Rare and Exotic Higgs Decay Prospects at the HL-LHC

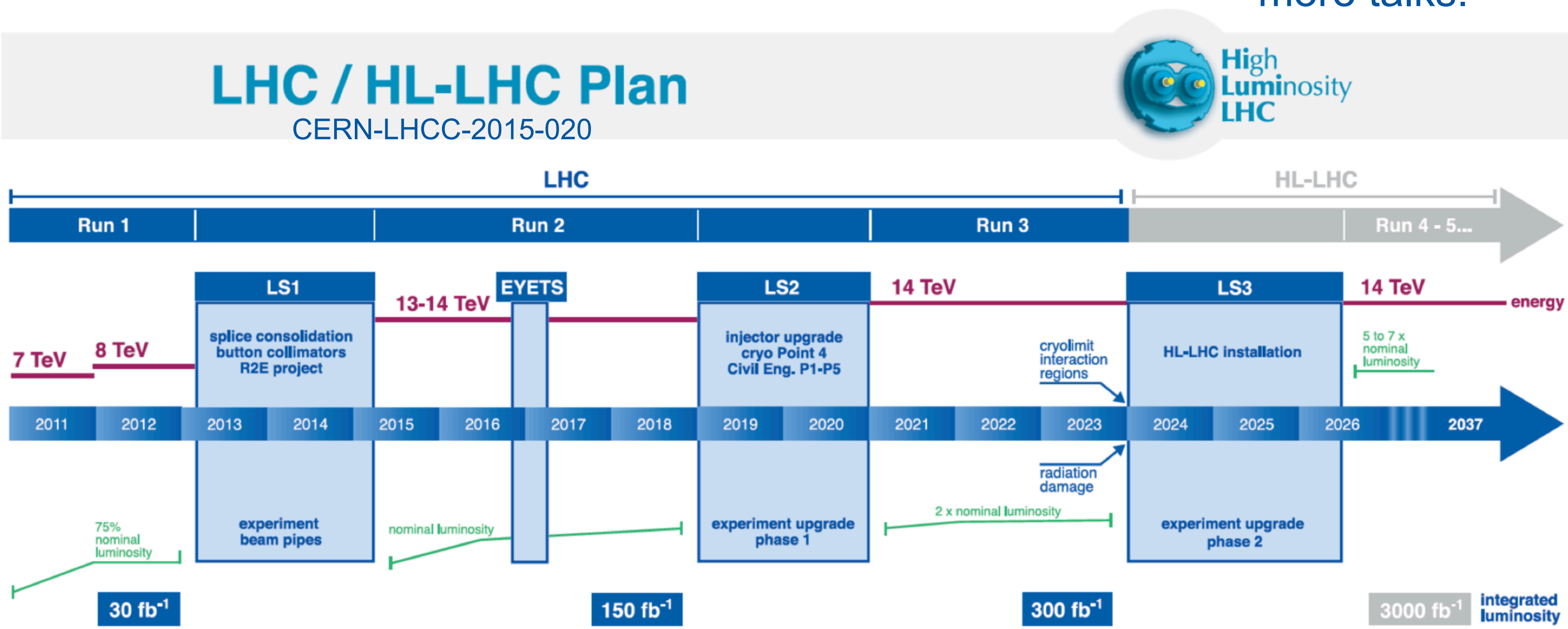
Allison McCarn | 11/08/2016

Introduction

The High Luminosity LHC (HL-LHC) and Phase 2 upgrades are planned to be ready in ~1 decade.

The increased integrated luminosity provided by the HL-LHC will be useful in the search for rare/exotic Higgs decays.

So please hang on for 2 more talks!



Introducing the HL-LHC

Goals of HL-LHC:

Design for 7.5x10^{34} $cm^{-2}s^{-1}$ peak luminosity (~200 collisions/crossing)

Enabling total integrated luminosity of 3000 fb^{-1} (~300 fb^{-1} per year)

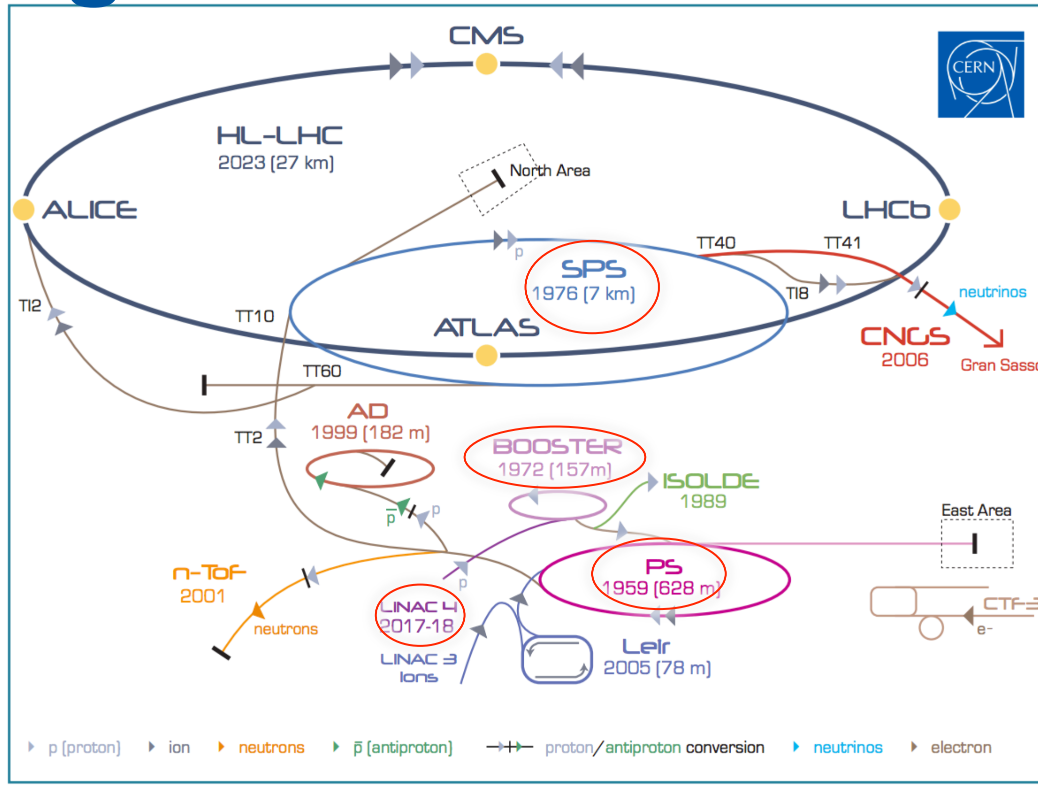
Many Upgrades:

