Searches for Rare Higgs Decays and an Additional Higgs Singlet

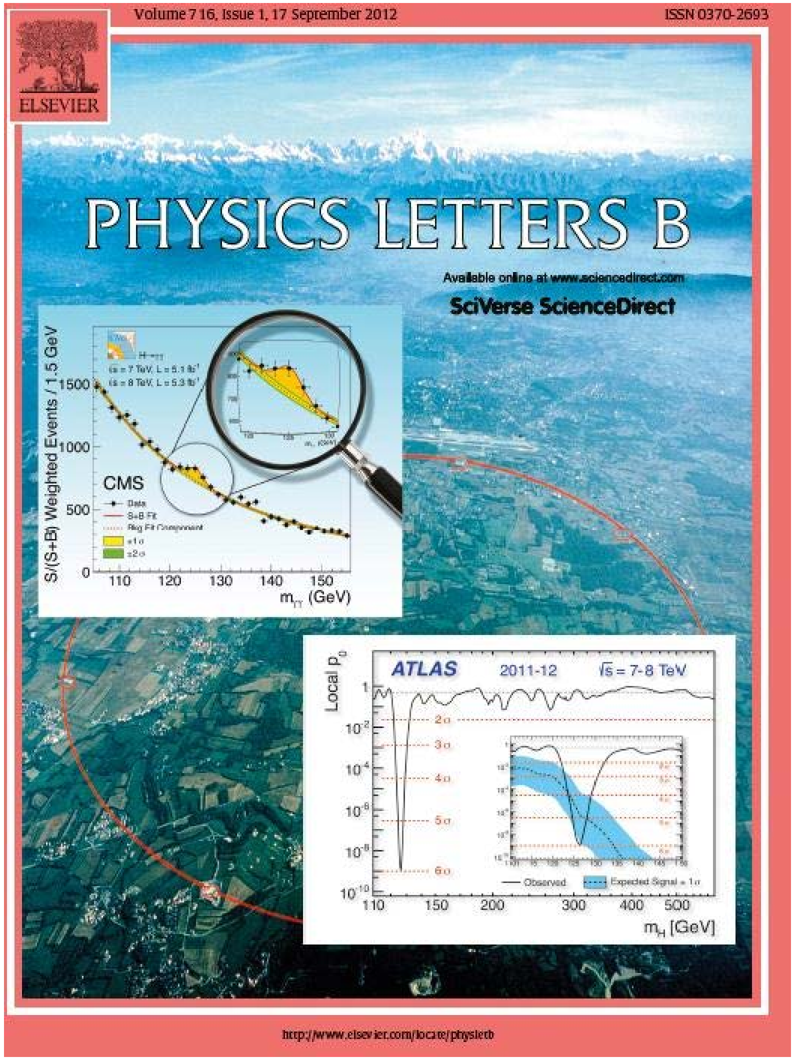
Learning from the current measurements
Searches for rare Higgs decays
Searches for an additional Higgs singlet

Jianming Qian
University of Michigan

Unlocking the Higgs Portal, UMass Amherst, May 1-3, 2014

What Now?

Discovery has been made…



Nobel prize has been awarded

But many questions remain

Is the new boson solely responsible for the electroweak symmetry breaking?

What's the nature of dark matter? Can the new boson help to understand it?

Two-pronged approaches

A precision program

measurements of Higgs properties

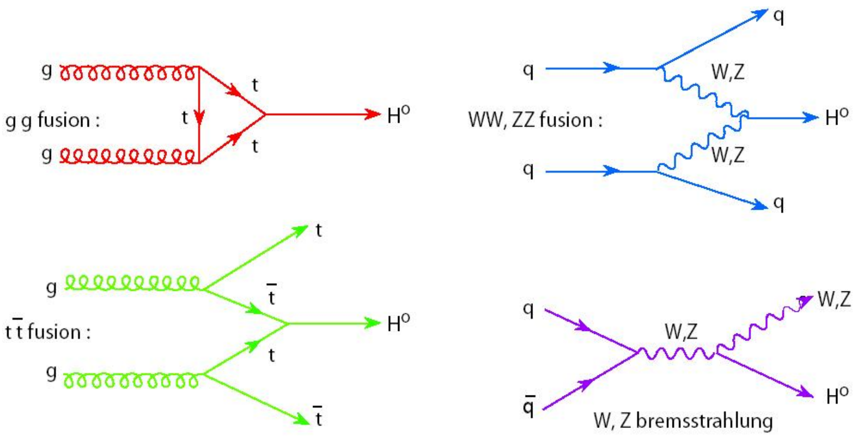
A search program

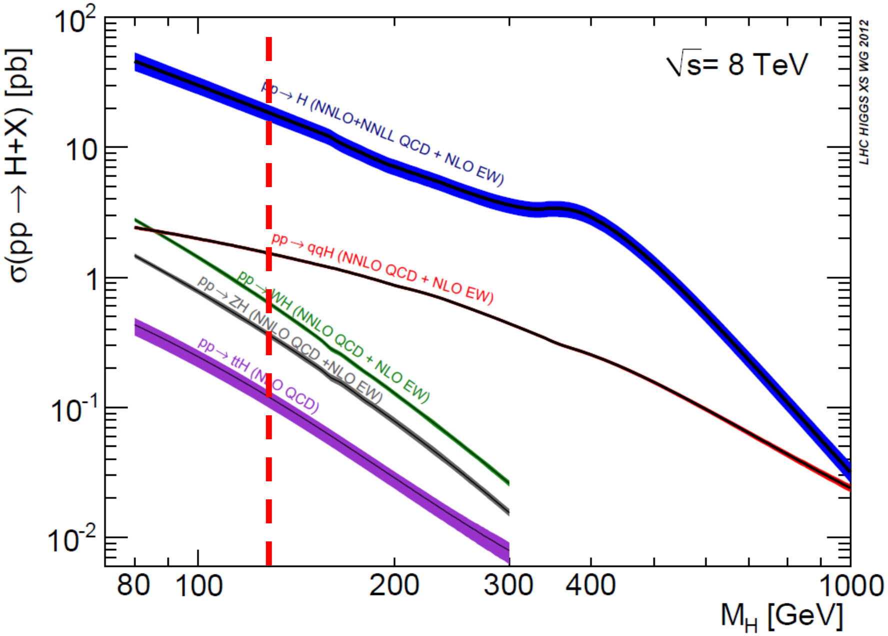
Use the newly discovered particle as a tool to explore potential new physics

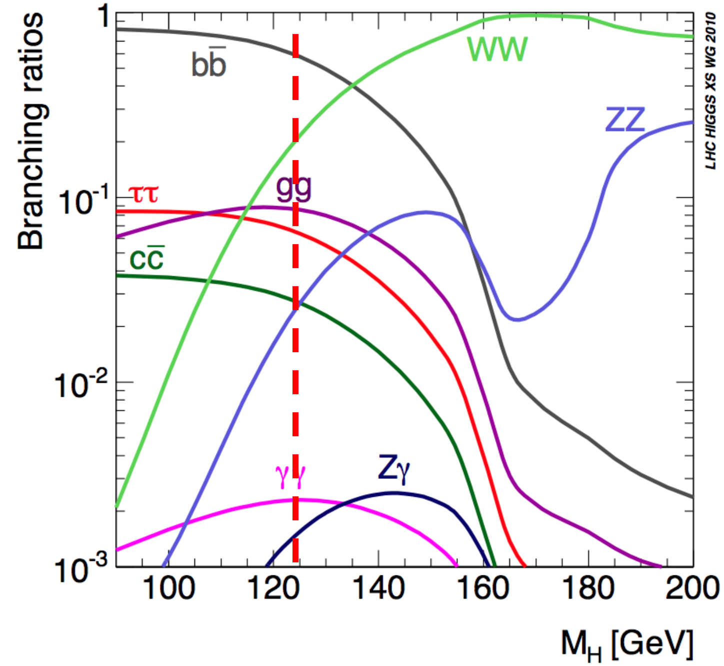
Productions and Decays

$m_H = 125$ GeV $\quad \sigma_H = 22.3$ pb

	Branching ratio
$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.32%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	0.23%

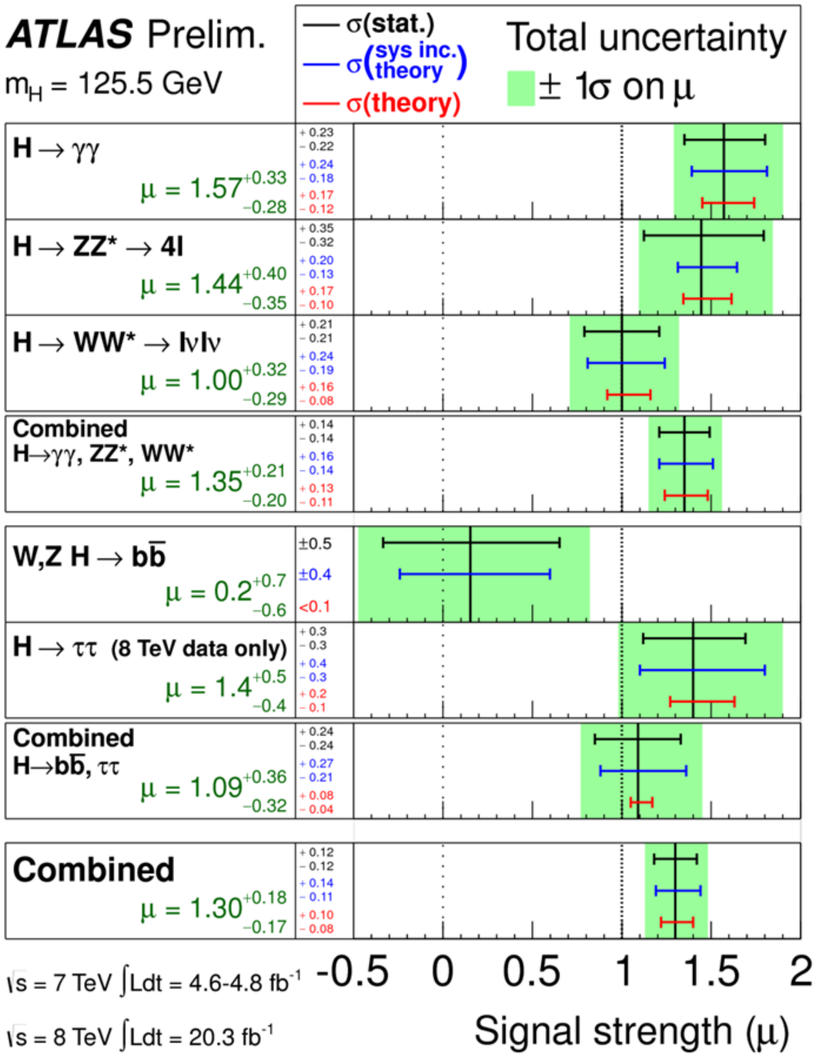






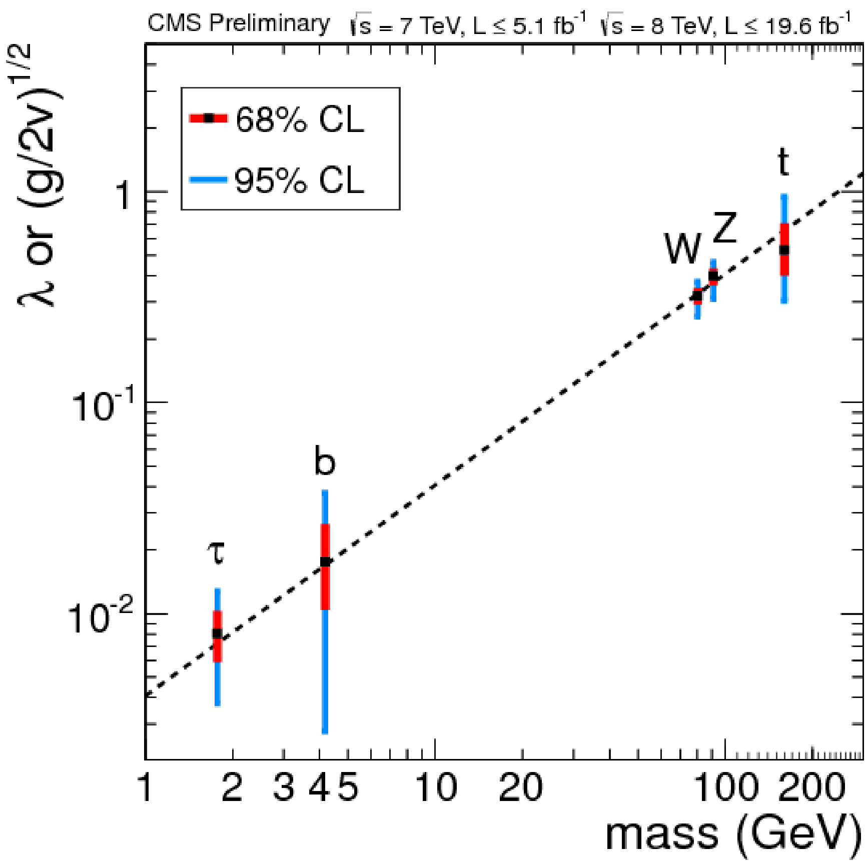
Over 1,000,000 Higgs bosons “produced” at LHC in Run 1!

