A Journey to the Lifetime Frontier

Cristiano Alpigiani

UNIVERSITY of WASHINGTON

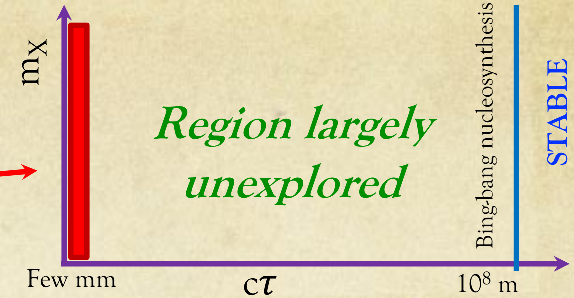
12th December 2019

QMUL

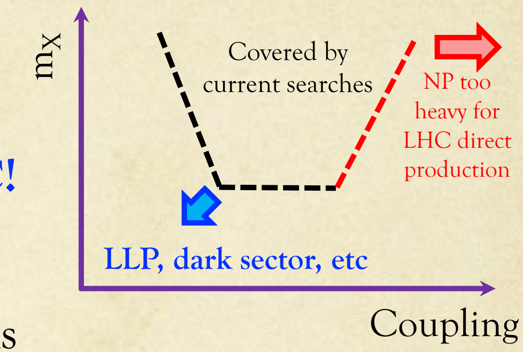
MATHUSLA

Why Long Lived Particles?

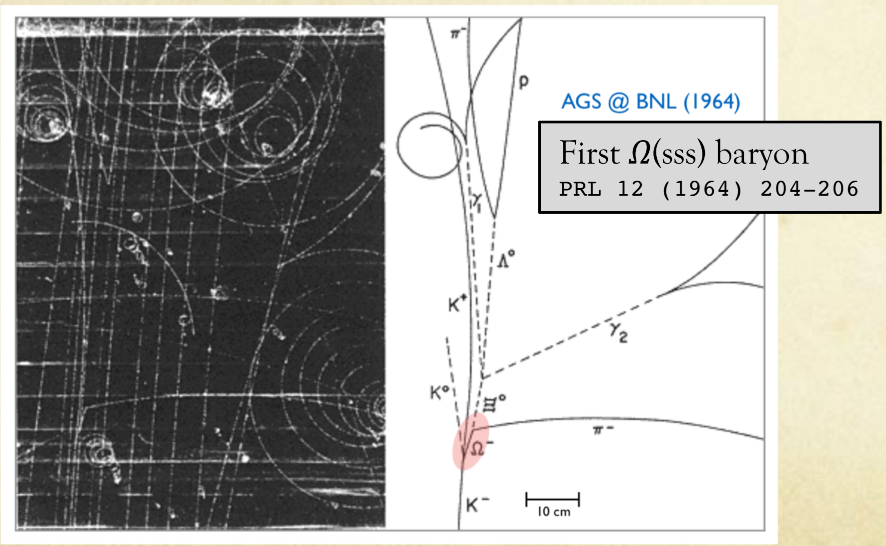
Most new physics searches focus on production and prompt decay at the p-p interaction point…

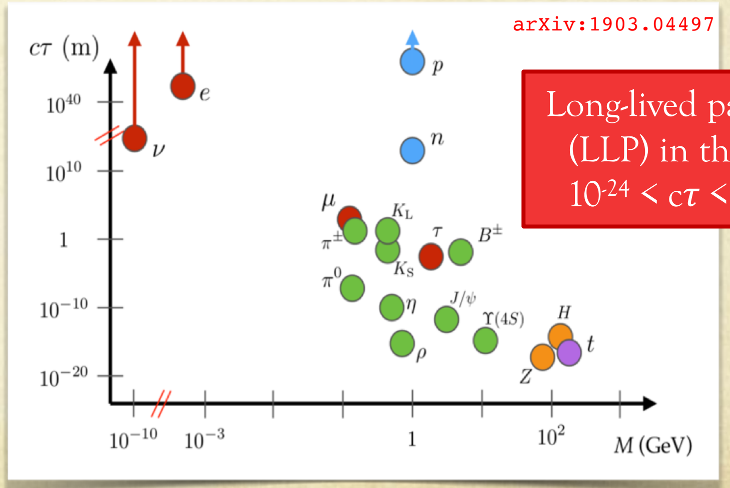


OR



- Current measurements in impressive agreement with SM expectations
- Why this lack of any evidence of new phenomena?
  - New particles might be more likely labelled as background
- Need to reduce to negligible the possibility of losing NP at the LHC!
- **Naturalness does not seem to be a guiding principle of Nature**
- Nature is plenty of particles with macroscopic detectable decay lengths





Long-lived particles (LLP) in the SM $10^{-24} < c\tau < 10^{41}$ s

Not surprising that LLP might exist also beyond the SM

What Makes the Lifetime Longer?

Let's start from the basic…

- An unstable particle **A** can decay into several daughter particles **i** with a **decay rate** (i.e. probability/time)

$$\Gamma_A = \Sigma_i \Gamma_{A\to i} \sim m_A$$

- The proper lifetime τ is given by the inverse of the decay width $\lambda = bc\tau = \frac{1}{\Gamma}$
    - → If $\Gamma \sim m_A$ the particle travel ~ a De Broglie wave length before decaying…but if $\Gamma \ll m_A$ the distance can be bigger…
- The decay width can be calculated in QFT as

$$d\Gamma \sim \frac{1}{m} |\mathcal{M}|^2 d\Pi$$

- To have a particle long-lived
    - The matrix element for decay could be suppressed due to an approximate symmetry (which would forbid the decay if it was precise) or a small effective coupling constant
    - A small coupling in the matrix element can be further distinguished by whether it originates from a dimensionless coupling constant, or a dimensionful scale, larger than m, from a higher-dimension operator that mediates the decay
    - Phase space can be suppressed due to the small breaking of an approximate symmetry that splits otherwise degenerate states, or can arise due to accidental degeneracies in the spectrum

What Makes the Lifetime Longer?

Two examples…

From David Curtin

Approximate Symmetry

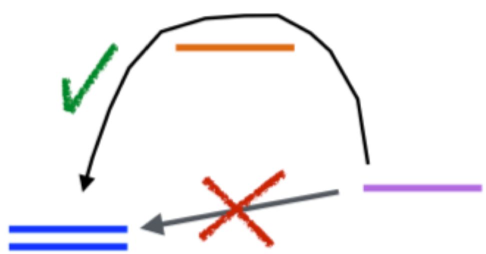
Multiplet of particles prevented from decaying by symmetry (e.g. isospin, baryon number, …)

Symmetry is *slightly* broken with small order parameter ϵ, but still a good approximation for most dynamics.

$$\Gamma \propto \epsilon m \ll m$$

Heavy Mediator (Virtual Intermediate State)

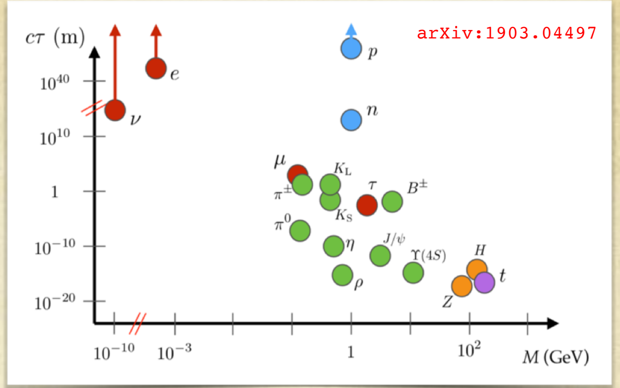
Particle is stable, except for possible transition that can only proceed by exciting a heavy intermediate particle from the vacuum.



Heisenberg uncertainty principle → borrowing energy is "expensive"

$$\Gamma \propto \frac{m^5}{M_{med}^4} \ll m$$

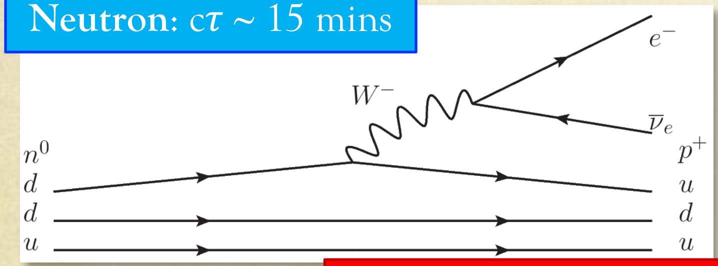
LLP in the SM



The proton decay is forbidden by baryon number which is an accidental symmetry of the SM

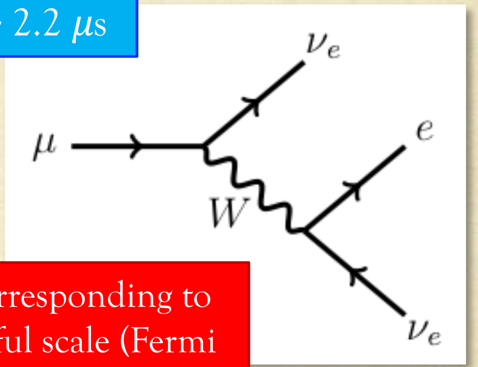
- The Higgs boson has a lifetime significantly greater than the similarly massive top quarks or W/Z bosons due to the **small dimensionless bottom Yukawa coupling** ($y_b \sim 0.02$) that dominates Higgs decay in the SM

Neutron: $c\tau \sim 15$ mins



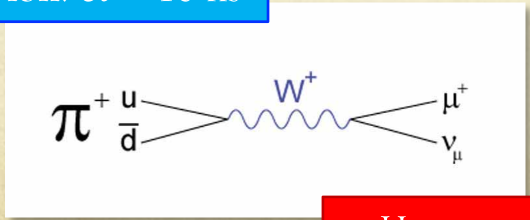
- Phase space suppression of weak decay to a proton and leptons
- Heavy mediator
- Approx symmetry (isospin)

Muon: $c\tau \sim 2.2\ \mu s$



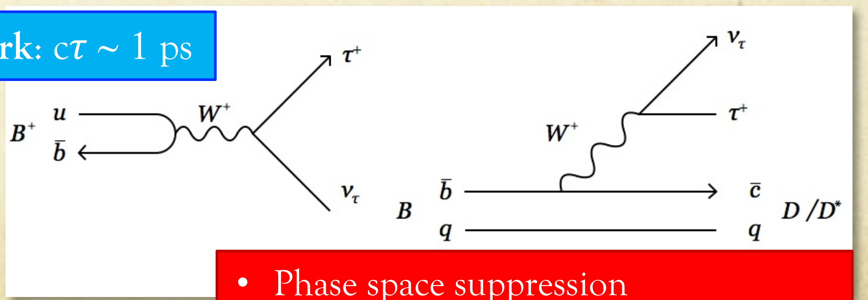
- Small coupling corresponding to a large dimensionful scale (Fermi constant G_F) , arising due to the high mass of the W boson

Pion: $c\tau \sim 10$ ns



- Heavy mediator

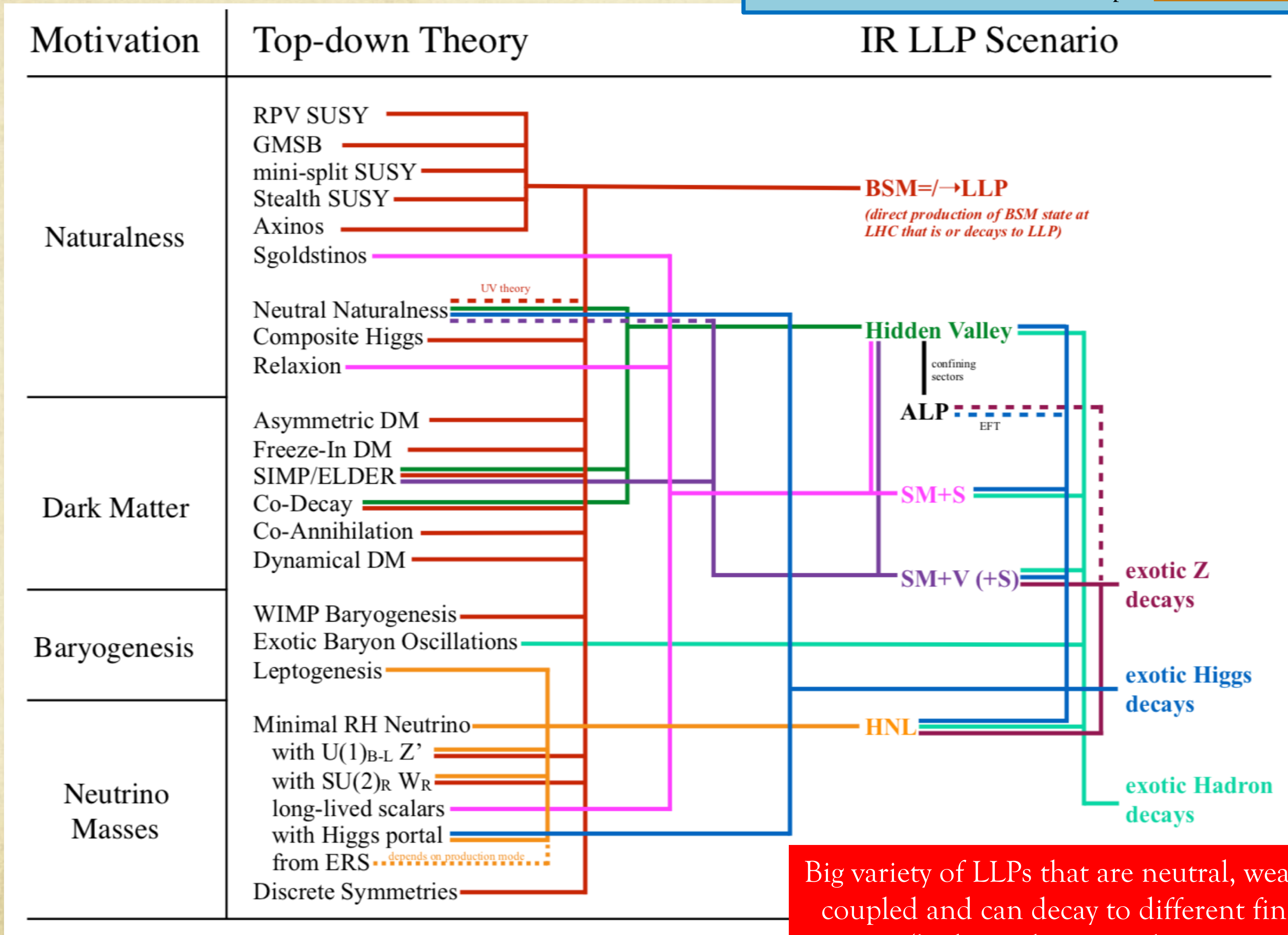
b-quark: $c\tau \sim 1$ ps



- Phase space suppression
- Approximate flavor symmetry
- Large dimensionful scale in the decay

LLP in BSM - Top-down Theoretical Motivations

From the MATHUSLA White Paper arXiv:1806.07396



Big variety of LLPs that are neutral, weakly coupled and can decay to different final states (hadrons, leptons, photons, etc)

LLP in BSM

Examples of LLP in different BSM models…

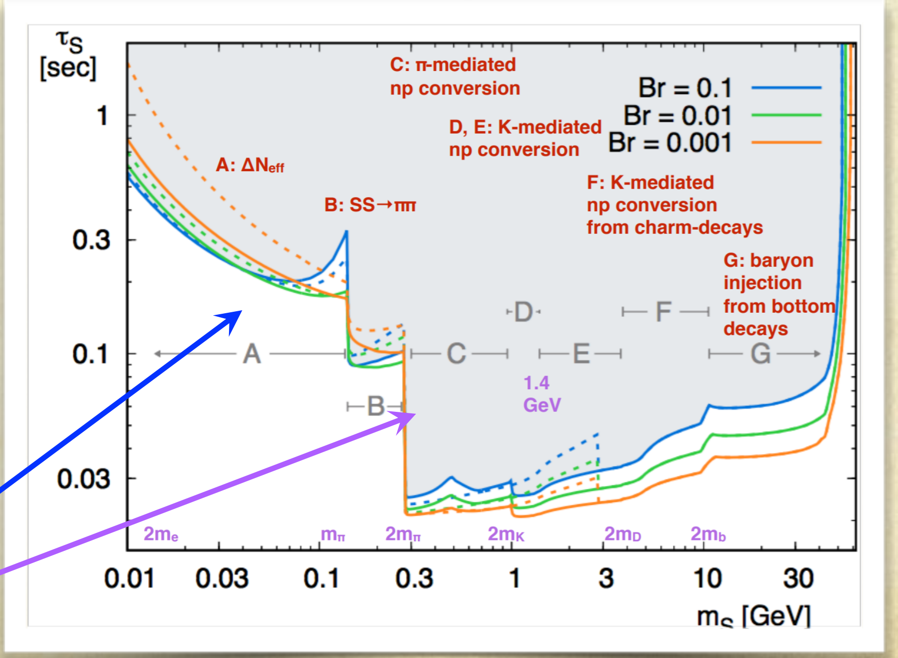
		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

But How Much Long?

arXiv:1706.01920v1

The lifetime of metastable particles can be limited by cosmology, in particular by the Bing Bang Nucleosynthesis (BBN)

- BBN very well understood within SM physics and well constrained
  - ✓ Happened in an interval between ~10 s – 15 minutes after the Big Bang
  - ✓ The LLP lifetime should be smaller of that limit or the **n/p ratio** should have been **raised by nucleonic and mesonic decays of the LLP** spoiling the final light nuclei abundances
- Constraint studied on a **scalar model** coupled through the Higgs portal, where the production occurs via $h \rightarrow ss$, where the decay is induced by the **small mixing angle of the Higgs field h and scalar s**



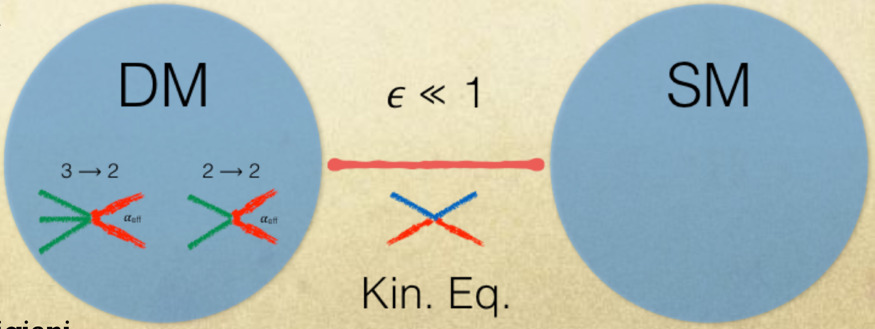
- ❖ For $m_s < 2m_\mu$ the lifetime τ can go up to 1 s
- ❖ For $2m_\mu < m_s < m_h/2$ the lifetime $\tau < 0.1$ s

