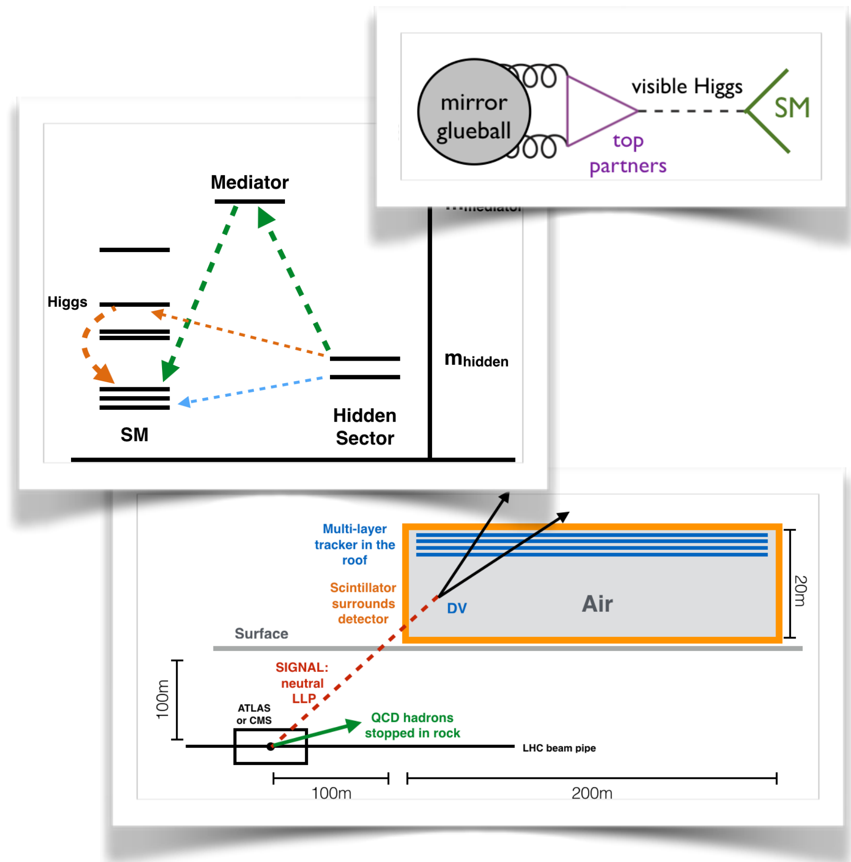
The Lifetime Frontier

New Searches & New Detectors

Aspen 2017 Winter Conference
From the LHC to Dark Matter and Beyond

22 March 2017

David Curtin
University of Maryland



Outline

1. Theory
2. The Lifetime Frontier at the LHC
3. New Detectors: milliQan
4. New Detectors: MATHUSLA

Definition

Lifetime Frontier

The study of **Long-Lived Particle (LLP)** signatures

(beyond MET)

Theory

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?

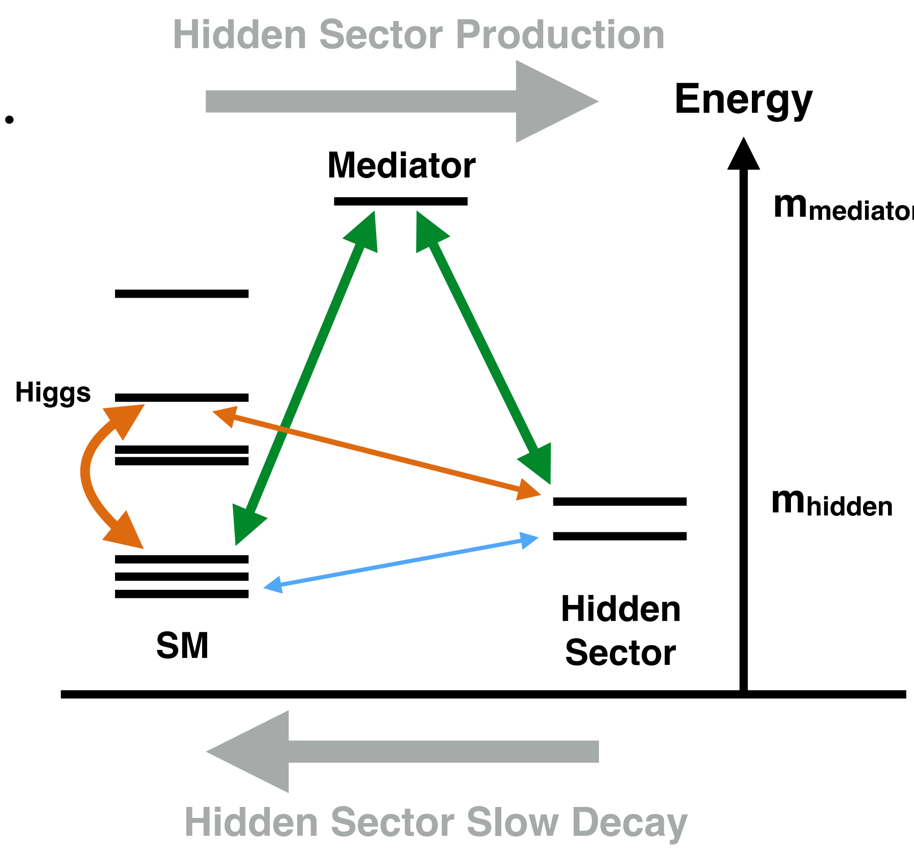
Hidden Sectors

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

Important Lessons

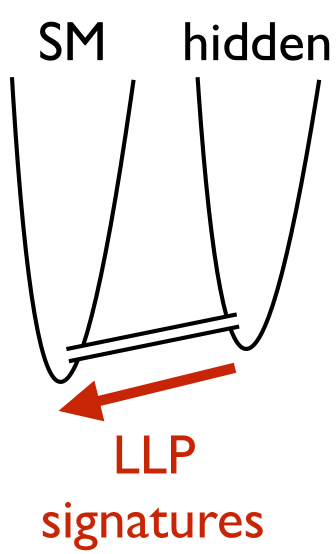
1. Exotic Higgs Decays

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

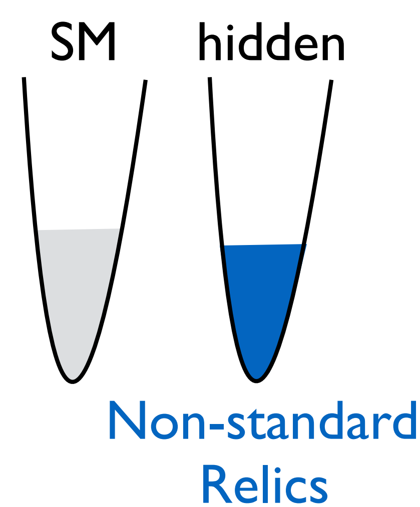
Once produced, Hidden Sector states can only decay back to SM via small portal couplings, generically leading to long lifetimes. **The LLP lifetime is (almost…) a free parameter!**

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.)



Unraveling Fundamental Mysteries with LLP searches

Neutral Naturalness

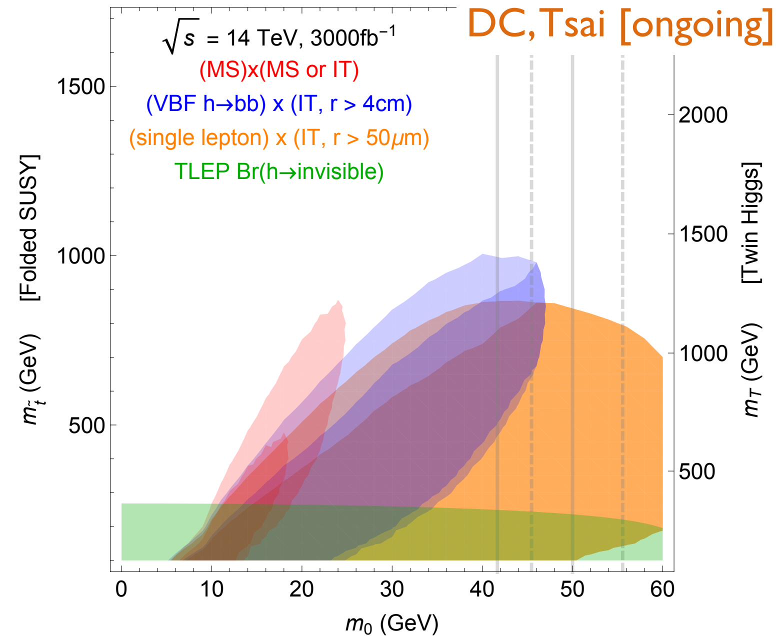
Hierarchy Problem can be addressed by **uncolored top partners** by introducing a discrete symmetry "twist" into SUSY/CH/… models.

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

Discrete symmetry introduces hidden copy of QCD talking to SM via Higgs Portal!

→ **LLP signatures of Naturalness!!**

DC, Verhaaren 1506.06141
DC, Tsai [ongoing]



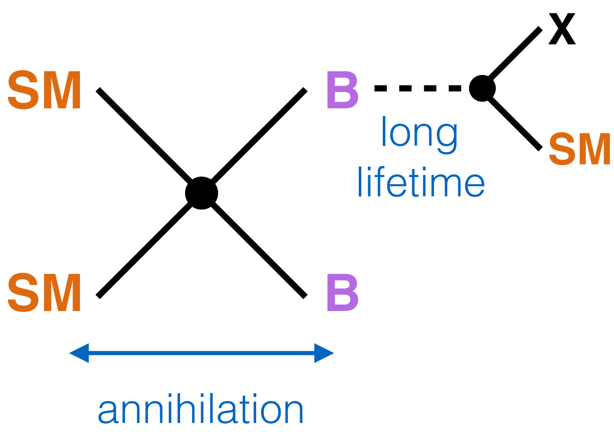
New LHC LLP searches would give TeV top partner sensitivity!

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]

FIMP Dark Matter

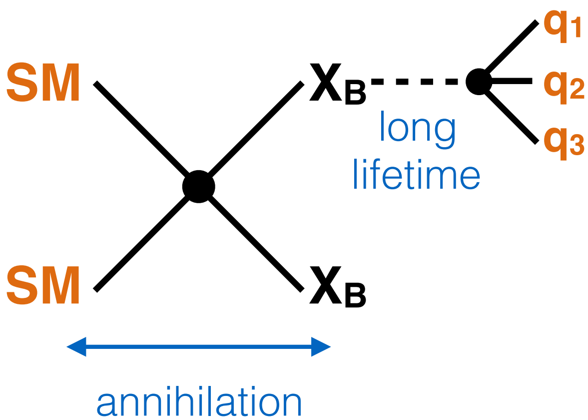
e.g. Hall et al, 0911.1120



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**!

WIMP Baryogenesis

Cui, Sundrum 1212.2973



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.

Upshot

LLPs are completely **generic** in BSM theories!

Hidden Sectors motivated by fundamental mysteries tend to be quite **predictive**, allowing us to think about very novel experimental probes!

