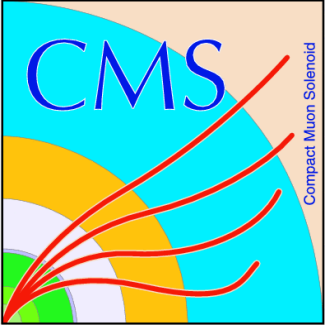


Higgs and Electroweak Physics at the HL-LHC

Sven Dildick
Texas A&M University

On behalf of the ATLAS and CMS Collaborations

International workshop on Future linear colliders
LCWS2018

22-26 October 2018
University of Texas, Arlington TX

High-Luminosity & High-Energy LHC

- The LHC will be upgraded to HL-LHC starting 2024 to increase sensitivity for precision SM studies and new physics searches
- HL-LHC: 3000 fb^{-1} @ 14 TeV, L = 5(7.5) 10^{34} cm^{-2} s^{-1} (~5/7.5 x design) **<PU>=200**
- HE-LHC: 15,000 fb^{-1} @ 27 TeV, **<PU>=800**

ATLAS Detector Upgrade

- New RPCs in inner barrel

- Replace MDT with small-diameter MDT

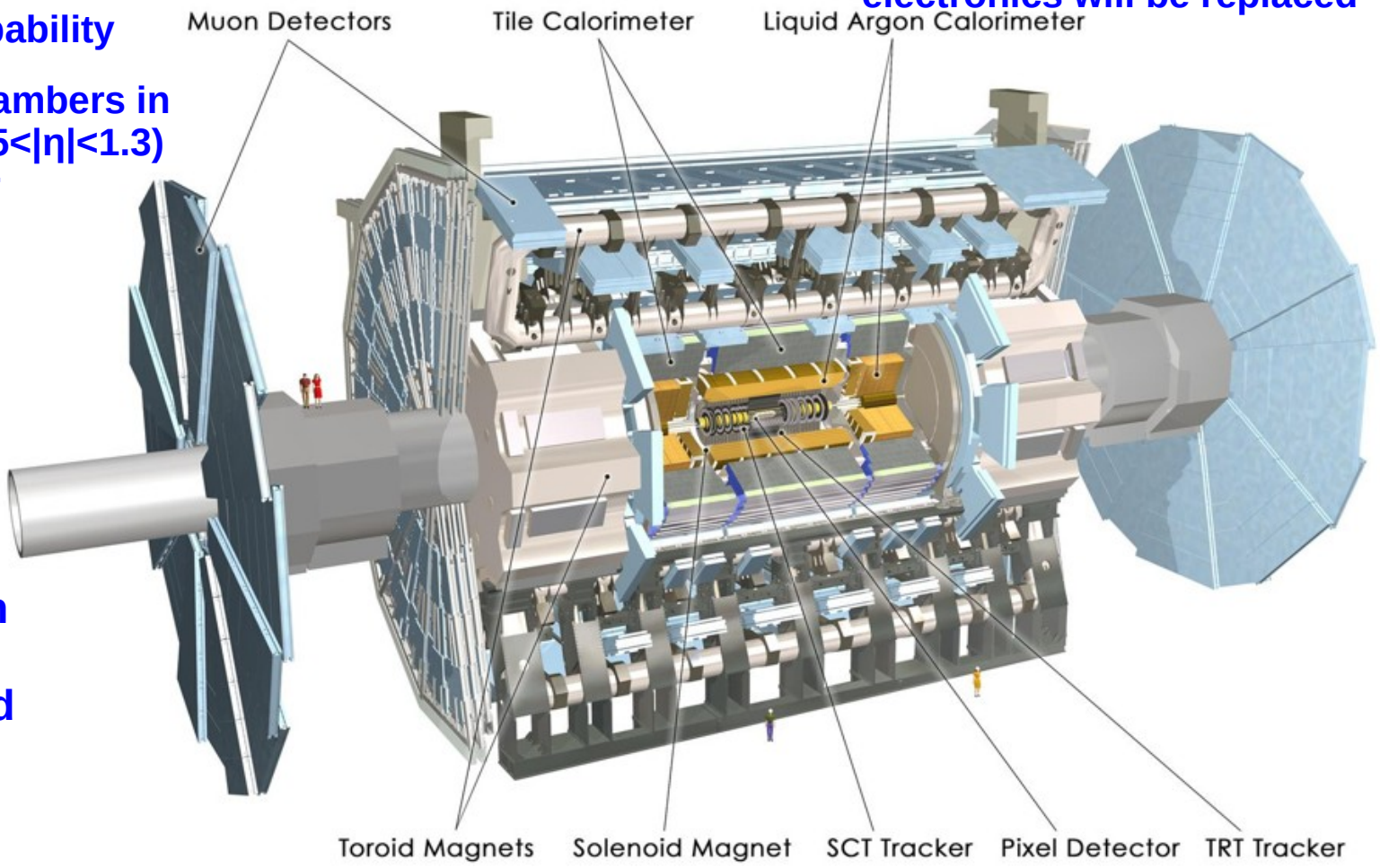
  → better rate capability

- Replace thin gap chambers in the inner endcap (1.05<|η|<1.3) to improve the trigger redundancy.

Tile Calo: Fully digital trigger electronics

Liquid Argon Calorimeter:

-Front-end and back-end electronics will be replaced



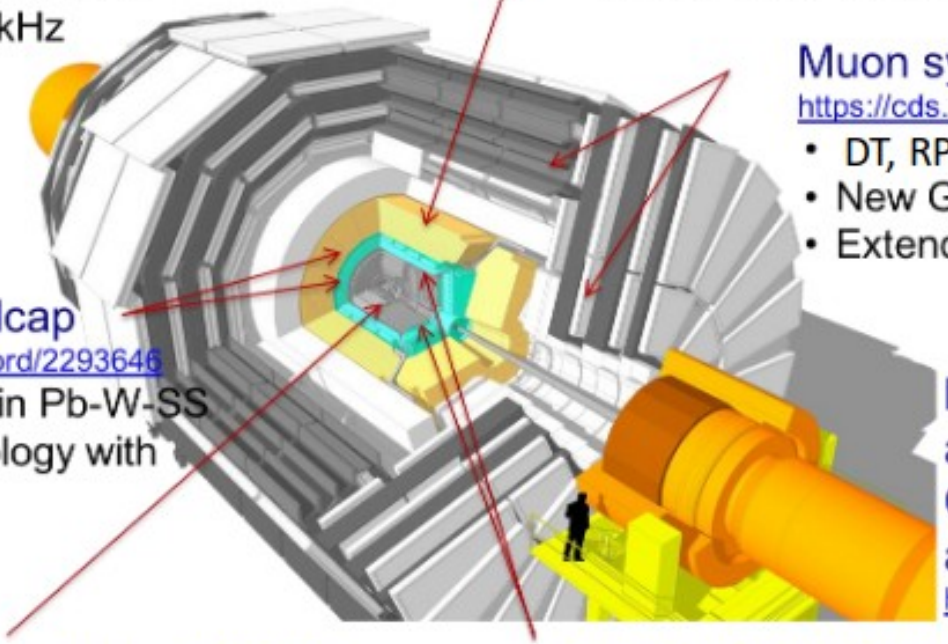
Installation of High Granularity Timing Detector in forward region

New all-silicon Inner Tracker (ITk)

CMS Detector Upgrade

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Muon systems
https://cds.cern.ch/record/2283189
- DT, RPC, CSC new electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Higgs & EW Physics Impact at HL-LHC

