Searches for Ultra Long-Lived Particles with MATHUSLA

PARTICLE PHYSICS SEMINAR

MCGILL

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Outline

- Theoretical Motivation
- LLP detectors at the HL-LHC
- MATHUSLA
  - Basic Concept
  - LLP Sensitivity
  - Cosmic Ray Telescope
  - Detector Design
  - Test Stand Results
- Next Steps & Opportunities
- Conclusions

Theoretical Motivation

Motivation for LLPs

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case 1806.07396

The usual fundamental mysteries (Hierarchy Problem, DM, Baryogenesis, Neutrinos, …) aren't going anywhere!

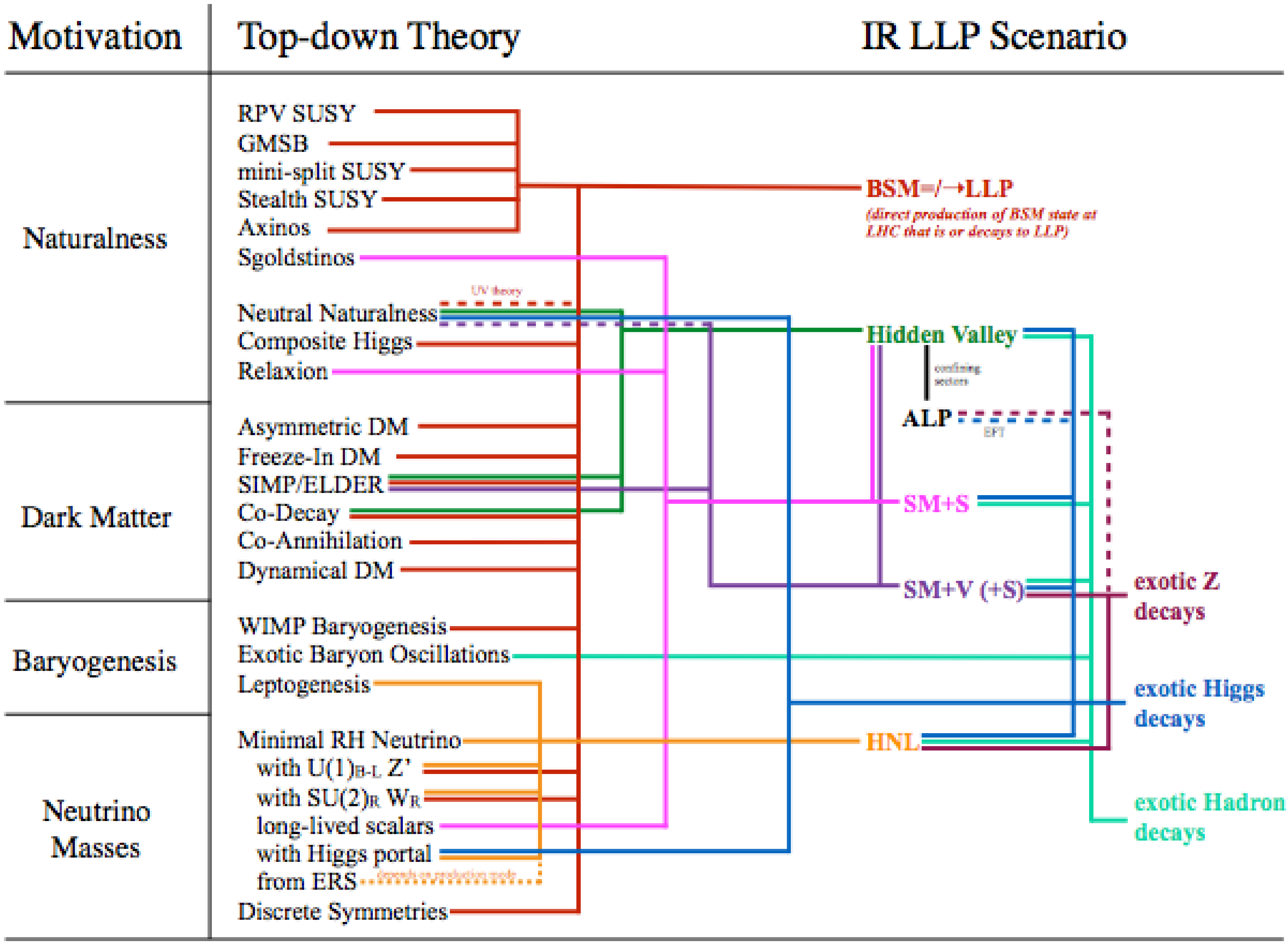
Maybe our prompt searches for high-p_T objects have been looking in the wrong place?

Long-Lived Particles (LLPs) occur in the SM. Tiny decay width for many reasons (approx symmetry, heavy mediator, etc…)

Bottom-up point of view:
same mechanisms → LLPs in BSM theories.

Top-down point of view:
LLPs can solve these fundamental mysteries!

Top-Down LLP Motivation



Most of these scenarios are still poorly constrained at LHC

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case 1806.07396

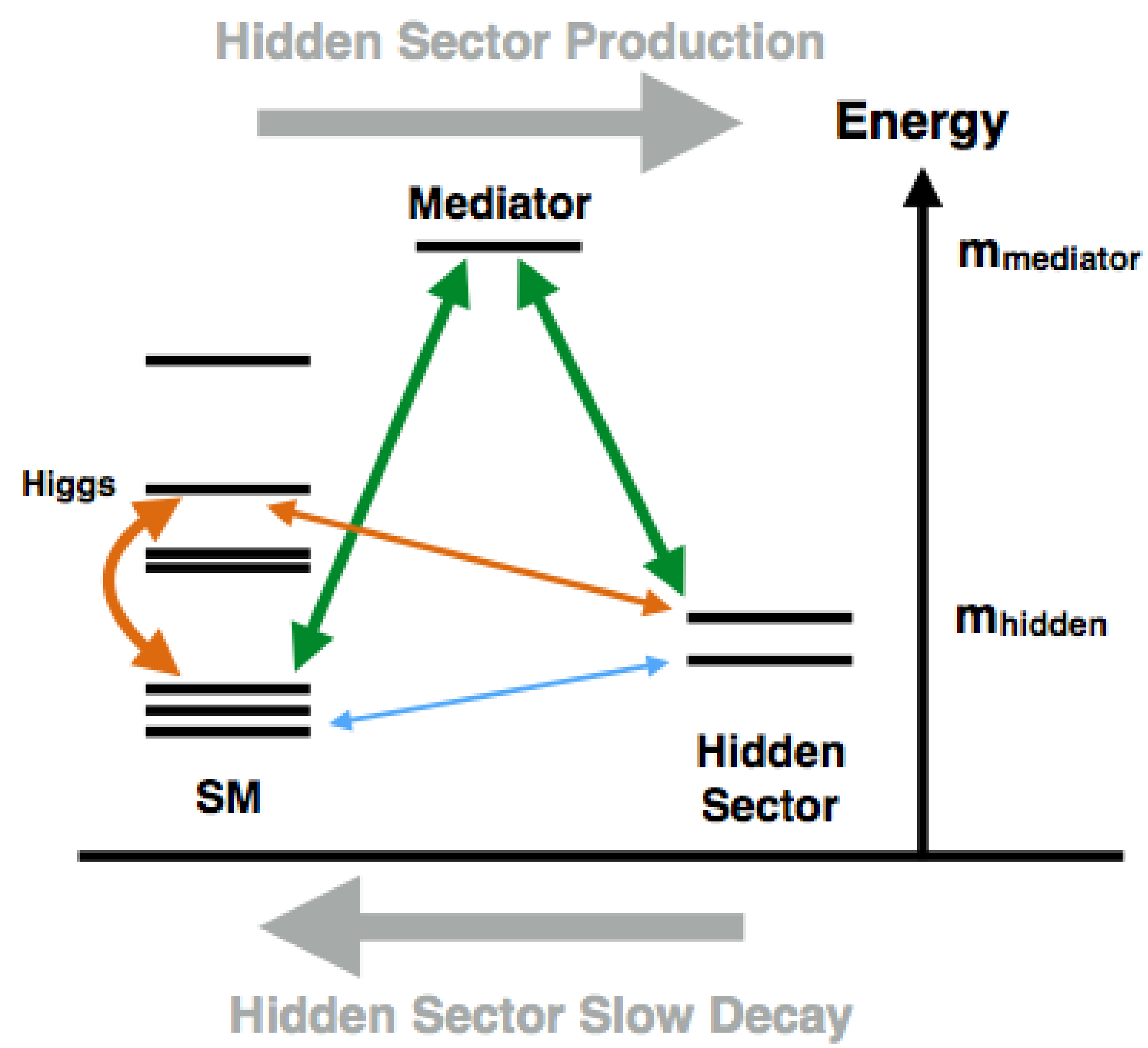
Bottom-up Motivation: Hidden Sectors

Particles & forces hidden from us due to small coupling, not high mass.

Generically arise due to the "grammar" of QFT.

Confirmed examples: ν's

Give non-minimal IR spectra from minimal theory input
(e.g. QCD cousins like Hidden Valleys)



Can talk to SM via small portal couplings, e.g.
Heavy Mediators **Higgs Portal** **Photon Portal**

Motivation for LLPs

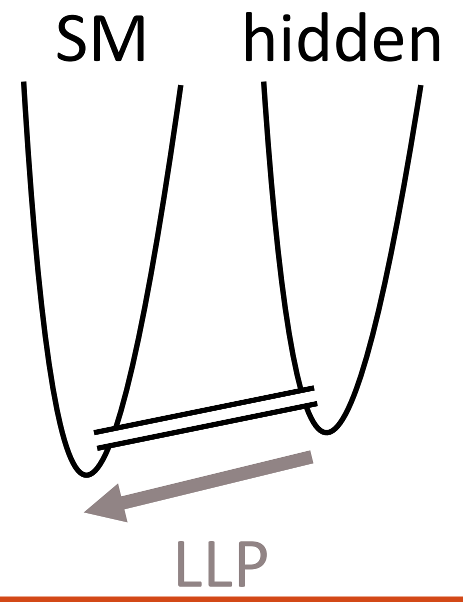
1. Exotic Higgs Decays as probes

LHC can probe tiny exotic branching ratios if decays are spectacular.
Sizable Higgs Portal couplings to new physics are generic.

2. Long Lived Particles (LLPs) are generic

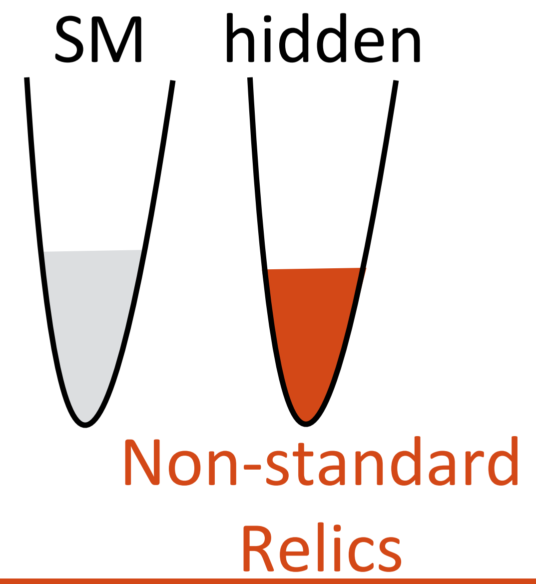
Once produced, Hidden Sector states can only decay back to SM via small portal couplings, generically leading to long lifetimes.
The LLP lifetime is (almost…) a free parameter!

3. Complementarity between Cosmology and Colliders



Models which avoid signatures in one will often show up in the other

(e.g. dark radiation,
DM with structure, etc.)



Motivation for LLPs

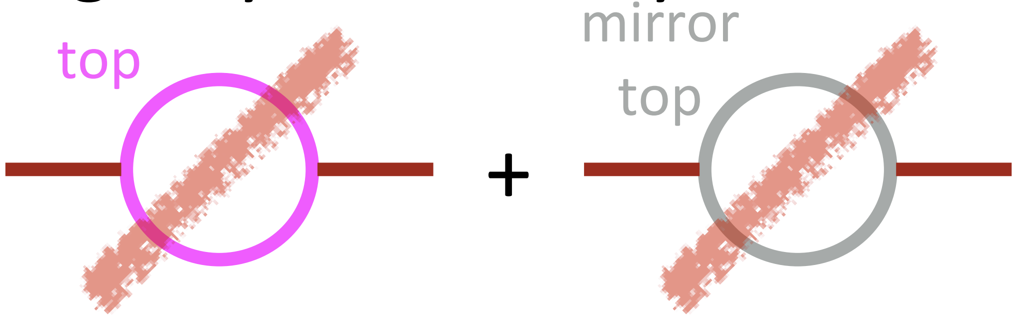
4. Weird DM

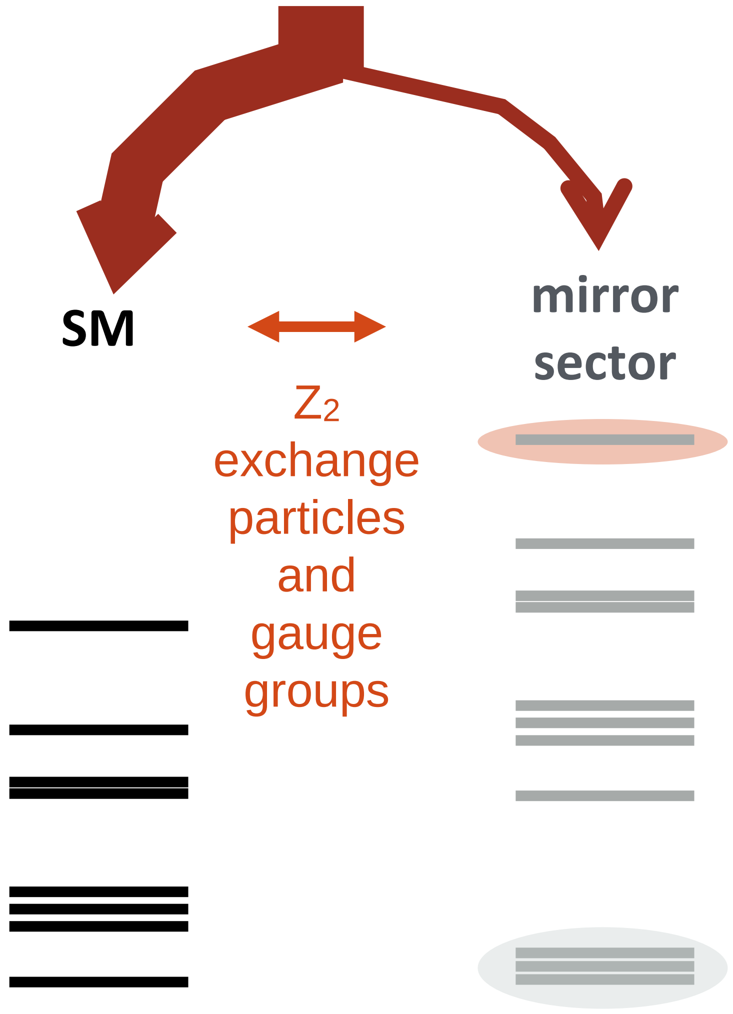
Closely related theories can give rise to **either or both:** metastable hidden sector particles (**LLPs**), and stable particles which are part or all of **Dark Matter**

Spectra & dynamics of the stable particles can be as rich and varied as the hidden sectors we can imagine.

Use top-down motivated hidden sectors as signature generators to understand DM complexity

e.g. Asymmetrically Reheated Mirror Twin Higgs



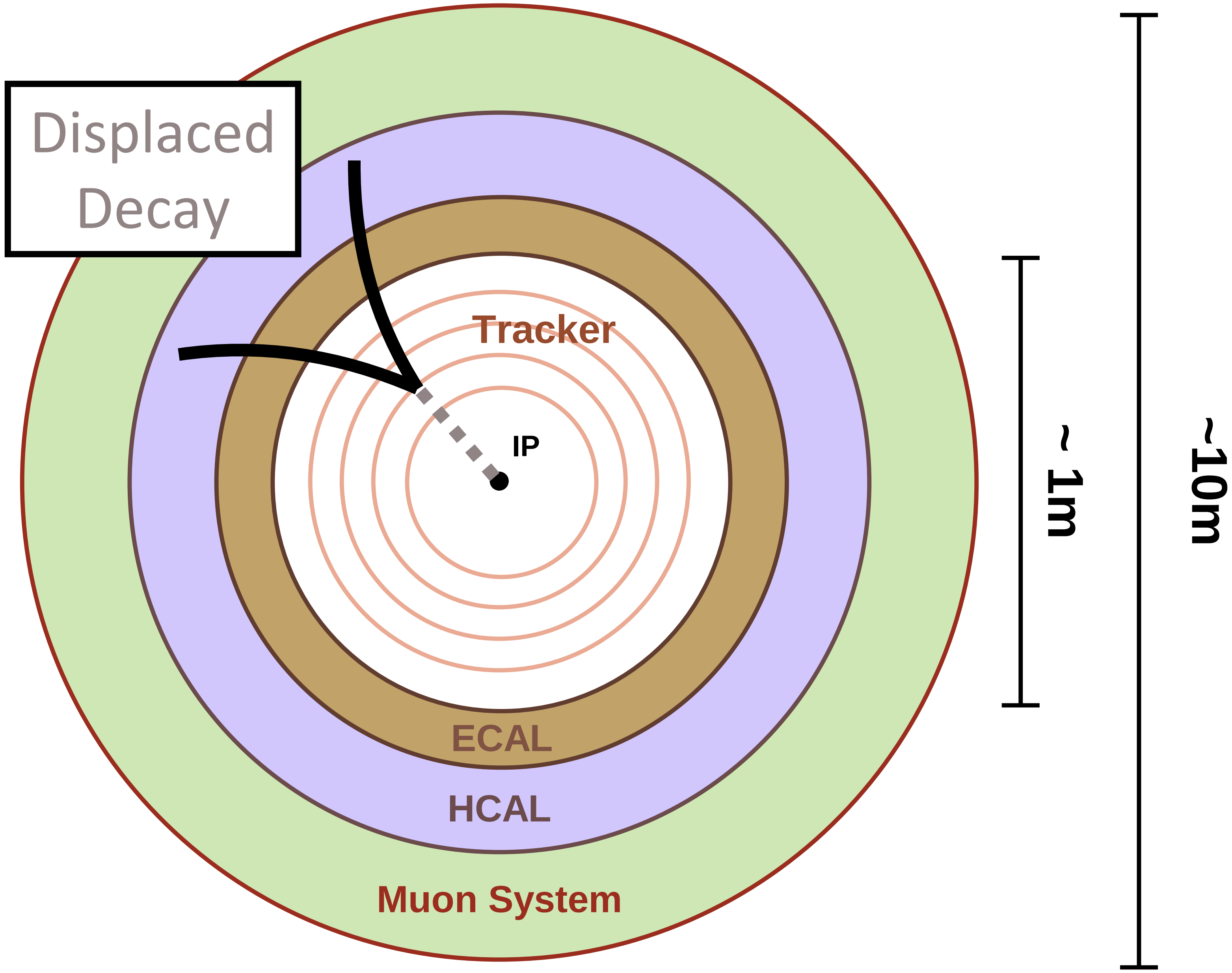


LLP Detectors at the HL-LHC

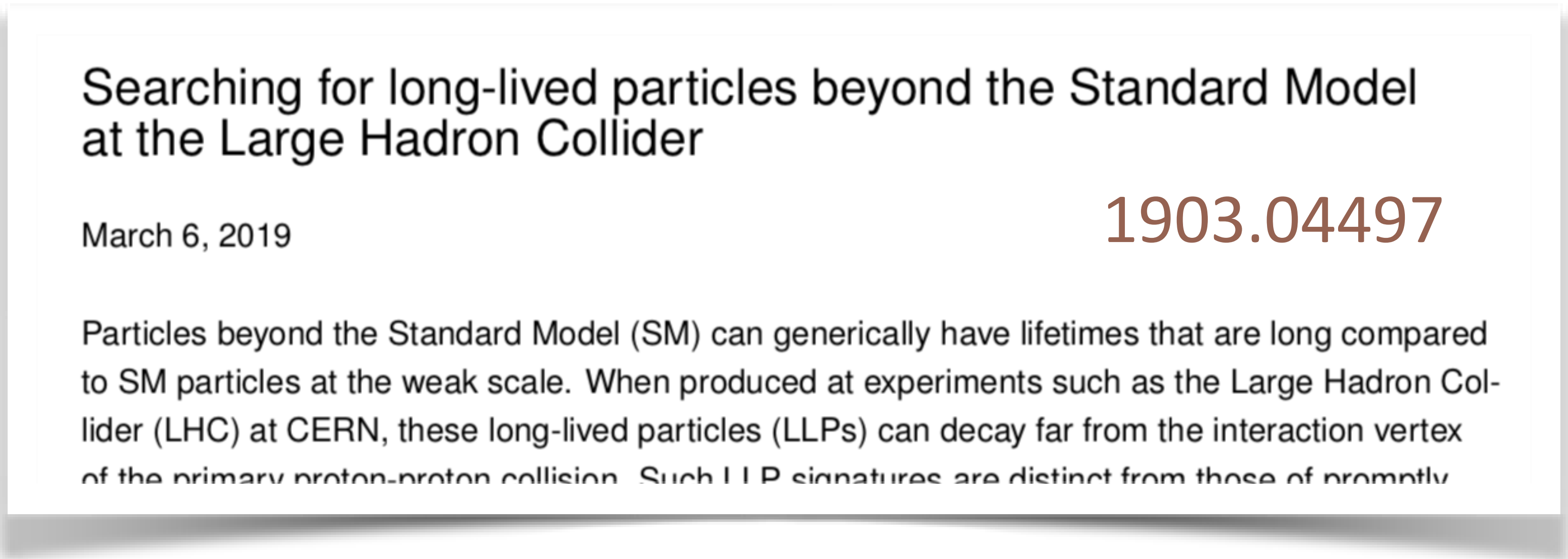
LLPs at the LHC

Neutral LLPs that decay in the detector are *spectacular* signatures that are missed by most standard searches, since **trigger** & **detector** are designed for *prompt* signals.

Comprehensive search program has been ramping up last few years.



