

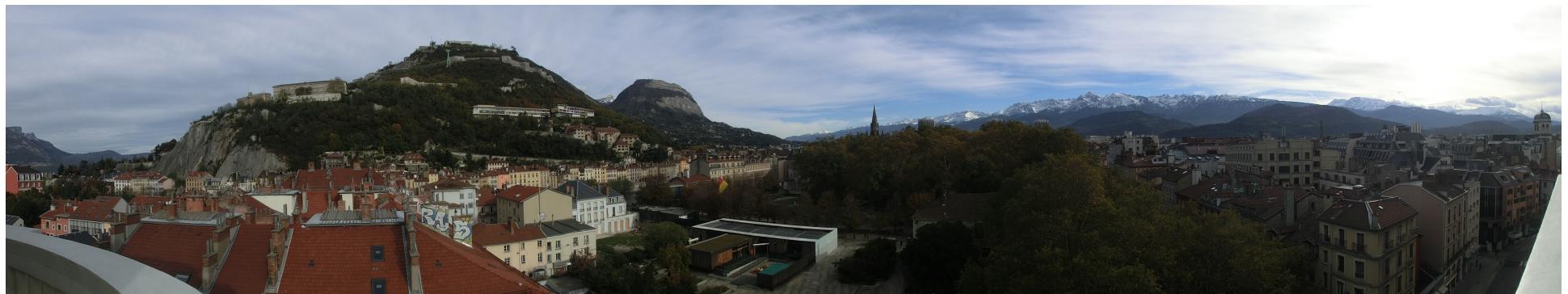
HL-LHC

Higgs prospects studies

(with emphasis on di-Higgs production)

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IRN Terascale@Strasbourg, 30 mai – 1^{er} juin 2018

Acknowledgements

A significant number of slides in this presentation are straight copies of slides from these two presentations:

Stéphane Jézéquel on behalf of the YR2018 Higgs Working group,
“Higgs @HL/HE-LHC”,
HL/HE-LHC Meeting, Fermilab, April 4-6, 2018
([clickable link](#))

Michael Kagan for the ATLAS and CMS collaborations,
“Di-Higgs results from ATLAS and CMS”,
Moriond Electroweak 2018, March 10-17, 2018
([clickable link](#))

Each one of the copied slides is clearly identified.

Introduction

Goal of this talk: try to share my enthusiasm about the recent progress in “HL-LHC prospects studies”, i.e. in studies that aim to quantify the physics reach of the HL-LHC programme for some key measurements of Higgs properties.

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

- aim for a Yellow Report by the end of this year (“YR2018”)
- now is the right time for this YR:
 - final CMS/ATLAS detector optimisations for HL-LHC are available
 - sophisticated Run 2 analysis are being published
 (“we are basing our extrapolations on pretty sophisticated analyses of real data”)
 - crucial input to the next update (2020) of the European Strategy for Particle Physics

Main problem of this talk: most of the studies for the YR2018 are not approved by the collaborations yet, so I can't show them.

Higgs target for YR18

- * Provide most complete picture of Higgs physics @ HL/HE-LHC
 - Update expected HL-LHC (3 ab^{-1} @ 14 TeV) results
 - Include new topics (appeared in Run-2 analysis or new ideas)
 - Combine ATLAS-CMS results when statistically limited
 - HE-LHC (15 ab^{-1} @ 27 TeV) : First publication of expected performances

- * Driven by
 - Final ATLAS/CMS detector optimisation for HL-LHC
 - Better understanding of particle/object reconstruction performances
 - Upgraded detector vs pileup ($\langle\mu\rangle = 200$) vs trigger (5-7x nominal luminosity)
 - Improved analysis methods developed for Run-2 (2015+2016 data : 36 fb^{-1})
 - Improved theoretical calculations and tools
 - Request from CERN management to evaluate physics potential of HE-LHC

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YR18: approach

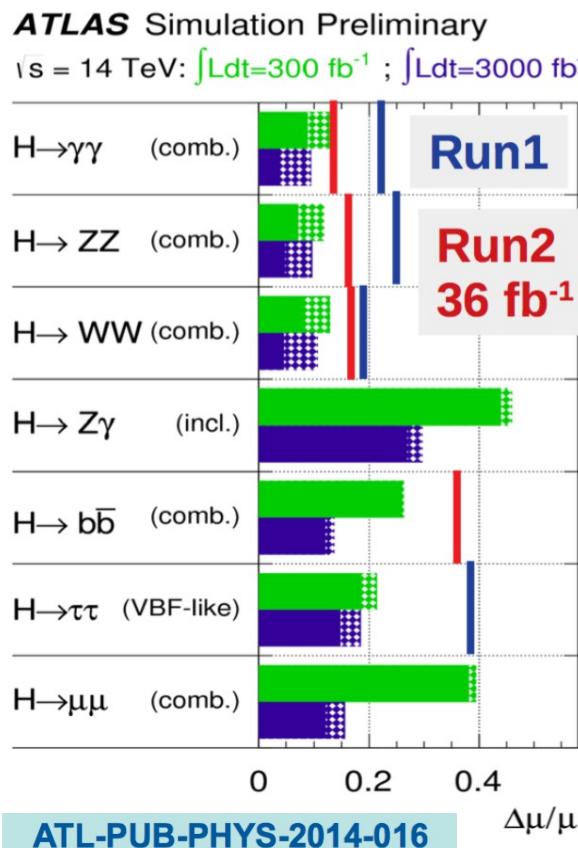
- * Do exhaustive and accurate review of physics channel performances
 - * Coherent approach between ATLAS/CMS and explore LHCb
 - * Benefit from recent analysis developments for Run2 publications
 - * Optimise available manpower
 - * Methodology :
 - Extrapolate Run2 results @ 14 TeV with HL-LHC integrated luminosity
 - When possible : apply HL-LHC detector performances
 - Few benchmark channels to validate Run-2 extrap. with fullsim/Delphes
 - Agree on scenarios for experimental systematics uncertainties
 - Conservative : Current Run-2
 - Optimistic : Define constant term limiting gain from high luminosity
 - Quantify impact of theoretical systematics uncertainties : cross-section, jet modeling, ...
- 