H(125): Rates and Couplings



SM: $\lambda \propto m$ (fermions)

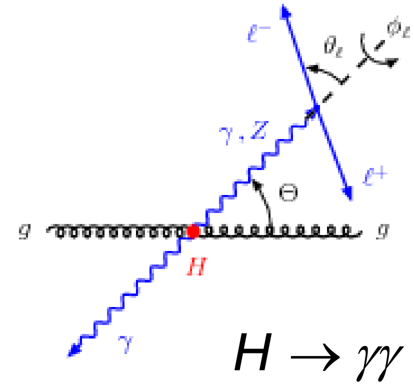
$g \propto m^2$ (bosons)

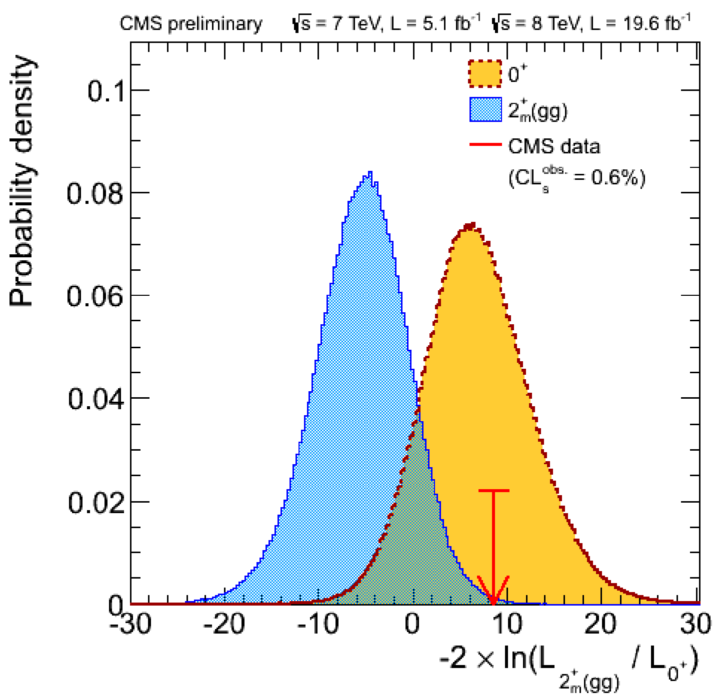


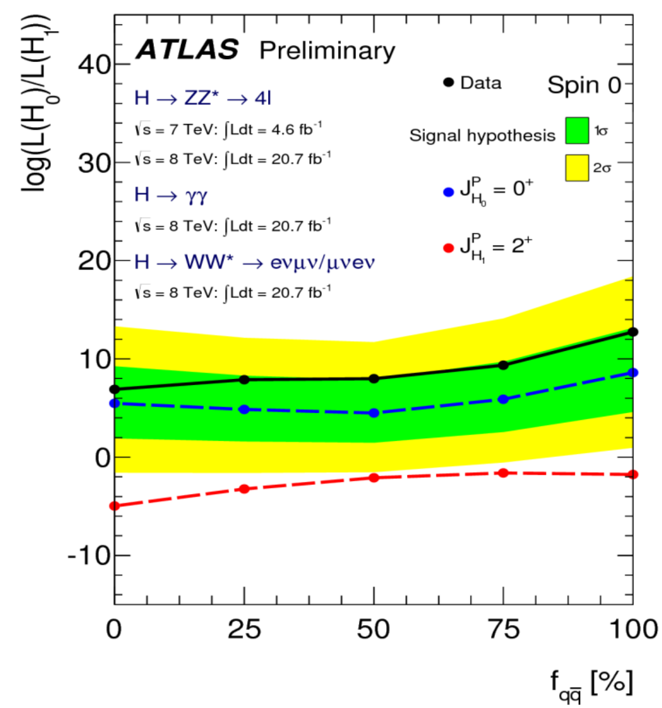
Rates and couplings are very Standard Model like

H(125): Spin and CP

Higgs decay kinematics depends on its properties of spin and parity. $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ final states have been analyzed to determine these properties.



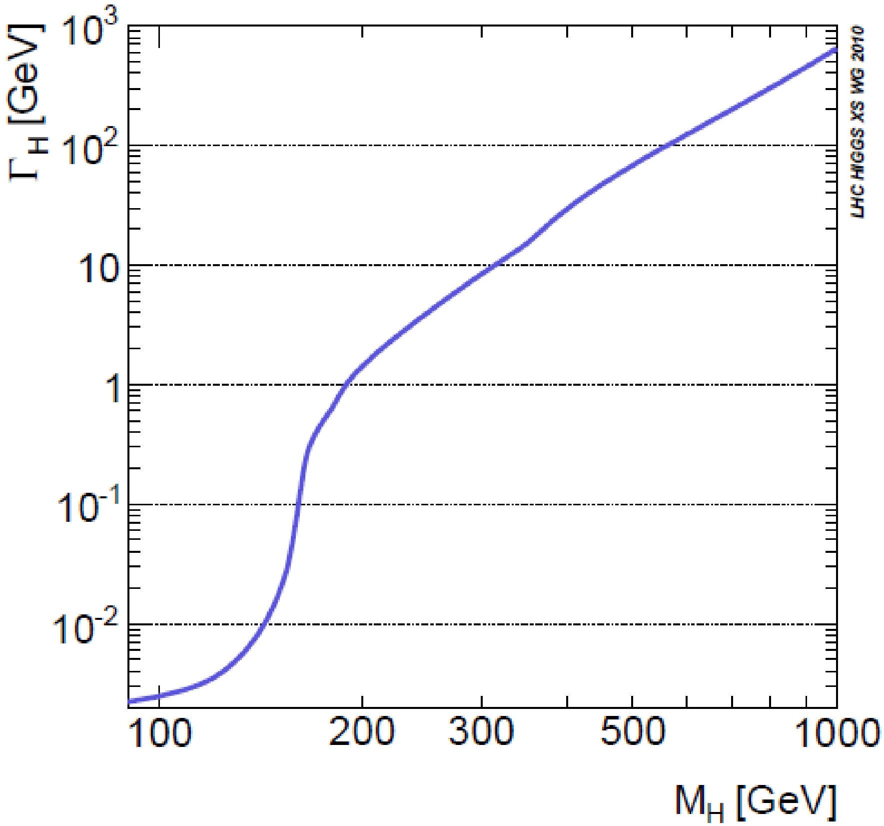




SM prediction of $J^p=0^+$ is strongly favored,
most alternatives studied are excluded @ 95% CL or higher

Higgs Boson Width

SM @ 125 GeV: $\Gamma_h \approx 4.07$ MeV $\ll$ smaller than the experimental resolutions of direct measurements



For measurements:

hard to measure experimentally though indirect measurements can significantly improve the precision

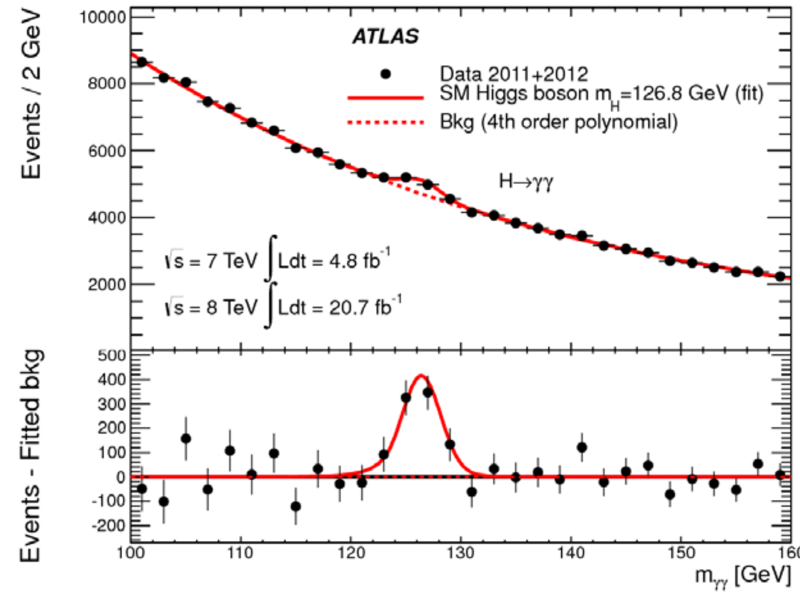
For searches:

Even a small contribution to the width from potential new physics can lead to a sizable decay BR

Direct Width Measurement

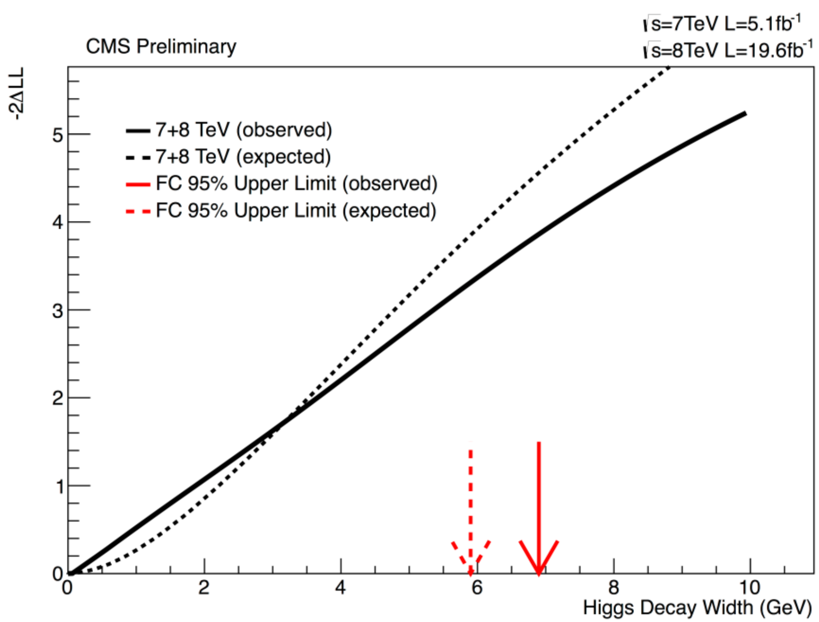
The Higgs width can be in principle extracted from the $m_{\gamma\gamma}$ or $m_{4\ell}$ distributions with the signal lineshape

$$\text{Breit-Wigner}(m, \Gamma_H) \otimes \text{Gaussian}(\sigma)$$



Limited by detector mass resolution and large background

CMS-PAS-HIG-13-016



Observed (expected) limit

$$\Gamma_H < 6.9(5.9) \text{ GeV @ 95\% CL}$$

$$\sim 1500 \times \Gamma_H^{SM}$$

Indirect Width Measurement

Process $i \to H \to f$: $\frac{d\sigma}{dm^2} \sim \frac{g_i^2 g_f^2}{\left(m^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$

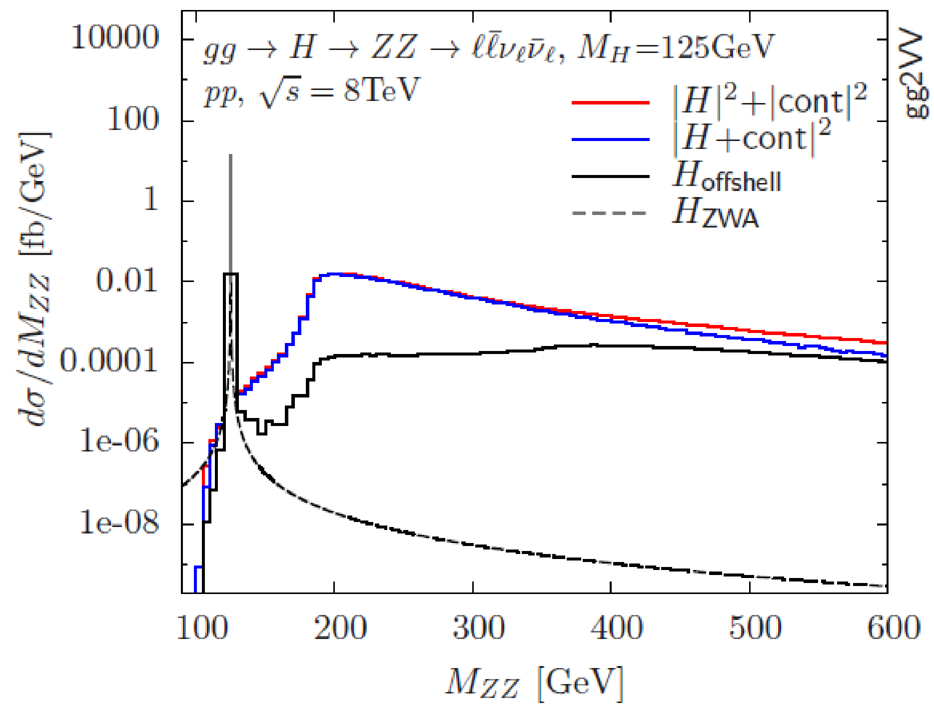
[Kauer & Passarino, arXiv:1206.4803](https://arxiv.org/abs/1206.4803)
[Campbell & Ellis, arXiv:1311.3589](https://arxiv.org/abs/1311.3589)

On-peak: $\frac{d\sigma}{dm^2} \sim \frac{\boxed{g_i^2 g_f^2}}{m_H^2 \boxed{\Gamma_H^2}}$

Off-peak: $\frac{d\sigma}{dm^2} \sim \frac{\boxed{g_i^2 g_f^2}}{\left(m^2 - m_H^2\right)^2}$

on-shell measures $\left(g_i g_f / \Gamma_H\right)^2$,

off-shell measures $\left(g_i g_f\right)^2$

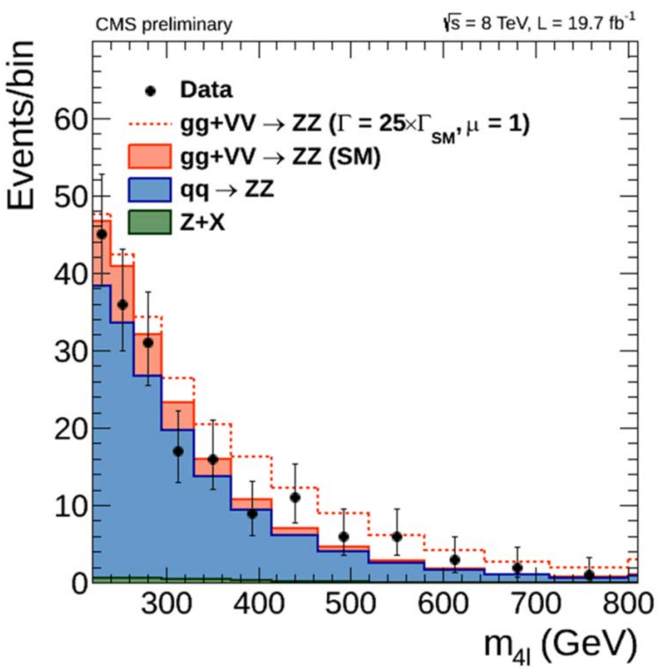


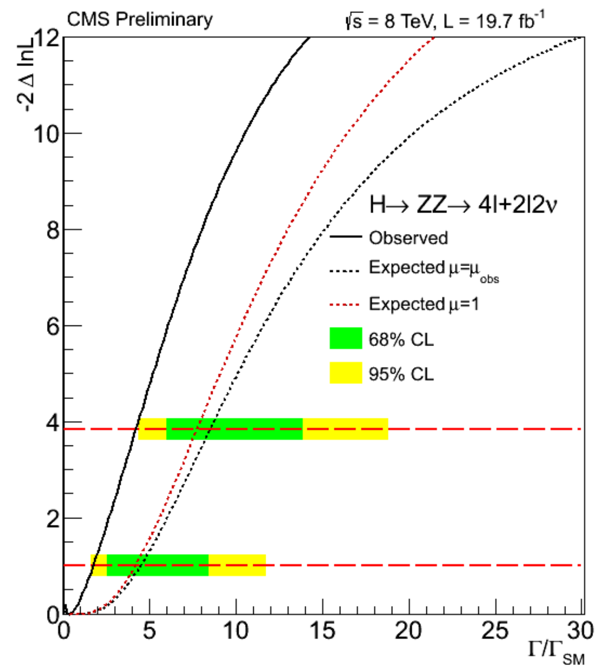
Extract Γ_H by comparing the two measurements (thanks to the large off-shell contributions)

	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

Indirect Width Measurement

The key is to isolate off-shell Higgs signal from the continuum background, such as $q\bar{q}/gg \to WW, ZZ$ for the case of $H \to WW, ZZ$





