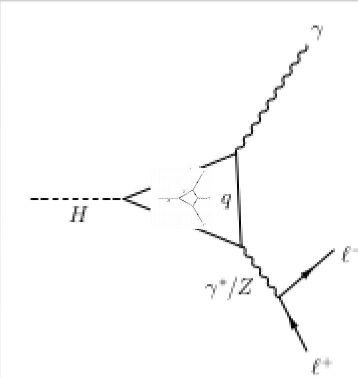
Maxime Gouzevitch

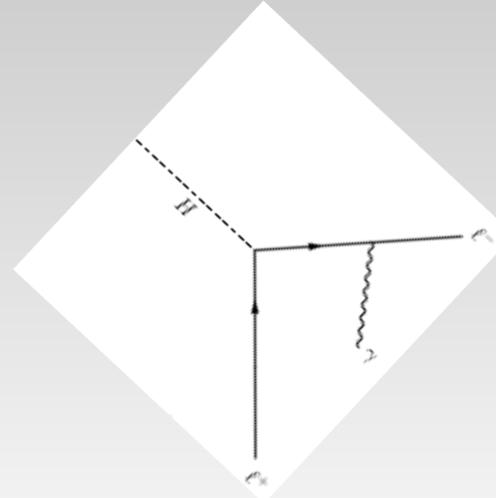
H in the photon : all what we want to see but have never seen till now

On behalf of CMS and ATLAS collaborations

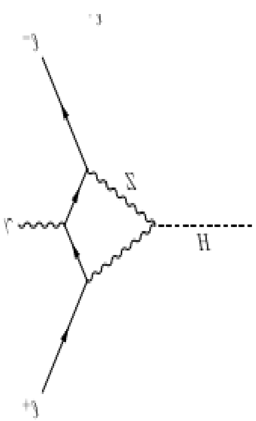
1) Introduction
2) H→ll + γ
3) BEH potential: HH→ 2γ2b

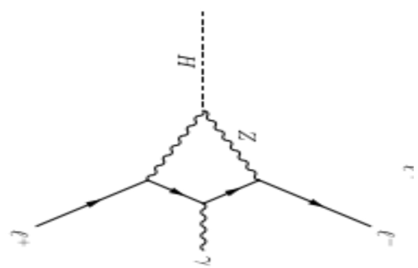
07/06/2019

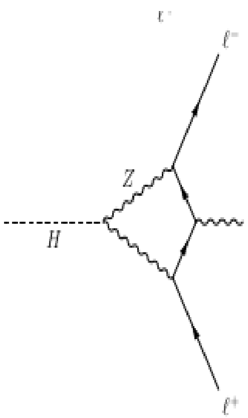




H→ llγ

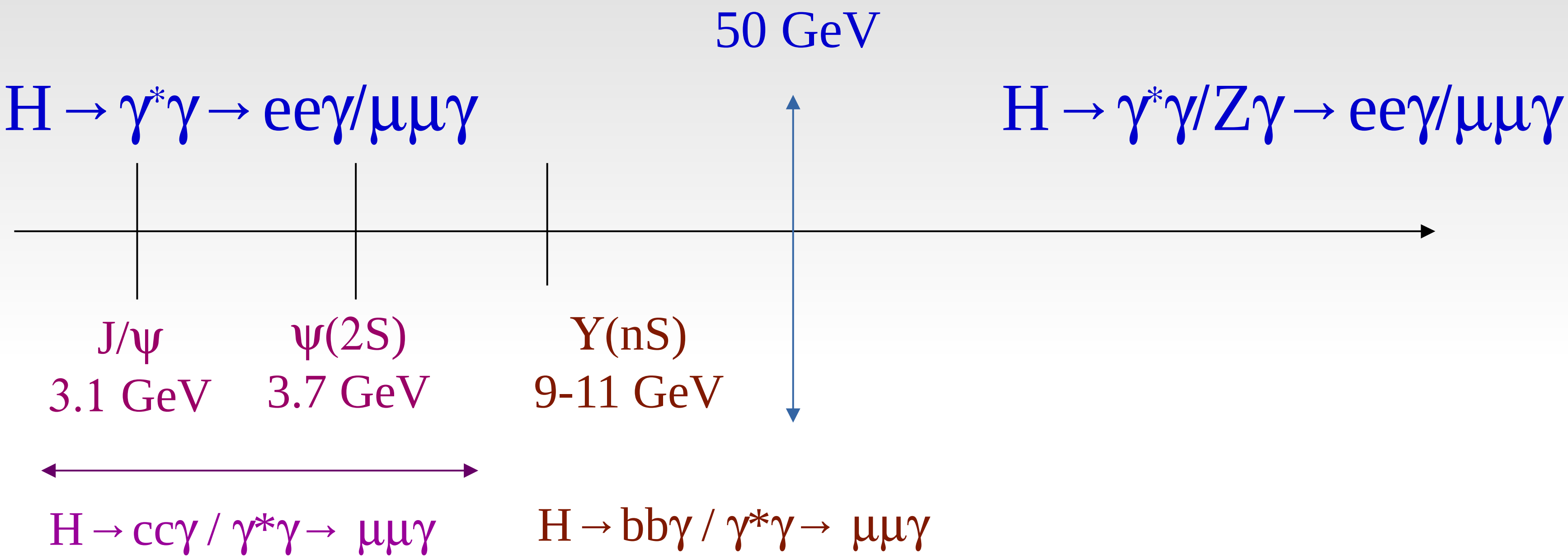






1.0) H → llγ: reach zoology

This rare final state can be enhanced within many BSM theories.



Small branchings but much rather pure signal than H → bb/cc → 2jets.

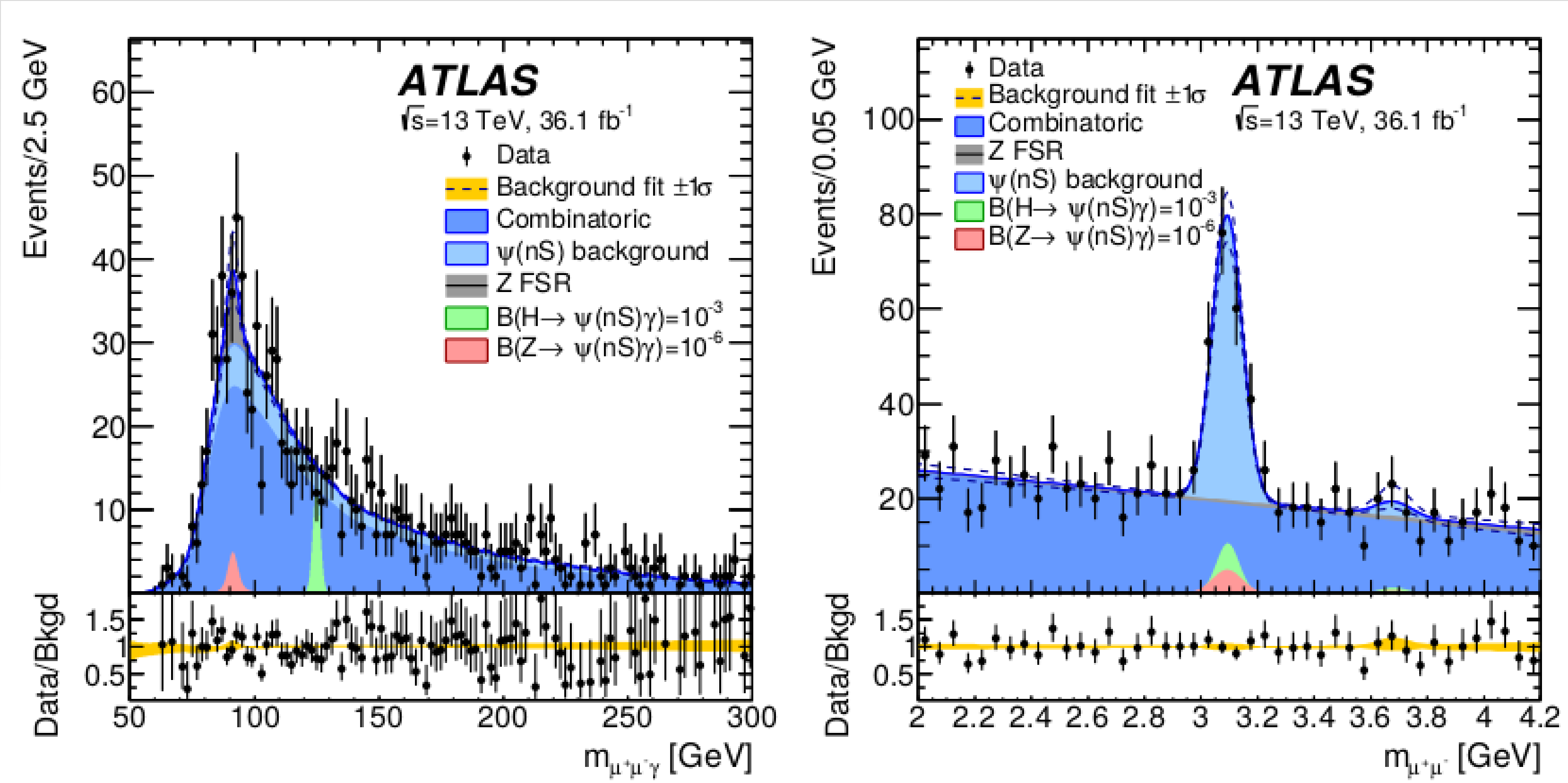
B(H → cc) ~ 3%
B(H → bb) ~ 60%

B(H → J/ψγ) ~ 3e-6
B(H → Υ*γ) ~ 8e-9

B(H → ψ(2S)γ) ~ 1e-6

1.1) Example of H → J/ψ(nS)γ

ATLAS – arXiv:1807.00802
CMS – arXiv:1810.10056 (only J/ψ γ)

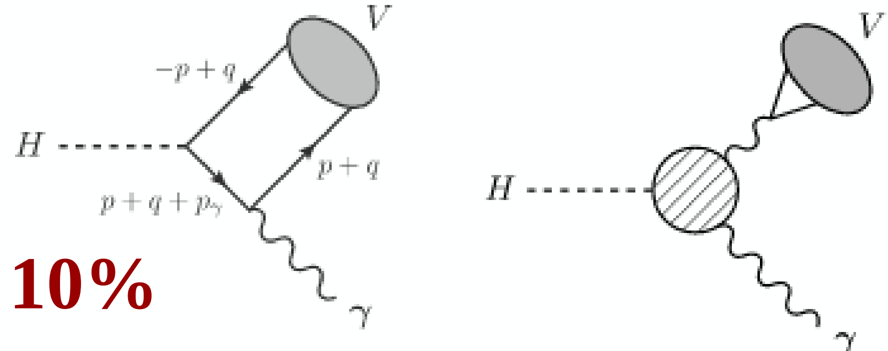


- Minimal 3-body mass defined by kinematic selections.
- Large combinatoric background strongly constraint by the presence of 2 masses.

