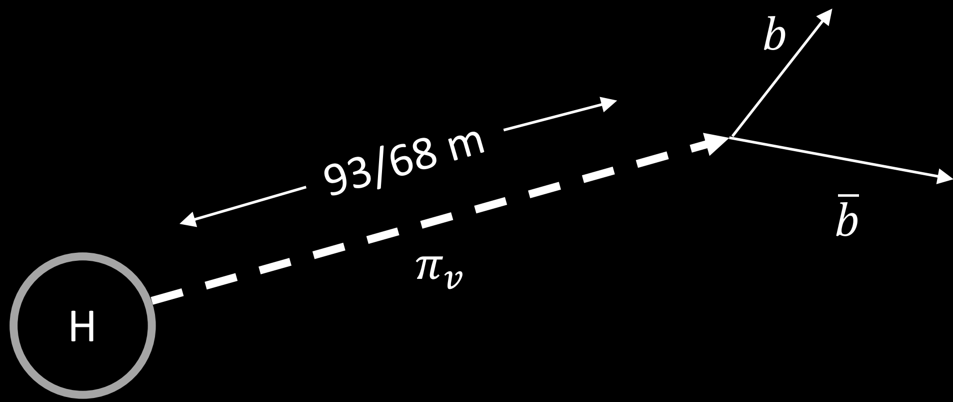


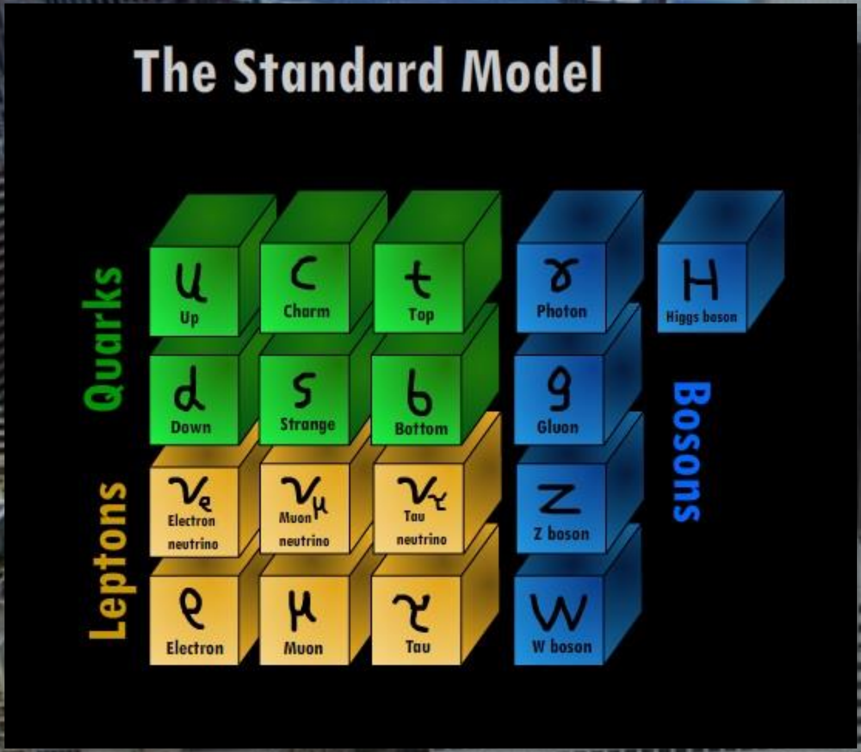
Living Long at the LHC

Gordon Watts

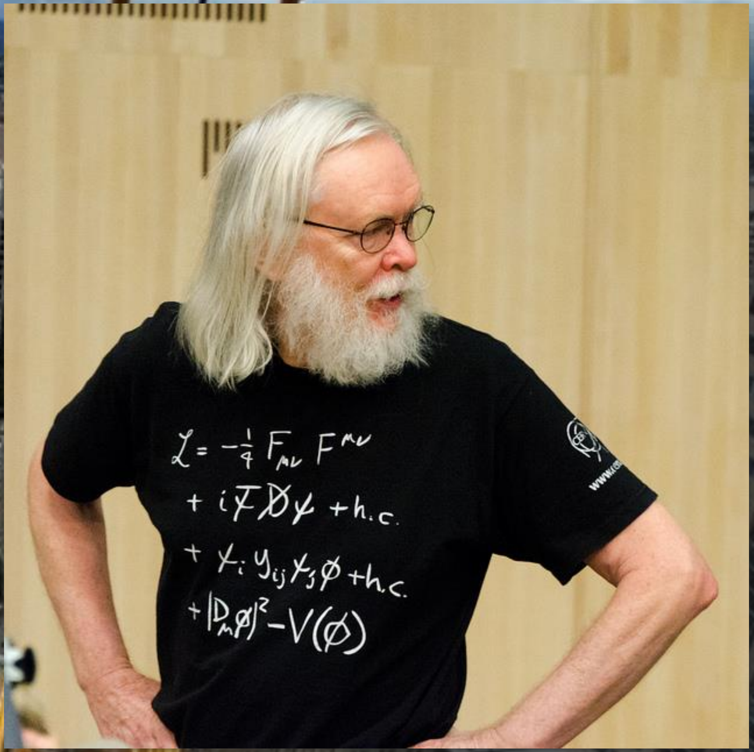
University of Washington – Seattle

DESY-Zeuthen

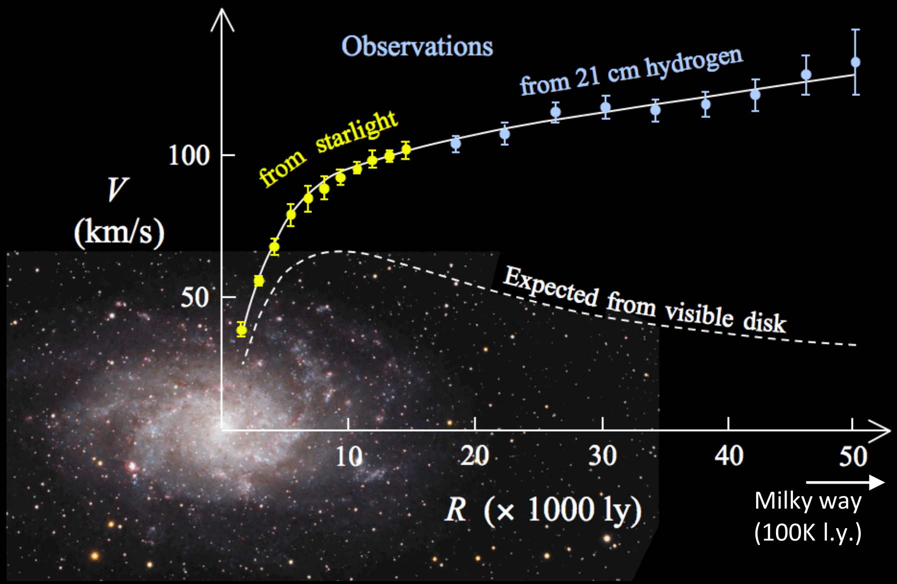
January 17, 2018



The Standard Model
Quarks
Leptons
Bosons
u Up
c Charm
t Top
d Down
s Strange
b Bottom
νe Electron neutrino
νμ Muon neutrino
ντ Tau neutrino
e Electron
μ Muon
τ Tau
γ Photon
g Gluon
Z Z boson
W W boson
H Higgs boson

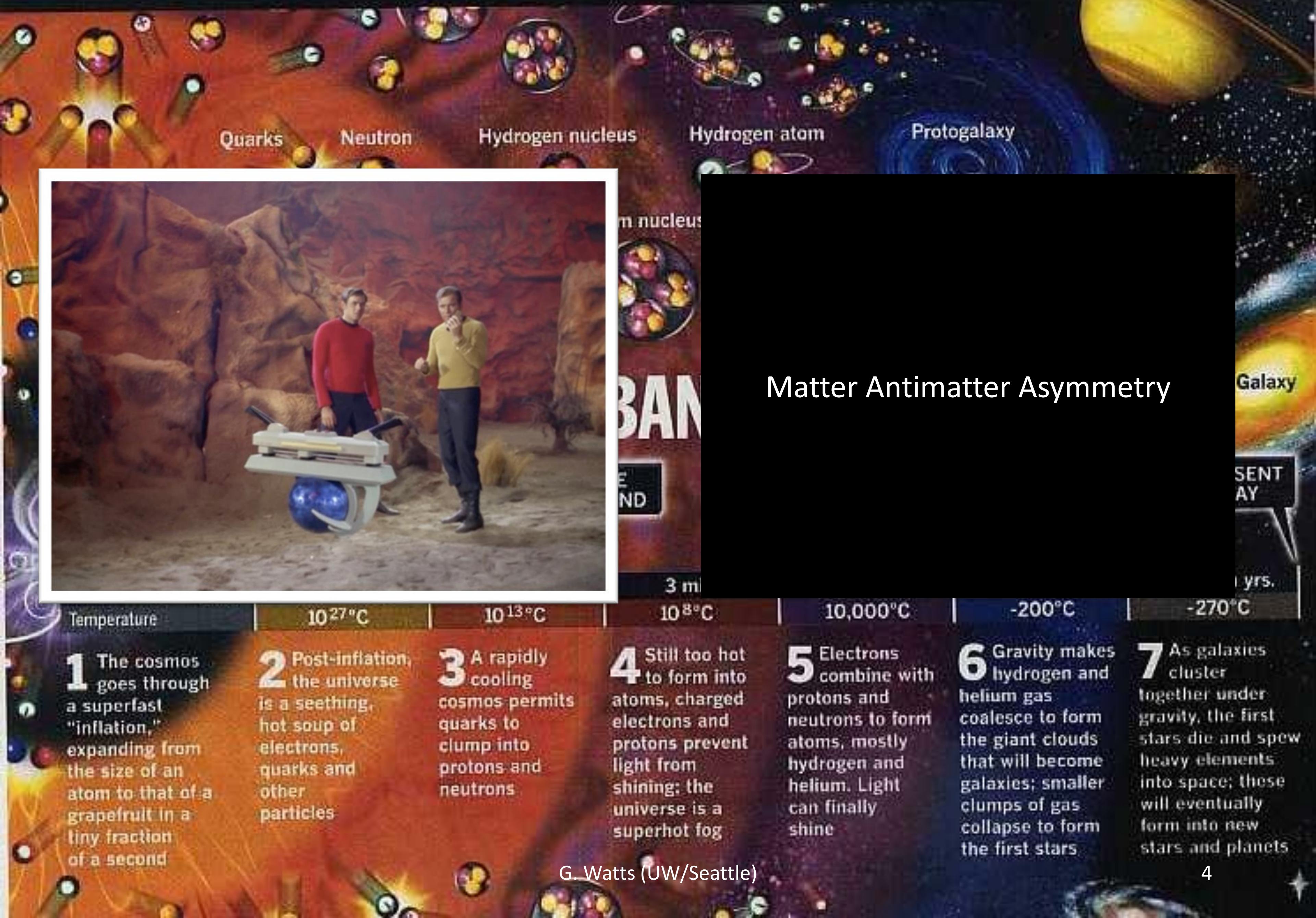


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$


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



What is Dark Matter?

Baryon asymmetry?

Why three families?

Why those masses?

Grand Unification? SUSY Breaking?

Or direct motivation unknown?

Super Symmetry

Little Higgs Model

Extra Dimensions

String Theories

Supergravity

Grand Unified Theories

MSSM

Hidden Sector Models

WIMPS

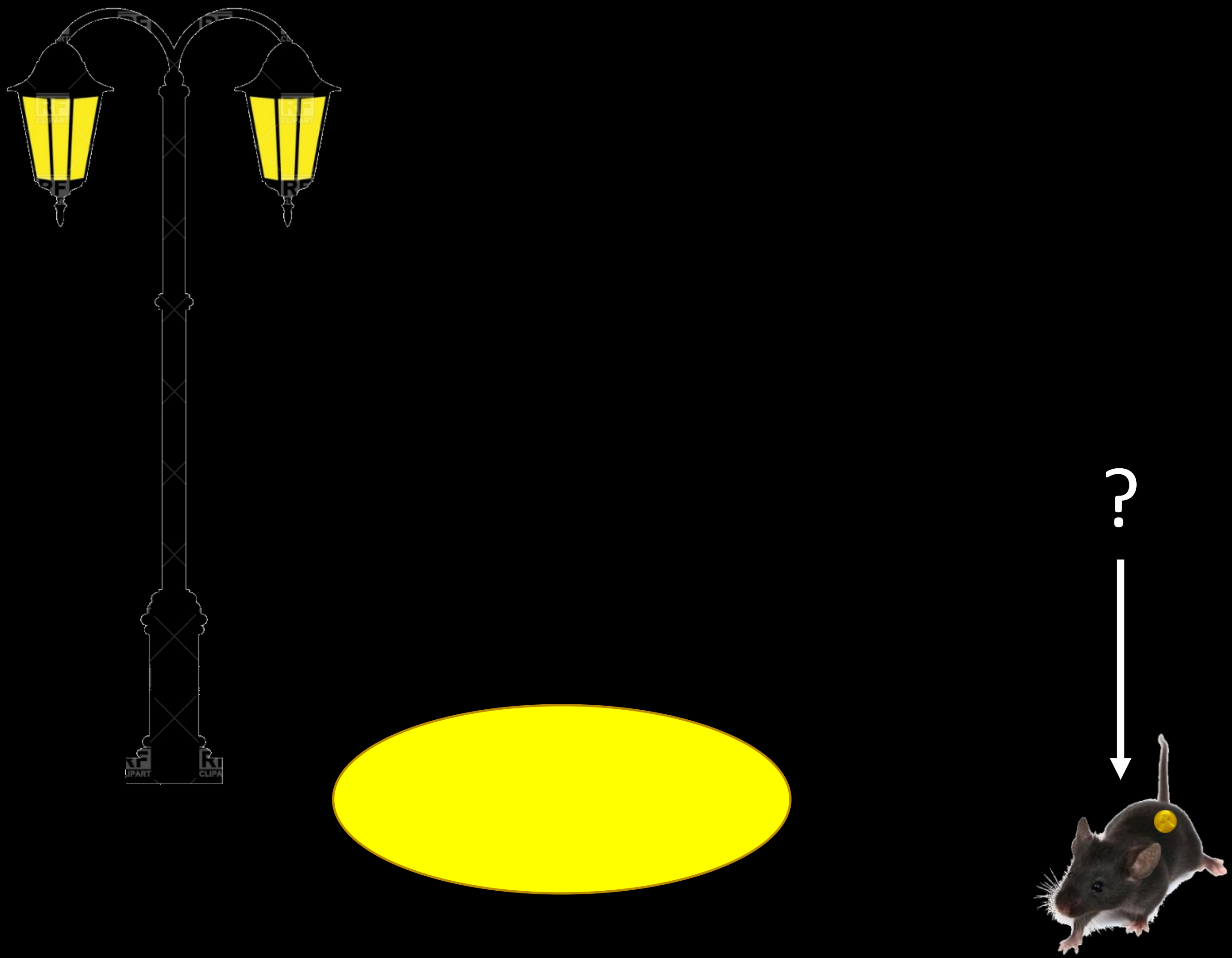
Higgs Doublet

Axions

$SU(3)^3$

No Evidence

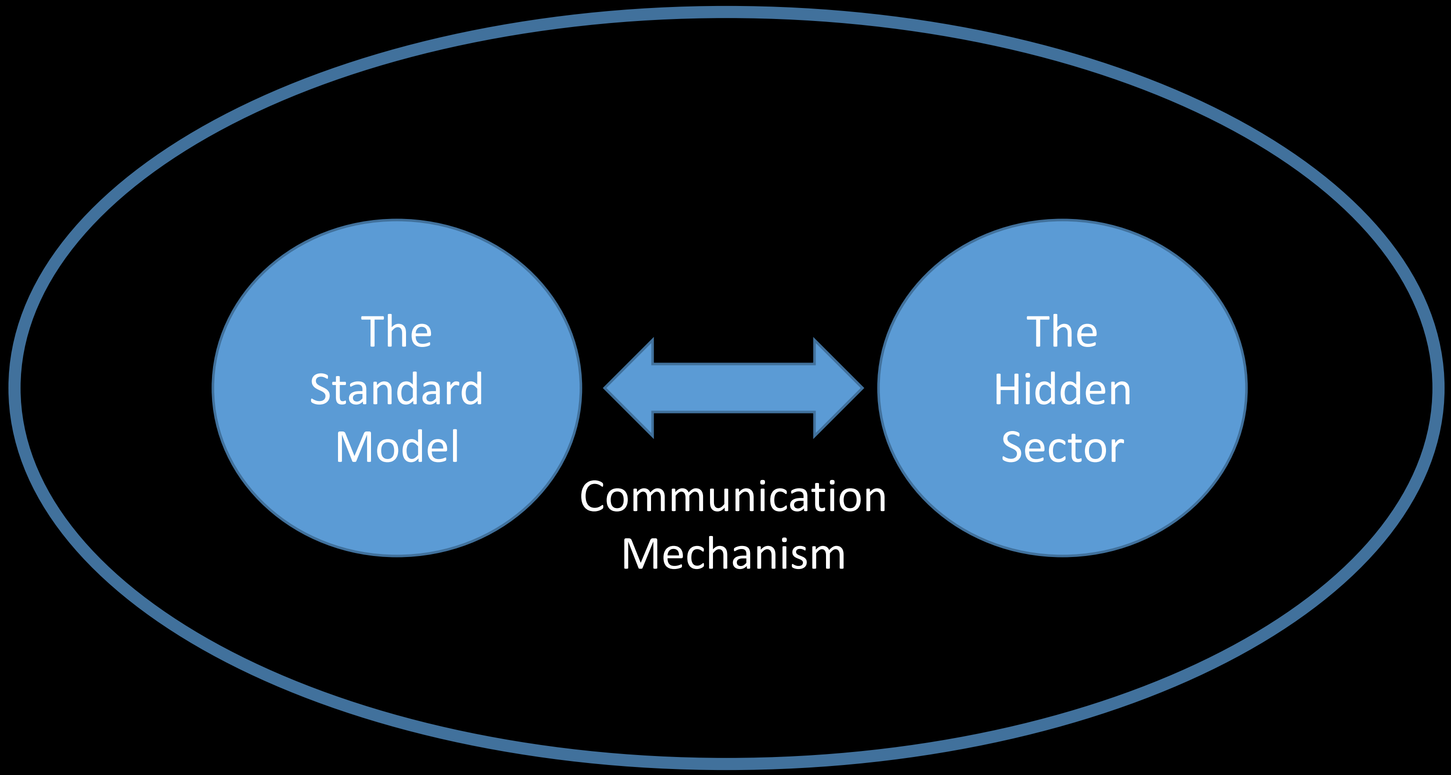
What did we miss?



