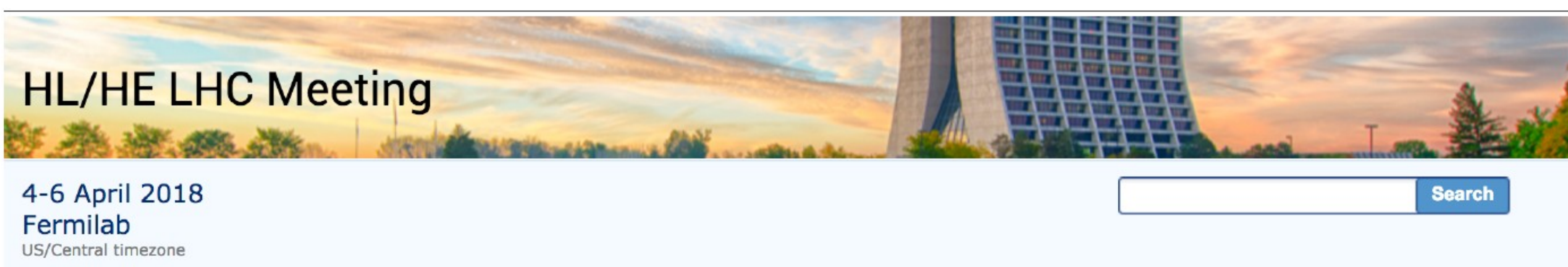
Higgs @HL/HE-LHC

S. Jézéquel (LAPP-IN2P3)

On behalf of the Higgs Working group (WG2)



Higgs target in 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 ($<\mu>= 200$) 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

WG2 - ¨Higgs and Electroweak symetry breaking¨

- Contacts :
  - Maria Cepeda (CMS), Philip Ilten (LHCb), Marumi Kado (ATLAS)
  - Theorists : Stefania Gori, Francesco Riva
- Informations : https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG2
- Mailing list to join effort: hllhc-wg2@cern.ch

Experimental timeline : 2016-2017

* Technical Design Reports (TDR) for sub-detector upgrades @ HL-LHC
  - Final detector optimisation associated with particle/object performances
  - Demonstrate benefit from detector upgrades on benchmarck physics channels (HL-LHC vs Run2 comparisons)
  - Analysis teams priority : Publish results with Run-2 data

→ Only few HL-LHC PUB notes

Experimental timeline : YR 18@ HL-LHC

* 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, ...

- Activity on theory side
  - Compute some inclusive and differential cross-sections @ 27 TeV
  - Estimation of physics achievements with detector performances assumptions
- Activity on experimental side
  - Reminder : Priority for LHC experiments is to complete HL-LHC prospects
  - → Only few selected analysis @ HE-LHC might be done by LHC exp. teams
    - HH : maybe
    - Others : probably not
- Contribution only as extension of HL-LHC approach assuming same detector performances even if :
  - Pileup per bunch-crossing **: 200** (HL-LHC) → **800** (HE-LHC)
  - Completly different detectors

Experimental timeline : Meetings

- Meetings among experiments : Already started
  - List analysed physics channels per experiment
  - Define coherent approach among experiments to prepare combination
    - Common data format
    - Build conservative and optimistic scenarios for experimental systematics uncertainties
  - First target : Apply this approach in Proto PUB notes

* **Vol. 1 : Synthesis of results (150 pages)**

  1. **Introduction**
  2. **Precision Higgs physics**
  3. **Di-Higgs production and Higgs self coupling**
  4. **Other high energy probes**
  5. The Higgs boson mass and width
  6. Invisible decays of the Higgs boson
  7. **Higgs flavor and rare decays**
  8. Global view with HE/HL-LHC
  9. **BSM Higgs**
  10. **Conclusions and outlook**

* **Vol. 2 : Collection of PUB notes**

Adressed in this presentation

Others in backup

Detailed outline

in WG2 Twiki

Disclaimer

- Quick review of subjects adressed in this workshop

- More detailed presentations during the Higgs session

More in J. Campbell talk

1. Collaboration with LHC Higgs XS WG

* Platform for publication of most precise SM cross-section computations
  * Present LHC studies (13 TeV)
  * Future HL-LHC (14 TeV) / HE-LHC (27 TeV)

* Overlap between SM (WG1) and Higgs

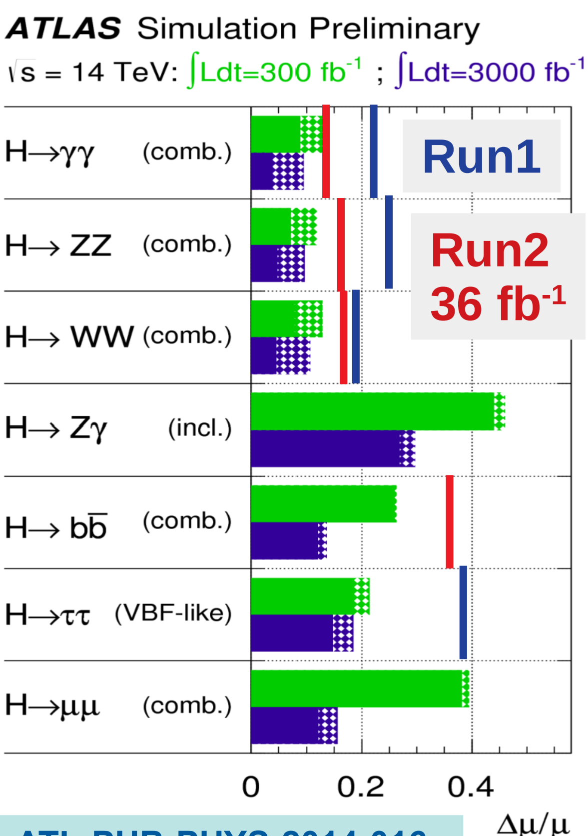
* First meeting with Steering Commitee last January
* Open meeting last week at CERN (link)

* Coordinated effort to decide on TH systematics scenarii
  * Define conservative/optimistic scenarios

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

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

SM coupling precision κ : few % level



ATL-PUB-PHYS-2014-016 + Run-1/Run-2 publications

CMS: arXiv:1307.7135v2

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]

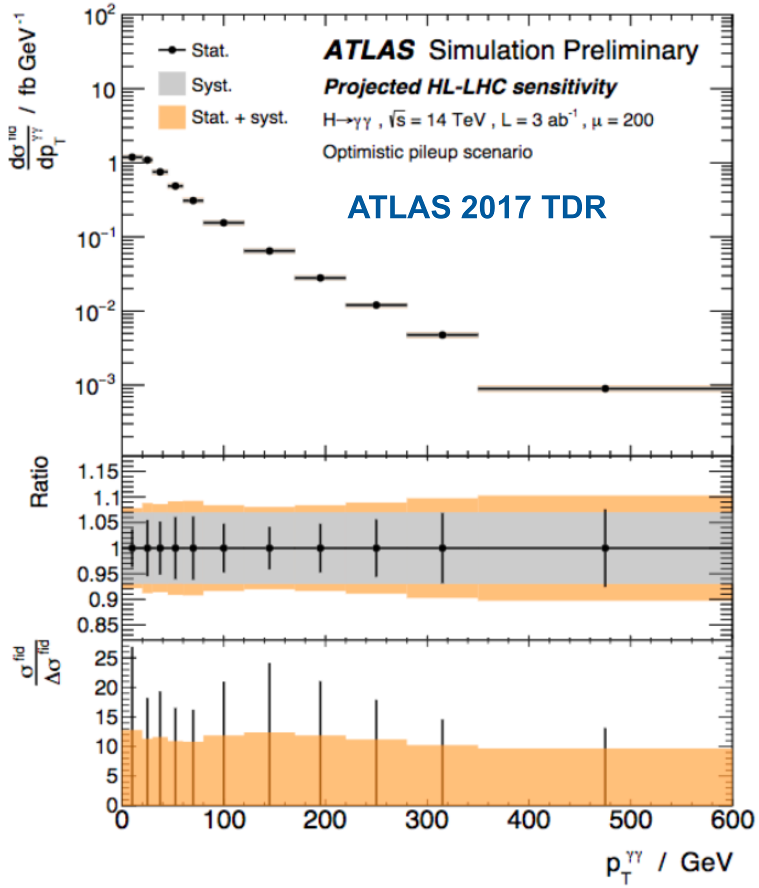
(%)

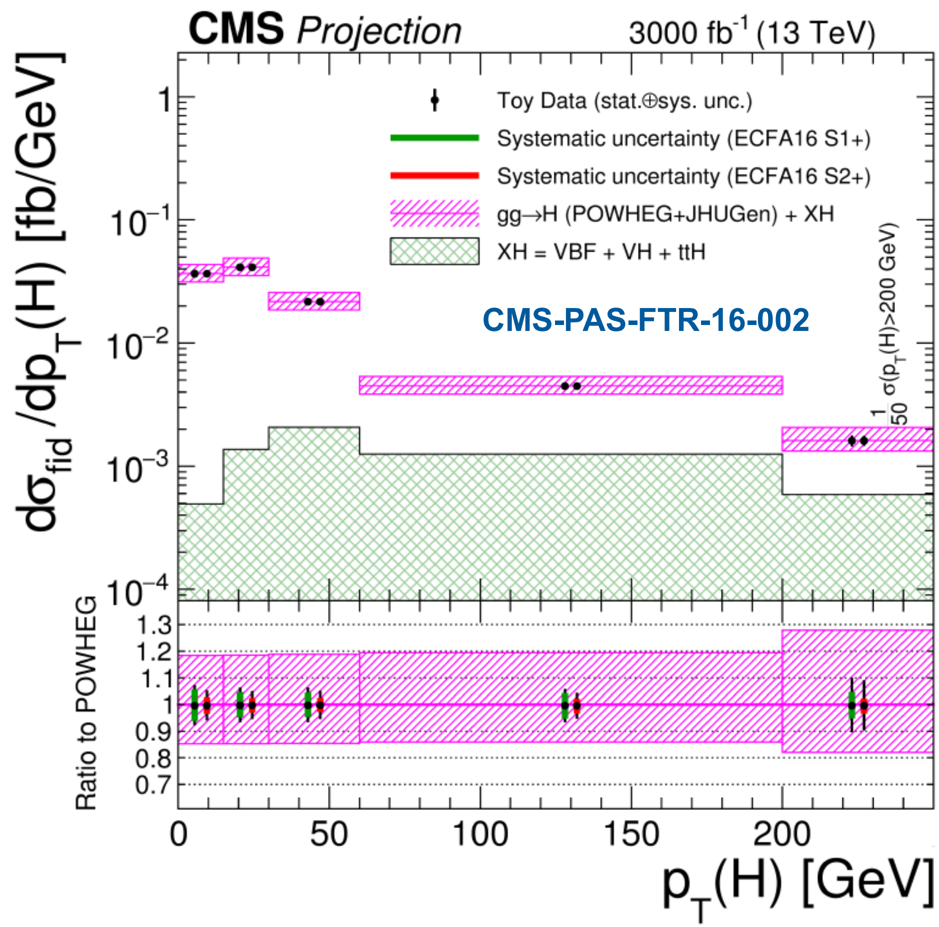
* YR18 : Rerun extrapolation from Run-2 results
  - μ, κ, κ ratios (not syst limited)
  - Expect significant gain

* Previous extrapolations dominated by systematics
  - TH/ Exp syst. scenarios to be revisited
    - Example : ggF NNLO → N3LO (G. Salam talk in ECFA 16)
      - Unc. QCD scale : (+7.4,-7.9) → 3.9 %
      - Unc. PDF + α_s : (+7.1,-6.0) → 3.2 %

