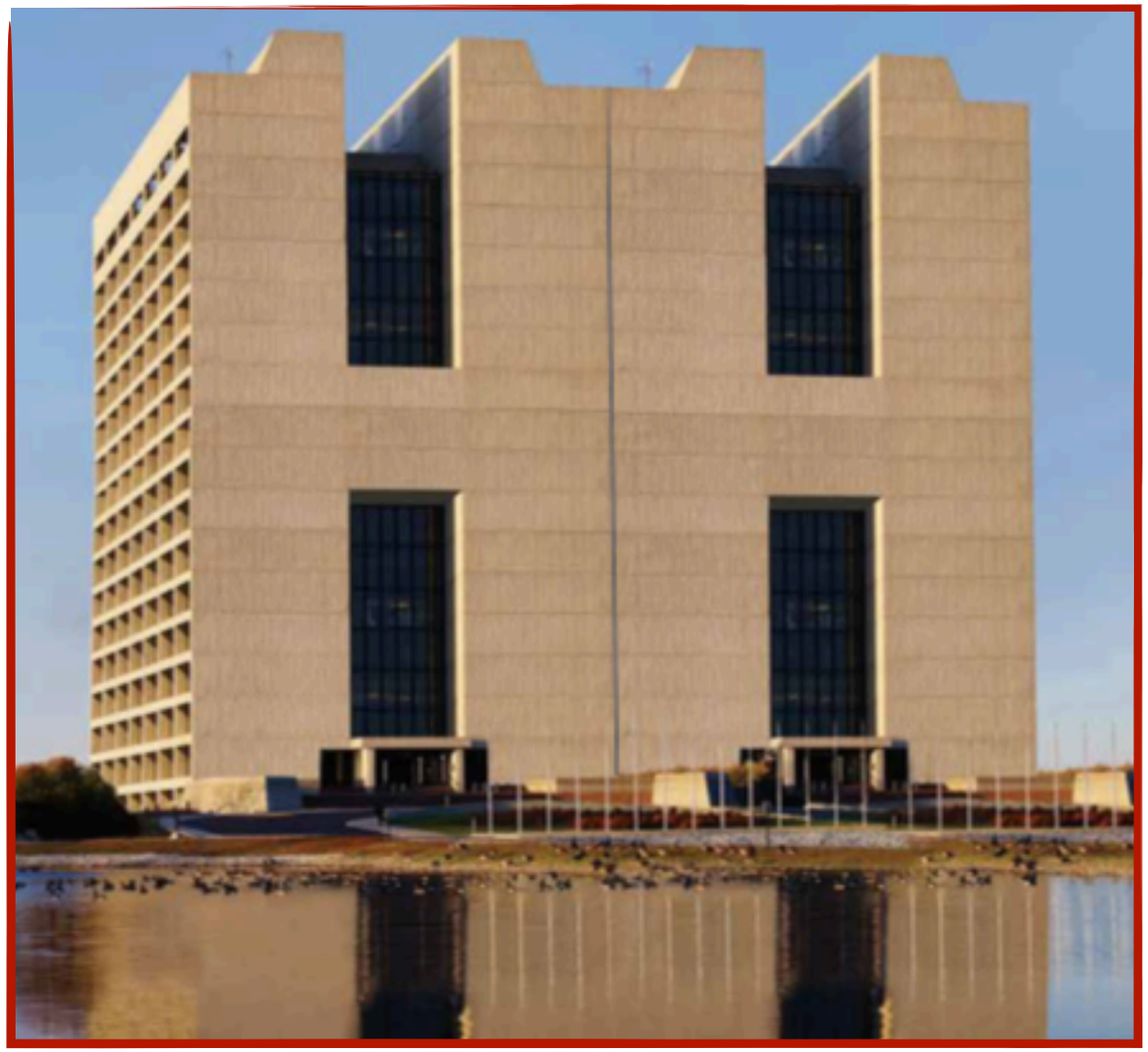
# Why do we care about di-Higgs Production?



From Double Higgs at Colliders Workshop

Tyler James Burch
US LHC Users Association
Fermilab - Batavia, Illinois
October 24-26, 2018

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ATLAS EXPERIMENT

# The Higgs Boson

**July 4, 2012 -**
Standard Model-like Higgs particle discovered by ATLAS and CMS!

- Mass reconstructed at ~125 GeV
- Observed in multiple channels with rates consistent with the Standard Model (SM)

NYTimes

**But, plenty of outstanding questions! Among these…**

- Does the discovered Higgs boson couple as predicted by the SM?
- Are there any additional Higgs bosons?
- Do particles beyond those predicted by the SM exist? If so, how do they couple to the Higgs boson?

**Searching for di-Higgs production gives insight into these questions**

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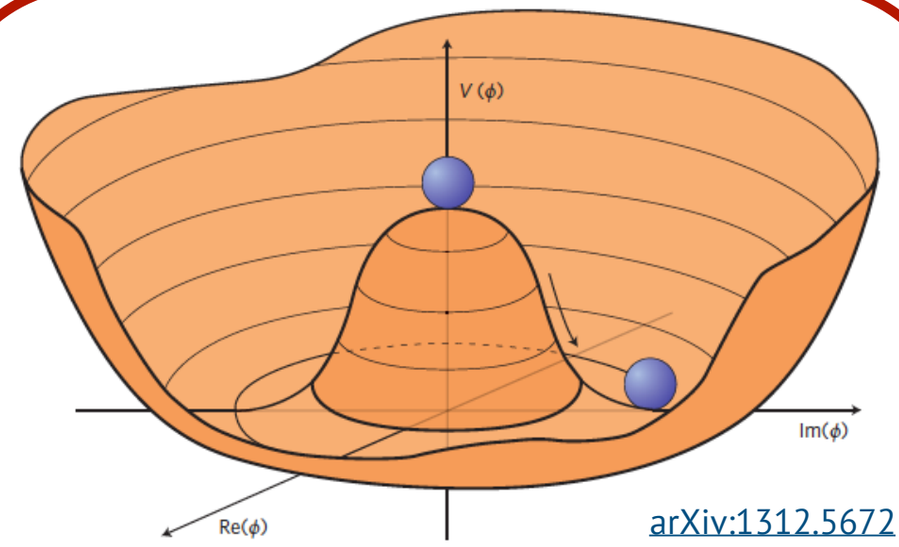
# The Higgs Mechanism

