CMS & LHCB:
HIGGS @ HL-LHC

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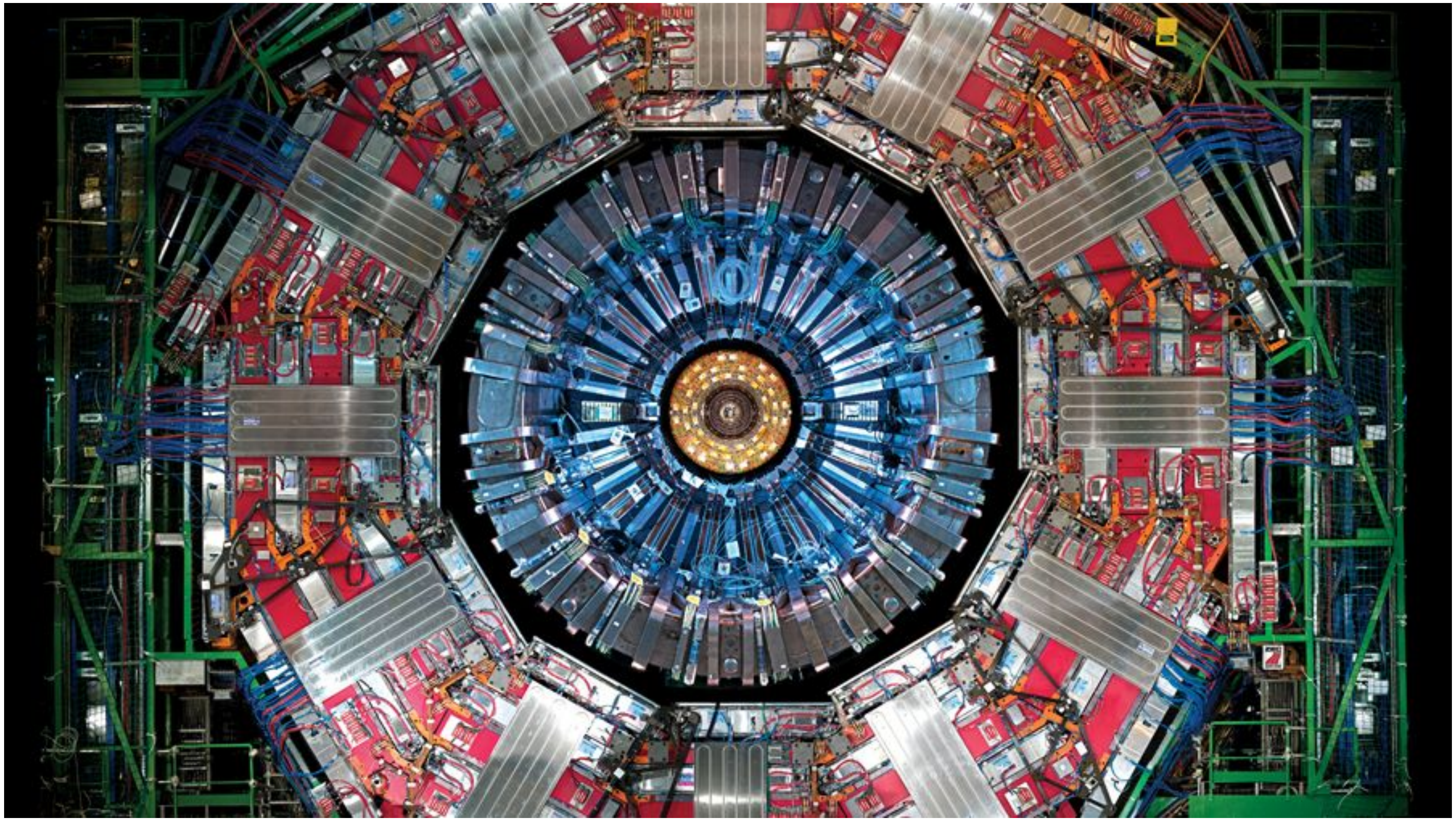
Workshop on the physics of HL-LHC, and perspectives at HE-LHC CERN
30 October 2017 - 1 November 2017

CMS: Higgs prospects at HL-LHC

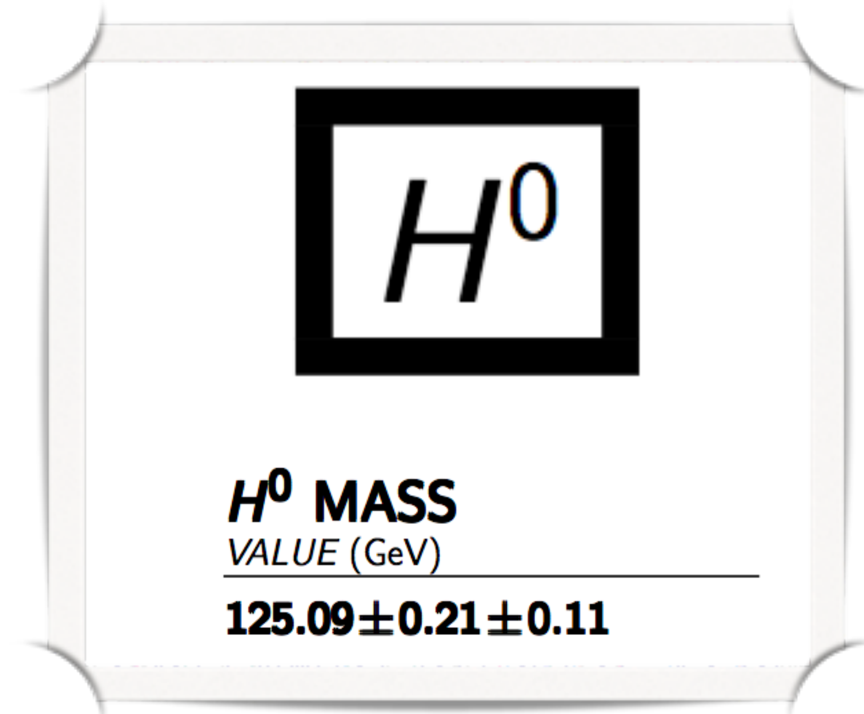
- Higgs boson studies are central to the HL-LHC program
- **CMS** has performed projections that exploit the upgrade of the detector planned for Phase II, to provide a picture of the experimental reach of Higgs boson measurements and searches with 3000 fb^{-1}

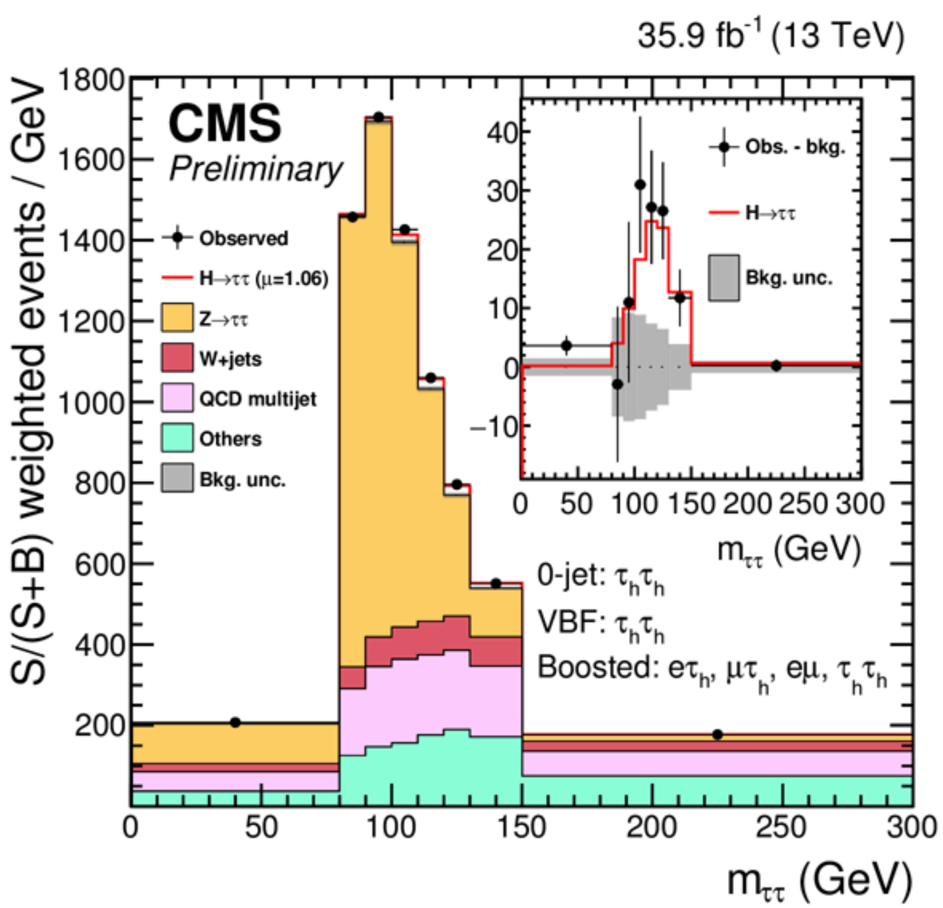


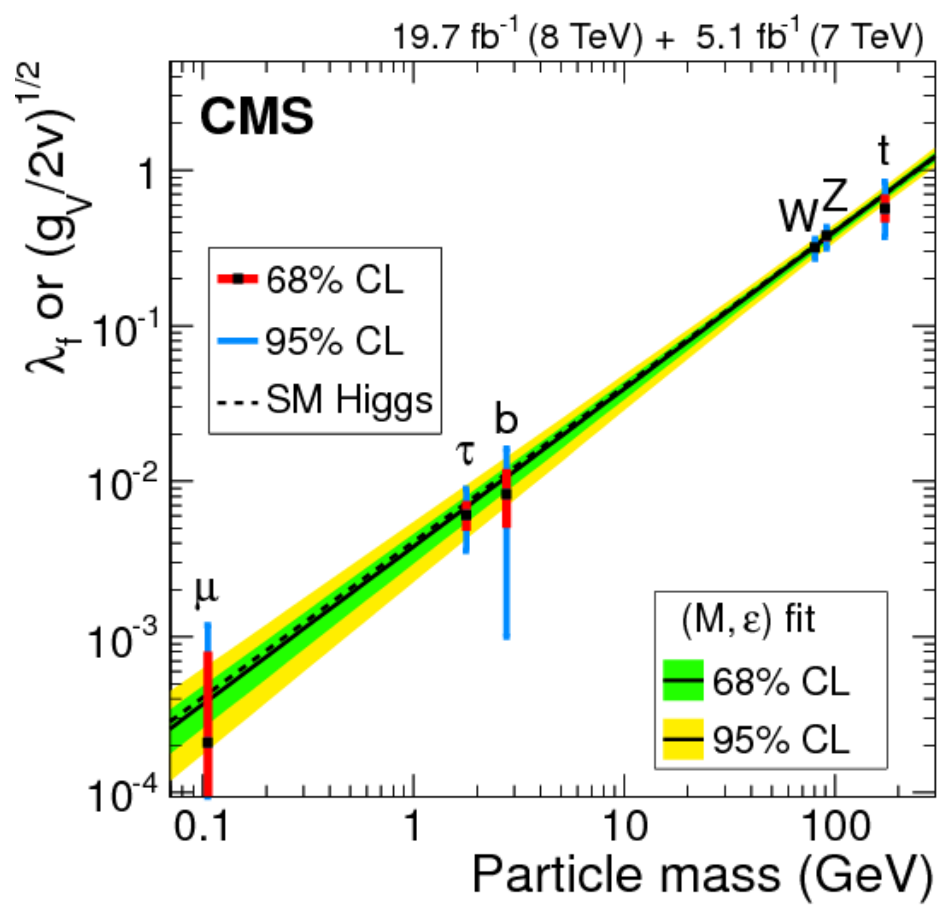
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

Higgs @ CMS Run2

- **Remains stubbornly Standard Model-like**
- Mass measured to 0.2%
- Main couplings to ~10%







Higgs @ HL-LHC

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

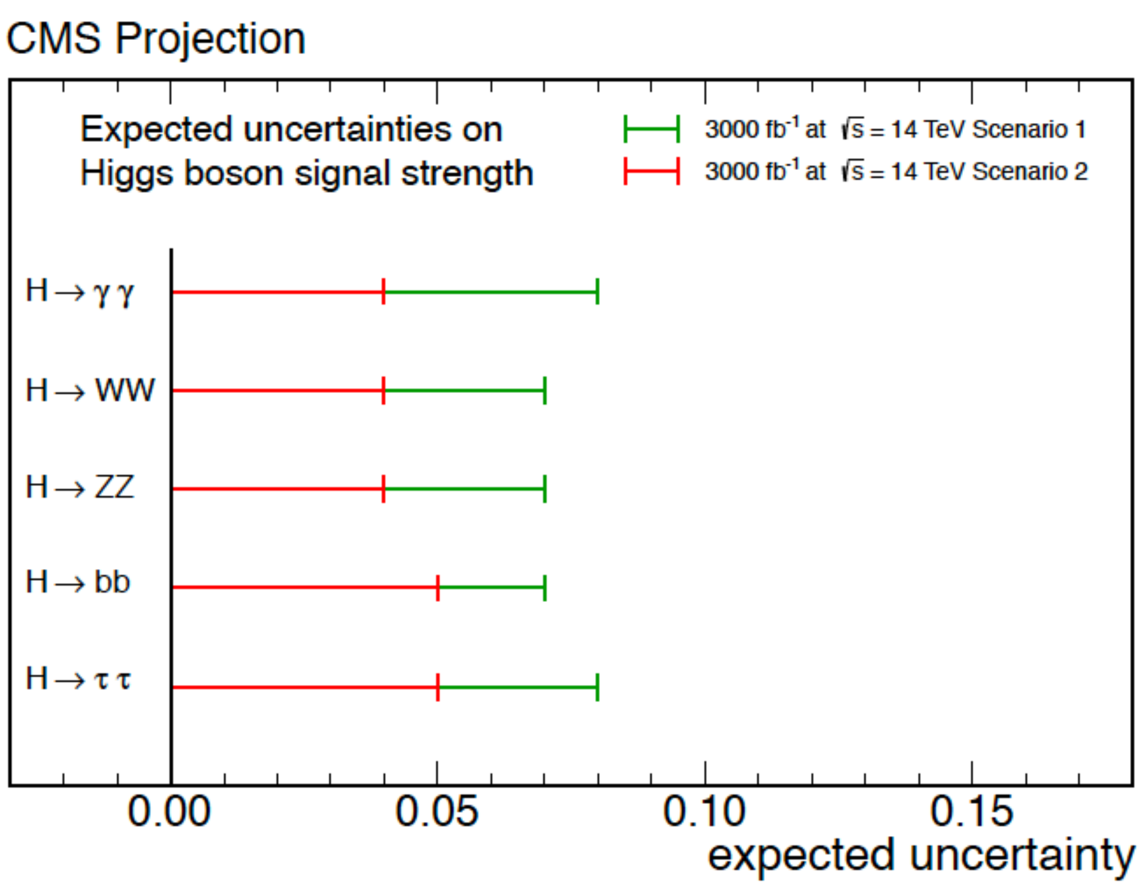
- **Precision Measurements** (Couplings to ~5%, Cross Sections, Differential Distributions, Width…)
- **Rare decays**
- **Di-Higgs production ➜** self coupling
- **BSM Higgs searches** (extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings)

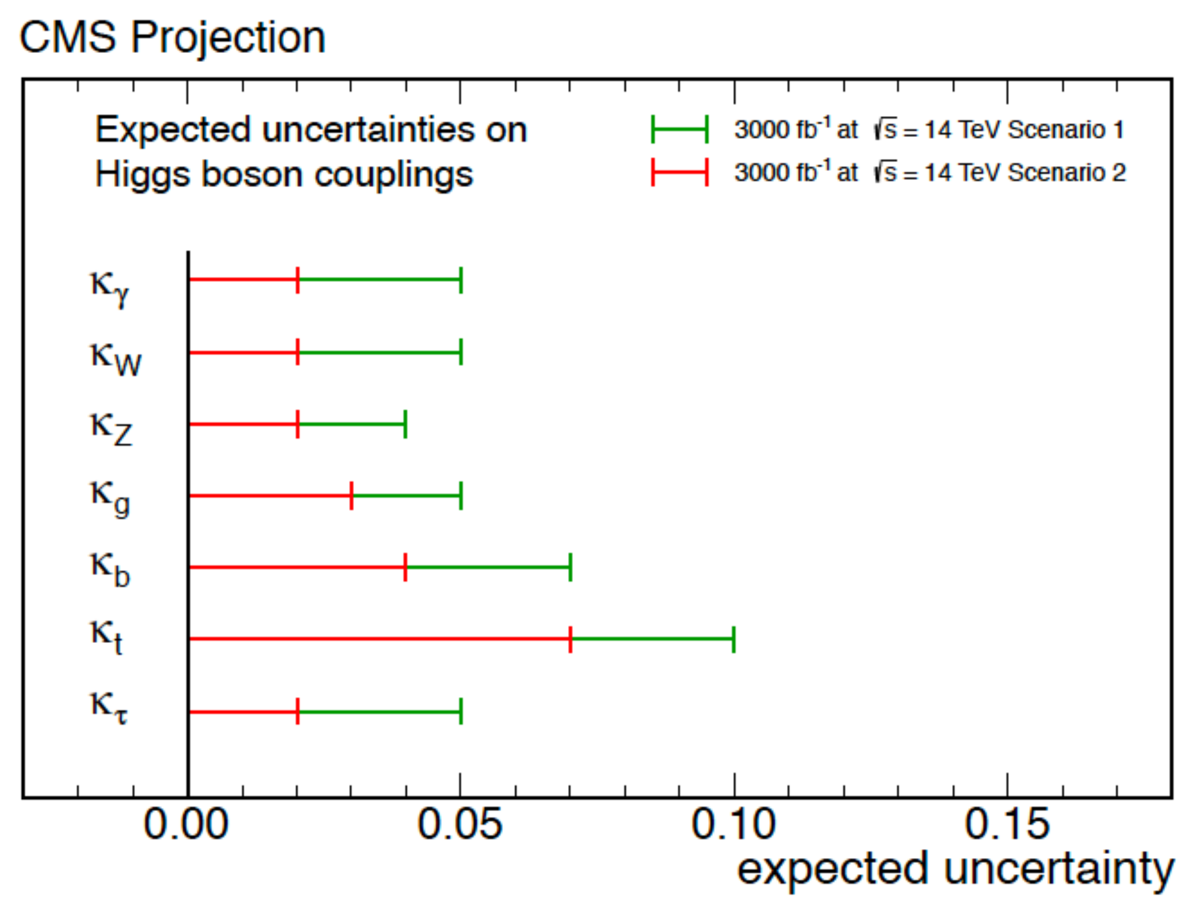
Technical Details

- Dual strategy:
  - **Extrapolation** of public results with 8 and 13 TeV to larger data sets of 300 and 3000 fb^{-1}. Different uncertainty scenarios:
    - **Scenario 1 :** Unchanged systematic uncertainties
    - **Scenario 2 :** Experimental uncertainties scaled $1/\sqrt{L}$; theory uncertainties halved
  - **Detector simulation of the upgraded CMS** (CMS-Delphes or Full Simulation) for specific channels, specially oriented to dedicated performance studies