More powerful niobium-tin dipole and quadrupole magnets

“Crab” cavities to tilt colliding beams

Reinforced machine protection

Linac4 & upgrades for PS Booster, PS, and SPS



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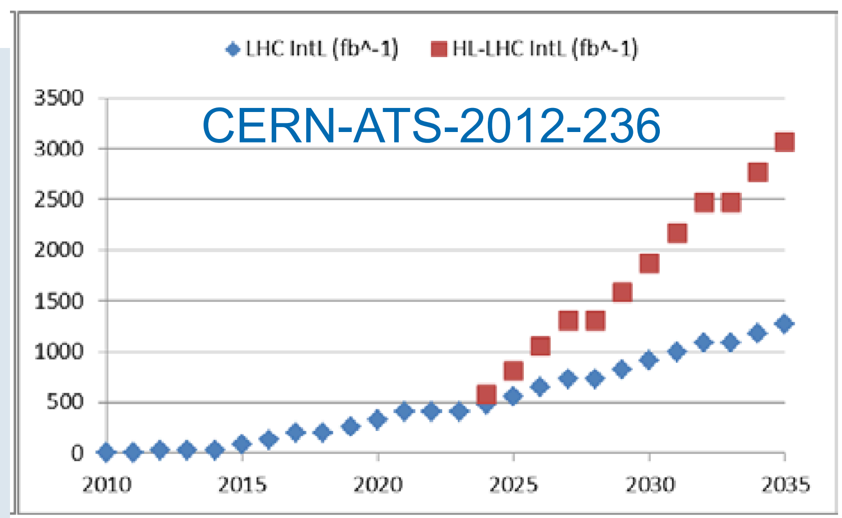
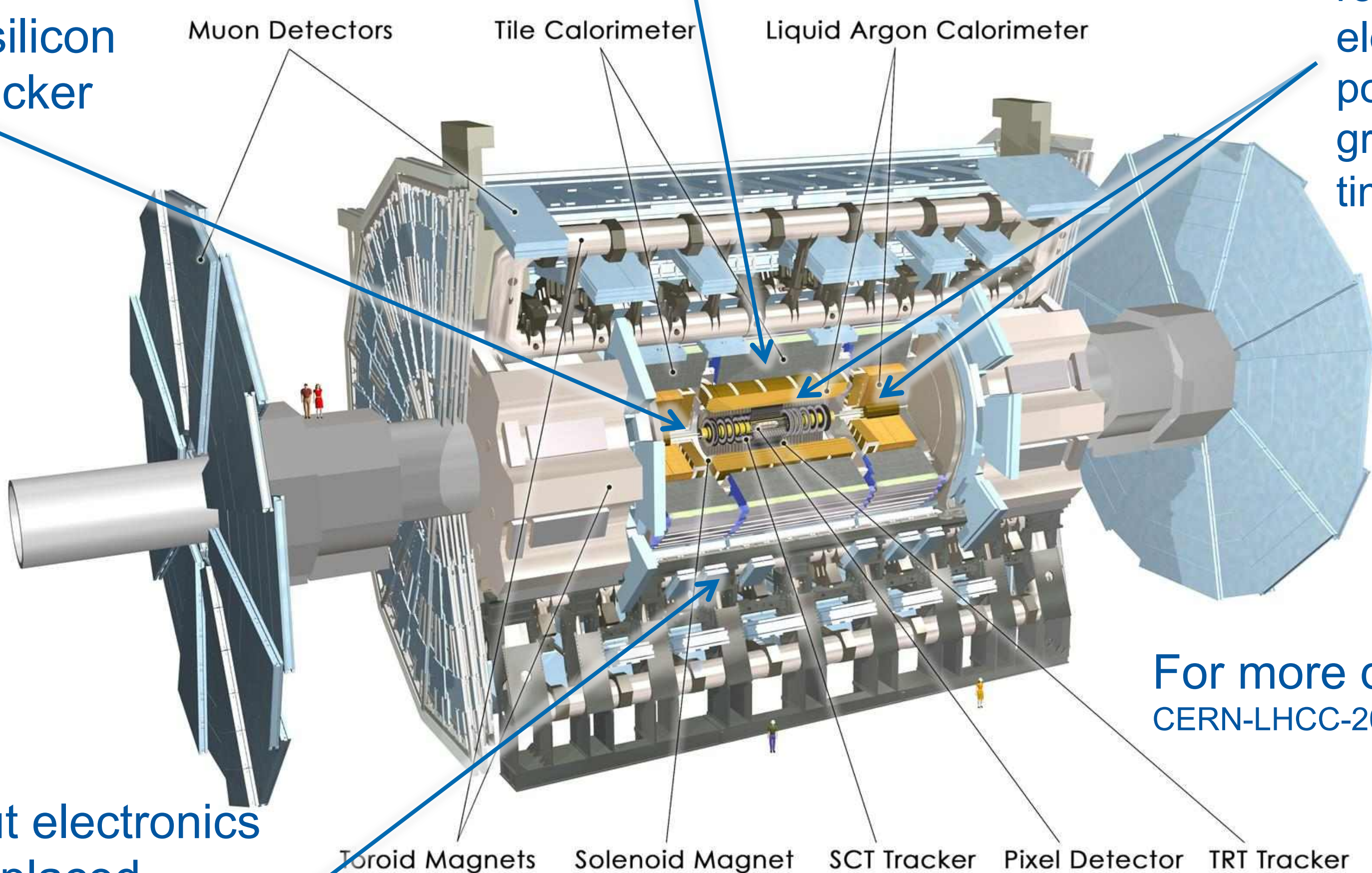


HL-LHC and ATLAS Upgrades

All FE and BE electronics to be replaced

Upgrade readout electronics, possible high-granularity timing detector.

New all-silicon Inner Tracker



For more details see
CERN-LHCC-2015-020

Readout electronics to be replaced, RPCs added to inner station

ATLAS will require a large program of Phase 2 upgrades to adapt to the new running conditions.

More details: CERN-LHCC-2015-019

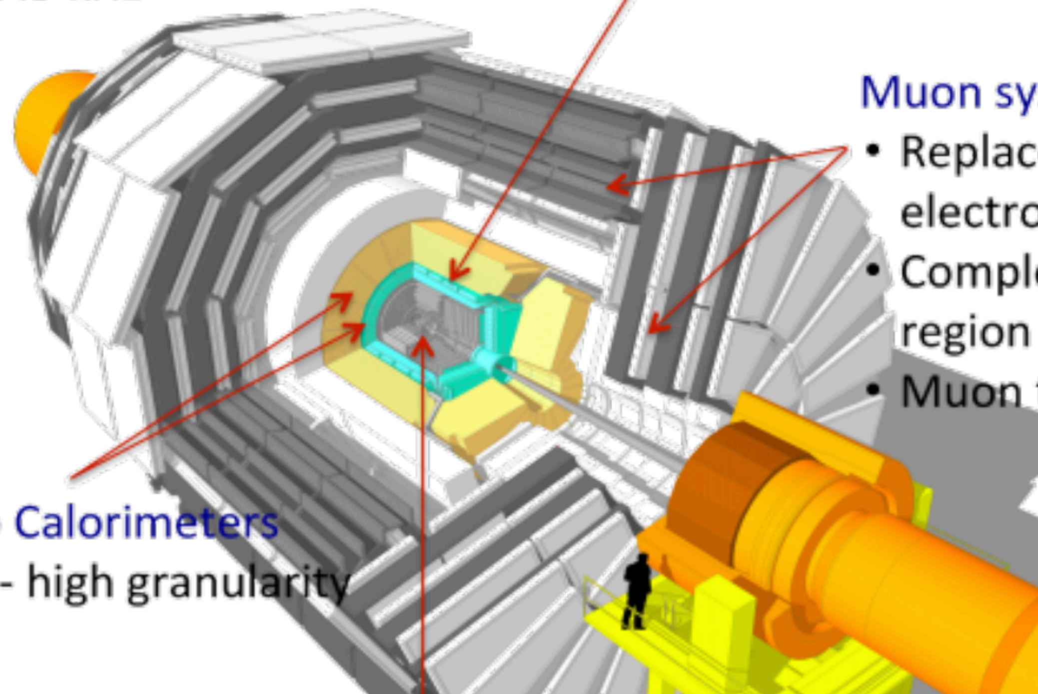
HL-LHC and CMS Upgrades

Trigger/HLT/DAQ

- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≈7.5 kHz

Barrel EM calorimeter

- Replace FE/BE electronics
- Lower operating temperature (8°)



Muon systems

- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

Replace Endcap Calorimeters

- Rad. tolerant - high granularity
- 3D capability

Replace Tracker

- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

From M. Narain, ECFA 2016

What will this mean for experimentalists?

