Di-Higgs and BSM Higgs Search at LHC

Lei Zhang (张雷)

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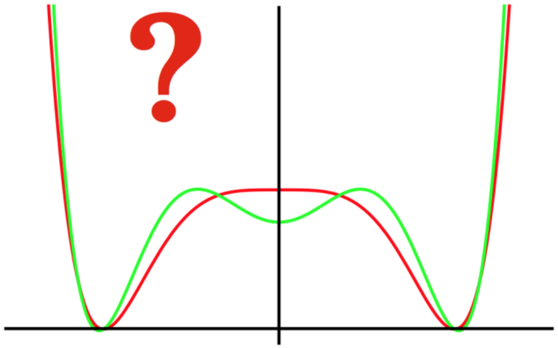
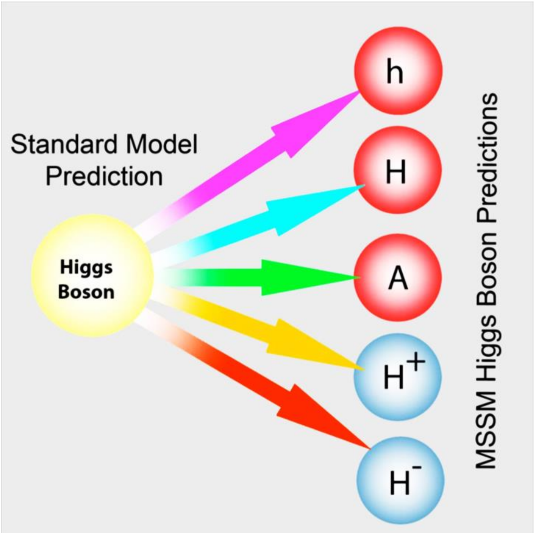


CLHCP in Dalian, 23-27 Oct. 2019



Disclaimer

- I am on behalf of ATLAS and CMS. Major results in this talk have been published by both, respectively. Due to my limited knowledge, the content was not balanced between two experiments.

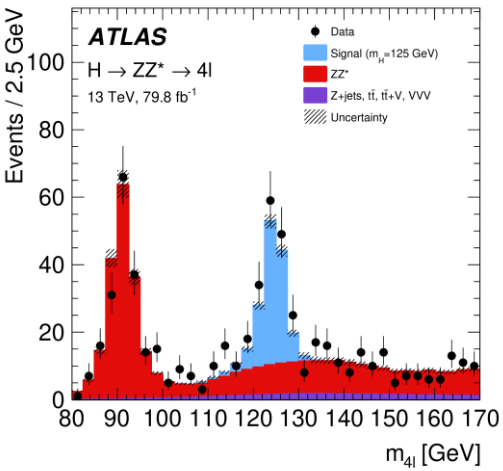
- If I put both references around the results, the slides will be too crowded. All presented public results of ATLAS and CMS can be found or ask/email us:
  - ATLAS public results

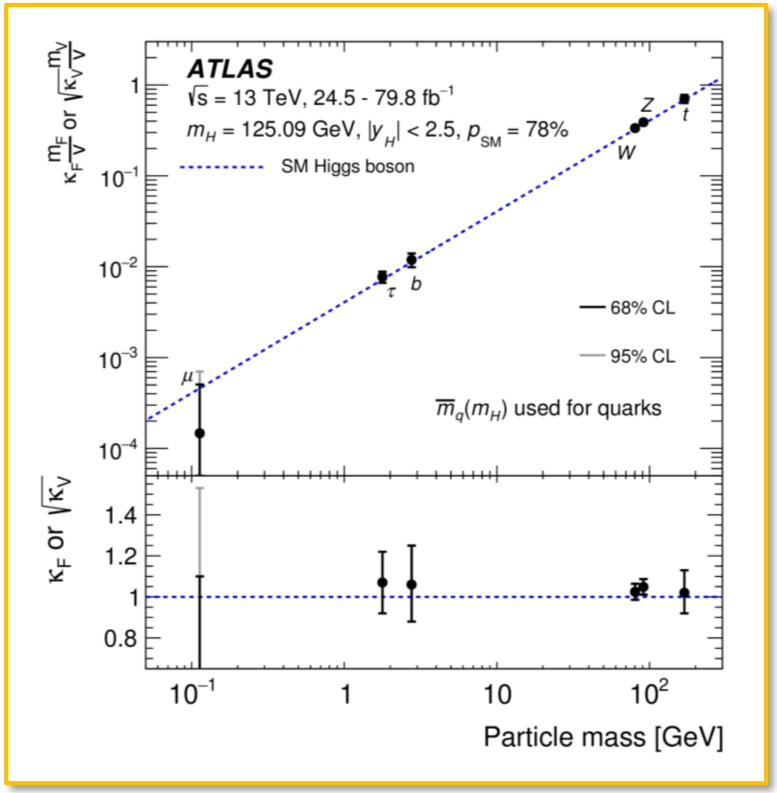
    https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - CMS public results

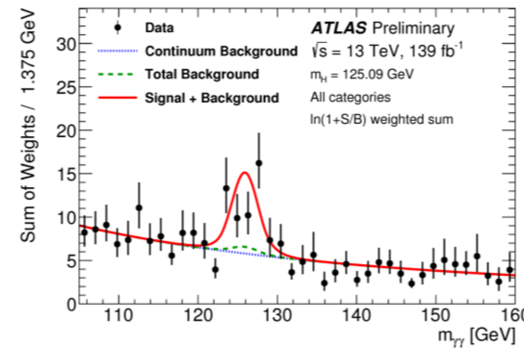
    http://cms-results.web.cern.ch/cms-results/public-results/publications/

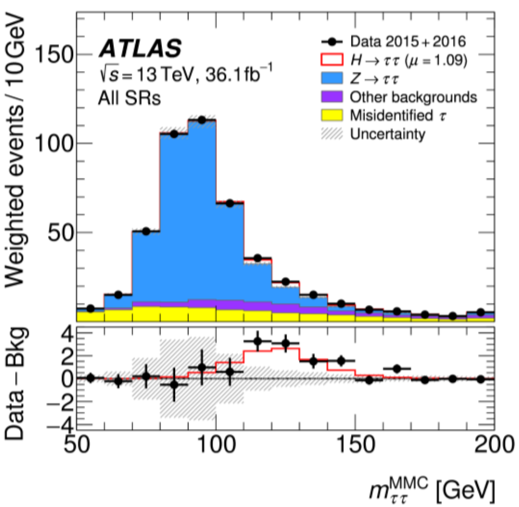
    http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/

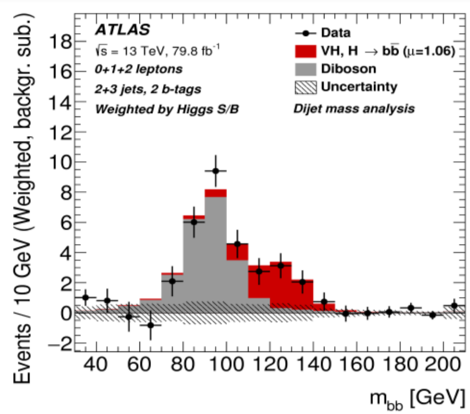
Higgs boson established, solidly!

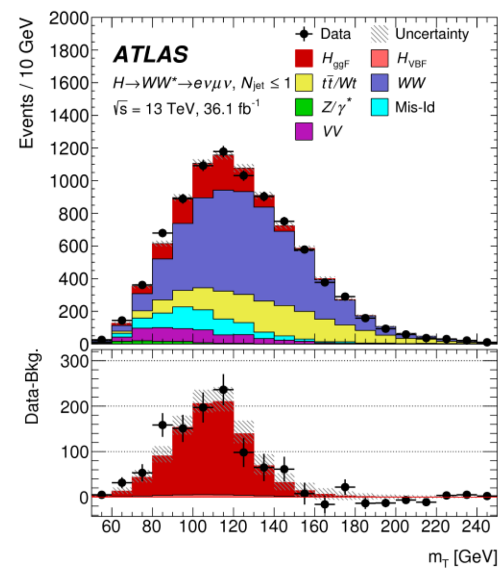




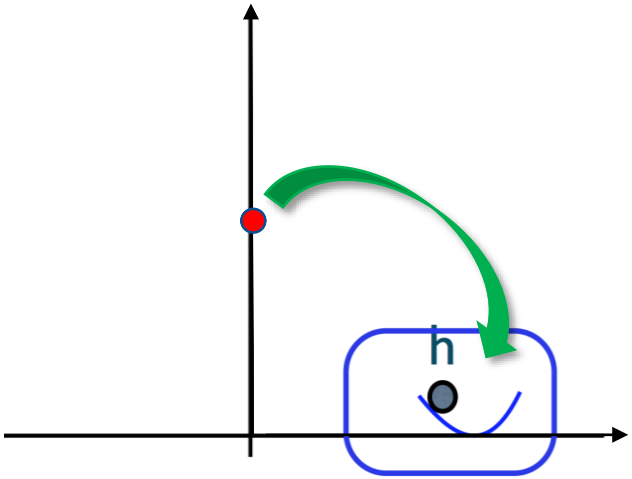






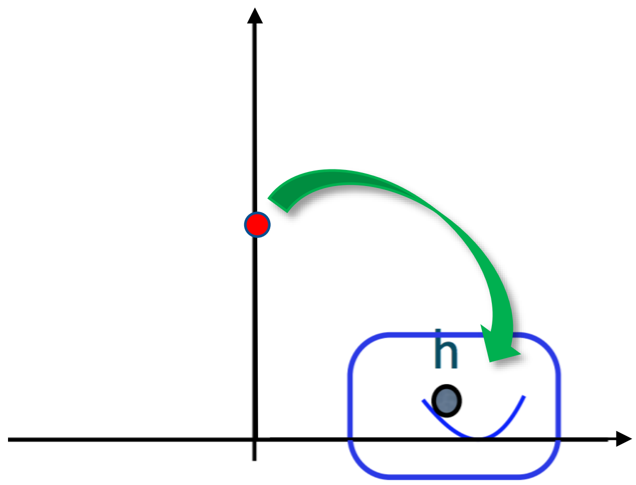


How it happened?



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

How it happened?



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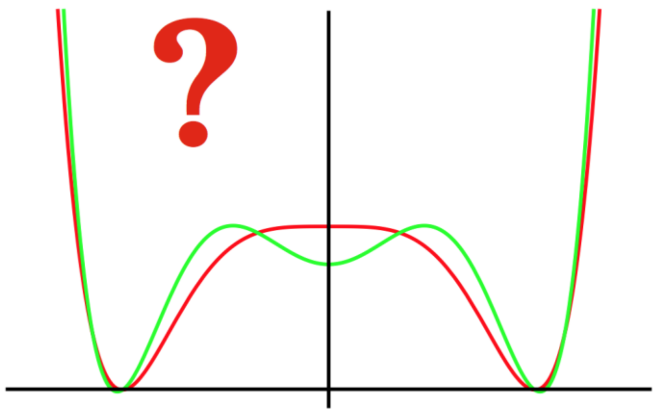


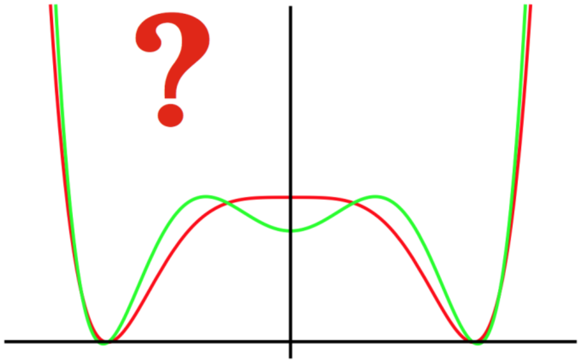
- SM assumed simplest form

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

- 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?



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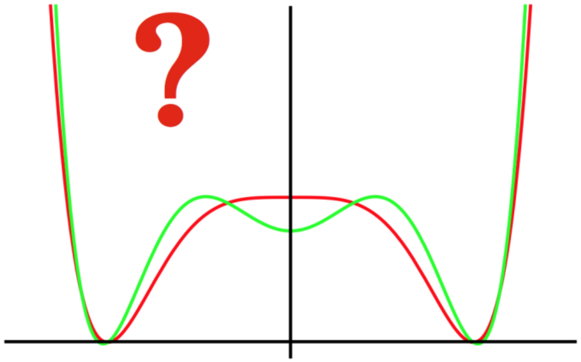
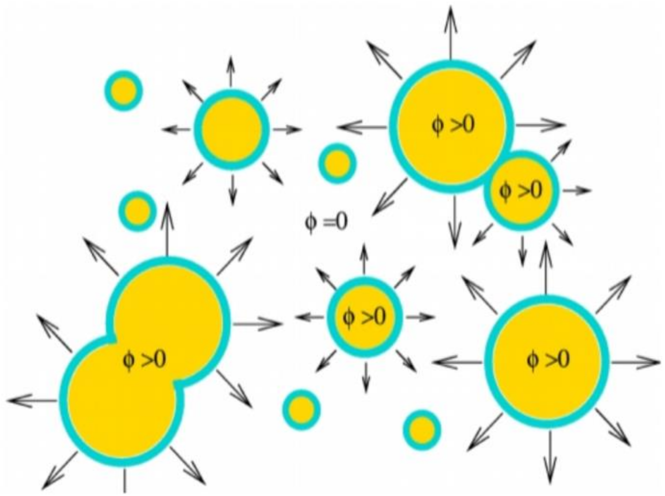




Sakharov Conditions

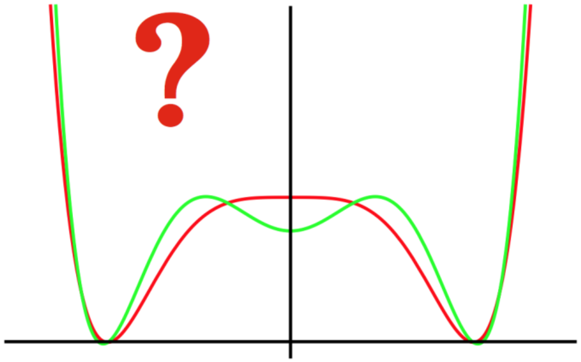
1) B Violation; 2) C/CP Violation

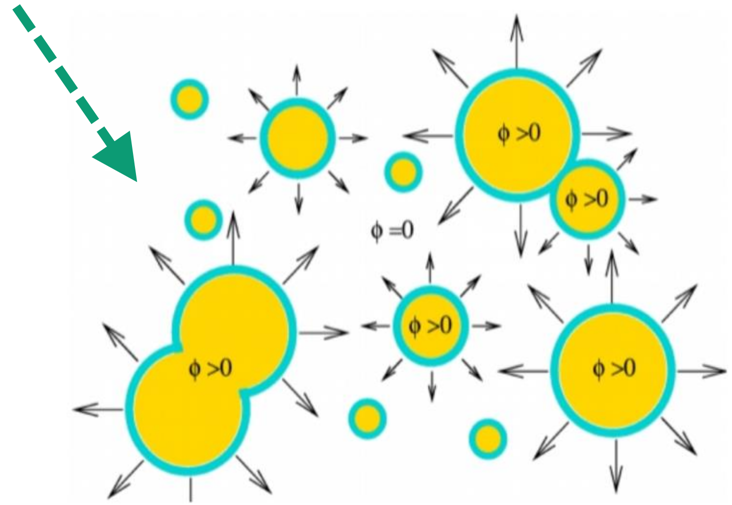
3) Departure from Thermal Equilibrium

(EW Phase Transition)

Who cares?

