Mathusla

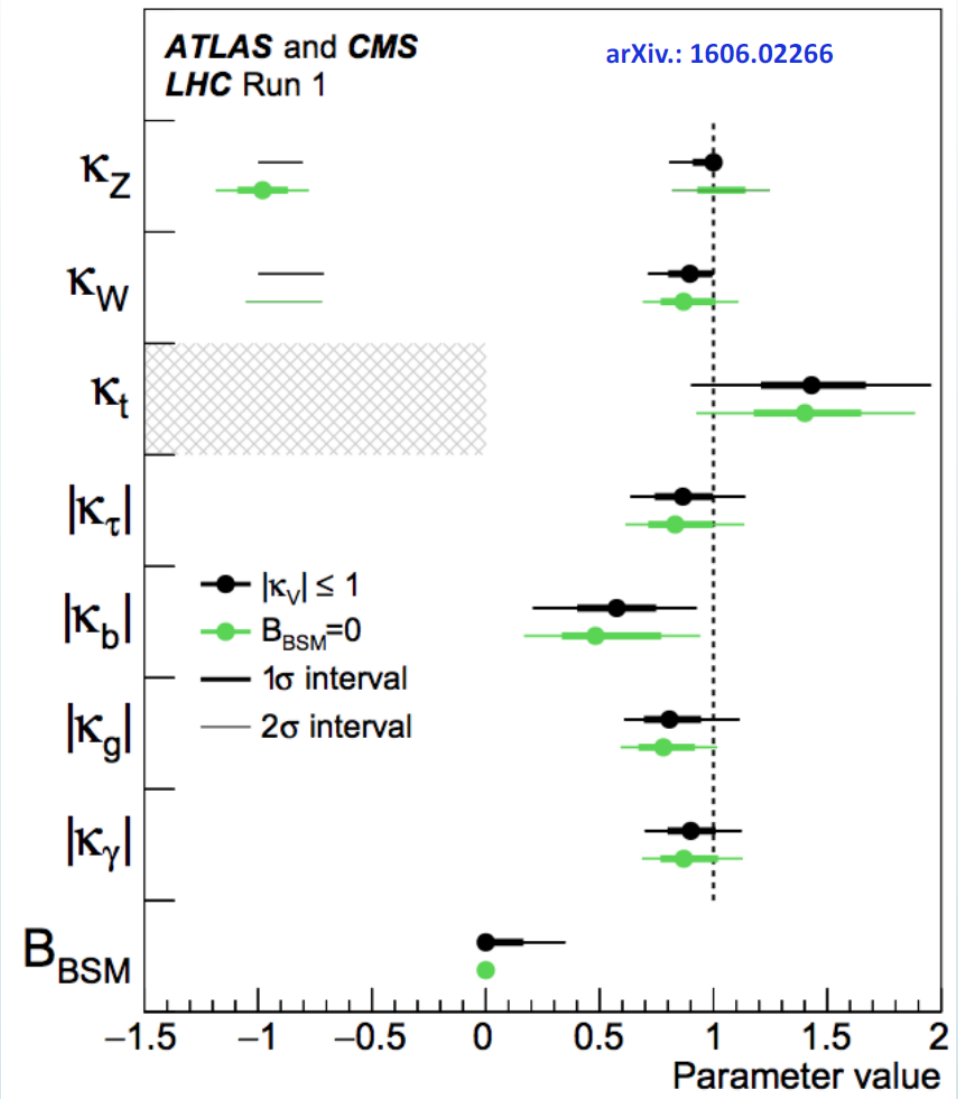
Henry Lubatti

Higgs boson *measured* decay modes or why worry about SM

Combined ATLAS-CMS Run 1 results wrt standard model expectations

Good agreement with SM

BUT

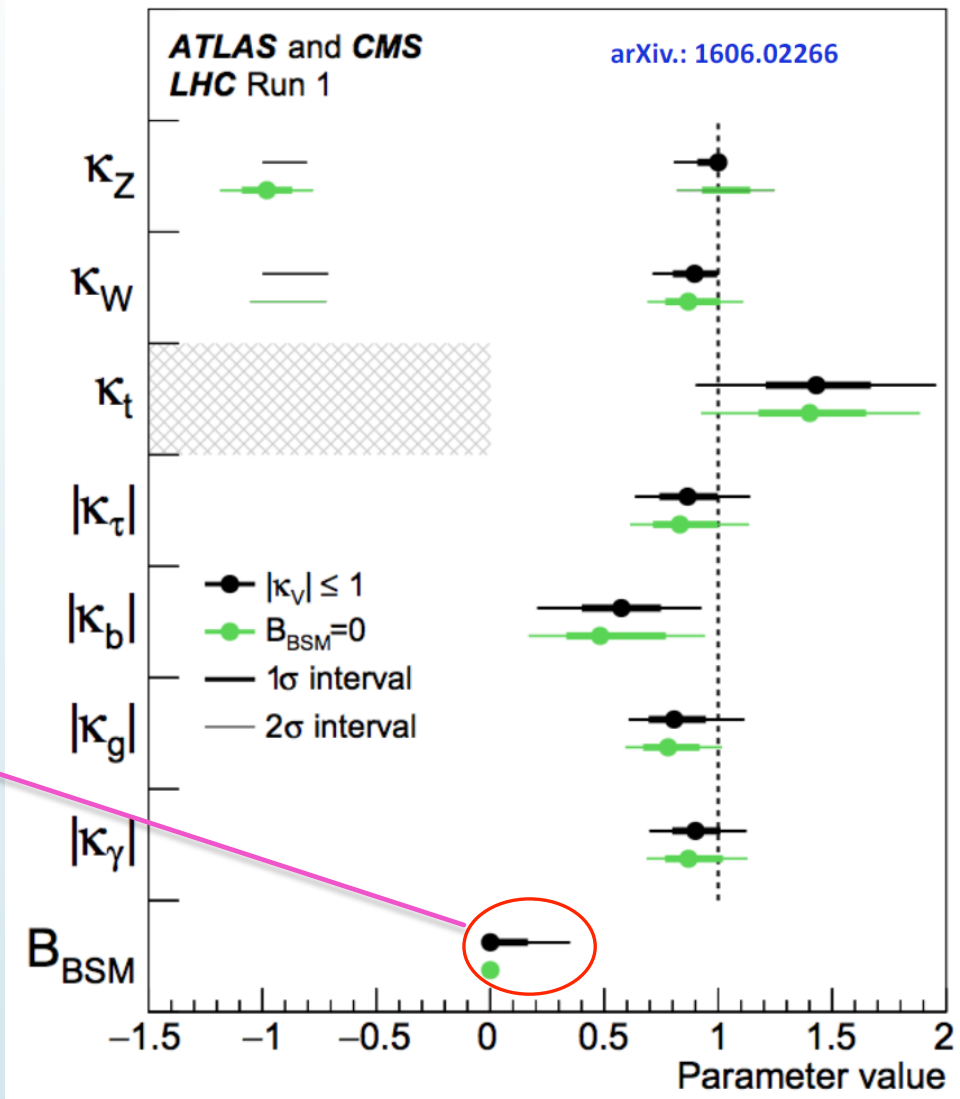


Higgs boson *measured* decay modes

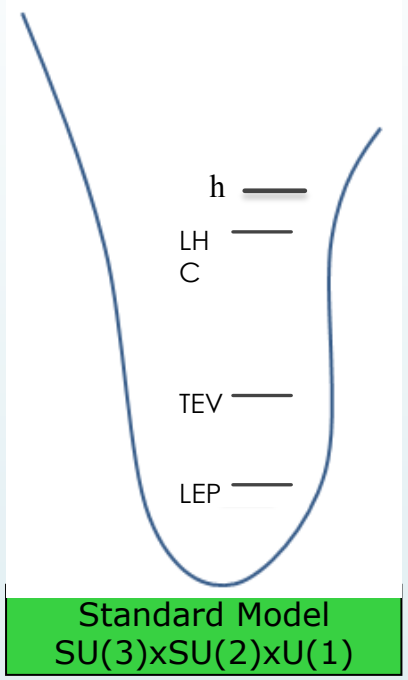
Combined ATLAS-CMS Run 1 results wrt standard model expectations

Good agreement with SM

BUT > 30% BSM allowed



The SM today and…



- SUSY models are constrained no evidence for SUSY particles
- Higgs couplings studies allow for 30-40% invisible decays
- m_h = 125 GeV is very low
- No evidence for other light scalars
- Dark matter not in SM

Hidden sectors?

higgs portal to the hidden sector

Let there be light

Hidden Sector

Much of the recent theoretical work and experimental work in particle physics is focused on three open *dark matter, particle asymmetry (Baryogenesis) and the hierarchy problem*. All of these have been connected to hidden sectors containing new particles and new forces that lead to long-lived particles

Why Long-lived Particles -summary

- Standard Model (SM) completed by **discovery** Higgs boson in 2012
- Focused attention on what SM does not address
  - Dark Matter
  - Matter-antimatter asymmetry of our universe
  - Naturalness of electro-weak scale, absent obvious TeV-scale signals of physics Beyond the SM (BSM)
- Virtually every theory/model that extends the SM to address these open issues either allows for or requires long-lived particles (LLPs)
  - Life-times ($c\tau$) can range from a few 100 μm to the Big Bang Nucleosynthesis (BBN) limit of $10^7 - 10^8$ meters
  - Covering such a large $c\tau$ range poses a major experimental challenge
- Higgs boson a particularly good place to search for LLPs
  - Very narrow width Γ/m almost two orders of magnitude smaller than most SM particles
  - Studies of Higgs couplings allow for 30-40% invisible decays
  - Higgs couples well to hidden sector scalar portals

Theories with Long-lived Particles

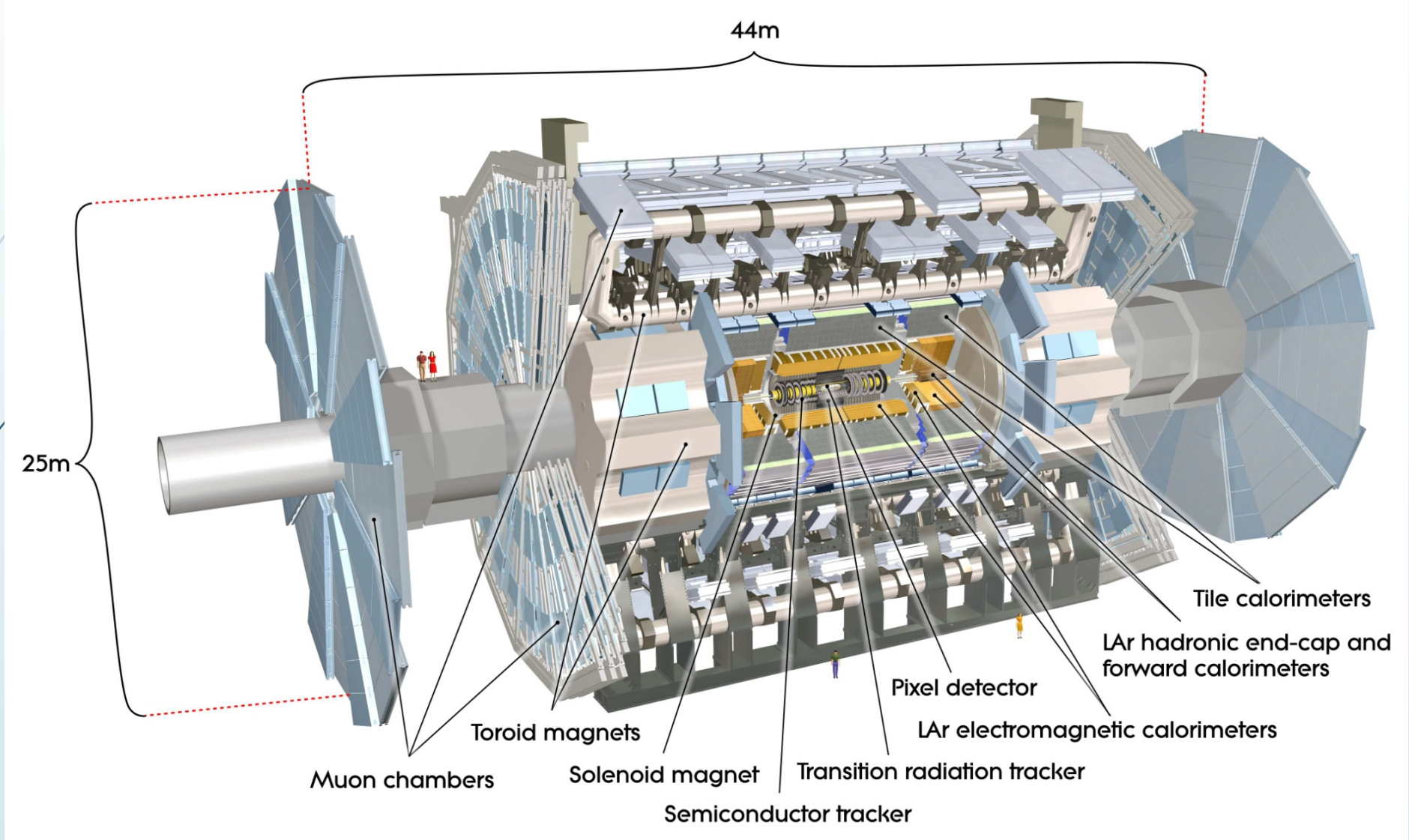
- BSM Theories that extend SM require or allow for LLPs*
  - Mini split supersymmetry (arXiv:1212.6971)
  - Gauge mediation (arXiv:hep-ph/9801271)
  - RPV (R-parity violating) SUSY (arXiv:1309.5957)
  - Models of Baryogenesis (arXiv:1409.6729)
  - Hidden Valleys (arXiv:hep-ph/0605193)
  - Dark Photons (arXiv:1604:00044)
  - Theories of Neutral Naturalness (arXiv:1512.05782)
  - Models generating neutrino masses (arXiv:1604.06099)

* Reference are to a relatively recent paper that contains earlier work.

