Combining di-Higgs decay channels to set limits on the di-Higgs cross-section with the ATLAS experiment

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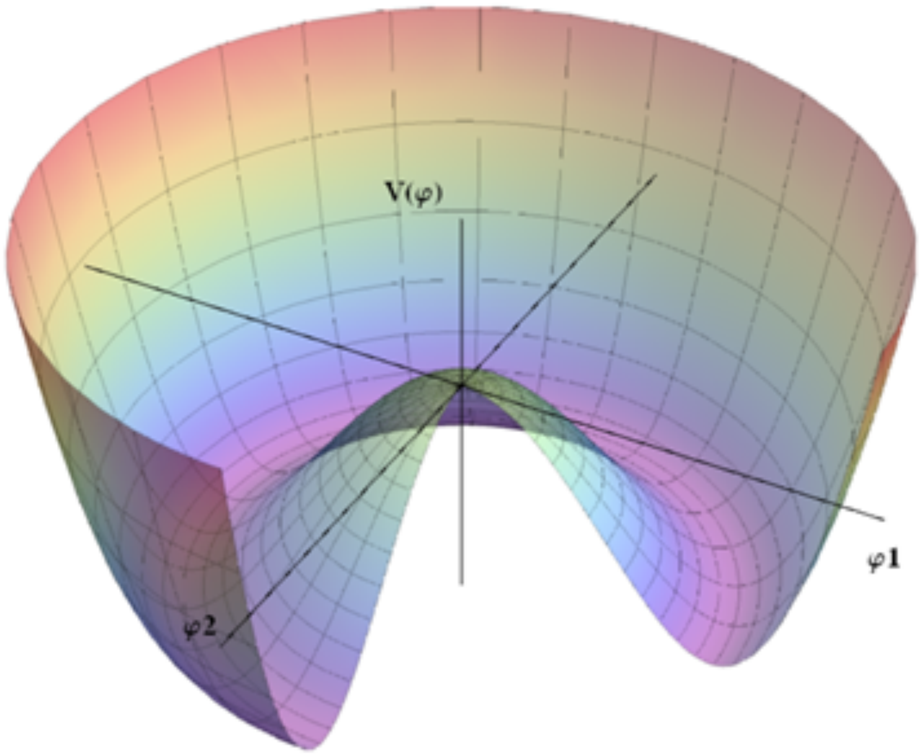
Introduction to di-Higgs Combination



- Since the discovery of the Higgs boson in 2012, the measurement of its couplings to other SM particles has become one of the main goal of the LHC
- One particular parameter of interest is the Higgs tri-linear self-coupling, $\boldsymbol{\lambda_3}$
- Measuring di-Higgs production allows the extraction of λ_3, and provides a probe into the accuracy of the SM or whether there are beyond SM physics present

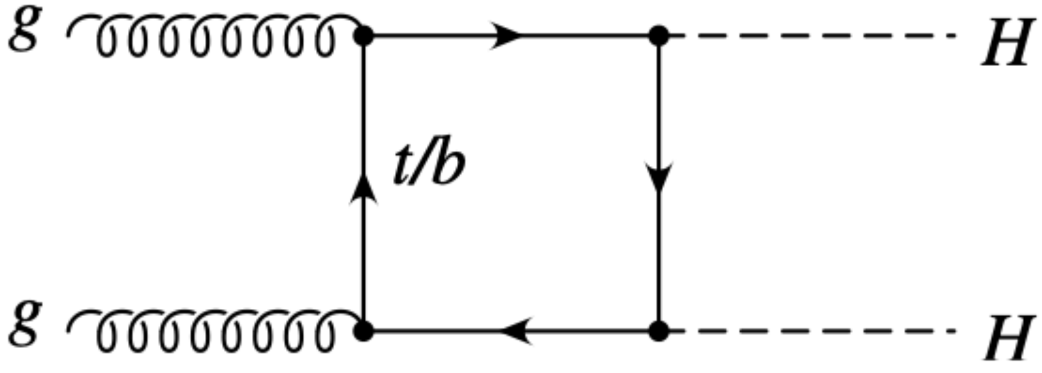
Introduction to di-Higgs Combination

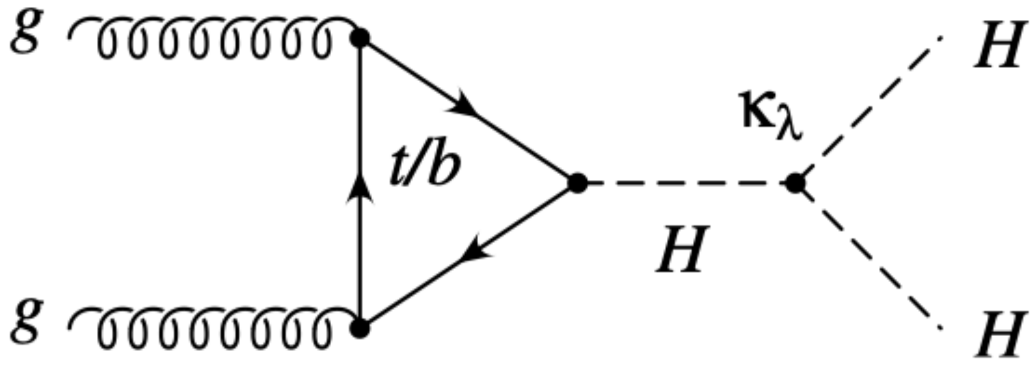
Goals of the HH combination:

Combine several di-Higgs analyses performed in different decay channels and different production modes in order to:

- set an upper limit on the overall di-Higgs production cross section (ggF + VBF)
- set constraints on Higgs couplings (κ_{λ}, κ_{t}, c_{2V}, c_{V}) and EFT benchmarks
- search for new physics in the form of new heavy resonances

di-Higgs Production: ggF





The Amplitude can be expressed as:

$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$$

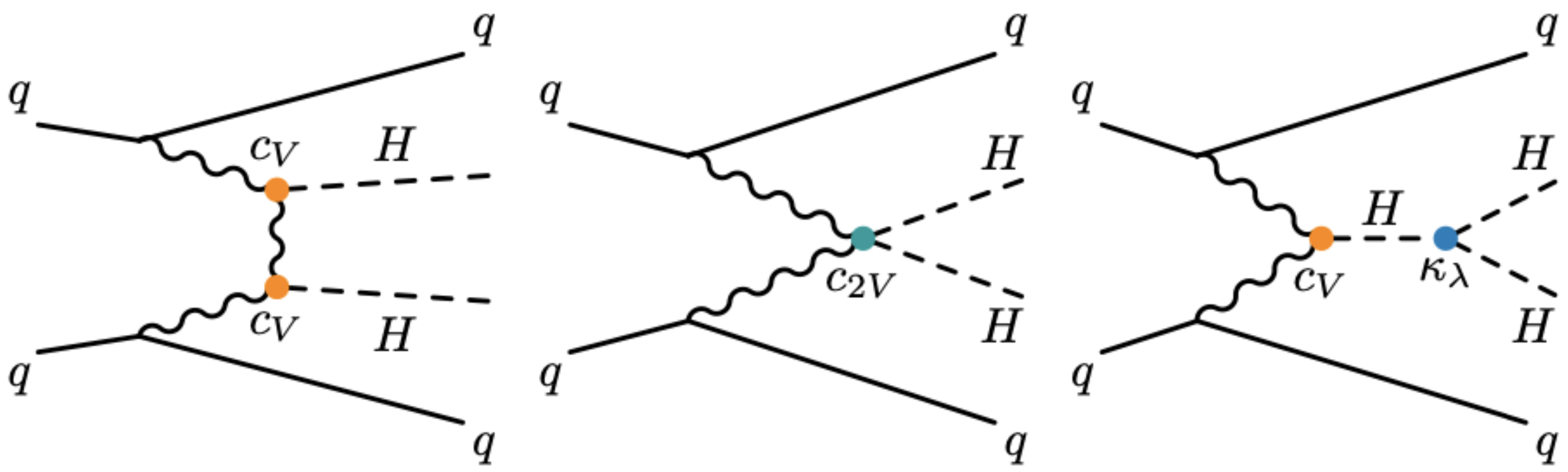
$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

