Prospects on Higgs Physics at the HL-LHC for ATLAS

Workshop on the physics of HL-LHC,
and perspectives at HE-LHC
CERN, 30 October 2017 - 1 November 2017

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on behalf of the ATLAS Collaboration

Introduction

- Higgs boson studies are a major component of HL-LHC physics program

- High luminosity of HL-LHC needed to achieve:
    - High precision O(1-10%) measurements of coupling across broad kinematics → can reveal new particles in loops or non-fundamental nature of Higgs
    - Sensitivity to coupling to 2nd generation **(H→ μμ)**
    - Exploration of Higgs potential (**HH** production)
    - Sensitivity to rare decays involving new physics

HL-LHC environment

- Design for peak leveled luminosity of $7.5\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$
  → average pileup of ~200 collisions/crossing

- Aim for integrated luminosity of 3000 fb^{-1} , x 10 data by end Run3
  → 170M of Higgs boson , 120k of Di-Higgs

- Good object reconstruction (b-tagging, jet/E_T^{miss}, leptons) in harsh environment is crucial to maximize physics potential
  - Essential to mitigate effects from pileup

→ Upgrade of ATLAS detector

Need to consider for prospect Higgs analysis at HL-LHC :
Higher $\sqrt{s}$, higher pile-up, upgraded detectors

Analysis strategy

Smearing function

- Smear generator level particle @ 14 TeV using parametrized performance of upgraded detectors from full simulation at <μ> = 140,200
- Pile-up jets are overlaid

Extrapolation from Run1/2

- Same analysis strategy as Run2/Run1
- Correct for higher √s = 14 TeV
- Correct for different object performance between Run2 and HL-LHC
- Scale yield of signal and background to 3000 fb^{-1}

- Can quantify impact of upgraded detector ✅
- Can quantify impact from pile-up jets ✅
- Large MC statistics required ❌
- Difficult to address mismodeling ❌

- Analysis is optimized (BDT,..) ✅
- QCD background from data ✅
- Tricky to evaluate impact of upgraded detectors and pile-up effects ❌

Systematic uncertainties:

- *Hard to predict how these will evolve with luminosity/time*
- Theoretical unc: same as Run 1/Run 2 analysis, reduced by 1/2 vs absent
- Experimental unc: scaled wrt current analyses in Run 1/Run 2 or current Run2

Higgs Signal Strength at HL-LHC

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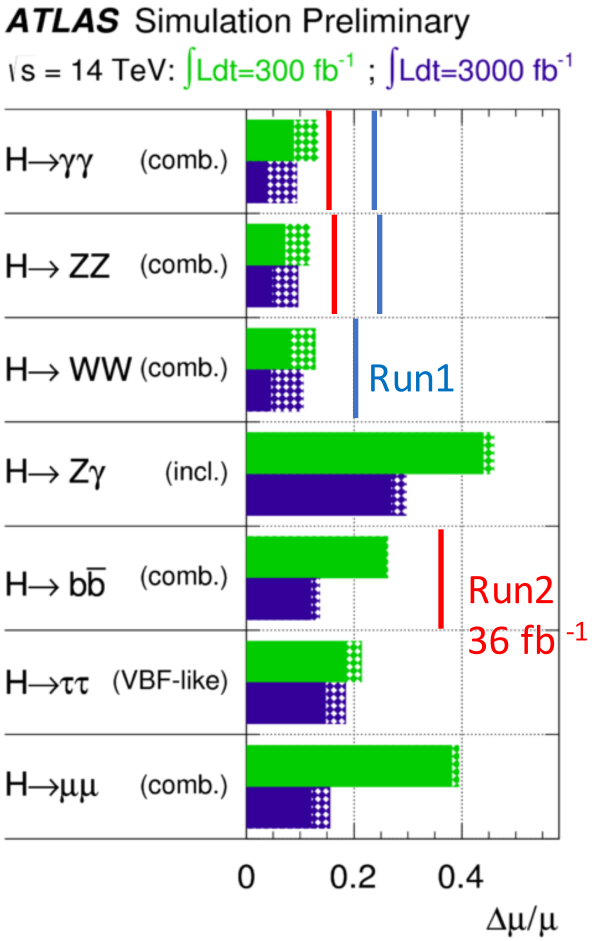
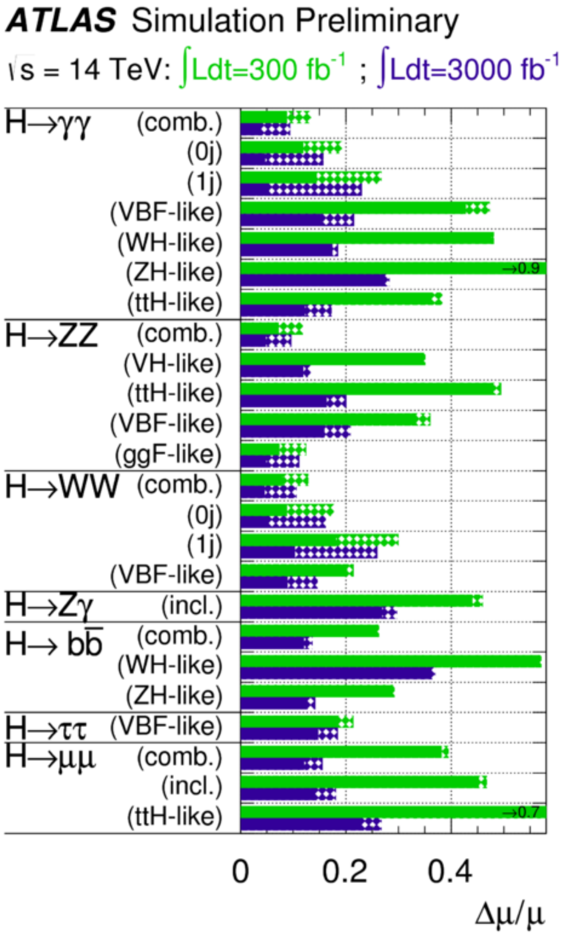
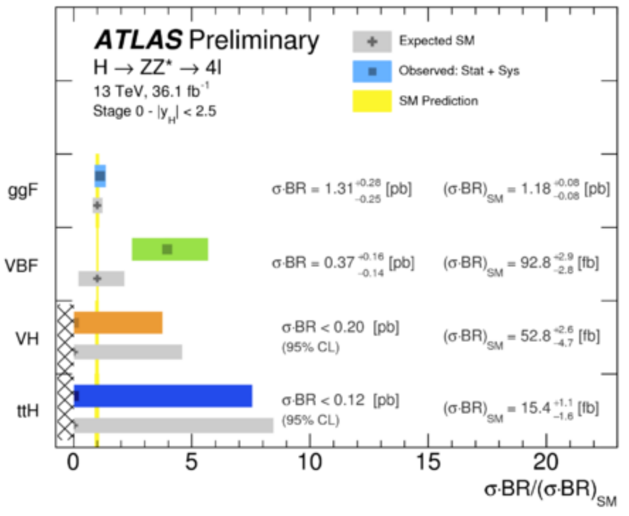
Run 1 analysis strategy with expected performance at <μ>=140





- 4-5% for main channels, 10~20% on rare modes
- Do not include improved detector designs or improvements in analysis techniques
- Impact of theoretical uncertainty (shadow band) not negligible for several channel
  - but already reduced a lot since then (see SL 8) → update really needed

Higgs Signal Strength at Run2



H → ZZ*→4l

Run2 36.1 fb^{-1}

$$\mu = 1.28^{+0.18}_{-0.17}(\text{stat.})^{+0.08}_{-0.06}(\text{exp.})^{+0.08}_{-0.06}(\text{th.}) = 1.28^{+0.21}_{-0.19}.$$

HL-LHC: $\Delta\mu/\mu$ = [0.09 , 0.04](all unc., no theory unc.)

