Di-Higgs and BSM Higgs Search at LHC

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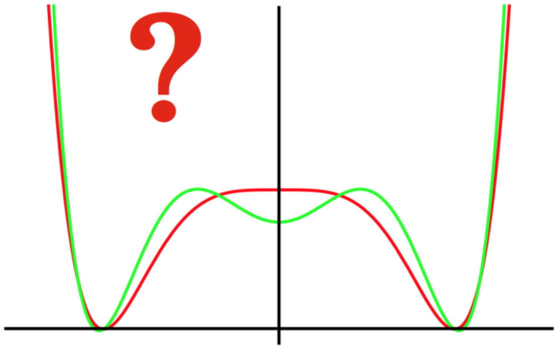
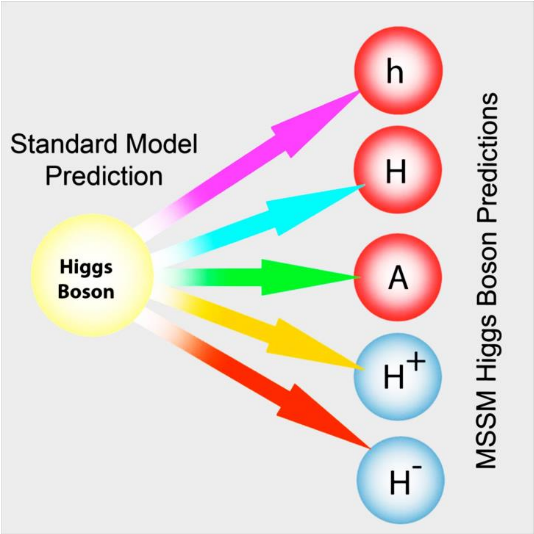
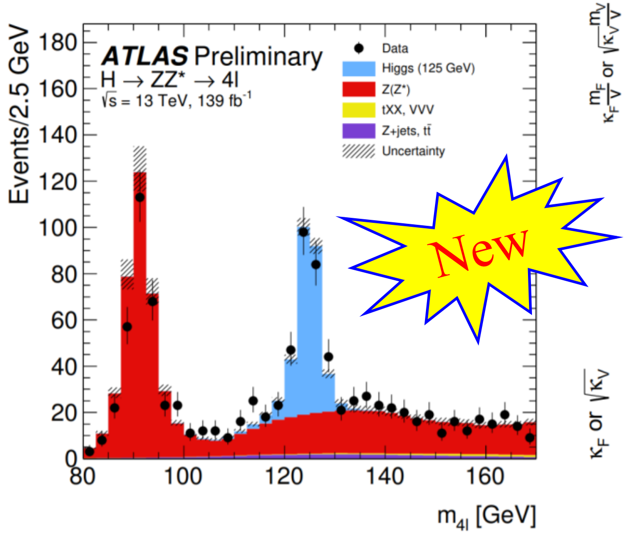
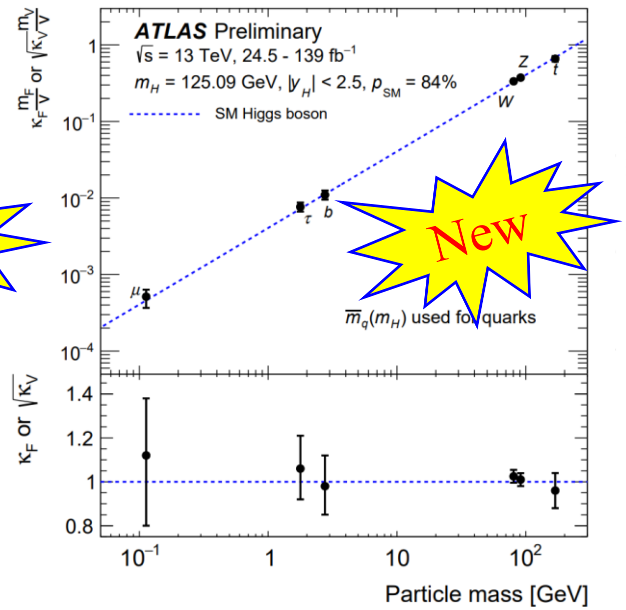


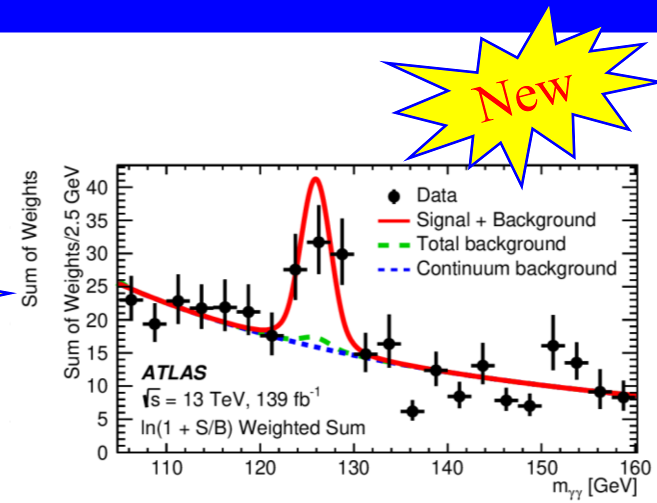


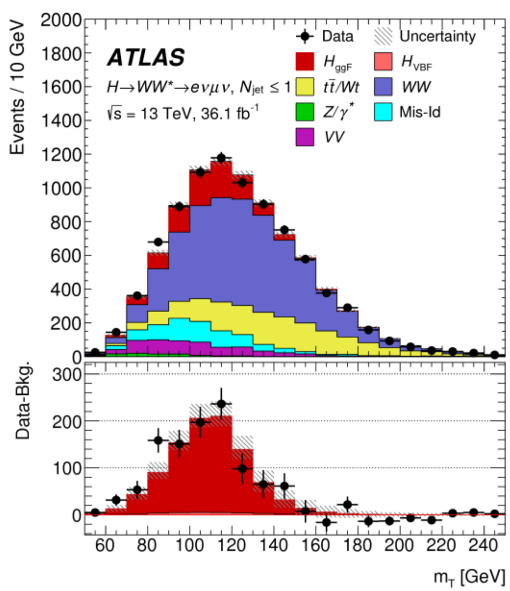
EWPT workshop at IHEP, 31 Jul. 2020

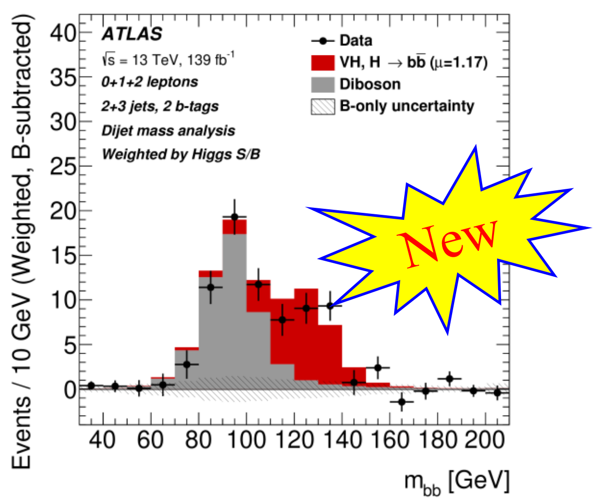
Higgs boson established, solidly!

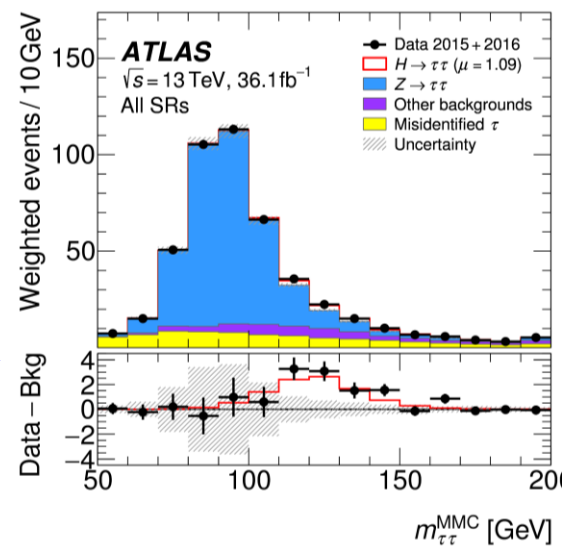




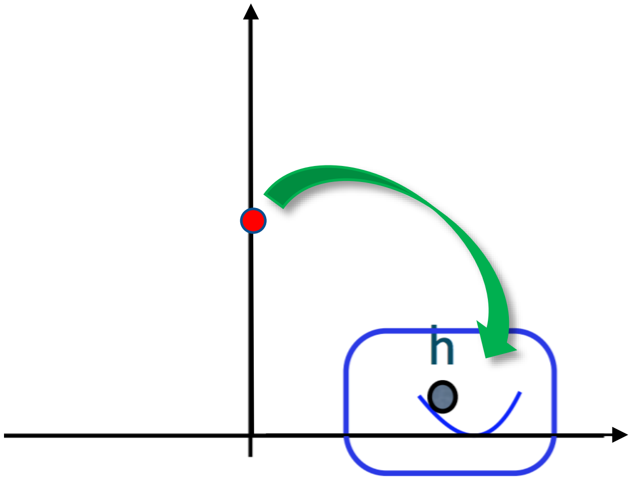






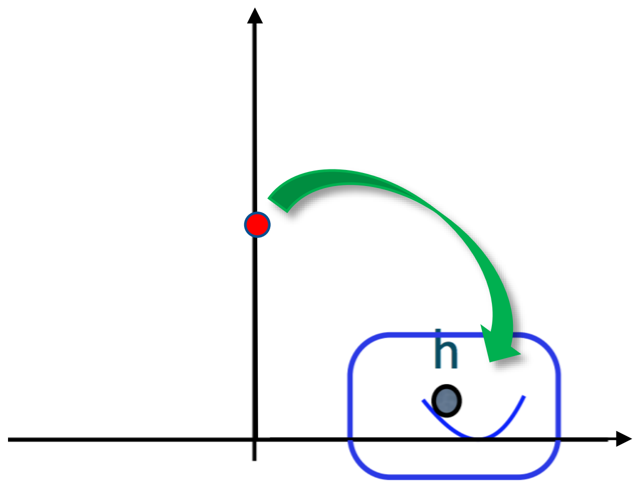


How it happened?



- We knows the beginning and we know the ending
- But no clue in between

How it happened?



- We knows the beginning and we know the ending
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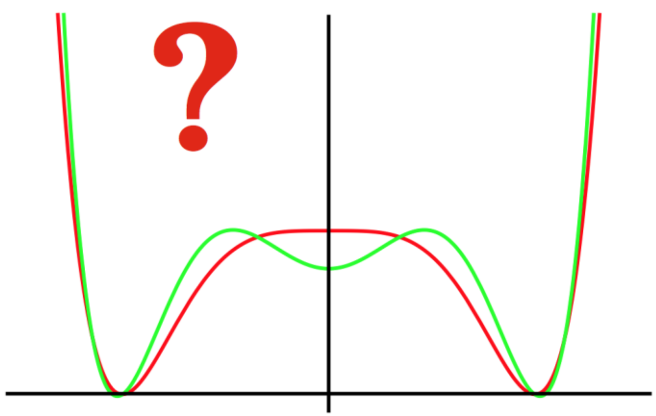


- SM assumed simplest form

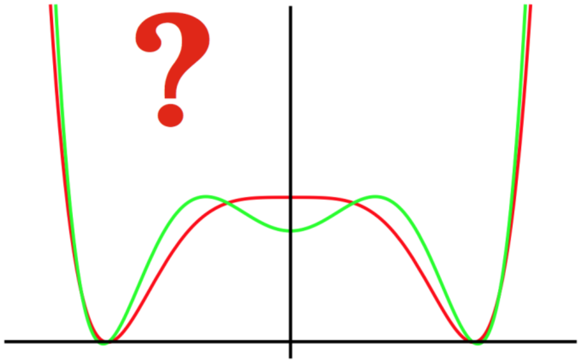
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

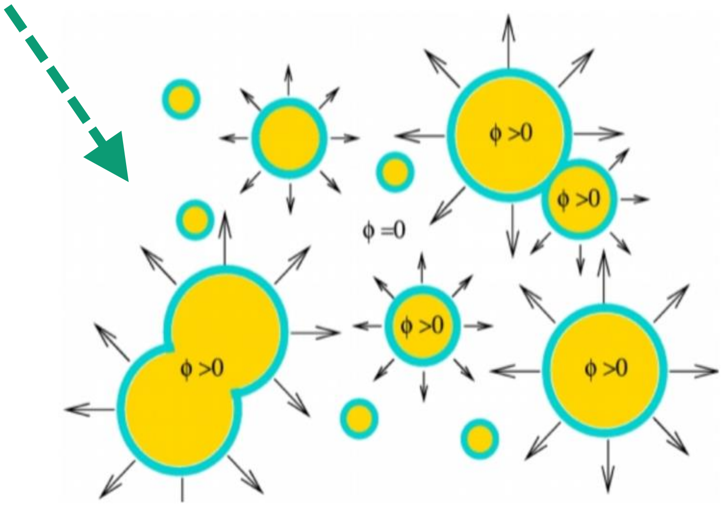
- Nature can be a bit more complicated

$$V' = V + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

Who cares?

Electro-Weak Phase Transition: **1st order** or **2nd order** ?





Sakharov Conditions

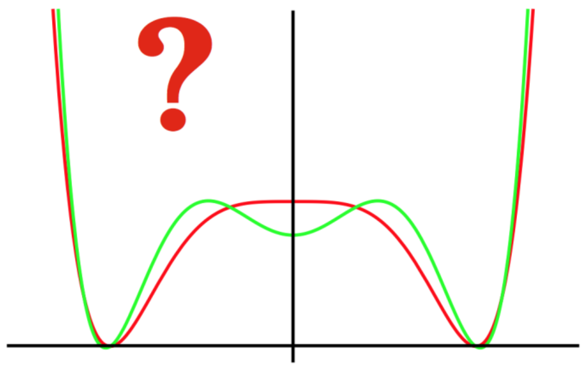
1) B Violation; 2) C/CP Violation

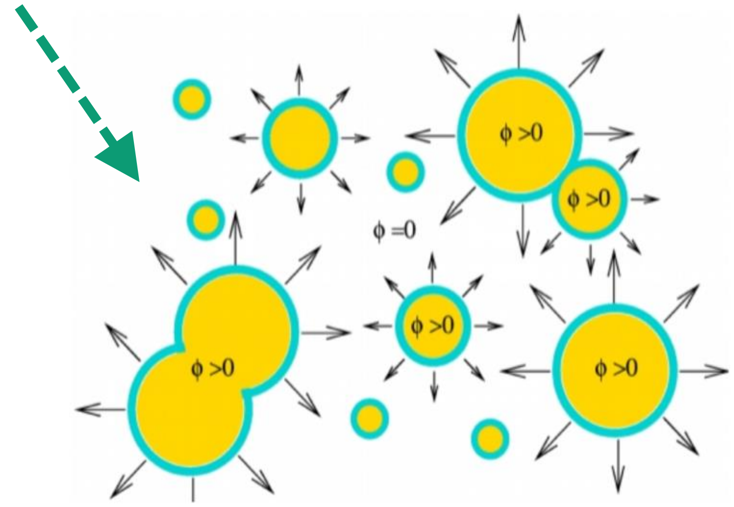
3) Departure from Thermal Equilibrium

(EW Phase Transition)

Who cares?