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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 κ :
few % level

CMS: arXiv:1307.7135v2

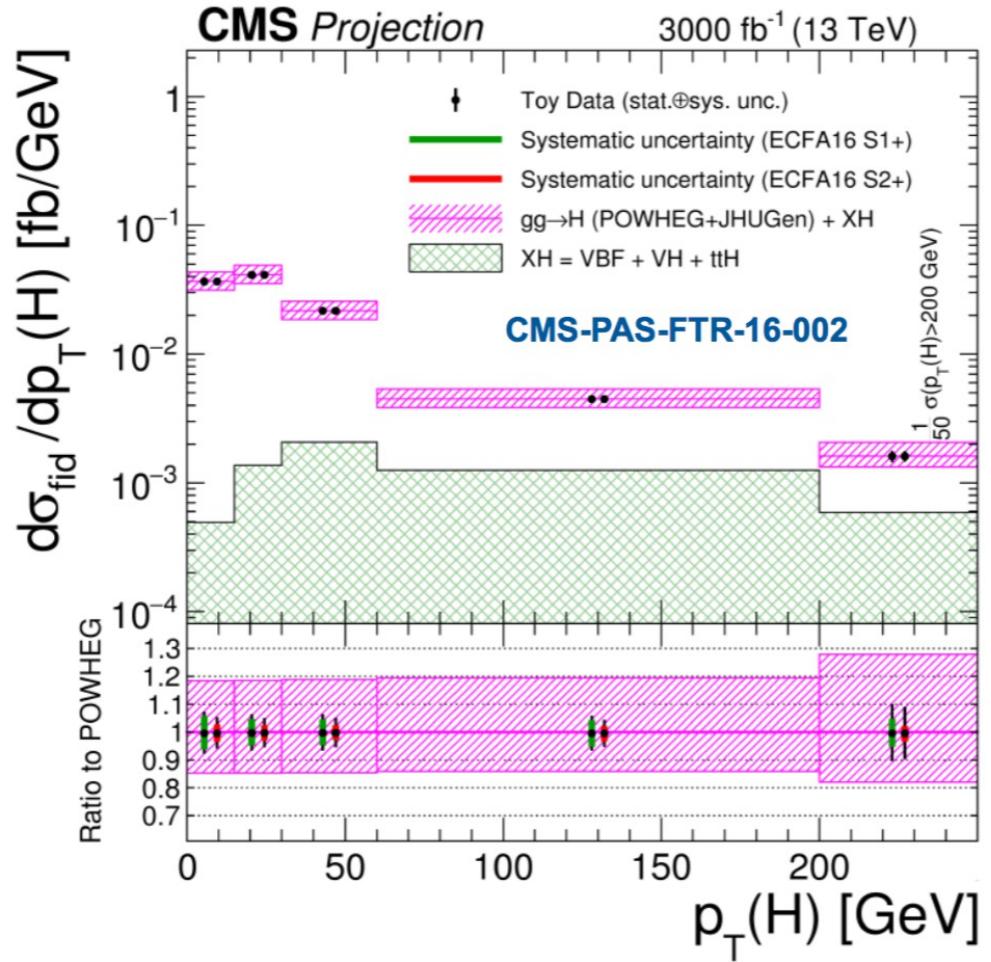
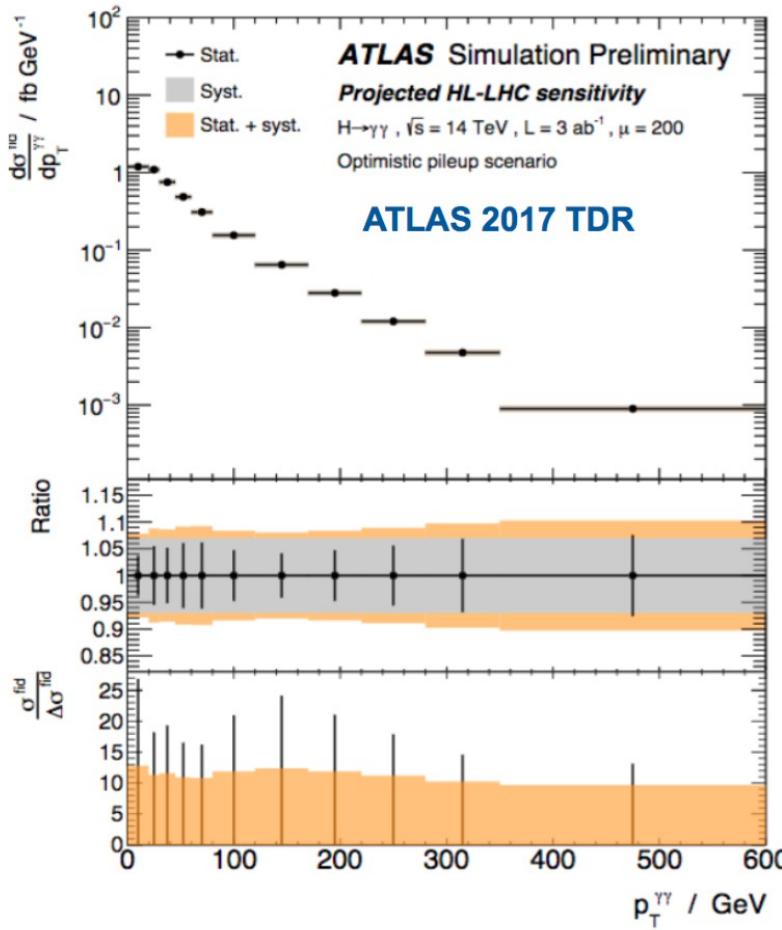
$L (\text{fb}^{-1})$	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