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





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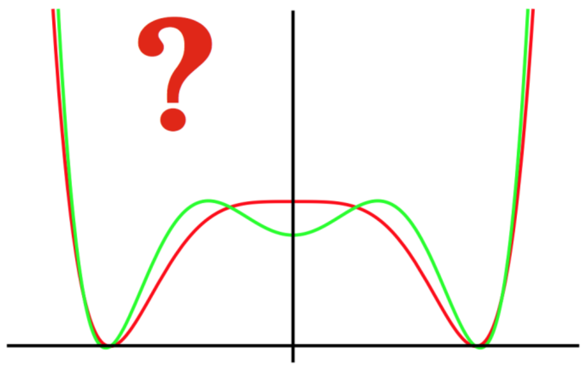

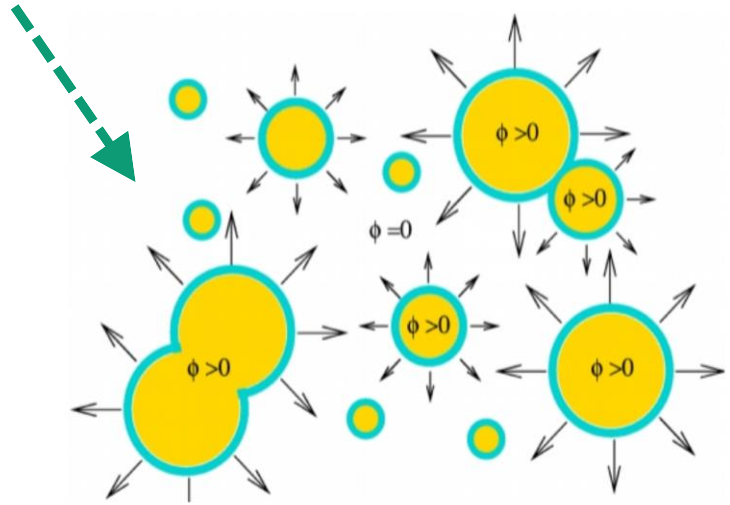

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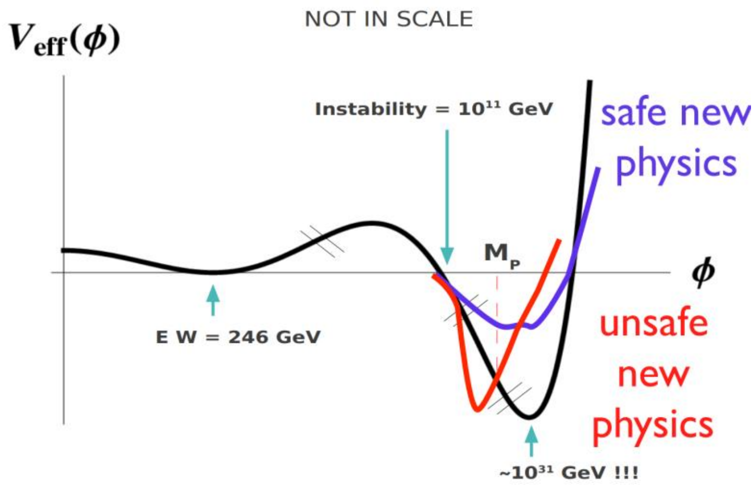

Is the current vacuum stable?

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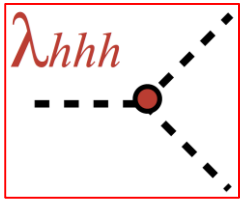
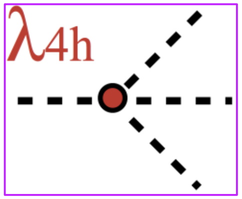
$$= V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

m_H对应曲率





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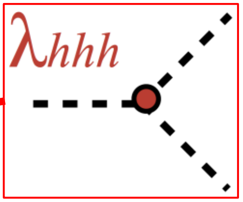
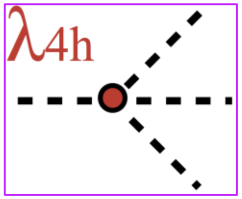
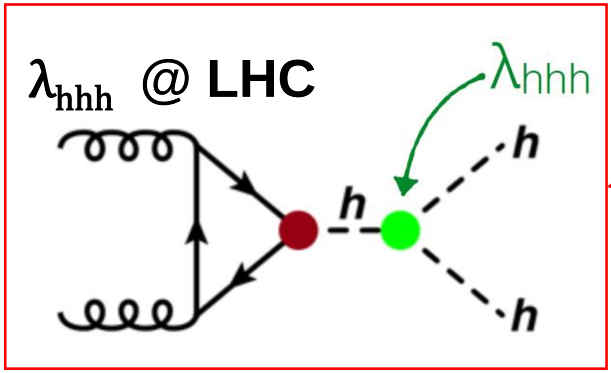






Standard Model:

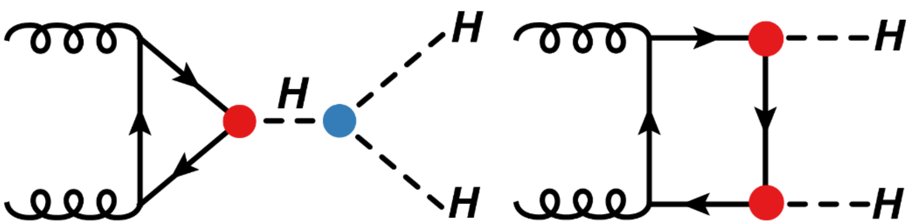
$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

- 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

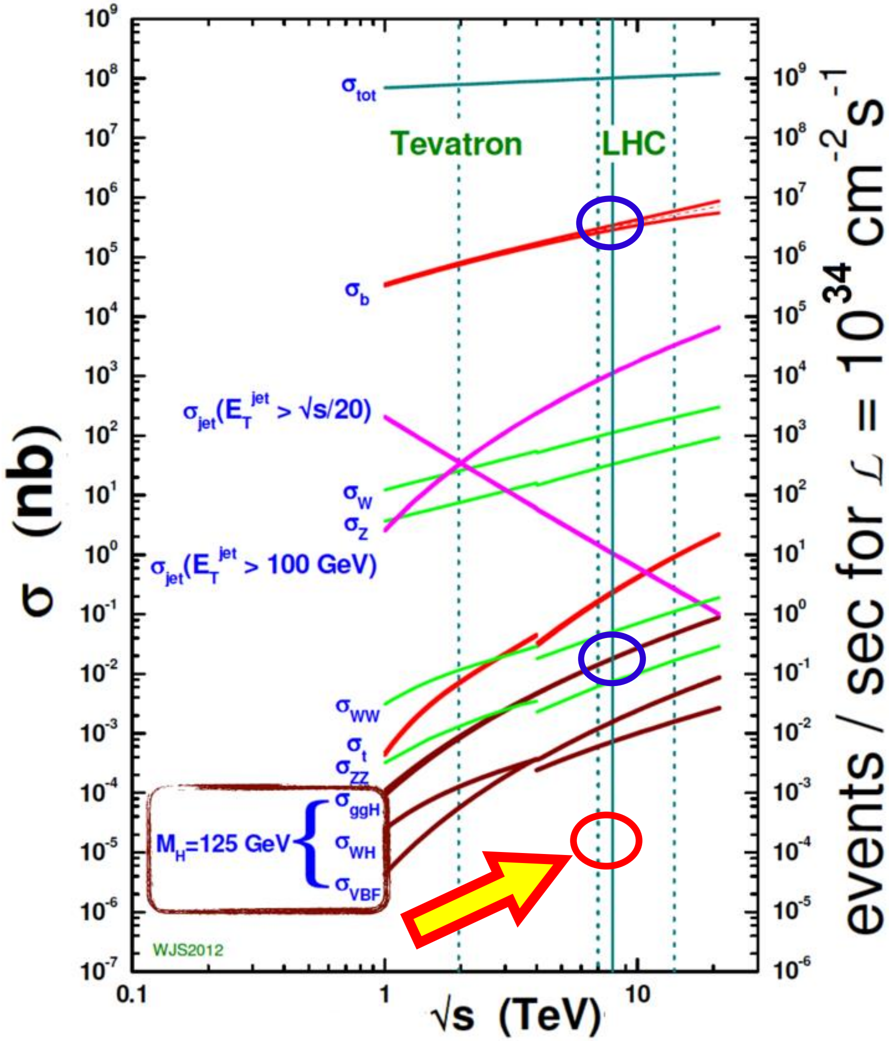
LHC @ 13 TeV

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



- Cross section: 1000+ times smaller than single Higgs

proton-(anti) proton cross section



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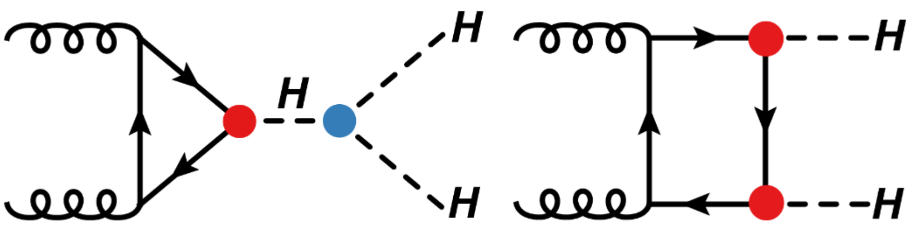

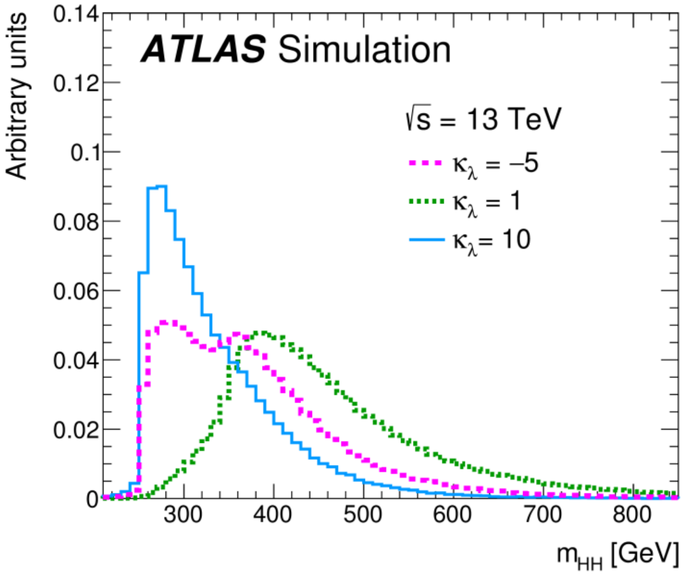

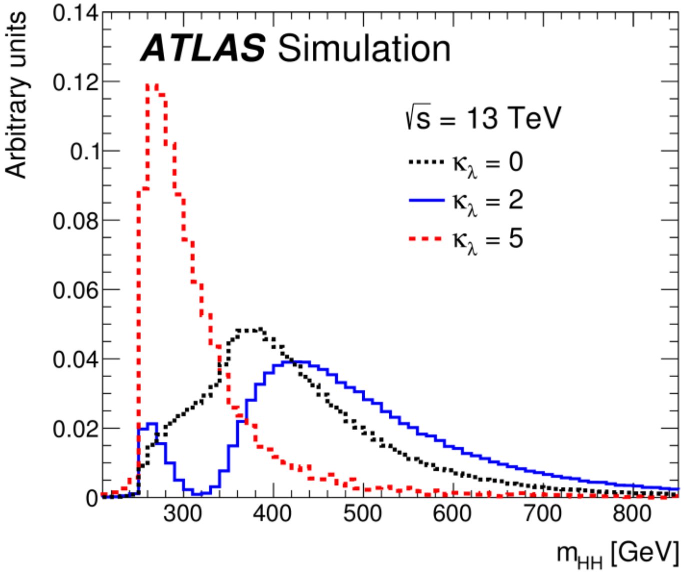

- Cross section: 1000+ times smaller than single Higgs
- Deconstructive interference, further adding difficulties

