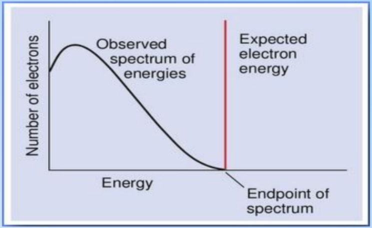
Decays to dark sector particles at ATLAS

Dark Interactions Workshop - BNL

Andrea Coccaro

dedicated to the memory of
Guido Ciapetti (1941-2016)

Hidden sector



Back in the '30s, the bricks of particle physics were just photons, electrons and nucleons

- spectrum of the β decay was a surprise
- Pauli proposed a radical solution involving the presence of a third particle
- $n \rightarrow p + e^- + \overline{\nu}$

Perfect example of a hidden sector:

1. neutrino is electrically neutral
2. very weakly interacting (and also light)
3. interaction through a portal - $(\overline{p}\gamma^\mu n)(\overline{e}\gamma_\mu \nu)$

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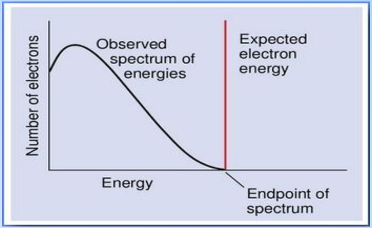
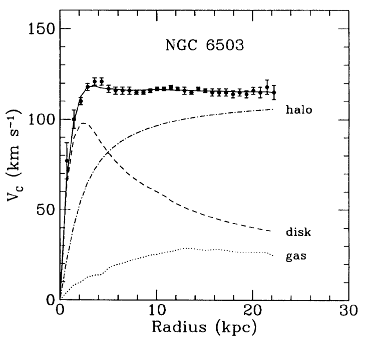
Do we have a "puzzling β decay spectrum" for searching for a hidden sector? Yes, and much more.





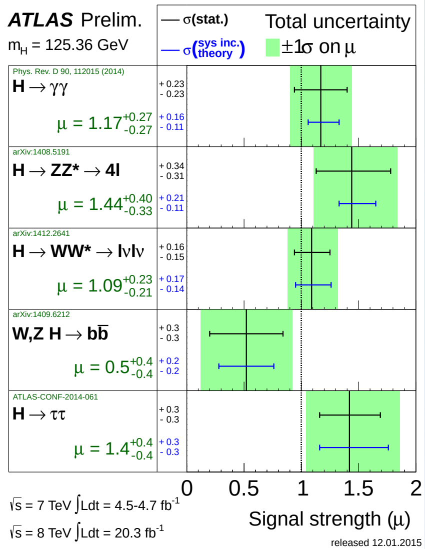
Exotic Higgs decays

New fundamental scalar consistent with SM Higgs boson.

Constraints from observing the Higgs boson in the various SM channels allow non-SM BR of $\mathcal{O}$(20-30%).

Large experimental uncertainties on the Higgs boson couplings.

Total width of $\sim$ 4 MeV from SM contributions



The best way to know if the Higgs has a $\sim$ 10% non-SM branching ratio is to directly look at exotic decays.

Projections of coupling measurements

New fundamental scalar consistent with SM Higgs boson.

Constraints from observing the Higgs boson in the various SM channels allow non-SM BR of $\mathcal{O}$(20-30%).