$$|A(\kappa_t, \kappa_\lambda)|^2 = \kappa_t^2\left[\kappa_t^2|B|^2 + \kappa_t\kappa_\lambda(BT^* + TB^*) + \kappa_\lambda^2|T|^2\right]$$

$$\sigma_{ggF}(pp \to HH) \propto \int \kappa_t^4\left[|B|^2 + 2\left(\frac{\kappa_\lambda}{\kappa_t}\right)\mathcal{R}(B^*T) + \left(\frac{\kappa_\lambda}{\kappa_t}\right)^2|T|^2\right]$$

The destructive interference causes a small SM cross section: 31.05 fb at $\sqrt{s} = 13$ TeV.

di-Higgs Production: VBF

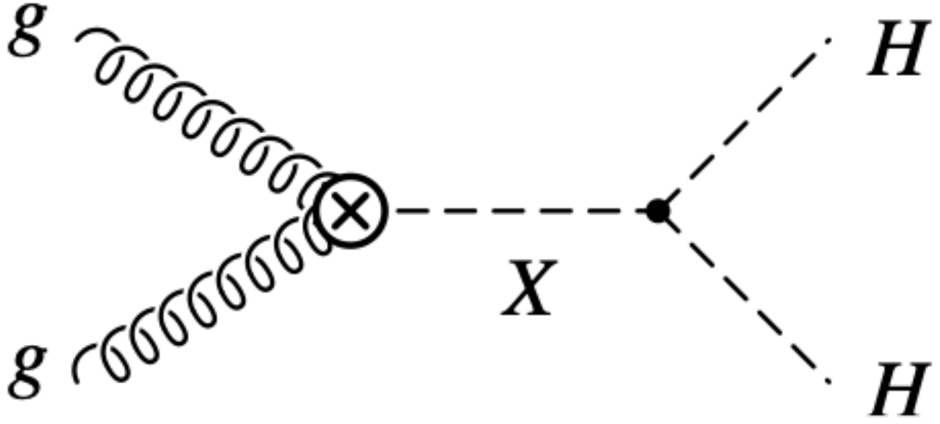


- VBF production cross section and kinematics depend on the VVHH (c_{2V}), VVH (c_V) and the HHH (κ_λ) couplings

- c_{2V} = c_v = 1 if Standard Model

SM cross section:
1.73 fb at $\sqrt{s} = 13$ TeV.
~ 17 times smaller than ggF.

di-Higgs Production: Resonant



- HH production can be used to search for new physics
- New matter which modifies the Higgs self-coupling and enhances the HH cross section:

$$\frac{\sigma}{\sigma_{SM}} > 1$$

X = New Particle

Examples:

- Spin 0 particle: X = S, S is a new scalar particle
- Spin 2 particle: X = G, Randall-Sundrum graviton

- Different models and different X masses allows for different sizes of enhancement to the cross section

di-Higgs Combination: Input Analyses

The full Run 2 di-Higgs analyses are performed in 6 channels:

- bbbb
- bbττ
- bbγγ
- bbll - covering bbVV, bbττ and bbZZ decays in 2 leptonic final states.
- bbVV - 1 lepton and 0 lepton.
- multilepton - covers all other decay channels

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

di-Higgs Combination: Input Analyses

Non-resonant combination:

- Combine all contributing channels for SM cross section limit (taking into account ggF and VBF)
- Combine most sensitive channels (bbbb, bbττ, bbγγ, bbll?) for κ_λ scan
- Combine most sensitive channels for c_{2V} scan
- Combine HH with H for couplings constraints

Resonant combination:

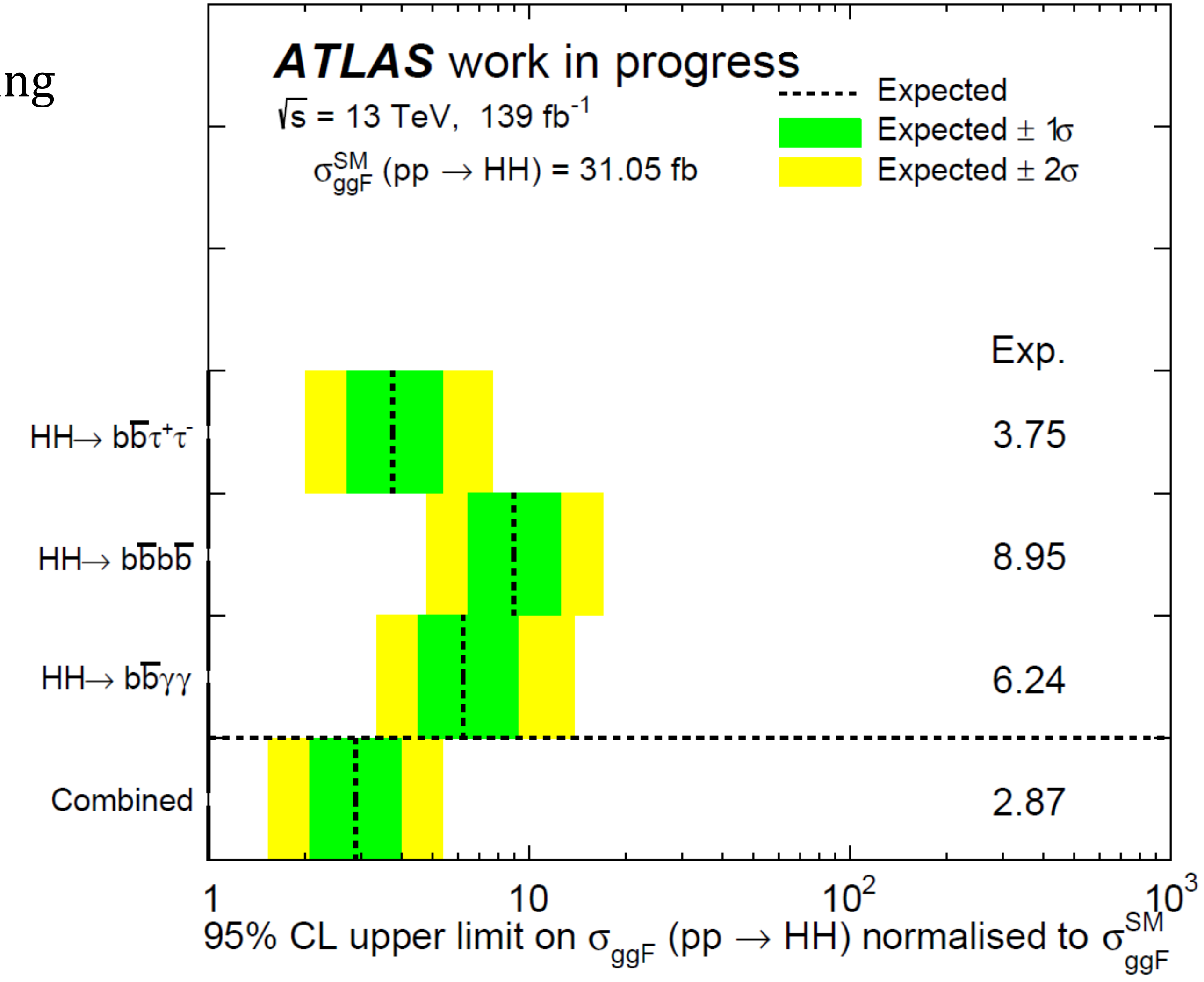
- Combine most sensitive channels for ggF $X \rightarrow HH$ search (bbbb, bbττ, bbγγ, bbll?)
- Combine ggF $X \rightarrow HH$ with Heavy Resonance combination

