HIGGS @ HL/HE-LHC

MARIA CEPEDA (CERN)

STATUS AND PLANS FOR THE 2018 YELLOW REPORT OF THE HIGGS WORKING GROUP (WG2)

2ND RED LHC WORKSHOP, MADRID, MAY 2018

Higgs @ HL-LHC

What do we need to know? Where will the HL-LHC impact?

- **Precision Measurements** (Couplings to ~5%, Cross Sections, Differential Distributions, Width, assessment of the top Yukawa)

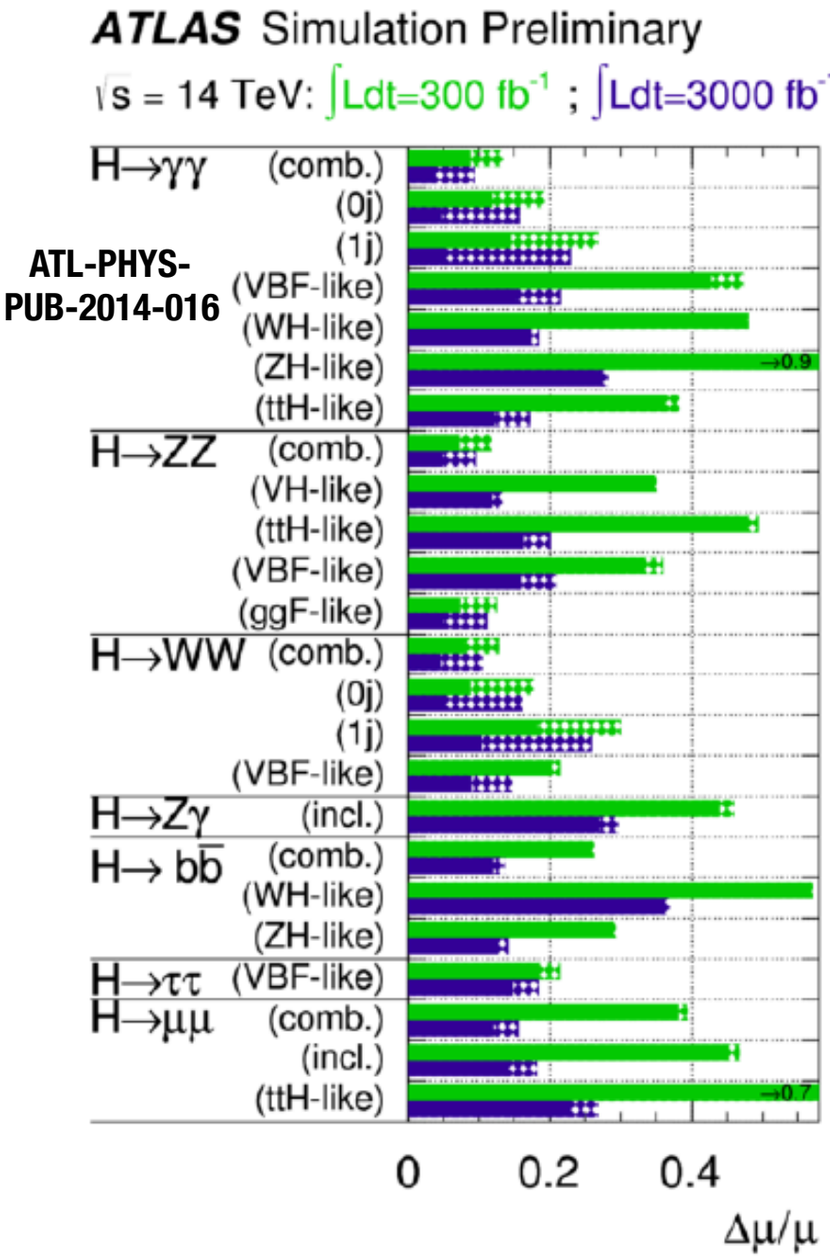
- **Rare & Exotic decays**

- **Di-Higgs production** ➜ self coupling

- **BSM Higgs searches** (extra scalars, BSM Higgs resonances, anomalous couplings)

Couplings @ HL-LHC

- Existing studies: comprehensive, but mostly based on extrapolations of Run1/ early Run2 results, plus specific analyses with parametrised full simulation



ATL-PHYS-PUB-2014-016

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]	[16,16]	[6, 17]	

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]	

Rates can be measured at the few % level (10-20% for rarer modes)

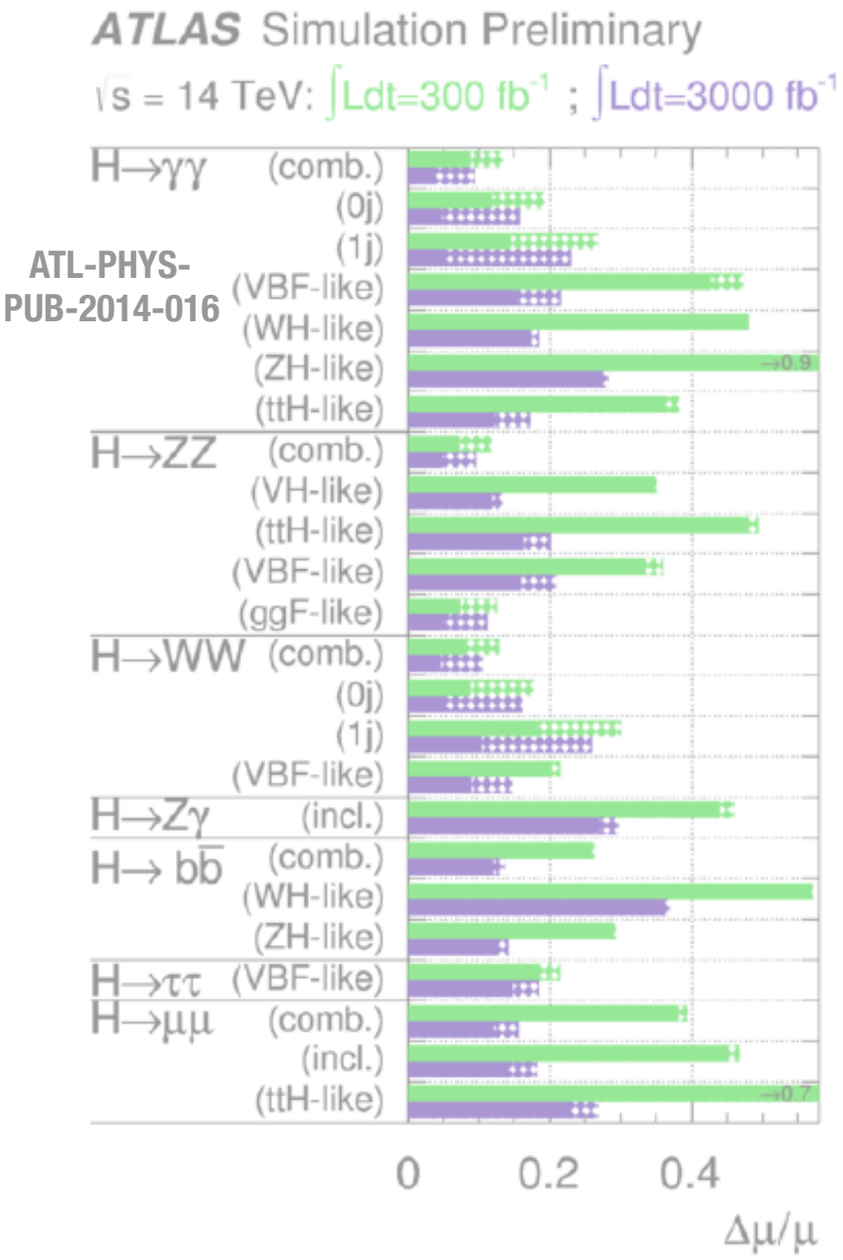
Coupling can be measured at the few % level

- Overall update needed to take in consideration the latest analysis improvements and revisit the uncertainty scenarios (example: kt prospects)
- Ratios of couplings: cancelation of uncertainties

- Goal: clear summary plot that shows the prospects for the couplings which is as accurate as possible.

Couplings @ HL-LHC

- Existing studies: comprehensive, but mostly based on extrapolations of Run1/ early Run2 results, plus specific analyses with parametrised full simulation



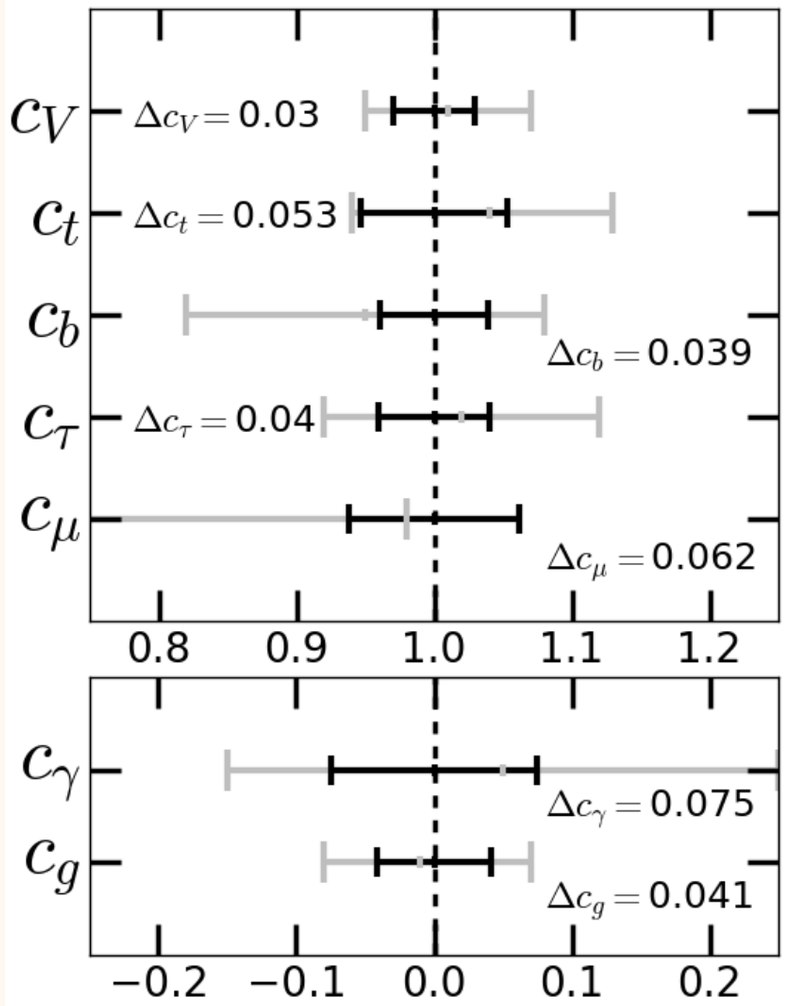
L (fb^{-1})	$\gamma\gamma$	WW	ZZ
300	[6, 12]	[6, 11]	[7, 11]
3000	[4, 8]	[4, 7]	[4, 7]

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]

Rates can be measur… the few % level (10-2… for rarer modes)

- Overall update need… latest analysis impro… uncertainty scenario…
- Ratios of couplings:
- Goal: clear summary… for the couplings whi…

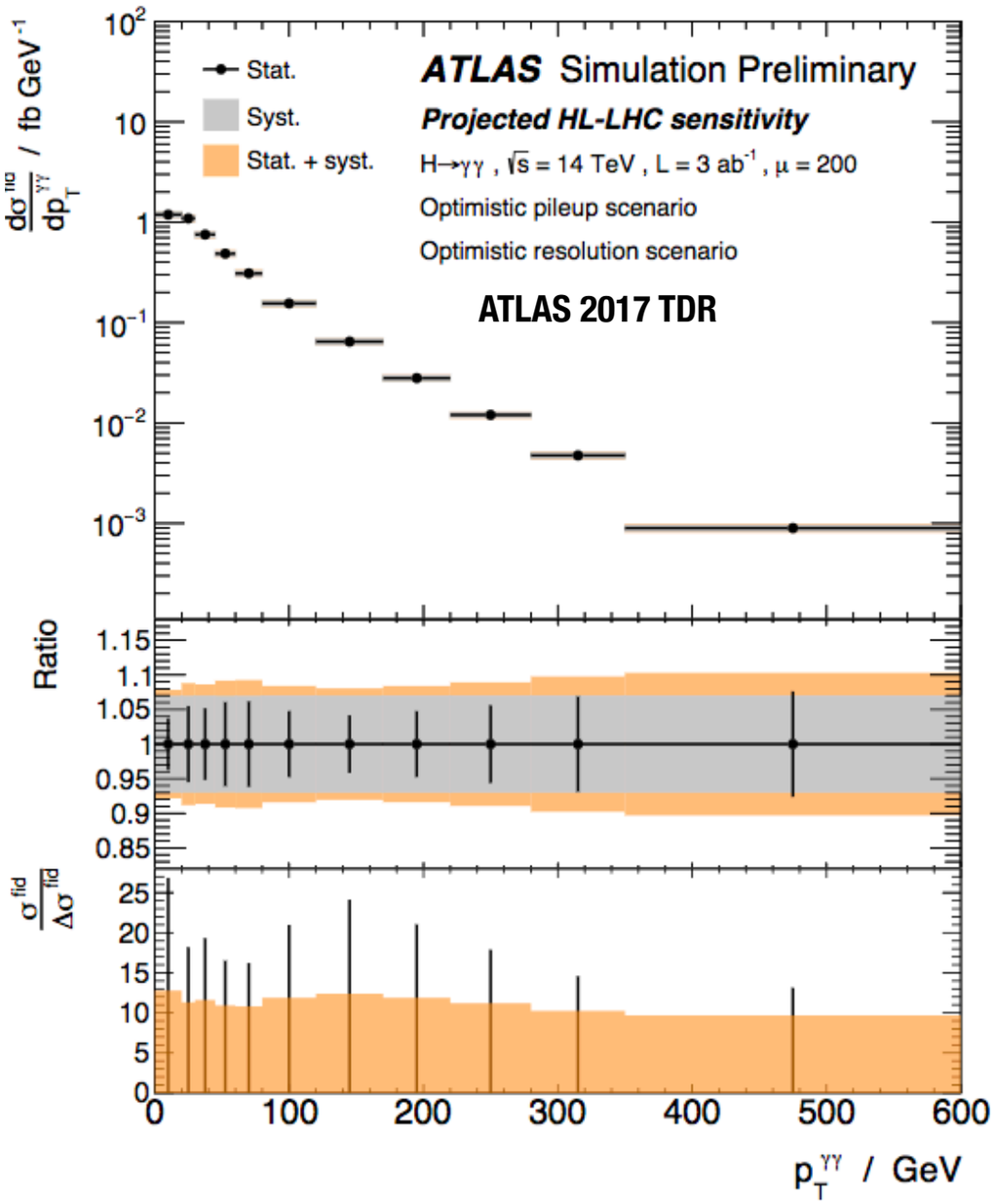
Coordination critical for the YR report! Exp. results will be combined w. theo. studies on EFT

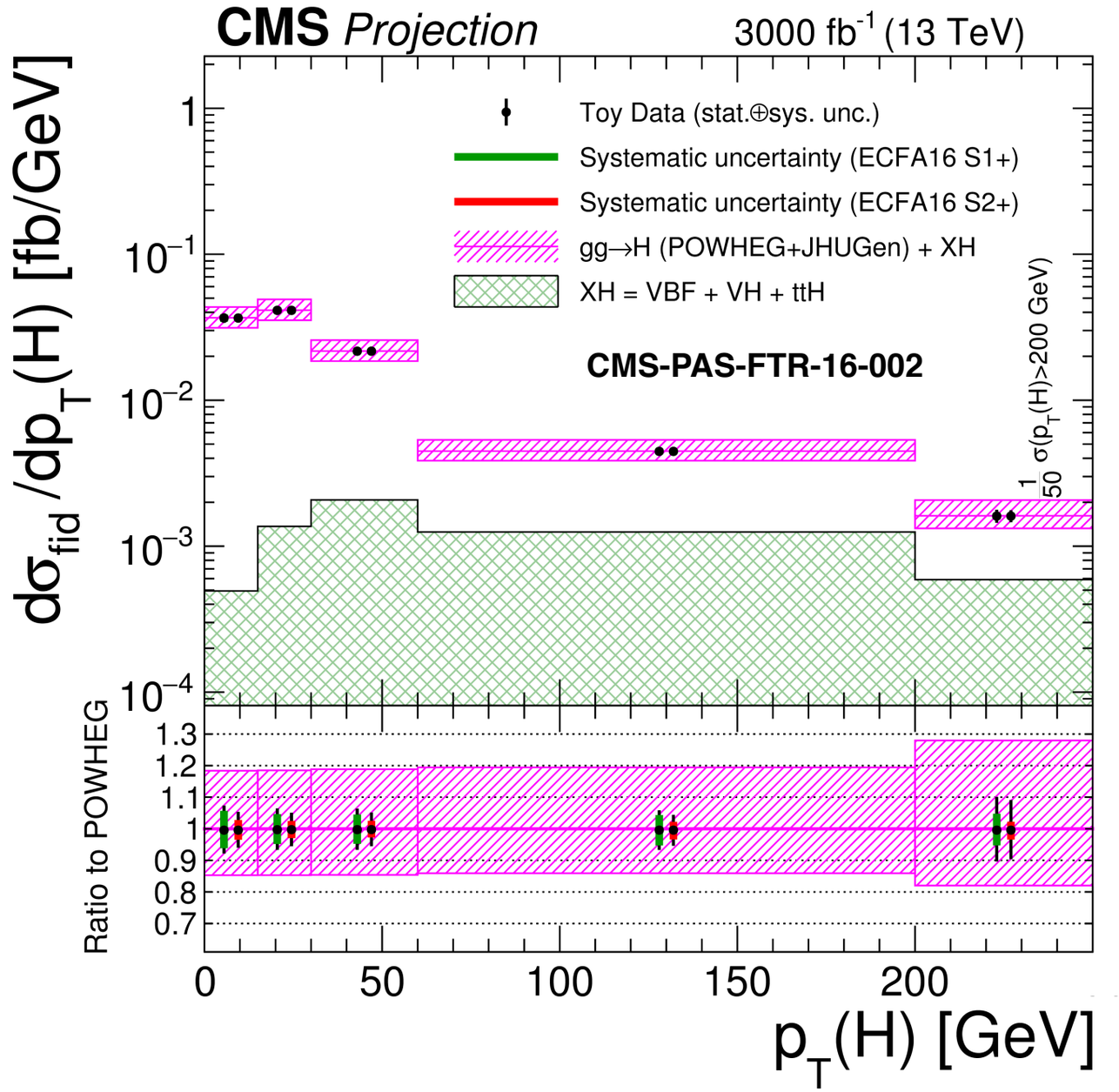


de Blas/Eberhardt/CK [1803.00939]