Snowmass13 couplings study

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





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]

(%)

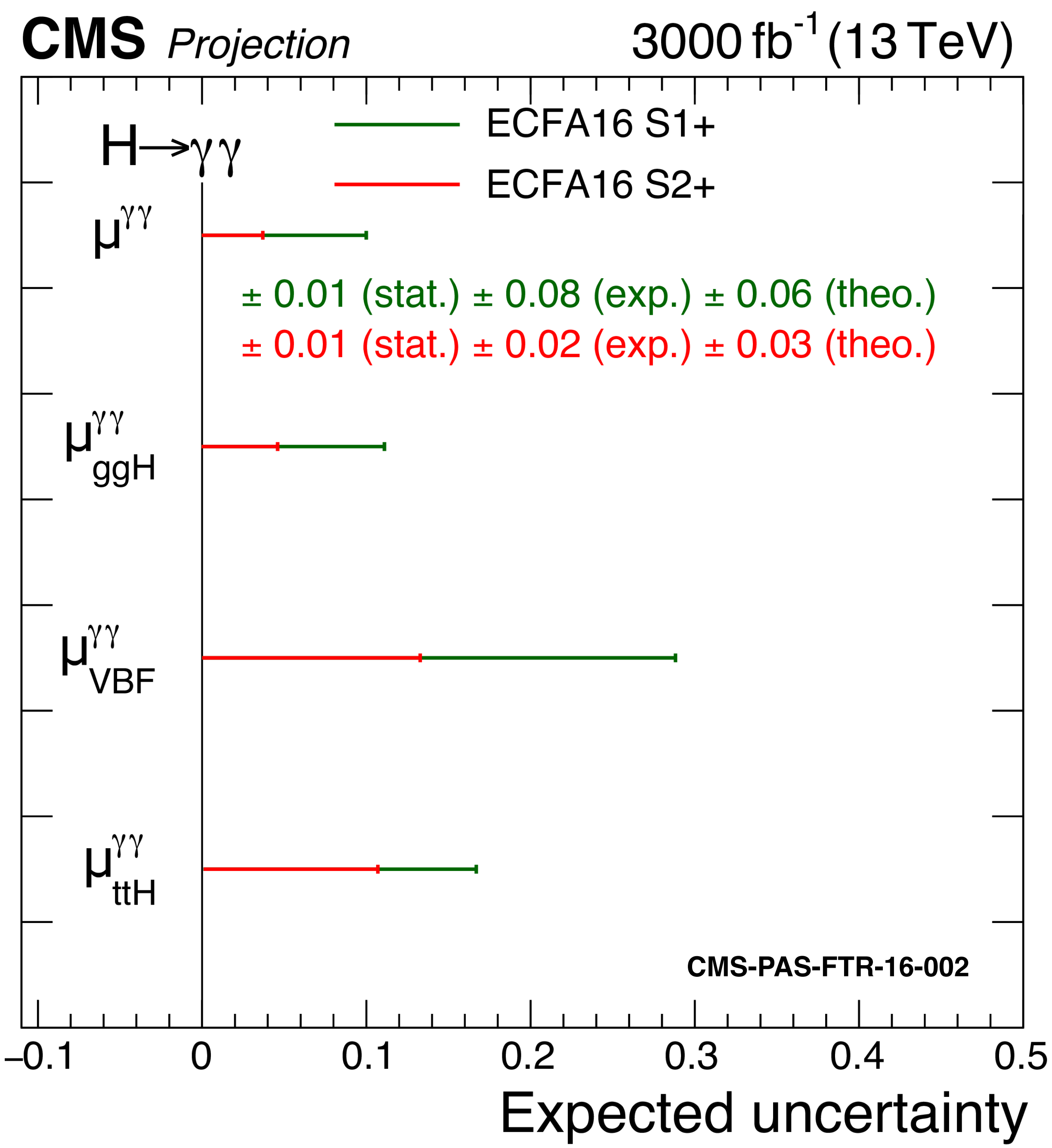
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

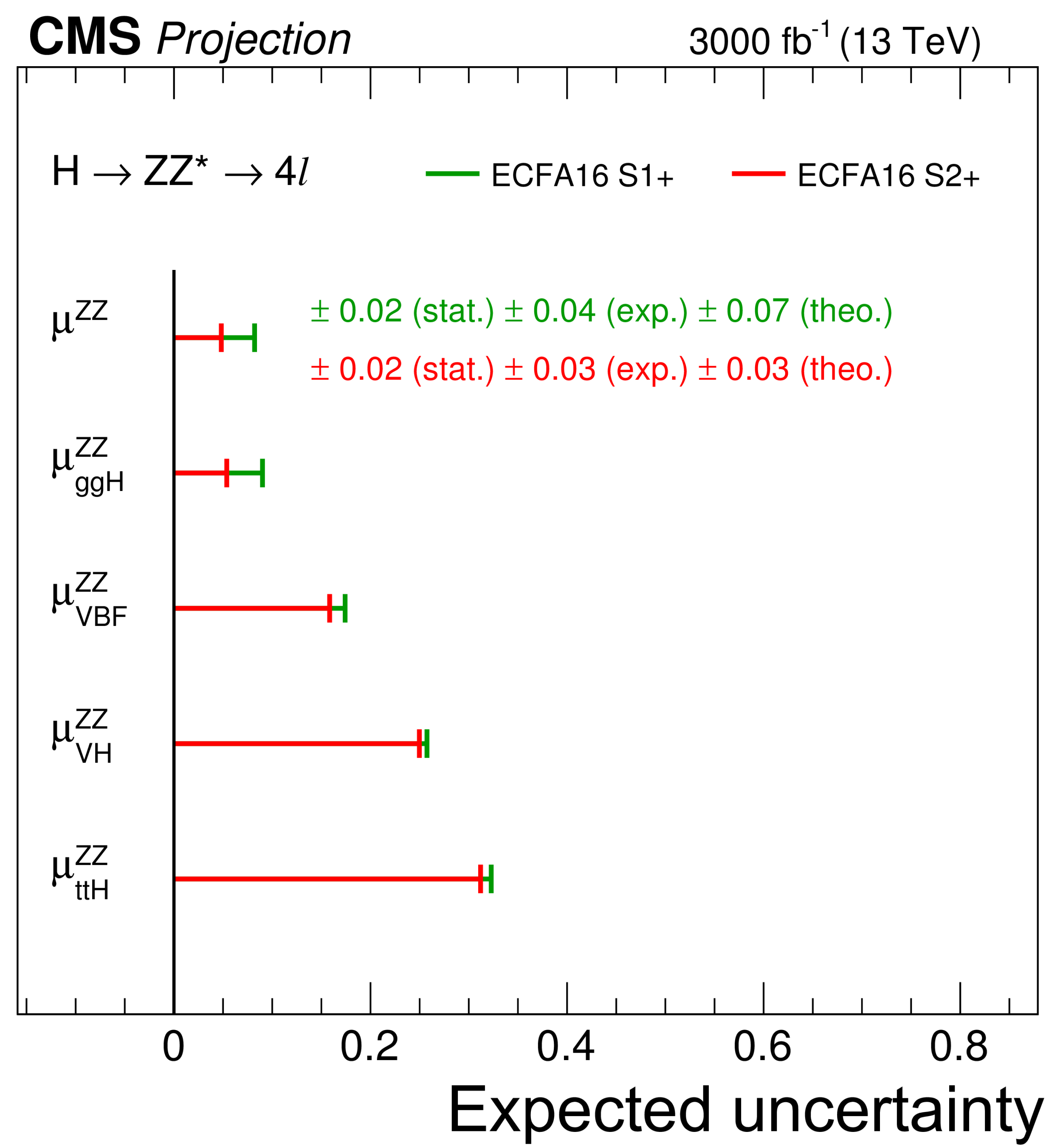
Coupling can be measured at the few % level

ECFA16 Update: H→γγ and H→ZZ

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

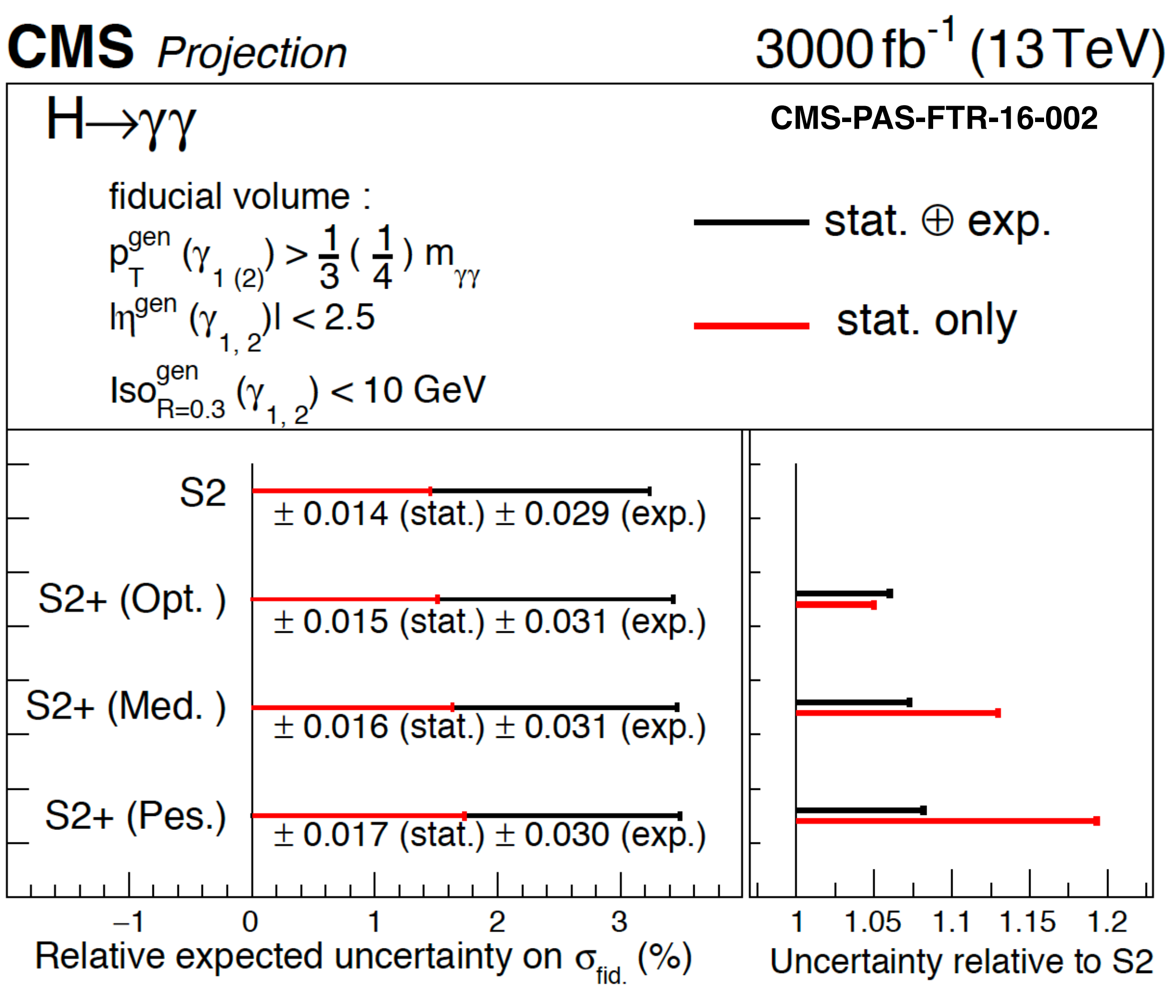
Effect of high pileup and detector performance considered based on the CMS Upgrade TP (LHCC-P-008)





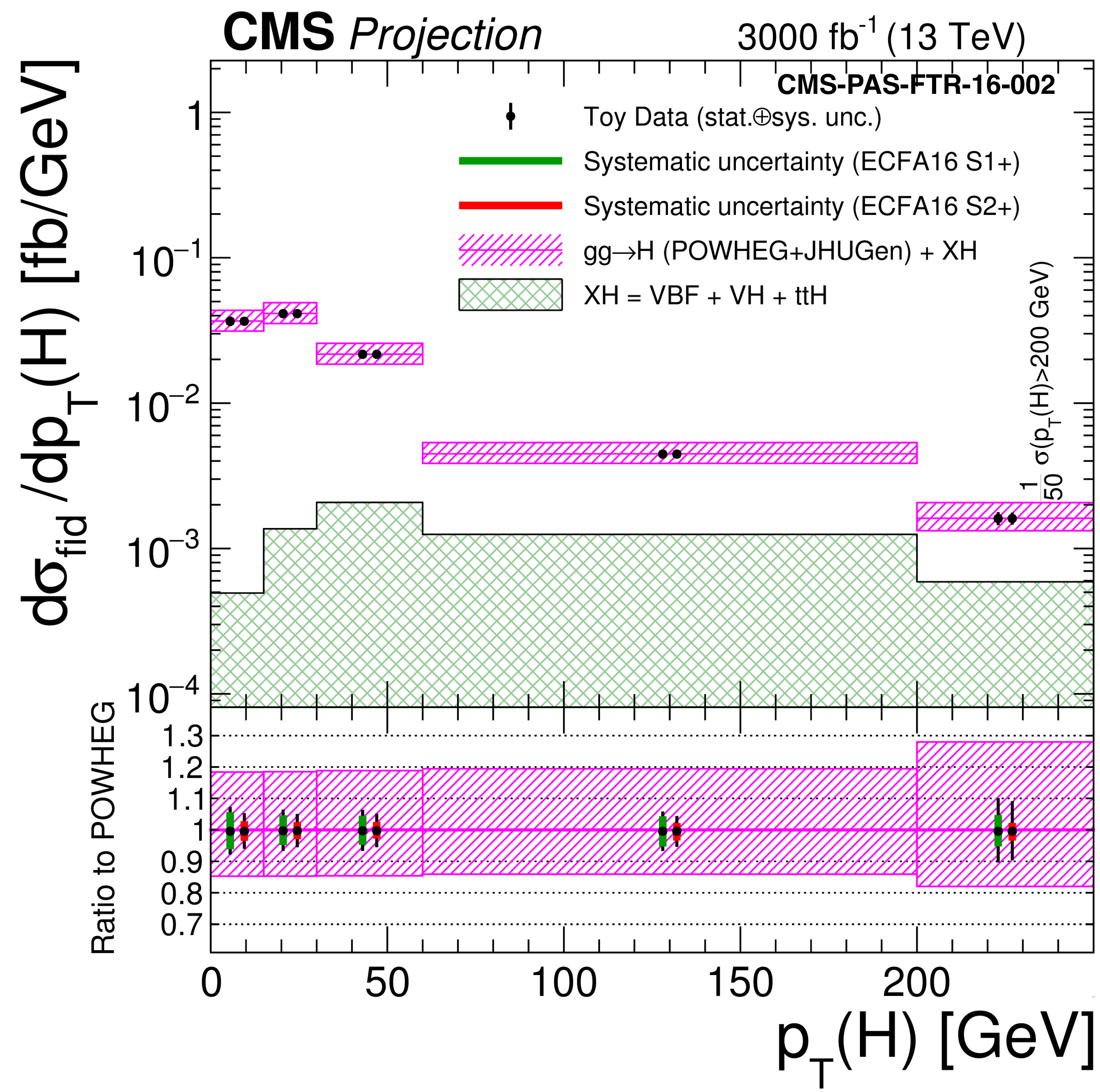
Precision Measurements

Fiducial Cross Sections:



- Independent of theoretical uncertainty
- Hγγ: Improvement in mass resolution and uncertainty thanks to timing O(30 ps) for photons and charged particles

Differential Cross Sections:



- 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}

HVV: Anomalous Couplings

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

SM

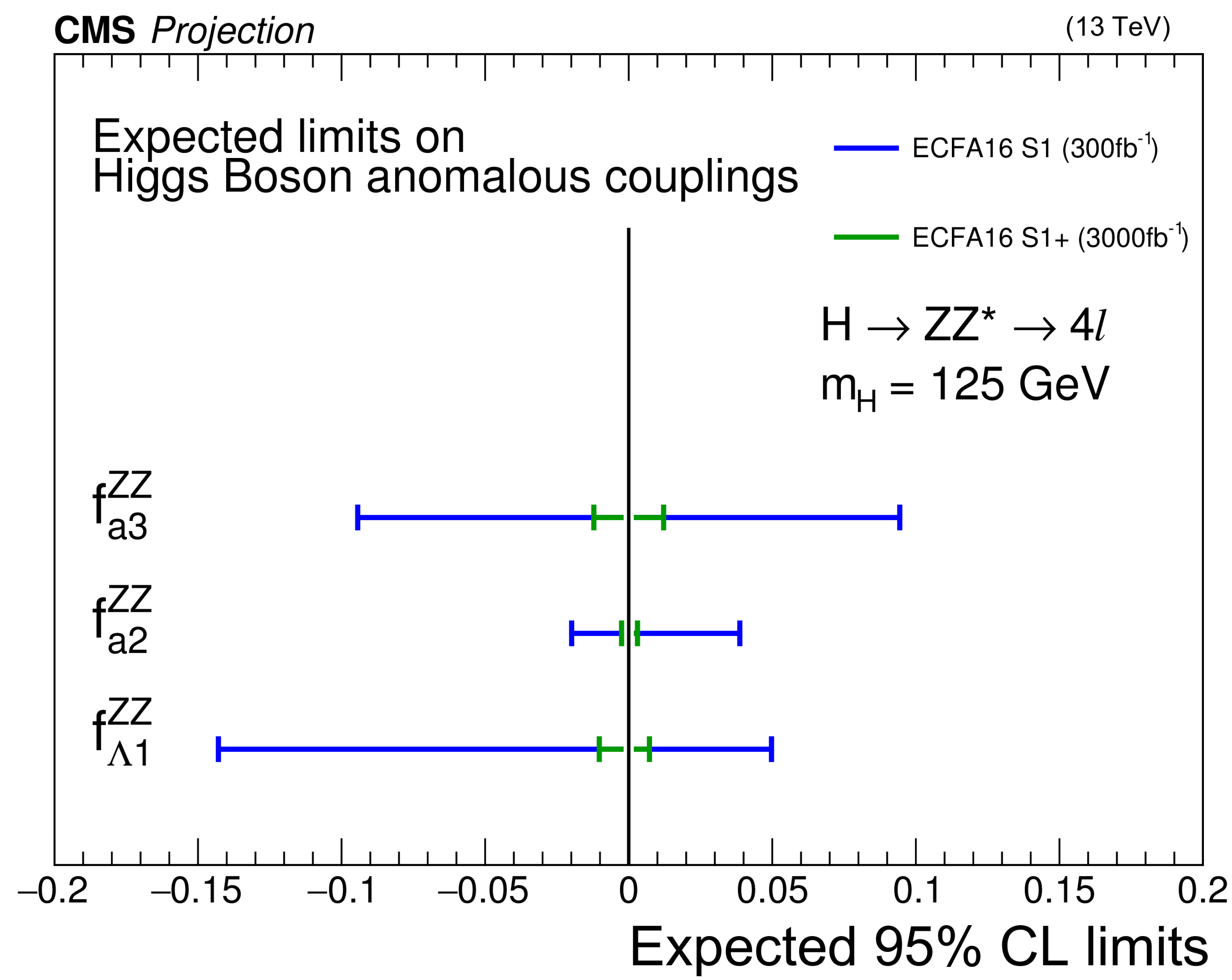
- Test for anomalous couplings:

$$f_{ai} = |a_i|^2 \sigma_i \Big/ \sum |a_j|^2 \sigma_j$$

$$\phi_{ai} = \arg\left(a_i / a_1\right)$$

- Statistically limited. 1% reach @ 3000 fb^{-1}

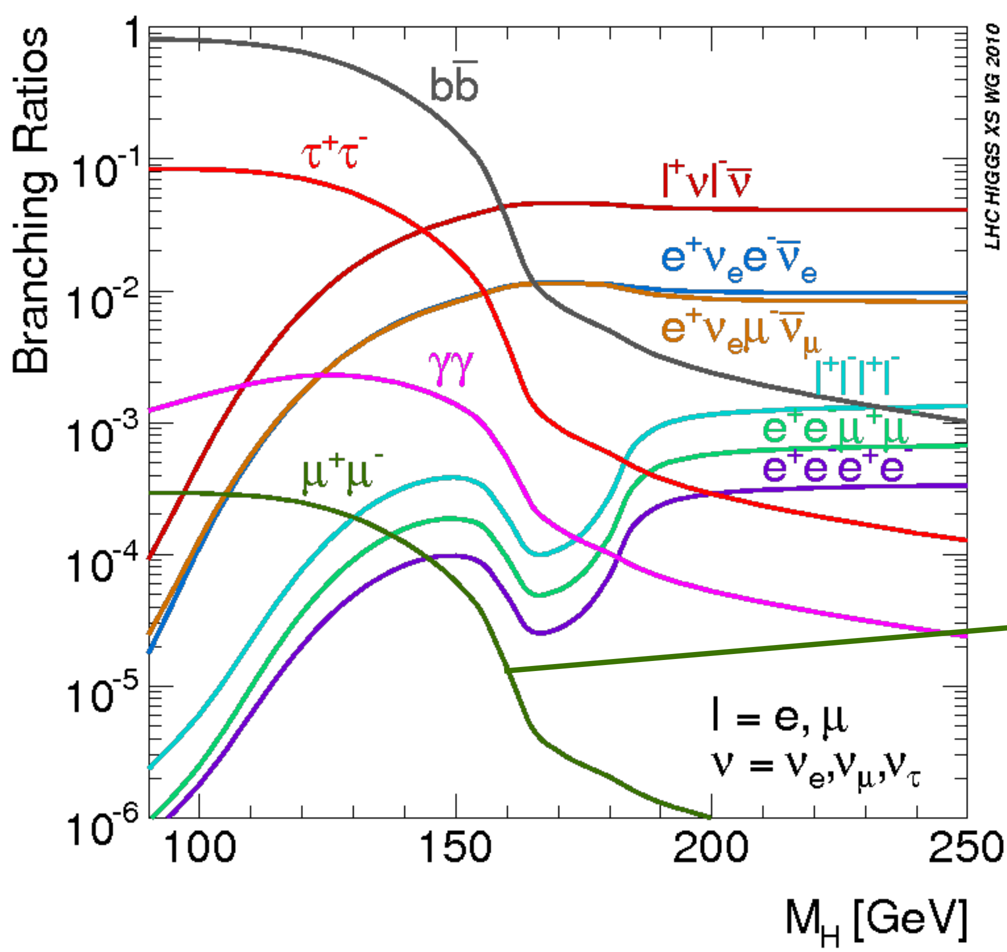
- Interference contribution becomes more dominant at smaller values of f_{ai} cos (f_{ai})

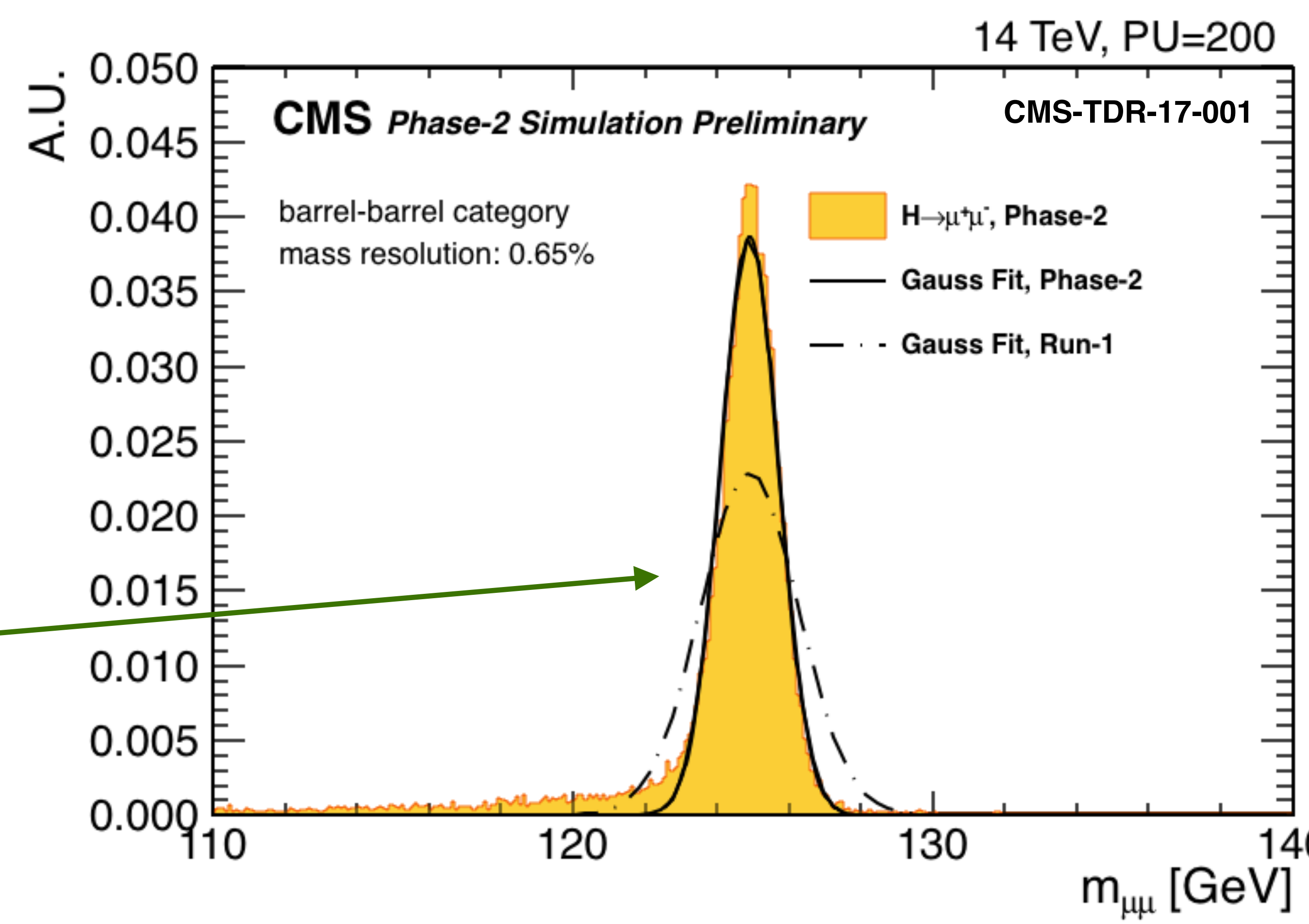


Rare decays: Hμμ

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

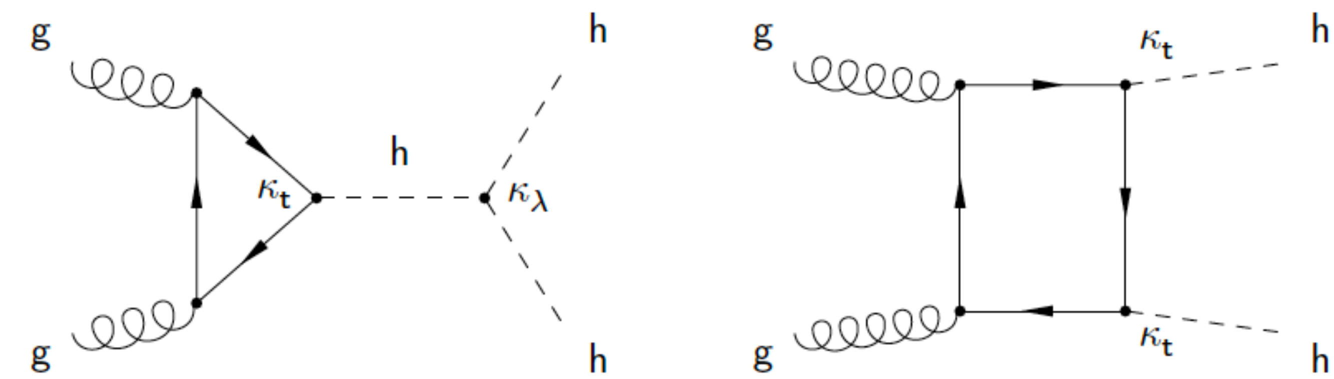
- Probe coupling to 2nd generation
- Hμμ: prospects for **cross section and coupling measurement → 8% & 5% uncertainty@3000fb^{-1}** respectively (including the improved resolution of the upgraded tracker)



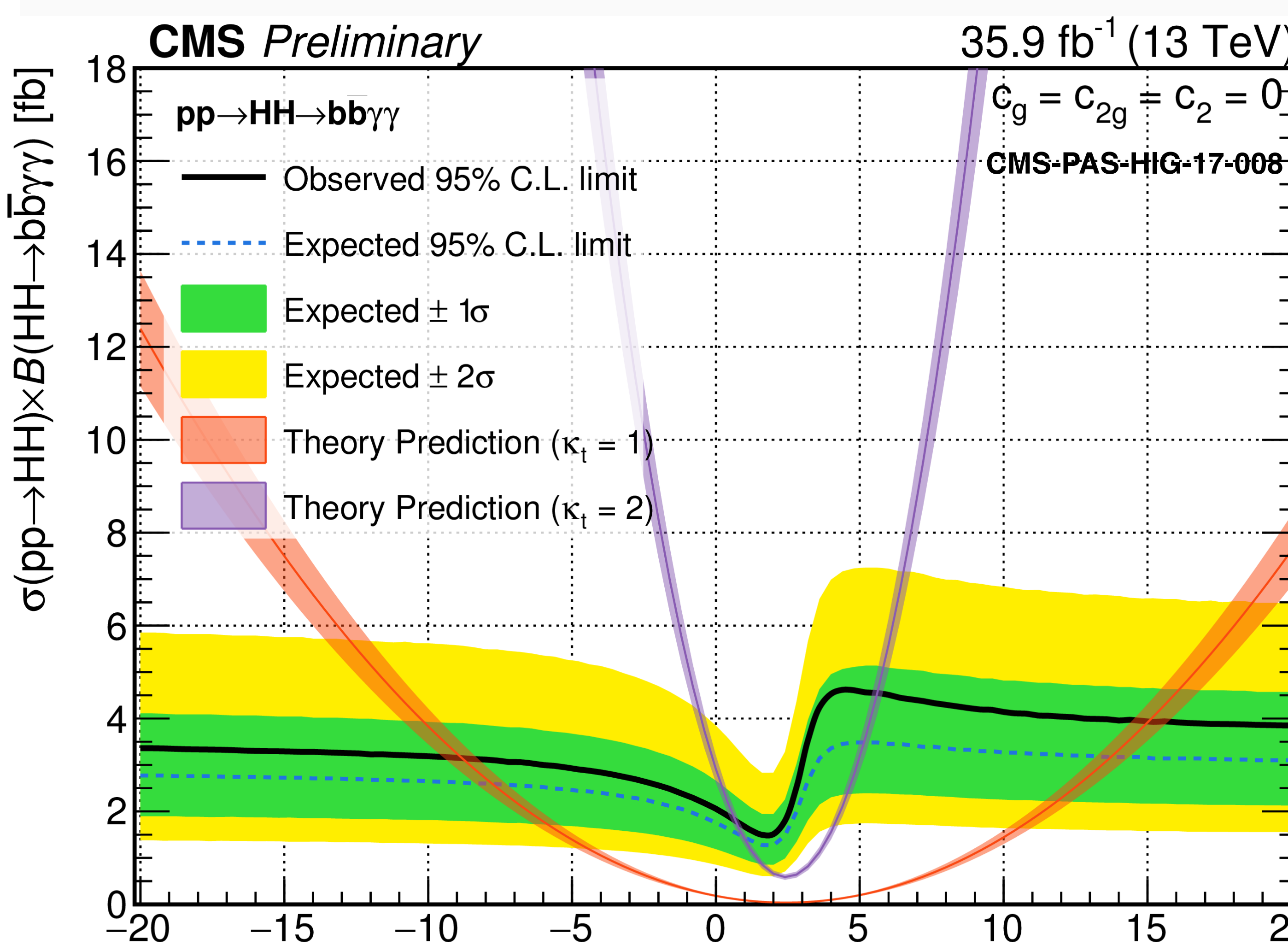


DiHiggs Production

- **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



Current Limits	σ/σ_{SM}
bbWW	79(89)
bbττ	28(25)
bbγγ	19(16)
bbbb (2.3 fb^{-1})	342(308)