2. Differential cross-section

- Benefit from large dataset and go beyond inclusive measurement

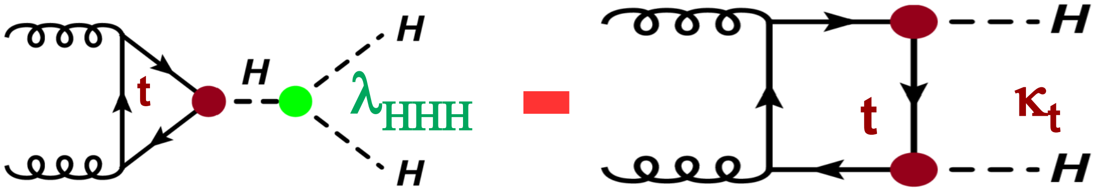




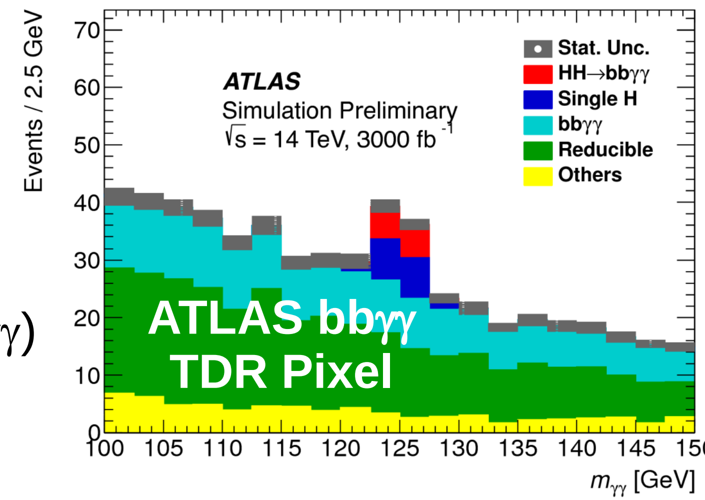
- Sensitive to κ_b/κ_c (low p_T) and κ_t/BSM (high p_T) with statistical limitation
- YR 18 : Combination between experiments and interpretation

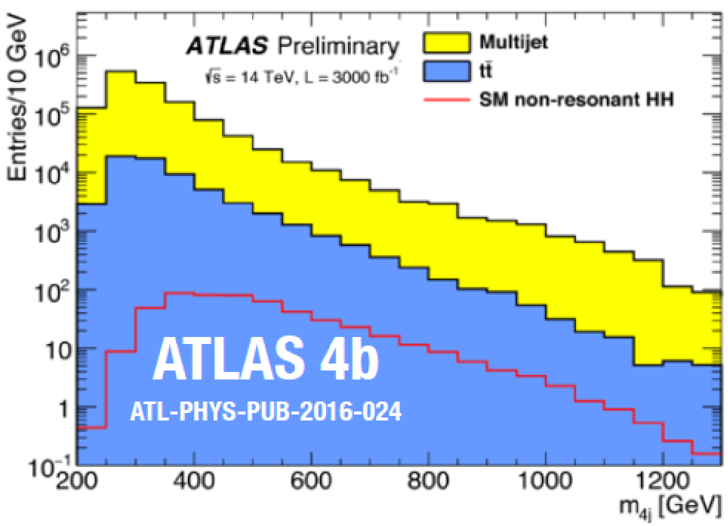
C. Vernieri, P. Bokan, M. Ramsey-Musolf

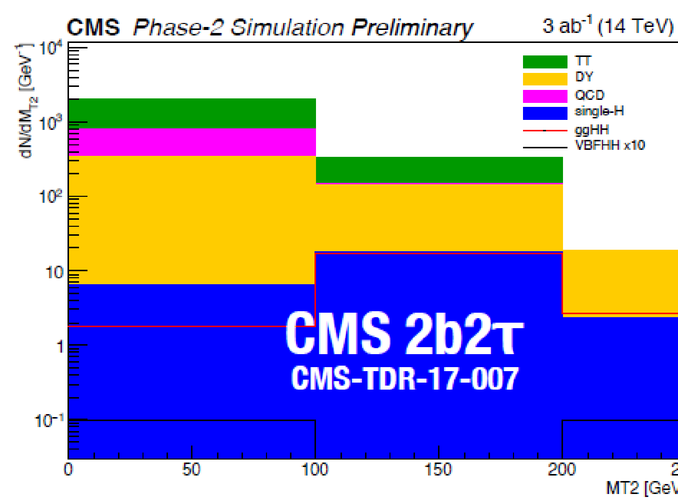
3. DiHiggs @ HL-LHC



- Context :
  - 120 k events produced
  - High background (bbbb, bbττ)or low B.R. (bbγγ)
- Targets :
  - First observation of HH production
  - Measure λ_{HHH} and κ_t (top-Yukawa coupling)







- Strong dependance on p_T(4jets) trigger threshold
- Precision limited by QCD multijet uncertainty

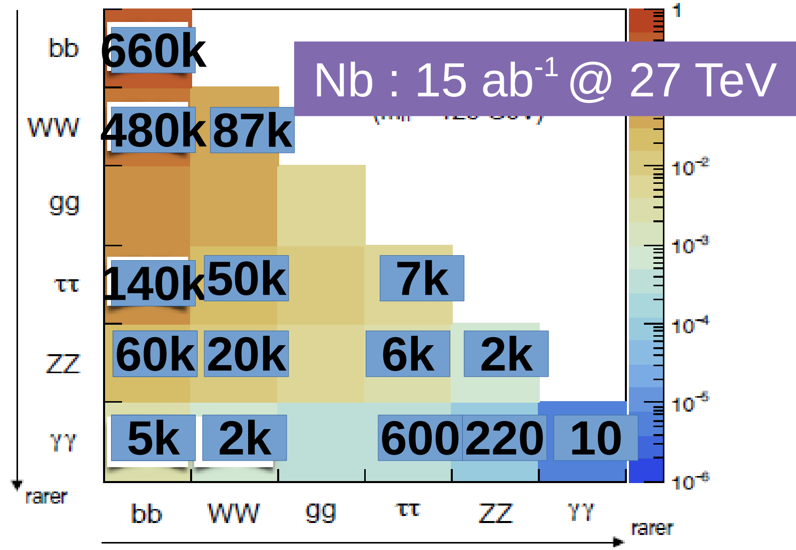
3. DiHiggs @ HL-LHC (2)

Channel	CMS	ATLAS
$HH \rightarrow bbbb$	$Z(\sigma_{HH}(SM))=0.39\ \sigma$	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L.
$HH \rightarrow bb\tau\tau$	1.6 xSM	$0.6\ \sigma$ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L.
$HH \rightarrow bb\gamma\gamma$	$1.43\ \sigma$	$1.5\ \sigma$ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only)
$HH \rightarrow WWbb$	$0.45\ \sigma$	
$tt(HH \rightarrow bbbb)$		$0.35\ \sigma$

- Most results will be updated for YR18 mainly based on Run2 extrapolation
  - Improve significance for HH production
  - Benefit from kinematic distributions (m_{HH}) for couplings (λ,...)
- Combination to be done: Channels and experiments (+ single H ?)

S. Homiller

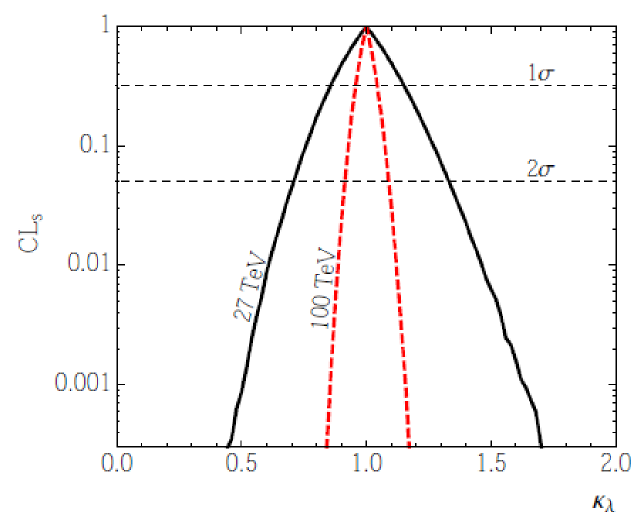
3. DiHiggs @ HE-LHC



* 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→ bb$\gamma\gamma$

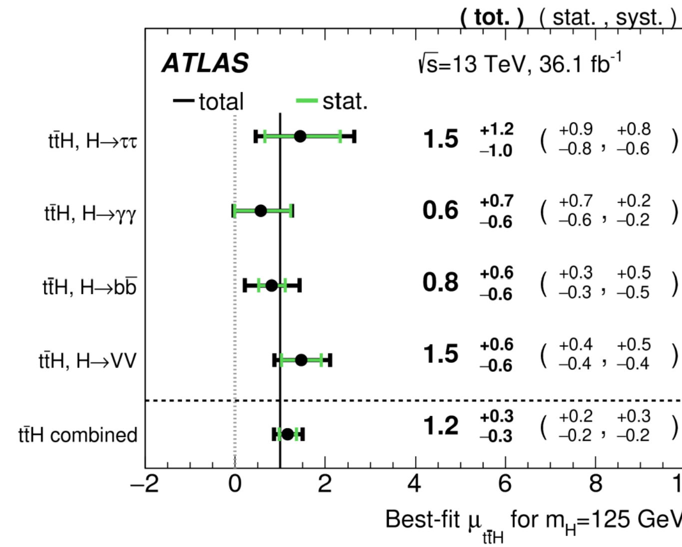


A. Calandri, C. Wagner

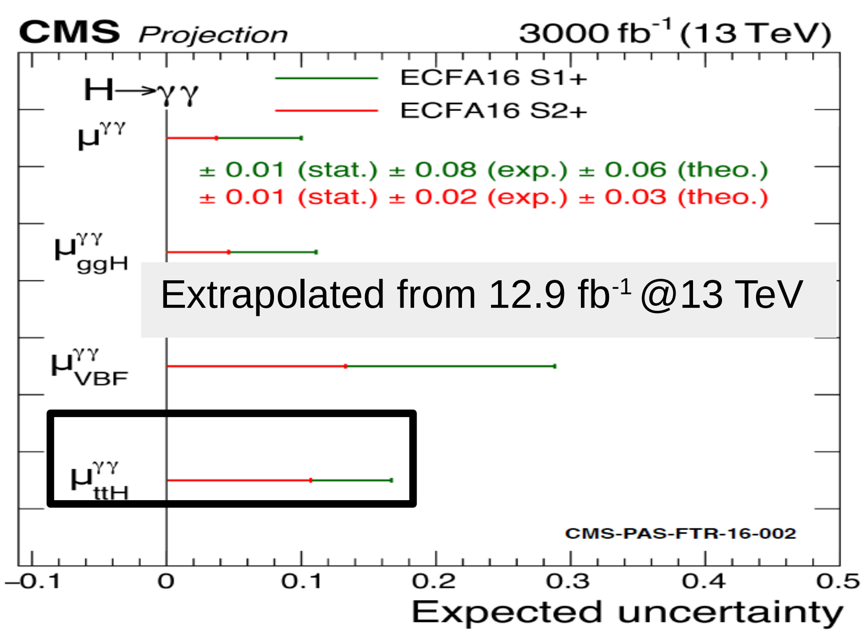
4. ttH : Top-Higgs Yukawa coupling

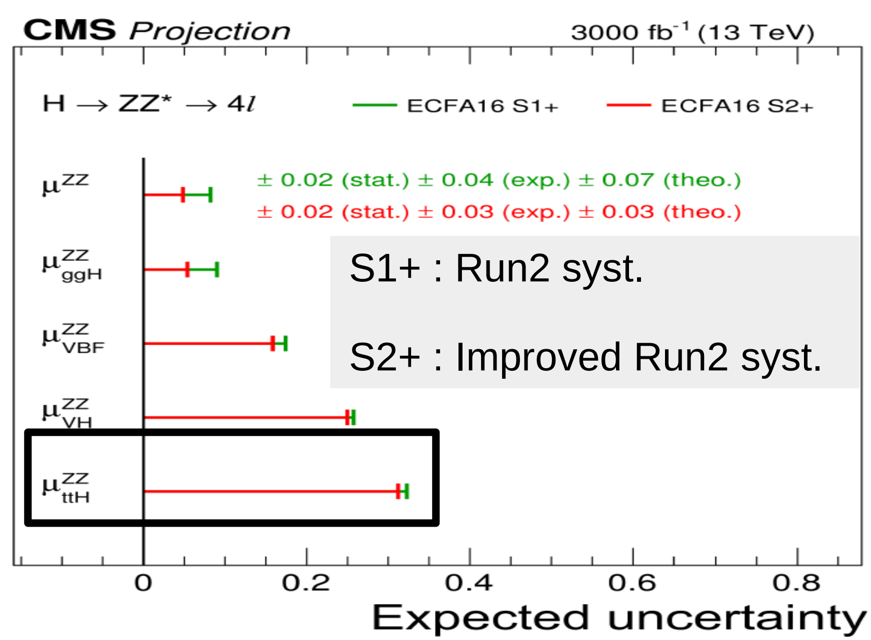
- Benchmark channel for HL-LHC
- First evidence of ttH production with Run-2 data (ATLAS+CMS)

