The Lifetime Frontier

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Lifetime frontier at the LHC and HL-LHC

Organization of talk

- Overview of LHC long-lived particles (LLPs) detector signatures.
- Overview of current ATLAS, CMS and LHCb triggers and searches.
  - With $c\tau$ reach of O(100) meters.
- Extending the life-time reach to Big Bang Nucleosyntheses limit, $c\tau \approx 10^7$ meters with new, proposed detector **MATHUSLA** for HL-LHC.

LHC detector signatures

- Strong dependence on the sub-detectors of ATLAS, CMS and LHCb.
  - Inner detectors, calorimeters an muon systems not the same in the three detectors
  - All LHC detectors need to overcome obstacles
- Boost of LLP determines opening angle(s) and that affects trigger efficiencies.
  - Efficiencies can also depend on trigger algorithm and subsystem readout at trigger level
  - Preaents a challenge for generic, model independent searches

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

Signatures of displaced decays

- ❑ Inner Tracker green
- ❑ EM Calorimeter Blue/green
- ❑ Hadronic calorimeter Blue
- ❑ Muon system Grey

Displaced decay signatures

1. Decay in muon system - jet
2. Two body decay (lepton jet)
3. Decay in HCAL of - jet
4. Emerging jets
5. Inner Tracker decay to jets
6. Decay to jets in the IT
7. Disappearing (invisible) LLP
8. Non-pointing $\gamma \rightarrow e^+e^-$

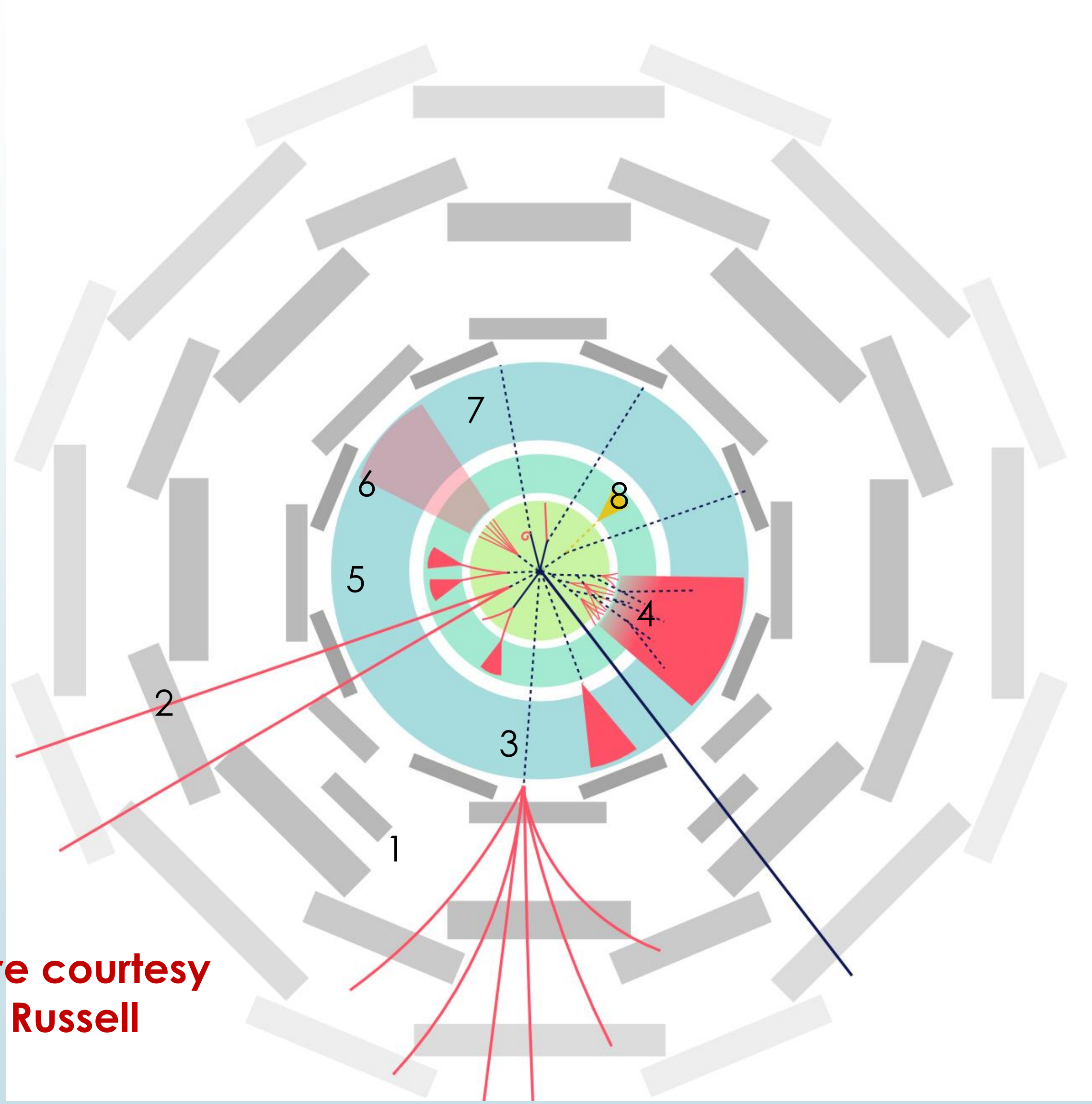
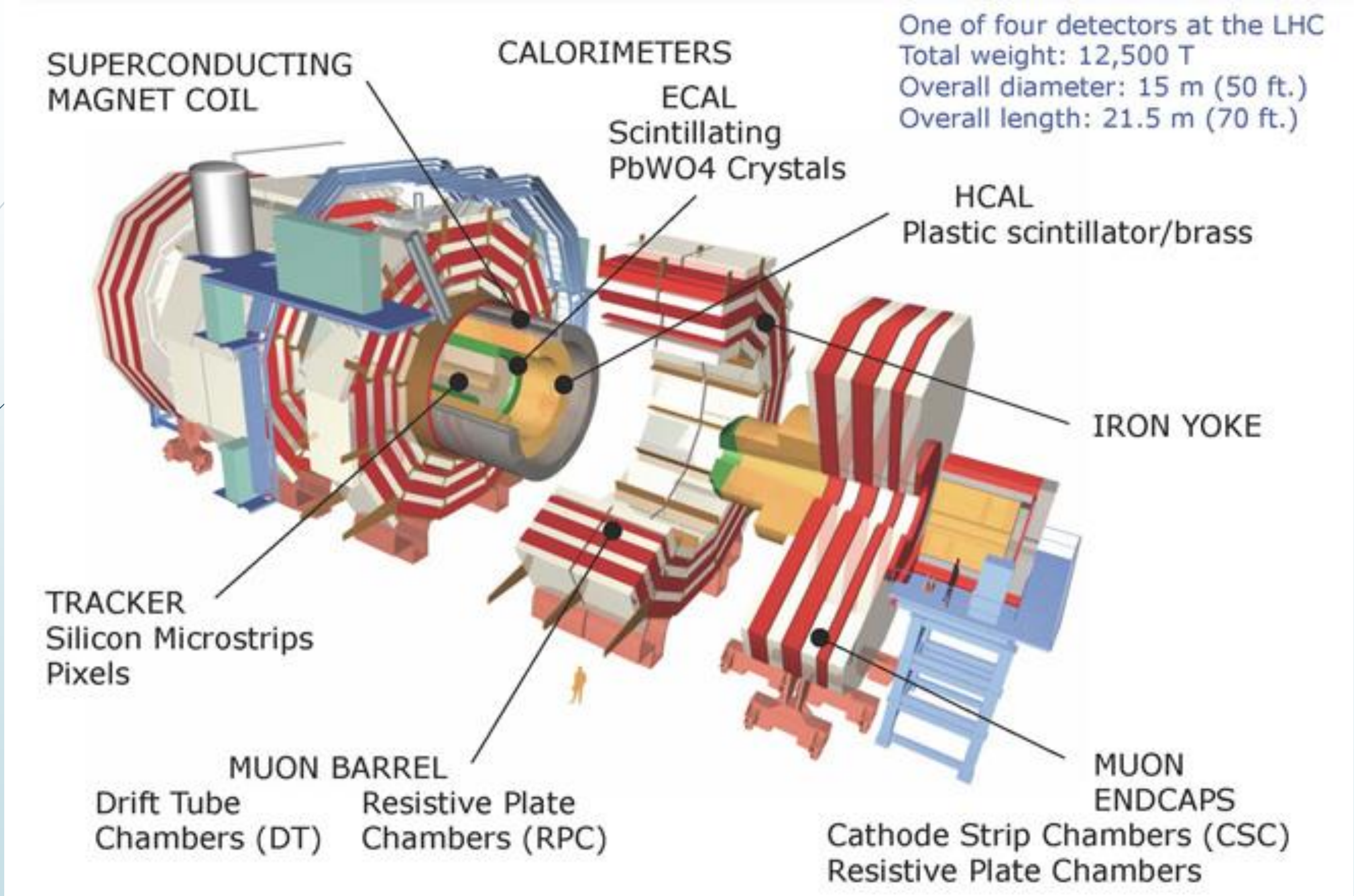


Figure courtesy of H. Russell

LHC Detectors Overview

CMS Detector

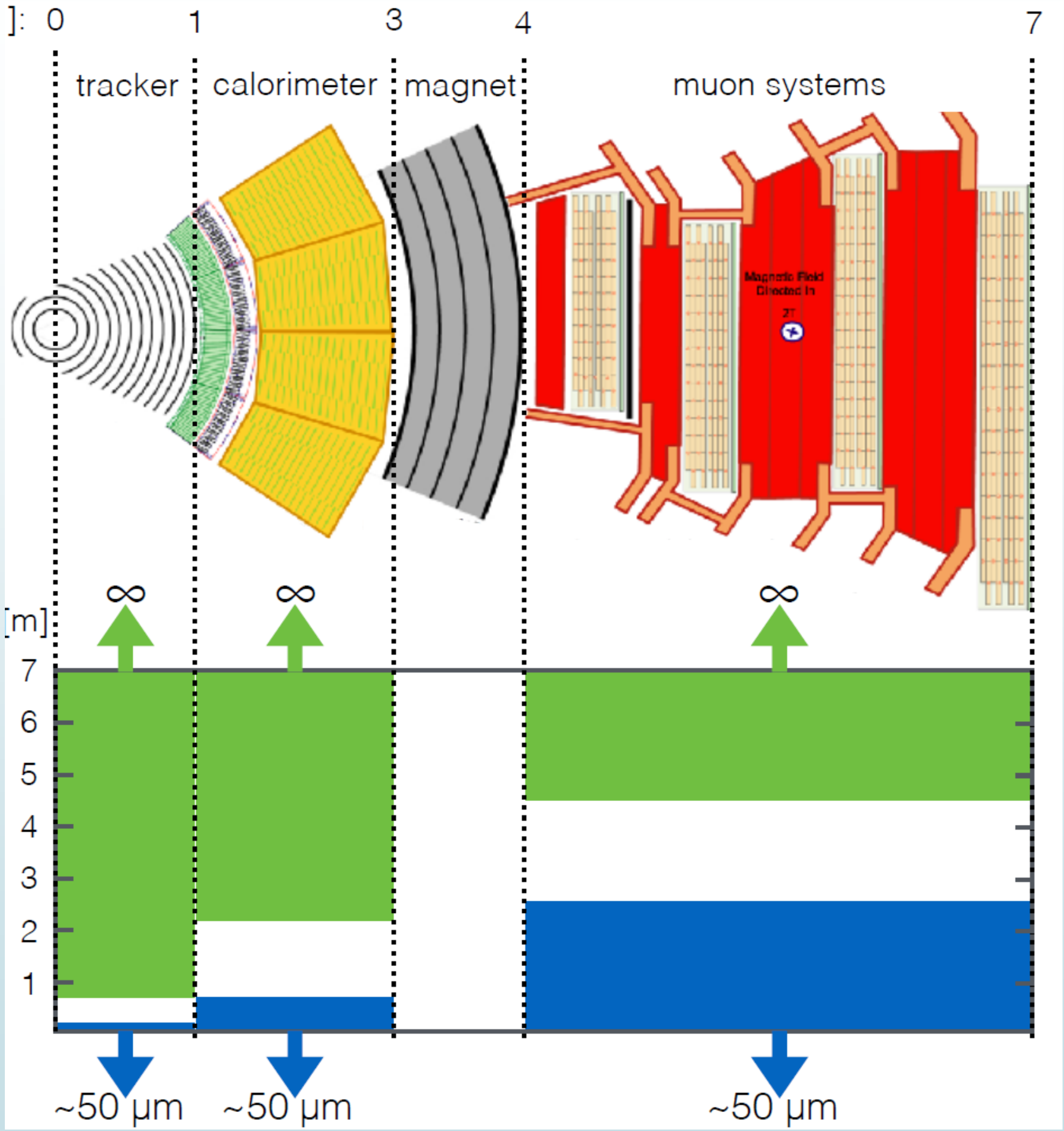


CMS

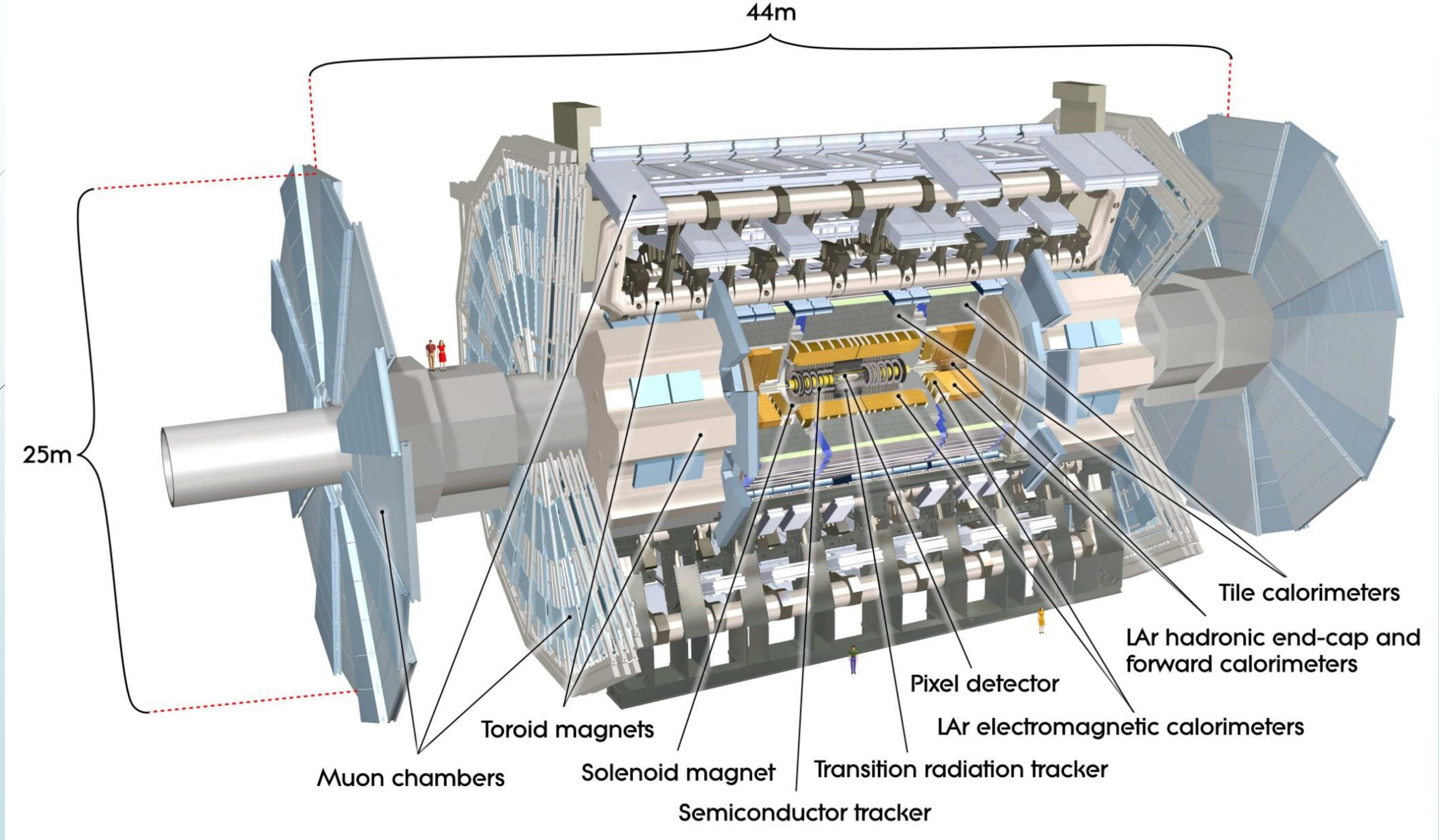
CMS inner tracking entirely silicon based (pixels + strips)

E_{CAL} uses $PbWO_4$ crystals – very good energy resolution

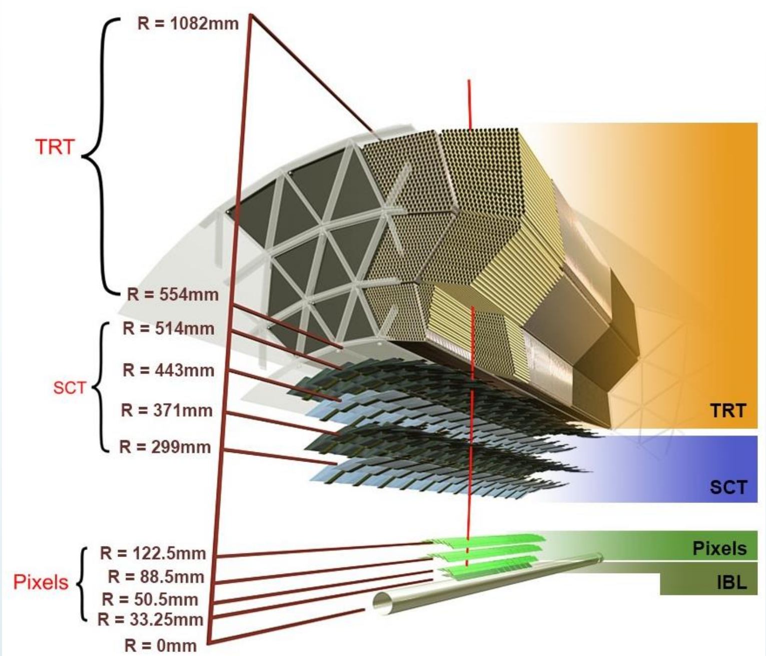
Muon system tracking chambers buried in Fe return yoke of magnet

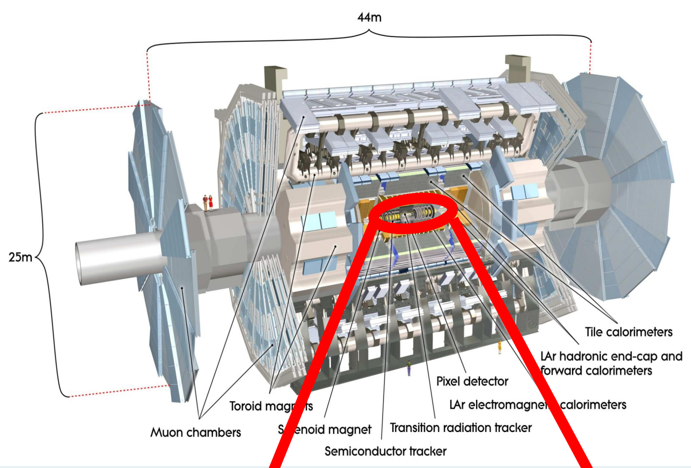


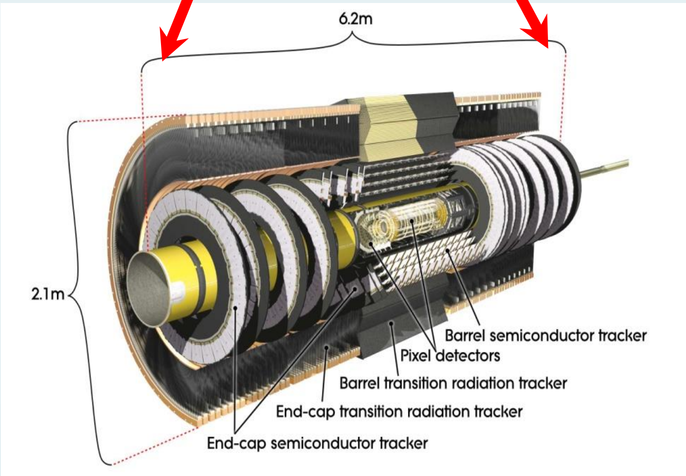
ATLAS


44m
25m
Muon chambers
Toroid magnets
Solenoid magnet
Semiconductor tracker
Transition radiation tracker
LAr electromagnetic calorimeters
Pixel detector
LAr hadronic end-cap and
forward calorimeters
Tile calorimeters

