HL/HE-LHC projections & Yellow Report status

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Double Higgs Production at Colliders Workshop

Fermilab,
September 4, 2018

The HL/HE LHC workshop

Timeline:

- Kick-off meeting, Oct 30-Nov.1, 2017, defining goals & timeline
- Fermilab meeting, April 4-6, 2018
- CERN meeting, June 18-20, 2018, outlines of the several chapters completed
- December 2018: Yellow Report completion
- 2019: European Strategy for Particle Physics

Goals:

- Detailed assessment of the physics reach of the upgraded detectors with 3 ab^{-1}
- Careful assessment of the systematic limitations for physics measurements
- Begin a more systematic study of the physics reach of the HE-LHC. New ideas? (27 TeV with ~ 5 times more lumi)

Structure:
5 working groups

- WG 1: Standard Model
- WG 2: Higgs
- WG 3: Beyond the Standard Model
- WG 4: Flavour
- WG 5: QCD matter at high density

The Higgs working group

Conveners: SG, F.Riva (theory), M.Kado (ATLAS), M.Cepeda (CMS), P.Ilten (LHCb)

1. Precision Measurements
(indirect BSM probe through EFT)

- 1.1 Low energy Higgs couplings
- 1.2 High energy differential measures.

2. Rare Higgs Processes & New resonances

- 2.1 SM Higgs boson
- 2.2 New Higgs bosons

High lumi → 1.1, 1.2

High energy → 2.1, 2.2

Twiki page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG2
194 subscribers as of Sept.1, 2018

Draft of the document @ https://www.overleaf.com/17188577twzzbtqqnyjf#/65498653/

Structure of the Higgs Chapter

After the CERN Kick-off meeting, we have defined the goals/topics:

1. Introduction: Main goals and timeline
2. Precision Higgs physics (parts in collaboration with **SM WG1**)
3. Di-Higgs production and Higgs self couplings
4. Other high energy probes
5. The Higgs boson mass and width
6. Invisible decays of the Higgs boson
7. Higgs flavor and rare decays (in collaboration with **flavor WG4**)
8. Global view with HE/HL-LHC
9. BSM Higgs
10. Conclusions and outlook

Budget of approximately 150 pages for Higgs

The di-Higgs effort

Editors: Luca Cadamuro (CMS), David Wardrobe (ATLAS), Marc Riembau (theory)

a. SM Calculation (Dawson, Heinrich et al.)
b. Double Higgs measurements and trilinear coupling (ATLAS: Elisabeth Petit)
c. Indirect probes of the trilinear coupling through differential distributions measurements (CMS: Wardle, Senz, Scott, Langford)
d. Indirect probes through single Higgs boson production (Maltoni et al., Englert et al., Bizon et al.)
e. HE prospects (Goncalves et al., Homiller & Meade)
f. Theory Implications (including a critical view of the validity of direct and indirect trilinear couplings measurements (Di Vita et al.)
g. Interpretation in the context of the chiral Lagrangian (Buchalla et al.)

\+ Implications for models for EW phase transition / SUSY models etc

Remote meeting, May 29, https://indico.cern.ch/event/731833/

The SM cross section

3a

* New recommendation of the LHC Higgs cross section WG
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGHH

$\sqrt{s}$	13 TeV	14 TeV	27 TeV (HE)
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$
$\mathrm{NLO_{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$
$\mathrm{NNLO_{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$
$\mathrm{NNLO_{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$
$\mathrm{NNLO_{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$
M_t unc. $\mathrm{NNLO_{FTapprox}}$	$\pm 2.6\%$	$\pm 2.7\%$	$\pm 3.4\%$
$\mathrm{NNLO_{FTapprox}/NLO}$	1.118	1.116	1.096

gg fusion

exact NLO contribution (full dependence on M_t) + NNLO corrections computed in the large-M_t approximation.

Grazzini et al., 1803.02463

* Sub-leading production modes available as well:

VBF

m_h (GeV)	√s = 7 TeV	√s = 8 TeV	√s = 13 TeV	√s = 14 TeV
124.5	$0.320_{-3.7\%}^{+3.2\%}$ ±2.7 %	$0.470_{-3.1\%}^{+2.4\%}$ ±2.6 %	$1.65_{-2.7\%}^{+2.4\%}$ ±2.3 %	$1.97_{-2.6\%}^{+2.3\%}$ ±2.3 %
125	$0.316_{-4.1\%}^{+3.7\%}$ ±2.7 %	$0.468_{-3.3\%}^{+2.8\%}$ ±2.6 %	$1.64_{-2.5\%}^{+2.0\%}$ ±2.3 %	$1.94_{-2.6\%}^{+2.3\%}$ ±2.3 %
125.09	$0.313_{-3.8\%}^{+3.2\%}$ ±2.6 %	$0.459_{-3.6\%}^{+3.2\%}$ ±2.6 %	$1.62_{-2.7\%}^{+2.3\%}$ ±2.3 %	$1.95_{-2.3\%}^{+1.8\%}$ ±2.4 %
125.5	$0.312_{-4.0\%}^{+3.6\%}$ ±2.7 %	$0.458_{-3.4\%}^{+2.9\%}$ ±2.6 %	$1.63_{-2.5\%}^{+2.0\%}$ ±2.3 %	$1.94_{-1.9\%}^{+1.3\%}$ ±2.3 %

27 TeV, work in progress

Di-Higgs in non-linear EFT

3g

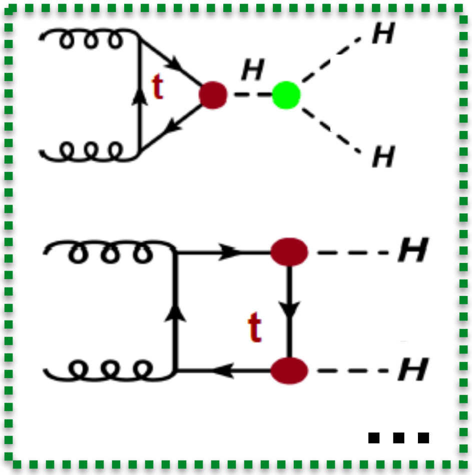
New Physics models can easily predict modified Higgs couplings.

