MATHUSLA (Status Report)

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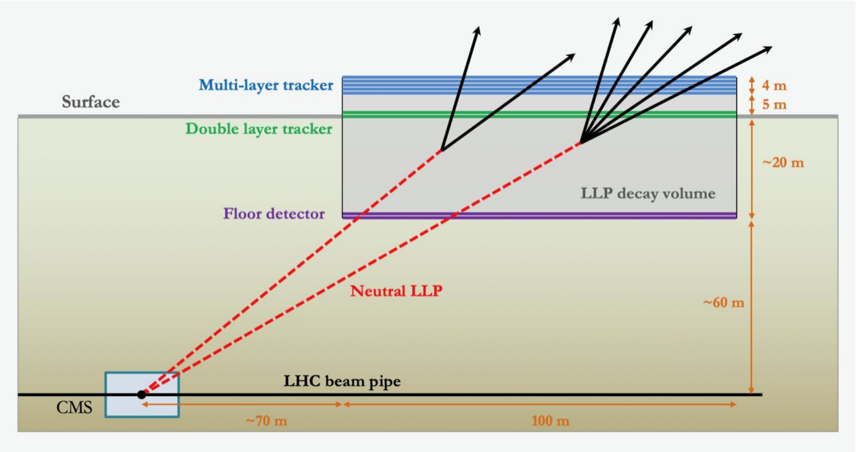
on behalf of the MATHUSLA collaboration

7th LHC LLP Community Workshop
25 May 2020

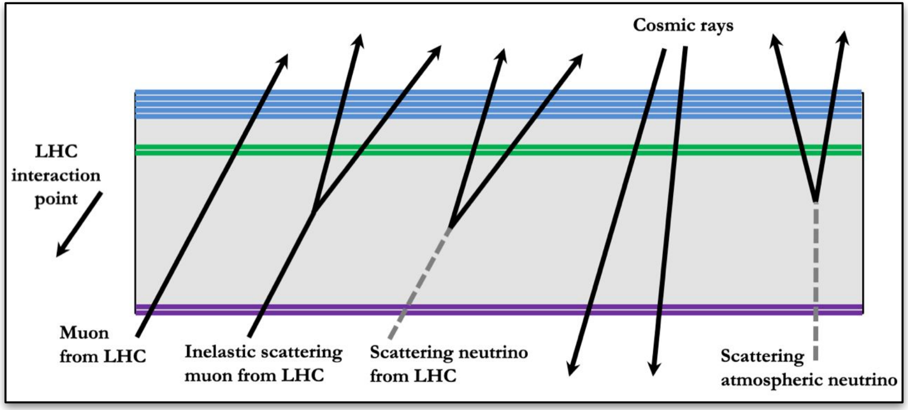
UNIVERSITY *of* WASHINGTON

Introduction/review

- **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles
- Dedicated LLP detector at ground level for HL-LHC
- Sensitive to ultra long-lived neutral particles:
  - Lifetimes up to the Big Bang nucleosynthesis limit, $c\tau$ ~ 10^7-10^8 m



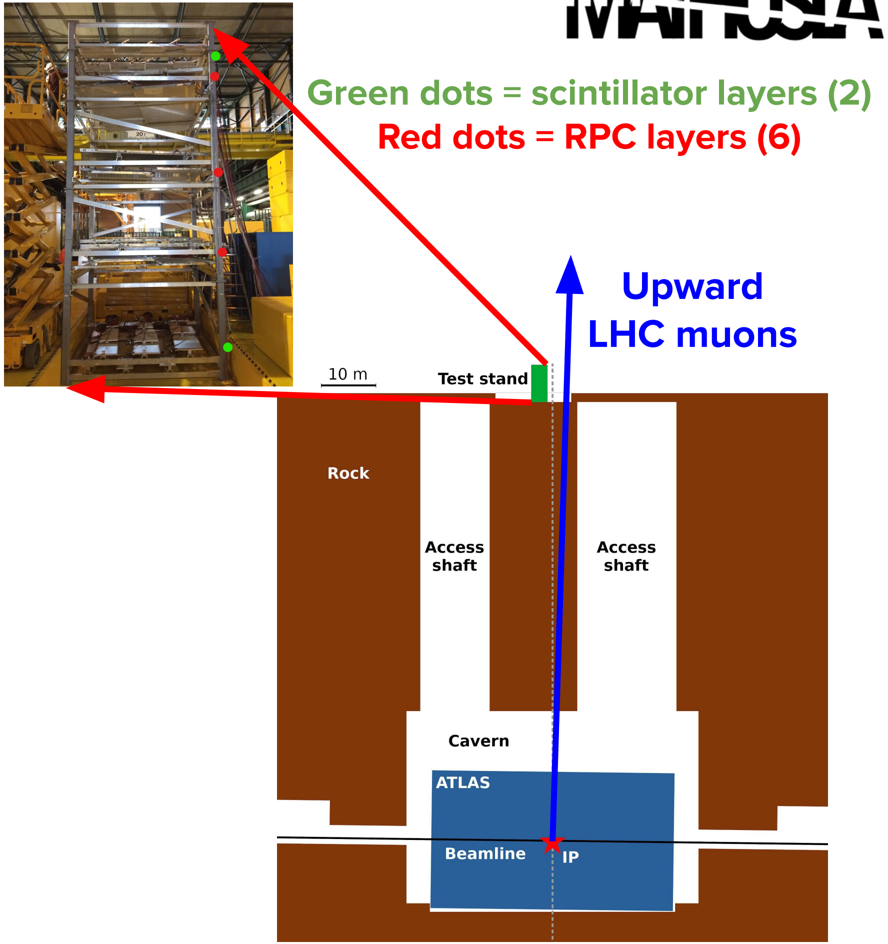
Background sources:



The MATHUSLA test stand

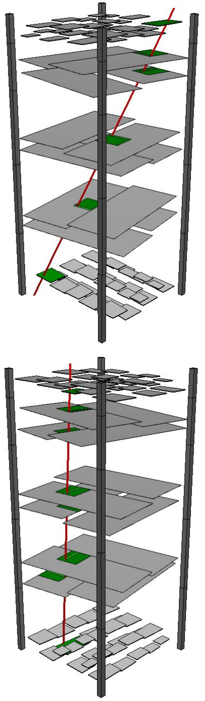
Test stand introduction

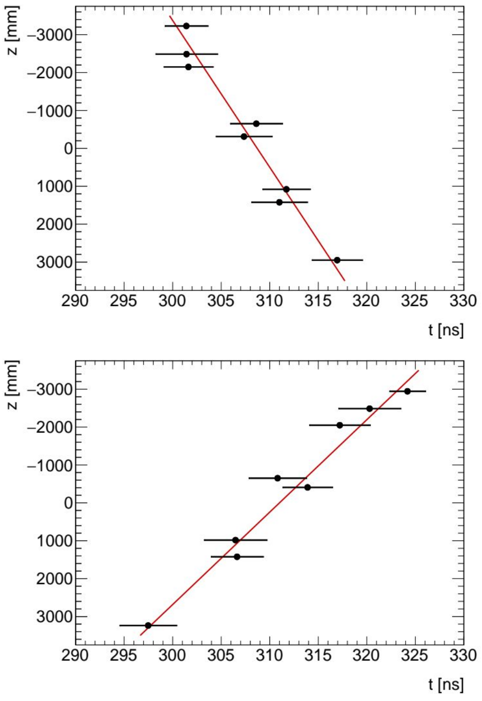
- To validate background simulations with real data from LHC:
  - MATHUSLA test stand built and run on surface above ATLAS in 2018
- Utilized spare detector components from defunct experiments:
  - 59 scintillation counters from DØ (Tevatron)
  - 12 RPCs from ARGO-YBJ (cosmic ray experiment in Tibet)
- Coincidence of top and bottom scintillator layers form trigger
- Tracking done with 6 RPC layers



Test stand tracking

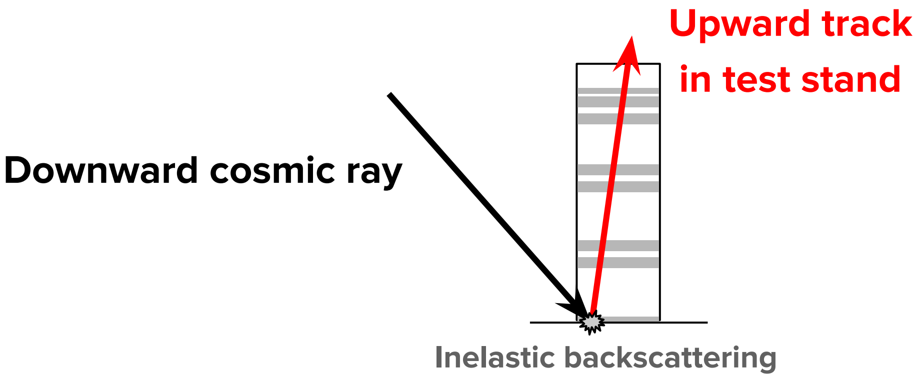
- ~6.2 m between top and bottom layers
- Separate triggers for downward and upward particles
- RPC strip spatial resolution ~2 cm
- Time resolution ~2-3 ns
- Shown on right: example of a downward track (top) and an upward track (bottom) from data

