Future prospects for Higgs measurements with CMS

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On behalf of the CMS Collaboration

CERN

PASCOS 2013 - Higgs Parallel session

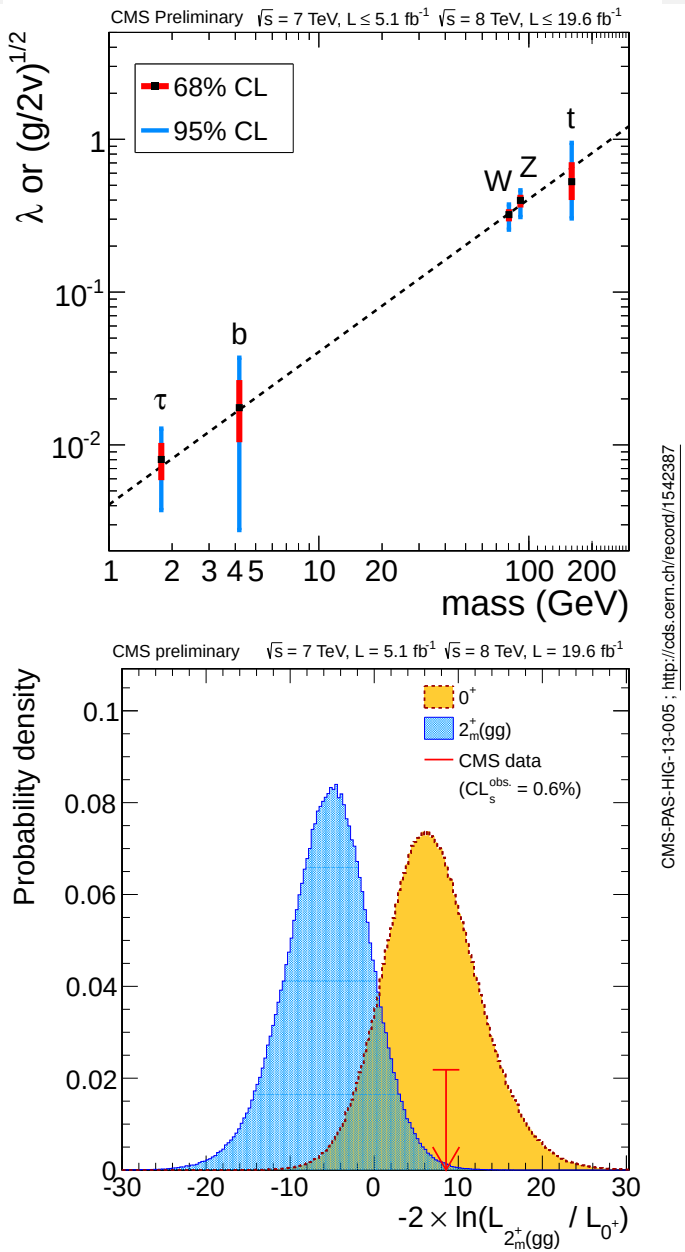
Introduction

We have found one Higgs boson...

- Current tests: couplings and spin/parity consistent with the Standard Model

What next?

- No other new particles discovered@LHC so far...
- Properties of the new boson
- Self-coupling (EWK processes)
- Additional Higgs bosons?
- Exotic Higgs decays?

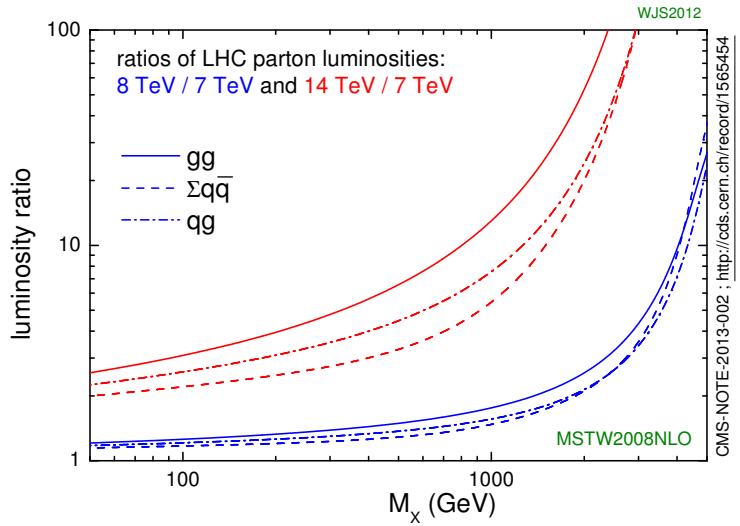


Future plans for the LHC

- Of the future accelerator options currently under study, the Large Hadron Collider is the only facility currently operating.

Period		$\sqrt{s}$ (TeV)	$\int L$ (fb^{-1})	L (cm^{-2}s^{-1})	$< pu >$	BX (ns)
2009-2012	Run 1	7 and 8	25	7×10^{33}	21	50
2013-2014	LS1	"Phase 1" upgrades				
2015-2017	Run 2	13	-	10^{34}	25	25
2018-2019	LS2	"Phase 1" upgrades				
$\approx$ 2021	Run 3	-	300	-	50	-
2022-2023	LS3	"Phase 2" upgrades				
$\approx$ 2024	HL-LHC	-	3000	5×10^{34}	128	-

		$\sqrt{s} = 14$ TeV $\int L = 3000$ fb^{-1}	$\sqrt{s} = 8$ TeV $\int L = 30$ fb^{-1}
	σ (pb)	Events	
ggH	50.4	150M	600K
VBF	4.2	13M	48K
WH	1.5	4.5M	21K
ZH	0.9	2.6M	12K
ttH	0.6	1.8M	4K



Phase I upgrades (1)