Many physicists in ATLAS & CMS have contributed to studying the prospects for discovery with the HL-LHC:

CMS:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
ATLAS:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

Also, prospects workshops, such as…
ECFA:
https://indico.cern.ch/event/524795/timetable/
Snowmass:
http://www.slac.stanford.edu/econf/C1307292/docs/EnergyFrontier.html

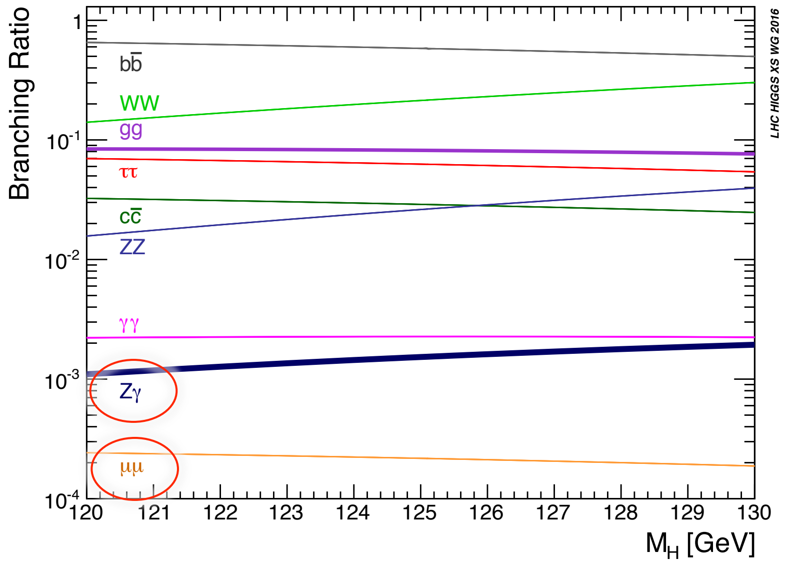
Today I will focus on prospects for rare and exotic decays of h(125)!

Rare and Exotic Higgs Decays

Rare SM Higgs Decays

B(H→Zγ): 0.00155
B(H→μμ): 0.00022
B(H→ee): 10^{-9}
B(H→J/ψγ, Υγ, Φγ): 10^{-6}, 10^{-9}, 10^{-6}

These are not currently observable at SM levels, but may be possible to probe at HL-LHC



SM Higgs Decays [CERN Yellow Report 4]

BSM Higgs Decays
B(H→BSM) < 0.34

H→2a: Occurs in NMSSM & 2HDM+S

H→invisible: decay to non-observable BSM particles (e.g. supersymmetric)

LFV H decays: predicted in many models (extended Higgs sector, composite Higgs, Randall-Sundrum, etc.)

Rare Higgs Decays: H→Zγ

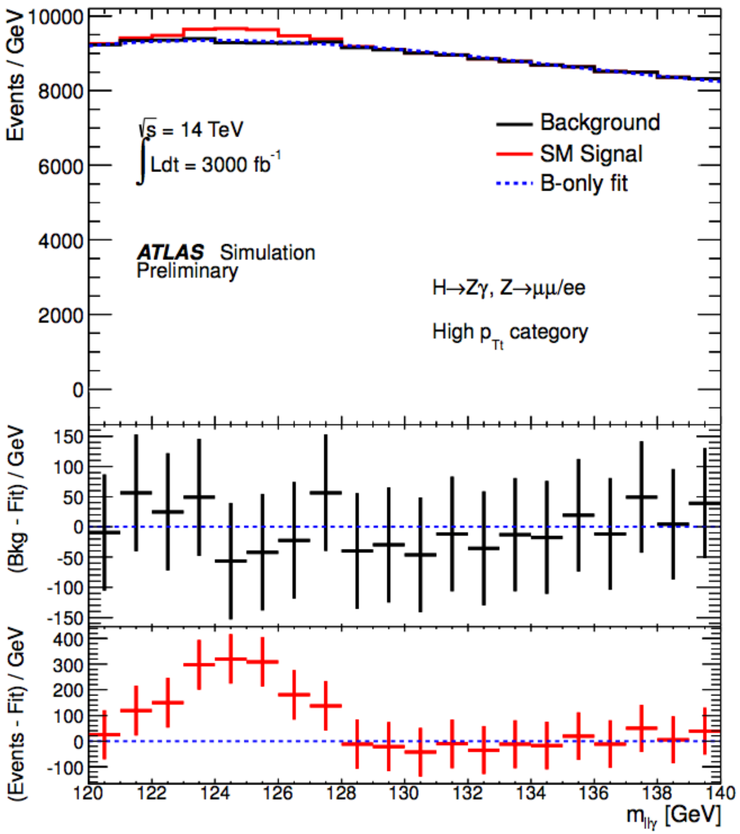
In Run-1, the observed (expected) **95% CL limit is 11 (9) ×σ_{SM}.**

Prospects are shown for the ATLAS detector with an integrated luminosity of **3000 fb^{-1} and average pile-up μ=140.**

Event selection follows the ATLAS run-1 search closely (Phys. Lett. B 732 (2014)):

- ✓ 2 same-flavor opposite-sign e or μ, p_T >10 GeV.
- ✓ 1 γ with E_T >15 GeV, separated from the selected leptons with ΔR >0.3.
- ✓ $m_{ll} > m_{PDG}^{Z} - 10$ GeV

Events are split into 3 categories, depending on Δη(Z,γ) and the projection of $P_T^{Z\gamma}$ onto the thrust axis.



Rare Higgs Decays: H→Zγ

The expected p_0, assuming the presence of a SM Higgs signal with mH=125 GeV, is 3.9σ.

The expected CL limit in the absence of a Higgs signal is $0.52\times\sigma_{SM}$.

The expected measured signal strength with the uncertainties is $1.00_{+0.25}^{-0.26}$(stat)$_{+0.17}^{-0.15}$(sys). The dominant systematic on the signal strength measurement is the signal mass resolution.

With the HL-LHC, we should have the sensitivity to see evidence of SM H→Zγ.