Differential & Fiducial Cross Sections

- Exploit the large dataset and go beyond inclusive measurements

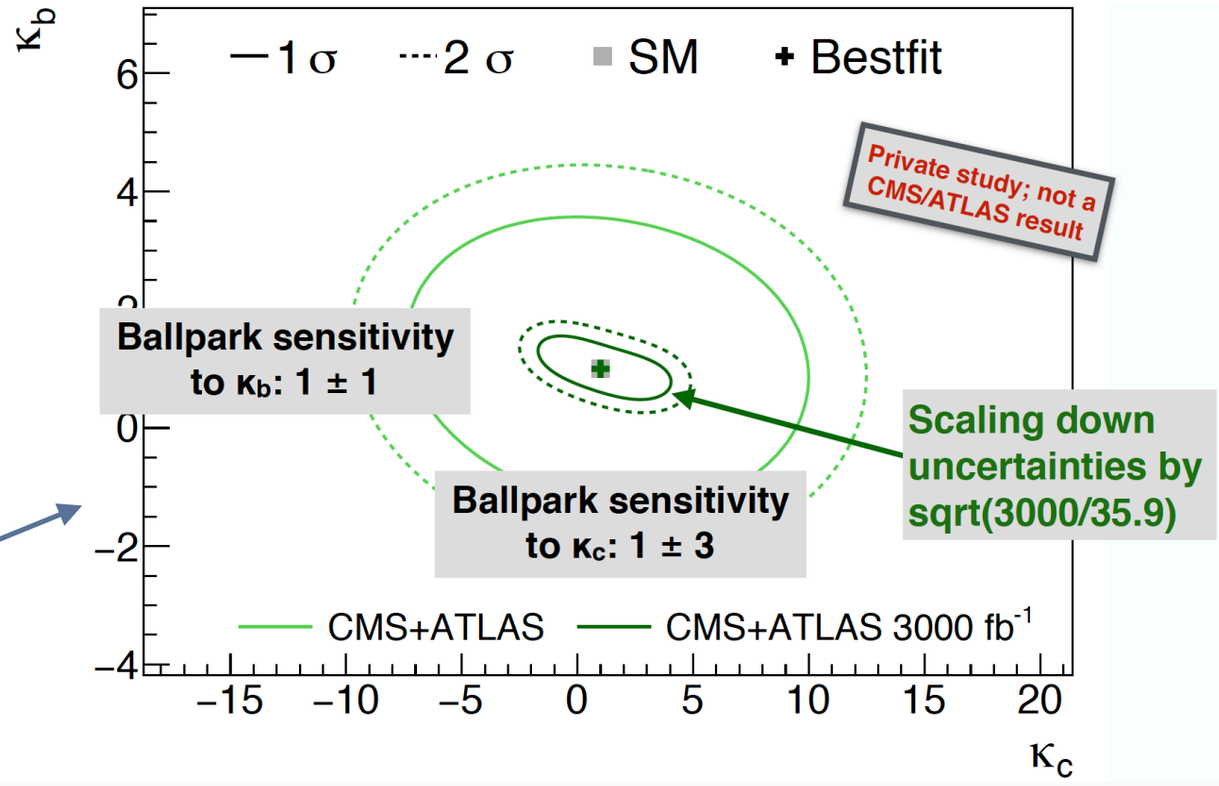


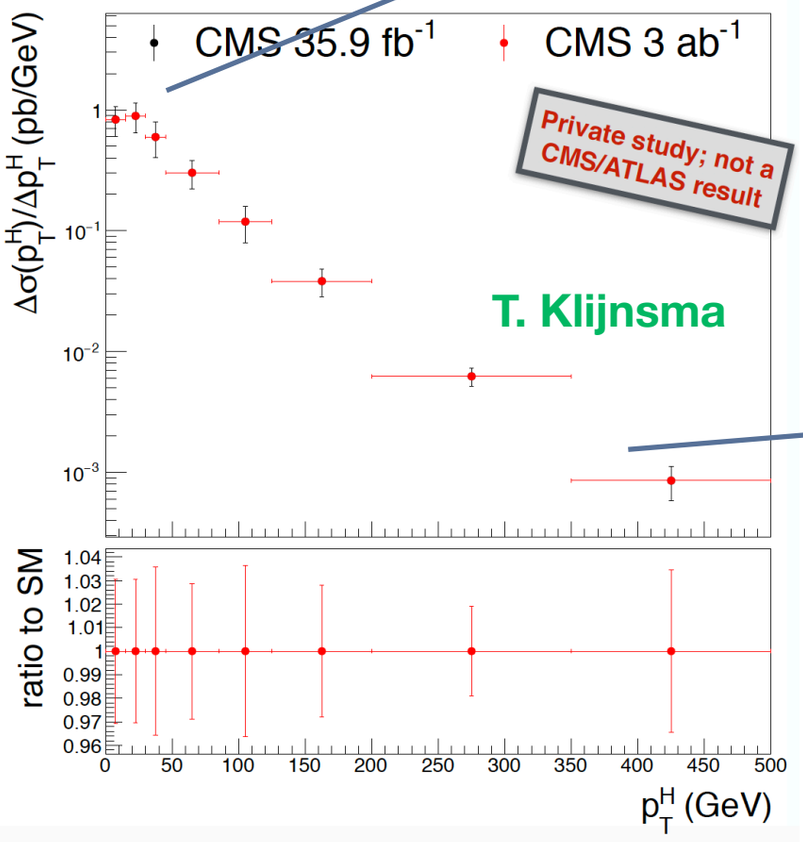


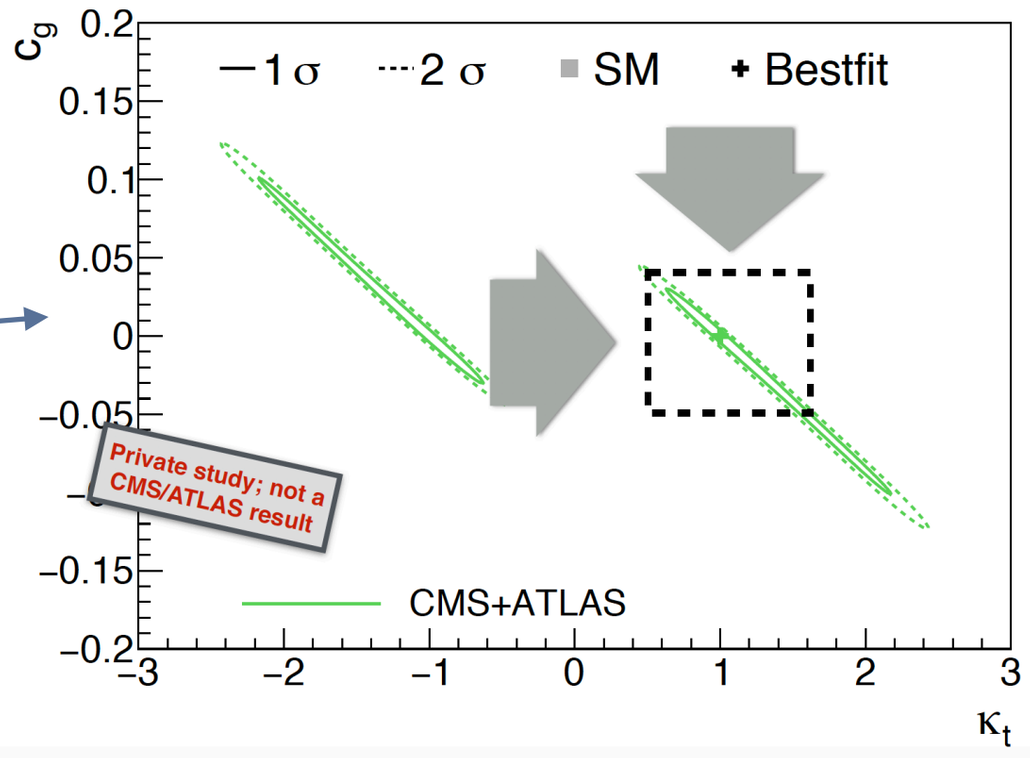
- Sensitive to k_b/k_c (low p_T) k_t/BSM (high)
- At high p_T, dominated by statistical uncertainty even @ 3000 fb^{-1}

Differential & Fiducial Cross Sections

- Sensitive to k_b/k_c (low p_T) k_t/BSM (high)
- Could be comparable to direct Hcc searches (also on the plans)
- At high p_T, dominated by statistical uncertainty even @ 3000 fb^{-1}





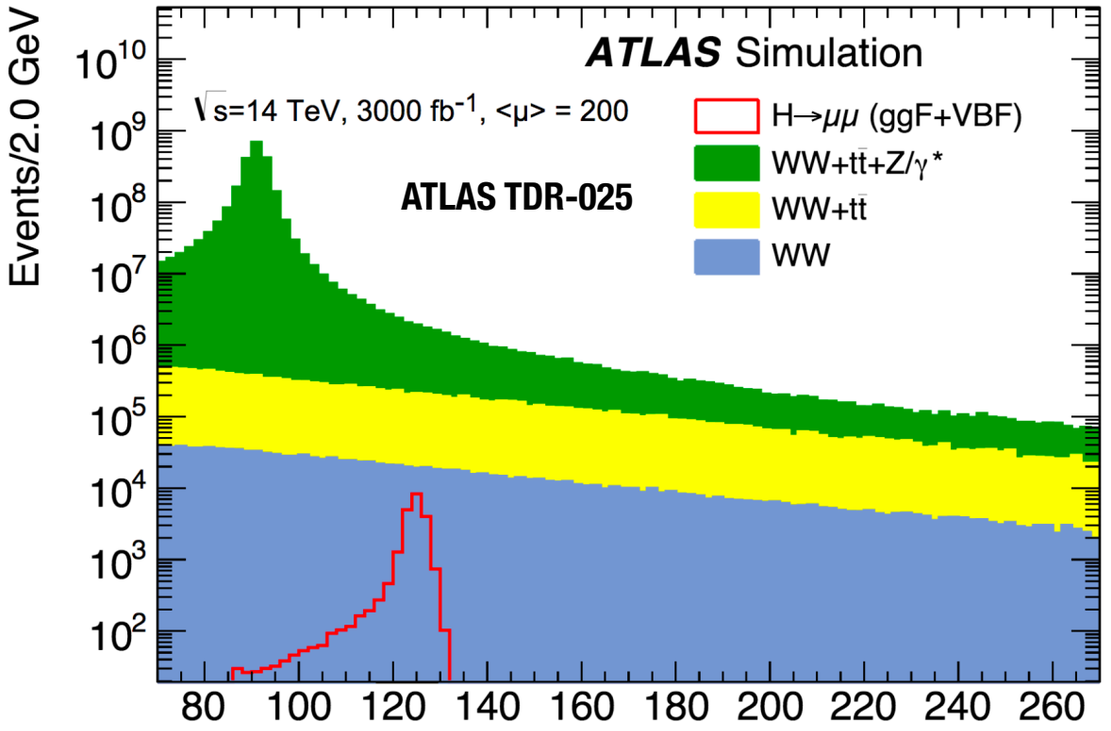


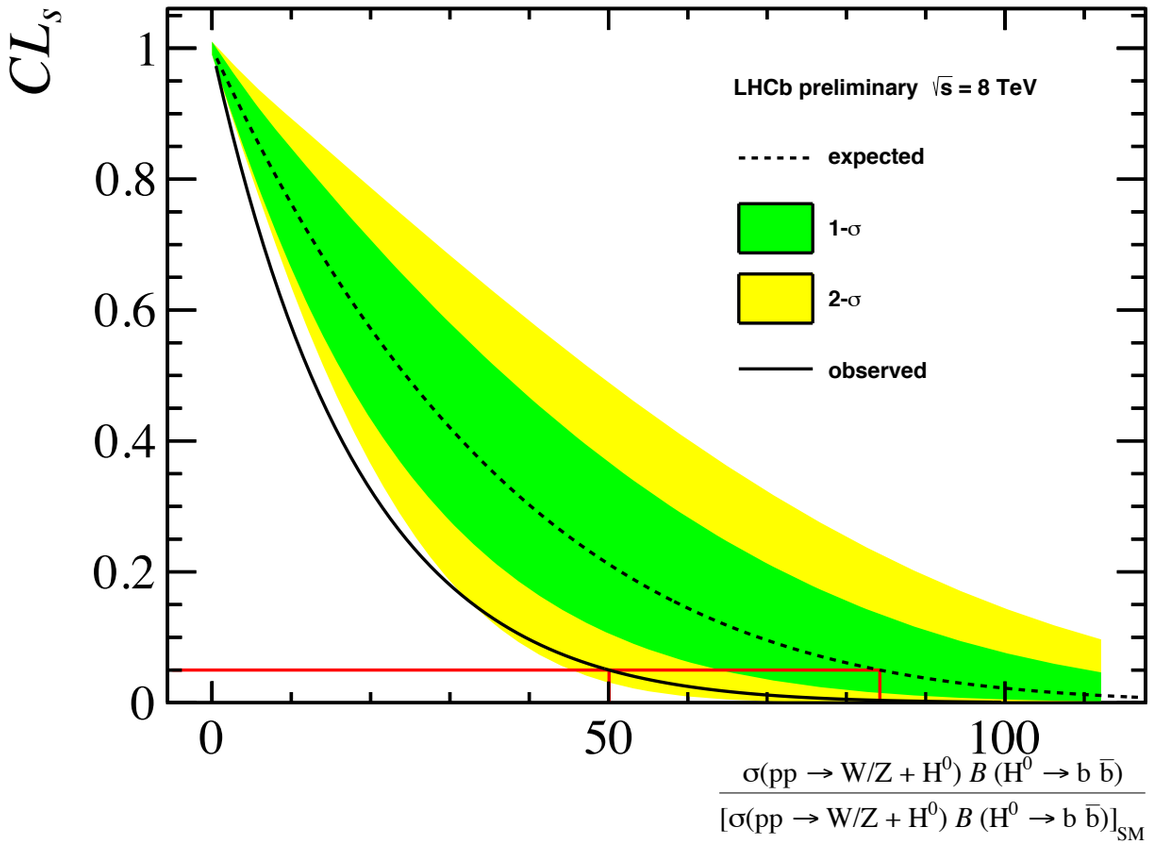
Rare decays

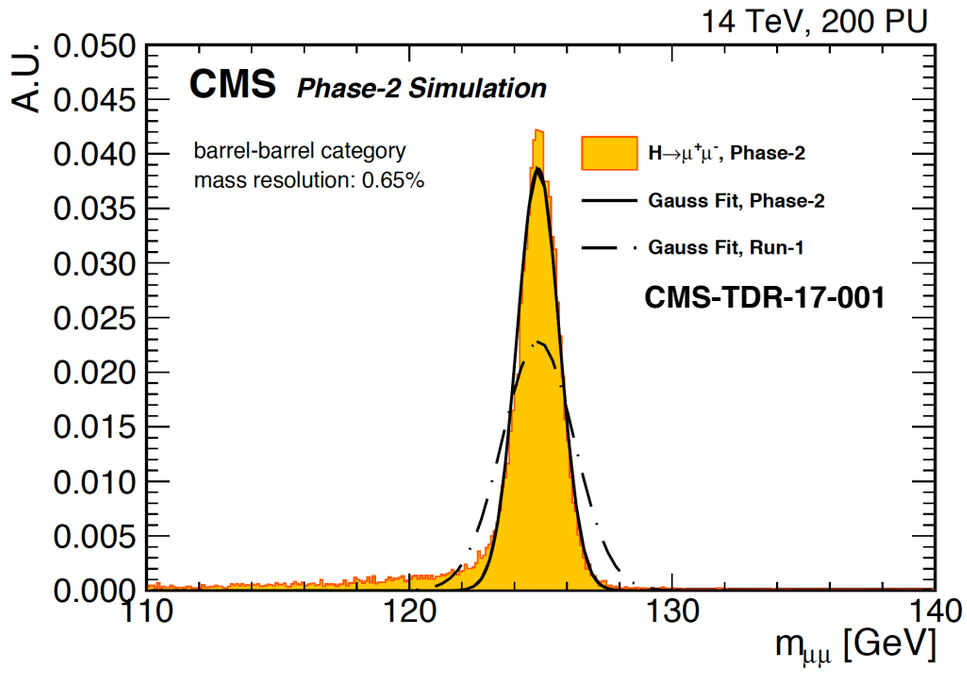
- **High statistics: rare decays become accessible**

- Probe coupling to 2nd generation
- H→μμ: prospects for **cross section and coupling measurement → 8% & 5% uncertainty@3000fb^{-1}** respectively

- **What about H→cc ? (bonus: LHCb)**

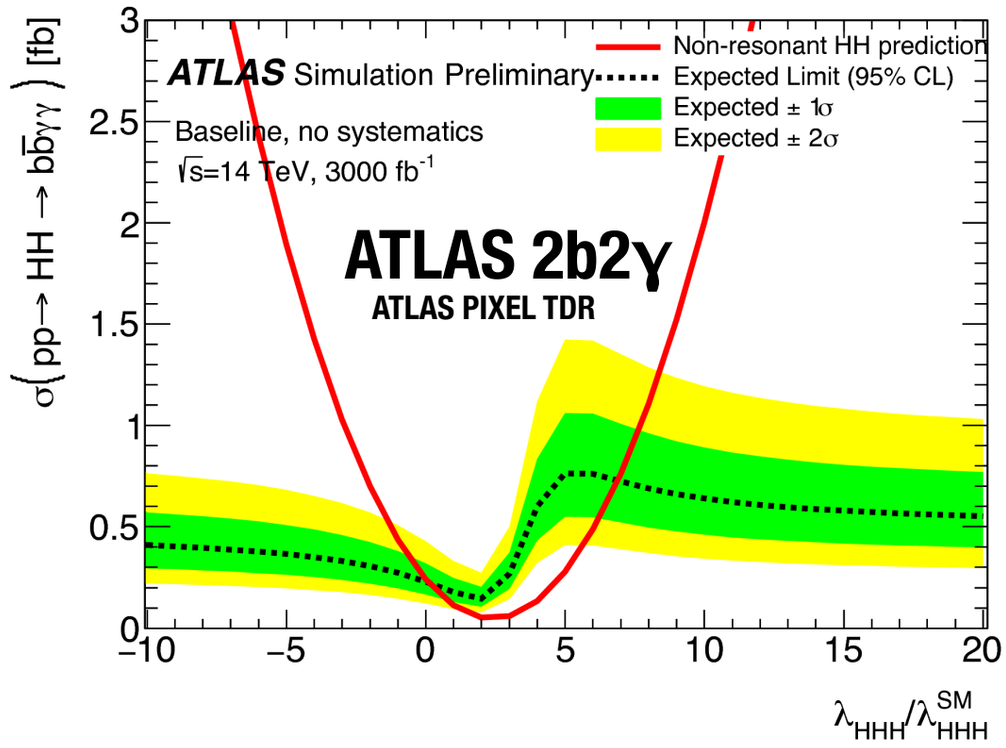


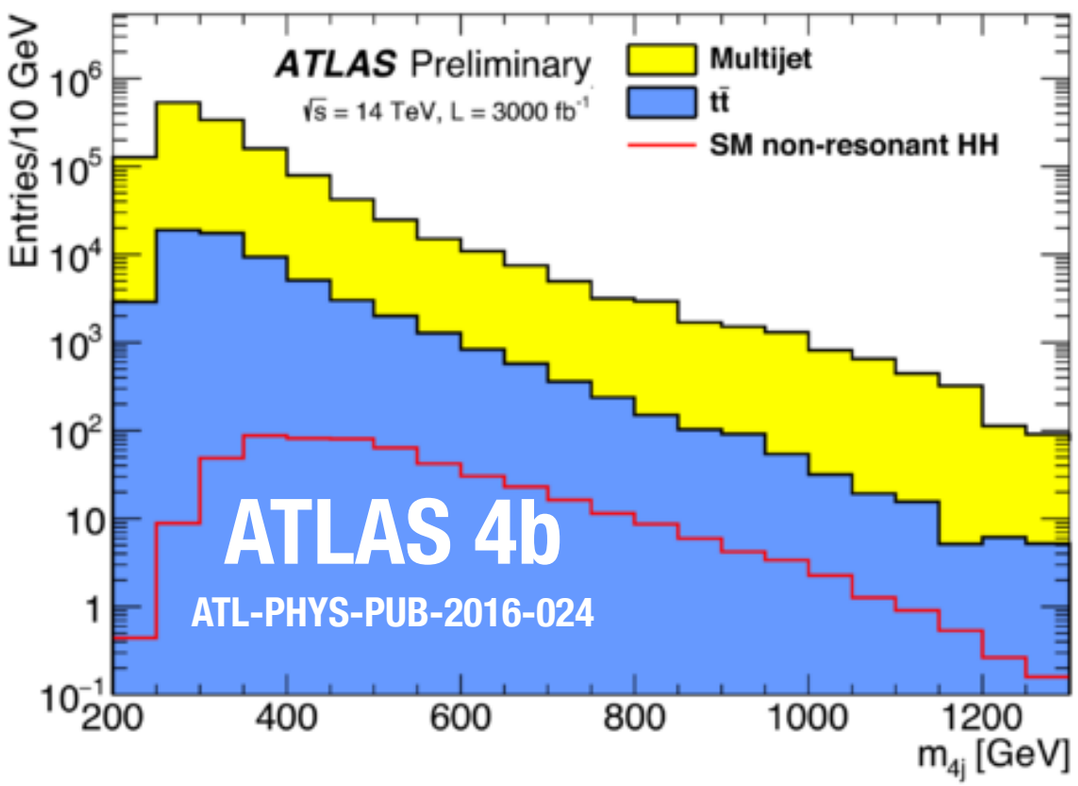


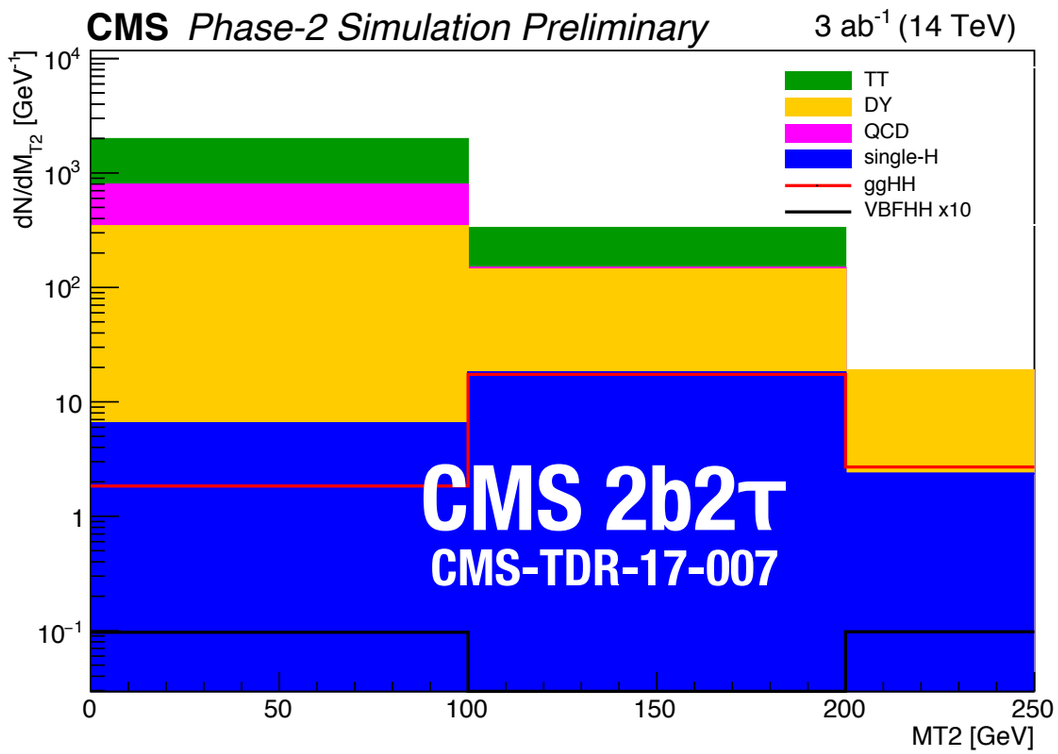


DiHiggs Production

- **σ~ 39.5 fb@14TeV → HL-LHC benchmark**
  - Access the H self-coupling λ
  - Low cross section: destructive interference
- Expanding list of final states w. Run2 & extrapolated to HL-LHC







