MATHUSLA
A New Detector to Probe the Life-time Frontier

Henry Lubatti
University of Washington, Seattle

New Physics with Exotic and Long-Lived Particles - Joint ICISE-CBPF Workshop
ICISE Conference Center, 1 – 6 July 2019
Quy Nhon, Vietnam

Lifetime Frontier at the LHC

- Going to BBN lifetime limit need to suppress SM backgrounds
- Put detector on surface above CMS or ATLAS detectors LHC O(90) meters of rock takes care of problem ☺
  - Requires large footprint (area) and large decay volume (height) for good acceptance.
- Exposed to cosmic rays and atmospheric neutrinos…☹
  - Requires veto of downward going cosmic rays (good timing)
- To establish decay vertex of Long-lived neutral particles to charged objects requires robust tracking for vertex reconstruction and good timing for separating upward going charged particles from downward going cosmic muons.

MATHUSLA

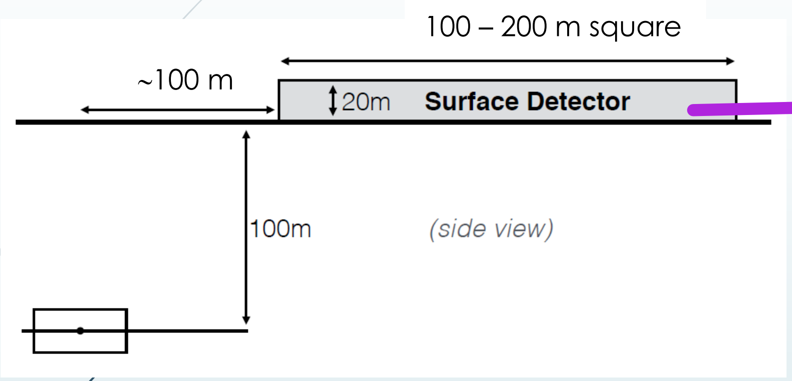
J.P Chou, D. Curtin, HL
arXiv:1606.06298

MAssive Timing Hodoscope for Ultra-Stable neutraL PArticles

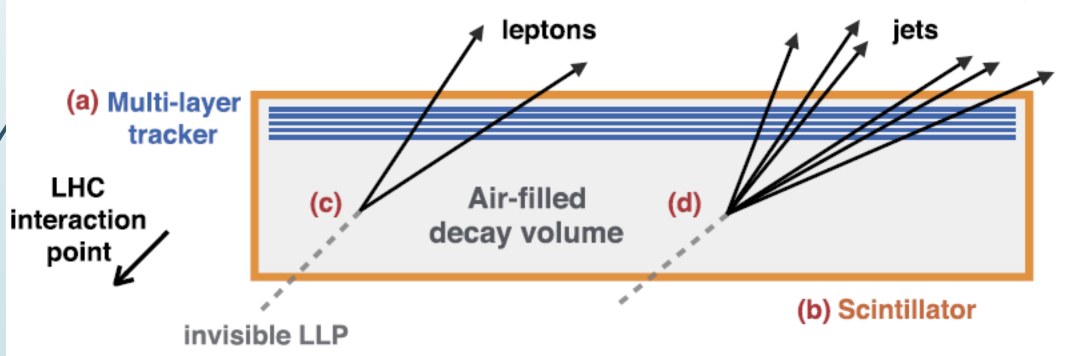
MATHUSLA

J-P Chou, D. Curtin, HL
arXiv 1606.06298

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



Proposed large area surface detector above an LHC pp IP dedicated to detection of ultra long-lived particles - air decay volume with tracking chambers



- We stressed the need for robust tracking and good background rejection.
- RPCs planes and extruded scintillators coupled to SiPMs are technologies that provide good time/space resolution needed for cosmic ray rejection and vertex reconstruction. – both are being evaluated.
- Further studies conclude scintillator veto surrounding entire volume is not need.
- Need a floor detectors (2) to reject interactions occurring near the surface.

No LHC Background, but Cosmic ray Background 1.7 MHz and 7 MHz for$(100)^2$ m and $(200)^2$ meter detector, respectively.

MATHUSLA - backgrounds

arXiv 1606.06298

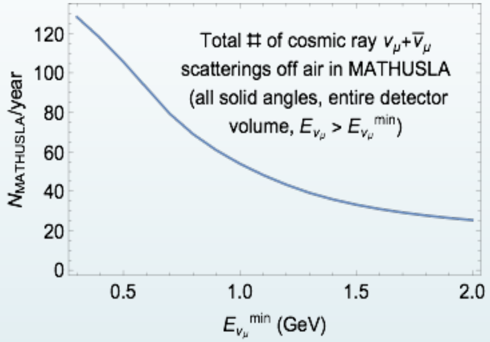
- Cosmic muon rate ~7MHz for 200mx200m and 1.6MHz for 100mx100m detector

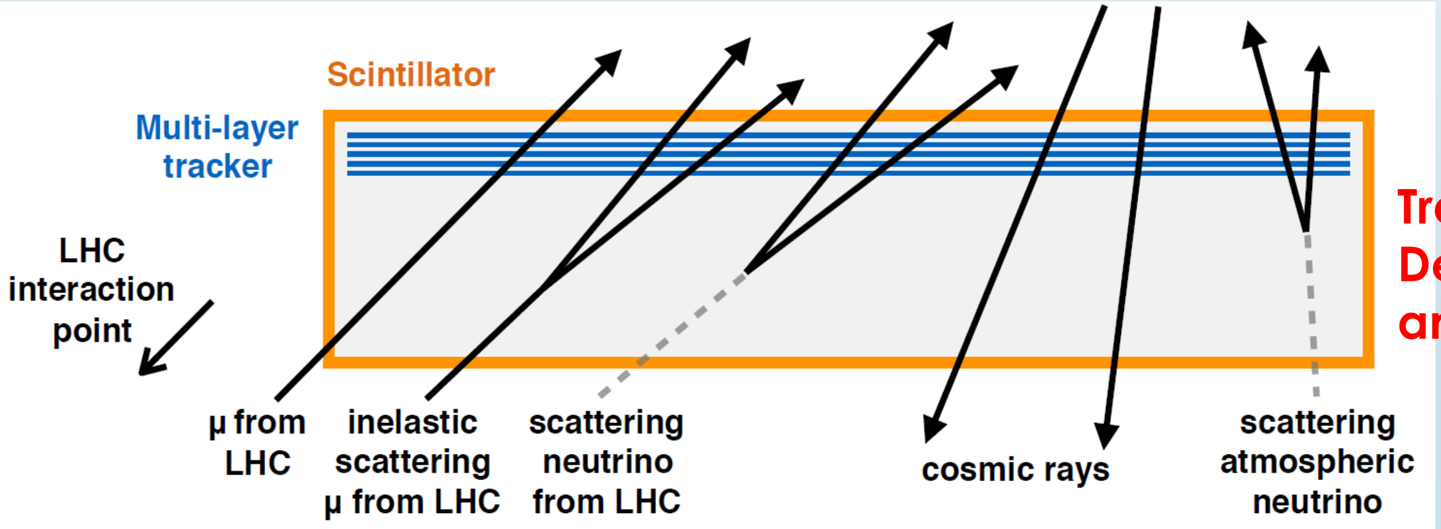
In 20 m gives $\Delta t \approx$ 70 ns in 20m - top to bottom