1.2) Constraints on H → J/ψ(nS)γ

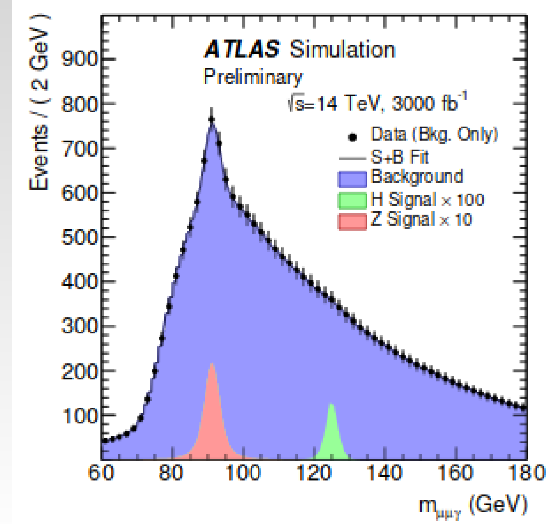
"Direct" contribution — **10%**

"Indirect" contribution — **90%**



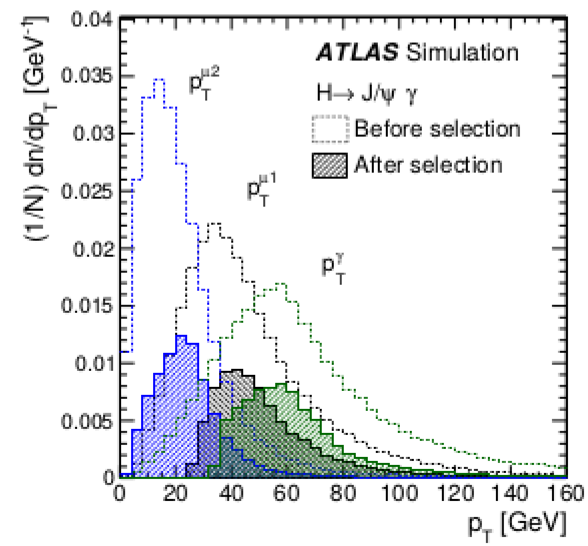
$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

Phys.Rev. D90 (2014) 11, 113010



- **BR Run I observed limit: 1.5e-3**
- **BR Run II observed limit: 3.5e-4**
- **BR HL-LHC expected limit: 4.4e-5**
- **BR SM Expectation: 3e-6**

- Observation of those decays in Higgs final state is tough at HL-LHC. Requires to keep a very low second muon threshold for reconstruction.
- But even if you see it you have to convince yourself you understand the "Indirect" contribution before claiming anything about H→ cc couplings.

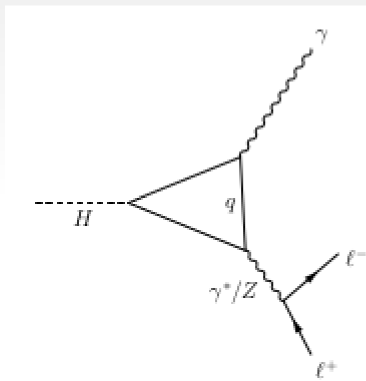


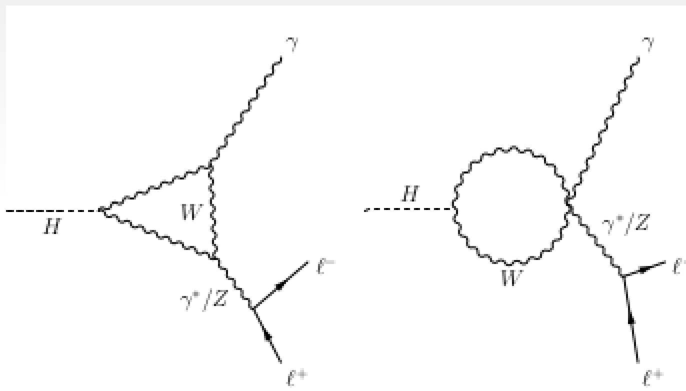
1.3) $H \rightarrow \gamma^{*}\gamma/Z\gamma$

M_{ll} < 50 GeV | **M_{ll} > 50 GeV**

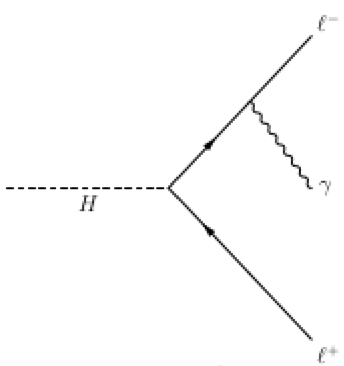
$$\frac{\mathcal{B}(H \to \gamma^{*}\gamma \to \mu\mu\gamma)}{\mathcal{B}(H \to \gamma\gamma)} = (1.69 \pm 0.10)\%, \quad \frac{\mathcal{B}(H \to Z\gamma \to e^{+}e^{-}\gamma/\mu\mu\gamma)}{\mathcal{B}(H \to \gamma\gamma)} = (2.27 \pm 0.14)\%$$

Rich and complex interference patters, small BF and lots of space for BSM contributions

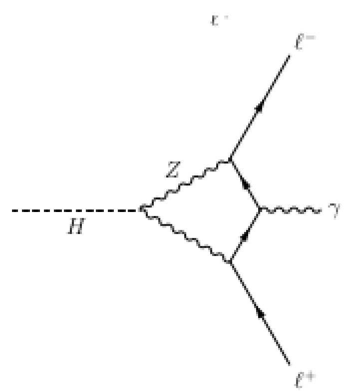




$H \rightarrow \gamma^{*}\gamma/Z\gamma$ component with loops.



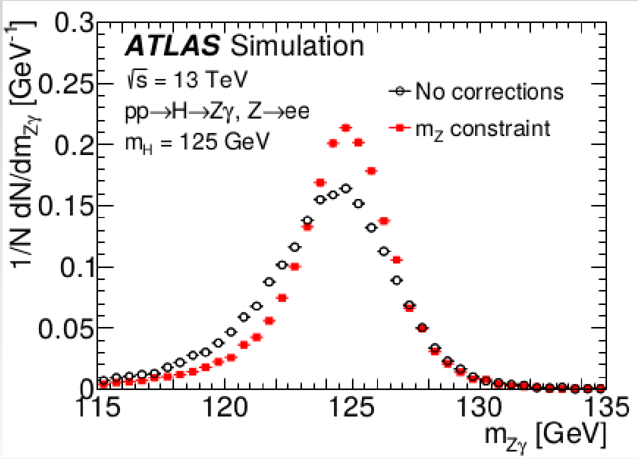
$H \rightarrow ll$+ FSR component with loops.



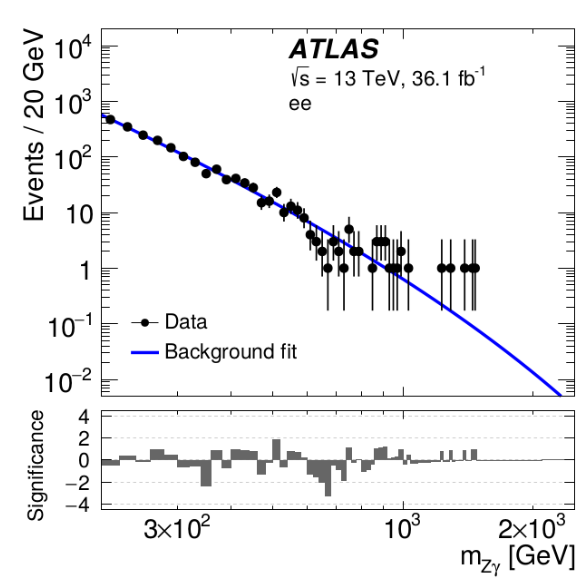
“Non-resonant” ll component.

1.4) H→ $\gamma^*\gamma$/Zγ : few words about analyses

- Excludes exclusive decays.
- For Z → ll part the kinematic fit and FSR corrections are extremely important to improve the sensitivity.
- Good signal acceptance: 30-40%.



- Multi-category analysis as for H → γγ. Signal extracted from parametric fit to llγ lineshape.



One of high purity categories ATLAS analysis

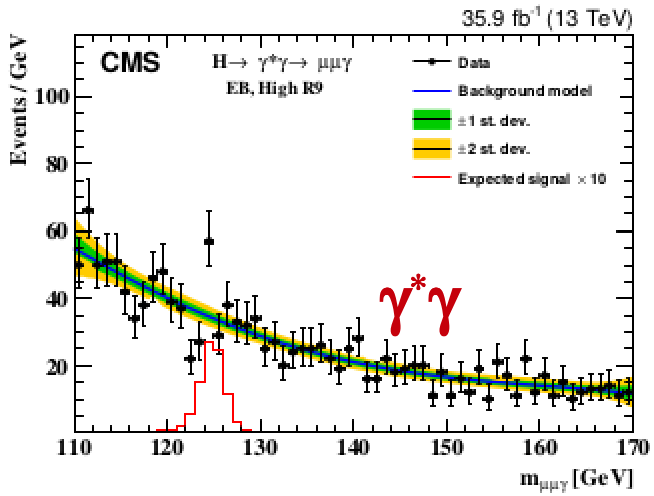
See also CMS: arXiv:1806.05996

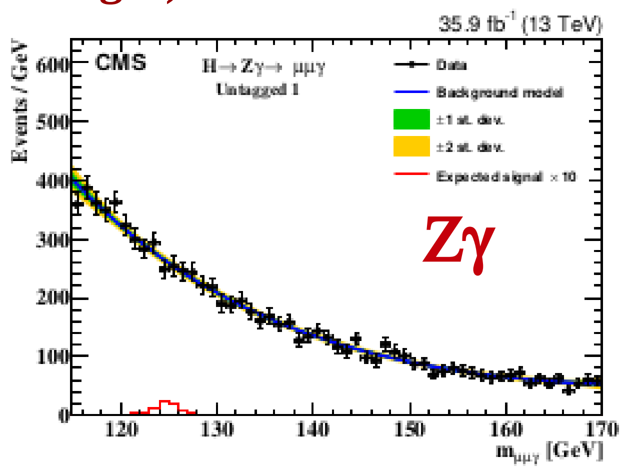
CMS: arXiv:1708.00212

1.5) H→ $\gamma^*\gamma$/Zγ : few words about analyses

- The Higgs Dialitz decay $\gamma^*\gamma$ exploited in CMS have a larger sensitivity to SM production that Zγ.
  - $\sigma(m_{\gamma*\gamma} < 50$ GeV) ~ **70%** $\sigma(m_{\gamma*\gamma} > 50$ GeV)
  - Background (Dialitz) << Background (Zγ) = SM Zγ production.
  - $p_{T\gamma}$(Dialitz, 35 GeV) >> $p_{T\gamma}$(Zγ, 15 GeV) because of less energy taken by the **ll** system.
  - No Dialitz ee channel because of « merged electron clusters » reconstruction requested → to come soon.