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

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Differential cross section

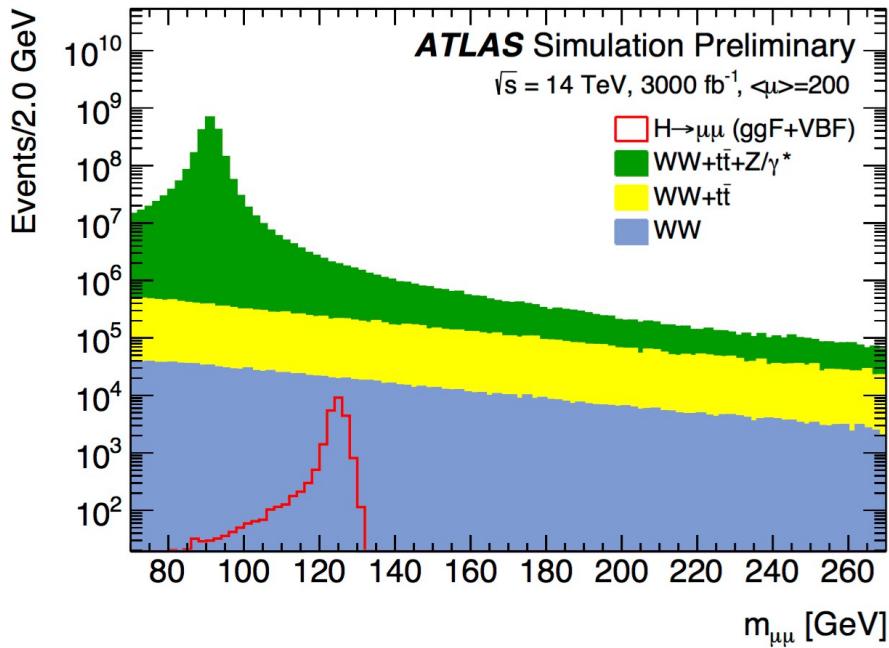
- * Benefit from large dataset and go beyond inclusive measurement



- * Sensitive to κ_b/κ_c (low p_T) and κ_t/BSM (high p_T) with statistical limitation
- * YR 18 : Combination between experiments and interpretation

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



ATL-PHYS-PUB-2018-006

Study Higgs coupling to second-generation fermions

Current limits: ~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 σ_G is the resolution of the core of the invariant mass distribution of signal events. The last rows 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 $\sqrt{s}=14 \text{ TeV}$ for the reference detector scenario.

Category	S	VBF	B	FWHM [GeV]	σ_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

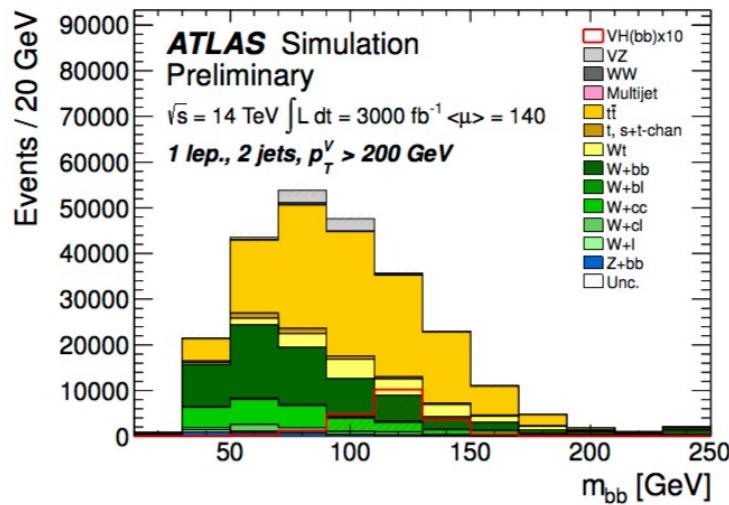
Table 6: The table compares the overall significance and signal strength uncertainty achievable with 3000 fb^{-1} in the three different detector scenarios defined in the ATLAS Scoping Document, based on the event categories defined in the text.

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

Examples of Run 2 projections in the pipeline

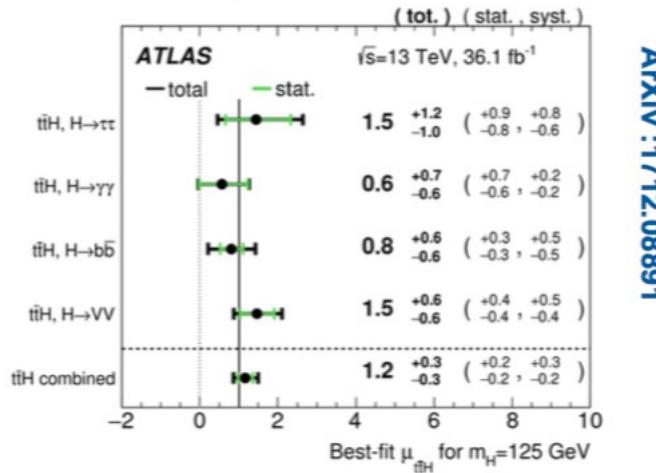
VH($b\bar{b}$)