- Adressing systematics uncertainties : critical
- YR 18 : Complete overview of decay channels



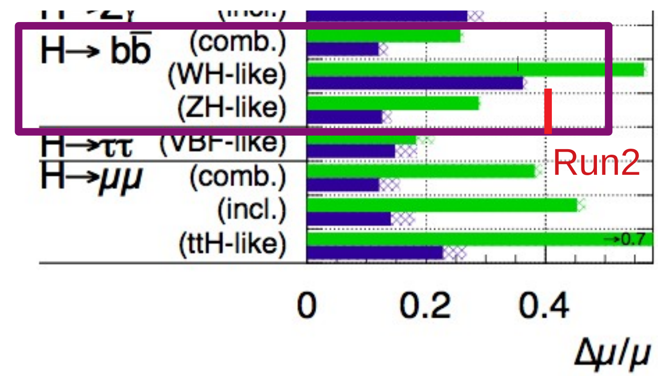
ArXiv :1712.08891



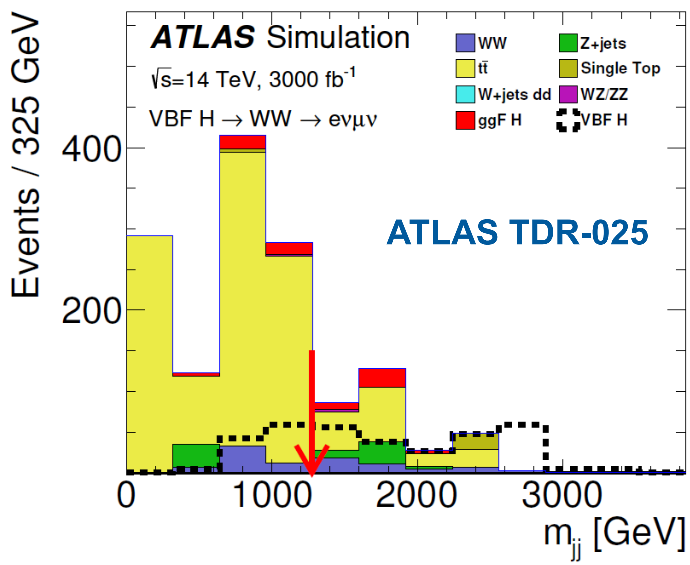


* VH : First observations @ Run-2
  - ATLAS : $\mu=1.20^{+0.42}_{-0.36}$ **JHEP 12 (2017) : 024**
  - CMS : $\mu=1.06^{+0.31}_{-0.29}$ **Phys. Lett. B 780 (2018) 501**

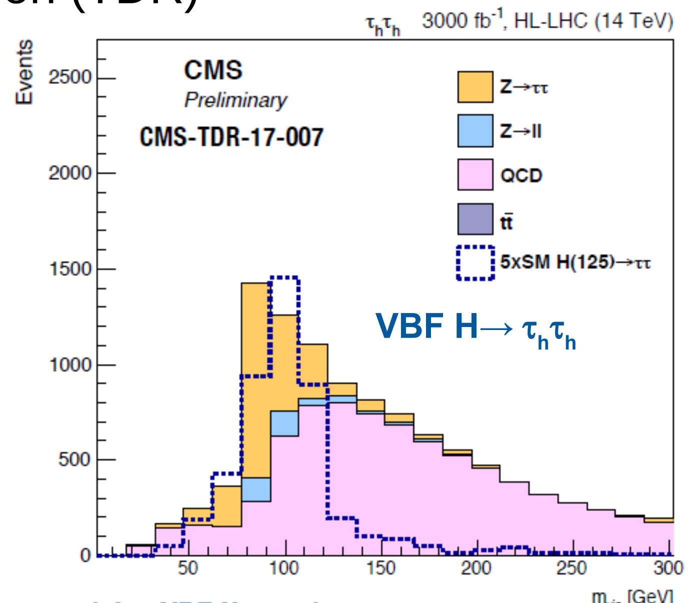
ATL-PUB-PHYS-2014-016 (HL-LHC)



* Vector Boson Fusion/Scattering :
  - Probe for ElectroWeak Symmetry Breaking
  - Benchmark for forward detector optimisation (TDR)

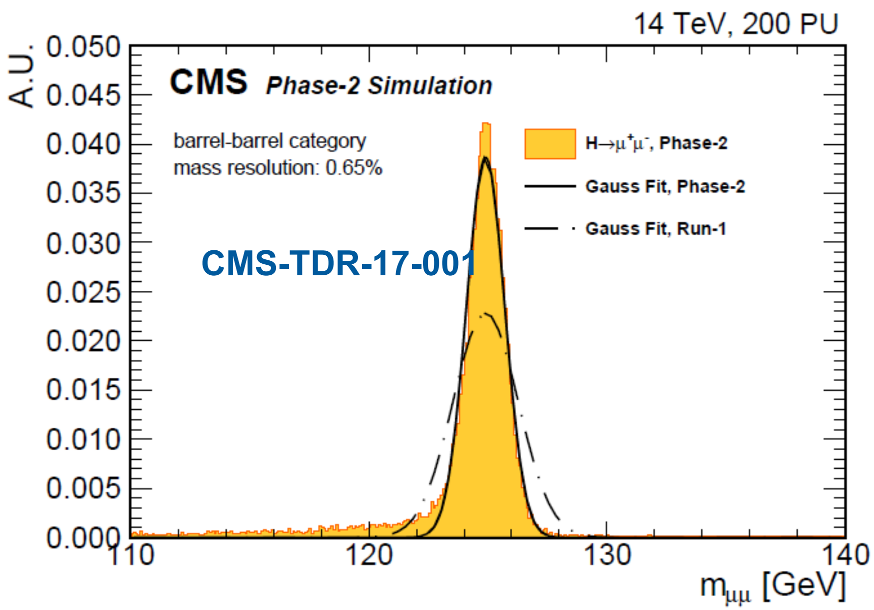


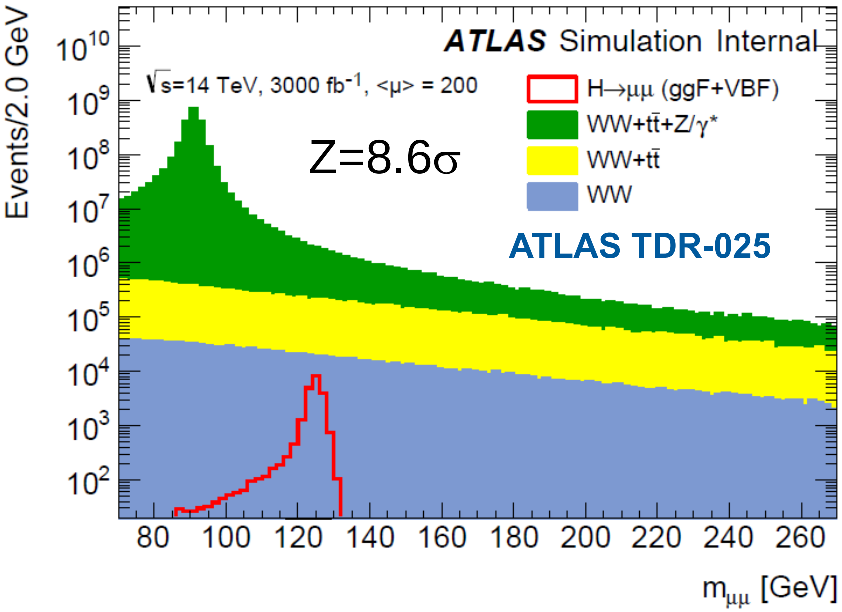
VBF ZZ→ 4 l : ATL-PHYS-PUB-2016-008



(also VBF H->γγ)

- Probe for fermion of second generation
- 0.02 % branching ratio

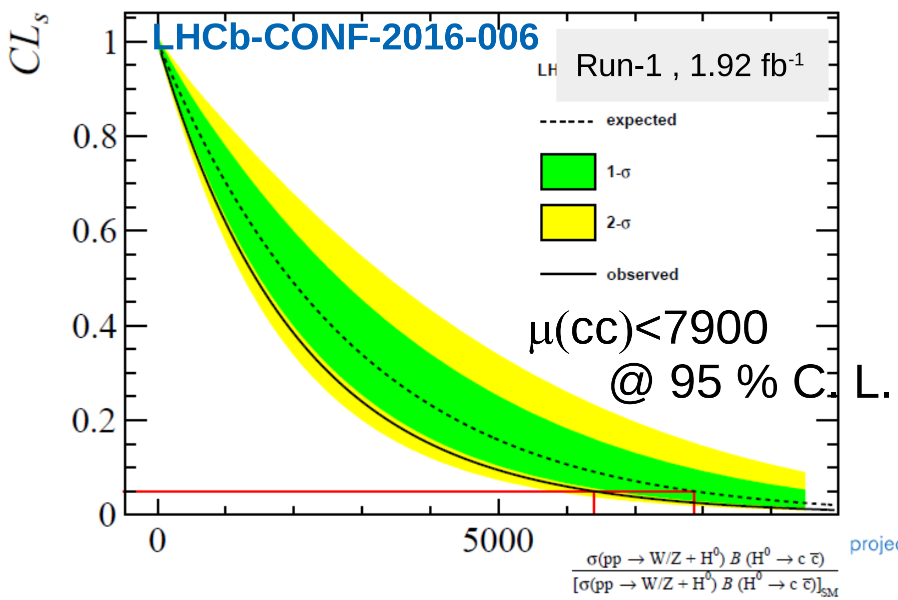


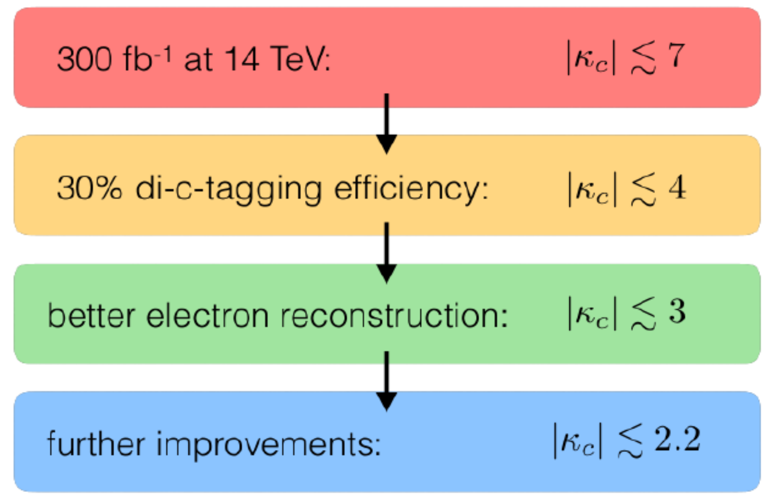


- Benchmark for detector upgrade
- Run-1 → Phase 2: Gain 65 % in $m_{\mu\mu}$

- Expected precision: $\mu \sim 8$ % / κ_{μ}~5 %

- Search for leptonic W/Z+ H→ bb/cc final states (Forward production)
- LHCb angular acceptance → Challenging for integrated cross sections and uncertainties

