# The Lifetime Frontier

Henry Lubatti

University of Washington, Seattle

LHCP 2017

Shanghai, China 15 – 20 May 2017

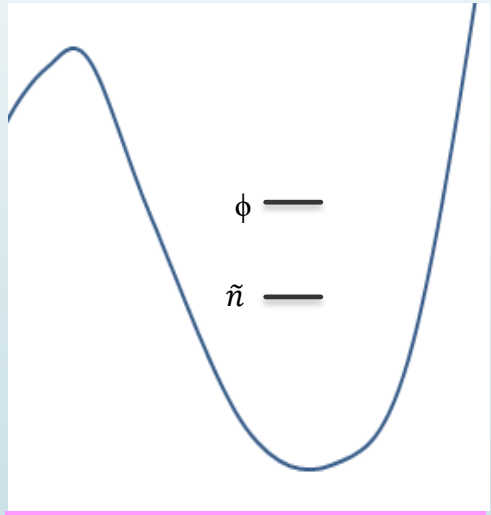
# Hidden Sectors



- The Standard Model (SM) is a great success, **but many open questions…**
  - Dark matter, particle asymmetry (Baryogenesis), hierarchy problem (naturalness)
  - Many of the BSM models proposed to address these phenomena contain long-lived particles (LLPs) with macroscopic decay lengths that are limited only by Big Bang Nucleosynthesis - $\mathcal{O}(10^7)$ meters.
  - LLPs occur naturally in coupling to a hidden sector via small portal couplings
  - For example, scalar (Higgs) and vector ($\gamma$, Z) portals.

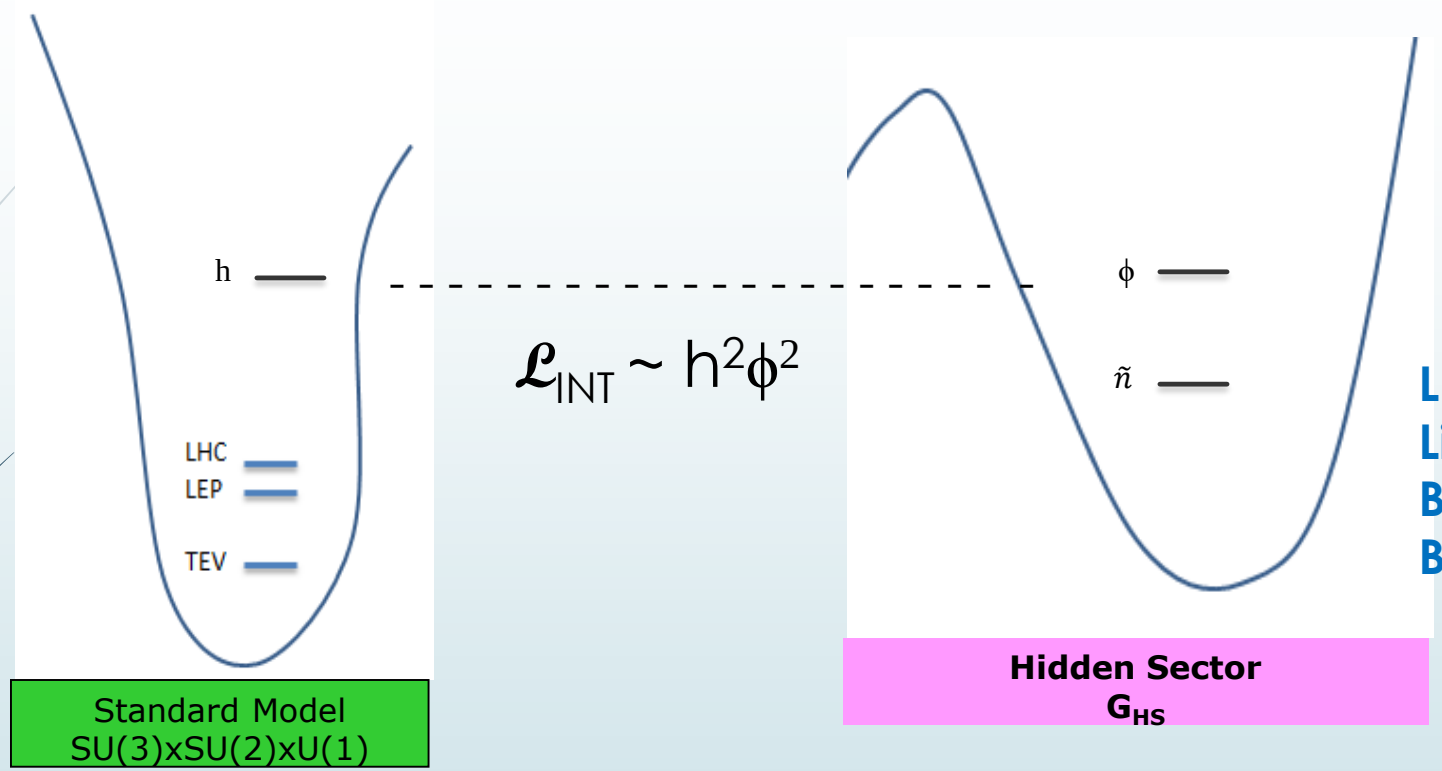
**The notion of a hidden sector with a gauge group $G_{HS}$ and a phenomenology similar to our standard model sector $G_{SM}$ described by Strassler and Zurek** (Phys. Lett. B6512 374-379, 2007)

**Mixing of Higgs with hidden sector (hs) scalar results in hs "Higgs" that decays to pair of hs long-lived scalars that decay to SM fermion pairs – small couplings result in long lifetimes**



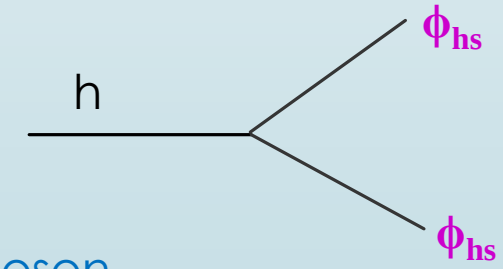

**Hidden Sector $G_{HS}$**

# Coupling to hidden sector




LHC detector searches
Limited by large QCD
Backgrounds – need LHC
Background-free detector