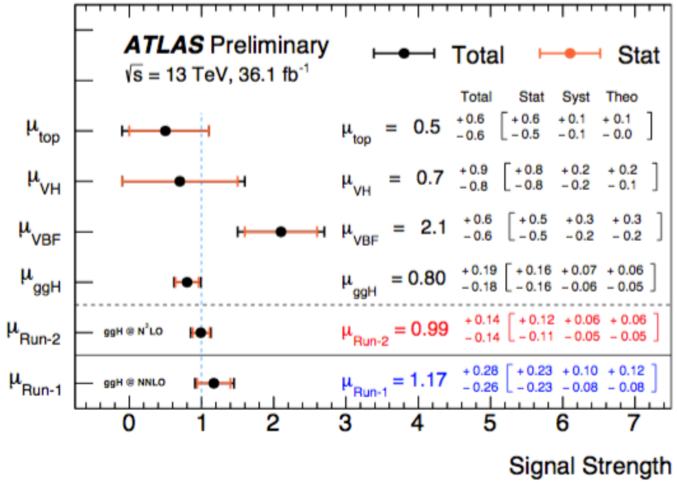
H → γγ

Run2 36.1 fb^{-1}

$$\mu = 0.99\,^{+0.14}_{-0.14} = 0.99\,^{+0.12}_{-0.11}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{exp.})\,^{+0.06}_{-0.05}\,(\text{theory})$$

Significant reduction of theory uncertainty from Run1 NNLO → Run2 N3LO

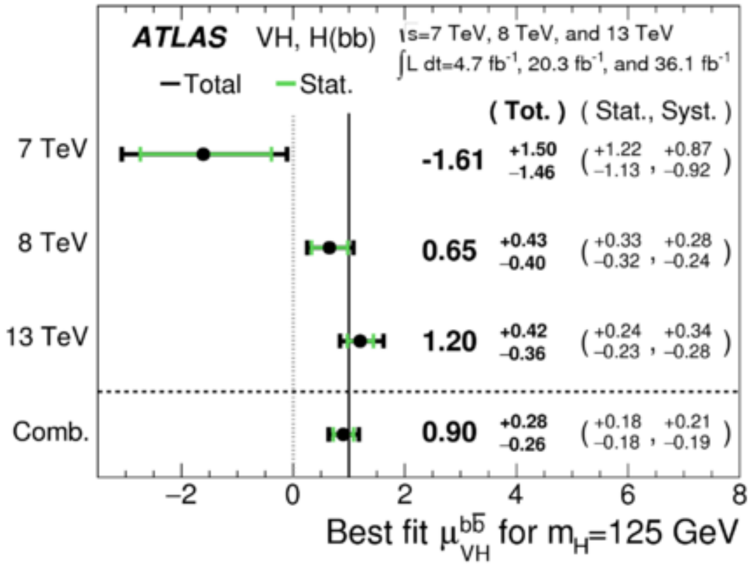
At HL-LHC: $\Delta\mu/\mu$ = [0.09 , 0.04](all unc., no theory unc.)



→Extrapolation of $\Delta\mu/\mu$ from Run2 to HL-LHC lumi gives stat. precision better by factor ~2 compared to latest prospect analysis (assuming exp syst. scales with √L)

→ **ZZ, γγ dominated by syst. uncertainty at HL-LHC**

Higgs Signal Strength at Run2



VH, H →bb

$$\mu = 1.20^{+0.24}_{-0.23}(\text{stat.})^{+0.34}_{-0.28}(\text{syst.}).$$

Leading systematic uncertainty is signal modelling

Dominated by PS-UE-HAD effects

At HL-LHC: Δμ/μ = [0.14,0.12]

(all unc., no theory unc.)

ttH

Significance = 4.2(3.8)σ obs (exp)

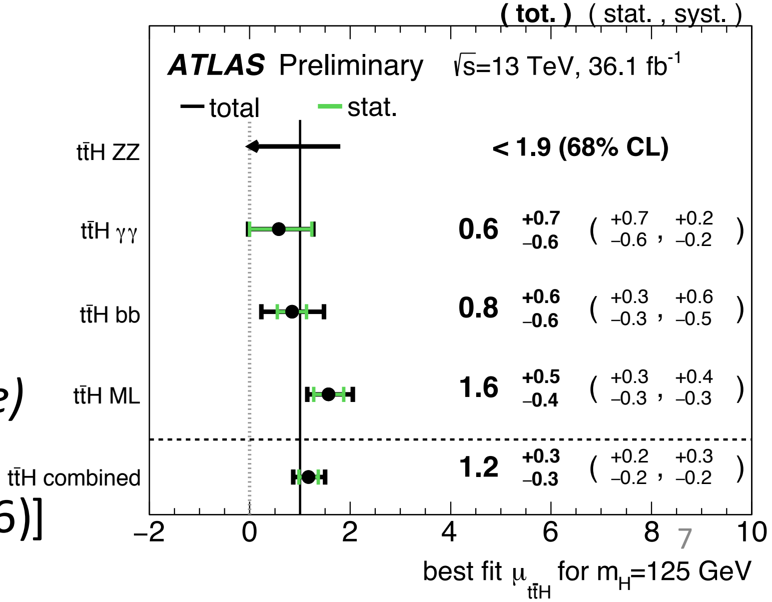
Evidence for *tt̄ H* production.

$$\mu = 1.17 \pm 0.19\,(\text{stat})\,^{+0.27}_{-0.23}\,(\text{syst})$$

Main systematics

- *ttH signal modelling and cross section (QCD scale)*
- *tt bkg modelling systematics in ttH(bb)*

At HL-LHC: ttH→γγ(ZZ) Δμ/μ = [0.17(0.20),0.12(0.16)]



Higgs Couplings I

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- Leading order tree level motivated framework
- Signal cross section scaled

$$\frac{\sigma \cdot B\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot B_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- κ_x determined from a combined fit to VV, γγ, bb, ττ, μμ, Zγ channels
- Use Parametrization of expected performance at <μ>=140
- Assumption
  - Single resonance of mass 125 GeV Zero width approximation
  - Tensor structure of Lagrangian assumed to be the same of SM
  - Effective couplings for loop induced processes: H→γγ, H→Zγ, and gg→H

$\Delta\kappa/\kappa$ = [no theory uncert., full theory uncert.] Model allowing contributions from new physics in loop

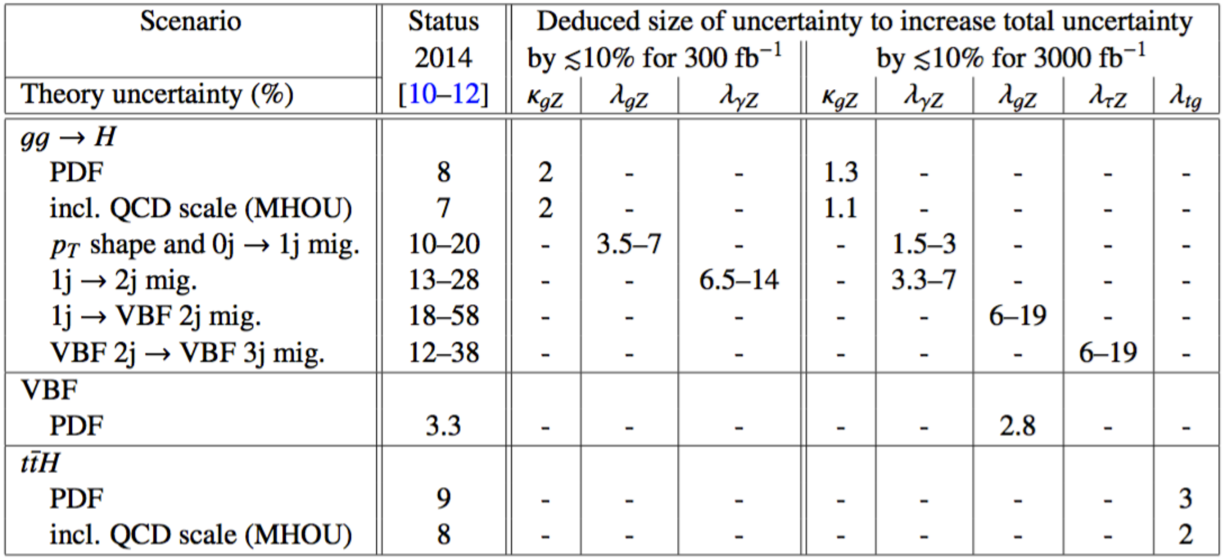
	$\kappa\gamma$	κW	κZ	κg	κb	κt	$\kappa\tau$	κZγ	$\kappa\mu$
300 fb^{-1}	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
3000 fb^{-1}	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[8,8]

Couplings can be determined with 4-12 % precision at 3000 fb^{-1}

Reduced theoretical uncertainties needed (already improvement since 2014)

Impact of theoretical uncertainties

- Theoretical uncertainties limit the precision of several coupling scale factor **k_X** and ratios **$\lambda xy = \kappa_X / \kappa_y$** measurements
- Size of each source of theory uncertainty to give a contribution to coupling measurement < *30%* of total experimental uncertainty



Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

"-" : theoretical uncertainty already small

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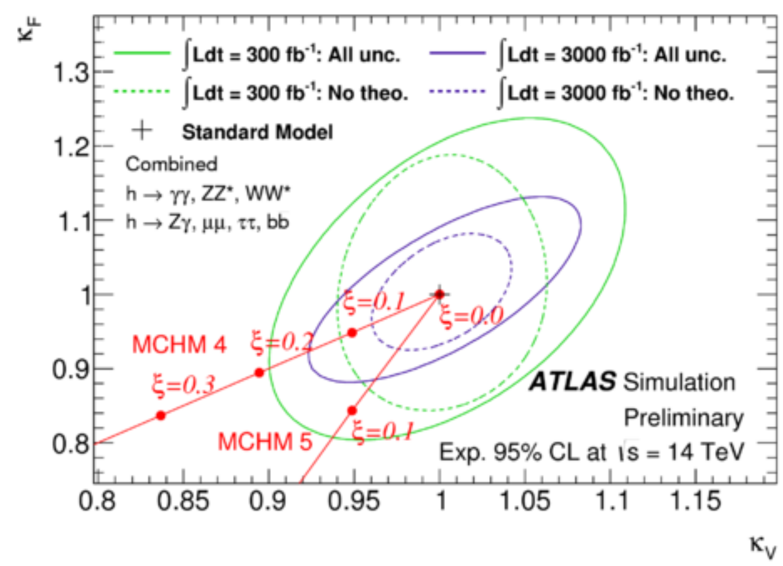
- Recent progress in theory (G. Salam talk at ECFA16) :
- Example of gluon fusion process: calculation at **N3LO** (NNLO) in Yellow Report4(3)
  - Δ From QCD scale: (-7.4, - 7.9) % → **3.9%**
  - Δ From (PDF + α_s): (+7.1 , -6.0) % → **3.2%**

New Physics in Higgs Couplings

Use VV, $\gamma\gamma$, bb, $\tau\tau$, $\mu\mu$, $Z\gamma$ channels



Minimal composite model:

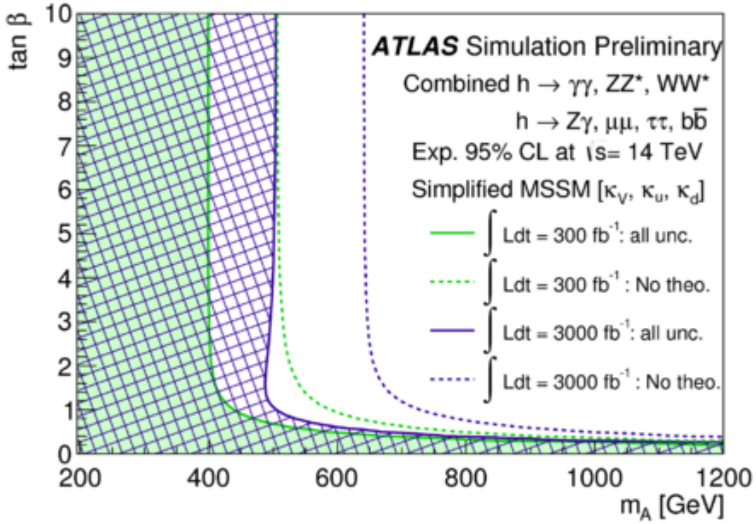
- Pseudo-Nambu-Goldstone boson instead of elementary particle
- Rescale the rates as functions of the modified couplings $\kappa = \kappa_V = \kappa_f = \sqrt{1-\xi}$ or $\kappa_V = \sqrt{1-\xi}$ and $\kappa_f = 1-2\xi / \sqrt{1-\xi}$

Higgs portal to Dark Matter:

- Fit parameters: κ_g, κ_γ, $\kappa_{Z\gamma}$, BR_{inv}
- No assumption on total width
- $BR_{inv}<0.13$(0.09 w/o the. unc.)
- Run2: $BR_{inv}<$ 67% (39%) obs.(exp)

2HDM models:

- Second Higgs doublet present in many BSM models
- Existence of 5 observable Higgs bosons
- Fit parameter: κ_V, κ_u, κ_d *couplings*



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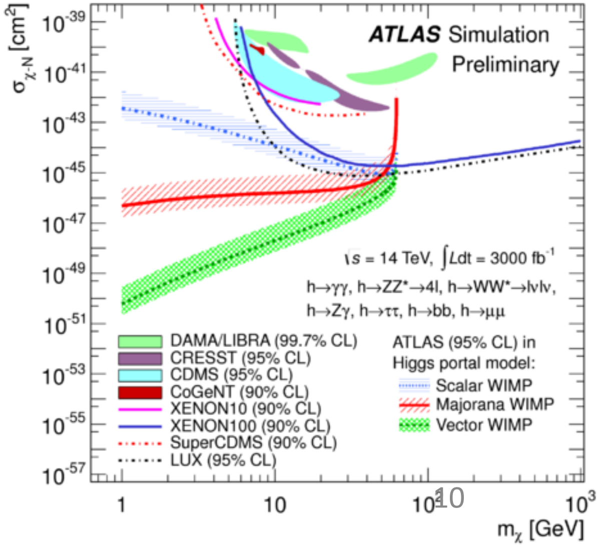
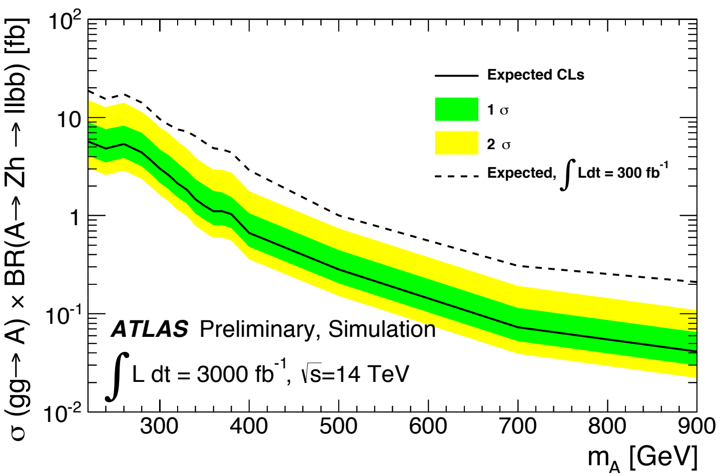


Searches for additional Higgs states



Two-Higgs-doublet models in many BSM models

- Existence of 5 observable Higgs bosons:

- ***A → Zh*** decay dominant at $m_Z+m_h < m_A < 2\ m_{top}$,
  - Relevant at low tanβ
  - *Consider Z h → llbb decay*
  - 30 % syst. unc. assumed

- **H,A →μμ** relevant at high tanβ
  - For masses $m_{H,A}$> 500 GeV large improvement in HL-LHC
  - Only stat. uncertainty

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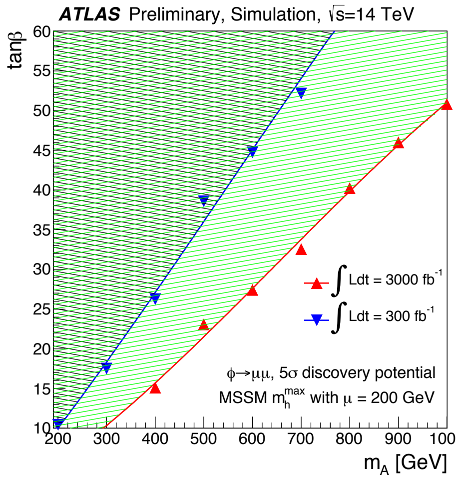
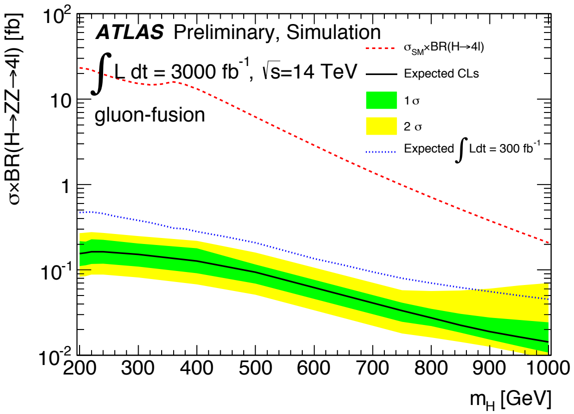
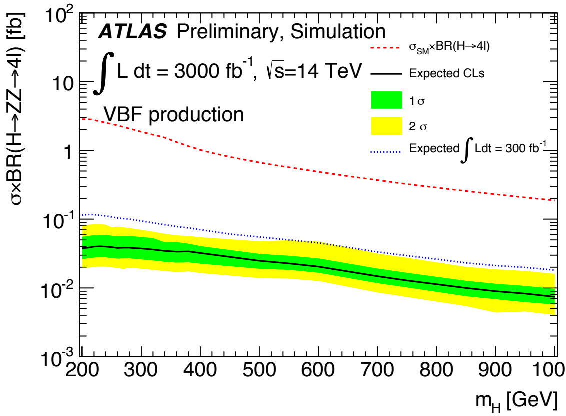