CMS public webpage

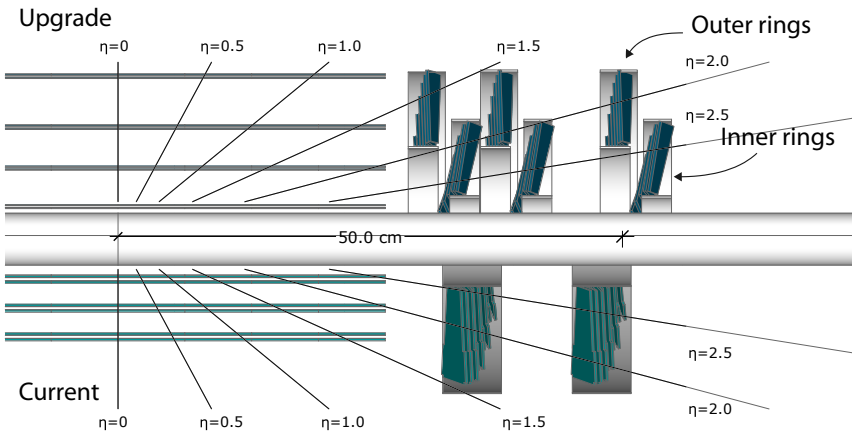
LS1: Already on-going

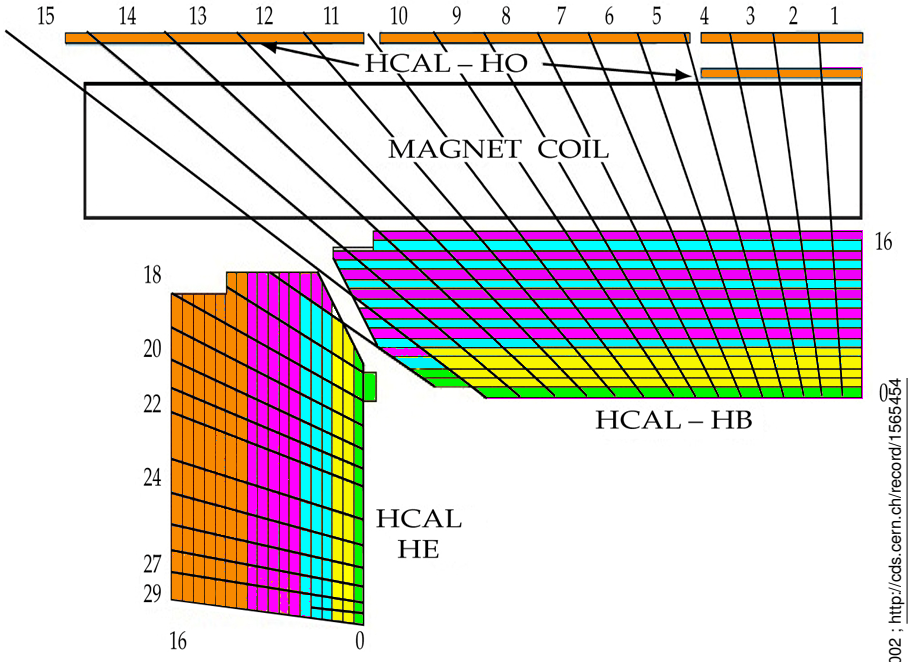
- Pixel: repairs, pilot blades
- Tracker: lower temperatures
- ECAL: repairs, crystal monitoring
- HCAL: new photo-diodes
- Muons systems:
  - DT: repairs, trigger boards
  - RPC: installation of the 4th disk
  - CSC: prep. for new electronics
- DAQ upgrade
- TDRs... and other "future studies"!

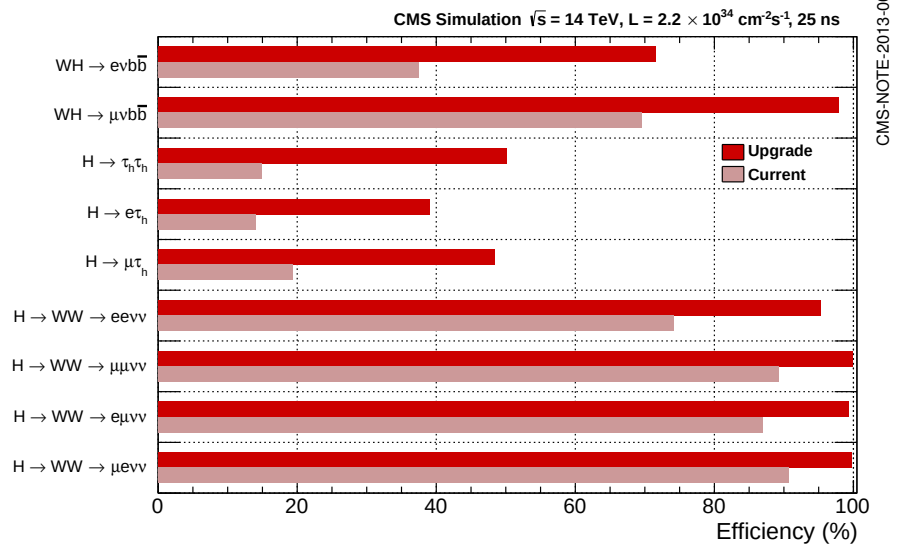
Phase I upgrades (2)

LS2: being finalized

- Pixel detector upgrade
  - Fourth layer, b-tagging
- Hadron calorimeter upgrade
  - improved readout, longitudinal segm. (PF)
- L1 trigger upgrade
  - Use HCAL/ECAL granularity
  - Flexibility and scalability







Phase II upgrades

Beyond LS2: radiation damage, aging, higher *L*

- New tracker:less material, improved tracking in dense charged particles environment, L1trigger
- Replacement of electromagnetic and hadronic calorimeters in the endcap region
- Extension of tracking beyond $\eta = 2.5$?
- Precision timing integrated into an EM preshower detector ?
- TDR with full-simulation studies anticipated for 2014

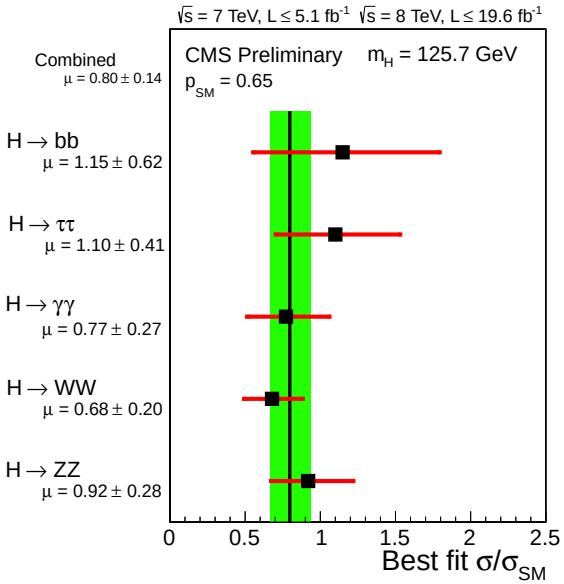
Now, let's start **extrapolating**

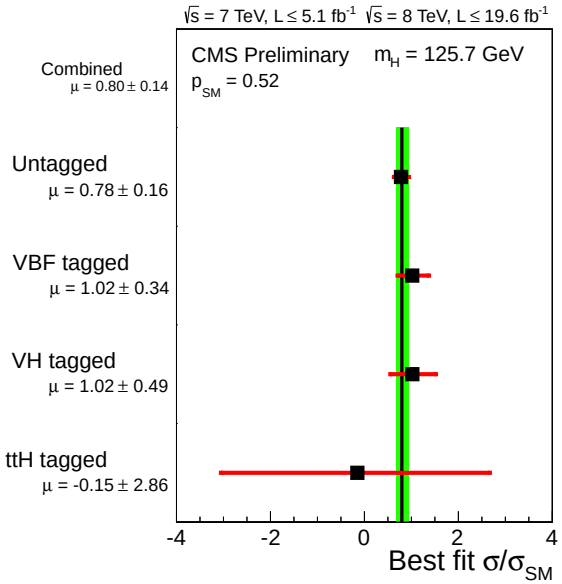
- **Keep in mind that changes are happening**, changes are planned, some still in design choice, detector is aging
- Dataset of 300 or 3000 fb^{-1}: 10 to 100 times what we have today!
- Evolution of systematic uncertainties (exp. and th.)?

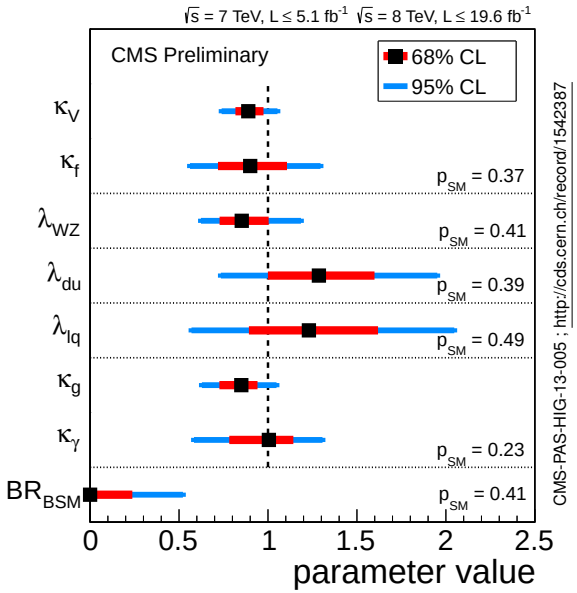
Menu

- Higgs coupling projections with 300 to 3000 fb^{-1}
- Upgrade layouts: $H \to ZZ^* \to 4\mu$
- Extending the search for (2HDM) neutral Higgses
- Probing EWK symmetry breaking: vector boson scattering and quartic gauge couplings
- Rare decays: $H \to \mu\mu$
- (SUSY: chargino-neutralino production with decays to a Higgs boson: cf. Snowmass report)
- (Exotics: Higgs production via vector-like quarks: cf. CMS-FTR-13-026)
- (Exotics: double Higgs production / Higgs self-couplings: no public projection)
- (Exotics: $H \to \text{invisible}$, MET hard to extrapolate to $< pu >= 140$)