CMS has studied $H \to ZZ^* \to 4\ell, \ell\ell\nu\nu$ with the combined observed (expected) limit: $\Gamma_H < 17.4(35.3)$ MeV or $4.3(8.7) \times \Gamma_H^{SM}$ @ 95% CL

Or as a measurement $\Gamma_H = 1.4^{+6.1}_{-1.4}$ MeV

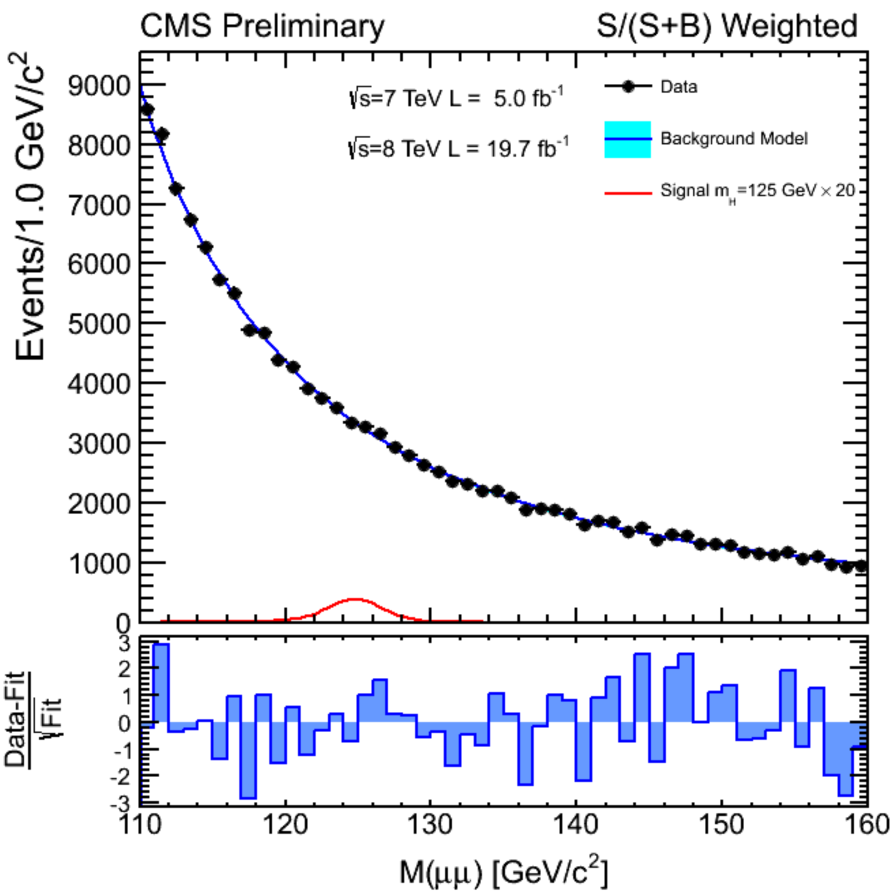
However, there is the issue whether theory uncertainty is under control.

Rate Decay: $H \to \mu\mu$

$$BR(H \to \mu\mu) \simeq \left(\frac{m_\mu}{m_\tau}\right)^2 \times BR(H \to \tau\tau) \approx 0.022\%$$

CMS-PAS-HIG-13-007
ATLAS-CONF-2013-010

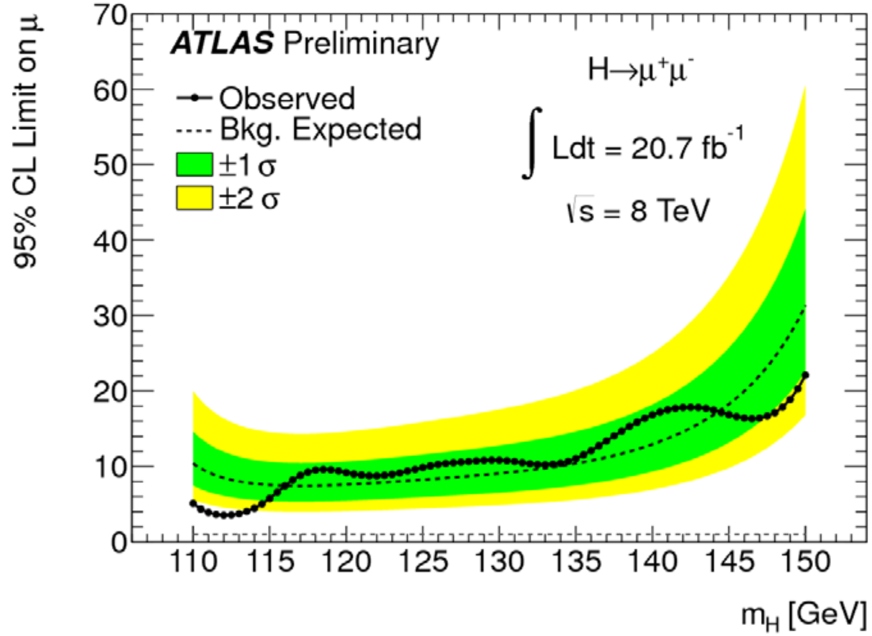
Clean signature, but suffer from large Drell-Yan background



Observed (expected) upper limits

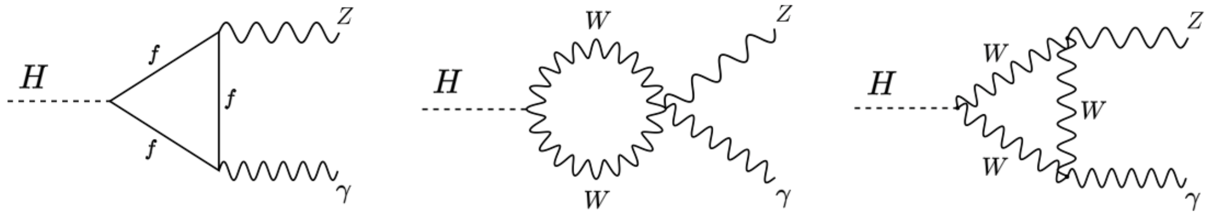
ATLAS: 9.8 (8.2) and CMS: 7.4 (5.1)

on $(\sigma \times BR)/(\sigma \times BR)_{SM}$ at 95% CL



Rare Decay: $H \to Z\gamma$

$BR(H \to Z\gamma) \approx 0.15\%$ @ 125 GeV



At $m_H = 125$ GeV:

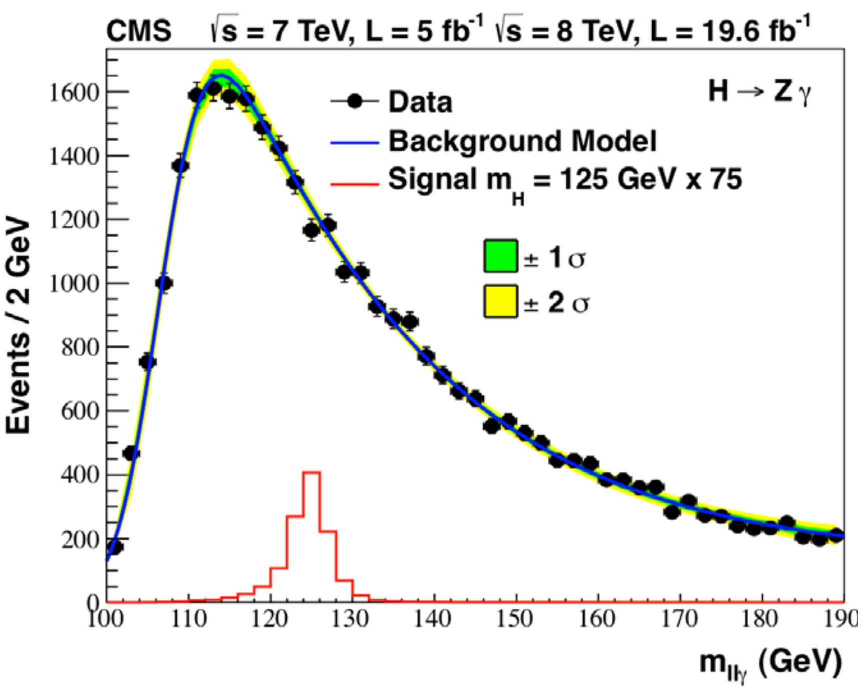
$\sigma_H \times Br(H \to Z\gamma \to \ell\ell\gamma) \sim 2.3$ fb

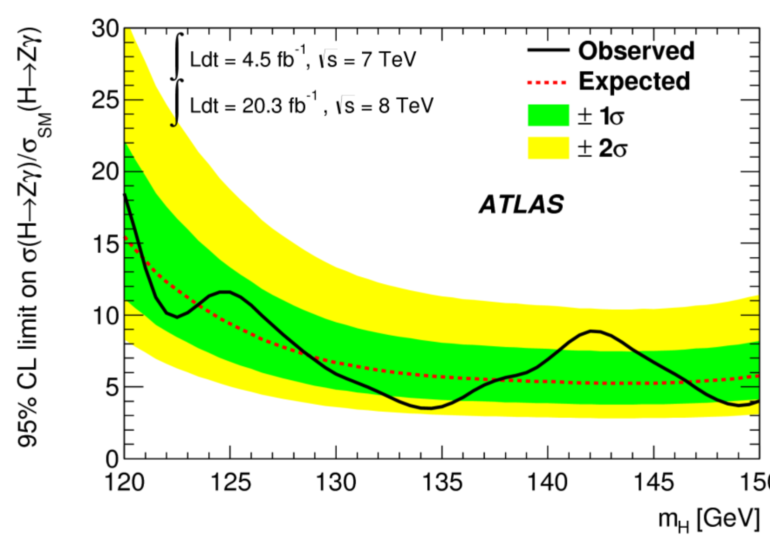
~ 55 events in 2011+2012 dataset

Search for a narrow resonance over continuum (mostly $Z\gamma$) backgrounds

Current sensitivity is about $10\times$ the standard model expectation

arXiv: 1307.5515 (CMS)





arXiv: 1402.3051 (ATLAS)

Other Rare Decays

$H \to J/\psi\,\gamma$ decay has been proposed as a way to access *Hcc* coupling, but the rate is very low: $N(H \to J/\psi\gamma \to \mu\mu\gamma) \approx N(H \to Z\gamma \to \mu\mu\gamma)/340$

$$\mathrm{BR_{SM}}(H \to J/\psi\,\gamma) = (2.46^{+0.26}_{-0.25}) \times 10^{-6},$$
$$\mathrm{BR_{SM}}(H \to \Upsilon(1S)\,\gamma) = (1.41^{+2.03}_{-1.14}) \times 10^{-8}.$$

Bodwin, Petriello, Stoynev and Velasco, arXiv:1306.5770

Relative easy to search, but rate is too late even for high luminosity LHC or even for any proposed lepton collider

There are other potential rare decays, but backgrounds are likely too large to be feasible

VP mode	$\mathcal{B}^{\rm SM}$	VP^* mode	$\mathcal{B}^{\rm SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	2.2×10^{-6}

Isidori, Manohar and Trott, arXiv:1305.0663

Higgs Portal Models

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Unlocking the Higgs Portal

Date: Thursday, May 1, 2014 - 9:00am to Saturday, May 3, 2014 - 5:00pm

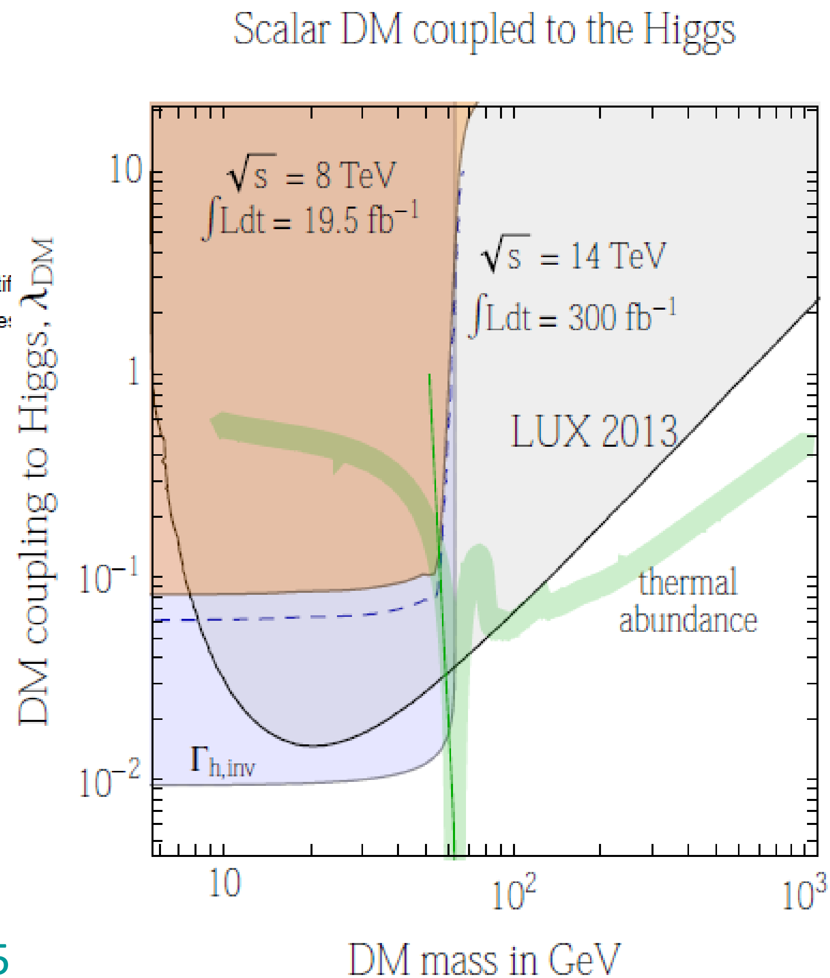
Location: Lederle Graduate Research Tower (LGRT) 419B, UMass Amherst

Higgs portal interactions can address two open problems in cosmology: dark matter and the baryon asymmetry. In anticipation of the 14 TeV phase of the LHC and the development of a future electron-positron collider, it is timely to delineate the most important scenarios, to identif their LHC and lepton collider signatures, and to determine the extent to which collider searche may probe Higgs portal scenarios in the cosmologically relevant regions of parameter space.

The addition of a singlet scalar leads to a rich phenomenology:

- a dark matter candidate and resulting $h \to$ invisible decays
- additional Higgs production processes such as $h \to aa$ or $X \to hh$

No & Ramsey-Musolf, arXiv:1310.6035



de Simone, Giudice & Strumia, arXiv:1402.6287

SM + Singlet

The simplest extension of the standard model Higgs sector is the addition of a singlet S:

$$V(\phi,S)=\mu^2\phi^\dagger\phi+m_S^2S^2-\lambda\left(\phi^\dagger\phi\right)^2-\rho S^4+\kappa\left(\phi^\dagger\phi\right)S^2$$

depending on the couplings, the two states can mix …

Scenario 1: *h(125)* is the heavier one

s is the lighter one. If $m_s < m_h/2$, then $h\to ss$ decay opens up.
If there is no mixing, s is stable $\Rightarrow$ $h\to ss\to$ invisible (see the presentation by Ketevi).
Otherwise $s\to f\bar{f}$ $\Rightarrow$ similar final states as $h\to aa\to f\bar{f}\,f'\bar{f}'$.