DiHiggs Prospects @ 3000 fb^{-1}

	CMS	ATLAS
HH->2b2g	1.43 σ	1.5 σ $0.2 < \lambda_{HHH} / \lambda_{SM} < 6.9$ (95%CL)
HH->2b2tau	1.6xSM 52.2xSM for VBF mode alone	0.6 σ $-4.0 < \lambda_{HHH} / \lambda_{SM} < 12.0$ (95%CL)
HH->4b	0.39 σ	$-4.1 < \lambda_{HHH} / \lambda_{SM} < 8.7$ (ggF, 95%CL) (0.35 σ for ttHH, HH->4b)
HH->2b2W	0.45 σ	

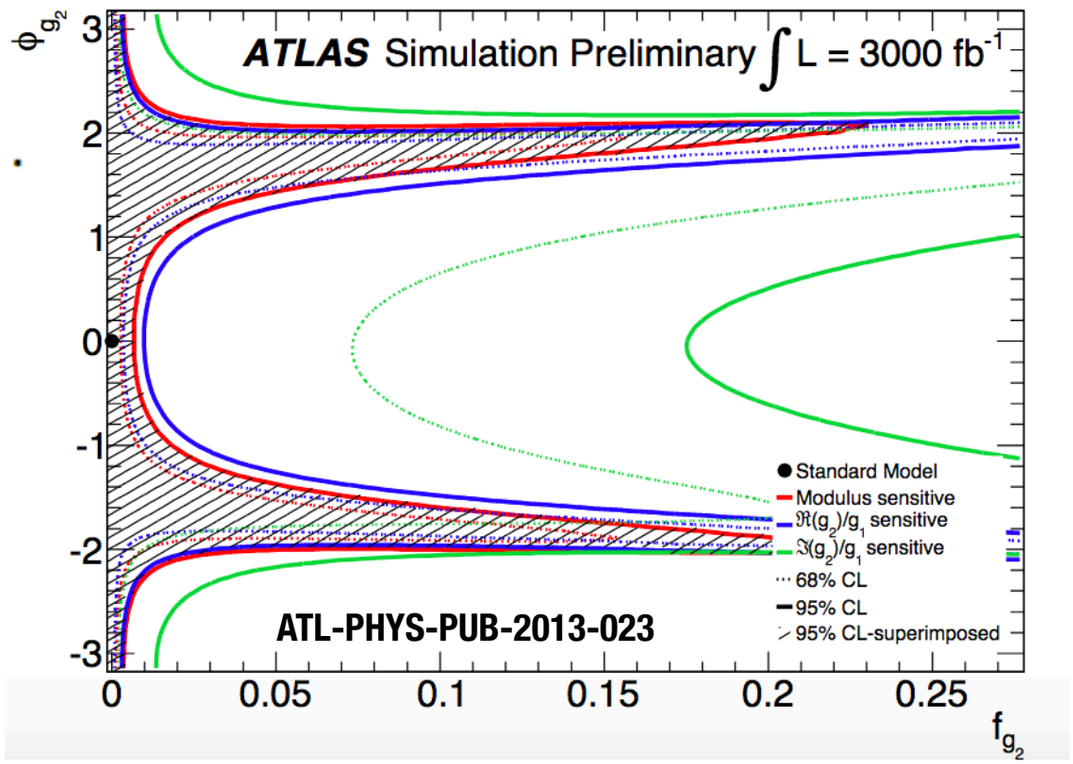
- Incomplete picture. Update needed to incorporate latest analysis improvements and increase robustness
- On the plans: combination to obtain the full picture both in terms of SM sensitivity and λ reach
- What about HE? —> large rates!

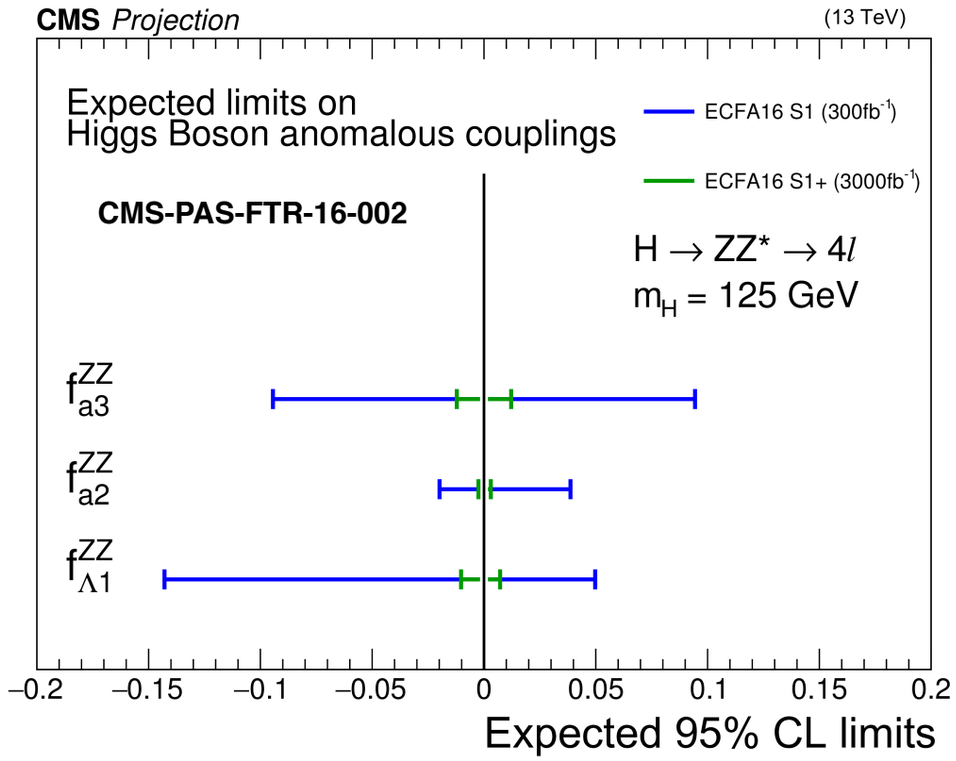
Anomalous Couplings

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

SM

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



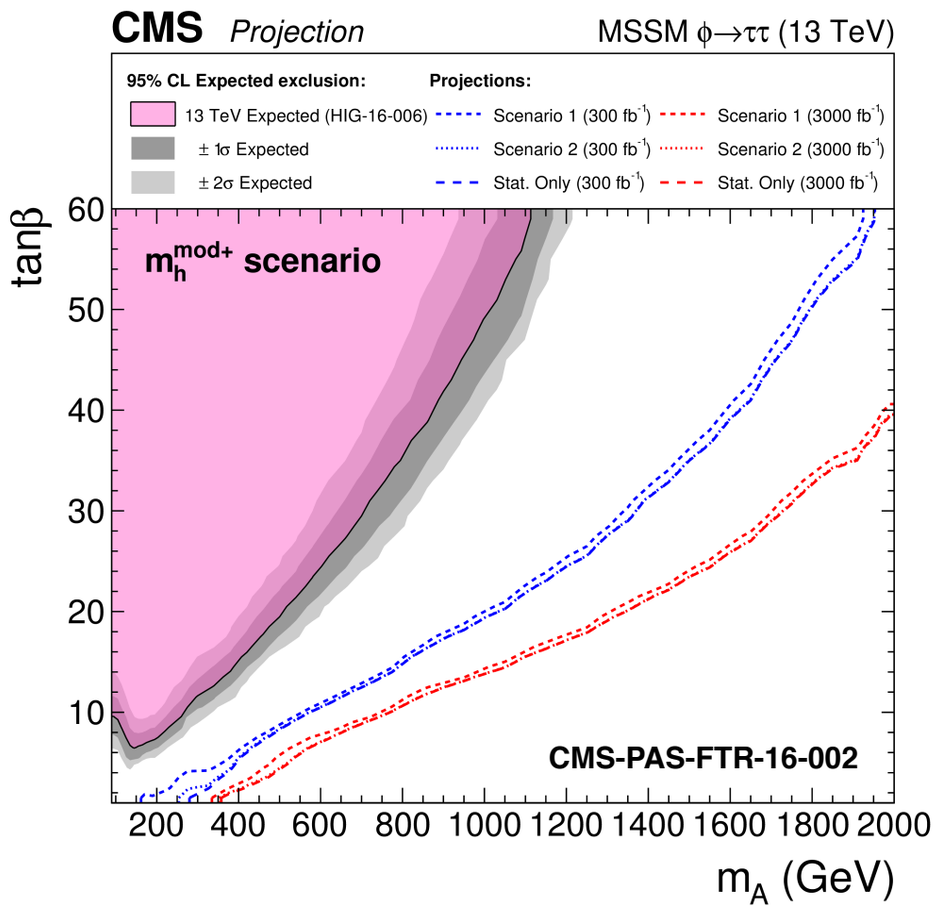


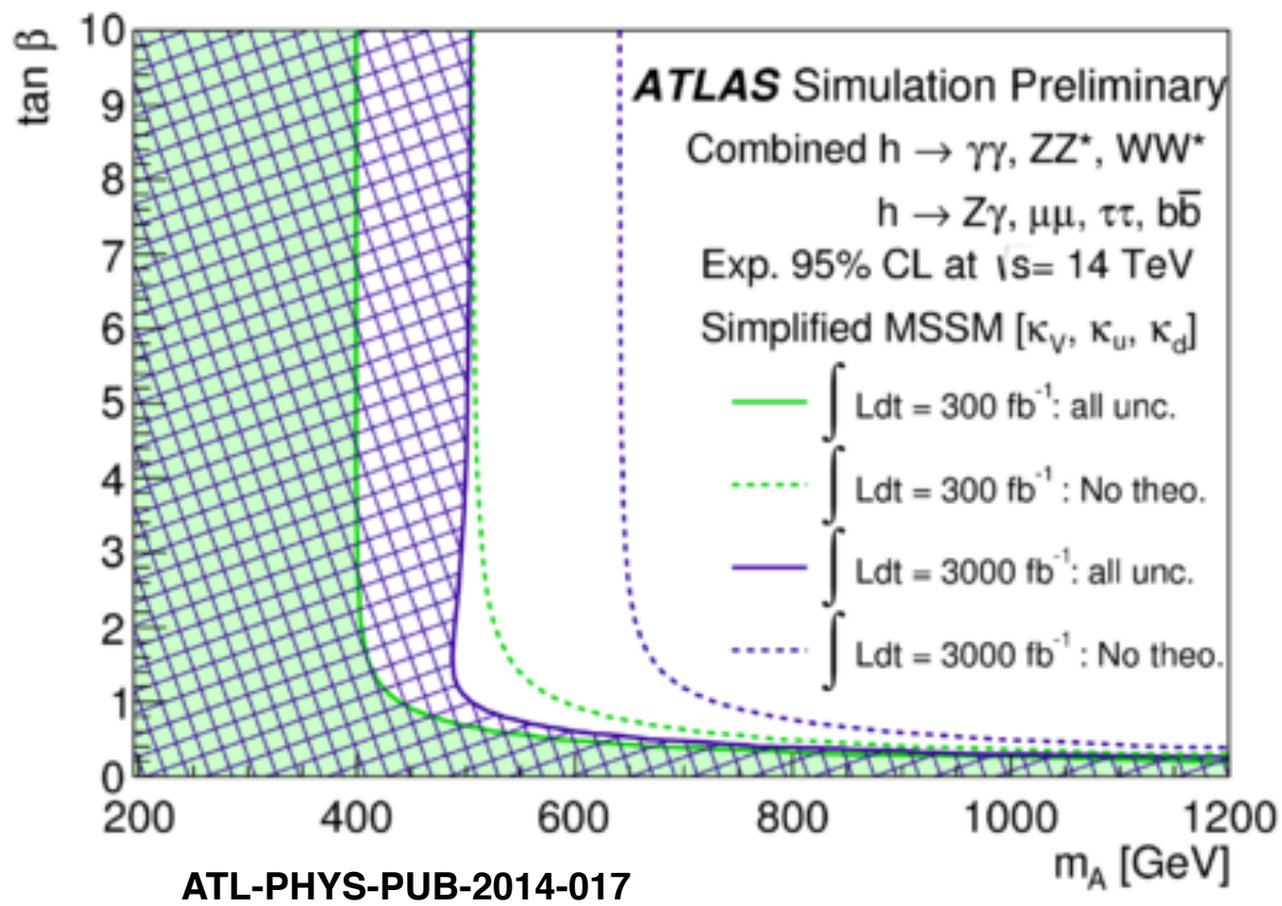
- Statistically limited. 1% reach @ 3000 fb^{-1} (based on Run1 methods)
- Interference contribution becomes more dominant at smaller values of $f_{ai} \cos(f_{ai})$

BSM Searches

How much BSM phase-space will we cover with 3000 fb^{-1} ?

- **Existing prospects for direct searches: H->μμ, H->ττ, A->Zh**
- **What about low / intermediate mass scalars? (example: CMS low mass γγ)**
- **What about H->tt ?**





Prospects Plans

- **Complement the existing prospects aiming for a coherent approach of the ATLAS and CMS studies.** Obtain the combined performance of ATLAS+CMS for key cases, if possible. Explore the LHCb reach.
  - We cannot cover all the phase space in time for the report—> cooperation with the theory community is key to broaden coverage
- **Extrapolations from Run 2 analyses to give more realistic projections,** supported by TDR-based understanding analyses with realistic detector performance; plus a number of dedicated Delphes-based analyses
  - **Extrapolation to 3000 fb^{-1} based on a double approach: conservative (current experimental uncertainties) vs optimistic (expected floor values for uncertainties)**
  - Joint discussion on how to deal with these floors already started
- **HE-LHC:** Only selected analyses (extrapolations with no account taken for effects such as a different detector and PU conditions) -> Mostly rely on theoretical studies for now!

