Overview of CMS Higgs Studies to be presented at the ECFA workshop

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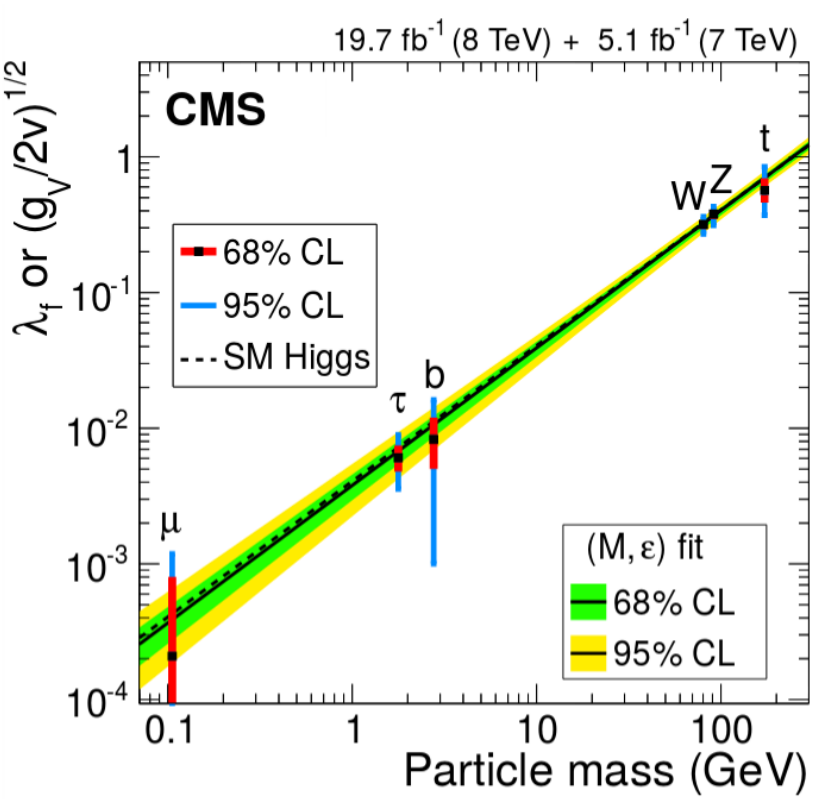
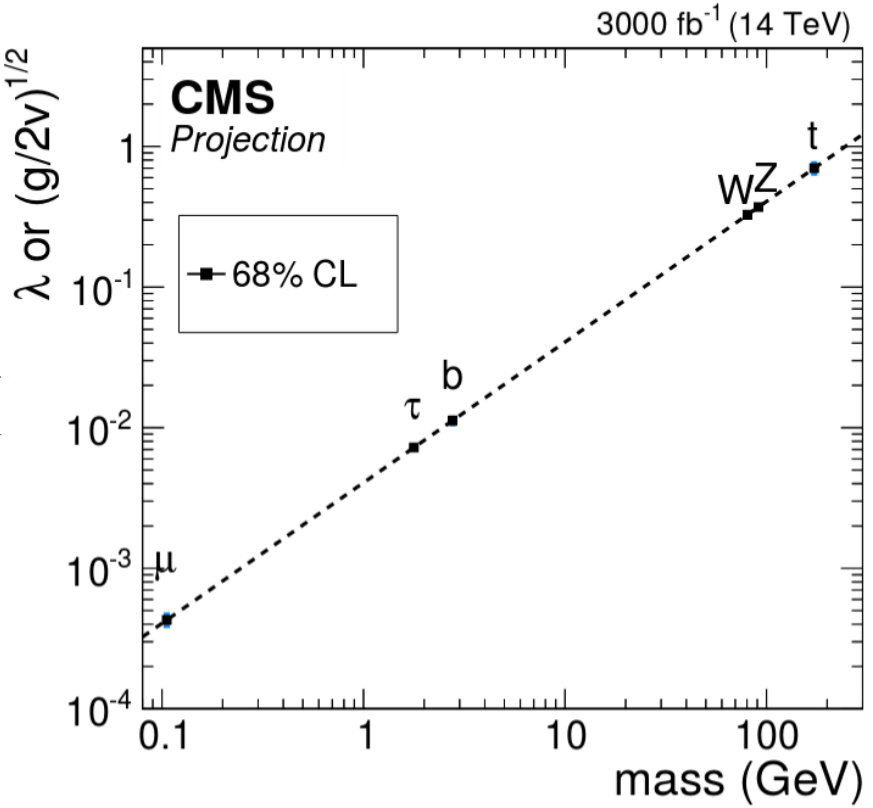
On Behalf of the CMS Collaboration

Introduction:

Higgs Physics Program for HL-LHC

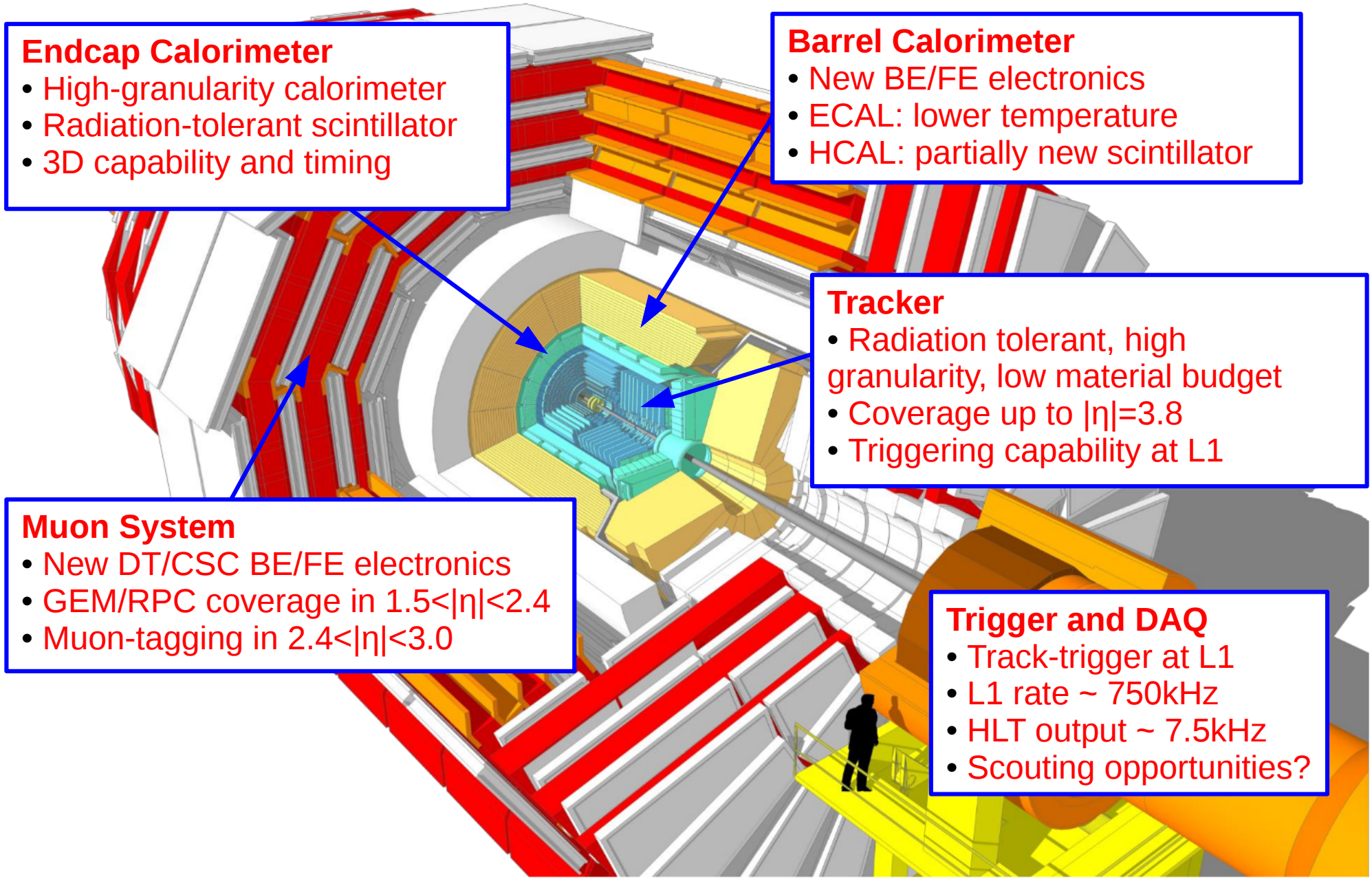
- The 125 GeV Higgs boson has been discovered (7+8) TeV) and rediscovered (13 TeV)
- There are some deviations, but well within the current uncertainties
  - ➔ No *striking* discrepancies from the SM have been observed so far
- The LHC experiments must continue to test the SM predictions for the Higgs sector
  - ➔ Increase the precision of the measurements
  - ➔ Search for rare and BSM signatures





CMS Phase II Upgrades

TDR-15-002



Endcap Calorimeter
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Triggering capability at L1

Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon-tagging in $2.4<|\eta|<3.0$

Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz
- Scouting opportunities?

Projection Scenarios

- Projections carried out by scaling event yields from 13 TeV analyses (2.3-12.9 fb^{-1}) to 300fb^{-1} (3000 fb^{-1}), two scenarios for systematics

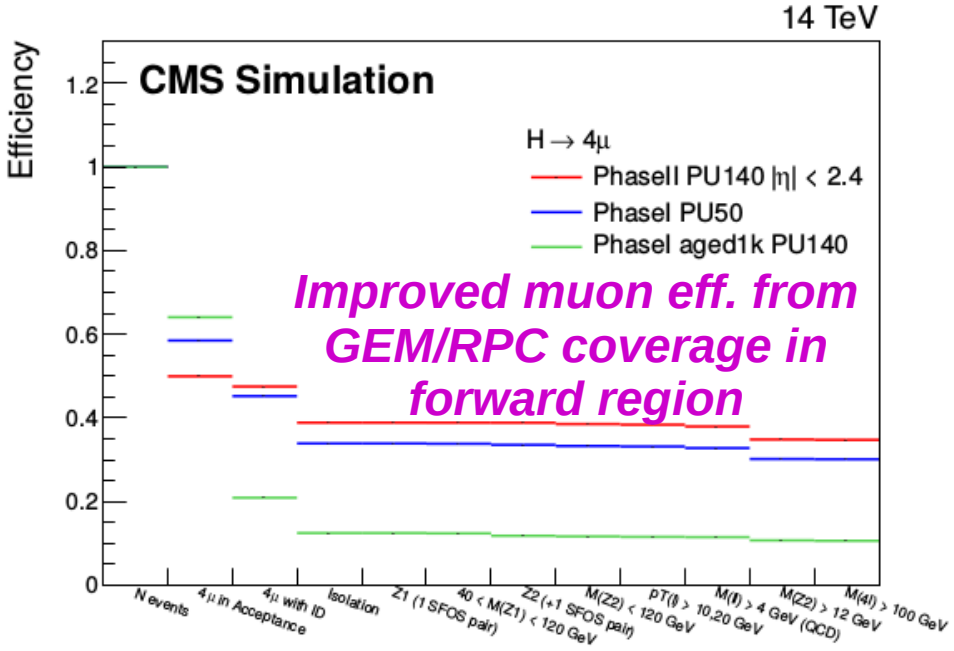
- Scenario 1: same systematic uncertainties as 13 TeV analysis
- Scenario 2: reduced systematic uncertainties
  - ➔ Experimental uncertainties scale with $1/\sqrt{\mathcal{L}}$ until they reach the “true” systematic level, e.g.:
    - Lepton eff. (1% per lepton)
    - Integrated Luminosity (1.5%)
  - ➔ Theoretical uncertainties scaled by ½

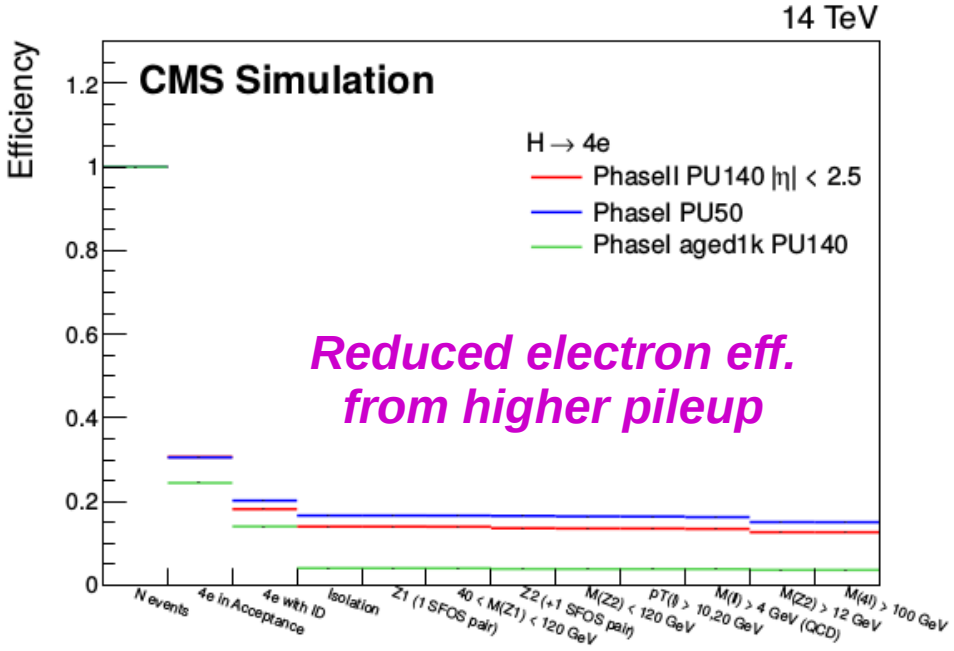
- Impact of increased pileup and detector upgrades included where possible using existing studies, e.g.

