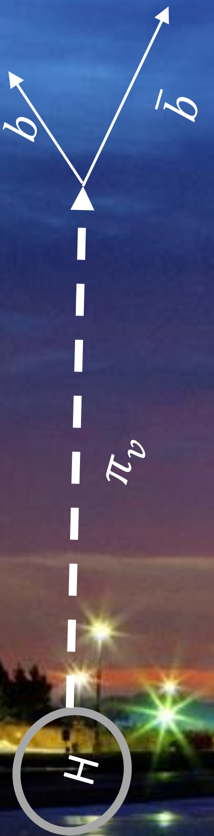
The Lifetime Frontier: To the LHC and Beyond!



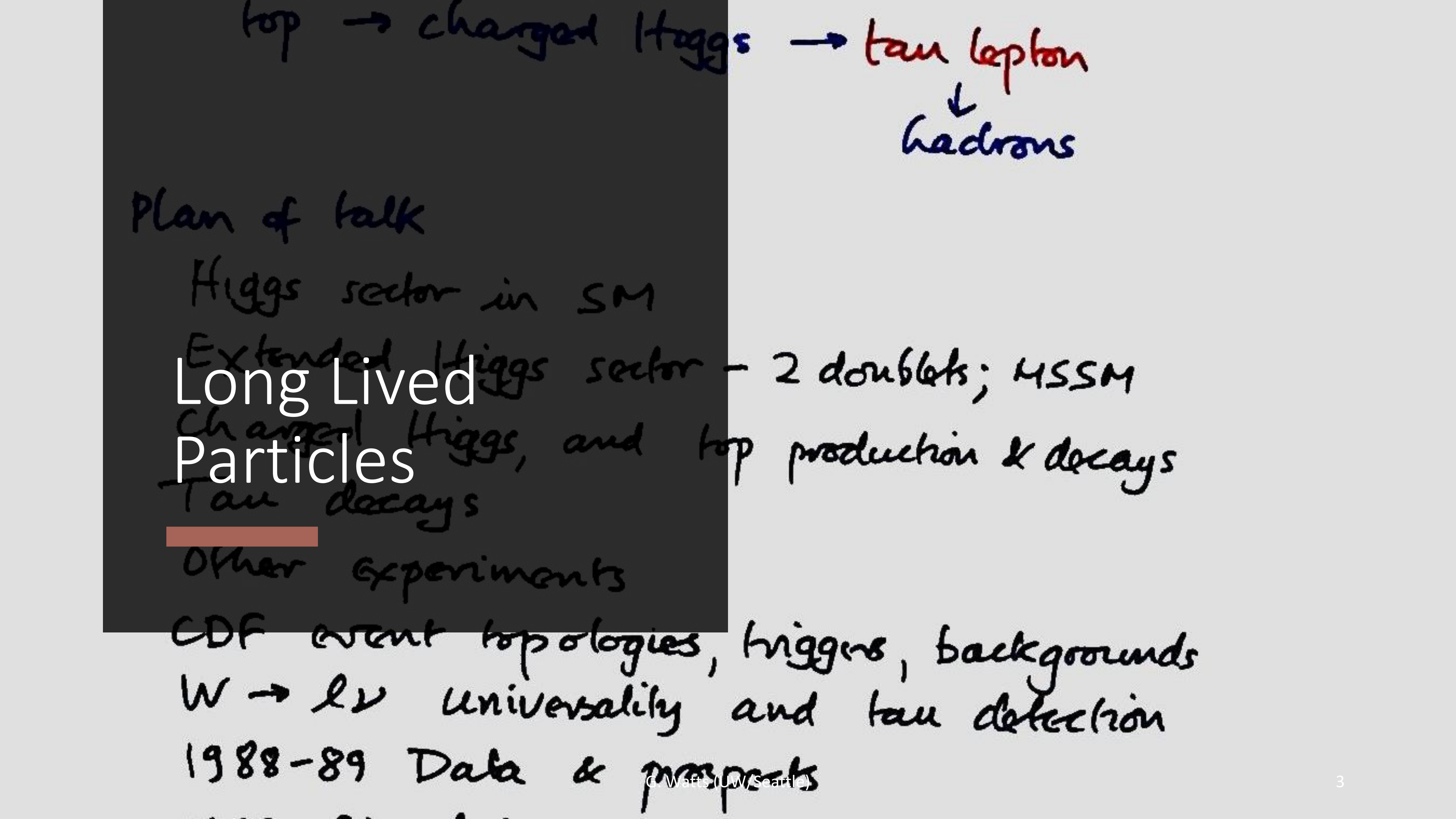
G. Watts (UW/Seattle)

Outline

Long Lived Particles

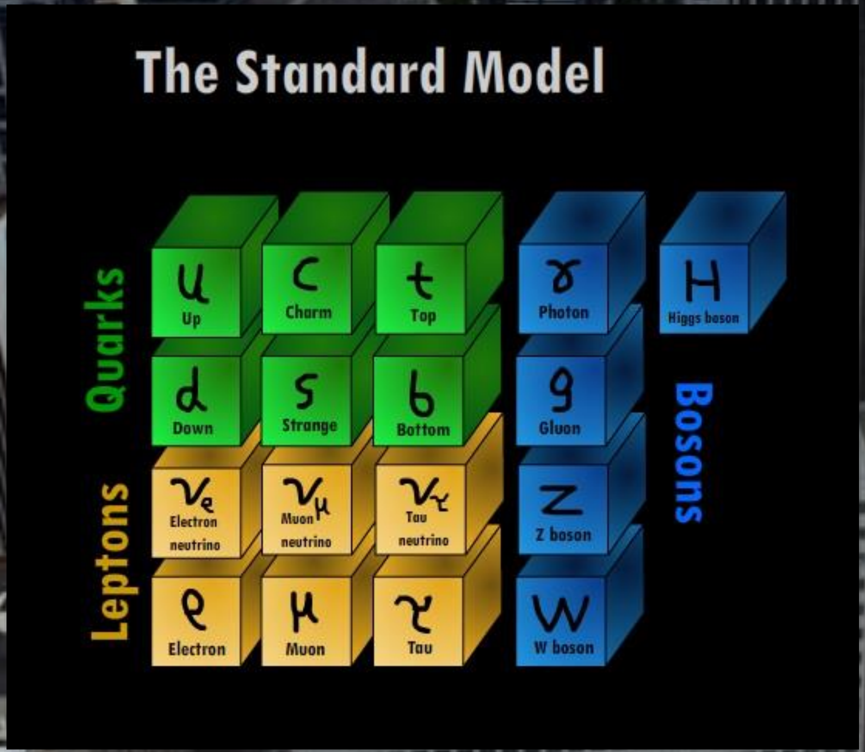
Searching for Long Lived Particles at the LHC

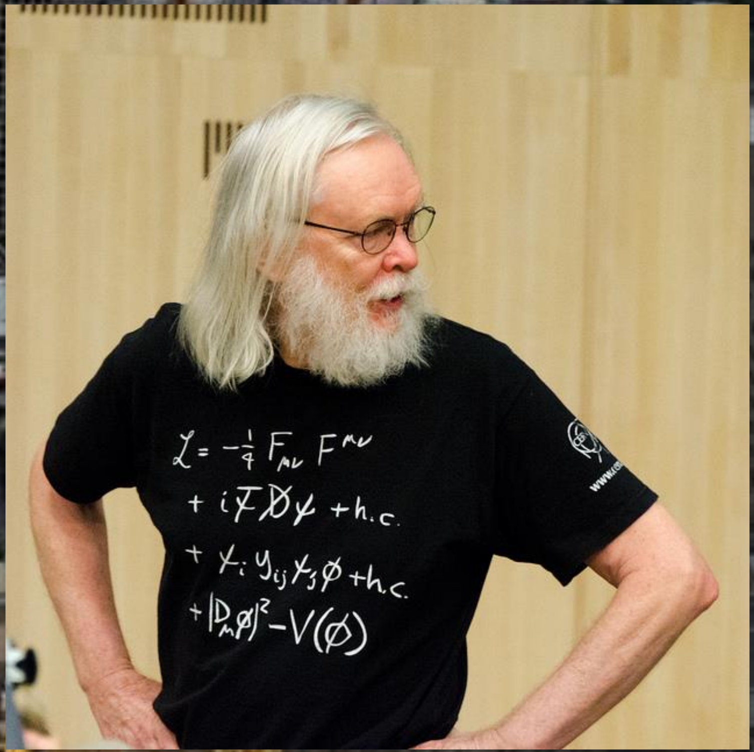
Searching for Ultra Long Lived Particles

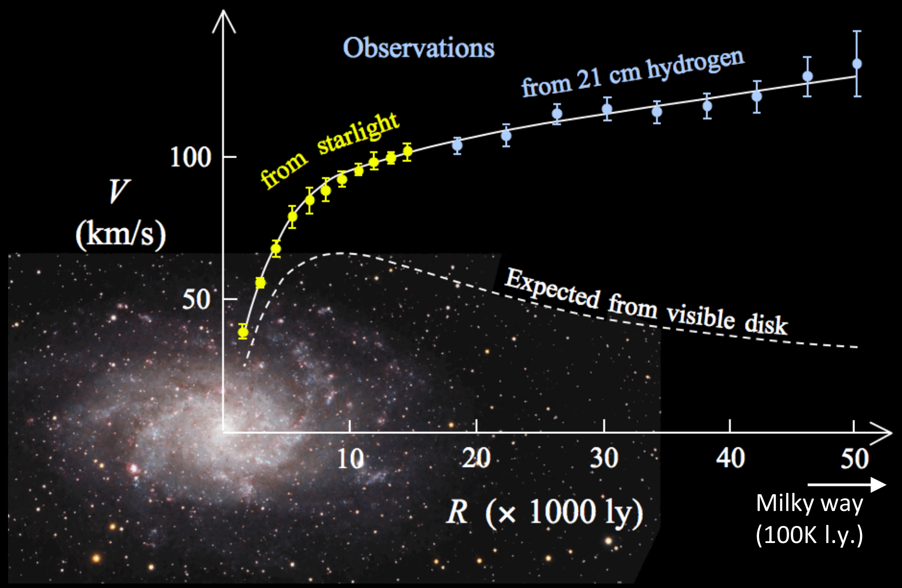


Long Lived Particles

2012 We completed the Standard Model

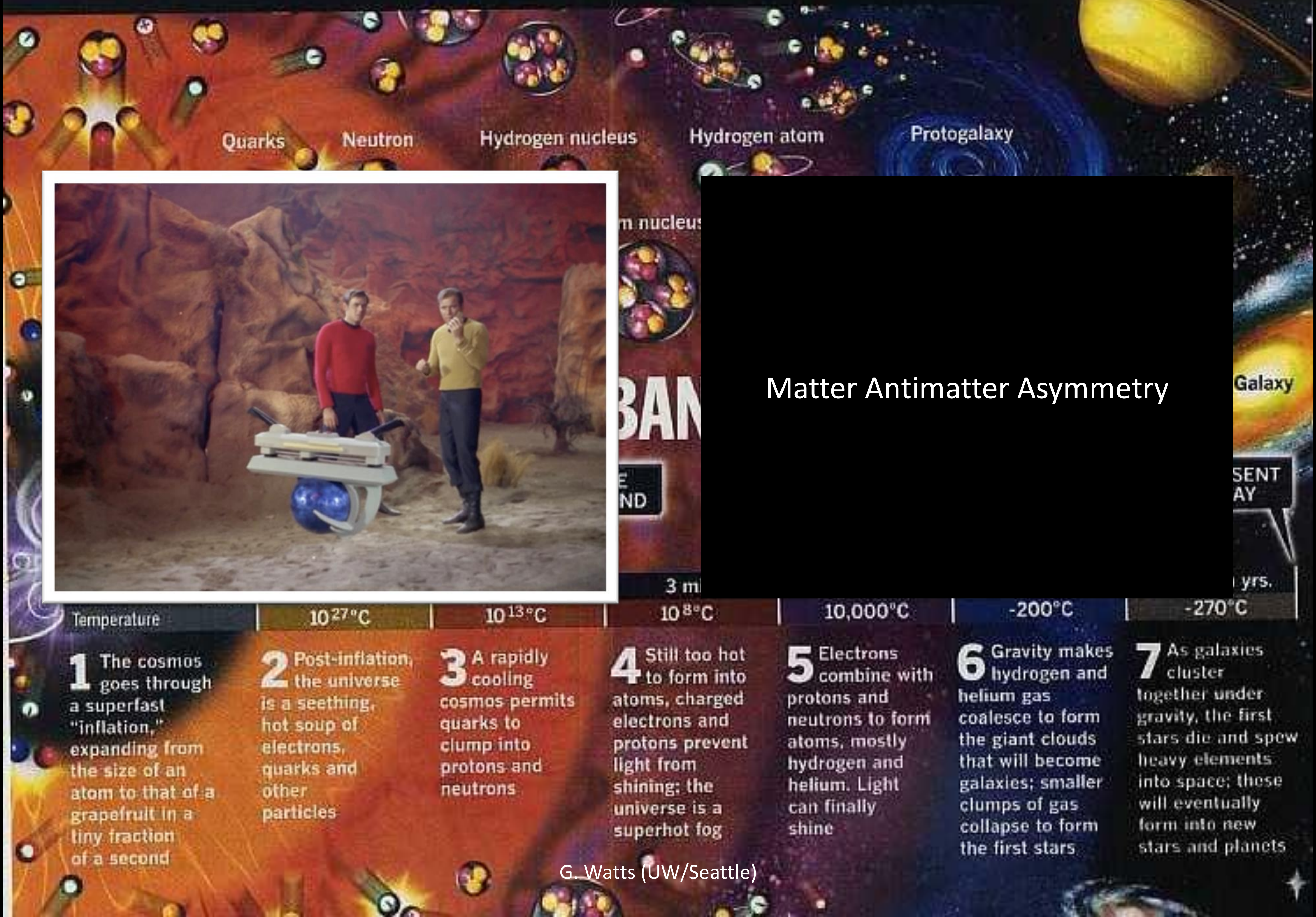





Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)
Milky way
(100K l.y.)

Dark Matter

Matter Antimatter Asymmetry



Super Symmetry

Little Higgs Model

String Theories

Extra Dimensions

Supergravity

Grand Unified Theories

MSSM

WIMPS

Higgs Doublet

Hidden Sector Models

$SU(3)^3$

Axions

No Evidence


SUSY
LLPs

Long Lived Particles

Almost every BSM theory accommodates them (some require them).

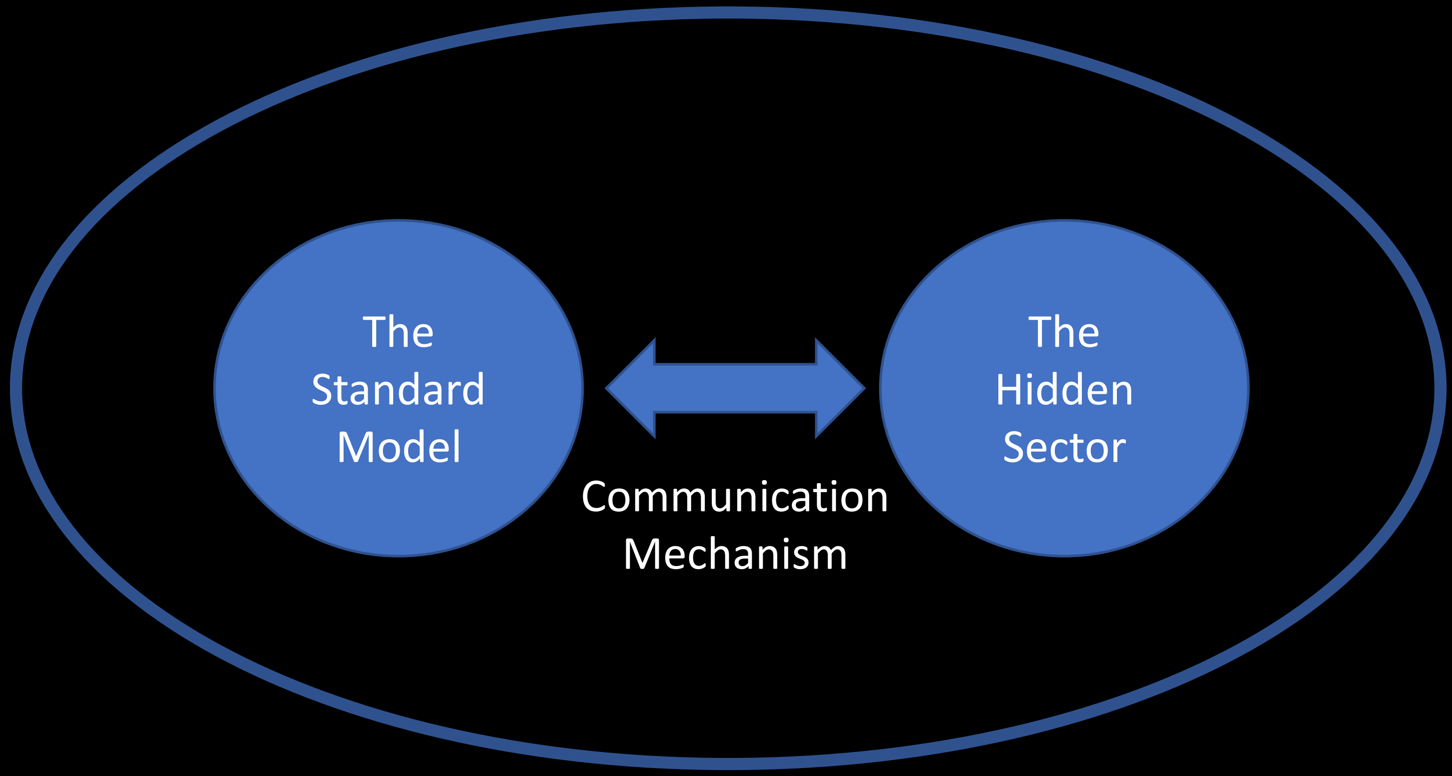
Some recent papers:

- 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/Z (arXiv:1604.00044)
- Theories of Neutral Naturalness (arXiv:1512.05782)
- Models generating neutrino masses (arXiv:1604.06099)
- Exotic Decays of the Higgs Boson (arXiv:1312.4992)

Lots of different possible detector signatures!

