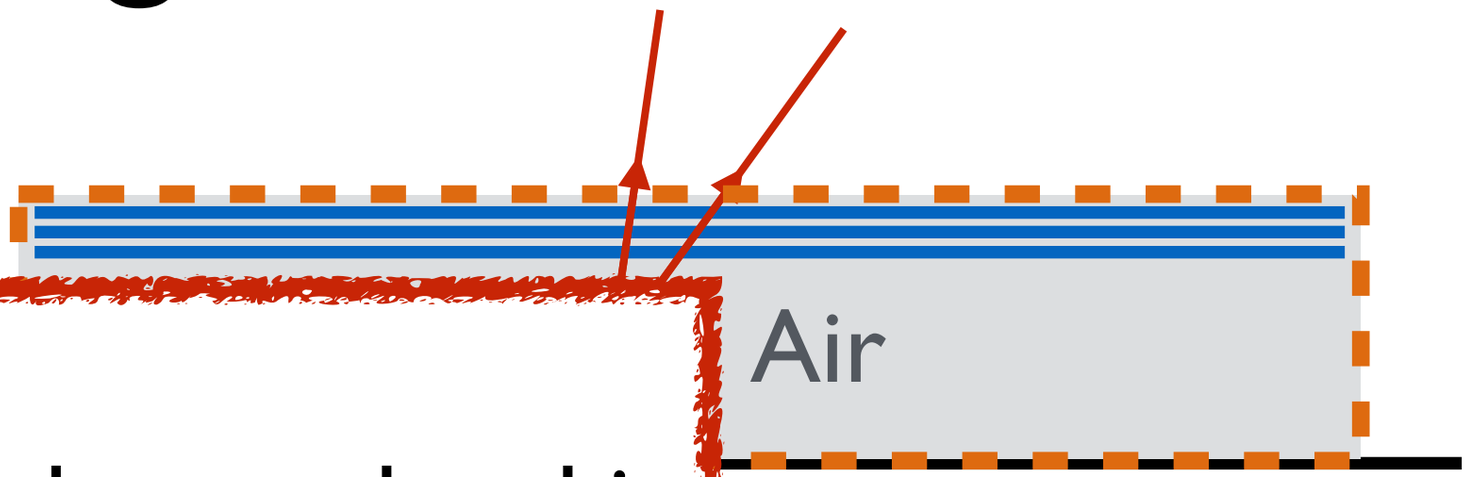


Low rate ~ 10-100 per year above 300 MeV.

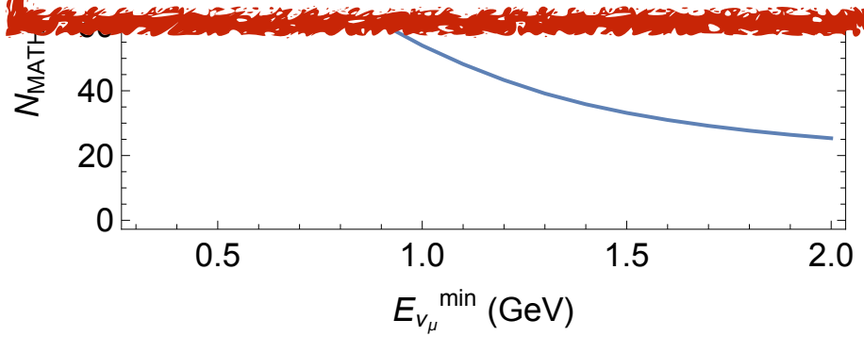
Final state proton is SLOW: can reject 99+% with time-of-flight measurement!