ATL-PHYS-PUB-2014-011



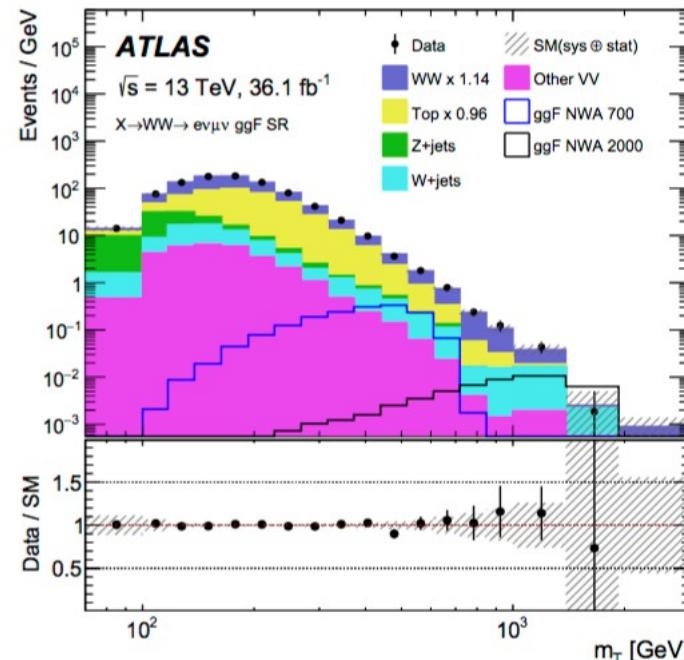
ttH

extrapolate from:

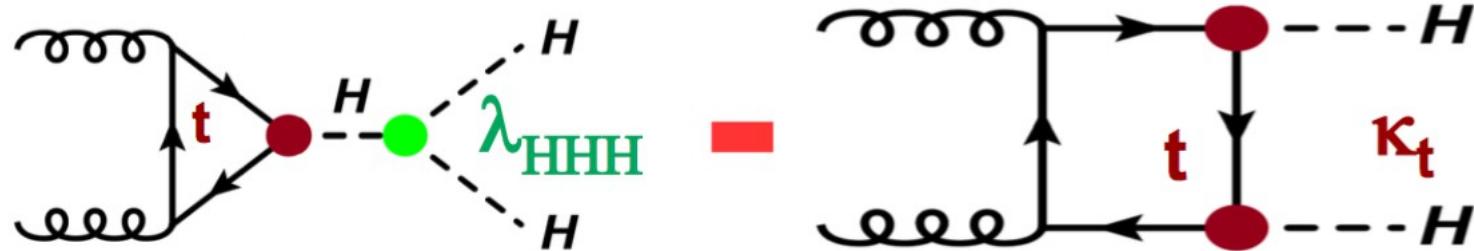


X \rightarrow WW \rightarrow e ν μ ν

extrapolate from
 Eur. Phys. J C 78 (2018) 24

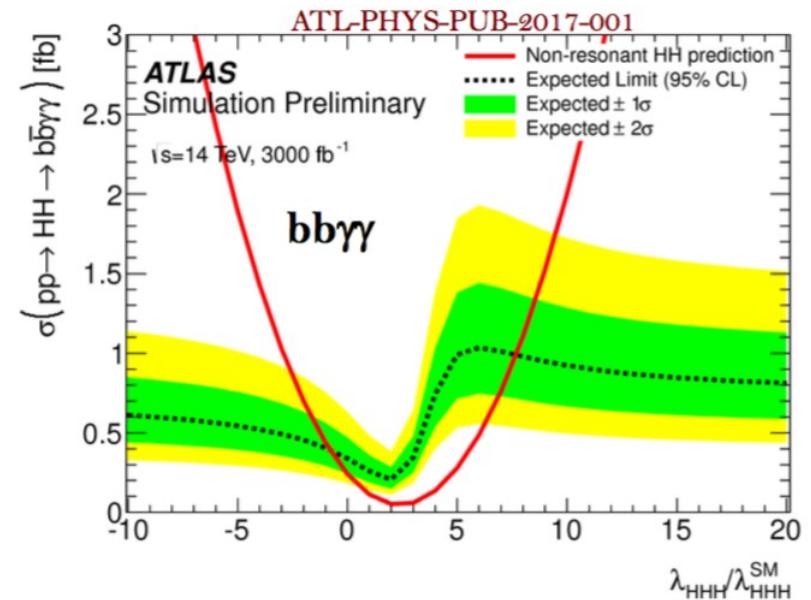
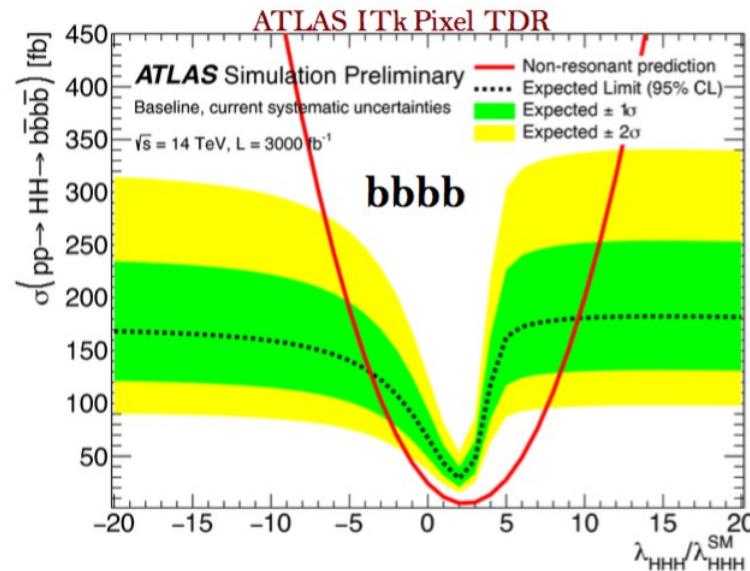