A Coordinated LLP Search Program

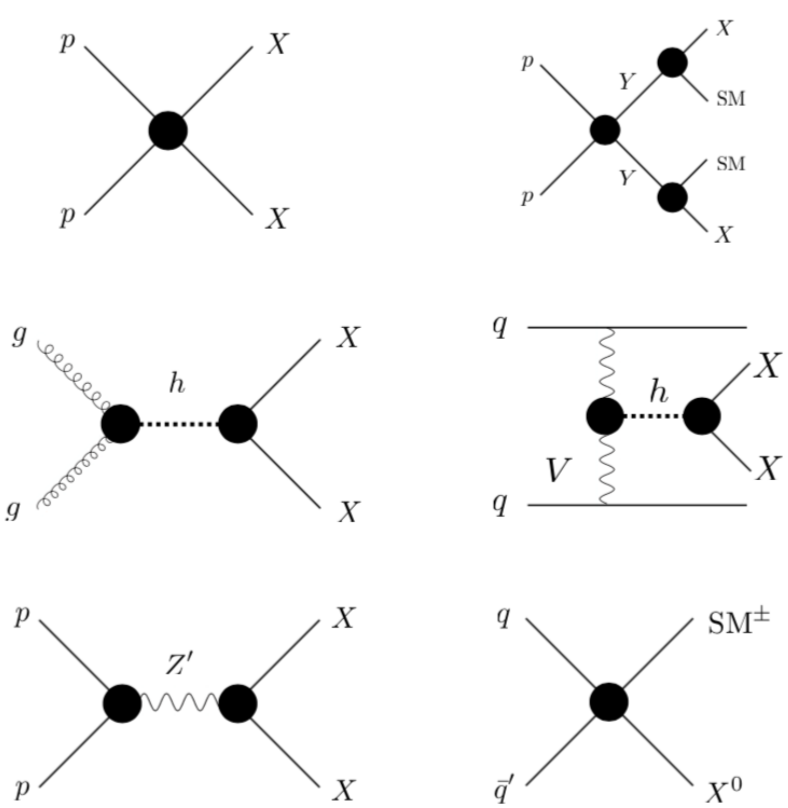

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

March 6, 2019

1903.04497

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly

Simplified Model Roadmap of LLP Signature Space:

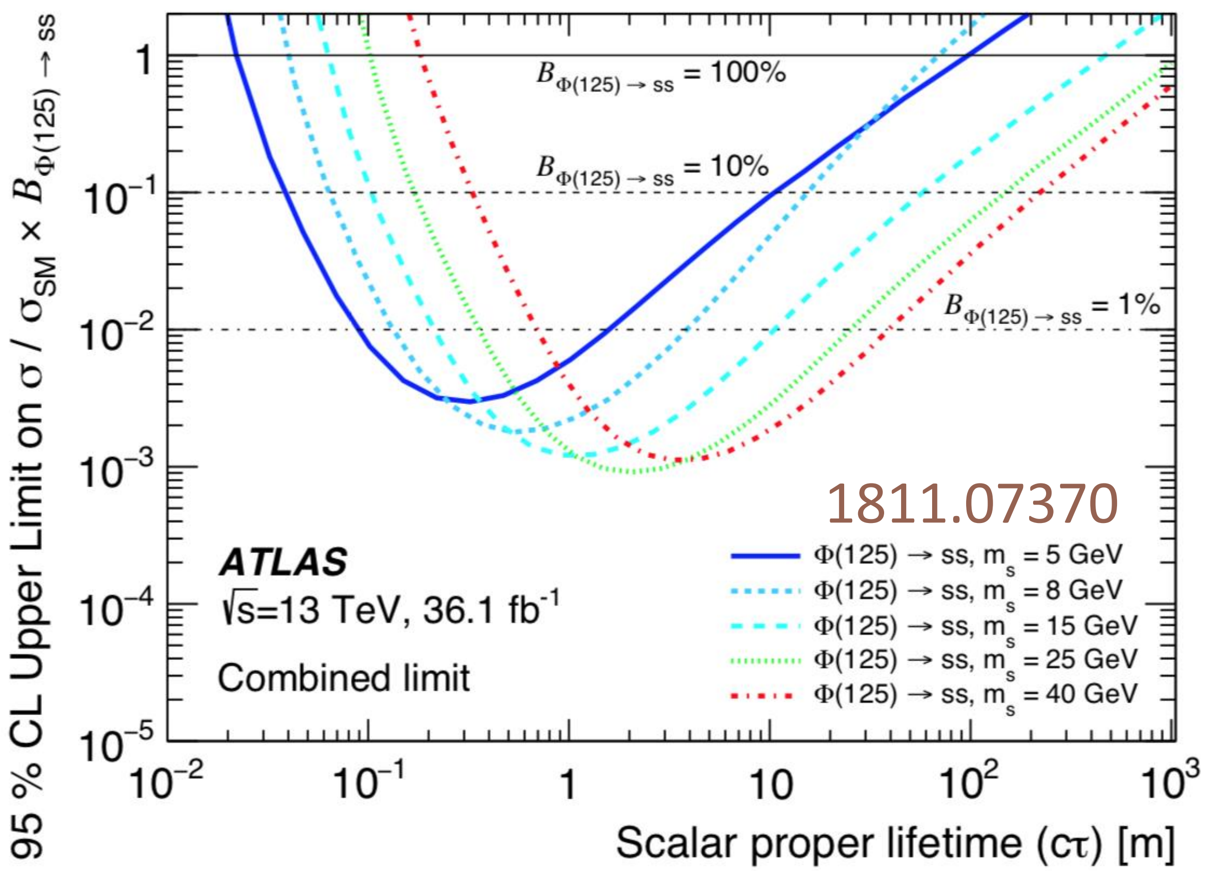


Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair or neutralino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

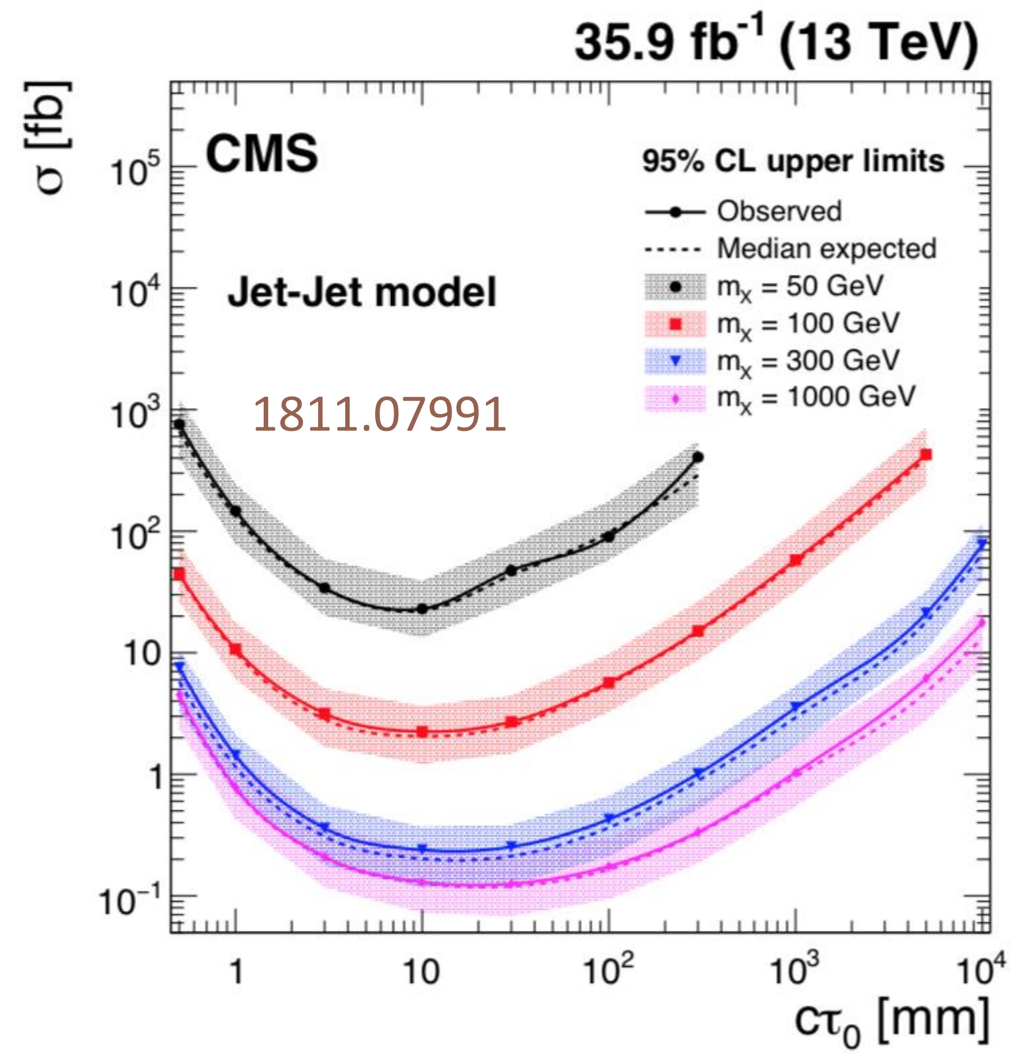
Lots of progress in past few years.

Searches are extremely labour-intensive due to customized event reconstruction, special triggers, complicated backgrounds

Higgs→LLPs in ATLAS Muon System



Displaced Jets in CMS tracker



First searches for “low-lying fruit” LLPs are underway or finishing!

The problem of long lifetimes: The LHC could be making LLPs that are invisible to its detectors!

Any LLP can have lifetime up to BBN limit ~ 0.1s ($c\tau \sim 10^7$-10^8 m)

If the LLP has lifetime >> detector size, most LLPs escape detector

Tiny rate of decays in detector ➞ searches at ATLAS/CMS become very vulnerable to even small backgrounds.

Low-background environment is critical!

Why search for LLPs at HL-LHC at all?

Searches at other facilities have also been proposed (e.g. SHiP, LDMX)

But HL-LHC has advantages:

- High center of mass energy, access to heavy states potentially coupled to LLP (e.g. Higgs) not easily produced at lower energies
- Large data sample
- Enormous investment in machine and experiments

2013 European Strategy: *"top priority should be the exploitation of the full potential of the LHC"*

2014 P5 Report: *"The LHC upgrades constitute our highest-priority near-term large project"*

Proposed New LHC Projects

- Aim for low background at trigger level by shielding, zero background in analysis
- When possible, leverage existing main detectors (ATLAS, CMS, LHCb) for additional event information
- Complementary to existing experiments at LHC and elsewhere

CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Complementarities in long-lived particle searches and enhancements in sensitivity might be achieved if new proposals for detectors and experiments such as MATHUSLA200, FASER, CODEX-b, MilliQan and LHeC are realised in parallel to the HL-LHC. As an example, with a zero-background hypothesis, MATHUSLA200 [422] would offer a coverage complementary to HL-LHC in terms of new particles with $c\tau$ in the range 100 m–20 km, targeting *R*-parity violating decays of gluinos, top squarks as well as sleptons and Higgsinos.

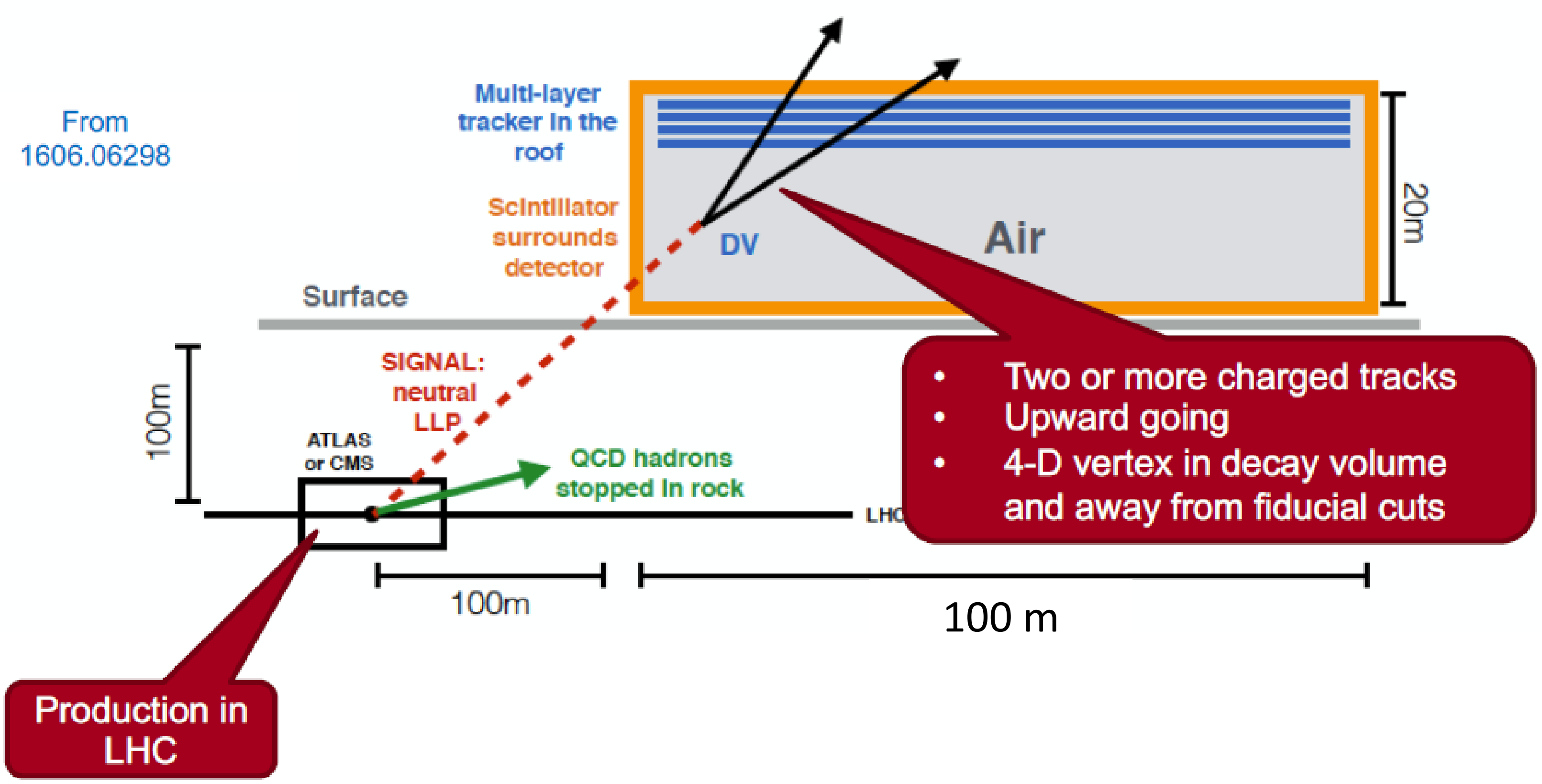
Overall, the combination of LHCb Upgrade II and CODEX-b, and of ATLAS/CMS and MATHUSLA would cover a very diverse and wide range of new physics options.

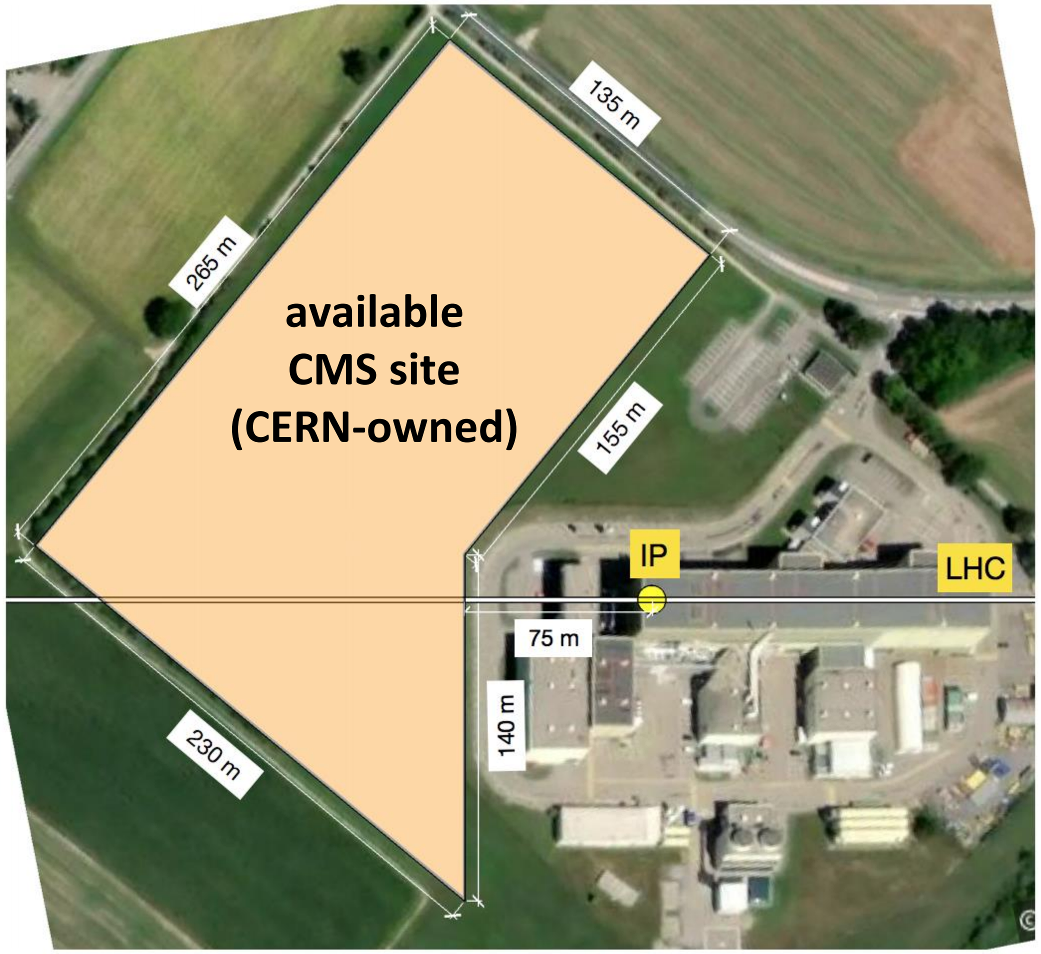
Basic Concept

MAssive **T**iming **H**odoscope for **U**ltra-**S**table Neutra**L** P**A**rticles

An external LLP detector for the HL-LHC

Basic idea: search for LLPs by reconstructing displaced vertices in air-filled decay volume, removed from LHC collision backgrounds

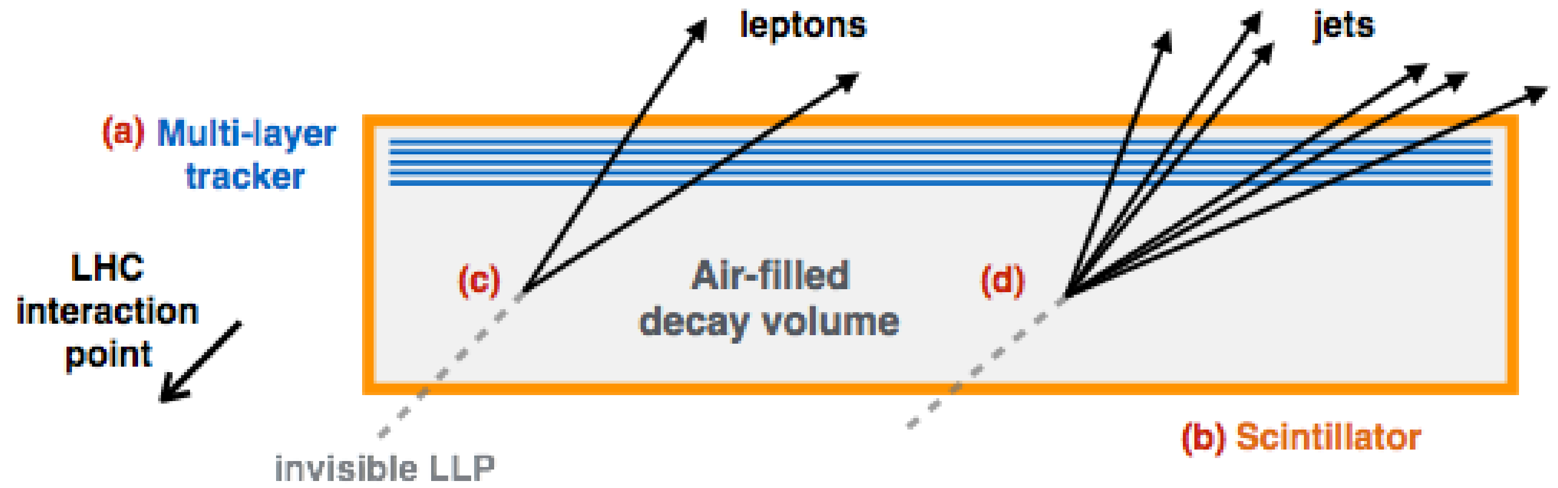




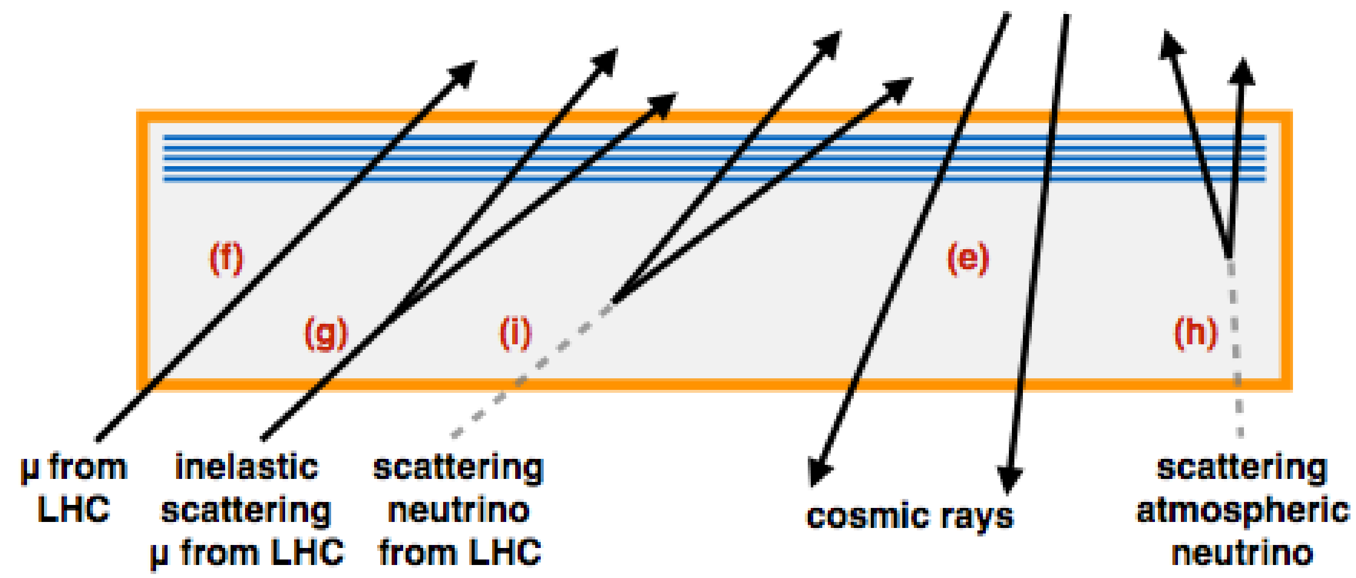
Simple instrumentation but highly robust tracking is essential!

Signal vs Background

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!

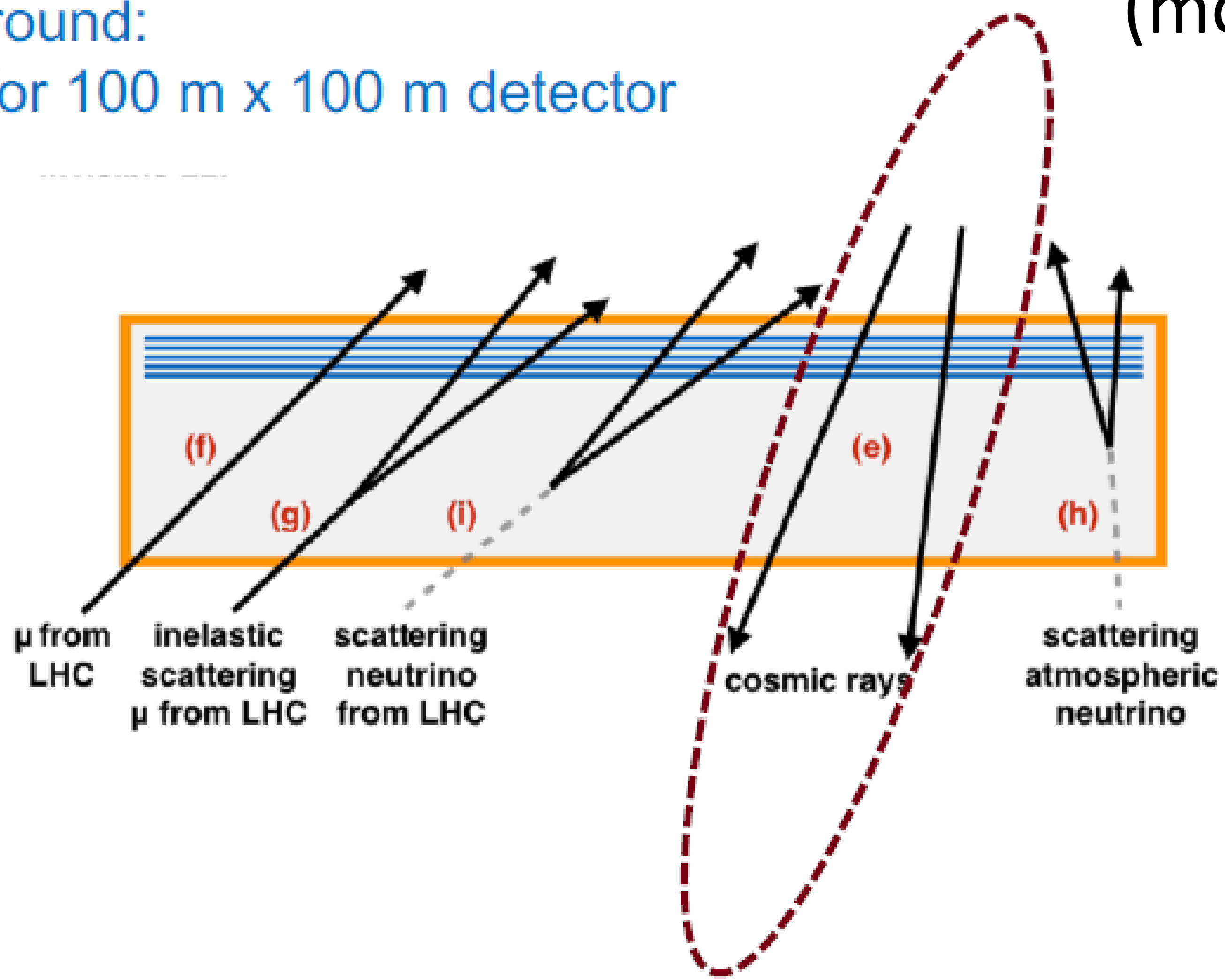


MATHUSLA should be able to search for neutral LLP decays with near-zero backgrounds!

