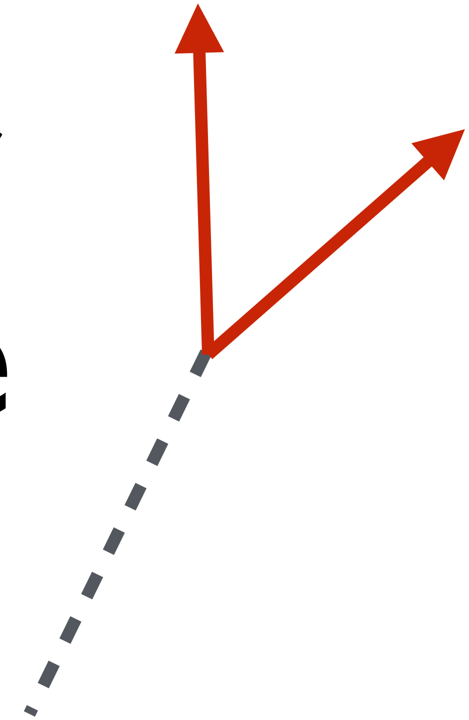
New Proposals for Long-Lived Particle Studies



Workshop on the physics of HL-LHC, and perspectives at HE-LHC
CERN, Geneva

31 October 2017

David Curtin
University of Maryland → University of Toronto

There has to be new physics…

The usual fundamental mysteries (Hierarchy Problem, DM, Baryogenesis, Neutrinos, …) aren't going anywhere.

Higgs discoveries and DM measurements sharpen these questions!

Canonical solutions (SUSY, WIMP DM, …) generally involve IR-minimal models, where the new degree of freedom which solves the mystery has sizable direct coupling to the SM.

This leads to irreducible signatures that haven't shown up so far.

… where is it?

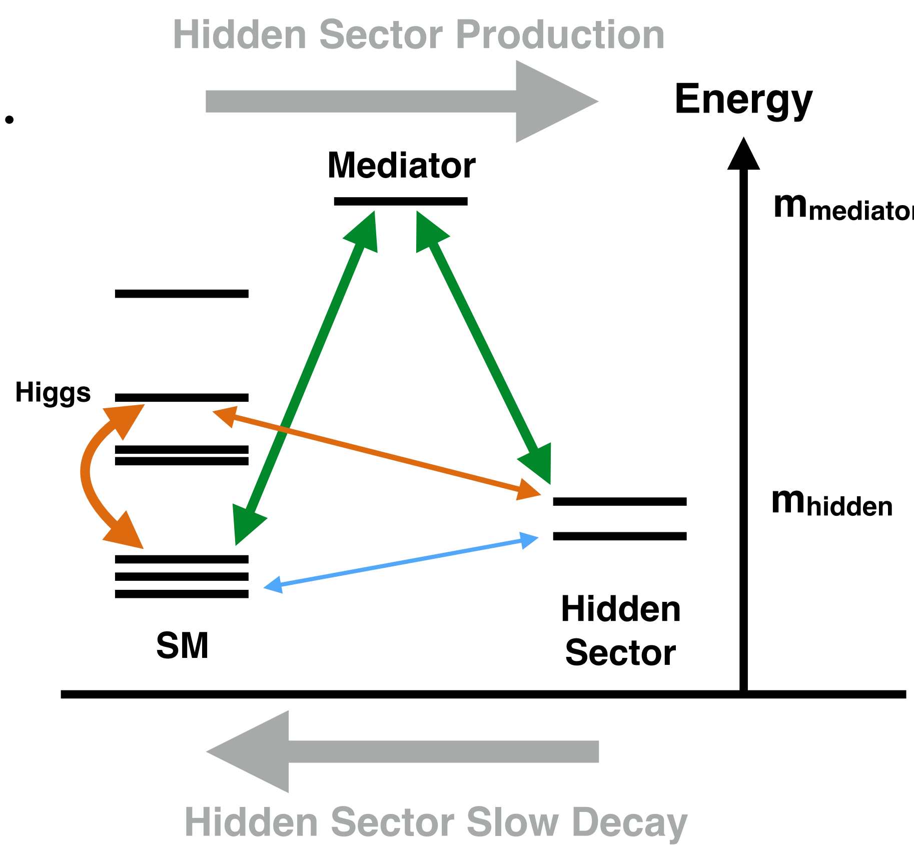
Hidden Sectors

Particles & forces hidden from us due to small coupling, not high mass.

Generically arise due to the grammar of QFT.

Confirmed examples: ν's, DM

Give non-minimal IR spectra from minimal theory input
(e.g. QCD cousins like Hidden Valleys)



Can couple to SM via small portal couplings, e.g.
Heavy Mediators Higgs Portal Photon Portal

Lessons

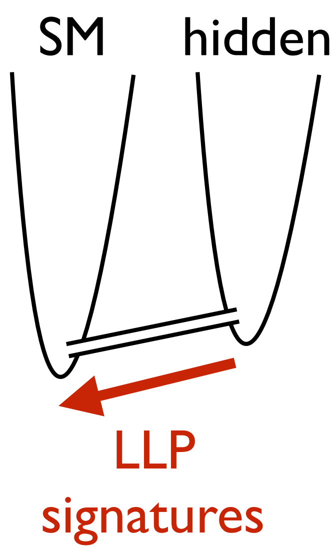
1. Exotic Higgs Decays

LHC can probe tiny exotic branching ratios if decays spectacular.
Sizable Higgs Portal couplings to new physics are generic.

2. Long Lived Particles are generic

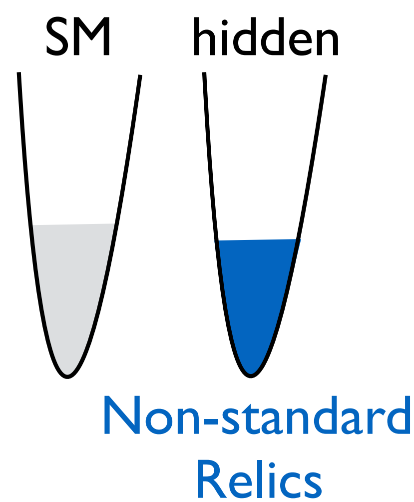
Once produced, Hidden Sector states can only decay back to SM via small portal couplings, generically leading to long lifetimes.
The LLP lifetime is (almost…) a free parameter!

3. Complementarity between Cosmology and Colliders



Models which avoid signatures in one will often show up in the other

(e.g. dark radiation,
DM with structure, etc.)

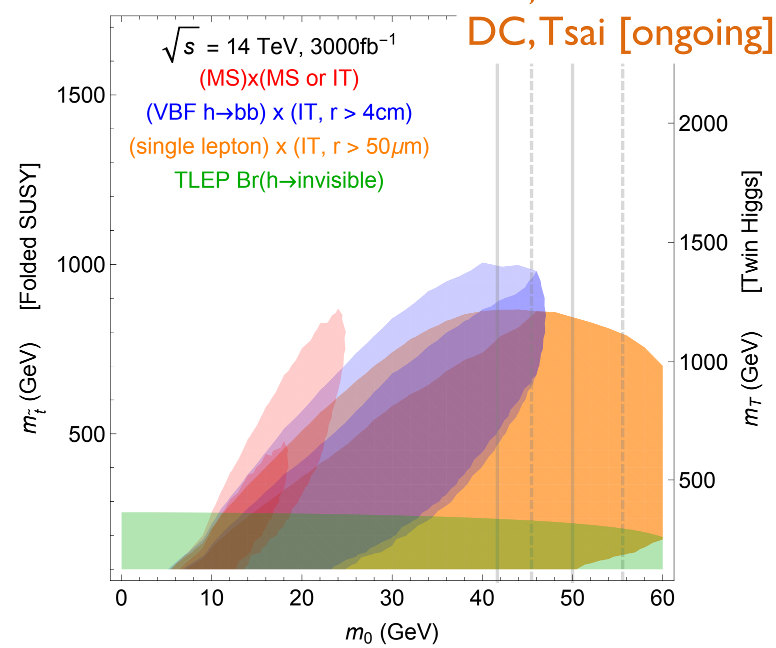


Neutral Naturalness

Hierarchy Problem can be addressed by **uncolored top partners** by introducing a discrete symmetry "twist" into SUSY/CH/… models.

This **eliminates colored production signatures** of e.g. SUSY! Consistent with LHC null results.

DC, Verhaaren 1506.06141
DC, Tsai [ongoing]



Discrete symmetry introduces hidden copy of QCD talking to SM via Higgs Portal!
→ **LLP signatures of Naturalness!!**

New LHC LLP searches would give TeV top partner sensitivity!

Many other exciting signatures (quirky top partner pair prod., indirect detection, non-standard cosmology, non-minimal DM sectors, …)

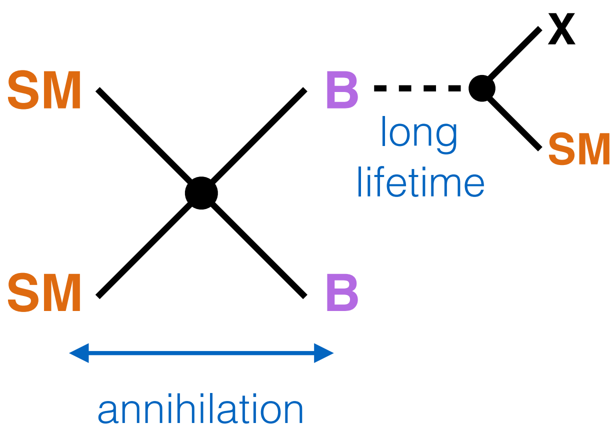
hep-ph/0609152 Burdman, Chacko, Goh, Harnik
hep-ph/0506256 Chacko, Goh, Harnik
1501.05310 Craig, Katz, Strassler, Sundrum

Chacko, Craig, Fox, Harnik 1611.0797
Craig, Koren, Trott 1611.07977
… <much more>

Chacko, DC, Verhaaren, 1512.05782
DC, Tsai, Tsai, Verhaaren [ongoing]
Chacko, DC, Geller, Tsai [ongoing]

e.g. Hall et al, 0911.1120

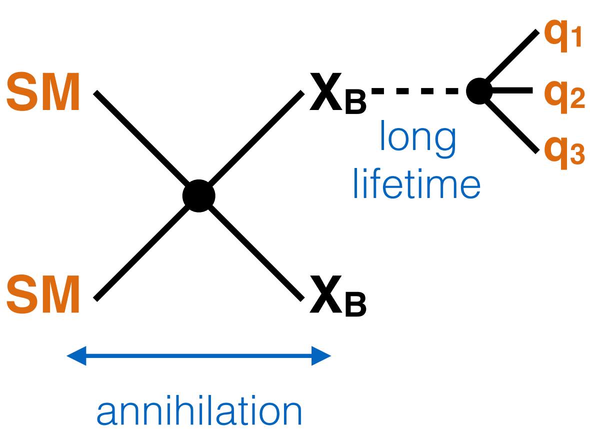
FIMP Dark Matter



The observed DM relic abundance could be set not by the interaction cross section of DM, but by the **lifetime** of a parent particle in thermal equilibrium with the SM: **freeze-in mechanism**!

Cui, Sundrum 1212.2973

WIMP Baryogenesis



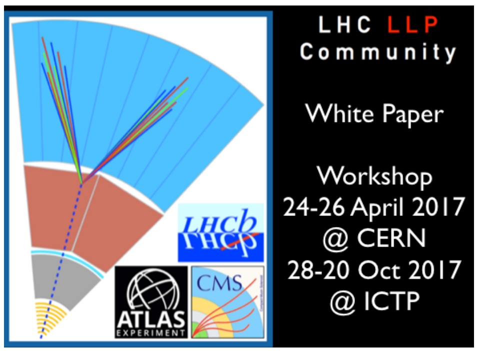
The observed baryon excess could be produced in the decay of a **meta-stable WIMP-like parent particle**.