Di-Higgs production

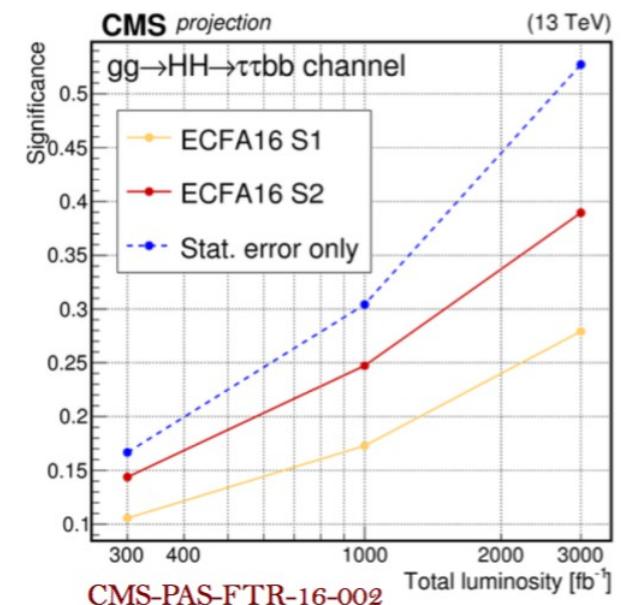


\bullet $m_h = 125.09 \text{ GeV}$ \bullet CERN-2017-002-M [arXiv:1610.07922]	$\sqrt{s} = 8 \text{ TeV}$ $\sigma_{\text{NLO}} [\text{fb}]$	$\sqrt{s} = 13 \text{ TeV}$ $\sigma_{\text{NLO}} [\text{fb}]$	$\sqrt{s} = 14 \text{ TeV}$ $\sigma_{\text{NLO}} [\text{fb}]$
$ggF \rightarrow hh$ (NNLO + NNLL with 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

Existing, public projections



- HL-LHC projections show a challenging future
- Cross section limits $\sim(\text{few}) \times \sigma_{SM}$ per channel
- Coupling limits $\sim \frac{\lambda}{\lambda_{SM}} \in [-1, 8]$ for single channel



adapted from M. Kagan

An exciting theory paper

PHYSICAL REVIEW D 97, 075008 (2018)

Probing baryogenesis through the Higgs boson self-coupling

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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

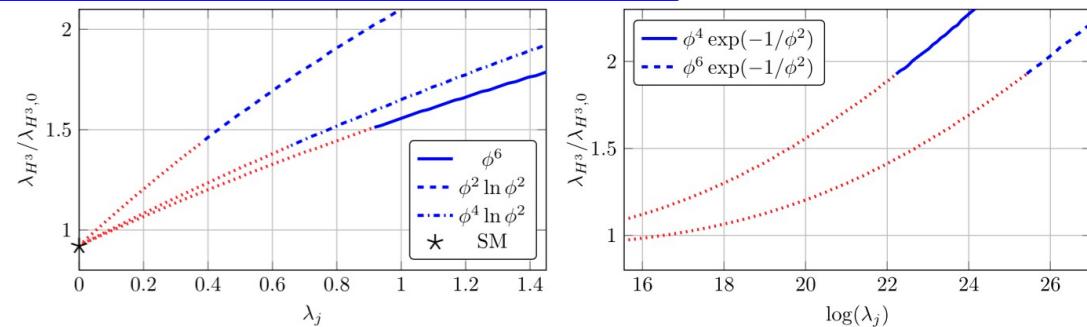
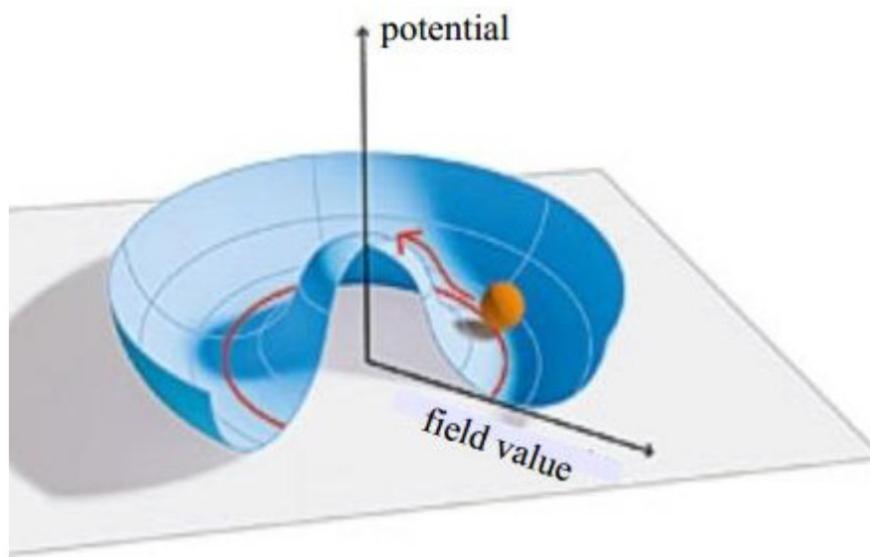


FIG. 8. Modification of the self-coupling $\lambda_{H^3}/\lambda_{H^3,0}$ as a function of the coefficients λ_j from the different UV potentials given in Eq. (11). Blue lines represent first-order phase transitions and red dotted lines second-order phase transitions. The cutoff is $\Lambda = 2$ TeV.

