Search for di-Higgs production at the LHC: recent results and prospects

Elisabeth Petit

CPPM

CPPM seminar

11th of March 2019

Self-introduction

2008-2011
PhD student at CPPM

2015-2018
CR at LPSC

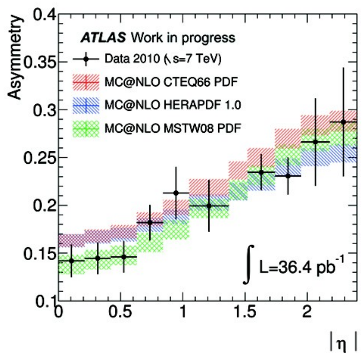
2011-2013
Post-doc at LAPP

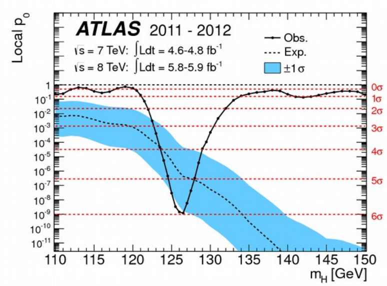
2013-2015
Post-doc at DESY

Self-introduction


Pierre-Simon et Elisabeth d'ATLAS : « Faire corps avec le calo »

2008-2011
PhD student at CPPM





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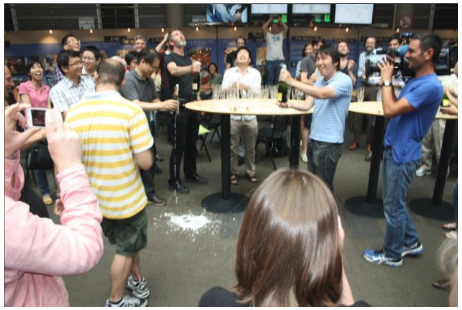
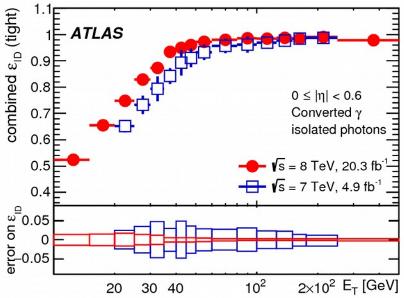
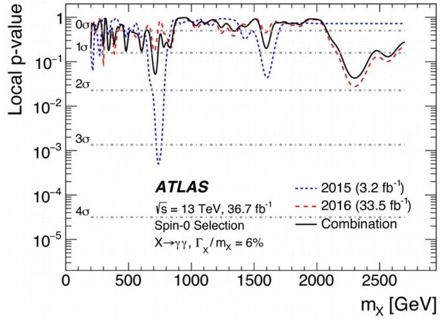


2013-2015
Post-doc at DESY





2015-2018
CR at LPSC

W boson physics

E_T^{miss}

Higgs boson discovery and properties

ITk upgrade

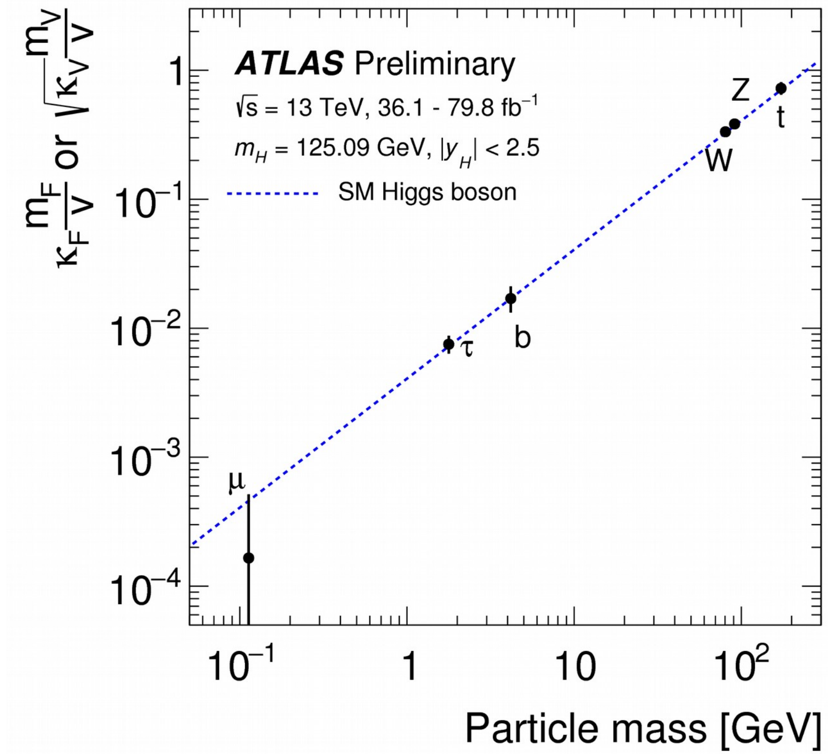
Search for diphoton resonances

HH → bbγγ

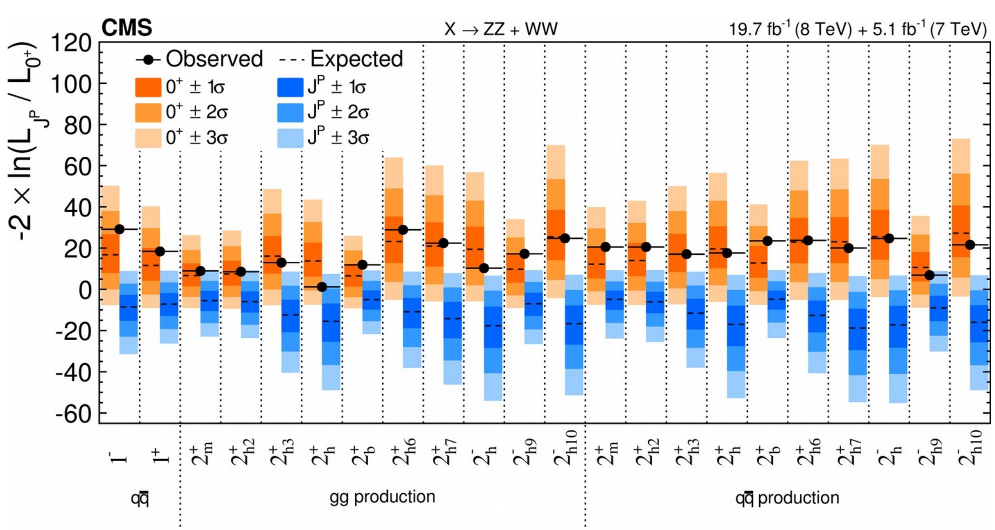
photon identification

Single-Higgs boson properties

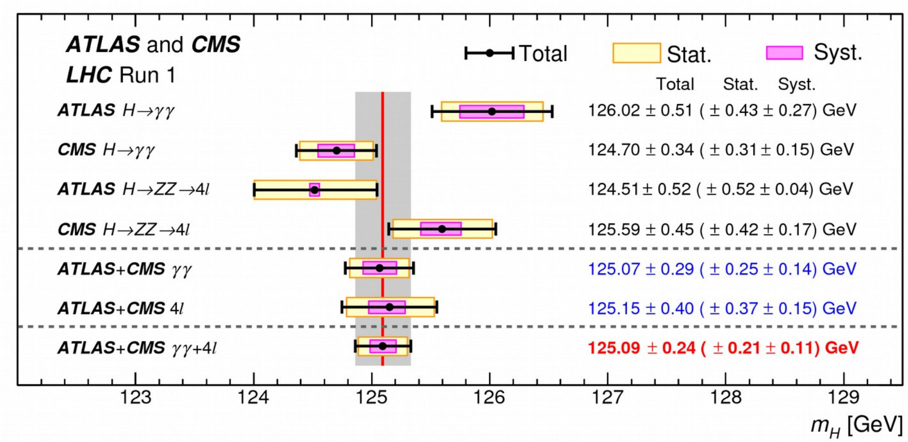
- All main production modes observed
  - couplings measured with 10-50% precision



- Spin/parity: $J^{PC} = 0^{++}$
  - spin 1 and 2 excluded at > 99% CL

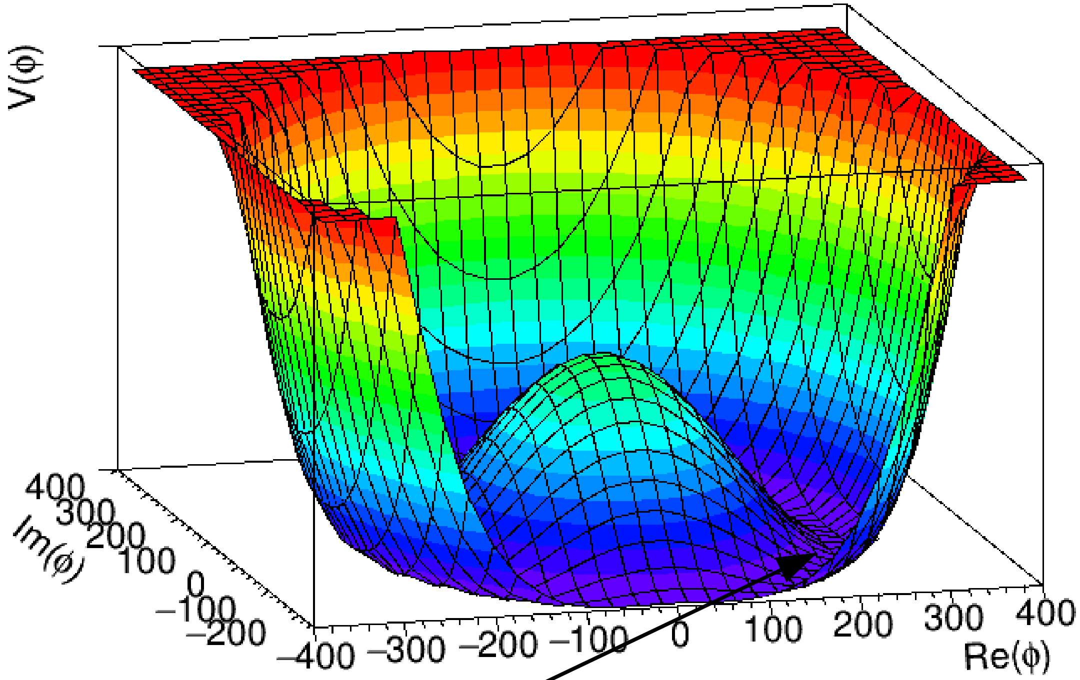


- Mass: precision < 0.2%



Higgs potential

- Higgs potential: $V(\Phi)=\frac{1}{2}\mu^2\Phi^2+\frac{1}{4}\lambda\Phi^4$



- Approximation around the v.e.v:

$$V(\Phi)\approx\underbrace{\lambda v^2 h}_{\text{mass term}}+\underbrace{\lambda v h^3+\frac{1}{4}\lambda h^4}_{\text{self-coupling terms}}$$

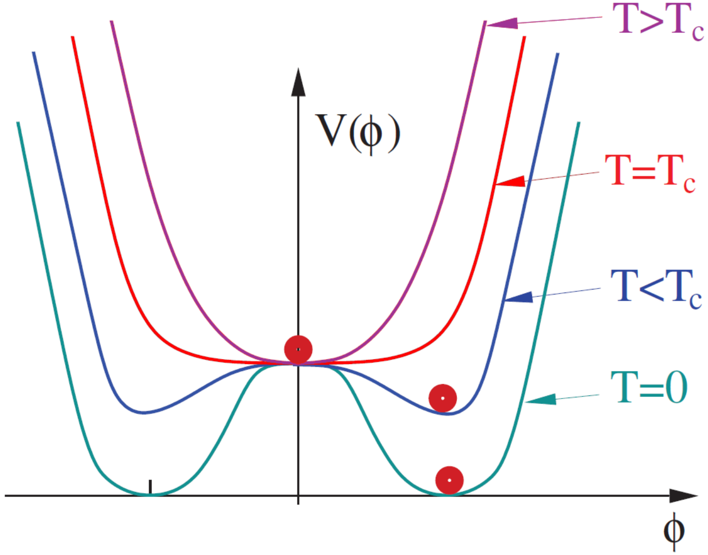
mass term self-coupling terms

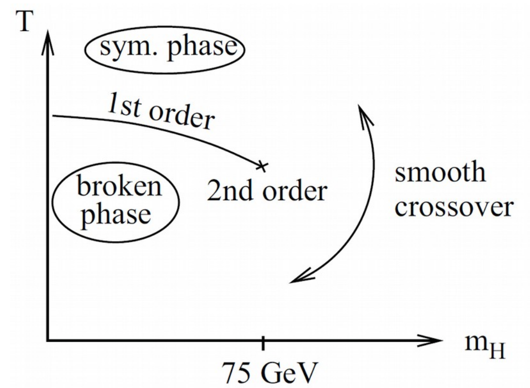
- λ known from v.e.v and Higgs mass: $\lambda=\frac{m_H^2}{2\cdot v^2}\approx 0.13$

- BSM effects could change λ ⇒ define $\kappa_\lambda=\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

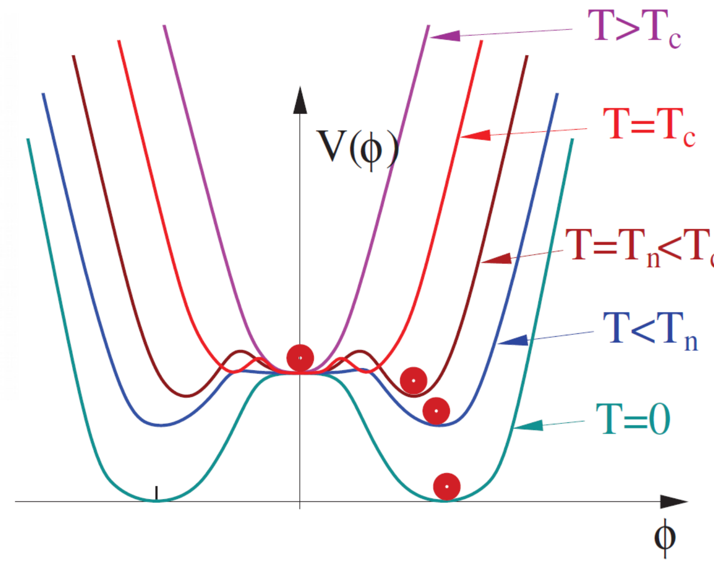
Higgs potential and electroweak phase transition

- Second order phase transition





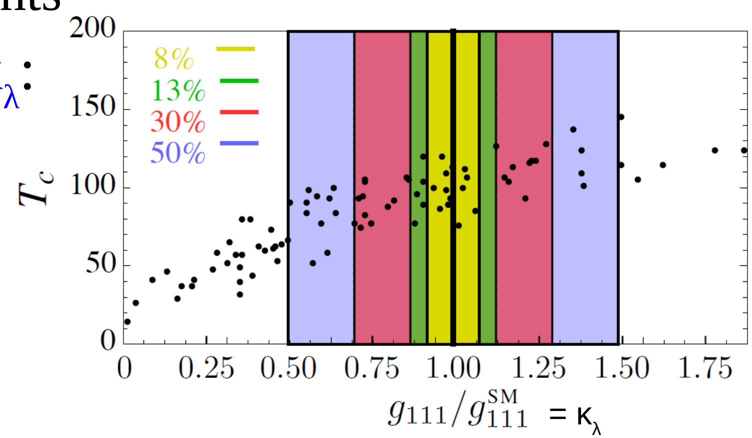
- First order phase transition

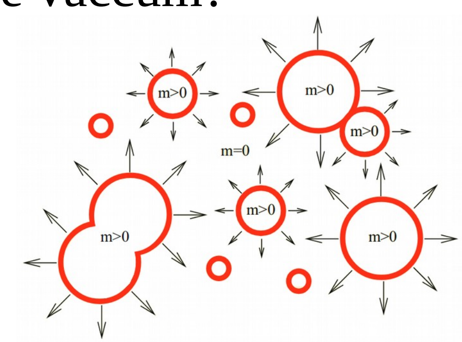


  - constantly at thermal equilibrium
  - not so interesting for cosmology
  - preferred option with the current measurements

  - matter-antimatter asymmetry?
  - domain walls?
  - gravitational waves created by bubbles of the vaccum?

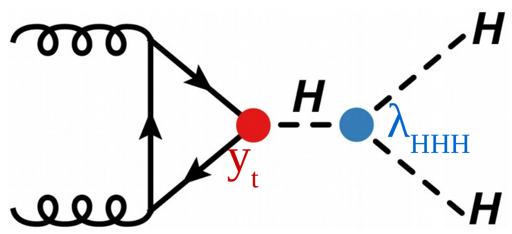
- T_C related to κ_λ:

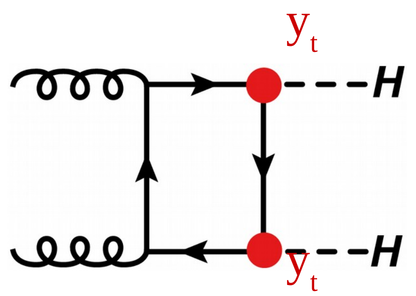


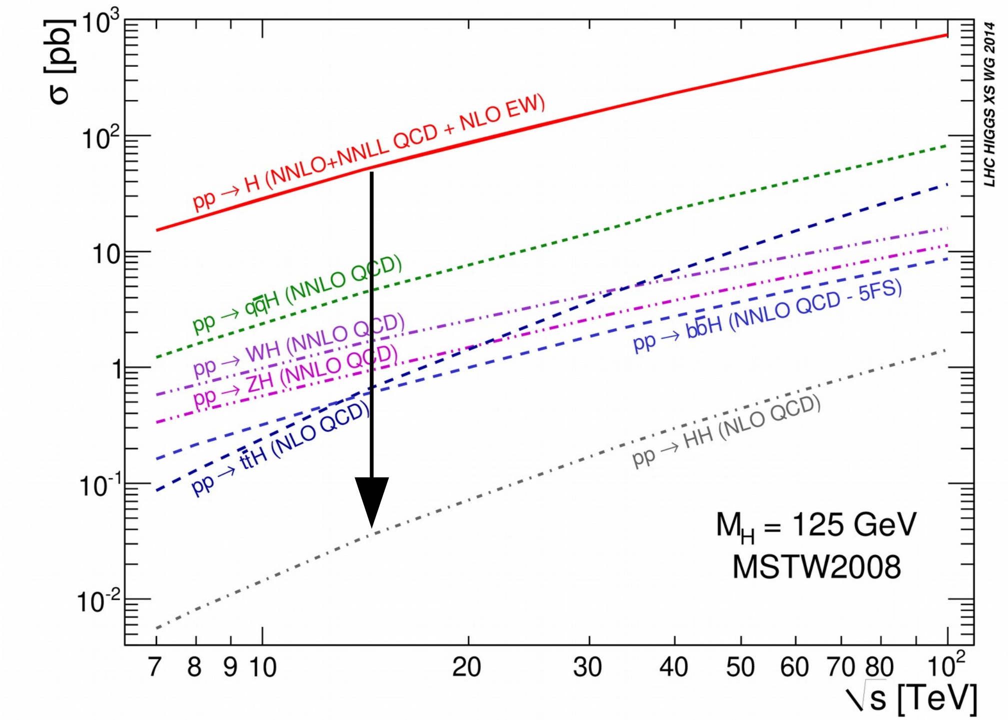


HH production (1)

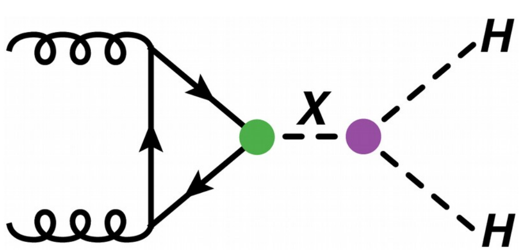
- Direct sensitivity to λ_{HHH}: di-Higgs production
- Non-resonant production: rare process of the SM
  - destructive interference
  - $\sigma(gg \rightarrow HH)$ = 33 fb ≈ 1‰*$\sigma(gg \rightarrow H)$