Scenario 2: *h(125)* is the lighter one

H is the heavier one. Assuming mixing, h and H have similar decay mode $\Rightarrow$ "SM-like" high mass searches such as $H\to WW, ZZ$.
If $m_h < m_H/2$, the decay $H\to hh$ opens up $\Rightarrow$ Higgs pair production.

Coupling Modifications

The mixing between the singlet scalar and the "SM" Higgs boson

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix} \begin{pmatrix} H_{SM} \\ S \end{pmatrix}$$

leads to the universal modification of the couplings of the $h(125)$ Higgs boson

to SM particles $$\frac{g}{g_{SM}} \sim 1 - \frac{\sin^2\theta}{2}$$

Therefore the coupling measurements can help to constrain the model which are described by 3 additional parameters:

$\cos\theta$ (mixing angle), $m_{s/H}$ (mass of the other Higgs), $\mathrm{BR}(H \to hh)$ or $\mathrm{BR}(h \to ss)$

The productions and decays of the $h(125)$ Higgs boson are therefore modified. For the case of $h(125)$ being the lighter one

$$\sigma_h = \kappa^2 \times \sigma_h^{SM}, \qquad \Gamma_h = \kappa^2 \times \Gamma_h^{SM}, \qquad \mathrm{BR}_h = BR_h^{SM}, \qquad \mu_h = \frac{(\sigma \times BR)_h}{(\sigma \times BR)_h^{SM}} = \kappa^2$$

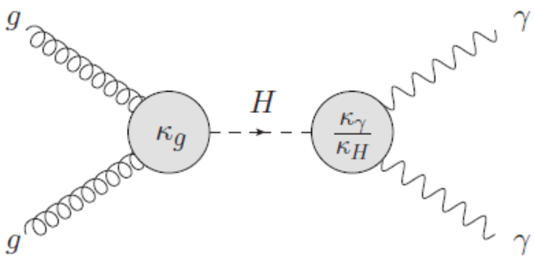
here $\kappa^2 = \cos^2\theta$.

Coupling Parametrization

Parametrizing deviations from SM using scale parameters: κ $(\text{SM: } \kappa = 1)$

$$g_{hff} = \frac{\sqrt{2}m_f}{\upsilon}, \qquad g_{hVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow$$

$$g_{hff} = \boxed{\kappa_f} \cdot \frac{\sqrt{2}m_f}{\upsilon}, \quad g_{hVV} = \boxed{\kappa_V} \cdot \frac{2m_V^2}{\upsilon}$$



For example: $(\sigma \cdot BR)(gg \to h \to \gamma\gamma) = \left[\sigma(gg \to h) \cdot BR(h \to \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_h^2}}$

assuming there is no new production processes.

κ_h^2 is the scale factor to the total Higgs decay width

$$\kappa_h^2 = \sum_x \kappa_x^2 \cdot BR(h \to xx) \xrightarrow{\text{No BSM decays}} \kappa_h^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(h \to xx)$$

$$\xrightarrow{\text{With BSM decays}} \kappa_h^2 = \sum_x \kappa_x^2 \cdot \frac{BR_{SM}(h \to xx)}{1 - BR_{BSM}}$$

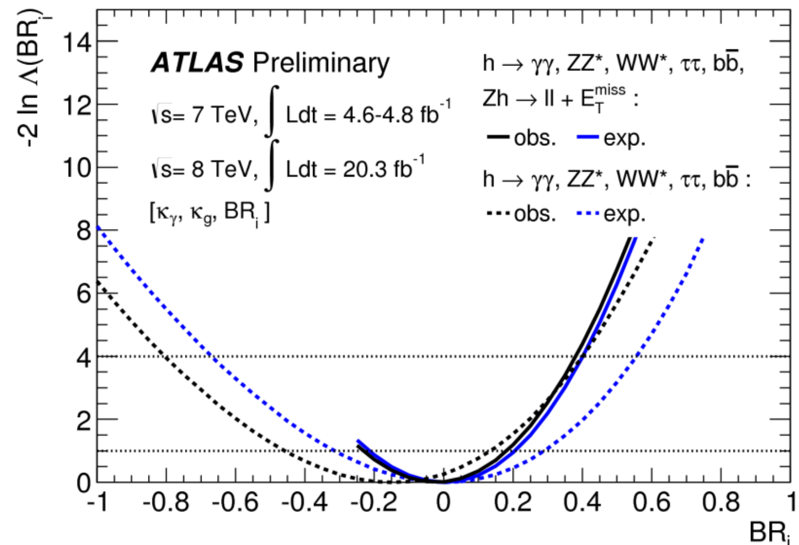
Constraints from Couplings

Higgs could have decays that are not accounted for in SM. The decays do not have to be invisible. They could be decays not detectable at LHC.
$\Rightarrow$ modified total Higgs decay width and therefore BRs of other decays, effectively leave the total decay width free.

$$\Gamma_h = \Gamma_h^{SM} \times \frac{\kappa_h^2}{1 - BR_{new}}, \quad BR(h \to xx) = BR_{SM}(h \to xx) \times (1 - BR_{new}) \cdot \frac{\kappa_x^2}{\kappa_h^2}$$

A model allows for potential new physics in vertex loops and additional decays

$$\kappa_\gamma, \ \kappa_g, \ BR_{new}$$



ATLAS-CONF-2014-010

$BR_{new} < 0.41$ (0.55) @ 95% CL
($BR_{inv} < 0.37$ (0.39) combining with $Z + \not{E}_T$ search)

Significant room for potential exotic decays

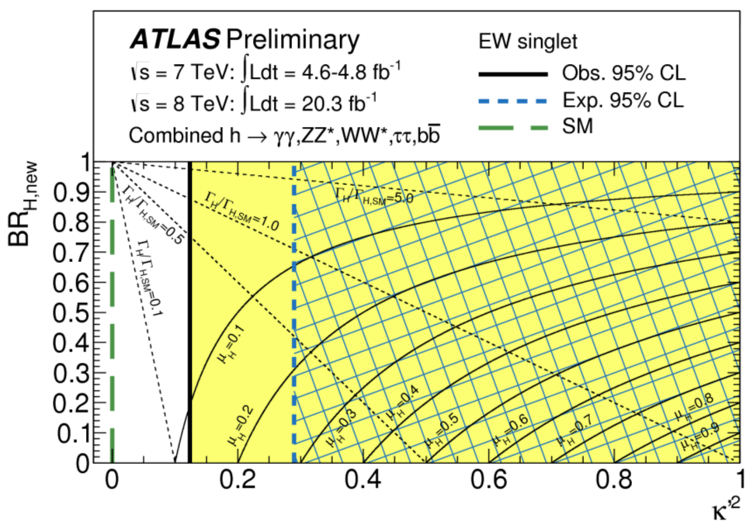
Constraints on the Heavy Higgs

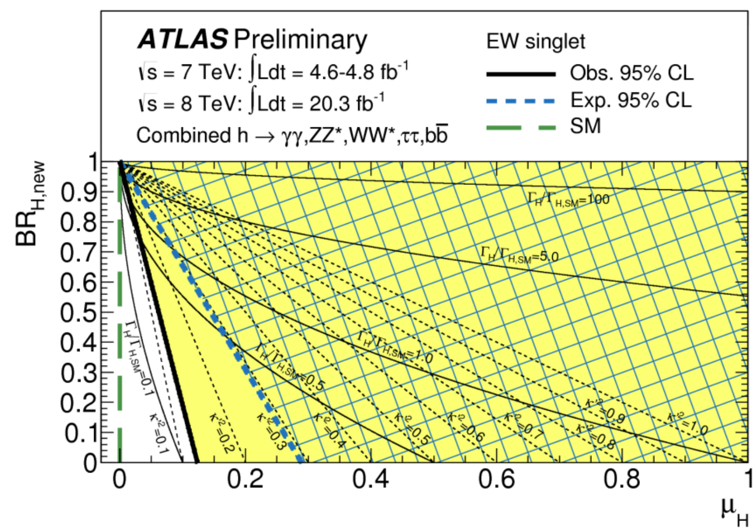
$$\sigma_H = \kappa'^2 \times \sigma_H^{SM}, \qquad \Gamma_H = \frac{\kappa'^2}{1-BR_{new}} \times \Gamma_H^{SM}, \qquad \mathrm{BR}_H = \left(1-BR_{new}\right) \times BR_H^{SM}$$

here $\kappa'^2 = \sin^2\theta = 1-\kappa^2$. The signal strength parameter for the heavy Higgs is

$$\mu_H = \frac{(\sigma \times BR)_H}{(\sigma \times BR)_H^{SM}} = \kappa'^2\left(1-BR_{new}\right) = \left(1-\mu_h\right)\left(1-BR_{new}\right)$$

From ATLAS measured value $\mu_h = 1.30^{+0.17}_{-0.18} \Rightarrow \kappa'^2 = -0.30^{+0.17}_{-0.18}$ which leads to an upper bound of $\kappa'^2 < 0.12$ @ 95% CL (restrict to physical region)

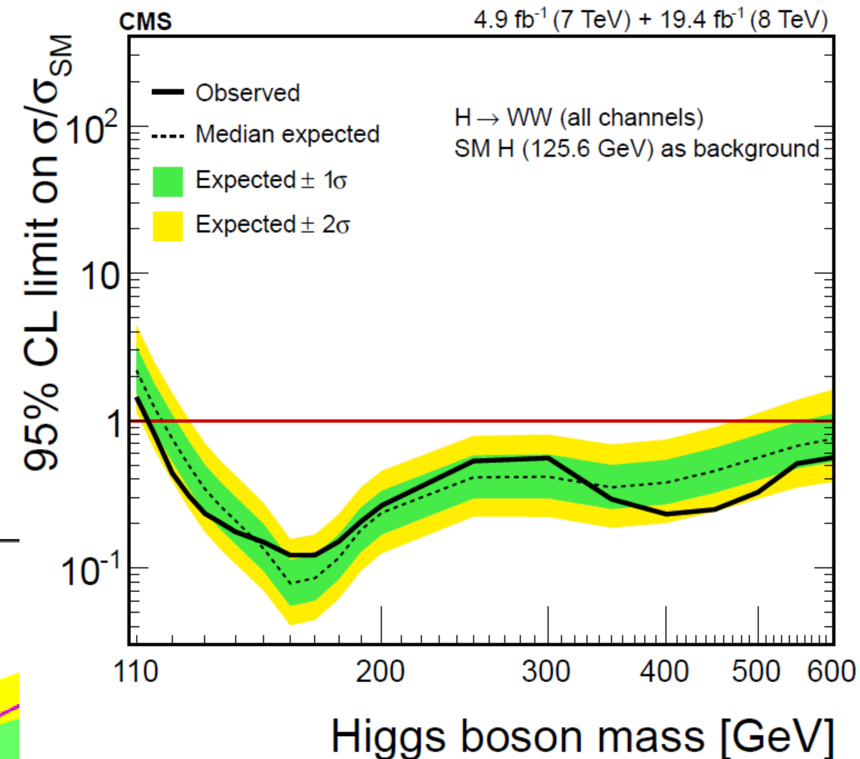




independent of the mass of the heavy Higgs boson m_H.

Searches for $H \to WW$ and ZZ

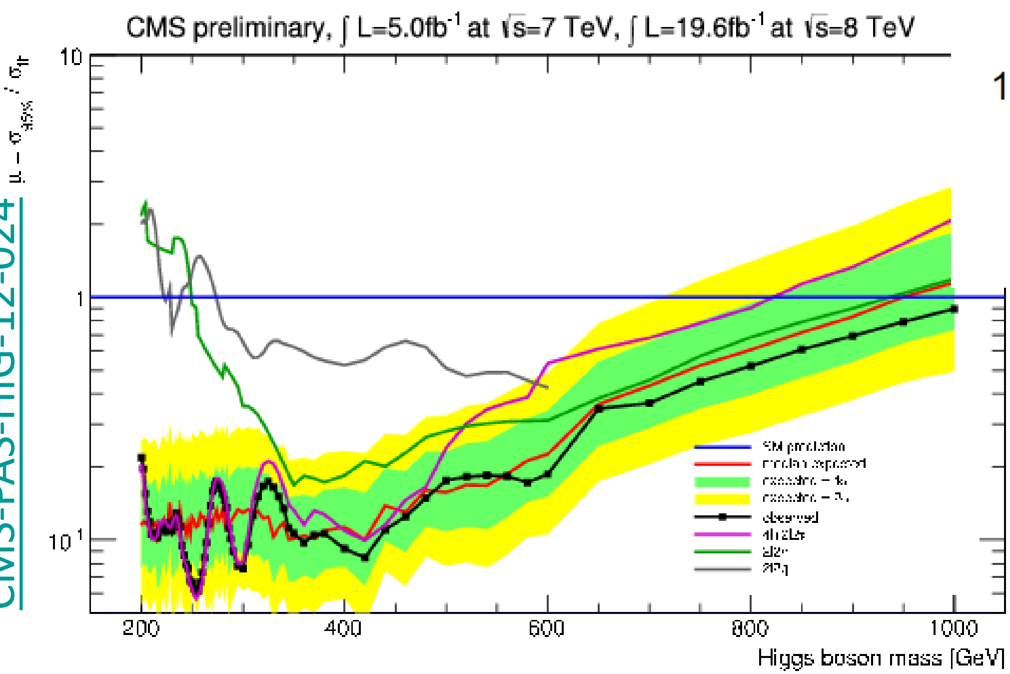
arXiv: 1312.1129 (CMS)



The heavy Higgs can also be searched directly from its decay to WW and ZZ

$$H \to WW \to \ell\nu\ell\nu,\ \ell\nu qq$$
$$H \to ZZ \to 4\ell,\ \ell\ell\nu\nu,\ \ell\ell qq$$

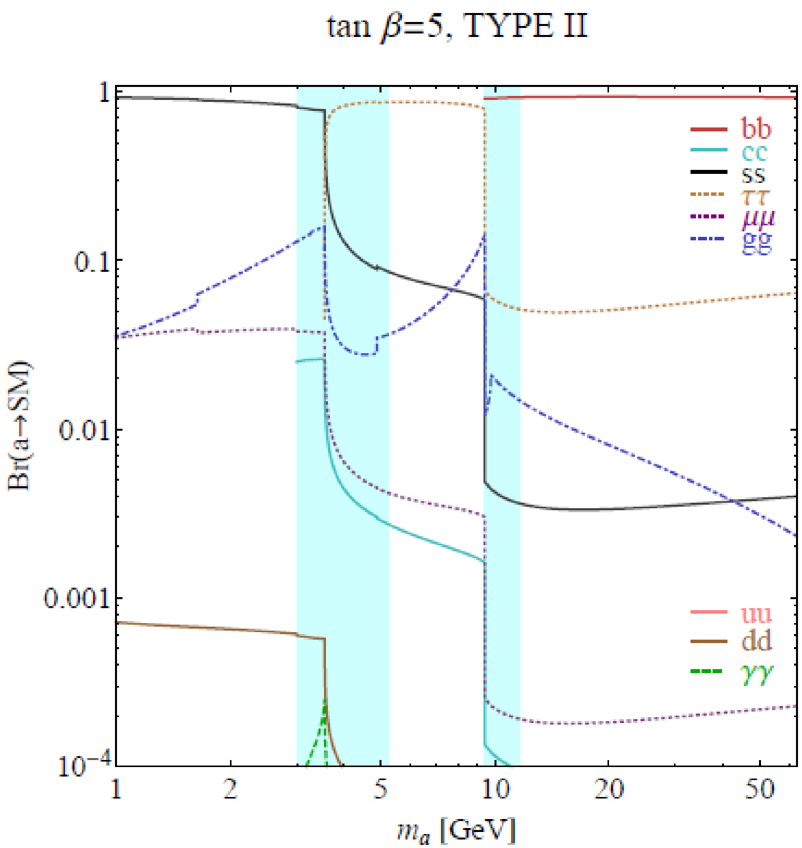
CMS-PAS-HIG-12-024



Such a Higgs boson with SM couplings is excluded with its mass up to $\sim$1 TeV. But the couplings in the singlet model are significantly reduced!

