Explore the Lifetime Frontier with MATHUSLA

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15^{th} Topical Seminar on
Innovative Particle and Radiation Detector

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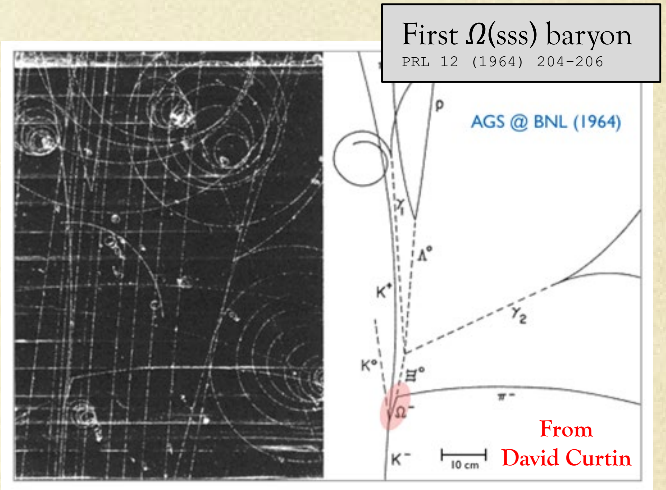
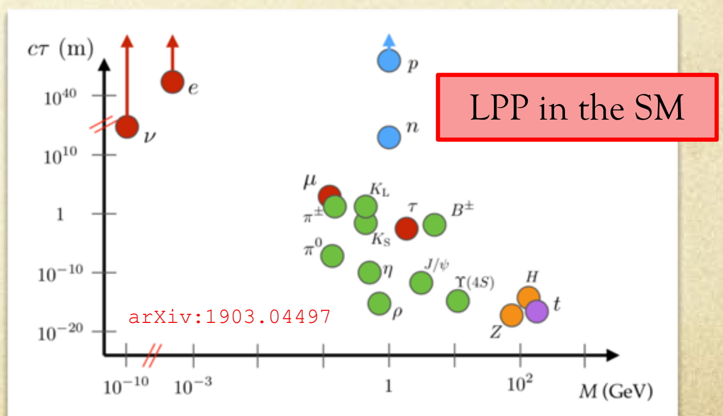
Siena

MATHUSLA

Unconventional Searches @ LHC

- Current searches at 13 TeV show an **impressive agreement with the SM expectations**
- New physics should be present at
  - ✓ High mass → no hints so far
  - ✓ **Small coupling → not fully explored**
- Many extensions of the SM include particles that
  - ✓ Are **neutral**, **weakly coupled**, and **long-lived** that can decay to different final states (hadrons, leptons, photons, etc)
    - Several mechanism behind long-lived particles (LLPs): approximate symmetry, heavy mediators, etc…
  - ✓ Are **charged** meta-stable/stable
    - Multi-charged particles predicted by Technibaryons, almost-commutative leptons, doubly charged Higgs

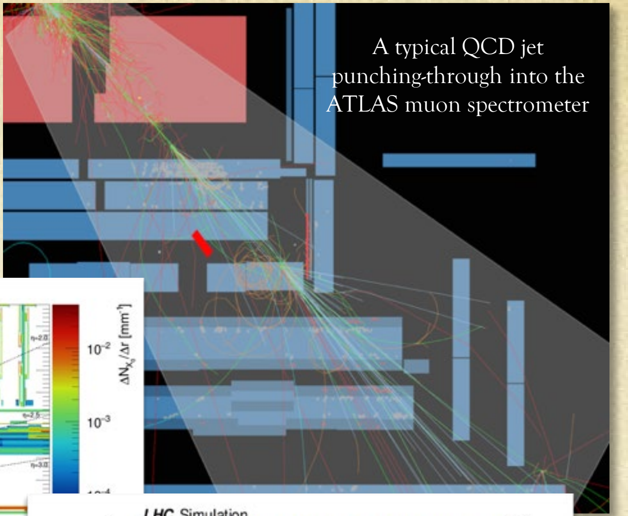


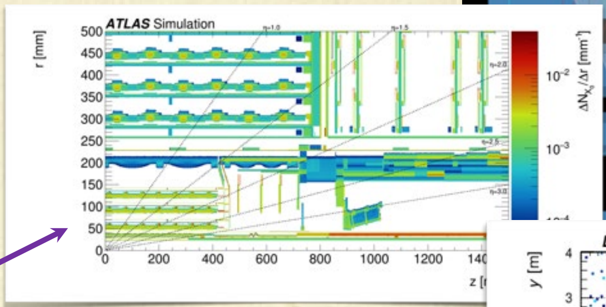


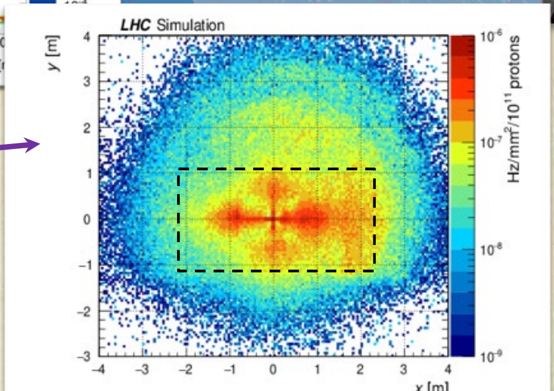
Need to **exploit the full LHC potential** and **reduce to negligible the possibility of losing new physics at the LHC!**

Unconventional Challenges

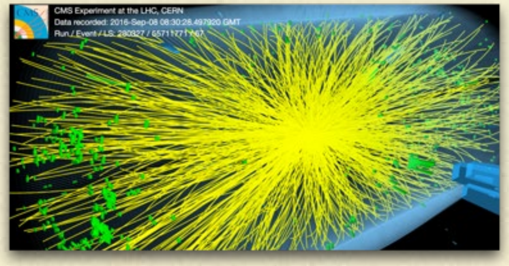
- BSM particles can produce **final states** that might be **very difficult to study** due to
  - ✓ Complicated backgrounds
    - Instrumental backgrounds
    - Large QCD jet production
    - Pile-up problems
    - Material interaction
    - Beam induced background (BIB)
    - Cosmic background
  - ✓ **Constraints in triggering**

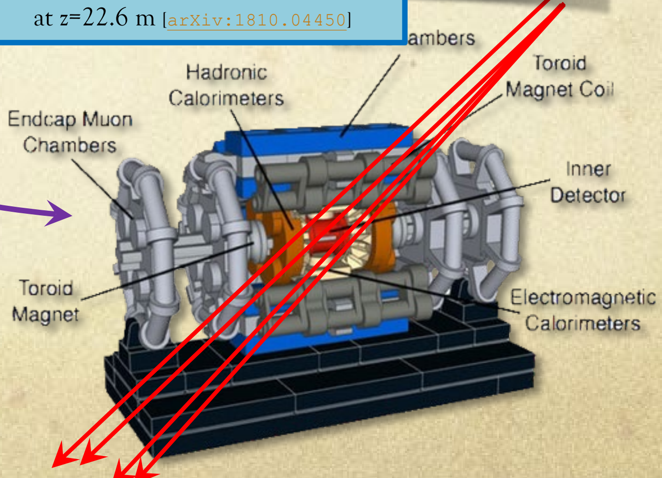






muons (E>20 GeV) entering ATLAS at z=22.6 m [arXiv:1810.04450]





- At HL-LHC → best possible sensitivity from ATLAS displaced vertex search in the muon spectrometer (**shielded and able to trigger on LLP at L1**), but searches (arXiv:1605.02742) suggest that various backgrounds (punch through, cosmics, etc) of the order 100 fb

MATHUSLA

(MAssive Timing Hodoscope for Ultra Stable neutraL pArticles)

MATHUSLA - Layout

- arXiv 1606.06298
- arXiv 1806.07396
- CERN-LHCC-2018-025

➢ Dedicated detector sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis (BBN) limit (10^7 – 10^8 m) for the HL-LHC