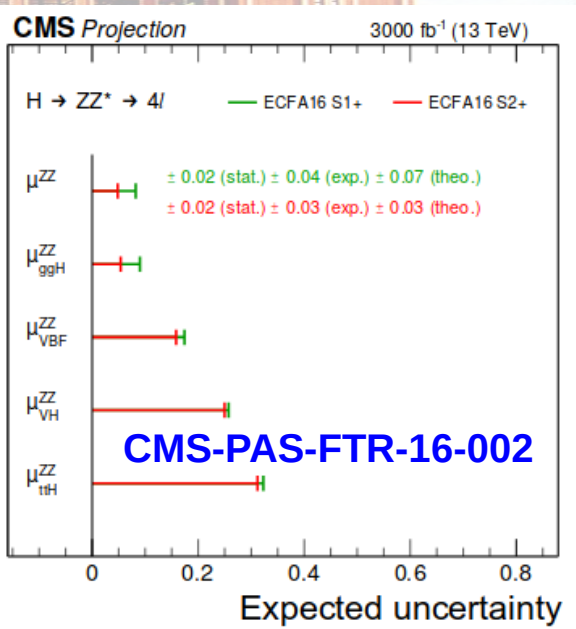
- **Higgs Precision Measurements**
  - Couplings to ~5%, cross sections, Higgs decay width
- **Rare decays**
  - Higgs decay to 2nd generation fermions, J/ψɣ
- **Di-Higgs production**
  - Measure self-coupling
- **BSM Higgs searches**
  - Extra scalars/vectors, BSM Higgs resonances, LLP, LFV
- **Vector boson scattering**
  - Measurements of EWSB & probe for BSM physics

Physics Projections at HL-LHC

- Analyses are being done by ATLAS and CMS Collaborations to study the prospects at HL-LHC
- Different approaches are taken to project the physics impact
- Extrapolations made with 13/14 TeV center of mass energy and 3000 fb^{-1}
- Treatment of systematic uncertainties:
  1. Scenario with Run-2 syst. unc.
  2. Scenario with syst. unc. scaled according to inverse square root of integrated luminosity
  3. Scenario with no systematic uncertainties
- Projections also done with full/fast sim at 14 TeV, 200 pileup and 3000 fb^{-1}
- Several ATLAS and CMS projections finished with many more in the pipeline for YR18
- Some results are included in the slides

Higgs Couplings at HL-LHC

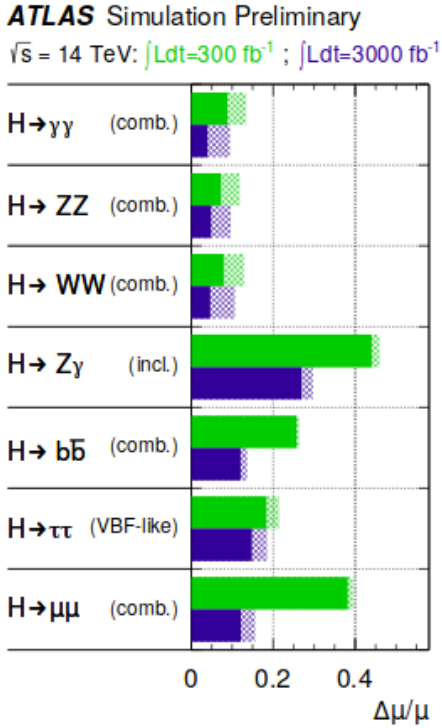
- Existing studies: comprehensive, but largely based on extrapolations of Run-1 results
- Few analyses were done with full SIM of upgrade detector
- Cross sections (translated to signal strengths) and couplings measured to **few % level**
- Projections will be updated to take into account analysis updates for YR18



L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

L (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]

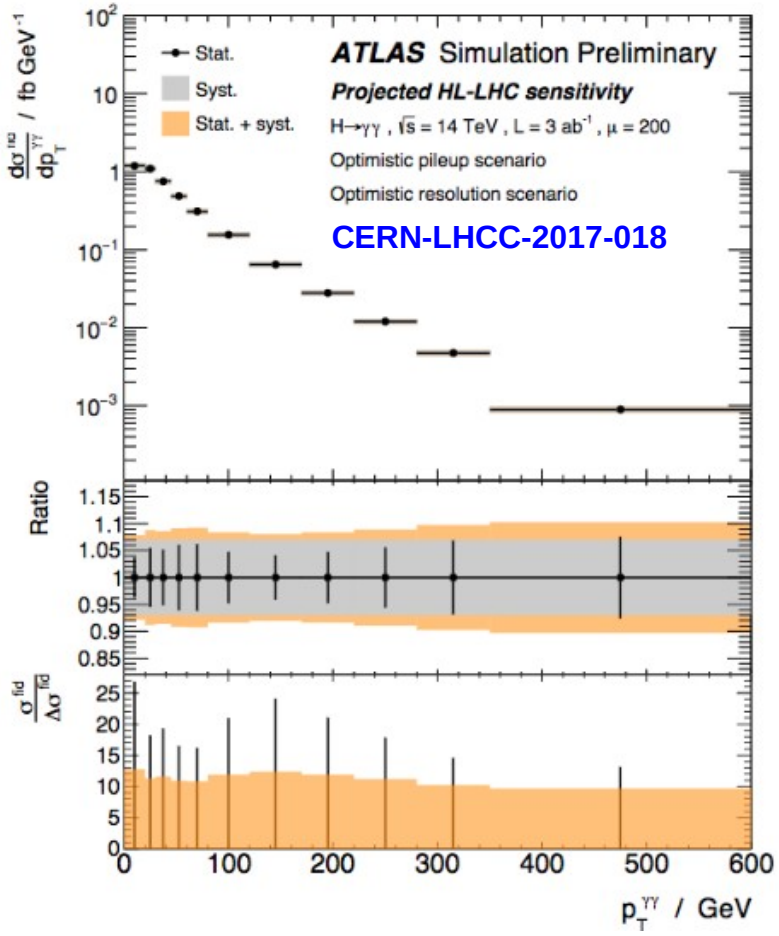
CMS-NOTE-13-002

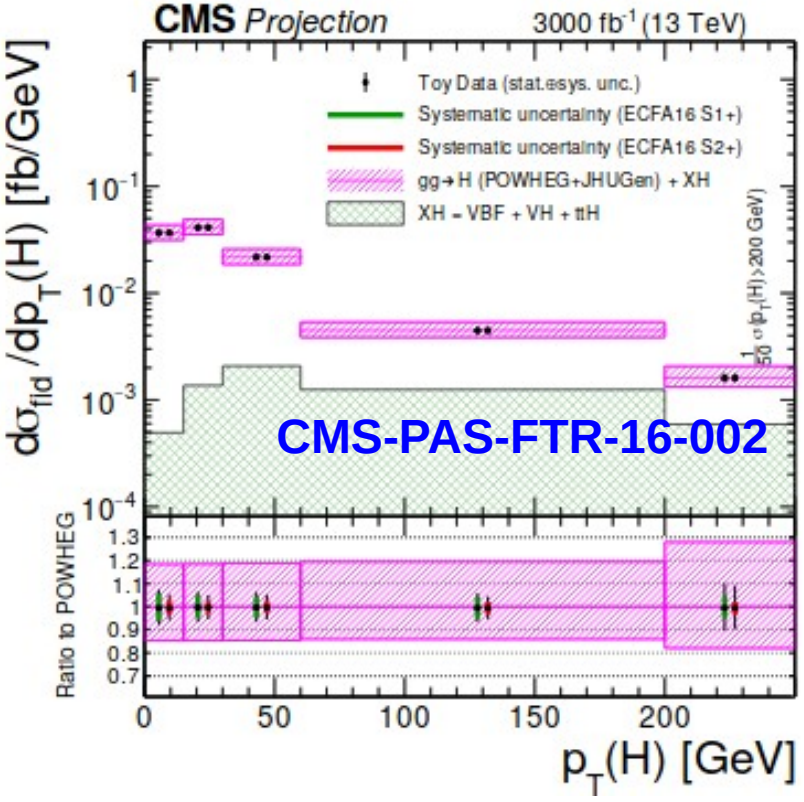


ATL-PHYS-PUB-2014-016

Differential Fiducial Cross Sections

- Large data sets at HL-LHC → precision measurements of differential fiducial cross section