Backgrounds

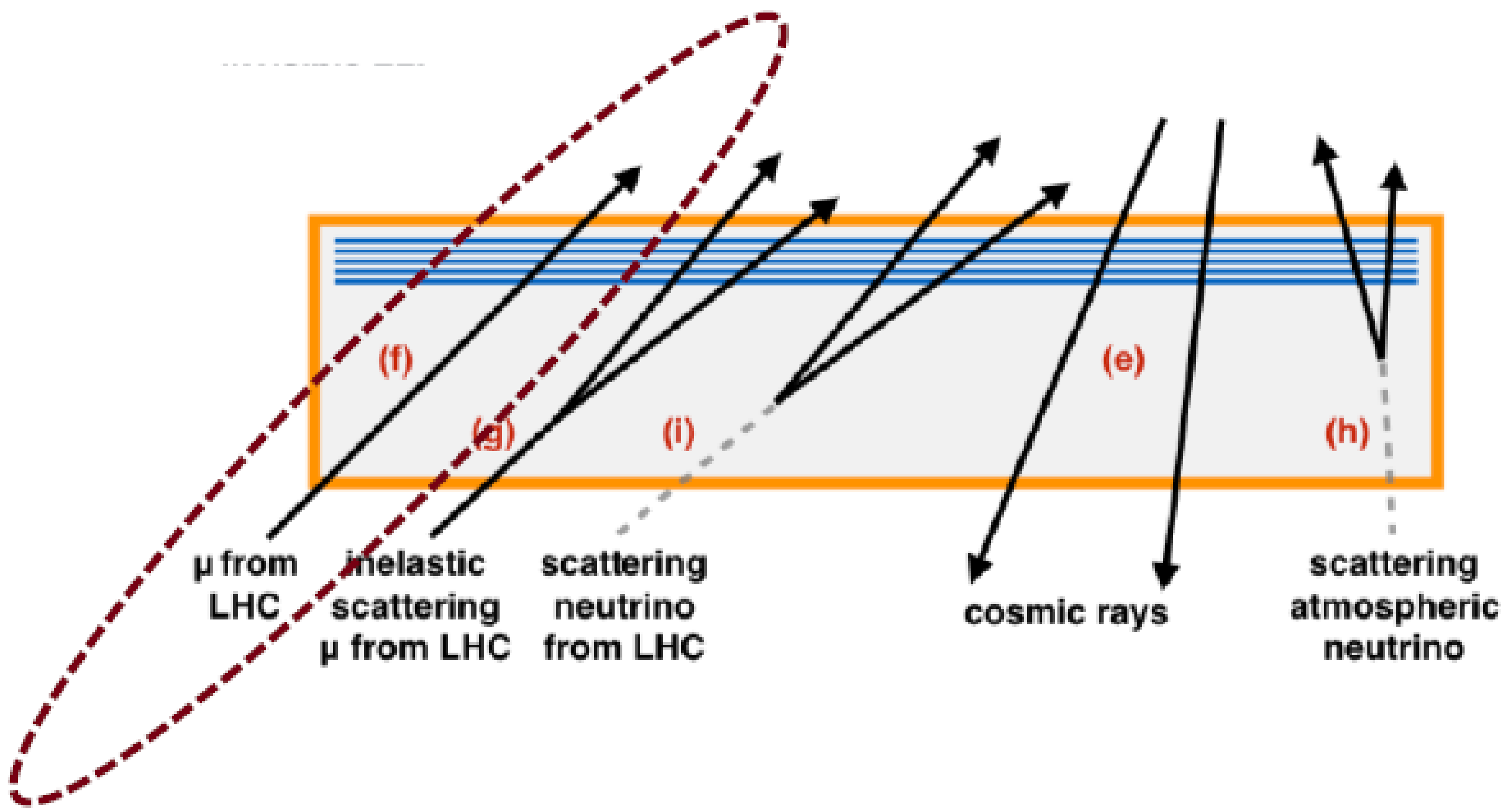
High enough rate to serve as cosmic ray telescope! (more on this later)

Highest rate background:
~2 MHz of cosmic for 100 m x 100 m detector



- Timing to discriminate between downward going cosmic from upward going signal tracks.
- Seven planes of detectors spanning 10 m (and two planes at bottom of 25-m deep decay volume) each with 1-nsec timing resolution
- 4D vertex of two or more cosmics that somehow evade timing cuts

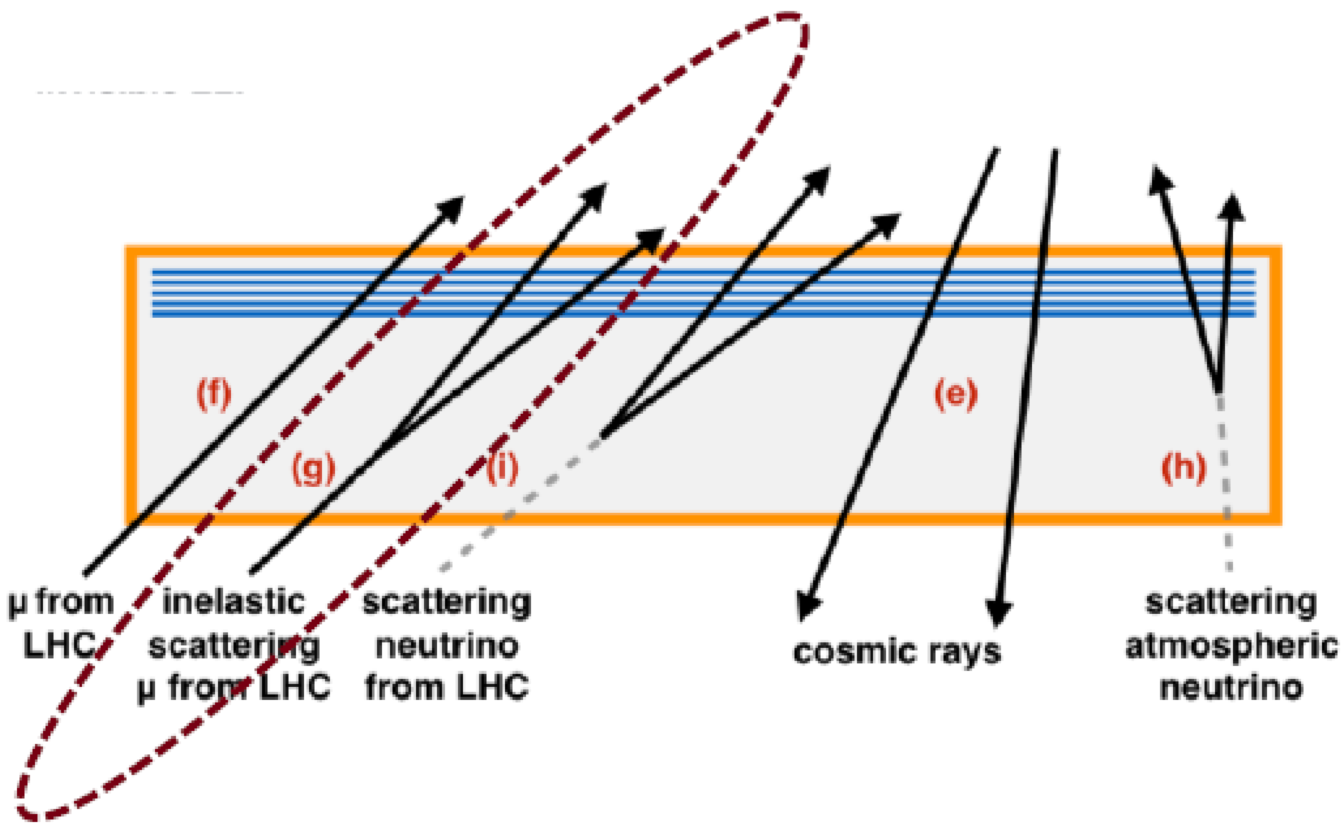
Backgrounds



Muons from LHC:

- ~10^7 during HL-LHC ⇒ ~ 0.1 Hz
- Single track topology incompatible with signal
- $BR(\mu \to eee\nu\nu) = 3.4{\times}10^{-5}$ ⇒ < 1 during HL-LHC
- Two detector planes on floor of decay volume to flag incoming muons

Backgrounds

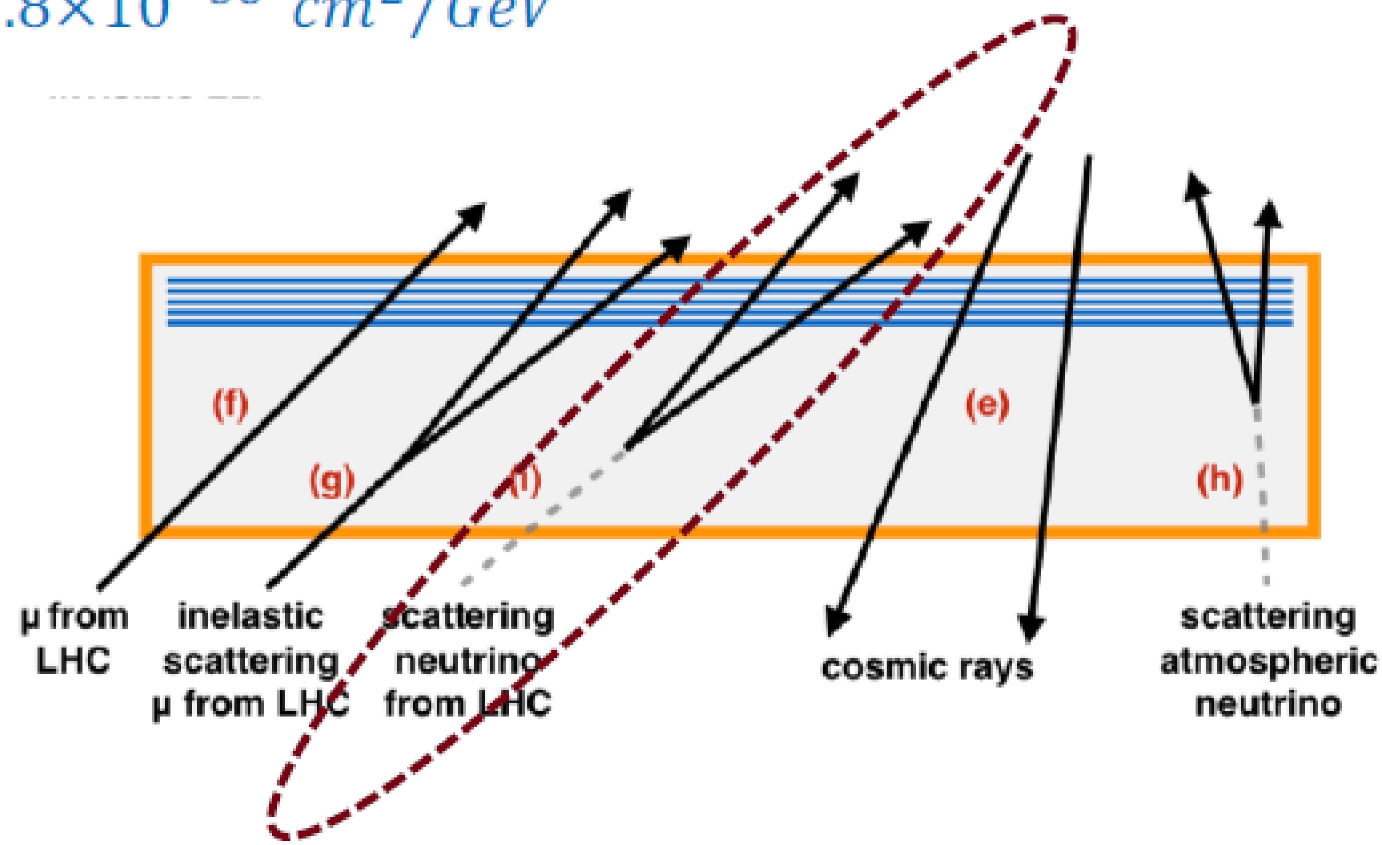


Inelastic scattering of muons produced in LHC

- Fiducial cuts around material in decay volume, e.g. support columns and floor. Also effective against cosmic ray albedo.
- Expect $10^2 - 10^3$ muon-air interactions during HL-LHC
- Two detector planes on floor of decay volume to flag incoming charged track

Backgrounds

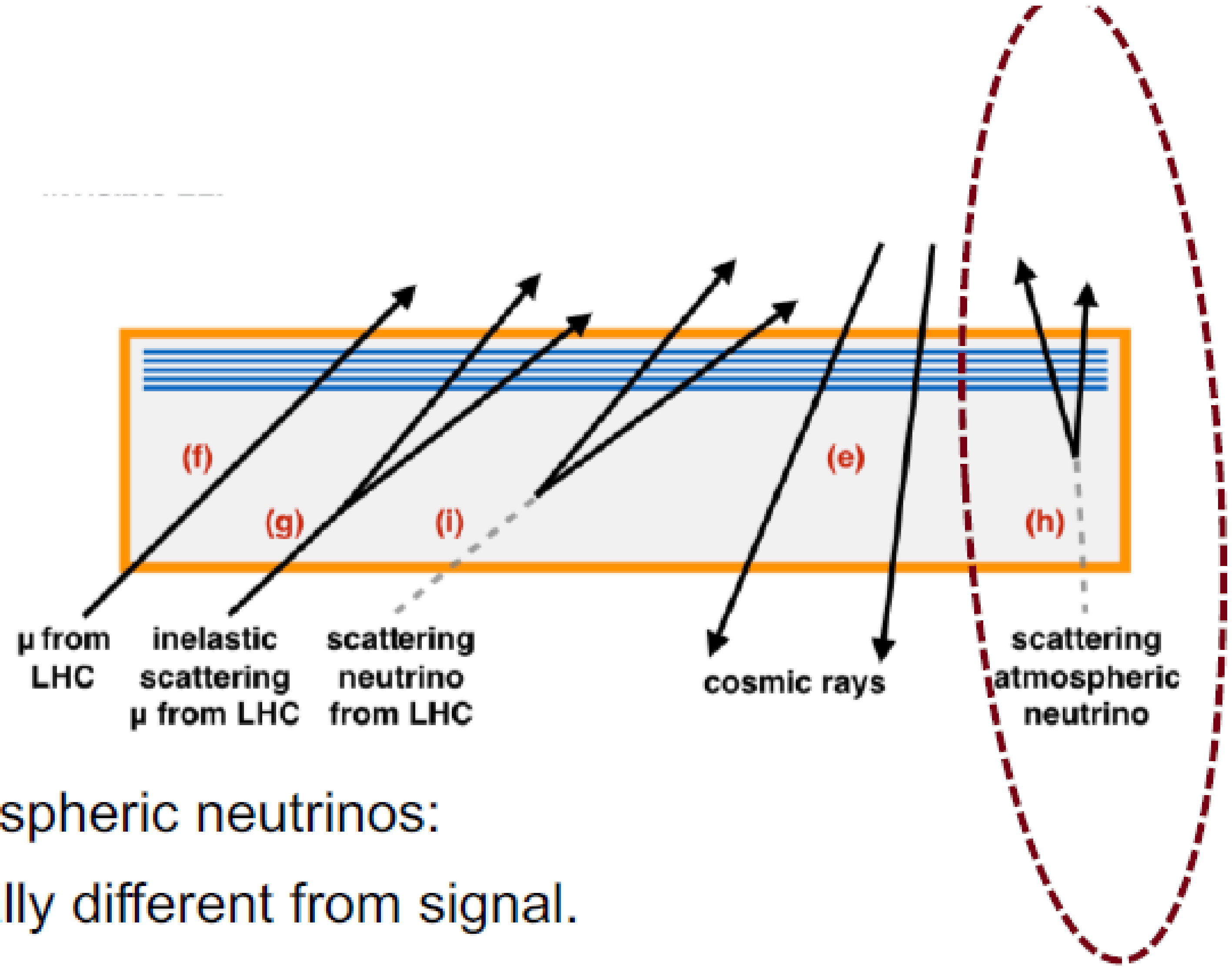
$\sigma_\upsilon/E_\upsilon \sim 0.8{\times}10^{-38}\ cm^2/GeV$



Interaction of neutrinos from LHC:

- Not fundamentally different from signal
- Calculated rate is small: 0.1 from high-energy neutrinos (W, Z, t, b) and 1 from low-energy neutrinos (π, K) integrated over HL-LHC

Backgrounds



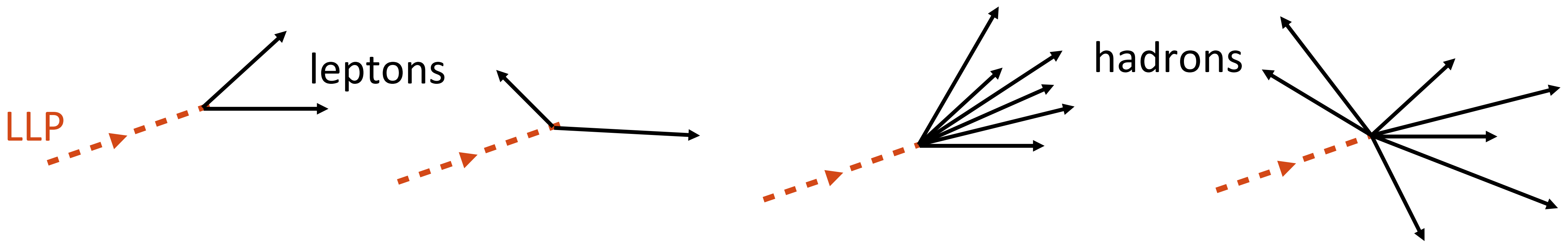
Upward-going atmospheric neutrinos:

- Not fundamentally different from signal.
- Expect ~25 interactions per year.
- Final state often has slow protons (due to small E_{υ}) and can be rejected by timing.
- Higher energy events with more collimated final state tracks can be rejected by requiring consistent with coming from CMS IP.
- Rejection efficiency based on kinematics etc found to be better than 99%.

Diagnosing LLPs with MATHUSLA

MATHUSLA can't measure particle momentum or energy, but:

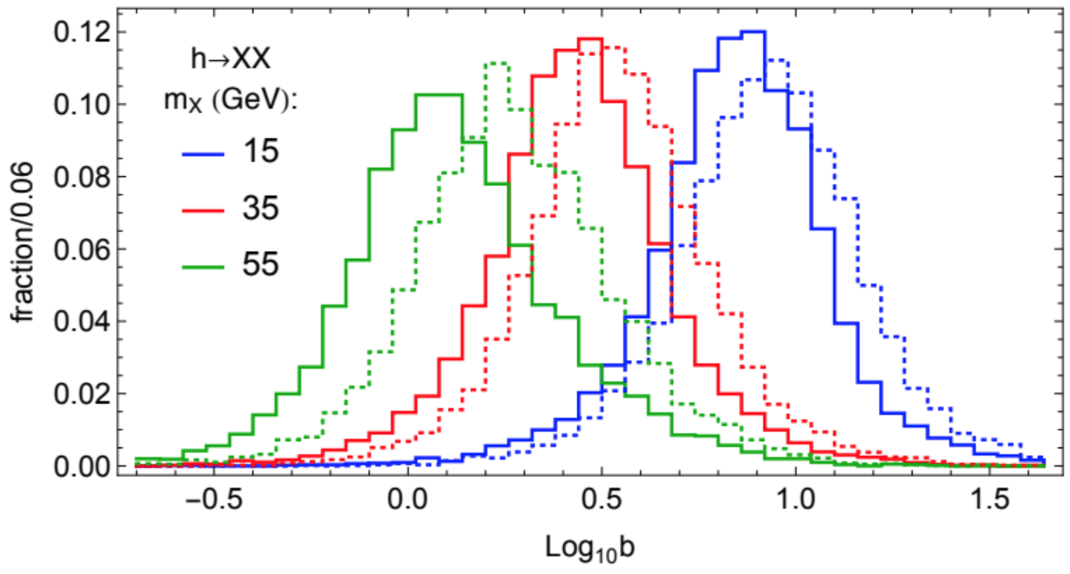
track geometry → measure of LLP boost event-by-event!

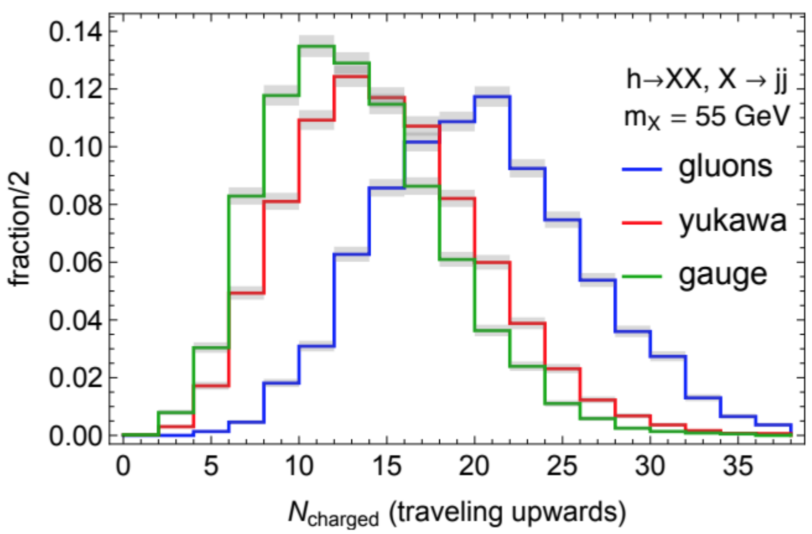


If production mode is known:

Boost distribution → LLP mass

DC, Peskin 1705.06327



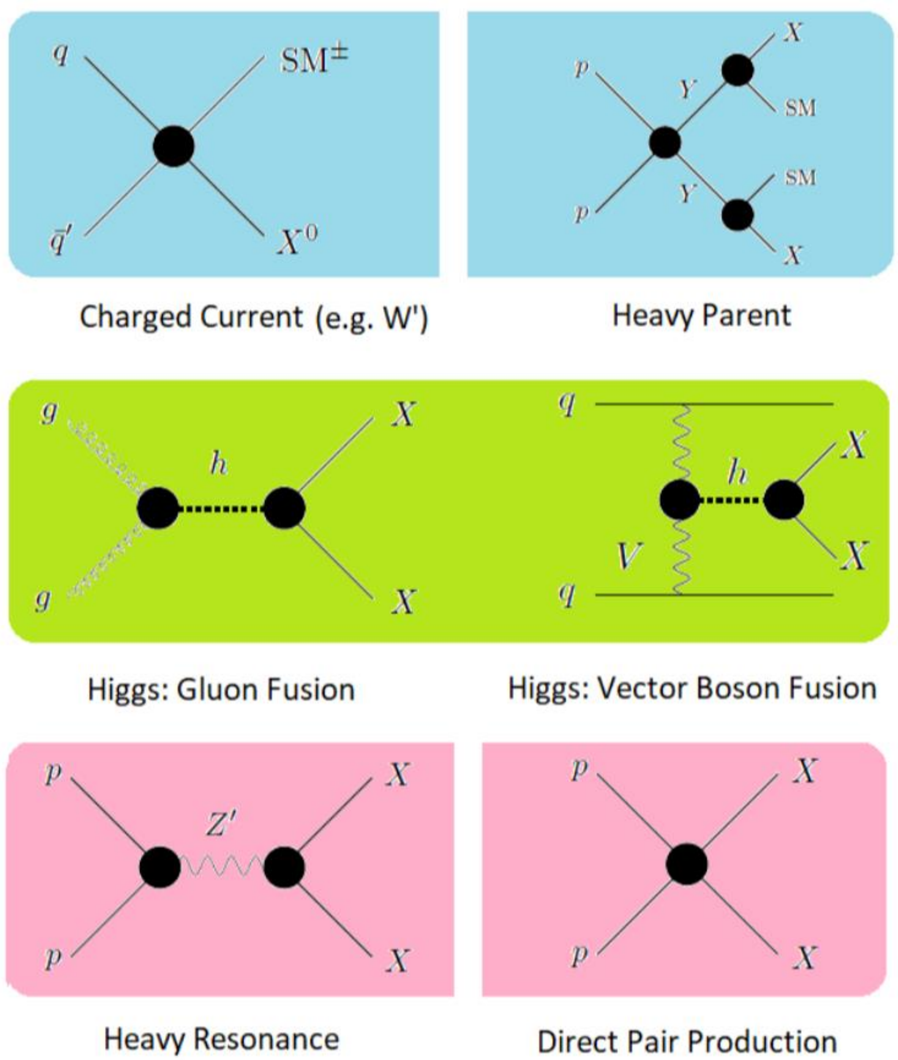


If LLP mass is known:

Track multiplicity → LLP decay mode

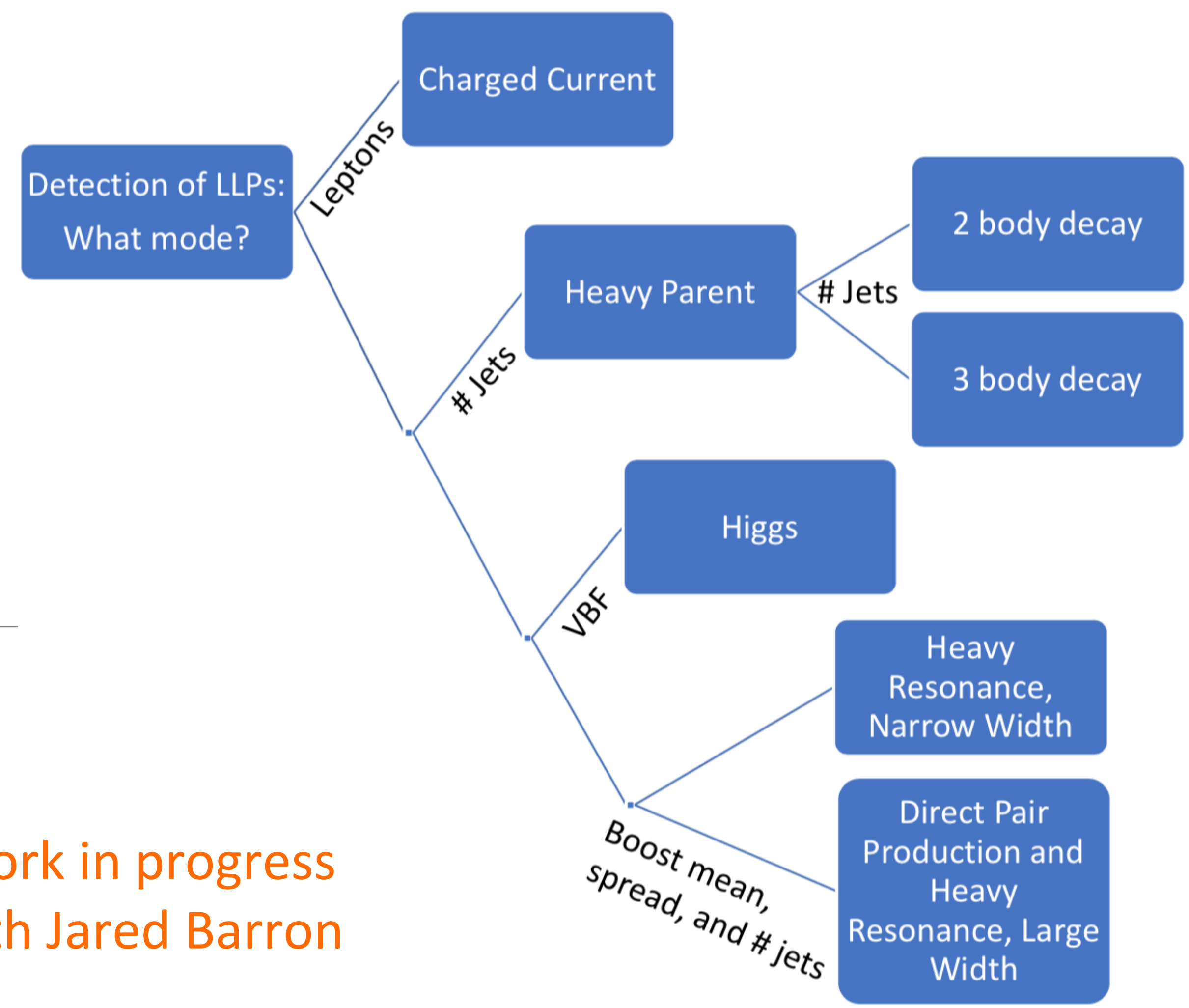
MATHUSLA - Main Detector Correlations

Let MATHUSLA be CMS L1 Trigger and correlate event information off-line to **determine production mode!**