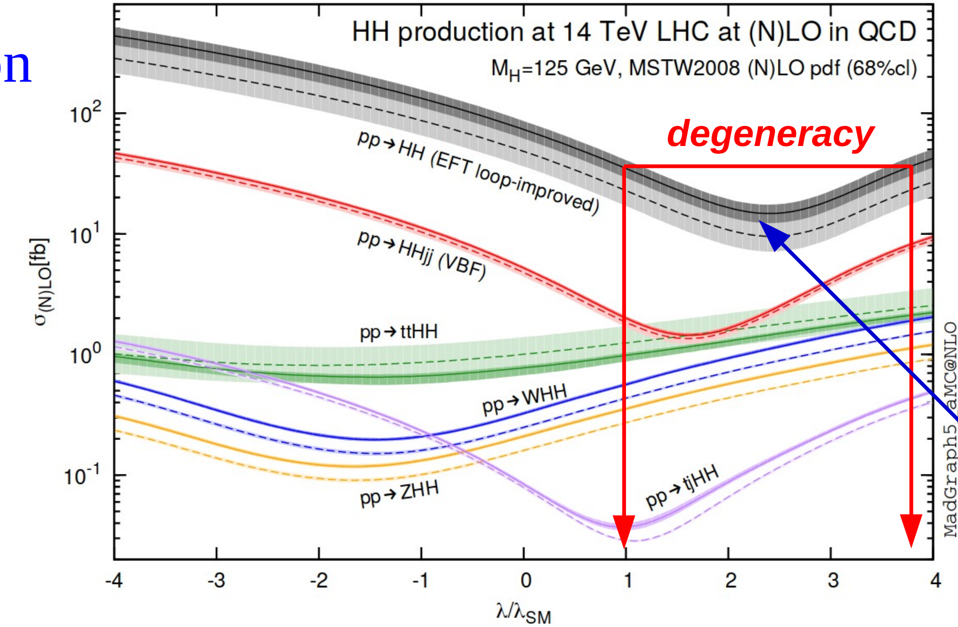
- Resonant production:
  - new heavy intermediate particle
  - KK graviton, radion, heavy Higgs bosons (2HDM), etc



HH production (2)

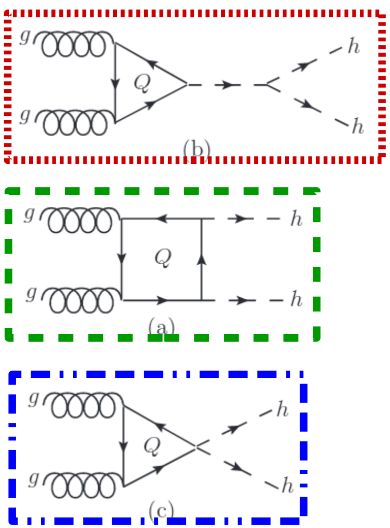
$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

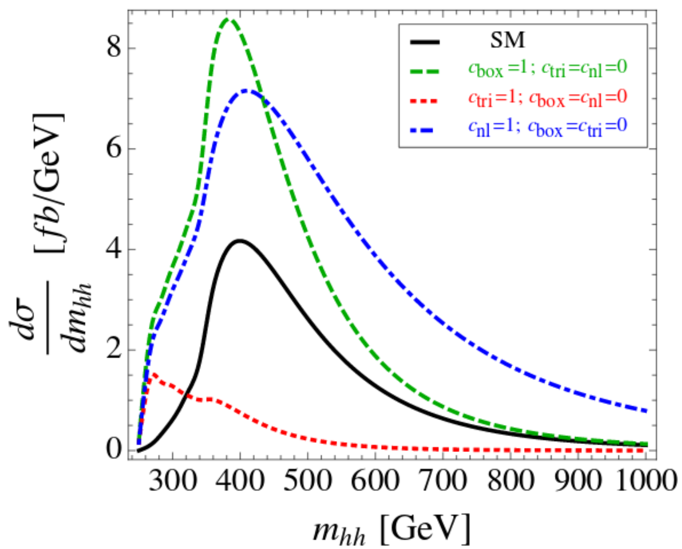
- Di-Higgs cross-section depends on κ_λ:

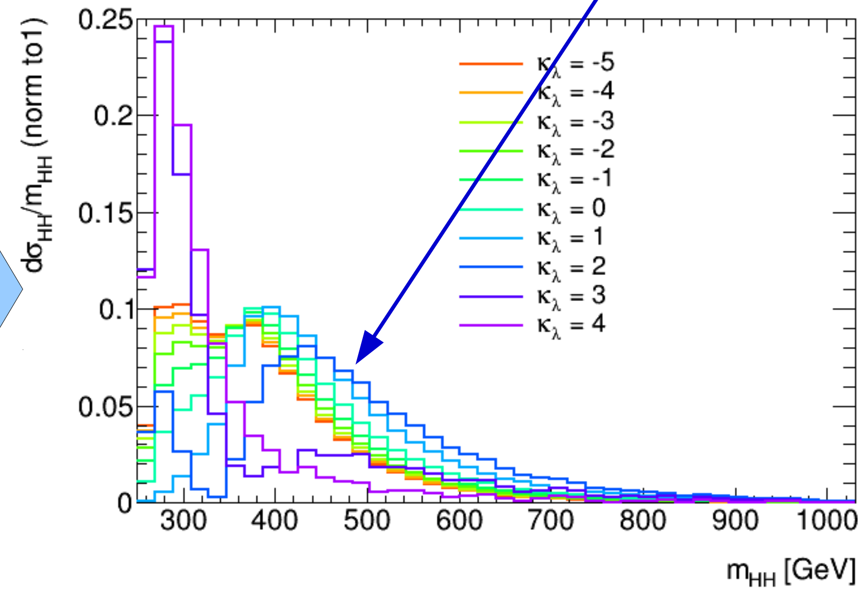


maximum interference κ_λ ~ 2.3

- Degeneracy can be removed using m_{HH} distribution:





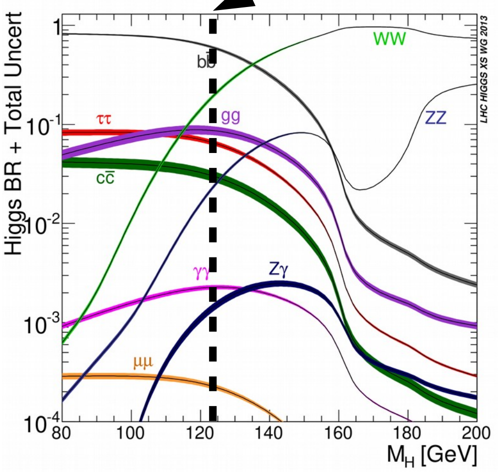


HH decays

- Many decay channels!

CERN seminar, 13th of Dec. 2011

It would be a <u>very nice</u> region for the Higgs to be → accessible at LHC in γγ, 4l, lνlν, bb, ττ



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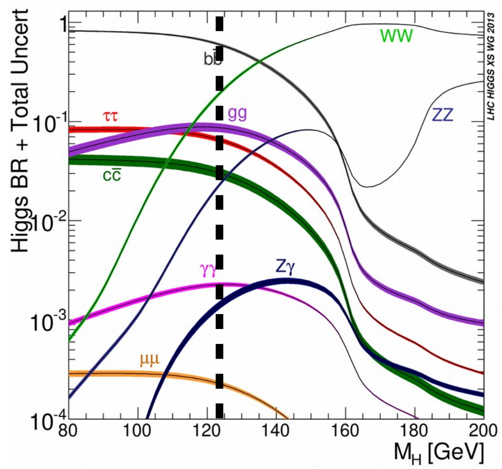

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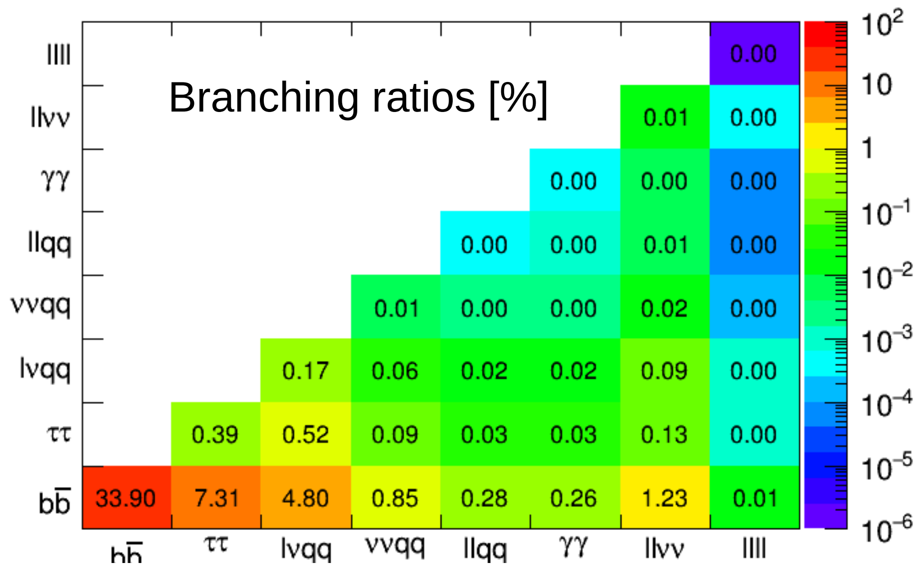
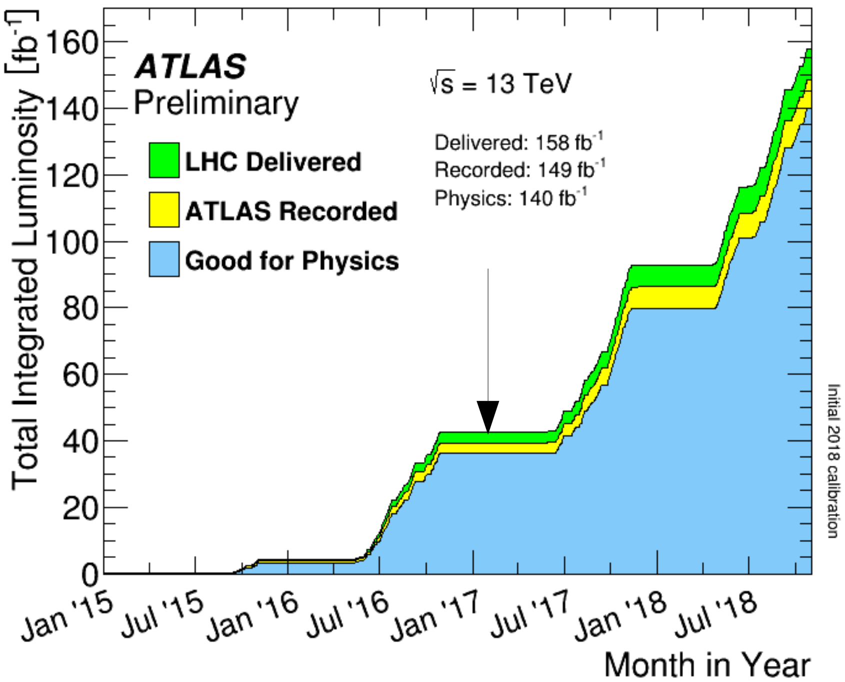


- In practice consider channels with $b\bar{b}$ (BR = 59%) to maximise the rate

Outline

- Current results with LHC Run-2 data
- Prospect studies at HL-LHC
- Comparison to future colliders

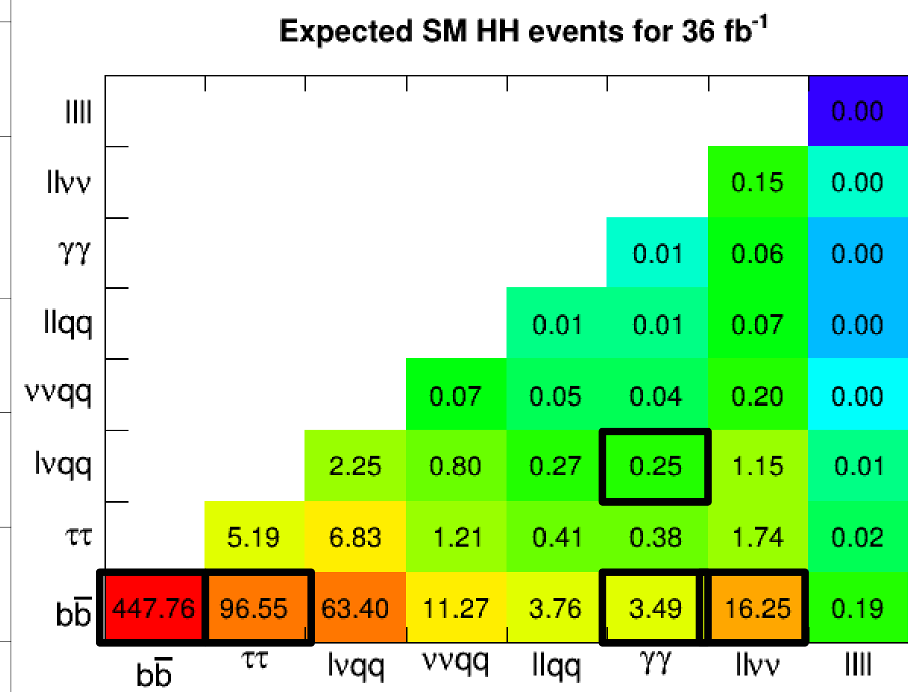
Analyses with Run-2 data
36 fb^{-1}, 2015+2016



Search for HH at LHC

- Channels for the Run 2 analyses:

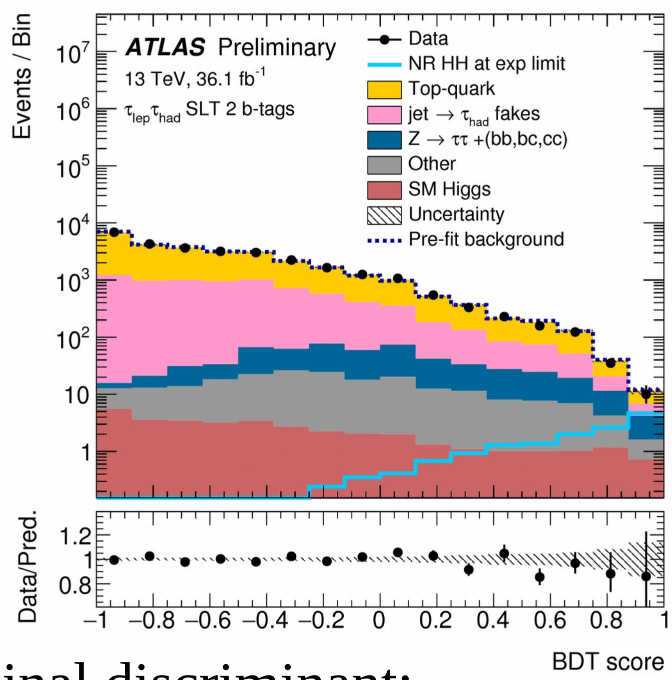
	ATLAS	CMS	
$b\bar{b}\tau\tau$	✔	✔	Sizeable BR ☺ Relatively small background ☺
$b\bar{b}\gamma\gamma$	✔	✔	Small BR ☹ Good diphoton resolution ☺ Relatively small background ☺
$b\bar{b}b\bar{b}$	✔	✔	Largest BR ☺ Large multijets and $t\bar{t}$ bkg ☹
$b\bar{b}VV$ ($\rightarrow l\nu l\nu$)		✔	Large BR ☺ Large bkg ☹
$\gamma\gamma WW$ ($\rightarrow l\nu qq$)	✔		Very small BR ☹ Good diphoton resolution ☺
combination	✔	✔	

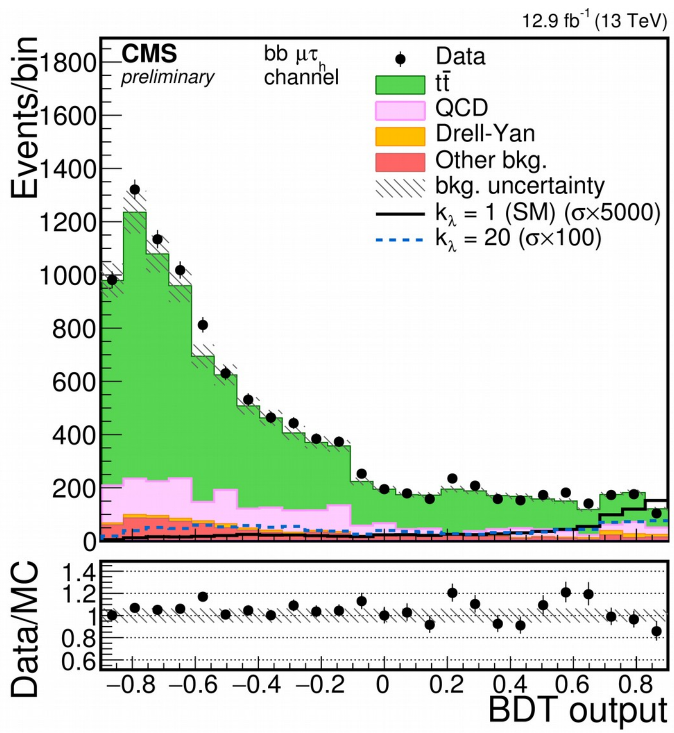


- General analysis strategy:
  - candidate mass consistent with SM Higgs boson
  - small angular separation between b-jets
    $\Rightarrow$ boosted regime above ~1 TeV
  - multivariate methods to reject background
  - use m_{HH} when possible

$HH \to b\bar{b}\tau\tau$

- Sizeable BR ☺, relatively small background ☺
- 2 b-jets + $\tau_{lep}\tau_{had}$ or $\tau_{had}\tau_{had}$
  - including boosted τ and b-jet for CMS
- BDT for resonant and non-resonant signal
  - ATLAS: on non-resonant + each resonant mass point
  - CMS: resonant mass < or > 350 GeV

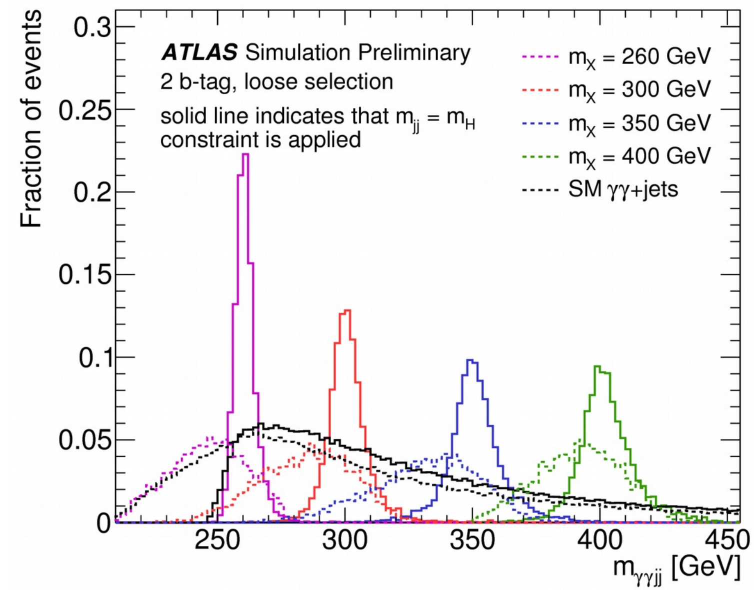




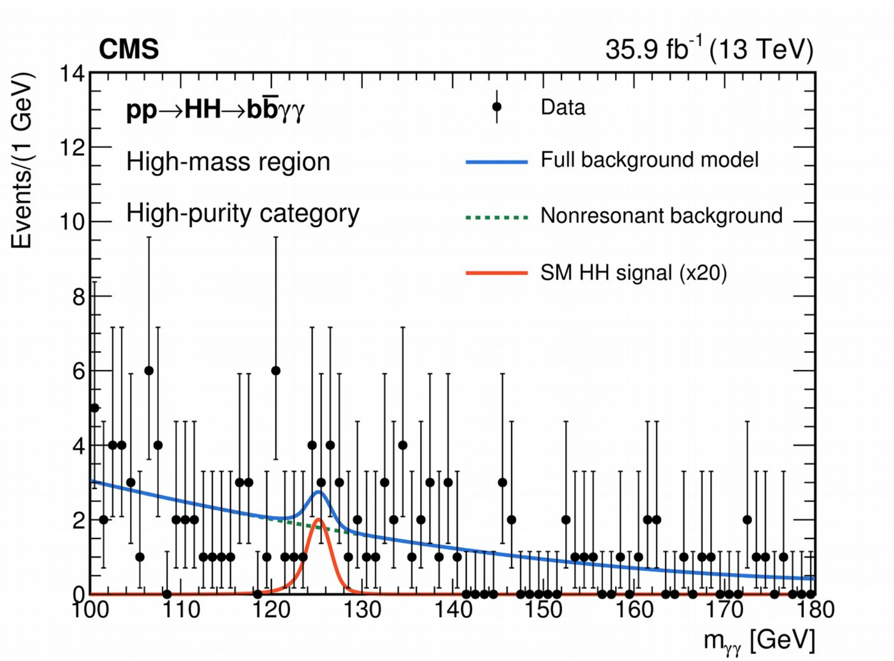
- Final discriminant:
  - BDT output (ATLAS)
  - modified m_{HH} for resonant, m_{T2} for non-resonant (CMS)