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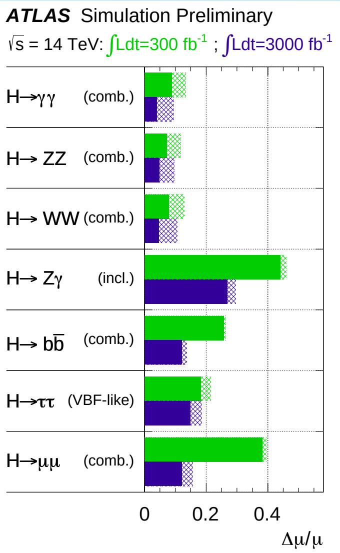
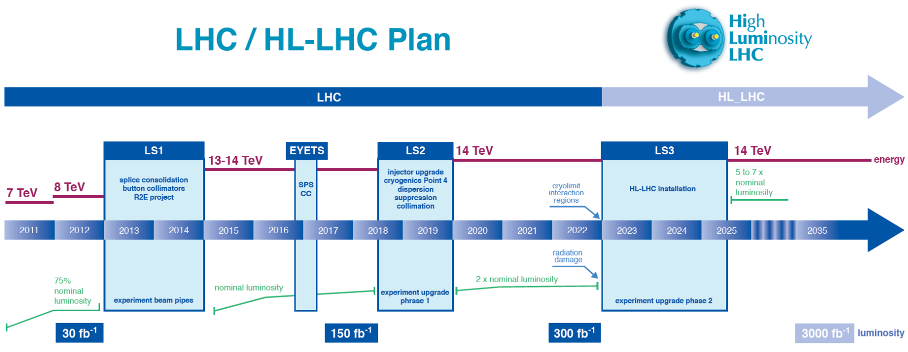
The best way **for the next decade** to know if the Higgs has a $\sim$ 10% non-SM branching ratio is to directly look at exotic decays.



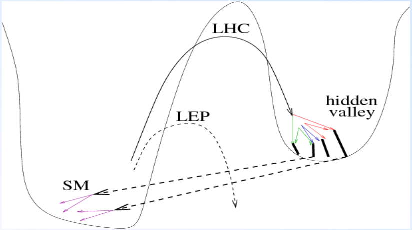

LHC / HL-LHC Plan
High Luminosity LHC
LHC
HL_LHC
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13-14 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
SPS
CC
injector upgrade
cryogenics Point 4
dispersion
suppression
collimation
cryolimit
interaction
regions
HL-LHC installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2035
radiation
damage
75%
nominal
luminosity
experiment beam pipes
nominal luminosity
experiment upgrade
phrase 1
2 x nominal luminosity
experiment upgrade phase 2
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
luminosity

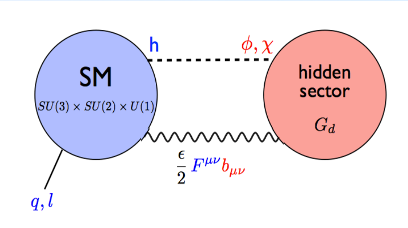
Portals to the hidden sector

Following an EFT approach, only three renormalizable portals are possible.

Neutrino portal	LHN
Higgs portal	$(\mu S + \lambda S^2) H^\dagger H$
Vector portal	$\frac{\epsilon}{2} B_{\mu\nu} Z^{\mu\nu}$

A wide phenomenology can be accomodated by connecting the SM to complex dark sectors (hidden valley, dark SUSY, etc.) **giving rise to a class of searches relying on unconventional signatures**.





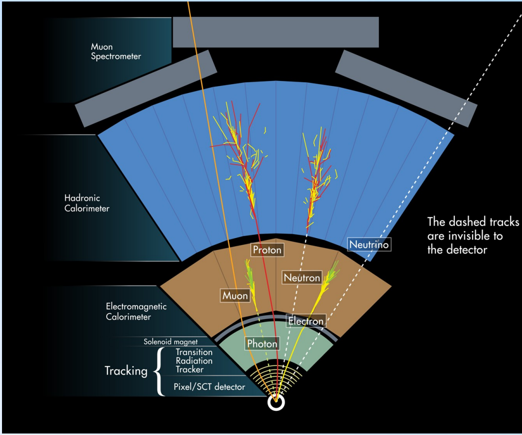
Unconventional signatures

The particle in the hidden sector may be

- weakly-coupled to the SM giving rise to long-lived particle decay
- light giving rise to collimated decay products

Various challenges easily arise, for example

- triggering on displaced decays of neutral long-lived particles
- triggering on low-mass objects
- reconstruction of physics objects
- access of control region for estimating backgrounds