Charged Current (e.g. W') | Heavy Parent | Higgs: Gluon Fusion | Higgs: Vector Boson Fusion | Heavy Resonance | Direct Pair Production

Work in progress with Jared Barron

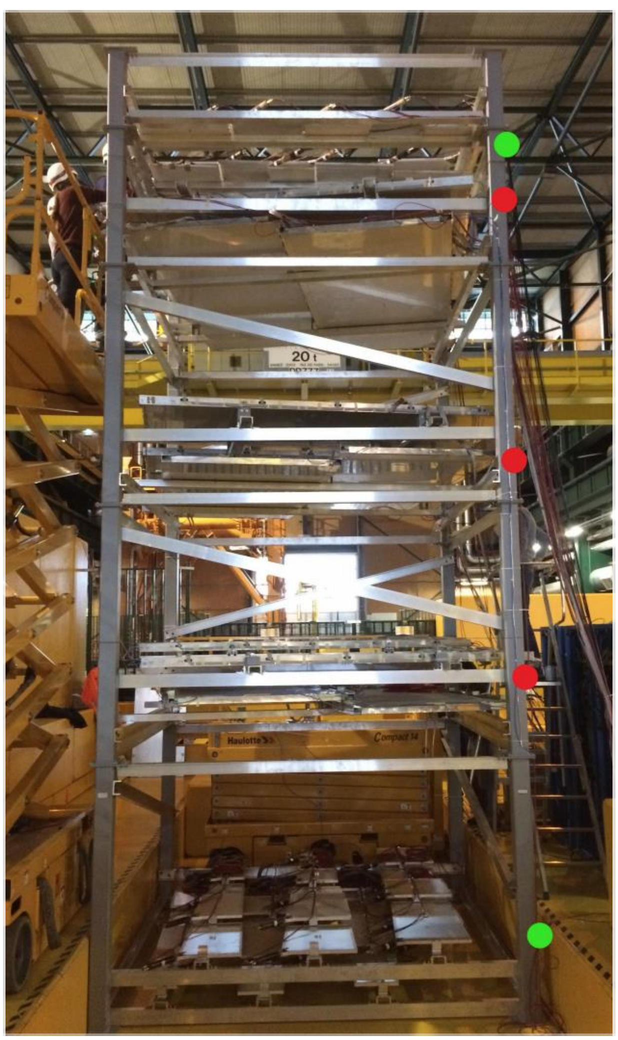


MATHUSLA Collaboration

1811.00927

A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beach…
Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario R…
John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe
Drewes,… …g,[q] Jared E…
Stefano … …kun Heng,
Ken Joh… …Kvam,[a] D…
Li,[af] Bar… …ovanni Ma…
McCullo… …l Mizrachi,
Meny Ra… …Piter A. …
Policicch… …o,[ad] Joe R…
Santonic… …ian Shuve
Vasquez… …ro Fernán…
Tejeda M… …ftah Silver
Emma T… …lázquez,[i]
Young,[e] …



mathusla.web.cern.ch

1901.04040

MATHUSLA

MATHUSLA:
A Detector Proposal to Explore
the Lifetime Frontier at the HL-LHC

Input to the update process of the European Strategy for Particle Physics
18. December 2018

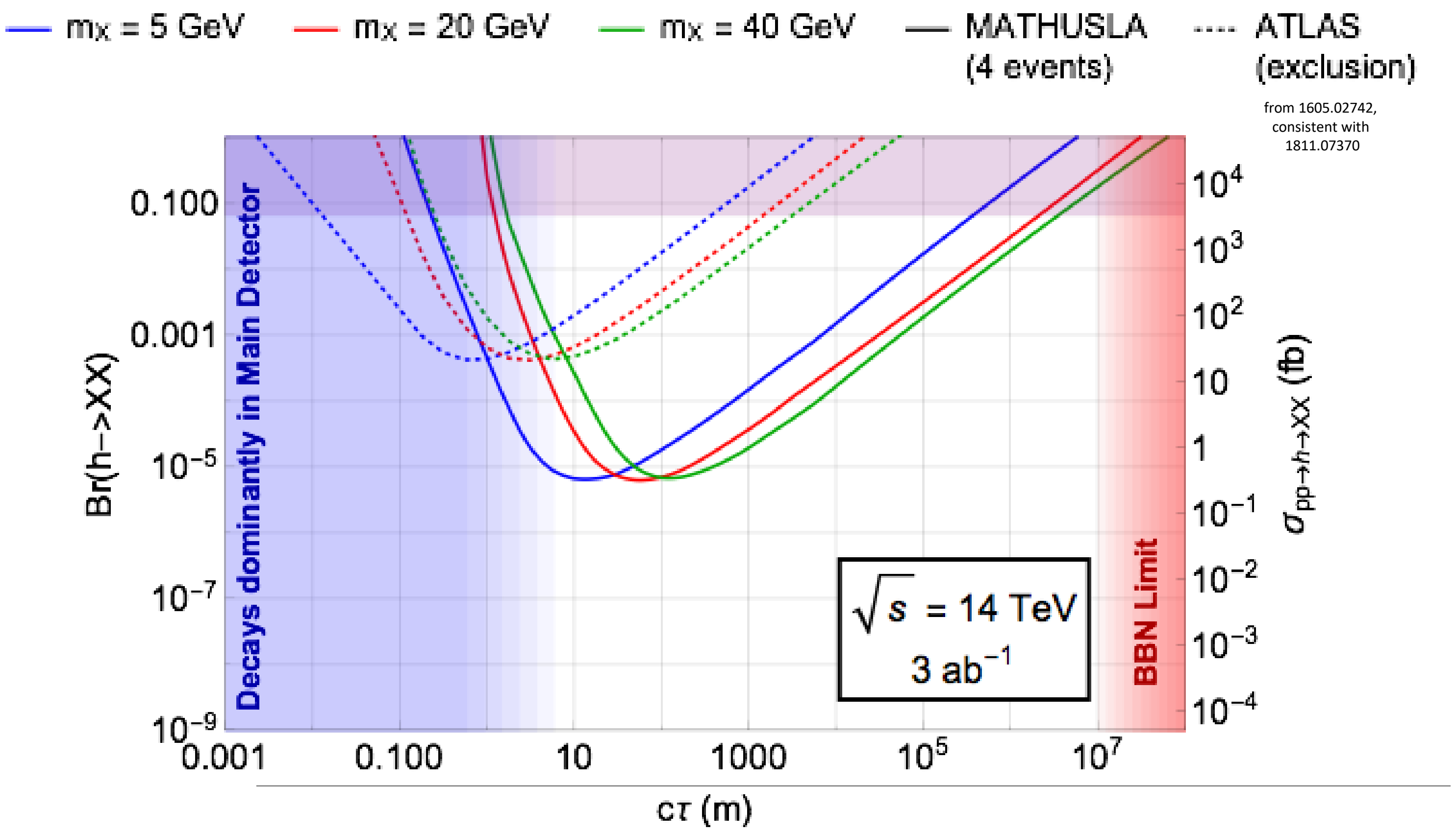
Henry Lubatti (Corresponding Author),[1,*] Cristiano Alpigiani,[1] Juan Carlos Arteaga-Velázquez,[2] Austin Ball,[3] Liron Barak,[4] James Beacham,[5] Yan Benhammo,[4] Karen Salomé Caballero-Mora,[6] Paolo Camarri,[7] Tingting Cao,[4] Roberto Cardarelli,[7] John Paul Chou,[8] David Curtin,[9] Albert de Roeck,[3] Giuseppe Di Sciascio,[7] Miriam Diamond,[9] Marco Drewes,[10] Sarah C. Eno,[11] Rouven Essig,[12] Jared Evans,[13] Erez Etzion,[4] Arturo Fernández Téllez,[14] Oliver Fischer,[15] Jim Freeman,[16] Stefano Giagu,[17] Brandon Gomes,[8] Andy Haas,[18] Yuekun Heng,[19] Giuseppe Iaselli,[20] Ken Johns,[21] Muge Karagoz,[11] Audrey Kvam,[1] Dragoslav Lazic,[22] Liang Li,[23] Barbara Liberti,[7] Zhen Liu,[11] Giovanni Marsella,[24] Piter A. Paye Mamani,[25] Mario Iván Martínez Hernández,[14] Matthew McCullough,[3] David McKeen,[26] Patrick Meade,[12] Gilad Mizrachi,[4] David Morrissey,[26] Meny Raviv Moshe,[4] Antonio Policicchio,[17] Mason Proffitt,[1] Marina Reggiani-Guzzo,[27] Mario Rodríguez-Cahuantzi,[14] Joe Rothberg,[1] Rinaldo Santonico,[7] Marco Schioppa,[28] Jessie Shelton,[29] Brian Shuve,[30] Yiftah Silver,[4] Daniel Stolarski,[31] Martin A. Subieta Vasquez,[25] Guillermo Tejeda Muñoz,[14] Steffie Ann Thayil,[8] Yuhsin Tsai,[11] Emma Torro,[1] Gordon Watts,[1] Charles Young,[32] and Jose Zurita[33]

LLP Sensitivity

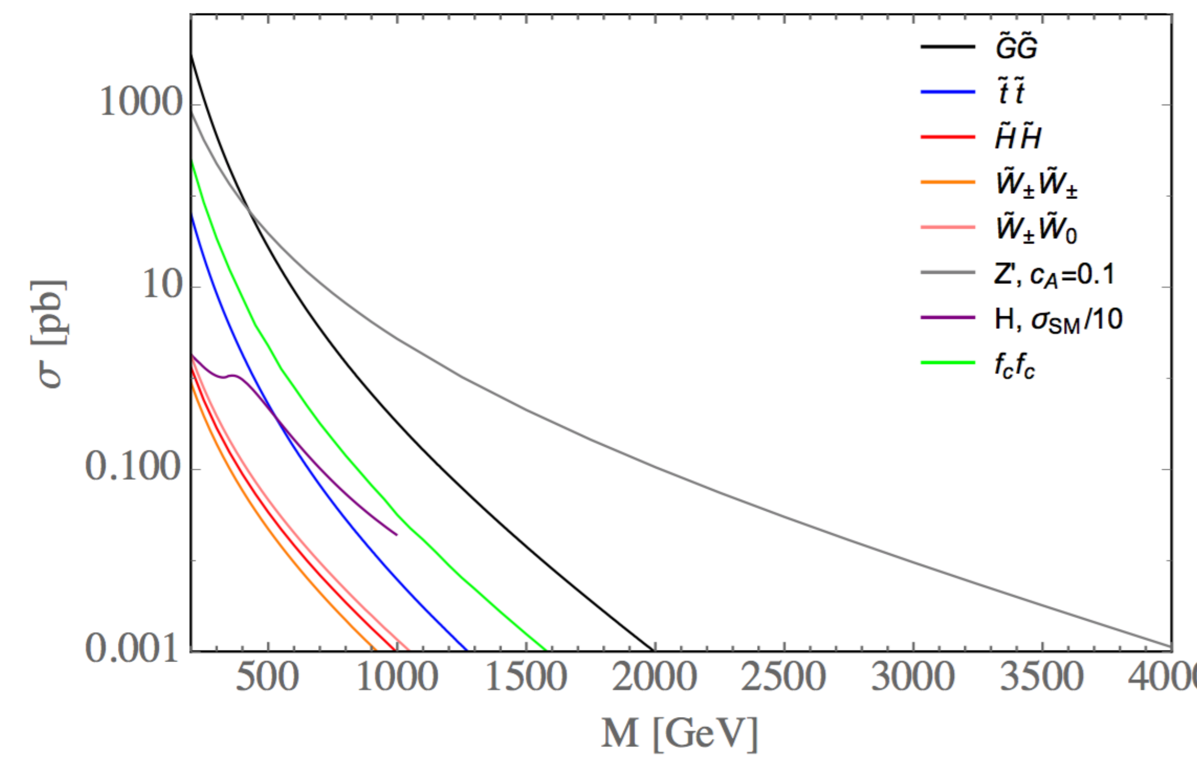
LLP Sensitivity

Physics Case
White Paper
1806.07396

LLP cross section reach
(exotic Higgs decay example)



Any LLP production process
with σ > fb can give signal.

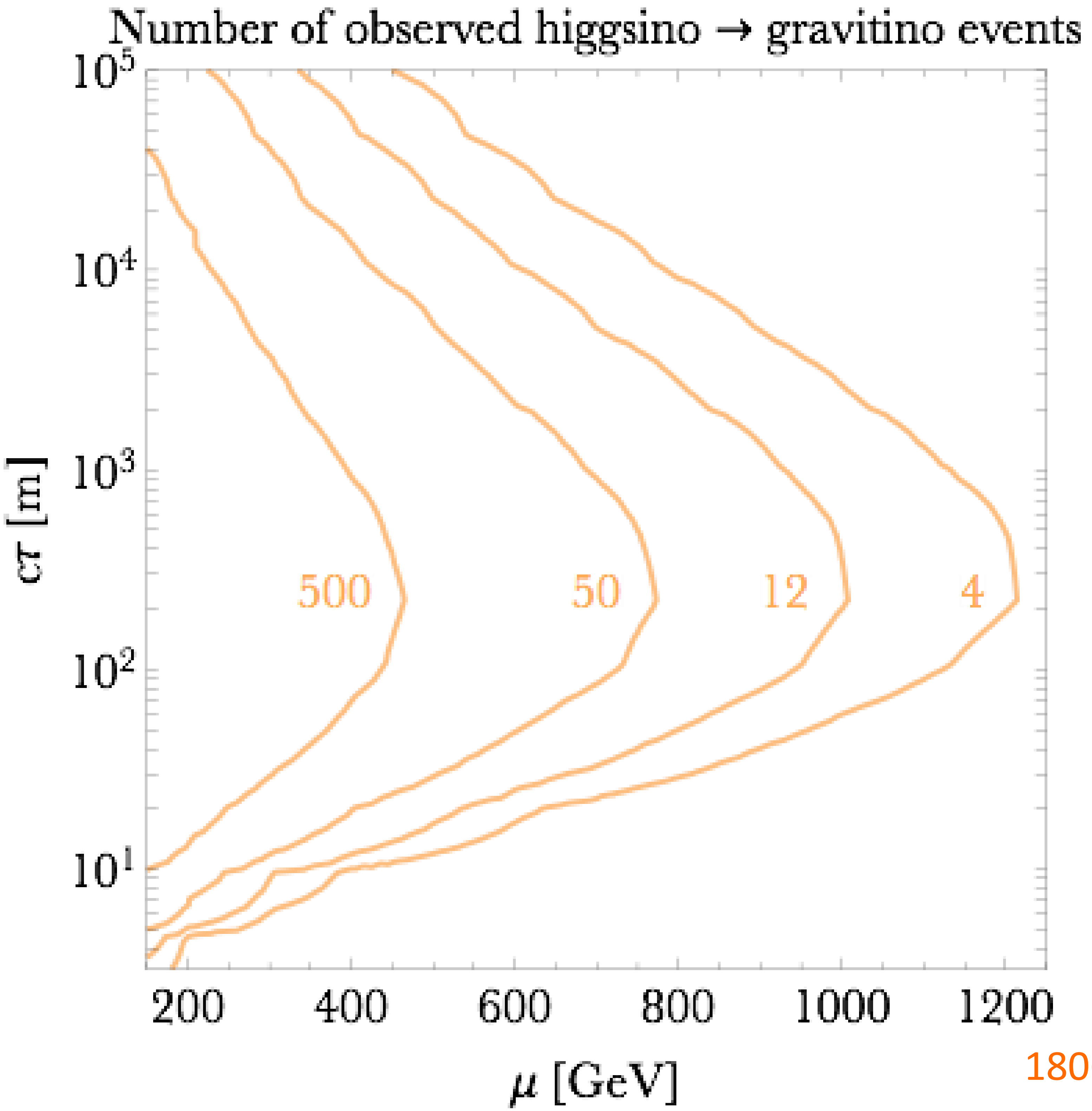


Up to 1000x better sensitivity than main detectors

Probe TeV+ scales!

This is for 200m x 200m x 20m **physics benchmark** detector volume.
Realistic and much smaller detectors can reach same sensitivity.

A high-mass LLP example: Higgsinos



1806.07396

Low-mass LLP scenarios

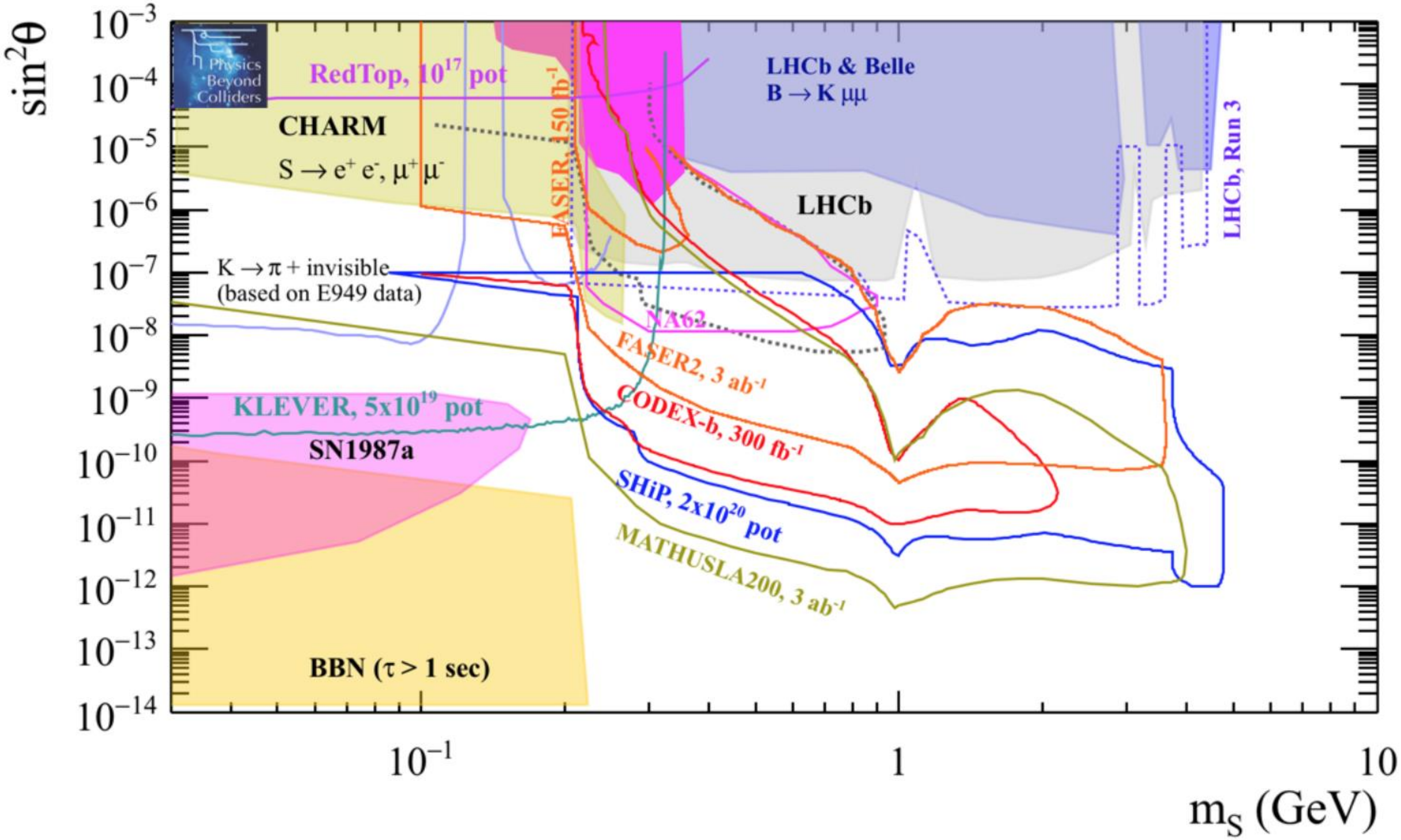
For scenarios like Dark Scalar or axion+fermion/gluon couplings, where the long-lifetime limit (>100m) is accessible, FASER, SHiP and MATHUSLA are highly complementary, covering lower, medium, high lifetimes.

For Dark Photon or axion+photon coupling scenarios, SHiP reigns supreme.

Sterile Neutrinos don't fall exactly into these categories. SHiP is generally best but MATHUSLA is close.

PBC BSM working group report 1901.09966

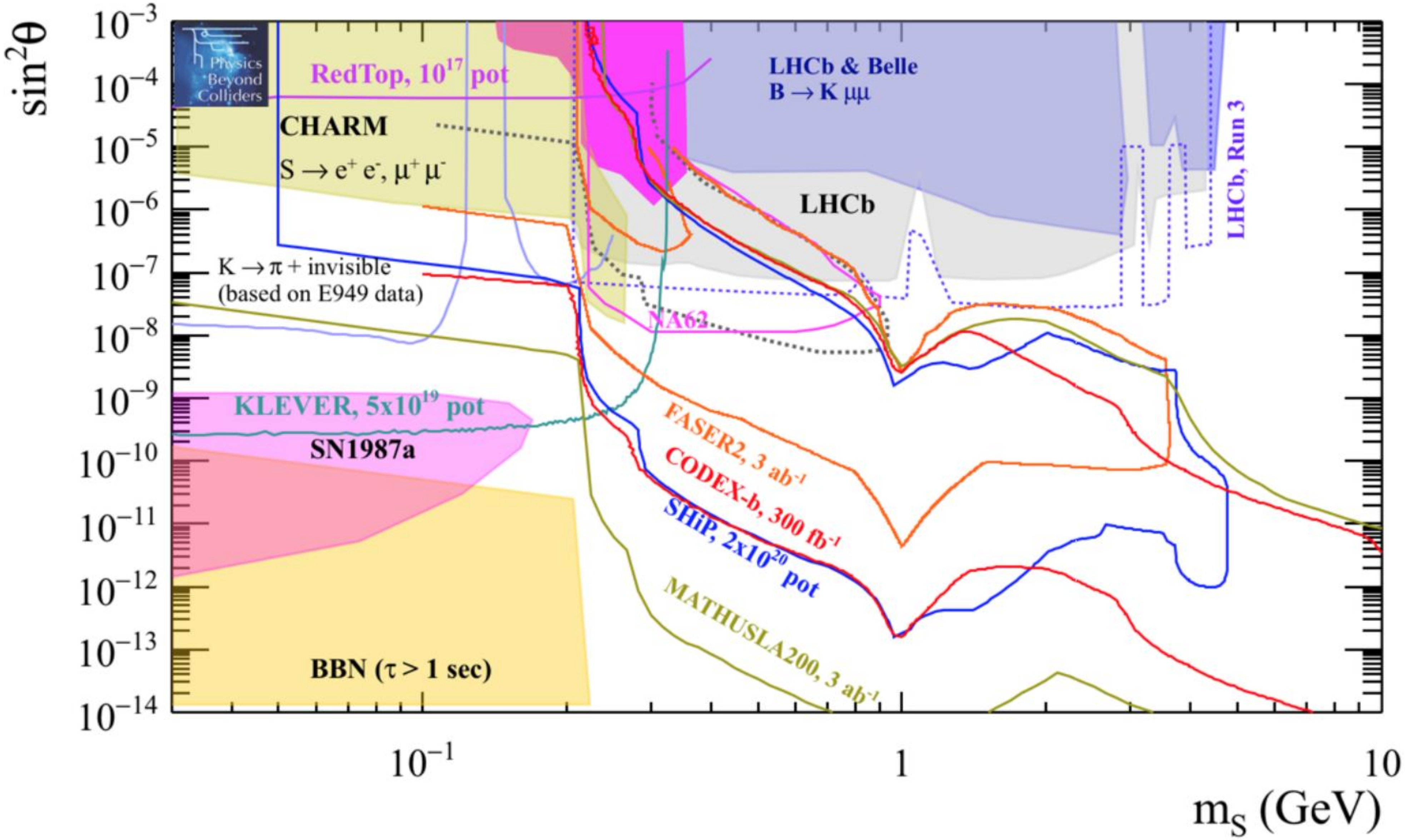
Dark Scalar only



very complementary coverage… MATHUSLA, SHiP and FASER cover longer, intermediate and shorter lifetimes.