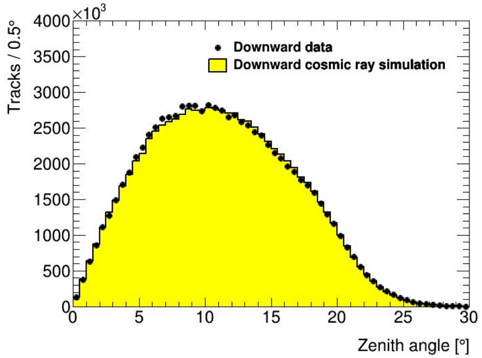


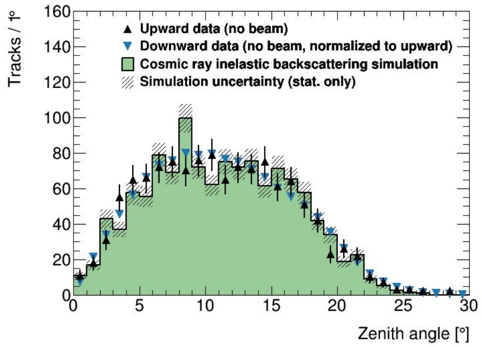


Test stand results without LHC beams

- Test stand data compared to simulated cosmic rays
- At right: zenith angle distribution of downward tracks (top) and upward tracks (bottom)
- Upward tracks are created by inelastic backscattering of incident downward cosmic rays

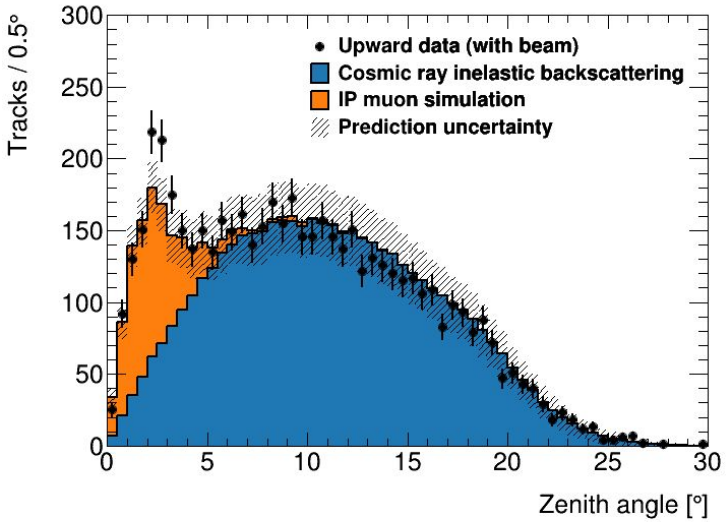


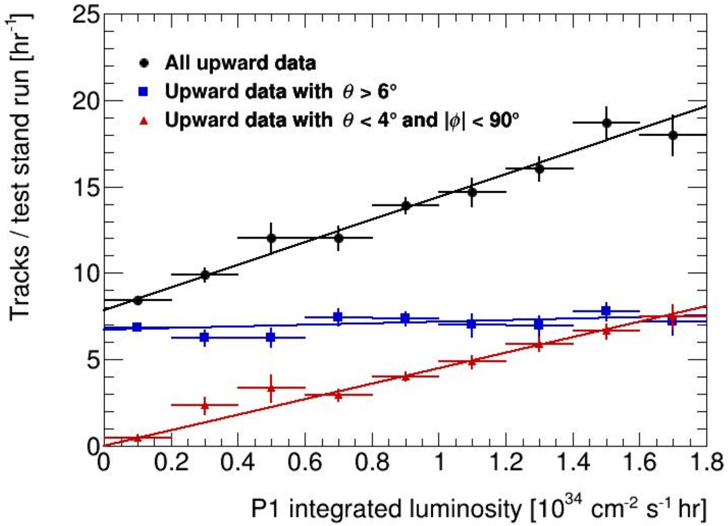




Test stand results from LHC collisions

- Left: Comparison of test stand data with active LHC beams to simulation of muons produced in 13 TeV *pp* collisions (orange)
- Right: Scaling of rate of upward test stand tracks vs. ATLAS luminosity

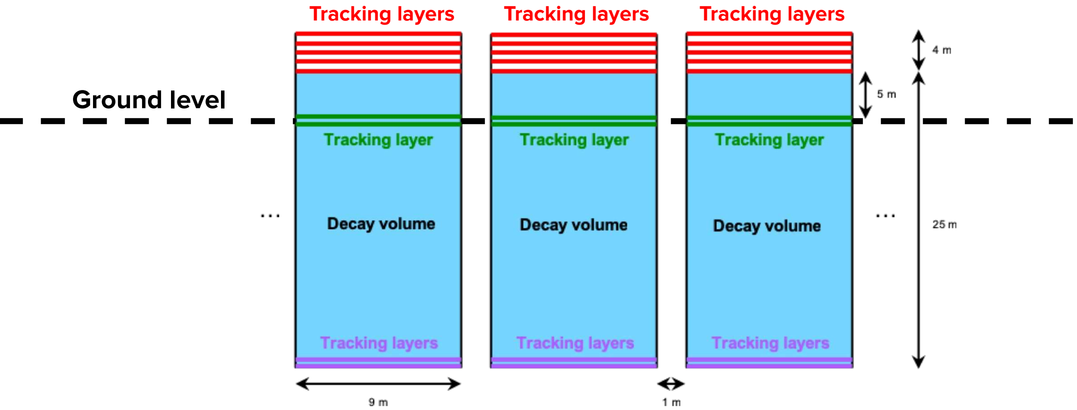


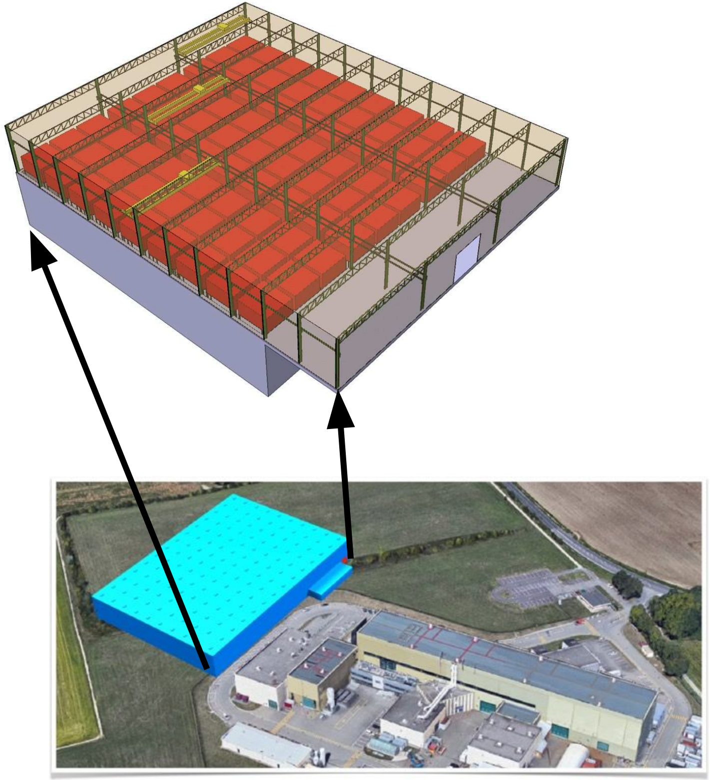


MATHUSLA (the full detector)

Baseline detector design

- 10 x 10 grid of modules
  - Each with an area of 9 m x 9 m
- 5 + 2 + 2 tracking layers
- Bottom two layers provide veto of upward SM charged particles