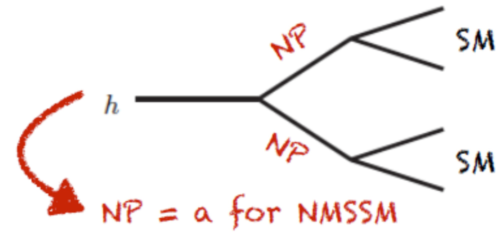




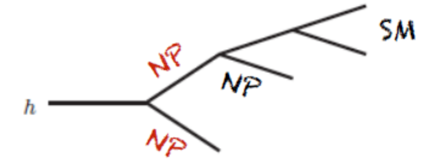
projections taken from talk by Mike Williams

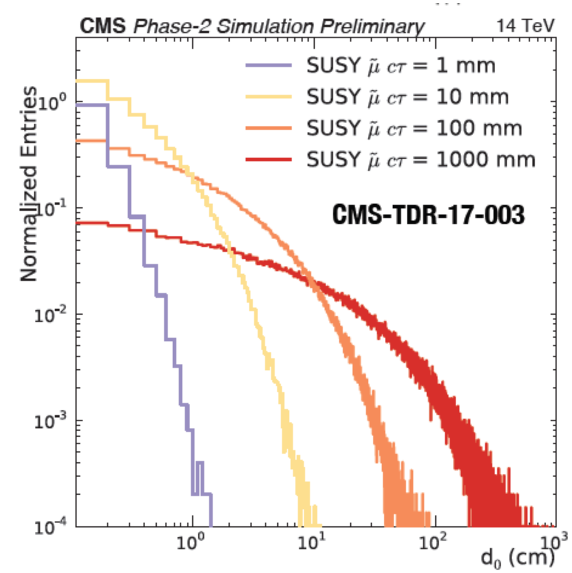
- First publication H→cc from LHCb → Possible reach 5 xSM @ 300 fb^{-1}
- Extrapolation H → J/Ψ γ @ HL-LHC : 15 xSM @ 3000 fb^{-1} (ATLAS)
- ZH→ cc @ Run-2 (arxiv:1802.04329): μ < 110 (150^{+80}_{-40}) @ 95 % C.L. (ATLAS)

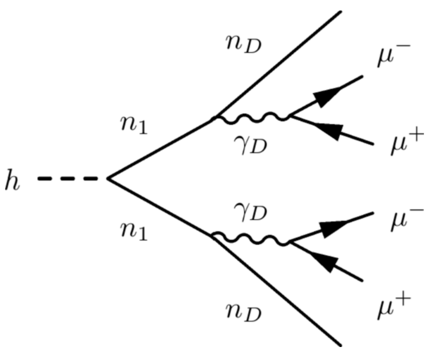
* B.R. (H → exotics) still allowed at 5 % level by Higgs fits @ HL-LHC

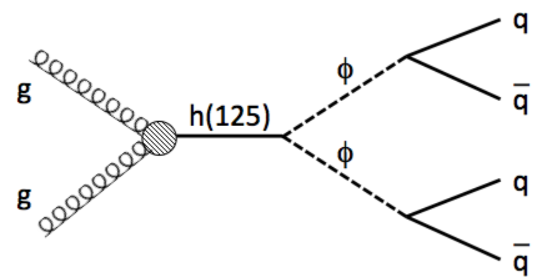


* Many Run-2 analysis published recently targeting new exotic decays but extrapolations to HL-LHC still to be done
  - Invisible
  - Lepton Flavor Violation (LFV)
  - Displaced vertices



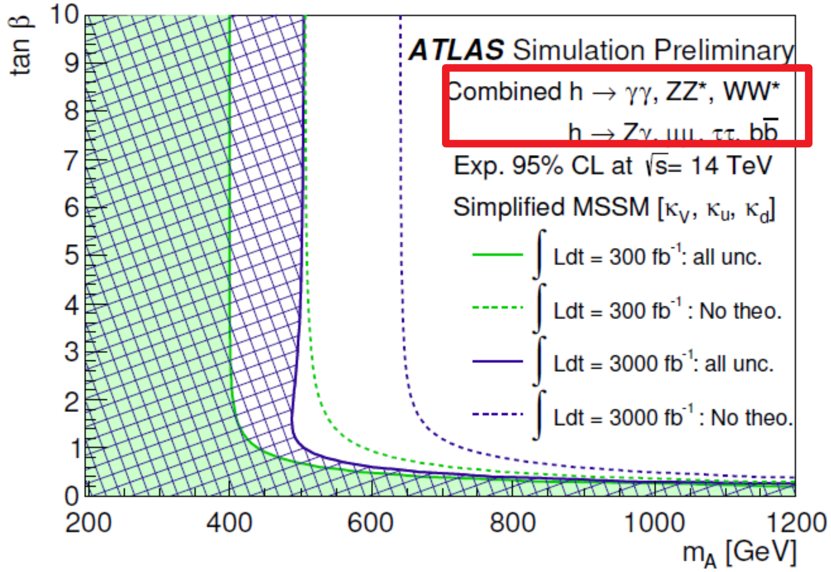




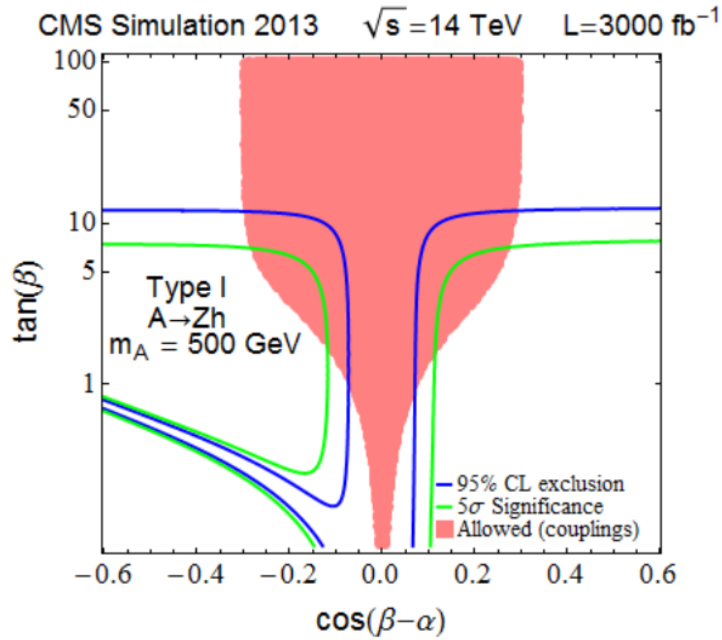


* Existing prospects for direct searches : $H \rightarrow \mu\mu$, $H \rightarrow \tau\tau$, $A \rightarrow ZH$

ATL-PHYS-PUB-2014-017



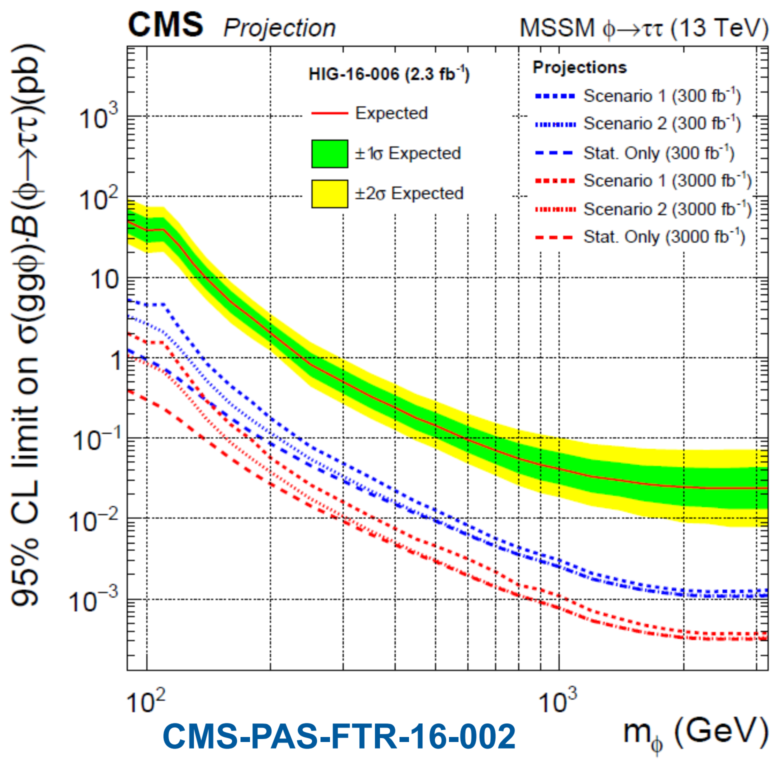
CMS-PAS-FTR-13-024



* Results revisited with Run2 expertise
* Not done
  - Search for scalars in other final states (ex : Low mass $\gamma\gamma$)
  - Search for $H \rightarrow t\bar{t}$

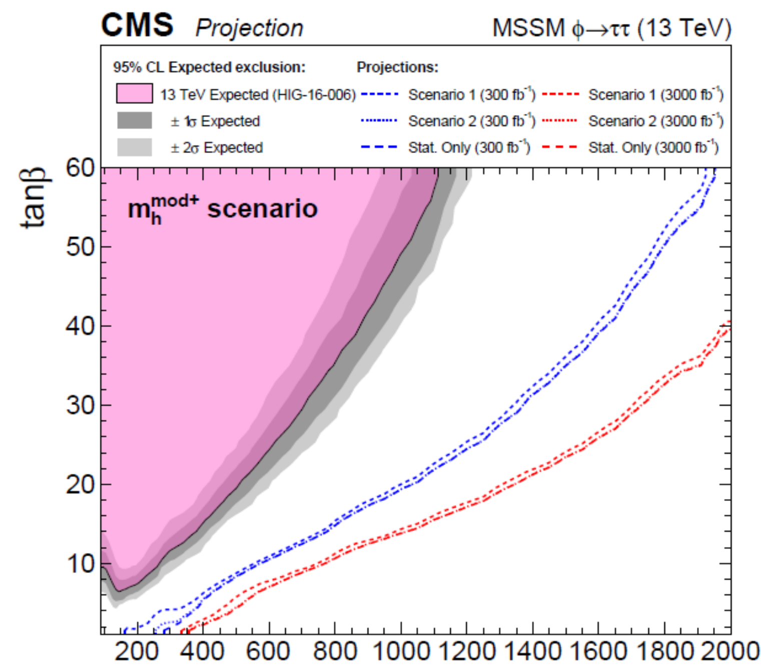
- Most sensitive final state for direct search of additional Higgs boson predicted by MSSM

Model independent : limit on ggF or bbH



CMS-PAS-FTR-16-002

Model dependent : m_A-tanβ



CMS-PAS-FTR-16-002

Limited by statistics especially at high mass

Expected coverage by LHC experiments

	CMS	ATLAS	LHCb
Couplings Studies	✔✔★	✔✔★	
Differential CrossSections	✔★	✔★	
Width		✔	
CPV	✔★	✔	
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

Courtesy M. Cepeda

Higgs at LHeC : U. Klein

Stay tuned : CMS public page , ATLAS public page

- HL-LHC : First Higgs factory
  - Higgs couplings and differential cross-sections : Precision regime
  - Rare decays accessible
  - Probe to New Physics
  - 2012-2014: First attempt to estimate Higgs physics potential (Run-1 based)
  - 2016-2017 : Transition period (Upgrade TDRs, Run-2 analysis, theory dev.)
    - Source of many improvements
  - 2018 : Common effort to :
    - recompute expected Higgs physics performances
      - Define conservative and optimistic scenarios for syst. uncertainties
    - → Document results in YR18

- HE-LHC physics potential: Based on scratch program recycling HL-LHC tools

Presentations in Higgs session :

Opportunity for lively discussions → Input for final work

Backup

Sections of Higgs chapter

1. **Introduction: Main goals and timeline**

2. **Precision Higgs physics**
   1. Channels reach in diboson decays, including fiducial and differential measurements.
   2. Channels reach in main Yukawa couplings, including fiducial and differential measurements.
   3. Special focus on direct and indirect probe of top Yukawa coupling
   4. Progress on TH uncertainties: what to expect?
   5. Impact from PDFs and alphaS on Higgs measurements.
   6. Progress on Higgs specific MC.
   7. Higgs couplings precision overview.
   8. Probes using differential distributions of CP sensitive observables (and other dimension -6).
   9. Interpretation in terms of Composite Higgs and the MSSM.

