Overview of Higgs Boson Searches in CMS

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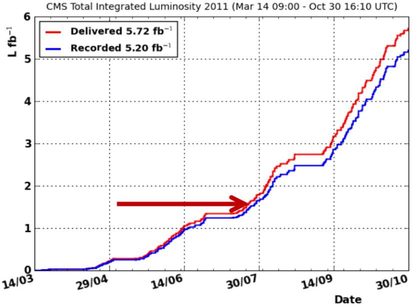
Outline

1. Standard Model Higgs searches at CMS
   - Low mass: $H \to \gamma\gamma$, $H \to \tau\tau$, ($H \to b\bar{b}$)
   - Intermediate and high mass: $H \to WW \to 2l2\nu$, $H \to ZZ \to 4l$, ($H \to ZZ \to 2l2\tau$, $H \to ZZ \to 2l2q$, $H \to ZZ \to 2l2\mu$)
2. Combination of Higgs searches (CMS and ATLAS+CMS)
   - Statistical combination procedure
   - Combination with ATLAS
   - Overview of theory uncertainties
3. Non Standard Model Higgses
   - MSSM $A, h \to \tau\tau$
   - Charged Higgses

LHC and CMS data

LHC has been running steadily in 2011: *pp* collisions at $\sqrt{7}\,\mathrm{TeV}$

- Delivered 5.7 fb^{-1} of data, CMS recorded 5.2 fb^{-1}
  85 – 90 % of this data is good for physics
- Report here on public Higgs results with 1.0 – 1.7 fb^{-1} (Summer 2011)

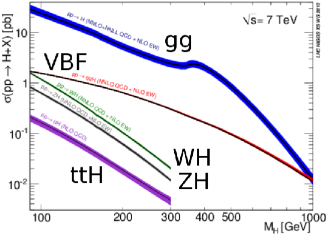


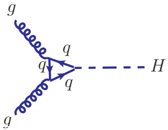
6 collisions per crossing (on average)

- 50 ns bunch spacing,
  peak luminosity: $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\sim$ 15 collisions in the later data ($L_{peak} = 3.5 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- tough high-pileup conditions
  $\rightarrow$ improved trigger, reconstruction and developed dedicated methods

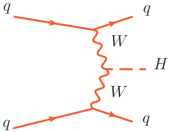
Higgs production and decay (*arXiv:1101.0593 [hep-ph]*)

- Cross-sections, branching-ratios, pseudo-observables and related errors studied/compiled by Higgs Cross Section WG (Atlas-CMS-Theory)

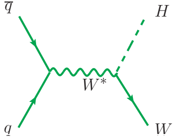




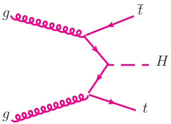
gluon fusion



vector-boson fusion



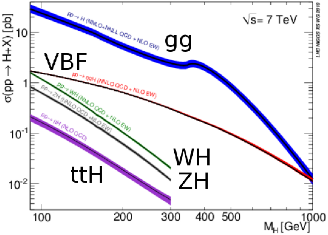
associated to W/Z

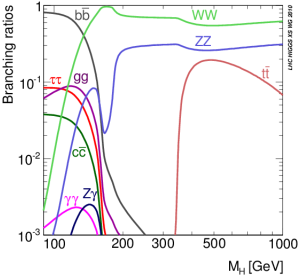


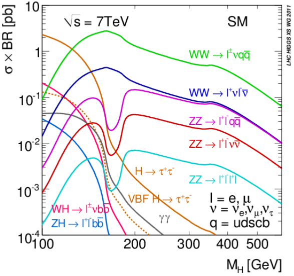
associated to $t\bar{t}$

Higgs production and decay *(arXiv:1101.0593 [hep-ph])*

- Cross-sections, branching-ratios, pseudo-observables and related errors studied/compiled by Higgs Cross Section WG (Atlas-CMS-Theory)







- Higgs $\sigma \times \mathrm{BR}$ tiny compared to QCD and EWK processes:
  $\sigma(W+j) \sim 28000$, $\sigma(Z+j) \sim 2800$, $\sigma(t\bar{t}) \sim 165$, $\sigma(WW) \sim 43$

CMS Higgs searches

Searched for SM Higgs in 8 decays modes:

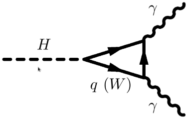
- signatures with isolated leptons or photons in the final states;
- also MET, jets, *b*-tagging and τ-ID

channel	mass range (GeV/c^2)	$\int \mathcal{L}\,\mathrm{d}t$ (fb^{-1})	reference
$H \to \gamma\gamma$	110 – 150	1.7	CMS-PAS-HIG-11-021
$H \to \tau^+\tau^-$	110 – 140	1.6	CMS-PAS-HIG-11-020
$H \to b\bar{b}$	110 – 135	1.1	CMS-PAS-HIG-11-012
$H \to WW^{(*)} \to l\nu l\nu$	110 – 600	1.5	CMS-PAS-HIG-11-014
$H \to ZZ^{(*)} \to llll$	110 – 600	1.7	CMS-PAS-HIG-11-015
$H \to ZZ^{(*)} \to ll\tau\tau$	180 – 600	1.1	CMS-PAS-HIG-11-013
$H \to ZZ^{(*)} \to ll\nu\nu$	250 – 600	1.6	CMS-PAS-HIG-11-016
$H \to ZZ^{(*)} \to llq\bar{q}$	225 – 600	1.6	CMS-PAS-HIG-11-017

$\to$ On-going analyses with $\sim 5\,\mathrm{fb}^{-1}$ (not presented here)

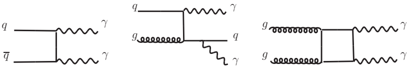
2 isolated, high-p_T photons forming a narrow peak

- very small branching fraction $\mathcal{O}(10^{-4})$
  but sensitive thanks to excellent performance of ECAL



Backgrounds: prompt QCD photons, fakes from jets, ...

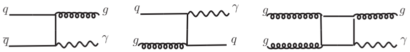
irreducible backgrounds



$\mathcal{O}(\alpha^2)$ $\mathcal{O}(\alpha_S\alpha^2)$ $\mathcal{O}(\alpha_S^2\alpha^2)$

theory uncertainty $\sim$ 25%

reducible backgrounds



$\mathcal{O}(\alpha_S\alpha)$ $\mathcal{O}(\alpha_S\alpha)$ $\mathcal{O}(\alpha_S^3\alpha)$

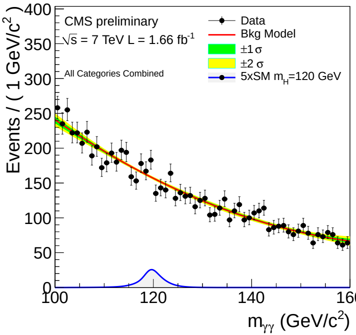
theory uncertainty $\sim$ 30%

Unbinned analysis based on $m_{\gamma\gamma}$:

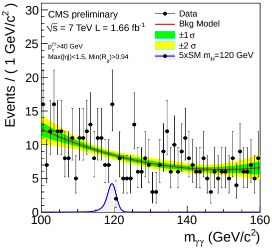
- narrow signal peak; width is resolution-dominated (3-8 GeV/c^2)
  - correction to photon efficiency, energy scale, energy resolution from $Z \to e^+e^-$ data events and MC smeared to match data resolution

- Analysis with 8 categories of varying mass resolution:
  - $p_T^{\gamma\gamma} > 40\,\mathrm{GeV}/c$ (or not)
  - η_γ: both photons in barrel (or not)
  - conversion probability: both photons likely non-converted (or not)

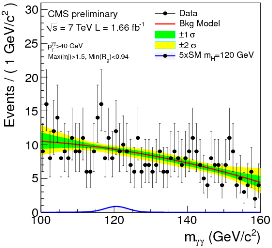
All categories merged



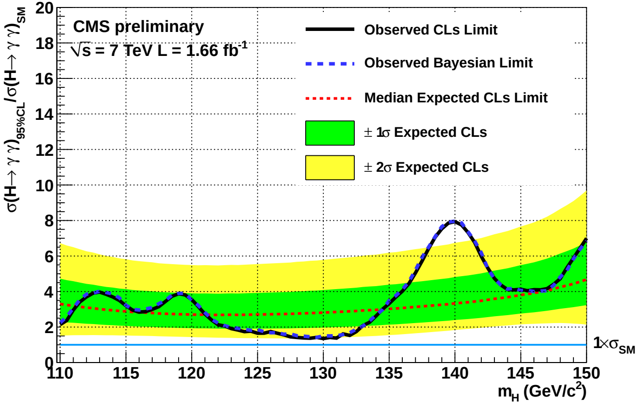
ECAL barrel, unconverted $p_T > 40$



ECAL endcap, 1-converted $p_T > 40$



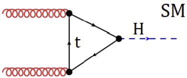
- Compute 95 % C.L. upper limits on σ_H/σ_H^{SM} versus m_H