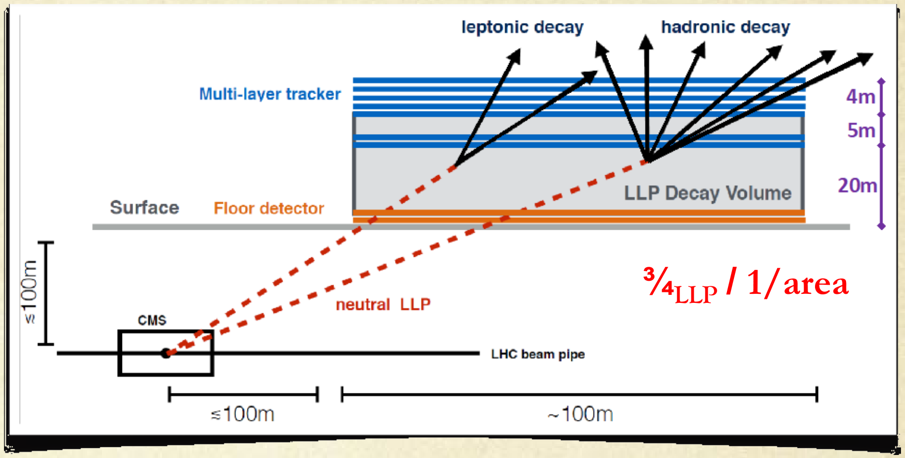
➢ Proposed a large area surface detector located above CMS

✓ Need robust tracking

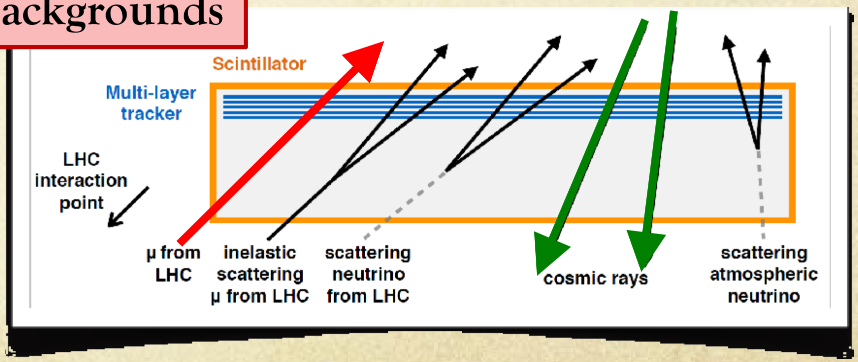
✓ Need excellent background rejection

✓ Need a floor detectors to reject interactions occurring near the surface

✓ Both RPCs and extruded scintillators coupled to SiPMs are considered (good time/space resolution



Backgrounds



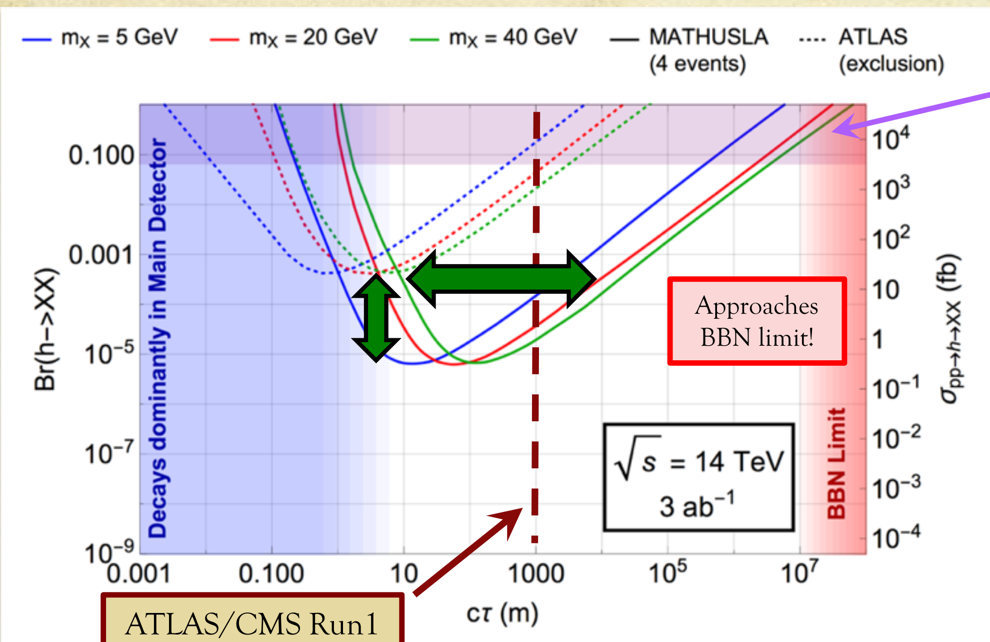
❖ Cosmic muon rate of about **1.7 MHz** ($100m^2$) and **10 Hz** LHC muon rejected with timing

❖ LHC neutrinos: expected 0.1 events from high-E neutrinos (W, Z, top, b), ~1 events from low-E neutrinos (π/K) over the entire HL-LHC run

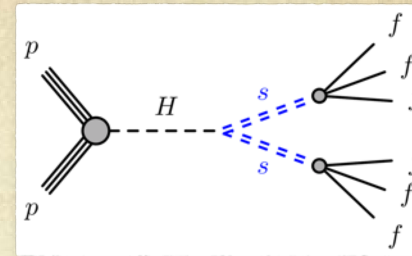
❖ Upward atmospheric neutrinos that interact in the decay volume (**70 events per year above 300 MeV**) “decaying” to low momentum proton

MATHUSLA – Physics Reach

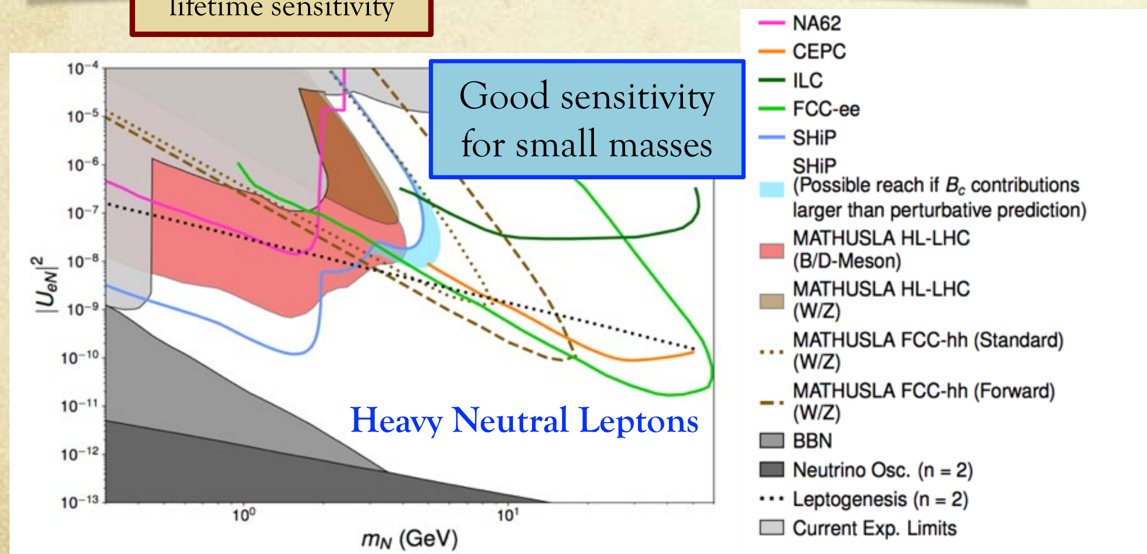
arXiv:1806.07396 [hep-ph]

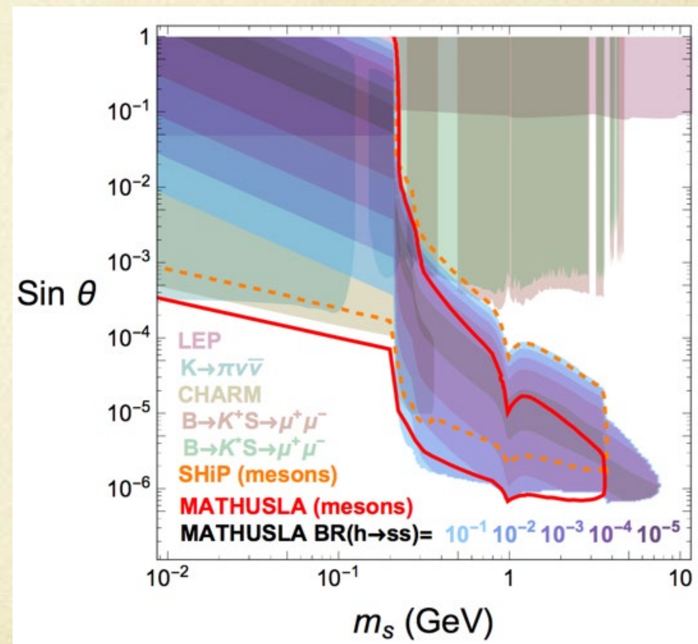


h ! inv
HL-LH limit



- **Can** probe LLPs at **GeV to TeV**
- **Good sensitivity** for mass scale **above ~ 5 GeV**, and for **lifetime >> 100** m even at low masses