- ❑ Conclusion does not depend strongly on $BR(h \rightarrow ss)$

Dark Matter and LLP

Variety of possible DM candidates whose experimental signals are intimately connected to the mechanism responsible for generating DM in the early universe

- These **DM models often** require new BSM states in addition to DM itself
  - In many cases, the **mechanism yielding the correct relic density** for DM naturally and generically **results in one or more of these BSM states having a long proper decay length**
  - In other cases, **long lifetimes are not a direct consequence of the mechanism determining the DM relic abundance**, but a generic feature of models that implement it
- Mechanisms giving a particle a long lifetime are naturally realised in well-motivated DM models
  - Small phase space → generic prediction of models where **WIMPs co-annihilate with an additional particle** in the early universe (small mass splitting between DM and co-annihilating partner)
  - Decays suppressed by high mass scales → theories of **asymmetric DM**
  - Small coupling → **SIMP**: dark sector consists of DM which annihilates via a $3 \to 2$ process. Small couplings to the visible sector allow for thermalisation of the two sectors, thereby allowing heat to flow from the dark sector to the visible one



LLP Phenomenology @ LHC

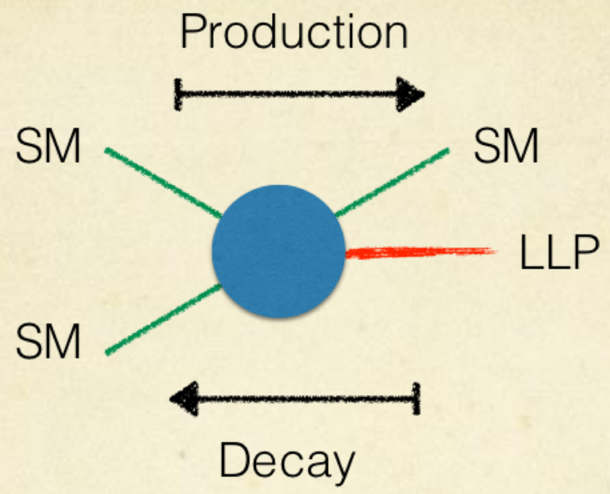
The LHC experiments can provide a **impressive sensitivity to exotic metastable massive particles** that decay significantly displaced from the IP

MET searches are undoubtedly crucial in probing NP giving rise to more than several hundred GeV of MET, but the sensitivity and the production rates drastically drops for softer signals

MET searches cannot define if the newly discovered state is a dark matter candidate or a meta-stable particle

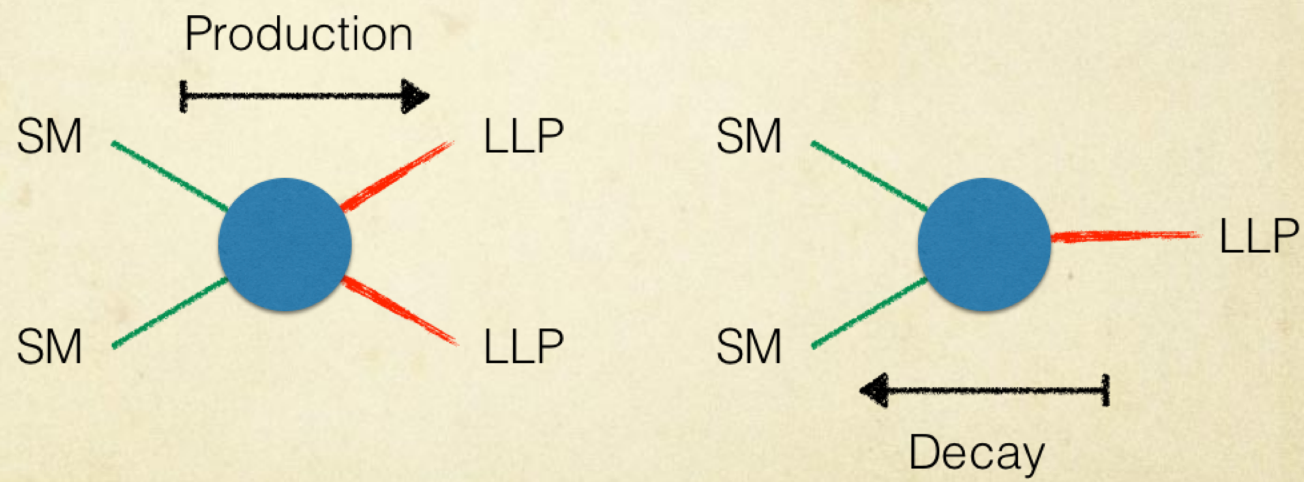
LLP Production and Decay

Simple model
(one effective coupling)



Difficult to have a sufficient rate and to keep a long lifetime

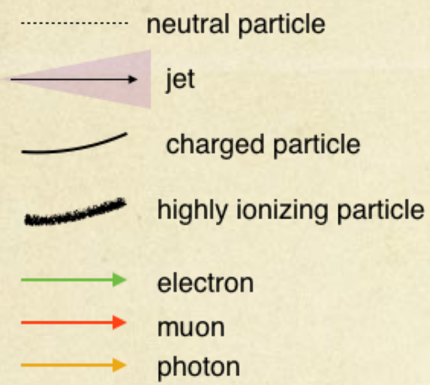
Ideal model
(production and decay are separated) – pair production

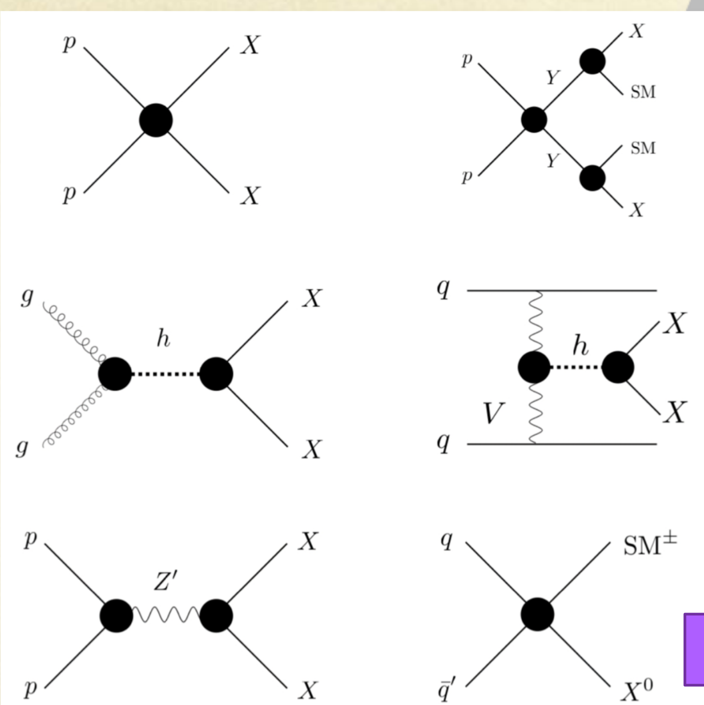


The best sensitivity is achieved with **models where the production and decay occur due to different coupling constants**, and the particle lifetime define the probability of decay within a detector

Unconventional Signatures

Mostly pair production





- Main LLP topologies
  - Other possible ones: displaced di-photon, displaced conversion, disappearing tracks
- **Signature-based program!**

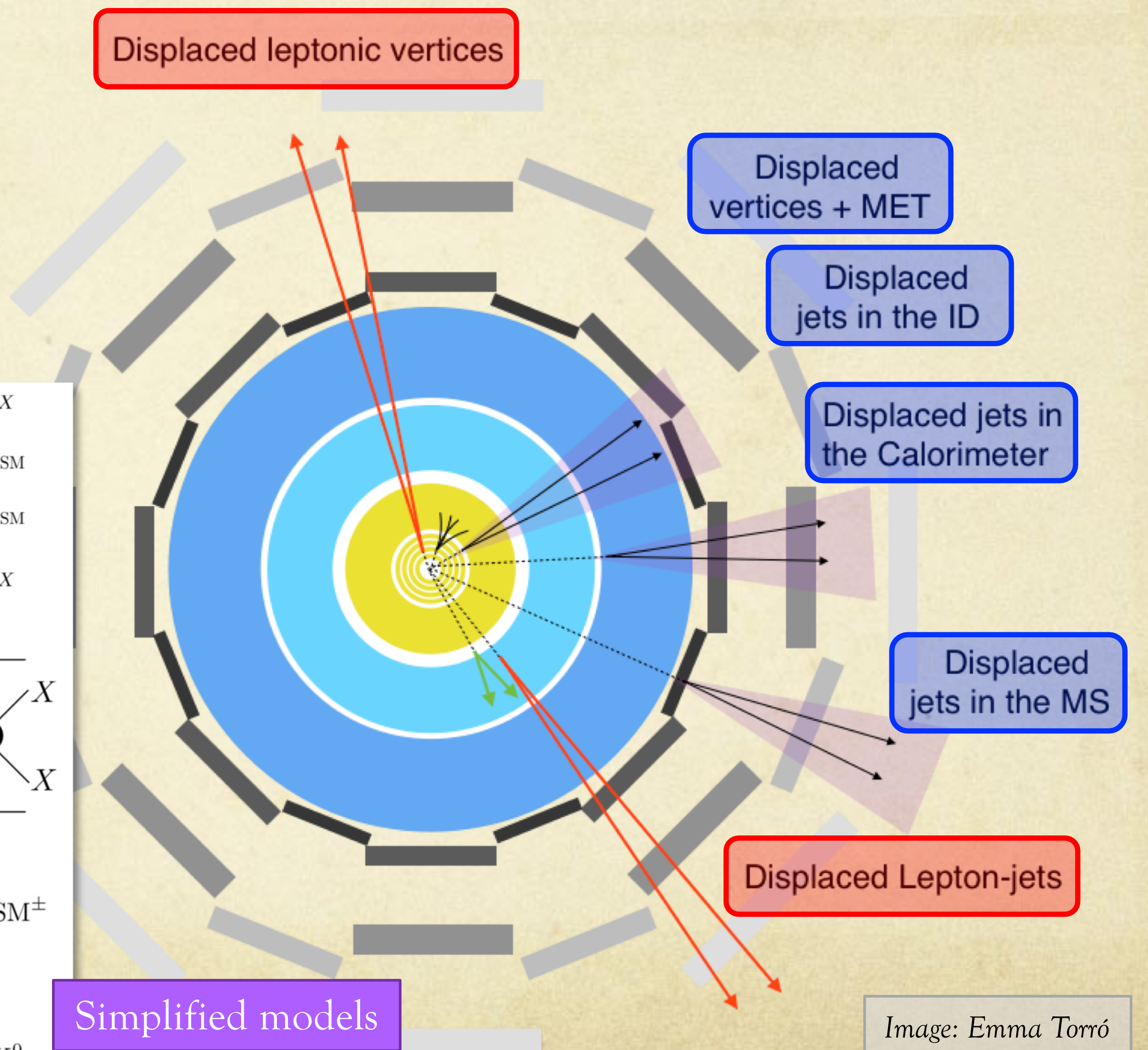


Image: Emma Torró

LLP - Geometrical Acceptance

What shapes the sensitivity as a function of $c\tau$?

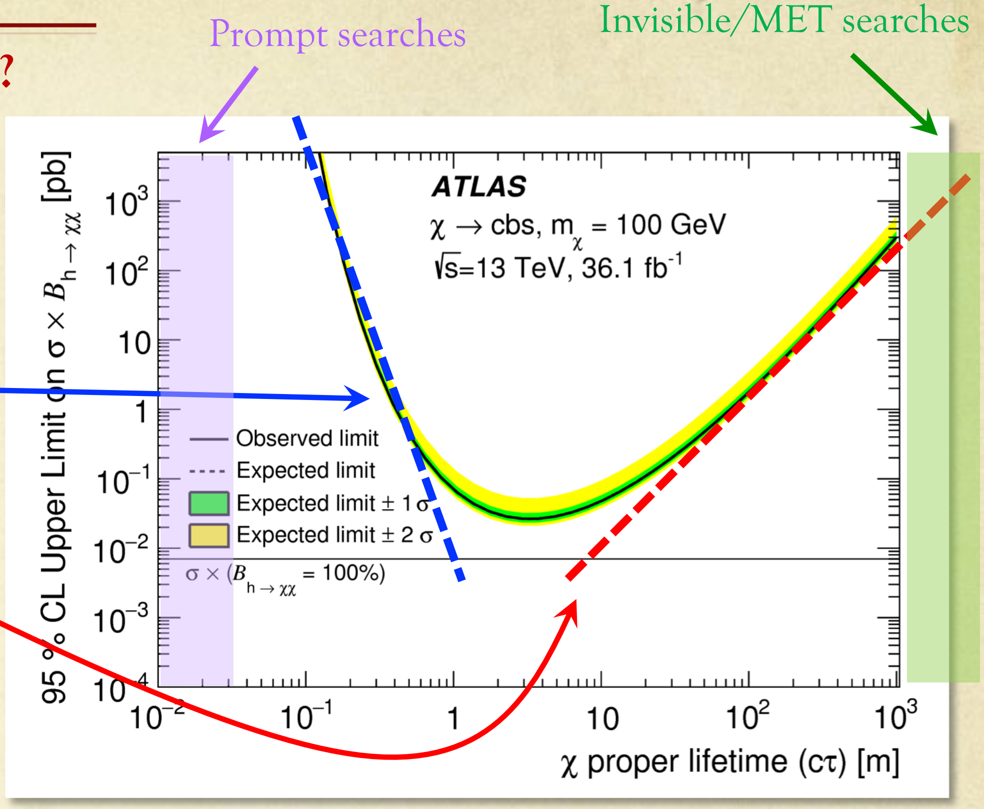
- P = geometrical acceptance

$$P = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL \frac{1}{d} e^{-\frac{L}{d}}$$

$$\approx \frac{\Delta\Omega}{4\pi}\, e^{-\frac{L_1}{d}}\, \frac{L_2 - L_1}{d}$$

Solid angle

- $L_2 - L_1$ = detector length
- d = average LLP decay length in lab frame



❖ Good solid angle coverage → lifetime independent

❖ For smaller lifetimes → need high efficiency close to the IP

❖ For larger lifetimes → longer detector

Unconventional Challenges

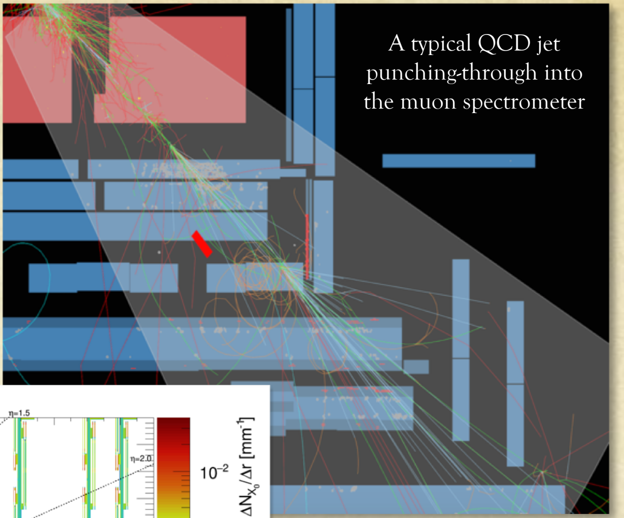
LHC detectors are optimised to detect prompt SM particles

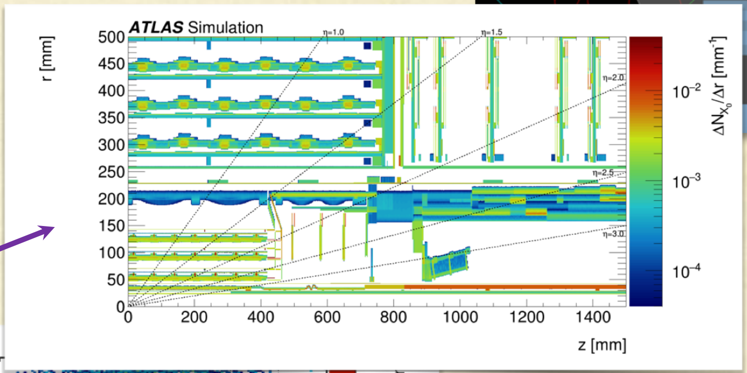
➢ BSM particles can produce **final states** that might be **very difficult to study** due to complicated backgrounds

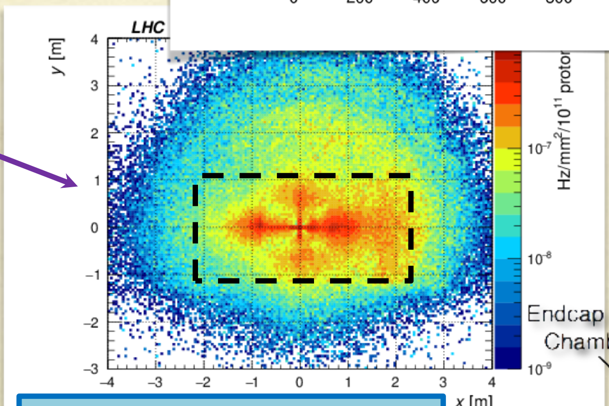
- ✓ Instrumental backgrounds
- ✓ Large QCD jet production
- ✓ Pile-up problems
- ✓ Material interaction
- ✓ Beam induced background (BIB)
- ✓ Cosmic background

❑ Need to develop

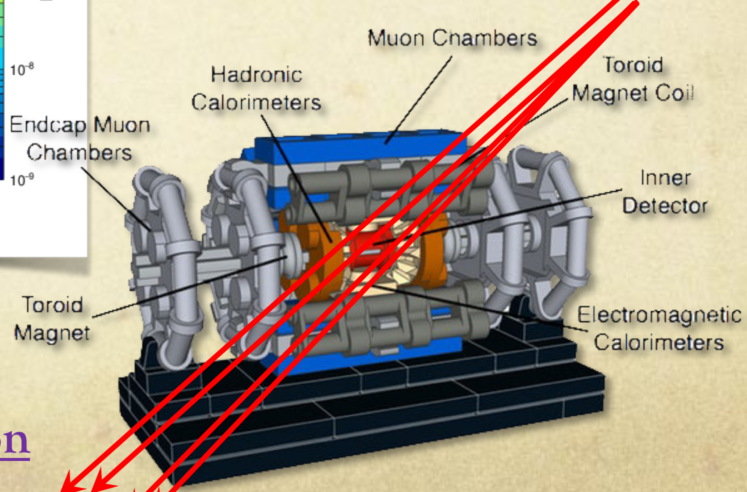
- Dedicated triggers
- Custom reconstruction tools
- Very robust background modelling and rejection







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



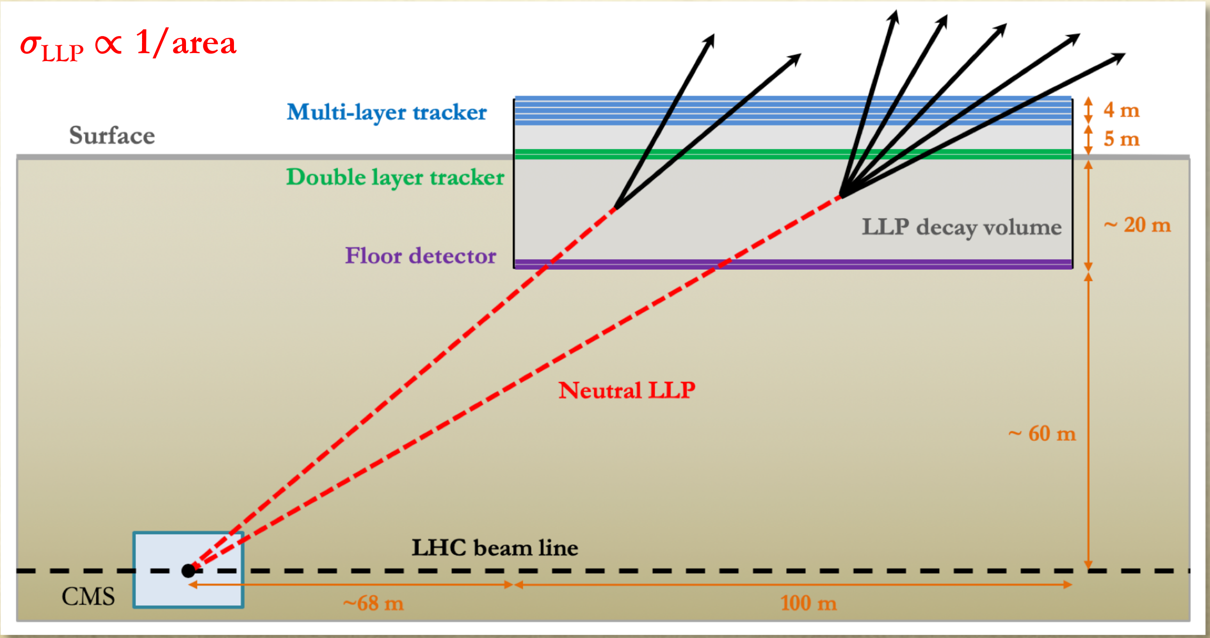
MATHUSLA

Need a background free environment with no trigger limitations...