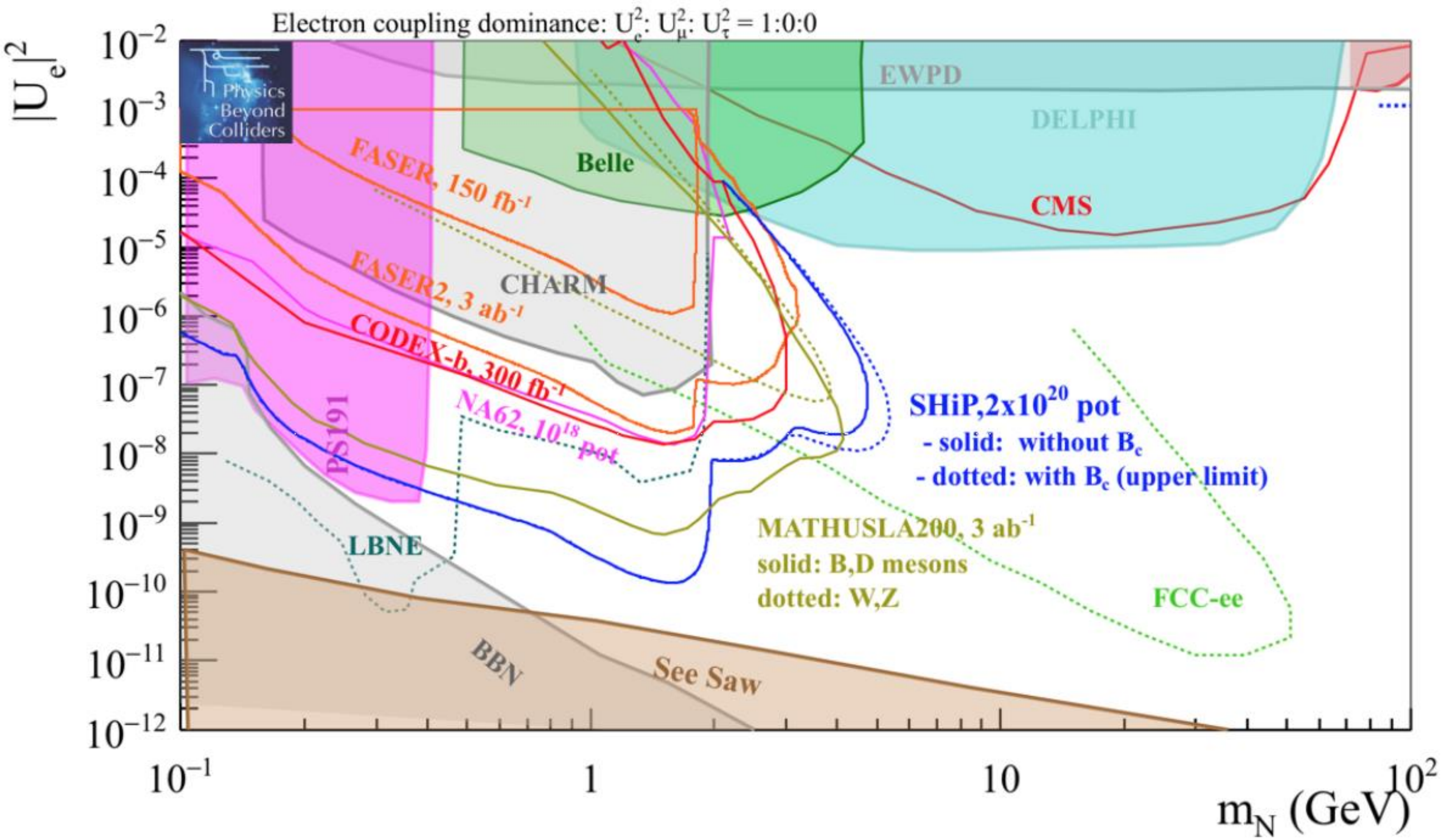
PBC BSM working group report 1901.09966

Dark Scalar with exotic higgs decays



LHC external detectors probe higher masses

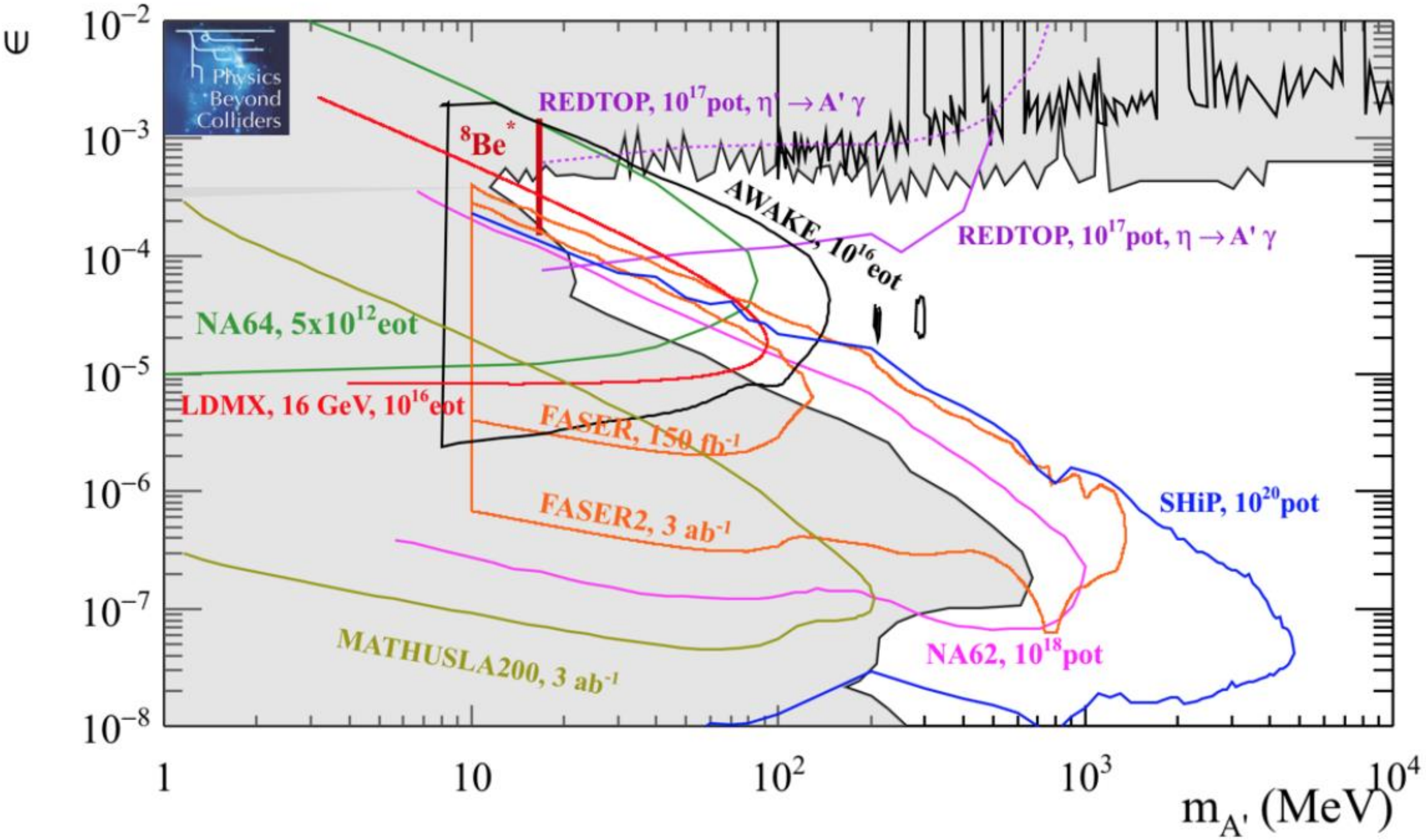
Sterile RH Neutrinos



very complementary coverage

PBC BSM working group report 1901.09966

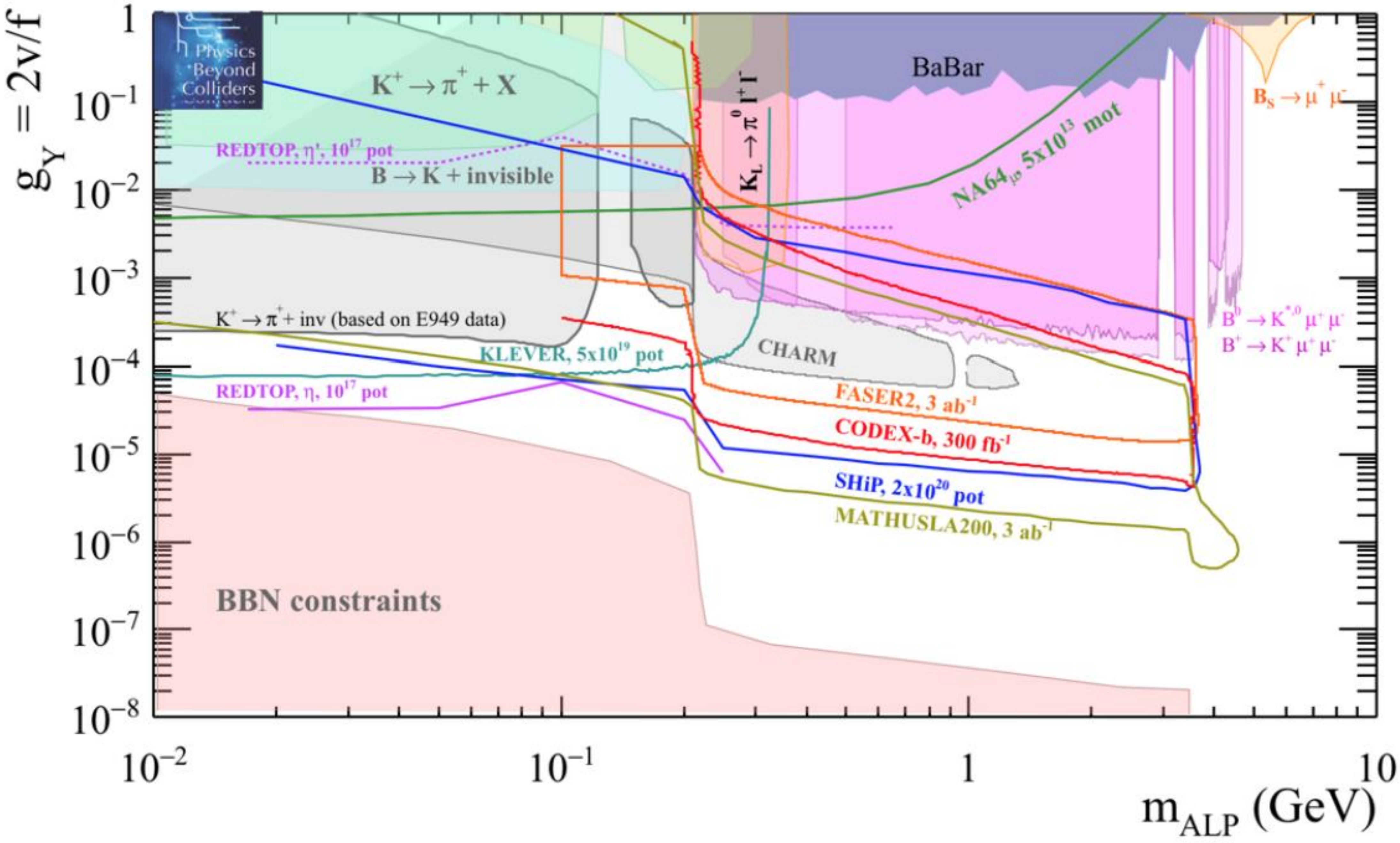
Dark Photon only



For < ~GeV or massless dark photon + invisible or milli-charged states, need LDMX, milliQan

PBC BSM working group report 1901.09966

Axion-like Particles: Pure fermion coupling



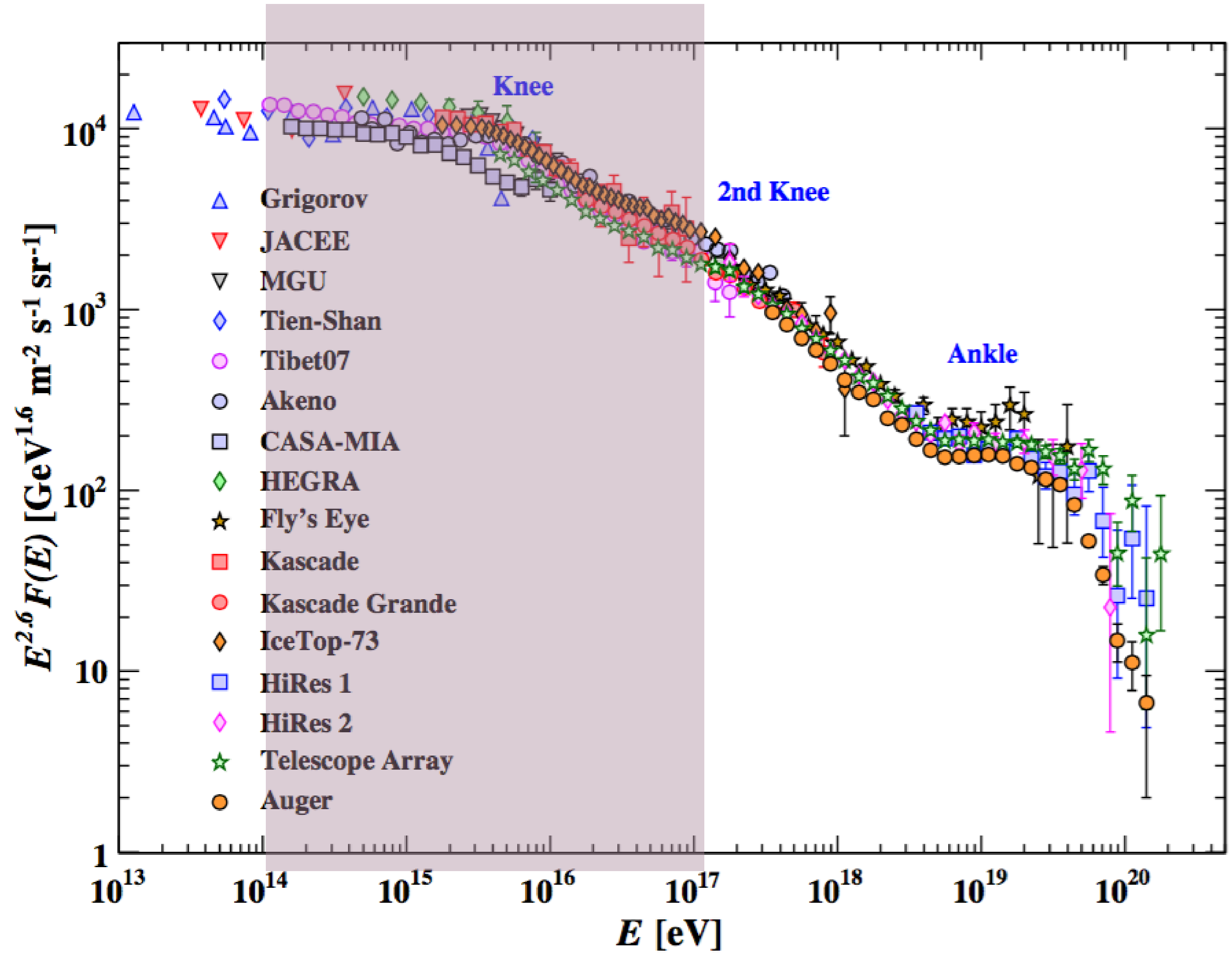
PBC BSM working group report 1901.09966

Cosmic Ray Telescope

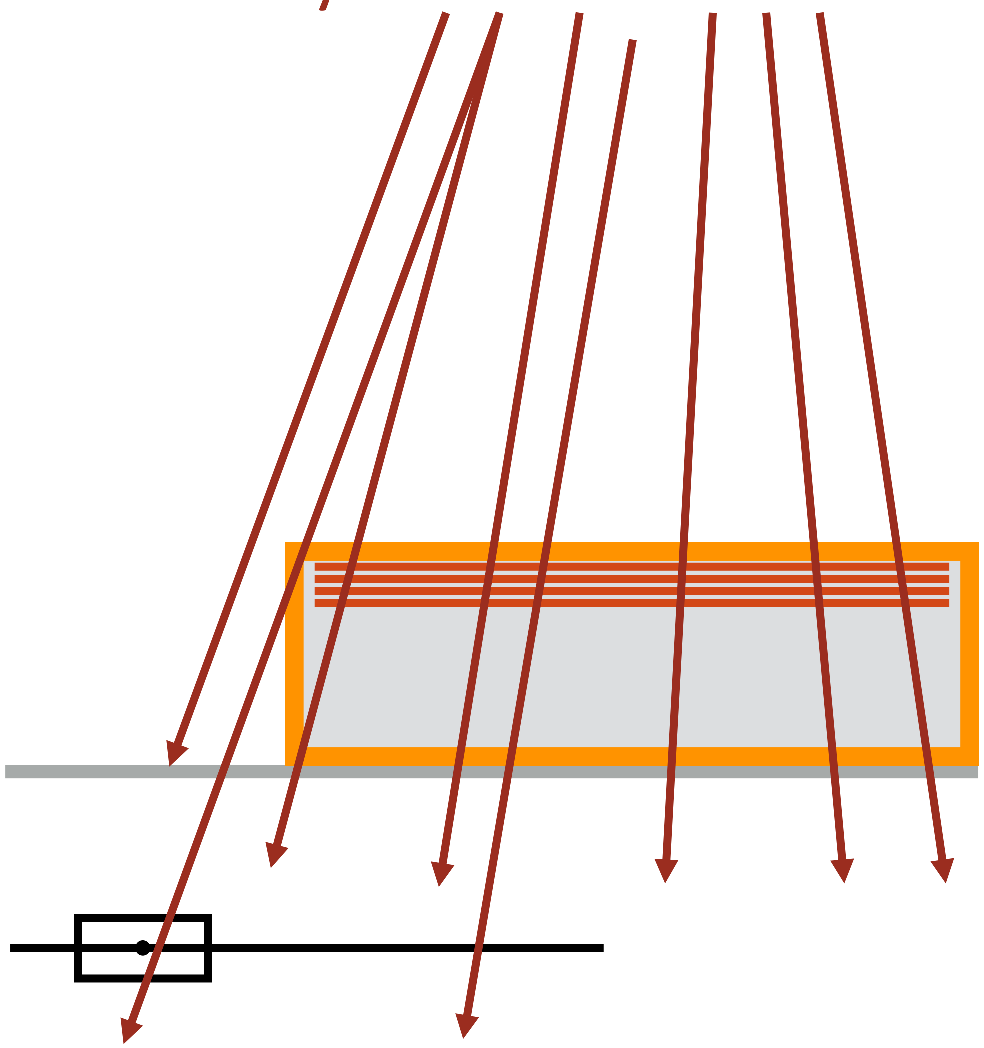
Guaranteed Physics Return

MATHUSLA is an excellent Cosmic Ray Telescope!

Has unique abilities in CR experimental ecosystem
(precise resolution, directionality, full coverage of its area)



mostly muons at sea level



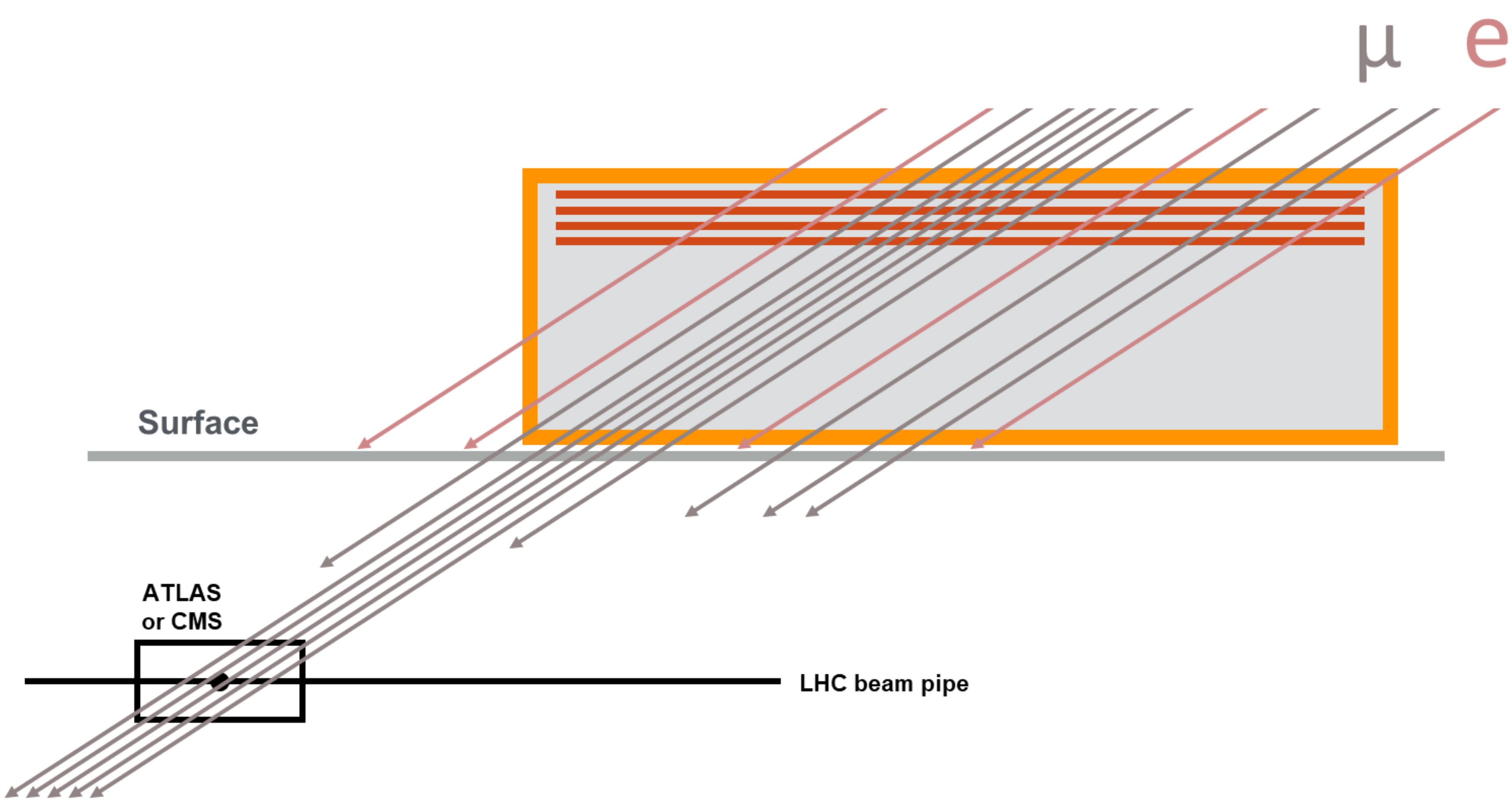
Guaranteed Physics Return

✓ **MATHUSLA standalone**

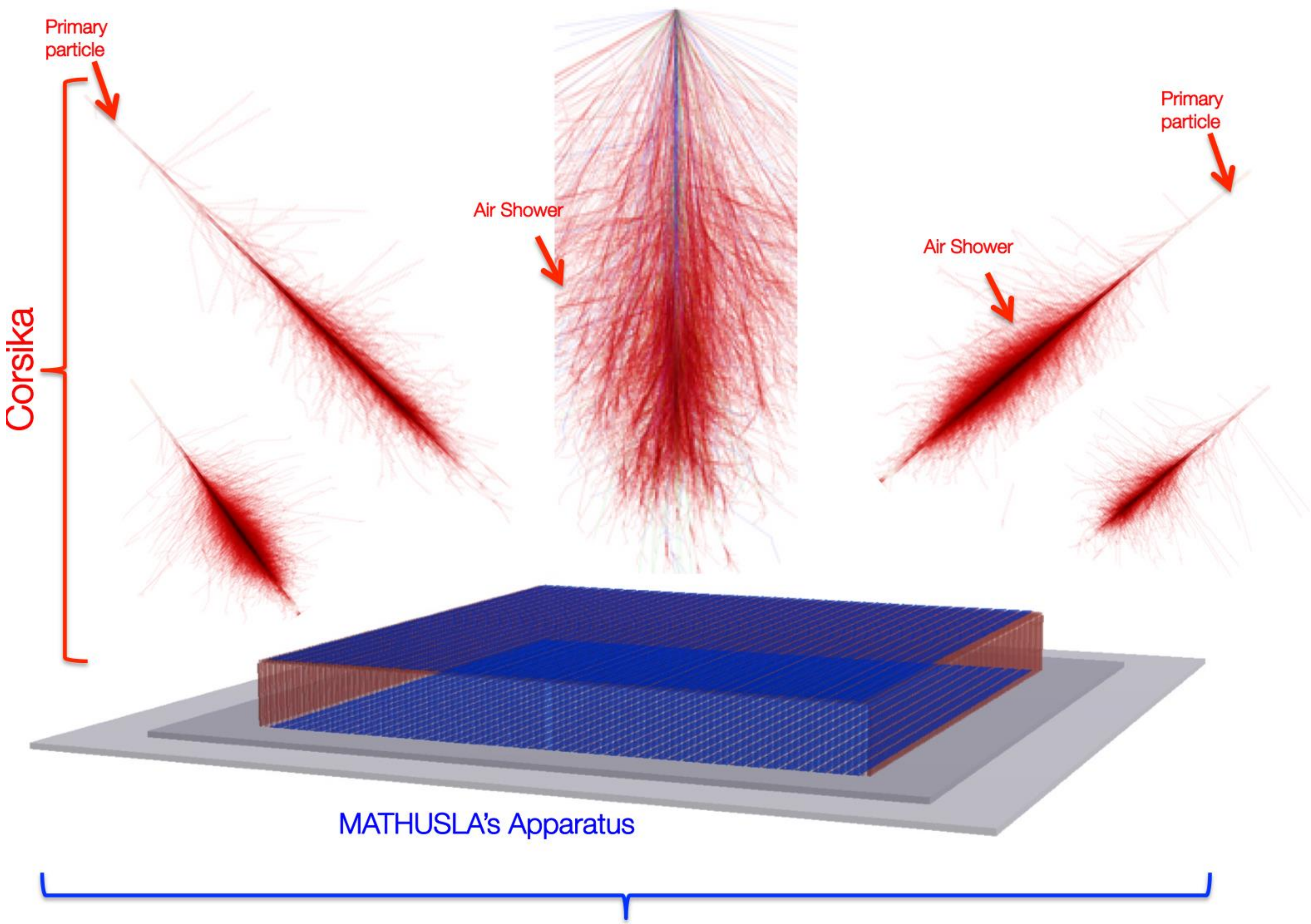
- Reconstruction of the core, direction of the shower, slope of the radii distribution of particle densities, total number of charged particles