di-Higgs Combination: Orthogonality Checks

- Most analyses are orthogonal by definition, few exceptions may still exist and need to be checked:
    - Check cross channels that enter the HH combination
    - Checks between single Higgs and HH channels
    - Checks with the Heavy resonance combination
- Several checks already completed and show healthy results between HH channels
- Overlap studies are now starting within single Higgs analyses

di-Higgs Combination: Preparation and Preliminary Results

- **Preliminary** expected limits set on the HH production cross-section assuming κ_λ =, 1, combining bbbb, bbττ and bbγγ
- Further improvements expected from analyses improvements which are being investigated and implemented
- Will also include bbll, bbVV and multilepton
- These limits are updated along side the individual analyses – **these are not final expected limits**

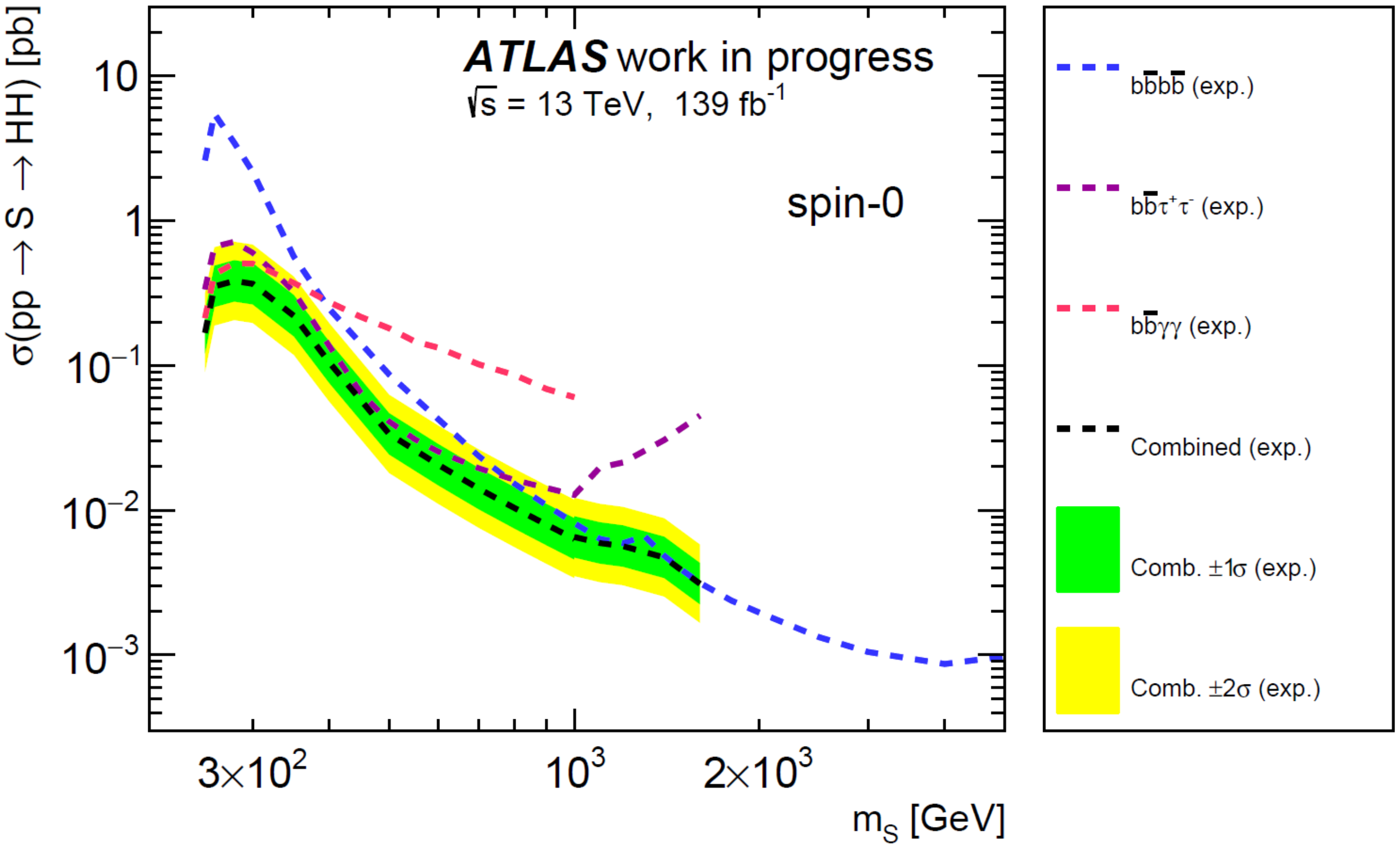


36 fb^{-1} result: 6.9 obs, 10 exp

arxiv:1906.02025

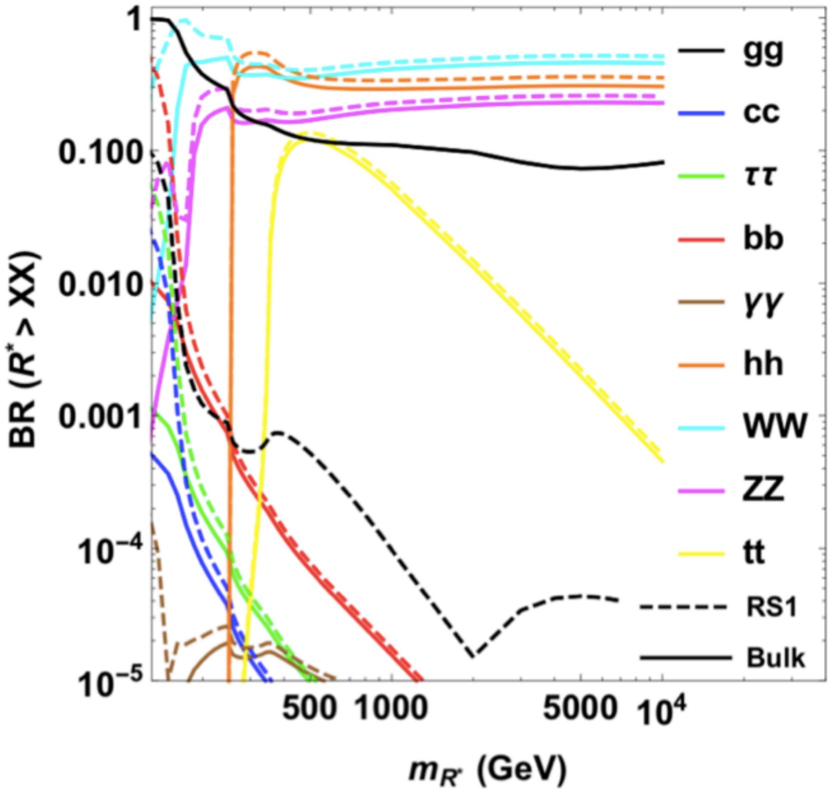
di-Higgs Combination: Preparation and Preliminary Results