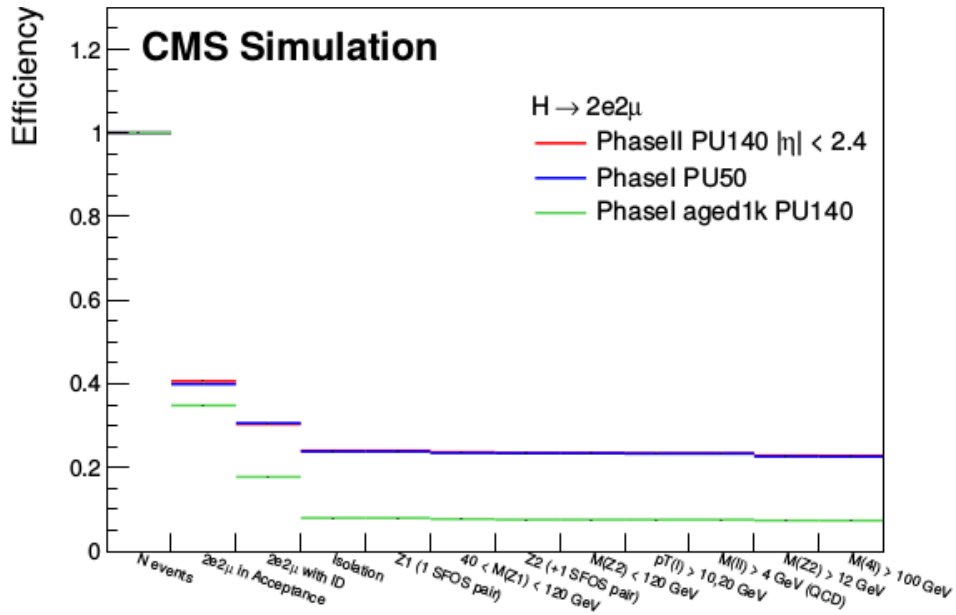
TDR-15-002

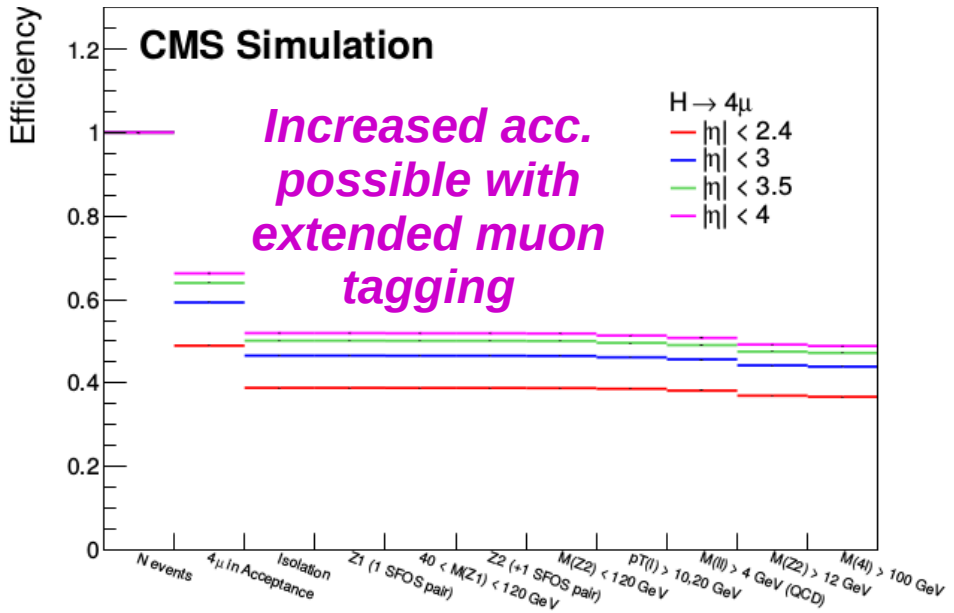
Phase 2 Upgrade Impact: H→ZZ

TDR-15-002



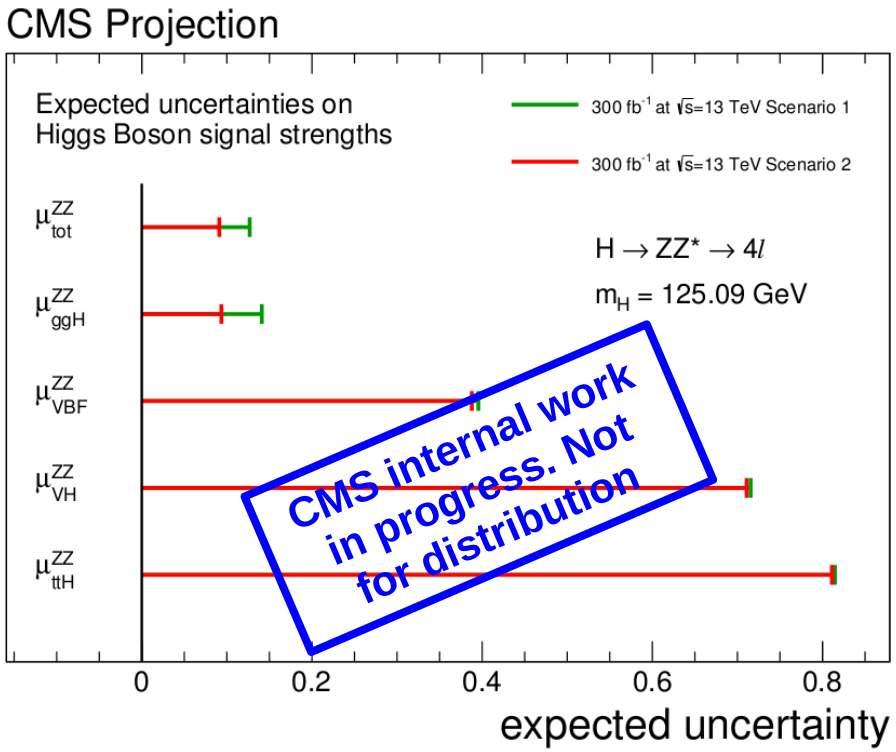


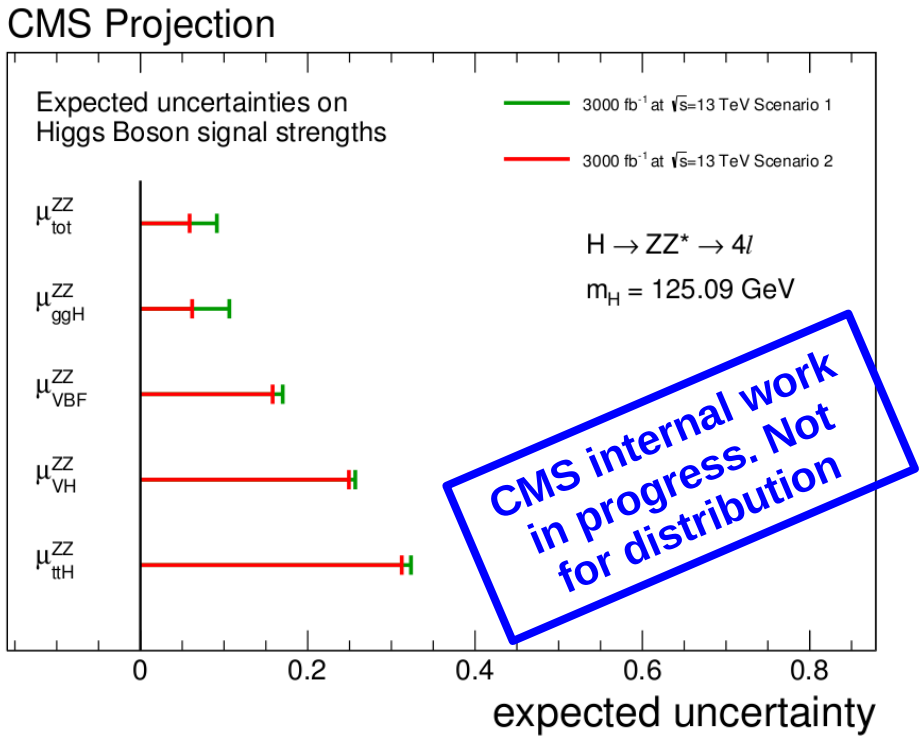




Prod. Modes with H→ZZ decay

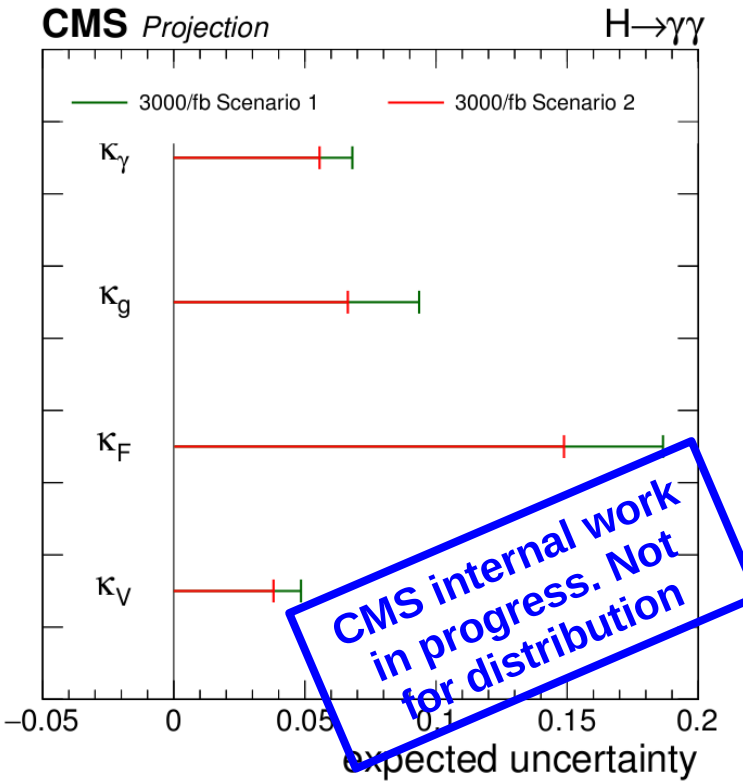
- Projections carried out by scaling ICHEP analysis to 300fb^{-1} (3000 fb^{-1})
- For Scenario 2, following experimental systematics have been reduced
  - ➔ Lepton eff. (1% per lepton) and Integrated Luminosity (1.5%)
- For 3000 fb^{-1}, changes in yields implemented based on TP studies
  - ➔ Z+X background yields (4μ: ~2.7x, 4e: ~4.7x, 2e2μ: ~3.2x)
  - ➔ Signal and ZZ background yields (4μ: ~1.17x, 4e: ~0.83x, 2e2μ: ~1.0x)

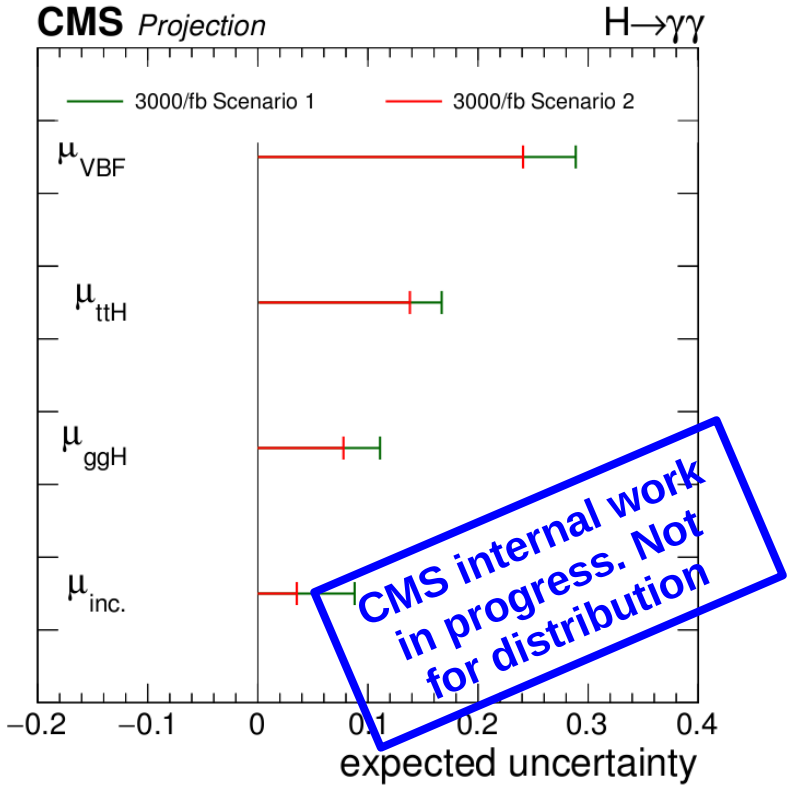




Prod. Modes/Couplings with H→γγ

- Width of interaction region assumed to be 5cm, instead of current 3.6cm
- Photon ID eff. decreased by 2.3%(10%) in EB(EE) (Signal and prompt Bkg.)
- Vertex Finding eff. reduced from 80% to 40%
- Photon energy resolution assumed to be unchanged
  → Fix μ_{VH}=1 (no VH category in ICHEP analysis)





