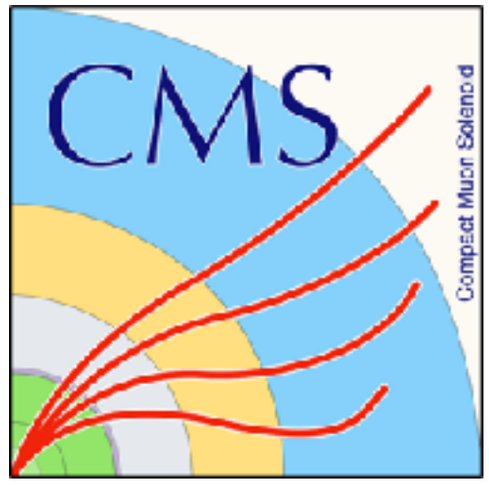
Imperial College London



Higgs measurements at the HL-LHC with CMS

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on behalf of the CMS collaboration

Outline

- Introduction
  - Higgs physics
  - HL-LHC
- SM Higgs boson measurements at the HL-LHC
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ$
  - Non-resonant HH
- BSM Higgs boson searches at the HL-LHC
  - Resonant HH
  - $A/H \rightarrow \tau\tau$
  - VBF $H \rightarrow$ invisible
- Summary and outlook

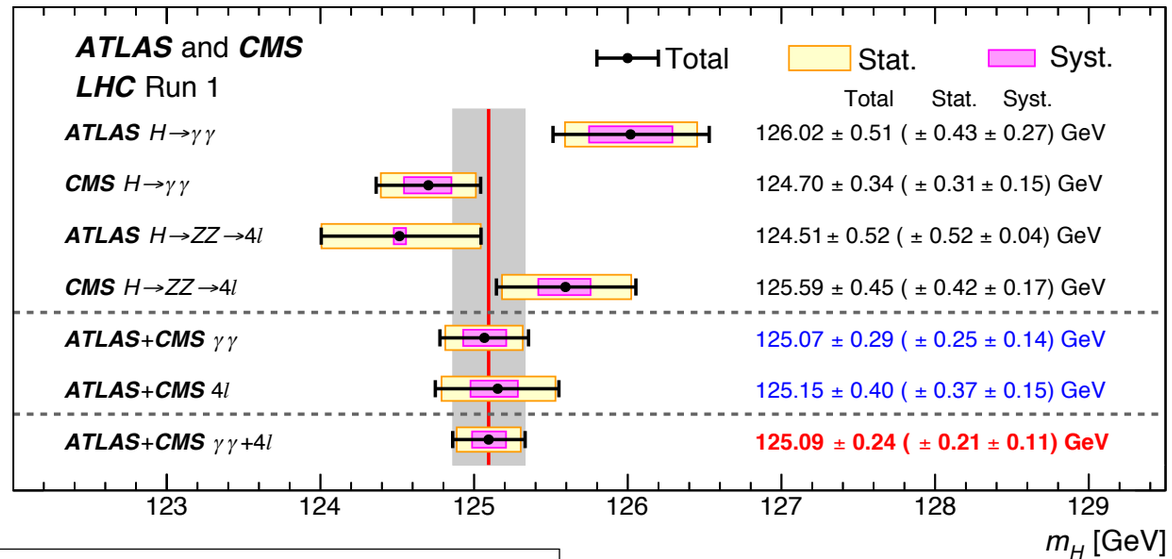
Introduction

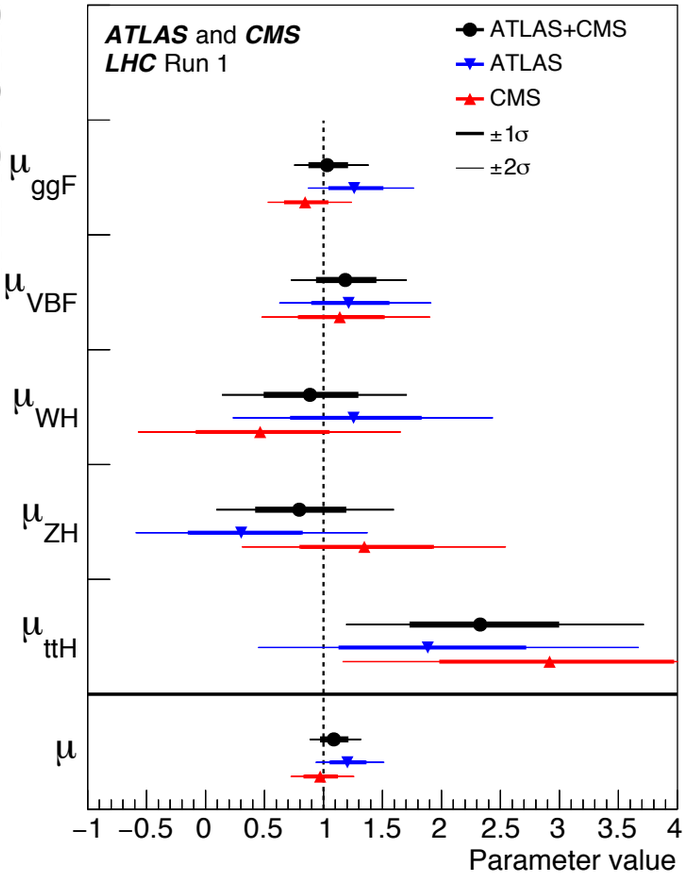
- **5 years since the discovery of the Higgs boson, what do we know?**