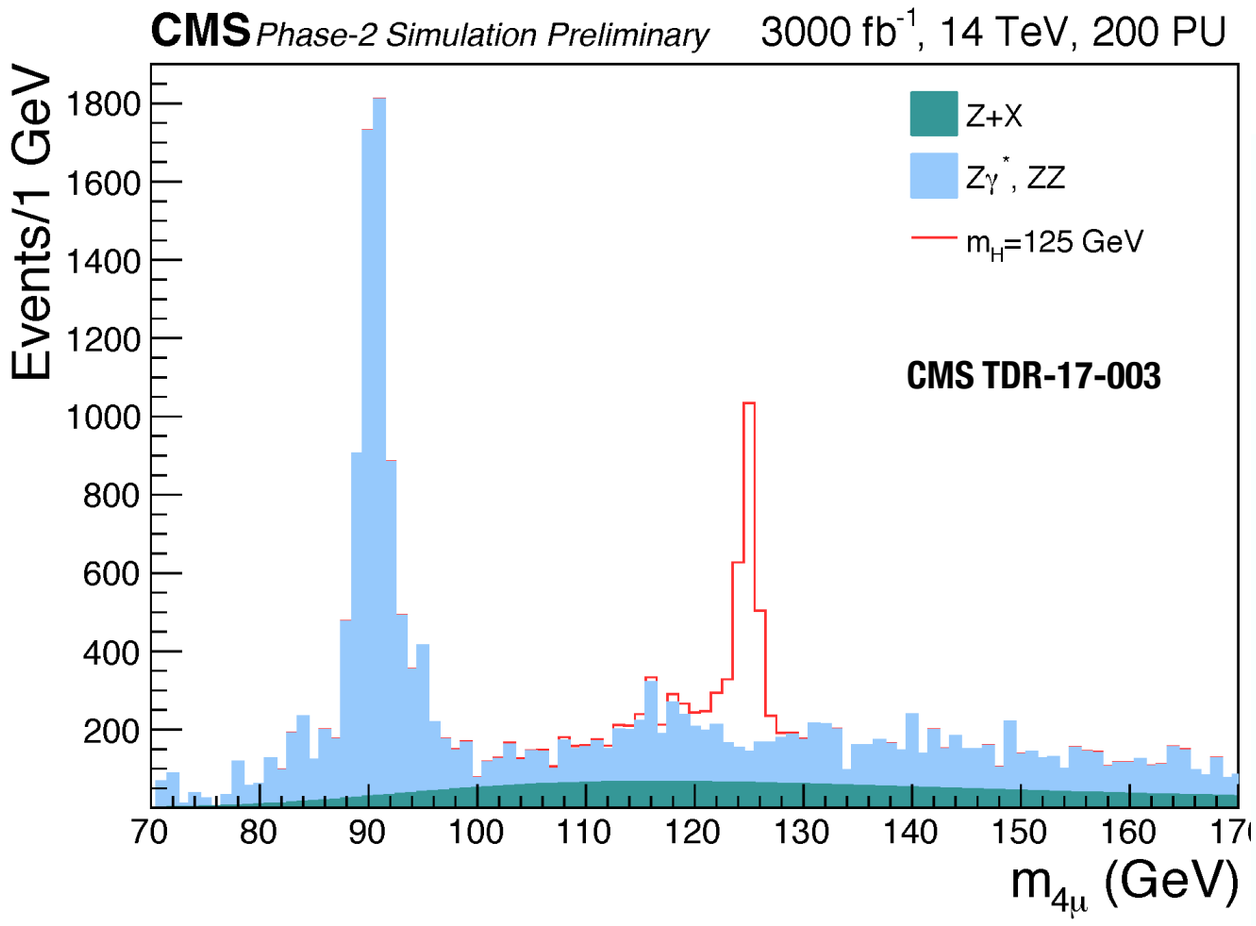
Experimental Wishlist for 2018

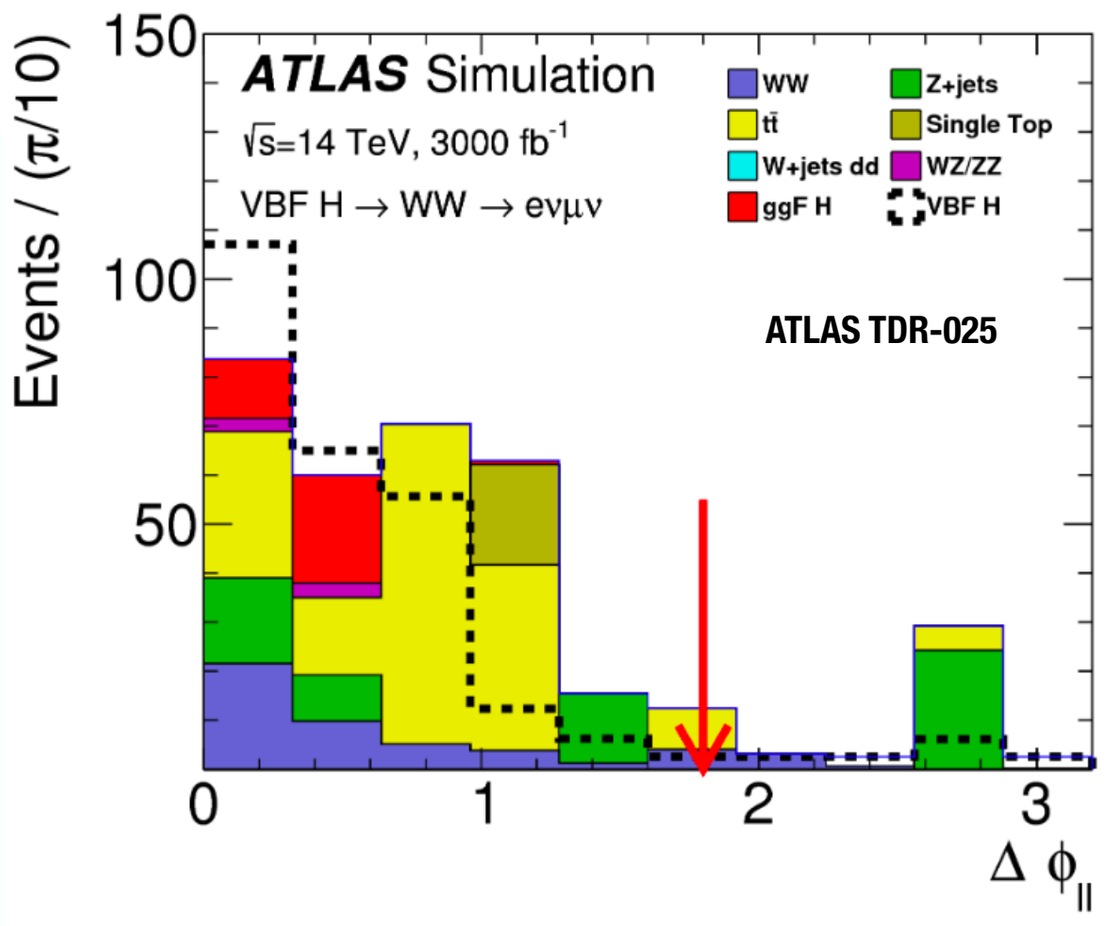
	CMS	ATLAS	LHCb
Couplings Studies	✔✔★	✔✔★	
Differential CrossSections	✔★	✔★	
Width		✔	
Anomalous couplings	✔★	✔	
Rare Decays	**μμ,cc**	**Zγ,J/ψγ,FCNC μμ,ργ,cc**	**Hcc/Hbb**
Exotic Decays	**LFV; Invisible, DarkSusy; 4jets**		
DiHiggs	✔✔★	✔✔★	
Additional Scalars	**A->Zh, high mass ττ, ttbar, low mass γγ**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

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

Impact of the Upgrades

- Technical Design Reports of 2017 -> Focus on detector performance with full simulation updates that complement & inform the physics reach shown in the studies presented here
- 200PU, 3000fb-1 -> but improved detectors -> impact on reach! (eg: forward performance, resolution (TK), timing, trigger)





Conclusions

- **Higgs studies are central to the HL(HE)-LHC program:**
  - Measurement of the Higgs couplings possible to few percent
  - Differential distributions and fiducial cross sections: probing interesting phase spaces and reducing dependence on theoretical uncertainties
  - High statistics: rare processes become accessible
  - Enhanced sensitivity to New Physics involving Higgs bosons

- **The 2018 Yellow Report aims to present a coherent view of the experimental and theoretical prospects for Higgs studies at the HL-LHC, and broach for the first time the HE-LHC**
- **Common effort for all the Higgs community!**

Future Higgs Studies are key *today*!

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG2

hllhc-wg2 mailing list subscription

Structure of the Higgs Chapter

1. Introduction: Main goals and timeline
2. Precision Higgs physics
3. Di-Higgs production and Higgs self couplings
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

Detailed outline in: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG2

HL-LHC/HE-LHC Workshop: towards a Yellow Report in 2018

- Objectives of the workshop:
  - Prepare a synthesis of current status of the HL-LHC physics program. Reappraise past projections, perform new analyses, complete partial analyses and combine to provide the most complete picture.
  - Begin a systematic study of the physics potential of the HE-LHC (27 TeV)
  - Harmonize results between LHC experiments and projections from the TH community.
  - Gather and discuss new ideas from the community and revisit prospects in the light of increased precision in SM measurements with the much larger data sample.
- The results of the workshop will be summarised in a Yellow Report to be submitted to the European Strategy group by the end of 2018.

Technicalities

- Five working groups: WG1 (SM), WG2 (Higgs), WG3 (BSM), WG4 (Flavour), WG5 (HI)

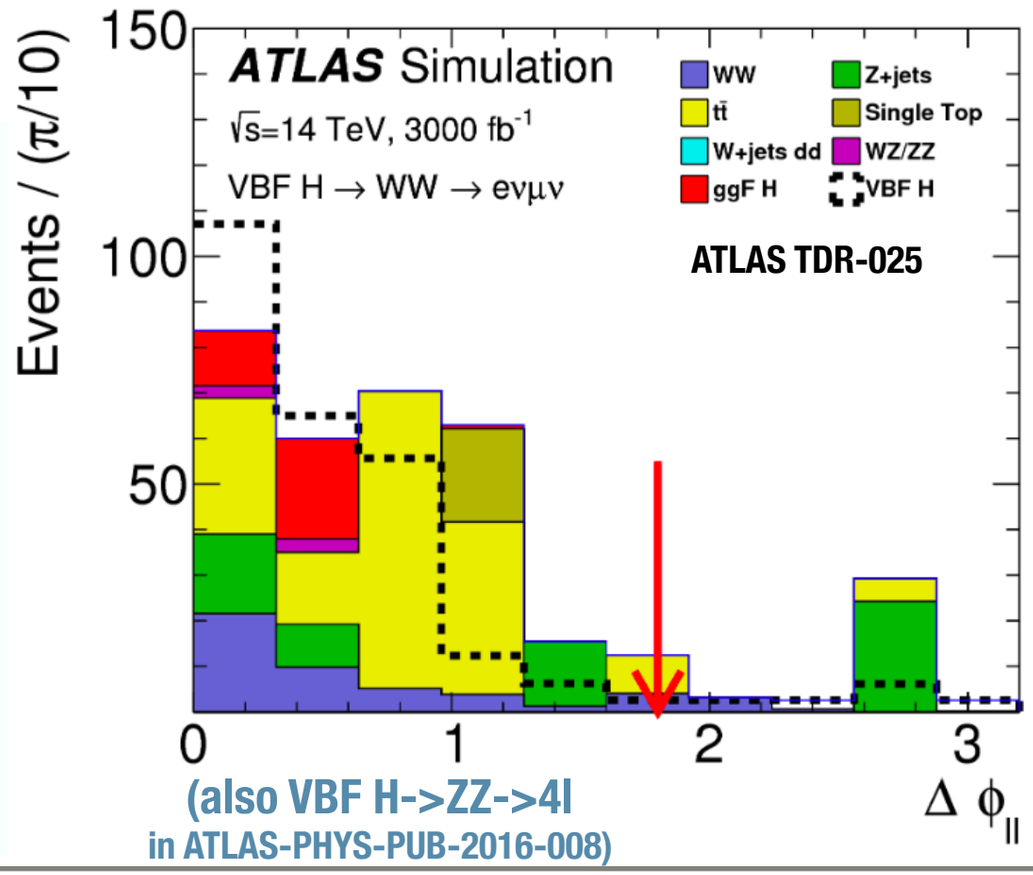
- **WG2 - "Higgs and EW Symmetry Breaking" :**
  - Contacts: Marumi Kado (ATLAS), Stefania Gori, Philip Ilten (LHCb), Francesco Riva, MC (CMS)
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG2
  - Subscribe: hllhc-wg2@cern.ch

- Two volumes YR: first volume devoted to a coherent and comprehensive review of the physics at HE/HL-LHC, second volume collection of experimental public notes on analyses.
  - Budget of approximately 150 pages for Higgs in Volume I

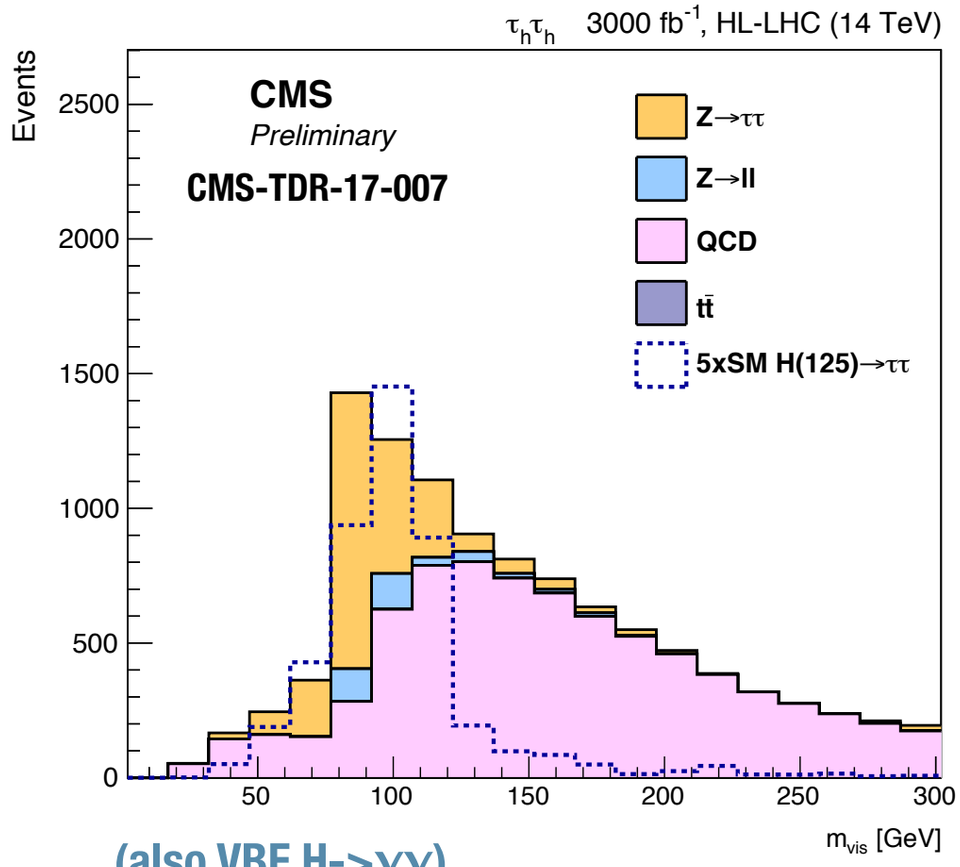
ttH, VH, VBF/VBS

- Probe higher energy scales
- NLO (in SM and BSM) are necessary

- VBF (WW, ττ, γγ, ZZ channels) recently used as a example case in the ATLAS and CMS upgrade TDRs (showcase of the detector performance vs PileUp)
- Plans for the report: expand coverage with special focus on ttH and incorporate the latest analysis techniques



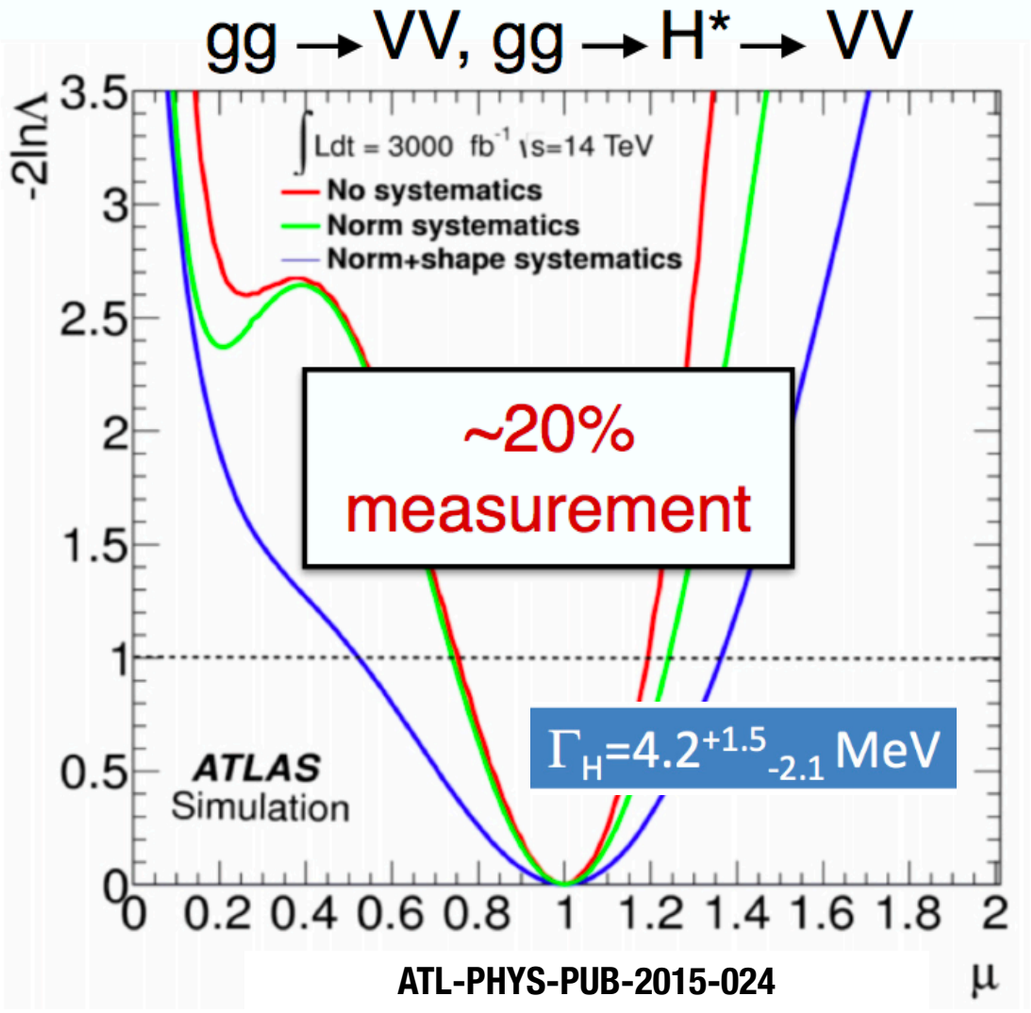
(also VBF H->ZZ->4l in ATLAS-PHYS-PUB-2016-008)



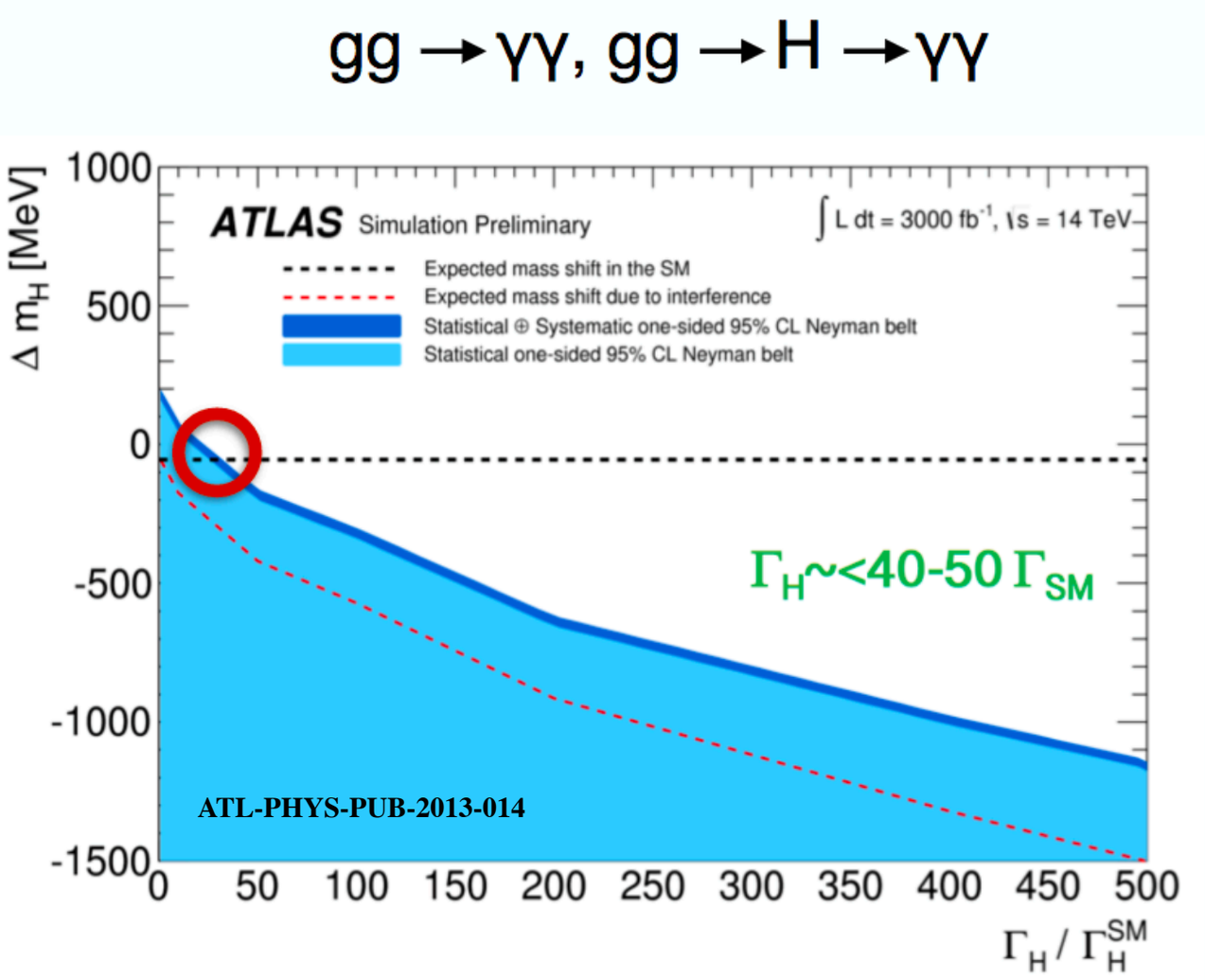
(also VBF H->γγ)

Width

- Probe New Physics in the Higgs domain at large momenta
- Direct measurement will be challenging also with HL-LHC statistics
- Indirect methods —> prospects for the HL-LHC prepared by ATLAS (2013/2015)



(20% experimental systematic - dominated by the theoretical uncertainties)



Stat dominated , if in presence of SM width

Rare and Exotic decays

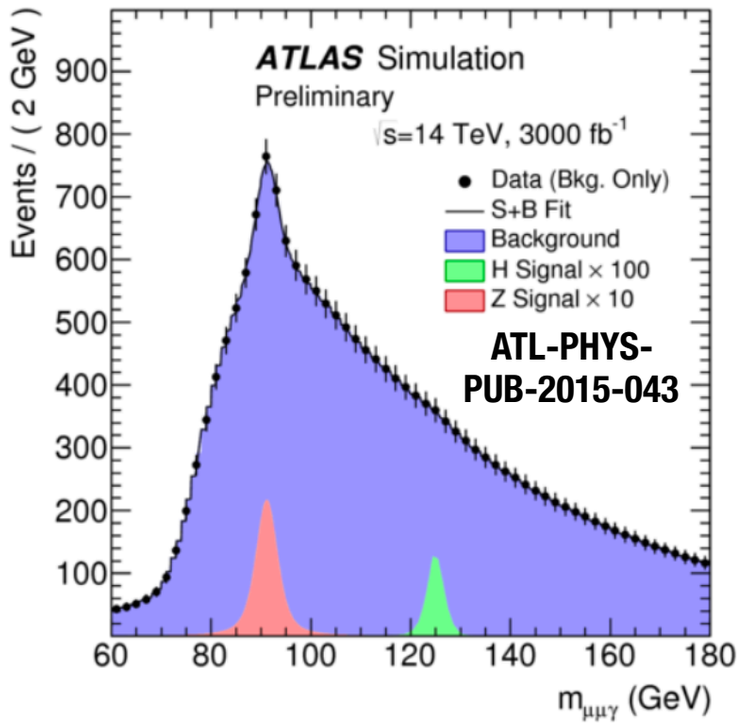
- **High statistics: rare decays become accessible, beyond Hμμ**
  - H->J/ψ γ (ATLAS) -> probe c coupling