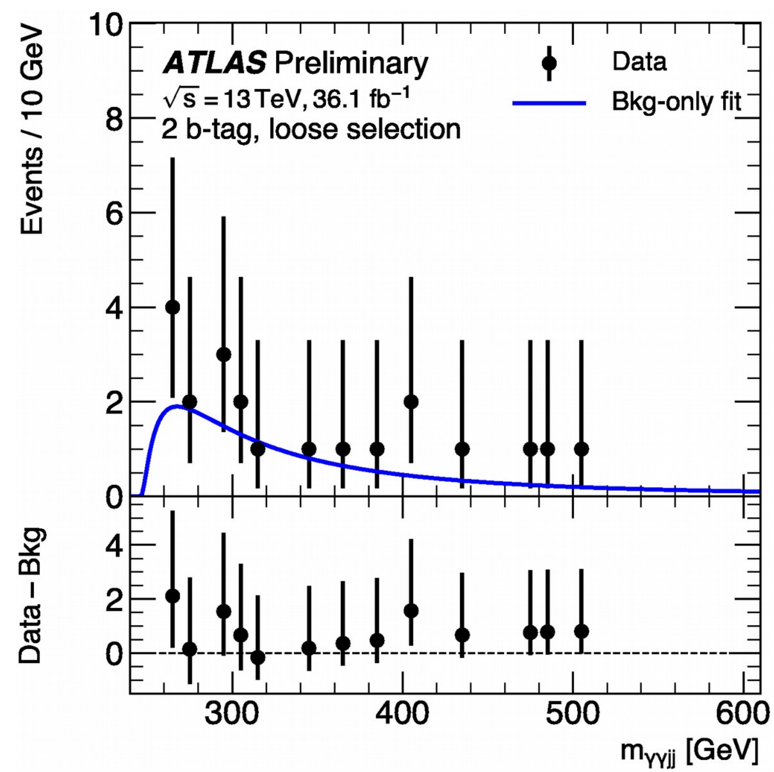
$HH \rightarrow b\bar{b}\gamma\gamma$

- Small BR☹, good diphoton resolution ☺
- 1 or 2 b-jets and two photons
  - corrected mass for resonant search
  - BDT selection (CMS)



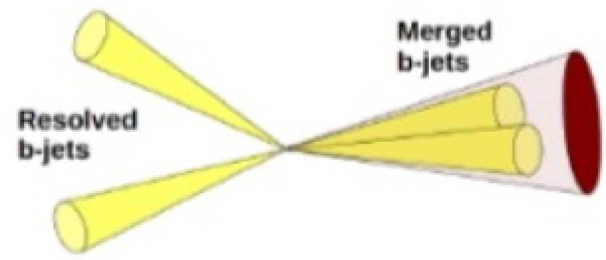
- Extraction of signal from parametric fits to:
  - $m_{\gamma\gamma}$ or $m_{\gamma\gamma jj}$ (ATLAS), $m_{\gamma\gamma}$ x m_{jj} (CMS)

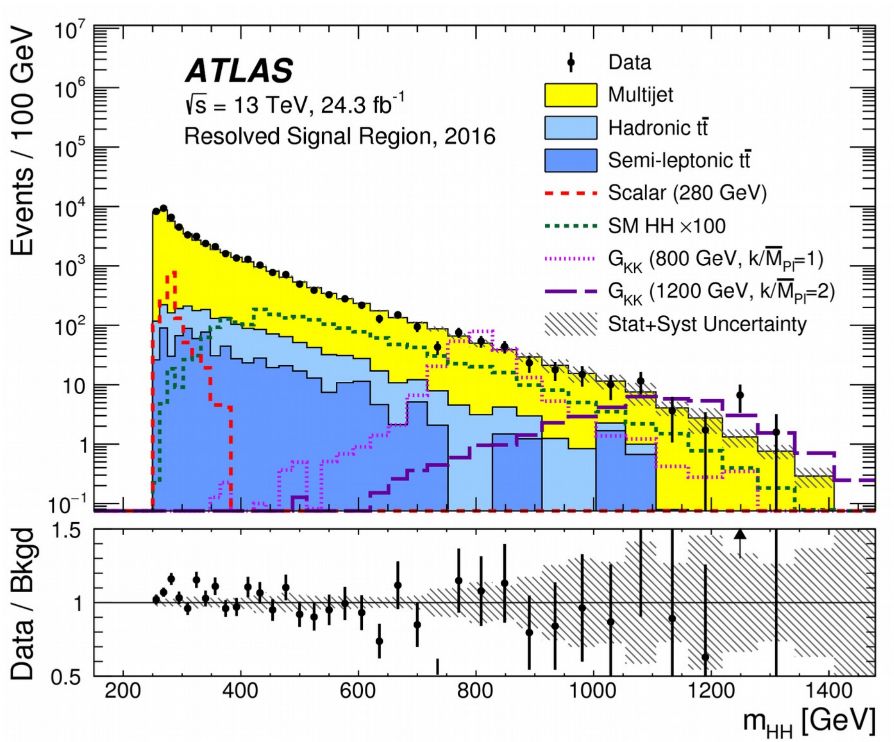


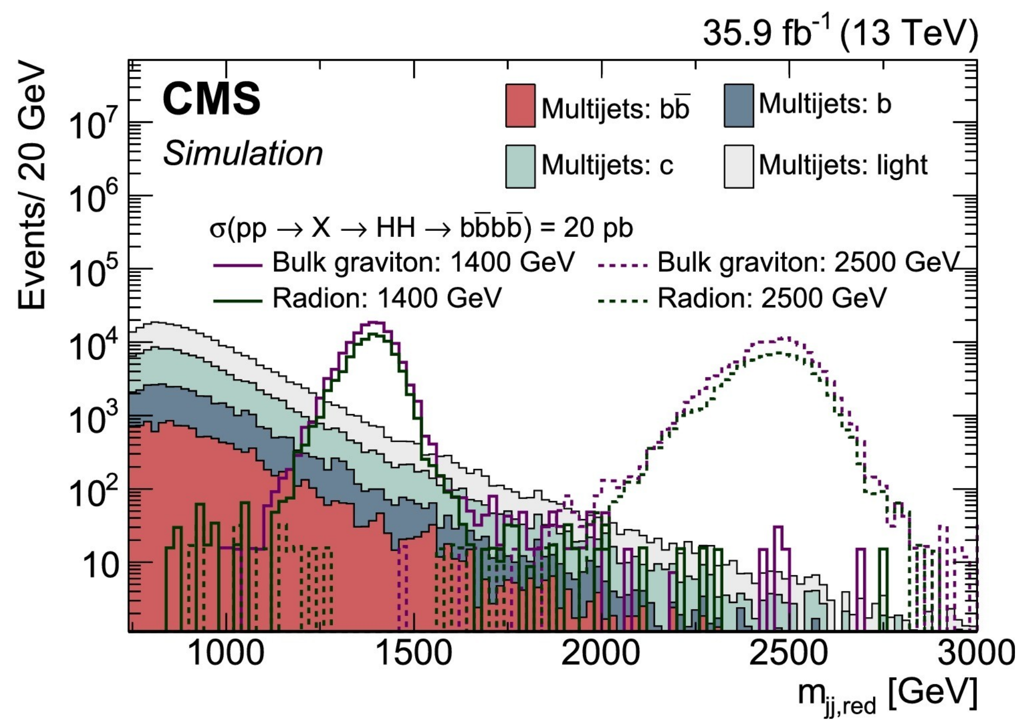


HH → $b\bar{b}b\bar{b}$

- Largest BR ☺, large QCD multijets and $t\bar{t}$ backgrounds ☹
- Large use of boosting techniques
  - 4 resolved b-jets: ~250-1200 GeV
  - semi-resolved (CMS): 750-~2000 GeV
  - 2 boosted b-jets: ~750-3000 GeV

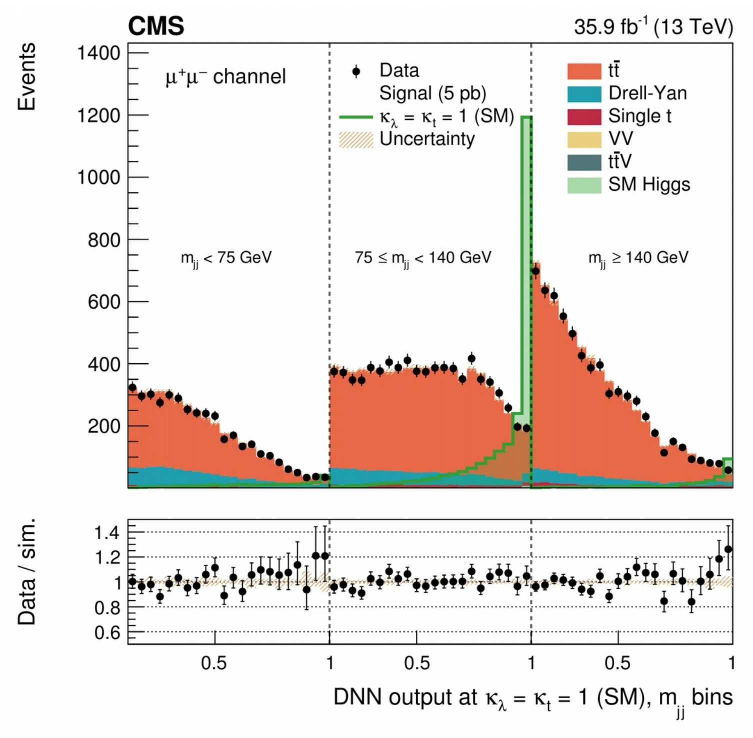




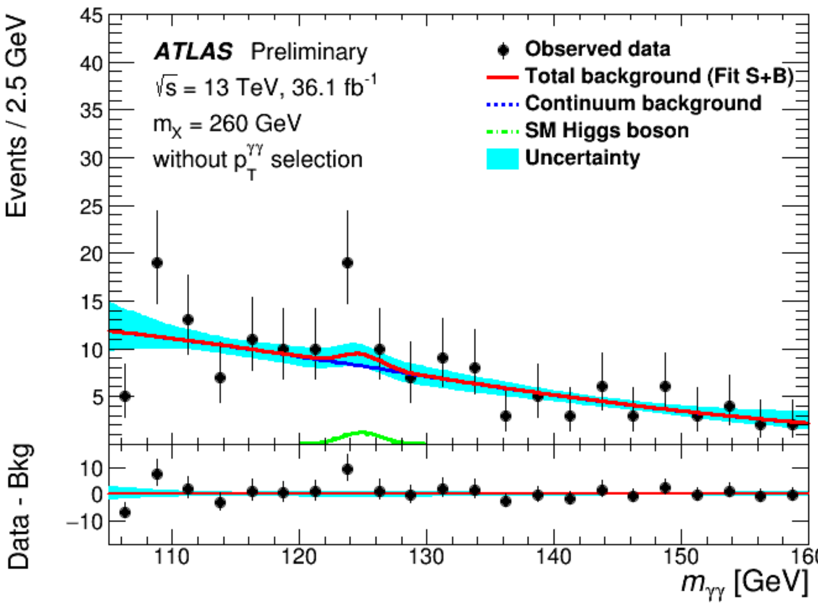


$HH \rightarrow b\bar{b}l\nu l\nu$ and $l\nu qq\gamma\gamma$

- CMS: $b\bar{b}VV(\rightarrow ll\nu\nu)$: large BR☺, large bkg ☹
- Two opposite sign leptons, two small-R b-tagged jets,
- $12 < m_{ll} < m_Z - 15$ GeV
- Neural network training + output used as discriminating variable

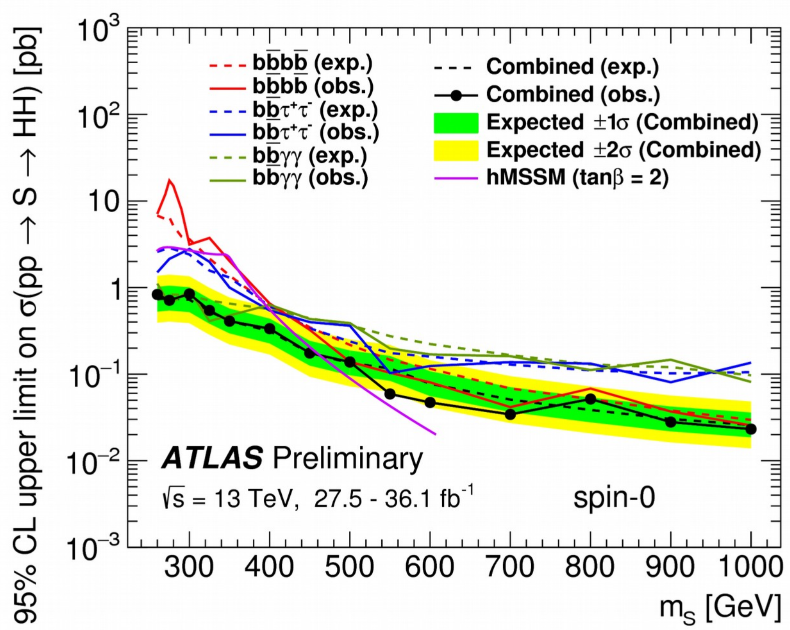


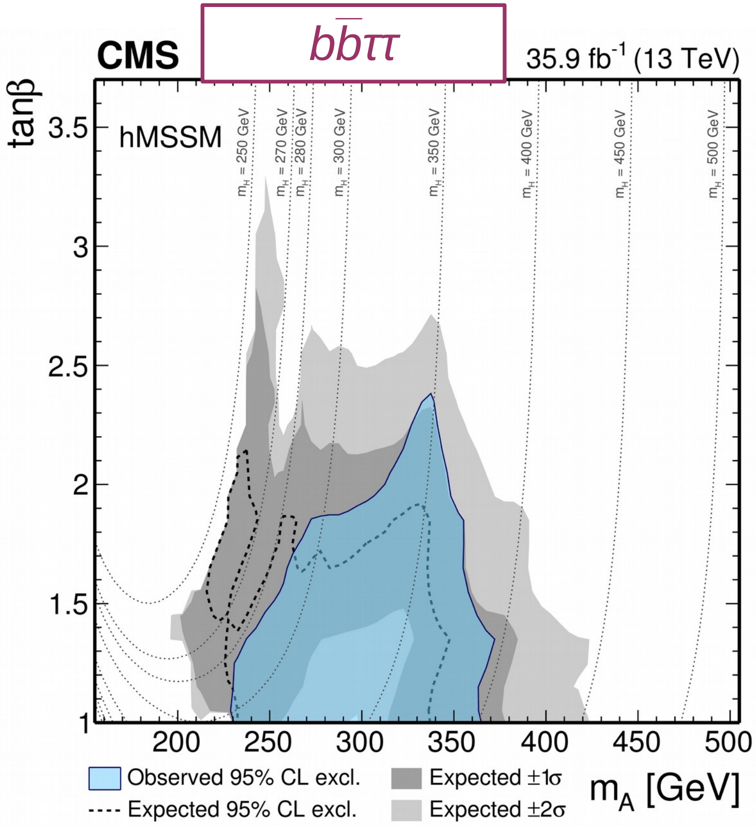
- ATLAS: $\gamma\gamma WW(\rightarrow l\nu qq)$: very small BR☹, good diphoton resolution ☺
- Two photons, one lepton (e or μ), two jets and no b-tagged jets
- $p_T^{\gamma\gamma} > 100$ GeV for non-resonant and resonant search for mx > 400 GeV



Results for resonant HH

- Limit set on spin-0 (THDM, hMSSM) and spin-2 processes (graviton, radion, ...):
  - complementarity of the different channels and analysis techniques (resolved/boosted), combination in back-up
  - no significant excess

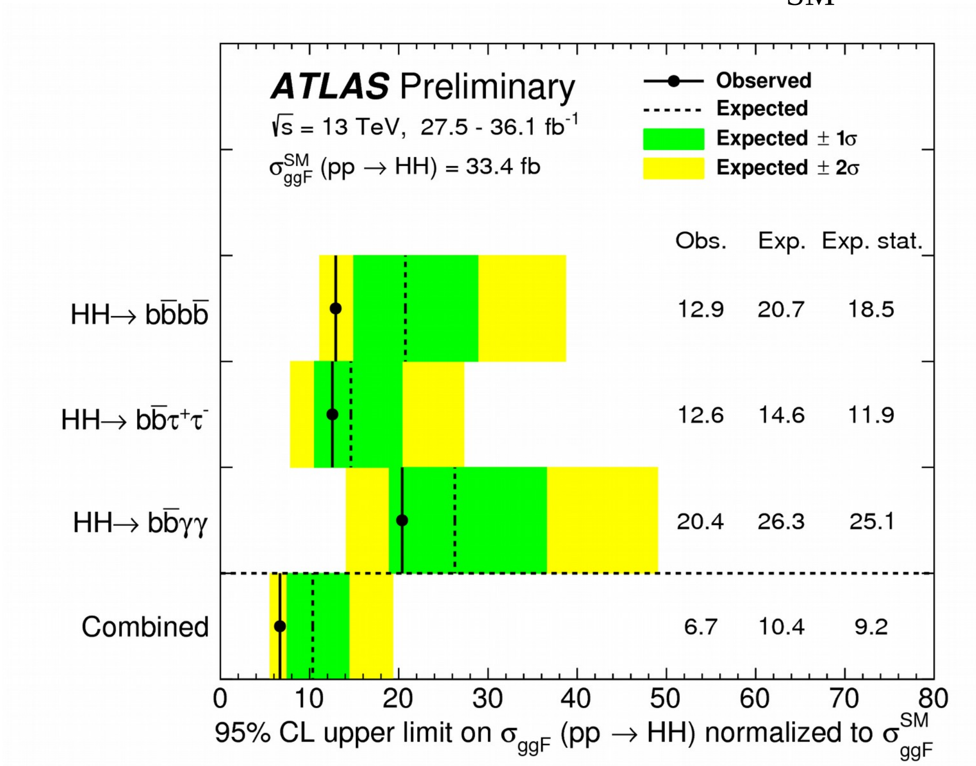


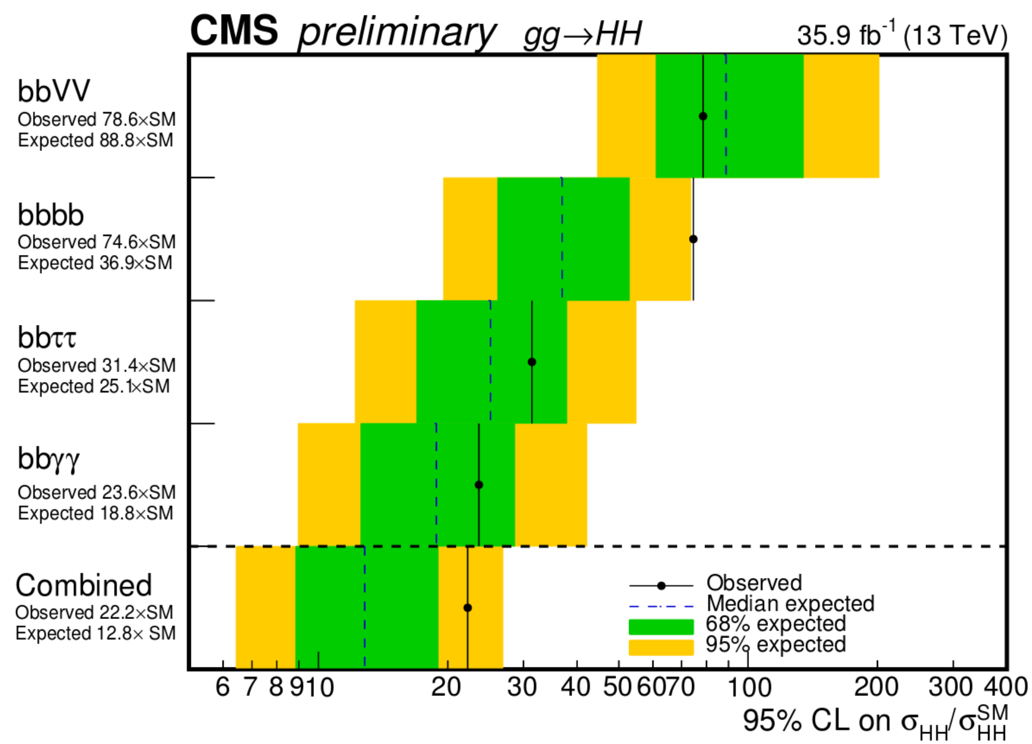


- Interpretation in hMSSM model
  - CP-even lighter scalar = h (125 GeV Higgs boson)
  - CP-even heavier scalar = H
  - CP-odd scalar = A

Result for non-resonant HH (1)

- Summary of limits on σ/σ_{SM}:





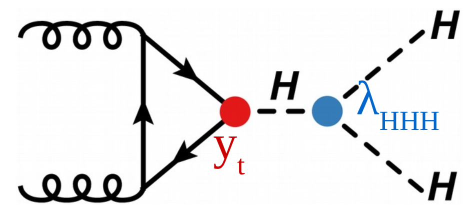
- Combined results: O(10*SM)
  - most sensitive channels: $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$
  - difference of sensitivity between experiments ⇒ room for improvement