No PU effects S1
$\mu = 1.000 \pm 0.086 = 1.000 \pm 0.011\ (\text{stat.})\ ^{+0.077}_{-0.072}\ (\text{syst.})\ ^{+0.045}_{-0.039}\ (\text{theo.})$

All PU effects S1
$\mu = 1.000 \pm 0.088 = 1.000 \pm 0.013\ (\text{stat.})\ ^{+0.079}_{-0.074}\ (\text{syst.})\ ^{+0.045}_{-0.038}\ (\text{theo.})$

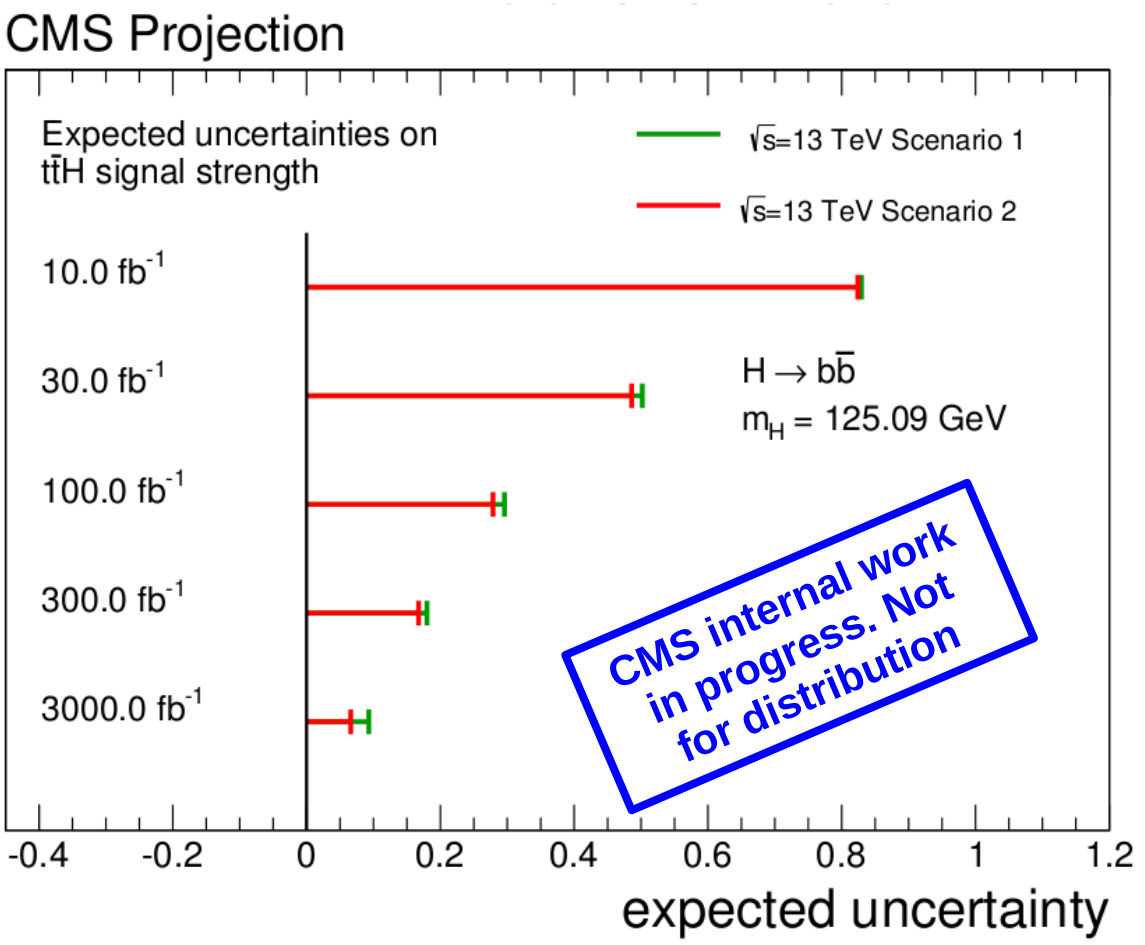
No PU effects S2
$\mu = 1.000 \pm 0.034 = 1.000 \pm 0.011\ (\text{stat.})\ ^{+0.018}_{-0.017}\ (\text{syst.})\ ^{+0.029}_{-0.025}\ (\text{theo.})$

All PU effects S2
$\mu = 1.000 \pm 0.036 = 1.000 \pm 0.013\ (\text{stat.})\ ^{+0.019}_{-0.019}\ (\text{syst.})\ ^{+0.029}_{-0.025}\ (\text{theo.})$

ttH Production with H→bb

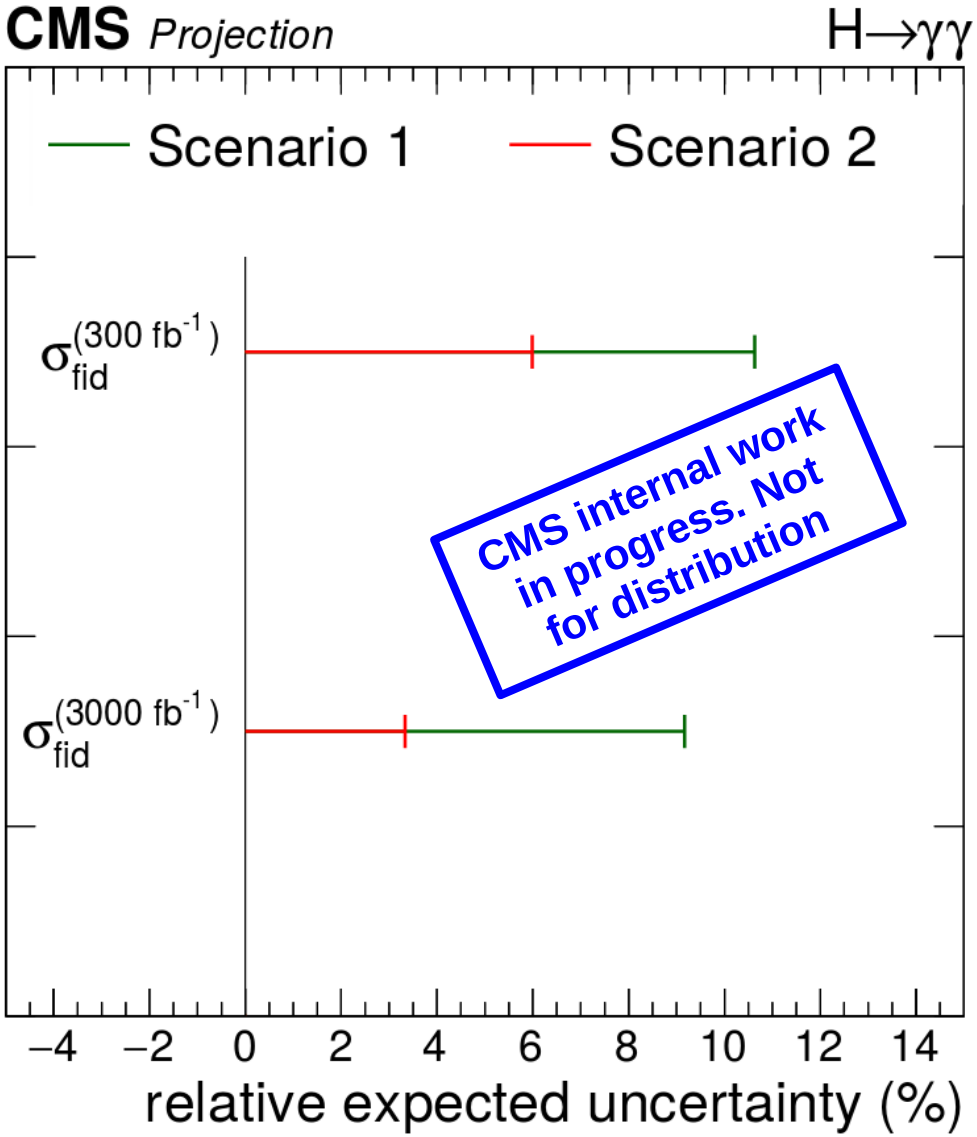
- Based on 2.7 fb^{-1} 2015 data, lepton+jets and dilepton channels
- Scenario 2: scale sys. unc. by $1/\sqrt{\mathcal{L}}$, th. unc. by 0.5

$\mathcal{L}$ [fb^{-1}]	scenario 1	scenario 2
10.0	1.0	1.1
30.0	1.7	1.8
100.0	3.1	3.2
300.0	5.2	5.5
3000.0	16.1	17.1



Fiducial Cross Section with H→γγ

- With increased integrated luminosity fiducial cross sections will become more important
  - ➔ Less sensitive with low luminosity due to removal of event categorization by production mode
- Theoretical uncertainty on the signal cross section is completely decoupled



Anomalous HVV Interactions

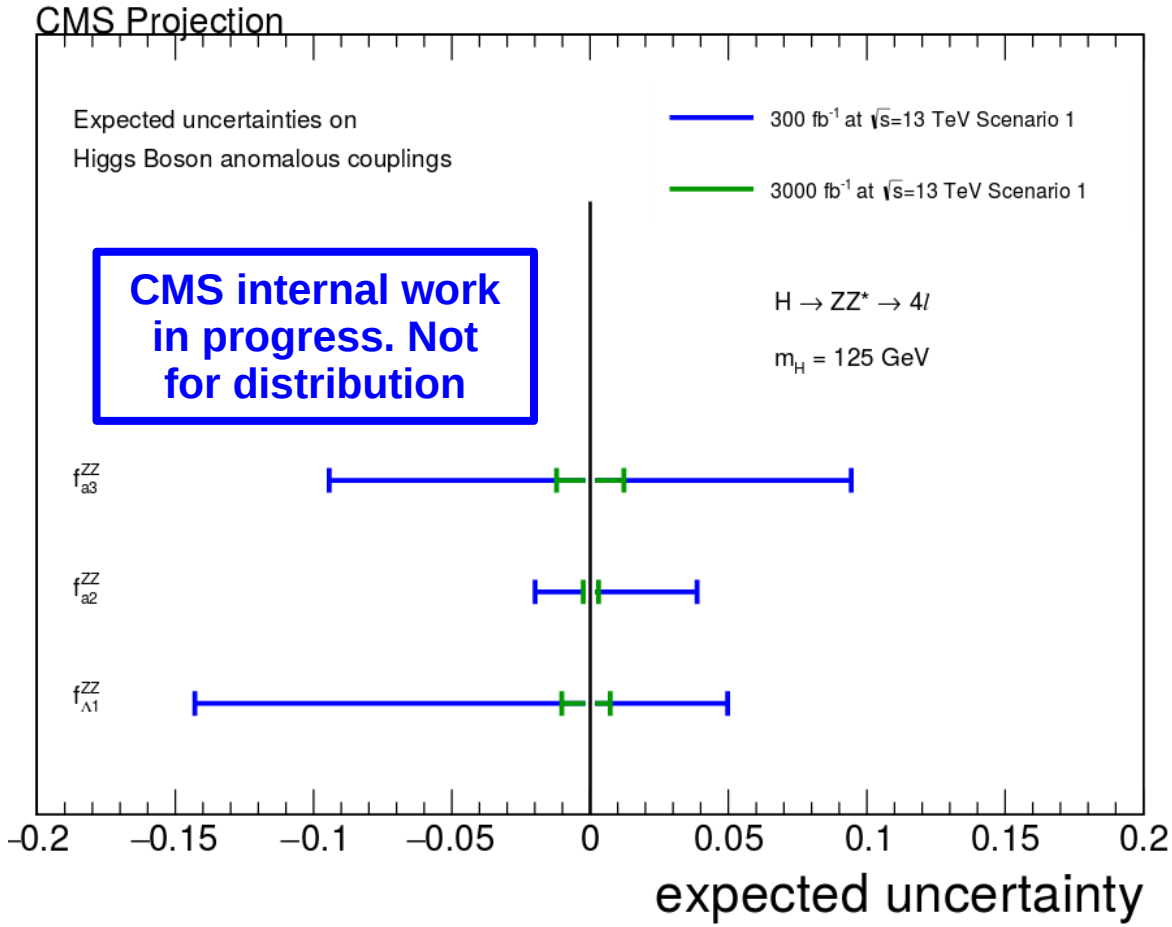
- Important to determine spin and quantum numbers of the particle accurately
- Generic amplitude of H→ZZ for spin-0 particle can be written as:

$$A(HVV)\sim\left[a_1 - e^{i\phi_{\Lambda Q}}\frac{(q_{V1}+q_{V2})^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}}\frac{(q_{V1}^2+q_{V2}^2)}{\Lambda_1^2}\right]m_V^2\epsilon_{V1}^*\epsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)}f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)}\tilde{f}^{*(2),\mu\nu}$$