Particularly, from the EFT prespective:

$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

In the SM: $c_t = c_{hhh} = 1$ and $c_{ggh} = c_{tt} = c_{gghh} = 0$

Di-Higgs cross section is affected by any of this coefficient



3g

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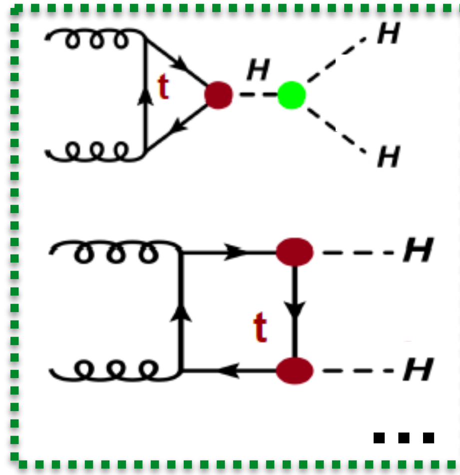


Benchmarks presented in the YR:

Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
5	1	1	0	8/15	1/3
7	5	1	0	2/15	1/15
8a	1	1	1/2	4/15	0
SM	1	1	0	0	0

from Buchalla et al., 1806.05162

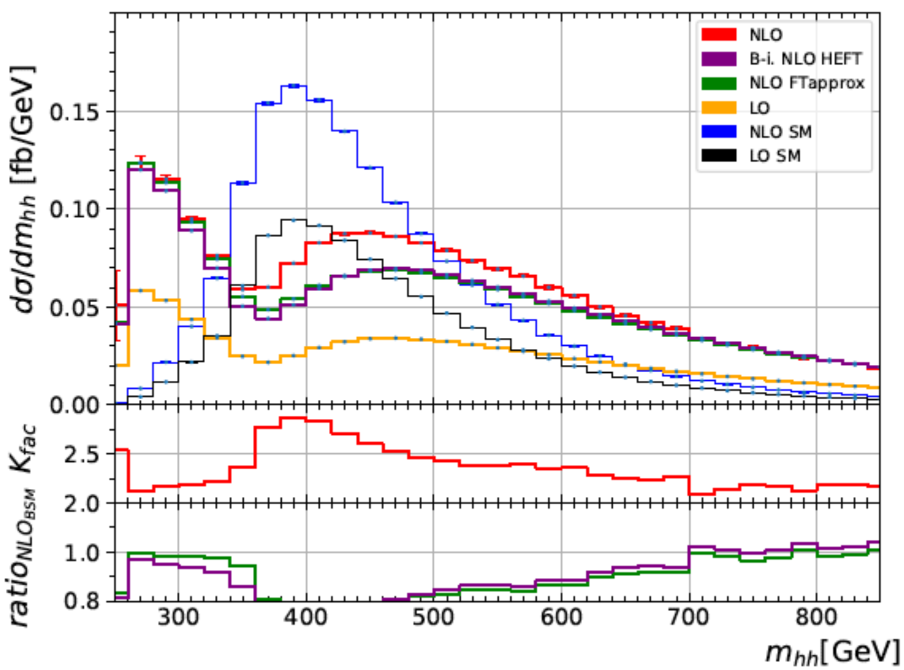
Benchmark	σ_{NLO} [fb]	K-factor	scale uncert. [%]	stat. uncert. [%]	$\frac{\sigma_{NLO}}{\sigma_{NLO,SM}}$
B_5 [14 TeV]	59.33	1.83	+4, −15	0.36	1.8
B_5 [27 TeV]	302.21	1.79	+2, −13	0.40	2.36
B_7 [14 TeV]	169.41	2.07	+9, −12	2.2	5.14
B_7 [27 TeV]	598.20	2.11	+8, −10	2.0	4.68
B_{8a} [14 TeV]	41.70	2.34	+6, −9	0.63	1.27
B_{8a} [27 TeV]	179.52	2.33	+4, −7	0.49	1.40