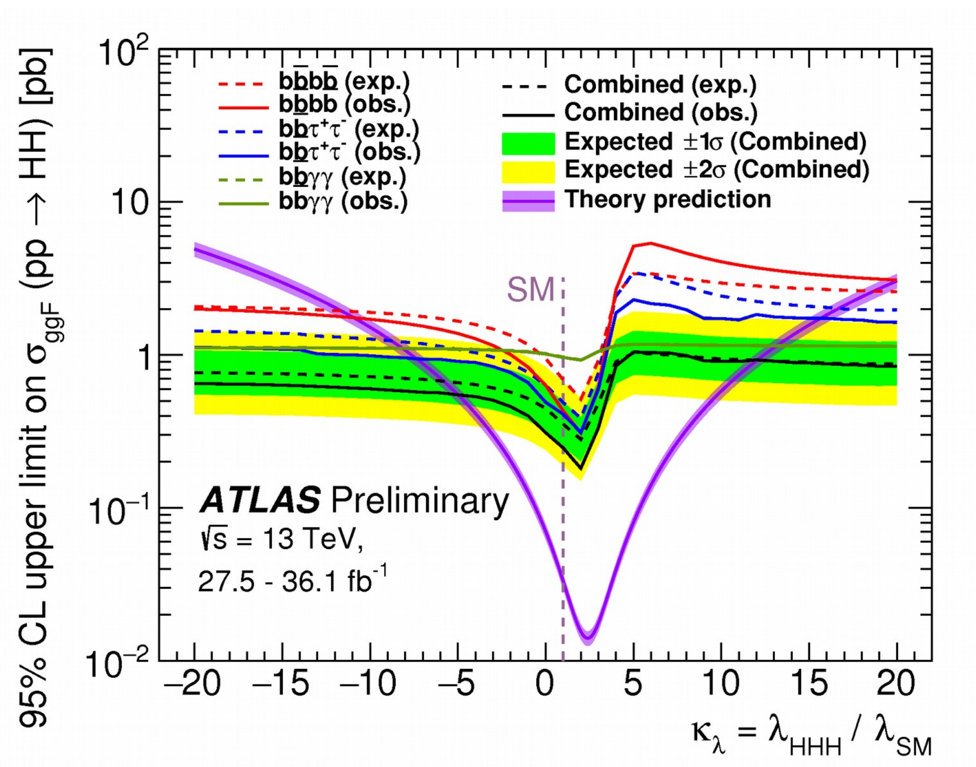
	expected limit on σ/σ_{SM}	
	ATLAS	CMS
bbττ	15	25
bbγγ	26	19
bbbb	21	37
bbllνν	-	89
lνqqγγ	160	
combination	10	13

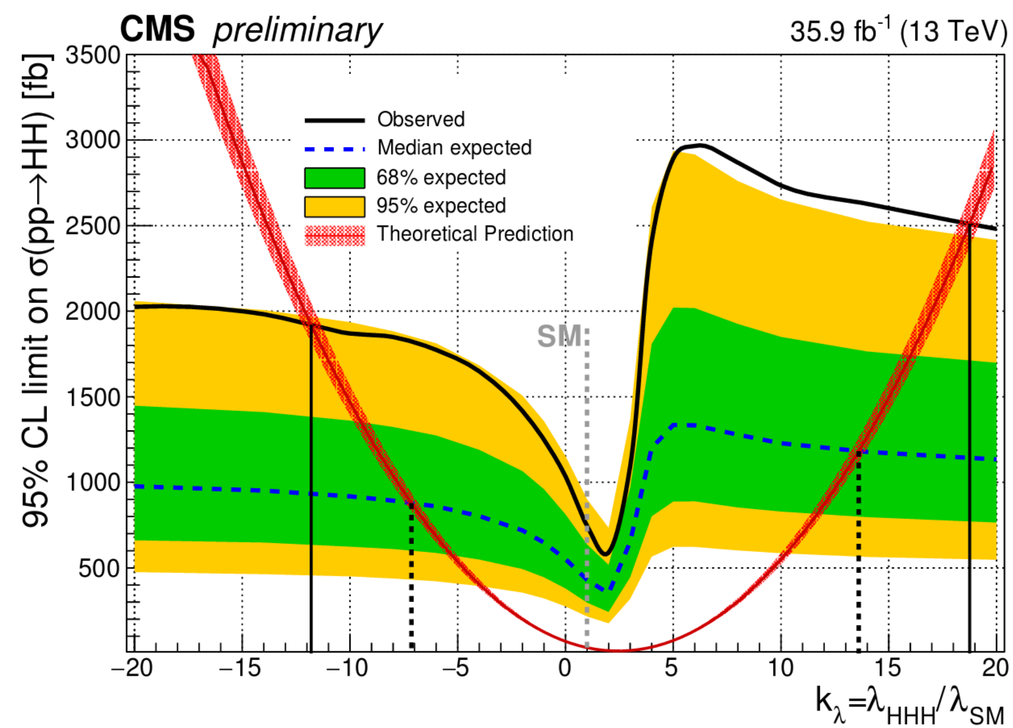
Result for non-resonant HH (2)

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

- Limit on anomalous couplings: κ_λ







- Current limit at 95% CL: ~-6 < κ_λ < 12

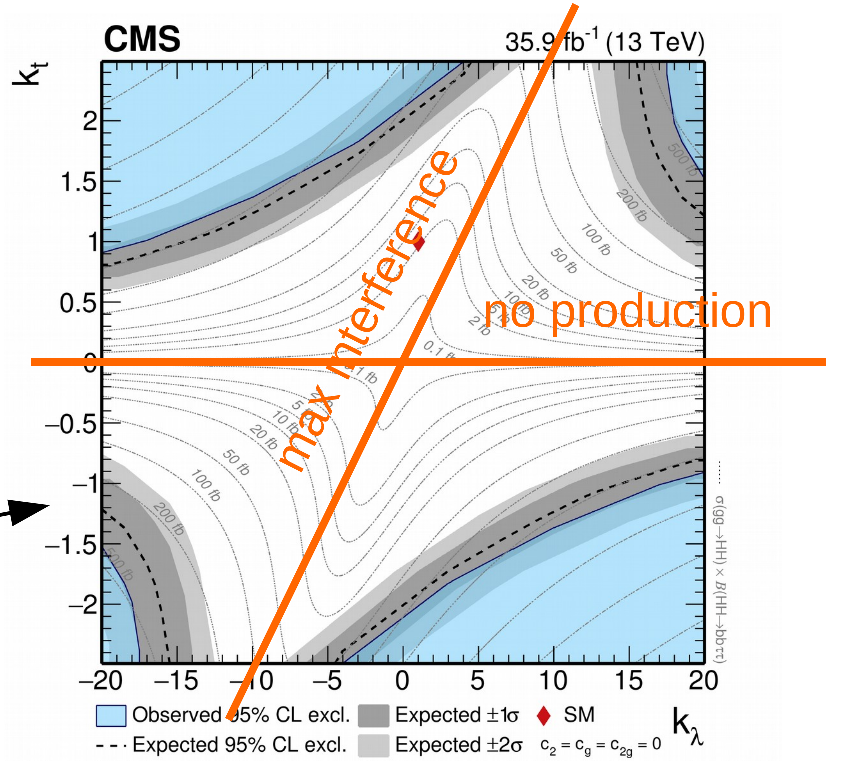
Result for non-resonant HH (3)

$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

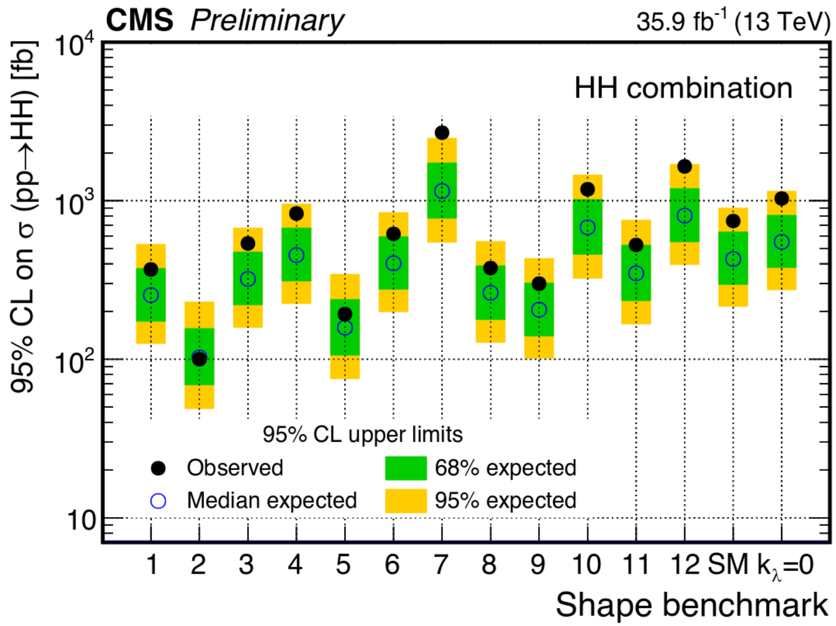
- EFT approach:

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v\, h^3 - \frac{m_t}{v}(v + \kappa_t h + \frac{c_2}{v} h\, h)(\bar{t_L} t_R + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi v}(c_g h - \frac{c_{2g}}{2v} h\, h)\, G^{\mu\nu} G_{\mu\nu}$$

- Limit in κ_λ-κ_t plane:

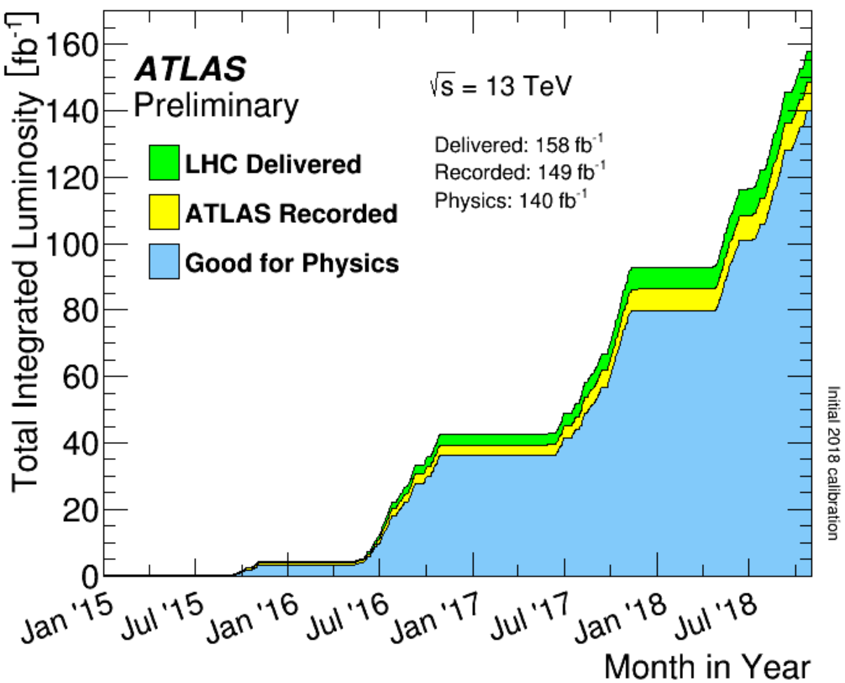


- Interpretation with benchmark points:



Conclusions on Run-2 studies

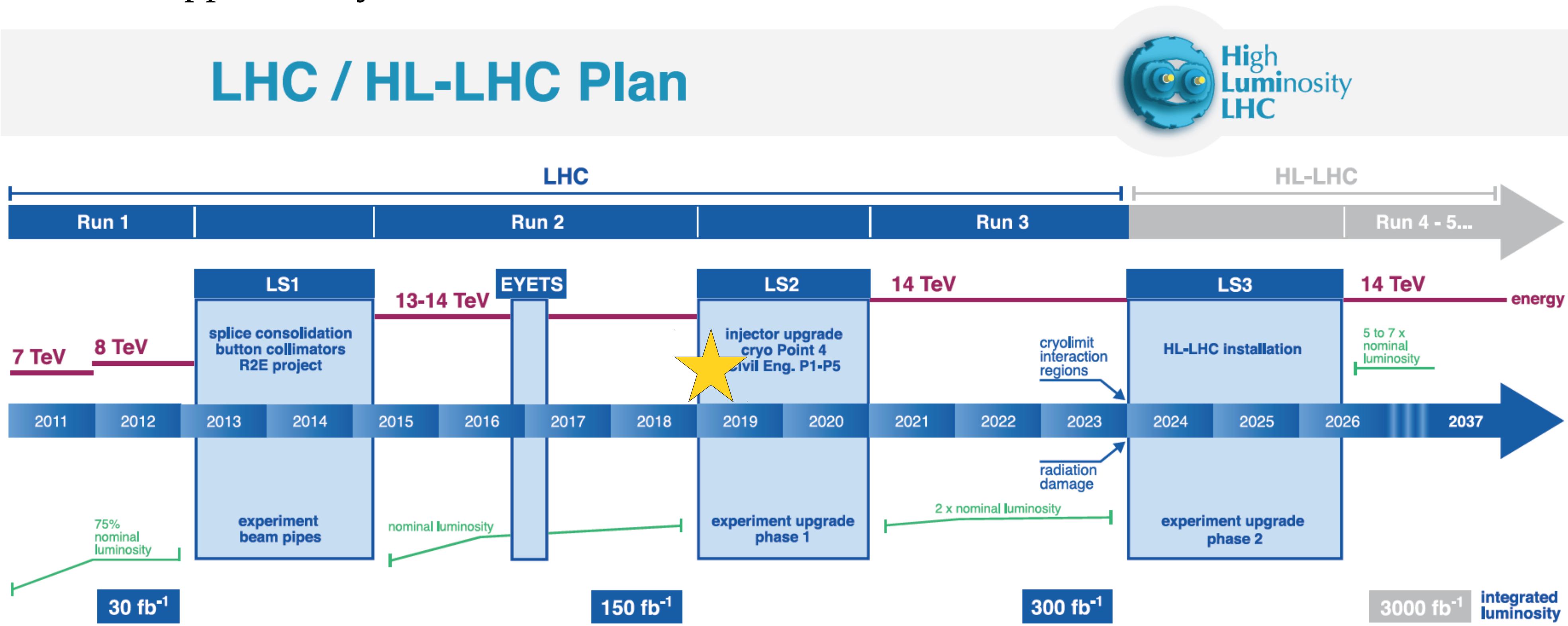
- Di-Higgs searches based on ~36 fb^{-1} of LHC Run-2 data
  - several final states studied: $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, etc
  - improved sensitivity using boosted technologies and machine learning
- No significant excess observed in resonant search
- No excess in non-resonant production, limit ~10*SM
- Integrated luminosity collected at the end of Run-2: ~140 fb^{-1}



HL-LHC Prospects

The HL-LHC and HE-LHC projects

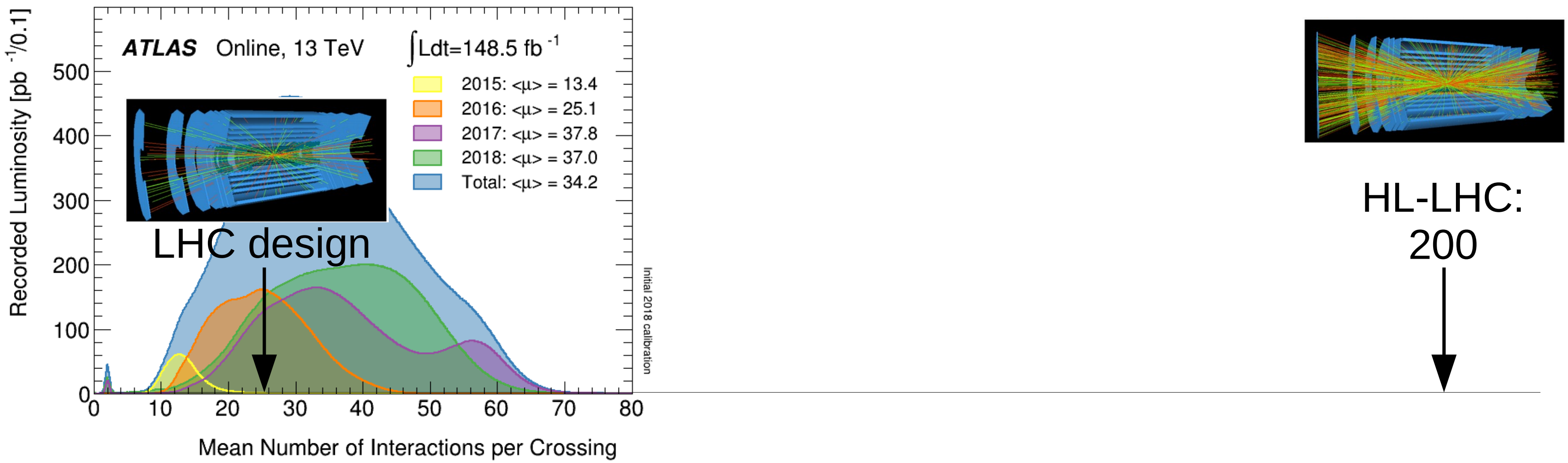
- Context: Yellow Report (YR) with CMS and theorists for European Strategy
- HL-LHC: $\sqrt{s}$ = 14 TeV, 3000 fb^{-1}
  - approved by CERN in 2016, until ~2035



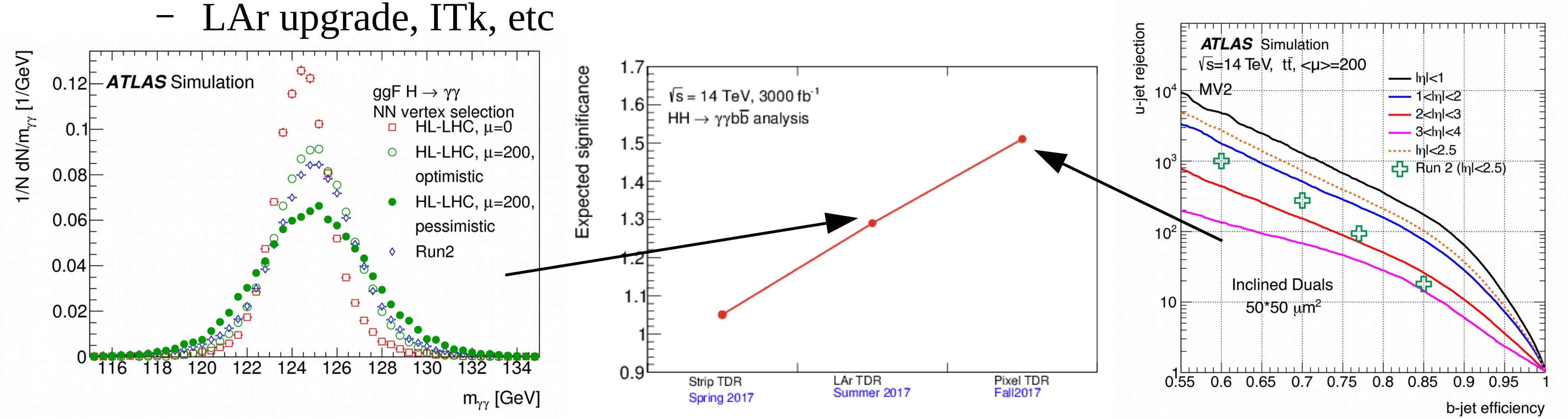
- HE-LHC: $\sqrt{s}$ = 27 TeV, 15000 fb^{-1}
  - in the LHC tunnel
  - would run from 2040 to 2060

Detector performance at HL-LHC

- Large pile-up at HL-LHC compared to LHC:



- Upgrades of ATLAS and CMS to cope with aging, pile-up, radiation
  - LAr upgrade, ITk, etc

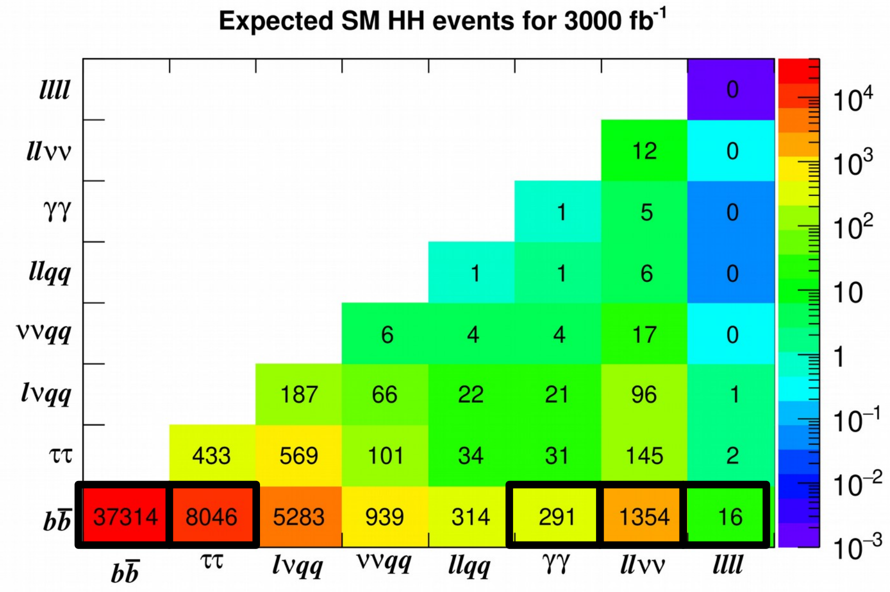


- Current resolutions/efficiencies could be kept at HL-LHC!