Higgs Potential is given by:

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

For fluctuations about the minima, $\phi \rightarrow v + h$

$$V = V_0 + \frac{m_h^2}{2}h^2 + \underbrace{\frac{m_h^2}{2v^2}}_{\lambda_{HHH}^{SM}}vh^3 + \underbrace{\frac{m_h^2}{8v^2}}_{\lambda_{HHHH}^{SM}}h^4$$

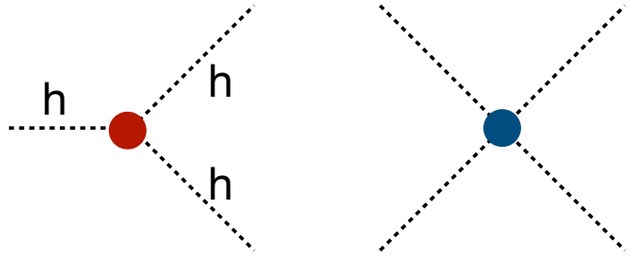



arXiv:1312.5672

minimum corresponds to:

$$\frac{\mu}{\sqrt{\lambda}} \equiv v \qquad \sim 246 \text{ GeV}$$

Higgs Vacuum expectation value (vev)




**Results in di-Higgs production!**

**Does the discovered Higgs boson couple as predicted by the SM?**

Di-Higgs searches look to better understand this by probing the trilinear coupling, providing another check that this is, in fact, the SM Higgs boson

Measuring $\lambda_{HHH}$ checks that Electroweak Symmetry Breaking follows from a $\phi^4$ potential

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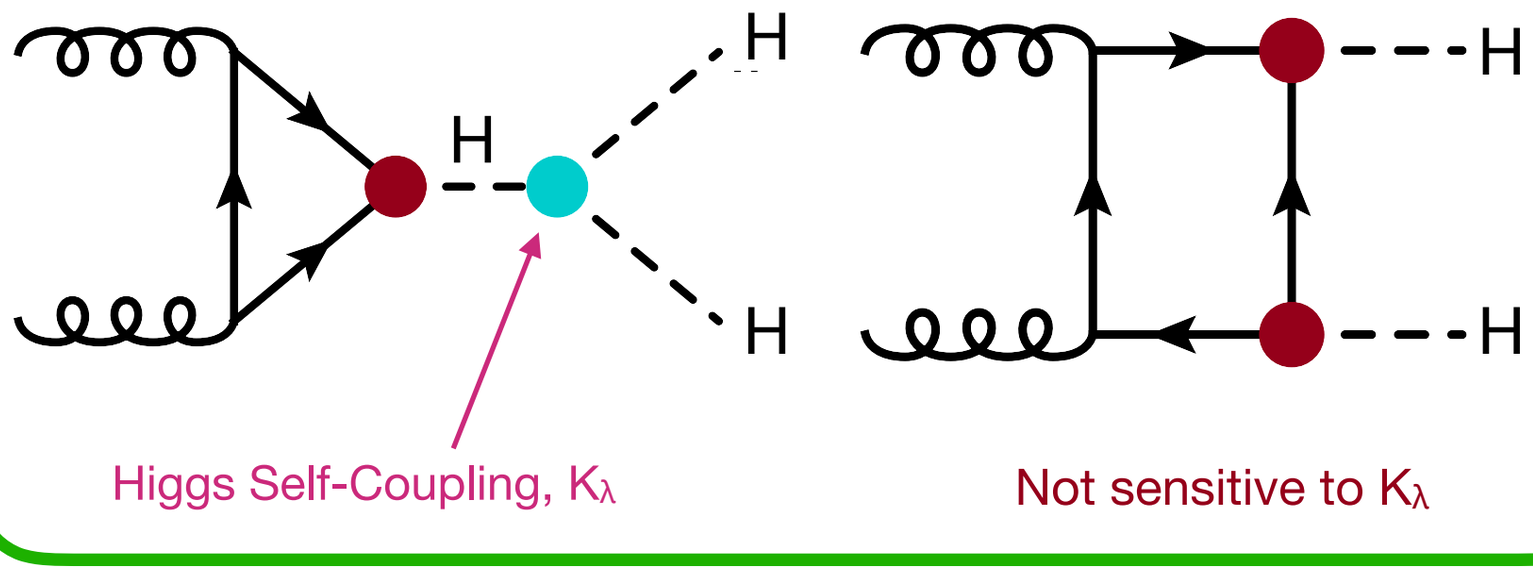
# di-Higgs Production

Gluon-gluon fusion (ggF) is the dominant di-Higgs production mode, accounting for ~87% of di-Higgs events at 13 TeV, current analyses target this production mode