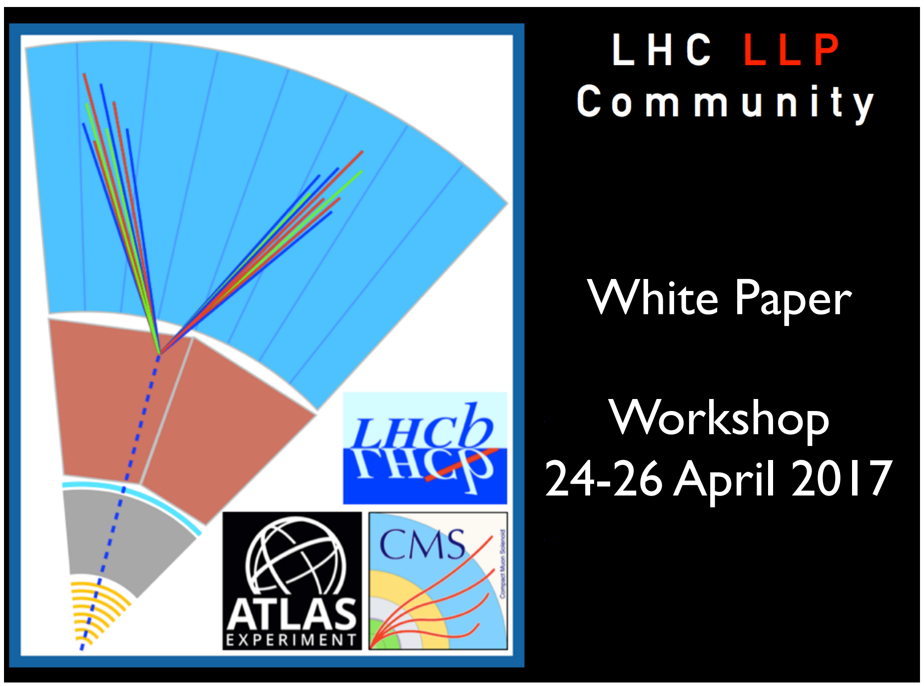
Looking for LLPs should be a high priority.

The Lifetime Frontier
at the LHC

LLPs at the LHC

Main detectors and standard searches were not designed for LLP final states.

Huge unexplored signature space.
Need systematic LLP search program!



Collaboration of theorists and ATLAS, CMS and LHCb experimentalists to create a **roadmap of required searches**, investigate **background** analysis and rejection strategies, and decide the most useful presentation of results for **easy re-casting**.

LLPs at the LHC

What are the hardest signatures?

Neutral LLPs are only detectable when they decay.
Reconstruction can be challenging.

Milli-charged LLPs (or stable particles) are tough to detect due to tiny ionization.

Neutral LLPs

A neutral LLP decaying in the detector
is a **spectacular** signature…

Distinctiveness of Signature in Detector:

Heavy charged track/deposition > **Displaced Decay** > Missing Energy

… but there can still be **some backgrounds.**

Rule of Thumb for LLP searches

DV + X ⇒ Very little background @ LHC

DV: High quality very macroscopic **displaced vertex**

X: **Something else** that's kinda rare (leptons, high-mass, another DV…)

⇒ Very little background @ LHC

X could be a property of the LLP itself

Performed Searches at ATLAS or CMS

DV + X ⇒ Very little background @ LHC

High quality very macroscopic **displaced vertex**

Something else that's kinda rare (leptons, high-mass, another DV…)

$d \gtrsim$ cm + X = distinctive LLP decay products (leptons, lepton jets…)
X = 'hard' LLP: has high mass and decays in tracker
X = another DV, especially if you can trigger on them

Performed Searches at ATLAS or CMS

DV

High
very ma
displace

d ≳ cm +

Very little
ground
LHC

epton jets…)
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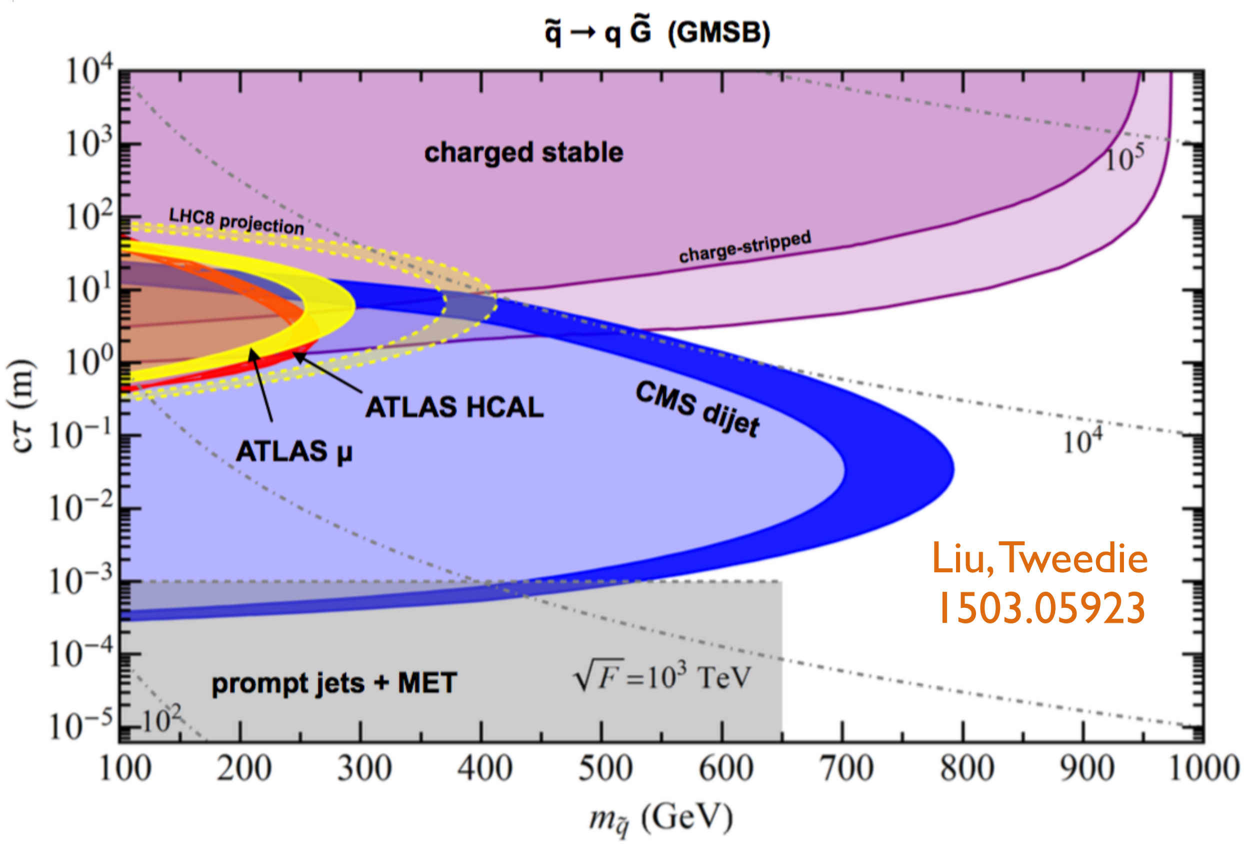
on them



In combination, together with charged LLP and prompt searches, this already gives very significant reach for many theories!

Most important required searches

DV	+	X	⇒	Very little background @ LHC
High quality very macroscopic **displaced vertex**		**Something else** that's kinda rare (leptons, high-mass, another DV…)		

1. Need sensitivity for "softer" LLPs, e.g. from **exotic Higgs decays, which is a highly motivated LLP production mode**
   ⇒ X = single lepton (Vh) or VBF jets *(events are on tape!)*

2. X = all of the above, **DV with d ~ 0.1mm - cm**
   (repurpose b-tagger? LHCb opportunity?)

3. LLP decay with **d >> detector size**
   (also relevant for testing if MET = DM)

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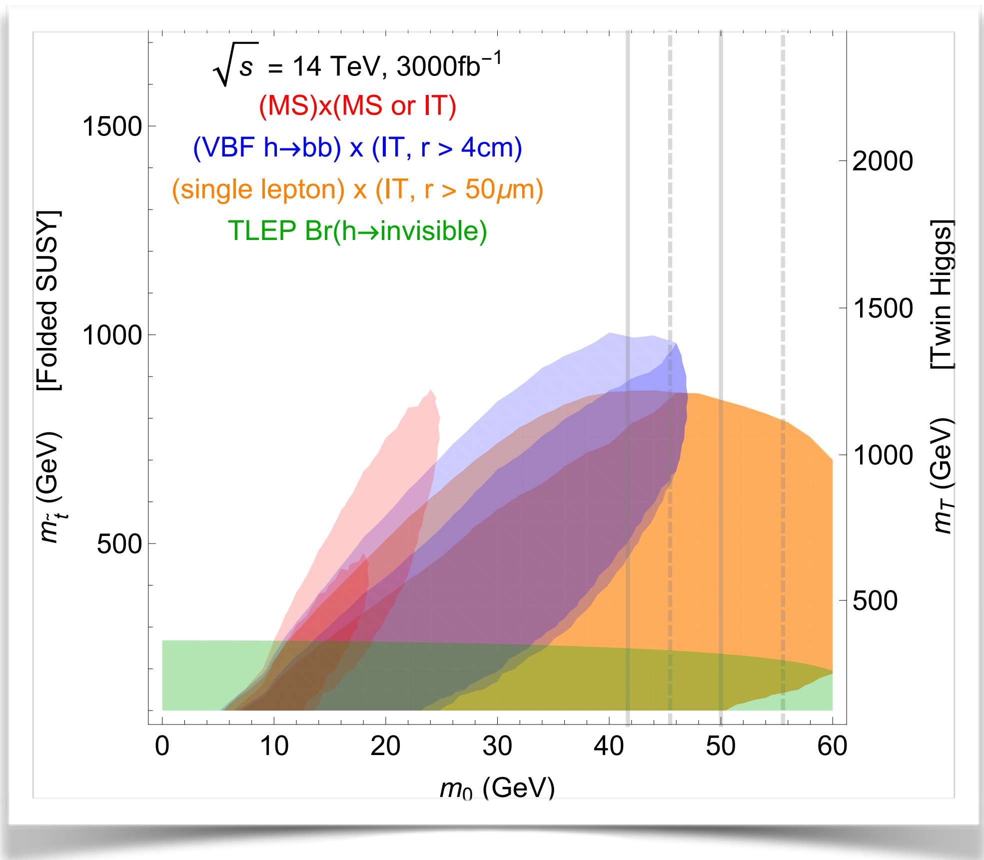
These searches are required to discover Neutral Naturalness:



Most important required searches

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Most important required searches

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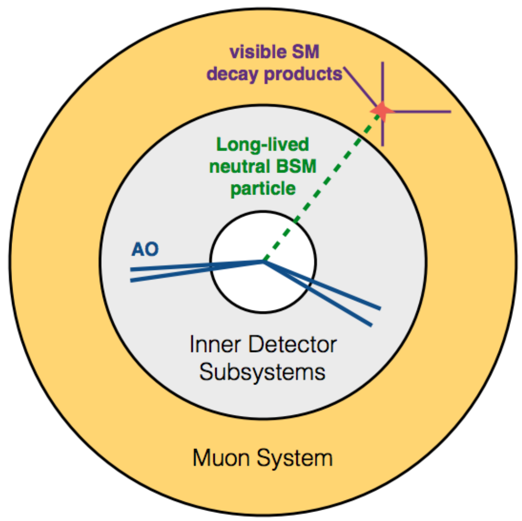
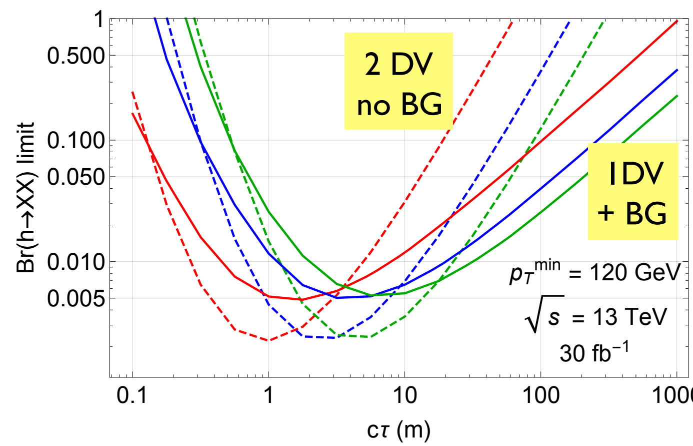
⇒ X = single le

2. X = all of the ab

3. LLP decay with **d** >

Best you can do at the LHC is an inclusive single-DV search in ATLAS Muon System





Will be implemented at run-2 and gives access e.g. to 5 GeV Neutral Naturalness glueballs, but longer lifetimes are challenging…

1605.02742 Andrea Coccaro, DC, Henry Lubatti, Heather Russell, Jessie Shelton

y?)