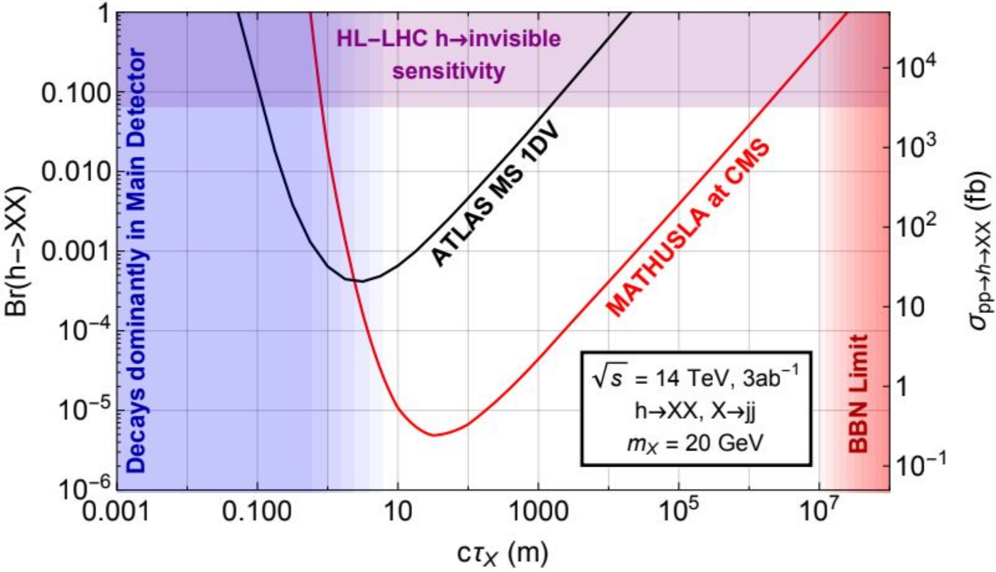


Point 5 (CMS)

MATHUSLA

Baseline detector LLP sensitivity

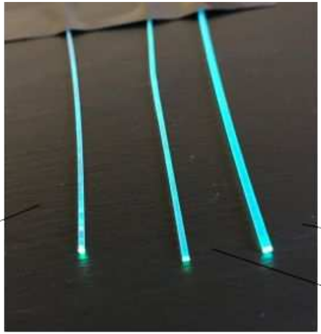
- Comparison of LLP sensitivity between ATLAS and baseline MATHUSLA design via exotic Higgs decays:
- Very nearly the same sensitivity as in the original proposal with a larger area (200 m x 200 m)
- Sensitivity recovered by getting closer to the IP than estimates in original paper (https://arxiv.org/abs/1606.06298)



Detector hardware

- Current focus for detector technology is on extruded scintillator bars + wavelength shifting (WLS) fibers + silicon photomultipliers (SiPMs)
- Some advantages over RPCs:
  - Don't require high voltage or gas systems
  - Relatively stable with temperature and pressure changes
- Very preliminary tests have already been done with a few different WLS fibers and SiPMs

Extruded scintillators from Fermilab

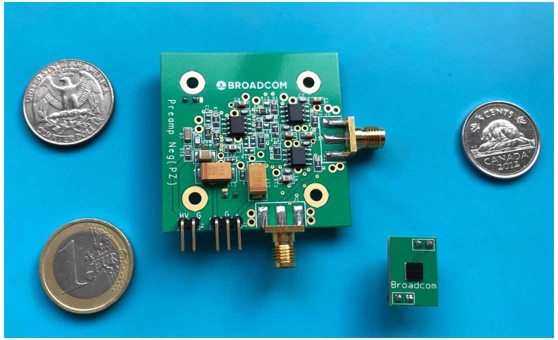


BCF-92

Belle II 1.5mm Y-11

1mm Y-11

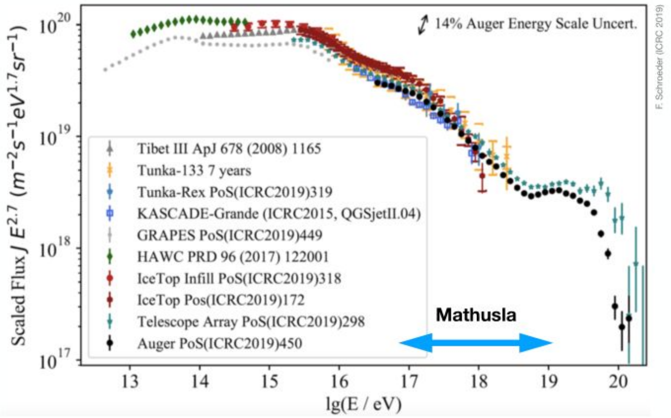
WLS fibers



SiPM

Cosmic ray physics

- Position on surface and large area makes MATHUSLA perfect for cosmic ray measurements
- Baseline detector can already provide useful energy spectrum information for inclined cosmic ray showers (>70° zenith angle)
- Studies ongoing of how to expand cosmic ray physics potential
  - For example, including an RPC layer may allow us to make similar measurements of more vertical showers as well
- Collaborating with cosmic ray experts and looking to bring in more of them!



Summary

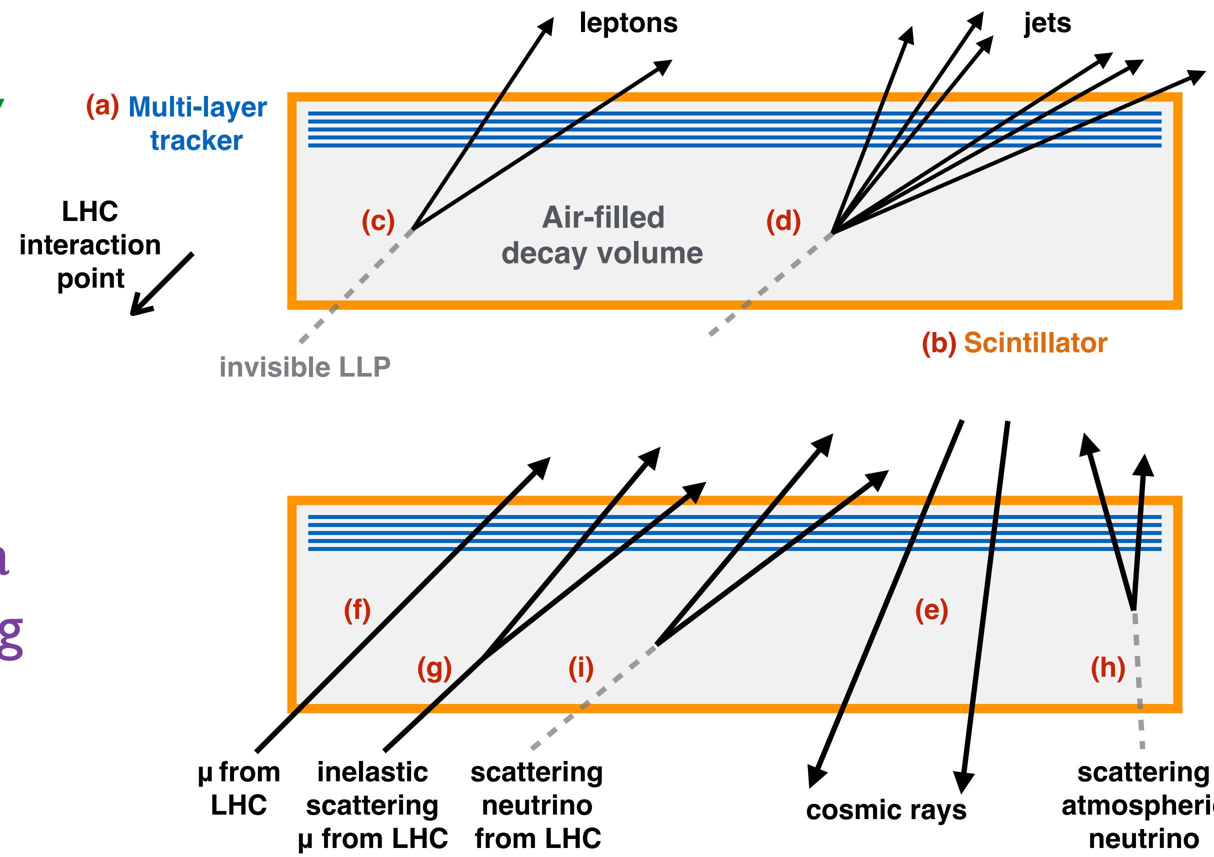
- Test stand data analysis complete and results public as of this month
  - https://arxiv.org/abs/2005.02018, submitted to NIM
  - Results confirm simulation predictions
- Full baseline detector design established
- Performing hardware tests on various scintillators, WLS fibers, and SiPMs
  - Will ramp up more as COVID-19 lockdowns/restrictions end
- In addition to searching for LLPs, MATHUSLA can be a competitive cosmic ray experiment -- a guaranteed physics payoff
  - Working with cosmic ray experts to study how to take full advantage of this
- Currently updating letter of intent (LOI) and planning to finish technical design report (TDR) near the end of 2020

MATHUSLA Collaboration

Backup

Background Rejection

LLP DV signal has to satisfy many stringent geometrical and timing requirements
("4D DV" with cm/ns precision)



These signal requirements + a few extra geometry and timing cuts veto all backgrounds!

