

# New estimates of the Higgs physics potential of the HL-LHC phase from the ATLAS experiment

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DESY Colloquium, December 12<sup>th</sup> 2018

# Two recent colloquia at DESY

**Halina Abramowicz**  
**December 5<sup>th</sup>**

Home / Zeuthen / Colloquia in 2018 / December 05, 2018

## Next update of the European Strategy for Particle Physics

Halina Abramowicz | Tel Aviv University | Secretary of the European Particle Physics Strategy Update  
Seminar room 3, 14:00

In October 2019, the CERN Council officially launched the process of updating the European Strategy for Particle Physics (EPPSU) to be completed by May 2020. The EPPSU, a community driven bottom-up approach, is meant to provide a clear prioritisation of European ambitions in advancing the particle physics science. It is supposed to take into account the worldwide particle physics landscape and developments in related fields, and to propose a program that maximises the scientific returns. In my presentation, I will discuss to which point the previous strategy recommendations brought us and the steps envisaged to converge on the next strategy update to guide the direction of the field to the mid-2020s and beyond.



**Andreas B. Meyer**  
**November 27<sup>th</sup>, DESY HH**

## “Physics at the HL-LHC”

### Standard Model



### Direct Searches



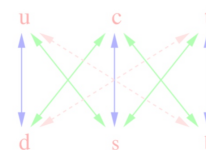
Supersymmetry, Long-Lived Particles, Dark Matter, Heavy Resonances

### Higgs



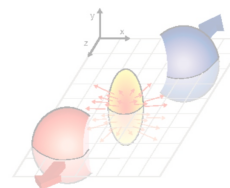
Precise Properties and Couplings for H(125)  
Searches in the Higgs Sector

### Flavour



Low  $p_T$  / High  $p_T$  Complementarity

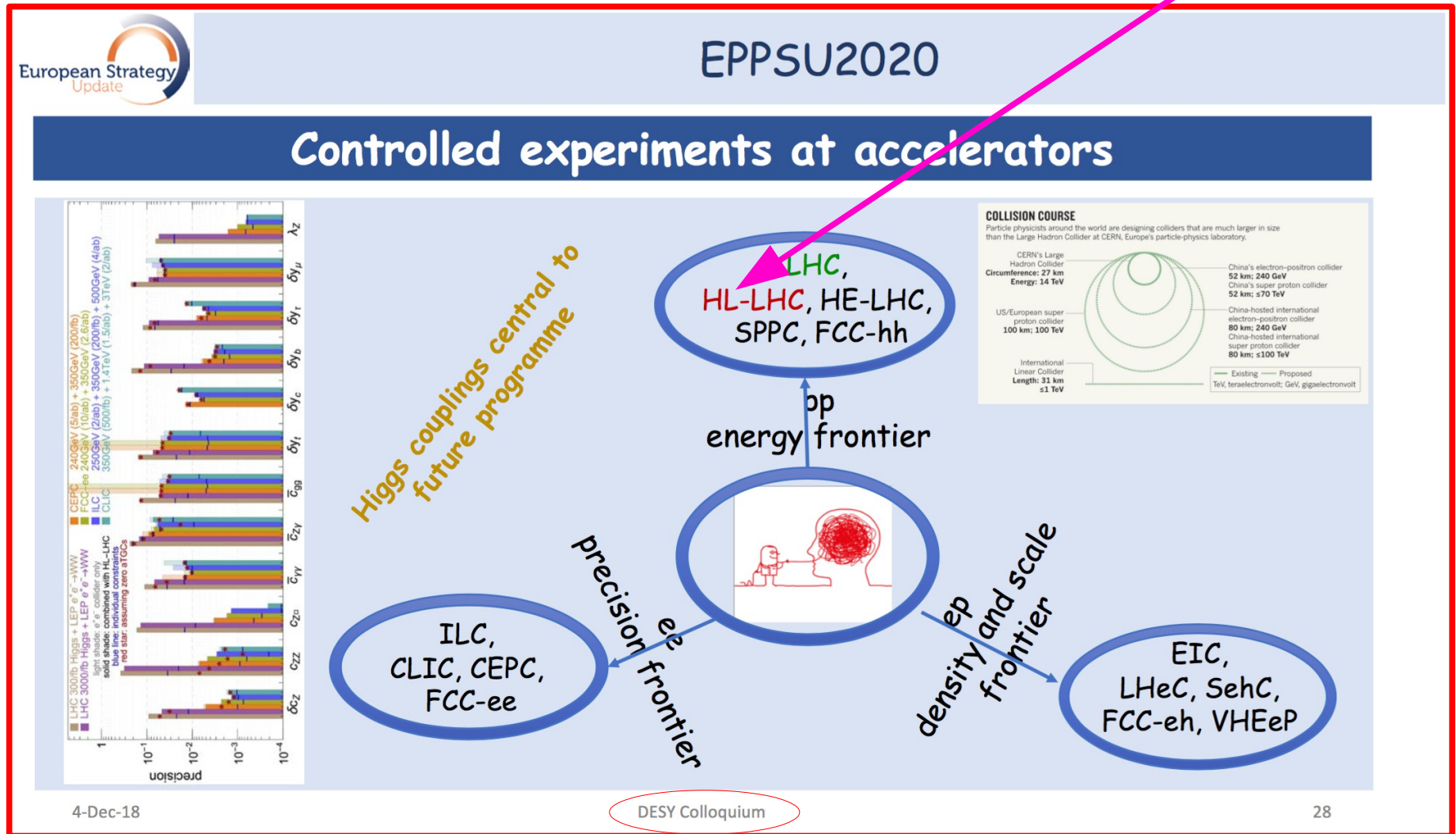
### Heavy Ion Physics



Precise Differential Measurements

# (Possible) Future colliders

- In this colloquium:
- *not* arguing about choice of future collider
  - prospects from the one project that is already approved (**HL-LHC**); the “baseline”



Halina Abramowicz



# The HL-LHC

## LHC / HL-LHC Plan



We are here

Major upgrades to LHC and to the experiments

10x more luminosity than “original” LHC  
(100x more than in 2016)

[current results discussed today  
are based on 2015+2016 data]

Unprecedented pile-up and event rates  
→ need detector upgrades

Timescale consistent with

- development of sophisticated analyses
- improved theory calculations



# ATLAS detector upgrades for the HL-LHC phase

## Small selection of highlights:

### New inner tracker

- extended coverage ( $|\eta| < 4$ )
- improved granularity

### Trigger/DAQ

- 10 kHz recorded

### Calorimeters

- new front end electronics;  
higher granularity of readout (40 MHz) for triggering
- High Granularity Timing Detector;  
Separate vertices (in addition to z0)

### Muon system

- extended trigger coverage ( $|\eta| < 4$ )

## Full list of TDRs for ATLAS upgrades:

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Upgrade\\_Projects\\_and\\_Physics\\_Pro](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Upgrade_Projects_and_Physics_Pro)



# Upcoming CERN Yellow Report

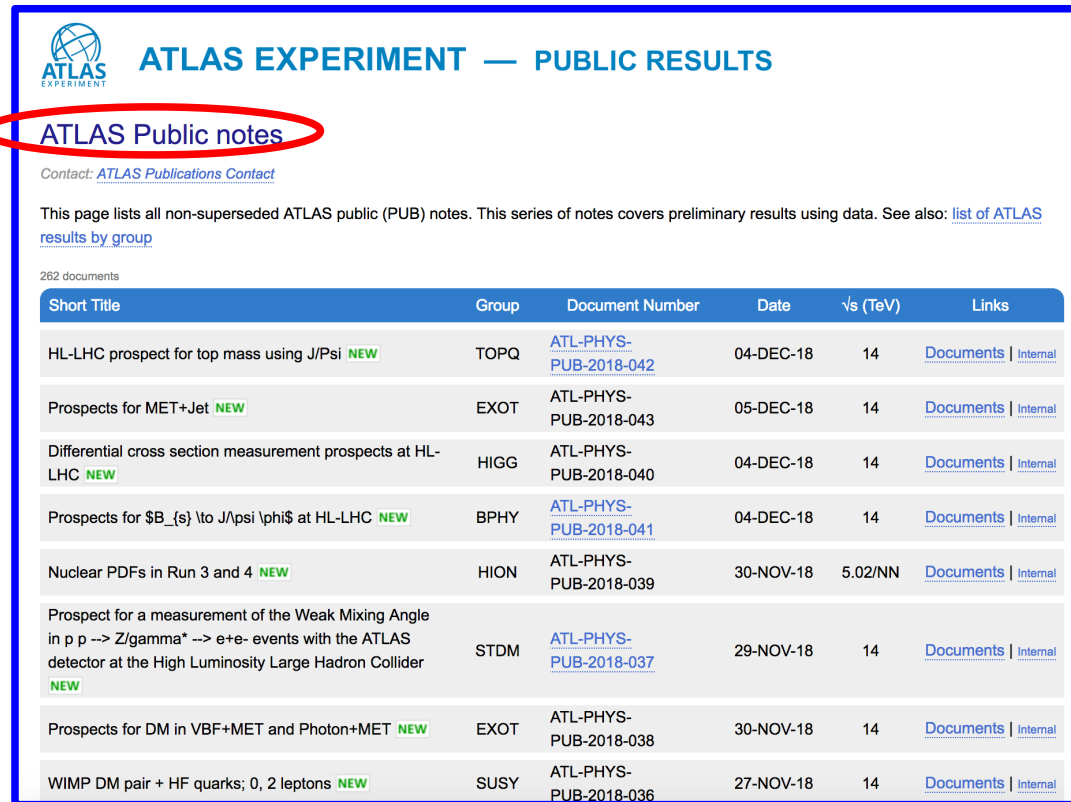
HL-LHC prospects studies  
are a very active area these days:

- aim for a **Yellow Report** by the end of this year
- first step for ATLAS: **PUB notes** !
- now is the right time for this YR:
  - crucial input to the next update (2020) of the European Strategy for Particle Physics
  - final CMS/ATLAS detector optimisations for HL-LHC are available

Approach(es) for estimation of precision  
at 3000 fb<sup>-1</sup>:

- **Extrapolation based on current**, published results
- **Or use new analysis**, based on generator-level event samples plus parameterised model of expected detector performance
- Present different scenarios for expected systematic uncertainties;  
**Try not to be overly pessimistic.**

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/PUBnotes>



ATLAS EXPERIMENT — PUBLIC RESULTS

**ATLAS Public notes**

Contact: [ATLAS Publications Contact](#)

This page lists all non-superseded ATLAS public (PUB) notes. This series of notes covers preliminary results using data. See also: [list of ATLAS results by group](#)

262 documents

Short Title	Group	Document Number	Date	√s (TeV)	Links
HL-LHC prospect for top mass using J/Psi <b>NEW</b>	TOPQ	<a href="#">ATL-PHYS-PUB-2018-042</a>	04-DEC-18	14	<a href="#">Documents</a>   <a href="#">Internal</a>
Prospects for MET+Jet <b>NEW</b>	EXOT	<a href="#">ATL-PHYS-PUB-2018-043</a>	05-DEC-18	14	<a href="#">Documents</a>   <a href="#">Internal</a>
Differential cross section measurement prospects at HL-LHC <b>NEW</b>	HIGG	<a href="#">ATL-PHYS-PUB-2018-040</a>	04-DEC-18	14	<a href="#">Documents</a>   <a href="#">Internal</a>
Prospects for $B_{\text{u}} \rightarrow J/\psi \ell \bar{\nu}_\ell$ at HL-LHC <b>NEW</b>	BPHY	<a href="#">ATL-PHYS-PUB-2018-041</a>	04-DEC-18	14	<a href="#">Documents</a>   <a href="#">Internal</a>
Nuclear PDFs in Run 3 and 4 <b>NEW</b>	HION	<a href="#">ATL-PHYS-PUB-2018-039</a>	30-NOV-18	5.02/NN	<a href="#">Documents</a>   <a href="#">Internal</a>
Prospect for a measurement of the Weak Mixing Angle in $p p \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events with the ATLAS detector at the High Luminosity Large Hadron Collider <b>NEW</b>	STDM	<a href="#">ATL-PHYS-PUB-2018-037</a>	29-NOV-18	14	<a href="#">Documents</a>   <a href="#">Internal</a>
Prospects for DM in VBF+MET and Photon+MET <b>NEW</b>	EXOT	<a href="#">ATL-PHYS-PUB-2018-038</a>	30-NOV-18	14	<a href="#">Documents</a>   <a href="#">Internal</a>
WIMP DM pair + HF quarks; 0, 2 leptons <b>NEW</b>	SUSY	<a href="#">ATL-PHYS-PUB-2018-036</a>	27-NOV-18	14	<a href="#">Documents</a>   <a href="#">Internal</a>

# Why look for New Physics ?

With the discovery of the Higgs boson, the Standard Model is now a

- ✓ complete
- ✓ coherent
- ✓ predictive

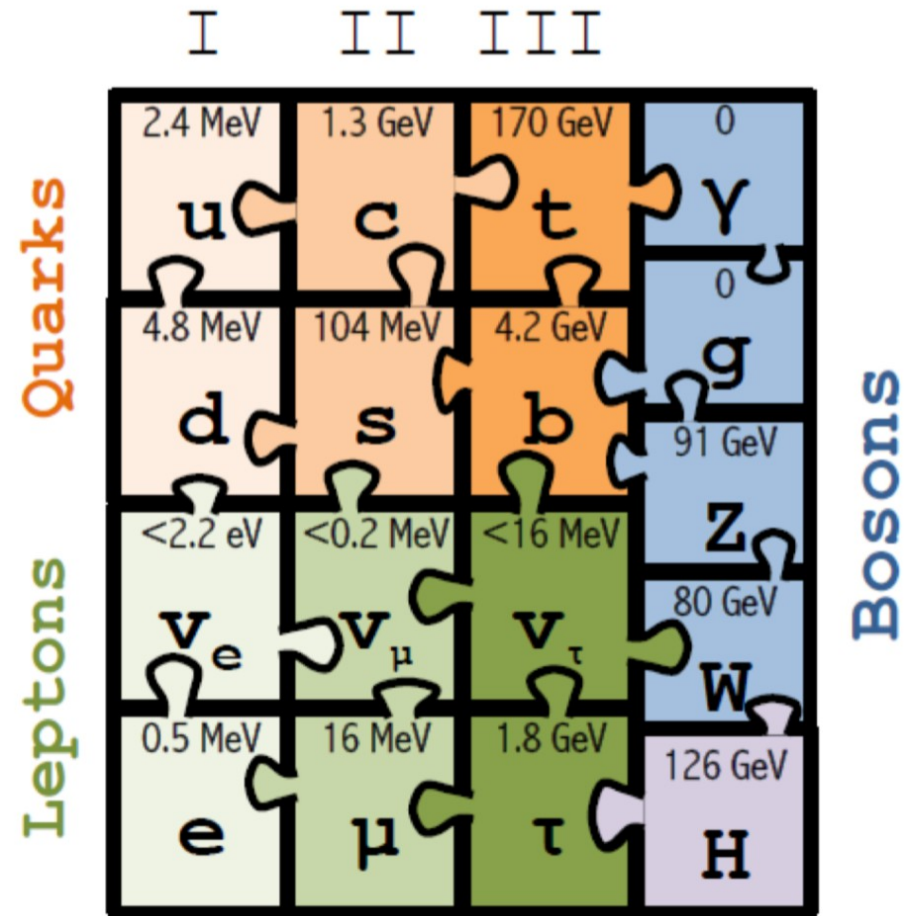
theory of particles and their interactions.

## Are we done ?

We are convinced that other particles and/or phenomena exist.

The Standard Model does **not** explain:

- dark matter
- matter/anti-matter asymmetry
- neutrino masses
- ... and it has problems explaining the light Higgs mass (hierarchy problem)
- ...



(c) Sfyrla



# The Higgs sector

At LHC, finally have **experimental access** to the Higgs sector.

→ study it in detail,  
test SM predictions: couplings, ...

5% precision on couplings:  
sensitive to BSM scales  $O(1 \text{ TeV})$ .

(sub-)1% precision →  $O(10 \text{ TeV})$

Higgs is first scalar fundamental particle.  
Is there an **extended scalar sector** ?

## Origin of the Higgs potential ?

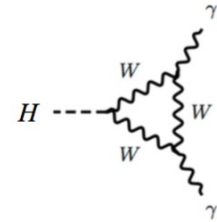
Postulated ad hoc in the SM.

