MATHUSLA *Status Report*

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on behalf of the MATHUSLA Collaboration

UNIVERSITY *of* WASHINGTON

Sixth Workshop of the LHC LLP Community

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University of Ghent

MATHUSLA

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

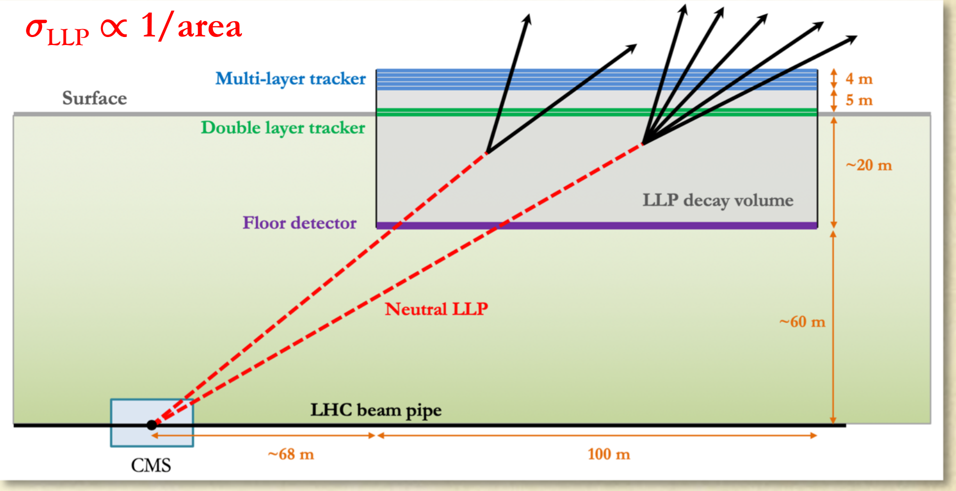
➢ Proposed a large area surface detector located above CMS

✓ Need **robust tracking**

✓ Need **excellent background rejection**

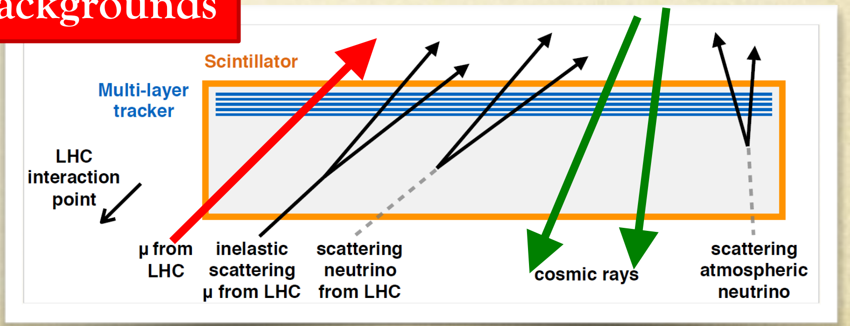
✓ Need a floor detectors to reject interactions occurring near the surface

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



❖ Cosmic muon rate of about **~2 MHz** (100m^2) and **0.1 Hz** LHC muon rejected with timing

Backgrounds

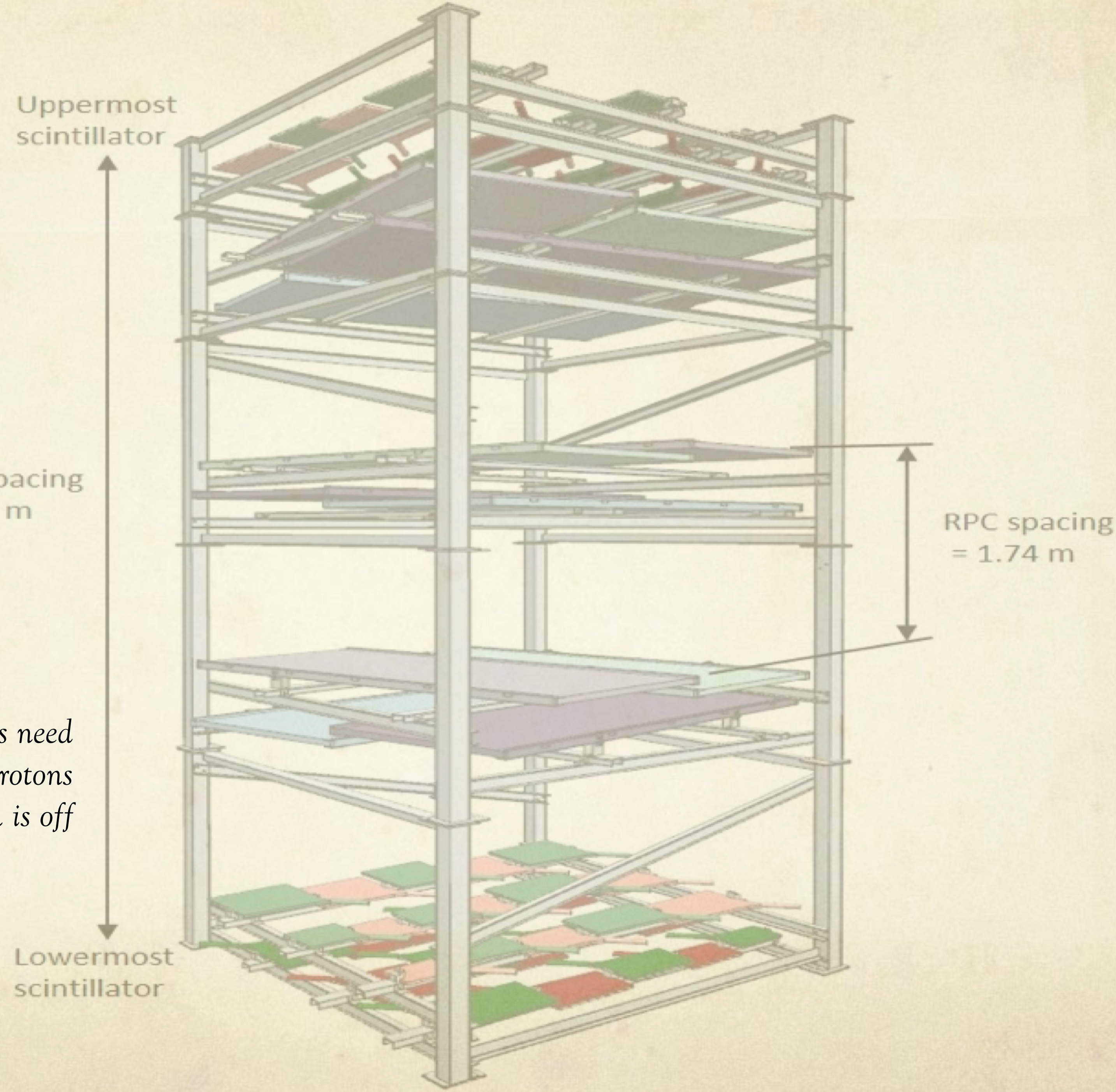


❖ **LHC neutrinos:** expected 0.1 events from high-E neutrinos (W, Z, top, b), ~1 events from low-E neutrinos (π/K) over the entire HL-LHC run

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

Updates outline

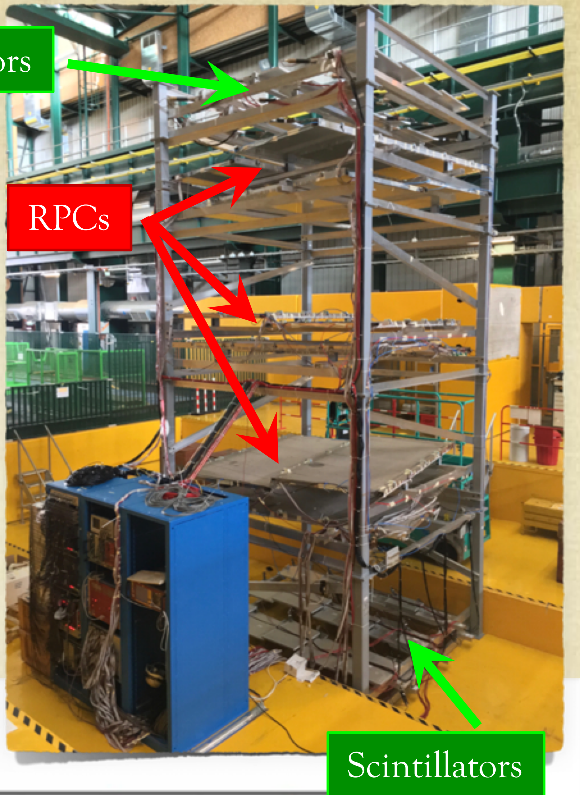
- Test stand data analysis
- Detector layout and technology
- Extensive Air Shower (EAS) Studies

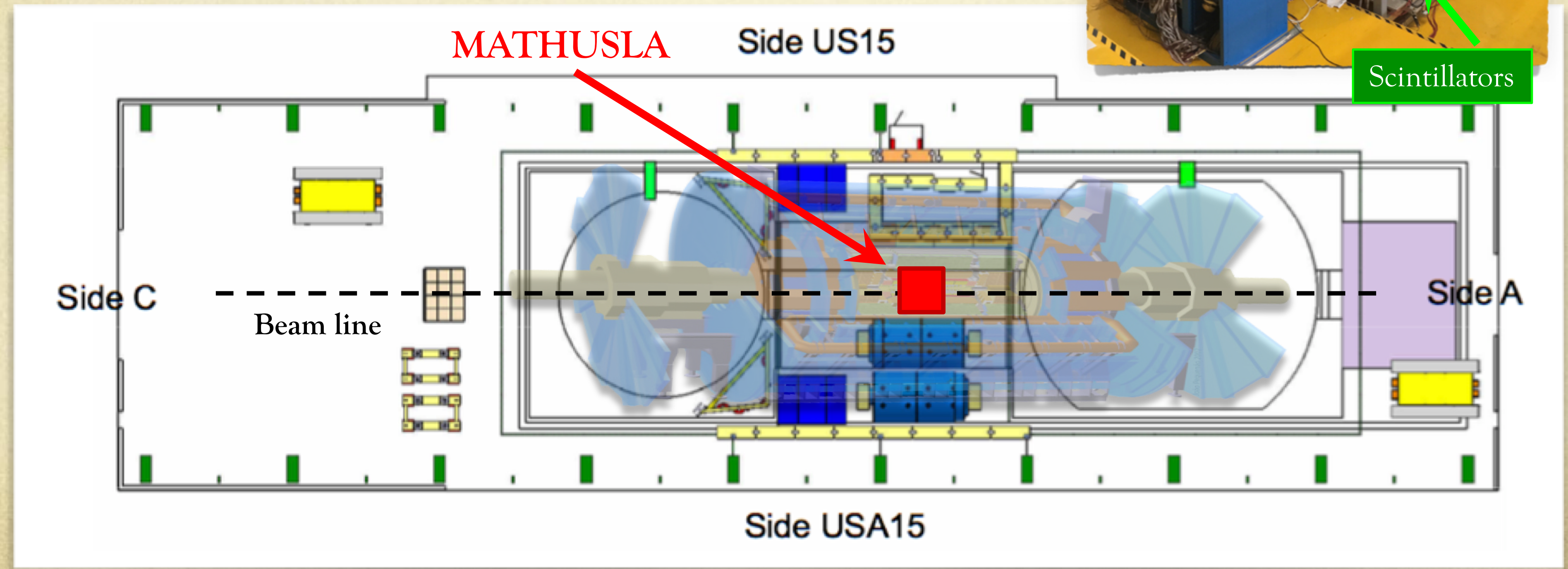


MC background simulations need data with LHC colliding protons and also when the beam is off

Test Stand @ P1

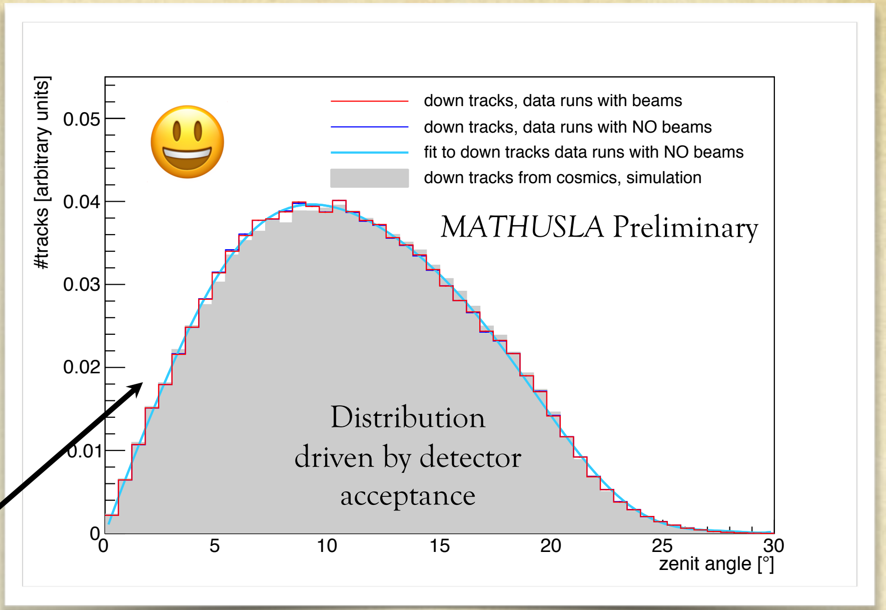
- Need to quantify the background from ATLAS
- Test stand installed on the surface area above ATLAS (~exactly above IP) in November 2017 (during ATLAS operations this space is empty)
    - ✓ Perform measurements with beam on and off during 2018