MATHUSLA can search for neutral LLP decays with near-zero backgrounds!

For the interested:
gory details on backgrounds and rejection strategies…

Background Rejection (gory details)

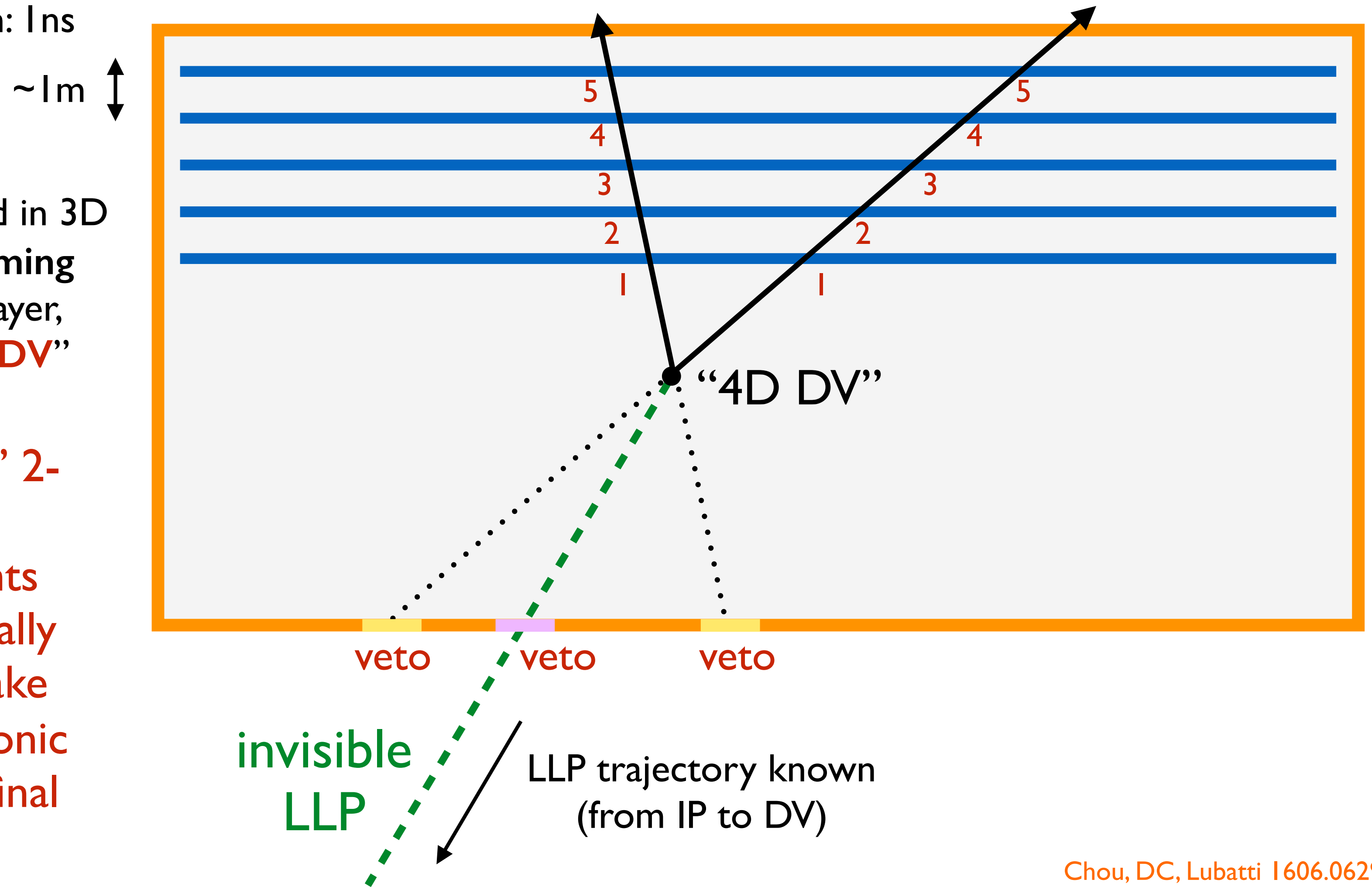
Most important part of background rejection is the *extremely* conspicuous, multi-faceted and tightly defined nature of LLP decay signal:

Δt ≳ 3.5ns per tracker layer, 17 ns for all 5 layers tracker time resolution: 1ns

tracks are reconstructed in 3D *and* with detailed **timing** information at each layer, so DV is really a "**4D DV**"

Shown is "leptonic" 2-body LLP decay. These requirements become exponentially more difficult to fake when decay is hadronic with ~10 charged final states!

most basic CR rejection: LLP decay products are upwards going tracks!



Chou, DC, Lubatti 1606.06298

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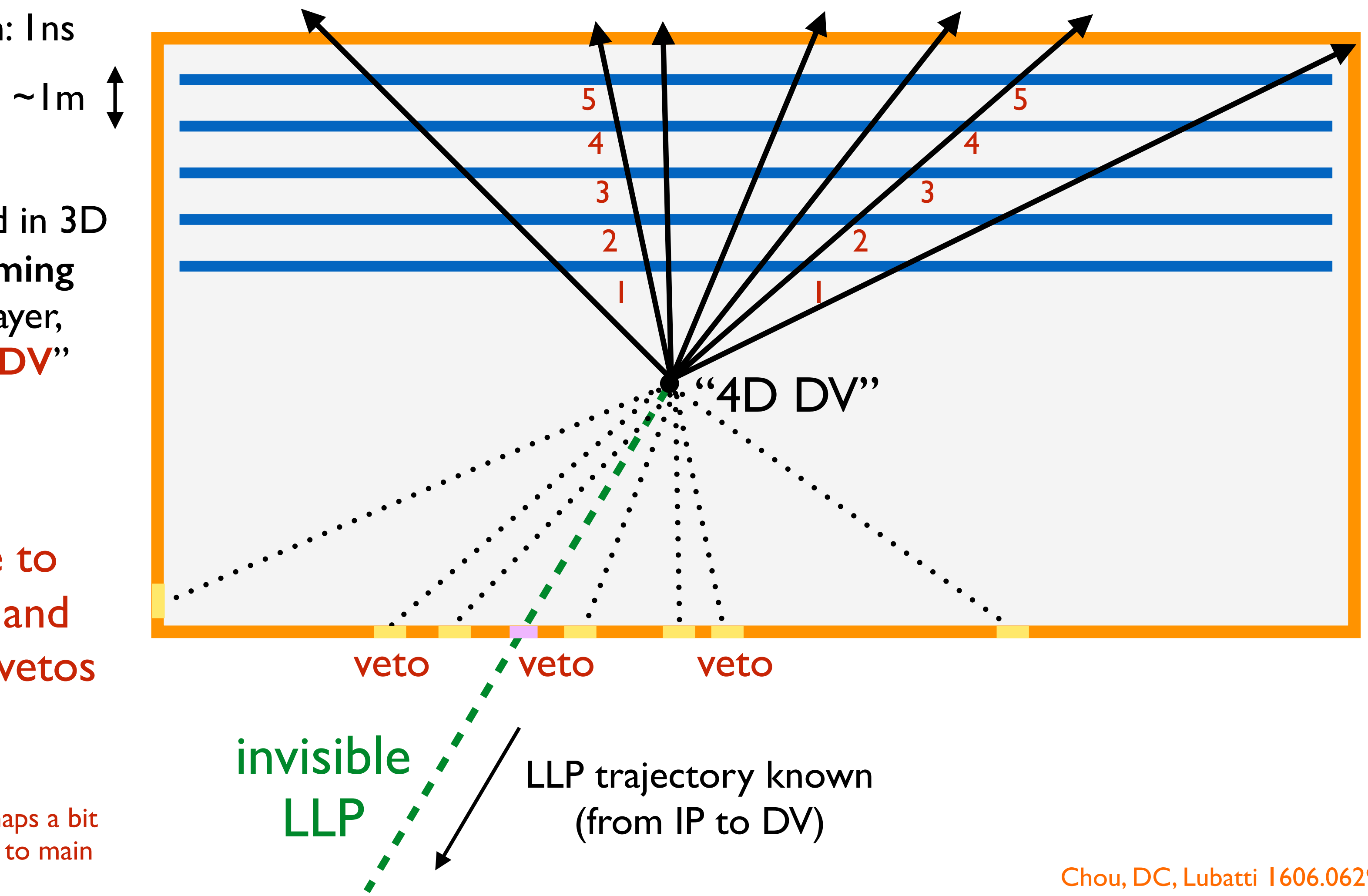

tracks are reconstructed in 3D *and* with detailed **timing** information at each layer, so DV is really a "**4D DV**"

Like so.

All ~10 tracks have to meet in both space and time at DV and pass vetos on floor/walls.