SM non-resonant HH Production via gluon-gluon fusion




Occurs through two diagrams which interfere destructively, which causes a very small cross section

$$\sigma(gg \rightarrow HH)_{SM} \approx 33 \text{ fb @ 13 TeV}$$

~5000 HH events produced in the projected 150 fb$^{-1}$ in Run-2

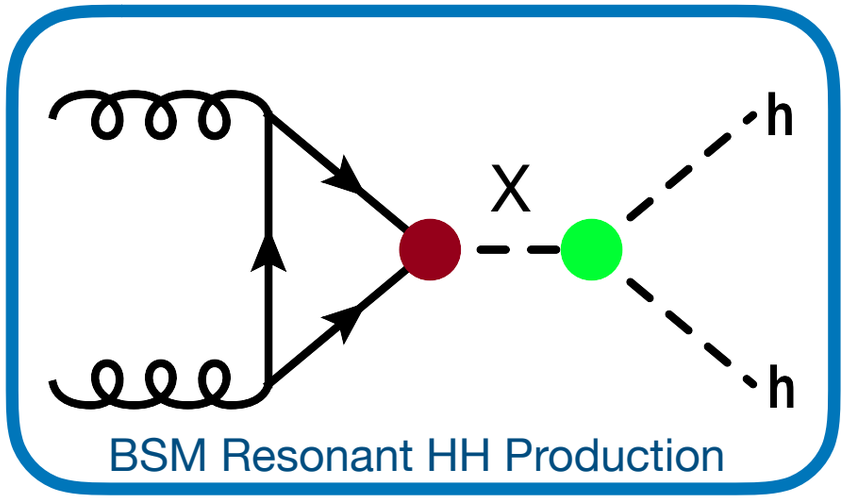
**di-Higgs production is a rare process, which will test the limits of the LHC**

# Probing BSM

**Are there any additional Higgs bosons?**
**Do particles beyond those predicted by the SM exist?**
di-Higgs searches look to investigate these questions by looking for Beyond the Standard Model (BSM) enhancements to di-Higgs production

**<u>Resonant enhancements:</u>**
Enhancements can occur through a resonance that decays to to two Higgs bosons

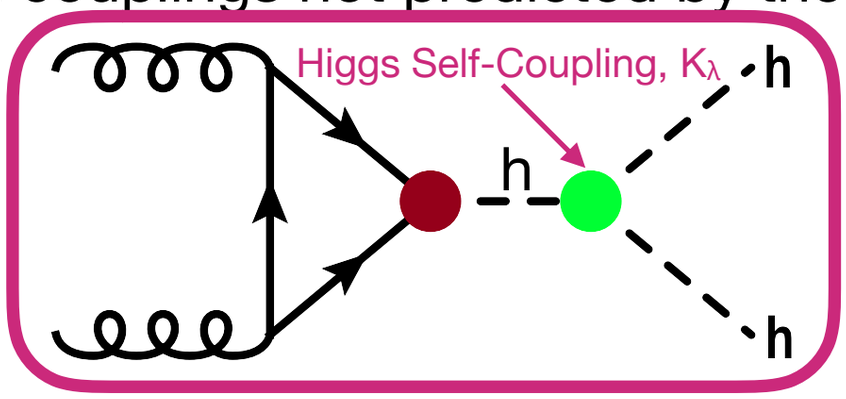
- Two-Higgs-doublet model (THDM) - Resonance is a heavy scalar
- Randall-Sundrum Model - Resonance is a Spin-2 Kaluza-Klein graviton

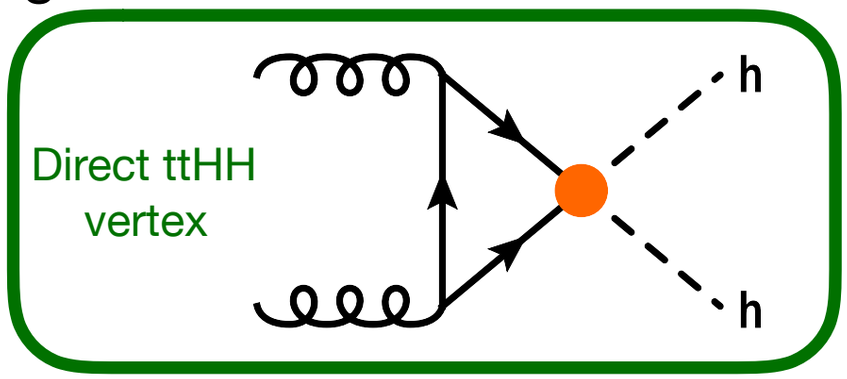


BSM Resonant HH Production

**<u>Non-Resonant enhancements:</u>**
Can also look toward enhanced production caused by couplings that differ from the SM

- Higgs Self-Coupling ($K_\lambda$) - strength of coupling deviating from SM value can lead to enhanced production
- Additional couplings not predicted by the SM, e.g. direct ttHH vertex




**Models with enhanced production make di-Higgs already interesting to study with Run-2 data**

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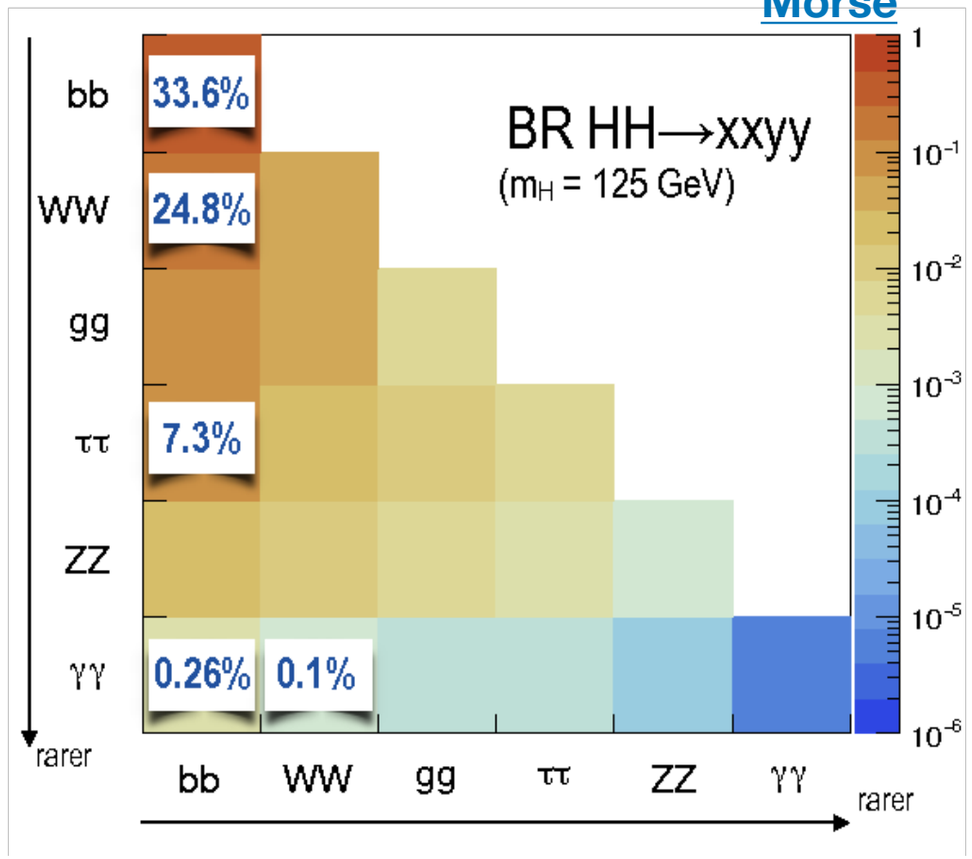
# di-Higgs Decays