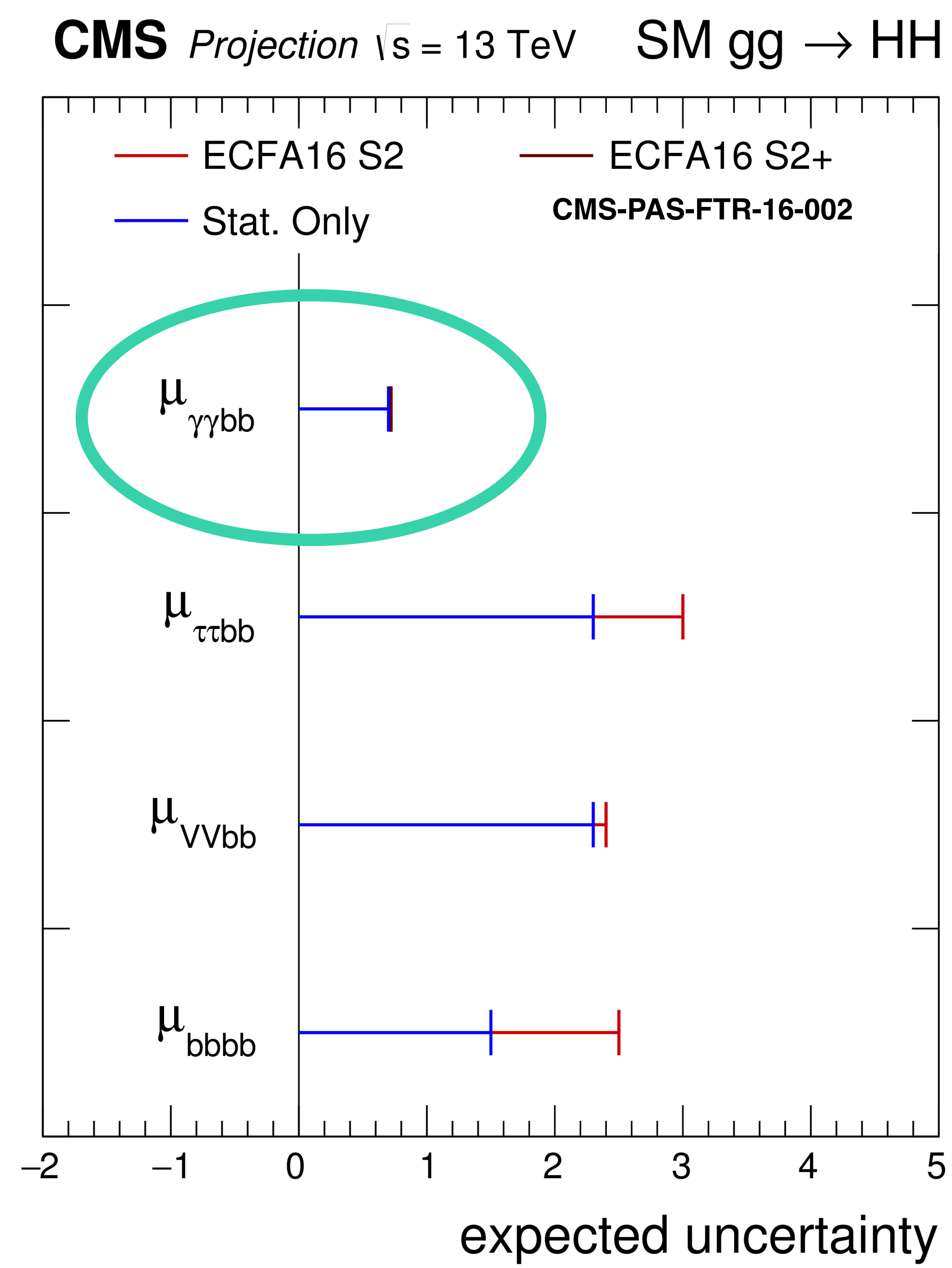


If k_t=1 (SM) → -8.82 < k_λ < 15.04

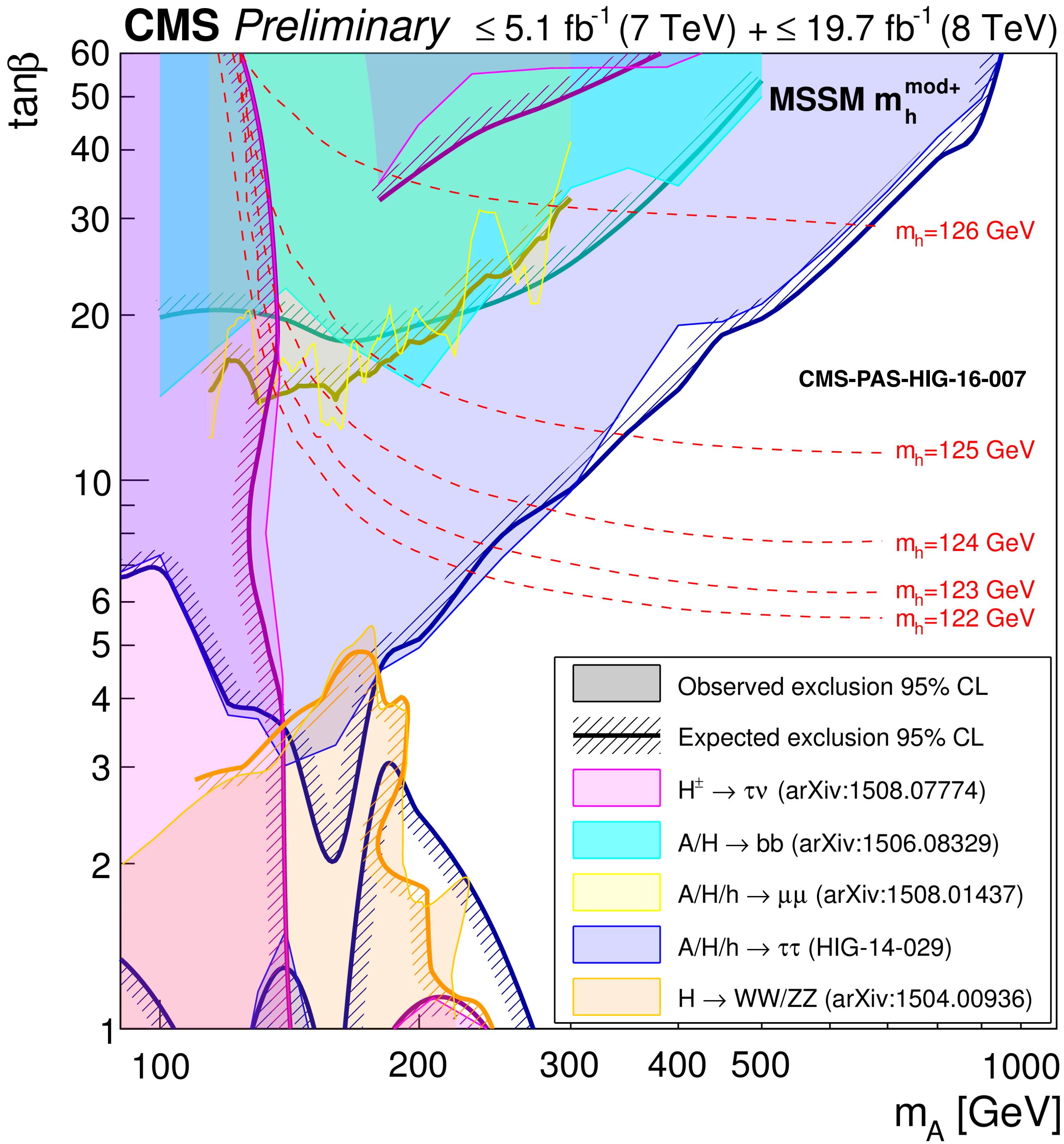
See poster by Sébastien Wertz

DiHiggs Production

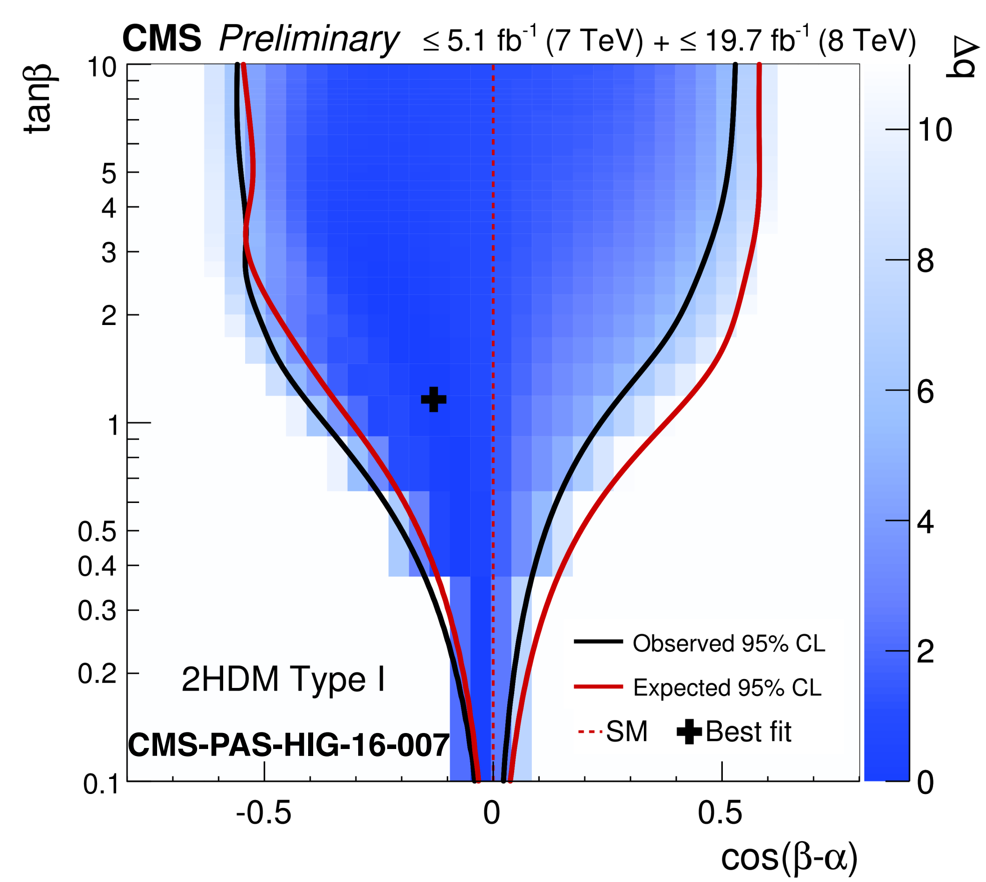
- **Technical Proposal (LHCC-P-008):** bbγγ, bbττ, bbWW studied using Delphes → combined 1.9 significance, 54% uncertainty on signal yield
- **ECFA16:** Updated projections from public analyses using 2015 data at 13 TeV
- Updated combination planned for next year
- Also: bbWW → bbjjlv preliminar study with Delphes (sensitivity vs background uncertainty)



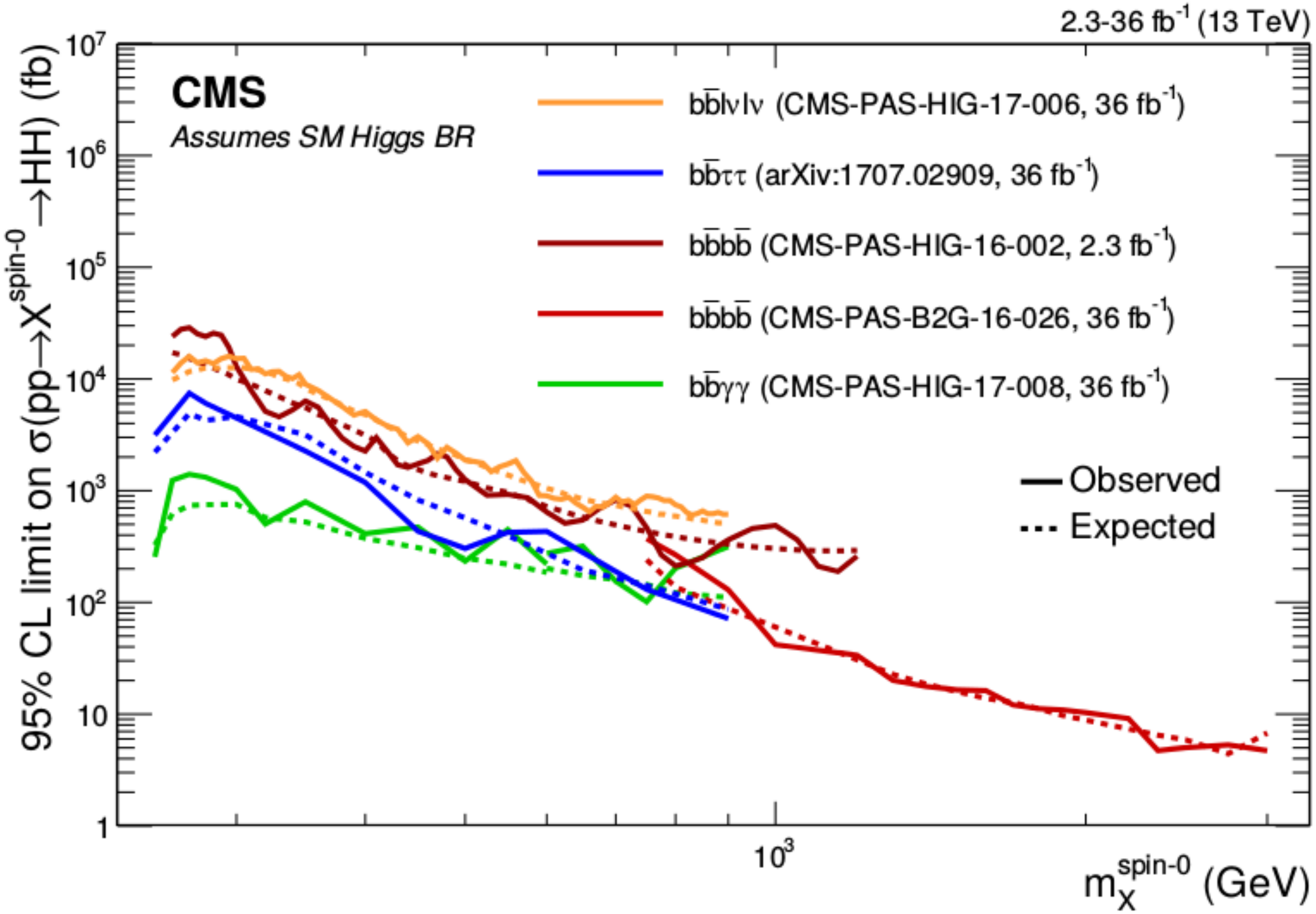
BSM Searches

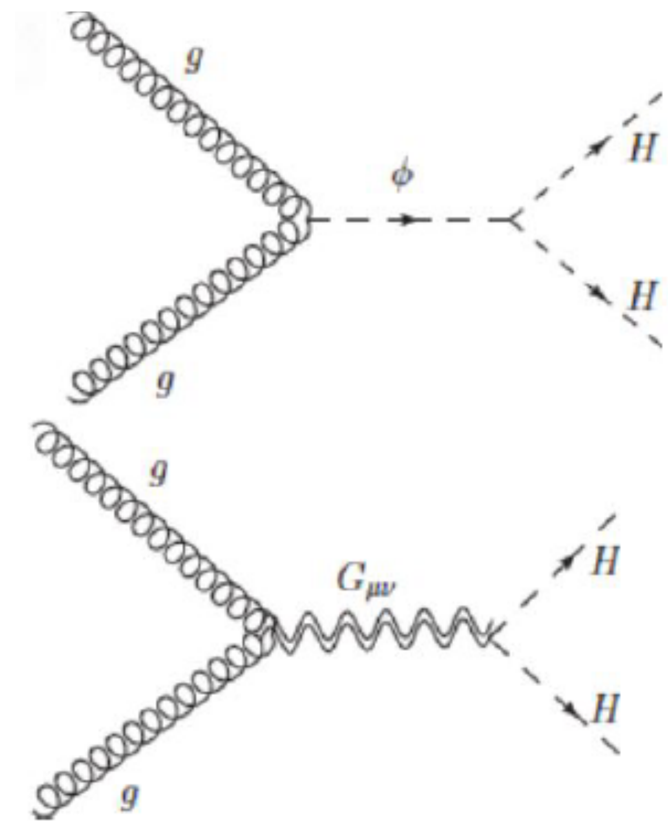


How much phase-space will we cover with 3000 fb^{-1} ?