The “WIMP-miracle” now works to ensure correct baryon number density.

In both cases: make parent at colliders with observable decay length.

Experimental upshot

This **Lifetime Frontier** requires systematic search program at LHC and future **pp**, **ee** and **ep** colliders!
Signature space still largely unexplored!



Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair		SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$		SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$		SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*		Higgs, DM*		Higgs, DM*	
HIG: $h \to X + \text{inv.}$	DM*		DM*		DM*	
ZP: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*		Z', DM*		Z', DM*	
ZP: $Z(Z') \to X + \text{inv.}$	DM		DM		DM	
CC: $W(W') \to \ell X$			RHν*	RHν	RHν*	RHν*

LHC LLP Community
→ LLP simplified model space
→ Search recommendations
(first document out soon!)

Production at colliders is vital to discover LLPs, but the main detectors have **blind spots** due to backgrounds, trigger, geometry:

very short lifetimes < mm
long lifetimes > 100m
low-ish masses (E < ~ 100 GeV)
hadronic/soft decays

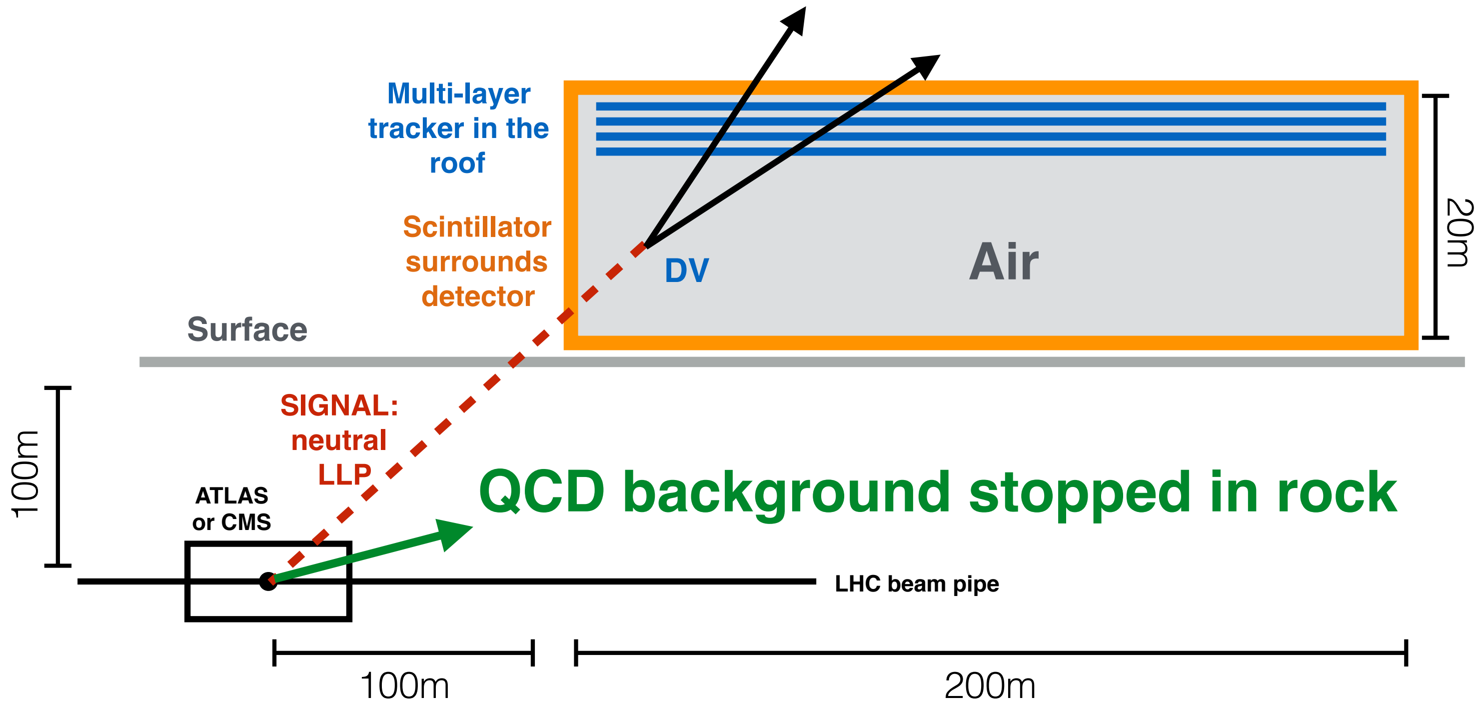
* MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

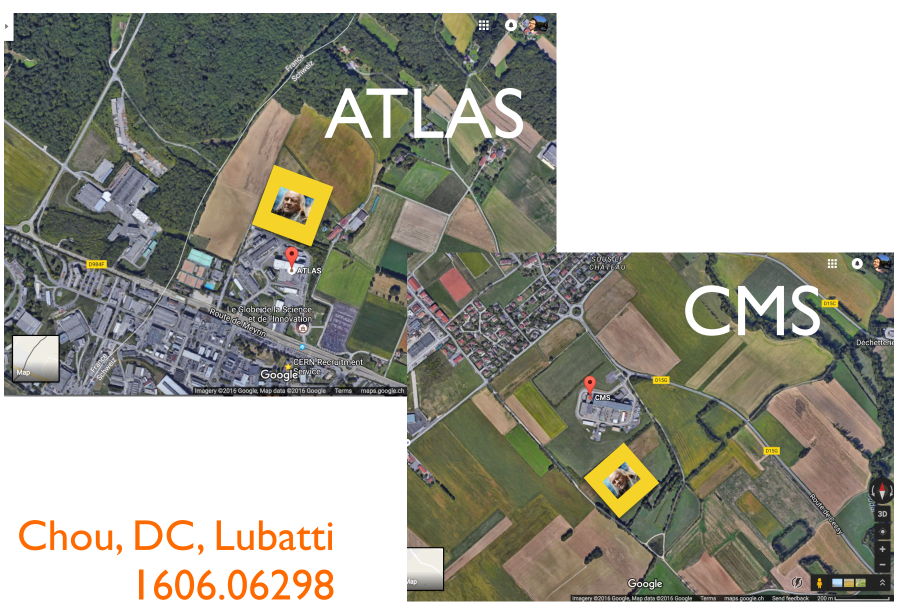
MATHUSLA

A general-purpose dedicated LLP detector for the HL/HE-LHC

Chou, DC, Lubatti 1606.06298
DC, Peskin 1705.06327
DC, Drewes, McCullough, Meade, Mohapatra, Shelton, Shuve, + 70 [in preparation]
… & more

An external LLP detector for the HL- or HE-LHC



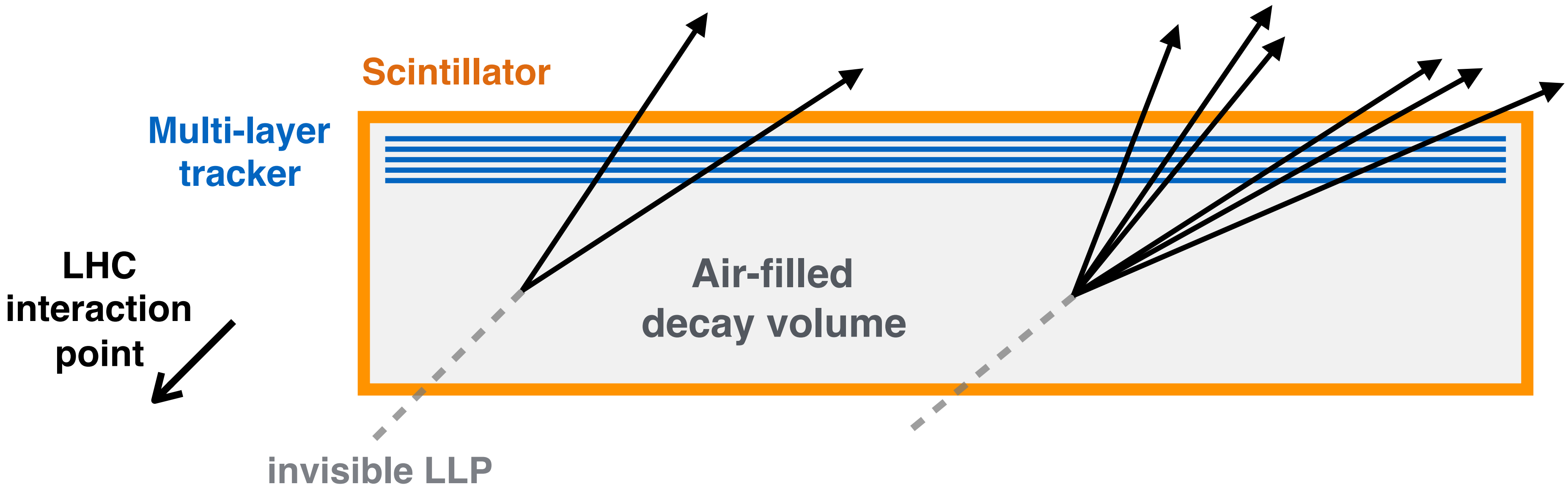


Chou, DC, Lubatti
1606.06298

Reliance on well-understood technology (RPC, plastic scintillators) means this could be implemented in time for the HL-LHC. **But design not set in stone, will explore other options!**

Unofficial cost estimates of current design: ~ 40 million USD

Signal Reconstruction



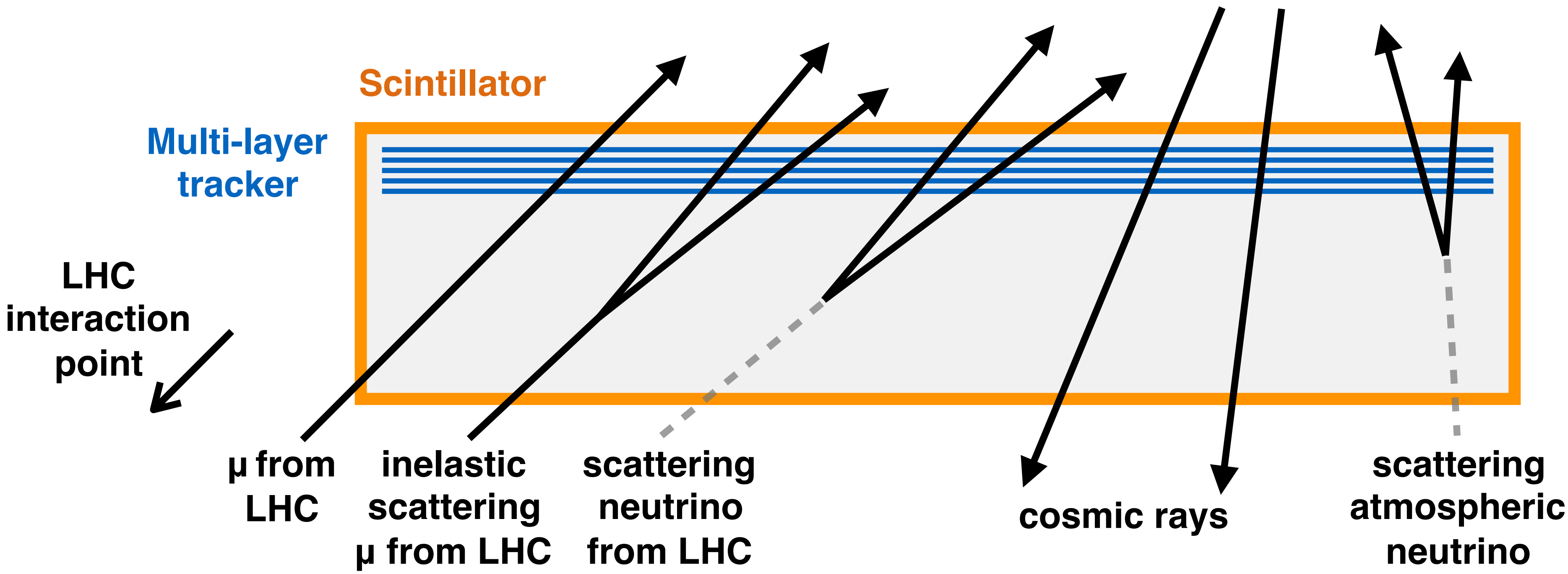
~5% geometric coverage.