Light Particles

Stealth XXX

Long Lived Particles


The
Standard
Model
The
Hidden
Sector
Communication
Mechanism

Hidden Sector

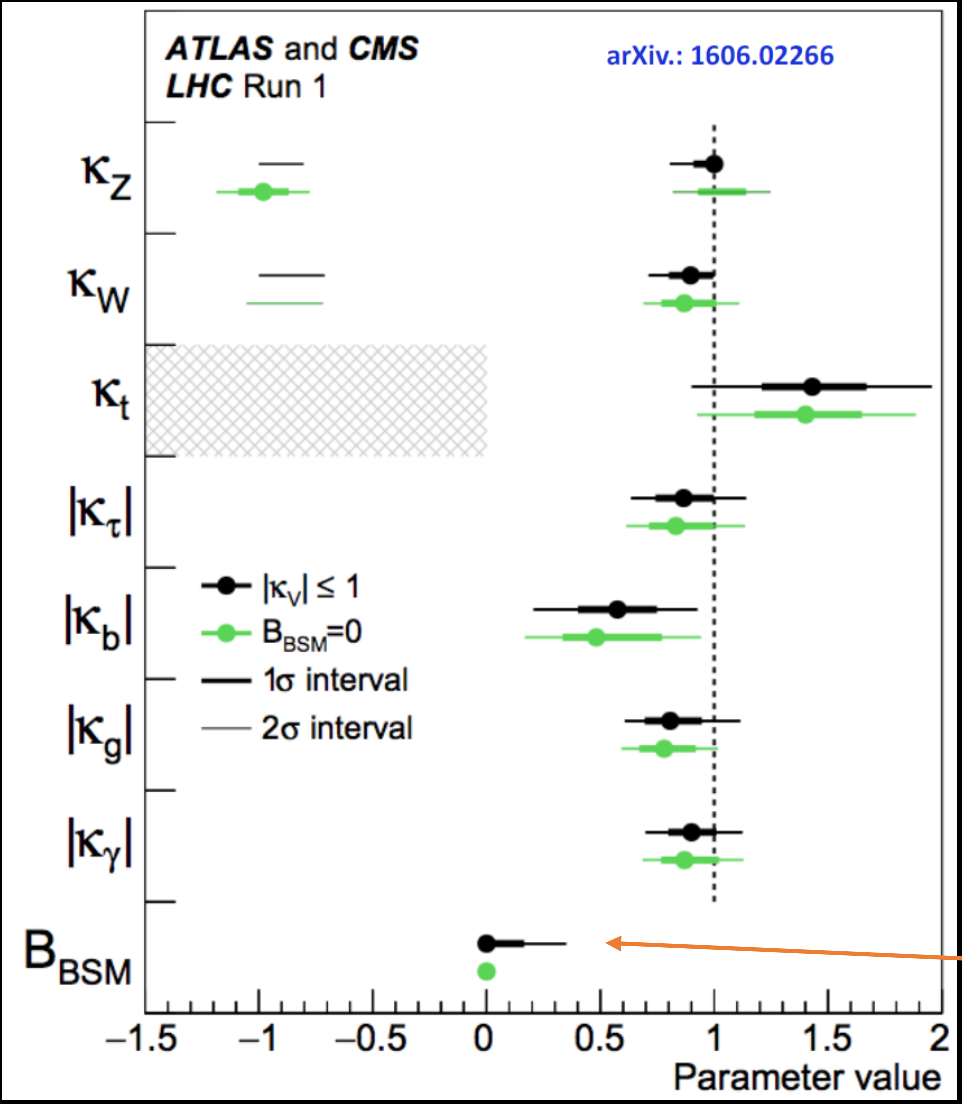
A gauge group that does not interact via the SM gauge fields

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

Hidden Valley

Some particles come back!

The Higgs as a Communicator



Room for a 30% invisible decay

Exotic Higgs Decays

Working Group

http://exotichiggs.physics.sunysb.edu

Home | Overview | Theories Producing Exotic Higgs Decays | Decay Channels | Contact | Admin

Exotic Decays of the 125 GeV Higgs Boson

1312.4992v4

David Curtin,[1] Rouven Essig,[1] Stefania Gori,[2,3,4] Prerit Jaiswal,[5]
Andrey Katz,[6] Tao Liu,[7] Zhen Liu,[8] David McKeen,[9,10] Jessie Shelton,[6]
Matthew Strassler,[6] Ze'ev Surujon,[1] Brock Tweedie,[8,11] and Yi-Ming Zhong[1,*]

scalars

NMSSM with exotic decays to fermions

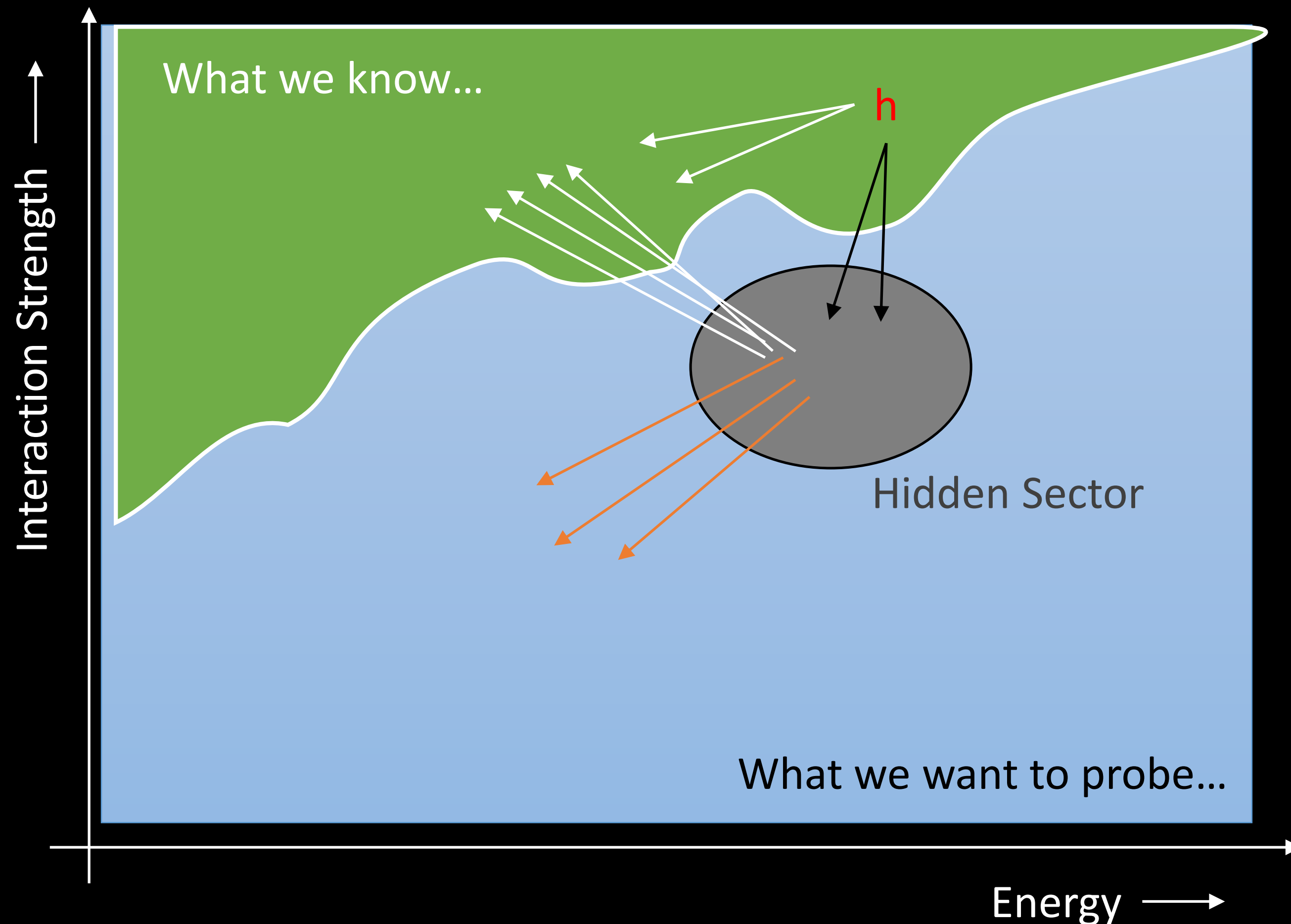
SM + Fermion

MSSM

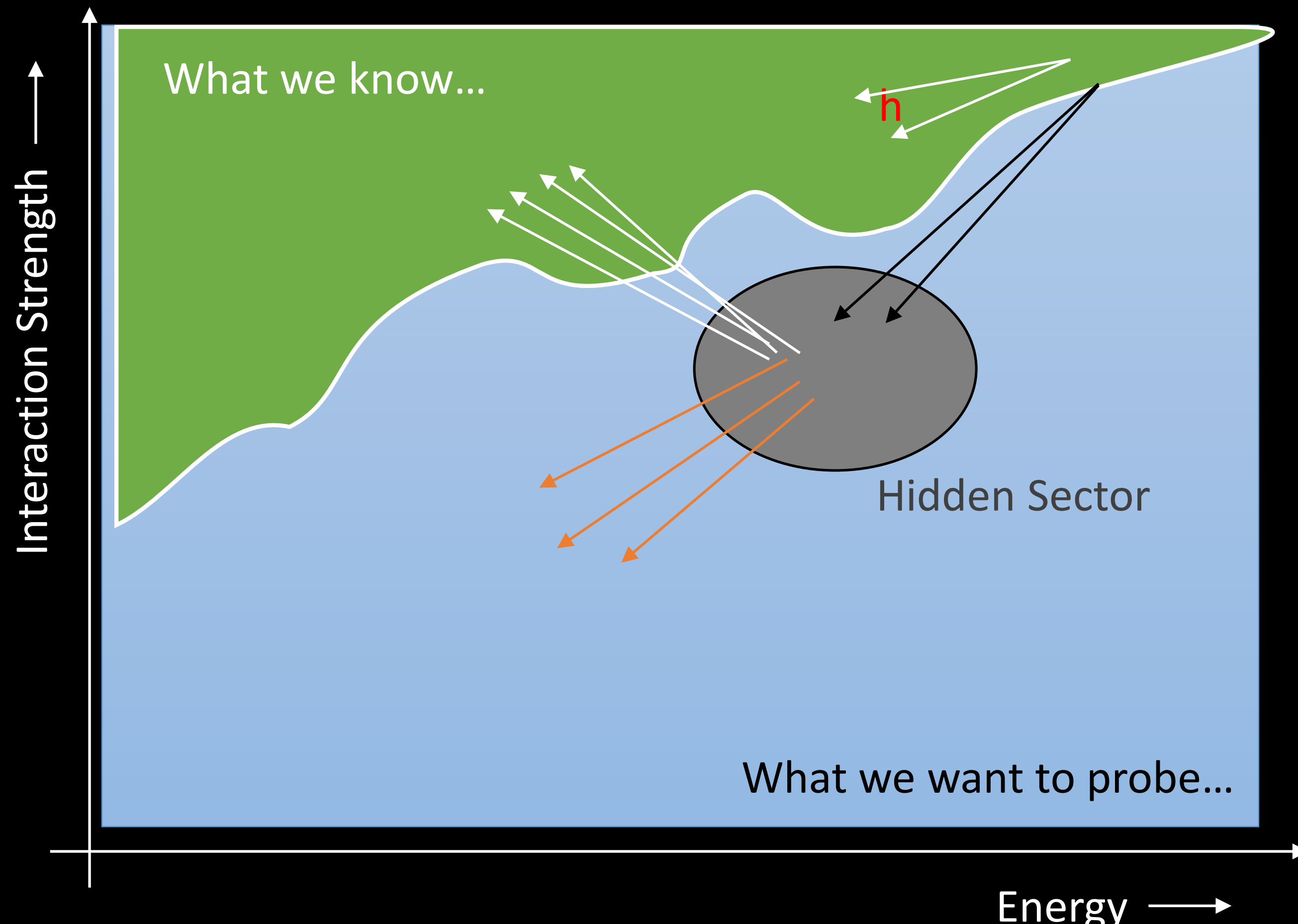
Hidden Valleys

SM + 2 Fermions

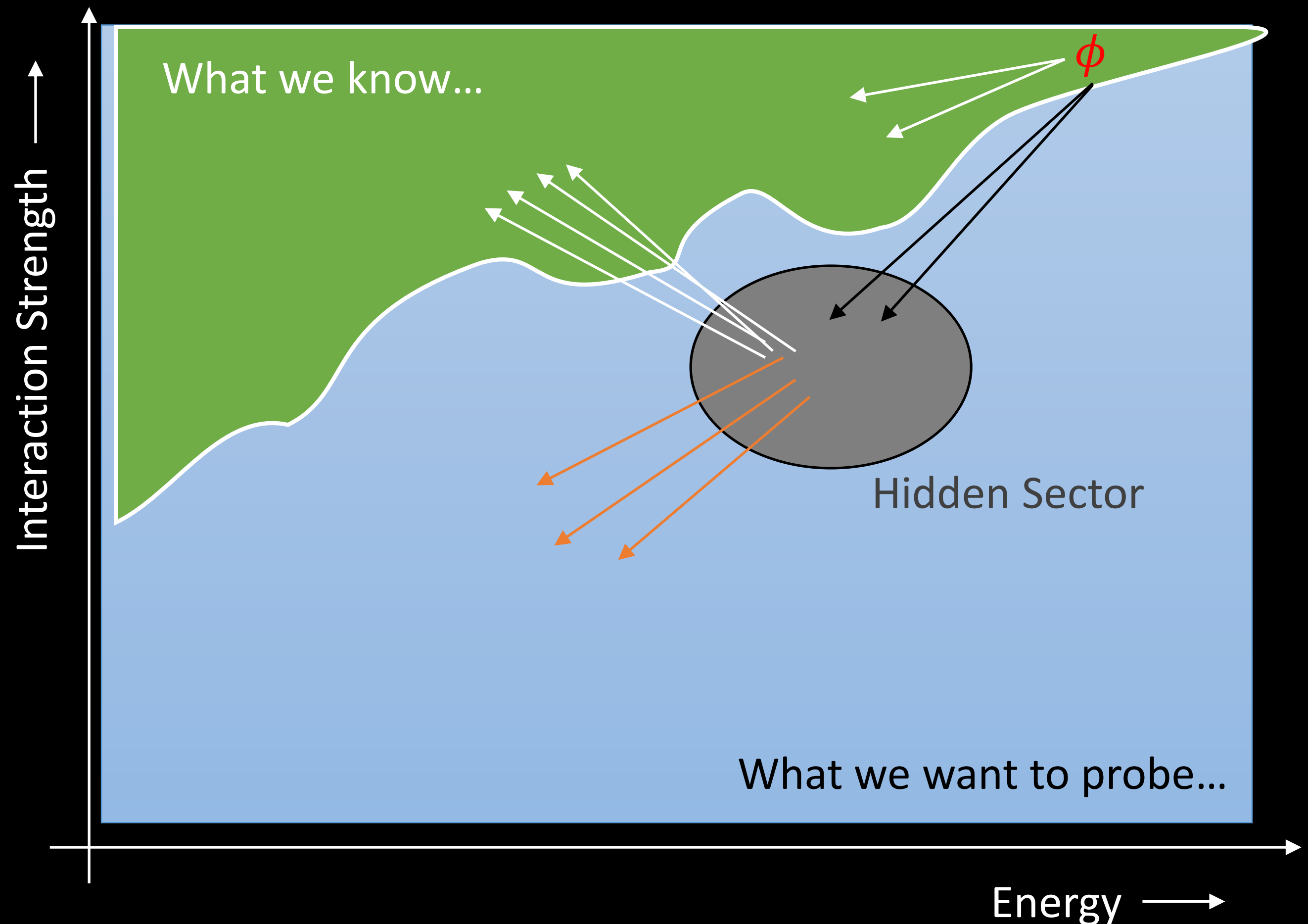
Little Higgs



(Idea for Schematic taken from Strassler)