- Can test for anomalous HVV couplings a_i

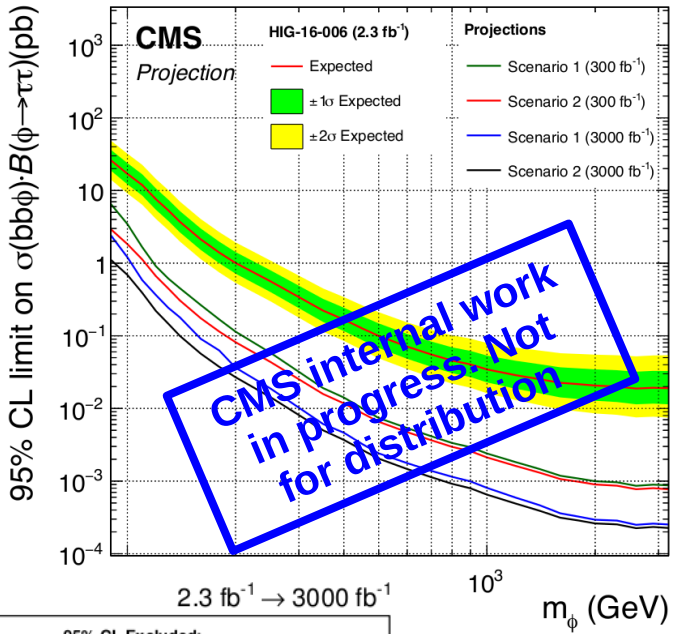
$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_j |a_j|^2\sigma_j} \qquad \phi_{ai} = \tan^{-1}(a_i/a_1)$$

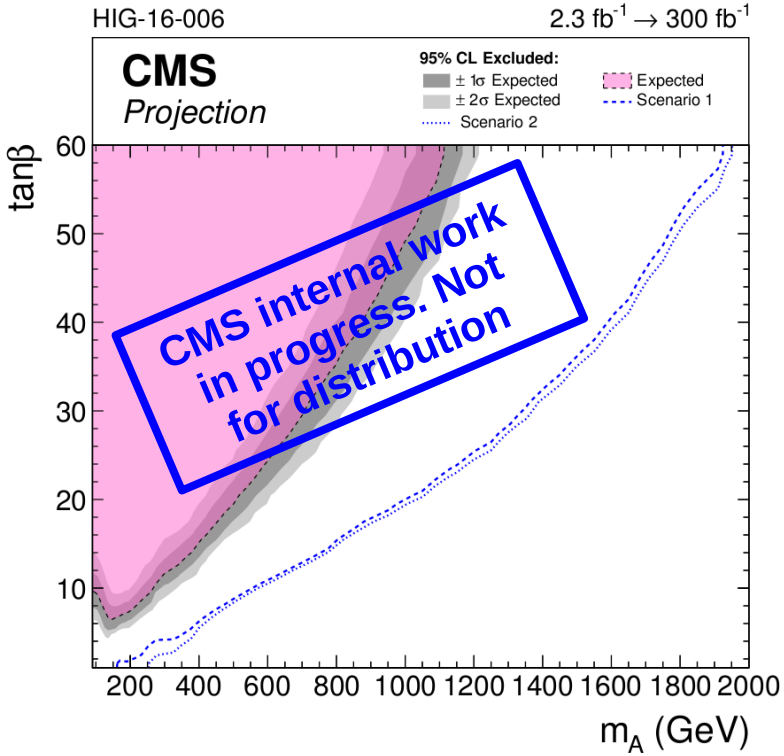
- Assume the same systematics as ICHEP (statistically limited)
  - Expect to constrain fraction f_{ai} < ~1% with 3000 fb^{-1}
  - Better than previous projections due to the inclusion of interference effects

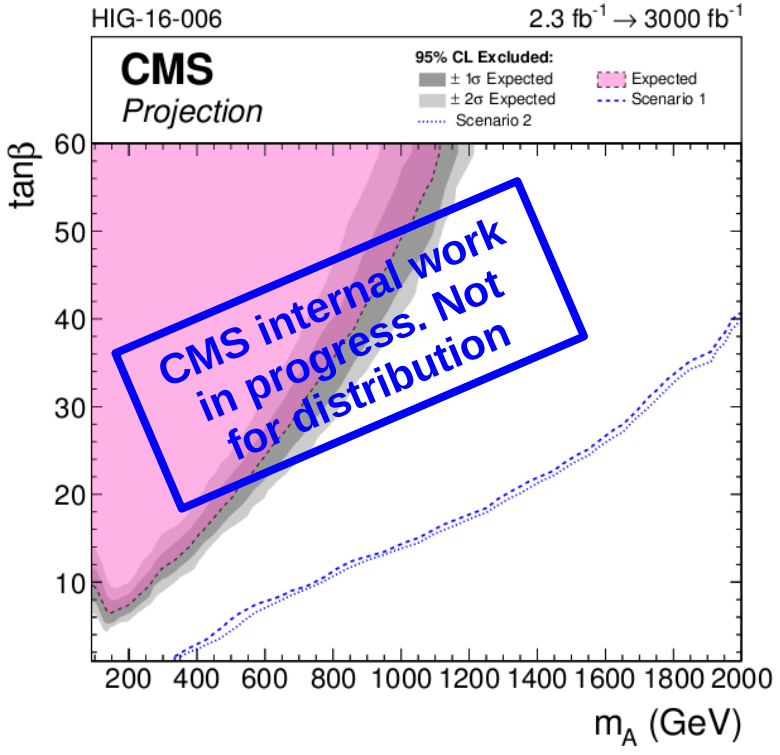


Projections for MSSM Φ→ττ

- One of the most sensitive channels for constraining extended Higgs sectors
  - ➔ Especially at large tanβ in TypeII 2HDM (e.g. MSSM)
- Projections based on 2015 analysis (2.3 fb^{-1})
- Single resonance model-independent limits:
  - ➔ H+A, $gg\Phi \rightarrow \tau\tau$ and $bb\Phi \rightarrow \tau\tau$
- Model-dependent limits with H+A: (m_h^{mod+} scenario)
- Still statistically limited for large values of m(A)



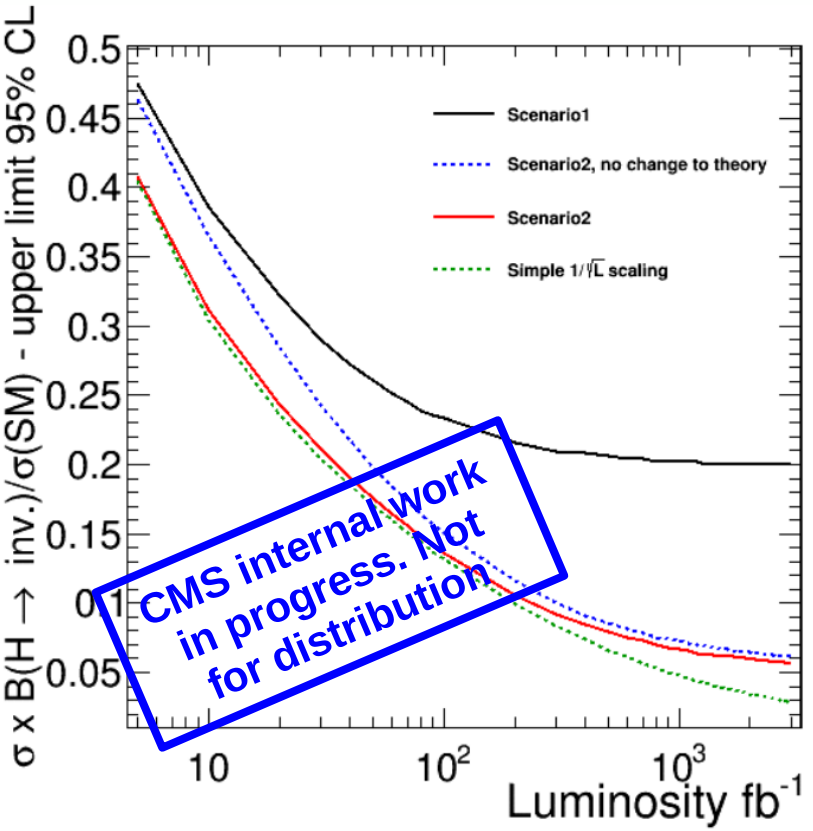




Projections for VBF H→Invisible

- For scenario 2, scale the sys. unc. on objects as in the table below
- Performance of tau ID and MET unclustered energy assumed constant
  ➔ Higher pileup, but algorithms/detector expected to improve

Syst	Scaling
Theory	1/2
Lepton (*)	1/√L until 1%
Lumi	1/√L until 1%
Jet Energy Scale	1/√L until 1/3 of current (~1% **)
Data Driven	1/√L
PU	Unchanged!



Extrapolation on the 95% CL upper level on B(H->Inv.) (M_H=125 GeV)

At 3000 fb^{-1}, in Scenario2, o(6%)

Planned Projections still in Progress

- A few other channels not ready today but may be ready for ECFA
  - e.g. VBF $H \rightarrow bb$

- Considering to have a combination of $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, and ttH analyses
  - Produce κ_V-κ_F 2D constraints
  - Perhaps other coupling measurements (e.g. ratios which are less systematically limited)

- Also considering making a projection of differential measurements
  - Statistically limited if considering large number of bins, or if measuring normalized distributions
  - Also, the high p_T region is of particular interest for BSM

Conclusions

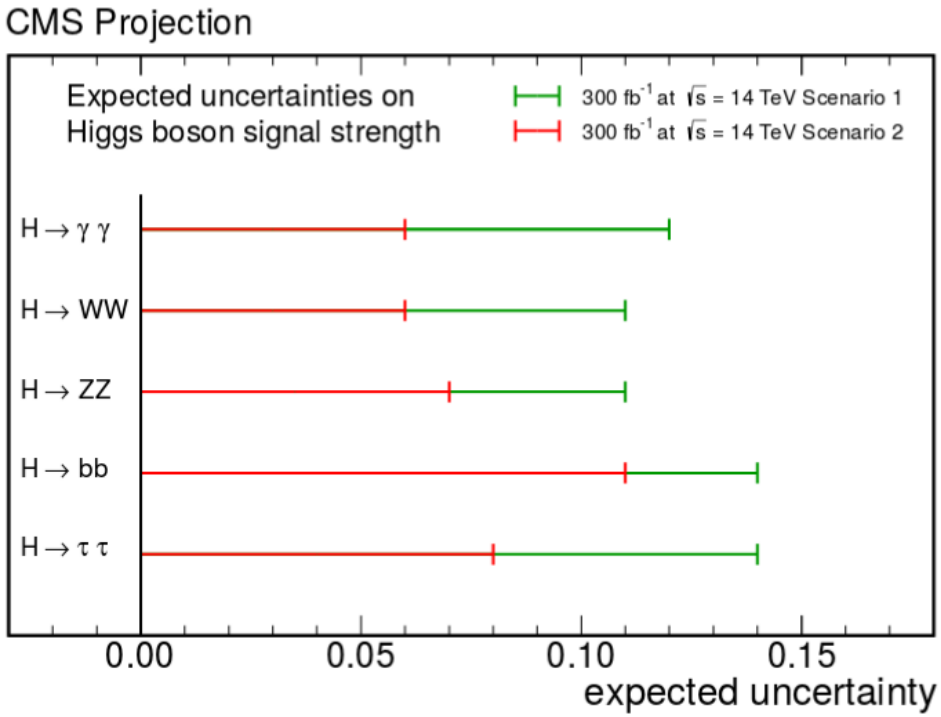
- **Projections for 300/3000 fb^{-1} have been made using 13 TeV analyses**
- **Experimental improvements/degradations derived from TP studies have been included where possible**
- **Additional studies with more detailed description of the upgrade scenarios will be performed in the coming months**