High purity categories of CMS analysis (slightly different selections for left and right)

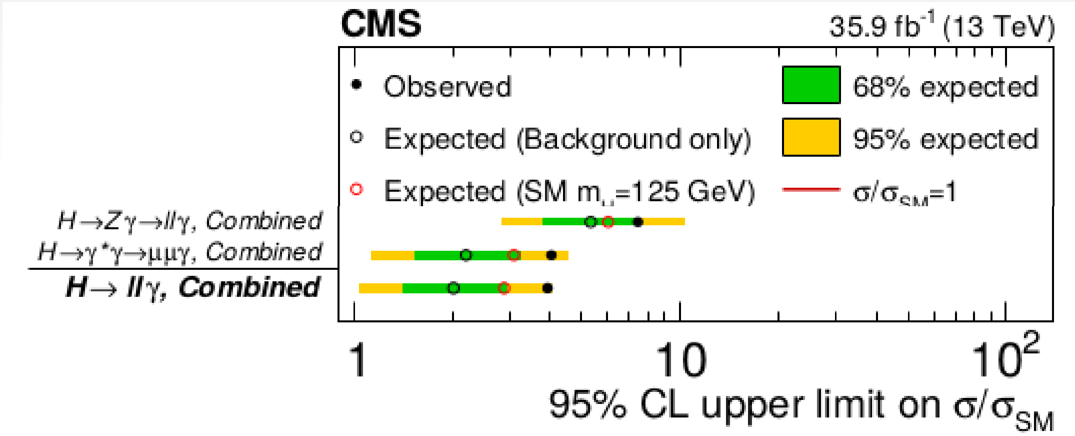




1.5) H→ $\gamma^*\gamma$/Zγ : Results

- ATLAS and CMS results similar on H→ Zγ channel excluding ~ 7-8 x SM (5-6 expected) using 1/3 of Run II data.

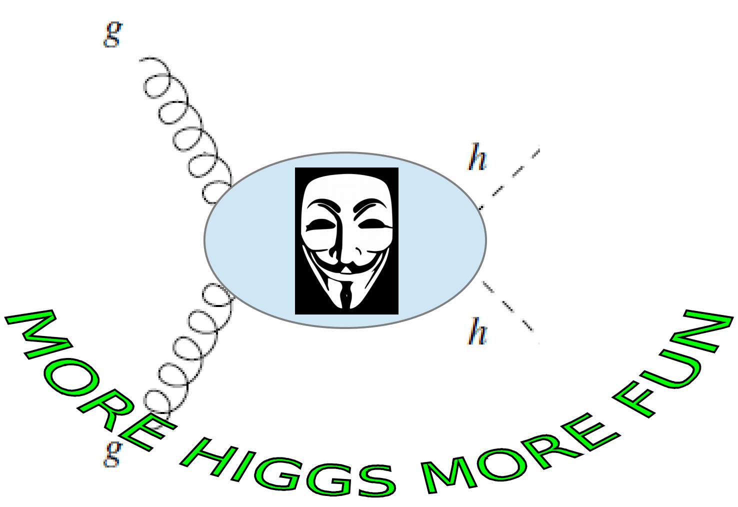
- Adding H→ $\gamma^*\gamma$ increases significantly the sensitivity to ~ 4 x SM (2-3 expected) → BSM physics can be different in both channels so the combination is ultimately the best interpretation.



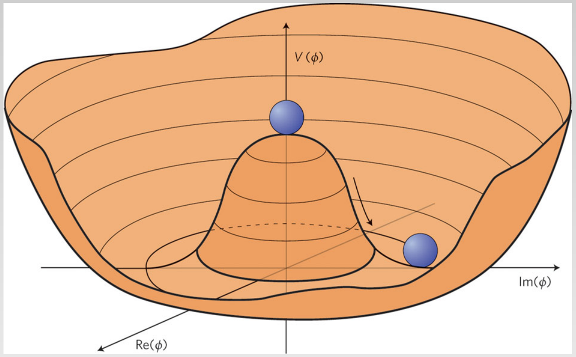
- Full Run II dataset is not enough, but Run III may provide enough data to have some hints combining CMS and ATLAS.

- The HL-LHC projection assuming same systematics predicts ~ 5 par experiment. Statistically dominated. YR - arXiv:1902.00134

HH→ γγbb



2.1) Short introduction



- Shape of the Higgs potential postulated but not taken from first principles.
- Indirectly constrained within SM assuming the shape.

$$\lambda_{\text{hhh}} \equiv \eta = \frac{m_H^2}{2v^2}$$

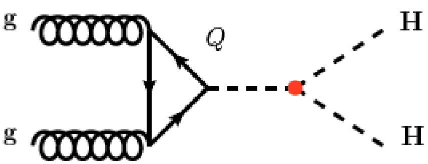
$$v = 2^{-1/4} \cdot G_F^{-1/2} \approx 246\ \text{GeV}$$

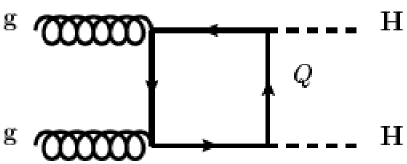
$$\frac{\delta\lambda_{\text{hhh}}}{\lambda_{\text{hhh}}} \approx 2\frac{\delta m_H}{m_H} \approx 0.4\%$$

$$\mathscr{L}^h = \frac{1}{2}m_h^2 h^2 + \eta v h^3 + \frac{\eta}{4}h^4$$

- Direct constraint theoretically possible through HH production:
  - The cross section 1000 times smaller than SM H.
  - Cross section dominated by top box digram, the sensitivity to Higgs self coupling is reduced due to destructive interference:

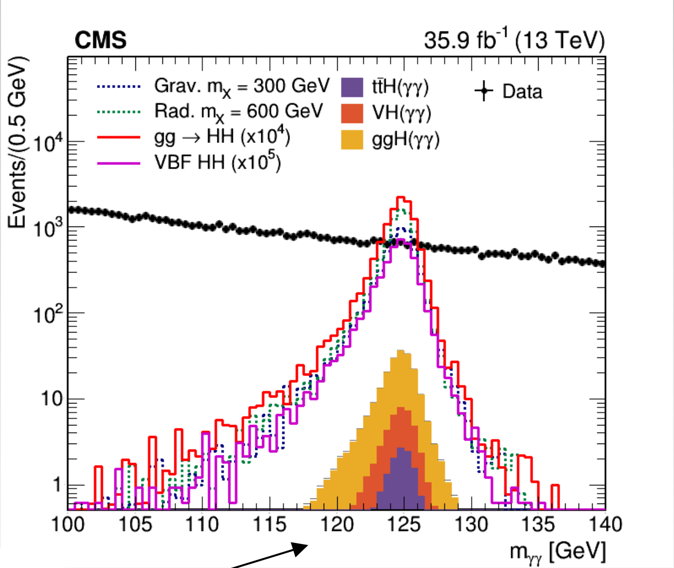
$$\frac{\sigma_T + \sigma_B}{\sigma_{hh}} \approx 2.5$$

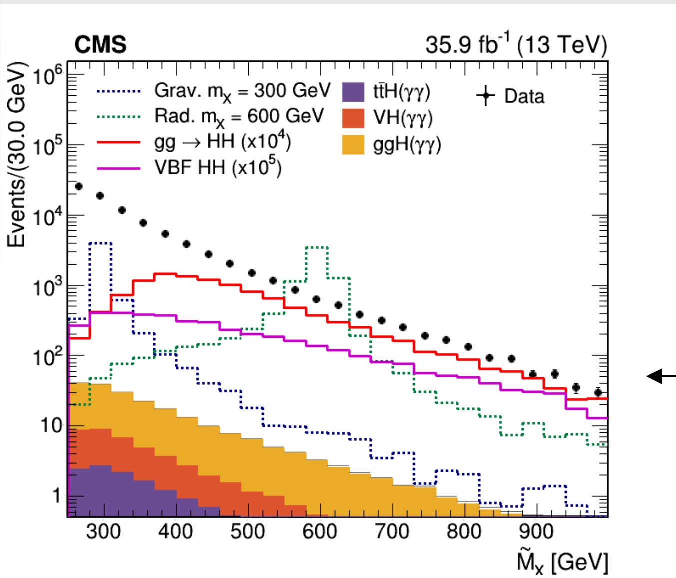


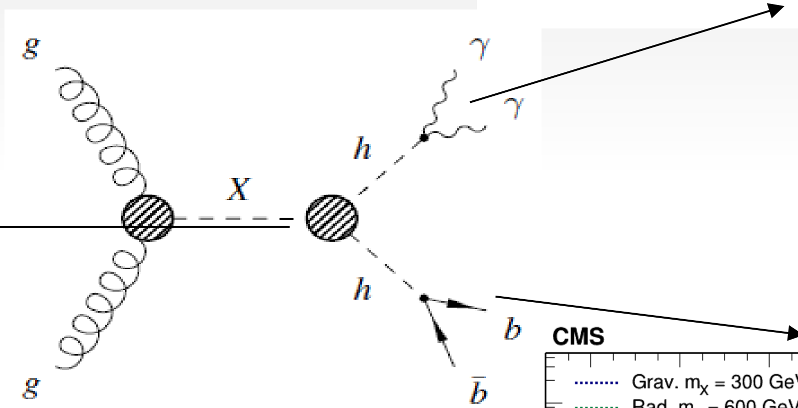


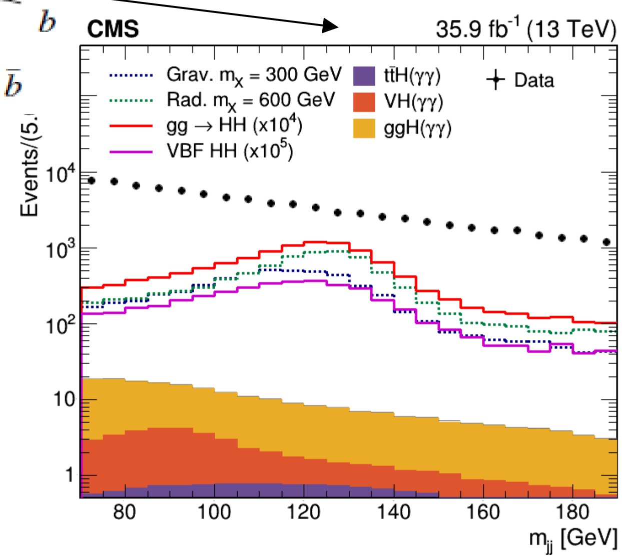
2.2) HH→ 2b2γ principle

- Fully reconstructible final state.
- Kinematically over-constrained analysis.