Category	high p_{Tt}		low p_{Tt} low $\lvert\Delta\eta_{Z\gamma}\rvert$		low p_{Tt} high $\lvert\Delta\eta_{Z\gamma}\rvert$	
Final states	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$
S	602	721	703	839	138	165
B	$2.56\cdot10^4$	$3.05\cdot10^4$	$1.09\cdot10^5$	$1.30\cdot10^5$	$2.56\cdot10^4$	$3.06\cdot10^4$
S/B (%)	2.4	2.4	0.64	0.64	0.54	0.54
$S/\sqrt{B}$	3.8	4.1	2.1	2.3	0.86	0.94

Table 4: Summary of number of expected signal and background events in each channel and signal to (square root) background ratios for 3000 fb^{-1} and $122 < m_{ll\gamma} < 128$ GeV

Rare Higgs Decays: H→μμ

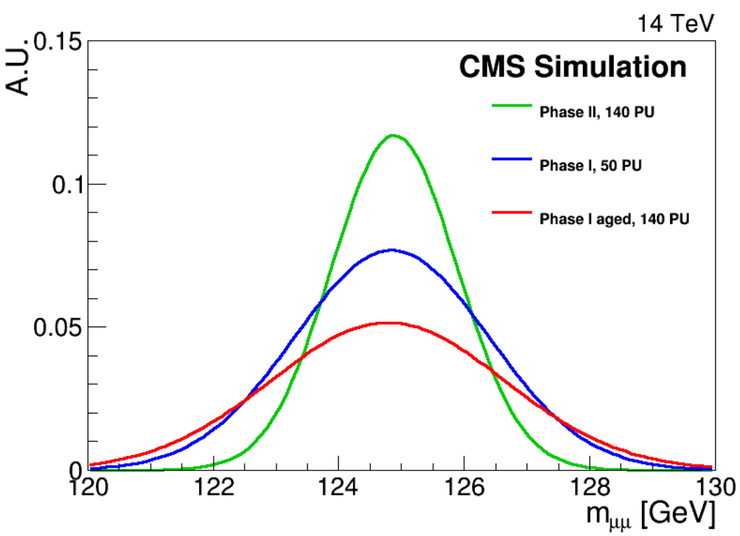
In Run-1, the observed **95% CL limit is 6 (7)×σ_{SM} for CMS (ATLAS)**.

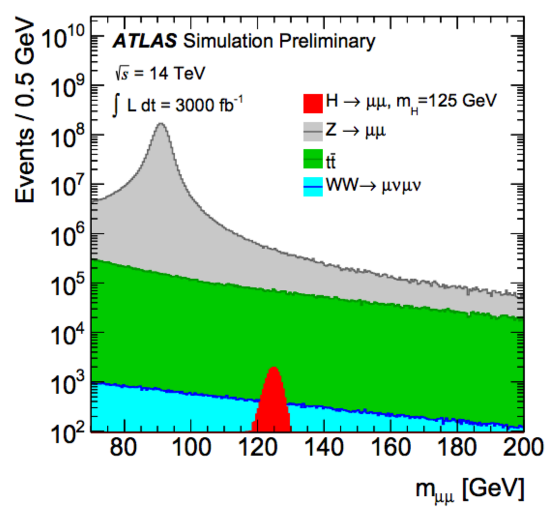
This channel could see hints using full dataset before HL-LHC.

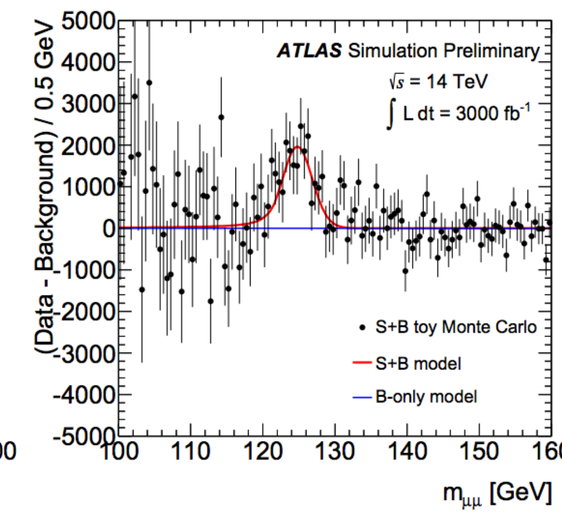
Phase 2 upgrades for the HL-LHC are expected to improve dimuon mass resolution.

ATLAS Prospects target VBF, ttH and VH production modes for H→μμ in HL-LHC.

Prospects are based on **2011 MSSM and 2012 SM H→μμ** analyses.







Rare Higgs Decays: H→μμ

$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
$\Delta^{\mathrm{sys}}_{Bkg}$ (model)	68	110
$\Delta^{\mathrm{sys}}_{Bkg}$ (fit)	190	620
$\Delta^{\mathrm{stat}}_{\mathrm{S+B}}$	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

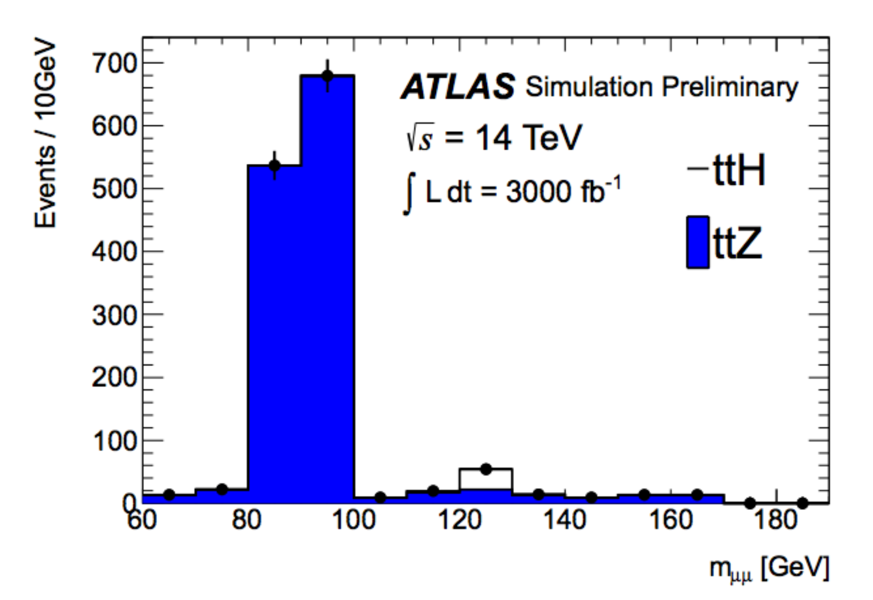
H→μμ should be observable at HL-LHC with 3000 fb^{-1}.

ttH→μμ is particularly interesting, because it probes the product of top- and μ- Yukawa couplings.