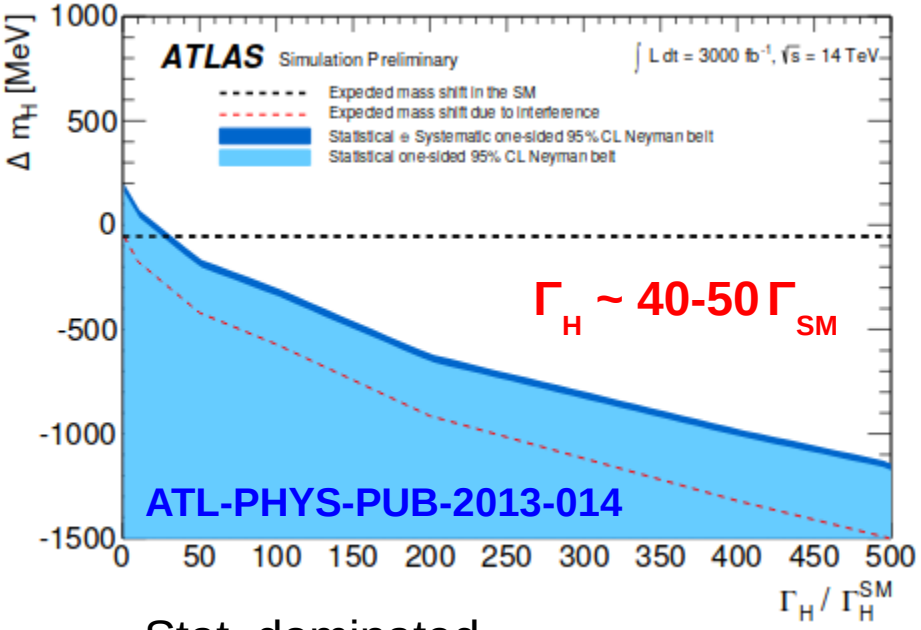
- At HL-LHC: sensitive to k_b/k_c @ low p_T and k_t/BSM @ high p_T
- At high p_T, dominated by statistical uncertainty even @ 3000 fb^{-1}

Results will be updated for YR18

Decay Width

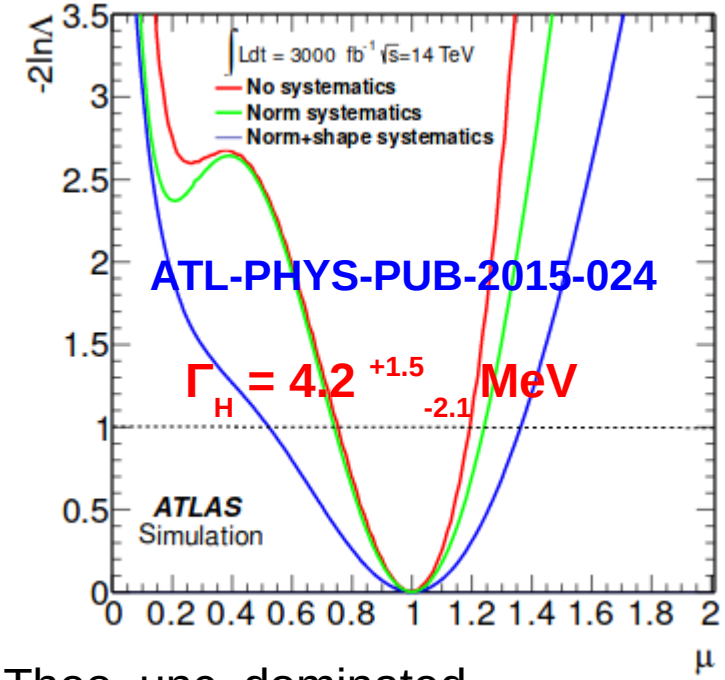
- BSM physics may affect Higgs properties at high momenta
  - e.g. Higgs decay width
- Even with 3000 fb^{-1}, precision measurements will be challenging
- Indirect methods may provide insights at HL-LHC

Interference of gg → H → γγ and gg → γγ



Stat. dominated

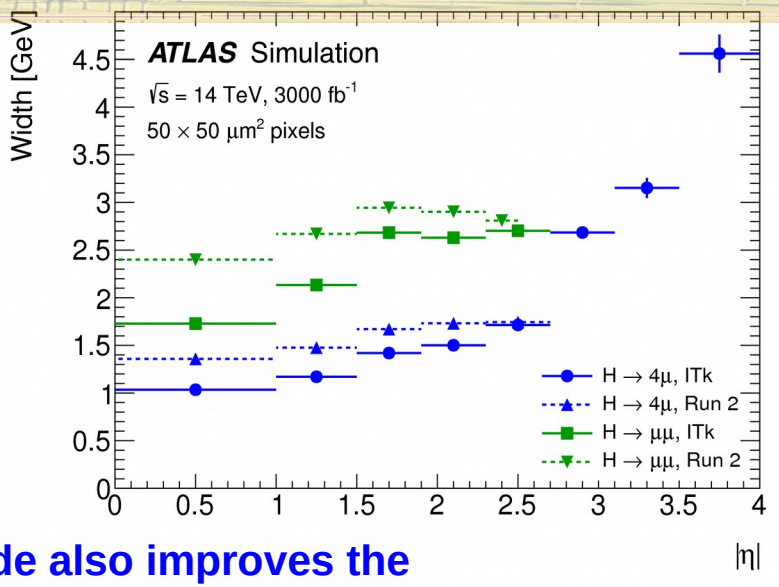
Off-shell width in gg → H* → ZZ and gg → ZZ