ATLAS Inner Detector



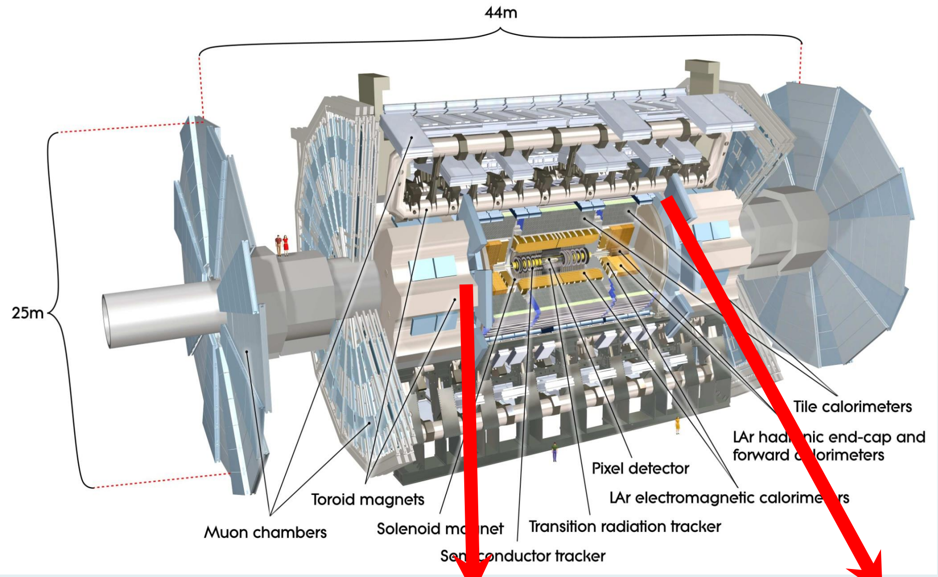


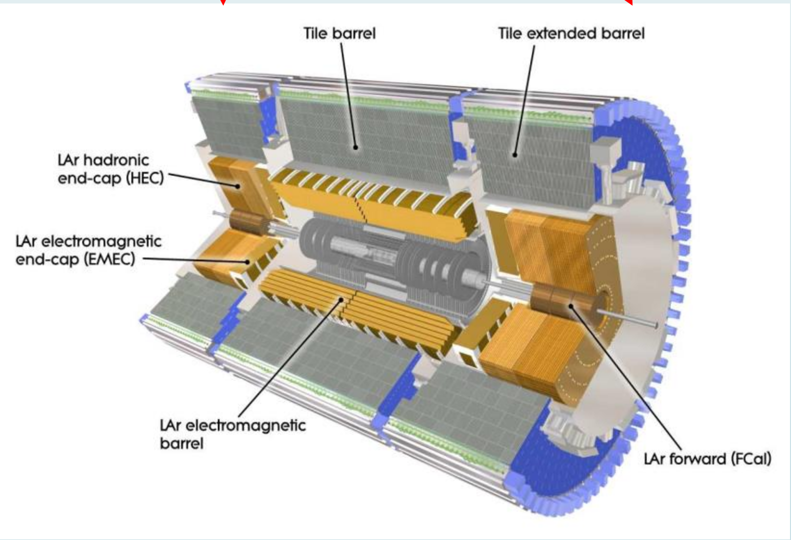


- Pixel Detector (Three + IBL layers - double sided)
  - $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 10$ μm, $\sigma_z \sim 115$ μm (80M channels)
- Semiconductor Tracker (SCT): single sided Si strips
  - stereo pairs
  - Four barrel layers and 2x9 end-cap disks stereo
  - $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 17$ μm, $\sigma_z \sim 580$ μm (6.3M channels)
- Pixel and strips provide good resolution tracking measurements
- Transition Radiation Tracker (tracking and e-p separation)
  - 73 barrel straw layers and 2x160 end-cap radial layers
  - $|\eta| < 2.0$ with $\sigma_{r\phi} \sim 130$ μm (350k channels)
  - Average of 32 hits/track
- The ID embedded in a 2 Tesla solenoidal magnetic field

ATLAS Calorimeters

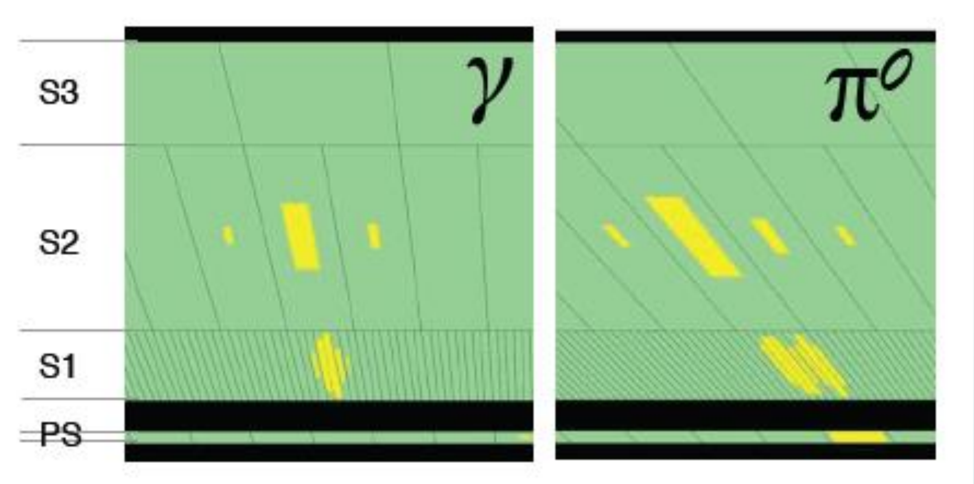
- Electromagnetic Calorimeter (ECAL)
  - **Lead accordion with liquid argon**
  - **Three longitudinal segments**
- Hadronic Calorimeter (HCAL)
  - **Barrel Fe Scintillator plates with polystyrene**
  - **Forward Cu Liquid Ar**
- Barrel Dimensions
  - ECAL 1.1m < r < 2.25m
  - HCAL 2.25m < r < 4.25m
- Calorimeters cover $|\eta| \leq 3.9$

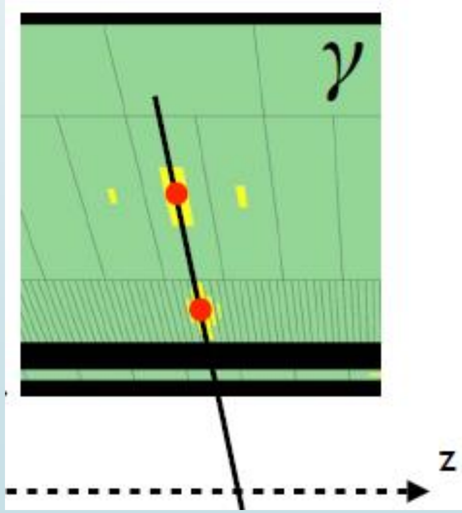


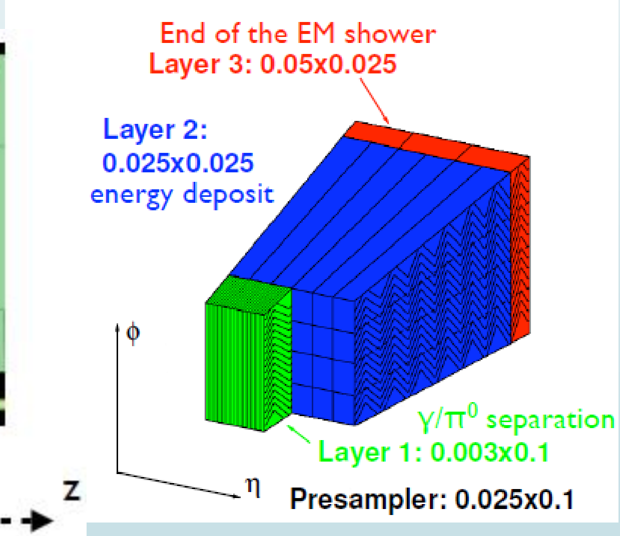


ECAL Segmentation

- Allows for Photon ID based on longitudinal and lateral segmentation of the ECAL (shower shapes)
- High granularity in S1 gives in good γ direction and separation power for π^0 decays to γγ
- Photon direction from shower centroids in layers 1 and 2 gives longitudinal (z) position
- For two γ (eg. H → γγ) cobine to improve z-resolution of interaction point (IP)
- For displaced decays get γ direction in layers 1 and 2 to determine z of closest approach







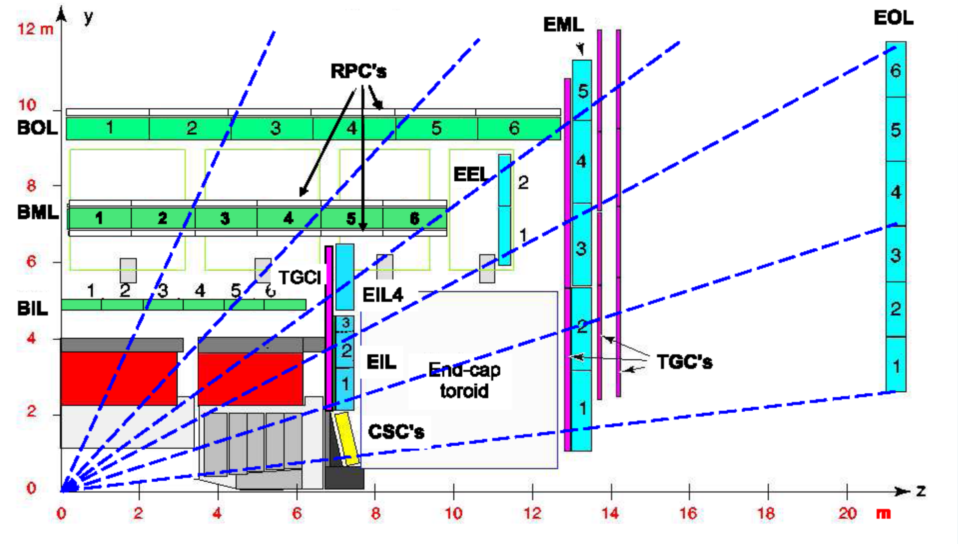
ATLAS Muon Spectrometer

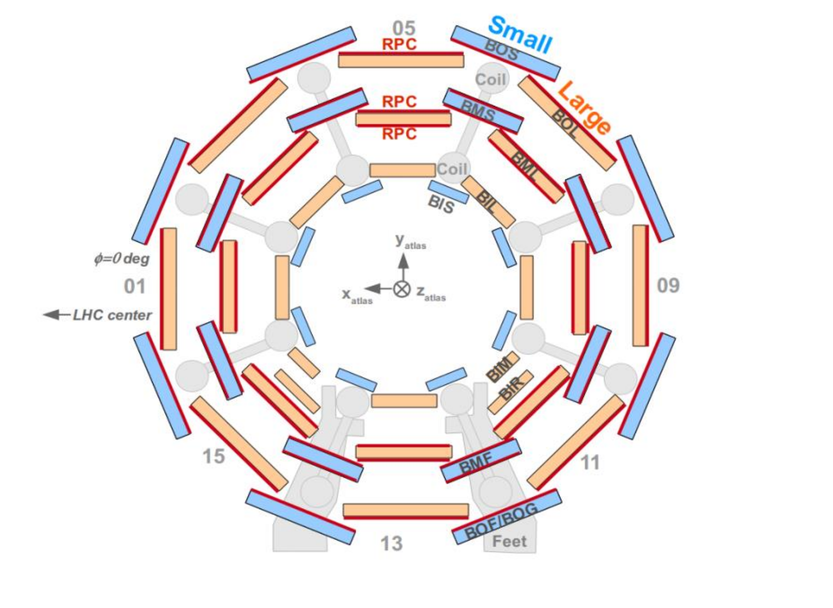
- Air core toroid - magnetic field allows for stand-alone momentum measurements

Trigger Chambers

RPC's in barrel region covering $|\eta|<1.05$ and TGC's in Forward region $1.05< |\eta|< 2.4$

Trigger chambers provide second coordinate (φ) for track reconstruction





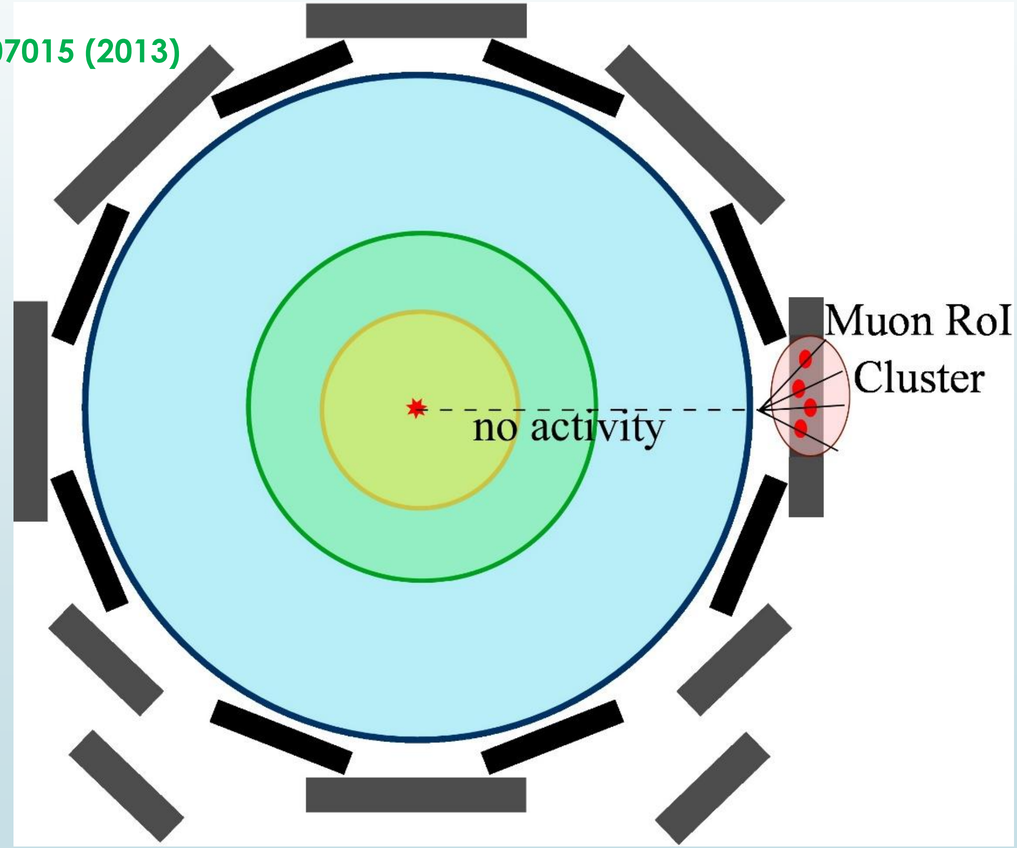
* Precision Chambers
  * Monitored Drift Tube (MDT) chambers in barrel and most of forward spectrometer
    * Barrel MDTs ~ 4.5, 7 and 10 m
    * Forward MDTs ~ 7.5 and 14 m
  * MDT chamber has two multilayers (ML) with 3 or 4 layers of MDT tubes
  * Multilayers separated: up to 32 cm
* Cathode Strip Chambers (CSC's) for $2.0 < \eta < 2.7$
* Resolution σ_{p_T}/p_T ~ 4% at 50 GeV and ~ 11% at 1 TeV

Neutral LLPs

- 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

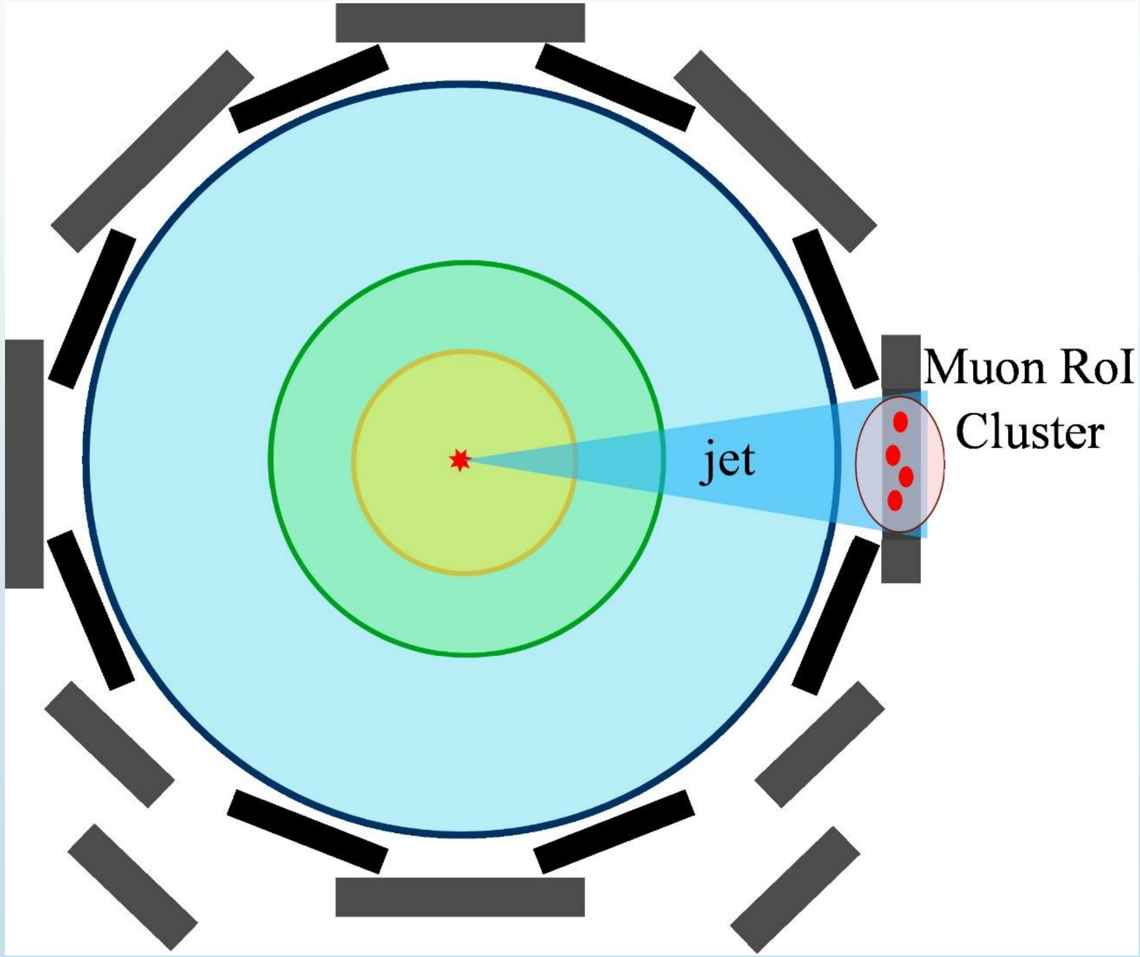
Signature Driven Displaced Decay Triggers