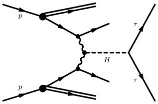


- Analysis also excludes fermiophobic Higgs in range $110 - 112\,\mathrm{GeV}$

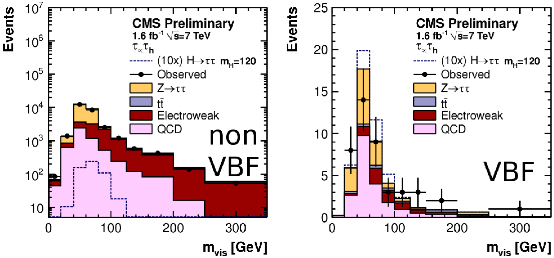
Studied channels with τ decaying into μ, e and hadrons:

$$\tau_e\tau_h,\ \tau_\mu\tau_h,\ \tau_e\tau_\mu$$





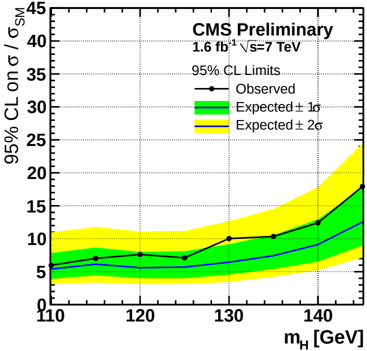
- Separate cleaner vector boson fusion topologies with:
  - 2 jets, $p_T > 30\,\mathrm{GeV}$, $M_{jj} > 350\,\mathrm{GeV}$
  - $|\Delta\eta_{jj}| > 3.5$, $\eta_1 \times \eta_2 < 0$



- Boosted visible τ-decay products and ν tend to be collinear:
  - apply topological cut based on p_T^{ll} and E_T^{miss}

Backgrounds:

- dominant irreducible background $Z \rightarrow \tau\tau$: shape from MC, normalization from $Z \rightarrow l^+l^-$ measurement and fit of m_{vis}
- W/Z+jets, QCD, $t\bar{t}$, WW/ZZ: estimated from control samples



Binned analysis based on $m_{\tau\tau}^{vis}$:

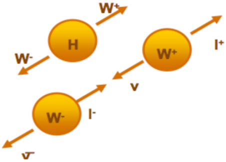
- computed from measured momenta of e, μ, τ_{had} (no ν recovery)

Working on adding $\tau_\mu\tau_\mu$ channel:

- errors mostly statistically dominated

$\rightarrow$ presentation of A. Bethani (yesterday)

$H \to WW \to 2l2\nu$ (PAS-HIG-11-014) $1.5\,\mathrm{fb}^{-1}$



- Scalar Higgs: small opening angle $\Delta\phi(l^+, l^-)$
- Large MET (missing ν's from W)
  - signal extracted from event counts (no mass peak)

Classification in categories with 0, 1 or 2 jets

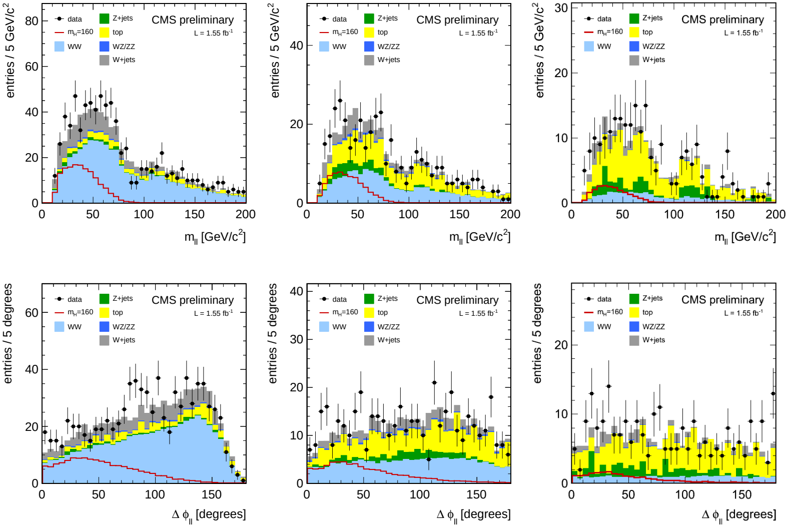
- exploit differences in production mechanisms (such as VBF)
- 5 categories: 0 and 1 jet splitted in same/different lepton-flavour groups