ttH→μμ

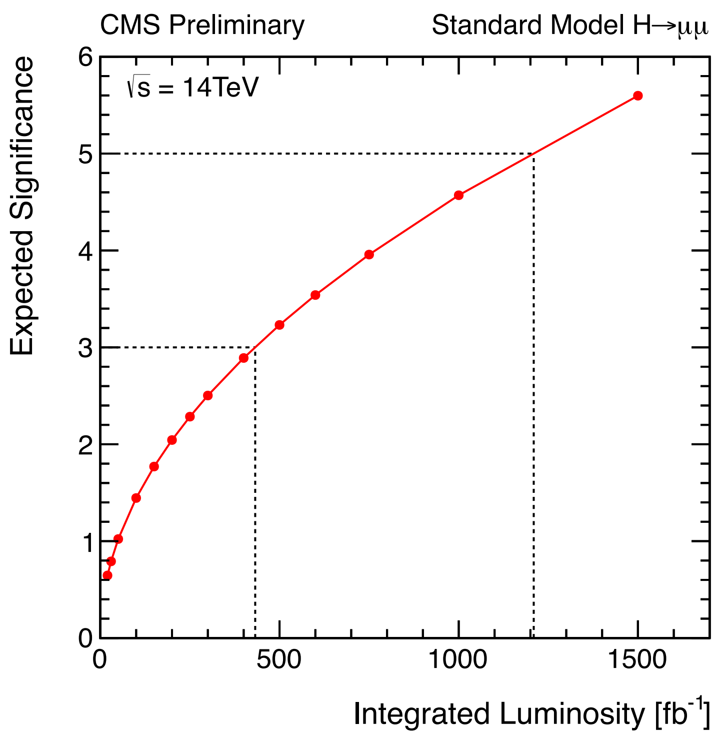
2-4 leptons, ≥4 jets, and a Higgs boson mass between 120-130 GeV.

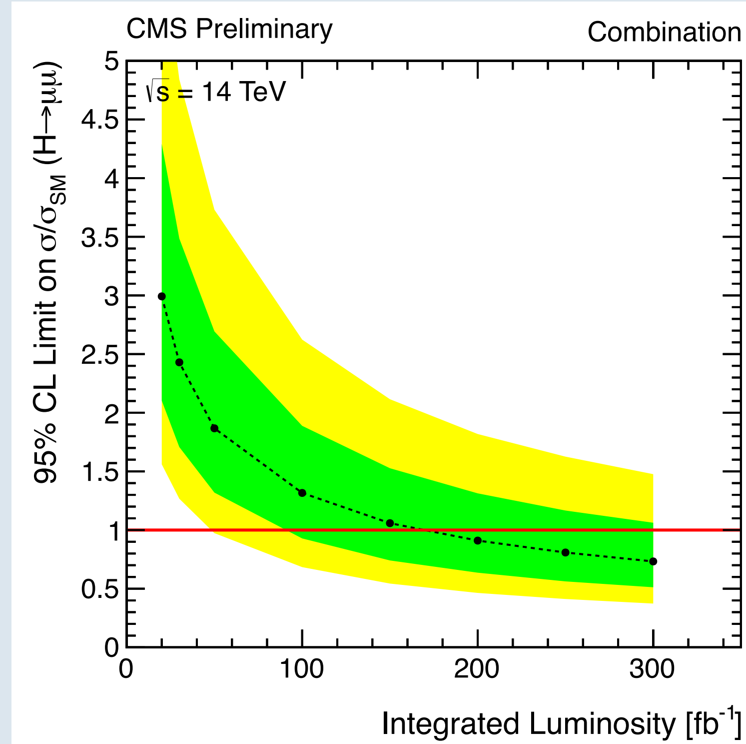
33 signal and 22 background after all selections.



ATL-PHYS-PUB-2013-014

Rare Higgs Decays: H→μμ





CMS prospects do not take into account affects of detector aging, pileup, etc., on the assumption that degradation in detector performance will be counteracted by improvements in analysis optimization.

CMS also expects to be able to observe H→μμ at the HL-LHC.

Scaled from run-1 result: CMS-PAS-HIG-13-007
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13007TWiki#Expected_Performance_at_s_14_TeV

ATL-PHYS-PUB-2015-043

Rare Higgs Decays: B(H→J/ψγ, Υγ, Φγ)

Current limits

B(H→J/ψγ) < 1.5x10^{-3}
(20.3 (19.7) fb^{-1} ATLAS (CMS), 8 TeV)

B(H→Υ(nS)γ) < (1.3, 1.9, 1.3)x10^{-3}
(20.3 fb^{-1}, 8 TeV)

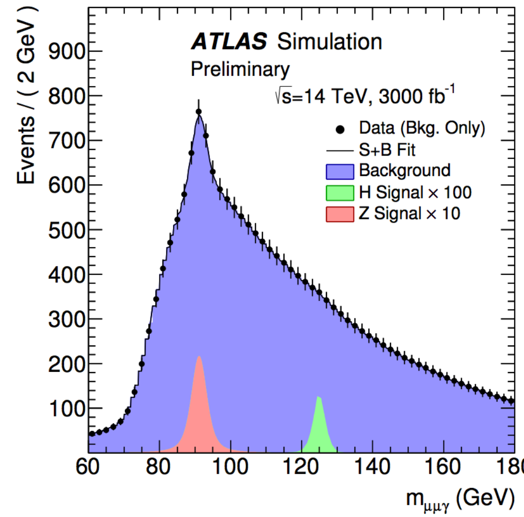
B(H→Φγ) < 1.4x10^{-3}
(2.7 fb^{-1}, 13 TeV)

Phys. Lett. B 753 (2016), Phys. Rev. Lett. 114, 121801 (2015), Phys. Rev. Lett. 117, 111802 (2016)

Reminder: SM BR are ~10^{-6} for J/ψγ and Φγ, ~10^{-9} for Υ(nS)γ.

These channels allow unique sensitivity to magnitude and sign of quark Yukawa coupling, which could be modified by BSM physics.

Prospects for **H→J/ψγ** evaluated with 14 TeV and pileup of 140, and an assumed detector equivalent to run-1 performance.



Expected Limits

	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]	
	Cut Based	Multivariate Analysis
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}

	Standard Model ex
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]
	2.9 ± 0.2

With MVA analysis, sensitive to 15*SM.

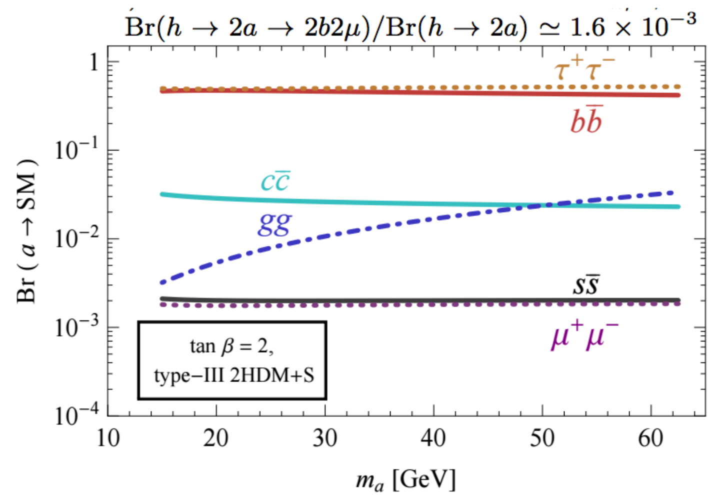
May be improved by introducing production-dependent categories, improving object reconstruction and MVA.

10.1007/JHEP06(2015)025
D. Curtin, R. Essig, Y. Zhong

Exotic Higgs: H→2a

This search is for a higgs decaying to new scalar particles (a), predicted by 2HDM+S/ NMSSM.

Many different decay modes have been investigated by ATLAS and CMS (2b2μ, 2τ2μ, 4μ, 4τ, 4γ, 4b).



Today considering **2b2μ**, a channel that benefits from the **clean dimuon signature** and the **high B(a→bb)**.