(also relevant for testing if MET = DM)

New Detectors for the Lifetime Frontier

New Detectors for the Lifetime Frontier:

MilliQan

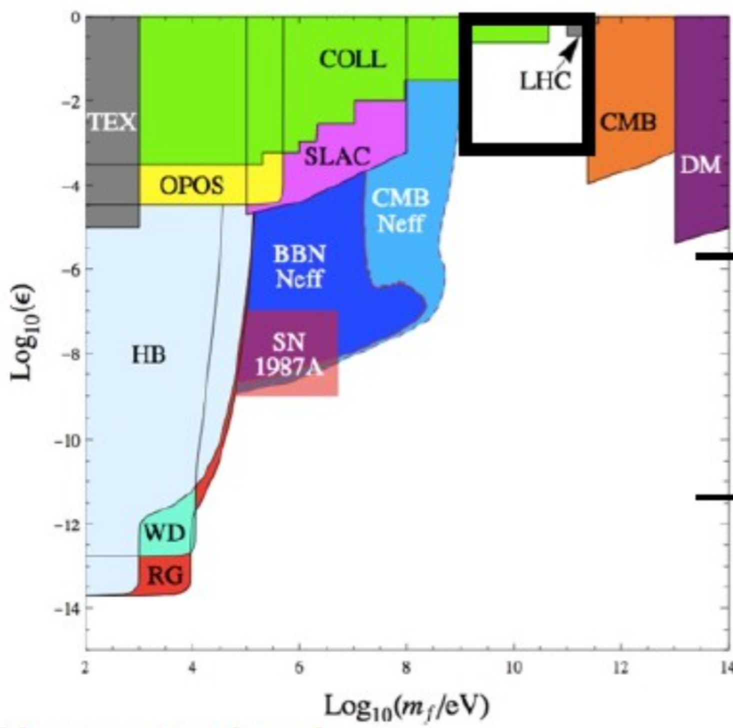
Detecting milli-charged particles at LHC Run 3

(with thanks to Andy Haas)

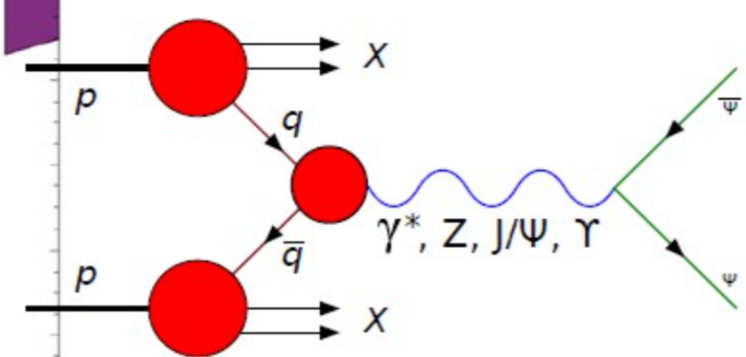
Milli-charged Particles

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

Existing Constraints



pp Colliders

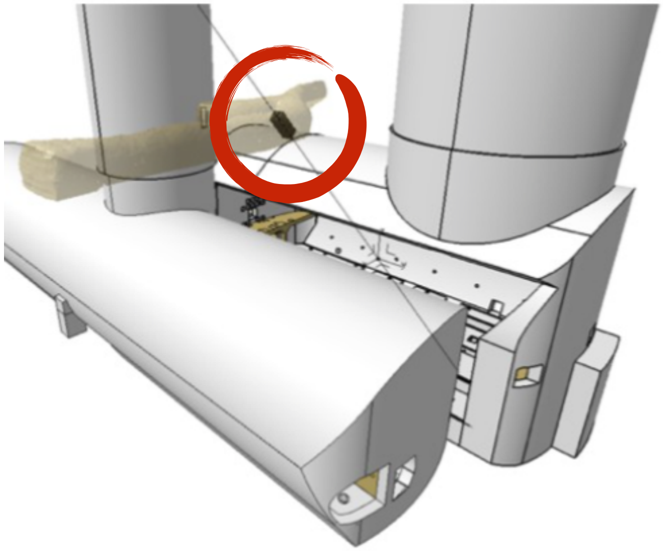


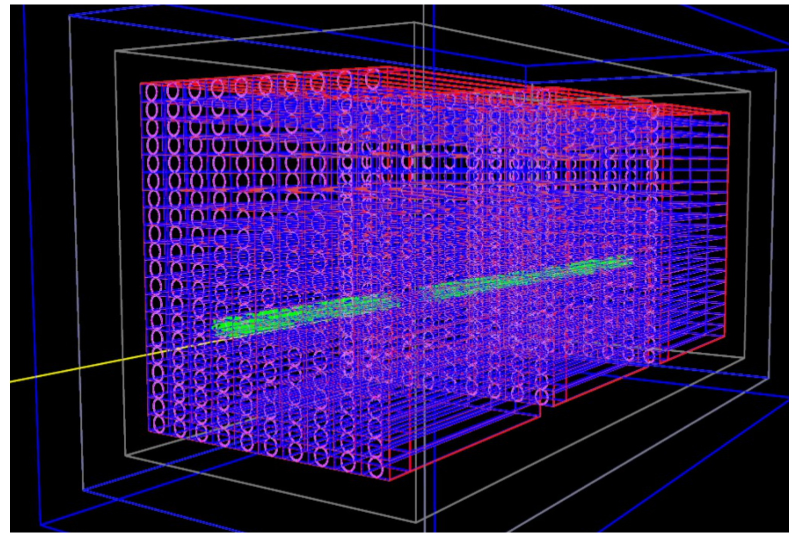
Unconstrained

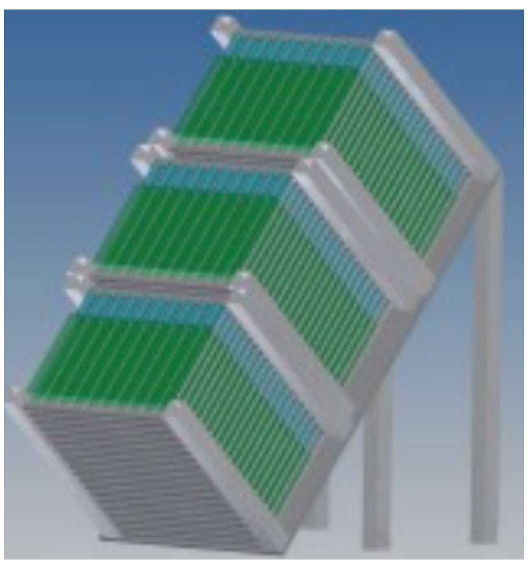
- $Q_{mCP} \in [0.001, 1]e$
- $M_{mCP} \in [0.1, 100]$ GeV

Many refs are in initial proposal: 1410.6816

MilliQan







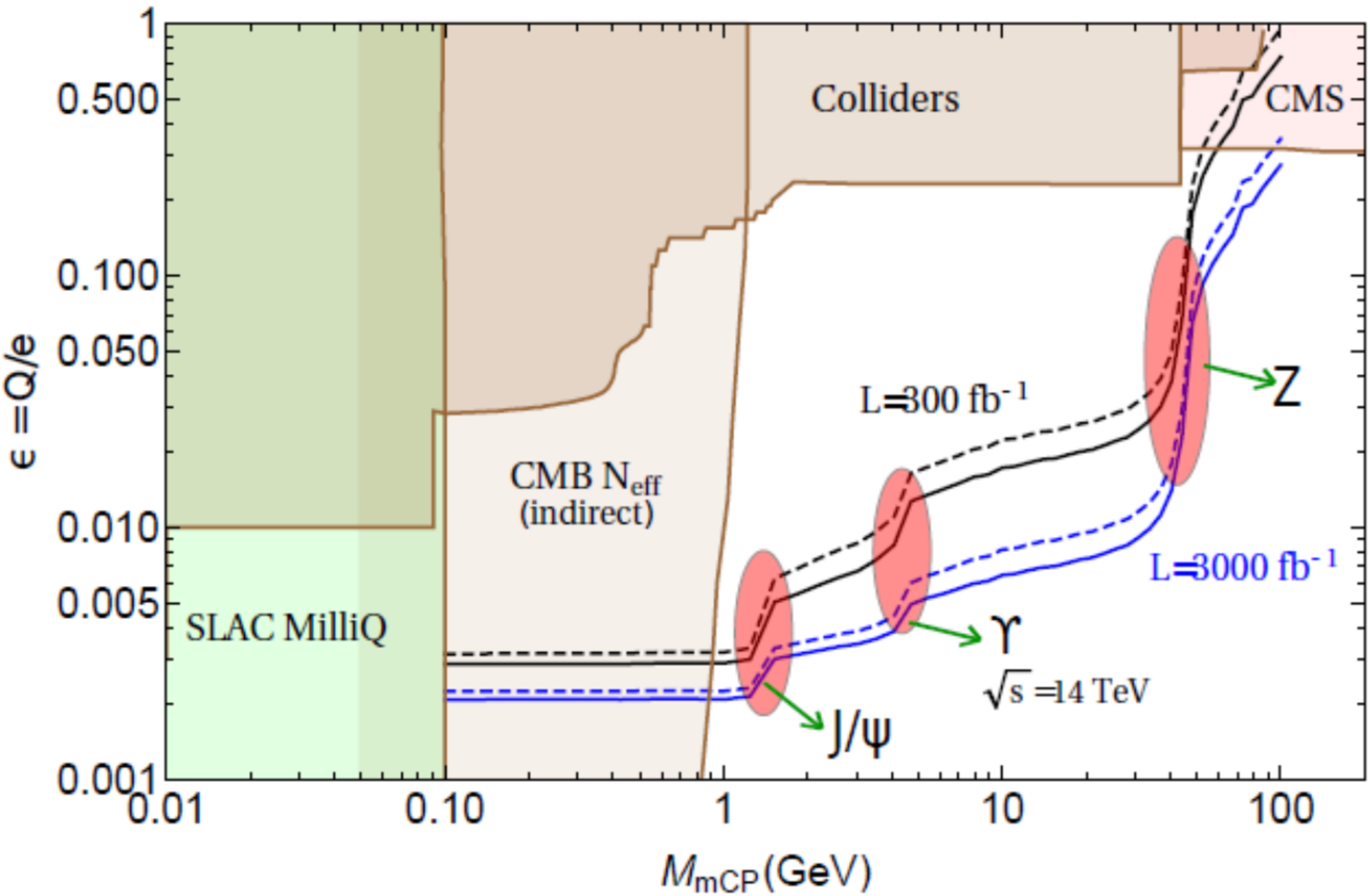
An Expression of Interest to Install a Milli-charged Particle Detector at LHC P5

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).

LHC Reach with milliQan



With Geant4, CMS B-field and Bethe-Bloch energy loss!

New Detectors for the Lifetime Frontier:

MATHUSLA

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

Chou, DC, Lubatti 1606.06298
… & more

Is there any way to detect neutral ultra-long-lived particles (ULLPs) near the BBN bound of $c\tau \lesssim 10^7$ - 10^8 m?