- **Heavy H→ZZ→4l**
  - Extrapolation from Run1 analysis
  - at HL-LHC × 10 – 150 better wrt SM Higgs boson production





Rare Higgs Boson decays

$H \rightarrow J/\psi(\mu\mu)\ \gamma$

- probe *c*-quark couplings
- SM expectation: **BR($H\rightarrow J/\psi\ \gamma$) = $(2.9 \pm 0.2) \times 10^{-6}$**
- ATLAS Run 1 limit: **BR($H\rightarrow J/\psi\ \gamma$) = 1.5×10^{-3}**
- Extrapolation from Run1 results and correct for performances at $< \mu > = 140$
- Using multivariate analysis, events in **$m(\mu+\mu-\gamma) \in$ 115-135 GeV**: **~3** signal, **1**700 background
- **BR ($H\rightarrow J/\Psi\ \gamma$) < $(44^{+19}_{-22} \cdot \times 10^{-6})$ @ 95% CL**

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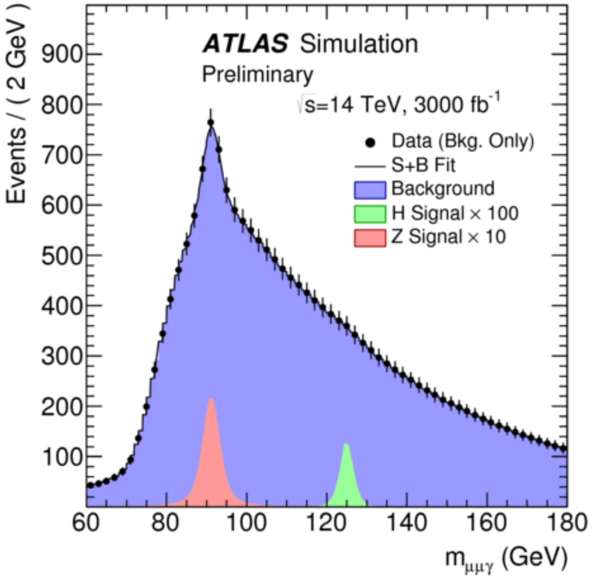

$H\rightarrow\Phi\gamma/\rho\gamma$ to probe *light*-quark couplings

Run2: B ($H \rightarrow \phi\gamma$)< 4.8×10^{-4} , exp SM $(2.31 \pm 0.11) \times 10^{-6}$

B ($H \rightarrow \rho\gamma$) <8.8×10^{-4} , exp SM$(1.68 \pm 0.08) \times 10^{-5}$ SM

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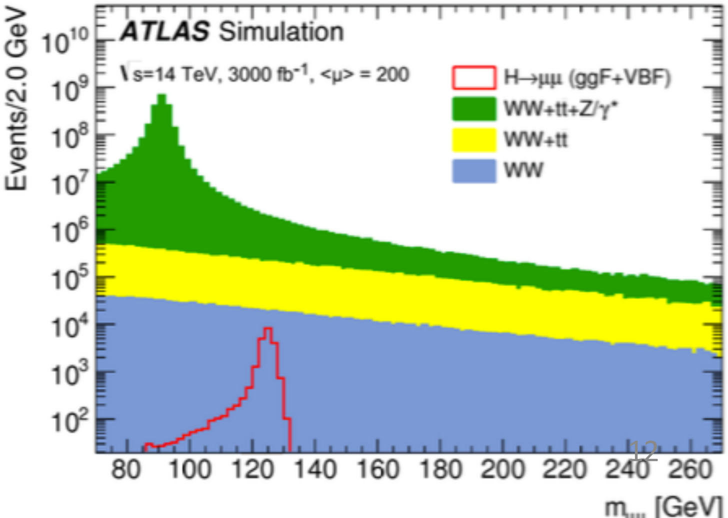

$H\rightarrow\mu\mu$: low BR with very large irreducible from Z/γ

- parametrization of exp. performances at <μ>=200
- Upgraded layout improves the di-muon invariant mass resolution by 25%
- Run2: $\sigma \times BR / (\sigma \times BR)_{SM} < 3.0(3.1)$, obs.(exp)
- HL-LHC (Run3 300 fb^{-1}): significance =7.0(2.3) σ

Γ_H from off-shell couplings

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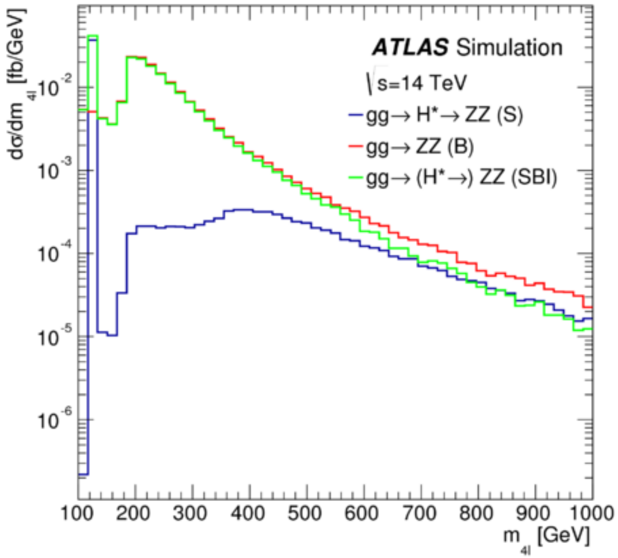
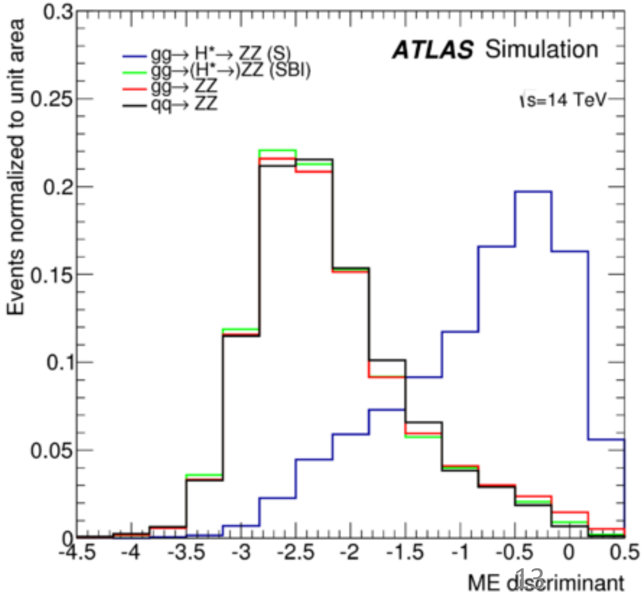
Off-shell production
to indirectly constrain
the Higgs boson width **Γ_H**

$$\boxed{\frac{\sigma^{gg\to H\to ZZ}_{off-shell}}{\sigma^{gg\to H\to ZZ}_{on-shell}} \propto \frac{\Gamma_H}{\Gamma_H^{SM}}}$$

- Using **H→ZZ*→4l** final state with m(4l)>220 GeV
- Use Run1 results with correction to √s=14 TeV
- Assume same detector performances at HL-LHC
- Use **m(4l)** shape and matrix element to discriminate between signal and background



- Signal strength $\mu_{\text{off-shell}} = 1.00^{+0.43}_{-0.50}$
- **$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys)**
- Run 1 limit: **$\Gamma_H < 22.7$ MeV**
- Large theory uncertainties, ~30%
  - dominated by LO-NNLO k-factor uncertainty for *pp→ H* → ZZ and gg → H* → ZZ*
  - Unc. on bkg/signal k-factor ratio expected to be reduced at HL-LHC→ ~ 10%
  - same treatment as in Run1 analysis



Spin and parity

Amplitude describing the interaction of a spin-0 particle and and two spin-one gauge bosons

$$A(X_{J=0} \to VV) = v^{-1}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f^{*(2)}_{\mu\alpha} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}\right)$$

- *Coupling g*1(*g*2) describe the tree-level(loop-induced) interaction of a CP even scalar
- *Coupling g*4 describes the interactions of a CP odd scalar
- *Coupling g3* can be absorbed into *g2*
- SM prediction, CP-conserving tree-level interaction:*g1* >0 and $g_{2,3,4}$ =0.