- LHC collision backgrounds
  - LHC muons about 10 Hz

Reject with timing and entrance hit position

- Upward atmospheric neutrinos that interact in air decay volume
  - Estimate Low rate ~ 10-100 per year above 300 MeV
  - Most have low momentum proton (~ 300 MeV - reject with time of flight)-





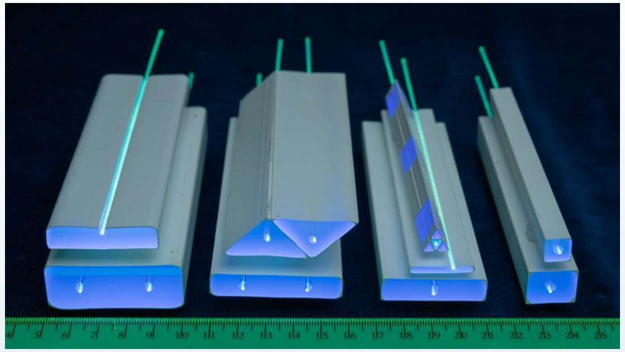
Tracking/timing Detectors (2) at bottom and no side/back vetoes

Tracker technologies being evaluated

- RPCs used in many LHC detectors.
- THE GOOD ☺
  - Proven technology with good timing and spatial resolution.
  - Costs per area covered are low.
- The Less GOOD ☹
  - 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.
  - RPC experts are attempting to find a replacement gas with lower GWP.

Extruded scintillators

- Extruded scintillator bars with wavelength shifting fibers coupled to SiPMs makes this technology cost wise competitive with RPCs.
- THE GOOD
  - 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)



- General concept is scintillator bar ~ 5mx4cmx2cm with wave-length shifting fiber readout at both ends.
  - Results in 700,000 channels
  - Transverse resolution $\sigma = 4\text{cm}/\sqrt{12} \approx 1$ cm.
  - Time difference between two ends gives longitudinal resolution.
    - Aiming for ~ 1 cm, R&D started to determine resolution achievable.
    - Propagation speed in fiber about 16 cm/ns
    - Need time difference resolution of ≈ 90 ps per SiPM.

MATHUSLA Workshop

- Workshop sponsored by the Simon's foundation held at State University of New York, Stoney Brook August 2018.
- Defined LoI submitted to LHCC.
- Got important comments from a review Panel (A. Ball, D. Denisov and W. Wisnewski).
- Defined MATHUSLA collaboration management structure.
  - Management Team
    - HL(contact), D. Curtin, E. Etzion, C. Young).
- MATHUSLA weekly meetings - Wednesday 16:00 CET.

MATHUSLA

Based on 200x200m^2 detector at 100m from IP on surface with IP100m below surface

Theory White Paper

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

1806.07396

Editors:
David Curtin[1], Marco Drewes[2], Matthew McCullough[3], Patrick Meade[4], Rabindra Mohapatra[5], Jessie Shelton[6], Brian Shuve[7,8].

Contributors:
Elena Accomando[9], Cristiano Alpigiani[10], Stefan Antusch[11], Juan Carlos Arteaga-Velázquez[12], Brian Batell[13], Martin Bauer[14], Nikita Blinov[8], Karen Salomé Caballero-Mora[15,16], Jae Hyeok Chang[4], Eung Jin Chun[17], Raymond T. Co[18], Timothy Cohen[19], Peter Cox[20], Nathaniel Craig[21], Csaba Csáki[22], Yanou Cui[23], Francesco D'Eramo[24], Luigi Delle Rose[25], P. S. Bhupal Dev[26], Keith R. Dienes[27,5], Jeff A. Dror[28,29], Rouven Essig[4], Jared A. Evans[30,6], Jason L. Evans[17], Arturo Fernández Tellez[31], Oliver Fischer[32], Thomas Flacke[33], Anthony Fradette[34], Claudia Frugiuele[35], Elina Fuchs[35], Tony Gherghetta[36], Gian F. Giudice[3], Dmitry Gorbunov[37,38], Rick S. Gupta[39], Claudia Hagedorn[40], Lawrence J. Hall[28,29], Philip Harris[41], Juan Carlos Helo[42,43], Martin Hirsch[44], Yonit Hochberg[45], Anson Hook[5], Alejandro Ibarra[46,17], Seyda Ipek[47], Sunghoon Jung[48], Simon Knapen[29,28], Eric Kuflik[45], Zhen Liu[49], Salvator Lombardo[22], Henry Lubatti[10], David McKeen[50], Emiliano Molinaro[51], Stefano Moretti[9,52], Natsumi Nagata[53], Matthias Neubert[54,22], Jose Miguel No[55,56], Emmanuel Olaiya[52], Gilad Perez[35], Michael E. Peskin[8], David Pinner[57,58], Maxim Pospelov[59,34], Matthew Reece[57], Dean J. Robinson[30], Mario Rodríguez Cahuantzi[31], Rinaldo Santonico[60], Matthias Schlaffer[35], Claire H. Shepherd-Themistocleous[52], Andrew Spray[33], Daniel Stolarski[61], Martin A. Subieta Vasquez[62,63], Raman Sundrum[5], Andrea Thamm[3], Brooks Thomas[64], Yuhsin Tsai[5], Brock Tweedie[13], Stephen M. West[65], Charles Young[8], Felix Yu[54], Bryan Zaldivar[55,66], Yongchao Zhang[26,67], Kathryn Zurek[29,28,3], José Zurita[32,68].

LoI submitted to LHCC

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

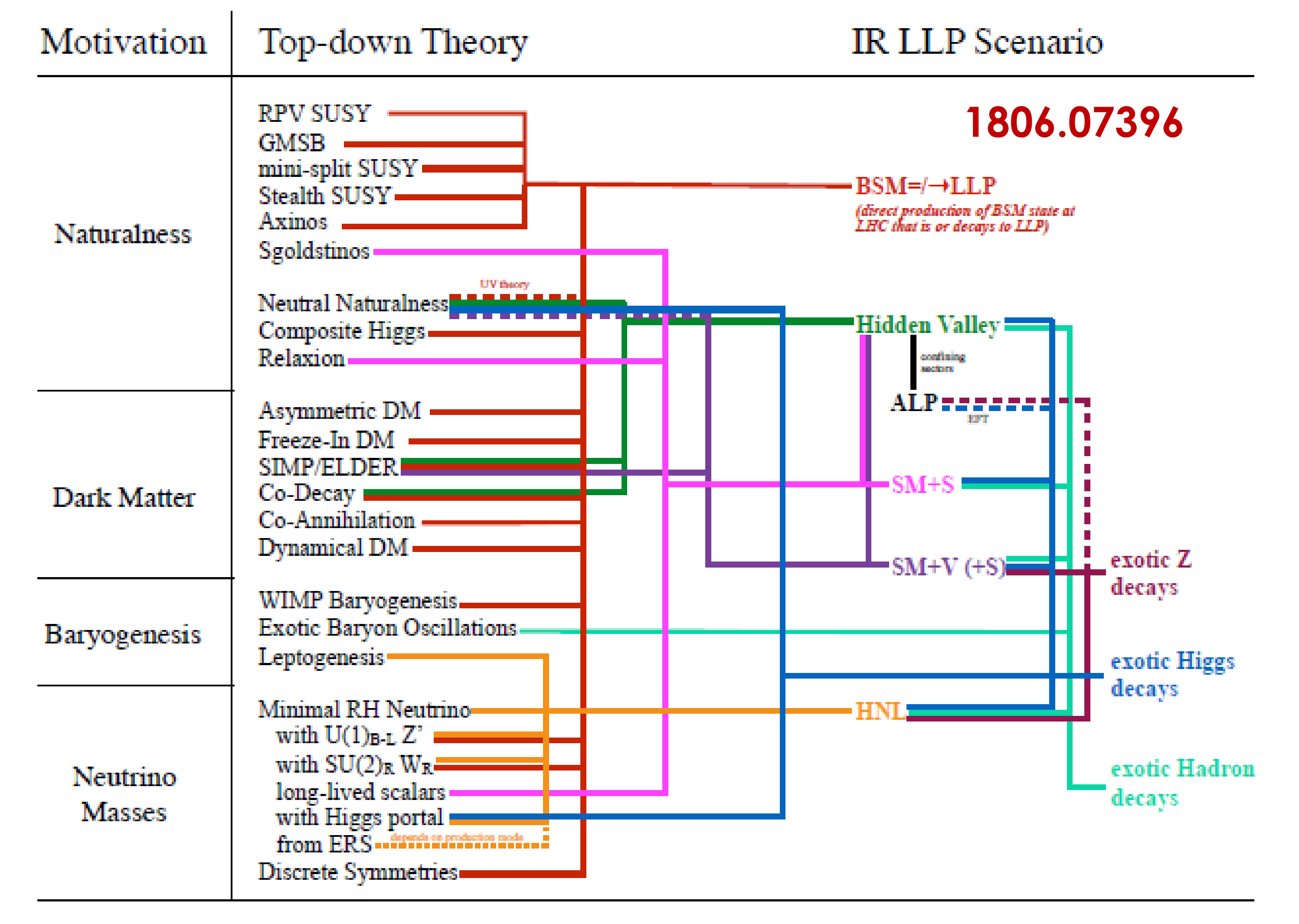
Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