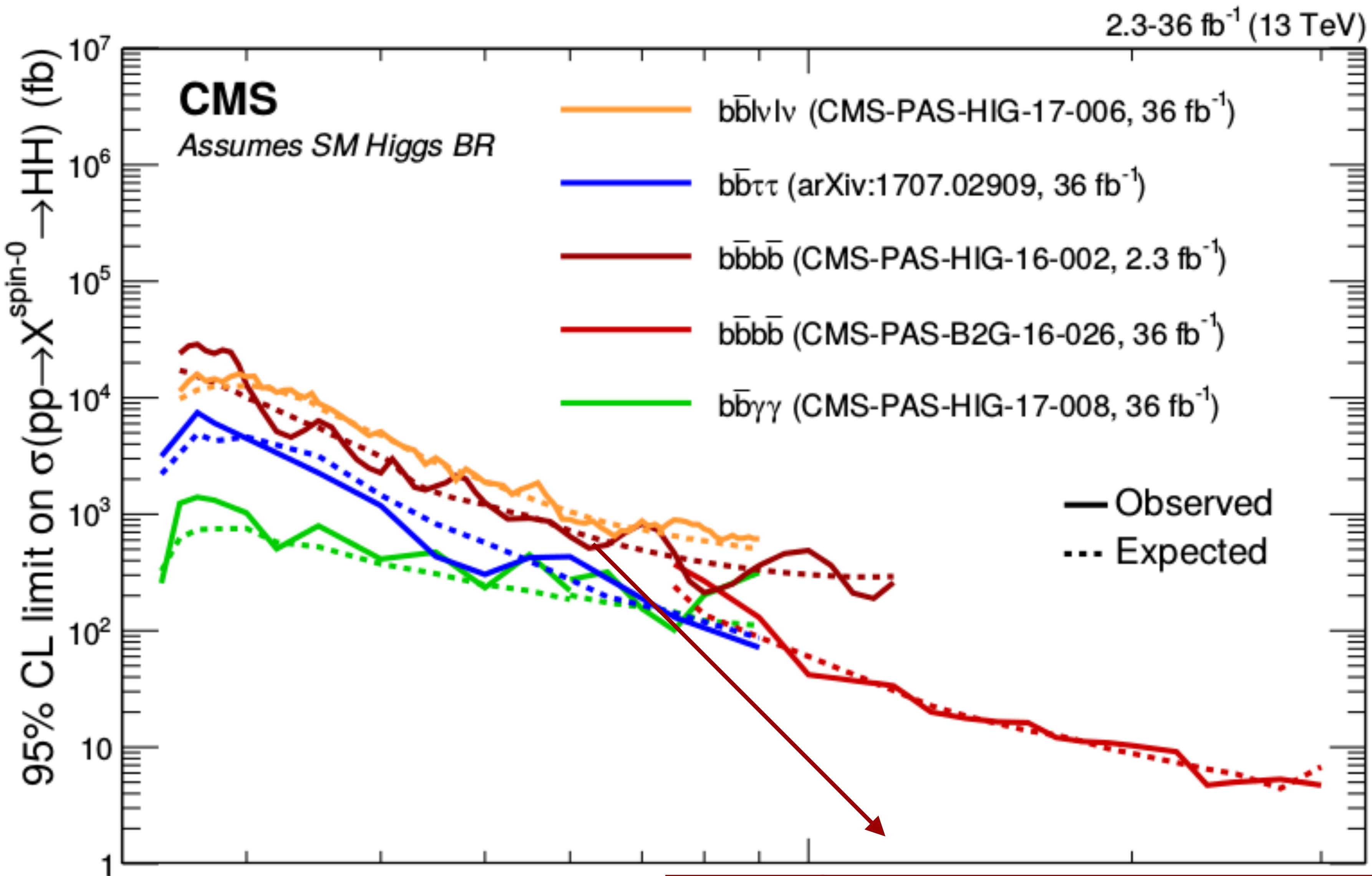


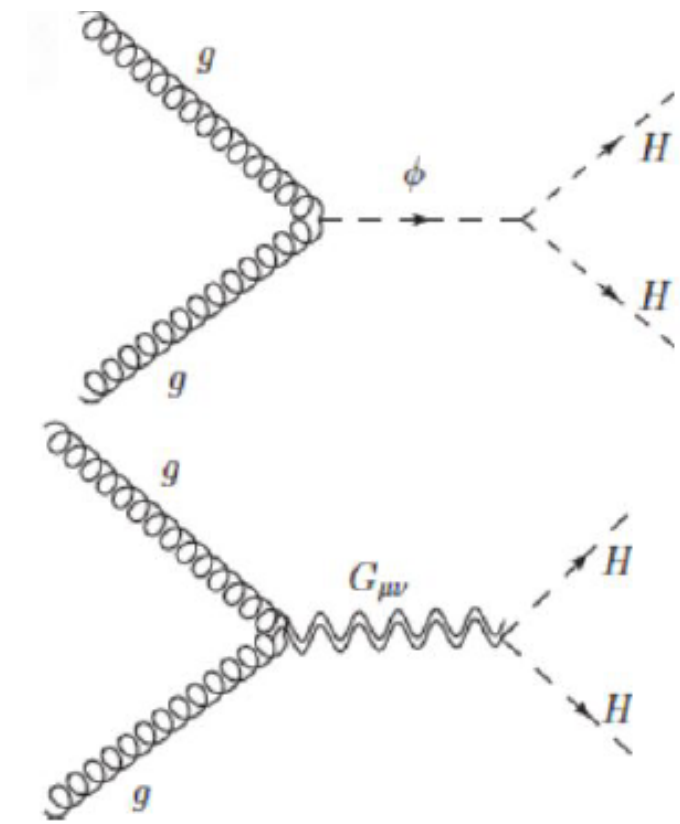
Resonant DiHiggs Searches





Resonant DiHiggs Searches





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

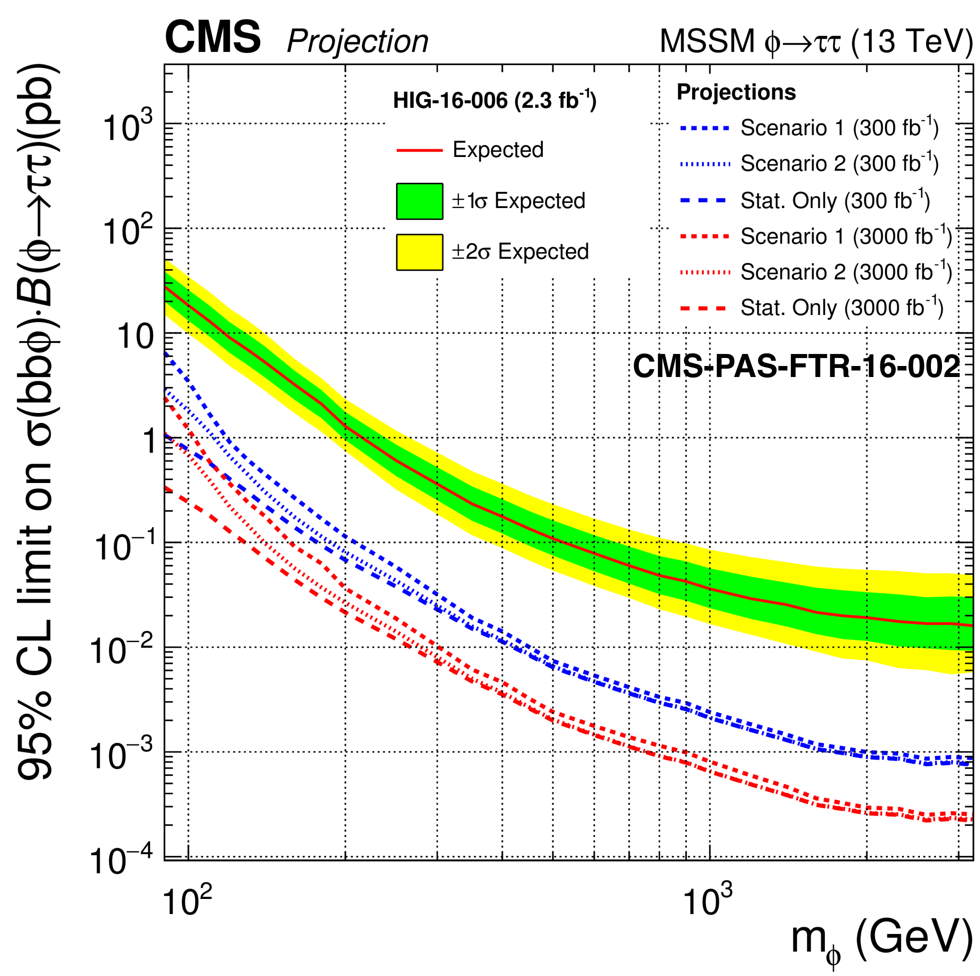
CMS-PAS-FTR-16-002

Projections from 2015 4b analysis

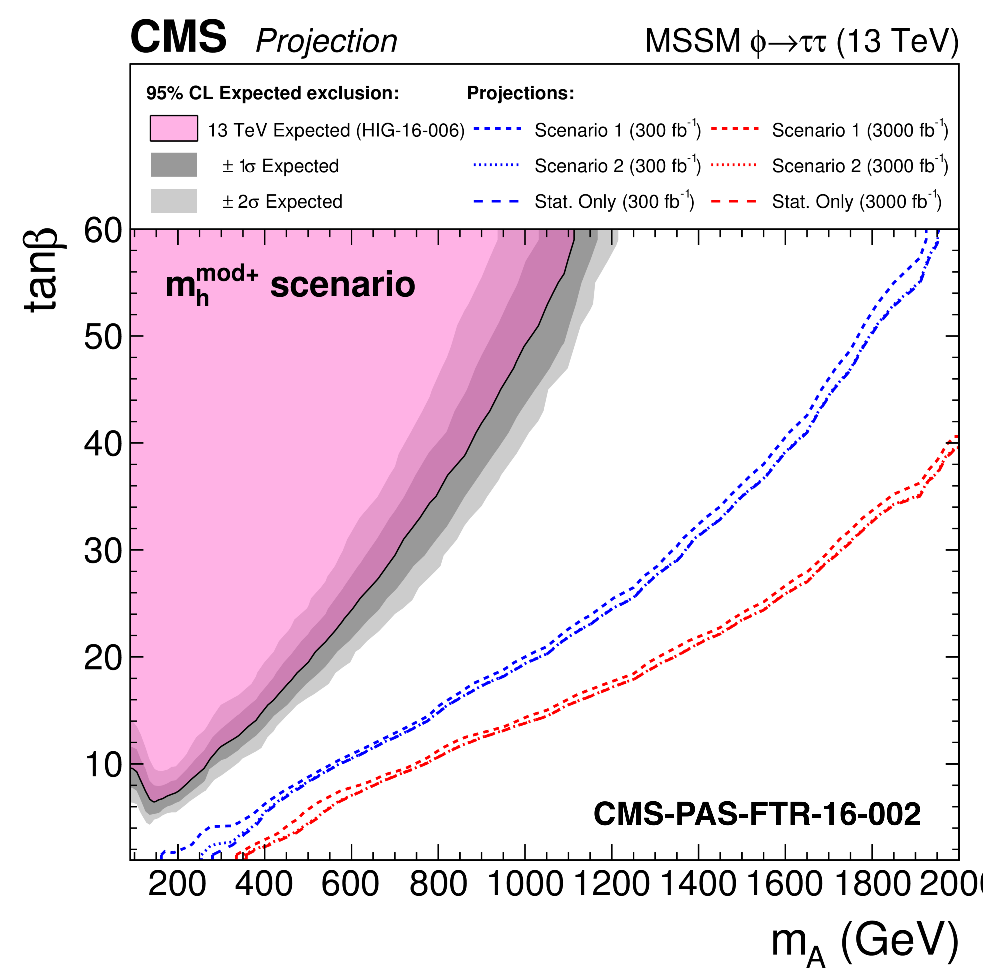
MSSM H→ττ

- **Key channel for constraining extended Higgs Sectors**
- Projection based on 2015 analysis (CMS-HIG-16-006)
- 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

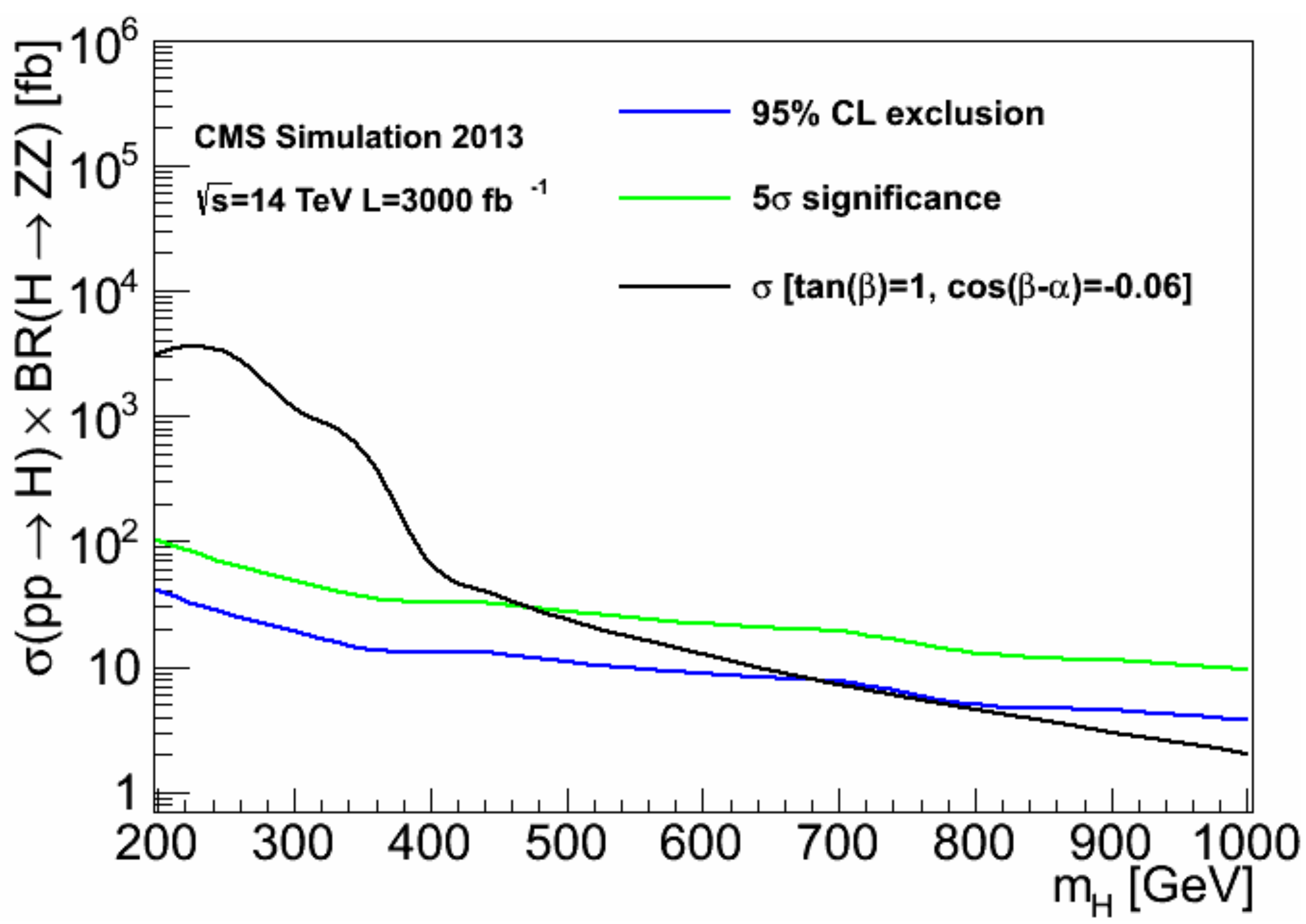


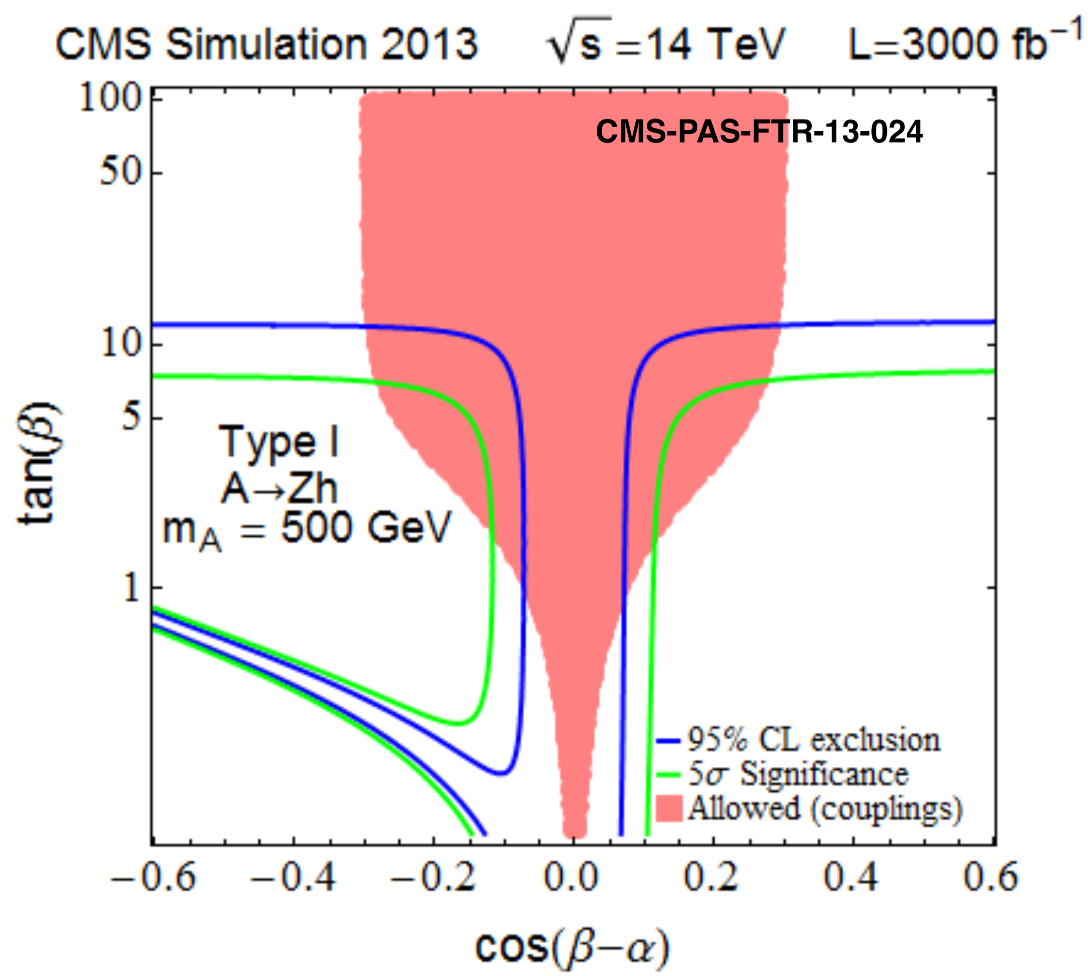
Limits on m^{mod+} benchmarks



Other BSM Higgs Searches

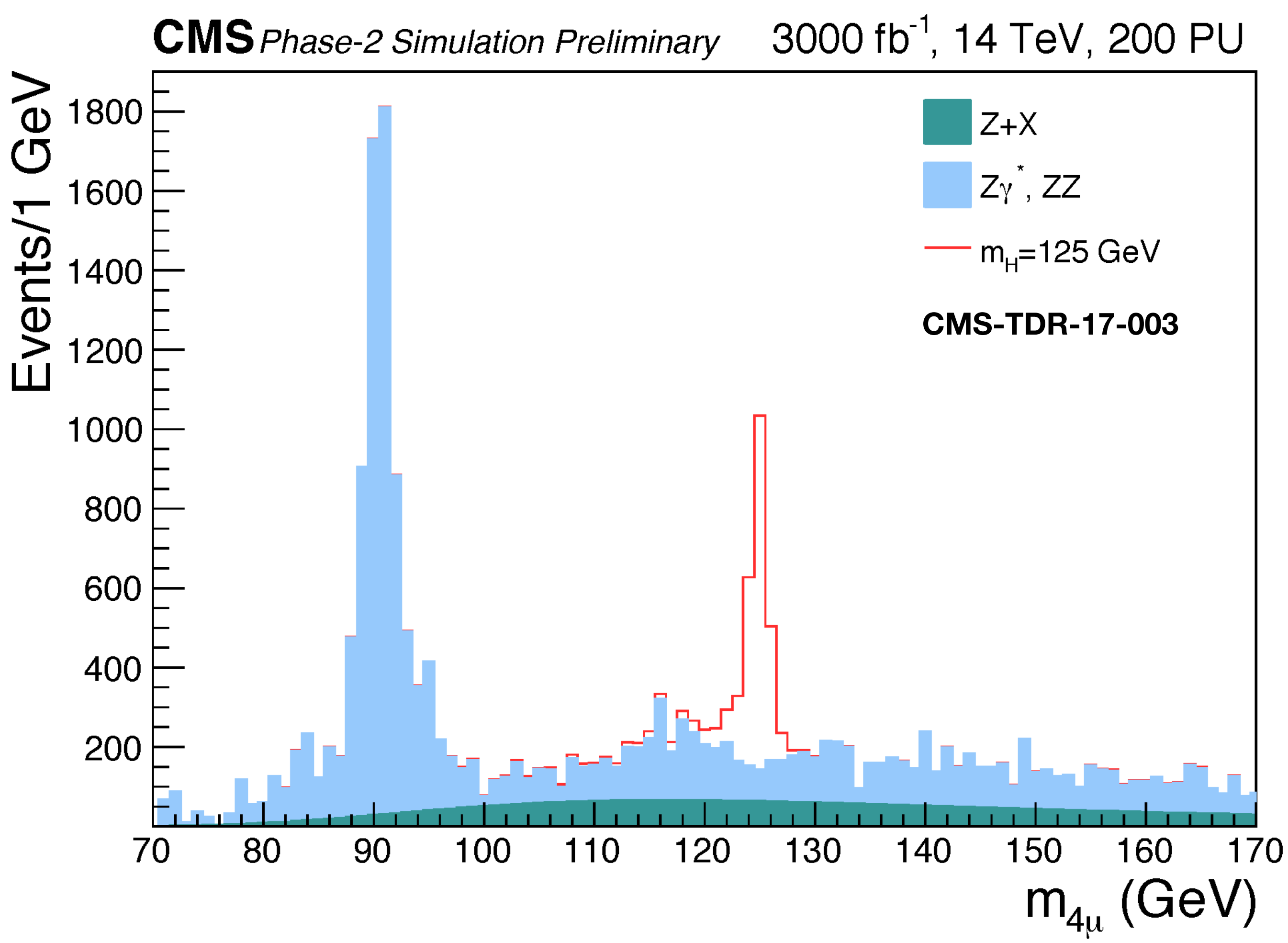
- $H \to ZZ \to 4l$ and $A \to Zh \to llbb$ searches in the 2HDM context
- Cross Section limits, and interpretation in terms of tanβ-cos(β-α) exclusion
- Complementary approach to precision measurements of the SM-like Higgs boson couplings in constraining the 2HDM phase space, for sufficiently low masses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