Differential distributions in EFT

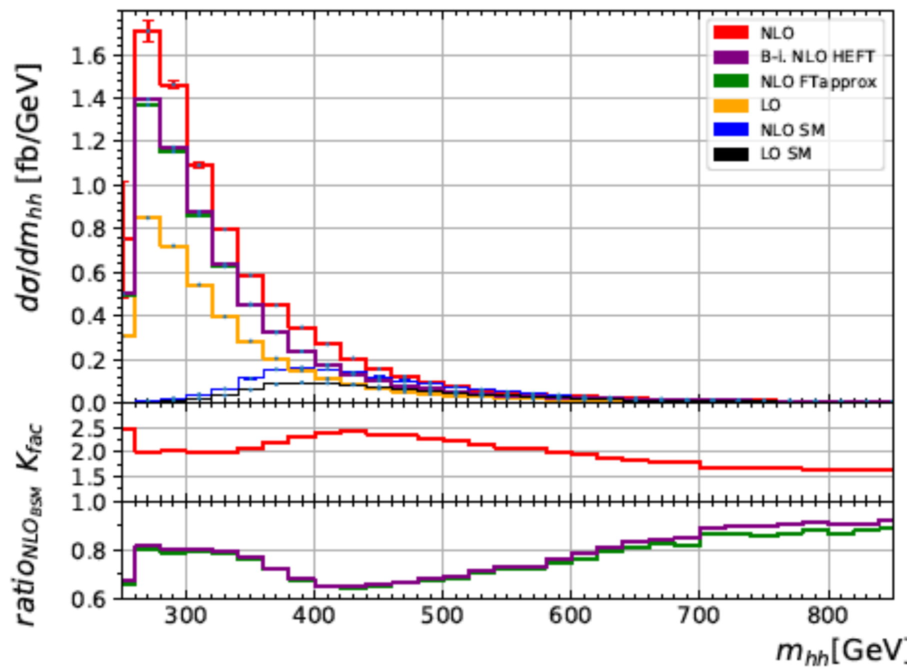
3g

Differential cross sections are also affected by any of this coefficient

14 TeV, benchmark 8a



14 TeV, benchmark 7



Distributions available also for the HE-LHC (27 TeV)