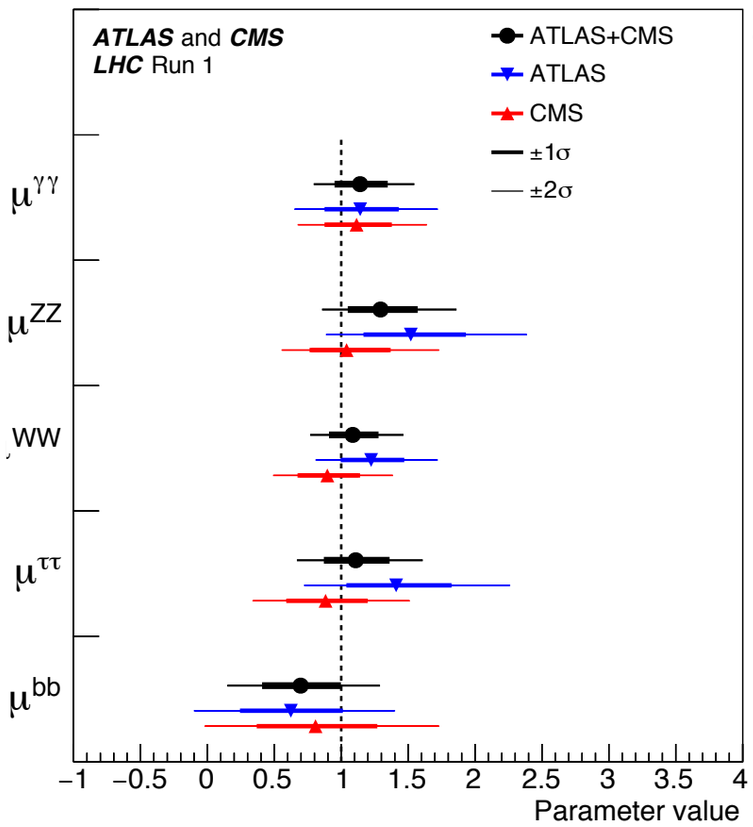
Run 1: good precision on mass and couplings

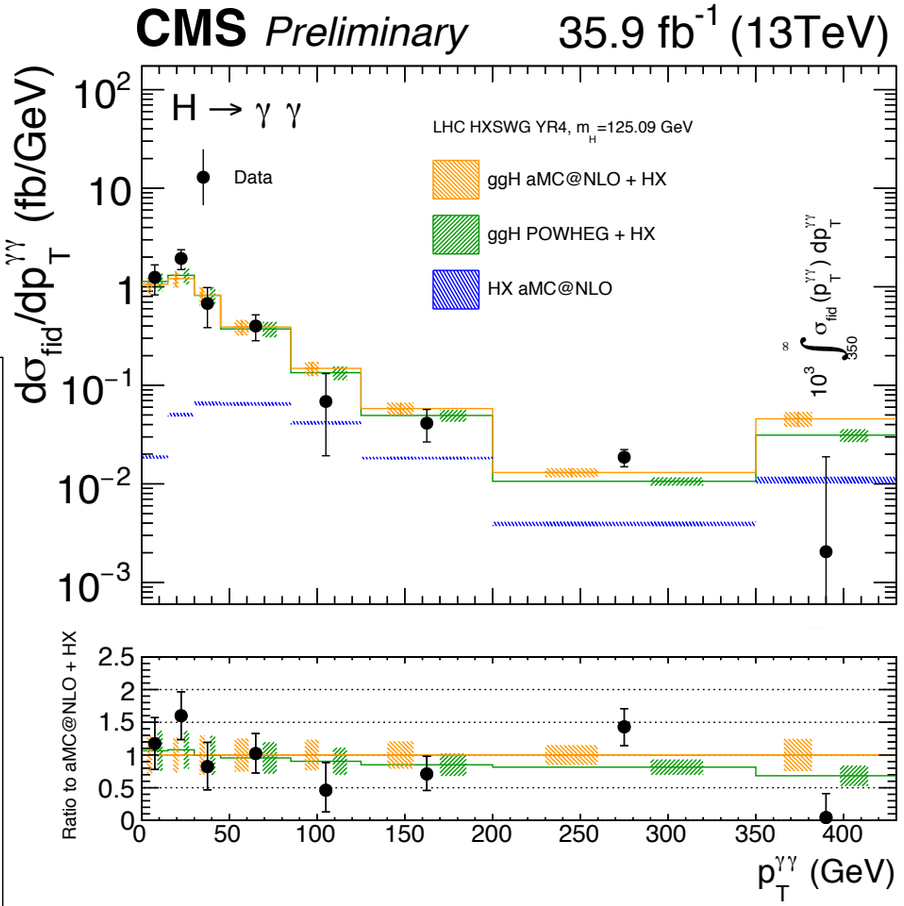
Run 2: re-discovery of the Higgs boson and fiducial/differential cross-sections

ATLAS+CMS PRL 114(2015) 191803
ATLAS+CMS JHEP 08 (2016) 045









CMS-PAS-HIG-17-015

Introduction

- The Higgs sector looks standard-model like… but is it?
- At the HL-LHC, expect L=3000 fb^{-1}
  - Precision measurements
  - Access to Higgs self coupling
  - Find BSM physics?
- High luminosity→high PU: Upgrades to various parts of the detector to function in this challenging environment