Electro-Weak Phase Transition: **1st order** or **2nd order** ?



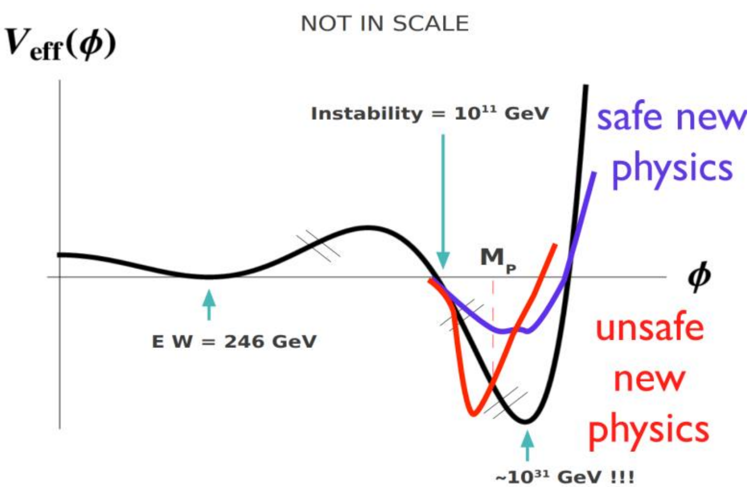


Sakharov Conditions

1) B Violation; 2) C/CP Violation

3) Departure from Thermal Equilibrium

(likely EW Phase Transition)



Is the current vacuum stable?

Probe Higgs potential

- Expand Higgs potential about the minimum

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \Rightarrow V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

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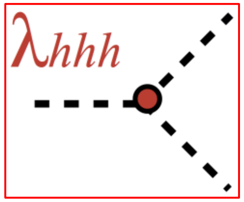
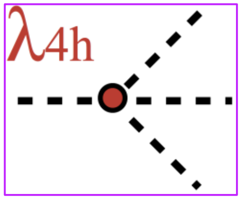
$$= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

m_H对应曲率





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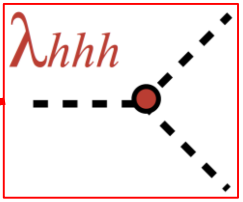
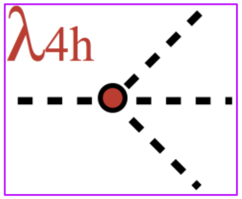
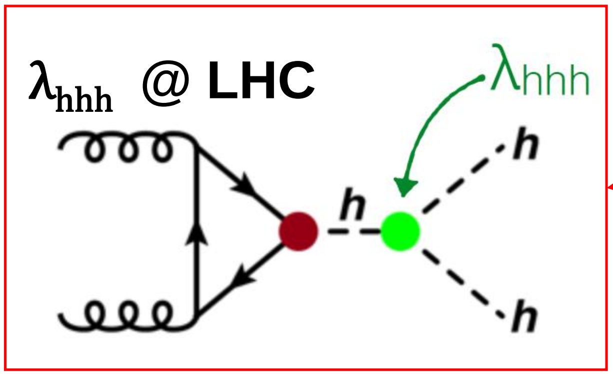






Standard Model:

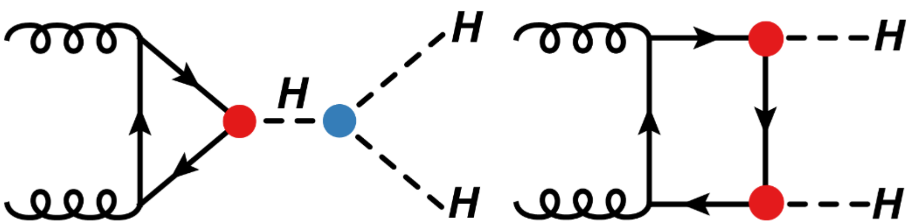
$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

- Higgs-self coupling (λ_{hhh}) is crucial for probing Higgs potential
- λ_{hhh} can be measured in double Higgs production (di-Higgs) at LHC

Di-Higgs at LHC

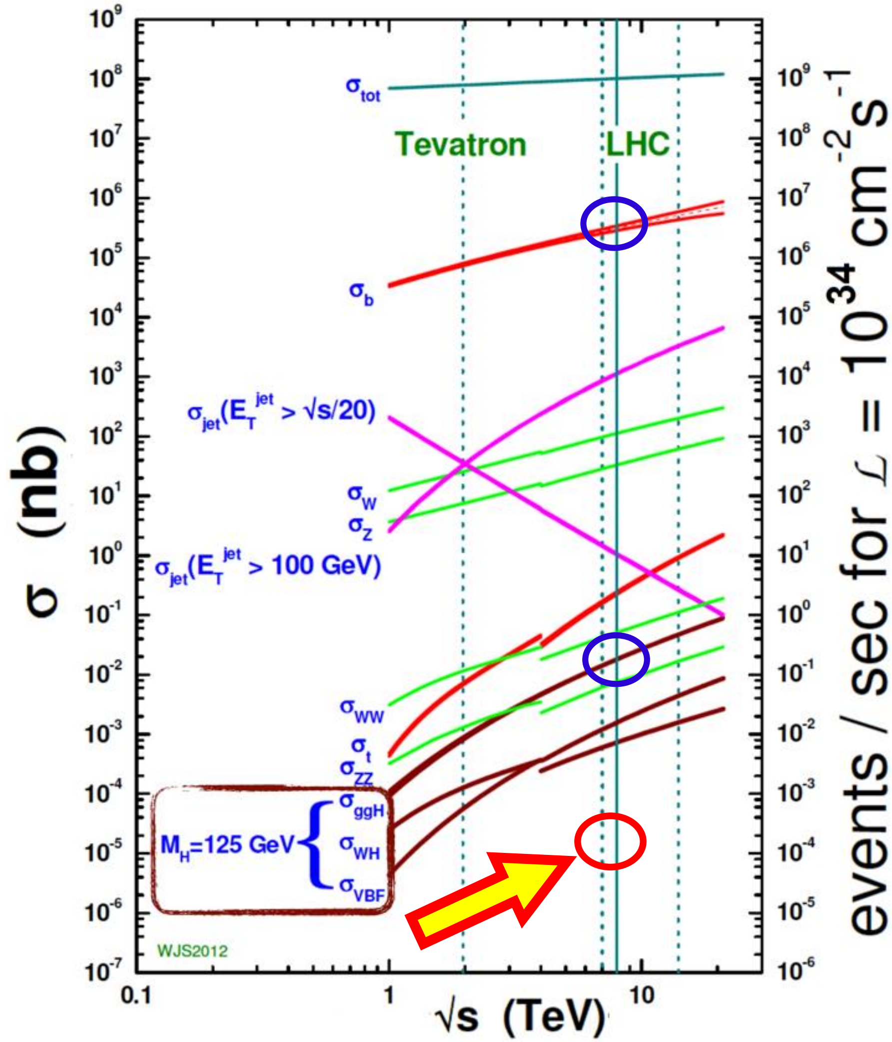
LHC @ 13 TeV

$$\sigma^{\mathrm{SM}}_{\mathrm{ggF}}(pp \rightarrow HH) = 33.5^{+2.4}_{-2.8}\ \mathrm{fb}$$



- Cross section: 1000+ times smaller than single Higgs

proton-(anti) proton cross section



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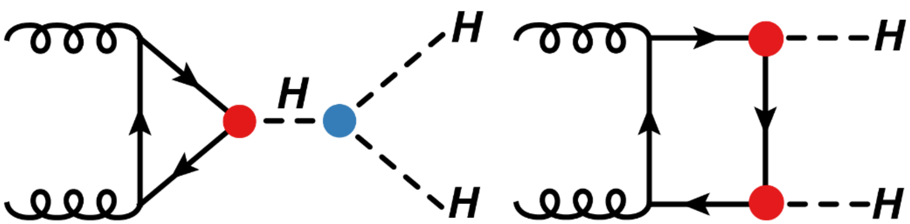
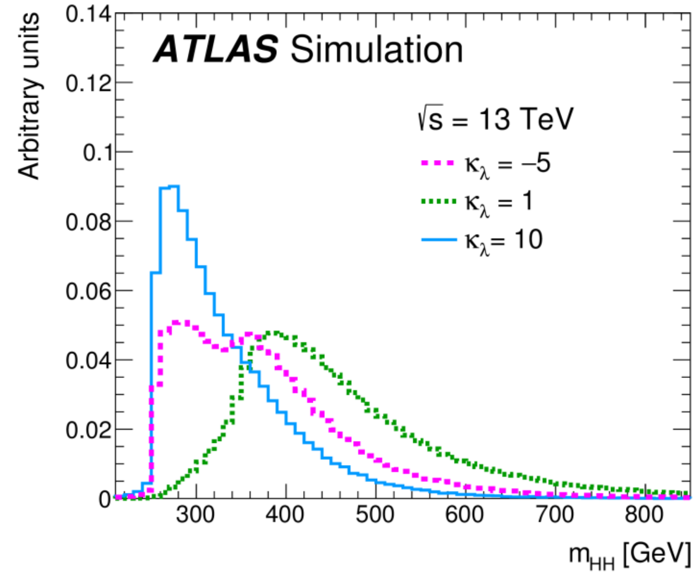
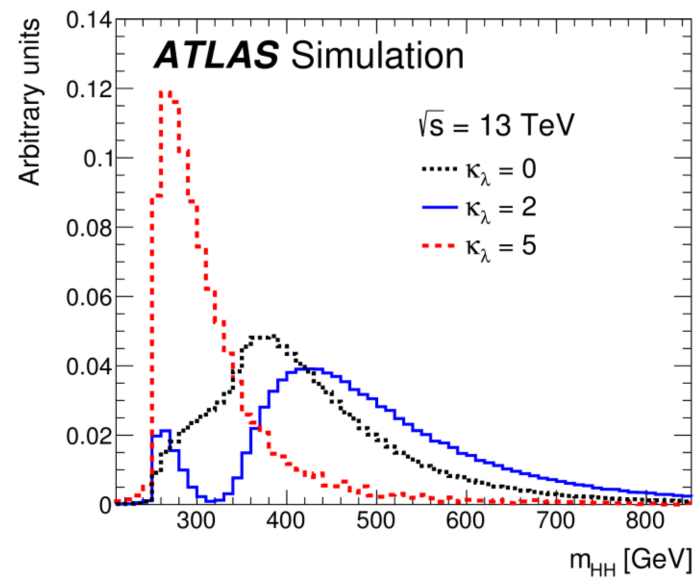


- Cross section: 1000+ times smaller than single Higgs
- Deconstructive interference, further adding difficulties





Di-Higgs at LHC

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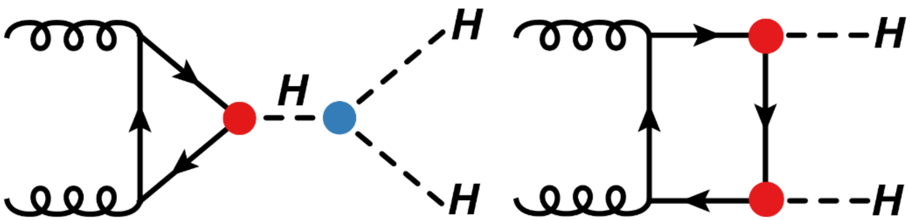
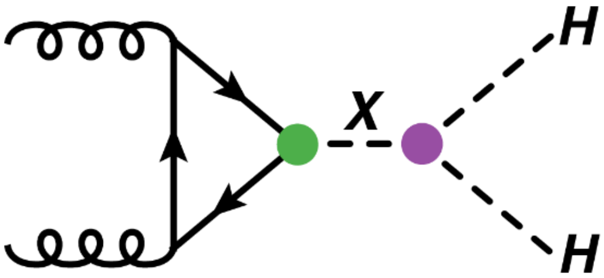
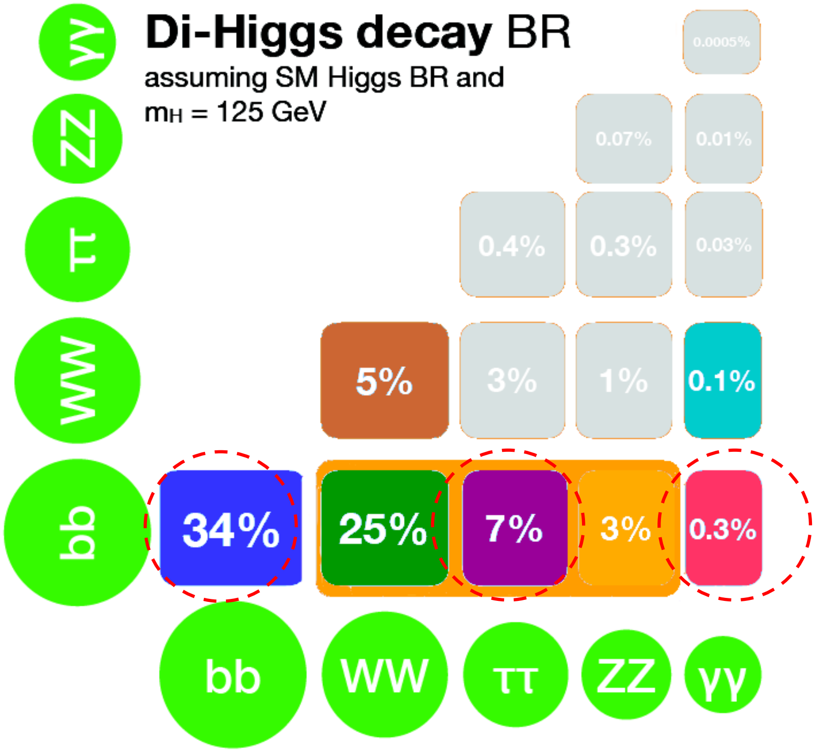


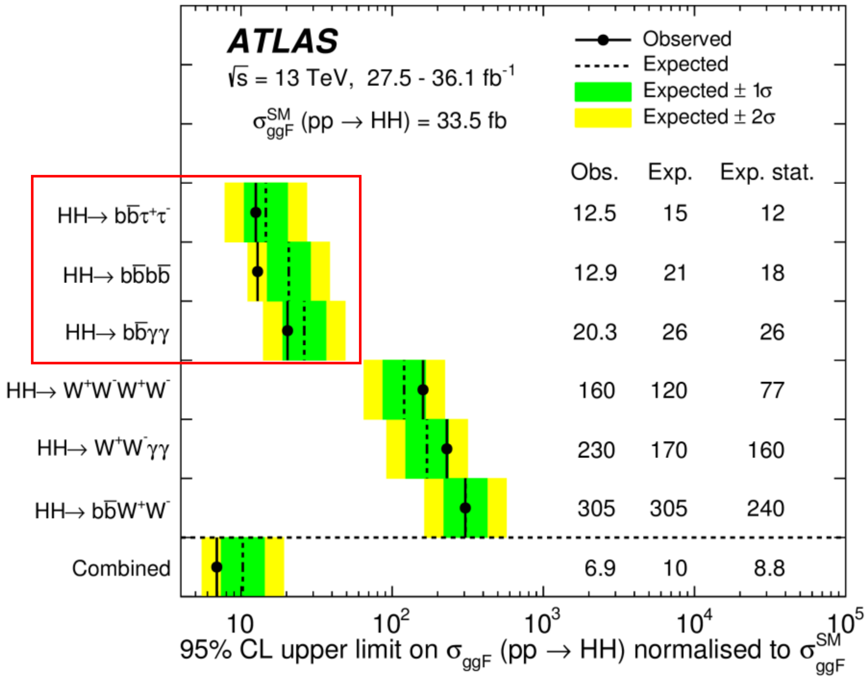
- Cross section: 1000+ times smaller than single Higgs
- Deconstructive interference, further adding difficulties
- BSM physics can also contribute