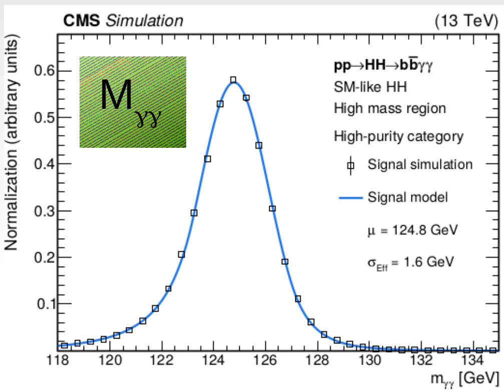
Main backgrounds:
- Non-resonant QCD = γγbb (>80%) + γjbb+jjbb (<20%).
- Resonant: SM H production – few events but positionned exactly under the diphoton peak.

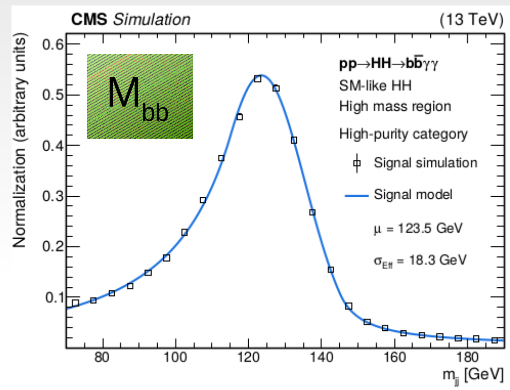
2.3) CMS analysis

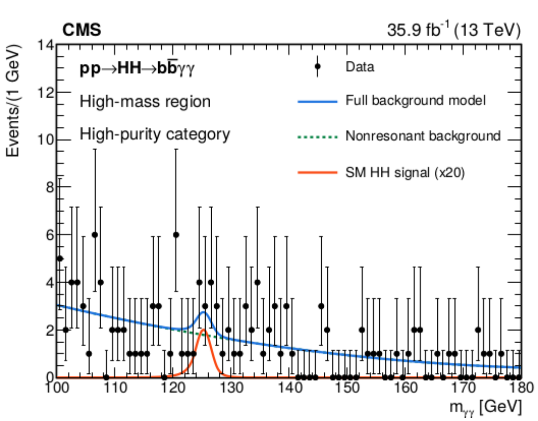
- Use 2D likelihood $M_{\gamma\gamma}$ x M_{bb}.
- Categorize in $M_{\gamma\gamma bb}$ (<>350 GeV) and MVA (low / high purity).

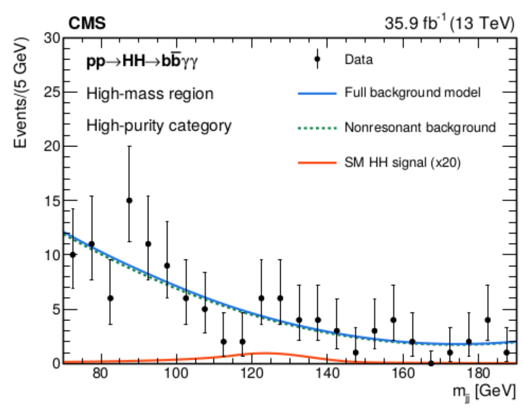
→ MVA: event kinematics and b-jet id.

- 2D analysis. It was verified that within stat uncertainties signal and background shapes are uncorrelated.
- 2D improves compared to 1D by ~ 10%.
- Keep b-jet p_T = 25 GeV





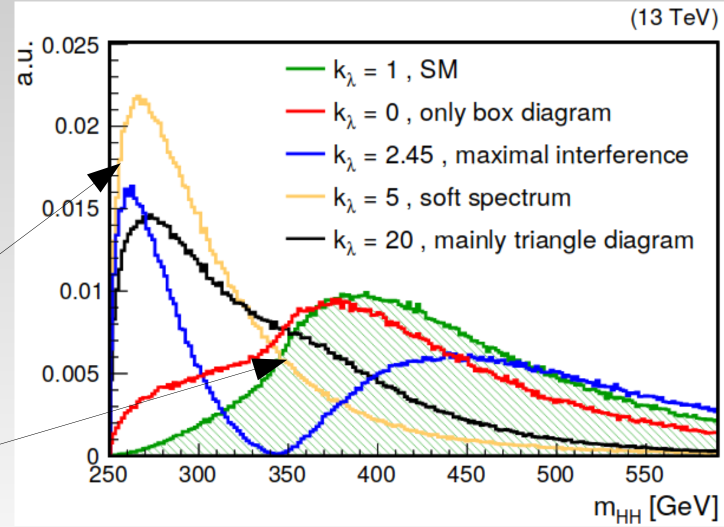




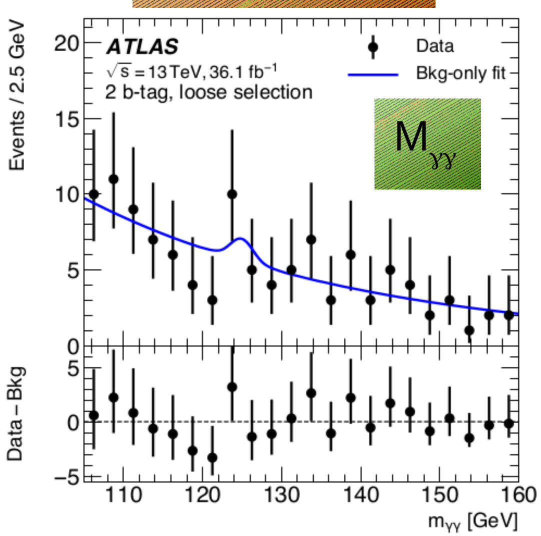
arXiv:1806.00408

2.4) ATLAS analysis

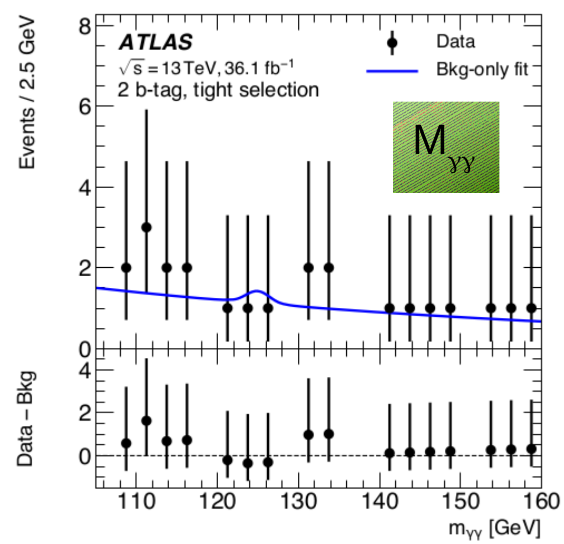
- Use 1D likelihood $M_{\gamma\gamma}$ and cut on M_{bb}.
- Categorize in 2 b-tag and 1 b-tag categories.
- Loose selection for self-coupling scan:
  → $p_{Tbj1} > 40$ GeV, $p_{Tbj2} > 25$ GeV
- Tight selection for SM production:
  → $p_{Tbj1} > 100$ GeV, $p_{Tbj2} > 30$ GeV