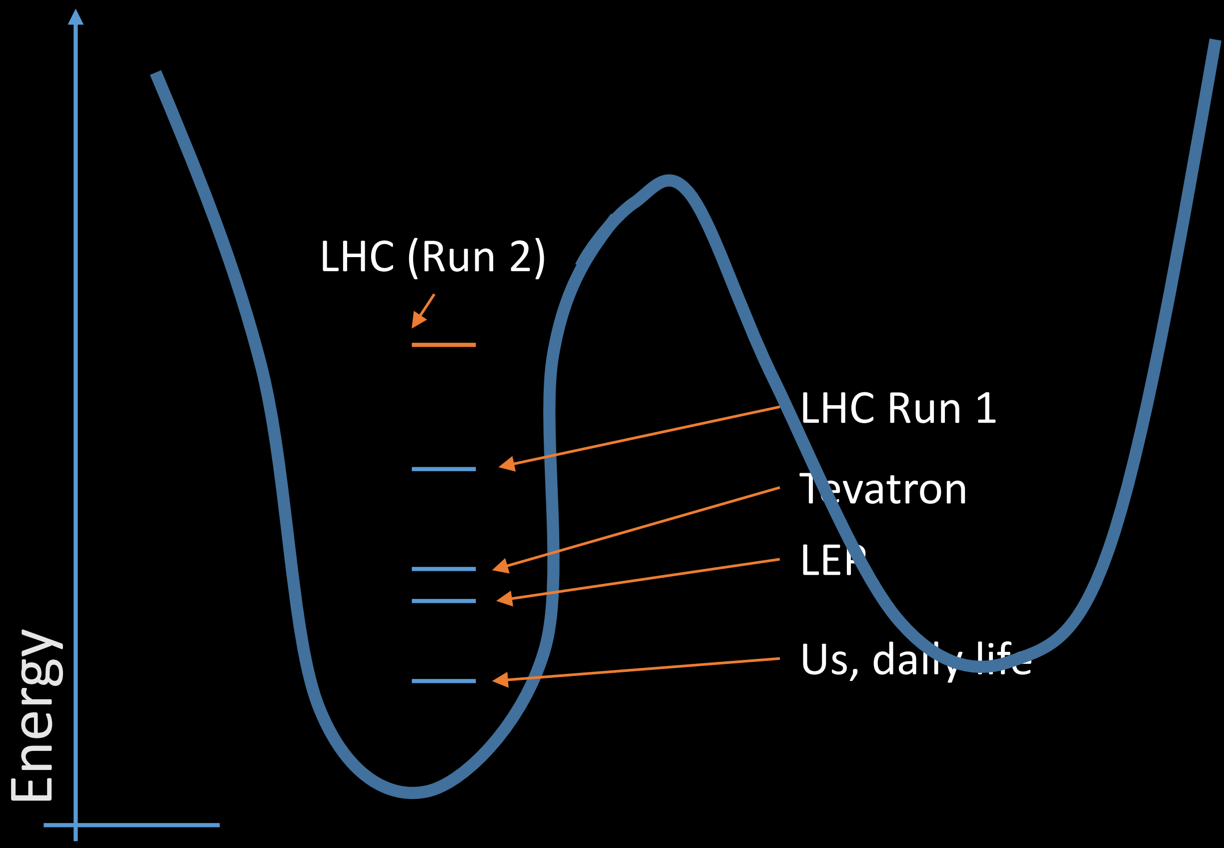
(Idea for Schematic taken from Strassler)



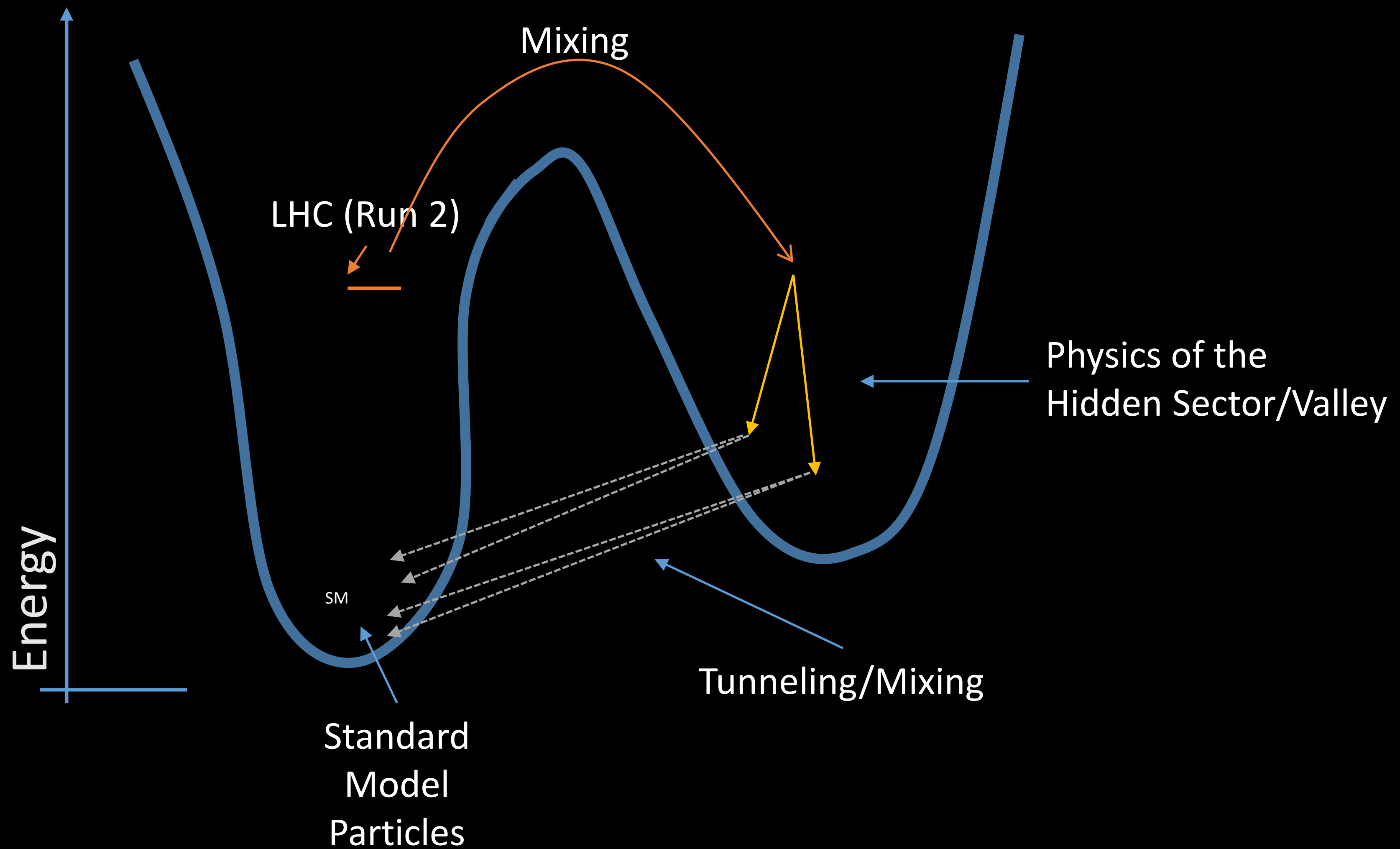
(Idea for Schematic taken from Strassler)

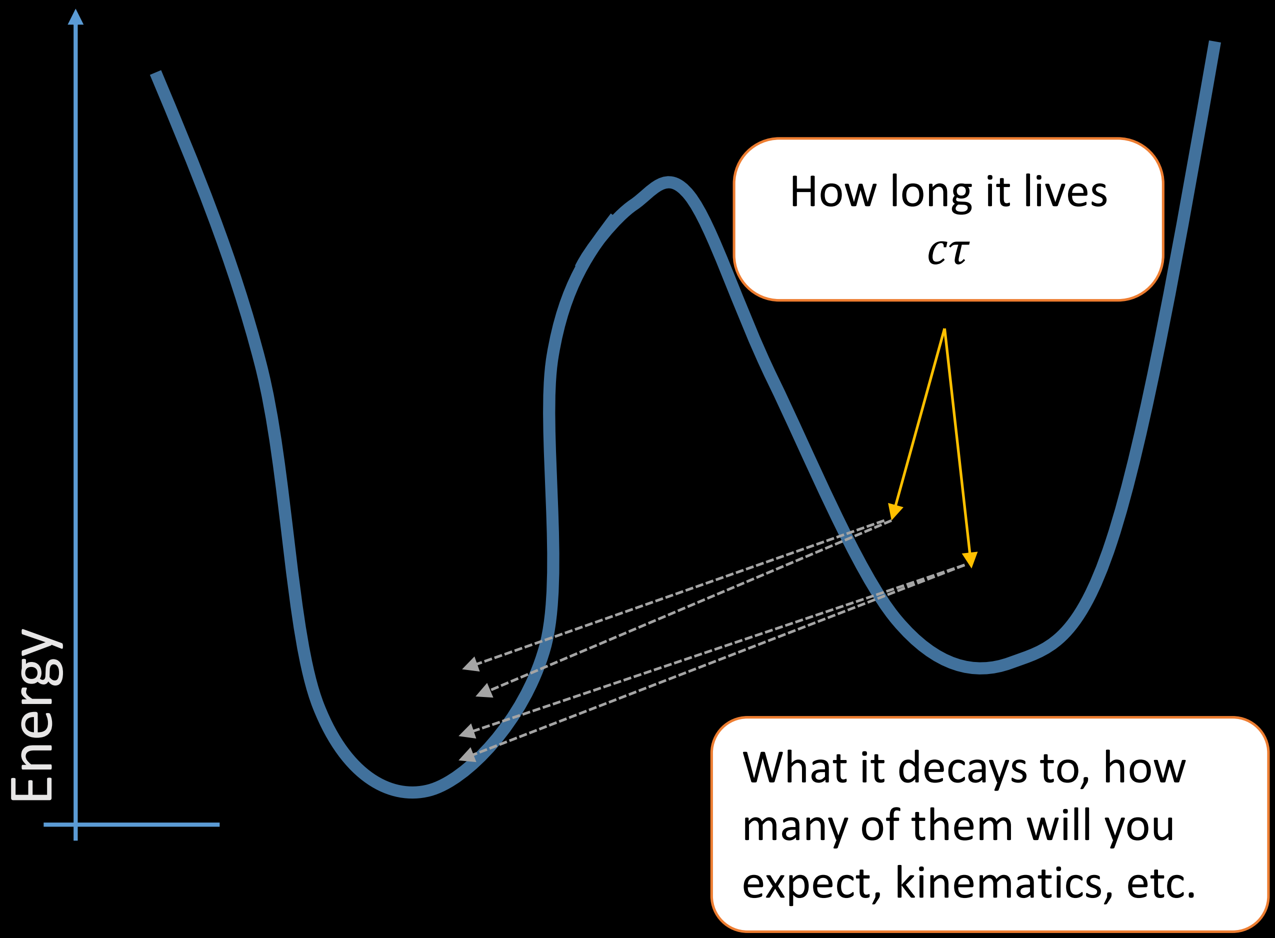
Why haven’t we seen anything yet?

Why haven't we seen anything yet?



Why haven't we seen anything yet?



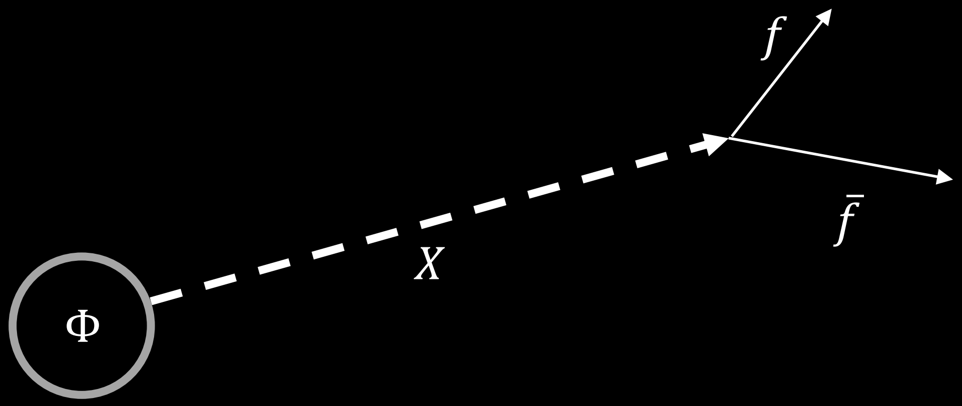

Energy
How long it lives
$c\tau$
What it decays to, how many of them will you expect, kinematics, etc.

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



Many BSM theories accommodate long-lived particles

- 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)