Does it have a more profound origin (analogy with Ginzburg-Landau theory of superconductivity)

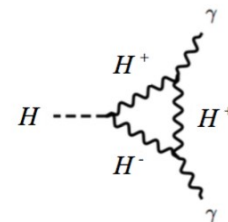
Dynamical origin ?

### Example $H \rightarrow \gamma\gamma$ :

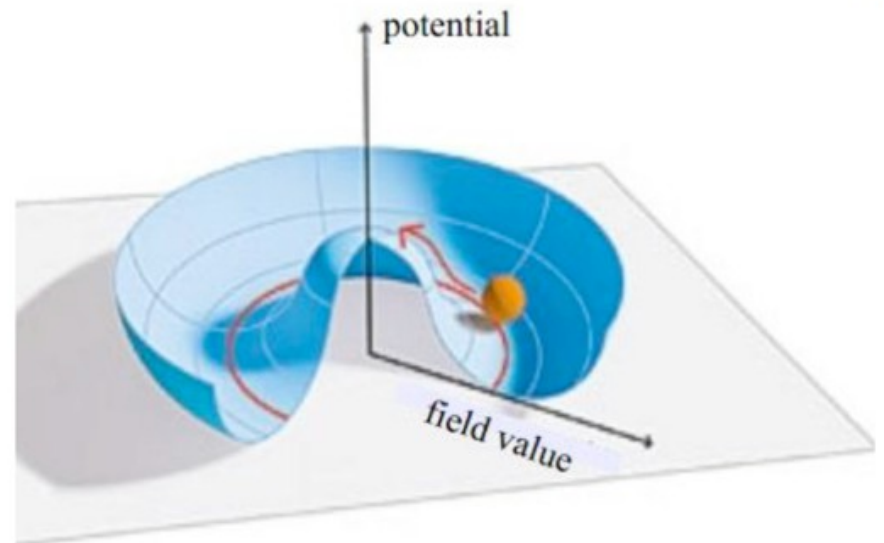
In the SM, this process is described by diagram like this one:



In extensions of the SM, this process could also proceed via this other diagram:

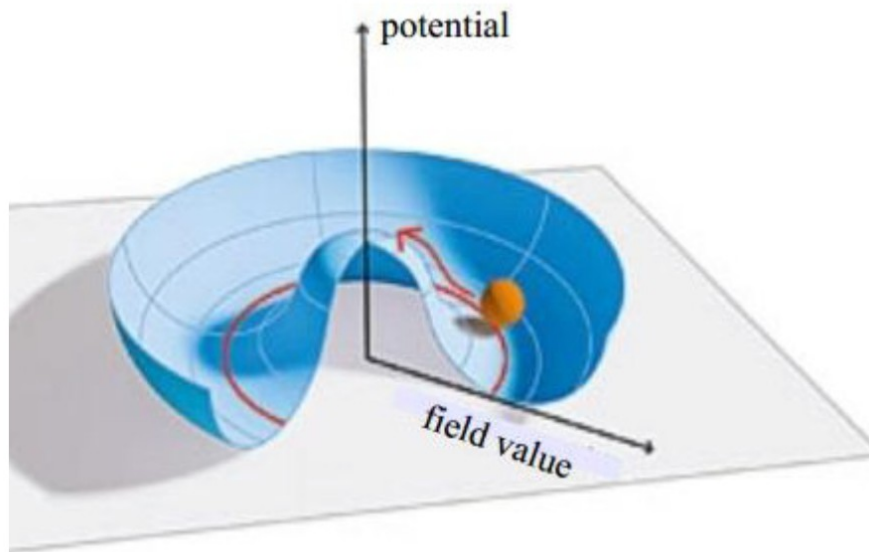


$H^+, H^-$  : hypothetical particles  
(part of extended Higgs sector)



# Higgs potential

A measurement of the Higgs self-coupling is the only way to experimentally reconstruct the Higgs potential (reconstruct its shape close to the minimum).



Higgs potential in the standard model:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \eta (\Phi^\dagger \Phi)^2$$

expansion around the minimum

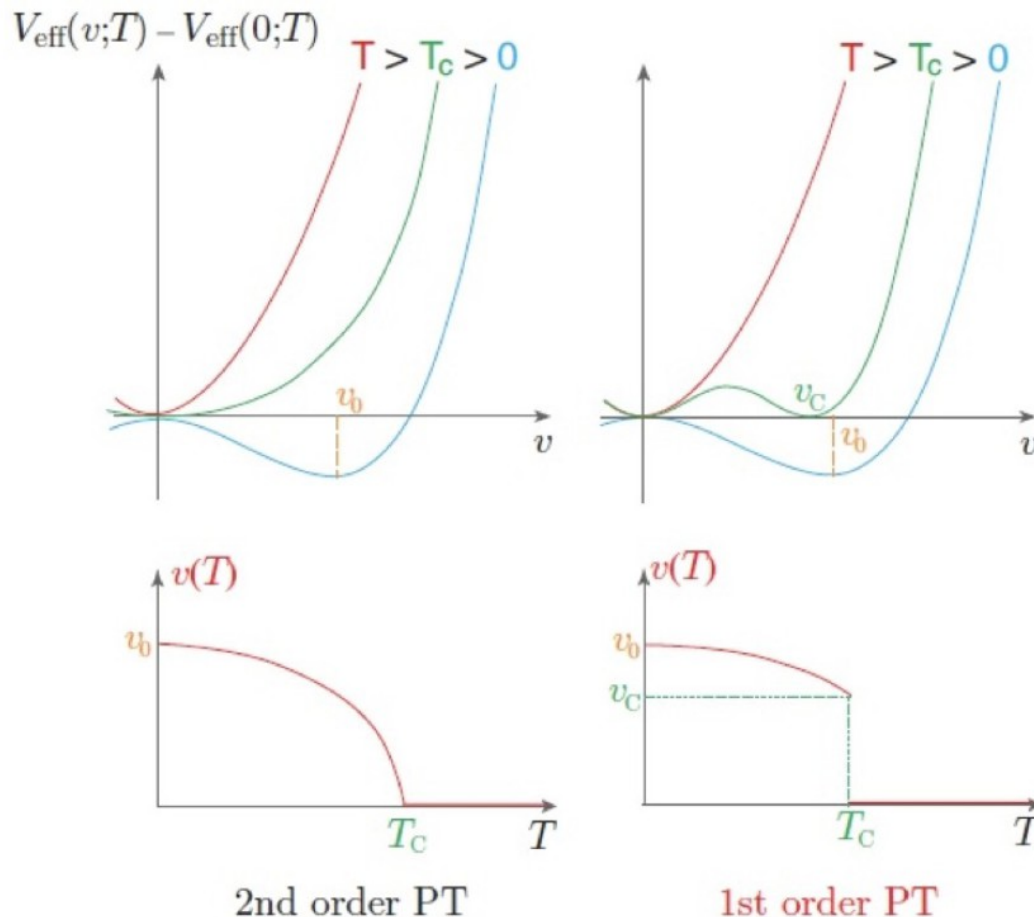
$$\frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4$$

The expansion is accompanied by Feynman diagrams. The red circle corresponds to the cubic term  $\sqrt{\frac{\eta}{2}} m_H h^3$  and is shown with a diagram of three Higgs bosons ( $h$ ) meeting at a vertex. The yellow circle corresponds to the quartic term  $\frac{\eta}{4} h^4$  and is shown with a diagram of four Higgs bosons ( $h$ ) meeting at a vertex.

# Electroweak baryogenesis

To get the observed baryon asymmetry of the universe from an initially baryon-symmetric universe, Sacharow's conditions must be satisfied.

- (1) Baryon number (B) violation
- (2) C and CP violation
- (3) Out of equilibrium



It is not easy to construct a credible mechanism that meets these conditions.

The mechanism that meets these conditions and that is considered to be the **most credible** one is **electroweak baryosynthesis**.

An effective potential (free energy density) is used to describe the Higgs potential during the electroweak phase transition.

**Electroweak baryosynthesis can only work if the electroweak phase transition is a first order phase transition (PT).**

First order PTs imply a system that is out of equilibrium (violent transition, large creation of entropy).



# An exciting theory paper

PHYSICAL REVIEW D **97**, 075008 (2018)

## Probing baryogenesis through the Higgs boson self-coupling

M. Reichert,<sup>1</sup> A. Eichhorn,<sup>1</sup> H. Gies,<sup>2,3</sup> J. M. Pawłowski,<sup>1,4</sup> T. Plehn,<sup>1</sup> and M. M. Scherer<sup>5</sup>

<sup>1</sup>*Institut für Theoretische Physik, Universität Heidelberg,  
Philosophenweg 16, 69120 Heidelberg, Germany*

<sup>2</sup>*Theoretisch-Physikalisches Institut, Abbe Center of Photonics,  
Friedrich-Schiller-Universität Jena, Max Wien Platz 1, 07743 Jena, Germany*

<sup>3</sup>*Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany*

<sup>4</sup>*Extreme Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung mbH,  
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<sup>5</sup>*Institut für Theoretische Physik, Universität zu Köln, 50937 Köln, Germany*



(Received 28 November 2017; published 4 April 2018)

The link between a modified Higgs self-coupling and the strong first-order phase transition necessary for baryogenesis is well explored for polynomial extensions of the Higgs potential. We broaden this argument beyond leading polynomial expansions of the Higgs potential to higher polynomial terms and to nonpolynomial Higgs potentials. For our quantitative analysis we resort to the functional renormalization group, which allows us to evolve the full Higgs potential to higher scales and finite temperature. In all cases we find that a strong first-order phase transition manifests itself in an enhancement of the Higgs self-coupling by at least 50%, implying that such modified Higgs potentials should be accessible at the LHC.

DOI: 10.1103/PhysRevD.97.075008

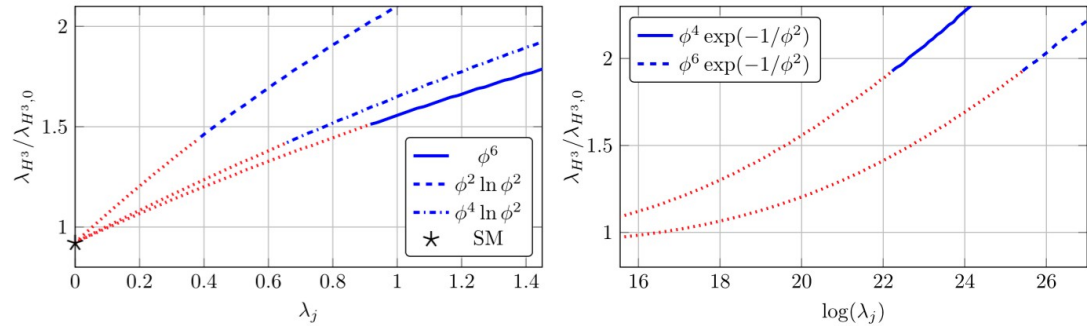
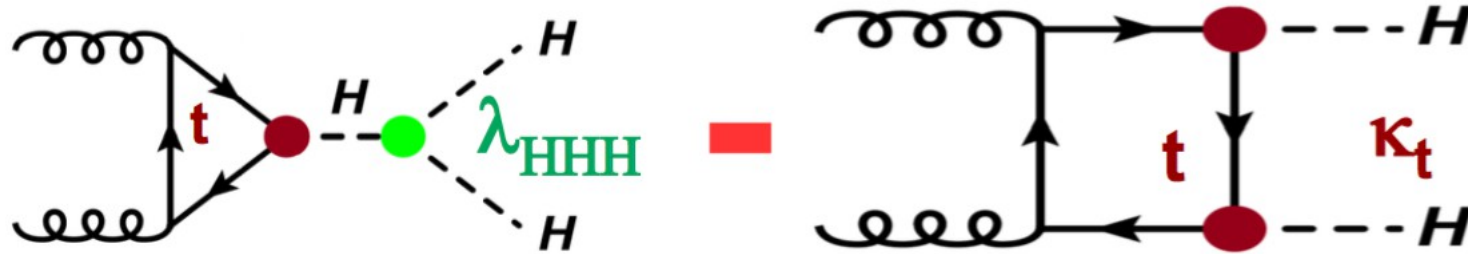


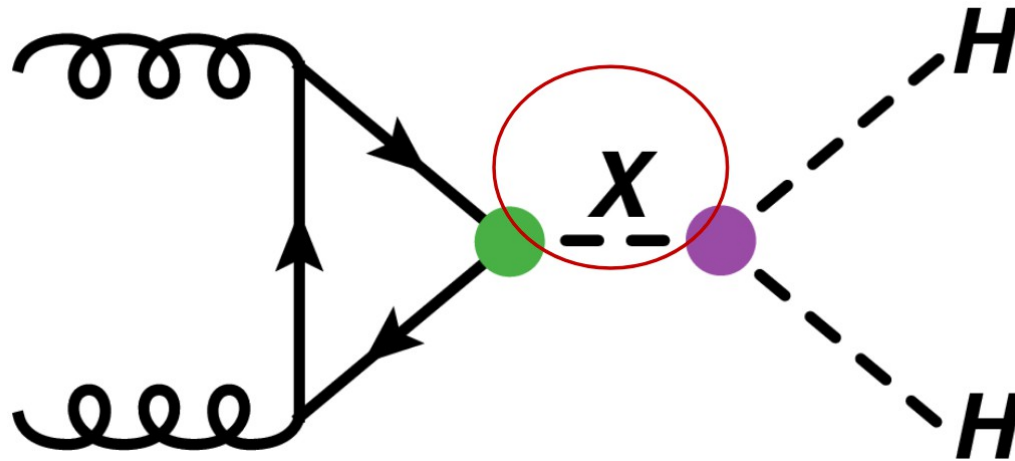
FIG. 8. Modification of the self-coupling  $\lambda_{H^3}/\lambda_{H^3,0}$  as a function of the coefficients  $\lambda_j$  from the different UV potentials given in Eq. (11). Blue lines represent first-order phase transitions and red dotted lines second-order phase transitions. The cutoff is  $\Lambda = 2$  TeV.

# Di-Higgs production at LHC



<ul style="list-style-type: none"> <li><math>m_h = 125.09 \text{ GeV}</math></li> <li><b>CERN-2017-002-M</b> [arXiv:1610.07922]</li> </ul>	$\sqrt{s} = 8 \text{ TeV}$ $\sigma_{\text{NLO}} [\text{fb}]$	$\sqrt{s} = 13 \text{ TeV}$ $\sigma_{\text{NLO}} [\text{fb}]$	$\sqrt{s} = 14 \text{ TeV}$ $\sigma_{\text{NLO}} [\text{fb}]$
ggF $\rightarrow hh$ (NNLO + NNLL with NLO top mass effects taken into account)	10.2	33.4	39.5
hhjj (VBF)	0.5	1.6	2.0
tthh	0.2	0.8	0.9
Whh+Zhh	0.3	0.9	1.0

# [Di-Higgs production at LHC: hypothetical new particles]



Not the focus of this talk.

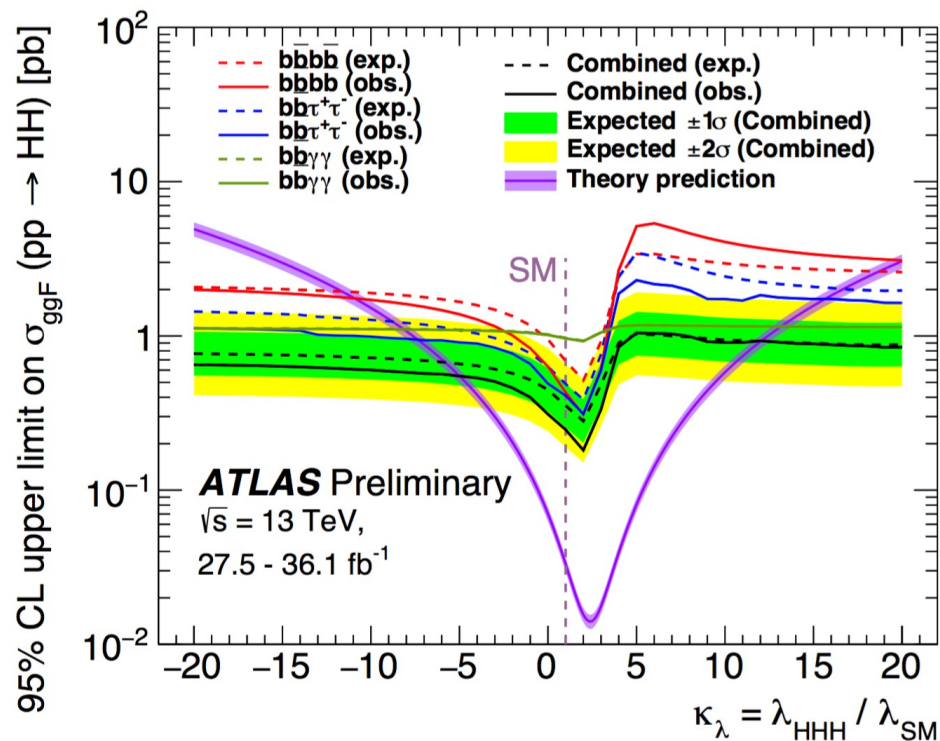
The search for new resonances that decay to two Higgs bosons is an exciting topic of its own. Especially with the move to high energy ( $\sqrt{s} = 13$  TeV) of the LHC.