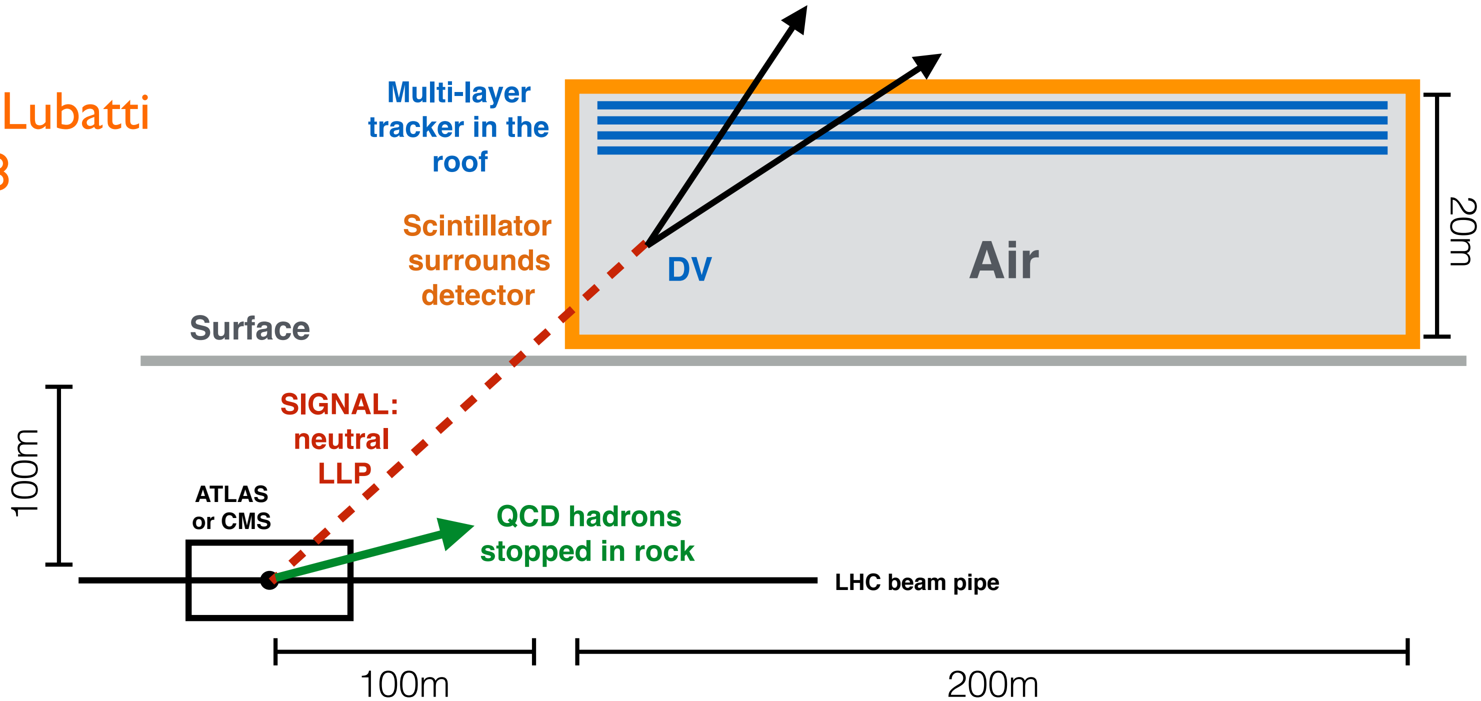
Main Detectors are in principle big enough to observe BBN-lifetime neutral LLPs produces in sizable exotic Higgs decays, but the search is **Background-limited!**

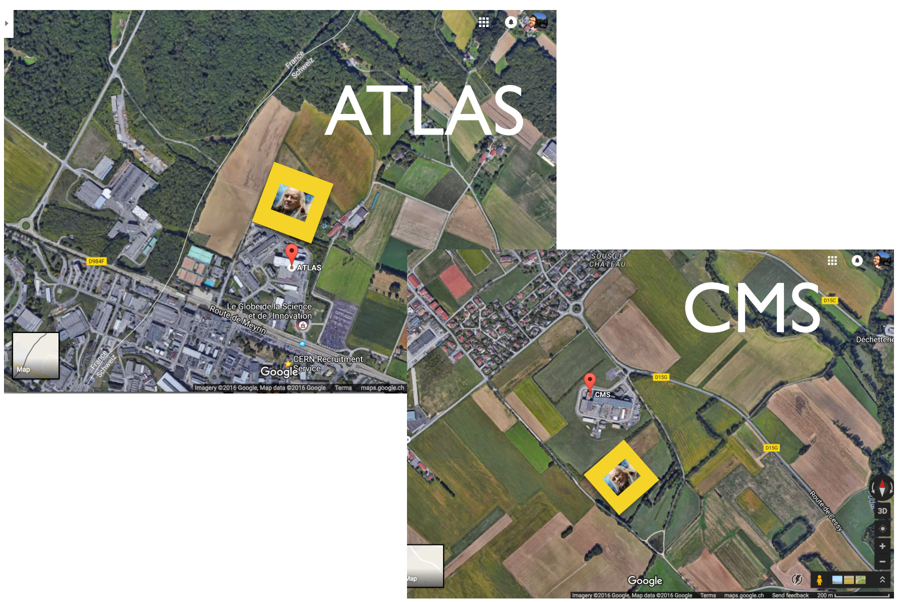
To detect LLPs near the BBN limit, we need

- **the high production rates of the LHC** ✓
- **a zero-background environment!** ✗

An external LLP detector for the HL-LHC

Chou, DC, Lubatti
1606.06298

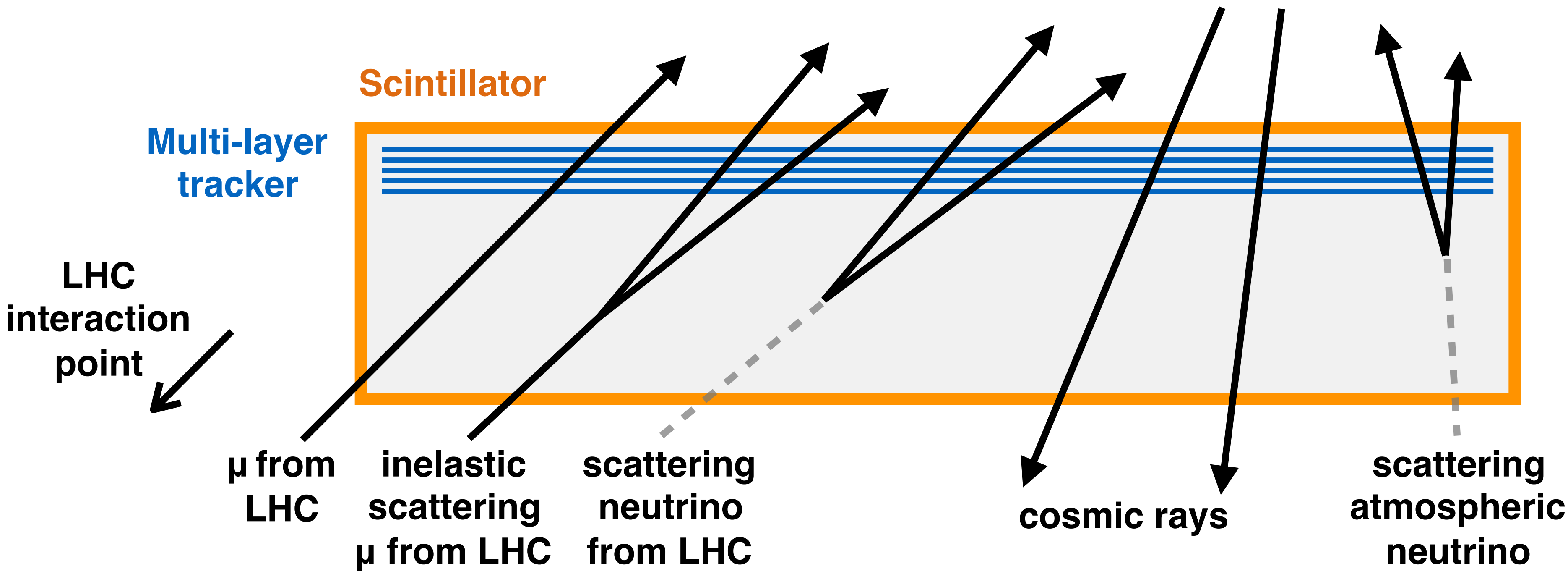




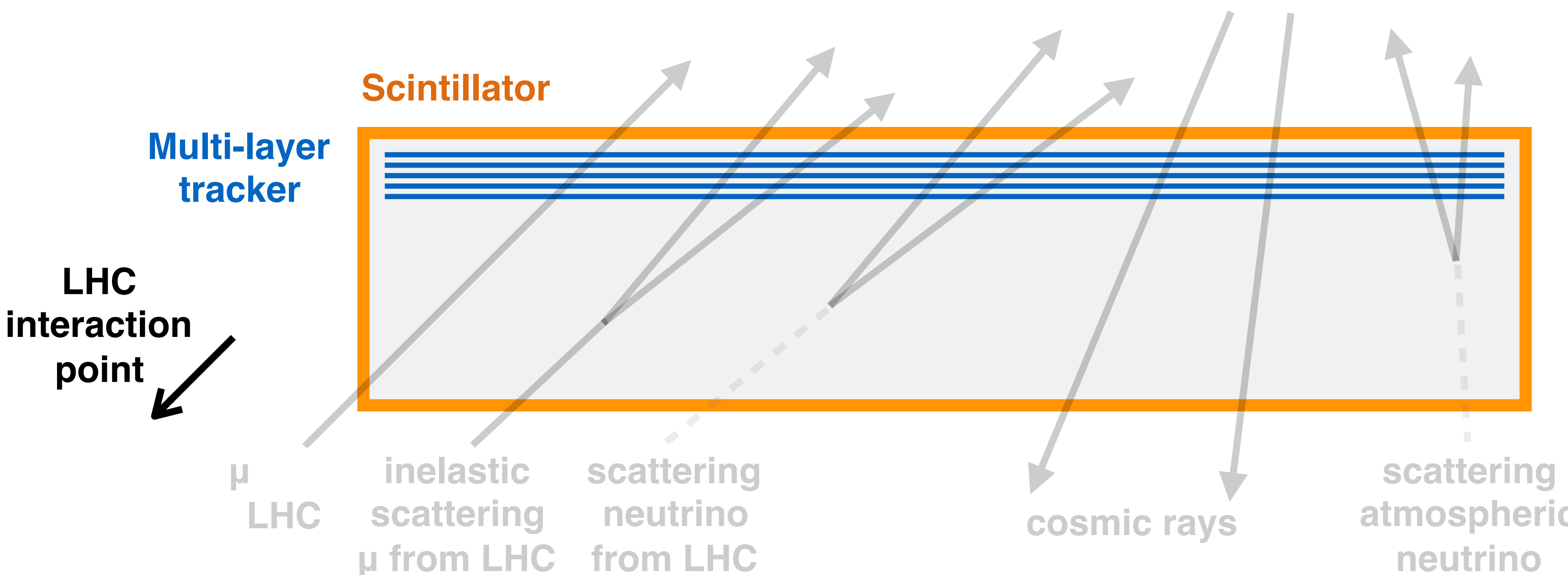
Reliance on well-understood technology (RPC, plastic scintillators) means this could be implemented in time for the HL-LHC.

Unofficial cost estimates:
~ O(50 million USD)

Background Rejection



Background Rejection



Geometry and timing of DV final states vetoes all BGs!

Near-zero-background regime can be reached!

