HH production at the HL-LHC with CMS

Sylvie Braibant
University of Bologna and INFN
on behalf of the CMS Collaboration

HH: why ?

- In the Standard Model (SM), the **Brout-Englert-Higgs** (BEH) self-coupling λ is **uniquely determined** by the structure of the **scalar potential**

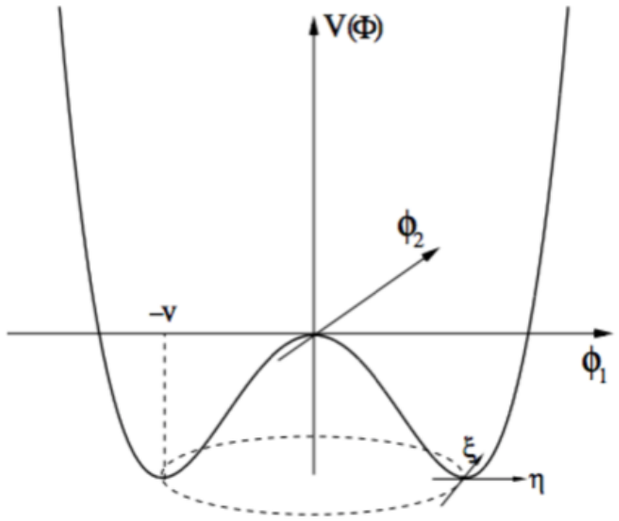
$$V = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4$$

where

$$\lambda_3 = \lambda_4 = m_h^2/(2v^2)$$

depends only on BEH field VEV and mass

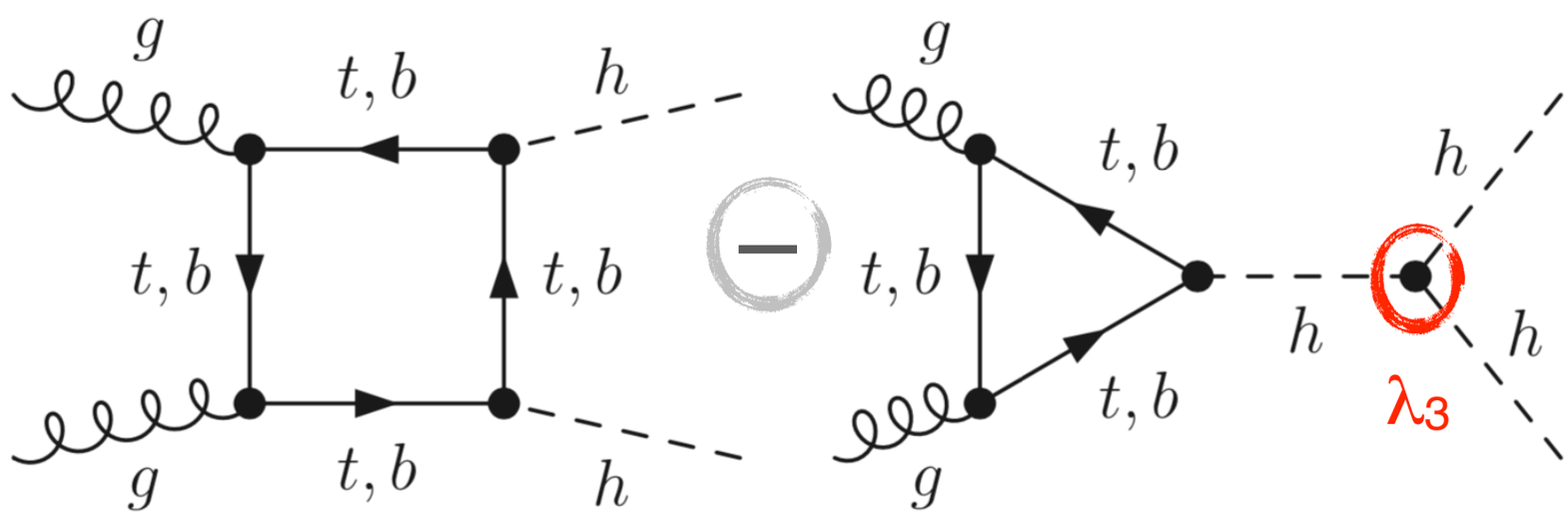
arXiv:1610.07922



- Experimental measurement of the trilinear BEH coupling λ_3
  - → Crucial **test of the ESB mechanism**
  - → Unique way to probe the **existence of BSM physics** as a modification of λ_3
    - Anomalous trilinear coupling
    - New resonance decaying to HH

HH Production

- Production dominated by **gluon-gluon fusion mode**



arXiv:1610.07922

- **Small inclusive cross section** due to negative interference between the two diagrams

$$\sigma = 36.59^{+2.1\,\%}_{-4.9\,\%}\ \text{fb at } \sqrt{s} = 14\ \text{TeV}$$

Value at the NNLO of the perturbative QCD calculation, including NNLL corrections and finite top quark mass effects

arXiv:1803.02463v1

→ need **HIGH LUMINOSITY**

HH Decay

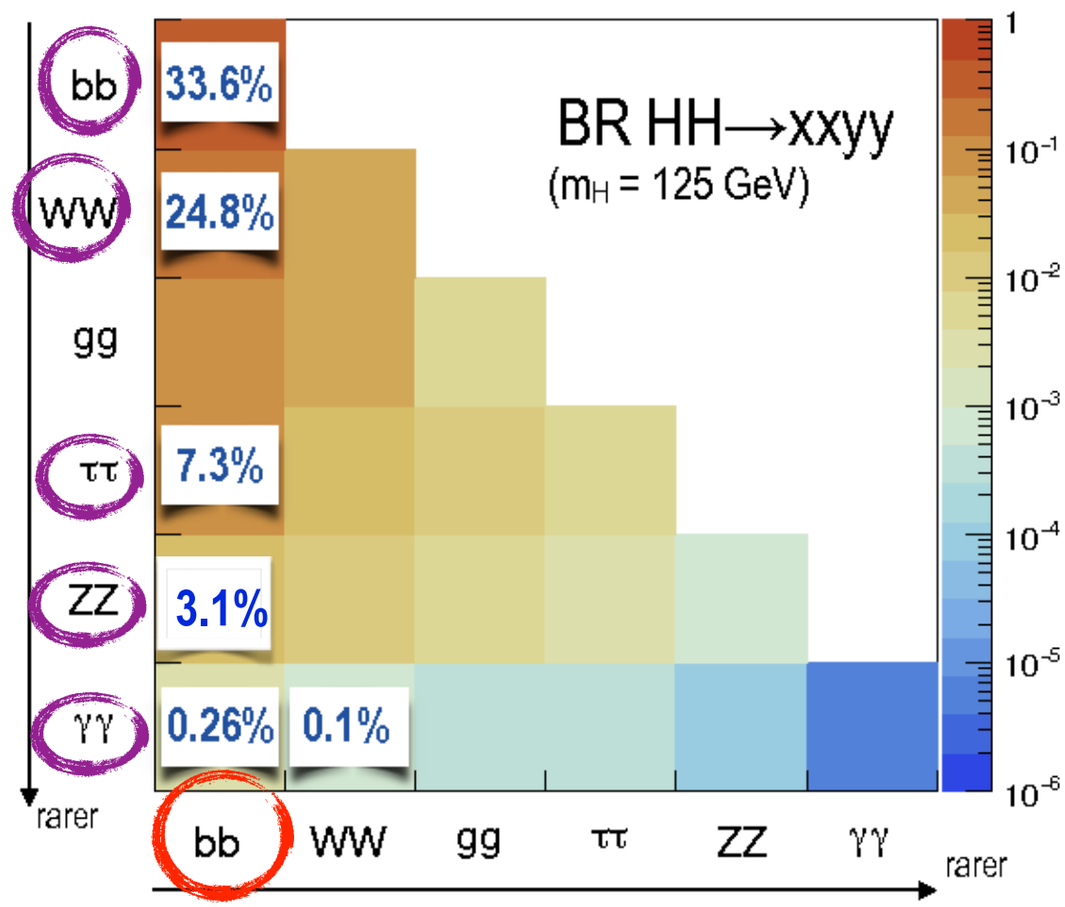
- **H → bb** chosen for one H boson to keep $\mathcal{BR}$ high enough