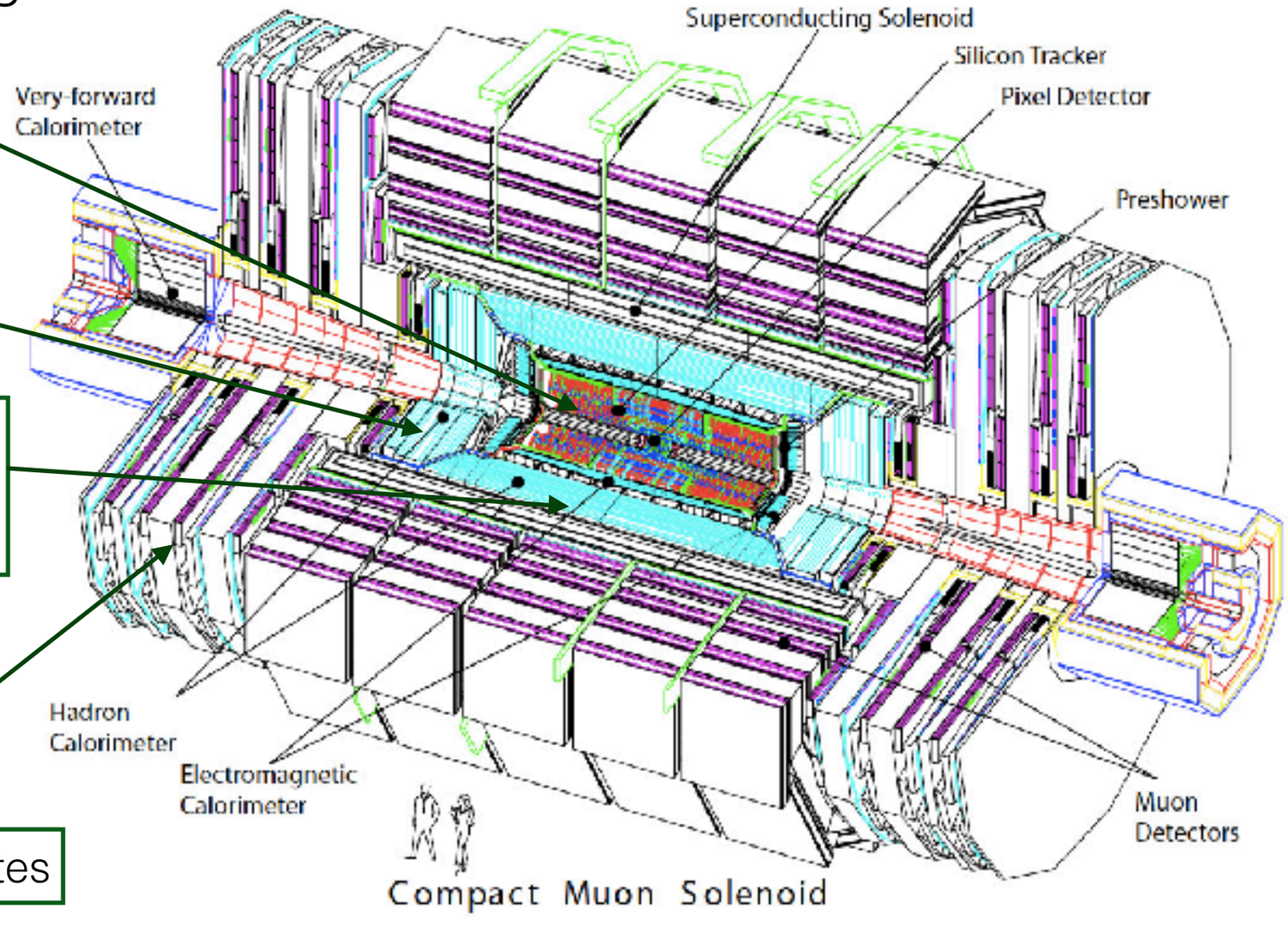
Tracker: coverage up to |η|<4, Increased granularity, L1 triggering capabilities

Calorimeter endcaps: highly granular calorimeter, 3D shower imaging

Barrel calorimeter: Upgrades to electronics, ECAL noise reduction, HCAL scintillators

Muon endcaps: additional systems covering 1.5<|η|<2.4, increased muon system coverage up to |η|<3

Trigger: Track-trigger at L1, higher rates



Extrapolation strategy

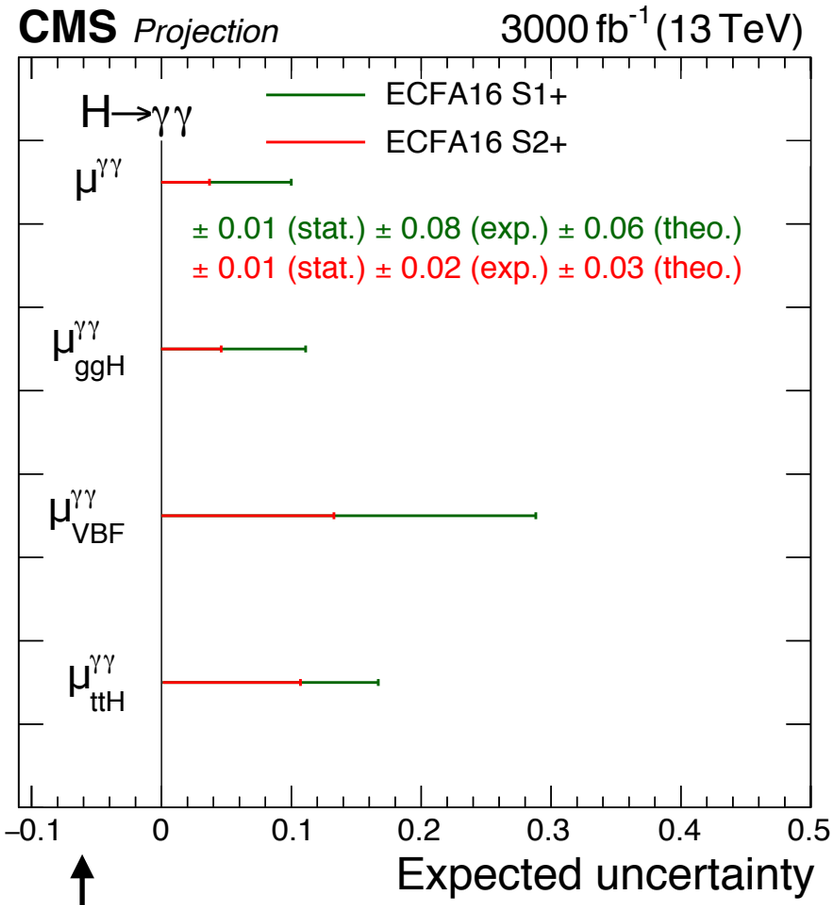
- Extrapolations of analyses at 13 TeV on 2015 dataset (2.3-2.7 fb^{-1}) or early 2016 dataset (12.9 fb^{-1})
- Several extrapolation scenarios considered:

	Uncertainties change	high-PU effects modelled	Description
S1	**no**	**no**	**systematic uncertainties constant**
S1+	**no**	**yes**	**systematic uncertainties constant, analysis-dependent modifications for high PU**
S2	**yes**	**no**	**theoretical uncertainties halved, experimental uncertainties scaled down by √L until a lower limit is reached**
S2+	**yes**	**yes**	**theoretical uncertainties halved, experimental uncertainties scaled down by √L until a lower limit is reached, analysis-dependent modifications for high PU**
Stat. Only.	**yes**	**no**	**only statistical uncertainties considered**