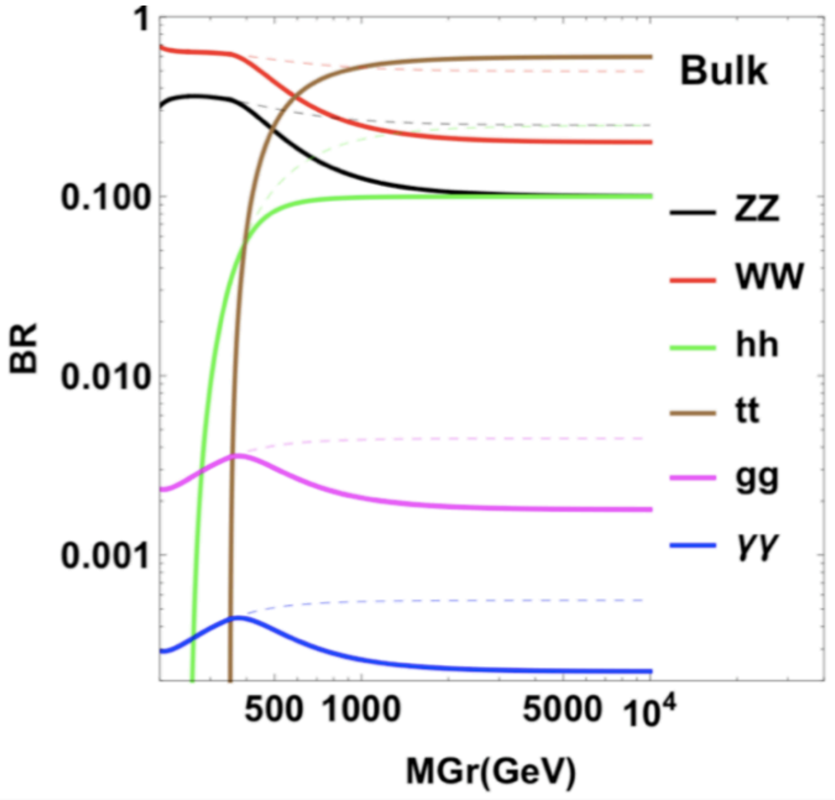
- **Preliminary** resonant expected upper limits for ggF spin 0, σ (pp→ X → HH)
- Limits set on the HH production cross section as a function of the resonance mass X in the hypothesis of a narrow width scalar produced via ggF
- Combined bbbb, bbττ, bbγγ in region 251 – 1000 GeV. bbbb and bbττ only in 1000 – 1600 GeV mass range. bbbb only between 1600 – 5000 GeV mass range
- These limits are updated along side the individual analyses



Future Plans: Resonant Combination

- Plan to combine HH channels with Heavy Resonance Combination for resonant searches
- Spin-0 Radion: HH BR in 300 GeV - 500 GeV is dominant and > 500 GeV above is comparable to WW/ZZ
- Spin-2 Graviton: HH BR above 1 TeV comparable to ZZ

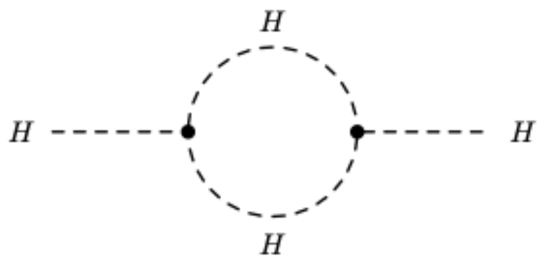


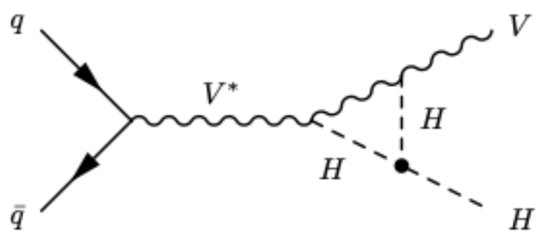


Future Plans: Non Resonant Combination

Plan to combine again HH and H analyses when individual combinations with full Run 2 data are ready:

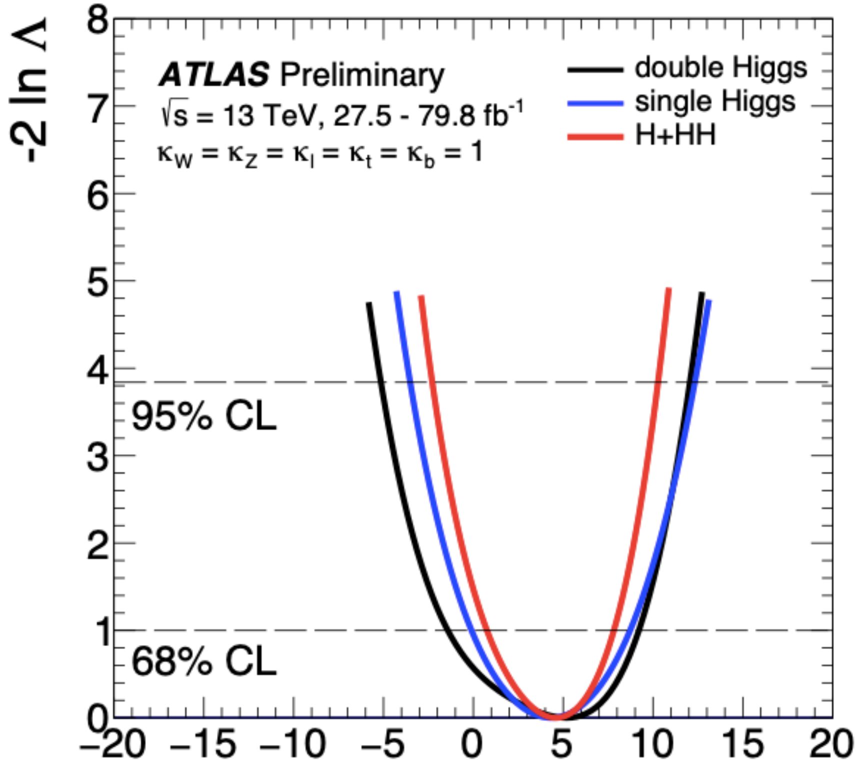
- κ_λ can be extracted in HH at LO and H at NLO EW





- Set more stringent constraints on κ_λ assuming other Higgs couplings take their SM values

- Set constraints on κ_λ and c_{2V} with less assumptions on the other Higgs couplings that can be constrained by the single-Higgs analysis



$$-2.3 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 10.3$$

ATLAS-CONF-2019-049

Summary

- By combining di-Higgs decay channels, we can set further constraints on the di-Higgs cross-section for both non-resonant and resonant searches using the full Run 2 data from the ATLAS experiment

- Continue to update and investigate combined workspaces as updates become available from individual channels

- Future plans to combine the di-Higgs channels with single-Higgs channels for further constraints on κ_λ and to combine di-Higgs with Heavy Resonance combination