The study includes only gluon-fusion and m_a = 15-60 GeV, so may be pessimistic.

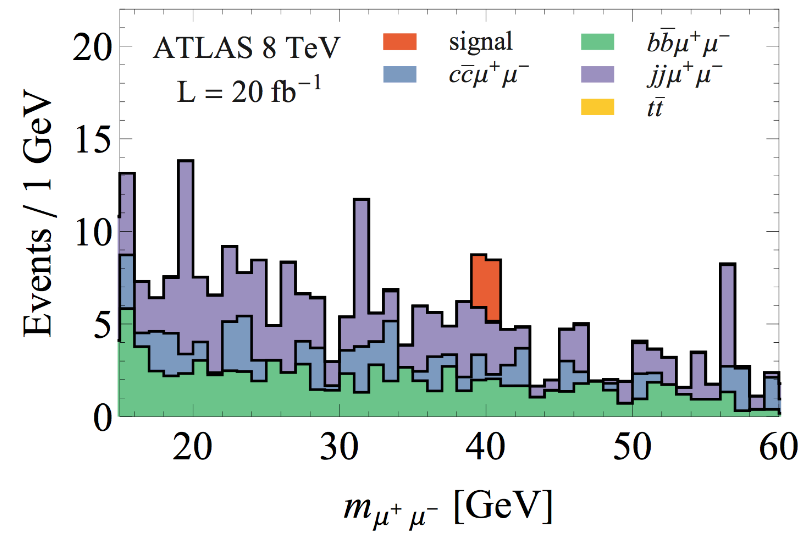
3 analyses considered:
"Conventional": R = 0.4-0.5 jets
"Smaller jet radius": R = 0.2 jets
"Jet substructure": R = 0.8 jets, using jet substructure to optimize the analysis.

Exotic Higgs: H→2a→2b2μ

Common Selection
Di-muon triggers
70% “MV1” b-tagging
$\Delta R(\mu_1,\mu_2) > 0.4$
$\Delta R(\mu,j) > 0.4$
$E_T^{miss} < 30$ GeV
$|m_{J1J2\mu1\mu2} - m_h| < 15$ GeV,
$|m_{J1J2} - m_a| < 15$ GeV,
$|m_{\mu1\mu2} - m_a| < 1$ GeV

Conventional/Small Radius
0 or 2 b-tagged jets
$\Delta R_{J1J2} > 0.4$

Jet Substructure
1 b-tagged fat jet and mass drop tagger
$\Delta R_{J1J2} > 0.2$

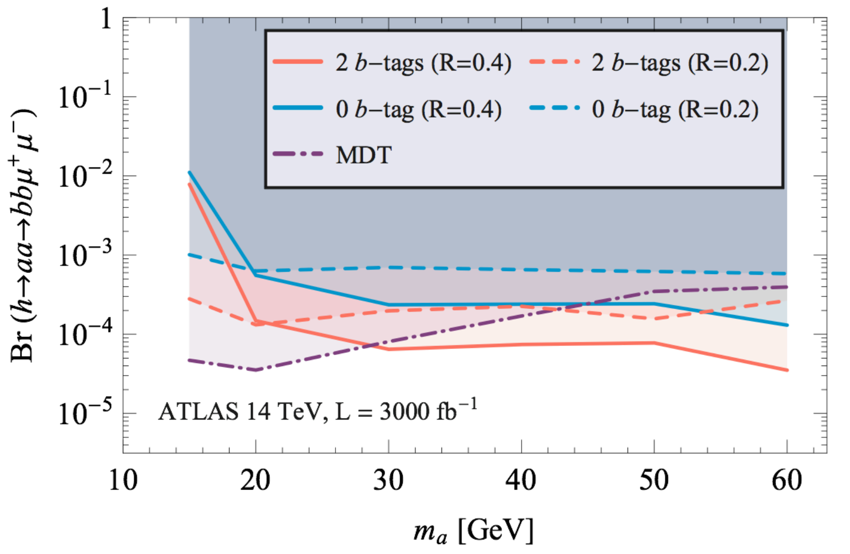


After all (but $m_{\mu1\mu2}$) of the 2-btag conventional selection in 8 TeV.

Using simple counting experiment, but expects experimentalists to derive SM backgrounds using sidebands in data.

Systematic uncertainties not considered.

Exotic Higgs: H→2a→2b2μ



Mass drop tagger

The two hardest subjets satisfy:

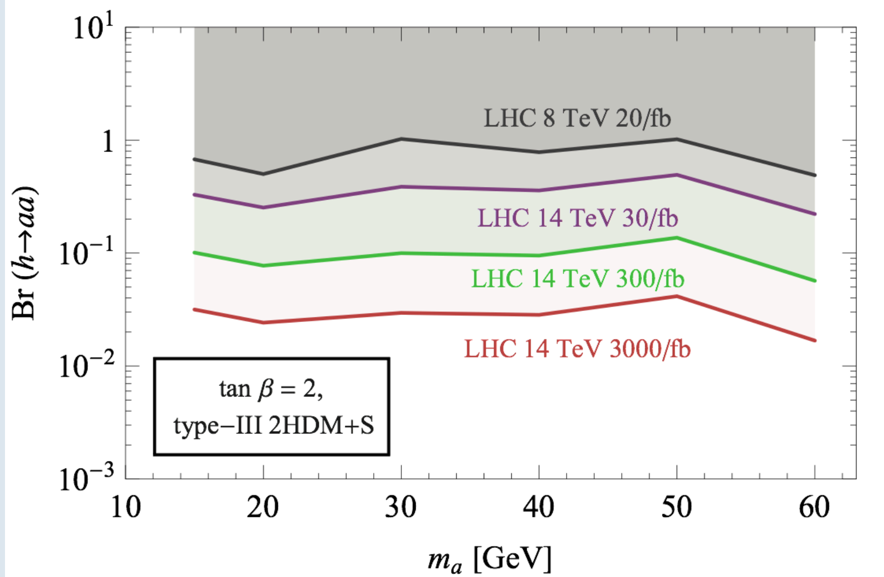
$$\mu \equiv \frac{\max(m_{j_1}, m_{j_2})}{m_j} < 0.67\,,$$

$$y \equiv \frac{\min(p_{T\,j_1}^2, p_{T\,j_2}^2)}{m_j^2}\Delta R_{j_1 j_2}^2 > 0.09\,,$$

and these subjets are used for the common selection.

The p_T threshold for b-tagging (25 GeV) reduces acceptance for requiring 2 b-tagged subjets.

The impact of jet→μ backgrounds would need to be investigated.



Exotic Higgs: ZH→ll(inv)

This analysis directly probes H→invisible, which could give insight into dark matter.

