Looking for a hidden sector in exotic Higgs boson decays with the ATLAS experiment

Séminaires de physique corpusculaire
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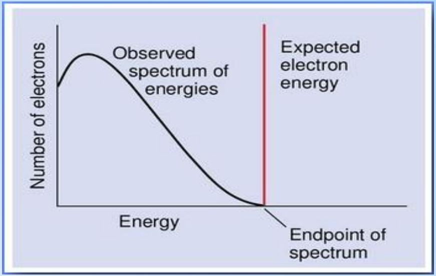
1. Overview
2. Hidden sector and unconventional signatures
3. Tools by ATLAS
4. Searches by ATLAS
5. Conclusions

Pauli's solution to the β decay

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
- $n \rightarrow p + e^- + \overline{\nu}$

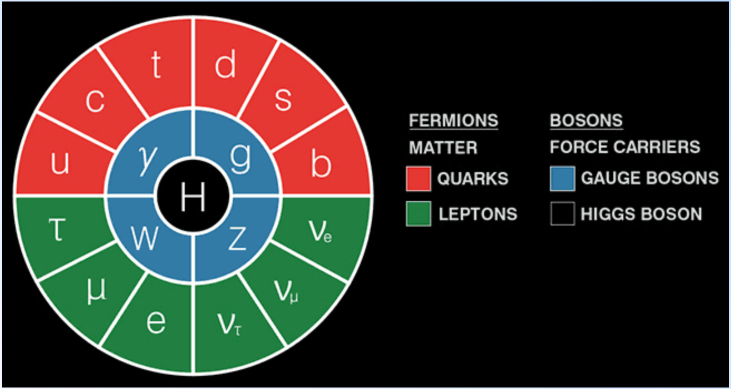


Perfect example of a hidden sector:

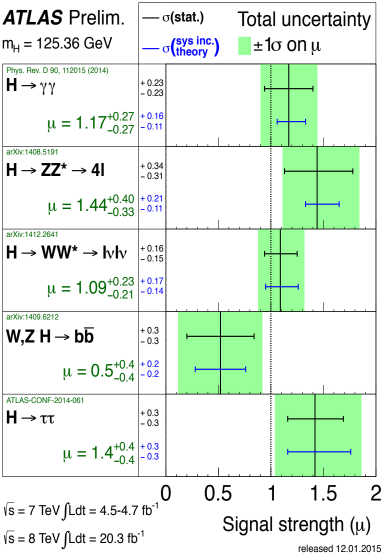
1. neutrino is electrically neutral
2. very weakly interacting (and also light)
3. interaction through a portal - $(\overline{p}\gamma^\mu n)(\overline{e}\gamma_\mu \nu)$

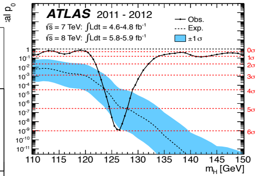
After ∼80 years

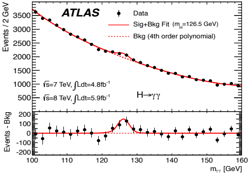
The SM is the theory to describe elementary particles and their interactions. It has been verified meticulously in the past decades and at the LHC. Legacy of LHC results: the first fundamental scalar at 125 GeV and no new physics (yet) at the TeV scale.