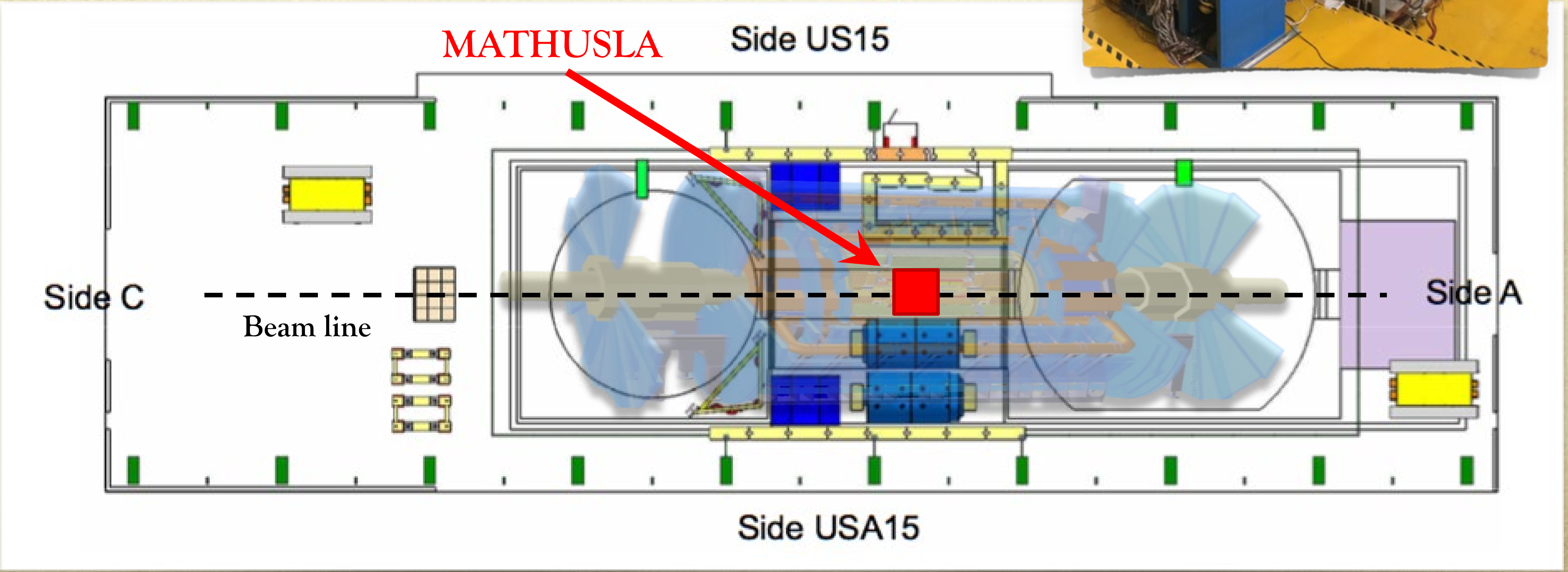




Higher sensitivity for long lifetimes

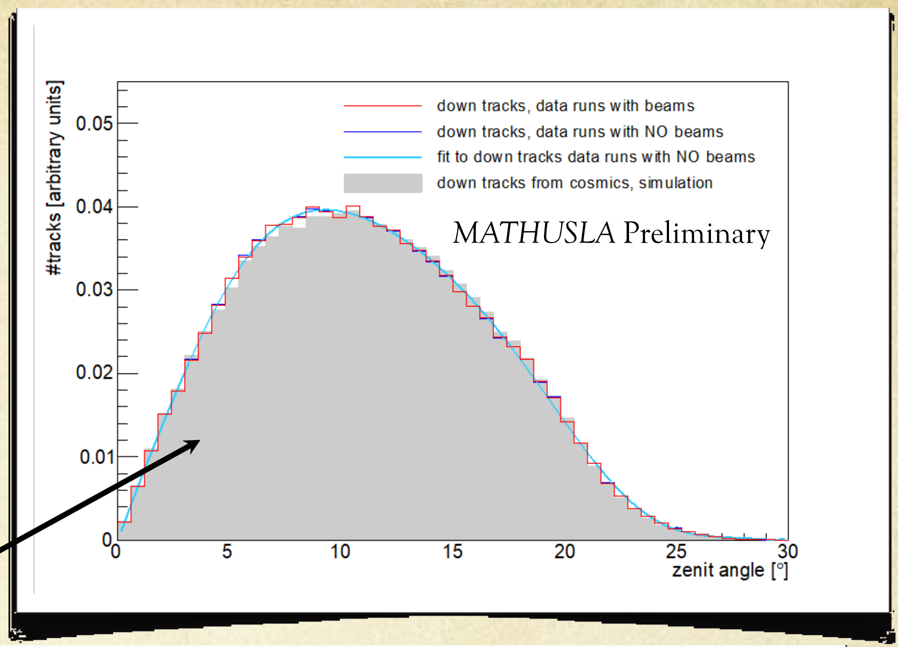
Test Stand @ P1

- Cosmic background (~) well understood
- Need to quantify the **background from ATLAS**
- Test stand installed in the (Buffer Zone) on the surface area above ATLAS (exactly above IP) in November 2017 (during ATLAS operations this space is empty)
  - ✓ **Perform measurements with beam on and off during 2018**

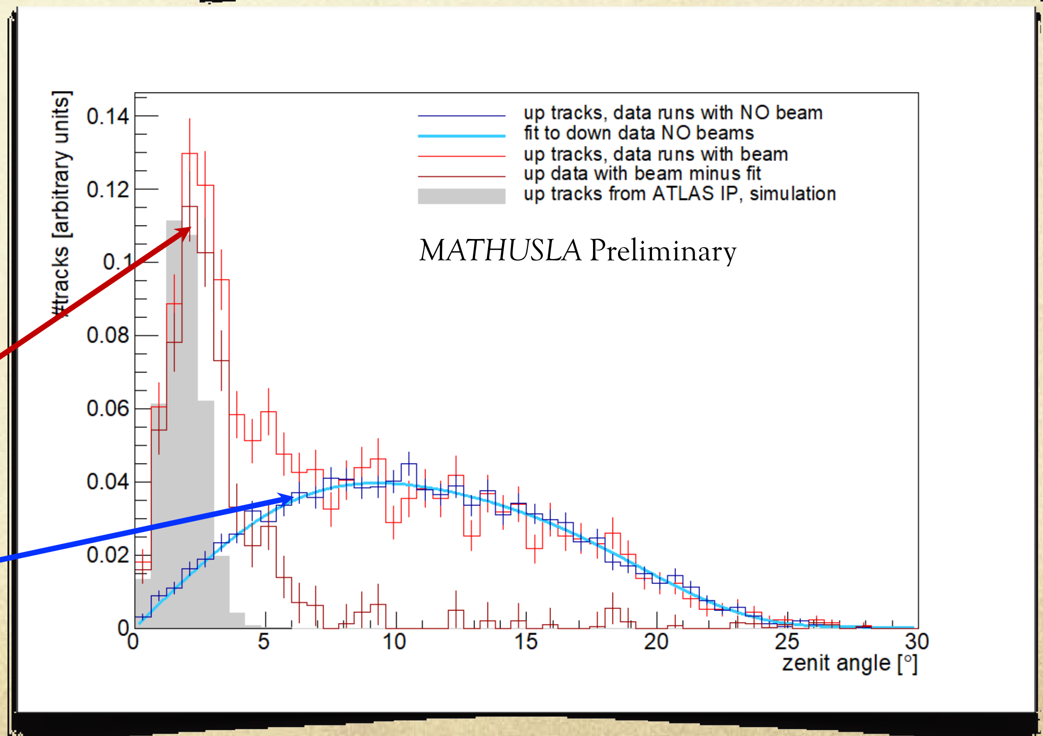


Test Stand Data Analysis

- Took data in different LHC conditions (w/wo beam)
- MC simulation for cosmic muons and for particles generated at the ATLAS IP
- Preliminary results – MC not corrected for efficiency or multiple scattering
  - **Angular distribution for down tracks (cosmic muons) match very well expected from MC**
  - Arbitrary normalization