2 b-tag, loose



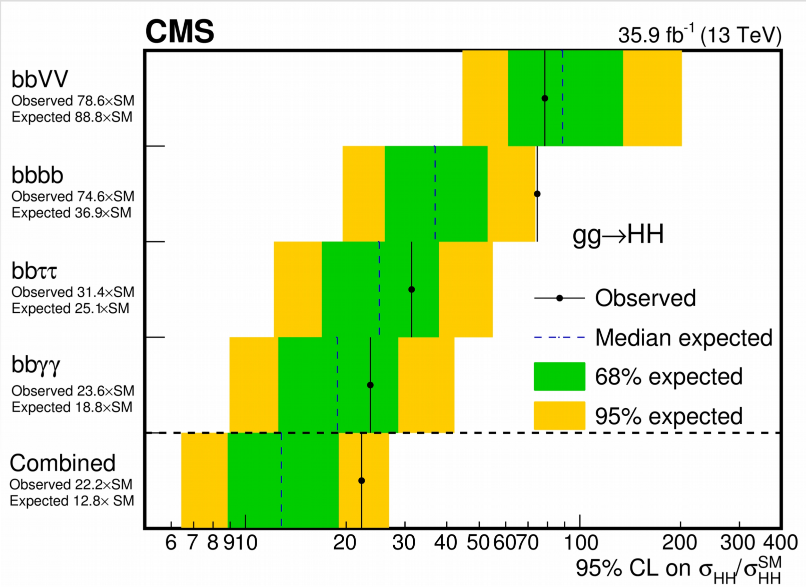
2 b-tag, tight



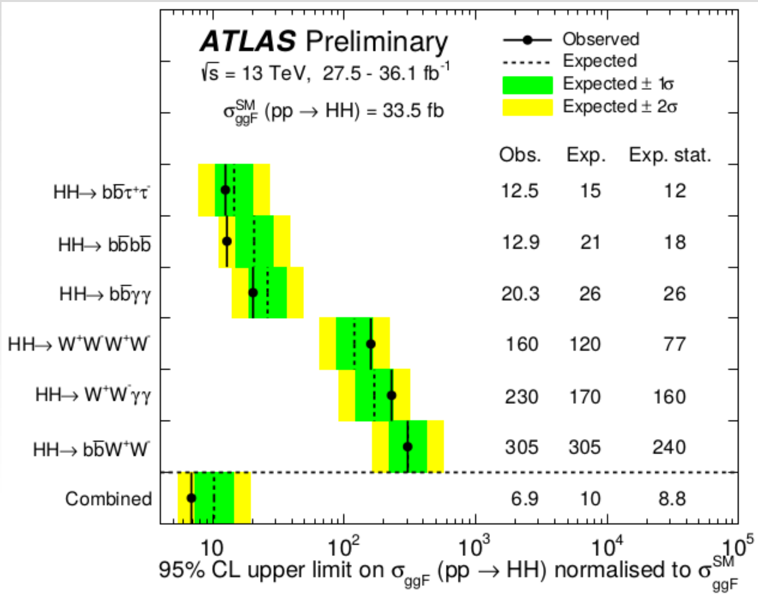
arXiv:1807.04873

2.5) SM-like results

arXiv:1811.09689



arXiv:1906.02025

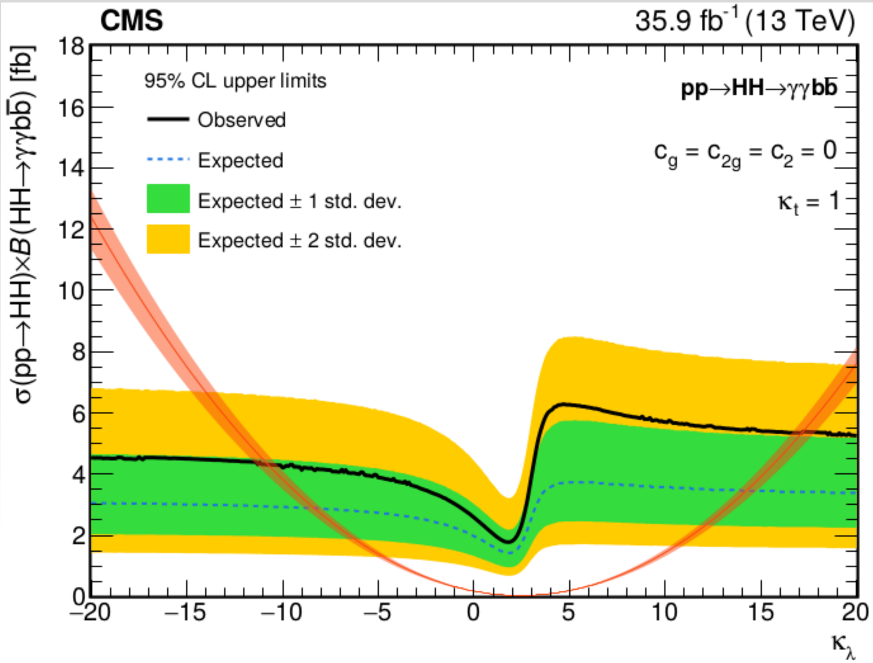


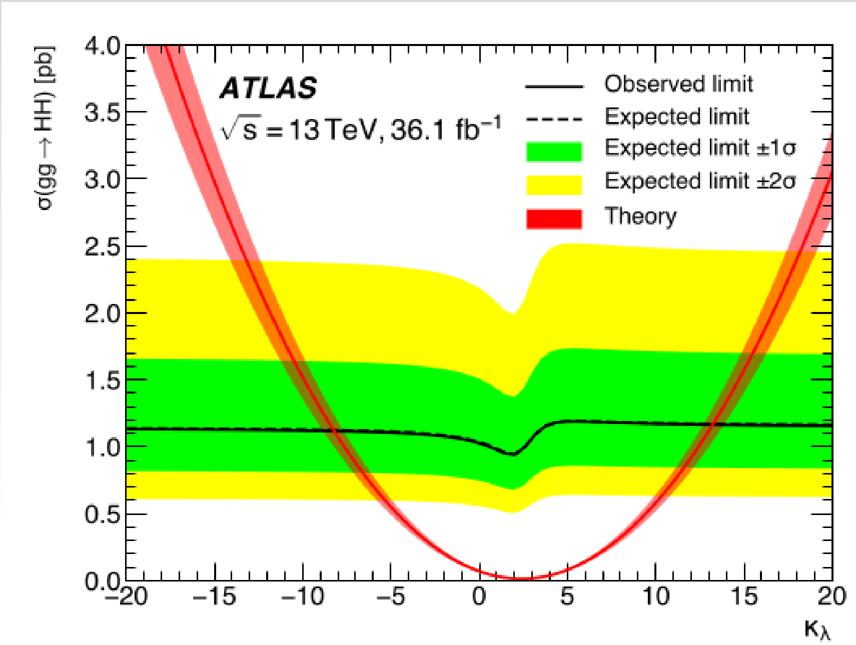
- The HH→ γγbb analysis is slightly more performant in CMS than in ATLAS possibly dut to the usage of 2D analysis and a different SM signal simulation (LO+PS in CMS and NLO+PS in ATLAS → 10% impact on the acceptance).

- It has a similar sensitivity to HH→4b and HH→ττbb channels. So all of them contribute to the final limit.

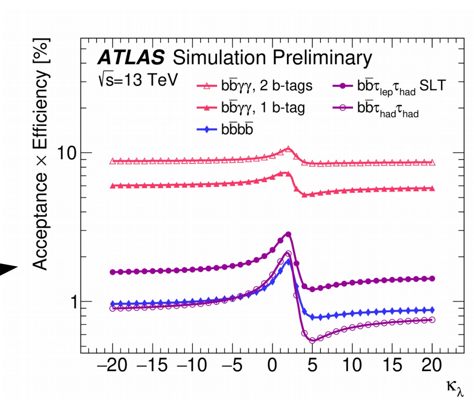
- The HH→ γγWW suffers from a too low BF.

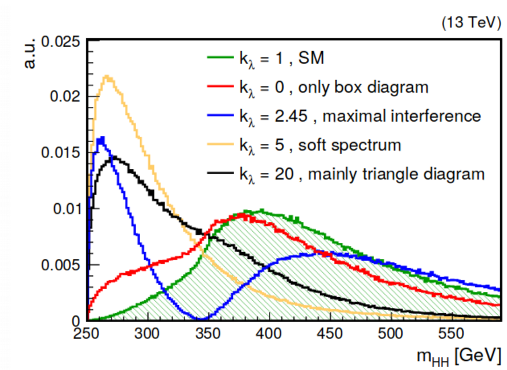
2.6) κ$_\lambda$ scan



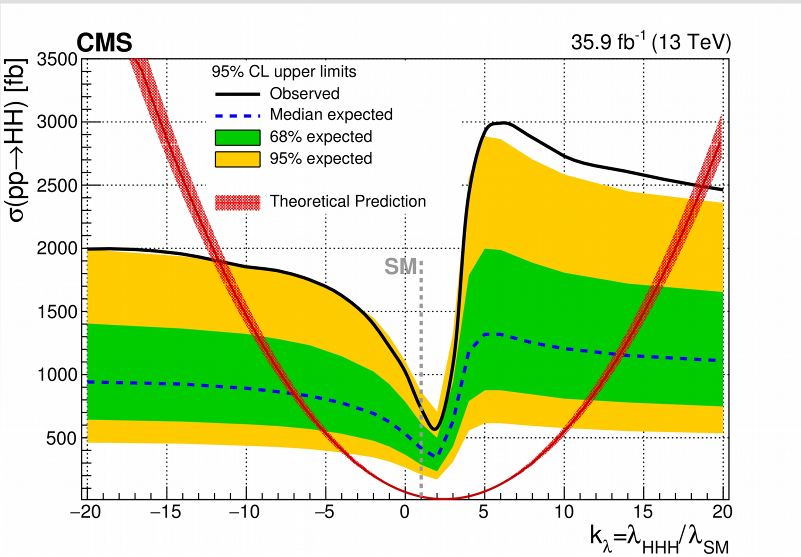


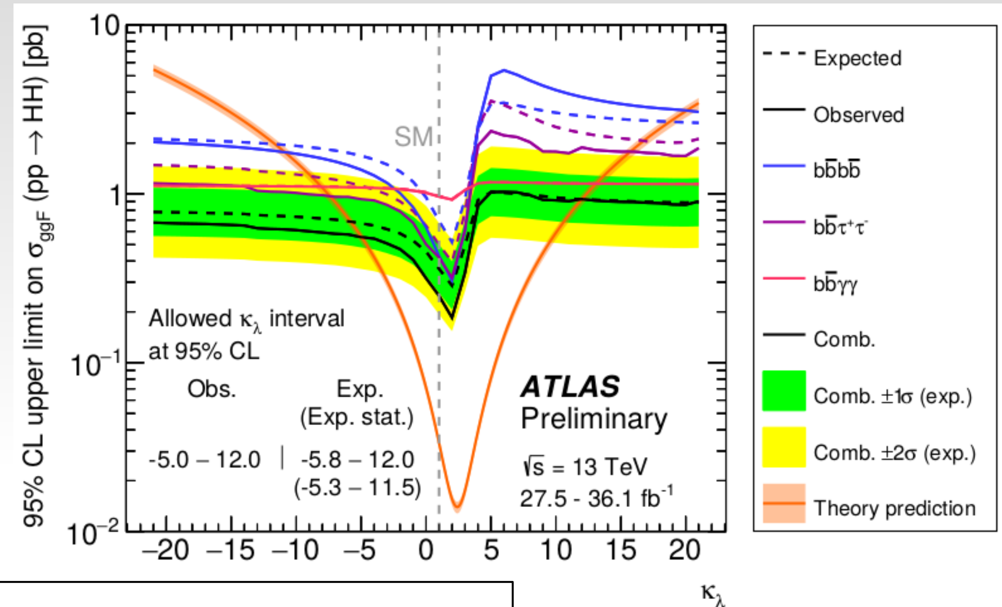
- The sensitivity is the best close to the maximal interference.
- The observable improvement in sensitivity around maximal interference kλ = 2 is purely an acceptance effect.





2.6) κ_λ scan: combinations

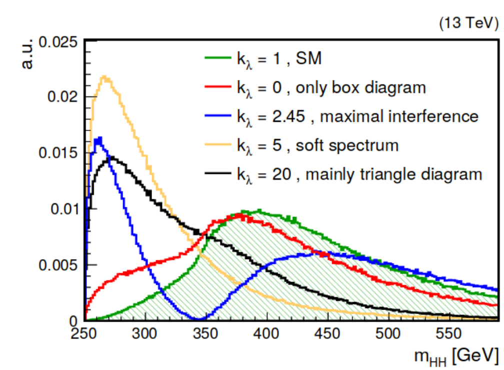




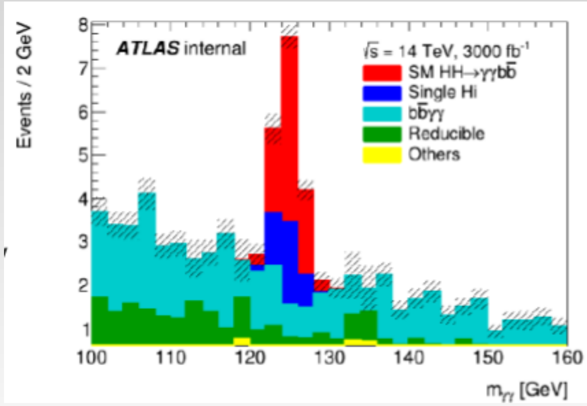
- k_λ is quite loosely constrained:

-6 < kλ < 12. It is a a region where the theory is not perturbative (arXiv:1802.07616).

- HH → 2γ2b provides among the best constraints since it is sensitive to low m_{HH} where self-coupling lives. Other channels have to cope with a rather complex low p_T trigger strategy (multi-jet trigger, or tau trigger).