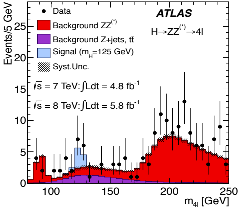


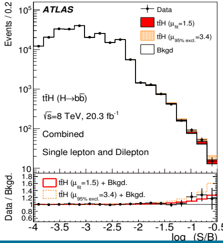
Higgs physics at ATLAS

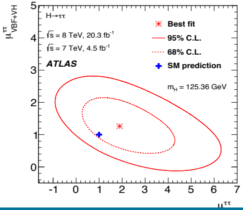


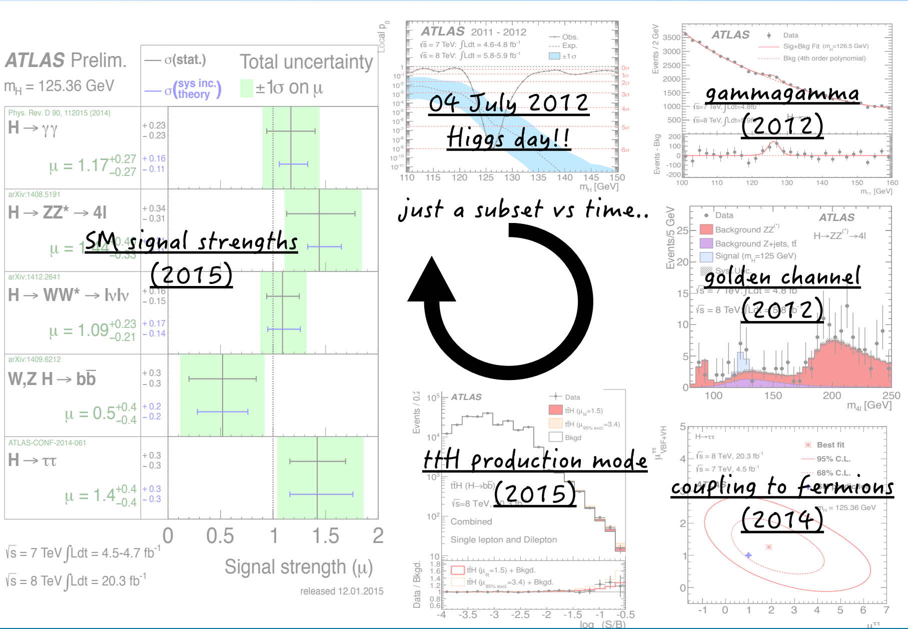











ATLAS Prelim.
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
Total uncertainty
±1σ on μ
Phys. Rev. D 90, 112015 (2014)
H → γγ
μ = 1.17 +0.27 −0.27
+0.23 −0.23
+0.16 −0.11
arXiv:1408.5191
H → ZZ* → 4l
+0.34 −0.31
arXiv:1412.2641
H → WW* → lνlν
μ = 1.09 +0.23 −0.21
+0.16 −0.15
+0.17 −0.14
arXiv:1409.6212
W,Z H → bb̄
μ = 0.5 +0.4 −0.4
+0.3 −0.3
+0.2 −0.2
ATLAS-CONF-2014-061
H → ττ
μ = 1.4 +0.4 −0.4
+0.3 −0.3
+0.3 −0.3
0 0.5 1 1.5 2
Signal strength (μ)
√s = 7 TeV ∫Ldt = 4.5-4.7 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
released 12.01.2015
SM signal strengths
(2015)
ATLAS 2011 - 2012
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb⁻¹
Obs.
Exp.
±1σ
Local p₀
m_H [GeV]
04 July 2012
Higgs day!!
just a subset vs time..
ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
Events / 2 GeV
Events - Bkg
m_γγ [GeV]
gammagamma
(2012)
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (m_H=125 GeV)
H→ZZ(*)→4l
Events/5 GeV
m_4l [GeV]
golden channel
(2012)
ATLAS
Data
tt̄H (μ_fit=1.5)
Bkgd
tt̄H (H→bb̄)
√s=8 TeV,
Combined
Single lepton and Dilepton
Events / 0.2
Data / Bkgd.
tt̄H (μ_fit=1.5) + Bkgd.
ttH production mode
(2015)
H→ττ
Best fit
95% C.L.
68% C.L.
√s = 8 TeV, 20.3 fb⁻¹
√s = 7 TeV, 4.5 fb⁻¹
m_H = 125.36 GeV
coupling to fermions
(2014)

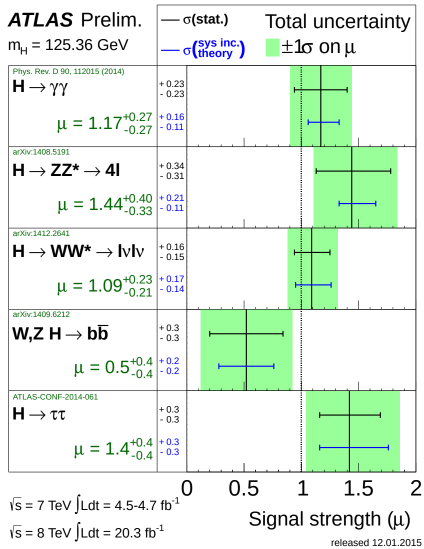
Exotic Higgs decays

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.

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



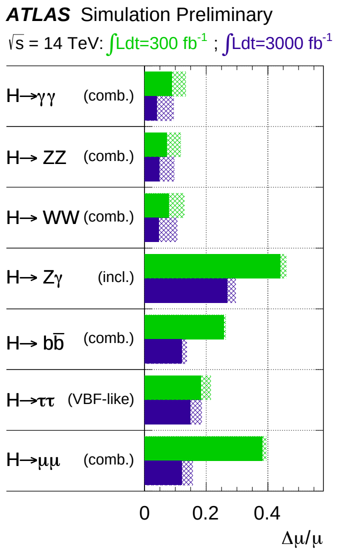
Projections of coupling measurements

New fundamental scalar consistent with SM Higgs boson.