- ATLAS has two specific displaced decay triggers that selects displaced decays to hadronic jets in the Muon Spectrometer (MS)
- MS triggers called muon RoI cluster triggers (L1 Region of Interest cluster triggers).
- MS *isolated RoI cluster trigger* JINST 8 P07015 (2013) selects a cluster of at least three (four) muon RoIs lying within a $\Delta R = 0.4$ radius in the MS barrel (endcaps) and required to be isolated from jets within $\Delta R < 0.7$ that have $\log_{10}[E_{HAD}/E_{EM}] < 0.5$ and no charged tracks with $p_T > 0.5$ in a $\Delta R < 0.4$ cone center on the RoI cluster barycenter. This trigger used to select events for Run-1 search for displaced Hadronic decays of neutral particles Phys. Rev., D92, 012010 (2015)

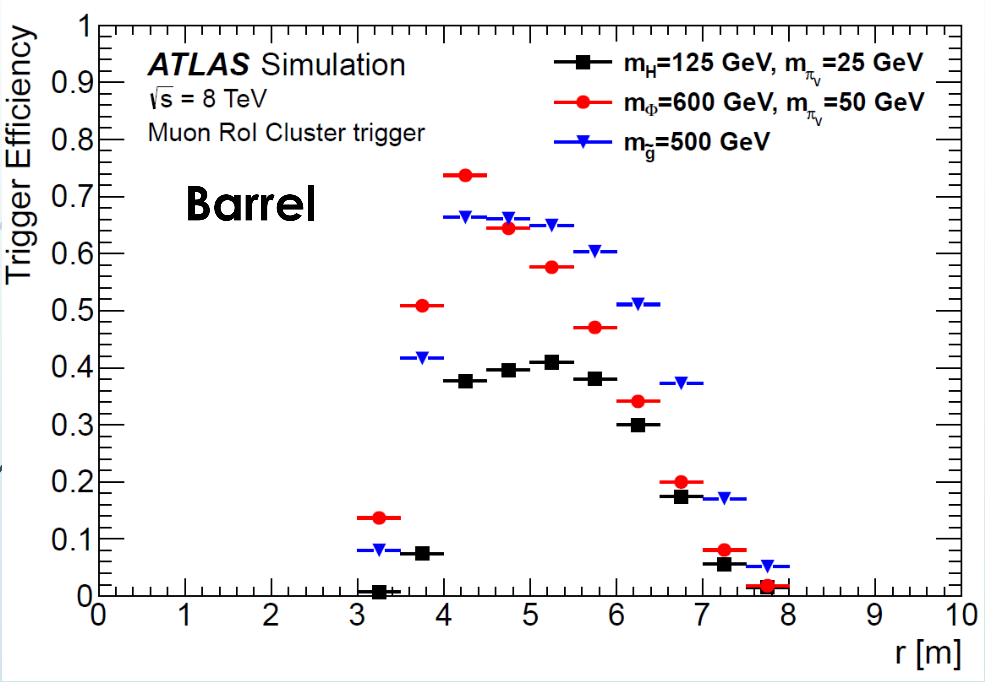


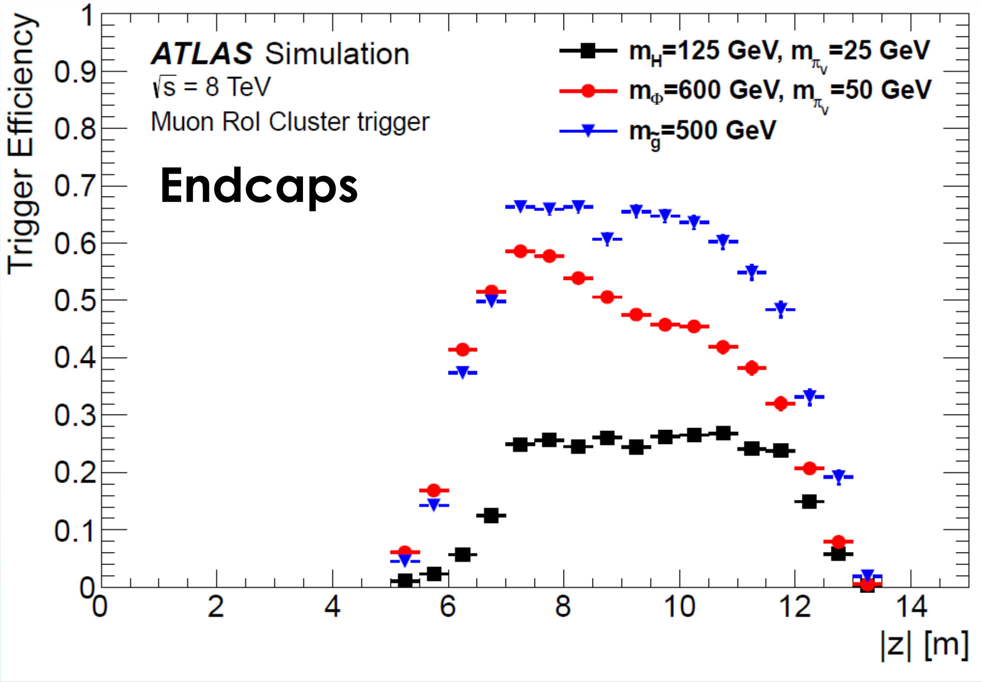
Signature Driven Displaced Decay Triggers

- *Muon non-isolated MS RoI cluster trig*ger uses the same MS cluster selection criteria, that is a cluster of at least three (four) muon RoIs lying within a ΔR = 0.4 radius in the MS barrel (endcaps).
- The non-iso cluster trigger does not have any isolation requirements with respect to either calorimeter jets or ID tracks, and consequently selects both signal-like events that are isolated, and an orthogonal sample of background events and signal-like events that have associated prompt objects such as jets and/or tracks.
- The non-iso is used for a search of displaced decays in the MS for Run-2 2016 data



ATLAS muon RoI trigger efficiency

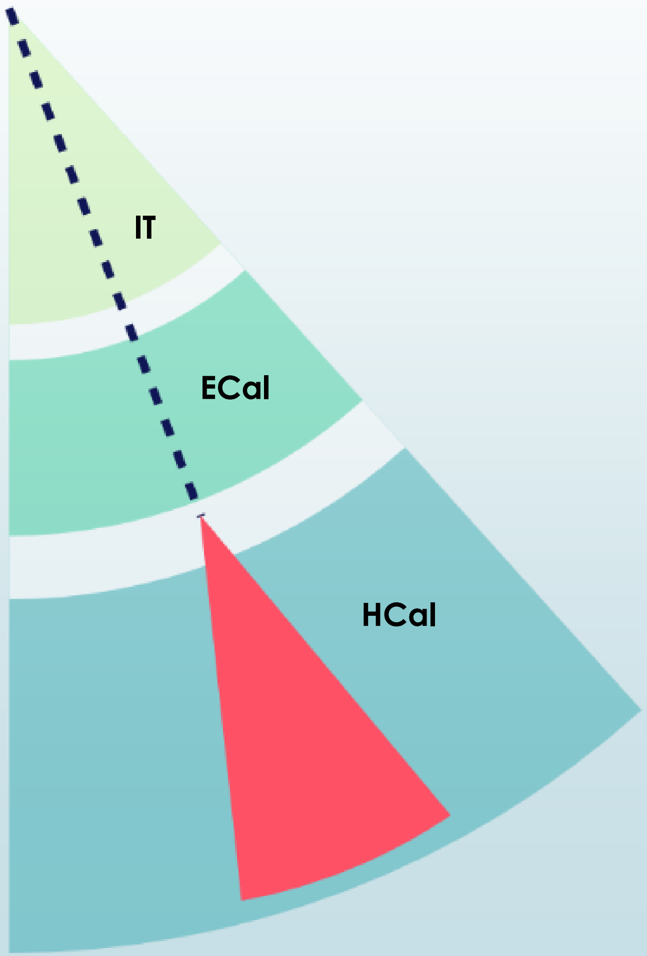




ATLAS RoI Trigger efficiency vs. decay position

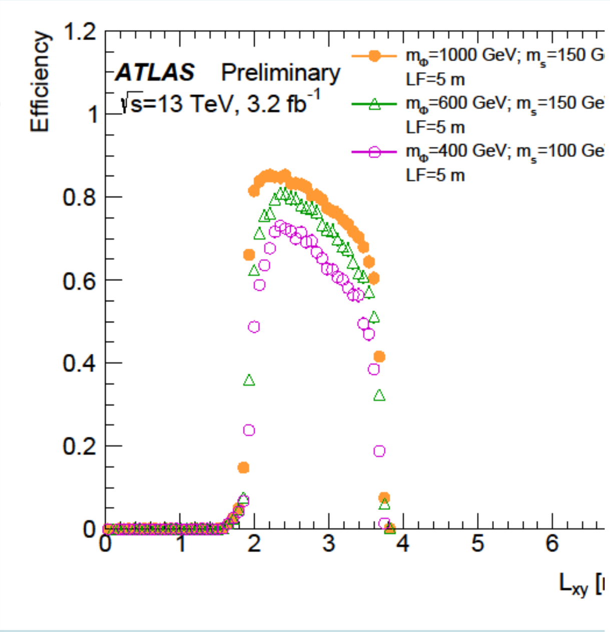
Signature Driven Displaced Decay Triggers

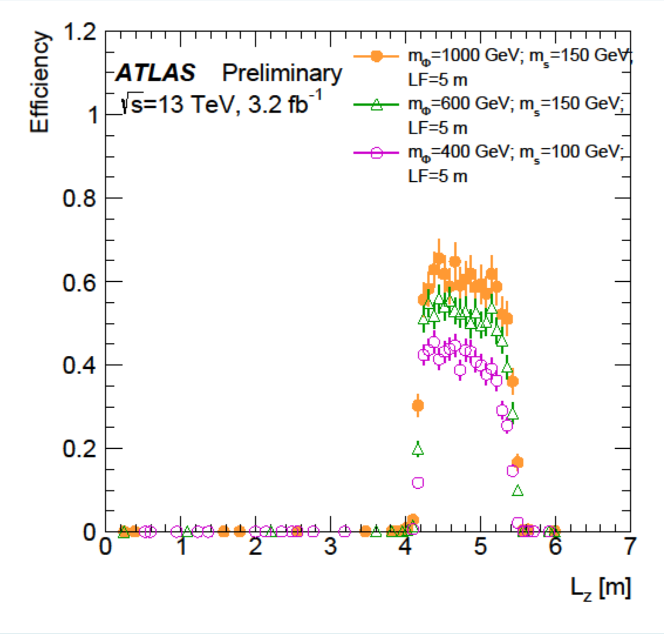
- ATLAS Calorimeter Ratio Trigger (Cal_Ratio trigger) selects narrow jets with little or no energy deposited in the EM calorimeter and no ID tracks pointing towards the jet
- Selects decays of neutral objects to hadronic jets in the HCal or end of ECal
- Requires $\log_{10}[E_{Had}/E_{EM}] > 1.2$ and defines a $\eta-\phi$ region of 0.8X0.8 centered on jet axis where tracking is performed and requires that in this region there are no tracks within $\Delta R < 0.2$ of the jet axis. A beam induced background removal algorithm is included to remove fake triggers resulting from beam halo muon bremsstrahlung in the HCal. A specific jet cleaning algorithm avoids contributions from LAr noise bursts. This trigger and earlier versions used for searches of long-lived neutral particles in the ATLAS HCal.
- The Cal_Ratio trigger has been used for ATLAS searches of displaced decays in the HCal for both Run-1 data Physics Letters B743 (2015),15–34 and Run-2 2015 data ATLAS-CONF-2016-103.

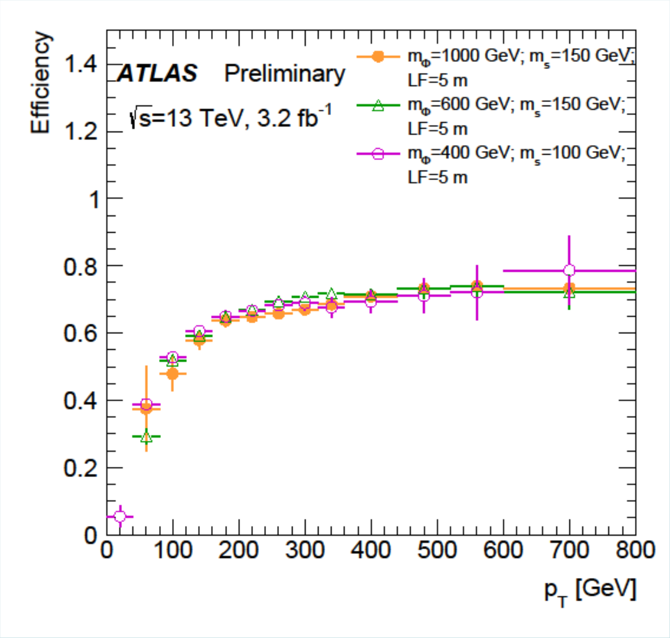


ATLAS Calorimeter Ratio Triger

- Efficiency as function of LLP decay position and vs. LLP p_T
  - Efficiency vs. decay position determined from number decaying and firing trigger at that length divided by number generated at that length
  - Efficiency vs. p_T determined from number firing trigger at that p_T divided by the number generated at that p_T
  - Trigger becomes efficient for p_T > 100 GeV

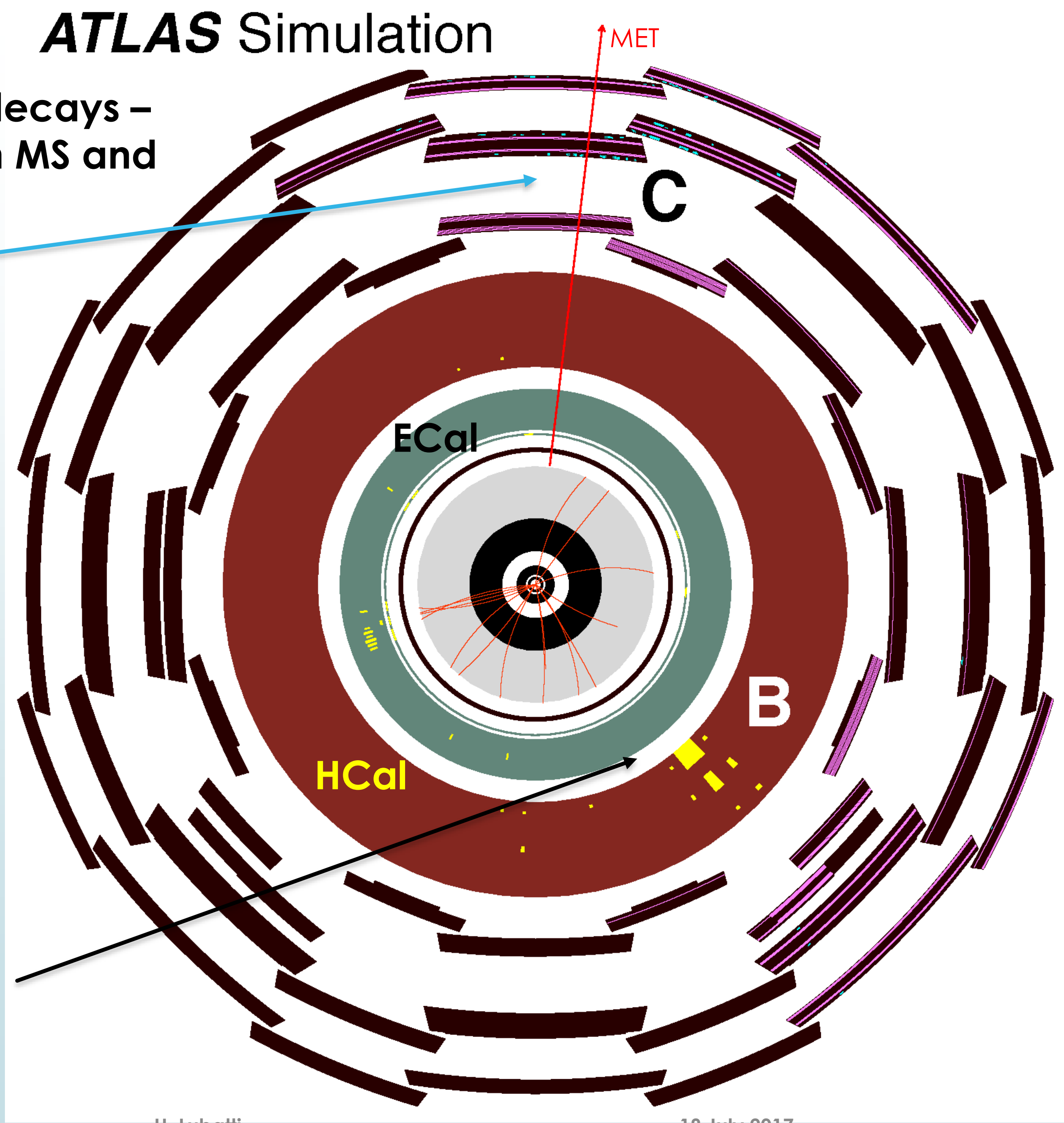






ATLAS simulation of two displaced decays – Note unique signatures of decays in MS and HCal (higgs boson simulated)

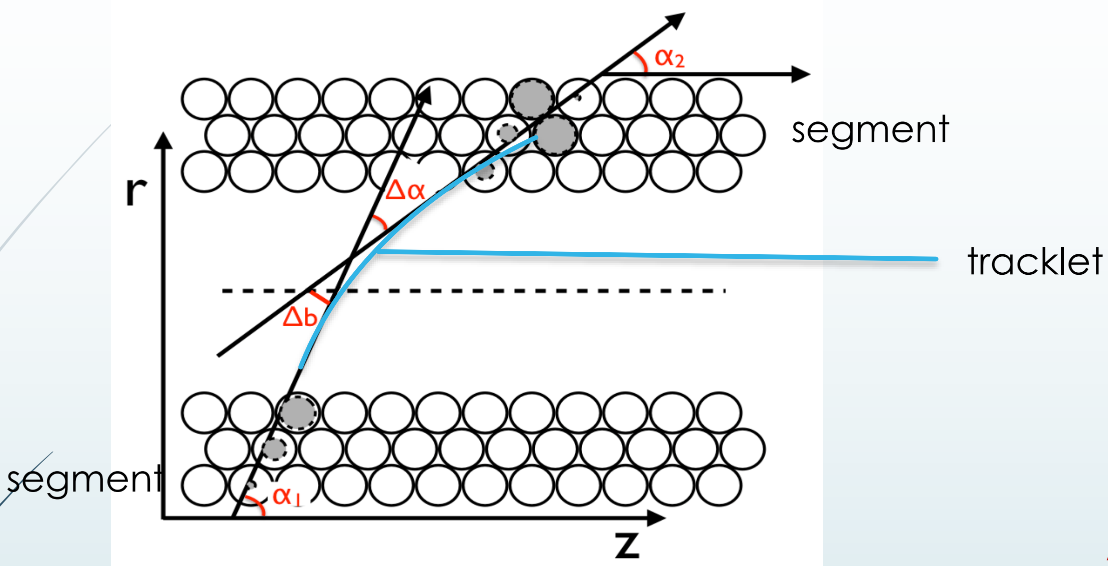
Decay in MS
Cluster of RPC and MDT hits

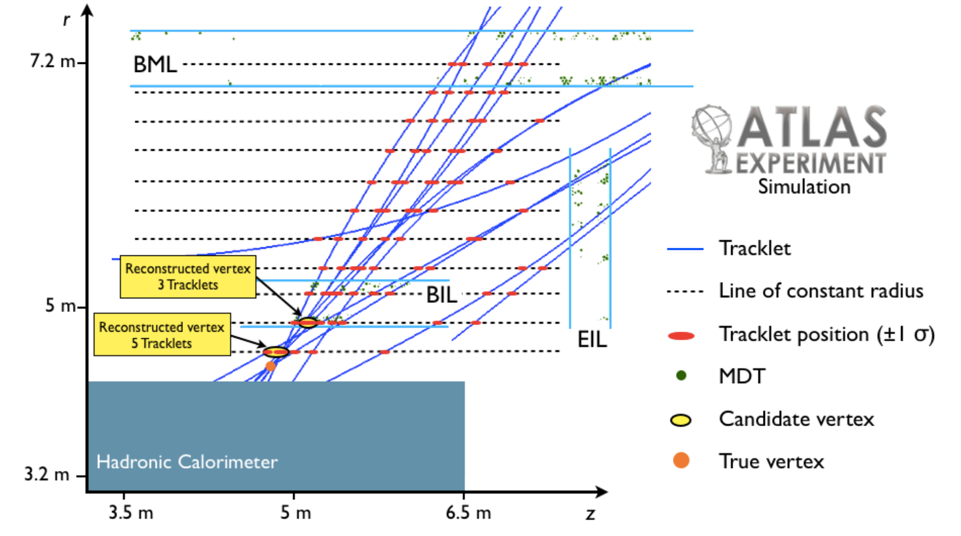


Decay at beginning of HCal
Low EM energy deposition

ATLAS Displaced Vertex reconstruction

- MS stand-alone vertex reconstruction (JINST 9 P02001, arXiv:1311.7070)





In barrel MS track segments formed in the two layers of muon chamber are combined to form a "tracklet" that are Grouped (cone algorithm).