Strong motivation to look at certain channels based on properties of decay products

Strongest contribution to current limits:

- $b\bar{b}b\bar{b}$: fully takes advantage of high bb branching ratio
- $\gamma\gamma b\bar{b}$: Excellent trigger and mass resolution for photons, high bb branching ratio
- $b\bar{b}\tau\tau$: Taus are relatively clean while still having a large branching ratio, high bb branching ratio

Morse



# SM Landscape

**Combination limits:**
SM di-Higgs production constrained to
Expected: 0.35 pb (10.4*$\sigma_{SM}$)
Observed: 0.22 pb (6.7*$\sigma_{SM}$)

**Prospect studies for HL-LHC (3 ab$^{-1}$):**

| Channel | Exclusion (95% CL) | Discovey Significance |
|---|---|---|
| $\gamma\gamma$bb | N/A | 1.5$\sigma$ |
| bb$\tau\tau$ | 4.3*$\sigma_{SM}$ | 0.6$\sigma$ |
| bbbb | 1.5*$\sigma_{SM}$ | N/A |

*Based on extrapolation of current analyses, likely will improve with more advanced analysis techniques

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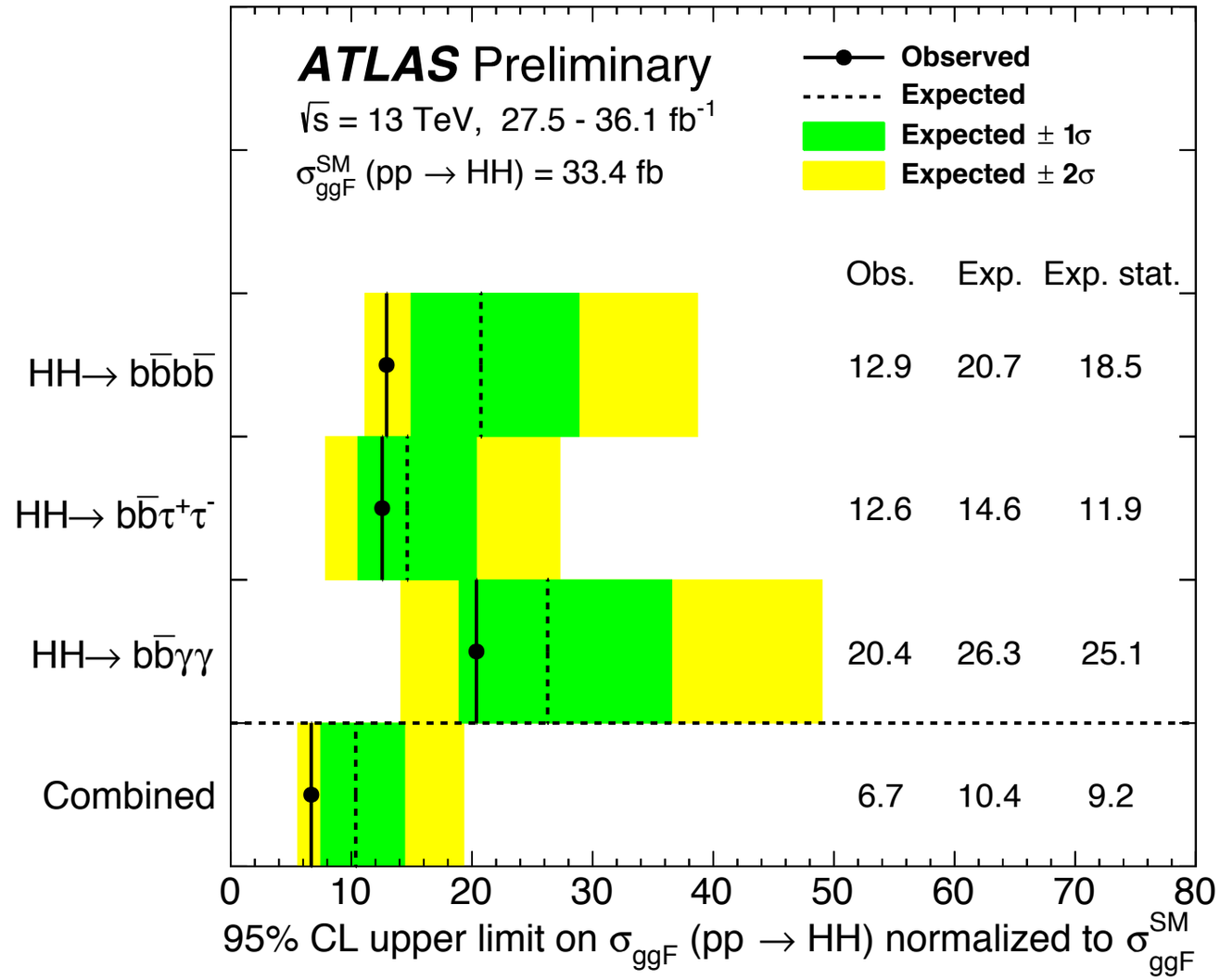
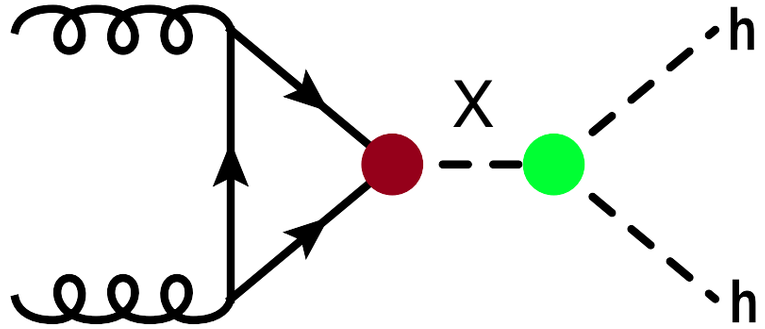
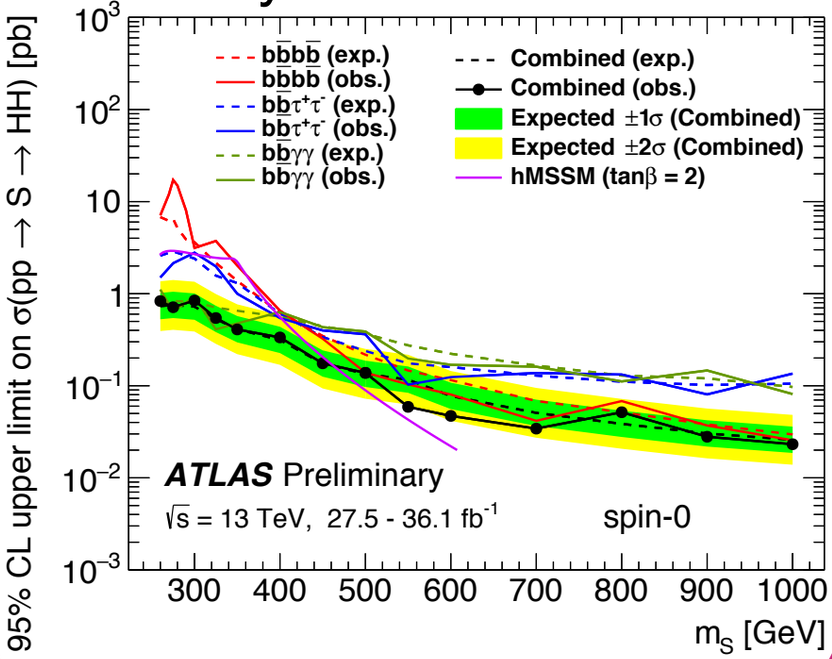