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

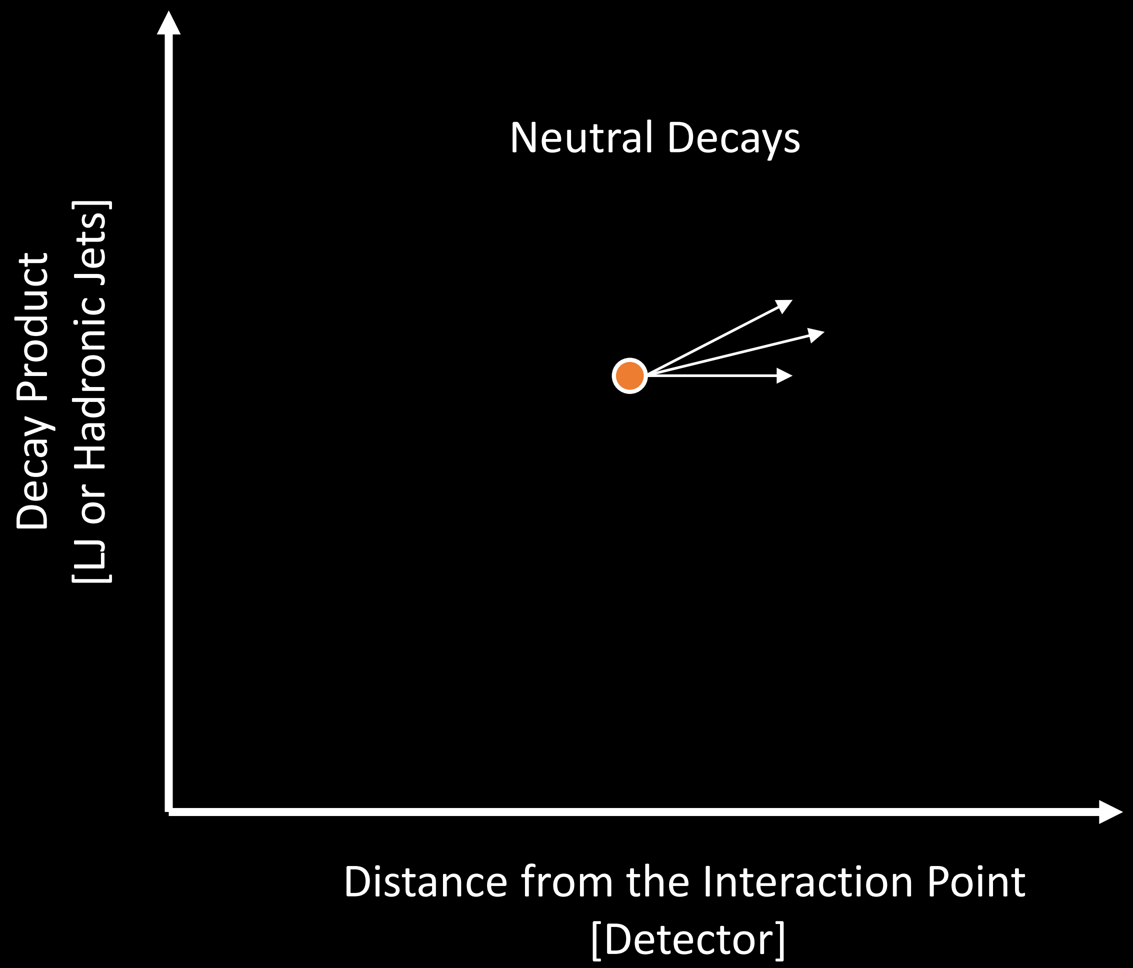
Hidden Valley
Neutral Naturalness

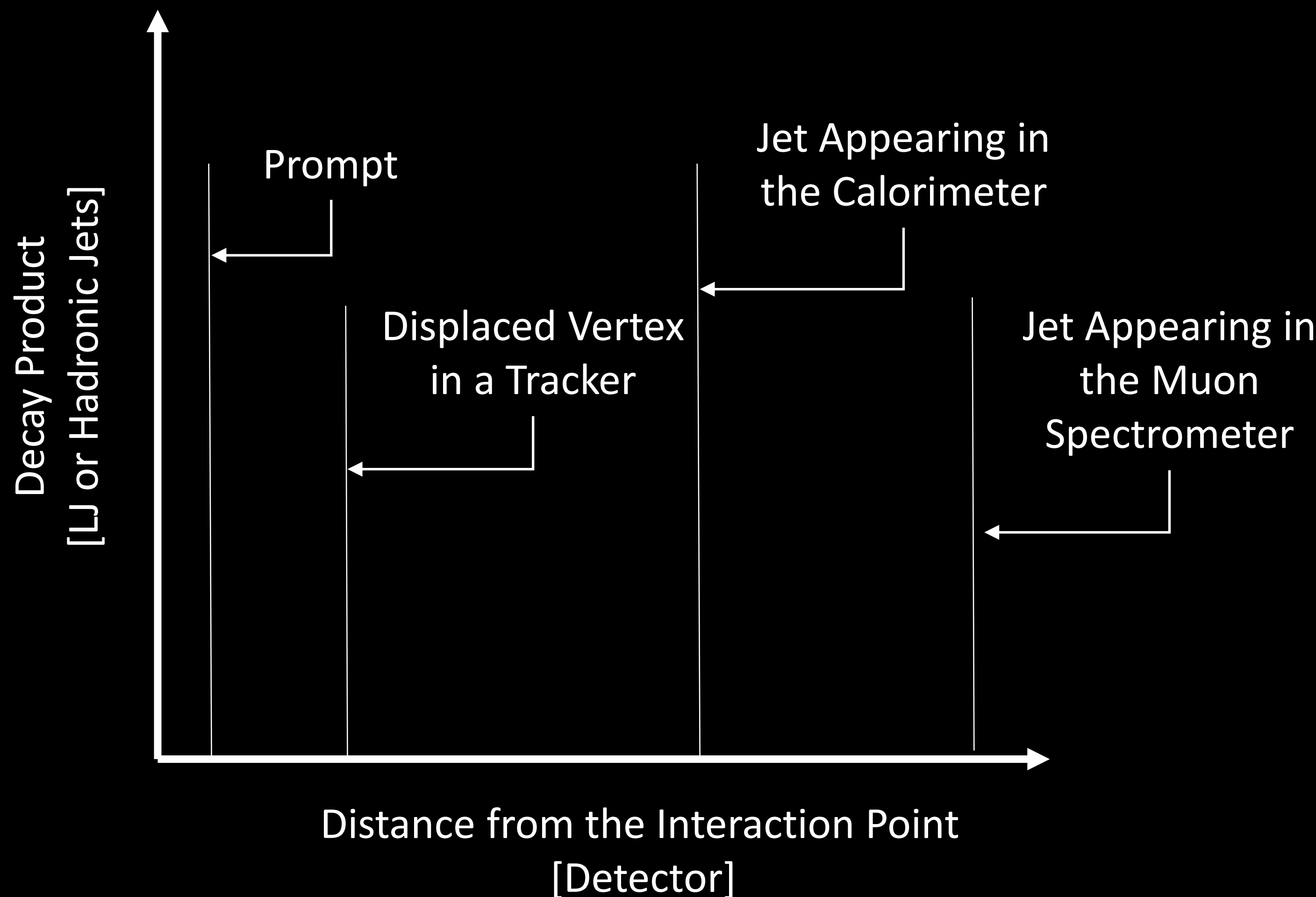
Associated Production and Decay

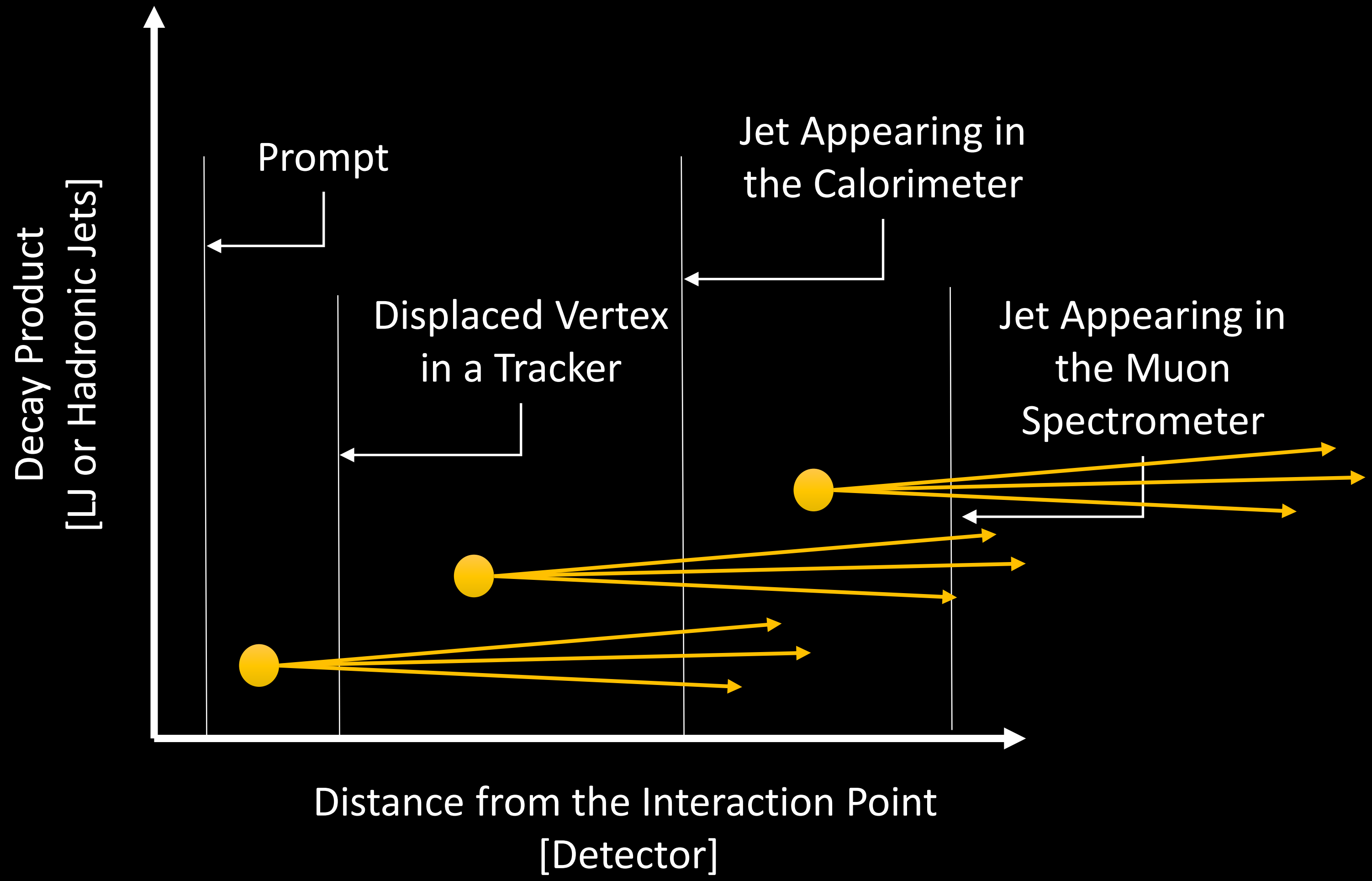
LLP is produced in association, or the decay contains other objects

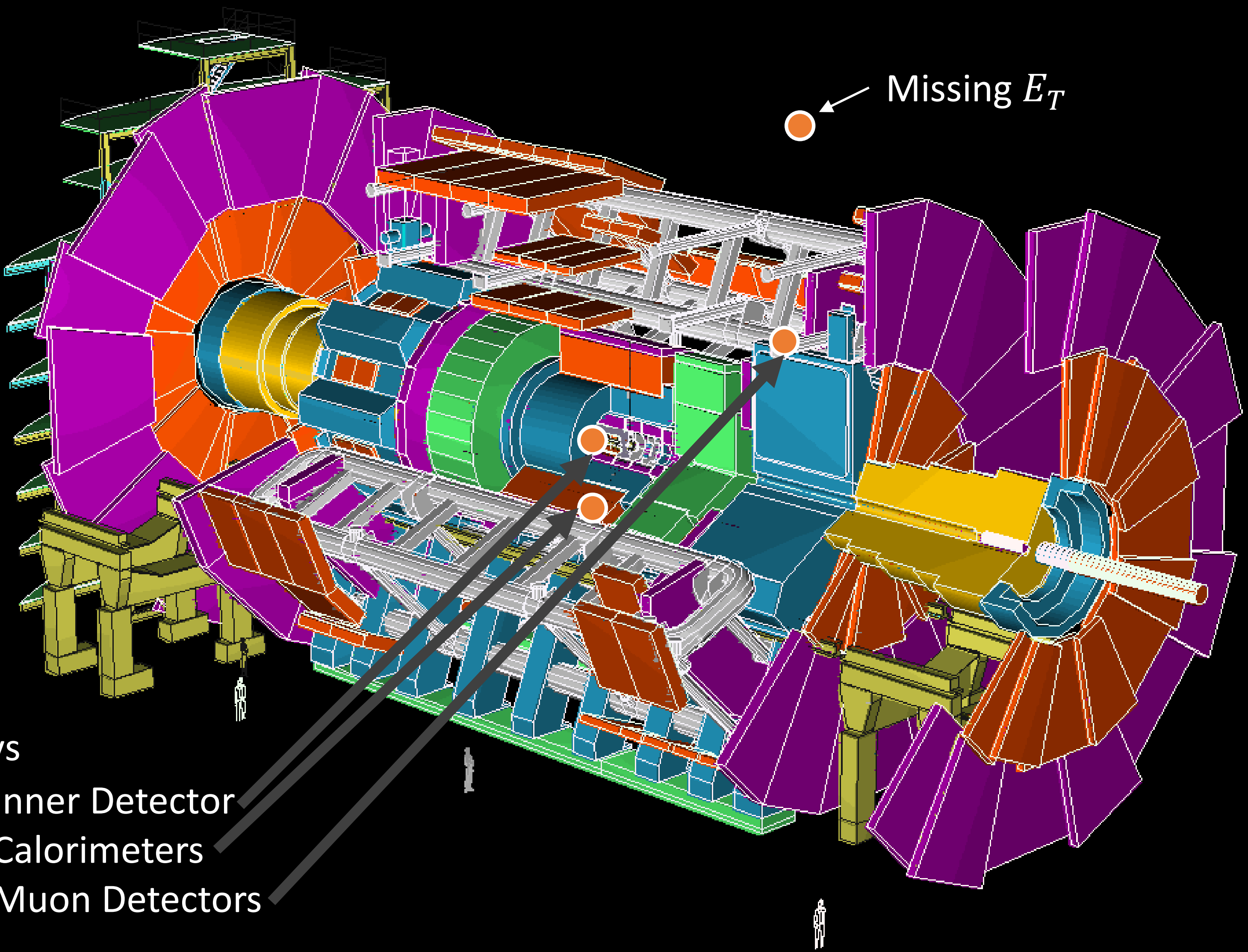
Jets – Colored Object
Leptons – EW interactions
Weak Bosons – Associated production
etc.

Life-time of the LLP is a free parameter


Neutral Decays
Decay Product
[LJ or Hadronic Jets]
Distance from the Interaction Point
[Detector]

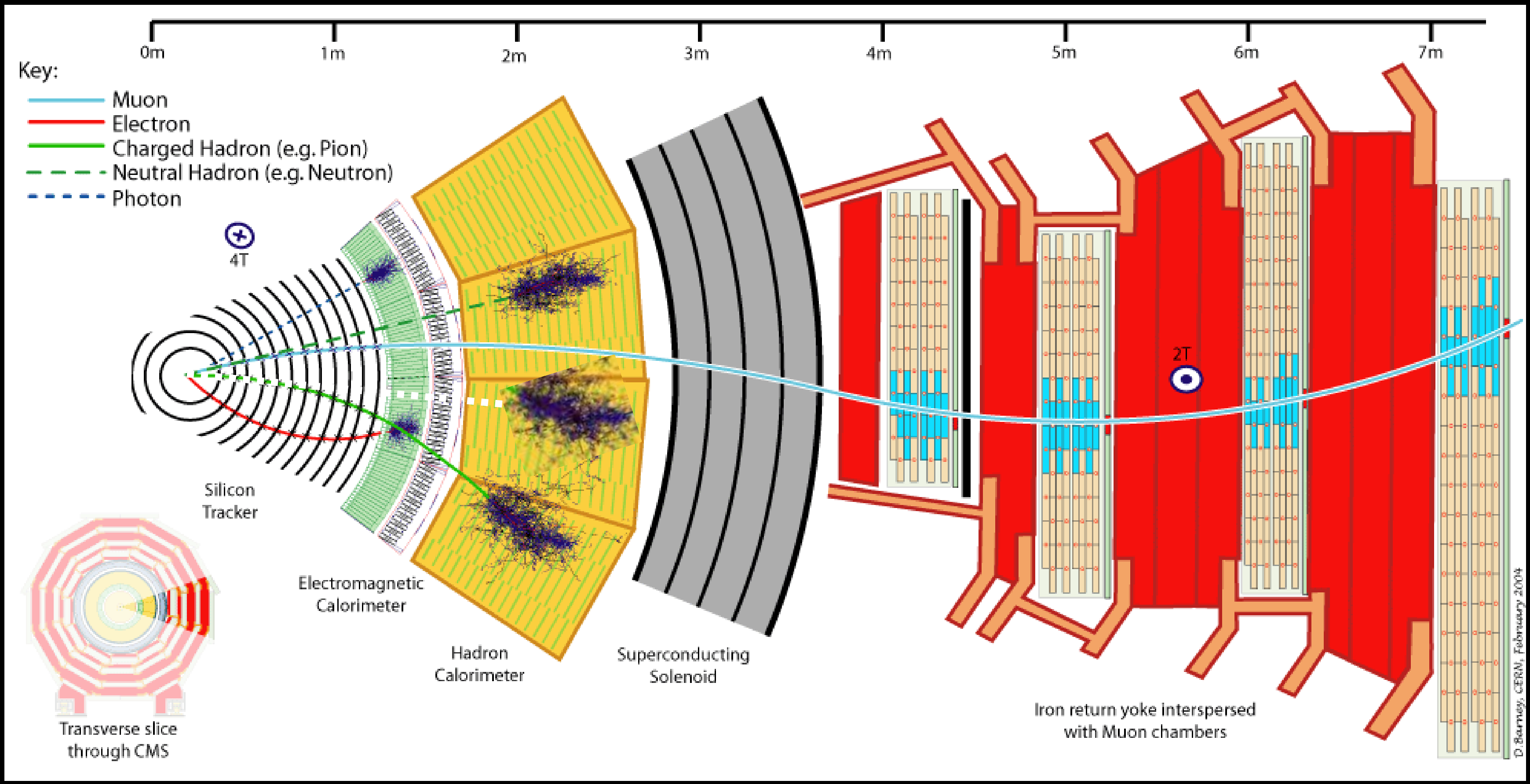

Prompt
Displaced Vertex in a Tracker
Jet Appearing in the Calorimeter
Jet Appearing in the Muon Spectrometer
Decay Product [LJ or Hadronic Jets]
Distance from the Interaction Point [Detector]