Will briefly show an example of a search later when we discuss the current di-Higgs results.

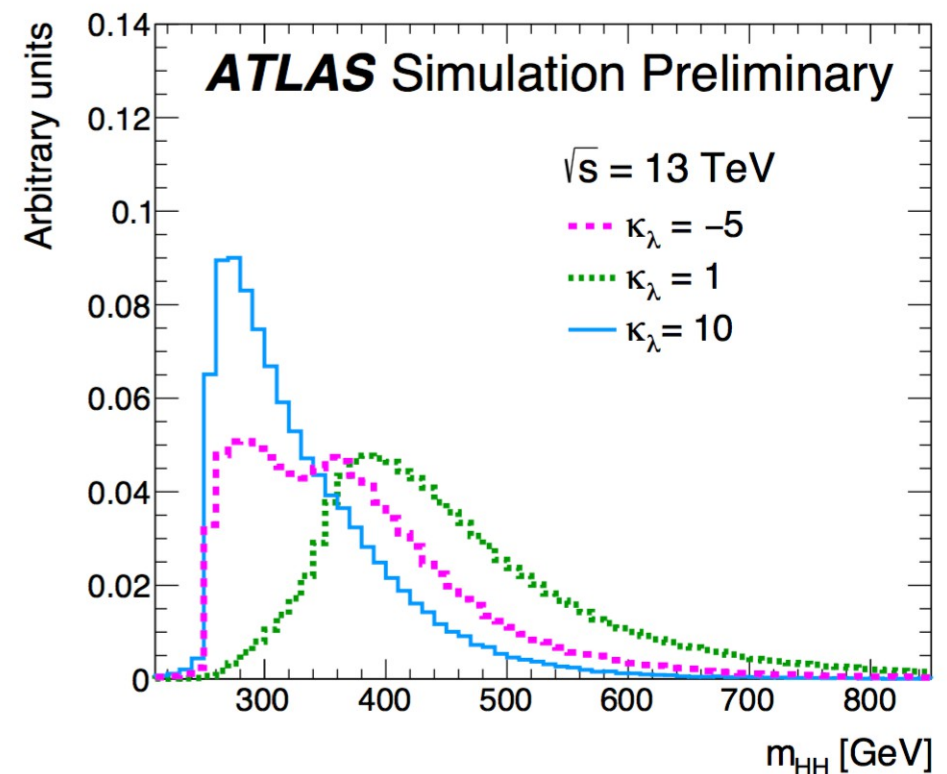


# Di-Higgs production at LHC: observables

Di-Higgs production cross section  
strongly depends on self-coupling strength:



Kinematics of the HH events,  
in particular  $m(\text{HH})$ ,  
depends on self-coupling strength:

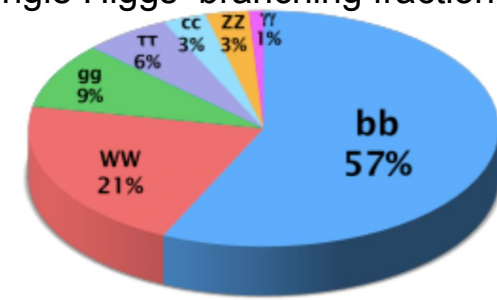


On this slide, and in the remainder of this talk: express coupling strength in multiples of Standard Model expectation ( $\lambda_{\text{SM}}$ ):

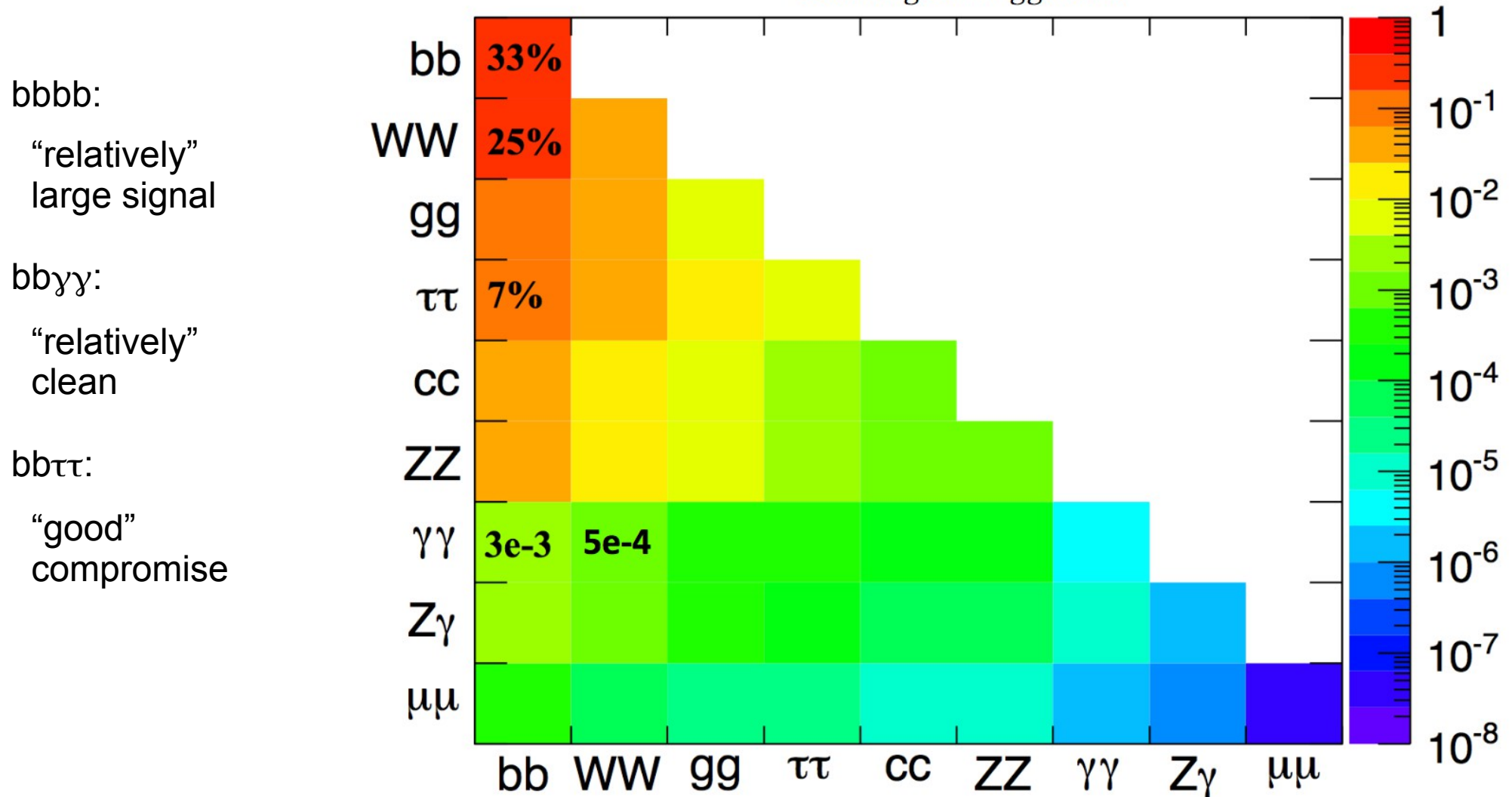
$$\kappa_\lambda = \lambda_{\text{HHH}} / \lambda_{\text{SM}}$$

# Di-Higgs: channels

Single Higgs branching fractions



Assuming SM Higgs BR's

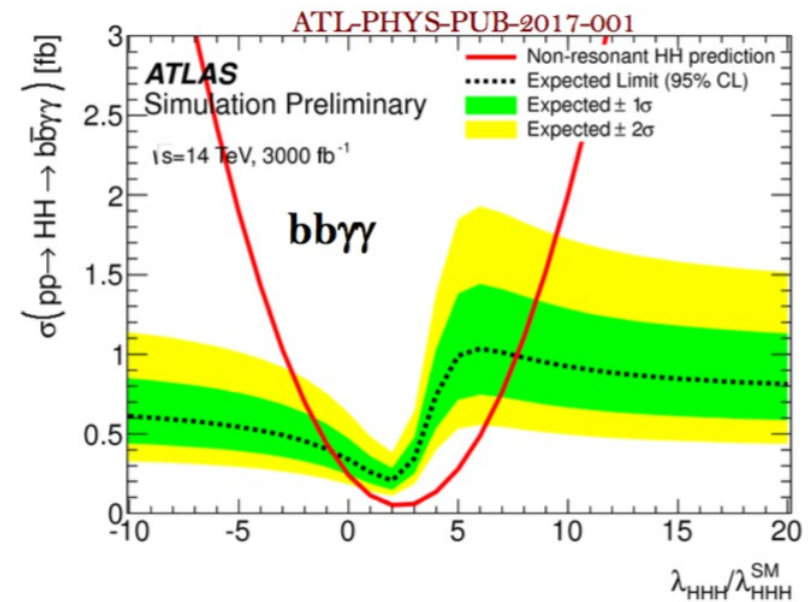
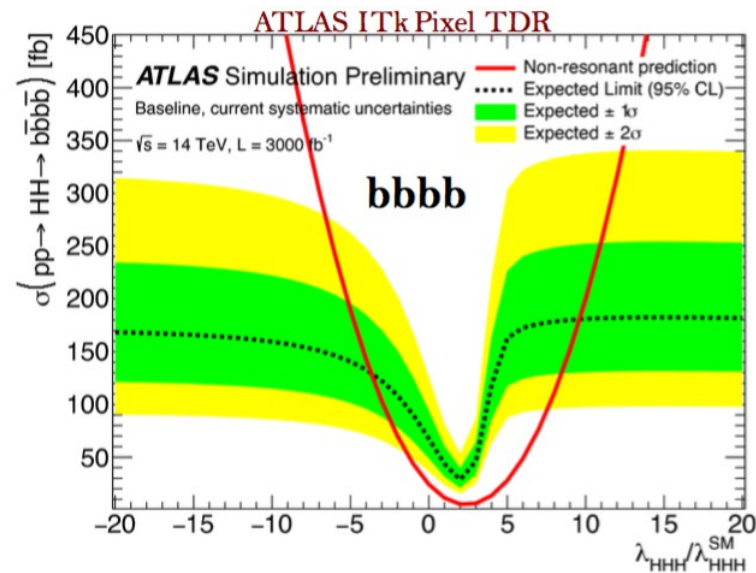


bbbb:  
“relatively”  
large signal

bb $\gamma\gamma$ :  
“relatively”  
clean

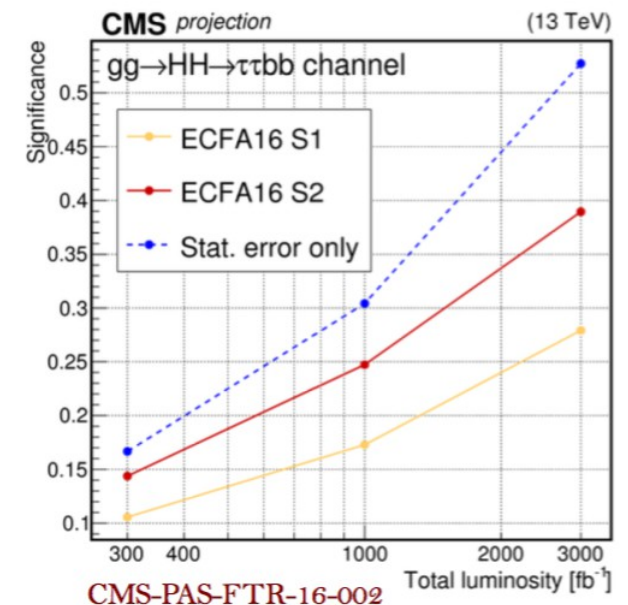
bb $\tau\tau$ :  
“good”  
compromise

# Existing, public projections



Published HL-LHC projections suggest a very challenging future.

Coupling limits  $\kappa_\lambda \in [-1, 8]$  for single channel.





# The “50% claim”

To get an idea of what to expect, we quote the optimal reach of the high-luminosity LHC run with  $3 \text{ ab}^{-1}$ , based on the Neyman-Pearson theorem applied to the  $b\bar{b}\gamma\gamma$  channel for self-couplings relatively close to the Standard Model [41],

$$\frac{\lambda_{H^3}}{\lambda_{H^3,0}} = 0.4 \dots 1.7 \quad \text{at 68\% C.L.}, \quad (9)$$

so any value for  $\lambda_{H^3}/\lambda_{H^3,0}$  outside the range given above will not be compatible with the vanishing di-Higgs amplitude in Eq. (8). This reach will be improved when we combine several Higgs decay channels, but will also suffer from systematic uncertainties. In addition, it assumes a perfect knowledge of the top Yukawa coupling. This implies that models which predict a change in the Higgs self-coupling by less than 50% will not be testable at the LHC.

Text on the left:  
from the paper on slide 11.

And this is Ref. [41]:

PHYSICAL REVIEW D **95**, 035026 (2017)

## Maximizing the significance in Higgs boson pair analyses

Felix Kling,<sup>1,2</sup> Tilman Plehn,<sup>3</sup> and Peter Schichtel<sup>4</sup>

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<sup>2</sup>*Theoretical Physics Department, Fermilab, Batavia, Illinois 60510, USA*

<sup>3</sup>*Institut für Theoretische Physik, Universität Heidelberg,  
Philosophenweg 16, 69120 Heidelberg, Germany*

<sup>4</sup>*Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LF, United Kingdom*  
(Received 28 September 2016; published 22 February 2017)

We study Higgs pair production with a subsequent decay to a pair of photons and a pair of bottoms at the LHC. We use the log-likelihood ratio to identify the kinematic regions which either allow us to separate the di-Higgs signal from backgrounds or to determine the Higgs self-coupling. We find that both regions are separate enough to ensure that details of the background modeling will not affect the determination of the self-coupling. Assuming dominant statistical uncertainties we determine the best precision with which the Higgs self-coupling can be probed in this channel. We finally comment on the same questions at a future 100 TeV collider.

DOI: 10.1103/PhysRevD.95.035026

$$\frac{\lambda}{\lambda_{\text{SM}}} = 0.4 \dots 1.7 \quad \text{at 68\% CL and for } 3 \text{ ab}^{-1} \quad (12)$$

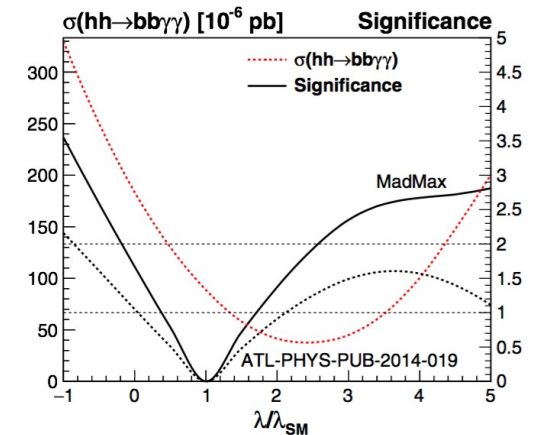


FIG. 6. Signal cross section (red dashed line) and maximum significance (black solid line) for observing an anomalous Higgs self-coupling at the LHC with an integrated luminosity of  $3 \text{ ab}^{-1}$ . We also show the significance from a cut-based rate measurement using the cuts suggested in Ref. [35] (black dashed line).