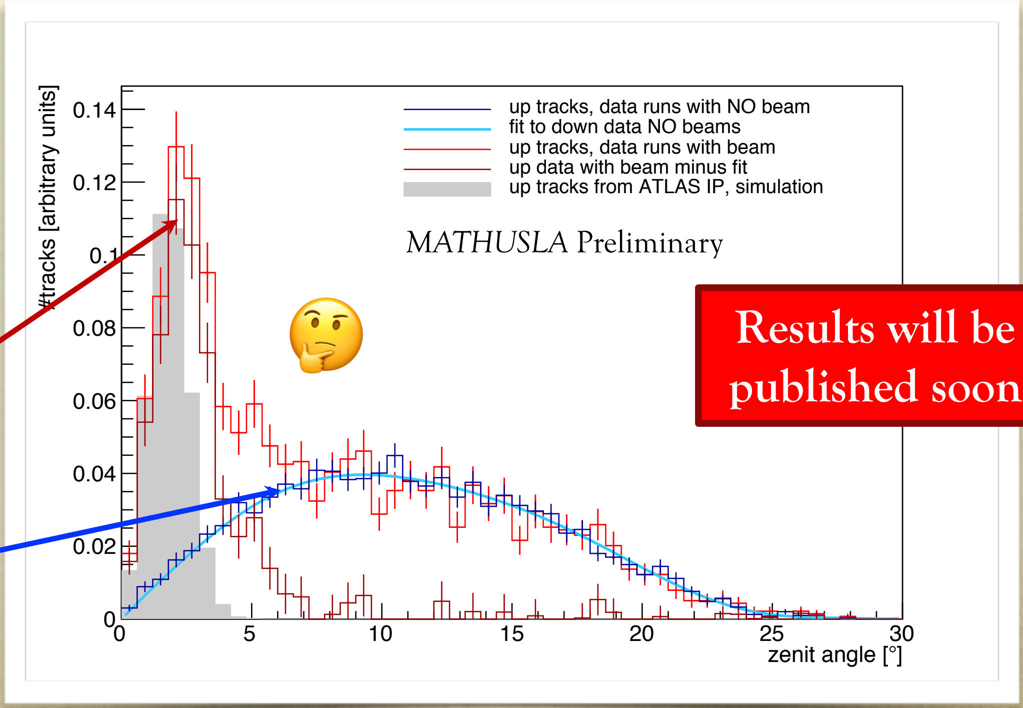


Test Stand Data Analysis

- 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

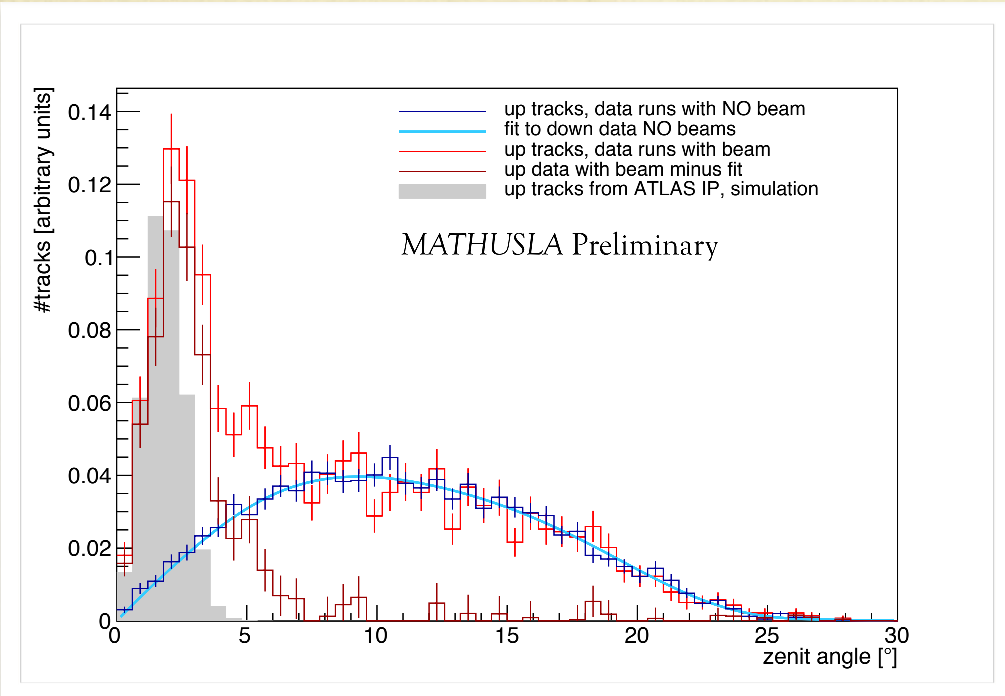


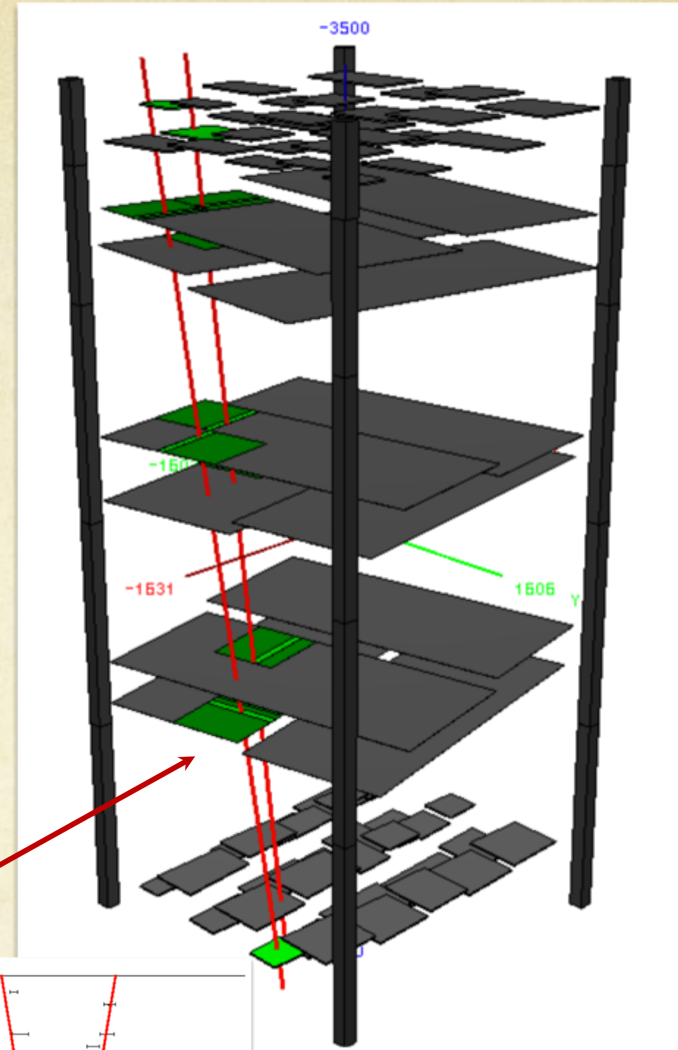
- Accumulation for zenith angle < ~ 4° consistent with **upward going tracks from IP when collisions occur**
- **Up tracks no beam** consistent with **downwards tracks faking upwards** tracks

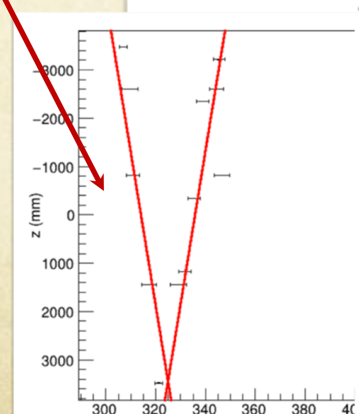


Results will be published soon

Test Stand Data Analysis





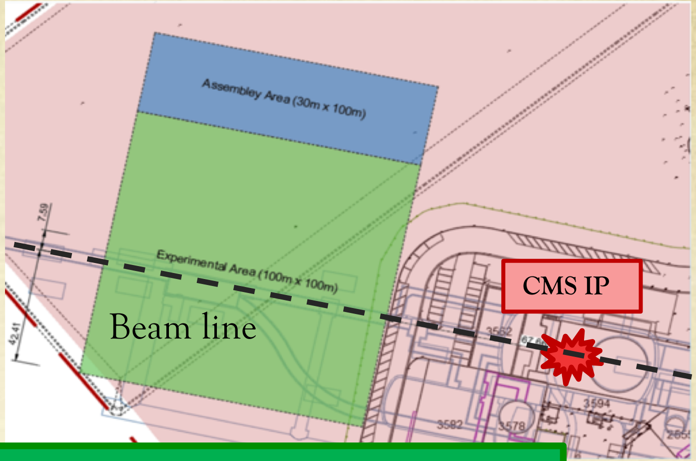


- Example of downward track followed by an upward tracks separated by ¼ of the muon lifetime
  - ✓ **Are upward tracks with no beam created by cosmic muon hitting the floor or decaying generating upward electrons?**
  - ✓ Analysis still on-going…but the hypothesis seems to be confirmed by simulation…

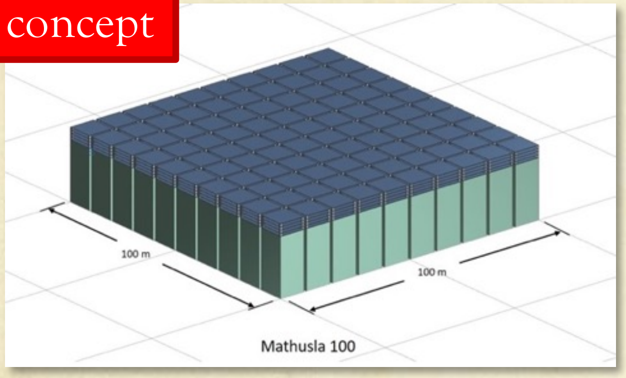
Results will be published soon

MATHUSLA @ 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

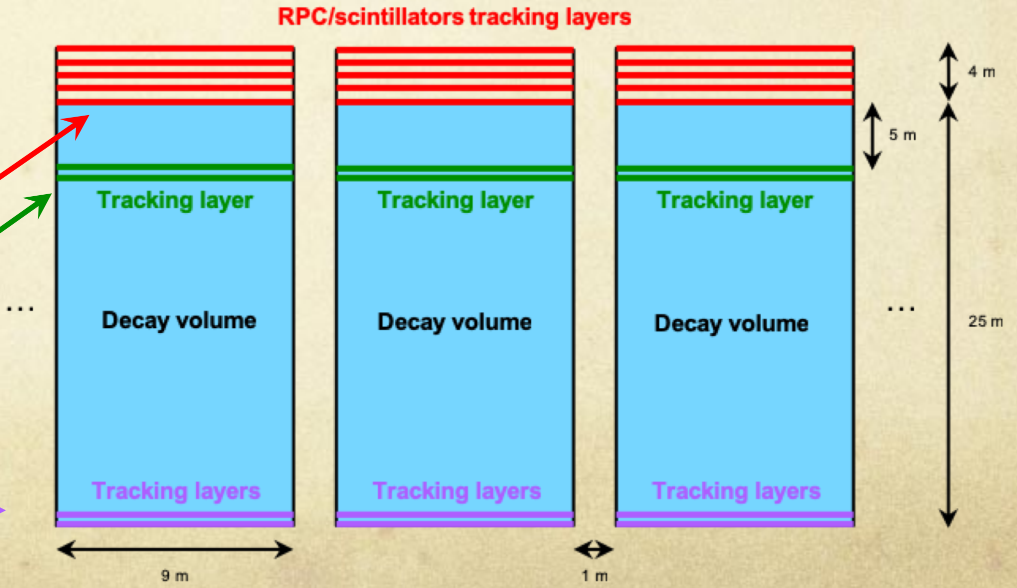


Modular concept



- 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 m^3**
- 5 layers of tracking/timing detectors separated by 1m
- Additional tracking/timing layer 5m
- Double layer floor detector (tracking/timing)