    BR (H→J/Ψ γ) < ($44^{+19}_{-22} \times 10^{-6}$) @ 95% CL

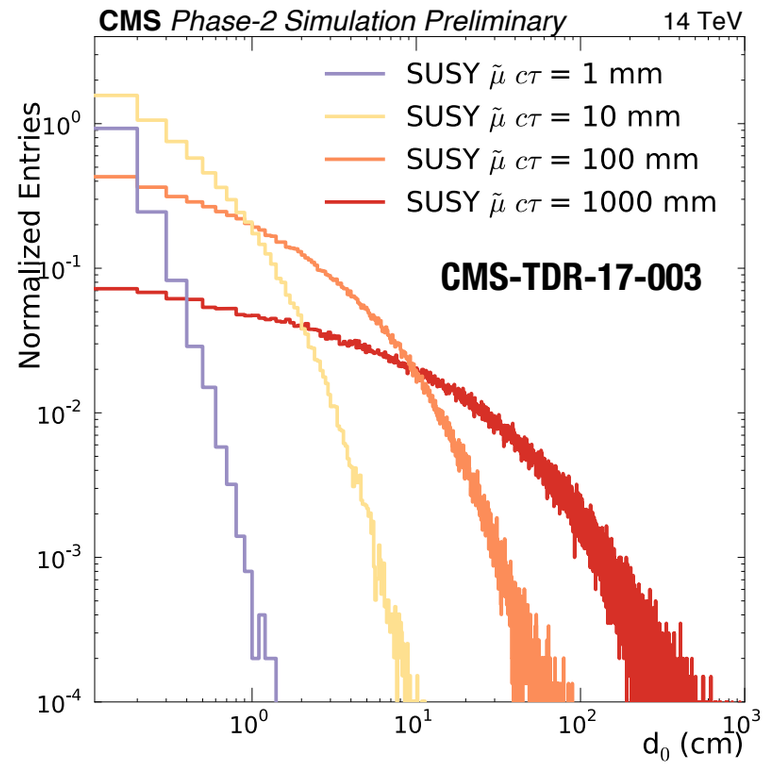
  - H->Φγ / ργ (ATLAS) -> probe light-quark couplings. ργ already close to expectation.

    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$(1.68 \pm 0.08) \times 10^{-5}$

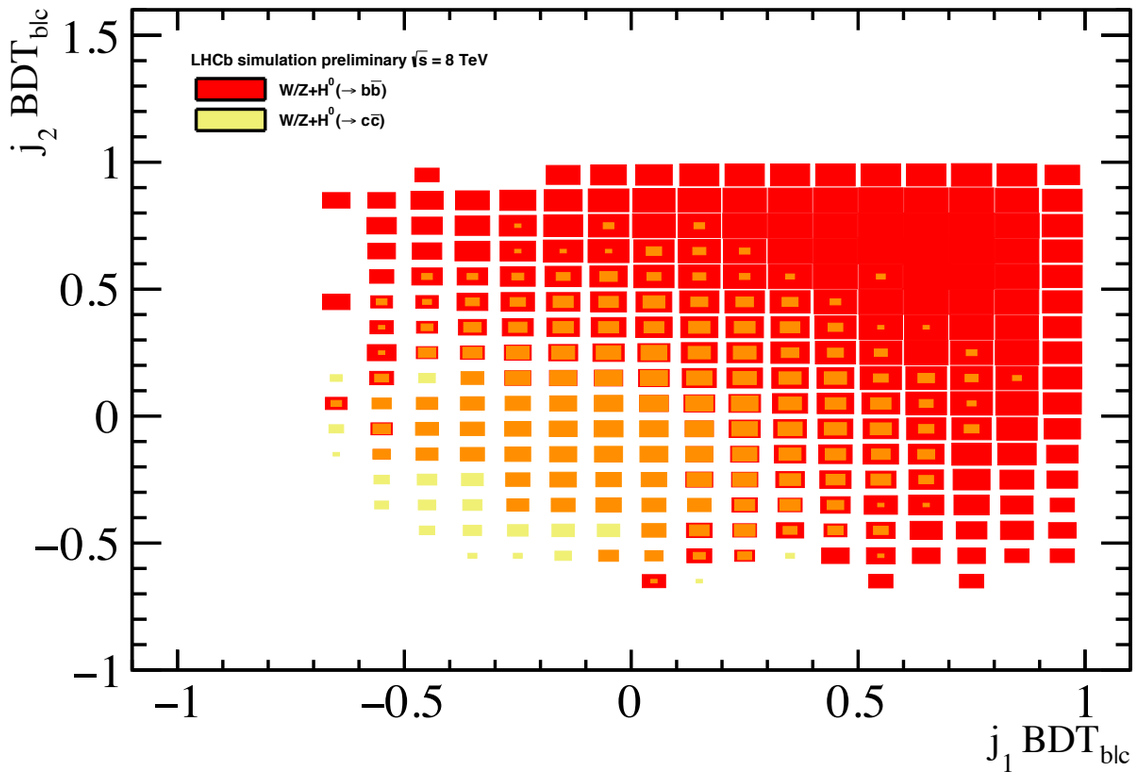


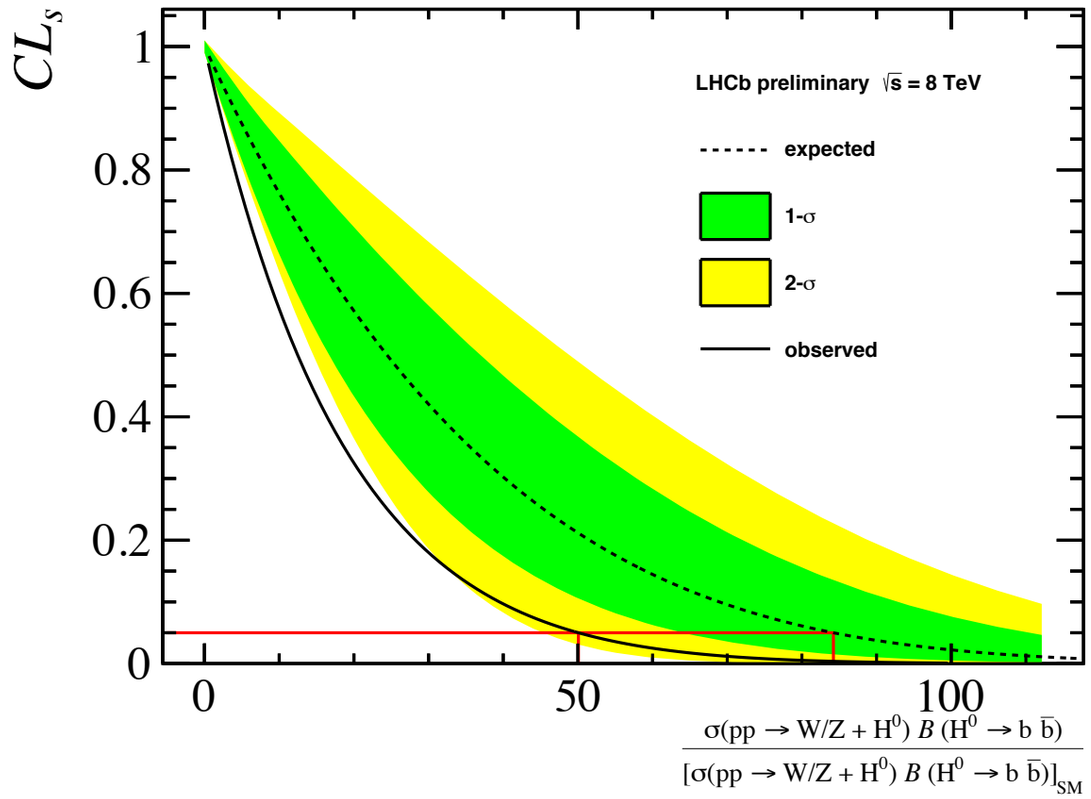
- **An increasing number of Run2 studies targeting exotic decays of the boson are becoming available, from Invisible decays to 2HDM signatures**
- Few HL-LHC prospects ready so far! (example: h(125)-> dark photons - displaced (CMS))
- The yellow report will extend the experimental coverage using some example signatures (LFV; Invisible Higgs)



$H \to c\bar{c}$

- First direct inclusive search for H→cc in LHCb, LHCb-CONF-2016-006
- Search for WH/ZH with H→bb and H→cc final states
- Require two jets with inclusive secondary vertex tags

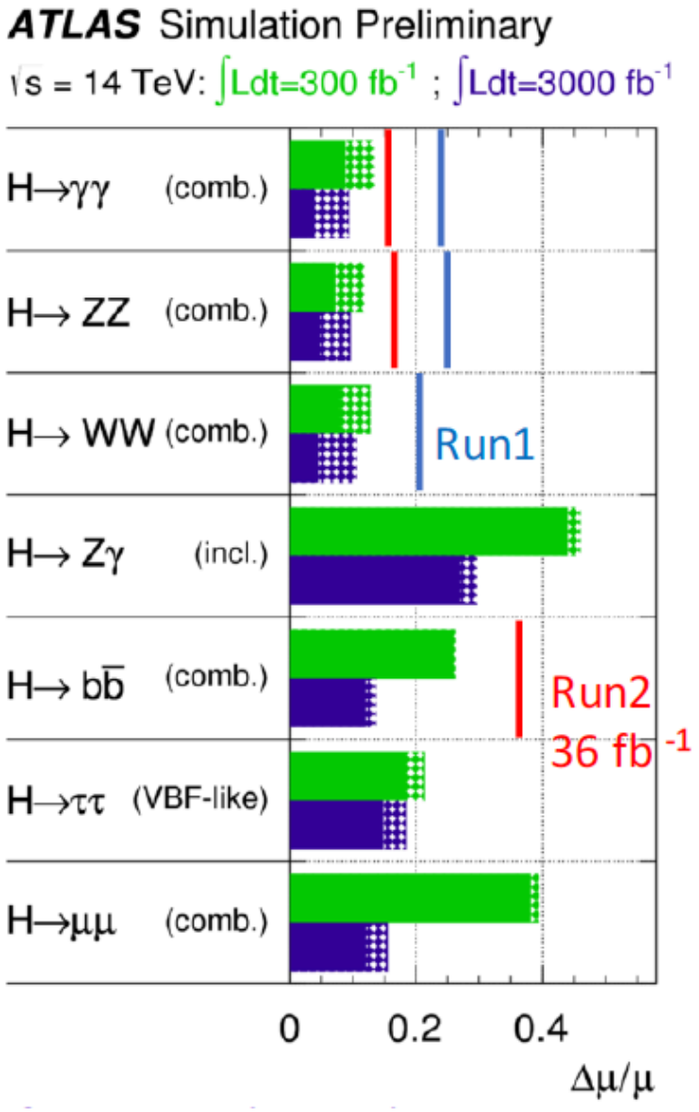


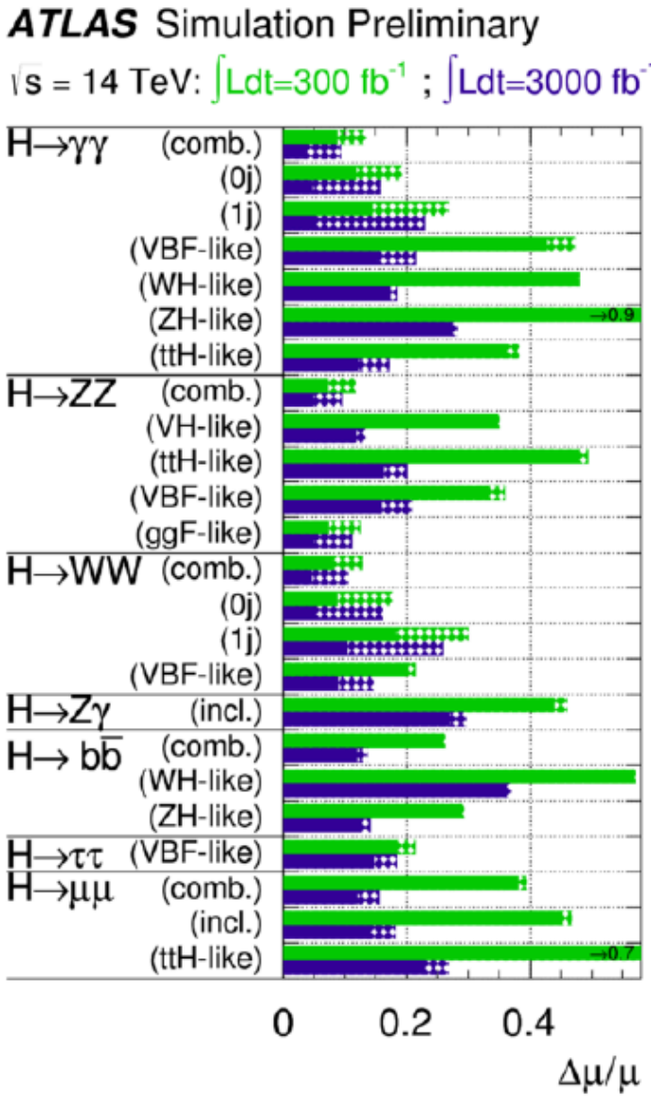


- **Possible reach for H→cc : 5xB(SM) with 300 fb^{-1} dataset**
- Note: LHCb acceptance presents a challenge when using integrated cross sections and uncertainties
- Recent Run2 ATLAS ZH, H→cc result: arxiv:1802.04329: $\mu<110(150^{+80}_{-40})$ @ 95%CL (36fb^{-1})

Run1-based couplings study

ATL-PHYS-PUB-2014-016





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
- Reduced theoretical uncertainties needed

Δκ/ κ = [no theory uncert., full theory uncert.] Model allowing contributions from new physics in loop

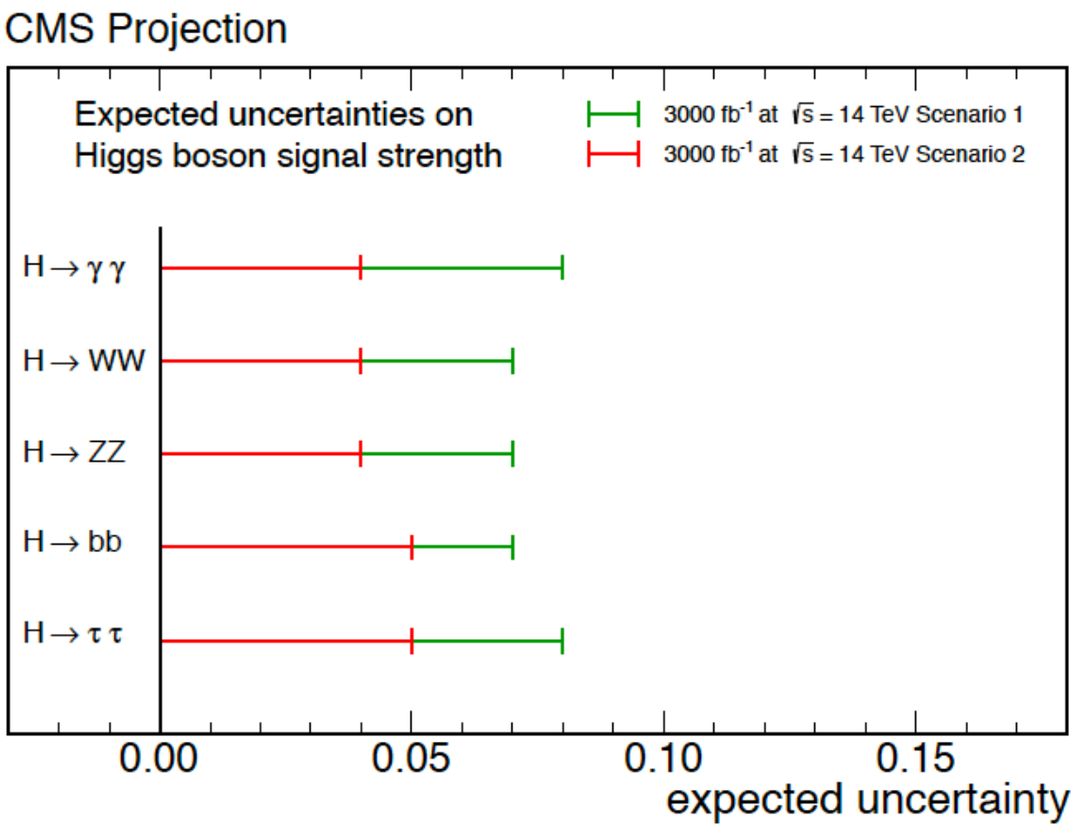
	κγ	κW	κZ	κg	κb	κt	κτ	κZγ	κμ
300 fb^{-1}	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
3000 fb^{-1}	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[8,8]

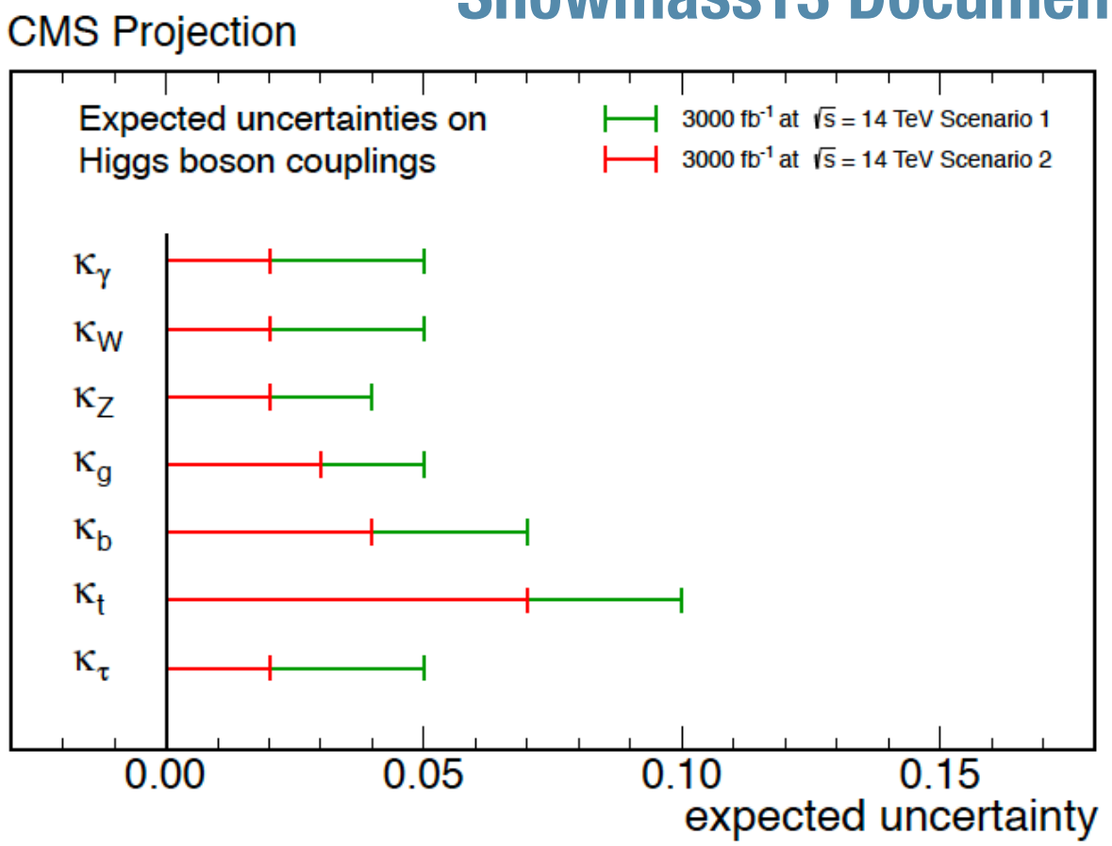
(%)