(also, hadronic decay mode is perhaps a bit more of a MATHUSLA target due to main detector gap in coverage.)

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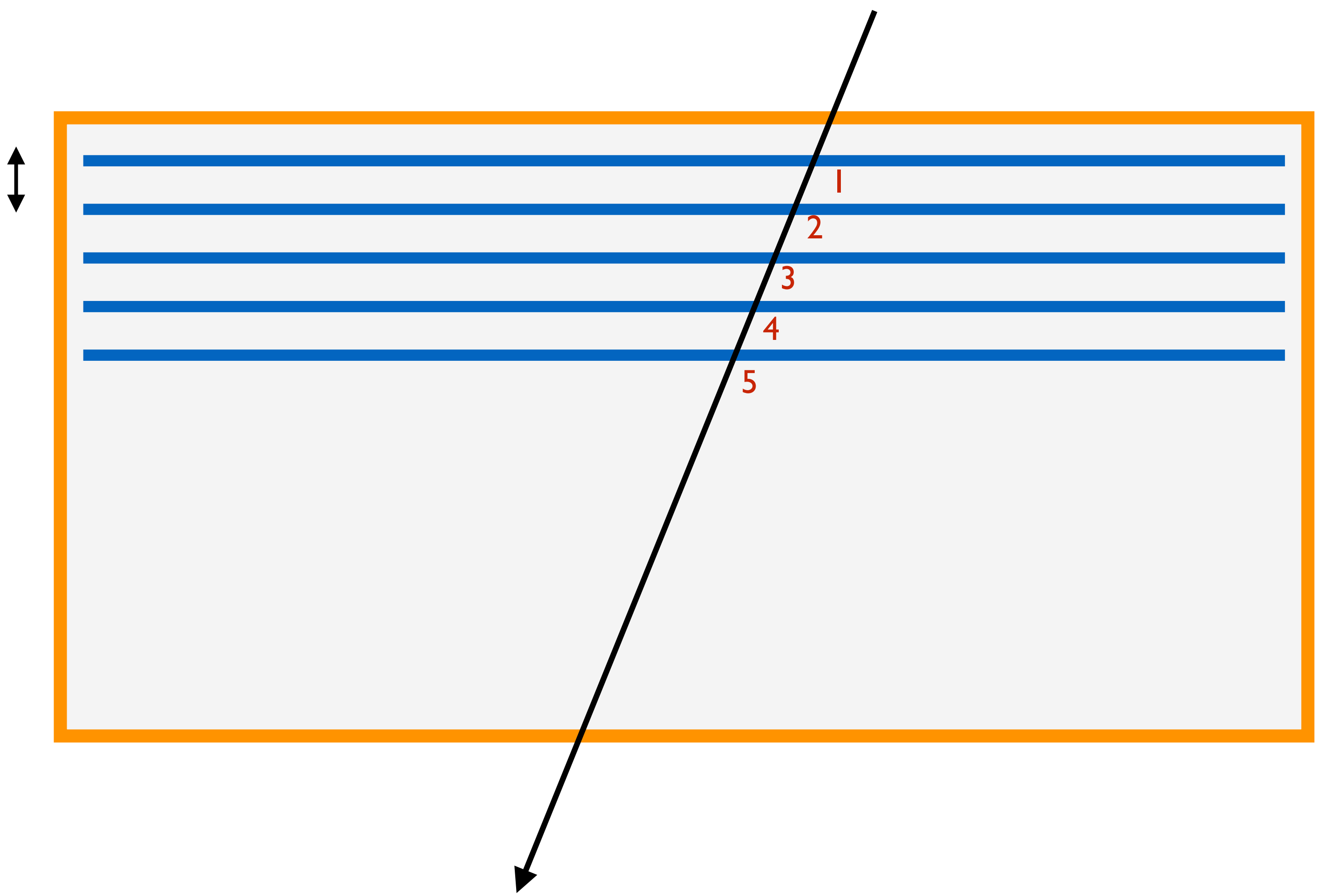
Background Rejection (gory details)

Compare to Cosmic Rays: about 10^{15} charged particles over HL-LHC run

$\Delta t \gtrsim$ 3.5ns per tracker layer,
17 ns for all 5 layers
tracker time resolution: 1ns

~1m



For *single* downward-traveling charged particle from CR, assuming only *three* layers with 1ns timing resolution within 5m, **chance of downward *consistently* reconstructing as upward going is $\epsilon_{down\rightarrow up} \lesssim 10^{-15}$**

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Background Rejection (gory details)

Com … run

$\Delta t \gtrsim 3$… 17 … tracker…

For *s… tra… par… assun… layers… resol… chan… *c… rec… up… ϵ_{do}…

In this naive estimate, simple up-vs-down rejection *easily* gets rid of *all* cosmic ray backgrounds by itself.

Of course, our estimate of $\epsilon_{down \to up}$ by itself is much too naive, based on purely gaussian time resolution, in reality tails are non-gaussian etc.

But this estimate only used 3 layers. We specified MATHUSLA to have 5.

Furthermore: single down→up fake does NOT fake the LLP signal. You need:

- ***two* down→up fakes** occurring `at same time' (so $\epsilon_{down \to up}^2$)
- they need to **cross in space to form a DV**: requires either spatial mismeasurements (most CRs don't do this) OR very rare CR trajectory crossings
- the huge timing errors made by 5 tracking layers for each track have to be such that the **tracks reconstruct to be coincident *in time* at the fake DV as well**
- the **scintillators have to fail** to register the two CRs on their way out of the decay volume.

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Background Rejection (gory details)

Com

run

$\Delta t \gtrsim 3$

17

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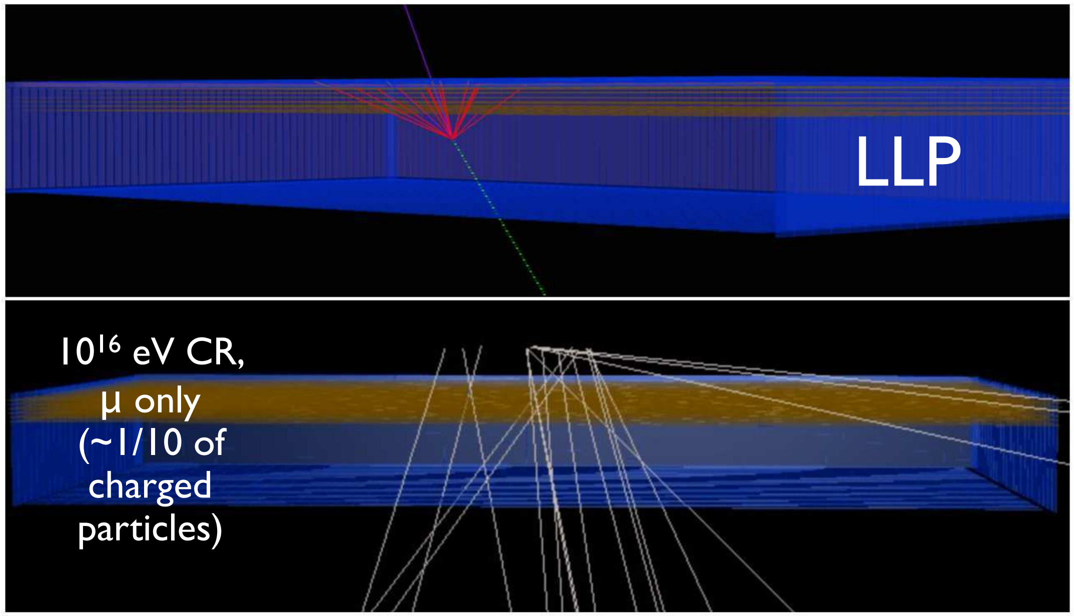
Most CR tracks are highly correlated, forming Extensive Air Showers:



Indeed, these showers are the best chance for all these unlikely things to occur and fake an LLP 4D-DV.

BUT YOU CAN JUST "BLIND" THE DETECTOR WHILE IT HAS HIGH OCCUPANCY THAT IS OBVIOUSLY FROM A CR SHOWER.

Blind time has negligible effect on uptime & LLP sensitivity.

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Background Rejection (gory details)

There might be very weird things that give rise to DVs in CR events: neutron decays, air scatterings of CR particles etc…

These much rarer occurrences will be studied in detail, but again, most of them would occur in highly correlated CR showers that are vetoed just based on occupancy.

Finally, this CR background is inherently *studyable*: during ~50% of time when HL-LHC beam is off, you can verify CR rejection strategies on data that is guaranteed to be only background.