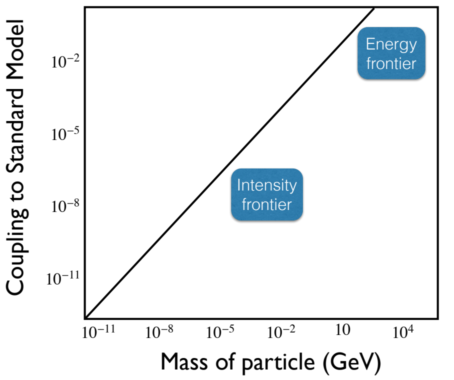
Constraints from observing the Higgs boson in the various SM channels allow non-SM BR of $\mathcal{O}$(20-30%).

Large experimental uncertainties on the Higgs boson couplings.

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



Where is the New Physics?



LHC operates at the energy frontier with an intensity frontier attitude. New physics may appear as a new bump (2015 golden year!) or when accumulating high luminosities.

The Higgs can be the candle for finding new physics!

Hidden sector

New physics not yet seen because at higher energy scale or because hidden in a separate sector weakly coupled to the SM.

Do we have a “puzzling β decay spectrum” for searching for a hidden sector?

YES! (Actually more than one...)

Galactic rotation curve for NGC 6503 showing disk
and gas contribution is not enough to match the data.

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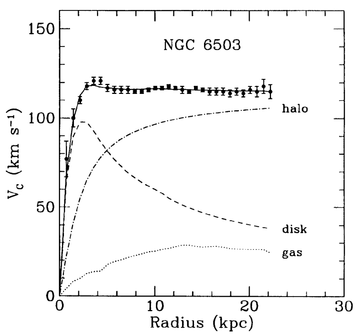


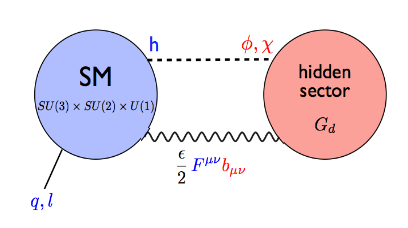
Galactic rotation curve for NGC 6503 showing disk and gas contribution is not enough to match the data.

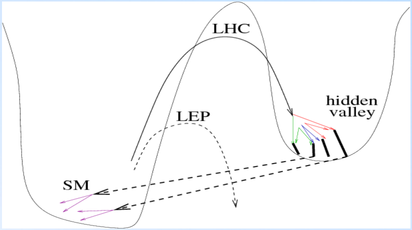
Portals to the hidden sector

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**.





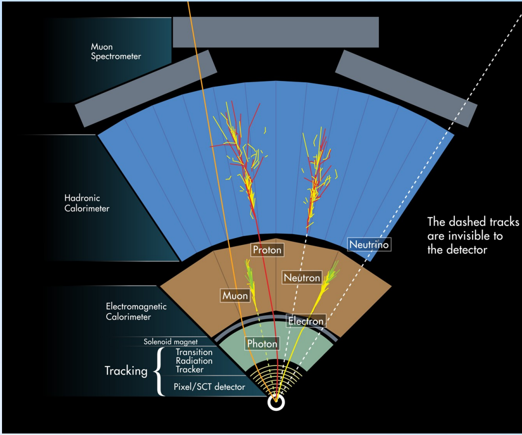
Unconventional signatures

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

Tools employed by ATLAS:

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

Experimental searches by ATLAS:

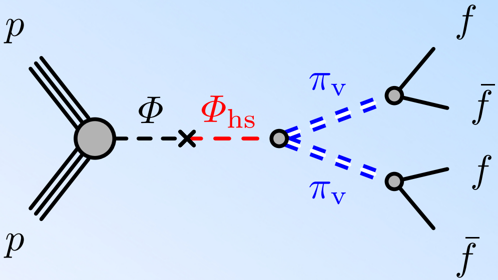
3. Higgs to displaced jets in the HCal [PLB 743 (2015) 15-34]
4. Higgs to displaced jets in the ID and MS [check out the arXiv today ;-)]
5. Higgs to dark photons [JHEP 11 (2014) 088]
6. Higgs to dark Z [ATLAS-CONF-2015-003]

