Pythagore , Portail Royal, Chartres

Higgs self-coupling: *Experimental vision*

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on behalf of the ATLAS and CMS collaborations

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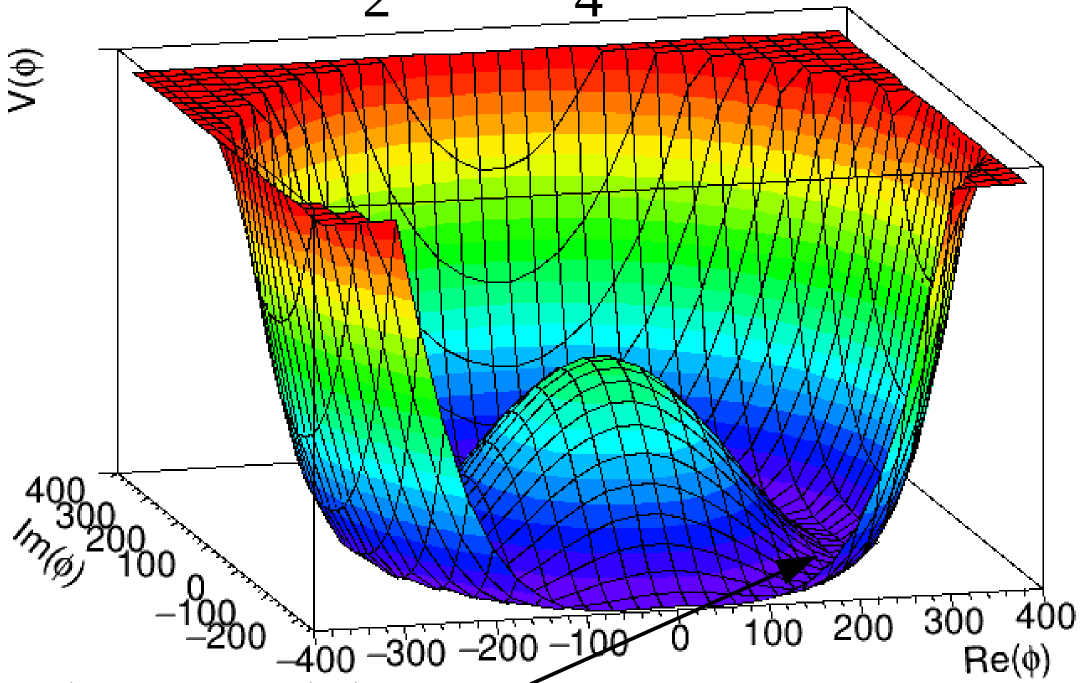
Ultimate Precision at Hadron Colliders
2nd of December 2019

CMS
ATLAS EXPERIMENT

Introduction

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



- Approximation around the v.e.v:

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

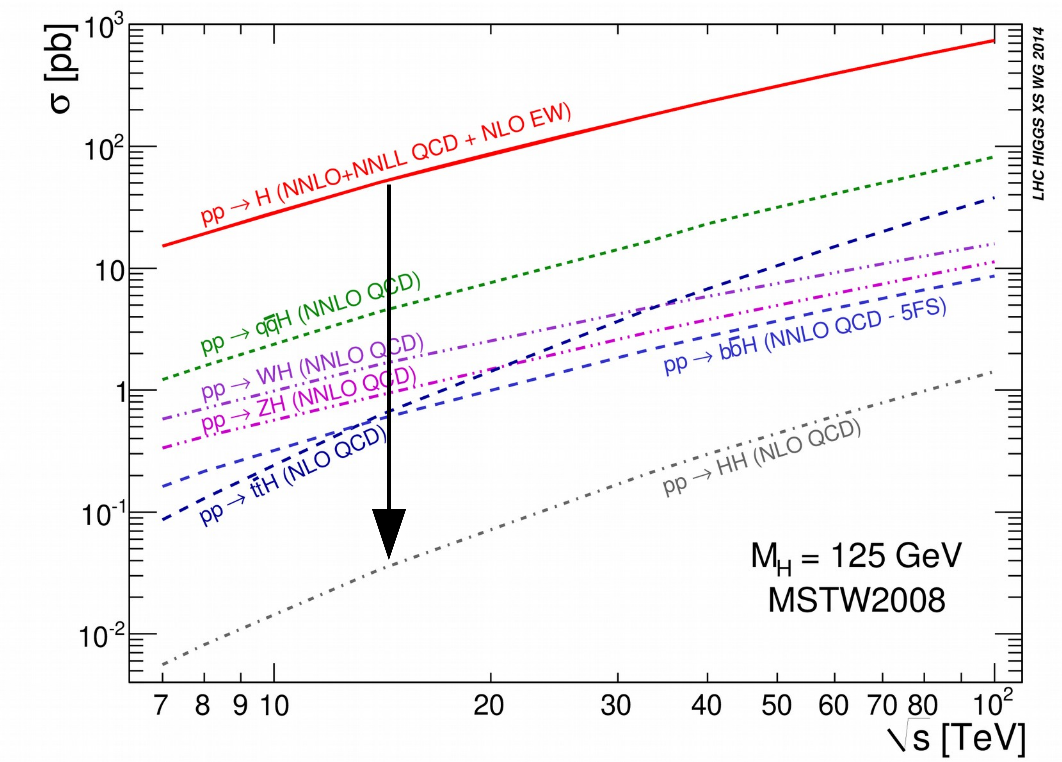
mass term self-coupling terms

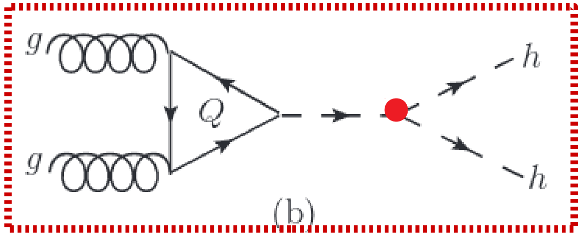
- λ known from v.e.v and Higgs mass: $\lambda = \frac{m_H^2}{2 \cdot v^2} \approx 0.13$
- BSM effects could change $\lambda \Rightarrow$ define deviation of tri-linear term: $\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$
  - no quartic terms considered here

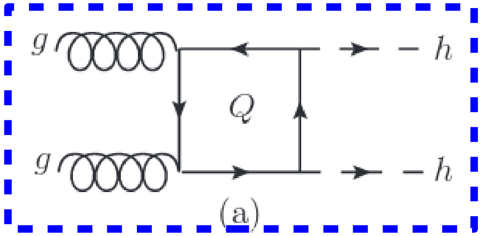
Self-couplings through di-Higgs measurements

Di-Higgs production at hadronic colliders (1)

- Main production mode: ggF
- Rare process of the Standard Model
  - destructive interference between triangle and box diagrams
  - σ(HH)/σ(H) = 0.1%



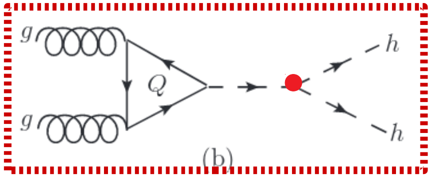


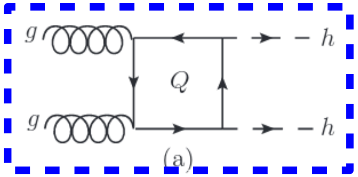


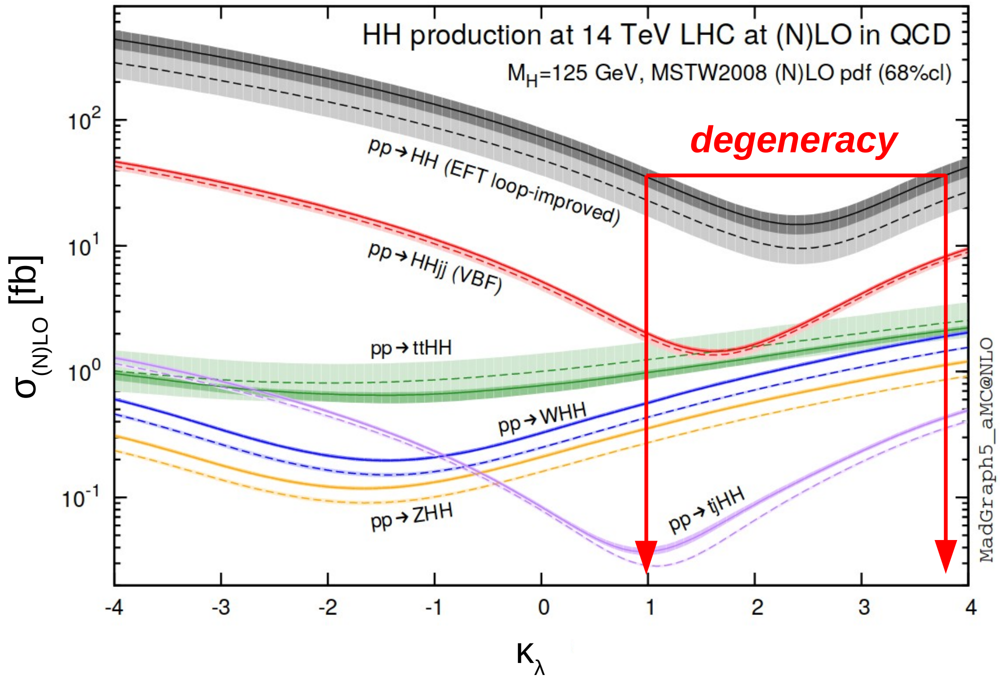
- For those results, state of the art NNLO calculation with finite m_t effects at NLO
  - -8% wrt Yellow Report 4, used in previous projections

Di-Higgs production at hadronic colliders (2)

- Self-couplings through
  - total HH cross section
  - differential cross section $d\sigma/dm_{HH}$







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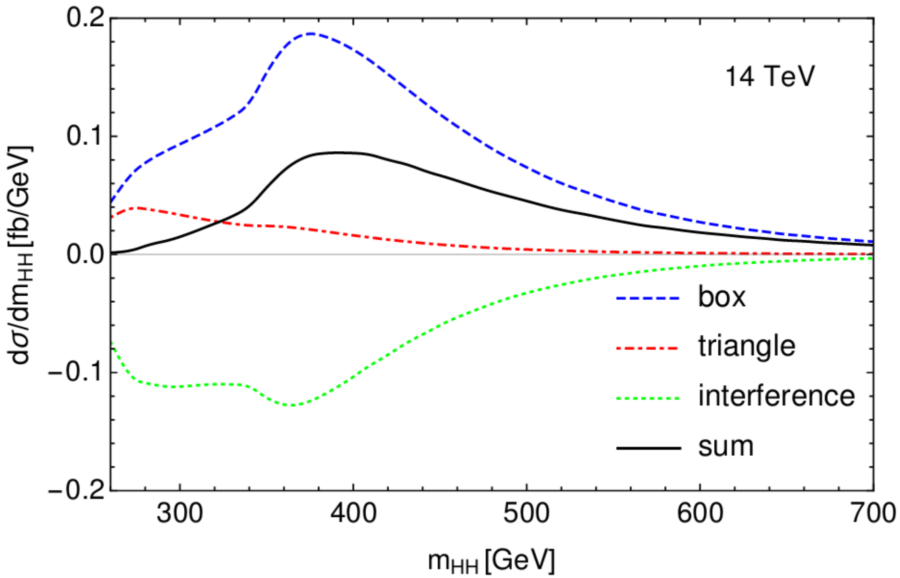
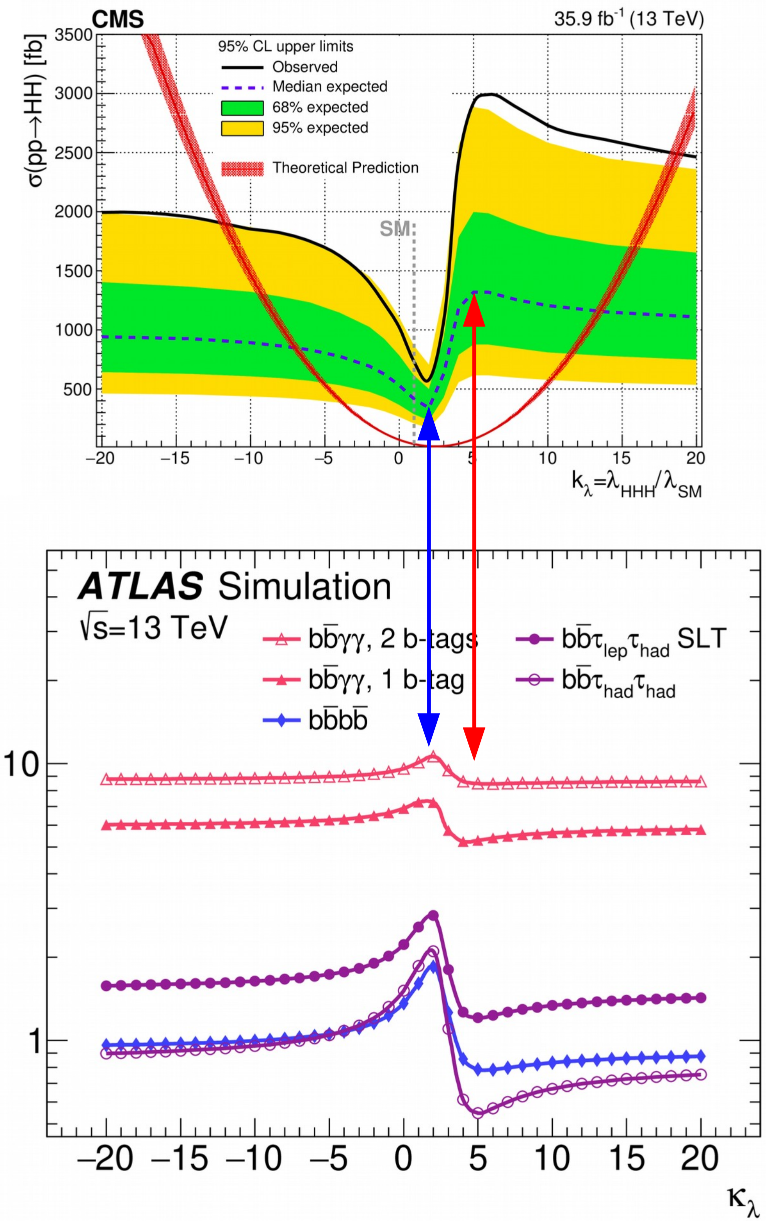
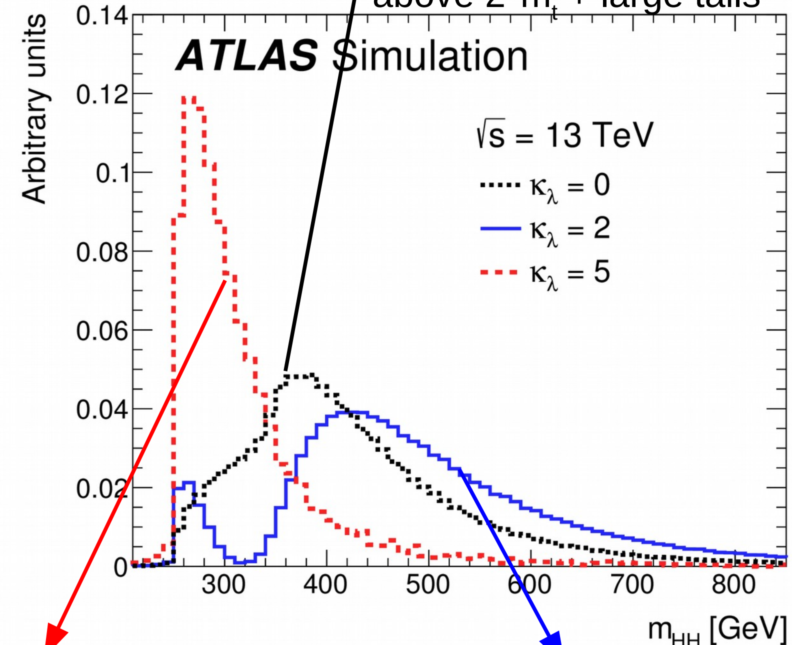


LHCHXSWG-2019-005

Di-Higgs production at hadronic colliders (3)

- Sensitivity to κ_λ directly related to the acceptance, so to the m_{HH} shape





κ_λ=0: no triangle ⇒ increase of cross-section above 2*m_t + large tails

κ_λ=5: interference at high m_{HH} ⇒ soft spectrum

κ_λ=2: max interference ⇒ deficit between 2*m_H and 2*m_t + large tails

$|\kappa_\lambda|$>10: trilinear dominant ⇒ peaks at 2*m_H

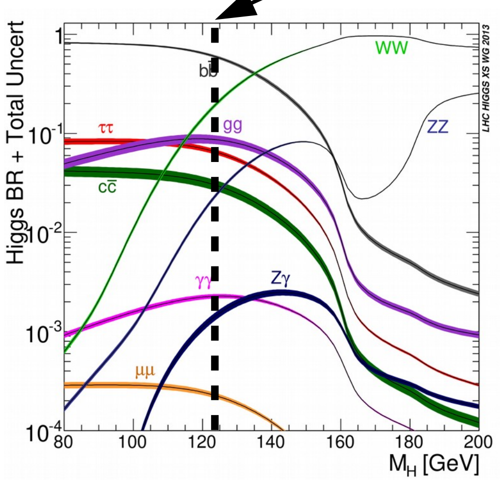
- NB: most analyses optimised for κ_λ=1

HH decays

- Many decay channels!