Charged particle tracks are reconstructed with ~cm spatial resolution and ~ns timing resolution.

→ determine charged particle *speed* with ~0.05c precision.

LLP decays are reconstructed as Displaced Vertices (DV) in both **space** and **time**, with strict **geometric requirements** and vetoes.

Backgrounds



Reject using tight DV signal requirements, geometry & timing.

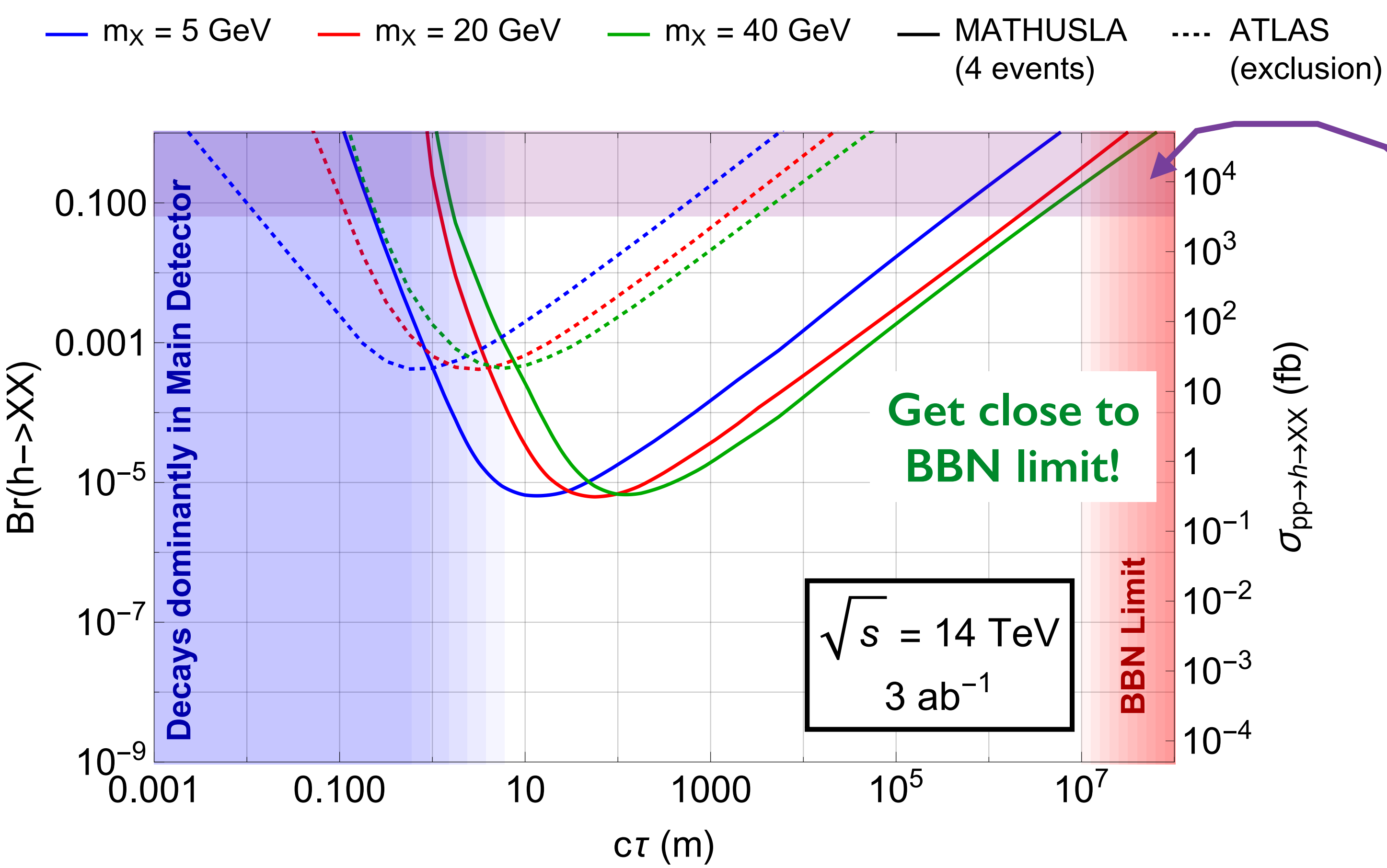
~Zero background regime can be reached!

Cosmic backgrounds can be measured and studied during beam down-time to verify rejection strategies.

Example of Achievable Sensitivity

For LLP production in exotic Higgs decays:

Chou, DC, Lubatti
1606.06298



Comparison: h→invis HL-LHC limit

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

3 orders of magnitude better cross section/lifetime reach than ATLAS search for single DV in MS (due to backgrounds!)

MATHUSLA Theory White Paper

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

Collaboration of 80+ theorists

Comprehensive theory motivation:

Aim: comprehensive report by early 2018

MATHUSLA collaboration

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~ 40 experimentalists @ ~10 institutions

MATHUSLA in the media

Physics Today article about LLPs and hidden sectors (DC, Raman Sundrum)

http://physicstoday.scitation.org/doi/10.1063/PT.3.3594

In-depth feature article in Quanta Magazine

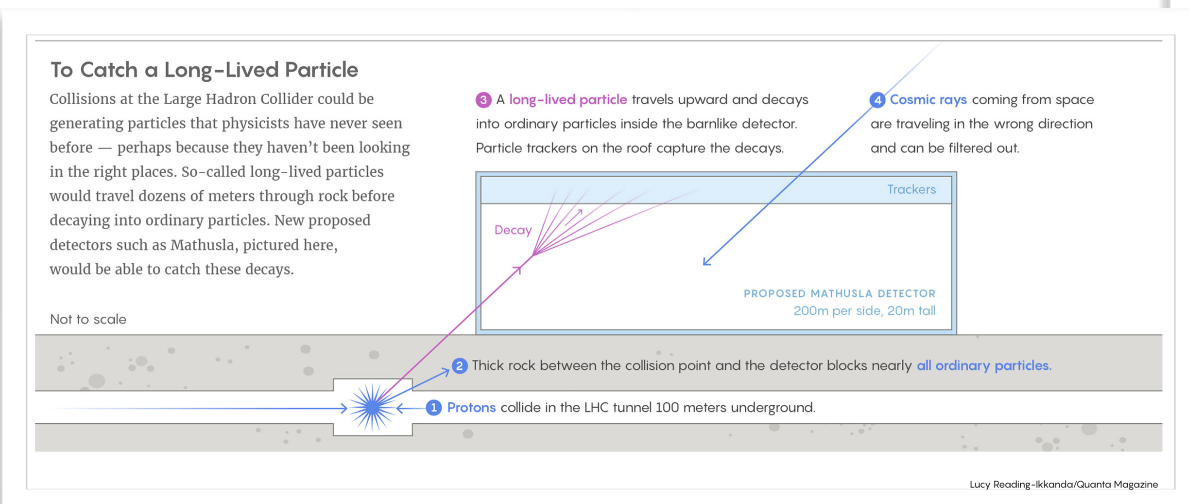
https://www.quantamagazine.org/how-the-hidden-higgs-could-reveal-our-universes-dark-sector-20170926/

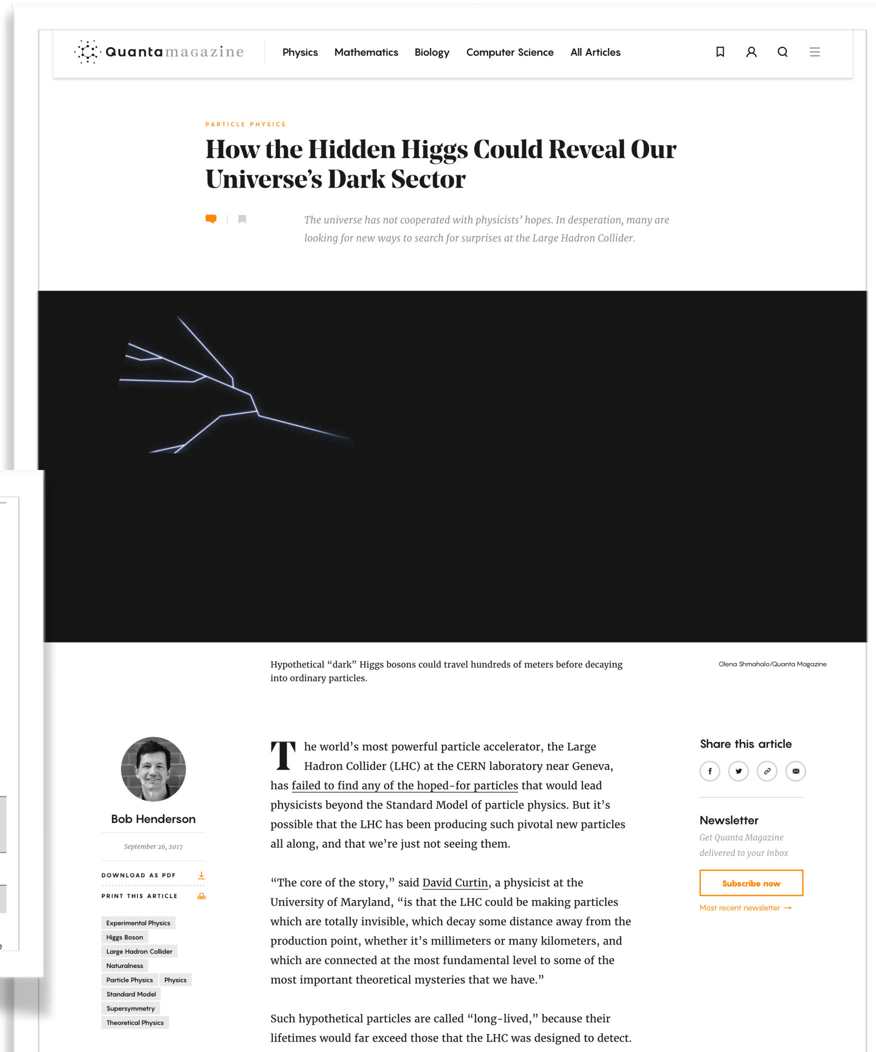
Picked up by Wired magazine:

https://www.wired.com/story/hidden-higgs-dark-sector/

JQI "Relatively Certain" Podcast: Long Live MATHUSLA

http://jqi.umd.edu/news/podcast/long-live-mathusla





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PARTICLE PHYSICS

How the Hidden Higgs Could Reveal Our Universe's Dark Sector

The universe has not cooperated with physicists' hopes. In desperation, many are looking for new ways to search for surprises at the Large Hadron Collider.

Hypothetical "dark" Higgs bosons could travel hundreds of meters before decaying into ordinary particles.

Olena Shmahalo/Quanta Magazine

Bob Henderson

September 26, 2017

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Experimental Physics | Higgs Boson | Large Hadron Collider | Naturalness | Particle Physics | Physics | Standard Model | Supersymmetry | Theoretical Physics

The world's most powerful particle accelerator, the Large Hadron Collider (LHC) at the CERN laboratory near Geneva, has failed to find any of the hoped-for particles that would lead physicists beyond the Standard Model of particle physics. But it's possible that the LHC has been producing such pivotal new particles all along, and that we're just not seeing them.

"The core of the story," said David Curtin, a physicist at the University of Maryland, "is that the LHC could be making particles which are totally invisible, which decay some distance away from the production point, whether it's millimeters or many kilometers, and which are connected at the most fundamental level to some of the most important theoretical mysteries that we have."