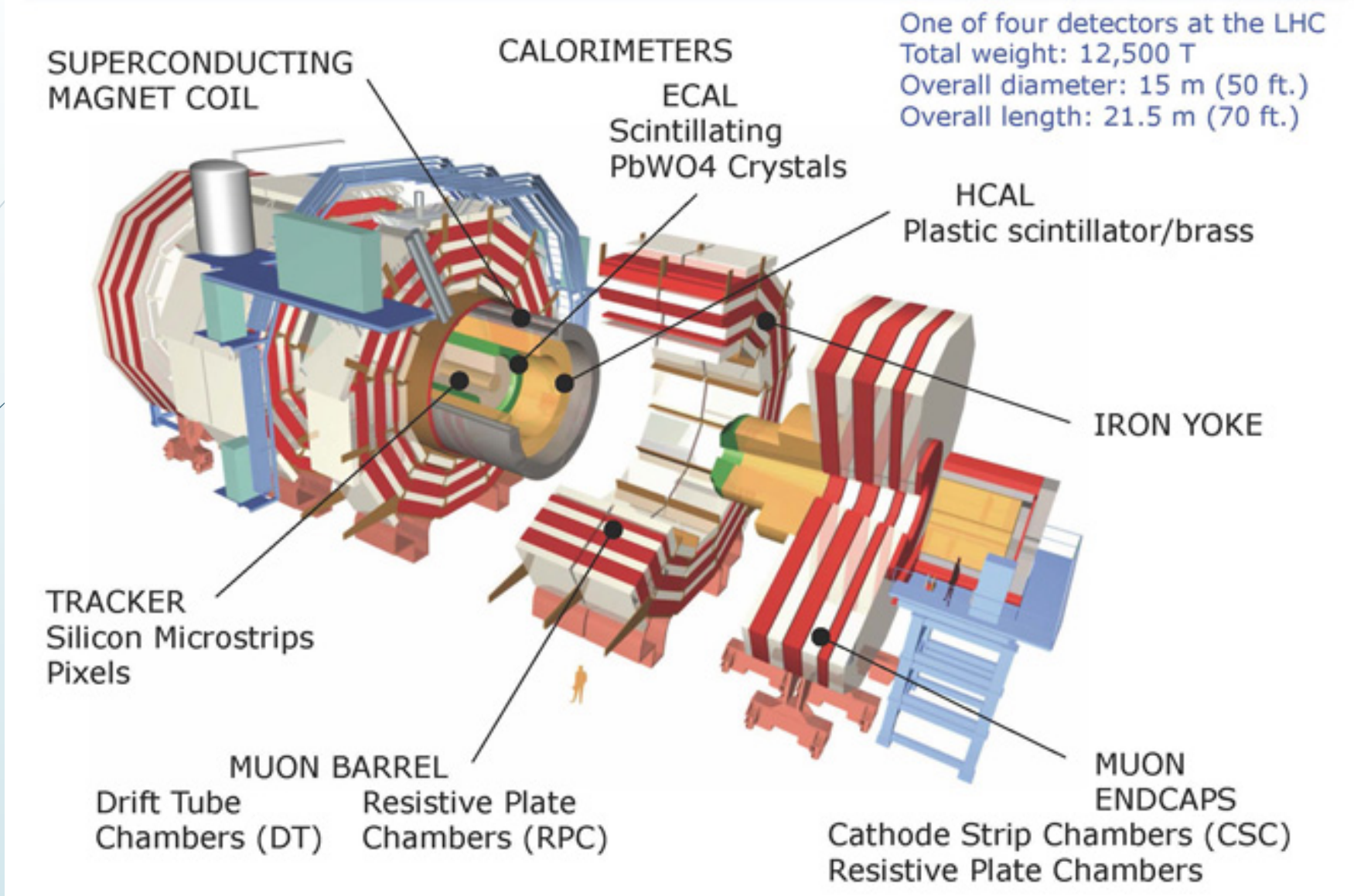
Neutral LLPs

- 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-$c\tau$)
- ATLAS search strategy for displaced decays - based on signature driven triggers that are detector dependent

ATLAS Detector



CMS Detector

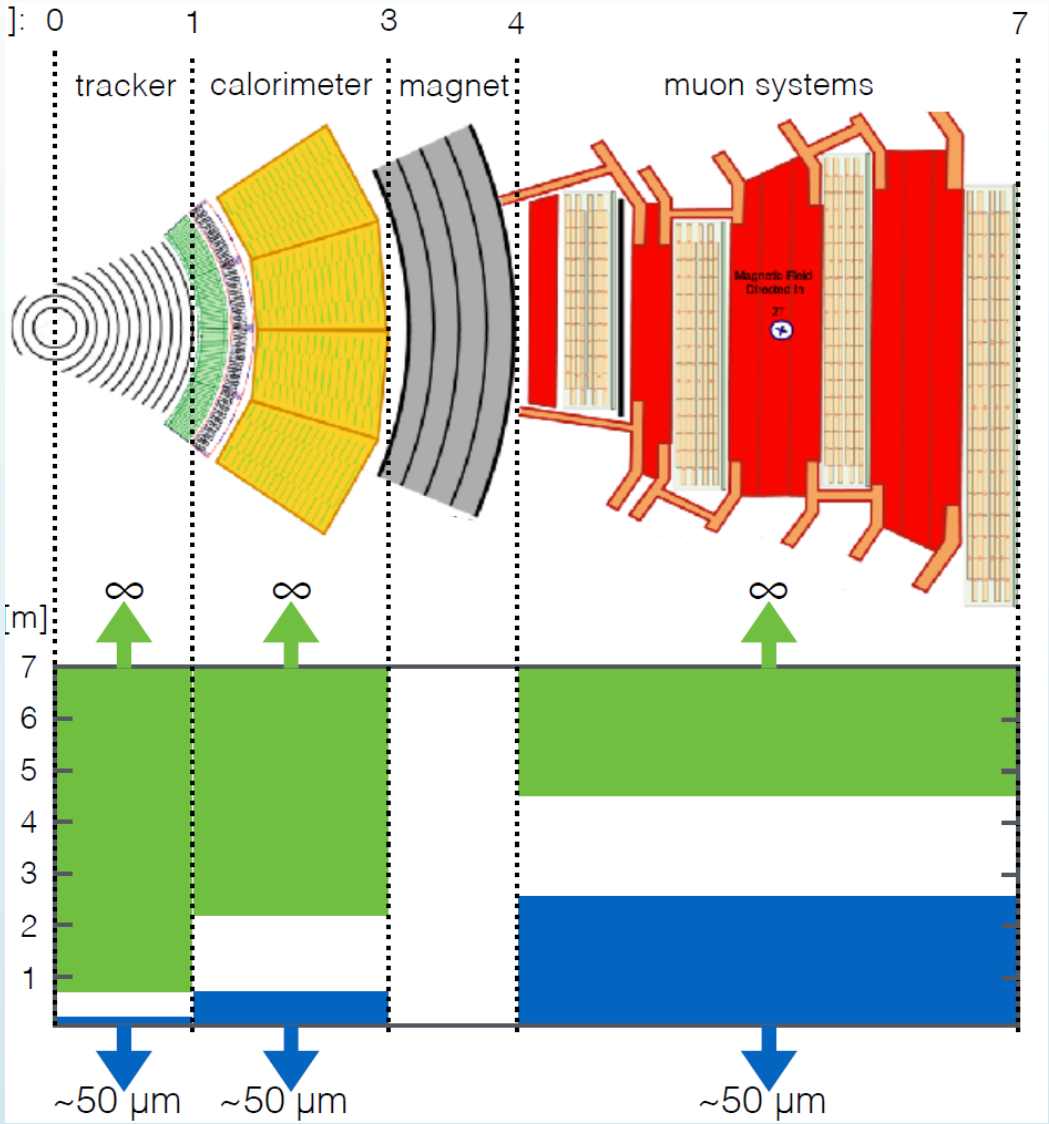


CMS

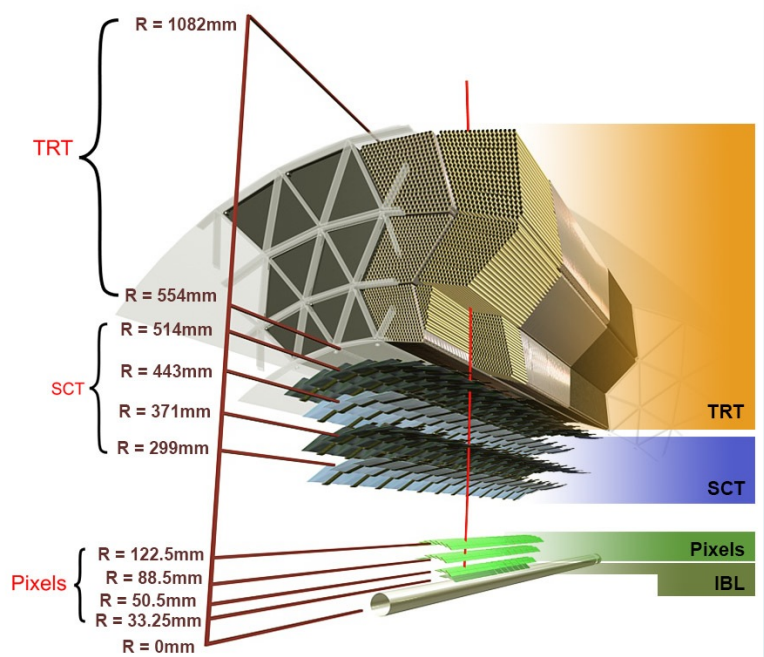
CMS inner tracking entirely silicon based (pixels + strips)

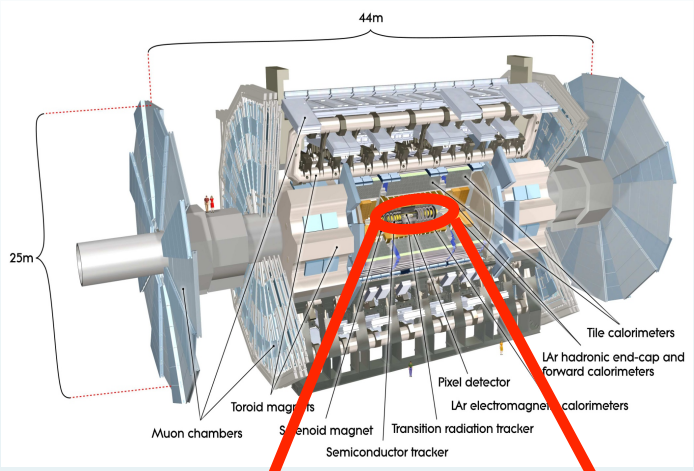
E_{CAL} uses $PbWO_4$ crystals – very good energy resolution

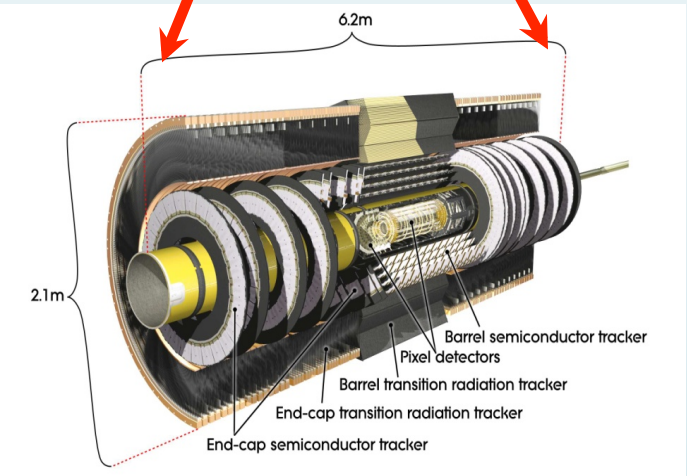
Muon system tracking chambers buried in Fe return yoke of magnet



ATLAS Inner Detector



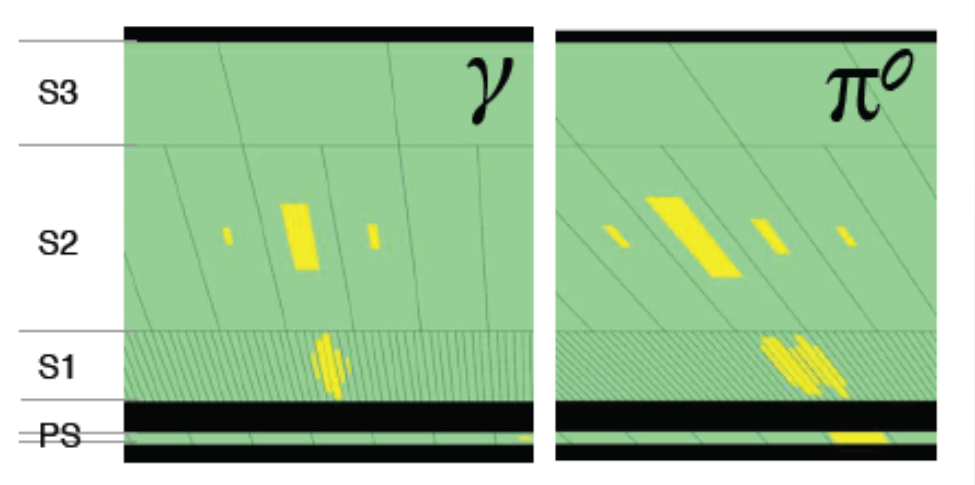


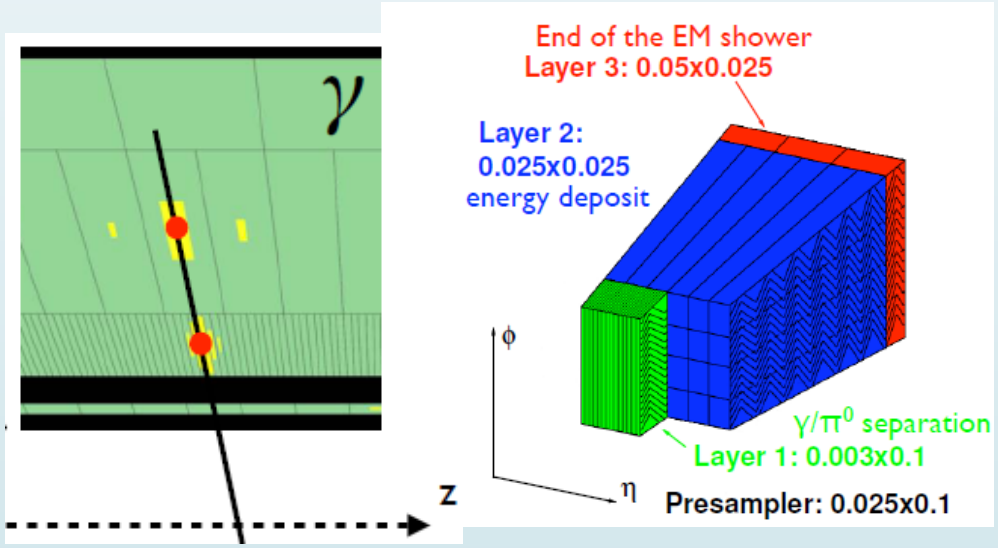


- Pixel Detector (Three + IBL layers - double sided)
  - $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 10\ \mu m$, $\sigma_z \sim 115\ \mu m$ (80M channels)
- Semiconductor Tracker (SCT): single sided Si strips
  - stereo pairs
  - Four barrel layers and 2x9 end-cap disks stereo
  - $|\eta| < 2.5$ with $\sigma_{r\phi} \sim 17\ \mu m$, $\sigma_z \sim 580\ \mu m$ (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 $\sigma_{r\phi} \sim 130\ \mu m$ (350k channels)
  - Average of 32 hits/track
- The ID embedded in a 2 Tesla solenoidal magnetic field

ATLAS E_{CAL} Segmentation

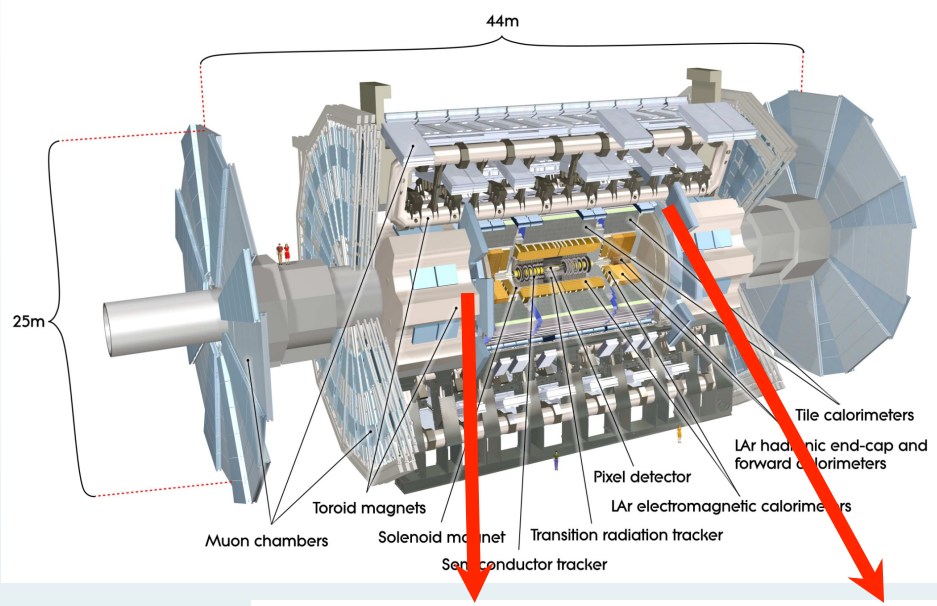
- Allows for Photon ID based on longitudinal and lateral segmentation of the ECAL (shower shapes)
- High granularity in S1 gives in good γ direction and separation power for π^0 decays to $\gamma\gamma$
- Photon direction from shower centroids in layers 1 and 2 gives longitudinal (z) position
- For two γ (eg. H → $\gamma\gamma$) combine 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