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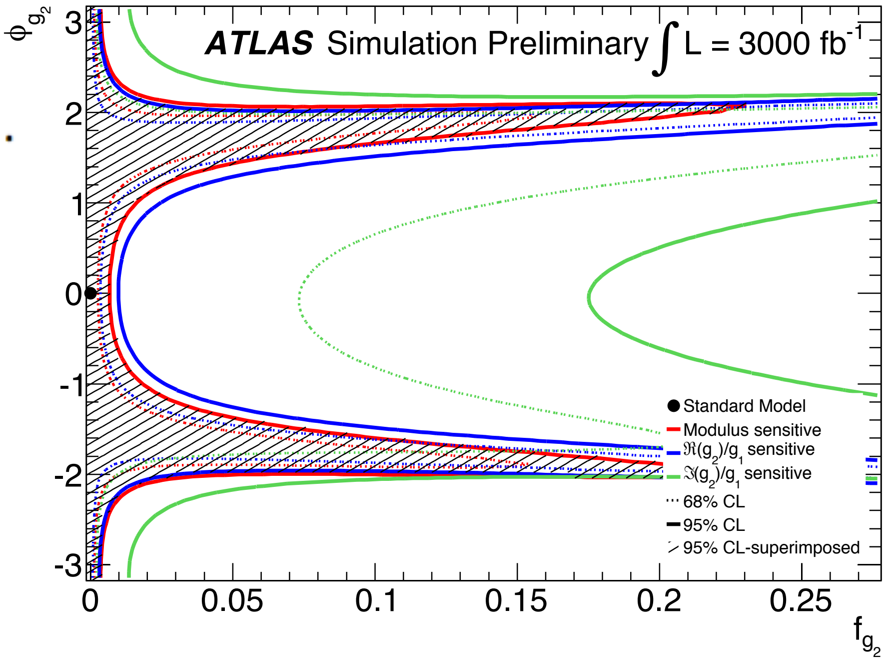
Parametrization:

$$f_{g_i} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right).$$

f_{g4} < 0.037 and f_{g2} < 0.12
at 95% CL for 3000 fb^{-1}

Sensitive test of the tensor structure of the *H* →*ZZ** couplings a the high luminosity LHC.



VBF H →WW→eν μν

- *Impact of recent layout of upgraded detector*
- jets, b-tagging from expected performances at $\langle\mu\rangle=200$
- e/μ efficiency from Run-1 detector

- Impact of acceptance of the new Inner tracker
  - pileup jet mitigation in the fwd region
  - b-jets veto (ttbar) in the fwd region

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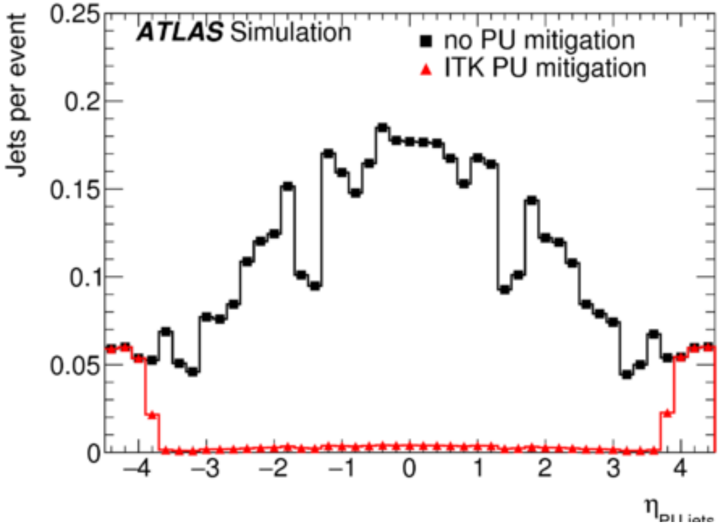
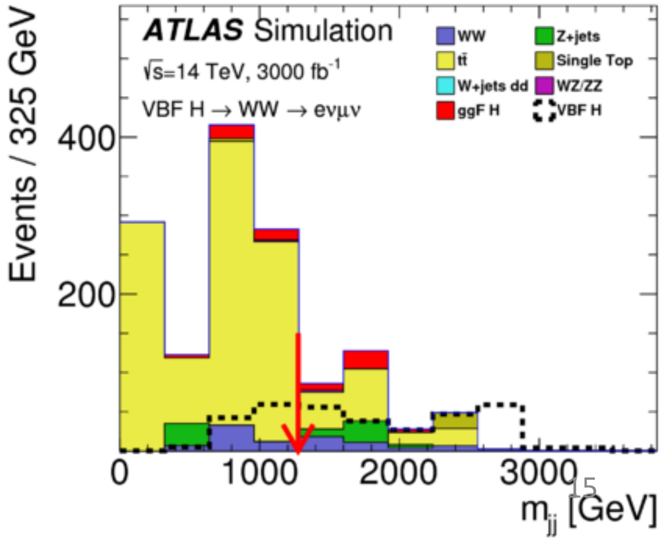


- precision on the visible cross- section measurement for these different scenario

Tracker acceptance	Expected precision
| η | < 4.0	12%
| η | < 3.2	18%
| η | < 2.7	22%



No theoretical uncertainties on VBF and ggF Higgs-boson production

VBF H→ZZ→4l

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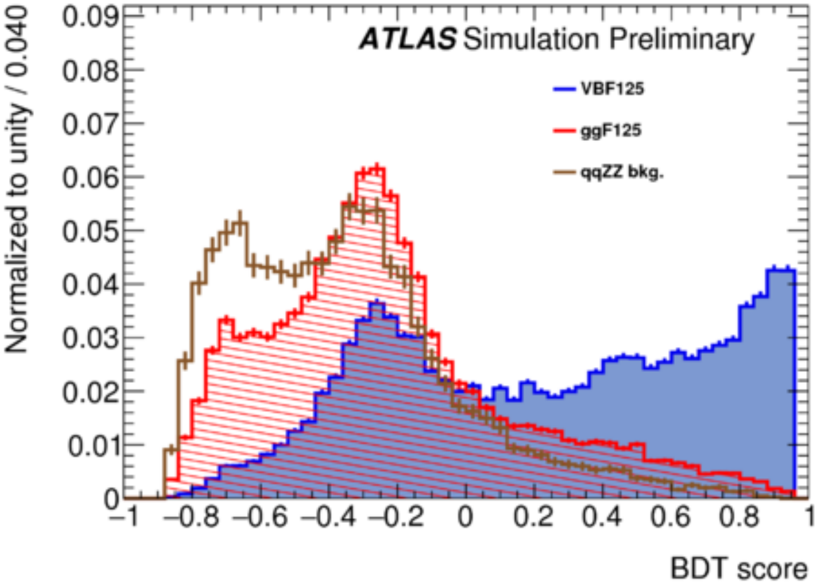
- *Impact of recent layout of upgraded detector*
- Use parametrization of expected performances at < μ > = 200
- The acceptance of the new Inner Tracker up to | η |<4.0 enables better separation between ggF and VBF kinematic distributions→ smaller $\Delta\mu/\mu$



Tracker acceptance	VBF + jets	ggF+2j	qqZZ+2j	Z_0	$\Delta\mu/\mu$
| η |<4.0	192	287	39	7.2(10.2)	0.182(0.152)
| η |<3.2	218	454	69	6.9(9.5)	0.192 (0.157)
| η |<2.7	259	803	124	6.2(8.6)	0.208 (0.165)

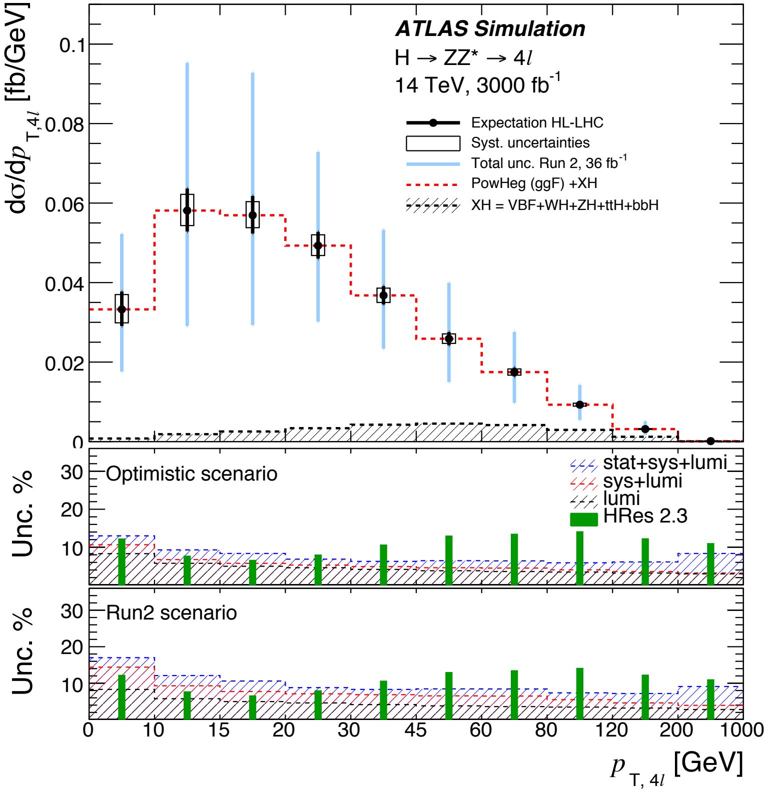
Last column: QCD scale variation systematic uncertainty: (included, not included)