# BSM Landscape - Resonances

**No significant excesses found, limits set**




## Heavy Scalar




tanβ = 2: ratio of the vacuum expectation values of the two Higgs doublets

mX < 462 GeV @ 95% CL in hMSSM

## KK-graviton

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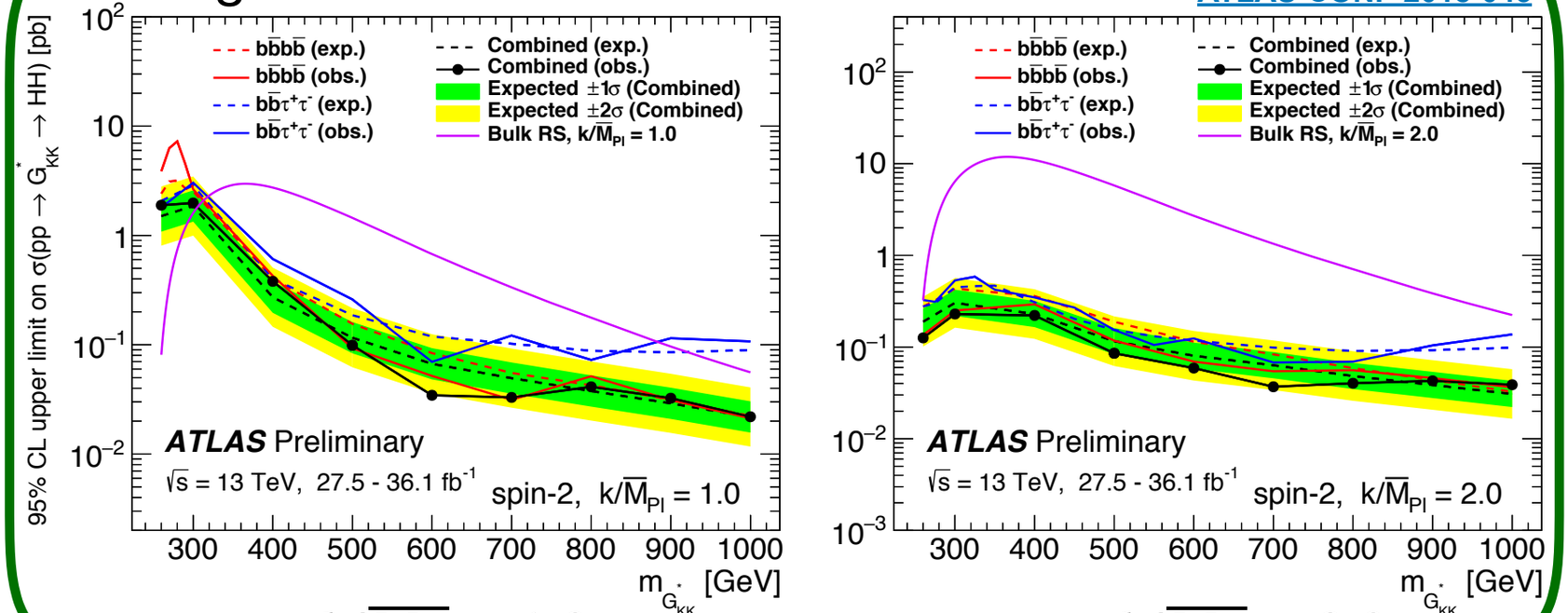