Backgrounds



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

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



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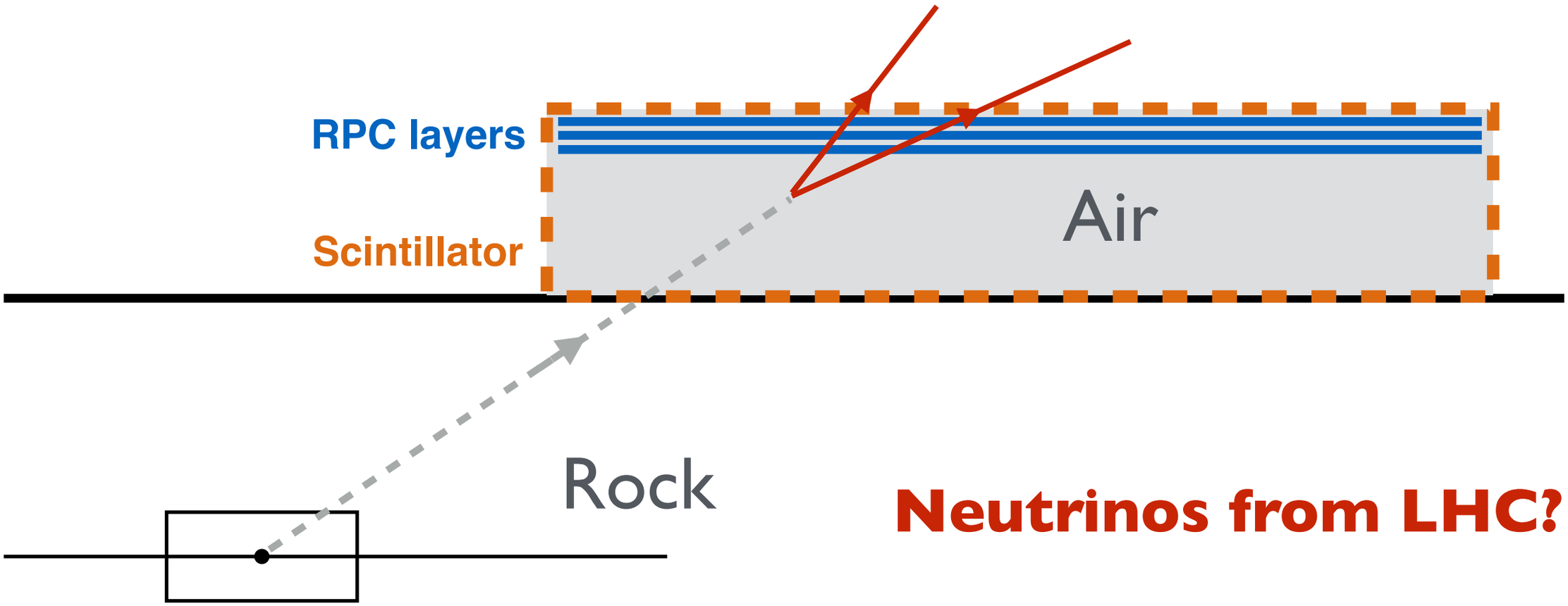
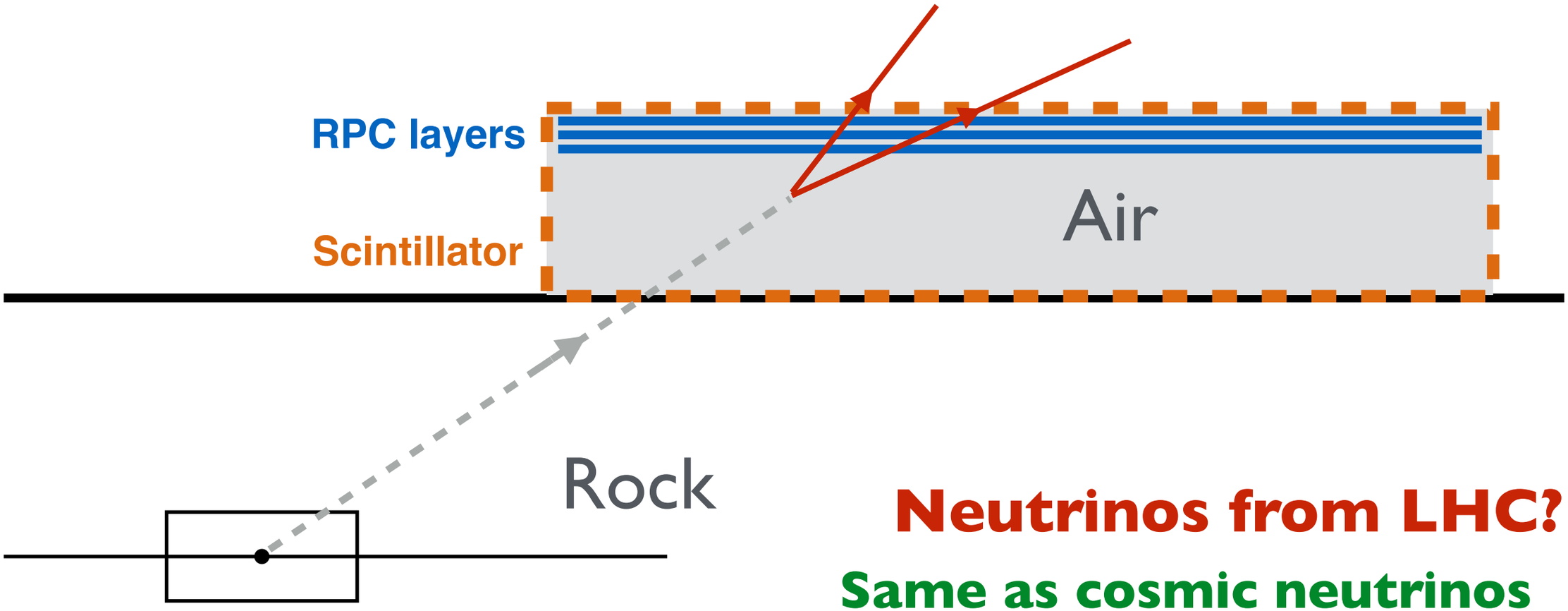
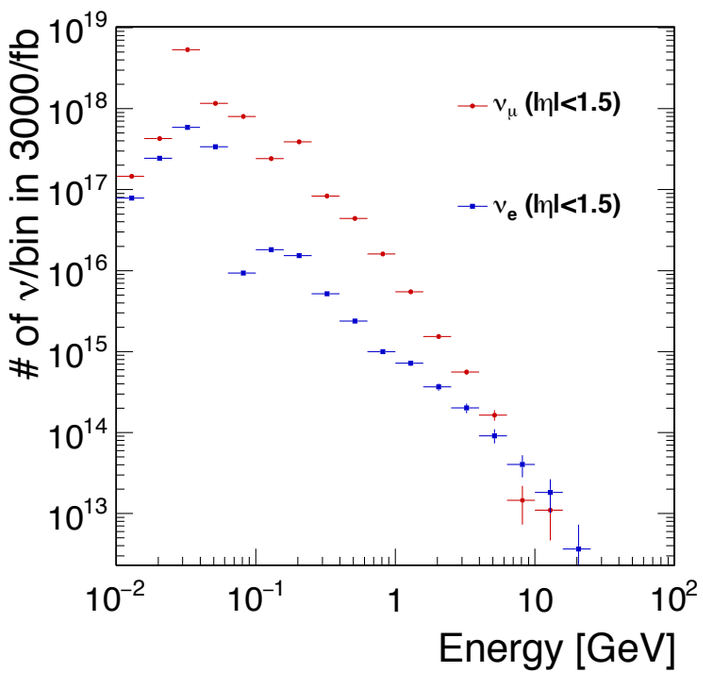
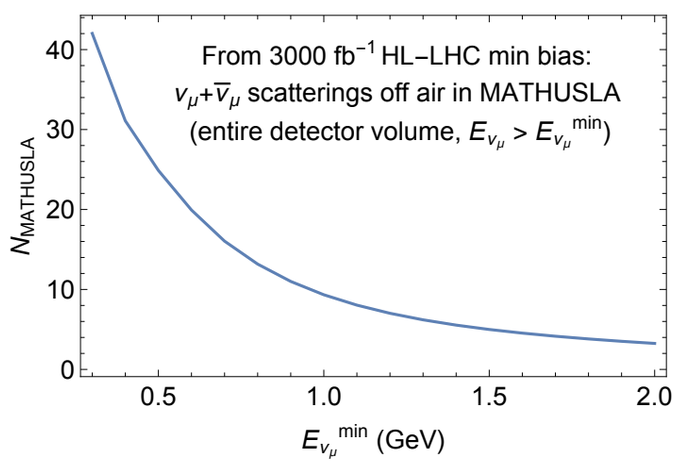


