A quel point le Higgs est-il Standard ? Dernieres nouvelles de CMS

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Le Higgs est-il Standard ? Update de CMS

We have found a Higgs boson

- Observed by ATLAS & CMS in July 2012
- So far VERY Standard Model-like:
 - Mass in the expected range (1.3 σ away from EW fit prediction)
 - Couplings match SM predictions
 - Spin-parity measurements favor 0⁺
- It is a Higgs boson beyond doubt
- SM looks complete, so why bother?







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Why bother: we have found *a* Higgs boson

- Existence of a Higgs boson has cleared a lot of tension
 - The Standard Model looks complete and consistent (p-value = 0.18 + 0.02 (0.9 σ))
 - Probe for ElectroWeak Symmetry Breaking mechanism
- **Open issues** unexplained by the Standard Model
 - Gravity, dark matter, matter-antimatter assymmetry, ...
 - No other particle discovered so far...
- New tensions have appeared:
 - In the global EW fit
 - ATLAS / CMS discrepancies



So what's the plan?

Current Status

- Standard Model has a minimal Higgs sector
- Many BSM theories can accomodate the new boson
- Youngest particle to date: may be connected to New Physics
- "Higgs boson and nothing else" was the worst-case outcome!
- There exist machine / experiments / (wo)manpower effort already in place, alive and kicking: just keep digging !

Alternatives: ways out

- Two Higgs Doublet Model (2HDM): e.g. needed by MSSM
- Extra vector-like quarks can couple to a Higgs boson
- Constraining other predicted couplings: HHH, WWHH
- Other exotic decays: invisible, μμ, ee,
- There exists other corners than the Higgs one...

Menu

- Experimental setup: the CMS detector
- 2 Run I analyses: 2010-2012, $\sqrt{s} = 7 8 \text{ TeV}$, $\int L = 25 \text{ fb}^{-1}$
- Future: upgrades planned, analyses projections

I) Experimental setup

The Large Hadron Collider



- Protons and lead ions collider
- Energy per proton of 3.5(4.0) TeV : c - 38.78(29.69) km/h
- $\bullet ~\sim 1.5 \times 10^{11} \text{ protons per bunch}$
- Ring of 27 km in circumference : 1232 superconducting dipoles cooled down to 1.9 K, magnetic field of 8.33 T to bend the trajectory of the beam
- Beam crossing every 50 ns : \sim 20 M collisions per second

$$L = rac{N_b^2 n_b f_{rev} \gamma_r}{4\pi\epsilon_n eta^*} F ~({
m Hz/nb})$$

	2012	Nominal
Energy per proton (TeV)	4.0	7
Nb of bunches	1374	2808
Bunch spacing (ns)	50	25
Inst. lumi. (cm ⁻² s ⁻¹)	$7.54 imes 10^{33}$	10 ³⁴

The Compact Muon Solenoid experiment



II) Run I analyses: Standard-like Higgs boson?

- Extended Higgs sector
- Higgs coupling to leptons
- Higgs coupling to invisible

Extended Higgs sector (I)

Two Higgs Doublet Model (2HDM)

- Simplest extension compatible with gauge invariance of the minimal Higgs sector
- 5 physical Higgs bosons: 2 CP-even scalars H and h, CP-odd pseudo-scalar A, a charged pair H[±]
- Constraints: 2HDMs may be parametrized by 9 variables
 - *m_h*, *m_H*, *m_A*, *m<sub>H<sup>±</sub>*</sub>, CP-even mixing angle *α*, ratio of Higgs vaccuum expectation values tan *β*, three scalar couplings *λ*₅, *λ*₆, *λ*₇
 </sub></sup>

HIG-13-025 \square : Search for $H \rightarrow hh$ and $A \rightarrow Zh$

- With *h*(125), leptons and photons in the final state
- Classification by N_l / OSSF pairs / off-on Z, N_τ, N_b, ∉_T

	$h \rightarrow WW^*$	$h \rightarrow ZZ^*$	$h \rightarrow \tau \tau$	$h \rightarrow bb$	$h \rightarrow \gamma \gamma$
$h \rightarrow WW^*$	√	√	~	Х	√
$h \rightarrow ZZ^*$	-	 ✓ 	~	~	~
$h \rightarrow \tau \tau$	-	-	~	x	~
$h \rightarrow bb$	-	-	-	X	х
$h \rightarrow \gamma \gamma$	-	-	-	-	х

	$h \rightarrow WW^*$	$h \rightarrow ZZ^*$	$h \rightarrow \tau \tau$	$h \rightarrow \gamma \gamma$
$Z \rightarrow II$	 ✓ 	~	 ✓ 	 ✓
$Z \rightarrow qq$	X	~	X	X
$Z \rightarrow \nu \nu$	X	~	X	X