Searching channels

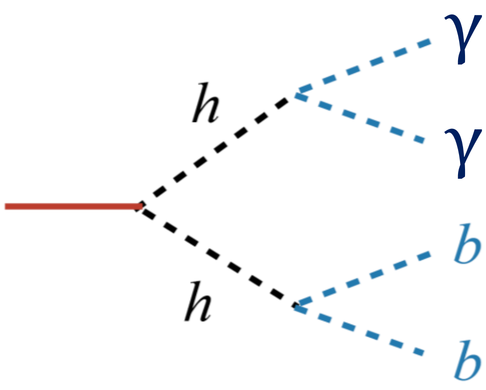


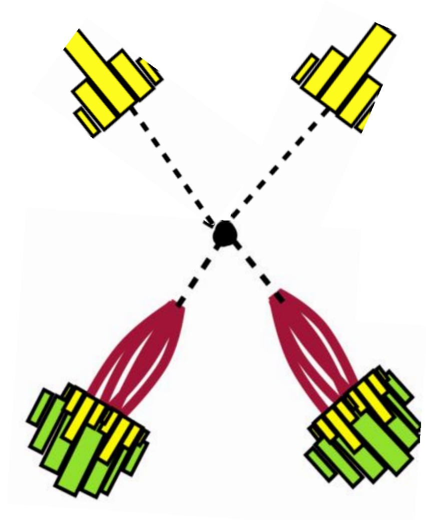
Summary Plot



- Various decay modes searched. lead channels: **bbγγ, bbττ, bbbb**

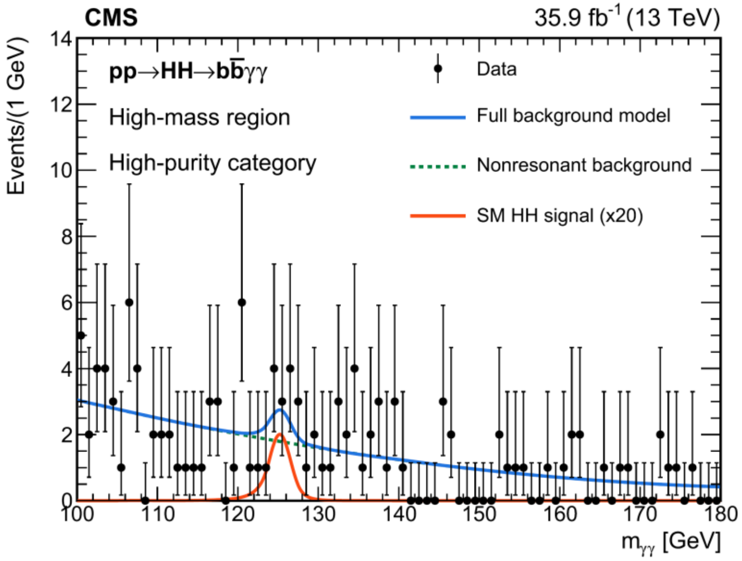
Di-Higgs: bbγγ





Backgrounds:

- QCD 2 jets+photon (or jet→γ)
- Single H: bbH, (t)tH, etc

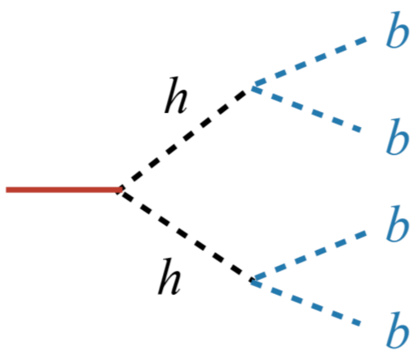


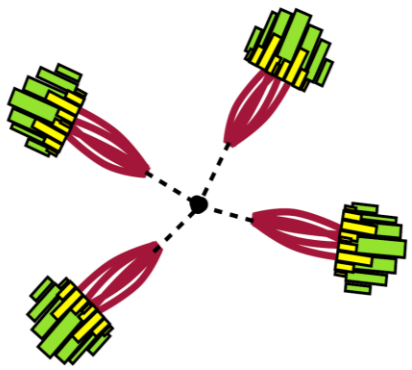
PLB 788 (2019) 7–36 , JHEP 11 (2018) 040

Analysis strategy

- m_{bb} and $m_{\gamma\gamma}$: to extract signal
- $m_{bb\gamma\gamma}$ important for λ_{hhh} extraction
  - $m_h=125$ to constrain m_{bb} and $m_{\gamma\gamma}$
- ATLAS: cut-based; CMS: MVA-based
- **Low Br., low bkg, high S/B**

Di-Higgs: bbbb



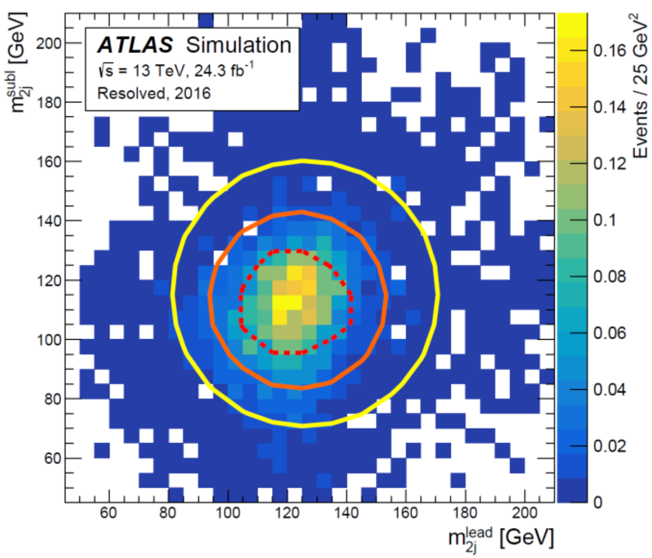


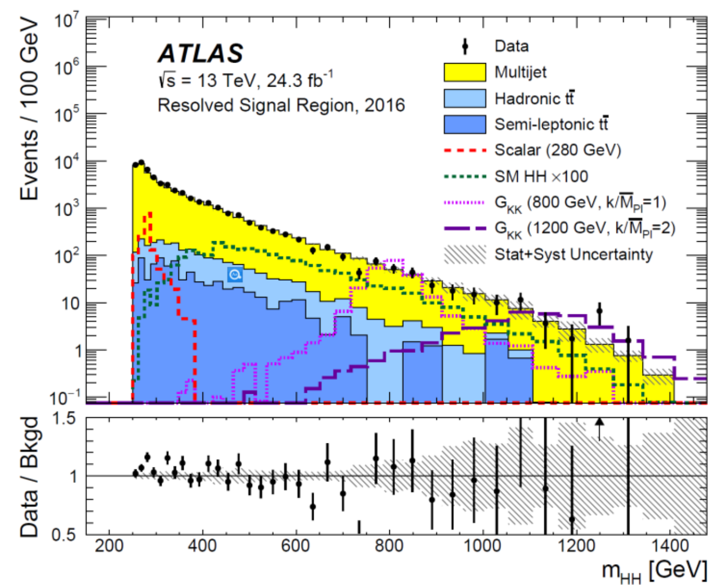
Event selection

- Resolved: anti-k_T R=0.4 Calo jet
- Boosted : anti-k_T R=1.0 Calo fat-jet with R=0.2 trk-jet

Backgrounds

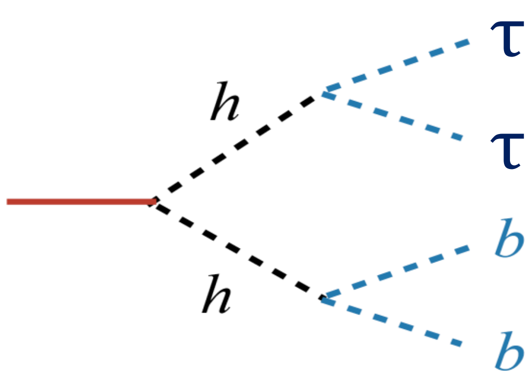
- Multi-jet(95%), top quark pair (ttbar) (5%)
- ATLAS: sideband
- CMS: shuffling two di-b systems

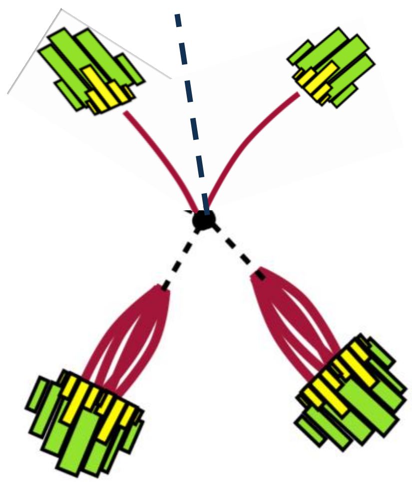




- Both use di-Higgs invariant mass to fit
- **High Br., high bkg, low S/B channel**

Di-Higgs: bbττ





Event selection

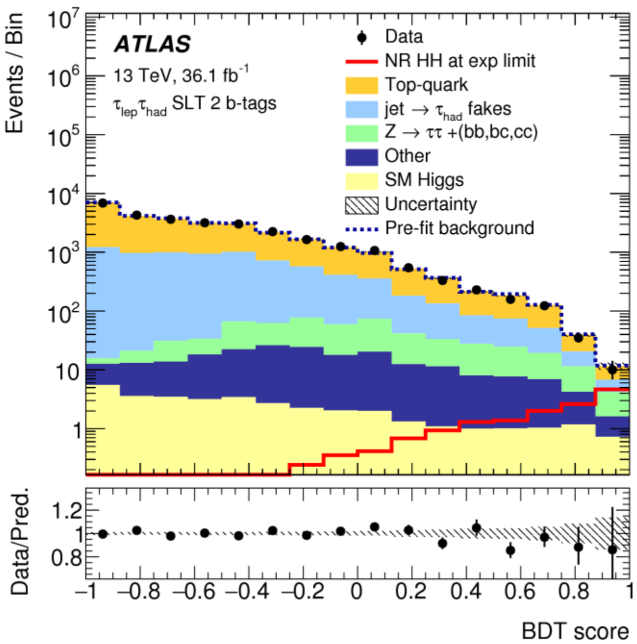
- $\tau_{had}\tau_{had}$: 2 hadronic decay τ
- $\tau_{lep}\tau_{had}$: 1 e/μ, 1 hadronic τ
- 2-3 neutrinos

Backgrounds:

- ttbar, Jet faking τ: QCD Multi-jet

Analysis strategy

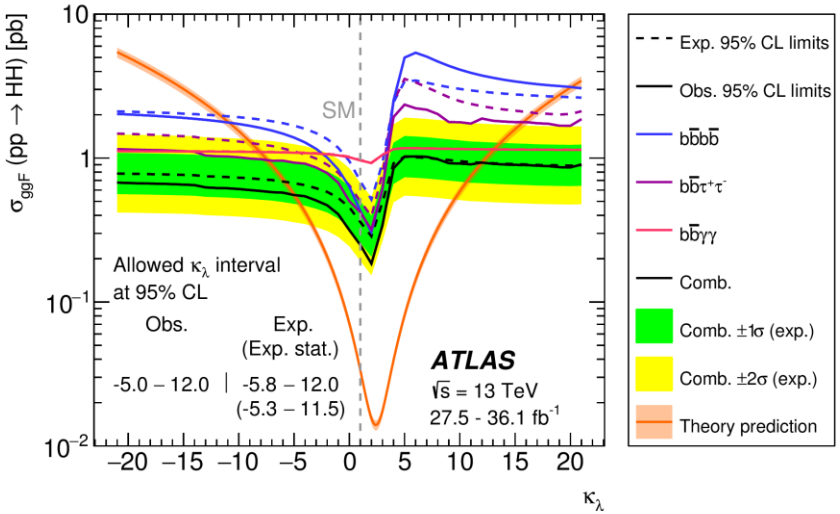
- ATLAS: MVA-based;
- CMS: Cut-based, MT_2 to fit **(PLB 728 (2014) 308–313)**

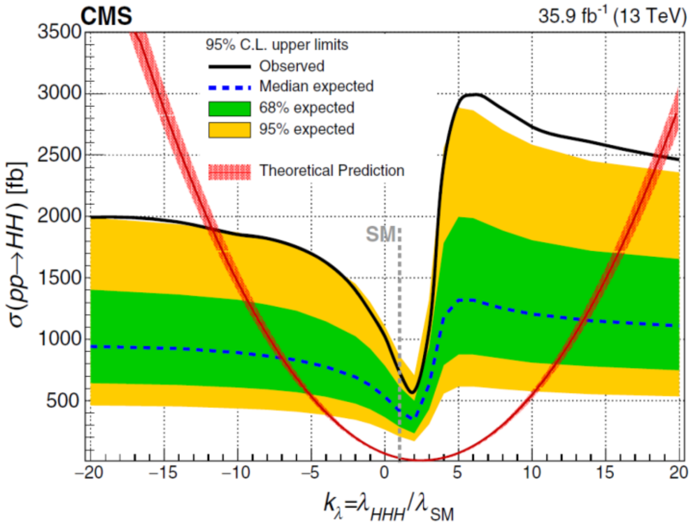


- **Medium Br., medium S/B**

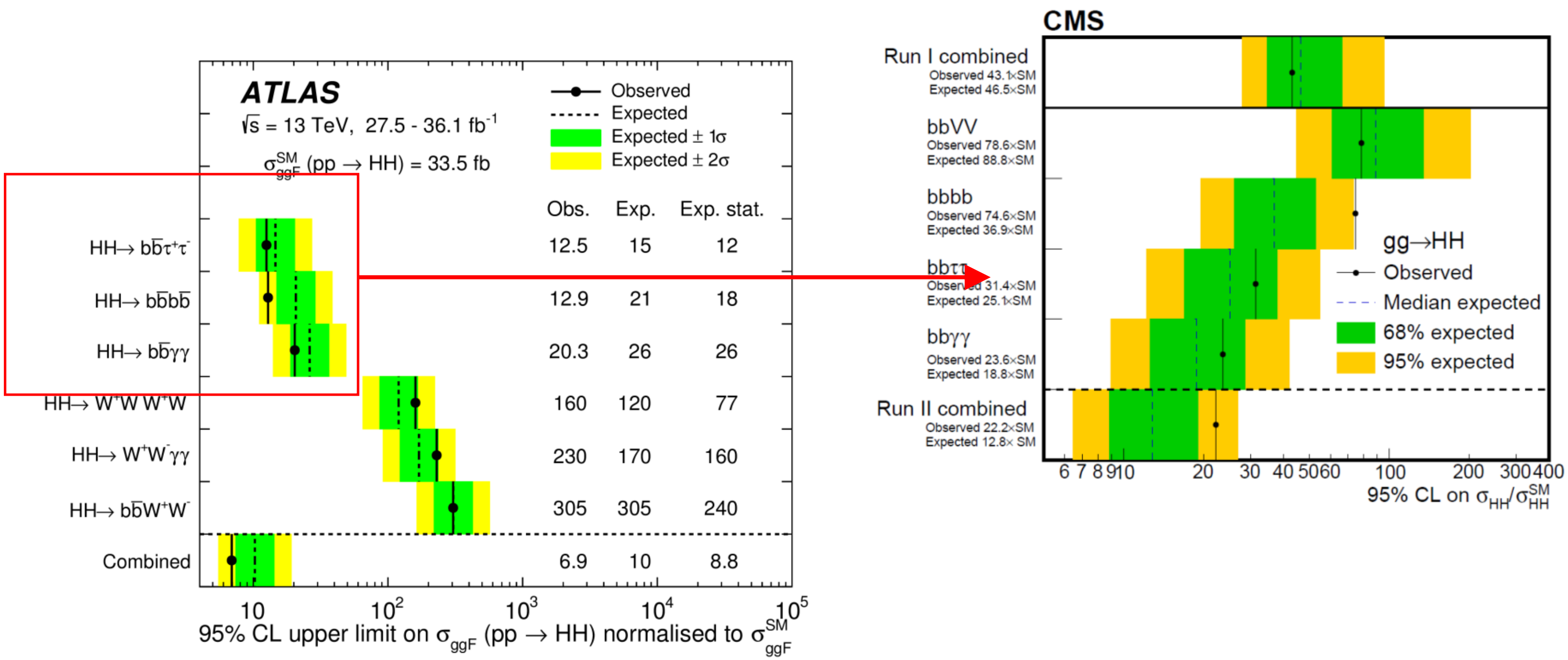
Di-Higgs summary: λ_{hhh}

- ATLAS: σ_{hh} <6.9 (10) SM, -5.0 <λ_{hhh}< 12.0
- CMS: σ_{hh} < 22.2 (12.8) x SM, -11.8 <λ_{hhh}<18.8 (-7.1 <λ_{hhh}< 13.6)