**Higgs decay to hidden sector scalars $\phi_{hs}$**




$\Phi_{hs}$ does not interact with SM

HL-LHC will produce ~$10^8$ Higgs boson

# MATHUSLA

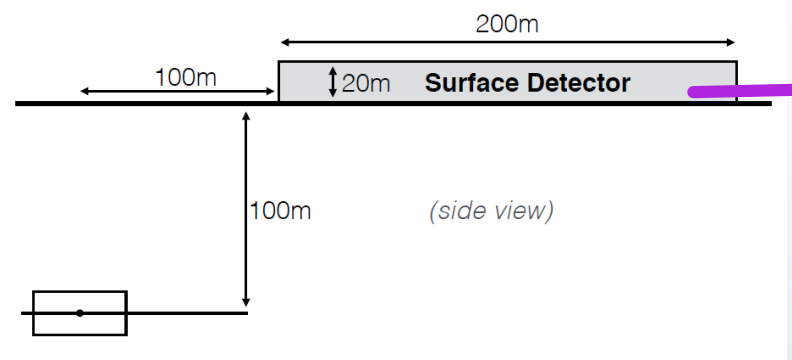


- **MATHUSLA Detector – MAssive Timing Hodoscope for Ultra Stable neutral pArticles** (arXiv:1606.06298v1 - J-P. Chou, D. Curtain, HL)
  - Dedicated detector sensitive to neutral long-lived particles that have lifetimes up to the Big Bang Nucleosynthesis (BBN) limit ($10^7$ – $10^8$ m) for the HL-LHC
  - 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: $N_{obs} \sim N_h \cdot Br(h \rightarrow ULLP \rightarrow SM) \cdot \varepsilon_{geom} \cdot \frac{L}{bc\tau}$
    - L-size of detector along ULLP direction of travel
    - $\varepsilon_{\mathrm{geom}}$ geometrical acceptance
    - $b(Lorentz\ boost) \sim \frac{m_h}{nm_X} \leq 3$ for Higgs boson decaying to $\mathrm{n} = 2\ m_X \geq 20\ GeV$
    - Requires $L \sim (20\ \mathrm{m}) \left(\frac{b}{3}\right) \left(\frac{0.1}{\epsilon_{\mathrm{geometric}}}\right) \frac{0.3}{\mathrm{Br}(h \rightarrow \mathrm{ULLP})}$
  - 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