Neutrinos from LHC?

Backgrounds





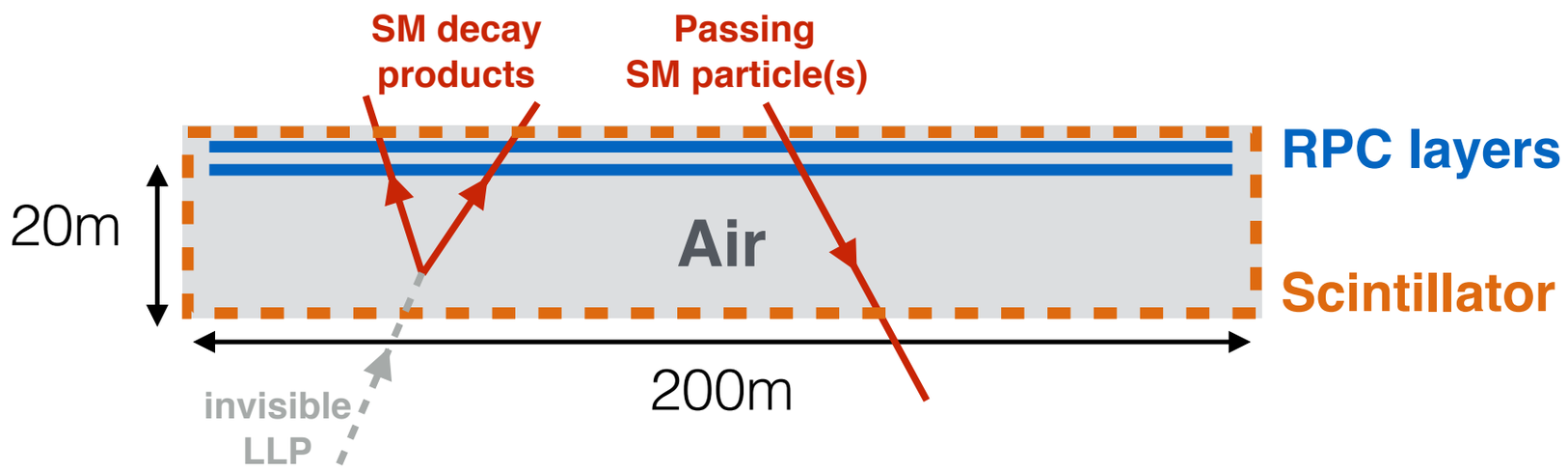


Neutrinos from LHC?

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**.

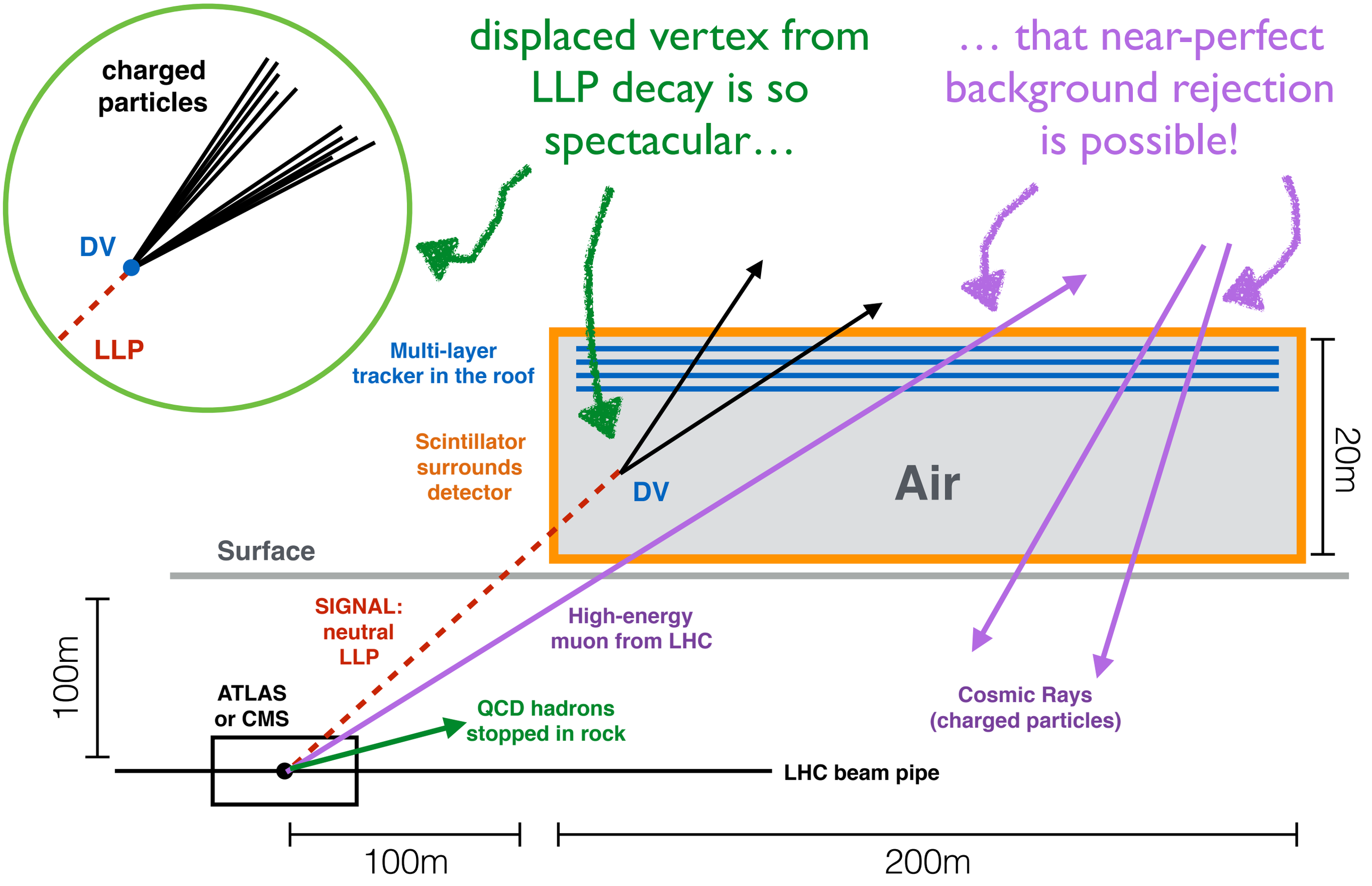
Scintillators give additional **veto**.