✓ **MATHUSLA+CMS**

- Uniquely able to analyse muon bundles going through both detectors. Powerful probe of heavy primary cosmic ray spectra and astrophysical acceleration



Guaranteed Physics Return

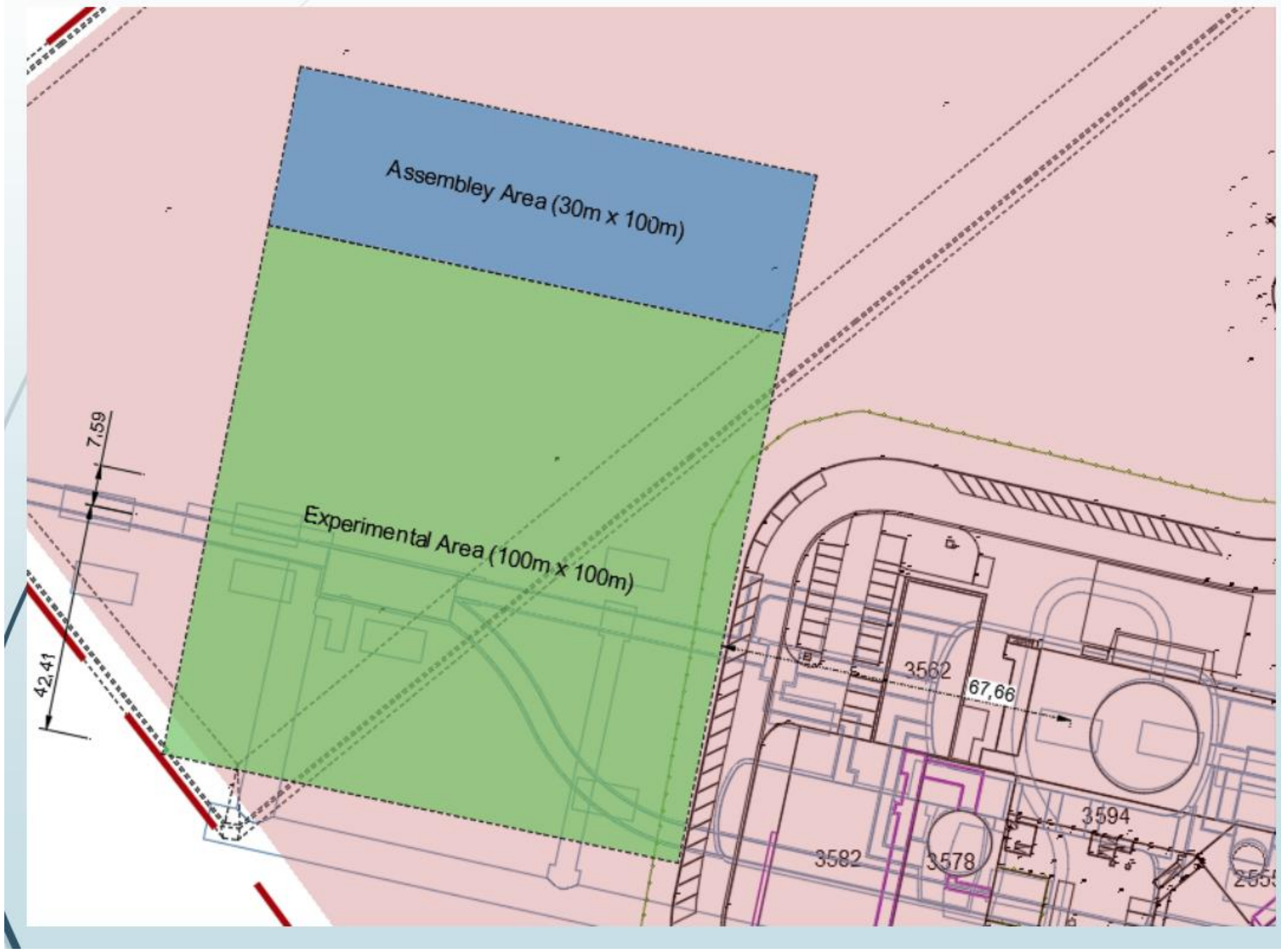


MATHUSLA's Apparatus simulation using VMC (G4-G3-ROOT): Detectors, particle tracking, whole geometry

Detector Design

Current MATHUSLA Layout Concept near CMS

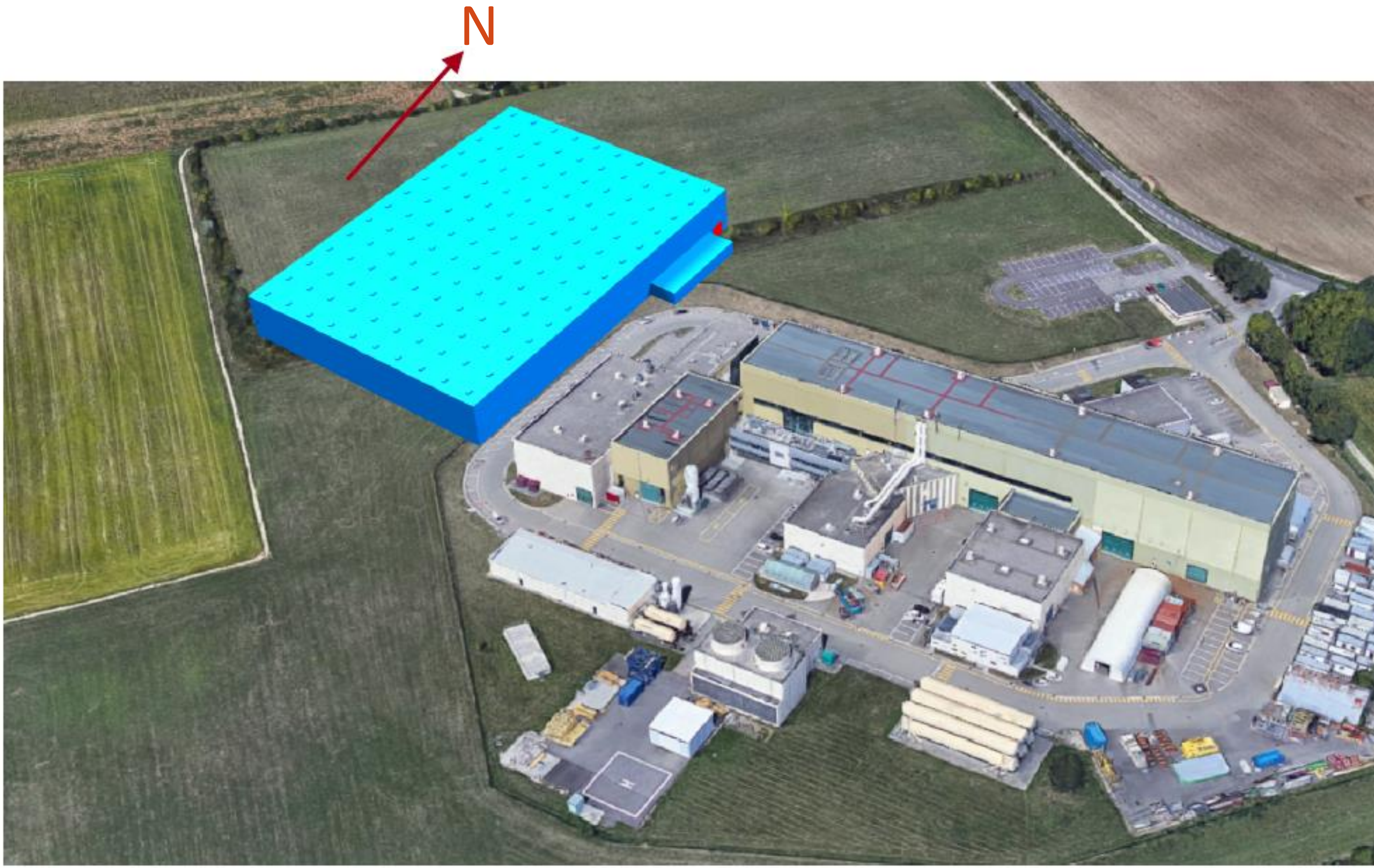
100m x 100m area detector fits on CERN-owned land near CMS!



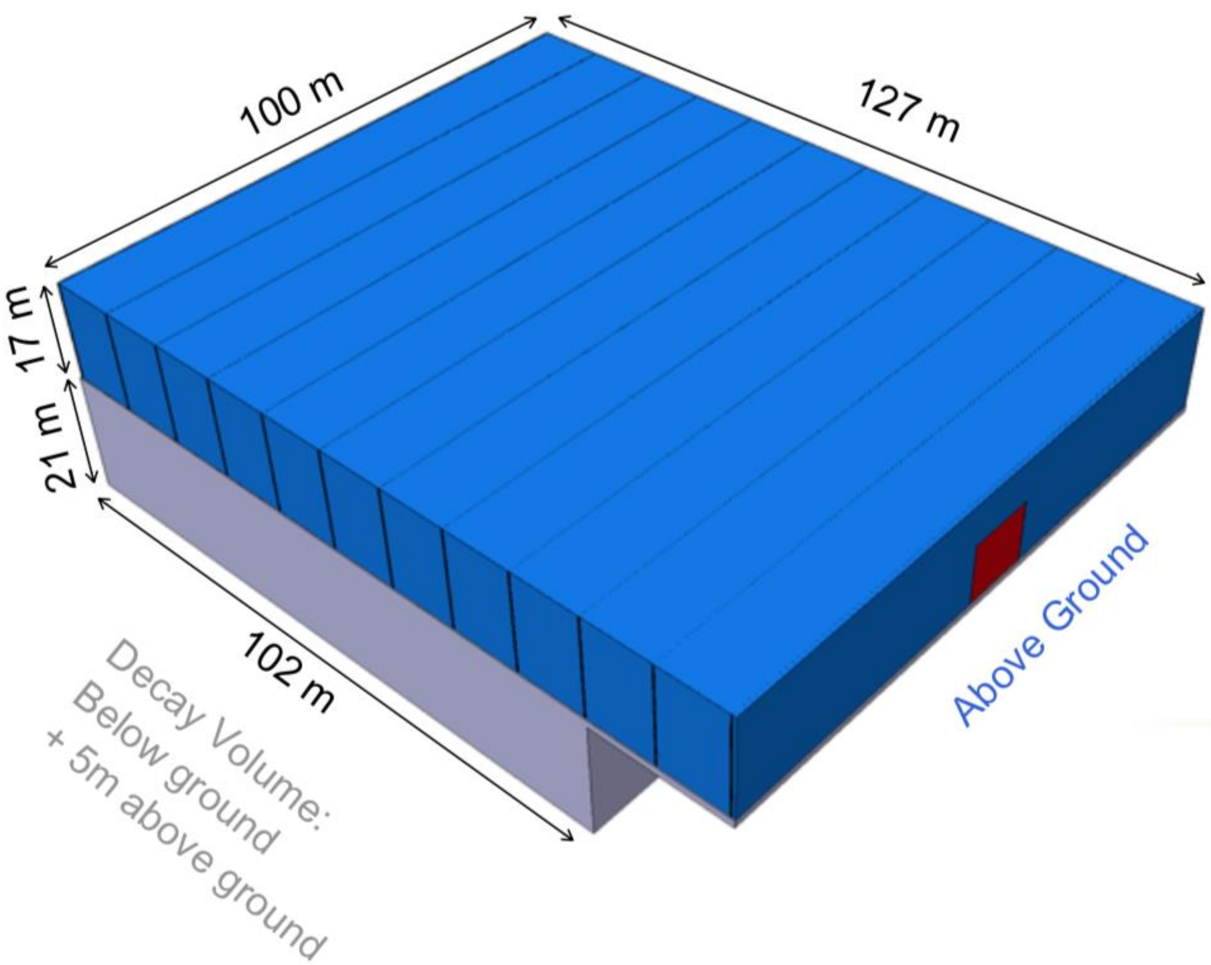
- Experimental and assembly area in an enclosed building with crane coverage
- Fits on CERN owned land and avoids <u>known</u> Roman artifacts
- NB 68 m to IP on surface and IP ≈ 80m below surface
- NB gain of 1.5 wrt detector at 100 m and IP 100 m below
- ~7.5m offset to centre of beam
- Other aspect ratios don't fit on CERN land.

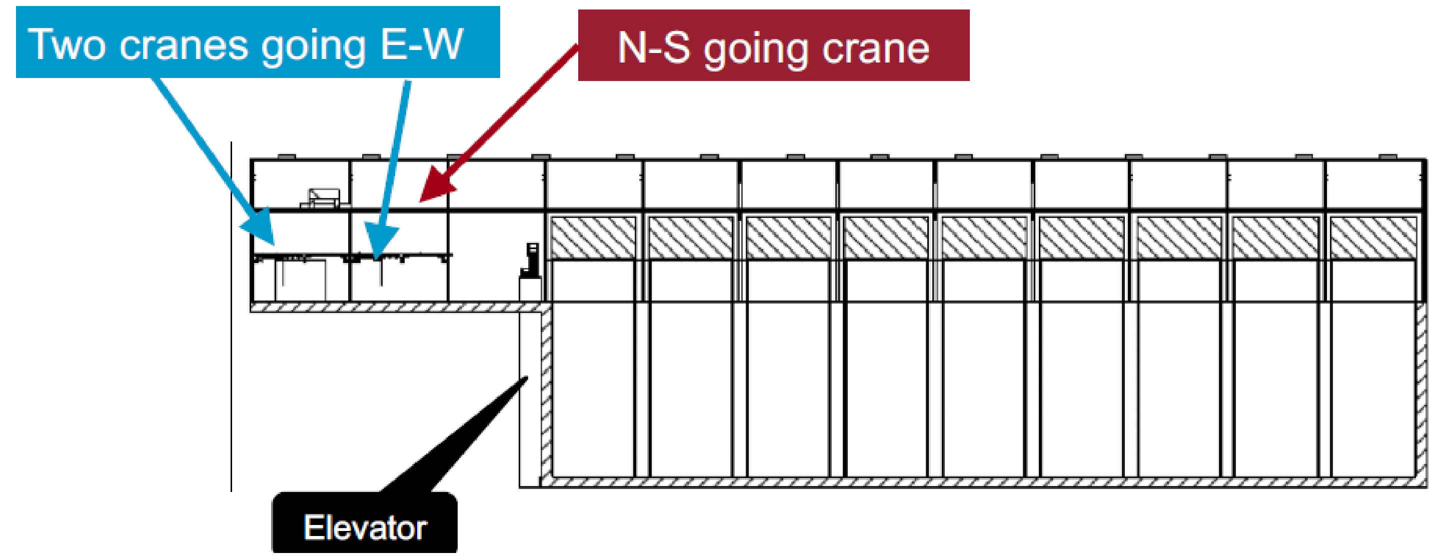
Engineering concept developed in collaboration with CERN engineers.

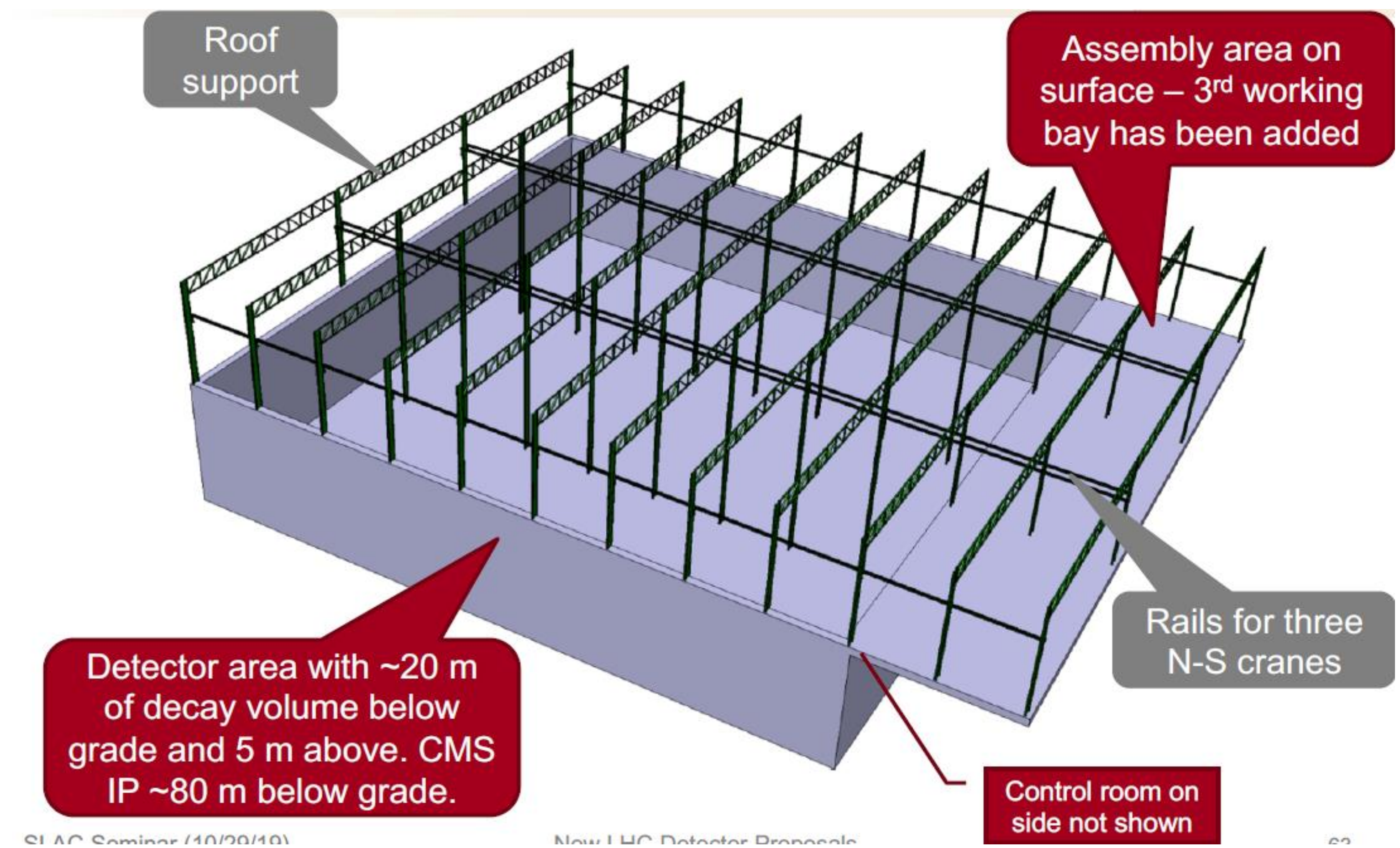
Current MATHUSLA Layout Concept near CMS