DISCLAIMER

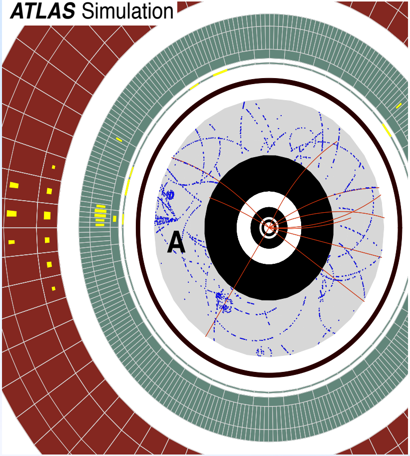
No time to cover all the details of these searches. Questions welcome.

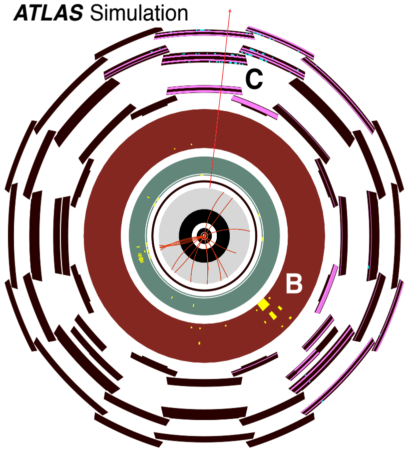
Benchmark model

Hidden sector with a confining gauge interaction connected to the SM via a communicator particle. The communicator can be the Higgs boson mixing with a hidden-sector scalar boson.

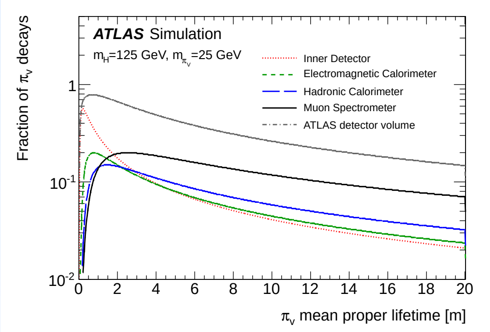


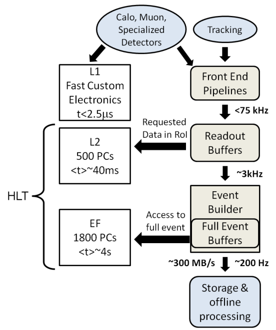
Benchmark model





Triggering on displaced decays





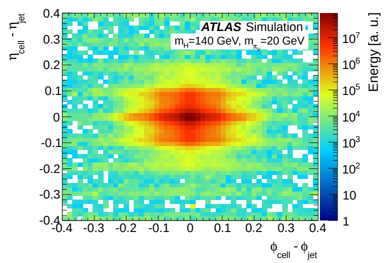
Three signature-driven triggers have been designed and deployed in Run-I.
Each trigger is dedicated for a particular region of the ATLAS detector.

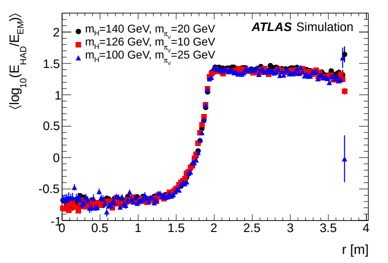
Detector region	Key feature	Trigger name
from SCT to ECal	Jet with track isolation	Trackless Jet trigger
HCal	Isolated jet with very low EM fraction	Calorimeter Ratio trigger
MS	Isolated cluster of muon RoIs	Muon RoI Cluster trigger

Decays in the hadronic calorimeter

Basic ingredients:

- tau item at L1
- track and jet reconstruction at HLT
- no tracks around the jet axis
- $\log(E_{HAD}/E_{EM}) > 1.2$ at L2
- beam halo removal using calorimeter cell timing

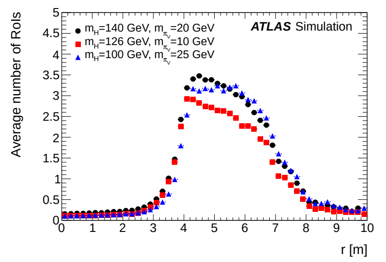


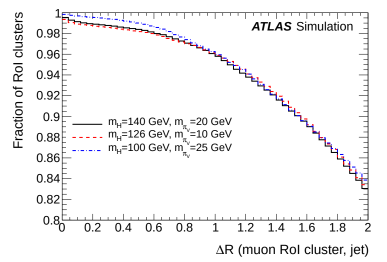


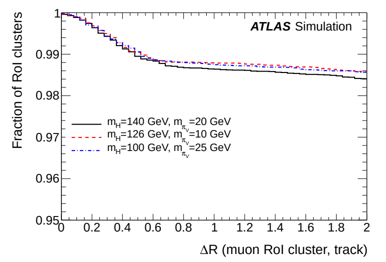
Decays in the MS

Basic ingredients:

- di-muon item at L1
- track and jet reconstruction at HLT
- muon cluster asking for at least 3 regions of interest in the MS barrel
- no tracks and jets around the muon cluster direction

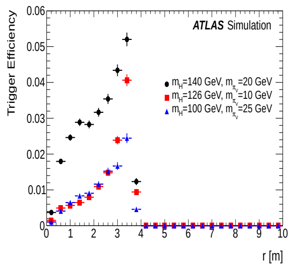




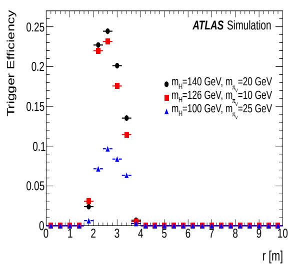


Trigger efficiency

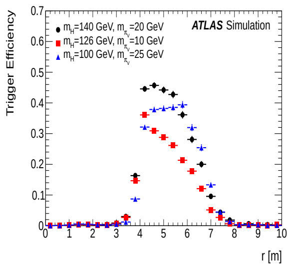
The efficiency is defined as the fraction of π_v's decaying at a distance r from the primary interaction point that pass one of the triggers for displaced decays of long-lived neutral particles.



Trackless Jet trigger

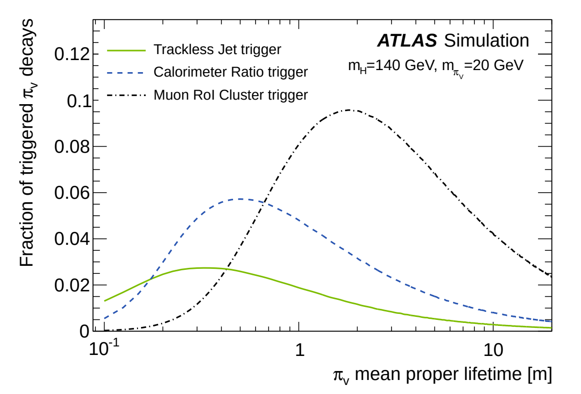


Calorimeter Ratio trigger



Muon RoI Cluster trigger

Expected fraction of triggered events

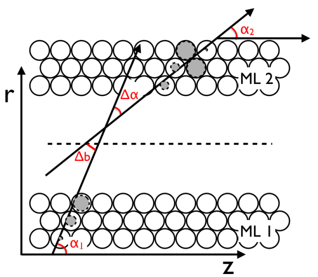


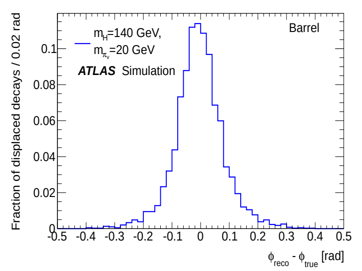
Nice complementarity between the three approaches!

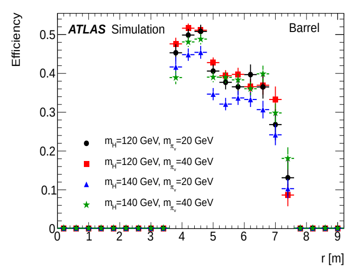
Reconstructing vertices in the muon spectrometer