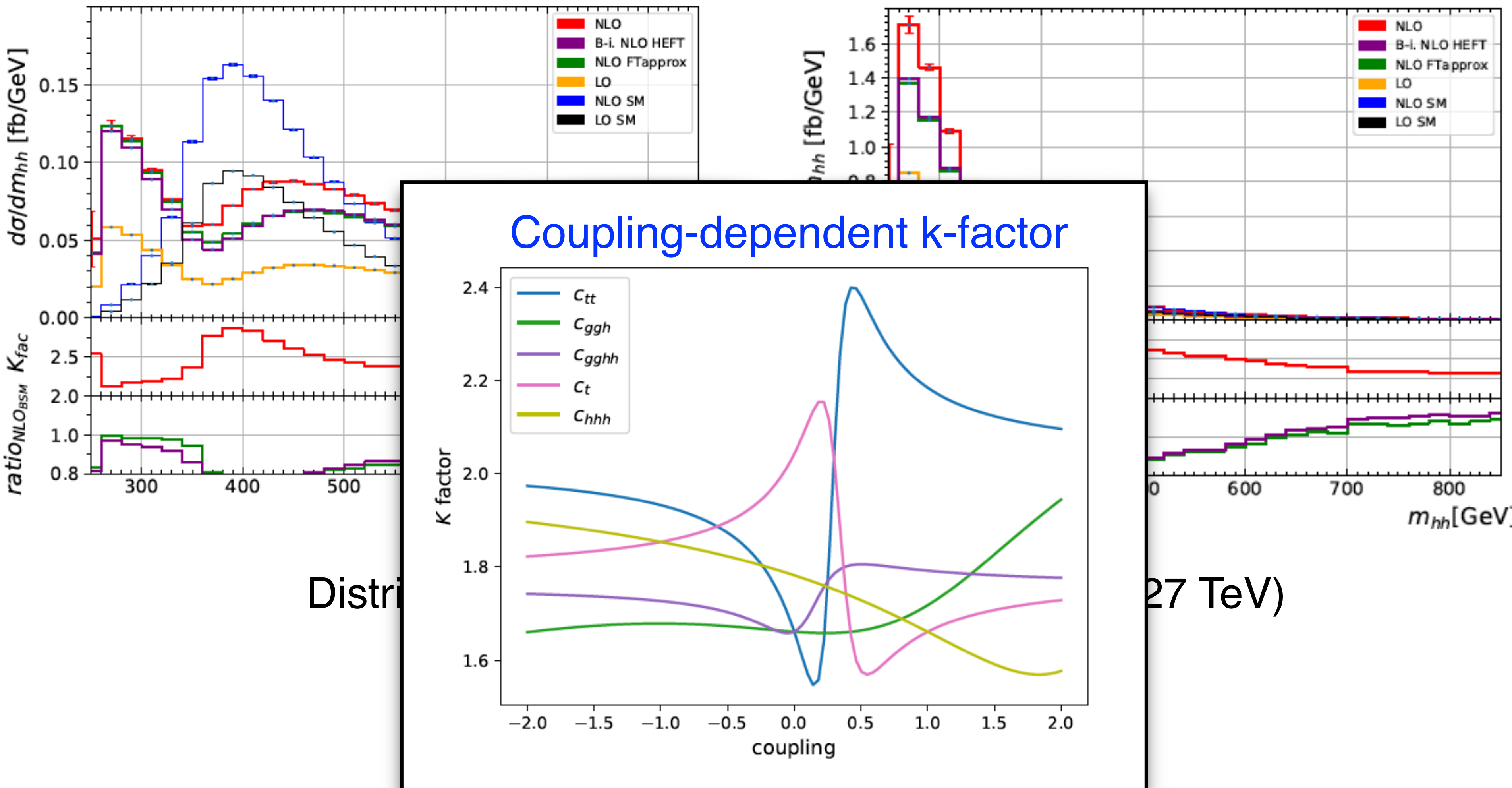
Differential distributions in EFT

3g

Differential cross sections are also affected by any of this coefficient

14 TeV, benchmark 8a

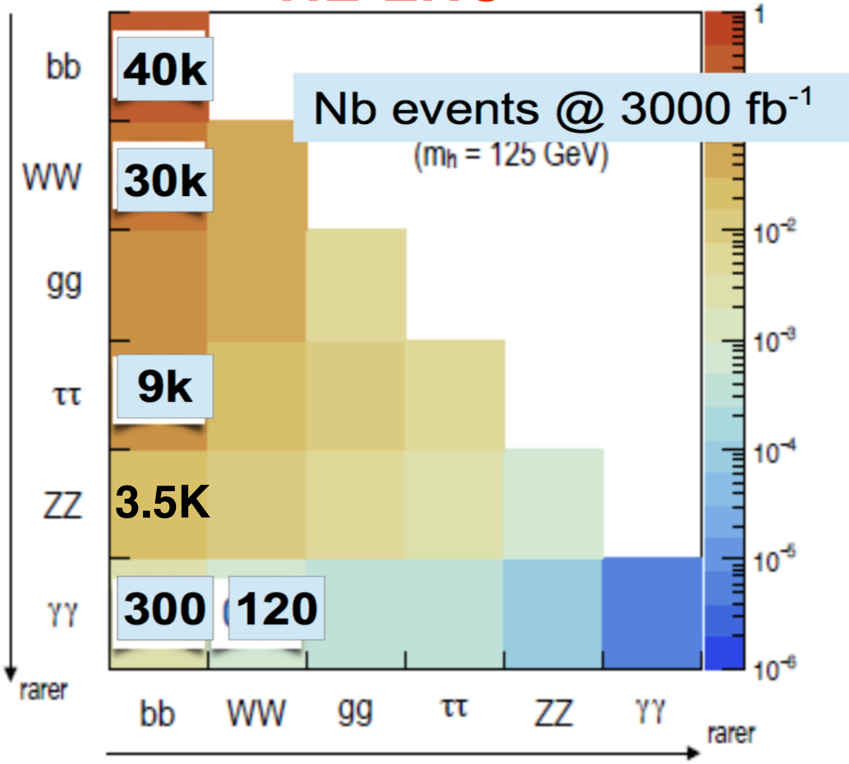
14 TeV, benchmark 7



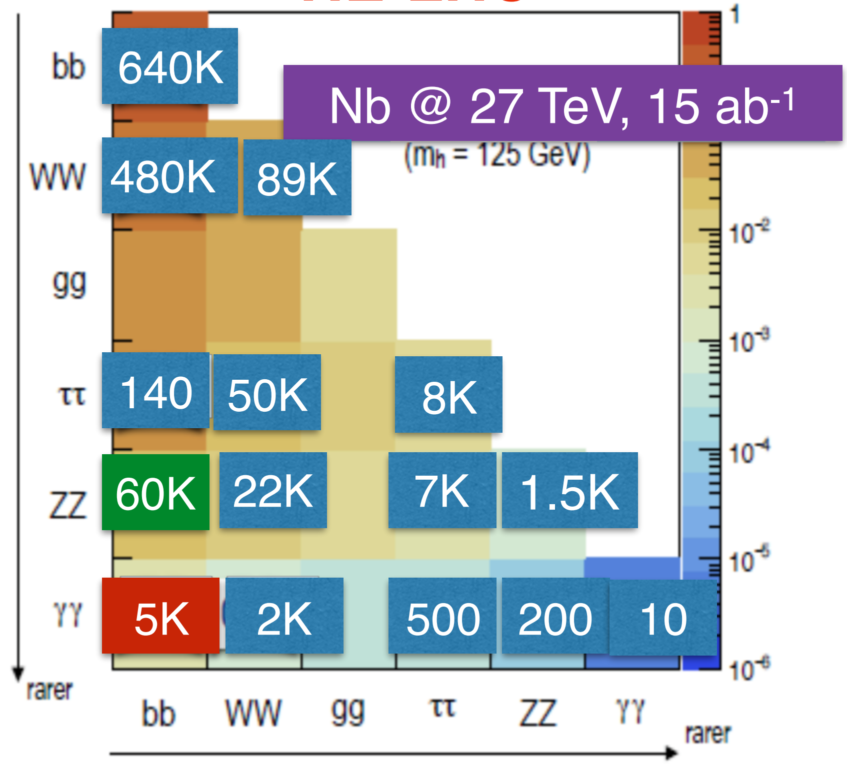
Signatures to search for

3b,c

HL-LHC



HE-LHC



More rare channels like bbZZ can become very important

Even sub-leading productions will lead to a sizable number of events at HE
eg. tthh, hh→bbbb: 20K events; VBF hh, hh→bb$\gamma\gamma$: 300 events

Available projections

3b,c

Channel	CMS	ATLAS
$HH \to bbbb$	$Z(\sigma_{HH}(SM))=0.39\ \sigma$ CMS PAS FTR-16-002	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L. ATLAS-TDR-030
$HH \to bb\tau\tau$	1.6 xSM CMS-TDR-019	$0.6\ \sigma$ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L. ATL-PHYS-PUB-2015-046
$HH \to bb\gamma\gamma$	$1.43\ \sigma$ CMS PAS FTR-16-002	$1.5\ \sigma$ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only) ATLAS-TDR-030
$HH \to WWbb$	$0.45\ \sigma$ CMS PAS FTR-16-002	
$tt(HH \to bbbb)$		$0.35\ \sigma$ ATL-PHYS-PUB-2016-023

Most results will be updated for YR18 mainly based on Run2

Combination to be done: Channels & experiments (ATLAS+CMS)

Additional information coming from single H measurements

Overview of the CMS effort

3b,c

- Section 3b: "Double Higgs measurements and trilinear coupling"
  development of full analyses based on fast simulation in the five main decay channels under HL-LHC conditions
- Section 3c: "Indirect probes of the trilinear coupling through differential distributions measurements"
  projected constrains of k_λ from $h \to \gamma\gamma$ differential measurements