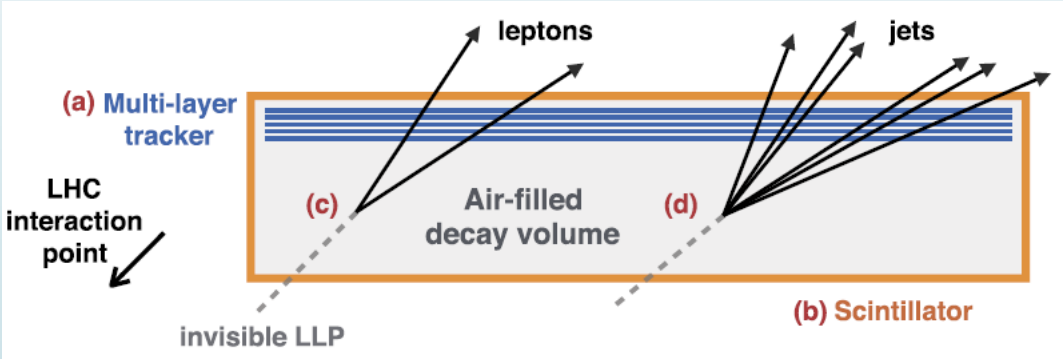
# MATHUSLA

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




- 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

No LHC Background, BUT…

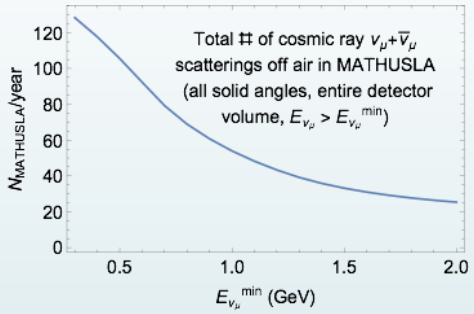
# MATHUSLA - backgrounds

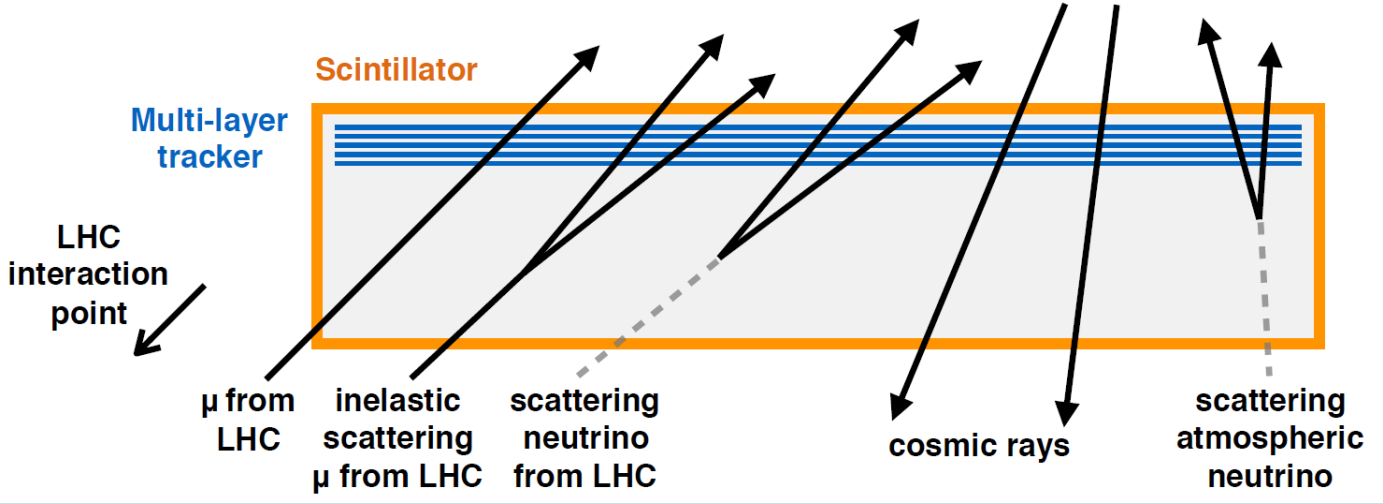


- Cosmic muon rate of about $10^6$ Hz

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

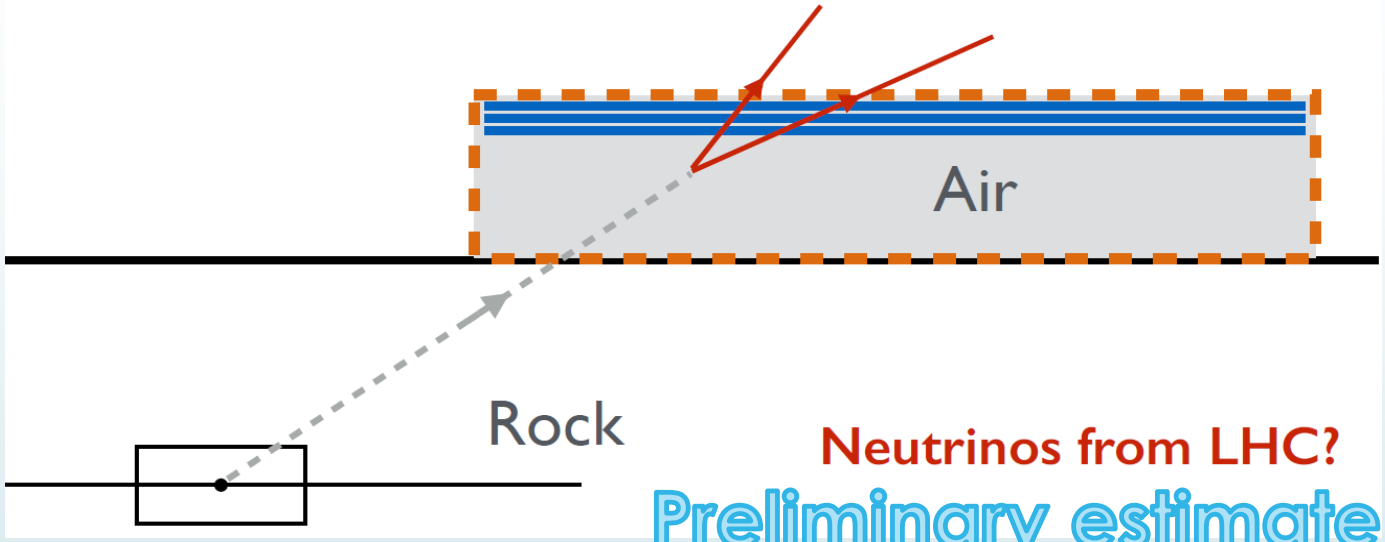


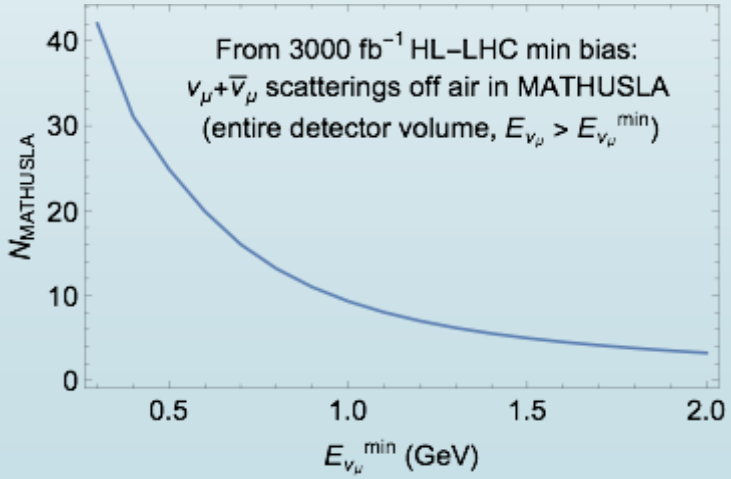



# MATHUSLA - backgrounds



- Neutrinos from LHC interactions (subdominant background)



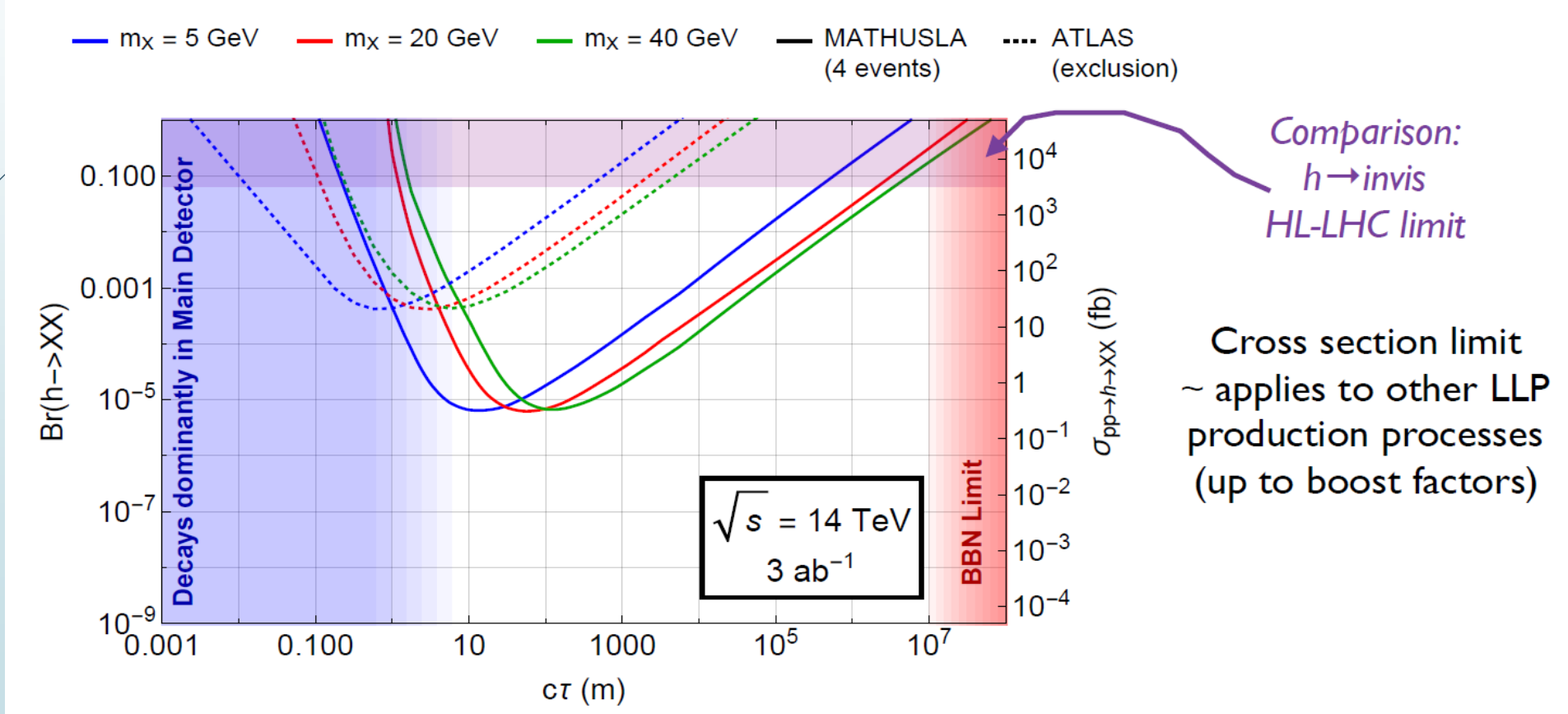




Preliminary estimate is that MATHUSLA should observe a few events during entire HL-LHC data taking period – needs more work, but appears to be subdominant