Methods

- Either extrapolations from Run-2 analyses, or dedicated studies with smeared/parameterised detector response
  - summary of channels/methods:

	ATLAS	CMS
bbbb	extrapolation	parameterised
bbττ	extrapolation	parameterised
bbγγ	smearing	parameterised
bbVV(llνν)	-	parameterised
bbZZ(4l)	-	parameterised

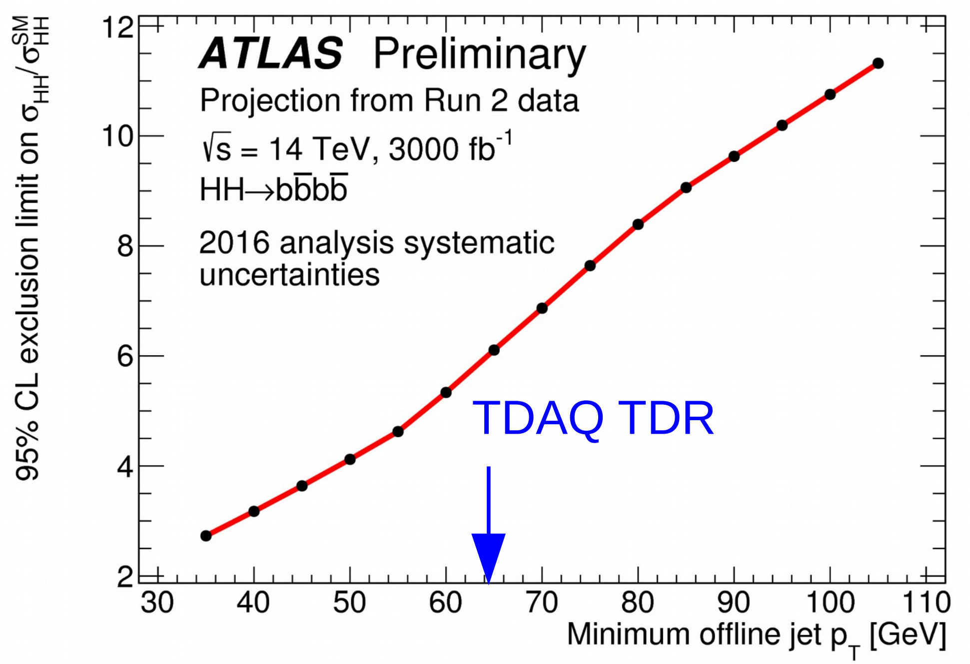


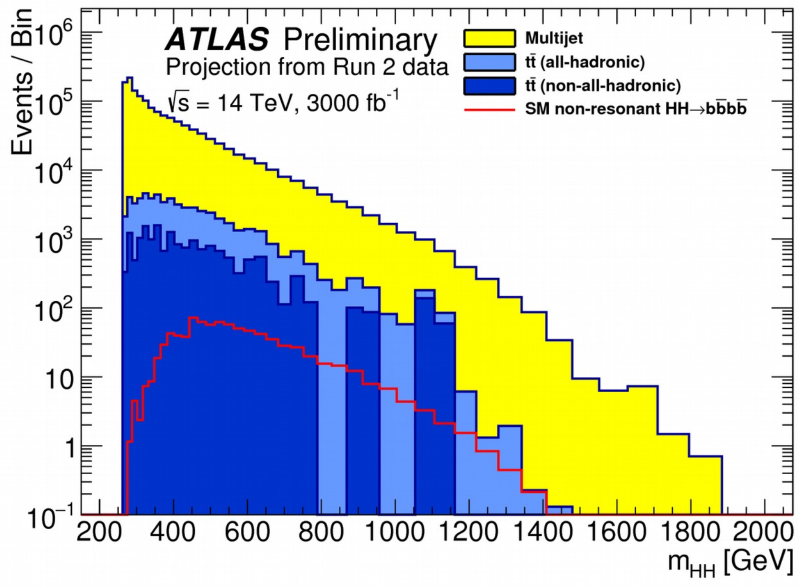
- MVA analyses used for almost all channels

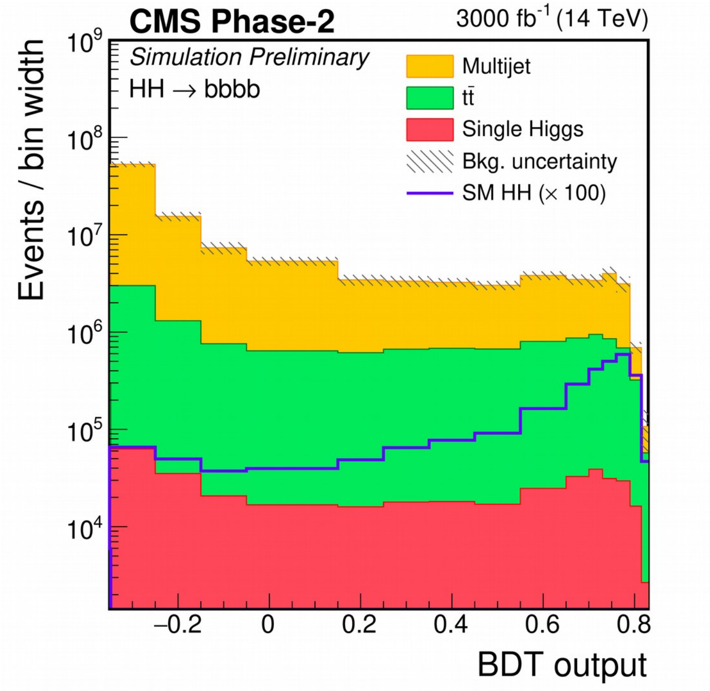
- Systematics: common agreement between ATLAS and CMS
  - performance uncertainties scaled by 0.5 to 1
  - theoretical uncertainties divided by 2
  - MC stat uncertainties neglected

HH → $b\bar{b}b\bar{b}$

- ATLAS: fit of m_{4j} distribution
- CMS: dedicated BDT
- Both experiments use the Run-2 p_T^{jet} cuts, different thresholds tested



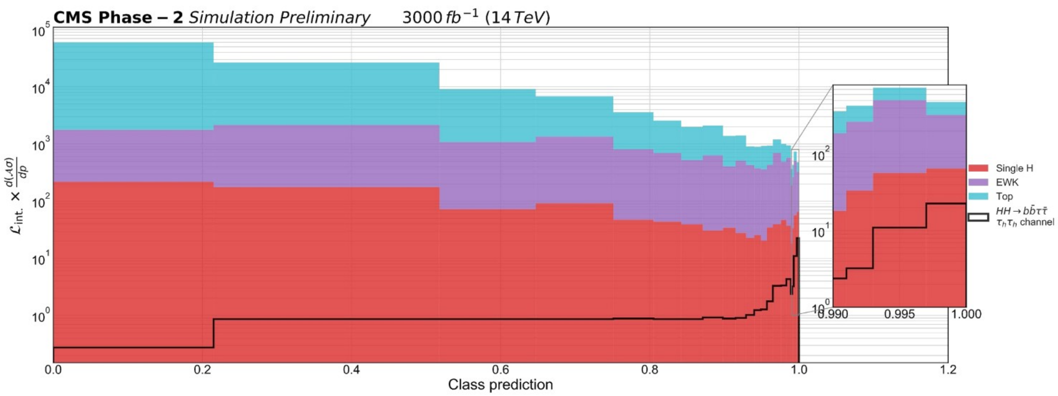


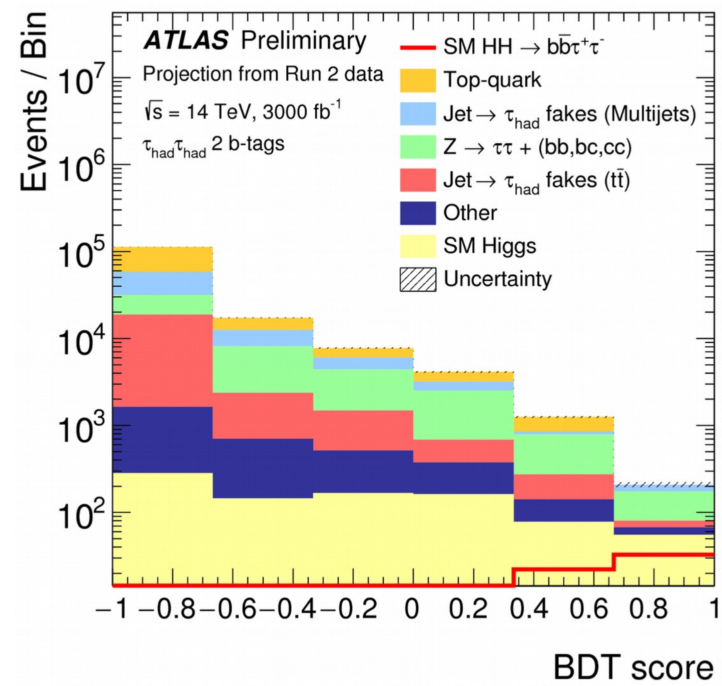


- Significance:
  - ATLAS: 1.4 wo/syst 0.61σ w/syst
  - CMS: 1.2σ wo/syst 0.95σ w/syst

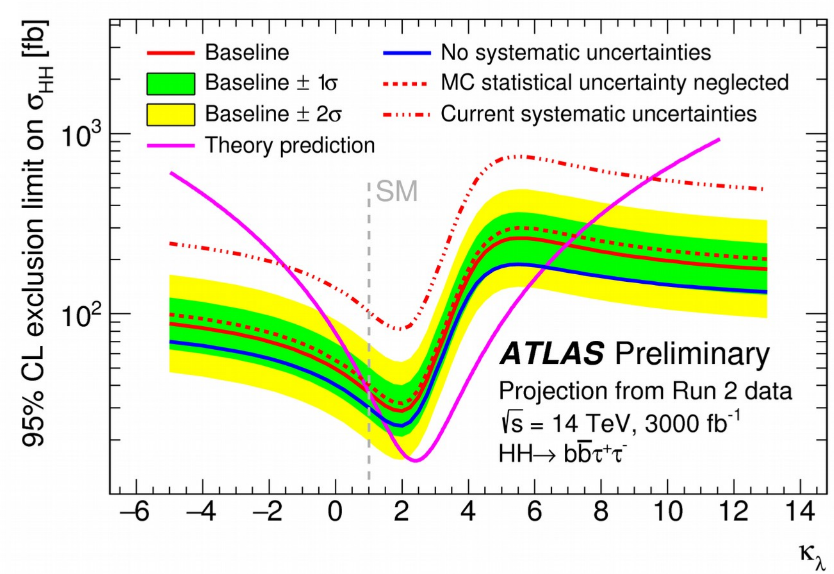
HH → $b\bar{b}\tau\tau$

- ATLAS: BDT output used as final discriminant
  - binning adapted to higher statistics
- CMS: Neural Network used as final discriminant
  - new for this study





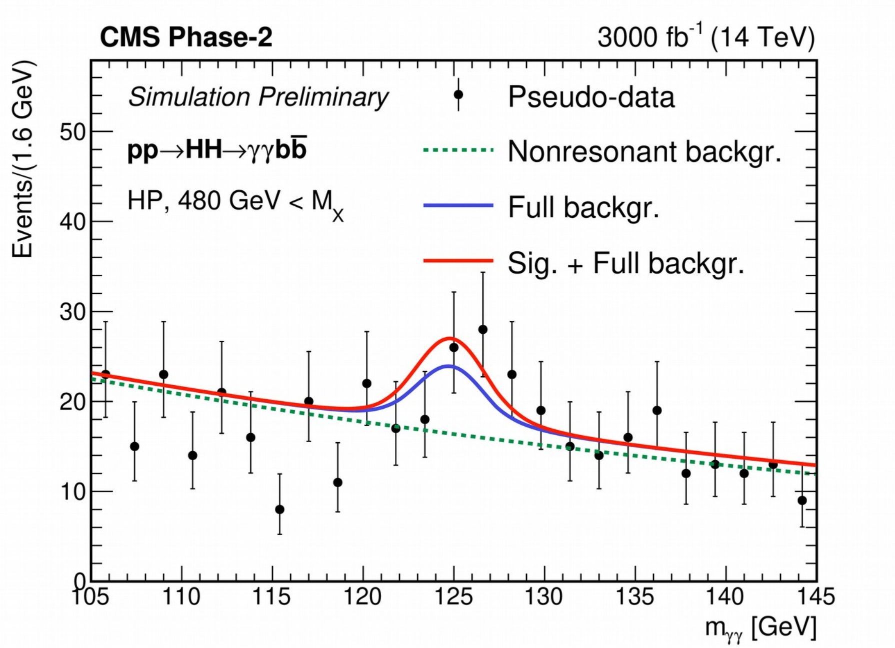
- Example of different assumptions for systematics

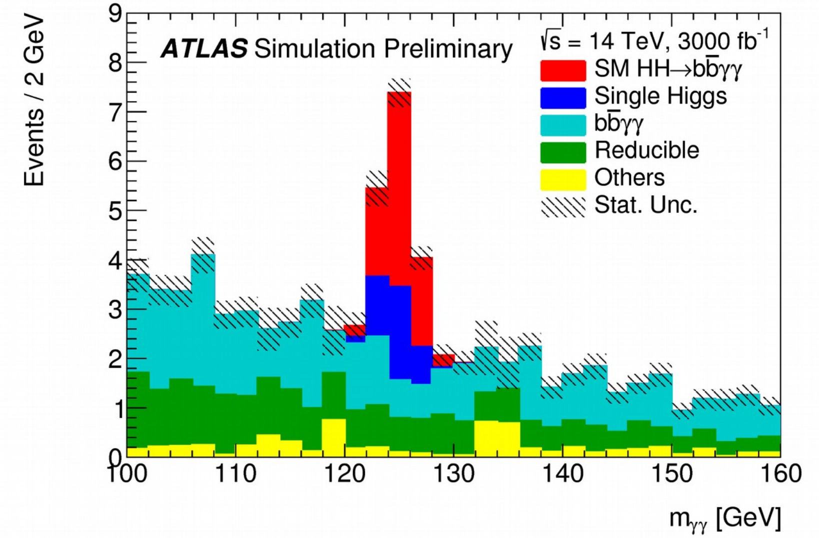


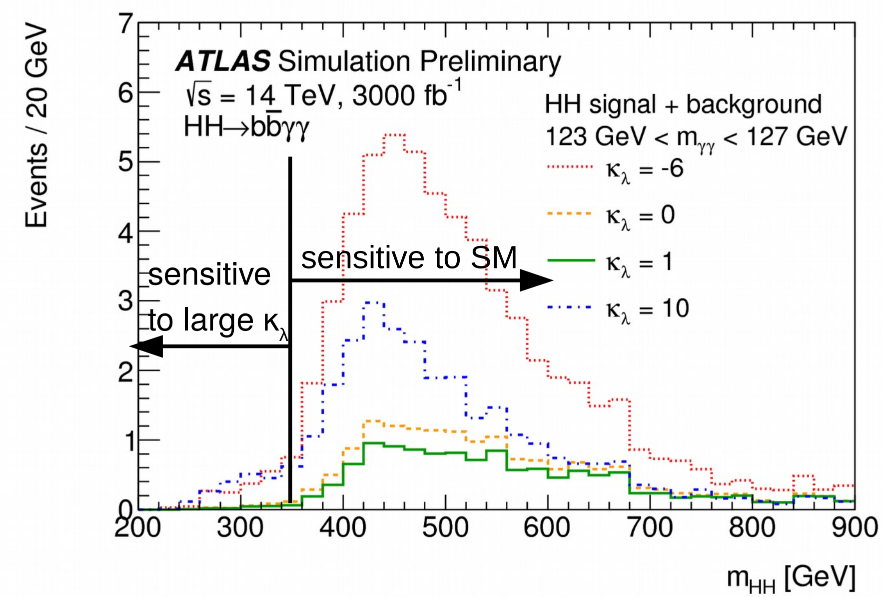
- Significance:
  - ATLAS: 2.5 wo/syst 2.1σ w/syst
  - CMS: 1.6σ wo/syst 1.4σ w/syst

HH → $b\bar{b}\gamma\gamma$

- ATLAS: dedicated BDT trained to remove continuum and main single-Higgs background ($t\bar{t}H$)
- CMS: dedicated BDT to reject $t\bar{t}H$ + BDT to reject continuum



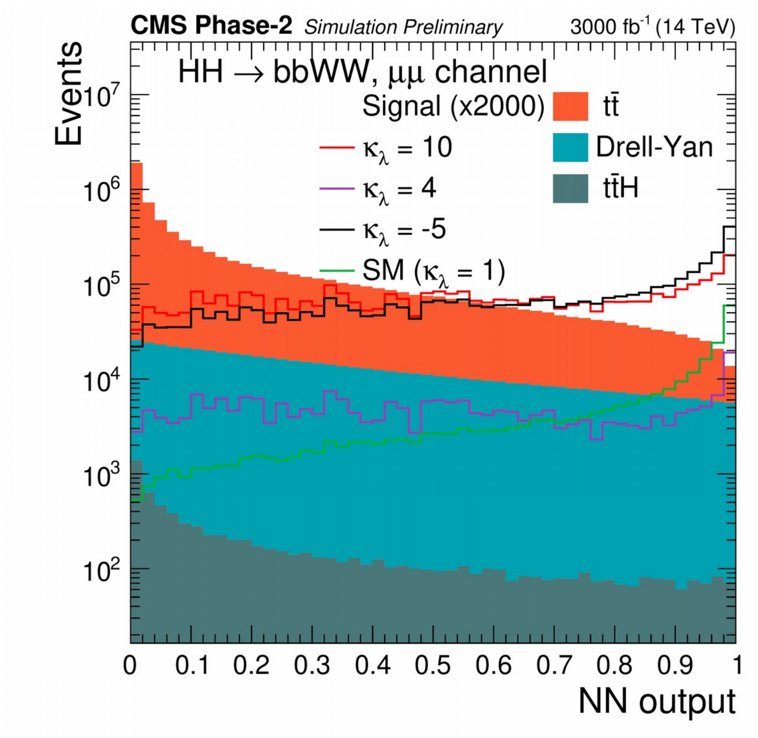




- Limit on κ_λ: use of $m_{b\bar{b}\gamma\gamma}$ categories
- Significance:
  - ATLAS: 2.1σ wo/syst 2.0σ w/syst
  - CMS: 1.8σ wo/syst 1.8σ w/syst
  - difference with partly due to $m_{\gamma\gamma}$ resolution

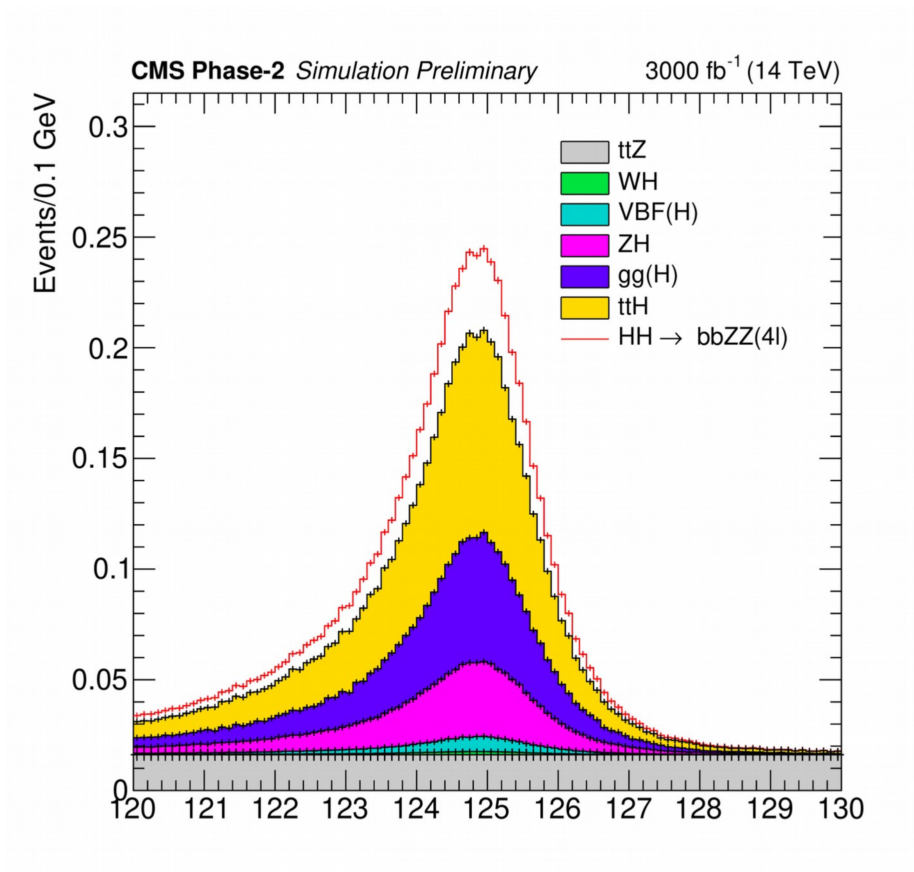
HH → b$\bar{b}$VV(lνlν) and HH → b$\bar{b}$ZZ(4l), CMS only