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higher BR

bbbb
evaluate the impact of trigger thresholds

bbWW ($2\ell 2\nu$)
show the importance of MVA methods by reproducing and optimizing the Run II analysis

bb$\tau\tau$
extend the work published for the HGCal TDR

bbZZ (4ℓ)
develop the analysis in a new final state

bb$\gamma\gamma$
full analysis + internal cross check with projections

VBF hh
for bbbb, bb$\tau\tau$, and bb$\gamma\gamma$

constraints on VVhh coupling

Interpretations in terms of di-Higgs significance + measurement of k_λ

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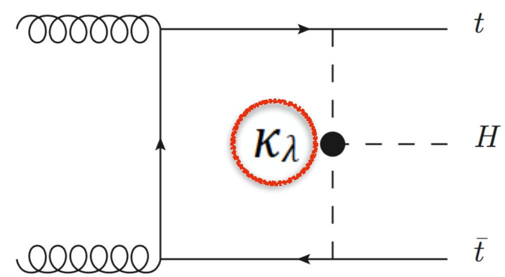
- Motivated by Maltoni et al. 1709.08649 (see talk by A.Shivaji)
- Focus on associated modes Vh and tth
- Use the $h \to \gamma\gamma$ decay mode
- The SM cross-section in bins of some observables (eg. $p_T(h)$):



$$\mu(\kappa_\lambda, C_1) = \left.\frac{\sigma_{\rm NLO}(\kappa_\lambda)}{\sigma_{\rm LO}(\kappa_\lambda = 0)}\right|_{C_1} = \frac{1 + \kappa_\lambda C_1}{1 - \kappa_\lambda^2 \delta Z_H}$$

process-dependent

wave function renormalisation

- Currently looking at $p_T(h)$ but also studying $p_T(Z)$, m_{tth}, …

Competitive & complementary with di-Higgs limits

Overview of the ATLAS effort

3b,c

Analysis mainly based on extrapolation of Run II results
Studying systematics and triggers in HL-environment

higher BR ↑

bbbb

extrapolation of 2015+2016 analyses (1804.06174).
Impact of improved b-tagging efficiency

bb$\tau\tau$

extrapolation from Run II

bb$\gamma\gamma$

dedicated HL-LHC prospects analysis based
on upgraded detector + new pile-up conditions

Extrapolation of the bb$\gamma\gamma$ result to HE?

Interpretations in terms of di-Higgs significance + measurement of k_λ

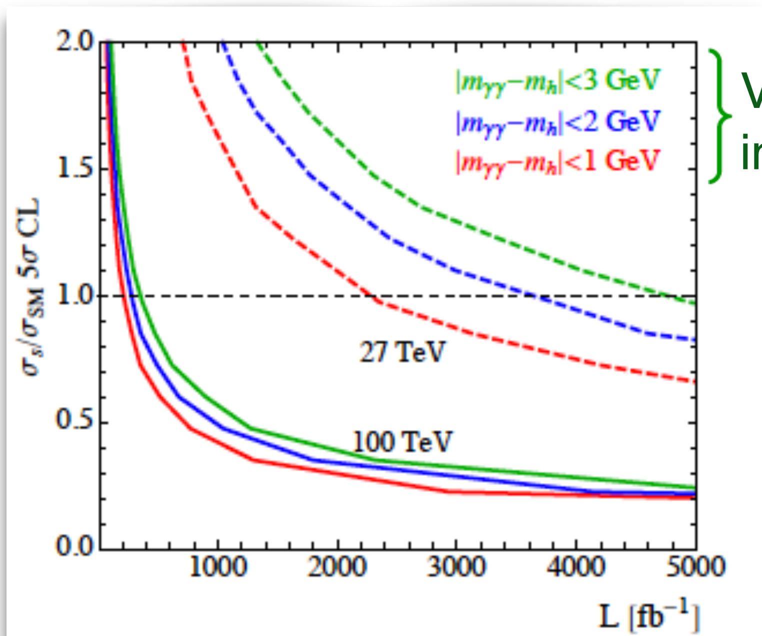
Prospects for the HE-LHC

3e

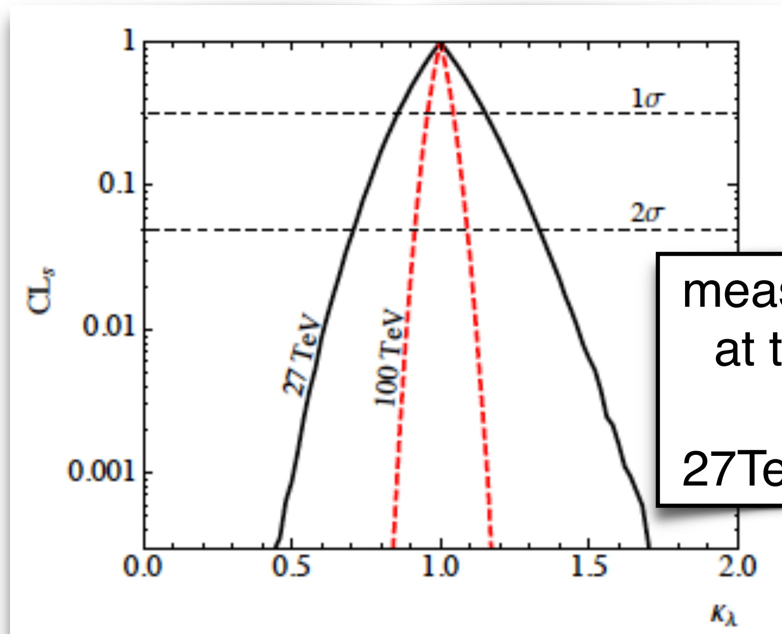
Two theory groups involved in the studies: Goncalves et al., Homiller & Meade

1802.04319

bb$\gamma\gamma$ studies are already available:



Very large impact



measurement at the 30% level 27TeV, 15ab^{-1}

Resolution used for this study:

$$|m_{bb} - m_h| < 25 \text{ GeV},$$

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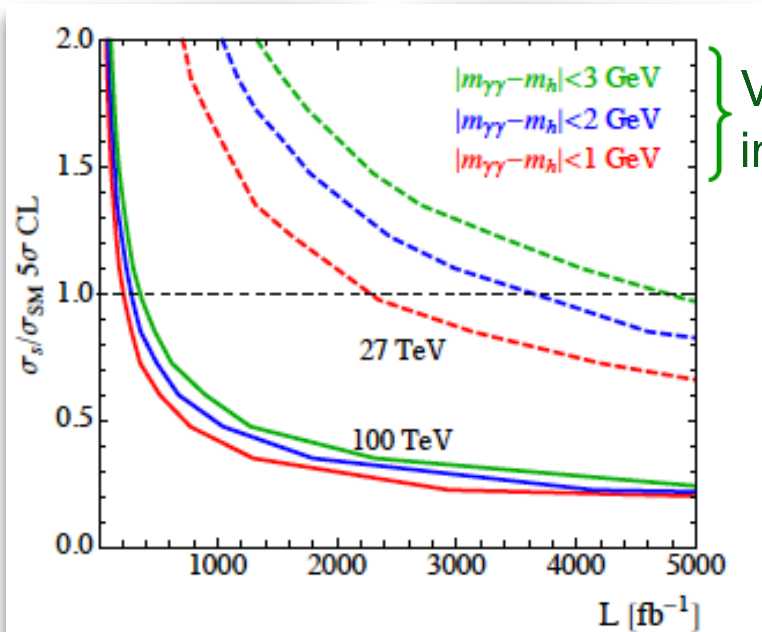

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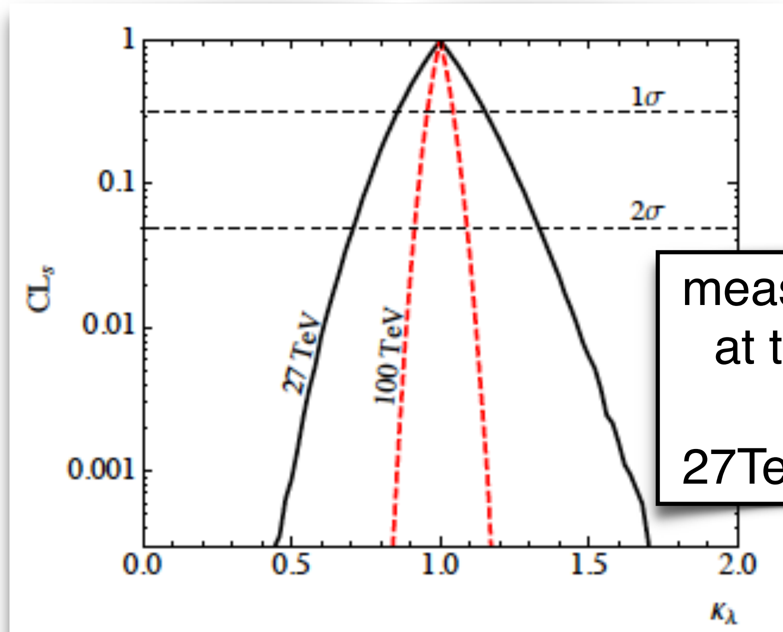

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Additional studies for additional channels are welcome!

Ongoing work:

Full 27 TeV Delphes analysis using upgraded detector configuration [M.Selvaggi+G.Ortona]

ATLAS rescaling of the HL $bb\gamma\gamma$ projection

Single Higgs vs. di-Higgs data

3d

Overview of the impact of single Higgs measurements in the determination of the Higgs trilinear coupling, k_λ

Bizon, Gorbahn, Haisch, Maltoni, Pagani, Shivaji, Zanderighi, Zhao

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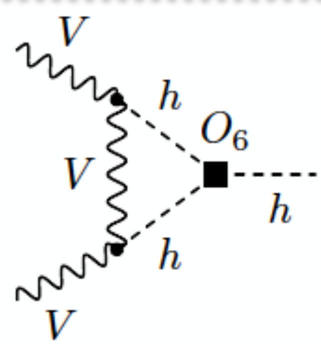
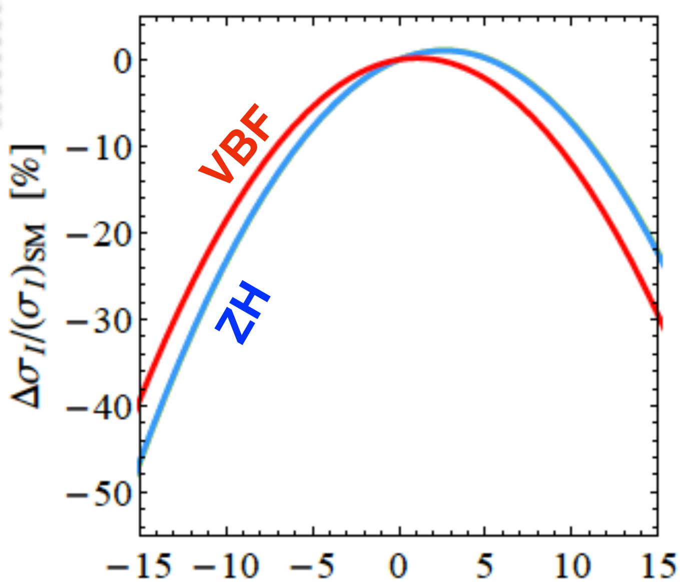
* A value of k_λ different from the SM one will modify the Higgs couplings to W and Z

example diagram:

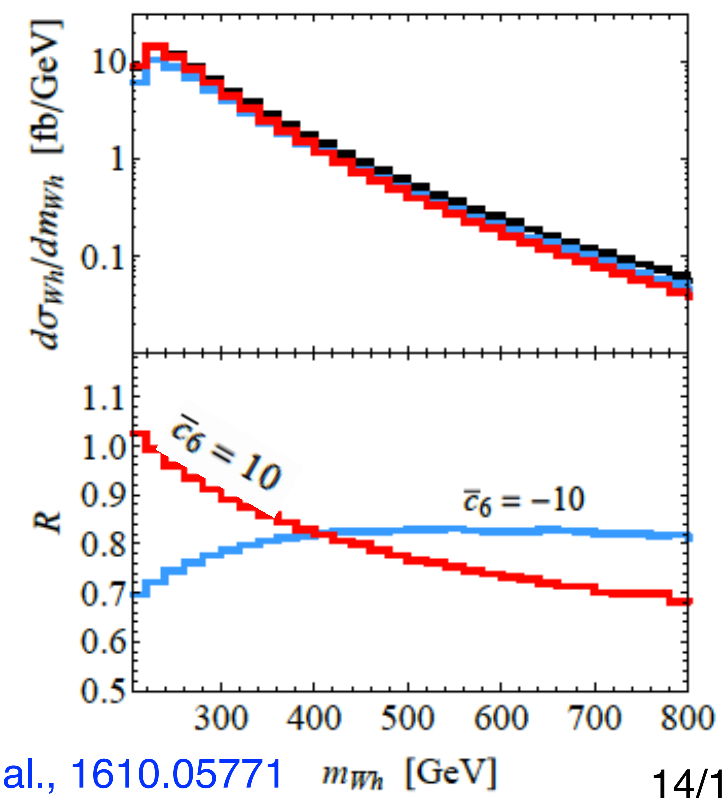


1. VBF and Z/W Higgs associated production cross section will be affected



$(-\lambda c_3 v h^3)$ $\bar{c}_6 = c_3 - 1$

2. NP effects in differential distributions, as well



Bizon et al., 1610.05771

Extracted k_λ is **competitive** with the one extracted from di-Higgs searches

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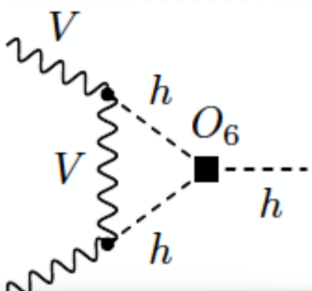

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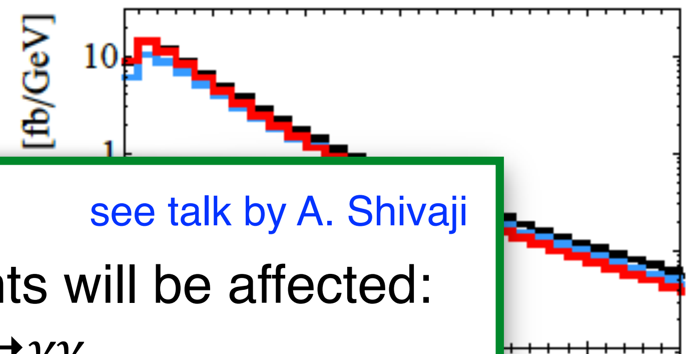
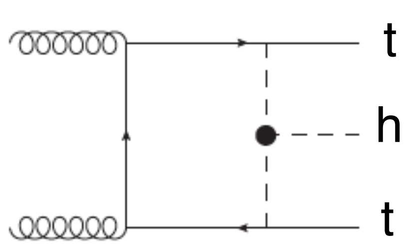
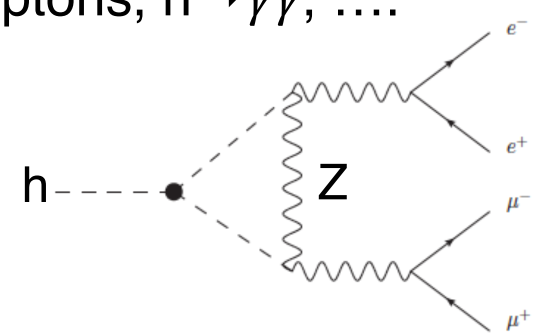


Maltoni et al., 1709.08649

see talk by A. Shivaji

Many additional single Higgs measurements will be affected:
tth production, h → 4leptons, h→$\gamma\gamma$, ….





Extracted k_λ with the one from di-Higg

Bizon et al., 1610.05771 m_{Wh} [GeV]

Global fits (di-Higgs+single Higgs)

3f

Importance of global fits to extract the maximum amount of information on k_λ

EFT fit performed in the 10-dimensional space: $\delta y_t,\ \delta y_b,\ \delta y_\tau,\ \delta c_z,\ c_{gg},\ c_{\gamma\gamma},\ c_{zz},\ c_{z\Box},\ c_{z\gamma},\ \kappa_\lambda$