# 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



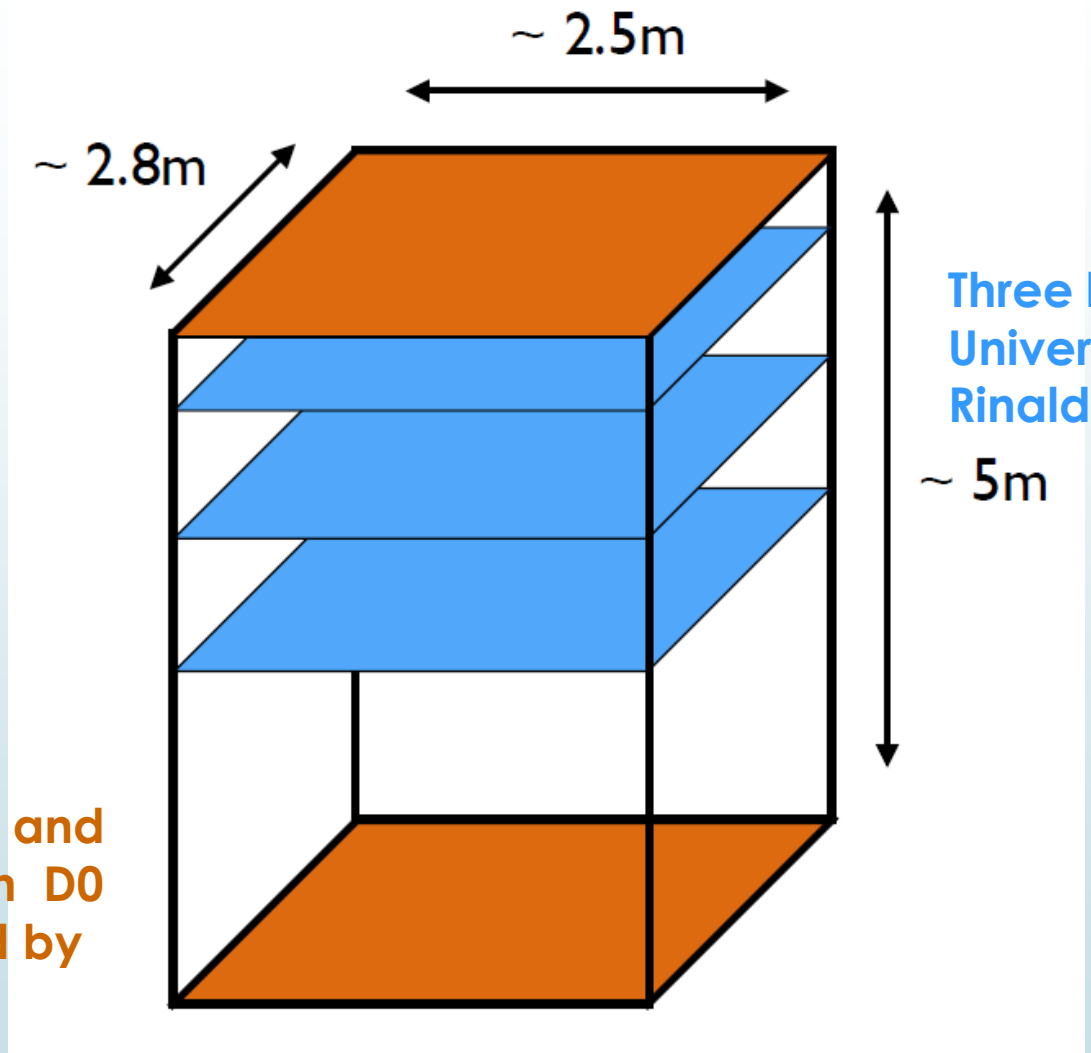
# MATHUSLA – background studies

- 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

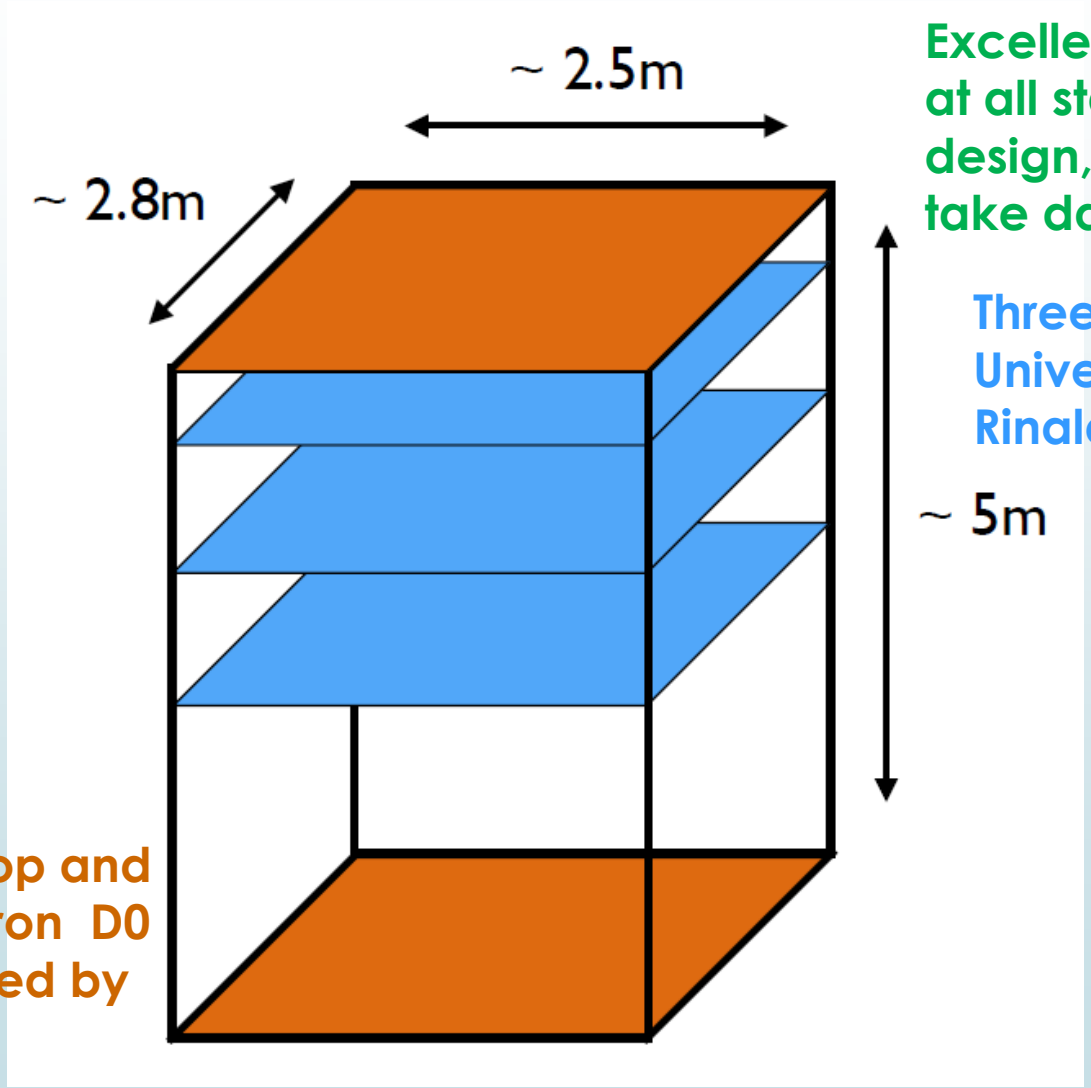





Three layers of RPCs provided by University of Rome, Tor Vergata Rinaldo Santonico and friends