~ns timing, ~cm position resolution.

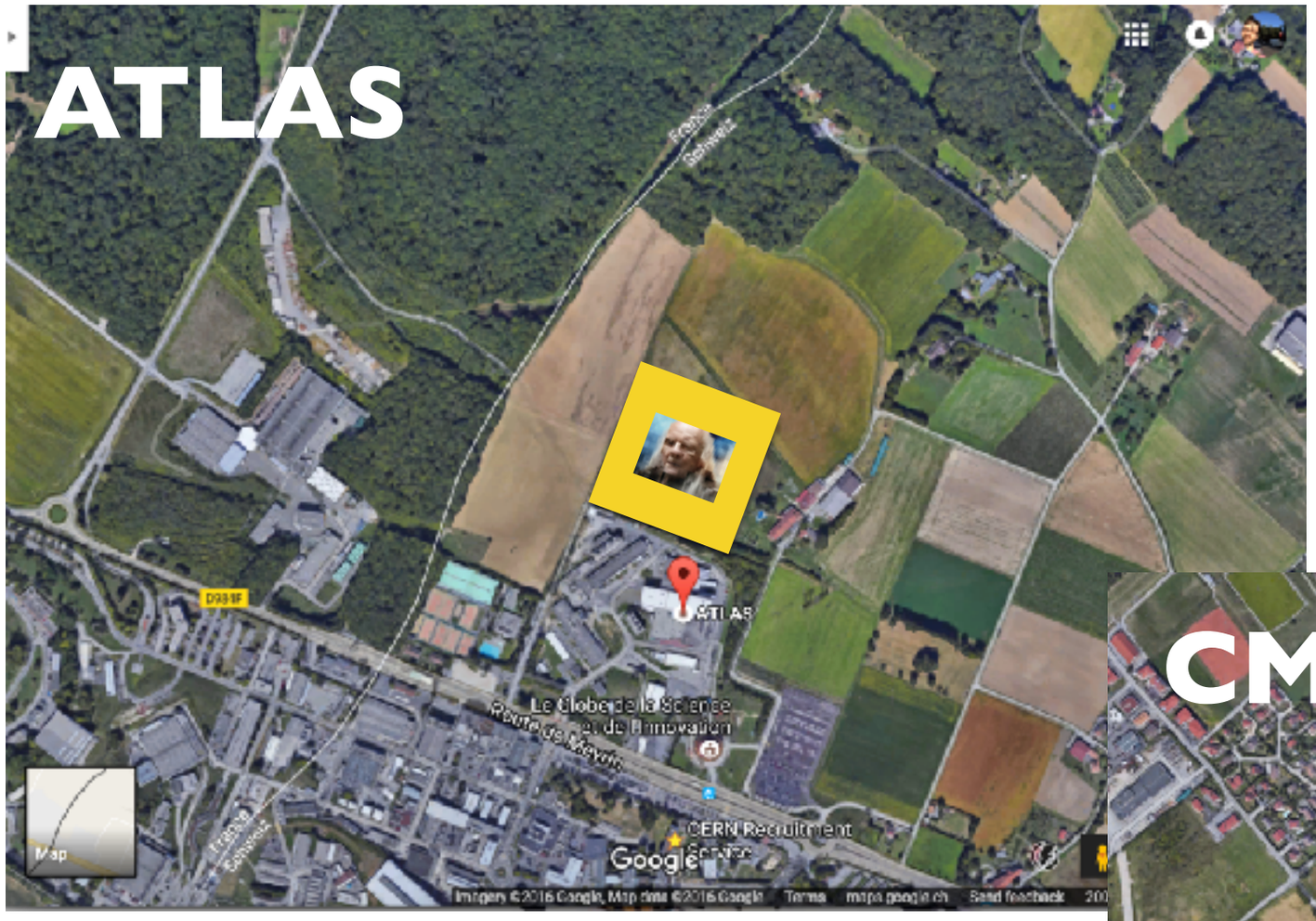
Reconstructed vertex and **time-of-flight measurement**

of final states allows for **near-background-free LLP search**

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


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
100m
ATLAS or CMS
QCD hadrons stopped in rock
Cosmic Rays (charged particles)
LHC beam pipe
100m
200m