Routine developed to reconstruct a vertex in the MS

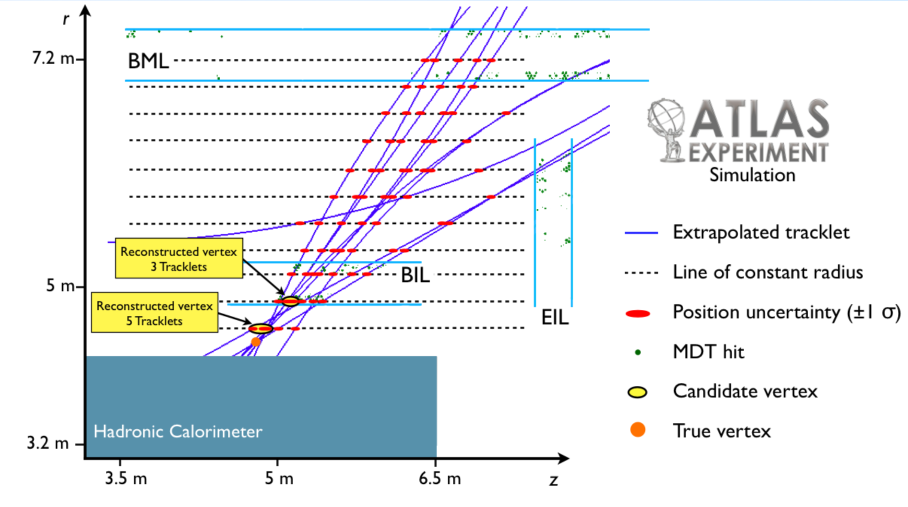
- tracklets are formed combining segments belonging to the same MDT chamber
- tracklets are clustered and back-extrapolated in the magnetic field
- vertices are found with an iterative min χ^2 fit
- the line-of-flight direction in Φ is reconstructed with a 50 mad accuracy







Reconstructing vertices in the muon spectrometer



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DISCLAIMER

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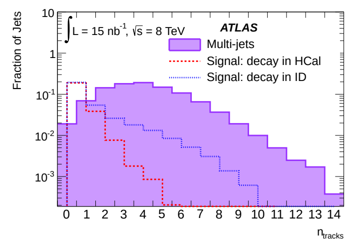
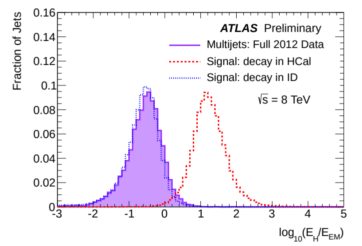
Higgs to displaced jet in the HCal

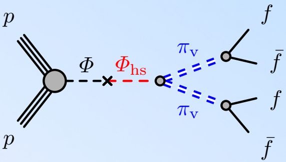
Main ingredients

- calorimeter-ratio trigger
- two object strategy looking for displaced hadronic jets with no connecting tracks and unbalanced energy deposit
- cosmic rays and non-collision events are rejected requiring $E_T^{miss} < 50$ GeV and jet timing $-1 < t < 5$ ns
- background dominated by QCD jets and estimated with a data-driven technique
- JES systematics evaluated as a function of the relative fraction of energy deposited in the hadronic calorimeter

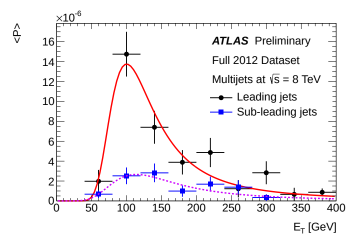




Higgs to displaced jets in the HCal



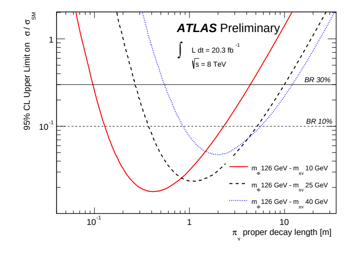
probability for a QCD jet to pass the cut flow



Exclusion limit considering a Higgs decay to a pair of long-lived pseudo-scalar π_v

MC sample m_H, m_{π_v} [GeV]	excluded range 30% BR [m]	excluded range 10% BR [m]
126,10	0.10 - 4.42	0.13 - 2.34
126,25	0.27 - 9.99	0.37 - 5.20
126,40	0.54 - 12.4	0.83 - 5.83

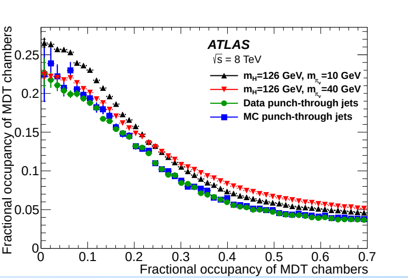
exclusion limit as a function of the lifetime



Higgs to displaced jet in the ID and MS

Main ingredients

- muon RoI cluster and jet plus $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers
- looking at decays in both ID and MS with explicit displaced vertex reconstruction
- two object strategy looking with a total of five different topologies
- background dominated by QCD jets in the ID and punch-through jets in the MS
- main systematics evaluated with K-short candidates for the ID and punch-through jets for the MS