Di-Higgs at LHC

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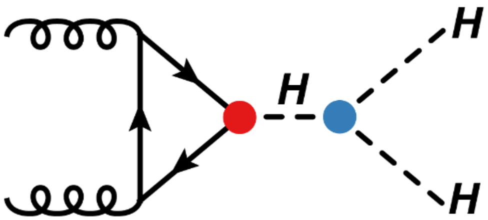
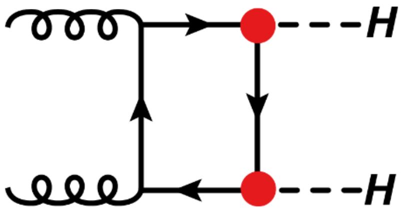
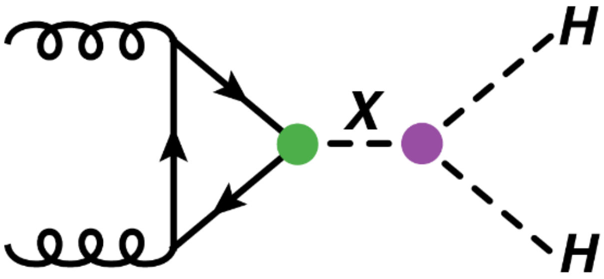
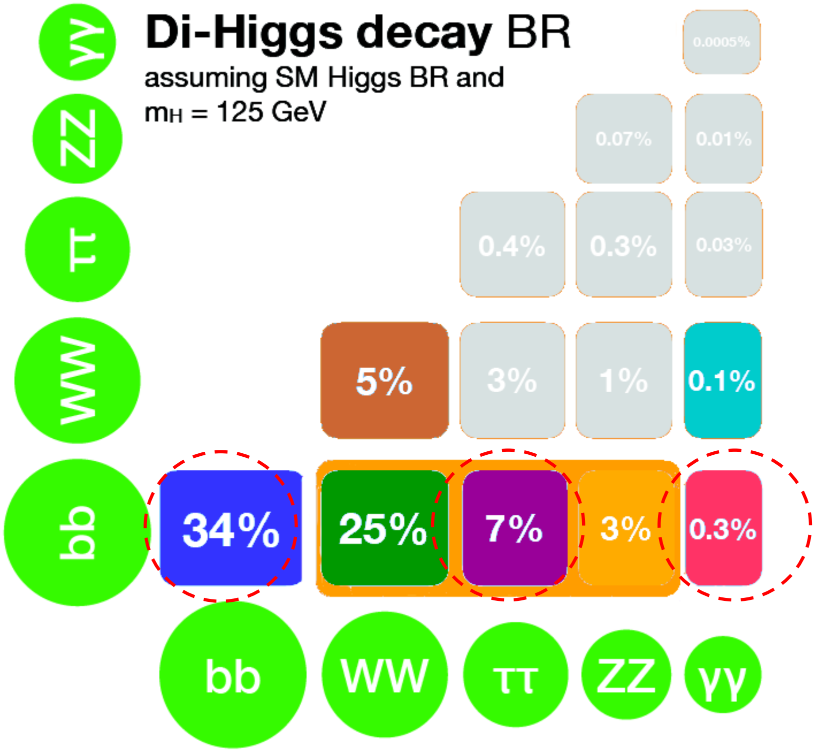




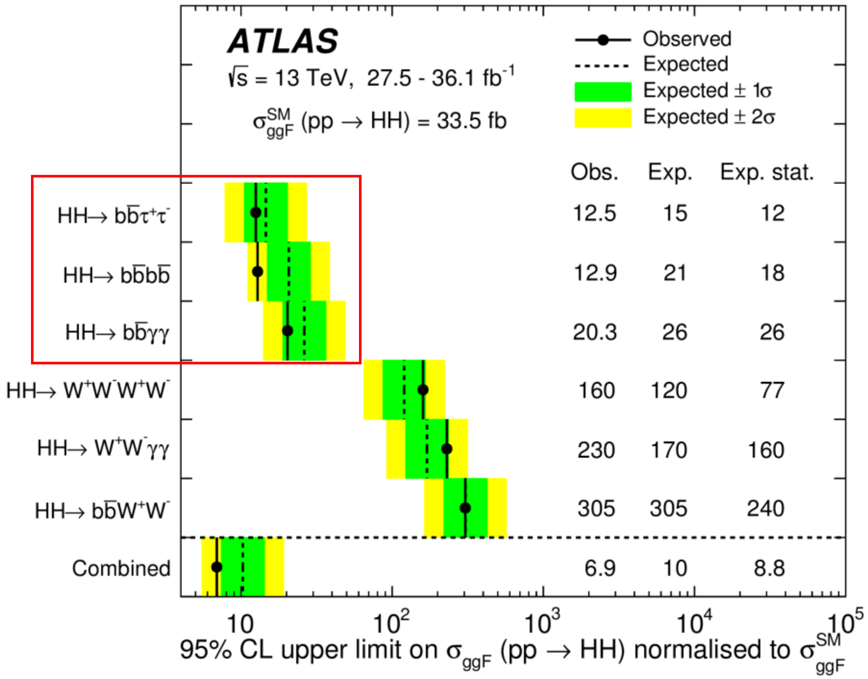
- Cross section: 1000+ times smaller than single Higgs
- Deconstructive interference, further adding difficulties
- BSM physics can also contribute



Searching channels

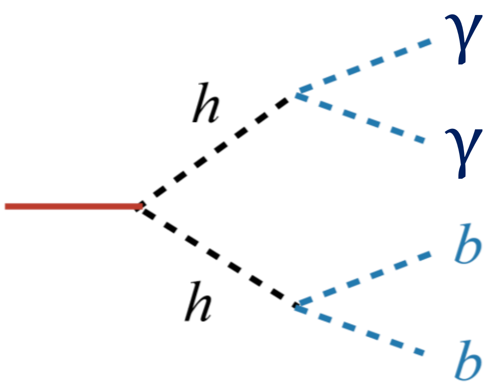


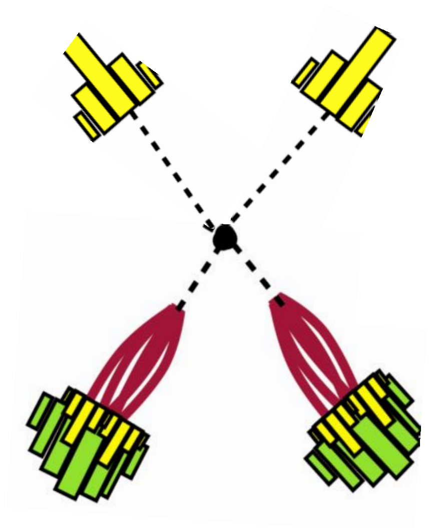
Summary Plot



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

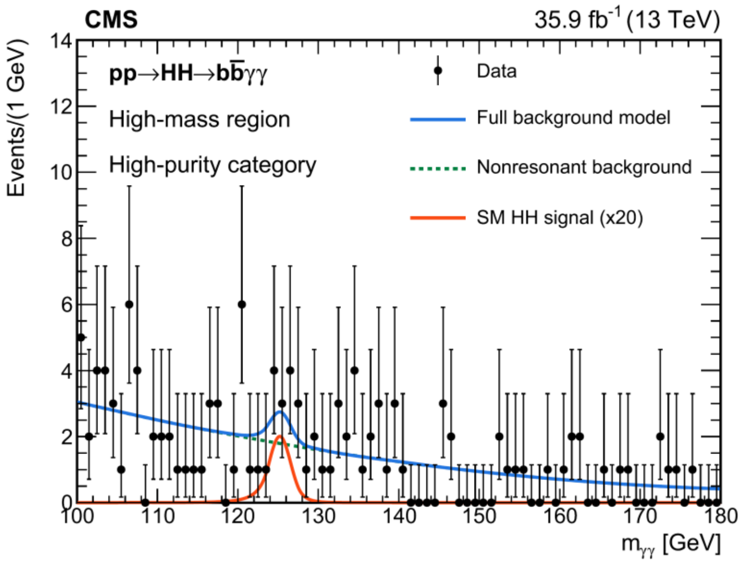
Di-Higgs: $bb\gamma\gamma$





Backgrounds:

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



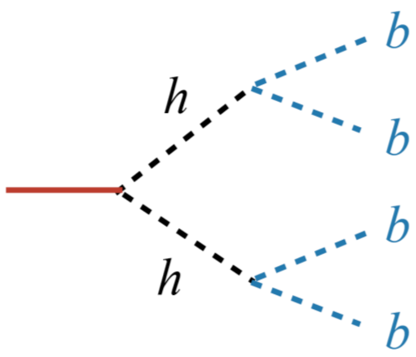
Analysis strategy

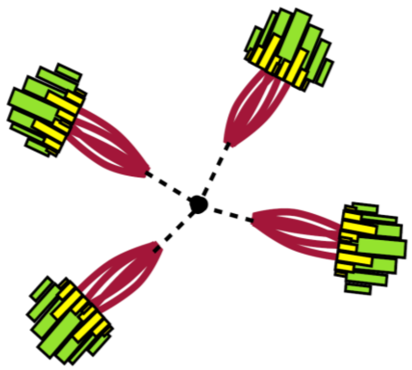
- m_{bb} and $m_{\gamma\gamma}$: to extract signal
- $m_{bb\gamma\gamma}$ important for λ_{hhh} extraction
  - m_h=125 to constrain m_{bb} and $m_{\gamma\gamma}$
- ATLAS: cut-based; CMS: MVA-based

- **Low Br., low bkg, high S/B**

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

Di-Higgs: bbbb



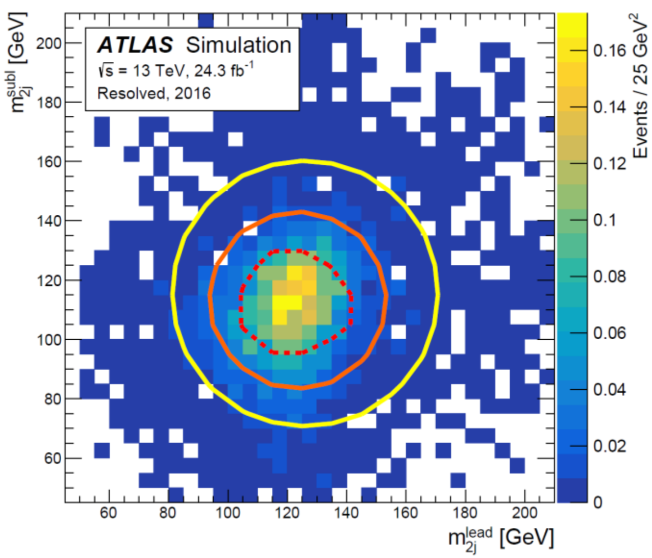


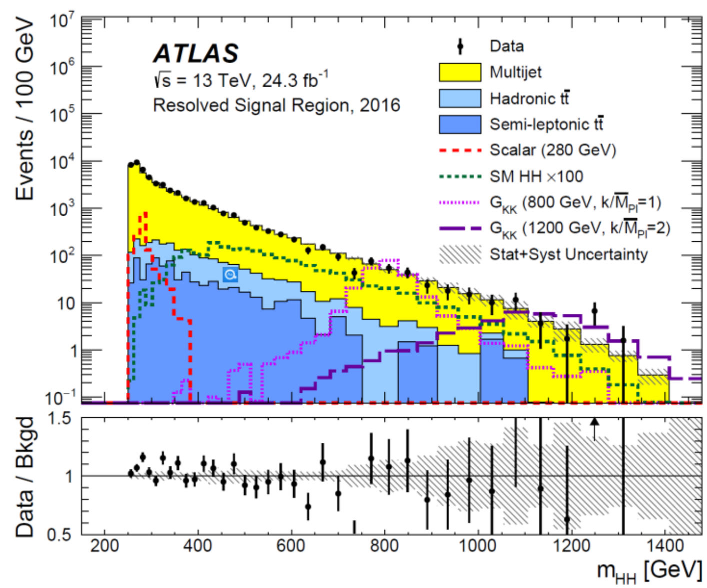
Event selection

- 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

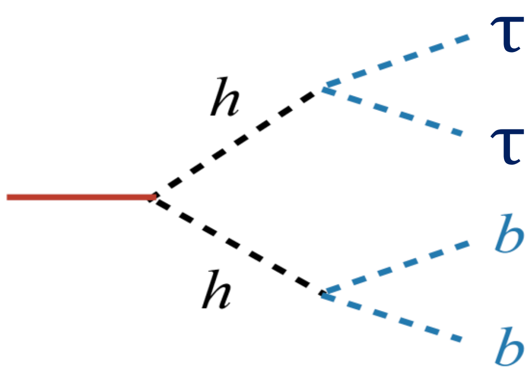
- Multi-jet(95%), top quark pair (ttbar) (5%)
- ATLAS: sideband
- CMS: shuffling two di-b systems

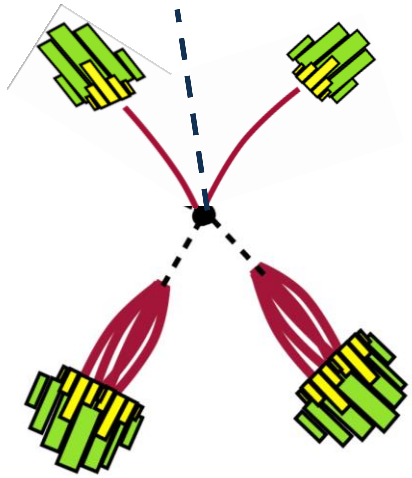




- Both use di-Higgs invariant mass to fit
- **High Br., high bkg, low S/B channel**