↑

Motivated by the signal model


The Standard Model
The Hidden Sector
Communication Mechanism

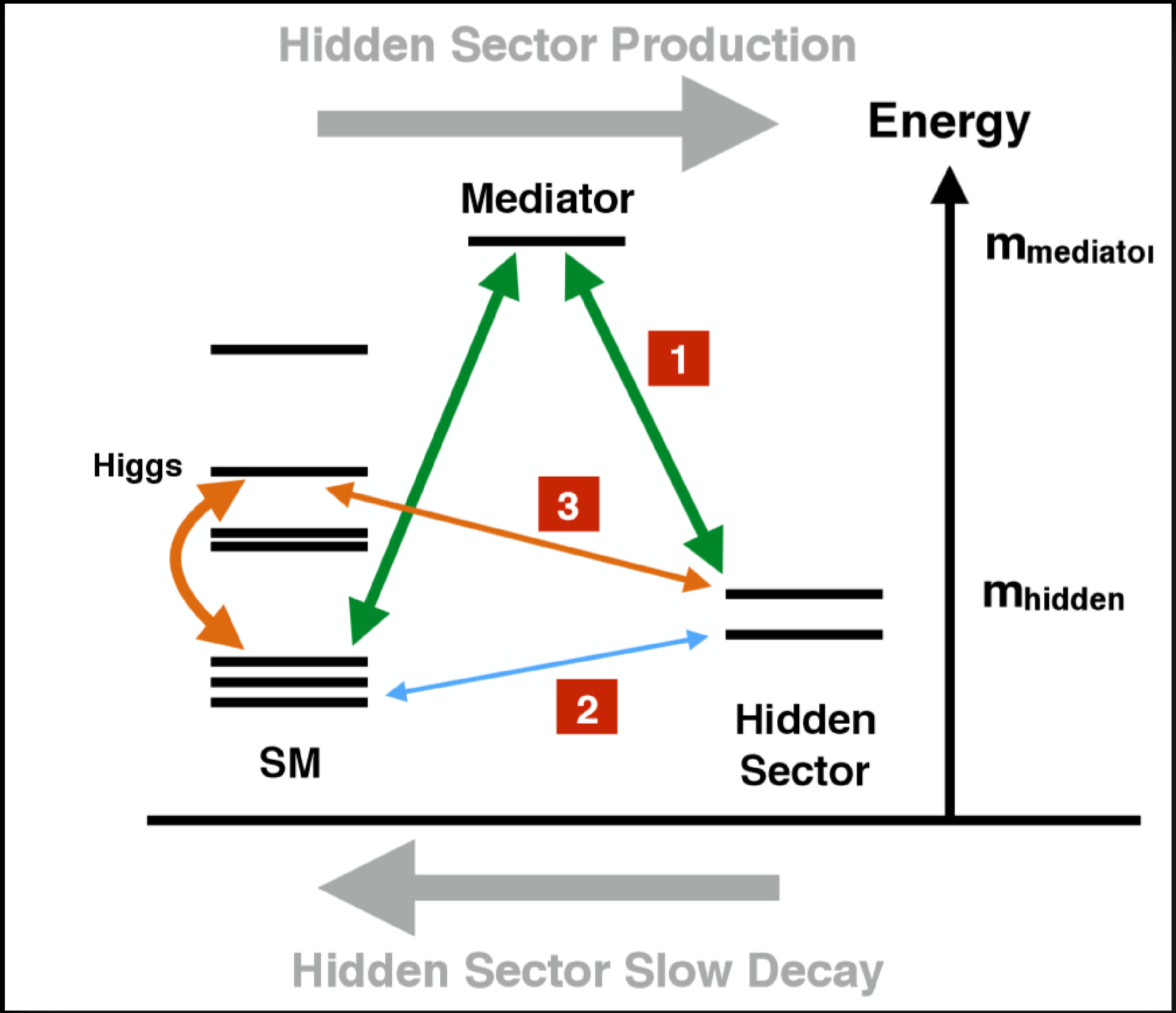
Hidden Sector

A gauge group that does not interact via the SM gauge fields

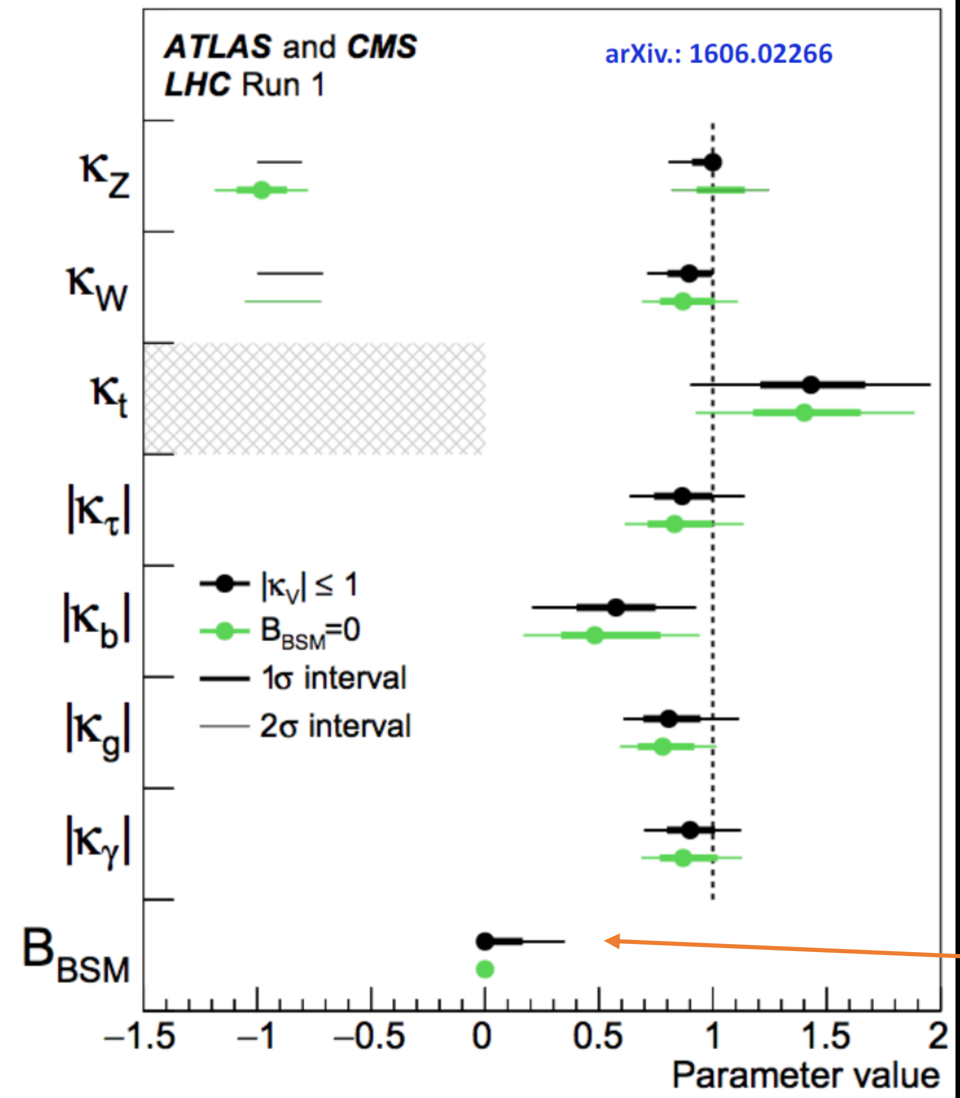
- A phenomenology of arbitrary complexity
- Does interact via gravity (DM)

Hidden Valley

Some particles come back!

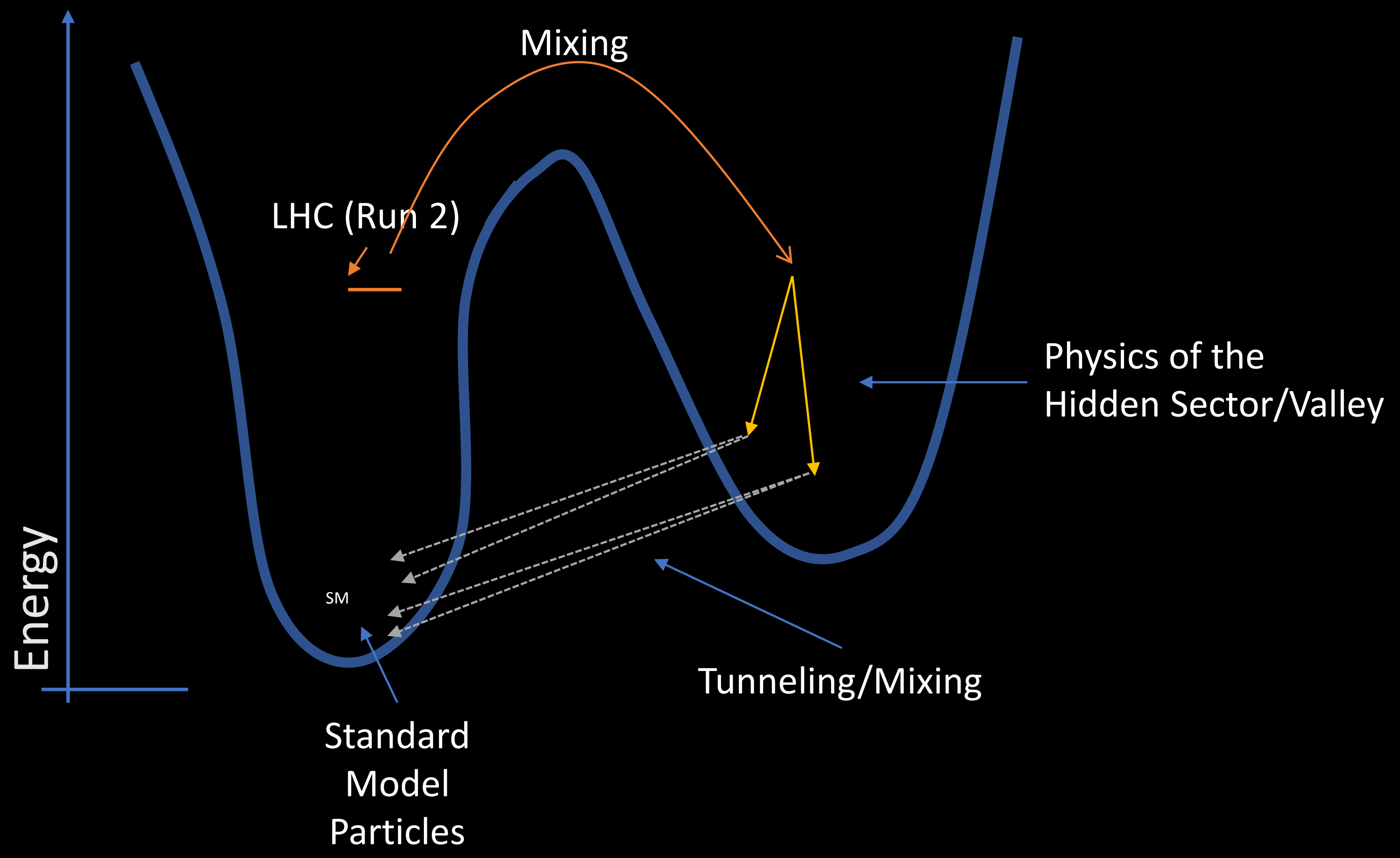

Hidden Sector Production
Energy
Mediator
$m_{mediator}$
1
Higgs
3
m_{hidden}
2
Hidden Sector
SM
Hidden Sector Slow Decay

The Higgs as a Communicator

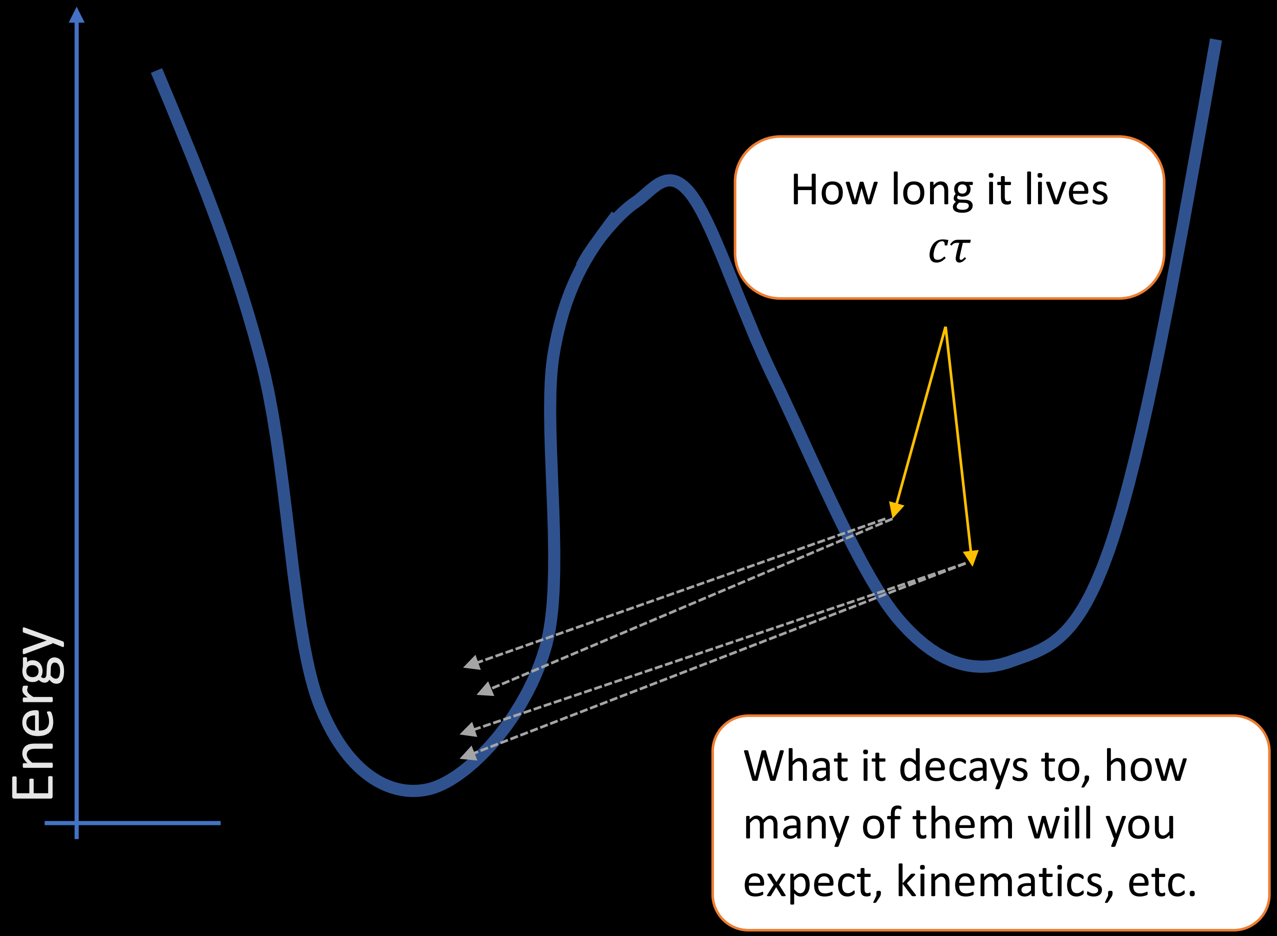


Room for a 30% invisible decay

Detector Signatures



Detector Signatures



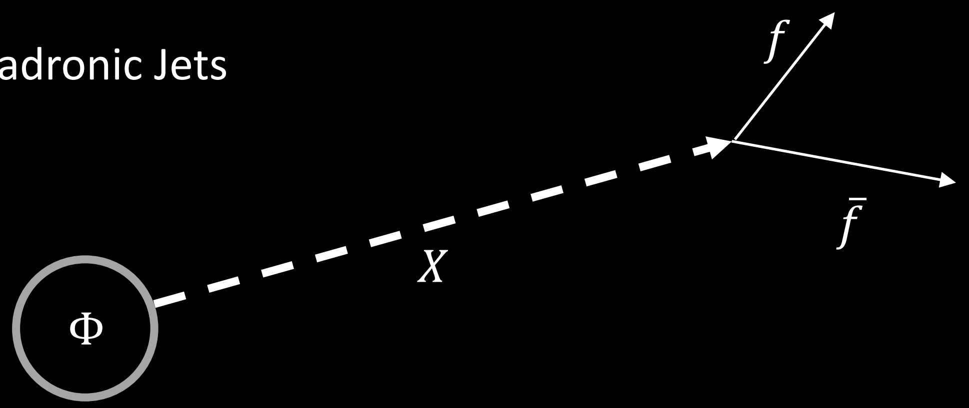
The mixing means the end result will be Standard Model Particles

- Couples to leptons (M_X small)

  "lepton-jets" – jets of leptons

- Couples to heavy fermions (M_X larger)

  Displaced Hadronic Jets



Analysis Strategy

Driven by the production and decay operators in the theory

Have We Covered Them All?

LLP Only Production

$\phi \rightarrow \pi_v \pi_v$

Often produced in pairs

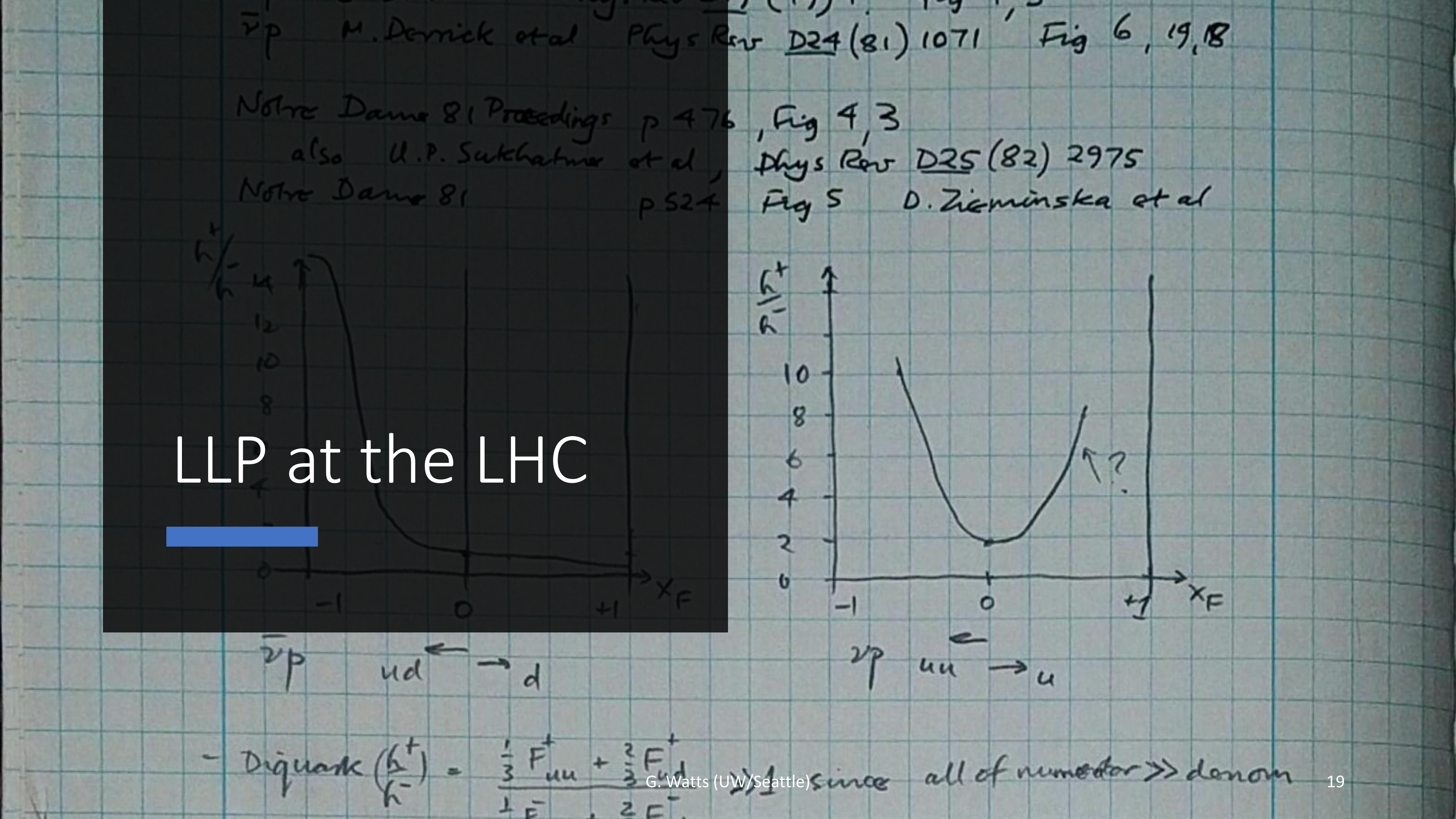
Hidden Valley
Neutral Naturalness

Associated Production and Decay

LLP is produced in association, or the decay contains other objects

Jets – Colored Object
Leptons – EW interactions
Weak Bosons – Associated production
etc.