Such hypothetical particles are called "long-lived," because their lifetimes would far exceed those that the LHC was designed to detect. If the LHC is indeed producing these particles, then it's likely that

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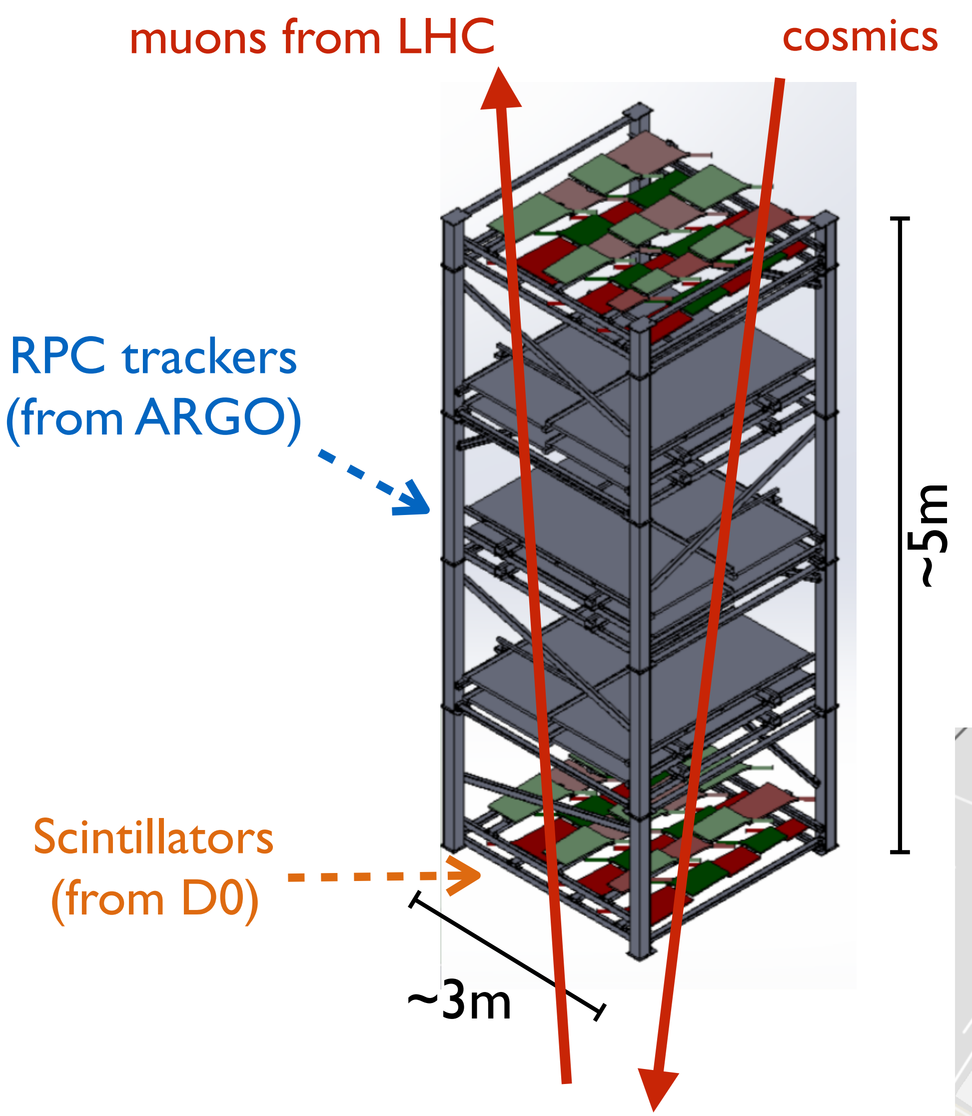
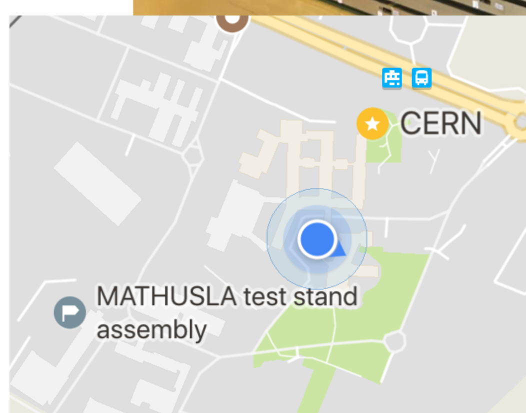
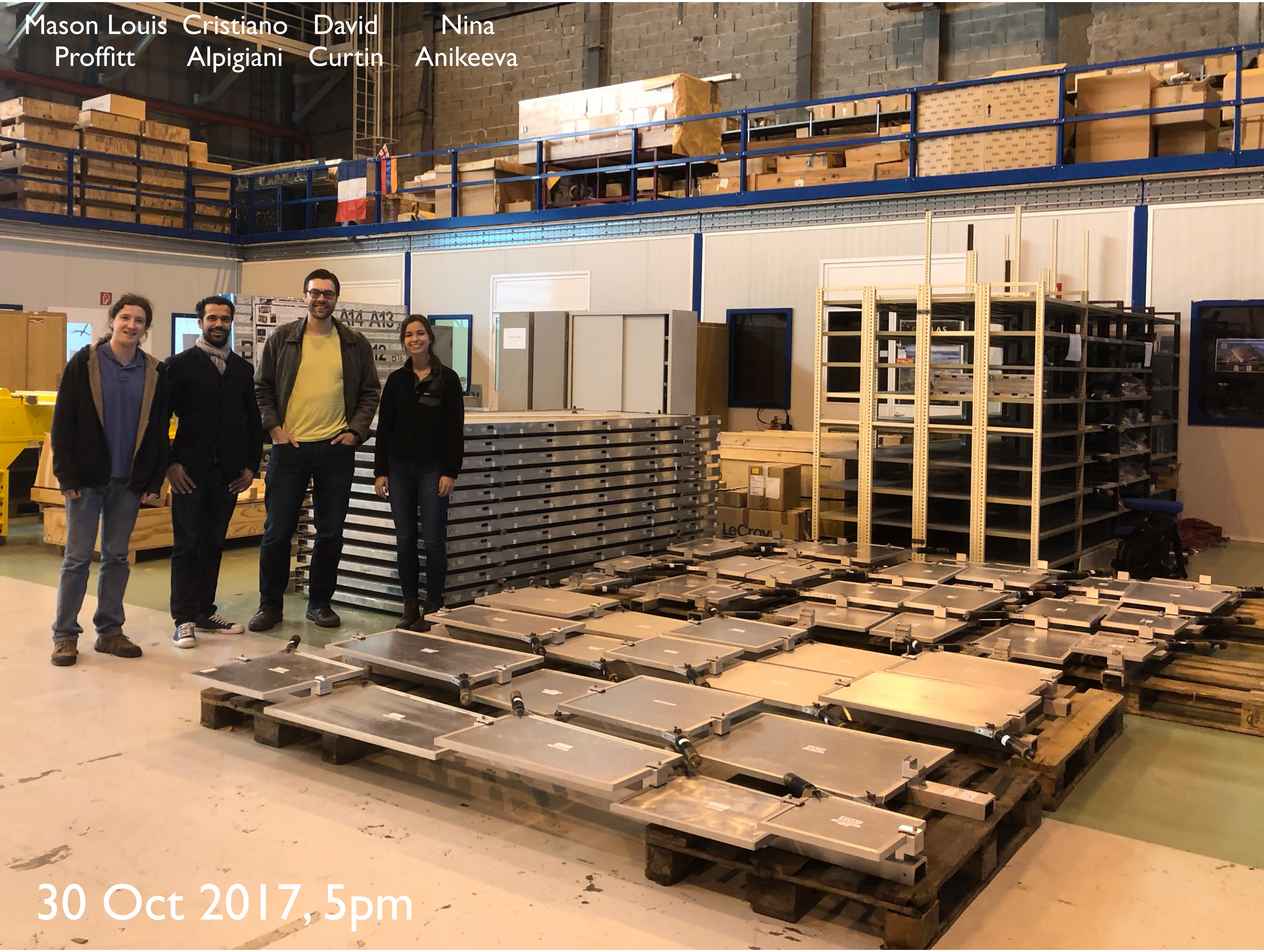
MATHUSLA Demonstrator

Demonstrator above ATLAS to demonstrate cosmic ray **rejection** and calibrate MC **currently under construction at CERN!**



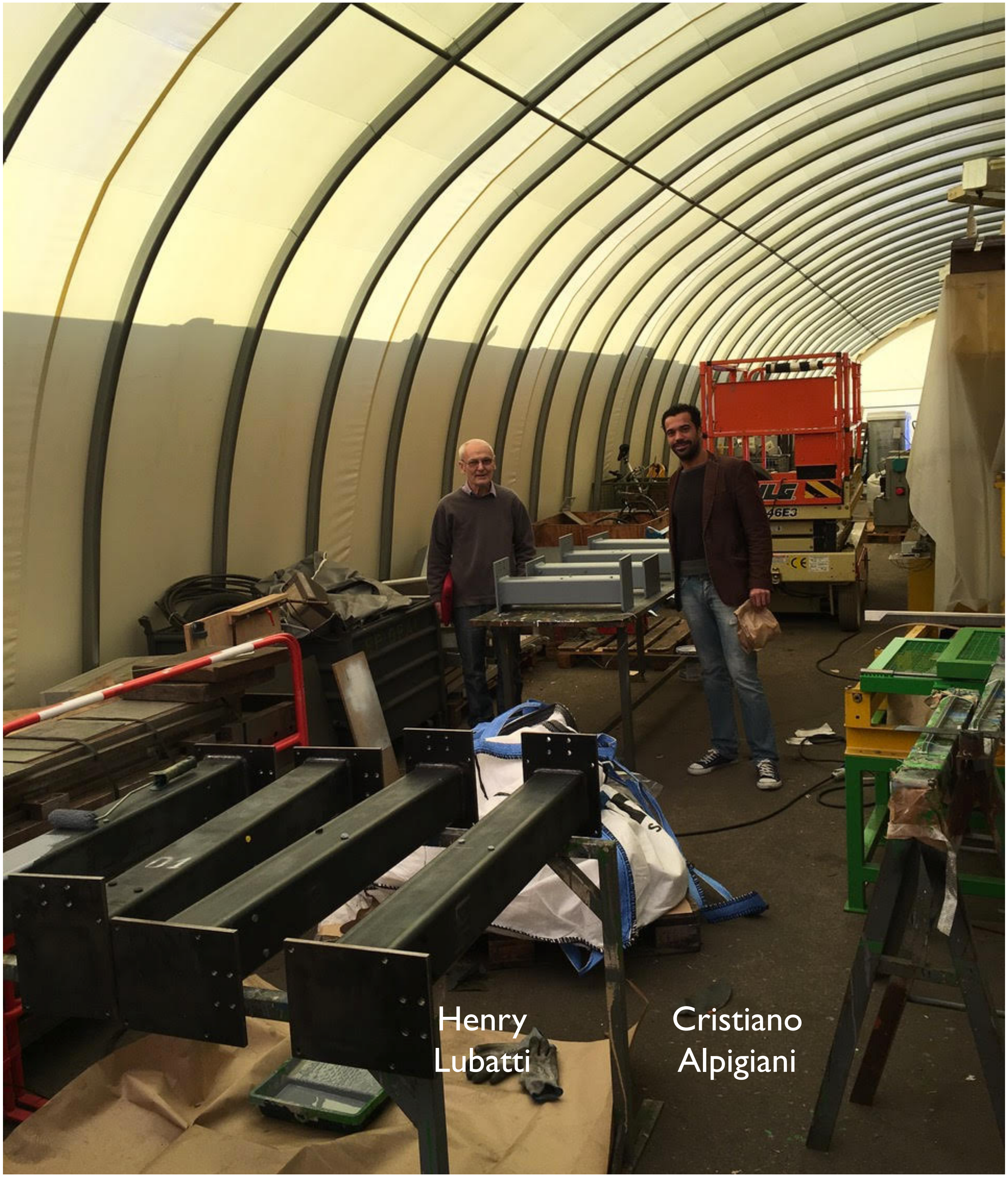
On track for "first light" in mid-November 2017!