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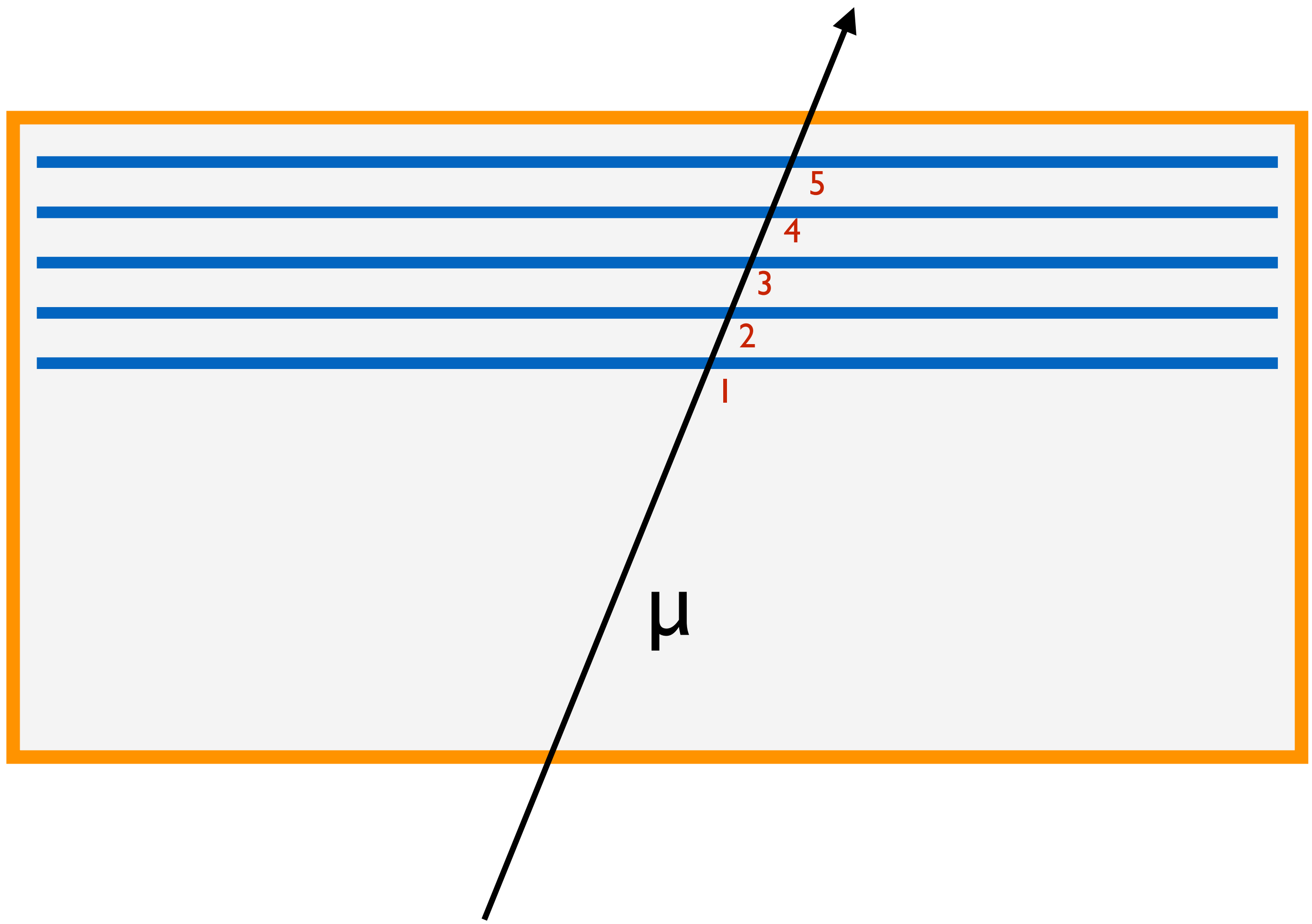
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

They do travel upwards, but they do not reconstruct a displaced vertex.



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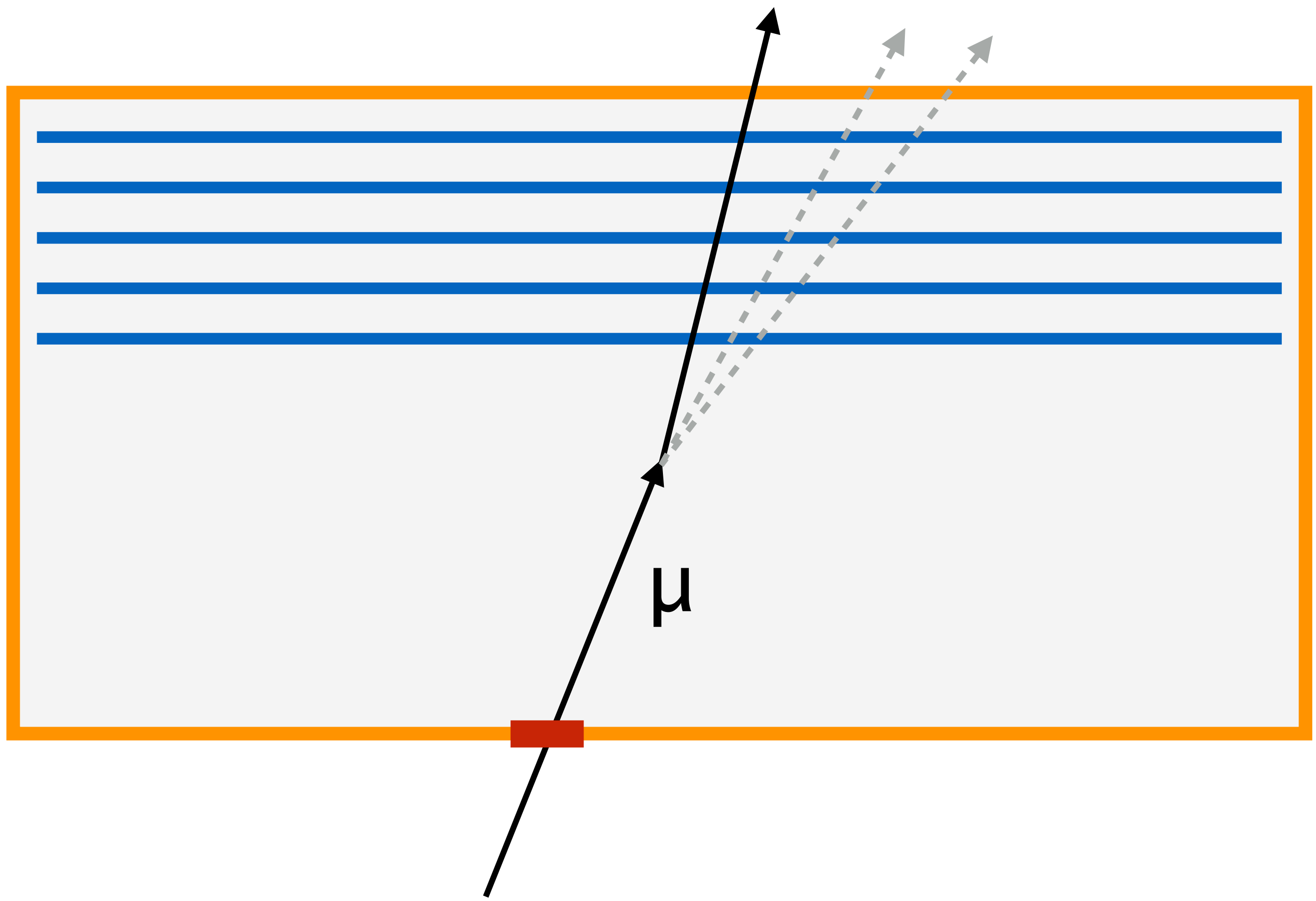
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

Ignoring orders-of-magnitude suppression from boost (!!)
<< 10^7 decay in volume,
but again,
no DV
(and detectable by intersection of final and initial state trajectory)