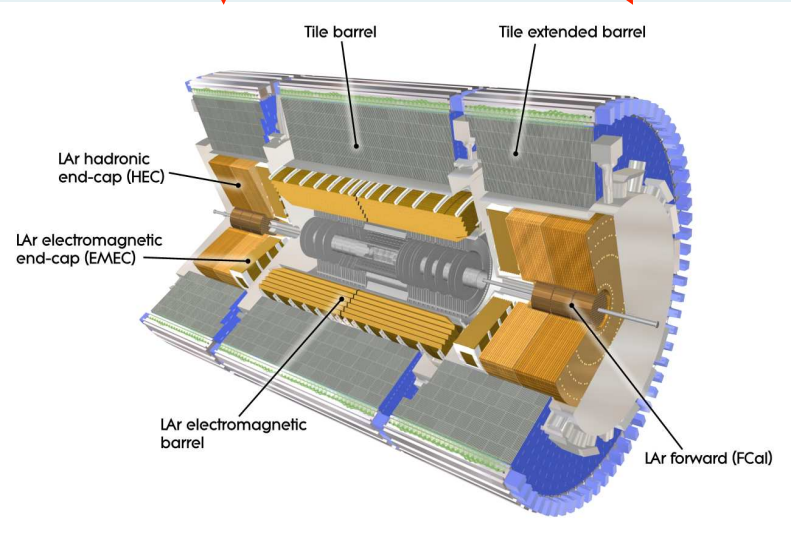




ATLAS Calorimeters

- 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 $|\eta| \leq 3.9$





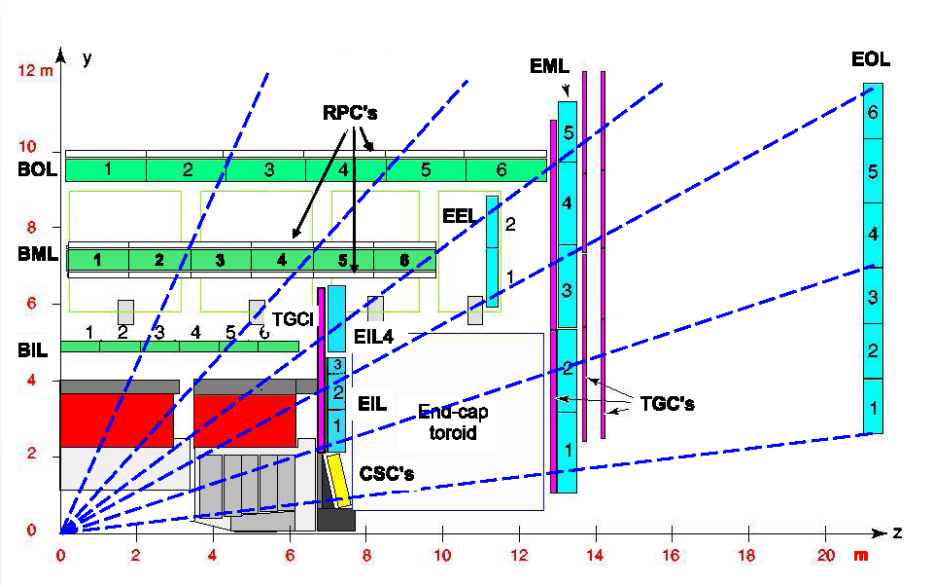
ATLAS Muon Spectrometer (MS)

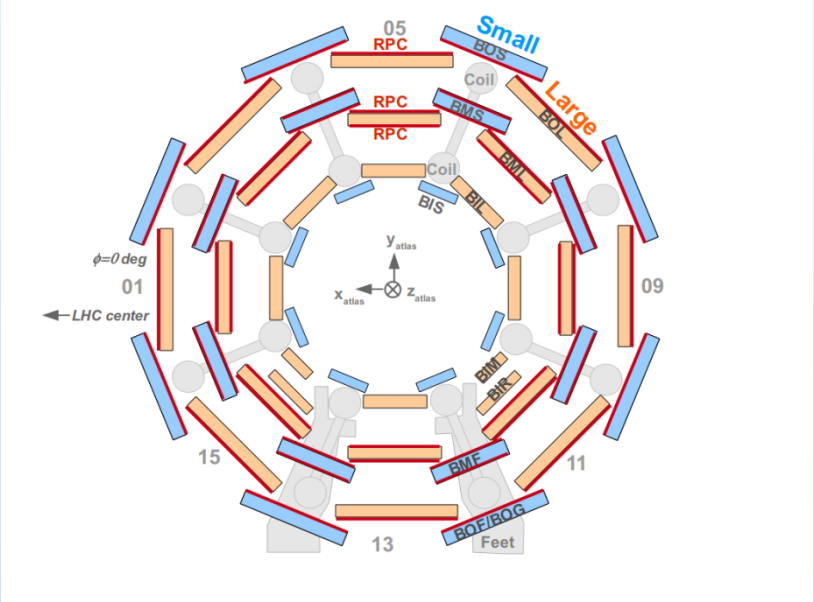
- Air core toroid - magnetic field allows for stand-alone momentum measurements and vertex reconstruction

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_{pT}/p_T ~ 4% at 50 GeV and ~ 11% at 1 TeV

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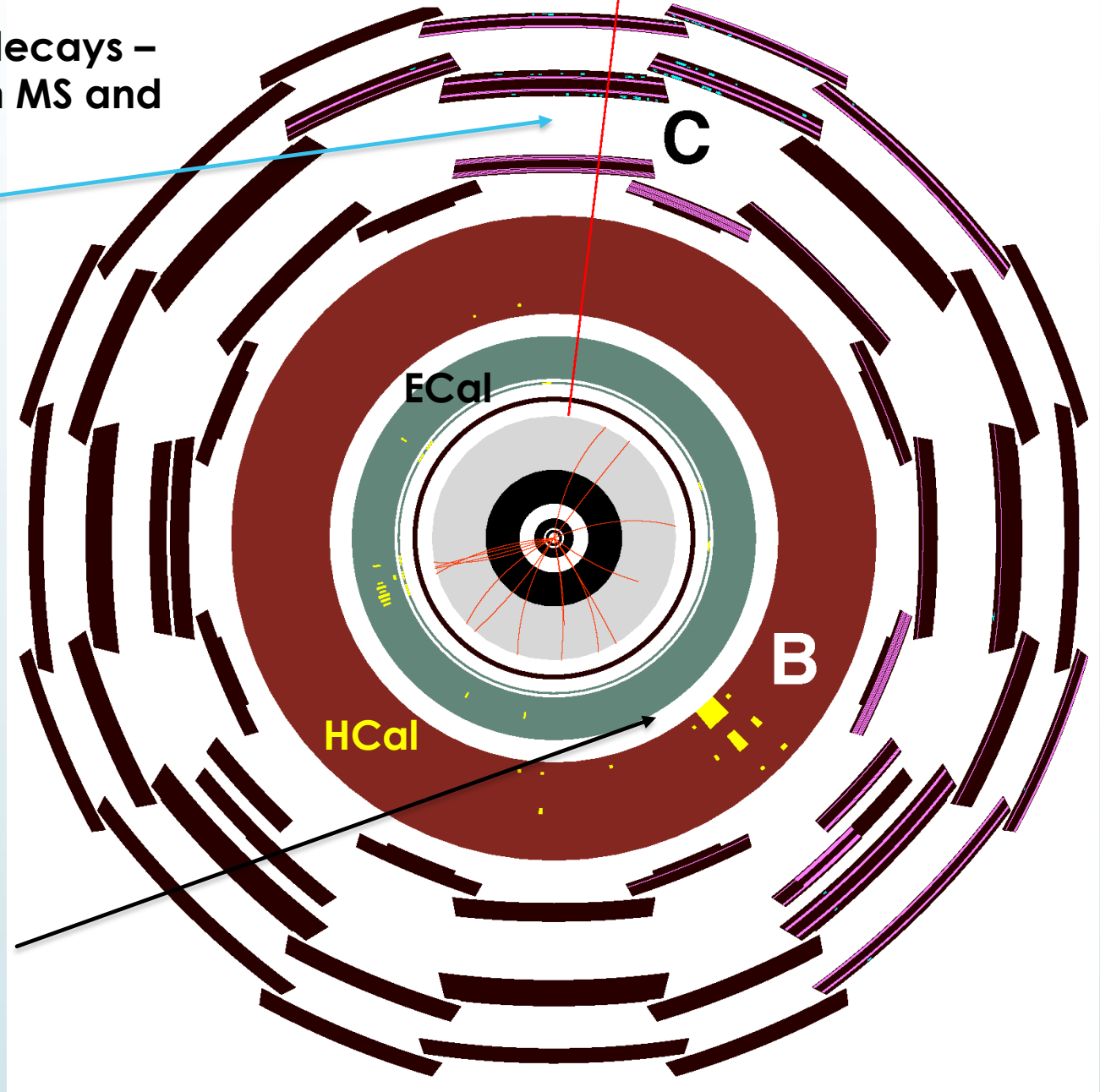
ATLAS Simulation

ATLAS simulation of two displaced decays – Note unique signatures of decays in MS and HCal

Decay in MS
Cluster of His in RPCs



Decay at beginning of HCal
Low EM energy deposition

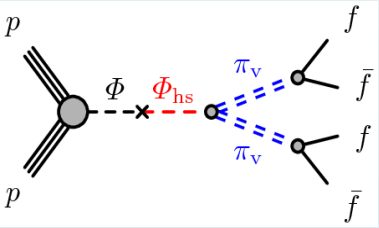
ATLAS Run-1 results

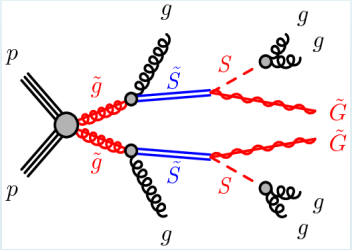
- Searches requiring two displaced decays
  - Two low EM fraction (EMF) jets (decays in the HCal)
  - Two reconstructed displaced vertices
    - 2MS vertices or MS vertex plus ID vertex
  - Sensitive to Higgs decaying to long-lived scalar pairs
  - **No evidence for two vertex events in the Run-1 data**
    set limits for Higgs decay to long-lived scalar pairs, Stealth SUSY and heavy Z' decay (long-lived particles indicated by double lines)

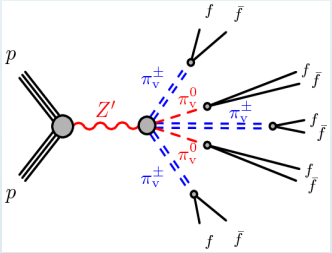
Scalar boson mass [GeV]	π_v mass [GeV]
100	10, 25
125	10, 25, 40
140	10, 20, 40
300	50
600	50, 150
900	50, 150

Z'mass [TeV]	π_v mass [GeV]
1	50
2	50
2	120

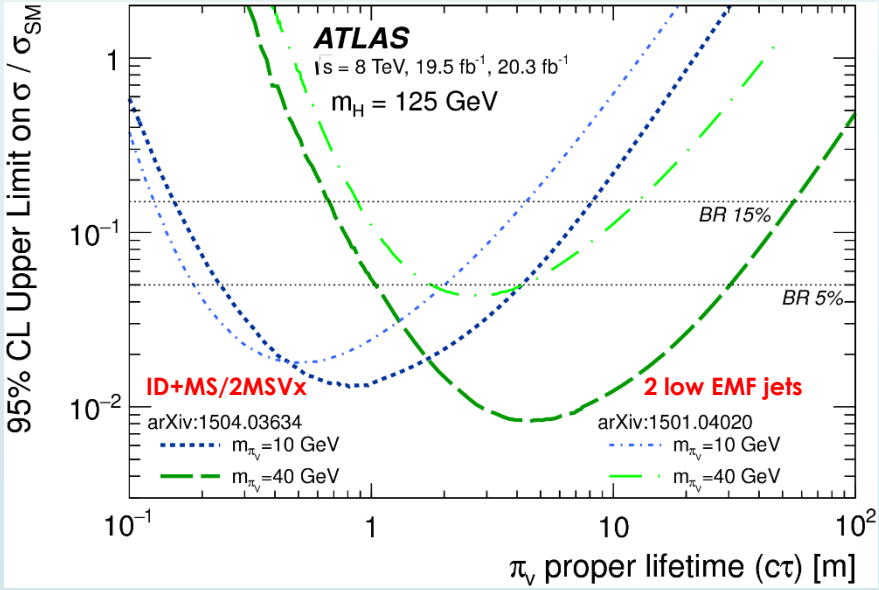
$\tilde{g}$ mass [GeV]	$\tilde{S}$, S mass [GeV]
110	100, 90
250	100, 90
500	100, 90
800	100, 90
1200	100, 90





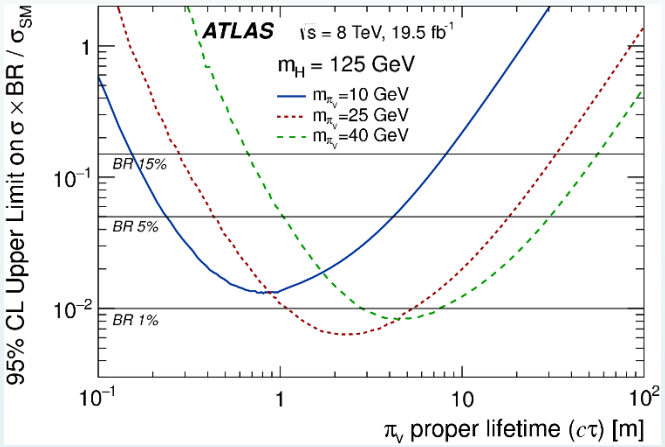


Trigger	Applicable topologies	Benchmarks
Muon RoI Cluster	IDVx+MSVx, 2MSVx	Scalar boson, Stealth SUSY
Jet+E_T^{miss}	2IDVx, IDVx+MSVx, 2MSVx	Z'



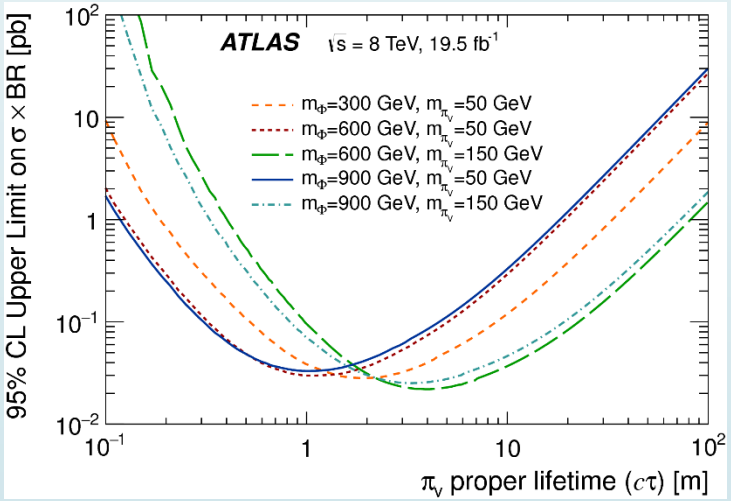
ATLAS Run-1 Results

- 2MS vertices or MS vertex plus ID vertex [arXiv:1504.03634, Phys. Rev D92, 012010 (2015)]
  - π_v proper decay lengths excluded at 95% CL assuming 30%, 15%, 5%, or 1% BR for m_H = 125 GeV.