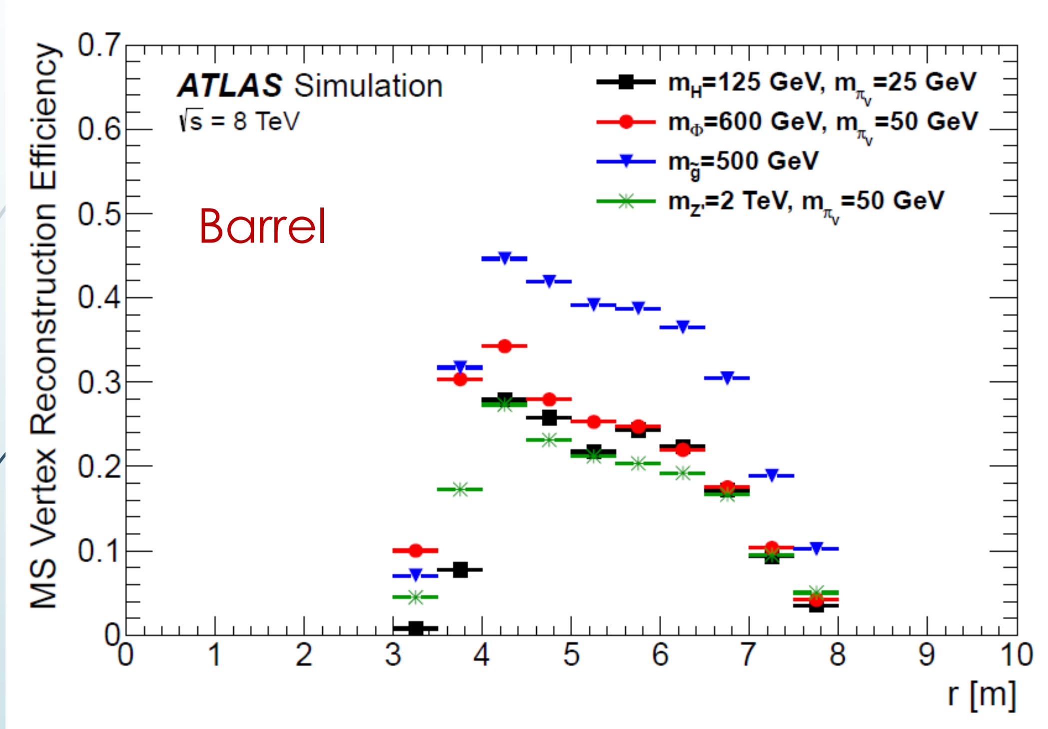
These tracklets are back extrapolated and an iterative fit made to get vertex position.

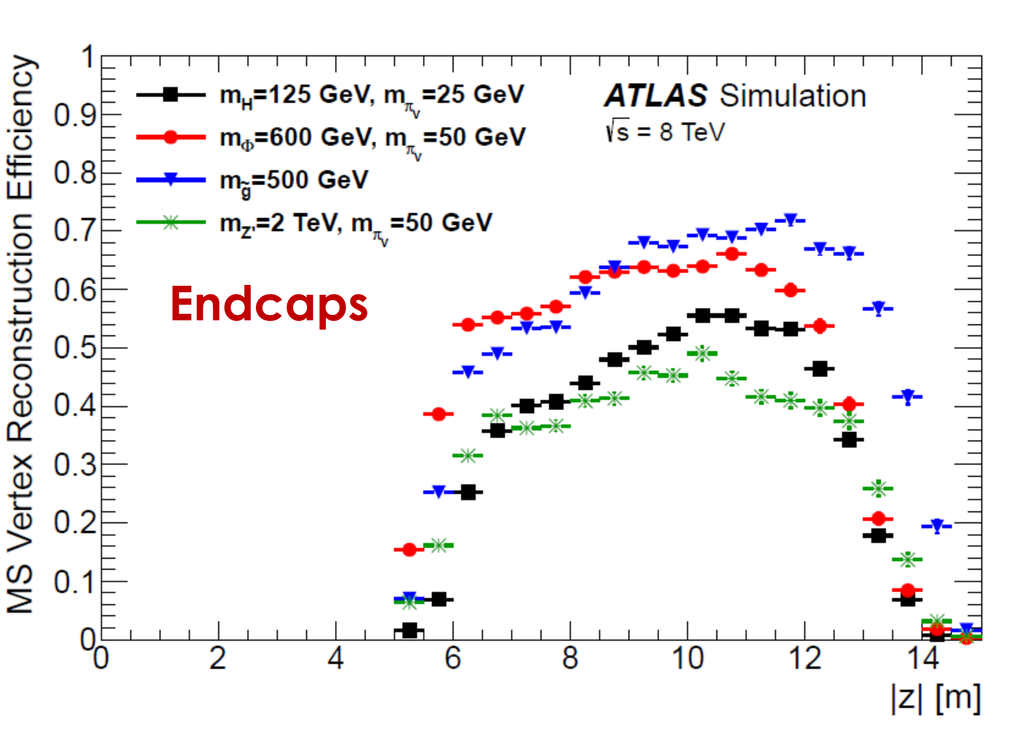
Analyses need to define "good vertex" Criteria (Jet isolation, MDT/TGC activity…)

MS vertex reconstruction used for the ATLAS Run-1 searches for displaced hadronic jets decaying in MS

NEW for Run- 2: MS vertex reconstruction run on every event accepted by an ATLAS trigger – part of data stream

ATLAS MS vertex reconstruction efficiency





MS vertex reconstruction efficiency as a function of the radial decay position of the long-lived particle for scalar boson, Stealth SUSY, and Z′ benchmark samples.

Signature Driven Displaced Decay Triggers

- CMS has developed and used both dedicated and generic triggers to search for LLPs that in general are signature driven.
  - Two dedicated trigger to search for long-lived objects decaying to pairs of jets where both triggers select on H_T, the scalar sum of p_T of the jets for jets with $p_T > 40$ GeV and $|\eta| < 3.0$.
    - Inclusive trigger requires $H_T > 500$ GeV and two or more jets with $p_T > 40$ GeV, $|\eta| < 2.0$ and each jet with no more than two associated prompt tracks.
    - Exclusive trigger requires $H_T > 350$ GeV, two or more jets with $p_T > 40$ GeV, $|\eta| < 2.0$, each jet with no more than two associated prompt tracks, one or more tracks with transverse impact parameter $bT^{2D} > 5\sigma_{bT2D}$
  - Triggers were used for CMS search in 2105 Rum-2 data CMS-PAS-EXO-16-003 that reported limits for pair-produced, long-lived scalar particles X^0 where one each decays to light quarks and pair produced long-lived stops (RPV SUSY models) in various decay modes.

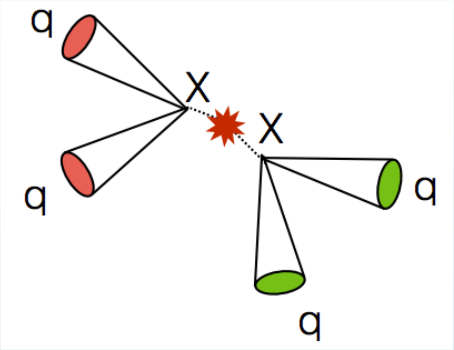


Image courtesy of K. McDermott

Signature Driven Displaced Decay Triggers

- CMS disappearing track signature targets BSM particle that decays to a low momentum particle plus non interacting particles, for example $\chi_1^{\pm} \rightarrow \chi_1^0 + \pi^{\pm}$
  - Run-2 dedicated trigger on E_T^{miss} from ISR jet recoiling from $\chi_1^{\pm}\chi_1^{\pm}$ with an isolated track at the high level trigger (HLT)
- CMS Run-2 dedicated trigger designed to select displaced e-μ pairs; targets stops decaying to b + leptons (e-μ).
  - Requires a muon with momentum perpendicular to the beam axis with p_T > 38 GeV, and no selection on on impact parameter or matching to a primary vertex are imposed.

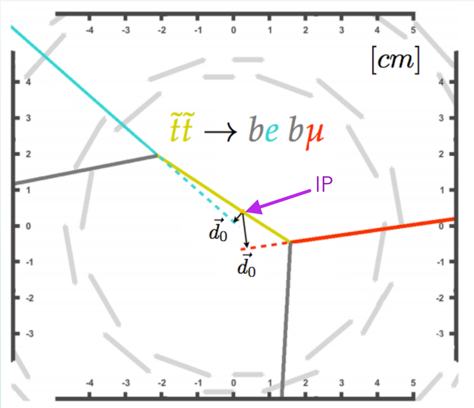


Image courtesy of K. McDermott

  - Electron selection requires a cluster in the EM calorimeter with E_T > 38 GeV leg of the trigger. To increase acceptance for displaced electrons, no tracking information is used in the electron leg of the trigger. This trigger use to select events for 2015 Run-2 data, see CMS-PAS-EX-16-022.

ATLAS Run 1 non-pointing Photon Search

- Gauge mediated SUSY Breaking (GMSB) – R-parity conserving
  - lightest neutralino $\tilde{\chi}_1^0$ is the NLSP, with finite lifetime
  - decays $\tilde{\chi}_1^0 \rightarrow \gamma\, \tilde{G}$
  - Signature: displaced, non-pointing gamma arrives late and MET from $\tilde{G}$
  - Snowmass Points and Slopes parameter set 8 (SPS8) interpretation

ATLAS Run-1 – 8 TeV
Phys. Rev. D. 90, 112005 (2014)
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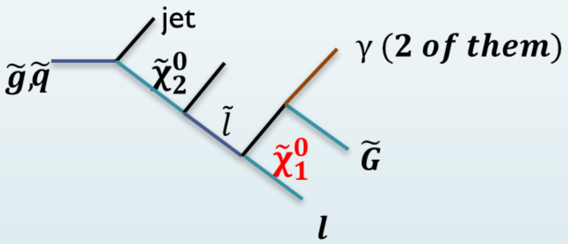
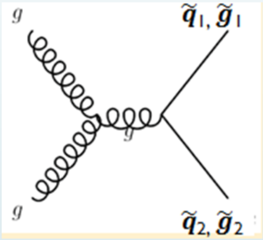
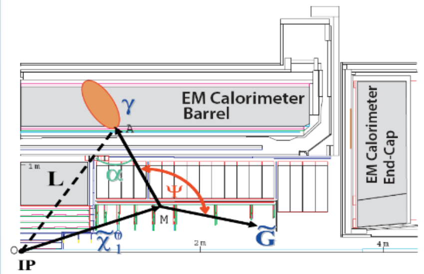




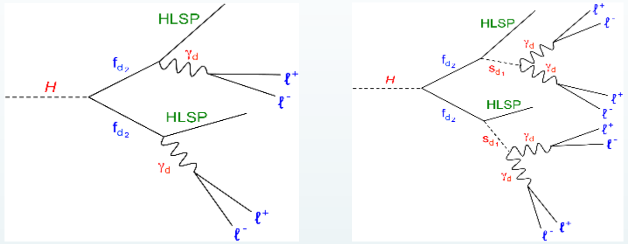
- LAr energy deposition in first two ECal layers gives measure of displacement from IP; identifies displaced photon candidate
- Set limits in context of GMSB SP8 model for region of (Λ, τ_{NLSP}) space

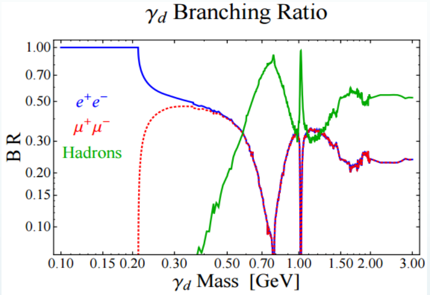


Potentially longer path plus slow NLSP gives late arrival
Use ECal timing information

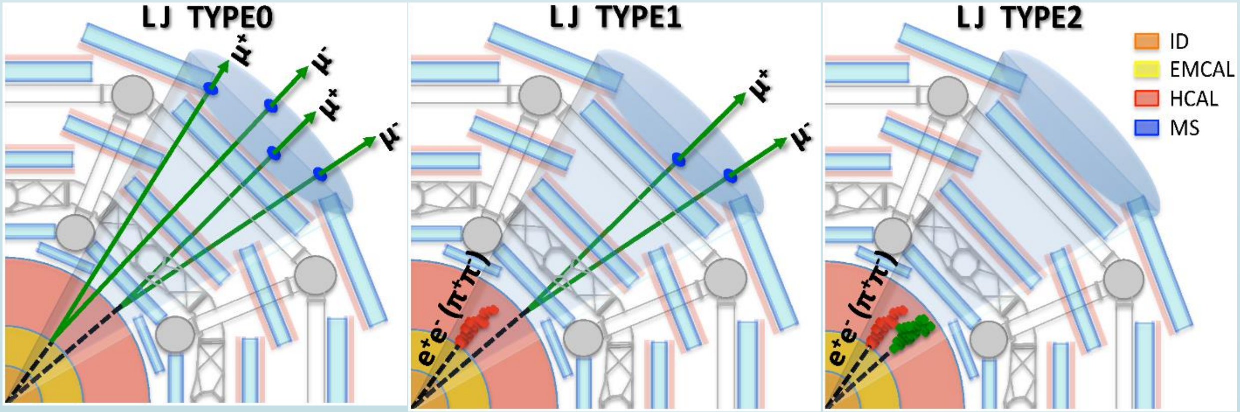
ATLAS Displaced lepton-jets Run-1Results

- Displaced Lepton-Jets arXiv:1409.0746 JHEP11(2014)088
  - kinetic mixing of light γ_d with SM γ through vector portal
  - ATLAS search based on FRVZ bench marks: JHEP 05 (2010) 077 [arXiv:1002.2952]





  - Searched for $2\gamma_d$ and $4\gamma_d$ decaying to lepton jets
  - Used a lepton-jet gun to simulate individual displaced LJs from one γ_d decay and hidden scalar $s_d \rightarrow \gamma_d \gamma_d$
  - Generate efficiency maps uniform in p_T, η, and decay position with LJ gun samples that are independent of a specific model



Type 0: all γ_d -> μ's
Type 1: $1\gamma_d$ -> ee or $\pi\pi$, $1\gamma_d$ -> 2μ
Type 2: all γ_d -> ee or $\pi\pi$

LHC LLP search limitations

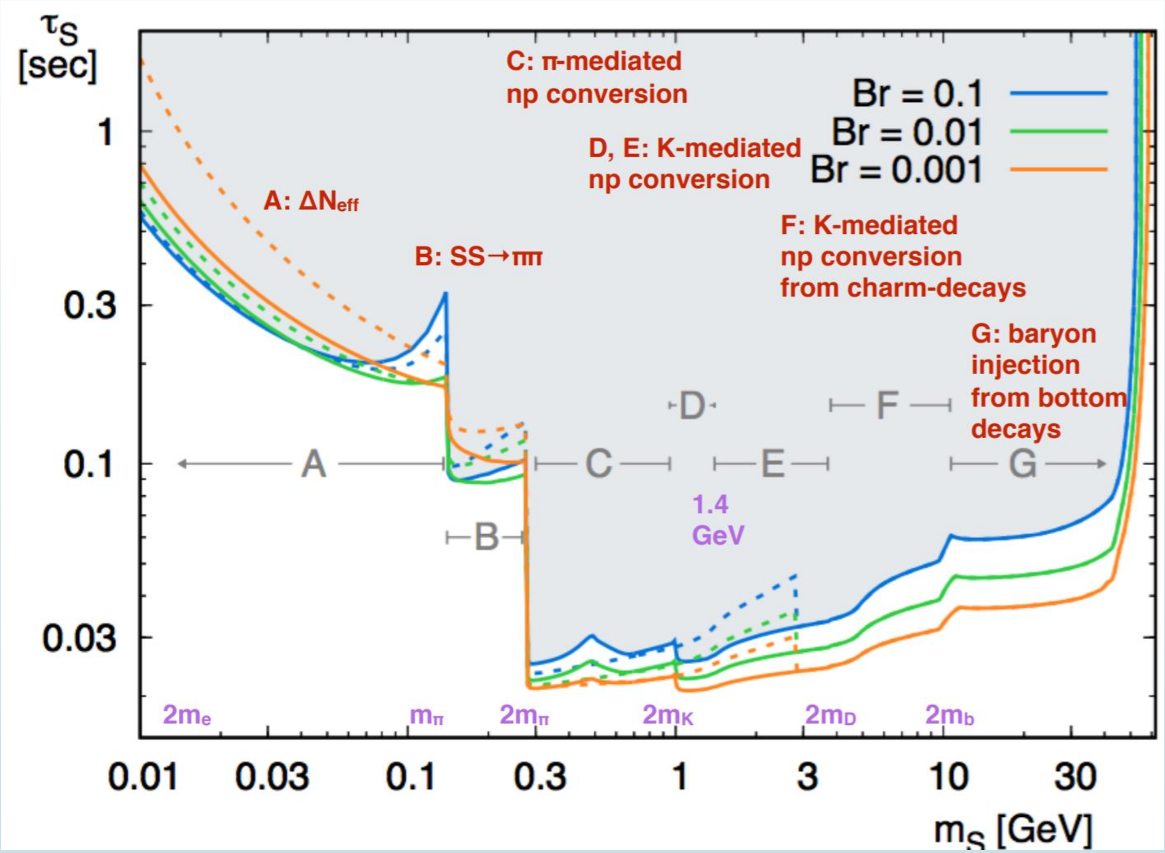
- LHC detector searches limited by large backgrounds
  - Large QCD jet production
  - Pile-up problems
  - Beam halo issues
  - …
- Need a background-free detector

MATHUSLA

- **MATHUSLA Detector – MAssive Timing Hodoscope for Ultra Stable neutral pArticles** (arXiv:1606.06298v1 - J-P. Chou, D. Curtain, HL)
  - Dedicated detector sensitive to neutral long-lived particles that have lifetimes up to the Big Bang Nucleosynthesis (BBN) limit (10^7 – 10^8 m) for the HL-LHC
  - A large-volume, air filled detector located on the surface above and somewhat displaced from ATLAS or CMS interaction points
- Order of N_h= 1.5 x 10^8 Higgs Bosons produced in full HL-LHC run
  - Observed decays: $N_{obs} \sim N_h \cdot Br(h \to ULLP \to SM) \cdot \varepsilon_{geom} \cdot \frac{L}{bc\tau}$
    - L-size of detector along ULLP direction of travel
    - ε_{geom} geometrical acceptance
    - $b(Lorentz\ boost) \sim \frac{m_h}{n m_X} \leq 3$ for Higgs boson decaying to $n = 2$ $m_X \geq 20\ GeV$
    - Requires $L \sim (20\ \mathrm{m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\mathrm{geometric}}}\right) \frac{0.3}{\mathrm{Br}(h \to \mathrm{ULLP})}$.
  - To collect a few ULLP decays with cτ ~10^7 m requires a 20 meter detector along direction of travel of ULLP and about 10% geometrical acceptance