# The latest measurements

# Latest Run 2 result: $HH \rightarrow bbbb$

arXiv:1804.06174 [hep-ex], submitted to JHEP

## Dominant backgrounds:

- multi-jet production
- $t \bar{t}$

## Event selection:

- $\geq 4$  b-tagged jets with  $p_T > 40$  GeV
- b-jets assigned to two  $H \rightarrow bb$  candidates using angular information
- requirement on Higgs candidate  $p_T$  dependent on  $m(HH)$
- veto events where Higgs candidate masses are not consistent with  $H \rightarrow bb$  decay
- veto events consistent with top quark decay

## Analysis strategy:

- Signal extracted from fit to  $m(HH)$  distribution
- Shape of  $t \bar{t}$  background taken from simulation
- Multijet background taken from data control region: events with  $\geq 4$  jets but only 2 b-tags.
  - reweighted to 4-b-tag data in sidebands
  - background model validated in 4-b-tag data in sidebands, close to the  $H \rightarrow bb$  mass peaks

# Latest Run 2 result: $HH \rightarrow bbbb$

arXiv:1804.06174 [hep-ex], submitted to JHEP

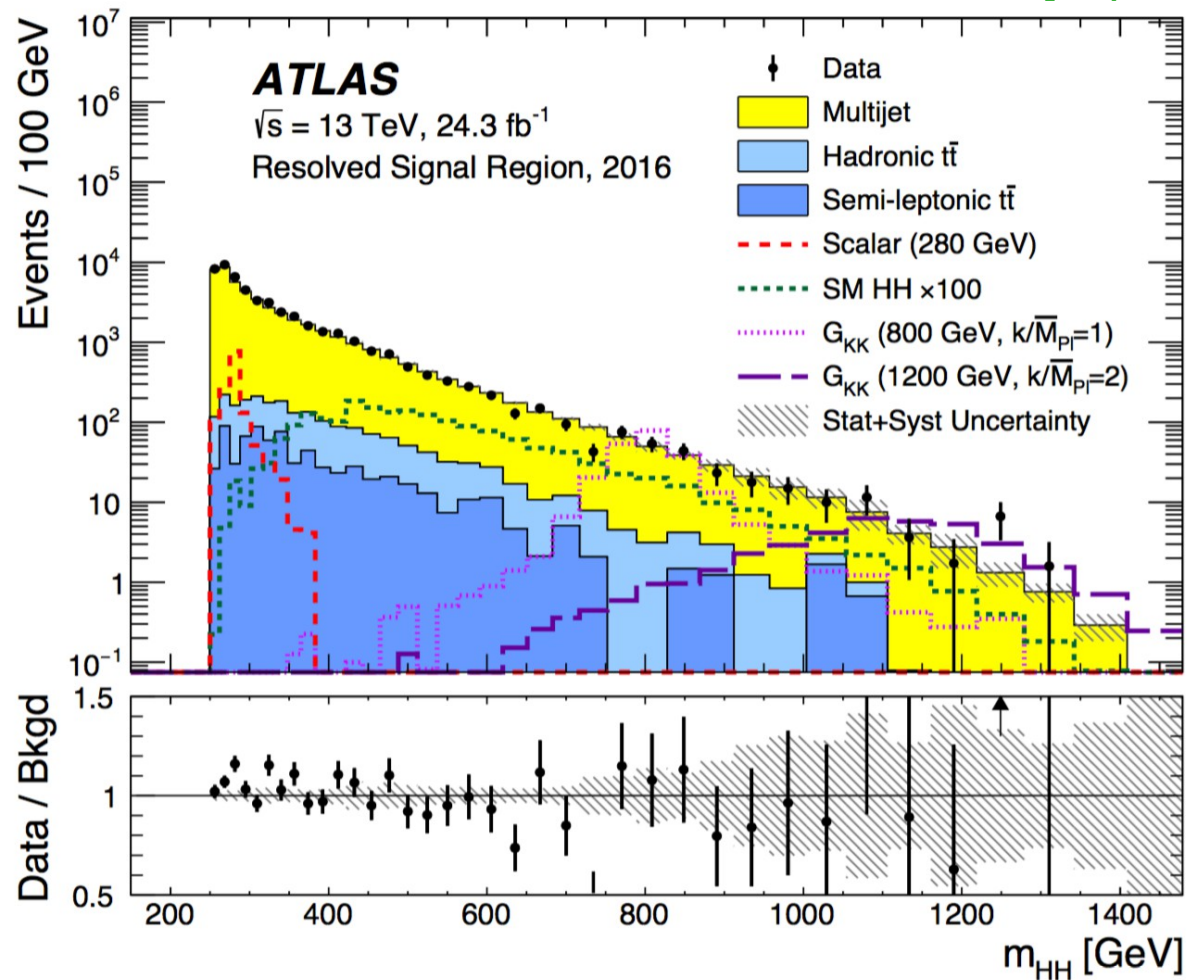


Table 8: 95% CL exclusion limits for SM non-resonant  $HH$  production, in units of the SM prediction for  $\sigma(pp \rightarrow HH \rightarrow bbbb)$ .

Observed	$-2\sigma$	$-1\sigma$	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5



# Latest Run 2 result: $HH \rightarrow bb\tau\tau$

Phys. Rev. Lett. 121, 191801 (2018)

## Dominant backgrounds:

- $t\bar{t}$

## Event selection:

- Two categories:  $\tau_{\text{lep}} \tau_{\text{had}}$  and  $\tau_{\text{had}} \tau_{\text{had}}$
- Boosted Decision Tree (BDT) used in each category.  
Exploits masses, angular variables and missing transverse energy.

## Analysis strategy:

- Signal extracted from fit to distribution of BDT score
- $t\bar{t}$  background with true  $\tau_{\text{had}}$  taken from simulation
- $t\bar{t}$  component with jets: faking had: MC + data-driven methods for fake rate

# Latest Run 2 result: $HH \rightarrow bb\tau\tau$

Phys. Rev. Lett. 121, 191801 (2018)

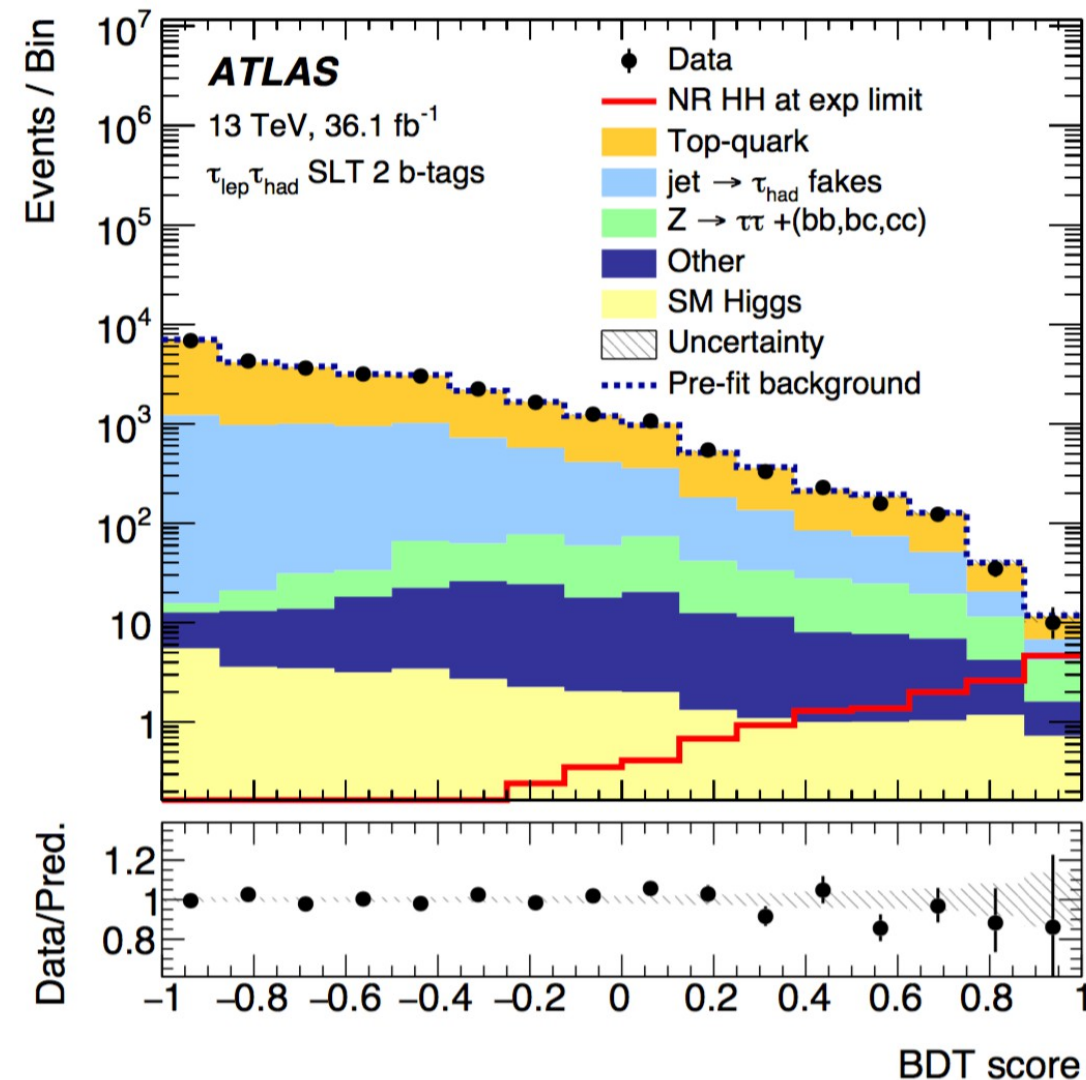


Table 3: Observed and expected upper limits on the production cross-section times the  $HH \rightarrow bb\tau\tau$  branching ratio or NR  $HH$  at 95% CL, and their ratios to the SM prediction. The  $\pm 1\sigma$  variations about the expected limit are also shown.

		Observed	$-1\sigma$	Expected	$+1\sigma$
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	57	49.9	69	96
	$\sigma/\sigma_{\text{SM}}$	23.5	20.5	28.4	39.5
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	$\sigma/\sigma_{\text{SM}}$	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \rightarrow bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	$\sigma/\sigma_{\text{SM}}$	12.7	10.7	14.8	20.6

single most stringent limit on non-resonant  $HH$  production to date.

# Latest Run 2 result: $HH \rightarrow b\bar{b}\gamma\gamma$

JHEP 11 (2018) 040

## Dominant backgrounds:

- $b\bar{b}\gamma\gamma$  and  $c\bar{c}\gamma\gamma$  non-resonant continuum background
- various single Higgs ( $H \rightarrow \gamma\gamma$ ) processes:  $Hbb$ ,  $ttH$ ,  $ZH$ , ...

## Event selection:

Very simple event selection:

- acceptance requirements ( $p_T, \dots$ )
- di-jet mass consistent with  $H \rightarrow b\bar{b}$
- two categories: one or two b-tags

## Analysis strategy:

- Signal extracted from fit  $m(\gamma\gamma)$  distribution  
→ continuum backgrounds from sidebands
- “Peaking” single Higgs backgrounds from simulation