Higgs couplings projections: starting point



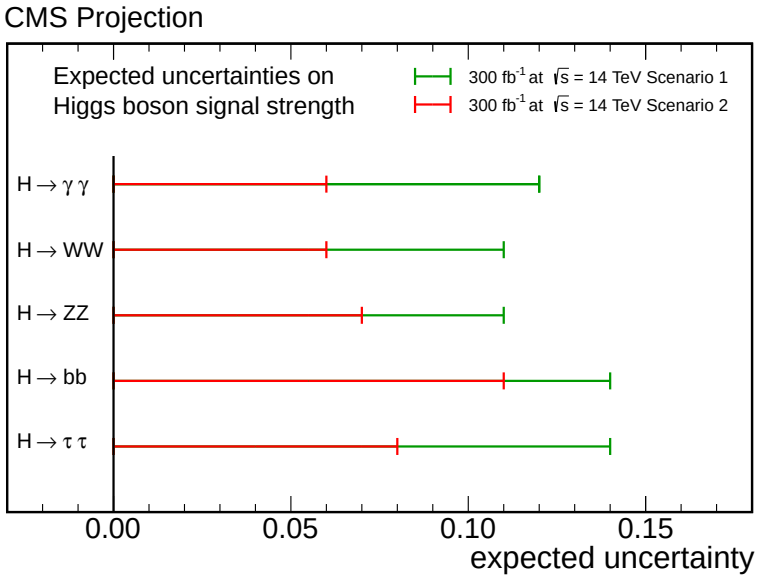


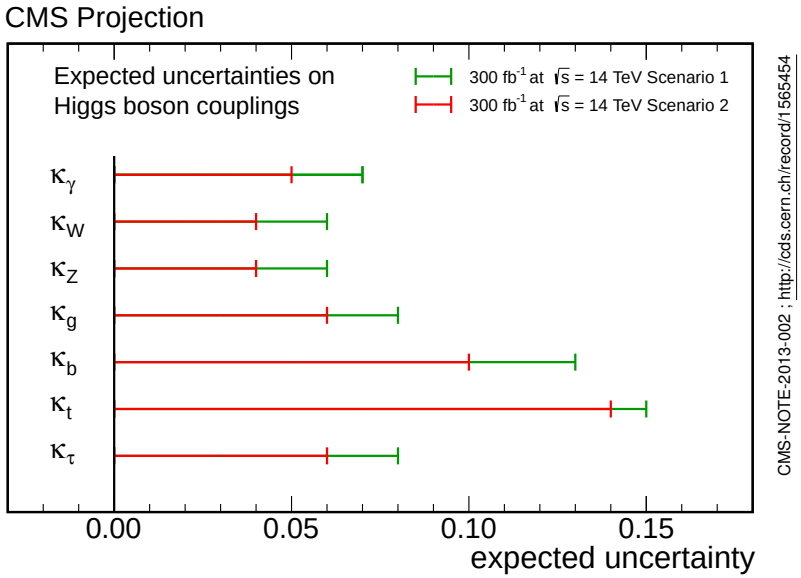


Discovery of a Higgs boson

- Analyzed 5.1 fb^{-1} at 7 TeV and 19.6 fb^{-1} at 8 TeV
- Mass $m_H = 125.7 \pm 0.4$ GeV
- Signal strength $\mu = \frac{\sigma}{\sigma_{SM}} = 0.80 \pm 0.14$

Higgs couplings projections





Strategy

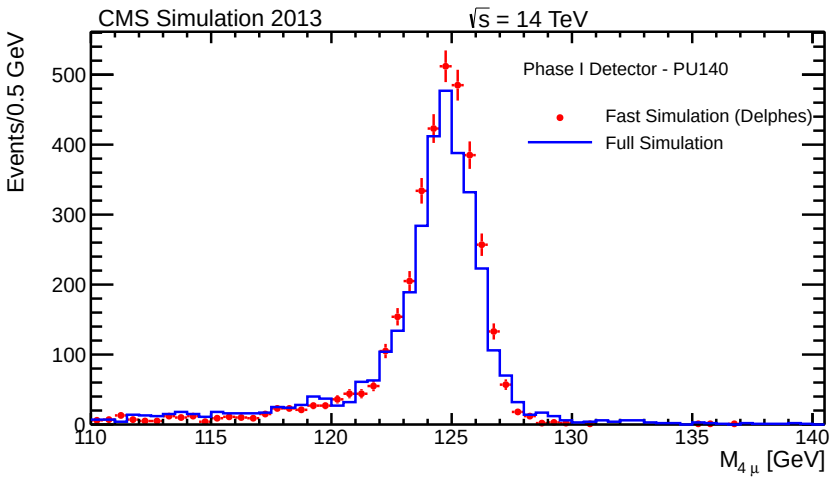
- Scale signal and bkg event yields to 300 fb^{-1} at $\sqrt{s} = 13$ TeV
- Assume 2012 CMS performance (no optimization)
- Scenario 1: systematic uncertainties unchanged
- Scenario 2: th. unc. scaled by $1/2$, exp. unc. scaled by $\sqrt{\int L}$

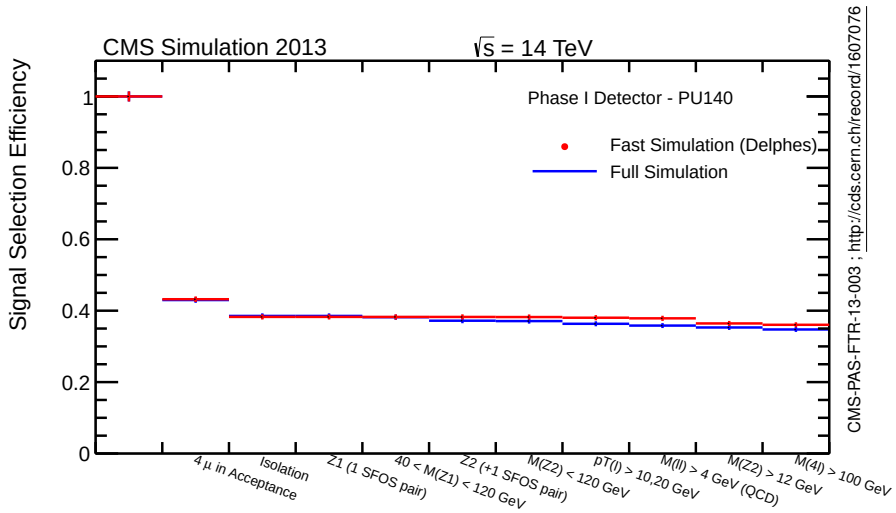
Phase II geometry: $H \to ZZ^* \to 4\mu$ (1)

Assumptions

- $\sqrt{s} = 14$ TeV ; $< pu >= 140$
- Configuration 3: new central tracker + new forward EM calorimeter (but no acceptance change)
- Configuration 4: extension from $|\eta| < 2.4$ to $|\eta| < 4.0$ of central tracking, EM and Had. calorimeters, muon detectors
- Only irreducible background considered (non-resonant SM $ZZ \to 4\mu$)
- No analysis reoptimization

Phase II geometry: $H \rightarrow ZZ^* \rightarrow 4\mu$ (2)