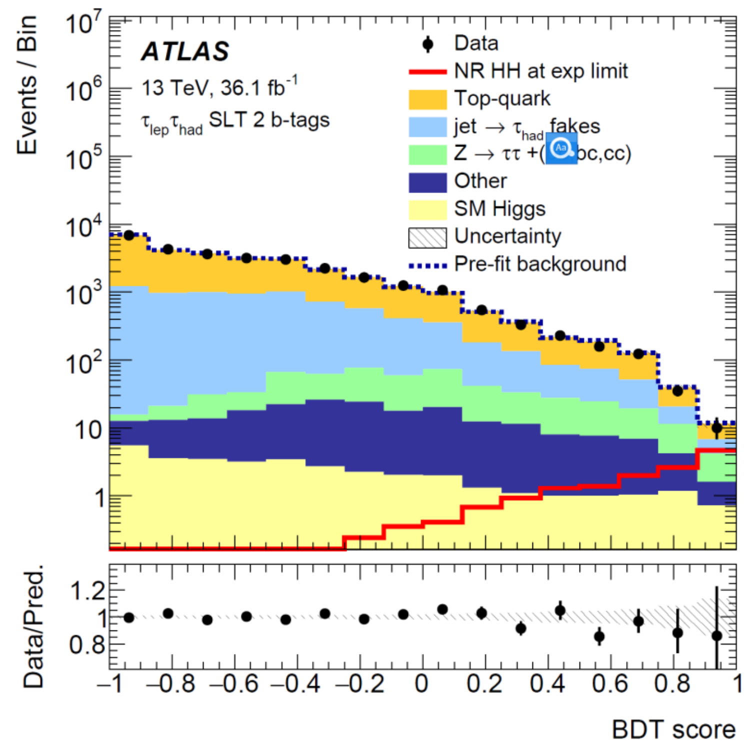
Di-Higgs: bbττ





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

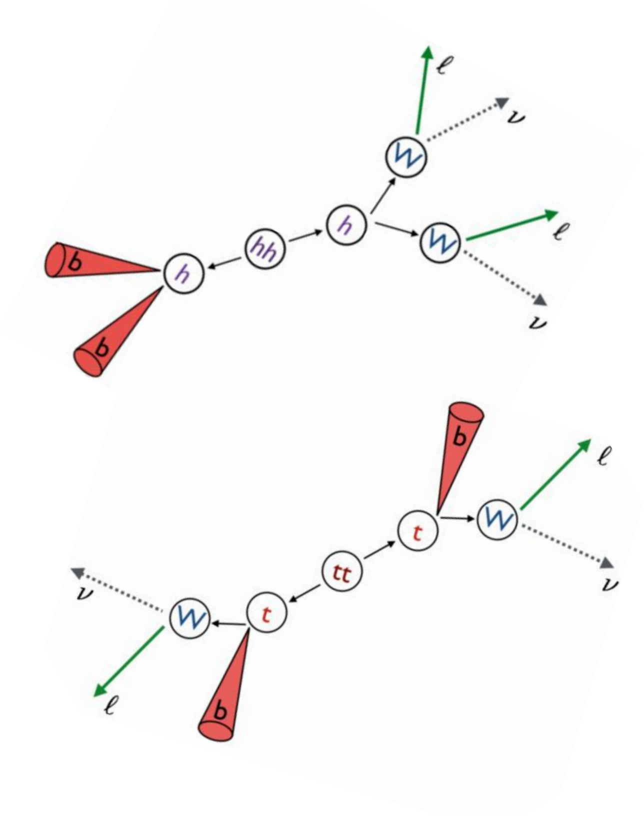
Analysis strategy

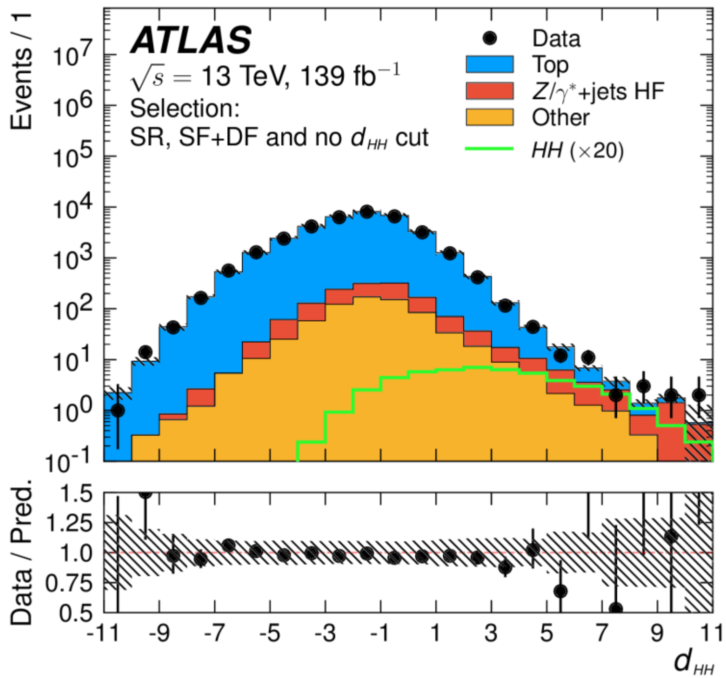
- ATLAS: MVA-based;
- CMS: Cut-based, MT_2 to fit **(PLB 728 (2014) 308–313)**

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

Complicated channels: hh→bbWW

- Large Br(~25%), but noncolinear neutrinos and huge ttbar background
- Final states: bblνlν (l=e/μ), bblνjj
- Deep learning (DNN) has been used in this analysis at ATLAS and CMS





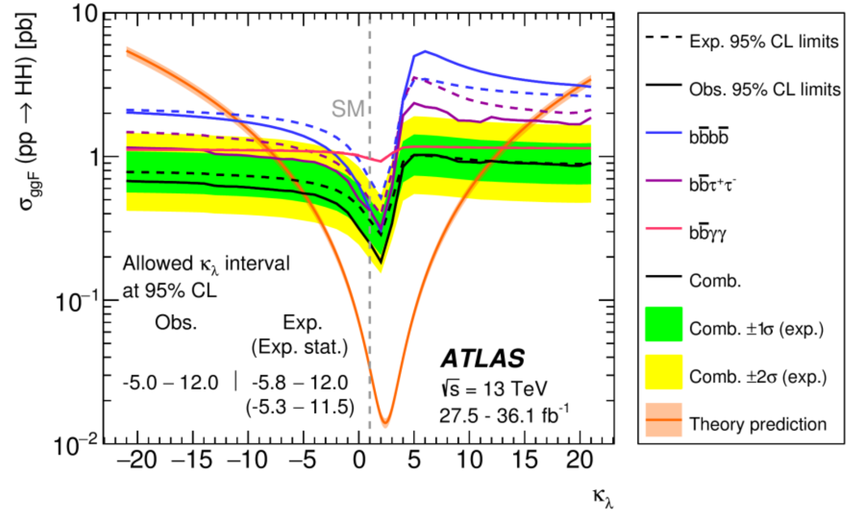
- Many theoretical studies:
  - e.g. m_{T2}, Top/Higgsness, (J. H. Kim, et al, arXiv:1807.11498)
- **Still room for theorists to play!**

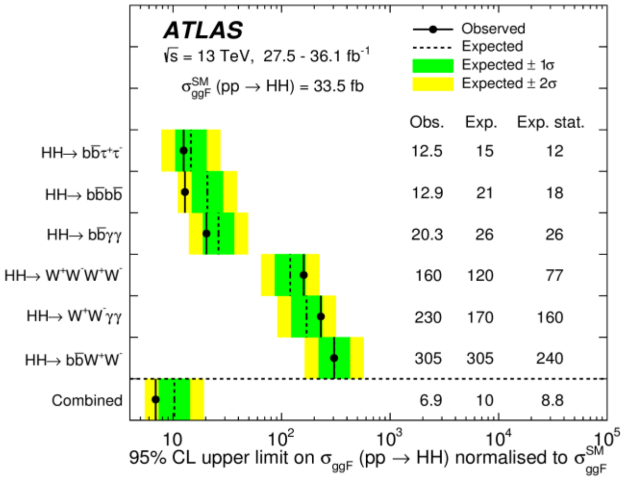
Di-Higgs summary: λ_{hhh}

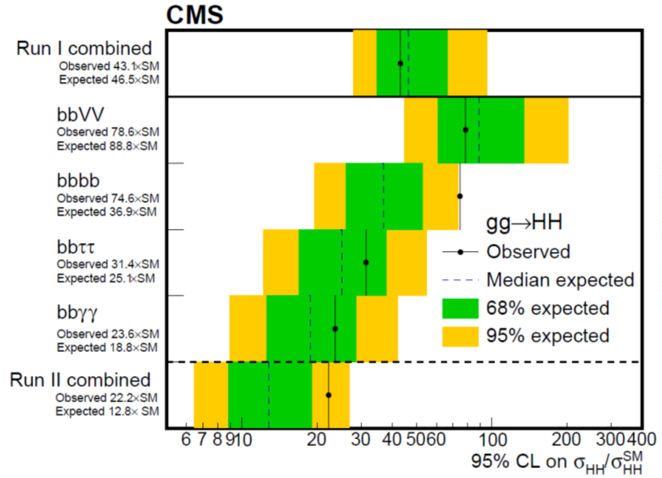
- ATLAS: σ_{hh} <6.9 (10) x SM, -5.0 <λ_{hhh}< 12.0
- CMS: σ_{hh} < 22.2 (12.8) x SM, -11.8 <λ_{hhh}<18.8 (-7.1 <λ_{hhh}< 13.6)

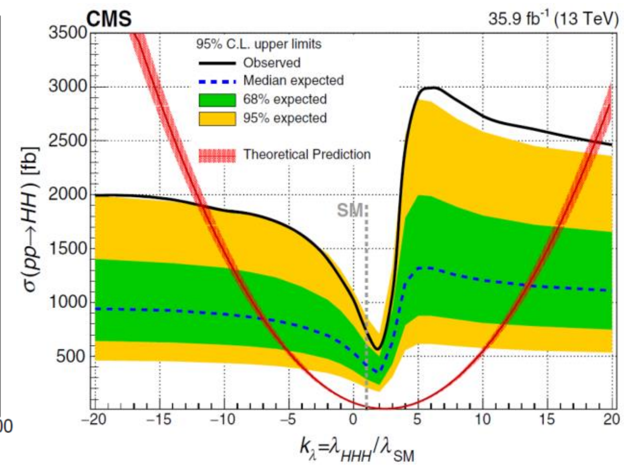
New results:

- λ_{hhh} can be constrained via Higgs precise measurement (Kunlin's talk)



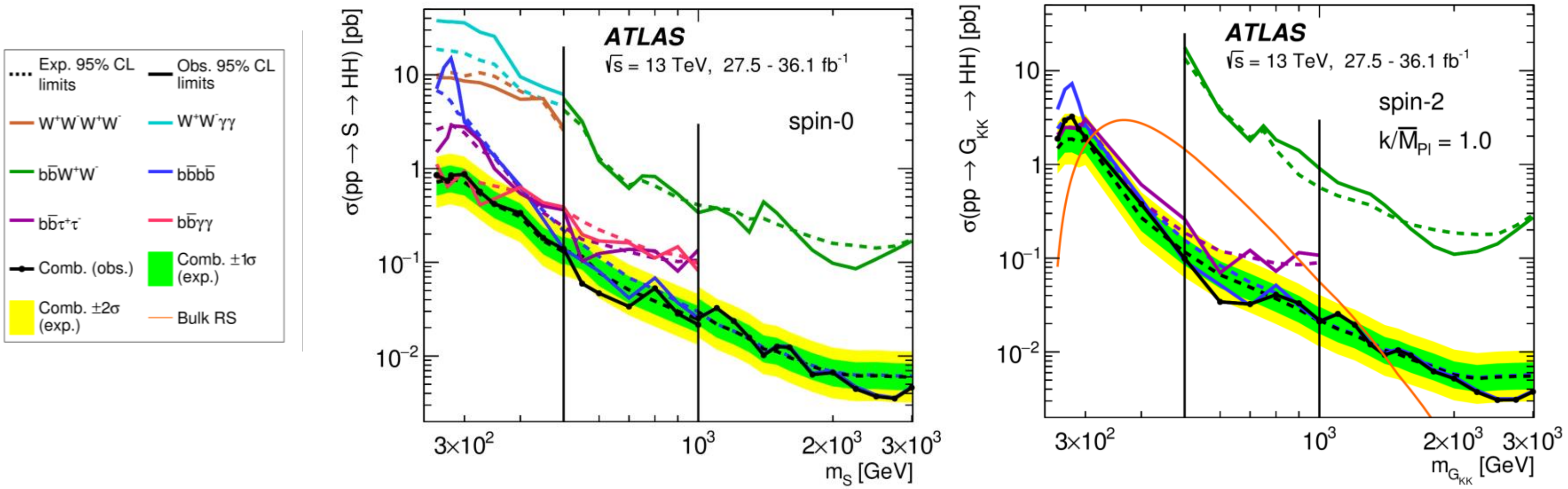




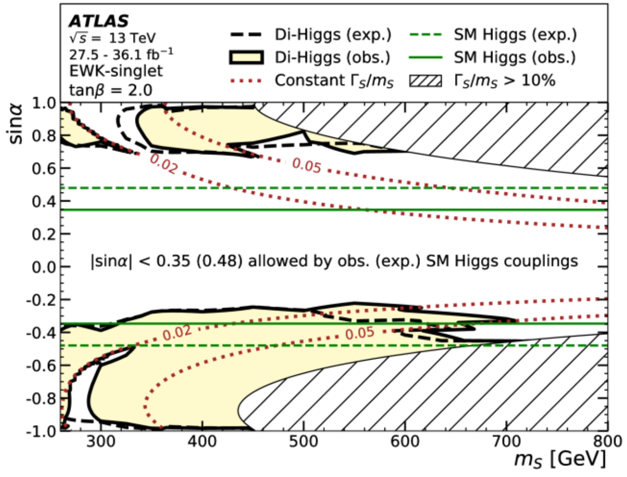


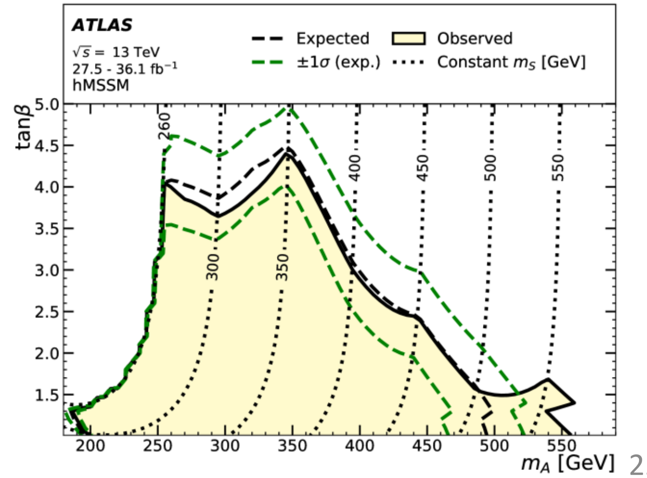
Di-Higgs summary: BSM

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



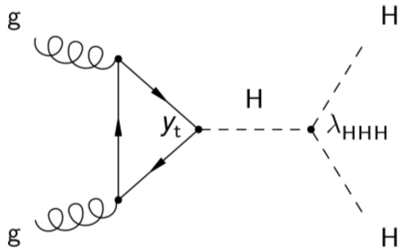
- Interpretation:
  - EW-singlet
  - MSSM