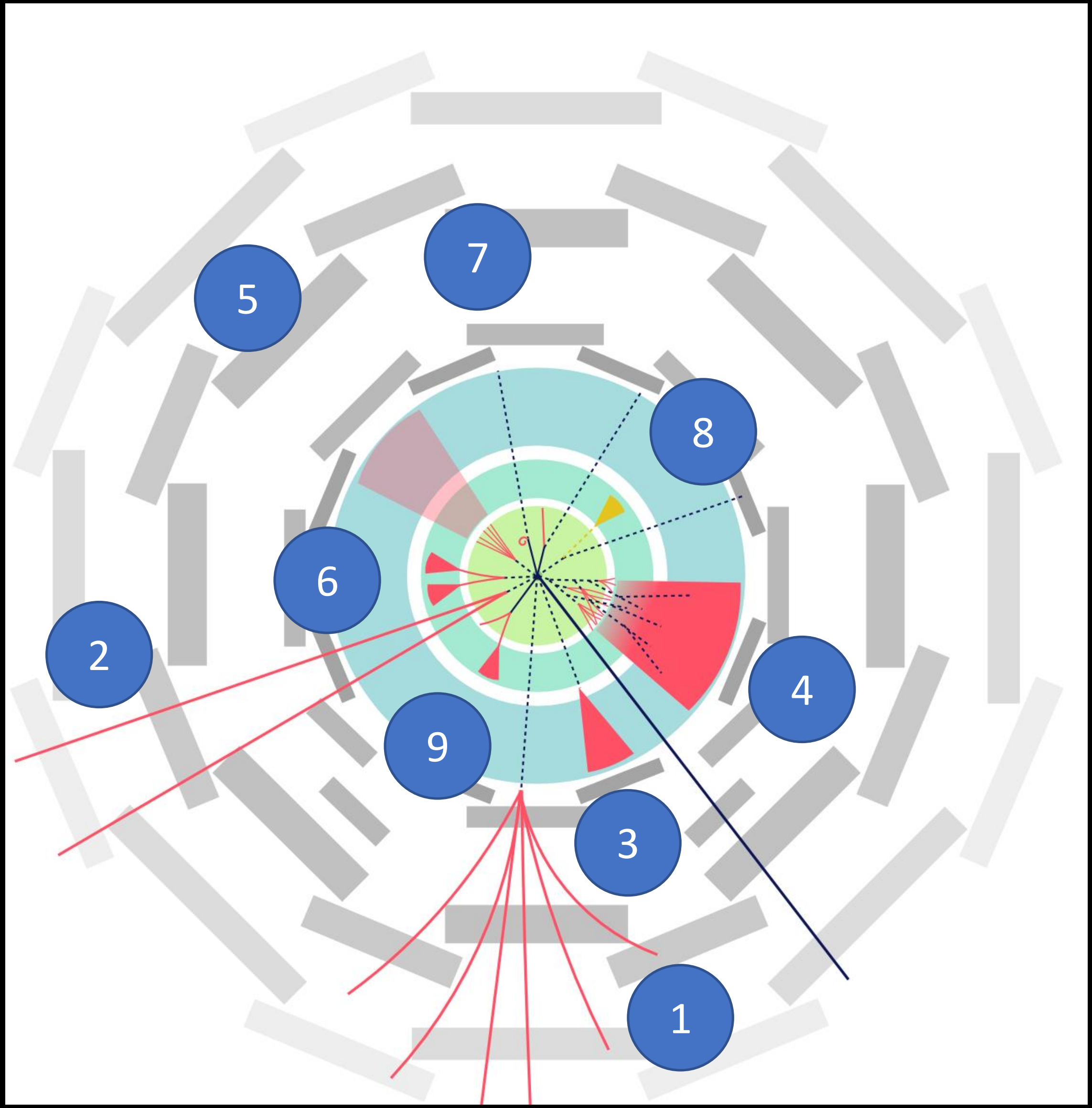
LLP at the LHC



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

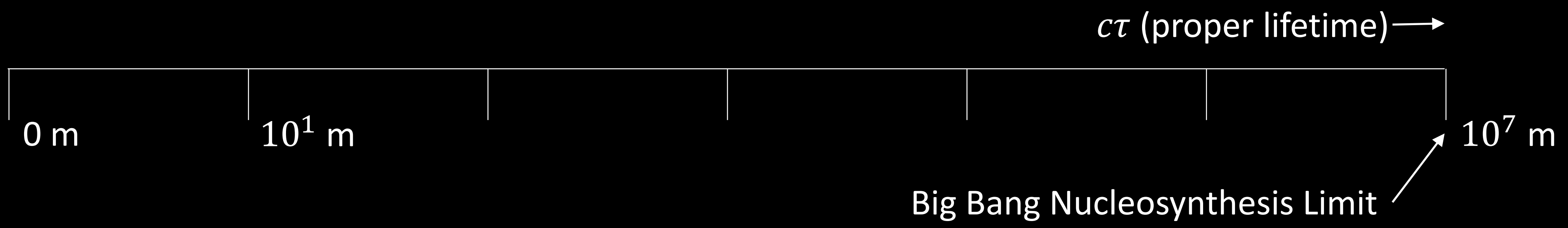
Displaced decay signatures

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



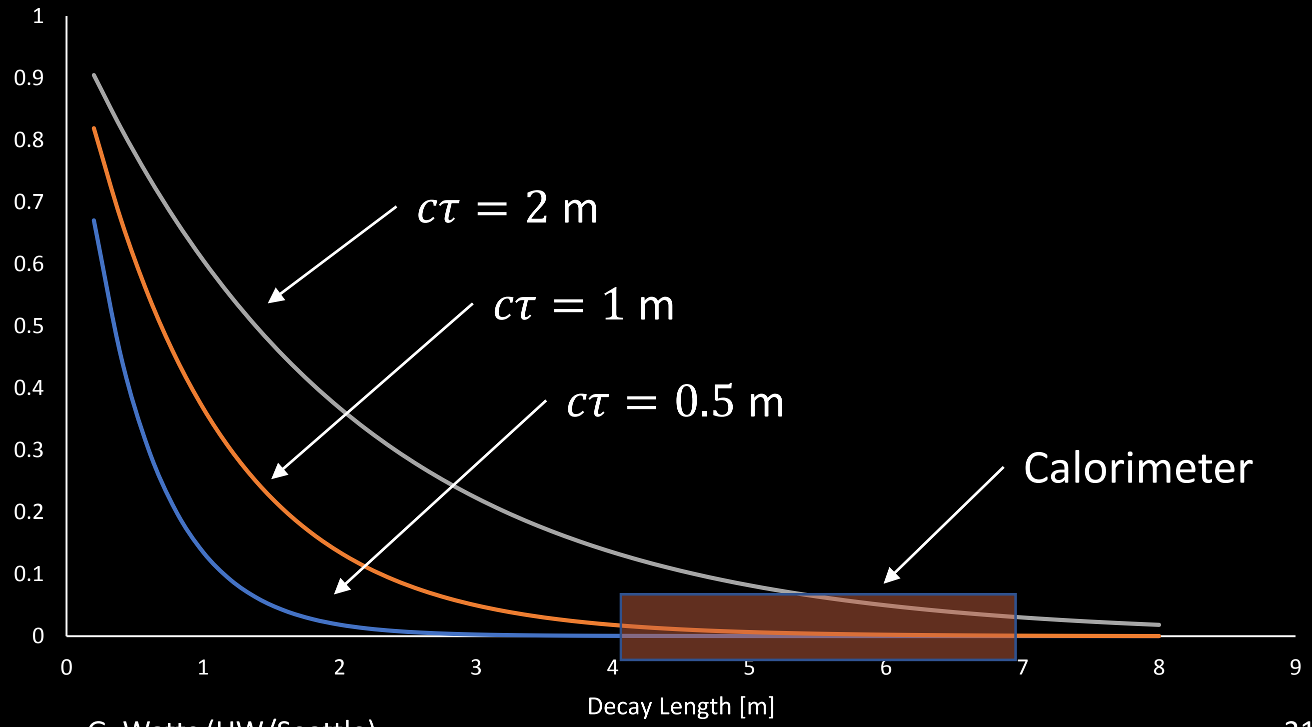
Long Lived Particles

No constraint on their proper lifetime

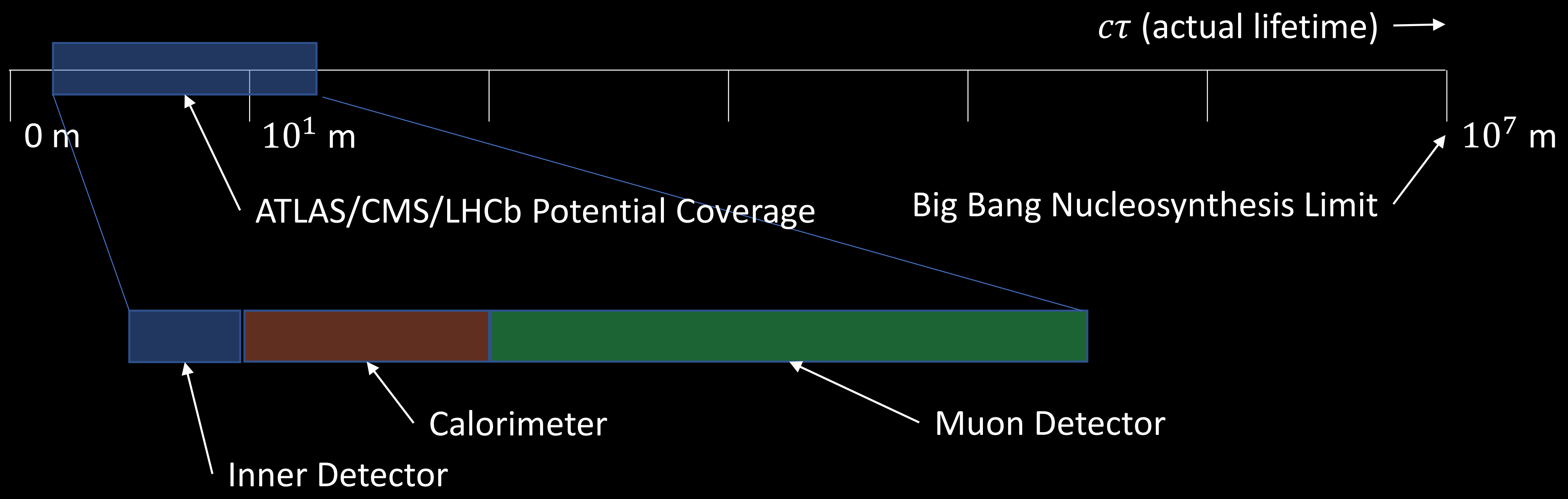


Lifetime of each LLP is a falling exponential of the proper lifetime

Gives us access to a much broader range of lifetimes



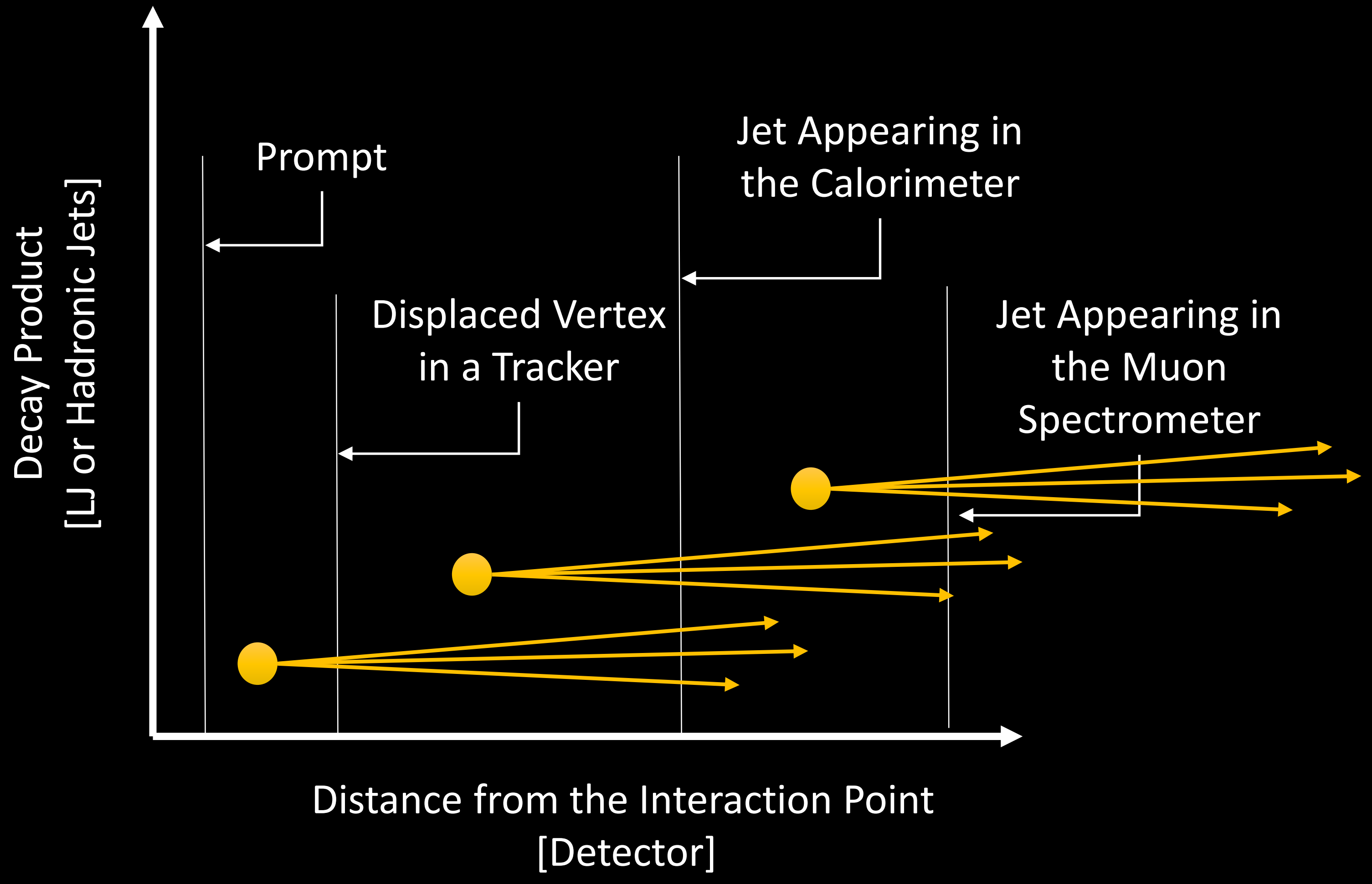
Long Lived Particles

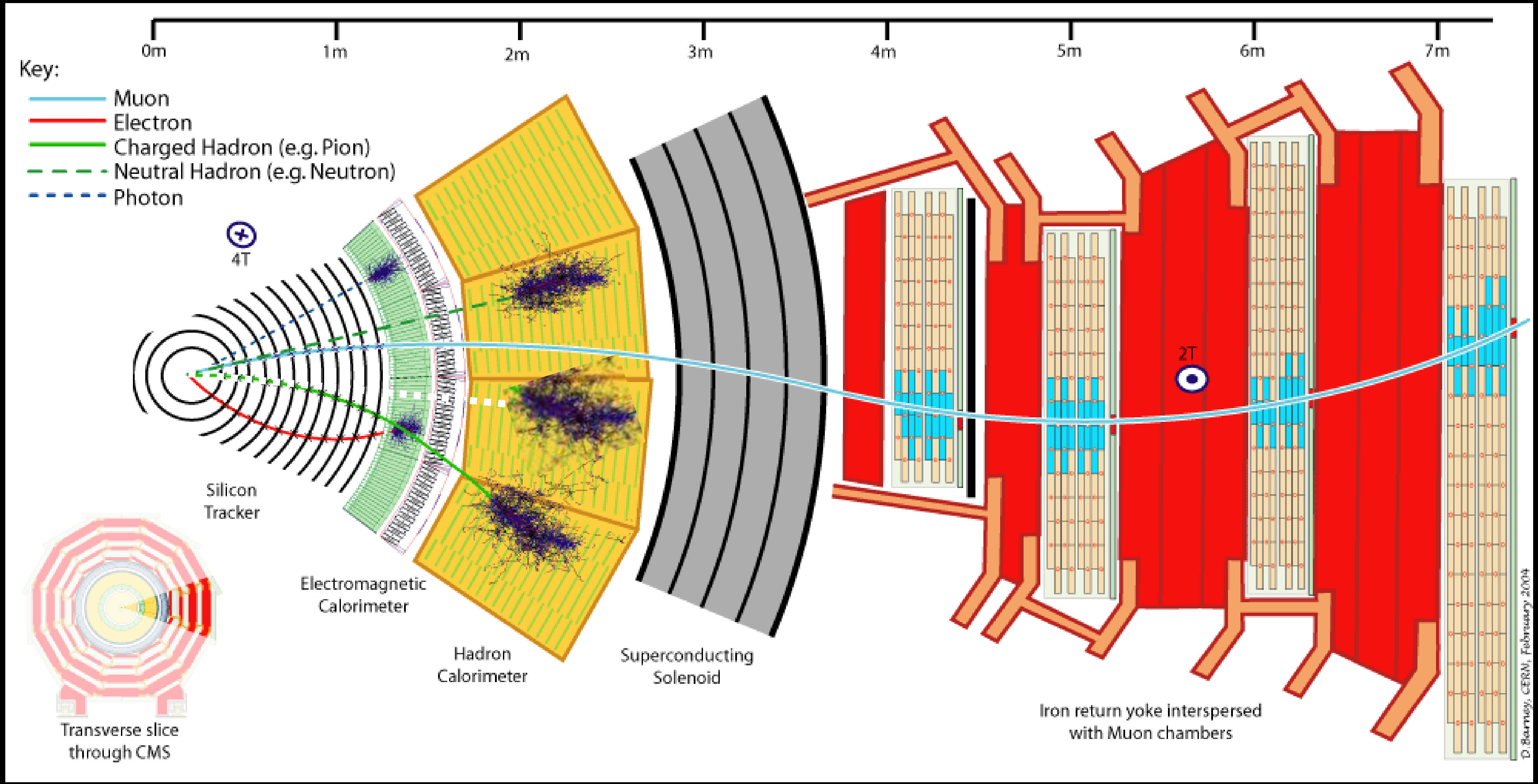


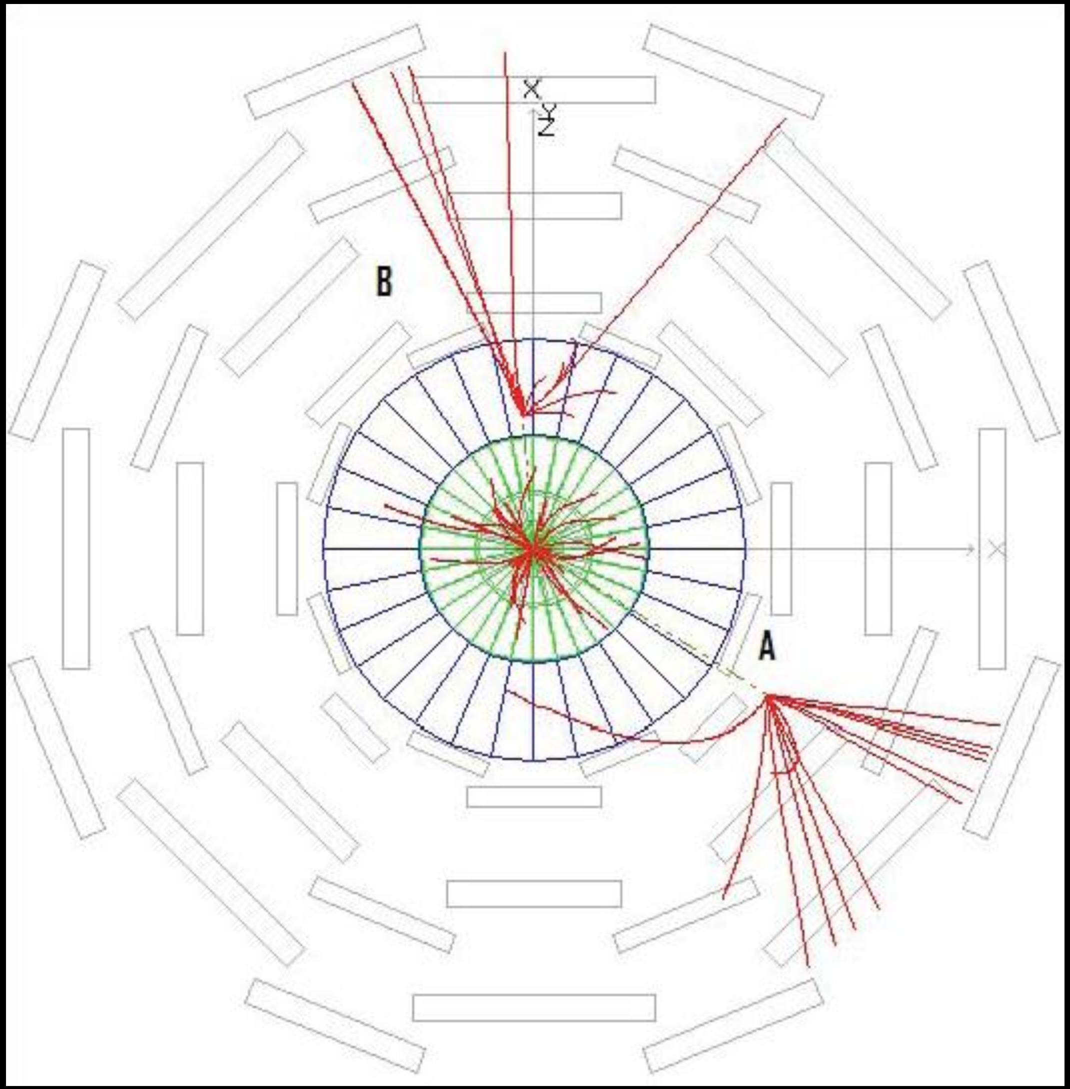
Significant Detector Challenges:

A different strategy is required in each region

Signatures in a LHC-Like Detector

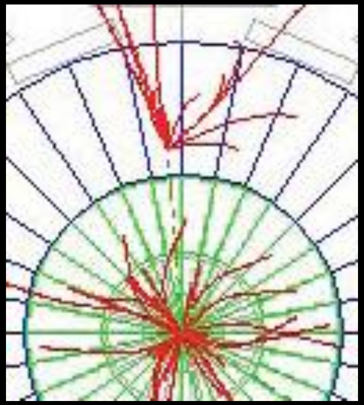


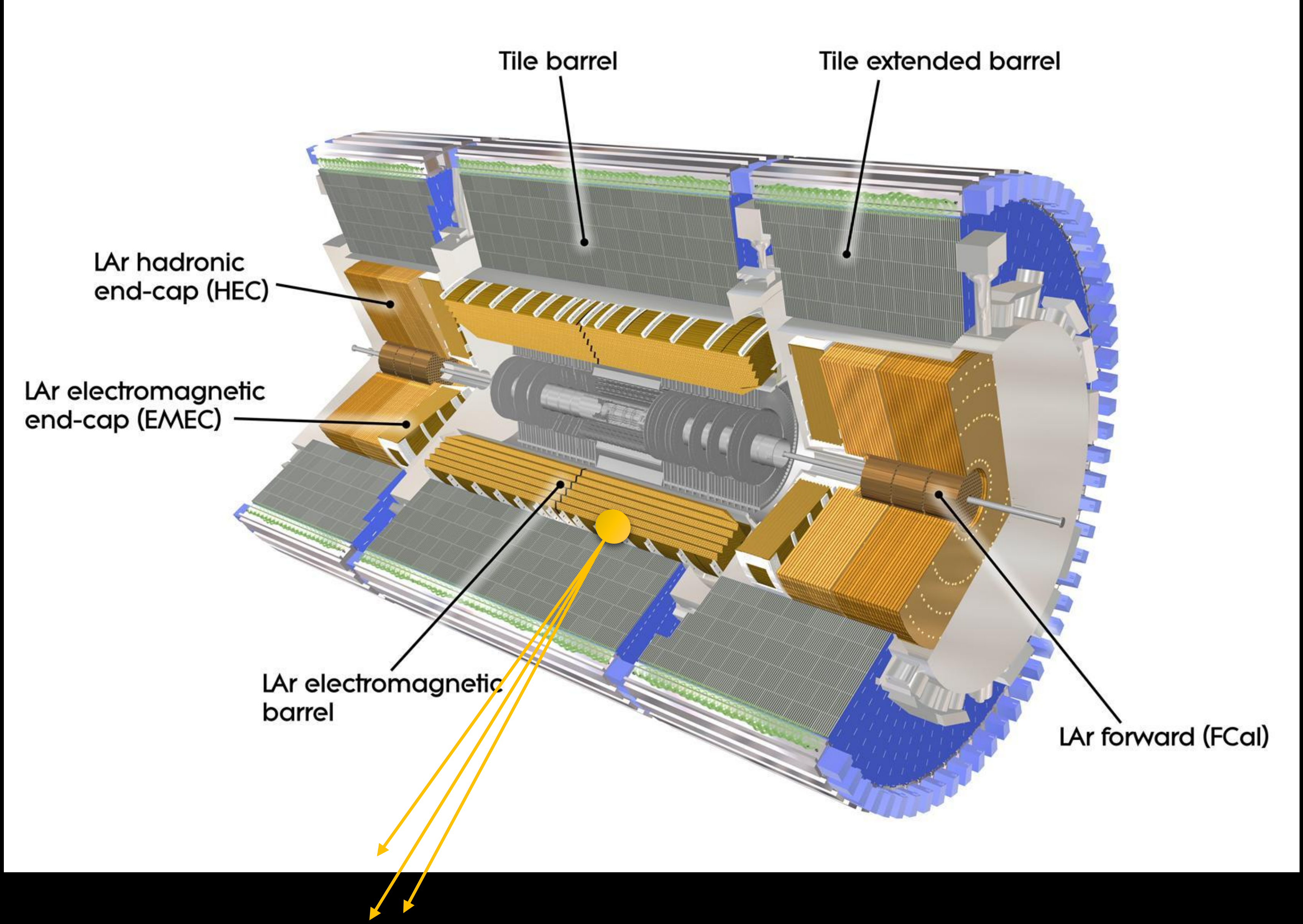

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS


X
Y
Z
B
A
X

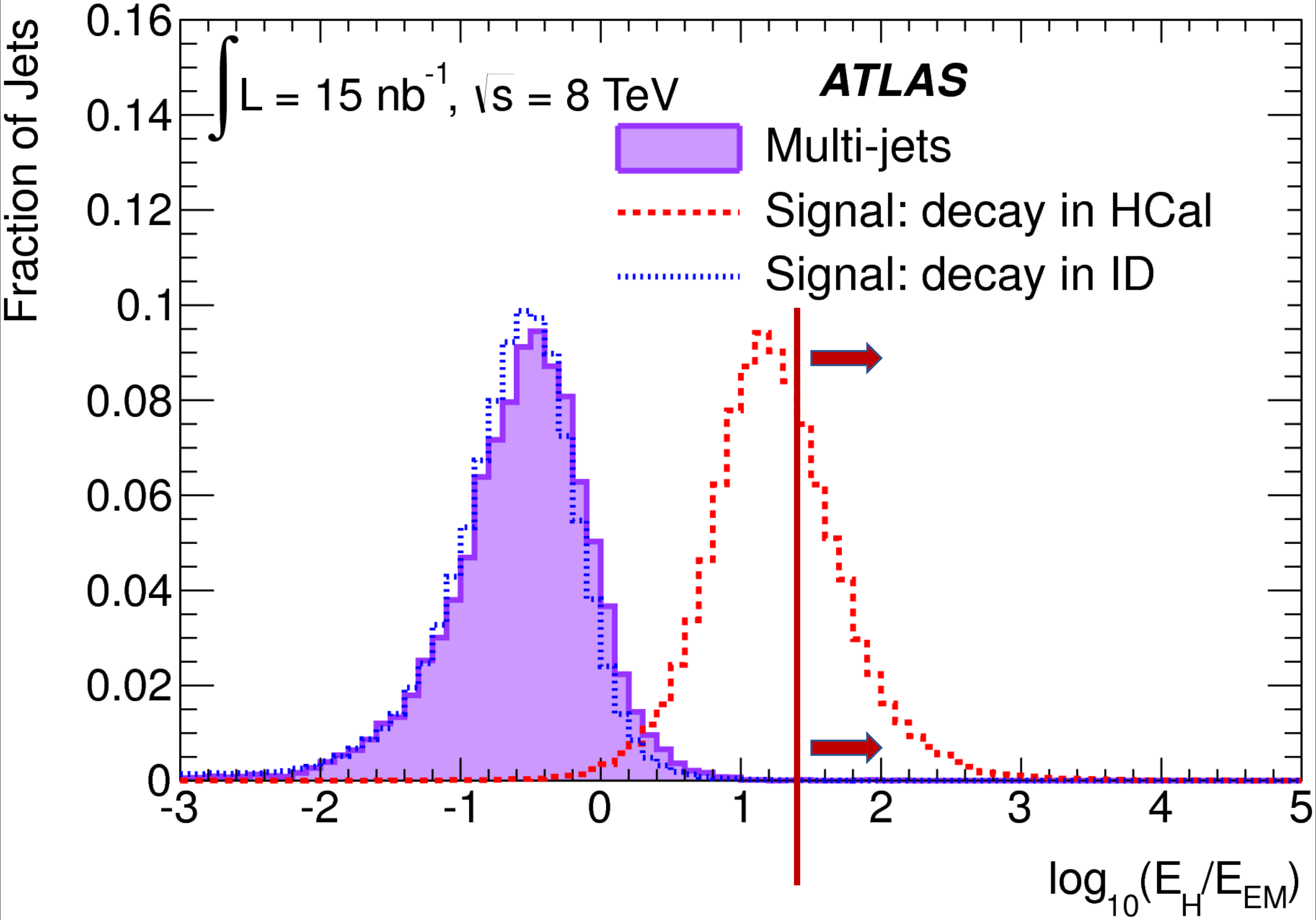
Decays in the Calorimeter

1. Look for the “appearance” of energy the Calorimeter
2. Little or no activity in the tracker

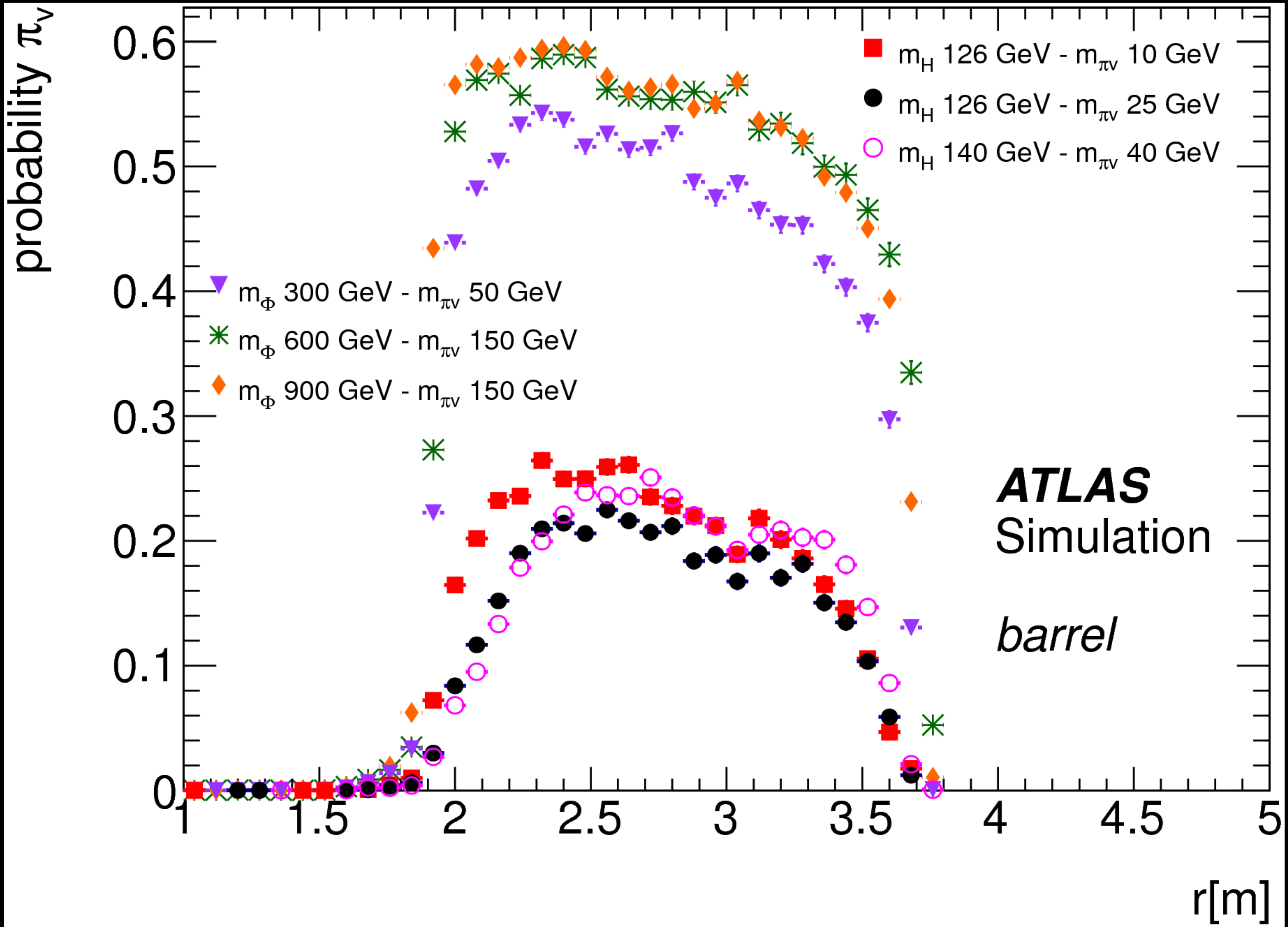


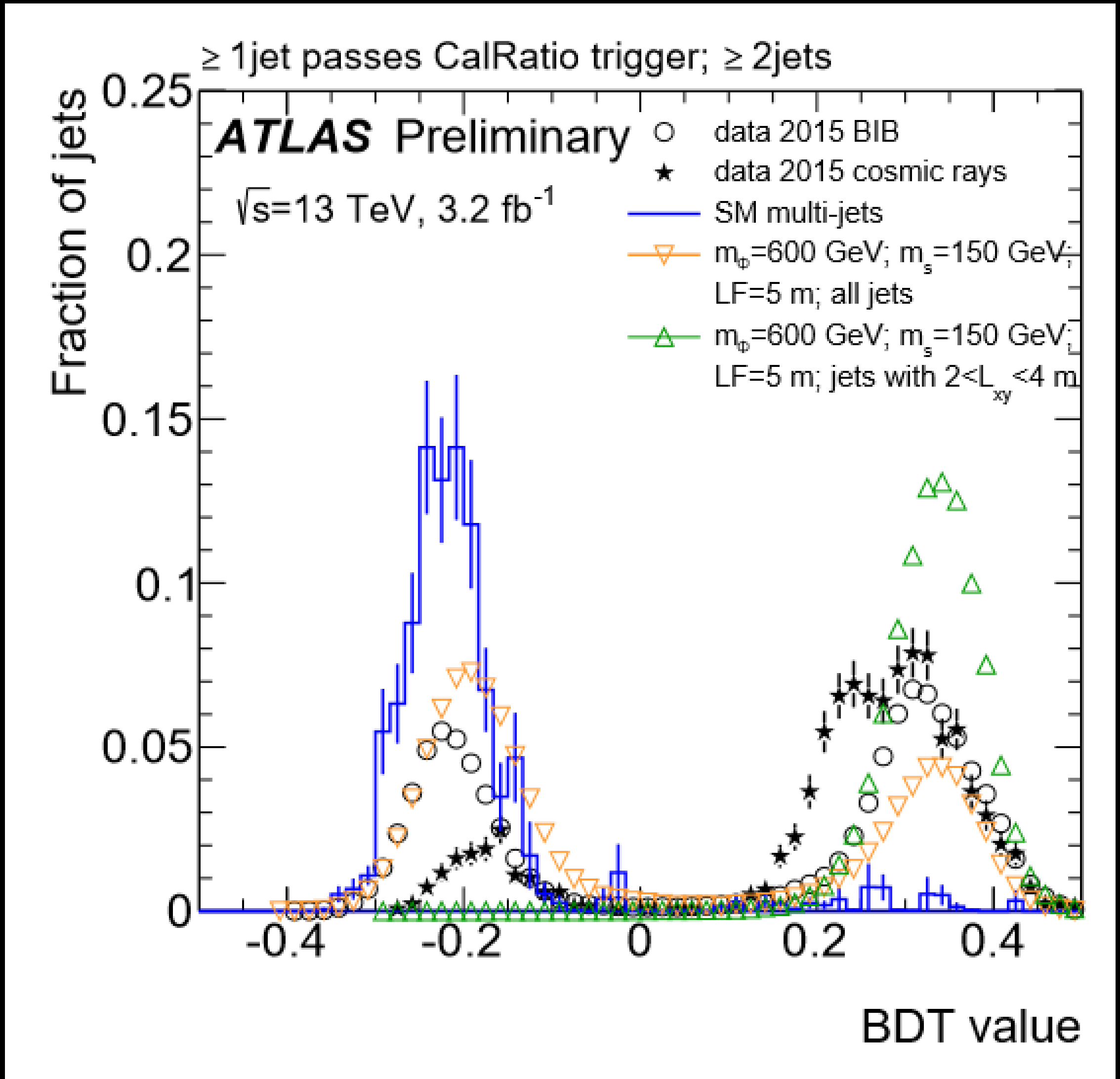

Tile barrel
Tile extended barrel
LAr hadronic end-cap (HEC)
LAr electromagnetic end-cap (EMEC)
LAr electromagnetic barrel
LAr forward (FCal)

“CalRatio”



Fraction of Jets
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
$\int L = 15\ nb^{-1}$, $\sqrt{s} = 8$ TeV
ATLAS
Multi-jets
Signal: decay in HCal
Signal: decay in ID
-3
-2
-1
0
1
2
3
4
5
$\log_{10}(E_H/E_{EM})$


probability π_v
m_H 126 GeV - $m_{\pi v}$ 10 GeV
m_H 126 GeV - $m_{\pi v}$ 25 GeV
m_H 140 GeV - $m_{\pi v}$ 40 GeV
m_Φ 300 GeV - $m_{\pi v}$ 50 GeV
m_Φ 600 GeV - $m_{\pi v}$ 150 GeV
m_Φ 900 GeV - $m_{\pi v}$ 150 GeV
ATLAS
Simulation
barrel
r[m]



There are lots of differences in shape to take advantage of

- $\log_{10}(\frac{E_H}{E_{EM}})$
- Jet Width
- Longitudinal Length
- Jet p_T
- Lateral Width
- Shower Center (radial)
- ΔR to closest 2 GeV track
- Cluster Energy Density
- Number of Tracks with $p_T > 2$ GeV
- Σp_T of all tracks
- Layer 1 HAD Energy Fraction
- Max track p_T

A 30% improvement in performance over straight cuts

The events must be written to tape…

1. Associated Production/Associated Decay

   e.g. WH production

   ↑ Trigger on isolated muon or missing E_T

   e.g. jets, missing E_T, etc.

2. Signature Driven Trigger

ATLAS has 3 signature driven triggers running since the start of 2011:

- Trackless Jet Trigger
- CalRatio trigger
- Muon RoI Cluster Trigger

All triggers must be below 1 Hz!

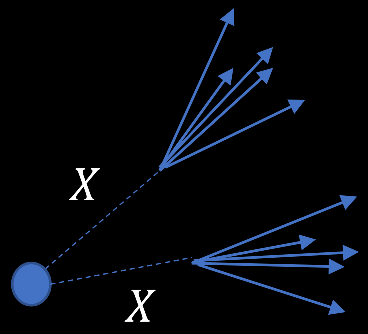
CMS has made great use of more traditional triggers

- Muon triggers
- Jet triggers
- Signature Displaced Jet Trigger

Acceptance

A single displaced vertex

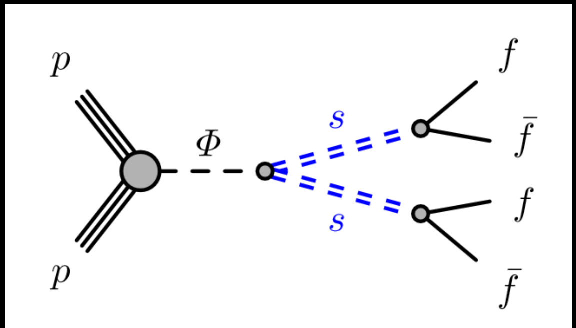
Displaced vertex + (jet, muon, missing E_T, etc.)