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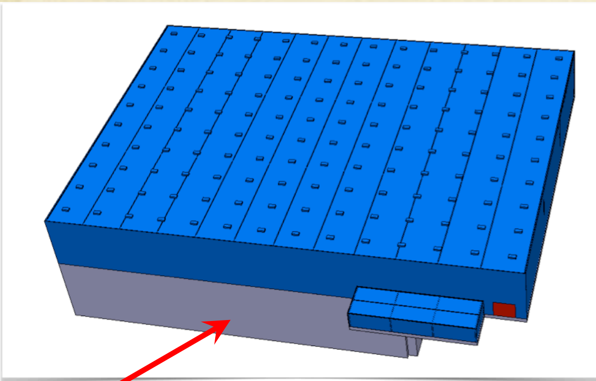
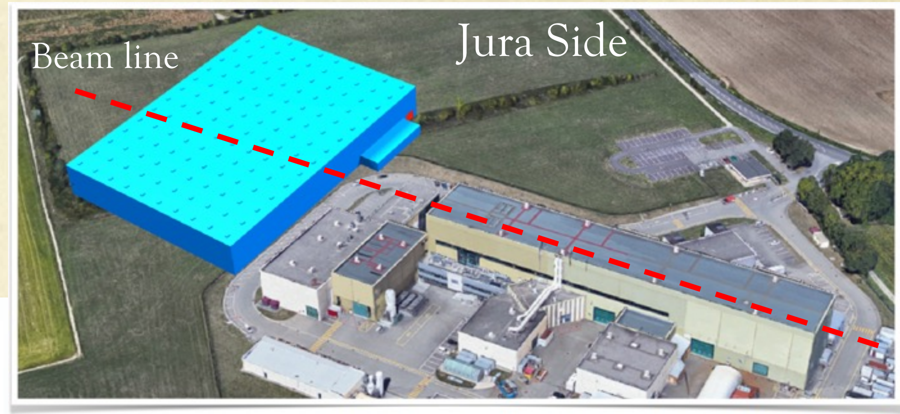
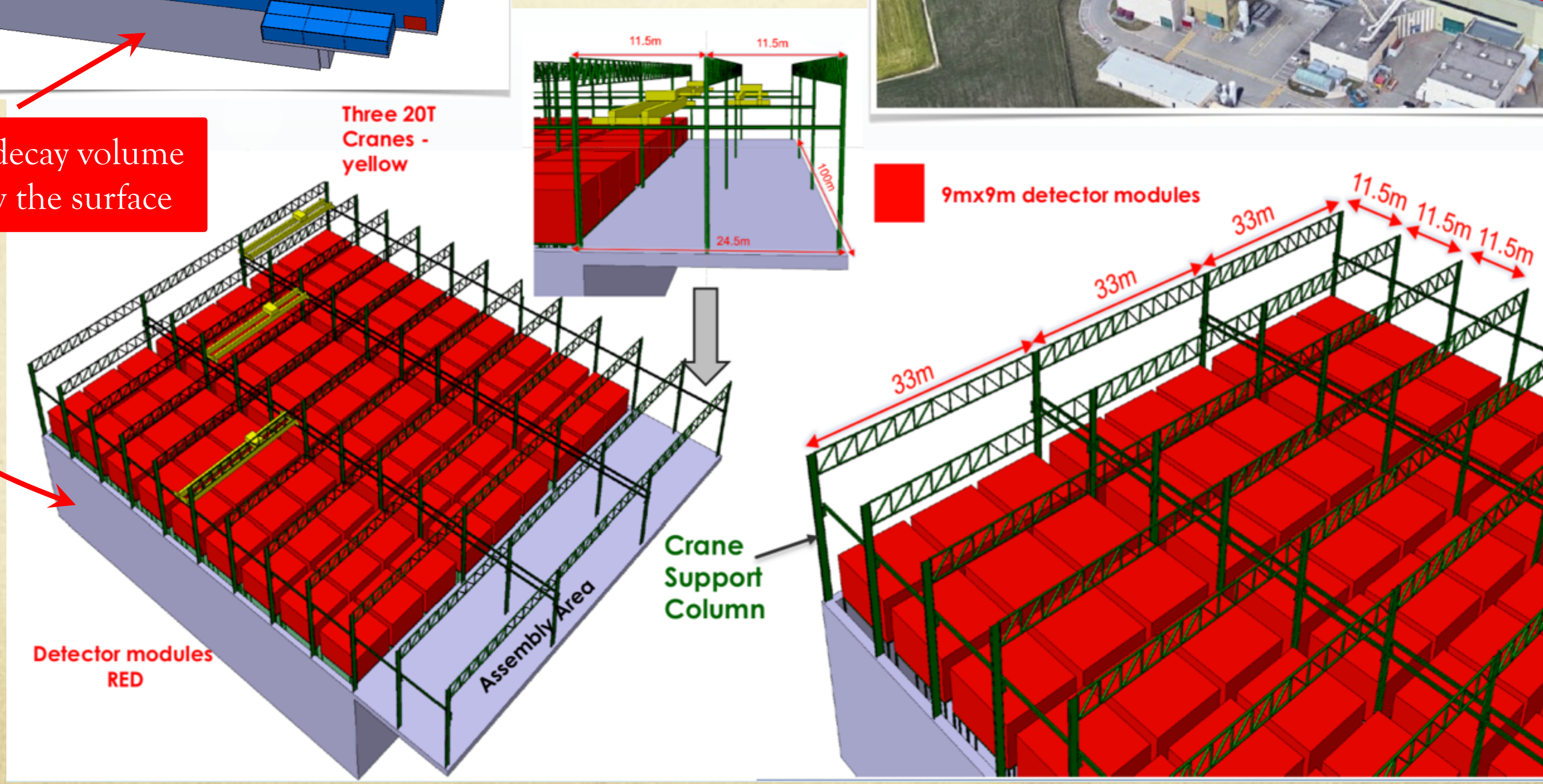




20 m decay volume
Below the surface



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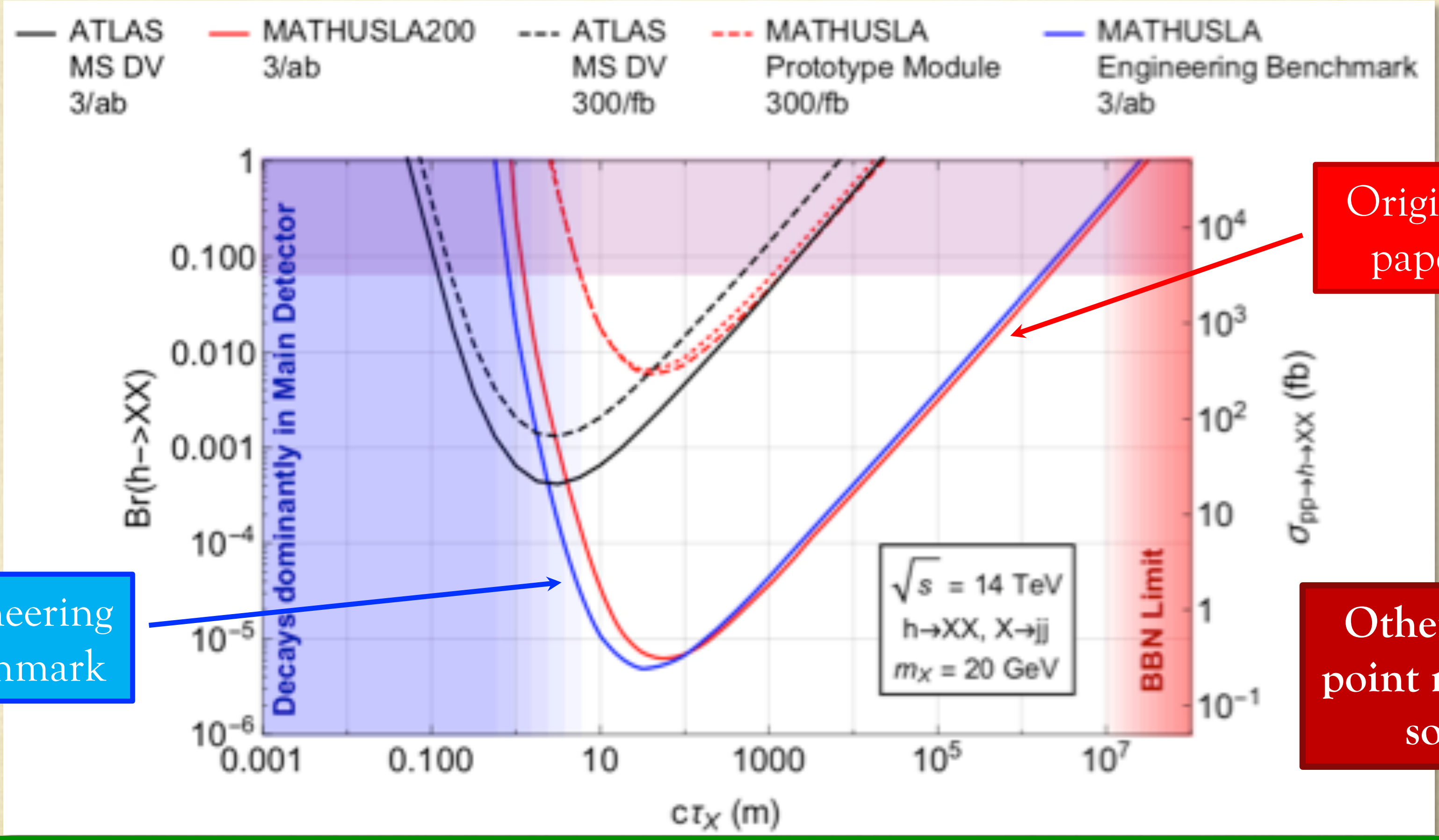

Original paper

Engineering benchmark

Other mass point released soon

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

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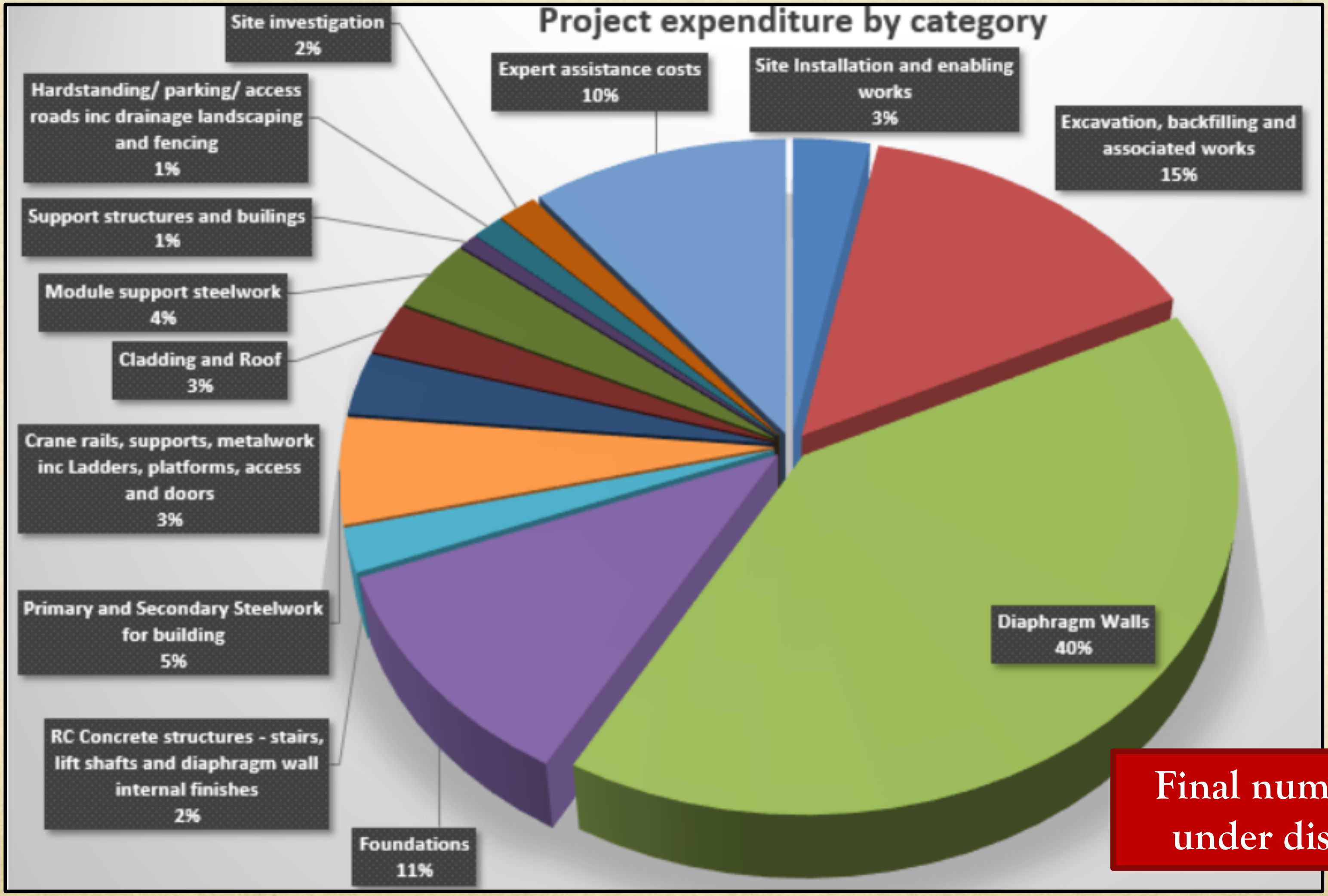


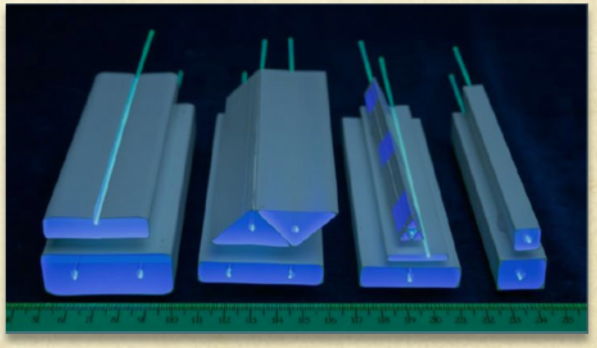
Final numbers still under discussion

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

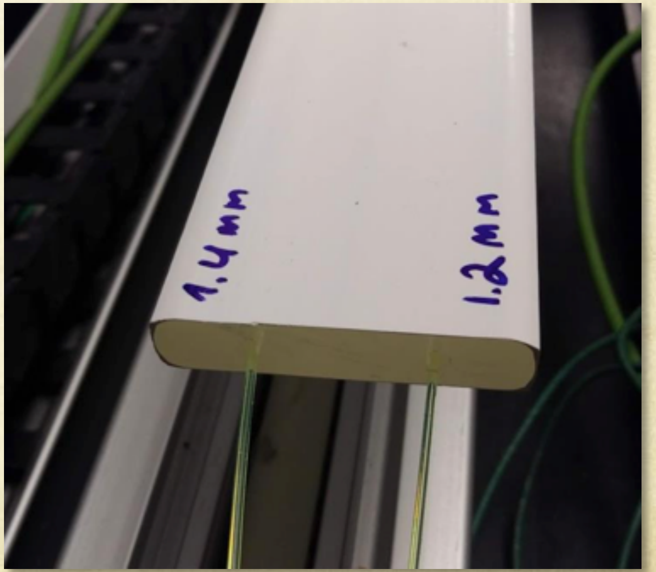
Extruded scintillator bars with wavelength shifting fibers coupled to SiPMs makes this technology cost wise competitive with RPCs