CERN-LHCC-2018-025

Physics Case White Paper 1806.07396 (To be published in Physics Reports)
Letter of Intent: CERN-LHCC-2018-025
Input to European Strategy for Particle Physics1901.04040v1

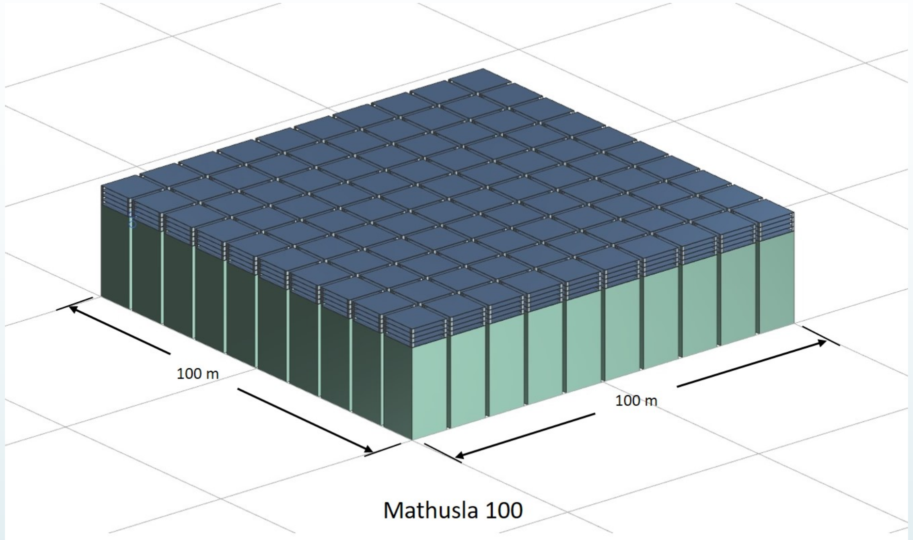
MATHUSLA PHYSICS POTENTIAL

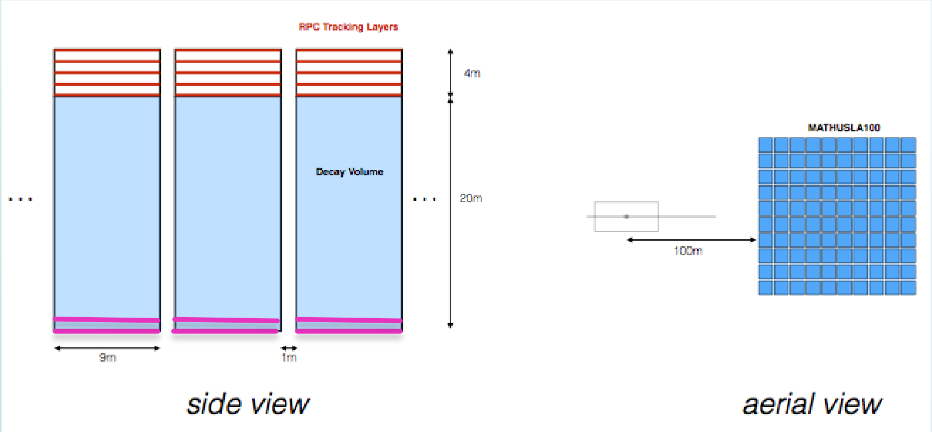
- LLPs arise in most BSM theory constructs (1806.07396)



Modular Concept

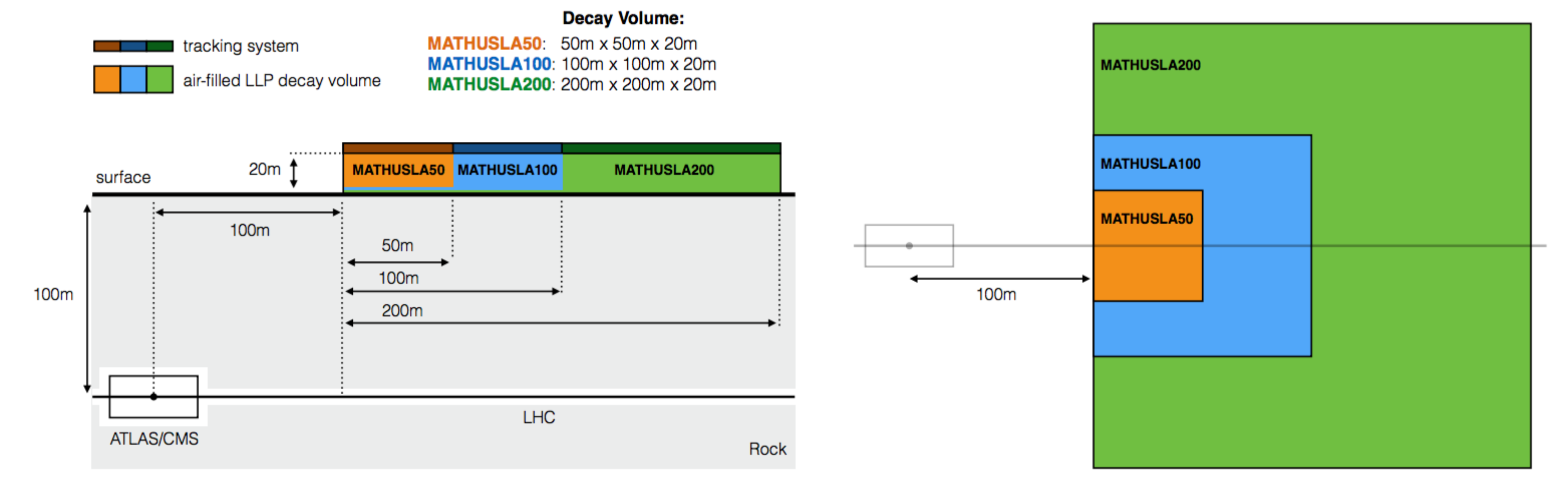
- Current layout has individual 9 m X 9 m modules
  - 5 tracking/timing planes (red) at top of 20 m decay volume and bottom detector layers (violet).
  - Easy to adapt to site specific conditions.
  - Allows for modular construction, staged installation of modules & incremental ramp-up.
- Allows for possibility of adding material for electron identification (e/μ in cosmic rays).
- Exploring housing modules in a large building.
- Trigger unit: 3 x 3 modules is the baseline.
  - Choice based on largest inclination angle for 200 m X 200 m detector and very safe for 100 m X 100 m detector.