- Five decay channels for the other H: **H→ bb, WW, ττ, ZZ, γγ**

Trade off between $\mathcal{BR}$ and purity

- H→γγ/ZZ channels: small $\mathcal{BR}$ but **strong sensitivity** given their low-background level

Channel	$\mathcal{B}$ [%]
bbbb	33.6
bbττ	7.3
bbWW($\ell\nu\ell\nu$)	1.7
bbγγ	0.26
bbZZ($\ell\ell\ell\ell$)	0.015



LHC → HL-LHC

LS3 (2024-2026): **LHC major upgrade**

Pileup [PU]: average number of proton-proton collisions per bunch crossing

→ **major challenge for the experiments**

LS3 → HL-LHC

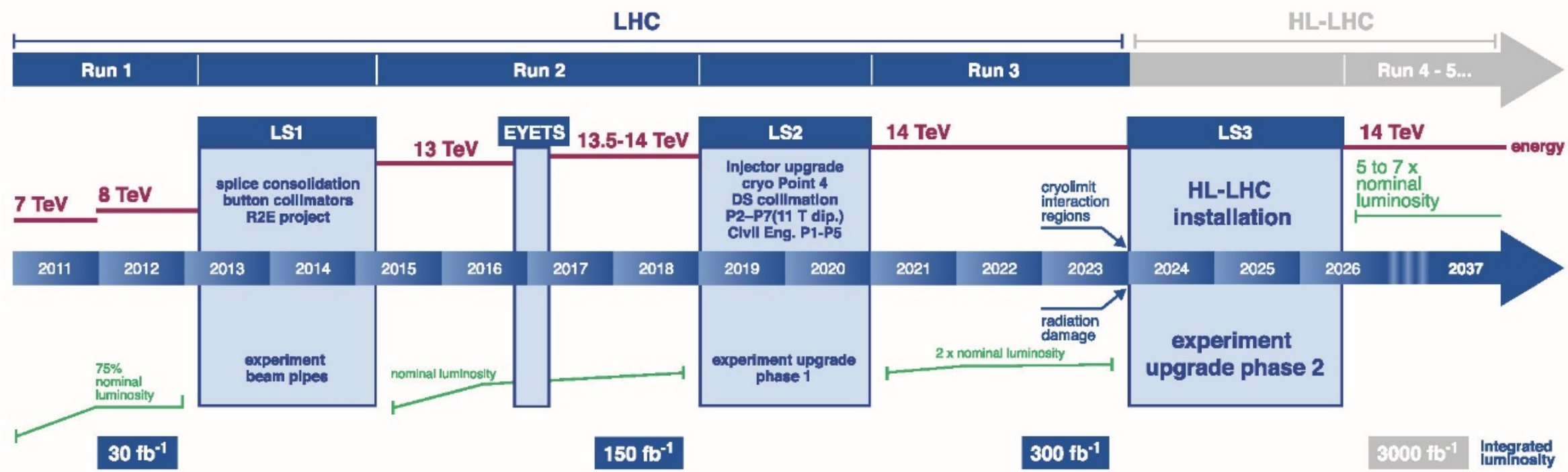
$\mathscr{L}$ = 5 (7.5) $\cdot 10^{34}$ cm^{-2} s^{-1}

$\sqrt{s}$ = 14 TeV

PU = 200

HL-LHC

~3000 fb^{-1} per experiment



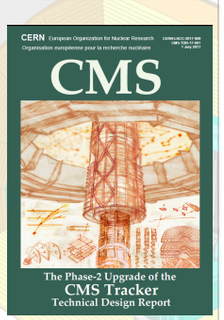
CMS Detector Upgrades

See Pallabi Das's talk

- Performance compromised by **radiation damage** and **increased pileup**
- Detector upgrades crucial to **maximise physics potential** and **maintain a good object reconstruction** in this harsh environment → increased radiation hardness, increased forward acceptance, higher granularity …

New Tracker

- Increased radiation hardness
- Higher granularity
- Increased forward acceptance up to $\eta = 4$
- Reduced material in the tracker volume
- Tracks in hardware trigger (L1)

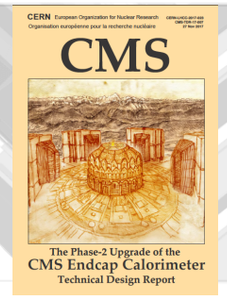


Muons

- In the forward region, improved RPC + new GEM detectors → Increased acceptance up to $\eta \sim 3$
- Front-end electronics upgrade for DT's and CSC's

New Endcap Calorimeter

- Radiation tolerant
- High granularity (HGCAL)
- Timing information



On-going efforts:

- MIP Timing Detector TDR (Oct 2019)
- L1/HLT TDR (2019/2020)

CMS Upgraded Detector Simulation

DELPHES

arXiv:1307.6346

- Fast ***parametric*** simulation software
  - Simulate the ***response of he CMS upgraded detector***
  - Account for the **PU: + 200** minimum bias interactions simulated with PYTHIA8
  - Extensively compared and tuned from full simulation based on GEANT4

Projections

arXiv:1902.00134v2

CMS PAS FTR-18-019

- Use DELPHES samples
- Optimised for a projected integrated luminosity of 3000 fb^{-1}
- Ultimate collider scenario with $\mathscr{L} = 7.5 \cdot 10^{34}$ cm^{-2} s^{-1} might provide up to 4000 fb^{-1}

HH → bbbb

- **Largest $\mathcal{BR}$ amongst** the HH final states
- Large contamination from the multijet background → **experimentally challenging**

"Resolved" event topology

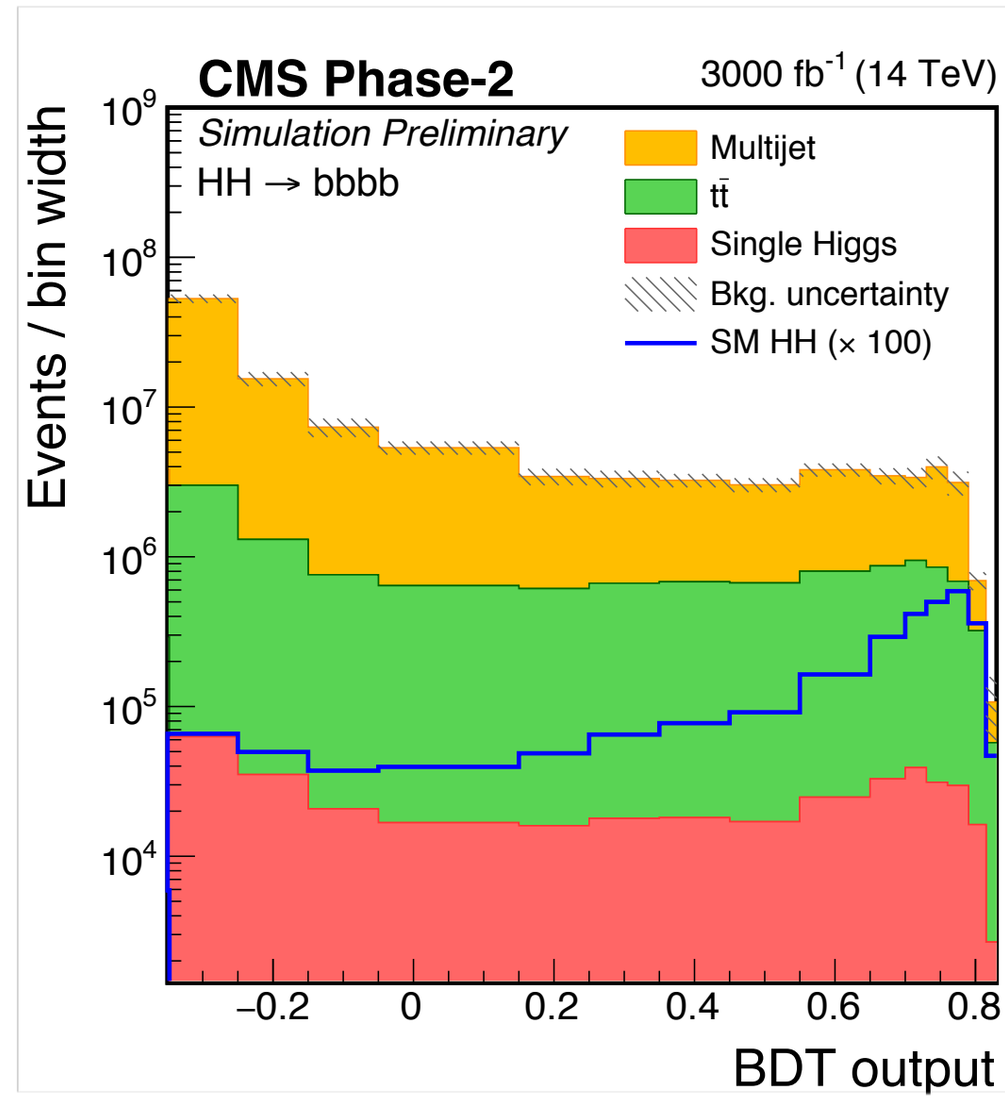
- 4 b-jets **all reconstructed** separately