# Latest Run 2 result: $HH \rightarrow b\bar{b}\gamma\gamma$

JHEP 11 (2018) 040

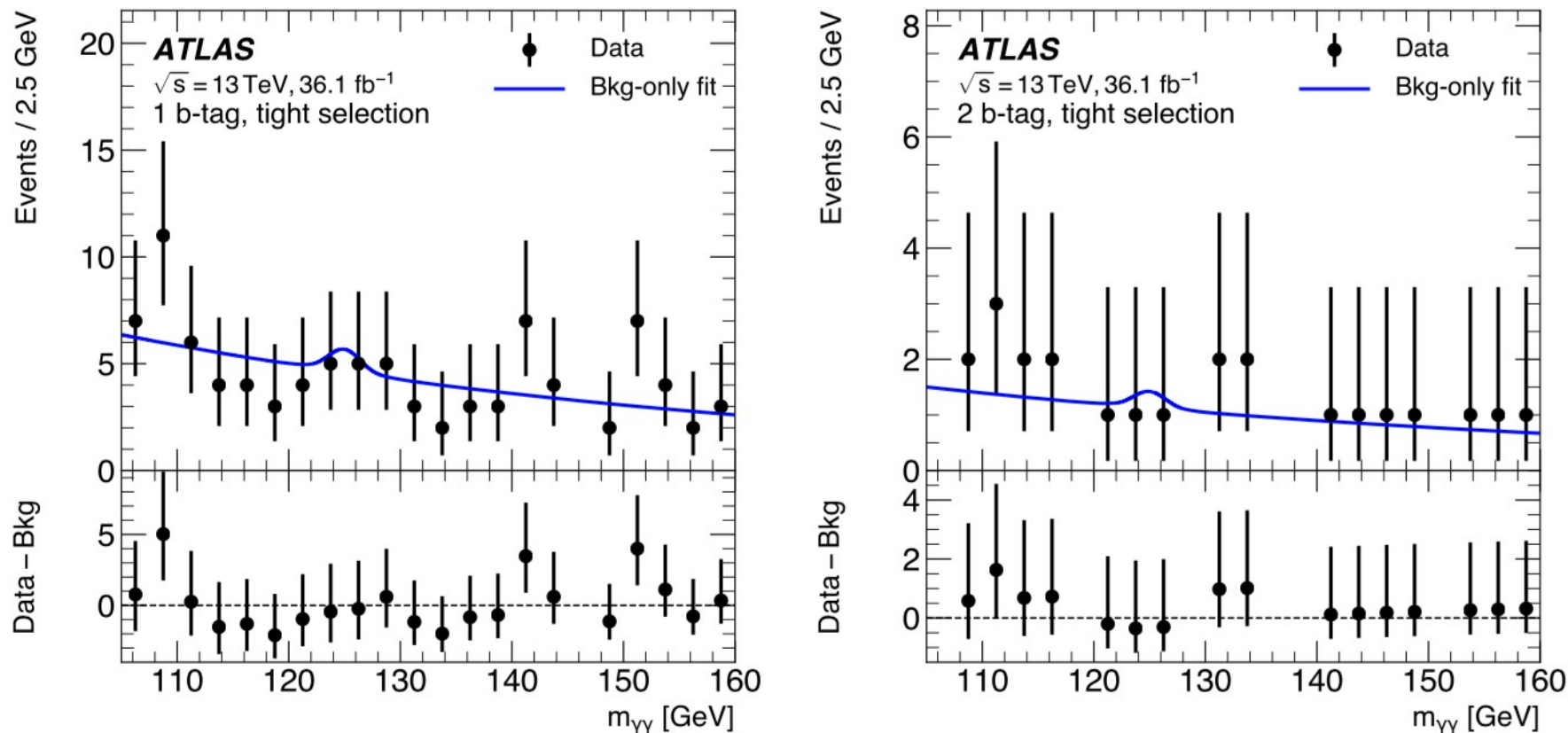


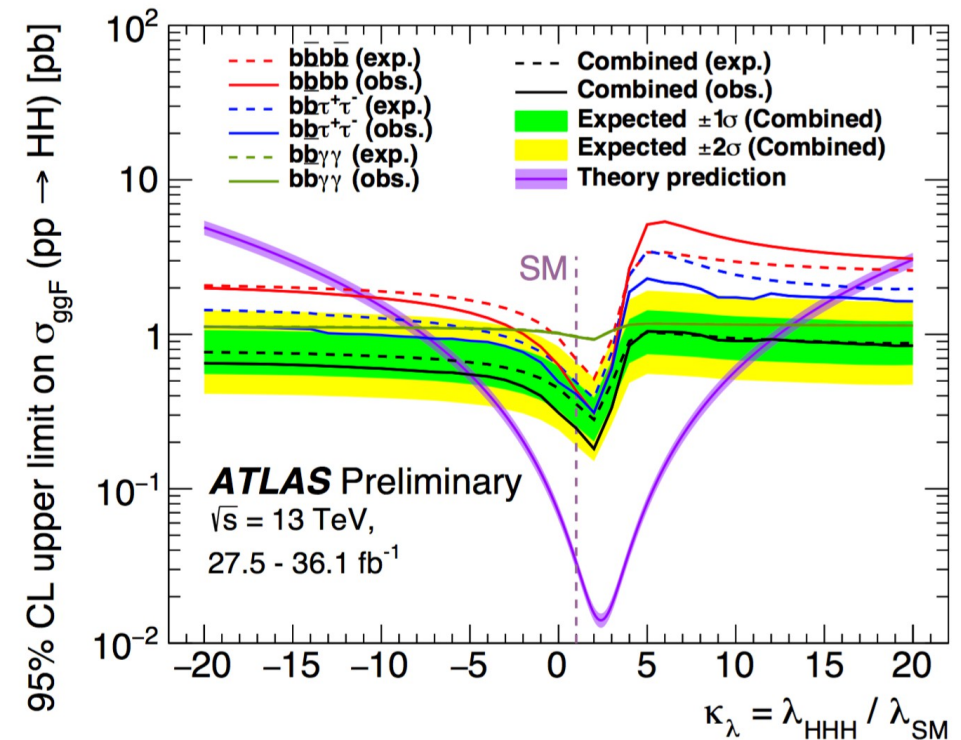
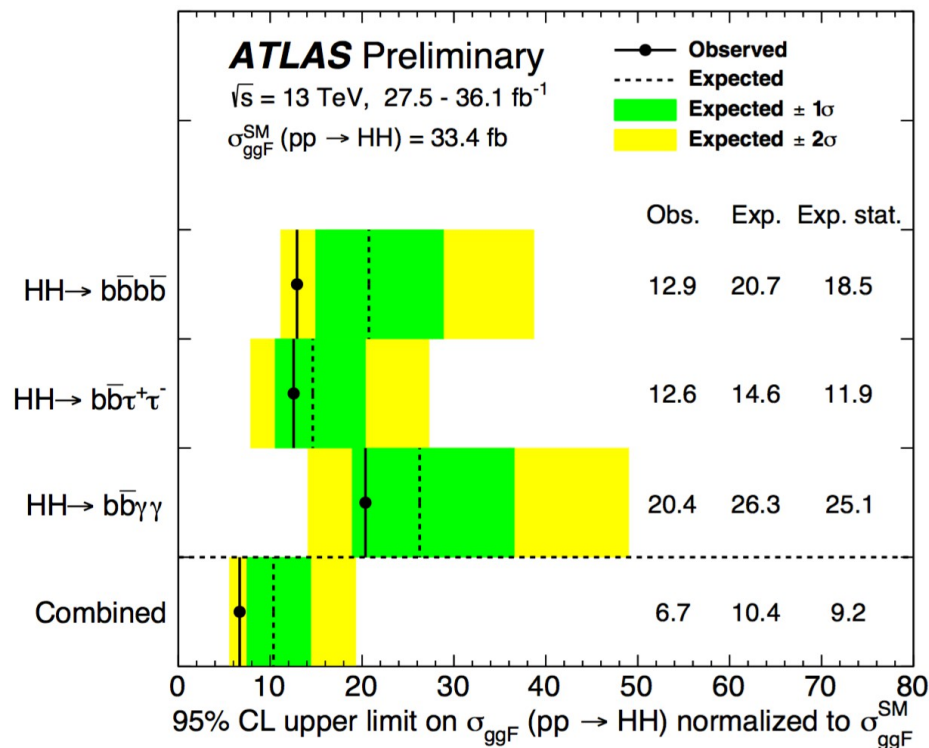
Table 4: The 95% CL observed and expected limits on the Higgs boson pair cross-section in pb and as a multiple of the SM production cross-section. The  $\pm 1\sigma$  band around each 95% CL limit is also indicated.

	Observed	Expected	$-1\sigma$	$+1\sigma$
$\sigma_{gg \rightarrow HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of $\sigma_{SM}$	22	28	20	40



# Latest Run 2 combination: HH

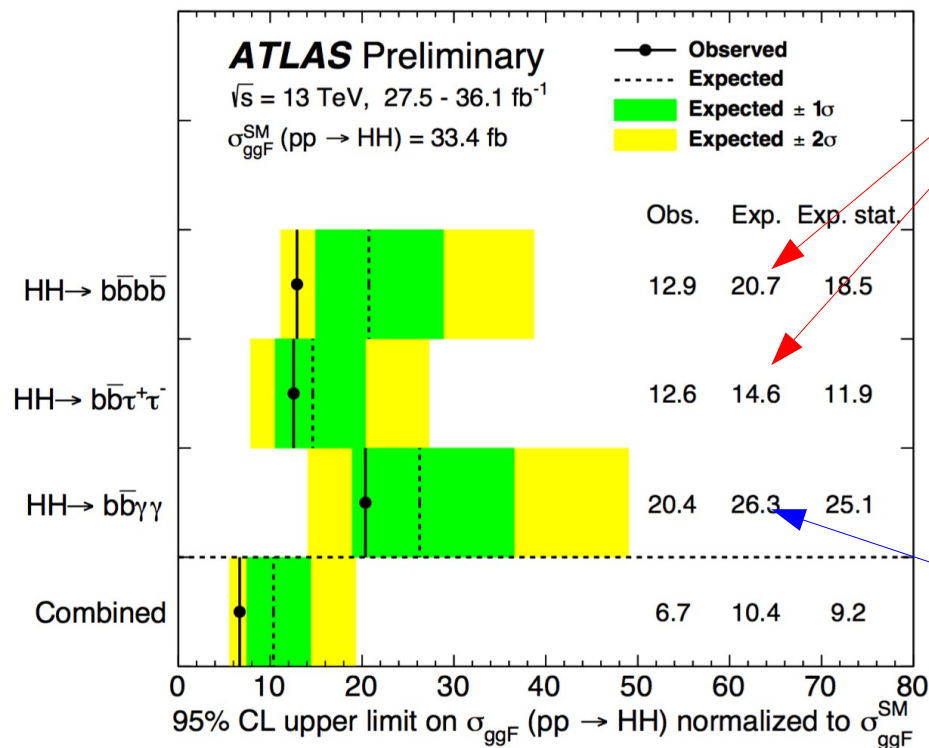
ATLAS-CONF-2018-043 (September 2018)





# Hot off the press: New HL-LHC projections

# Updated HL-LHC projections



The new projections for  $\text{bbbb}$  and  $\text{bb}\tau\tau$  are **extrapolations** based on the measurements that we just discussed.

The new projections for  $\text{bb}\gamma\gamma$  are based on a **new analysis** that uses more sophisticated techniques than the current measurement.

# Updated HL-LHC projections: $HH \rightarrow b\bar{b}\gamma\gamma$

Analysis proceeds  
in two steps:

## Simple preselection

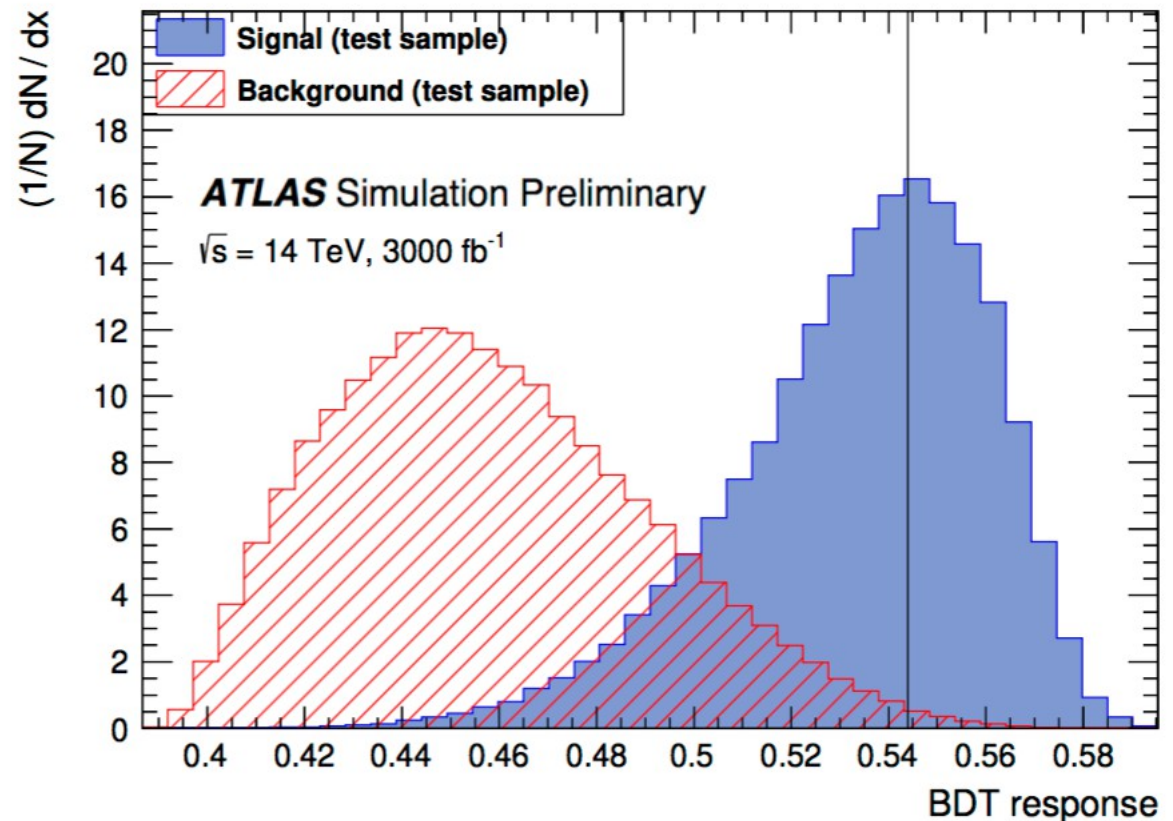
after preselection:

39000 events from  
continuum background

180 events from single Higgs  
Boson background

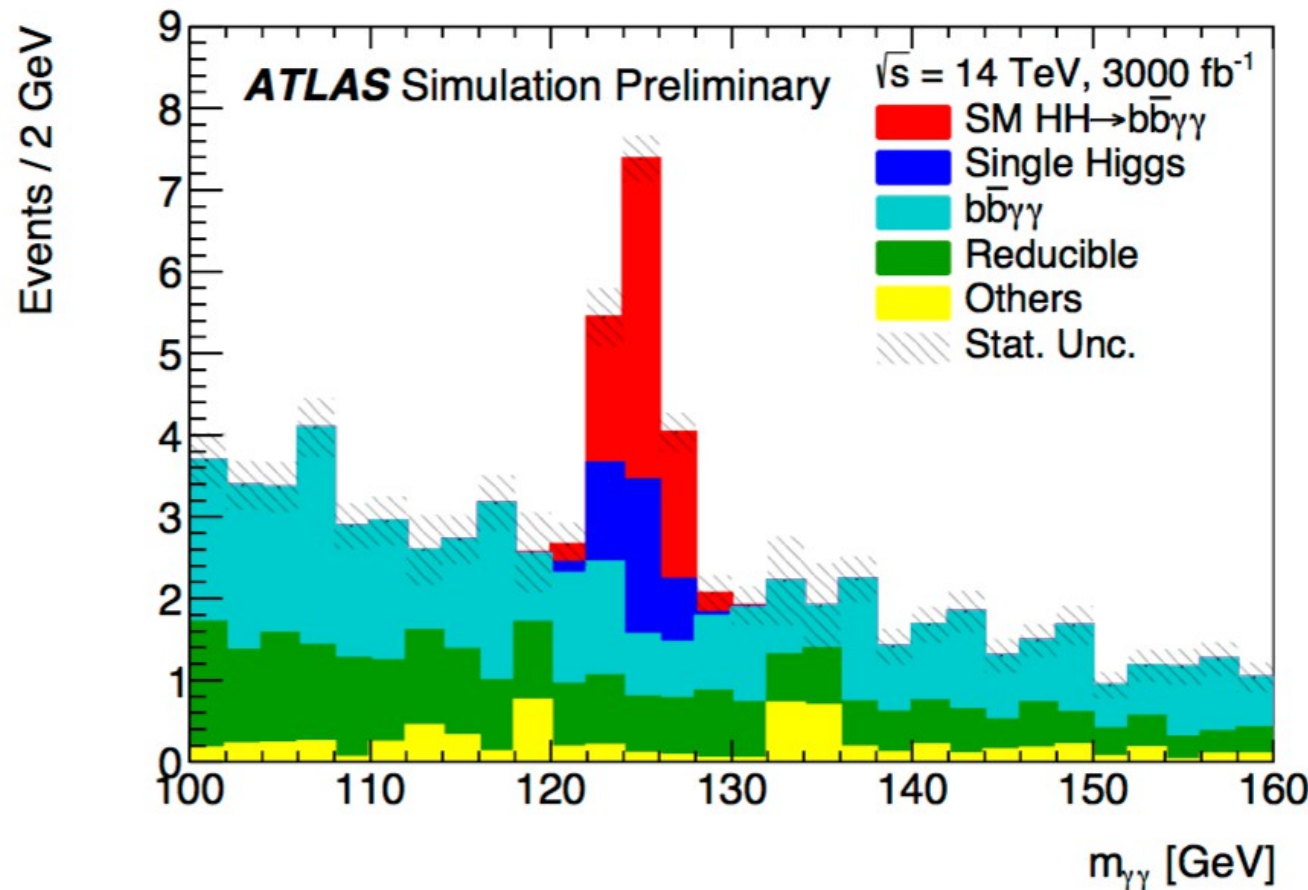
## Boosted Decision Tree (BDT)

for background rejection,  
21 variables





# Updated HL-LHC projections: $HH \rightarrow b\bar{b}\gamma\gamma$



After BDT requirement  
and  $123 < m(\gamma\gamma) < 127 \text{ GeV}$ :

3.7 events continuum  
background

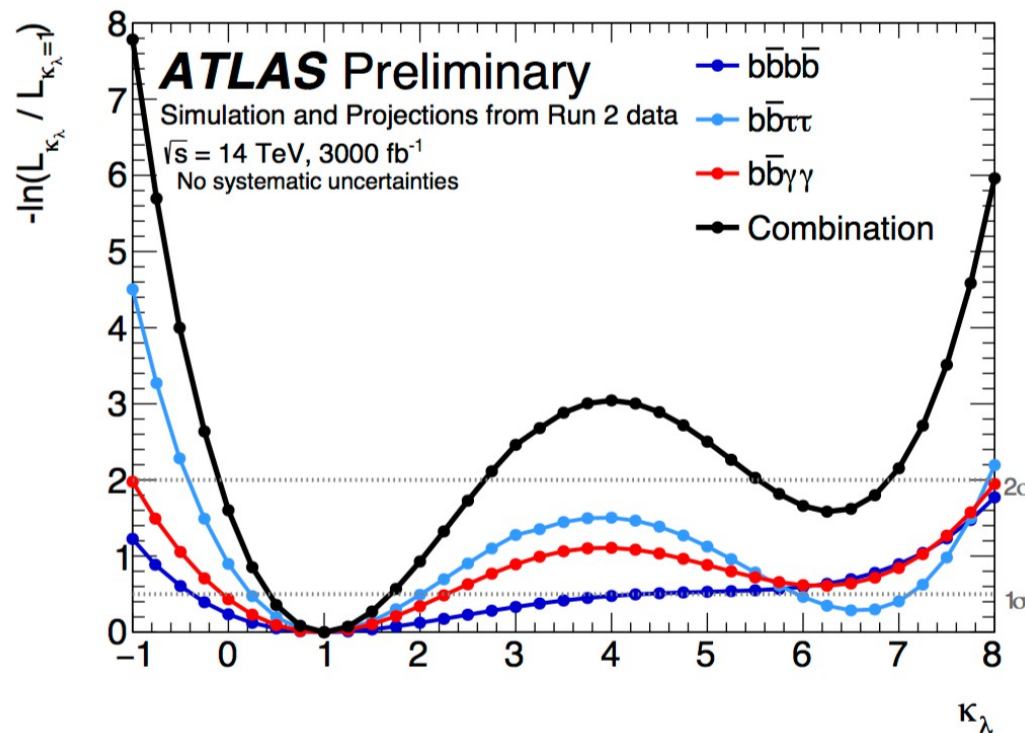
3.2 events single Higgs  
background  
( $t\bar{t}H$ ,  $ZH$ ,  $Zb\bar{b}$ , ...)

6.46 di-Higgs signal  
events for  $\kappa_\lambda = 1$ .