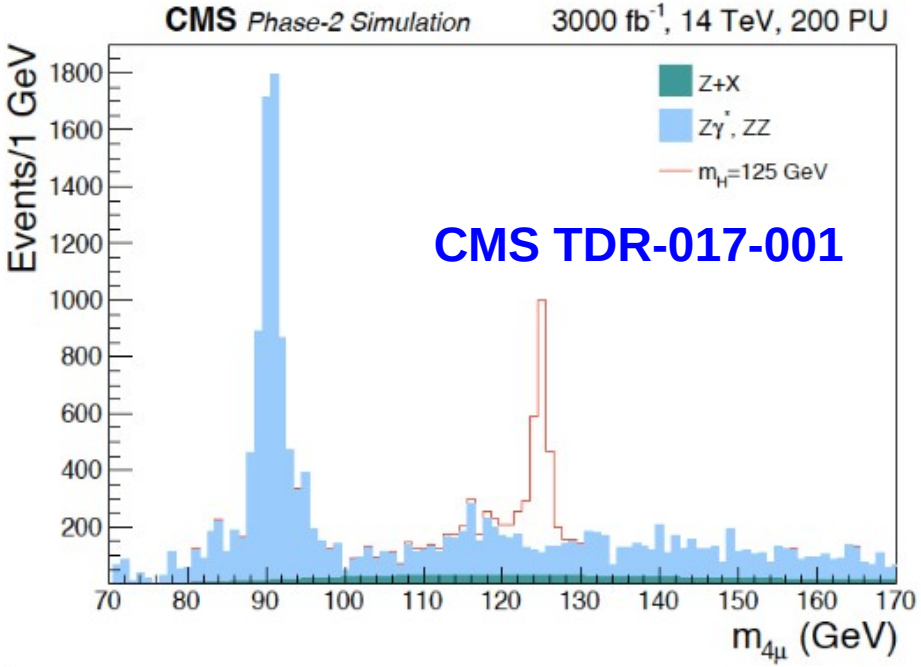
Theo. unc. dominated

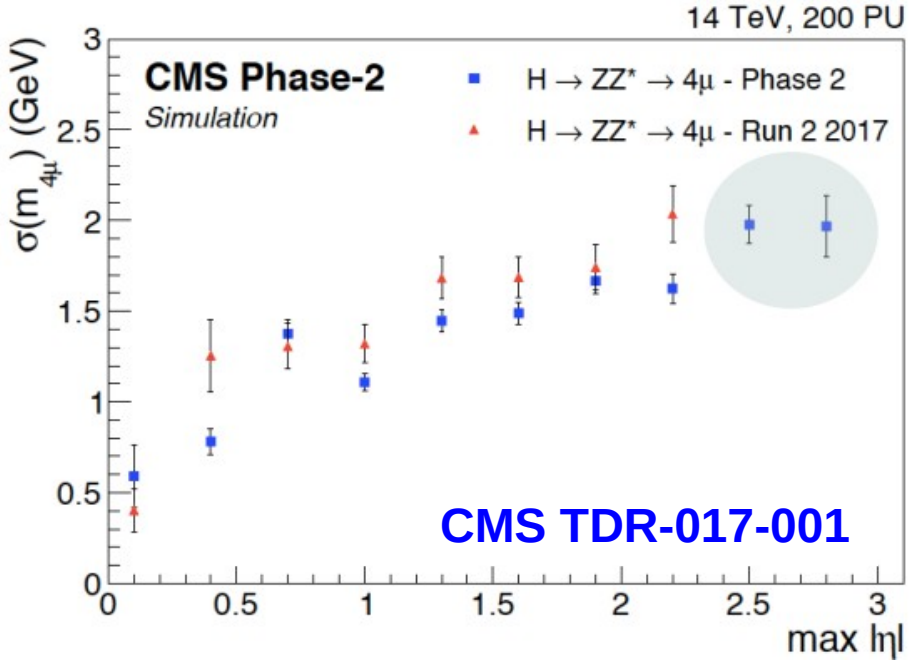
$H \rightarrow ZZ^* \rightarrow 4\mu$

- Neary 20,000 ggF + ~1500 VBF events expected
- CMS & ATLAS muon detectors will be upgraded
- Muon system not as much affected to high pileup as other subdetectors
  - Signal acceptance and mass resolution not influenced by pileup



ITK upgrade also improves the invariant mass resolution H->ZZ->4mu

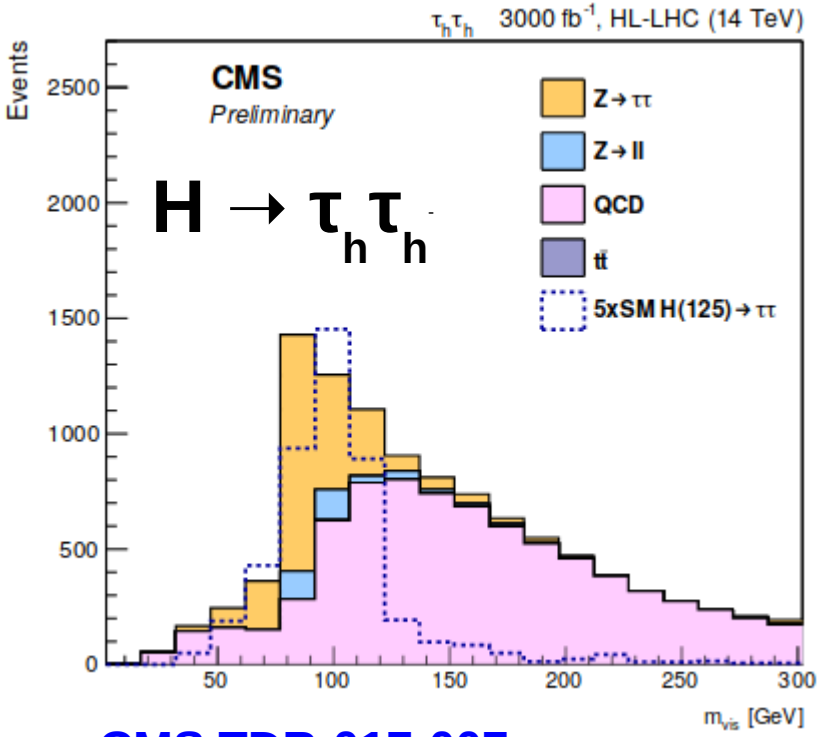




VBF H → $\tau^+\tau^-$

- VBF characterized by forward jets: → higher signal purity than ggF
- Installation of a high granularity calorimeter and precision timing instruments (~ 30 ps/mip) in forward region helps with
  - Forward jet reconstruction and ID for VBF jets
  - Pileup suppression, jet isolation, jet shape observables and MET
- **ATLAS: HGTD; CMS: HGCal+MIP**

- Nearly 1M H → $\tau^+\tau^-$ events allow to probe the tau-Yukawa coupling
- Requires good understanding of entire detector to use all final states
- Need excellent m_{vis} resolution to separate Higgs and Z boson mass peak

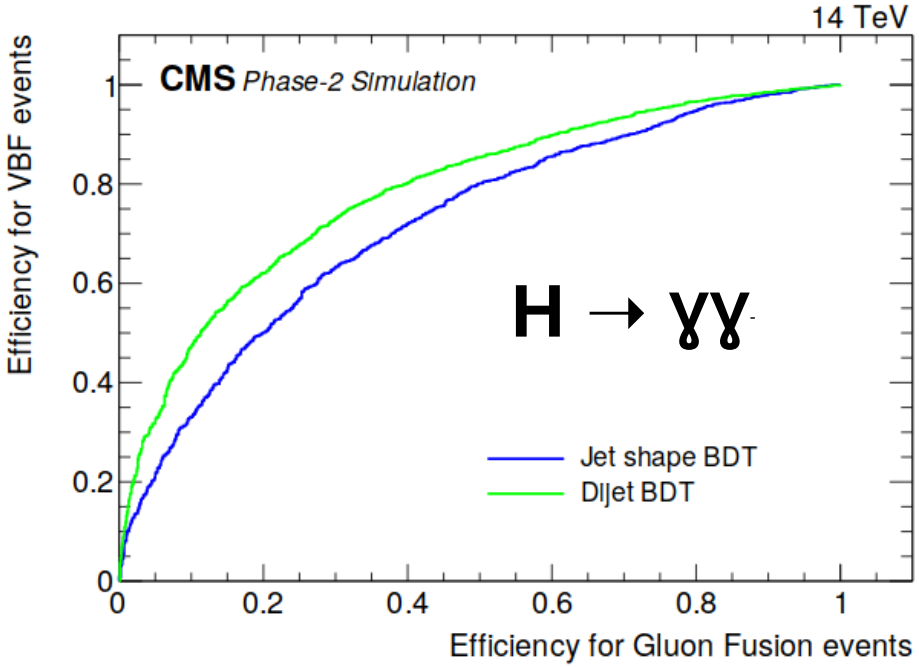


CMS TDR-017-007

VBF H → γγ

- VBF characterized by forward jets: → higher signal purity than ggF
- Installation of a high granularity calorimeter and precision timing instruments (~ 30 ps/mip) in forward region helps with
  - Forward jet reconstruction and ID for VBF jets
  - Pileup suppression, jet isolation, jet shape observables and MET
- **ATLAS: HGTD; CMS: HGCal+MIP**

- **H → γγ analysis**
  - BDT as discriminator
  - VBF vs ggF discriminating power in Phase-2 similar as in Run-2
    - Probably conservative results; improvement expected with full granularity in analysis