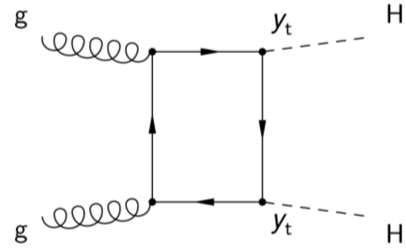




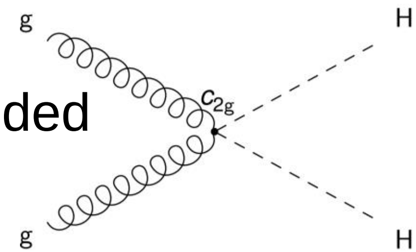
Di-Higgs summary: BSM

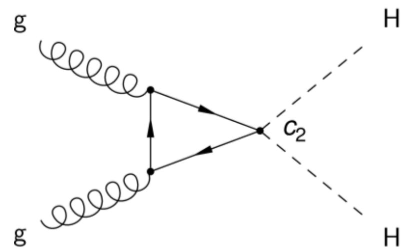
$$\mathcal{L}_{\mathrm{HH}} = \kappa_\lambda \, \lambda^{\mathrm{SM}}_{\mathrm{HHH}} v \, H^3 - \frac{m_\mathrm{t}}{v}\left(\kappa_\mathrm{t} \, H + \frac{c_2}{v} \, H^2\right)\left(\bar{\mathrm{t}}_\mathrm{L}\mathrm{t}_\mathrm{R} + \mathrm{h.c.}\right) + \frac{1}{4}\frac{\alpha_S}{3\pi v}\left(c_\mathrm{g}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

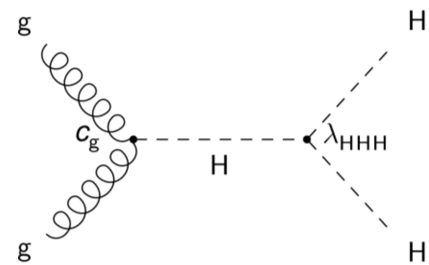




- CMS explored 5 EFT operators, divided parameter space into 12 samples

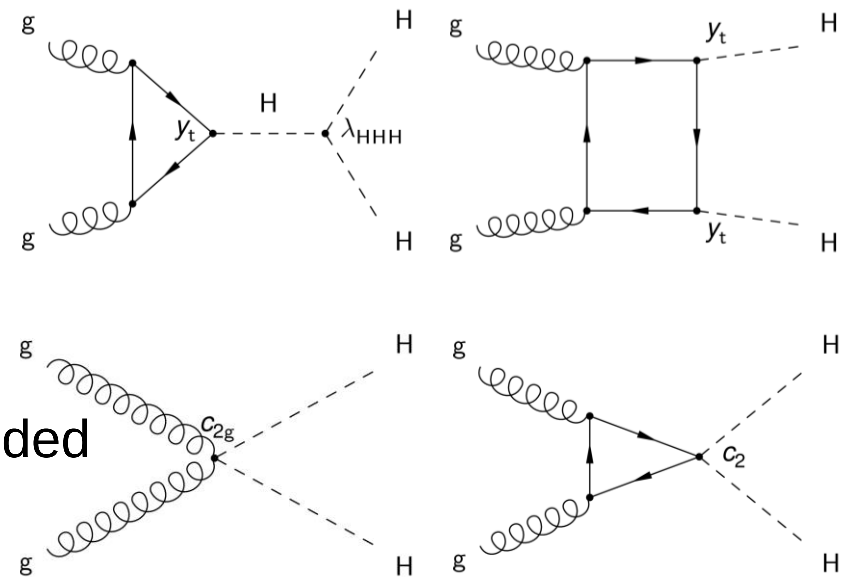




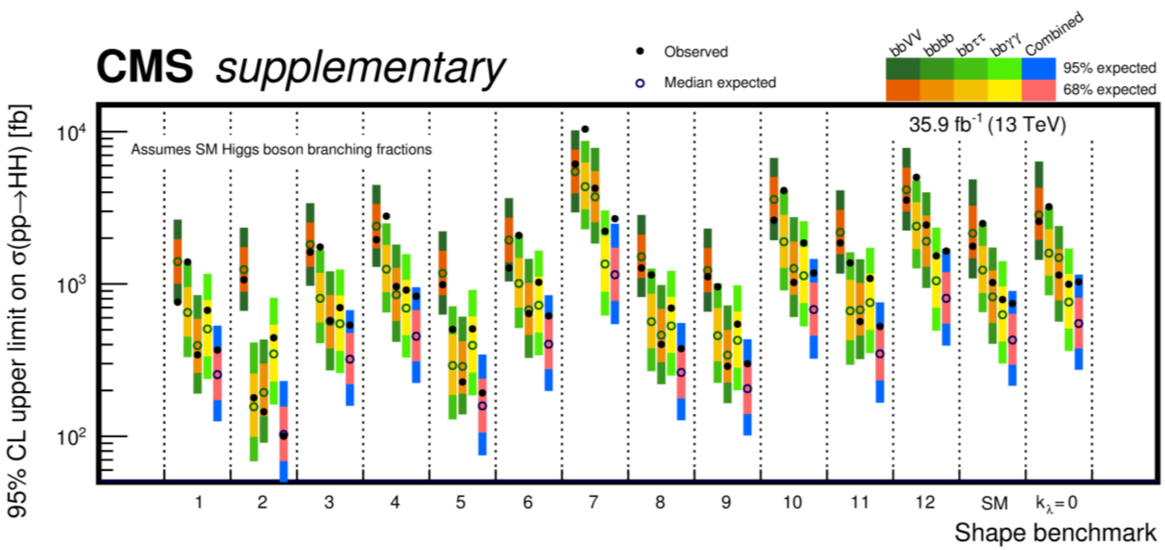


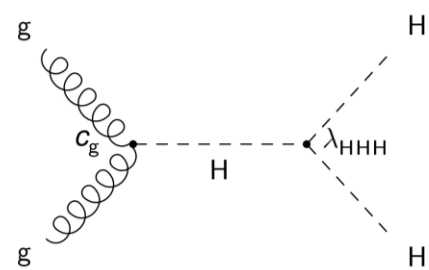
Di-Higgs summary: BSM

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

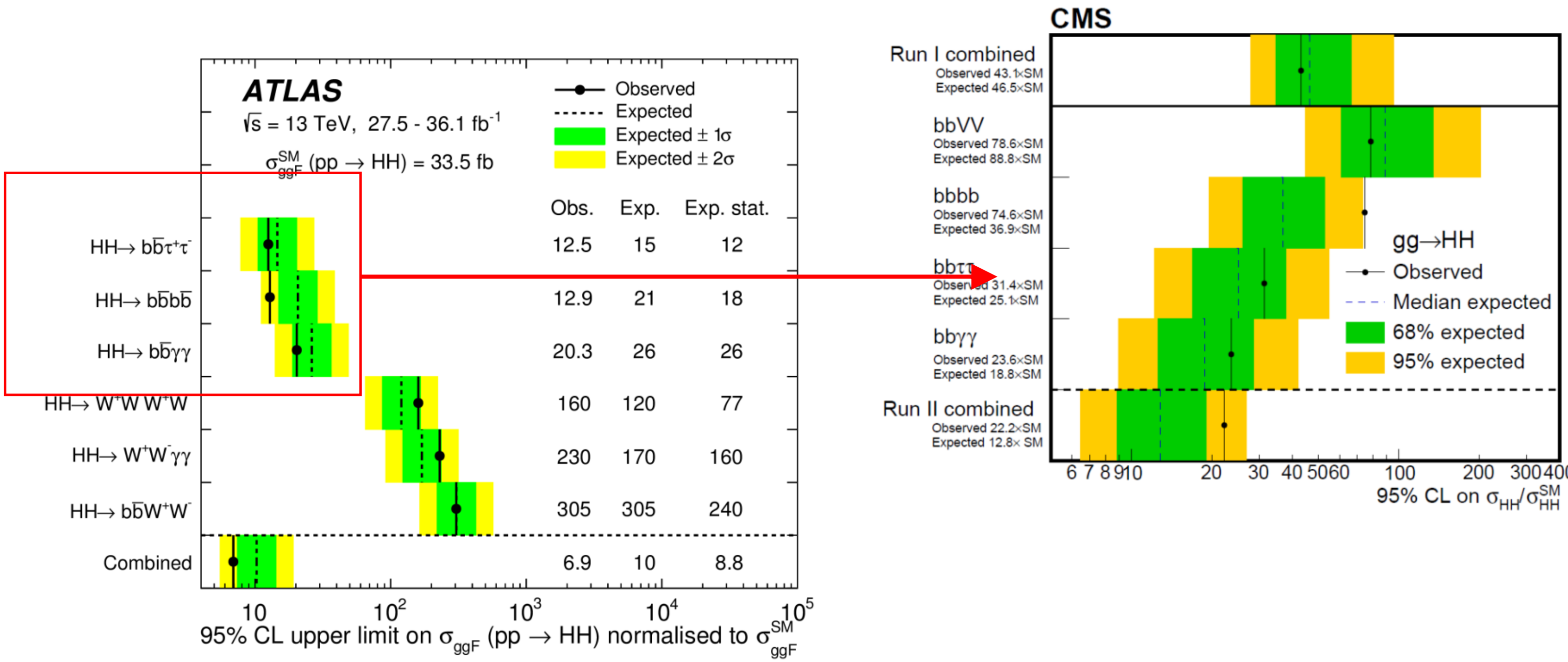


- CMS explored 5 EFT operators, divided parameter space into 12 samples





Some personal reflections

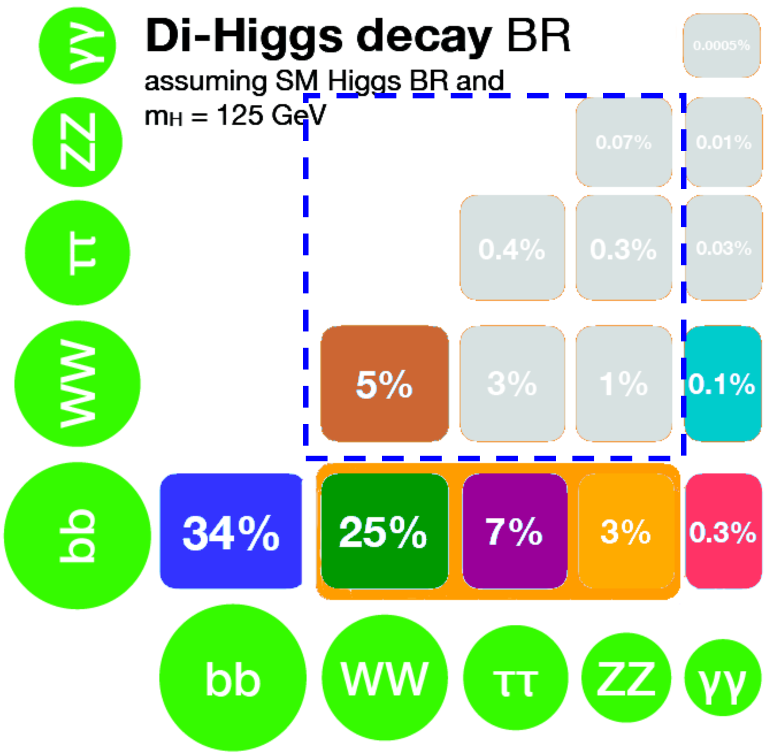


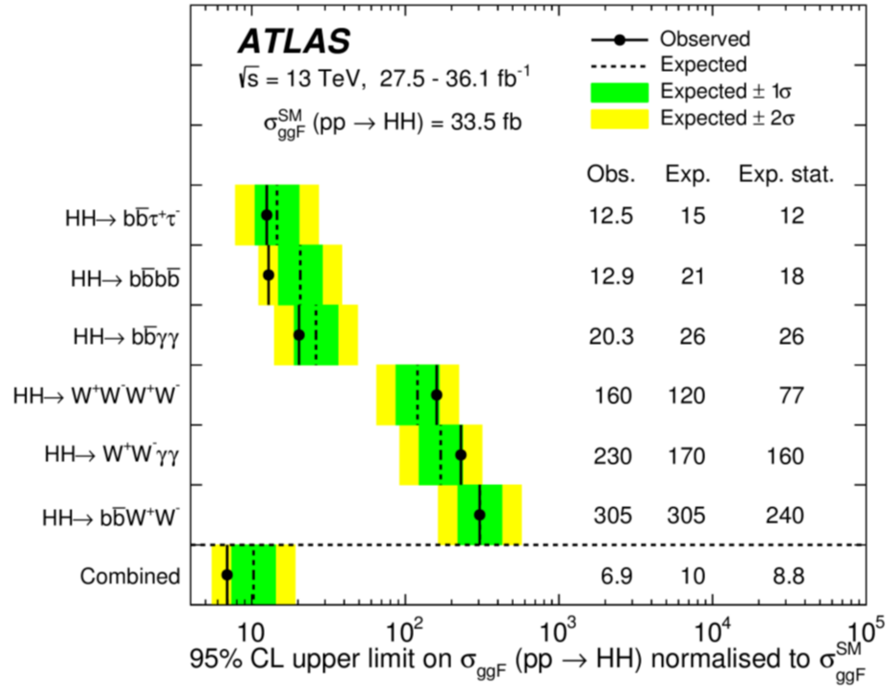
- Performance of ATLAS and CMS are generally the similar. However, sensitivity order are different among three channels
- The difference maybe due the person-power. There are room for improvement.