CERN seminar, 13th of Dec. 2011

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



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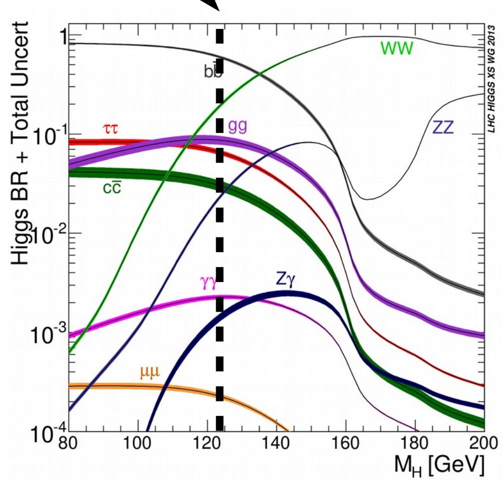

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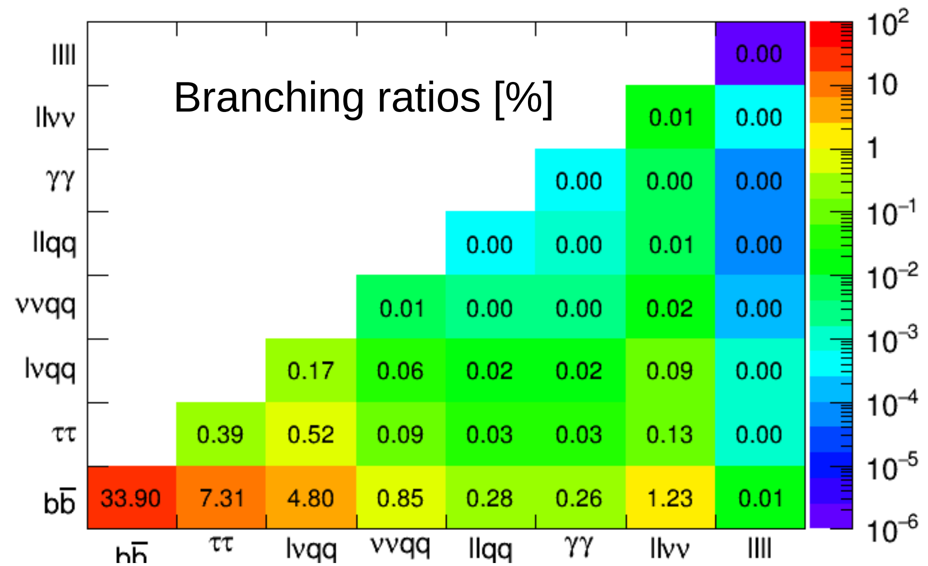
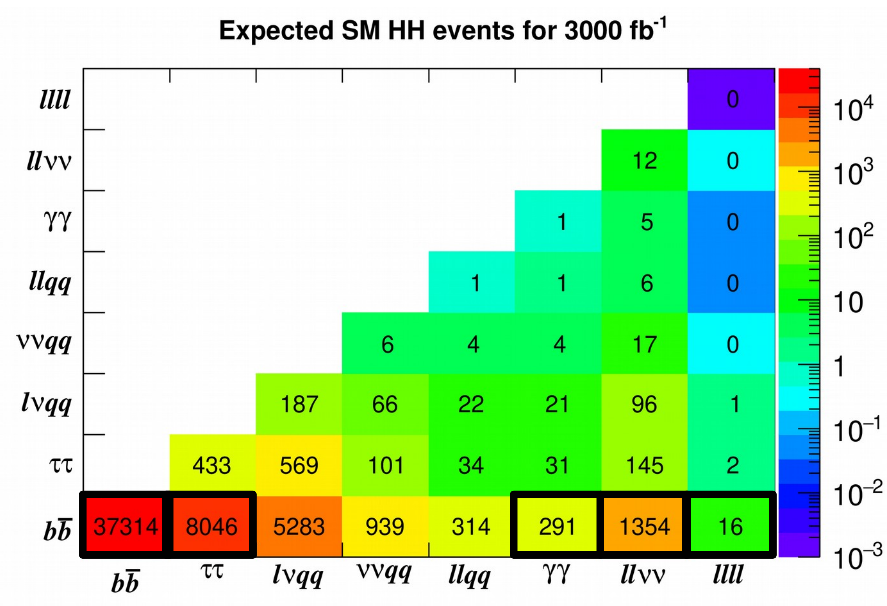


- In practice consider channels with $b\bar{b}$ (BR = 59%) to maximise the rate

Di-Higgs search, introduction

- Summary of channels/methods for HL-LHC studies:

	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric	Very small BR ☹ Very small bkg ☺

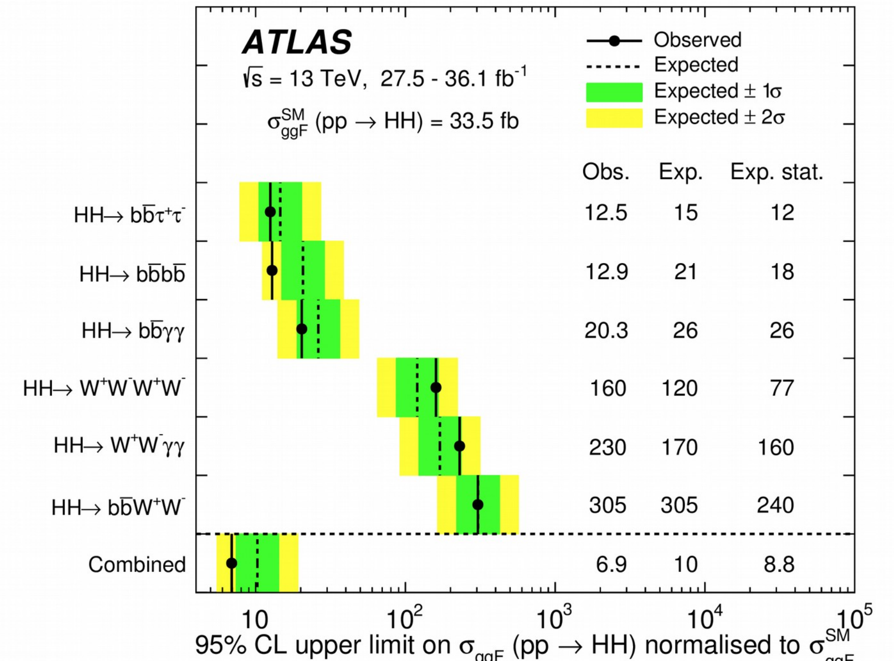


- Benefit from performance work of Technical design reports

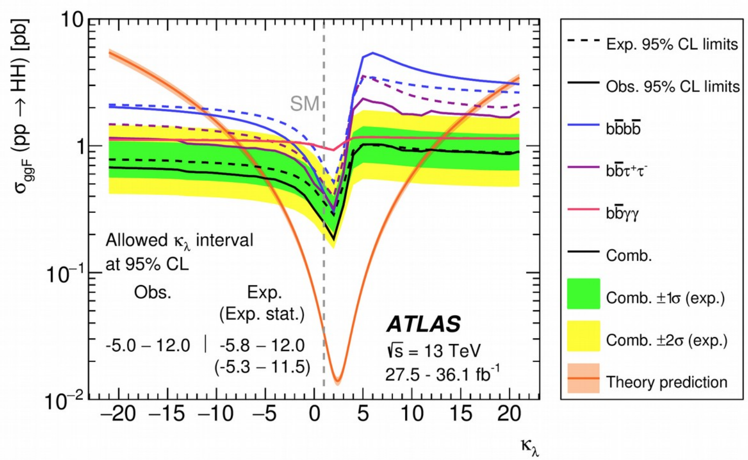
- New analyses, either
  - extrapolations from Run-2 analyses
  - dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200

Run-2 results

- ATLAS

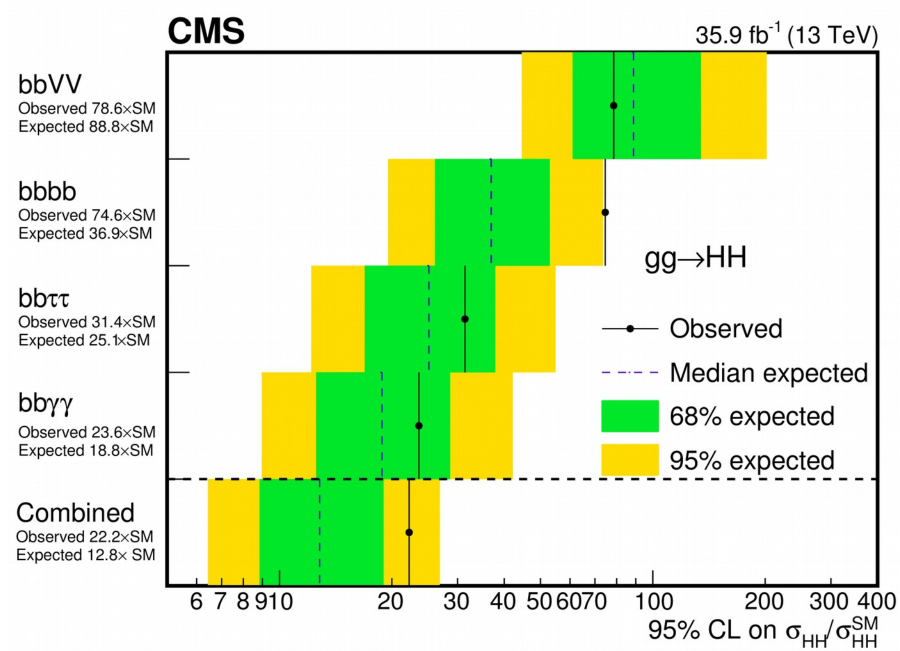


- Expected limit on σ(HH): 10*SM

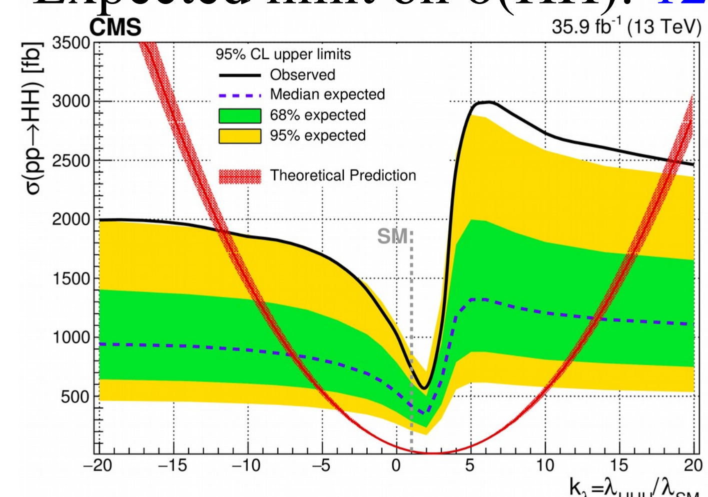


- $-5.0<\kappa_\lambda<12.0$ at 95% CL

- CMS



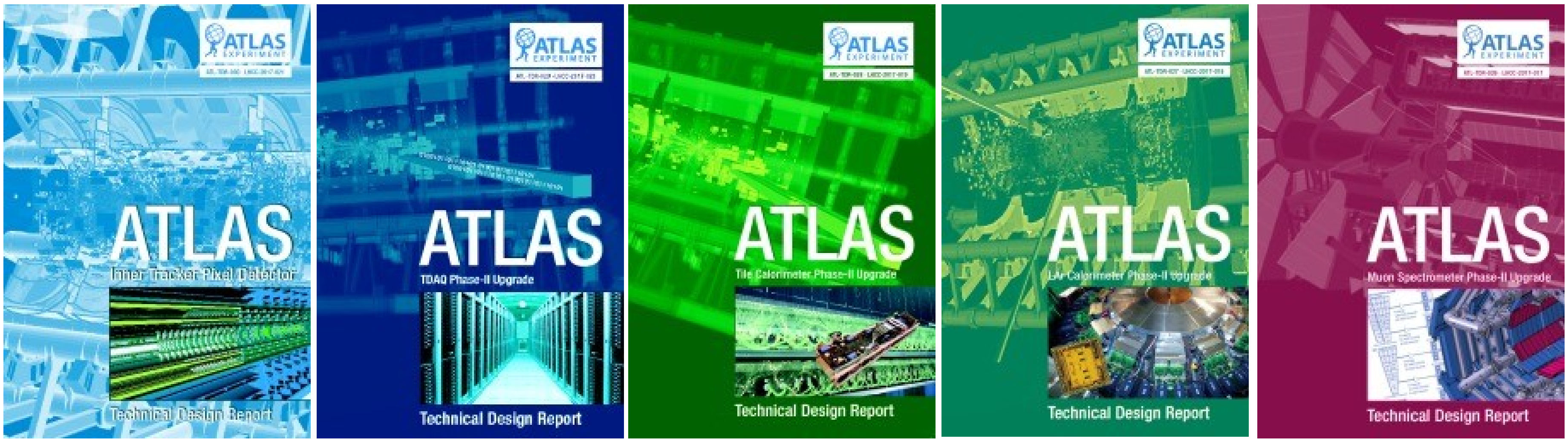
- Expected limit on σ(HH): 12.8*SM



- $-7.1<\kappa_\lambda<13.6$ at 95% CL

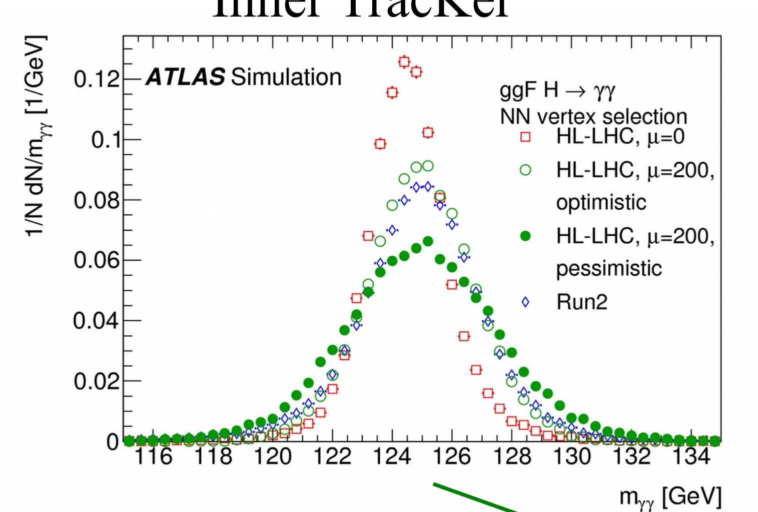
Detector performance at HL-LHC (1)

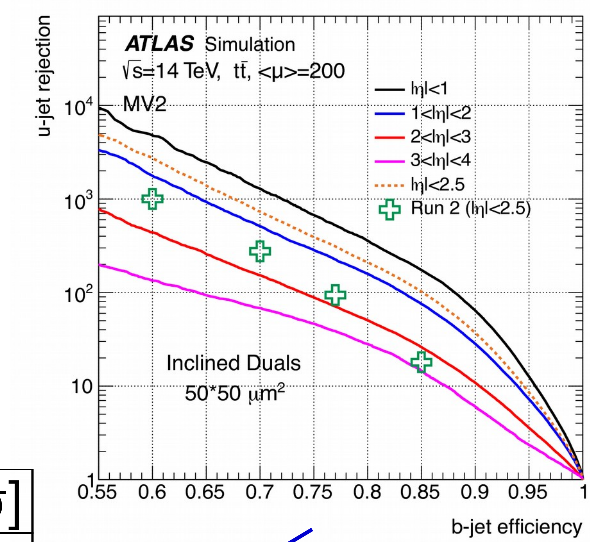
- Upgrades of ATLAS and CMS to cope with aging, pile-up, radiation
- 2017-2019: >4500 pages of Technical Design Reports



Detector performance at HL-LHC (2)

- Outcome of TDRs: current resolutions/efficiencies could be kept at HL-LHC!
- Example for ATLAS HH → $b\bar{b}\gamma\gamma$ analysis
  - Electromagnetic calorimeter
  - Inner TracKer



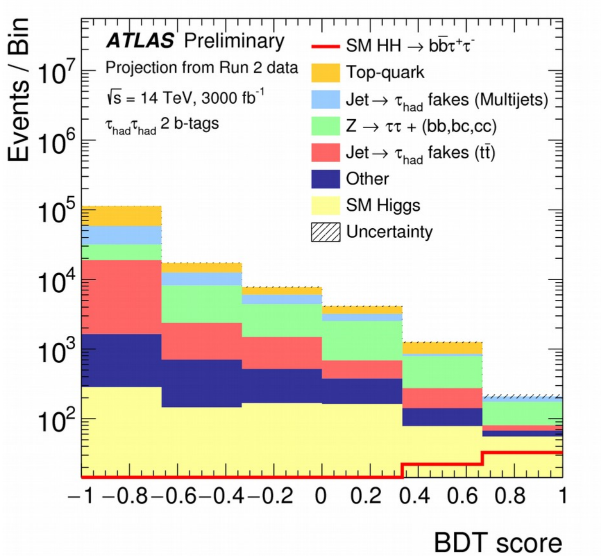


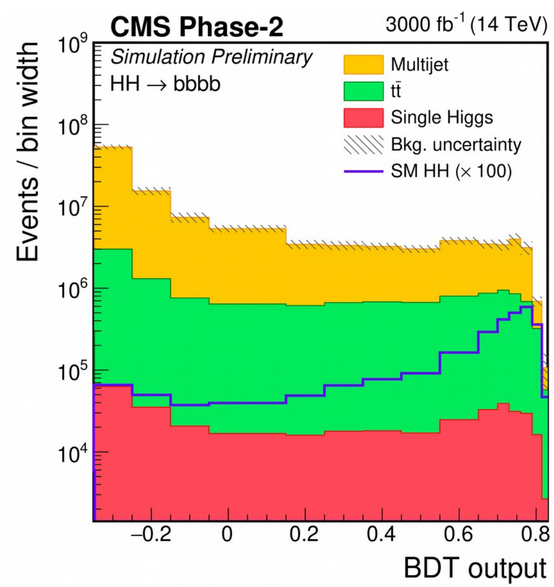
	significance [σ]
Strip TDR	1.05
LAr TDR	1.29
Pixel TDR	1.51