MATHUSLA LoI Layouts

- Geometries considered and discussed in LoI.



side view *aerial view*

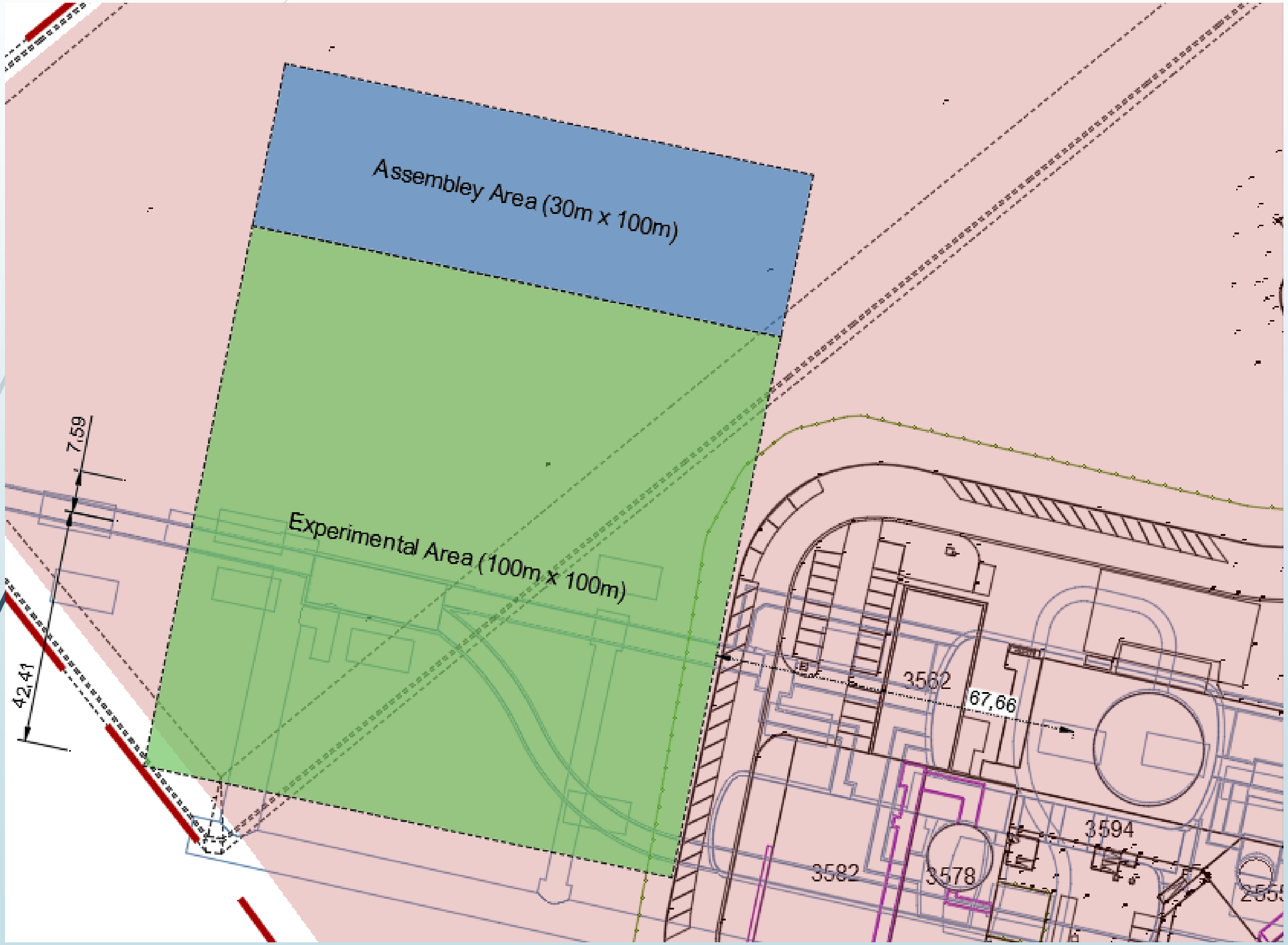
- LoI bench mark is ~100m x 100m x 25m
  - Have ~ 20 m decay volume
  - 5 layers of tracking chambers (RPCs) separated by 1 m
  - Bottom tracking layers.

MATHUSLA Detector at P5

Recent Developments

- Working with Civil Engineers from CERN EN-ACE group (J. Gall and L. Dougherty) to define building and the layout of MATHUSLA at P5.
- Must fit on CERN owned land at P5.
  - Layout restricted by existing structures is based on current concept and engineering requirements.
    - Individual detector units to cover the ~10^4 m^2 detector area
    - Assume ~ 20 meter decay volume.
    - Five layers of tracking/timing detectors separated by one meter.
    - Floor detector - 2 layers.
    - No side veto walls.
  - Building to include an adjacent detector assembly area.
  - Crane coverage from assembly area to detector building.
- A 3-d model of detector building and basic structures exists and will continue to evolve.