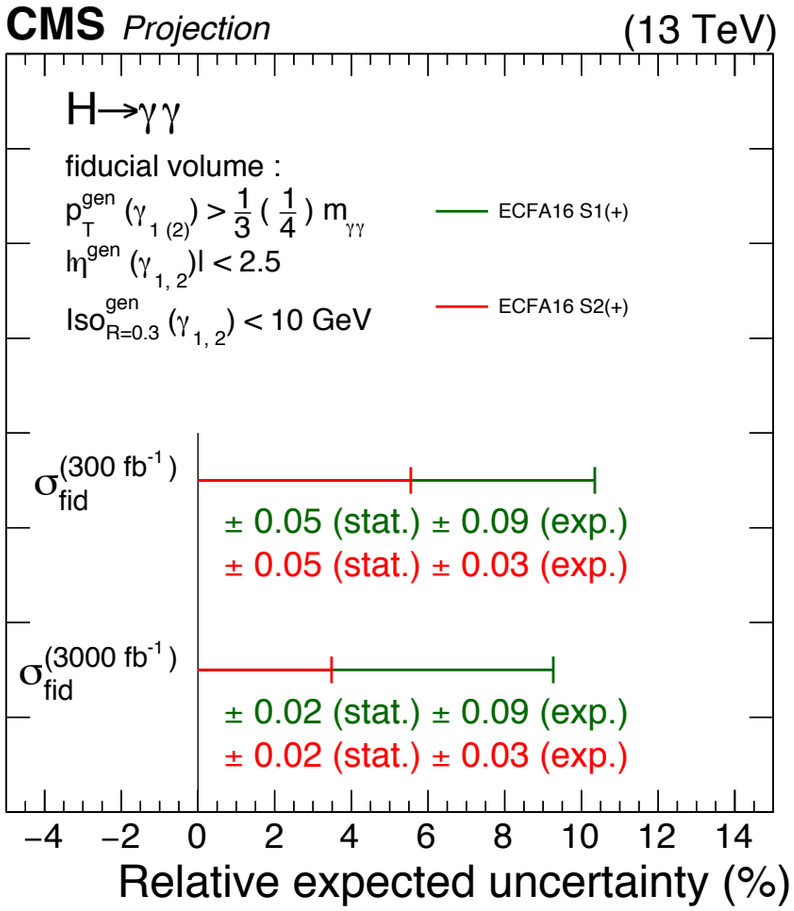
SM Higgs boson measurements

$H \rightarrow \gamma\gamma$

- Projection of analysis on 12.9 fb^{-1} to 300(0) fb^{-1}
- 2 scenarios considered for projection:
  - **S1: all systematic uncertainties kept constant**
  - **S2: theoretical uncertainties scaled down by 1/2, experimental uncertainties scaled down by √L until a lower limit is reached**
- At 3000 fb^{-1}, modifications for high PU included:
  - Reduction of vertex identification efficiency and photon identification efficiency



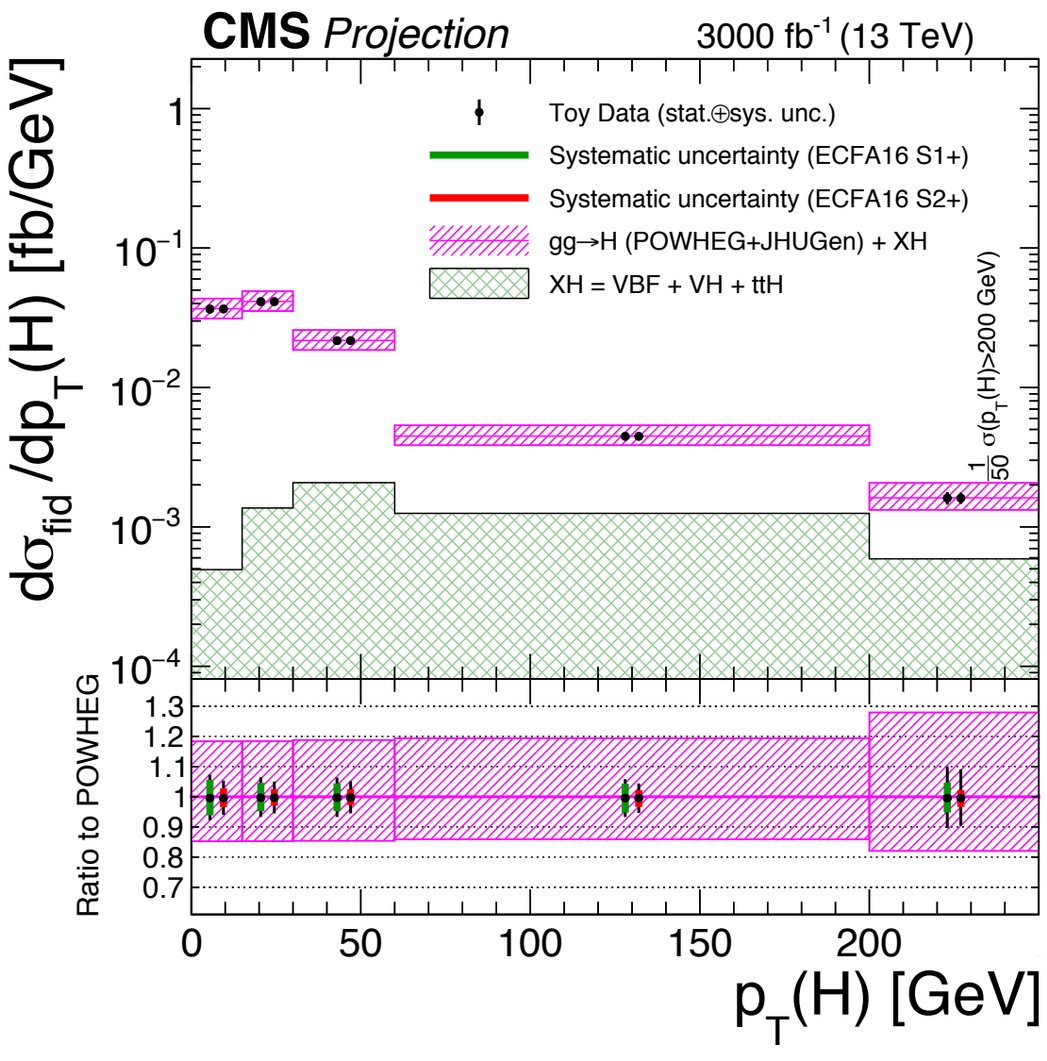
Projection to 3000 fb^{-1} of uncertainty on the signal strength measurement:
experimental and theoretical uncertainties limit the precision.