Outline / References

ATLAS public results based on 13-TeV data

1. Displaced jets in the hadronic calorimeter [ATLAS-CONF-2016-103]
2. Displaced lepton-jets [ATLAS-CONF-2016-042]

ATLAS public results based on 8-TeV data

3. Higgs to ZZ_d and $Z_d Z_d$ [ATLAS-CONF-2015-003]
4. Displaced jets in the tracker and muon spectrometer [PRD 92 (2015) 012010]
5. Displaced jets in the hadronic calorimeter [PLB 743 (2015) 15-34]
6. Displaced lepton-jets [JHEP 11 (2014) 088]
7. Prompt lepton-jets [JHEP 02 (2016) 062]

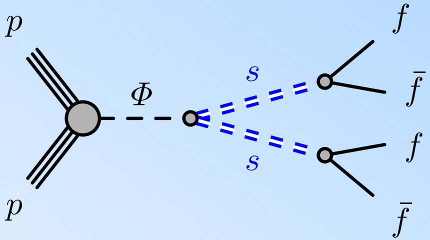
ATLAS tools for unconventional signatures

8. Triggering on long-lived neutral particles [JINST 8 (2013) P07015]
9. Vertexing in the muon spectrometer [JINST 9 (2014) P02001]

I will be mainly talking of 1., 2., 3.
plus some Run-II improvements and prospects
for new results with the entire 2015-2016 dataset.

Displaced jets in the hadronic calorimeter

Benchmark model

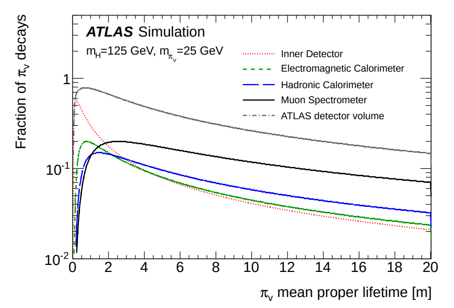


	lumi [/fb]	m_Φ [GeV]	m_s [GeV]
8 TeV result	20.3	$100 \div 900$	$10 \div 150$
13 TeV result	3.2	$400 \div 1000$	$50 \div 400$

Major analysis changes

1. BDT for discriminating signal and QCD jets
2. simplified data-driven estimate of QCD jets
3. exotics Higgs channel to be restored with a new topological algorithm running at L1

Triggering on displaced decays

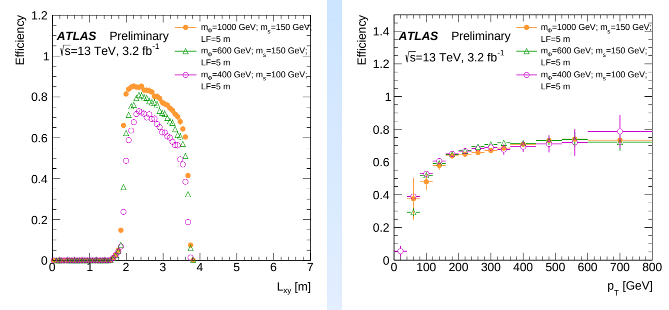


Signature-driven triggers for displaced decays of neutral long-lived particles.
Each trigger is dedicated for a particular region of the ATLAS detector.

Detector region	Key feature	Trigger name
Tracker	Jet with track isolation	Trackless Jet trigger
Hadronic calorimeter	Isolated jet with very low EM fraction	Calo-ratio trigger
Muon spectrometer	Isolated cluster of muon RoIs	Muon RoI Cluster trigger

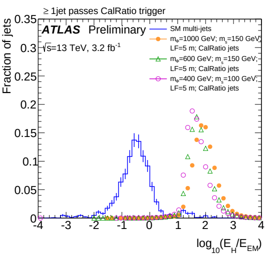
Calo-ratio trigger

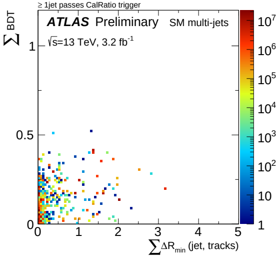
- tau candidate at L1 with at least 60 GeV
- no tracks above 2 GeV in the jet cone
- $\log(E_{HAD}/E_{EM}) > 1.2$
- beam halo removal using calorimeter cell timing