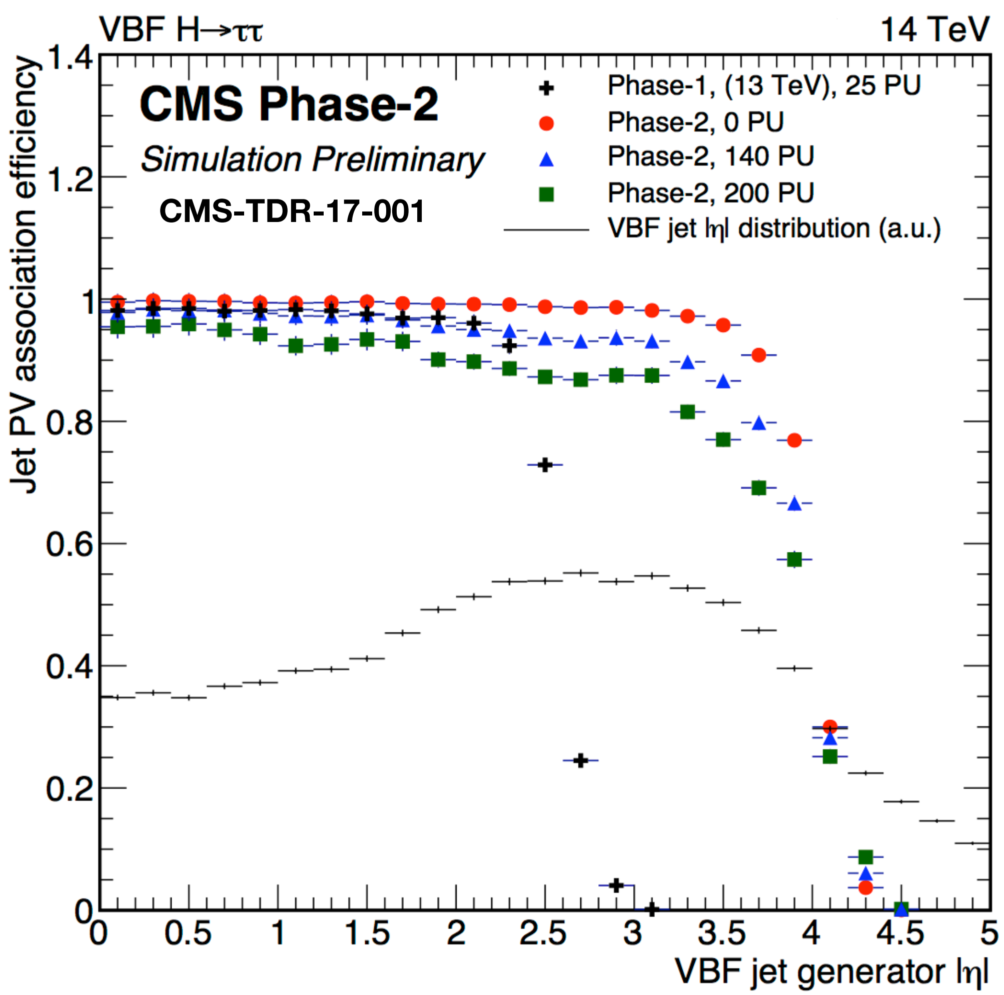




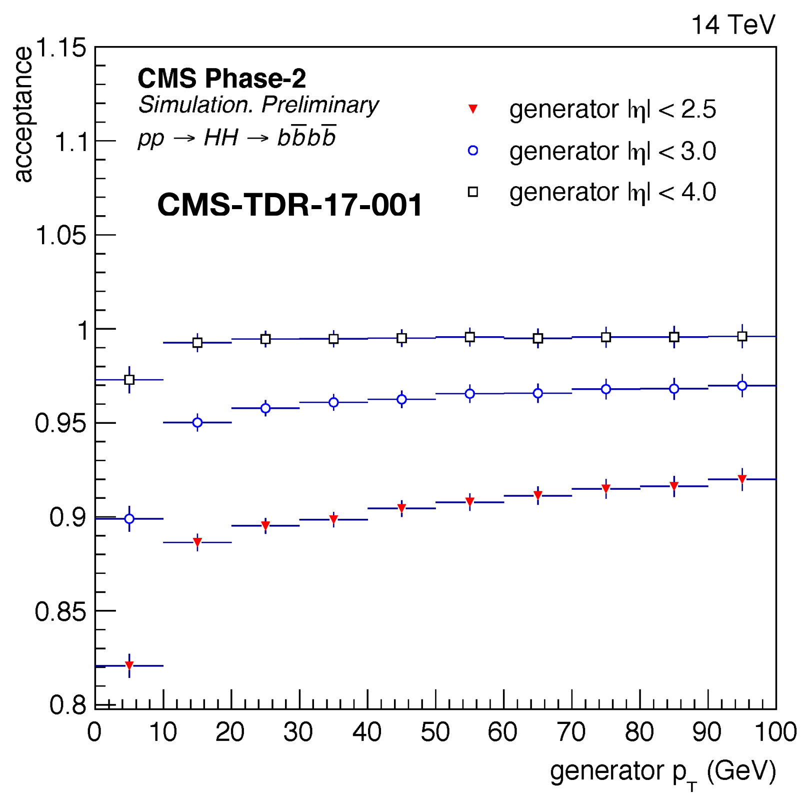
2017 Phase II Upgrade TDRs

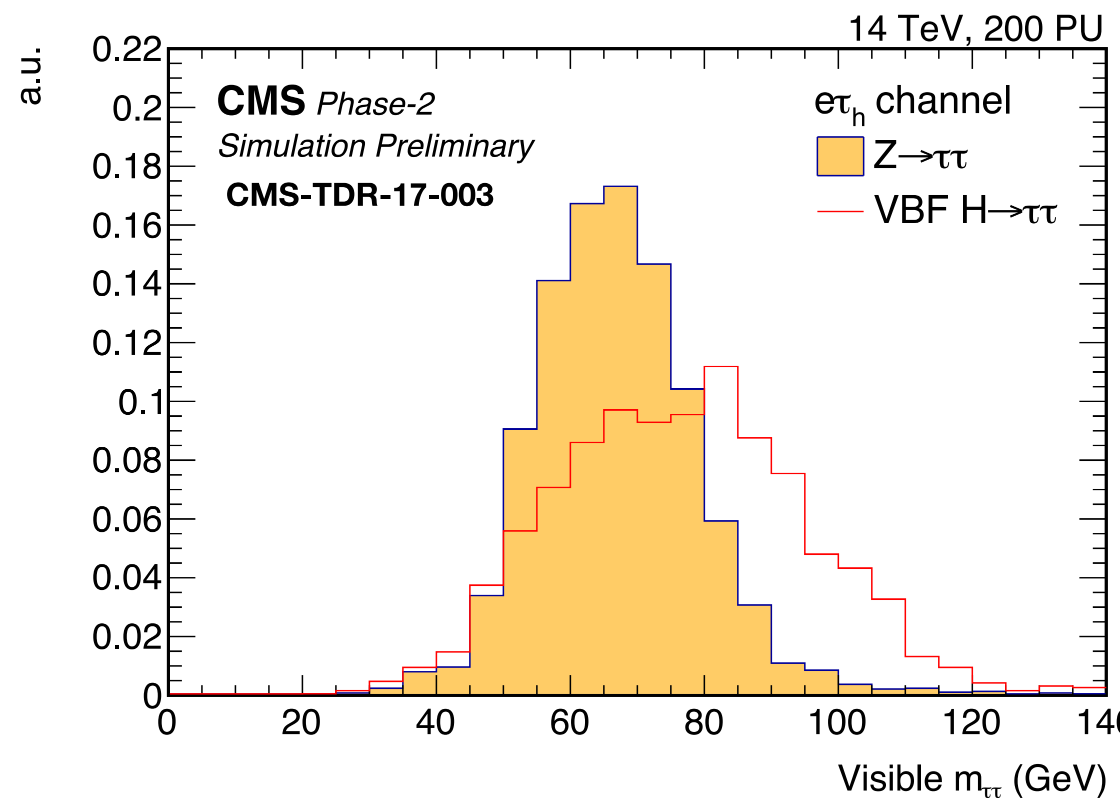
- Tracker, Muon, Barrel Calorimeter, Endcap Calorimeters TDRs, DAQ, Trigger and Timing detectors ID in the pipeline
- Focus on detector performance with full simulation updates that complement the physics reach shown in the studies presented here

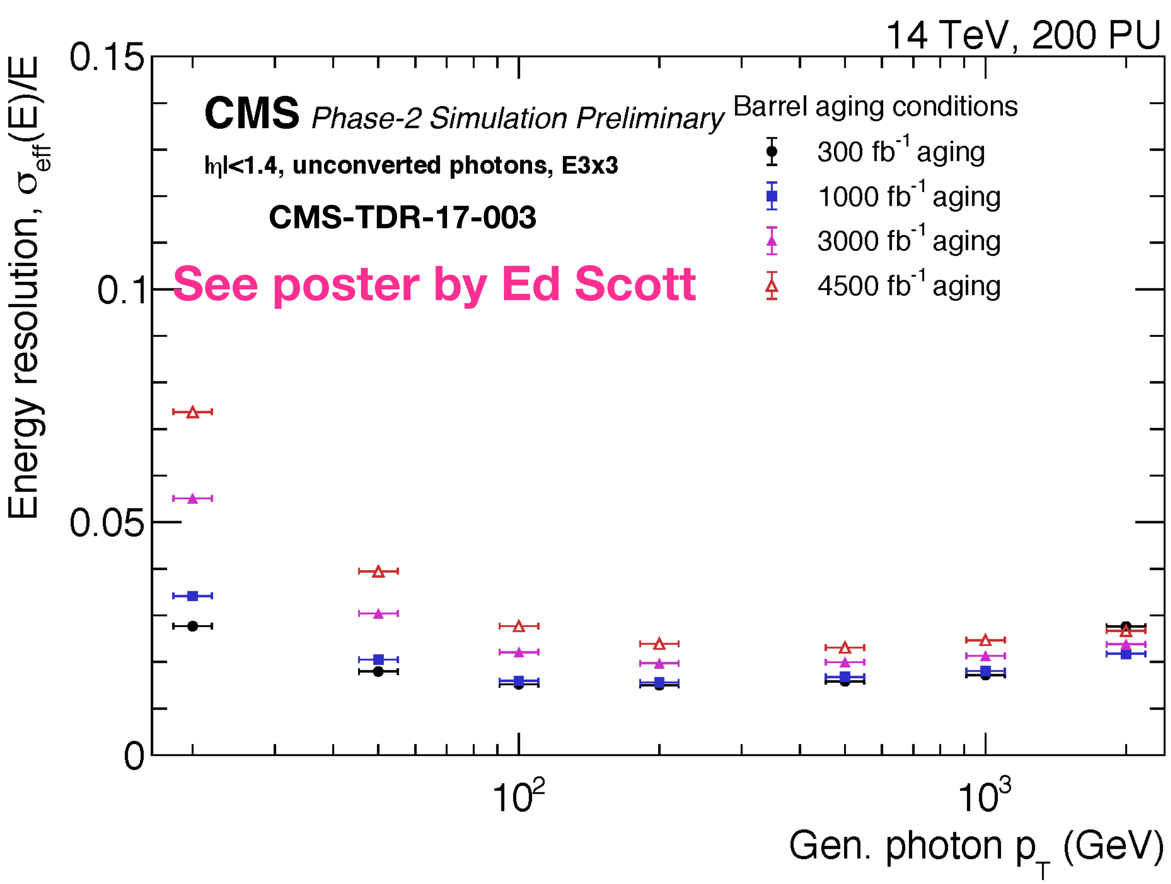


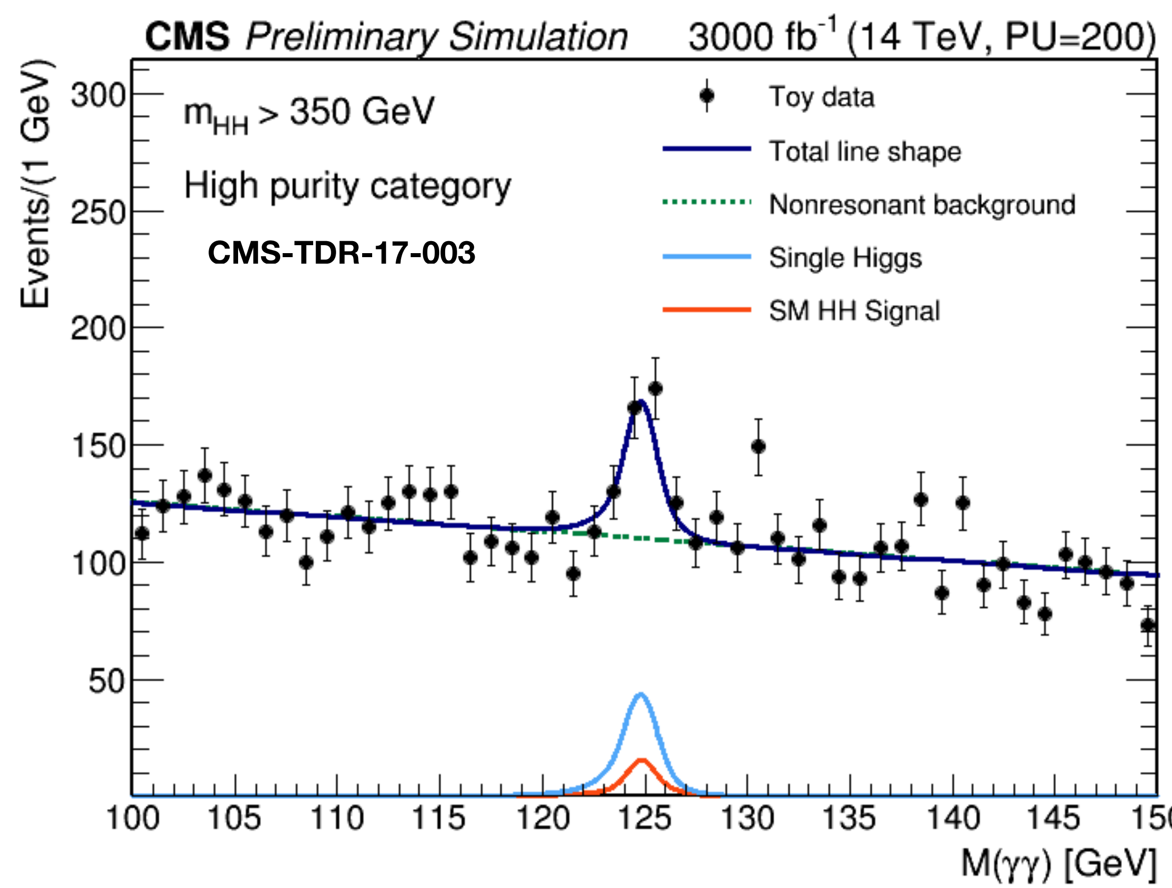


2017 Phase II Upgrade TDRs



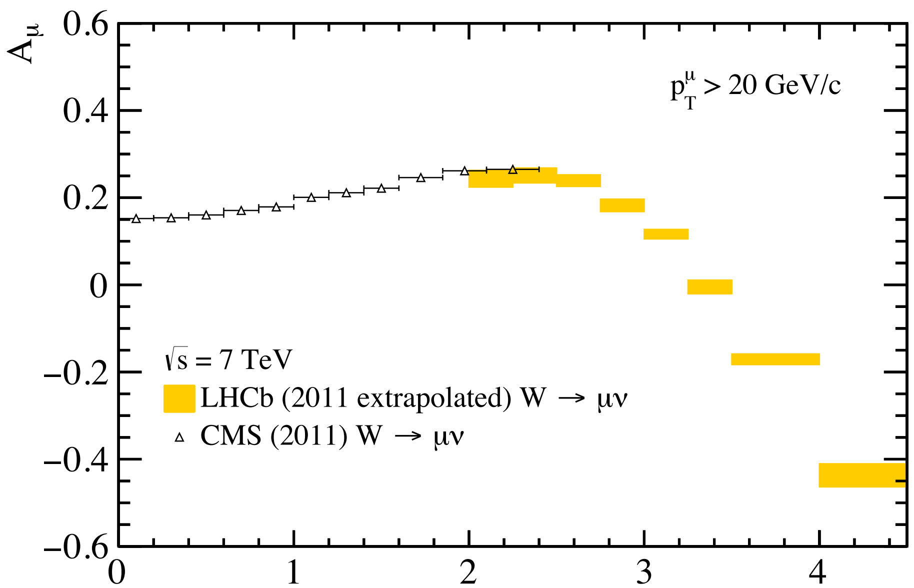


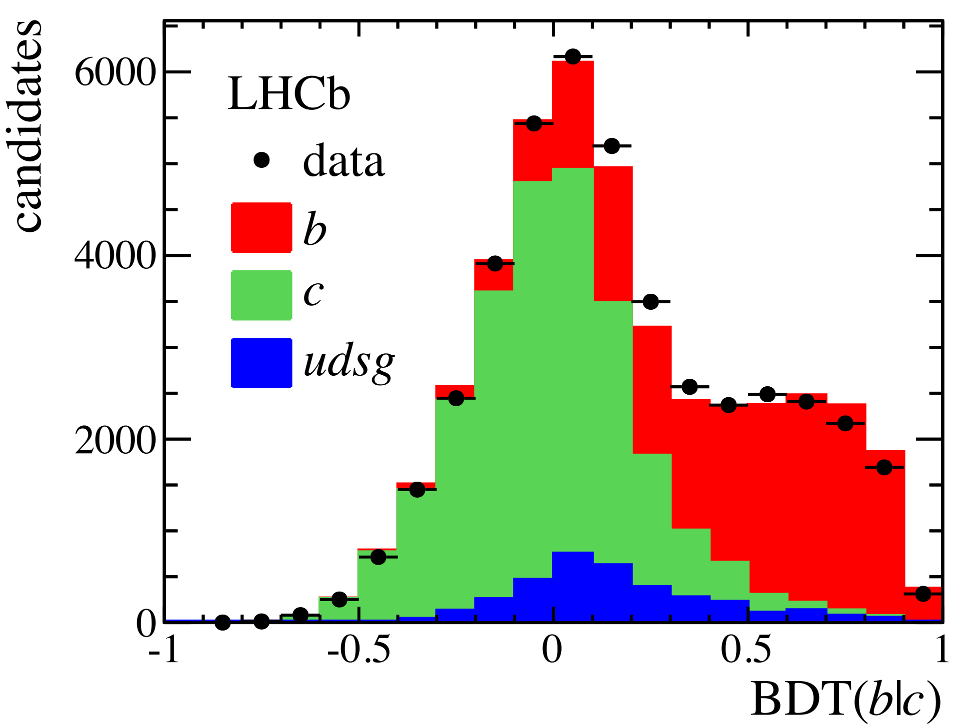




LHCb & Higgs Physics

- **LHCb** was not designed for Higgs physics, but can contribute, utilizing the strengths of LHCb
- Reduced statistics from luminosity leveling and acceptance