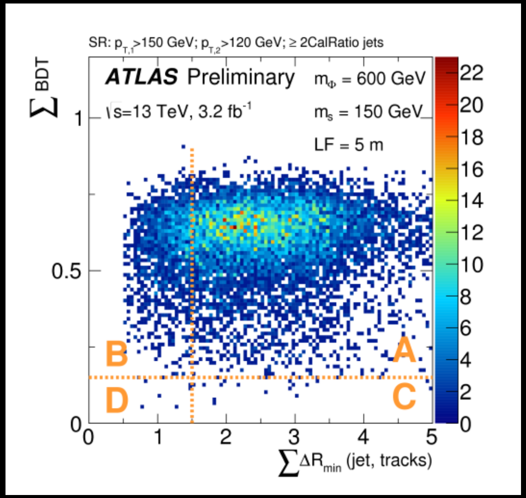


Two displaced vertices

Small Backgrounds

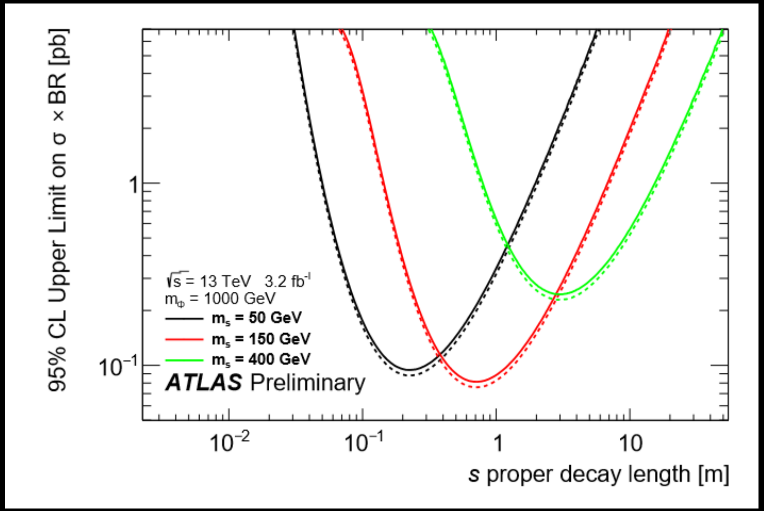
Run 2 – Search for two LLP's in the calorimeter





The ABCD Method is used to estimate backgrounds

There are limits for 200 GeV and 400 GeV as well.
125 coming with next update.



A Few Other Results

2 Jet

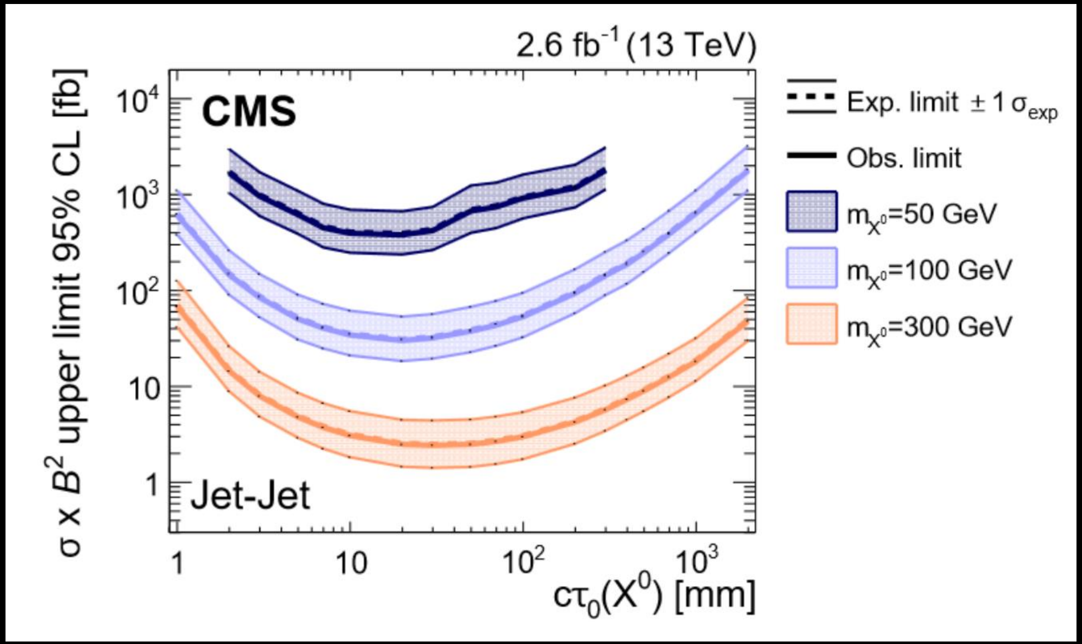
Recent result that looks for 2 jets with displaced tracks

- Impact Parameter – based tagging
- Multijet background
- Requires two Jets
- Most signal is RPV based

Background:
- Data based
- Start with events with smaller number of tags
- Extrapolate

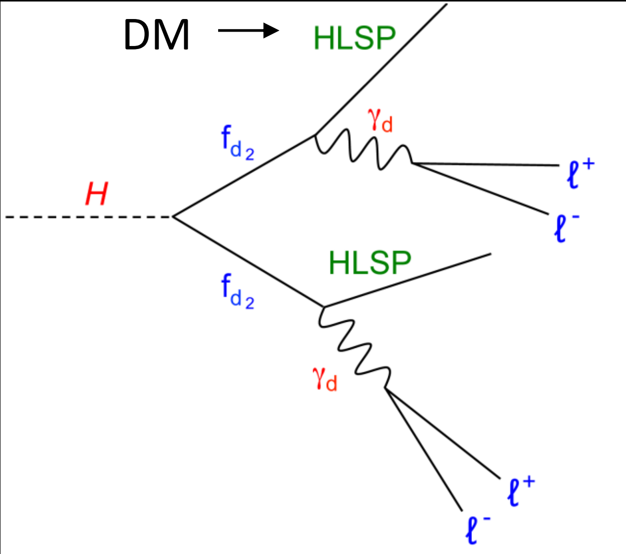
This seems like an excellent analysis for "recasting"

RPV "Jet-Jet" model



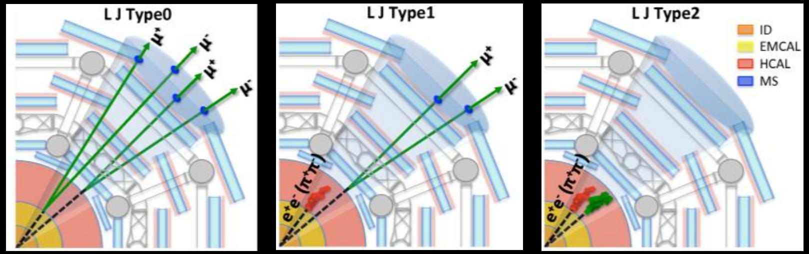
Run 2 Search for Displaced Lepton-Jets

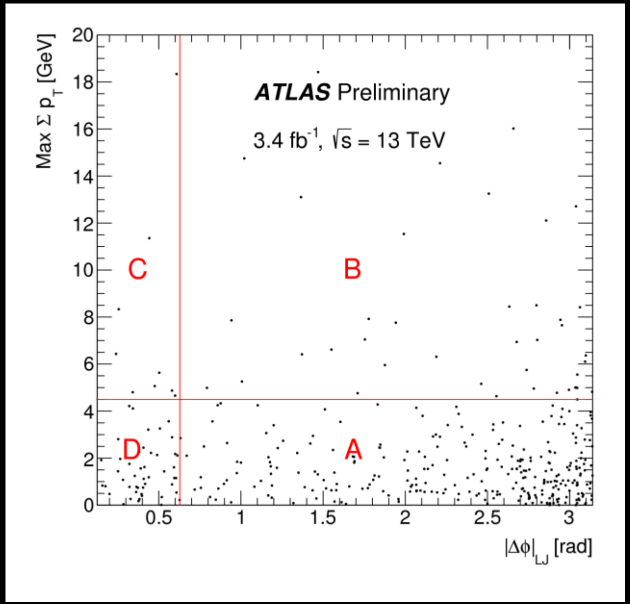
$H \rightarrow f_{d_2} f_{d_2}, f_{d_2} \rightarrow \gamma_d HLSP$



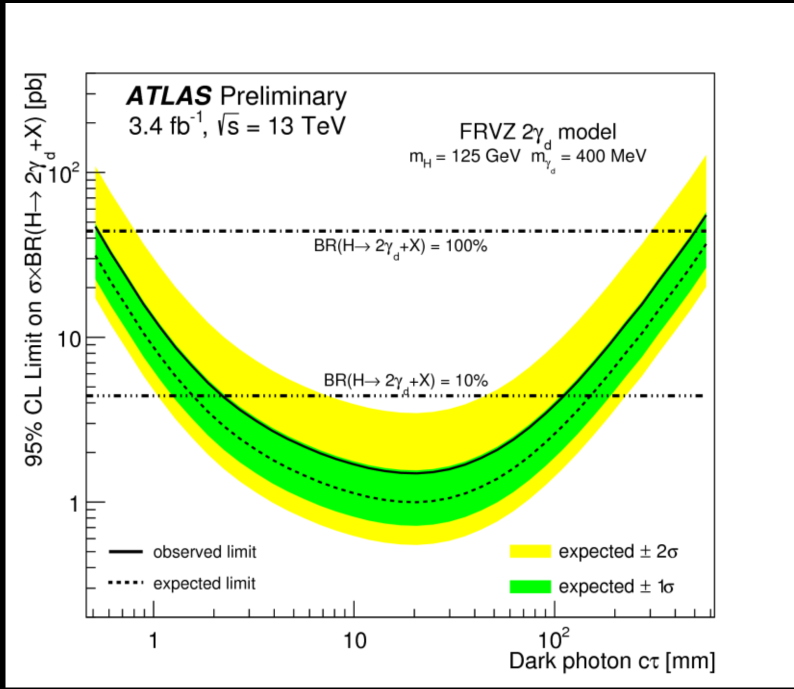
3 Long Lived Final State Objects:

- Muons Only (type 0)
- Muons in a jet (type 1)
- Jet only (type 2)





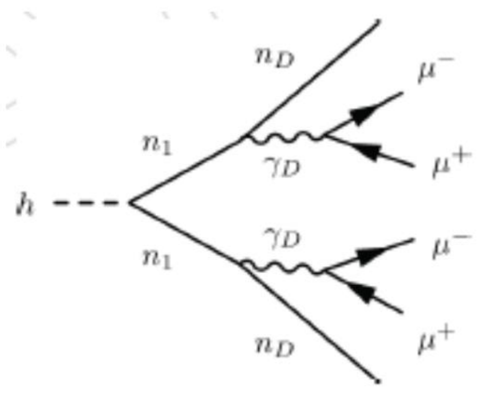
The ABCD Method is used to determine the backgrounds.

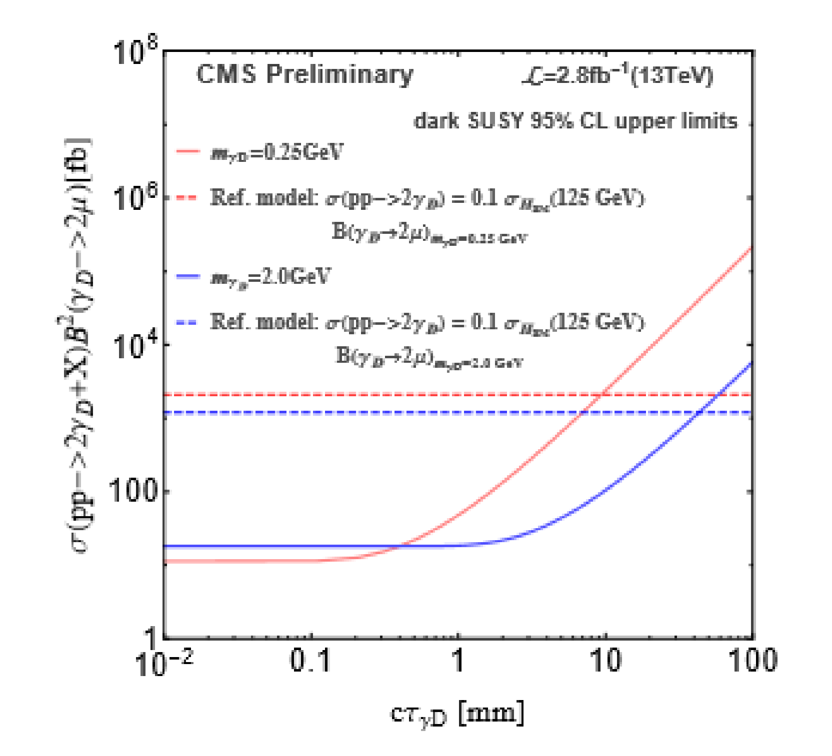


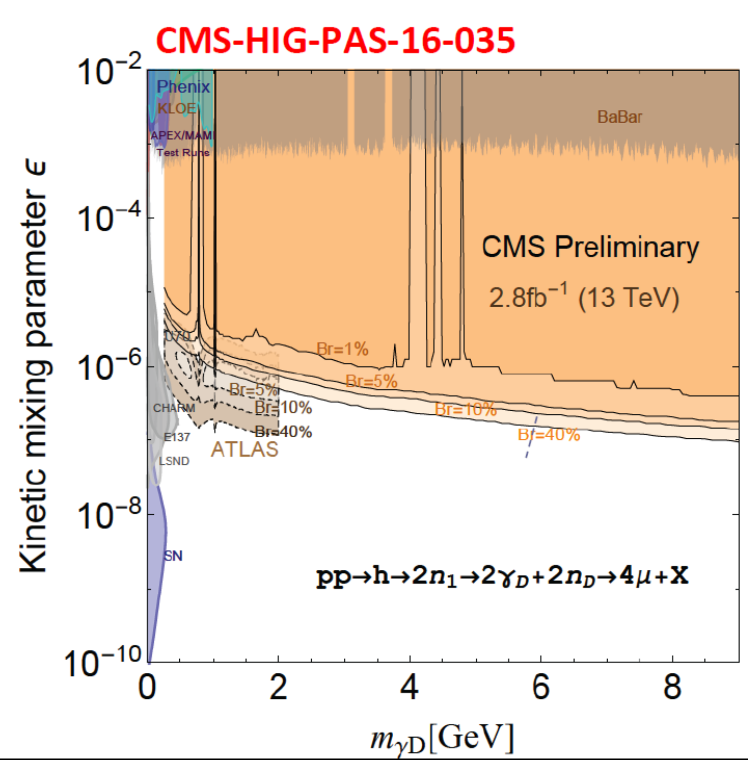
Limit is also set for a 800 GeV scalar.

CMS 4 Muon Lepton Jets

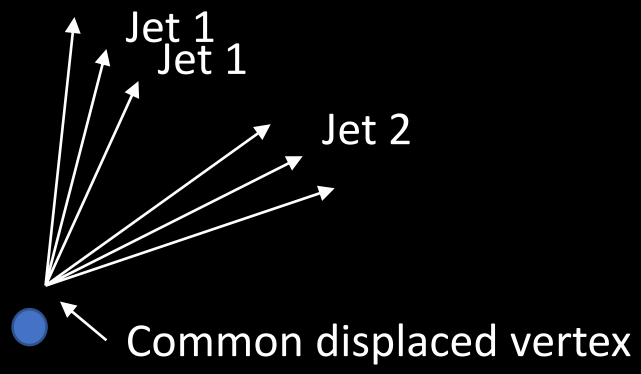
Run 2 Search for 4 muons in η < 2.4 In topology with two pairs of (closely spaced) muons γ_D is the LLP





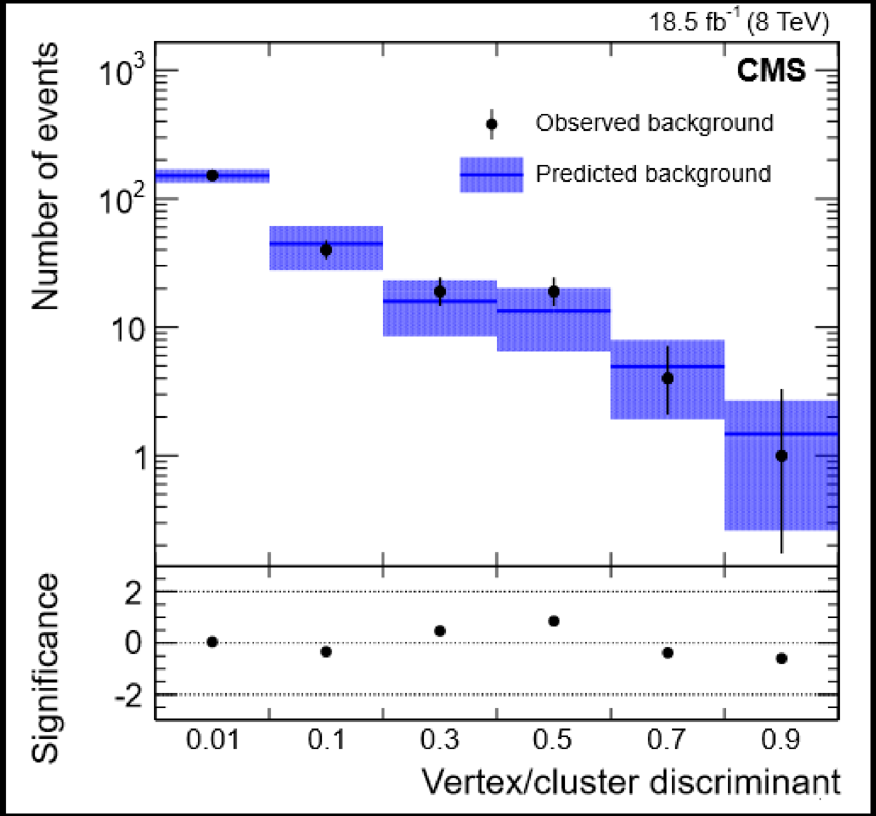


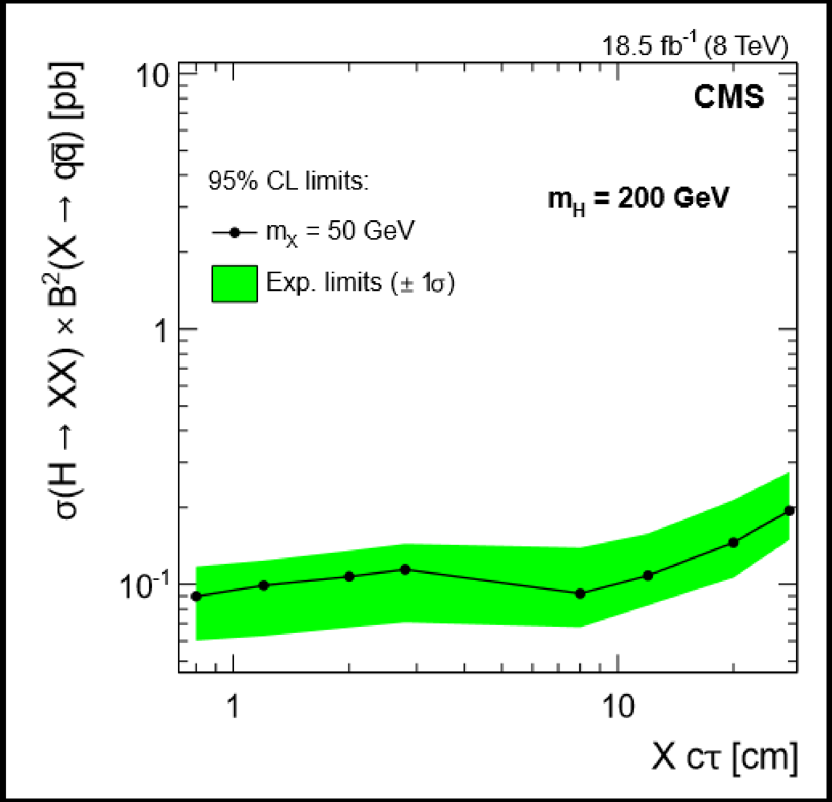
CMS also has an interesting displaced $e\mu$ search…