- HH → b$\bar{b}$VV(lνlν)
  - optimised on WW, but ZZ signal included for the results
  - Neural Network discriminant



- Results: 0.6σ significance

- HH → b$\bar{b}$ZZ(4ll)
  - very rare but clean final state
  - 1 signal event after selection



- Results: 0.4σ significance

Combined results (ATLAS)

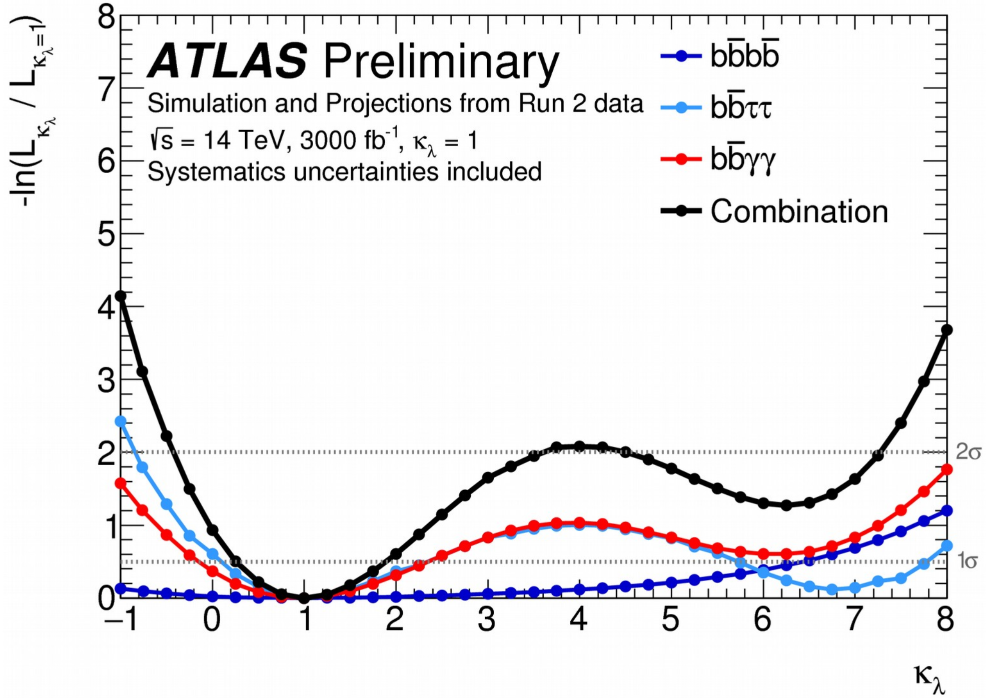
$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

- Expected significance with and without systematics
  - for SM:

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

- Measurement of μ (SM signal injected): ~30% (40%) without (with) systematics

- Maximum likelihood fits with and without systematics
  - extract limit on κ_λ at 95% CL: $-0.4 \le \kappa_\lambda \le 7.3$ with syst
  - extract measurement of κ_λ at 68% CL: $0.25 < \kappa_\lambda < 1.9$ with syst



Combined results (CMS)

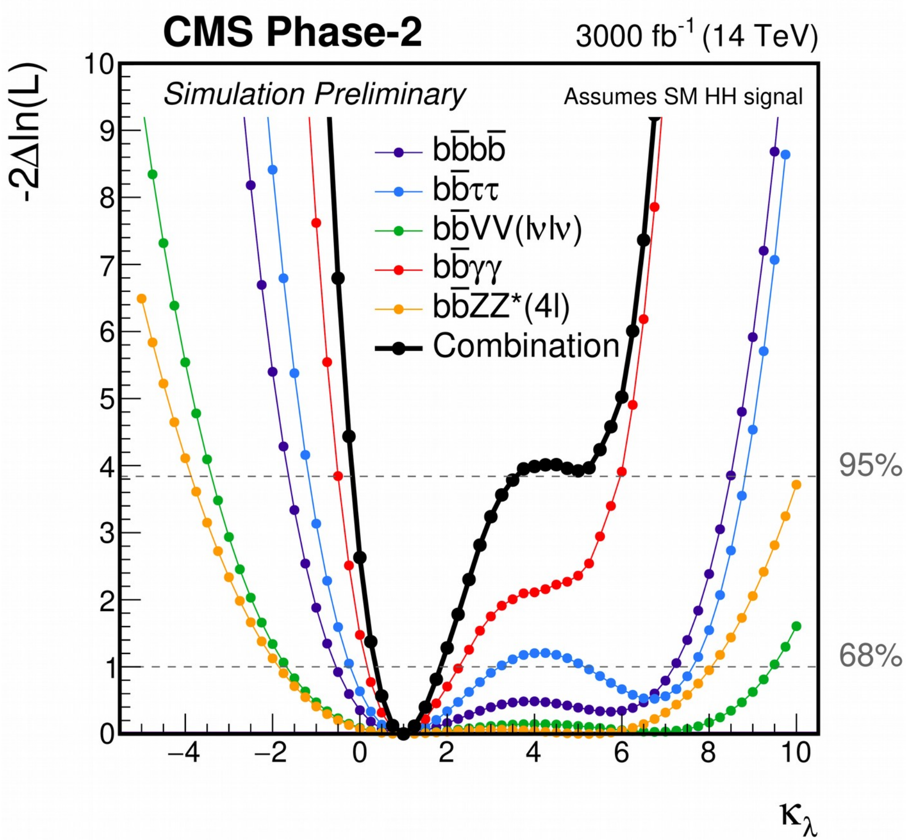
$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

- Expected significance with and without systematics
  - for SM:

Channel	Significance Stat. + syst.	Stat. only
bbbb	0.95	1.2
$bb\tau\tau$	1.4	1.6
$bbWW(\ell\nu\ell\nu)$	0.56	0.59
$bb\gamma\gamma$	1.8	1.8
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37
Combination	2.6	2.8

- Measurement of μ (SM signal injected): ~40% (36%) without (with) systematics

- Maximum likelihood fits with and without systematics
  - extract limit on κ_λ at 95% CL: $-0.18 \le \kappa_\lambda \le 3.6$ with syst
  - extract measurement of κ_λ at 68% CL: $0.35 < \kappa_\lambda < 1.9$ with syst

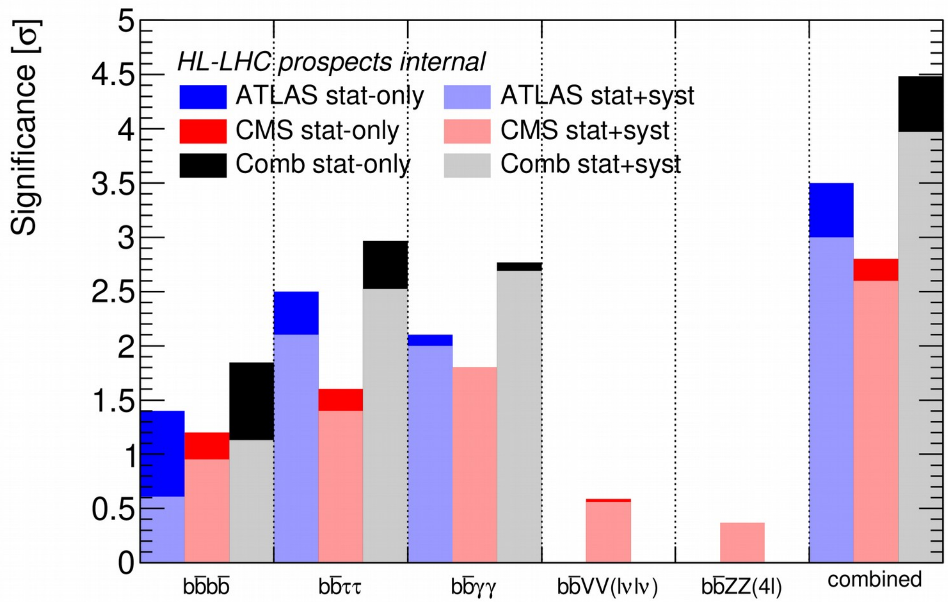


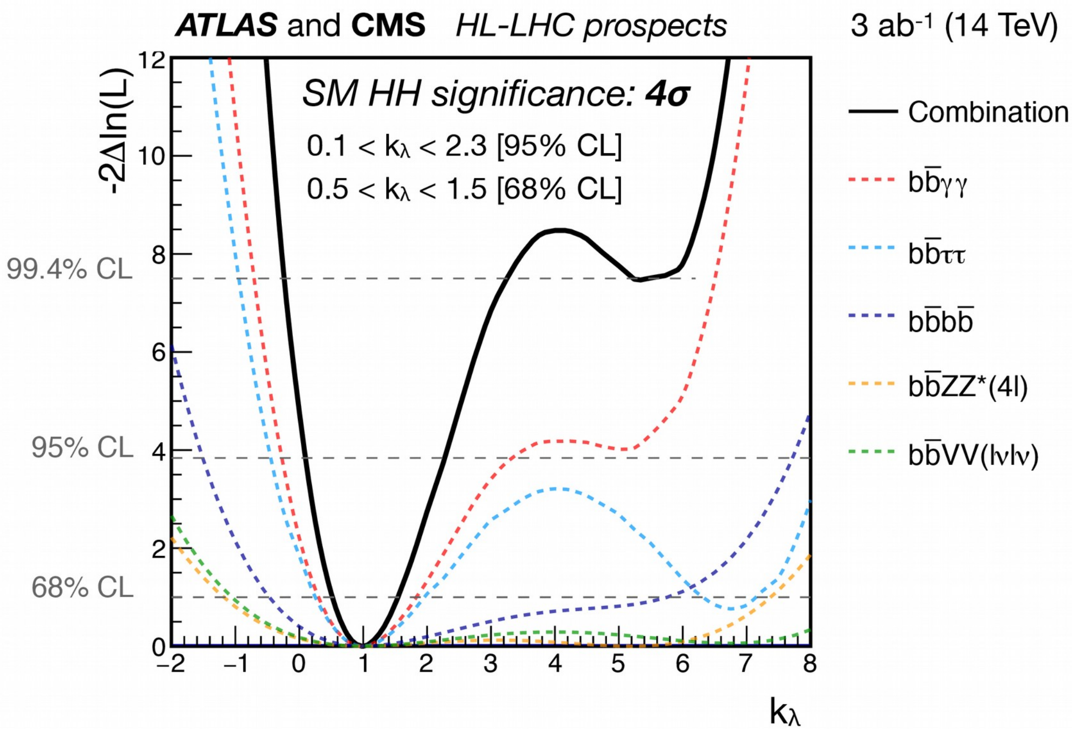
Combined results (ATLAS+CMS)

$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

- Combined values channel-by-channel
  - no correlation considered (shown to have negligible impact)
  - systematic uncertainties included
  - $b\bar{b}VV(l\nu l\nu)$ and $b\bar{b}ZZ(4l)$ are CMS only ⇒ scaled to 6000 fb^{-1}

- Combined significance: 4.5/4.0σ without/with systematics



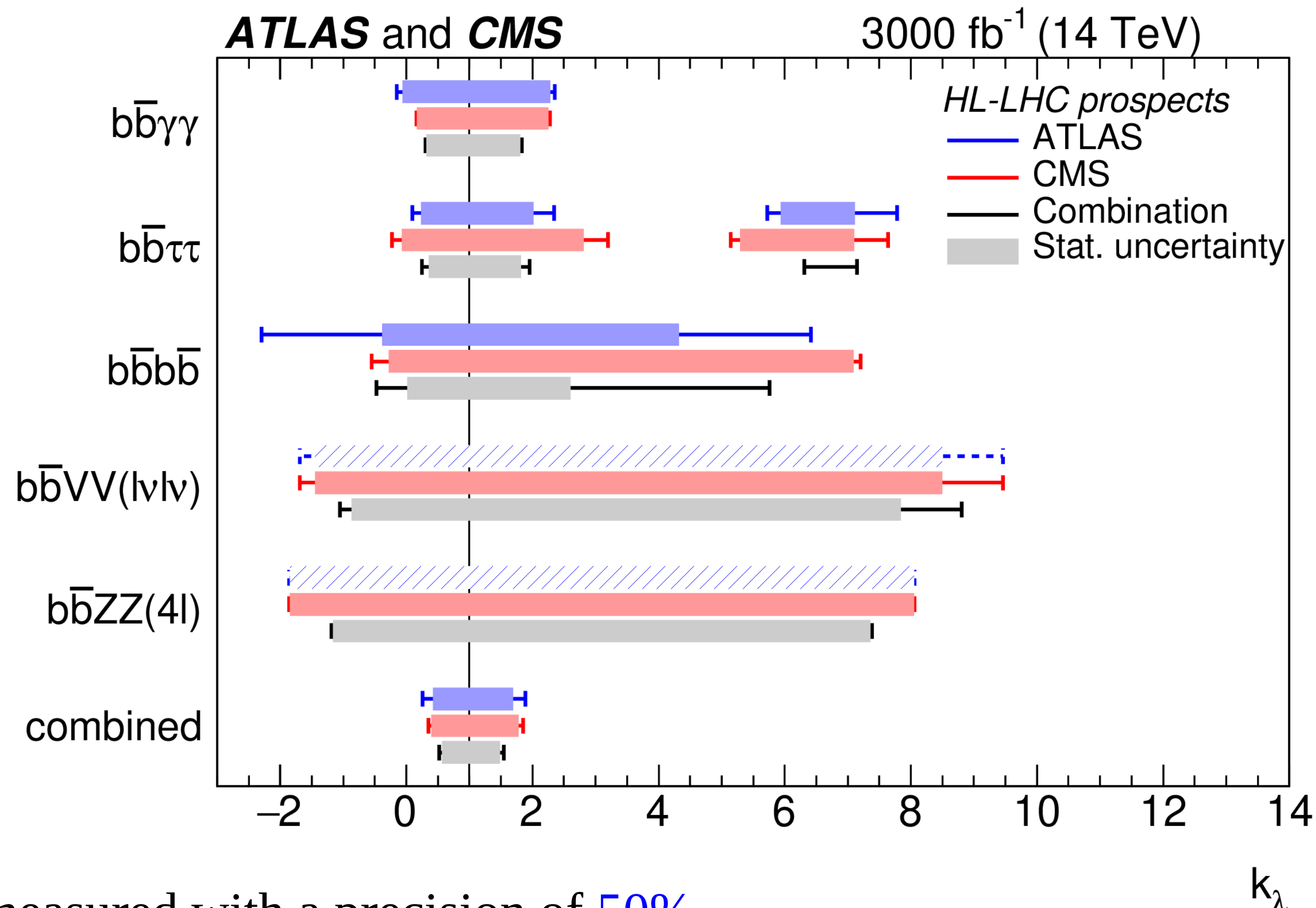


- κ_λ measured with a precision of 50%
  - second minimum excluded at 99.4% CL

Combined results (ATLAS+CMS)

$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

- 68% CI, channel by channel
- Dashed line = no ATLAS analysis, using value from CMS

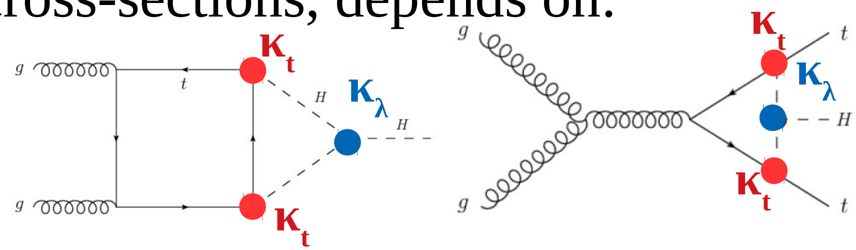


- κ_λ measured with a precision of 50%
  - many channels limited by statistics

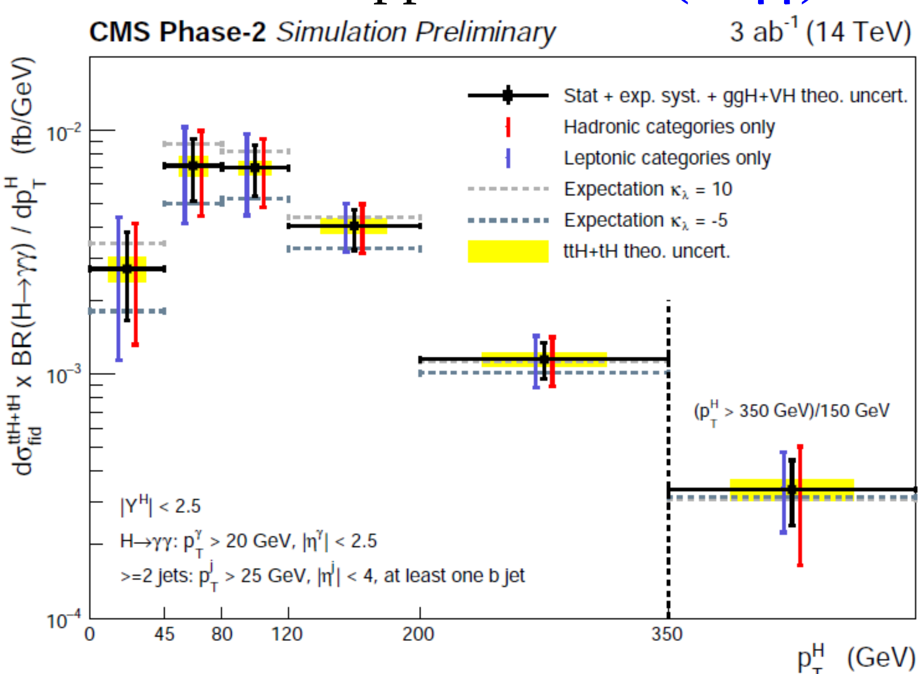
Indirect probes via single-Higgs (1)

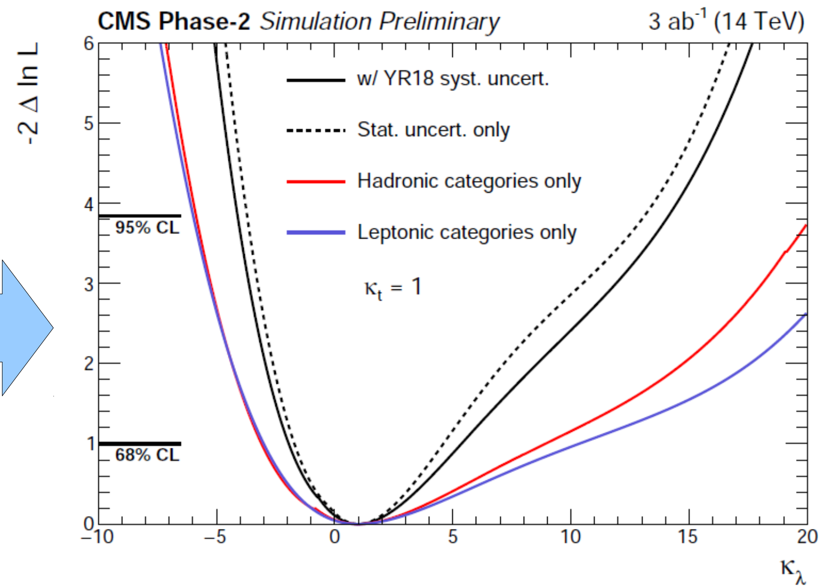
$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

- Single-Higgs production: Higgs self-interaction only via one-loop corrections (ie two loop-level for ggF)
- κ_λ-dependent corrections to the tree-level cross-sections, depends on:
  - production mode → mainly $t\bar{t}H$, tH, VH
  - kinematics properties of the event



- Method applied to $t\bar{t}H(\rightarrow\gamma\gamma)$ differential cross-section measurement:



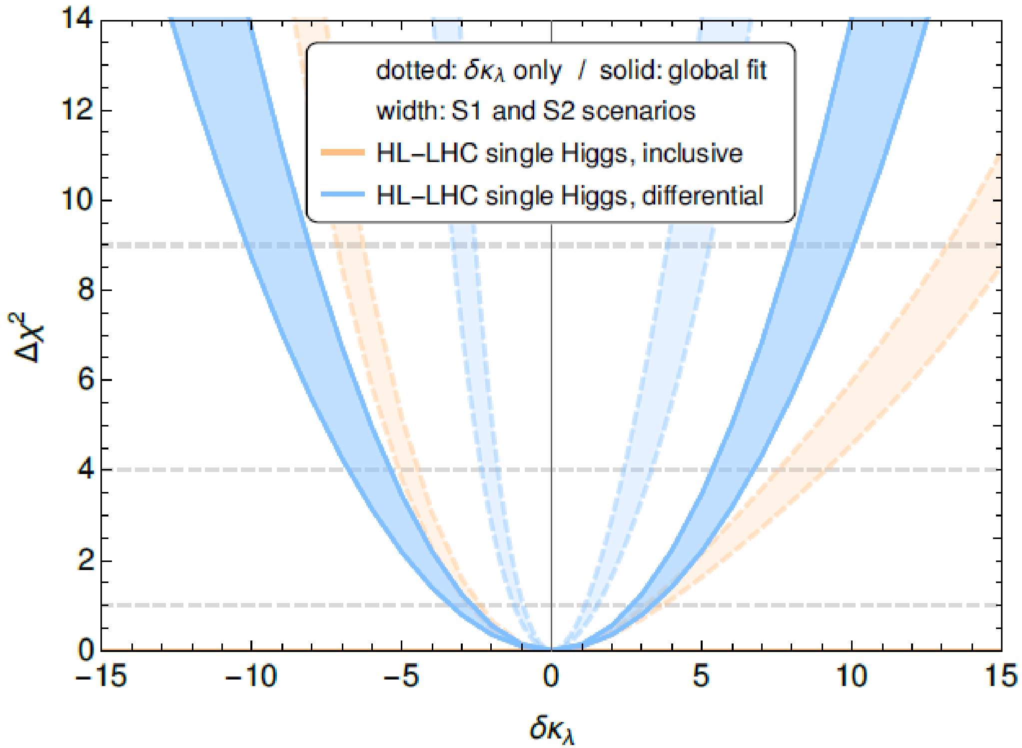


- 68% CI: $-1.9 < \kappa_\lambda < 5.3$ if only κ_λ varied
- First test with experimental "data", more channels to be added