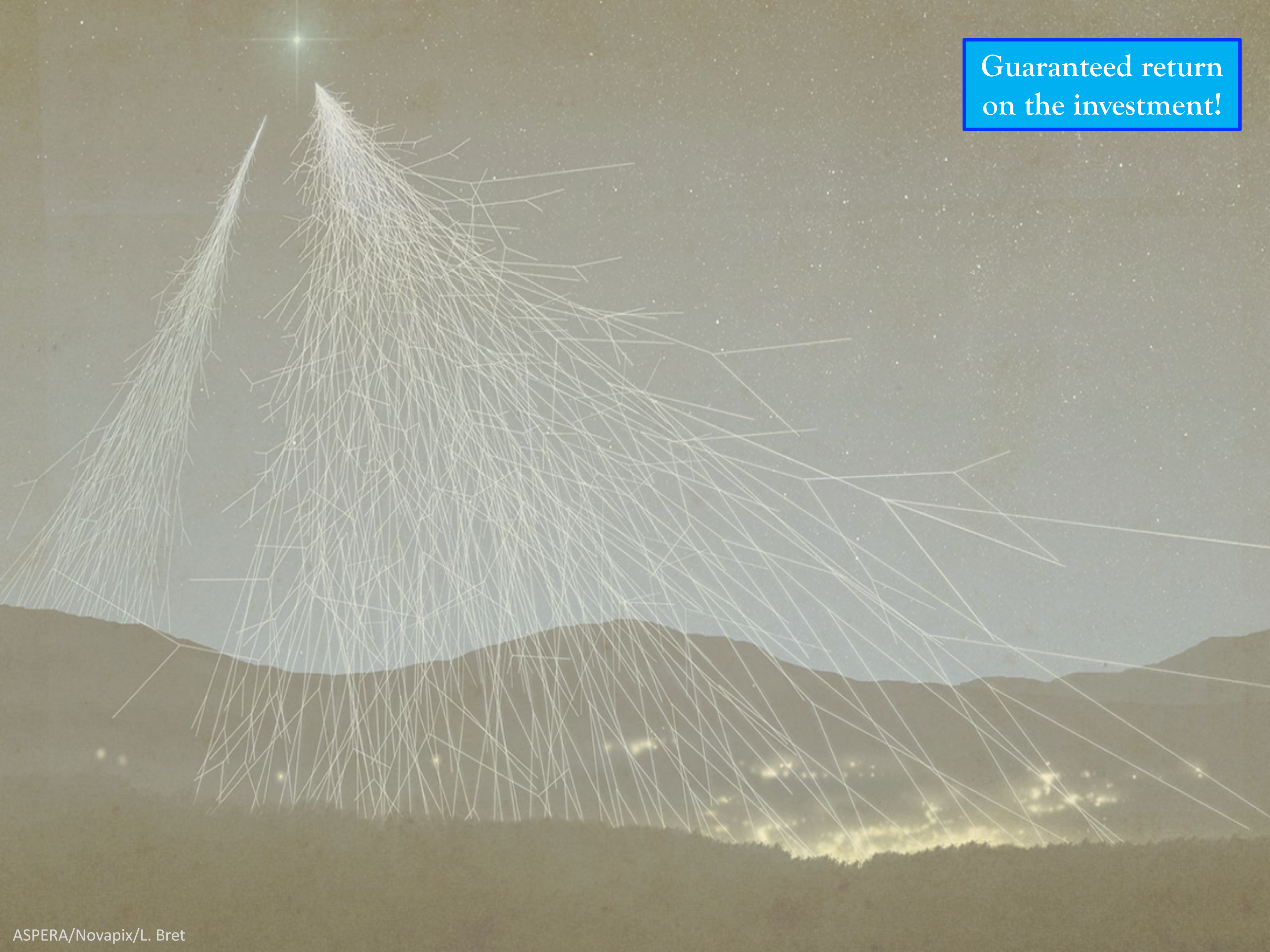


- ✓ Pros ☺
  - SiPMs operate at **low-voltage** (25 to 30 V)
  - **No gas** involved
  - **Timing resolution can be competitive with RPCs**
  - Tested extrusion facilities - FNAL and Russia. Used in several experiments: Bell muon system trigger upgrade (scintillators from FNAL and Russia), Mu2E, and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

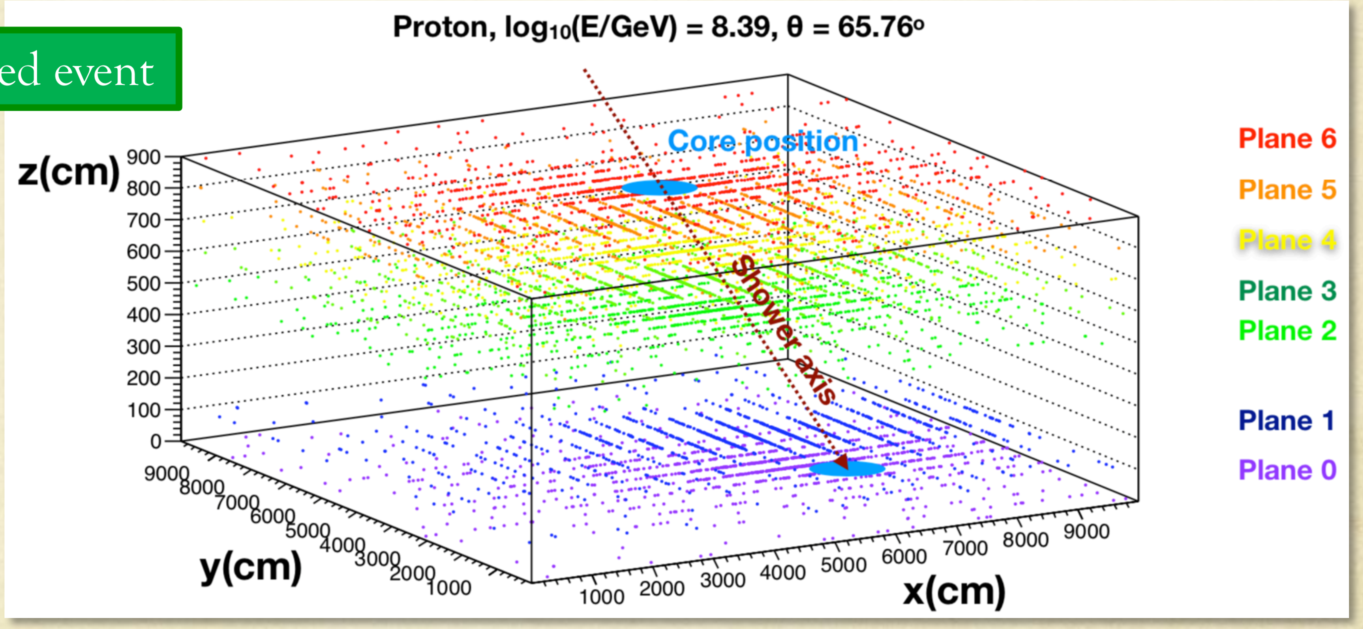



Guaranteed return on the investment!
ASPERA/Novapix/L. Bret

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

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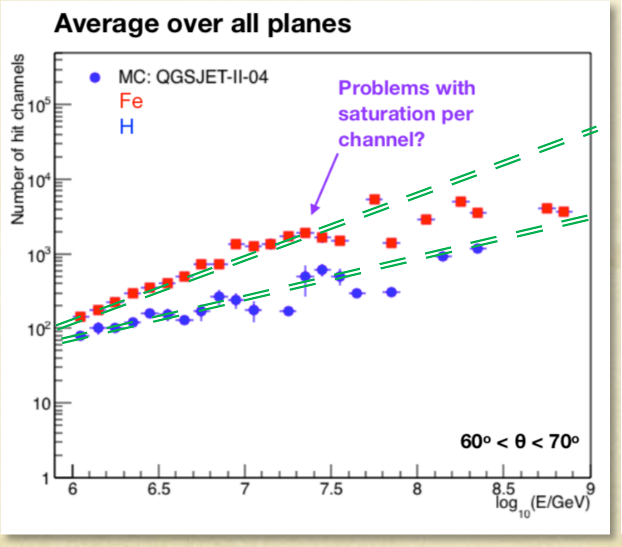
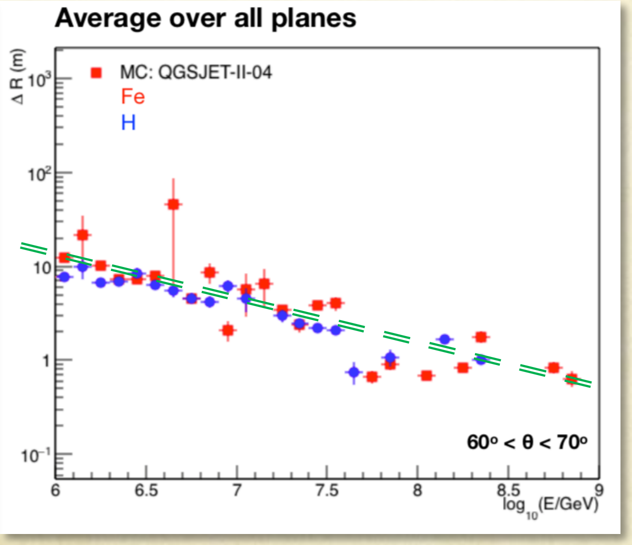
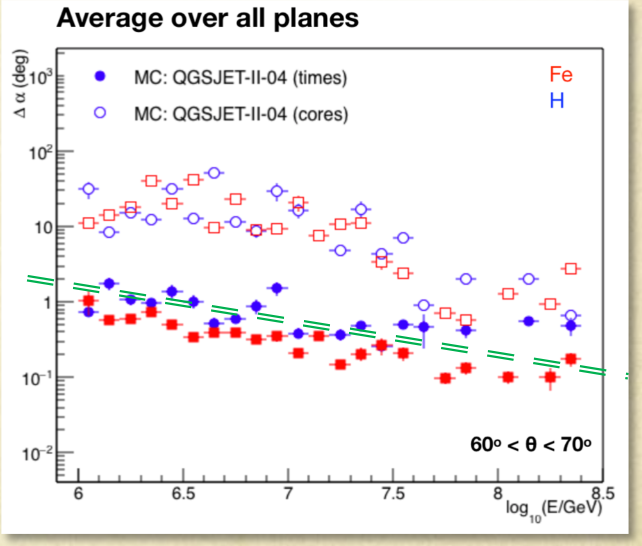
Energy estimation



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

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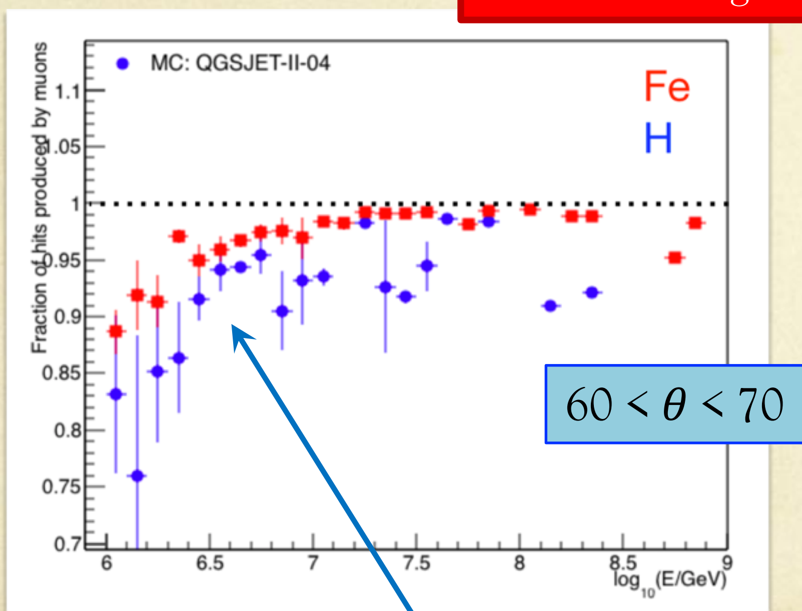
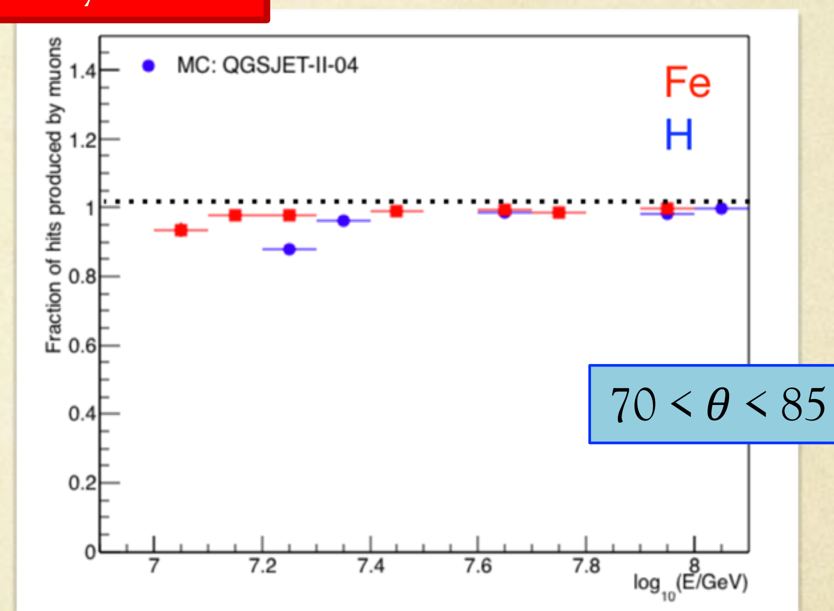
Fraction of signals induced by muons