MATHUSLA - Layout

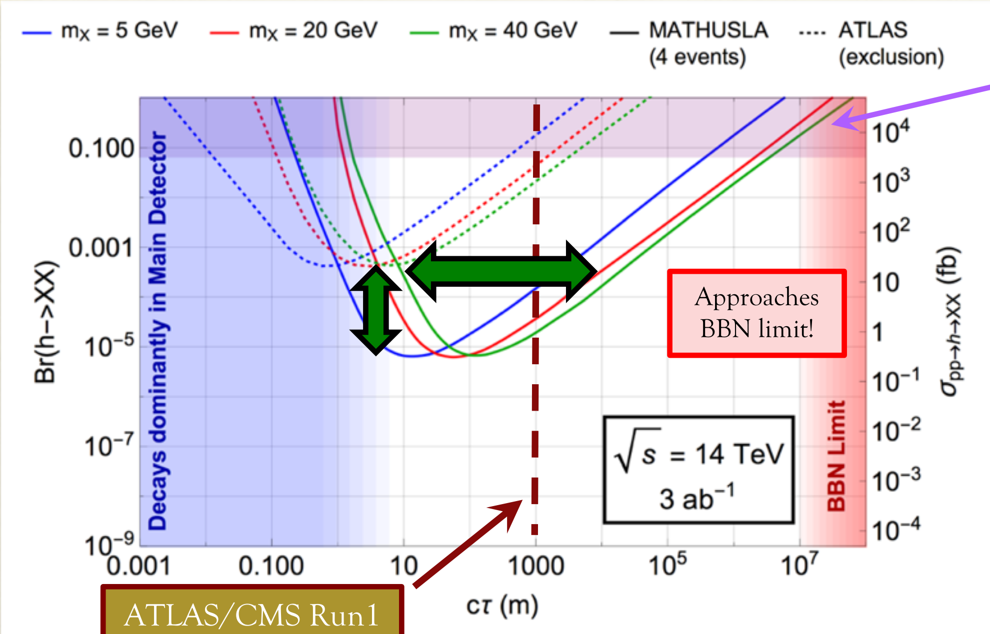
- arXiv 1606.06298
- arXiv 1806.07396
- CERN-LHCC-2018-025

- 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 + SiPMs** are considered (good time/space resolution)



MATHUSLA – Physics Reach

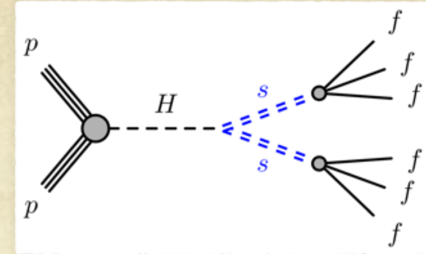
arXiv:1806.07396 [hep-ph]



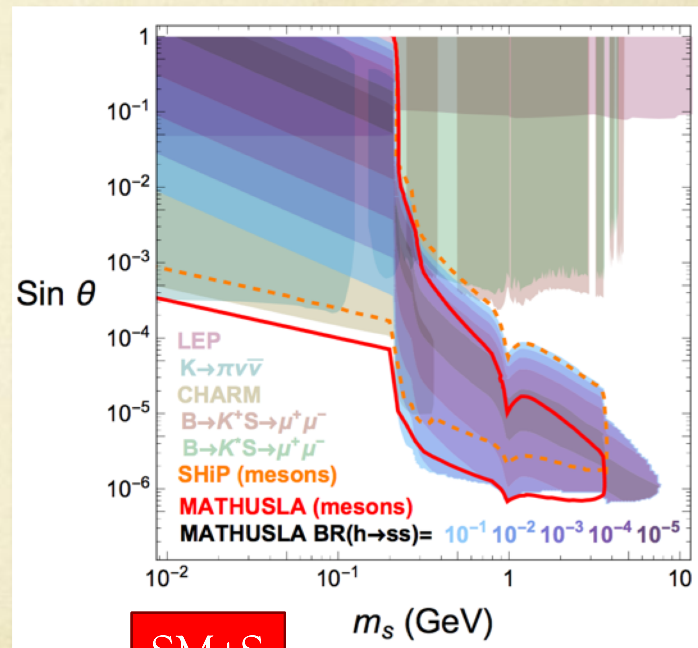
h → inv
HL-LH limit

Approaches BBN limit!

ATLAS/CMS Run1 lifetime sensitivity

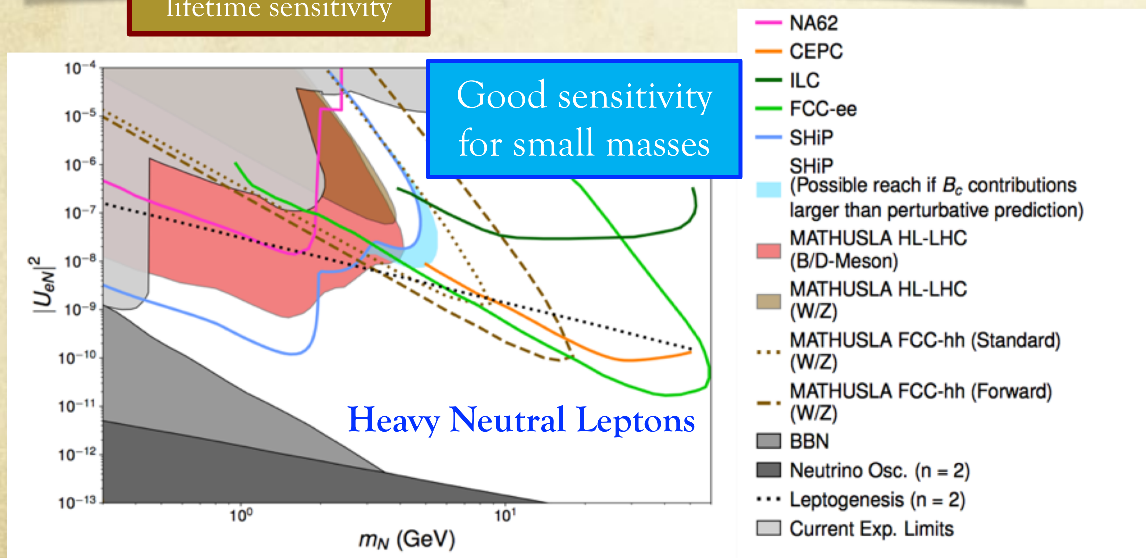


- **Can** probe LLPs at **GeV to TeV**
- **Good sensitivity** for mass scale **above ~ 5 GeV**, and for **lifetime >> 100** m even at low masses



SM+S

Higher sensitivity for long lifetimes

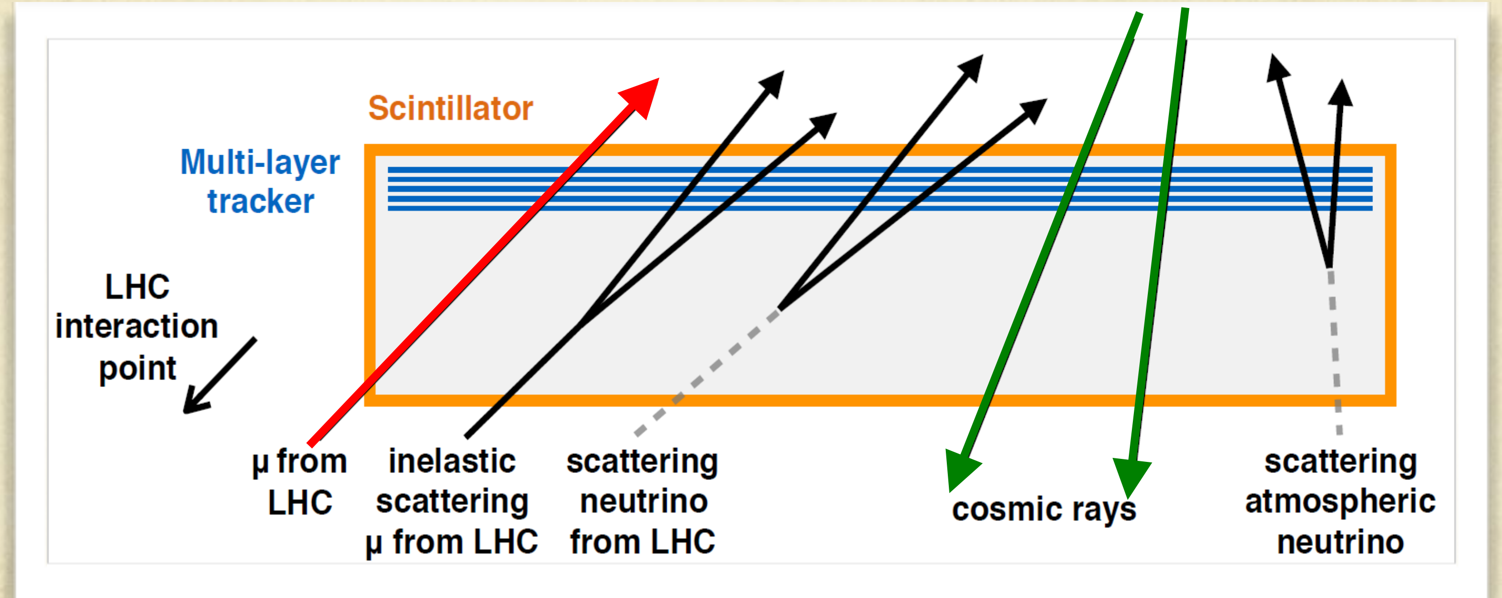


Good sensitivity for small masses

Heavy Neutral Leptons

MATHUSLA – Backgrounds (Part 1)

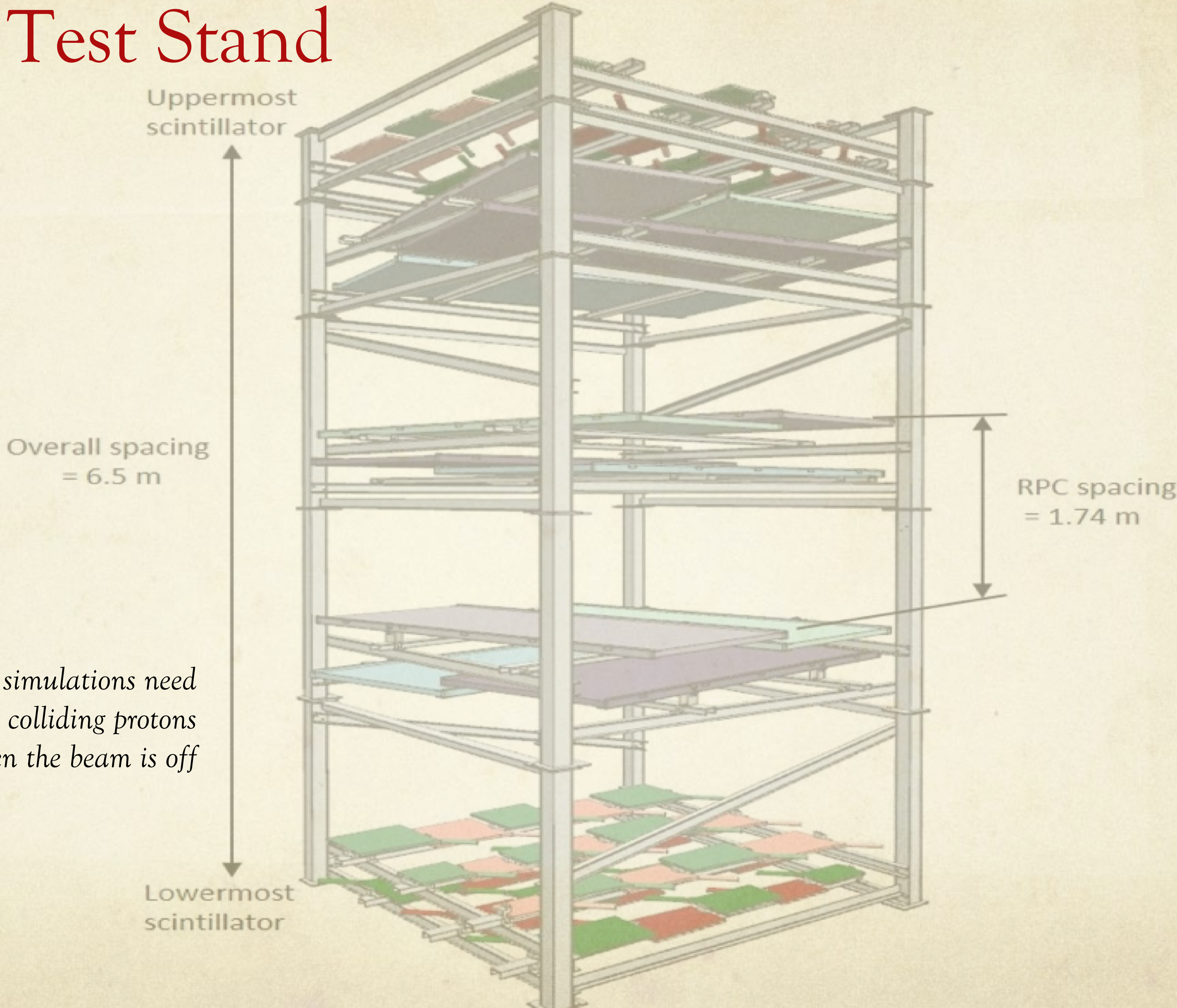
Main backgrounds…



- Cosmic muon rate of about **~2 MHz** (100m^2) and **0.1 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 (reject by timing and geometrical constraints)

…will come back on other possible background sources later

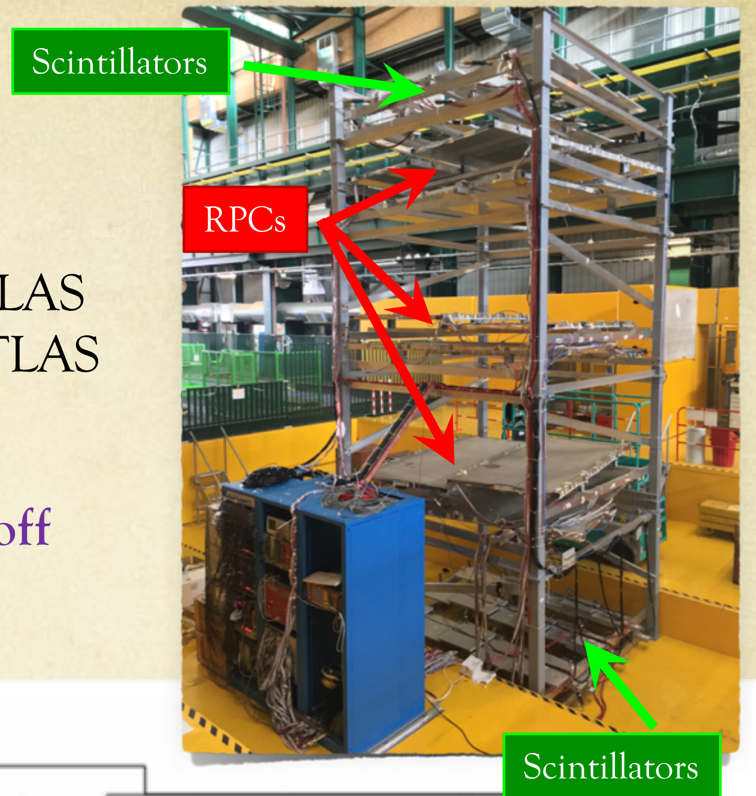
The Test Stand

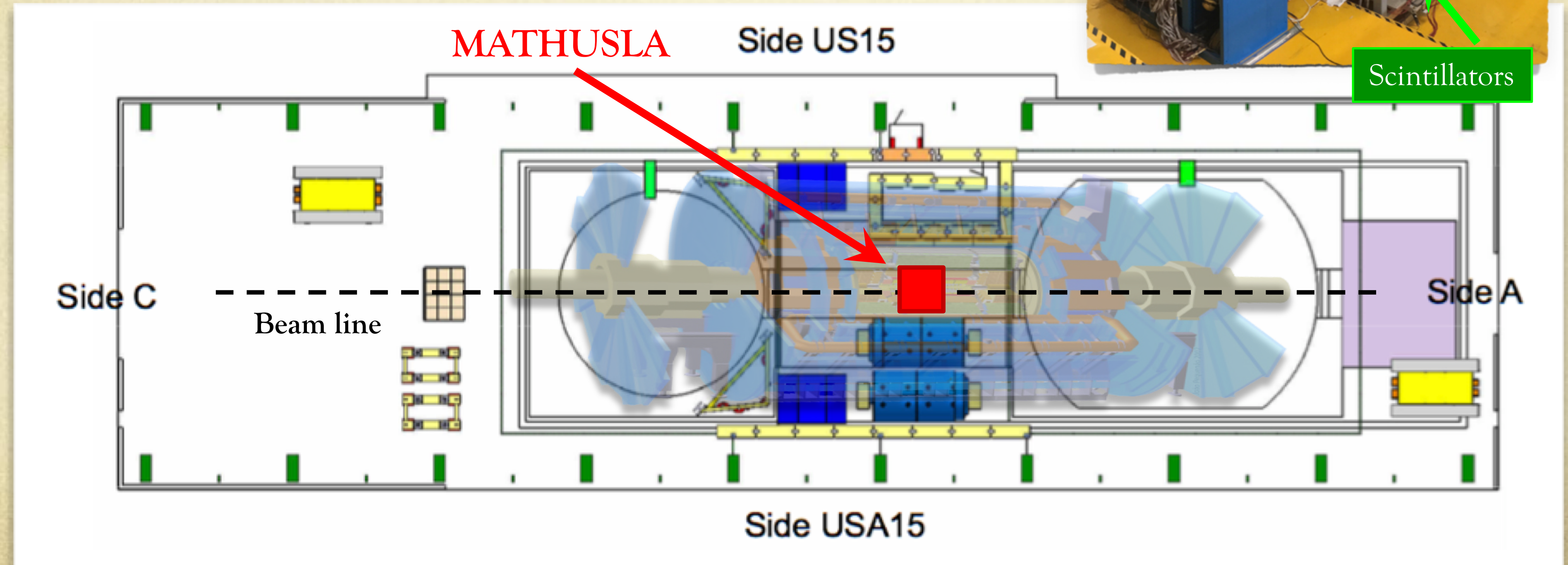


MC background simulations need data with LHC colliding protons and also when the beam is off