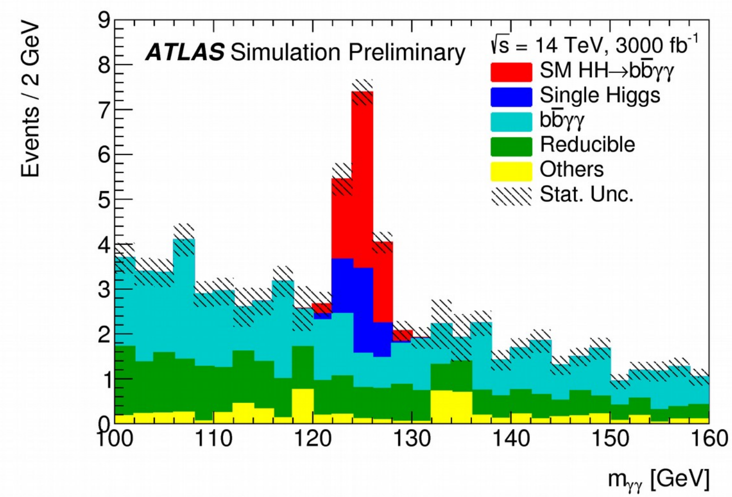
- Systematic uncertainties: common agreement between ATLAS and CMS
  - performance uncertainties scaled by 0.5 to 1
  - theoretical uncertainties divided by 2
  - MC stat uncertainties neglected

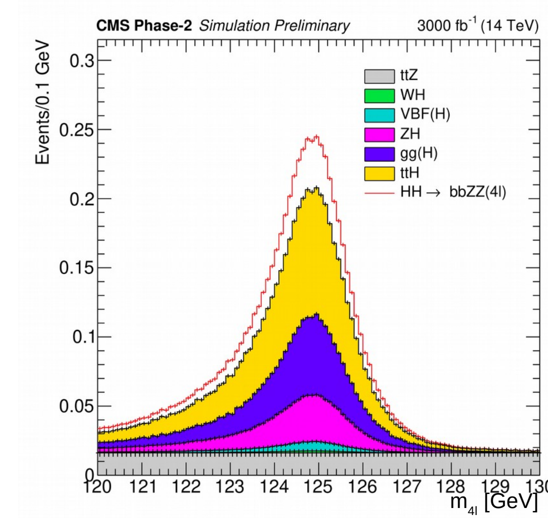
Di-Higgs search, methods

- General analysis strategy:
  - candidates mass consistent with SM Higgs boson
  - multivariate methods to reject background
  - use m_{HH} when possible
- A few examples:







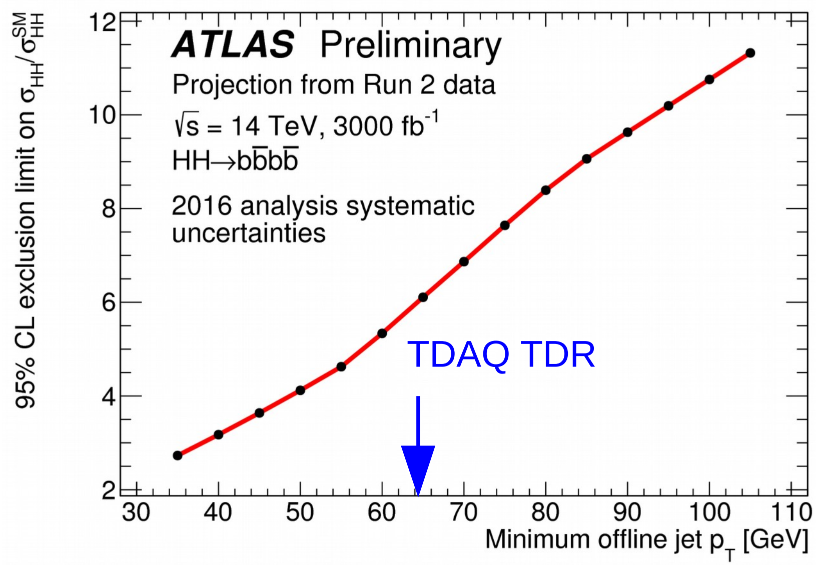


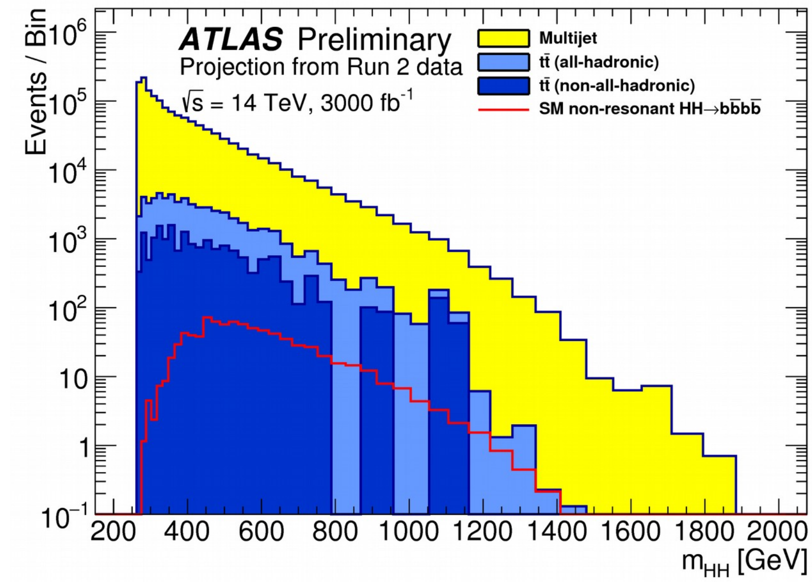
- NB: some inputs or systematics with large unknowns
  - multijet bkg modelling for $HH \to b\bar{b}b\bar{b}$
  - τ fake-rate
  - …

⇒ room for improvement

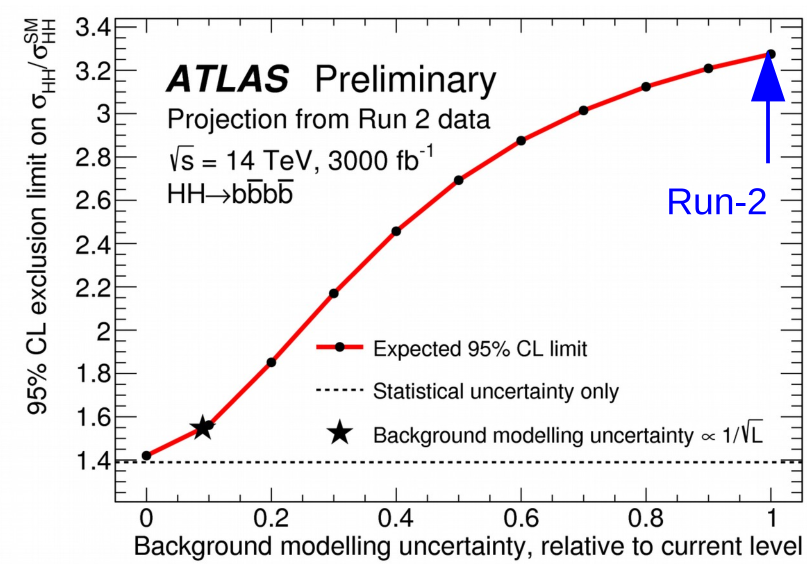
HH→$b\bar{b}b\bar{b}$ (ATLAS)

- Extrapolation from Run-2 analysis
  - fit of m_{4j} distribution
  - $p_T^{jet} > 40$ GeV, different thresholds tested





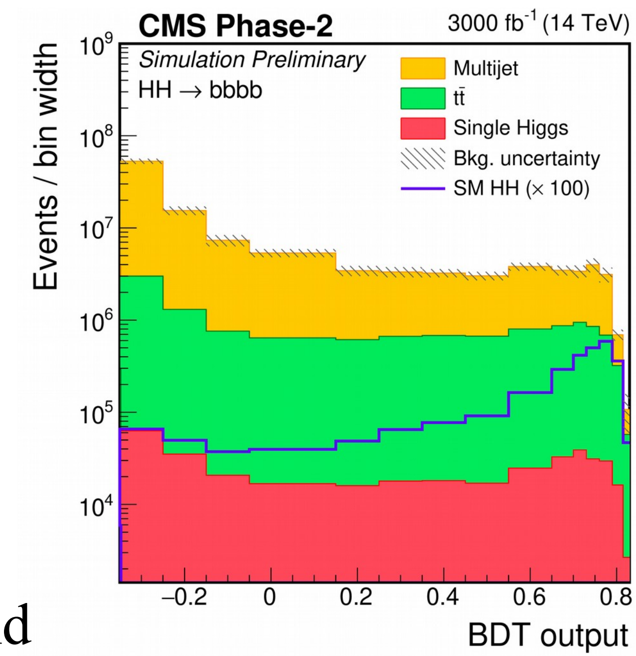
- Systematics
  - dominated by multijet data-driven model
  - conservative assumption: Run-2 systematics used



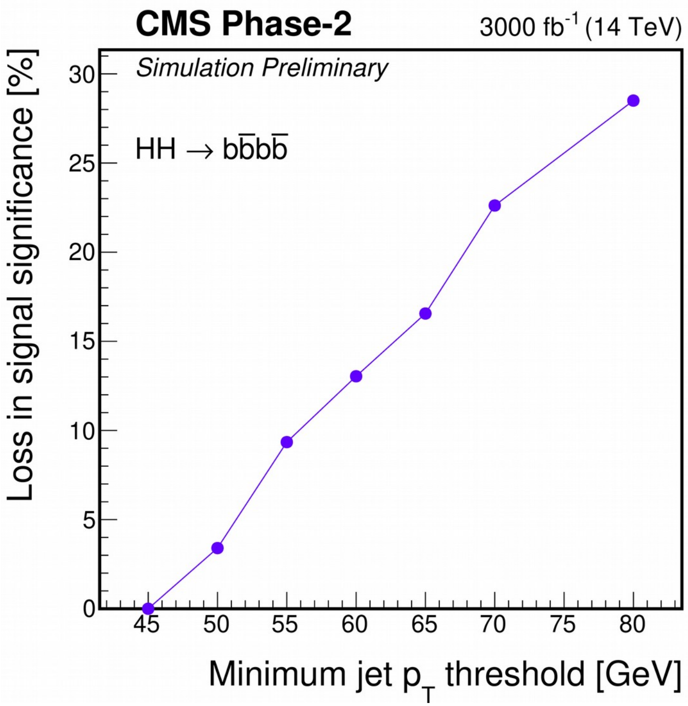
- Significance:
  1.4/0.61σ without/with syst

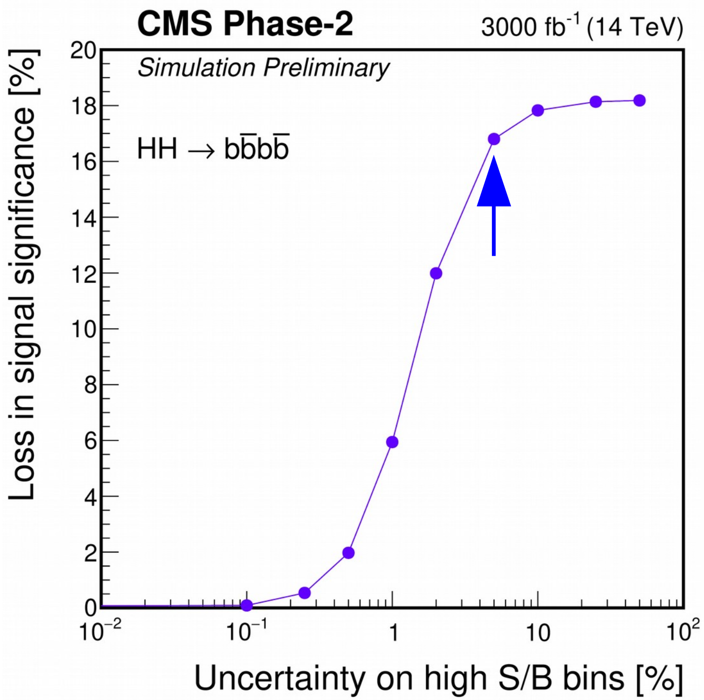
HH→$b\bar{b}b\bar{b}$ (CMS)

- SM sigmal + BSM benchmark points
- Resolved and boosted b-jets
  - boosted topologies more sensitive to BSM scenarios where high m_{HH} is enhanced
- Resolved:
  - p_T > 45 GeV, different thresholds tested
  - BDT against multijet bkg + $t\bar{t}$ and single-Higgs
- Small uncertainty considered for multijet background



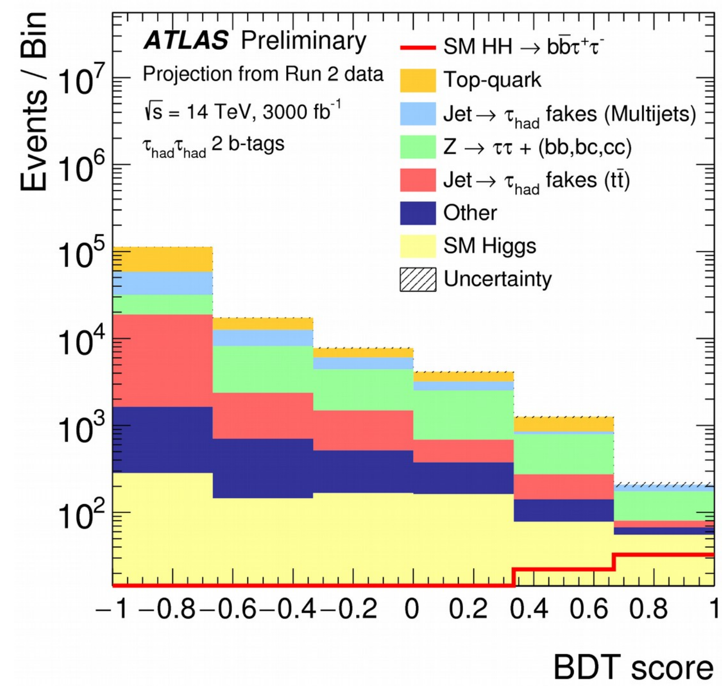
- Significance:
  1.2σ wo/syst
  0.95σ w/ syst

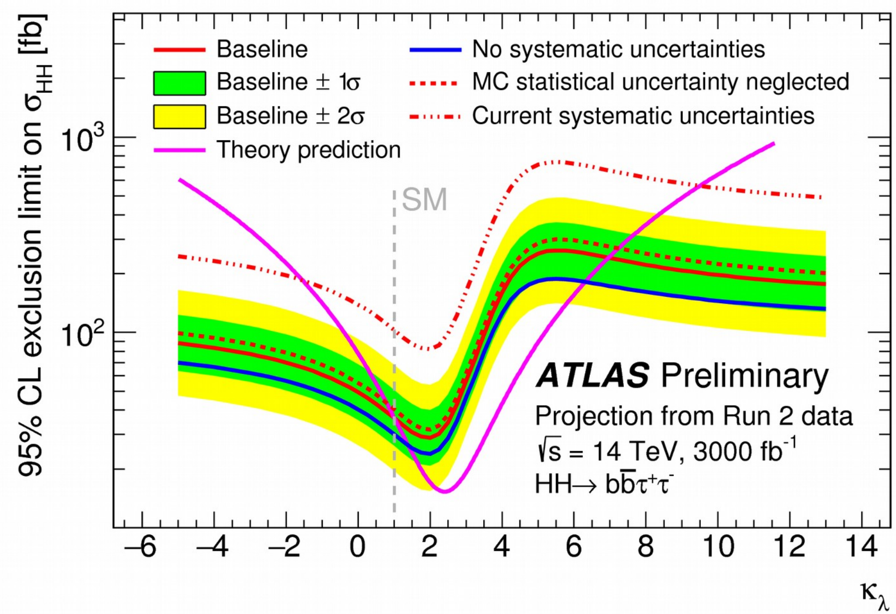




HH→$b\bar{b}\tau\tau$ (ATLAS)

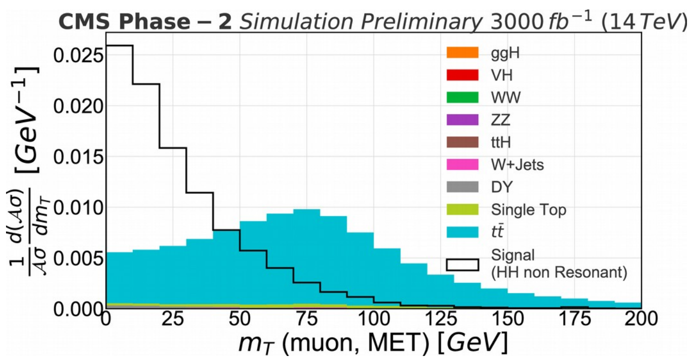
- Extrapolation from Run-2 analysis
- Three signal regions:
  - $\tau_{lep}\tau_{had}$ (Single Lepton Trigger)
  - $\tau_{lep}\tau_{had}$ (Lepton Tau Trigger)
  - $\tau_{had}\tau_{had}$ (Single Tau Trigger and Di-Tau Trigger)
- BDT output used as final discriminant
  - binning adapted to higher statistics
- Limit on κ_λ: LTT category not included and dedicated BDT trained on $\kappa_\lambda = 20$
- Different assumptions for systematics
  - from current to baseline for HL-LHC
- Significance: 2.5/2.1σ without/with syst