m_{π_v} [GeV]	Excluded $c\tau$ range [m] 1% BR	5% BR	15% BR	30 % BR
10	no limit	0.24–4.2	0.16–8.1	0.12–11.8
25	1.10–5.35	0.43–18.1	0.28–32.8	0.22–46.7
40	2.82–7.45	1.04–30.4	0.68–55.5	0.52–79.2

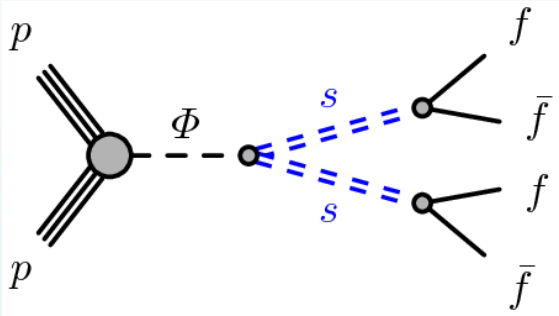
  - σ × BR 95% CL limits for scalar boson samples: m_Φ = 300 GeV, 600 GeV, and 900 GeV



ATLAS Run-2 Results (13 TeV)

- Limits for hidden-sector, heavy Higgs-like scalars decaying to hadronic jets in the ATLAS hadronic calorimeter in 3.2 fb^{-1} (2015 13 TeV data set)

m_Φ [GeV]	m_s [GeV]
400	50, 100
600	50, 150
1000	50, 150, 400



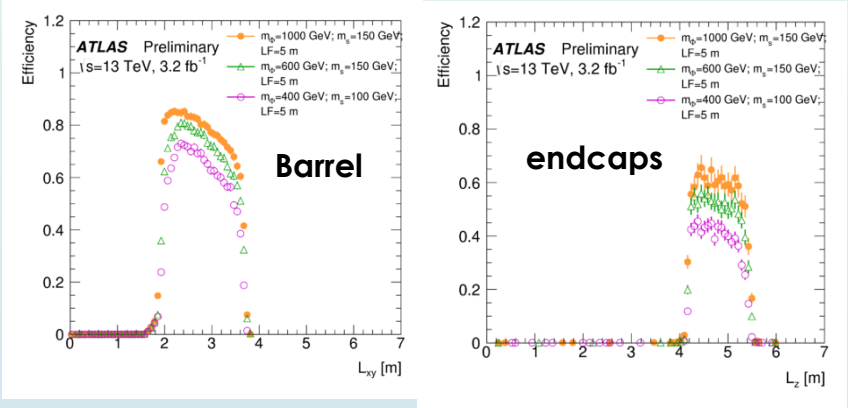
ATLAS-CONF-2016-103

$s \rightarrow bb$

Yukawa coupling heavy quarks dominant

- Trigger selects narrow jets in Hcal [60 GeV in 0.2x0.2 ($\Delta\eta,\Delta\phi$) region] and $\log_{10}(E_H/E_{EM}) > 1.2$ and no track pointing to jet
- Uses Boosted Decision Tree (BDT) to discriminate between QCD-like and signal-like jets (jet p_T, jet width, track variables,…)

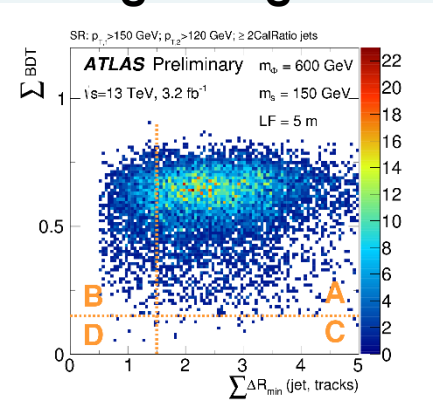
Trigger Efficiency



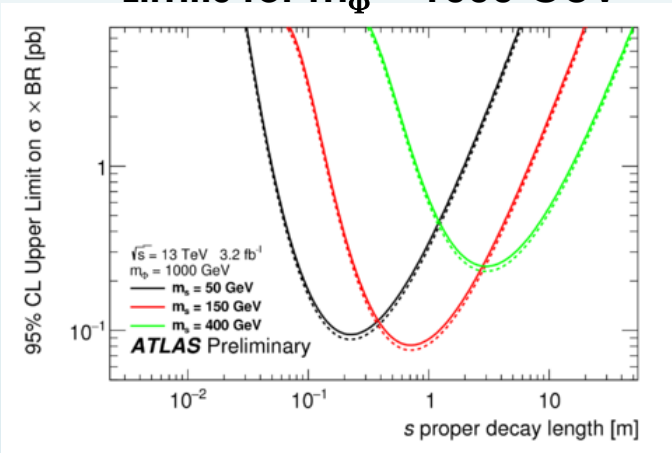
ATLAS Run-2 Results (13 TeV)

- Multijet backgrounds estimated using ABCD method using uncorrelated variables ΣBDT [sum of two jets having highest BDT values] and $\Sigma\Delta R_{min}$(jet,tracks) [sum angle between jet axis and closest track with p_T>2 GeV]

A-signal region



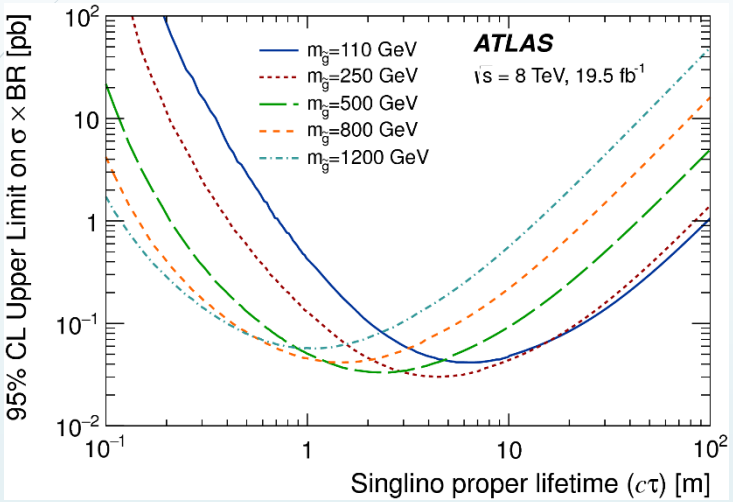
Limits for m_Φ = 1000 GeV

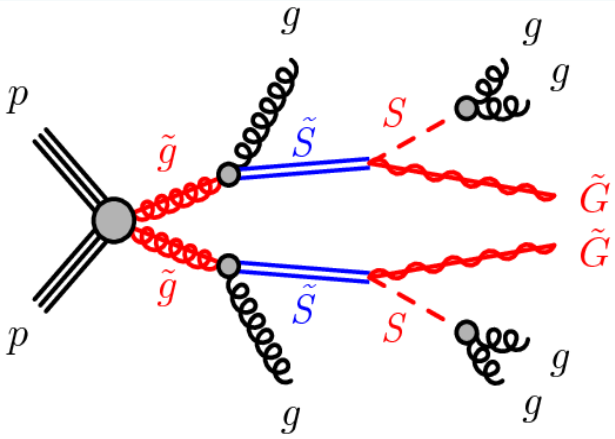


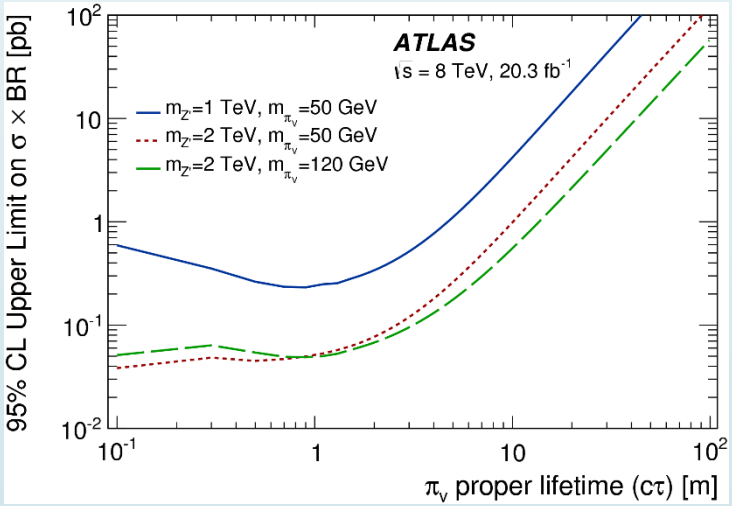
	$m_s = 50\ GeV$	$m_s = 100\ GeV$	$m_s = 150\ GeV$	$m_s = 400\ GeV$
	Decay length range excluded at 95% CL for $\sigma\times$ BR = 1 pb			
$m_\Phi = 400\ GeV$	(0.20, 2.4) m	(0.52, 4.6) m	–	–
$m_\Phi = 600\ GeV$	(0.09, 2.7) m	–	(0.38, 8.2) m	–
$m_\Phi = 1$ TeV	(0.05, 2.0) m	–	(0.14, 7.2) m	(0.78, 16) m

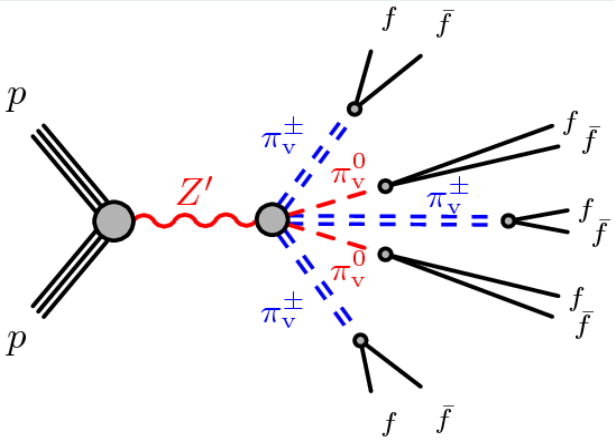
ATLAS Run-1 Results

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





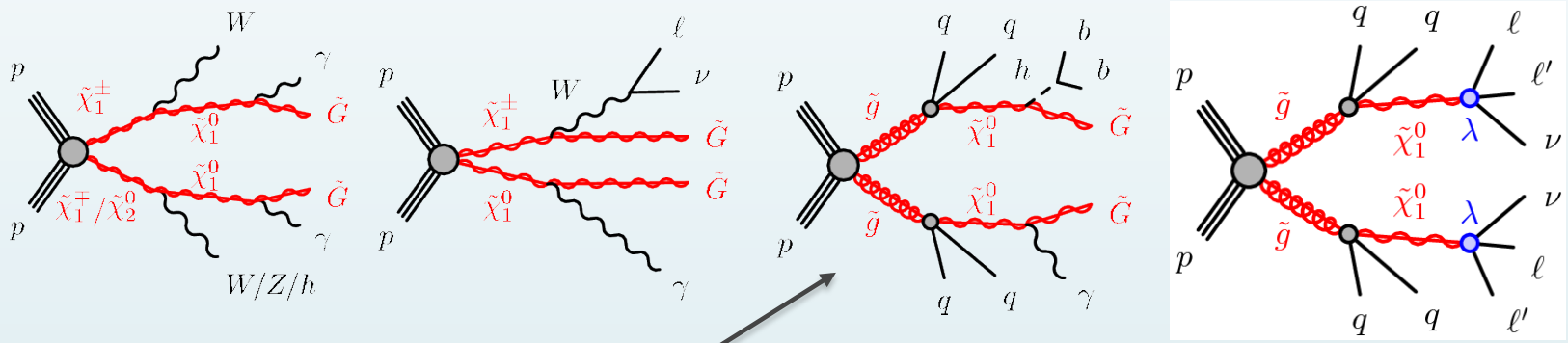


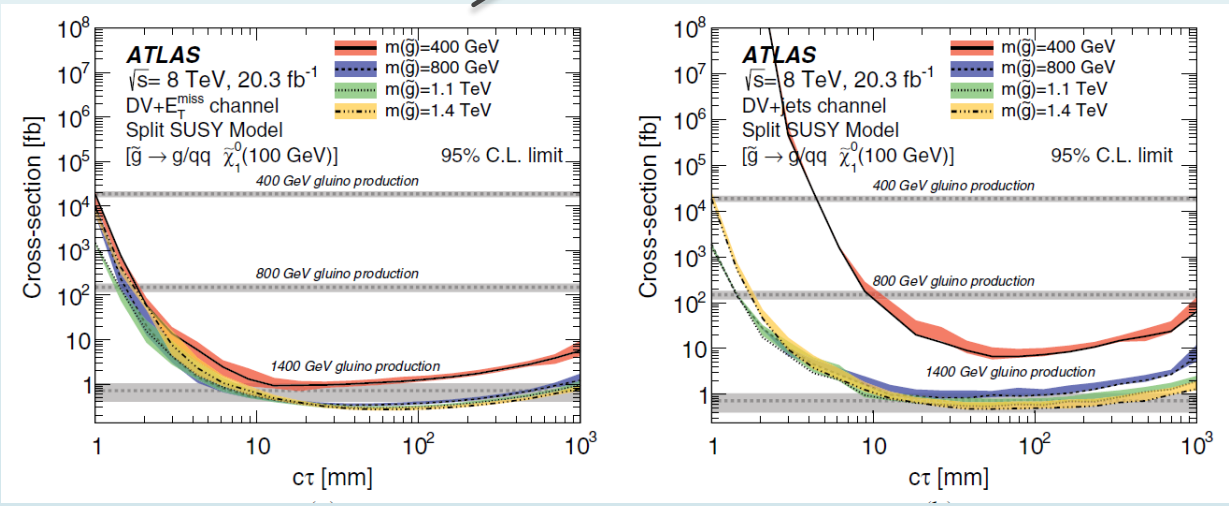


ATLAS Run 1 RPV SUSY LLP Searches

PhysRevD.92.072004
arXiv:1504.05162

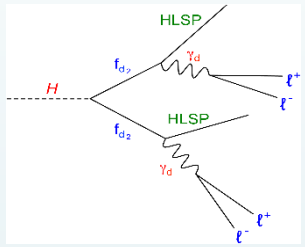
- Extensive Analysis with no observed events
- Require DV with hi-p_T μ or e that comes from DV, missing E_T and one DV per event
  - Limits for various scenarios

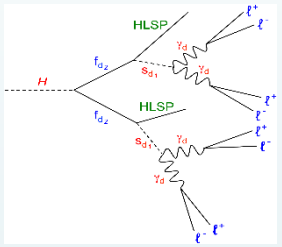


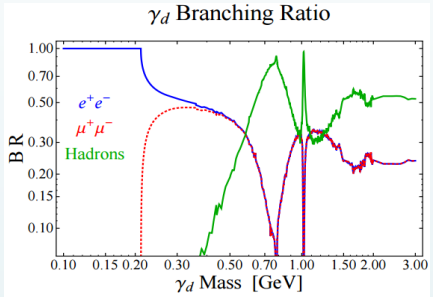


ATLAS Displaced lepton-jets Run-1Results

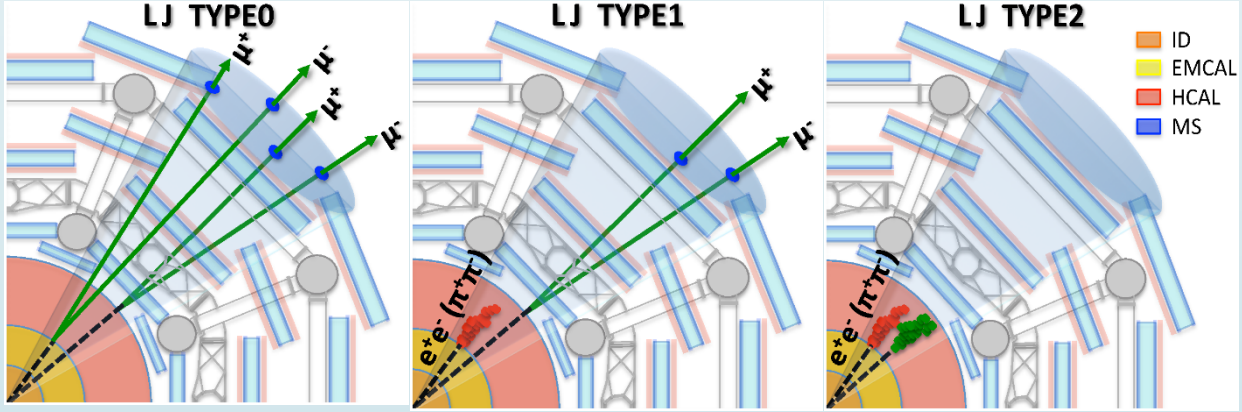
- Displaced Lepton-Jets arXiv:1409.0746 JHEP11(2014)088
  - kinetic mixing of light γ_d with SM γ through vector portal
  - ATLAS search based on FRVZ bench marks: JHEP 05 (2010) 077 [arXiv:1002.2952]