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

Very high efficiency

What we can 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**
  - ✓ **CosmoLEP and ALICE measured muon bundle rates higher than expected from CR primary spectrum** which is dominated by light elements (as suggested by other measurements) [arXiv:1507.07577]
  - ✓ **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 we can 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

Universitas Major Pacensis Divi Andreae

Shanghai Jiao Tong University

Stanford

KIT Karlsruher Institut für Technologie

Universität Hamburg
Der Forschung | Der Lehre | Der Bildung

University of Toronto

NISER

Universidad Tecnica Federico Santa Maria

Fermilab

Virginia Tech

Boston University

University of Oxford

Tel Aviv University

UNACH Universidad Autónoma de Chiapas

SLAC National Accelerator Laboratory

Benemérita Universidad Autónoma de Puebla

Cal State East Bay

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Università di Roma Tor Vergata

Universidad Michoacana de San Nicolás de Hidalgo

INFN Istituto Nazionale di Fisica Nucleare
Sezione di Bari

cnrs IN2P3

Universidad Nacional de La Plata

Università del Salento

CERN

Rutgers The State University of New Jersey

Tsinghua University

The University of Arizona

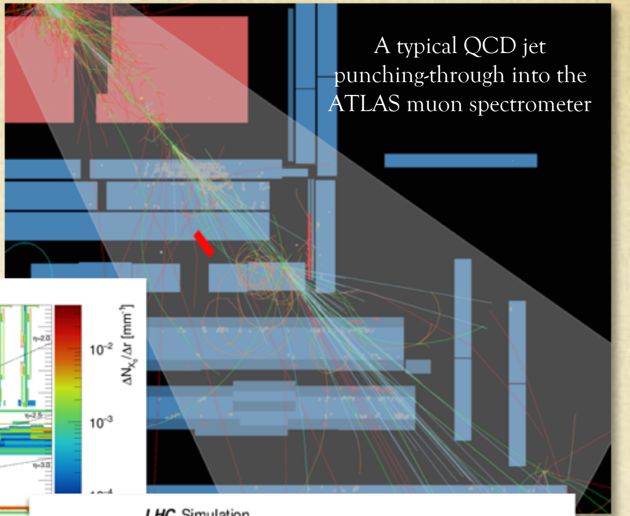
University of Washington

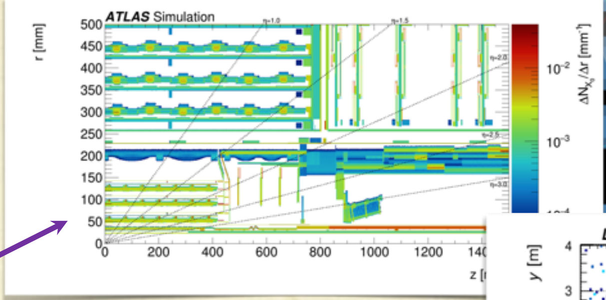
Institute of High Energy Physics
Chinese Academy of Sciences

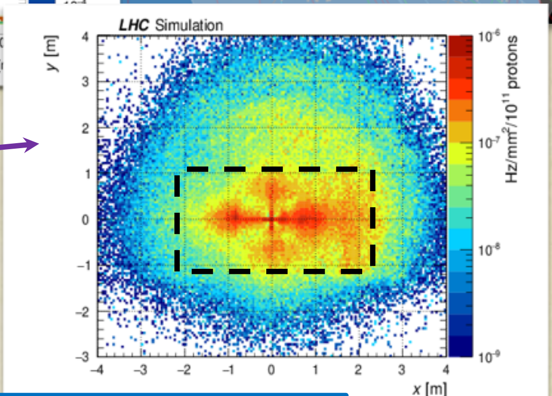
BACKUP

Unconventional Challenges

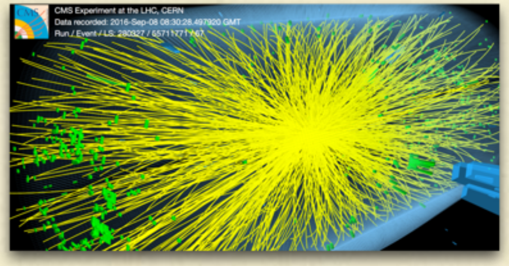
- BSM particles can produce **final states** that might be **very difficult to study** due to
  - ✓ Complicated backgrounds
    - Instrumental backgrounds
    - Large QCD jet production
    - Pile-up problems
    - Material interaction
    - Beam induced background (BIB)
    - Cosmic background
  - ✓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

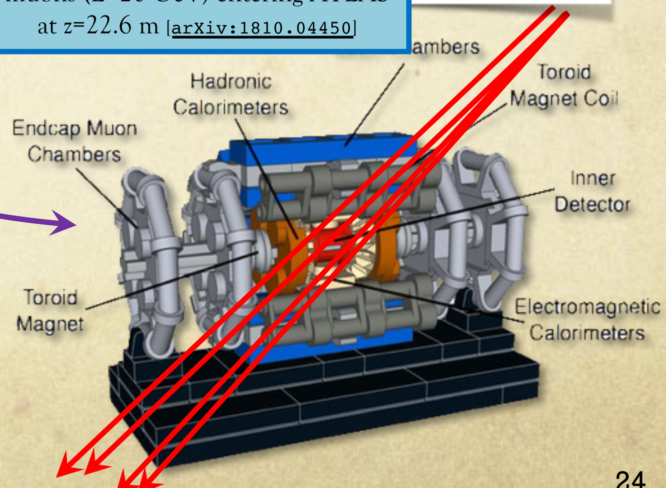






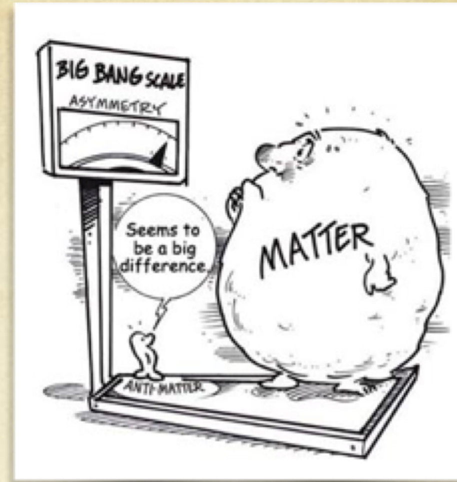
muons (E>20 GeV) entering ATLAS at z=22.6 m [arXiv:1810.04450]





- 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

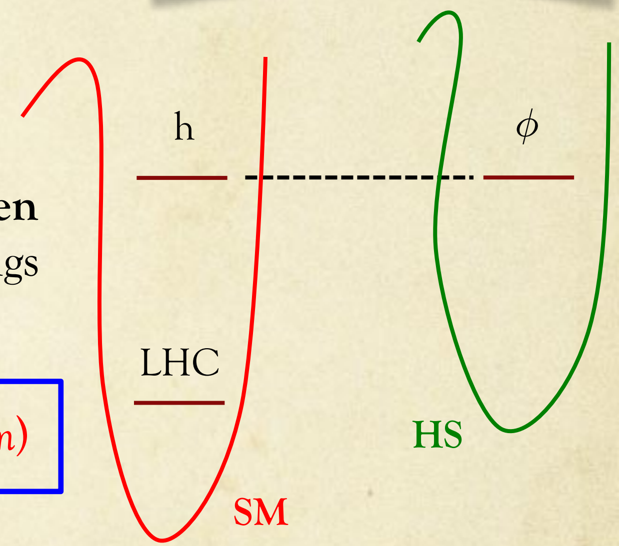
The Hidden Sector



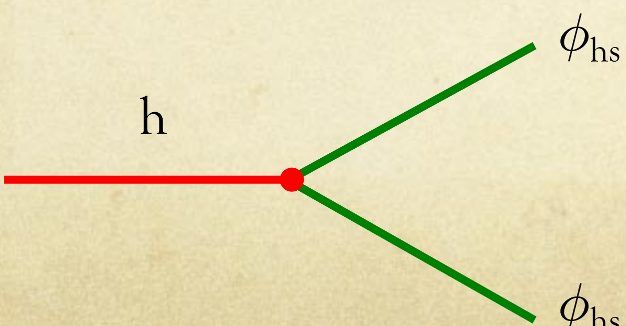
- The Standard Model (SM) is in amazing agreement with the experimental data, but **still some problems remain unsolved**: dark matter, neutrinos masses, hierarchy, matter-antimatter asymmetry…

- 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:

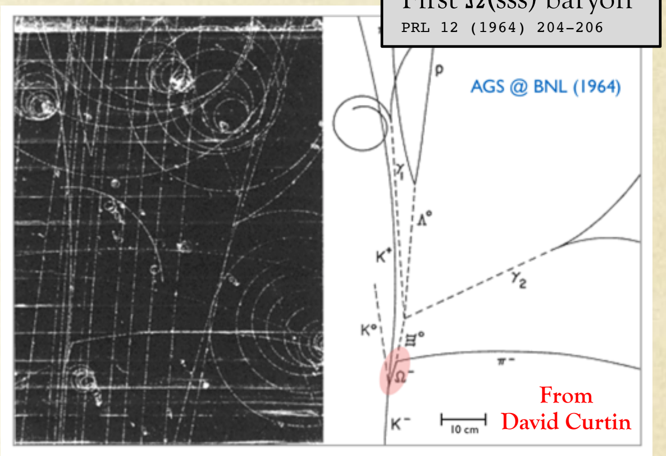
small coupling → long lifetimes [Phys. Lett. B6512 374-379, 2007]

~ 10^8 Higgs boson @ HL-LHC

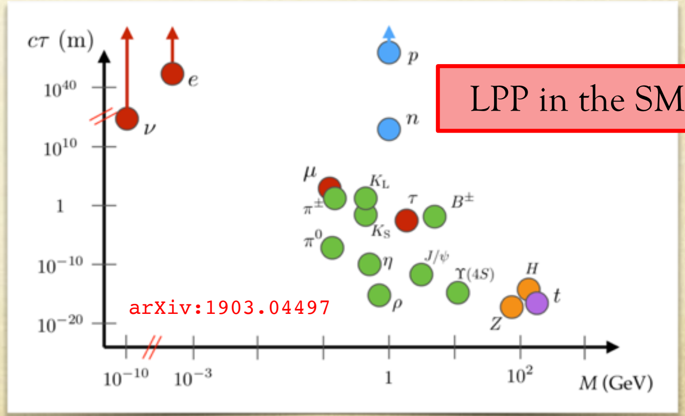
Unconventional Searches @ LHC

- 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

First Ω(sss) baryon
PRL 12 (1964) 204-206



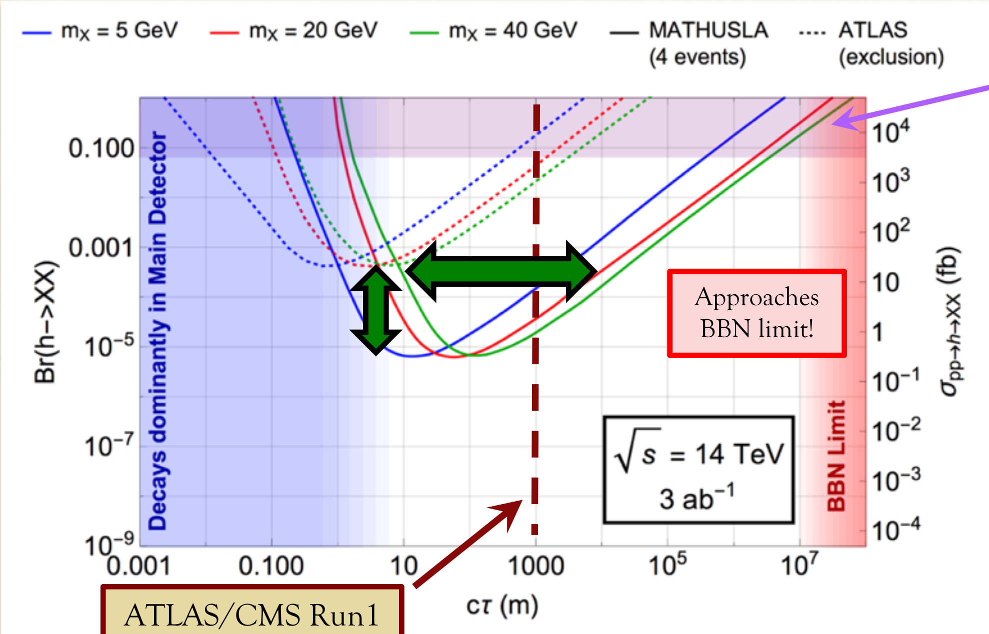
LPP in the SM



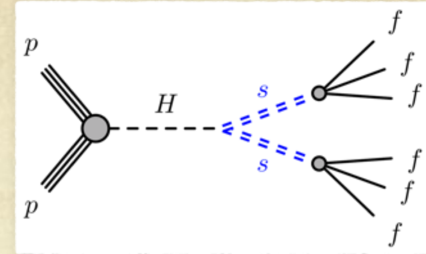
Need to **exploit the full LHC potential** and **reduce to negligible the possibility of losing new physics at the LHC!**