3. **Di-Higgs production and Higgs self couplings**
   1. SM calculation
   2. Double Higgs measurements and trilinear coupling.
   3. Indirect probes of the trilinear coupling through differential distributions measurements.
   4. Indirect probes through single Higgs boson production.
   5. Theory Implications (including a critical view of the validity of direct and indirect trilinear couplings measurements.

4. **Other high energy probes**
   1. Measuring Offshell couplings
   2. tth differential measurements
   3. WH/ZH at high energy/luminosity
   4. WW WZ at high energy/luminosity
   5. VBF
   6. longitudinal VBS and di-higgs

5. **The higgs boson mass and width**
   1. Theory review
   2. Measurement of the Higgs boson mass.
   3. Mass shift from the diphoton interference: constraints on the width.
   4. Direct constraints from the Higgs boson lineshape.
   5. Direct constraints from the Higgs boson lifetime measurements.
   6. Width from Off-Shell higgs boson coupling.
   7. Width from the diphoton interference rate.

6. **Invisible decays of the Higgs boson**
   1. Main channels for direct searches.
   2. Interpretation and combination with precision Higgs boson measurements.
   3. Higgs portal interpretations.

7. **Higgs flavor and rare decays**
   1. Flavor aspects Yukawa modifications in flavor models
   2. Exclusive Higgs decays
   3. Flavor tagging (charm and strange) exp mostly
   4. LFV decays of the Higgs exp mostly (CMS can try to cover this)
   5. Yukawa constraints from Higgs distributions
   6. CP violation in Higgs couplings (tau, ttH) exp mostly.

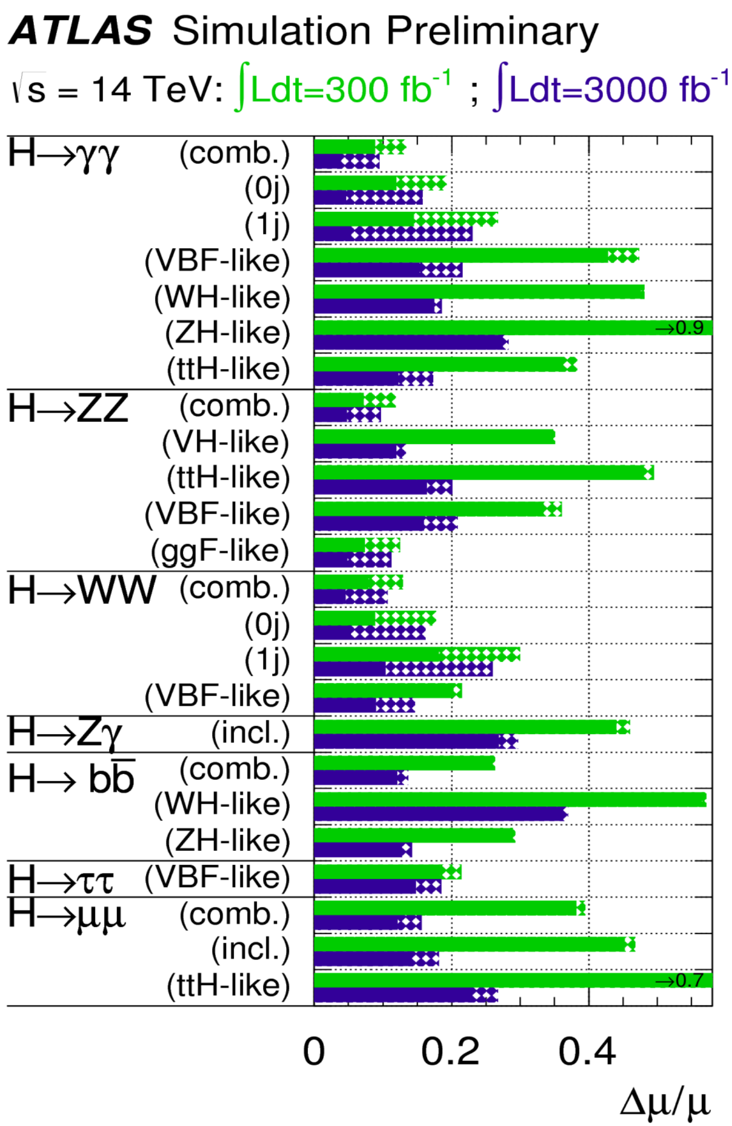
8. **BSM Higgs**
   1. Searches for additional Higgs bosons in fermionic final states (taus, b's, muons and tops)
   2. Searches for additional Higgs bosons in diboson final states.
   3. Searches for intermediate mass Higgs bosons (60 GeV - 120 GeV)
   4. Searches for low mass Higgs bosons (up to 60 GeV).
   5. Covering the MSSM, 2HDMs and the NMSSM, composite Higgs.
   6. Searches for unconventional signatures of additional Higgs bosons
   7. Searches for exotic decays of the Higgs boson

9. **Conclusions and outlook**

ECFA scenarios

- https://cds.cern.ch/record/2266165/files/FTR-16-002-pas.pdf

- **ECFA S1 :** All systematic uncertainties are kept constant with integrated luminosity. The performance of the CMS detector is assumed to be unchanged with respect to the reference analysis;
- **ECFA S1+ :** All systematic uncertainties are kept constant with integrated luminosity. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account [4];
- **ECFA S2 :** Theoretical uncertainties are scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are not taken into account;
- **ECFA S2+ :** Theoretical uncertainties scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account [4].

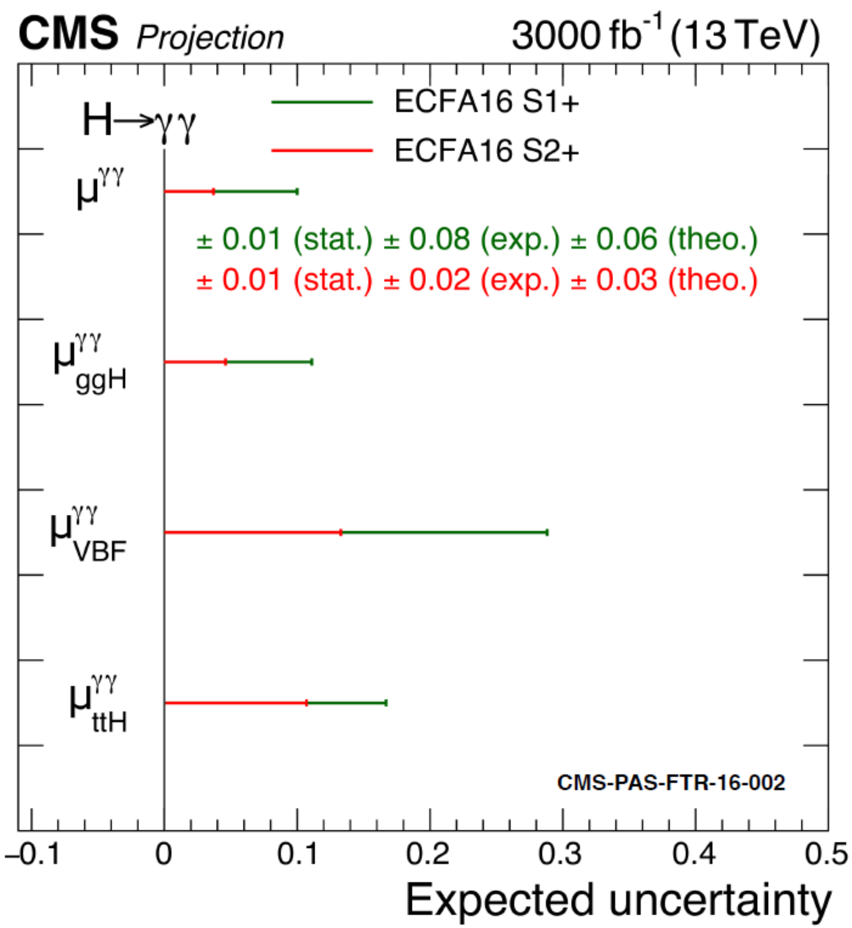


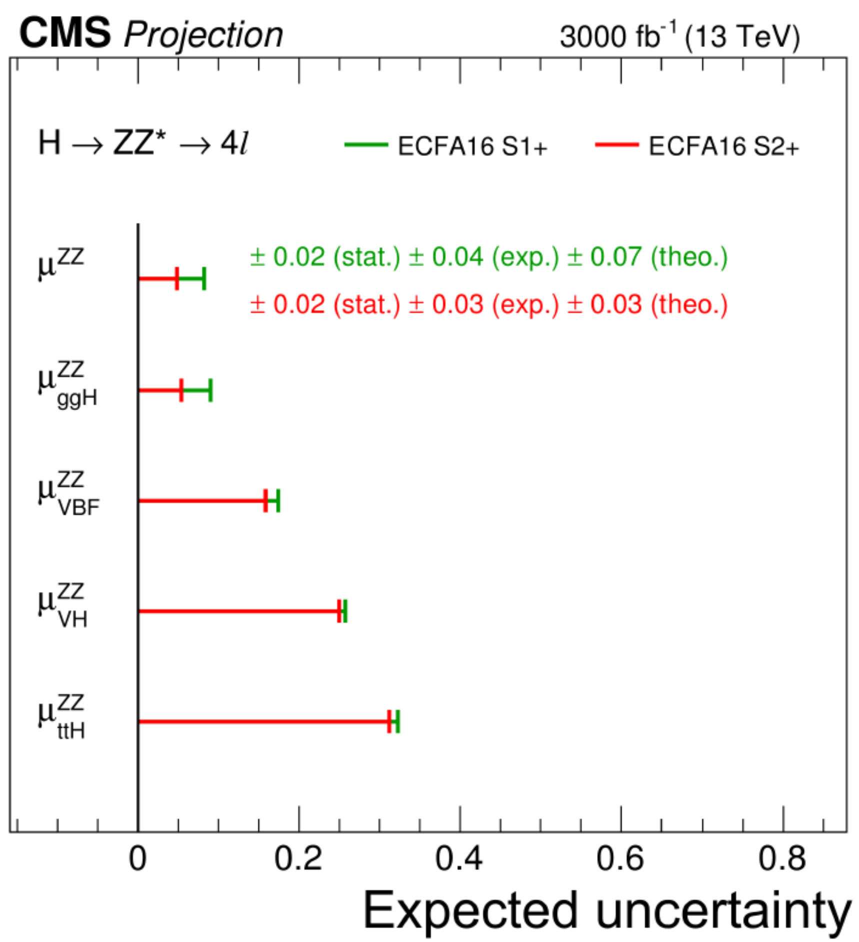
Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by ≲10% for 300 fb^{-1}			by ≲10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
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

ATL-PUB-PHYS-2014-016

Update based on 12.9 fb^{-1} of data at 13 TeV

Effect of high pileup and detector performance considered based on the CMS Upgrade TP (LHCC-P-008)