Thank you

BACK – UP

Future Plans: Non Resonant Combination

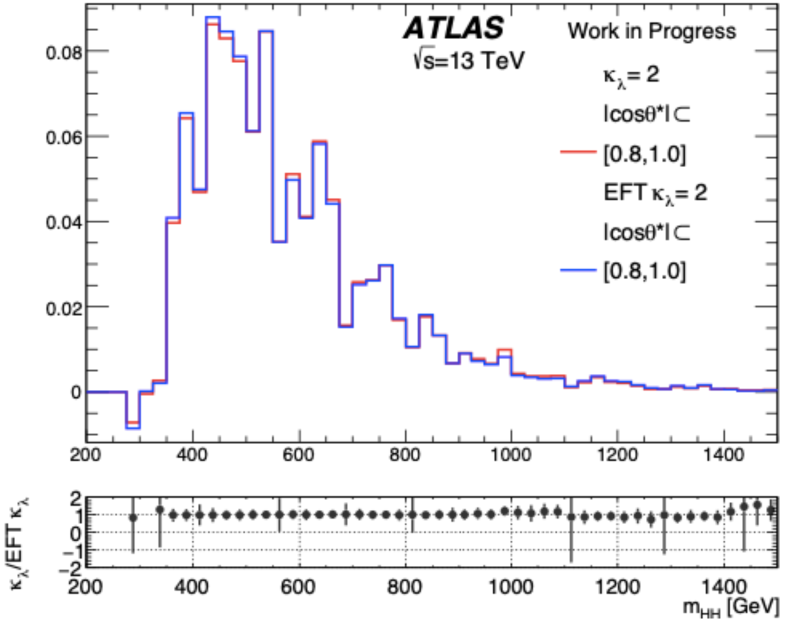
Started investigating possible EFT interpretation in HH, investigating both:

- **HEFT** (non-linear, Higgs field is an EW singlet, non SM-like, in chiral Lagrangian)

  - Benchmark points presented in JHEP04(2016)126 and already used by CMS and investigated for LO.

  - Reweighting in m_{HH} and cosθ* based on the parameterisation in arxiv:1710.08261 being implemented, method checked against old reweighting method for κ_λ when turning off all other coefficients (enough to reweight in m_{HH}).

  - Now possible to do EFT interpretations at NLO.



- **SMEFT** (linear, respects the SM symmetries where the Higgs is an SU(2) doublet)

  - Starting generating distributions with different SM EFT parameters using the model SMEFTatNLO and studying effects on HH kinematic (1D and 2D scans to investigate correlations).

di-Higgs Combination: Non Resonant Signal Reweighting

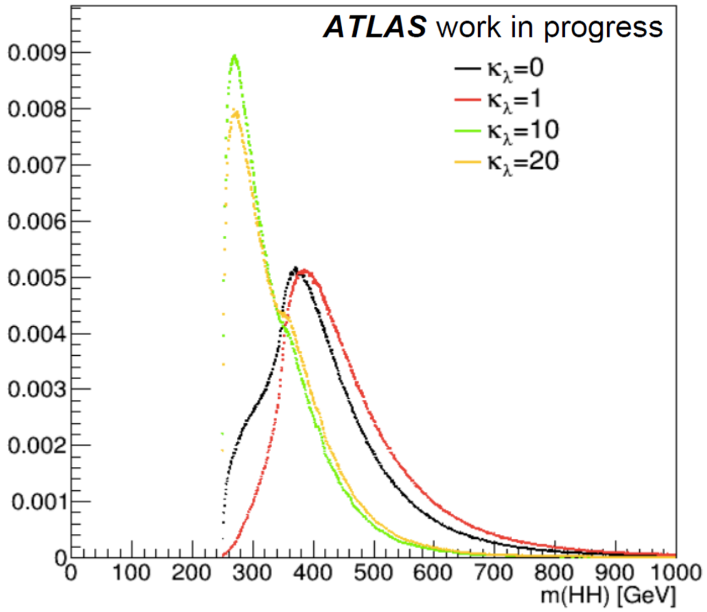
- For the couplings scans, analyses need simulations for many couplings values; computationally expensive → reweight from SM samples.
- For κ_λ scan:
  1. Generate truth m_{HH} distributions for κ_λ =0, 1, 10, 20

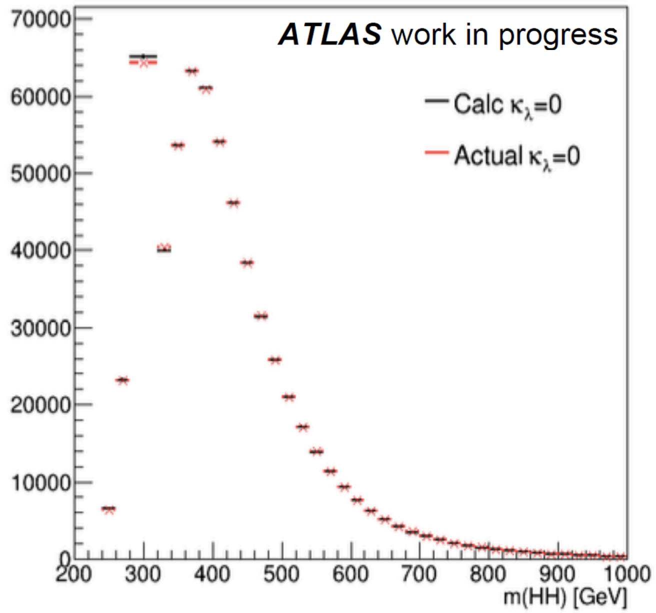
  2. Obtain general κ_λ distribution from 3 generated distributions (κ_λ =0, 1, 20) from
  $$\frac{d\sigma}{dm_{HH}}(m_{HH}) = A(m_{HH}) + B(m_{HH})\kappa_\lambda + C(m_{HH})\kappa_\lambda^2$$