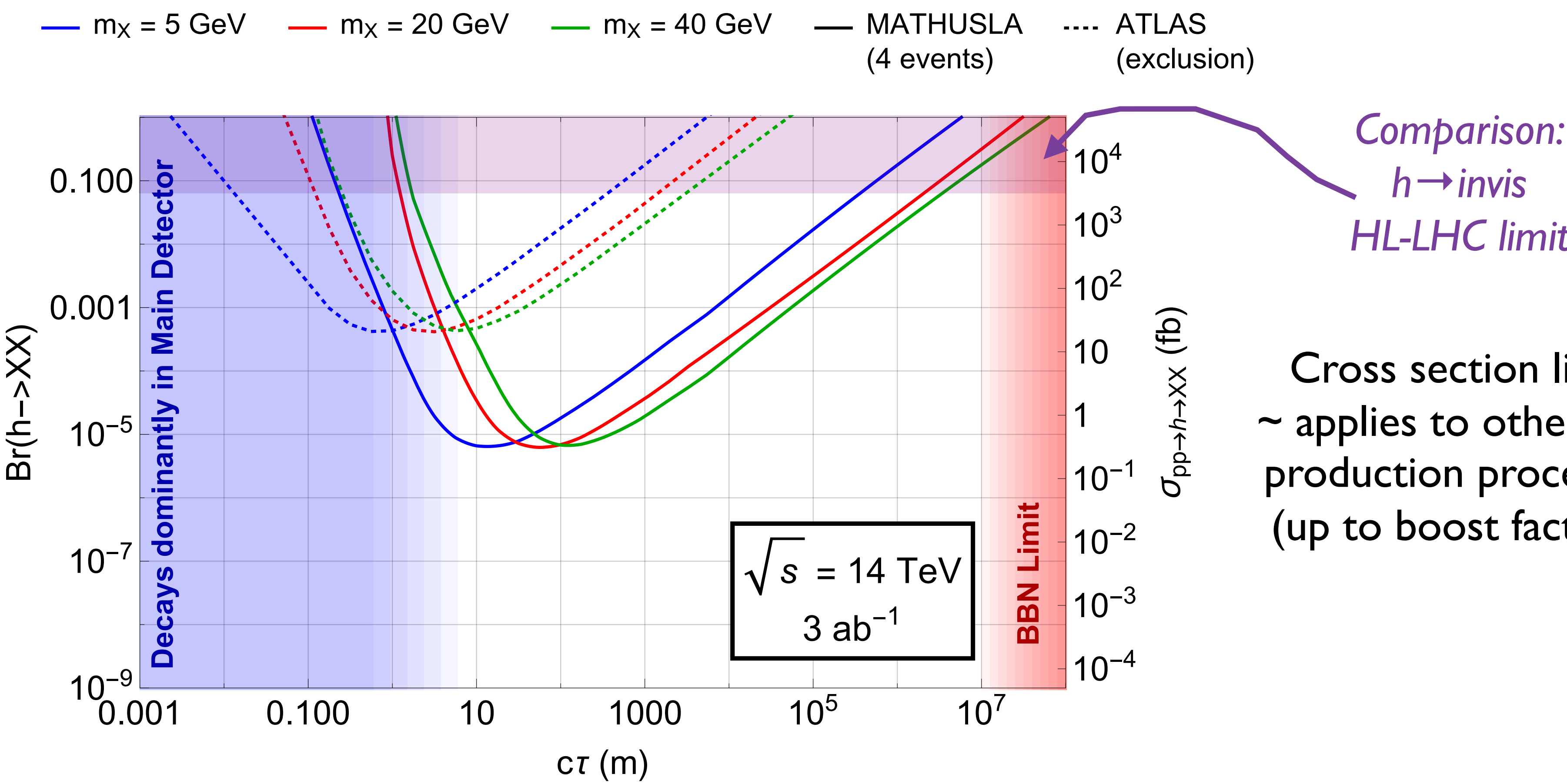
Cosmic backgrounds can be measured and studied during beam down-time to verify rejection strategies.

Example of Achievable Sensitivity

For LLP production in exotic Higgs decays:

Chou, DC, Lubatti
1606.06298

Get close to BBN limit!



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

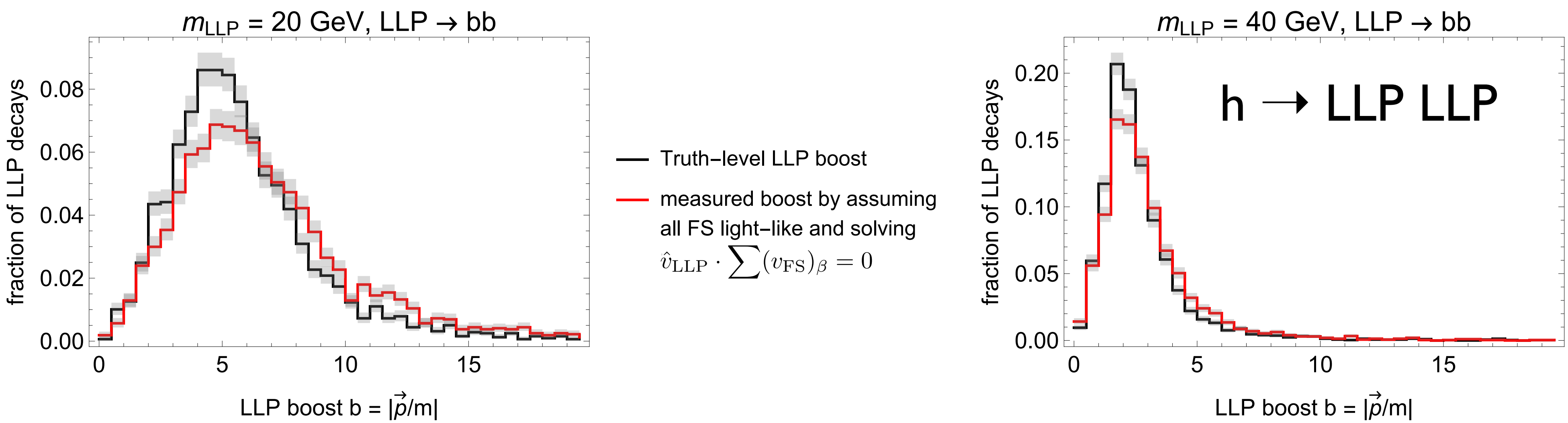
3 orders of magnitude better than ATLAS search for single DV in MS

LLP Diagnosis

DC, Peskin
1705.xxxxx

Known velocity of final states allows us to do Lorentz Transformations!

Boost of LLP can be determined event-by-event using spherical symmetry of decay, for both leptonic and hadronic decays!



Boost distribution → **LLP mass** for given **production mode**, (maybe both).

Final state multiplicity and angular correlations determine
LLP decay mode and spin

Complete LLP characterization possible with O(100) events!

So what has to happen now?

MATHUSLA collaboration

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Cristiano Sebastian	Cristiano.Sebastiani@cern.ch	Sapienza Università di Roma

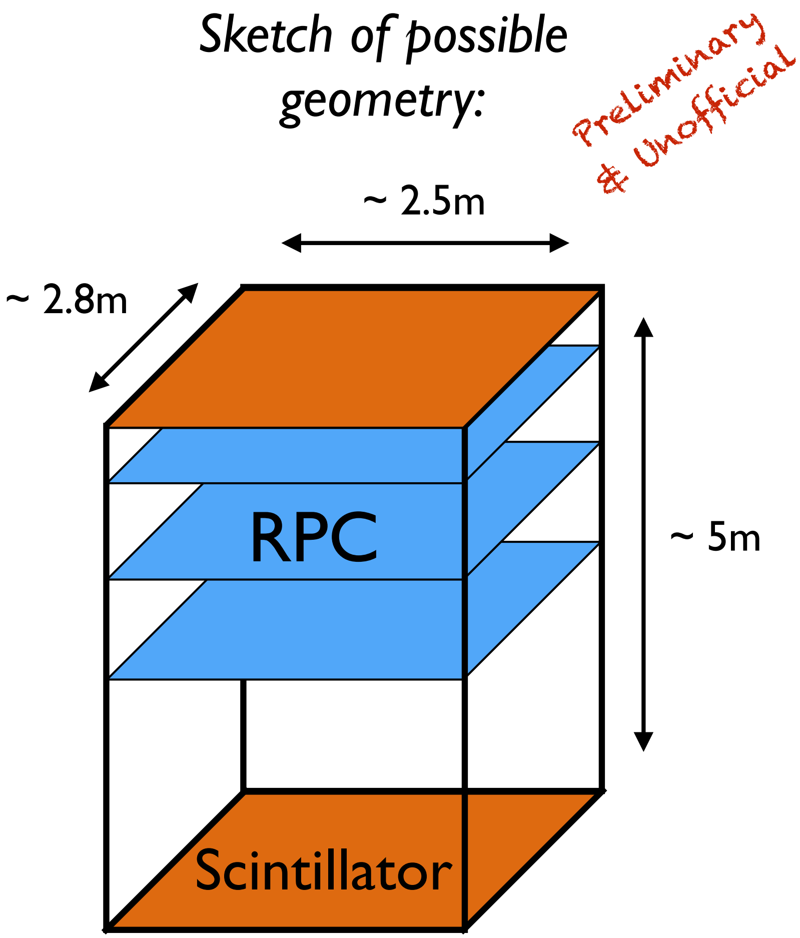
~ 40 experimentalists @ ~10 institutions

Join us!

Prototype

Required to validate design, background estimates, etc..

Sketch of possible geometry:



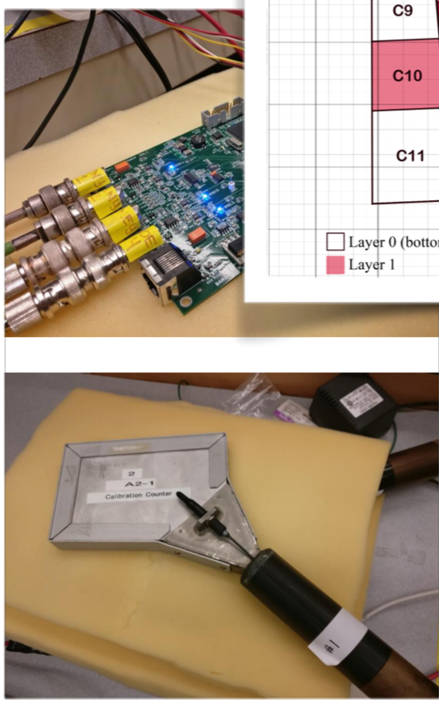
Procured detector components left-over from D0 and ARGO

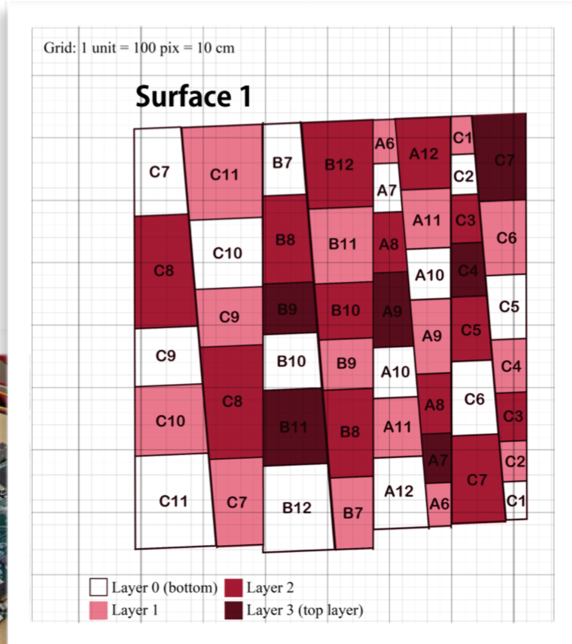
Place in ATLAS installation pit, get data with and without LHC collisions.
→ *approved by Technical coordinator, get access to gas for RPCs!*

On track for installation May 2017!