Mason Louis Proffitt
Cristiano Alpigiani
David Curtin
Nina Anikeeva
30 Oct 2017, 5pm


Mason Louis Proffitt
Cristiano Alpigiani
David Curtin
Nina Anikeeva
30 Oct 2017, 5pm


Cristiano
Alpigiani
Henry
Lubatti
CMS


Henry
Lubatti
Cristiano
Alpigiani

MATHUSLA Demonstrator

Lost of work in next few weeks & beyond.

Assembling detector

DAQ/monitoring/storage

<much more>

Cosmic ray analysis

Setting some toy BSM limits to demonstrate timed-DV reconstruction

Results from test stand + theory white paper will form raw material for letter-of-intent & official proposals in 2018!

We need more people! Join us if you're interested!

* COmpact Detector for EXotics at LHCb

see Dean Robinson's talk

CODEX-b

A dedicated LLP detector for LHCb

1708.09395 Gligorov, Knapen, Papucci, Robinson

CODEX-b @ LHCb

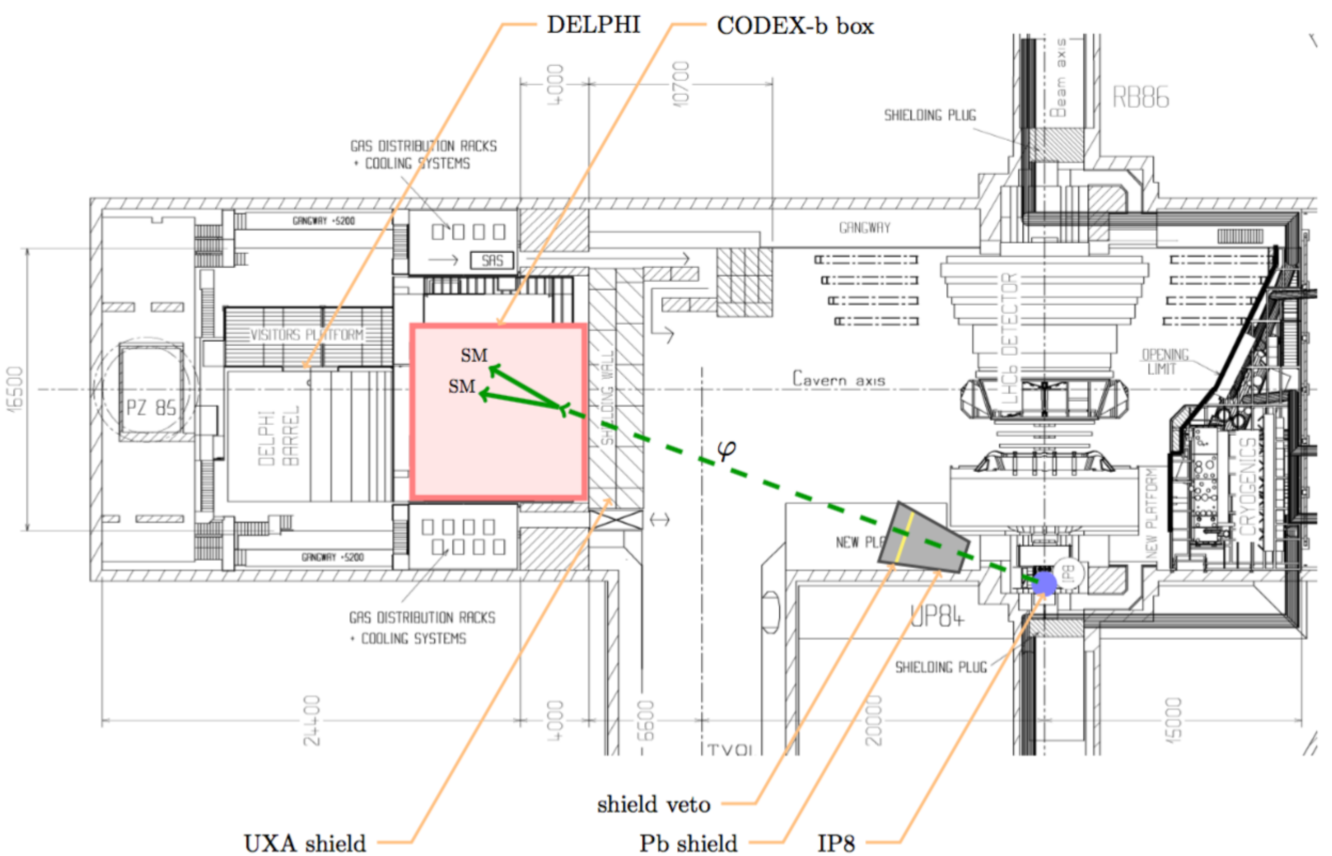
DAQ will be moved out of LHCb cavern in 2020. Opportunity to instrument ~ $(10\text{m})^3$ to detect LLPs, same principle as MATHUSLA.

(Double the volume if DELPHI museum piece could be moved…)

Requires additional shielding and vetos.

Could be integrated LHCb subdetector.

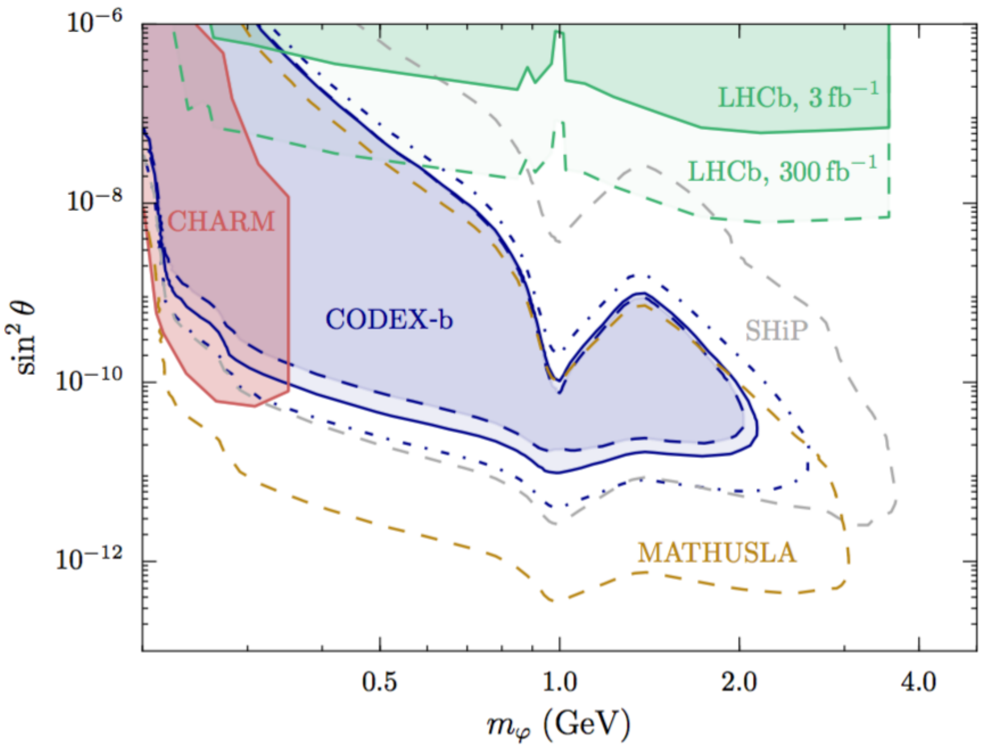
Collision BGs can be estimated by putting small cosmic ray telescope in cavern. Doing this soon!?



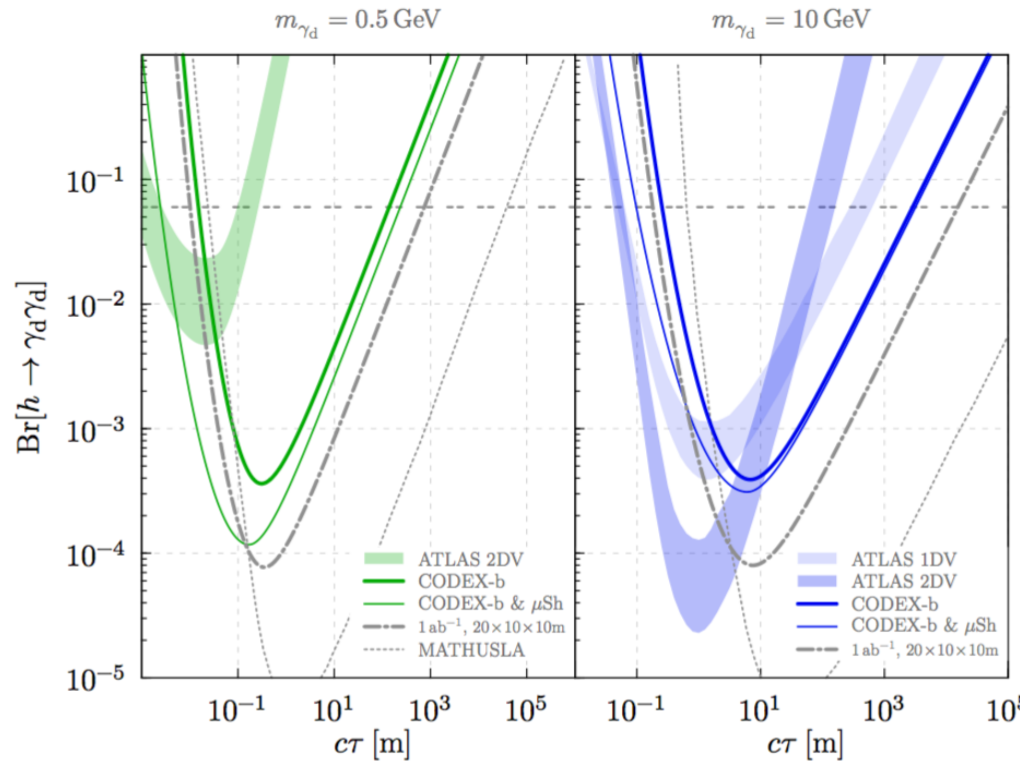
General strategy: Look for decays-in-flight of LLPs from IP8

CODEX-b Sensitivity

Higgs-portal LLP produced in B-decays



LLPs produced in Higgs decays



CODEX-b is much smaller than MATHUSLA and LHCb has lower lumi than ATLAS/CMS collision point, but highly complementary.

→ at long lifetimes, only 1/200 the LLP xsec sensitivity (1/50 if fry VELO)

→ probably cheaper

→ could afford more granular instrumentation

⇒ might have advantage in reconstructing very light LLPs < ~GeV?