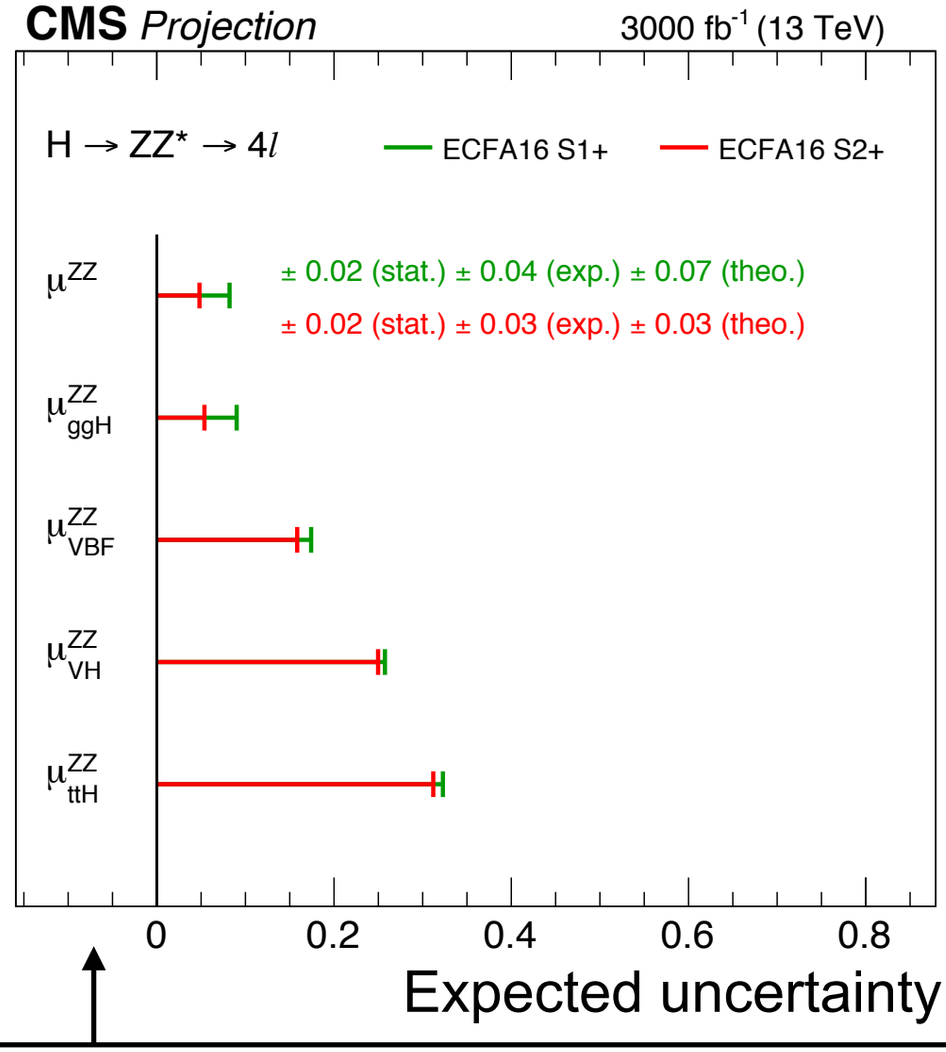


Projection to 300 and 3000 fb^{-1} of uncertainty in fiducial cross-section measurement:
at 3000 fb^{-1} measurement again limited by size of experimental uncertainties.

H→ZZ

- Projection from 12.9 fb^{-1} to 300(0) fb^{-1}
  - Same two scenarios as for H⟶ γγ
  - High-PU effects taken into account at 3000 fb^{-1}
    - Effects on lepton efficiency/ misidentification rates



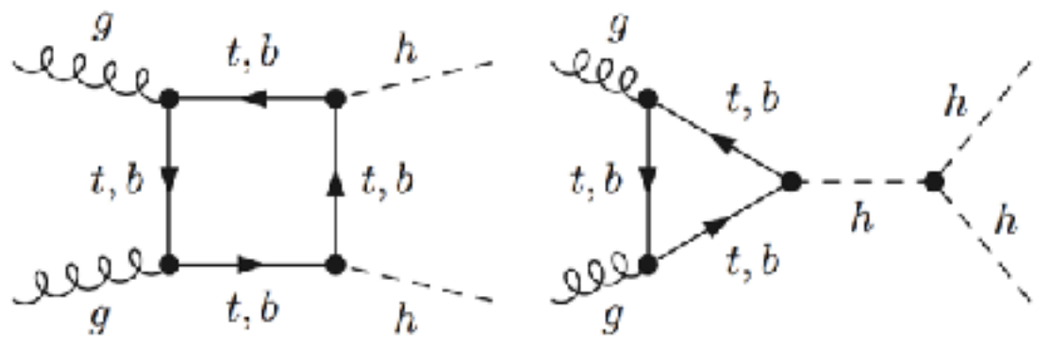


Projection to 3000 fb^{-1} of uncertainty on the signal strength measurement: measurement theoretically and systematically limited.

Projection to 3000 fb^{-1} of uncertainty in differential cross-section measurement: relative uncertainty 4-10%

Non-resonant HH

- **Access to the Higgs self-coupling via Higgs boson pair production**
  - Destructive interference ⟶ σ(pp ⟶ HH) = 33.4 fb
- Projections of 4 non-resonant HH final states, 2.3-2.7 fb^{-1} projected to 3000 fb^{-1}
  - Scenario with systematic uncertainties scaled down + a scenario without systematic uncertainties (stat. only)