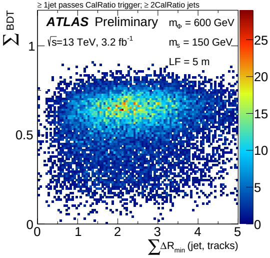


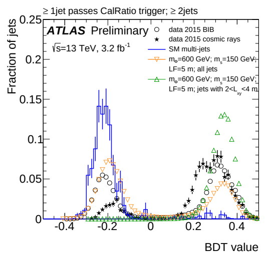
Analysis ingredients

- two displaced hadronic jets to suppress the background
- removal of cosmic rays and non-collision events
- BDT with 13 input variables to discriminate between by signal-jets and QCD-jets
- ABCD for the QCD background
- 24 observed events and $18.4 \pm 6.3 \pm 6.6$ predicted

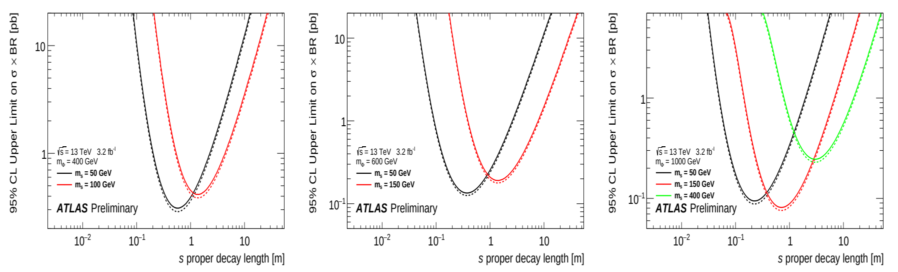








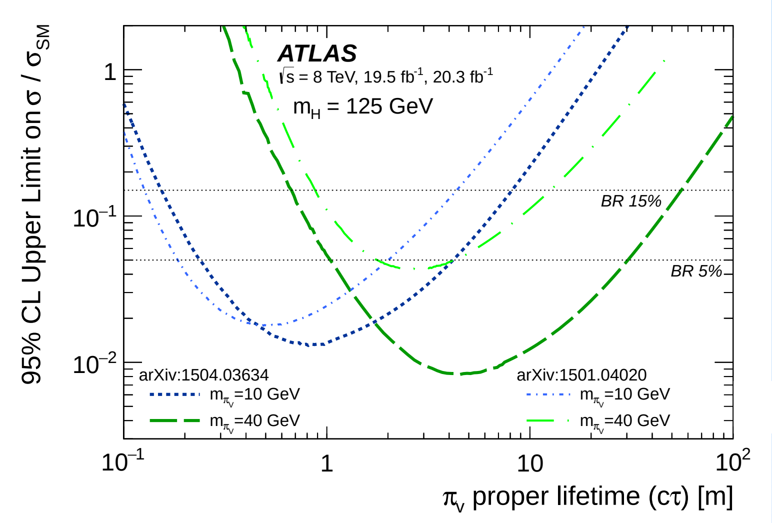
Results



	$m_s = 50\ GeV$	$m_s = 100\ GeV$	$m_s = 150\ GeV$	$m_s = 400\ GeV$
	Decay length range excluded at 95% CL for $\sigma\times$ BR = 1 pb			
$m_\Phi = 400\ GeV$	(0.20, 2.4) m	(0.52, 4.6) m	–	–
$m_\Phi = 600\ GeV$	(0.09, 2.7) m	–	(0.38, 8.2) m	–
$m_\Phi = 1$ TeV	(0.05, 2.0) m	–	(0.14, 7.2) m	(0.78, 16) m

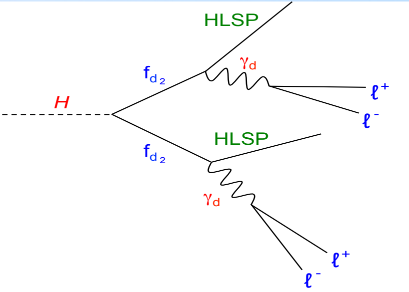
Mass Point (GeV, GeV)	JES (%)	JES EMF (%)	JER (%)	Trigger (%)	Pile-up (%)	Luminosity (%)
(400,150)	3.3	14	0.43	2.3	4.0	2.1
(600,150)	1.5	5.4	0.40	1.5	0.56	2.1
(1000,150)	0.51	1.8	0.05	1.0	2.0	2.1