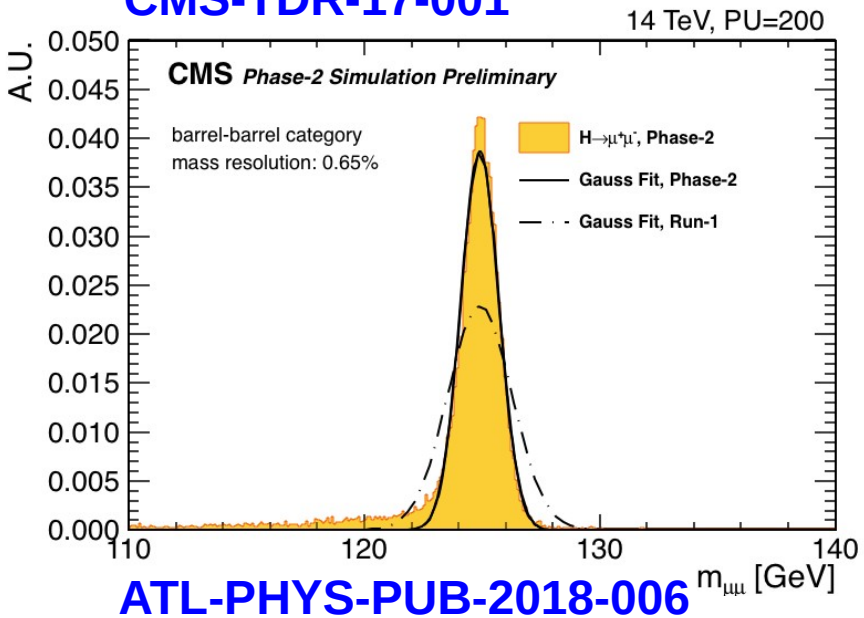


CMS TDR-017-007

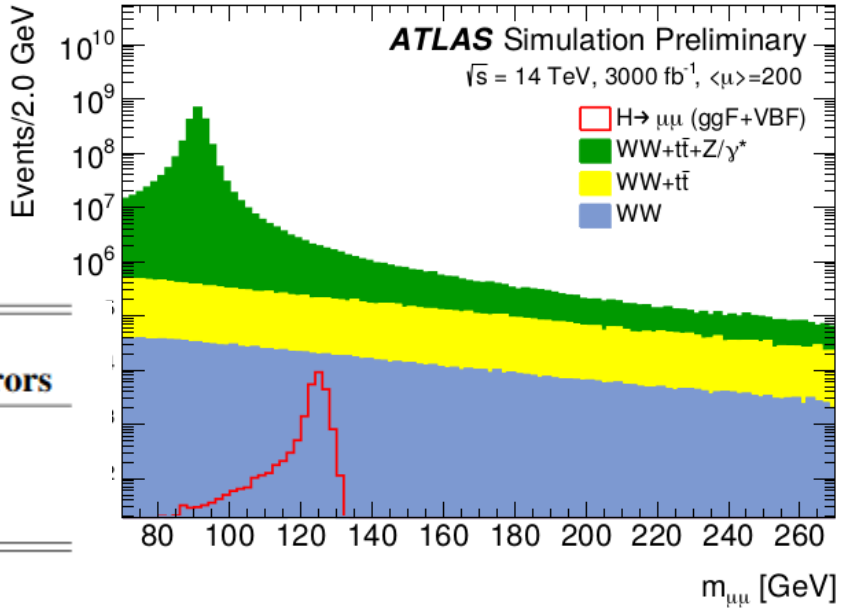
$H \rightarrow \mu^+\mu^-$

- Recent result by CMS using Run-1 and Run-2 data
  - Production rate < 2.92 (2.16) times SM value @ 95% CL
- Improved dimuon mass resolution expected at CMS and ATLAS with muon upgrades
- Recent projection by ATLAS using 3000 fb^{-1} @14TeV with 200 PU
- Significance >9 can be expected

CMS-TDR-17-001



ATL-PHYS-PUB-2018-006

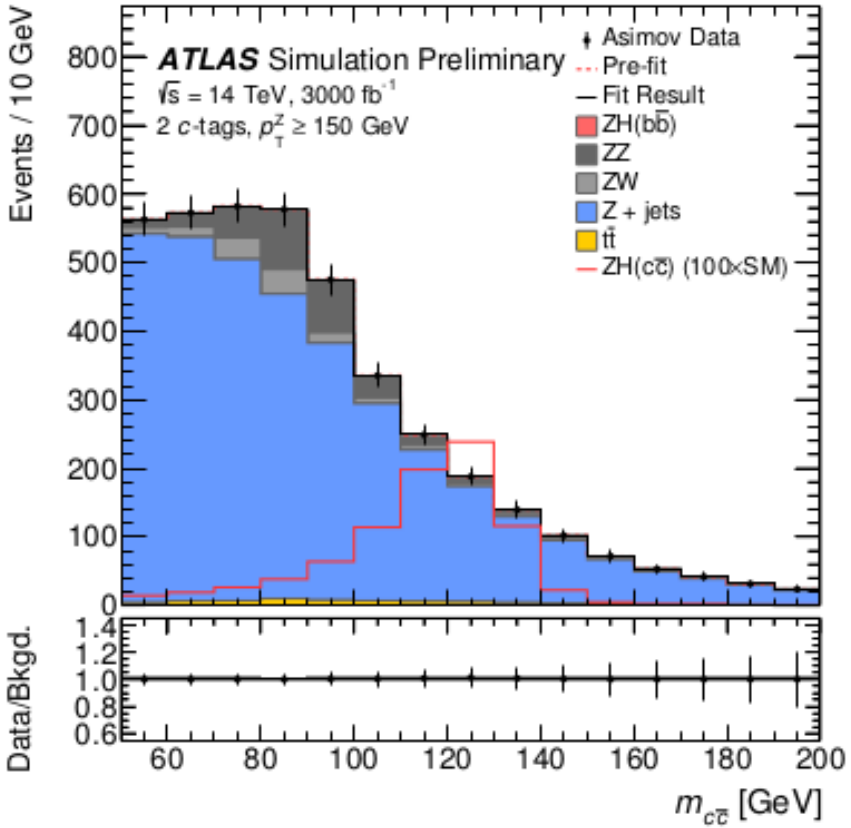


Scoping Scenario	$\langle\mu\rangle$	Overall significance	$\Delta\mu$ w/ syst. errors	$\Delta\mu$ w/o syst. errors
reference	200	9.5	±0.13	±0.12
middle	200	9.4	±0.14	±0.12
low	200	9.2	±0.14	±0.13

$H \to c\bar{c}$

- After $H(\mu^+\mu^-)$ most interesting decay mode with 2nd generation fermions
- ATLAS results using Run-2 data: $\sigma(pp \to ZH) \times B(H \to c\bar{c}) < 2.7$ pb @ 95% CL (110 times SM)
- Recent projection done by ATLAS at 3000 fb^{-1} with 14 TeV
- Pair of electrons or muons to suppress large background
- Upper limit on production rate in ZH mode reduces to $6.3^{+2.5}_{-1.8}$ times SM @ 95% CL
  - Without syst. uncertainties

(ATL-PHYS-PUB-2018-016)

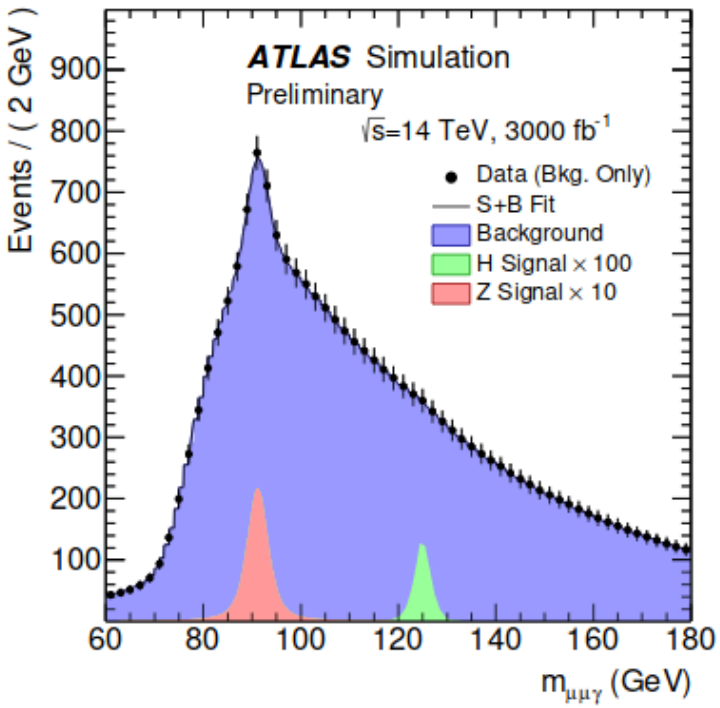


Source of uncertainty	Change in limit
Background shape	+36%
Jet energy scale and resolution	+17%
Lepton reconstruction and identification	+12%
c-jet tagging efficiency	+11%