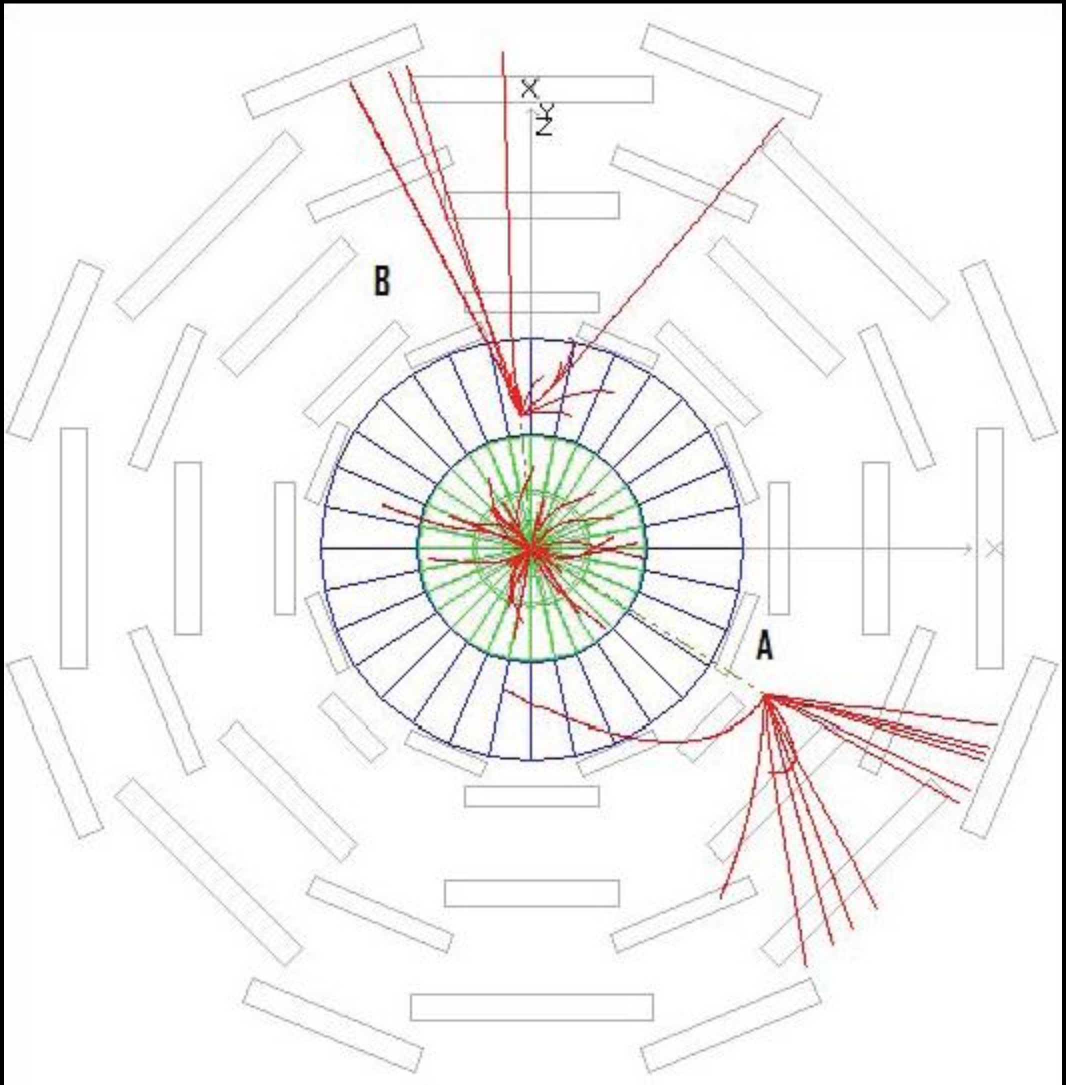

Decay Product
[LJ or Hadronic Jets]
Prompt
Displaced Vertex
in a Tracker
Jet Appearing in
the Calorimeter
Jet Appearing in
the Muon
Spectrometer
Distance from the Interaction Point
[Detector]



Decays

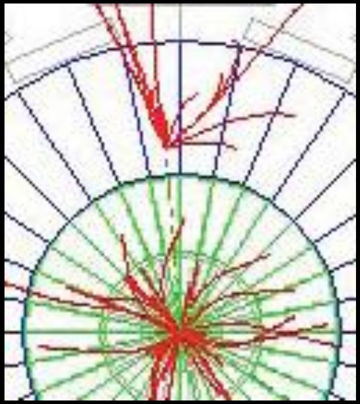
- Inner Detector
- Calorimeters
- Muon Detectors

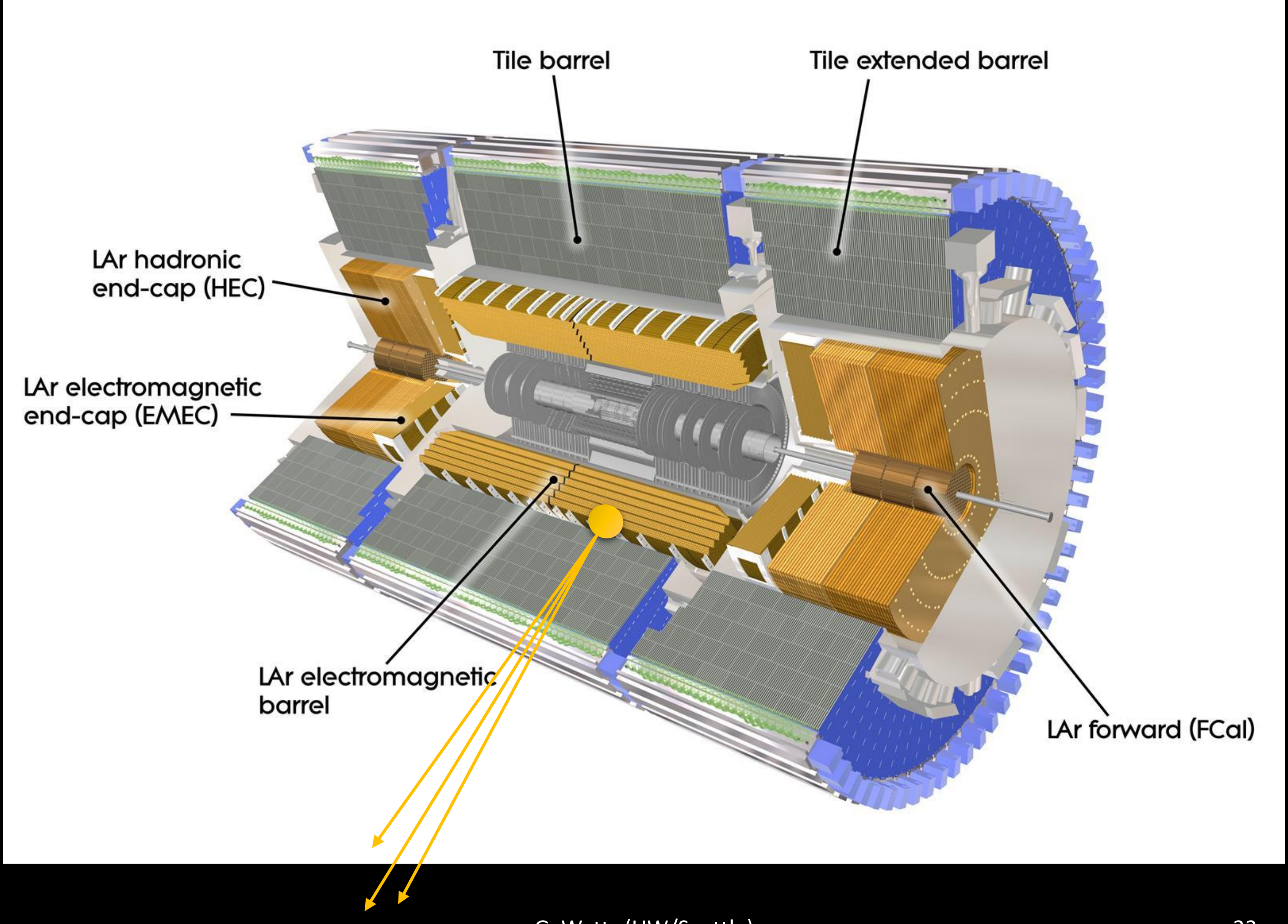

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004


X
Y
Z
B
A

Decays in the Calorimeter

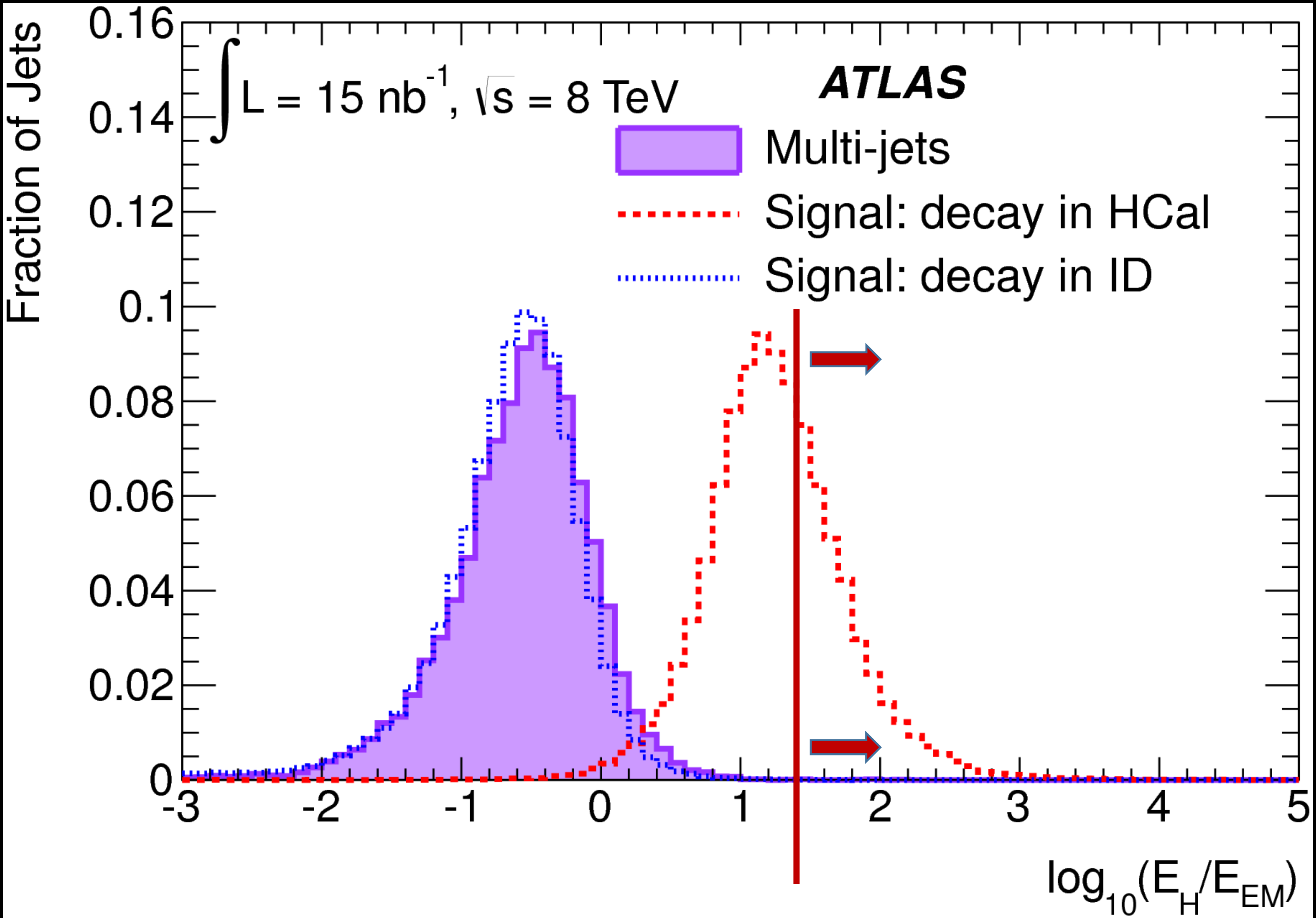
1. Look for the “appearance” of energy the Calorimeter
2. Little or no activity in the tracker



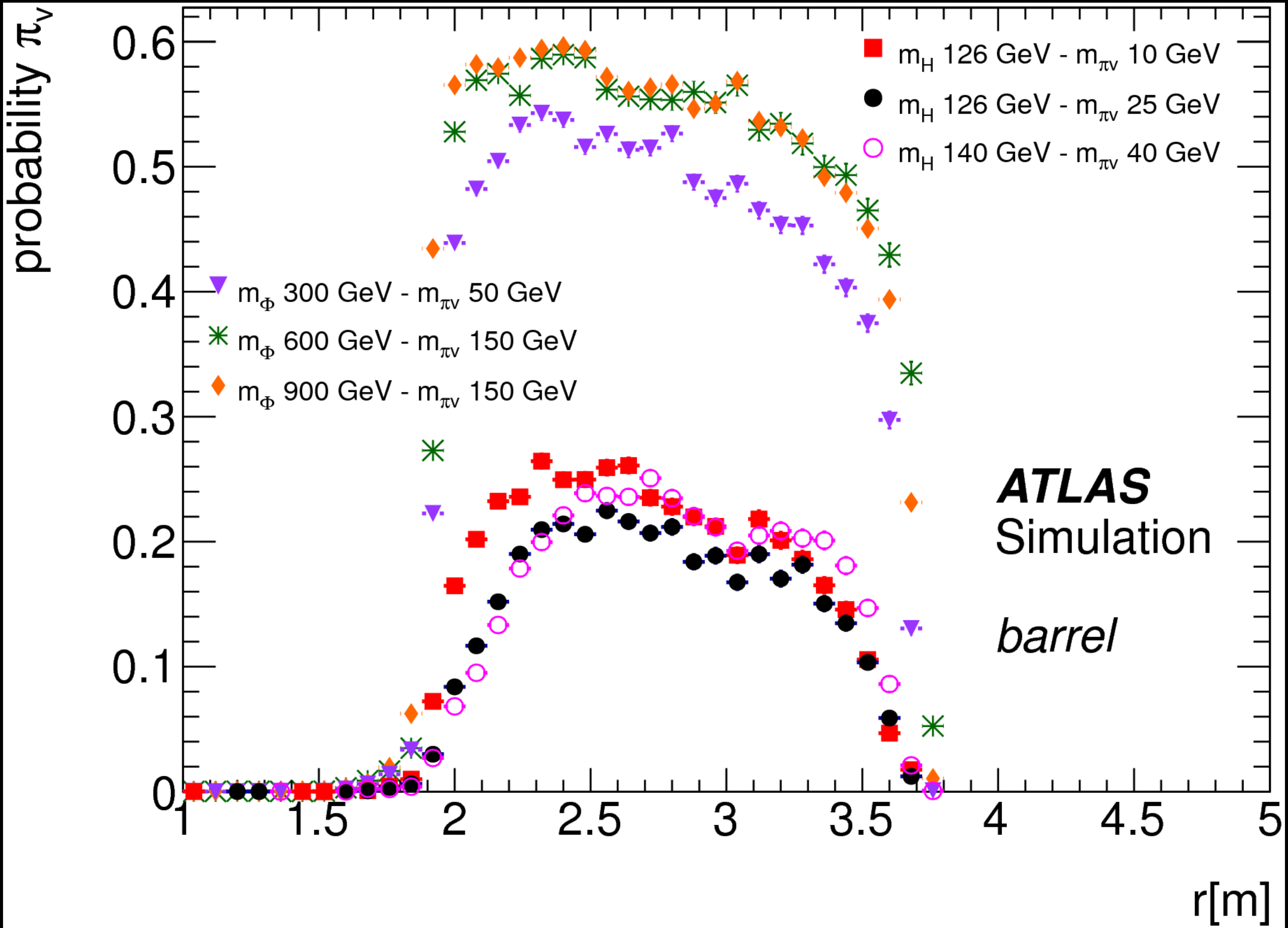


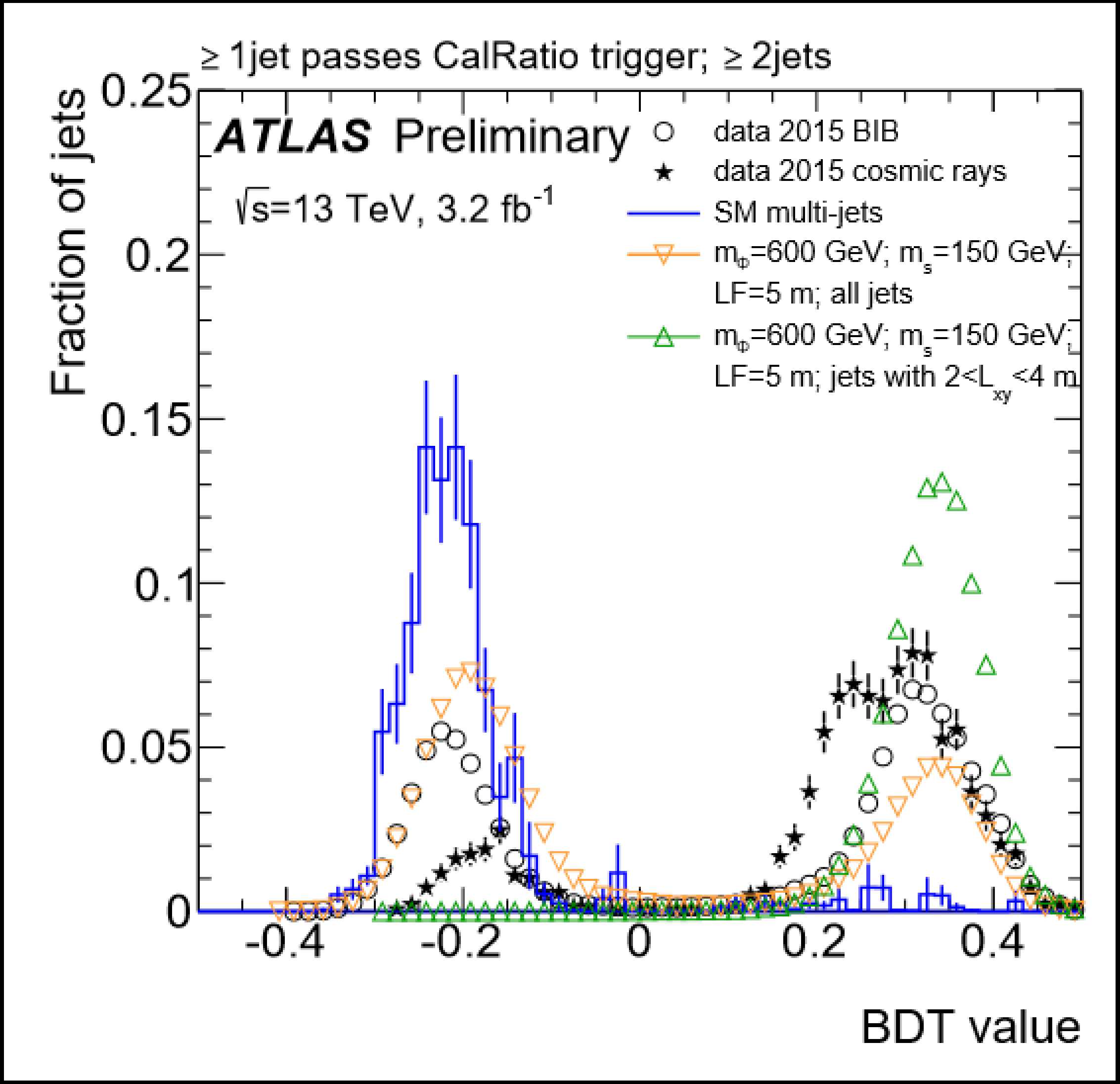
Tile barrel
Tile extended barrel
LAr hadronic end-cap (HEC)
LAr electromagnetic end-cap (EMEC)
LAr electromagnetic barrel
LAr forward (FCal)

“CalRatio”



Fraction of Jets
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
∫L = 15 nb⁻¹, √s = 8 TeV
ATLAS
Multi-jets
Signal: decay in HCal
Signal: decay in ID
-3
-2
-1
0
1
2
3
4
5
log10(EH/EEM)


probability π_v
0.6
0.5
0.4
0.3
0.2
0.1
0
1
1.5
2
2.5
3
3.5
4
4.5
5
r[m]
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


≥ 1jet passes CalRatio trigger; ≥ 2jets
ATLAS Preliminary
√s=13 TeV, 3.2 fb-1
data 2015 BIB
data 2015 cosmic rays
SM multi-jets
mΦ=600 GeV; ms=150 GeV;
LF=5 m; all jets
mΦ=600 GeV; ms=150 GeV;
LF=5 m; jets with 2<Lxy<4 m
Fraction of jets
0.25
0.2
0.15
0.1
0.05
0
-0.4
-0.2
0
0.2
0.4
BDT value

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!