Current MATHUSLA Layout Concept - CMS

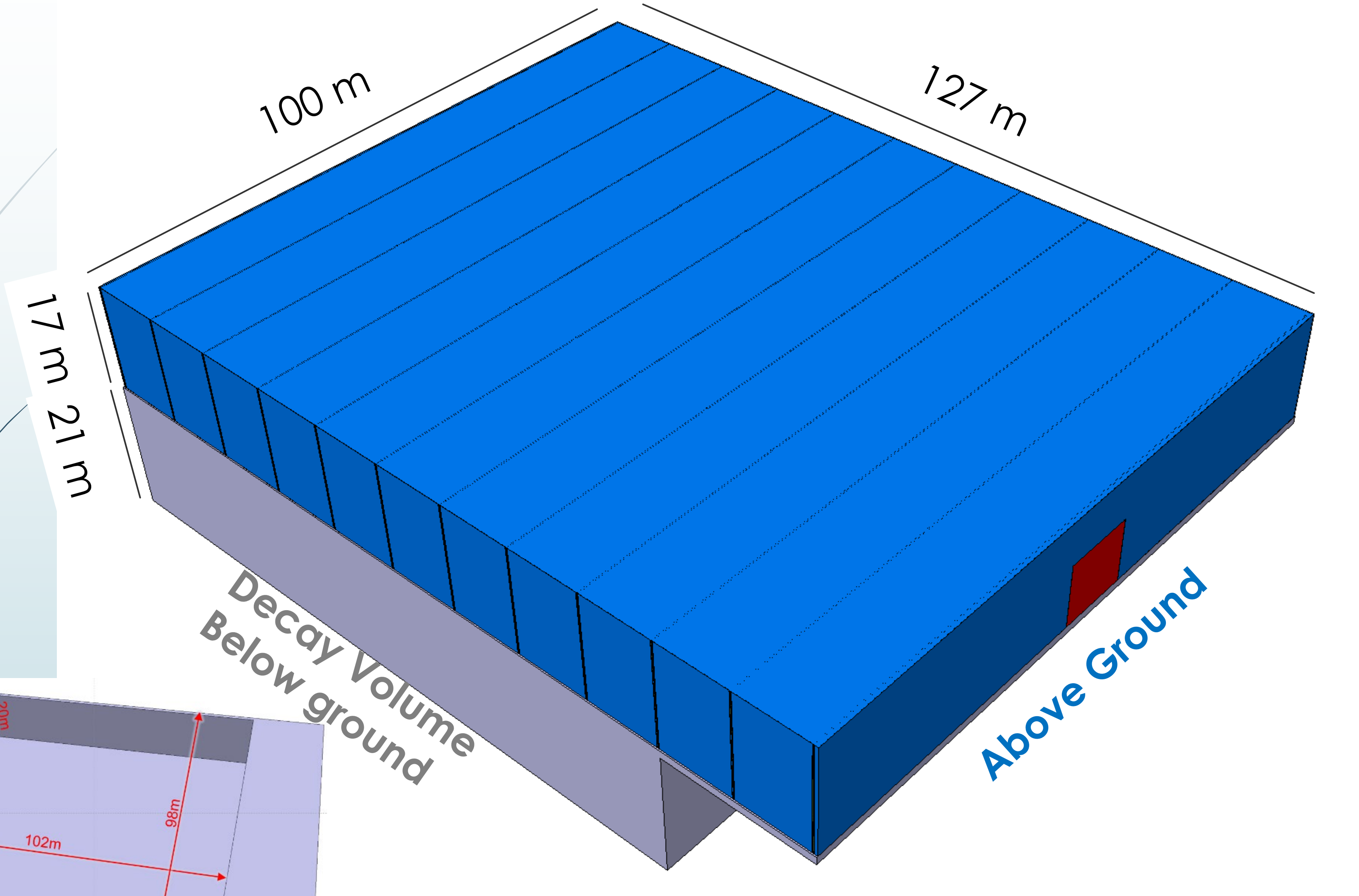


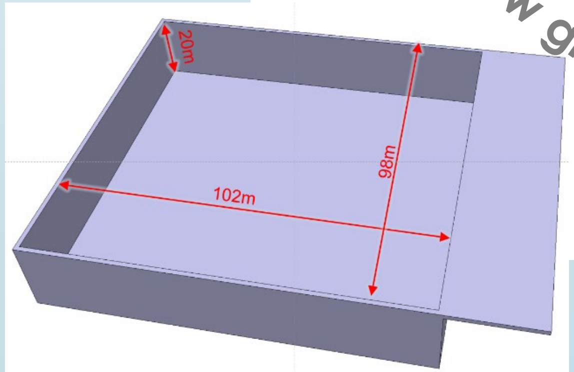
- Experimental and assembly area in an enclosed building with crane coverage
- Fits on CERN owned land and avoids <u>known</u> Roman artifacts
- NB 68 m to IP on surface and IP ≈ 80m below surface
- NB gain of 1.5 wrt detector at 100 m and IP 100 m below
- ~7.5m offset to centre of beam
- Other aspect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

Design Constraints

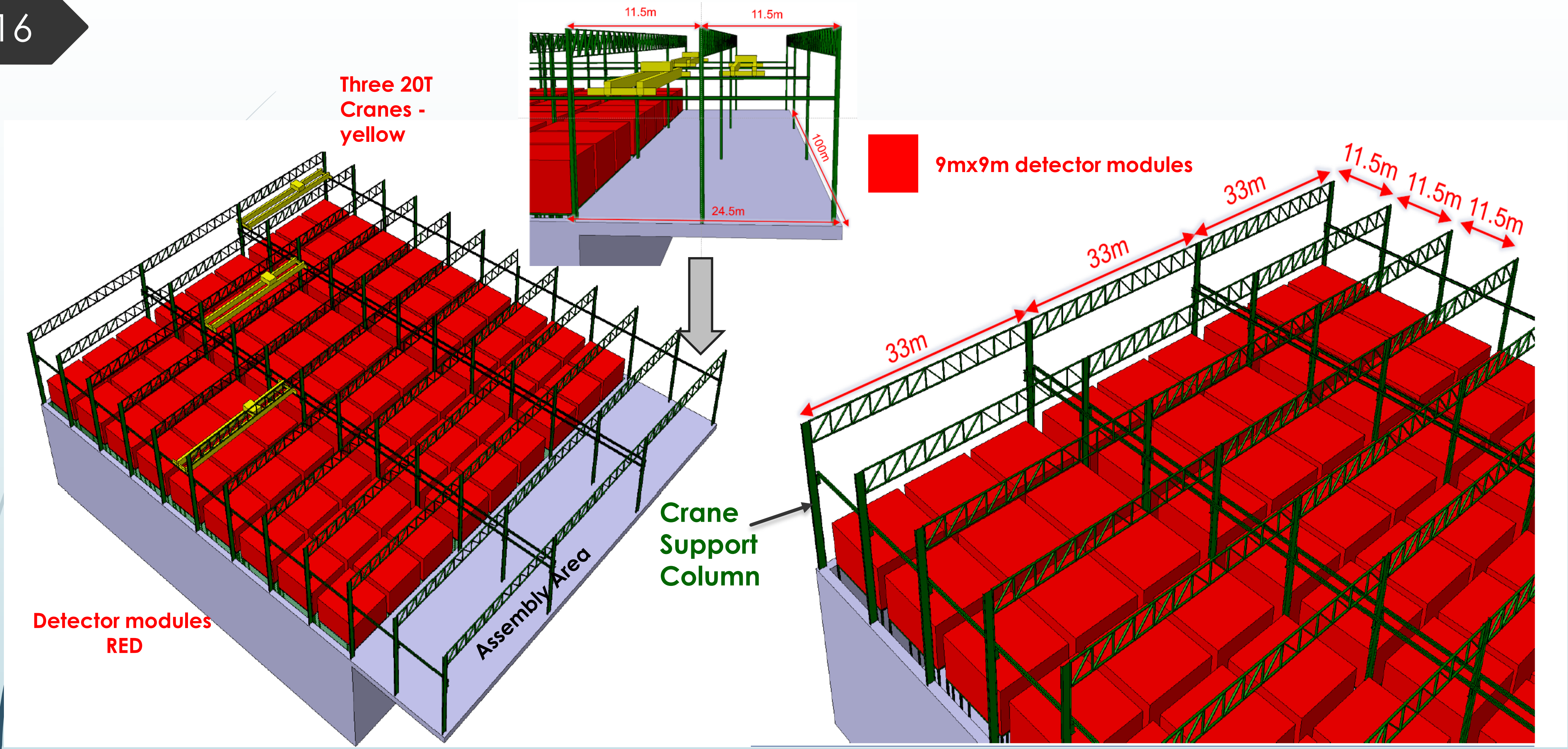
- Basic concept of modular detector units ~ 9mX9m – allows for phased construction and simplifies installation.
- Cover approximately 10^4 m^2 – Physics requirement.
- Minimum decay volume ~ 20 m – Physics requirement.
- Geometry driven by CERN owned space at P5, existing structures, HSE, HE and CE requirements.
- Maximum width 100 m – CE requirement.
- Maximum height above ground level 17 m – CE requirement.
- Space for access between modules 1 m – HSE requirement.
- Space between columns supporting crane and detector units 1.5 m - HE requirement.