Event selection:

- ≥ 4 b-jets with $p_T > 45$ GeV and $|\eta| < 3.5$
- Jet pairing based on combination minimising difference in invariant mass of the two jet pairs

	Event Yields
HH signal	1370
Background	$1.1 \cdot 10^7$

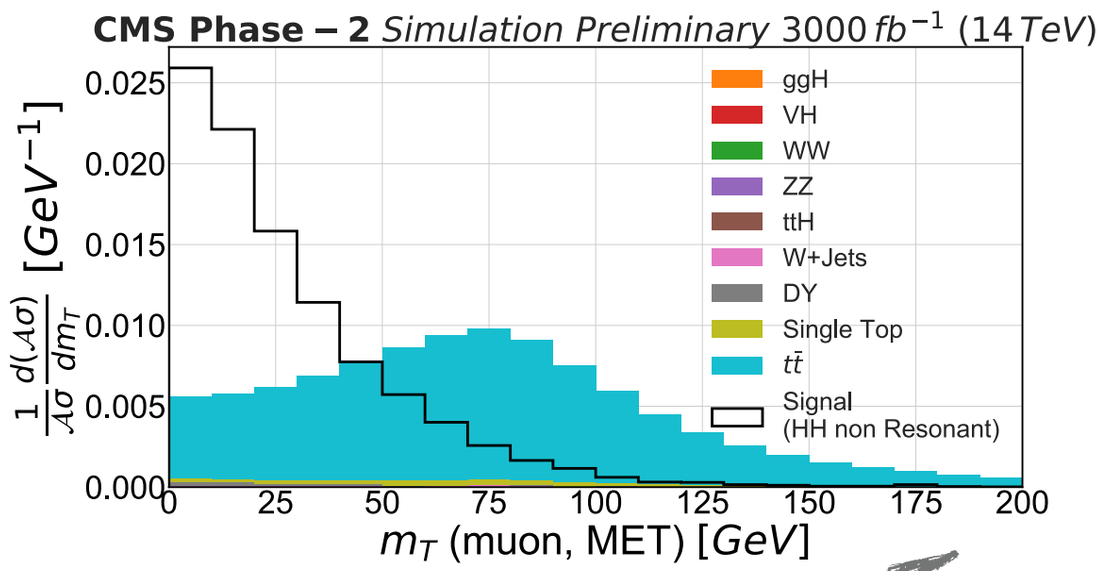
- → **Use of BDT** to identify the signal contribution in the overwhelming background



HH → bbττ

- Sizeable $\mathcal{BR}$ = 7.3% → experimentally favourable

- Events exclusively selected into 3 final states with ≥ 1 τ_{had} (85%): $e\tau_{had}$, $\mu\tau_{had}$, $\tau_{had}\tau_{had}$
- ≥ 2 b-jets with $p_T > 30$ GeV and $|\eta| < 2.4$



Transverse mass

Event Yields	$\mu\tau_{had}$	$e\tau_{had}$	$\tau_{had}\tau_{had}$
HH signal	100	70	60
Background	$4.3 \cdot 10^6$	$2.9 \cdot 10^6$	$1.25 \cdot 10^3$

- → **Neural-network based discriminant** to separate the signal from the background
- 52 input variables

HH → bbWW → bb$\ell\nu\ell\nu$

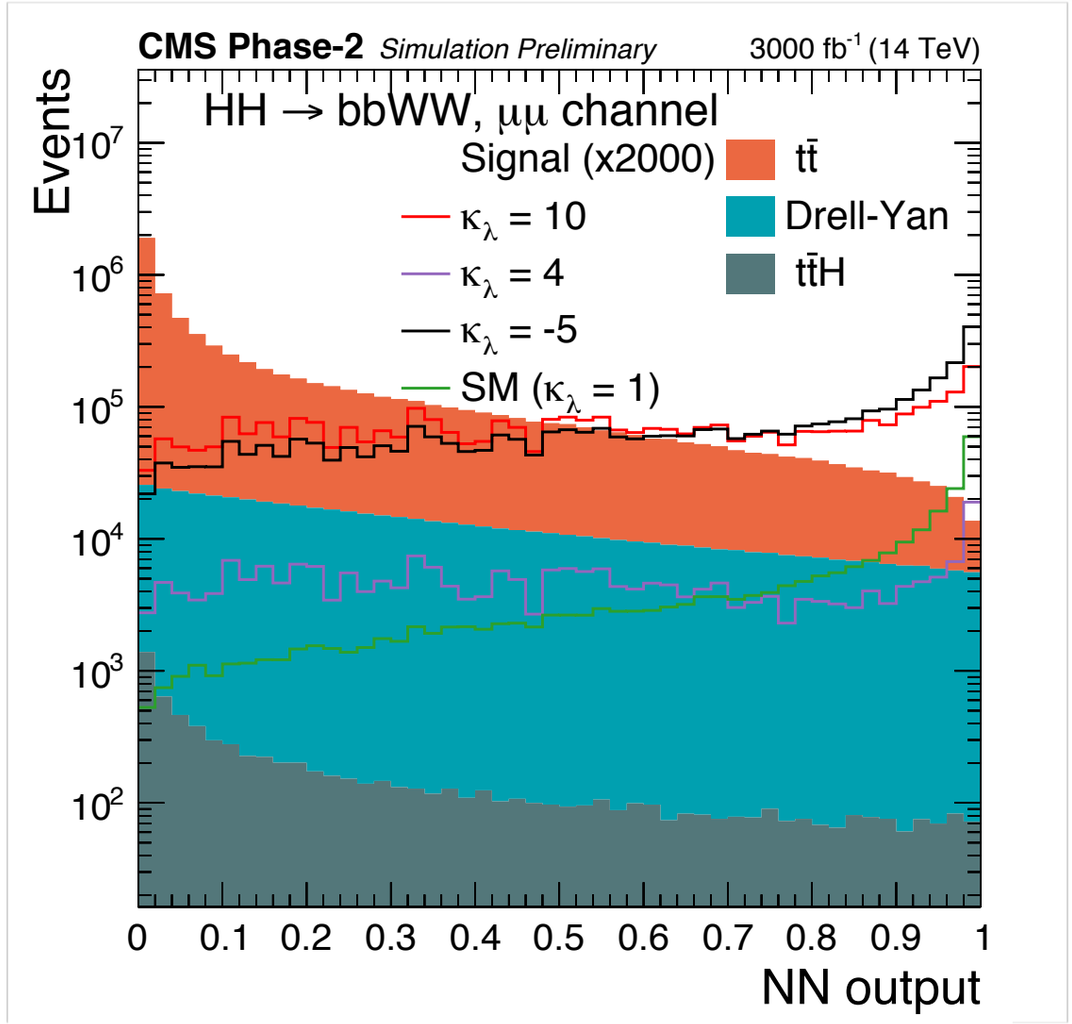
- bb$\ell\nu\ell\nu$ final states with ℓ = e, μ

Dominant backgrounds are irreducibile:

- tt production in fully leptonic decay mode
- Drell-Yan production of lepton pairs + jets

Event Yields	*ee*	μμ	eμ+μe
HH signal	50	150	120
Background	$2.9 \cdot 10^6$	$8.4 \cdot 10^6$	$7.5 \cdot 10^6$

- Kinematic properties combined in a **Neural Network** (NN) discriminant to enhance sensitivity (9 input variables)