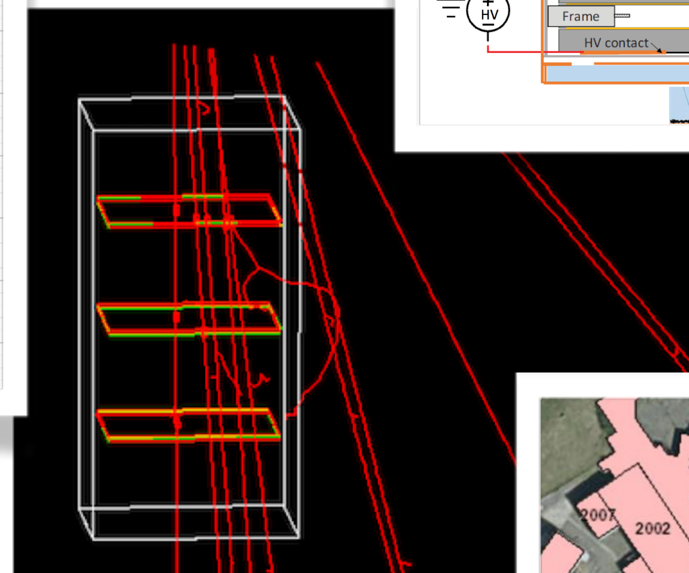
Aim: official letter-of-intent for full detector ~late 2017!

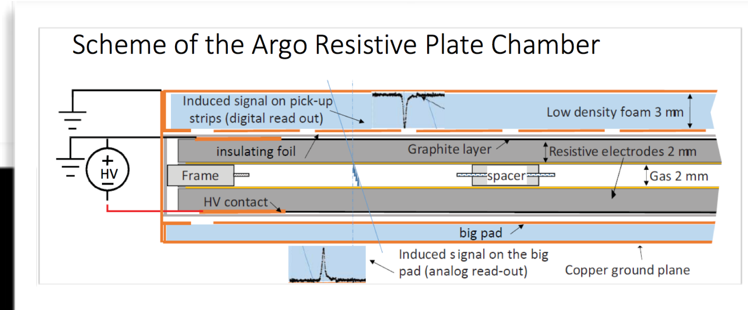
Prototype





Grid: 1 unit = 100 pix = 10 cm
Surface 1
Layer 0 (bottom)
Layer 1
Layer 2
Layer 3 (top layer)





Scheme of the Argo Resistive Plate Chamber
Induced signal on pick-up strips (digital read out)
Low density foam 3 mm
insulating foil
Graphite layer
Resistive electrodes 2 mm
Frame
spacer
Gas 2 mm
HV
HV contact
big pad
Induced signal on the big pad (analog read-out)
Copper ground plane

2003
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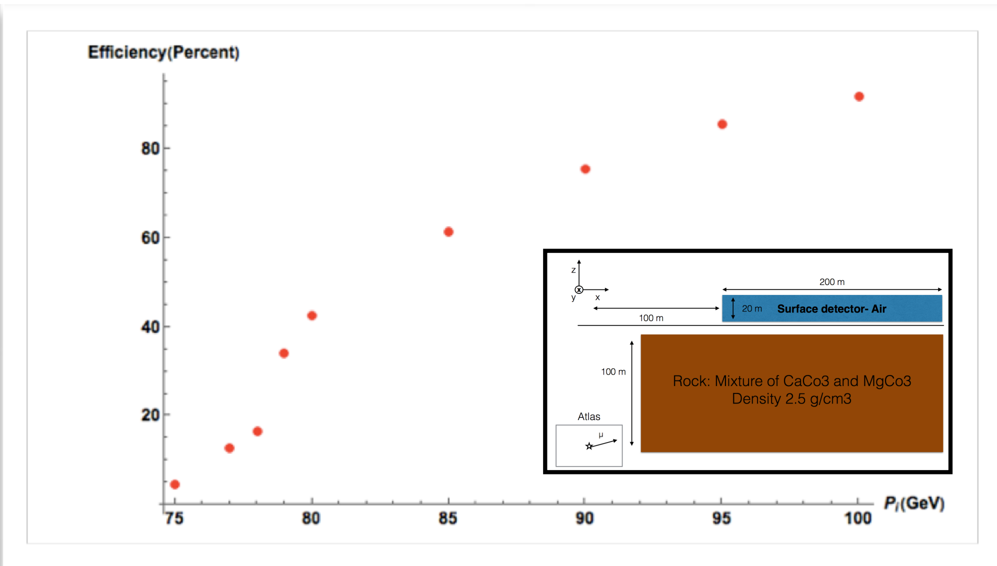
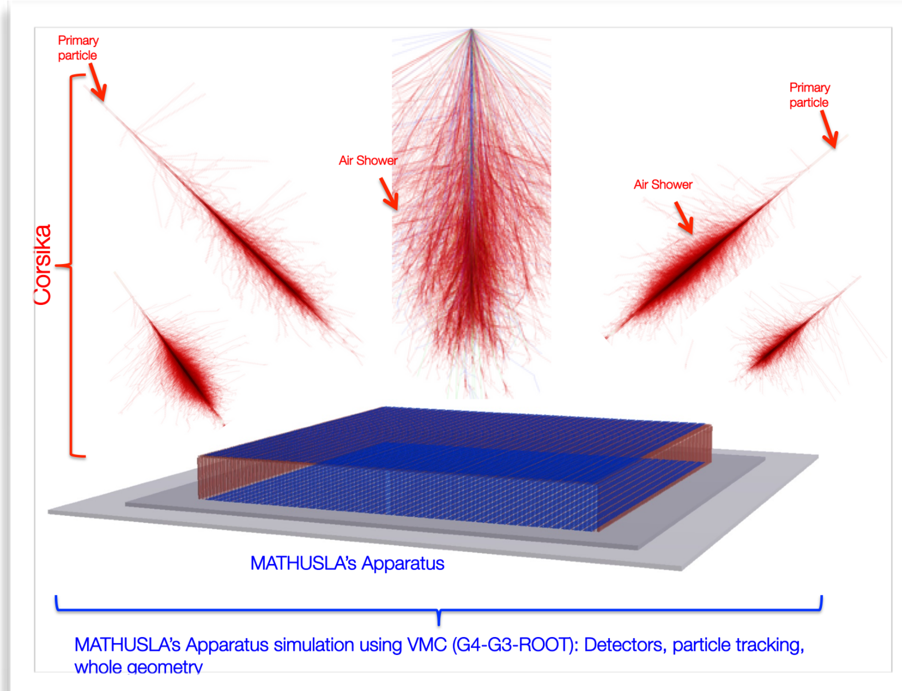
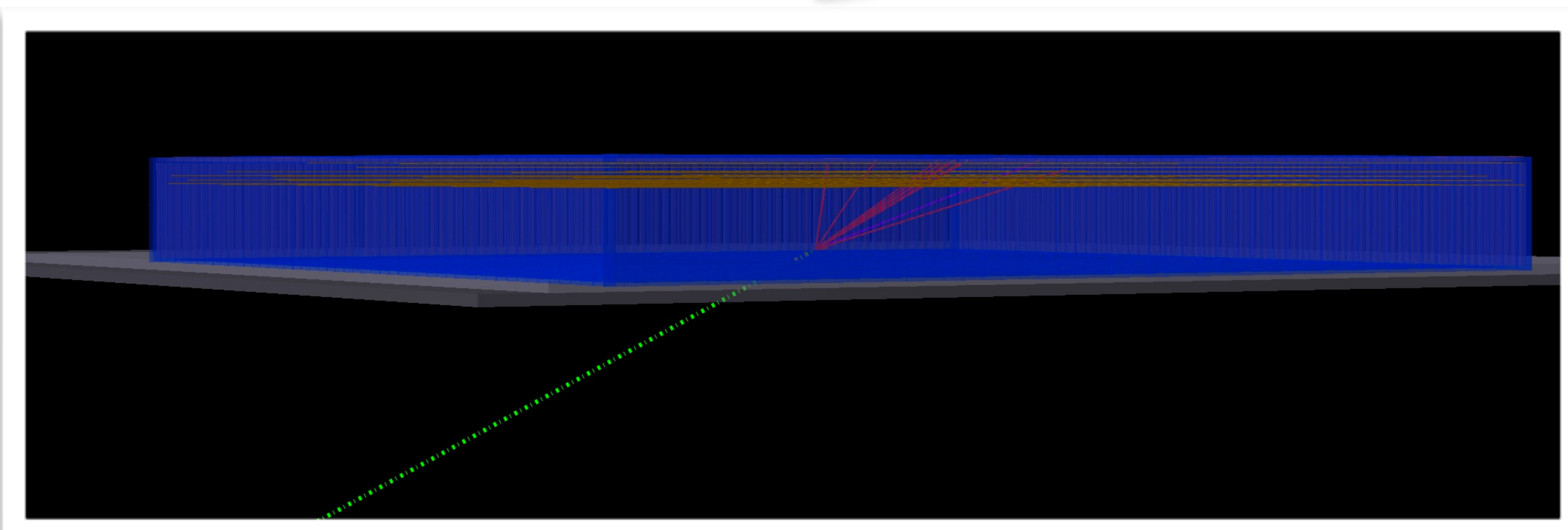
Route NEWTON
Route WU
CLIC Experiment
Route GAUSS
Route BAKKER
Route SALAM

Preparing for the Big Detector







MATHUSLA Theory White Paper

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

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Collaboration of 70+ theorists

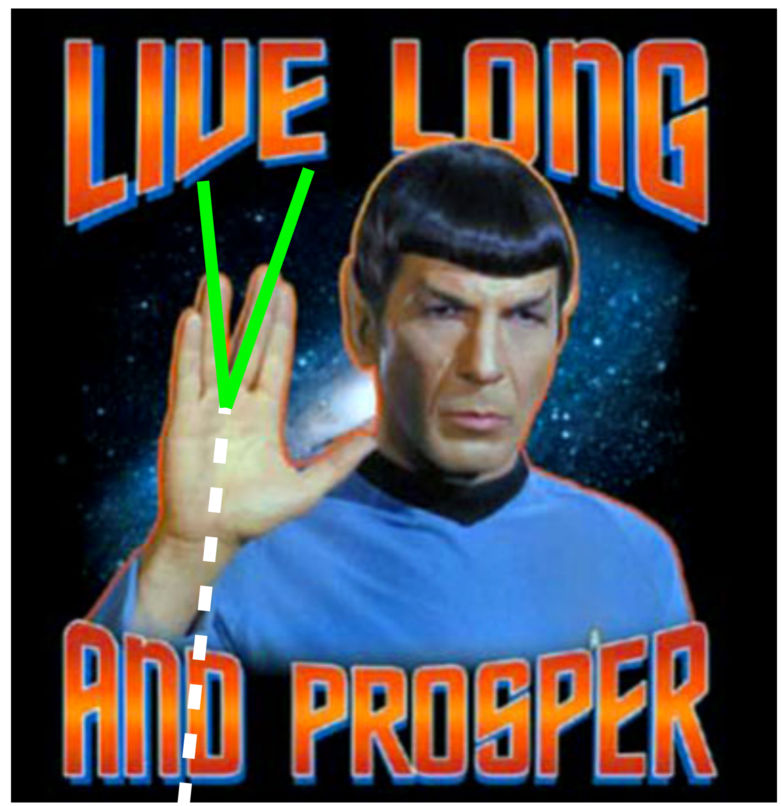
Aim: comprehensive report by mid-2017

MATHUSLA represents our only chance to detect many of the best-motivated **Long-Lived Particle** scenarios.