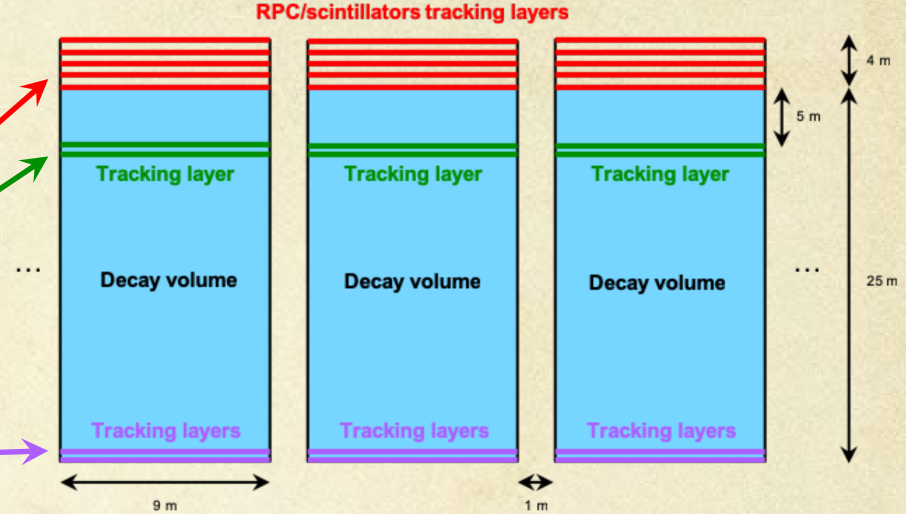
- Accumulation for zenith angle < ~ 4° consistent with **upward going tracks from IP when collisions occur**
- **Up tracks no beam** consistent with **downwards tracks faking upwards** tracks

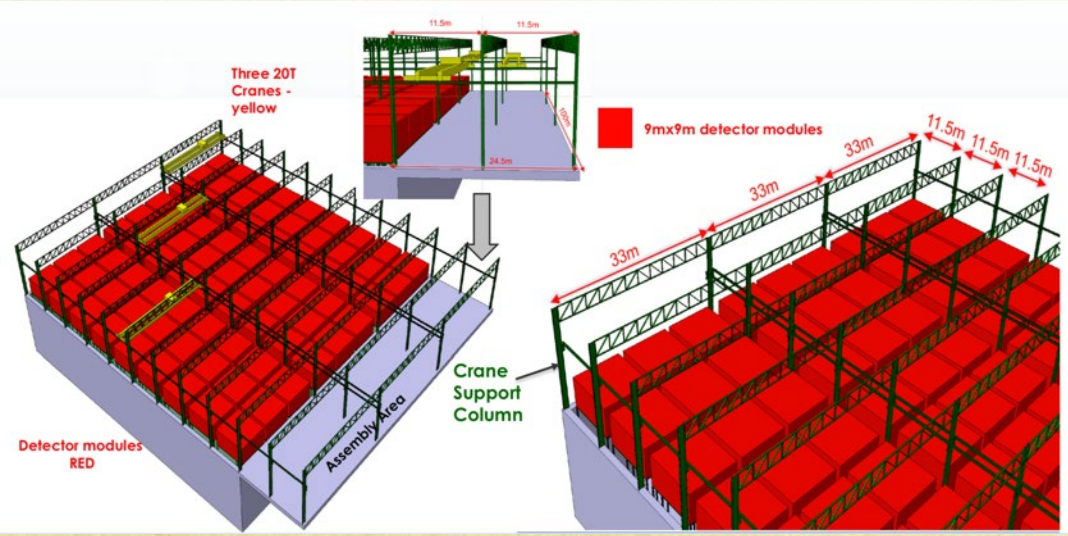


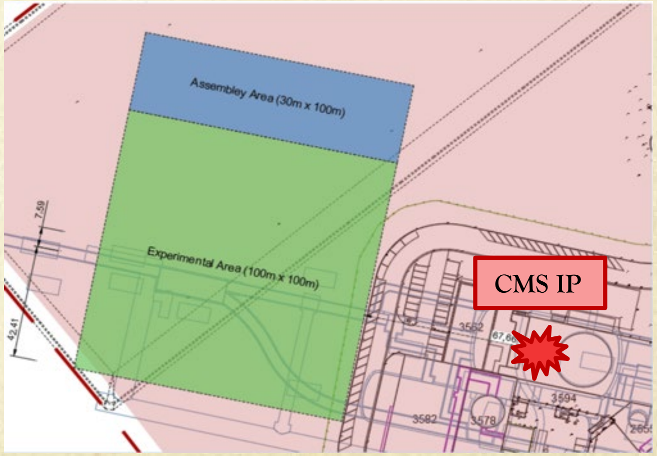
MATHUSLA @ P5

Finalised soon!

- Working with Civil Engineers to define the building and the layout of MATHUSLA at P5
- Layout restricted by existing structures based on current concept and engineering requirements
  - Assume ~ 25 meter decay volume
  - Individual detector units **9 x 9 x 30 m^3**
  - 5 layers of tracking/timing detectors separated by 1m
  - Additional tracking layer 5m
  - Double layer floor detector







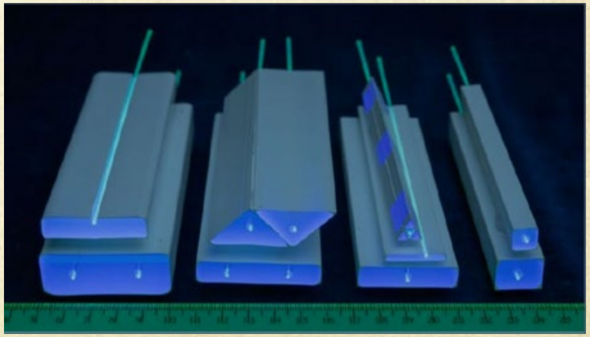
- ❖ Gain of 1.5 wrt detector at 100 m and IP 100 m below!
- ❖ 68 m to IP on surface and IP ~80m below surface
- ❖ ~7.5m offset to centre of beam

What's the best tracking technology?

RPCs used in many LHC detectors

- ✓ Pros ☺
  - Proven technology with good timing and spatial resolution
  - Costs per area covered are low
- ✓ Cons ☹
  - Require HV ~10 KV
  - Gas mixture used for ATLAS and CMS has high Global Warming Potential (GWP) and will not be allowed for HL-LHC (attempting to find a replacement gas)
  - Very sensitive to temperature and atmospheric pressure

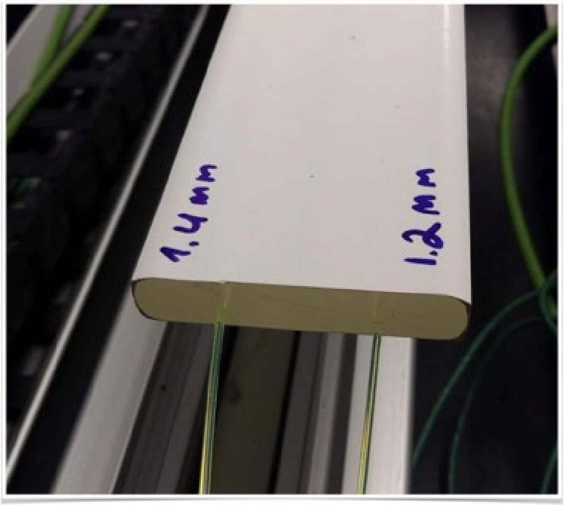
Extruded scintillator bars with wavelength shifting fibers coupled to SiPMs makes this technology cost wise competitive with RPCs