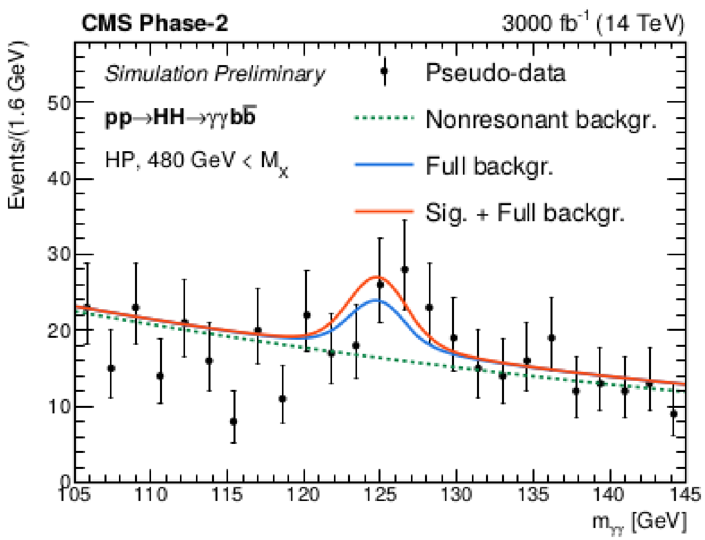
2.7) HL-LHC projections

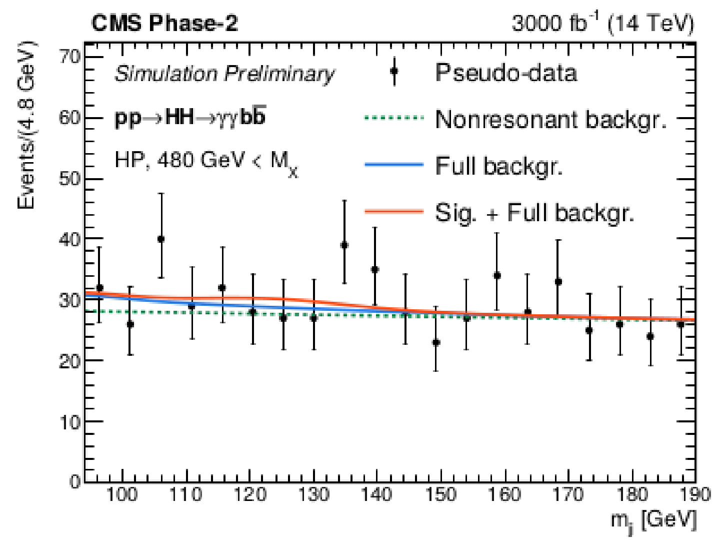


YR - arXiv:1902.00134

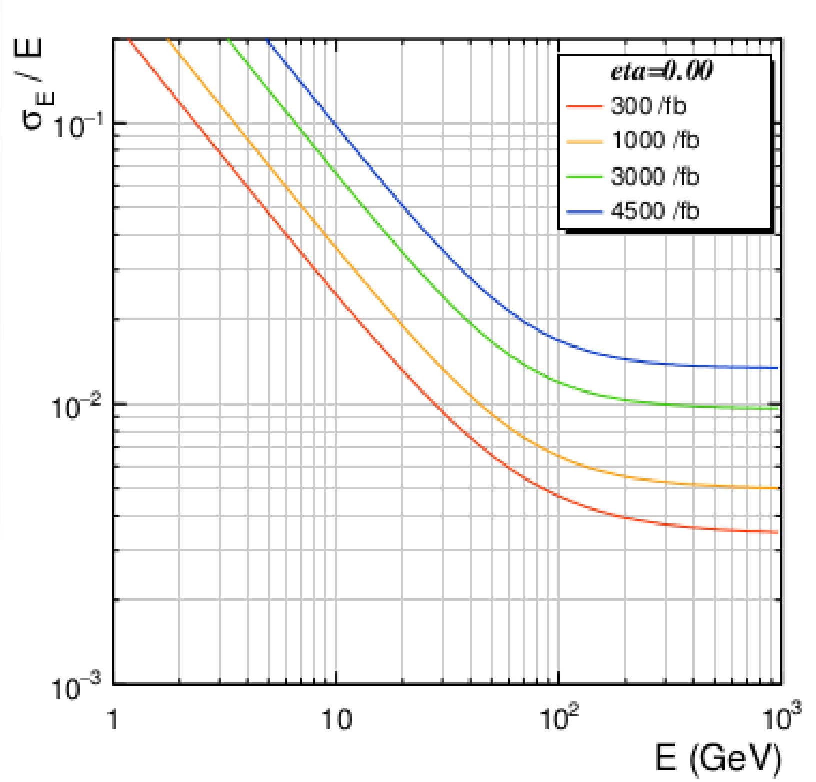
- Analysis approach:
  - ATLAS: 1D + MVA classification
  - CMS: 2D + MVA x M_{HH} classification
- Samples:
  - ATLAS: truth level particles convoluted with the detector resolution extracted from full simulation. Very large samples.
  - CMS: Delphes simulation. Limited statistics compared with ATLAS.

→ More efficient training done by ATLAS → Higher purity of the best category.





2.8) HL-LHC projections: assumptions



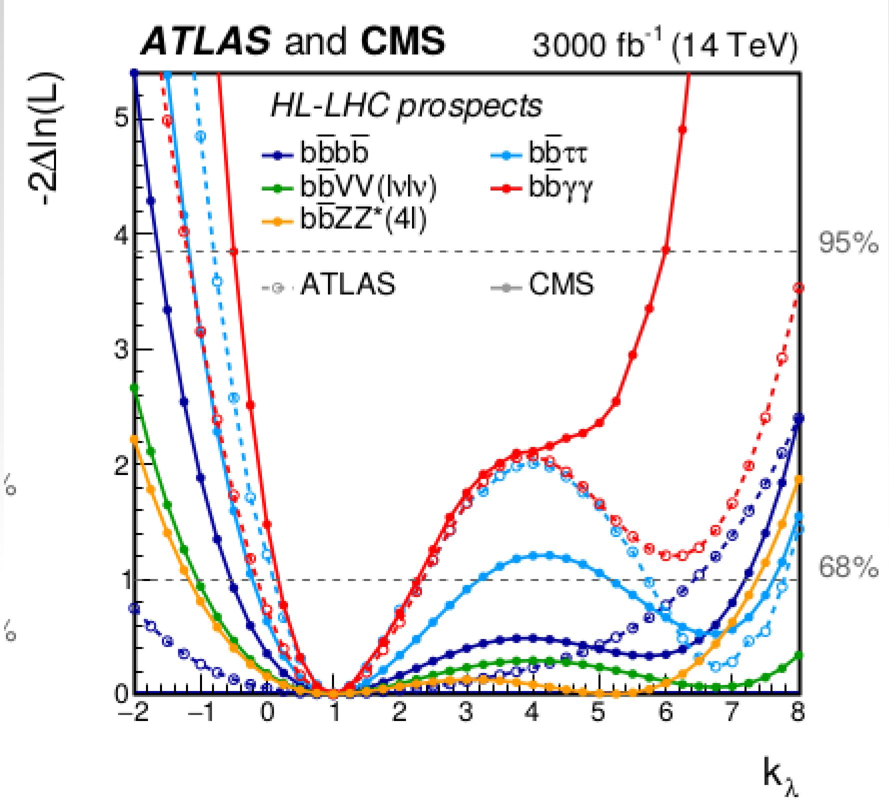
CMS-TDR-17-002
BARREL

Constant term: crystal non uniformity dominates the showers in our energy range.

- B-tagging: assumed to improve by ~ 8 % in each experiment due to much better Phase II trackers.
- $M_{\gamma\gamma}$ resolution in the barrel:
  - is nearly unchanged for LAr calorimeter of ATLAS (no major aging) around **1.6 GeV.**
  - Is slowly degradating for Crystal calorimeter of CMS with ageing. We use the resolution of 1ab^{-1} as average estimate: **2.4 GeV**.
- $M_{\gamma\gamma}$ resolution in the endcap:
  - In CMS we would have HGCAL that would keep the resolution stable over time (minor effect for the analysis).

2.8) Self-coupling measurement

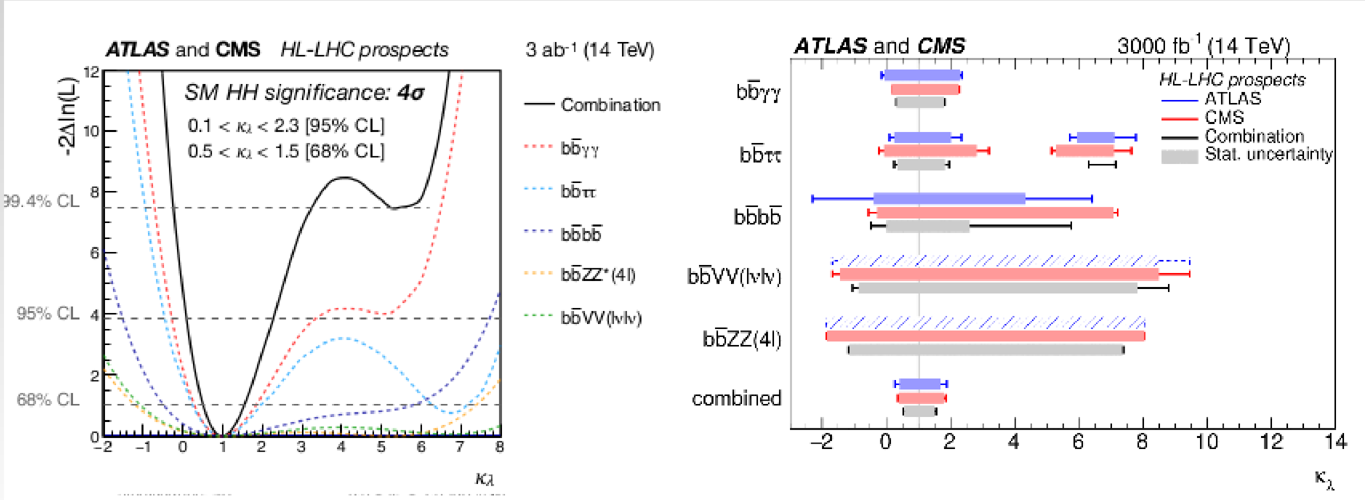
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



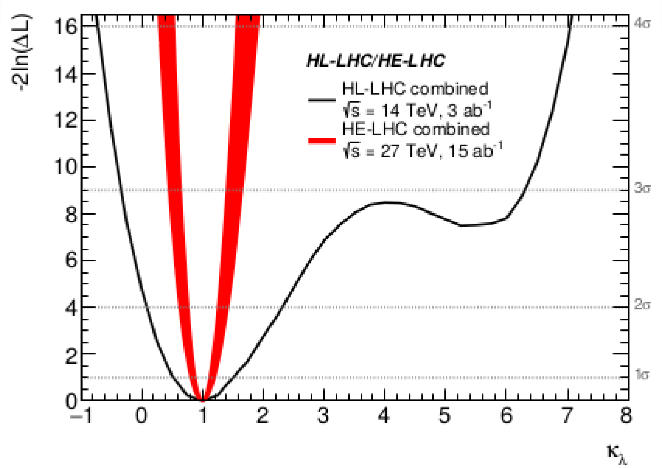
- HH → 2b2γ provides one of the best sensitivity among the channels. ATLAS projection is slightly better:
    - Background MC statistics allows for a more refined training.
    - ECAL barre resolution is slowly degradating for CMS not for ATLAS ECAL.

- HH → 2b2γ is the most sensitive channel for scan.
- The usage of multiple MHH categories help to disqualify the second minimum around kλ = 6 and improve the measurement precision.