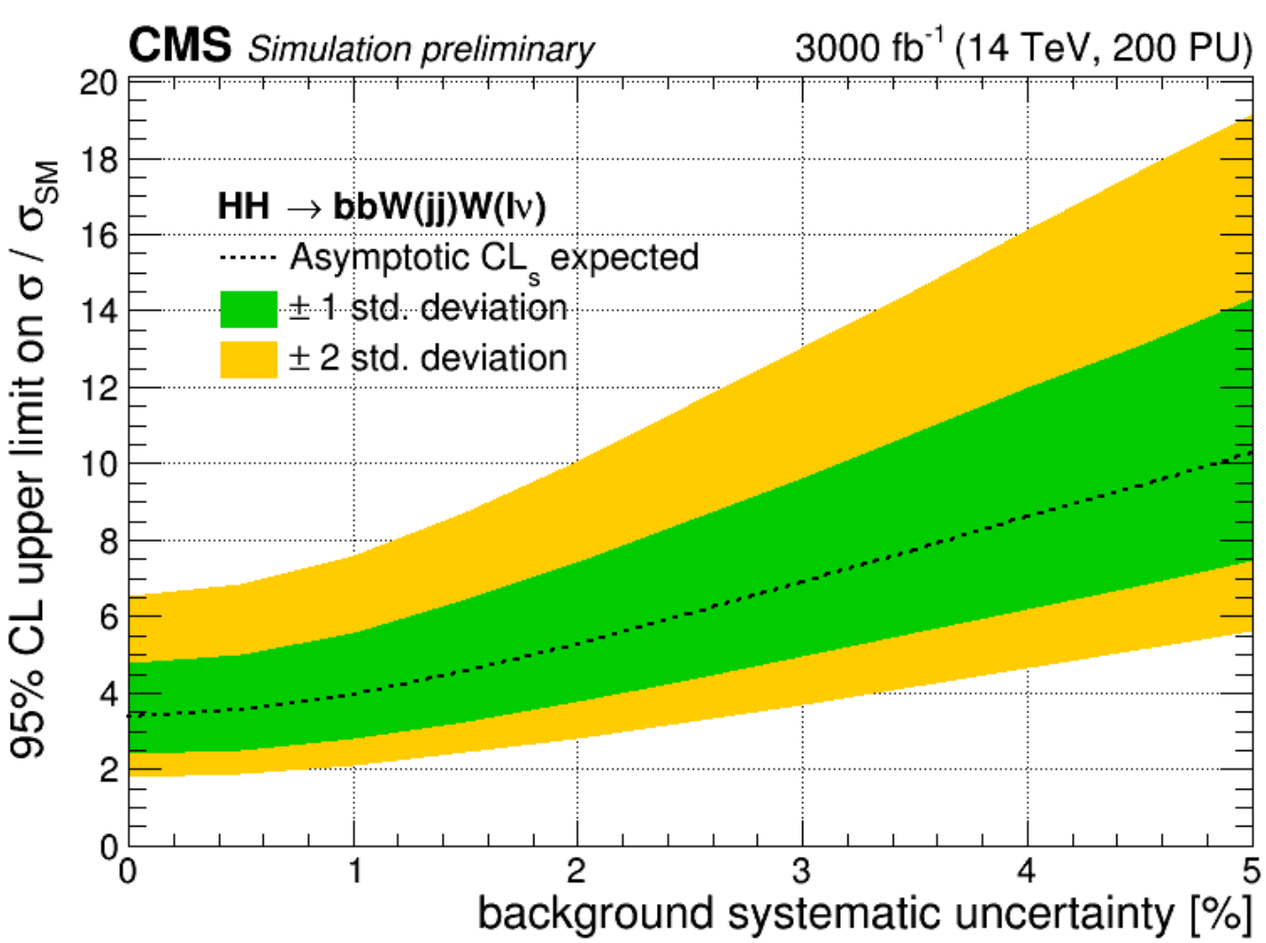
Channel	Median expected limits in μ_r		Z-value		Uncertainty as fraction of $\mu_r = 1$	
	ECFA16 S2	Stat. Only	ECFA16 S2	Stat. Only	ECFA16 S2	Stat. Only
$gg \to HH \to \gamma\gamma bb$ (S2+)	1.44	1.37	1.43	1.47	0.72	0.71
$gg \to HH \to \tau\tau bb$	5.2	3.9	0.39	0.53	2.6	1.9
$gg \to HH \to VVbb$	4.8	4.6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

Expected upper limits on $\sigma_{HH}/\sigma_{HHSM}$ projected to 3000 fb^{-1}

HH→bbWW→bbqqlv

- Analysis has not yet been performed with Run-2 data
  - **Instead, study based on simulation using Delphes to model the upgraded detector performance**
  - Conditions:
    - Centre-of-mass energy 14 TeV, 200 PU, integrated luminosity 3000 fb^{-1}
    - Only the dominant $t\bar{t}$ background considered as background process

Expected upper limit on $\sigma_{HH}/\sigma_{HHSM}$ as a function of the relative uncertainty on the background: median expected limit
3.5xSM for 0% uncertainty
10.5xSM for 5% uncertainty