  - 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



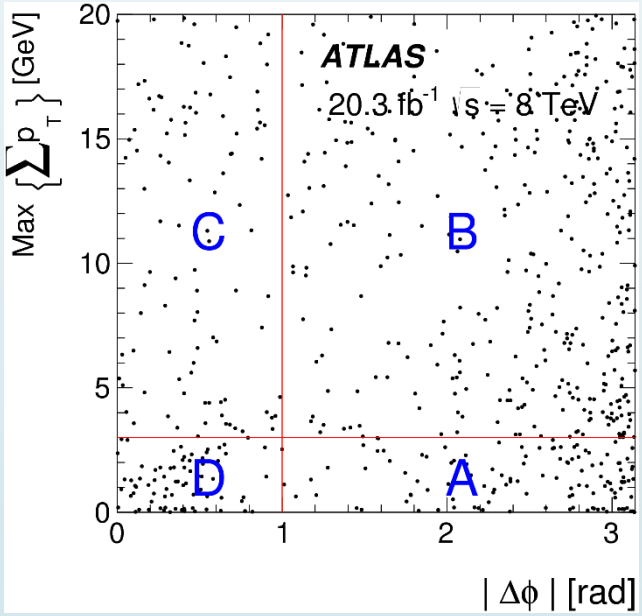
Type 0: all γ_d -> μ's
Type 1: $1\gamma_d$ -> ee or $\pi\pi$, $1\gamma_d$ -> 2μ
Type 2: all γ_d -> ee or $\pi\pi$

ATLAS Displaced lepton-jets Run-1Results

- Main Backgrounds are cosmic and QCD jets
  - Used empty bunches to determine cosmic background

Data Type	Events in B	Events in C	Events in D	Expected Events in A
Cosmic-ray data	0	0	60 ± 13	40 ± 10
Data (cosmic rays subtracted)	362 ± 19	99 ± 10	19 ± 16	70 ± 58

  - QCD jets is irreducible background - evaluated using ABCD method where $\Delta\phi$ is azimuthal angle between the two lepton jet
  - Data is consistent with expected backgrounds
  - Type2-Type2 have largest background – most sensitive limit by excluding these events



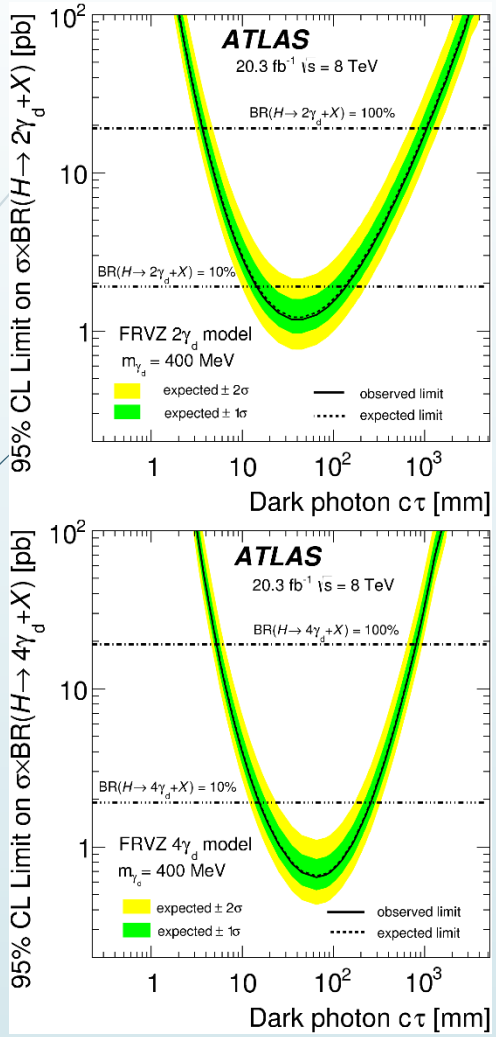
	All LJ pair types	TYPE2-TYPE2 LJs excluded
Data	119	29
Cosmic rays	$40 \pm 11 \pm 9$	$29 \pm 9 \pm 29$
Multi-jets (ABCD)	$70 \pm 58 \pm 11$	$12 \pm 9 \pm 2$
Total background	$110 \pm 59 \pm 14$	$41 \pm 12 \pm 29$

No Type2-Type2

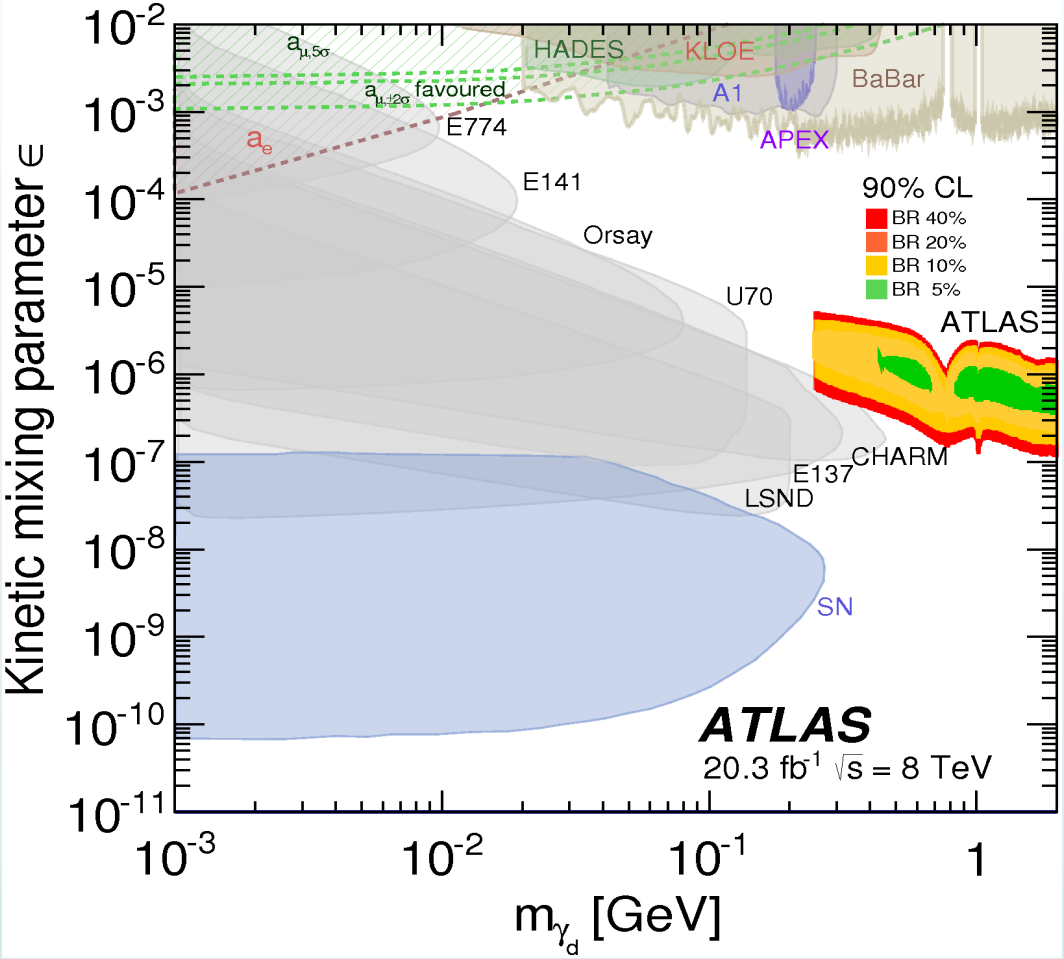
FRVZ model	Excluded $c\tau$ [mm] BR(10%)
$H \to 2\gamma_d + X$	$14 \leq c\tau \leq 140$
$H \to 4\gamma_d + X$	$15 \leq c\tau \leq 260$

ATLAS Run 1 displaced lepton jet results

- Results obtained from the lepton-gun MC efficiencies



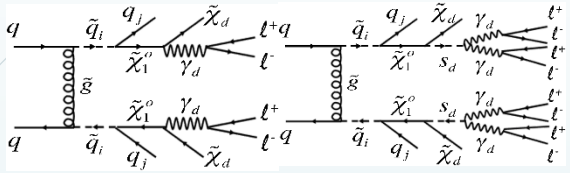
Type 0 and 1 only limits



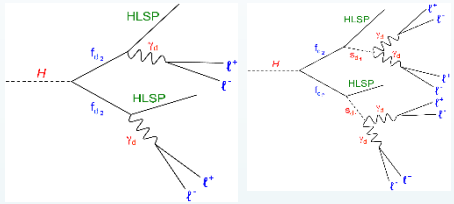
ATLAS limits in the global ε vs $m_{\gamma d}$ plot
NB: ATLAS result depend on BRs and are for specific final states.

ATLAS Prompt lepton-jets Run-1 results

- **Prompt Lepton-Jets** [JHEP02(2016)062, arXiv:1511.05542]
  - **Benchmark models:**



SUSY production of dark χ



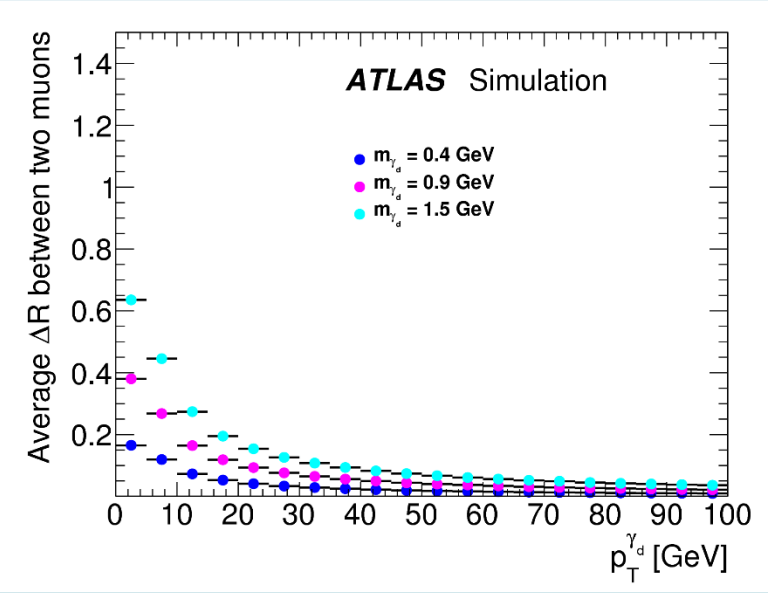
FRVZ Higgs-portal

  - Two scenarios $\gamma_d \rightarrow$ ee, $\mu\mu$ or $\pi\pi$ and $s_d \rightarrow \gamma_d\, \gamma_d$
  - Event selection: requires 2 LJs from combinations of e-jet (eLJ), μ-jet (μLJ), mixed (eμLJ) where jet ≥ 2 tracks

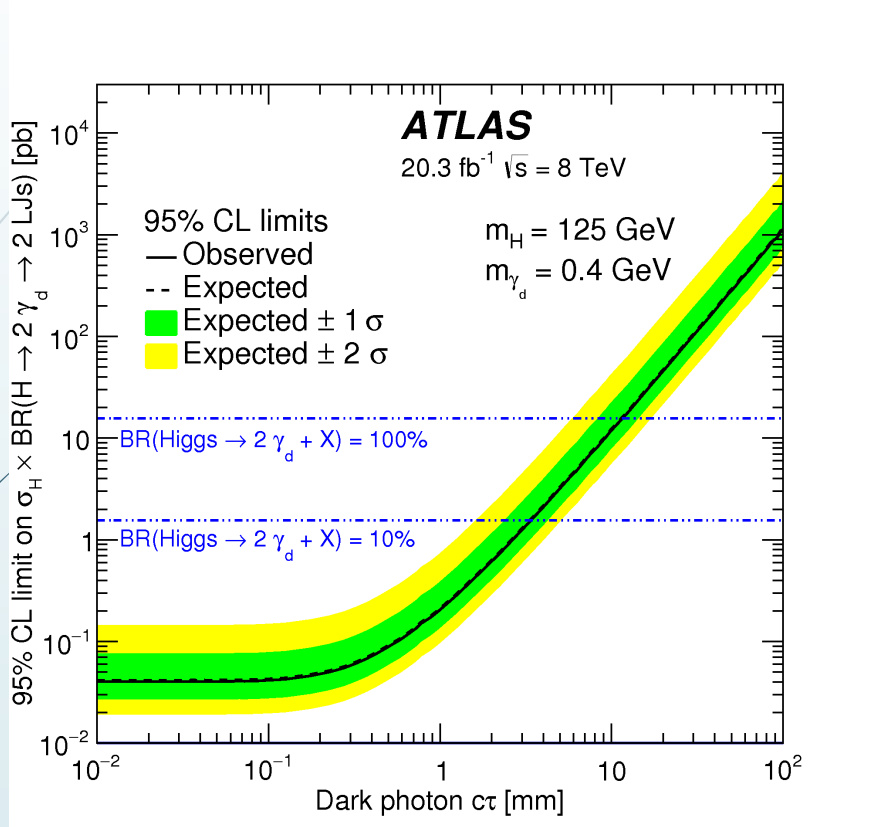
Use EM-Cal segmentation to separate electrons from π^o

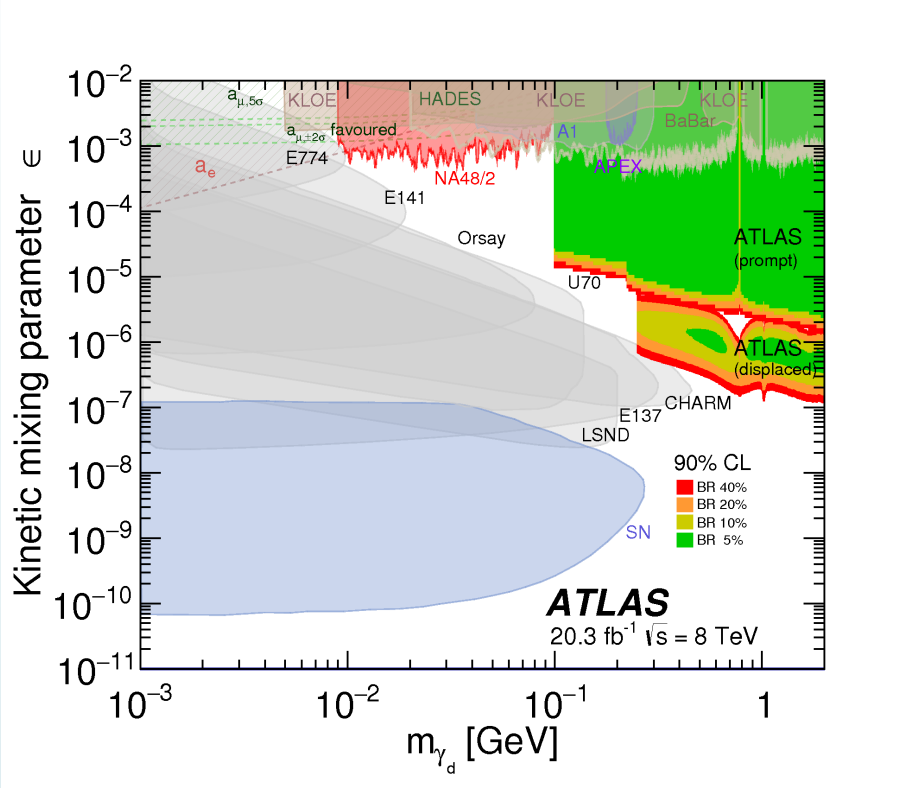
➡ **6 categories of events:**
eLJ-eLJ, μLJ-μLJ, eLJ- μLJ
eLj-e μLJ, μLJ-e μLJ, e μLJ-eμLJ