- **Very powerful discrimination** against background

HH → bbγγ

- Tiny $\mathcal{BR}$ but experimentally very clean → large sensitivity

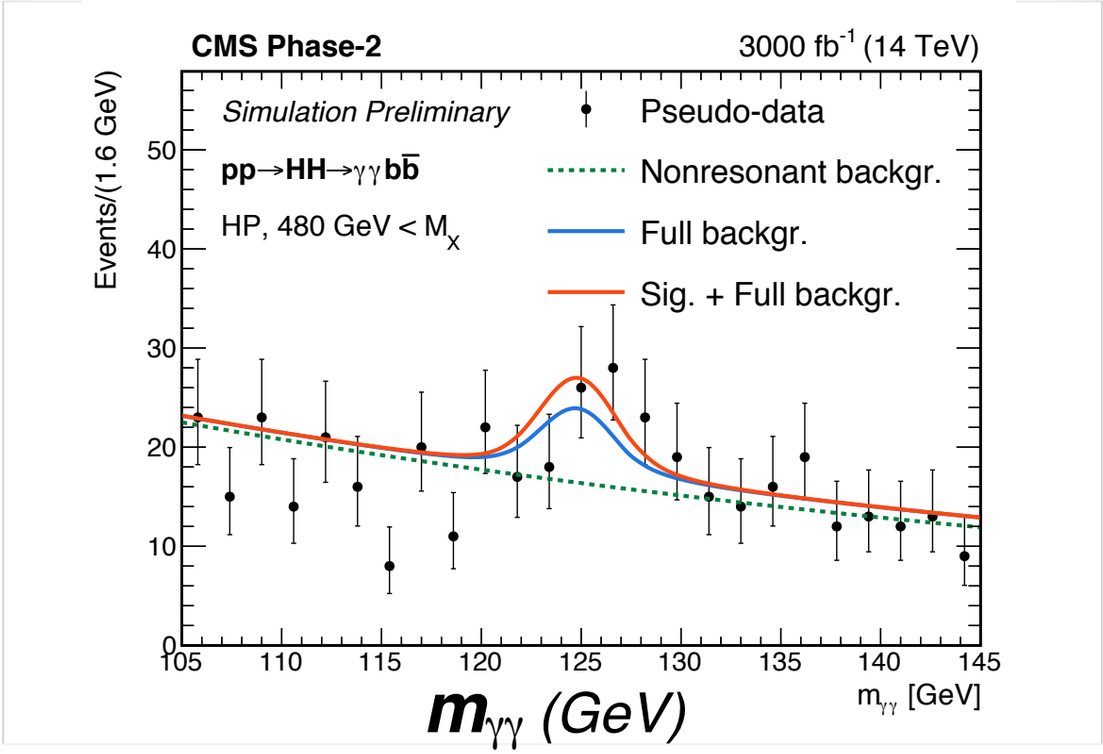
Backgrounds:

- **Non-resonant** di-photon events
- **Resonant background**: Higgs boson production in association with two top quarks (ttH):

→ suppressed by a dedicated multivariate discriminant with 12 variables

→ rejection of 75% of the ttH contamination for a signal efficiency of 90%

	Event Yields
HH signal	40
Res. bckg	190
Non-res. bckg	3600

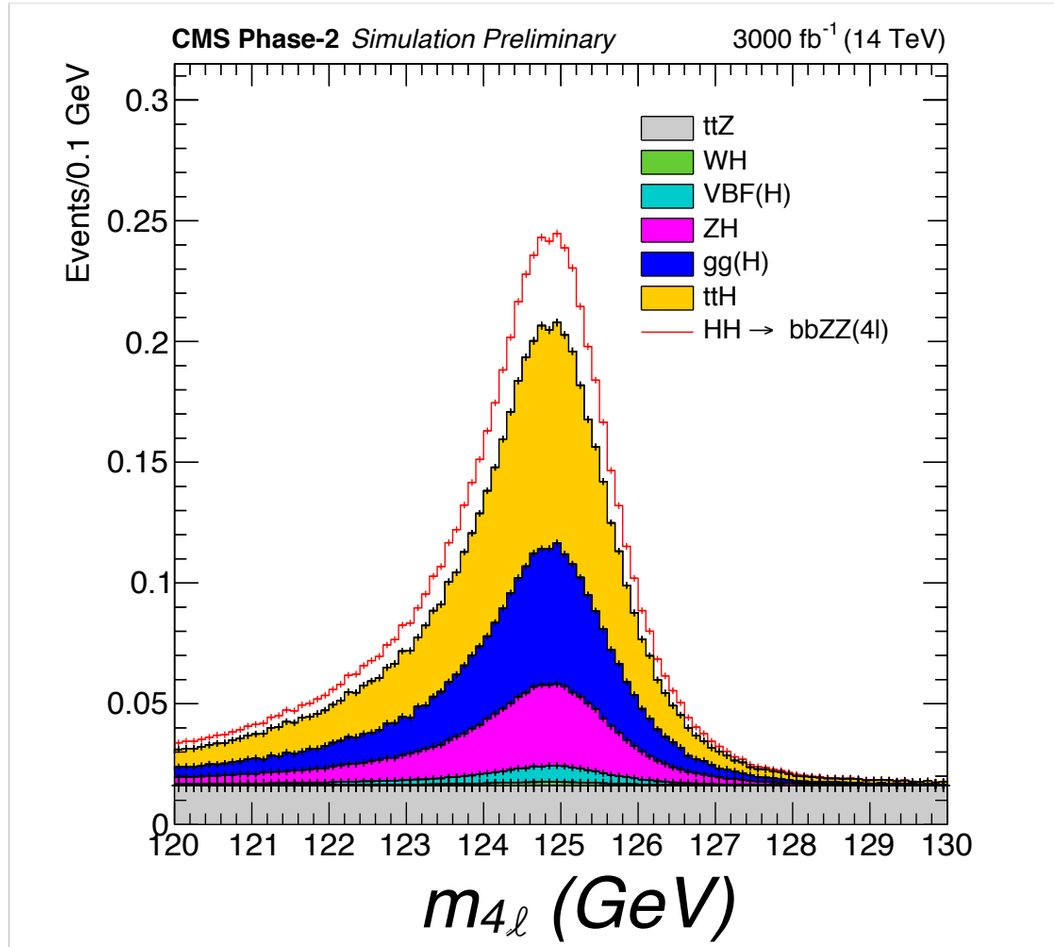


HH → bbZZ → bb$\ell\ell\ell\ell$

- Very rare but clean final states:
  4e, 4μ, 2e2μ channels
- Background processes are mostly single H production
  - ttH, ggH, ZH, WH, VBF
- Other backgrounds: ttZ, ttZZ

Events selection:

- ≥ 4 isolated muons (electrons) with $p_T > 5(7)$ GeV and $|\eta| < 2.8$
- Z candidates from pairs of $\ell^+\ell^-$ → Z_1 and Z_2
- $50 \leq Z_1 \leq 100$ GeV and $12 \leq Z_2 \leq 60$ GeV
- ≥ 1 ℓ with $p_T > 20$ GeV and ≥ 1 ℓ with $p_T > 10$ GeV
- $120 \leq m_{4\ell} \leq 130$ GeV



HH → bb4ℓ	***Event Yields***
HH signal	1.0
Background	6.8

Combined Results on Signal Strength

- Statistical combination of the 5 decay channels
- Both systematic and statistical uncertainties considered
- In analyses using DELPHES and L = 3000 fb^{-1}:
  → systematic uncertainties are "floor" values