H→ll differential cross section

Accurate measurement of Higgs boson p_T distribution

- probes perturbative QCD calculations
- information about (new) particles contributing to the gluon fusion loop

$$\sigma_{\mathrm{i,fid}} = \sigma_{\mathrm{i}} \times A_{\mathrm{i}} \times BR = \frac{N_{\mathrm{i,fit}}}{\mathscr{L} \times C_{\mathrm{i}}}, \quad C_{\mathrm{i}} = \frac{N_{\mathrm{i,reco}}}{N_{\mathrm{i,part}}},$$

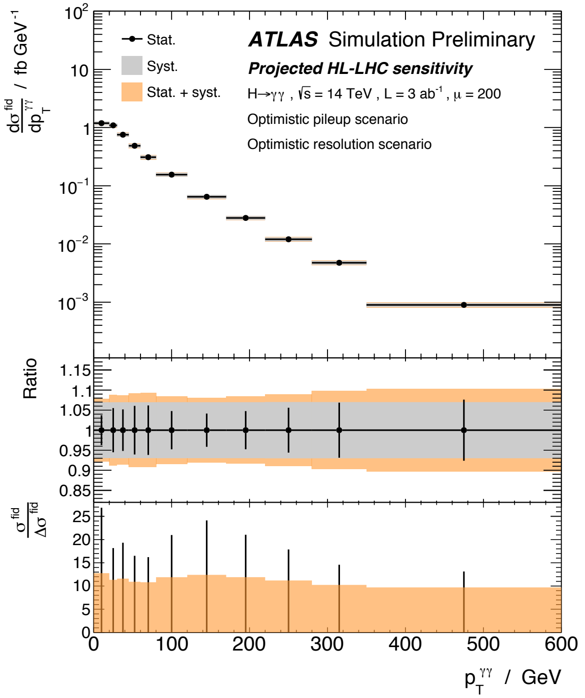


- Use parametrization of expected performance
- Assume Run2 systematic uncertainties dominated by
  - lepton efficiency and resolution 3%
  - unfolding method 3-4%
  - *qqZZ* modelling 2-5%

- Optimistic scenario: experimental uncertainties of Run2 reduced by × 2

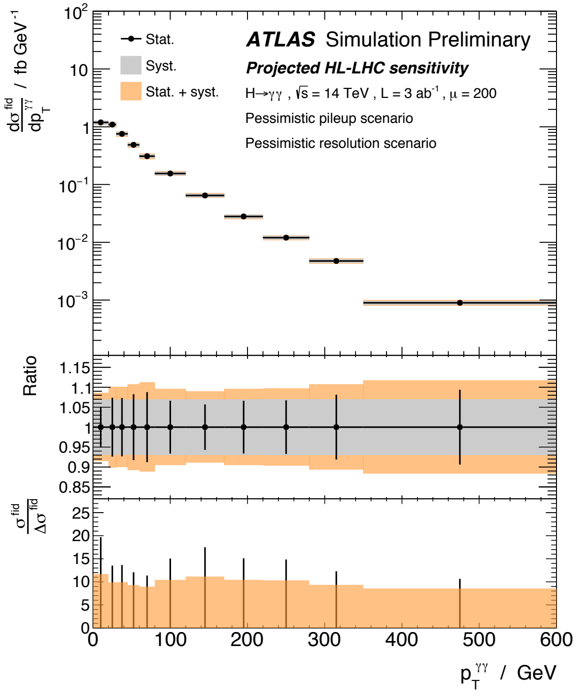
- Theory unc. ~ experimental unc. at HL-LHC

H→γγ differential cross section



- Run2 strategy with correction due to expected performances and pile-up effects

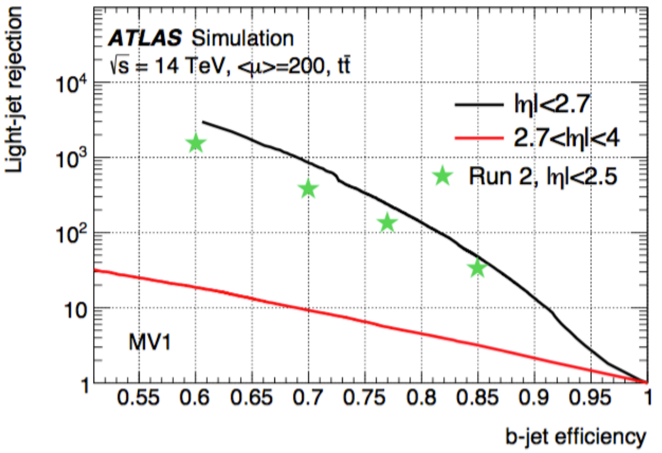
- Systematics uncertainties from Run2 = 6.8% dominated by
  - background modelling 3.7%
  - theoretical modelling 4.2%
  - both expected to be reduced for HL-LHC



- Optimistic(pessimistic) scenario for photon energy resolution
  - Constant term = 0.7% (1% barrel-1.4% endcap)
  - pileup noise = value from full simulation at <μ>=75(200)

- Optimistic(pessimistic) scenario for pile-up jets faking photons:
  - same as Run2 (scaled by 200 / μ_{evt})
  - Constant term = 0.7% (1% barrel-1.4% endcap)
  - pileup noise = value from full simulation at <μ>=75(200)

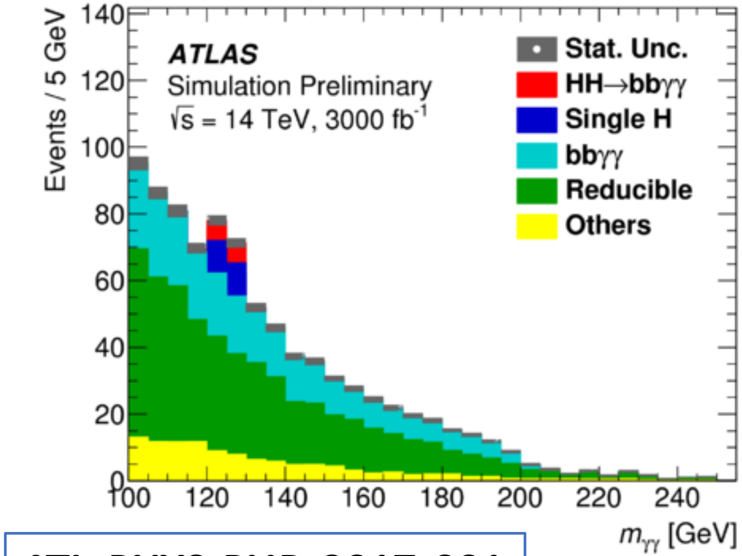
Higgs self-couplings: HH →bb γγ

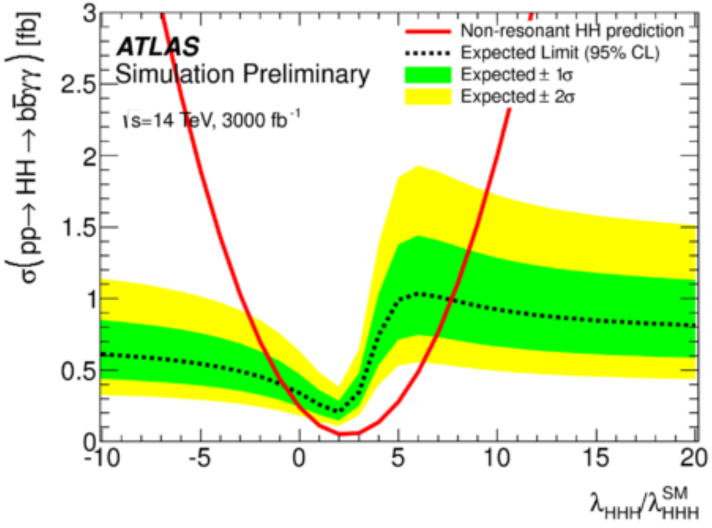


- Very promising channel thanks to narrow mass peak of H→γγ but low BR = 0.3%
- Use parametrization of expected performances of upgrade detector at <μ>=200
- Photon ID and b-tagging critical
- Main background
  - non resonant bbγγ and bbjγ
  - single H background production