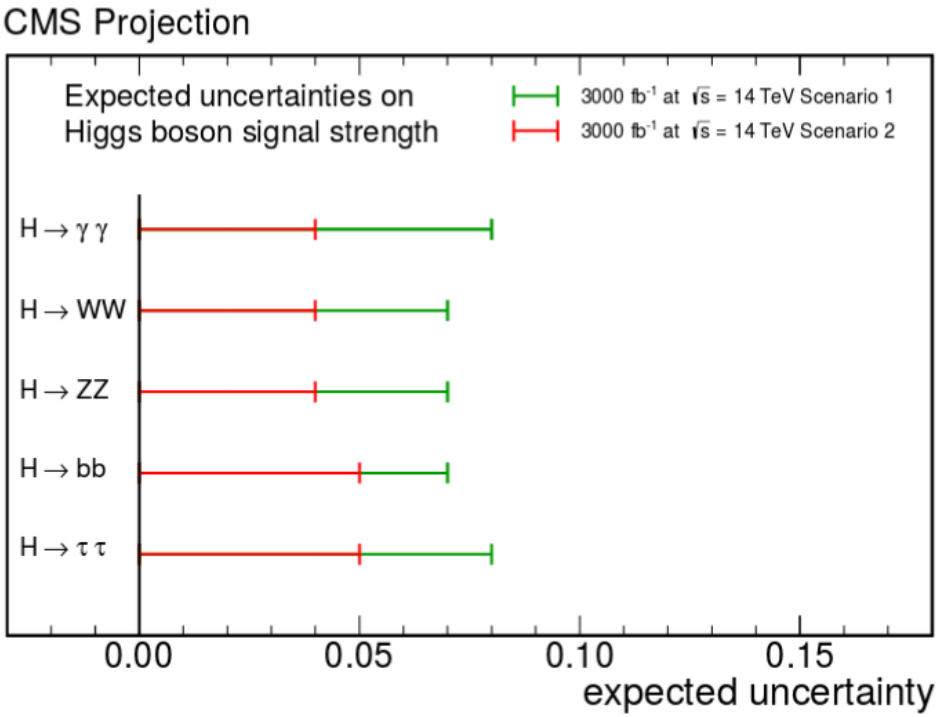
Backup

CMS-NOTE-2013-002

Higgs Boson Signal Strength

- Projections have been obtained by scaling event yields to 300(0) fb^{-1} at $\sqrt{s}$ = 14 TeV
- Use Run 1 Legacy results (7+8 TeV) and assume performance unchanged
- Two scenarios for systematic uncertainties were considered:
  - ➔ Scenario 1: systematic unc. unchanged
  - ➔ Scenario 2: theoretical unc. scaled by 1/2, experimental unc. scaled by $1/\sqrt{\int \mathcal{L}}$





End of Run 3 (300 fb^{-1}): 6-14% uncertainty on signal strengths
HL-LHC (3000 fb^{-1}): 4-8% uncertainty on signal strengths

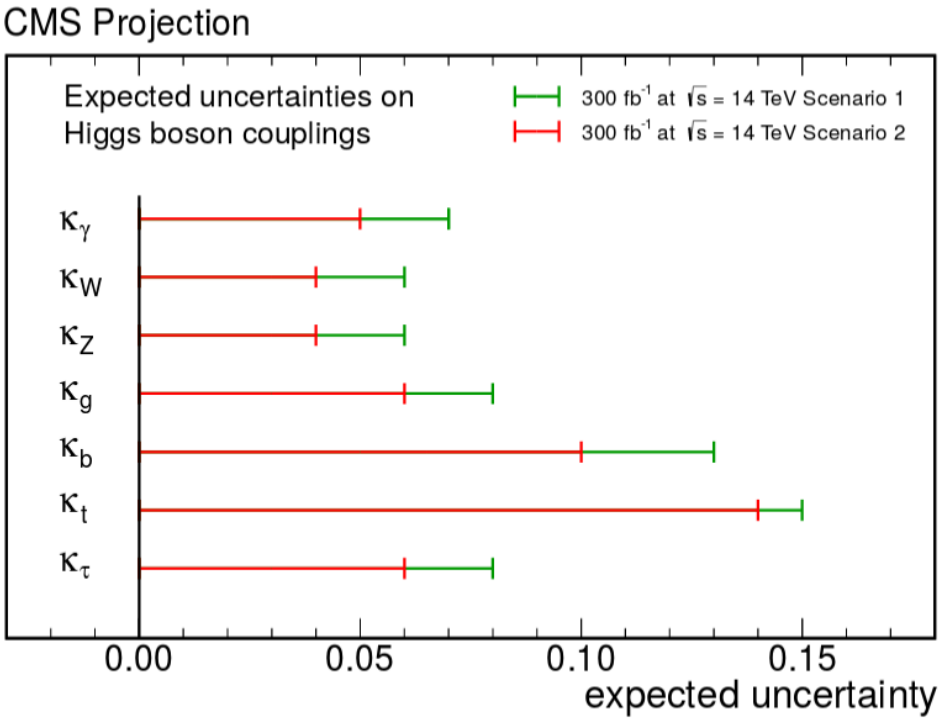
Higgs Boson Couplings

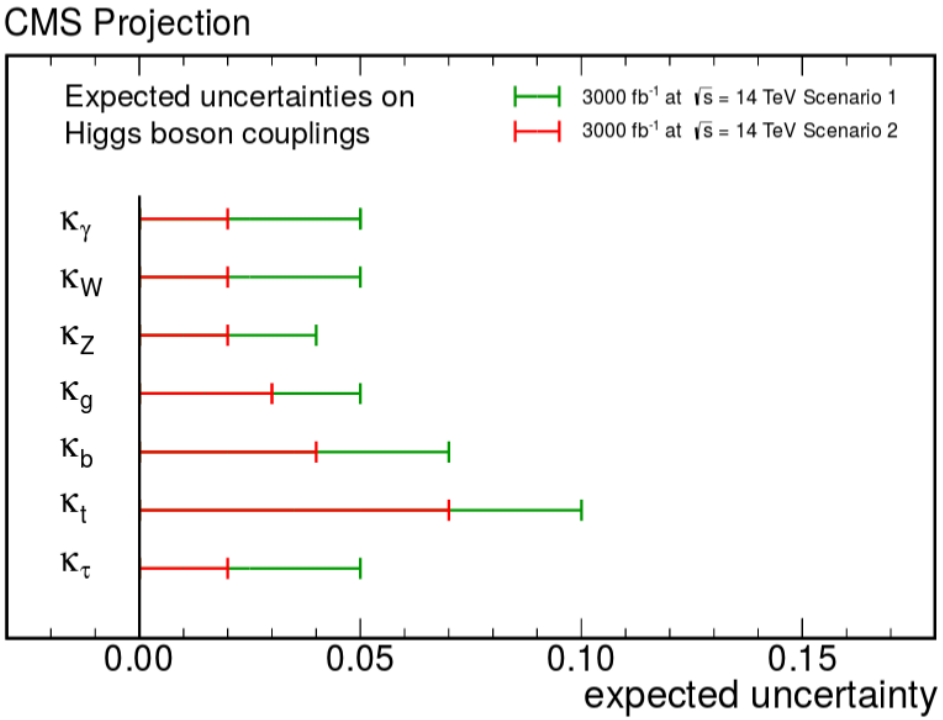
CMS-NOTE-2013-002

- Projected couplings have been obtained using the kappa framework

$$\sigma \cdot \mathrm{BR}(xx \to \mathrm{H} \to ff) = \sigma_{\mathrm{SM}}(xx \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to ff) \cdot \frac{\kappa_x^2 \cdot \kappa_f^2}{\kappa_{\mathrm{H}}^2}$$

- Theoretical uncertainties have been dominant in the projections
  - ➔ In the last year N^{3}LO gg→H predictions have been produced (unc. almost halved)



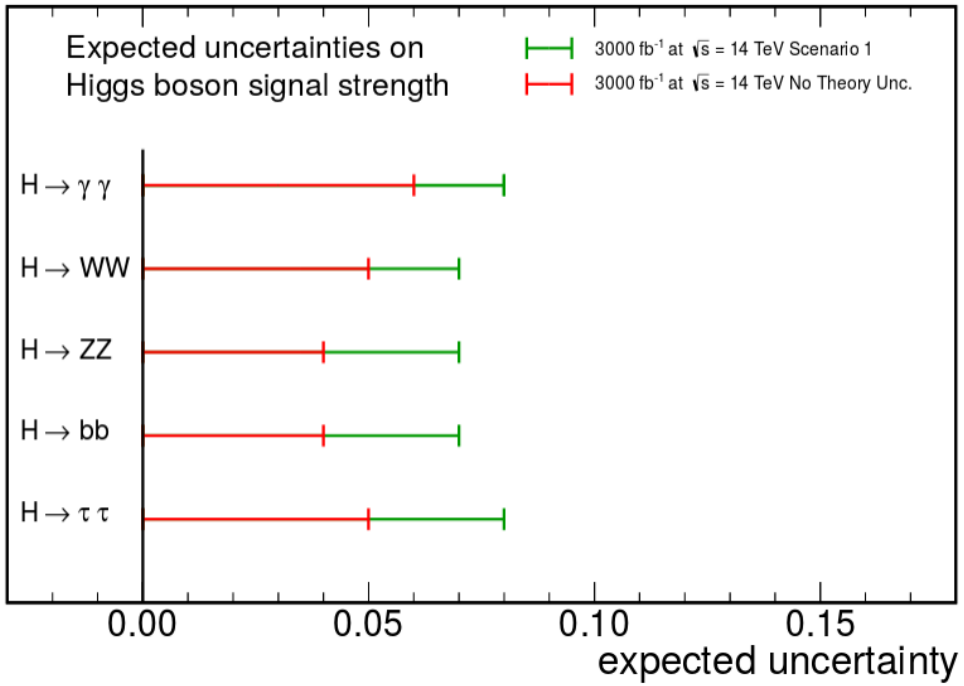


End of Run 3 (300 fb^{-1}): 5-15% uncertainty on couplings
HL-LHC (3000 fb^{-1}): 2-10% uncertainty on couplings