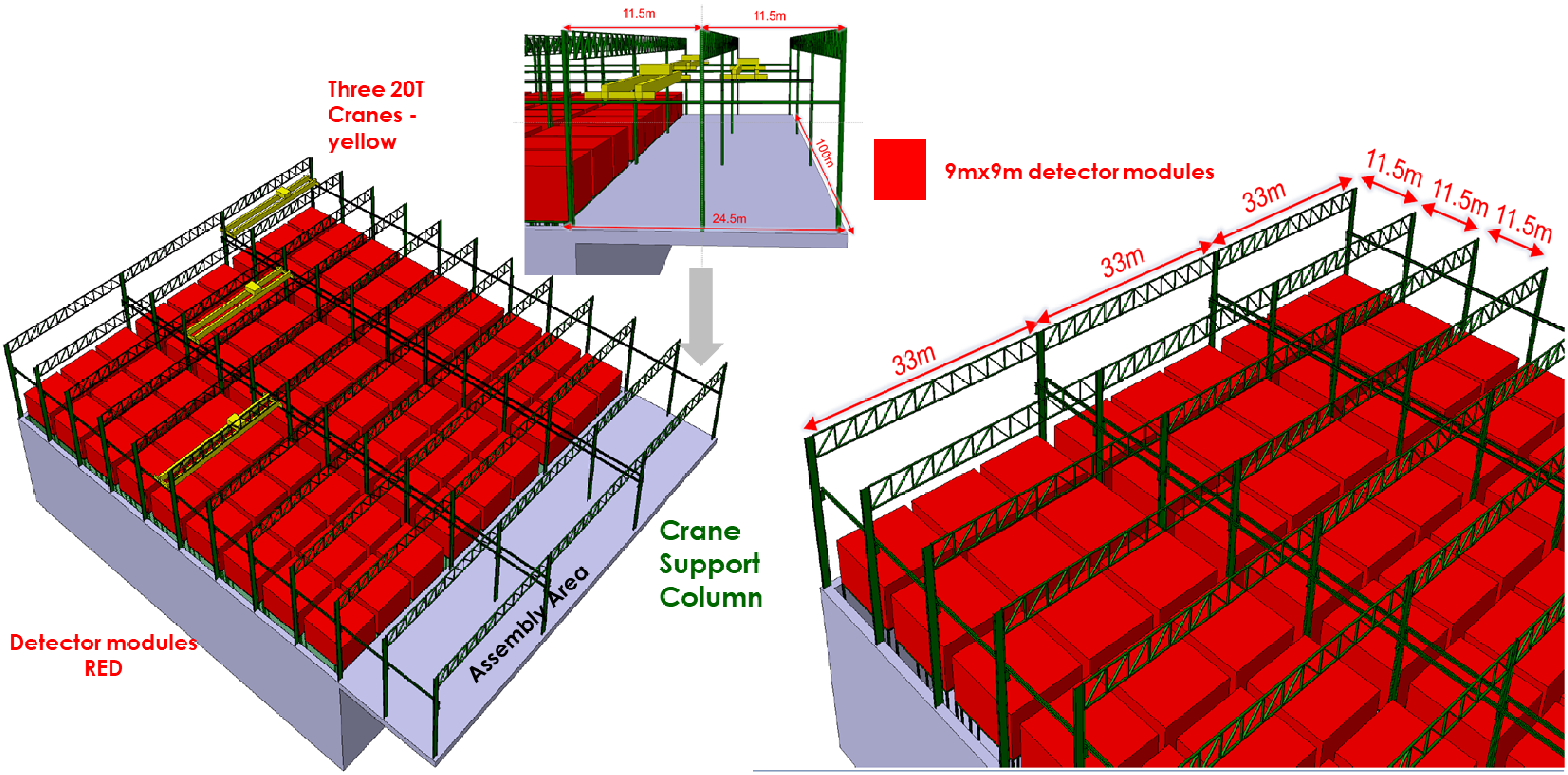
Preliminary Design



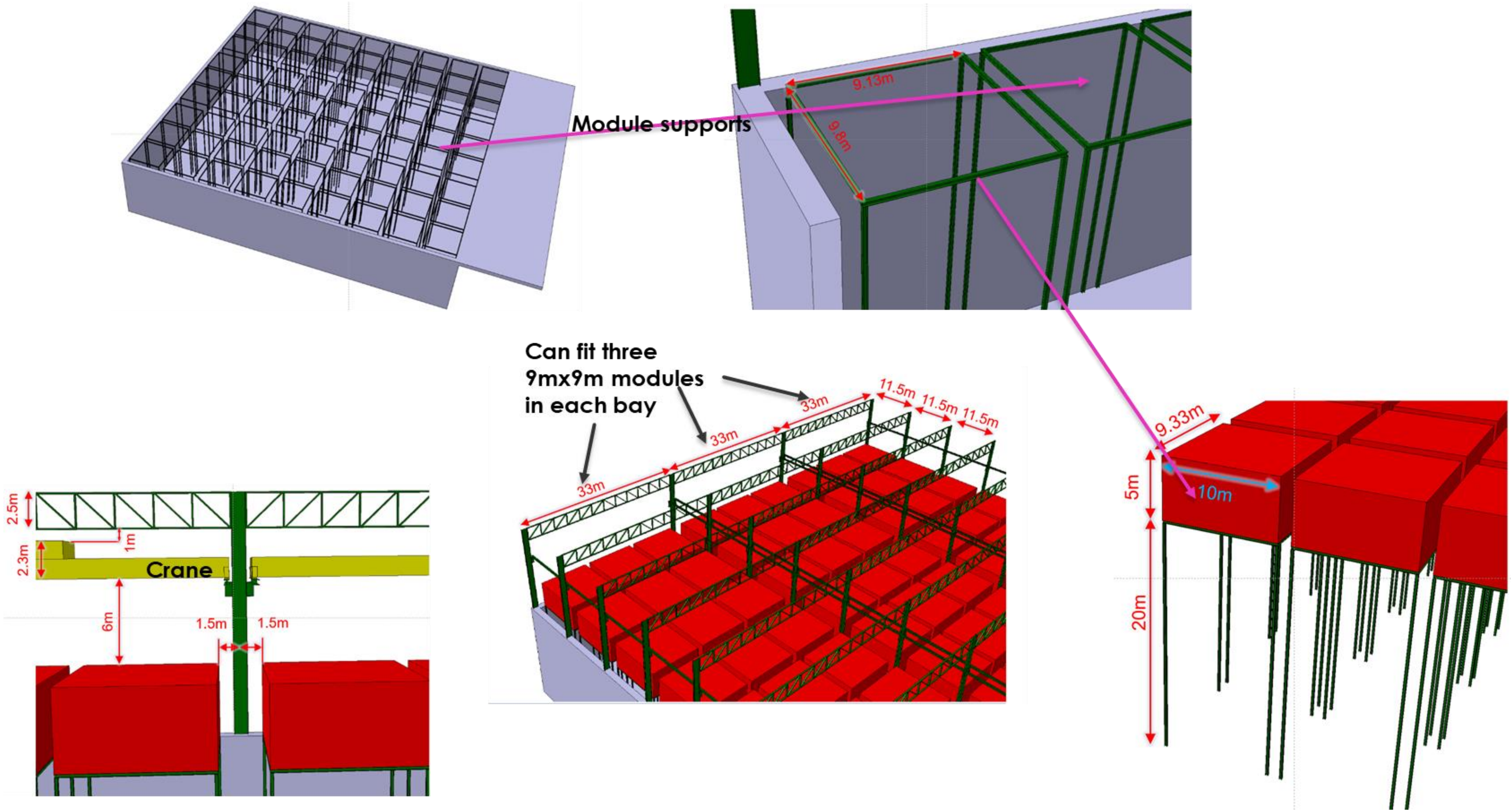




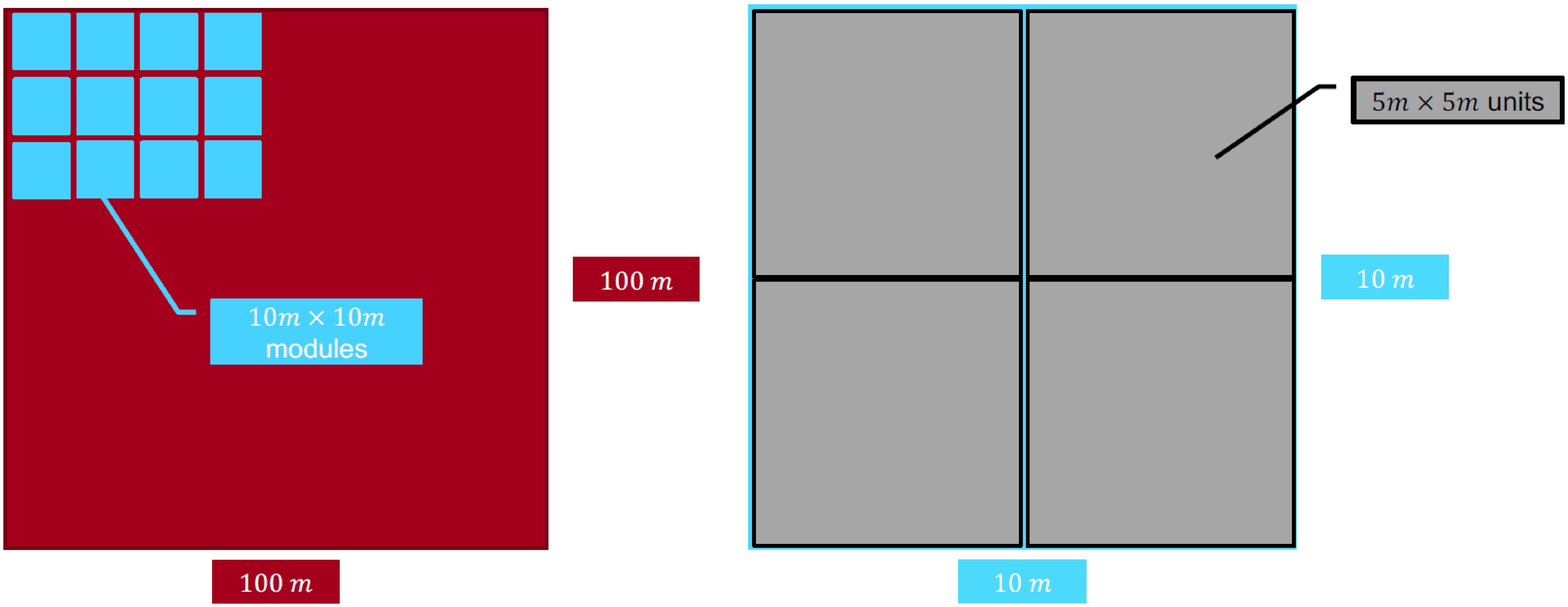
Preliminary Design



Preliminary Design

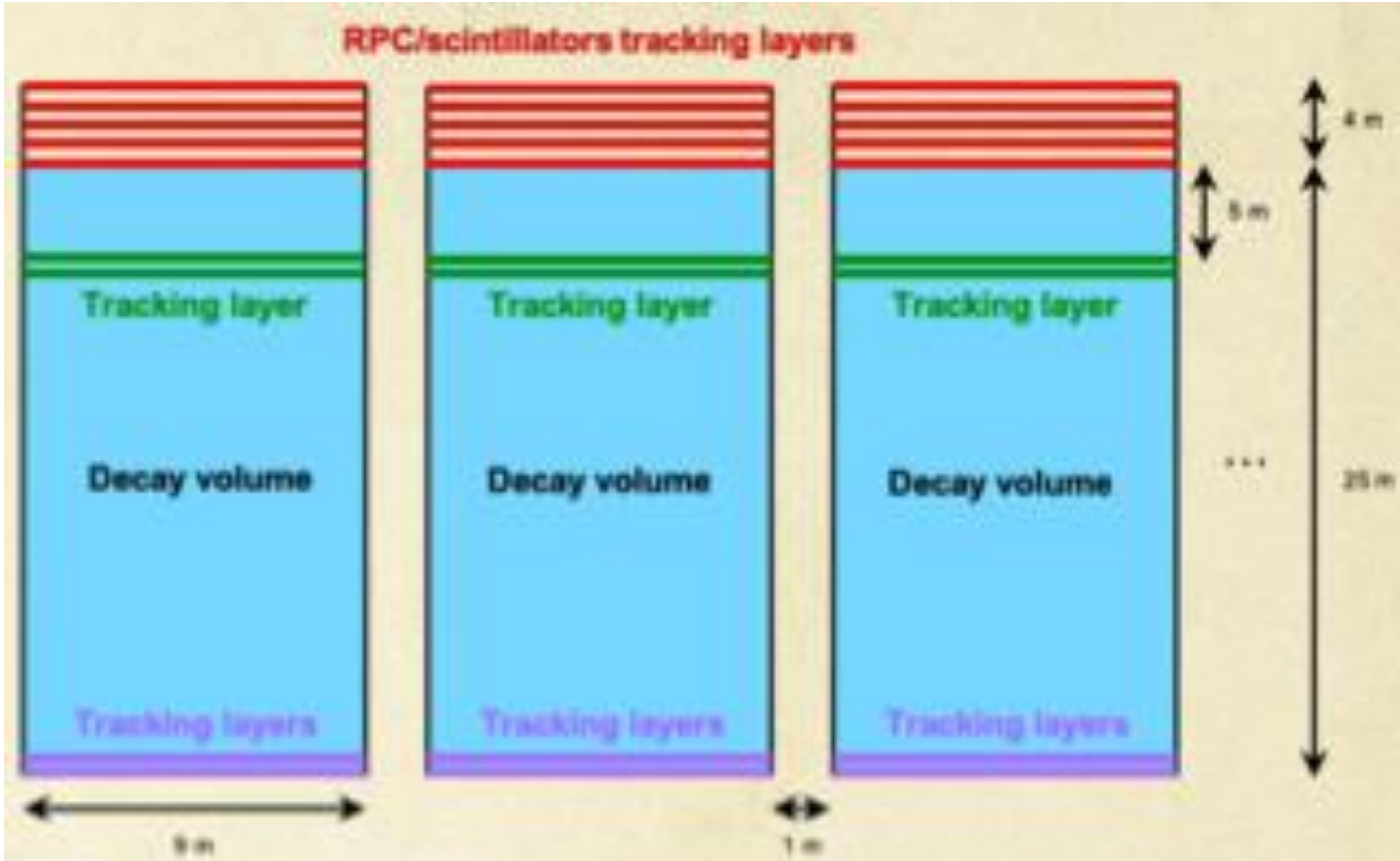


Modularity



100 Modules In $100m \times 100m$ Footprint
4 Detector Units in Each Module Plane

Modularity



Modular design to facilitate construction and staged commissioning

5 tracking layers on top + floor layer + mid-level layer

Tracker Technologies: RPCs

Resistive Plate Chambers used in many LHC detectors

THE GOOD ☺
- Proven technology with good timing and spatial resolution
- Low costs per area covered

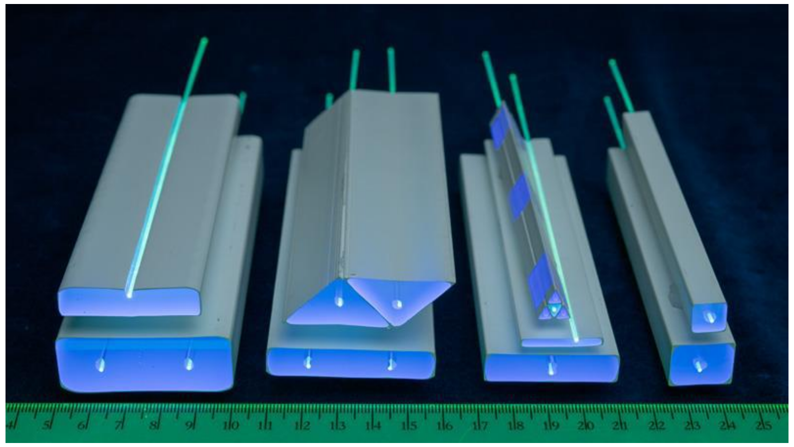
The Not-So-Good ☹
- Require high voltage (~10 KV)
- Gas mixture currently used in ATLAS & CMS has high Global Warming Potential and will not be allowed for HL-LHC

Tracker Technologies: Scintillators

Extruded scintillator bars with wavelength-shifting fibers coupled to Silicon Photo Multipliers: cost-competitive with RPCs

THE GOOD

- SiPMs operate at low-voltage (25 - 30 V)
- No gas
- Timing resolution can be competitive with RPCs
- Tested extrusion facilities in FNAL
- Used in several experiments, e.g. Belle muon trigger upgrade, Mu2e



Each scintillator bar ~ 5m x 4cm x 2cm, with readout at both ends

- Transverse resolution $\sigma \approx 1$ cm
- Time difference between two ends gives longitudinal resolution: need ≈ 90 ps per SiPM

Readout & Trigger

- Readout: 700,000 channels
  - Does not require sophisticated ASIC
  - Goal for front-end: $1/channel

- Collect all detector hits with no trigger selection
  - Separately record trigger data and move it to central trigger processor
- Want to associate trigger with CMS bunch crossings
  - MATHUSLA will have ~9 μs to form trigger and get the data to CMS Level-1 trigger
- Trigger rate $\sim$ 2 MHz
- Trigger unit: 3 x 3 modules
  - ~1 MB/s (~30 TB/year) per module

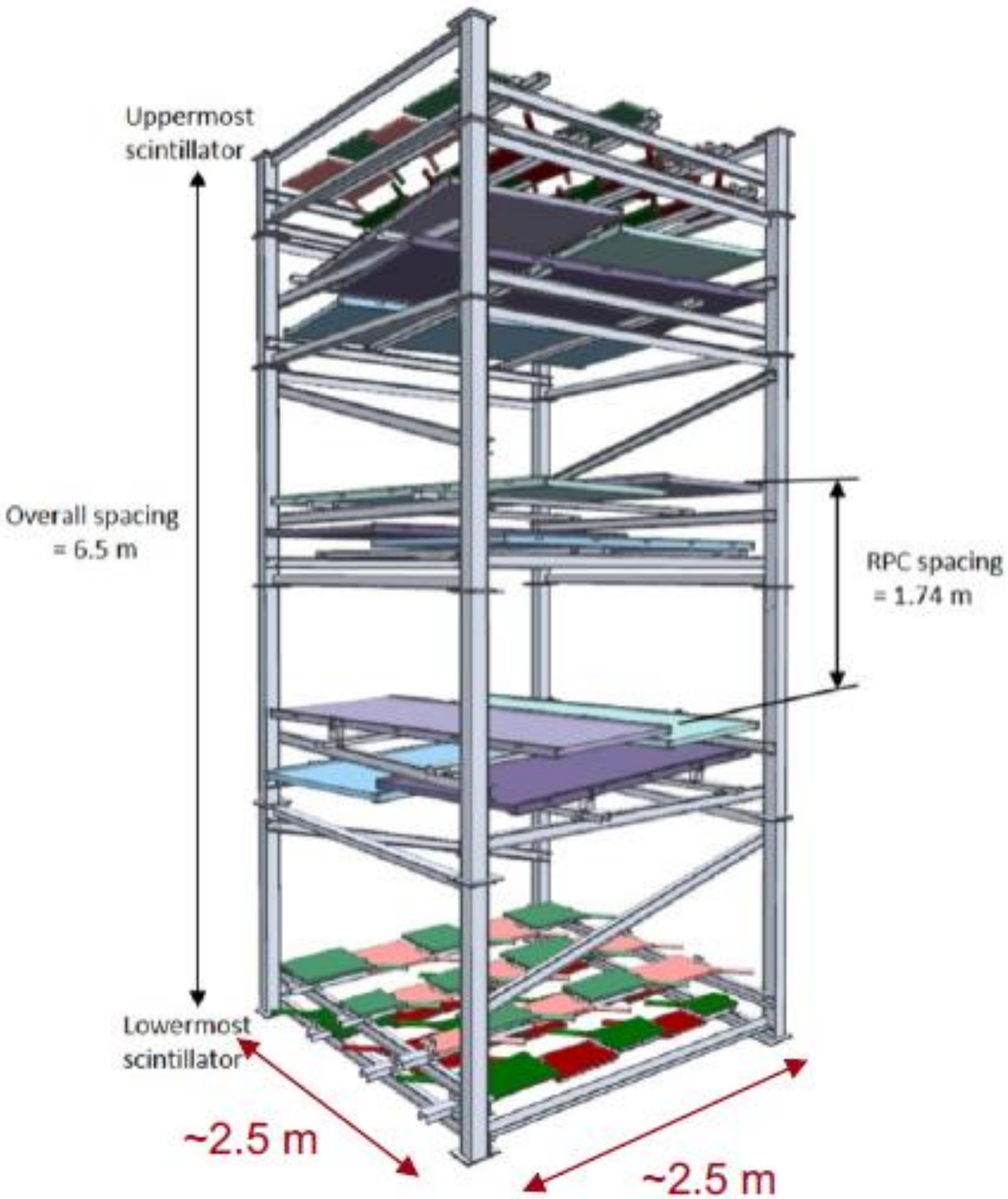
Test Stand Results

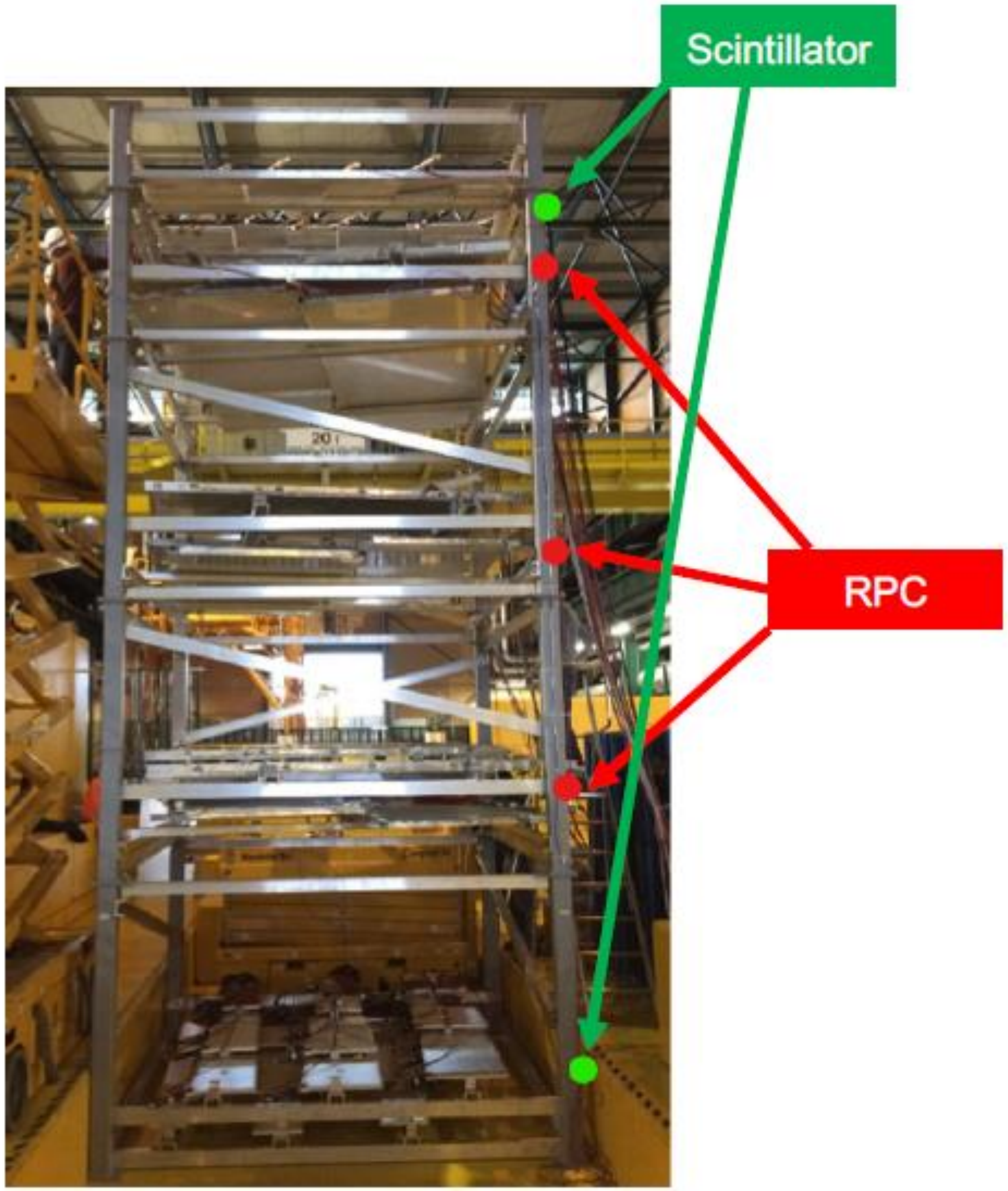
Test Stand

- To understand LHC collision backgrounds (upward-going muons), built a test stand
- ~2.5 x 2.5 x 6 m^3 , 3 layers of RPCs plus top and bottom scintillator layers
  - RPCs from Rinaldo Santonico Rome -- spares from ARGO experiment
  - Scintillators recycled from D0 forward muon trigger wall
- RPCs and scintillators had timing resolution σ ~ 2.5 ns
- Top-to-bottom $\Delta t \sim$ 20 ns or 8σ
- Two triggers running simultaneously:
  - Downward trigger for cosmic rays
  - Upward trigger for tracks from IP

Took data above the ATLAS IP in 2018!

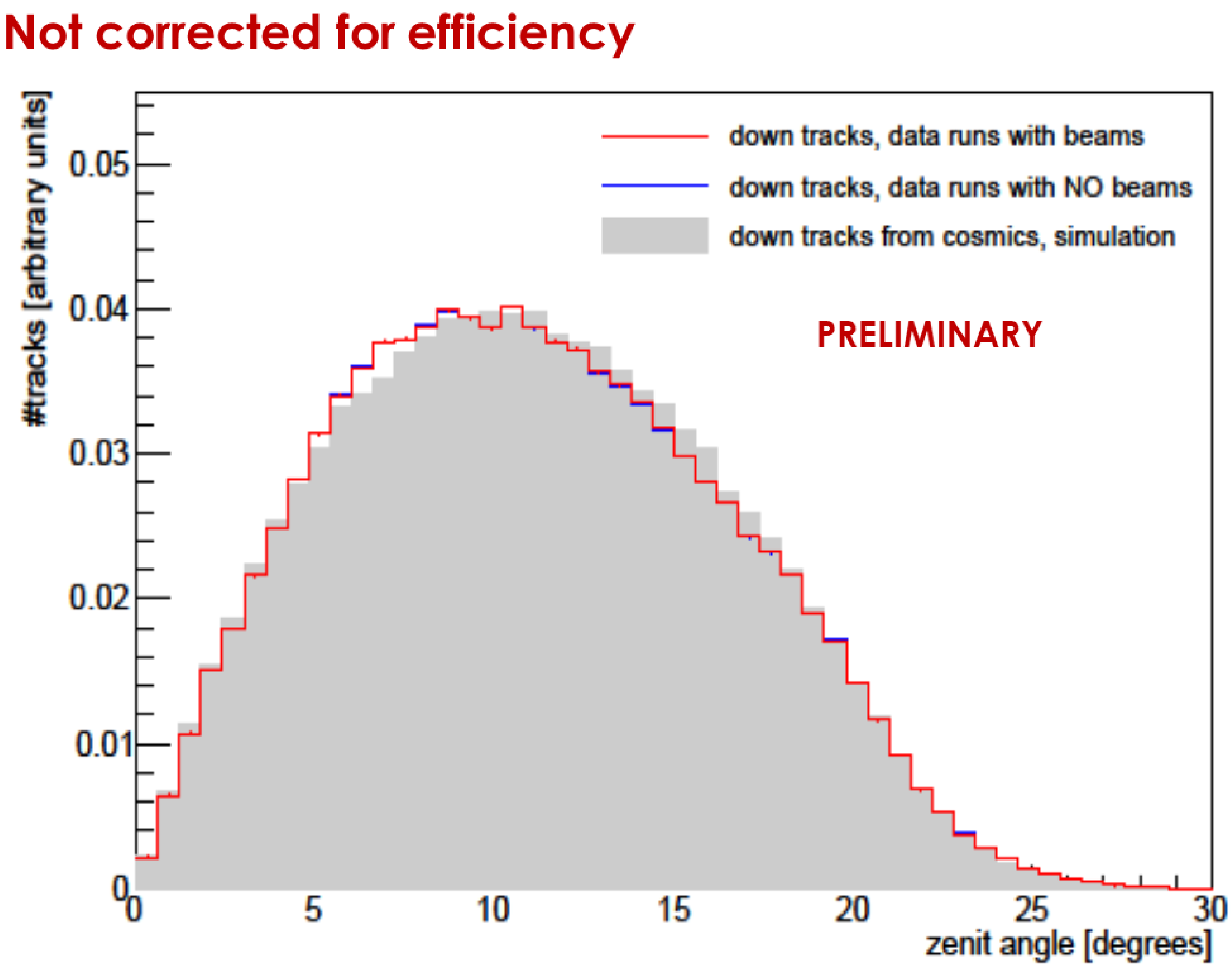
Test Stand


Uppermost scintillator
Overall spacing = 6.5 m
RPC spacing = 1.74 m
Lowermost scintillator
~2.5 m
~2.5 m


Scintillator
RPC

Test Stand: Results

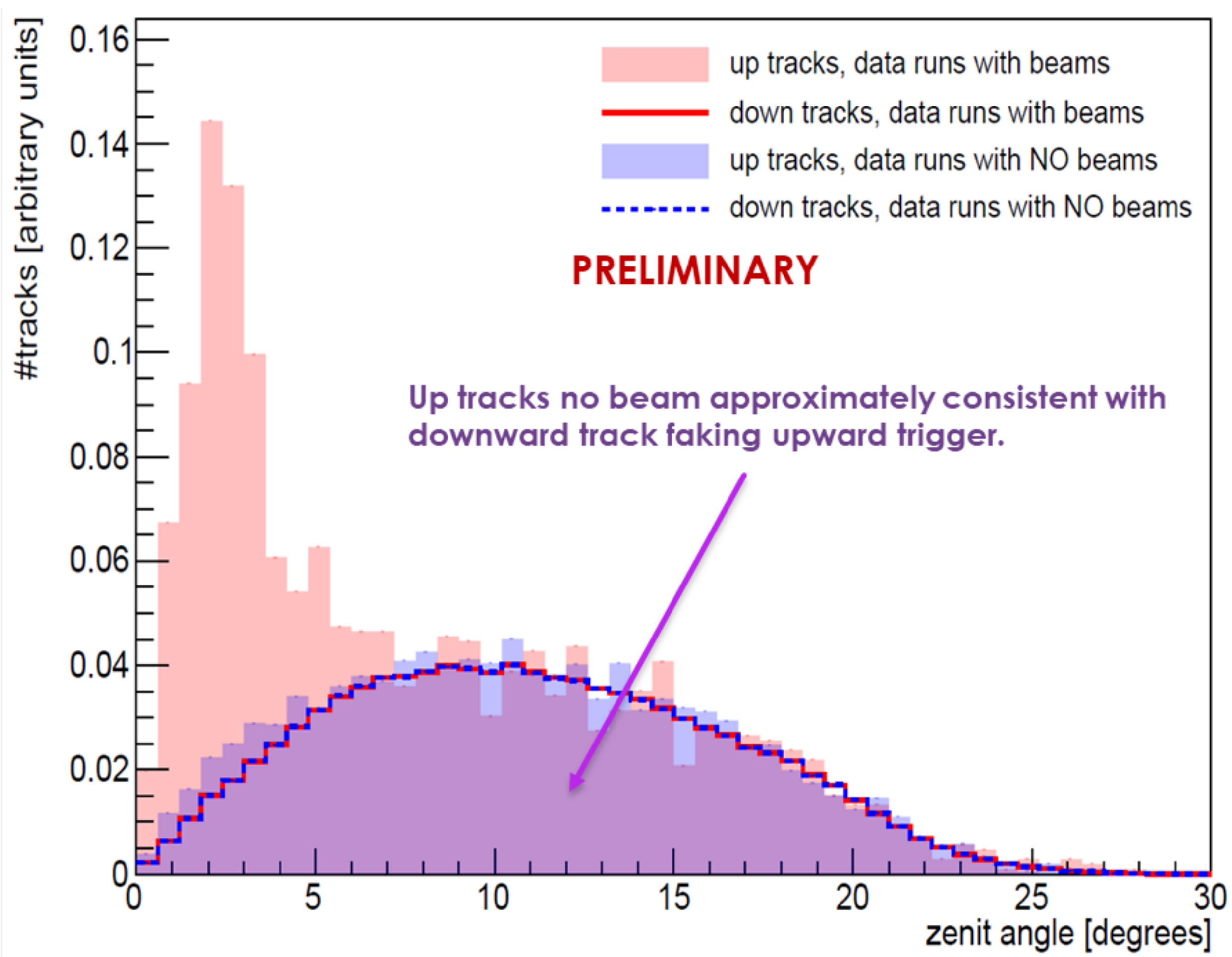
Downward-going tracks consistent with cosmic-ray simulations