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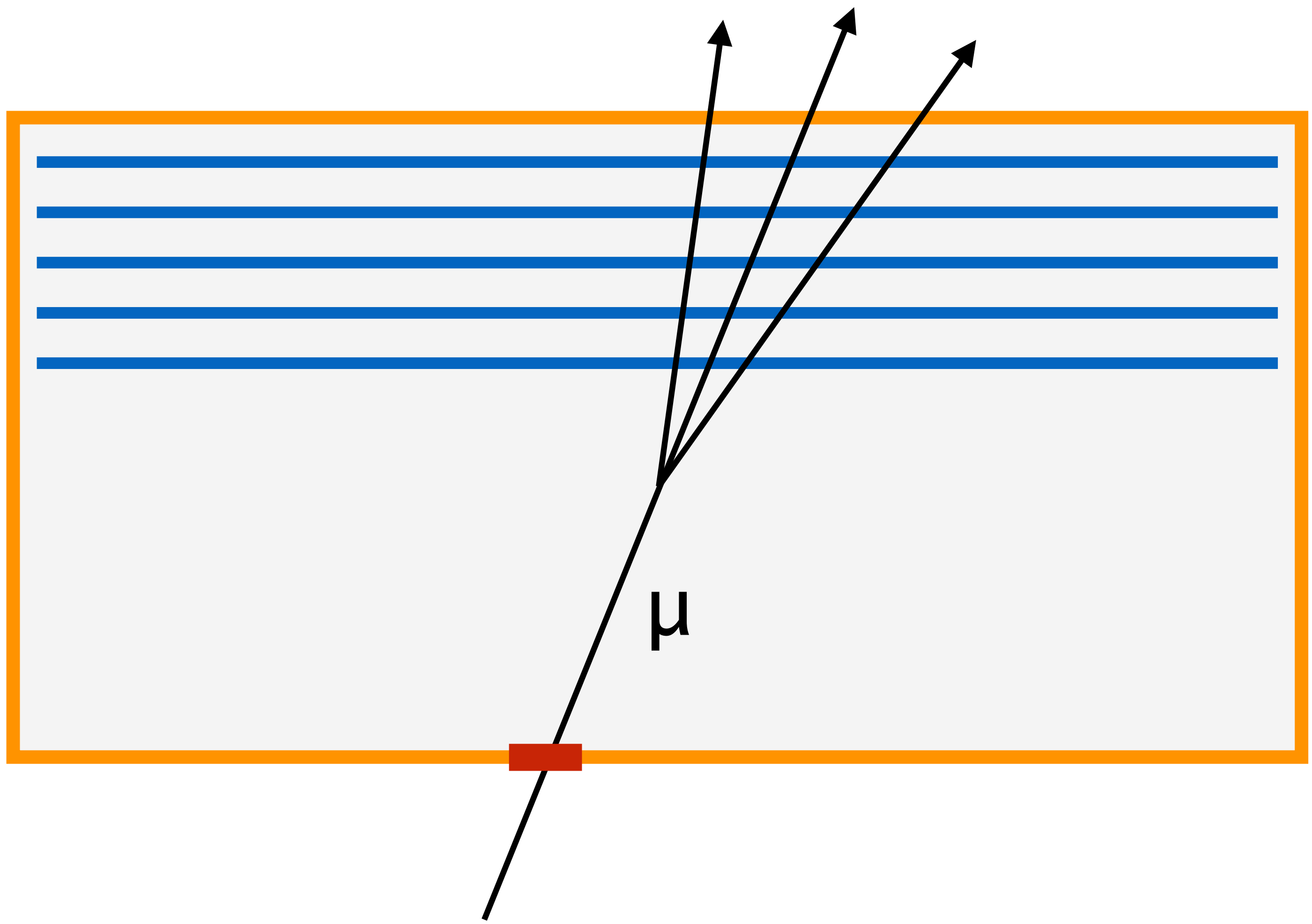
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

~ 1000 undergo rare decay into eeeνν (Br ~ 3 × 10^{-5}) → genuine DV!



Two possible rejection strategies:

1) reject *narrow* decay cones (where all particles are caught by tracker) with *odd* numbers of tracks, indicating charged parent particle
2) reject with **scintillator** and **main detector** vetoes (assuming efficiencies 99% and 90% respectively)

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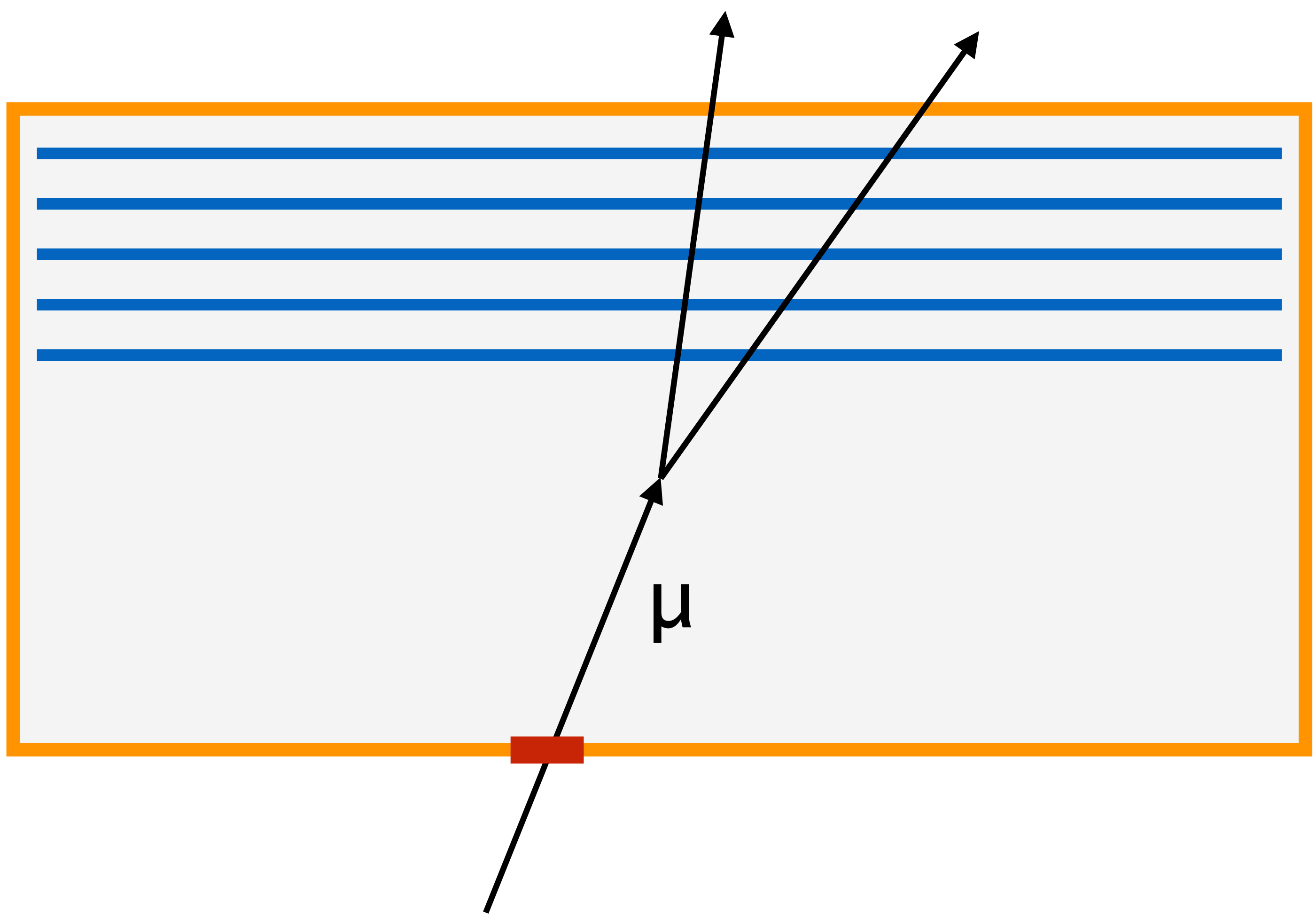
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

~ 10 scatter off air and form genuine DV

easily veto with scintillator alone.