Effect of syst. unc. on limit

Rare Higgs decays

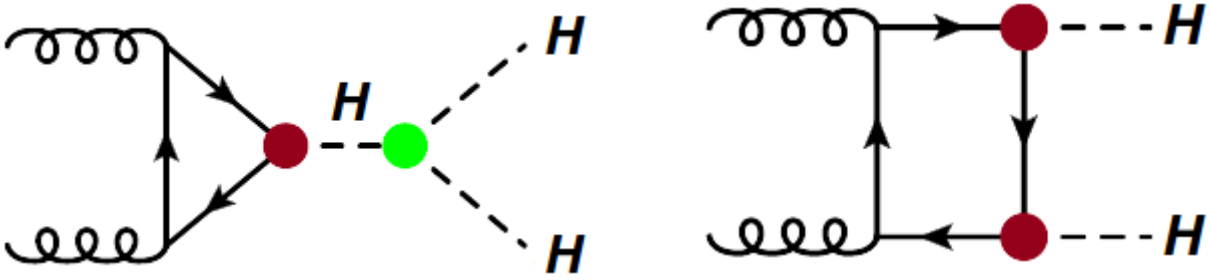
- High stat. at HL-LHC allows to probe rare decays, e.g. h → J/ψ γ
  - Goes through c-quark pair as in previous slide
- J/ψ selected through dimuon final state
- Results from MVA-based analysis:
  - $B(h \rightarrow J/\psi\,\gamma) < 44^{+19}_{-22} \times 10^{-6}$ (~15 times SM value)
  - SM expectation : $(2.9 \pm 0.2) \times 10^{-6}$
- Similar results from cut-based cross-check

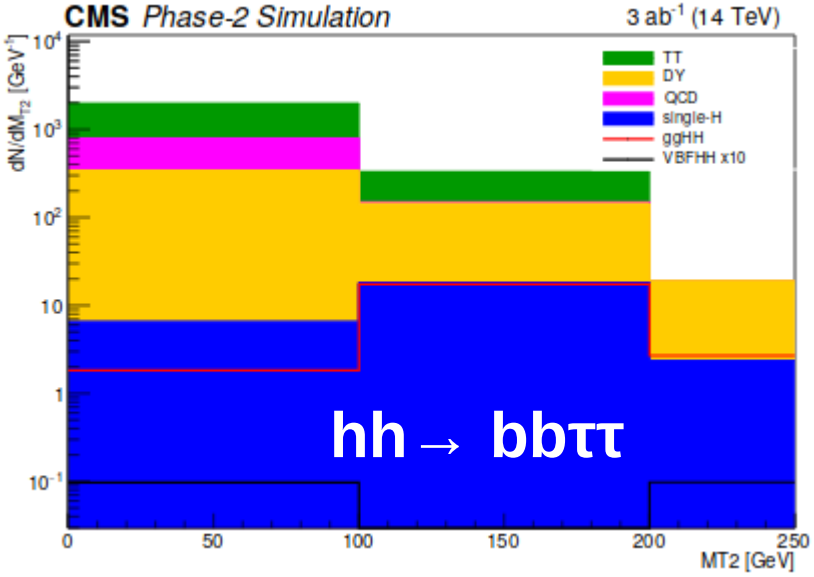


ATL-PHYS-PUB-2015-043

Double Higgs production

- Two leading production modes
- Ideal to measure **Yukawa** coupling constants and **Higgs trilinear** self-coupling





CMS-TDR-17-007

Sensitivity close to 1.5 times SM value

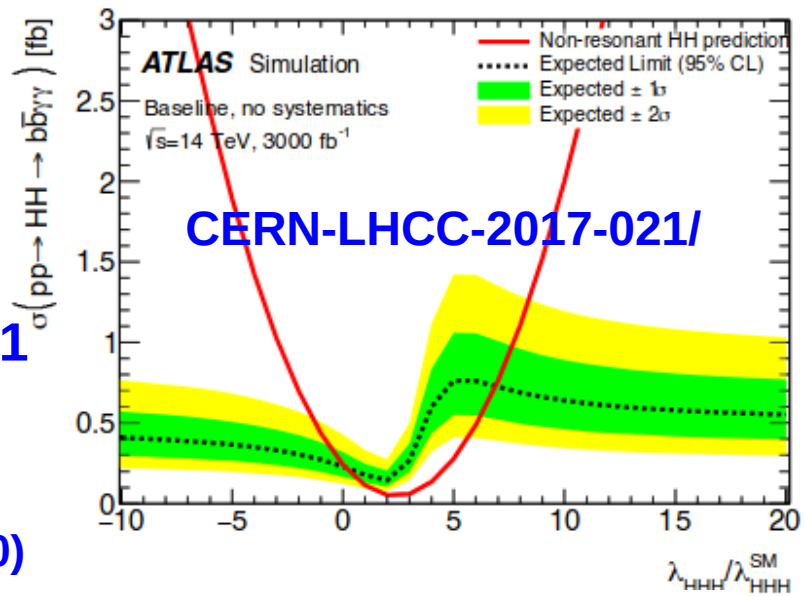
Category	σ_{HH}/σ_{SM}	$\sigma_{ggHH}/\sigma_{SM}$	σ_{VBF}/σ_{SM}
2b0j	1.8	3.0	72.6
VBF	3.9	5.4	86.6
Combined	1.6	2.8	52.2

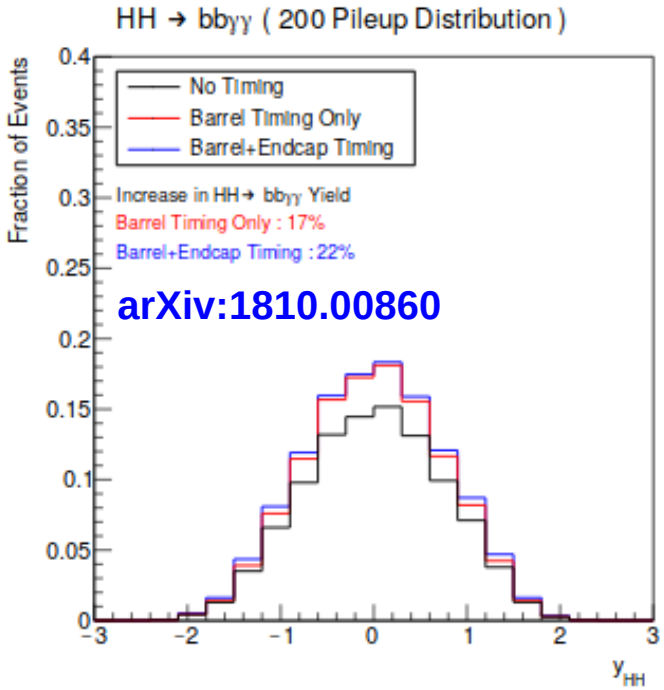
Double Higgs production hh → bbɣɣ

- ATLAS projection: Higgs boson self-coupling constrained to

  $-0.2 < \lambda/\lambda_{SM} < 6.9$ @ 95% CL (neglect syst. unc.)