Some personal reflections

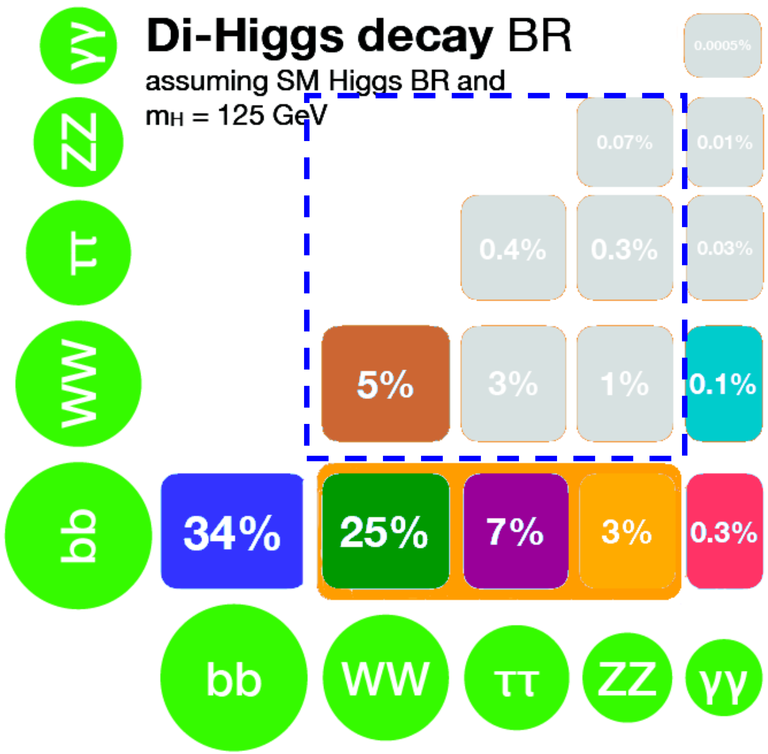


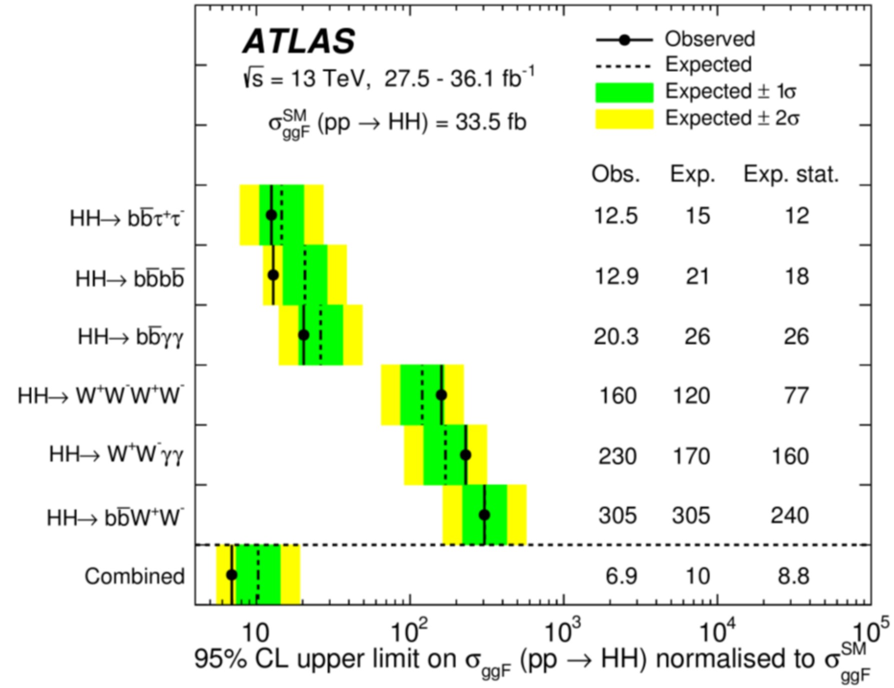
- Performance of ATLAS and CMS are generally the similar. However, sensitivity order are different among three channels
- The difference maybe due the person-power. There are room for improvement.

Some personal reflections

Different final states different S/B

- bbbb: High Br., low S/B
- ττbb: Medium Br., medium S/B
- γγbb: Low Br., large S/B



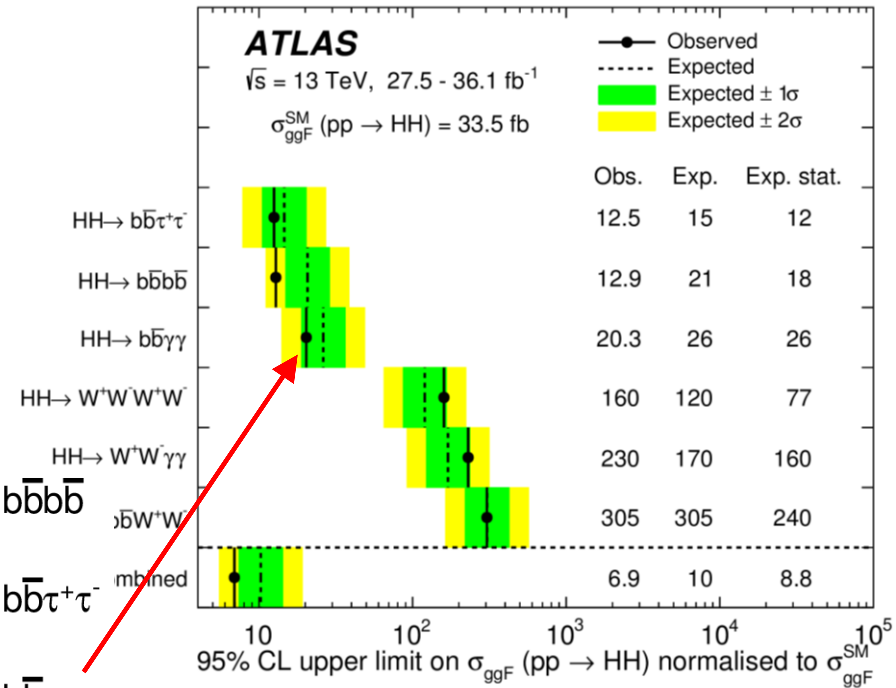


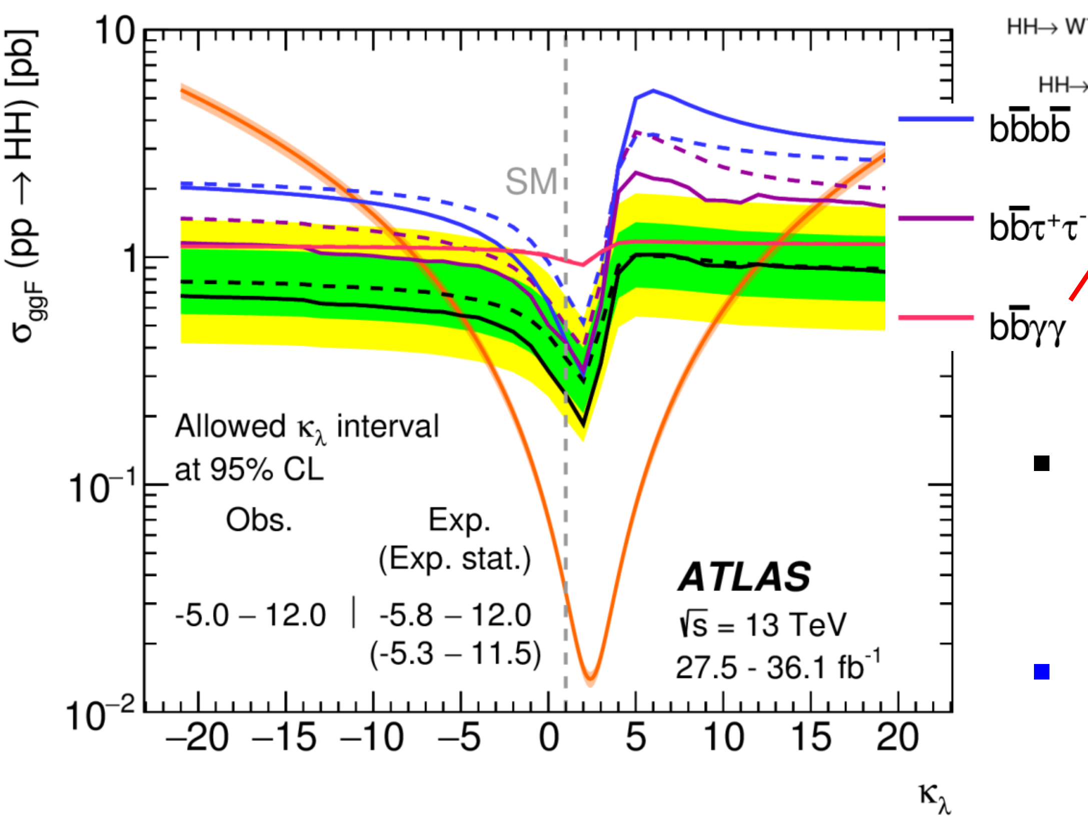
As Run 3 and even HL-LHC,

- Statistical uncertainty will go down easily, not sure systematical one
- Background uncertainty become critical and hard to reduce
- Explore those high S/B final state

Some personal reflections

- **γγbb** is the worst among the best three on HH Xsec
- However, it is the best for λ_{hhh}

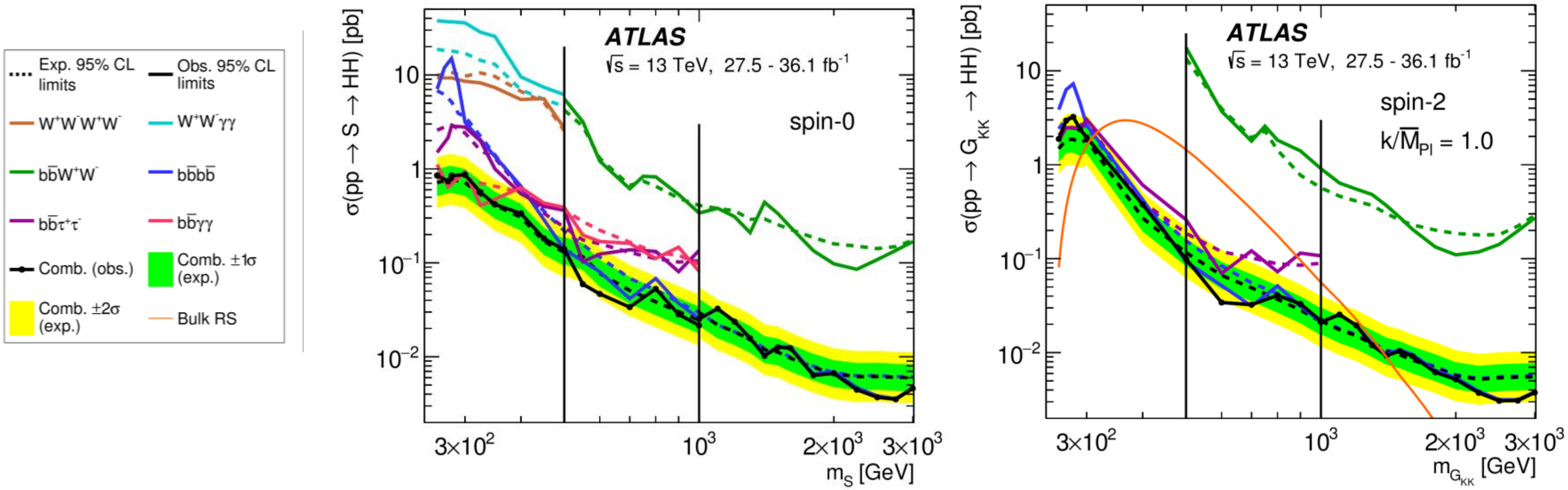




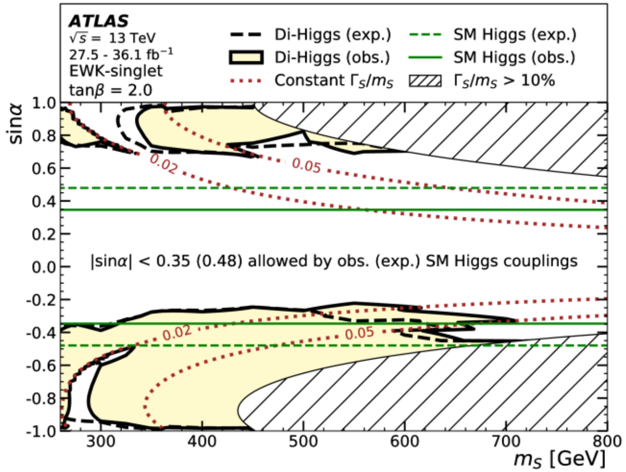
- **γγbb** with good resolution can reconstruct the variables that are sensitive to λ_{hhh}, e.g. m_{hh}
- Can we find or build an even better one?