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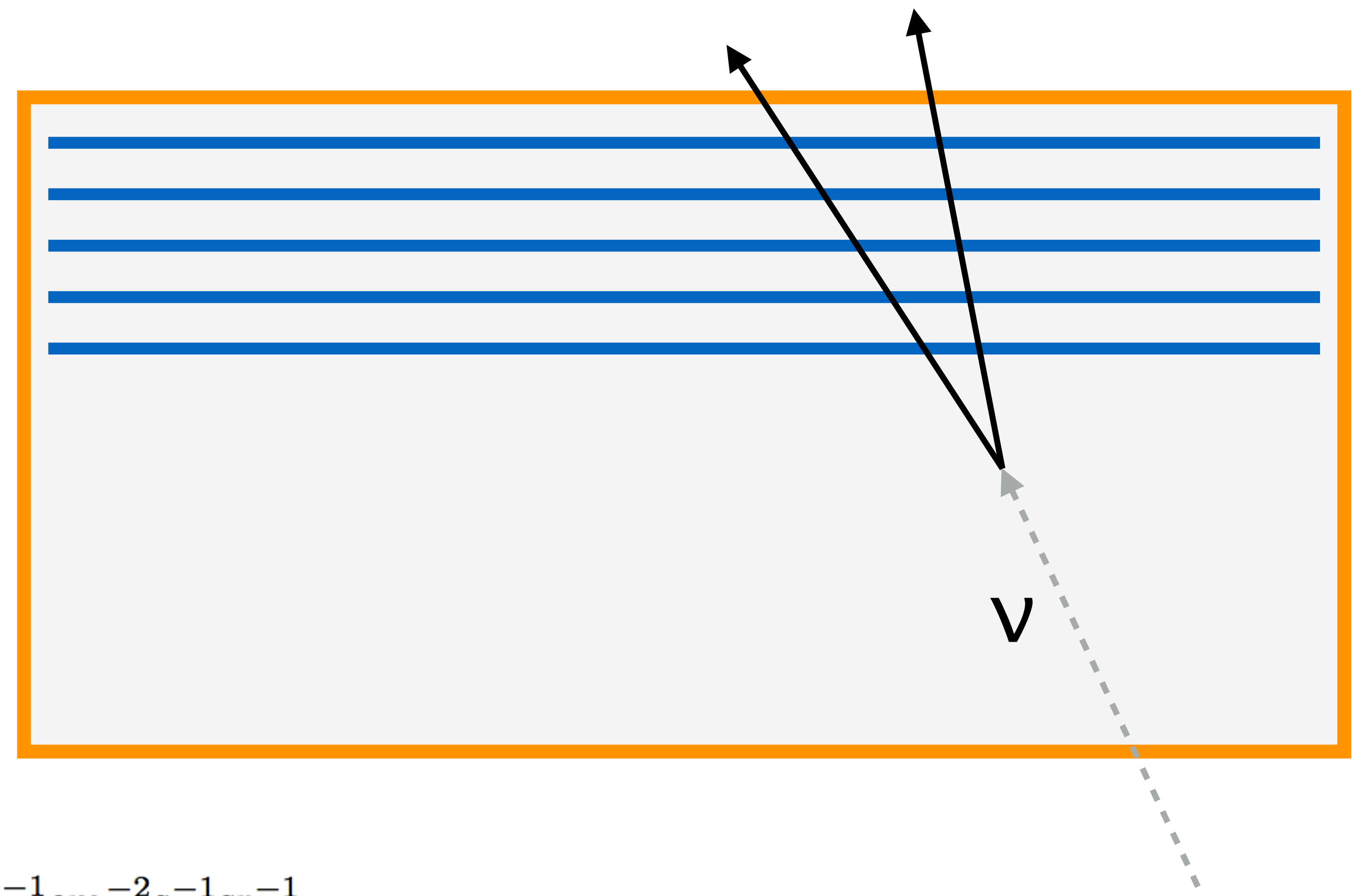
Background Rejection (gory details)

Isotropic neutrino haze from CR interactions with atmosphere:

Most dangerous BG, naively it looks exactly like LLP signal

Can compute rate using Frejus measurements of atmospheric ν_μ flux. (ν_e much lower, can be dealt with similarly)



$$\frac{d\Phi}{dE_\nu} \sim 0.06 \left(\frac{\text{GeV}}{E_\nu}\right)^3 \ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

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Background Rejection (gory details)

Only have to worry about neutrino scatters that give 2+ charged particles to give DV.

Exclusive scattering cross sections known at ~30% level Formaggio, Zeller, 1305.7513

Get about 60 events per year with proton in final state.

- Most of these protons are highly non-relativistic, can be tagged using MATHUSLA's ~0.05c **speed resolution** on charged particle tracks.
- Vetoing low-multiplicity DVs with single highly-NR track eliminates most of these BG events.
- Can also use geometric cuts: LLPs decaying to visible particles are either narrow cones pointing back to IP or broad cones. Neutrino final states (especially relatively high-energy ones with relativistic protons) are very narrow cones, mostly not pointing at IP.
- **applying both NR-proton-veto (v < 0.6c) and geometric cut, get < 1 event/year (using very low cut on v and pessimistic estimates of final state kinematics)**

Get about 10 events per year without protons in final state

- This small number can be vetoed using above geometry cut alone

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$\frac{d\Phi}{dE_\nu} \sim$

1606.06298

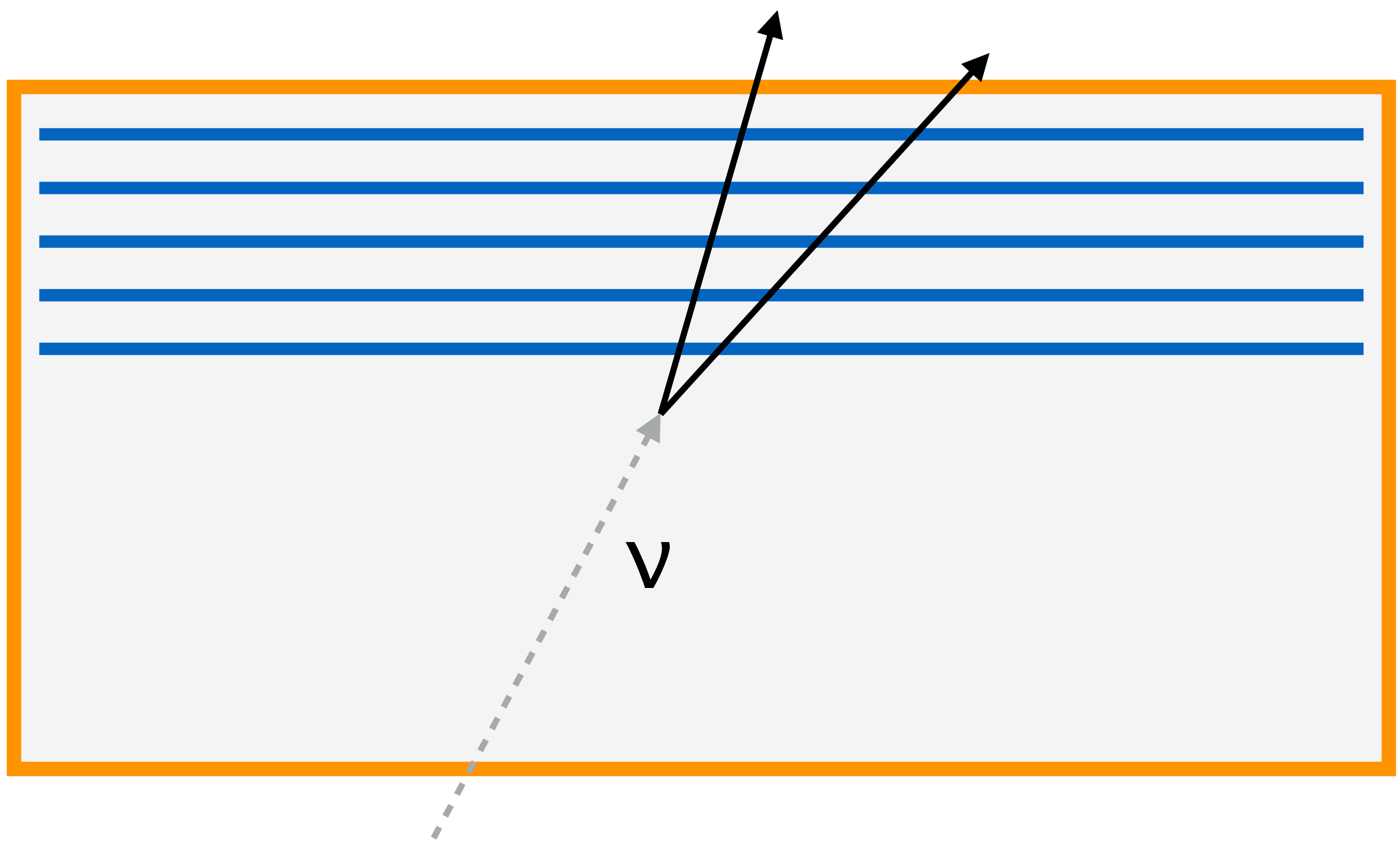
Background Rejection (gory details)

Also get neutrinos from LHC collisions, mostly low-energy , from hadron decays

Can estimate rate using generic GEANT simulation of main detector.

Cannot use naive geometric cut used on CR neutrinos, but after NR-proton-veto, only left with O(1) events per year.

There are other handles on their decay (detailed geometry, multiplicity, speed, …)
→ with further study should easily be able to reject.



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Background Rejection (gory details)

None of these BG rejection strategies seriously affect signal efficiency.

*Rarer BG processes: production of *isolated* Kaons in rocks from CR scattering that migrate to detector and decay, etc… estimates of rates << previous BGs*

ALL OF THIS HAS TO BE STUDIED IN MORE DETAIL WITH MORE SIMULATIONS. Most importantly:

- CR simulations & MATHUSLA test stand data to sanity-test rejection strategies to the extent possible using MC statistics (+ some cleverness to go beyond simple statistical?)

- Full simulation of neutrino background and rejection strategies. Refine geometric veto, especially for neutrinos from LHC.
  Get more realistic estimate of NR-proton-veto efficiency (will be better than our estimates, due to pessimistic assumptions we made about final state kinematics, and by ignoring remnants of shattered nucleus)