Preliminary Layout



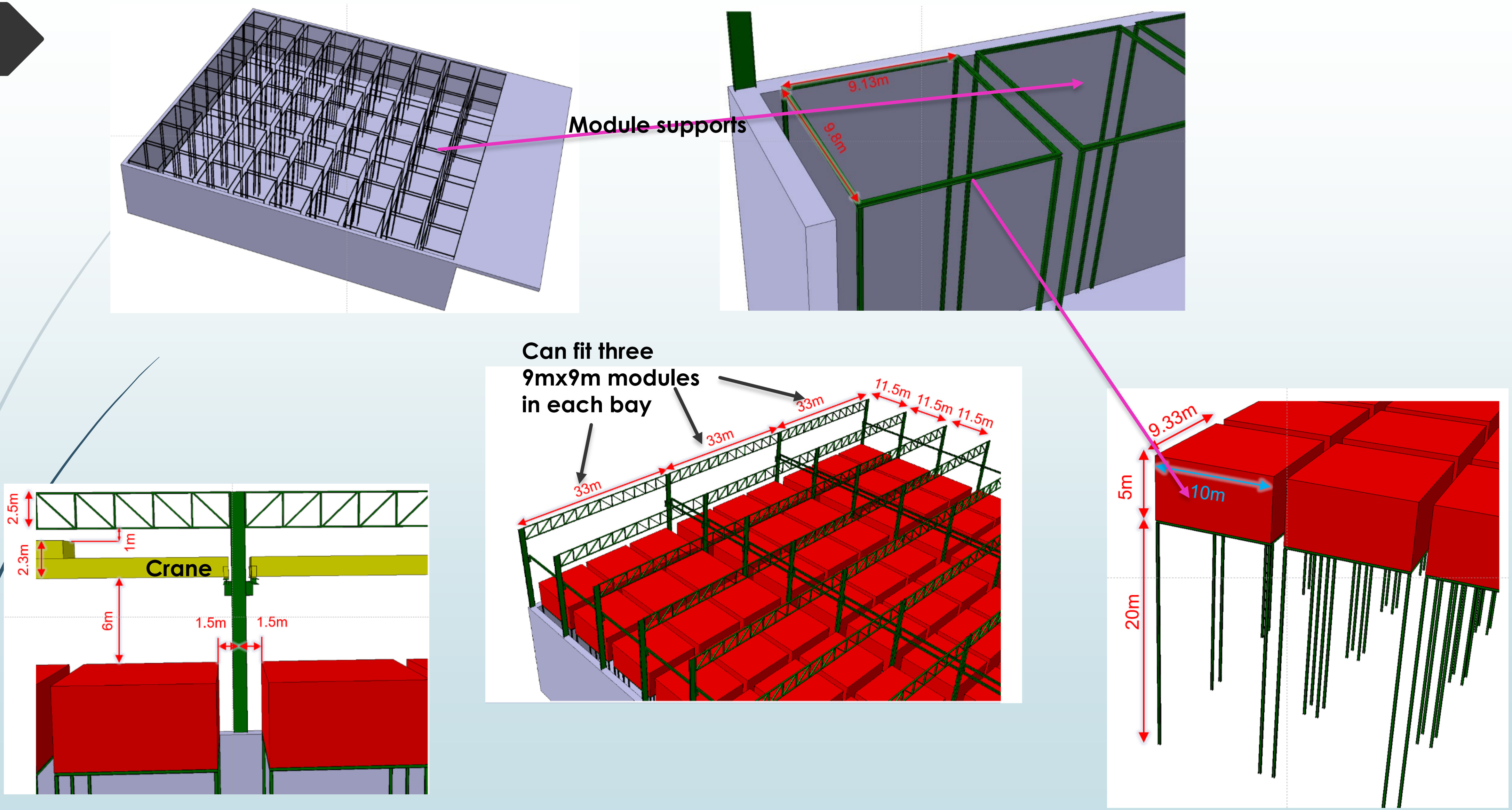


Current Concept - Layout



- ❑ One meter between modules – HSE requirement
- ❑ Need 1.5m center of column to edge of modules for crane maneuvering - HE requirement

Details



Module supports
9.13m
9.8m
Can fit three 9mx9m modules in each bay
33m
33m
33m
33m
11.5m
11.5m
11.5m
9.33m
10m
5m
20m
2.5m
1m
2.3m
Crane
6m
1.5m
1.5m

P5 Building - Next Iteration

- Height above modules will be reduced by ~ 5m.
  - By stacking modules sequentially.
  - Keep building and pit height the same and increase decay volume by ~ 5m ➡ ~ 25% increase in decay volume.
  - Combined gain of larger decay volume 17m below ground and 68 m from IP results in factor of 2 so100mx100m^2 has sensitivity approaching the 200x200m^2 detector considered in 1806.07396.☺
- Add Shaft to assembly area with lift and stair access to lower level.
- Assembly area design to include space for temporary module storage, work space, equipment storage.
- Define space for control room and welfare facilities.

Acronym Definitions

- **CE** – Civil Engineering
- **HSE** - CERN's occupational Health & Safety and Environmental protection Unit
- **HE** - Handling Engineering Group
  - Prepares, organizes and coordinates all transport and handling operations for the CERN accelerators and experiments – trucks, overhead cranes, lifts…

Channels and triggering

- Have 7 layers (5 tracking chambers + 2 on floor)
- Assuming 4 cm scintillators with readout at both ends results in 700,000 channels.
- Rates dominated by cosmic ray rate (~ 2 MHz)
  - Does not require sophisticated ASIC.
  - Aiming for $1 per channel for frontend.

Data Collection

- Baseline is to collect to 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 9x9 m^2 modules, two hits/module with 4 bites per readout and readout 7 layers to readout gives ~ 1 MB/sec or $\sim 30\mathrm{TB/year}$ per module
- Trigger unit consists of 3x3 modules.
- Move information to central trigger processor
- Trigger separately recorded and used for connecting to CMS detector bunch crossing.

Channels and triggering

- Have 7 layers (5 tracking chambers + 2 on floor)
- Assuming 4 cm scintillators with readout at both ends results in 700,000 channels.
- Rates dominated by cosmic ray rate (~ 2 MHz)
  - Does not require sophisticated ASIC.
  - Aiming for $1 per channel for frontend.