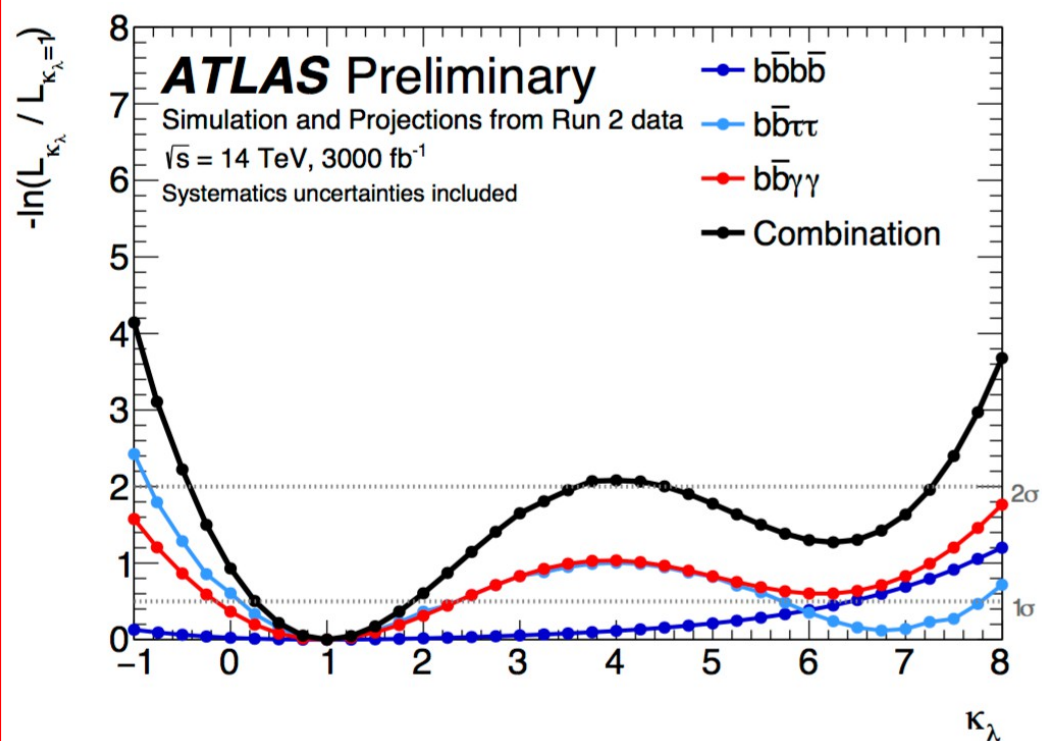
# Updated HL-LHC projections: combination of channels, extraction of $\kappa_\lambda$

These plots assume a signal as predicted by the SM ( $\kappa_\lambda = 1$ ).

Stat uncertainties only



Including systematic uncertainties



Projected measurement uncertainties:

$$\kappa_\lambda = 1.0^{+0.9}_{-0.8}$$

# For the future: even more observables in the extraction of $\kappa_\lambda$

From slide 17:

And this is Ref. [41]:

PHYSICAL REVIEW D **95**, 035026 (2017)

## Maximizing the significance in Higgs boson pair analyses

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<sup>2</sup>*Theoretical Physics Department, Fermilab, Batavia, Illinois 60510, USA*

<sup>3</sup>*Institut für Theoretische Physik, Universität Heidelberg,  
Philosophenweg 16, 69120 Heidelberg, Germany*

<sup>4</sup>*Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LF, United Kingdom*  
(Received 28 September 2016; published 22 February 2017)

We study Higgs pair production with a subsequent decay to a pair of photons and a pair of bottoms at the LHC. We use the log-likelihood ratio to identify the kinematic regions which either allow us to separate the di-Higgs signal from backgrounds or to determine the Higgs self-coupling. We find that both regions are separate enough to ensure that details of the background modeling will not affect the determination of the self-coupling. Assuming dominant statistical uncertainties we determine the best precision with which the Higgs self-coupling can be probed in this channel. We finally comment on the same questions at a future 100 TeV collider.

DOI: 10.1103/PhysRevD.95.035026

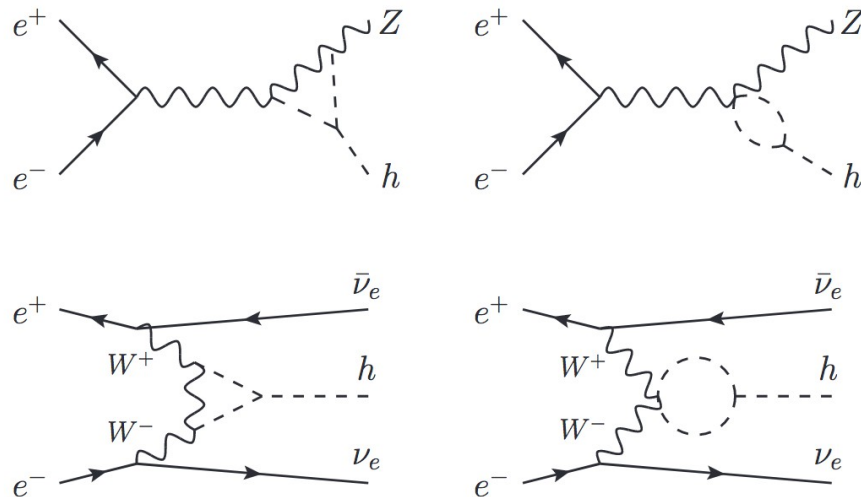
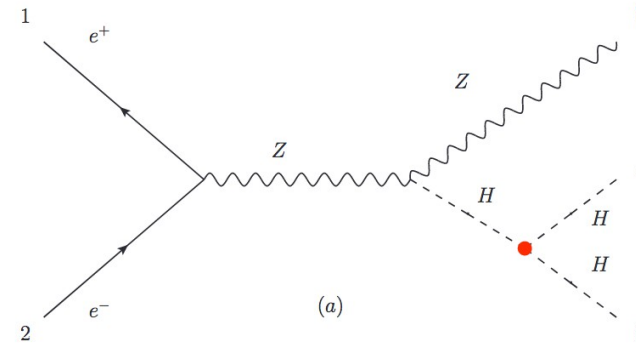
An analysis that is based on the same log-likelihood ratios that are mentioned in this paper (on the right) would be the matrix element method.

# Higgs self-coupling at (possible) future colliders

ILC at  $\sqrt{s} = 500 \text{ GeV}$ ,  $2 \text{ ab}^{-1}$ :  $\sigma(\kappa_\lambda) = 44\%$

ILC at  $\sqrt{s} = 1 \text{ TeV}$ ,  $2 \text{ ab}^{-1}$ :  $\sigma(\kappa_\lambda) = 18\%$

(from ILC TDR and LC-REP-2013-003)



FCC-ee:  $\sigma(\kappa_\lambda) = 44\%$

Very indirect:  
measuring centre-of-mass-energy-dependent  
effects on single Higgs observables  
(such as the HZ and  $\nu\nu H$  production cross sections)

$\sqrt{s} = 240 \text{ GeV}$  and  $\sqrt{s} = 365 \text{ GeV}$

(from  
FCC CDR)

FCC-hh:  $\sigma(\kappa_\lambda) = \sim 5\%$

Table 10.2: Precision of the direct Higgs self-coupling measurement in  $gg \rightarrow HH$  production, for various decay modes, from the FCC-hh detector performance studies.

	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\rightarrow 4\ell]$	$b\bar{b}WW^*[\rightarrow 2j\ell\nu]$	$4b+\text{jet}$
$\delta\kappa_\lambda$	6.5%	14%	40%	30%

(from  
FCC CDR)

Question: so what about the *quartic*  
Higgs self-coupling ?



# Summary

At LHC, finally have experimental access to the Higgs sector.

Studying the Higgs sector in detail:

- Additional Higgs bosons ?
- Measurements of the properties of the Higgs boson: mass, couplings, ...

Measuring the Higgs self-coupling is key test of the Standard Model.

- Hope to learn more about the origin of the Higgs potential
- Implications for Electroweak baryogenesis

The measurement of the self-coupling is notoriously difficult and will require very large datasets.

In this talk, showed, for the first time in public, updated projections for the HL-LHC phase from the ATLAS collaboration.

In the past: “Can we discover di-Higgs at the LHC ?”.

We are moving towards the new question: “When will we discover di-Higgs at the LHC ?”

# **Additional material**

# Current HH combination: acceptances

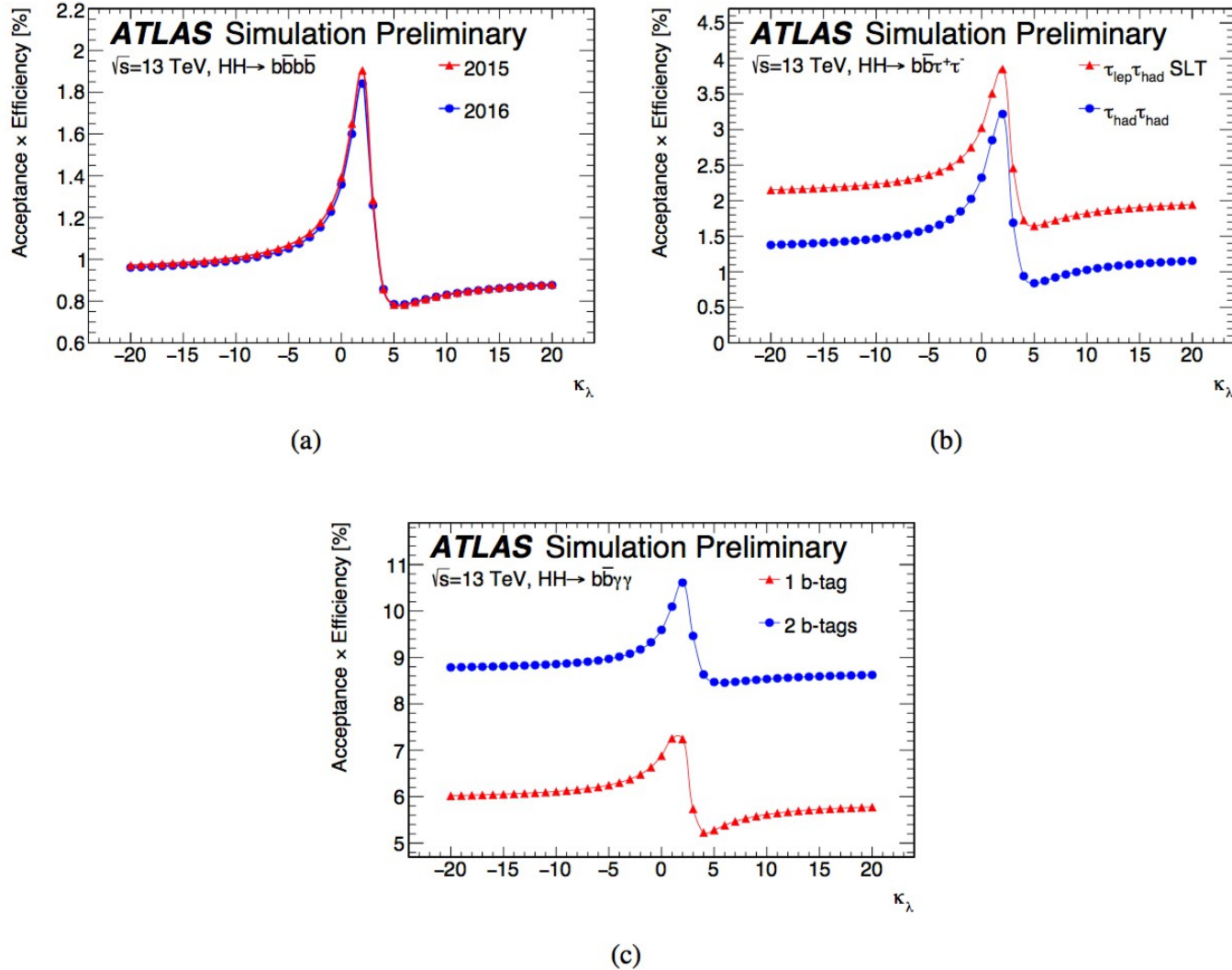


Figure 4: Signal acceptance times efficiency as a function of  $\kappa_\lambda$  for (a)  $HH \rightarrow b\bar{b}b\bar{b}$ , (b)  $HH \rightarrow b\bar{b}\tau^+\tau^-$  and (c)  $HH \rightarrow b\bar{b}\gamma\gamma$ . The acceptances are split by years for the  $HH \rightarrow b\bar{b}b\bar{b}$  analysis, due to different trigger configurations, and by event categories for the  $HH \rightarrow b\bar{b}\tau^+\tau^-$  and  $HH \rightarrow b\bar{b}\gamma\gamma$  analyses.

# Measuring the Higgs self-coupling in $e^+ e^-$ collisions

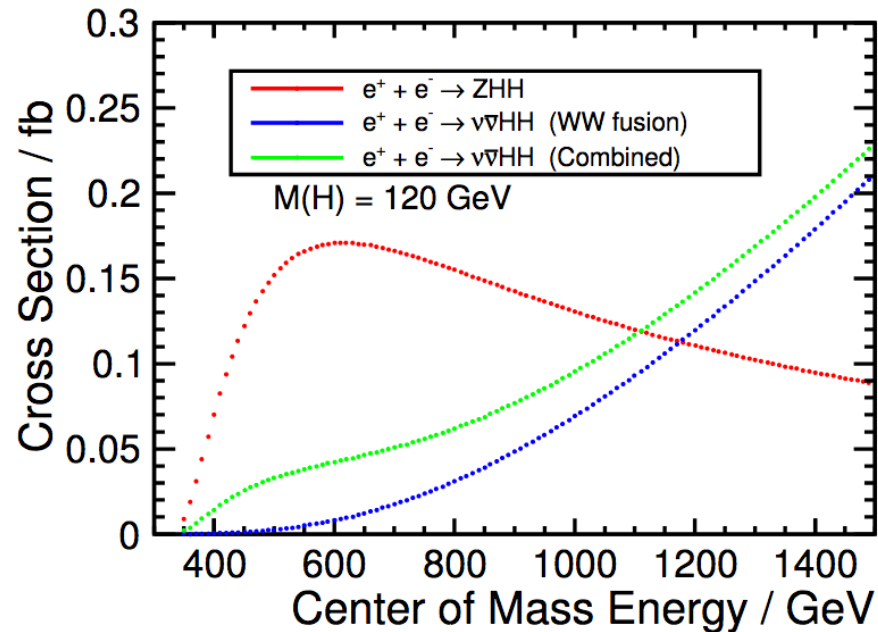


FIG. 1: The separate and combined production cross sections for the  $ZHH$  and  $\nu\bar{\nu}HH$  processes as a function of the center of mass energy assuming the Higgs mass of 120 GeV. The red line is for the  $ZHH$  process, the blue line is for the  $\nu\bar{\nu}HH$  fusion process and the green line is for the combined result.

Figure extracted from: J. Tian, LC-REP-2013-003.