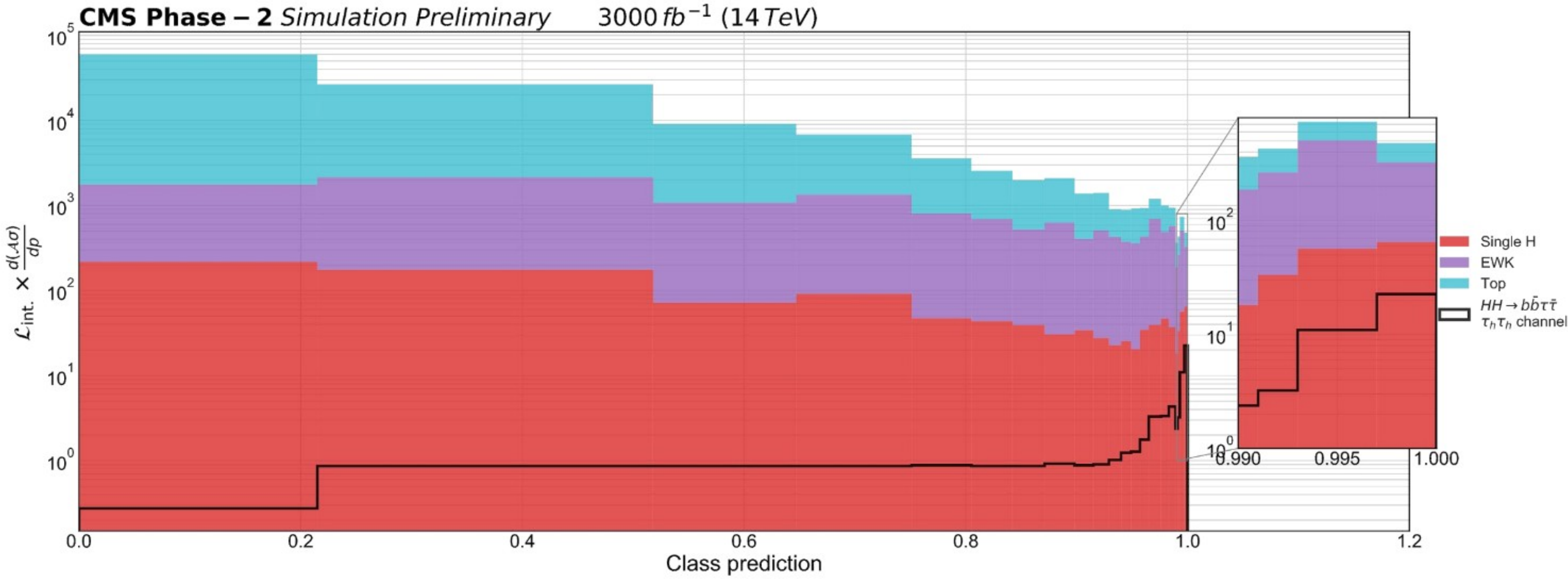


HH→$b\bar{b}\tau\tau$ (CMS)

- 3 categories: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$



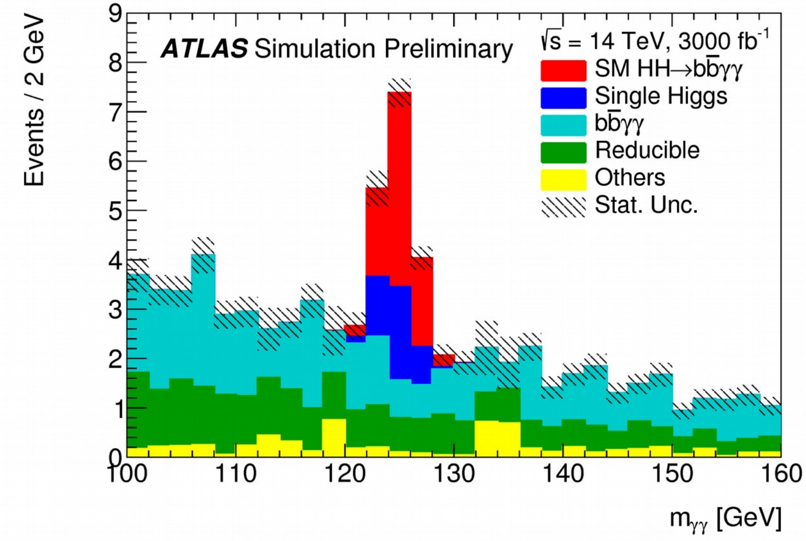
- Use of a Deep Neural Network
  - 27 basic + 21 reconstructed + 4 global features
  - deep learning techniques, with optimal data preprocessing, study of the activation functions, and data augmentation

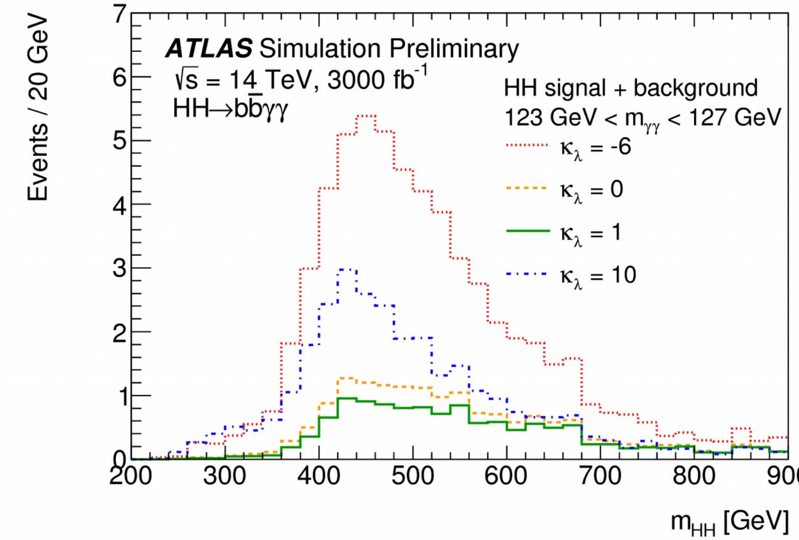


- Simultaneous fit of the NN output for the 3 decay channels
  - discriminant binned per decay channel via adaptive binning
- Significance: 1.6/1.4σ without/with syst

HH→$b\bar{b}\gamma\gamma$ (ATLAS)

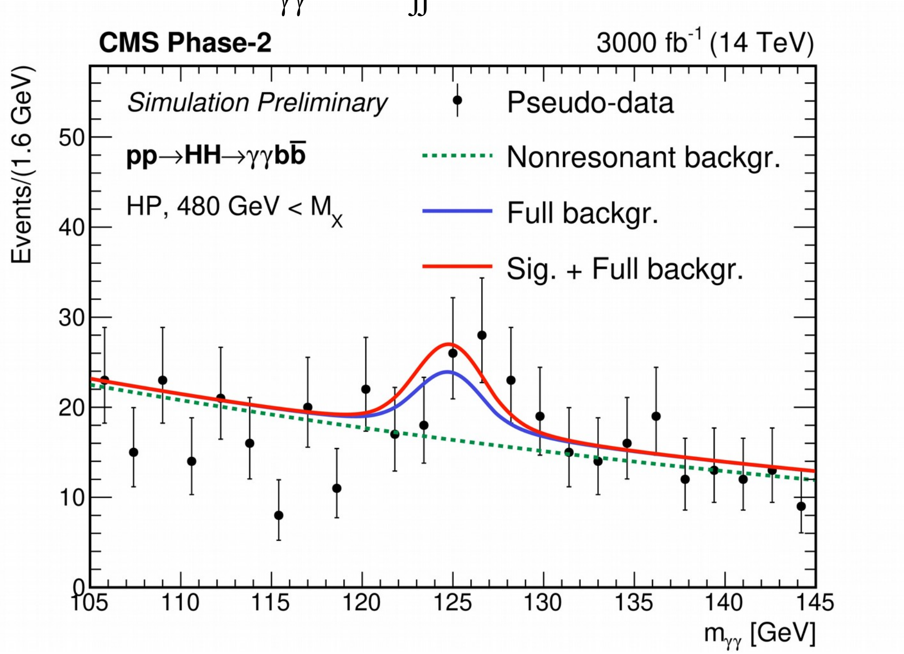
- Dedicated analysis with smearing functions: upgraded detector geometry and performance functions
  - $m_{\gamma\gamma}$ resolution ~ 1.6 GeV
- Dedicated BDT trained to remove continuum background and main single-Higgs background ($t\bar{t}H$)
- Limit on κ_λ: use of the $m_{b\bar{b}\gamma\gamma}$ distribution for events with 123 < $m_{\gamma\gamma}$ < 127 GeV
- Systematics: very small impact in general
- Significance: 2.1/2.0σ without/with syst

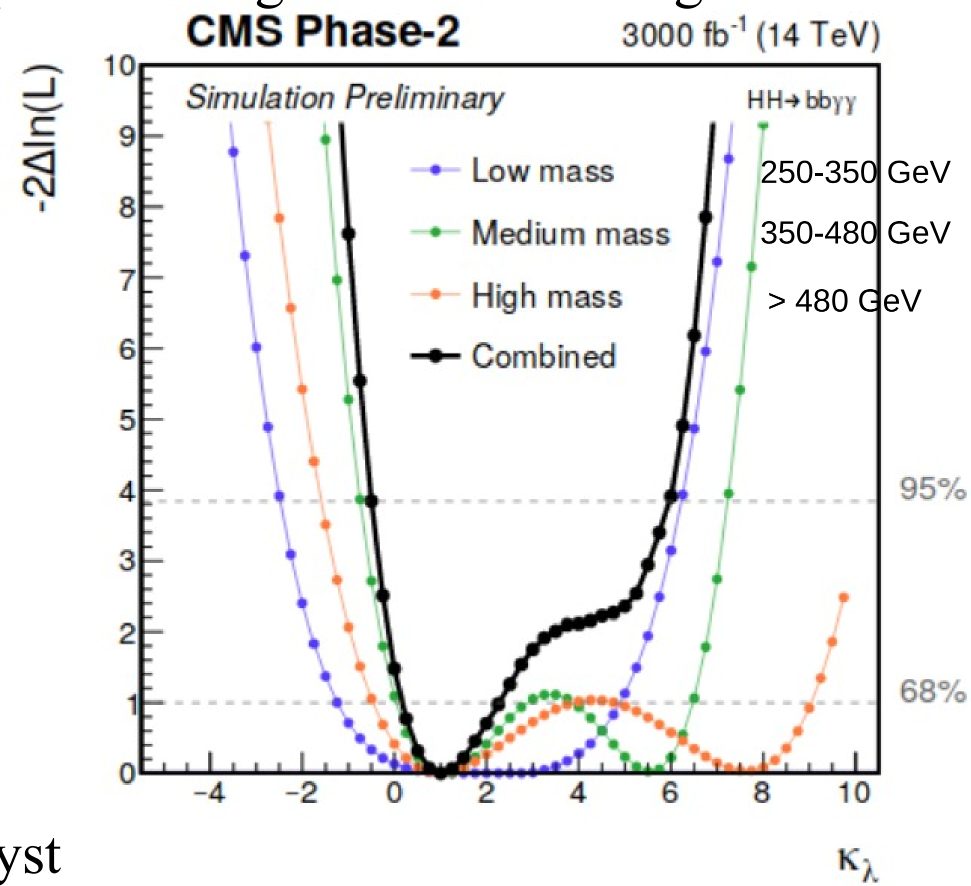




HH→b$\bar{b}$γγ (CMS)

- Dedicated BDT to reject t$\bar{t}$H
  - 75% reduction for 90% signal efficiency
- Classification of events based on $M_X = m_{jj\gamma\gamma} - m_{\gamma\gamma} - m_{jj} + 250$ GeV into low and high mass categories
- MVA event categorisation BDT to separate background and HH signal into medium (MP) and high (HP) purity
- Fit of $m_{\gamma\gamma}$ x m_{jj}

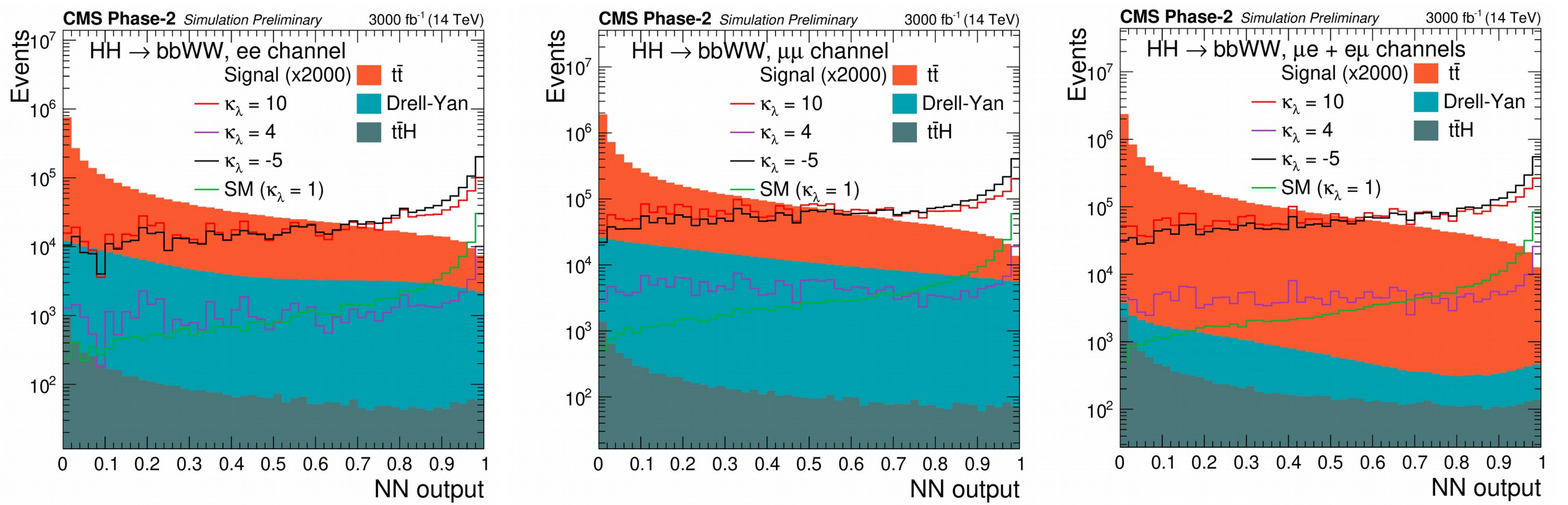




- Significance: 1.8/1.8σ without/with syst
  - difference with ATLAS partly due to $m_{\gamma\gamma}$ resolution

HH→b$\bar{b}$VV(lνlν), CMS only

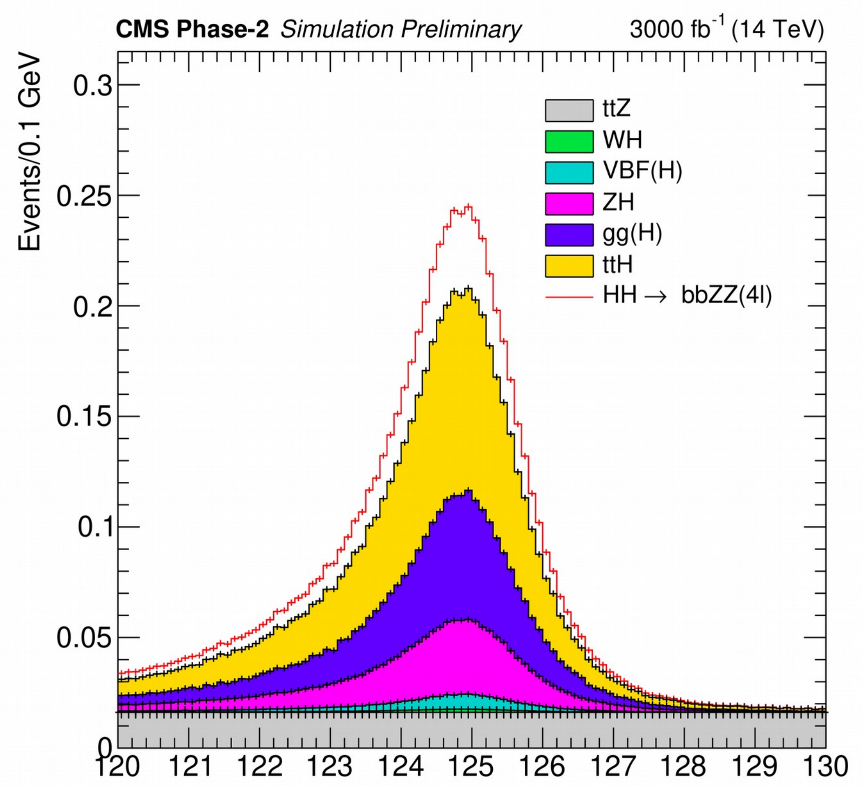
- Optimised on WW, but ZZ signal included for the results
- Large irreducible backgrounds: t$\bar{t}$, DY
- Neural Network discriminant
  - 9 input angular and mass variables
  - signal extracted from the NN ouput (3 categories ee, μμ, eμ)



- Results: 0.6σ significance

HH→b$\bar{b}$ZZ(4l), CMS only

- Very rare but clean final state, yet unexplored at the LHC
- Powerful H→4ℓ signature ⇒ single Higgs dominant background
- Select events with m4ℓ compatible with m_H
- Counting experiment with events around m_H