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



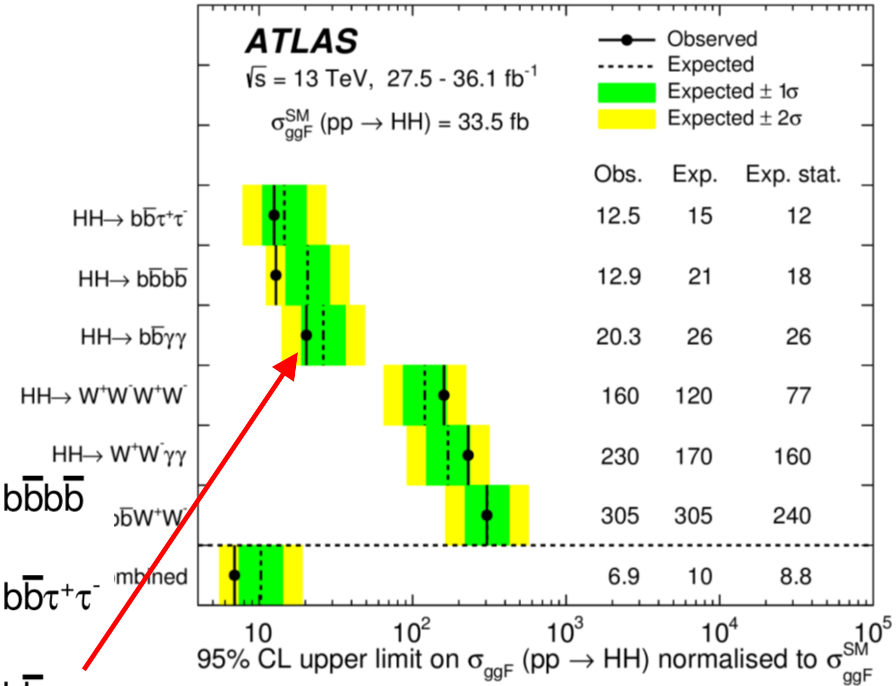


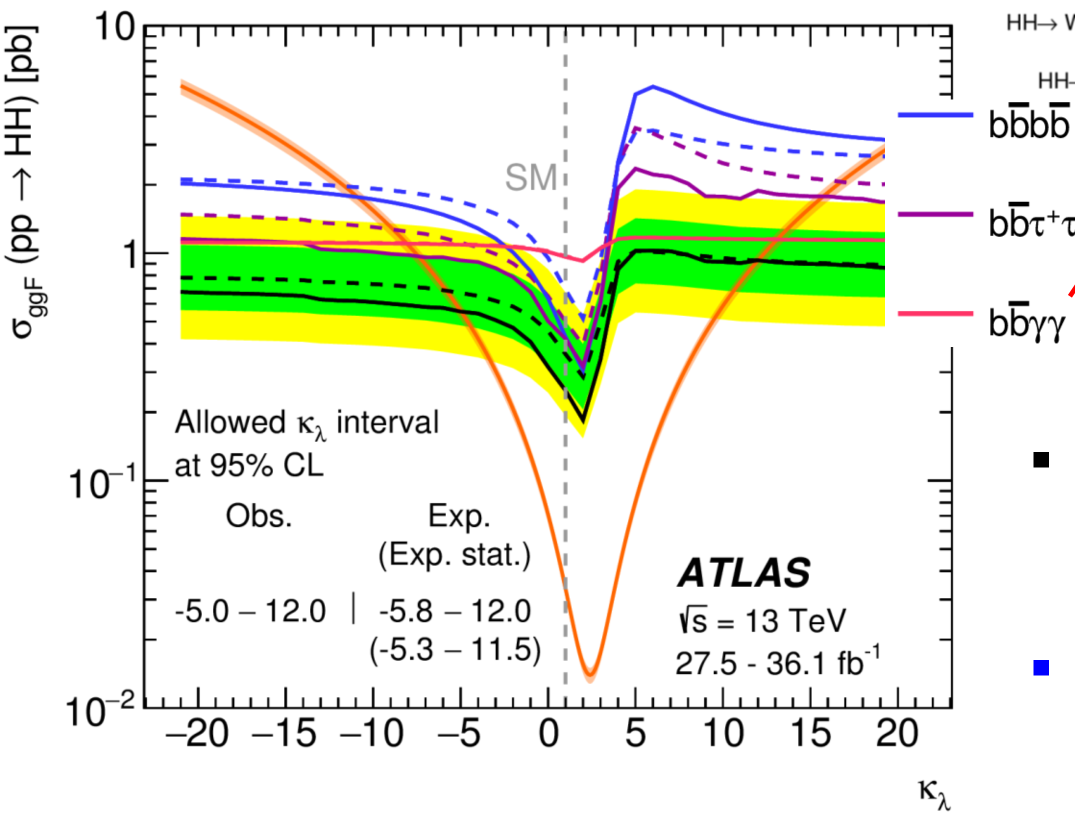
As Run 3 and even HL-LHC,

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



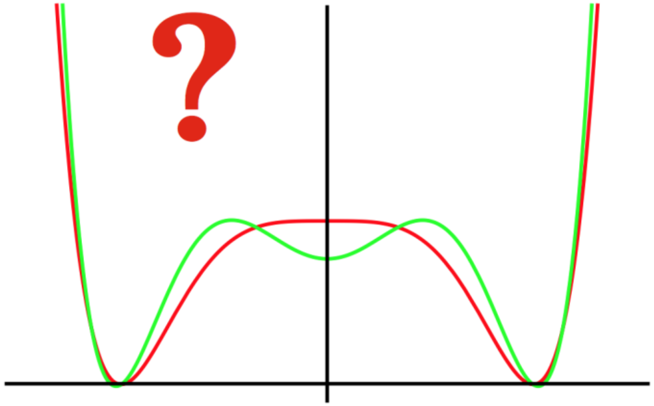


- **γγbb** with good resolution can reconstruct the variables that are sensitive to λ_{hhh}, e.g. m_{hh}
- Can we find or build an even better one?

Beyond SM Higgs boson search

Extended Higgs sector

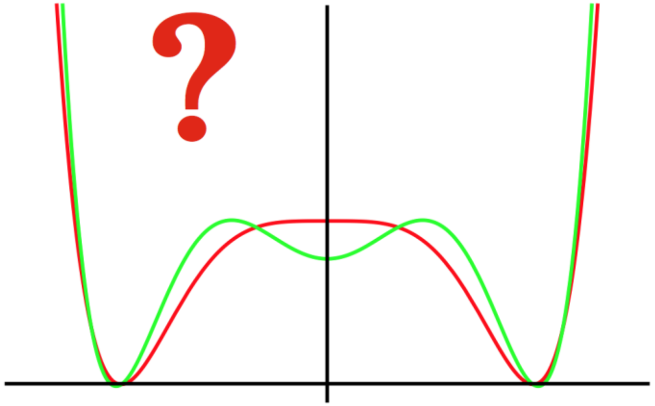
- Extension of Higgs sector could change the Higgs potential.



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

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



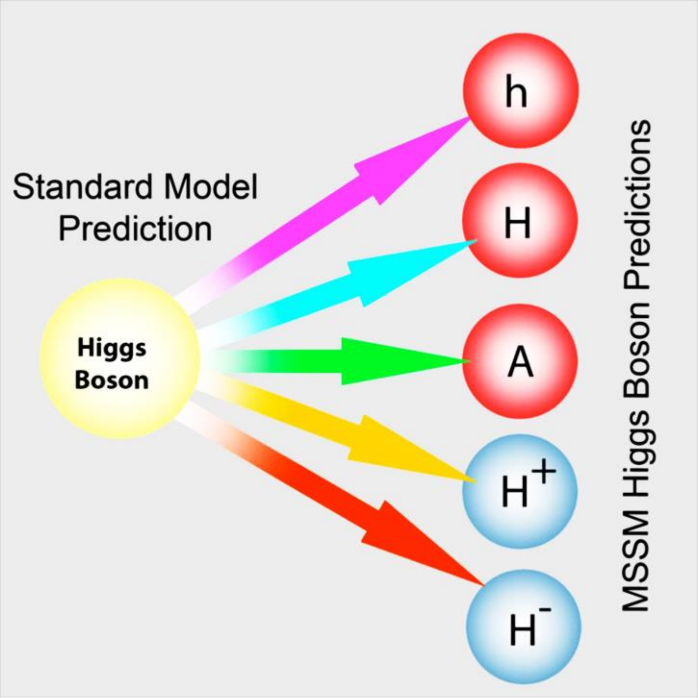
$$V_{\mathrm{CxSM}} = \frac{m^2}{2}\mathrm{H}^\dagger\mathrm{H} + \frac{\lambda}{4}(\mathrm{H}^\dagger\mathrm{H})^2$$

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

Benchmark models

Two-Higgs Doublets Model (2HDM)

- Minimum extension of Higgs sector
- Requested by MSSM



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

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

- 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	$\sin(\beta-\alpha) \;\to 1$	$\cos\alpha/\sin\beta \;\to\; 1$	$-\sin\alpha/\cos\beta \to\; 1$

For $m_A \gg m_Z$: $\alpha \to \beta - \pi/2$ (coupling to down-type fermions enhanced by $\tan\beta$).

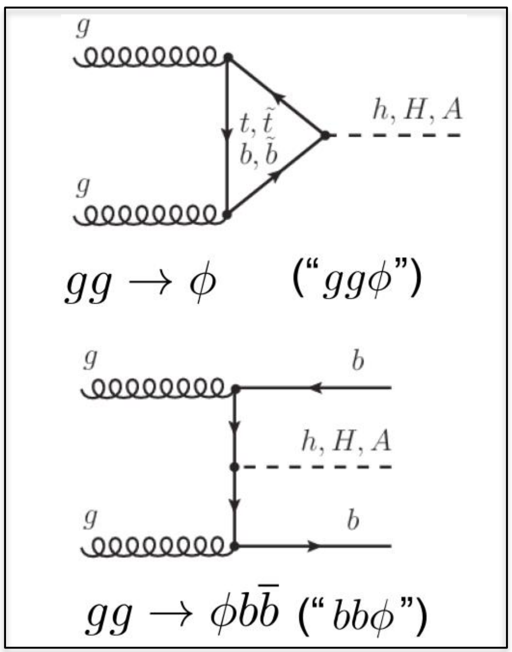
Neutral Higgs bosons: MSSM as example

Coupling strength:

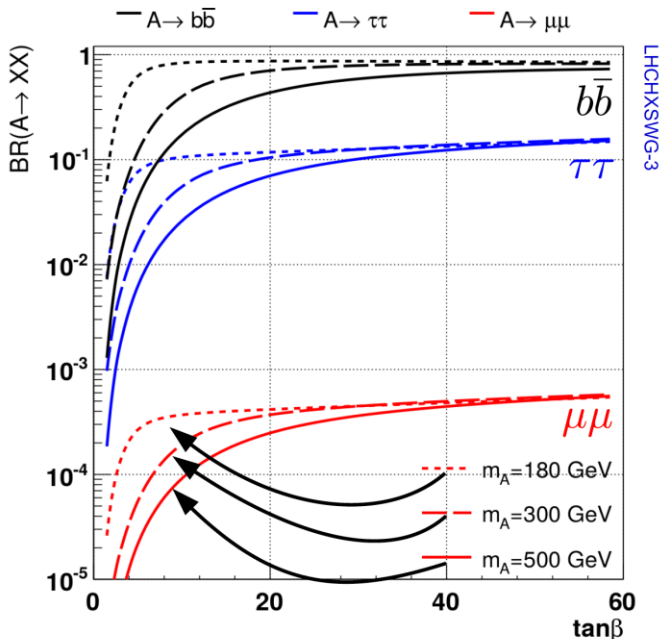
	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \;\to 0$	$\sin\alpha/\sin\beta \;\to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \;\to 1$	$\cos\alpha/\sin\beta \;\to\; 1$	$-\sin\alpha/\cos\beta \to\;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

For $m_A \gg m_Z$: $\alpha \to \beta - \pi/2$ (coupling to down-type fermions enhanced by $\tan\beta$).

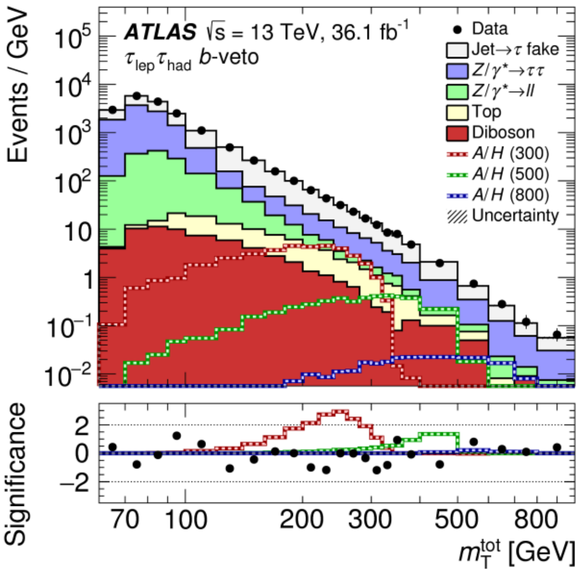
Production modes:



Decay channels:

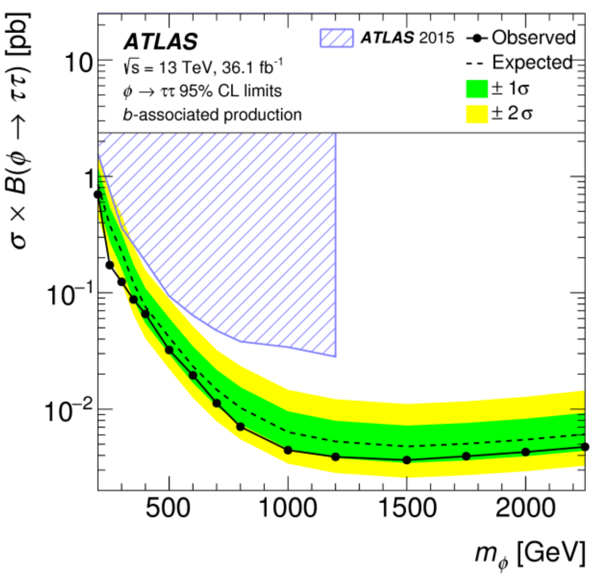


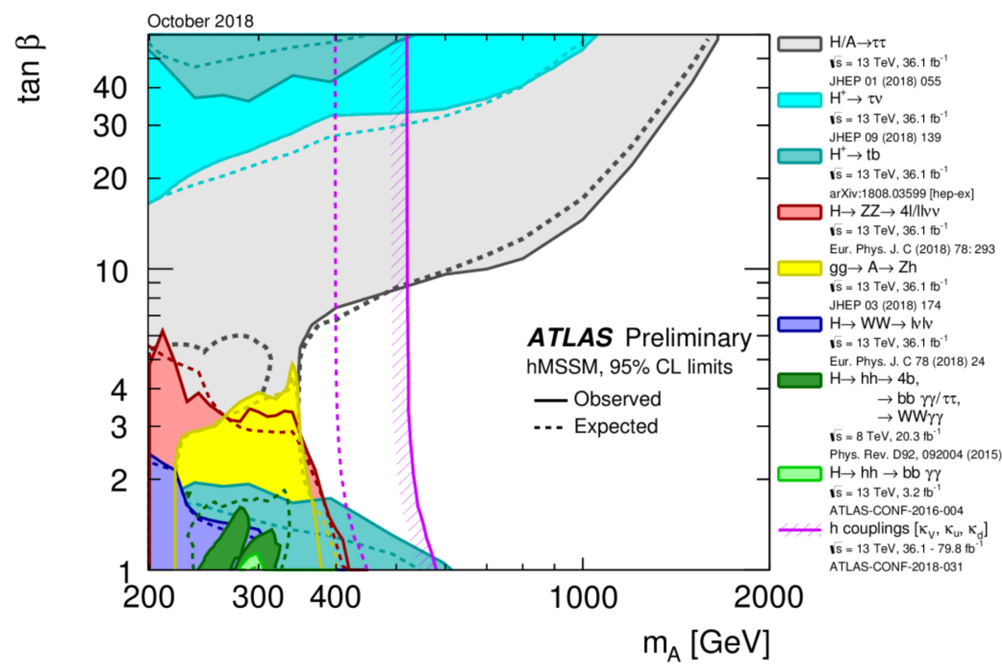
Neutral Higgs: A/H→ττ



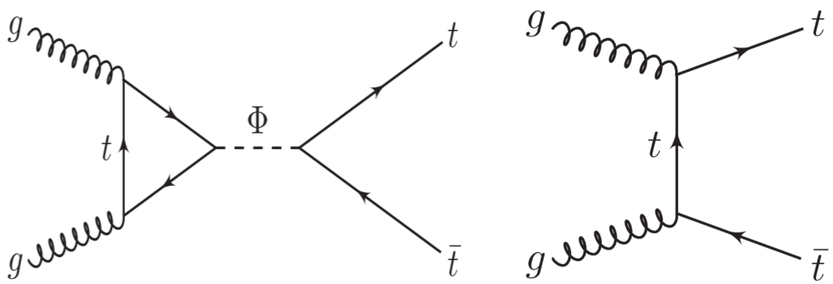
- Final states: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
- Mass range 200–2250 GeV
- Categories: b-veto (ggh) and b-tag (bbh)
- Discriminant: total transverse mass

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

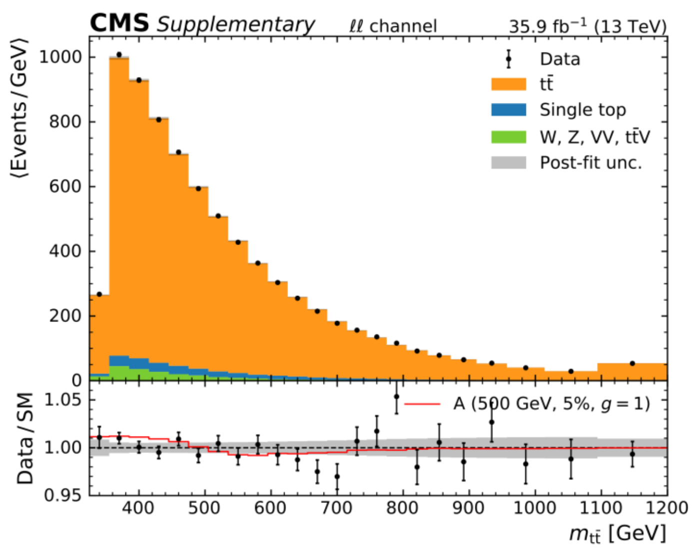


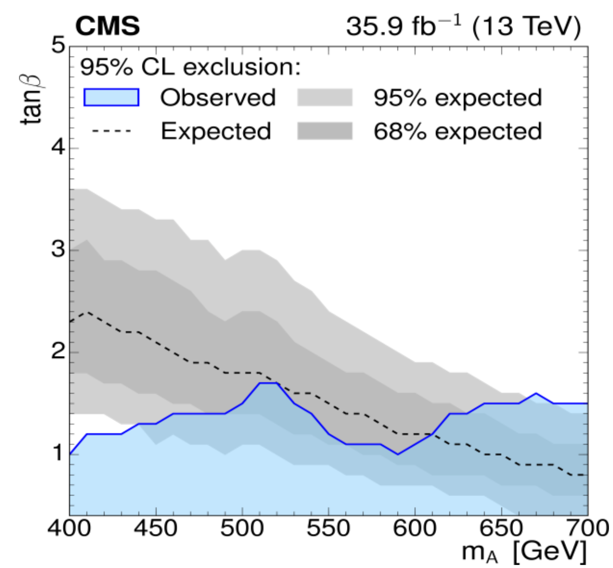


Neutral Higgs: A/H→ $t\bar{t}$



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

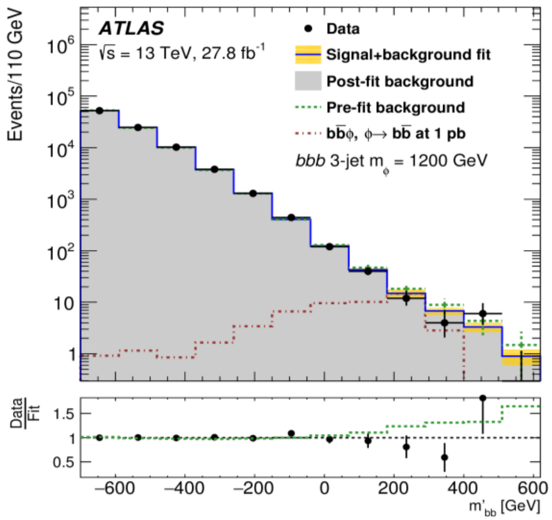


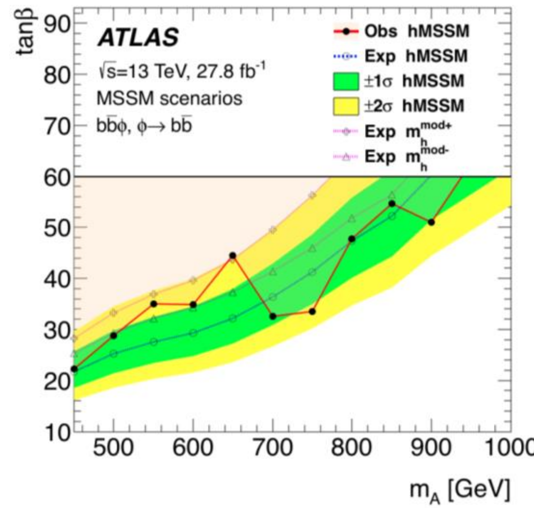


- Search range: 400-750 GeV, width Γ/m={0.5-25}%
- Exclusion in hMSSM
  - an mild excess at mA =400 GeV with Γ/m=4% 1.9σ global (3.5σ local)