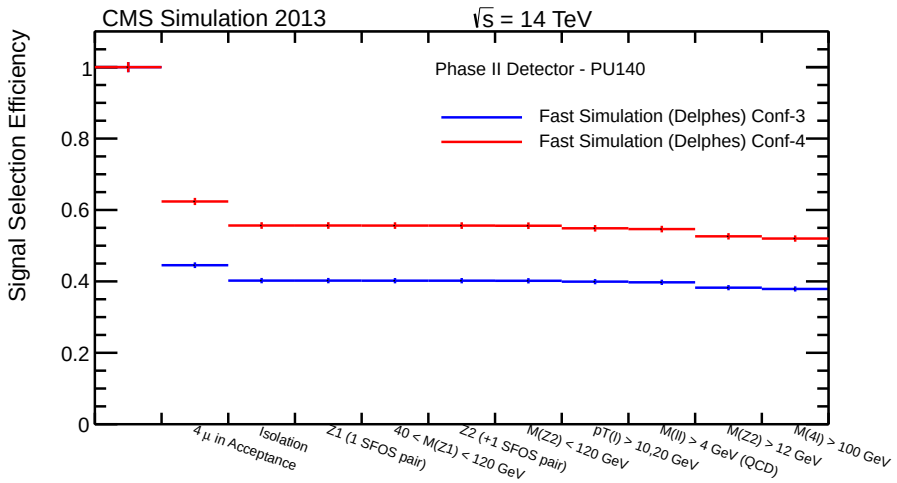


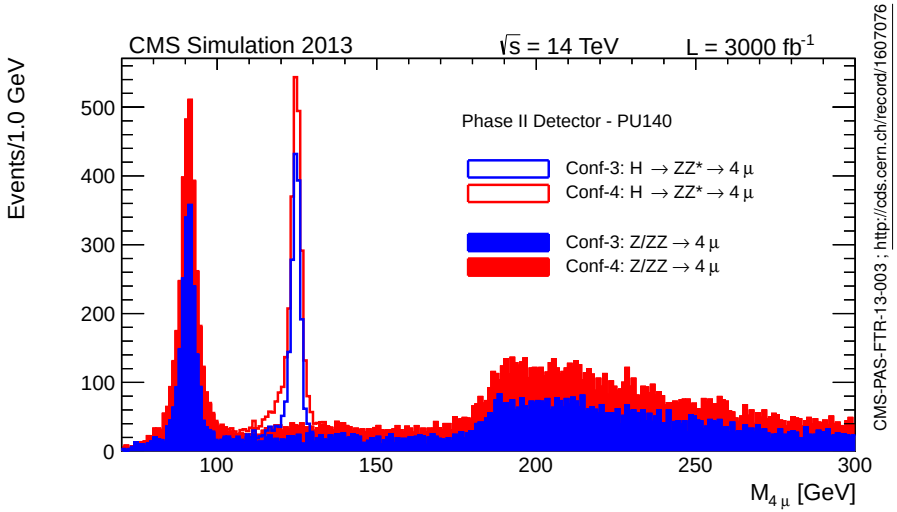


Delphes tuning

- Full- and Fast-sim samples in "2017" detector geometry
  - a.k.a. Pixel Phase I upgrade but no HCAL upgrade
- Compare signal and irr. bkg. for $< pu >= 70$ and $< pu >= 140$
  - muon reconstruction efficiencies, single muon momentum resolution, muon isolation, $m_{4\mu}$, cut-flow, etc.
- **Only then**, trust Delphes to simulate Phase II geometry

Phase II geometry: $H \rightarrow ZZ^* \rightarrow 4\mu$ (3)





- Configuration 3 shows similar selection efficiency as with Phase I detector simulation
- Configuration 4: η acceptance increase signal acceptance (40 % relative!), slightly degraded mass resolution
- Accuracy of future measurements dominated by signal yields... but reducible background yet to be studied

Extending the search of the Higgs sector: 2HDM (1)

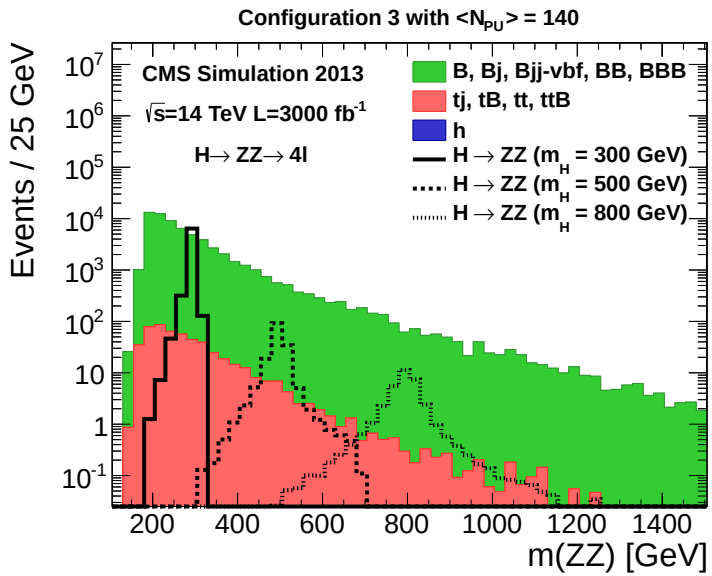
2 Higgs Doublet Model (2HDM)

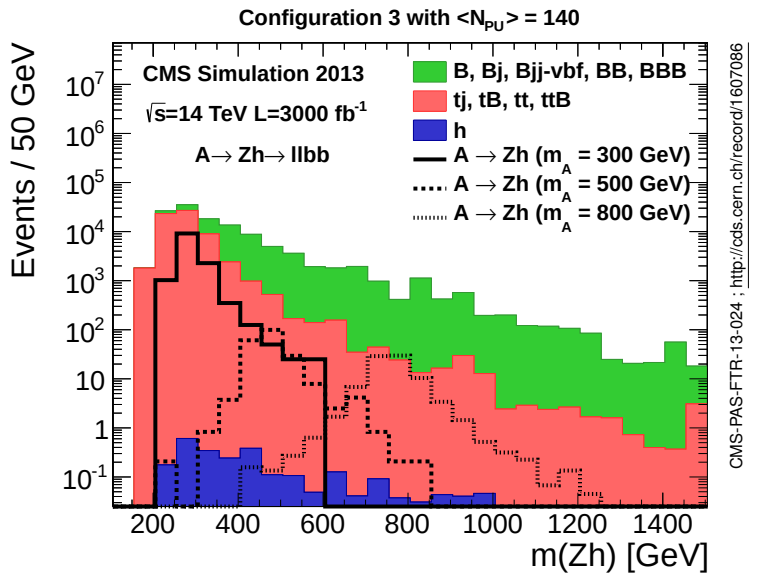
- EWK symmetry breaking sector need not be minimal (i.e. SM)
- 5 physical Higgs bosons: 2 CP-even scalars H and h, CP-odd pseudo-scalar $\mathcal{A}$, a charged pair $H^{\pm}$
- Constrains: 2HDMs may be parametrized by 9 variables
  - m_h, m_H, $m_{\mathcal{A}}$, $m_{H^{\pm}}$, CP-even mixing angle α, ratio of Higgs vaccuum expectation values tan β, three scalar couplings λ_5, λ_6, λ_7
  - Will assume here λ_5, λ_6, $\lambda_7 = 0$ (tree-level MSSM values)