- ~1 signal event after selection
  - S/B ~0.1
- Results: 0.4σ significance

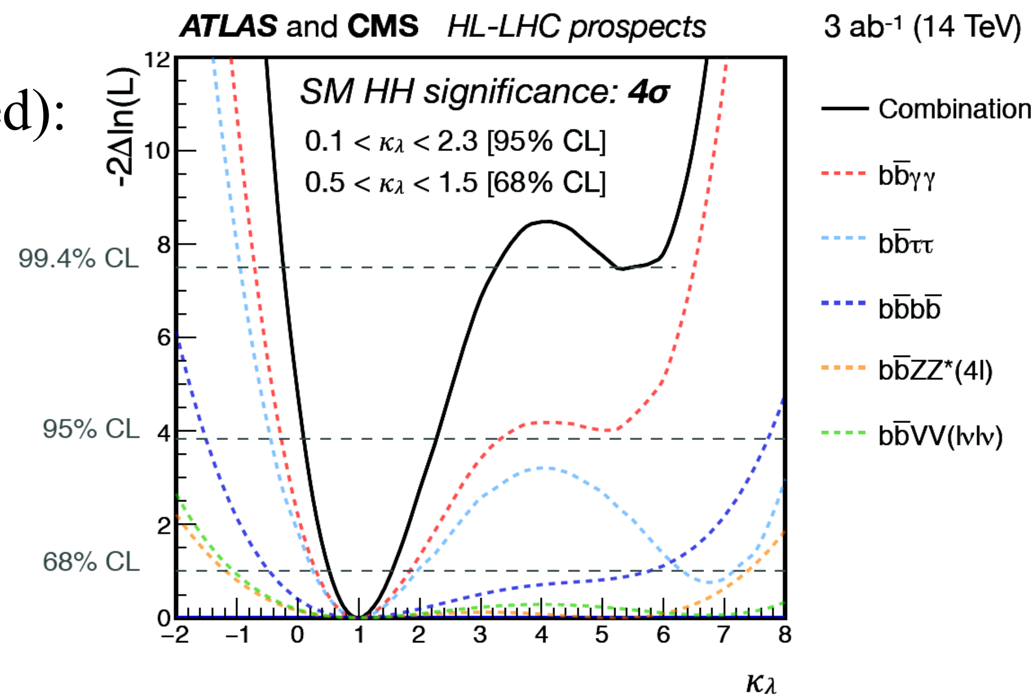
Combined results (1)

- Expected significance (SM) with and without systematics at HL-LHC

	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	

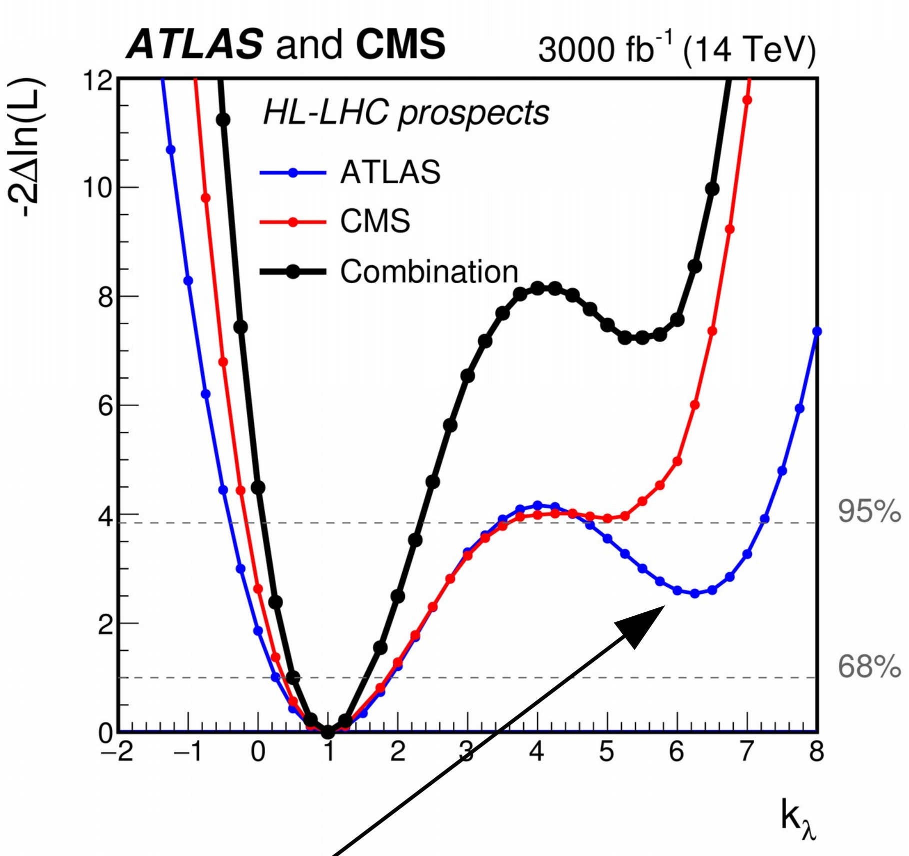
  - 4σ expected with ATLAS+CMS!

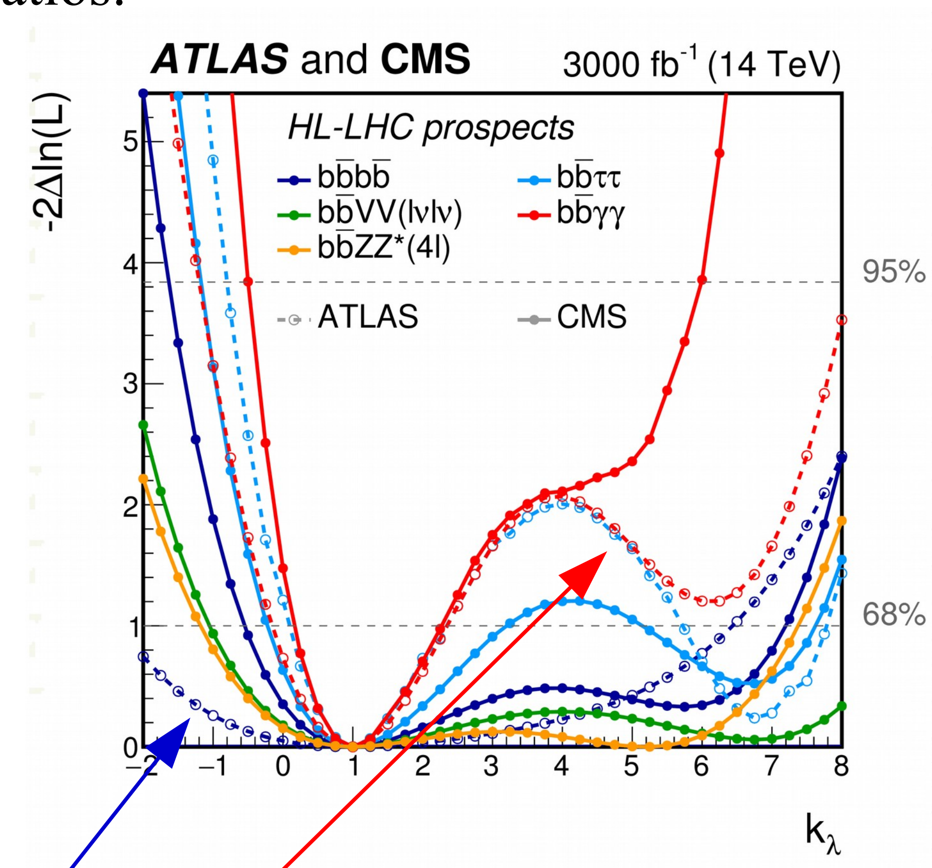
- Measurement of μ (SM signal injected):
  - δμ/μ ~25% (30%) without (with) systematics
- μ = 0 (no SM HH signal) excluded at 95% CL
- Measurement of κ_λ:
  - 68% CI: [0.5; 1.5]
  - 2nd minimum excluded at 99.4% CL thanks to the m_{HH} shape information



Combined results (2)

- Comparison of negative log-likelihood ratios:

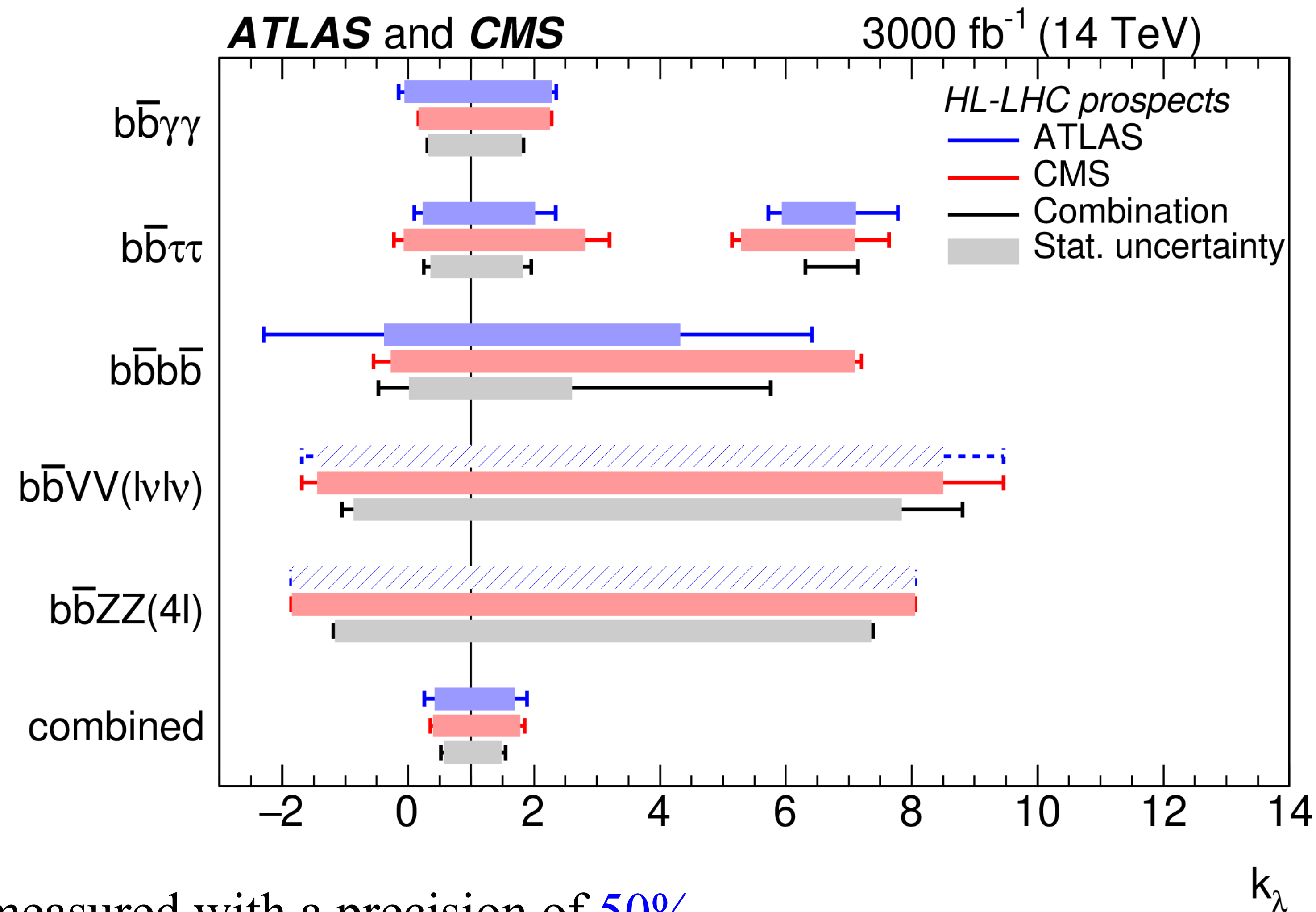




- Difference on 2nd minimum mainly from the $b\bar{b}\gamma\gamma$ channel: 3 categories of m_{HH} (especially a low-m_{HH} one) to remove the degeneracy around κ_λ=6 (while this low-m_{HH} category has no effect around 1)
- CMS slightly better below 1: $b\bar{b}b\bar{b}$ + other smaller channels

Combined results (3)

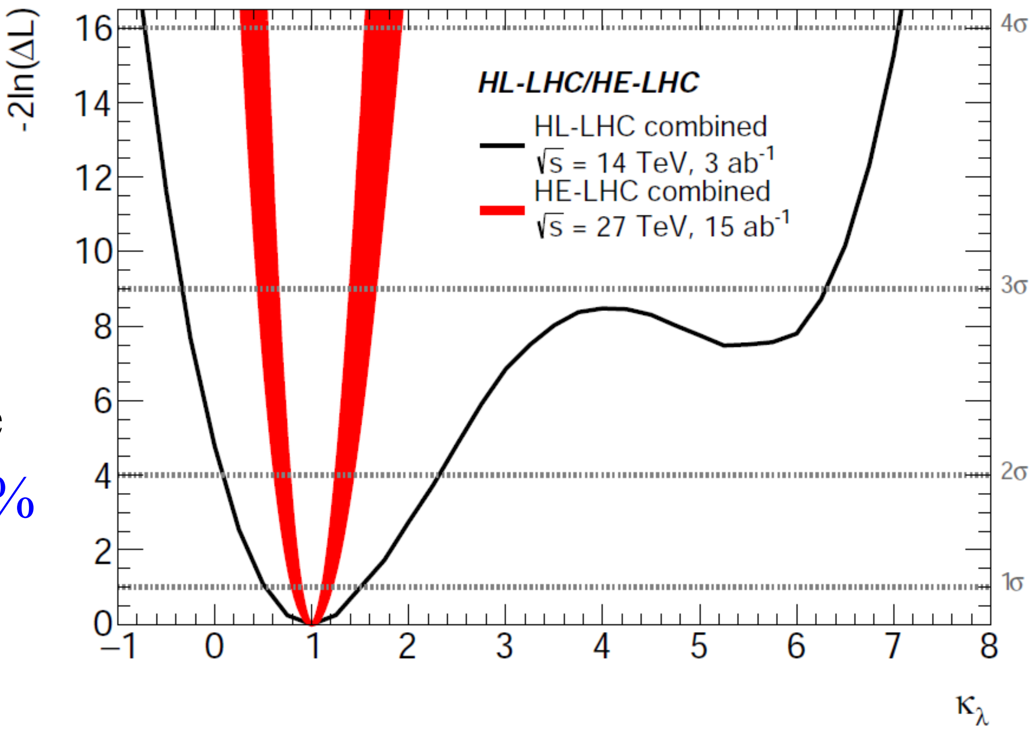
- 68% CI, channel by channel
- Dashed line = no ATLAS analysis, using value from CMS (as for Higgs couplings)



- κ_λ measured with a precision of 50%

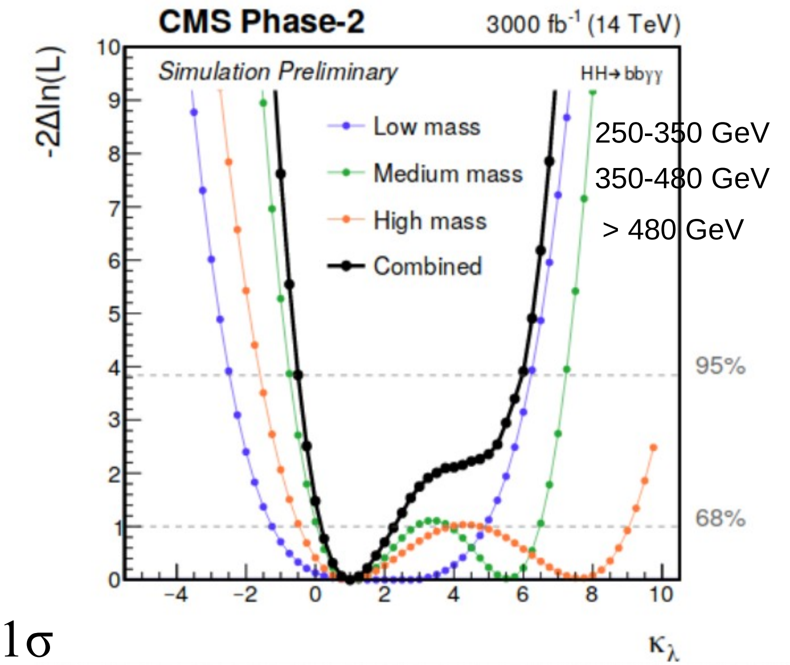
HE-LHC, HH measurements

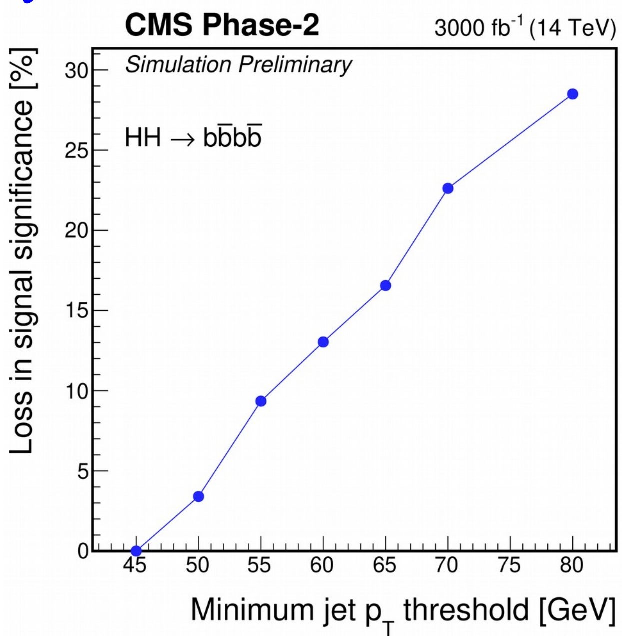
- Extrapolation of ATLAS HL-LHC results to HE-LHC
  - scale cross-section to 27 TeV (*4) and luminosity to 15 ab^{-1} (*5), no systematic uncertainties
  - $b\bar{b}\tau\tau$ channel: significance: 10.7σ, precision on κ_λ: 20%
  - $b\bar{b}\gamma\gamma$ channel: significance: 7.1σ, precision on κ_λ: 40%
    - pessimistic because analysis not optimised for measurement of κ_λ
- Phenomenology study for $b\bar{b}\gamma\gamma$: 15% precision on κ_λ
  - realistic detector performance
  - no pile-up considered (μ=800-1000)
- Combination of channels: κ_λ could be measured with a 68% CI of 10 to 20 %

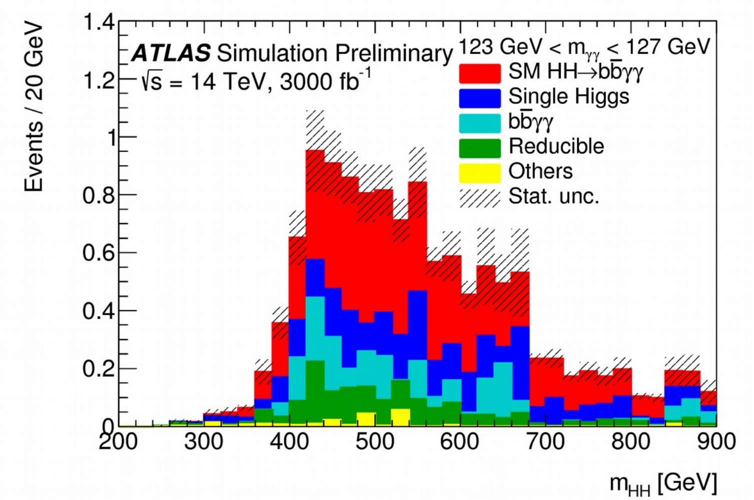


Possible improvements

- Analyses extrapolated from Run-2:
  - for the moment not aiming for κ_λ measurement (eg no use of m_{HH} categories)
- Dedicated HL-LHC analyses:
  - optimised for HH production, not always for κ_λ
  - eg ATLAS vs CMS HH $\rightarrow b\bar{b}\gamma\gamma$
- Improvement of background modelling
  - eg ATLAS HH $\rightarrow b\bar{b}b\bar{b}$, significance $1.4\sigma \rightarrow 0.61\sigma$
- Improvement of signal yields
  - object efficiencies
  - trigger
- Adding new variables and improved MVA techniques (DNN, ...)