Test Stand @ P1

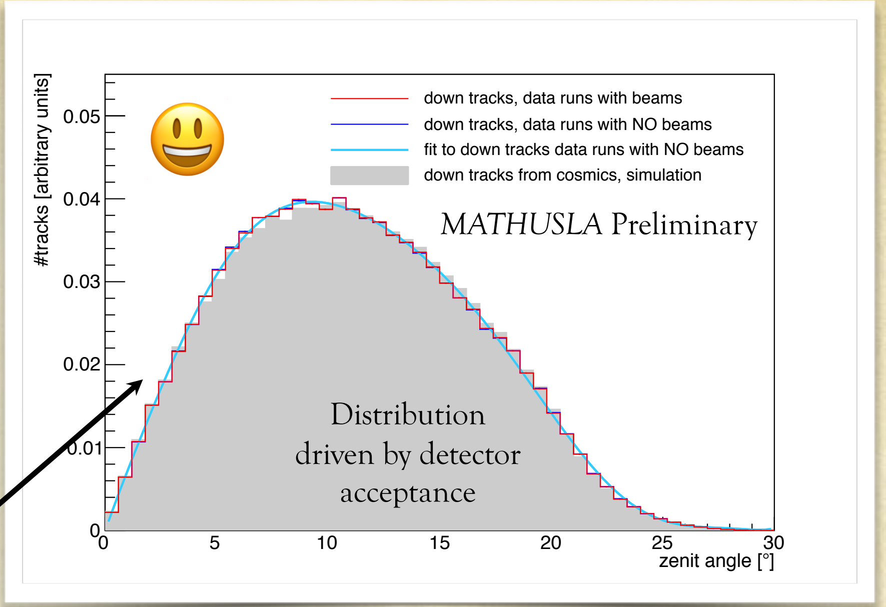
- Need to quantify the background from ATLAS
- Test stand installed on the surface area above ATLAS (~exactly above IP) in November 2017 (during ATLAS operations this space is empty)
  - ✓ Perform measurements with beam on and off during 2018





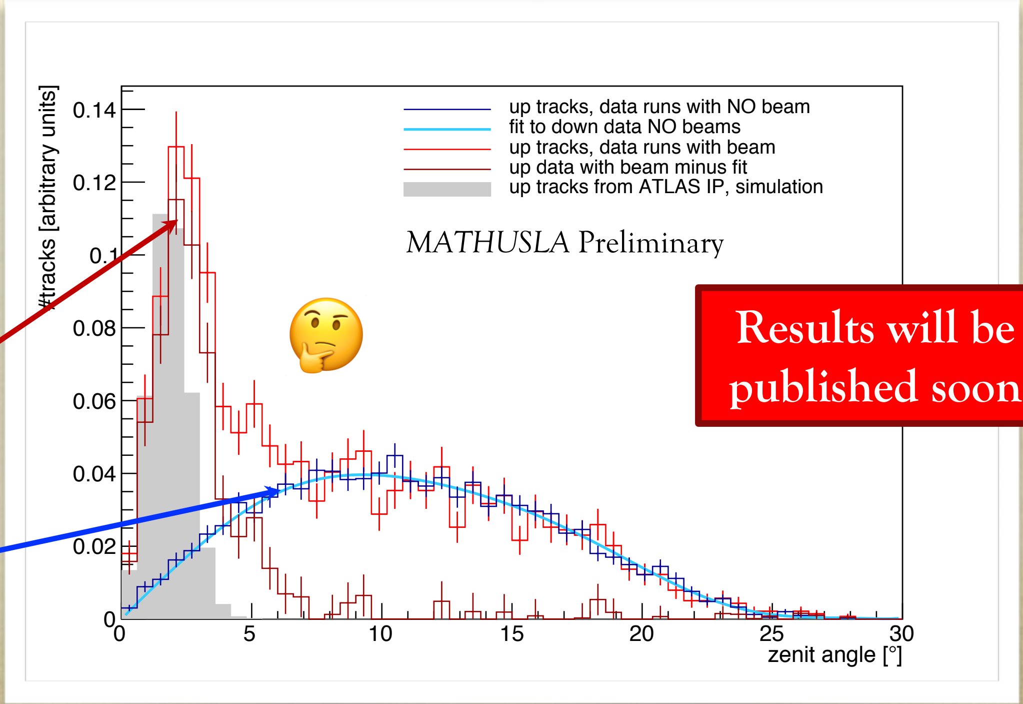
Test Stand Data Analysis

- 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



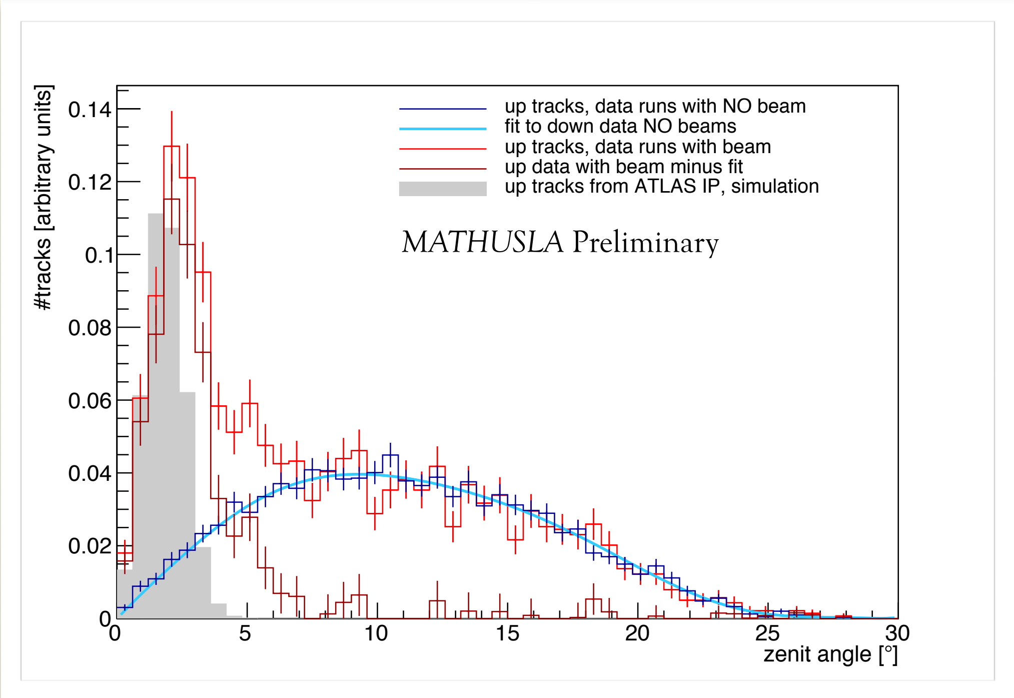
❖ Accumulation for zenith angle < ~ 4° consistent with **upward going tracks from IP when collisions occur**

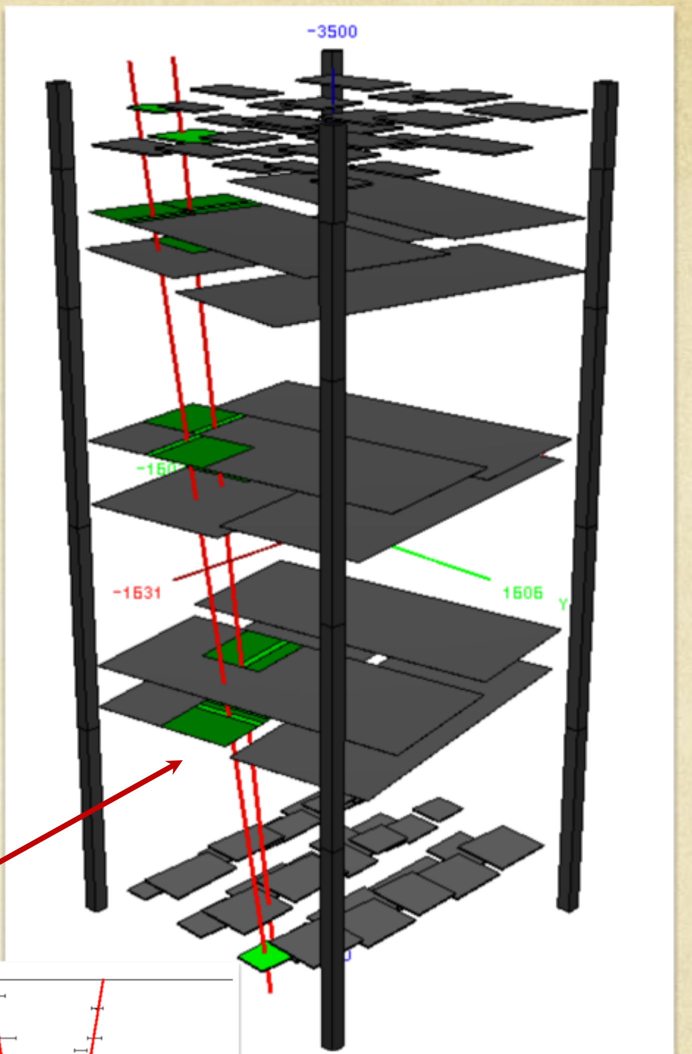
❖ **Up tracks no beam** consistent with **downwards tracks faking upwards** tracks



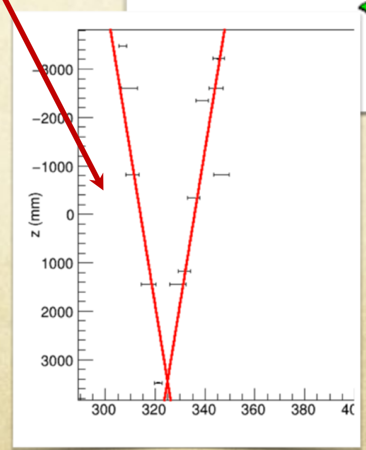
Results will be published soon

Test Stand Data Analysis





- Example of downward track followed by an upward tracks separated by ¼ of the muon lifetime
  - ✓ Are upward tracks with no beam created by cosmic muon hitting the floor or decaying generating upward electrons?
  - ✓ Analysis still on-going…but the hypothesis seems to be confirmed by simulation…



Results will be published soon

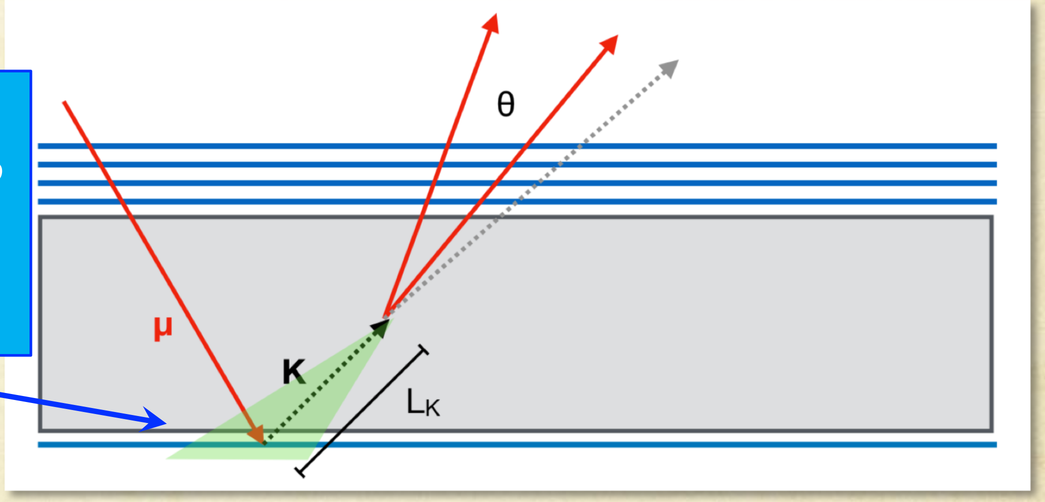
MATHUSLA – Backgrounds (Part 2)

We have learned a lot from the test stand data…

- From preliminary simulations: the albedo that creates SM LLP is made of **muons** (~91%), **e^+-e^-** (~8%), and **protons** (~1%)
- **Expect ~10^8 up-tracks at MATHUSLA** (during entire HL-LHC, assuming LHC always running)
  - ✓ If these particles are fast, they can fake a low-mass boosted BSM LLP
- **K^0_L most dangerous background**

Consider a relativistic K^0_L with b >> 1
→ angle between the charged tracks **~ 1/b**

K^0_L originated from a region of the floor of area ~ $(1/b\ L_K)^2$



- Chance that a real boosted two-pronged LLP decay fails this veto is < ~ 0.01 * $1/b^2$
- Point-back-veto will reduce background from fast SM LLPs

Search for light BSM LLPs should be unaffected by fast SM LLP background!

MATHUSLA – Backgrounds (Part 2)

We have learned a lot from the test stand data…

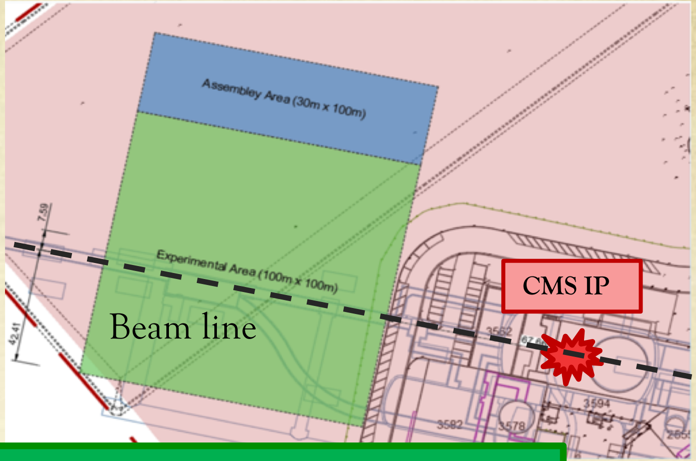
- CRs hitting the floor/walls of MATHUSLA might produce, over its full run,
  - O(1) **pion decaying** to *e e e*
  - O(10-100) probably **fast muons decaying** to *e e e*
  - **Neutrons** are only observable if they are very fast (precise estimations are on-going)
  - O(10^5) K^0_L , mostly non-relativistic

- **Possible requirements (for DVs from LLPs) to eliminate this background**
  1) If the DV has **large opening angle** ($\theta > \theta_{max}$), have at least 3 charged tracks,
     - ✓ LLPs with mass > several GeV decaying to hadrons will pass with efficiency ~ 1
  2) OR if DV has **small opening angle** ($\theta < \theta_{max}$), require no CRs hitting the possible floor/wall areas where a kaon could have come from, AND to point back to IP
     - ✓ A light LLP produced in meson decays will almost always pass
  3) OR if DV **has two charged tracks** with large opening angle, require no CRs in detector within ~500ns of DV
     - ✓ Heavy LLPs decaying to two leptons will always fail 1), 2), and 3) (with some O(1) chance) → some reduction in sensitivity (BUT least motivated physics target)