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

# MATHUSLA test team

| Name | Email | Institution |
|---|---|---|
| Giovanni Marsella | giovanni.marsella@cern.ch | INFN Lecce e Universita del Salento |
| Cristiano Alpigiani | Cristiano.Alpigiani@cern.ch | University of Washigton - Seattle |
| Akaxia Danae Cruz | a.cruz@cern.ch | University of Washigton - Seattle |
| Audrey Katherine Kvam | audrey.katherine.kvam@cern.ch | University of Washigton - Seattle |
| Henry Lubatti | lubatti@u.washington.edu | University of Washigton - Seattle |
| Mason Louis Proffitt | mason.louis.proffitt@cern.ch | University of Washigton - Seattle |
| Joseph Rothberg | Joseph.Rothberg@cern.ch | University of Washigton - Seattle |
| Rachel Christine Rosten | rachel.rosten@cern.ch | University of Washigton - Seattle |
| Gordon Watts | gwatts@uw.edu | University of Washigton - Seattle |
| Emma Torró Pastor | emma.torro.pastor@cern.ch | University of Washigton - Seattle |
| Nina Anikeeva | nina.anikeeva@gmail.com | University of Washigton - Seattle |
| | | |
| Sunna Banerjee | Sunanda.Banerjee@cern.ch | Fermi National Accelerator Laboratory |
| | | |
| Yan Benhammou | Yan.Benhammou@cern.ch | Tel Aviv University |
| Meny Ben Moshe | Menyb@post.tau.ac.il | Tel Aviv University |
| Tingting Cao | Tingting.cao@cern.ch | Tel Aviv University |
| Erez Etzion | Erez.Etzion@cern.ch | Tel Aviv University |
| Tamar Garbuz | tgarbuz137@gmail.com | Tel Aviv University |
| Gilad Mizrahi | giladmiz01@gmail.com | Tel Aviv University |
| Yiftah Silver | yiftahsi@gmail.com | Tel Aviv University |
| Abi Soffer | Abner.Soffer@cern.ch | Tel Aviv University |
| | | |
| Dan Levin | dslevin@umich.edu | University of Michigan |
| | | |
| David Curtin | david.r.curtin@gmail.com | University of Maryland |
| Sarah Eno | Sarah.Eno@cern.ch | University of Maryland |

| | | |
|---|---|---|
| Mario Rodriguez Cahuantzi | mario.rodriguez.cahuantzi@cern.ch | Autonomous University of Puebla |
| Martin Hentschinski | martin.hentschinski@gmail.com | Autonomous University of Puebla |
| Mario Ivan Martinez Hernandez | Mario.Martinez.Hernandez@cern.ch | Autonomous University of Puebla |
| Guillermo Tejeda Munoz | Guillermo.Tejeda.Munoz@cern.ch | Autonomous University of Puebla |
| Arturo Fernandez Tellez | Arturo.Fernandez.Tellez@cern.ch | Autonomous University of Puebla |
| Martin Alfonso Subieta Vasquez | martin.alfonso.subieta.vasquez@cern.ch | Autonomous University of Puebla |
| | | |
| John Paul Chou | john.paul.chou@cern.ch | Rutgers, State University of New Jersey |
| Luke Kasper | lukekasper25@gmail.com | Rutgers, State University of New Jersey |
| Amitabh Lath | Amitabh.Lath@cern.ch | Rutgers, State University of New Jersey |
| Steffie Ann Thayil | steffie.ann.thayil@cern.ch | Rutgers, State University of New Jersey |
| | | |
| Charlie Young | young@slac.stanford.edu | SLAC |
| Robert Arthur Mina | robmina@stanford.edu | SLAC |
| | | |
| Paolo Camarri | paolo.camarri@cern.ch | Università di Tor Vergata |
| Roberto Cardarelli | roberto.cardarelli@roma2.infn.it | Università di Tor Vergata |
| Rinaldo Santonico | santonic@roma2.infn.it | Università di Tor Vergata |
| Barbara Liberti | barbara.liberti@roma2.infn.it | Università di Tor Vergata |
| Roberto Iuppa | roberto.iuppa@cern.ch | Università di Tor Vergata |
| Luca Pizzimento | luca.pizzimento@cern.ch | Università di Tor Vergata |
| | | |
| Antonio Policicchio | Antonio.Policicchio@cern.ch | Università della Calabria |
| Marco Schioppa | Marco.Schioppa@cern.ch | Università della Calabria |
| | | |
| Stefano Giagu | Stefano.Giagu@cern.ch | Sapienza Università di Roma |
| Cristiano Sebastian | Cristiano.Sebastiani@cern.ch | Sapienza Università di Roma |

# 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, ...*

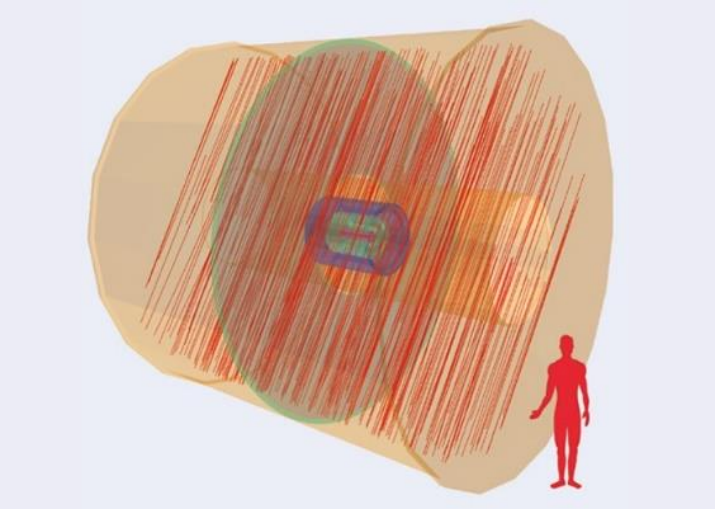
# MATHUSLA and cosmic rays

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



# Milli-charged particles search

- Quantization of charge – **WHY**
- Many searches for mcps (milli-charged particles) with $\varepsilon = Q_{mcp}/e$
- Current limits on mass and charge of fractionally charged particles cover large region of mass and charge of mcps.
  - Indirect constraints from CMB, Big-Bang nucleosynthesis, and Universe over-closure bounds (could avoid with extra degrees of freedom)
  - Constraints from direct searches at accelerators, but significant region of ($M_{mcp}$, $\varepsilon$) space not explored [$10^{-3} < \varepsilon < 10^{-1}$ for $0.1 < M_{mcp} < 100$GeV]
  - The challenge: dE/dx proportional to $Q_{mcp}^2$ ➡ $10^{-6}$ of mip
  - If produced in LHC detector, not enough energy loss to see a track
- A new dedicated detector proposed to cover $10^{-3} < \varepsilon < 10^{-1}$ and $0.1 < M_{mcp} < 100$GeV