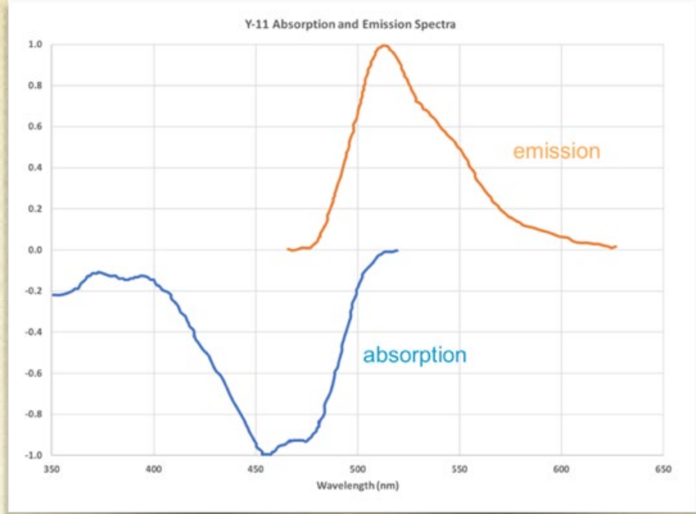
- ✓ Pros ☺
  - SiPMs operate at **low-voltage** (25 to 30 V)
  - **No gas** involved
  - **Timing resolution can be competitive with RPCs**
  - Tested extrusion facilities - FNAL and Russia. Used in several experiments: Bell muon system trigger upgrade (scintillators from FNAL and Russia), Mu2E, and KIT (FNAL scintillators)

Extruded scintillators @ Fermilab

- Extruded scintillator facility at Fermilab
  - 100 ton per year using 6 hour shifts 4 days per week (2 shifts → 200 t/y)
  - Typical production 50t/y, demand driven
  - Used for many experiments, most recently **Mu2e**, **KIT**
  - Cost $20/kg in small-ish quantity (1/2 labor, 1/2 chemicals)
  - Target of **$10/kg in large quantity**
- Already tested
  - 3.2 m Mu2e extrusion (**co-extruded with white polyethylene reflector**)
  - Scintillator extrusion has lots of light (>70 pe/MIP worst case in middle)
  - Spatial resolution 15 cm with simple algorithm, can likely do better
- Tests done with **1 cm thick bars**
  - Try 0.5 cm ?
  - Two fibers present in extrusion, second fiber eating some (half?) of the light



WLS fibre & SiPM



- For **WLS** considering **Kuraray Y-11** (< $5/m)
  - Cutoff below ~500 nm by self-absorption
  - Peak at ~520nm **(green)**
- SiPM used in HEP
  - Detection efficiency typically peaks around **450 nm**
  - Drops off for longer wavelengths
  - Reasonably matched to scintillation light (blue) but not as well for WLS
  - Best(?) that can be done with off-the-shelf items
- Possible **improvements in SiPM spectral response**?
  - Green light penetrates deeper in silicon than blue light
  - Sometimes electrons liberated beyond collection layer
  - Manufacturing process can be tweaked to increase thickness of the collection layer
  - Improvement over standard processing by a factor of 1.5 seems possible (for wavelengths away from peak efficiency)
  - Engineering R&D effort guesstimated to be 3 person-months

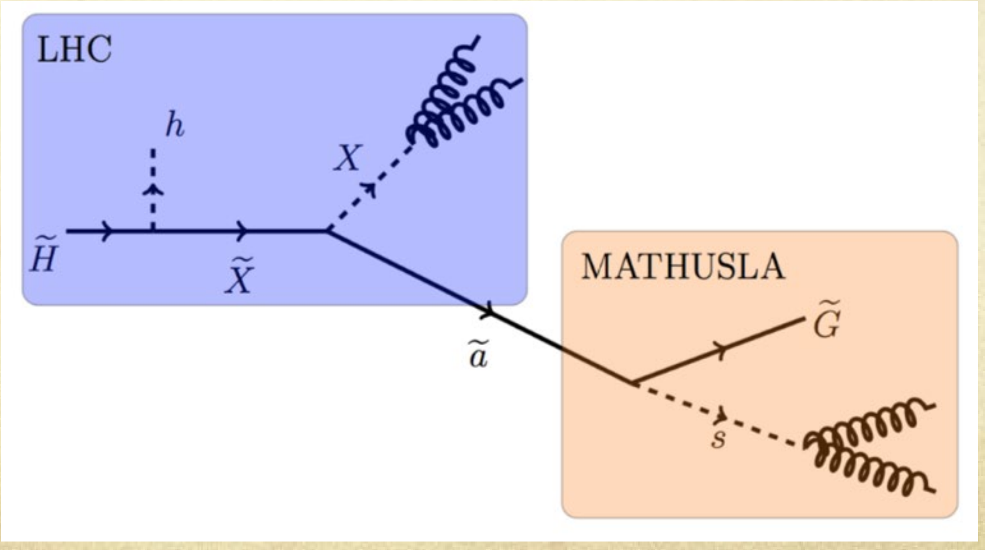
Possible options:
- S14160-3050HS: 3x3mm
- S14160-6050HS: 6x6mm

Readout & Data Taking

- Readout
  - **8 tracking layers** (5 tracking layers + 5m below + 2 on the floor)
  - 4 cm scintillators with readout in both ends results in 800K channels
  - Rates dominated by cosmic ray rate (~2 MHz)
    - ✓ Does not require sophisticated ASIC
    - ✓ **Aiming for 1 CHF per channel for frontend**
- Data taking
  - Baseline is to **collect all detector hits** with no trigger selection and **separately record trigger information**
  - Data rate dominated by cosmic rays 1/(cm^2-minute) which gives ~ 2MHz rate. With 9 x 9 m^2 modules, two hits/module with 4 bites per readout and readout 7 layers to readout gives **~ 30 TB /y per module**
  - Move information to central trigger processor
  - Trigger separately recorded (and used for connecting to CMS detector bunch crossing in the future main detector)

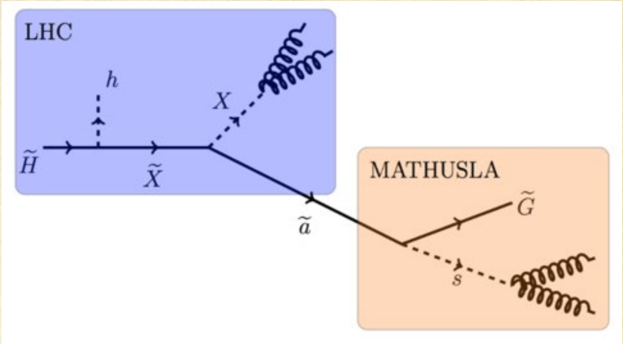
Trigger

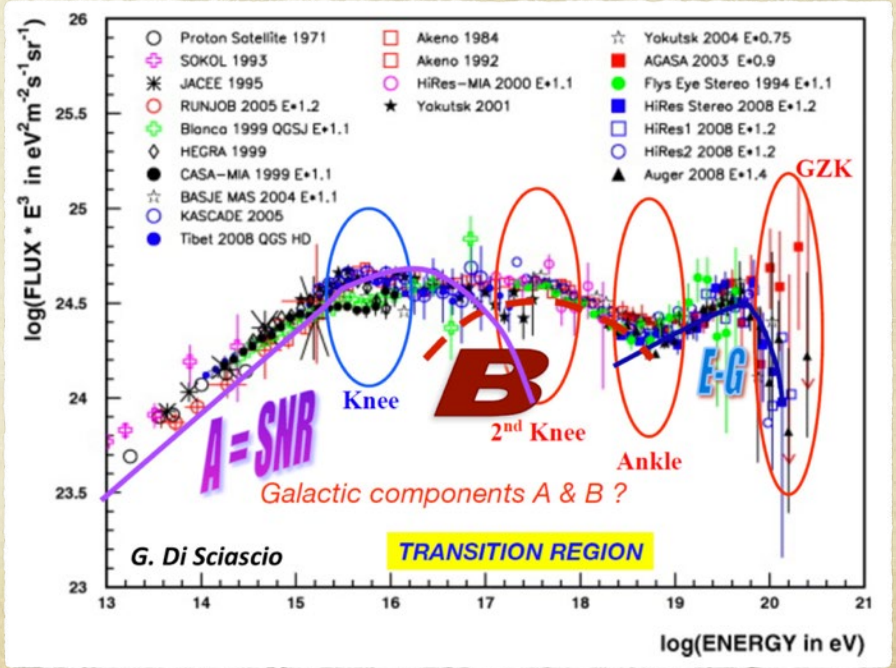
- **CMS Level-1 trigger** latency is 12.5 μs for HL-LHC
  - ✓ Conservatively assuming a 200m detector with height = 25m located 100m from IP, LLP with β = 0.7, optical fiber transmission to CMS with v_{fiber} = 5 μs/100m
  - ✓ MATHUSLA has 9 μs or more to form trigger and get information to CMS Level-1 trigger
  - ✓ If problem to associate MATHUSLA trigger to unique bunch crossing (b.c.) the approved CMS HL-LHC Level-1 allows for recording multiple b.c's
- Running **CMS and MAHUSLA in "combined" mode** will be crucial for both cosmic ray studies and LLP searches