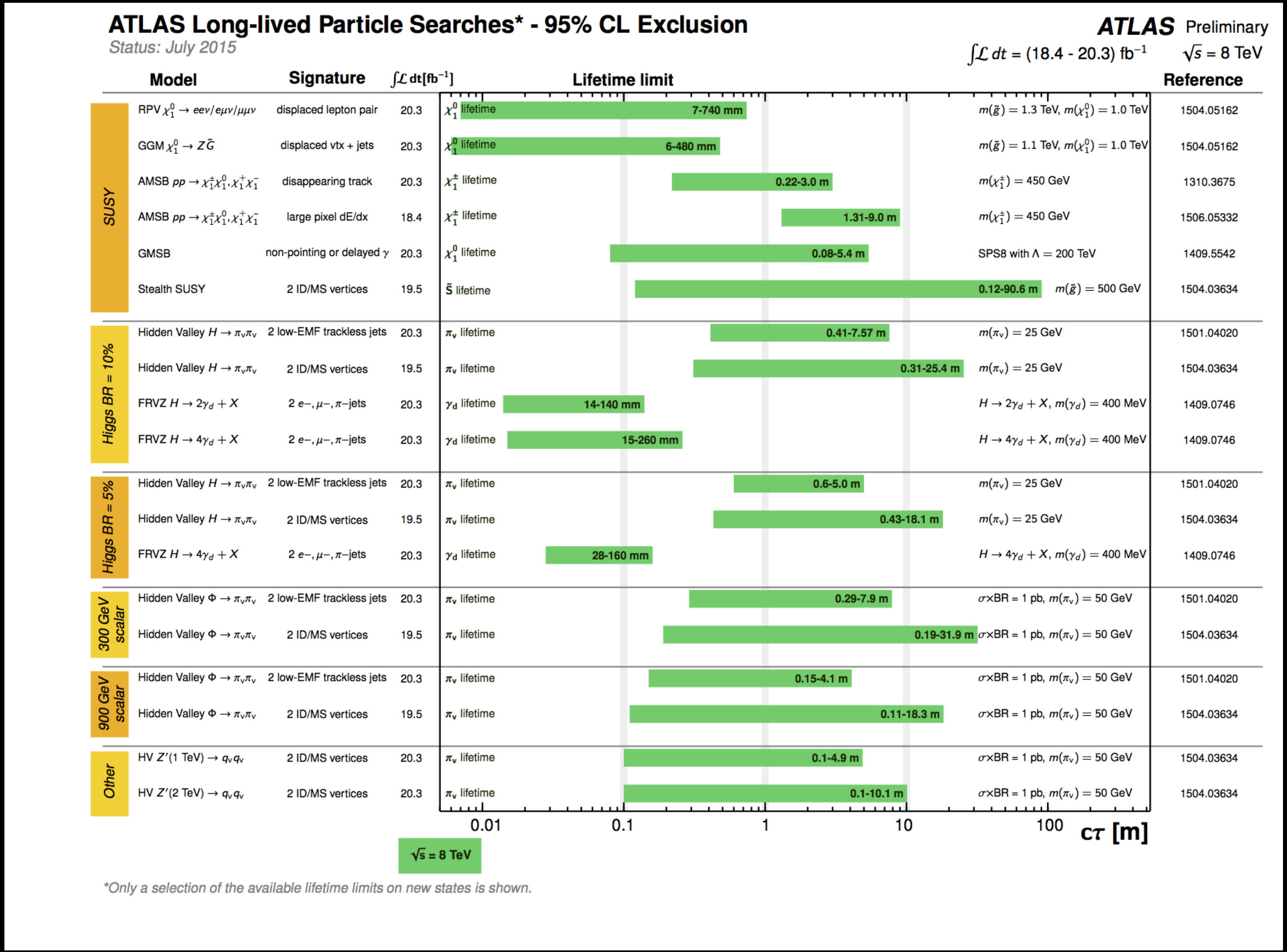


Run 1 Displaced Jet Search

$$H \to XX$$
$$X \to q\bar{q}$$ (long lived, Higgs Portal)





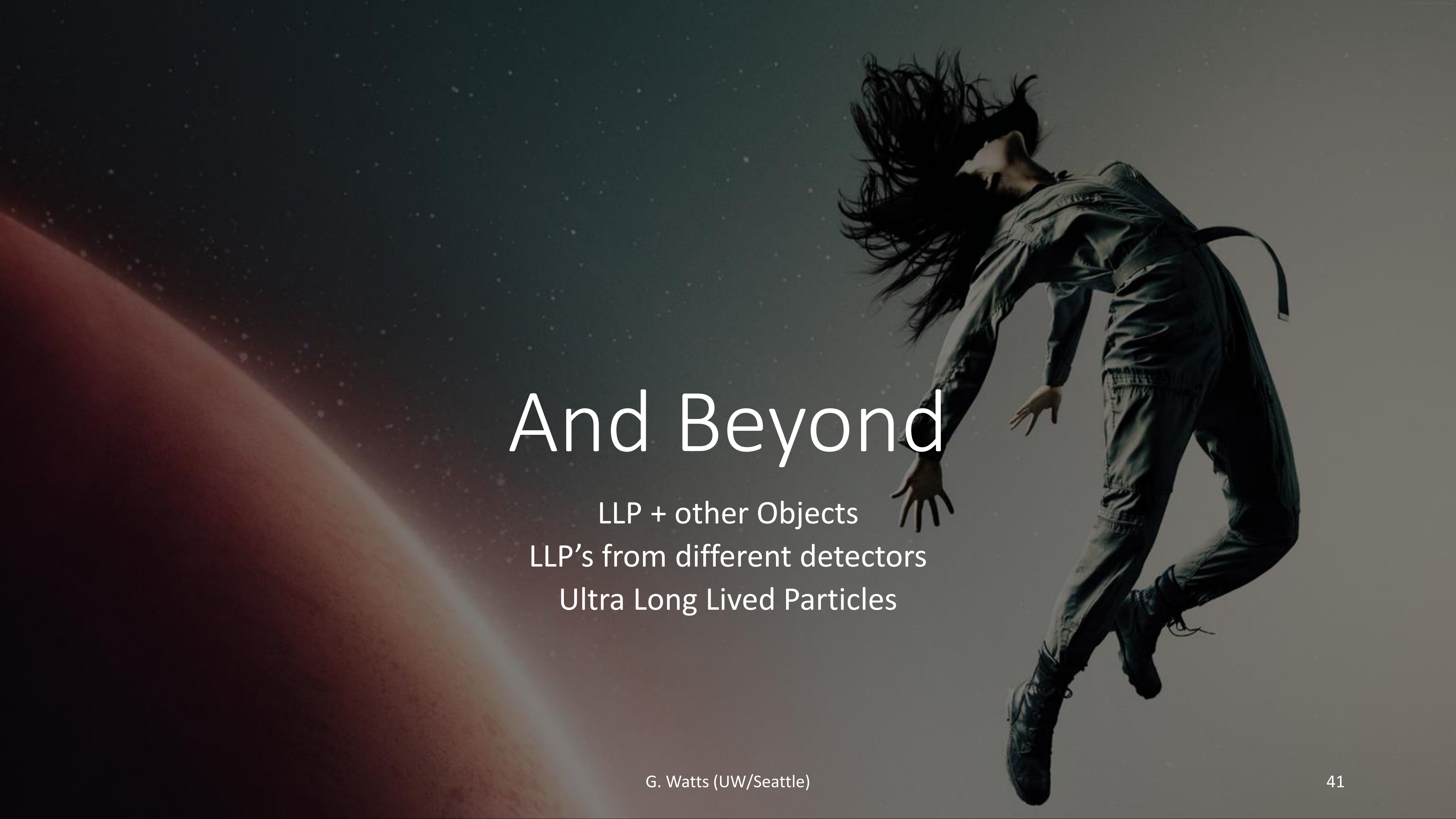


ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: July 2015
ATLAS Preliminary
$\int \mathcal{L}\, dt$ = (18.4 - 20.3) fb^{-1}
$\sqrt{s}$ = 8 TeV
Model
Signature
$\int \mathcal{L}\, dt [fb^{-1}]$
Lifetime limit
Reference
SUSY
RPV $\chi_1^0 \rightarrow ee\nu/e\mu\nu/\mu\mu\nu$
displaced lepton pair
20.3
χ_1^0 lifetime
7-740 mm
$m(\tilde{g})$ = 1.3 TeV, $m(\chi_1^0)$ = 1.0 TeV
1504.05162
GGM $\chi_1^0 \rightarrow Z\tilde{G}$
displaced vtx + jets
20.3
χ_1^0 lifetime
6-480 mm
$m(\tilde{g})$ = 1.1 TeV, $m(\chi_1^0)$ = 1.0 TeV
1504.05162
AMSB $pp \rightarrow \chi_1^\pm \chi_1^0, \chi_1^+ \chi_1^-$
disappearing track
20.3
$\chi_1^\pm$ lifetime
0.22-3.0 m
$m(\chi_1^\pm)$ = 450 GeV
1310.3675
AMSB $pp \rightarrow \chi_1^\pm \chi_1^0, \chi_1^+ \chi_1^-$
large pixel dE/dx
18.4
$\chi_1^\pm$ lifetime
1.31-9.0 m
$m(\chi_1^\pm)$ = 450 GeV
1506.05332
GMSB
non-pointing or delayed γ
20.3
χ_1^0 lifetime
0.08-5.4 m
SPS8 with Λ = 200 TeV
1409.5542
Stealth SUSY
2 ID/MS vertices
19.5
$\tilde{S}$ lifetime
0.12-90.6 m
$m(\tilde{g})$ = 500 GeV
1504.03634
Higgs BR = 10%
Hidden Valley $H \rightarrow \pi_v \pi_v$
2 low-EMF trackless jets
20.3
π_v lifetime
0.41-7.57 m
$m(\pi_v)$ = 25 GeV
1501.04020
Hidden Valley $H \rightarrow \pi_v \pi_v$
2 ID/MS vertices
19.5
π_v lifetime
0.31-25.4 m
$m(\pi_v)$ = 25 GeV
1504.03634
FRVZ $H \rightarrow 2\gamma_d + X$
2 $e-, \mu-, \pi-$jets
20.3
γ_d lifetime
14-140 mm
$H \rightarrow 2\gamma_d + X$, $m(\gamma_d)$ = 400 MeV
1409.0746
FRVZ $H \rightarrow 4\gamma_d + X$
2 $e-, \mu-, \pi-$jets
20.3
γ_d lifetime
15-260 mm
$H \rightarrow 4\gamma_d + X$, $m(\gamma_d)$ = 400 MeV
1409.0746
Higgs BR = 5%
Hidden Valley $H \rightarrow \pi_v \pi_v$
2 low-EMF trackless jets
20.3
π_v lifetime
0.6-5.0 m
$m(\pi_v)$ = 25 GeV
1501.04020
Hidden Valley $H \rightarrow \pi_v \pi_v$
2 ID/MS vertices
19.5
π_v lifetime
0.43-18.1 m
$m(\pi_v)$ = 25 GeV
1504.03634
FRVZ $H \rightarrow 4\gamma_d + X$
2 $e-, \mu-, \pi-$jets
20.3
γ_d lifetime
28-160 mm
$H \rightarrow 4\gamma_d + X$, $m(\gamma_d)$ = 400 MeV
1409.0746
300 GeV scalar
Hidden Valley $\Phi \rightarrow \pi_v \pi_v$
2 low-EMF trackless jets
20.3
π_v lifetime
0.29-7.9 m
$\sigma\times$BR = 1 pb, $m(\pi_v)$ = 50 GeV
1501.04020
Hidden Valley $\Phi \rightarrow \pi_v \pi_v$
2 ID/MS vertices
19.5
π_v lifetime
0.19-31.9 m
$\sigma\times$BR = 1 pb, $m(\pi_v)$ = 50 GeV
1504.03634
900 GeV scalar
Hidden Valley $\Phi \rightarrow \pi_v \pi_v$
2 low-EMF trackless jets
20.3
π_v lifetime
0.15-4.1 m
$\sigma\times$BR = 1 pb, $m(\pi_v)$ = 50 GeV
1501.04020
Hidden Valley $\Phi \rightarrow \pi_v \pi_v$
2 ID/MS vertices
19.5
π_v lifetime
0.11-18.3 m
$\sigma\times$BR = 1 pb, $m(\pi_v)$ = 50 GeV
1504.03634
Other
HV Z'(1 TeV) $\rightarrow q_v q_v$
2 ID/MS vertices
20.3
π_v lifetime
0.1-4.9 m
$\sigma\times$BR = 1 pb, $m(\pi_v)$ = 50 GeV
1504.03634
HV Z'(2 TeV) $\rightarrow q_v q_v$
2 ID/MS vertices
20.3
π_v lifetime
0.1-10.1 m
$\sigma\times$BR = 1 pb, $m(\pi_v)$ = 50 GeV
1504.03634
0.01
0.1
1
10
100
$c\tau$ [m]
$\sqrt{s}$ = 8 TeV
*Only a selection of the available lifetime limits on new states is shown.

Exotica Publications — Long-Lived Particles

144	EXO-16-044	Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at $\sqrt{s} = 13$ TeV	Submitted to JHEP	19 April 2018
135	EXO-16-004	Search for decays of stopped exotic long-lived particles produced in proton-proton collisions at $\sqrt{s} = 13$ TeV	Accepted by JHEP	31 December 2017
132	EXO-16-003	Search for new long-lived particles at $\sqrt{s} = 13$ TeV	PLB 780 (2018) 432	25 November 2017
110	EXO-15-010	Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV	PRD 94 (2016) 112004	27 September 2016
87	EXO-13-006	Constraints on the pMSSM, AMSB model and on other models from the search for long-lived charged particles in proton-proton collisions at $\sqrt{s}$ = 8 TeV	EPJC 75 (2015) 325	9 February 2015
85	EXO-12-036	Search for decays of stopped long-lived particles produced in proton-proton collisions at $\sqrt{s}$ = 8 TeV	EPJC 75 (2015) 151	22 January 2015
81	EXO-12-037	Search for long-lived particles that decay into final states containing two electrons or two muons in proton-proton collisions at $\sqrt{s}$ = 8 TeV	PRD 91 (2015) 052012	25 November 2014
80	EXO-12-038	Search for long-lived neutral particles decaying to quark-antiquark pairs in proton-proton collisions at $\sqrt{s}$ = 8 TeV	PRD 91 (2015) 012007	25 November 2014
79	EXO-12-034	Search for disappearing tracks in proton-proton collisions at $\sqrt{s}$ = 8 TeV	JHEP 01 (2015) 096	21 November 2014

Both experiments now have an excellent arsenal of tools with which to search for LLP's



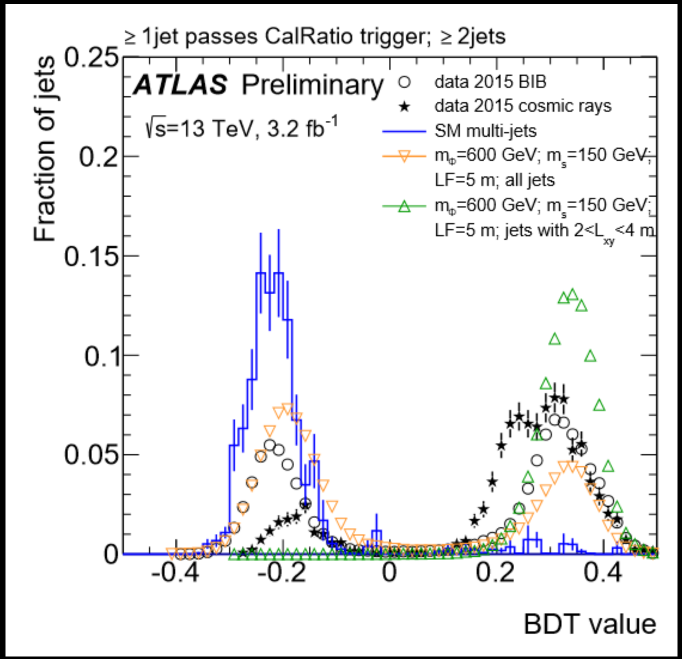
And Beyond

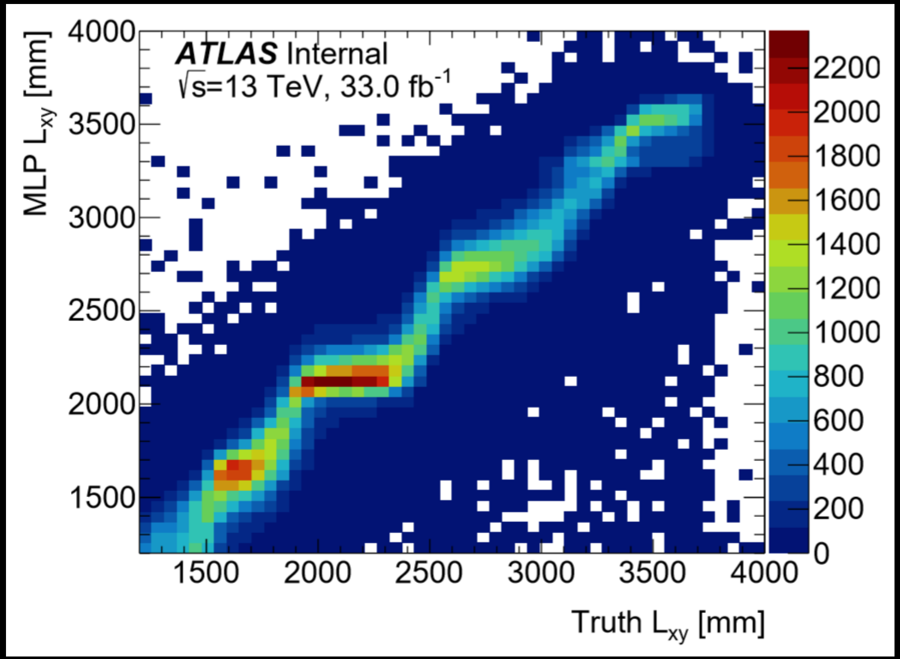
LLP + other Objects

LLP's from different detectors

Ultra Long Lived Particles

Better Identification Of LLP's





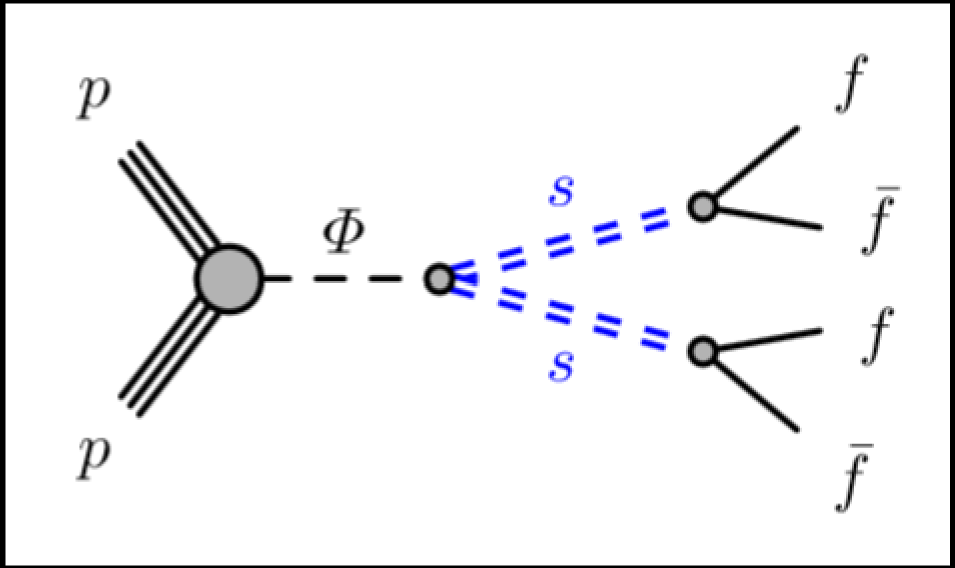
- Improved BDT to identify LLP
- Could we do image recognition in calorimeter?

- Vertexing in the Calorimeter!