$k/\overline{M_{Pl}} = 1.0$ $k/\overline{M_{Pl}} = 2.0$

k: curvature of the warped extra dimension

M⁻ Pl: the effective four-dimensional Planck scale

$k/M_{Pl}$ =1.0 constraints: 307 < $m_G$ < 1362 GeV

$k/M_{Pl}$ =2.0 constraints: $m_G$ < 1744 GeV

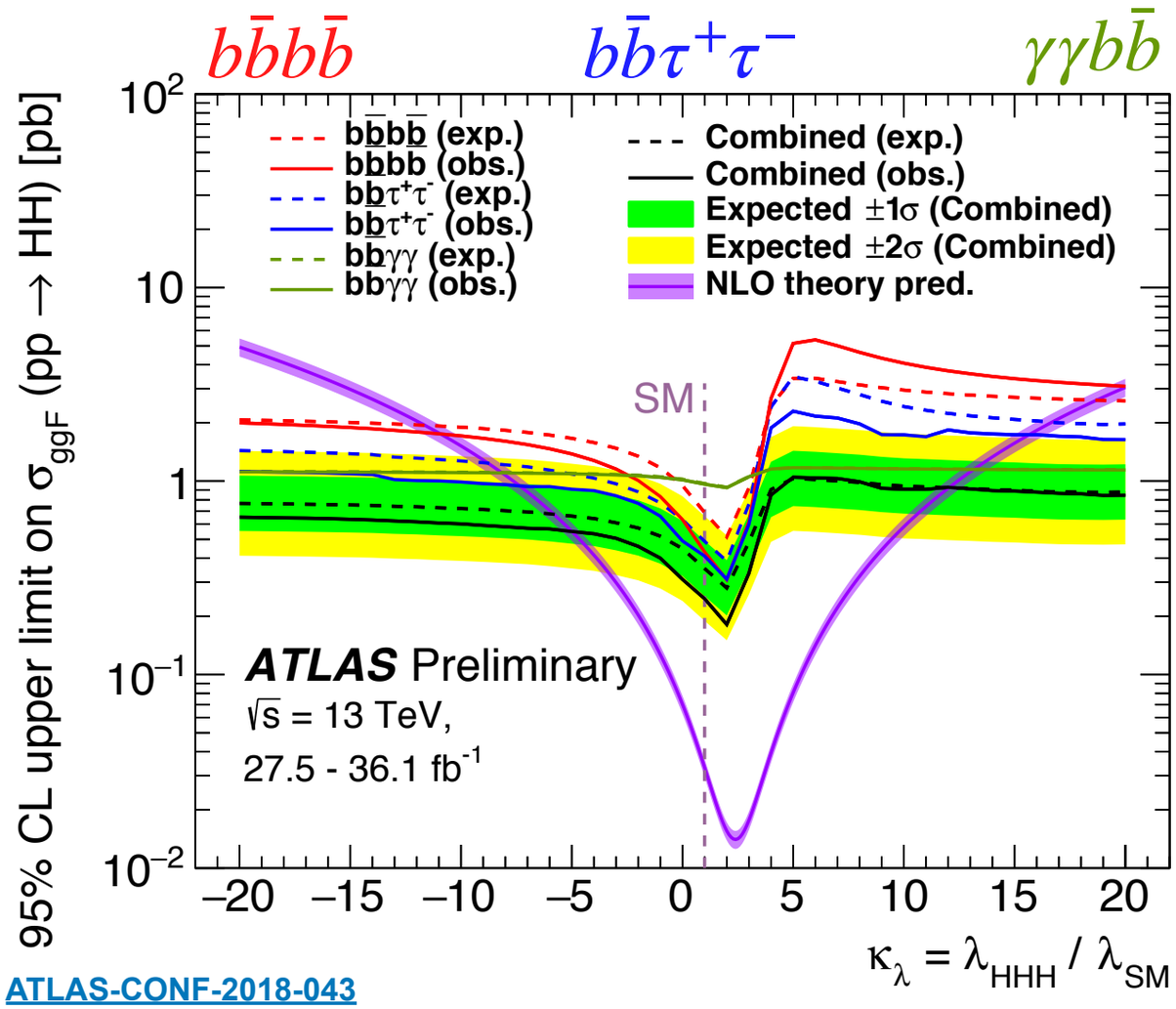
# BSM Landscape - $\lambda_{HHH}$

**Combination limits:**
Expected: $-5.8 < K_\lambda < 12.0$
Observed: $-5.0 < K_\lambda < 12.1$

**Prospect studies for HL-LHC (3 ab$^{-1}$):**

| Channel | Exclusion @ 95% CL |
|---|---|
| HH→bbbb | $-4.1 < \kappa_\lambda < 8.7$ |
| HH→$\gamma\gamma$bb | $0.2 < \kappa_\lambda < 6.9$ |
| HH→bb$\tau\tau$ | $-4.0 < \kappa_\lambda < 12.0$ |

Stefania Gori

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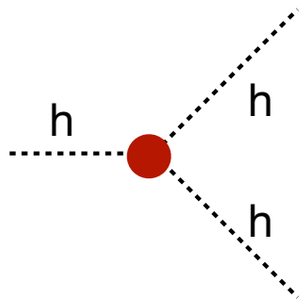
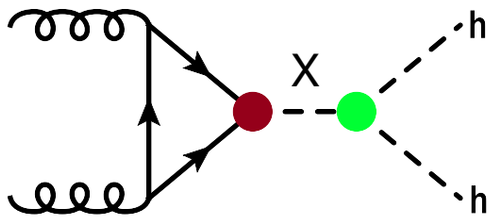
# So, Why Do We Care?