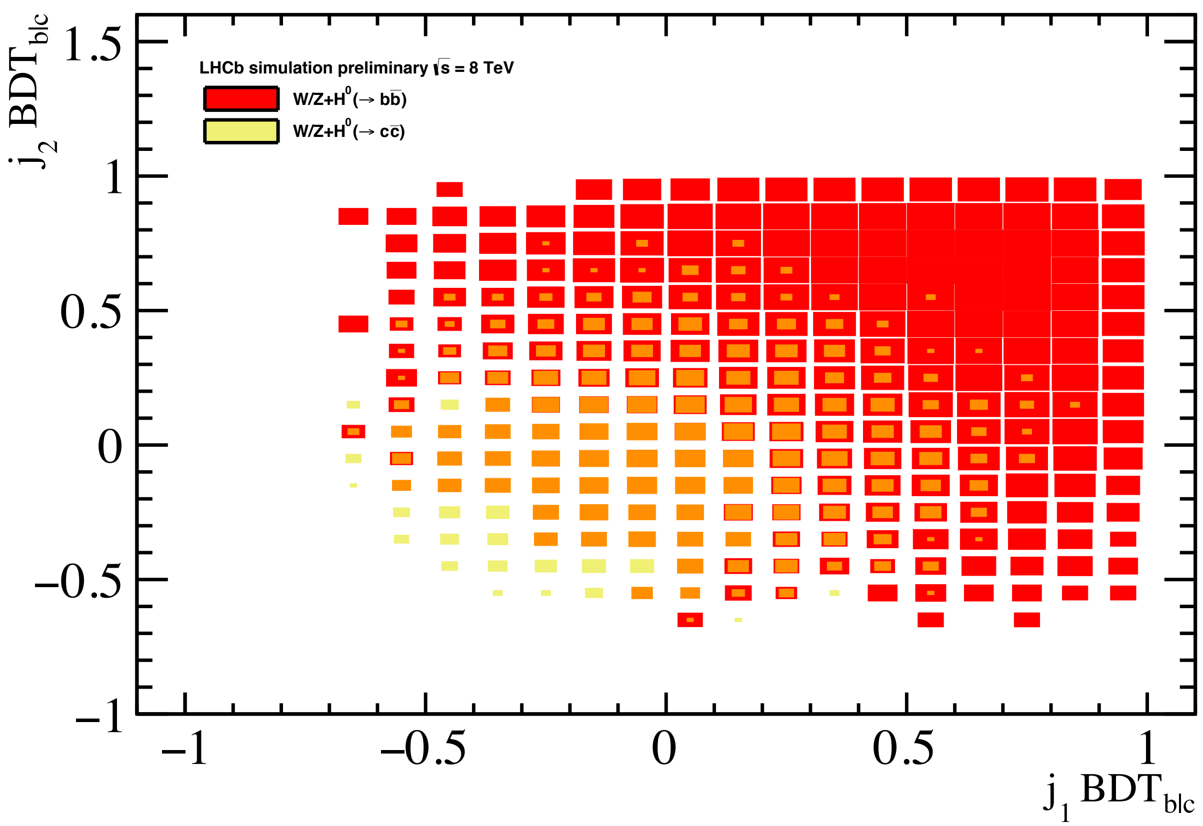


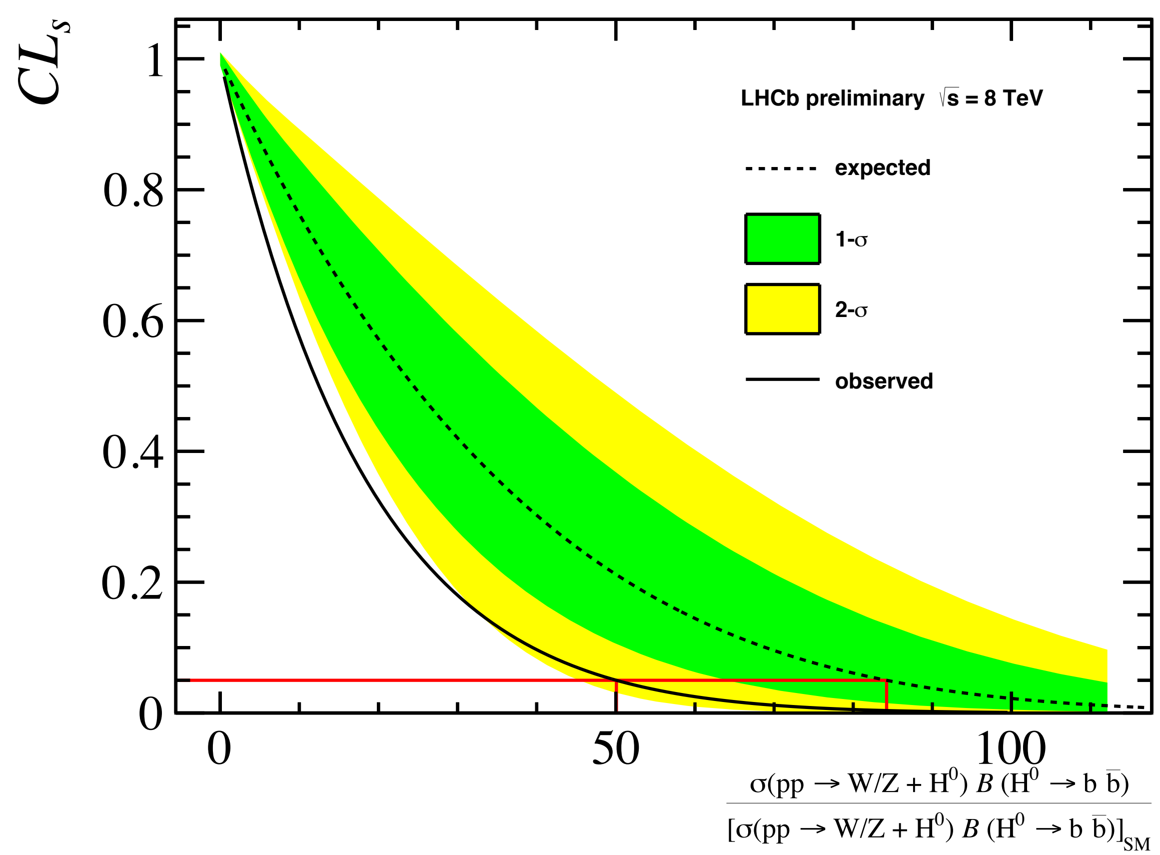


- Full instrumented forward coverage, 2 <|η|< 5
  - complimentary results for differential cross sections
  - eg: JHEP 08 (2015) 039, example W&Z cross-sections
- Charged particle identication with ring imaging Cherenkov detectors
  - possibility of strange-jet tagging in the future
- Excellent secondary vertex resolution
  - unique inclusive c/b-jet tagging and separation
  - JINST 10 (2015) P06013

H→cc̄ and H→bb̄ in LHCb

- First direct inclusive search for H→cc, 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**
- See talk by O. Francisco on Tuesday for more details

Conclusions

- **Higgs studies are central to the HL-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
- **CMS** has presented a large variety of projection studies to HL-LHC statistics, accounting for the impact of detector improvements that target the full exploitation of the challenging High luminosity regime
  - Ongoing updates of the existing analysis and expansion of the phase-space covered (2017 Phase II TDRs)
- **LHCb** complements the searches with forward coverage, exploiting their particle ID and vertex identification capabilities → focus on H→cc / bb

Higgs Experimental Talks This Week

Tuesday

- **Higgs 1**
  - HH prospects- Stephane Jezequel
- **Higgs + SM**
  - VV, VBS prospects - Claire Lee
- **Higgs + Flavour + BSM**
  - Prospects on light Yukawa - Oscar Francisco
- **Higgs + BSM**
  - High mass searches (fermions) -Kerstin Hoepfner
  - High mass searches (bosons) -Stephane Willocq
  - DarkMatter and Higgs Portal - AnneMarie Magnan

Wednesday

- **Higgs 2**
  - Off-shell production and width- Roberto Di Nardo
  - ttH and tH prospects - Matthias Schröder
- **Higgs 3**
  - Couplings / main channels- Giacomo Ortona

ATLAS Speaker CMS Speaker LHCb Speaker

BACKUP

Extrapolation Strategy

Public results are extrapolated to larger data sets 300 and 3000 fb1 . In order to summarize the future physics potential of the CMS detector at the HL-LHC, extrapolations are presented under different uncertainty scenarios:

- **S1** All systematic uncertainties are kept constant with integrated luminosity. The performance of the CMS detector is assumed to be the unchanged with respect to the reference analysis
- **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
- **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 not taken into account
- **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

	systematics unchanged	exp. sys. scaled* $1/\sqrt{L}$	theo. sys. scaled 1/2	high PU effects
ECFA16 S1	✓	✗	✗	✗
ECFA16 S1+	✓	✗	✗	✓
ECFA16 S2	✗	✓	✓	✗
ECFA16 S2+	✗	✓	✓	✓

(*) until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector.

ECFA16 Update: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$

ECFA16 update with 12.9 fb^{-1} of data at 13 TeV

- Run2 analyses updated to 36fb^{-1} but not yet extrapolated to HL-LHC conditions

Higgs properties projected to 300 (3000) fb^{-1}:

$H \rightarrow \gamma\gamma$

- Signal strength per production mode
- Fiducial cross section measurement
- Timing studies

$H \rightarrow ZZ$

- Signal strength per production mode
- Differential cross section for $p_T(H)$
- Anomalous couplings

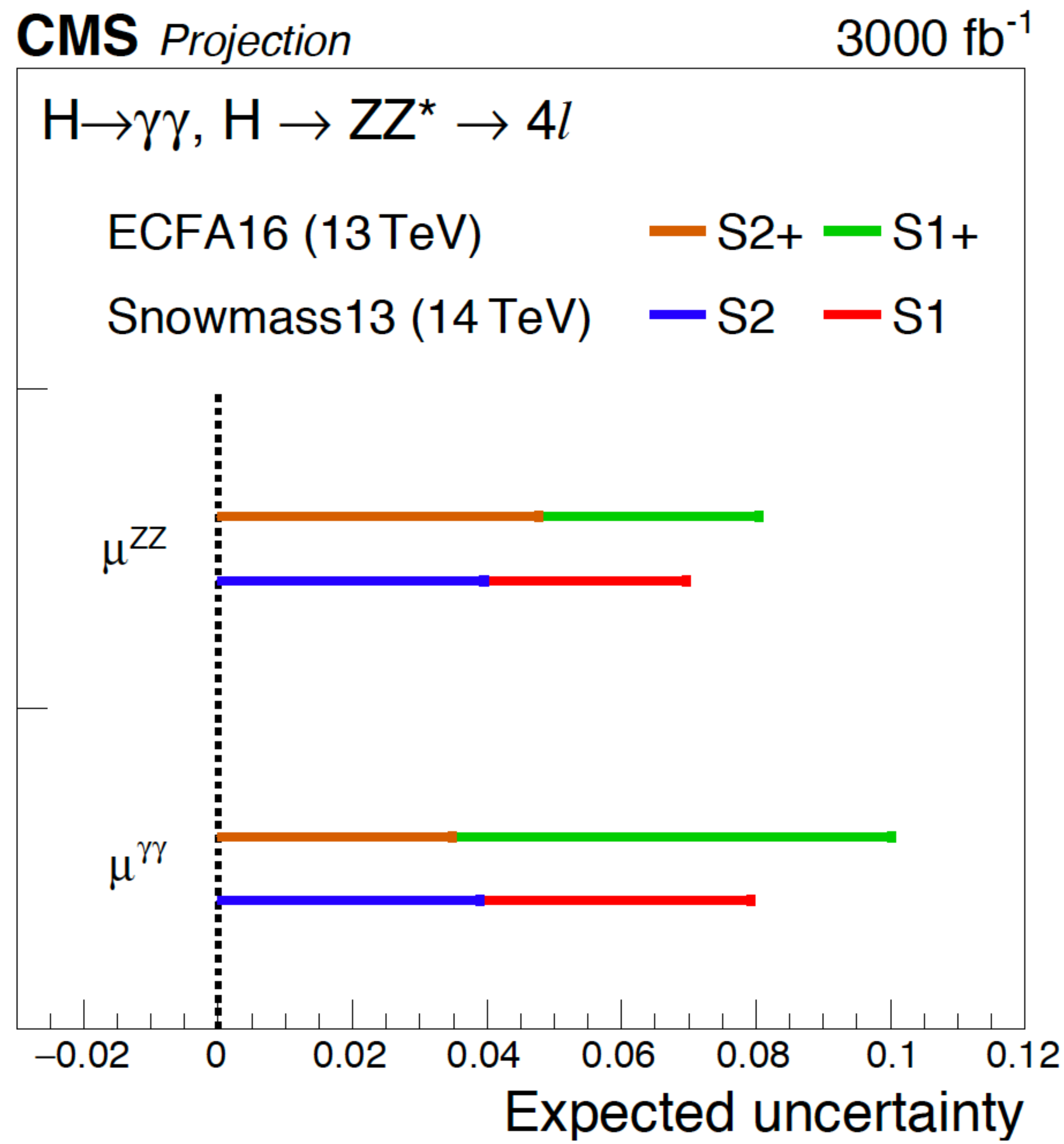
For 3000 fb^{-1}, the effect of high pileup and detector performance are considered (based on the CMS Upgrade TP, LHCC-P-008):

- The beamspot is simulated to be 5cm
- Vertex association efficiency reduced from 80% to 40%
- Photon ID efficiency decreased by 2.3% (10%) in EB (EE)