2HDM + Singlet

The 2 Higgs doublet model (2HDM) can also be extended by including a singlet. For a large parameter space, $h \to aa$ decay can lead to interesting signatures.



Curtin et al., arXiv:1312.4992

Final states depending on how *a* decays. Dominant/interesting decay modes are:

Low mass: $a \to ee, \mu\mu$

"lepton-jets" analysis

$h \to aa \to 4\mu$

Medium mass (3.5-10 GeV): $a \to \tau\tau$

$h \to aa \to 4\tau$ hard!

$h \to aa \to 2\mu 2\tau$ doable

$h \to aa \to 4\mu$

High mass (>10 GeV): $a \to bb$

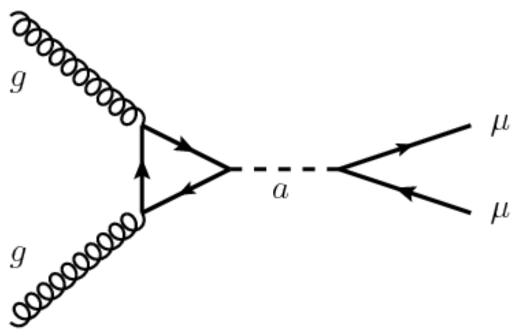
$h \to aa \to 4b$ hard !

$h \to aa \to bb\tau\tau / bb\mu\mu$ hopeful ?

See yesterday's presentation by Alexei Safonov

Search for $a \to \mu\mu$

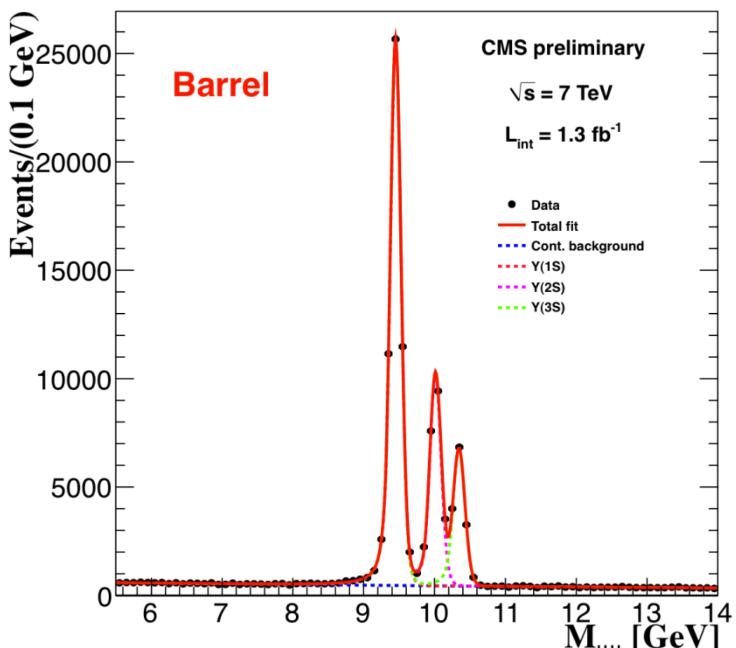
CMS arXiv:1206.6326
(7 TeV results)

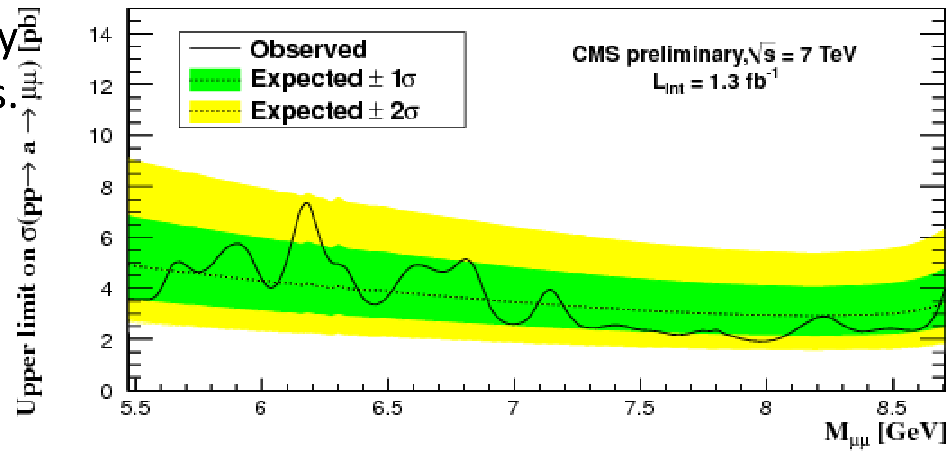


Trigger: two muons with $p_T > 3.5$ GeV
Offline: two muons with $p_T > 5.5$ GeV

MSSM pseudoscalar A is used to model the signal using PYTHIA

Searching for narrow $\mu\mu$ resonance away from the known quarkonium resonances.





Warning:

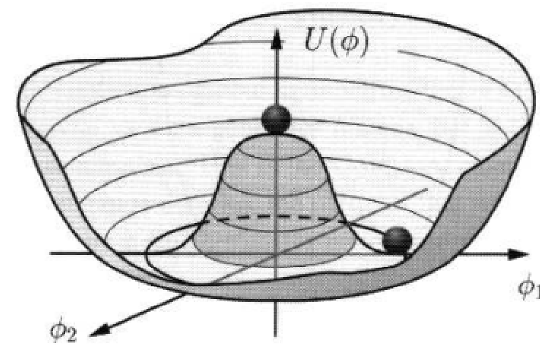
For small values of $m_a \left(<\sim 2p_T\right)$, only highly boosted signal events are selected. Can we really trust PYTHIA to model the p_T of the Higgs boson?

Higgs Pair Production

Higgs pair productions, both non-resonant and resonant, will be one of the major research areas in the upcoming LHC runs. It is an important final state for both SM physics and BSM phenomena.

Non-resonant production

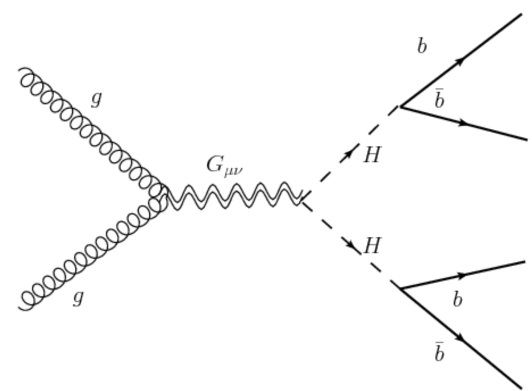
offers a direct way to measure the Higgs potential, vital in validating the SM and even our existence



Resonant production

Expected from many extensions of the SM:

2 Higgs doublet models (2HDM);
SM or 2HDM + singlet;
Extra dimensions, …

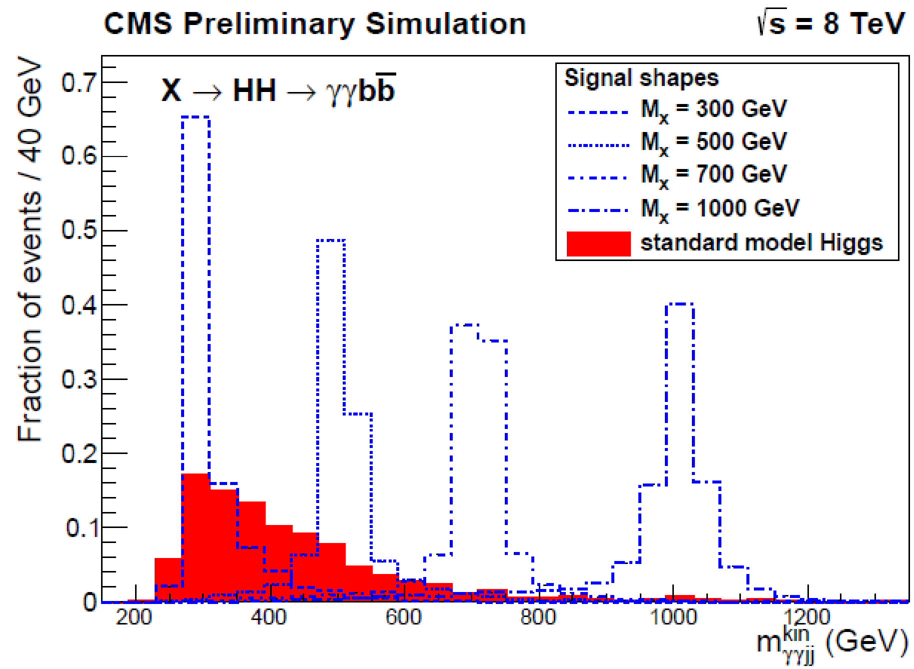


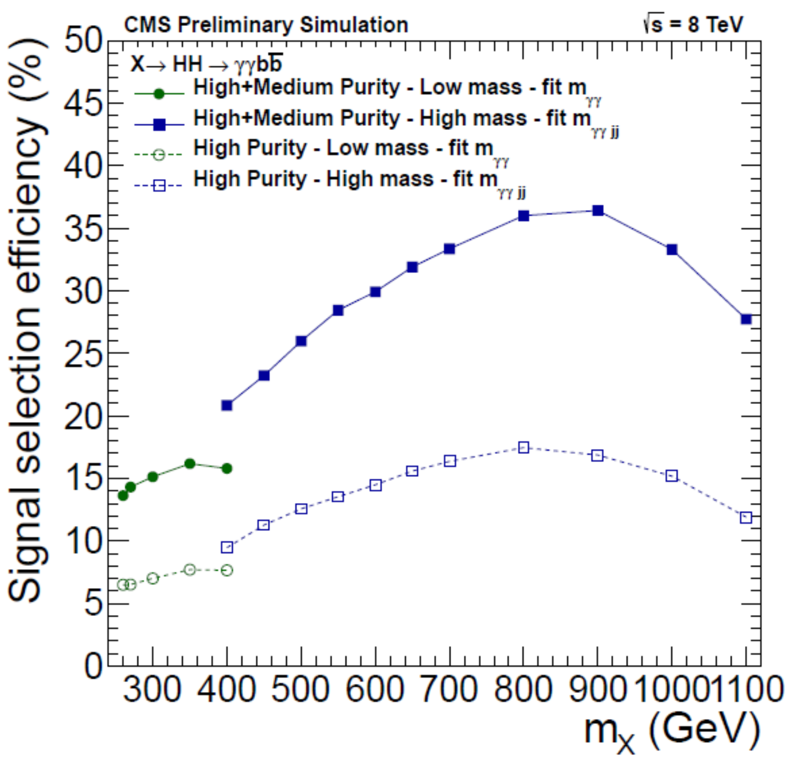
Search for $X \to hh \to bb\gamma\gamma$

CMS-PAS-HIG-13-031

Clear signature with two photons and two b-tagged jets and resonances in 3 mass distributions: $m_{\gamma\gamma}$, m_{jj}, $m_{\gamma\gamma jj}$.

A constant *width of 1 GeV* is assumed for the resonances that are simulated using MadGraph5.





Optimized for two mass regions:

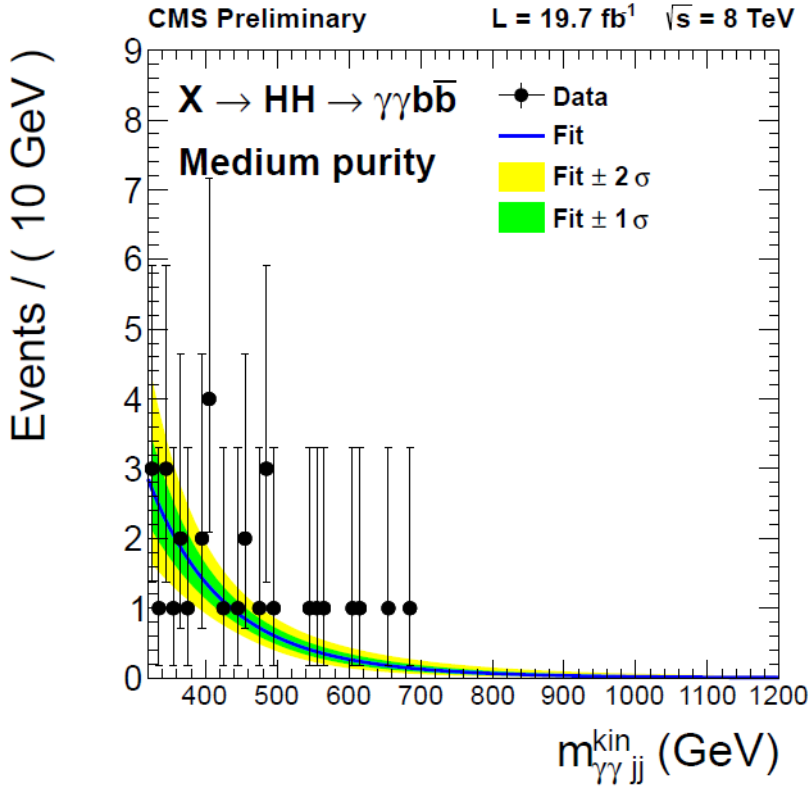
- Low mass: $260 \leq m_X \leq 400$ GeV
- High mass: $400 \leq m_X \leq 1100$ GeV

Jet merging led to efficiency loss for m_X above ~ 800 GeV.