MATHUSLA

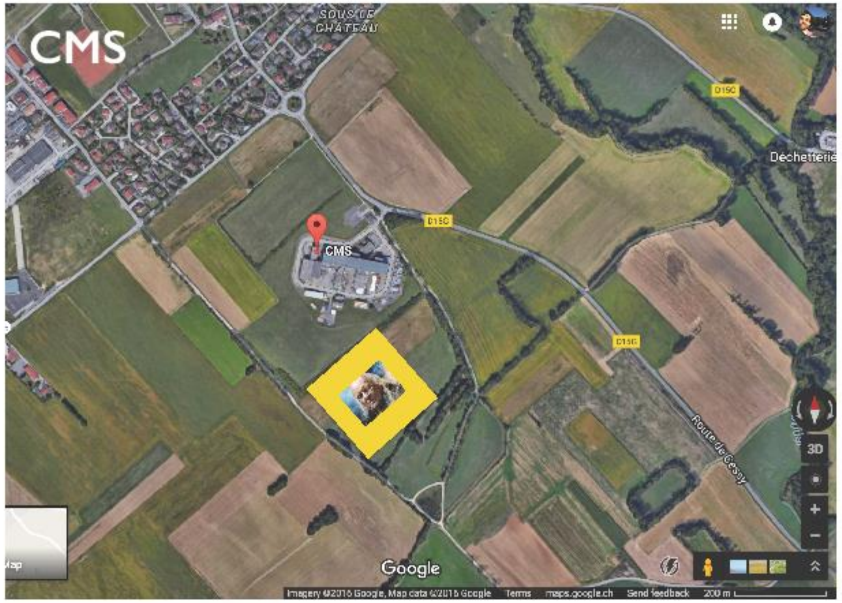
- A recent paper [A. Fradette and M. Pospelov, arXiv:1706.01920v1] examines the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via $h \rightarrow SS$, where the decay is induced by the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

MATHUSLA

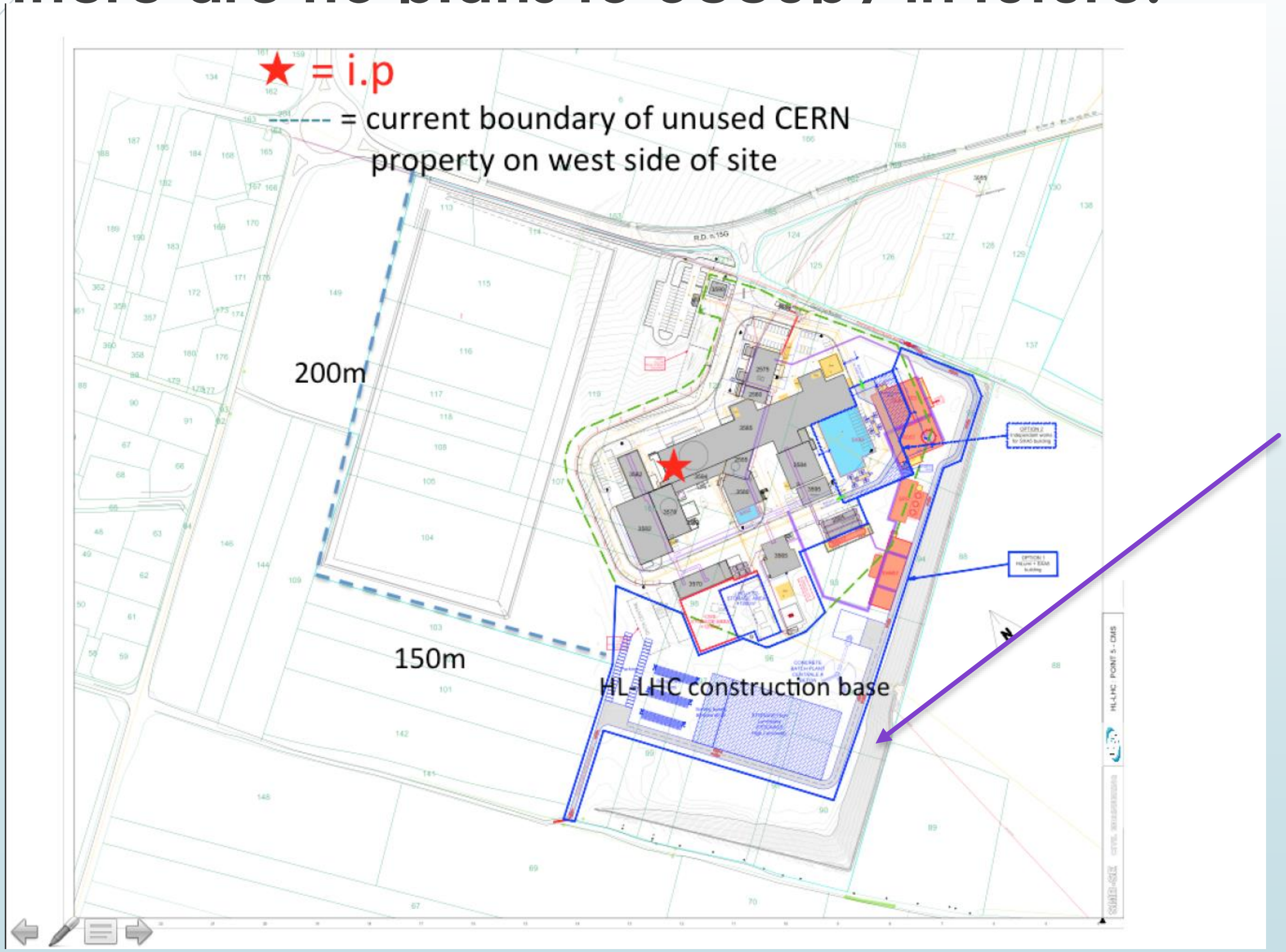
Could be located above either ATLAS or CMS



Need large surface space near
A pp intersection point (IP)
→ ATLAS or CMS

Where…

- CMS site has a large area that is owned by CERN and there are no plans to occupy in future.

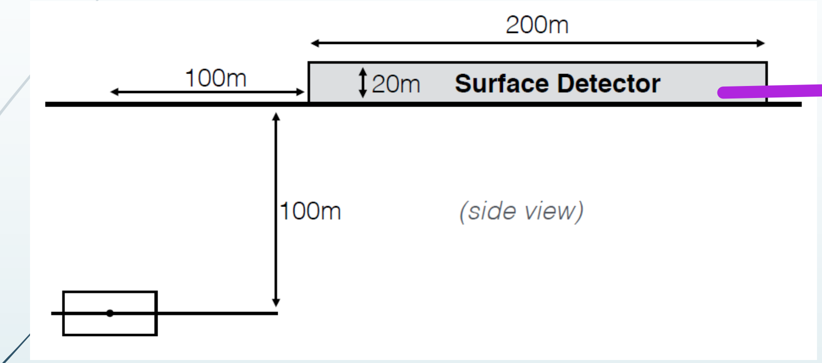


HL-LHC construction base available during HL-LHC run

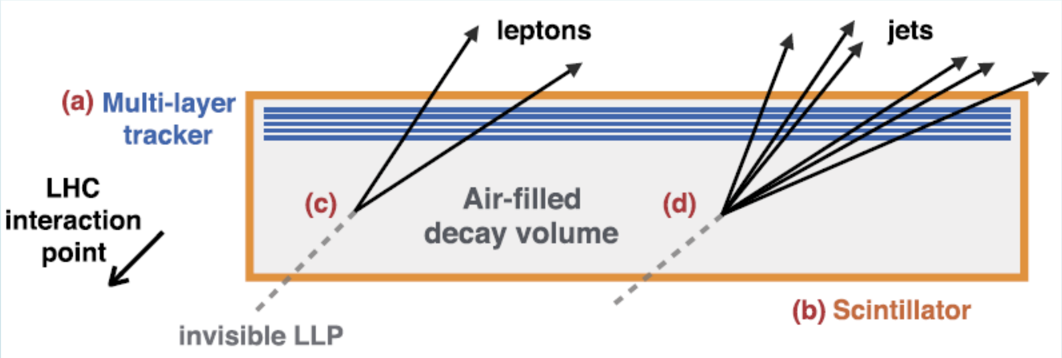
MATHUSLA

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

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



Large area surface detector above an LHC pp IP dedicated to detection of ultra long-lived particles. Air decay volume with tracking chambers surrounded by scintillators



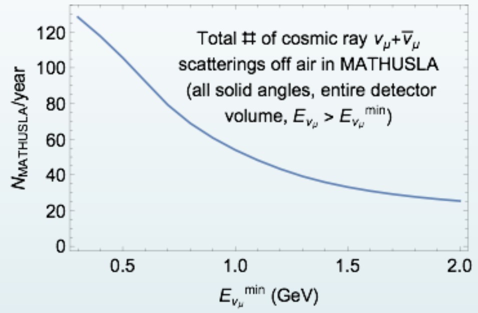
No LHC Background, BUT…

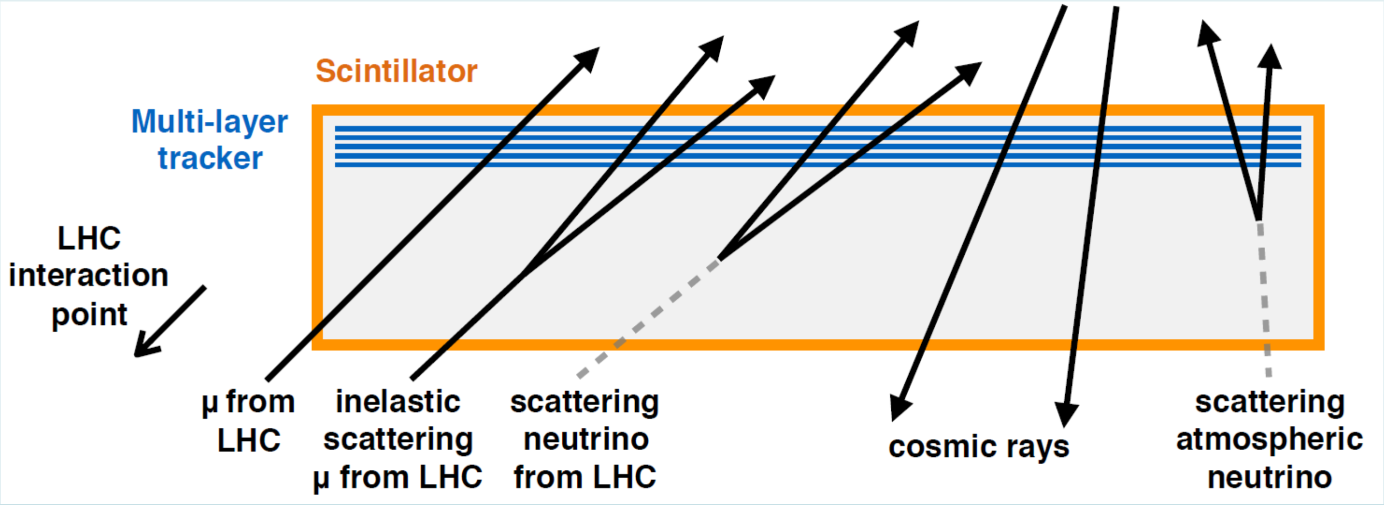
- ❑ Need robust tracking
- ❑ Excellent background rejection
- ❑ RPCs planes are an attractive choice
  - ❑ Good space and time resolution for vertex reconstruction and cosmic ray rejection
- ❑ Scintillator planes for redundant background rejection - timing

MATHUSLA - backgrounds

- Cosmic muon rate of about 10^6 Hz

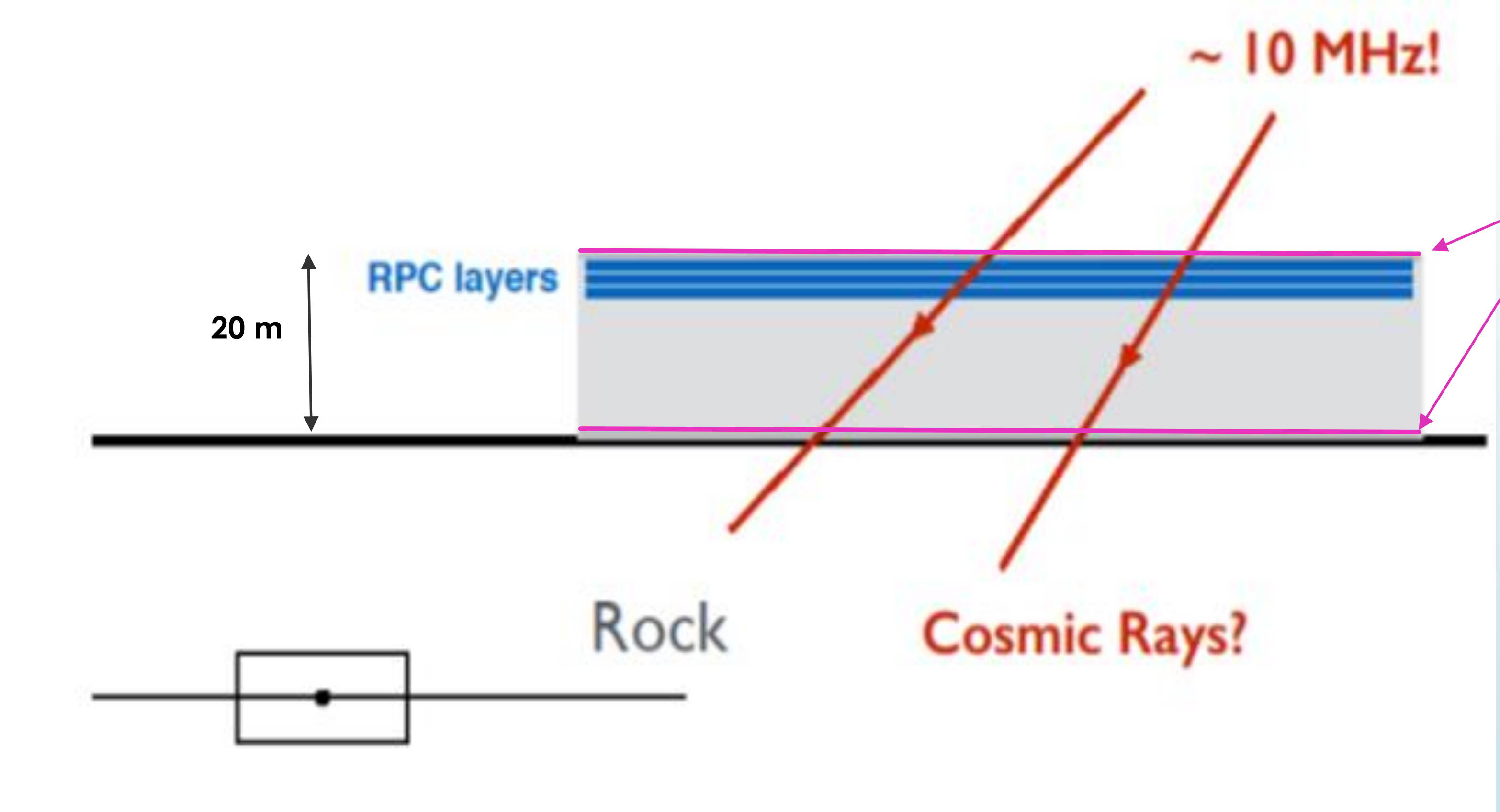
  Scintillators 1.5 ns timing resolution in 20 m have $\Delta t \approx 70$ ns top to bottom
- LHC collision backgrounds
  - LHC muons about 10 Hz — Reject with scintillator timing and entrance hit position
- Upward atmospheric neutrinos that interact in air decay volume
  - Estimate Low rate ~ 10-100 per year above 300 MeV
  - Most have low momentum proton - reject with time of flight - **non-collision backgrounds can be measured when no LHC collisions**





MATHUSLA - backgrounds

- Cosmic muon rate or order 10 MHz (200 m^2)



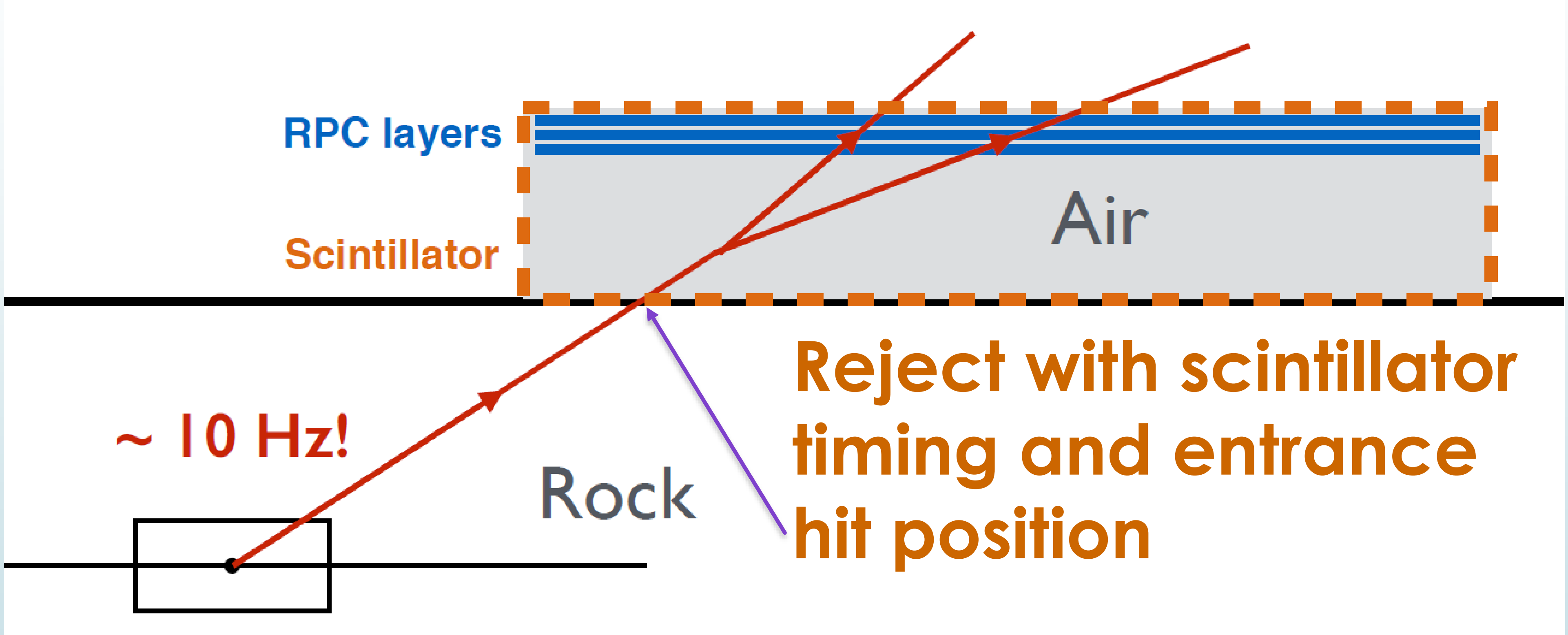
Scintillators 1.5 ns timing resolution

➧ in 20 m have $\Delta t \approx 70$ ns top to bottom

If these muons have inelastic interaction in air decay volume they will not result in a reconstructed vertex; in addition, scintillator timing also can be used to reject