- Lepton efficiency
- Misidentification rates

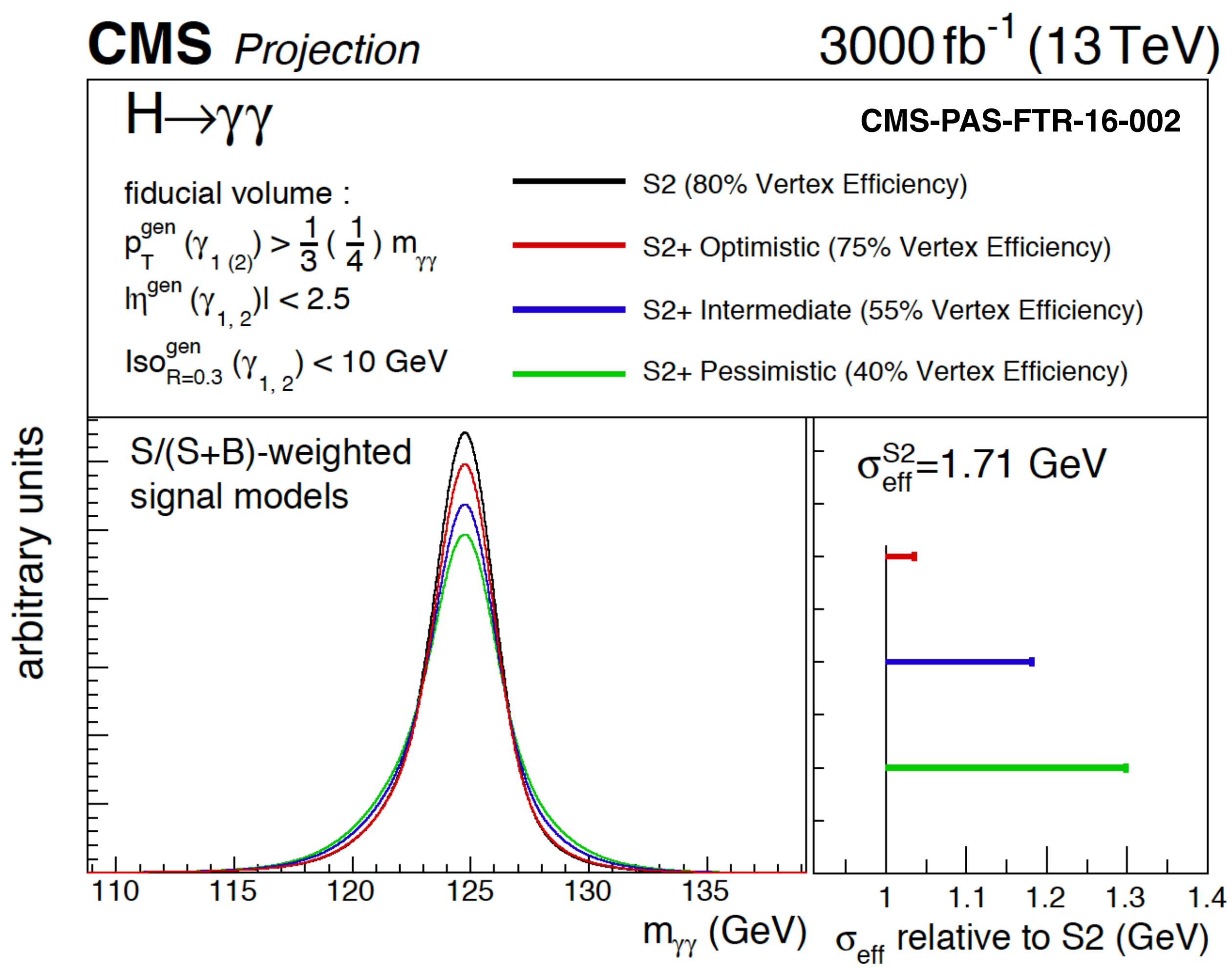
ECFA16 vs Snowmass13

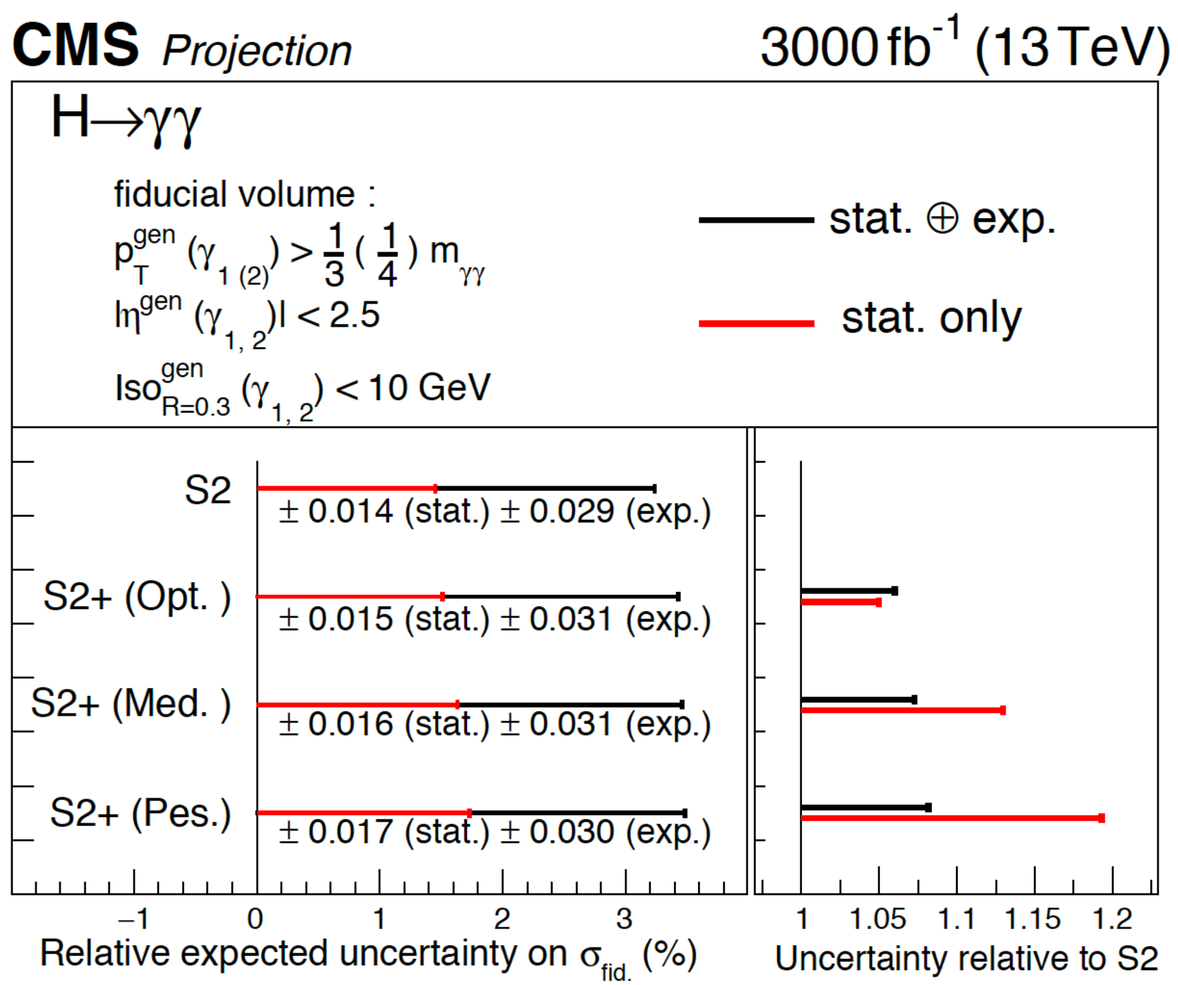
- Energy and integrated luminosity of base analysis
  - Energy extrapolated from 8 TeV to 14 TeV (Snowmass) or 13 to 14 TeV (ECFA16)
- Theory uncertainties from YR3 (Snowmass) to YR4 (ECFA16)
- Revisited S2 scenario lower bound when scaling down the experimental uncertainties



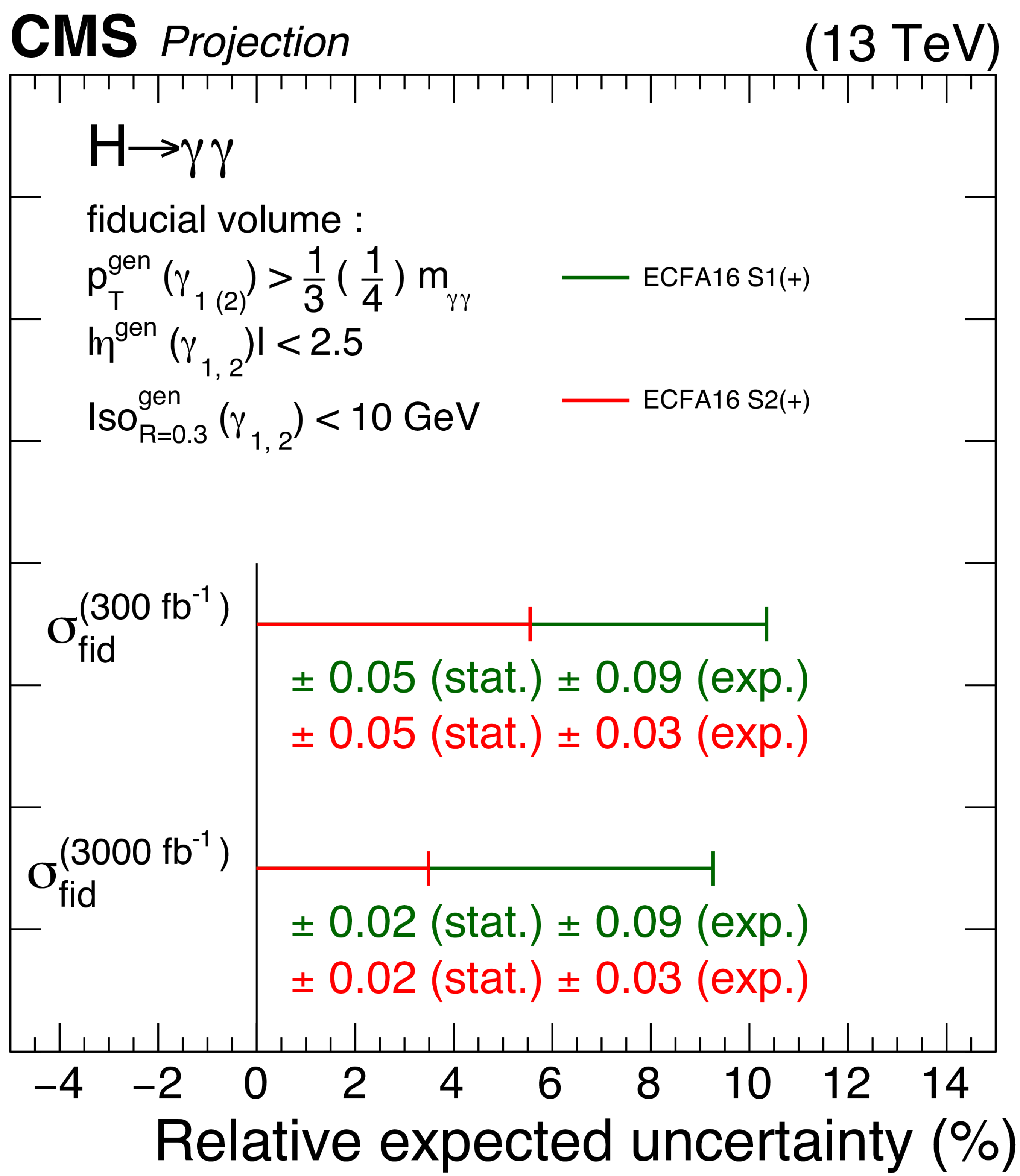
Precision timing studies

- Improvement in vertex association for photons in Hgg decay ➜ impact on mass resolution and fiducial cross section uncertainty



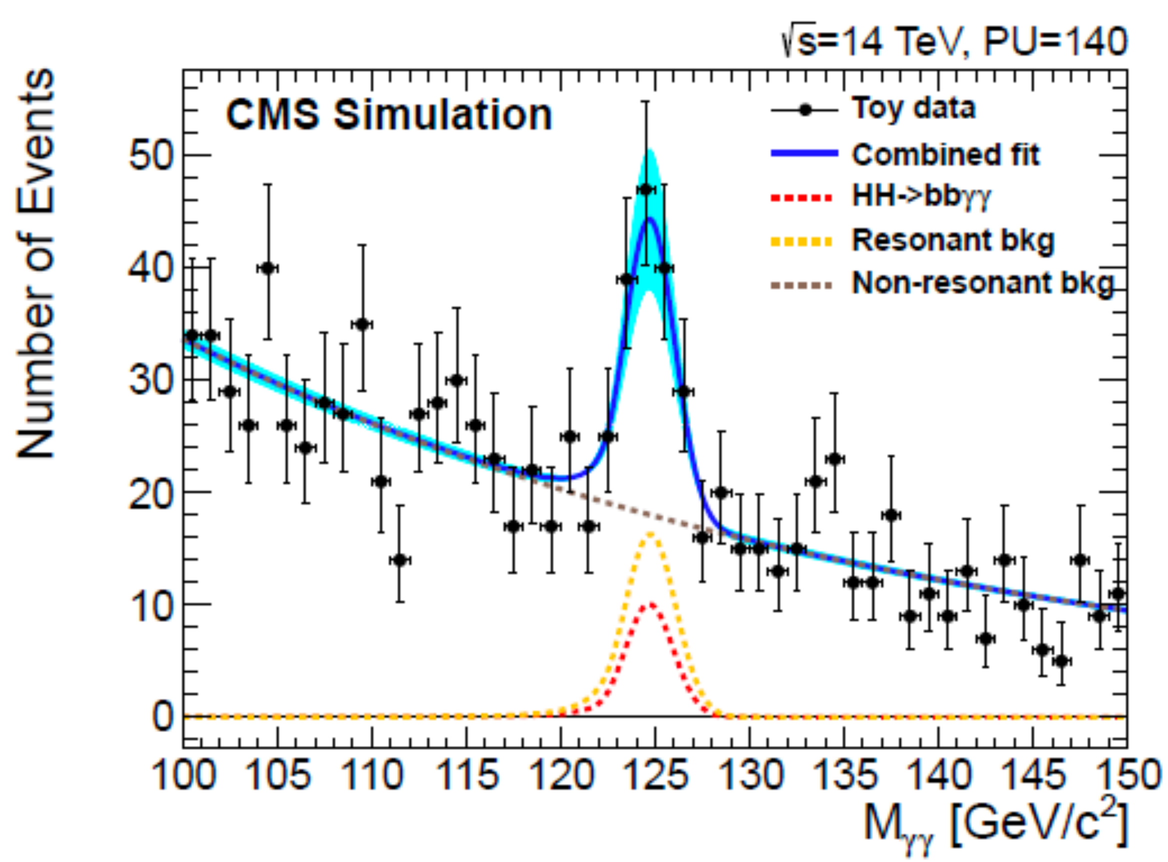


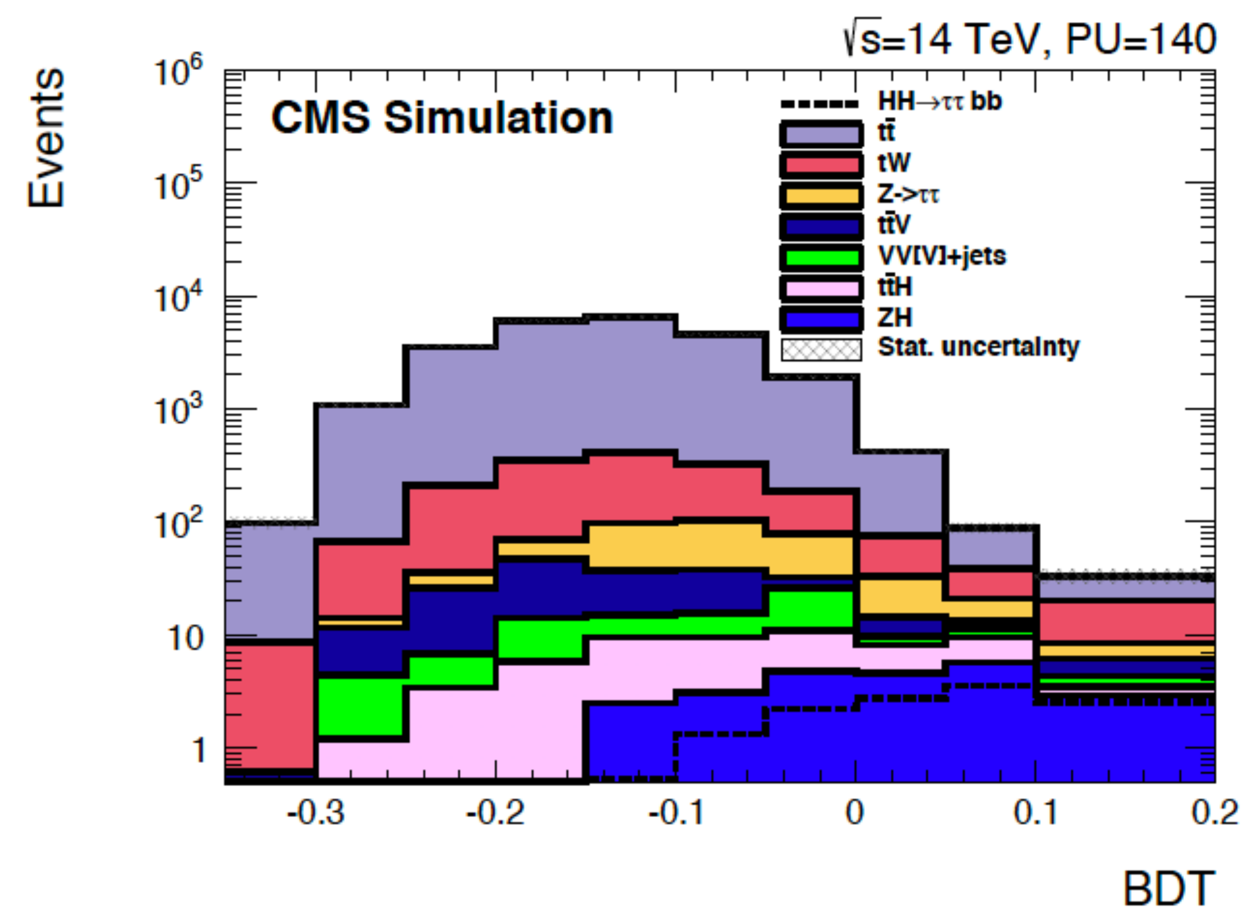
Fiducial Cross Section



DiHiggs Production @ LHCC-P-008

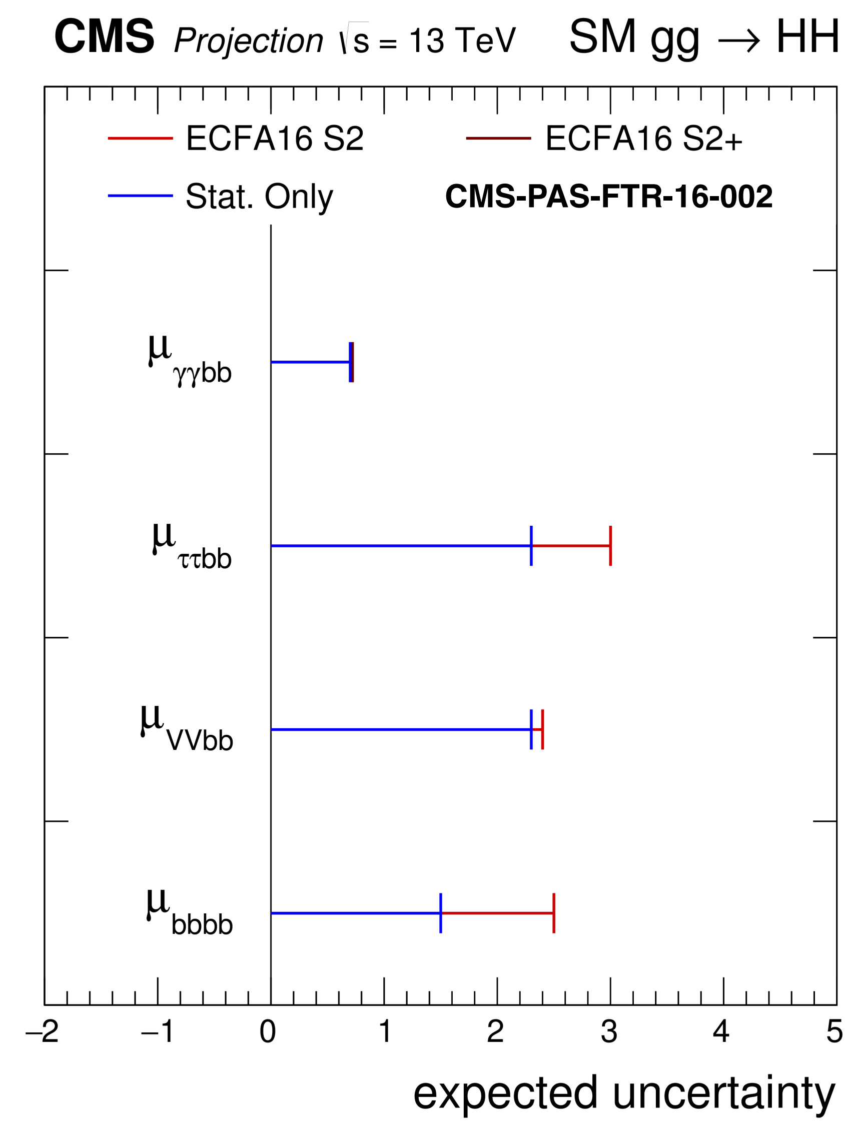
- Focus on detector performance
- bbgg, bbtautau, bbWW studied using Delphes
- ~1.9 combined significance, 54% uncertainty on signal yield





DiHiggs Production

- **ECFA16:** Updated projections from public analyses using 2015 data at 13 TeV



Channel	Median expected limits in μ_r ECFA16 S2	Median expected limits in μ_r Stat. Only	Z-value ECFA16 S2	Z-value Stat. Only	Uncertainty as fraction of $\mu_r = 1$ ECFA16 S2	Uncertainty as fraction of $\mu_r = 1$ Stat. Only
$gg \to HH \to \gamma\gamma bb$ (S2+)	1.44	1.37	1.43	1.47	0.72	0.71
$gg \to HH \to \tau\tau bb$	5.2	3.9	0.39	0.53	2.6	1.9
$gg \to HH \to VVbb$	4.8	4.6	0.45	0.47	2.4	2.3
$gg \to HH \to bbbb$	7.0	2.9	0.39	0.67	2.5	1.5