MATHUSLA – Physics Reach

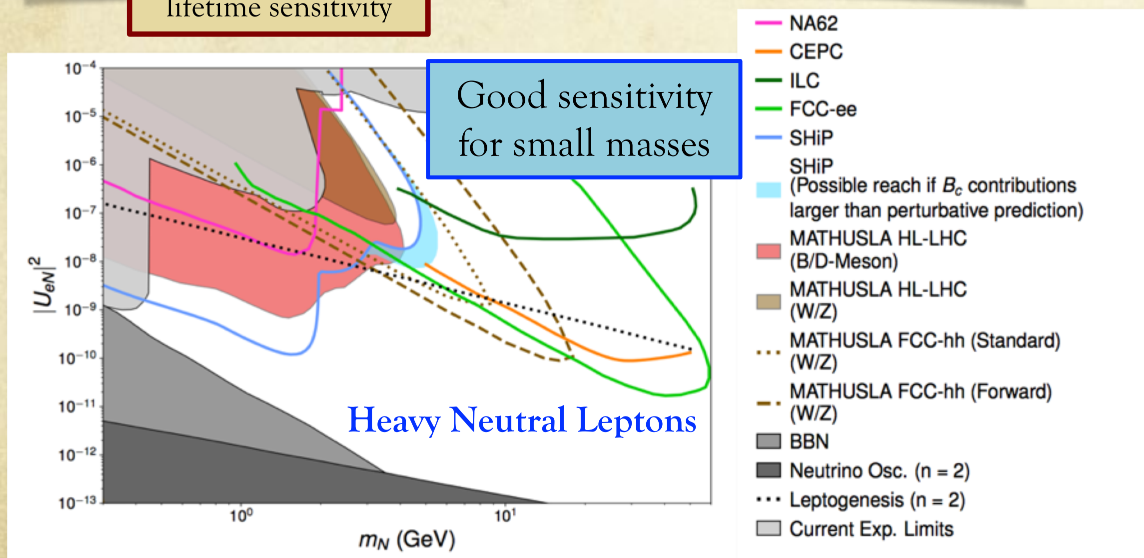
arXiv:1806.07396 [hep-ph]



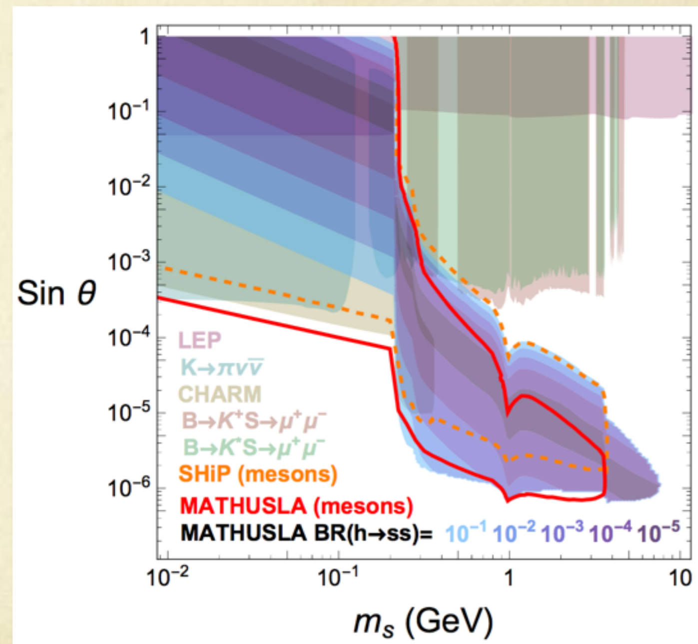
h → inv
HL-LH limit



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



Good sensitivity for small masses



Higher sensitivity for long lifetimes

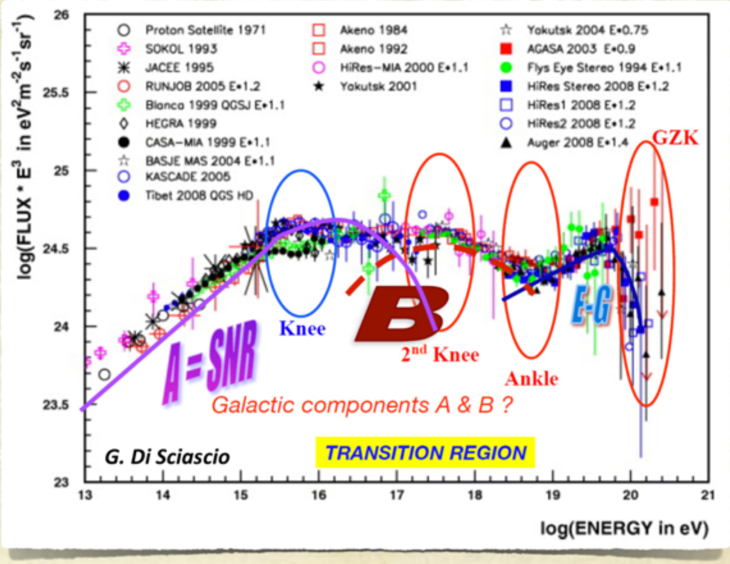
Signature Space of Displaced Vertex Searches

- 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-$c\tau$)
- 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)**

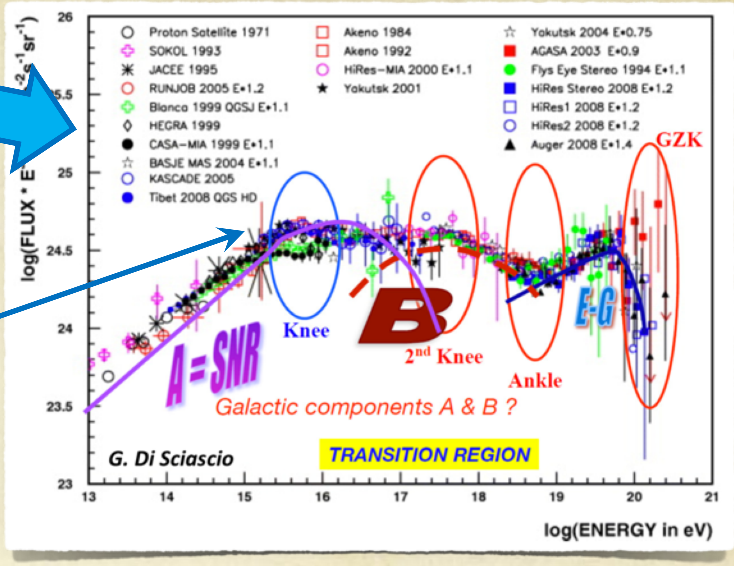
❑ **MATHUSLA+CMS/ATLAS**

- ✓ 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:

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

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 ~ 3×10^{-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**

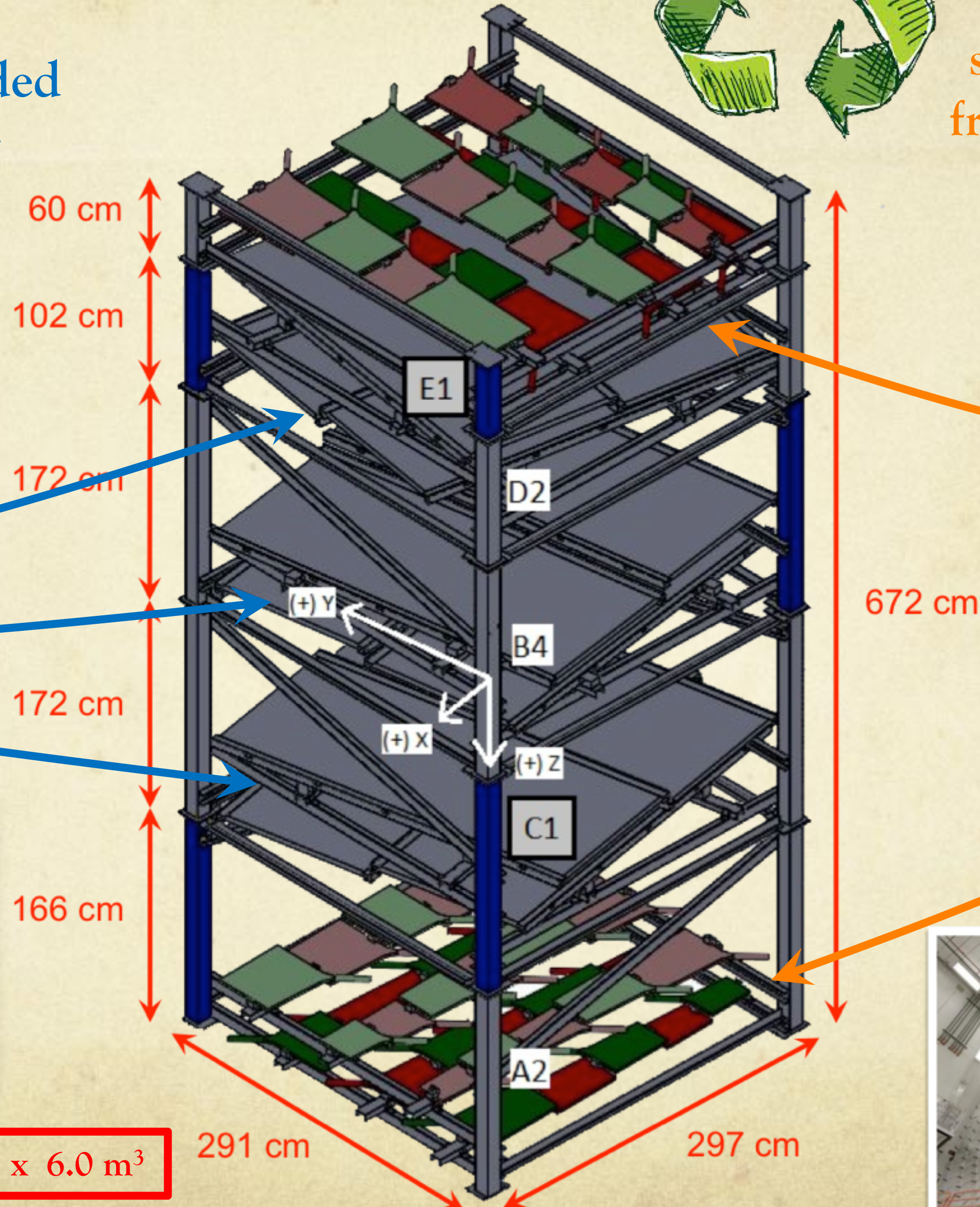
The past…

- **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)

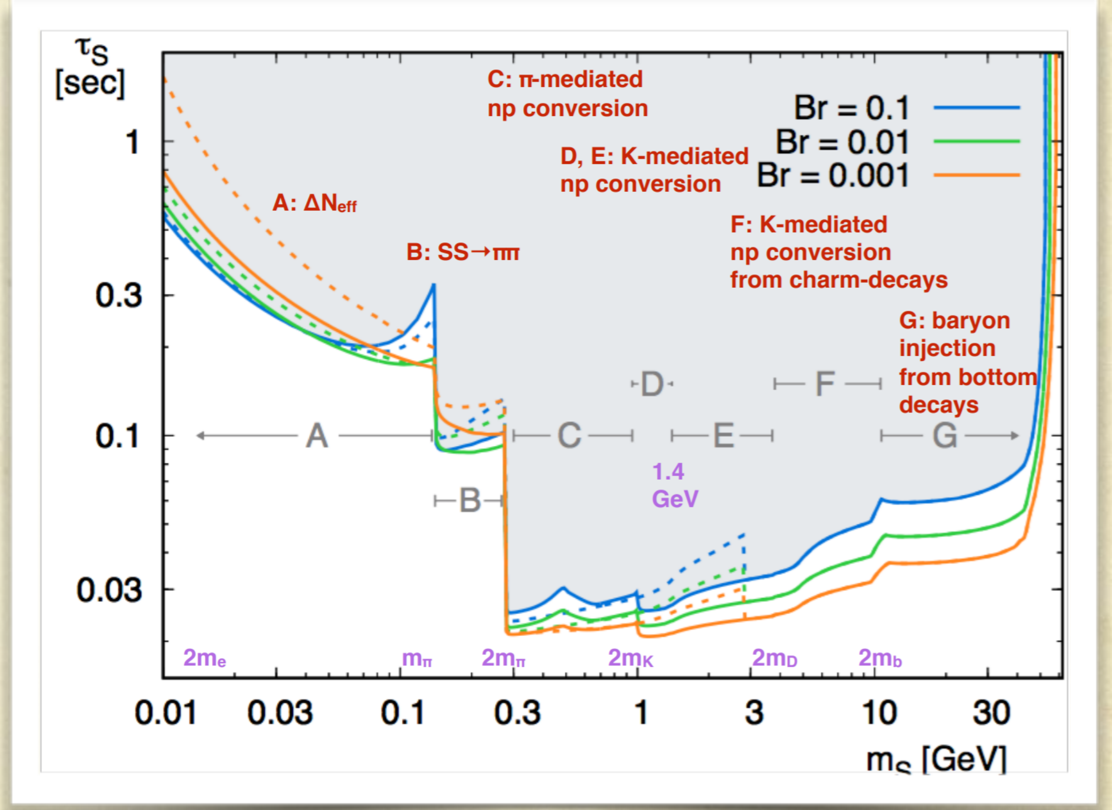
Top and bottom scintillator layers from Tevatron DØ provided by Dmitri Denisov