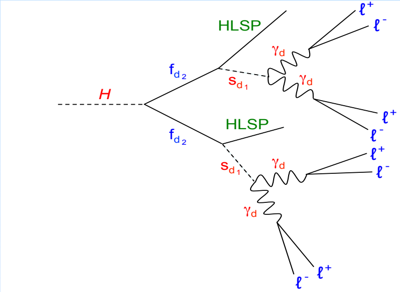
Run-I decay in the hadronic calorimeter vs Run-I decay in the muon spectrometer



Displaced lepton-jets

Benchmark model



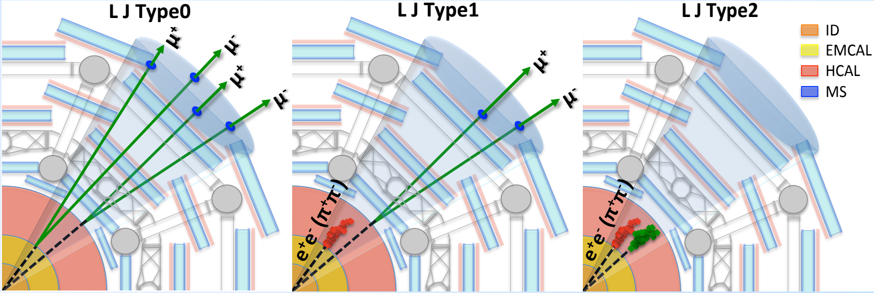


	lumi [/fb]	m_H [GeV]	m_{γ_d} [MeV]
8 TeV result	20.3	125	400
13 TeV result	3.4	125, 800	400

Major analysis changes

1. dedicated displaced muon trigger
2. enhancement in the reconstruction of collimated muons
3. result in the ϵ vs m_{γ_d} to be reconsidered

Lepton-jet definition



γ_d branching ratios at 400 MeV

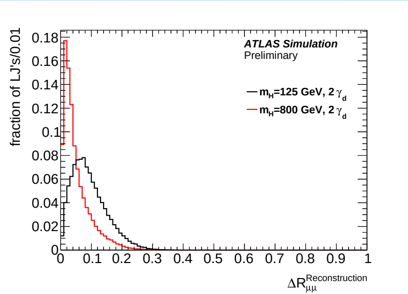
- $BR(e^+e^-) = 45\%,\ BR(\mu^+\mu^-) = 45\%,\ BR(\pi^+\pi^-) = 10\%$

Analysis ingredients

New dedicated trigger available since Run-II

Higgs $\rightarrow 2\gamma_d + X$	Run2 m=125 GeV	Run1 m=125 GeV	Run2 m=800 GeV
Tri-muons	2.0	2.9	2.4
Narrow-scan	10.6	N/A	23.0
Calo-ratio	0.3	2.3	9.7
OR of all	11.9	4.6	32.0

Higgs $\rightarrow 4\gamma_d + X$	Run2 m=125 GeV	Run1 m=125 GeV	Run2 m=800 GeV
Tri-muons	4.9	5.8	7.8
Narrow-scan	8.3	N/A	38.4
Calo-ratio	0.1	0.5	7.4
OR of all	11.8	6.2	44.8



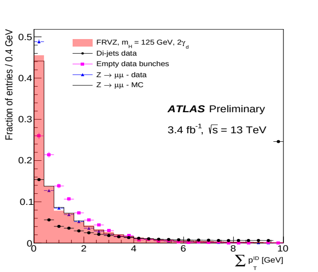
Narrow-scan approach

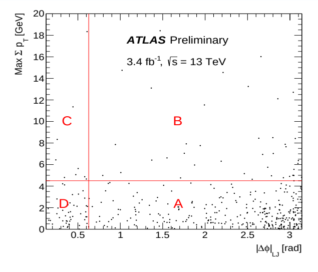
- leading muon seeded by a L1 muon
- sub-leading muon without a L1 seed searched at the HLT in a “narrow” cone by “scanning” the MS detector