CMS NOTE -2018/006

- Signal strength:

$$\mu = \frac{\sigma_{HH}}{\sigma_{HH}^{SM}} < 0.77 \text{ @ 95\% C.L.}$$

→ with a corresponding significance of 2.6 σ

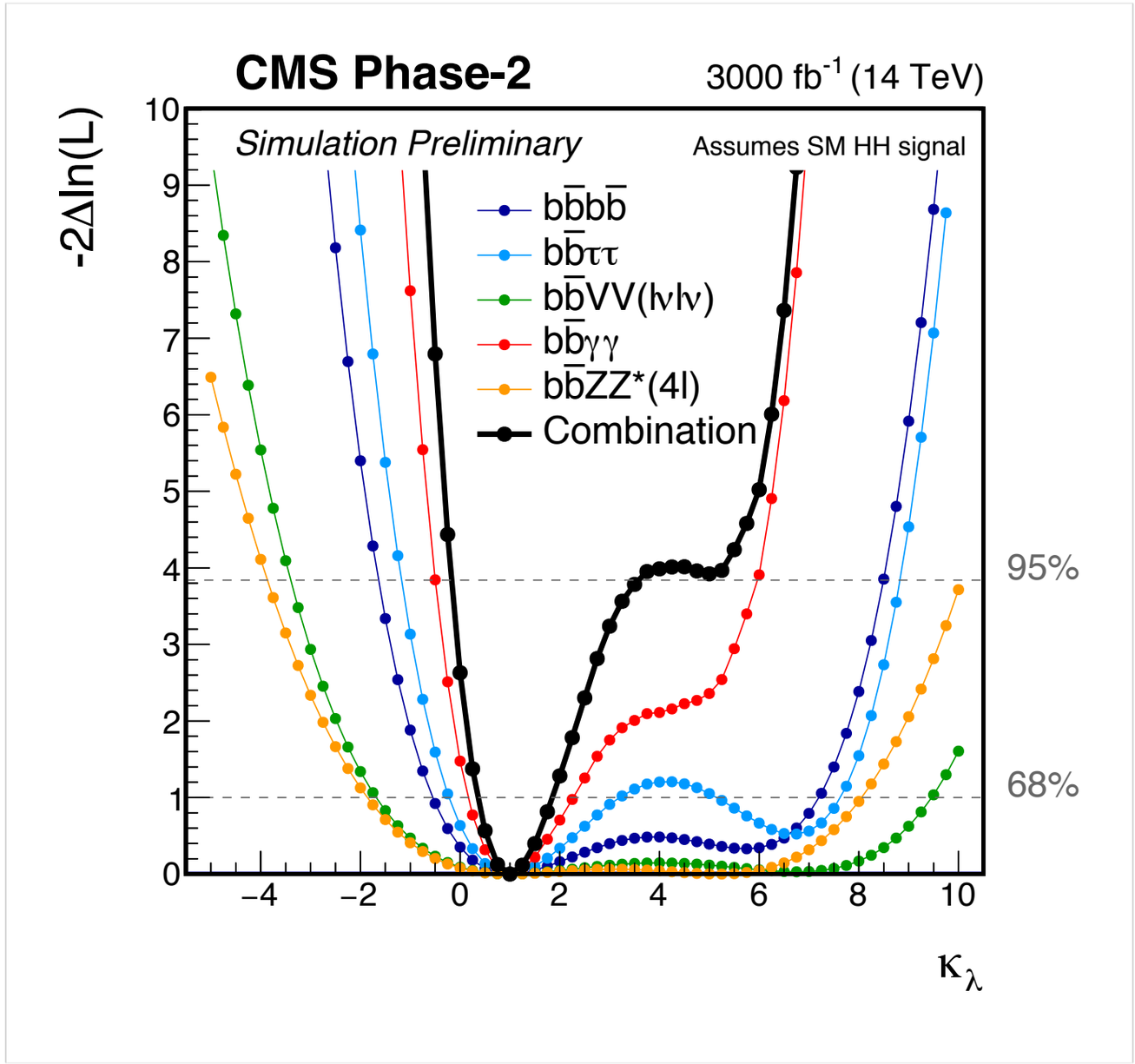
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

Combined Results on K_λ

- Prospects for the measurement of λ_3
- Scan of the likelihood as a function of the coupling modifier K_λ:

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

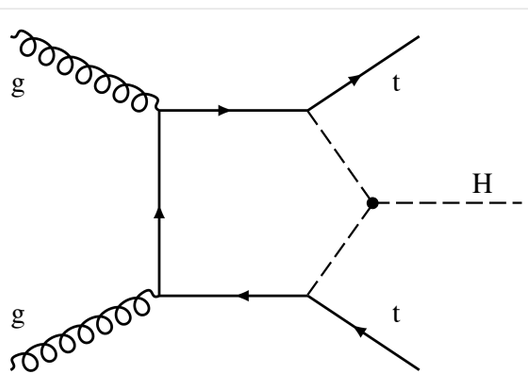
- Projected confidence interval on K_λ:
  - [0.35, 1.9] at the 68% CL
  - [-0.18, 3.6] at the 95% CL



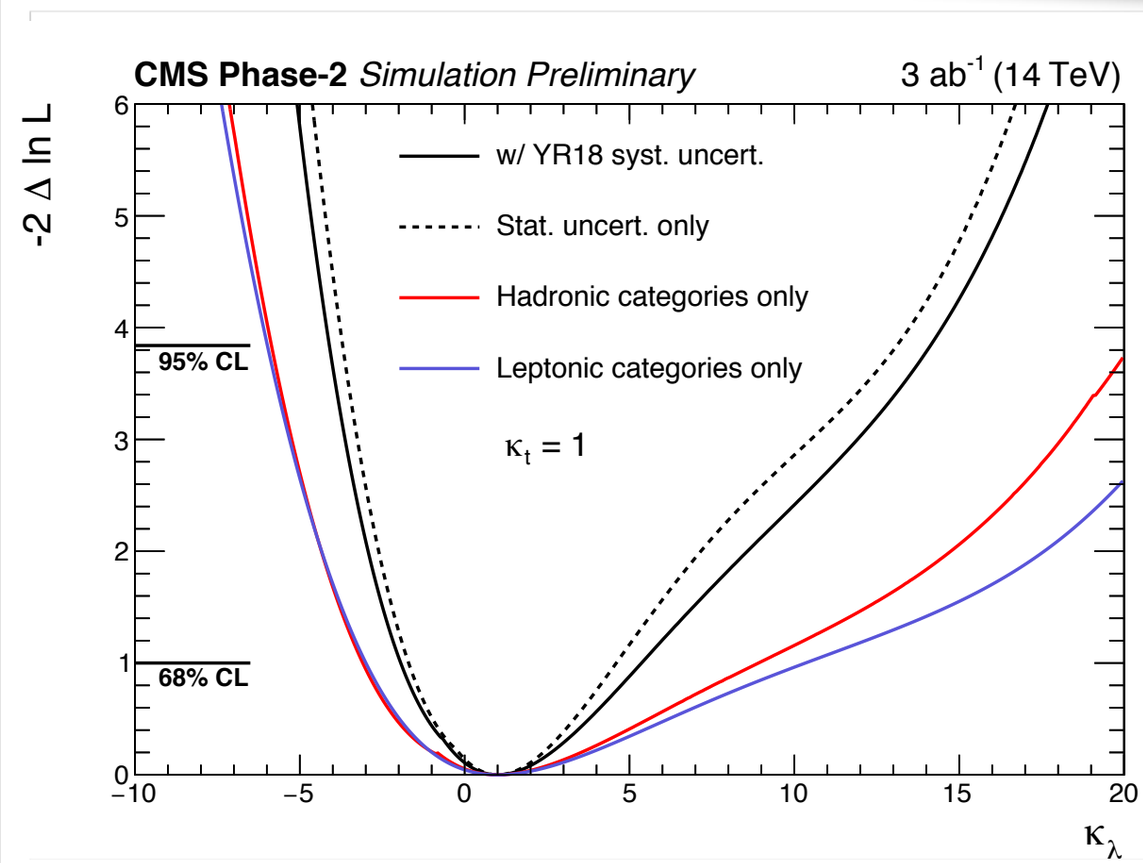
Constraint on k_λ from Differential Cross Section

- Differential cross section measurement using Higgs p_T can disentangle the H self-coupling effects from anomalous top-Higgs coupling
- ttH and tH events with $H \rightarrow \gamma\gamma$ decay selected in hadronic or leptonic final states depending on top decay

See Pallabi Das's talk



- Projected confidence interval on K_λ:
  - [-4.1,14.1] at the 95% CL



Summary

- HL-LHC will **significantly increase physics reach** of LHC experiments BUT
  - **Challenging experimental conditions** for experiments (unprecedented pileup)
  - → **Extensive detector upgrades** will preserve performance and provide new capabilities