Result

- S/√B significance ~1.05 (only stat.)
- **$-0.8 < \lambda_{HHH} / \lambda_{SM} < 7.7$ at 95 CL**
  - No systematic uncertainty
- Run2 (3.2 fb^{-1}): $\sigma < 3.9$ (5.4) pb obs.(exp)
  $\sigma_{SM} = 37.9$ fb @13 TeV





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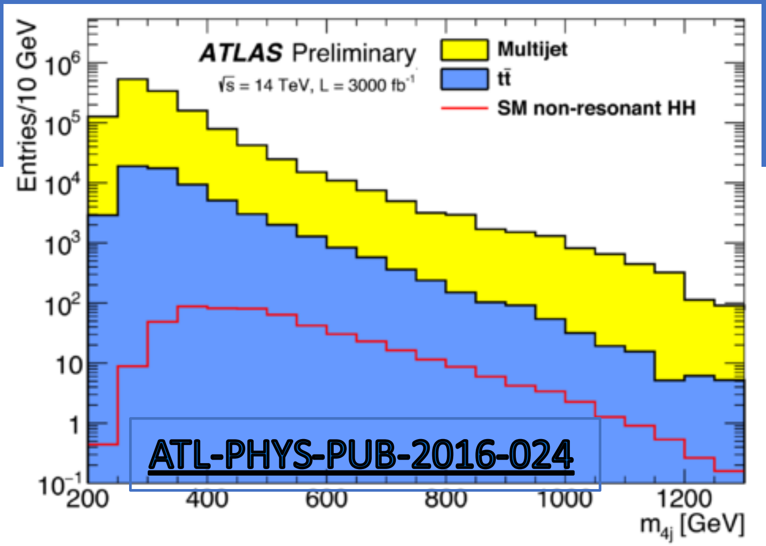
Higgs self-couplings: HH →4 b

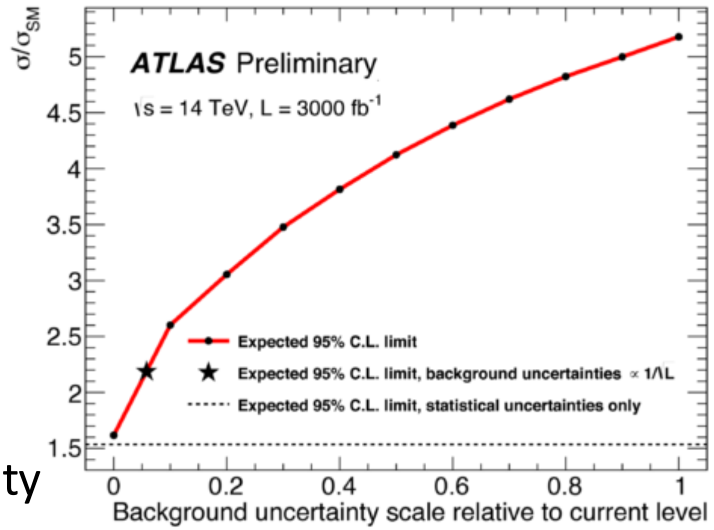
- Higher BR 33% but large QCD background
- Need excellent b-tagging
- Extrapolation and systematic uncertainties from Run2 (10fb^{-1})
  - Assume the current performance in jet reconstruction and b-tagging

- High sensitivity to jet trigger threshold:
  - Trigger system upgrade critical

- $-3.5 < \lambda_{HHH}/\lambda_{SM} < 11$ @ 95% CL
  - Largest systematics from b-tagging and ttbar background modeling
  - Improvements expected with increased luminosity



ATL-PHYS-PUB-2016-024

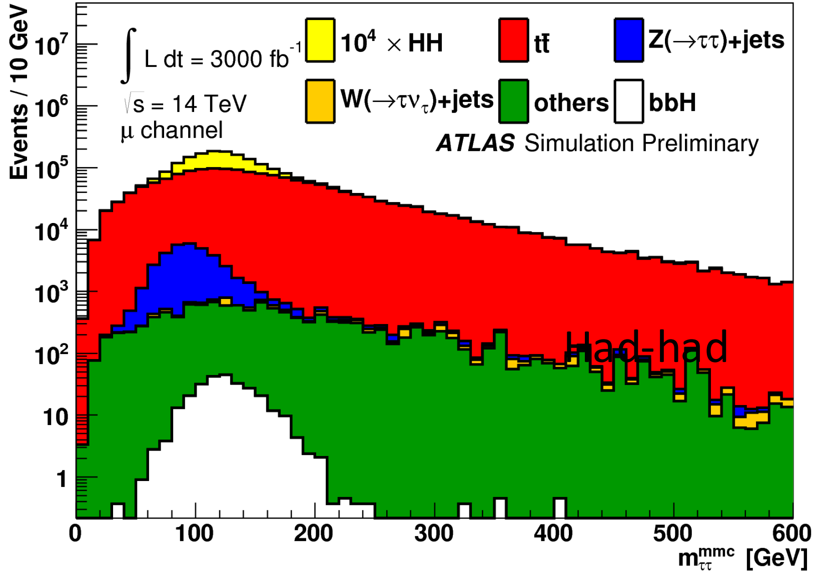


	p_T^{jet} >75 Gev, Full unc	p_T^{jet} >75 GeV, stat only	p_T^{jet} >30 Gev, Full unc	p_T^{jet} >30 Gev, Stat only
$\lambda_{HHH}/\lambda_{SM}$	[-7.4, 14]	[-3.4,12]	[-3.5,11]	[0.2,7]
σ/σ_{SM} excluded	11.5	2.0	5.2	1.5

HH →bb ττ and λ_{HHH}

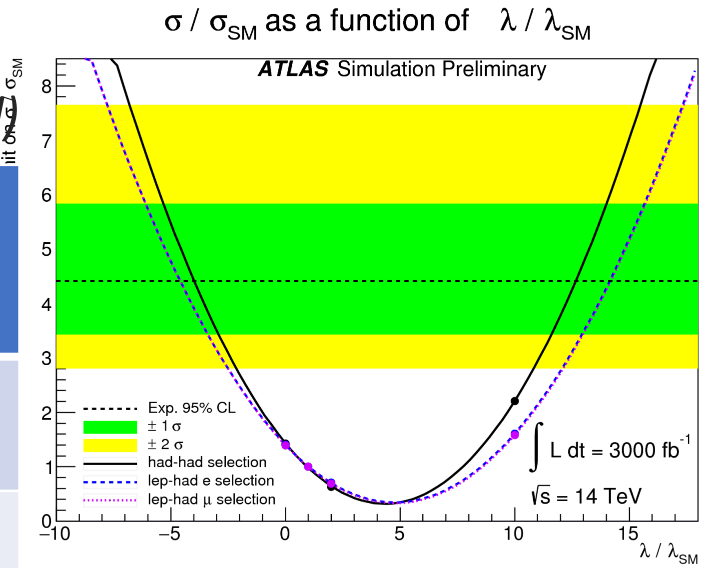
- BR *HH→bbττ* = 7.3%
- had-had, lep-had tau final states
- Use parametrization of expected performances of upgrade detector at $<\mu>=140$
- Main systematic uncertainty: background modeling uncertainty (Run 1)

ATL-PHYS-PUB-2015-046



- Combined significance (no syst. error): **0.6 σ**
- $\sigma/\sigma_{SM} < 4.3$ @ 95% C.L
- $-4 < \lambda_{HHH}/\lambda_{SM} < 12$ @ 95% C.L.

(reco. efficiency dependence on λ_{HHH} neglected)



	trigger	Signal events	Bkg events
$\tau_{lep}\,\tau_{had}$	Single e or mu $p_T>25$ GeV	20	880
$\tau_{had}\,\tau_{had}$	Di-τ: $p_T^{vis} > 40$ GeV	19	830

Conclusions

A lot of progress in the prospect of Higgs analysis in last 5 years:

- Benefit from new detectors has been addressed
- Impact of performances of reconstruction under HL-LHC pile-up condition addressed
  - more will come with TDR next year

- Take into account improvements in Run2 analysis for more realistic sensitivity studies