Available Space

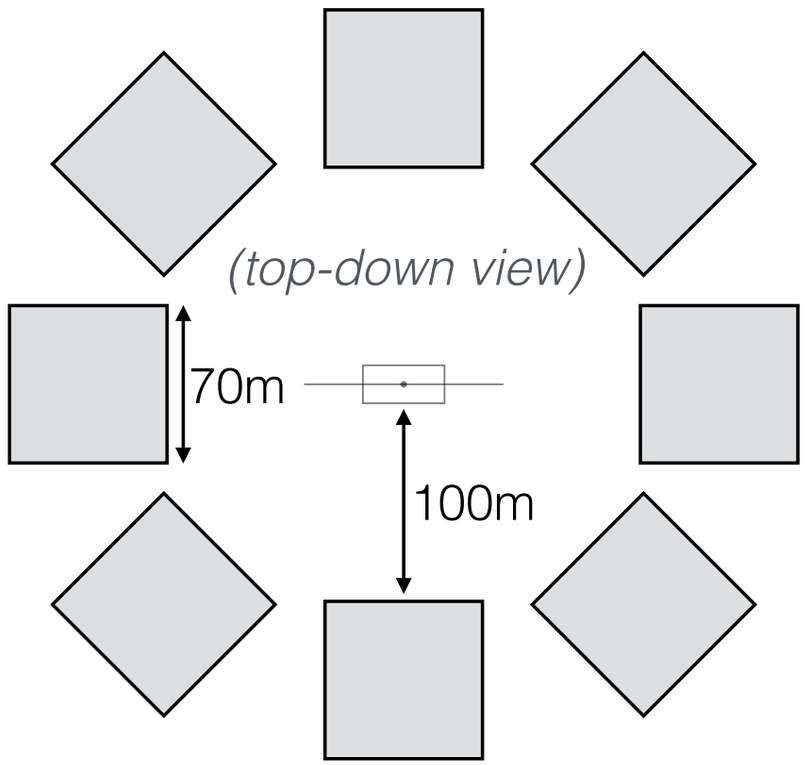


need ~ one
nearby farm plot

Available Space

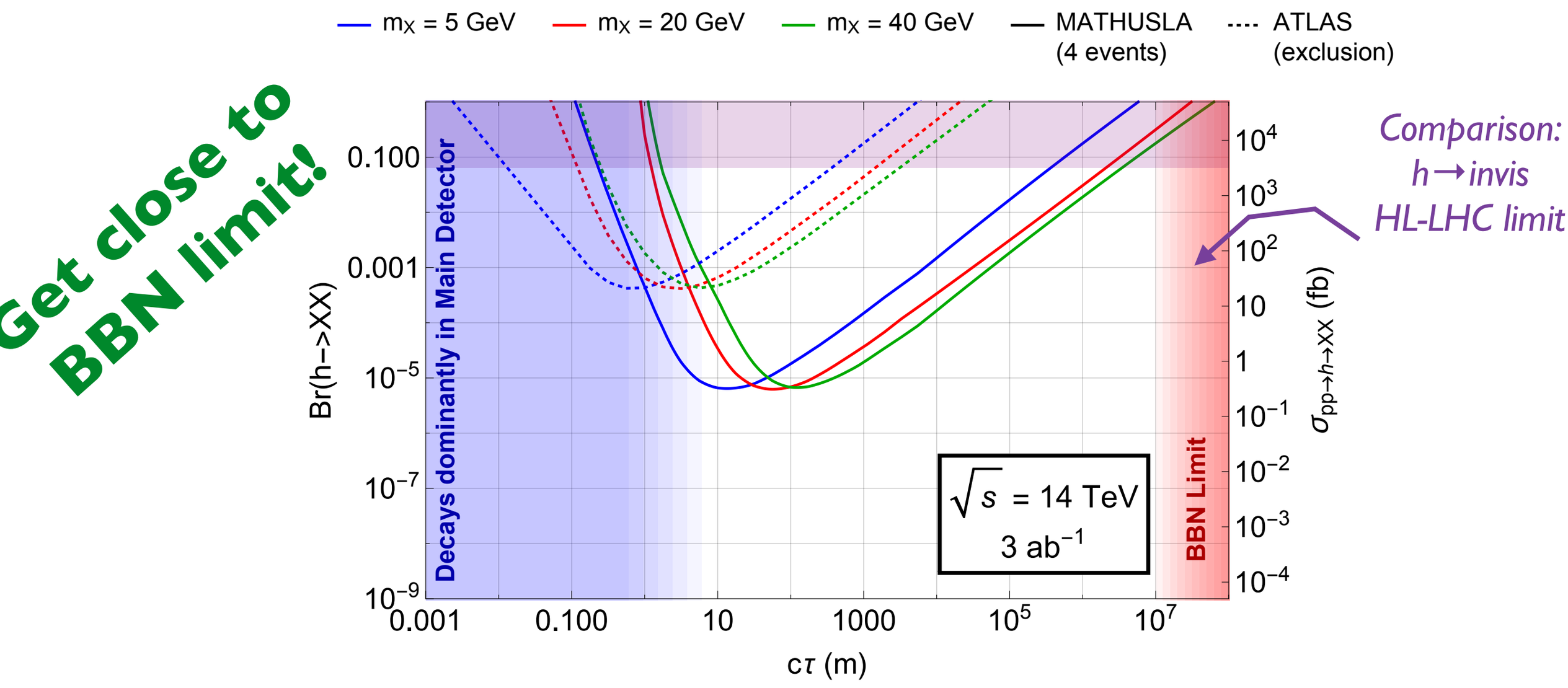
Geometry is very flexible!