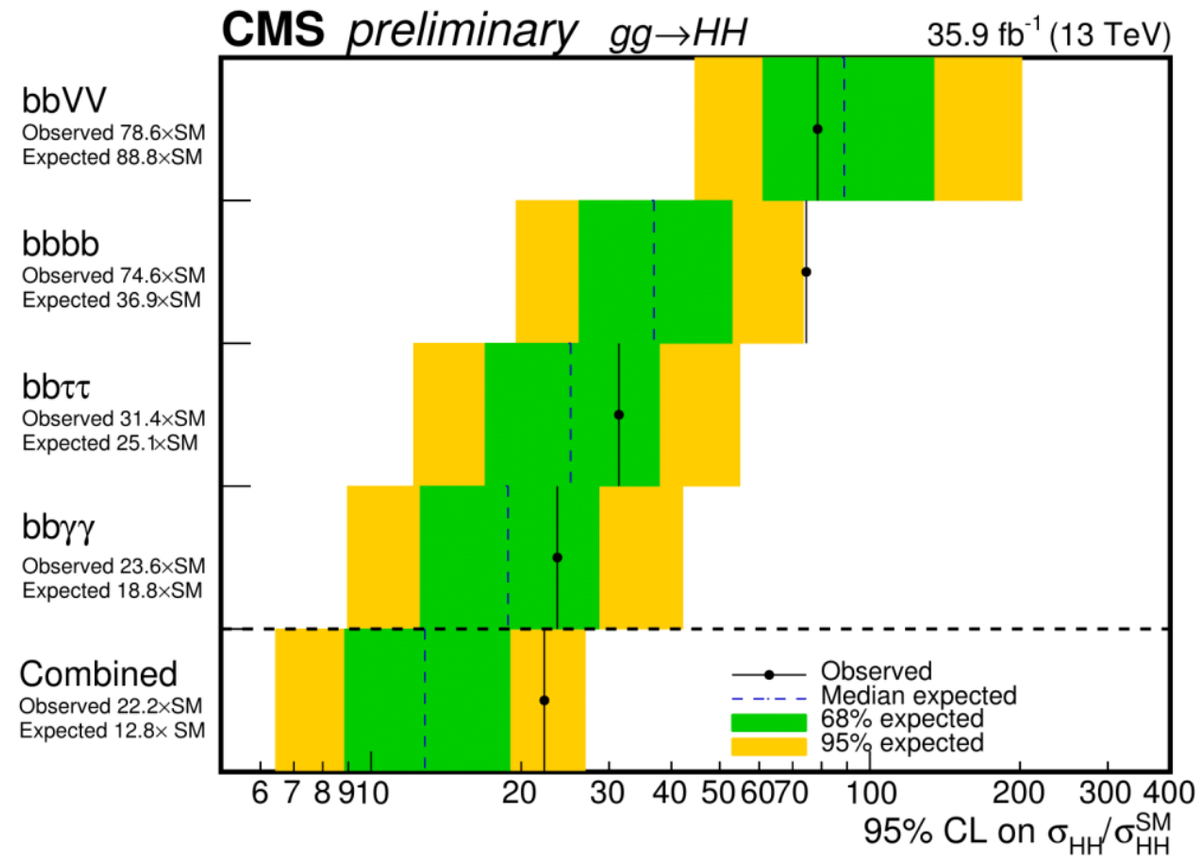
- HH production: **a top priority research subject**
  - Rate limited due to the small HH cross-section → **excellent case for the HL-LHC**
  - Direct access to the shape of the scalar potential
  - Sensitive to BSM physics effects

- **Current prospects**
  - Importance of **exploring and combining many decay channels**
  - Projected sensitivity to SM HH is **~3** σ
  - Projected confidence interval on the K_λ coupling modifier:
    - **[0.35, 1.9] at the 68% CL**
    - **[-0.18, 3.6] at the 95% CL**

Backup

HH@Run 2 (2016)

- **HH@LHC Run2 (2016): not yet sensitive** to SM HH production because of small cross section and large backgrounds



- Observed (expected) signal strength:

$$\mu = \frac{\sigma_{HH}}{\sigma_{HH}^{SM}} < 22.2 \ (12.8) \ @ \ 95\% \ C.L.$$

→ Decay channel **combination essential for an evidence** of HH production

Event and Detector Simulation

Parton level generation

- Madgraph5_aMC@NLO for signal and most backgrounds
- POWHEG for top processes (i.e., ttH)

arXiv:1405.0301

PYTHIA8

- Parton shower and decay

arXiv:1410.3012

DELPHES

arXiv:1307.6346

- Fast ***parametric*** simulation software
  - Simulate the ***response of he CMS upgraded detector***
  - Account for the **PU: + 200** minimum bias interactions simulated with PYTHIA8
  - Extensively compared and tuned from full simulation based on GEANT4

Analyses

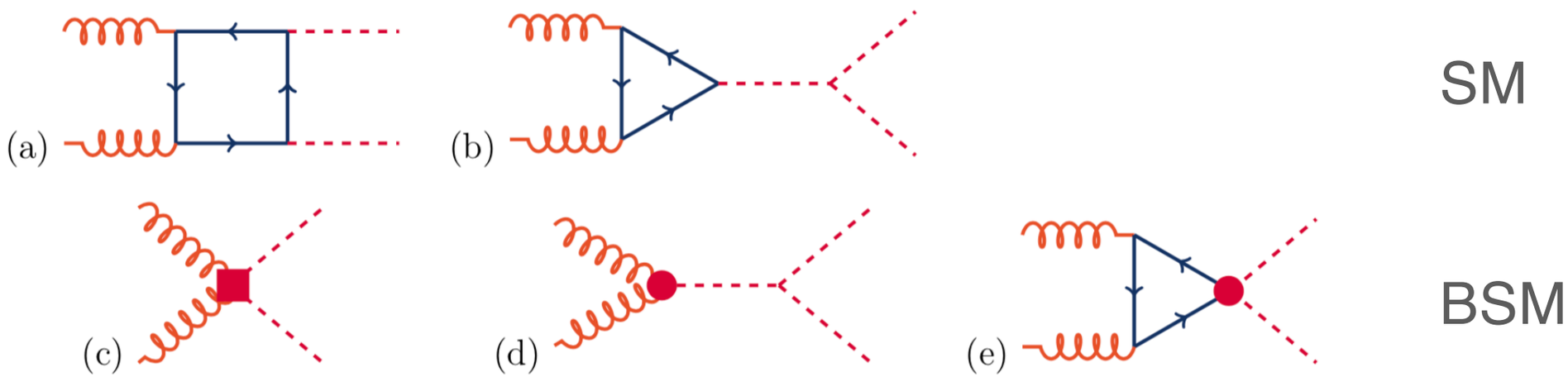
arXiv:1902.00134v2

CMS PAS FTR-18-019

- Optimised for a projected integrated luminosity of 3000 fb^{-1}
- Ultimate collider scenario with $\mathscr{L} = 7.5 \cdot 10^{34}$ cm^{-2} s^{-1} might provide up to 4000 fb^{-1}

EFT

- Feynman diagrams that contribute to HH production by gluon-gluon fusion (LO):



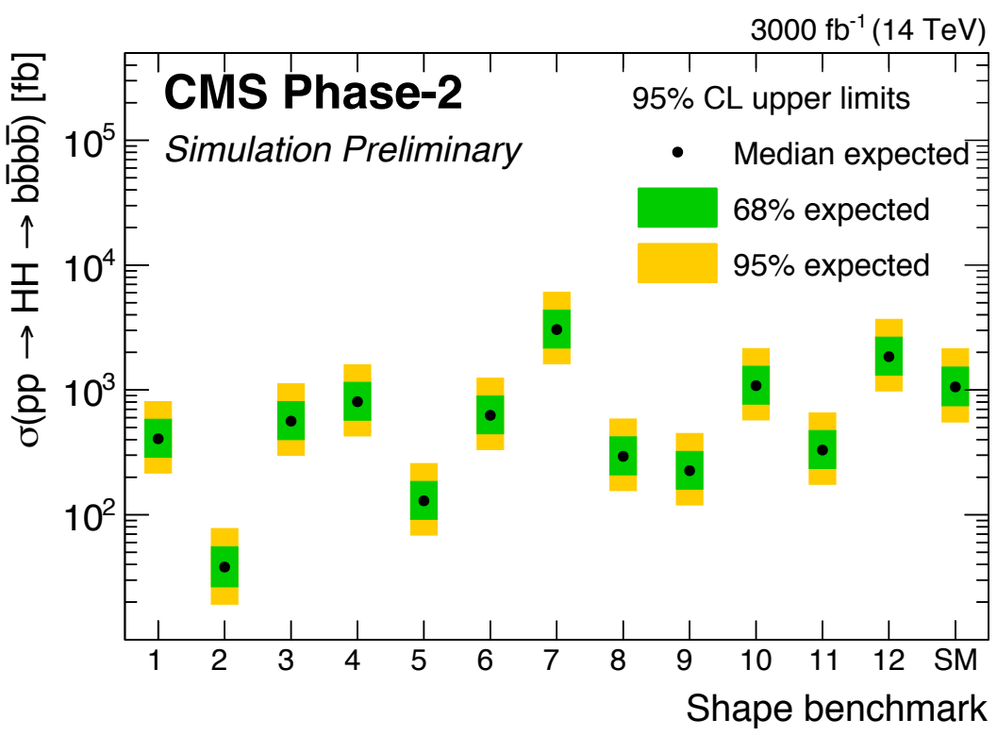
- Gluon fusion HH production described by 5 parameters: κ_λ, κ_t, c_g, c_{2g} and c_2
- Deviations from SM values parametrized with multiplicative factors κ_λ and κ_t
- Contact interactions ggH, gg2H, ttHH parametrized with absolute couplings c_g, c_{2g}, and c_2
- Relevant part of the Lagrangian then takes the form