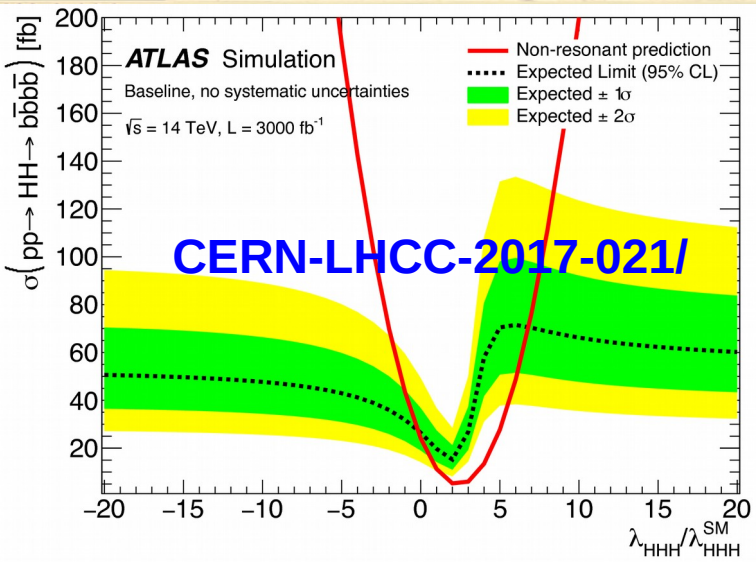
- Similar conclusions found in **arXiv:1804.07130v1**
  - λ/λ_{SM}~1 @ 95% CL with **8.5 ab^{-1}** (~3 x HL-LHC)
- Recent study with CMS detector **(arXiv:1810.00860)**
  - Improvements expected from new MIP timing layer (30ps resolution)
  - 20% gain in effective luminosity for hh → bbɣɣ
- Improvements with upgraded ATLAS Pixel and LAr detector
  - Better b-tagging with new ITK and review of photon energy resolution





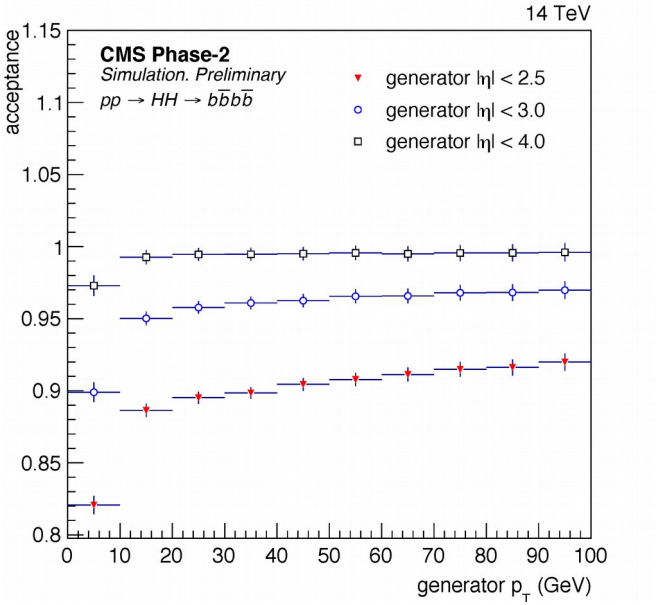
Double Higgs production hh → bbbb

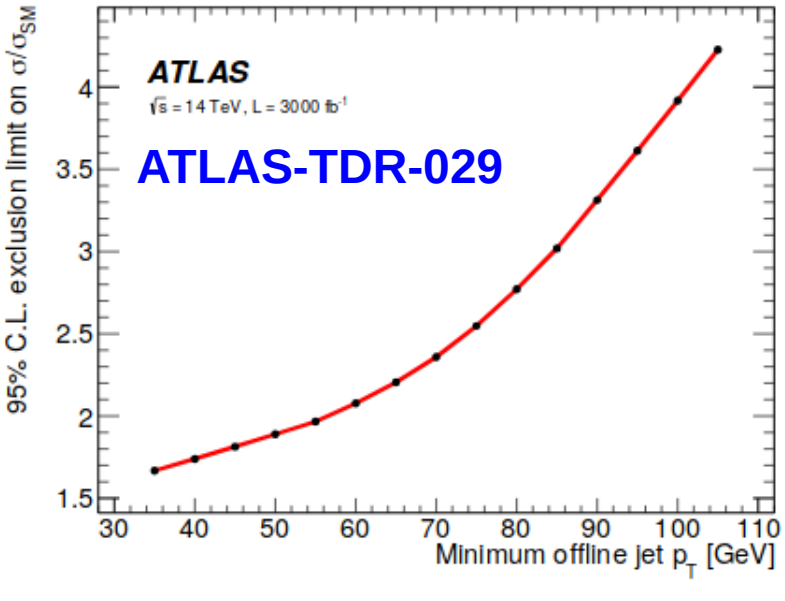
- Projection for bbbb less restrictive than bbγγ
- Limits on Higgs trilinear coupling
  - $-1.2 < \lambda/\lambda_{SM} < 8.0$ @ 95% CL (without syst.)
  - $-4.1 < \lambda/\lambda_{SM} < 8.7$ @ 95% CL (with syst.)
- Non-negligible syst. unc. compared to hh → bbγγ
- Important to keep jet trigger pT low (~65 GeV)



(No systematic uncertainties)

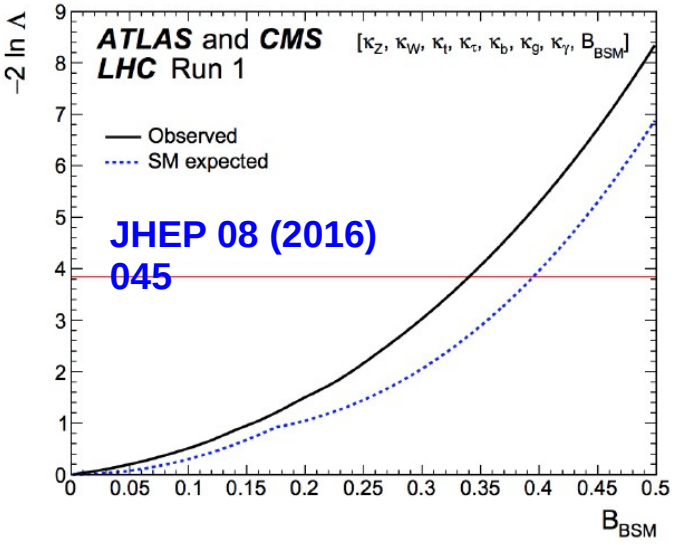
- Similar projection to be done by CMS
  - 10% increase in acc. with Phase-2 tracker
  - Similar gains with Phase-2 ATLAS tracker

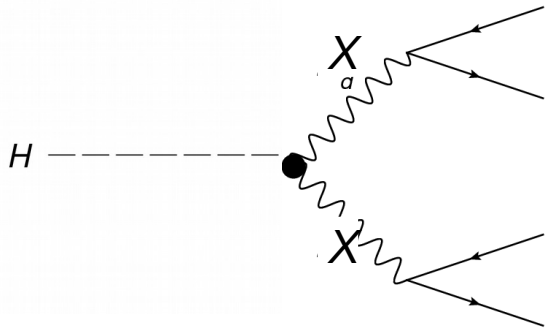




Exotic Higgs decays

- Higgs to BSM particles or forbidden SM decays
- Currently B_{BSM}<34% at 95% CL (ATLAS+CMS)
- Sets upper limit to all exotic branching ratios
- Popular set of models include **Higgs decays to light bosons, $h \rightarrow 2x$, with $m_X < m_h/2$**
  - NMSSM: CP-odd pseudo-scalar light boson
  - 2HDM + S: extra singlet scalar
  - Dark sector models with $U(1)_D$: extra dark vector boson
- **Many** different final states! 2b2μ, 4τ, 4b, 2τ2b, 2τ2μ,…