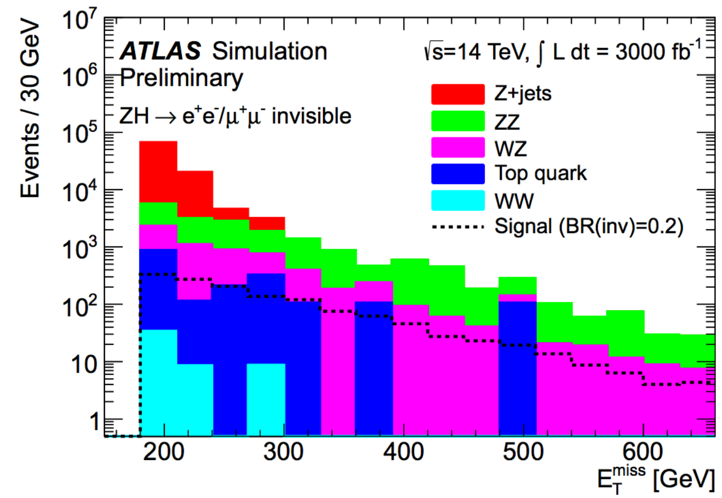
Previous limits set at 65% (~40%) for ATLAS (CMS).

Event selection is based on run-1, with some changes:

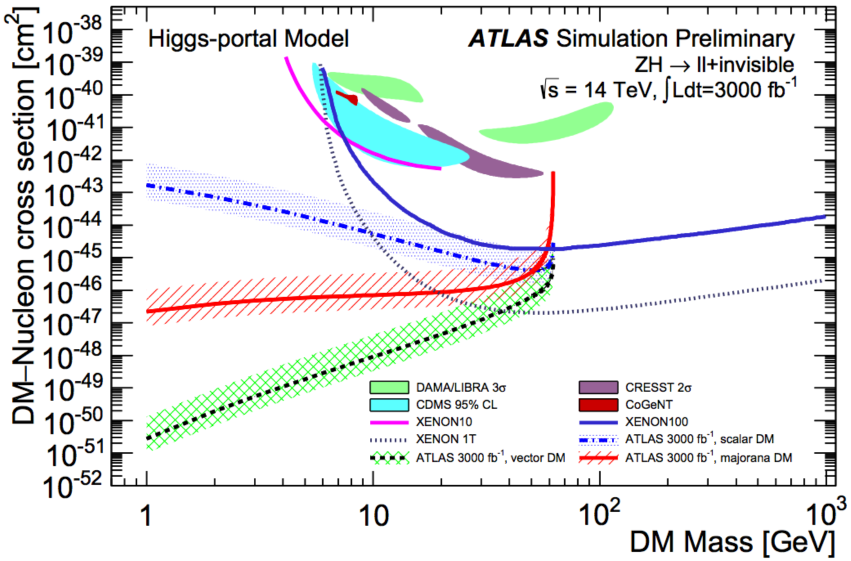
- ✓ Track-based E_T^{miss} is not considered.
- ✓ E_T^{miss} and angular cuts relaxed due to degradation of performance with pileup.
- ✓ $\Delta\varphi$ (E_T^{miss}, p_T^{miss}) cut not used.

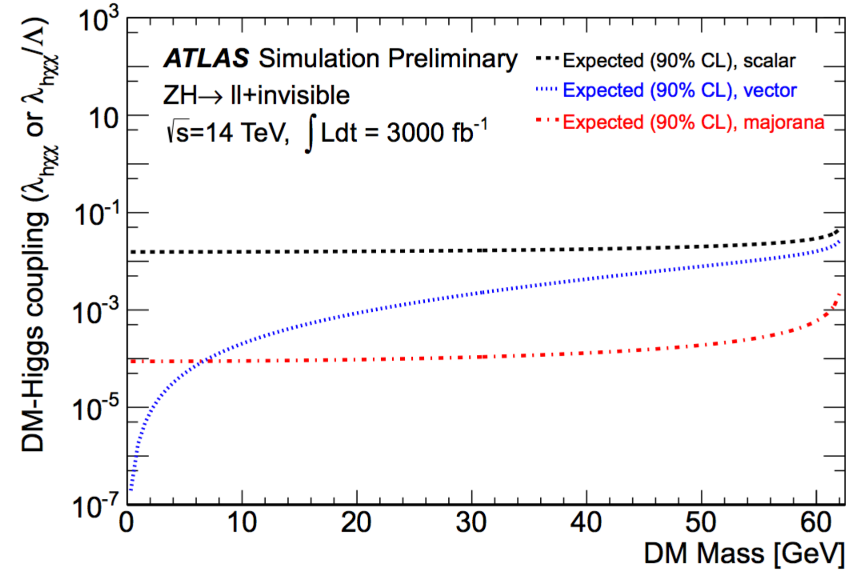
Cut variables	Thresholds
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 180 GeV
$\mathrm{d}\phi(\ell,\ell)$	< 1.2
$\mathrm{d}\phi(\vec{p}_{\mathrm{T}}^{\,\ell,\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})$	> 2.7
$\lvert E_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{\ell,\ell}\rvert / p_{\mathrm{T}}^{\ell,\ell}$	< 0.6
Jet veto	> 25 GeV

Expected yields	300 fb^{-1}	3000 fb^{-1}
ZZ	1321 ± 53	12000 ± 500
WZ	440 ± 2	4501 ± 22
WW	0.9 ± 0.9	52 ± 21
Top	127 ± 37	1810 ± 440
Z+jets	172 ± 87	82000 ± 6100
Signal (125 GeV, BR($H \to$ inv.)=20%)	154 ± 2	1379 ± 21



Exotic Higgs: ZH→ll(inv)





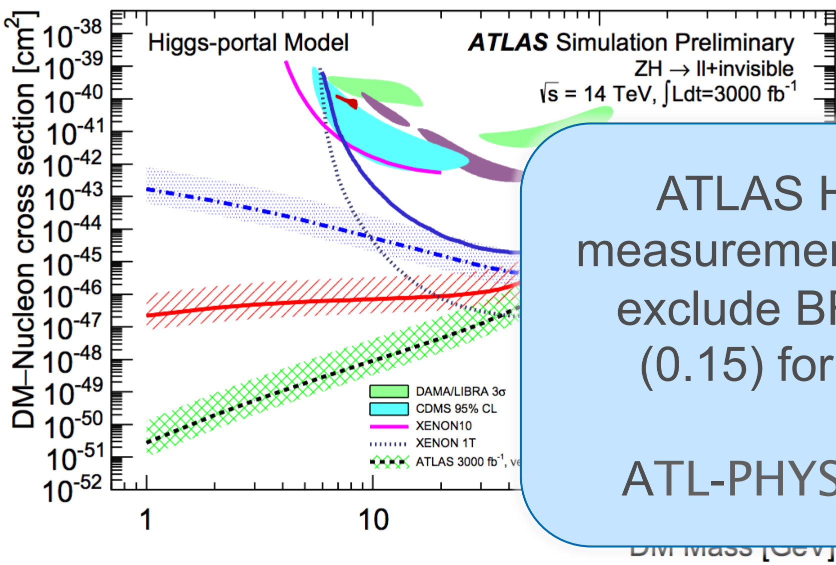
BR($H \to$inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)