Run1-based couplings study

- **Comprehensive study of Higgs couplings at HL-LHC**
- Run1 extrapolations for the main decay channels and production modes

Snowmass13 Document





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]	[16,16]	[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]

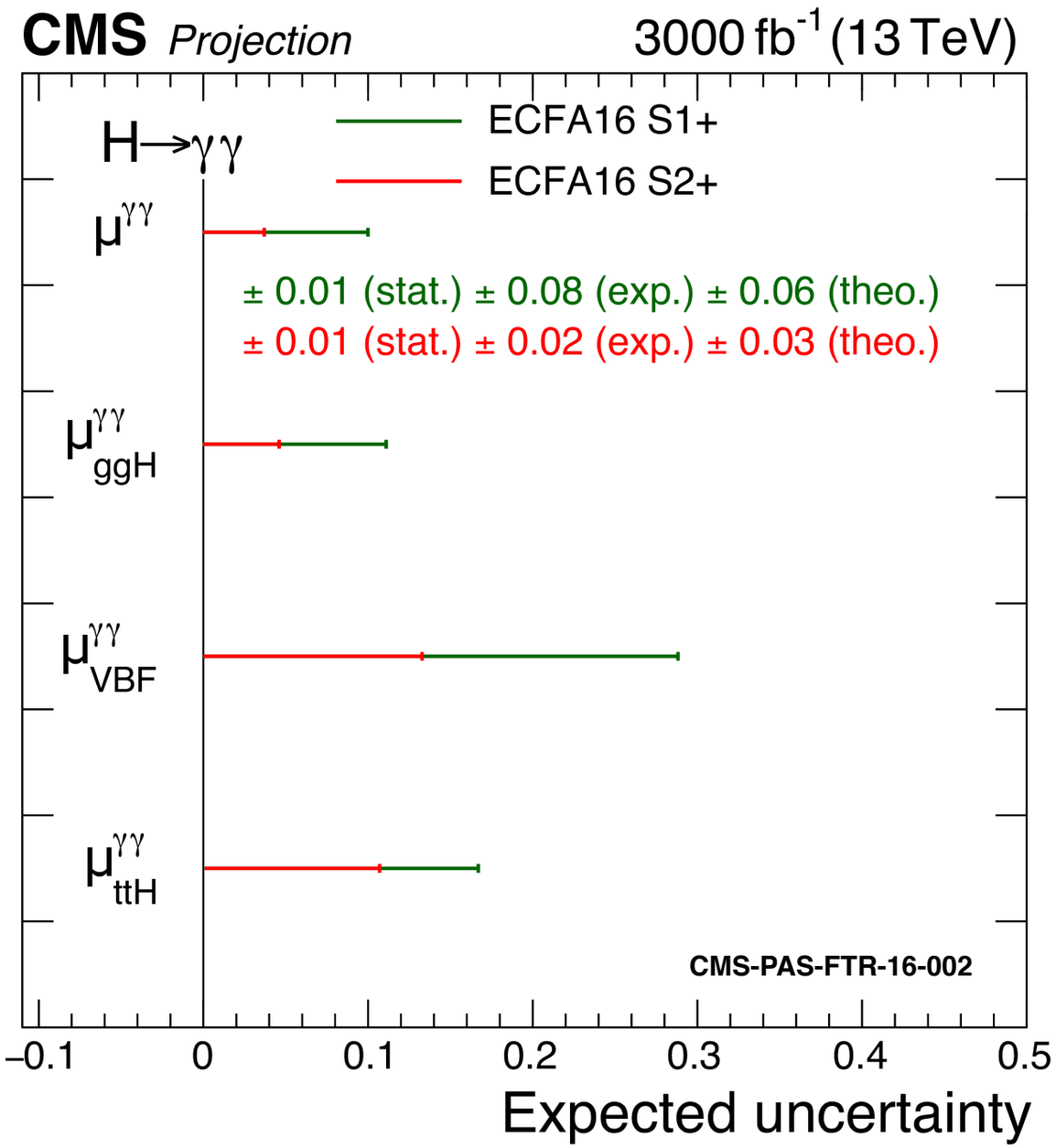
Coupling can be measured at the few % level

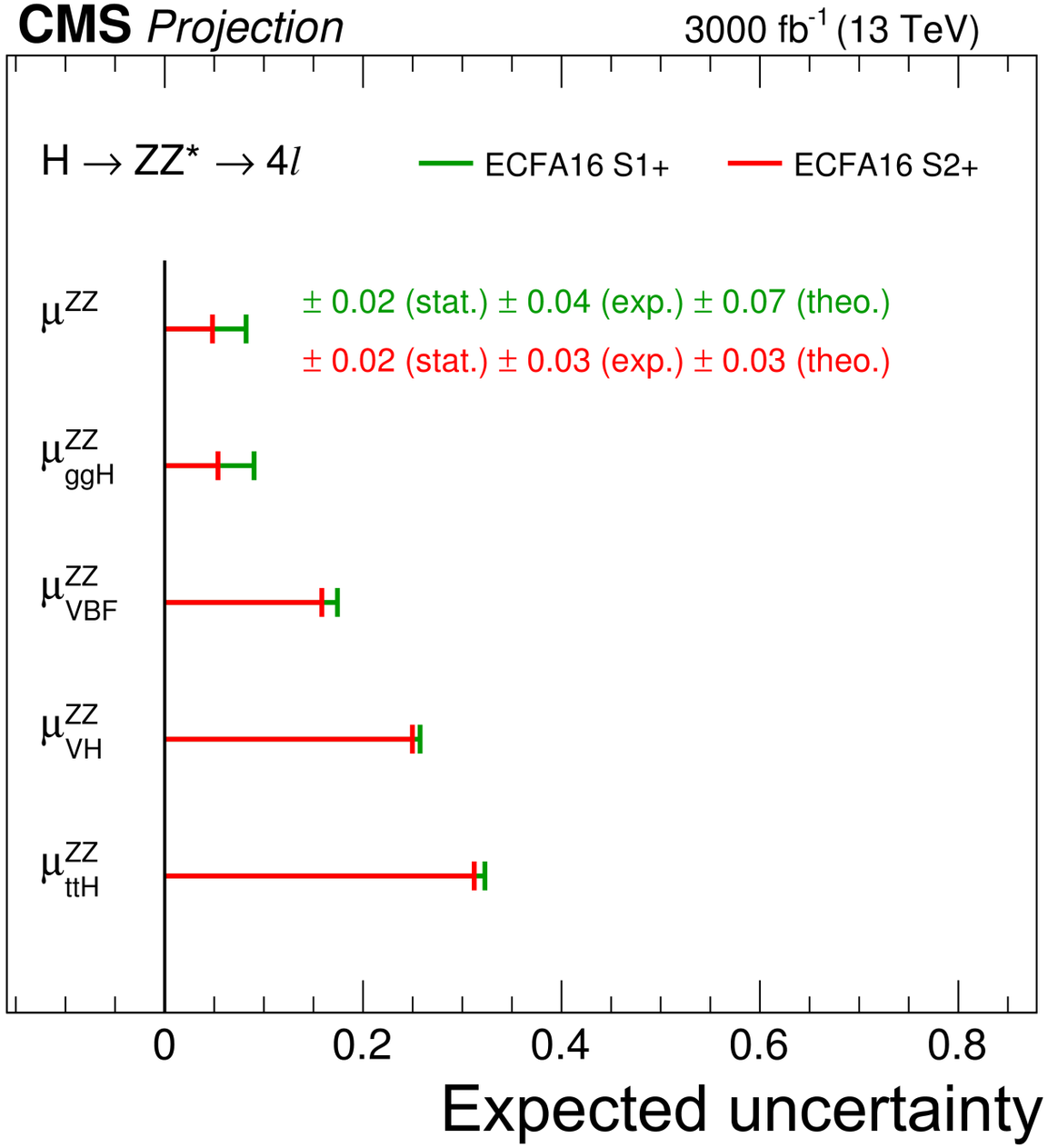
example: kt expected to improve substantially with the inclusion of latests channels

ECFA16 Update: H→γγ and H→ZZ

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

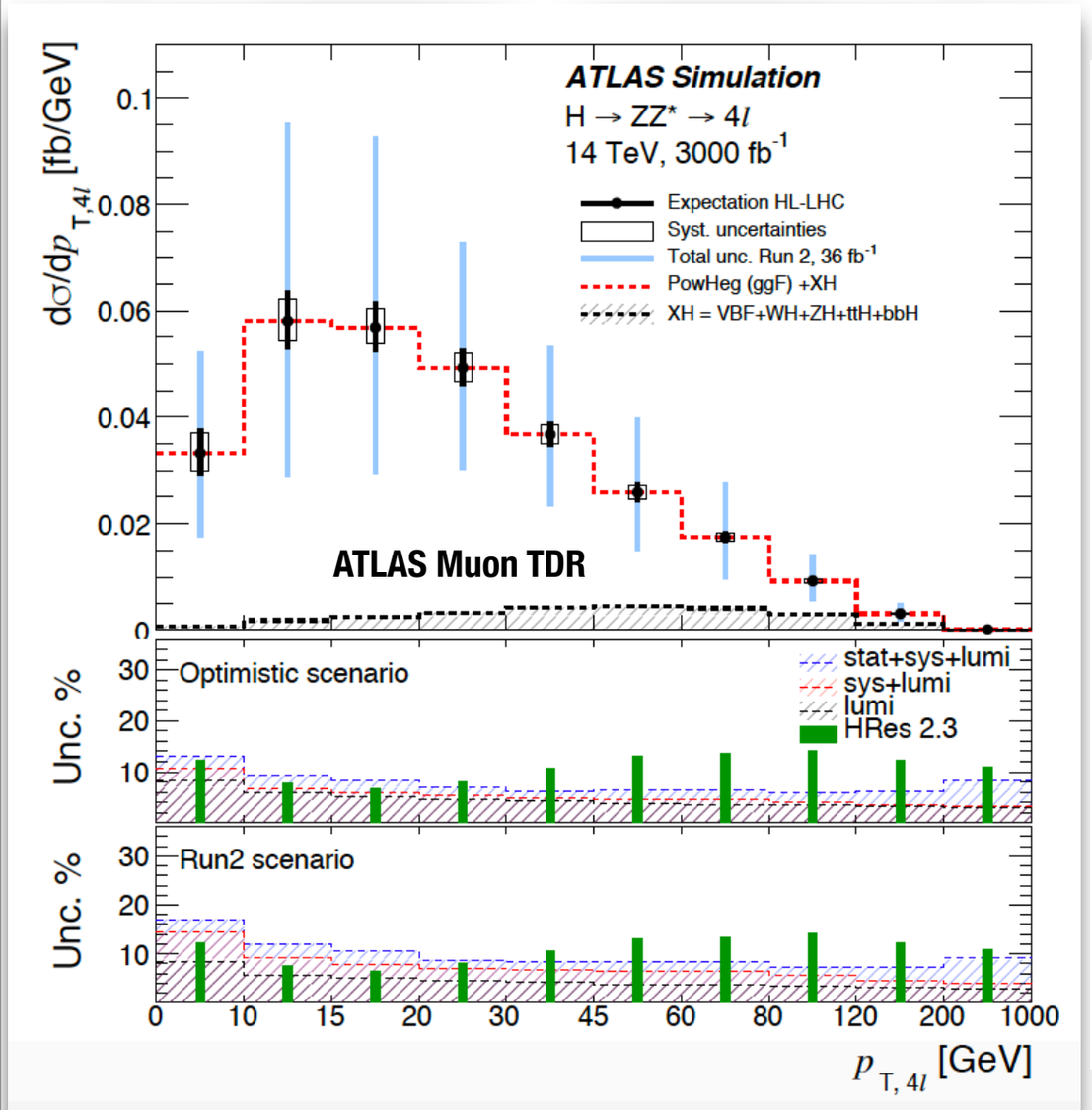
Effect of high pileup and detector performance considered based on the CMS Upgrade TP (LHCC-P-008)

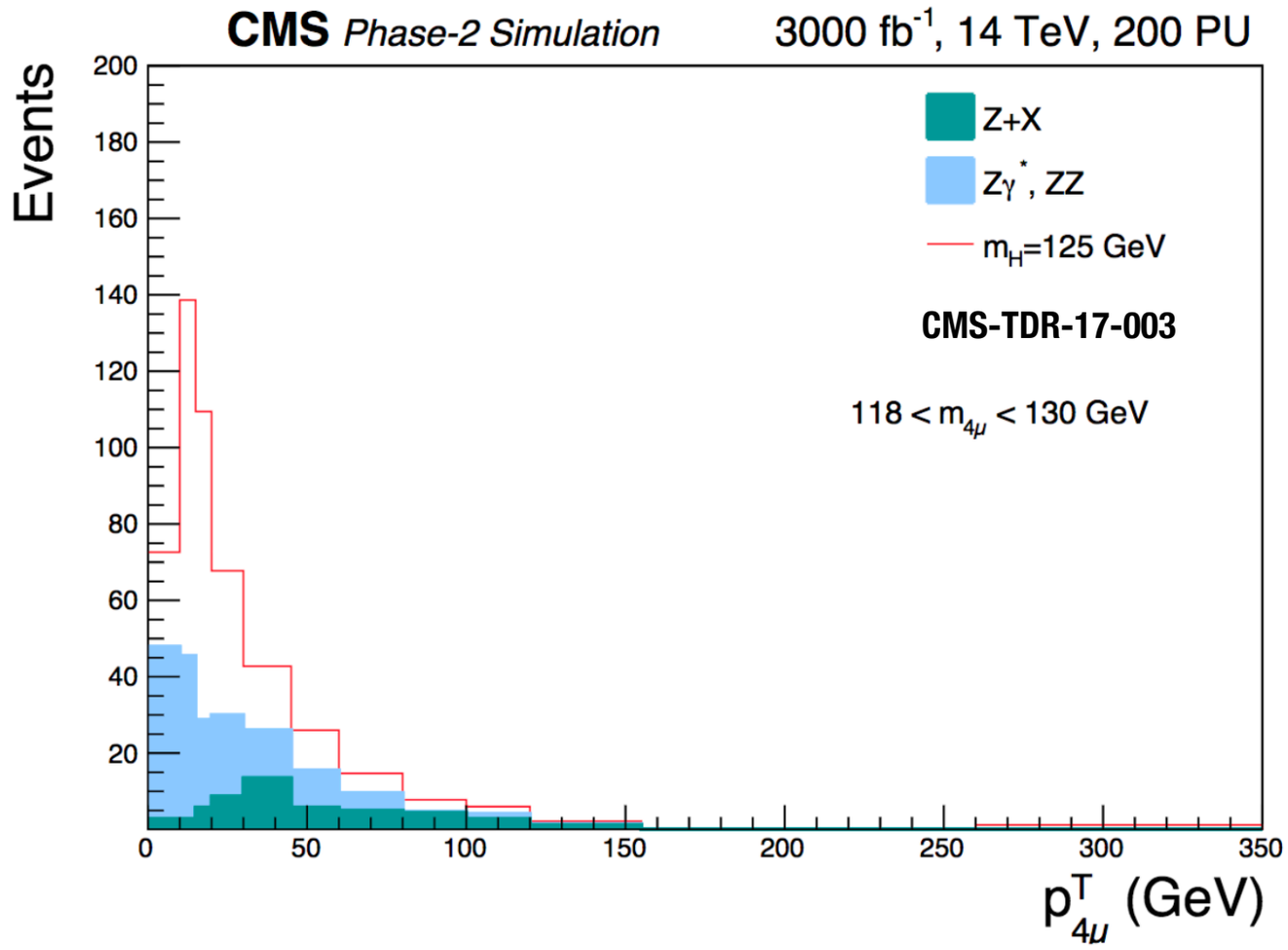




Differential & Fiducial Cross Sections

- Exploit the large dataset and go beyond inclusive measurements



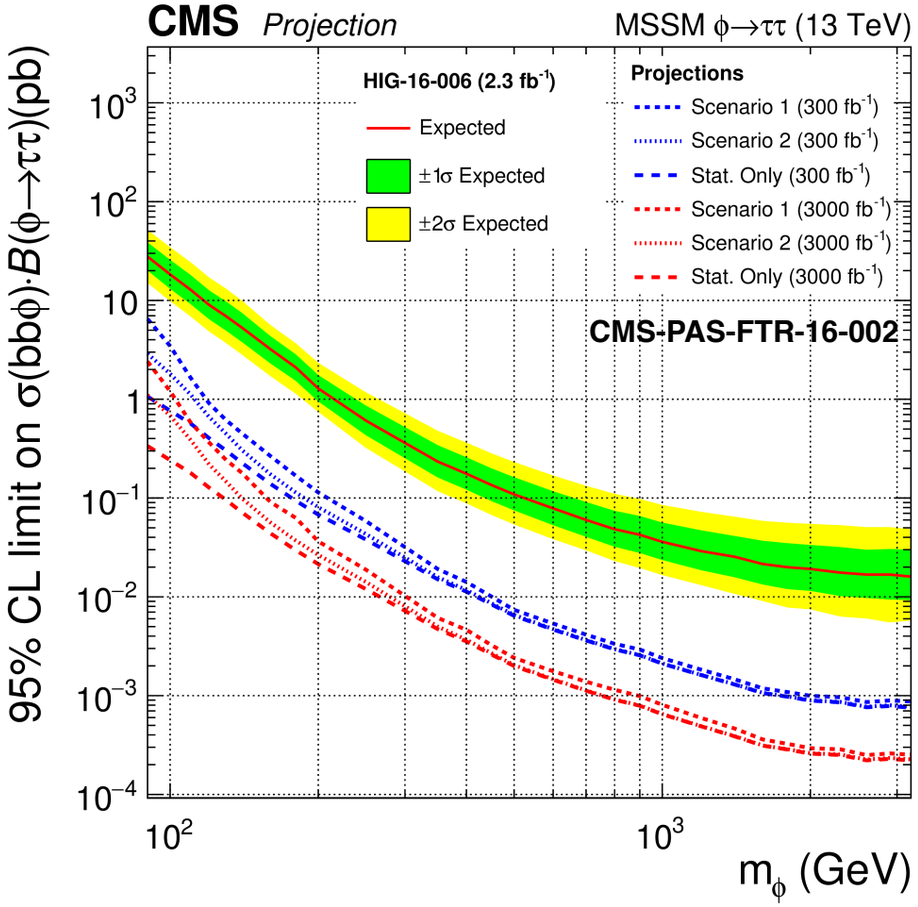


- Sensitive to k_b/k_c (low p_T) k_t/BSM (high)
- At high p_T, dominated by statistical uncertainty even @ 3000 fb^{-1}