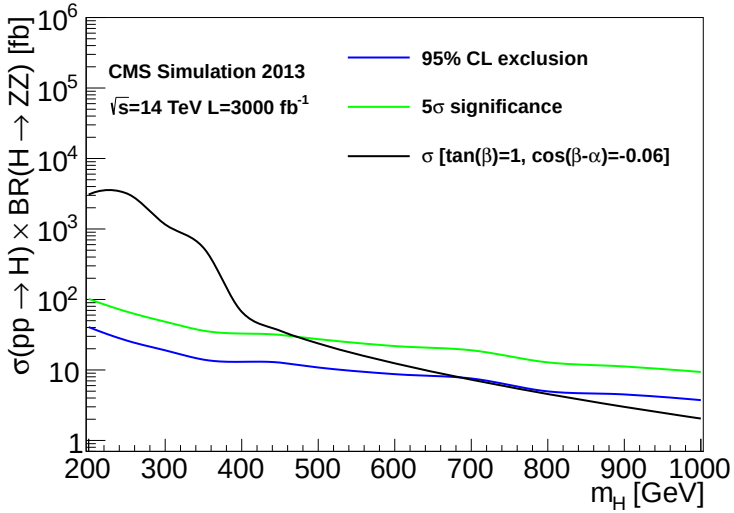
Scope of the study

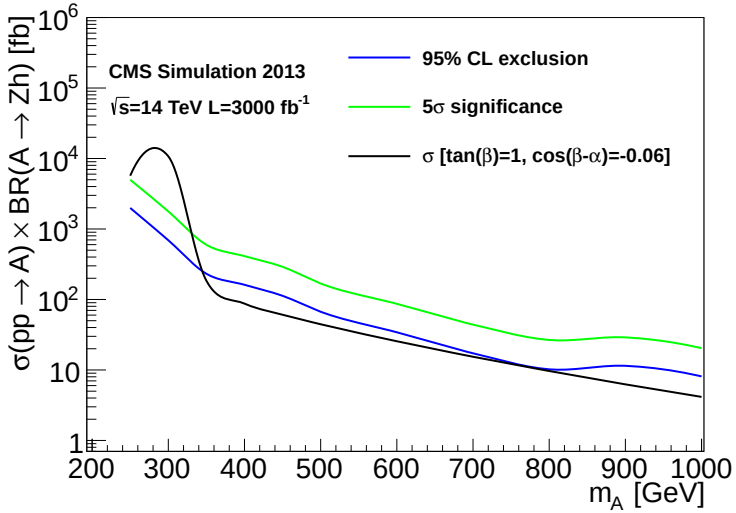
- Heavy scalar H boson: $H \to ZZ \to llll$
- Pseudo-scalar $\mathcal{A}$ boson: $\mathcal{A} \to Zh \to llbb$
- Figures done for tan $\beta = 1$ and cos $(\beta - \alpha) = -0.06$

Extending the search of the Higgs sector: 2HDM (2)









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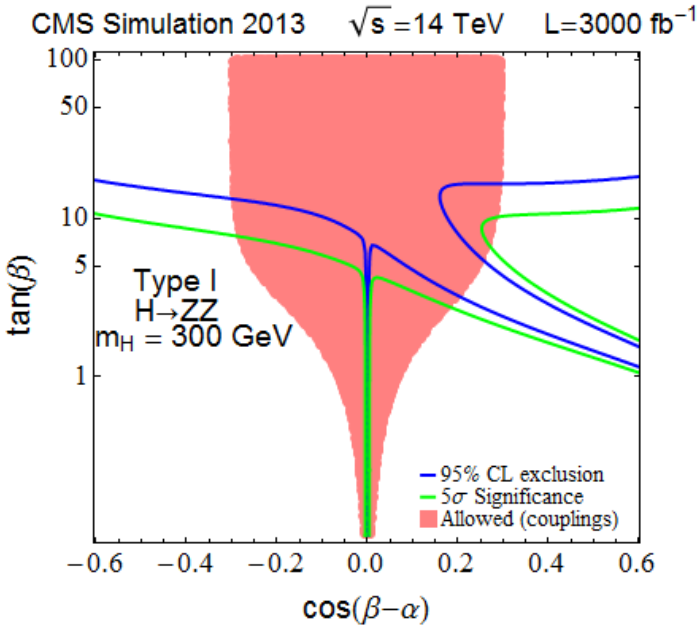
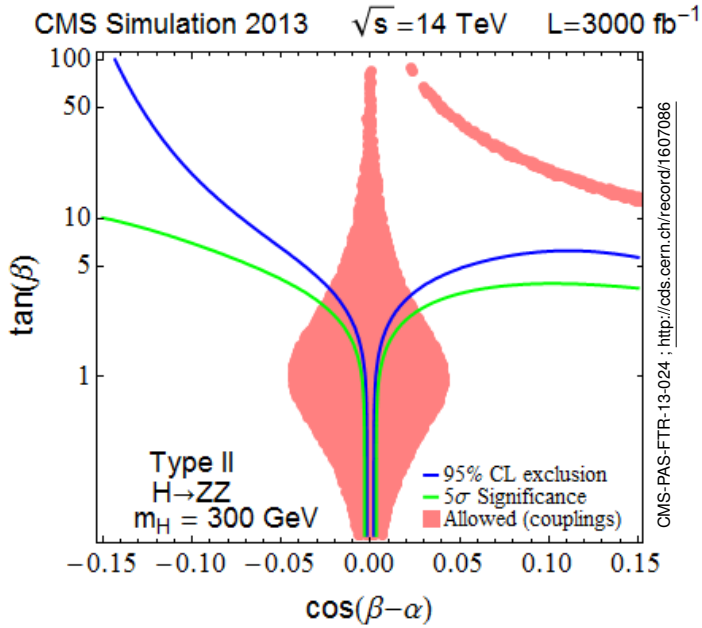
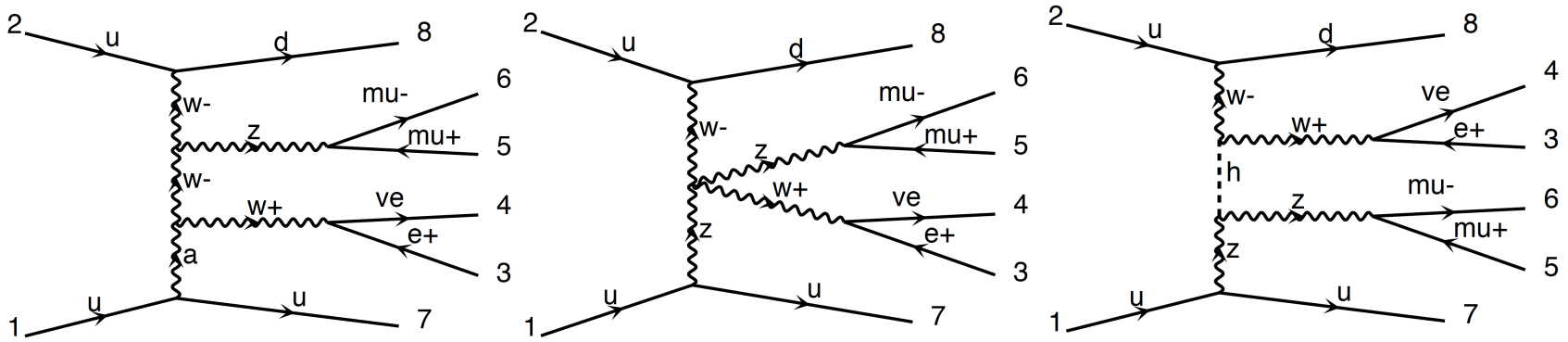




Conclusion

- There is some phase space still allowed where exclusion or discovery of either H or $\mathcal{A}$ is possible
- Constraints coming from h boson couplings measurement
- Coverage of parameter space by the two strategies are **complementary** at low masses

Probing EWK symmetry breaking: QGC (1)



WZ scattering (leptonic decays)

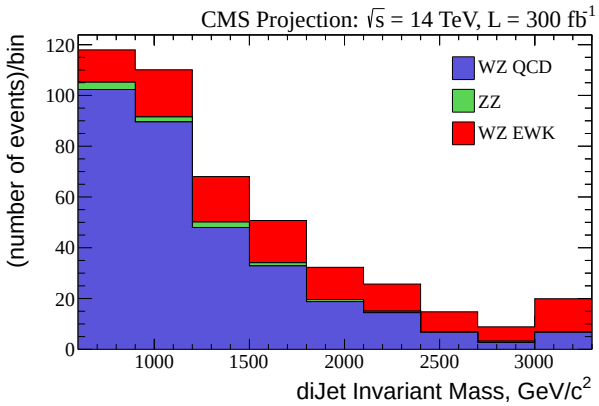
- Double TGC, QGC, t-channel Higgs boson scattering
- Strong interference, σ_{NLO} predicted (Higgs boson mass)
- Scattering topology $\rightarrow$ new physics in the EWKSB sector