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



Examples of Achievable Sensitivity

For LLP production in exotic Higgs decays:



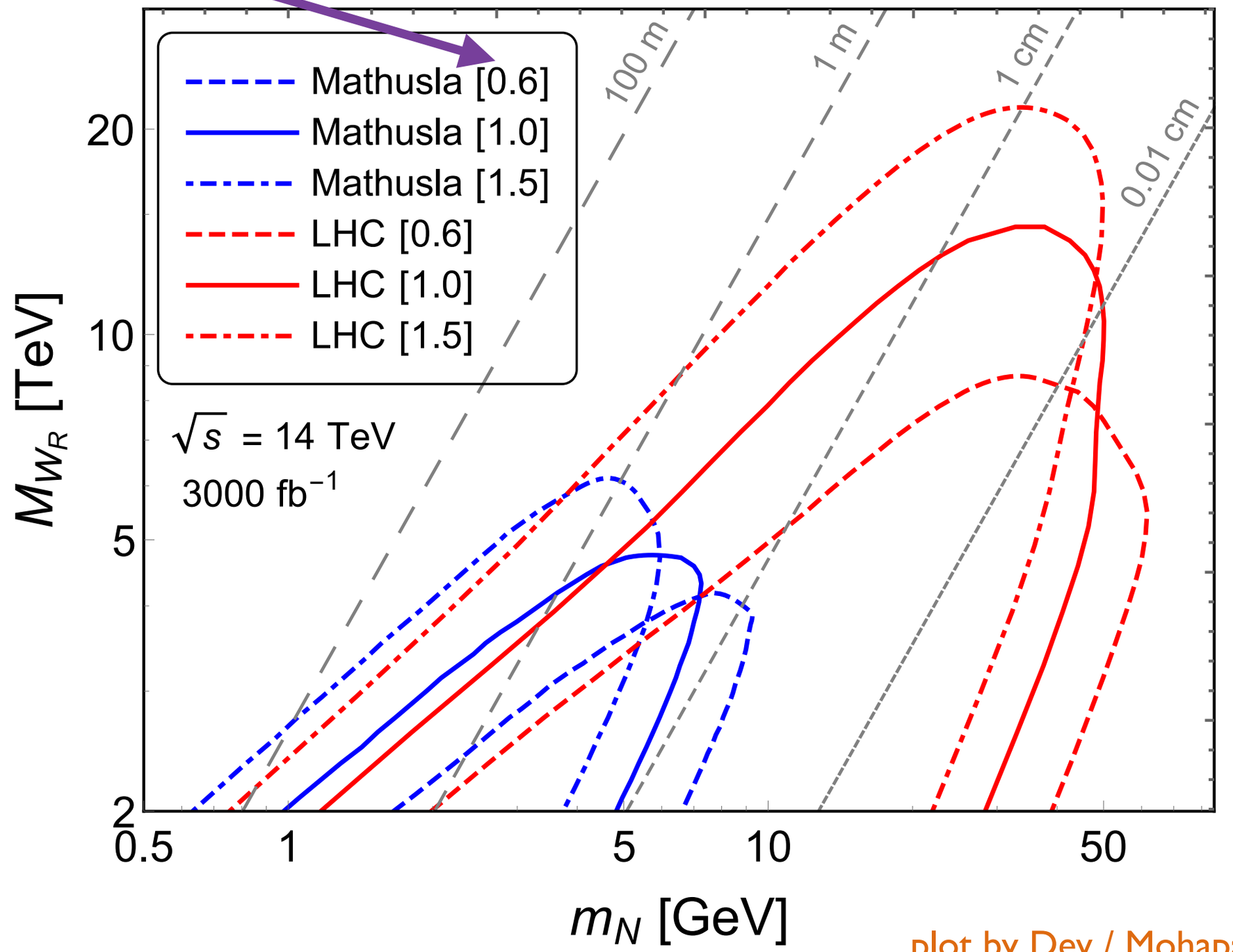
3 orders of magnitude better than ATLAS search for single DV in MS