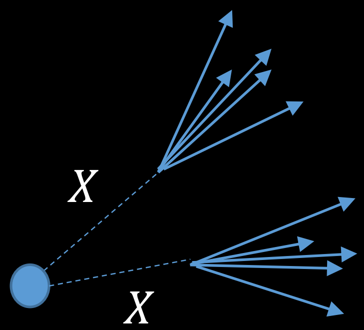
CMS has made great use of more traditional triggers

- Muon triggers
- Jet triggers

Acceptance

A single displaced vertex

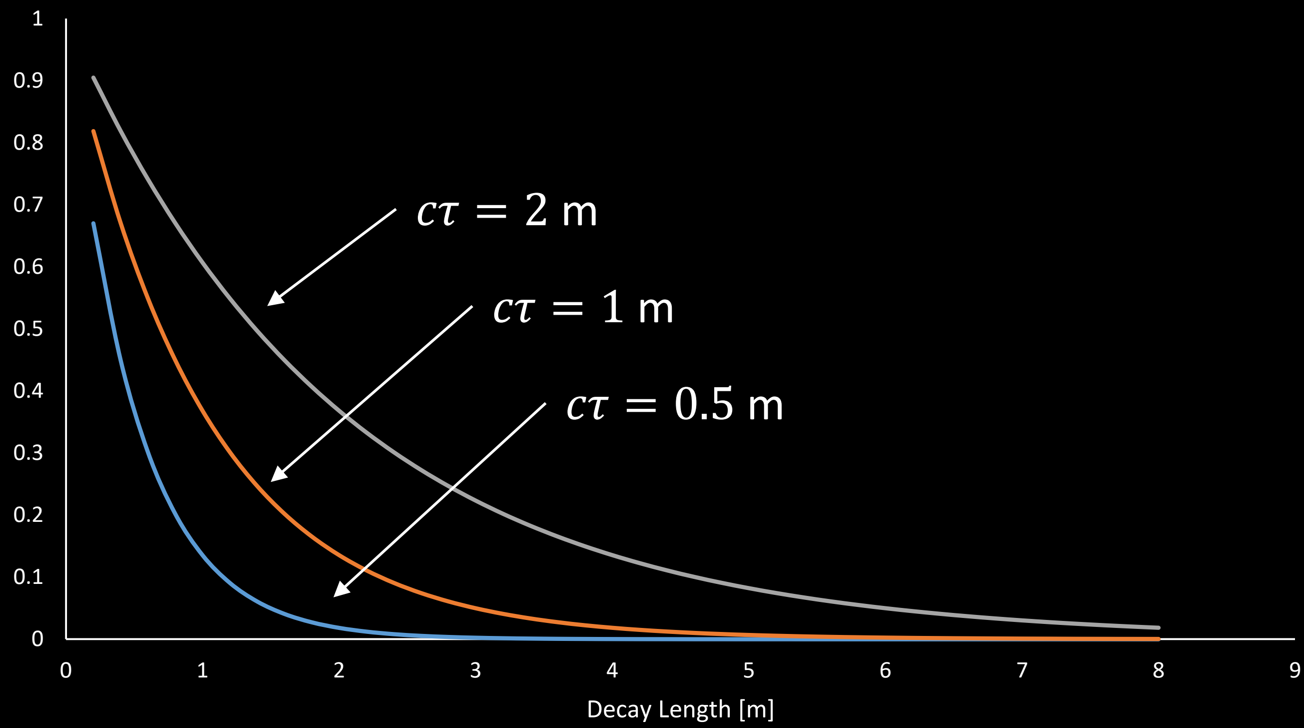
Displaced vertex + (jet, muon, missing E_T, etc.)



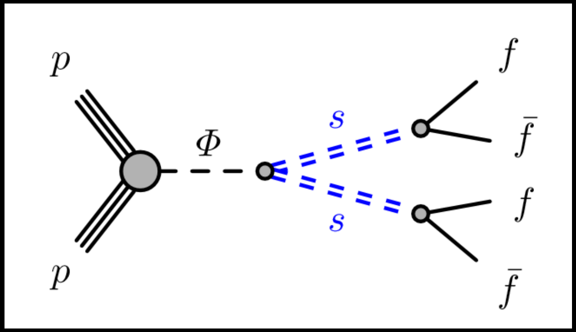
Two displaced vertices

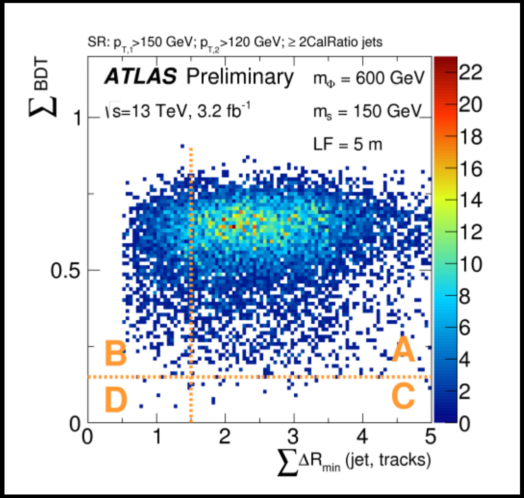
Small Backgrounds

Sensitivity



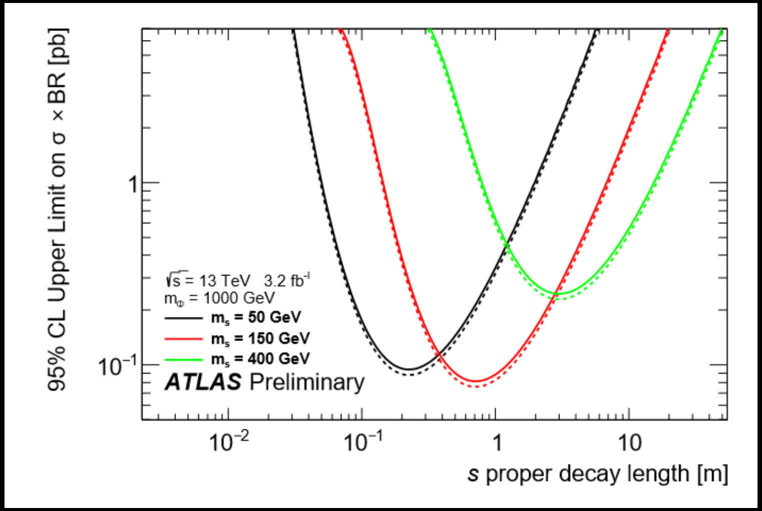
Run 2 – Search for two LLP's in the calorimeter





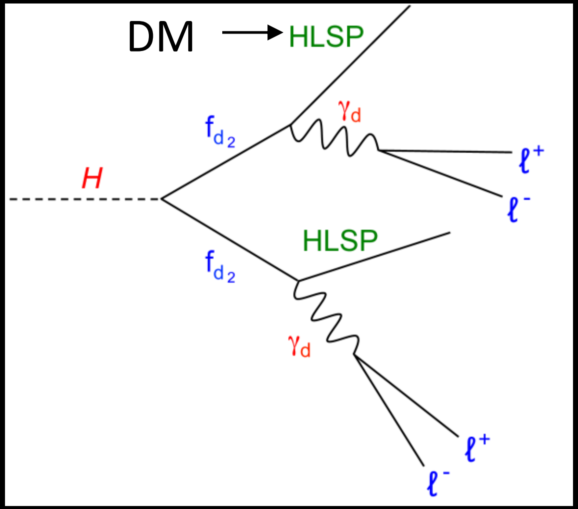
The ABCD Method is used to estimate backgrounds

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



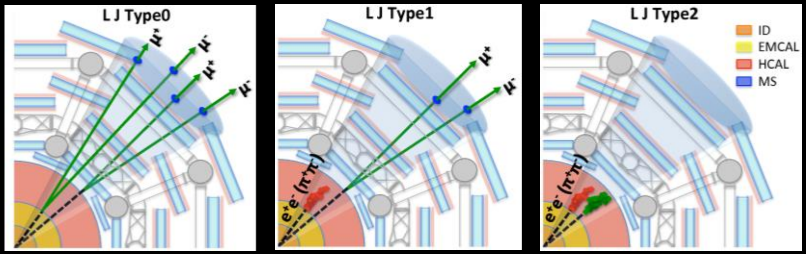
Run 2 Search for Displaced Lepton-Jets

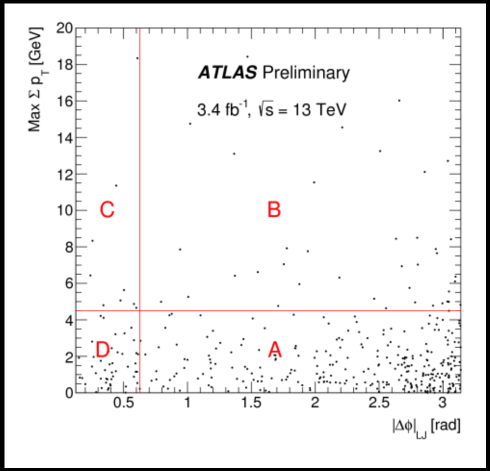
$$H \rightarrow f_{d_2} f_{d_2}, f_{d_2} \rightarrow \gamma_d HLSP$$



3 Long Lived Final State Objects:

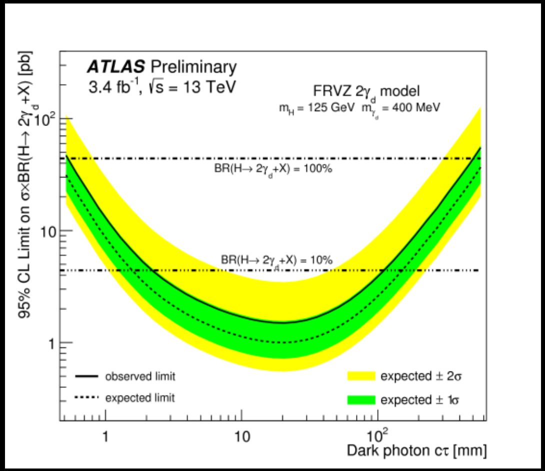
- Muons Only (type 0)
- Muons in a jet (type 1)
- Jet only (type 2)

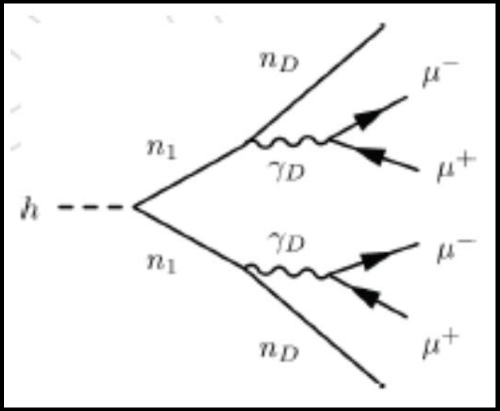




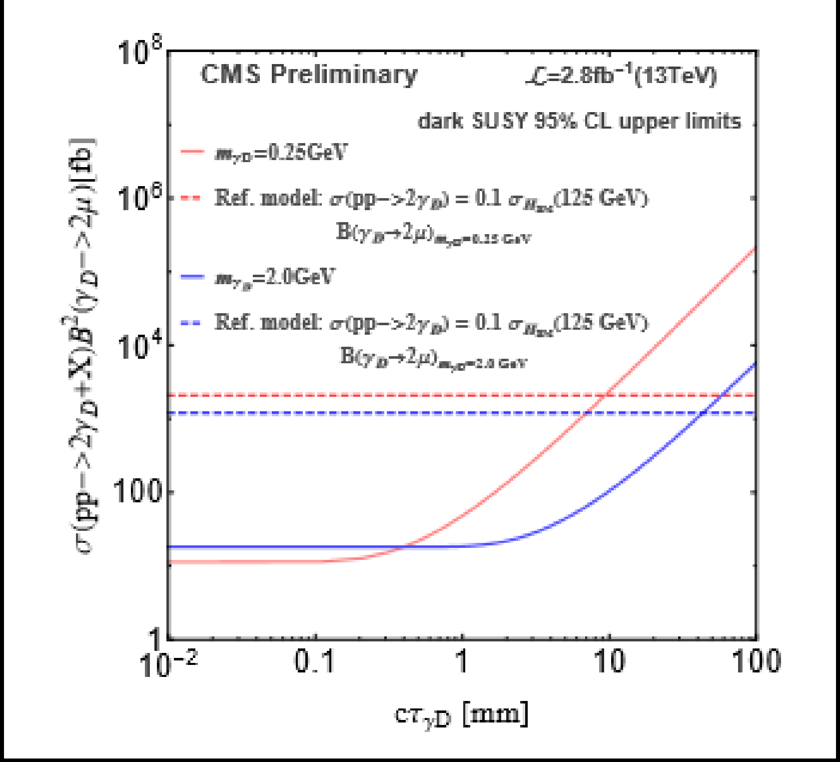
The ABCD Method is used to determine the backgrounds.

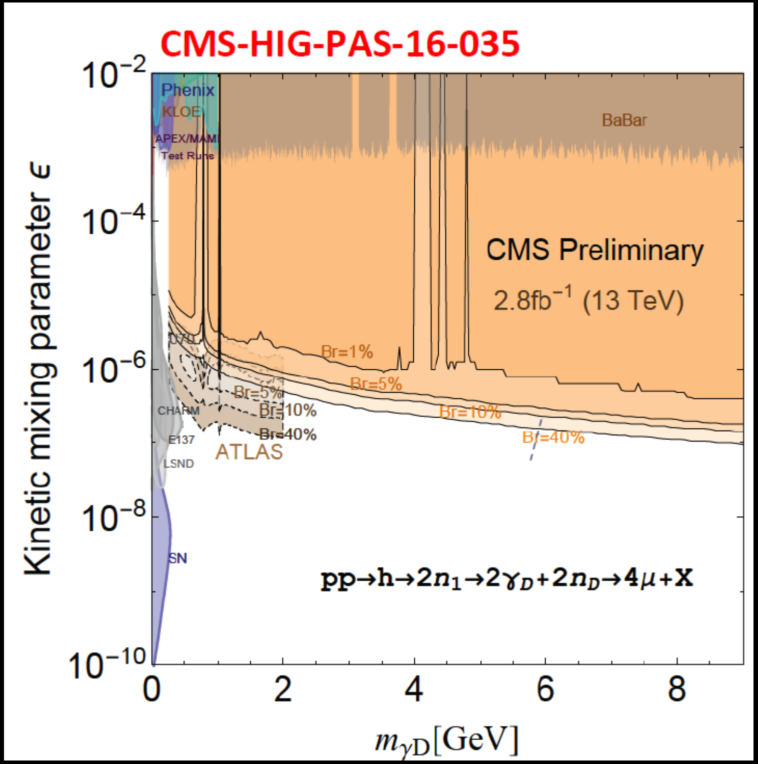
Limit is also set for a 800 GeV scalar.