2.Cross-sections @Run2 : H→ ZZ and H→ γγ

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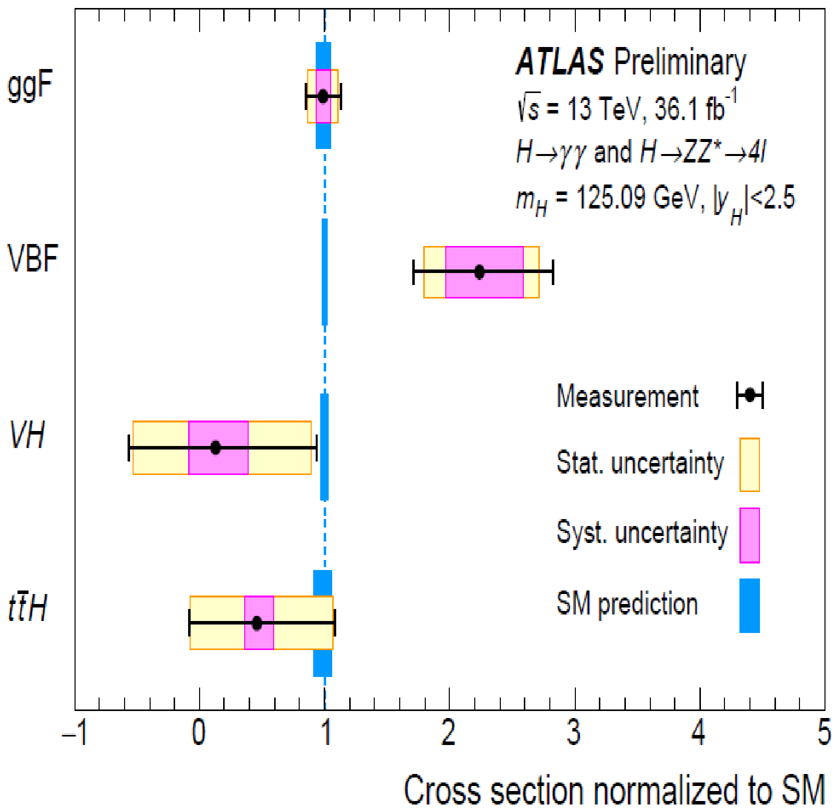
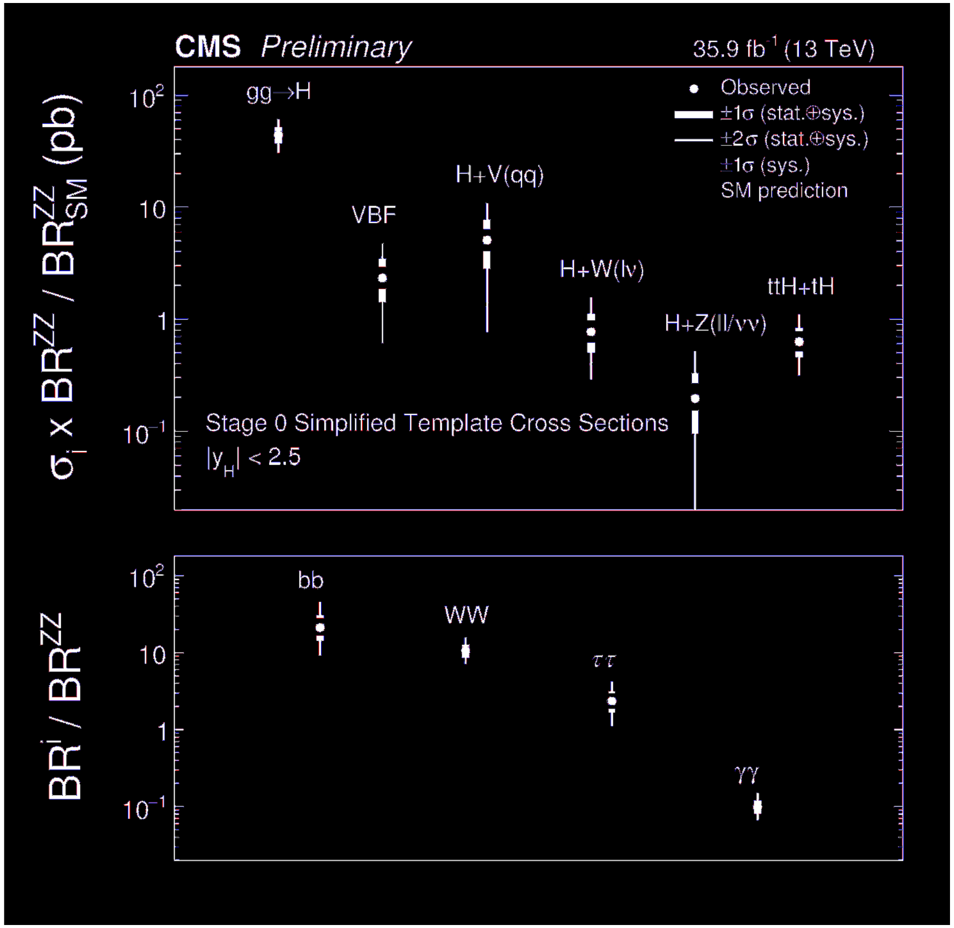
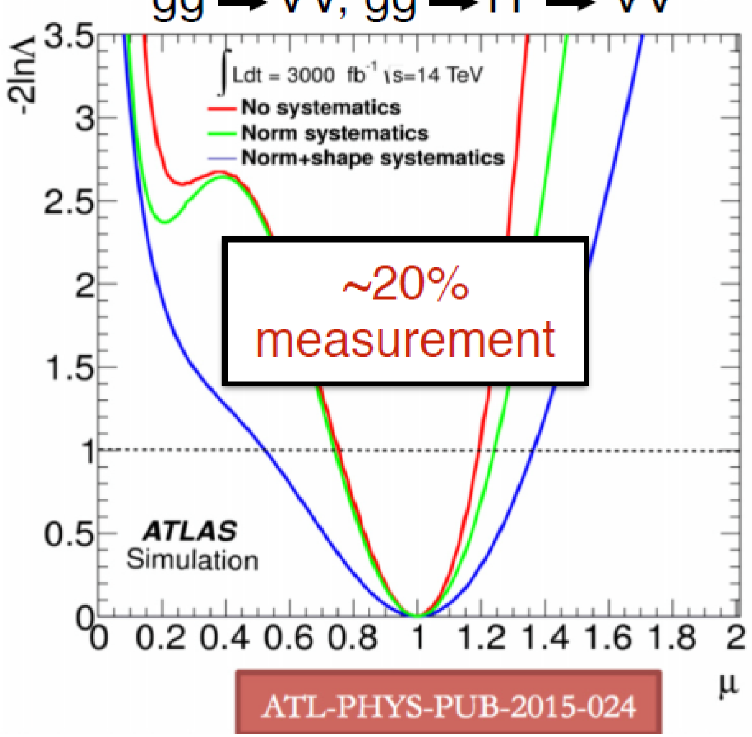