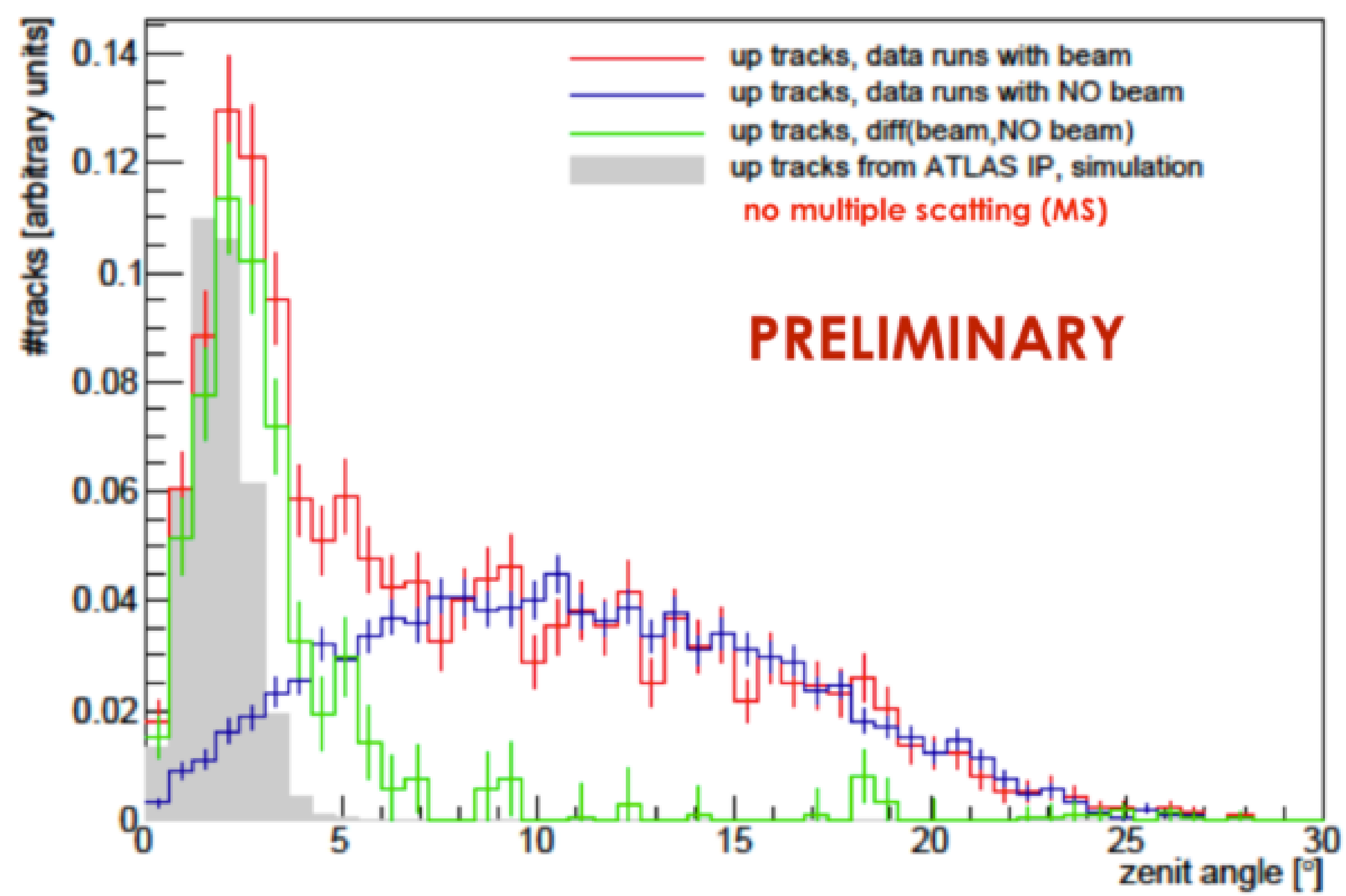


Test Stand: Results

Accumulation for zenith angle $< \sim 4^\circ$ consistent with upward-going tracks from IP when collisions occur

Not corrected for efficiency





MATHUSLA

Next Steps

Tying up preliminary efforts

Simulation:

- muon and neutrino studies should wrap up soon
- cosmic ray details need more work

Test Stand Data Analysis:

- data taking & analysis framework completed
- analysis almost completed
- measurements of up & down tracks, w/ & w/o beam provide vital input for detector design & MC

Engineering:

- CERN engineers preparing cost estimate for structure

Cosmic Ray Physics Case:

- simulation and initial studies planned out, but very short on person-power. Help welcome!

R&D Plan

For MATHUSLA to go online ~2026, R&D needs to be completed over next few years:

- Finalize detector technology choice
- Design frontend electronics
- Develop trigger (simple concept, nontrivial implementation)
- Overall detector design (module parameters, tracking chamber support structure, installation procedures…)
- COST OPTIMIZATION of detector components (scintillator, WLS, SiPMs)
- Detailed cost estimate

R&D Plan

Over the next 2-3 years, need to

1. **produce a prototype MATHUSLA module**
2. **produce a Technical Design Report.**

Currently applying for O($ few million) over O(few) years to fund the R&D program.

Government grants and private foundations in USA, Europe, Israel, Canada including NFRF Transformation Stream

A few funding opportunities are for more money, which could go towards building the full detector.

A call to Canadian PI’s!

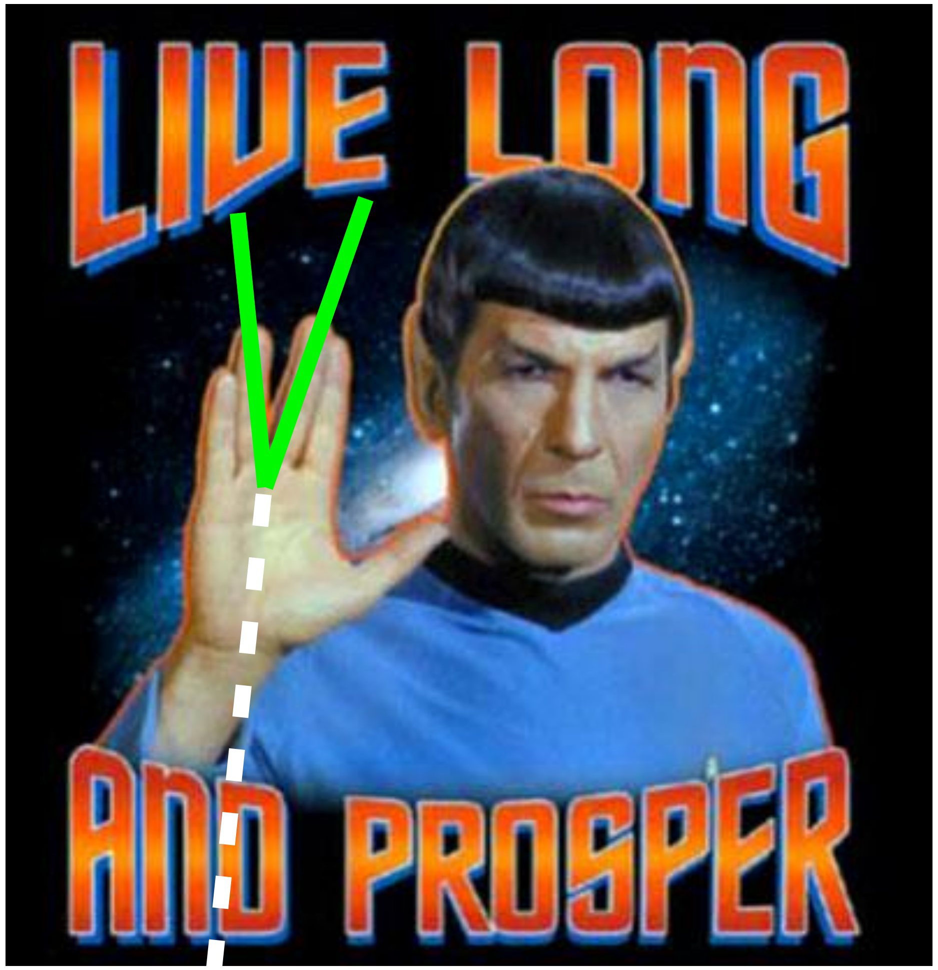
We are planning to prepare a MATHUSLA application for the Transformation fund. Current Canadian PIs:

- Miriam Diamond (UToronto & MI, hep-ex)
- David Curtin (UToronto, hep-th)
- Steven Robertson (McGill, hep-ex)
- Ue-Li Pen (Utoronto & CITA, astro-ph)

We are looking for other PI’s to join, with a commitment of contributing to MATHUSLA if serious $ gets awarded!

This is a chance for Canada to assume a world-leading position in exploring the lifetime frontier!

Conclusions



Conclusions

Exploration of the Lifetime Frontier has to be central to the future of the LHC program to discover new physics.

MATHUSLA is the only way to probe deep into the LLP lifetime parameter space a wide range of masses.

Unique opportunity for Canada to assume leadership role at the lifetime frontier.

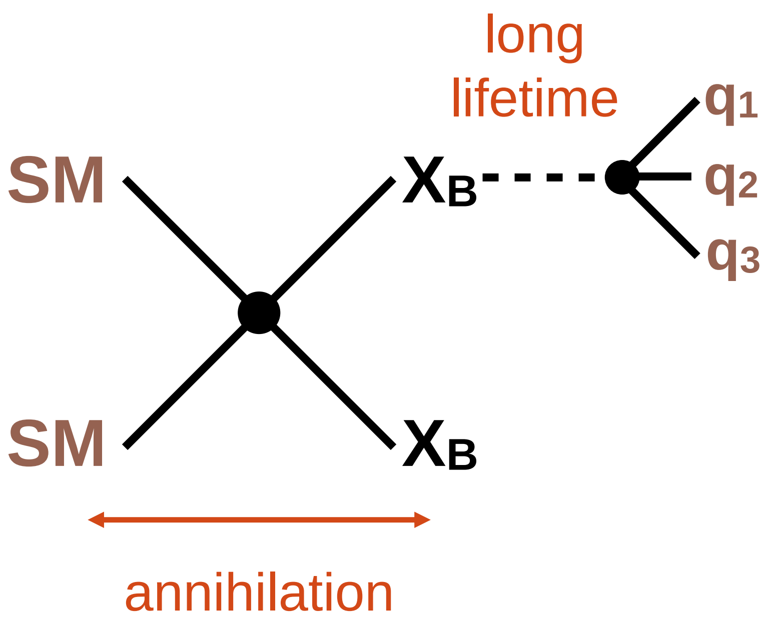
Need experimentalist PIs to join the NFRF Transformation proposal ASAP!

BACKUP

Top-Down Motivation: Examples

WIMP Baryogenesis:

Cui, Sundrum 1212.2973



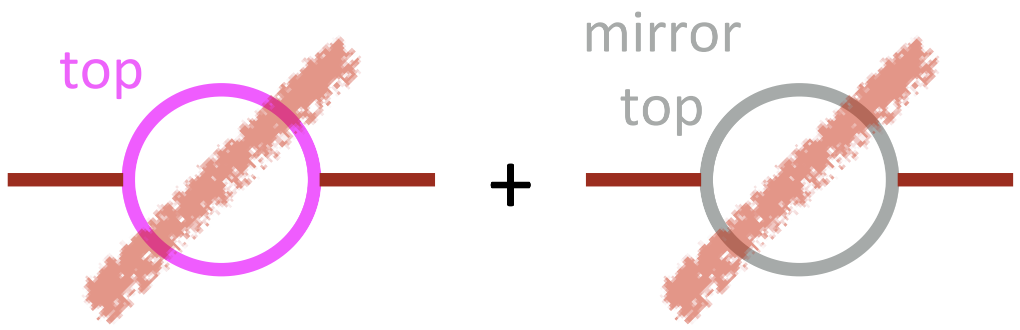
decays produce baryon asymmetry

Meta-stable WIMP-like parent can be made at colliders with observable decay length.

Neutral Naturalness:

hep-ph/0506256 Chacko, Goh, Harnik
hep-ph/0609152 Burdman, Chacko, Goh, Harnik

Discrete Symmetry relates SM to mirror copy with its own set of gauge forces

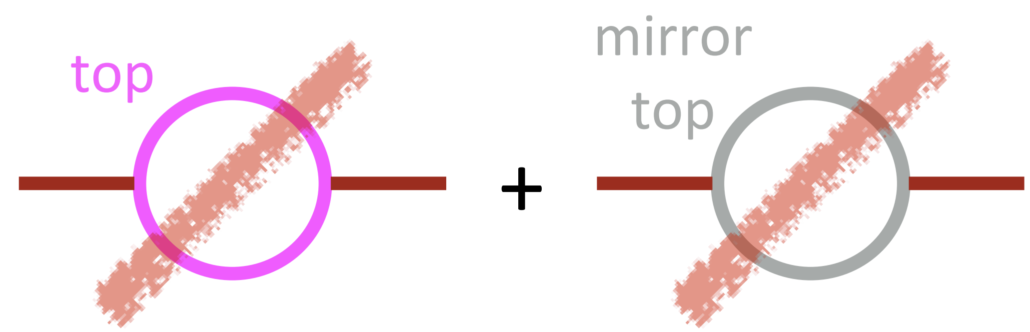


Neutral top partners stabilize Higgs mass

Hidden valley LLP signatures!

Asymmetrically Reheated Mirror Twin Higgs

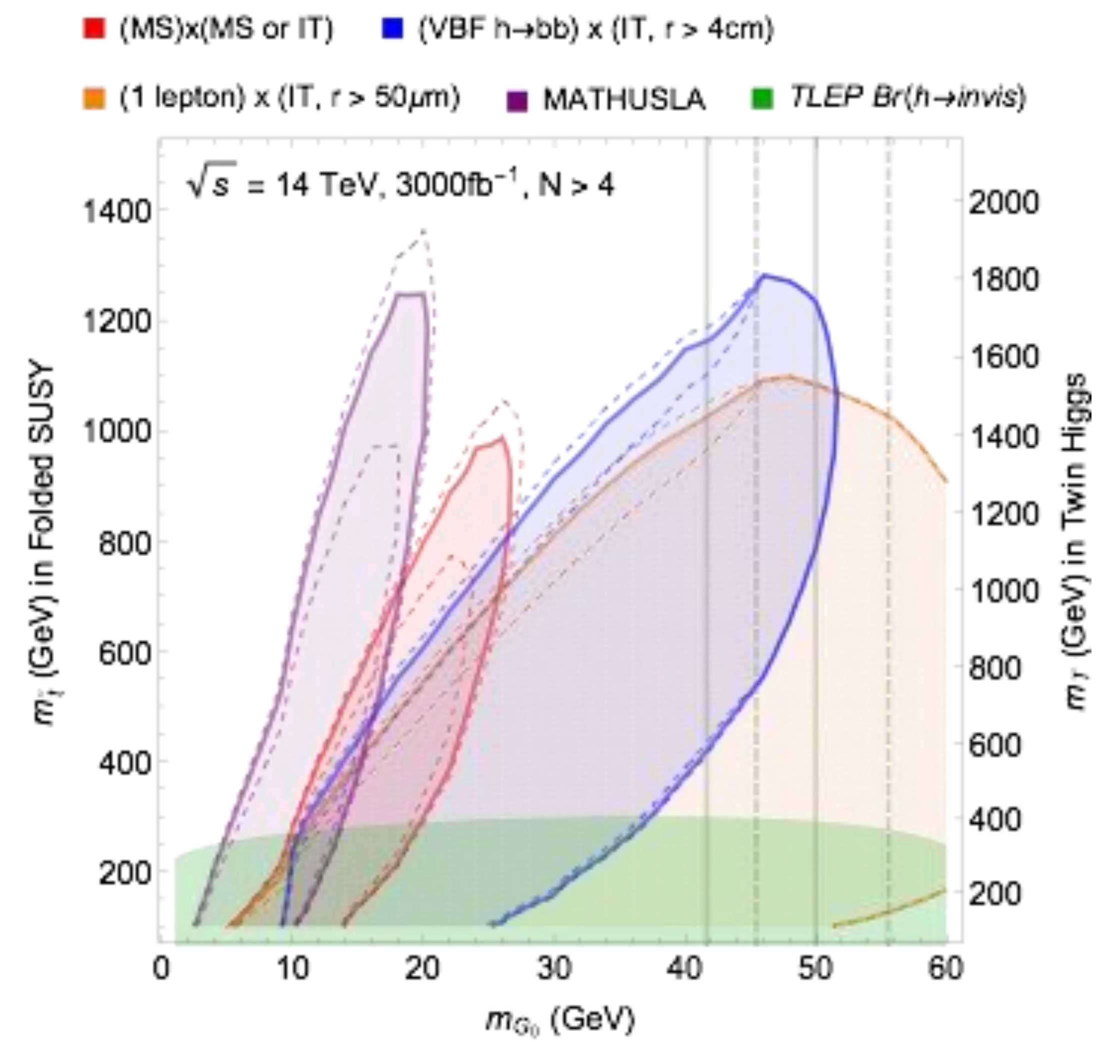
In MTH model, Z2 symmetry predicts **perfect SM copy** to protect the Higgs mass.



Cosmologically unacceptable: mirror Y, ν → ΔN_{eff} ~ 5

Model building solution:
hard Z2 breaking removes light degrees of freedom.

This makes some or all hidden sector dof unstable.
→ LLPs @ LHC via Higgs Portal



Craig, Katz, Strassler, Sundrum 1501.05310
DC, Verhaaren 1506.06141, and much more

Asymmetrically Reheated Mirror Twin Higgs

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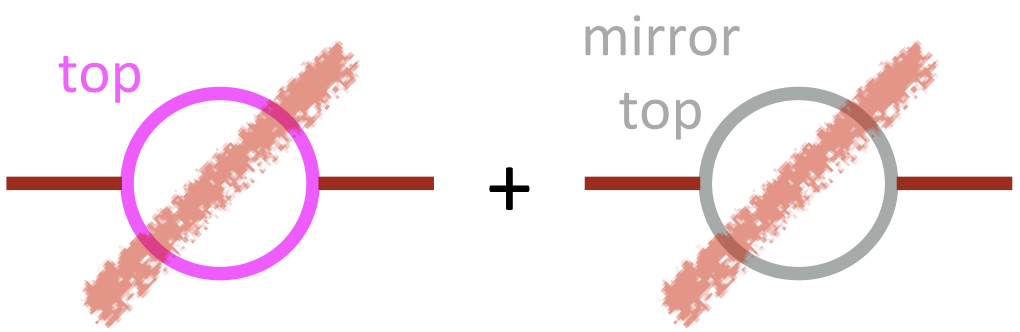
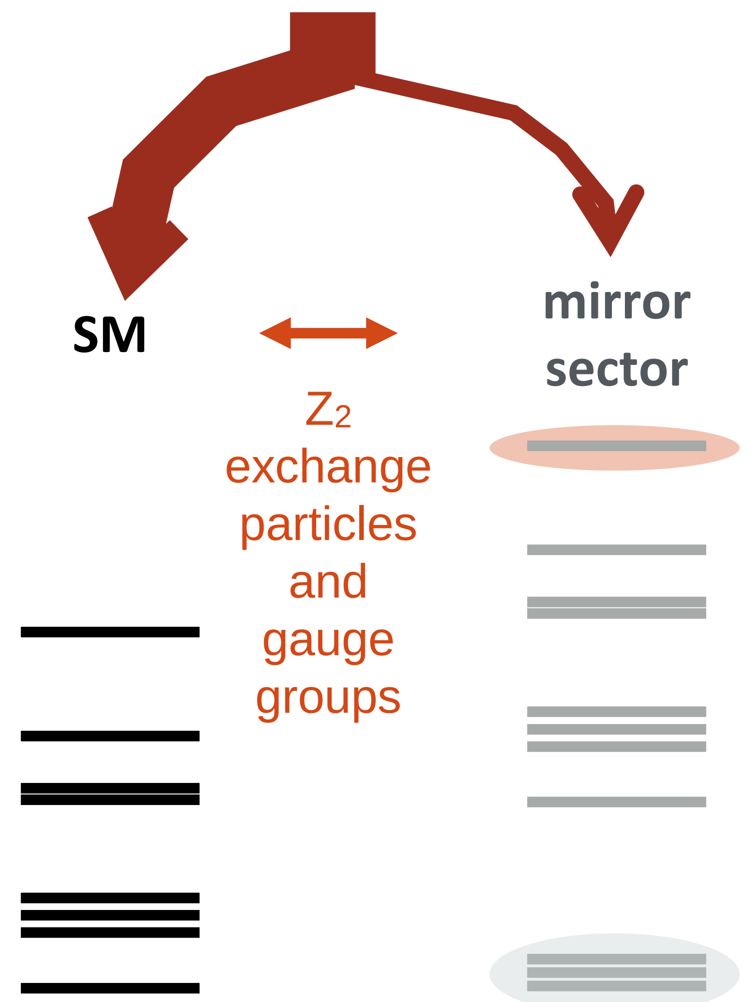


Cosmologically unacceptable: mirror Y, ν → ΔN_{eff} ~ 5

Cosmological solution:
make hidden sector colder than visible sector by dumping entropy into the SM particles.

Easy in natural MTH extensions, e.g. adding RH neutrinos



Chacko, Craig, Fox, Harnik 1611.07975
Craig, Koren, Trott 1611.07977

Asymmetric MTH Cosmology

- mirror-BBN: predicts ~ 75% mirror Helium mass fraction in mirror sector (compare to 25% SM).
- Mirror-baryo-acoustic oscillations modify matter power spectrum, shows up in CMB & LSS:
  Current Ly-α constrains r_{all} < ~ 10%
  CMB Stage IV will probe r_{all} ~ 1%
- ΔN_{eff} ~ 0.few
  same free-streaming vs scattering fraction as SM

- Mirror baryons part of our galaxy, but cool slower than SM baryons. **Feedback is complicated**.
  Distribution may be disk-like or halo-like.

1803.03263, 1910.XXXX Chacko, DC, Geller, Tsai

Signal Acceptance

Geometrical acceptance for LLP decays in the *long lifetime limit* studied for a variety of LLP production modes & masses.

Results:

- Engineering benchmark design is nearly optimal.
- Engineering benchmark design has 80% the LLP acceptance of 200m x 200m original physics benchmark. (Likely much better for shorter lifetimes.)
- Original sensitivity estimates apply to realistic detector geometry with 1/4 the area of original benchmark.

Work by Imran Alkhatib

Simulating MATHUSLA events

GEANT4 detector model of test stand and toy full detector.

LLP signal simulation is “easy”. Verified that modular design can have good displaced vertex reconstruction efficiencies.

Neutrino background:
analytical calculation of scatterings in detector from atmospheric and LHC neutrinos predict O(10) events per year, >99% rejection with track-speed and geometrical cuts.
Detailed study with GENIE neutrino event generator in progress.

Muons from the LHC:

upwards rate is O(1-10 Hz) with tiny fraction of inelastic scatters that can be vetoed by floor detector.

Full study of LHC muon production (W/Z, tt, bb) and propagation in rock nearly completed.

Cosmic Rays:

- Rate of ~2 MHz over full 100m detector.
- Can be rejected with timing and tight requirements on displaced vertex reconstruction.
- Detailed study is challenging due to large rate.

Detailed MC study with CORSIKA in progress.

Cosmic Ray FastSim is in beginning stages of development.

Canadian NFRF Transformation Stream

The Transformation stream is designed to support large-scale, Canadian-led **interdisciplinary** research projects that address a major challenge with the potential to realize real and lasting change (**high reward**). The challenge may be fundamental, leading to a scientific breakthrough, or applied, with a social, economic, environmental or health impact. Projects are expected to be world-leading, drawing on **global** research expertise, where relevant.

Value and duration of support

- The planned budget for the first competition is $144m over 6 years
- Up to 6 awards of $24m ($4m per year), including indirect costs, may be awarded

Proposed Competition Stages and Review Process

The anticipated program launch is October 2019. There are 3 proposed stages for the Transformation competition: Notice of Intent to Apply (NOI), Letter of Intent (LOI), and Full Application. No firm timelines for any of these stages has been announced.

Perfect for MATHUSLA R&D!

(And even part of full detector?)