**Searches for di-Higgs production seek to answer important outstanding questions still surrounding the discovered Higgs boson**

Studying the Higgs Trilinear coupling investigates if the discovered Higgs couples as predicted by the SM
- Provides insight into Electroweak Symmetry Breaking, a long-term goal of the LHC




Searching for enhanced di-Higgs production targets BSM physics
- Opportunity to discover additional Higgs bosons or new BSM particles
- Due to small SM hh cross section, BSM enhancements may be noticeable even with the full Run-2 dataset

**However, SM di-Higgs production is a rare process that will challenge the limits of the LHC**
- With more data and improved analysis techniques, evidence *may* be possible with full LHC dataset

**Significant current work towards di-Higgs in ATLAS**
- Combination result recently published for 36.1 $fb^{-1}$ (2015+2016 data), set best limits on Higgs trilinear coupling to date
- Work toward full Run-2 analyses ramping up now!

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# Thank you!

# Backup

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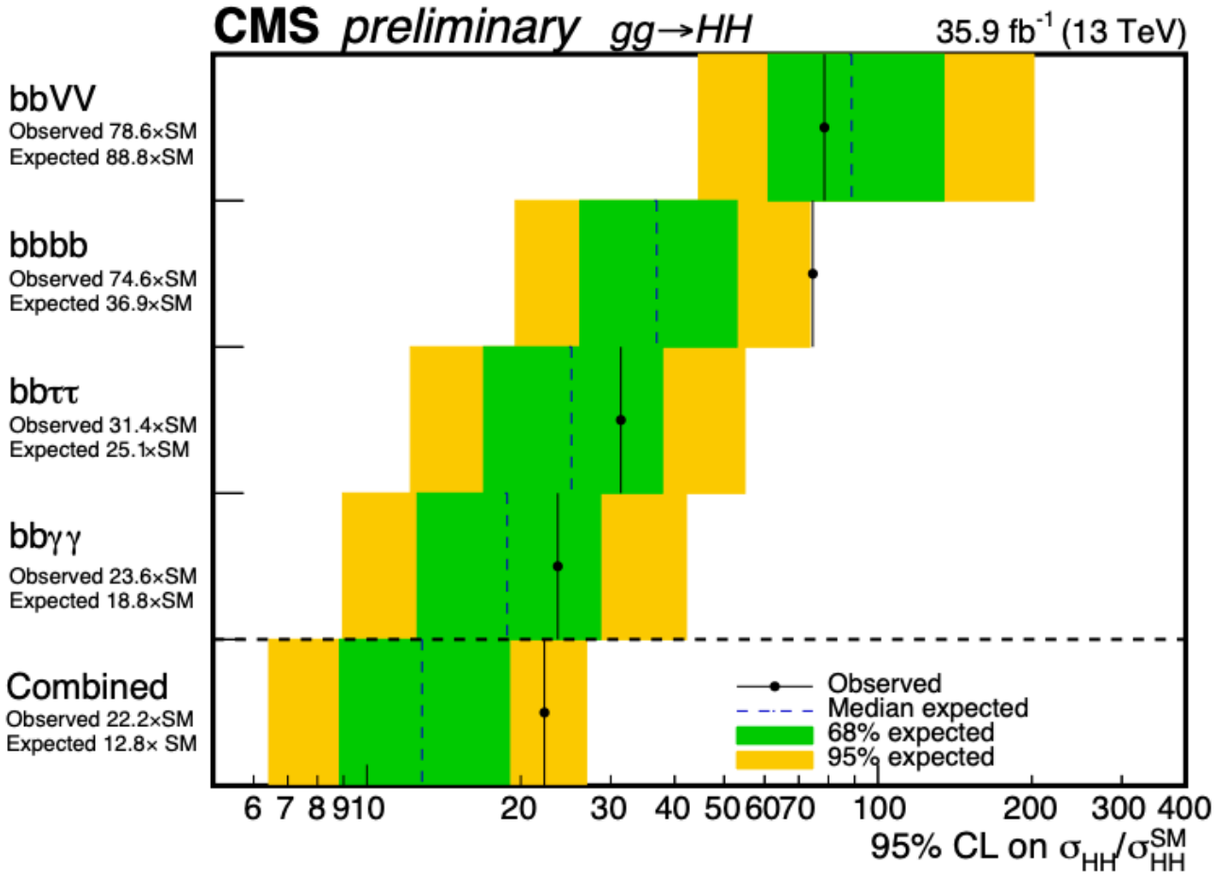
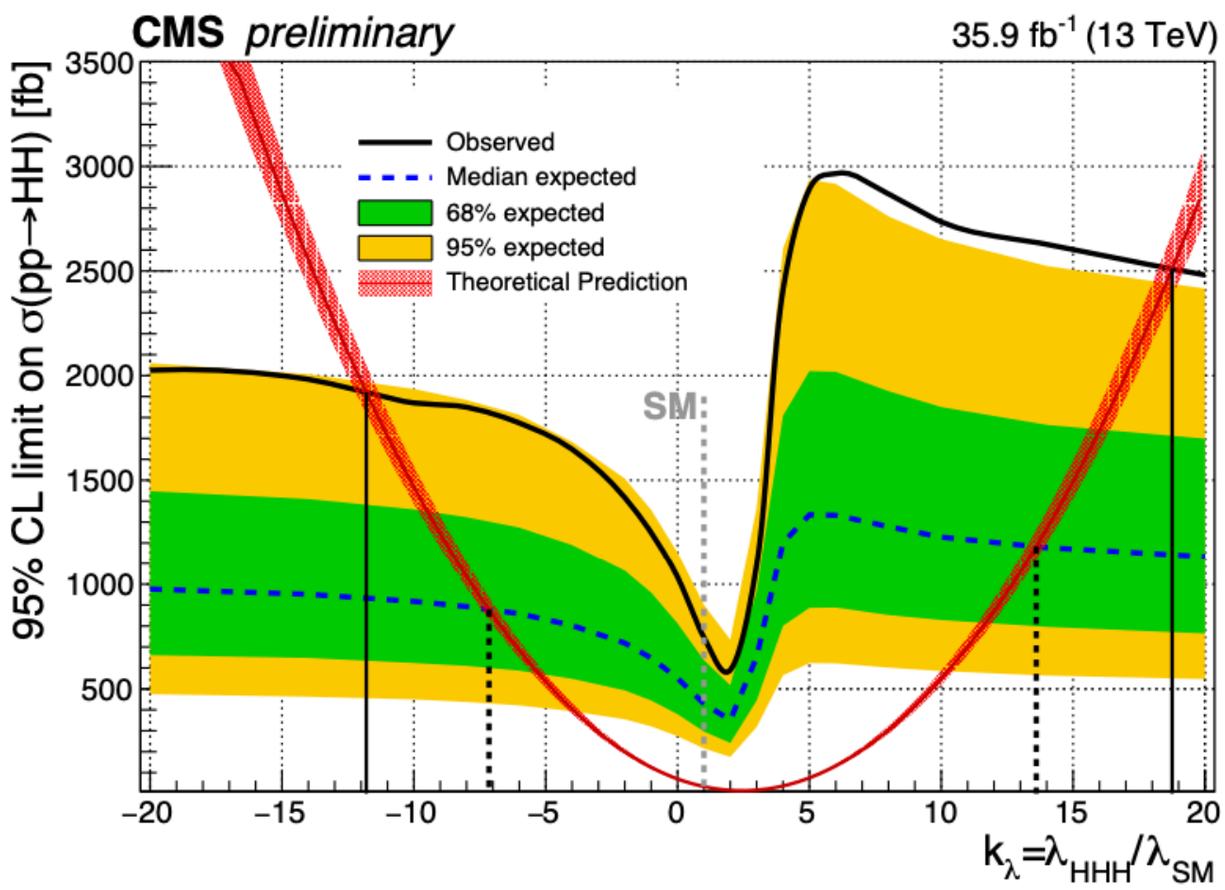
# CMS Results