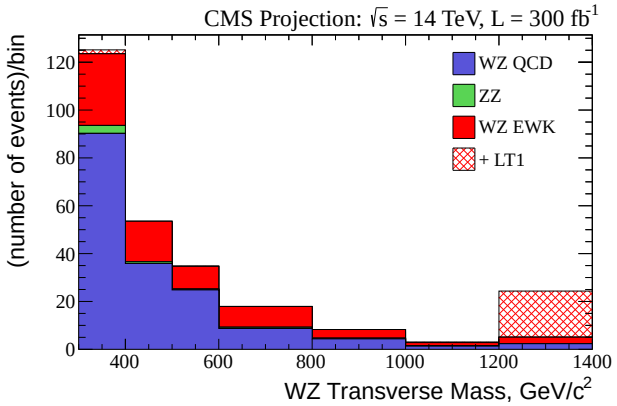
σ_{NLO} (fb)	WZ EWK	WZ QCD	ZZ	L_{T1} $(f_{T1}/\Lambda^4 = 1.0)$
Total	7.7	270	16	3.1
Fiducial (2.4)	0.69	0.96	0.038	0.57
Fiducial (4.0)	1.3	1.6	0.0016	0.58

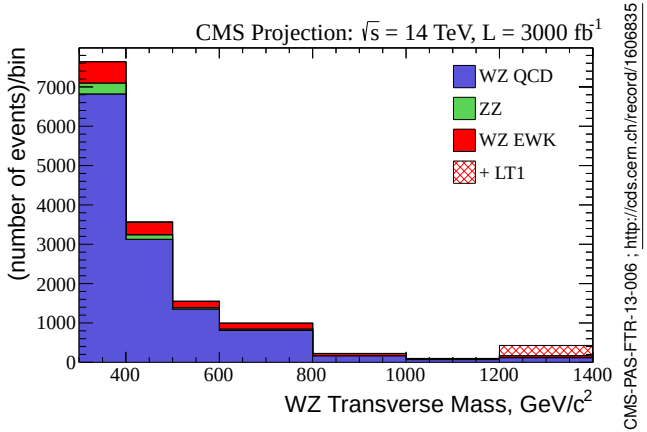
Probing EWK symmetry breaking: QGC (2)

EFT approach

- EFT for modelling aQGCs (no new physics (yet) at the LHC)
- Operator: $L_{T1} = (f_{T1}/\Lambda^4) Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] Tr[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$

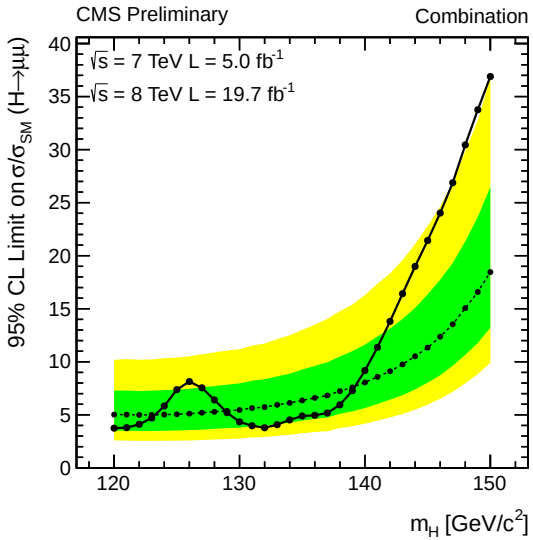






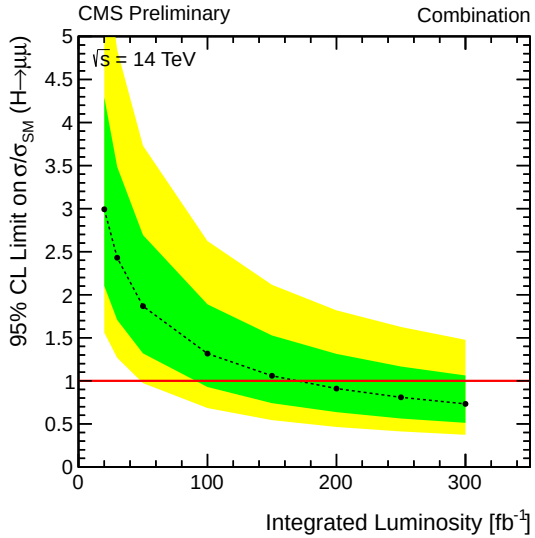
Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

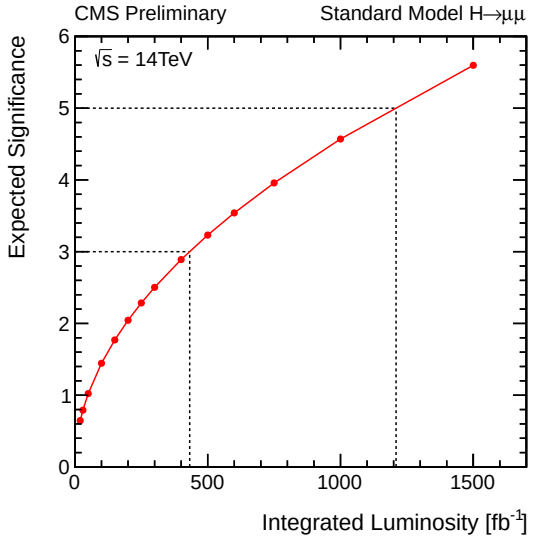
$H \to \mu\mu$

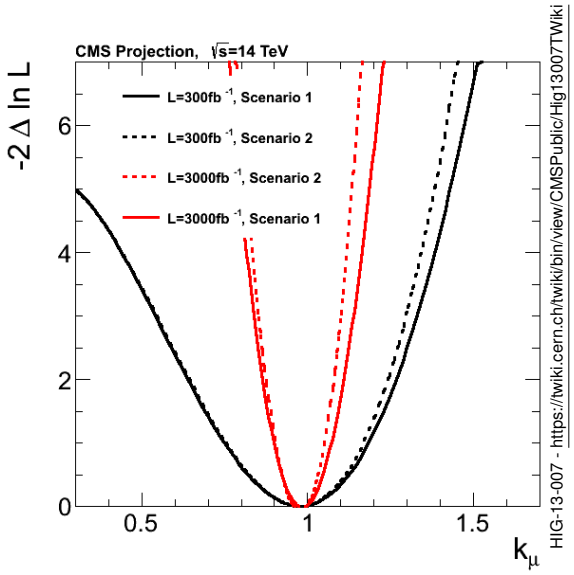


Excess at $m_H = 125$ GeV in the search for $H \to \mu\mu$

- Exclusion can be settled with < 200 fb^{-1}
- Evidence (discovery) can be settled with $< 5000(1250)$ fb^{-1}