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

EFT

- Parameter values of the 12 benchmarks and the SM point

- Expected upper limits for non-resonant HH → bbbb in the SM and shape benchmarks (1–12)



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

HH → bbbb

- **Largest $\mathcal{BR}$ amongst** the HH final states
- Large contamination from the multijet background → **experimentally challenging**

Two complementary strategies:

"Resolved" event topology

- 4 b-jets **all reconstructed** separately

"Boosted" event topology:

- large m_{HH} → high Lorentz boost of both Higgs bosons
- 2 b-jets overlap → **single large-area jet**

Event selection:

- ≥ 4 b-jets with $p_T > 45$ GeV and $|\eta| < 3.5$
- Jet pairing based on combination minimising difference in invariant mass of the two jet pairs

Event selection:

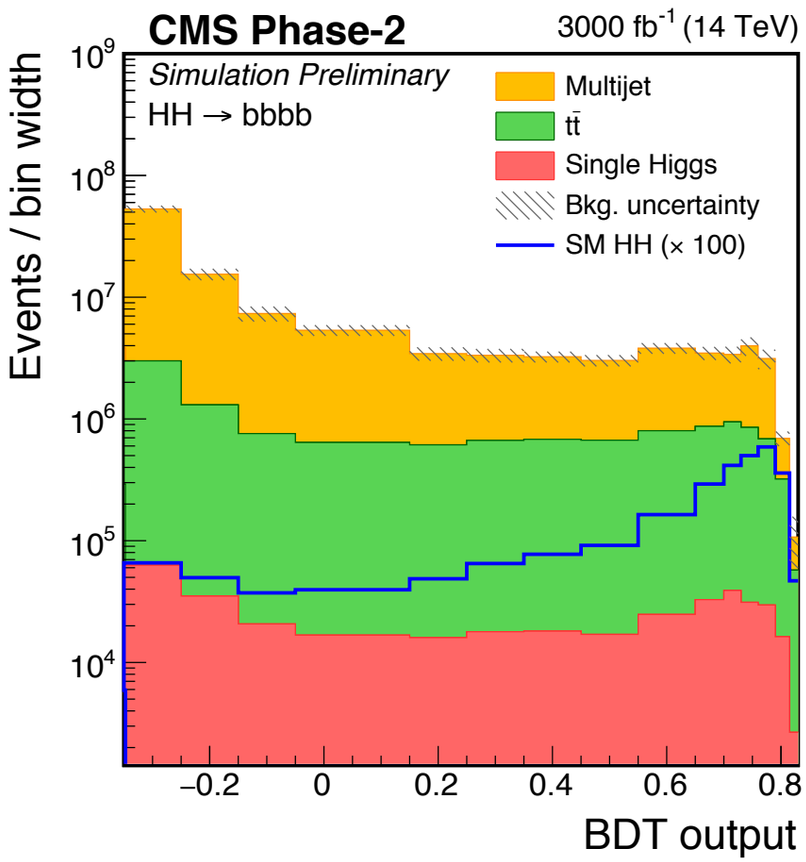
- 2 boosted H→bb, each associated with a single AK8 jet
- 2 leading-p_T AK8 jets with $p_T > 300$ GeV and $|\eta| < 3.0$
- Events classified as having exactly 3 or exactly 4 b-tagged subjets

HH → bbbb

"Resolved" event topology

	Event Yields
HH signal	1370
Background	$1.1 \cdot 10^7$

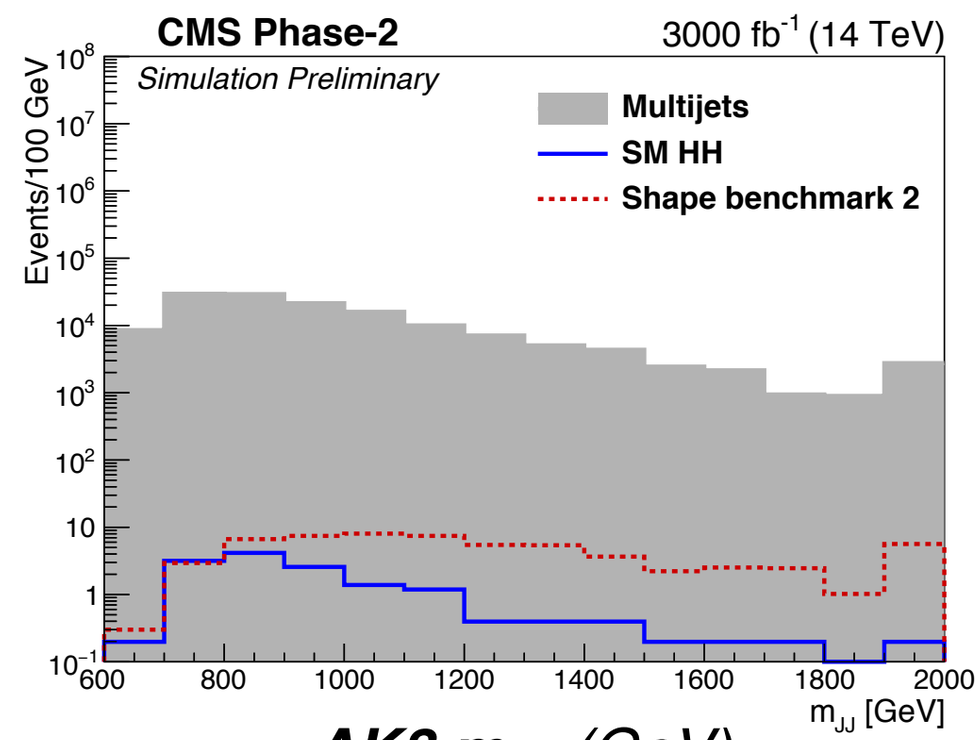
- → **Use of BDT** to identify the signal contribution in the overwhelming background



"Boosted" event topology

- Use **AK8 m_{JJ}** invariant mass

Event Yields	*3b cat*	*4b cat*
HH signal	95	15
Background	$1.08 \cdot 10^6$	$1.4 \cdot 10^5$



AK8 m_{JJ} (GeV)