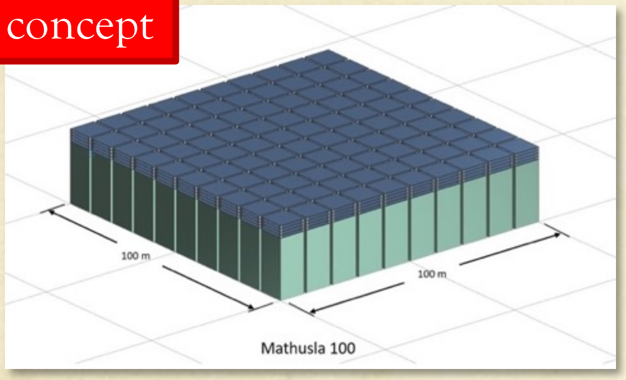
Detector layout and technology

MATHUSLA @ P5

- Worked 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

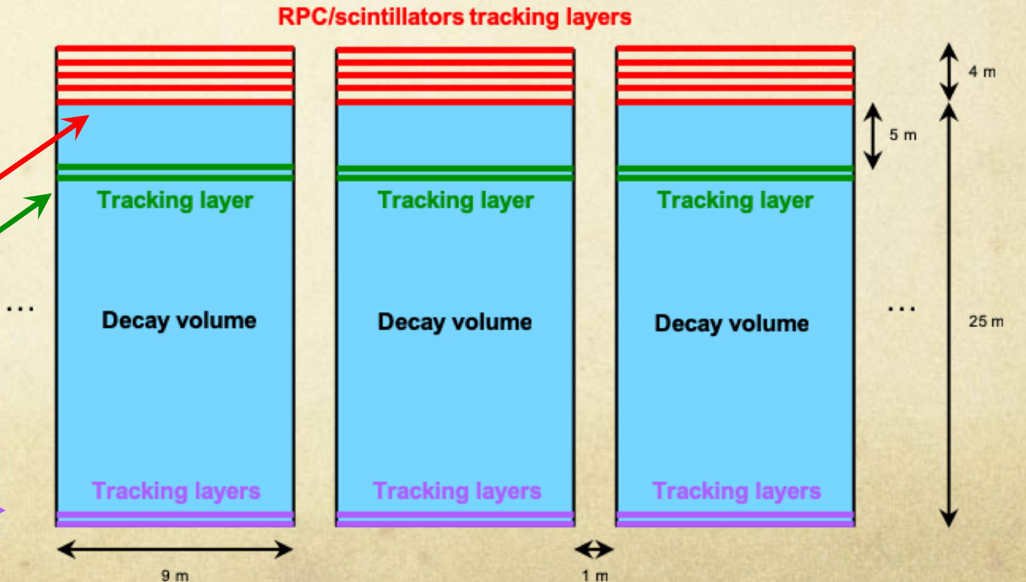


Modular concept



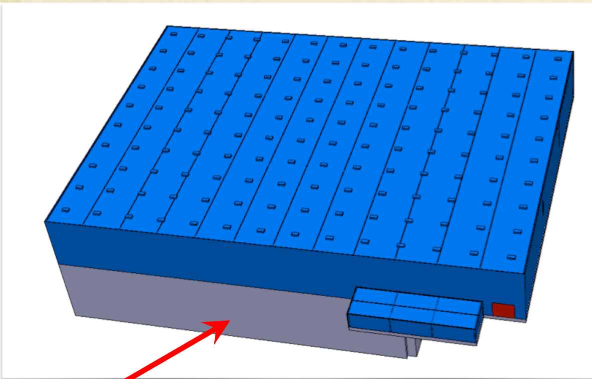
- 68 m to IP on surface and IP ~80m below surface
- ~7.5m offset to the beam line

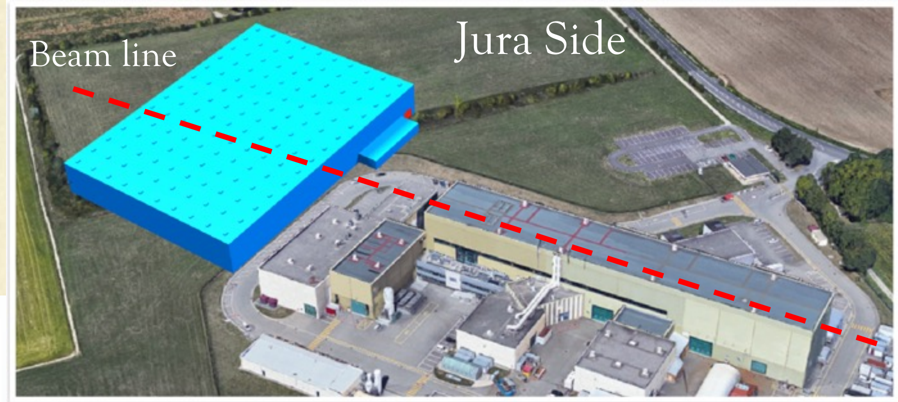
- Assume ~ 25 meter decay volume
- Individual detector units **9 x 9 x 30 m³**
- 5 layers of tracking/timing detectors separated by 1m
- Additional tracking/timing layer 5m
- Double layer floor detector (tracking/timing)



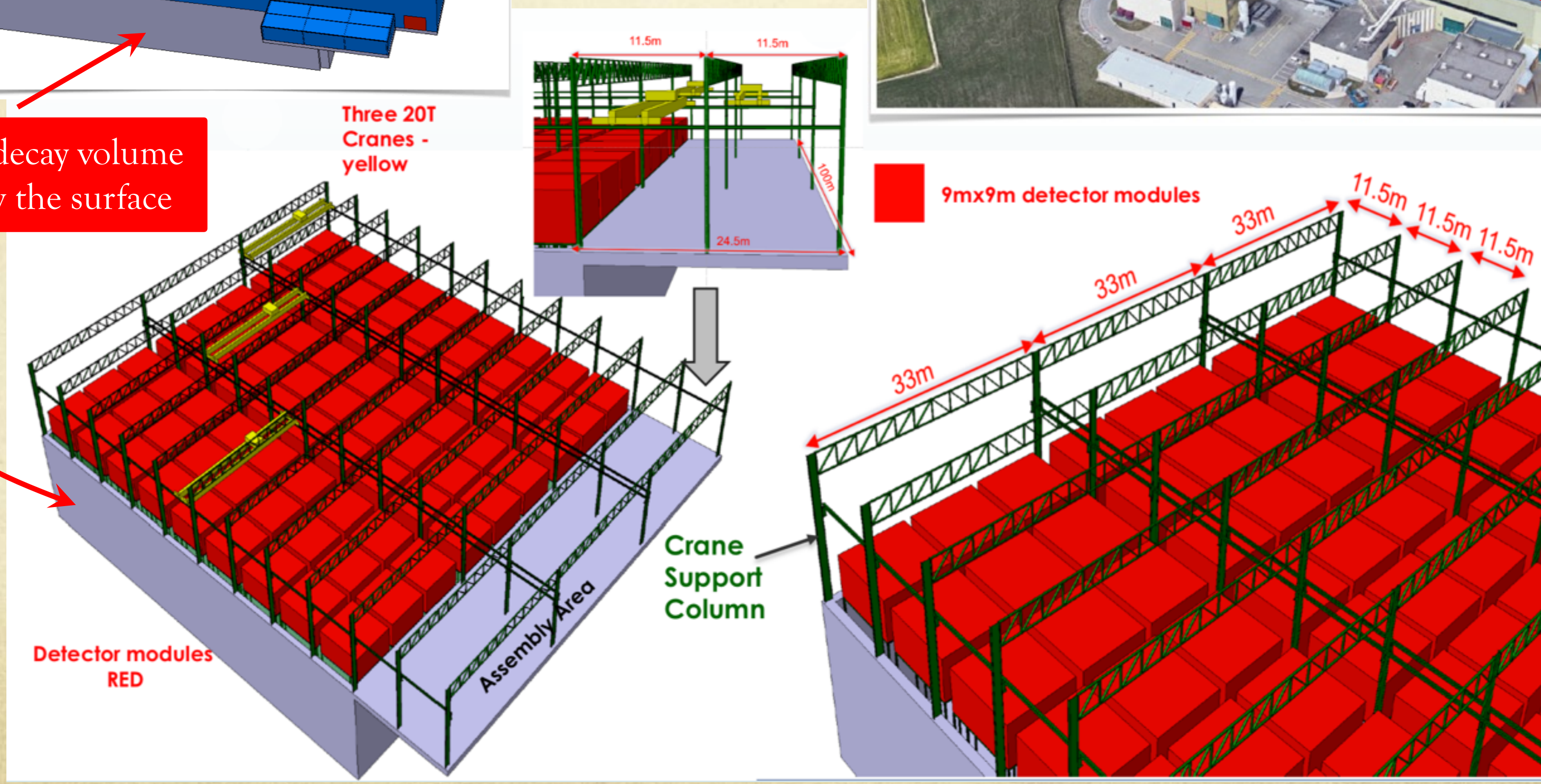
MATHUSLA @ P5

- Worked 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



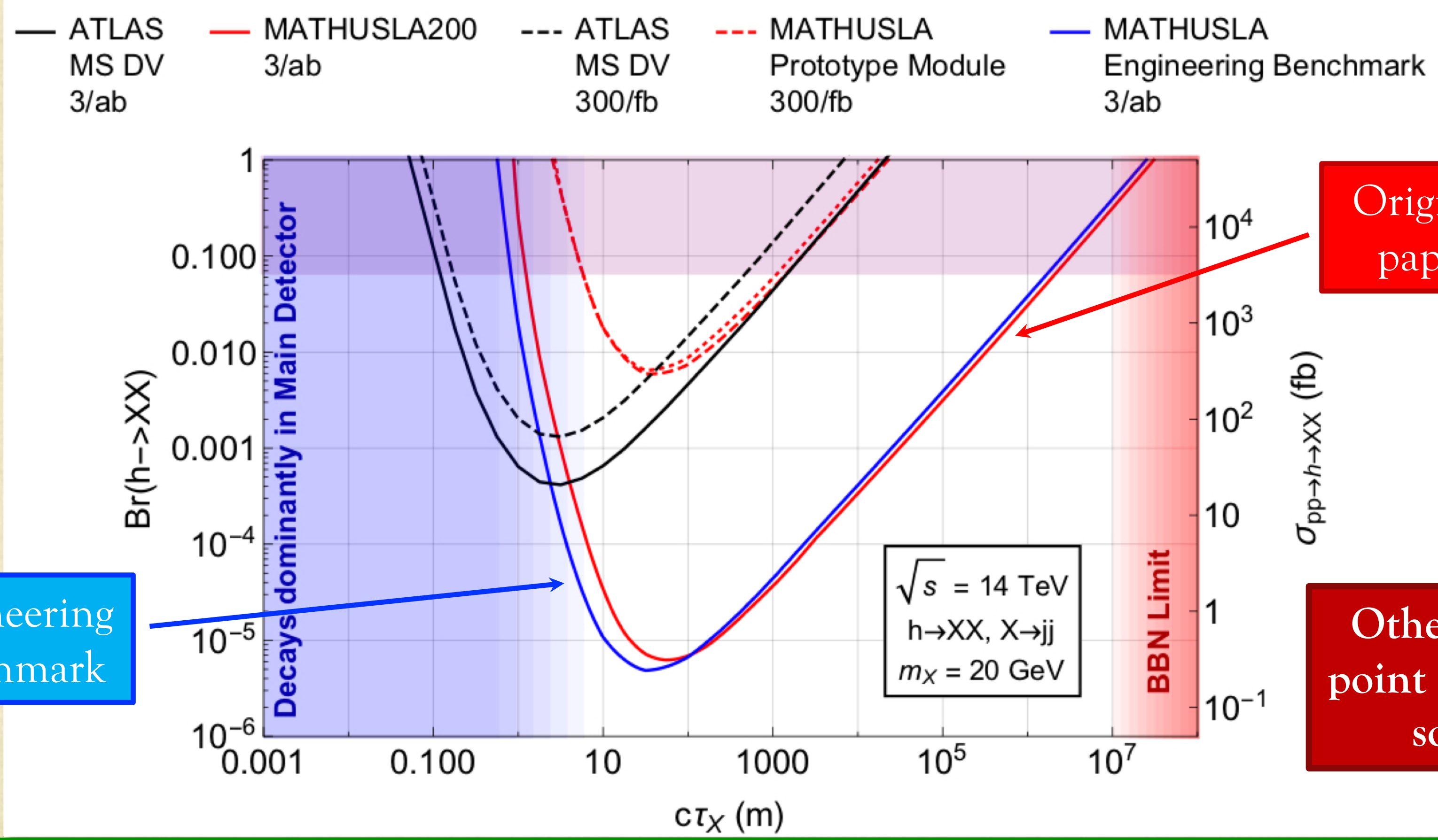


20 m decay volume
Below the surface



MATHUSLA @ P5

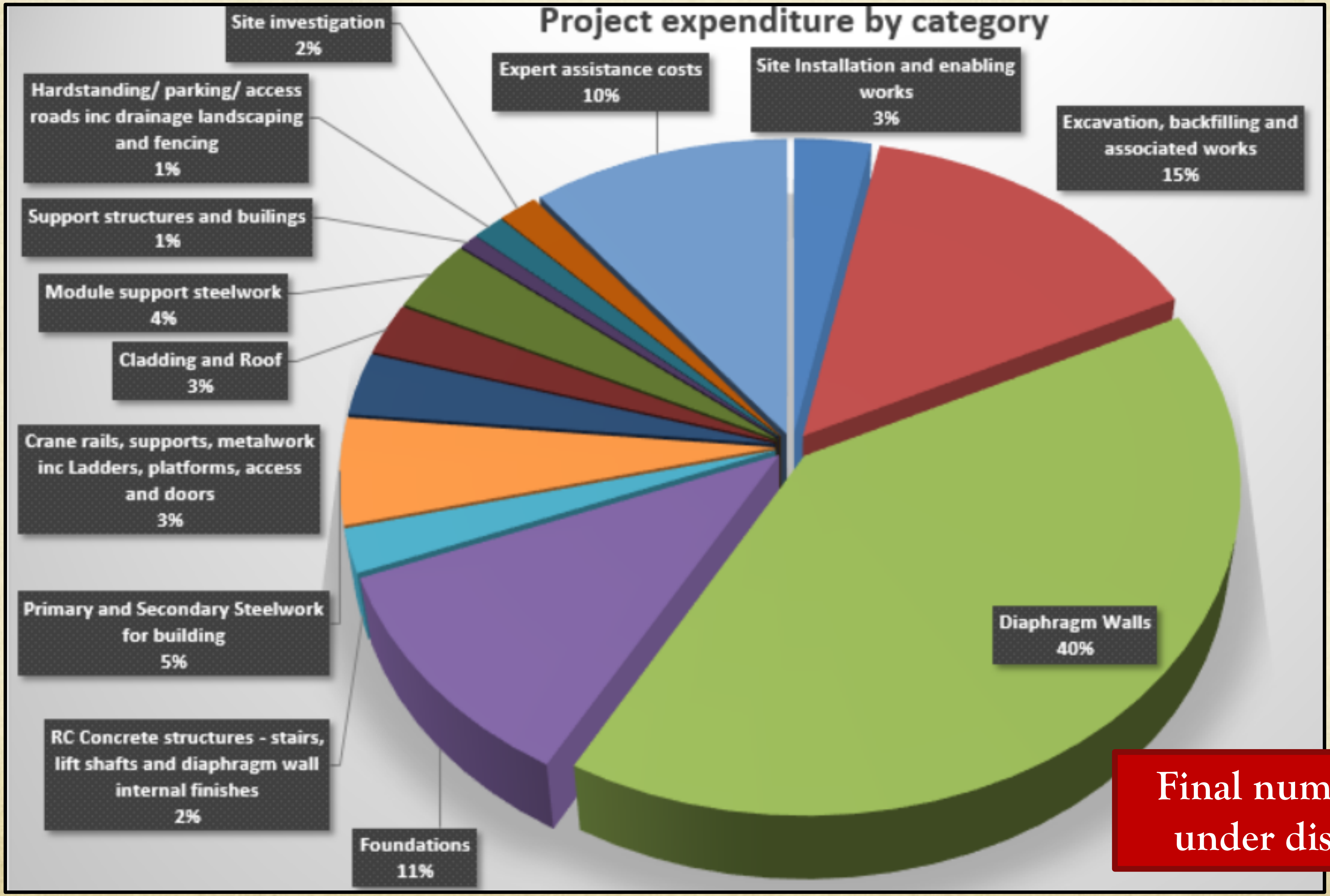
- Worked with Civil Engineers to define the **building and the layout of MATHUSLA at P5**
- **Layout restricted by existing structures** based on current concept and engineering requirements



More details on the comparison MATHUSLA200/Engineering benchmark in
Imran Alkhatib thesis, "*Geometric Optimization of the MATHUSLA Detector*" - arXiv:1909.05896

MATHUSLA @ P5

- Worked 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



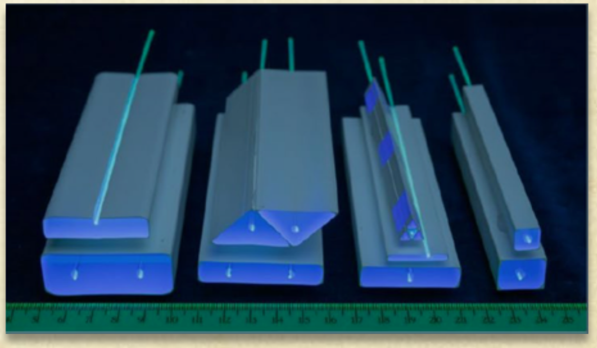
Final numbers still under discussion

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

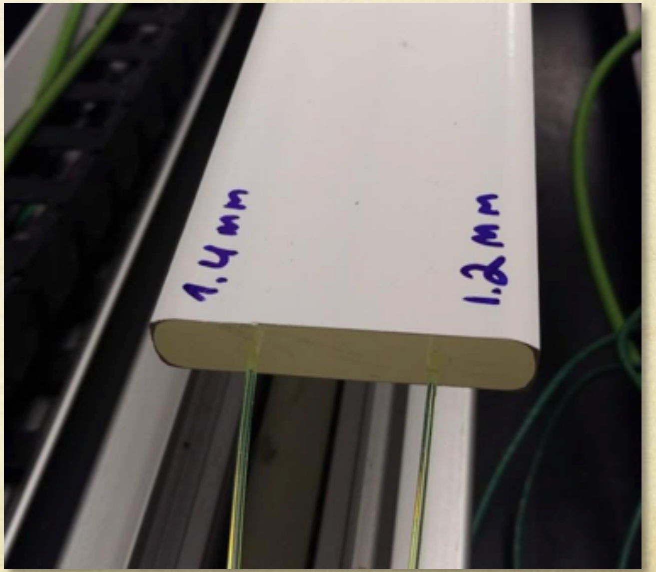
Extruded scintillator bars with wavelength shifting fibers coupled to SiPMs makes this technology cost wise competitive with RPCs