  - γ_d high boost – small opening angles
  - μLJ requires at least two muons with p_T > 10 GeV within ΔR = 0.5 of LJ



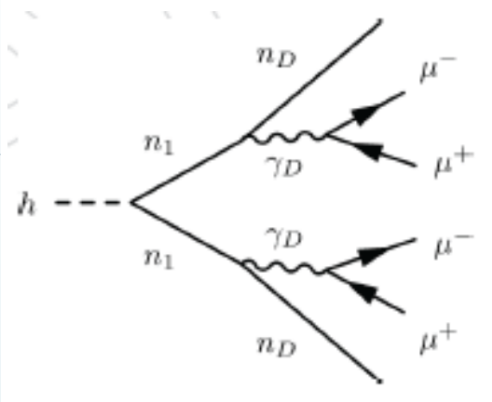
Run-1 ATLAS combined lepton-jet results



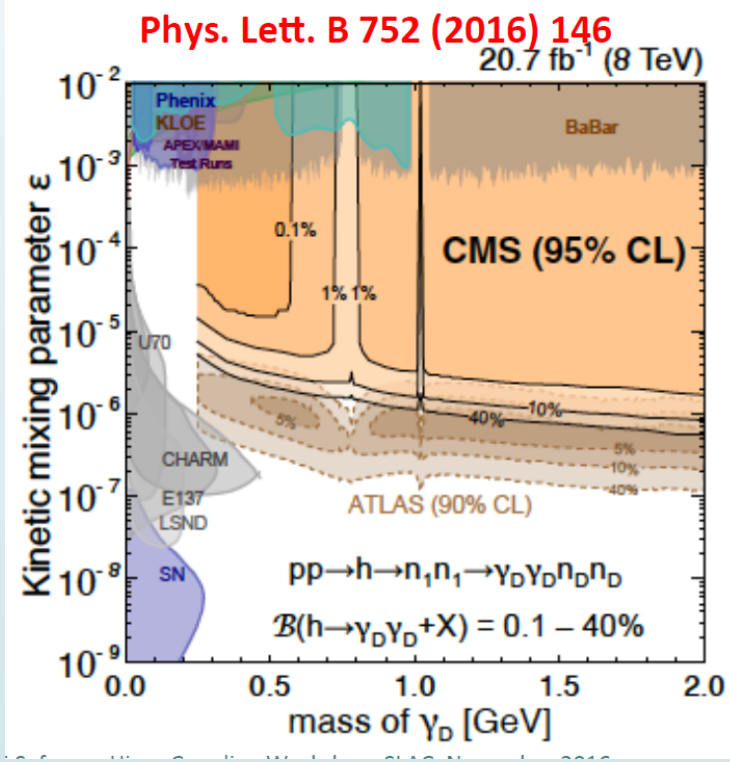


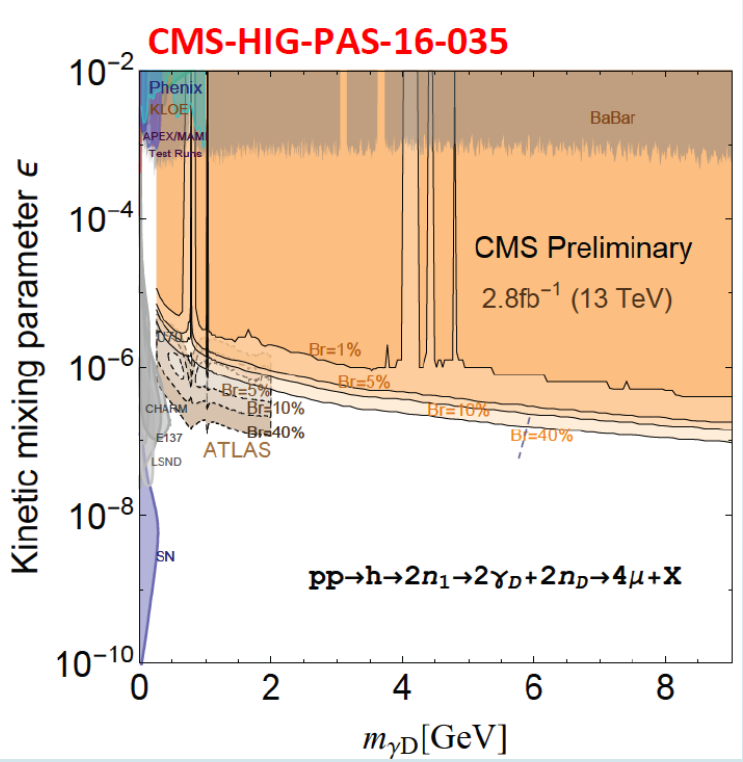
NB the ε vs $m_{\gamma d}$ results from both prompt and displaced LJs is model dependent (FRVZ)

CMS Lepton Jets – Higgs Portal



Search for 4 muons in $\eta < 2.4$
In topology with two pairs of closely spaced muons



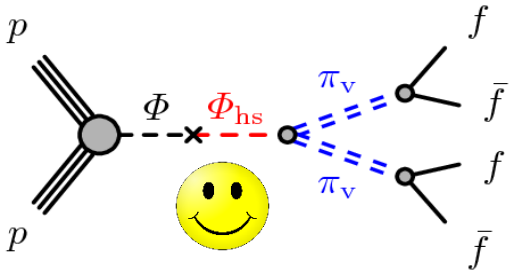


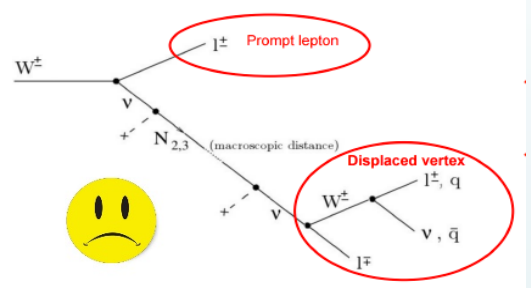
Run-2 displaced analysis – can we do better

- Run 1 displaced decay searches either

  (I) Required two displaced object per event

  - Works only for LLPs that are produced in pairs



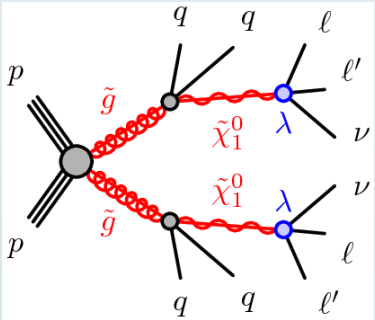


  - reduced lifetime sensitivity - scales like $1/(c\tau)^2$

  (II) Required one displaced vertex plus an associated high energy object (m, MET..)

  - OK for SUSY models but not for many other BSM models

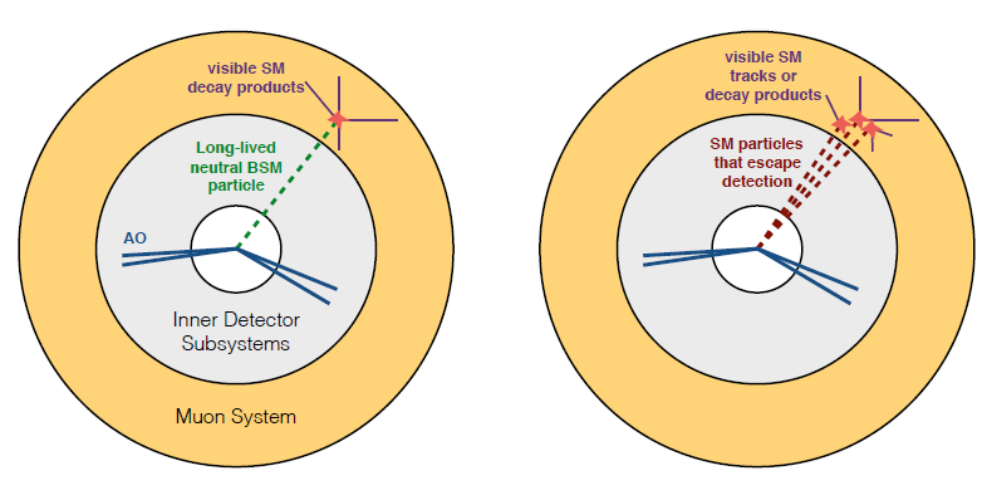
e. g. RPV with long-lived neutralino



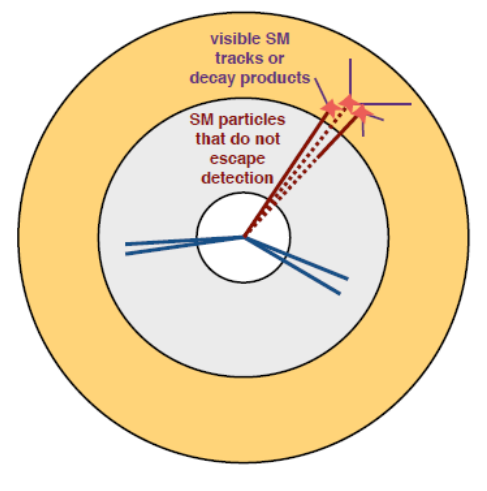
Single vertex analyses – New approach

A.Cocaro, D. Curtin, HL, H. Russell, J. Shelton, arXiv:1605.02742

- No SM displaced objects, but plenty of jet production
  - Main source of background for neutral LLP displaced JETS searches from jets that fake a displaced object in HCal or punch through to MS and reconstruct as a displaced vertex that looks exactly like expected signal
    - Requiring 2 reconstructed displaced vertices in MS (Run-1) kills this background
- **MS displaced decay in MS - trigger selection**



MS RoI cluster trigger selects cluster of isolated MS activity



Orthogonal MS RoI non-isolated cluster trigger selects events rejected by the RoI cluster trigger

- **NB life-time reach of 2 vertex analysis scales like $1/(c\tau)^2$ while for single vertex scales like $1/c\tau$**

ABCD Method

- Can use ABCD method to estimate background in signal region
- If axis are independent and no correlations, then AD = BC
- Rescaling function $r_{noiso \rightarrow iso} = N_C/N_D$

non-iso	B	D
iso	A	C
	SR_Y	CR_Y

$\longrightarrow Y$

Choice of Y depends on search goals –tailored To a specific model or class of models

What about ultra-long lived particles

ULLPs

Near the Big Bang Nucleosyntheses limit $\lesssim 10^7$ m – 10^8 m

What about ultra-long lived particles

ULLPs

Near the Big Bang Nucleosyntheses limit $\lesssim 10^7$ m – 10^8 m

Existing detectors limited by size and very large SM QCD backgrounds

What about ultra-long life times

Higgs boson a particularly good place to search for exotic, neutral long-lived particles (scalar portal)

Higgs production at HL-LHC

- HL-LHC will produce order of $N_h = 1.5 \times 10^8$ Higgs Bosons
  - Observed decays: $N_{obs} \sim N_h \cdot Br(h \to ULLP \to SM) \cdot \varepsilon_{geom} \cdot L/b c\tau$
    - L-size of detector along ULLP direction of travel
    - ε_{geom} geometrical acceptance
    - b(Lorentz boost)$\sim m_h / n m_X \leq 3$ for Higgs boson decaying to n=2 $m_X \geq 20$ GeV

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

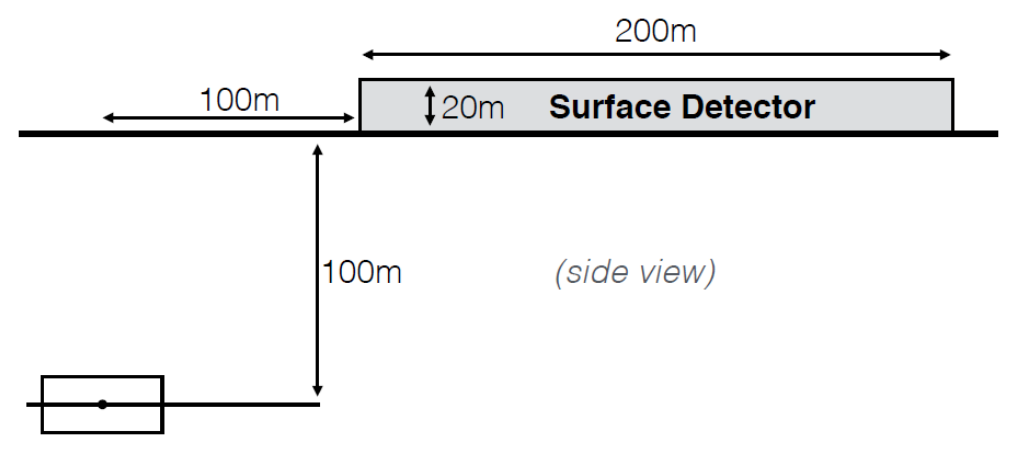
- Assuming b ≤ 3 ys 100% to SM particles conclude that a detector with linear size of 20 m in direction of ULLP travel and about 10 m decay length can detect ULLPs near BBN limit

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

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

MATHUSLA

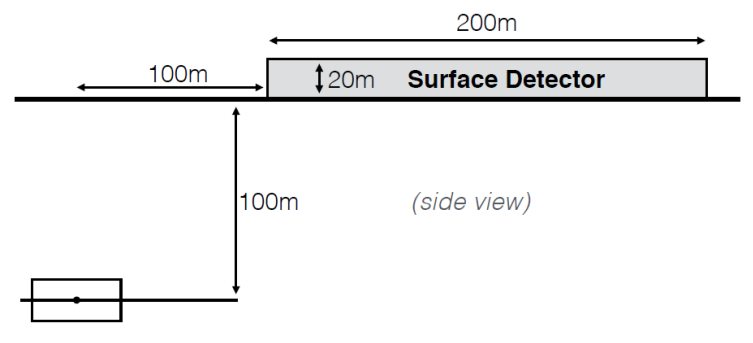
Could be located above either ATLAS or CMS

Surface space available near both IPs
Equivalent to two soccer pitches

MATHUSLA

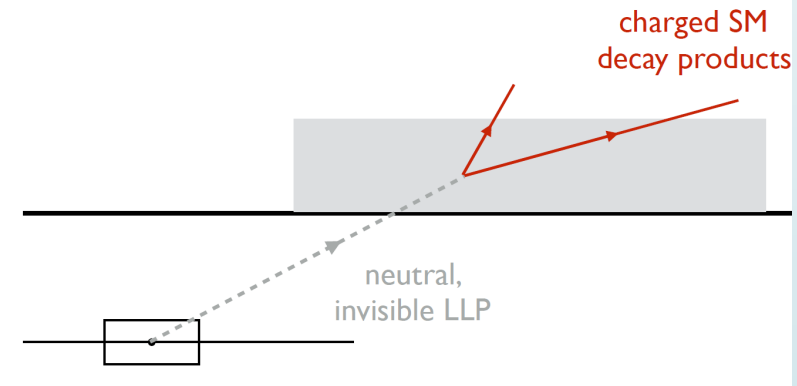
J-P Chou, D. Curtin, HL
arXiv 1606.06298