due to much lower (or ~ zero) backgrounds

Examples of Achievable Sensitivity

Heavy Neutrinos in L-R symmetric model

ratio of gauge coupling constants



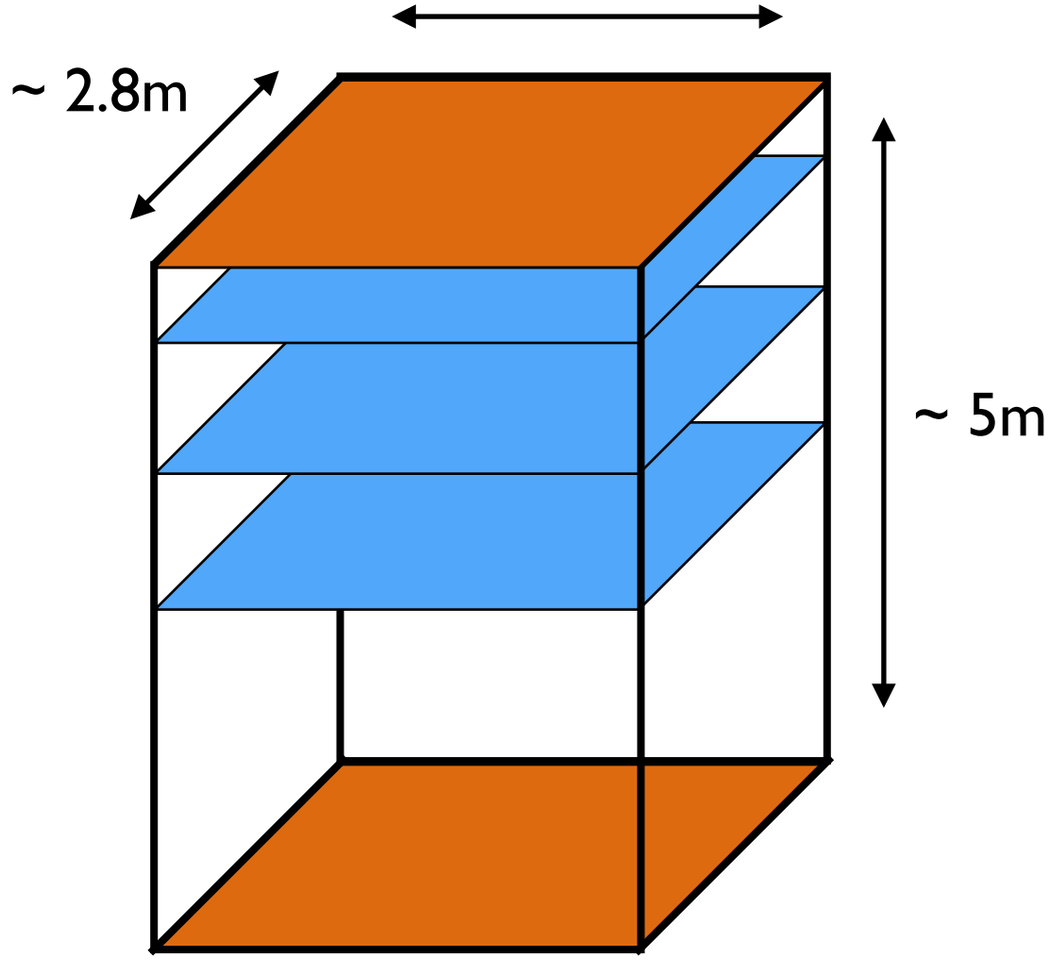
plot by Dev / Mohapatra / Zhang

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!*

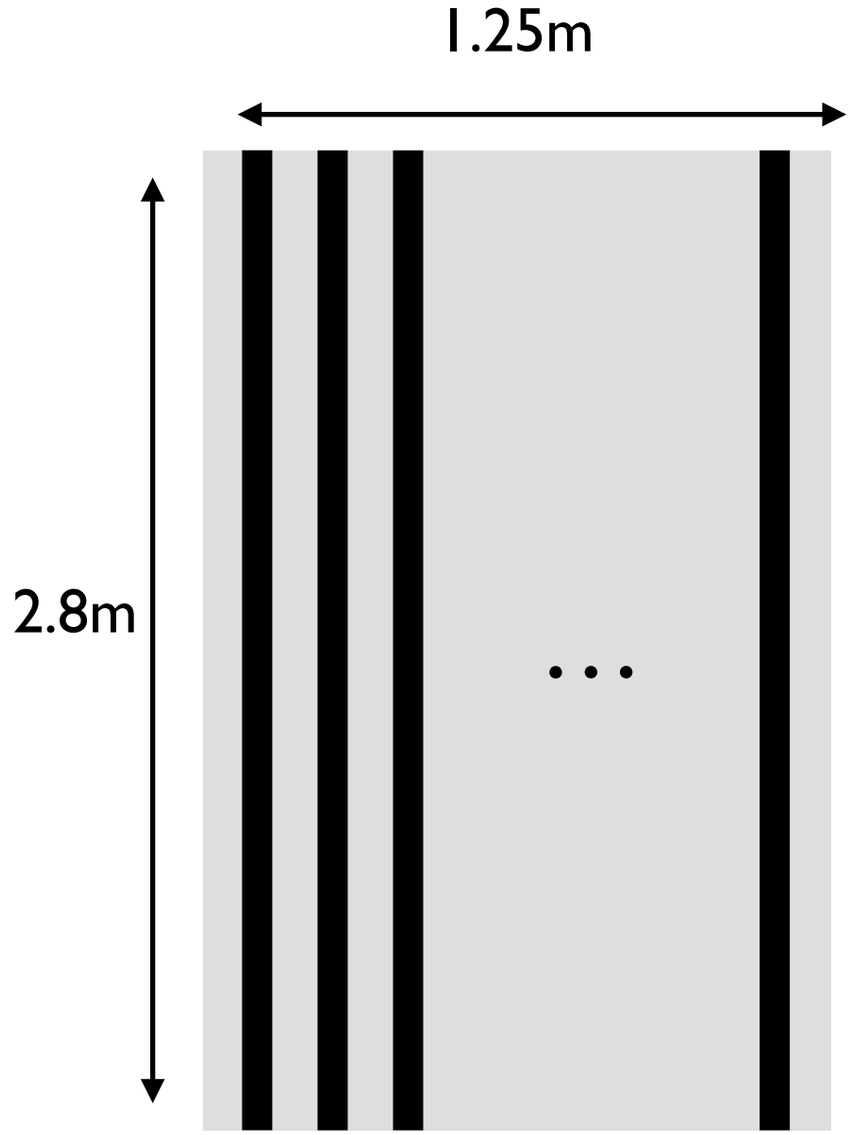
RPCs

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

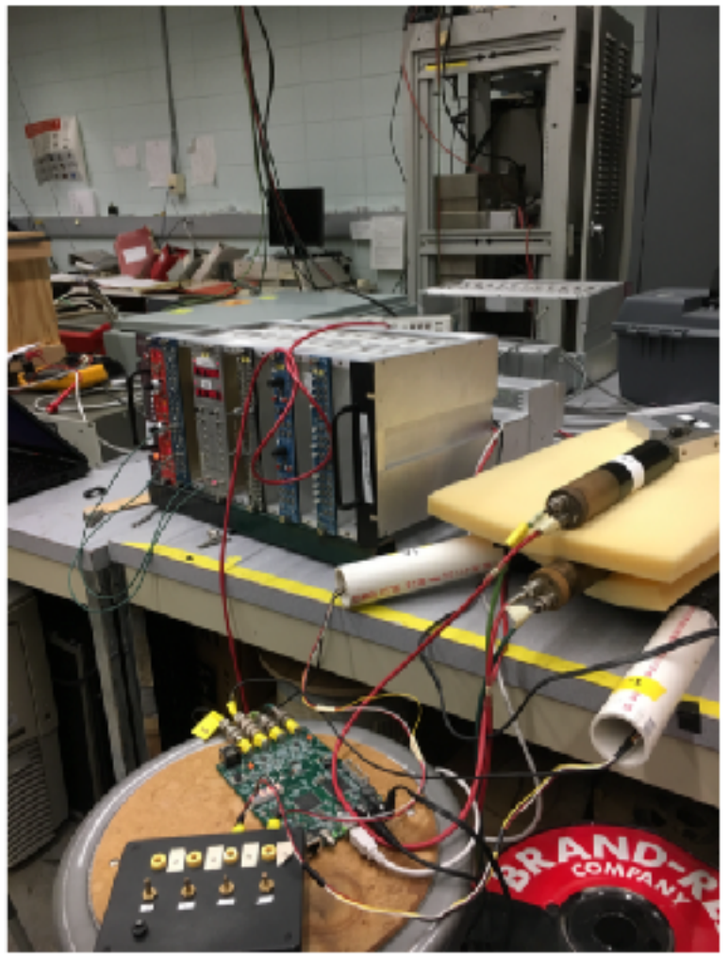
Use gas supply in ATLAS instrument hall

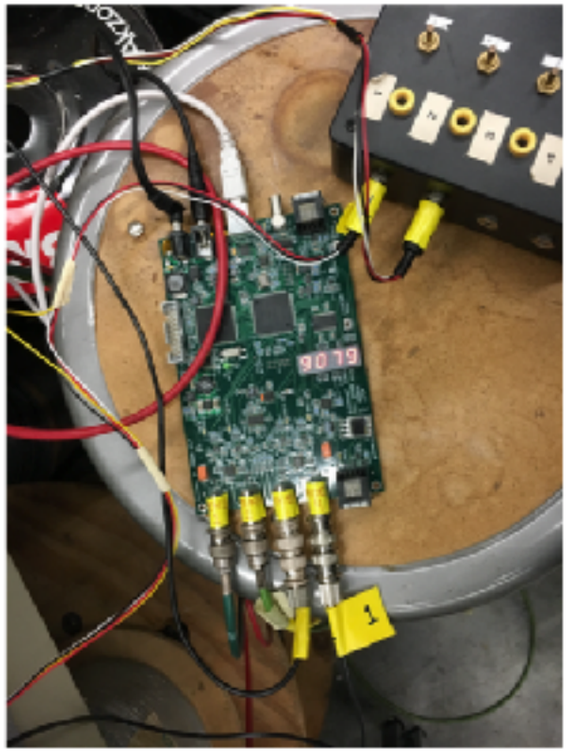


Strips 3cm wide, 2cm spacing

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

UNIVERSITY of WASHINGTON

Henry Lubatti
Gordon Watts
Cristiano Alpigiani
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TEL AVIV UNIVERSITY

Erez Etzion

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

Join us! We're growing fast...

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!

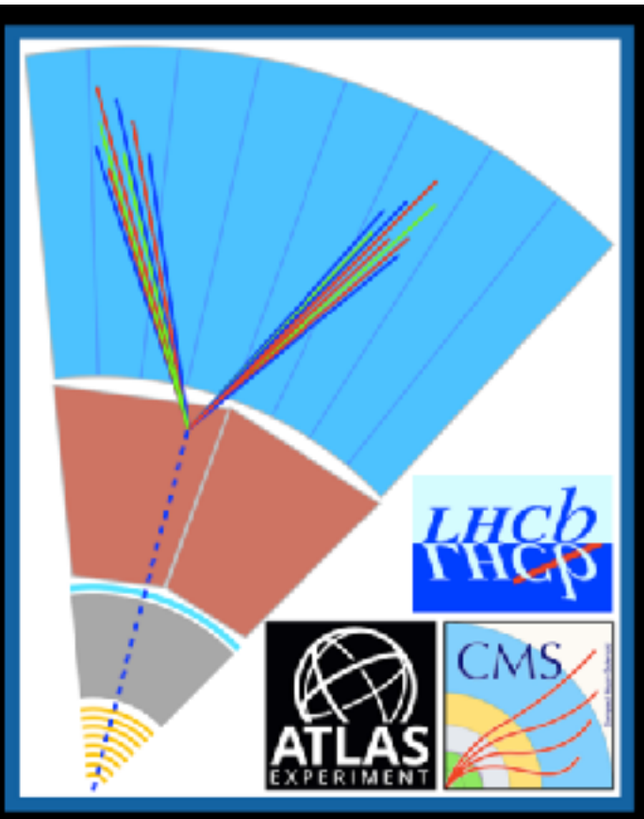
Qualitatively new opportunity at HL-LHC: MATHUSLA can extend LLP sensitivity by factor of 10^3!!

Similar concept could be applied to FCC-hh/FCC-ee

What are the FCC-ep possibilities???

LHC LPP Mini Workshop

https://indico.cern.ch/event/607314/



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

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Hong Kong University of Science and Technology June 24-30

Quantum Chromodynamics at Hadron Collider
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Dark Matter
(Jianglai Liu / Marc Schumann / Yannis Semertzidis / Patrick Fox)

Neutrino Physics
(Nakaya Tsuyoshi / Kam-Biu Luk / Masahiro Kuze)

Physics After LHC
(Michelangelo Mangano / Lyn Evans)

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(Masahiro Takada / Teruaki Suyama)

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Further information and registration

Gordon Research Conference:
https://www.grc.org/programs.aspx?id=16933

Gordon Research Seminar:
https://www.grc.org/programs.aspx?id=17516
https://indico.cern.ch/event/597024/overview