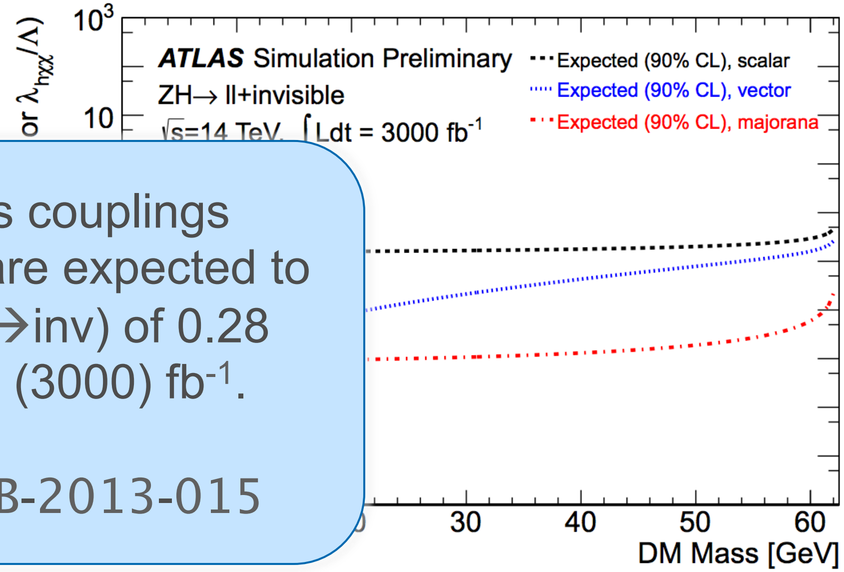
Shown are the 95% (90%) CL expected limits on the BR, assuming SM ZH production. These results contain estimates of systematic uncertainties, which are assumed to decrease with the large dataset in the 'realistic' case.

CMS expects to exclude 28 (17)% and 17 (6.4)% for conservative and realistic scenarios for 300 (3000) fb^{-1}.

CMS-NOTE-13-002 ATL-PHYS-PUB-2013-014

Exotic Higgs: ZH→ll(inv)





ATLAS Higgs couplings measurements are expected to exclude BR(H→inv) of 0.28 (0.15) for 300 (3000) fb^{-1}.

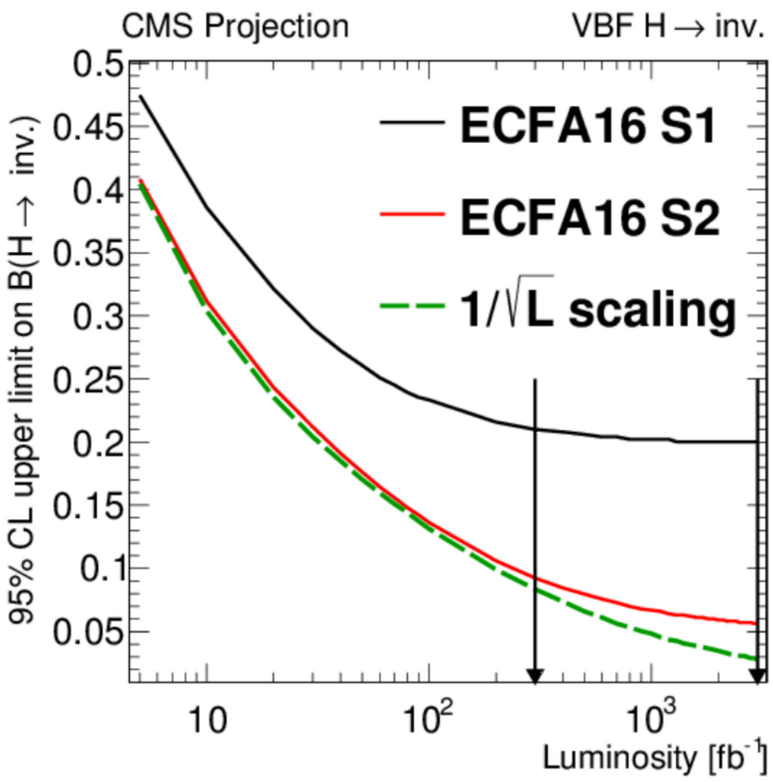
ATL-PHYS-PUB-2013-015

BR(H →inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)

Shown are the 95% (90%) CL expected limits on the BR, assuming SM ZH production. These results contain estimates of systematic uncertainties, which are assumed to decrease with the large dataset in the 'realistic' case.

CMS expects to exclude 28 (17)% and 17 (6.4)% for conservative and realistic scenarios for 300 (3000) fb^{-1}.

Exotic Higgs: VBF H→inv



Expected 95% upper limit on BR(H→inv) as a function of luminosity. The black solid line, labelled ECFA16 S1, corresponds to a scenario in which systematic uncertainties fixed to the 2015 Run II values. The red solid line, ECFA16 S2, corresponds to a scenario in which the experimental systematic uncertainties decrease with integrated luminosity until a lower bound based on the current understanding of the performance of the upgraded detector at 200 PU is reached, and theoretical uncertainties are scaled by 1/2 compared to the current values. Finally, the dashed green line shows a simple scaling with luminosity of the experimental uncertainties, without a lower bound, and a 1/2 factor for the theoretical uncertainties.

HIG-16-016

	ECFA16 S1	ECFA16 S2	$1/\sqrt{L}$ scaling
300 fb^{-1}	0.210	0.092	0.084
3000 fb^{-1}	0.200	0.056	0.028

Run 2 Result: CMS-PAS-HIG-16-016

Exotic Higgs: H→LFV

JHEP07(2016)059
S. Banerjee, B. Bhattacherjee, M. Mitra, M. Spannowsky

Lepton-flavor violating Higgs decays are highly suppressed and unobservable in the SM, so would be an indication of BSM.

In run-1, ATLAS & CMS had **a mild excess in H→μτ**.
- ✓ Excess is not yet excluded by run-2 (CMS)

Latest limits for ATLAS (CMS) are…
- ✓ B(H→μτ) < 1.43 (1.20)%
- ✓ B(H→eτ) < 1.04 (0.69)%
- ✓ B(H→eμ) < (0.048)%

Prospects study considers all 3 channels for 3000 fb^{-1}.

Study considers all τ decays modes, and uses a CMS-like cut-based selection.

In H→eτ, a BDT is shown to improve sensitivity, using:

$$|\vec{p}_T^{\,e}|,\ |\vec{p}_T^{\,\tau_{\rm had}}|,\ \Delta\phi_{\vec{e}-\vec{\not{E}}_T},\ \Delta\phi_{\vec{\tau}_{\rm had}-\vec{\not{E}}_T},\ \Delta\phi_{\vec{e}-\vec{\tau}_{\rm had}},$$
$$M_T(e),\ M_T(\tau_{\rm had}),\ M^{\rm vis.}_{e\tau_{\rm had}},\ M^{e\tau_{\rm had}}_{collinear},\ \not{E}_T,\ \phi_{\vec{\not{E}}_T}.$$

Strongest expected BR sensitivity in each category of decay modes:

	2σ	**5σ**
B(H→μτ_e)	0.76%	1.90%
B(H→eτ_μ)	0.61%	1.53%
B(H→eμ)	0.0193%	0.0482%

Able to probe run-1 best-fit B(H→μτ): (0.53±0.51)% ATLAS; (0.84±0.39)% CMS

Summary

The HL-LHC will provide the opportunity to search for many rare and exotic decays of the 125 GeV Higgs boson.

Sensitivity will be greatly improved at 3000 fb^{-1}, but expertise in data-driven techniques and MVA will be needed to reach maximum discovery potential.

Let's hope the next few years provide us exciting directions to search in the HL-LHC!

High
Luminosity
LHC