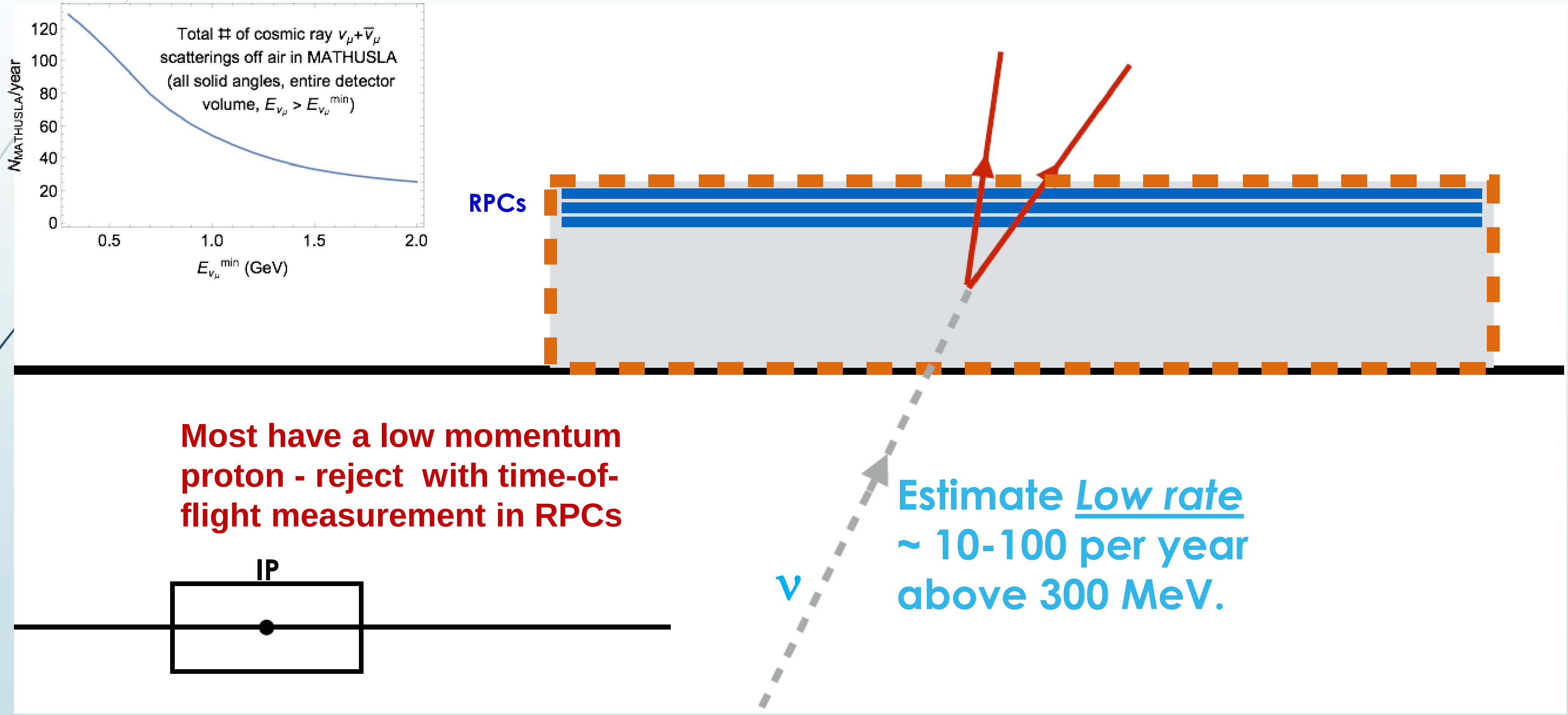
MATHUSLA - backgrounds

- Upward going muons from LHC with inelastic interaction



MATHUSLA - backgrounds

- Cosmic neutrinos traveling upwards that have inelastic interactions in the decay volume

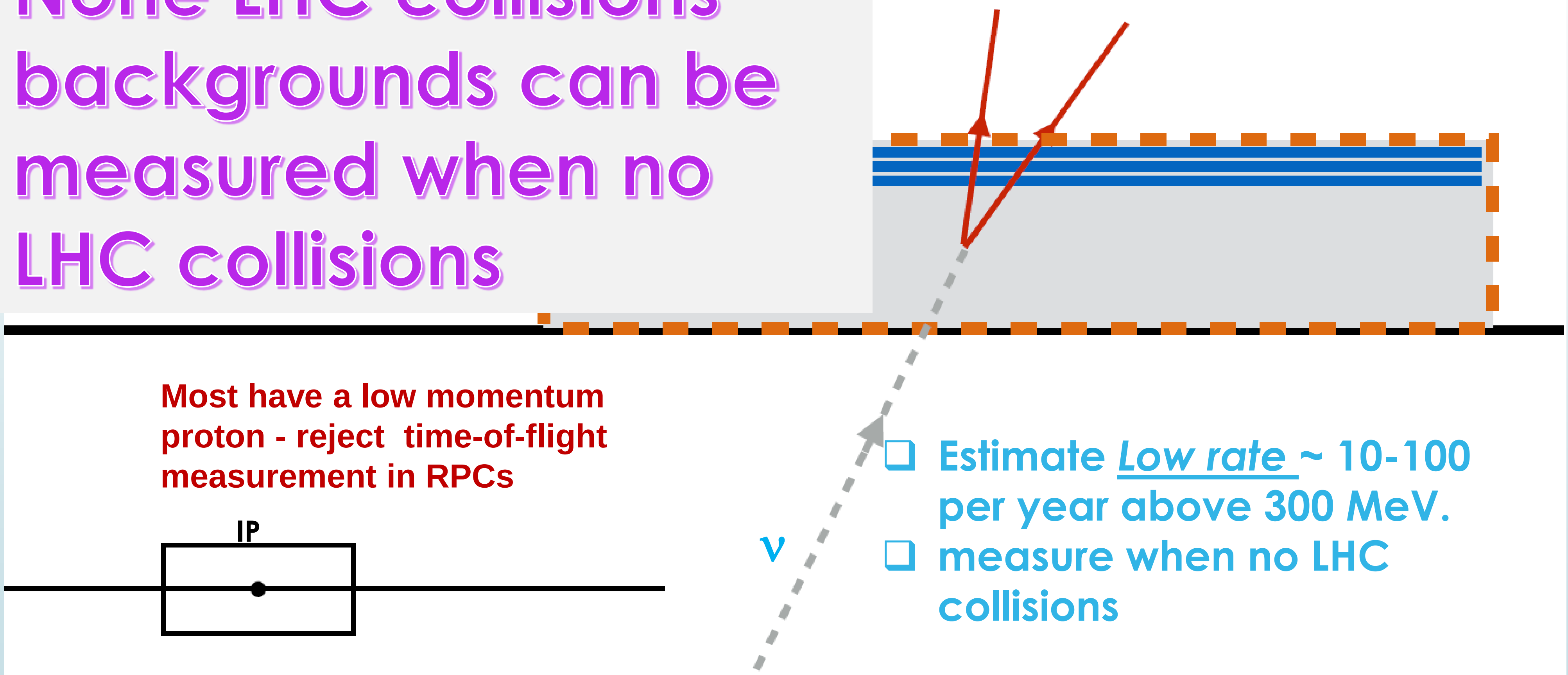


MATHUSLA - backgrounds

- Cosmic neutrinos traveling upwards that have inelastic interactions in the decay volume

None LHC collisions backgrounds can be measured when no LHC collisions

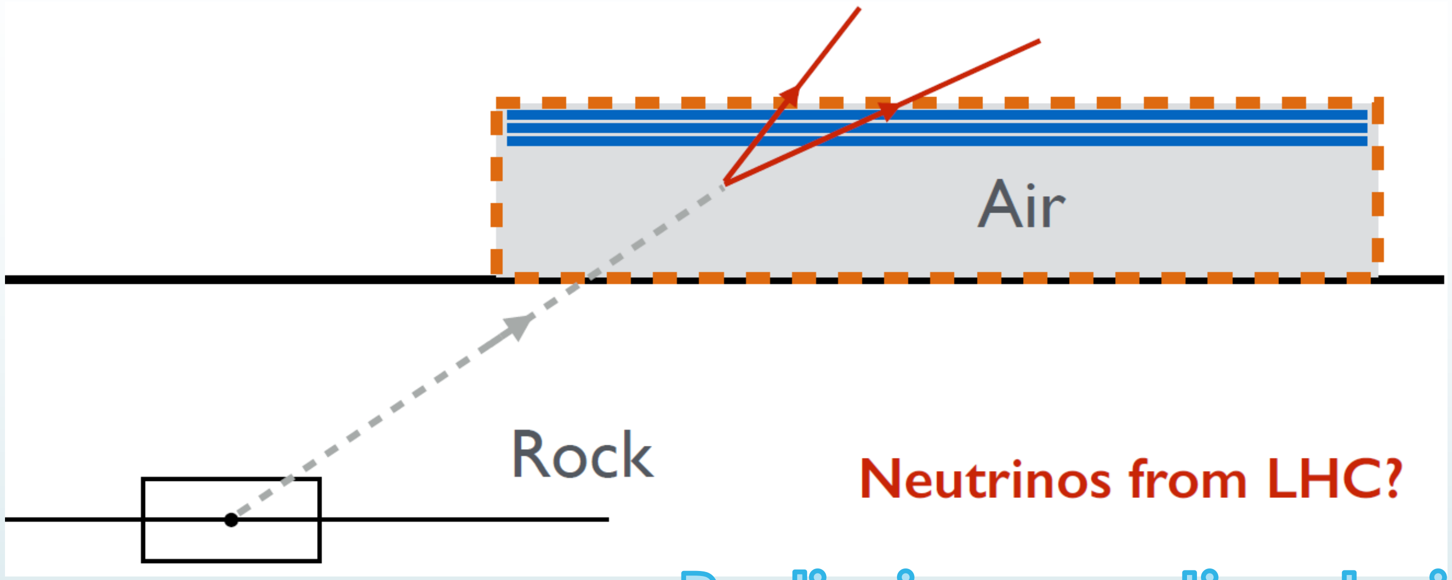
Most have a low momentum proton - reject time-of-flight measurement in RPCs

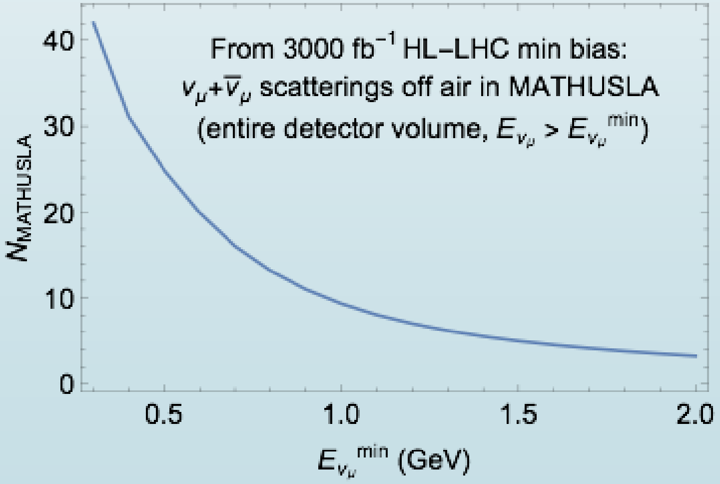


- Estimate *Low rate* ~ 10-100 per year above 300 MeV.
- measure when no LHC collisions

MATHUSLA - backgrounds

- Neutrinos from LHC interactions (subdominant background)



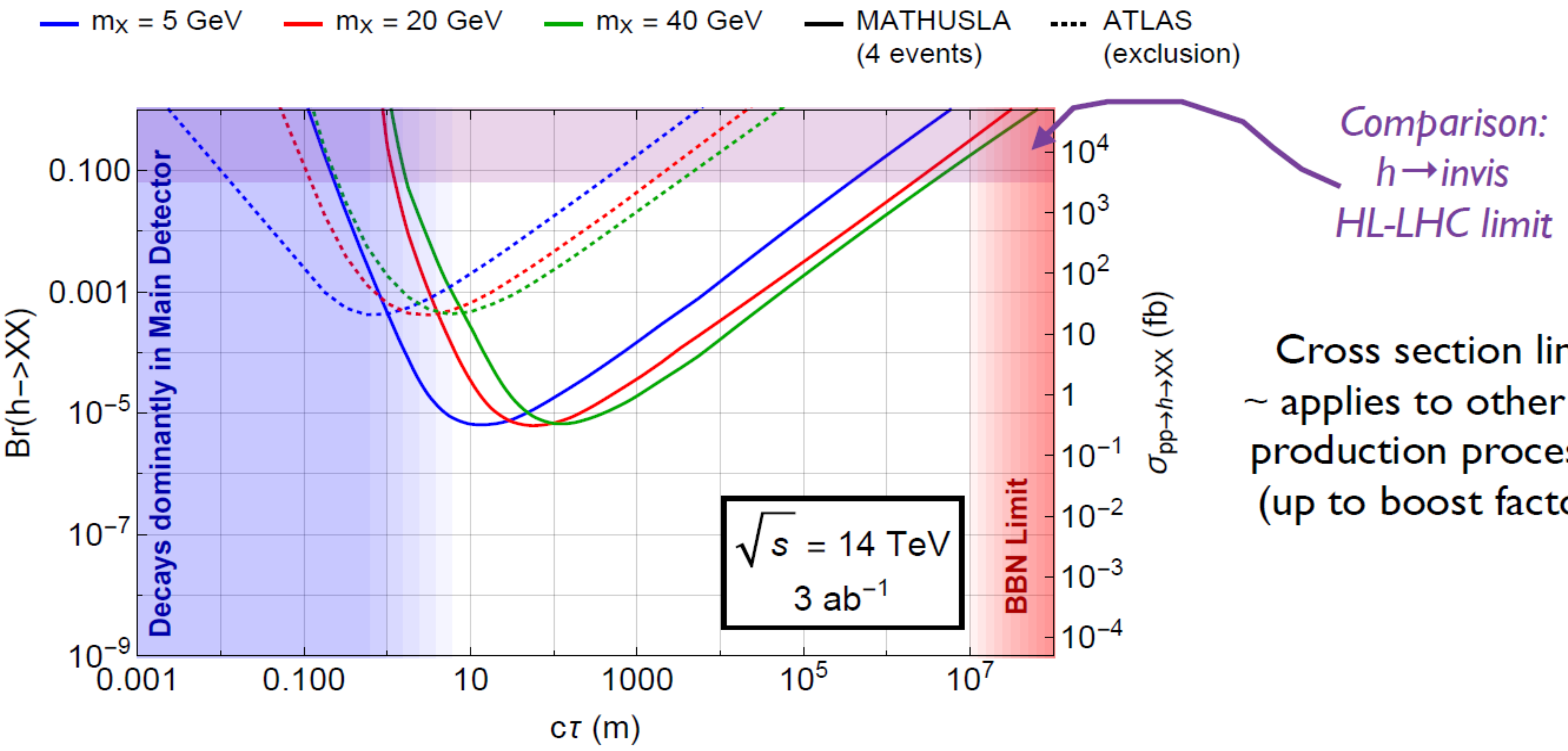


Preliminary estimate is that MATHUSLA should observe a few events during HL-LHC data taking period – needs more work, but appears to be subdominant

Sensitivity estimate

- Decay of Higgs boson to pair of scalars, x, for several m_x
- No QCD backgrounds → sensitivity gain
- Can approach BBN limit

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



Cross section limit
~ applies to other LLP production processes (up to boost factors)

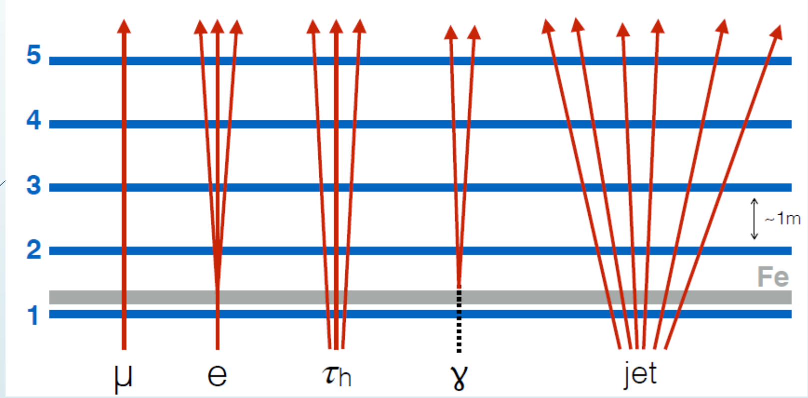
MATHUSLA – background studies

- Effort underway to develop GEANT simulations of the backgrounds discussed above
  - Current plan to deal with muons and neutrinos traveling upwards is to create a “gun” that shoots particles into MATHUSLA
  - For cosmic muons from above plan to use standard cosmic muon simulation code
  - Simulation/data anchor with LHC colliding protons and also when there are no pp collisions in LHC – beam OFF

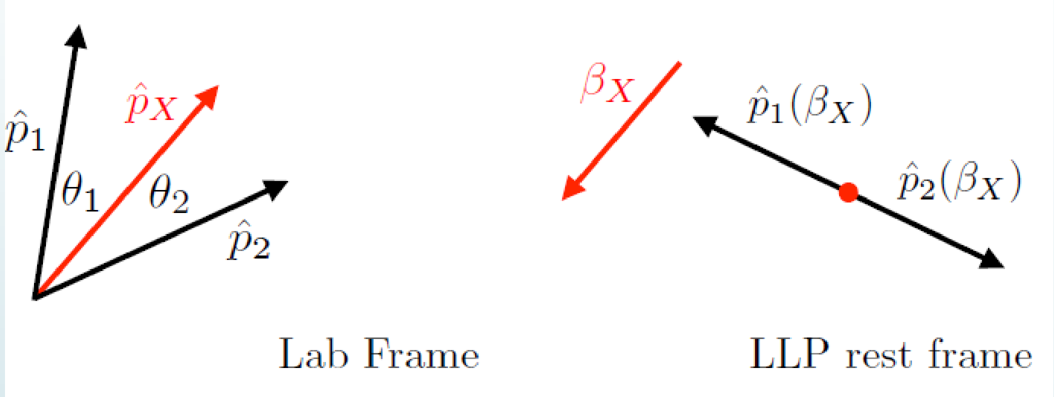
TEST Module

MATHUSLA analysis

- Recent paper D. Curtain and M. Peskin (arXiv:1705.06327) argue that it is possible to determine mass of LLPs and production mode



various decay signatures



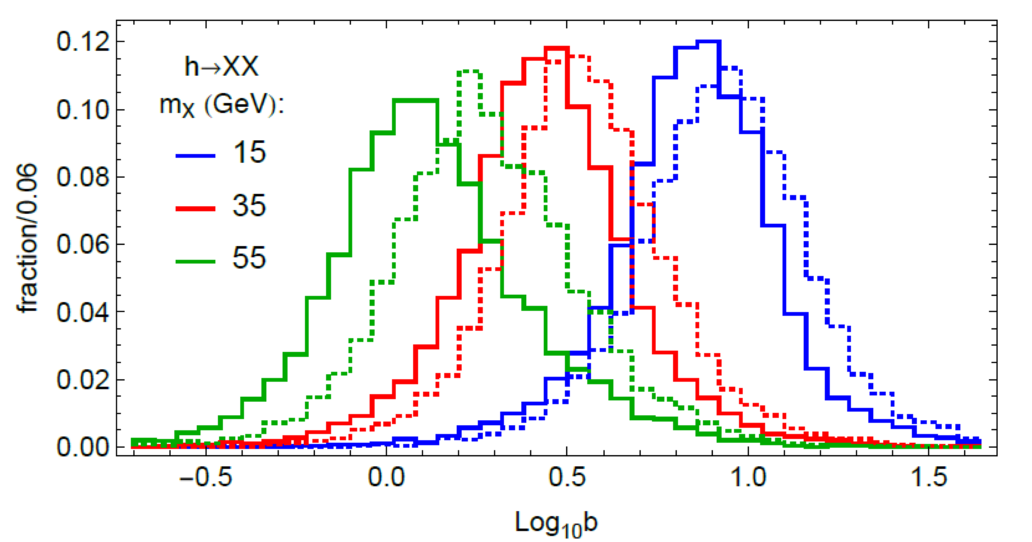
Boost 2-body decayto its rest frame

$$\beta_X = \frac{\beta_1 \beta_2 \sin(\theta_1 + \theta_2)}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_1}$$