CMS-PAS-HIG-17-031



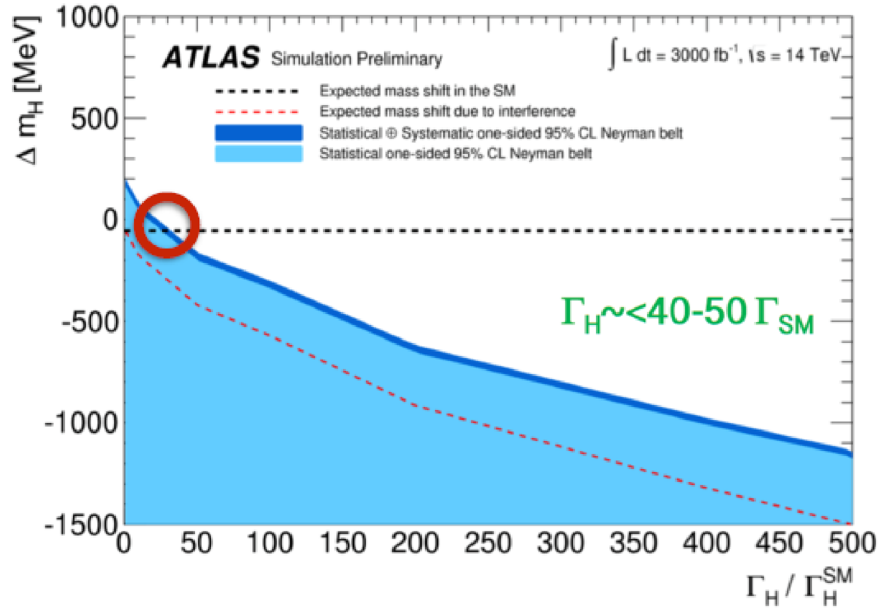
Off-shell measurements

gg → VV, gg → H* → VV



Interference in

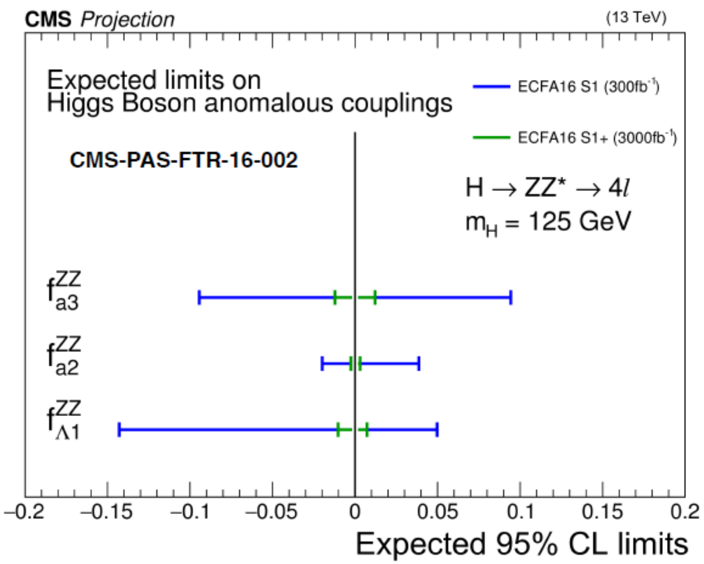
gg → γγ, gg → H → γγ

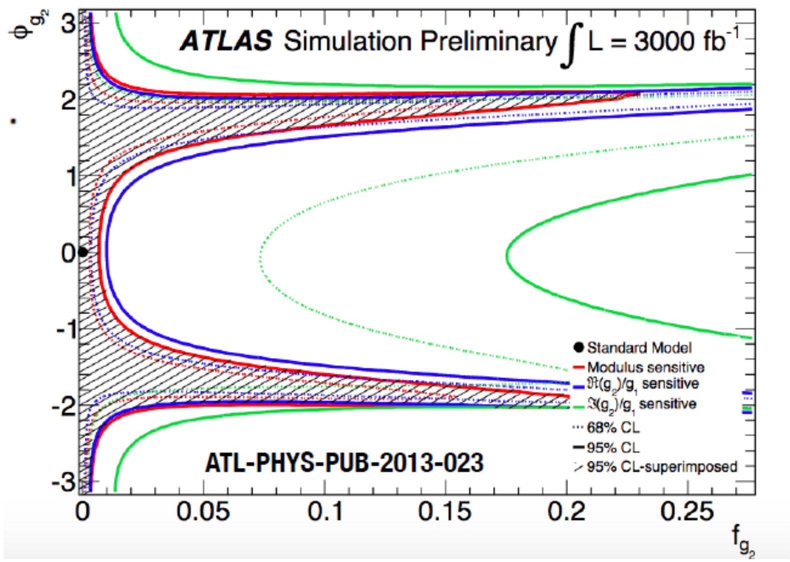


$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}.$$

SM

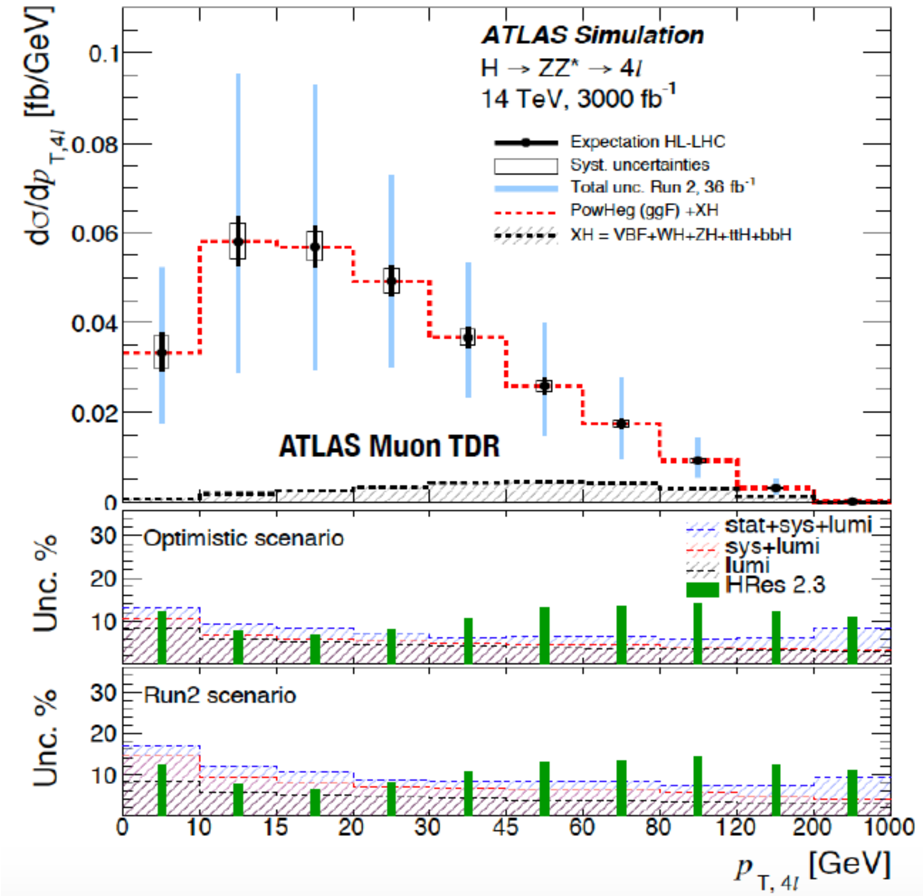
- Parametrisation of anomalous couplings : $f_{ai} = |a_i|^2 \sigma_i / \sum |a_j|^2 \sigma_j \quad \phi_{ai} = \arg(a_i/a_1)$

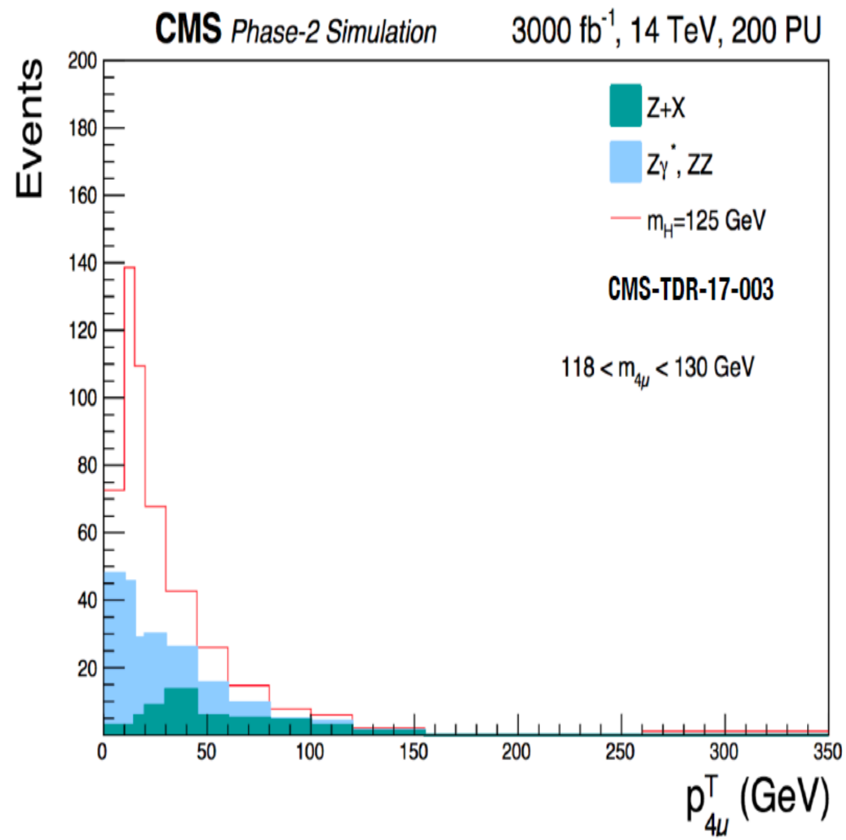




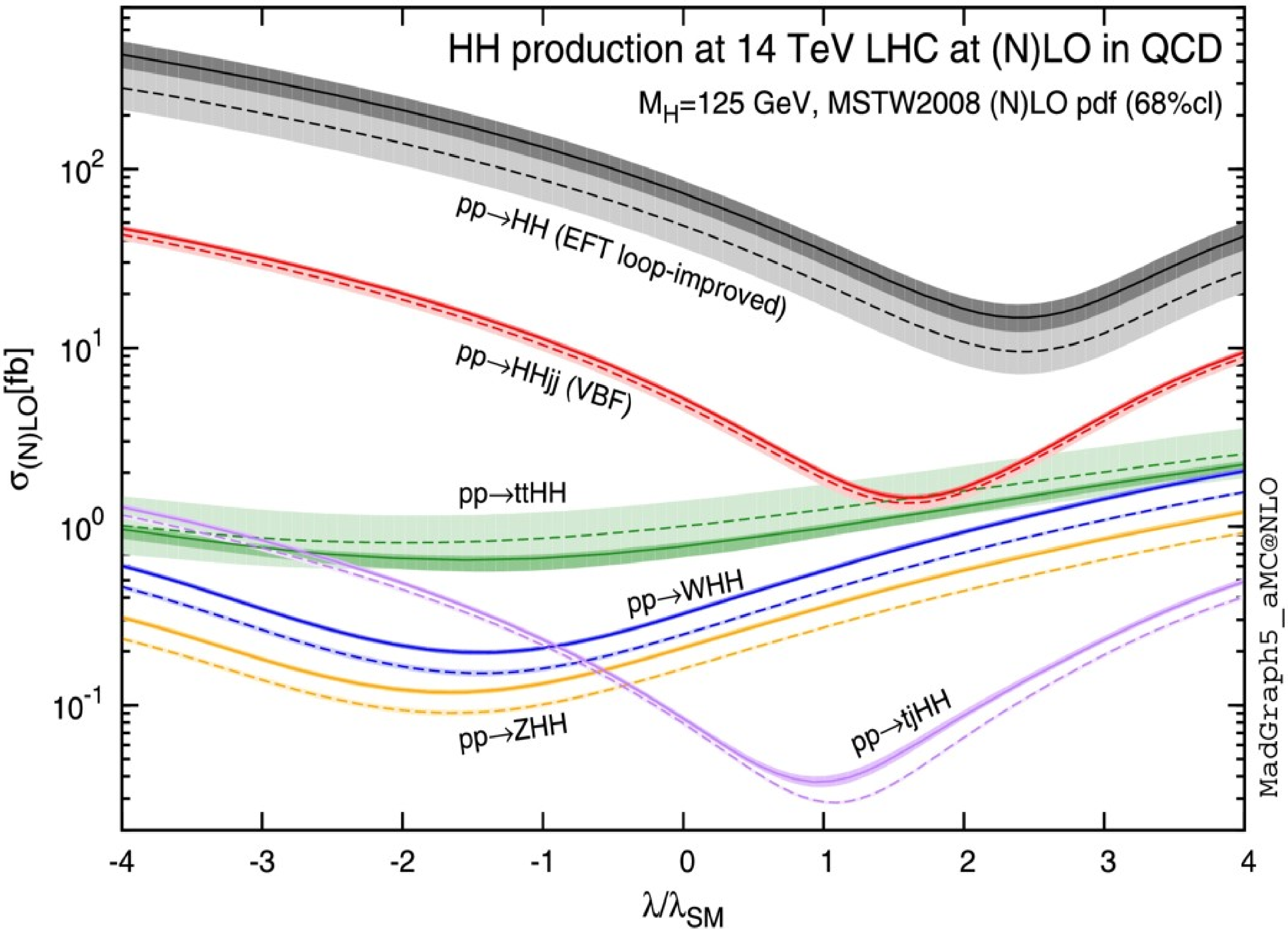
- Reach percent level but still stat. limited