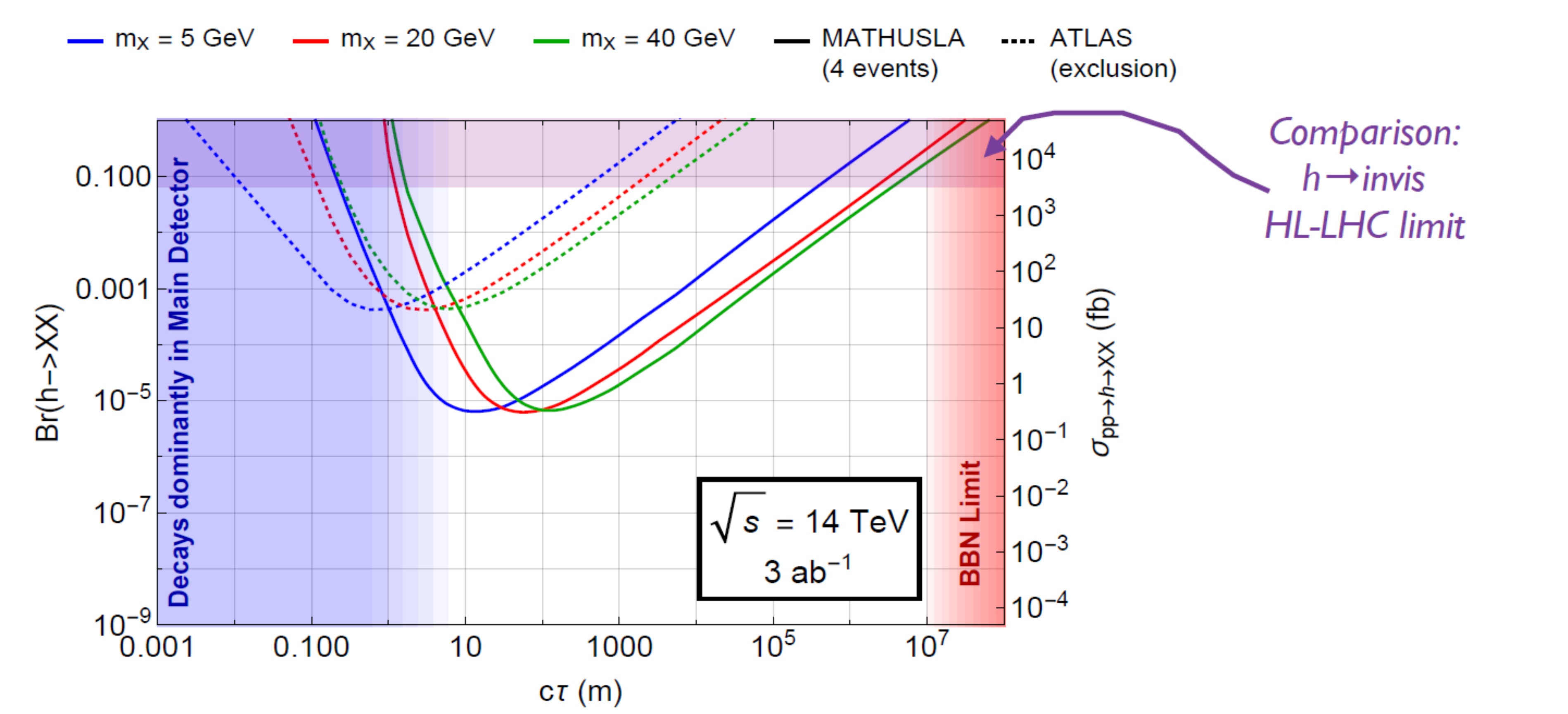
Associating with CMS Bunch Crossing

- CMS Level-1 trigger latency is 12.5 μs for HL-LHC
- Conservatively assuming a 200m detector with height = 25m located100m 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.
- Thanks to Alex Tapper for information about CMS HL-LHC Level-1 trigger.

Sensitivity estimate

arXiv 1606.06298

- Decay of Higgs boson to pair of scalars, x, for several m_x
- Mathusla has no QCD backgrounds → sensitivity gain
- Can approach BBN limit of ~ 0.1s



MATHUSLA – Test Stand

To help guide background studies and understand LHC collision backgrounds we built a

TEST STAND

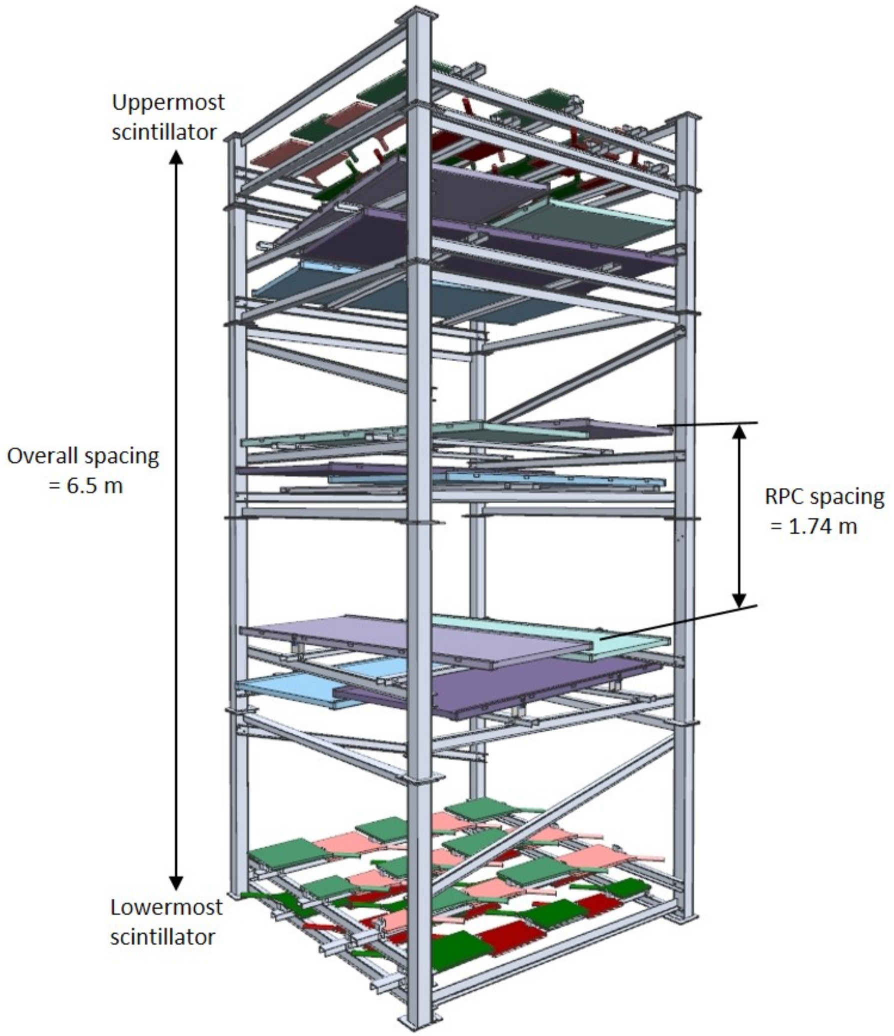
… and took data above the ATLAS IP in 2018

Test Stand at PI above ATLAS IP

- Built a ~ 2.5x2.5x6 m^3 test stand with three layers of RPCs and top and bottom scintillator layers
  - RPCs from Rinaldo Santonico Rome, Tor Vergata – spares from ARGO experiment
  - Scintillators are recycled from D0 forward muon trigger wall - thanks to Dmitri Denisov.
- Goal to get some idea of upward LHC backgrounds (muons)
- Photo at right shows the structure installed at LHC point-1, above ATLAS IP.