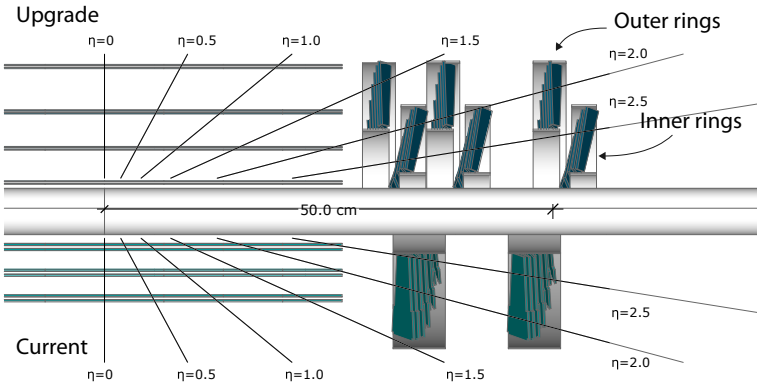


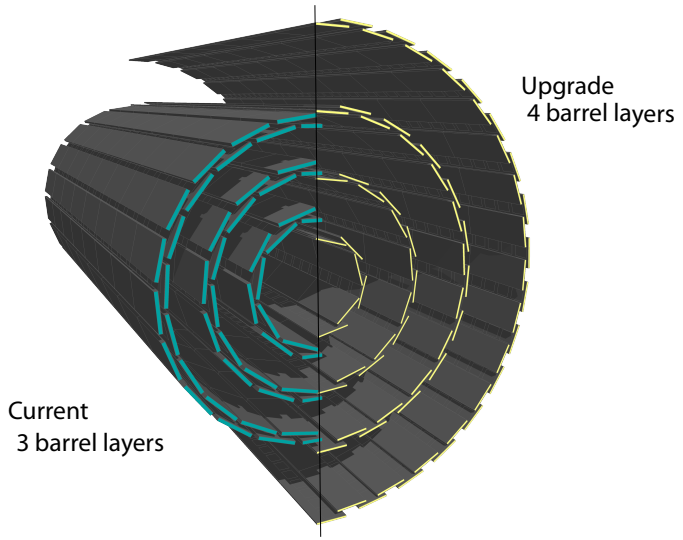
Conclusion

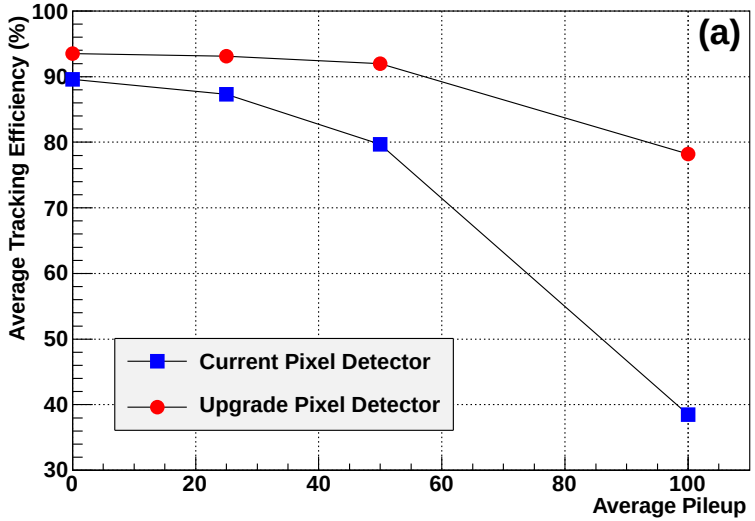
- A new particle (a Higgs boson) has been discovered with 30 fb^{-1} at LHC at $\sqrt{s} = 7, 8$ TeV
- Upgrade planned for $\sqrt{s} = 13$ TeV and $\int L = 300\ \text{fb}^{-1}$
- Besides (directly) looking for new physics, Higgs and Higgs-related studies are priority
  - Couplings of the new boson
  - Other Higgses (2HDM)
  - EWK symmetry breaking sector (QGC, self-couplings)
  - Exotic Higgs decays ($H \to \mu\mu$, $H \to \text{invisible}$)
  - Higgs with SUSY/Exotics (vector-like quarks, WED)
- Important interplay between upgrade plans and these studies