  3. Weights evaluated as ratio of two m_{HH} histograms.

  4. Central re-weighting tool to be used by all analyses to apply the weights.

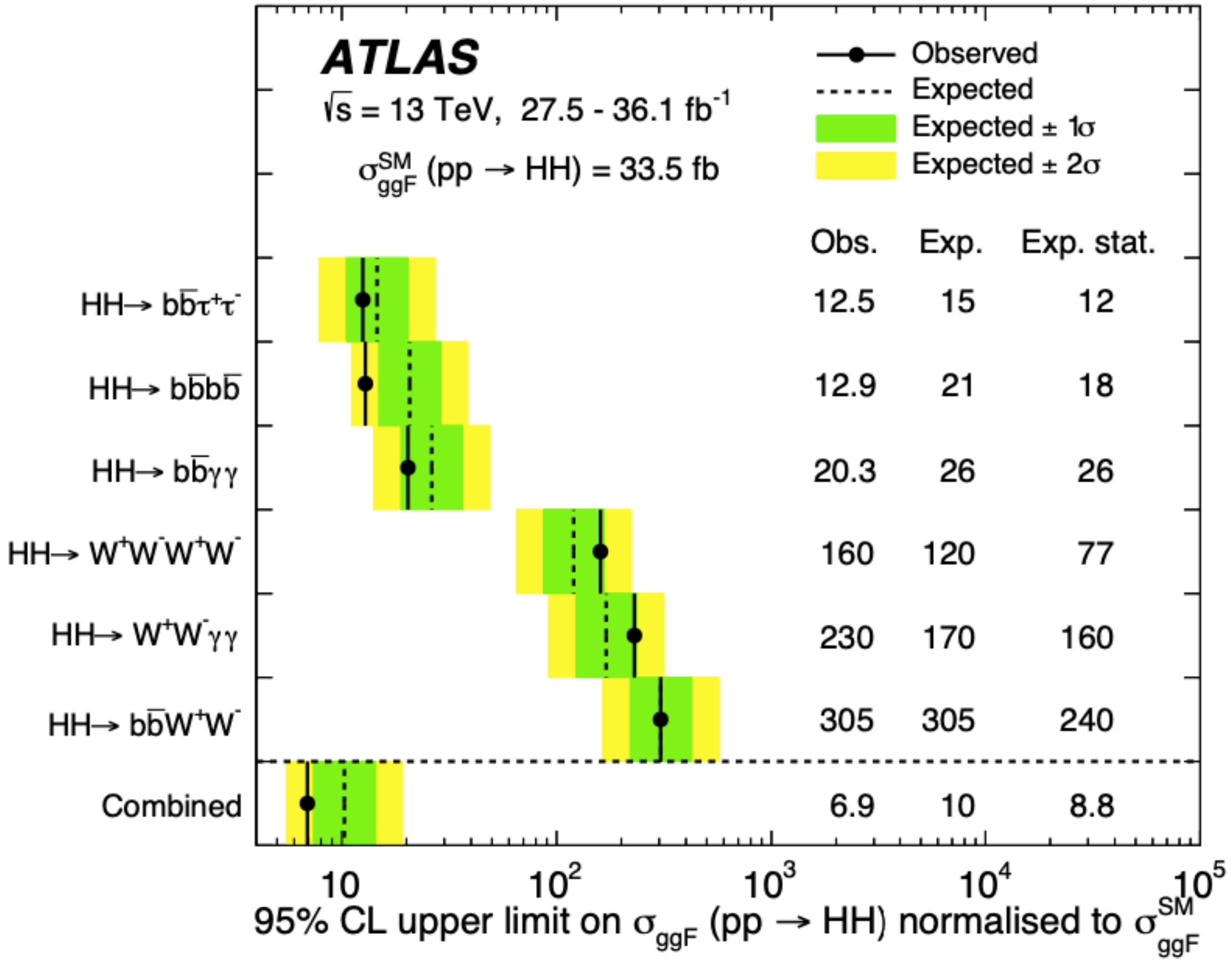
Michael Hank





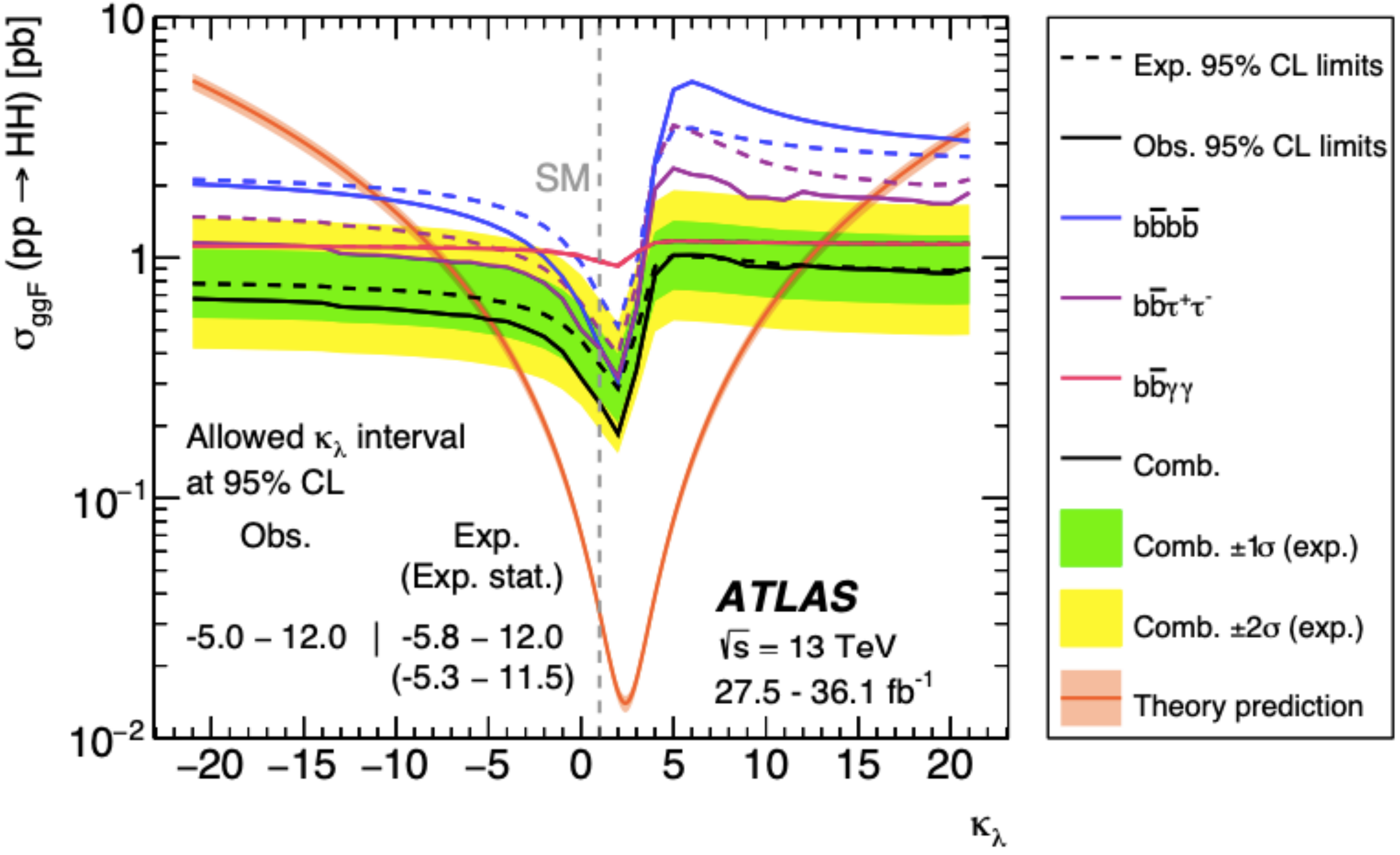
- Reweighting method in place for ggF κ_λ variations
  Plan to also include VBF κ_λ and c_{2V} variations and as well as EFT couplings variations.