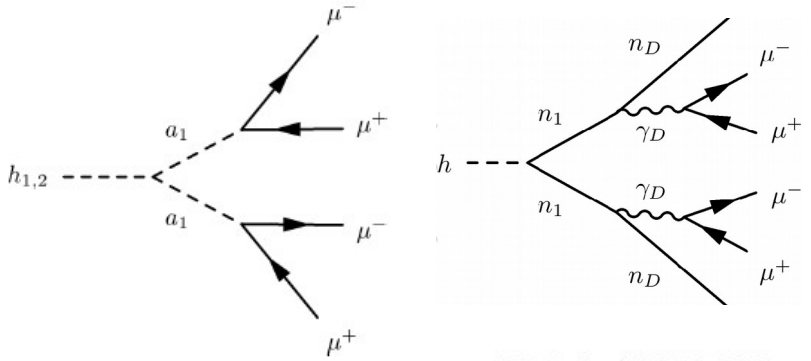


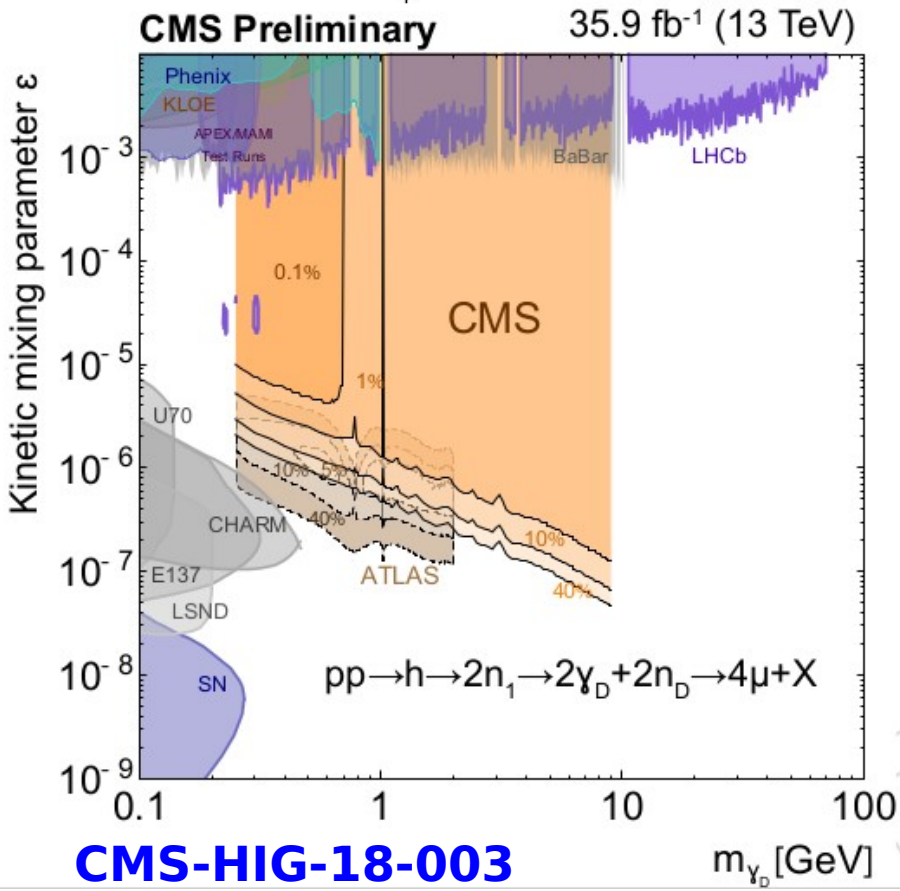


Exotic Higgs decays: h → 2a → 4μ

Run-2 (2016) data: 35.9 fb^{-1} @ 13 TeV

- Light boson decays to pair of opposite-sign muons
- Two benchmark models
  - NMSSM: a_1 is pseudo-scalar
  - Dark SUSY: γ_D is vector boson
    - long-lived if it mixes with photon → **displaced muons**
- Projections are being done in context of HL-LHC
- Also for other final states
  - h → 2a → 4τ, 2μ2τ, 2μ2b



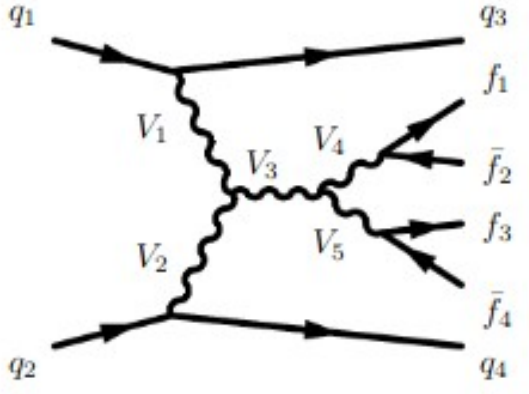


CMS-HIG-18-003

Same-sign WW + jj scattering

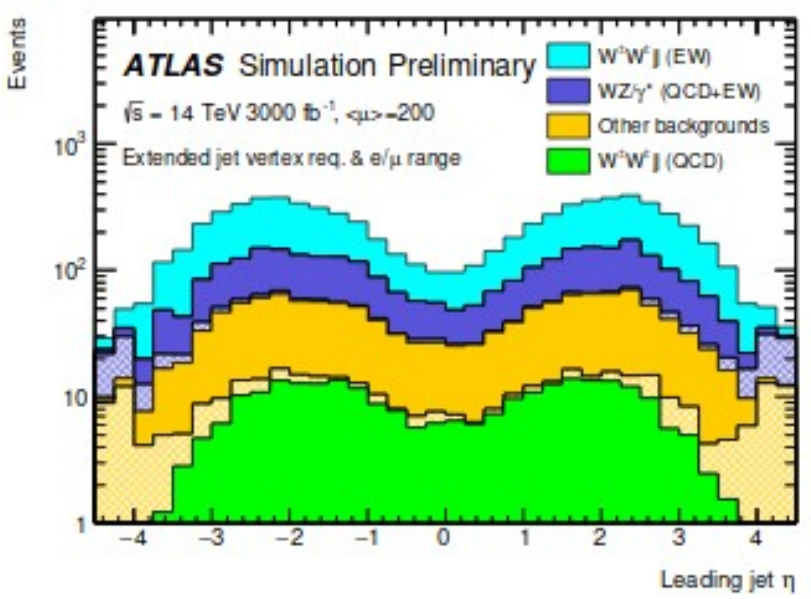
ATL-PHYS-PUB-2017-023

- **Does Higgs boson preserve unitarity for longitudinal VBS amplitude?**
  - VBS processes provide opportunity for precision studies of EWSB + serve as probe for BSM physics
- ATLAS studied effect of extended silicon tracker and a forward muon tagger (New Small Wheel) in 2.7 < |η| ≤ 4.
- Exactly 2 leptons (e,μ), >=2 jets, MET
- Cut-based projection with upgraded ATLAS detector



+ several other QCD & EW diagrams

	Z_σ				Z_σ
	ee	$e\mu$	μe	$\mu\mu$	Combined
No forward tracking	3.9	6.3	7.1	13	17
Forward tracking for jets only	3.8	6.1	7.0	13	16
Forward tracking for jets and electrons	3.9	6.2	7.1	13	16
Forward tracking for jets, electrons and muons	3.9	6.7	7.8	16	19



Wishlist for CERN YR18

	CMS	ATLAS	LHCb
Couplings Studies	✔✔★	✔✔★	
Differential CrossSections	✔★	✔★	
Width		✔	
Anomalous couplings	✔★	✔	
Rare Decays	**μμ,cc**	Zγ,J/ψγ,FCNC **μμ,ργ,cc**	**Hcc/Hbb**
Exotic Decays	**LFV; Invisible, DarkSusy; 4jets**		
DiHiggs	✔✔★	✔✔★	
Additional Scalars	A->Zh, **high mass ττ, low mass γγ**	μμ, ZZ, A->Zh, **ττ, WW**	

Legend: Past Studies, **2017 TDRs**, **Wishlist for 2018**

Higgs @ HL/HE-LHC - Autumn WG2 Meeting (https://indico.cern.ch/event/756370/)

Summary

- Broad Higgs & electroweak program at LHC
- Critical to carry out precision measurements and searches at future colliders to determine Higgs boson properties
- Important to understand the physics potential of Higgs boson at HL/HE-LHC
- Projections for measurements and searches are being compiled into the CERN Yellow Report to be made public in December