Active area ~ 2.5 x 2.5 x 6.0 m^3

MATHUSLA – Scalar LLP Lifetime Constraints

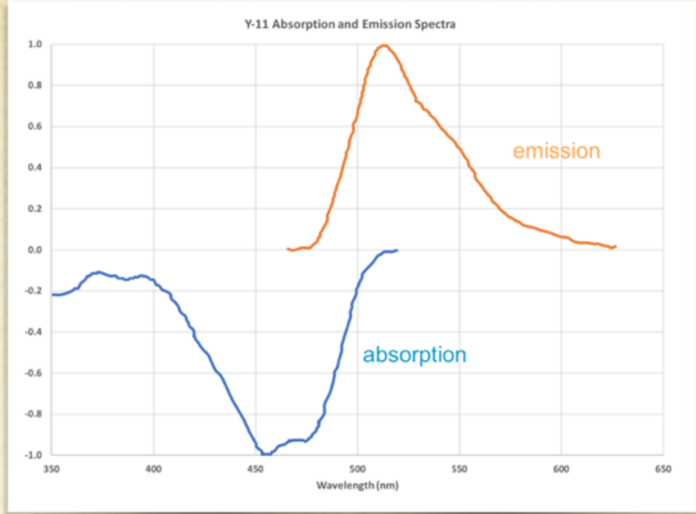
- A recent paper [A. Fradette and M. Pospelov, arXiv:1706.01920v1] examines the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via $h \to ss$, where the decay is induced by the small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

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:

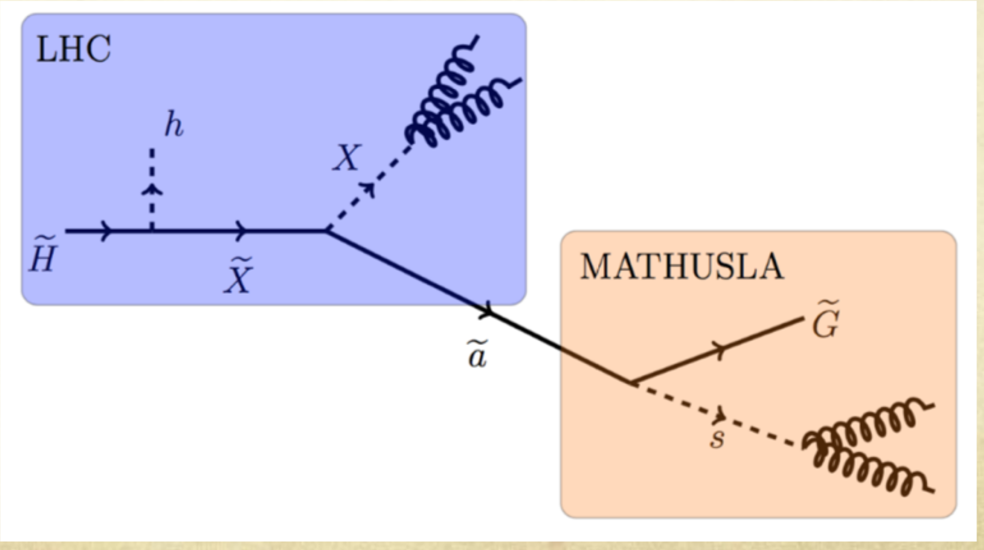
- S14160-3050HS: 3x3mm
- S14160-6050HS: 6x6mm

Readout & Data Taking

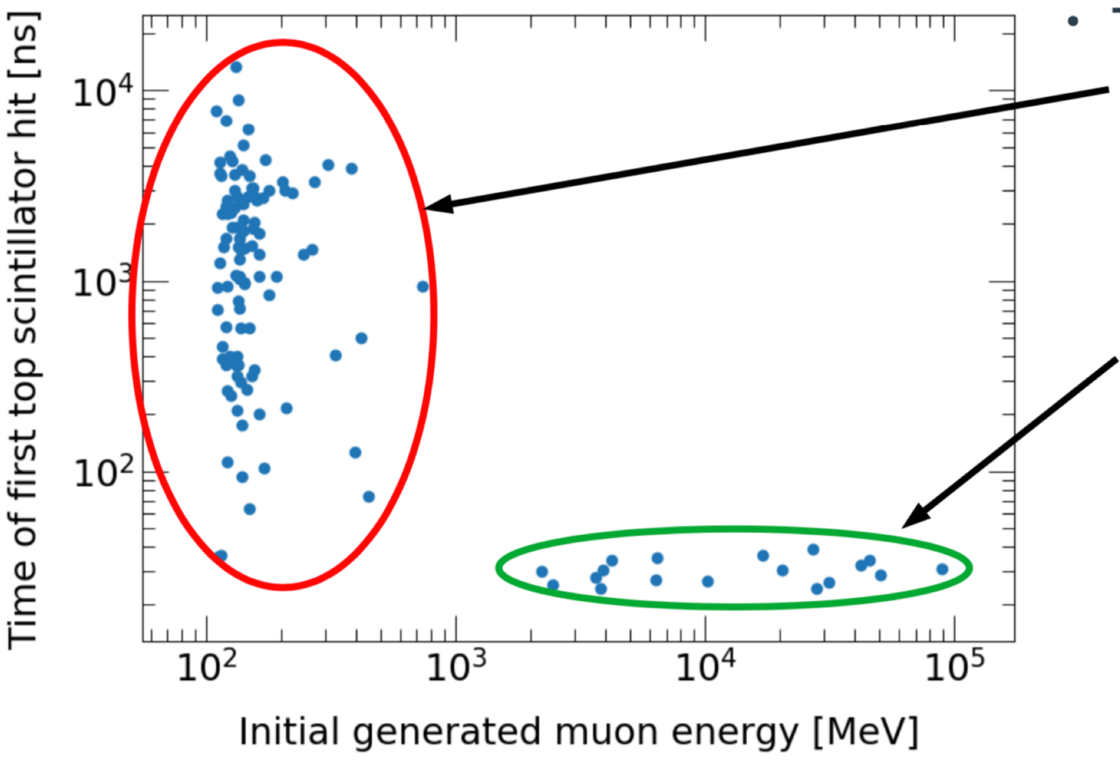
- Readout
  - **8 tracking layers** (5 tracking layers + 5m below + 2 on the floor)
  - 4 cm scintillators with readout in both ends results in 800K channels
  - Rates dominated by cosmic ray rate (~2 MHz)
    - ✓ Does not require sophisticated ASIC
    - ✓ **Aiming for 1 CHF per channel for frontend**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



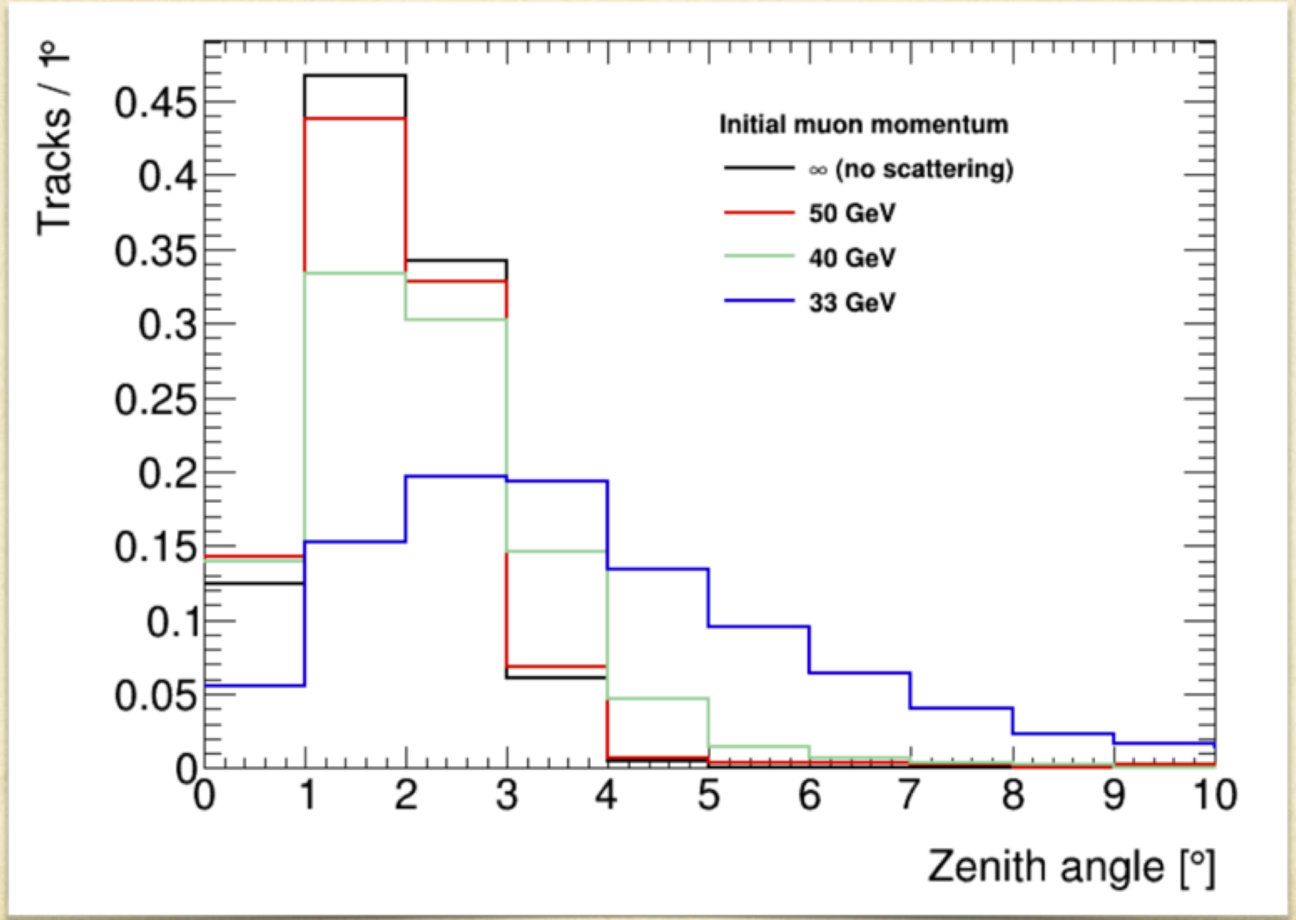
Time Upward Tracks vs Initial Muon Energy



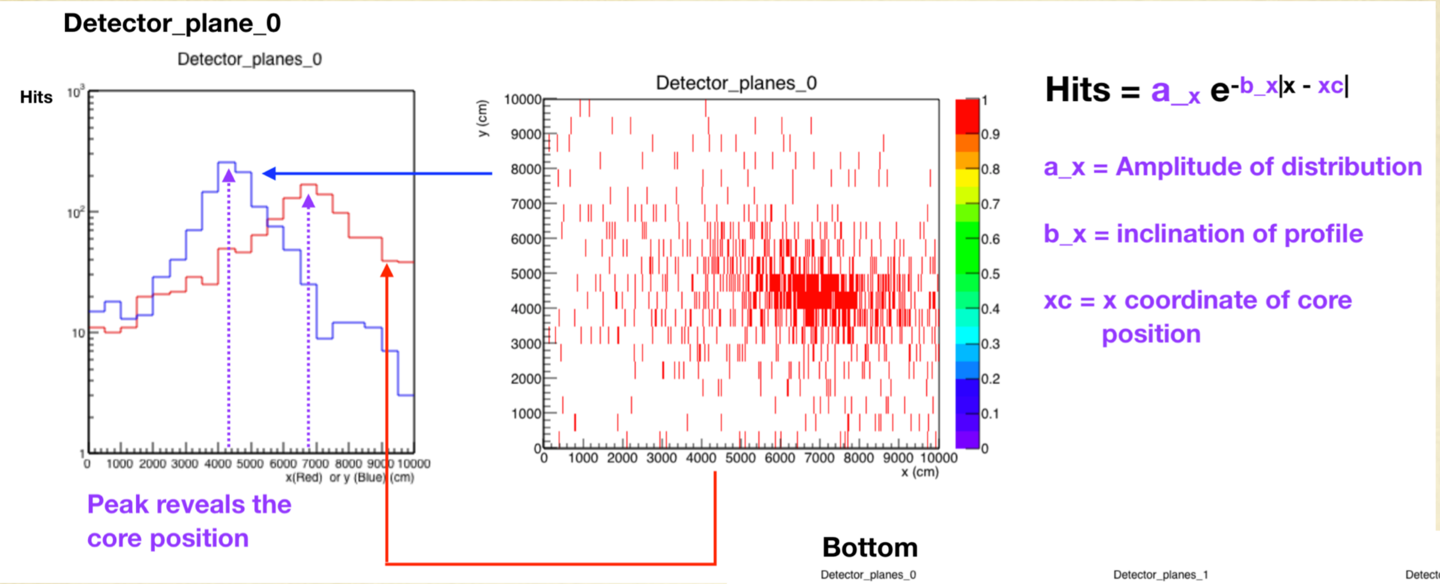
- **Two distinct populations!**
  - Late/delayed upward tracks
    - Predominantly from very low energy muons
    - These are muon decay products (e^+/e^-)
  - Prompt upward tracks
    - From relatively high energy muons
    - True "albedo"
    - These are secondary particles (from muon ionization/radiation)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