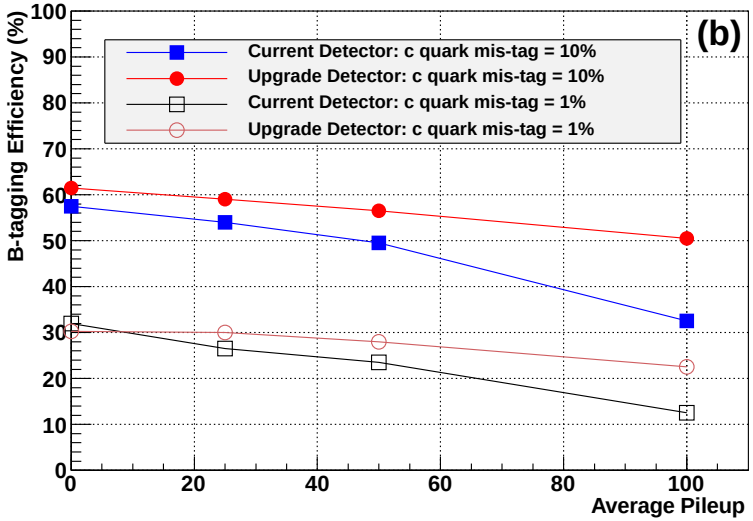
BACKUP

Pixel upgrade





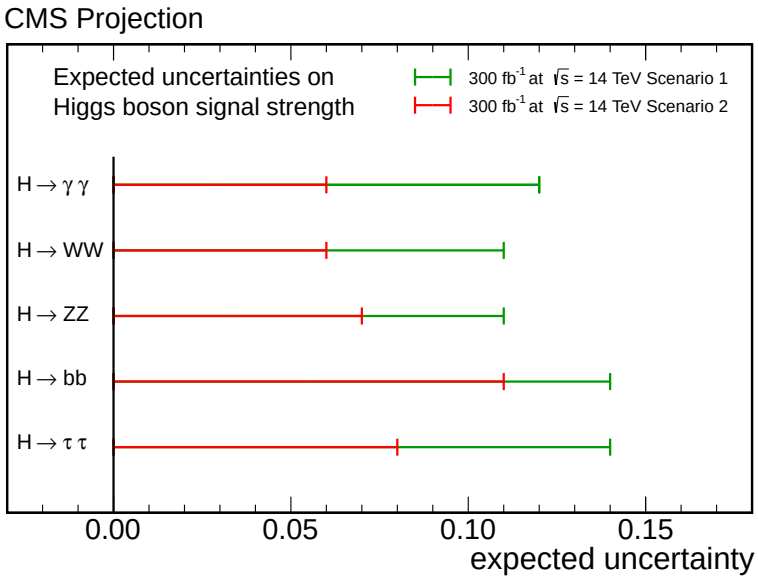


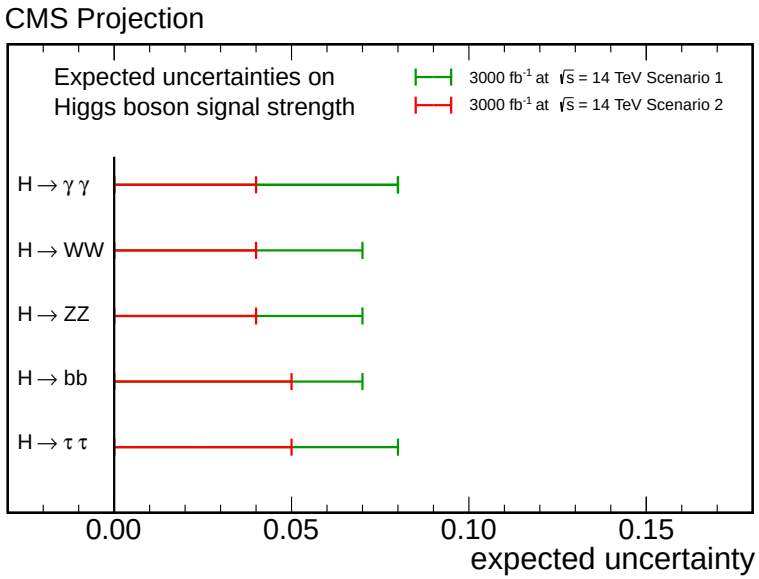


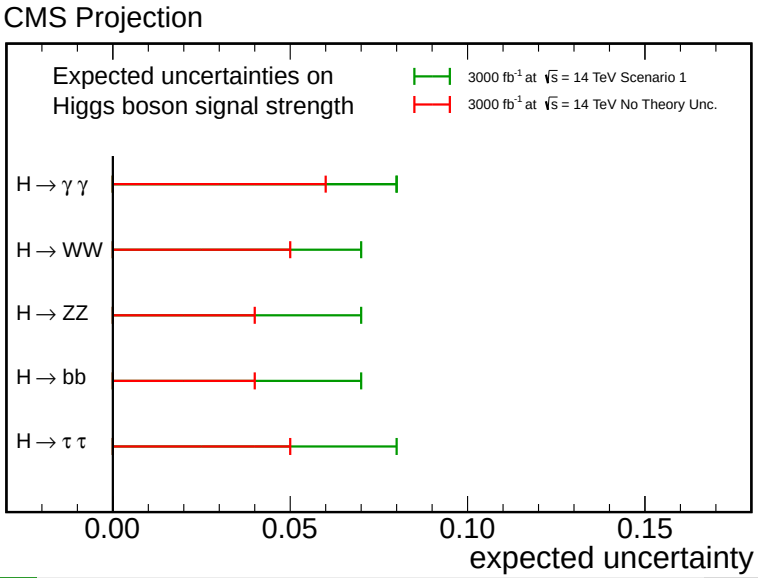
L1 trigger upgrade

- Improved electromagnetic object isolation using calorimeter energy distributions with pile-up subtraction;
- Improved jet finding with pile-up subtraction;
- Improved hadronic tau identification with a smaller fiducial area;
- Improved muon transverse momentum (p_T) resolution in difficult regions;
- Isolation of muons using calorimeter energy distributions with pile-up subtraction;
- Improved global Level-1 trigger menu with a greater number of triggers and with more sophisticated relations involving the input objects.

Higgs couplings projections (1)

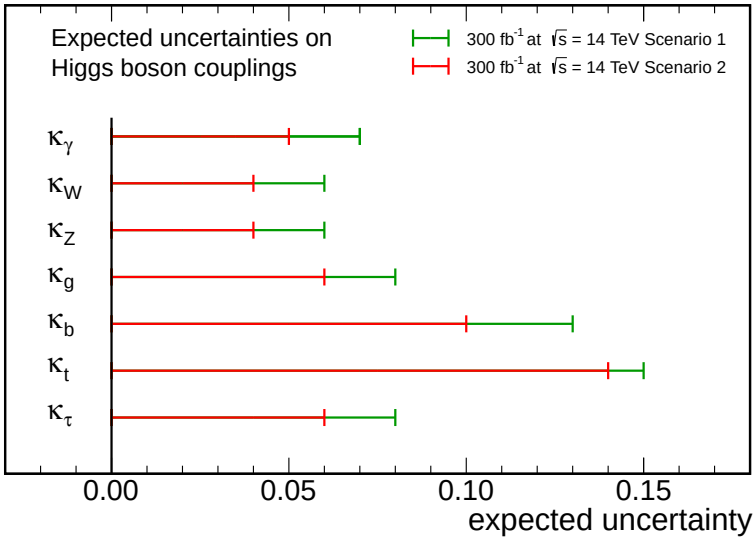




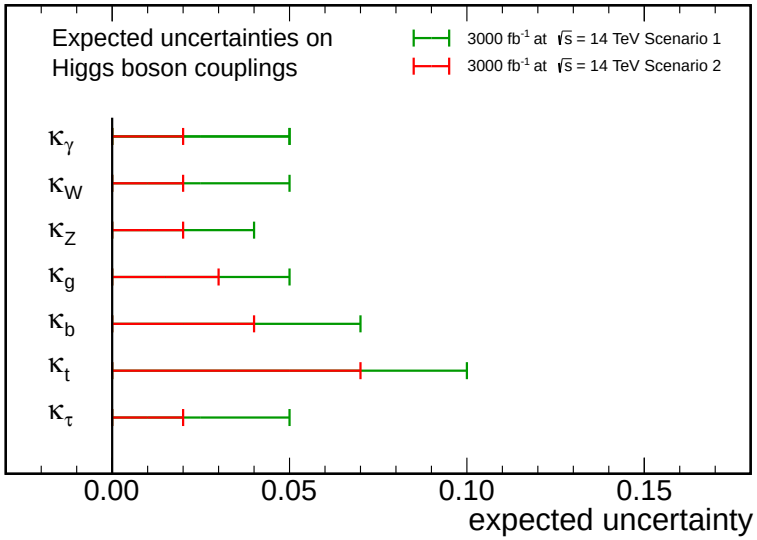


Higgs couplings projections (2)

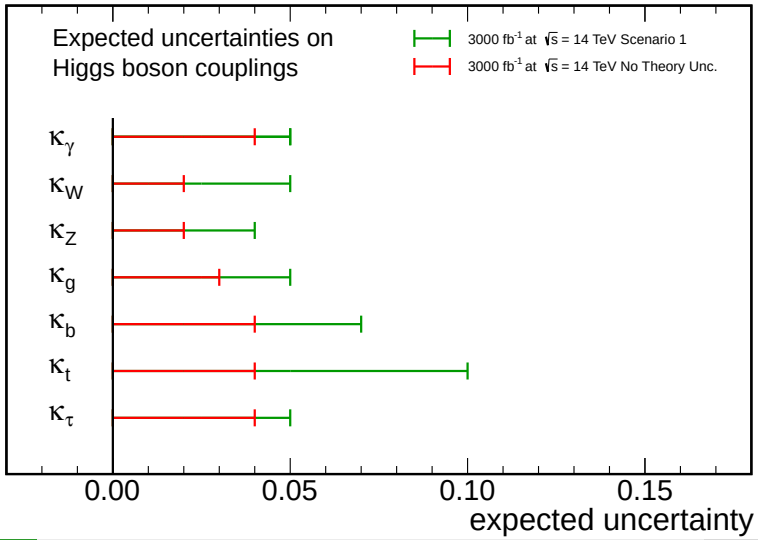
CMS Projection



CMS Projection



CMS Projection



Inputs to the higgs projections

H decay	prod. tag	exclusive final states	cat.	res.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$	2	<1.5%
	VH-tag	$\gamma\gamma + (e, \mu, MET)$	3	<1.5%
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%
$ZZ \to 4\ell$	$N_{jet} < 2$	4e, 4μ, 2e2μ	3	1-2%
	$N_{jet} \geq 2$		3	
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	20%
	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons)	2	20%
	WH-tag	3ℓ3ν (same-sign SF and otherwise)	2	
$\tau\tau$	0/1-jet	(eτ_h, $\mu\tau_h$, eμ, $\mu\mu$)$\times$ (low or high p_T^τ)	16	15%
	1-jet	$\tau_h\tau_h$	1	
	VBF-tag	(eτ_h, $\mu\tau_h$, eμ, $\mu\mu$, $\tau_h\tau_h$) + $(jj)_{VBF}$	5	
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, eτ_h, $\mu\tau_h$, eμ)	8	
	WH-tag	$\tau_h\mu\mu$, τ_heμ, e$\tau_h\tau_h$, $\mu\tau_h\tau_h$	4	
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, eν, $\mu\nu$ with 2 b-jets)$\times$x	13	10%
	ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	6	
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-jets)	3	
$Z\gamma$	inclusive	(ee, $\mu\mu$) $\times$ (γ)	2	
$\mu\mu$	0/1-jets	$\mu\mu$	12	1-2%
	VBF-tag	$\mu\mu + (jj)_{VBF}$	3	
invisible	ZH-tag	(ee, $\mu\mu$) $\times$ (MET)	2	