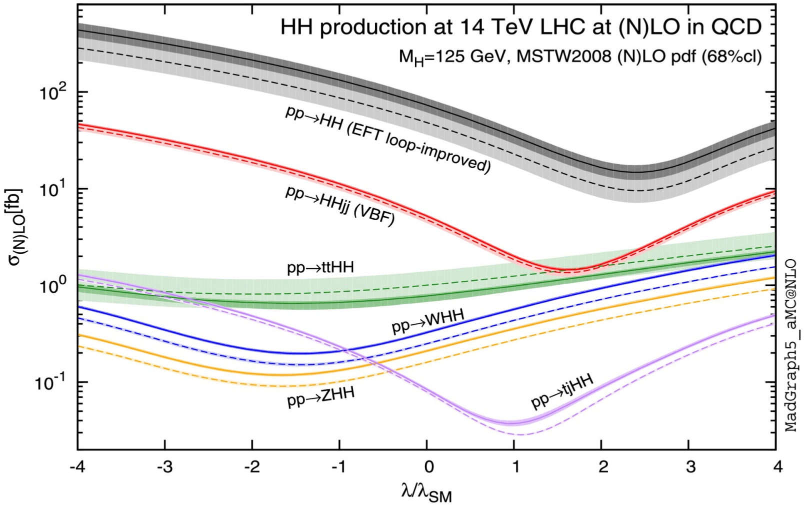
- Need to update some prospect analysis
  (for ex. Higgs couplings) with current theoretical uncertainties

Backup

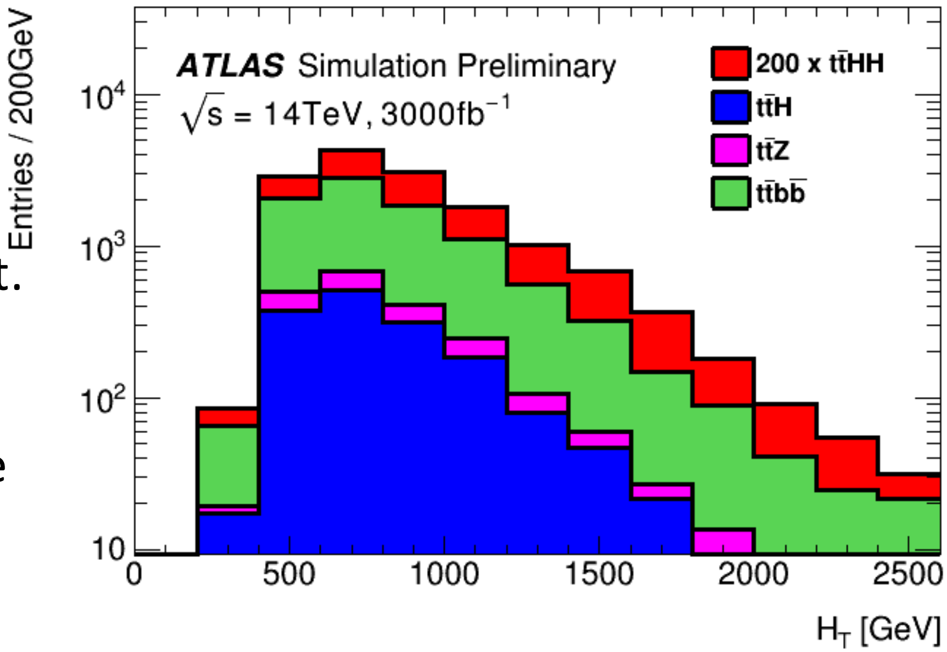
$t\bar{t}HH$ production

ATL-PHYS-PUB-2016-023

- σ($t\bar{t}HH$) ~ 1 fb
- Use $HH \to b\bar{b}\,b\bar{b}$ final state
  and semi-leptonic final state of $t\bar{t}$
- single lepton trigger requirement (*e*, *μ*)
- 6 *b*-jets, 2 light jets, *e*/*μ* and missing-*ET*



- For ≥5 *b*-tags: 25 signal events, 7100 background
- background is dominated by *c*-jets mis-tagged as *b*-jets from *W*→*cs*
- significance of $t\bar{t}HH$ production (no syst. error): **0.35 σ**
- With systematic uncertainties, the SM $t\bar{t}HH$ production found to give small contribution to HH production.



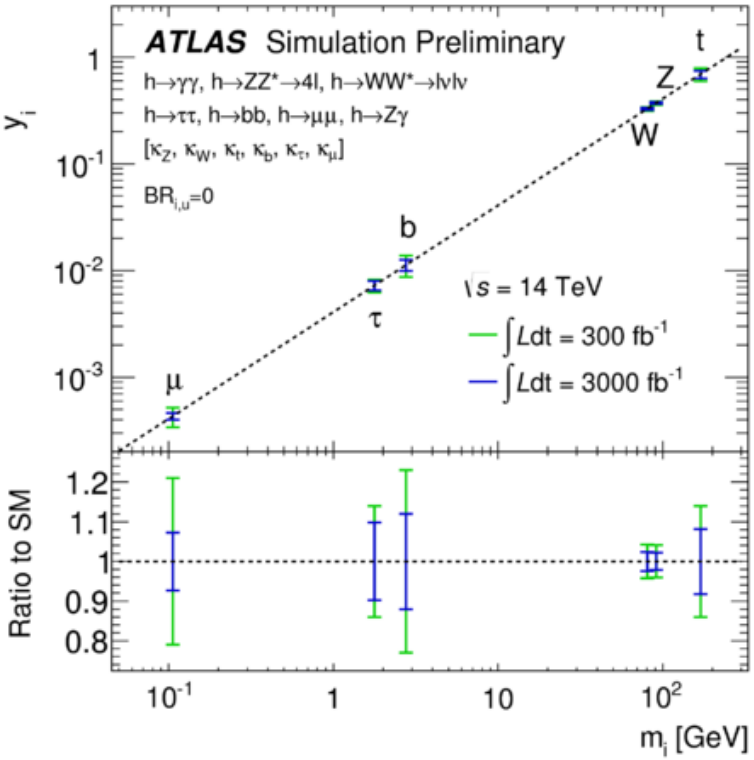
Higgs Couplings: mass dependence

ATL-PHYS-PUB-2014-016

- Higgs boson couplings versus the SM particle masses
- Define 'reduced' coupling parameters

$$y_{V,i} = \sqrt{\kappa_{V,i} \frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}} \frac{m_{V,i}}{v}$$

$$y_{F,i} = \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i} \frac{m_{F,i}}{v}$$



- Use results from fit with 6 parameters

[no theory uncert., full theory uncert.]

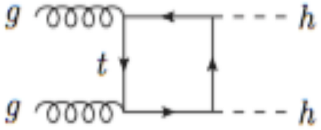
	κW	κZ	κb	κt	κτ	κμ
300fb^{-1}	[8,9]	[8,8]	[22,23]	[11,14]	[13,14]	[21,21]
3000fb^{-1}	[4,5]	[4,4]	[10,12]	[5,8]	[9,10]	[7,7]

HH and λ_{HHH}

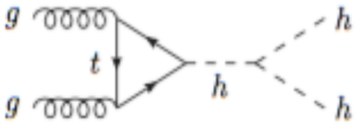
Higgs production crucial for the measurement of Higgs *self- coupling*
Last piece missing in the Standard Mode

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \boxed{\lambda_3} \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4 \,,$$

SM: $\lambda_3 = \lambda_4 = 1$;



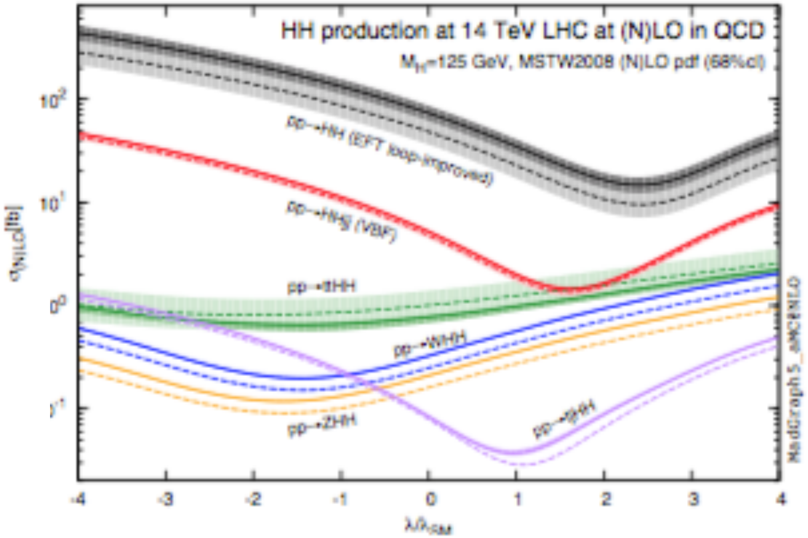
$\sim const.$



$\sim \lambda_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$

Very challenging measurement:

- **Prospective at HL-LHC still not clear**
- **Room to impact for optimal trigger and reconstruction and detector design**



Strong dependence near λ~1
High sensitivity to deviations from SM

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

Higgs ratio Couplings

ATL-PHYS-PUB-2014-016

- Remove the assumption on the total width
- Only ratios of the coupling scale factors can be determined at LHC
- Some uncertainties cancel in the ratio
- But Reduced theoretical uncertainties needed