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



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

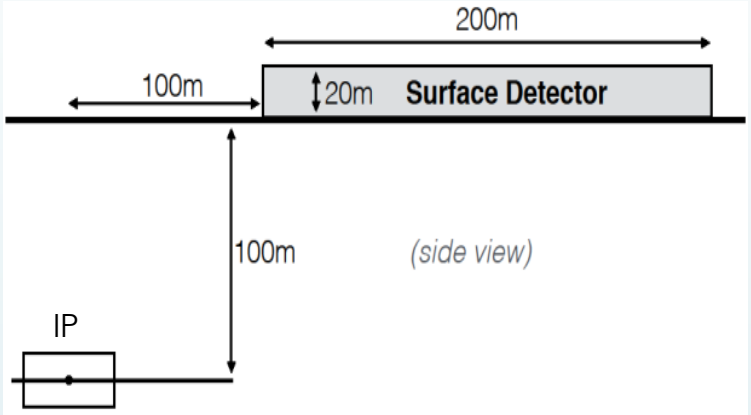
Air filled detector located on the surface above and somewhat displaced from ATLAS or CMS interaction points



Goal to search for long-lived particles that have no SM interactions and decay with a finite life to SM particles

MATHUSLA

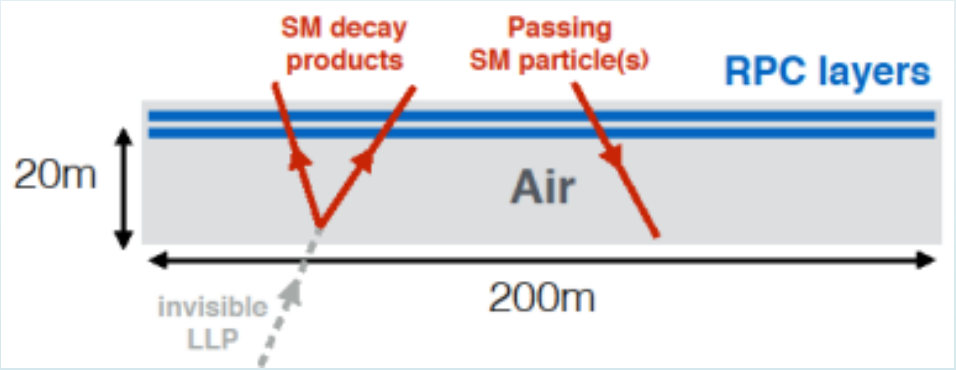
- Placing MATHUSLA on the surface above ATLAS or CMS provides shielding from pp interaction particles but requires a very large detector



LHC detector

Approximately 5% geometrical coverage

- To establish a displaced decays requires robust tracking and good cosmic background rejection
  - RPCs planes can be attractive choice for tracking and vertex reconstruction
  - Scintillator planes for redundant background rejection - timing

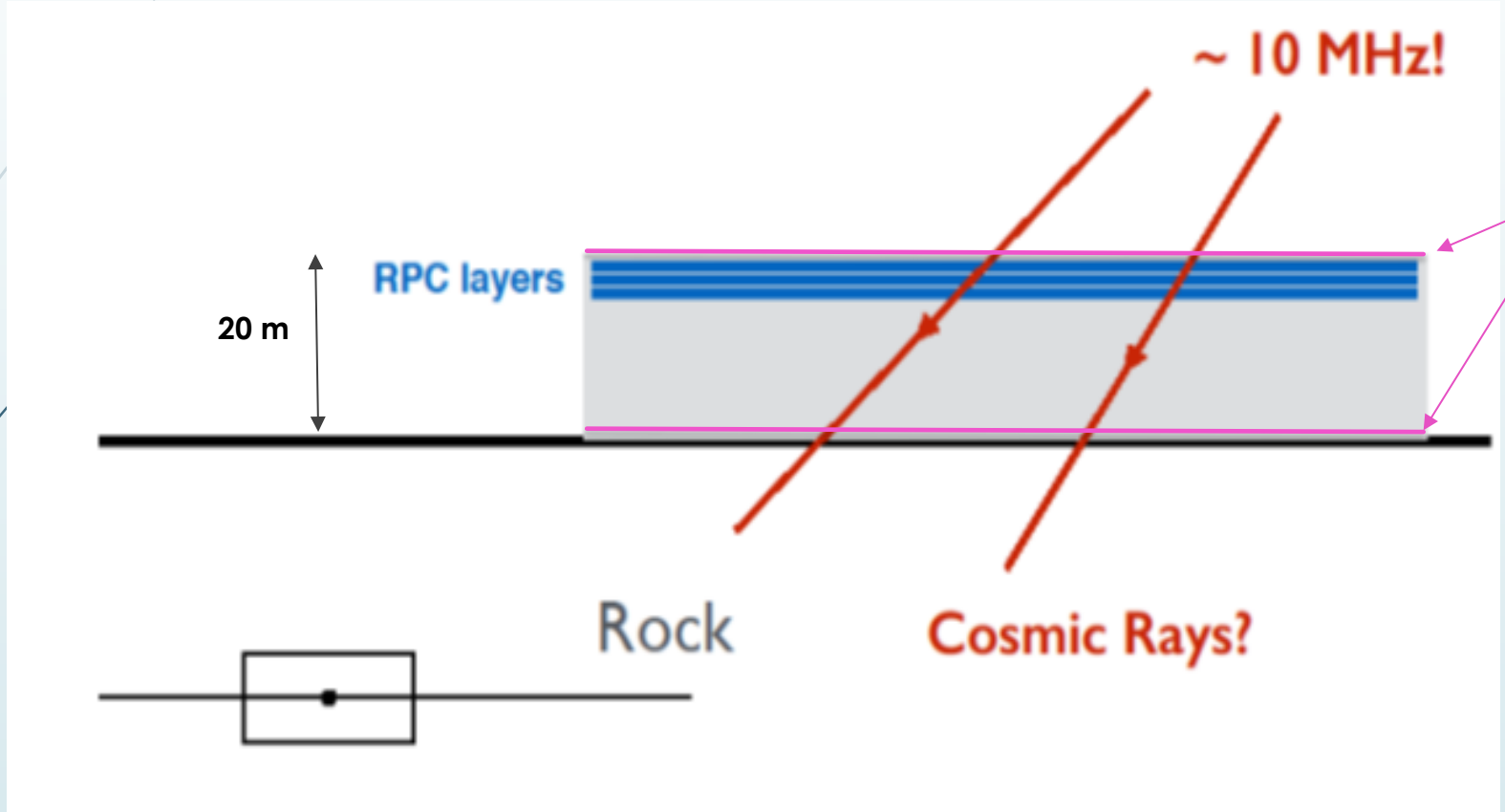


MATHUSLA

- **MATHUSLA Detector – Massive Timing Hodoscope for Ultra Stable neutral pArticles** (arXiv:1606.06298v1 - J-P. Chou, D. Curtain, HL)
  - Dedicated detector sensitive to long-lived 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
- HL-LHC will produce order of N_h= 1.5 x 10^8 Higgs Bosons
  - Observed decays: $N_{obs} \sim N_h \cdot Br(h \to ULLP \to SM) \cdot \varepsilon_{geom} \cdot L/b c\tau$
    - L-size of detector along ULLP direction of travel
    - ε_{geom} geometrical acceptance
    - $b(Lorentz\ boost) \sim m_h / n m_X \leq 3$ 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 $c\tau \sim 10^7$ m requires a 20 meter detector along direction of travel of ULLP and about 10% geometrical acceptance

MATHUSLA - backgrounds

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



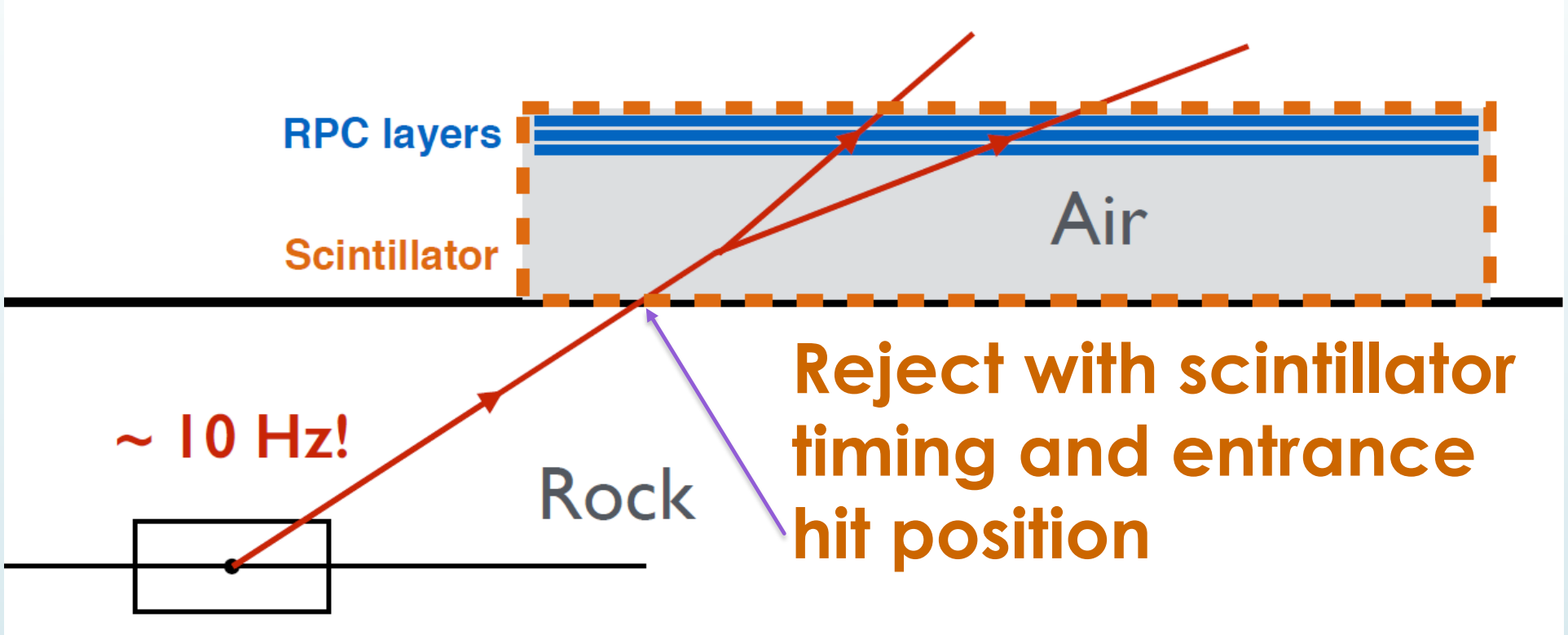
Scintillators 1.5 ns timing resolution

- in 20 m have $\Delta t \approx 7$ ns top to bottom

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

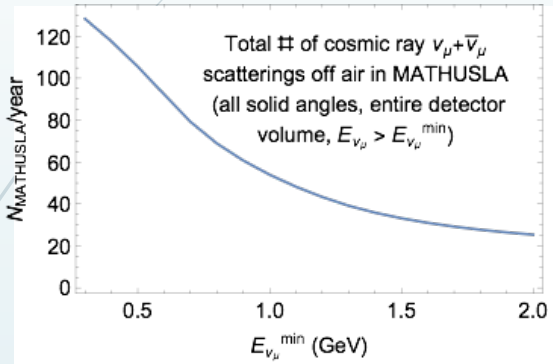
MATHUSLA - backgrounds

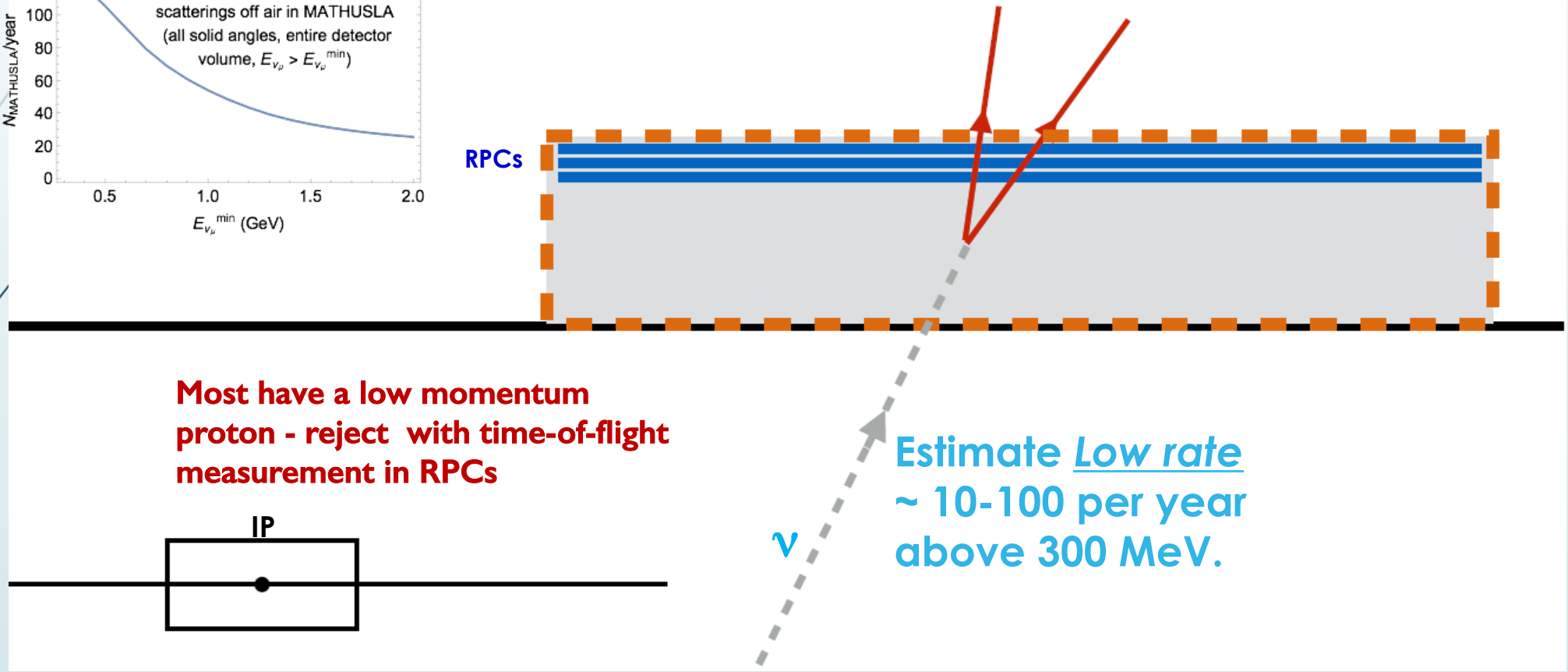
- Upward going muons from LHC with inelastic interaction