This is strongly motivated both **theoretically** and by **LHC null** results so far.

If we can make this detector a reality in the next decade, revolutionary discoveries of Hidden Sectors could be our reward!

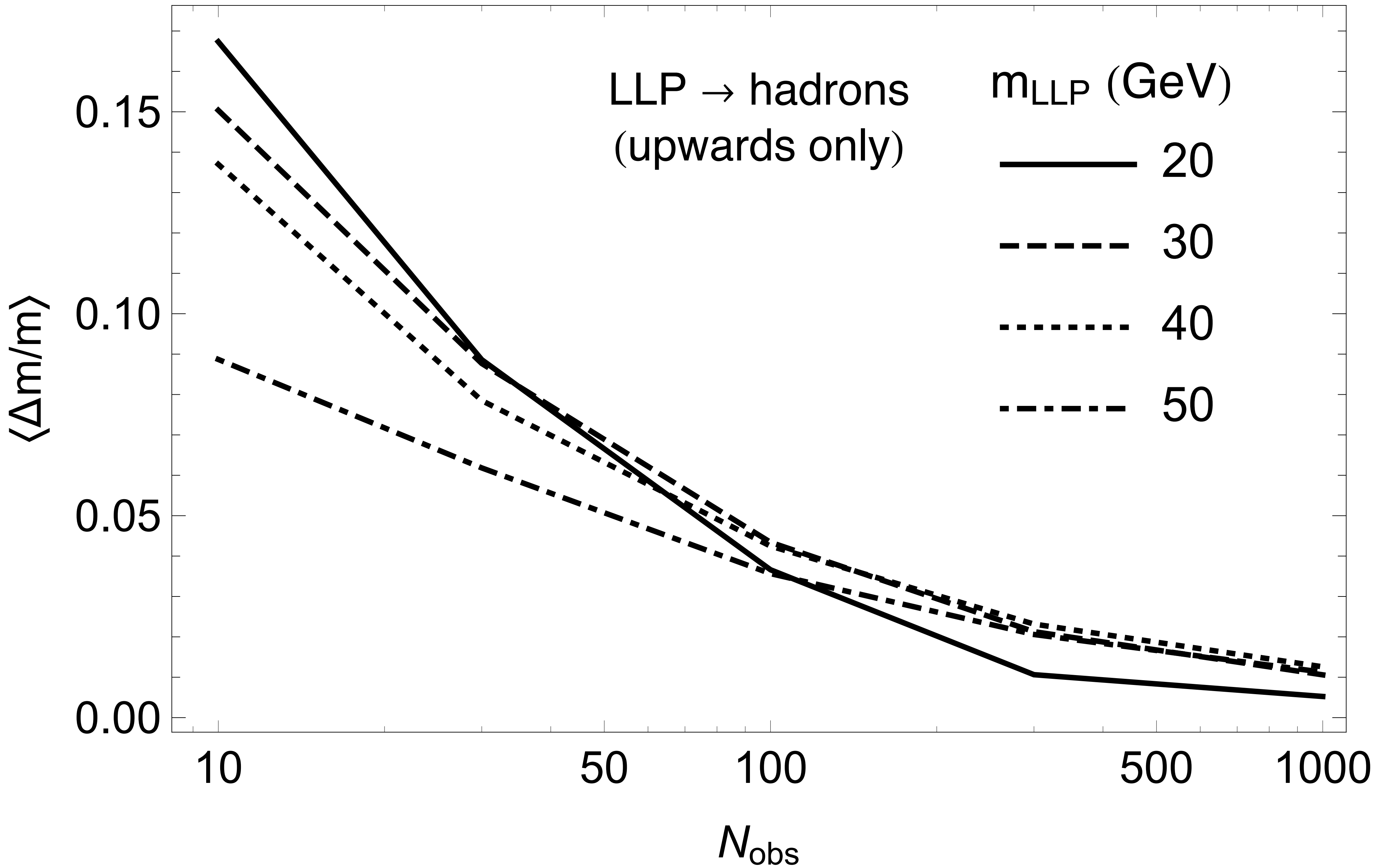
— *Thank you!* —



Backup

LLP Mass Measurement at MATHUSLA

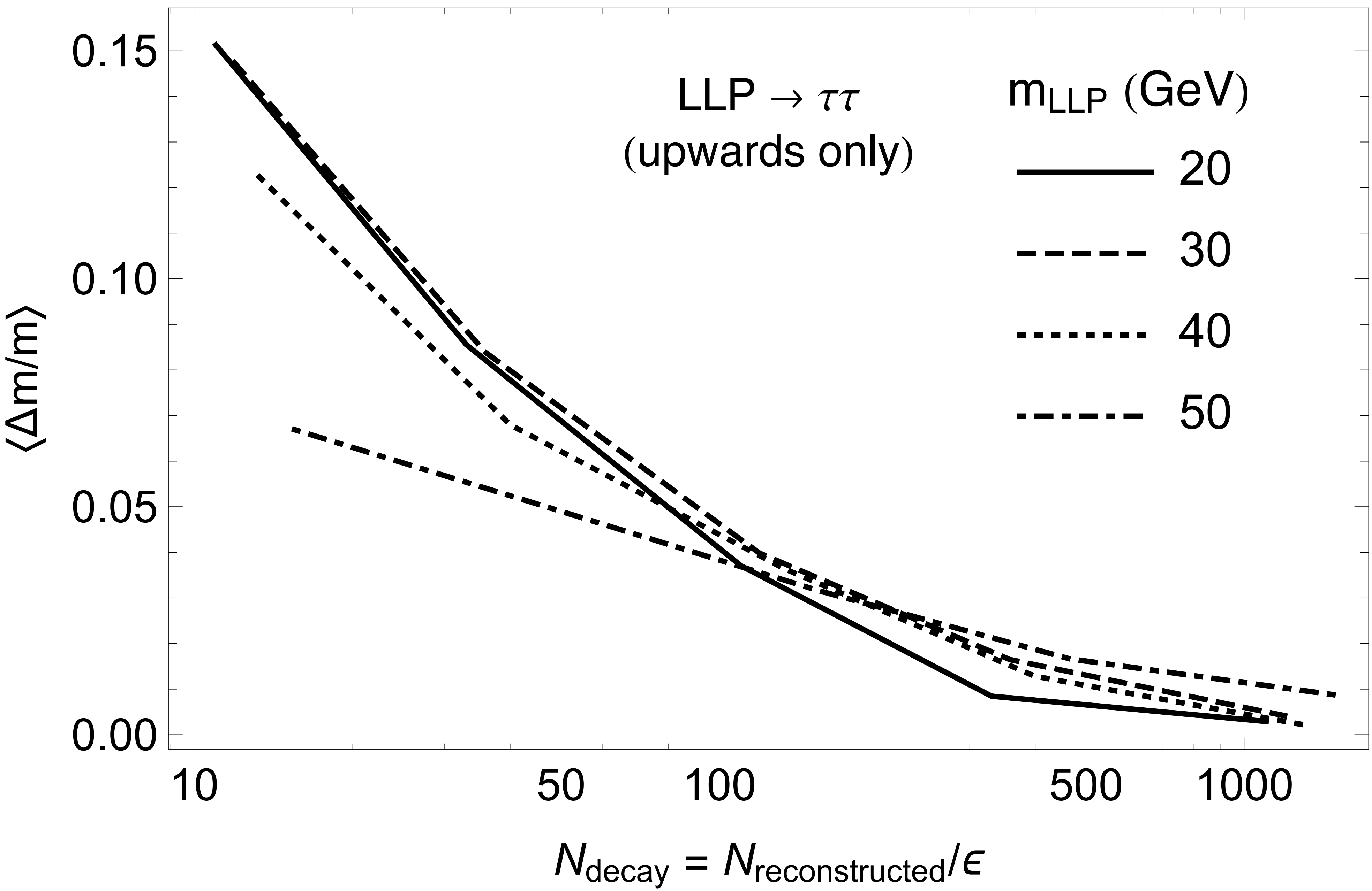
DC, Peskin
1705.xxxxx



PRELIMINARY

LLP Mass Measurement at MATHUSLA

DC, Peskin
1705.xxxxx



PRELIMINARY

LLP Mass Measurement at MATHUSLA