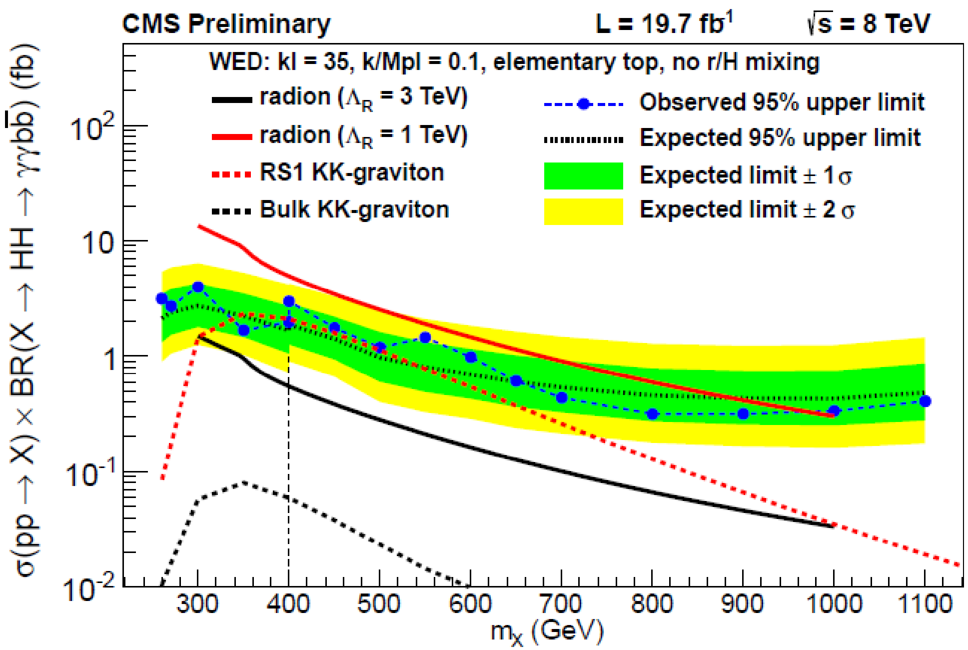
Search for $X \to hh \to bb\gamma\gamma$

Two signal categories:
- medium purity (1 b-tagged jet)
- high purity (2 b-tagged jets)

Fit either the $m_{\gamma\gamma}$ (low mass) or $m_{\gamma\gamma jj}$ (high mass) distribution to extract the $X \to hh$ signal



CMS-PAS-HIG-13-031



Compare to benchmark radion and KK-graviton models

More a proof of principle for now, is getting interesting...

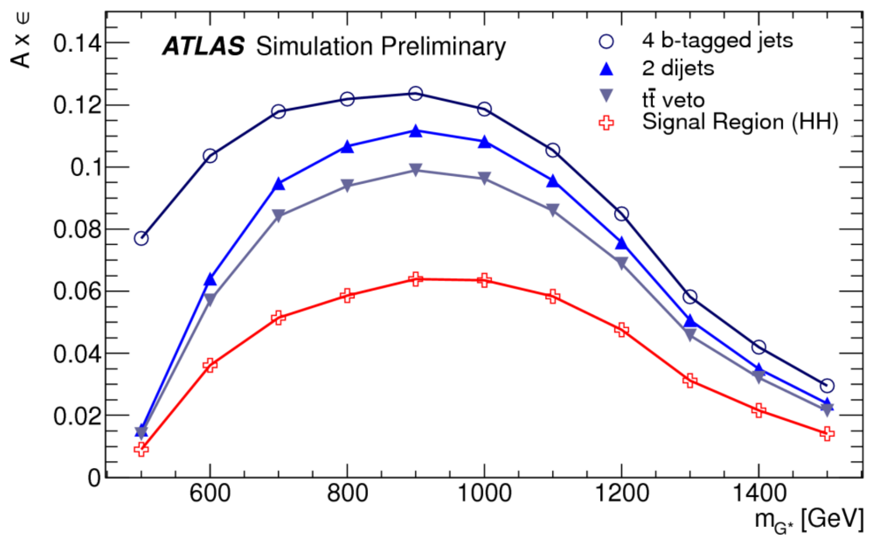
Search for $X \to hh \to 4b$

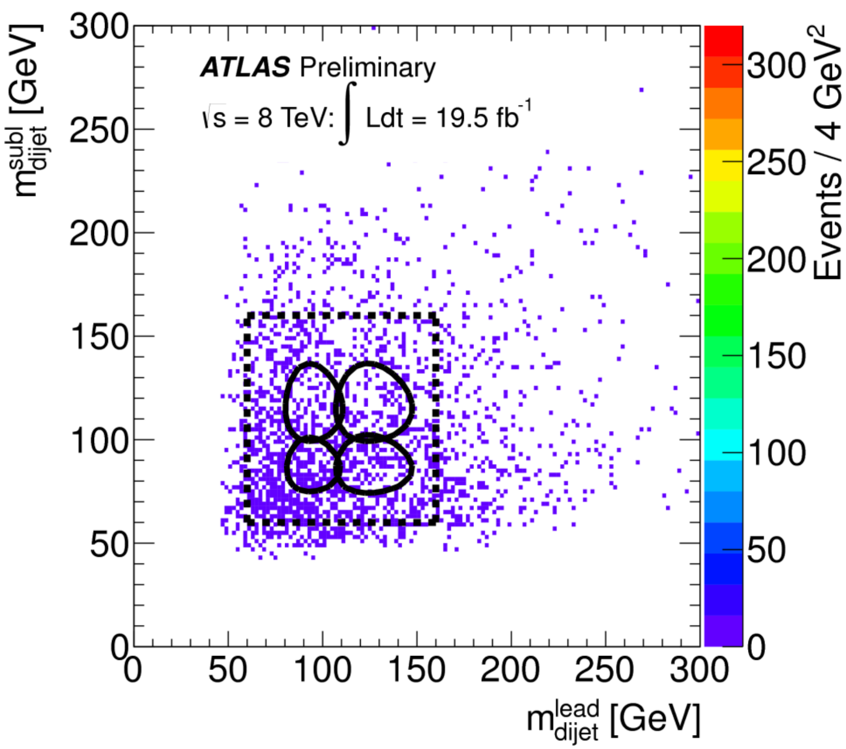
ATLAS-CONF-2014-005

RS graviton with $m_{G*} = 500 - 1500$ GeV and $\kappa/\bar{M}_{Pl} = 1.0$ as the signal model

Trigger: a combination of high E_T jet triggers w/o b-tagging at HLT,
$> 99\%$ efficient for $G^* \to hh \to 4b$ stuided.

Offline: two pairs of b-jets with $p_T^j > 40$ GeV and $p_T^{jj} > 200$ GeV, m_{jj} consistent with the mass of the Higgs boson.



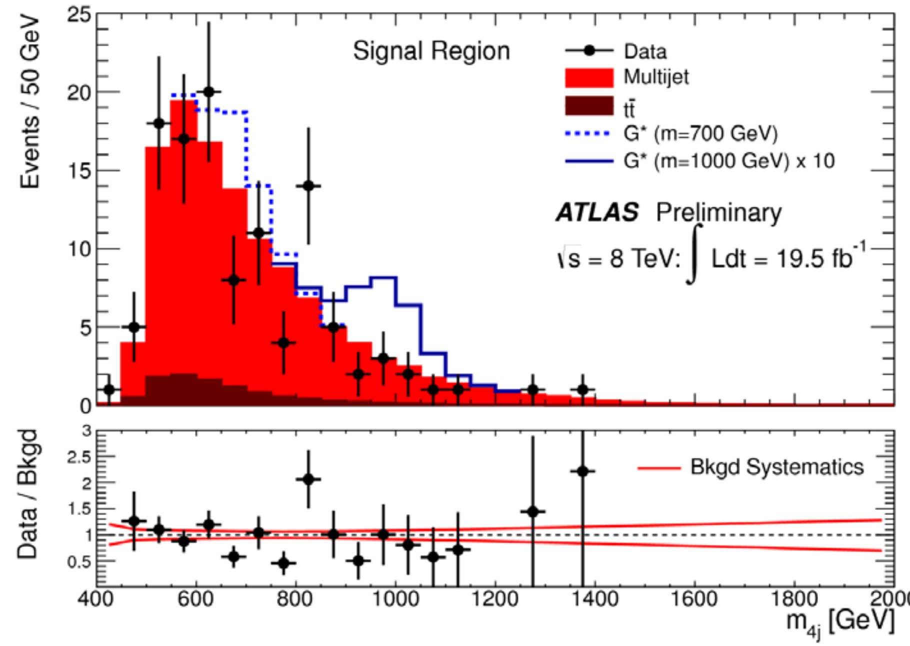


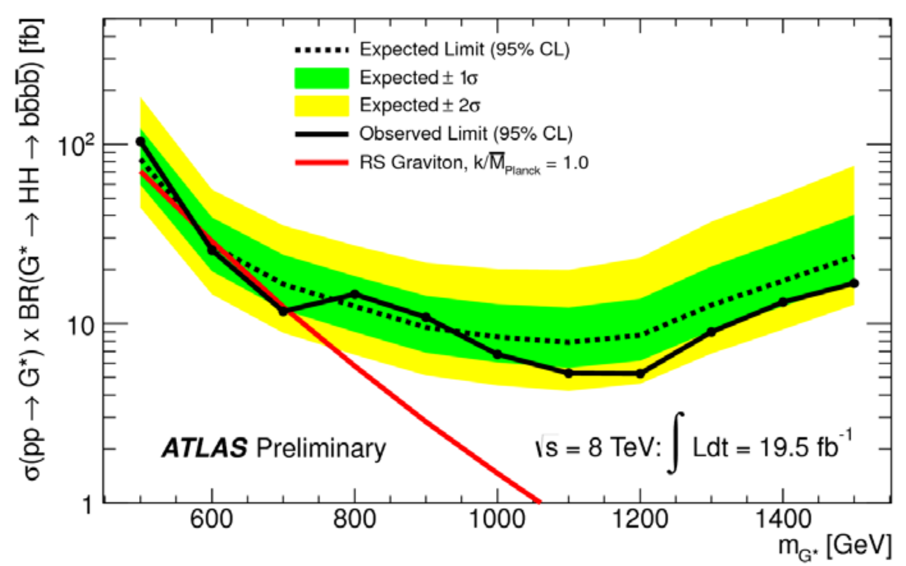
Efficiency loss at high mass due to jet merging.

χ^2 kinematic fitting to reduce ZZ, ZH and top backgrounds

Search for $X \to hh \to 4b$

Type	Signal Region
Multijet	109 ± 5
$t\bar{t}$	10 ± 6
Z+jets	0.7 ± 0.2
Total Bkgd	120 ± 8
Data	114
G^* (m_{G^*} = 500 GeV)	12.5 ± 0.4
G^* (m_{G^*} = 700 GeV)	12.5 ± 0.2

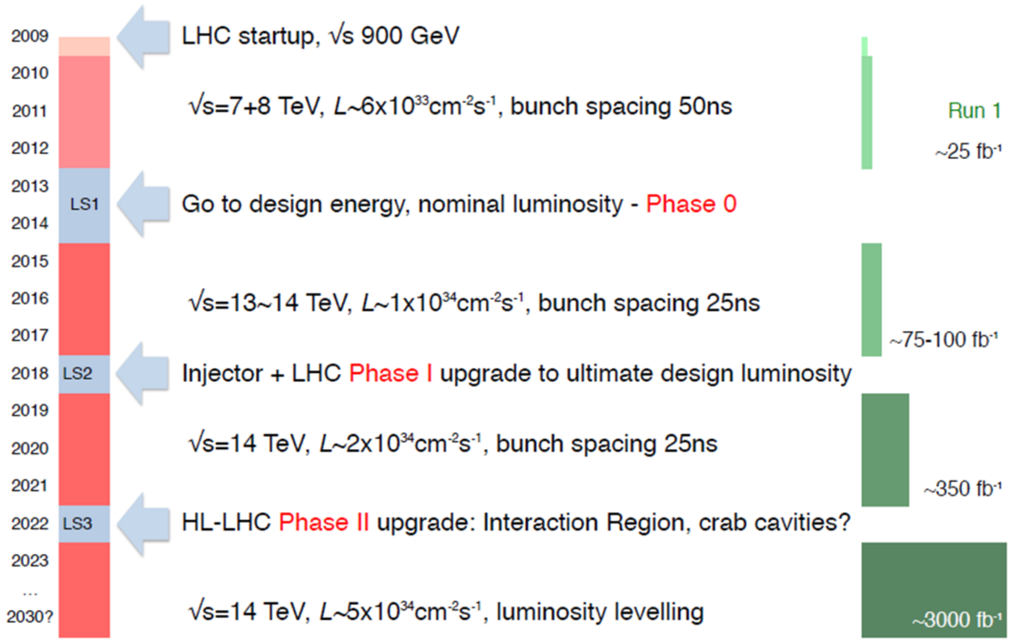




Background dominated by multijets and estimated using data sidebands.

Sensitivity degrades at high mass due to jet merging and systematics.