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

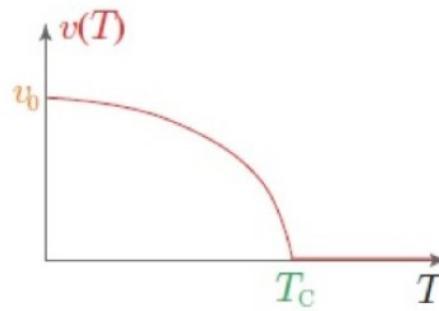
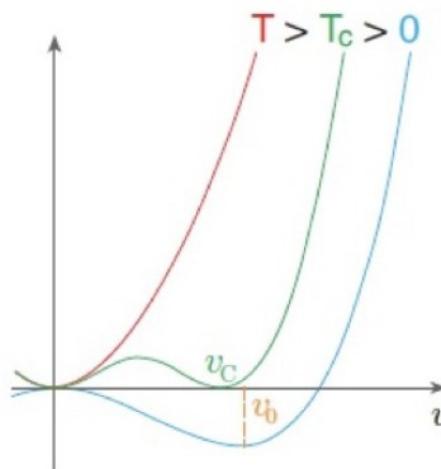
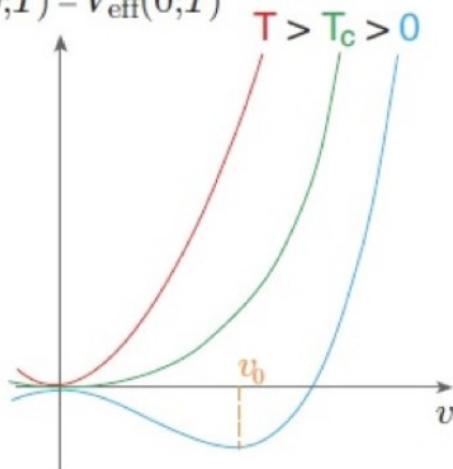
$$\frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4$$

Electroweak baryogenesis

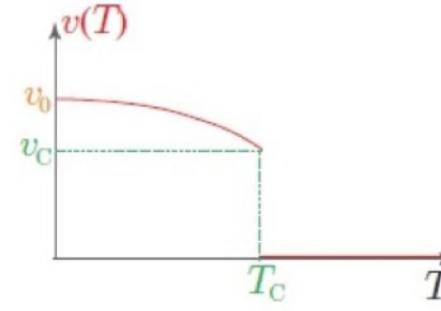
To get the observed baryon asymmetry of the universe from an initially baryon-symmetric universe, Sacharow's conditions must be satisfied.

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

$$V_{\text{eff}}(v;T) - V_{\text{eff}}(0;T)$$



2nd order PT



1st order PT

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 **a first order phase transition (PT)**.

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

The “50% claim”

To get an idea of what to expect, we quote the optimal reach of the high-luminosity LHC run with 3 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 12.

And this is Ref. [41]:

PHYSICAL REVIEW D 95, 035026 (2017)

Maximizing the significance in Higgs boson pair analyses

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(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

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

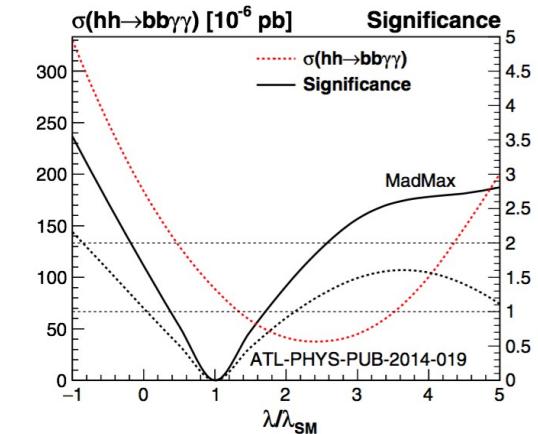
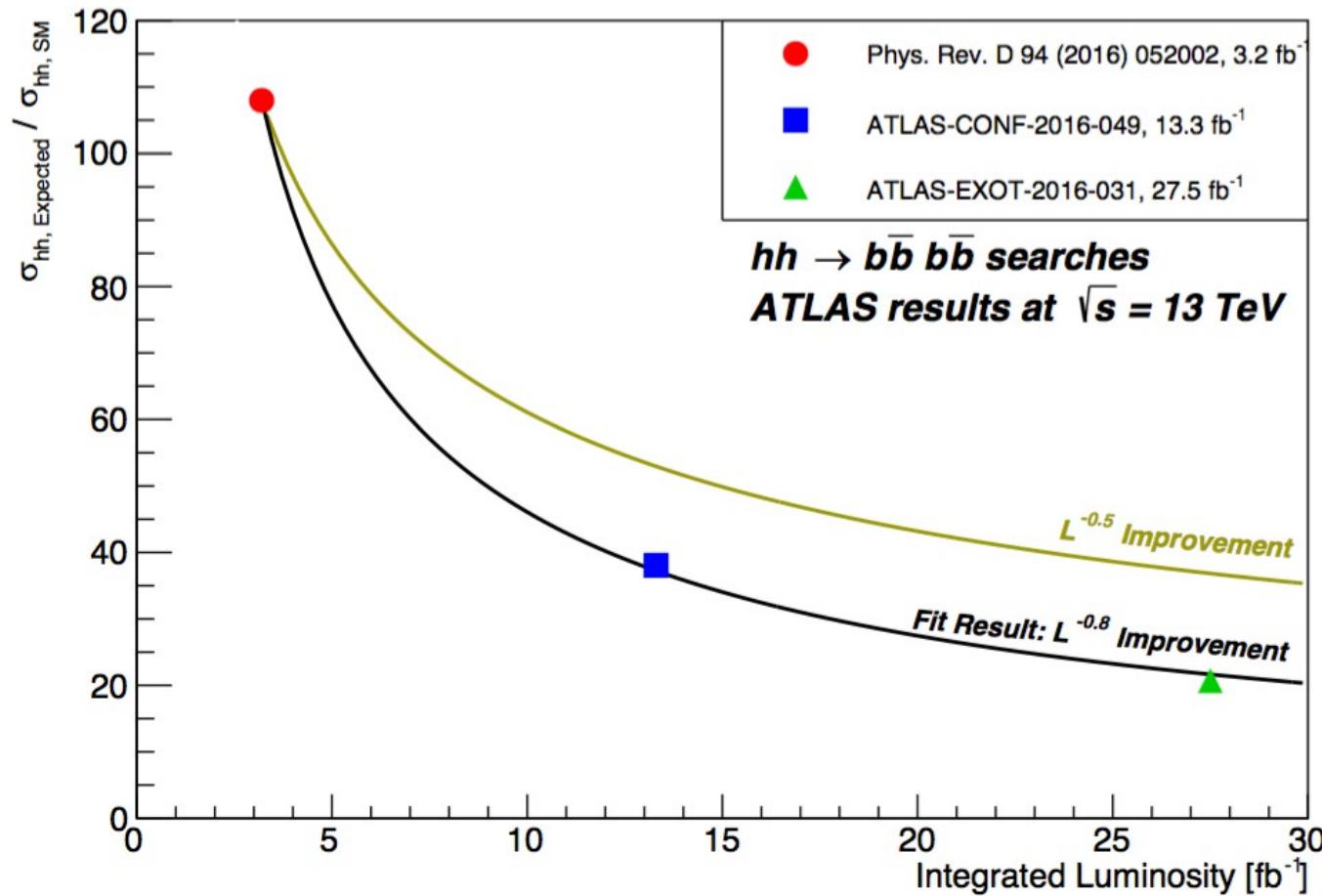