# Measuring the Higgs self-coupling in $e^+ e^-$ collisions

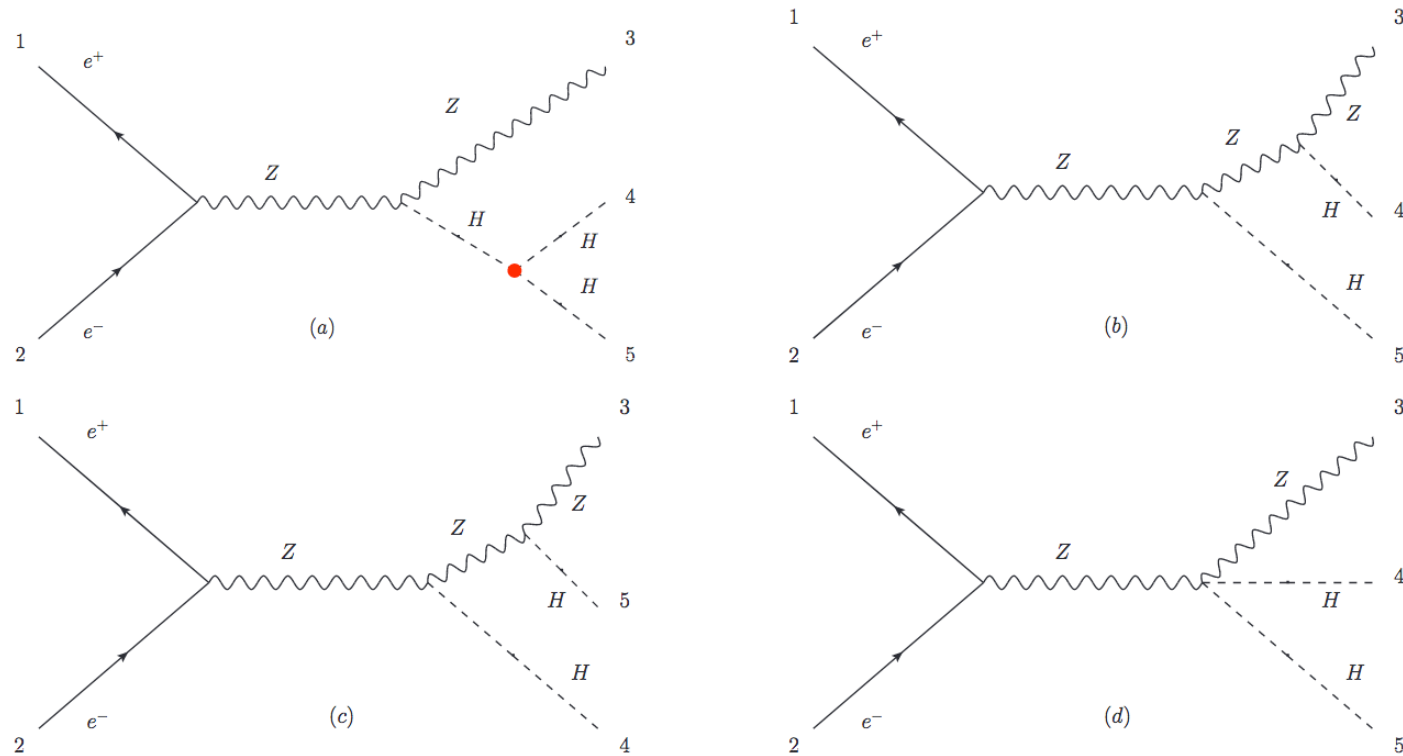


FIG. 2: Feynman diagrams for the double Higgs strahlung process  $e^+ e^- \rightarrow Z H H$ . (a): involving trilinear Higgs self-coupling; (b), (c), (d): the irreducible diagrams.

At  $\sqrt{s} = 500 \text{ GeV}$ :  $\frac{\delta\lambda}{\lambda} = 1.8 \frac{\delta\sigma}{\sigma}$  (dilution due to presence of diagrams without trilinear coupling)

Figure extracted from: J. Tian, LC-REP-2013-003.



# Measuring the Higgs self-coupling in $e^+ e^-$ collisions

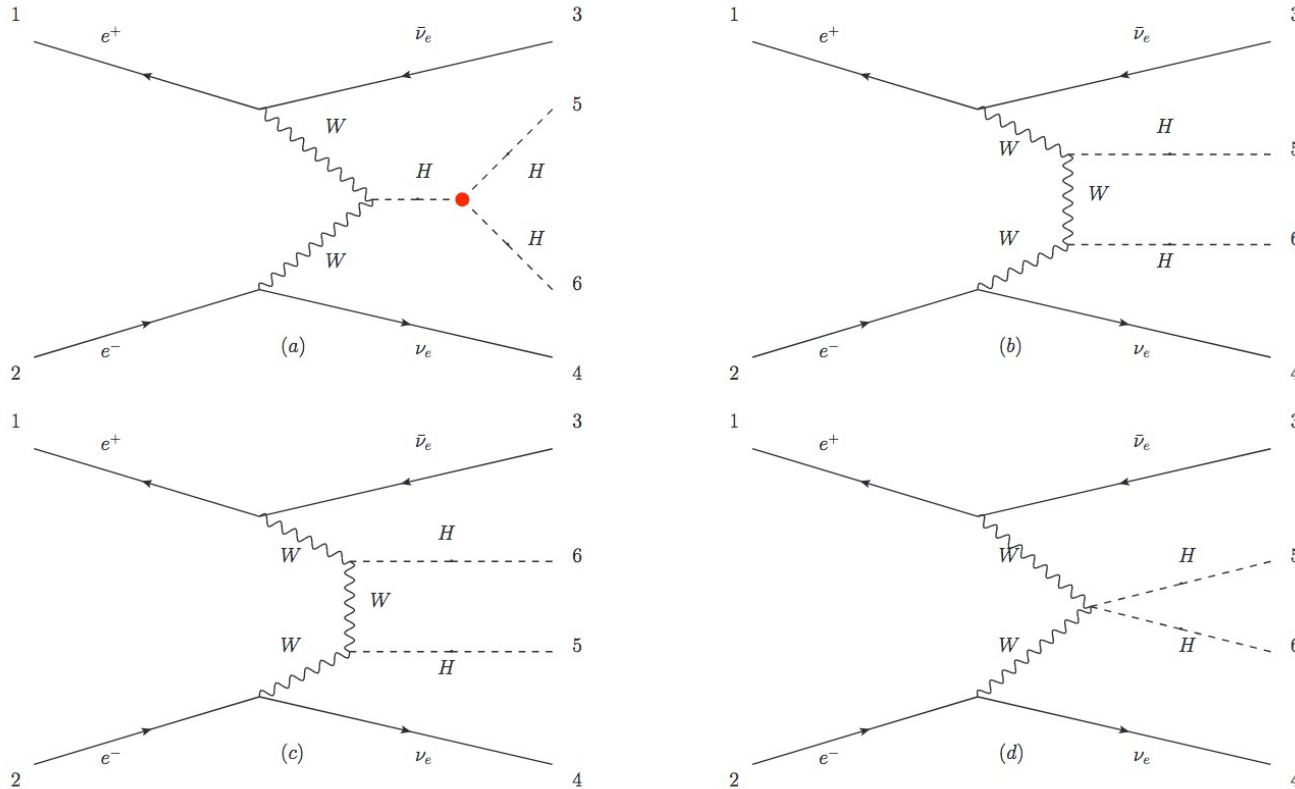


FIG. 3: Feynman diagrams for the WW fusion process  $e^+ e^- \rightarrow \nu \bar{\nu} H H$ . (a): involving trilinear Higgs self-coupling; (b), (c), (d): the irreducible diagrams.

At  $\sqrt{s} = 1 \text{ TeV}$ :  $\frac{\delta\lambda}{\lambda} = 0.85 \frac{\delta\sigma}{\sigma}$  (dilution due to presence of diagrams without trilinear coupling)

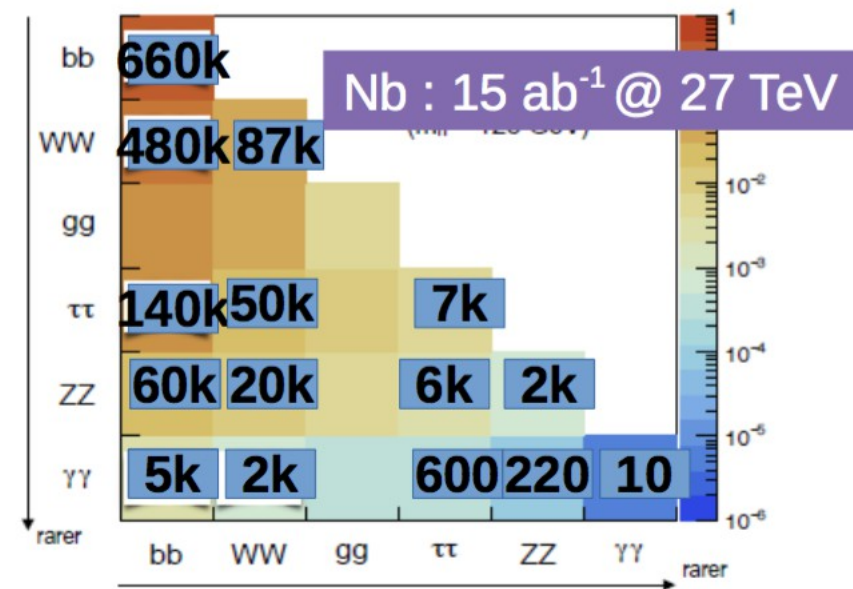
Figure extracted from: J. Tian, LC-REP-2013-003.

# Di-Higgs at HE-LHC

## \* Gain compared to HL-LHC

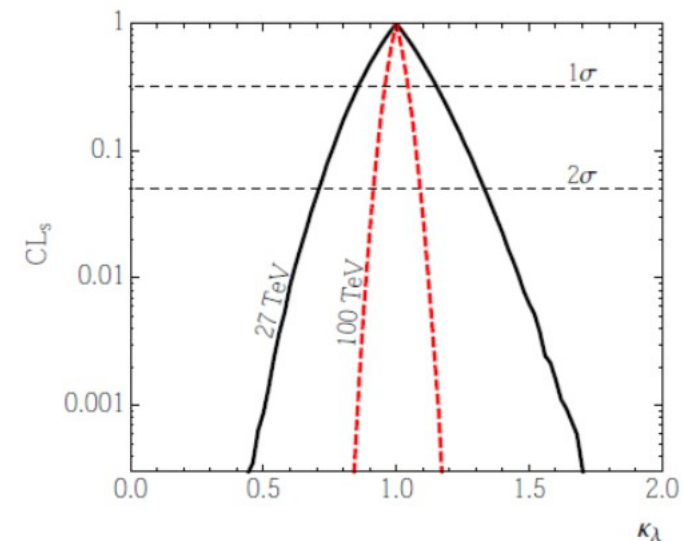
- Signal cross-section : x4
  - Same factor or lower for background
- Integrated luminosity : x 5

- Possibility to observe rare final states
- Reduction of stat. error by factor  $\sim 4$



## Recent theory study on HE-LHC prospect (arXiv :1802.04319)

- $\sim 30 \%$  precision in  $\lambda$  just from  $HH \rightarrow b\bar{b}\gamma\gamma$



# Higgs cross sections and couplings

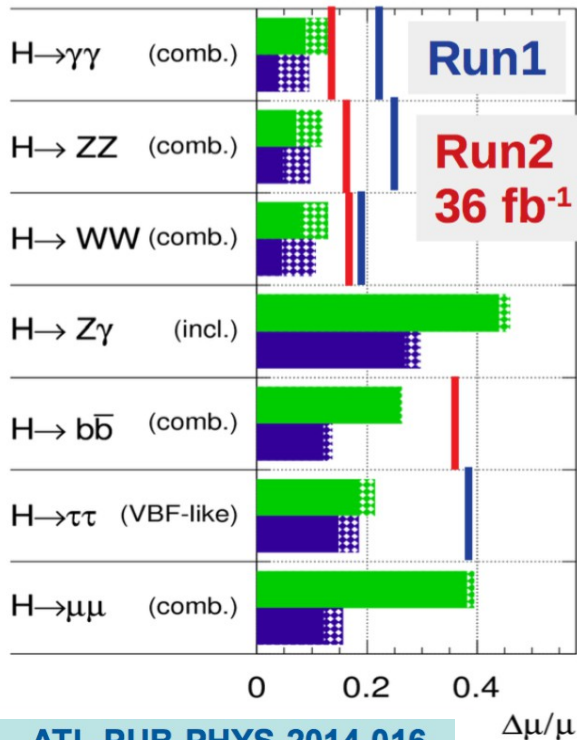
- \* Current public results based Run-1 extrapolation + few early Run-2 studies + specific studies based on full simulation

Signal strength precision  $\mu = \sigma/\sigma_{\text{SM}}$ :  
from few % level to 10-20 %

SM coupling precision  $\kappa$ :  
few % level

**ATLAS** Simulation Preliminary

$\sqrt{s} = 14$  TeV:  $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$  ;  $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



ATL-PUB-PHYS-2014-016

+

Run-1/Run-2 publications

CMS: arXiv:1307.7135v2

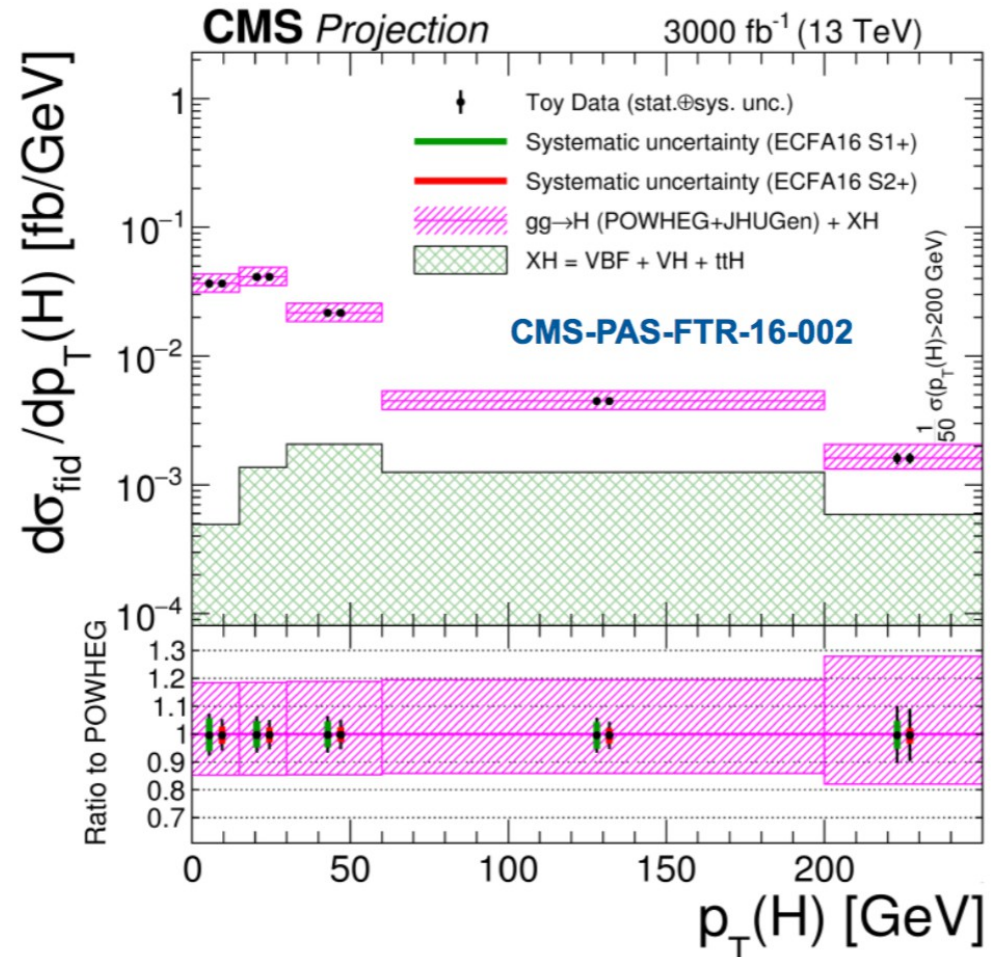
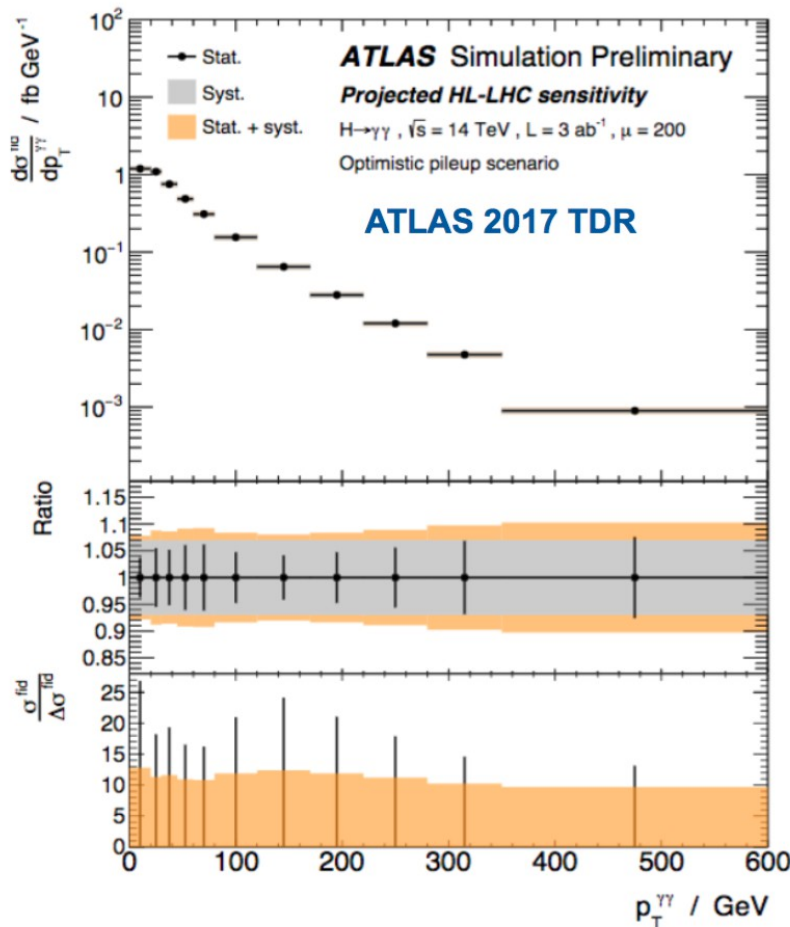
$L (\text{fb}^{-1})$	$\kappa_\gamma$	$\kappa_W$	$\kappa_Z$	$\kappa_g$	$\kappa_b$	$\kappa_t$	$\kappa_\tau$	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	$\text{BR}_{\text{SM}}$	(%)
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]	
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]	