Previous Results: Non Resonant



arxiv:1906.02025

Previous Results: Non Resonant



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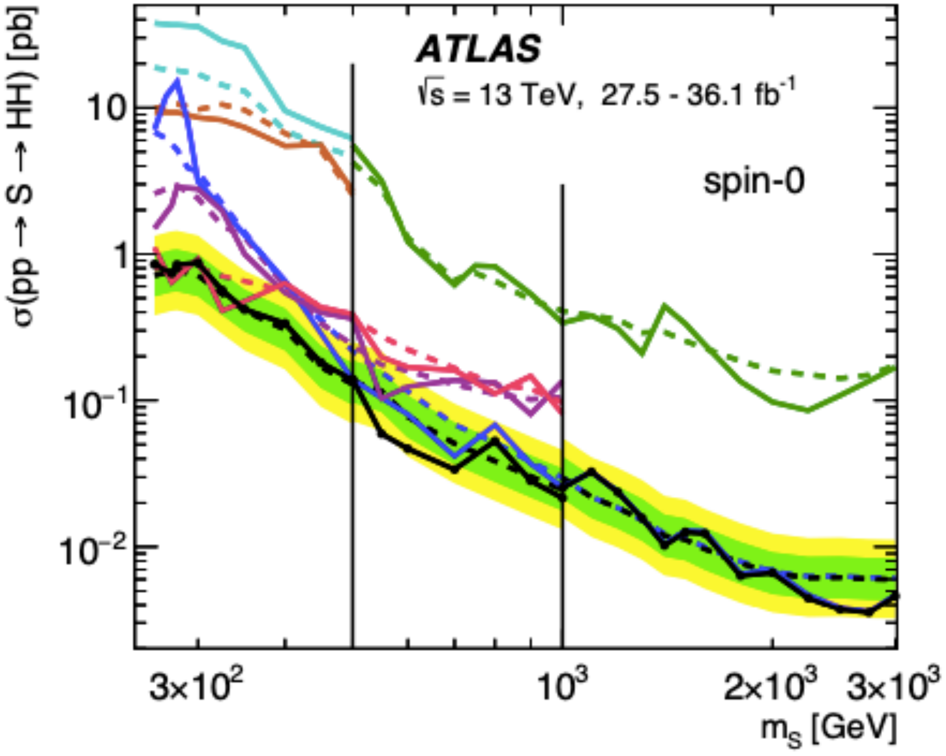
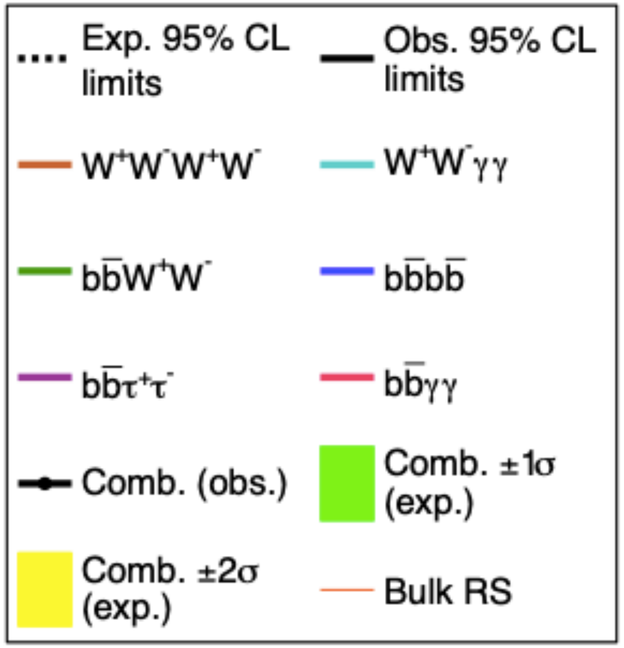
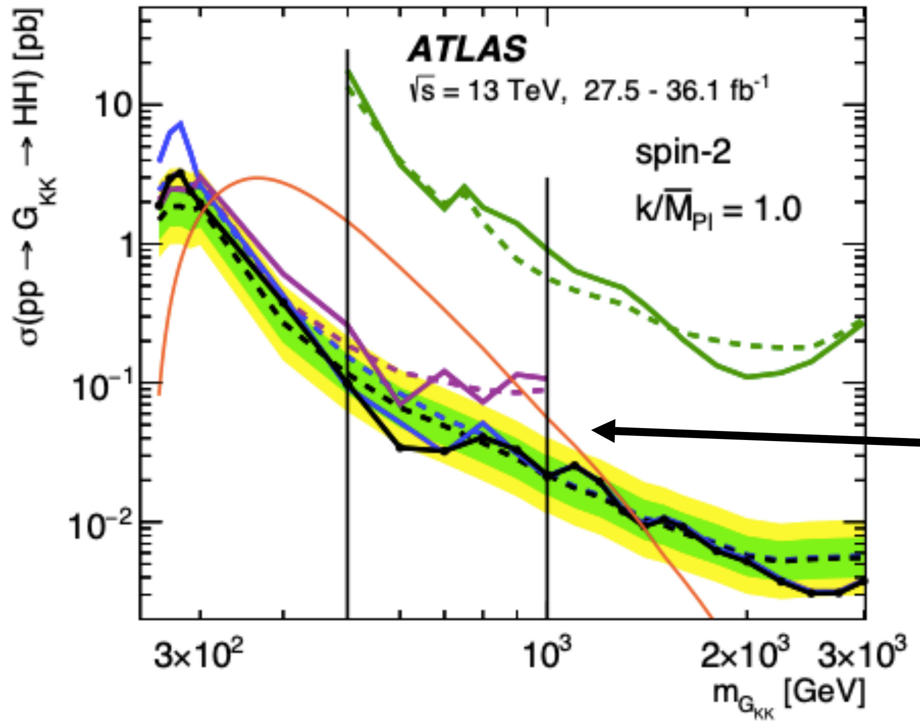
Previous Results: Resonant Spin-0



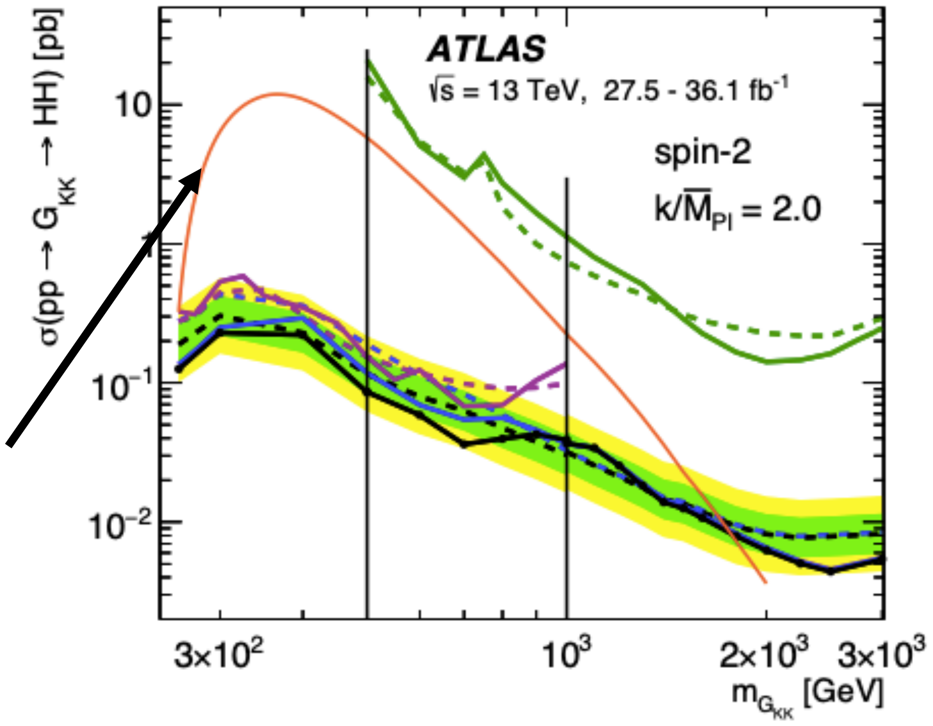


[arxiv:1906.02025](https://arxiv.org/abs/1906.02025)