Analysis ingredients

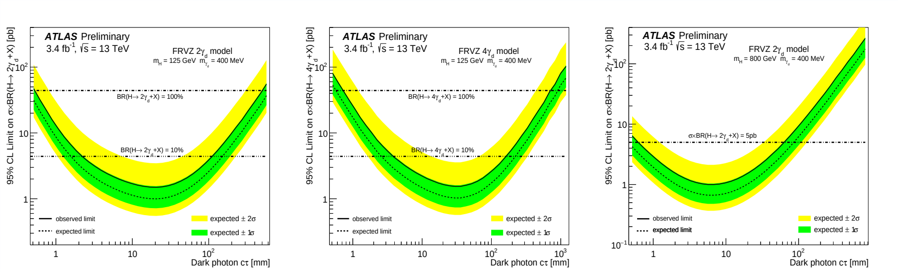
- track isolation implemented for removing multi-jet background and validated in $Z \rightarrow \mu\mu$ events
- cosmics background estimated in the empty bunches
- QCD multi-jet background calculated with ABCD method
- main systematics evaluated using $J/\Psi \rightarrow \mu\mu$ events
- 285 observed events and $231 \pm 12 \pm 62$ predicted

Systematic uncertainty	Value
Luminosity	2.1%
Trigger: Narrow Scan	6.0%
Trigger: Tri-muon-MS-only	5.8%
Trigger: CalRatio	11.0%
Reconstruction efficiency of single γ_d	15.0%
Effect of pile-up on Σp_T^{ID}	5.1%
Reconstruction of the p_T of the γ_d	10.0%



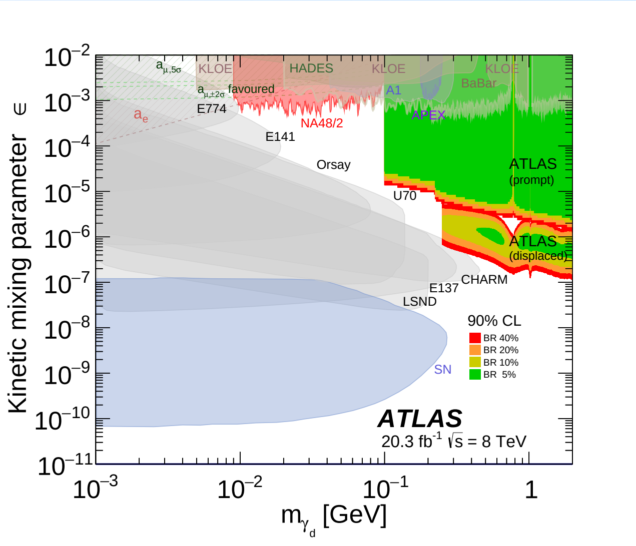


Results



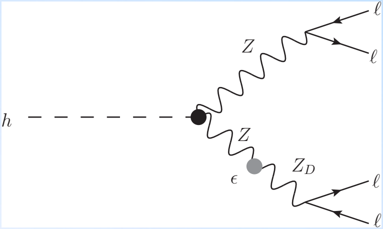
FRVZ model	m_{H} (GeV)	Excluded $c\tau$ [mm]
Higgs $\rightarrow 2\gamma_{\mathrm{d}} + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs $\rightarrow 4\gamma_{\mathrm{d}} + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs $\rightarrow 2\gamma_{\mathrm{d}} + X$	125	$0.6 \leq c\tau \leq 63$
Higgs $\rightarrow 4\gamma_{\mathrm{d}} + X$	800	$0.8 \leq c\tau \leq 186$

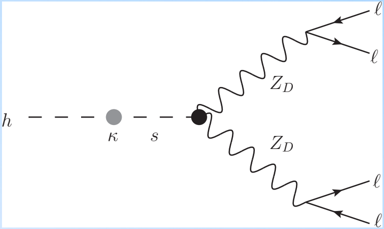
Hadron-collider experiments entered into the mass vs ϵ plot of the vector-portal interpretation