FIG. 6. Signal cross section (red dashed line) and maximum significance (black solid line) for observing an anomalous Higgs self-coupling at the LHC with an integrated luminosity of 3 ab^{-1} . We also show the significance from a cut-based rate measurement using the cuts suggested in Ref. [35] (black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

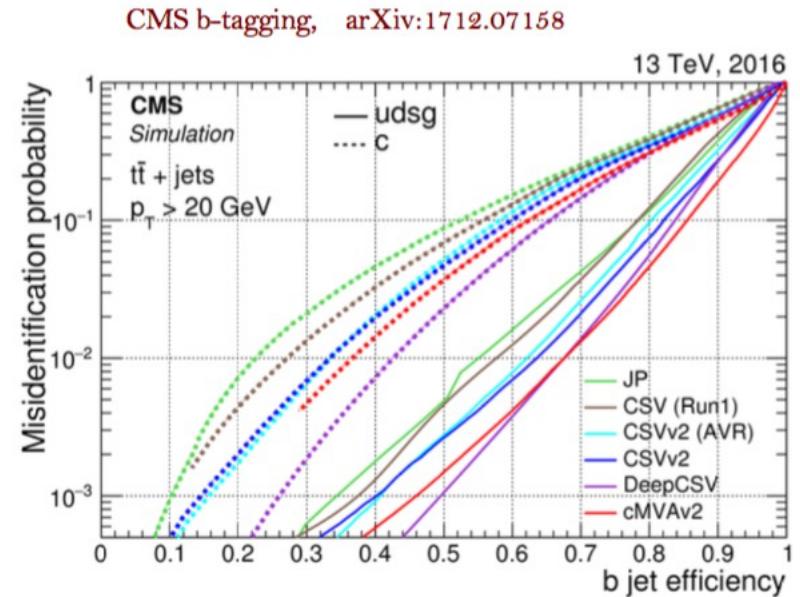
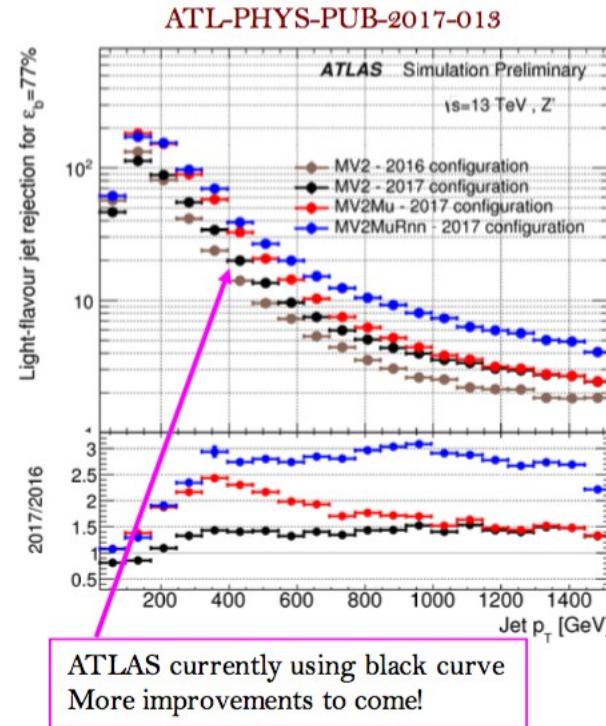


- What is driving this improvements?