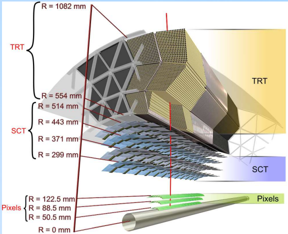


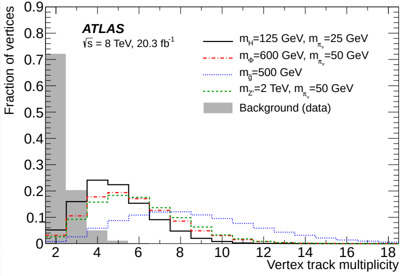
Trigger	Topology	Background prediction
Jet+$E_{\mathrm{T}}^{\mathrm{miss}}$	2IDVx	$(1.8 \pm 0.4) \times 10^{-4}$
Jet+$E_{\mathrm{T}}^{\mathrm{miss}}$	IDVx+MSVx	$(5.5 \pm 1.4) \times 10^{-4}$
Jet+$E_{\mathrm{T}}^{\mathrm{miss}}$	2MSVx	$(0.0\,^{+1.4}_{-0.0}) \times 10^{-5}$
Muon RoI Cluster	IDVx+MSVx	2.0 ± 0.4
Muon RoI Cluster	2MSVx	$0.4\,^{+0.3}_{-0.2}$

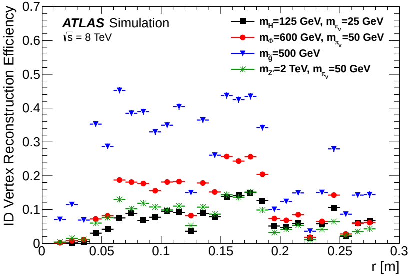
Higgs to displaced jet in the ID and MS

Reconstruction of displaced decays in the ID:

- second iteration of track finding using hits left as unassociated by the standard reconstruction
- vertexing algorithm based on the default primary vertex with loosened constraints
- hadronic interactions with the material are removed

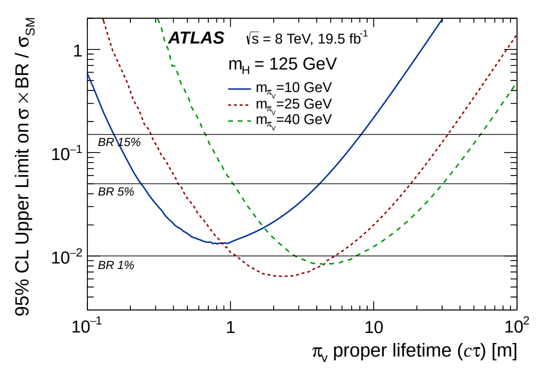




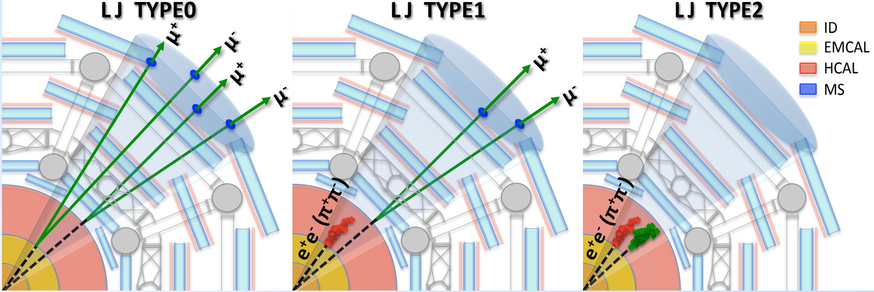


Higgs to displaced jet in the ID and MS

m_{π_v} [GeV]	Excluded $c\tau$ range [m]		
	1% BR	5% BR	15% BR
10	no limit	0.24–4.2	0.16–8.1
25	1.10–5.35	0.43–18.1	0.28–32.8
40	2.82–7.45	1.04–30.4	0.68–55.5



Higgs to dark photons



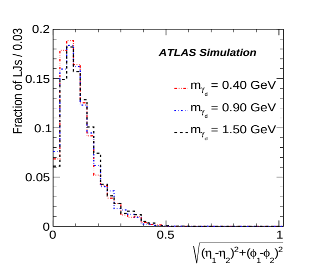
Analysis optimized for looking into displaced lepton-jets in a model-independent way

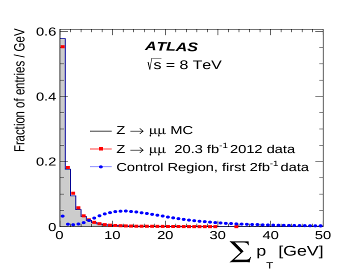
- QCD multi-jet background calculated with ABCD method
- cosmics background estimated in the empty bunches
- benchmarks targeting dark photon production through exotic Higgs decay