A. Haas, C. Hill, E. Izzaguirre, I. Yavin arXiv:1410:6816 , Phys.Lett.B746 117 2015

arXiv:1607.04669v1

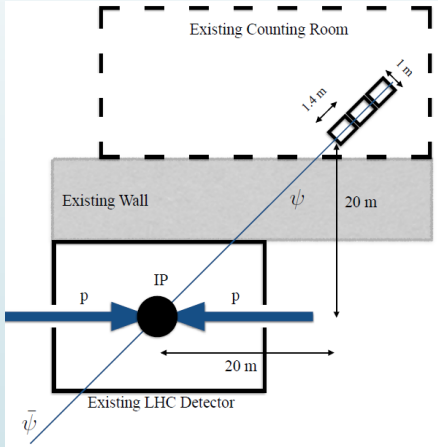
A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]

# milliQan experiment

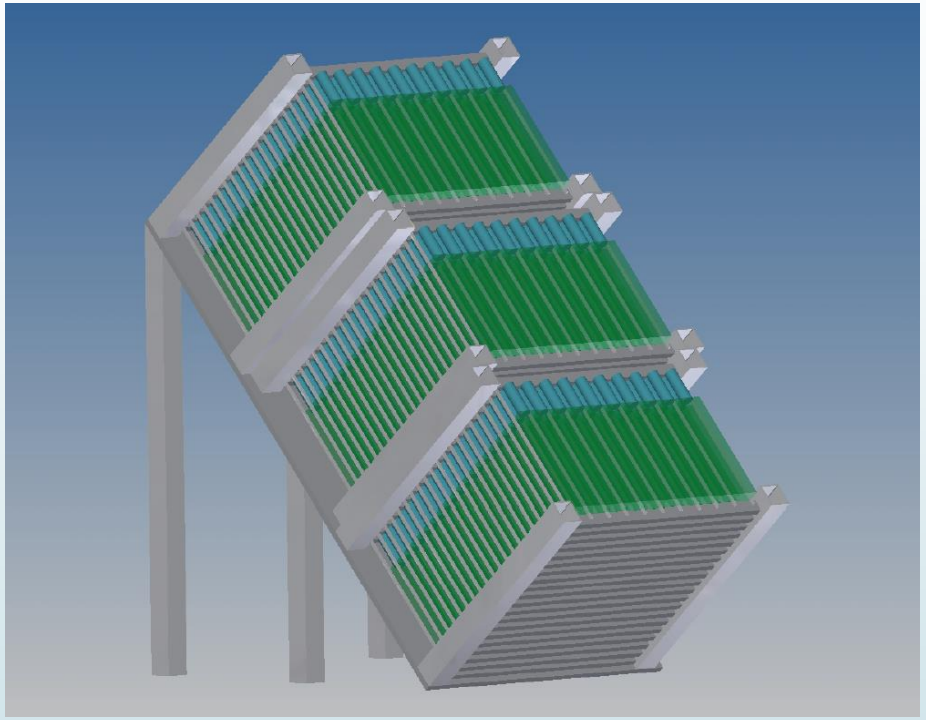
- Phys. Lett. adds new U(1)′ that mixes with SM U(1)
  - charge carriers of U(1)′ have charge proportional to mixing (small) $O(10^{-2} – 10^{-3})$
  - Not detectable in current LHC detectors [$10^{-6} – 10^{-4}$ mip]
- Propose dedicated scintillator detector pointed towards IP and isolated by sufficient material to absorb standard SM particles from pp collisions.
  - Small charge requires sensitivity to 1 photo-electron.
  - Sensitivity scales like 1/(distance to IP)$^2$
  - Team found an almost ideal space at CMS, the PX56 drainage gallery, where they plan to install an approximately 1 m X 1m x 3 m scintillator array that points toward IP
  - PX56 is 33 m from IP (17 m rock absorber) and ~43° inclination
  - Backgrounds from PM dark current pulses and muons believed to be manageable
    - Three fold coincidence in 15 ns window suppresses PMT dark current pulses
      - For 1 kHz dark current rate, 3-fold coincidence in 15 ns window gives O(50) events in 3000 fb$^{-1}$.
    - Muons result in very large number of photons in scintillator – no problem
    - Can measure backgrounds when no collisions in LHC

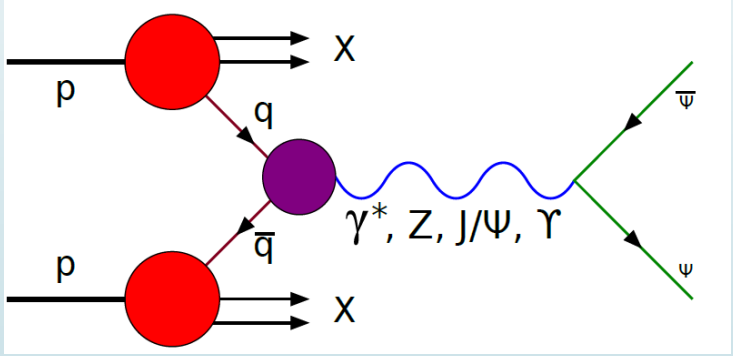
Desired conditions



# milliQan detector

- Detector consists of a 20 by 20 by 3 array 5 $cm^2$ by 80 cm long BC408 plastic scintillator bars – covers 0.01 of solid angle
- Dimensions driven by space available
  - Each bar has a HPK R7725 PMT
- Estimate sensitivity by simulating production of mcps using modified Drell-Yan and propagate particles through CMS and rock