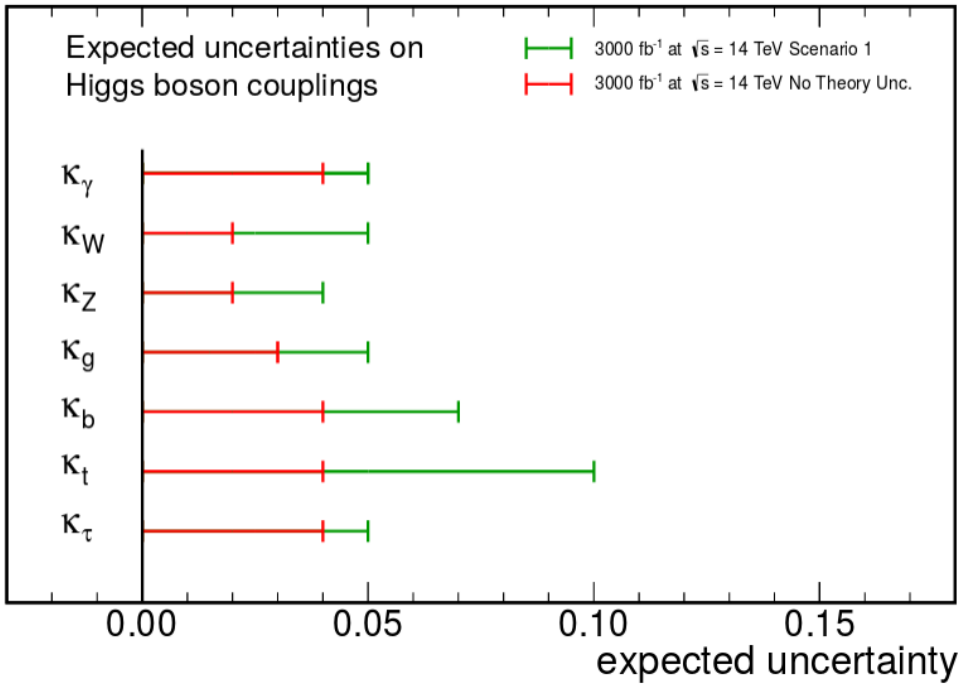
Extrapolated Coupling Precision

CMS-NOTE-2013-002

CMS Projection



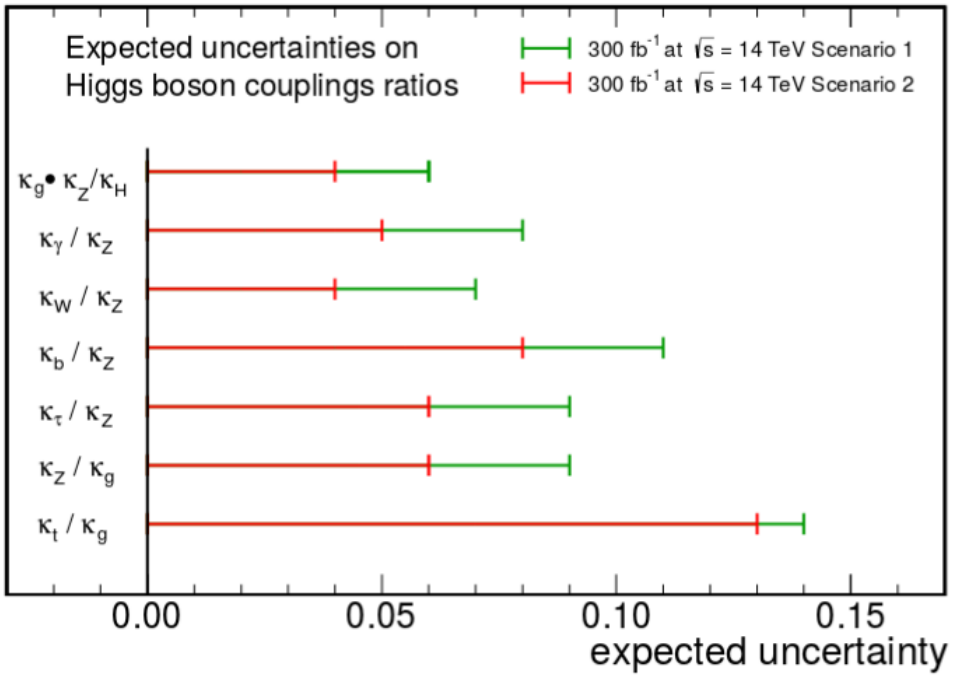
CMS Projection



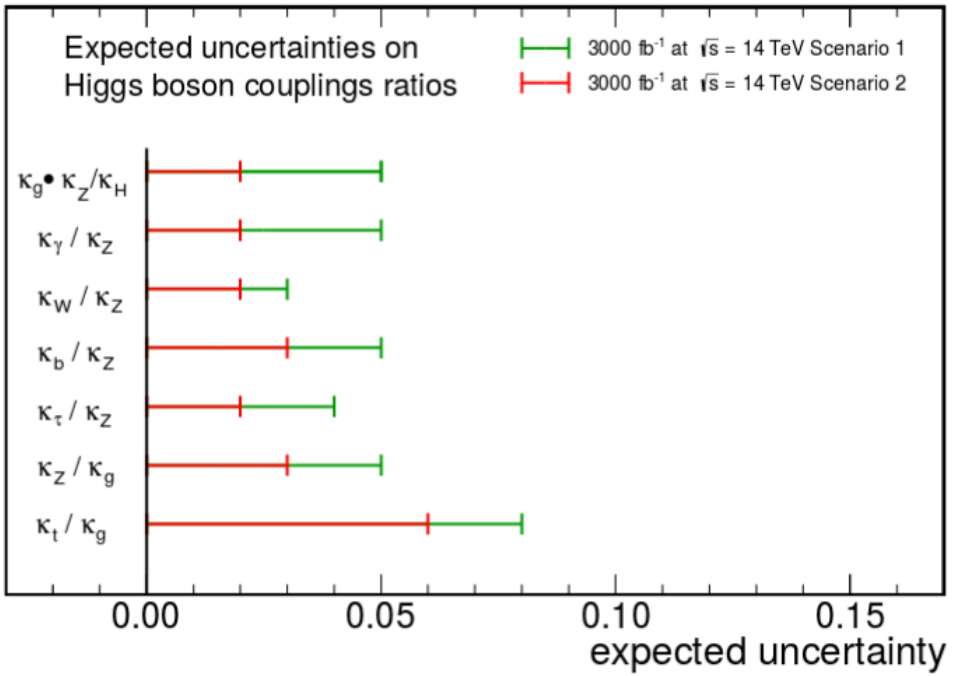
Extrapolated Coupling Precision

CMS-NOTE-2013-002

CMS Projection



CMS Projection



CMS-NOTE-2013-002

Extrapolated Coupling Precision

H decay	prod. tag	exclusive final states	cat.	res.	ref.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%	[6]
	VBF-tag	$\gamma\gamma + (jj)_{\mathrm{VBF}}$	2	<1.5%	
	VH-tag	$\gamma\gamma + (\mathrm{e}, \mu, \mathrm{MET})$	3	<1.5%	
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%	[23]
$\mathrm{ZZ} \to 4\ell$	$N_{\mathrm{jet}} < 2$	4e, 4μ, 2e2μ	3	1-2%	[7]
	$N_{\mathrm{jet}} \geq 2$		3		
$\mathrm{WW} \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	20%	[8]
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\mathrm{VBF}}$ (DF or SF dileptons)	2	20%	[24]
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2		[25]
$\tau\tau$	0/1-jet	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu) \times$ (low or high p_T^{τ})	16	15%	[10]
	1-jet	$\tau_h\tau_h$	1		
	VBF-tag	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\mathrm{VBF}}$	5		
	ZH-tag	$(\mathrm{ee}, \mu\mu) \times (\tau_h\tau_h, \mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu)$	8		[26]
	WH-tag	$\tau_h\mu\mu, \tau_h\mathrm{e}\mu, \mathrm{e}\tau_h\tau_h, \mu\tau_h\tau_h$	4		
bb	VH-tag	$(\nu\nu, \mathrm{ee}, \mu\mu, \mathrm{e}\nu, \mu\nu$ with 2 b-jets$) \times$x	13	10%	[27]
	ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	6		[28]
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-jets)	3		
$\mathrm{Z}\gamma$	inclusive	$(\mathrm{ee}, \mu\mu) \times (\gamma)$	2		[29]
$\mu\mu$	0/1-jets	$\mu\mu$	12	1-2%	[30–32]
	VBF-tag	$\mu\mu + (jj)_{\mathrm{VBF}}$	3		
invisible	ZH-tag	$(\mathrm{ee}, \mu\mu) \times (\mathrm{MET})$	2		[21]

Anomalous Couplings

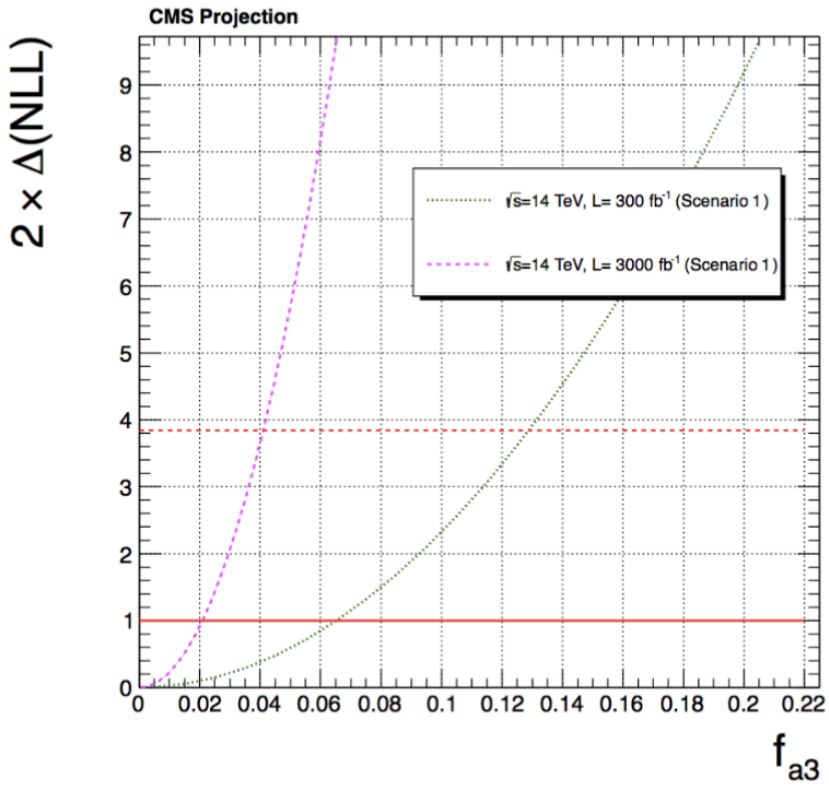
CMS-NOTE-2013-002

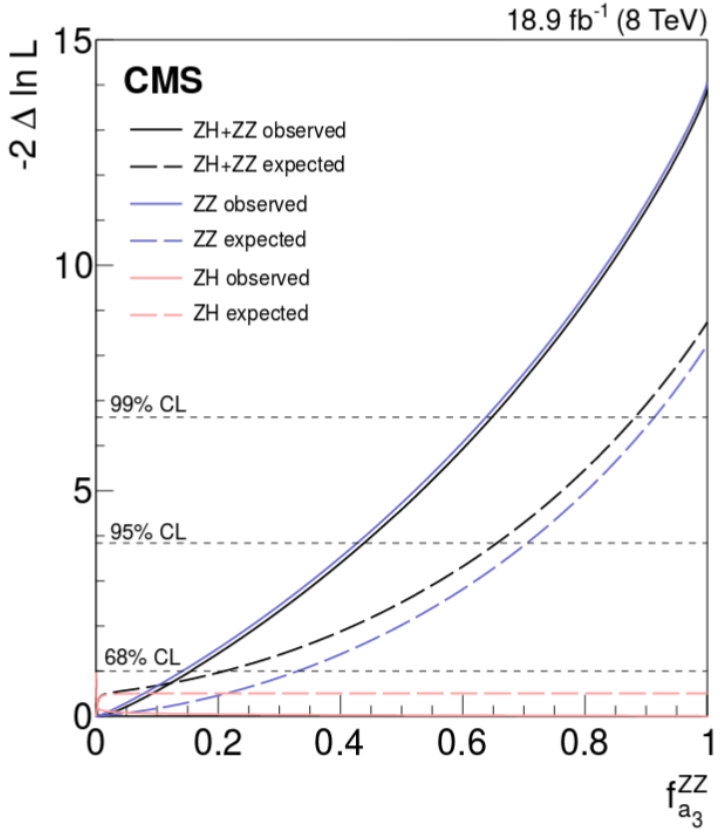
HIG-14-035

- Important to determine spin and quantum numbers of the particle accurately
- Generic amplitude of H→ZZ for spin-0 particle can be written as:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{HVV}} + \frac{\kappa_1^{\mathrm{HVV}} q^2_{\mathrm{V}_1} + \kappa_2^{\mathrm{HVV}} q^2_{\mathrm{V}_2}}{\left(\Lambda_1^{\mathrm{HVV}}\right)^2}\right] m^2_{\mathrm{V}_1} \epsilon^*_{\mathrm{V}_1} \epsilon^*_{\mathrm{V}_2} + a_2^{\mathrm{HVV}} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu} + a_3^{\mathrm{HVV}} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2)\mu\nu}$$

- Can test for anomalous CP-odd coupling a_3
  - ➔ Expect to constrain fraction $f_{a3} < 0.13$ (0.04) 95% CL with 300 fb^{-1} (3000 fb^{-1})
- Even tighter constraints combining with VH channels, which has now been done

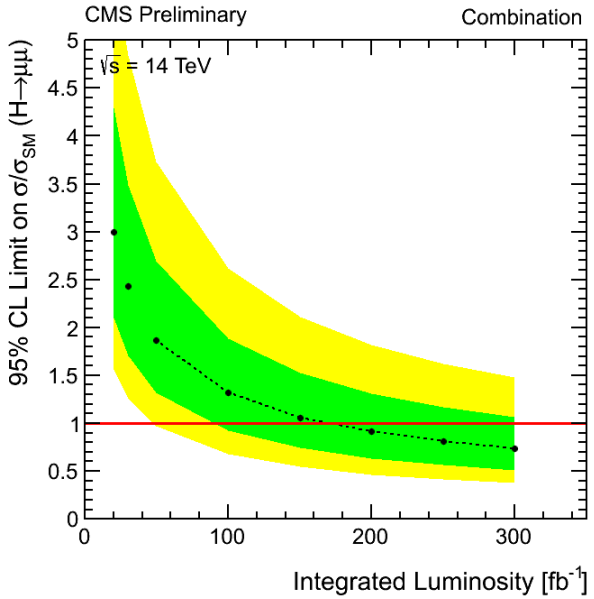


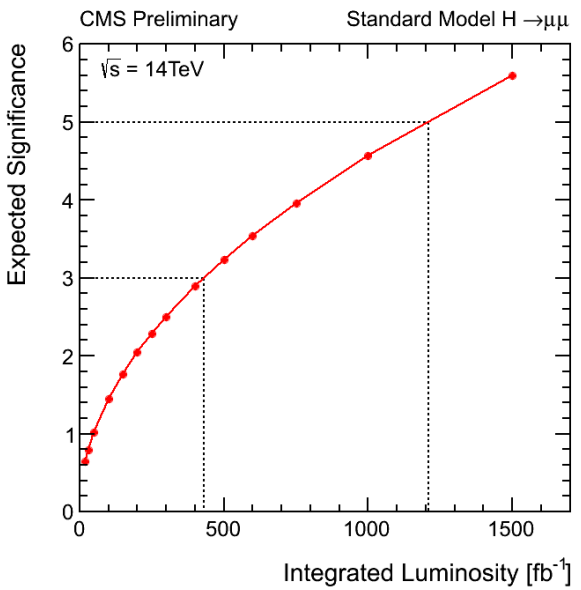


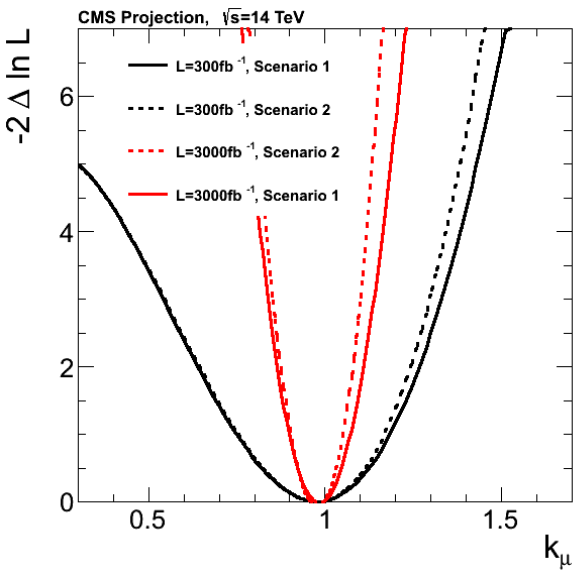
Rare Decays: H→μμ, H→J/ψ γ

HIG-13-007
HIG-14-003

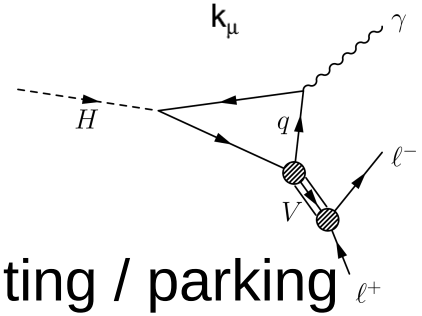
- H→μμ decay allows for a test of second generation leptonic coupling
  - ➔ Challenging experimentally due to large Drell-Yan background
- Very mild excess observed in the Run 1 search
  - ➔ 3σ (5σ) evidence (observation) expected with ~450 fb^{-1} (~1200 fb^{-1})