M. Kagan, Moriond EW 2018

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

16

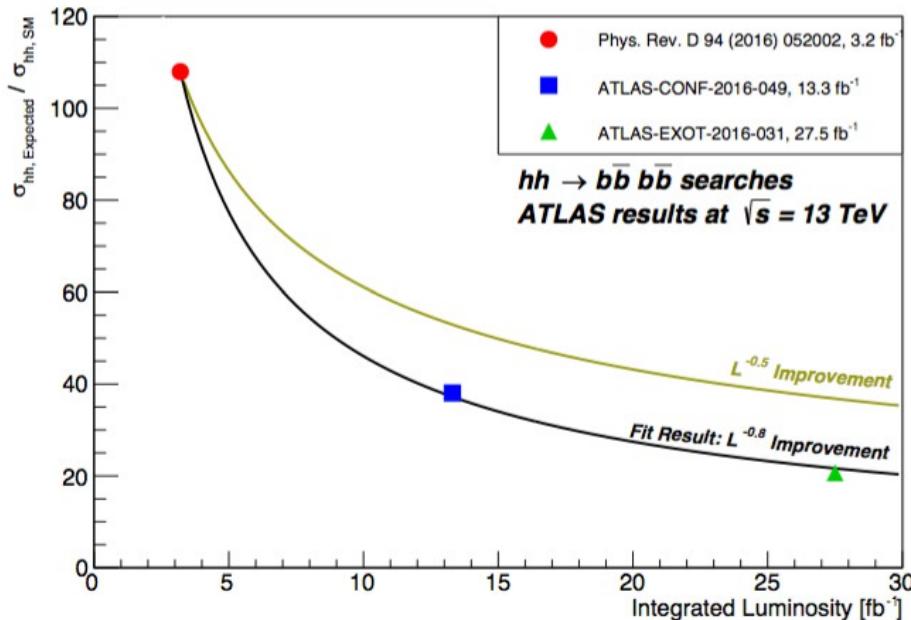


- Improvements include:
 - Improved jet and b-tagging performance and calibration
 - Better background discrimination from selection optimization
 - Better background modeling
 - Improved signal acceptance

M. Kagan, Moriond EW 2018

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

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

M. Kagan, Moriond EW 2018

- 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?

M. Kagan, Moriond EW 2018

More observables

The previous slides talk about improved object selection and such.

They do not include the improvements from the use of “kinematic regions” (use observables other than the event yield to constrain lambda) yet.

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).

From slide 15:

And this is Ref. [41]:

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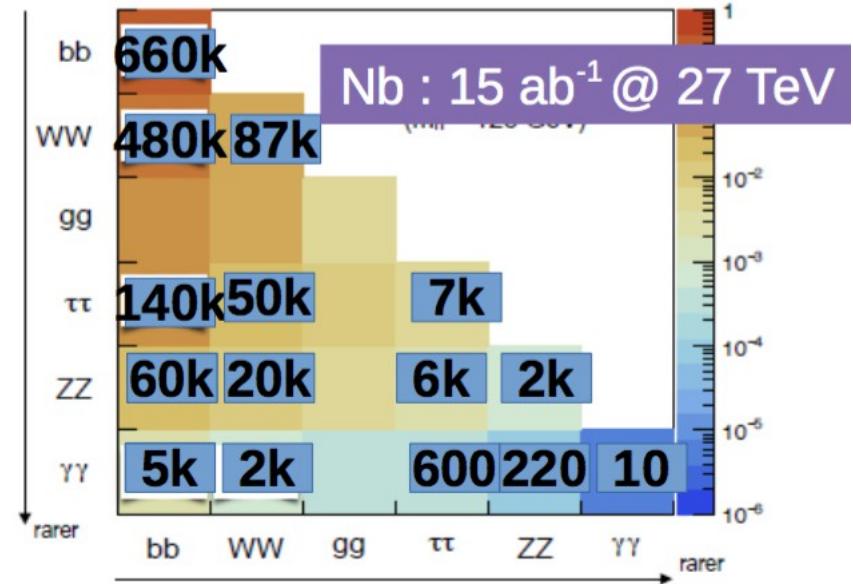
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DOI: [10.1103/PhysRevD.95.035026](https://doi.org/10.1103/PhysRevD.95.035026)

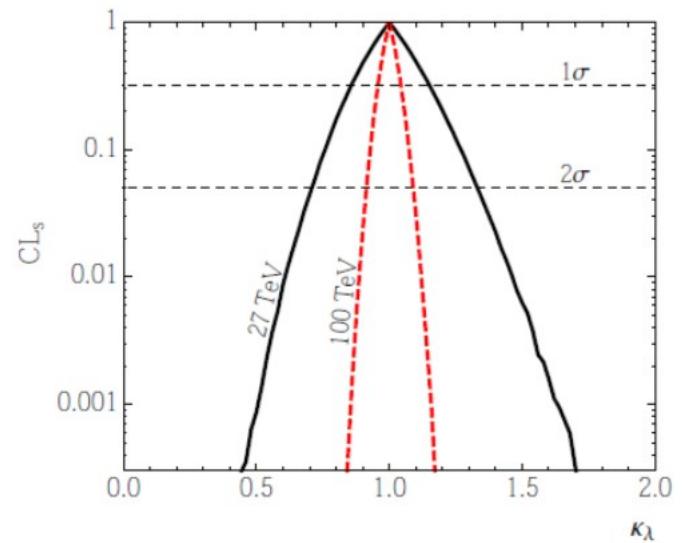
Di-Higgs at HE-LHC

- * 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 ~4



- : Recent theory study on HE-LHC prospect
(arXiv :1802.04319)
 - ~30 % precision in λ just from $HH \rightarrow bb\gamma\gamma$



S. Jézéquel

Conclusions

Exciting progress in the Higgs prospects studies for the HL-LHC;
updated projections will largely exceed the previous estimates.

The result of this work is not “just projections”.

For many of the more involved analyses, we are developing new analysis techniques,
establishing the basis of the analyses of the HL-LHC data.

Ample room for anybody in this audience to contribute:

- members of the experimental collaborations,
- theorists (precision calculations of signal and background processes, ...)
- experiment/theory collaboration

e.g. on the matrix method for the measurement of the Higgs self-coupling
(if you are a theorist interested in this, please drop me a line)