Indirect probes via single-Higgs (2)

$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

- Global fits of single-Higgs inclusive couplings and $t\bar{t}H$ differential measurements



- Different BSM scenarios
  - only κ_λ can be varied (dotted line)
  - EFT framework (solid line)
- Different scenarios for systematics (bands)
- Biggest impact from diff. cross-section
- Improvement of di-Higgs direct measurements (for variations of κ_λ only)
- HL-LHC: 68% CI (optimistic systematics):
  - $-0.1 < \kappa_\lambda < 2.3$ if only κ_λ varied
  - $-2 < \kappa_\lambda < 3.9$ for global fit

Conclusions on HL-LHC studies

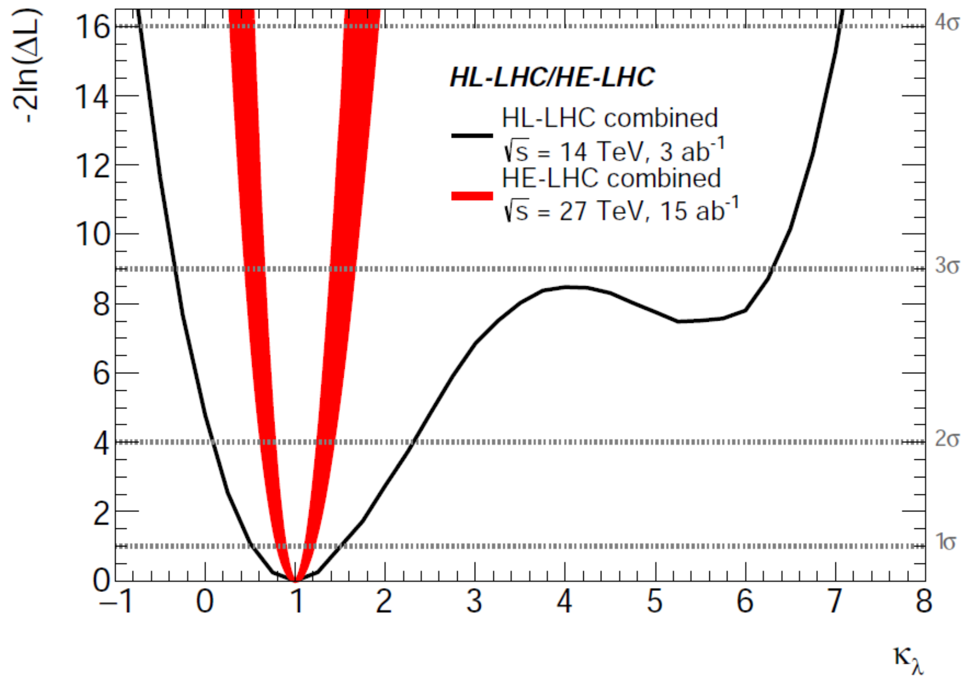
- State-of-the art experimental studies on direct measurements
  - coherent results by ATLAS and CMS
  - went from ~2σ last year to a combined significance of 4σ!
  - first real measurements possible, eg precision on κ_λ: 50%
  - much room for improvement
- Some ideas collected to improve the Run-2 measurements
- Realistic systematic uncertainties from current knowledge
  - still margin from improvement: data-driven background estimates, data-driven constrains on single-Higgs (eg ggF+ 2 b-jets), etc
- Interesting developments on indirect constrains
  - single-Higgs differential cross-sections, global fits
- All Higgs physics at HL-LHC and HE-LHC in the Yellow Report (1902.00134)

Summary and comparison to future colliders

HE-LHC results

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda^{SM}_{HHH}}$$

- Extrapolation of HL-LHC results to HE-LHC
  - scale cross-section to 27 TeV (*4) and luminosity to 15 ab^{-1} (*5)
  - no systematic uncertainties included
- $b\bar{b}\tau\tau$ channel: significance: 10.7σ, precision on κ_λ: 20%
- $b\bar{b}\gamma\gamma$ channel: significance: 7.1σ, precision on κ_λ: 40%
  - pessimistic because analysis not optimised for measurement of κ_λ
  - theory study in the YR claim 15% precision on κ_λ
    - realistic detector performance
    - no pile-up considered (μ=800-1000)
    - interesting categorisation of b-jets

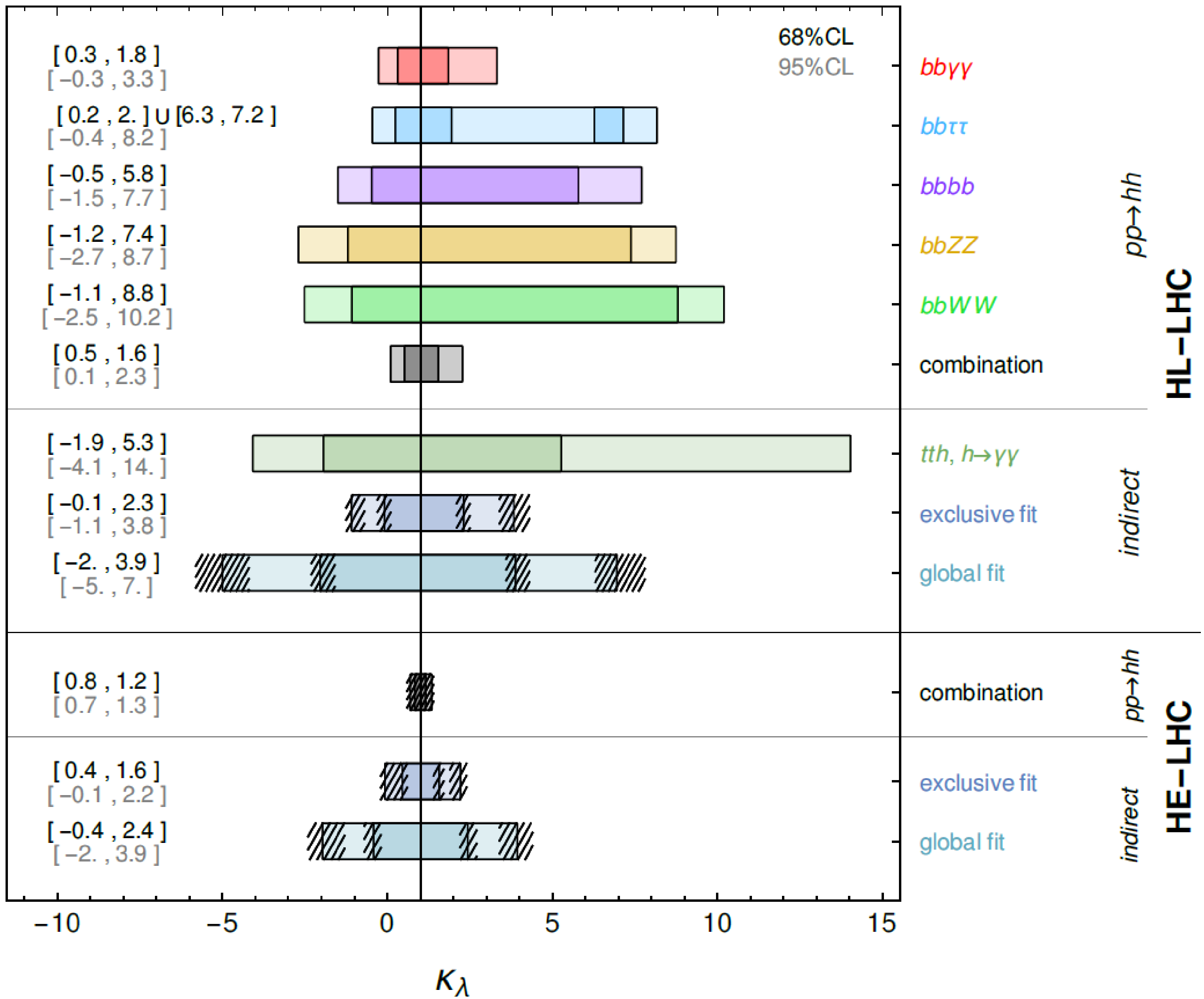


- κ_λ could be measured with an uncertainty of 10 to 20 %
  - without uncertainties
  - effect of pile-up?
  - contribution of ggF+jets?

Summary of HL(HE)-LHC prospects

$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

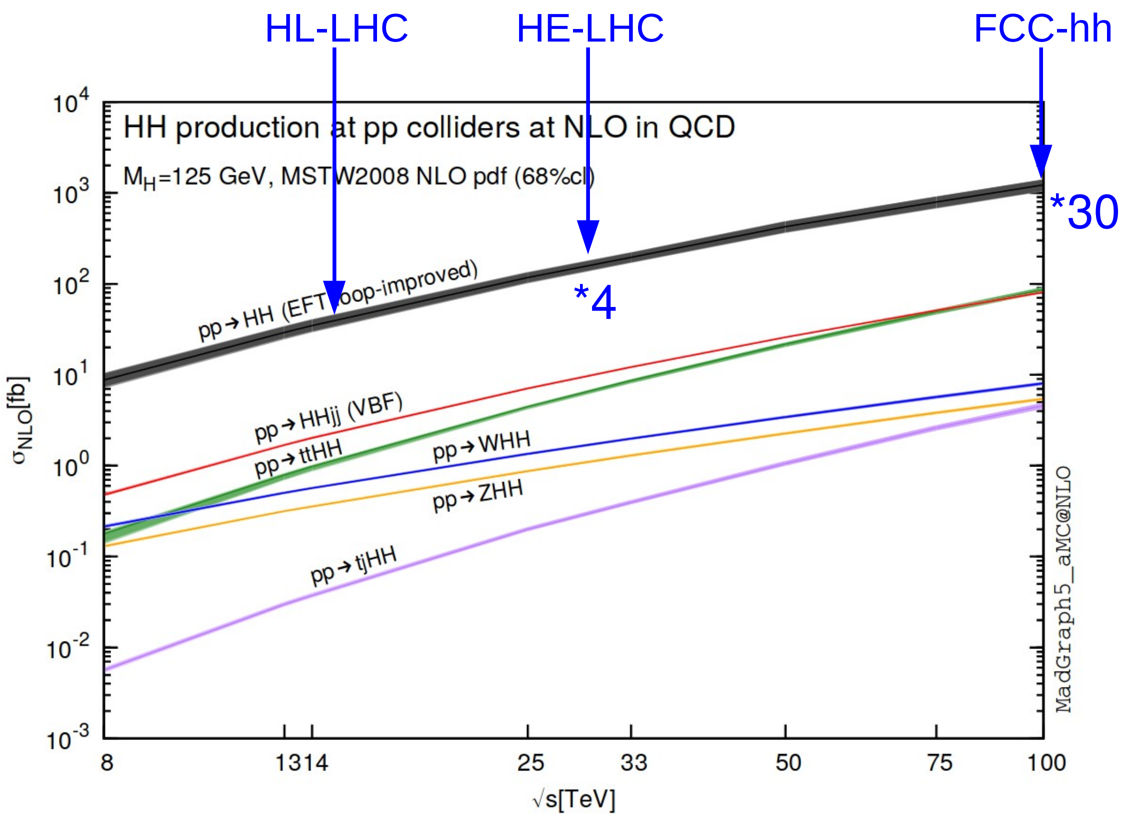
- Nice summary plot in the Yellow Report:



Comparison to future colliders (1)

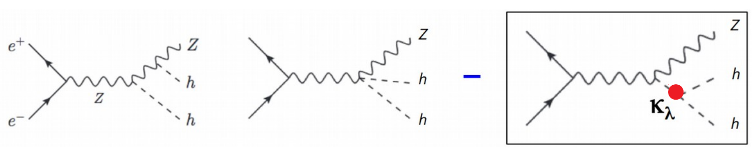
- pp circular colliders:
  - HE-LHC: $\sqrt{s}$ = 27 TeV, 15 ab^{-1}
  - FCC-hh: $\sqrt{s}$ = 100 TeV, 30 ab^{-1}

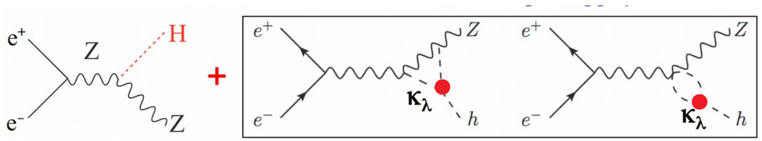
- ggF production increases quickly with energy
  - but κ_λ mostly affecting m_{HH} near threshold



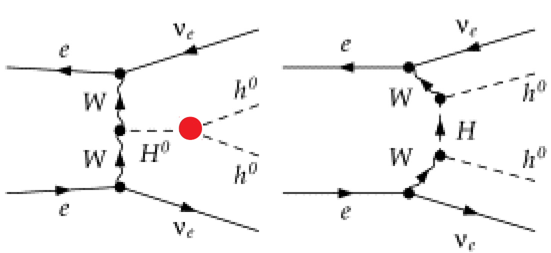
Comparison to future colliders (2)

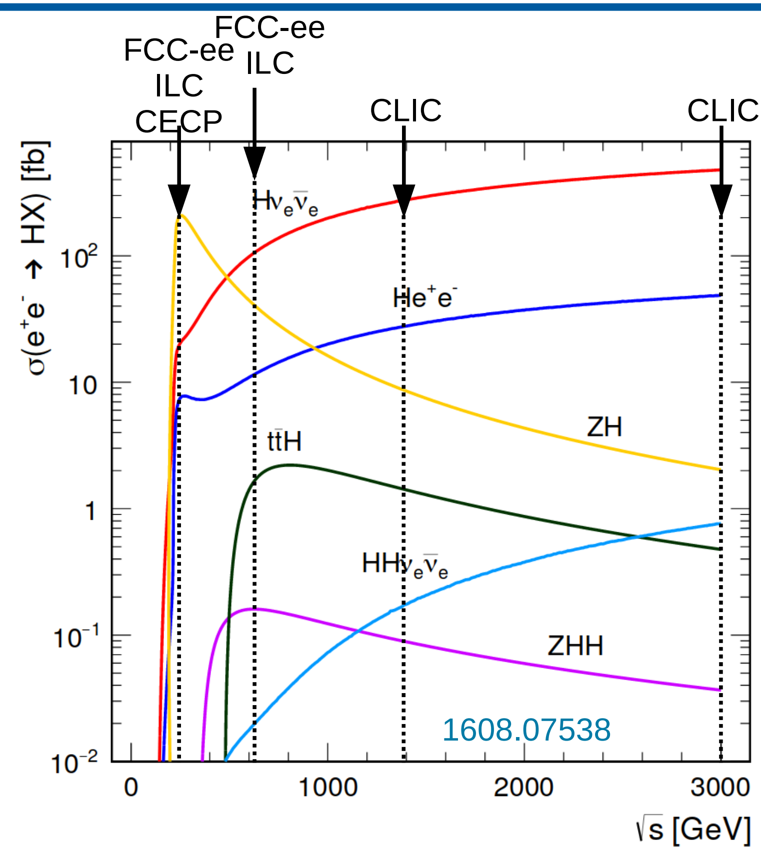
- ee colliders:
  - linear: ILC, CLIC
  - circular collider: FCC-ee, CEPC
- Di-Higgs production with ee colliders:
  - ZHH
    - direct and indirect
    - stronger constraints for $\kappa_\lambda > 0$

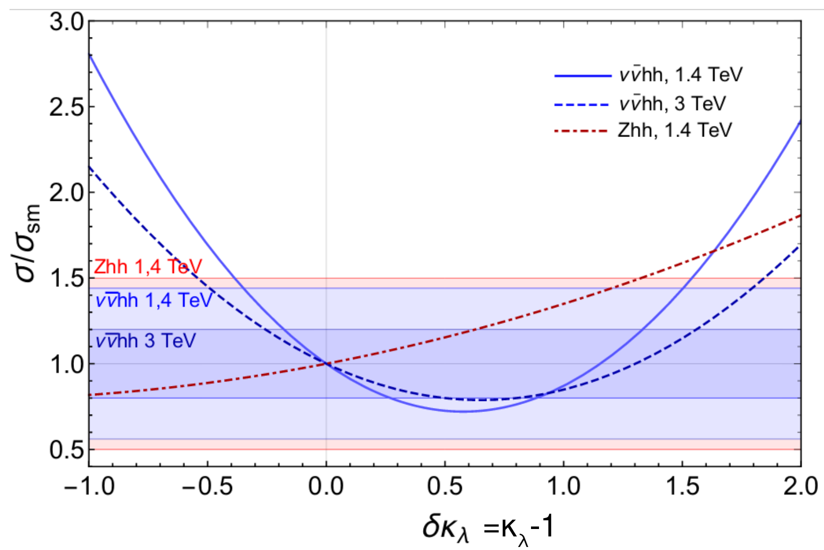




  - $\nu\bar{\nu}$HH
    - stronger constraints for $\kappa_\lambda > 0$



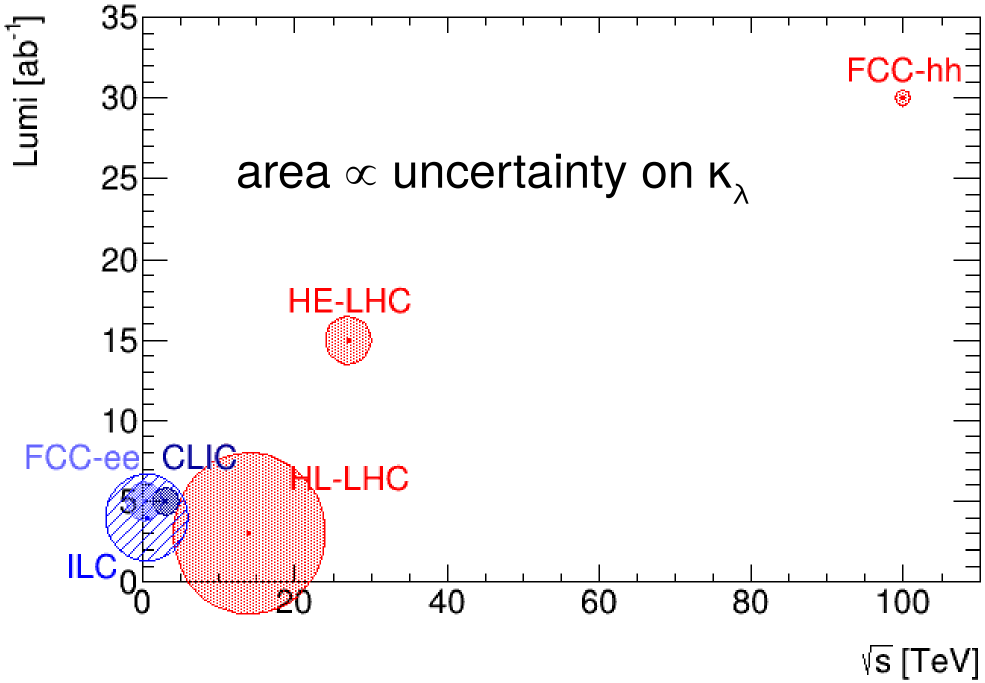


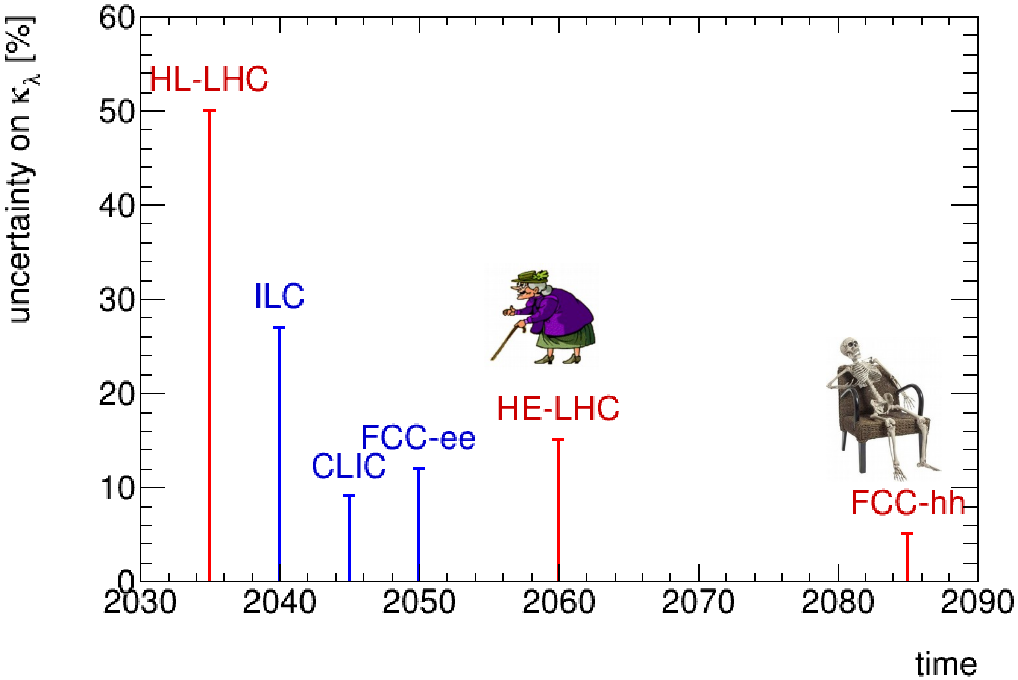


Comparison to future colliders (3)