MATHUSLA – Major Challenges and Strengths

- **Access to much longer lifetimes** up to BBN and very high masses
- HL-LHC CMS trigger latency 12 μs
- **Large detector →** constraints on instrumentation options
- Need a building and associated infrastructure
- **Cosmic ray physics** (guaranteed return on the investments)
  - ✓ 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





Summary & Conclusions & Plans

- MATHUSLA is a **complementary detector**
  - ✓ Might made the LHC LLP search program more comprehensive
  - ✓ Might have the potential to significantly **enhance and extend the new physics reach** and capabilities of the current LHC detectors
- Planning to build a **demonstrator** ~ $(9\text{m})^2$ made up of a **few construction units**
  - ✓ **Will validate the design and construction procedure of individual units**. It will provide **reliable input to the cost and schedule for MATHUSLA**
- Goal to complete the Technical Design Report (TDR) by end 2020
- **Need expertise to develop the detector technology** and build the demonstrator/MATHUSLA
- **Several applications** for **resources** on-going in **Europe (>1 ERC proposals), USA and Canada**

- ❖ We are a small group → lots of possibilities/visibility for postdocs, PhD, grad students
- ❖ We might be able to start working on the demonstrator at the beginning of next year
- ❖ **Consider joining the Collaboration!**
  - ❑ If interested: Cristiano.Alpigiani@cern.ch , mathusla.experiment@cern.ch

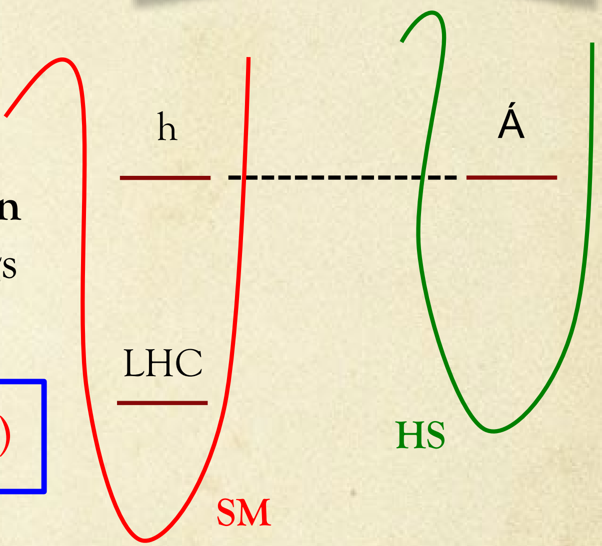
BACKUP

The Hidden Sector

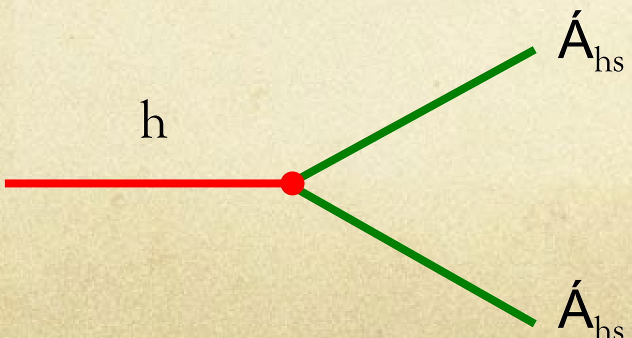
- The Standard Model (SM) is in amazing agreement with the experimental data, but **still some problems remain unsolved**: dark matter, neutrinos masses, hierarchy, matter-antimatter asymmetry…

- Many extensions of the SM (Hidden Valley, Stealth SUSY, 2HDM, baryogenesis models, etc) include particles that are **neutral**, **weakly coupled**, and **long-lived** that can decay to final states containing several hadronic jets

- Long-lived particles (LLPs) occur naturally in **coupling to a hidden sector (HS)** via small scalar (Higgs) or vector (°, Z) portal couplings



❖ Wide range of possible lifetimes from $\mathcal{O}$(*mm*) up to $\mathcal{O}$(*m/km*)



The mixing of Higgs with HS results in a Higgs like particle decaying into LLPs:

small coupling → long lifetimes [Phys. Lett. B6512 374-379, 2007]

~ 10^8 Higgs boson @ HL-LHC

Signature Space of Displaced Vertex Searches

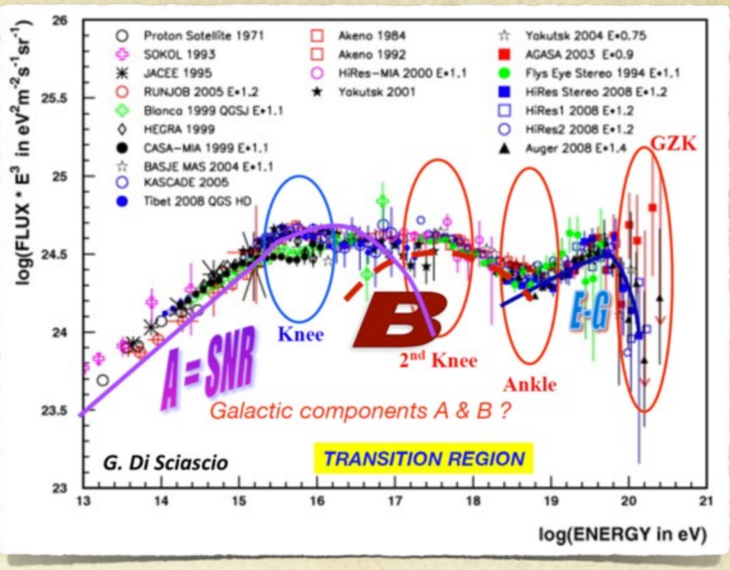
- Detector signature depends of production and decay operators of a given model
  - Production determines cross section and number and characteristics of associated objects
  - Decay operator coupling determines life time, which is effectively a free parameter
- Common Production modes
  - Production of single object - with No associated objects (AOs)
    - Higgs-like scalar Φ that decays to a pair of long-lived scalars, ss, that each in turn decay to quark pairs – Hidden Valley, Neutral Naturalness, …
    - Vector (γ_{dark},Z′) mixing with SM gauge bosons – kinetic mixing
  - Production of a single object P with an AO – Many SUSY models
    - AO jets if results from decay of a colored object
    - AO leptons if LLP produced via EW interactions with SM
- Common detector signatures ⇒ generic searches

Neutral Long-lived Particles

- Neutral LLPs lead to displaced decays with no track connecting to the IP, a distinguishing signature
    - **SM particles predominantly yield prompt decays (good news)**
    - **SM cross sections very large (eg. QCD jets) (bad news)**
- To reduce SM backgrounds many Run 1 ATLAS searches required two identified displaced vertices or one displaced vertex with an associated object
    - **Resulted in good rejection of rare SM backgrounds**
    - **BUT limited the kinematic region and/or lifetime reach**
- None the less, these Run 1 searches were able to probe a broad range of the LLP parameter space (LLP-mass, LLP-c¿)
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent

MATHUSLA - Cosmic Rays - EAS

- **KASCADE** is currently a leading experiment in this energy range
  - ✓ Has larger area than MATHUSLA100 (**40,000 m^2 vs 10,000 m^2**) but ~100 % detector coverage in MATHUSLA vs < 2 % in KASCADE
- MATHUSLA has **better time**, **spatial** and **angular resolution**, and five detector planes



❑ MATHUSLA standalone

- ✓ Measurements of arrival times, number of charged particles, their spatial distributions → allow for reconstruction of the **core**, the **direction of the shower** (zenith and azimuthal angles), **slope of the radii distribution of particle densities**, total **number of charged particles** (**core shape is not well studied → MATHUSLA could provide new information**)