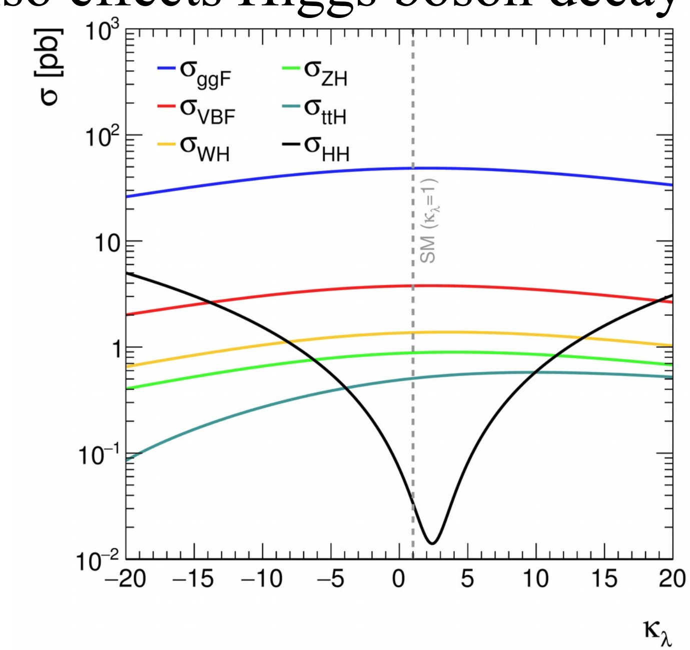


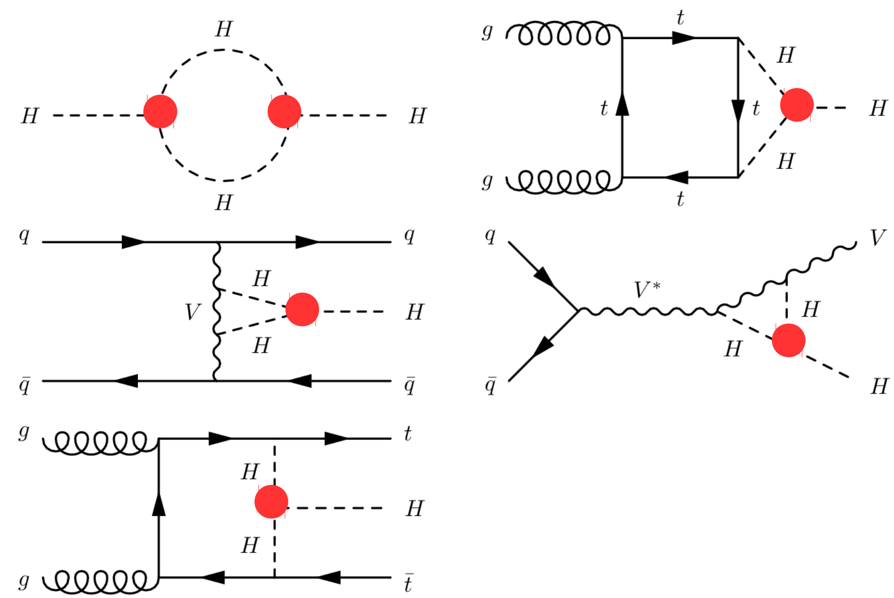


Self-couplings through single-Higgs measurements

Single-Higgs, introduction

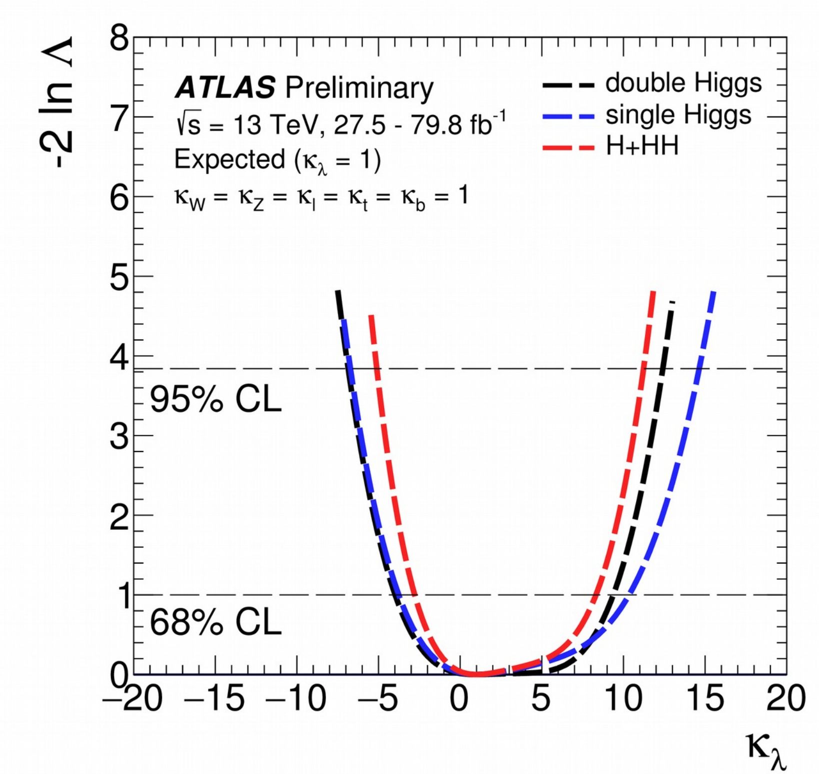
- Single-Higgs production: Higgs self-interaction only via one-loop corrections (ie two loop-level for ggF)
- κ_λ-dependent corrections to the tree-level cross-sections
  - valid for $|\kappa_\lambda| < 20$
  - production mode
    - eg for $\kappa_\lambda = 2$ $\sigma(pp \to t\bar{t}H)$ modified by 3%
  - kinematics properties of the event
    - eg p_T^{Higgs} for $t\bar{t}H$ and VH
- Also effects Higgs boson decay BR

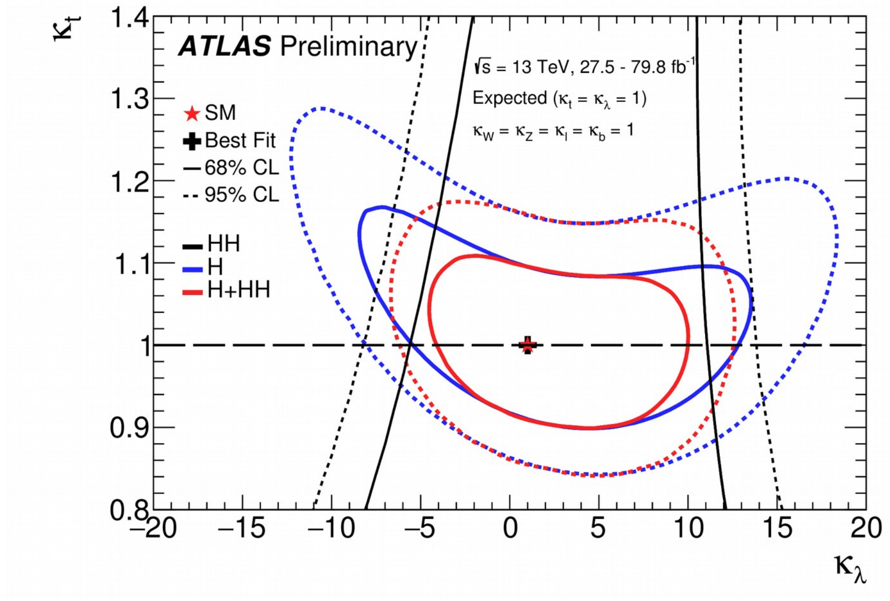




Single-Higgs for Run-2

- Run-2 result using coupling measurements





- Combined fit result (κ_λ only variation):

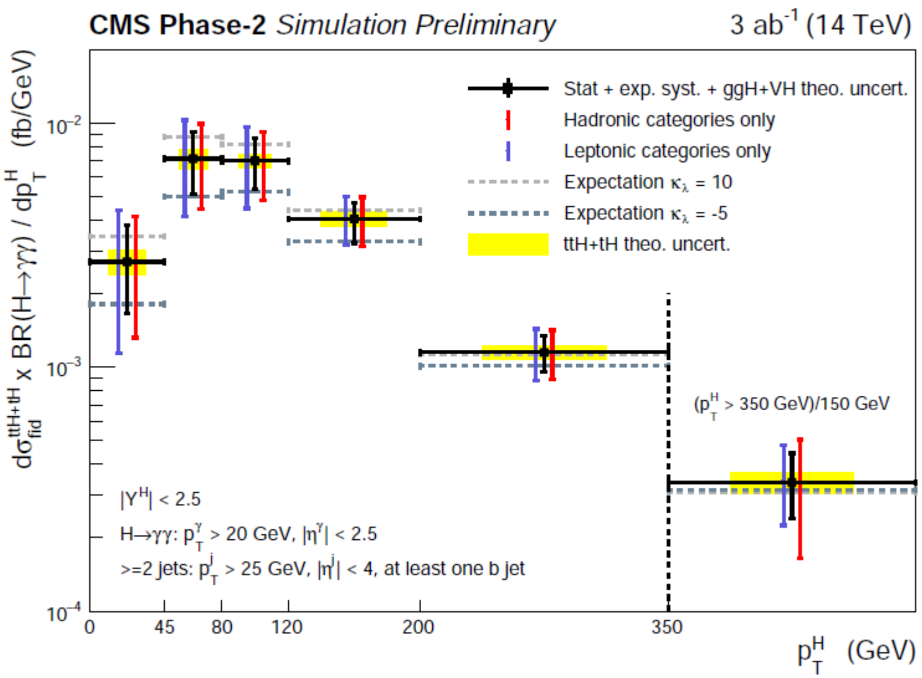
$$\kappa_\lambda = 4.6^{+3.2}_{-3.8} = 4.6^{+2.9}_{-3.5}\,(\text{stat.})\,^{+1.2}_{-1.2}\,(\text{exp.})\,^{+0.7}_{-0.5}\,(\text{sig. th.})\,^{+0.6}_{-1.0}\,(\text{bkg. th.})\;[\text{observed}]$$

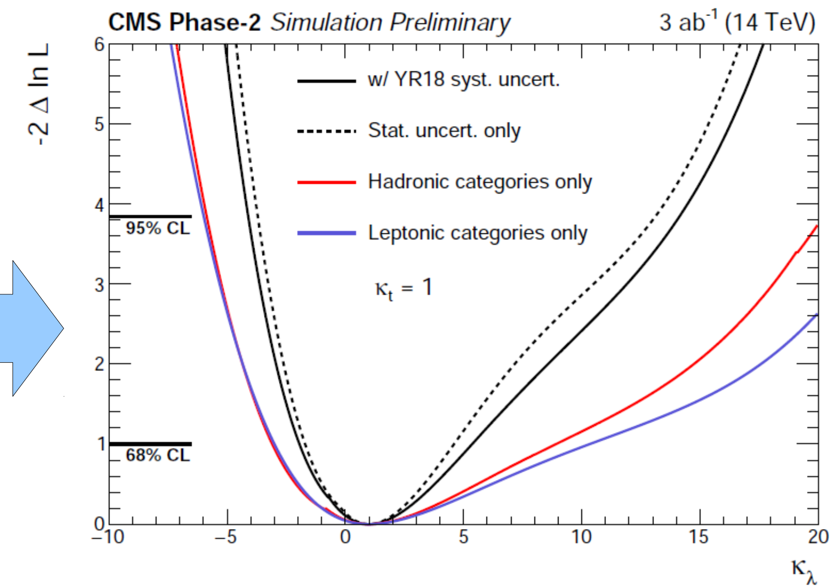
$$\kappa_\lambda = 1.0^{+7.3}_{-3.8} = 1.0^{+6.2}_{-3.0}\,(\text{stat.})\,^{+3.0}_{-1.7}\,(\text{exp.})\,^{+1.8}_{-1.2}\,(\text{sig. th.})\,^{+1.7}_{-1.1}\,(\text{bkg. th.})\;[\text{expected}]$$

- Similar sensitivity between single-Higgs and di-Higgs with the current luminosity

Single-Higgs at HL-LHC (1)

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

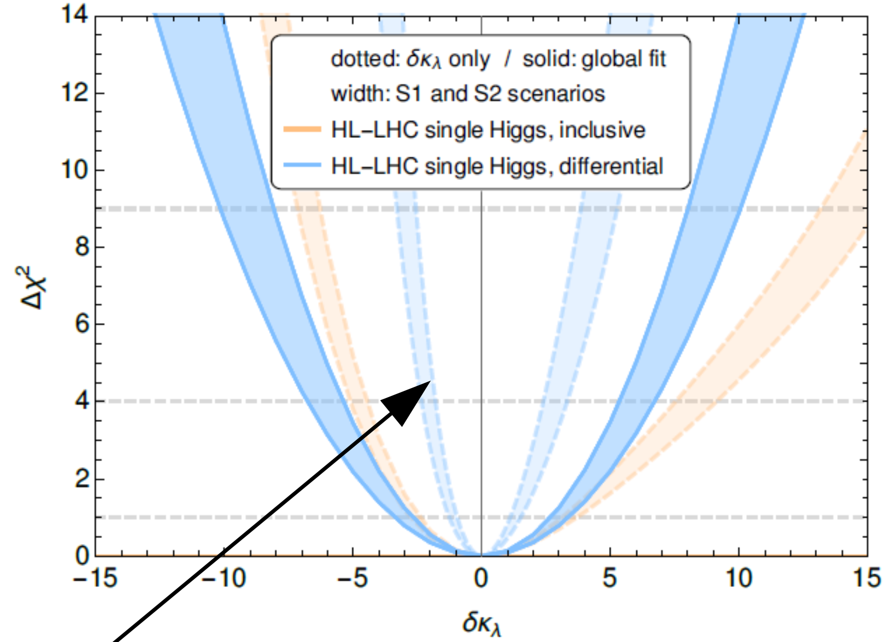


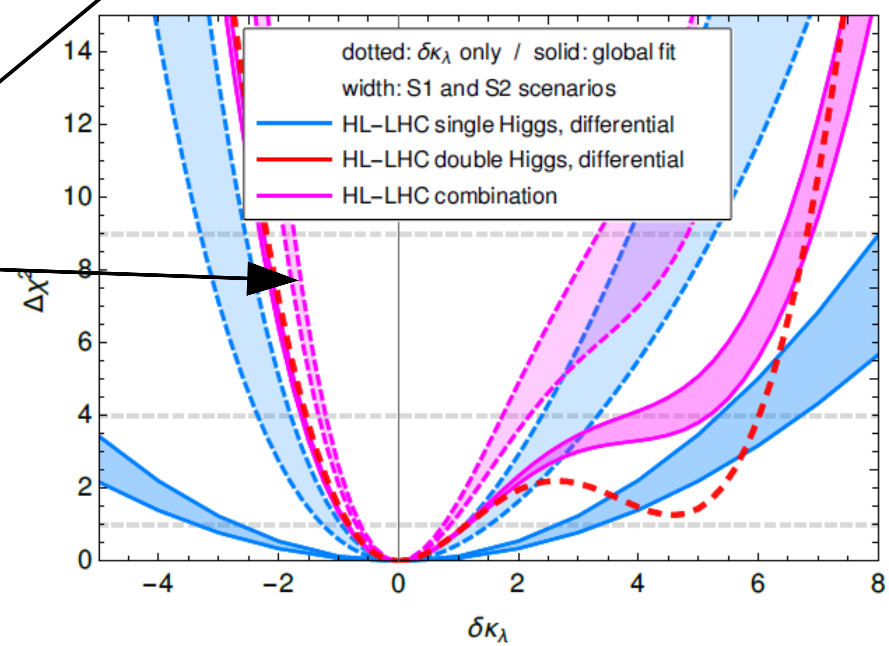


- 68% CI: $-1.9 < \kappa_\lambda < 5.3$ if only κ_λ varied
- First test with experimental “data”, more channels to be added