- Uncertainty on κ_λ vs $\sqrt{s}$, luminosity, time:
  - ee colliders, pp colliders

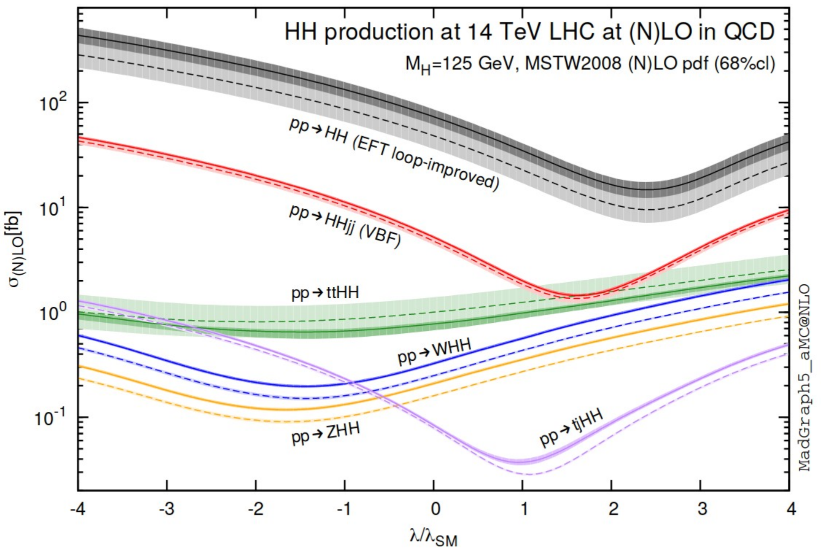
- NB: not official plots, personal collections of results





Conclusion

- Run-2 data:
  - mainly aiming for resonant production
  - first methods developed
  - current sensitivity: ~10*SM
- HL-LHC:
  - expected significance: 4σ
  - κ_λ measured with precision of 50%
- Room for improvement
  - systematic uncertainties
  - more sophisticated methods
  - more channels
  - indirect contraints (in particular for Run-3)

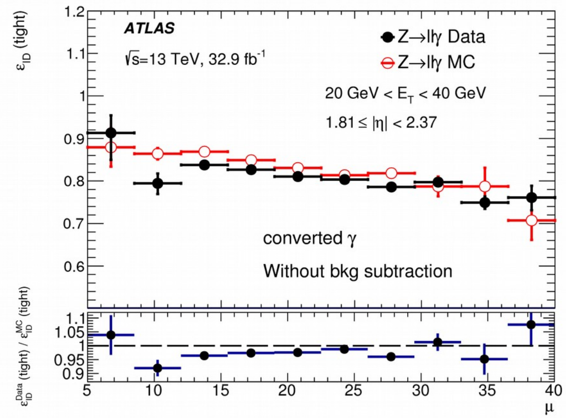


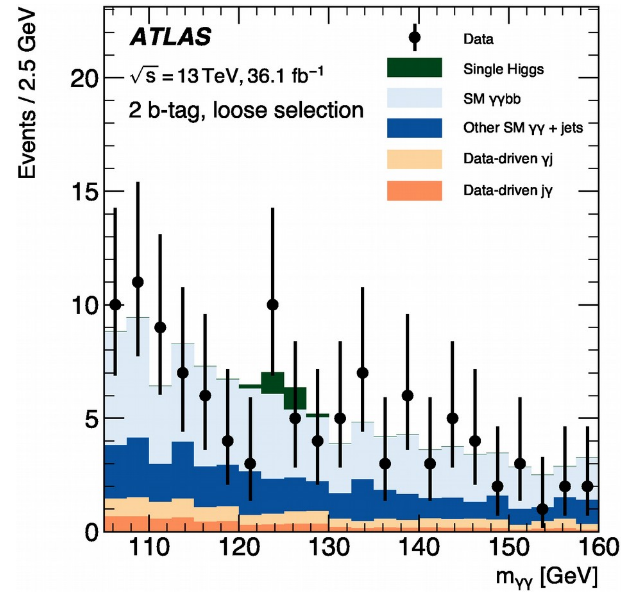
- Tri-linear couplings also studied in future colliders
  - CERN Council Open Symposium on the Update of European Strategy for Particle Physics: 13/16 May, Granada (Spain)

Back-up

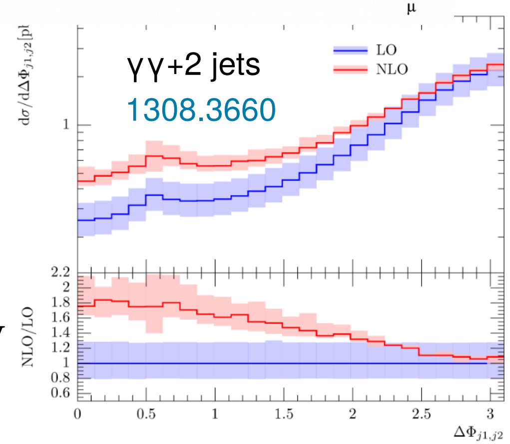
HH → b$\bar{b}$γγ: from Run2 to Run3 to Run4

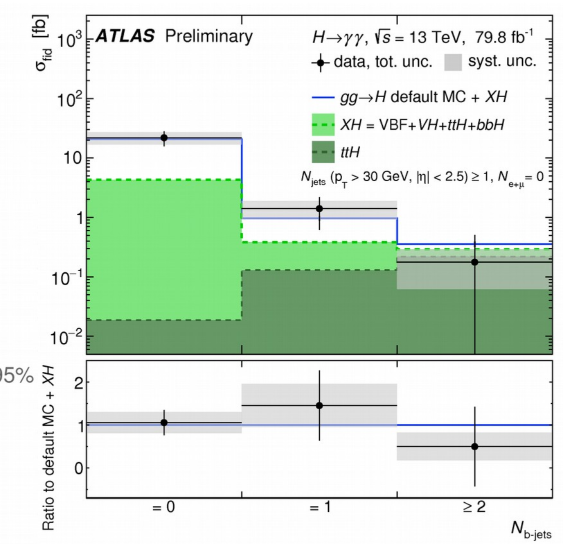
- Performance vs pile-up
  - photon calibration
  - photon identification
  - b-tagging



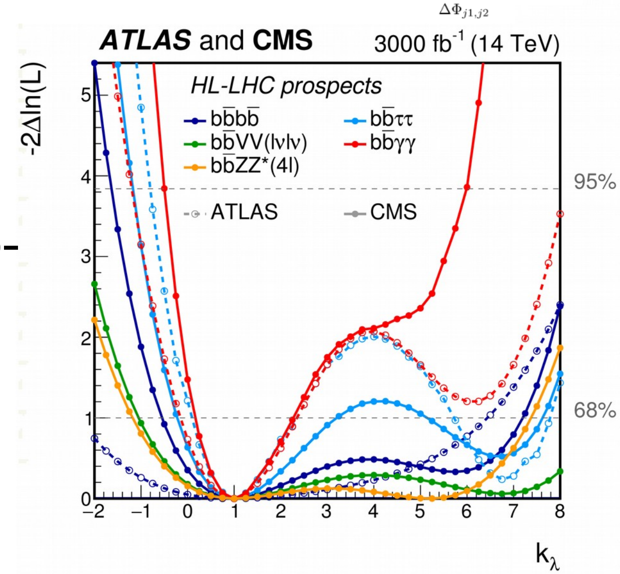


- Understanding the backgrounds
  - bbγγ: up to a factor 2 data/MC normalisation discrepancy
  - fakes
  - single-Higgs: 100% uncertainty on ggF+ b-jets production





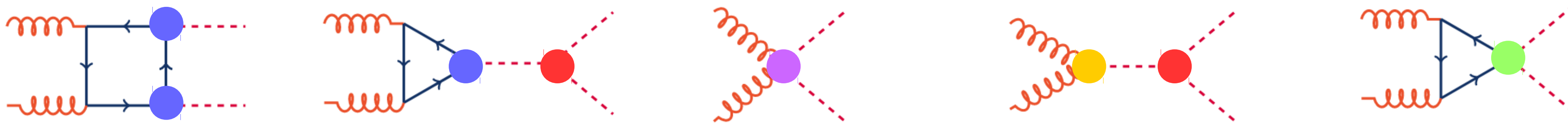
- Improvements of analysis
  - very photon-oriented so far, extract more information from b-jets
  - previous focus on resonant, present focus on non-resonant SM, future focus on κ_λ measurement



EFT approach

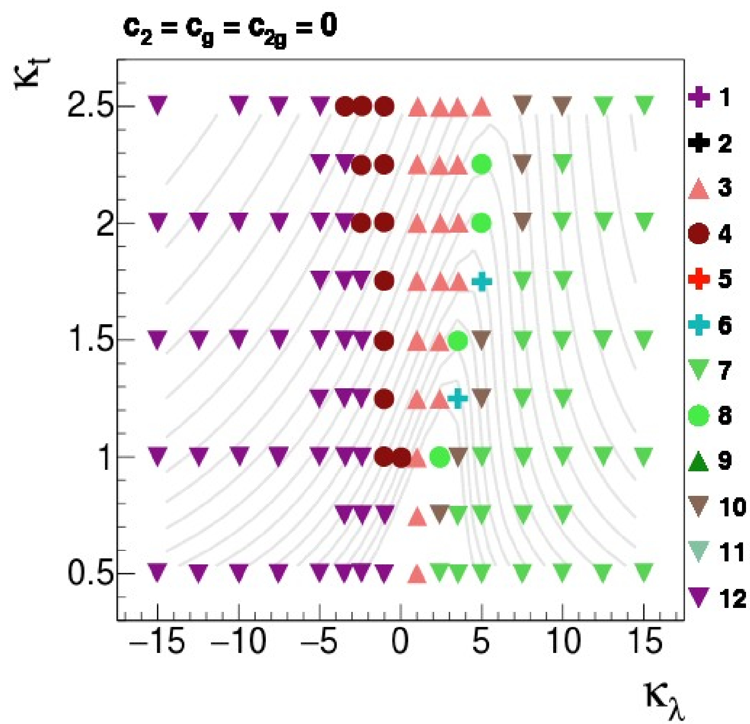
- From JHEP04(2016)126

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}\left(v + \kappa_t h + \frac{c_2}{v} h h\right)(\bar{t}_L t_R + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g h - \frac{c_{2g}}{2v} h h\right) G^{\mu\nu} G_{\mu\nu}$$



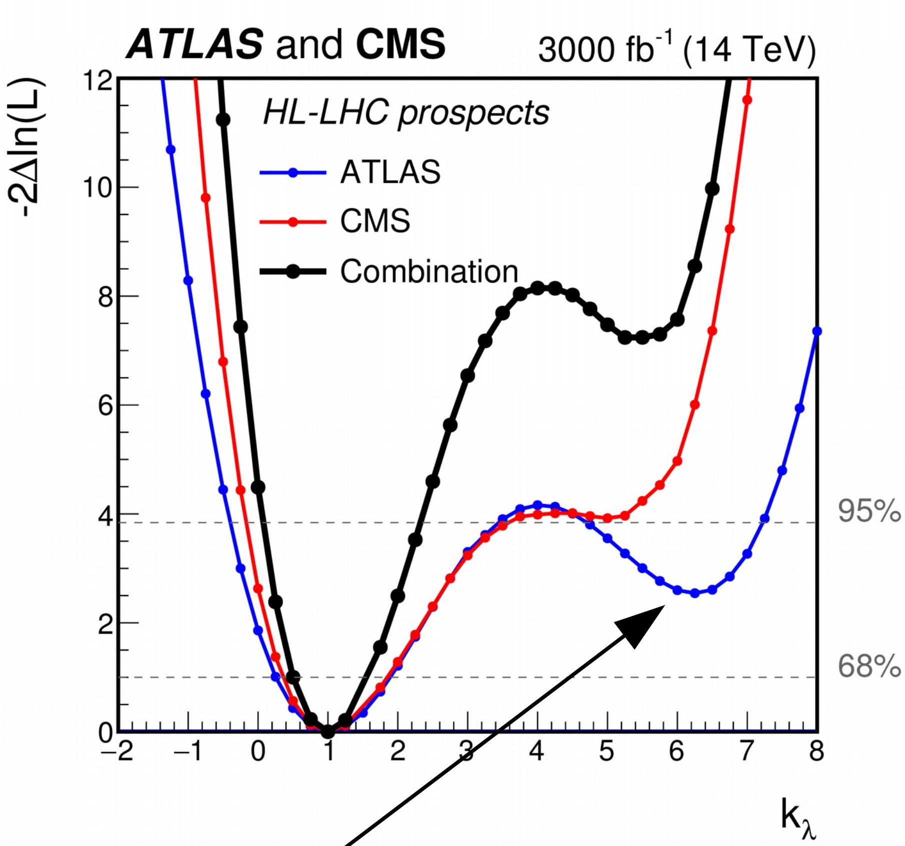
- 12 benchmark points:

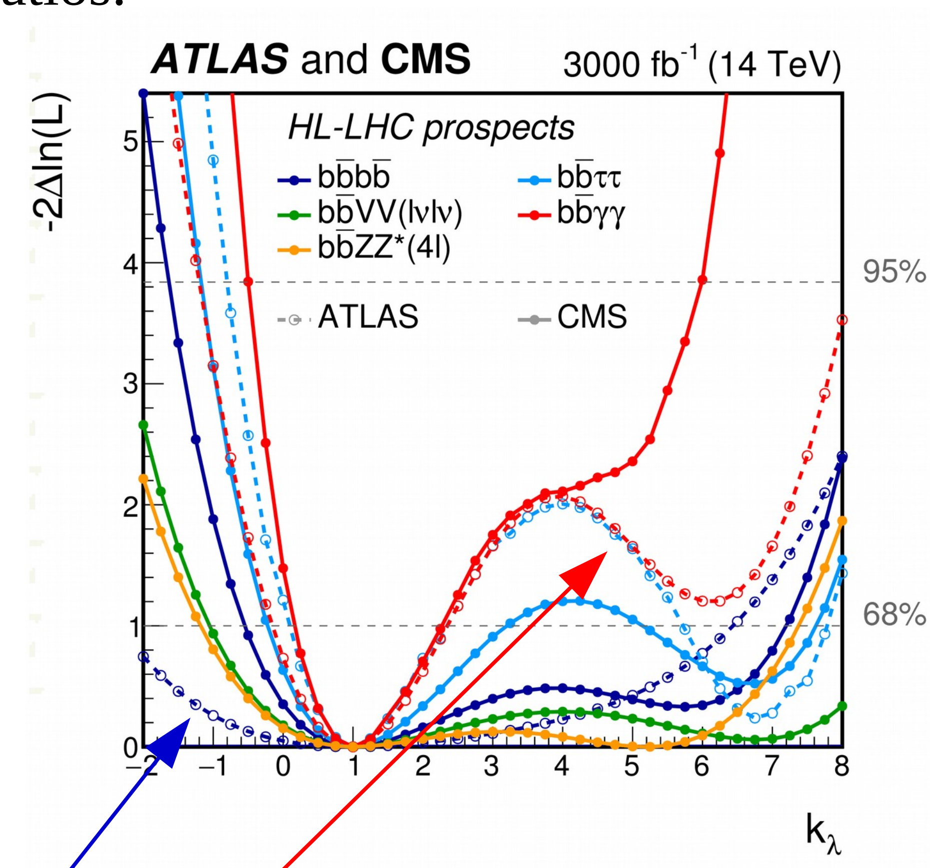
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0



Combined results (ATLAS+CMS)

- Comparison of negative log-likelihood ratios:

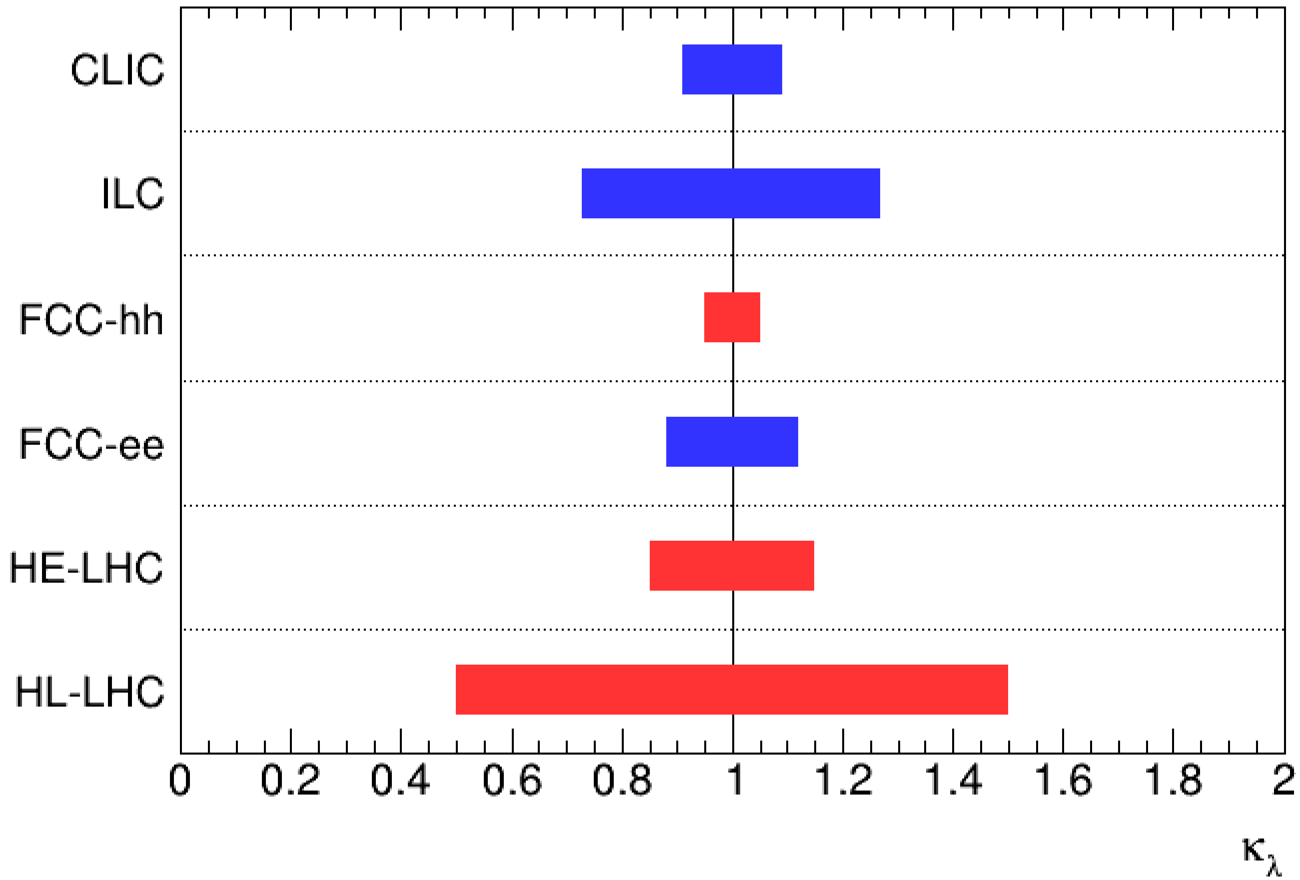




- Difference on 2nd minimum mainly from the $b\bar{b}\gamma\gamma$ channel: 3 categories of m_{HH} (especially a low-m_{HH} one) to remove the degeneracy around κ_λ=6 (while this low-m_{HH} category has no effect around 1)
- CMS slightly better below 1: $b\bar{b}b\bar{b}$ + other smaller channels

Future colliders

- Uncertainty on κ_λ:



Prospects for Higgs couplings

- Extrapolation of Run-2 results, ATLAS+CMS