MATHUSLA - backgrounds

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

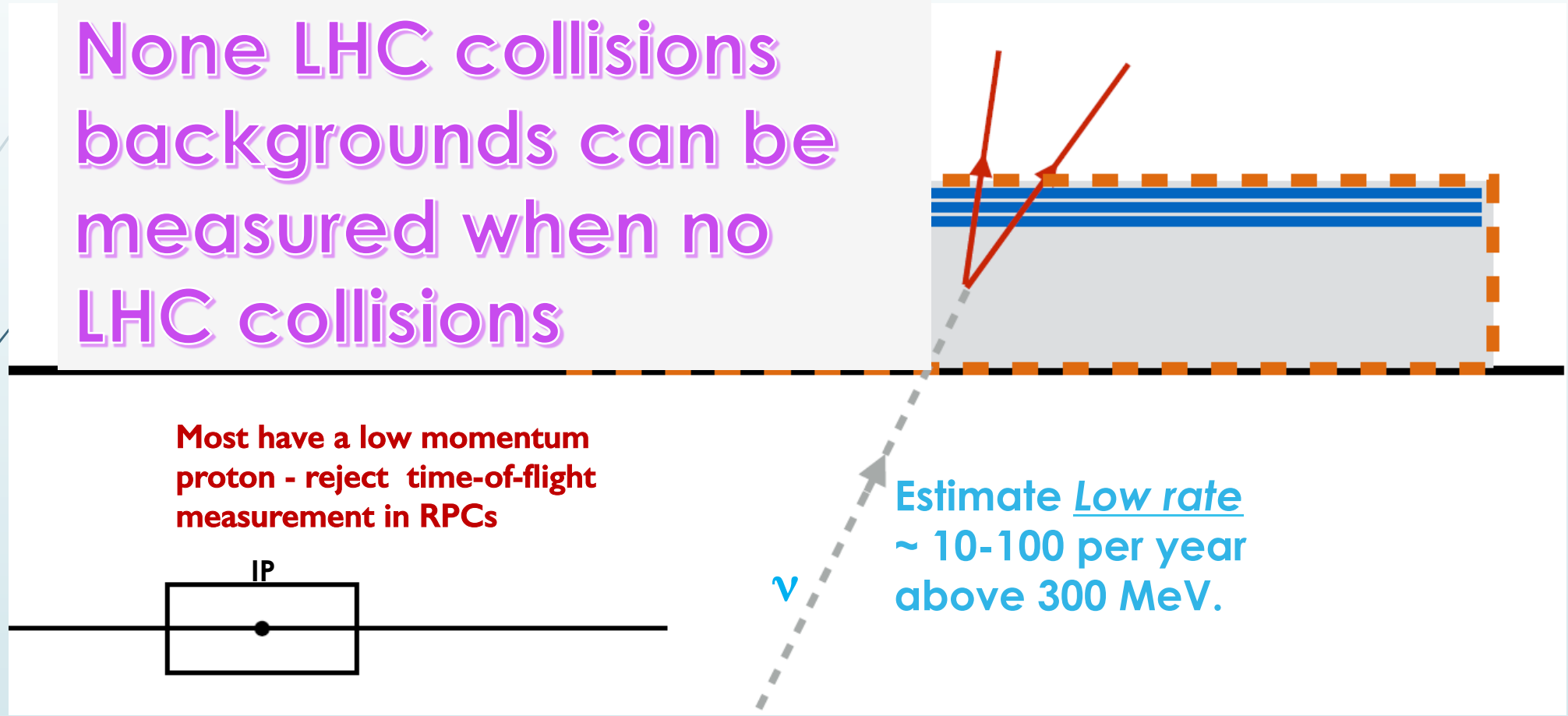




MATHUSLA - backgrounds

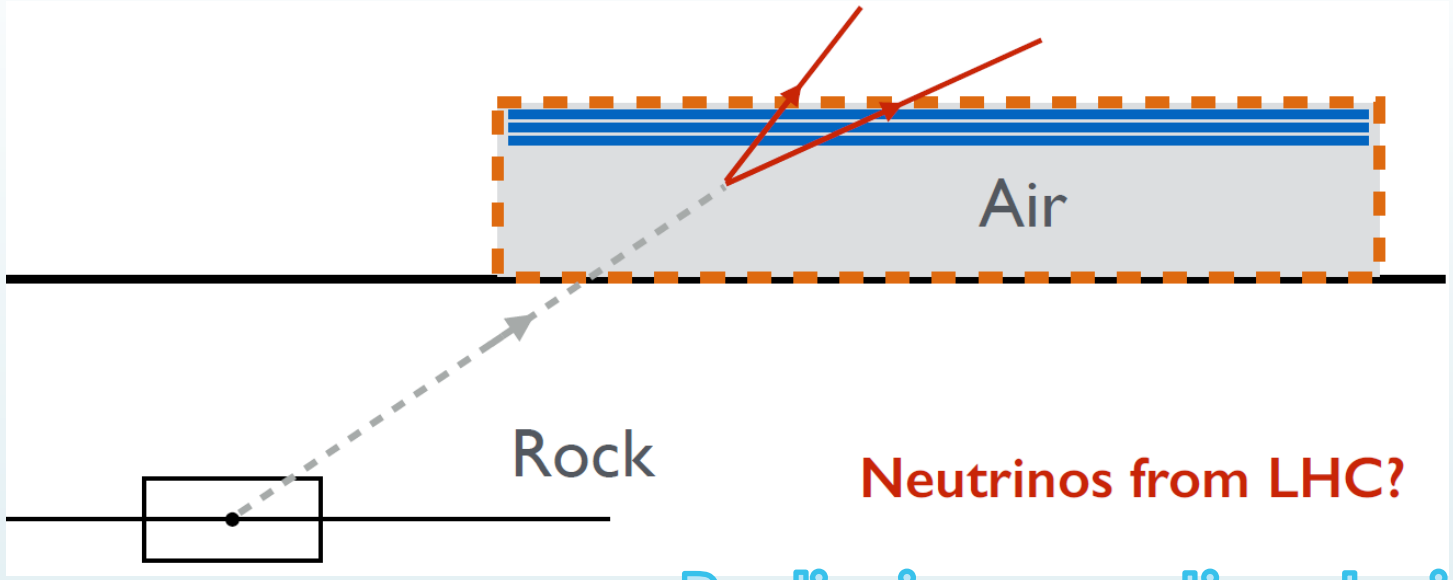
- Cosmic neutrinos traveling upwards that have inelastic interactions in the decay volume

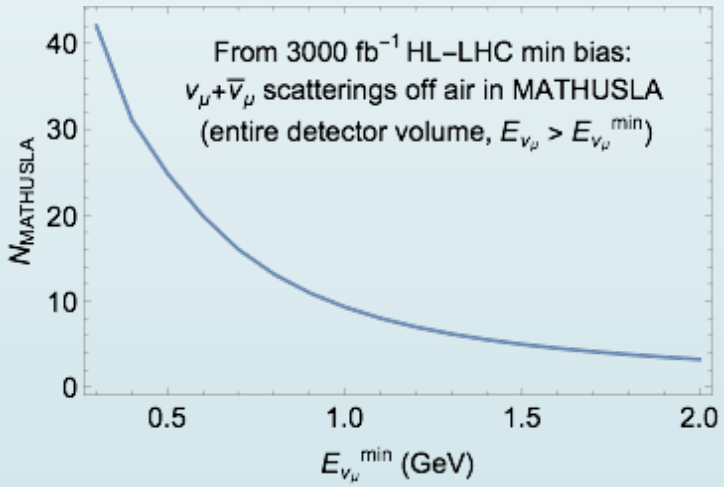
None LHC collisions backgrounds can be measured when no LHC collisions



MATHUSLA - backgrounds

- Neutrinos from LHC interactions (subdominant background)





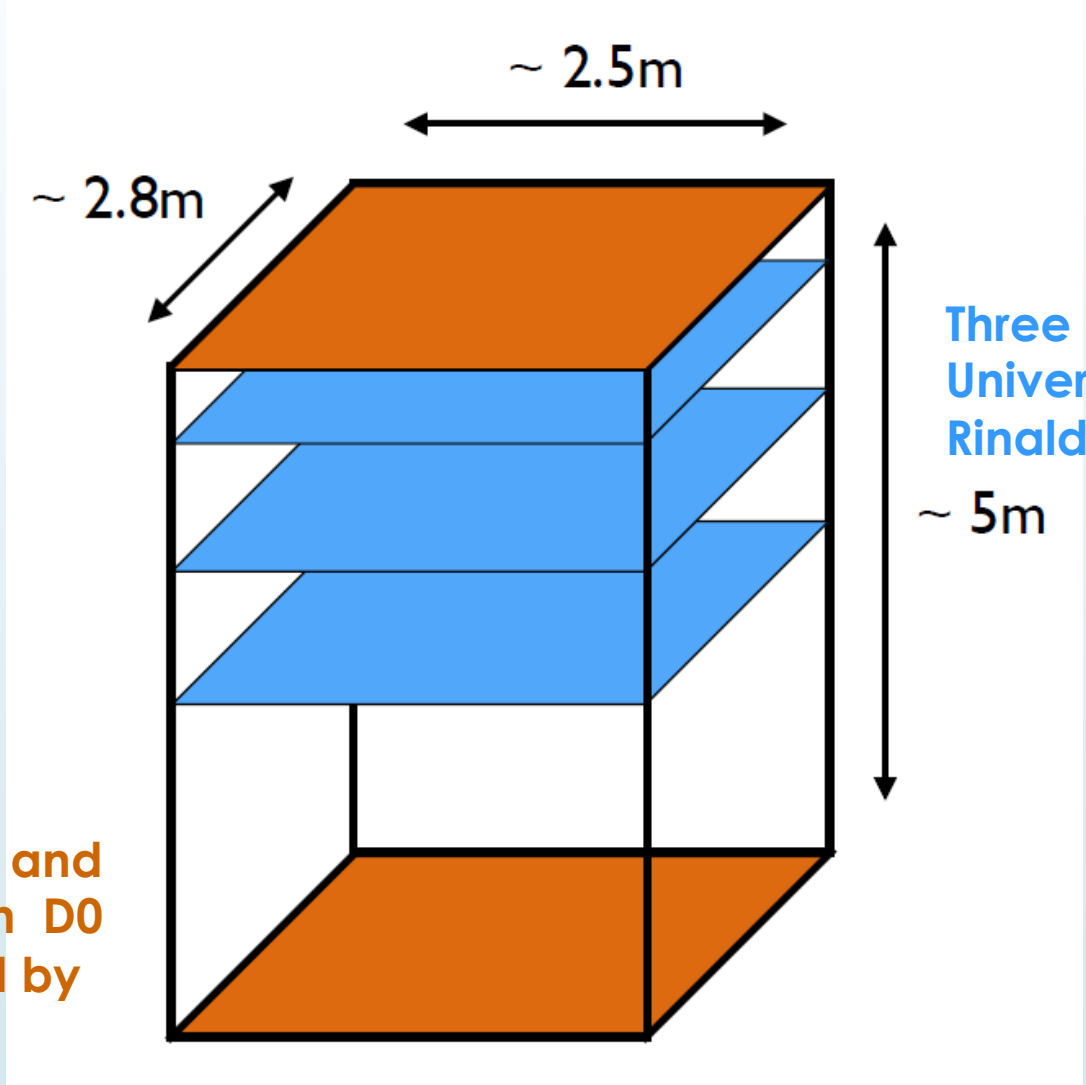
Preliminary estimate is that MATHUSLA should observe a few events during HL-LHC data taking period – needs more work, but appears to be subdominant

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 Arturo & colleagues
  - Simulation needs data anchor with LHC colliding protons and also when there are no pp collisions in LHC – beam OFF
  - To anchor our MC simulations need data

TEST Module

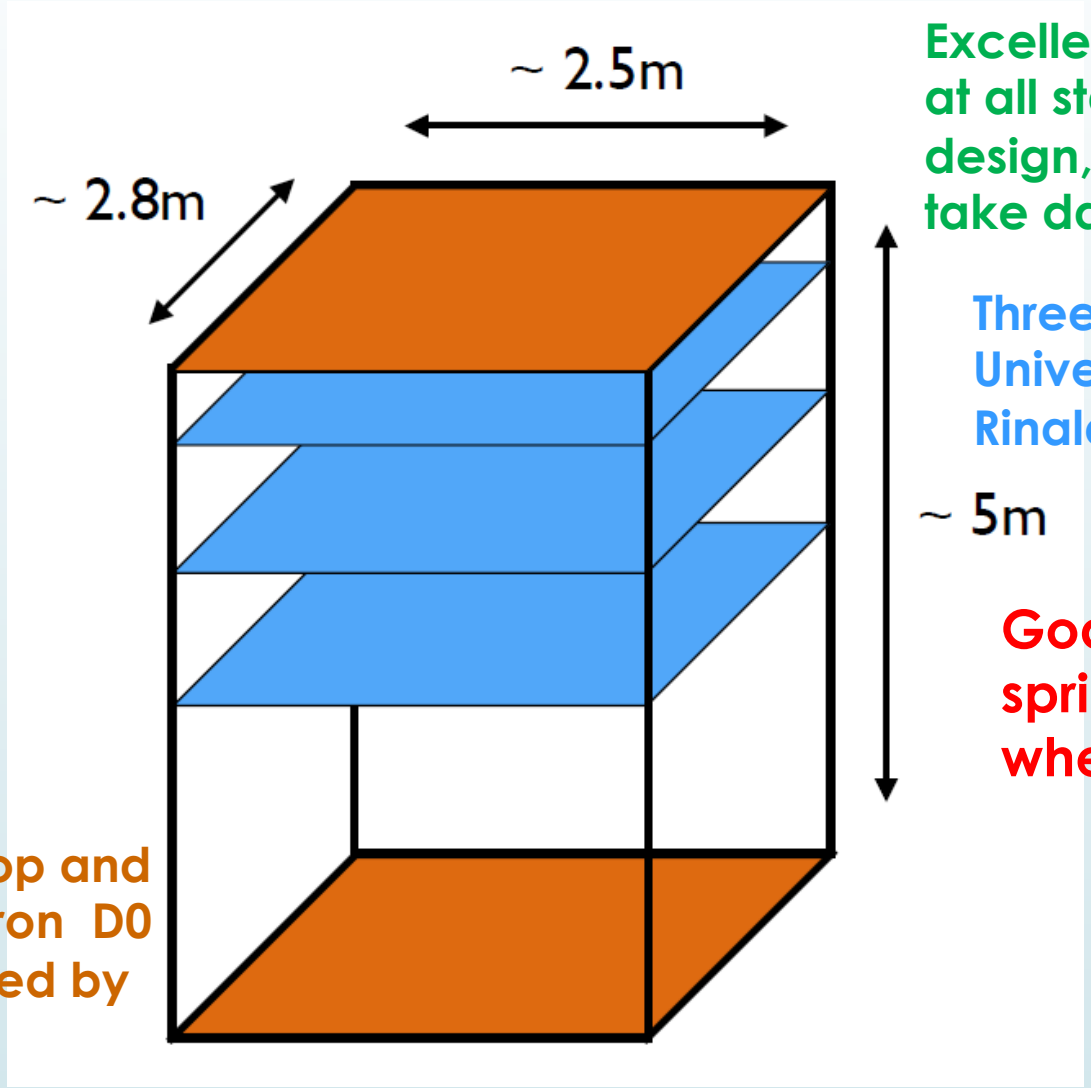
MATHUSULA Test Module



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 in late spring 2017 and be ready when pp data taking begins

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

MATHUSLA Theory White Paper

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

Editors:
David Curtin[1], *Matthew McCullough*[2], *Patrick Meade*[3], *Michele Papucci*[4], *Jessie Shelton*[5]

Goal is to have comprehensive document finished by early 2017

Contributions from broad spectrum of theory community

Current Test Module Participants

UNIVERSITY of WASHINGTON

Henry Lubatti
Gordon Watts
Cristiano Alpigiani
Audrey Kvam

RUTGERS

John Paul Chou
Amit Lath
Steffie Thayil

SLAC NATIONAL ACCELERATOR LABORATORY

Charles Young
Robert Mina

Fermilab

Sunanda Banerjee

Università di Roma Tor Vergata

Rinaldo Santonico
Roberto Cardarelli

UNIVERSITY OF MARYLAND 1856

David Curtin
Theory input

Future – Life-time Frontier

Go
where no one has
gone before HL-LHC

13-14 TeV, > 100s fb^{-1}