DC, Peskin
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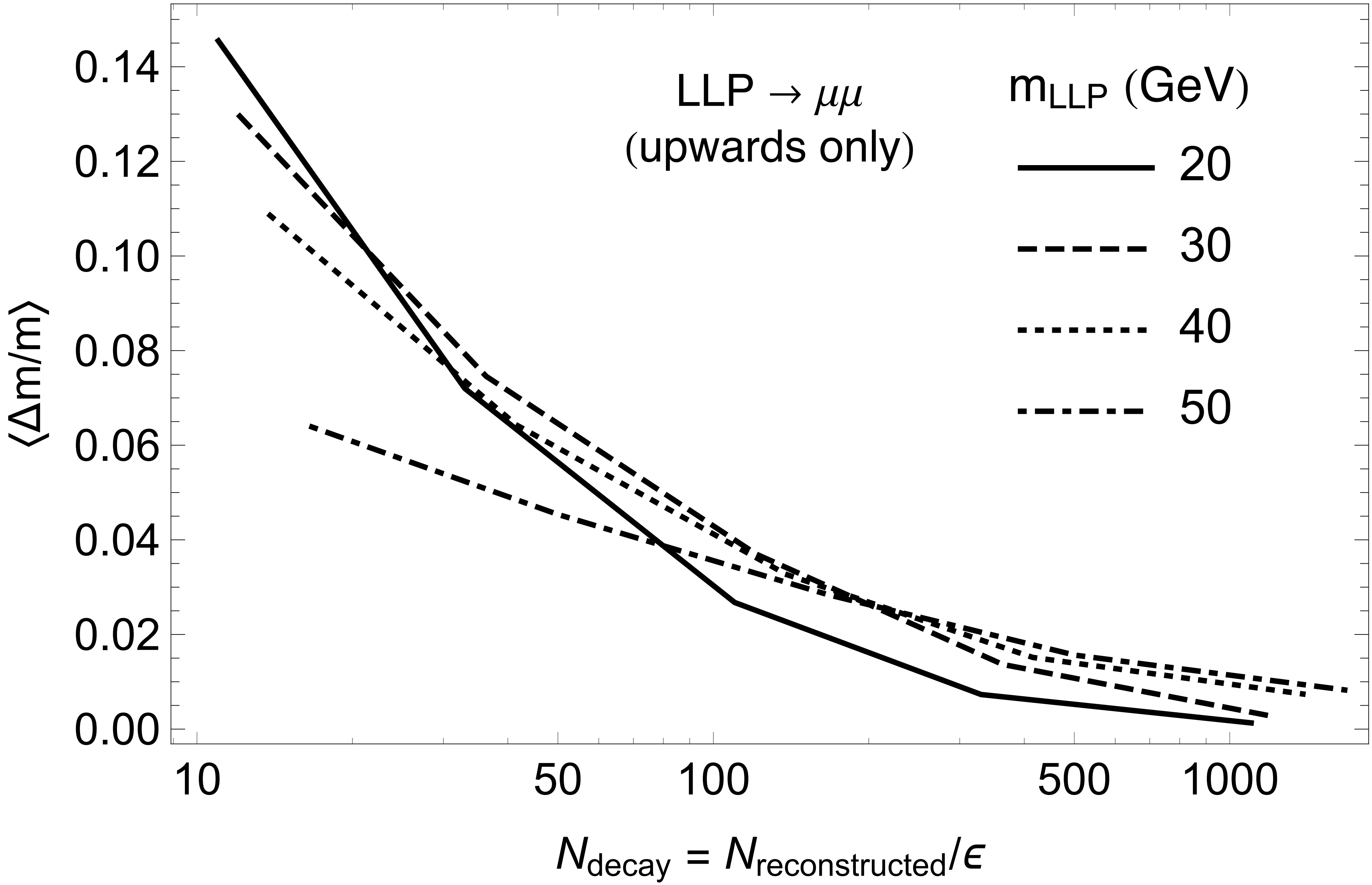
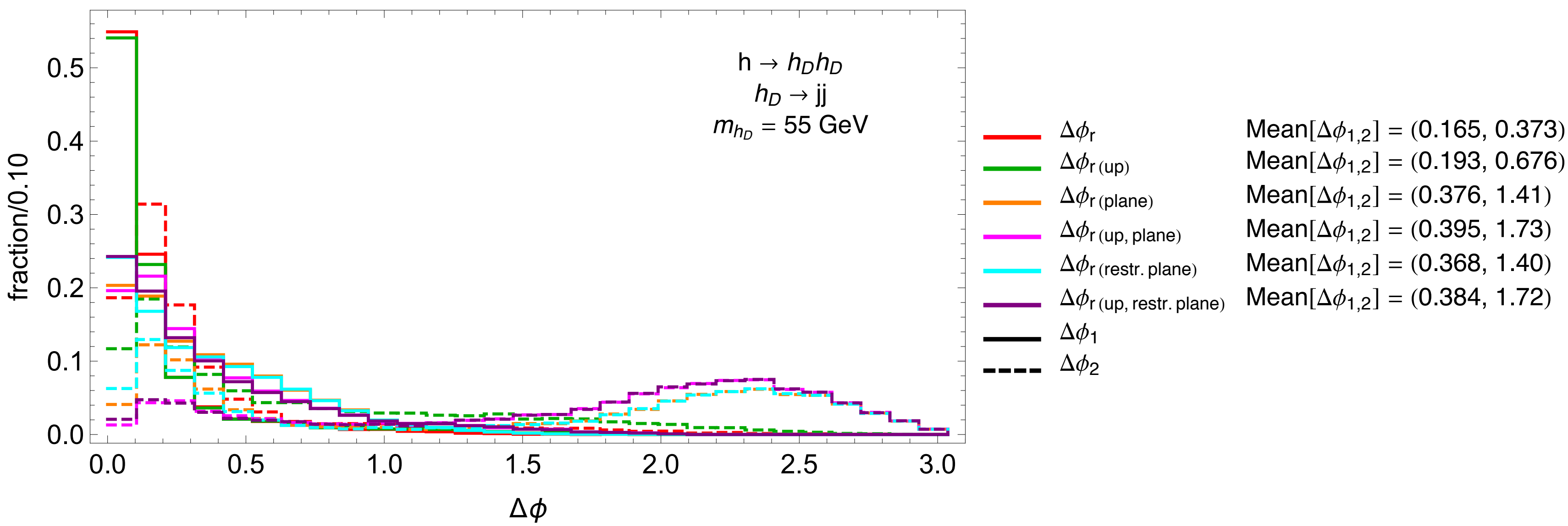
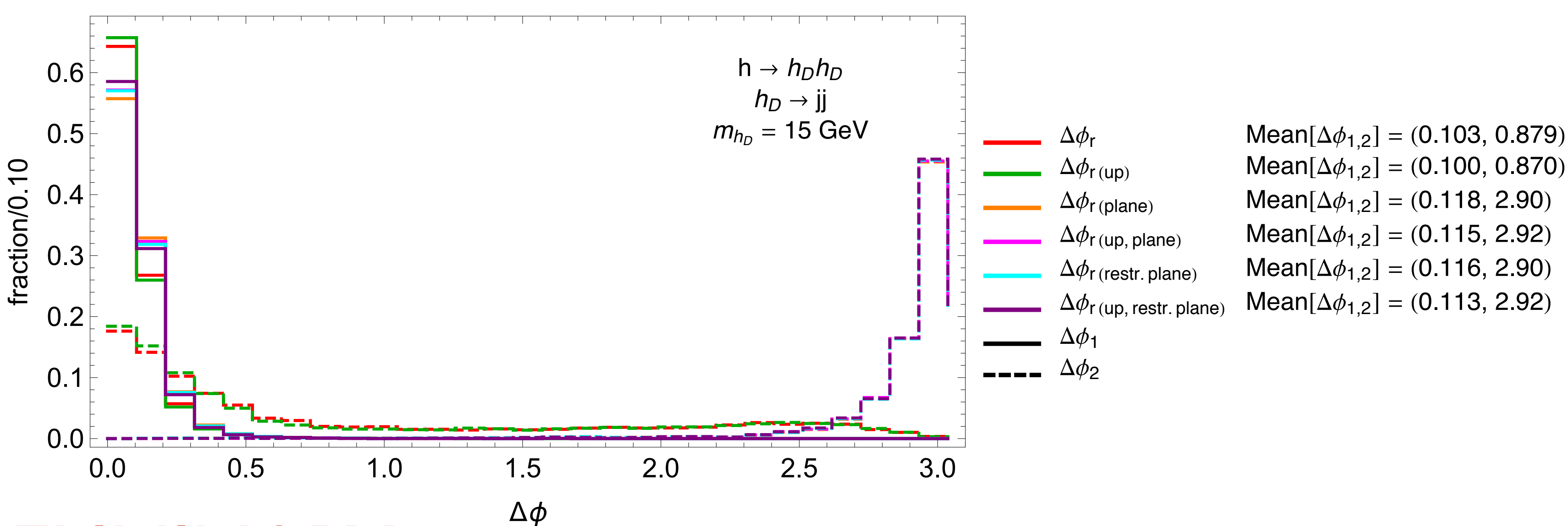


PRELIMINARY

LLP Decay Jet Axis Measurement at MATHUSLA





PRELIMINARY

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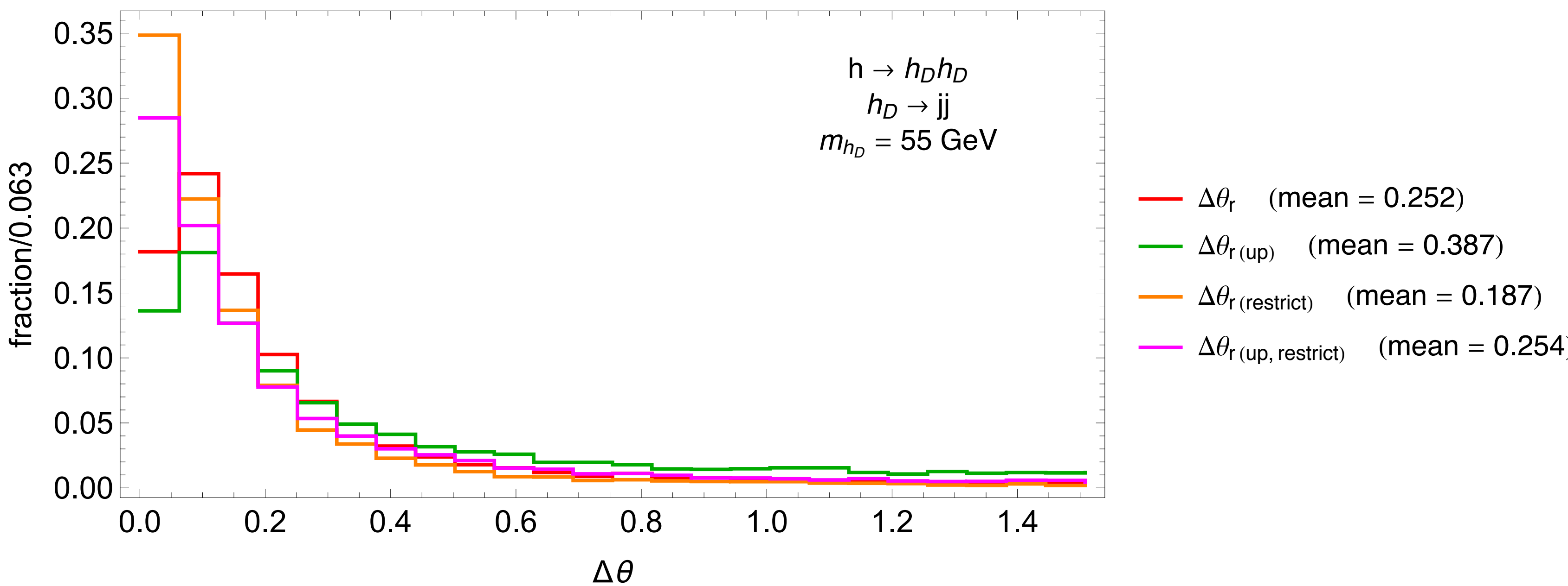
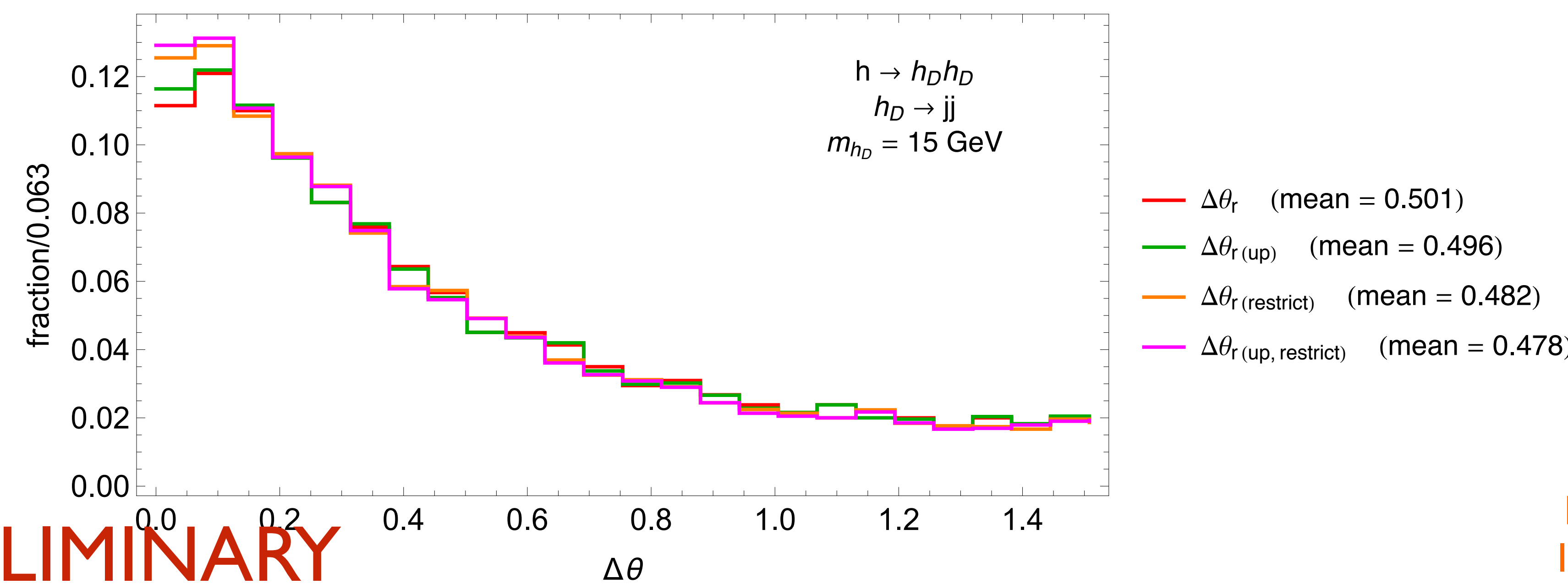
LLP Decay Plane Measurement at MATHUSLA





PRELIMINARY

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