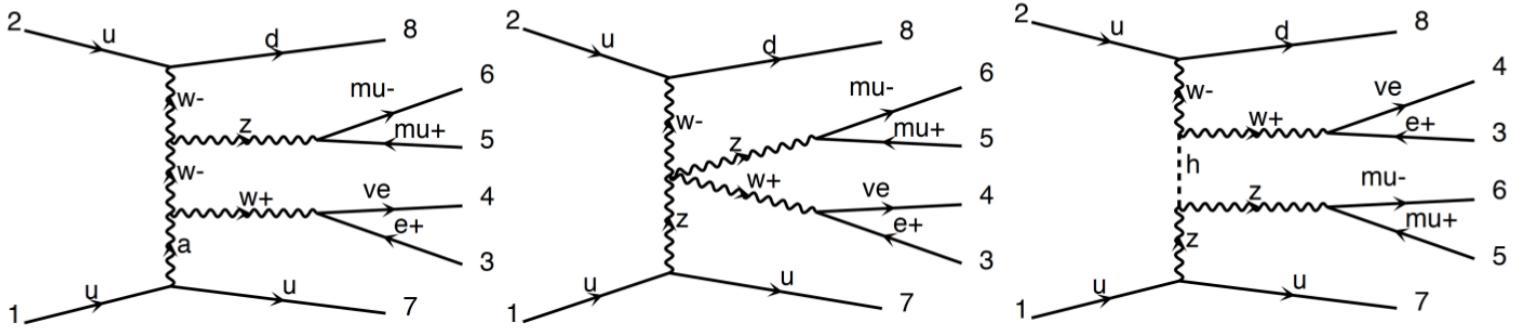
- 2nd generation coupling in quark sector even more challenging
  - ➔ BR(H → J/Ψ γ) tiny in the SM (~3×10^{-6}), current limit 1.5×10^{-3}
  - ➔ May require non-standard analysis techniques like data scouting / parking
  - ➔ OR new ideas (many good ones in this conference!)



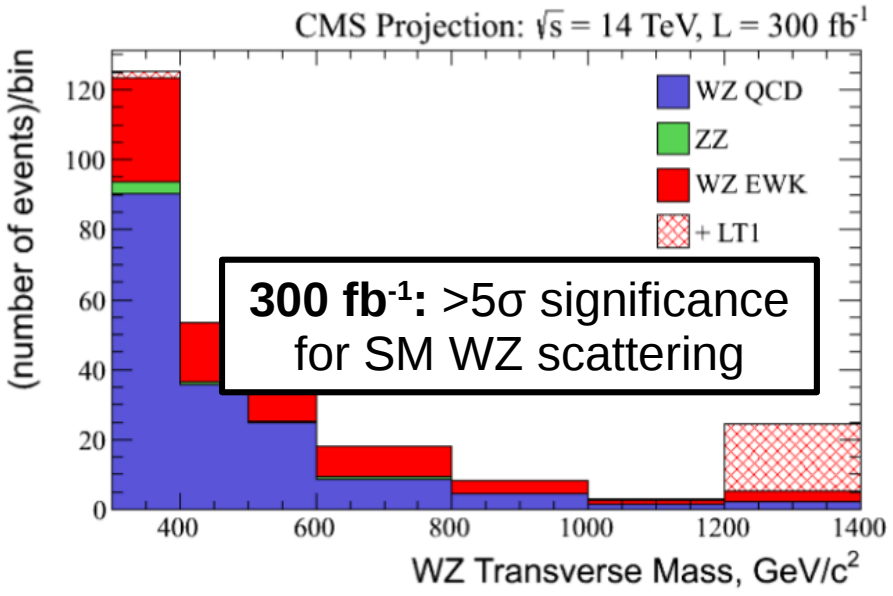
VV Scattering

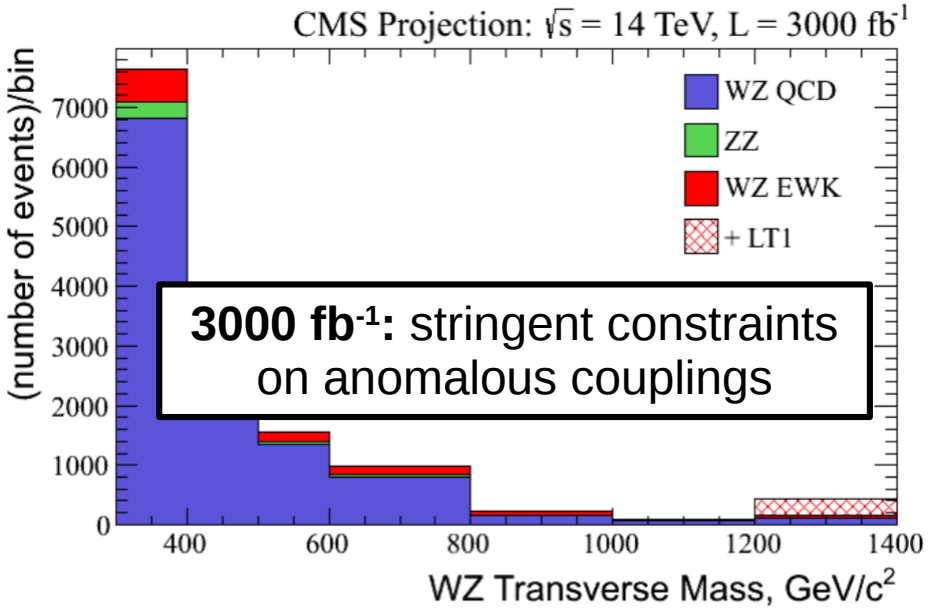
FTR-13-006

- Can test whether VV scattering unitarity is restored as predicted in the SM
  - ➔ An important role of the Higgs boson
- New physics in the EWK Symmetry Breaking sector can alter the cross section



- Projections carried out using dedicated simulation of upgraded CMS detector





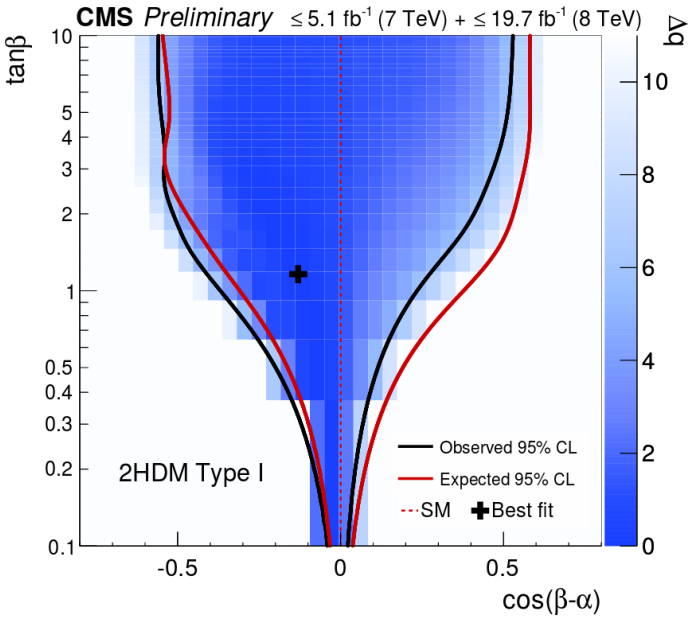
Extended Higgs Sector

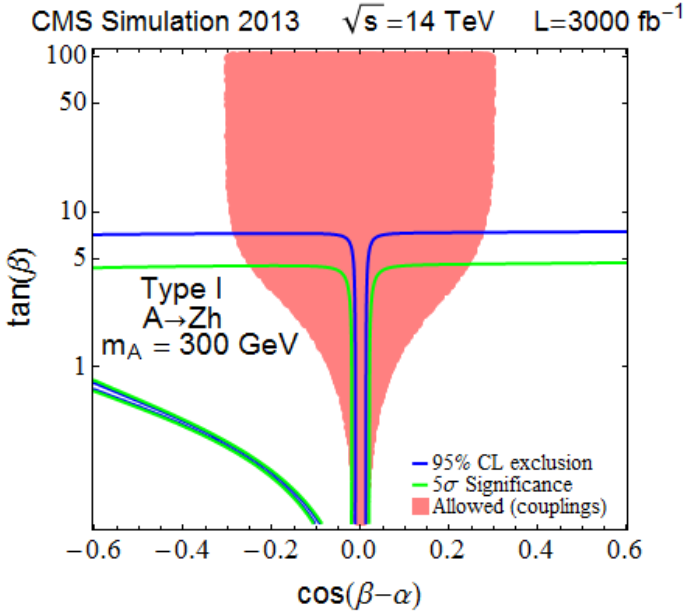
HIG-16-007
FTR-13-024

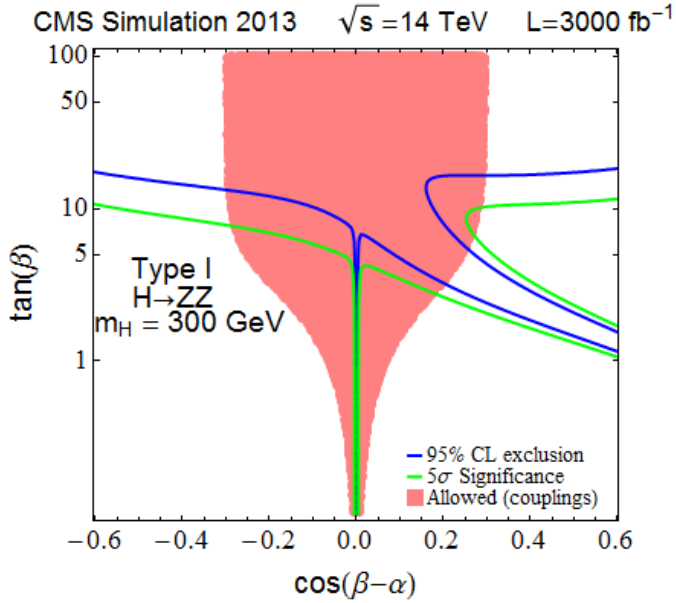
- Many models of new physics (e.g. SUSY) predict an extended Higgs sector
- 2HDM parameters are constrained by Higgs couplings measurements
  - ➔ Recent result from CMS using combined Run 1 couplings measurements

	2HDM	
	type I	type II/MSSM
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$

- Complemented by direct searches for additional Higgses
- Projection with dedicated simulation of CMS upgrades
- Large parameter space available for a discovery
  - ➔ Or else, stringent limits on the model parameters