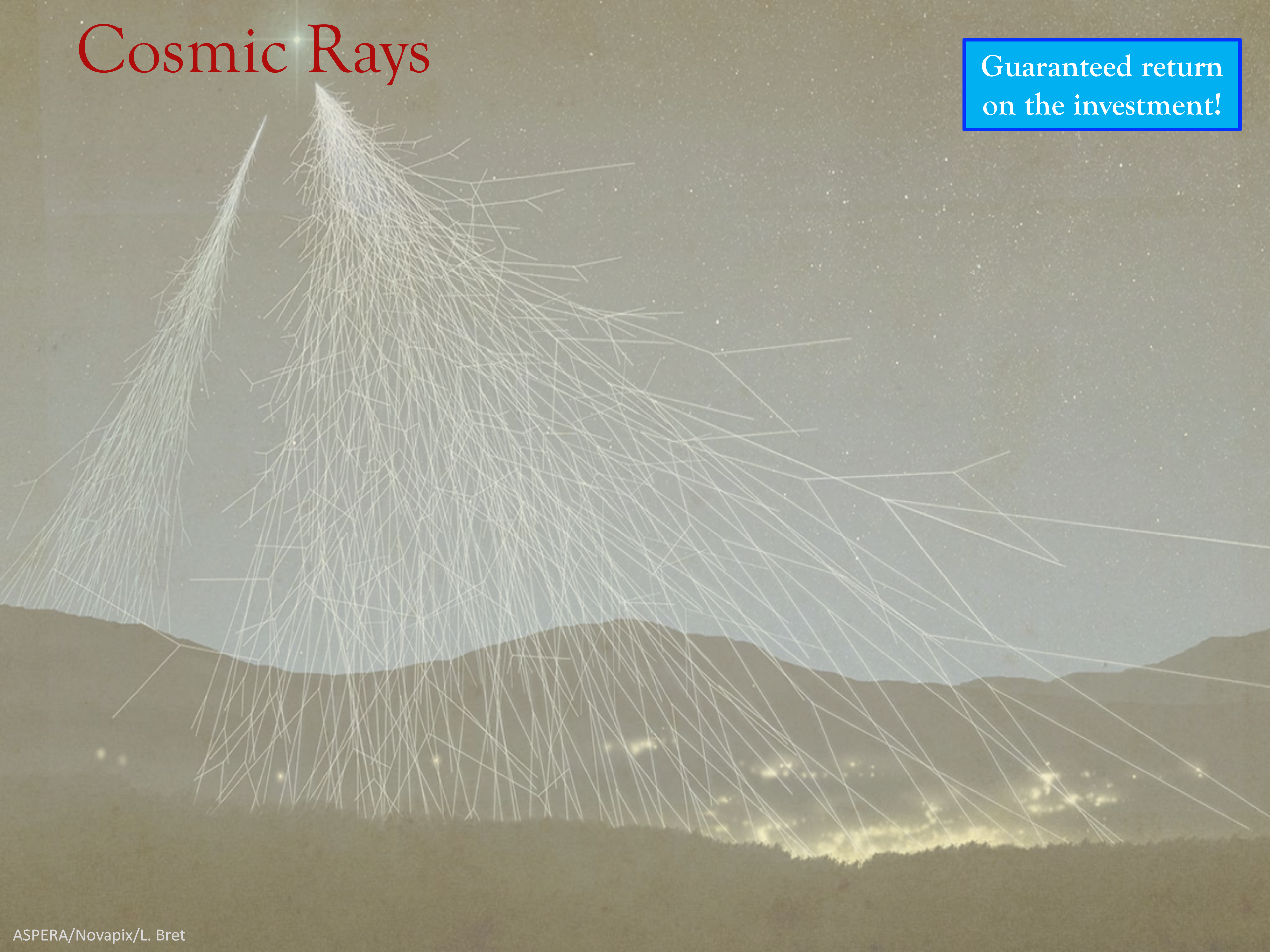
- ✓ Pros ☺
  - SiPMs operate at **low-voltage** (25 to 30 V)
  - **No gas** involved
  - **Timing resolution can be competitive with RPCs**
  - Tested extrusion facilities - FNAL and Russia. Used in several experiments: Bell muon system trigger upgrade (scintillators from FNAL and Russia), Mu2E, and 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 quantity (1⁄2 labor, 1⁄2 chemicals)
  - Target of **$10/kg in large quantity**
- Tested at Fermilab
  - 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 **Other solutions are possible**
  - **0.5 cm** thick bars? 1 cm thick bars.
  - **Two fibers** present in extrusion

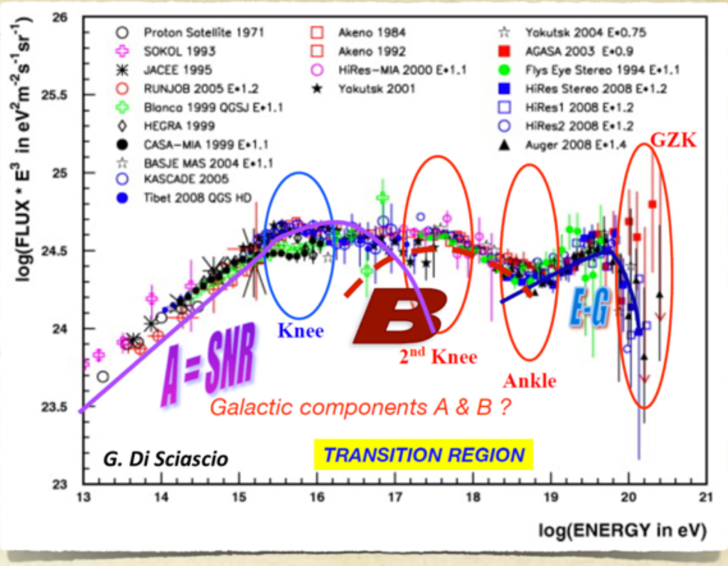


Cosmic Rays



ASPERA/Novapix/L. Bret

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**)

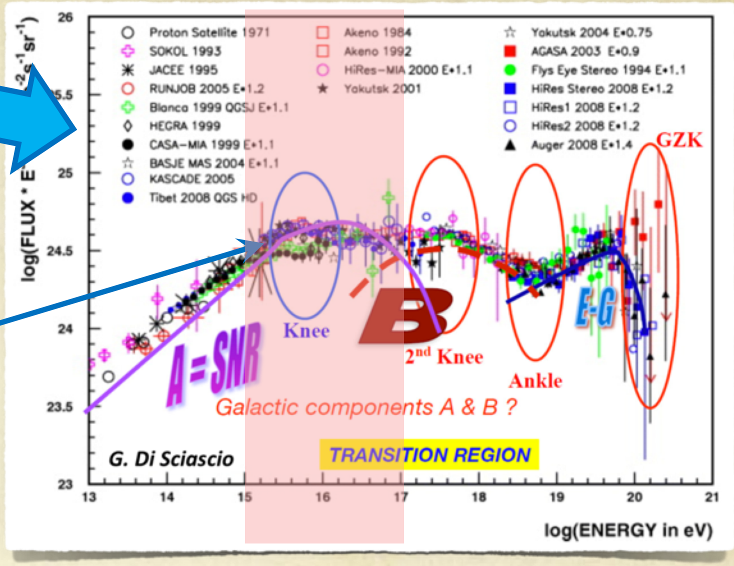
❑ MATHUSLA+CMS

- ✓ 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 bunch crossing (at HL-LHC trigger has ~12 microsecond latency)

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)

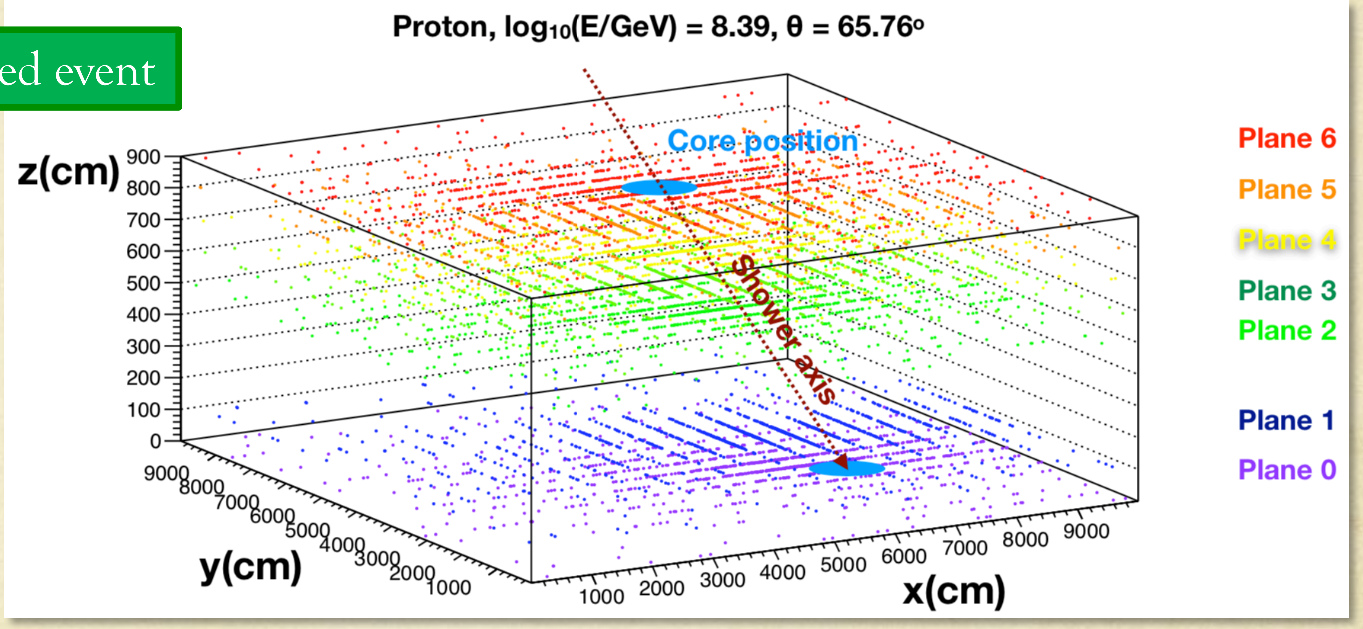


- The full coverage of **MATHUSLA100** will allow a lower energy threshold (~ 100 GeV) than KASCADE (~ 1 PeV)
  - ✓ Lower threshold allows **comparison with satellite measurements** (CREAM, Calet, HERD)
- With the ability to measure several different parameters it should be possible to **separate** with 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)

Extensive Air Showers Studies

- Studied MATHUSLA performance for **inclined** (> 60 degrees) **EAS** induced by **Fe/H nuclei**
- CR simulated using **CORSIKA**. Core of the EAS put at the center of MATHUSLA
- For these tests considered **4 cm x 5 m** scintillator bars. **Coordinate of the hit = center of the bar**
- Only register the **arrival time of the 1st particle** that reaches the bar (in a **1 ns window**)

Reconstruction of inclined event

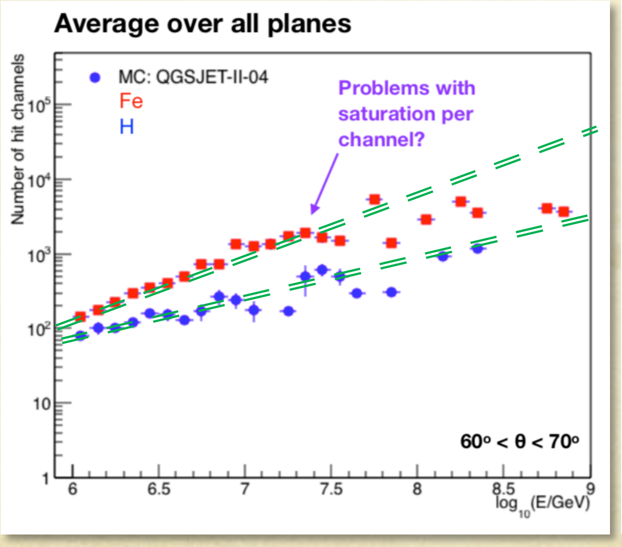


- The **number of hits depends on** the **amplitude of the distribution**, the **inclination of the profile**, and **x coordinate of the core position**

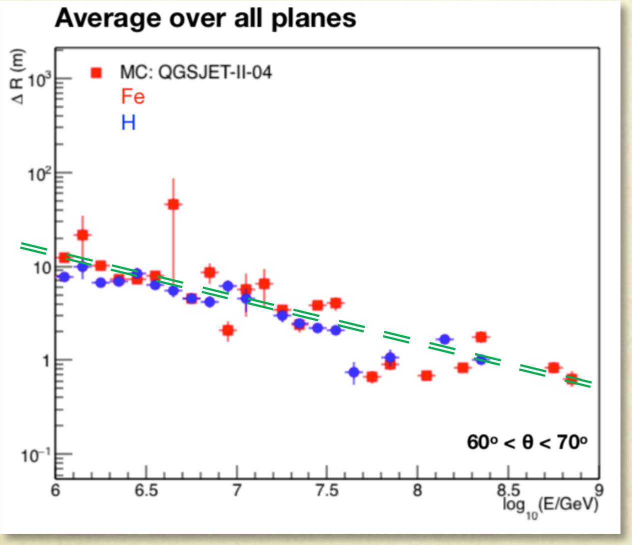
Extensive Air Showers Studies

- Studied MATHUSLA performance for inclined (> 60 degrees) EAS induced by **Fe/H nuclei**
- CR simulated using **CORSIKA**. Core of the EAS put at the center of MATHUSLA
- For these tests considered **4 cm x 5 m** scintillator bars. **Coordinate of the hit = center of the bar**
- Only register the arrival time of the 1st particle that reaches the bar (in a 1 ns window)

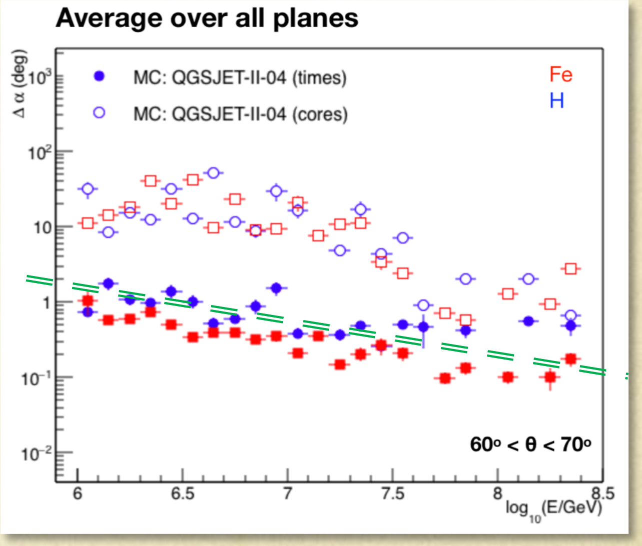
Energy estimation



Core position meas. bias



Core direction meas. bias



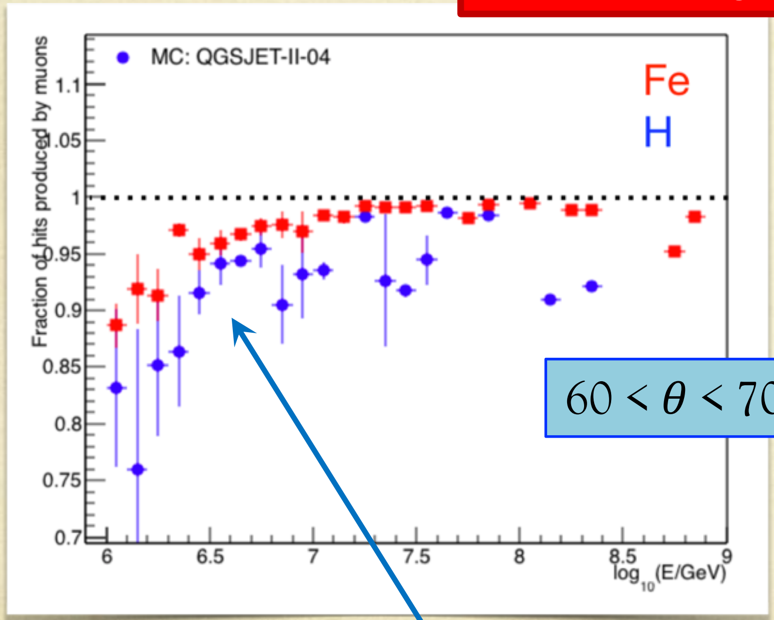
The number oh hits increases with E

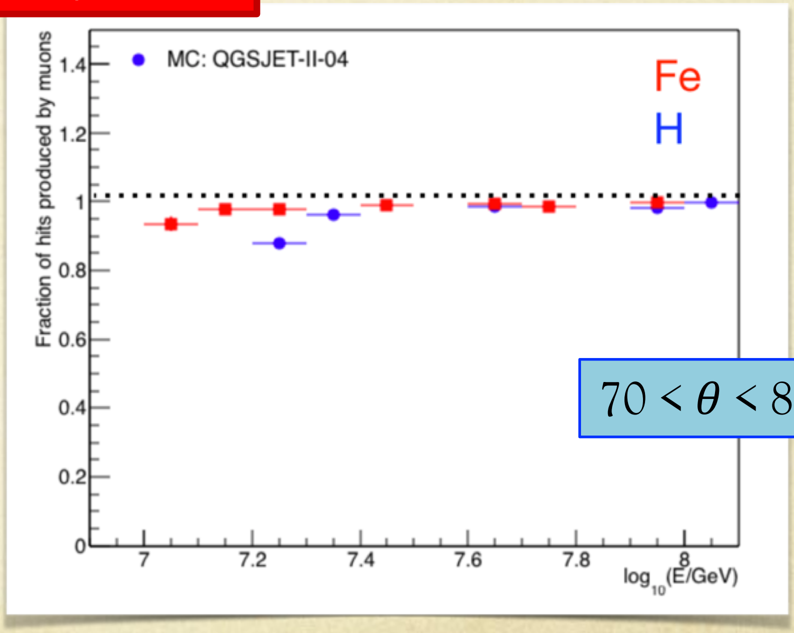
- Used only events with $N_{hits} > 100$
- Bias decreases with primary energy

Extensive Air Showers Studies

- Studied MATHUSLA performance for **inclined** (> 60 degrees) **EAS** induced by **Fe/H nuclei**
- CR simulated using **CORSIKA**. Core of the EAS put at the center of MATHUSLA
- For these tests considered **4 cm x 5 m** scintillator bars. **Coordinate of the hit = center of the bar**
- Only register the arrival time of the 1st particle that reaches the bar (in a 1 ns window)

Fraction of signals induced by muons





Fraction of muons > 90% for E > $10^{6.5}$ GeV

Very high efficiency

What Can We Learn From CM? (1)

- MATHUSLA's excellent tracker will allow to study the **spatial distribution of the arrival direction of cosmic rays with high precision**
  - ✓ **PHYSICS OUTCOMES**
    - Study **cosmic ray anisotropies** in more detail
    - Important to constrain the **propagation of cosmic rays in the interstellar space**
    - Constrain models of **the interstellar magnetic field**

- MATHUSLA's detector planes will allow to study **muon bundles for inclined air showers**
  - ✓ **Origin of muon bundles is unknown!** New physics? Problem with hadronic interaction models? Differences due to the heavy component of CRs?
  - ✓ **PHYSICS OUTCOMES**
    - Set limits to BSM physics
    - **Test hadronic interaction models at high energies**
    - Sensitive to the relative abundances mass groups of cosmic rays

What Can We Learn From CM? (2)

- MATHUSLA's design will allow to measure the **muon content of inclined air showers**
  - ✓ Time structure of EAS, truncated muon number, radial densities, production height
  - ✓ General distribution of directional tracks and spatial structure
  - ✓ **Measurements at the shower cores are possible for very inclined events**
  - ✓ PHYSICS OUTCOMES
    - **Constrain QCD at the highly forward**, high $\sqrt{s}$ region: this region is mostly non perturbative in QCD and it is treated with phenomenological models, which are tuned with results of particle accelerators at energies lower than what found in cosmic rays
    - **May help to make ALL OTHER CR measurements (spectra, composition,…) more reliable, including other experiments that probe higher energy ranges and CR from extra galactic origin**