*ForwArd Search ExpeRiment

FASER

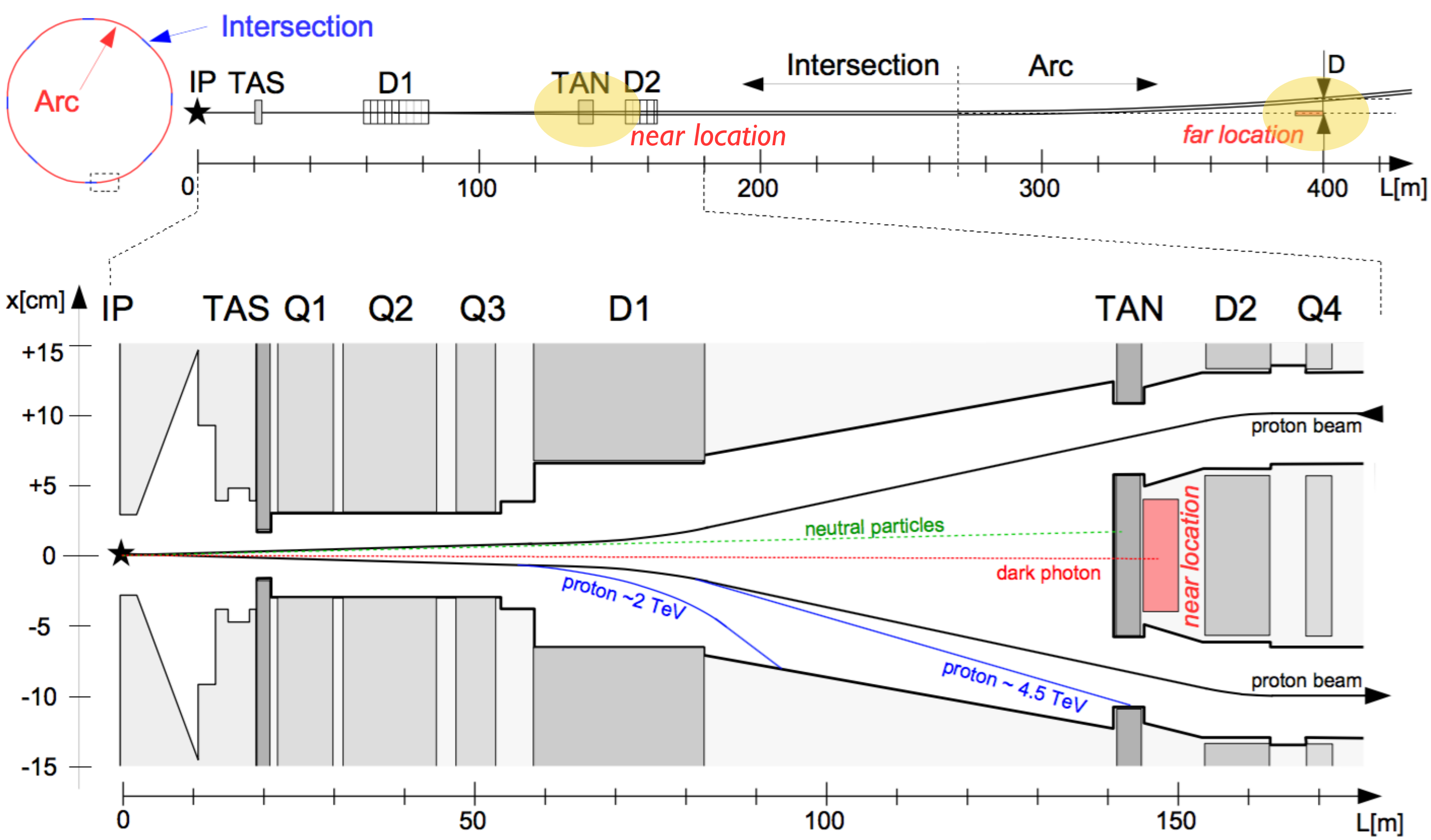
Exploiting forward LLP production at the LHC

1708.09389 Feng, Galon, Kling, Trojanowski

FASER

Exploit extremely high rates of forward proton inelastic scattering ($\sim 10^{17}$) in HL-LHC collisions to produce light LLPs.

Small cylindrical detector r ~ 0.1m, L ~ 5-10m, with modest 0.1T B field to split final states of LLP decay.



Consider three possible locations:

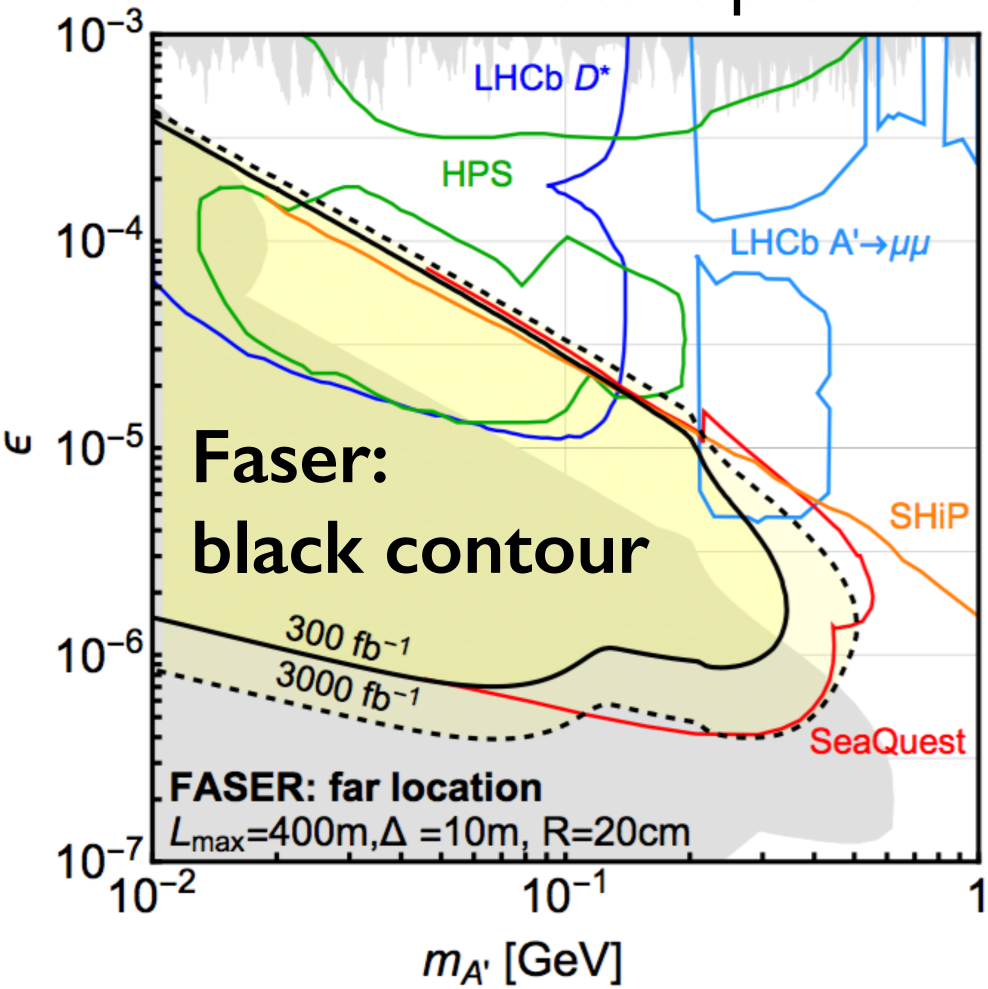
near on-axis (150m)

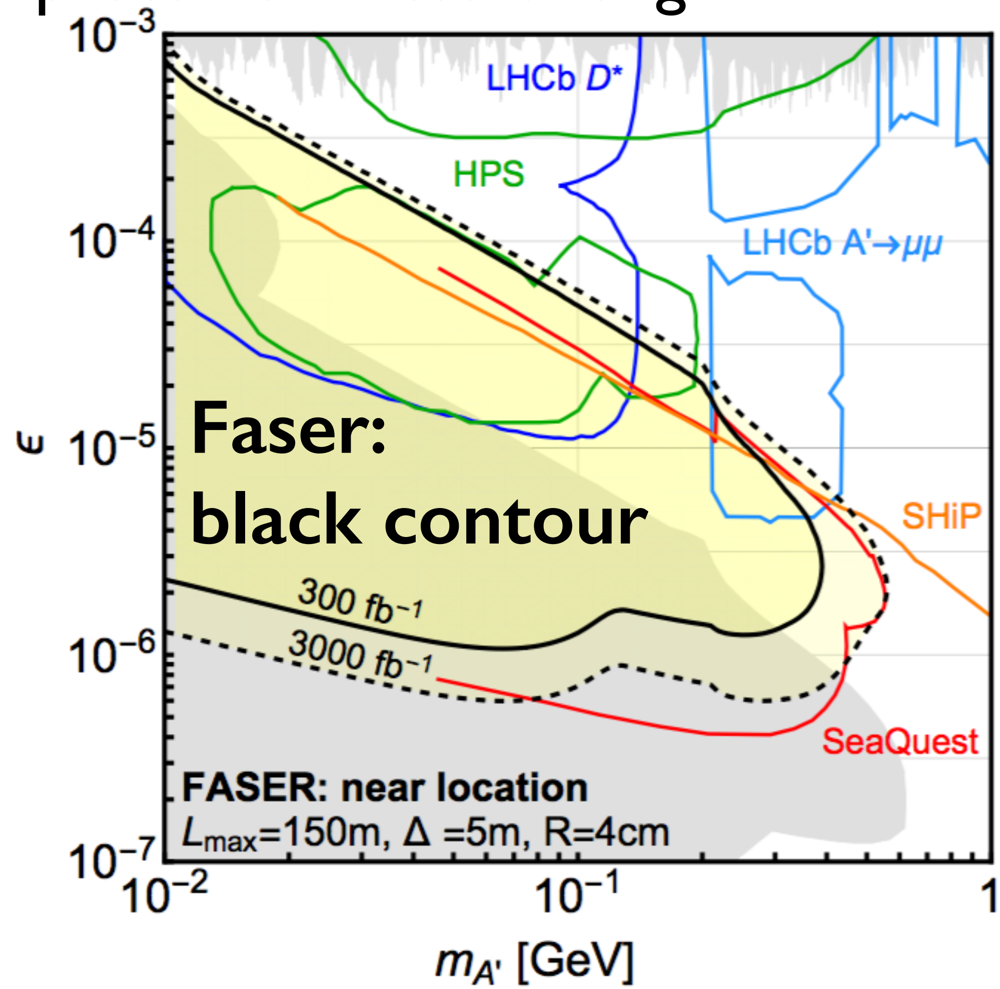
far on-axis (400m, better BG rejection)

off-axis

FASER Sensitivity @ (HL-) LHC

Dark Photons produced in proton bremsstrahlung





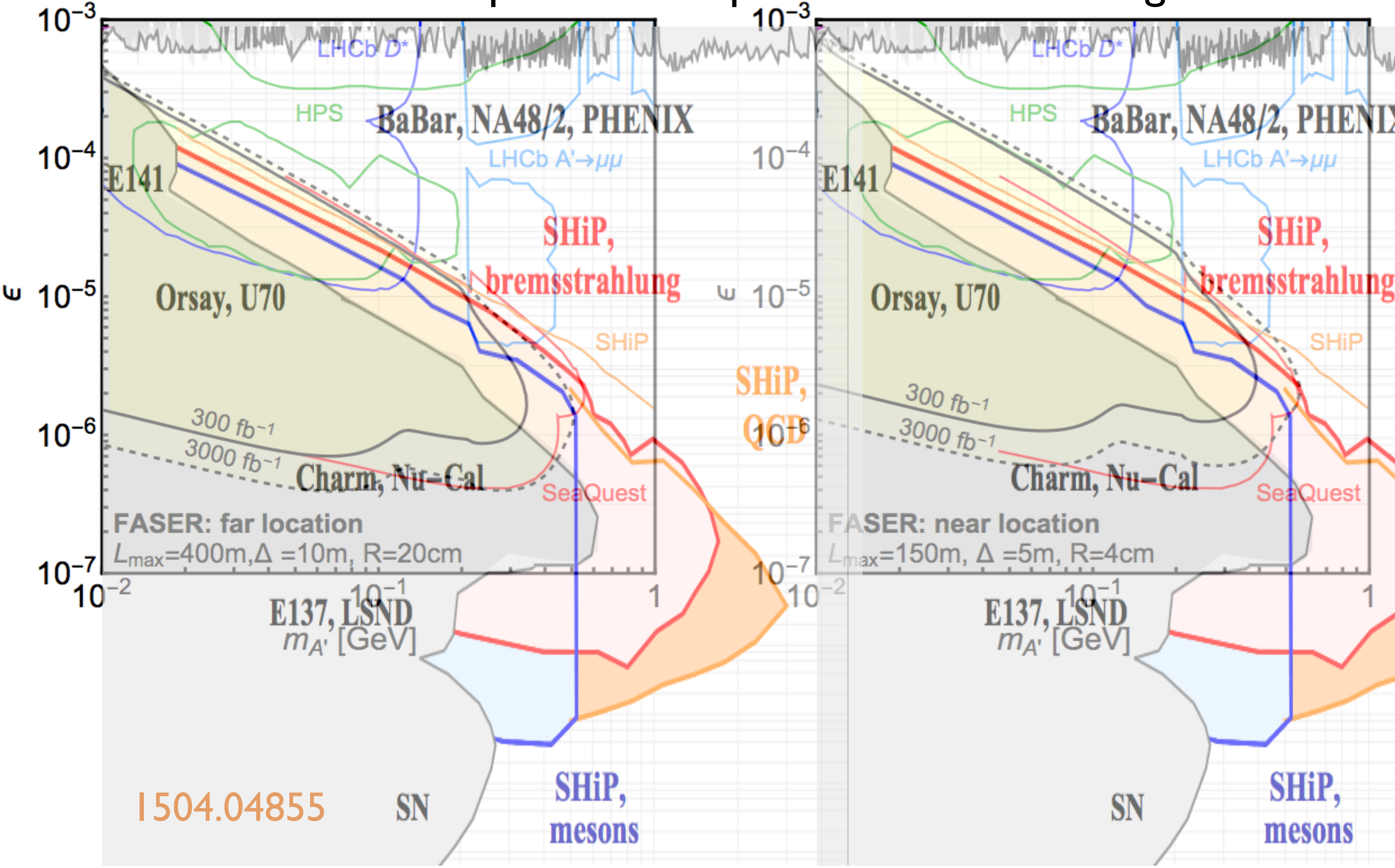
Very similar to proposed fixed-target experiments like SeaQuest