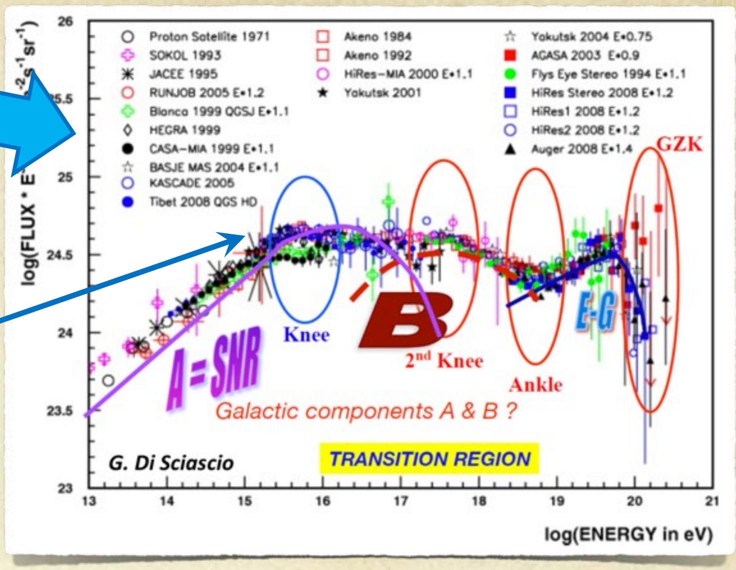
❑ MATHUSLA+CMS/ATLAS

- ✓ Uniquely able to analyse muon bundles going through both detectors. This is a **powerful probe of heavy primary cosmic ray spectra and astrophysical acceleration**
- ✓ Lot of time to connect MATHUSLA with CMS/ATLAS bunch crossing (at HL-LHC trigger has ~12 microsecond latency)

Guaranteed return on the investment!

MATHUSLA - Cosmic Rays – Energy Spectrum

Several structures in the current measurements



- Good measurements in the energy range 10^{15}-10^{17} eV is crucial to understand the **transition** from **galactic to extragalactic cosmic rays**
- Understanding the **knee** may be the **main open problem in cosmic ray physics** (requires high statistic and good measurements to establish the components of source and distribution of incident particles)
- The full coverage of **MATHUSLA100** will allow a **lower energy threshold** (~ 100 GeV) than KASCADE (~ 1 PeV)
  - ✓ Lower threshold allows **comparison with satellite measurements** (CREAM, Calet, HERD)
- With the ability to measure several different parameters it should be possible to **separate** with decent statistics **p+He**, **intermediate mass nuclei** and **Fe** up to 10^{16} eV
- MATHUSLA **multiple tracking layers** may help to **understand the energy spectrum**
- Extending the linearity of analog measurements by a factor of 10 greater than ARGO-YBJ MATHUSLA may be able to **measure shower energies above a PeV** (~10^{17} eV)

Guaranteed return on the investment!

MATHUSLA

J-P Chou, D. Curtin, H. Lubatti
arXiv 1606.06298

MATHUSLA detector → **MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles

- Dedicated detector **sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis** (BBN) limit (10^7 – 10^8 m) for the HL-LHC
- **Large-volume, air filled detector located on the surface** above and somewhat displaced from ATLAS or CMS interaction points
- HL-LHC → **order of N_h = 1.5 x 10^8** Higgs boson produced
- Observed decays:

$$N_{\text{obs}} \sim N_h \cdot \text{Br}(h \to \text{ULLP} \to \text{SM}) \cdot \epsilon_{\text{geometric}} \cdot \frac{L}{bc\tau}$$

² = geometrical acceptance along ULLP

L = size of the detector along ULLP direction

b ~ m_h /(n¢m_X) · 3 for Higgs boson decaying to n = 2, m_X ¸ 20 GeV

❖ To collect a few ULLP decays with c¿ ~ 10^7 m requires a 20 m detector along direction of travel of ULLP and about 10% geometrical acceptance

$$L \sim (20\text{ m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\text{geometric}}}\right) \frac{0.3}{\text{Br}(h \to \text{ULLP})}$$

MATHUSLA – Muon Rates from LHC

- Simulated muons coming from LHC and passing 100 m of rocks made of **45.3m of sandstone,** **18.25m of marl (calcium and clay), 36.45m mix (marl and quartz)**
- Minimum energy ~ 70 GeV
- What a muon can do inside the detector?
  - ✓ **Pass through** → detected as a single upwards track
  - ✓ **Decay** → entirely to **e$\nu\nu$** (single e deflected wrt muon direction), but also to **eee + $\nu\nu$** with BR ~ $3\text{x}10^{-5}$ (looks like a genuine DV decay, but rejected through floor layer veto or main trigger muon trigger)
  - ✓ **Inelastic scattering** → off the air or the support structure (rejected using floor layer veto)

❖ **Over the entire HL-LHC** run expected ~ **10^6 muons pass through MATHUSLA,** corresponding to ~ 0.1 Hz

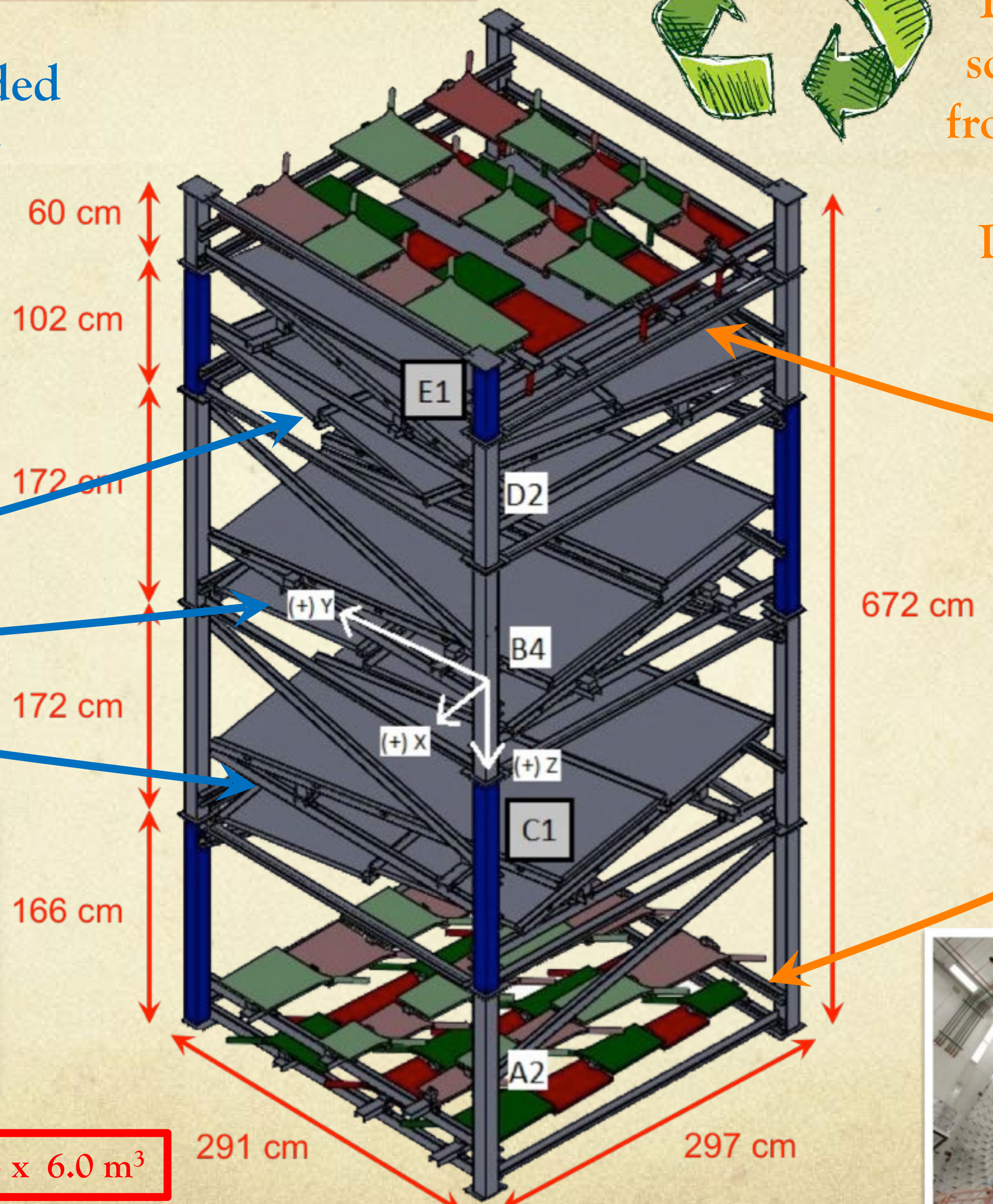
- ❑ **3000 muons** decaying to **e$\nu\nu$** (electron deflected from original muon trajectory by angle ~1/muon boost **(~ 5-10 degrees)**
- ❑ **0.1 muons** decaying to **eee + $\nu\nu$**
- ❑ **< 1 muon scattering off air**