BSM Higgs boson searches

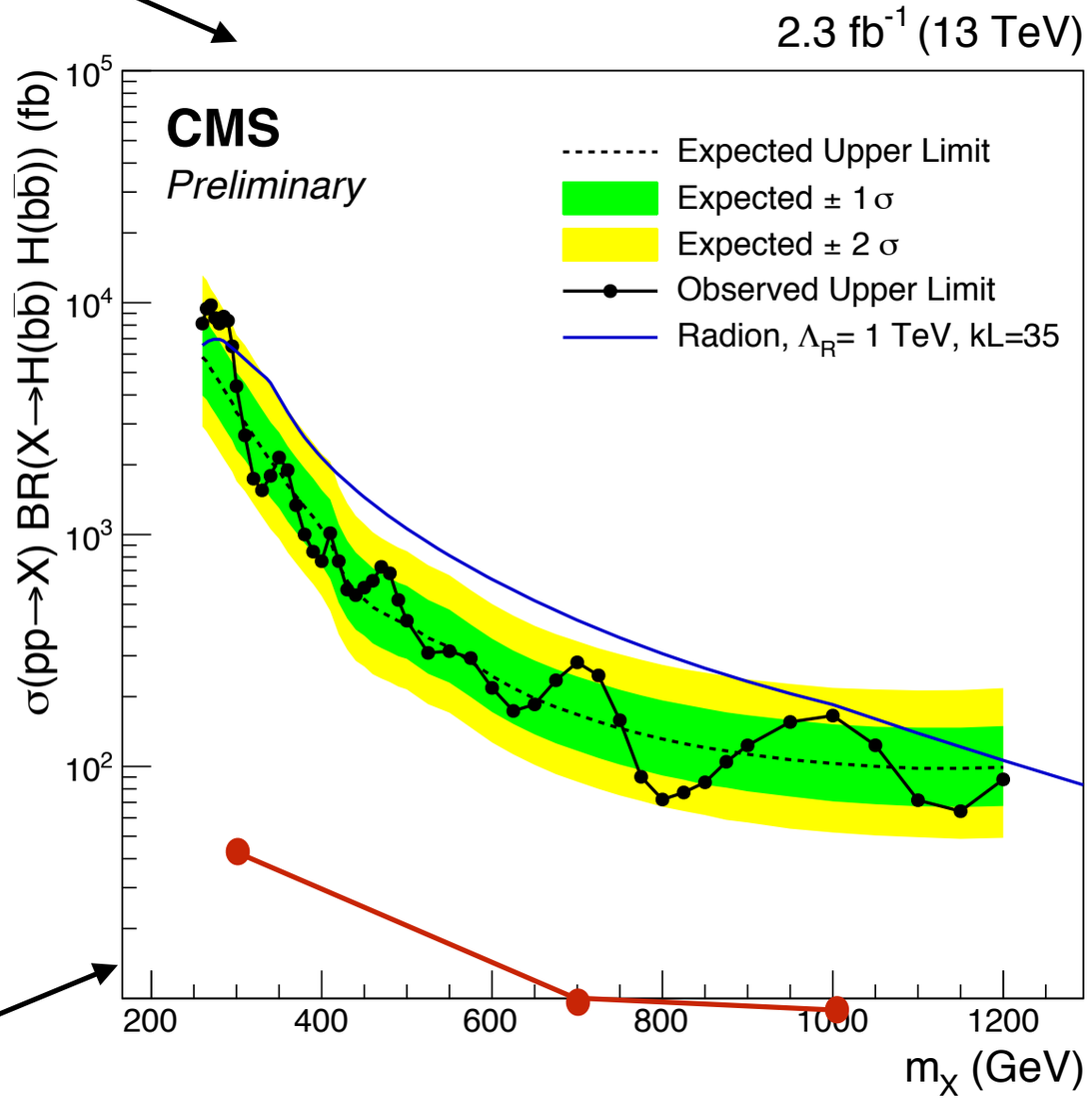
CMS-PAS-HIG-16-002
CMS-PAS-FTR-16-002

Resonant HH→4b

- Heavy resonance X decaying to pair of 125 GeV Higgs bosons
  - Access to models with warped extra dimensions, SUSY
- Projection of analysis on 2.3 fb^{-1} to 3000 fb^{-1}
  - **2 scenarios used**:
    - Statistical uncertainty only
    - Systematic uncertainties scaled down with √L, theoretical uncertainties halved

3 mass points: 300 GeV, 700 GeV, 1 TeV

	Median expected limits on σ (fb)	
m_X (TeV)	ECFA16 S2	Stat. Only
0.3	46	41
0.7	7.3	3.4
1.0	4.4	2.4



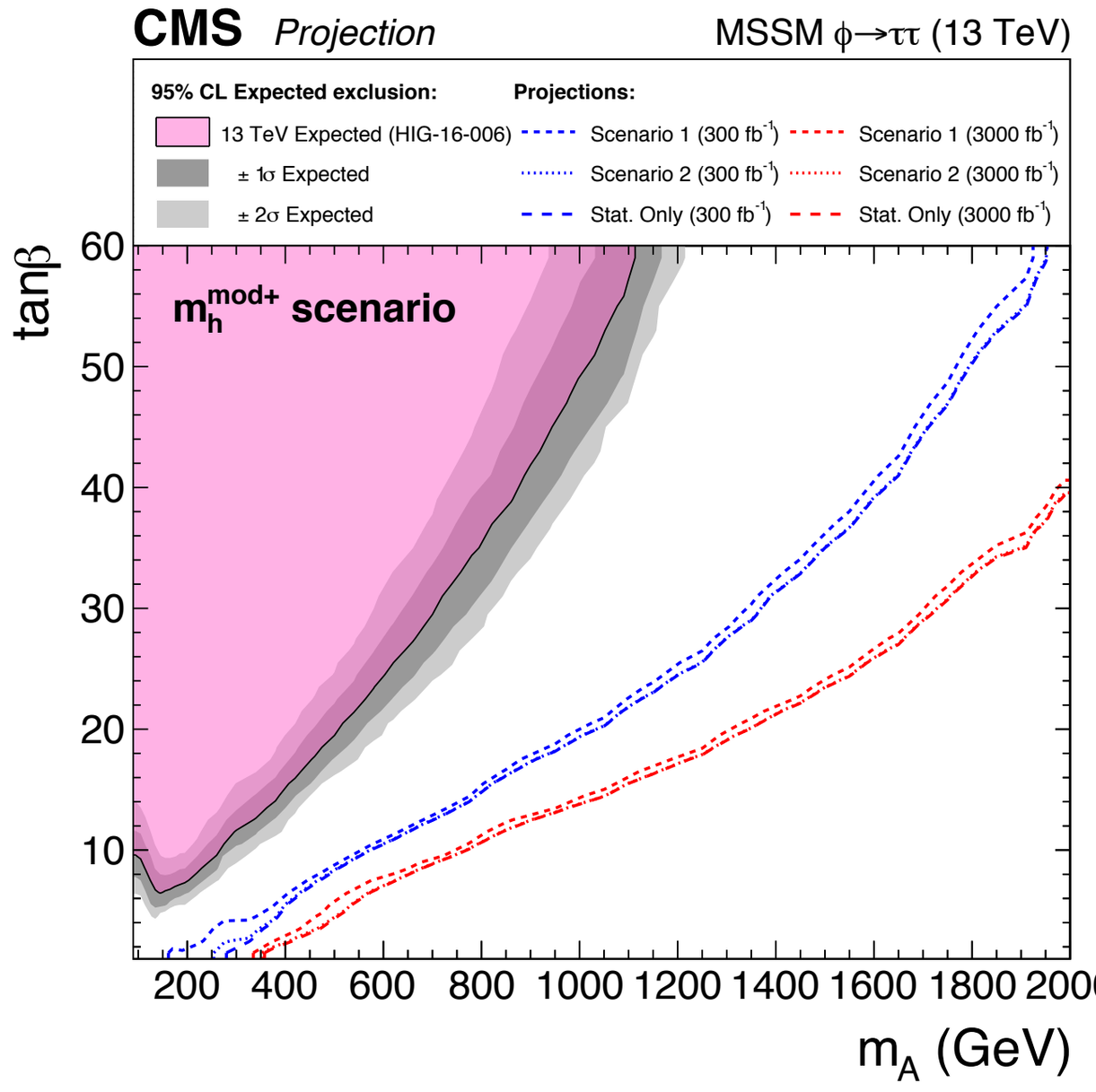
Limits indicated on the reference analysis results in red