Angles θ_1 and θ_2 well measured

MATHUSLA

- For $h \rightarrow XX$ find distribution of boost p_X/m_X

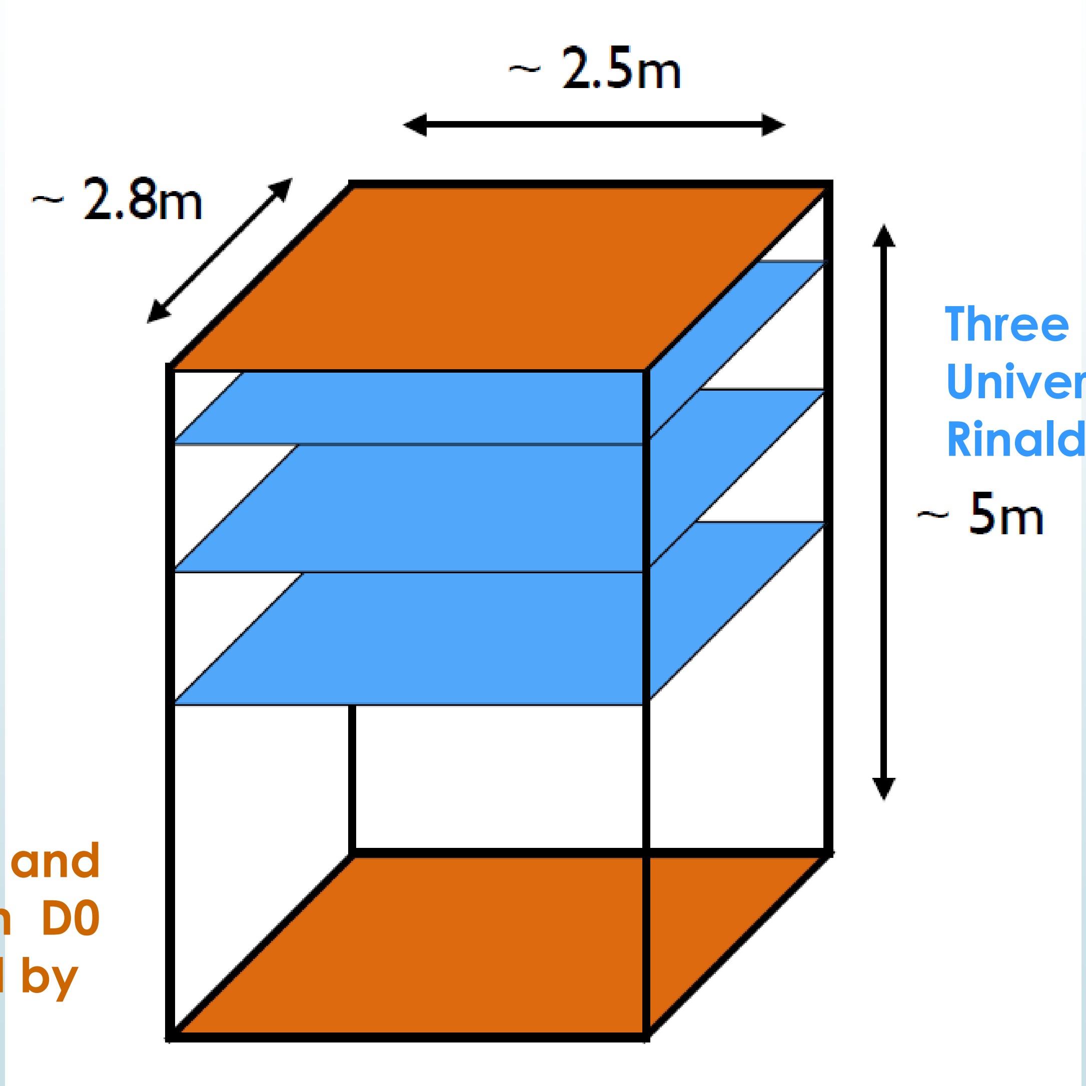


Solid histograms truth-level value of b and dotted histograms the reconstructed distributions

- May be possible with O100) events obtain mass of X to ~ 1 GeV
- For $X \rightarrow \tau\tau$ where τ undergoes a 3-body decay they obtain similar results; see figure 5 of their paper. [jet axis two axis p_a and p_b from maximizing

$$V_2 = \sum_i \max(\hat{p}_a.\hat{p}_i, \hat{p}_b.\hat{p}_i)$$

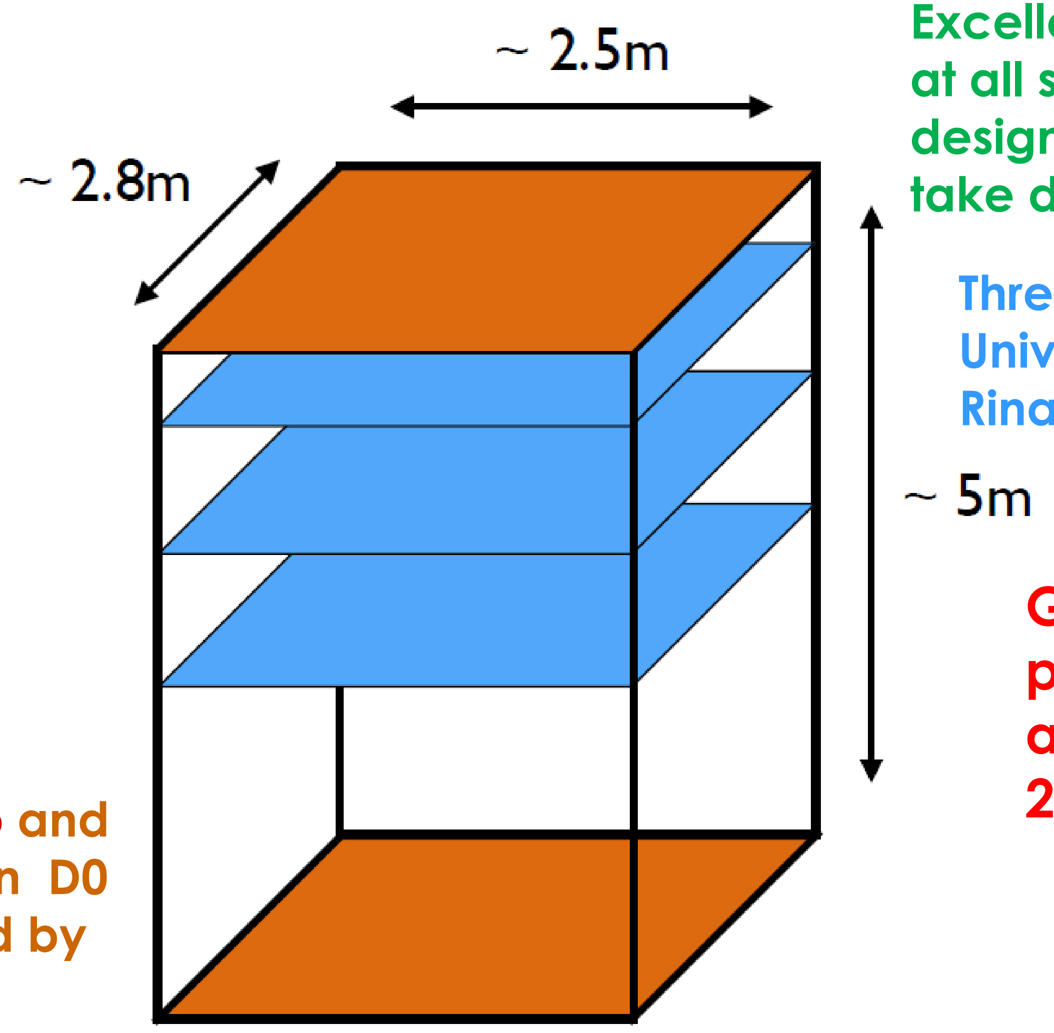
MATHUSULA Test Module



Three layers of RPCs provided by University of Rome, Tor Vergata, Rinaldo Santonico

Scintillator layers top and bottom from Tevatron D0 experiment provided by Dmitri Denisov

MATHUSULA Test Module



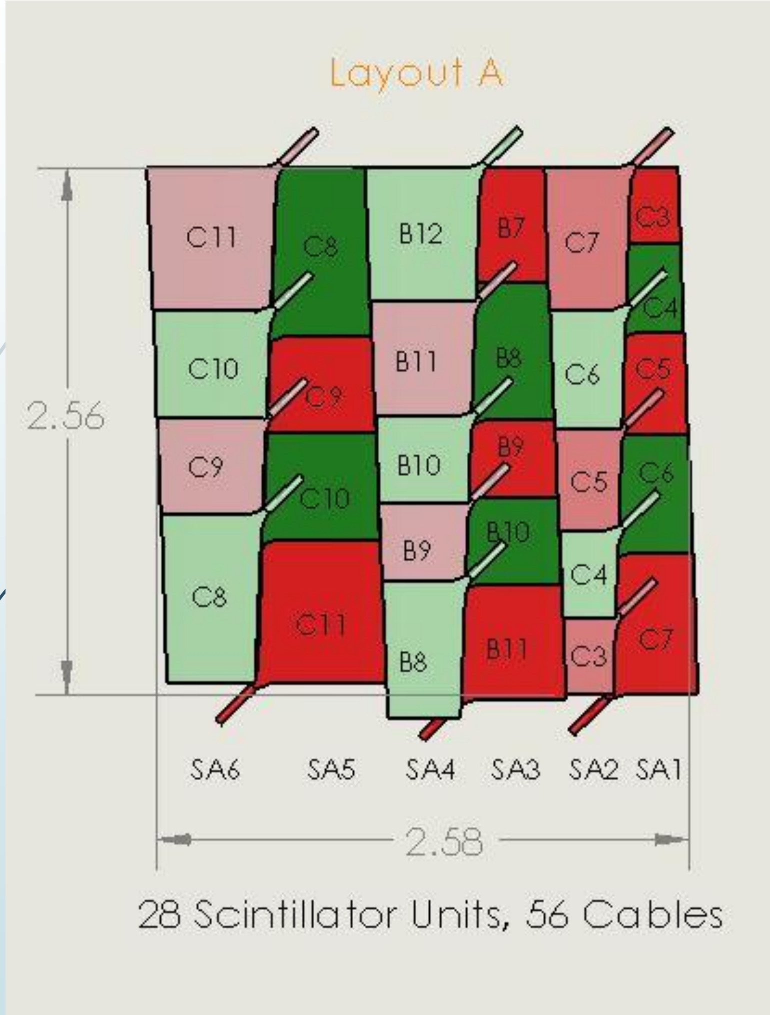
Excellent for students - participation at all stages of an experiment: design, test components, install, take data and analysis

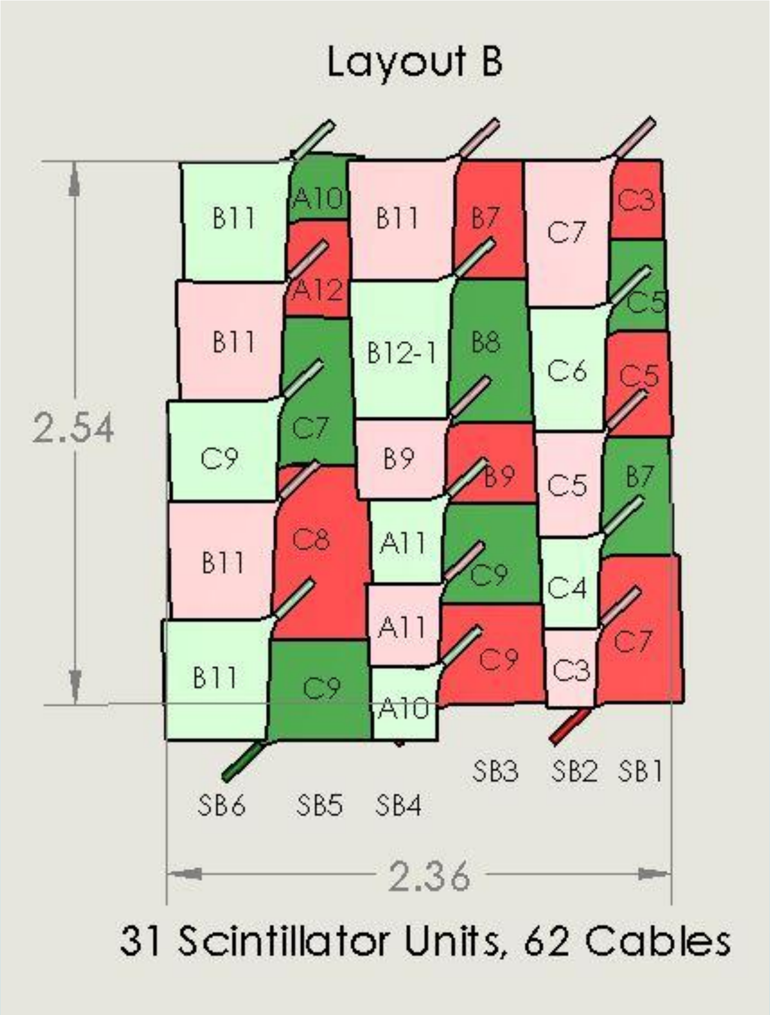
Three layers of RPCs provided by University of Rome, Tor Vergata Rinaldo Santonico

Goal is to install at ATLAS point during September 2017 and collect data to end of 2017 pp collision run

Scintillator layers top and bottom from Tevatron D0 experiment provided by Dmitri Denisov

Test MODULE sintilator planes



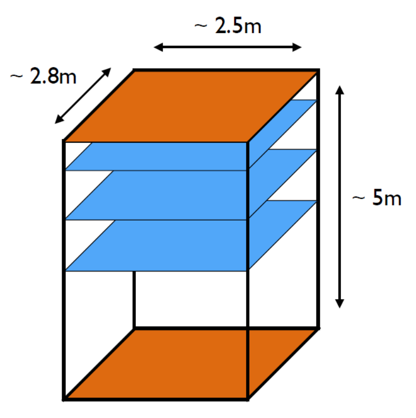


D0 forward MUON Trigger scintillator

Scintillator layers top and bottom

MATHUSLA Test Module Status

- Scintillators at CERN and undergoing certification to establish HV setting, noise rates, and efficiency.
  - Will be assembled into tow planes shown on previous slide.
- RPCs provided by R. Santonico University of Rome, Tor Vergata to be shipped to CERN early August
  - Twelve RPC chambers 1.25 m X 2.8 m (spares from VIRGO experiment) measure one coordinate.
  - For test module will have 3 RPC planes composed of 4 RPCs
  - Each RPC plane has two horizontal and two vertical planes covering an area of approximately 2.5X2.8 m^2 providing 3 pairs of (x,y) coordinates for a charged track
- RPCs and scintillator planes will be assembled into the test module and transported and installed on the surface above the ATLAS detector



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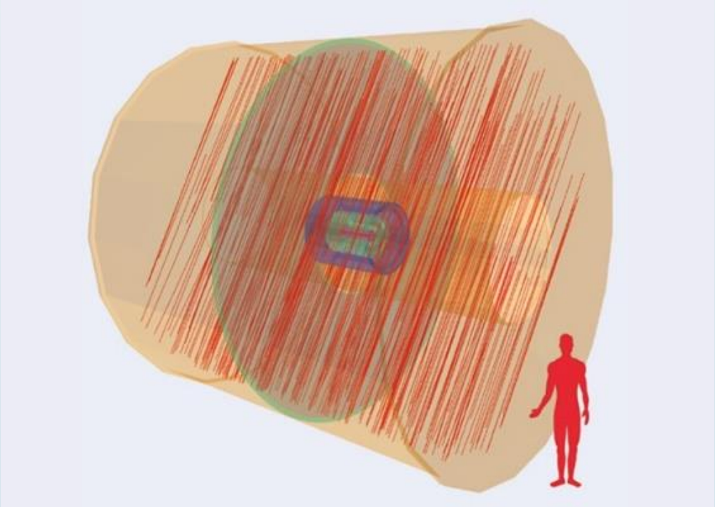
MATHUSLA and cosmic rays

Courtesy of Rinaldo Santonico and Arturo Fernandez Tellez

- Detection of cosmic showers with a full coverage surface detector allows a detailed study of the core structure, giving crucial information to determine the atomic number Z of the primary cosmic particle.

- The combination of a large area detector of atmospheric showers that observes both the muon and e, electron component of the shower with a LHC detector where only muon component is observed provides a more complete picture of Air Showers (EAS)

- Muon bundles in a LHC detector



MATHUSLA theory white paper

- Collaboration of 70+ theorists
- Aiming for publication in 2017

Detecting Ultra-Long-Lived Particles: The MATHUSLA Physics Case

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

Contributors: B. Batell, Timothy Cohen, Nathaniel Craig, Csaba Csaki, Yanou Cui, Francesco D'Eramo, B. Dev, Keith Dienes, Marco Drewes, Rouven Essig, Jared Evans, Marco Farina, Thomas Flacke, Claudia Frugiuele, Elina Fuchs, Dmitry Gorbunov, M. Graesser, Peter Graham, C. Hagedorn, Lawrence Hall, Philip Harris, J. Helo, M. Hirsch, Yonit Hochberg, Anson Hook, A. Ibarra, Seyda Ipek, Sunghoon Jung, S. King, Simon Knapen, Joachim Kopp, Gordan Krnjaic, Eric Kuflik, Salvator Lombardo, Rabindra Mohapatra, S. Moretti, Duccio Pappadopulo, Gilad Perez, David Pinner, Maxim Pospelov, Mattthew Reece, Rick S., Brian Shuve, Daniel Stolarski, Brooks Thomas, Yuhsin Tsai, Brock Tweedie, Stephen West, Y. Zhang, Kathryn Zurek, . . .

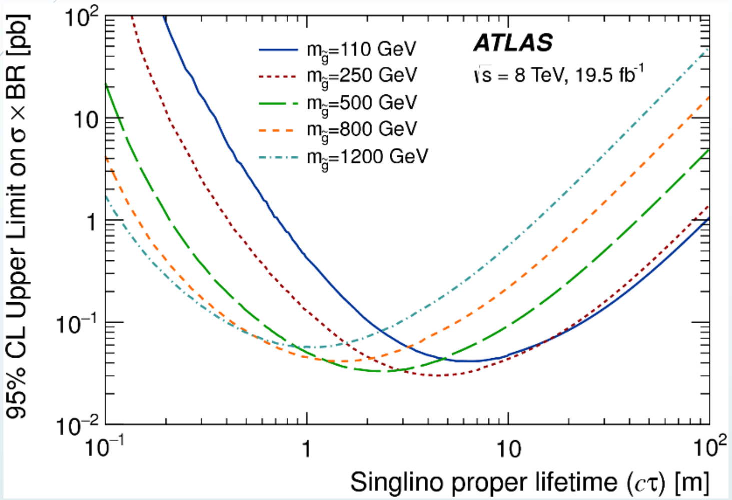
MATHUSLA theory white paper Organization

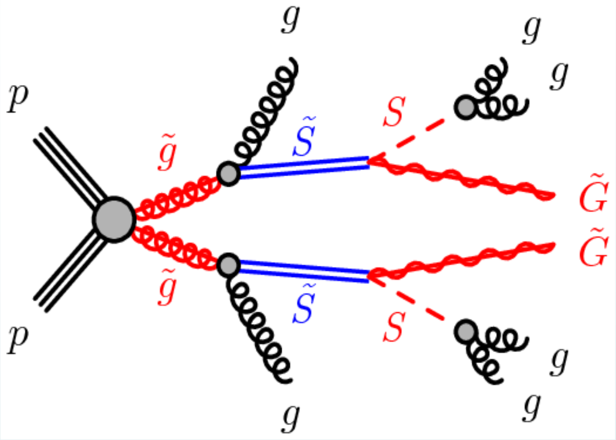
- 1. Foreword
- 2. Introduction
- 3. Summary of MATHUSLA experiment
- 4. Letters of Support
- 5. LLPs at the LHC and MATHUSLA
- 6. Theory Motivation for ULLPs: Naturalness
- 7. Theory Motivation for ULLPs: Dark Matter
- 8. Theory Motivation for ULLPs: Baryogenesis
- 9. Theory Motivation for ULLPs: Neutrinos
- 10. Theory Motivation for ULLPs: Bottom-Up Considerations
- 11. Signatures
- 12. Cosmic Ray Physics prospects with MATHUSLA
- 13. Conclusions