2.9) Self-coupling measurement



(a) (b)



- Extremely challenging In 2035 we expect a 30-50% precision.
- Need to wait FCC-hh (2050?) for more precision.

Conclusions

- We presented few critical topics at the edge of the LHC sensitivity that have to be explored to understand the Higgs sector of the SM:
  - $H \rightarrow cc$ coupling
  - $H \rightarrow Z\gamma/\gamma^{*}\gamma$ coupling
  - Higgs potential measurement and double Higgs production.
- In all those topics the photons plays a unique and unavoidable role.
- This discussion clearly shows that the photon reconstruction at HL-LHC remains one of the priorities and full attention shall be payed to the future ECAL and tracker during next years.

BACKUP

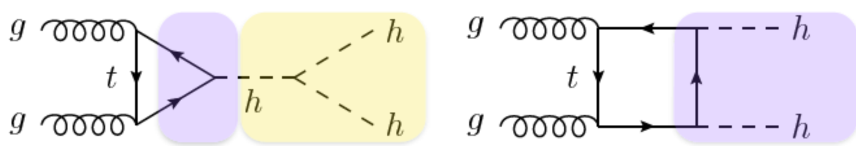
4.1) Non-resonant HH production: EFT and BSM

The relevant lagrangian terms of gg→HH production in D=6 EFT

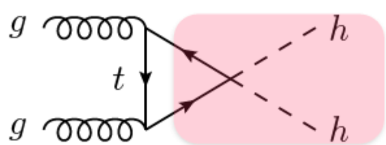
$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3 + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a$$
$$- \left[\frac{m_t}{v}\left(1 - \frac{c_H}{2} + c_t\right)\bar{t}_L t_R h + \text{h.c.}\right] - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2} - \frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \text{h.c.}\right]$$

arXiv:1410.3471

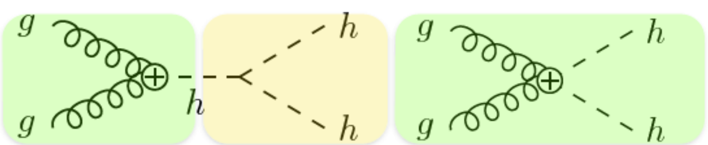
Non SM Yukawa coupling is not considered



SM diagrams



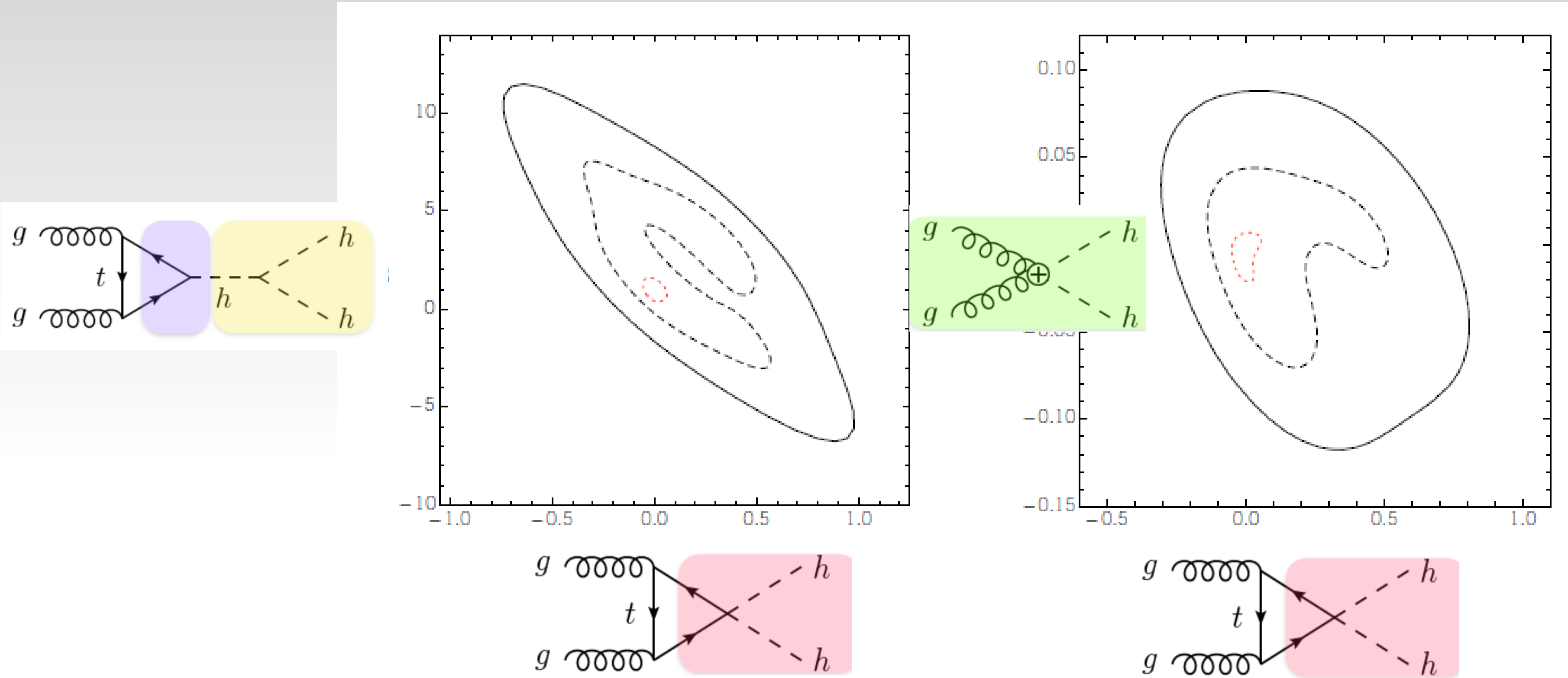
ttHH non-linear interaction



Higgs-gluon contact interactions

- Five D6 operators for HH sector.

4.1) Non-resonant HH production: EFT and BSM



	LHC$_{14}$	HL-LHC	FCC$_{100}$
$\sqrt{s}$	14 TeV	14 TeV	100 TeV
Luminosity	$L = 300\,\text{fb}^{-1}$	$L = 3\,\text{ab}^{-1}$	$L = 3\,\text{ab}^{-1}$

arxiv:1502.00539

Idea: set limits in 5-D parameters space and constraint progressively the phase-space with ellipses converging (if no new physics observed) to SM point.

4.2) We need: predicted cross section

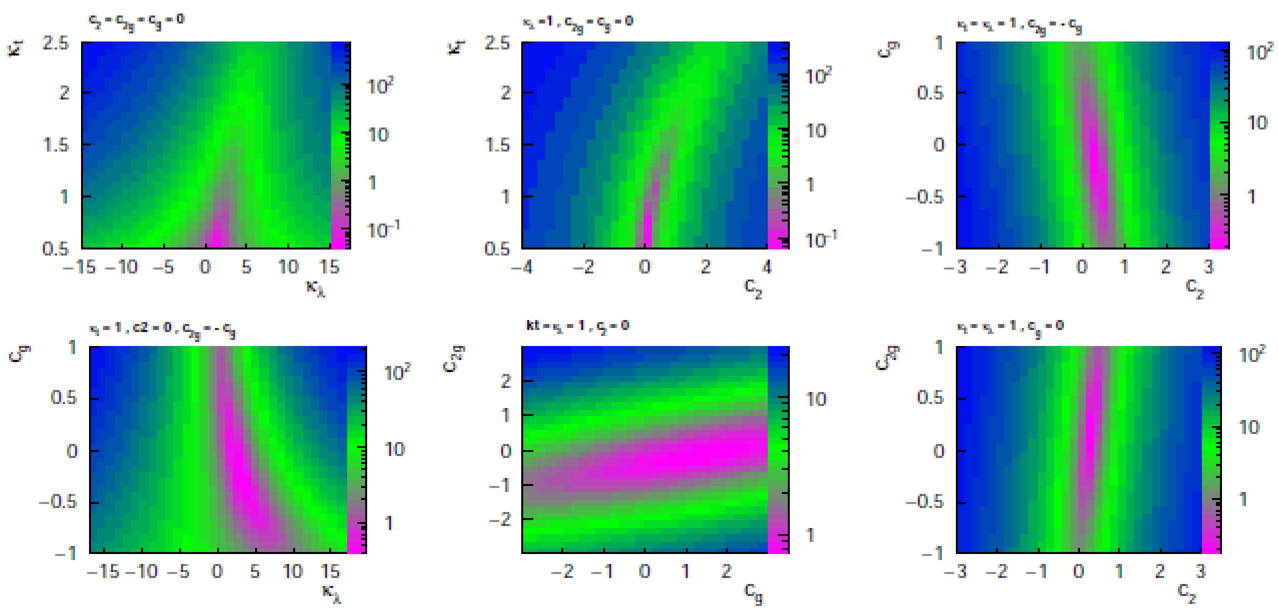
- Within some approximation (top loop predominant contribution)

k = NNLO+NNLL/LO is expected to be similar within 5% to the one of SM.

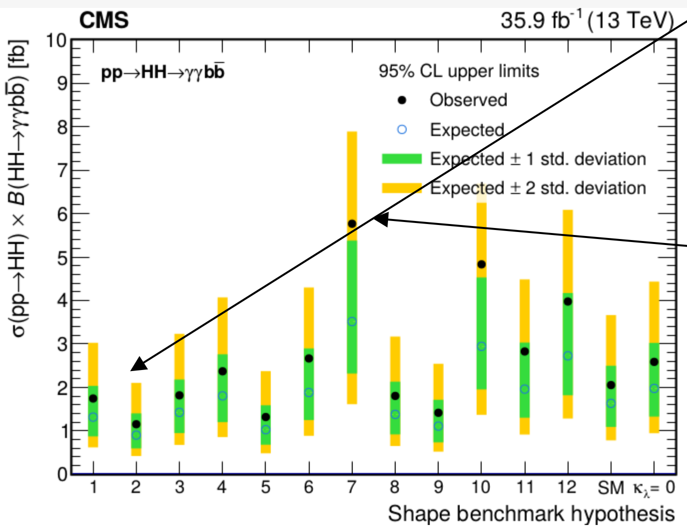
$$\sigma_{\mathrm{HH}} = \sigma^{\mathrm{SM}}_{\mathrm{HH,NNLO+NNLL}} \cdot R_{\mathrm{HH}}$$