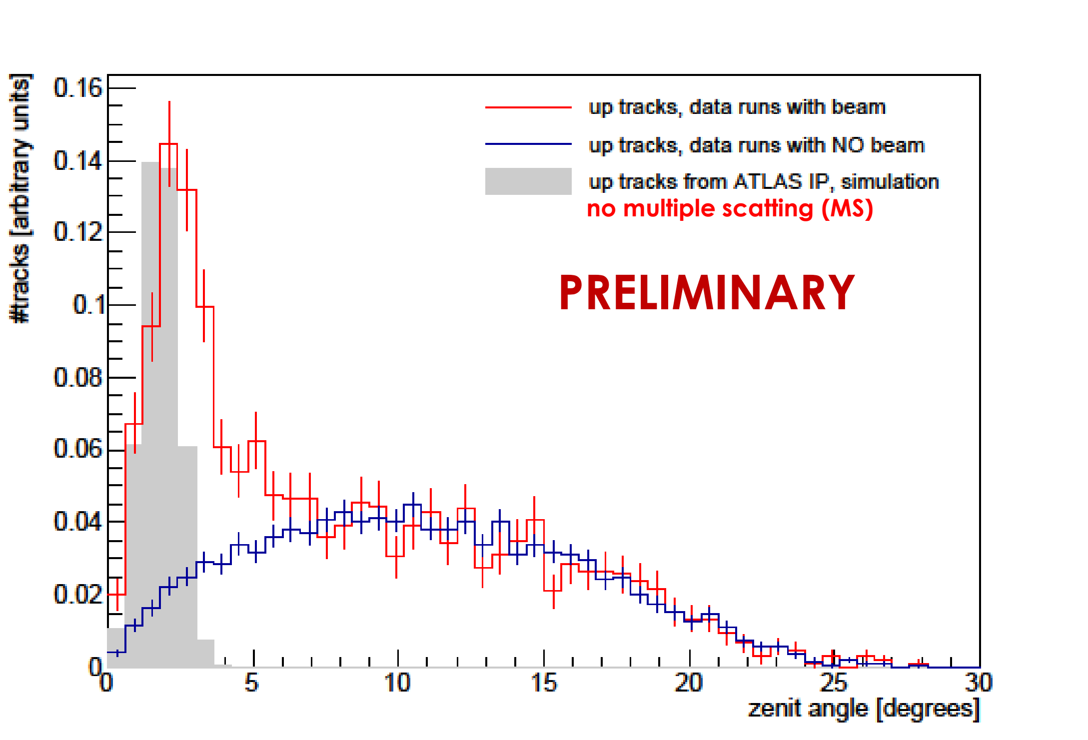
Test Stand

- Scintillators top and bottom with three layers of RPCs separated by 1.74 m.
- RPCs and scintillators have timing resolution of $\sigma \sim 2.5$ ns.
- A $\beta = 1$ particle takes 3.3 ns to travel 1 m, so with a total length of ~ 6 m we have top to bottom time difference of ~ 20 ns or 8 σ.
- Two triggers running simultaneously.
  - Downward trigger for cosmic rays
  - Upward trigger for tracks from IP
- Took data in 2018 to end of Run-2.



Preliminary Test Stand Results

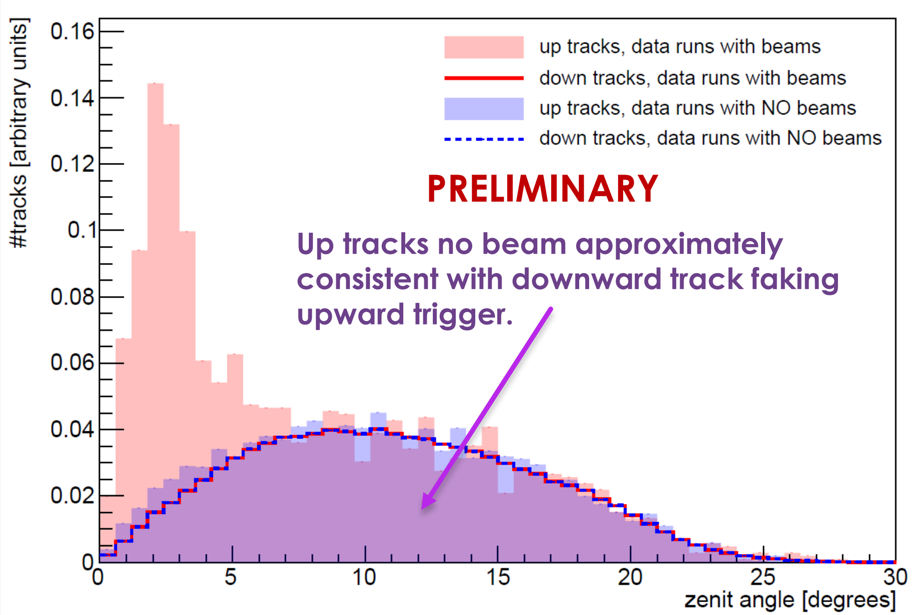
- Preliminary results – **Not corrected for efficiency**
- **Arbitrary normalization**
- **Accumulation for zenith angle < ~ 4° consistent with upward going tracks from IP when collisions occur**



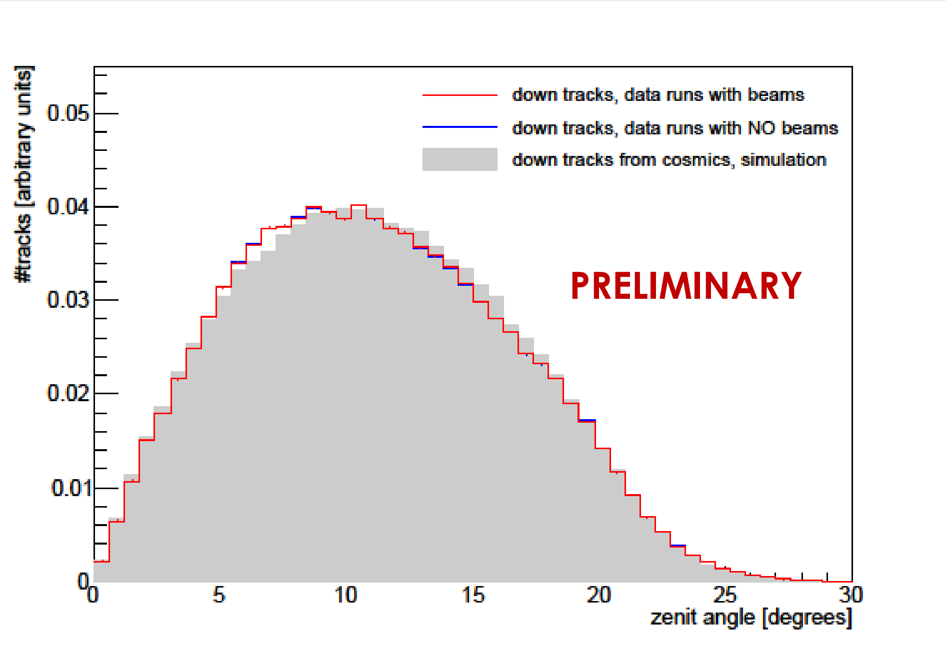
Preliminary Test Stand Results

- Preliminary results – **Not corrected for efficiency**
- **Arbitrary normalization**
- **Accumulation for zenith angle < ~ 4° consistent with upward going tracks from IP when collisions occur**

Test Stand Data



MC simulation-NO MS



Going Forward

- Detector footprint at CMS to be finalized
- Building details coming together and goal is to have a preliminary cost estimate this year.
- Goal is to make tracker technology choice early next year.
- Open items to fixed include:
  - Frontend electronics
  - Trigger details
  - Cabling
  - Tracking chamber support structure
  - Installation procedures
- Complete Technical Design Report (TDR) by end 2020.

Cảm ơn bạn