Expanding Final States

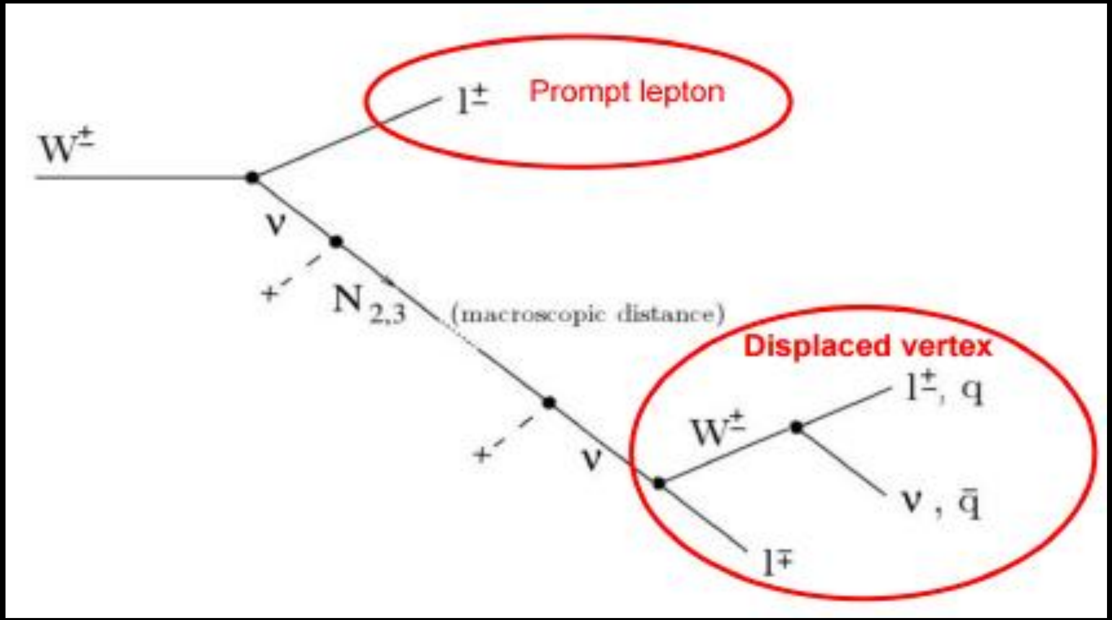
The current strategy works only for a two (or more) displaced vertices.

- In a single detector



Expand to using different detectors

LLP + Object

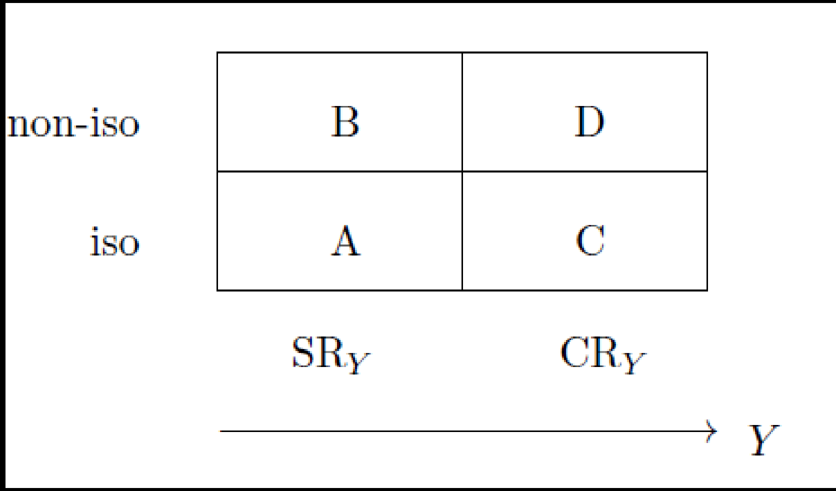


The backgrounds are too large with a single LLP

Look for a second object in the event!

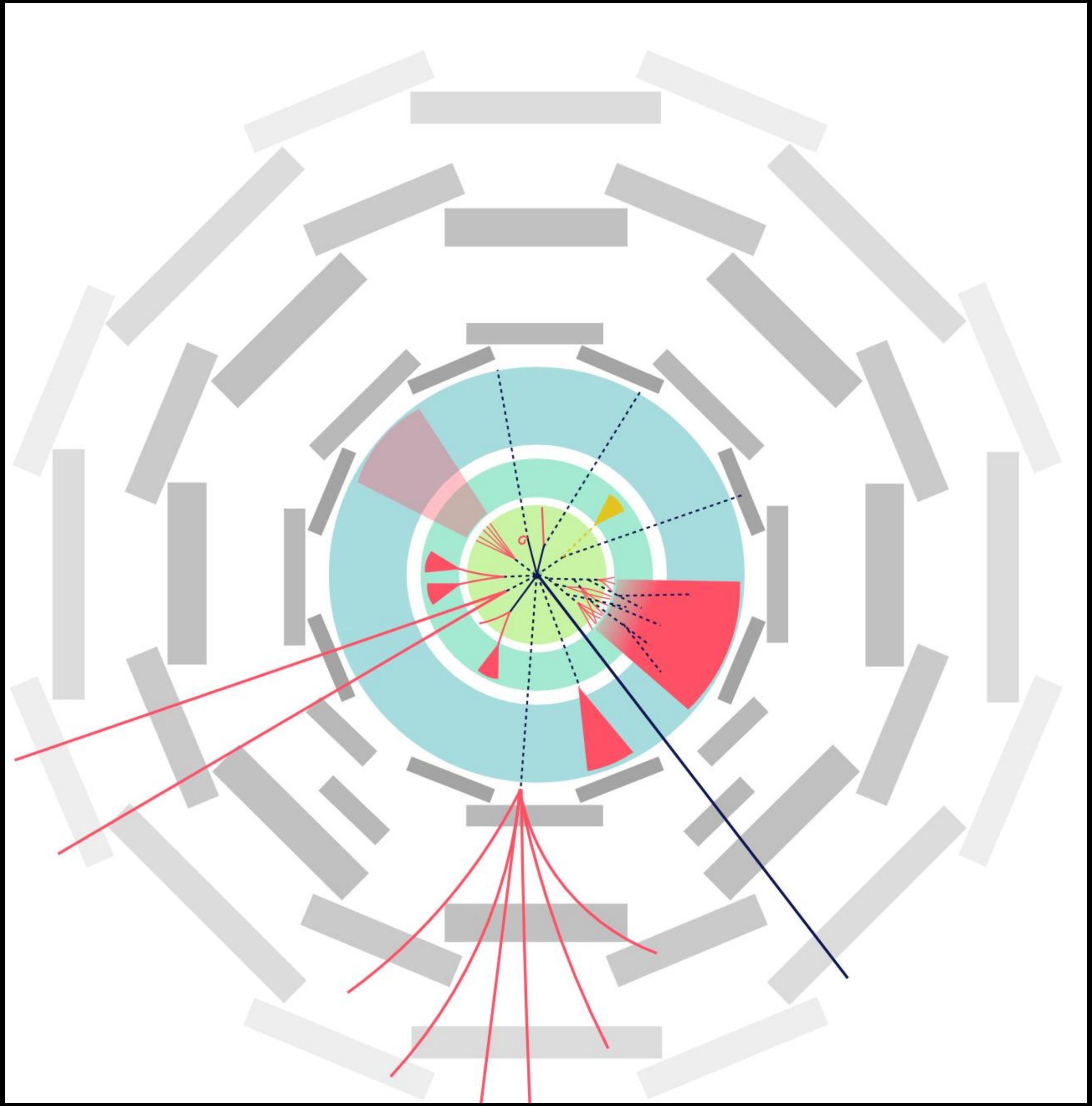
Use ABCD method to calculate backgrounds

- Iso/Non-Iso: Displaced object with nothing else near it
- The uncorrelated Y variable will depend on the analysis
  - Missing E_T, jet p_T, etc.



arXiv:1605.02742

Plenty more work to do with other signatures!



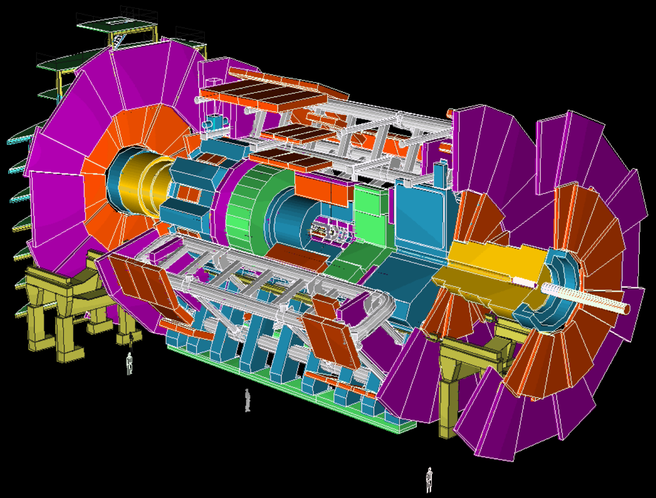
What about life-time sensitivity?

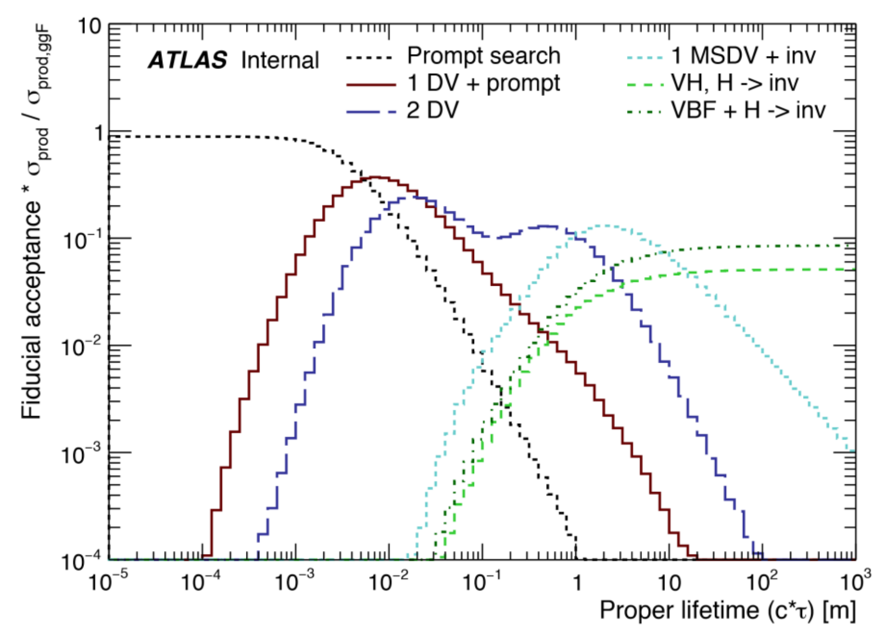
Lifetime is a free parameter…

But it is constrained by Big Bang Nucleosyntheses - $c\tau \sim 10^7$ m

ATLAS/CMS Detectors can only see to $c\tau \sim 100$ m

Escaped Particles become missing E_T…





➡ Acceptance isn't great

➡ Can't tell if they are stable or large $c\tau$…

Increasing The Base Line

MATHUSLA

Decay distance is about $100\sqrt{2}$ m

Gives one access to much longer decay lifetimes.

To be sensitive to $c\tau \sim 10^7$ m we must have zero background.

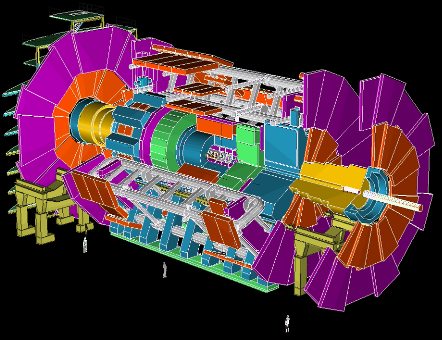
- Cosmic Rays
- Upward going muons
- Neutrino Interactions

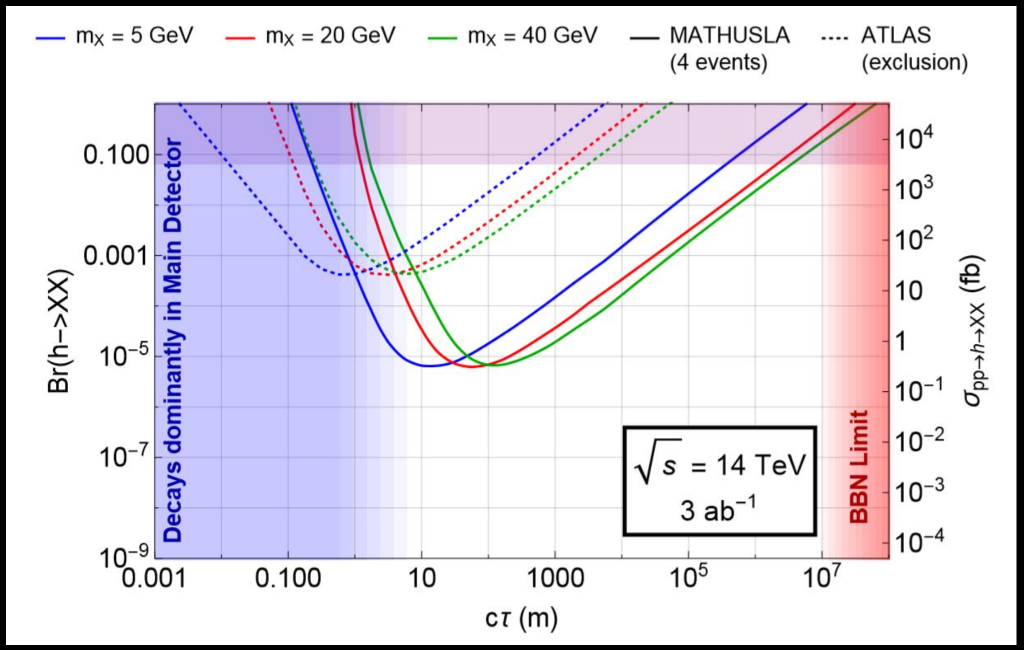
MATHUSLA Detector (~100x100 sq m)

Surface

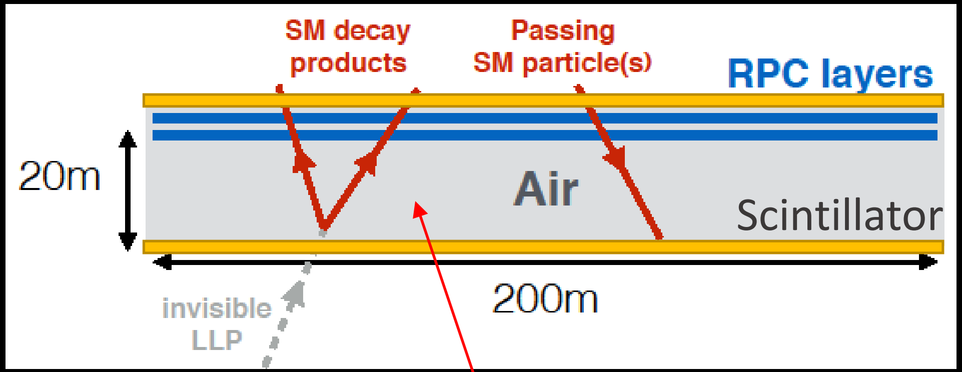
~100 m

~100 m





Minimizing the Background



70 ns travel time

- Scintillator for 1.5 ns timing resolution
- RPC layers for track reconstruction (and vertex finding)

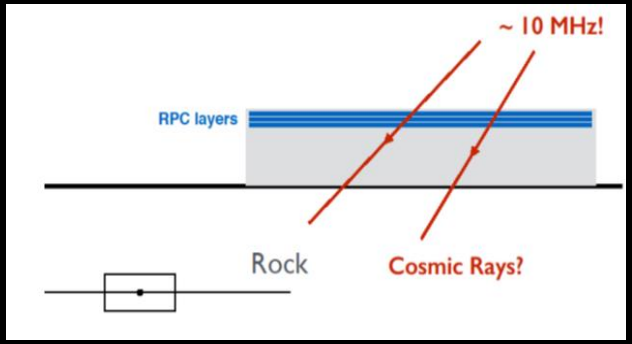
Resistive Plate Chambers (RPCs) have great timing resolution as well

The LLP must decay within the Decay Volume (Air) → Decays before the Decay Volume are vetoed

Vetoing Backgrounds

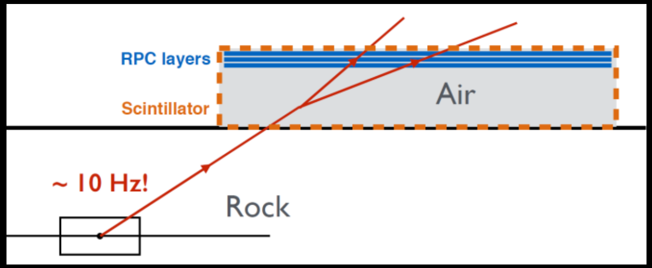
Cosmic Muons

- Precision timing from scintillators & RPC's
- Tracking from RPC's
- May also be some interesting physics



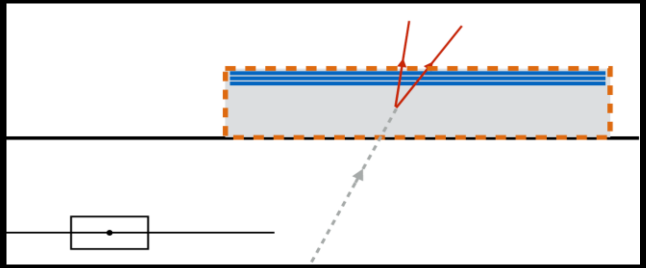
Upward going LHC Muons

- Precision timing from scintillators
- Bottom of Decay Volume veto



Upward going cosmic neutrinos

- Irreducible?
- Rate expected to be very low



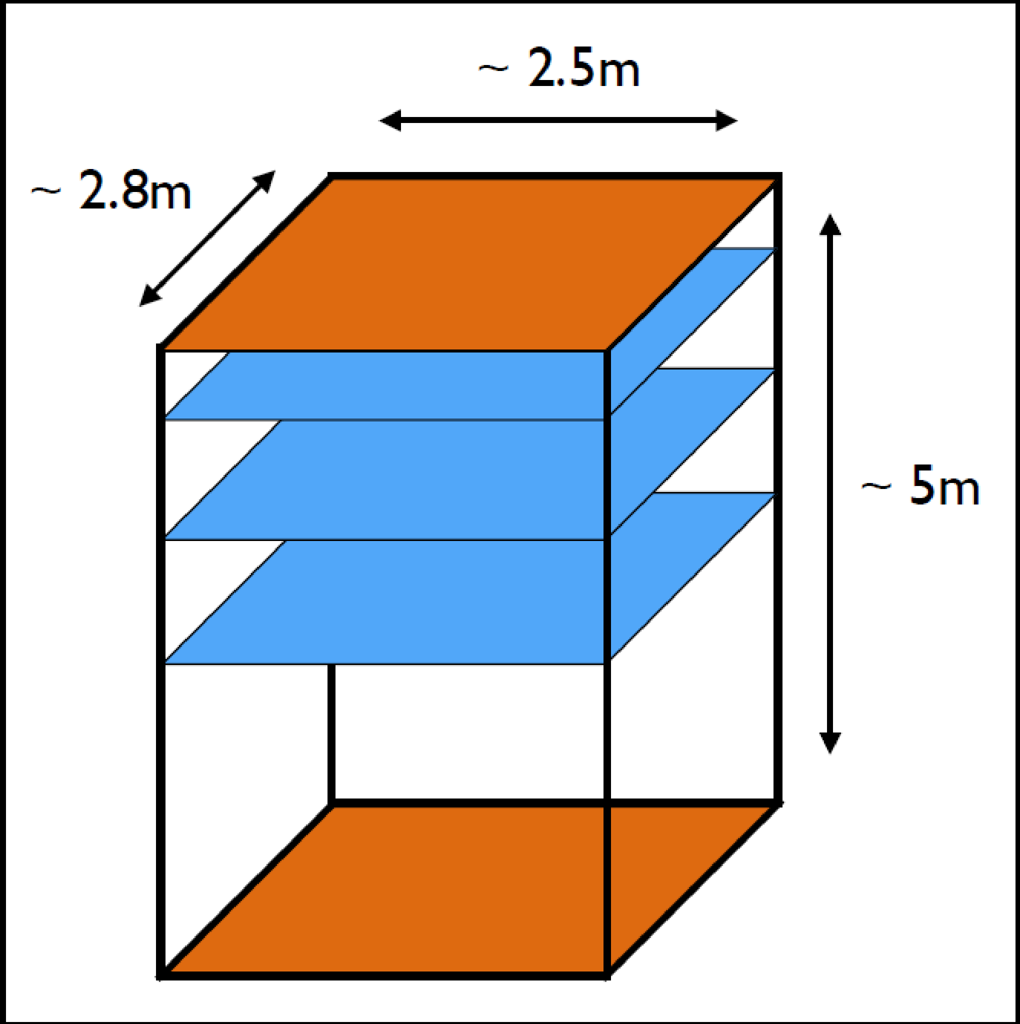
Test Stand

Do these rejection techniques work?