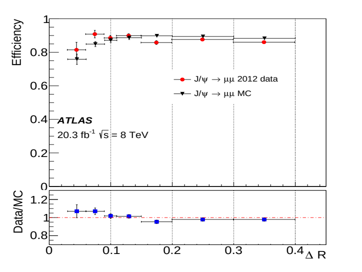
Higgs to dark photons

Main ingredients

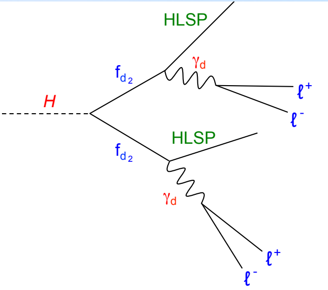
- trigger asking for three muon-only tracks and calorimeter-ratio trigger
- reconstruction of near-by tracks in the muon spectrometer
- track isolation implemented for removing multi-jet background and validated in $Z \rightarrow \mu\mu$ events
- main systematics evaluated using $J/\Psi \rightarrow \mu\mu$ events

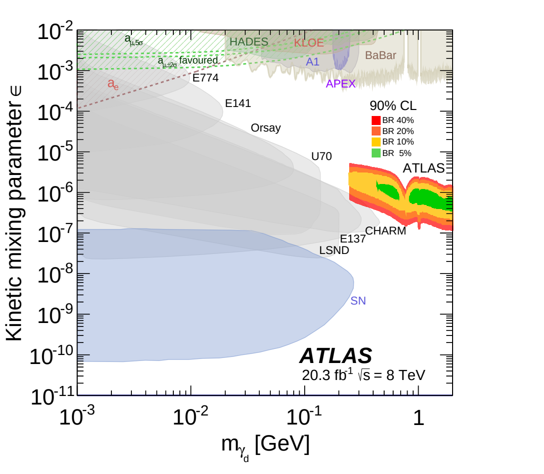






Higgs to dark photons

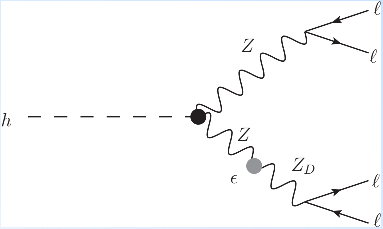


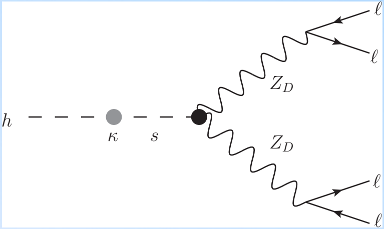


Hadron-collider experiment entering into the mass vs ϵ plot of the vector-portal interpretation

Higgs to dark Z

Dark sector coupling with the SM thorough kinetic mixing with the hypercharge gauge boson. Also considering the case of a dark Higgs boson mixing with the SM Higgs boson.

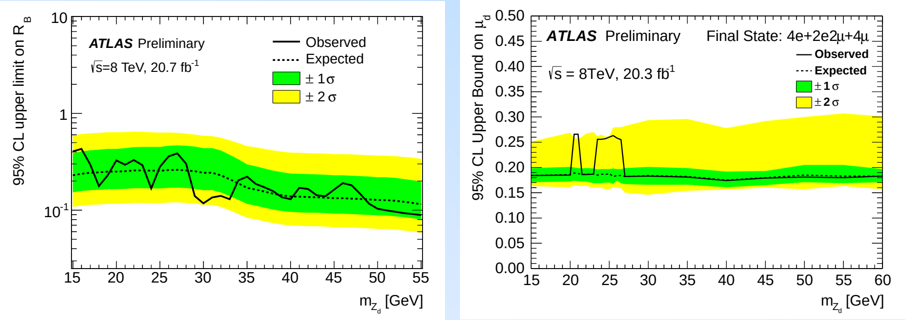




Main ingredients:

- 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



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

Conclusions

Strong empirical hints for new physics and the associated scale can be light

- exotic decays of the Higgs boson plays a crucial role in the quest
- the Higgs boson can be the candle for finding new physics

Looking for hidden sector poses experimental challenges

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

Various possible improvements in Run-II

- take advantage of the various Higgs production mechanisms
- new triggerring ideas
- systematically looking for “blind spots”

It took almost 30 years to confirm Pauli's intuition ...

... it's a long way (if you wanna rock 'n' roll)!

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