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



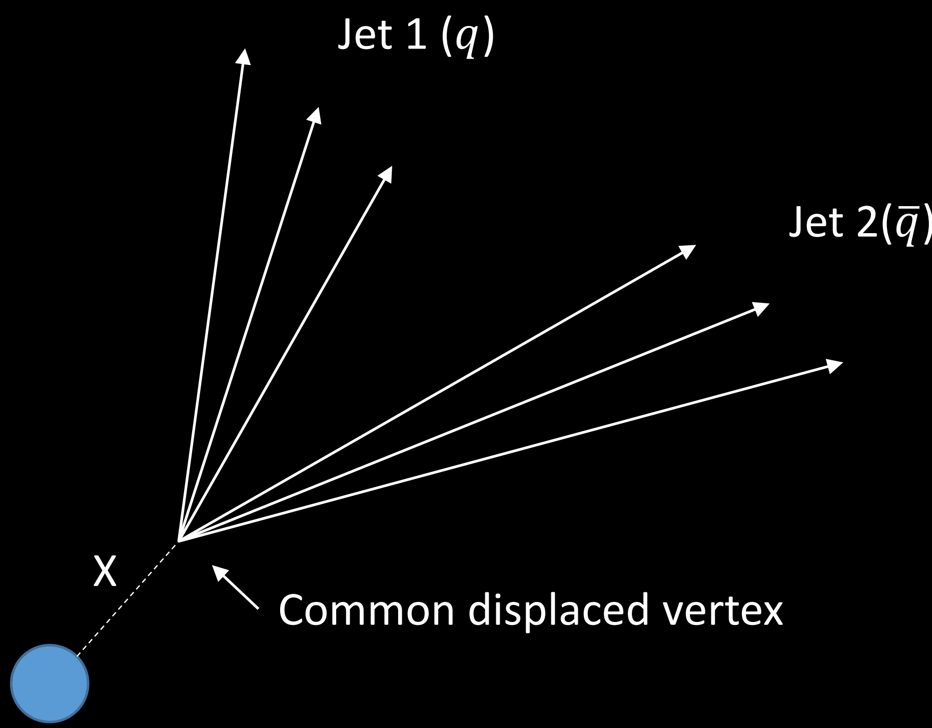


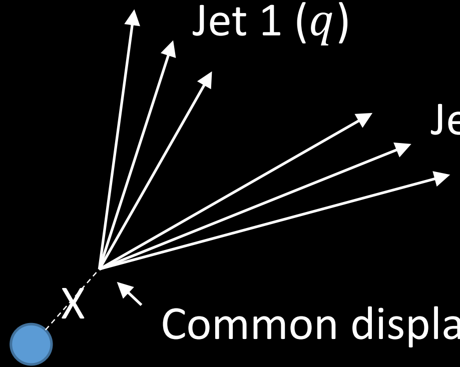
CMS also has an interesting displaced $e\mu$ search…

CMS Run 1 Displaced Jet Search

$H \to XX$

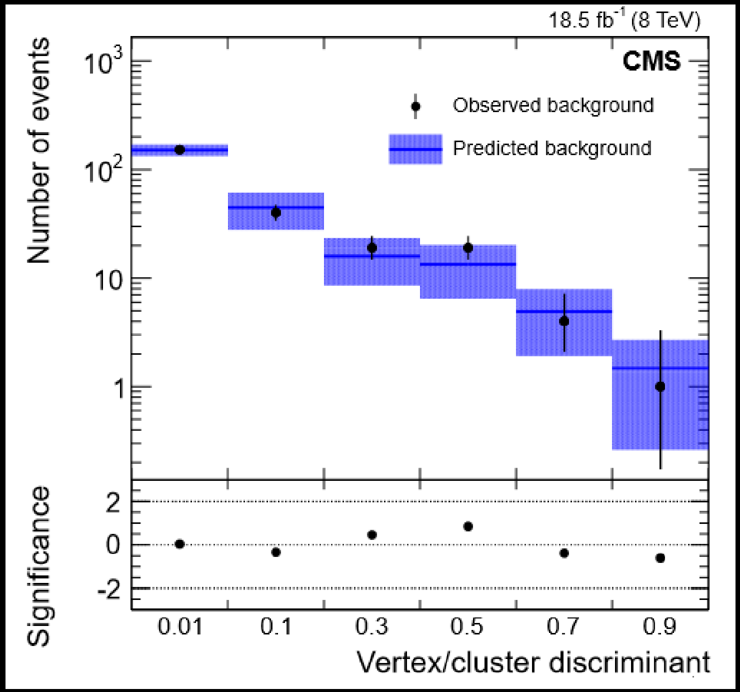
$X \to q\bar{q}$ (long lived, Higgs Portal)

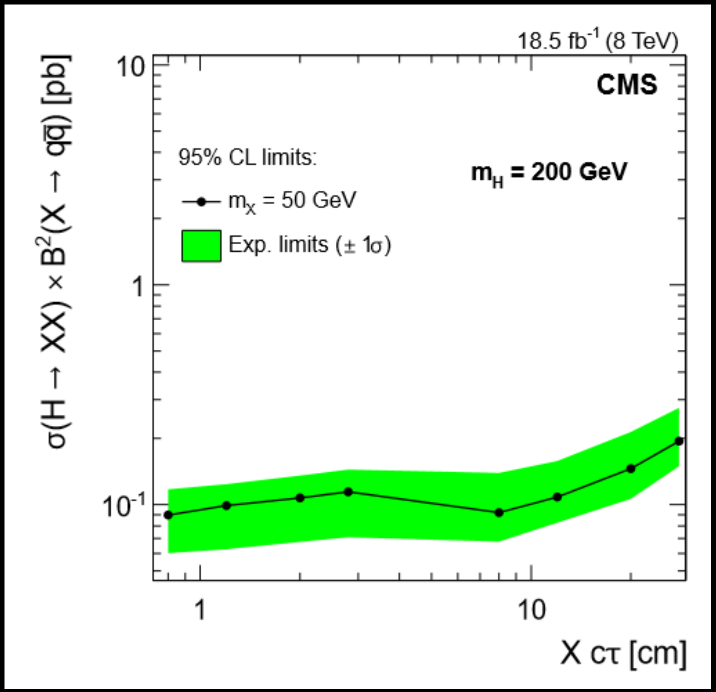


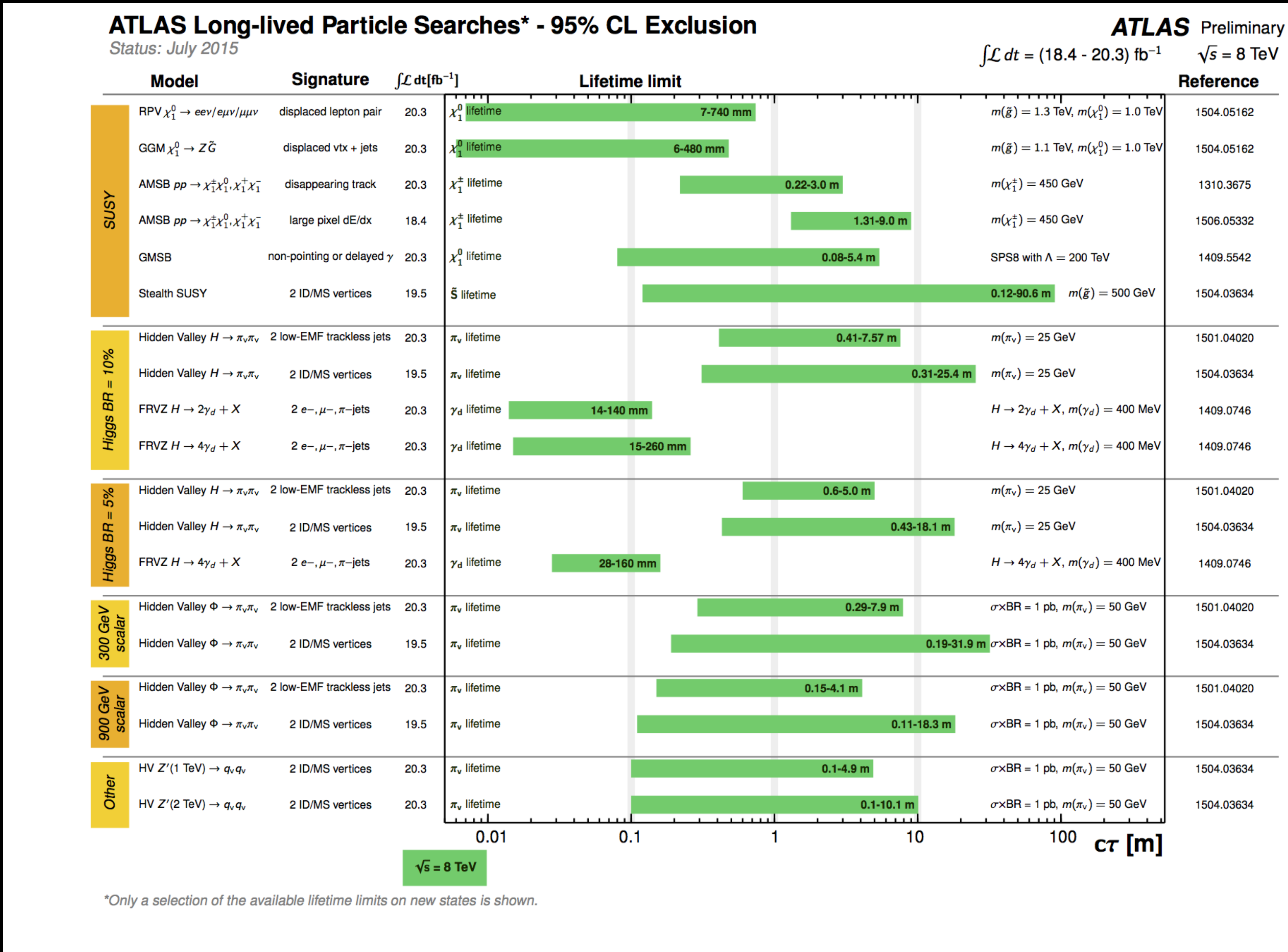


Run 1 Displaced Jet Search

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







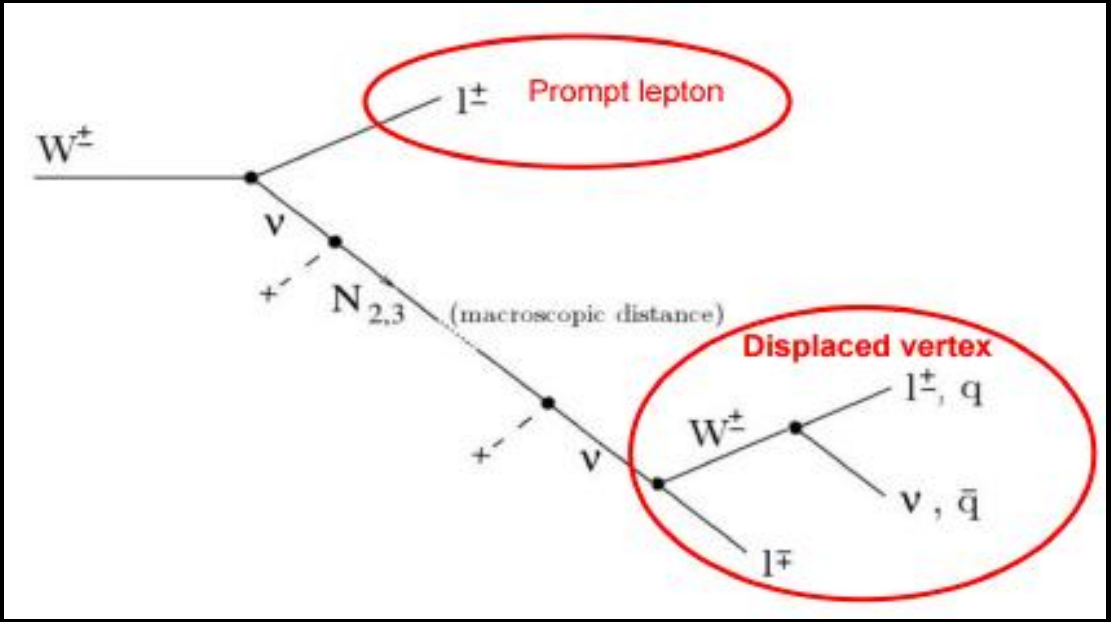
ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: July 2015
ATLAS Preliminary
$\int \mathcal{L} dt = (18.4 - 20.3)$ fb^{-1} $\sqrt{s} = 8$ TeV
Model
Signature
$\int \mathcal{L}$ dt[fb^{-1}]
Lifetime limit
Reference
SUSY
RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$ | displaced lepton pair | 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 $\chi_1^0 \to Z\tilde{G}$ | 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 $pp \to \chi_1^{\pm}\chi_1^0, \chi_1^+\chi_1^-$ | disappearing track | 20.3 | $\chi_1^{\pm}$ lifetime | 0.22-3.0 m | $m(\chi_1^{\pm}) = 450$ GeV | 1310.3675
AMSB $pp \to \chi_1^{\pm}\chi_1^0, \chi_1^+\chi_1^-$ | 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 $\Lambda = 200$ 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 $H \to \pi_v\pi_v$ | 2 low-EMF trackless jets | 20.3 | π_v lifetime | 0.41-7.57 m | $m(\pi_v) = 25$ GeV | 1501.04020
Hidden Valley $H \to \pi_v\pi_v$ | 2 ID/MS vertices | 19.5 | π_v lifetime | 0.31-25.4 m | $m(\pi_v) = 25$ GeV | 1504.03634
FRVZ $H \to 2\gamma_d + X$ | 2 $e-, \mu-, \pi-$jets | 20.3 | γ_d lifetime | 14-140 mm | $H \to 2\gamma_d + X$, $m(\gamma_d) = 400$ MeV | 1409.0746
FRVZ $H \to 4\gamma_d + X$ | 2 $e-, \mu-, \pi-$jets | 20.3 | γ_d lifetime | 15-260 mm | $H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV | 1409.0746
Higgs BR = 5%
Hidden Valley $H \to \pi_v\pi_v$ | 2 low-EMF trackless jets | 20.3 | π_v lifetime | 0.6-5.0 m | $m(\pi_v) = 25$ GeV | 1501.04020
Hidden Valley $H \to \pi_v\pi_v$ | 2 ID/MS vertices | 19.5 | π_v lifetime | 0.43-18.1 m | $m(\pi_v) = 25$ GeV | 1504.03634
FRVZ $H \to 4\gamma_d + X$ | 2 $e-, \mu-, \pi-$jets | 20.3 | γ_d lifetime | 28-160 mm | $H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV | 1409.0746
300 GeV scalar
Hidden Valley $\Phi \to \pi_v\pi_v$ | 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 $\Phi \to \pi_v\pi_v$ | 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 $\Phi \to \pi_v\pi_v$ | 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 $\Phi \to \pi_v\pi_v$ | 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) $\to q_v q_v$ | 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) $\to q_v q_v$ | 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.

110	EXO-15-010	Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV	Accepted by PRD	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
86	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-12-038	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
80	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
79	EXO-12-034	Search for disappearing tracks in proton-proton collisions at $\sqrt{s}$ = 8 TeV	JHEP 01 (2015) 096	21 November 2014
66	EXO-12-026	Searches for long-lived charged particles in pp collisions at $\sqrt{s}$ = 7 and 8 TeV	JHEP 07 (2013) 122	2 May 2013
57	EXO-11-035	Search for long-lived particles in events with photons and missing energy in proton-proton collisions at $\sqrt{s}$ = 7 TeV	PLB 722 (2013) 273-294	9 December 2012
55	EXO-11-101	Search in leptonic channels for heavy resonances decaying to long-lived neutral particles	JHEP 02 (2013) 085	12 November 2012
49	EXO-11-074	Search for fractionally charged particles in pp collisions at $\sqrt{s}$ = 7 TeV	PRD 87 (2013) 092008	8 October 2012
38	EXO-11-067	Search for new physics with long-lived particles decaying to photons and missing energy in pp collisions at $\sqrt{s}$ = 7 TeV	JHEP 11 (2012) 172	3 July 2012
37	EXO-11-020	Search for stopped long-lived particles produced in pp collisions at $\sqrt{s}$ =7 TeV	JHEP 08 (2012) 026	30 June 2012
31	EXO-11-022	Search for heavy long-lived charged particles in pp collisions at $\sqrt{s}$ = 7 TeV	PLB 713 (2012) 408-433	2 May 2012
8	EXO-10-011	Search for Heavy Stable Charged Particles in pp collisions at $\sqrt{s}$ = 7 TeV	JHEP 03 (2011) 024	9 January 2011
3	EXO-10-003	Search for Stopped Gluinos in pp collisions at $\sqrt{s}$ = 7 TeV	PRL 106 (2011) 011801	26 November 2010

Expanding the Program

More final states
Longer $c\tau$

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

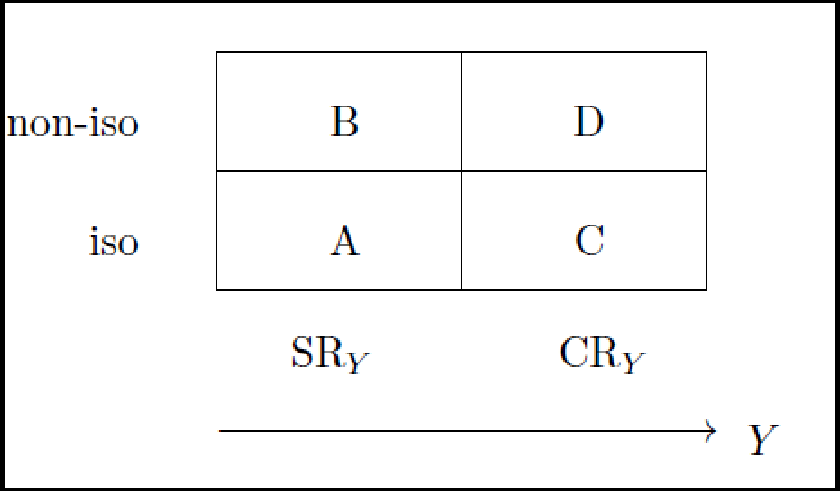


Backgrounds?