Extended Higgs sector (II)

Multileptons final states

- Contribution of non-prompt 3rd lepton in Z+ jets, WW+ jets estimated in data control-sample
- *tt*, diboson backgounds estimated from MC simulation validated in control regions
- Contribution from asymmetric photon conversions estimated in data



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Extended Higgs sector (III)

Diphoton final states

• Background evaluated in $m_{\gamma\gamma}$ sidebands (\notin [120, 130] GeV) in 1 – 2 τ_h , 2 γ and $\not\!\!\!E_T <$ 30 GeV





Limit settings

Add channels by sensitivity until 90 % of the signal is covered

Extended Higgs sector (IV)



- Limits combining lepton and photon channels
- Excess in $3(e/\mu) + \tau_h$ off-Z channels with no b-tags:

• obs. (exp.) 11(5.1 \pm 1.7), 4(2.4 \pm 0.5), 5(2.6 \pm 0.6) for the 3 $\not\!\!\!E_T$ bins

• p-value: local = 1.5 %, global (40 channels): sum of $\not\!\!E_T$ bins = 46 %, all three $\not\!\!E_T$ bins = 5 %

Extended Higgs sector (V)

- Recast σ × BR limits in 2HDM Type I and Type II parameter space:
 - α (mixing H h)
 - β (relative contribution of each doublet to EWSB)

1	2HDM I	2HDM II
hVV	$sin(\beta - \alpha)$	$sin(\beta - \alpha)$
hQu	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$
hQd	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$
hLe	$\cos \alpha \sin \beta$	sin $\alpha \cos \beta$
HVV	$\cos(\beta - \alpha)$	$\cos(\beta - \alpha)$
HQu	$\sin \alpha \sin \beta$	$\sin \alpha \sin \beta$
HQd	$\sin \alpha \sin \beta$	$\cos \alpha \sin \beta$
HLe	$\sin \alpha \sin \beta$	$\cos \alpha \sin \beta$
AVV	0	0
AQu	cot β	$\cot \beta$
AQd	$-\cot \beta$	$\tan \beta$
ALe	$-\cot \beta$	$\tan \beta$



Higgs coupling to leptons

$H \rightarrow \tau \tau$: HIG-13-021 \square $H \rightarrow \mu \mu$: HIG-13-007 \square $H \rightarrow ee$: HIG-13-007 \square

- Enhanced for MSSM at large tan β
- $gg \rightarrow \phi$ and $gg \rightarrow bb\phi$ $(\phi = H, h, A)$

- BR(SM, $m_H = 125 \text{ GeV})$ $= 2.19 \times 10^{-4}$
- Classification: jets (VBF / ggH), muon resolution
- Similar $\sigma \times BR$ sensitivity as $H \rightarrow \mu\mu$ search
- Classification: dijet, electron resolution







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Invisible Higgs decays

No direct constraint on the total width

- Only SM-expected invisible decay: $H \rightarrow Z(\nu\nu)Z(\nu\nu)$
- Z(bb)H(inv.): HIG-13-028
 □
- Z(II)H(inv.): HIG-13-018 BR($H(125 \text{ GeV}) \rightarrow inv.) < 75 \%(91 \%)$



III) Future Studies: upgrading

- CMS upgrade plans
- Projections
 - Couplings projection ; $H \rightarrow ZZ \rightarrow 4\mu$: geometry picking
 - Extending the Higgs sector
 - Rare / exotic decays
 - Probe EWK sector

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)	< p u >	BX (ns)
-	2009-20	12 Run 1	7 and 8	25	$7 imes 10^{33}$	21	50
	2013-20	14 LS1		"Pha	ase 1" upgrade:	S	
	2015-20	17 Run 2	13	-	10 ³⁴	25	25
	2018-20	19 LS2		"Pha	ase 1" upgrade:	S	
	pprox 2021	Run 3	-	300	-	50	-
	2022-202	23 LS3		"Pha	ase 2" upgrade:	S	
	pprox 2024	HL-LHC	-	3000	$5 imes 10^{34}$	128	-
					100		WJS20
		$\sqrt{s} = 14 \mathrm{Te}$	eV $\sqrt{s} =$	8 TeV	ratios of LHC p	arton luminosities:	
		$\int L = 3000 \text{f}$	b^{-1} $\int L =$	30 fb ⁻¹			
	σ (pb)		Events		<u>Σqq</u>		
ggН	50.4	150M	60	00K	2 qg		
/BF	4.2	13M	4	8K	in .		
WΗ	1.5	4.5M	2	1K	3		
ΖH	0.9	2.6M	1	2K		-	COLOR WAY
ttH	0.6	1.8M	4	4K	1 100		MSTW2008NL0
						M _v (Ge	eV)