Is FASER cheaper/better than e.g. SeaQuest in some way?

SHiP is the light-LLP super power…

FASER Sensitivity @ (HL-) LHC

Dark Photons produced in proton bremsstrahlung



1504.04855

milliQan

The only game in town for weak-scale millicharges

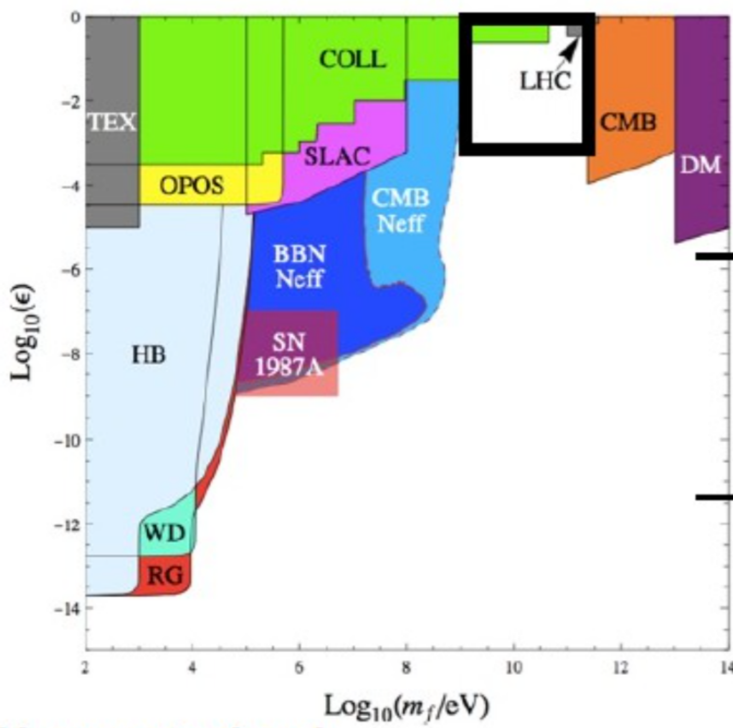
1410.6816 Haas, Hill, Izaguirre, Yavin
1506.04760 Izaguirre, Yavin
Letter of Intent: 1607.04669

Slides by Andi Haas

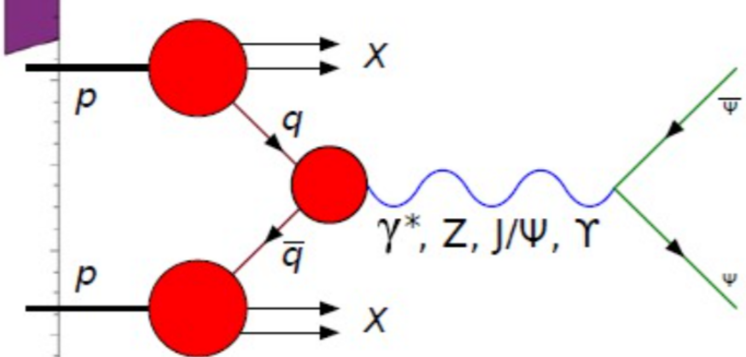
Milli-charged Particles

If the Hidden Sector includes an **unbroken** U(1), kinetic mixing gives new states a $U(1)_{EM}$ milli-charge!

Existing Constraints



pp Colliders

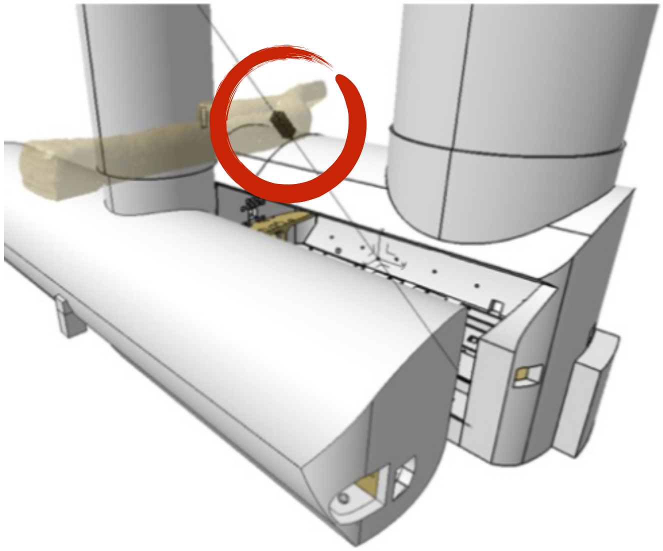


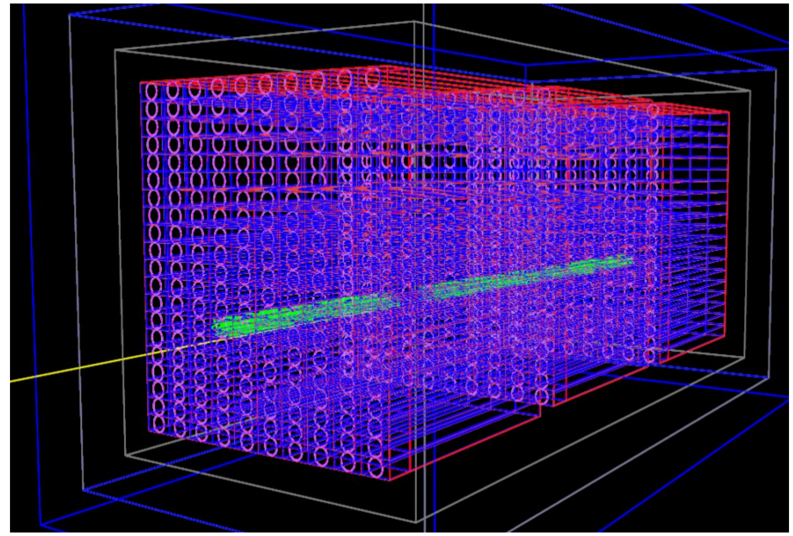
Unconstrained

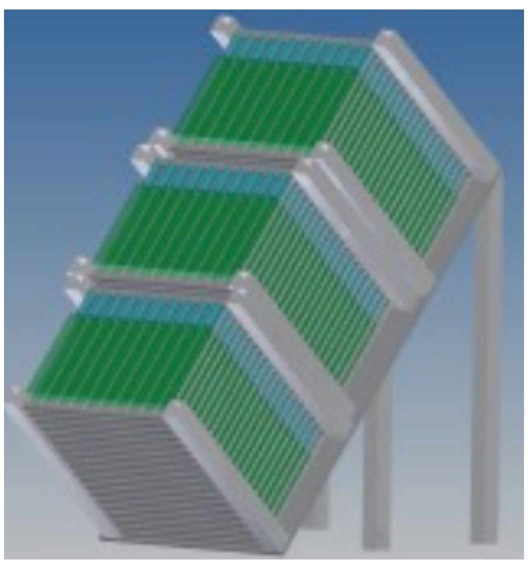
- $Q_{mCP} \in [0.001, 1]e$
- $M_{mCP} \in [0.1, 100]$ GeV

Many refs are in initial proposal: 1410.6816

MilliQan







An Expression of Interest 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]

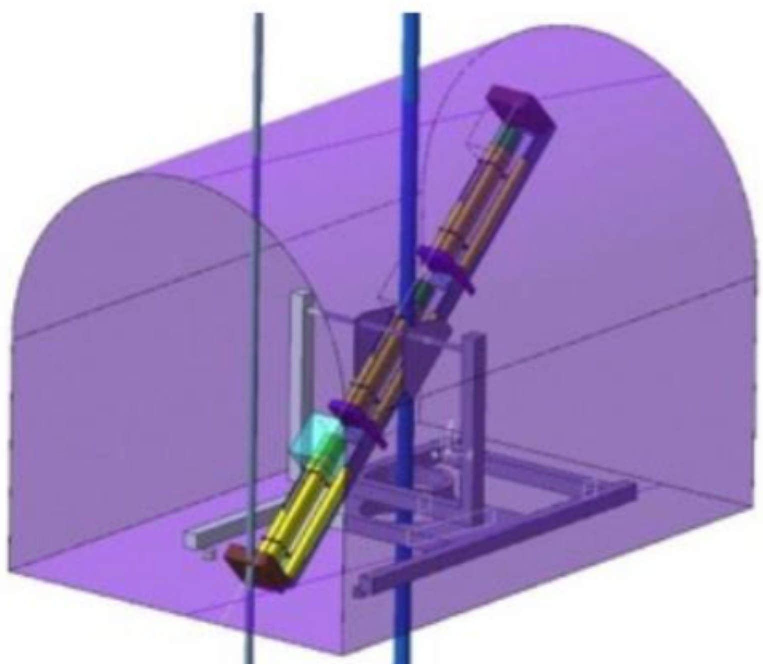
Latest schedule for ENGINEERING RUN 2017:
Summer (TS1)- install support structure, cables, services, etc. in tunnel
Fall (TS2) - install 12 PMTs/scintillators, electronics, perform calibrations
Take data with beam through the end of 2017, and in 2018!