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
  - Lepton p_T, Missing E_T, jet p_T, etc.



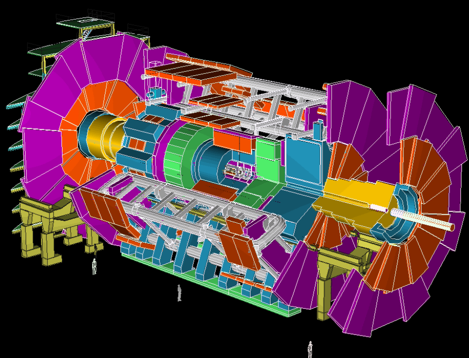
What about life-time sensitivity?

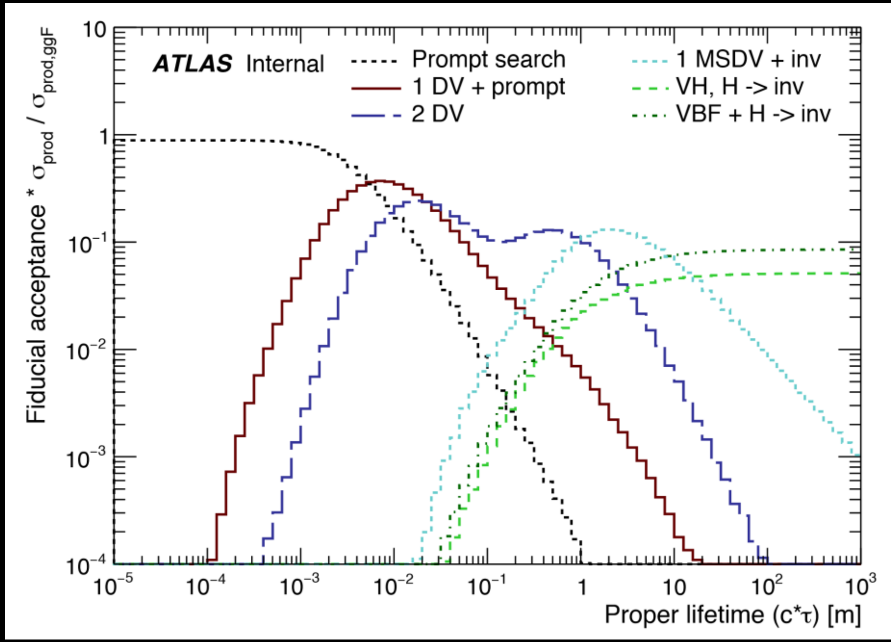
Lifetime is a free parameter…

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

ATLAS/CMS Detectors can only see to ~100 m

Escaped Particles become missing E_T…





Acceptance isn't great

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

Increase the base-line: put a detector on the surface

A new experiment to look at Ultra Long Lived Particles (ULLP)

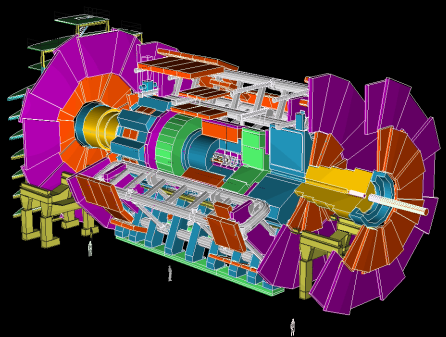
- Scintillator for 1.5 ns timing resolution
- RPC layers for track reconstruction (and vertex finding)

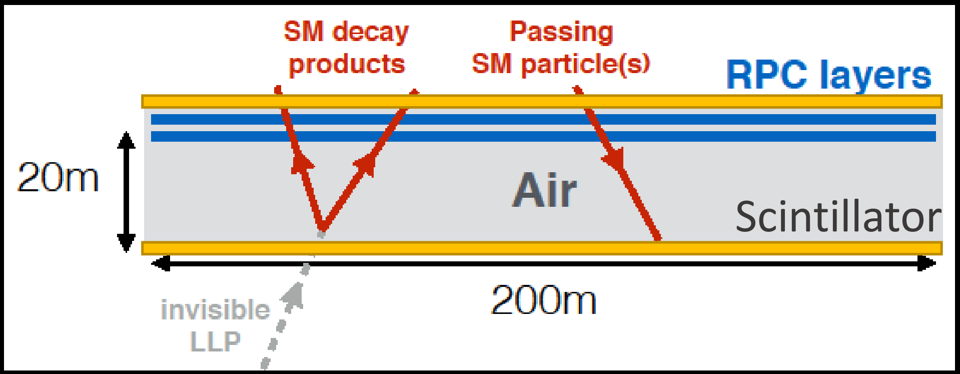
Mathusla Detector (~200 sq m)

Surface

~100 m

~100 m

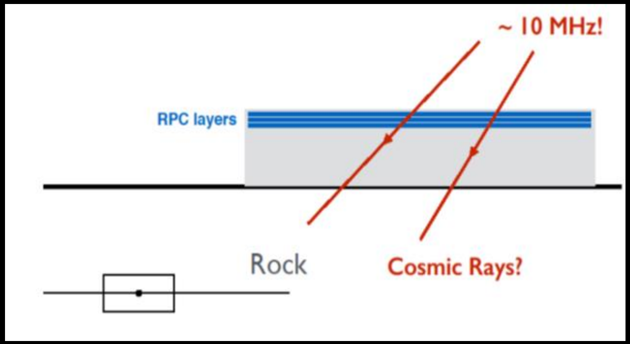




Backgrounds

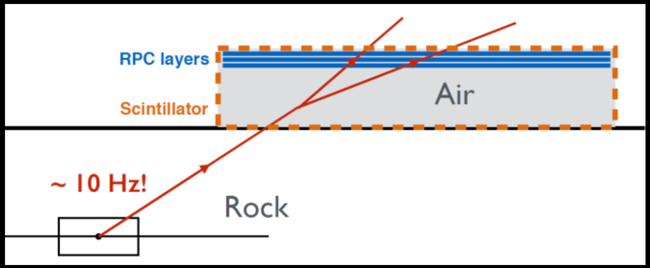
Cosmic Muons

- Precision timing from scintillators
- Tracking from RPC's
- 20 m height
    - 70 ns travel time
- May also be some interesting physics
- 10 MHz (200 m^2)



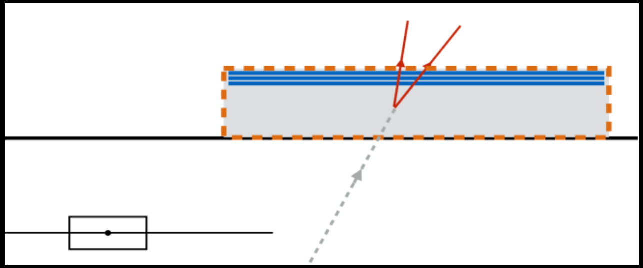
Upward going LHC Muons

- Precision timing from scintillators
- 10 Hz from the LHC



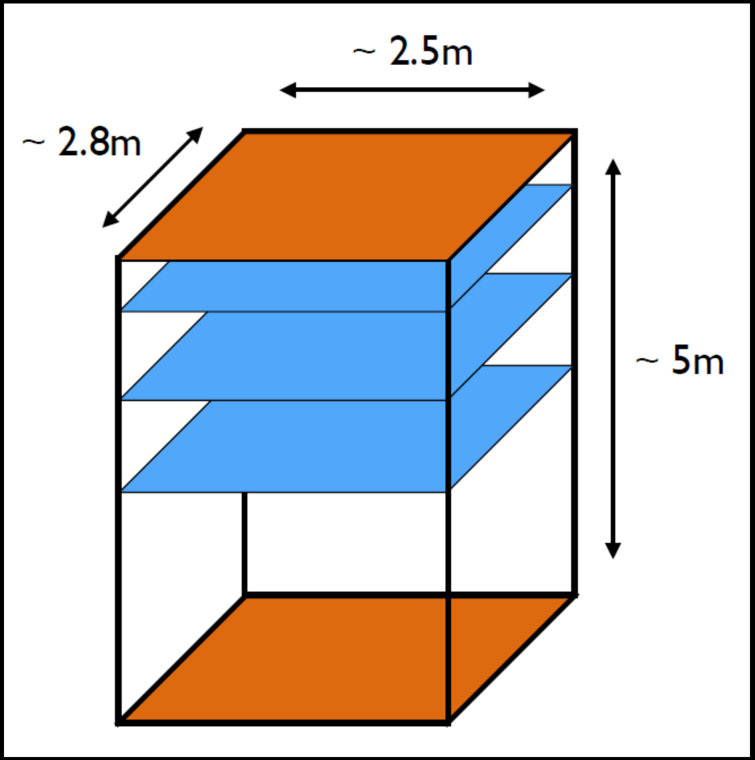
Upward going cosmic neutrinos

- Inelastic interaction in the decay volume
- 10-100 interactions per year



Building test stand

- Scintillator from DZERO end-station muon chambers
- RPC's from Rome (Argo experiment)



Hoping to run this summer/fall

If GEANT4 model holds, then work towards a full experiment.

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

Editors:
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Goal is to have comprehensive document finished by early 2017

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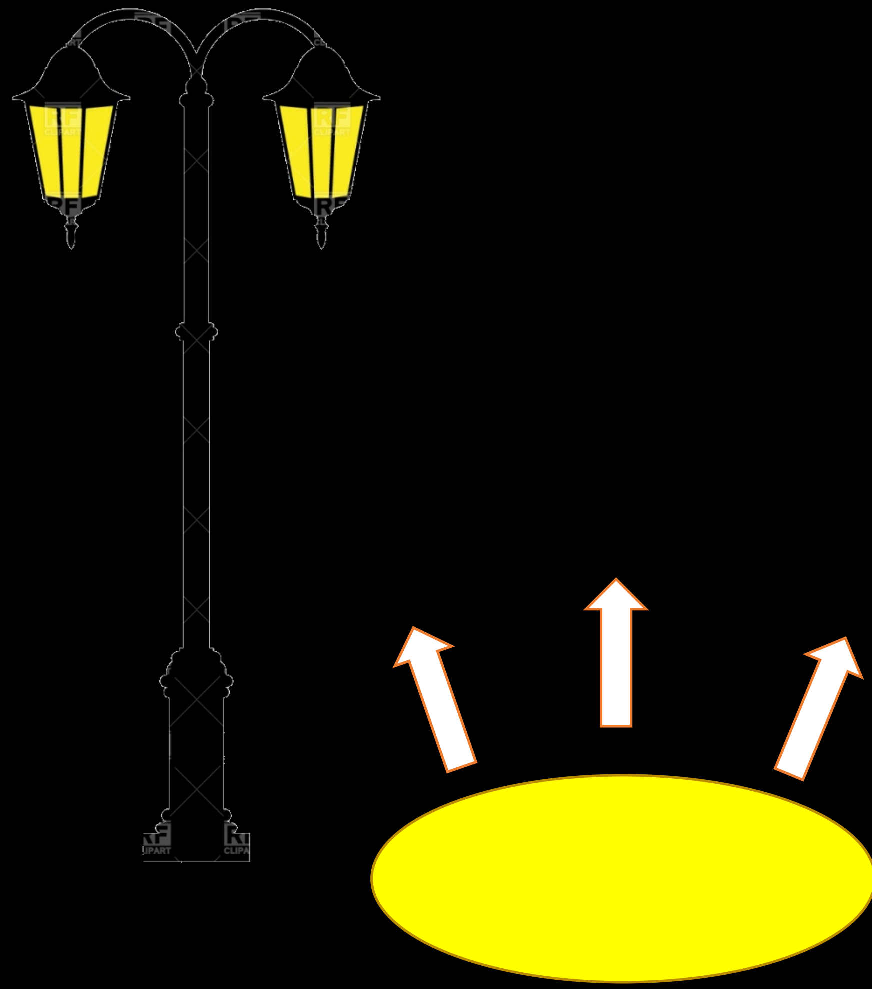


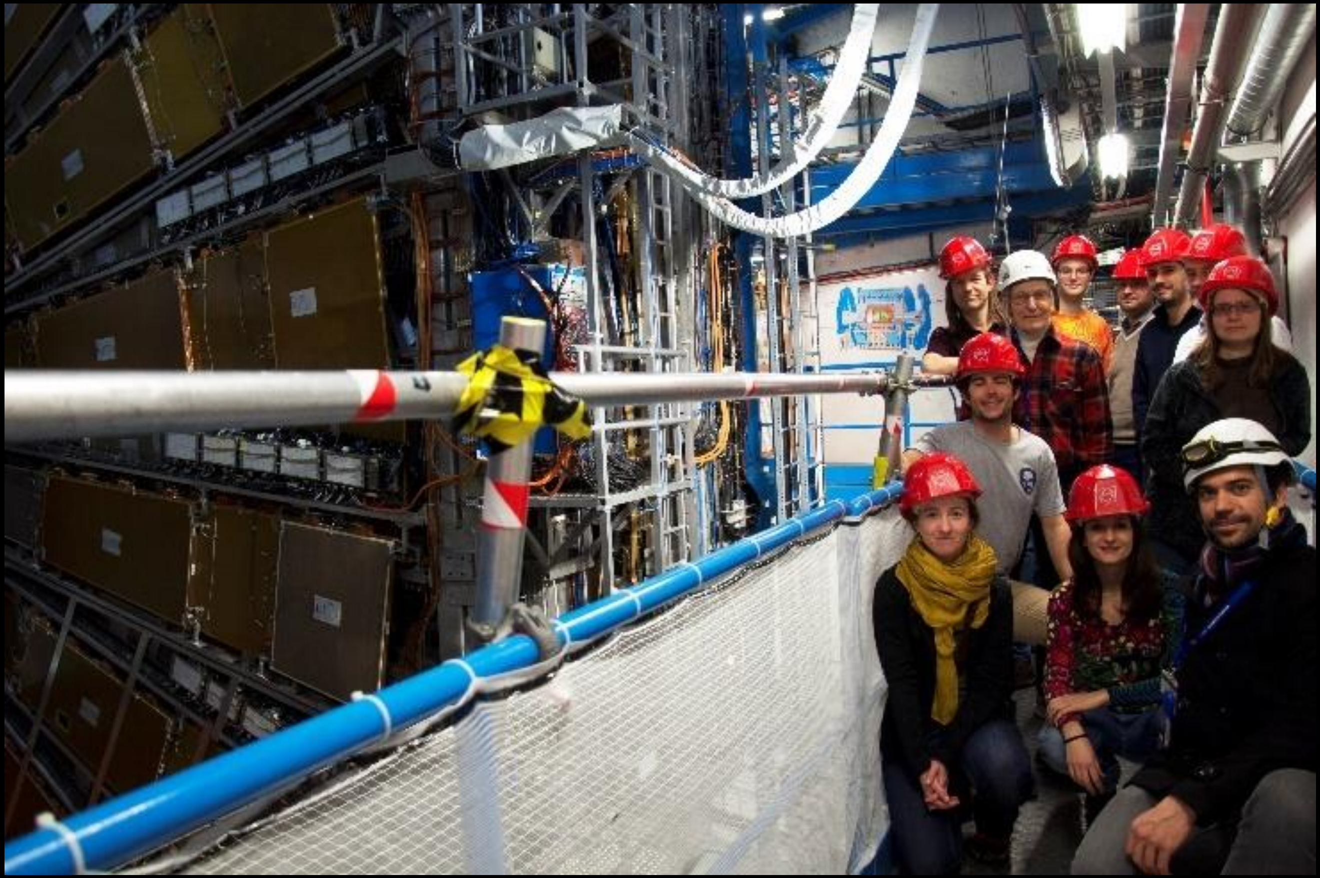
Why stop at long lived jets?

- Lepton-Jets
- Kinked Tracks
- Disappearing Tracks
- Quirks
- Highly Ionizing Particles
- Emerging Jets

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!

ACAT 2017
21-25 August 2017
University of Washington, Seattle

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- **New algorithms for Particle Physics**
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