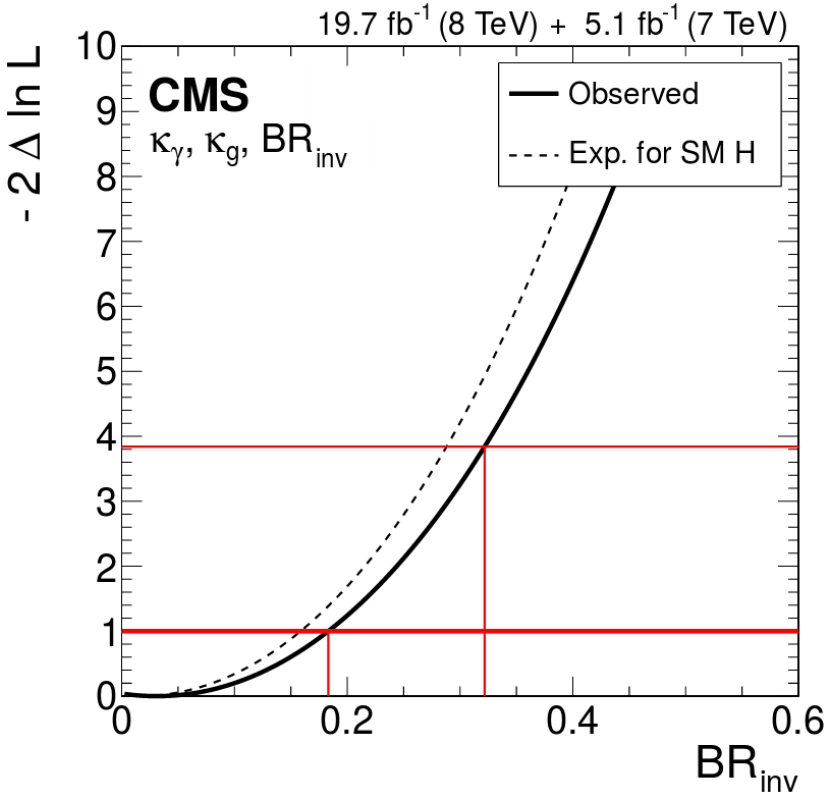


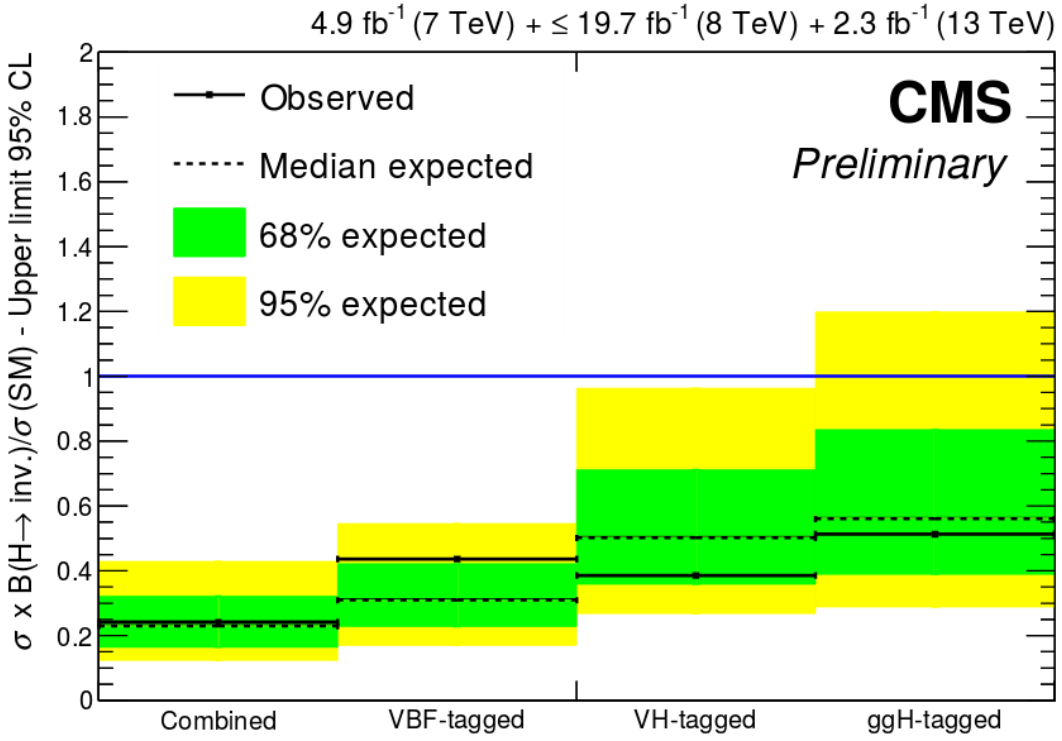
Invisible Decays

CMS-NOTE-2013-002

HIG-16-016

- Since the Higgs couples to all massive particles, it may be a portal to Dark Sector
  - Also, the BR_{BSM} is an important parameter in couplings measurements
- Projections assuming 2012 performance for 300, 3000 fb^{-1}
  - Using Higgs coupling combination and ZH-tagged direct search





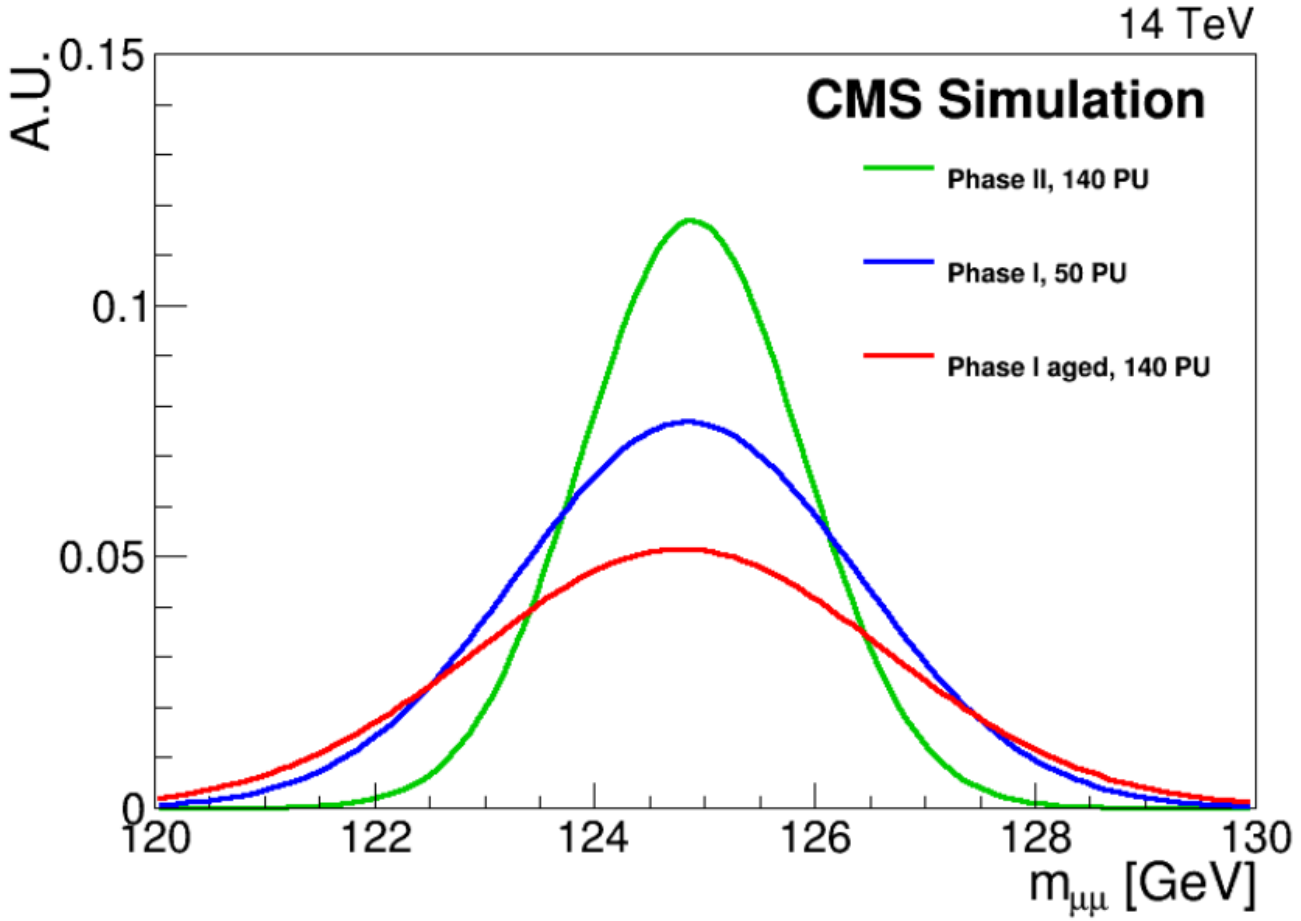
End of Run 3 (300 fb^{-1}): BR_{BSM}<0.17-0.28

HL-LHC (3000 fb^{-1}): BR_{BSM}<0.06-0.017

- Limits improved by including VBF channel
  - Already at conservative end of 300 fb^{-1} projection!

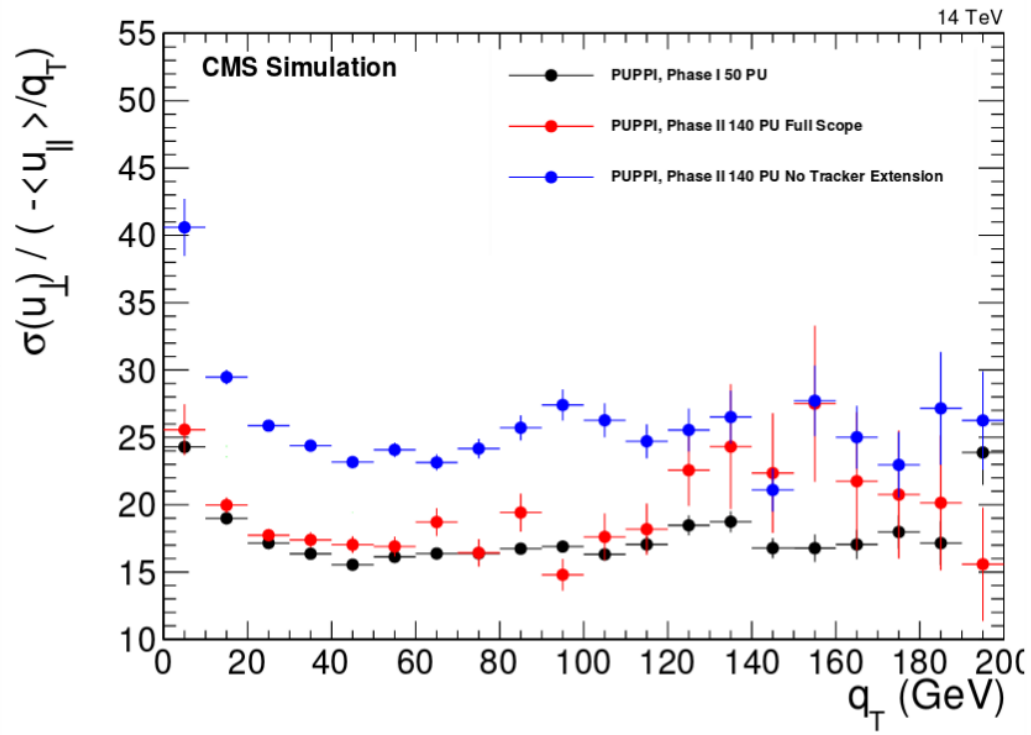
Phase 2 Upgrades: H→μμ

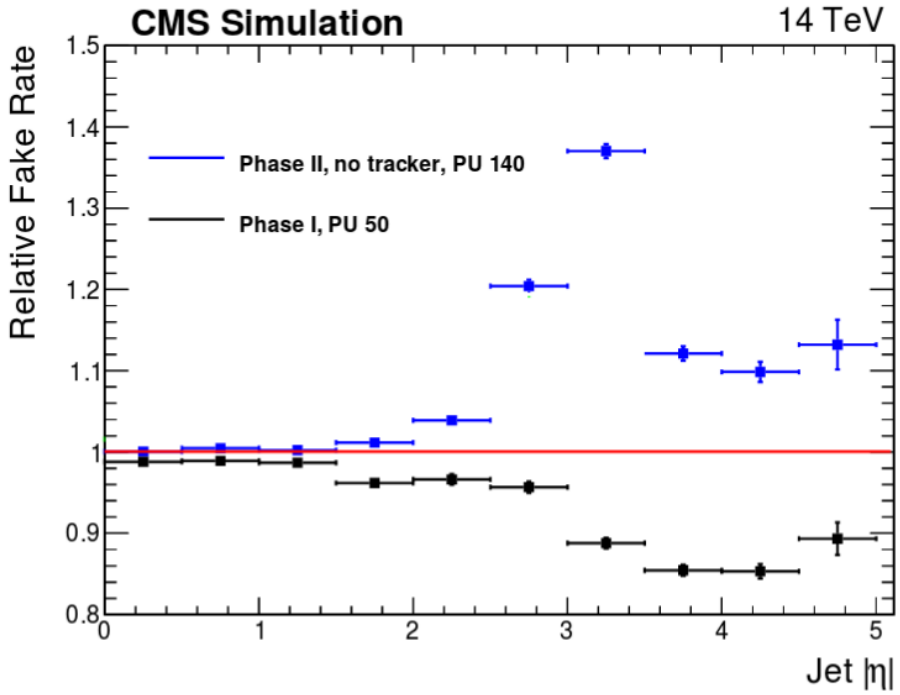
TDR-15-002



Phase 2 Upgrades: Jets/MET

LHCC-G-165





Phase 2 Upgrades: H→ττ

TDR-15-002