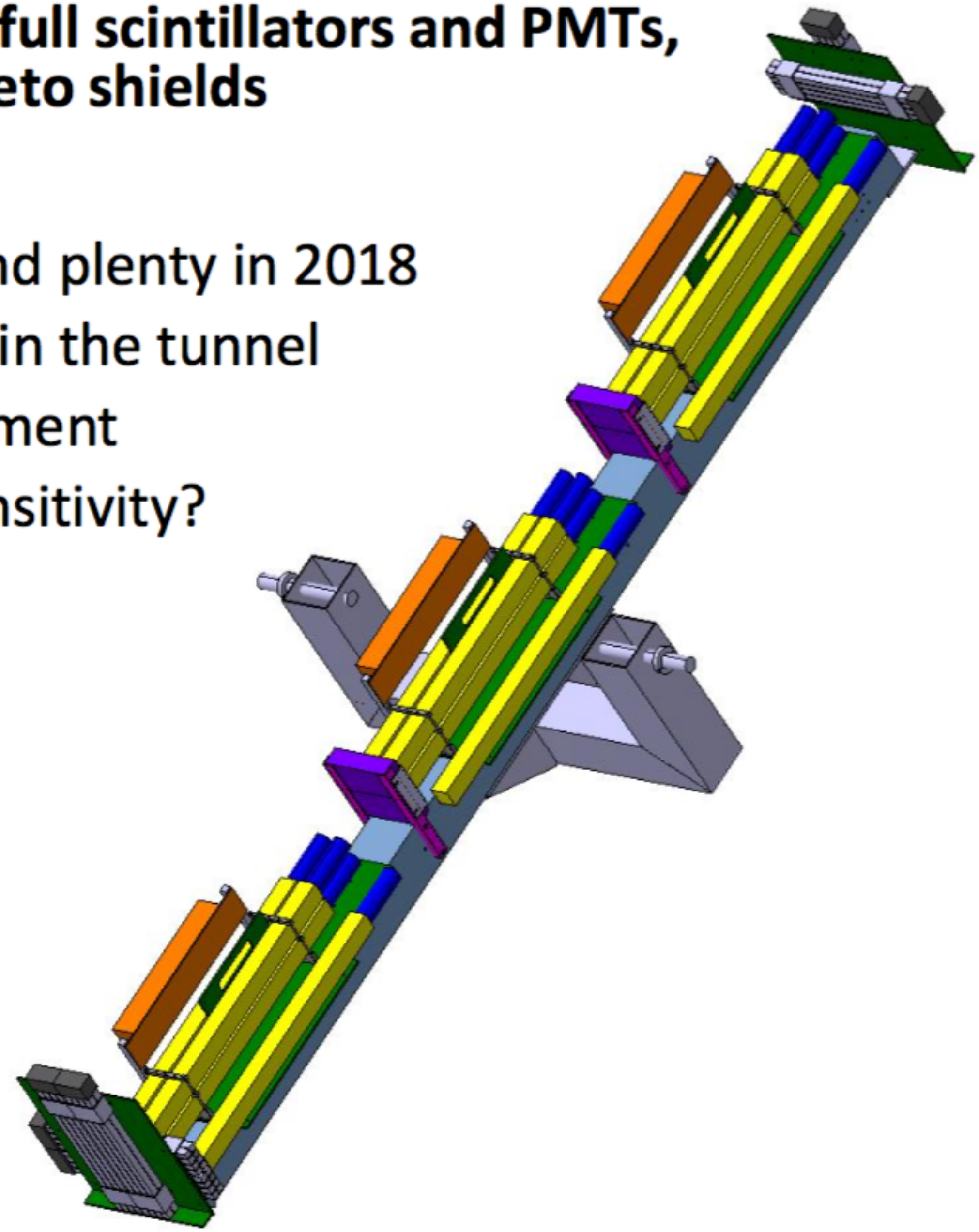
Install full detector in 2018-20 in time for Run3 (300/fb).

Next step: mini-milliQan demonstrator test

Fall 2017 – end of 2018:
1% test of milliQan in tunnel, with 12 full scintillators and PMTs, plus 2 hodoscopes, and some muon veto shields

- Installed in tunnel Sept. 18-20!!
- Get some collision data this year and plenty in 2018
- Learn about operating experiment in the tunnel
- Measure backgrounds, check alignment
- New heavy milli-charge particle sensitivity?





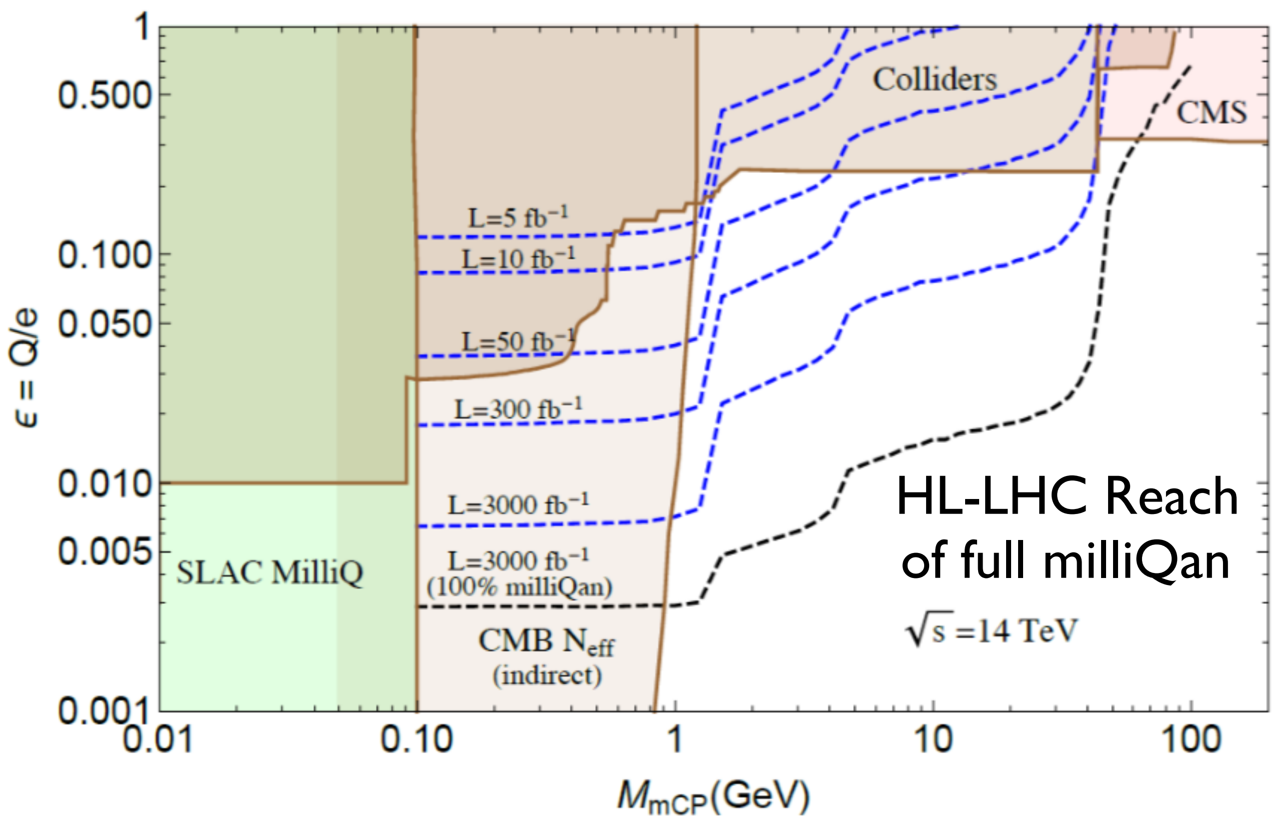
1% milliQan

Current Prototype

Specifications

Location: LHC mCP distributions
Bar #: 2 x 2 x 3
Bar dim: 80cm x 5cm x 5cm
2nd layer offset: None
Inter-Scintillator Space: 1cm
Backgrounds: Same * 1%
Shield: 1mm G4_AIR, 1mm G4_AIR
Reflectivity/Wrapping: 0.99/tyvek
Scintillator: BC-408
PMT: R329-02
Lumi: 5,10, 50, 300, 3000/fb
Backgrounds: 1, 1, 1, 3, 5
Coincidence Threshold: 15ns
Dark-Current Rate: 700
Strategy: Back-to-Back

95%CL Projected Sensitivities



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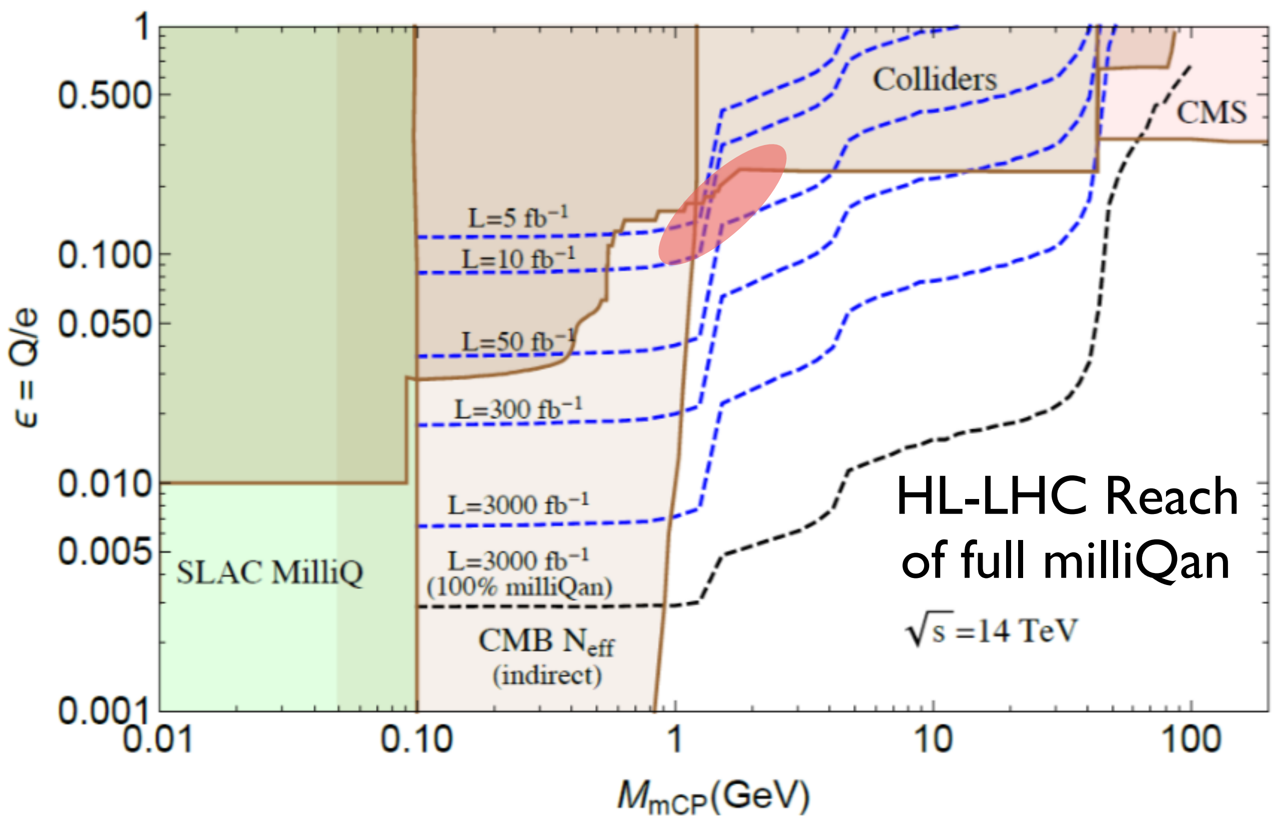

Landscape of HE/HL-LHC Proposals

Landscape of HE/HL-LHC Proposals

These proposals are *relatively* low-cost (1-10s of million $) and go after LLP signals that the collider may already produce, but the main detectors can't catch! **Should really have these at any pp collider!!**

MATHUSLA is the largest, most sensitive general-purpose LLP detector. **Gain of 10^3!** Instrumentation for the ~10^6 m^3 volume not finalized. Can << ~GeV LLPs be reconstructed? If yes, compete w/ SHiP @ low mass!

CODEX-b is smaller and may be cheaper. Finer instrumentation could complement MATHUSLA, in particular for lower-mass LLPs.

FASER goes after similar physics, but in spirit is more analogous to low-E or fixed-target experiments. Questions: Can it be cheaper/better than SeaQuest? SHiP is ~1/4 billion $. Could FASER do better with more $?

milliQan goes after a different but very generic hidden sector signal. Sensitivity beyond $\epsilon \sim 10^{-3}$ needs scintillator R&D (1/10), 100x more money and space (1/10). Beyond: electron-recoil DM detector near IP!