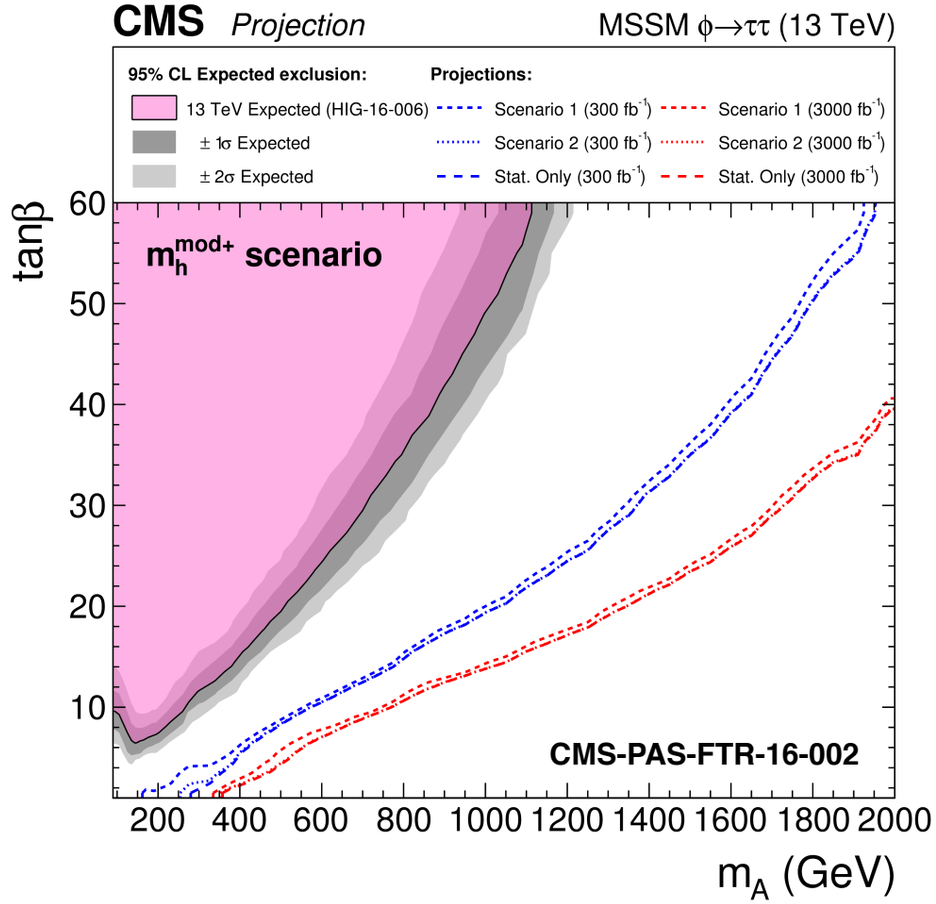
MSSM H→ττ

- **Key channel for constraining extended Higgs Sectors**
- Plan to update it for the YR taking into account latest analysis improvements
- Sensitivity at high mass dominated by statistics even at 3000fb^{-1}
- MSSM parameter space can be heavily constrained, even up to 2 TeV of mass

Limits on ggH / bbH cross section

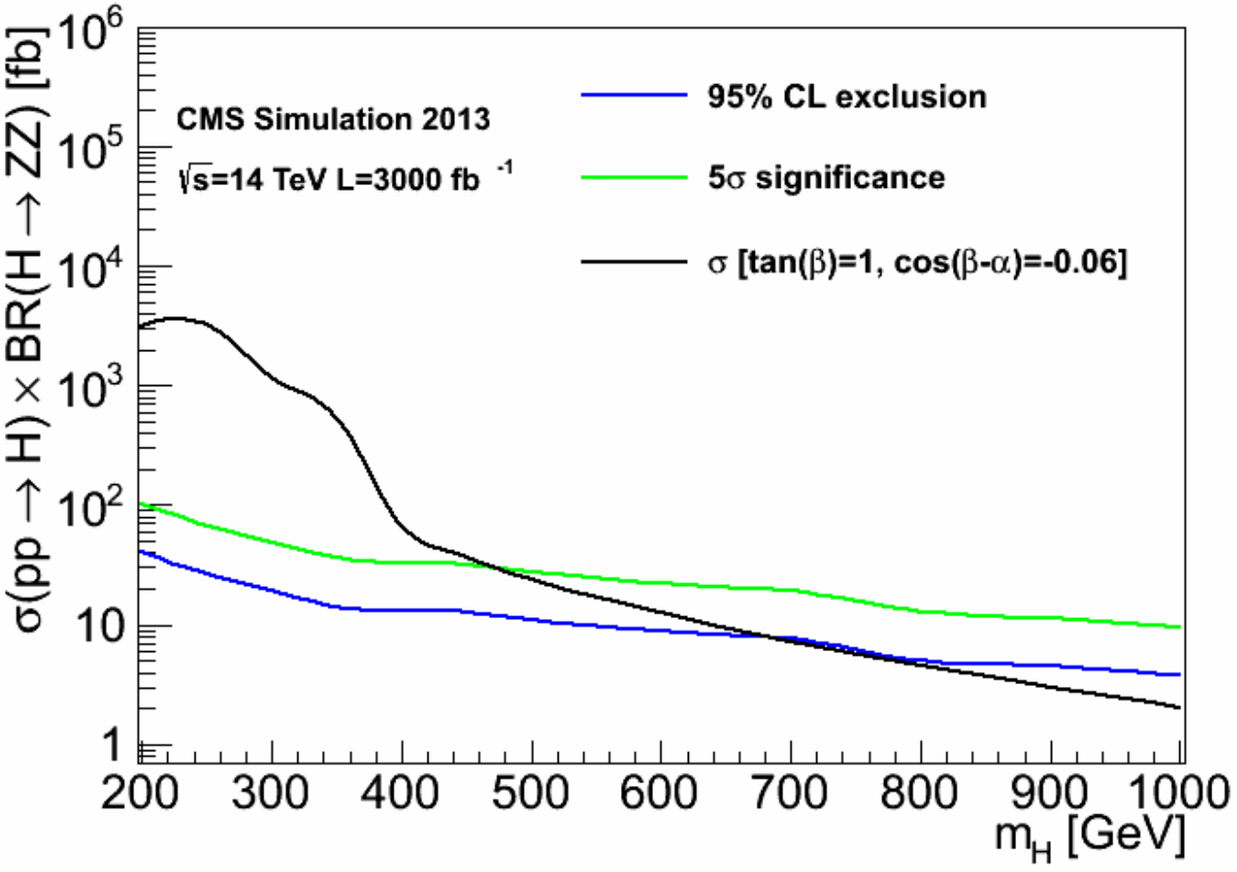


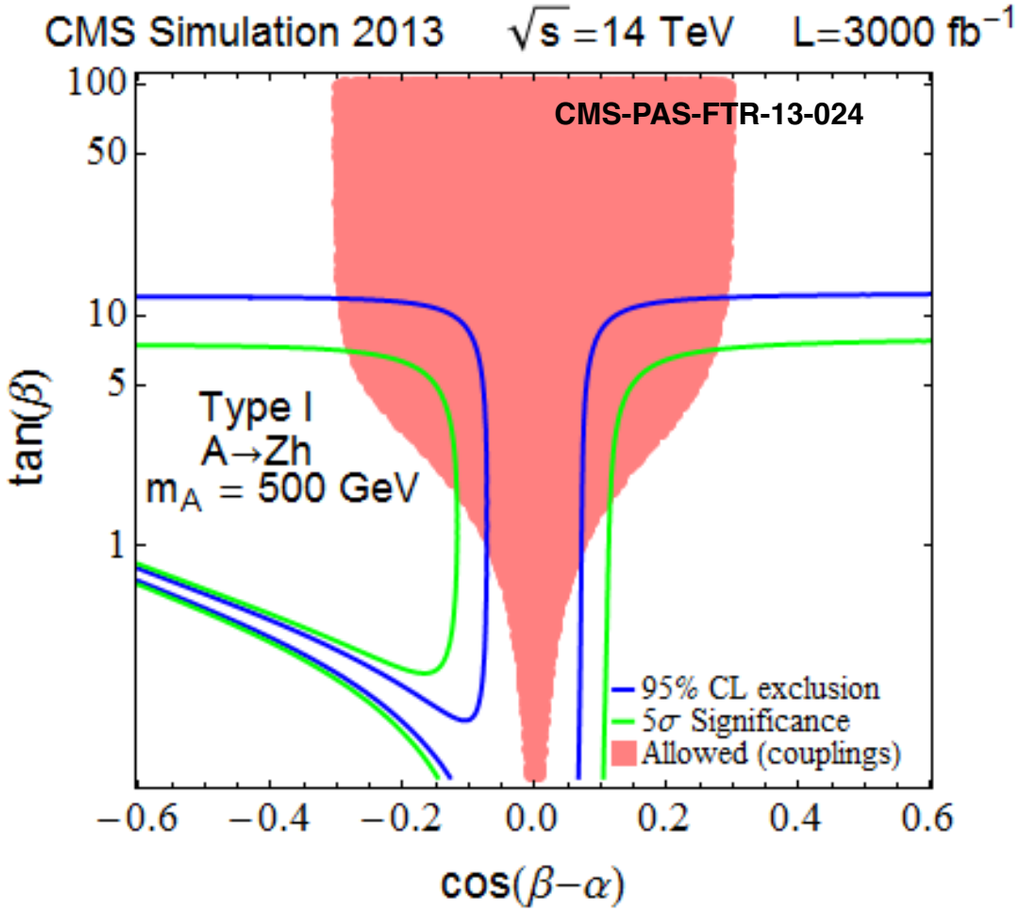
Limits on m^{mod+} benchmarks



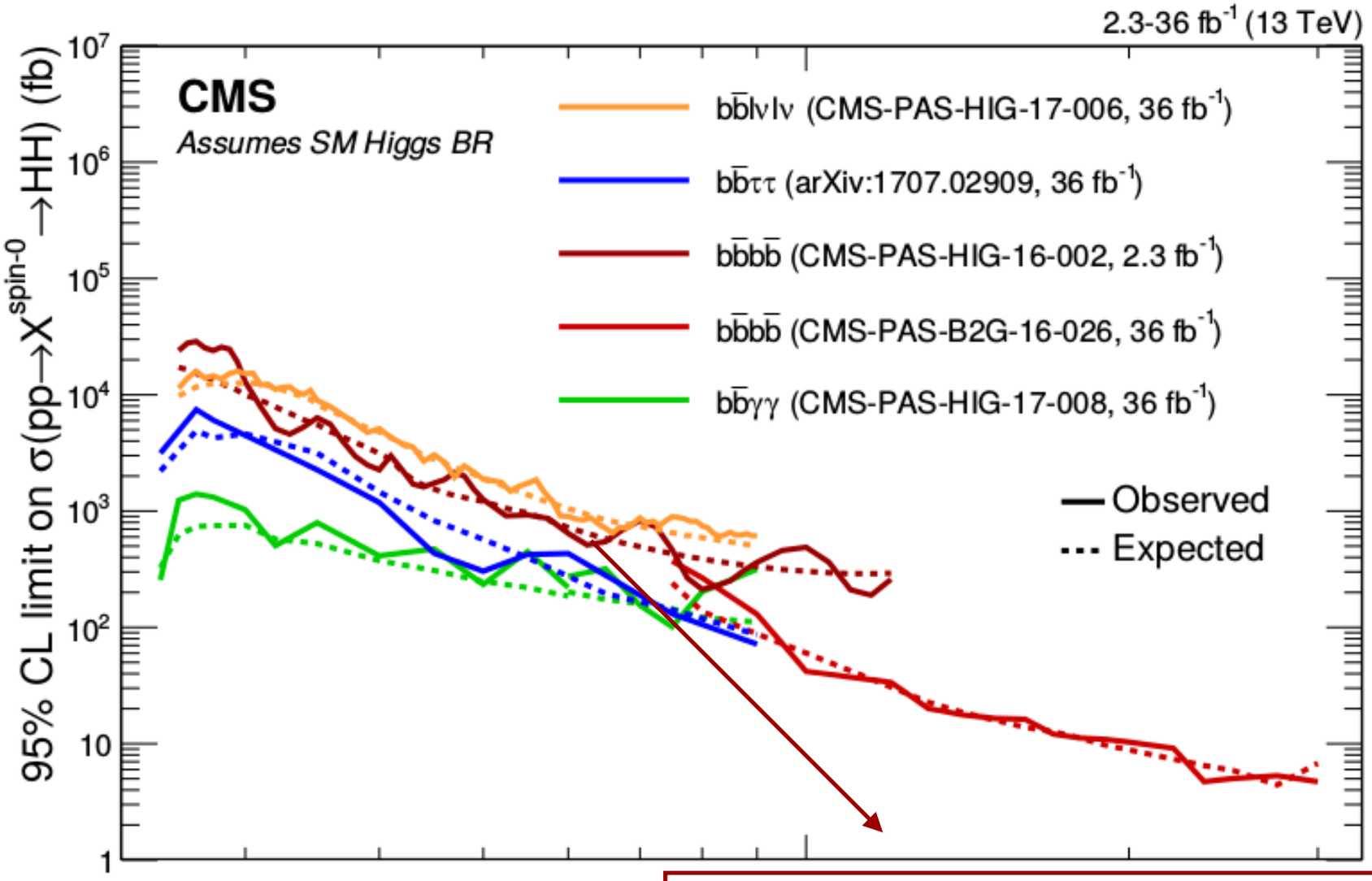
Other BSM Higgs Searches

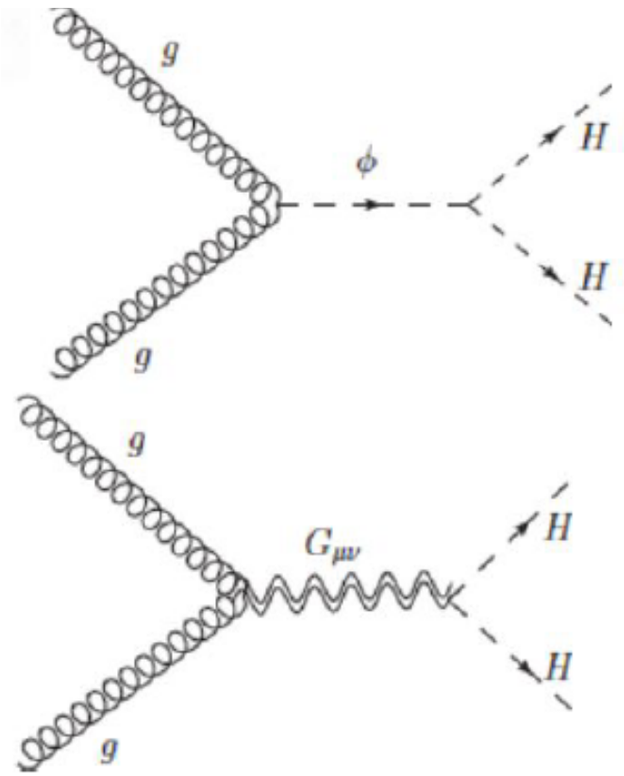
- H→ZZ→4l and A→Zh→llbb searches in the 2HDM context
- Cross Section limits, and interpretation in terms of tanβ-cos(β-α) exclusion
- Complementary approach to precision measurements of the SM-like Higgs boson couplings in constraining the 2HDM phase space, for sufficiently low masses of the heavy Higgs bosons





Resonant DiHiggs Searches



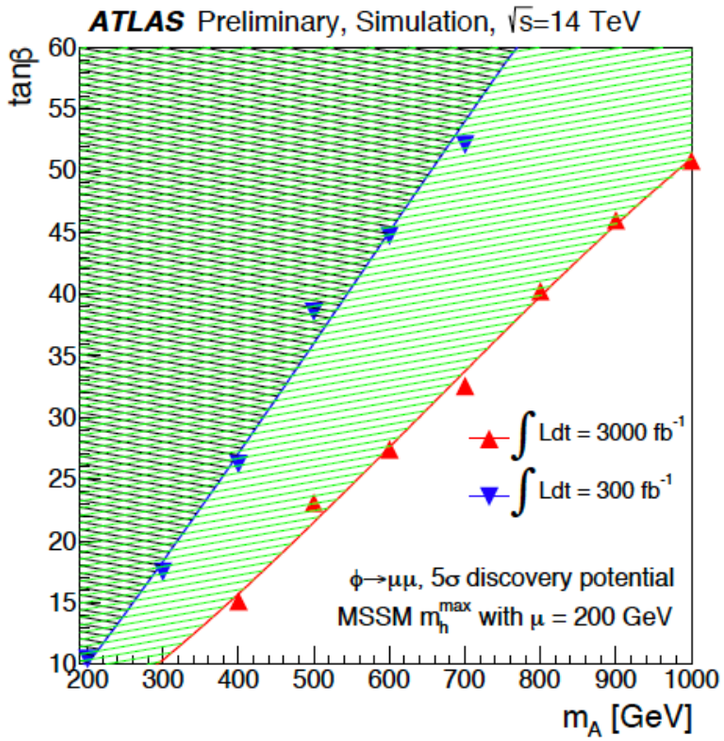


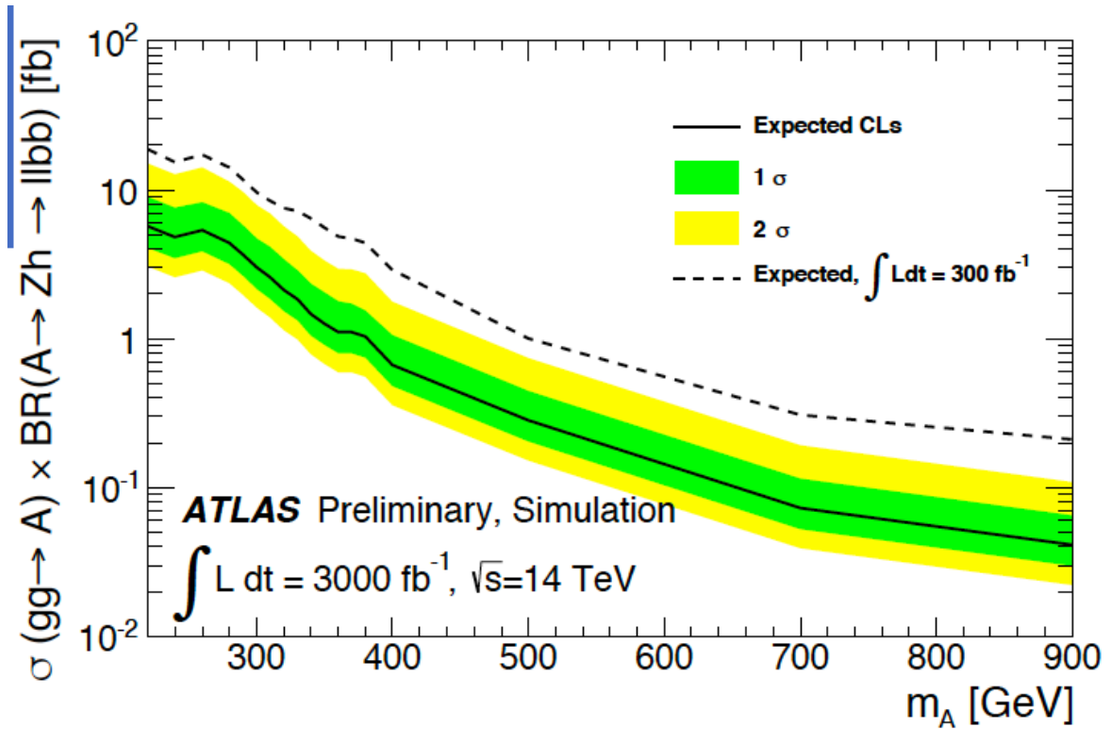
Projections from 2015 4b analysis

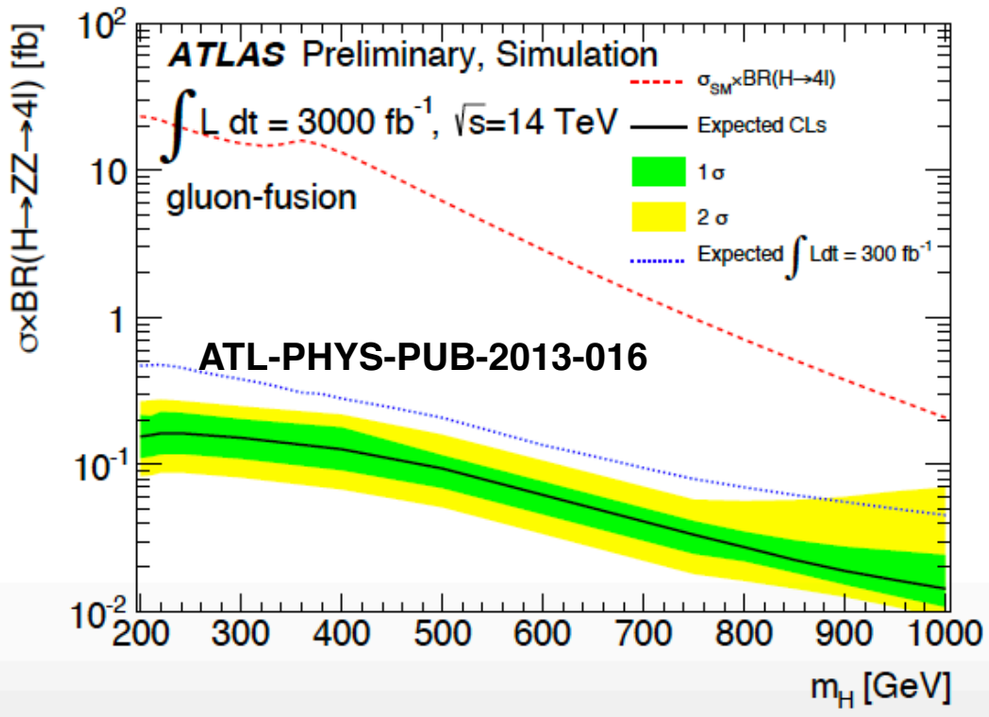
m_X (TeV)	Median expected limits on σ (fb) ECFA16 S2	Stat. Only	$\sigma_R^{NLO}(\Lambda_R = 1\,\text{TeV})$ (fb)	Λ_R (TeV) excluded ECFA16 S2
0.3	46	41	7130	13
0.7	7.3	3.4	584	8.9
1.0	4.4	2.4	190	6.6