Looking Ahead…



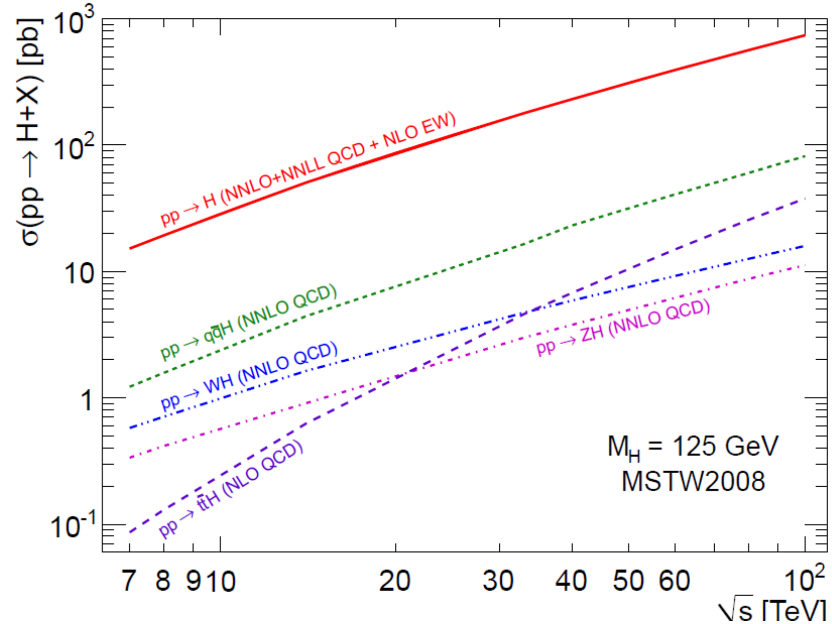
A long physics program ahead, time to think about and plan for the future:

- better understand physics potentials,
- ensure key searches are performed ,

……

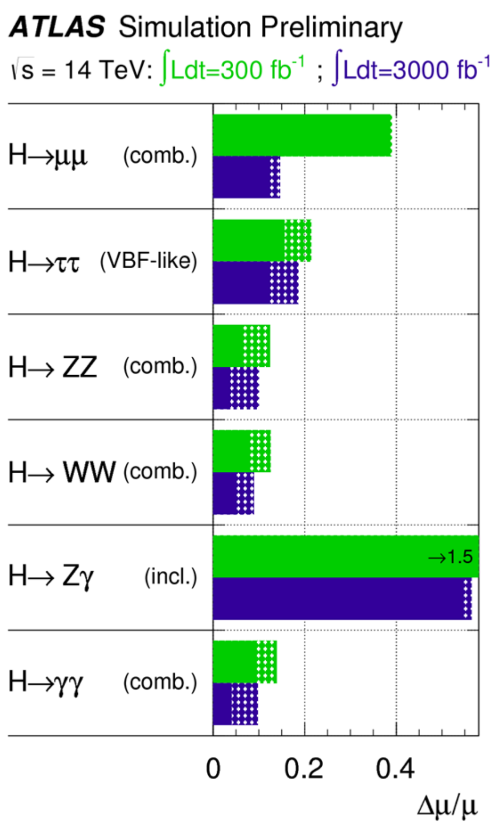
Run 2 is expected to run at 13 TeV $\Rightarrow$ significant increase in Higgs cross sections

Higgs production cross section (pb)				
$\sqrt{s}$	ggF	VBF	VH	$t\bar{t}H$
8 TeV	19.3	1.58	1.12	0.129
13 TeV	43.9	3.75	2.25	0.512
σ_{13}/σ_8	2.28	2.38	2.01	3.96

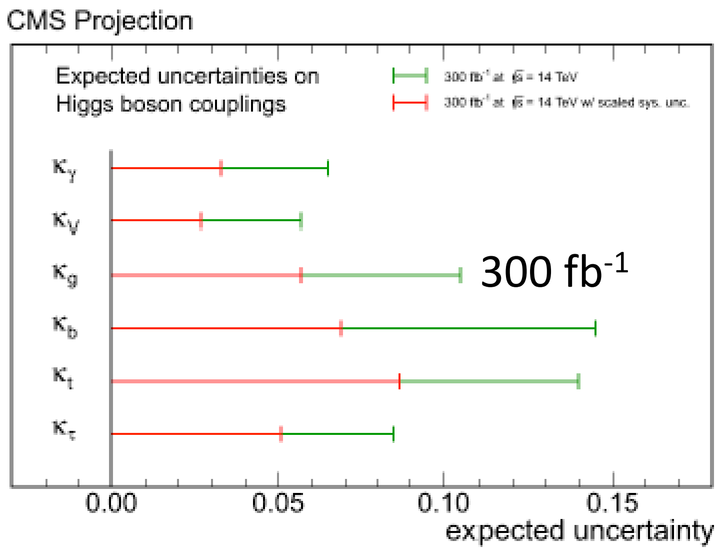


Coupling Projections

Many studies done for US Snowmass process, Europe ECFA studies.



(Based on parametric simulation)



(Extrapolated from 2011/2012 results)

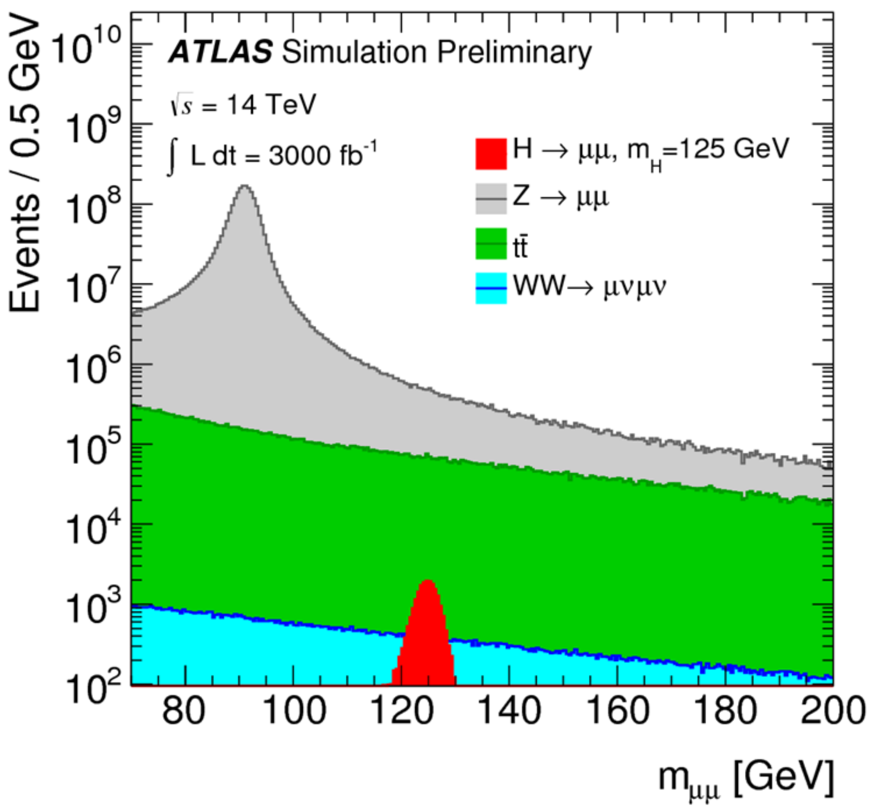
Two assumptions on systematics:

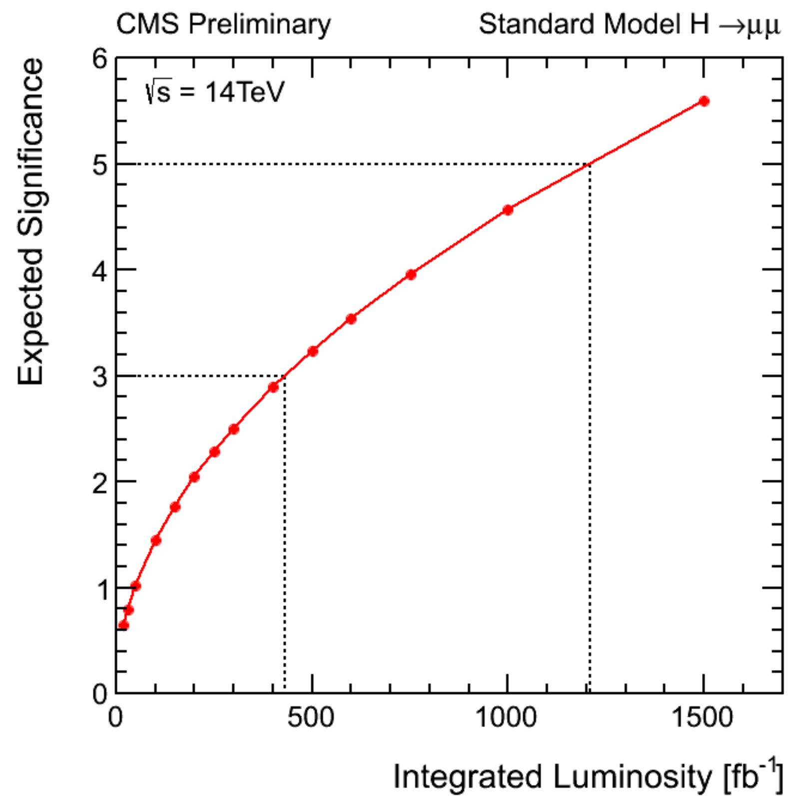
1. no change
2. $\Delta(\text{theory})/2$, rest $\propto 1/\sqrt{Lumi}$

Even with the projected precisions at HL-LHC, BR_{new} is not expected to be constrained better than $\sim 5-10\%$ from the coupling measurements.

Rare Decay Prospects

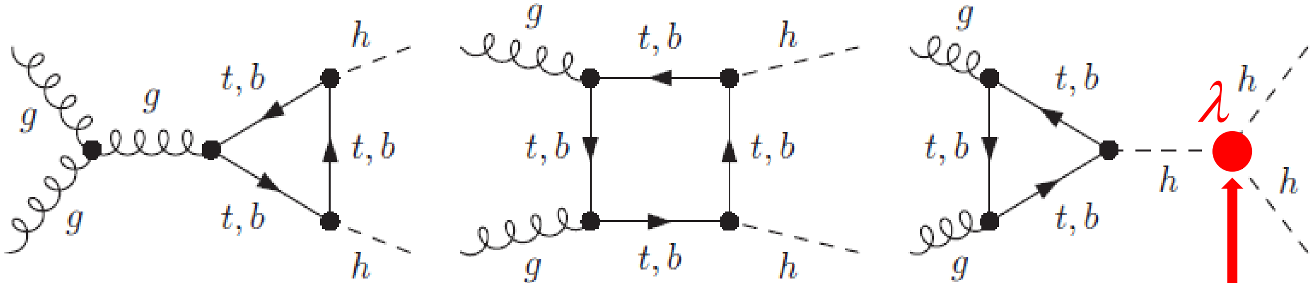
$H \rightarrow \mu\mu$: Projections from both ATLAS and CMS indicate a 5σ observation with $\sim$1000 fb^{-1} at 14 TeV.





$H \rightarrow Z\gamma$: $\sim 4\sigma$ per experiment significance is expected with 3000 fb^{-1}

Higgs Self-Coupling



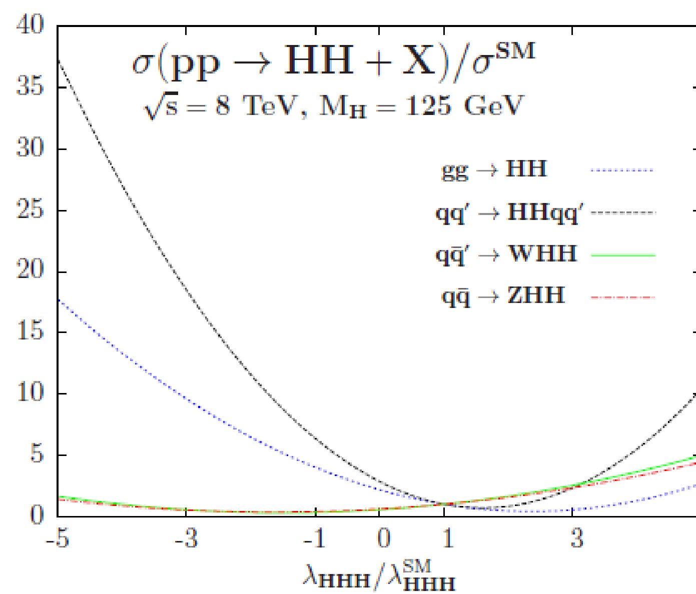
$$V(\phi) = \mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2$$

$\sigma(pp \to hh)$@14 TeV	40.2 fb (NNLO)

Events in 3000 fb^{-1}	
$hh \to bb\gamma\gamma$	320
$hh \to bb\tau\tau$	8,800
$hh \to bbWW$	29,900
$hh \to bbbb$	40,200

Small cross section and the destructive interference between self- and non-self-coupling diagrams.

$bb\gamma\gamma$ appears to have the best sensitivity, $bb\tau\tau$ should help too, *bbWW* and *bbbb* have higher rates, but also large backgrounds.



Baglio et al, arXiv: 1212.5581

Expect to achieve $\frac{\Delta\lambda}{\lambda} \sim 30\%$

(two experiments at HL-LHC)

Summary

We have so far had a successful Higgs program focused on the search and discovery of a Standard Model like Higgs boson.

With the discovery, the physics landscape has changed and more effort has been directed towards searches for BSM phenomena.

Some results from the searches so far, but expect many more from the analyses of 7/8 TeV data this year.

As an experimenter, I think we need to do a better job

The upcoming LHC runs may well offer us a glimpse of new physics beyond the current paradigm.

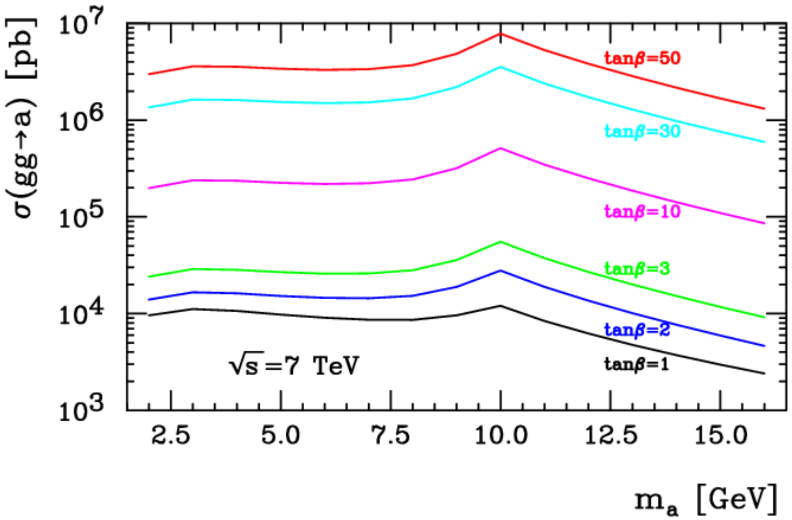
we need to have some ideas on what to look, but equally important prepare for surprises.

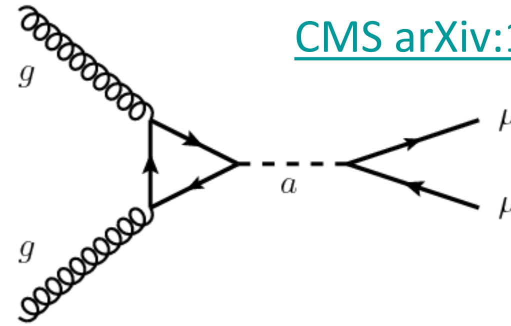
As an experimentalist, what I'd like to get out of this workshop is a list of well motivated final states and their likely physics impact.