Higgs to ZZ_d and Z_dZ_d

Higgs to dark Z



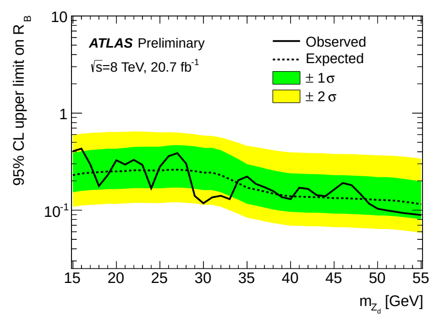


Main ingredients:

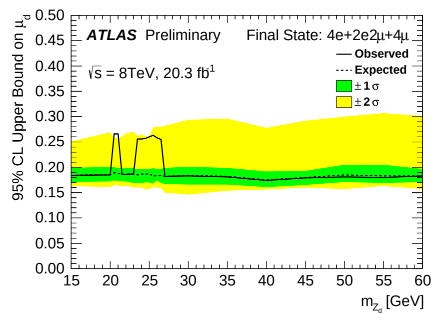
- analysis explicitly exploiting the Higgs decay topology requiring the four-lepton invariant mass to be within 115 and 130 GeV
- similar to the SM Higgs analysis in many aspects with different requirements in the di-lepton invariant mass
- main backgrounds are $t\bar{t}$, Z+jets and SM Higgs

Higgs to dark Z

Higgs to ZZ_d



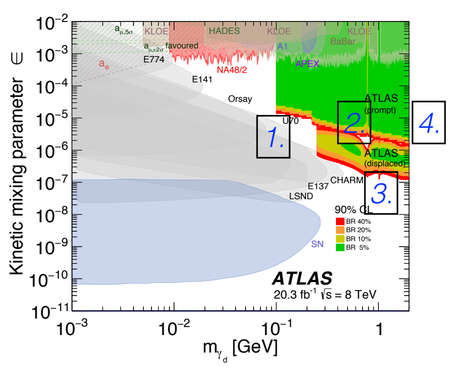
Higgs to $Z_d Z_d$



No events above the background prediction,
limits on the branching ratio relative to the SM Higgs process

$$R_B = \frac{BR(H \to ZZ_d \to 4\ell)}{BR(H \to ZZ_d 4\ell) + BR(H \to ZZ^* 4\ell)} \; ; \; \mu_d = \frac{\sigma \times BR(H \to Z_d Z_d \to 4\ell)}{\sigma \times BR(H \to ZZ^* \to 4\ell)}$$

Prospects (just a few words)



1. Low-mass / New triggers for overlapping energy deposits?
2. Mass-gap / Decays to pion-jets? Displaced search in the outer part of the tracker?
3. Very-displaced region / Single LLP decays? (1605.02742) MATHUSLA? (1606.06298)
4. High-mass / Z_d search

Data-driven model-independent searches for LLP

LLP searches typically working in a zero-background regime

- by requiring stringent cuts and two displaced objects

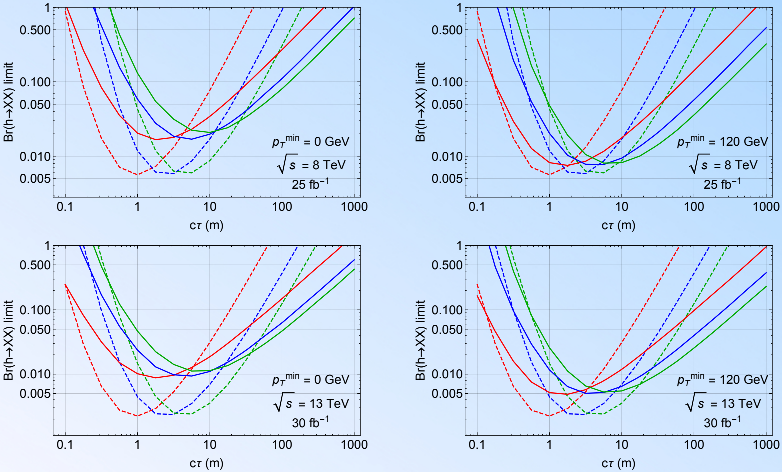
A new strategy has been proposed in 1605.02742
(AC, D. Curtin, H. Lubatti, H. Russell, J. Shelton)