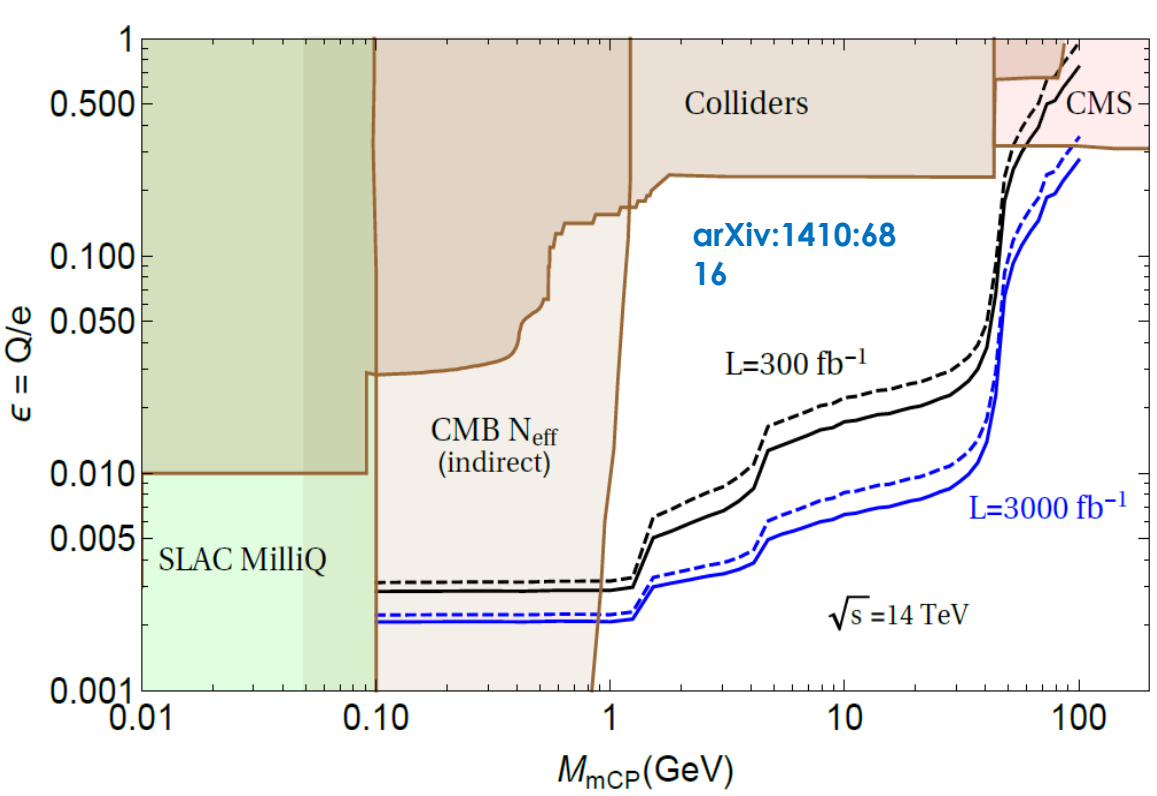



mcp ψ couples to the photon and Z boson with a fractional charge

- Model reflectivity, light attenuation length and scintillator shape
- Simulation inputs include input the PMT quantum efficiency, spectrum of scintillator light time constants, and digitized waveforms.

# milliQan Sensitivity

- The 95% (dashed) and 3σ (solid) exclusion limits for 300 $fb^{-2}$ (black) and 3000 $fb^{-2}$ (blue) from A. Hass, C. Hill, E. Izzaguirre, I. Yavin arXiv:1410:6816, Phys.Lett.B746 117 2015 modified for current detector dimensions.



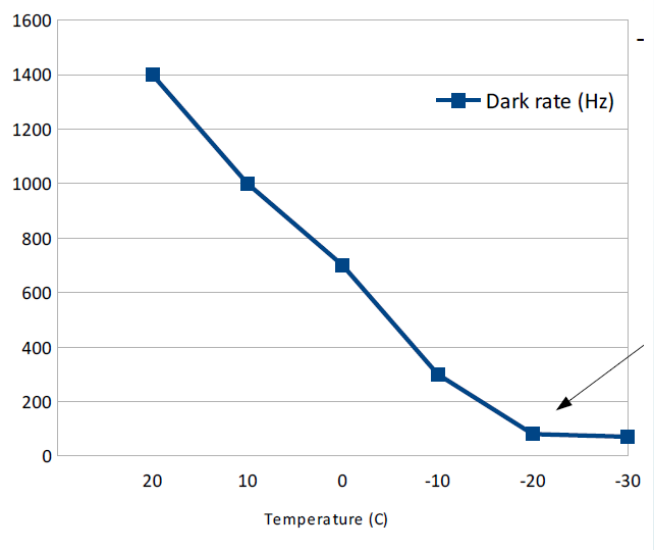

From Cristopher Hill, Long-lived particle workshop CERN 26-4-17 https://indico.cern.ch/event/607314/timetable/

## Going forward

- Install 1/100 detector during TS2 (end of 2017)before end of Run 2 (2018)
- Determine beam-on backgrounds
- Install full scale detector to be ready for Run 3 data taking

# Going forward

- Cooling of PMT to -20° C reduces dark current to 80 Hz
- Sensitivity estimate on previous slide assumed 550 Hz
- Investigating impact on infrastructure and safety issues

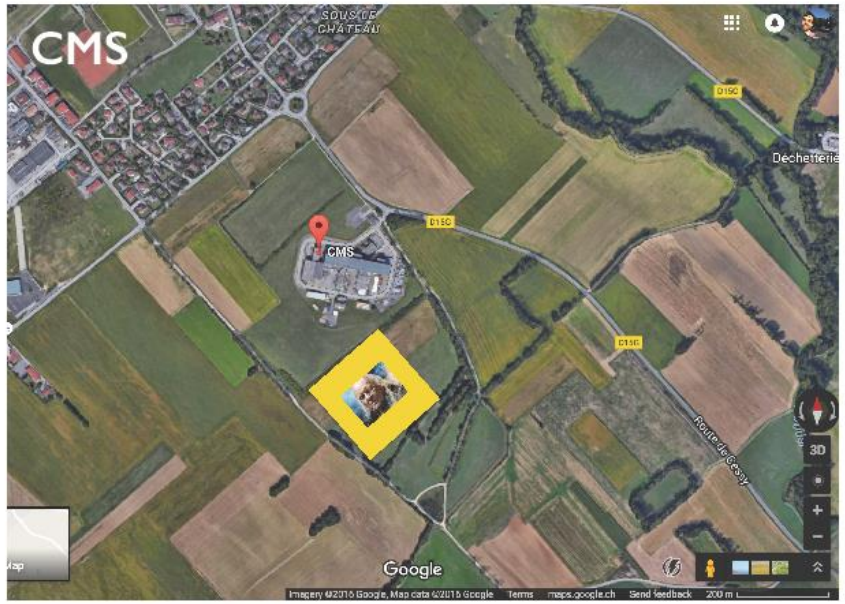



- Plan to test a small prototype during 2018 LHC data taking period
- milliQAN is an independent experiment - CMS asked only to provide power, Ethernet, delivered luminosity and LHC clock.
- **GOAL is to have full detector ready for data taking at beginning of Run 2**