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Phase I upgrades (I)



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 (II)

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: $H \rightarrow ZZ^* \rightarrow 4\mu$
- Extending the search for (2HDM) neutral Higgses
- Probing EWK symmetry breaking: vector boson scattering and quartic gauge couplings
- Rare decays: $H \rightarrow \mu \mu$
- (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)

Higgs couplings projections: starting point



Discovery of a Higgs boson: HIG-13-005

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

Higgs couplings projections



Strategy: Snowmass report

- Scale signal and bkg event yields to 300 fb⁻¹ at $\sqrt{s} = 13 \text{ TeV}$
- 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: $H \rightarrow ZZ^* \rightarrow 4\mu$ (I)

FTR-13-003 E: Projection assumptions

•
$$\sqrt{s} = 14 \text{ TeV}$$
; < 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
- $\bullet\,$ Only irreducible background considered (non-resonant SM $ZZ \rightarrow 4 \mu)$
- No analysis reoptimization

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



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: $H \rightarrow ZZ^* \rightarrow 4\mu$ (III)



- 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 (I)

Scope of the study FTR-13-024 I

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





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



Conclusion

- There is some phase space still allowed where exclusion or discovery of either *H* or *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

Probing EWK symmetry breaking: QGC (I)



WZ scattering (leptonic decays): FTR-13-006

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

$\sigma_{\it NLO}$ (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

Probing EWK symmetry breaking: QGC (II)

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

 $H \rightarrow \mu \mu$



Excess at $m_H = 125 \text{ GeV}$ in the search for $H \rightarrow \mu \mu$

- Exclusion can be settled with < 200 fb⁻¹
- Evidence (discovery) can be settled with $< 500(1250) \text{ fb}^{-1}$



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Conclusion

Conclusion

- A new particle (a Higgs boson) has been discovered with 30 fb⁻¹ at LHC at $\sqrt{s} = 7,8$ TeV
- Run I : analyses still in the pipeline
 - $X \rightarrow HH$ final states
 - $t' \rightarrow tH$ final states
 - More (MSSM/2HDM) Higgses

Beyond LS1: Upgrade and plans for Run II-III / HL-LHC

- Upgrade planned for $\sqrt{s} = 13 \text{ TeV}$ and $\int L = 300 \text{ fb}^{-1}$
- Higgs and Higgs-related studies are a priority
 - SM- and exotic- couplings of the new boson
 - Other Higgses (2HDM)
 - EWK symmetry breaking sector (QGC, self-couplings)
 - Higgs with SUSY/Exotics (vector-like quarks, WED)
- Important interplay between upgrade plans and these studies

Exciting future ahead! Merci de votre attention !

BACKUP

Pixel upgrade



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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)



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Higgs couplings projections (2)



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Inputs to the higgs projections

H decay	prod. tag	exclusive final states	cat.	res.
	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$	2	<1.5%
1 111	VH-tag	$\gamma\gamma + (e, \mu, MET)$	3	<1.5%
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%
77 \ 10	$N_{\rm jet} < 2$	4. 4. 2020	3	1 00/
$LL \rightarrow 4\ell$	$N_{\rm jet} \ge 2$	$+c, +\mu, 2c2\mu$	3	1-2 /0
	0/1-jets	(DF or SF dileptons) \times (0 or 1 jets)	4	20%
$WW \rightarrow \ell \nu \ell \nu$	VBF-tag	$\ell \nu \ell \nu + (jj)_{VBF}$ (DF or SF dileptons)	2	20%
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2	
	0/1-jet	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu) \times (low or high p_T^{\tau})$	16	
	1-jet	$ au_{h} au_{h}$	1	15%
ττ	VBF-tag	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\rm VBF}$	5	
	ZH-tag	$(ee, \mu\mu) \times (\tau_h \tau_h, e \tau_h, \mu \tau_h, e \mu)$	8	
	WH-tag	$\tau_h\mu\mu, \tau_h e\mu, e\tau_h\tau_h, \mu\tau_h\tau_h$	4	
	VH-tag	$(\nu\nu, ee, \mu\mu, e\nu, \mu\nu \text{ with 2 b-jets}) \times x$	13	10%
bb	ttU too	(ℓ with 4, 5 or \geq 6 jets) \times (3 or \geq 4 b-tags);	6	
	till-tag	(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or \geq 3 b-jets)	3	
Ζγ	inclusive	(ee, $\mu\mu$) × (γ)	2	
μμ	0/1-jets	$\mu\mu$	12	1-2%
	VBF-tag	$\mu\mu + (jj)_{\rm VBF}$	3	1-270
invisible	ZH-tag	(ee, $\mu\mu$) × (MET)	2	