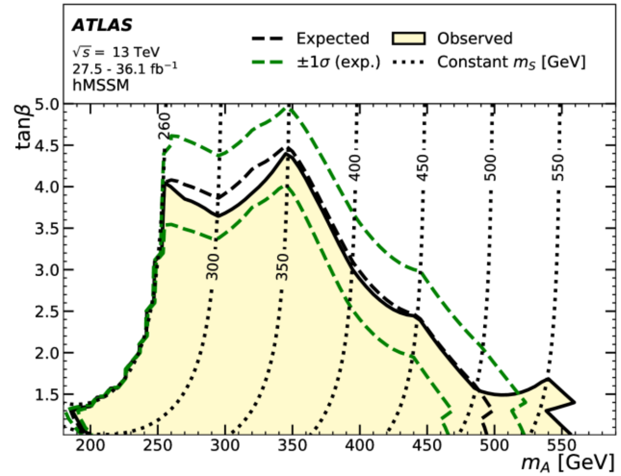
Di-Higgs summary: BSM

- Resonance search for spin-0 and spin-2 particles



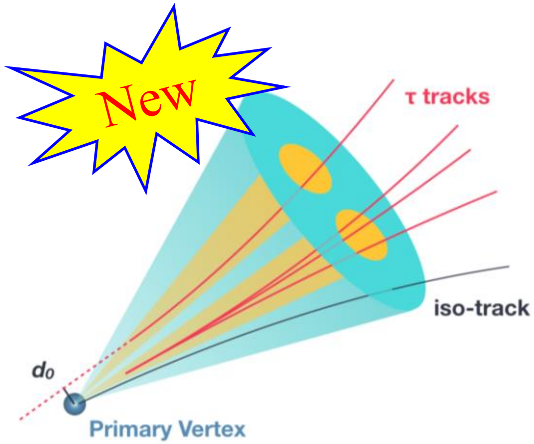
- Interpretation:
  - EW-singlet
  - MSSM

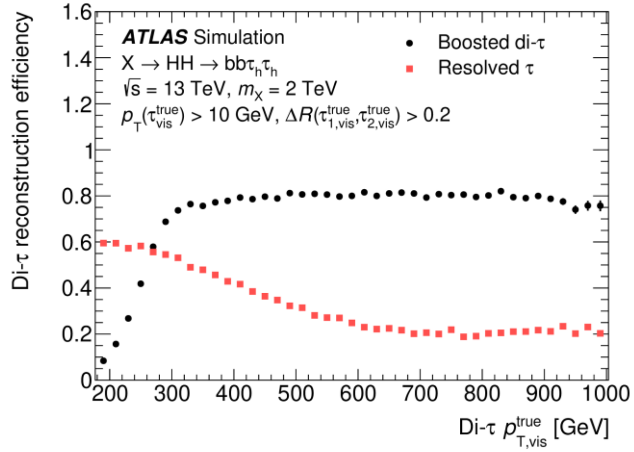


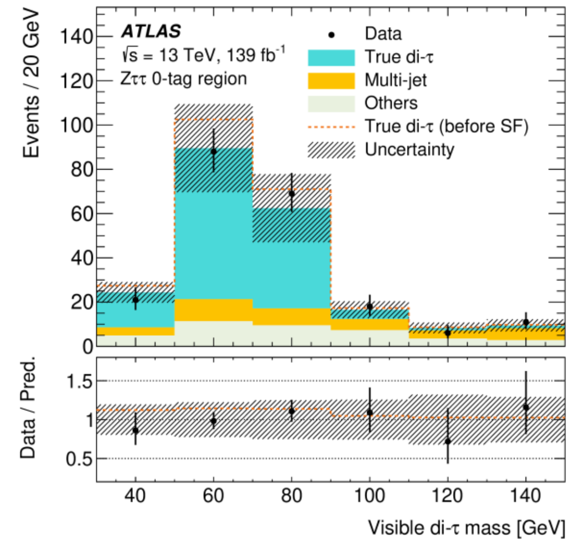


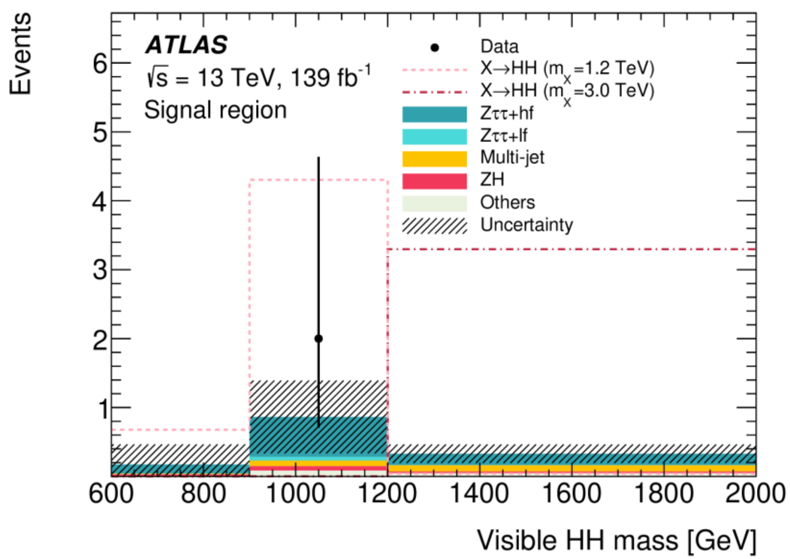
Boosted di-Higgs search in bbττ

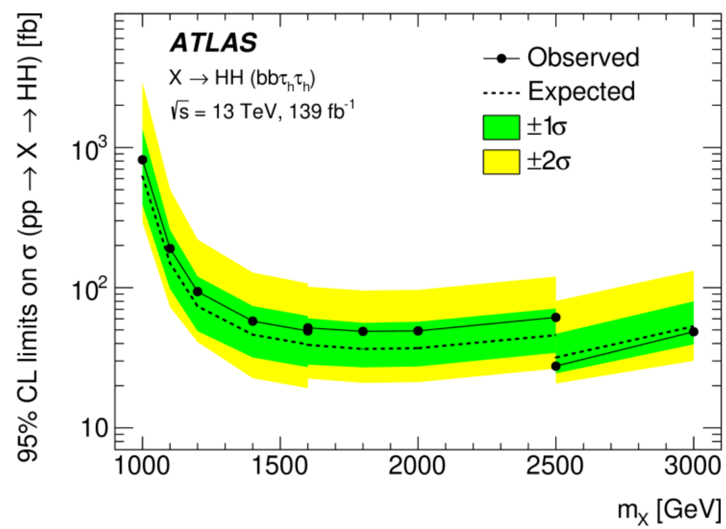
- Boosted di-tau tagger





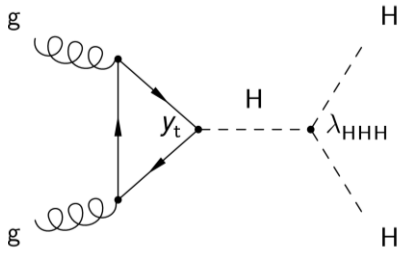


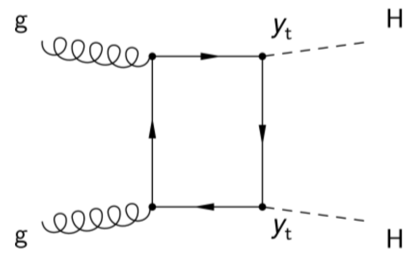




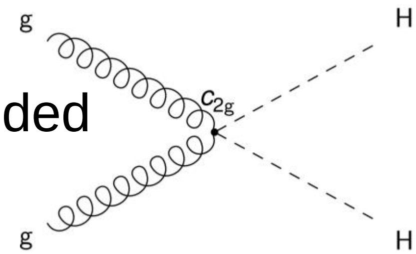
Di-Higgs summary: BSM

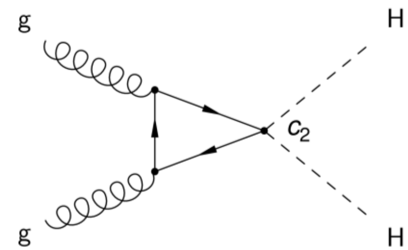
$$\mathcal{L}_{\mathrm{HH}} = \kappa_\lambda \lambda_{\mathrm{HHH}}^{\mathrm{SM}} v H^3 - \frac{m_\mathrm{t}}{v}\left(\kappa_\mathrm{t} H + \frac{c_2}{v} H^2\right)\left(\bar{\mathrm{t}}_\mathrm{L}\mathrm{t}_\mathrm{R} + \mathrm{h.c.}\right) + \frac{1}{4}\frac{\alpha_S}{3\pi v}\left(c_\mathrm{g} H - \frac{c_{2\mathrm{g}}}{2v} H^2\right) G^{\mu\nu} G_{\mu\nu},$$

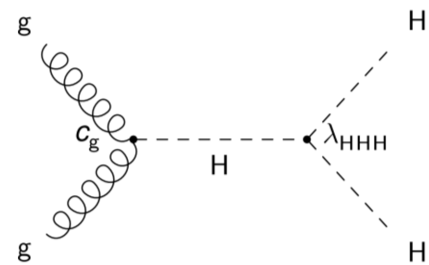




- CMS explored 5 EFT operators, divided parameter space into 12 samples

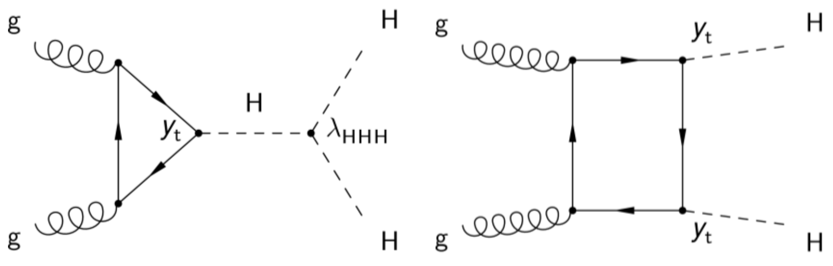




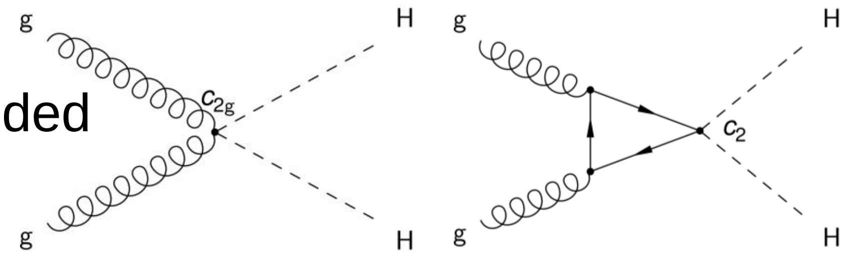


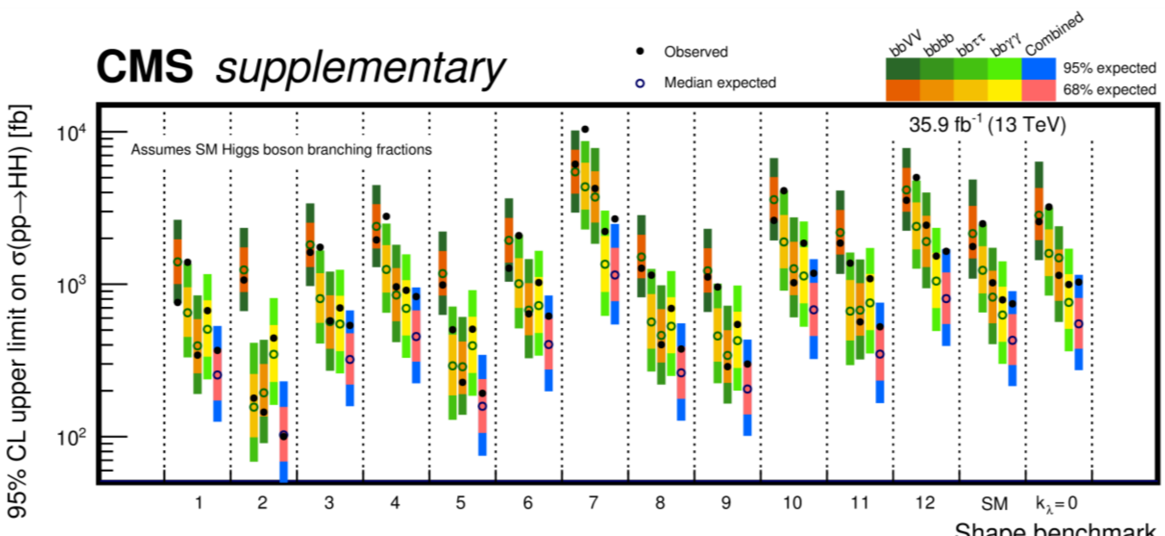
Di-Higgs summary: BSM

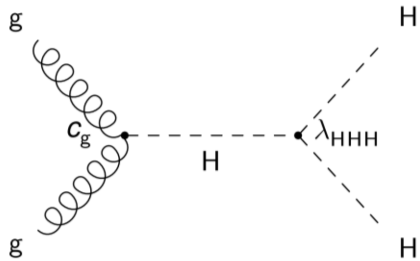
$$\mathcal{L}_{\mathrm{HH}} = \kappa_\lambda \lambda_{\mathrm{HHH}}^{\mathrm{SM}} v H^3 - \frac{m_t}{v}\left(\kappa_t H + \frac{c_2}{v} H^2\right)\left(\bar{t}_L t_R + \mathrm{h.c.}\right) + \frac{1}{4}\frac{\alpha_S}{3\pi v}\left(c_g H - \frac{c_{2g}}{2v} H^2\right) G^{\mu\nu} G_{\mu\nu},$$



- CMS explored 5 EFT operators, divided parameter space into 12 samples

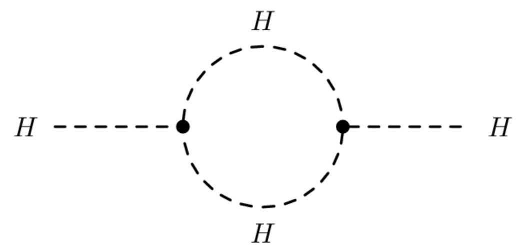


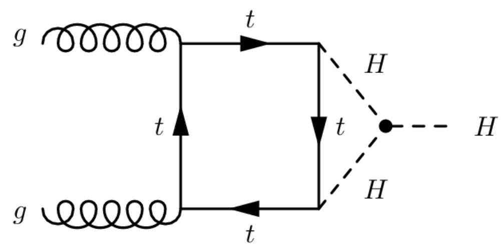


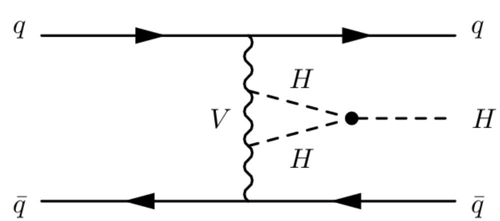


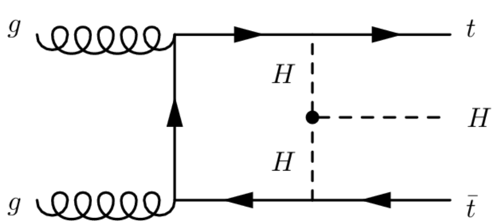
λ_{hhh} measurement with Single Higgs

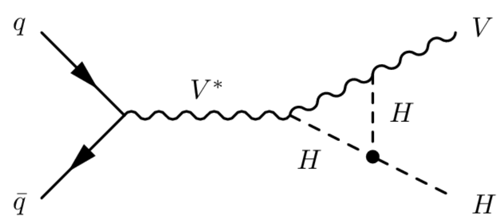
- NLO EW corrections give Higgs cross-section, branching ratios, and kinematics dependence on κ_λ
- Single Higgs final states can also be sensitive to κ_λ