# BACKUP

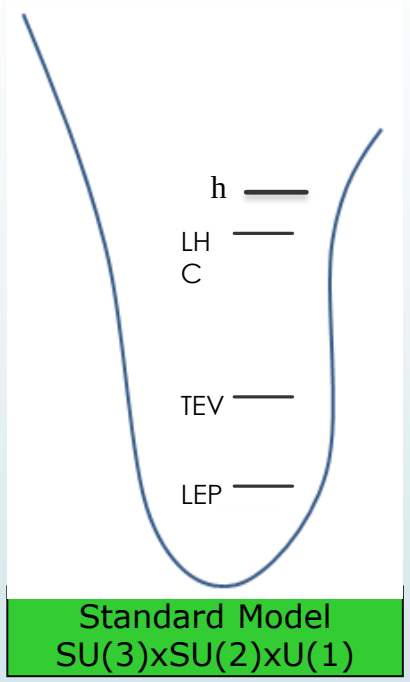
# MATHUSLA


**Could be located above either ATLAS or CMS**



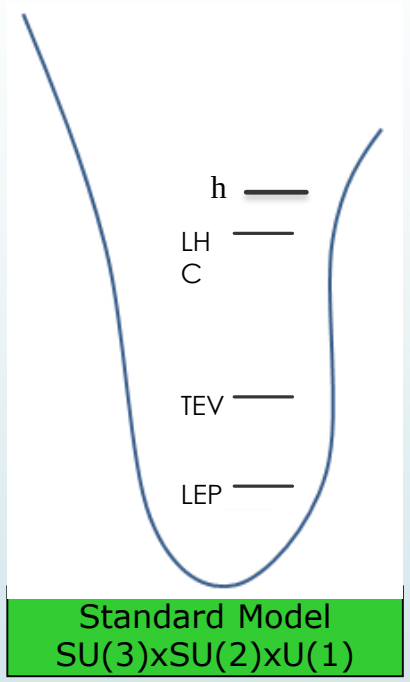

**Surface space available near both IPs**
**Equivalent to two soccer pitches**

# The Standard Model




- 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

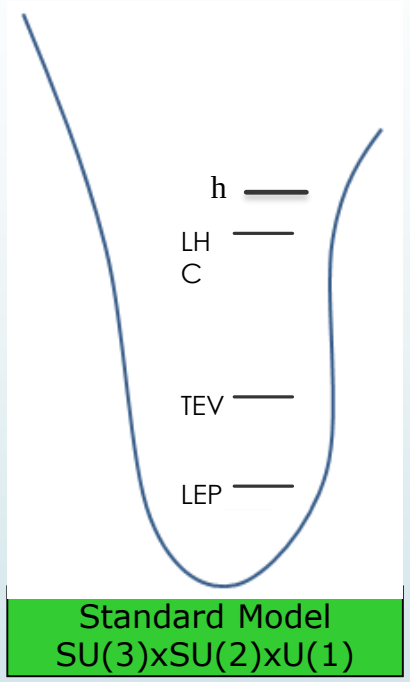
## Hidden SM like sectors?




- 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 SM like sectors?

# The Standard Model




- 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

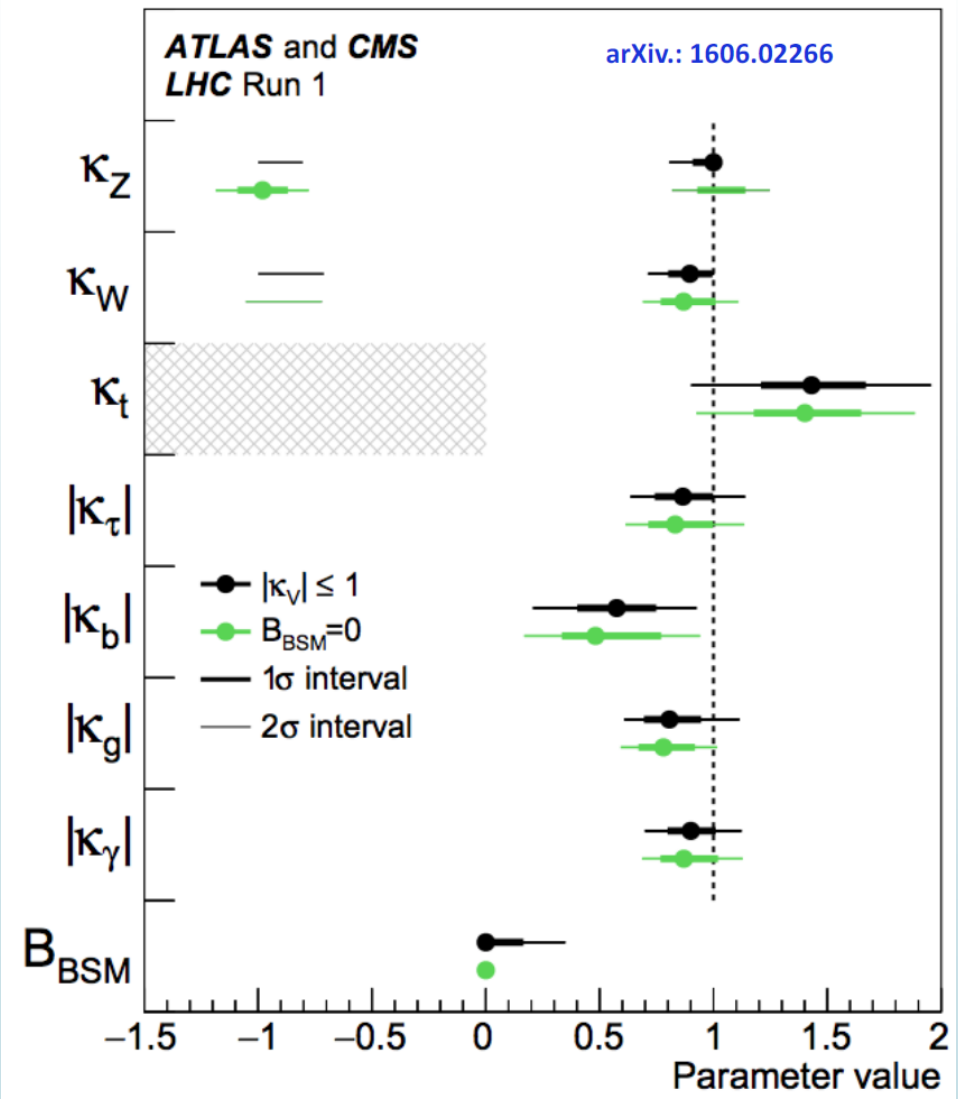
Hidden SM like sectors?

# 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**