Contribution by di Vita, Durieux, Gu, Liu, Panico, Riembau, Vantalon

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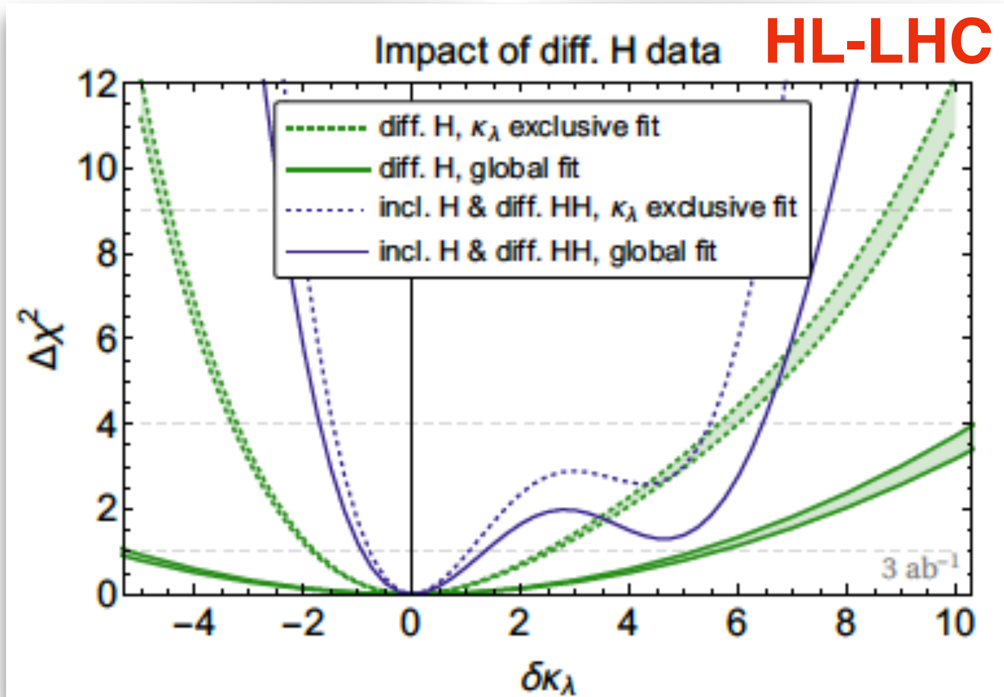
HL-LHC



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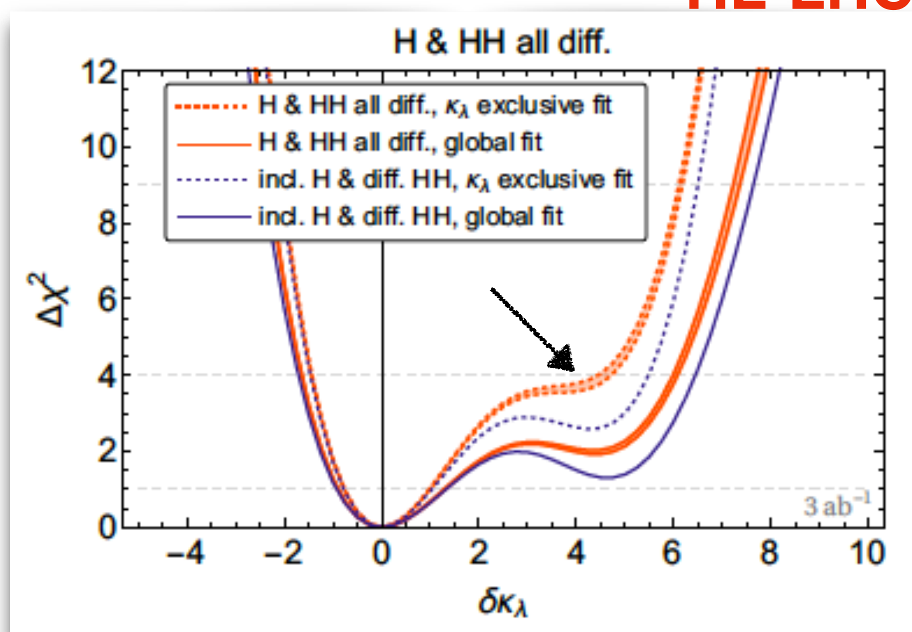
HL-LHC



Crucial impact of systematic uncertainties.
Several benchmarks for HE will be presented

Di Vita et al., 1704.01953

Results available also for the HE-LHC

Implications for NP models

The measurement of the Higgs trilinear coupling

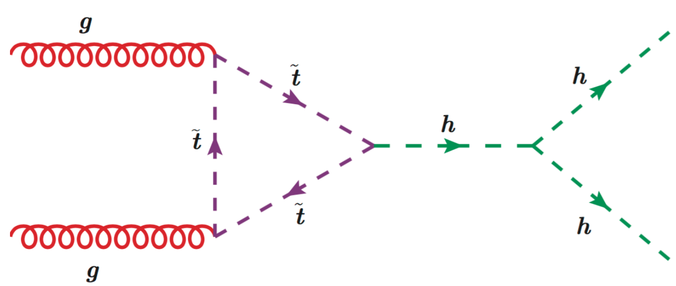
- is crucial for a self-consistency check of the SM potential
- **has implications on many NP models**

Origin of the baryon asymmetry:
models for strong first order phase transitions
example: scalar singlet extended SM

see eg.
Profumo et al., 1407.5342
Huang et al., 1512.00068
Carena et al., 1801.00794

Hierarchy problem:
SUSY models with light stops

see eg.
Huang et al., 1711.05743



Complementarity with the Higgs coupling precision program and direct searches for new particles

Plan & timeline

Now

- Experimental results ready by the end of September
- Final public notes, mid. October
- "Simple" combination of ATLAS and CMS di-Higgs results, end of October
  - Implementation: combining CMS full sim studies w/ ATLAS projections
  - need to understand correlations in systematics (theory+experiment)

- Deadline for theory contributions, end of October
- Final edits and revisions, November
- Higgs chapter of the Yellow Report ready! mid. December

Conclusions & outlook

Di-Higgs production is a crucial process for the HL and HE LHC programs.
Opportunities for new measurements!

Complementarity with the Higgs precision program

Plenty of interesting studies on the way for the HL/HE CERN Yellow report

Please contact us, if you are interested participating!
SG, F.Riva (theory),
M.Kado (ATLAS), M.Cepeda (CMS), P.Ilten (LHCb)