**Combined limit on σ / $\sigma_{SM}$**
**Observed : 22.2**
**Expected : 12.8**

**Constraint on $k_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$**
**Observed : $-11.8 < k_\lambda < 18.8$**
**Expected : $-7.1 < k_\lambda < 13.6$**

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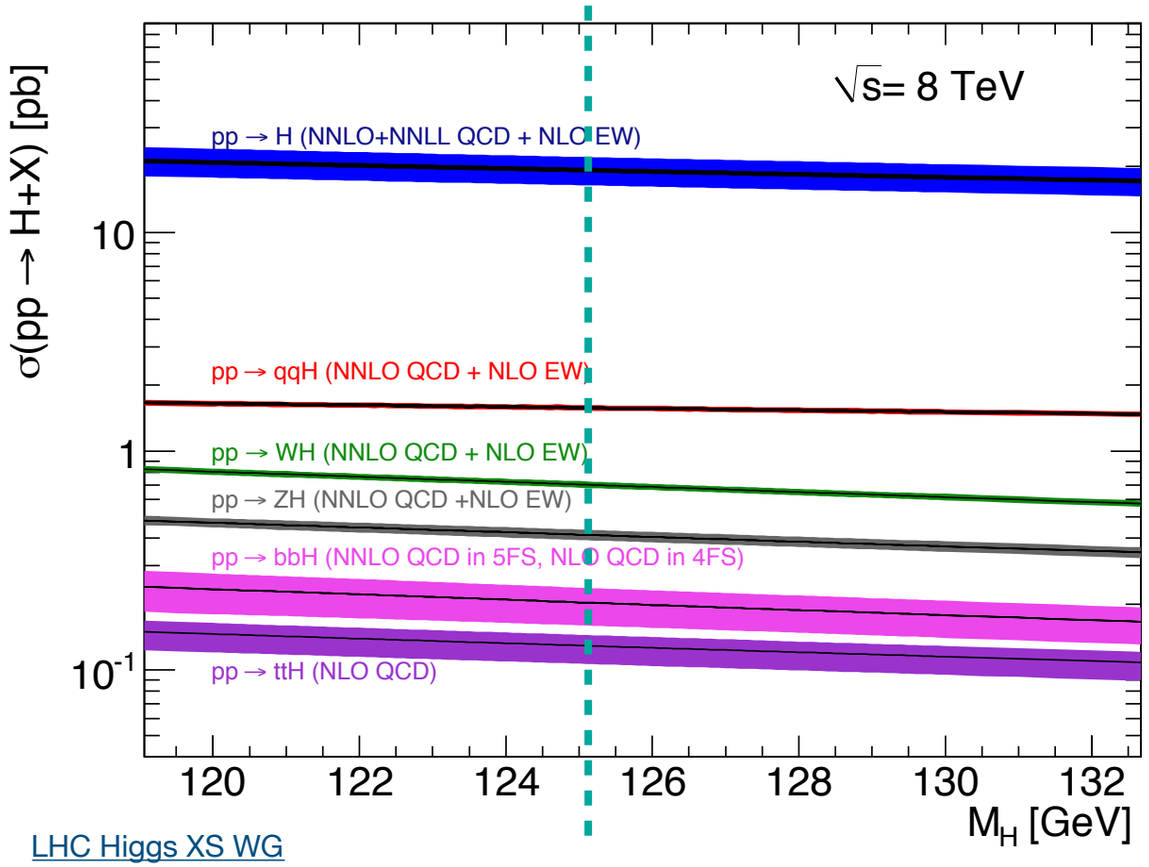
# The Higgs Boson




LHC Higgs XS WG

(for 13 TeV)

ggF = 87.3 %

VBF = 6.8%

}VH = 4.1%

}ttH + bbH = 1.8%



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