- just one displaced object with data-driven background estimate
- generalised ABCD method with (DV isolation variable) vs (some kinematic variable capturing the rest of the event)
- full toy estimate demonstrated the superior reach at longer lifetimes
- methodology relies on background triggers implemented in ATLAS

Single-displaced analyses should become possible

- displaced object + X

Data-driven model-independent searches for LLP



dashed lines	ATLAS-like displaced search with 2 vertices in the muon spectrometer
full lines	analogous search with just one displaced vertex

Conclusions

Exciting program of dark sector searches at colliders

- exotic Higgs boson decays play a crucial role in the quest

Looking for hidden sector poses experimental challenges

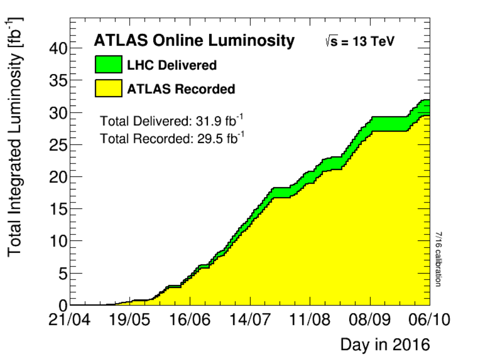
- detectors are designed for prompt physics
- triggers and reconstruction may not be adequate

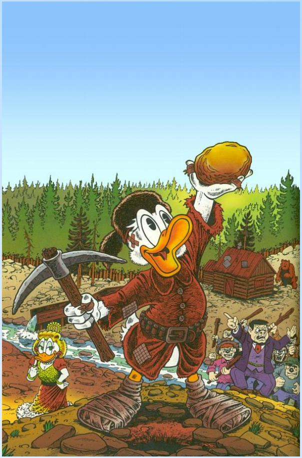
Improvements in Run-II despite higher pile-up and harsher conditions

- narrow-scan muon triggers
- topological algorithm at L1 for decays in the hadronic calorimeter
- vertexing in the muon spectrometer running for every triggered event
- more to come

Outlook

Most of the searches targeting 2017 winter conferences, x10 luminosity already recorded!





BACK-UP

$\log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}})$	The base-10 logorithm of the ratio of the energy in the HCal to ECal. If no energy is present in the ECal, a large number is used as input to the BDT instead.
Jet Width	The p_{T}-weighted sum of the ΔR between each cluster the jet is built from and the jet axis.
Leading cluster Longitudinal length	How far the highest p_{T} cluster has spread in the longitudinal direction
Jet p_{T}	Training events are reweighed so that the jet p_{T} distribution is flat. This allows the BDT to look for correlations between other variables and the jet p_{T} without using jet p_{T} directly as a discriminating variable.
Leading cluster lateral width	How far the highest p_{T} cluster has spread in the latitudinal direction.
Leading Jet Cluster Shower Center	The distance from the inner edge of the ECal to the highest p_{T} cluster's center along the jet axis. A zero would mean this was on the edge of the ECal.
ΔR to Closest 2 GeVTrack	The ΔR between the jet axis and the closest 2 GeV track. Or 0.4 if there is no such track.
Radius of the leading cluster	The radius from the beam spot to the highest p_{T} cluster.
Cluster Energy Density	The $\frac{\sum E_i^2/V_i}{\sum E_i}$, where E_i is the energy of each cell, and V_i is the volume of the cell in the highest p_{T} cluster in the jet. Only positive energy cells are considered.
Number of tracks	The number of tracks with $p_{\mathrm{T}} > 2\ GeV$ within a $\Delta R < 0.2$ of the jet axis.
Sum p_{T} of all tracks	The sum p_{T} of all tracks within $\Delta R < 0.2$.