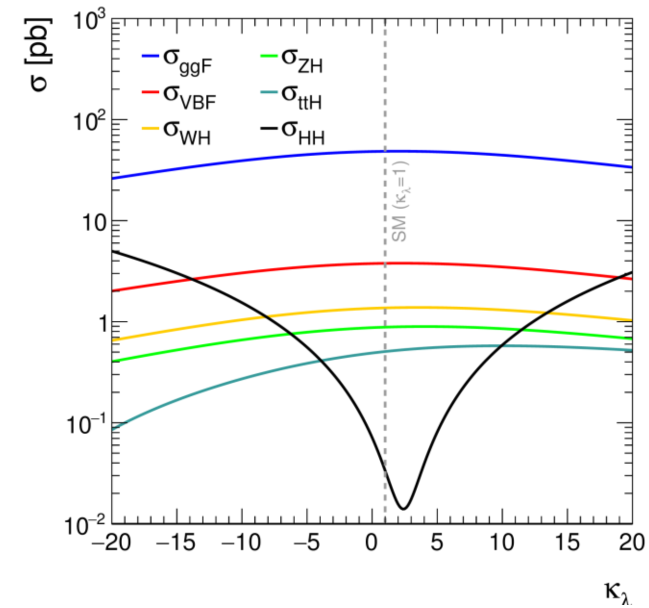


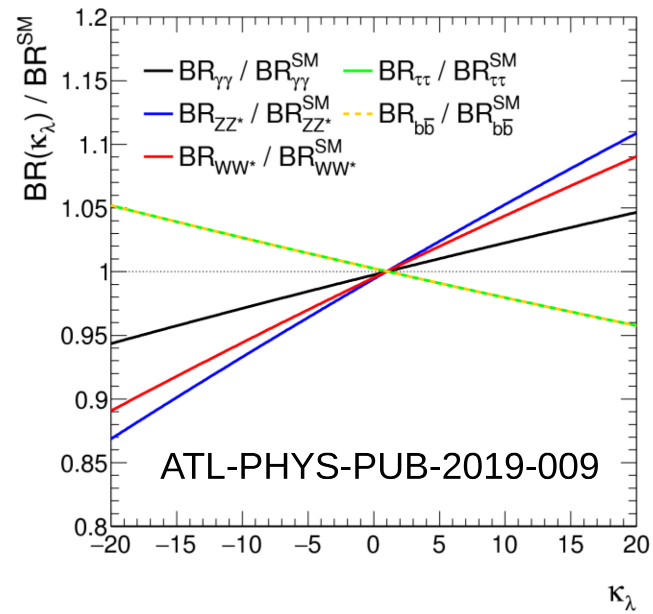












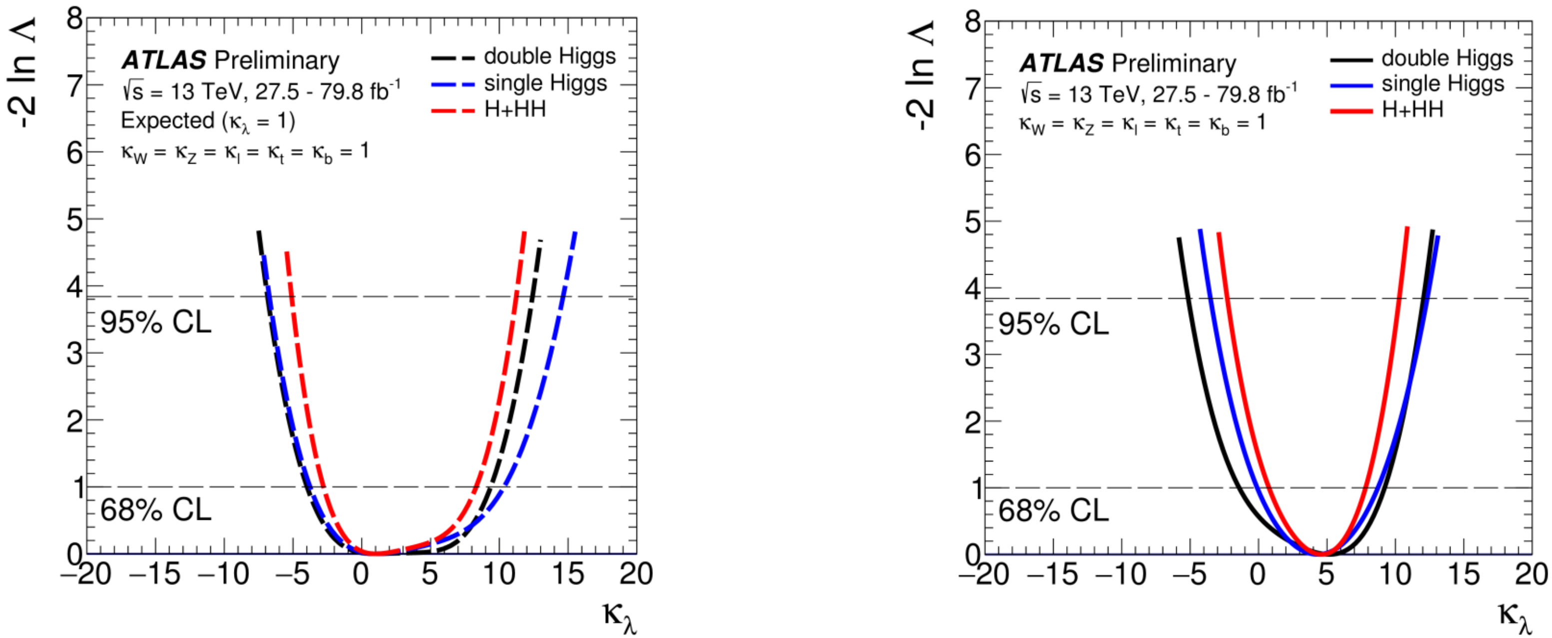
λ_{hhh} measurement with Single Higgs

New

- Kinematics change taken into account

$$n_{i,f}^{\text{signal}}(\kappa_\lambda, \kappa_m) \propto \mu_i(\kappa_\lambda, \kappa_m) \times \mu_f(\kappa_\lambda, \kappa_m) \times \sigma_{\text{SM},i} \times \text{BR}_{\text{SM},f} \times (\epsilon \times A)_{if}$$

- $\mu_i(\kappa_\lambda, \kappa_m)$ and $\mu_f(\kappa_\lambda, \kappa_m)$ varies according to VH production mode on the STXS bin while STXS on ggF production is not considered



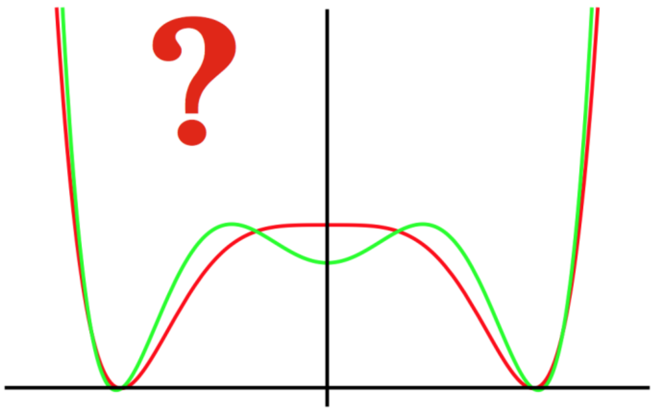
$$\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.6^{+2.9}_{-3.5}\,(\text{stat.})\,^{+1.2}_{-1.2}\,(\text{exp.})\,^{+0.7}_{-0.5}\,(\text{sig. th.})\,^{+0.6}_{-1.0}\,(\text{bkg. th.})\,[\text{observed}]$$

$$\kappa_\lambda = 1.0^{+7.3}_{-3.8} = 1.0^{+6.2}_{-3.0}\,(\text{stat.})\,^{+3.0}_{-1.7}\,(\text{exp.})\,^{+1.8}_{-1.2}\,(\text{sig. th.})\,^{+1.7}_{-1.1}\,(\text{bkg. th.})\,[\text{expected}]$$

Beyond SM Higgs boson search

Extended Higgs sector

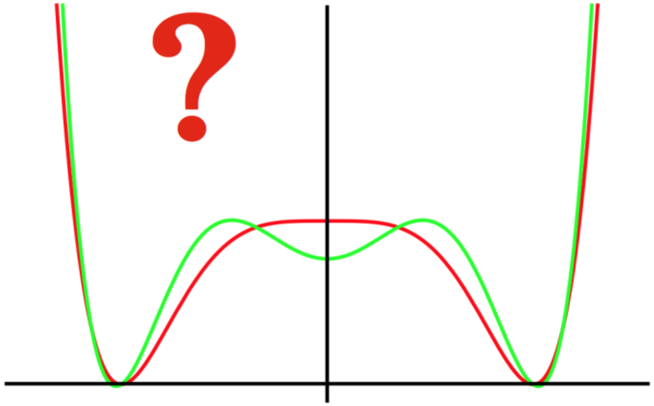
- Extension of Higgs sector could change the Higgs potential.



$$V_{\mathrm{CxSM}} = \frac{m^2}{2}\mathrm{H}^\dagger\mathrm{H} + \frac{\lambda}{4}(\mathrm{H}^\dagger\mathrm{H})^2$$

Extended Higgs sector

- Extension of Higgs sector could change the Higgs potential.
- For example, SM plus one singlet extension
  - Allow 1st order EW phase transition



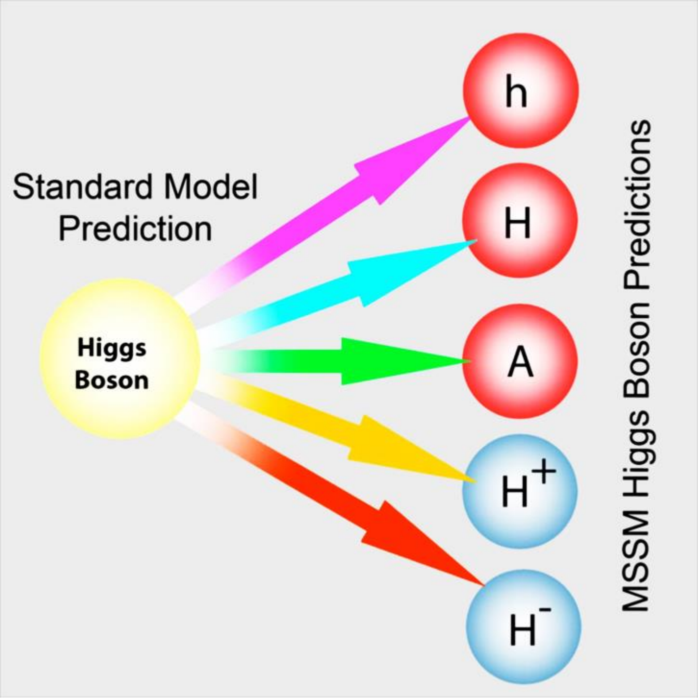
$$V_{\mathrm{CxSM}} = \frac{m^2}{2}\mathrm{H}^\dagger\mathrm{H} + \frac{\lambda}{4}(\mathrm{H}^\dagger\mathrm{H})^2$$

$$+\frac{\delta_2}{2}\mathrm{H}^\dagger\mathrm{H}|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1\mathbb{S} + c.c.\right)$$

Benchmark models

Two-Higgs Doublets Model (2HDM)

- Minimum extension of Higgs sector
- Requested by MSSM



$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix} \qquad v_u : \ \ \mathrm{VEV}_u$$

$$\phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix} \qquad v_d : \ \ \mathrm{VEV}_d$$

- Two free parameters at tree level: m_A, $\tan\beta = v_u/v_d$

Neutral Higgs bosons: MSSM as example

Coupling strength:

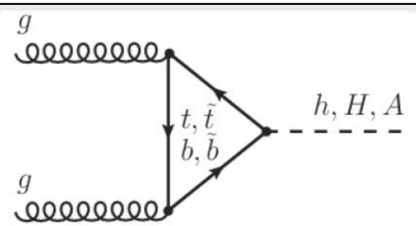
	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \to 0$	$\sin\alpha / \sin\beta \to \cot\beta$	$\cos\alpha / \cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \to 1$	$\cos\alpha / \sin\beta \to 1$	$-\sin\alpha / \cos\beta \to 1$

Neutral Higgs bosons: MSSM as example

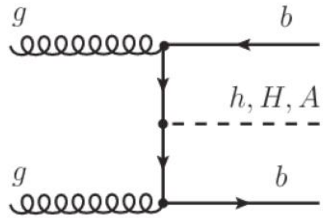
Coupling strength:

	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \rightarrow 0$	$\sin\alpha/\sin\beta \rightarrow \cot\beta$	$\cos\alpha/\cos\beta \rightarrow \tan\beta$
h	$\sin(\beta-\alpha) \rightarrow 1$	$\cos\alpha/\sin\beta \rightarrow 1$	$-\sin\alpha/\cos\beta \rightarrow 1$

Production modes:

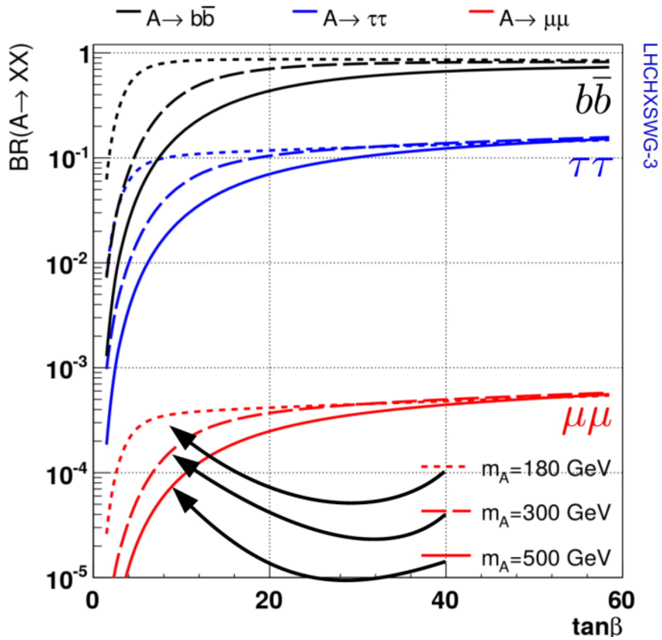


$gg \rightarrow \phi$ ("$gg\phi$")



$gg \rightarrow \phi b\bar{b}$ ("$bb\phi$")

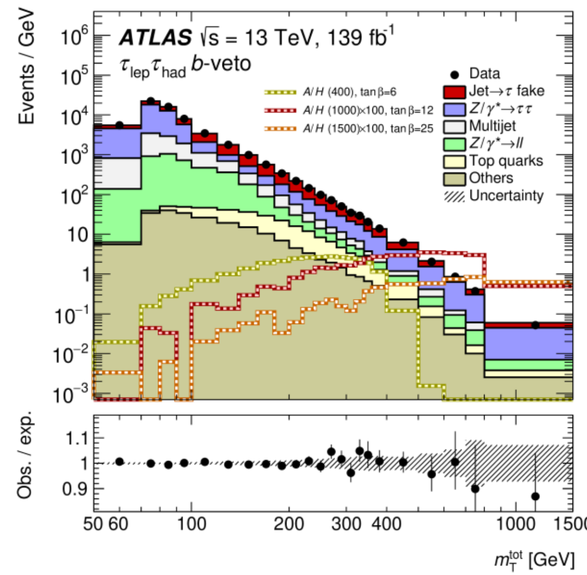
Decay channels:



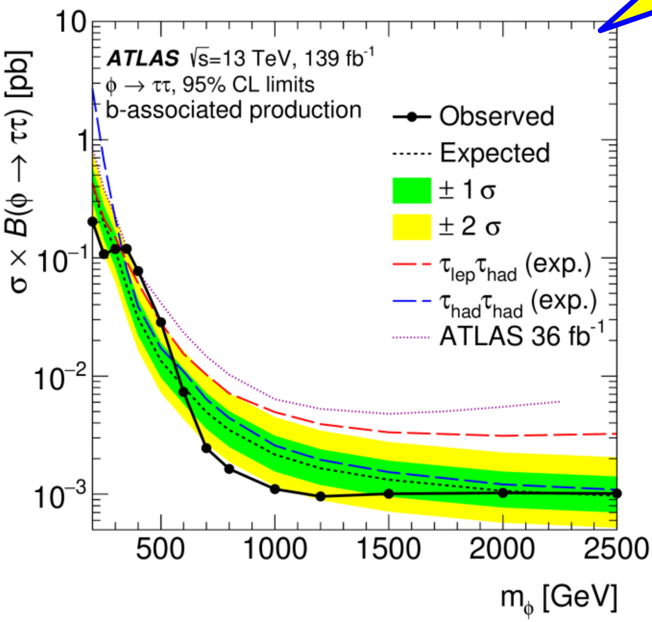
Neutral Higgs: A/H→ττ

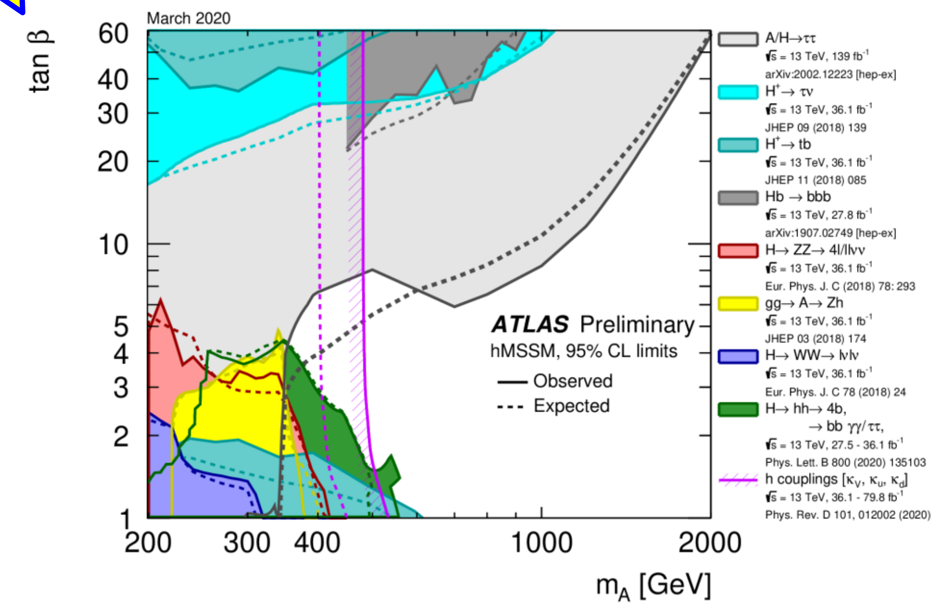
- Final states: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
- Mass range 200–2500 GeV
- Categories: b-veto (ggh) and b-tag (bbh)
- Discriminant: total transverse mass

$$m_T^{tot} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{miss})^2}$$

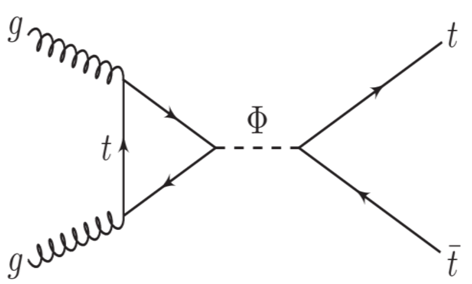


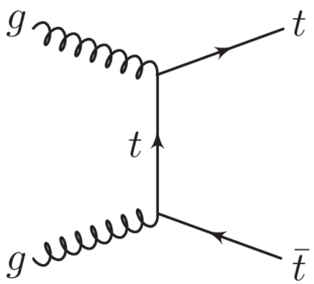
New



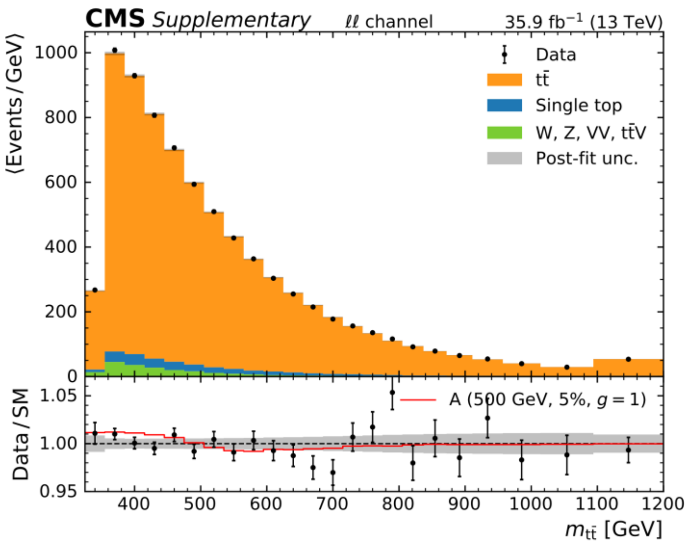


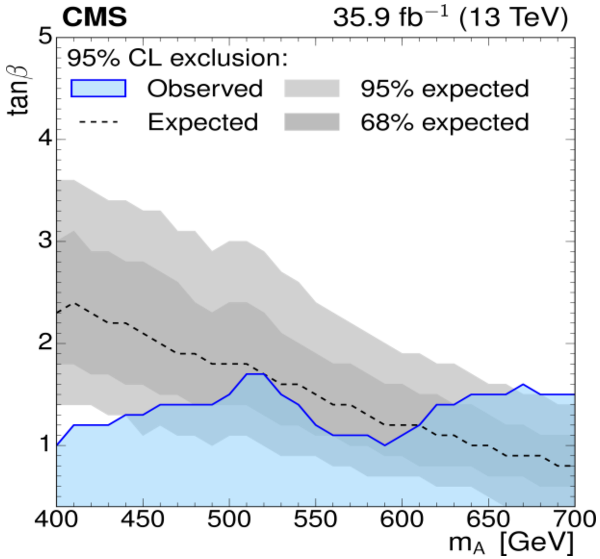
Neutral Higgs: A/H→ $t\bar{t}$





- Dominant production from ggH
- Key: Interference with SM ttbar leads a peak-dip signal shape

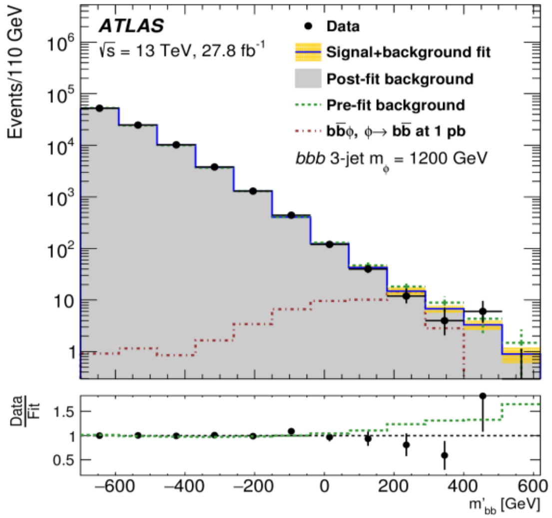


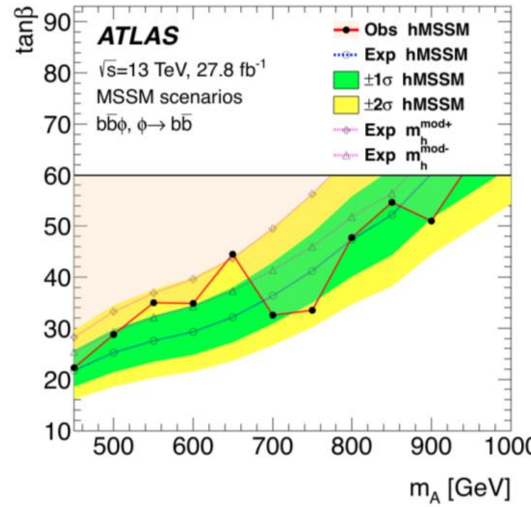


- Search range: 400-750 GeV, width Γ/m={0.5-25}%
- Exclusion in hMSSM
  - an mild excess at mA =400 GeV with Γ/m=4% 1.9σ global (3.5σ local)

Neutral Higgs: A/H→ bb **or** μμ

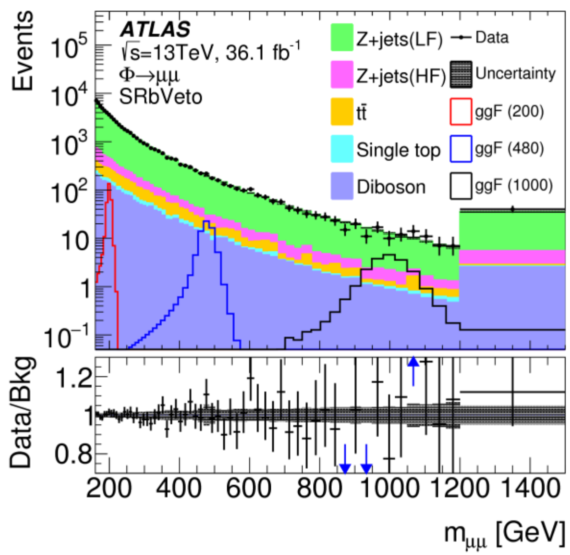
A/H→bb

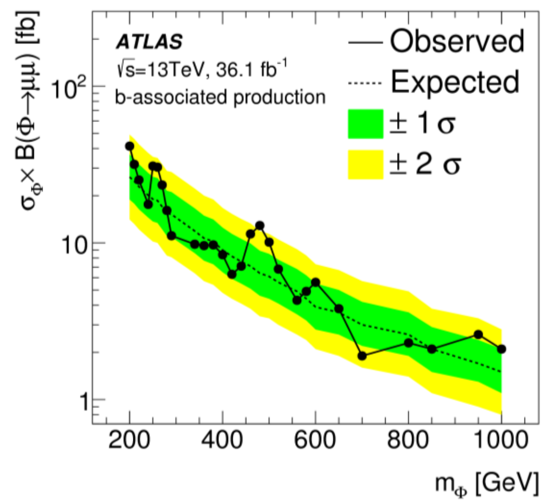




- Type II and Flipped 2HDM

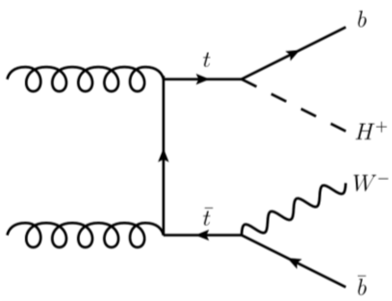
A/H→μμ: 2nd generation fermion

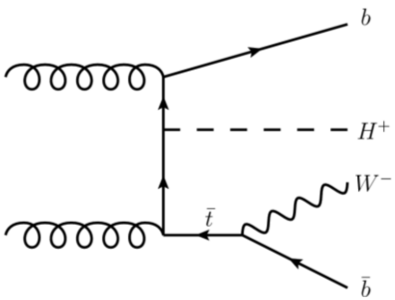




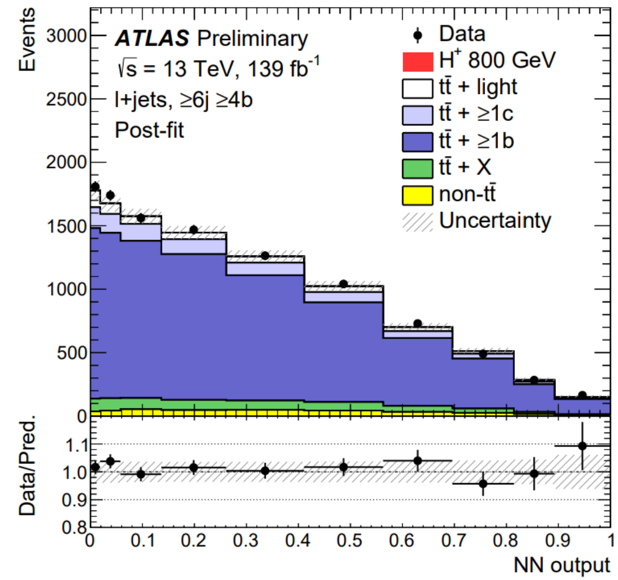
- Flavourful Higgs model

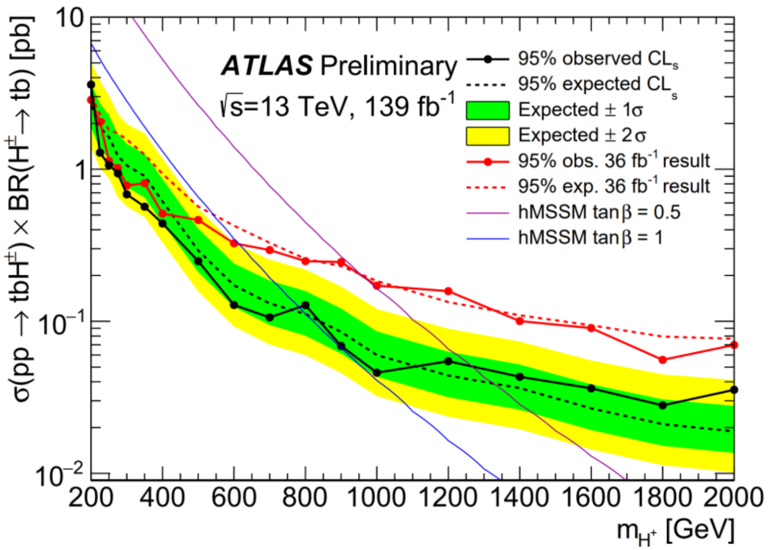
Charged Higgs $H^{\pm} \rightarrow$ top+b



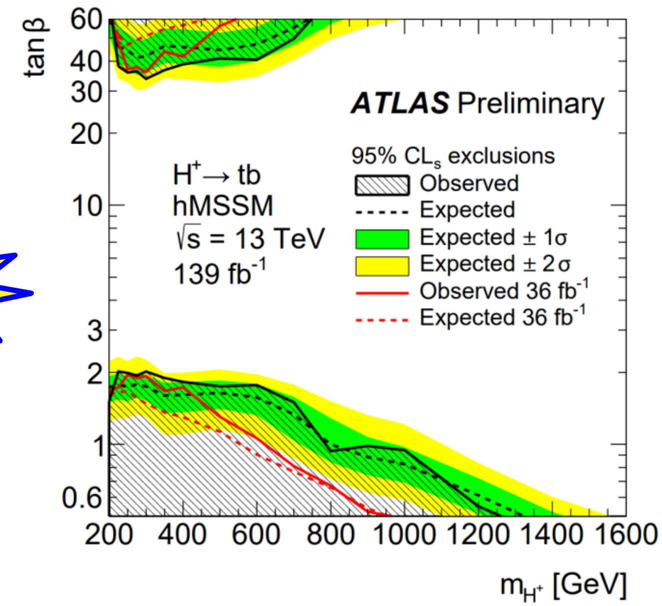


- categorization w.r.t. N_{jets} and $N_{b\text{-}jets}$
- Parameterized Deep Neural Network technique used