- \* YR18 : Rerun extrapolation from Run-2 results
  - $\mu$ ,  $\kappa$ ,  $\kappa$  ratios (not syst limited)
  - Expect significant gain
- \* Previous extrapolations dominated by systematics
  - TH/ Exp syst. scenarios to be revisited
    - Example : ggF NNLO → **N3LO**  
(G. Salam talk in ECFA 16)
      - Unc. QCD scale : (+7.4,-7.9) → **3.9 %**
      - Unc. PDF +  $\alpha_s$  : (+7.1,-6.0) → **3.2 %**



# Differential cross section

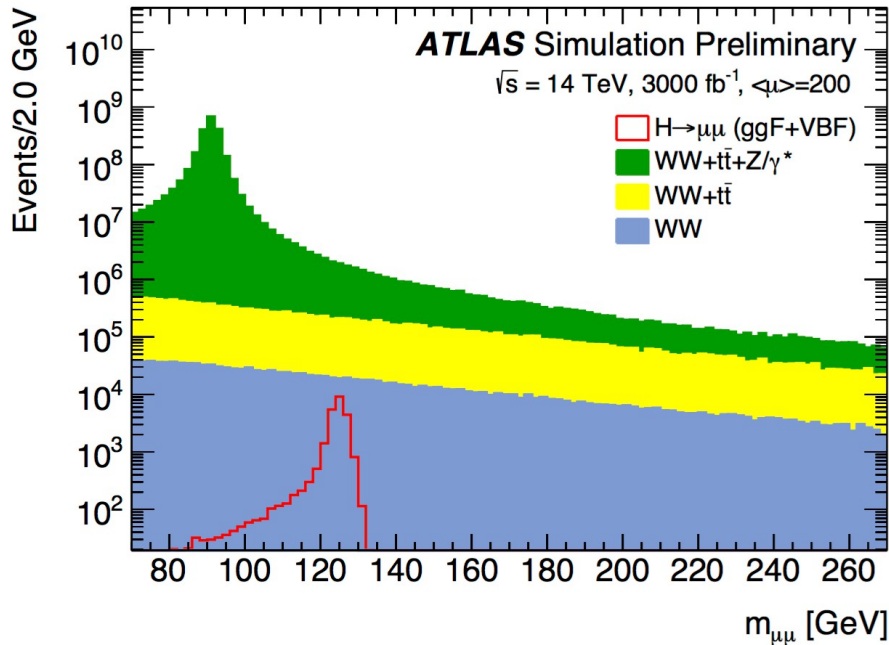
- \* Benefit from large dataset and go beyond inclusive measurement



- \* Sensitive to  $\kappa_b/\kappa_c$  (low  $p_T$ ) and  $\kappa_t/\text{BSM}$  (high  $p_T$ ) with statistical limitation
- \* YR 18 : Combination between experiments and interpretation

# Example of a rare decay: $H \rightarrow \mu\mu$

ATL-PHYS-PUB-2018-006



Study Higgs coupling to second-generation fermions

Current limits:  $\sim 3$  times SM cross section

Based on projected HL-LHC detector performance

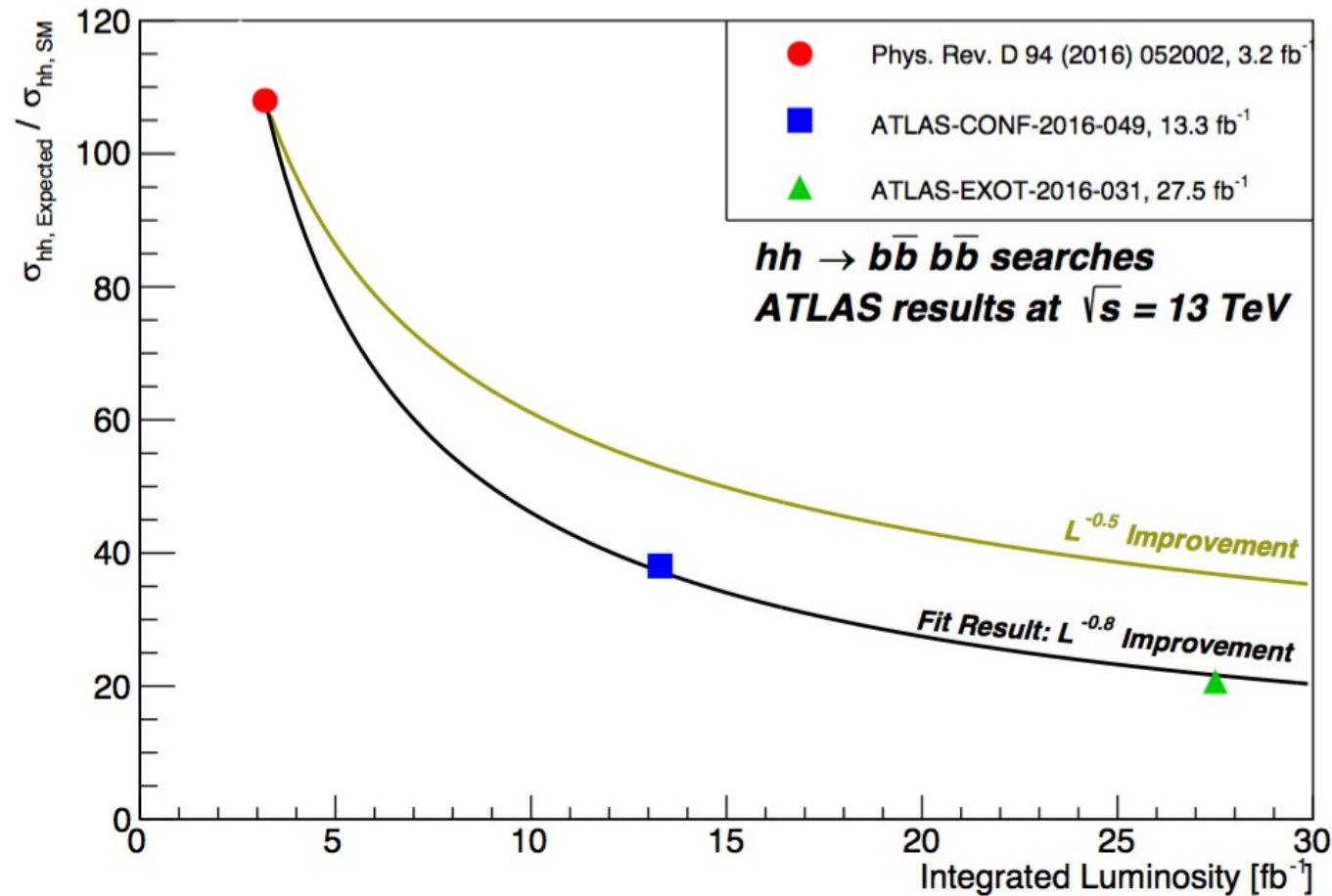
Table 5: Expected signal and background yields and signal significance in a  $\pm 1.5\sigma_G$  invariant-mass window around  $m_{\mu\mu} = 125$  GeV for each category, where  $\sigma_G$  is the resolution of the core of the invariant mass distribution of signal events. The last row shows the total signal and background yields, the average invariant mass resolution, and the sum in quadrature of the significance of each category. The projections correspond to an integrated luminosity  $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$  for a center-of-mass energy  $\sqrt{s}=14$  TeV for the reference detector scenario.

Category	S	VBF	B	FWHM [GeV]	$\sigma_G$ [GeV]	$S/\sqrt{S+B}$
VBF-like	386	197	19430	4.37	1.88	2.75
low $p_T$ , central	921	11	350500	3.21	1.37	1.55
med $p_T$ , central	2210	84	300500	3.08	1.32	4.01
hi $p_T$ , central	1810	242	211800	3.50	1.56	3.91
low $p_T$ , non central	2460	28	1740500	4.11	1.79	1.86
med $p_T$ , non central	5860	230	1483600	4.24	1.80	4.80
hi $p_T$ , non central	4380	588	829000	4.70	1.92	4.80
Total	18020	1380	4935500	3.93	1.69	9.53

Table 6: The table compares the overall significance and signal strength uncertainty achievable with  $3000 \text{ fb}^{-1}$  in the three different detector scenarios defined in the ATLAS Scoping Document, based on the event categories defined in the text.

Scoping Scenario	$\langle \mu \rangle$	Overall significance	$\Delta\mu$ w/ syst. errors	$\Delta\mu$ w/o syst. errors
reference	200	9.5	$\pm 0.13$	$\pm 0.12$
middle	200	9.4	$\pm 0.14$	$\pm 0.12$
low	200	9.2	$\pm 0.14$	$\pm 0.13$



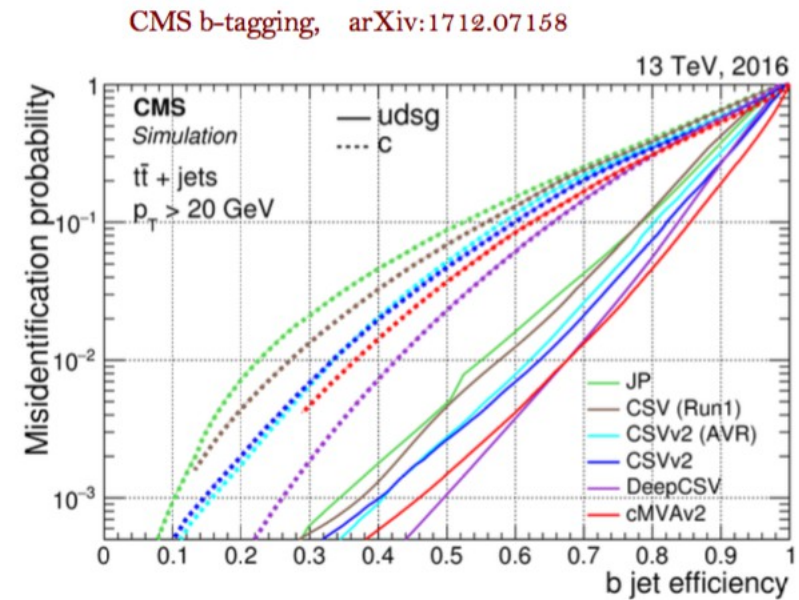
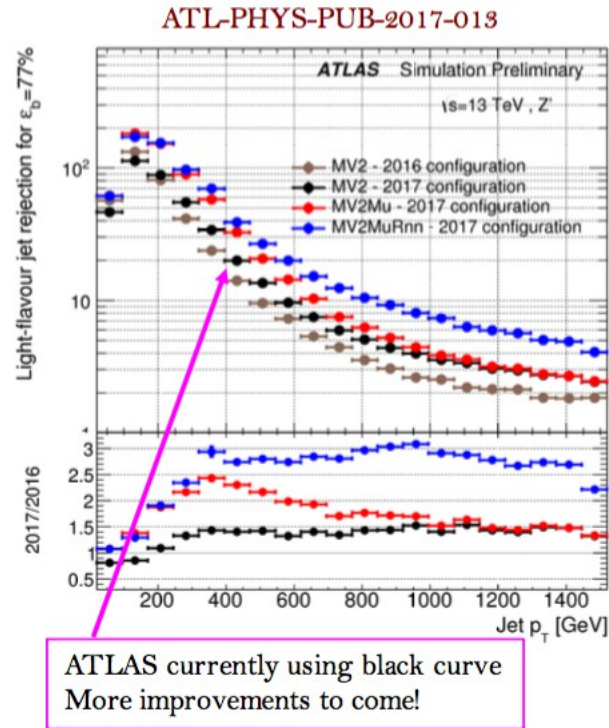


- What is driving this improvements?

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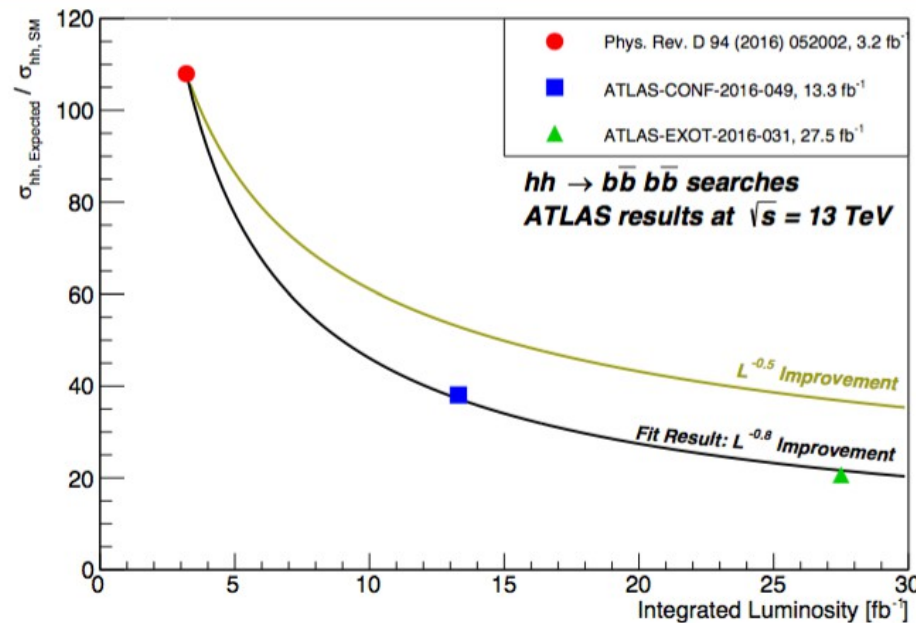
# ATLAS $hh \rightarrow b\bar{b}b\bar{b}$ Meta-Analysis: A Case For Optimism?

16



- Improvements include:
  - Improved jet and b-tagging performance and calibration
  - Better background discrimination from selection optimization
  - Better background modeling
  - Improved signal acceptance

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$hh \rightarrow 4b$ extrapolation on upper limit on $\frac{\sigma}{\sigma_{SM}}$	Run II ( $120 \text{ fb}^{-1}$ )	Run II+III ( $450 \text{ fb}^{-1}$ )	HL-LHC $3000 \text{ fb}^{-1}$
HL-LHC Prospects Studies (using current systematics)	-	-	$\sim 3.7$
$L^{-0.5}$ improvement on $27.5 \text{ fb}^{-1}$ result	$\sim 10$	$\sim 5.2$	$\sim 2$
$L^{-0.8}$ improvement on $27.5 \text{ fb}^{-1}$ result	$\sim 6.5$	$\sim 2.2$	$< 1$

**Caution:** these are my own extrapolations  
with many assumptions

- Some thoughts (my own opinions)
  - Prospect studies don't account for analysis improvements
    - Conservative?
  - Is continued improvement like  $L^{-0.8}$  over optimistic?
    - Hard to indefinitely improve analysis... will we run into “systematics wall”?
  - Currently there are 3 channels with similar sensitivity
    - Run III and HL-LHC will be exciting!

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- Can we discover di-Higgs at the HL-LHC?
  - If we can continue to improve analyses at the current rate, better ask:

**When will we** discover di-Higgs at the HL-LHC?

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