Summary & Conclusions & Plans

- MATHUSLA is a complementary detector
  - ✓ Can made the LHC LLP search program more comprehensive
  - ✓ Can have the potential to significantly **enhance and extend the new physics reach** and capabilities of the current LHC detectors
- **Test stand analysis almost finalised and results will be published soon**
  - ✓ Results will be crucial for the design of the main detector
- Several **cosmic ray studies** on-going
  - ✓ Simulations showed good performance for **inclined EAS** (**quite good angular resolution**)
  - ✓ MATHUSLA can do nice and **competitive measurements for very inclined showers**
- 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

The MATHUSLA Collaboration

STANFORD

KIT
Karlsruher Institut für Technologie

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

UNIVERSITY OF TORONTO

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Fermilab

Virginia Tech

BOSTON UNIVERSITY

NISER

UNIVERSITY OF OXFORD

TEL AVIV UNIVERSITY

UNACH Universidad Autónoma de Chiapas

SLAC NATIONAL ACCELERATOR LABORATORY

Università di Roma Tor Vergata

CAL STATE EAST BAY

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

INFN Istituto Nazionale di Fisica Nucleare
Sezione di Bari

cnrs IN2P3

UNIVERSIDAD NACIONAL DE LA PLATA

UNIVERSITÀ DEL SALENTO

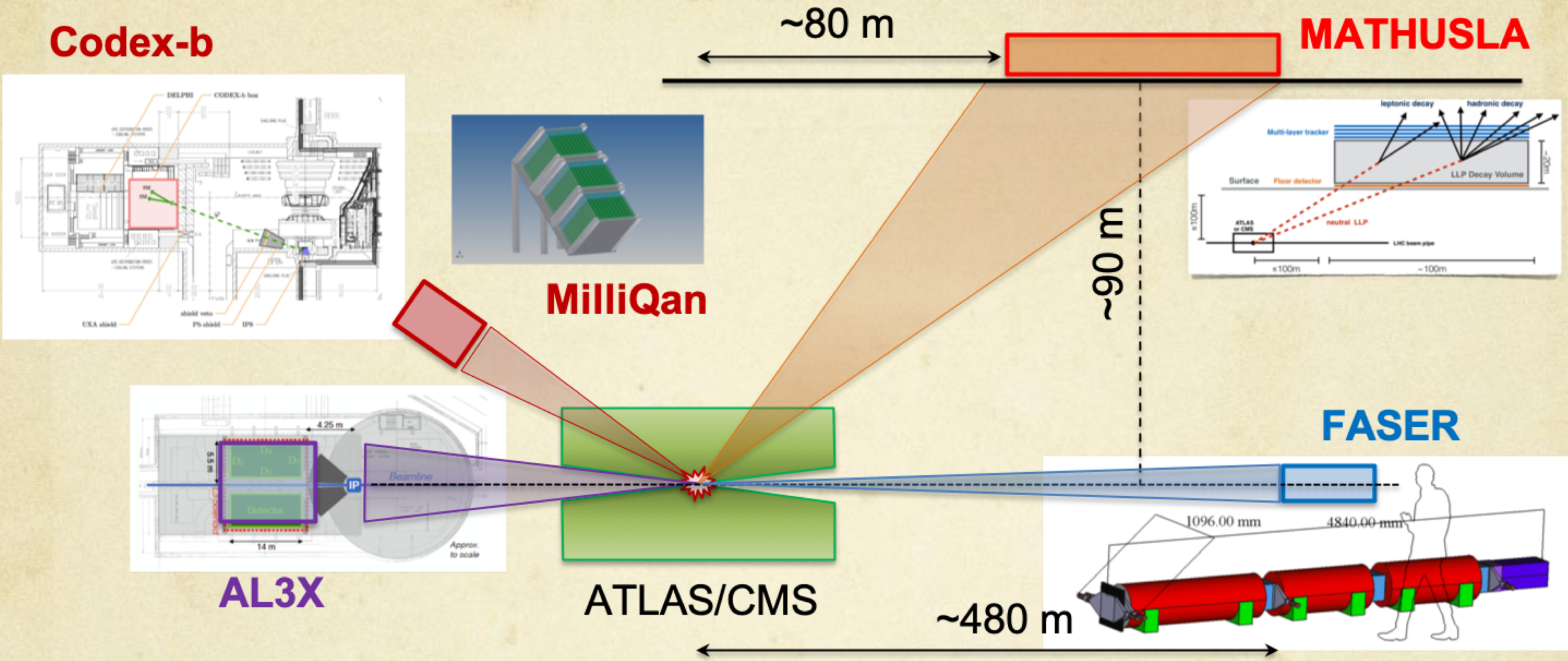
CERN

Institute of High Energy Physics
Chinese Academy of Sciences

THE UNIVERSITY OF ARIZONA

BACKUP

New Projects @ LHC

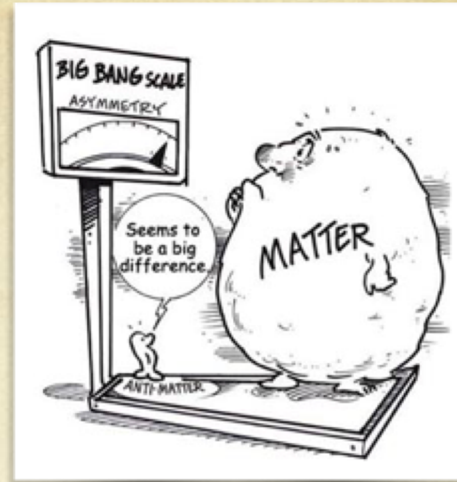


- For long c∗τ detector sensitivity ∝ angular coverage and detector size

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!**

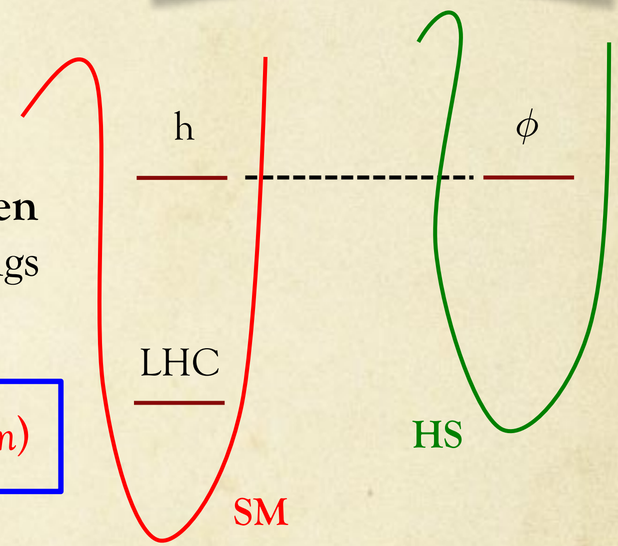
The Hidden Sector



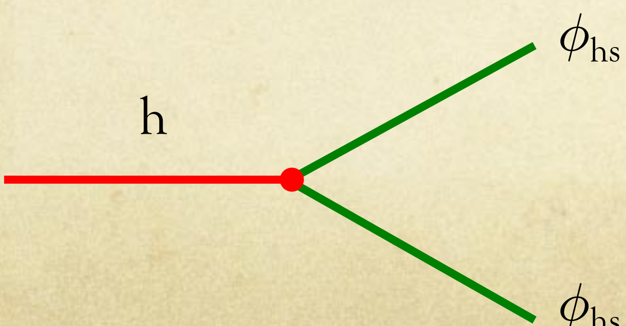
- The Standard Model (SM) is in amazing agreement with the experimental data, but **still some problems remain unsolved**: dark matter, neutrinos masses, hierarchy, matter-antimatter asymmetry…

- 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 (γ, 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 $\Rightarrow$ 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-cτ)
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent

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:

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

ϵ = geometrical acceptance along ULLP

L = size of the detector along ULLP direction

$b \sim m_h/(n \cdot m_X) \leq 3$ for Higgs boson decaying to n = 2, $m_X \geq 20$ GeV

❖ **To collect a few ULLP decays with $c\tau \sim 10^7$ 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**

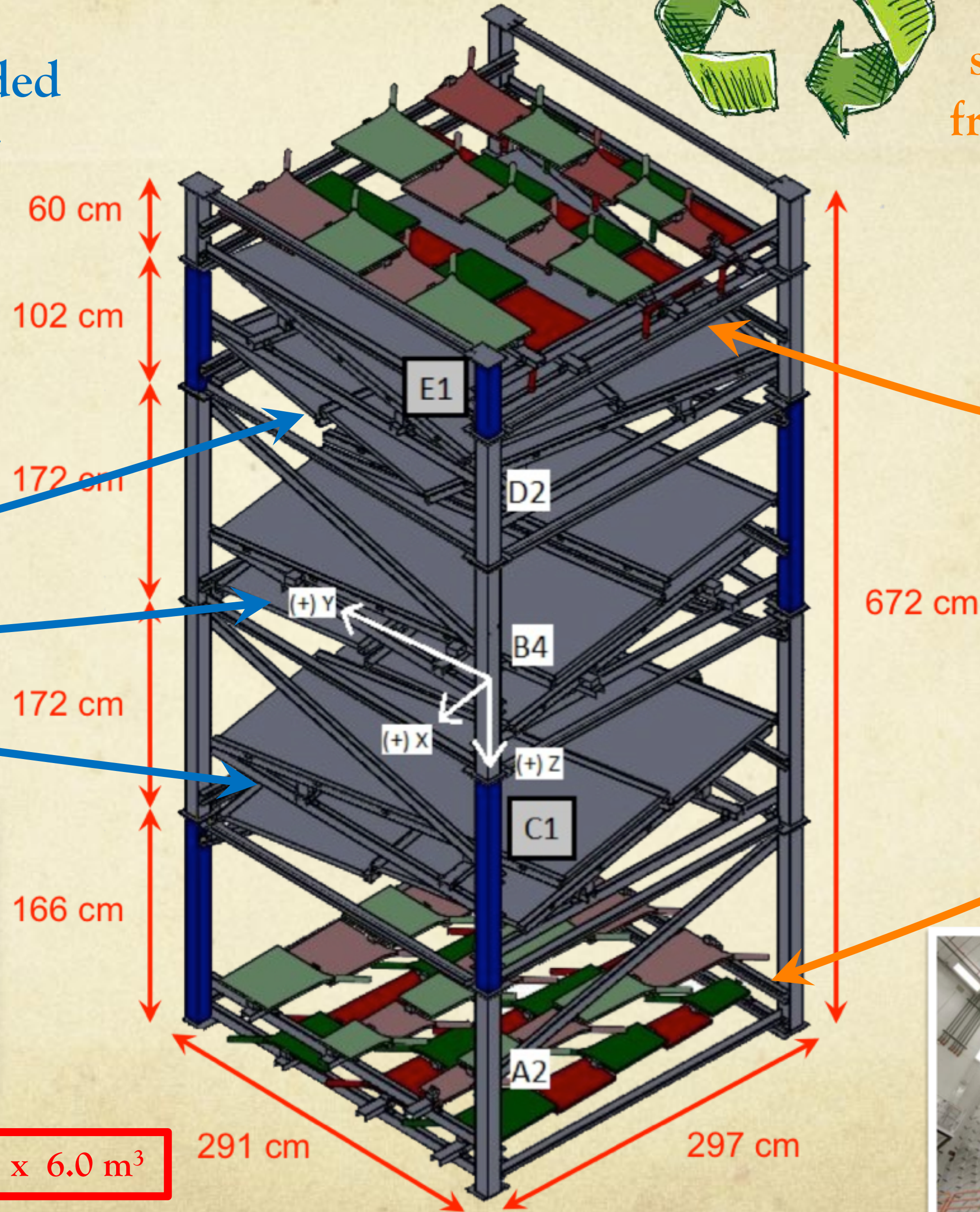
The past…

- **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

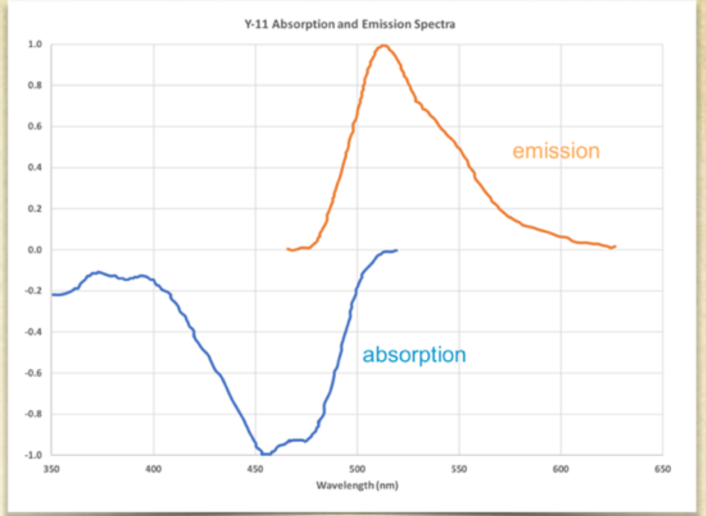
3 layers of RPCs provided by University of Tor Vergata (Rome) by Rinaldo Santonico (from Argo-YBJ Experiment)

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



Active area ~ 2.5 x 2.5 x 6.0 m^3

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

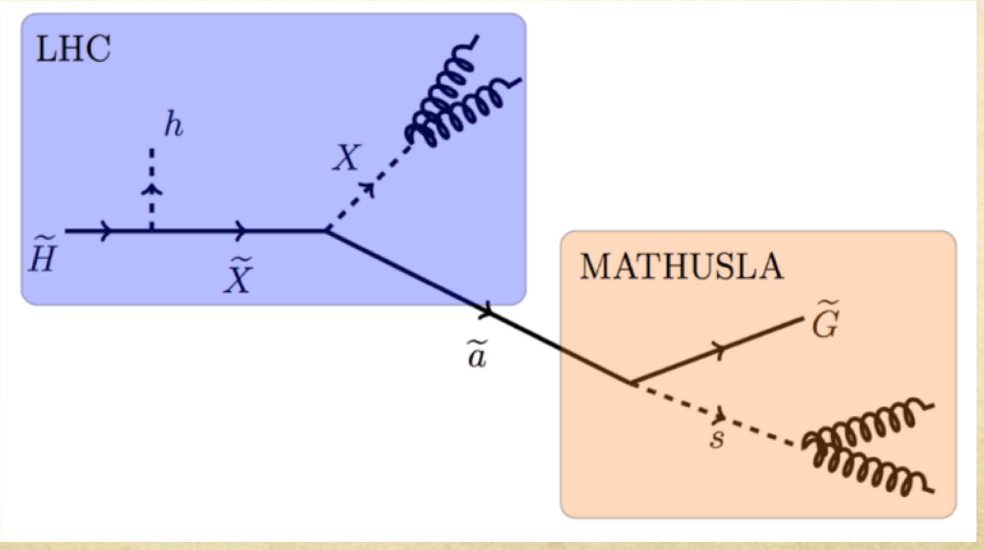
Possible options:
- S14160-3050HS: 3x3mm
- S14160-6050HS: 6x6mm

Readout & Data Taking

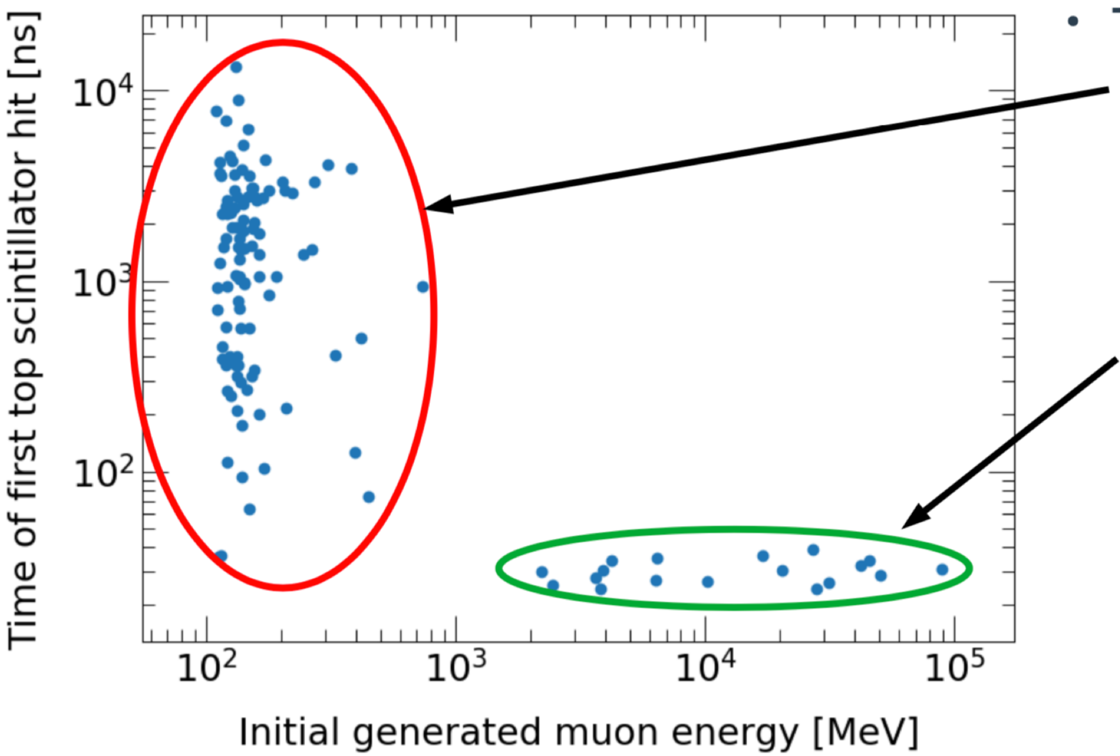
- **Readout**
  - **8 tracking layers** (5 tracking layers + 5m below + 2 on the floor)
  - 4 cm scintillators with readout in both ends results in 800K channels
  - Rates dominated by cosmic ray rate (~2 MHz)
    - ✓ Does not require sophisticated ASIC
    - ✓ Aiming for 1 CHF per channel for frontend
- **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