Additional Slides

Search for $a \rightarrow \mu\mu$

CMS arXiv:1206.6326

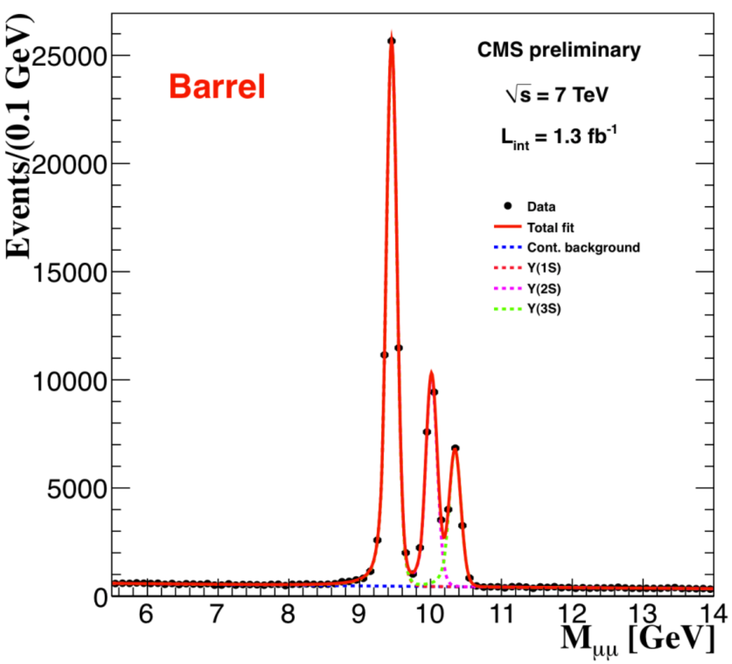


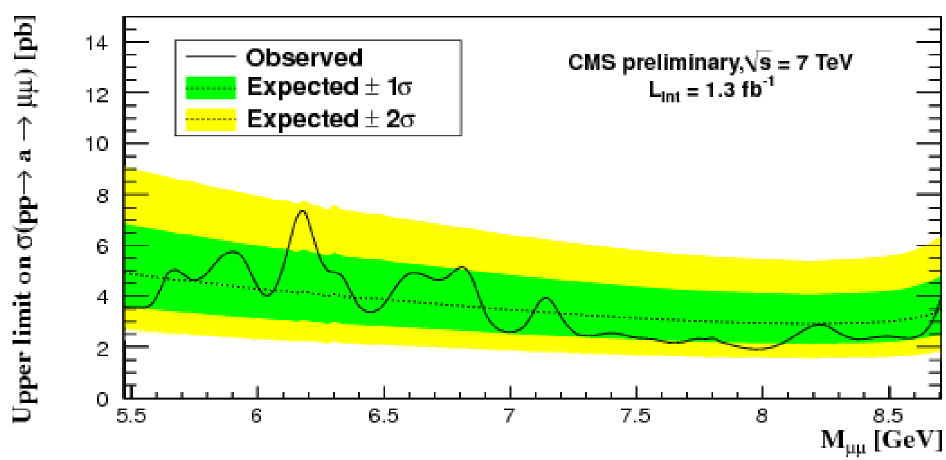


a can be singularly produced in *gg* fusion with a relative large cross section, can be searched in $a \rightarrow \mu\mu$ decay.

Searching for narrow $\mu\mu$ resonance away from the known quarkonium resonances.

Only 7 TeV results from CMS are public available so far

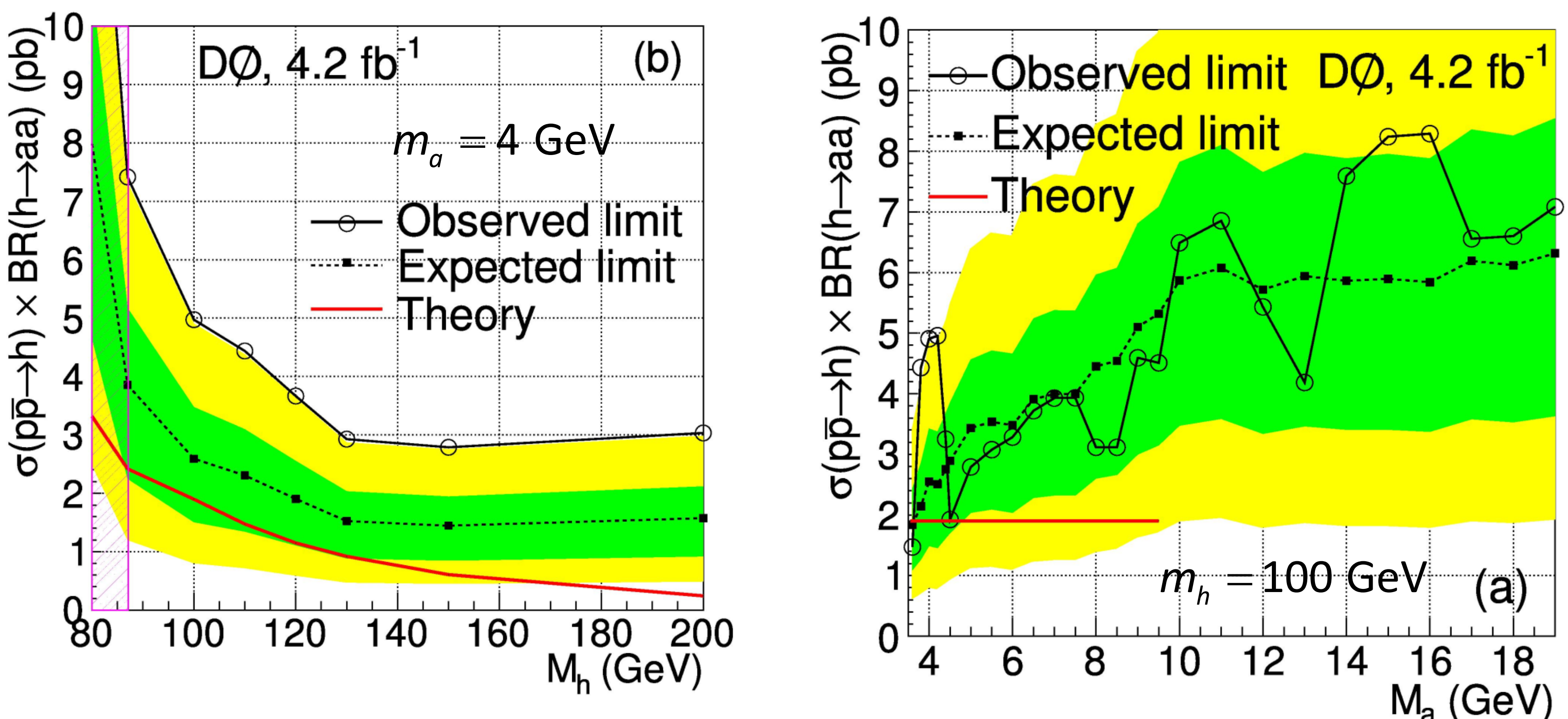




Search for $h \to aa \to 4\mu$, $2\mu 2\tau$

Public result from CMS on $h \to aa \to 4\mu$, clean signature but relative low rate $\Rightarrow$ presentation by Alexei Safonov

$h \to aa \to \mu\mu\tau\tau$ should significantly improve the search sensitivity as D0 has done. LHC should be able to explore interesting parameter space.



arXiv:0905.3381 (D0)

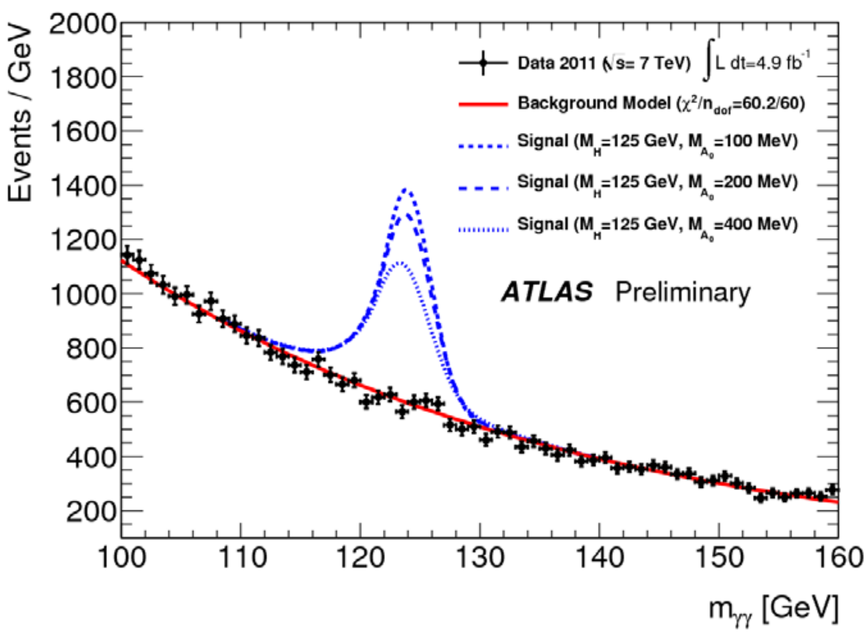
Search for $h \to aa \to 4\gamma$

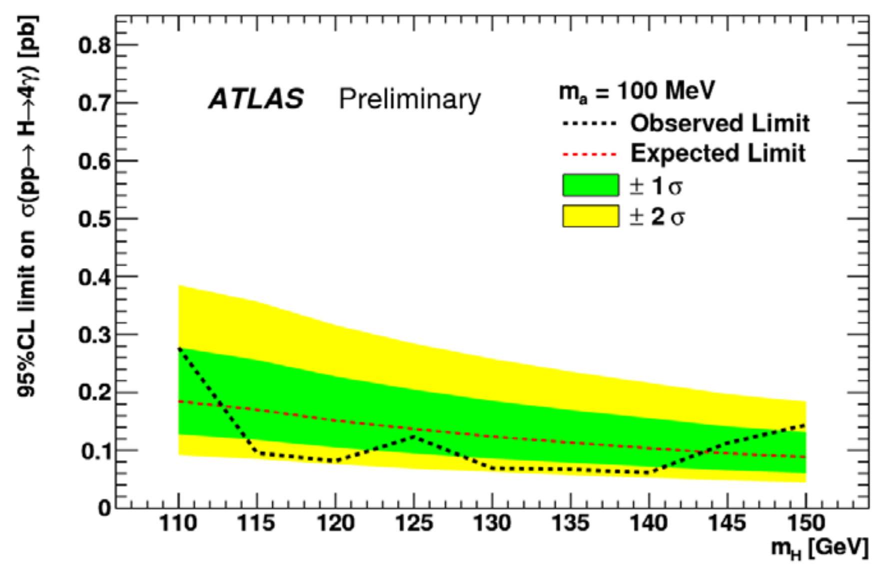
ATLAS-CONF-2012-079

An old analysis, partly motivated by the excess in $h \to \gamma\gamma$.

The pseudoscalar a from $h \to aa$ decay will be highly boosted if a is very light ($m_a <\sim 1$ GeV). The two photons from $a \to \gamma\gamma$ decay will be collimated, contributing effectively to the $h \to \gamma\gamma$ signal.

Search for two "photon-like" objects with $E_T > 40,25$ GeV. Upper cross section limits are set for $100 < m_a < 400$ MeV.





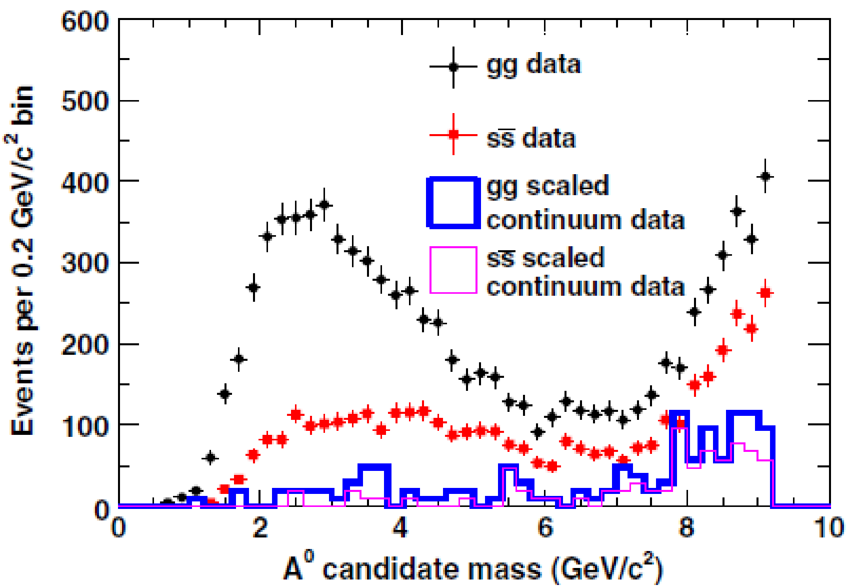
Searches at BABAR

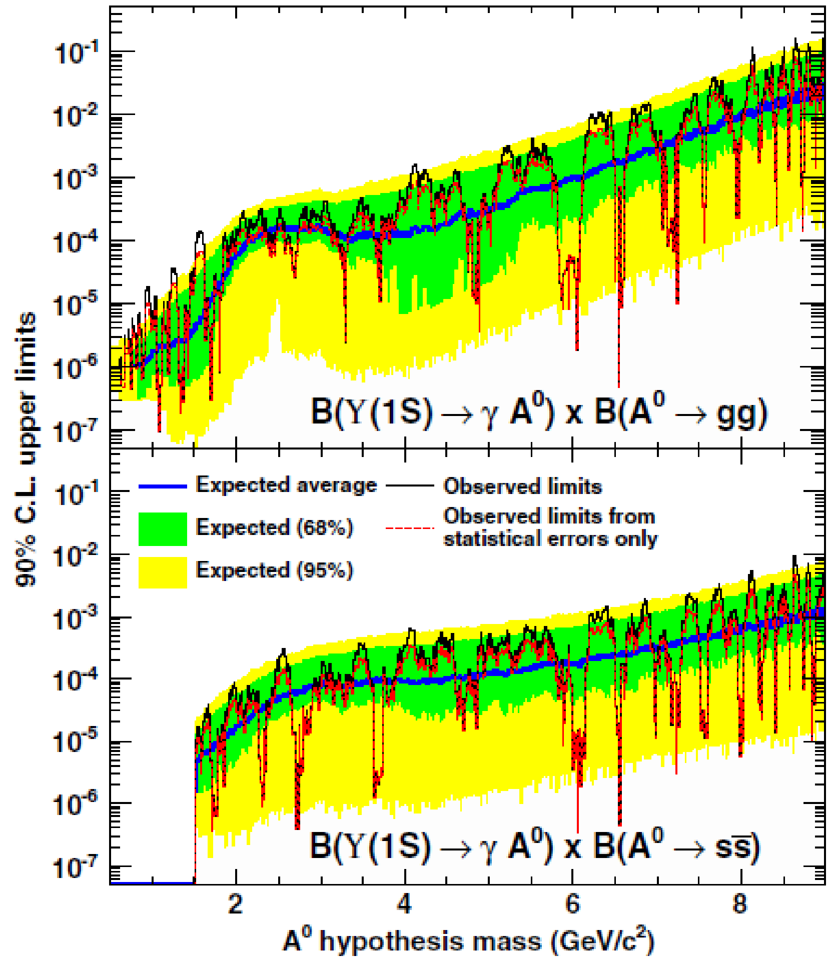
Hadronic decays such as $a \to c\bar{c}$, gg (dominant below $2m_\tau$) are not feasible at hadron colliders, but can be searched in $\Upsilon(nS) \to a\gamma$ decays at B-factories.

The radiative $\Upsilon \to a\gamma$ decay is predicted to have a BR up to 10^{-5}.

Full reconstruction of *a* decays in exclusive final states.

No sign of *a* !





BABAR: Phys. Rev. D 88, 031701 (2013)