MSSM $\phi \rightarrow \tau\tau$

- Projection of search on 2.3 fb^{-1} to 300 and 3000 fb^{-1}
- Three scenarios considered:
  - Systematic uncertainties unchanged (scenario 1)
  - Experimental uncertainties scaled down with $\sqrt{L}$, theoretical by factor 1/2 (scenario 2)
  - Statistical uncertainties only (stat. only)
- Analysis considers two heavy Higgs boson production modes (gluon fusion, b-associated production)
  - Interpretation in MSSM m_h^{mod+} benchmark scenario

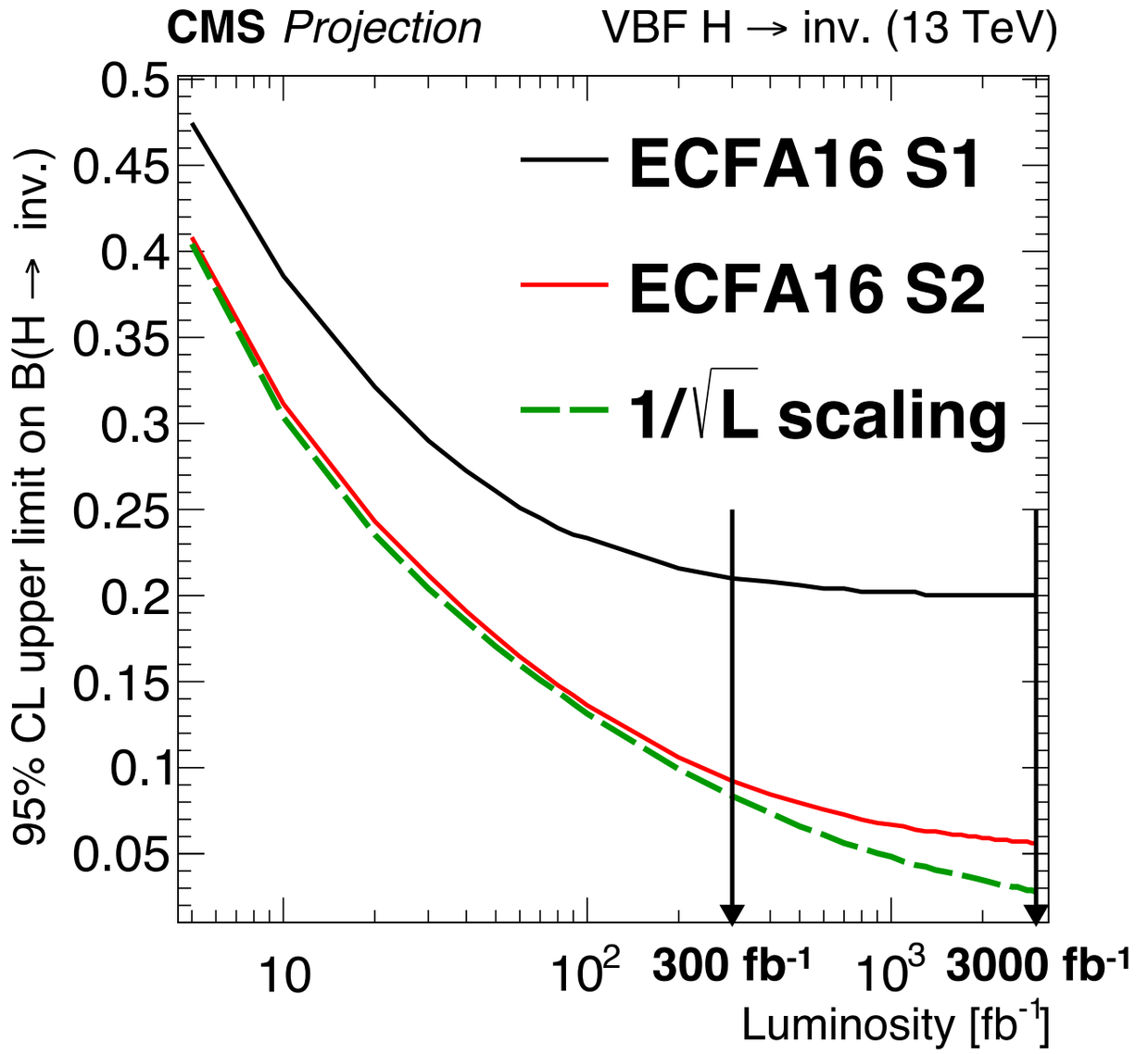
Pink shaded area: expected exclusion from reference analysis
Grey bands: pm 1/2σ expected (reference analysis)
Blue lines: projection to 300 fb^{-1}
Red lines: projection to 3000 fb^{-1}

Even at 3000 fb^{-1}, analysis remains statistically limited at high mass



VBF H→invisible

- Projecting search for invisibly decaying Higgs boson produced via vector boson fusion using 2.3 fb^{-1}
- Scenarios considered:
  - Unchanged systematic uncertainties
  - Exp uncertainties scaled down by √L until lower bound is reached, theoretical uncertainties scaled by 1/2
  - Uncertainties scaled down by √L (No lower bound), theoretical uncertainties scaled by 1/2



With **unchanged systematic uncertainties**, upper limit on **BR(H→ inv) plateaus around 300 fb^{-1},**
scaling systematic uncertainties by √L allows **upper limit of BR(H→inv)=5%** at 3000 fb^{-1}

Summary and outlook

- **Projections to 300(0) fb^{-1} of analyses using Run-2 data and studies based on simulation of upgraded detector shown**
  - Expected precision of property measurements
  - Access to HH production
  - Physics reach in BSM scenarios

- **Next steps:** studies of analysis improvements with upgrades to specific subsystems
  - TDRs for subsystems to be submitted throughout the remainder of 2017
    - Higgs analysis studies to feature in all of these TDRs

  → **Increasingly clear picture of the prospects for Higgs physics at the HL-LHC**

Backup

Projected analyses

- H->γγ: CMS-PAS-HIG-16-020
- H->ZZ->4l: CMS-PAS-HIG-16-033
- HH->bbγγ: CMS-PAS-HIG-16-032
- HH->bbbb (non resonant): CMS-PAS-HIG-16-026
- HH->bbbb (resonant): CMS-PAS-HIG-16-006
- HH->bbττ: CMS-PAS-HIG-16-012
- HH->bbWW->bblvlv: CMS-PAS-HIG-16-024
- MSSM H->ττ: CMS-PAS-HIG-16-006
- VBF H->inv: CMS-PAS-HIG-16-016