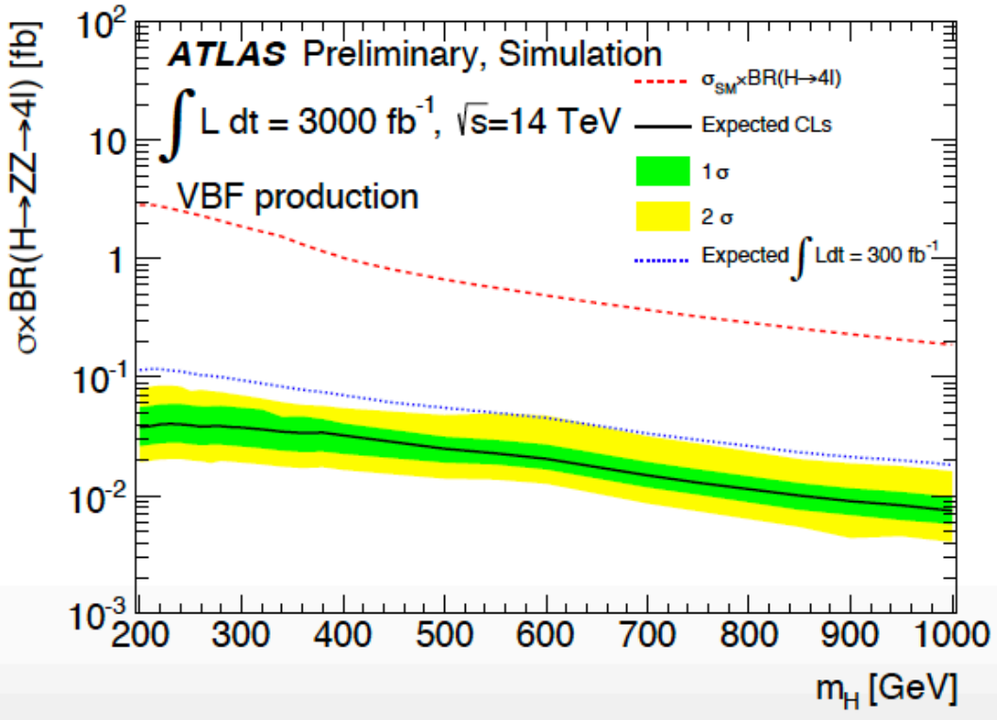
CMS-PAS-FTR-16-002

Other BSM Higgs Searches









Indirect BSM probes and EFT

- Thanks to HXSWG for developing the SM EFT framework for parametrisation of EFT effects

- Specific theoretical projects within HL/HE working group:
  - differential measurements of tth
  - differential measurements of WH/ZH at high energy
  - exploit polar and azimuthal distributions in WW and WZ processes
  - longitudinal VBS and di-Higgs
  - improved global fits at high-energy/luminosity

BSM Higgs Searches

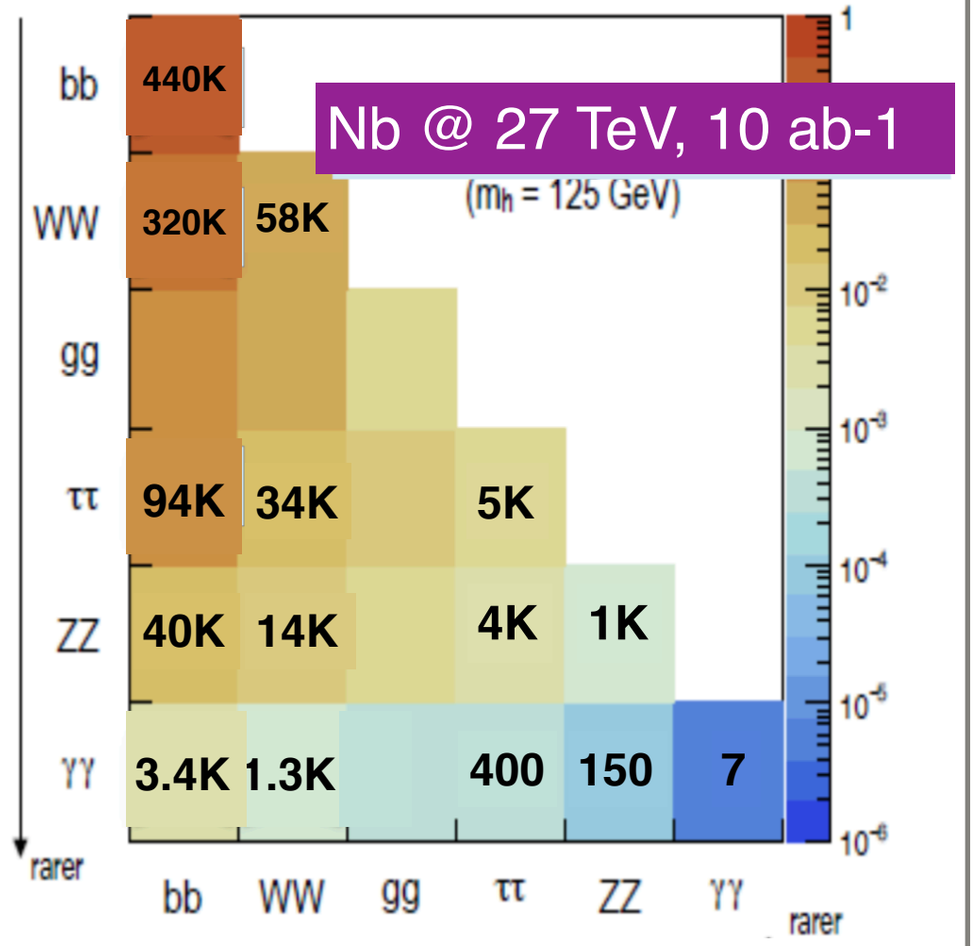
- Thanks to HXSWG for the study of benchmark models to be adopted by ATLAS+CMS and proposing new channels to search for additional Higgs bosons/new Higgs decays

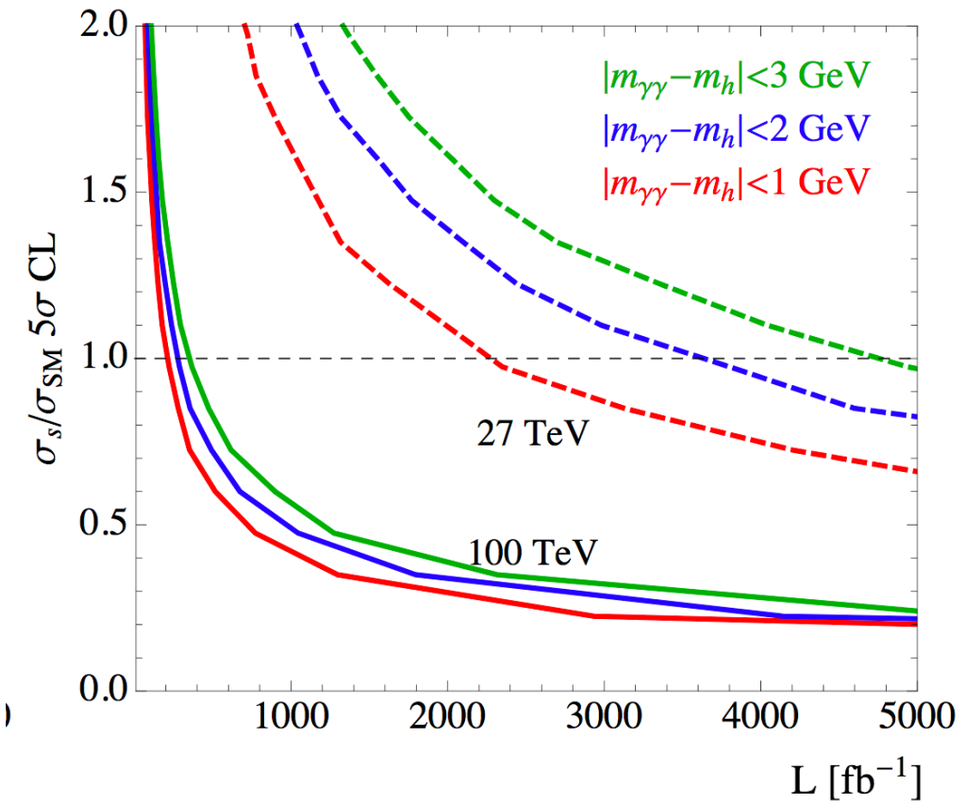
- Theoretical developments planned for the HL/HE workshop:
  - interpretation of Higgs coupling measurements in SUSY and 2HDMs
  - study of Higgs rare decays to NP particles (particular focus on HE)
  - study of light (m<125GeV) new Higgs bosons. What can the HL and HE offer?
  - New techniques for highly boosted new Higgs bosons

Work in progress!

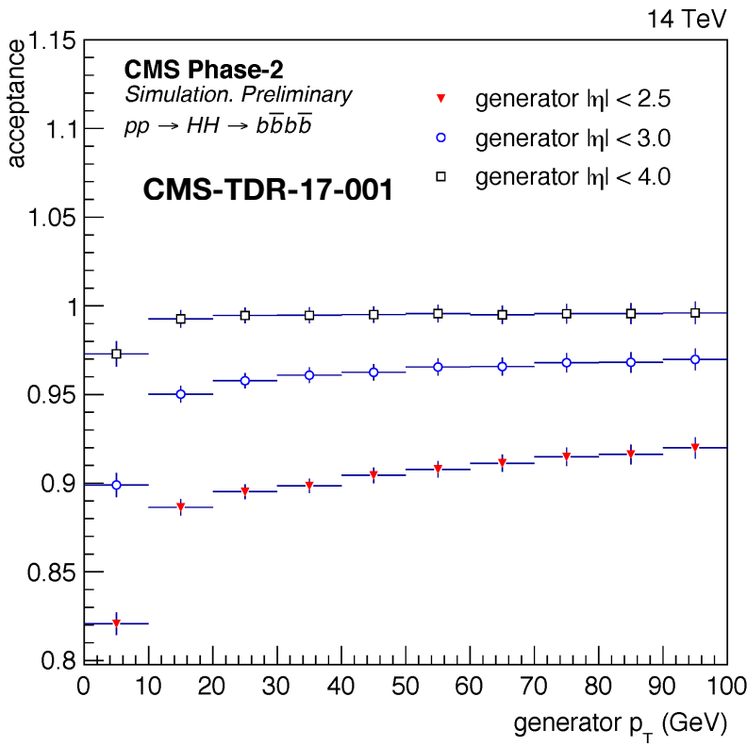
DiHiggs at HE?

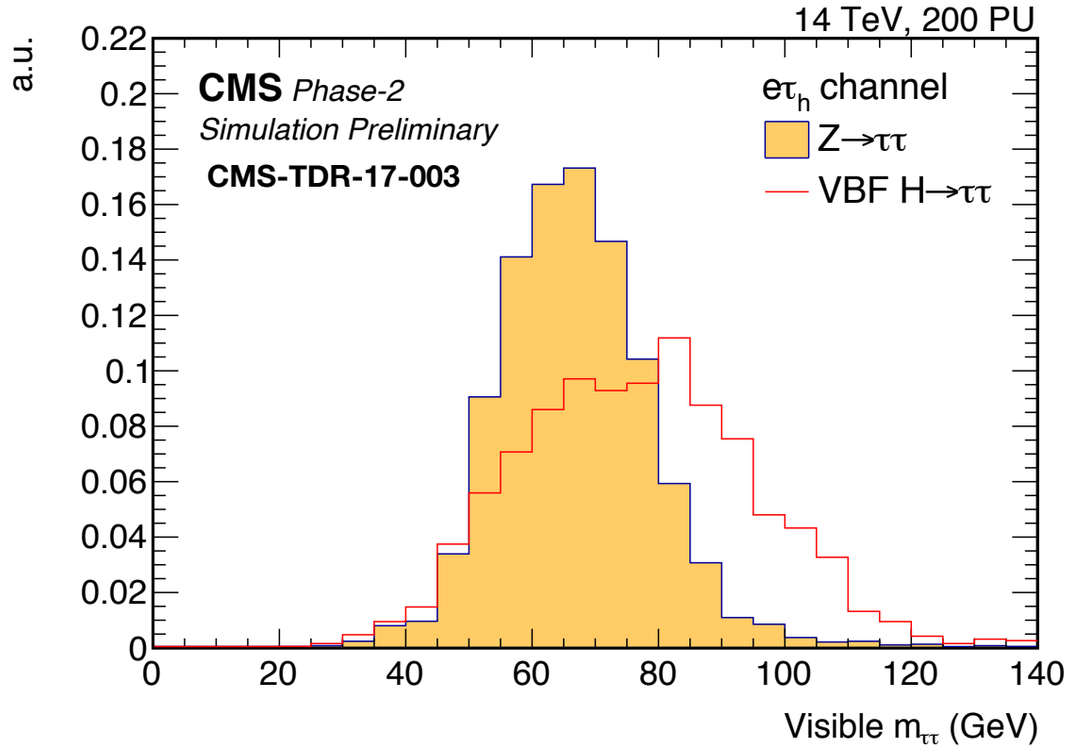
- Large rates at HE (NLO xsec 127.88+-11%fb, G. Heinrich)
- Recent theory study for the prospects at HE: https://arxiv.org/pdf/1802.04319.pdf (~30% accuracy in the measurement of the Higgs self-coupling using pp->hh->bb gamma gamma, 15ab-1 luminosity assumed).

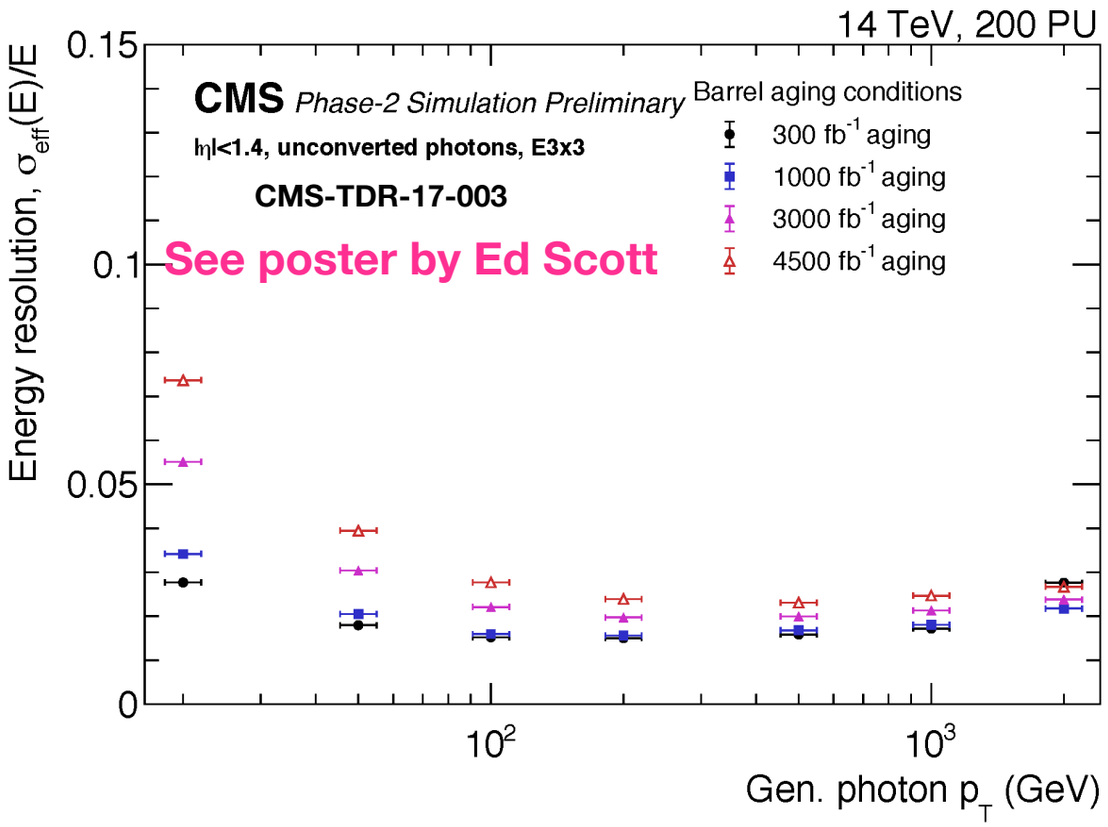


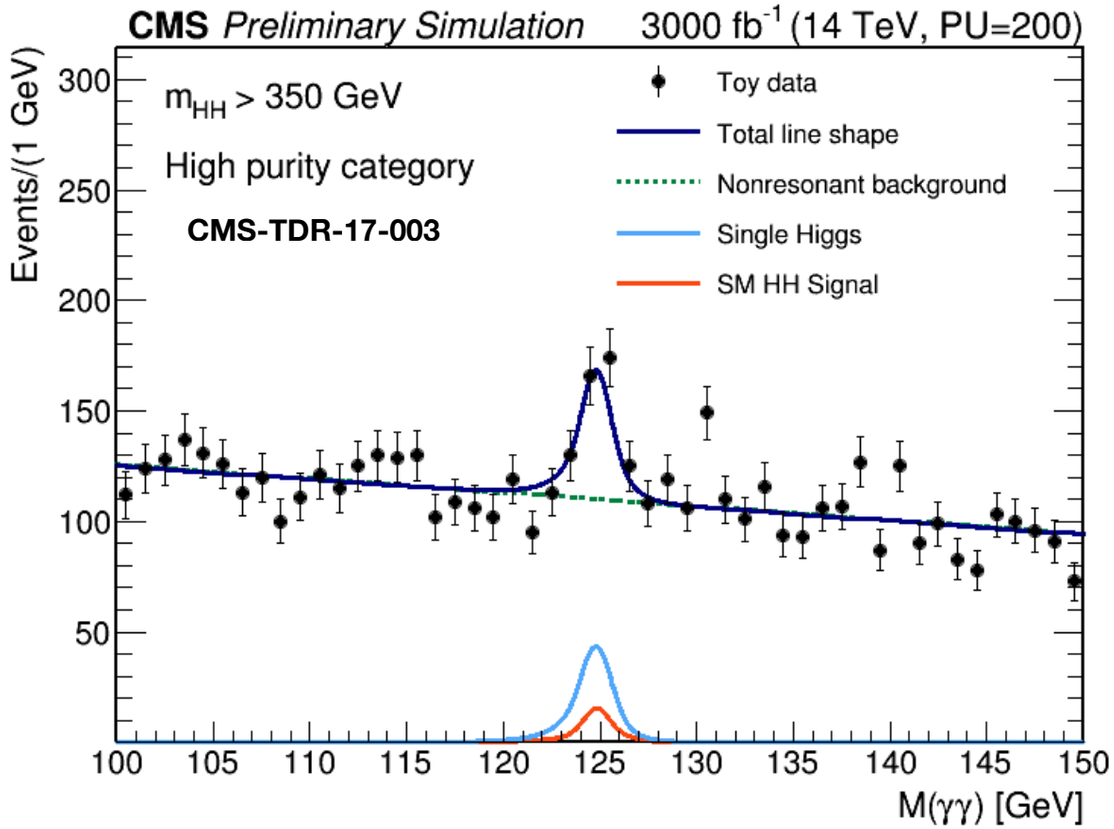


2017 Phase II Upgrade TDRs









Higgs Studies in the Report

1. Precision Measurements
(indirect BSM probe through EFT)

- **1.1** Low energy Higgs couplings
- **1.2** High energy differential measures.

2. Rare Higgs Processes & New resonances

- **2.1** SM Higgs boson
- **2.2** New Higgs bosons

High lumi

High energy

From Stefania Gori's Summary talk at the KickOff meeting in November