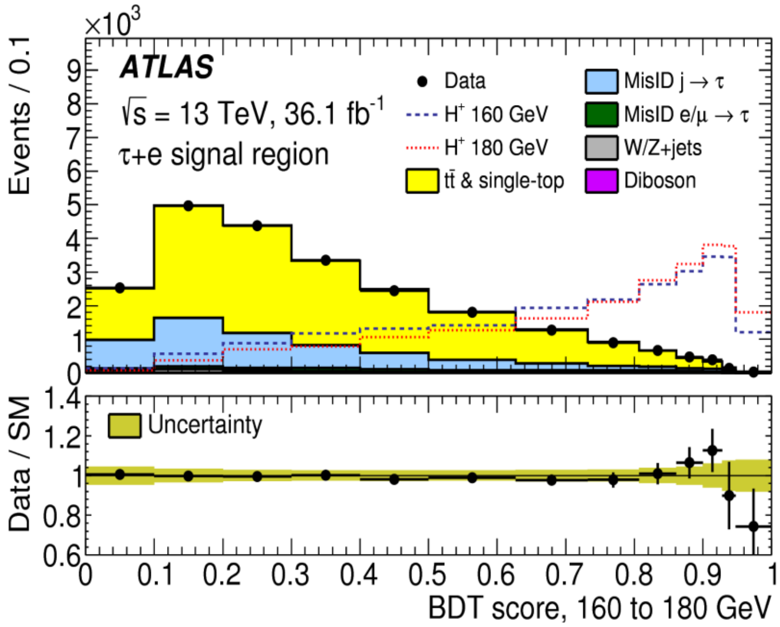


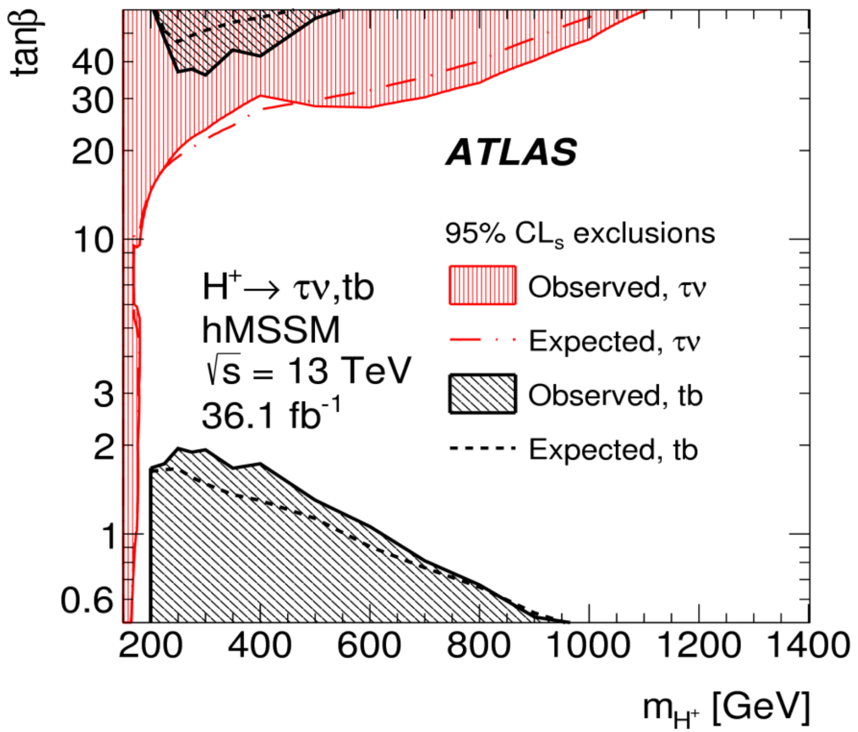
New



Charged Higgs $H^{\pm}\to\tau\nu$

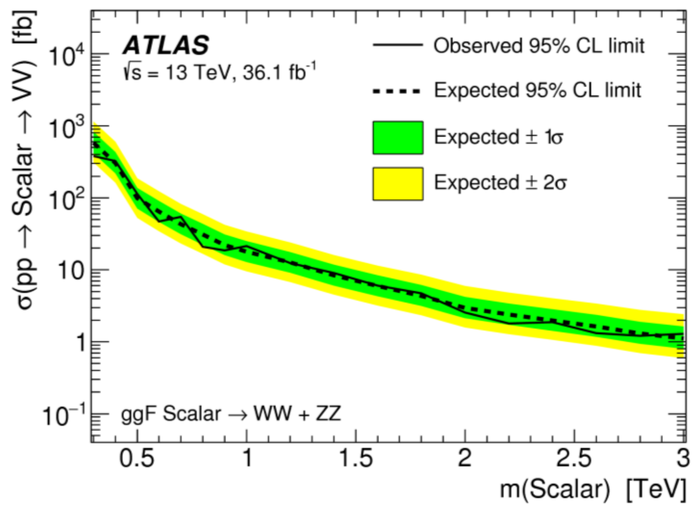
- $H^{\pm}\to\tau\nu$: τ_{had}+jets, τ_{had}+lep final state
- MVA technique used





Searches in various di-bosons

- Inspired by RS, 2HDM, GUT, etc.
- Diboson resonance searches
  - Vh, WW, WZ, ZZ
  - Big combination: qqqq, ννqq, lνqq, llqq, lνlν, llνν, lνll, llll, qqbb, ννbb, lνbb, and llbb



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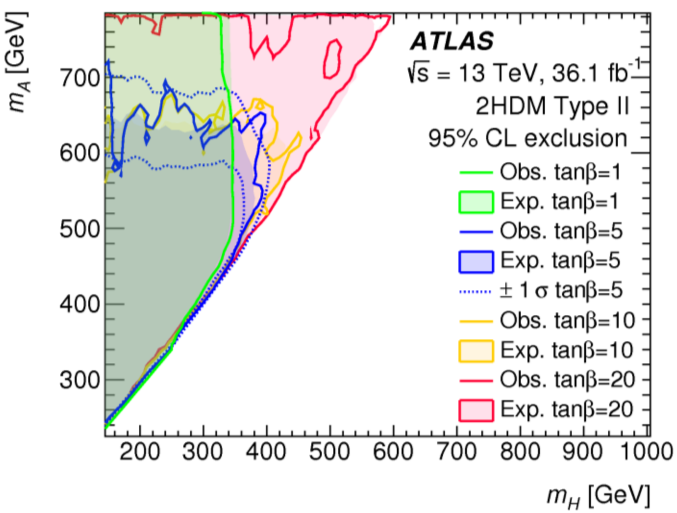
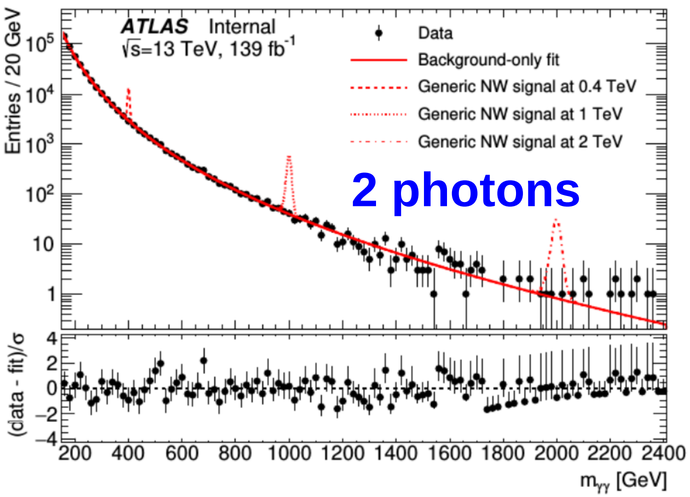
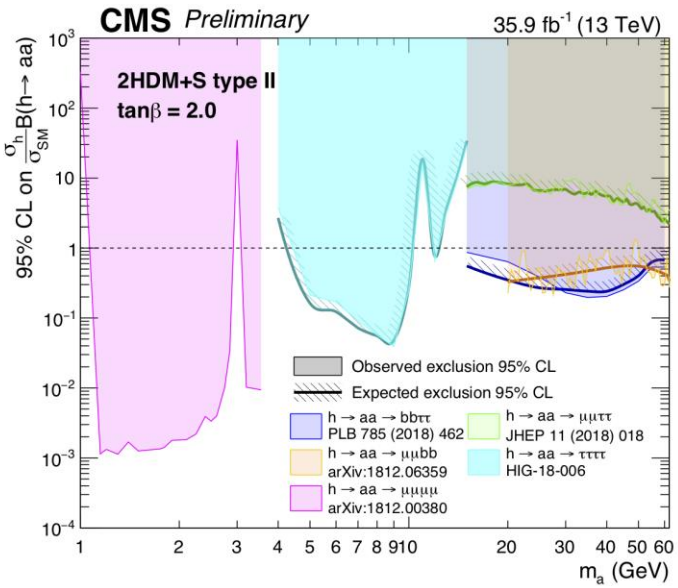


Motivated by 1st order phase transition
(PRL 113 (2014) 211802)

Di-photon resonance

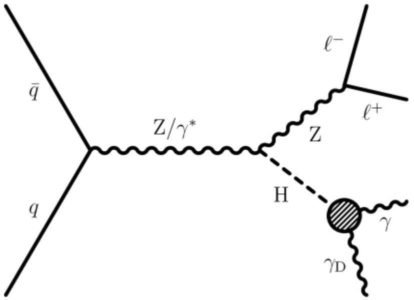


Light boson searches

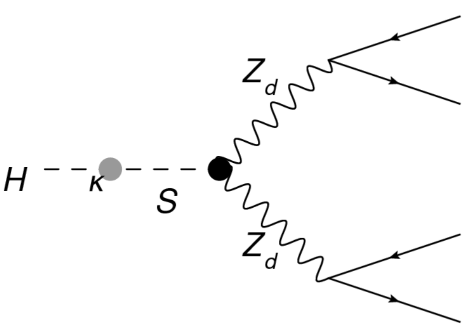


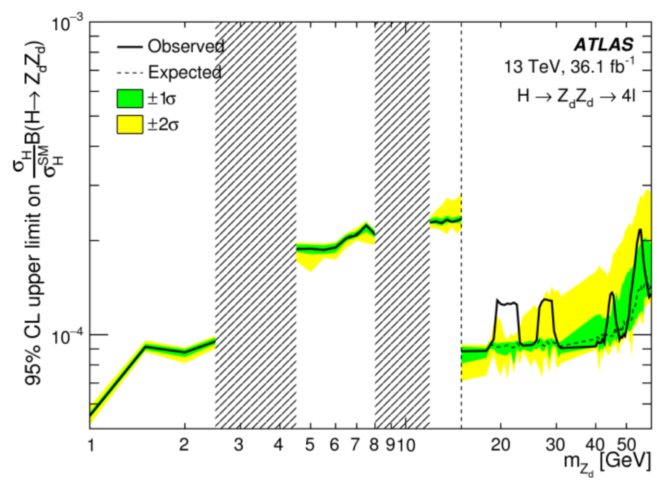
Light bosons motivated by by

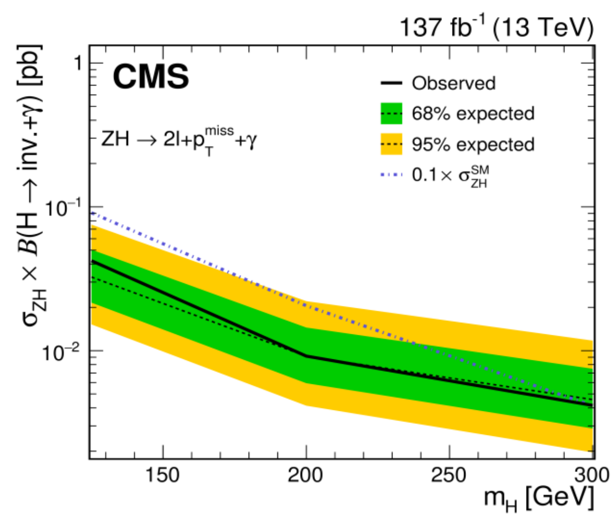
- Extended Higgs sector
  - NMSSM (2HDM+S), SM/2HDM+V
- 1st EW phase transition
- Dark matter



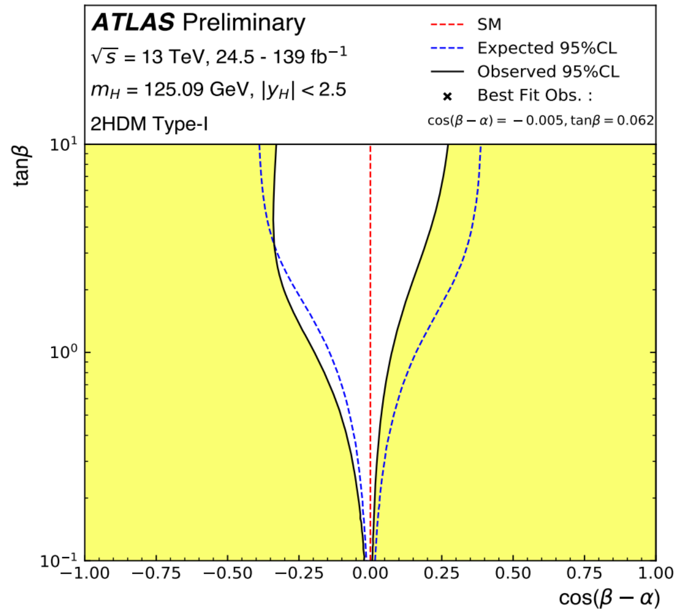
$h \to Z_d Z_d \to 4l$

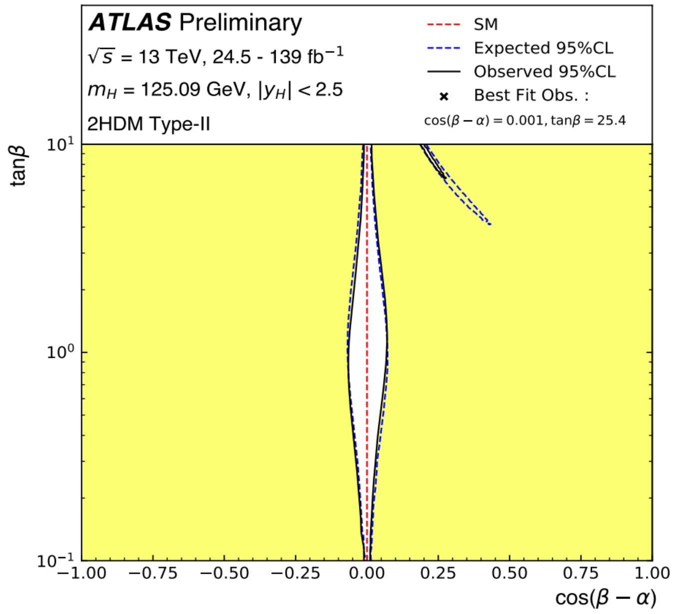






Constrain from h(125) measurement





Precise measurement of h(125) constraint BSM Higgs sector

- Benchmark models: 2HDMs (Type-I, II, Lepton-specific, Flipped)
- Assumed that only the 2HDMs responsible for the potential BSM effects
- As functions of the alpha and tan beta

Summary

- Nature of EW spontaneous symmetry breaking is one of the most important topic in HEP
- Probing Higgs self coupling via di-Higgs production carried on extensively at ATLAS and CMS
  - One of most challenging measurement, need coherent effort from both experimentalists and theorists.
- Additional Higgs bosons, predicted from the extended Higgs sector, searched extensively at ATLAS and CMS
  - Crucial aspects for BSM physics study
  - Only some representative results shown, more can be found below
- Some studies on the CP nature of the Yukawa coupling performed in ttH and $H \to \tau\tau$, recently.

For reference and more results: ATLAS public results and CMS public results