- Scintillator from DZERO end-station muon chambers (thank you D. Denisov!)
- RPC's from Rome (Argo experiment)

Ran in November, being set up again at ATLAS P1

- Great Learning Platform for Graduate Students!
- Timing in portions of the detector
- Learning how finicky RPC's can be




Henry Lubatti
Audrey Kvam
Gordon Watts
Charlie Young
RPCs


Mason Proffitt
Louis Alpigiani
Cristiano Alpigiani
David Curtin
Nina Anikeeva
Scintillator planes

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

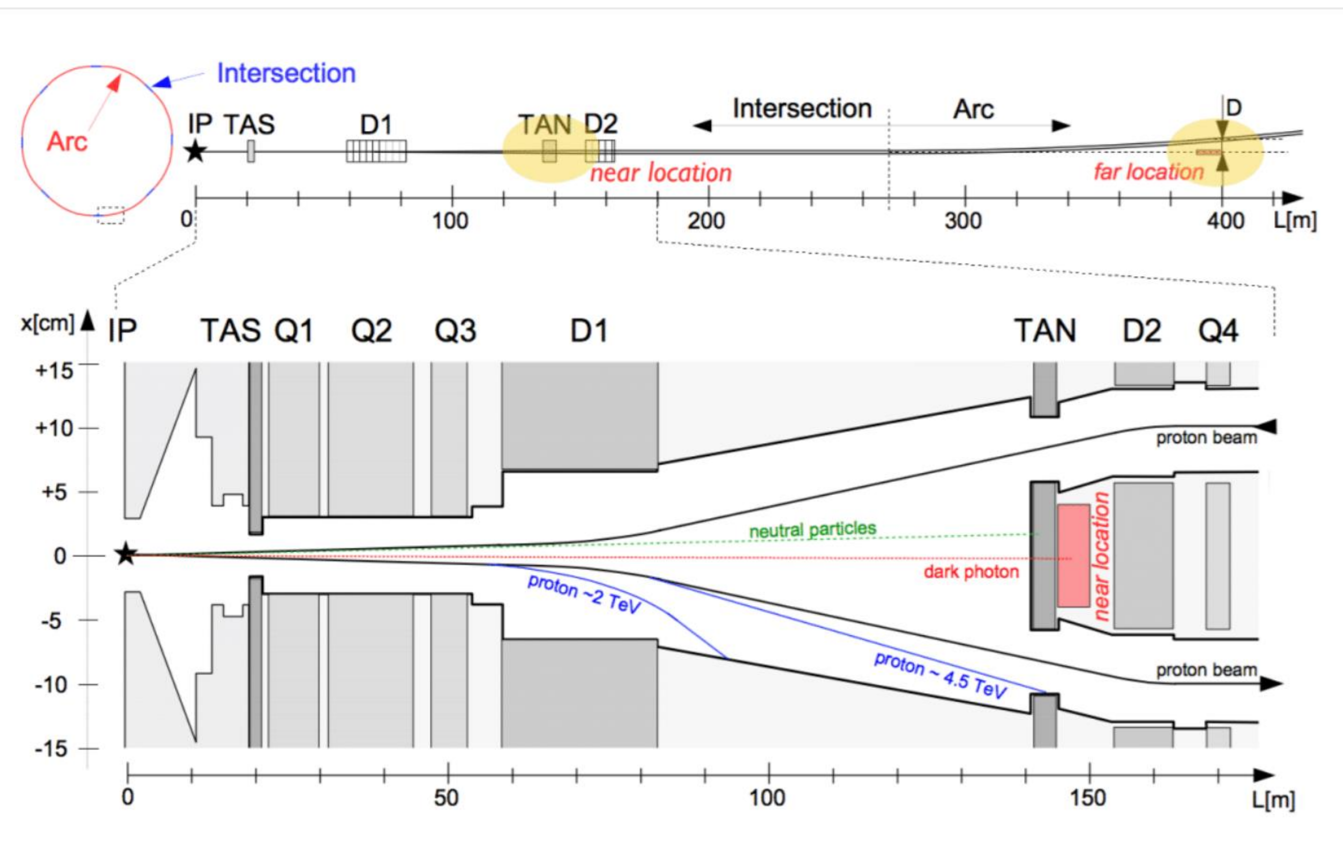
Editors:
David Curtin[1], *Matthew McCullough*[2], *Patrick Meade*[3], *Michele Papucci*[4], *Jessie Shelton*[5]

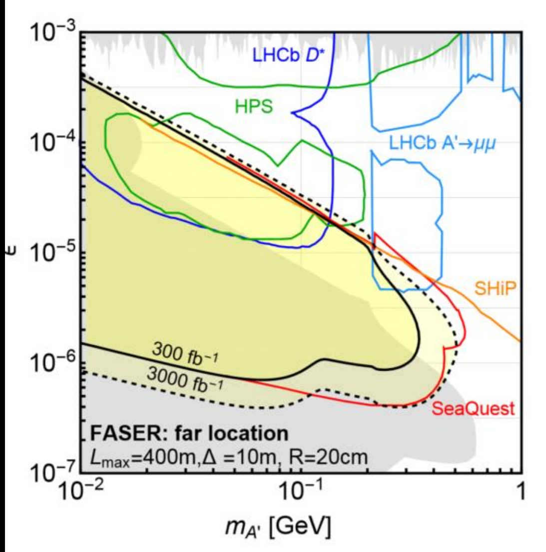
Goal is to have comprehensive document finished by end of 2018

Contributions from broad spectrum of theory community

FASER

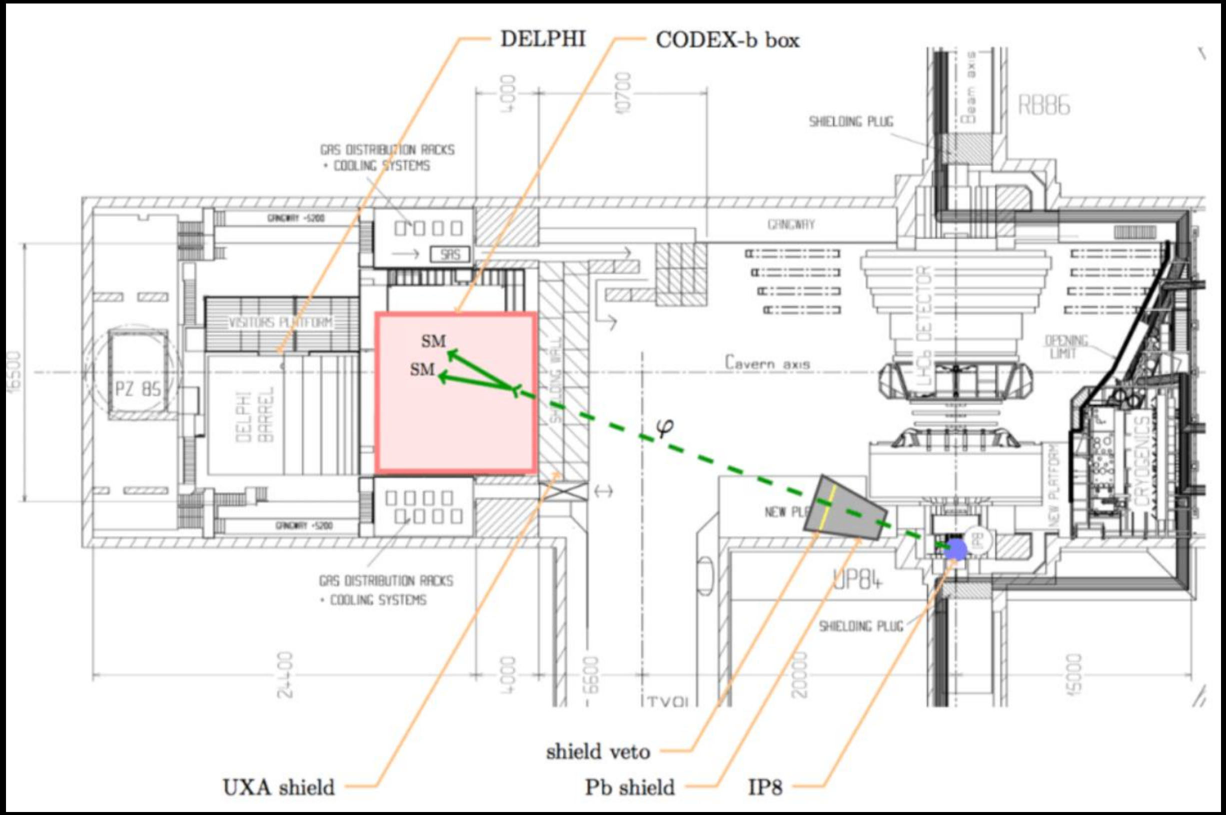
- Forward cylindrical detector in ATLAS tunnel with 0.1 Tesla field
- Advantage – large forward pp cross sections for light particles decaying to lepton
- Original concept considered three locations: near and far on axis and off axis





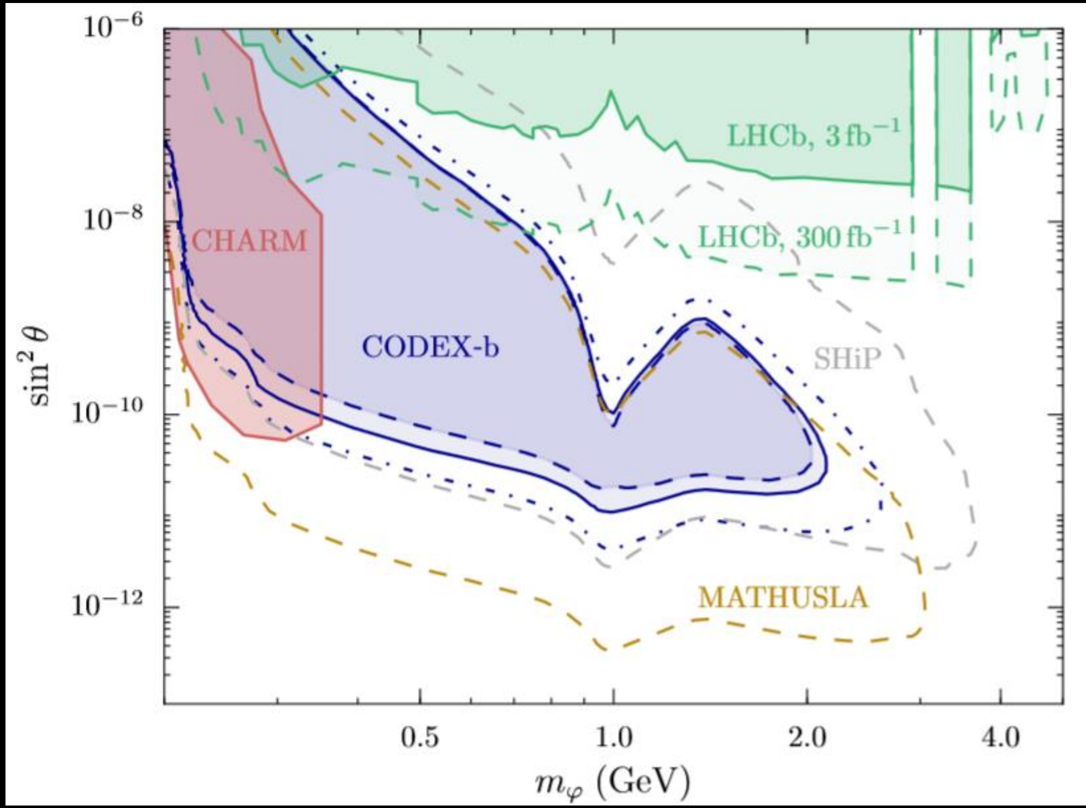
CODEX-b

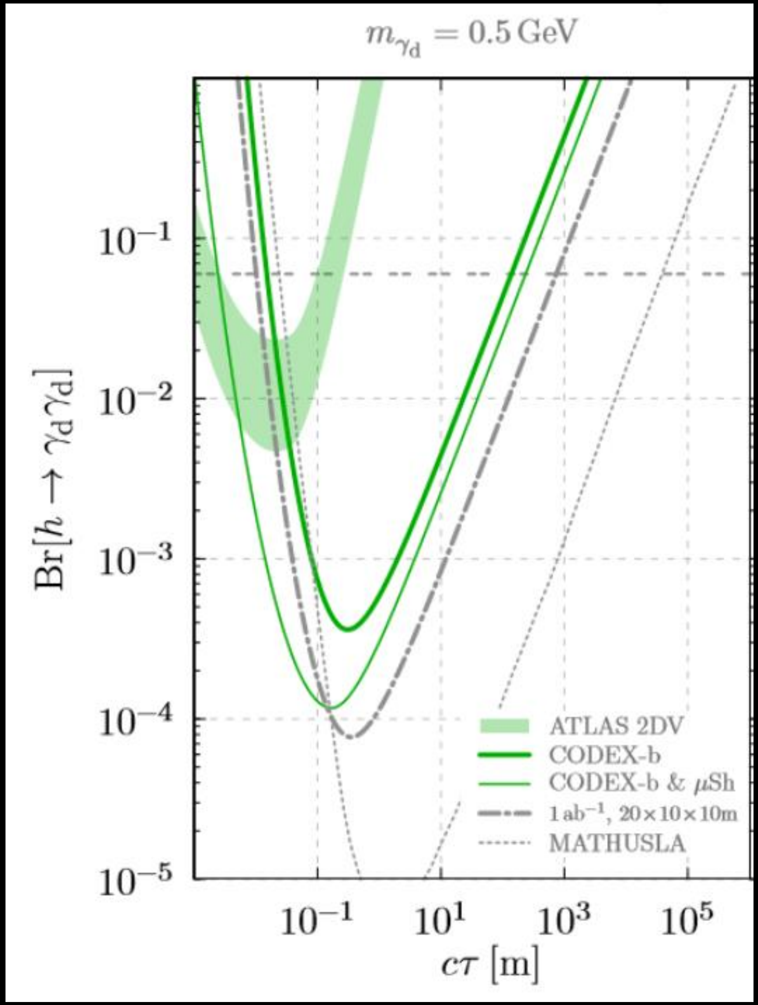
- Instrument current LHC-b DAQ space ~ 1000 m^3
  - Part of LHC-b detector
  - Physics goals similar to MATHUSLA
- Requires more shielding
- LHC-b luminosity lower than pp CMS /ATLAS
- Has some attractive features



CODEX-b

$$B \to X_s \varphi$$





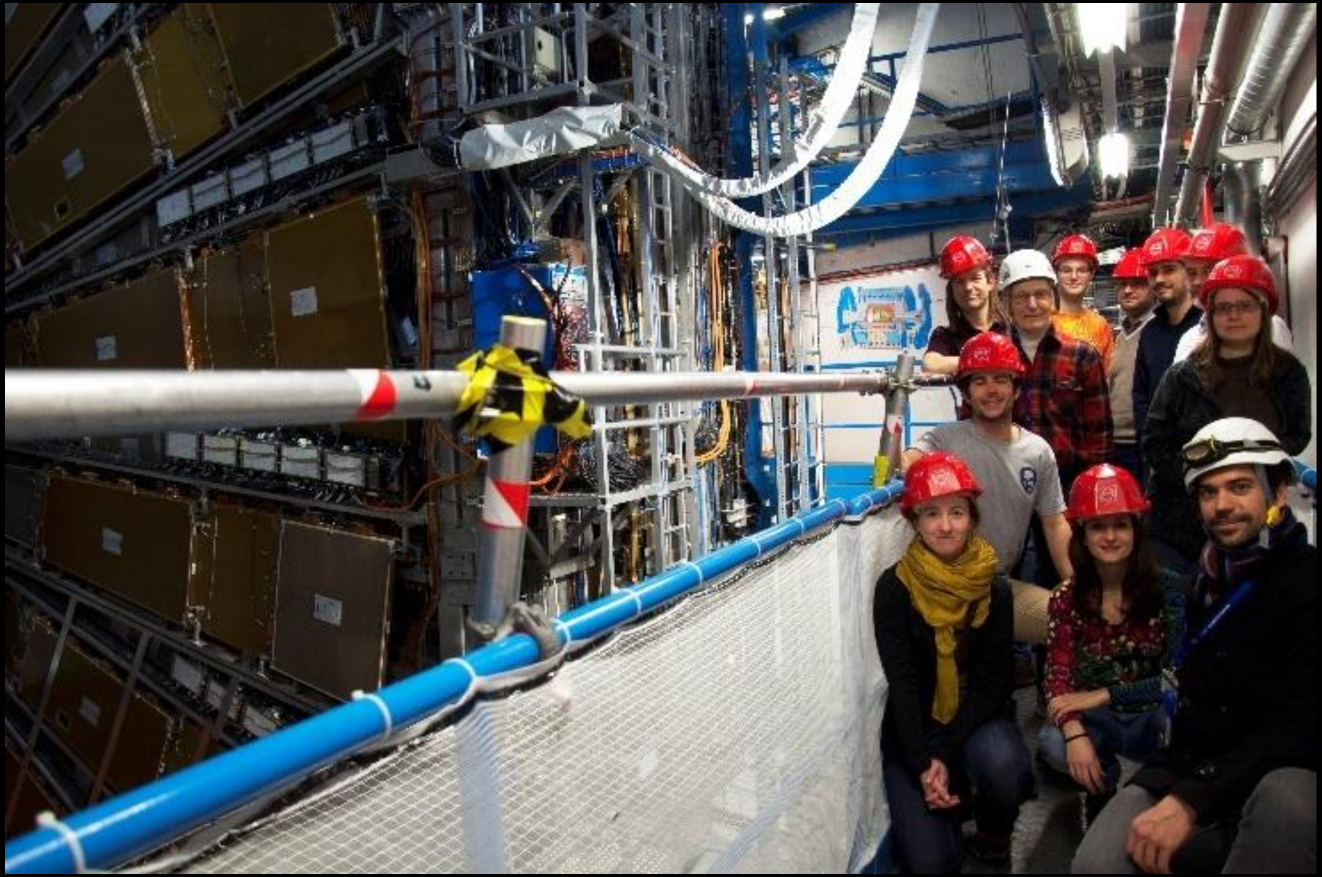
Physics Beyond Colliders

- PBC (Physics Beyond Colliders) at CERN study group to evaluate proposals for detectors to go beyond current LHC detectors
  - report expected by end of 2018
  - http://pbc.web.cern.ch/
- Charge is to evaluate various new proposals
  - SHIP 400 GeV beam dump - weakly coupled particles in the few GeV mass range
  - FASER (1708.09389) proton inelastic scattering in HL-LHC collisions to produce light LLPs (dark photons)
  - CODEX-b (1708.09395) physics goal similar to MATHUSLA
  - MATHUSLA
  - MilliQan (1410.6816 Haas, Hill, Izaguirre, Yavin, 1506.04760 Izaguirre, Yavin, Letter of Intent: 1607.04669) Search for milli-charged particles at Point-5 (CMS)

Conclusions

- The LHC has completed a fairly comprehensive set of searches for long lived particles decaying to jets!
  - SUSY searches not discussed here!
- Substantial parts of phase space for exotic Higgs decays have been ruled out
  - As well as heavier mass scalar decays
- A lot of room for improvement in Run 2
  - Combined analyses, better results for theorists
  - Include other objects besides displaced vertices
  - A huge amount of work already done… just not public. ☹
- ULLP Searches
  - MATHUSLA detector, test stand
  - Initial collaboration of 5 or 6 institutions formed (and growing)

Thanks!



And to ATLAS

And the LHC!