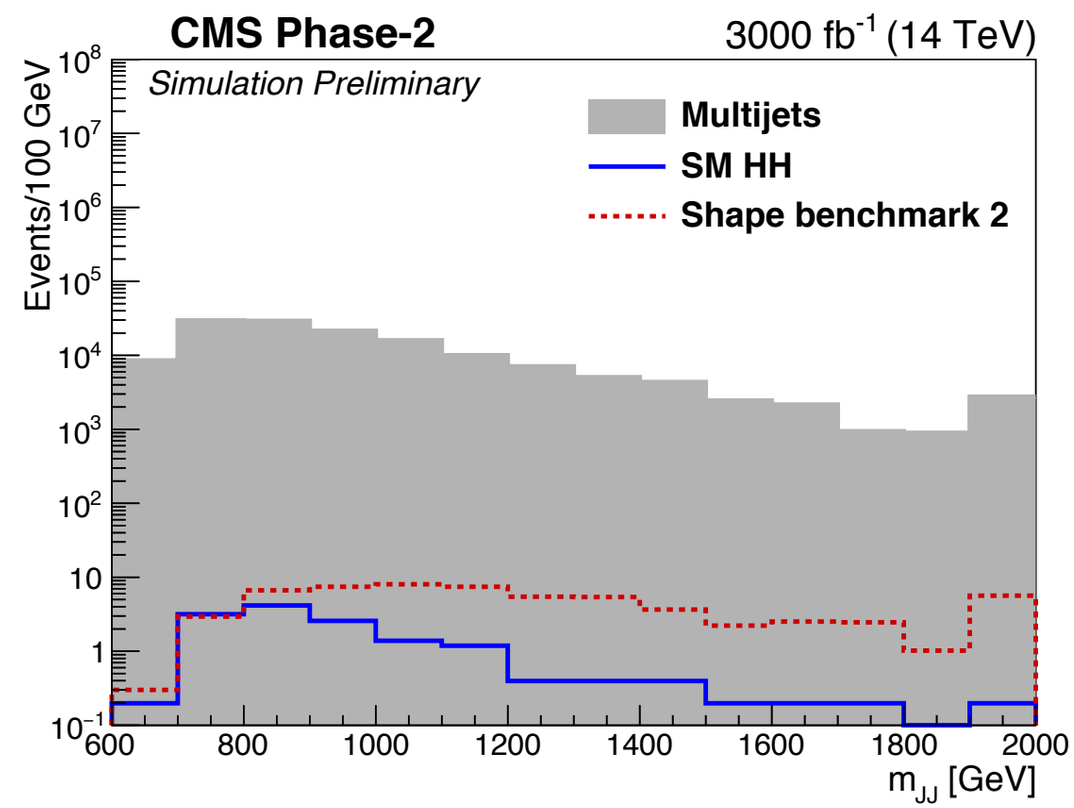
HH → bbbb

"Boosted" event topology

arXiv:1507.02245

- Most sensitive to EFT shape benchmark 2 → contact interactions

Event Yields	*3b cat*	*4b cat*
HH signal	95	15
Benchmark 2 σ ***= 10 fb***	537	61
Background	$1.08 \cdot 10^6$	$1.4 \cdot 10^5$



AK8 m_{JJ} *(GeV)*

Systematic Uncertainties

- In analyses using DELPHES and an integrated luminosity at the HL-LHC of 3000 fb^{-1}
  → systematic uncertainties are the "floor" values reported in table

CMS NOTE -2018/006

Table 1: The "floor" systematic uncertainties for the HL-LHC.

Uncertainty	Working point/ component	Value
Electron ID	All WPs, $p_T > 20$ GeV	0.5%
	All WPs, $10 < p_T < 20$ GeV	2.5%
Photon ID		2%
Muon ID	All WPs	0.5%
Tau ID	All WPs	2.5%
Jet energy scale	Total	1–2.5%
	Absolute scale	0.1–0.2%
	Relative scale	0.1–0.5%
	PU	0–2%
	Jet flavor	0.75%
Jet energy resolution		3–5% as a function of η
b-tagging	b jets (all WPs)	1%
	c jets (all WPs)	2%
	Light jets, loose WP	5%
	Light jets, medium WP	10%
	Light jets, tight WP	15%
	Subjet b tagging	1%
	Double c tagging	
p_T^{miss}	Propagate jet energy corrections uncertainties (must)	
	Propagate jet energy resolution uncertainties (recommended)	
	Vary unclustered energy by 10% (recommended)	
Integrated luminosity		1%

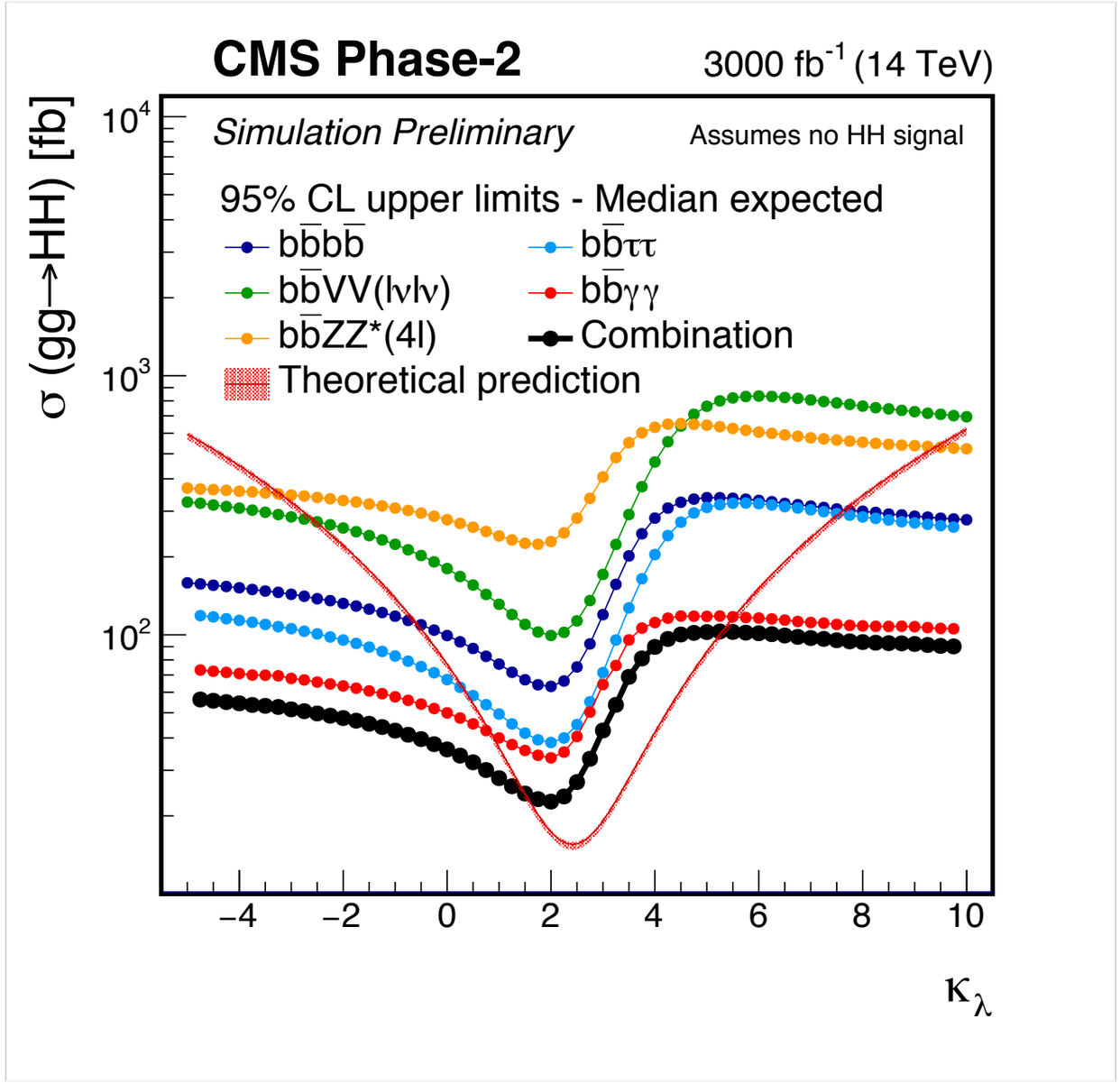
Combined Results on HH Production Cross section

- Assuming no HH signal, 95% CL upper limits on the SM HH production cross section as a function of the coupling modifier K_λ

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

- Total HH cross section has a quadratic dependence on K_λ with a minimum at $K_\lambda = 2.45$

- Variation of the excluded cross section directly related to changes in the HH kinematic properties



Combined ATLAS and CMS Results

- A simple combination is performed of the measurements from the ATLAS and CMS collaborations
- The significances are added in quadrature and the negative-log-likelihood are simply added together

	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		Combined	
	4.5		4.0	

- Combined significance of 4 σ achieved with all systematic uncertainties included

Combined ATLAS and CMS Results

- Projected confidence interval on the K_λ coupling modifier:
  - **[0.52, 1.5] at the 68% CL**