Single-Higgs at HL-LHC (2)

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

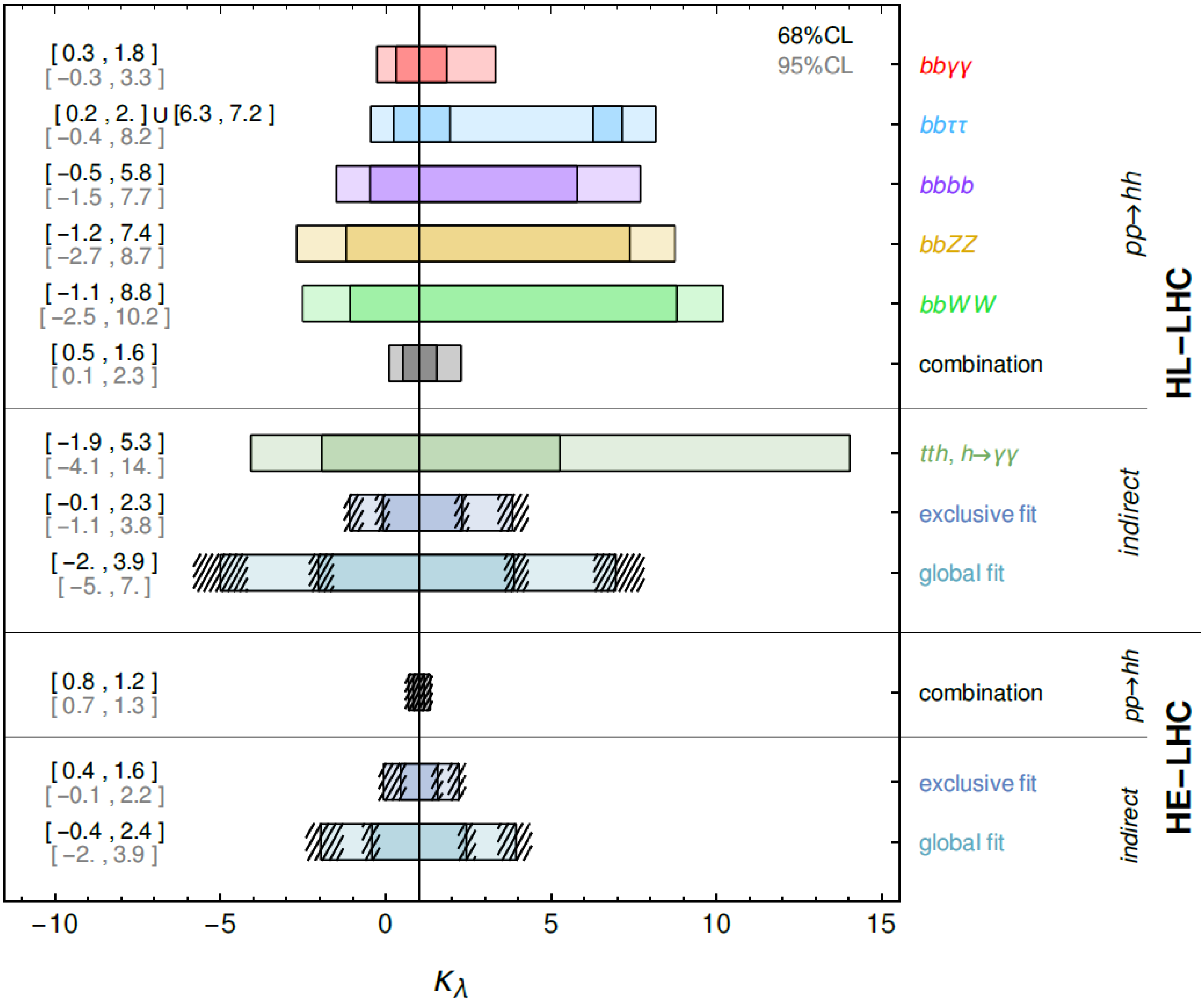




Summary

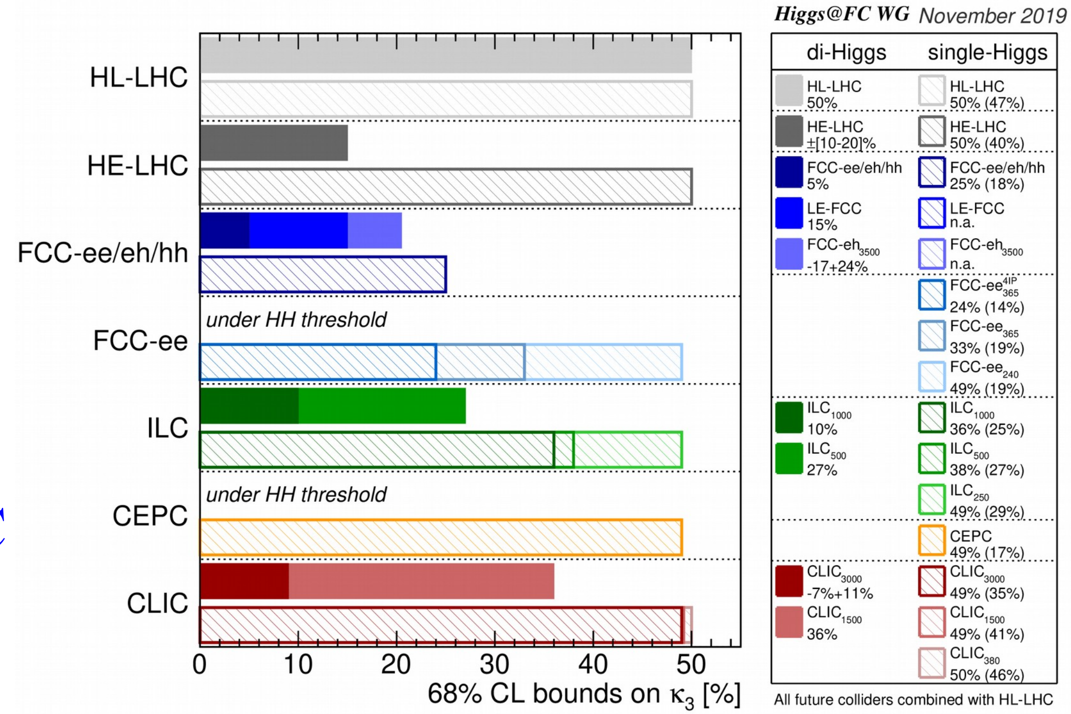
Summary of HL(HE)-LHC prospects

♦



Conclusion

- State-of-the art experimental studies on HH 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
- Nice developments on single-Higgs constrains
  - differential cross-sections, global fits
- Estimates of sensitivity at HE-LHC
  - experimental and phenomenology



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- HL-LHC measurement of the Higgs self-coupling will remain the most precise until the high-energy phase of the next generation of Future Colliders around 2050
- More on the global interpretation in the talk by C. Grojean tomorrow

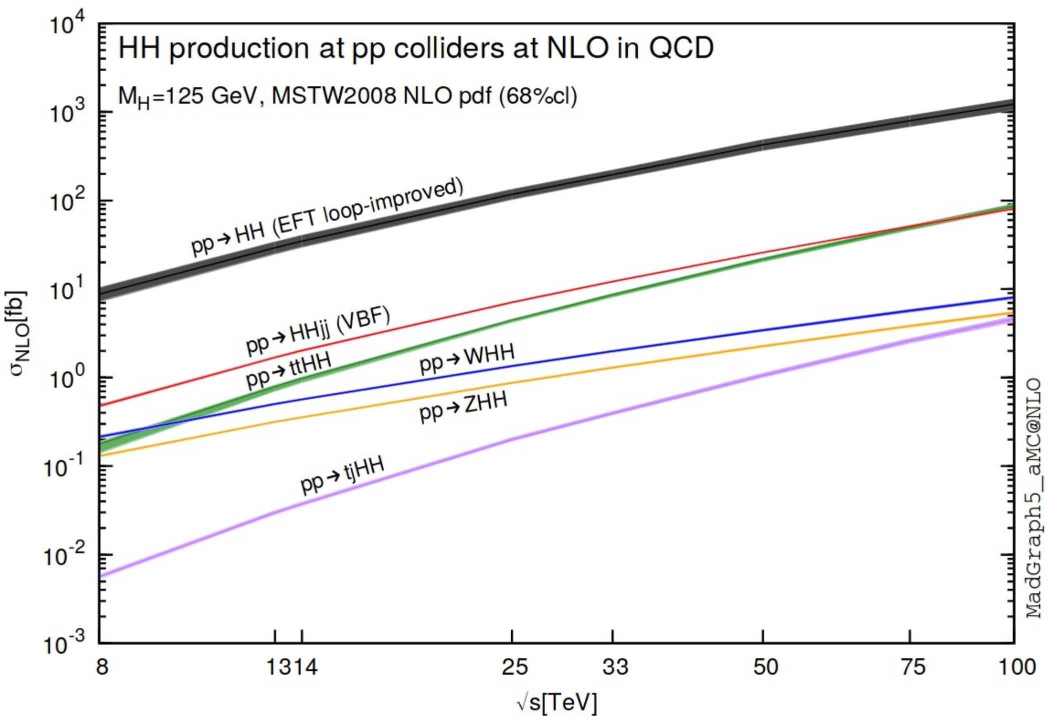
References

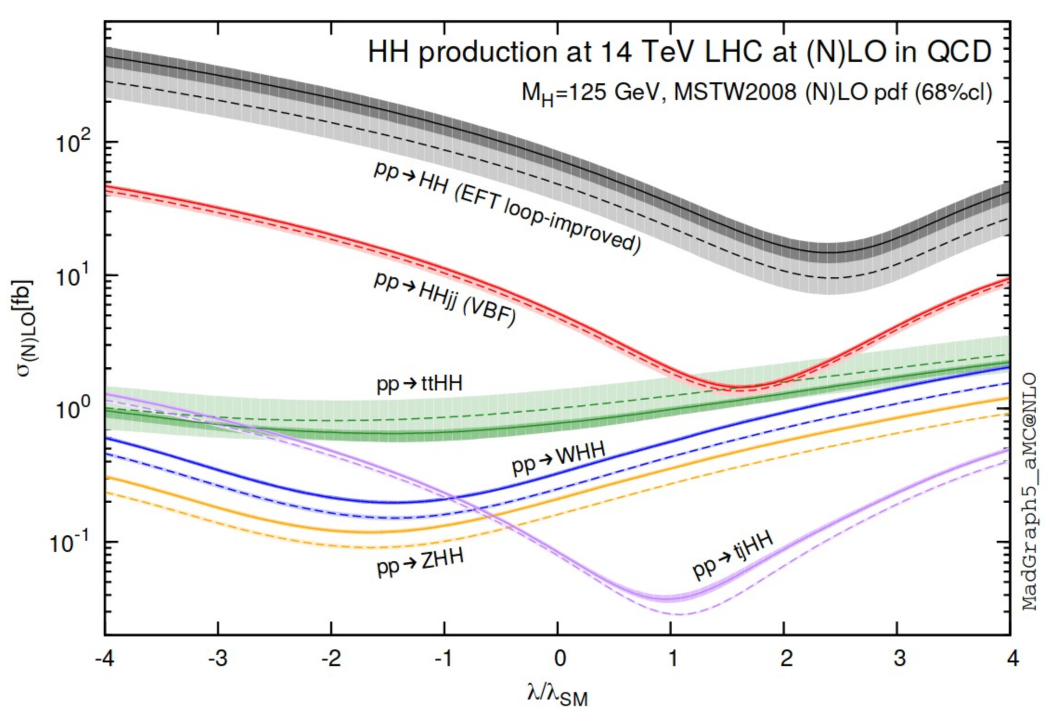
- Measurement prospects of the pair production and self-coupling of the Higgs boson with the ATLAS experiment at the HL-LHC, ATL-PHYS-PUB-2018-053
- Prospects for HH measurements at the HL-LHC, CMS-FTR-18-019
- Higgs Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-04
- Constraint of the Higgs boson self-coupling from Higgs boson differential production and decay measurements, ATL-PHYS-PUB-2019-009
- Constraints on the Higgs boson self-coupling from the combination of single-Higgs and double-Higgs production analyses performed with the ATLAS experiment, ATLAS-CONF-2019-049
- Expected performance of the ATLAS detector at the High-Luminosity LHC, ATL-PHYS-PUB-2019-005
- Expected performance of the physics objects with the upgraded CMS detector at the HL-LHC, CMS-NOTE-2018-006
- Combination of searches for Higgs boson pairs in pp collisions at s√=13 TeV with the ATLAS detector HDBS-2018-58
- Combination of searches for Higgs boson pair production in proton-proton collisions at $\sqrt{s}$= 13 TeV HIG-17-030

Back-up

Di-Higgs production

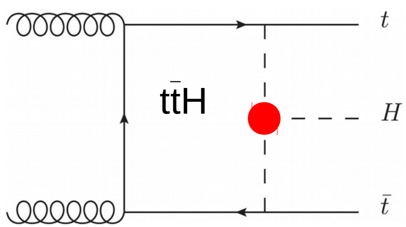
- Only ggF production considered at present

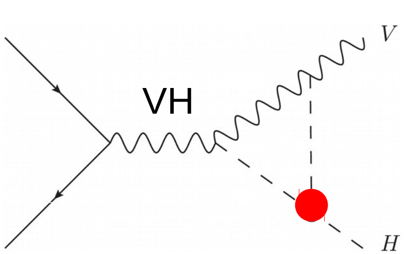


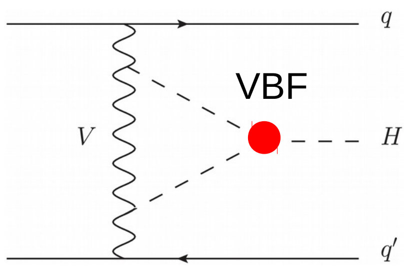


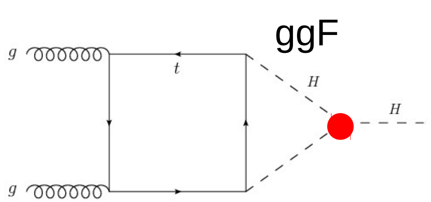
Single-Higgs couplings (1)

- Higgs self-interaction via one-loop corrections of the single-Higgs production
  - κ_λ-dependent corrections to the tree-level cross-sections
- pp colliders:

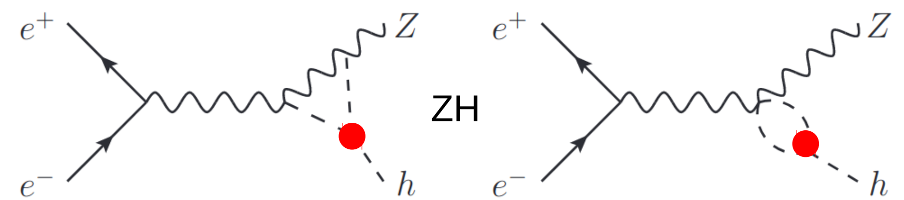


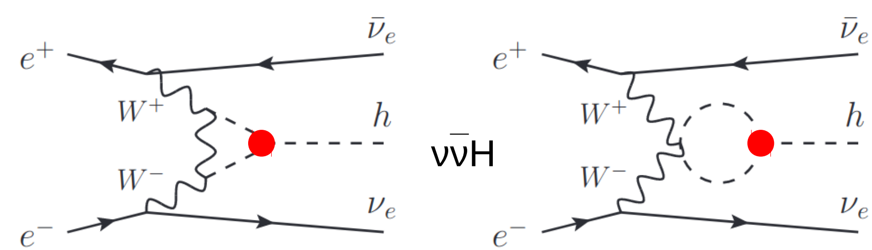






- ee colliders:





- ex. for $\kappa_\lambda = 2$:
  - $\sigma(pp \rightarrow t\bar{t}H)$ modified by 3%
  - $\sigma(ee \rightarrow ZH)$ modified by 1%

Single-Higgs couplings (2)

- More global view: SMEFT_{ND}
- Deformation of the single-Higgs + EW processes:

$$\text{SMEFT}_{\text{ND}} \equiv \{\delta m,\, c_{gg},\, \delta c_z,\, c_{\gamma\gamma},\, c_{z\gamma},\, c_{zz},\, c_{z\Box},\, \delta y_t,\, \delta y_c,\, \delta y_b,\, \delta y_\tau,\, \delta y_\mu,\, \lambda_z\}$$
$$+\left\{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{Z\nu})_{\ell}, (\delta g_L^{Ze})_{\ell}, (\delta g_R^{Zu})_{q_i}, (\delta g_R^{Zd})_{q_i}, (\delta g_R^{Ze})_{\ell}\right\}_{q_1=q_2\neq q_3,\ \ell=e,\mu,\tau}$$

+ correction to the trilinear Higgs self-coupling: $\delta\kappa_\lambda = \kappa_\lambda - 1$

- Can also consider the effect of $\delta\kappa_\lambda$ on the other parameters
  - a few examples:

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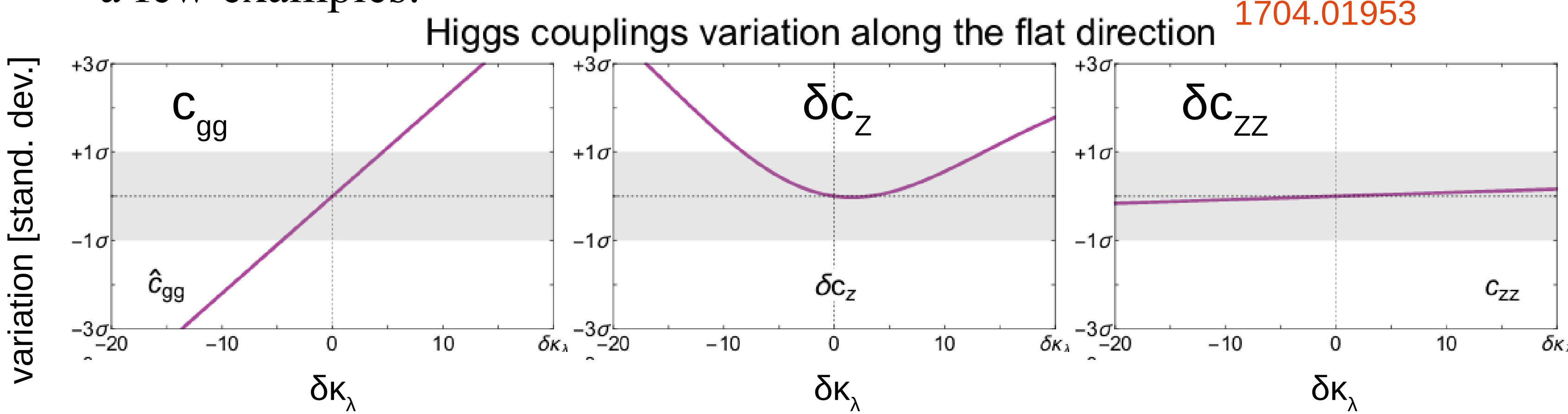
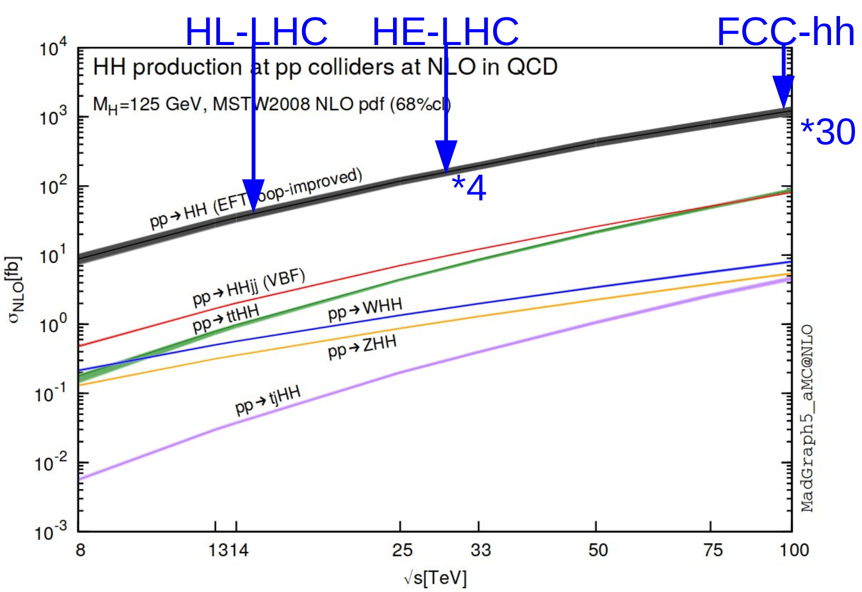
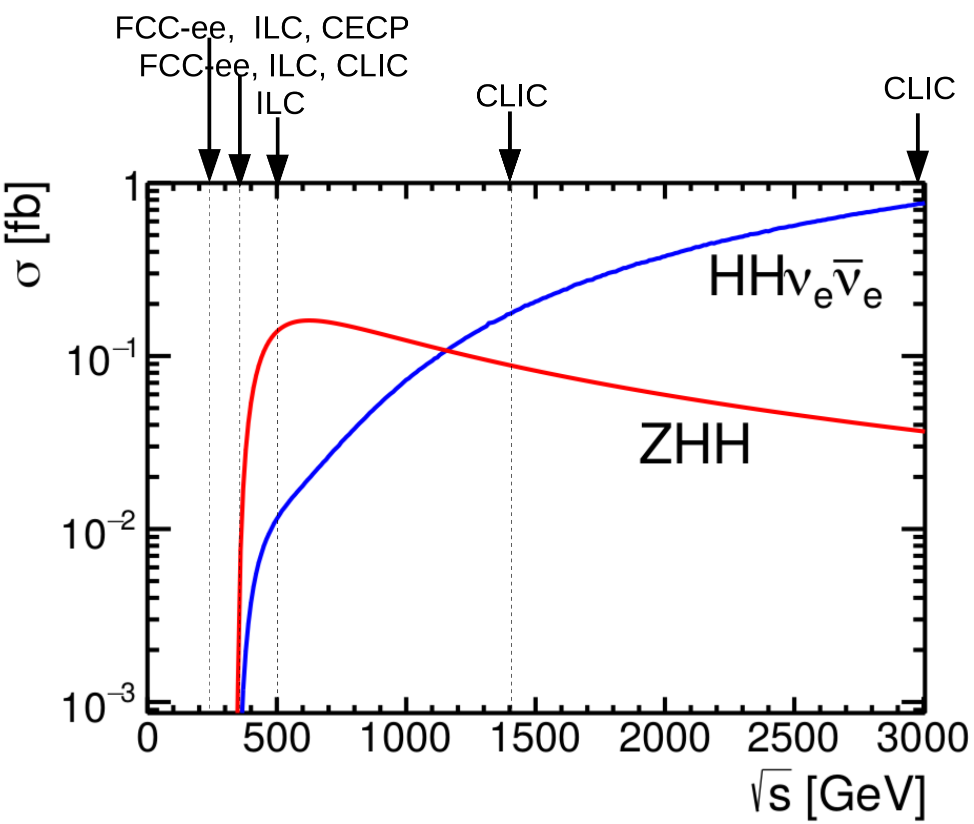


  - could also affect EW precision observables at NNLO

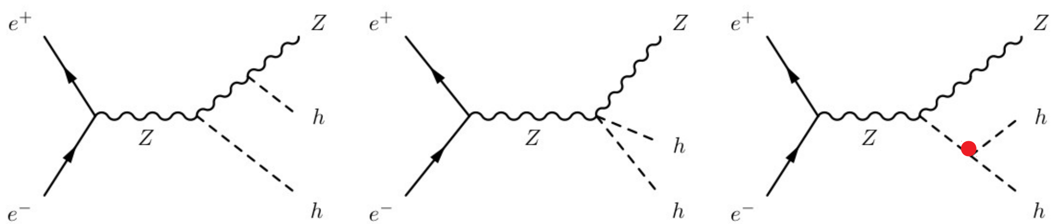
Di-Higgs at Future Colliders



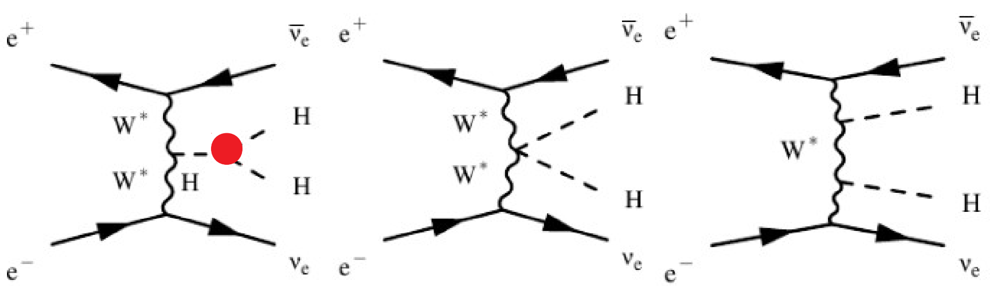


Di-Higgs production: ee colliders

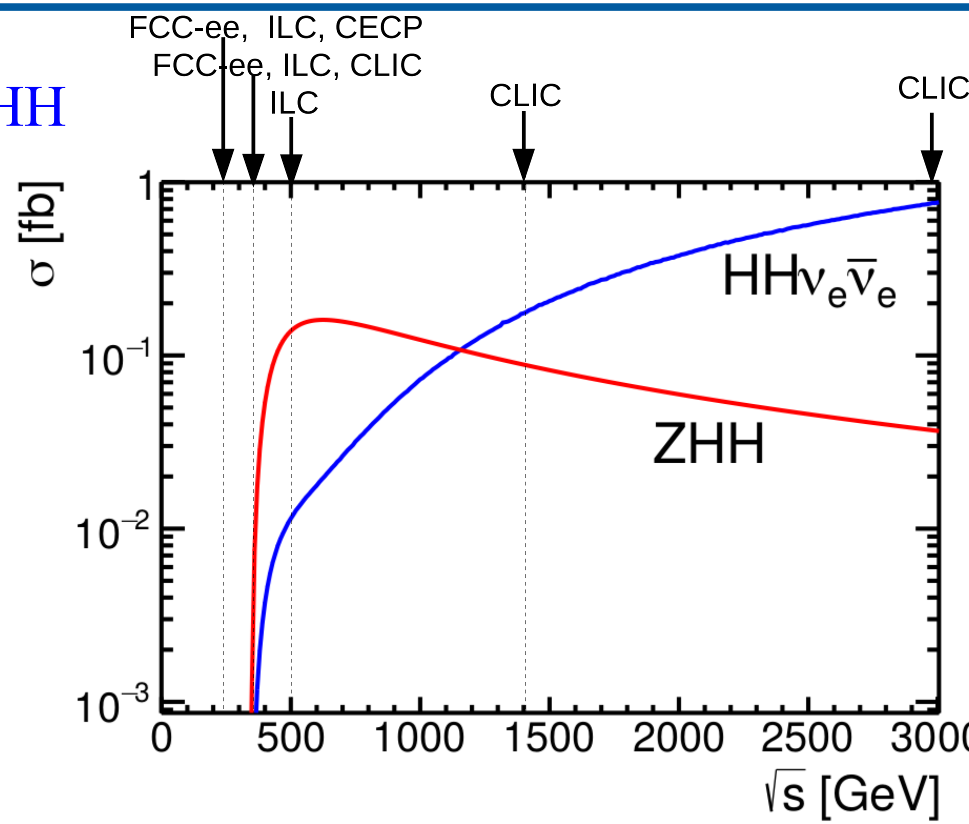
- Main production modes: ZHH and $\nu\bar{\nu}HH$
  - ZHH

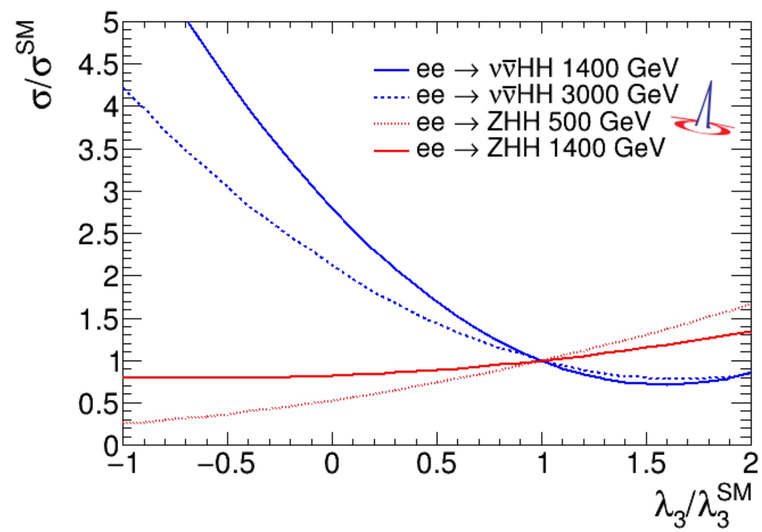


  - VBF $\nu\bar{\nu}HH$



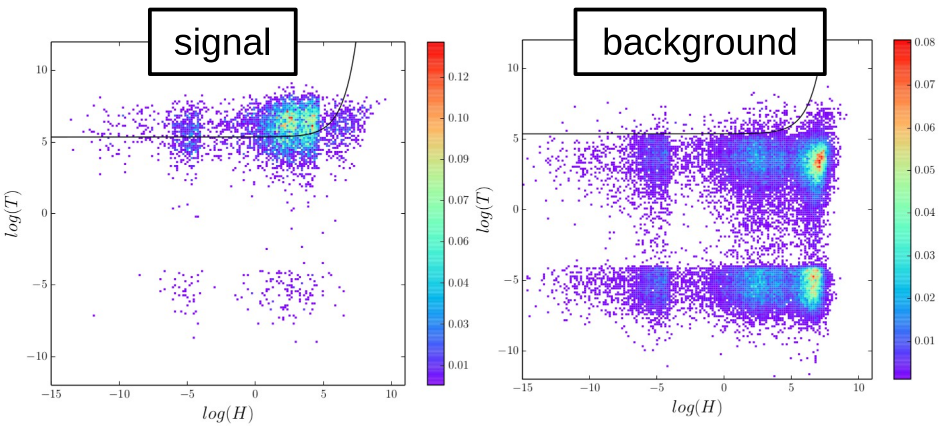
- Self-couplings through HH cross-section at different $\sqrt{s}$ + production modes + m_{HH}
  - ZHH stronger constraints for $\kappa_\lambda > 1$
  - $\nu\bar{\nu}HH$ stronger constraints for $\kappa_\lambda < 1$





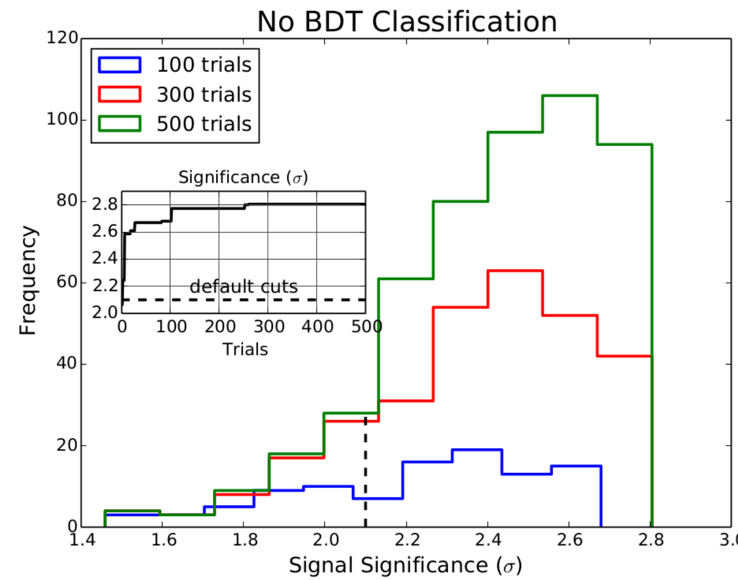
HL-LHC, ‘alternative’ methods

- $HH \to b\bar{b}WW(\to l\nu l\nu)$:
  Introduce two new variables
  - Topness (T): degree of consistency with di-lepton tt production
  - Higgsness (H): compatibility with Higgs and W masses



- Could enhance the significance from 0.6 to 1.4-3.0σ
  - effect of pile-up on those variables?

- $HH \to b\bar{b}\gamma\gamma$:
  Bayesian optimisation and BDT compared to cut-based



- No pile-up included, but shows the potential of sophisticated techniques: could achieve up to 4σ
  - illustrated in the YR with ATLAS and CMS using MVA techniques

HOW TO APPROACH SYSTEMATICS

- The large HL-LHC dataset will enable accurate measurements and unprecedented sensitivity to very rare phenomena
- In several analyses **systematic uncertainties will become a limiting factor**
- Several sources of systematics to consider:

Detector driven

Luminosity

Data statistics in control regions

Method uncertainties

Theory normalization and modeling

MC statistics

- Synergy of ATLAS and CMS in many physics projections and complexity of the problem required development of a **common set of guidelines**
  - Focus on experimental systematics that are most important for the projection studies we need (can't be comprehensive!)
    - Jet Energy Scale/Resolution, MET, B-tagging, Tau-ID, and many more…
  - Evaluation of theory uncertainties improvement

7 COMMON GUIDING PRINCIPLES FOR YR18

* Statistics-driven sources: data → $\sqrt{L}$, simulation → 0
    * account for larger data sample statistics available
    * to better understand full potential of HL-LHC
* Theory uncertainties typically halved
    * applies to both normalization (x-sec) and modeling
    * due to higher-order calculation and PDF improvements
* Uncertainties on methods kept as latest published results
    * Trigger thresholds same or better(lower) than current
    * assumption that pile-up effects are compensated by detector upgrades improvement and algorithmic developments
* Intrinsic detector limitations stay ~constant
    * usage of full simulation tools for detailed analysis of expected performance, thanks to the large effort for TDRs preparation
    * detector understanding and operational experience may compensate for e.g. detector aging
    * harmonized definition of « floor » values for experimantal systematics
* Luminosity uncertainty 1%

MORE DETAILS ON PROCEDURE

- Whenever feasible present results as

value ± stat ± syst_exp ± syst_theory [± syst_lumi]

- Baseline scenario defined as:
  - **YR18(S2):** based on synchronised estimates of ultimate performance for experimental and theory uncertainties, and applying guidelines as in previous slide

Summary (simplified) table of some values of experimental systematics harmonized between ATLAS & CMS

Object	WP	Value
Muons	reco+ID(+ISO)	0.1%(0.5%)
Electrons	reco+ID+ISO	0,5%
Taus	reco+ID+ISO	5%(as in Run2)
B-jet tag	30<pt<300GeV (pt>300GeV)	~1%(2-6%)
c-jet tag		~2%
Light jets	L/M/T WP	5/10/15%
JES	abs/rel scale	0.1-0.2%(0.1-0.5%)
JEC	Pile-Up	0-2%
JEC	Flavor	0,75%
Integrated Luminosity		1%