The past…

- **2016**
  - MATHUSLA idea proposed for the first time
- **2017**
  - Started working on the test stand design and construction
  - First (short data taking period in P1) then cosmic ray tests in 887
- **2018**
  - P1 data taking
  - Main detector design
  - MATHUSLA White Paper
  - MATHUSLA LoI submitted to LHCC (July 2018, arXiv:1811.00927)
- **2019**
  - Cost estimate

The MATHUSLA Test Stand

3 layers of RPCs provided by University of Tor Vergata (Rome) by Rinaldo Santonico (from Argo-YBJ Experiment)

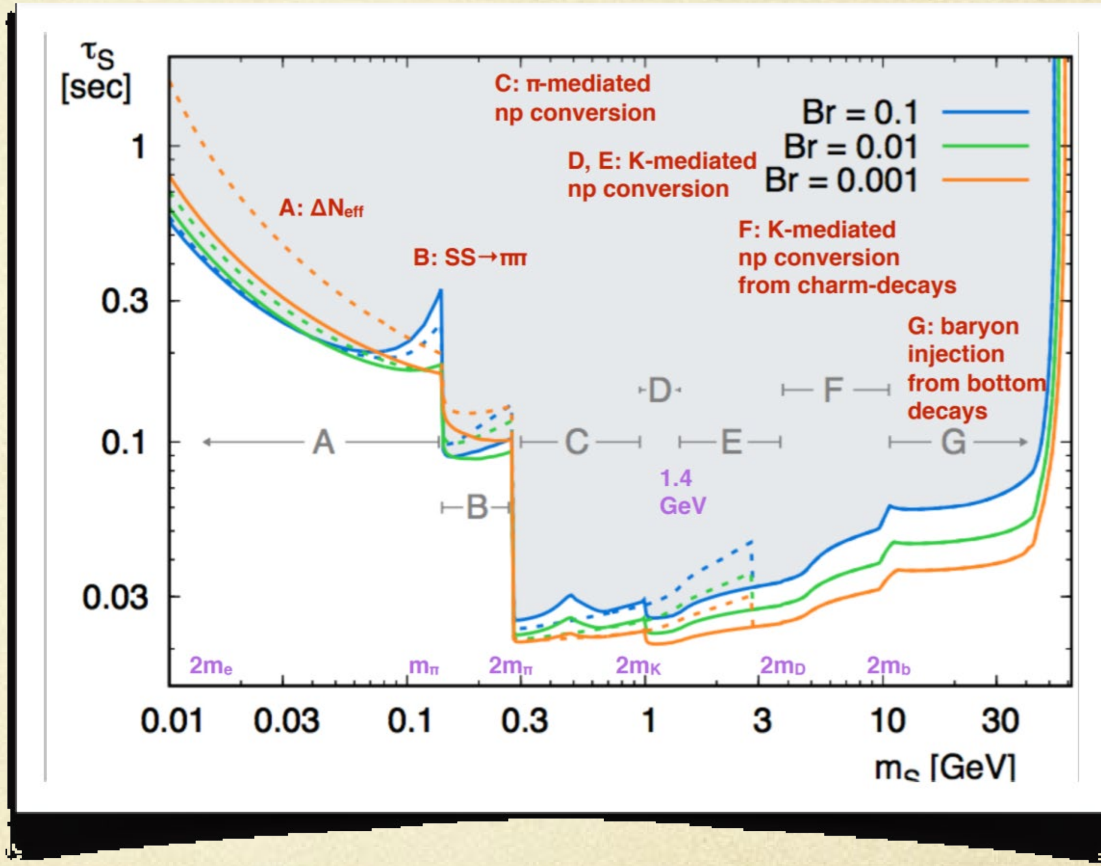


Top and bottom scintillator layers from Tevatron DØ provided by Dmitri Denisov

Active area ~ 2.5 x 2.5 x 6.0 m^3

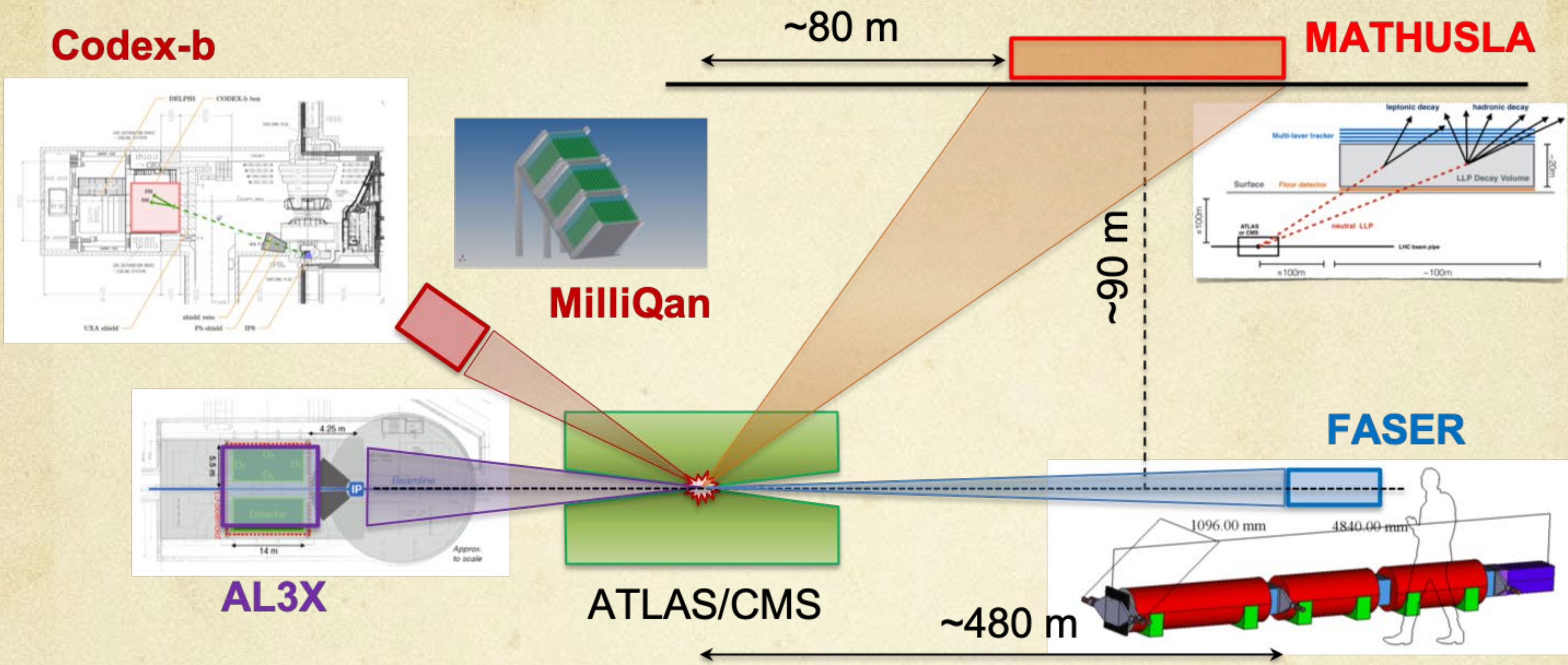
MATHUSLA – Scalar LLP Lifetime Constraints

- A recent paper [A. Fradette and M. Pospelov, arXiv:1706.01920v1] examines the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via h ! ss, where the decay is induced by the small mixing angle of the Higgs field h and scalar s.



- For $m_s > m_\pi$ the lifetime $\tau < 0.1$ s.
- Conclusion does not depend strongly on BR(h ! ss)

New Projects @ LHC



- ❑ For long c∗τ detector sensitivity ∝ angular coverage and detector size

Experiment	η coverage
MATHUSLA	0.9 – 1.4
AL3X	0.9 – 3.7
Codex-b	0.2 – 0.6

These experiments can **exploit the full LHC potential** and **reduce to negligible the possibility of losing new physics at the LHC!**