Previous Results: Resonant Spin-2



Bulk RS



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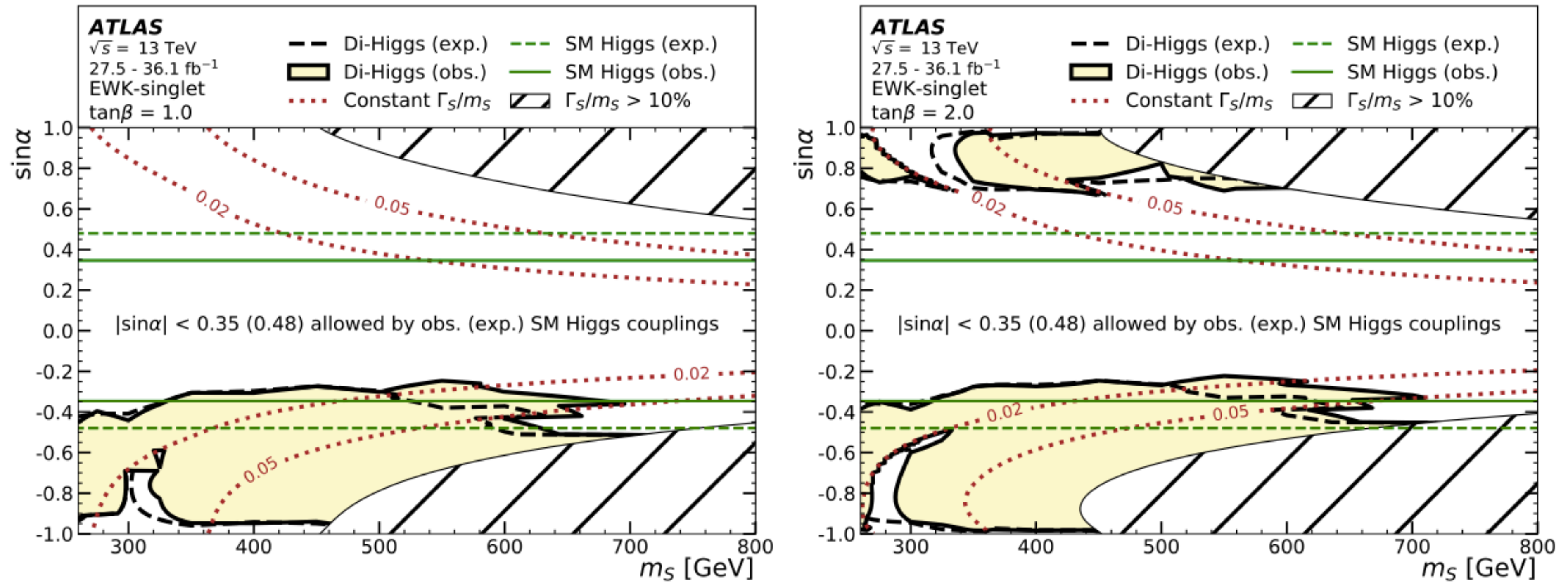
Previous Results: Resonant Spin-0

Exclusion limits were presented also as constraints on the hMSSM and EWK-singlet models.
Excluded regions for the EWK-singlet model in the plane mS–sin α for for tan β = 1 and for tan β = 2:



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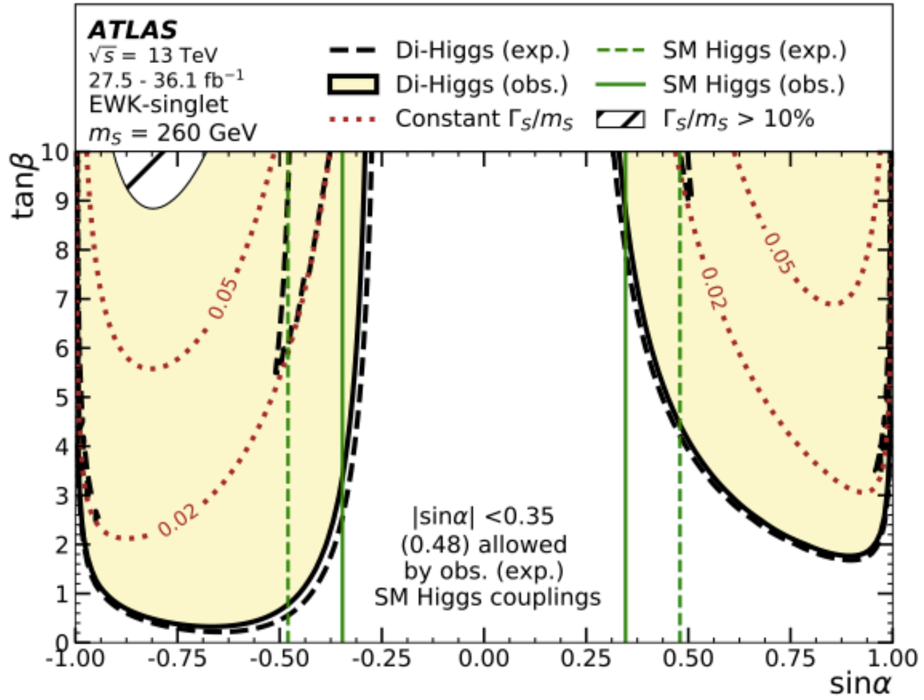
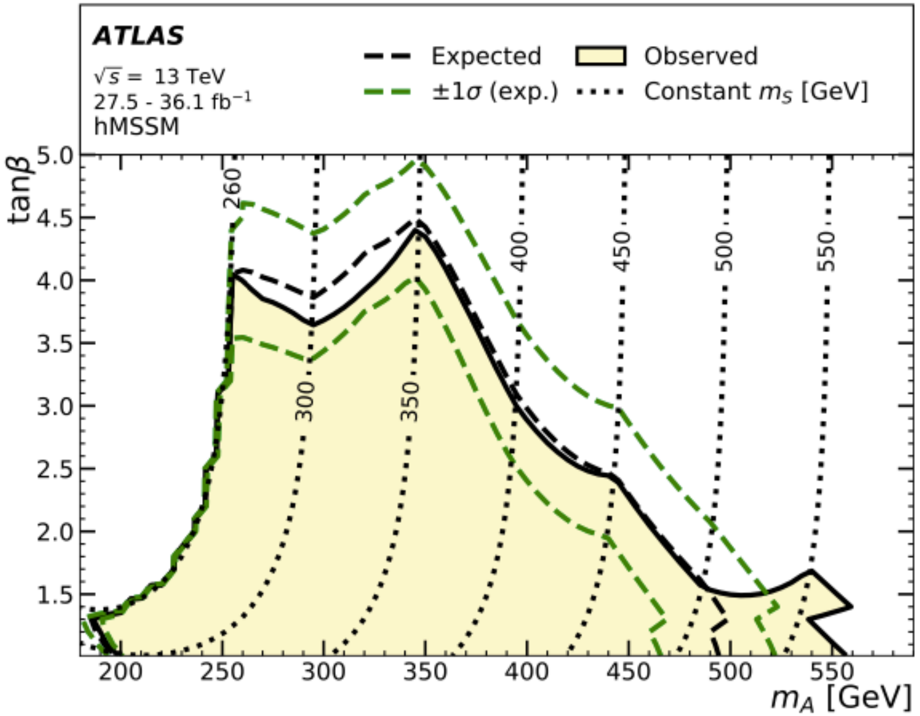
Previous Results: Resonant Spin-0

Exclusion limits were presented also as constraints on the hMSSM and EWK-singlet models.
Excluded regions for the EWK-singlet model in the plane (sin α, tan β) for mS = 260 GeV and for the hMMSM model in the plane mA–tan β:





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