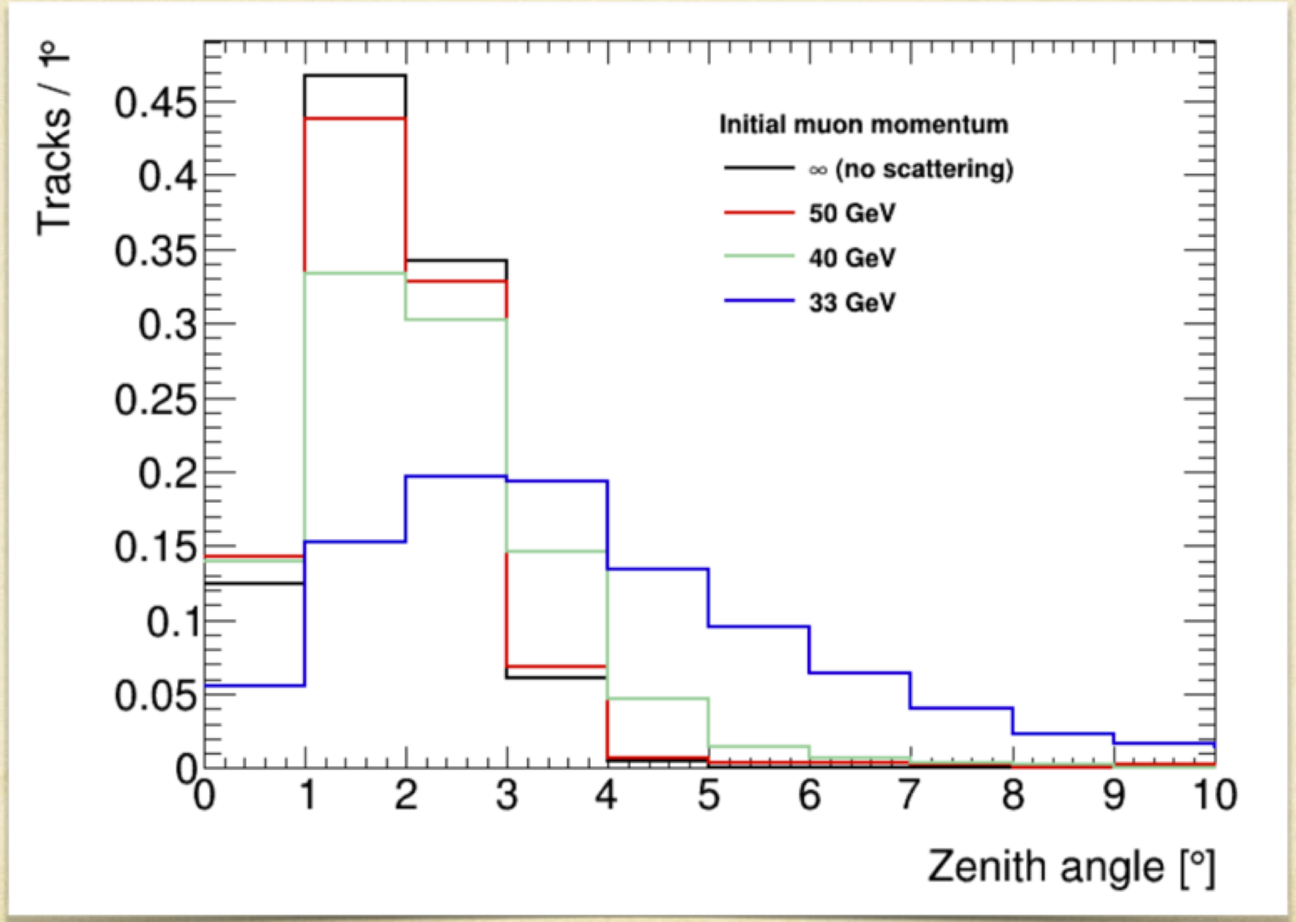
Time Upward Tracks vs Initial Muon Energy



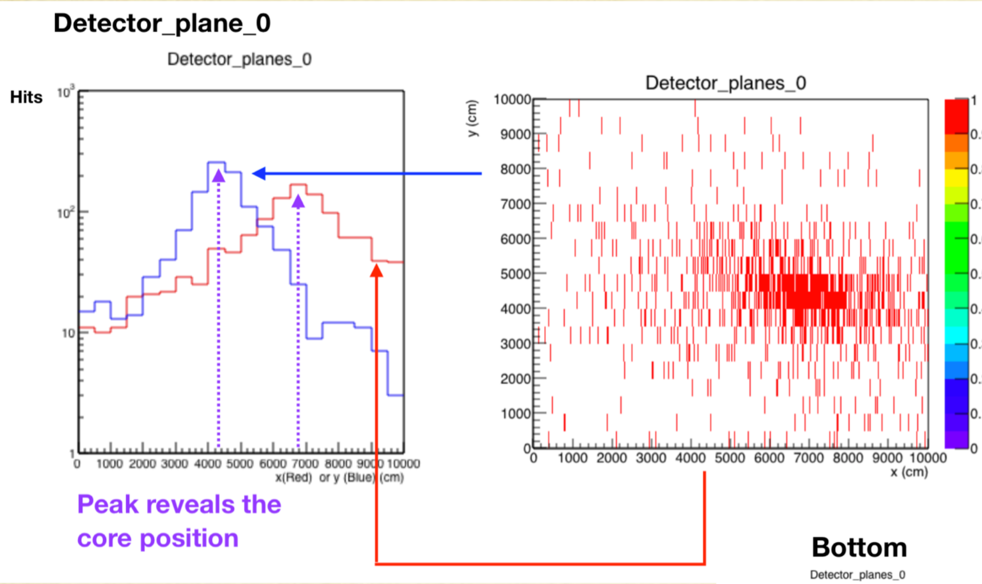
- **Two distinct populations!**
  - Late/delayed upward tracks
    - Predominantly from very low energy muons
    - These are muon decay products (e^+/e^-)
  - Prompt upward tracks
    - From relatively high energy muons
    - True "albedo"
    - These are secondary particles (from muon ionization/radiation) which happen to be emitted upward or scatter upward
    - e^+/e^-, π^+/π^- ($\rightarrow \mu^+/\mu^-$), p^+, ...

Multiple Scattering Contributions

- Energy of upward IP muon has significant effect on track zenith angle



EAS Core Position Estimation - Details



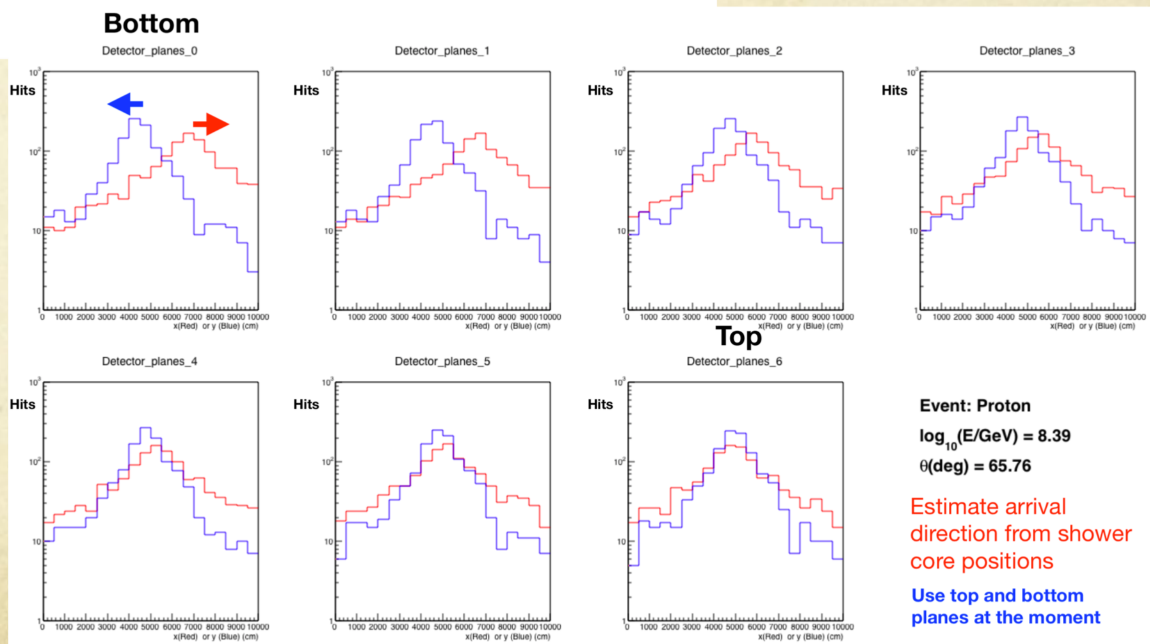
Hits = a_x $e^{-b_x|x - xc|}$

a_x = Amplitude of distribution

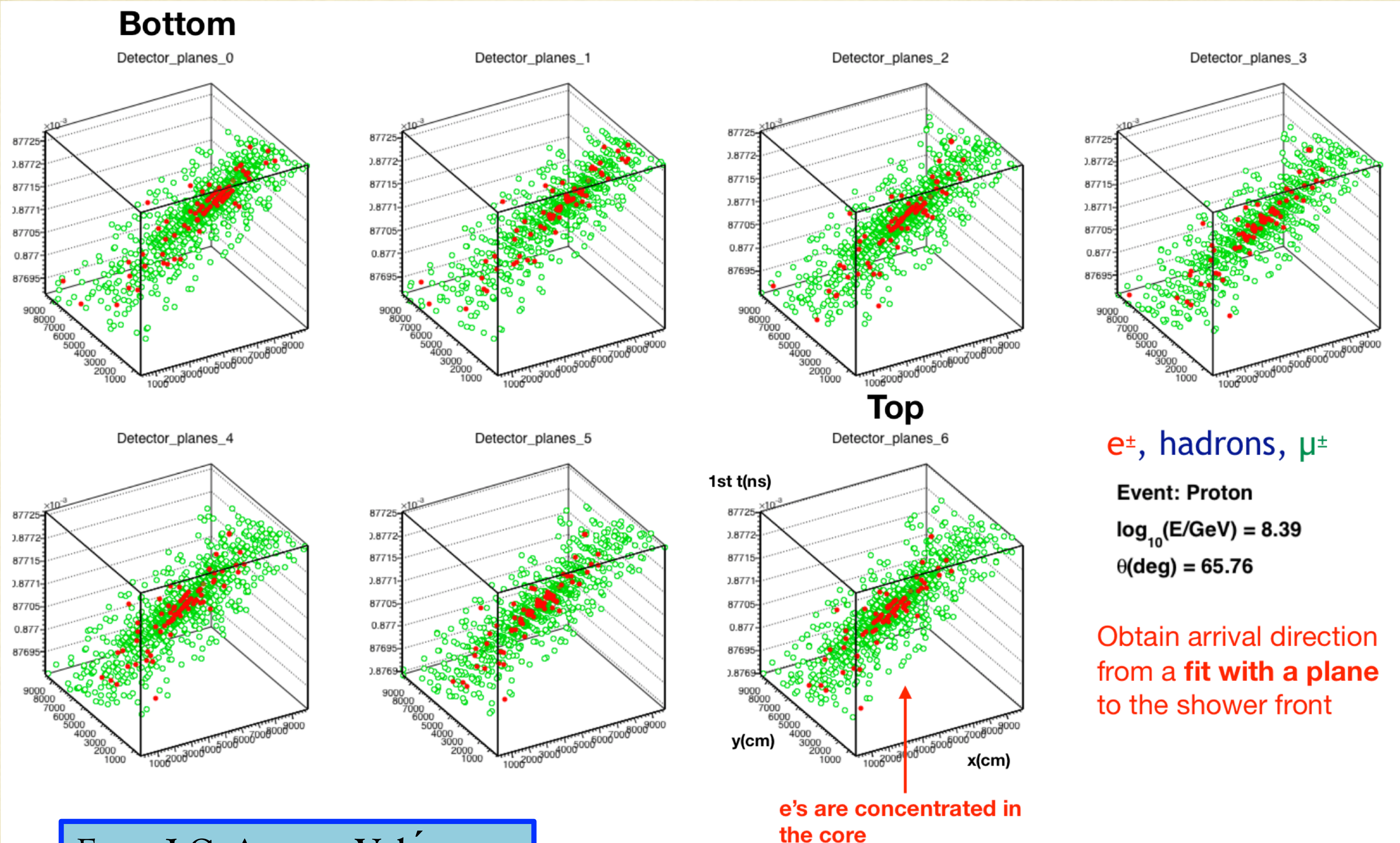
b_x = inclination of profile

xc = x coordinate of core position

From **J.C. Arteaga-Velázquez**

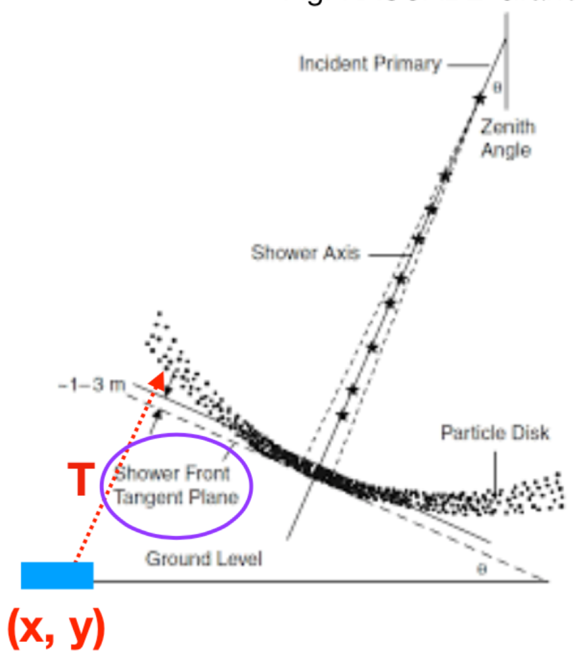


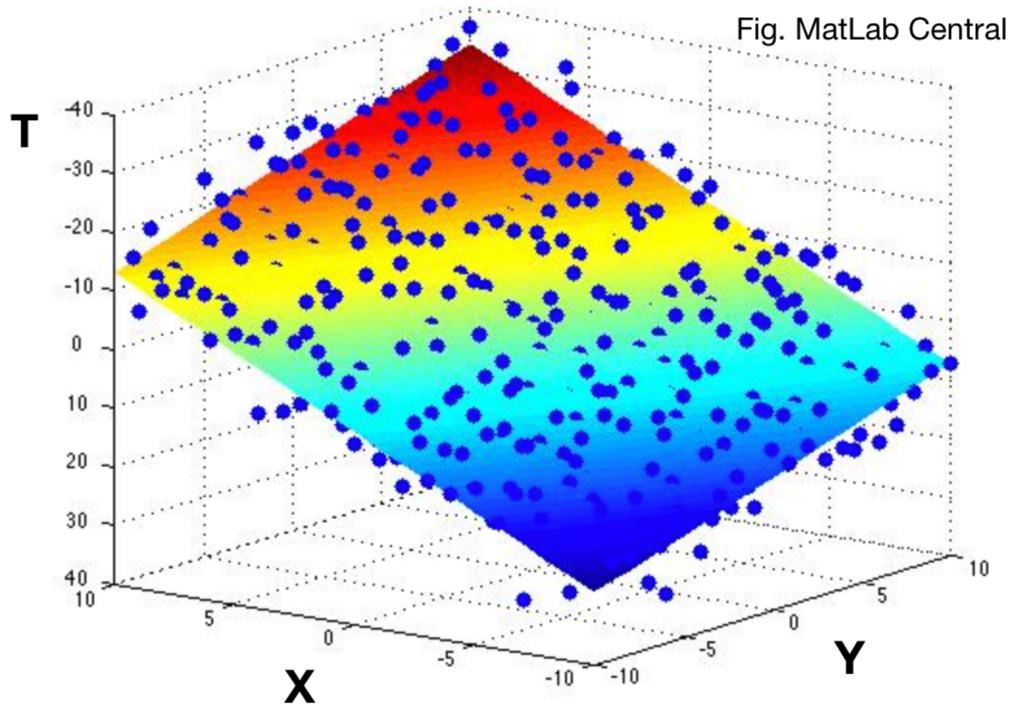
EAS Core Position Estimation - Details



From **J.C. Arteaga-Velázquez**

EAS Core Position Estimation - Details





Result of the **3D fit** with a plane to a set of points (x, y, t):

From the fit, we get the arrival direction **(θ, ϕ)** of the shower plane that best describes the data

From **J.C. Arteaga-Velázquez**

More Considerations About Backgrounds

- Four SM particles with lifetimes above a mm: K^0_L, μ, π+, neutrons
- Qualitative consideration that are under validation using MC simulation
  - K^0_L → most dangerous particle: decays to 2 charged particles + neutrals almost all the time, its decays are not phase space squeezed (next slide)
  - Neutron→ to make a 50 MeV electron, the neutron has to have a boost of about 40, i.e. ~40 GeV momentum! Cosmic ray showers where individual particles have enough energy to liberate such neutrons are far **too rare for this to be a serious background**
  - μ → of course could be a problem if they fly backwards (LHC rate dominant)
  - π+ → should **not be dangerous**. It has a $e^+e^-e^+$nu decay mode with Br ~ 10^{-9}, but ~10^{14} charged particles from cosmic ray hitting the floor
    - ✓ From test stand analysis
      - Several particles from μ hitting the floor are genuine albedo, i.e. π, not just slow decaying μ
      - N_{up}/N_{down} is 10^{-4}
      - In MATHUSLA100 N_{up}/N_{down} 10^{-6} (better acceptance for downward tracks)

        → 10^8 upward going particles at MATHUSLA from cosmic ray albedo. If they are all pions with Br(pi+ → $e^+e^-e^+$nu) ~ 10^{-9} the contribution is small
      - π can be very easily studied in simulation, since the pion production rate in muons hitting the floor is large enough (unlike kaons) to be seen in simulations

More Considerations About Backgrounds

- How likely is it that a Kaon produced from a downwards traveling muon hitting the floor flies upwards with a chance for its decay products to hit the MATHUSLA ceiling?
  - Even without knowing the cross section or the matrix elements for kaon production, we can OVERESTIMATE this dangerous kaon fraction by assuming **kaons are made in 2→3 processes involving a n/p initial or final state**. In reality, the final state often has higher multiplicity, which will lower the chance the kaon makes it into the decay volume
  - Assuming isotropic muon distribution hitting the floor, the result for 0.7 - 10 GeV muons is always about the same: the chance for produced kaon to be dangerous is 2-4% (gross overestimate, the real answer is 1-2 orders of magnitude lower)
- What is the Kaon production rate from muons hitting the floor?
  - Estimate number of produced kaons by treating muons hitting floor as a fixed target experiment, with target width of order ~ hadron interaction length (if the kaon is produced too deep, it won't escape the floor)
  - For 10^{14} muons, this gives $N_{kaon} \sim 10^3$ * (Kaon production xsec in pb) given the 10^{-2} (calculated) phase space suppression, we can therefore write
    - **$N_{kaon\_LLP\_background} \sim 10$ * (Kaon production xsec in pb)** → O(0.1 pb) kaon production xsec to be dangerous (much larger than typical kaon production xsecs from 1 - 10 GeV leptons hitting a fixed target)