Neutral Higgs: A/H→ bb or μμ

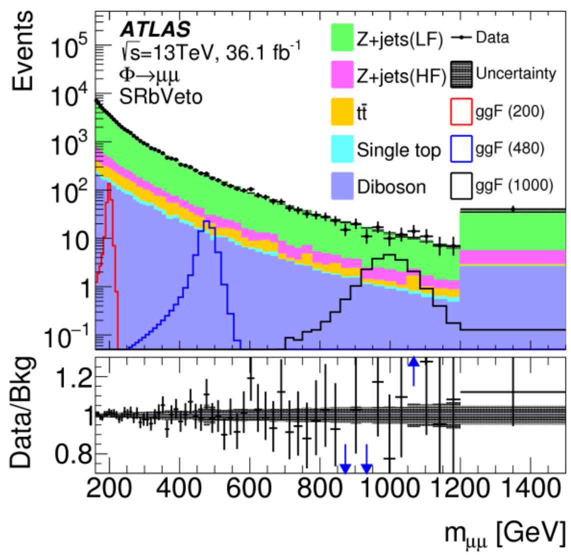
A/H→bb

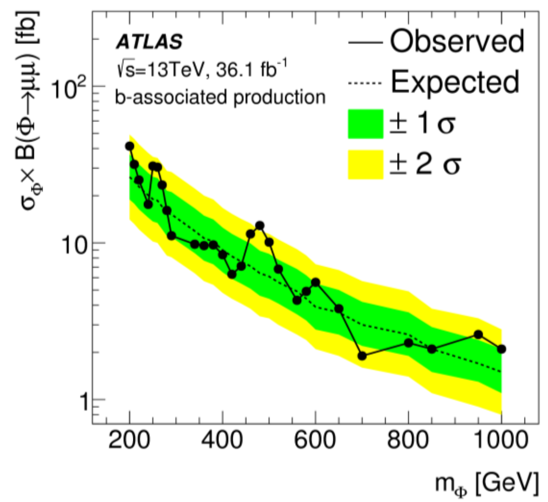




- Type II and Flipped 2HDM

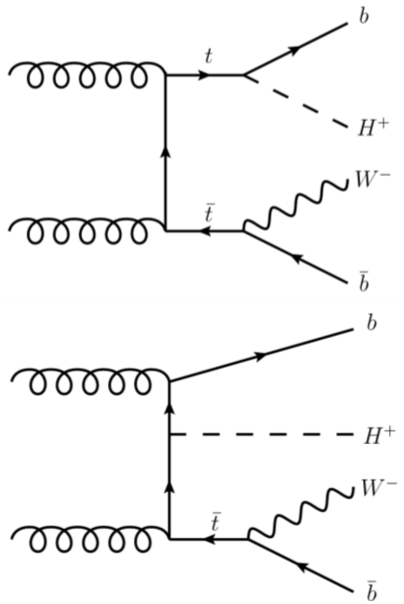
A/H→μμ: 2nd generation fermion

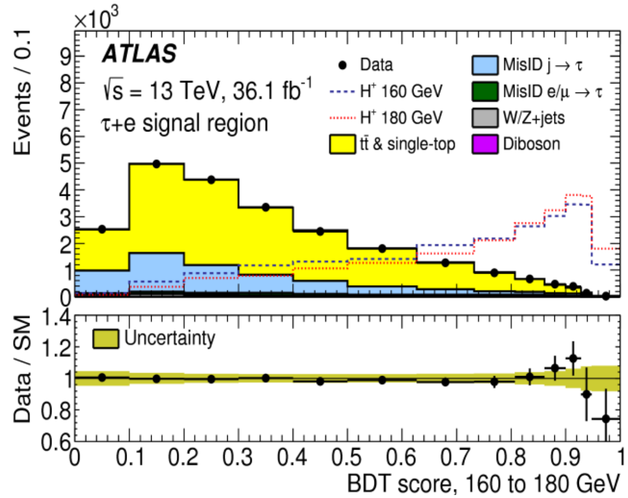


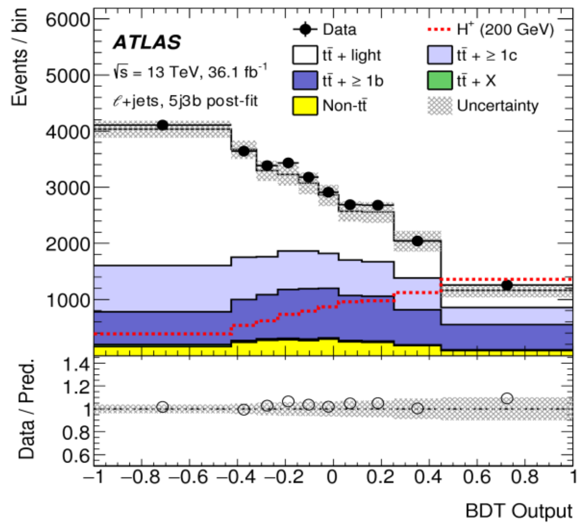


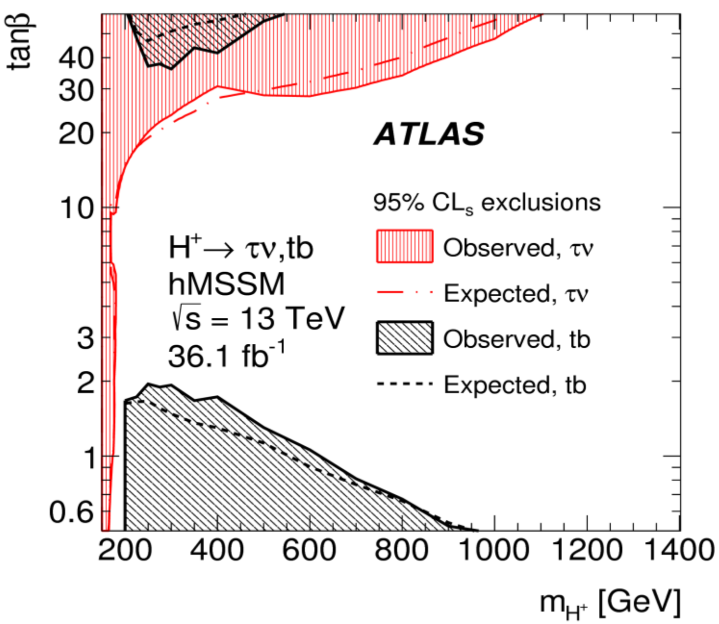
- Flavourful Higgs model

Charged Higgs H±→τν or top+b









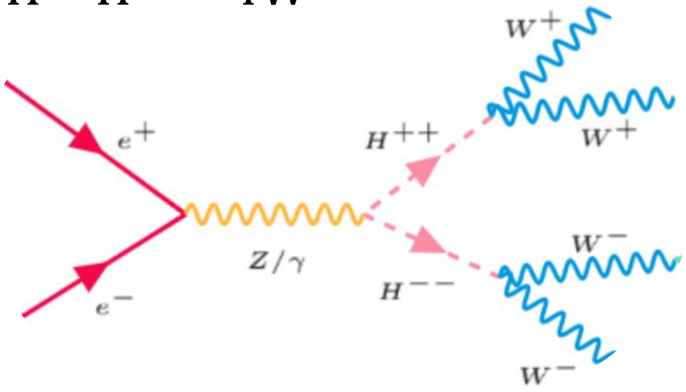
Two final search channels

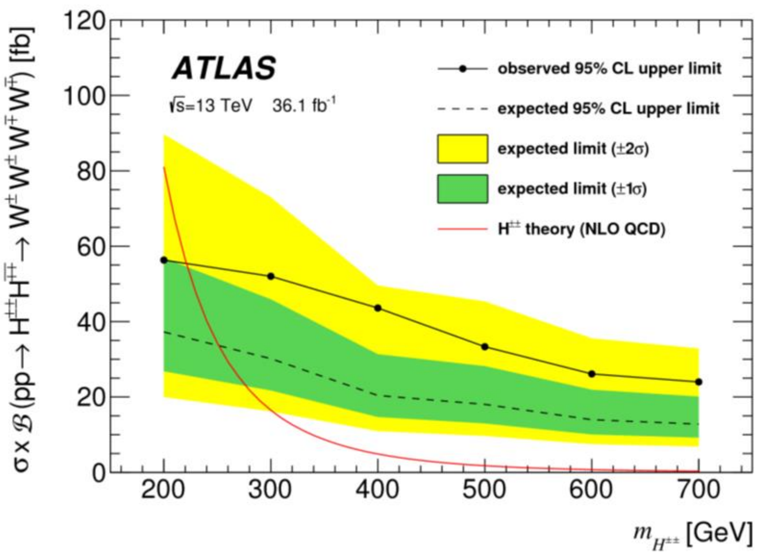
- $H^{\pm}\rightarrow\tau\nu$: τ_{had}+jets, τ_{had}+lep final state
- $H^{\pm}\rightarrow tb$: categorization w.r.t. N_{jets} and $N_{b\text{-}jets}$
- MVA technique used both channels

Doubly charged Higgs: $H^{\pm\pm}H^{\mp\mp} \rightarrow 4W$, 4l

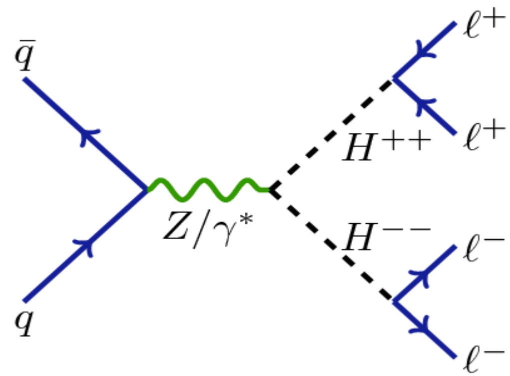
Inspired by Type II Seesaw Model

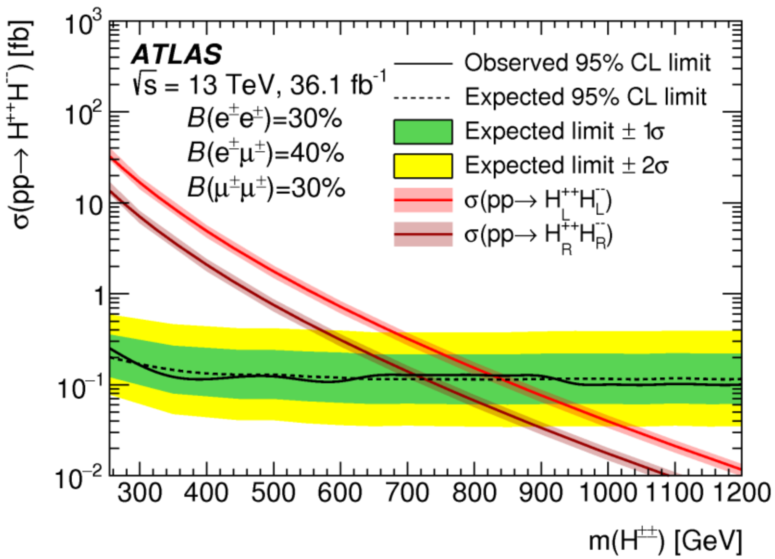
- $H^{\pm\pm}H^{\mp\mp} \rightarrow 4W$





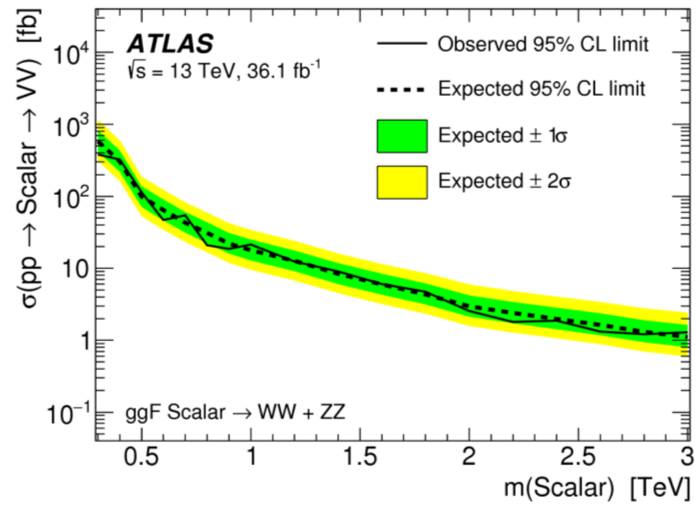
- $H^{\pm\pm}H^{\mp\mp} \rightarrow 4l$





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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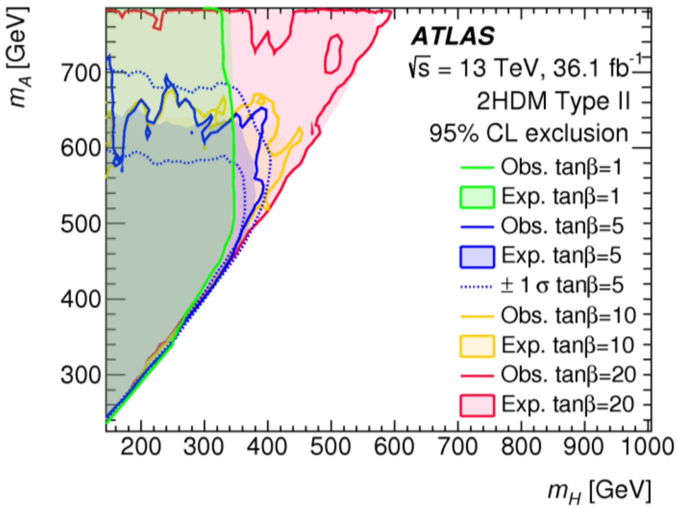
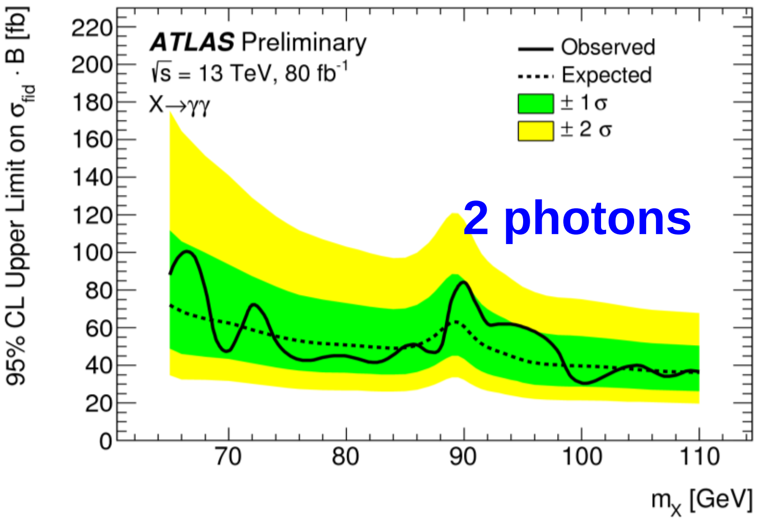
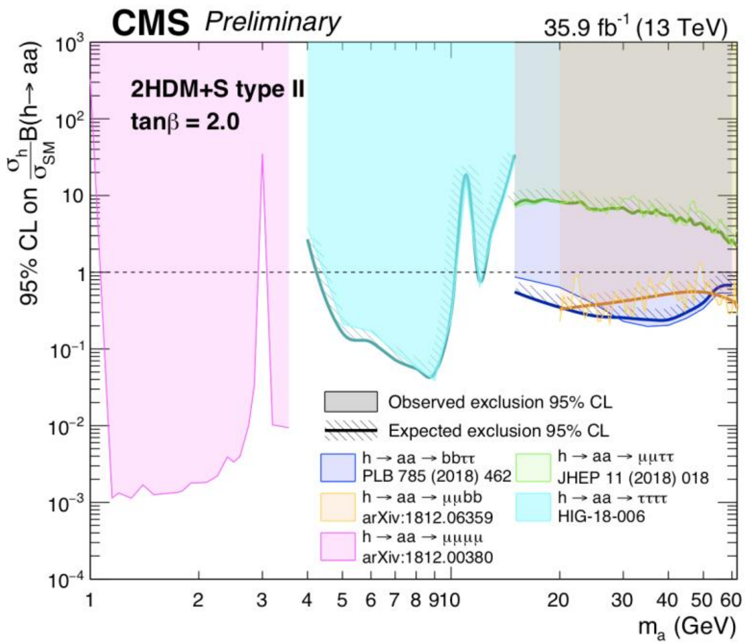


Low mass di-photon resonance

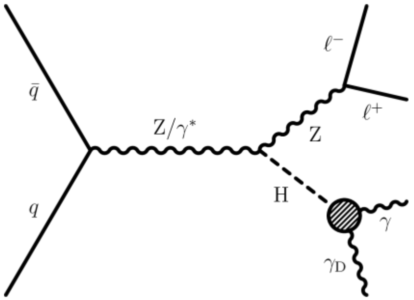


Light boson searches

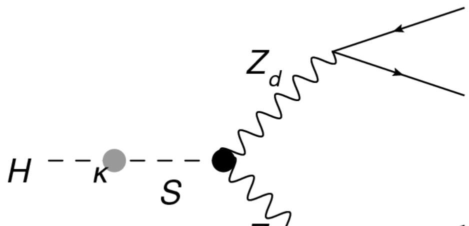


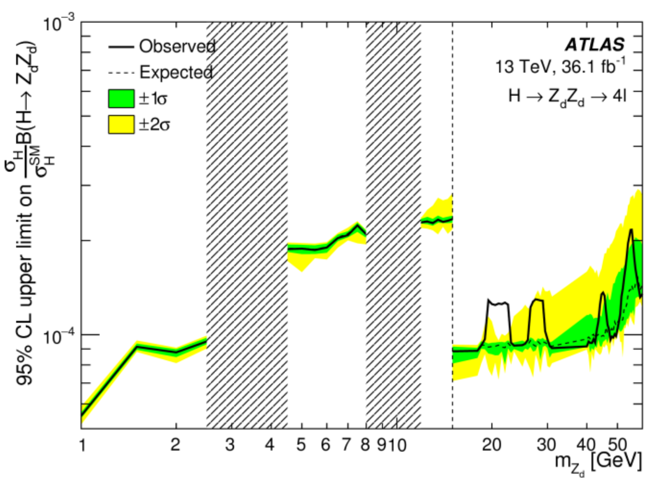
Light bosons motivated by by

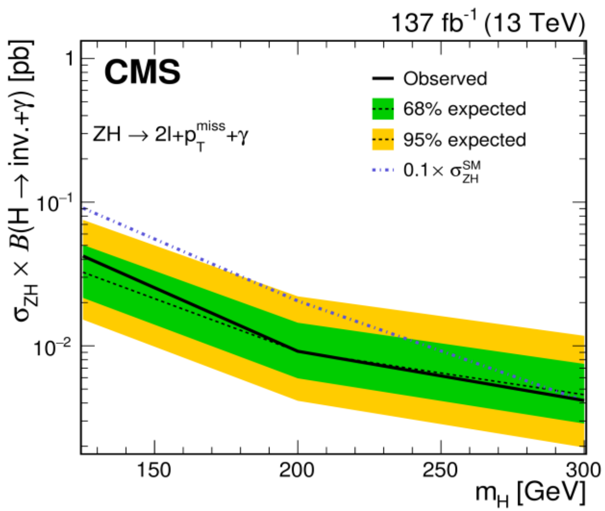
- Extended Higgs sector
  - NMSSM (2HDM+S), SM/2HDM+V
- 1st EW phase transition
- Dark matter



$h \to Z_d Z_d \to 4l$







Summary

- The 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

ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

CMS public results

- http://cms-results.web.cern.ch/cms-results/public-results/publications/
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/

Backup

Atlas bbgg background

	1-tag		2-tag	
	Loose selection	Tight selection	Loose selection	Tight selection
Continuum background	117.5 ±4.7	15.7 ± 1.6	21.0 ± 2.0	3.74 ± 0.78
SM single-Higgs-boson background	5.51 ±0.10	2.20 ± 0.05	1.63 ± 0.04	0.56 ± 0.02
Total background	123.0 ±4.7	17.9 ± 1.6	22.6 ± 2.0	4.30 ± 0.79
SM Higgs boson pair signal	0.219±0.006	0.120± 0.004	0.305± 0.007	0.175± 0.005
Data	125	19	21	3