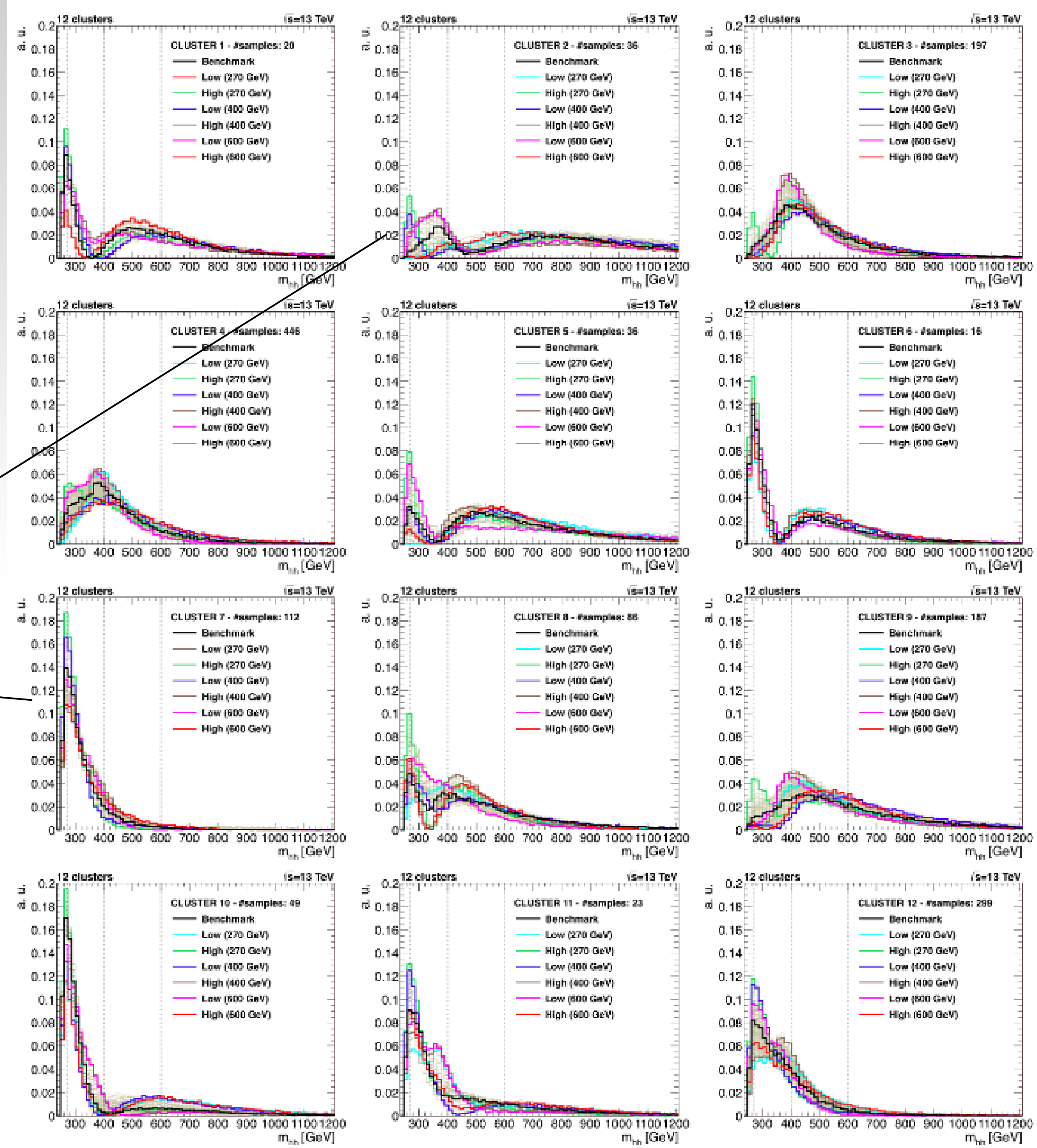
YR4
arXiv:1608.06578

$$\begin{aligned} R_{\mathrm{HH}} \equiv \frac{\sigma_{\mathrm{HH}}}{\sigma^{\mathrm{SM}}_{\mathrm{HH}}} \overset{LO}{=} & A_1\,\kappa_t^4 + A_2\,c_2^2 + (A_3\,\kappa_t^2 + A_4\,c_g^2)\,\kappa_\lambda^2 + A_5\,c_{2g}^2 \\ & + (A_6\,c_2 + A_7\,\kappa_t\kappa_\lambda)\kappa_t^2 + (A_8\,\kappa_t\kappa_\lambda + A_9\,c_g\kappa_\lambda)c_2 \\ & + A_{10}\,c_2 c_{2g} + (A_{11}\,c_g\kappa_\lambda + A_{12}\,c_{2g})\,\kappa_t^2 \\ & + (A_{13}\,\kappa_\lambda c_g + A_{14}\,c_{2g})\,\kappa_t\kappa_\lambda + A_{15}\,c_g c_{2g}\kappa_\lambda\,. \end{aligned}$$



3.7) Benchmark limits





3.3) Why is it important?

$$V(T,H) \;=\; \lambda(H^2 - v^2)^2 + b\,T^2H^2 + a\,TH^3$$

Example: Electroweak phase transition in early universe:

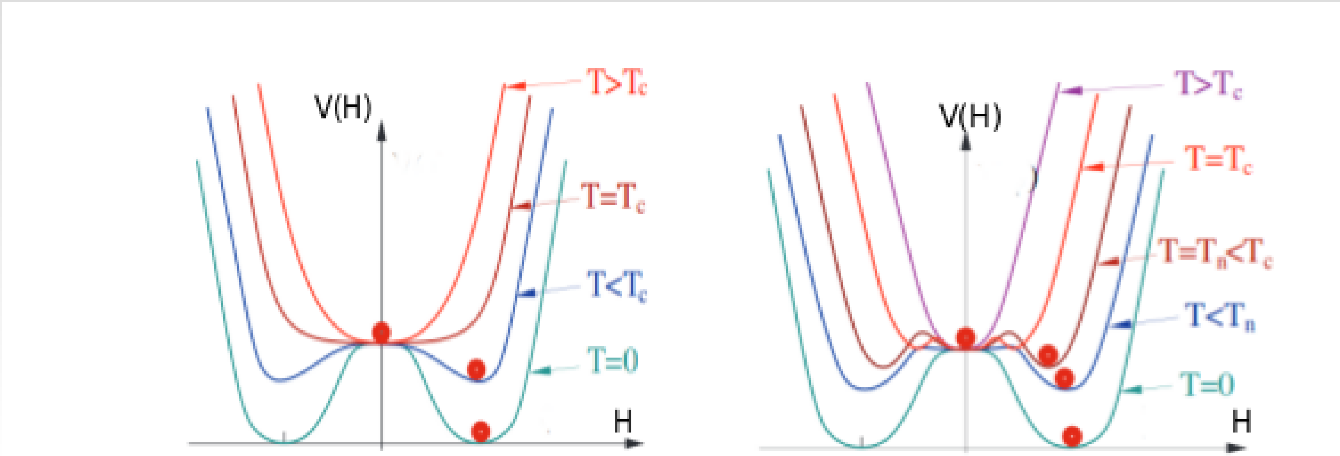
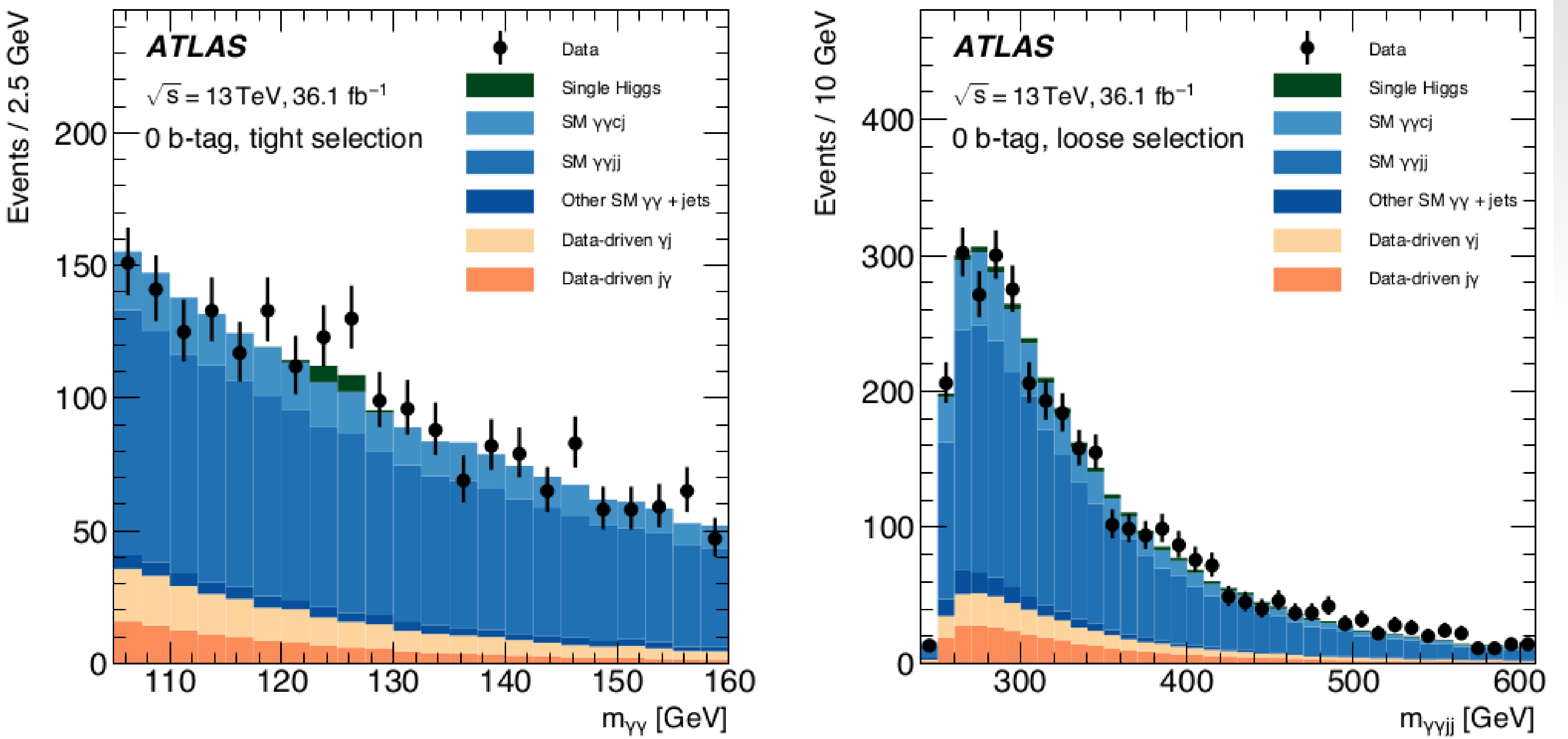


Figure 2: Left: Crossover or second order phase transition [1]. Right: First order phase transition [1].

In some models the « boiling » universe can generate naturally particle/anti-particle asymmetry.


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
0 b-tag, tight selection
Data
Single Higgs
SM γγcj
SM γγjj
Other SM γγ + jets
Data-driven γj
Data-driven jγ
Events / 2.5 GeV
$m_{\gamma\gamma}$ [GeV]
ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
0 b-tag, loose selection
Events / 10 GeV
$m_{\gamma\gamma jj}$ [GeV]