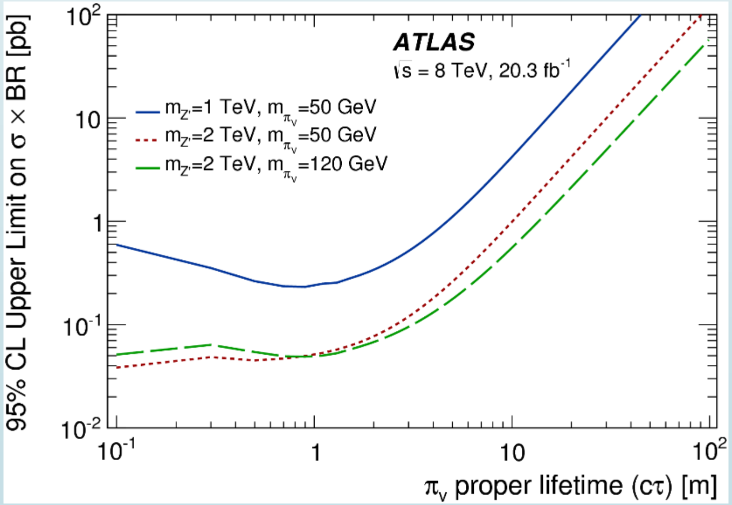
Backup

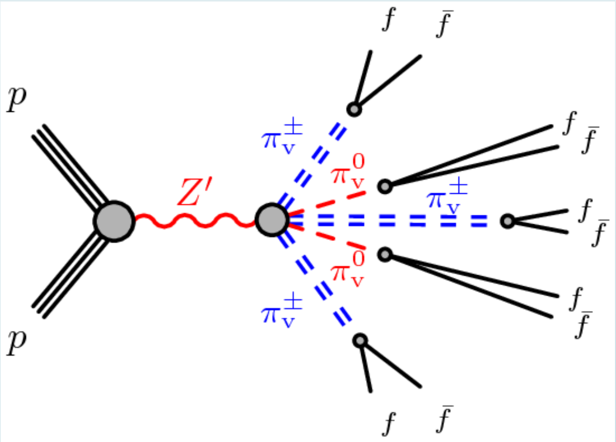
ATLAS Run-1 Results

- 2MS vertices or MS vertex plus ID vertex [arXiv:1504.03634, Phys. Rev D92, 012010 (2015)]



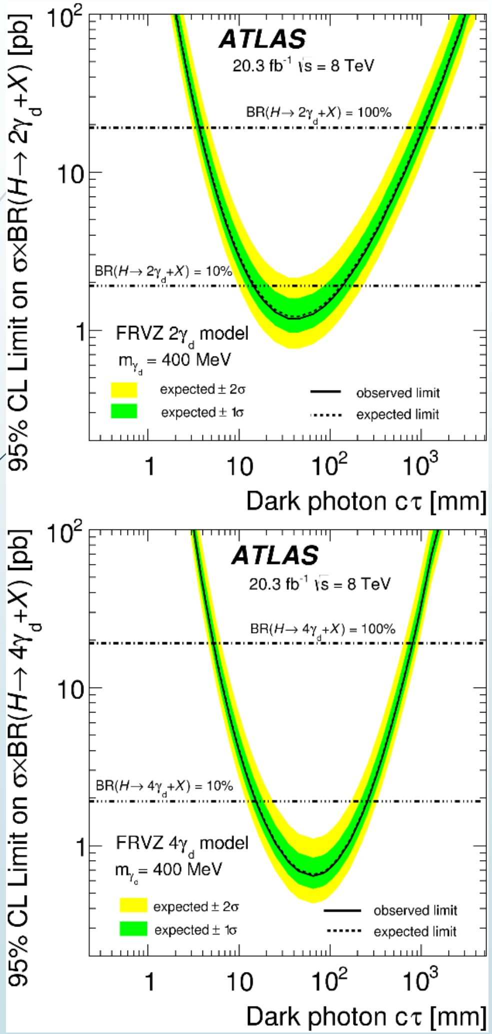




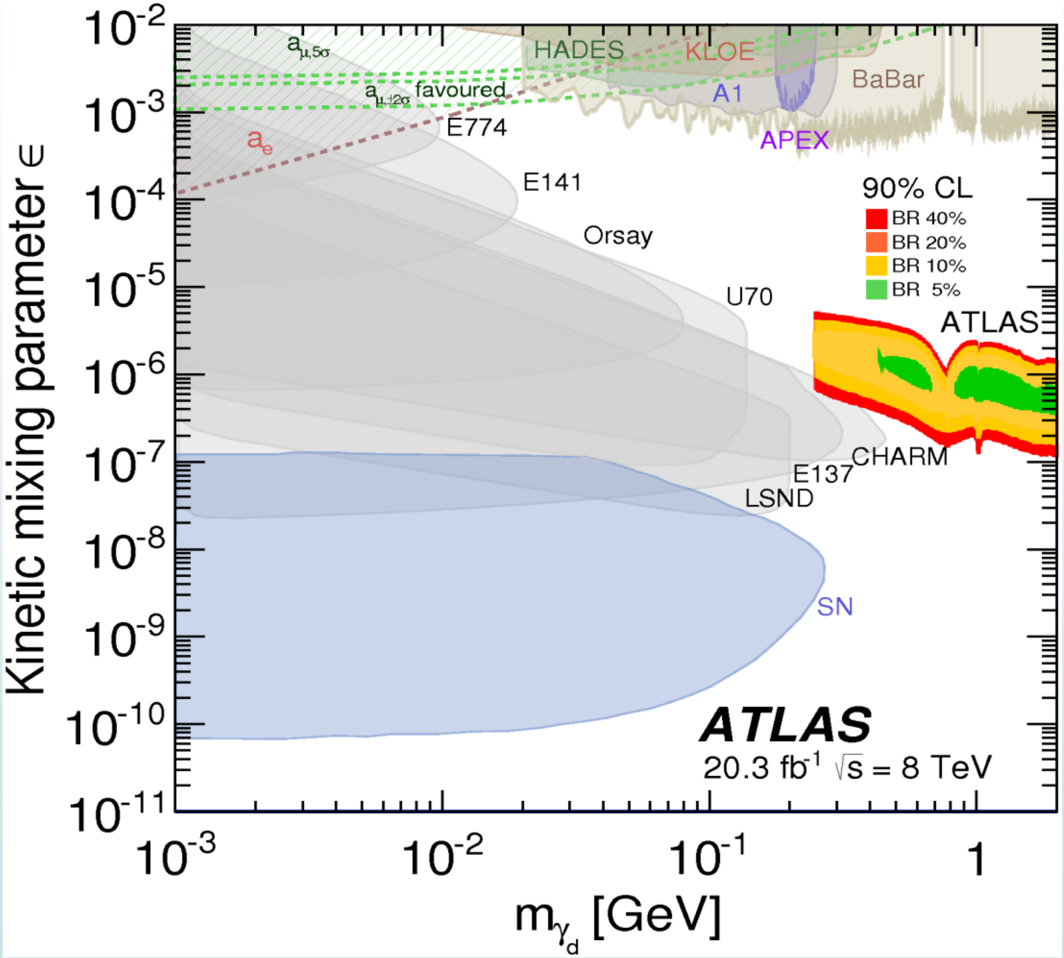


ATLAS Run 1 displaced lepton jet results

- Results obtained from the lepton-gun MC efficiencies

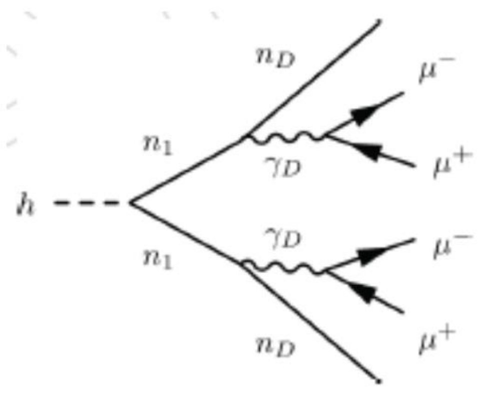


Type 0 and 1 only limits

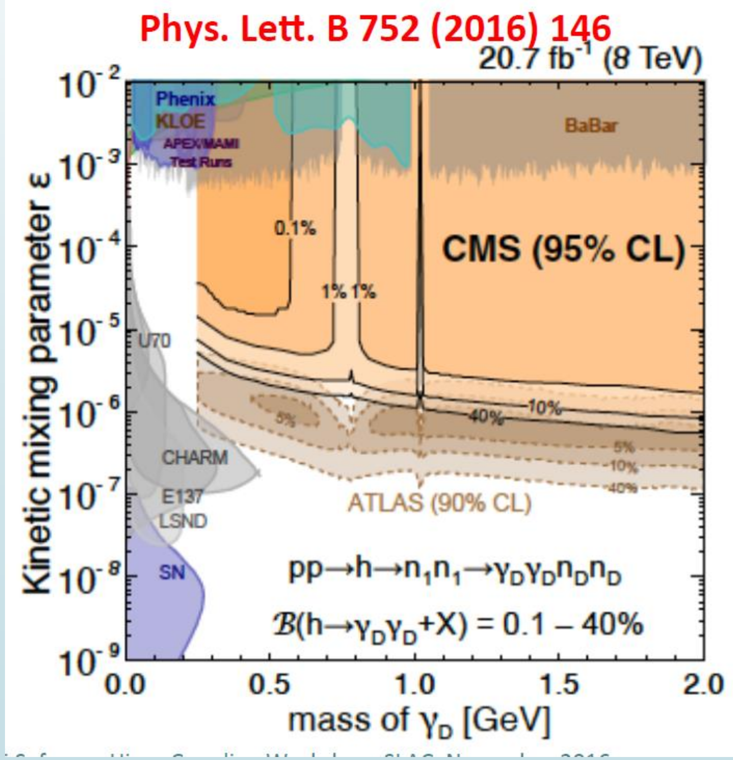


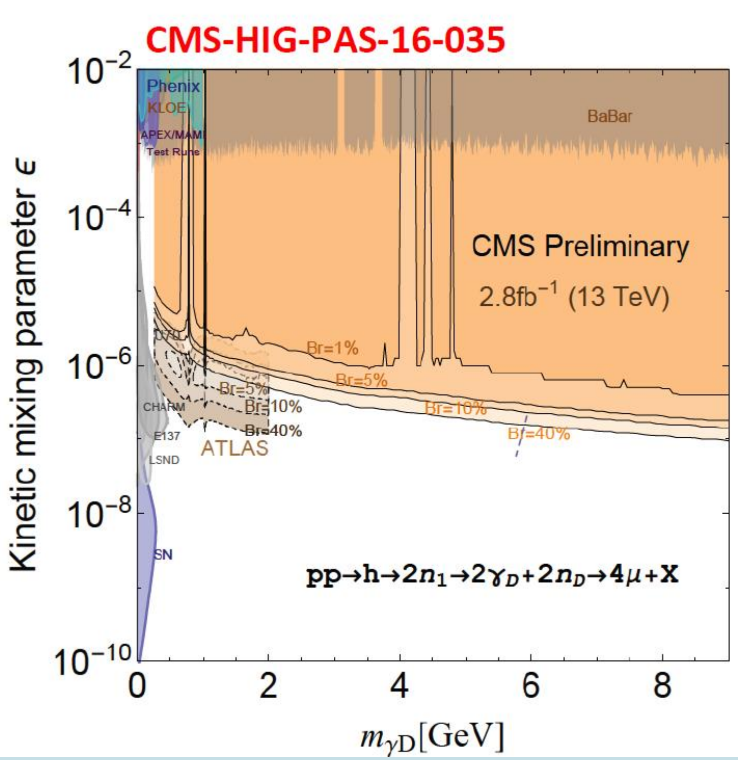
ATLAS limits in the global ε vs $m_{\gamma d}$ plot
NB: ATLAS result depend on BRs and are for specific final states.

CMS Lepton Jets – Higgs Portal



Search for 4 muons in η < 2.4
In topology with two pairs of closely spaced muons





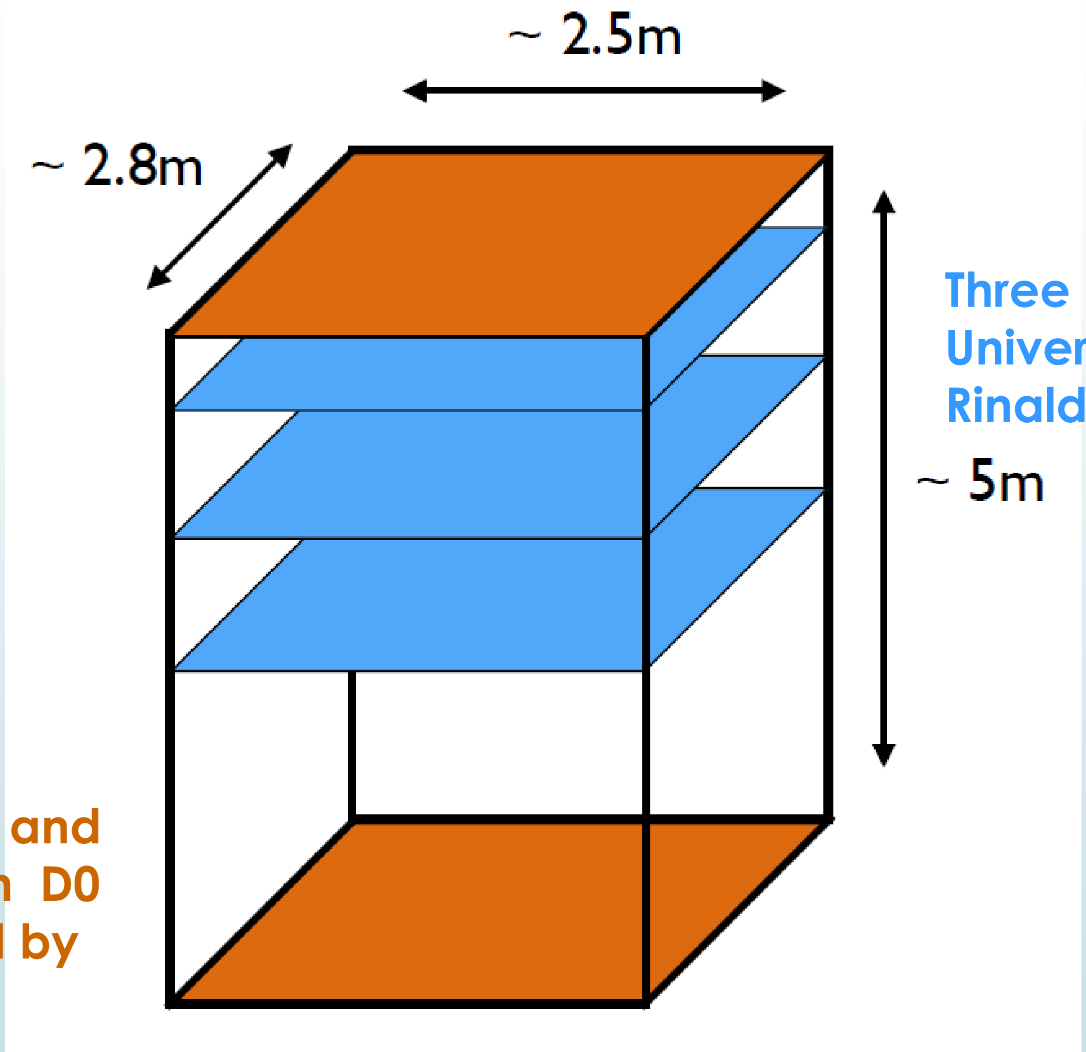
MATHUSLA

MATHUSLA – background studies

- Effort underway to develop GEANT simulations of the backgrounds discussed above
  - Current plan to deal with muons and neutrinos traveling upwards is to create a "gun" that shoots particles into MATHUSLA
  - For cosmic muons from above plan to use standard cosmic muon simulation code - will seek input from colleagues.
  - Simulation needs data with LHC colliding protons and also when there are no pp collisions in LHC – beam OFF

TEST Module

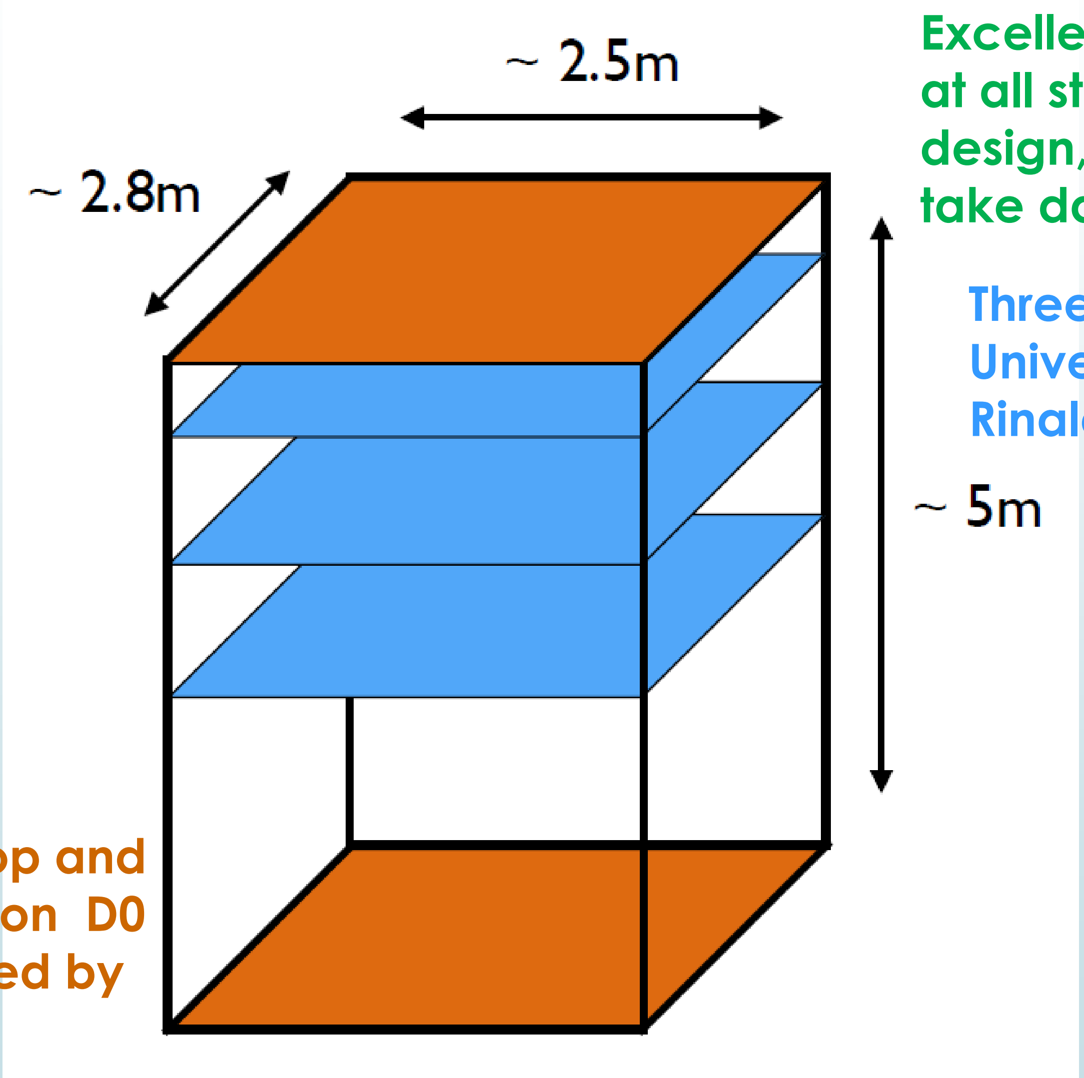
MATHUSLA Test Module



Three layers of RPCs provided by University of Rome, Tor Vergata Rinaldo Santonico and friends

Scintillator layers top and bottom from Tevatron D0 experiment provided by Dmitri Denisov

MATHUSLA Test Module



Excellent for students - participation at all stages of an experiment: design, test components, install, take data and analysis

Three layers of RPCs provided by University of Rome, Tor Vergata Rinaldo Santonico

Goal is to install at Point 1 in late summer 2017

Scintillator layers top and bottom from Tevatron D0 experiment provided by Dmitri Denisov

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MATHUSLA theory white paper

- Collaboration of 70+ theorists
- Aiming for publication in 2017

Detecting Ultra-Long-Lived Particles: The MATHUSLA Physics Case

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