2. Differential xsection

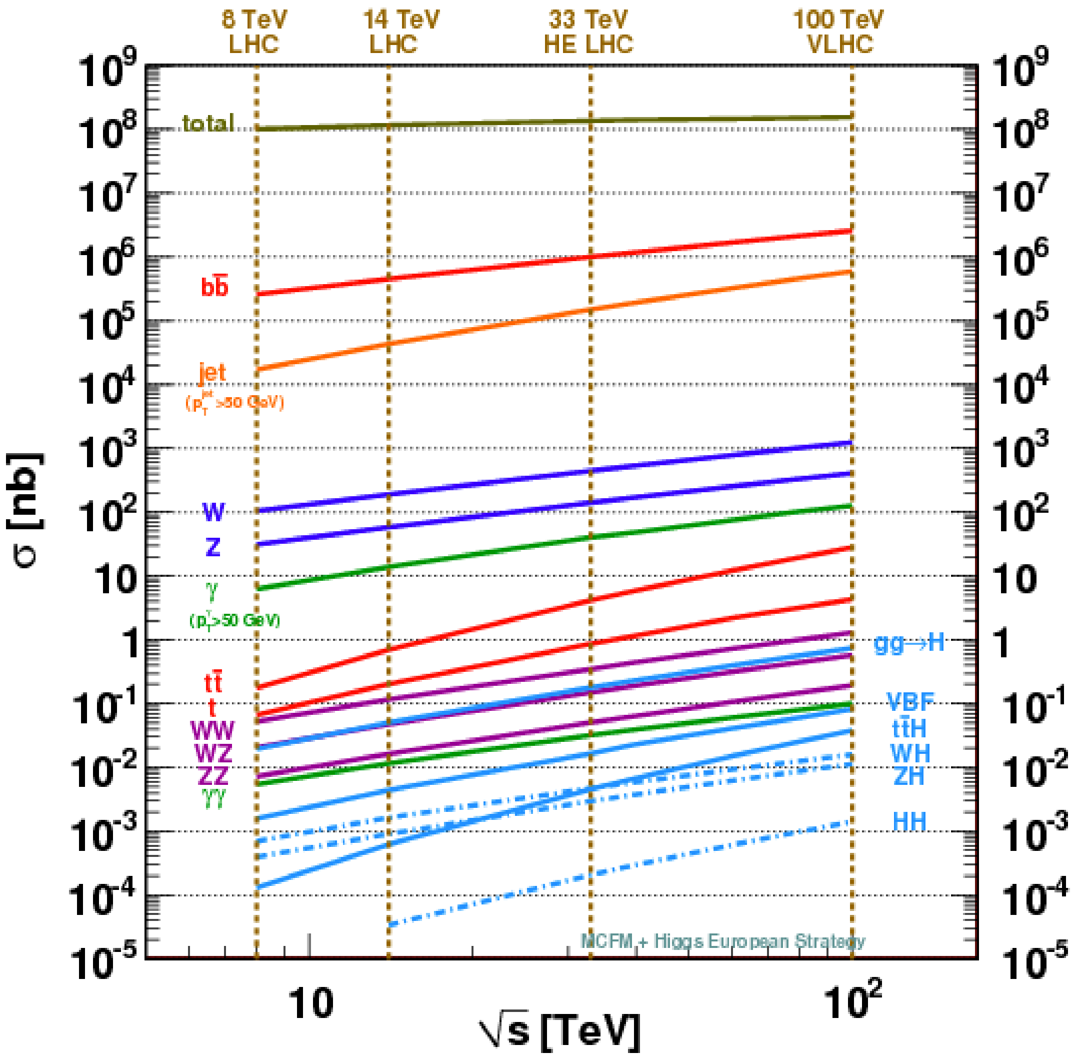




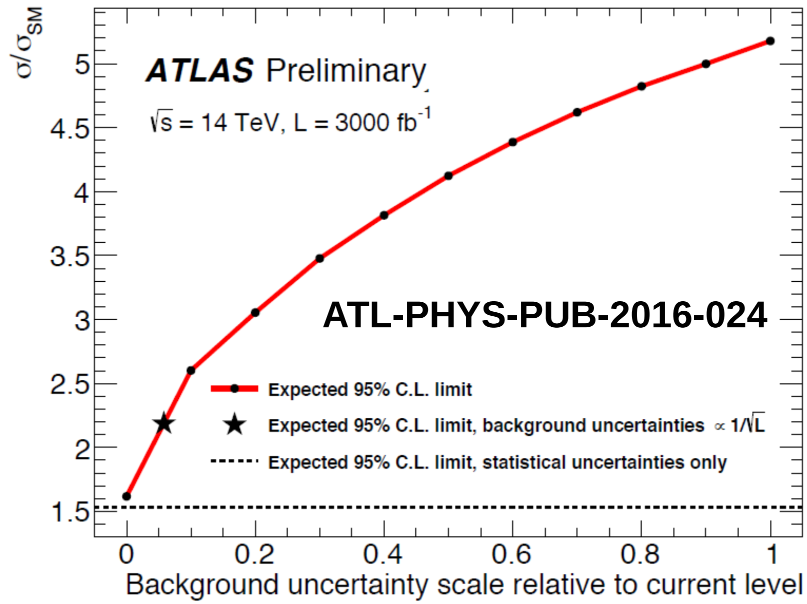
3.DiHiggs @ HL-LHC

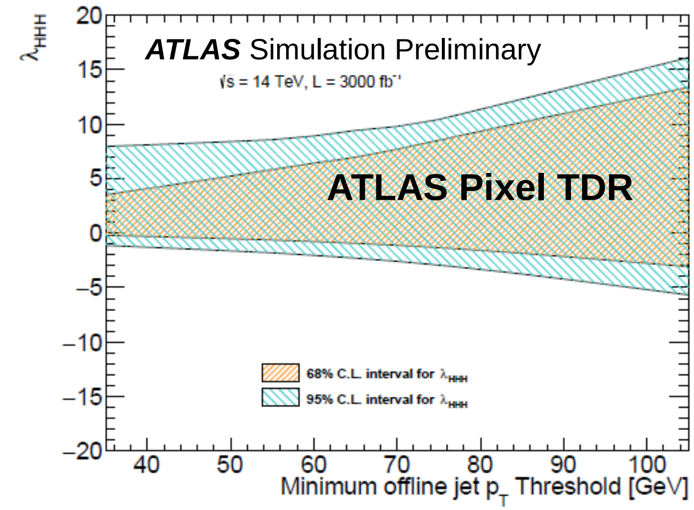


3.Cross-sections HH and background

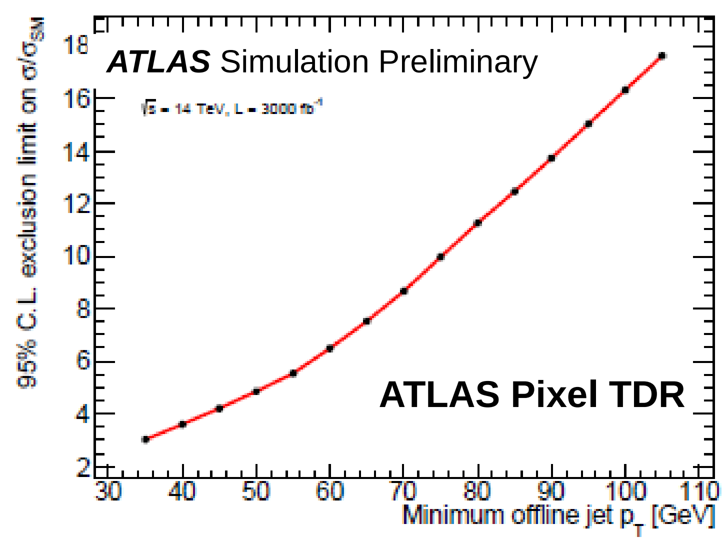


3.HH → bbbb

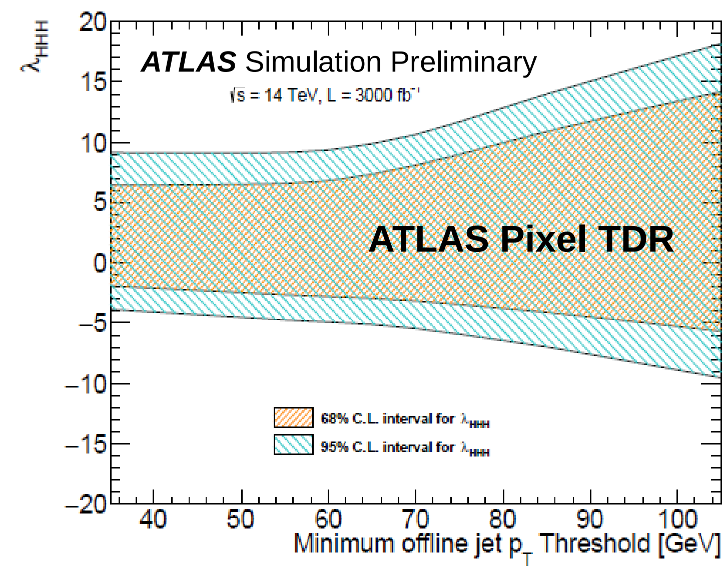




(a) No Systematics

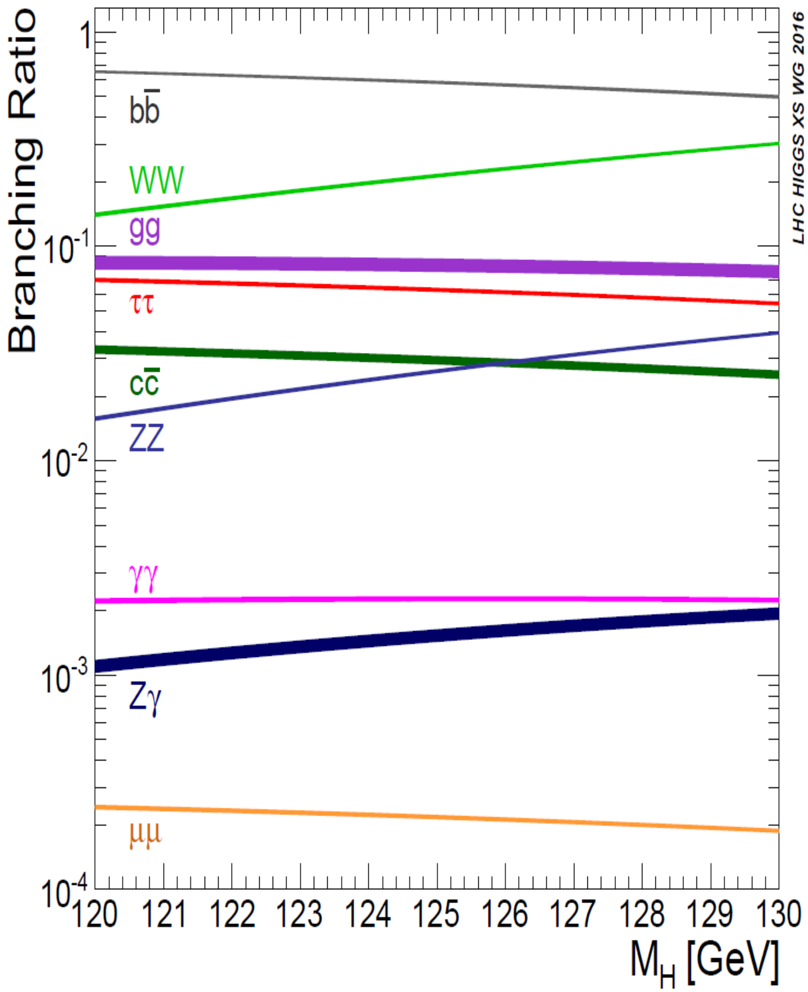


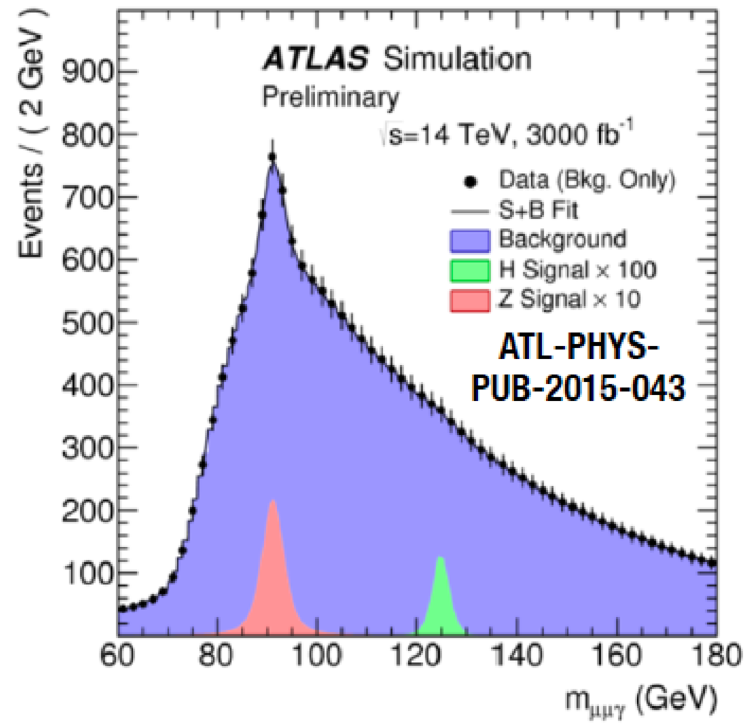
(b) With Systematics



(b) With Systematics

Je



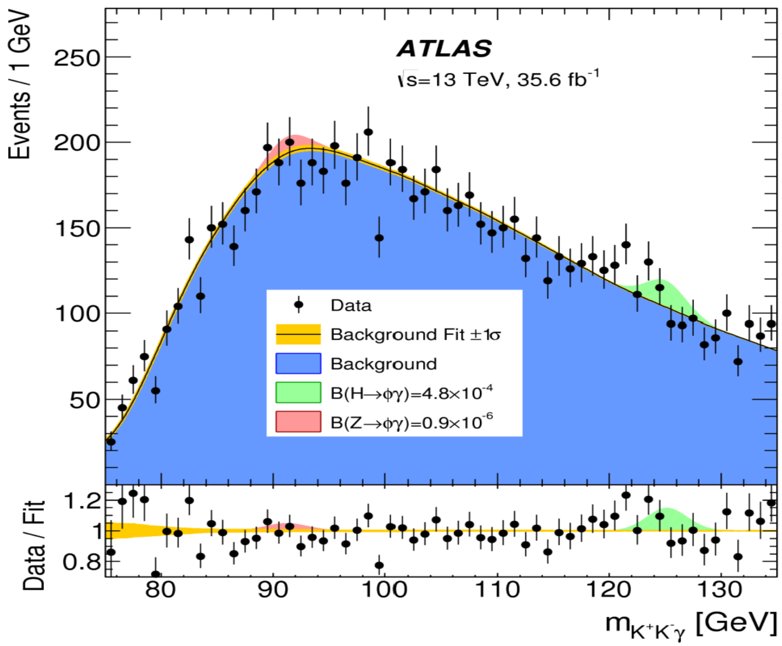


Expected branching ratio limit (no syst.) :

$\mathcal{B}$ (H→ J/Ψ γ) < $(44^{+19}_{-12})\times10^{-6}$ @ 95% C.L.

Standard Model expectation : $(2.9\pm0.2)\times10^{-6}$

* Probe for fermion of second/first generation



arXiv:1712.02758

Channel	Final state	Exp. SM $x10^{-6}$	Run2 limit @ 95 % C.L. $x10^{-6}$
$H\rightarrow \rho\gamma$	$\pi^+\pi^-\gamma$	16.8±0.8	880
$H\rightarrow \phi\gamma$	$K^+K^-\gamma$	2.31±0.11	480

9.Other BSM searches