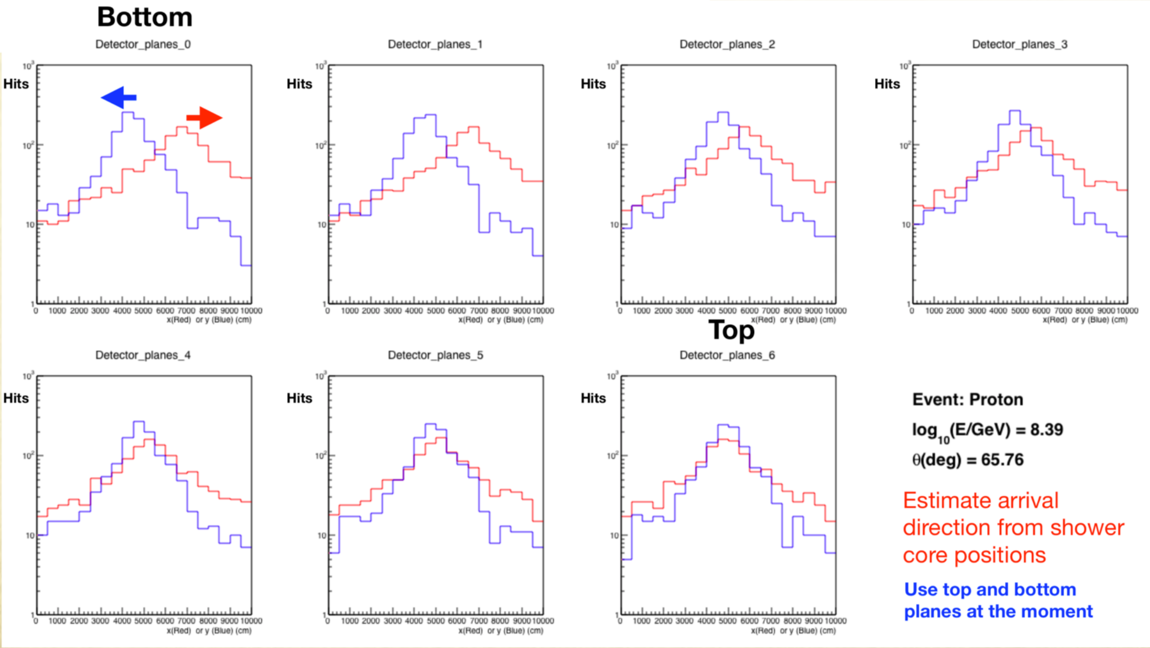
Multiple Scattering Contributions

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



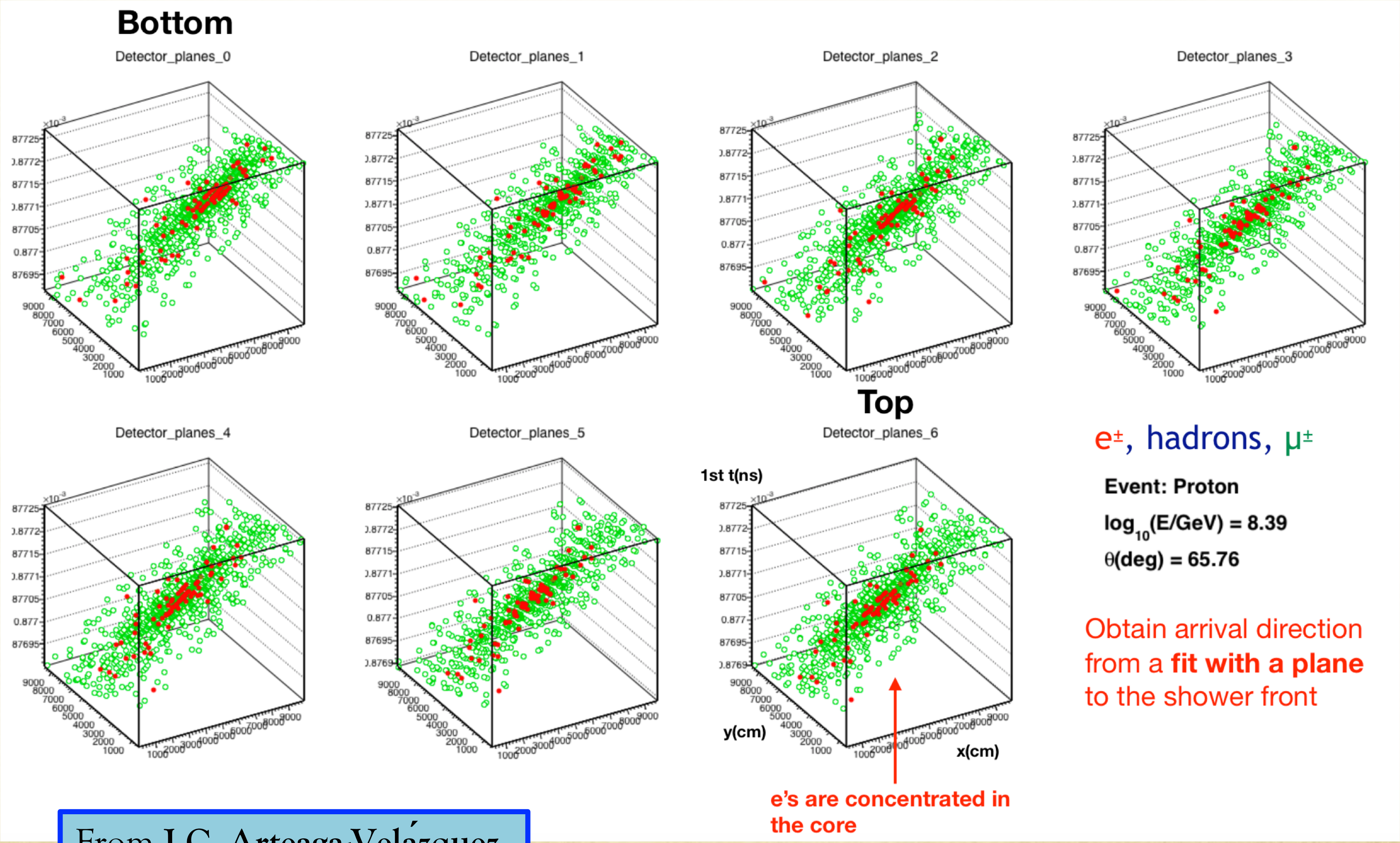
EAS Core Position Estimation - Details





From **J.C. Arteaga-Velázquez**

EAS Core Position Estimation - Details



From J.C. Arteaga-Velázquez

EAS Core Position Estimation - Details

Fig. KASCADE-Grande

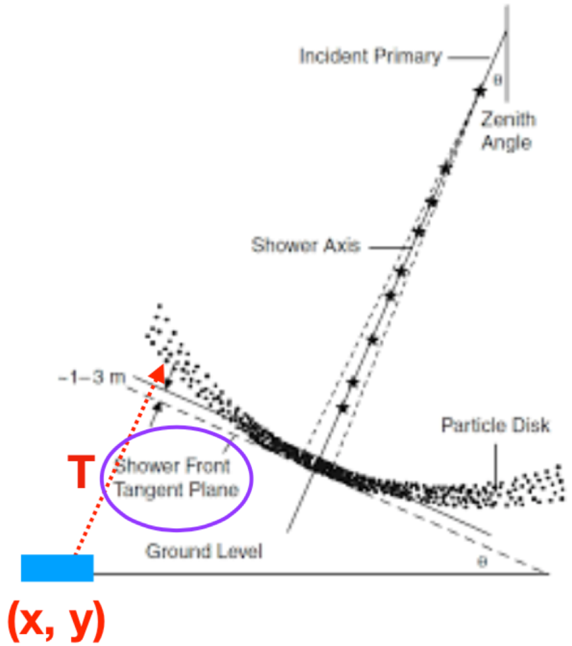
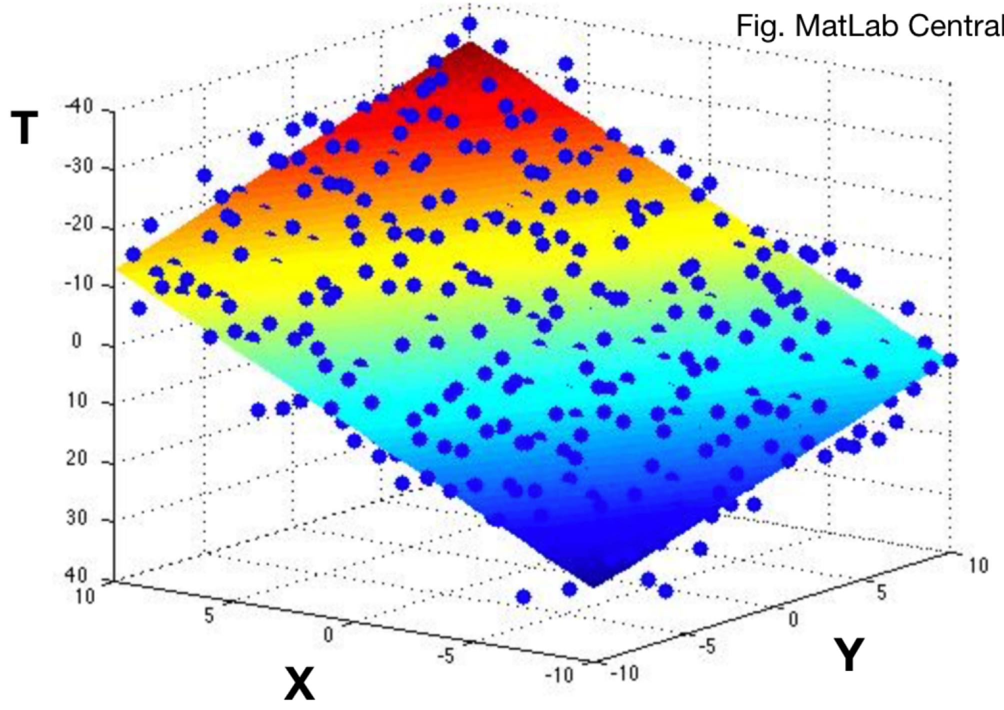


Fig. MatLab Central



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

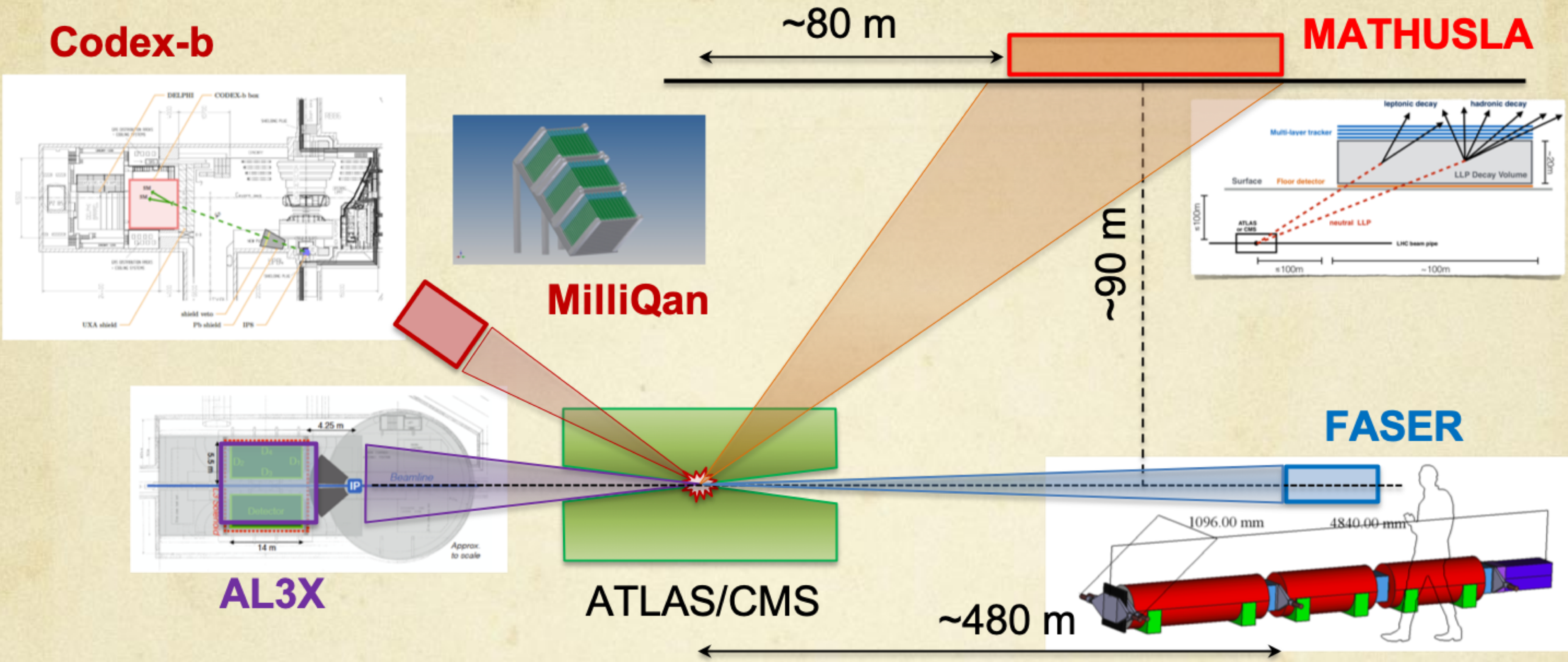
- Four SM particles with lifetimes above a mm: K^0_L, μ, π+, neutrons
- Qualitative consideration that are under validation using MC simulation
  - K^0_L → most dangerous particle: decays to 2 charged particles + neutrals almost all the time, its decays are not phase space squeezed (next slide)
  - **Neutron**→ 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)

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!**