Controled reduction of background crucial to the analysis:

- QCD and $W + j$: require lepton $p_T > 10\,\mathrm{GeV}$, tight ID and isolation
- Drell-Yann: strongly reduced with MET cut; veto $Z \to \mu\mu/ee$
- top backgrounds: apply jet-veto (in particular on b-jets)
- $pp \to WW$ continuum: irreducible; use kinematic discrimination
- estimated with data-driven techniques;
  - except WW at high m_H and WZ/ZZ: taken from MC

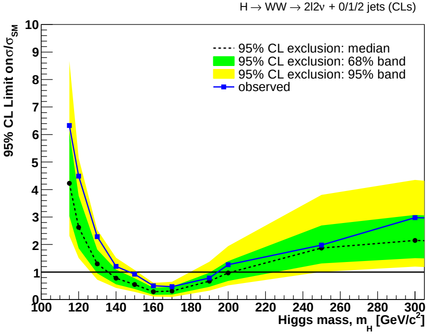
Optimizations, dependant on m_H: M_{ll}, $\Delta\phi_{ll}$, p_T^{l1}, p_T^{l2}, $M_T(ll, MET)$

Main kinematic observables: M_{ll} and $\Delta\phi(l^+, l^-)$ for 0, 1, 2-jets events



- Event counts at $140\,\mathrm{GeV}$

process	0-j ee, $\mu\mu$	0-j $e\mu$	1-j ee, $\mu\mu$	1-j $e\mu$	2-j
backgrounds	44.0 ± 6.2	40.6 ± 7.0	17.8 ± 3.5	12.6 ± 3.7	5.3 ± 1.7
Higgs	19.1 ± 4.3	16.1 ± 3.6	7.7 ± 2.6	5.3 ± 1.8	2.5 ± 0.3
data	46	41	23	23	7

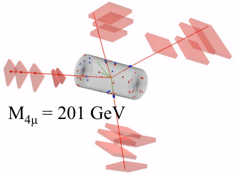


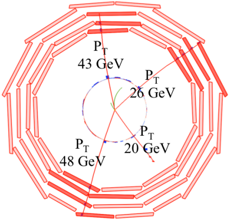
Higgs excluded at 95% CL in range $147 - 194\,\mathrm{GeV}$

- Currently working on an improved analysis using MVA discrimination
- See also presentation of Ch. Hackstein on theory uncertainties

Golden channel: fully reconstructed event, m_H resolution $2 - 4\,\mathrm{GeV}$

- Selections:
  - Z_1: $p_T^{min} > 10$, $p_T^{max} > 20$, $60 < M_{ll} < 120\,\mathrm{GeV}$
  - Z_2: $20 < M_{ll} < 120\,\mathrm{GeV}/c^2$
  - $M_{4l} > 120\,\mathrm{GeV}/c^2$
  - impact parameter significance > 4



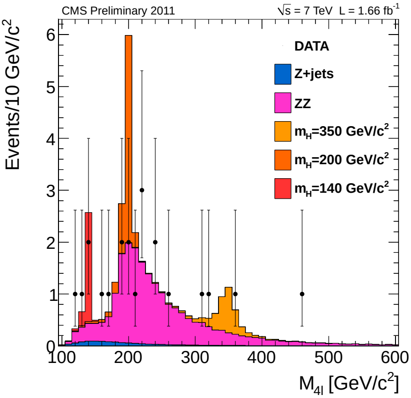


- mainly $pp \rightarrow ZZ^{(*)}$ irreducible background after selection (shape taken from MC; rate from Z yield in data and theory predictions for σ_{ZZ}/σ_Z)

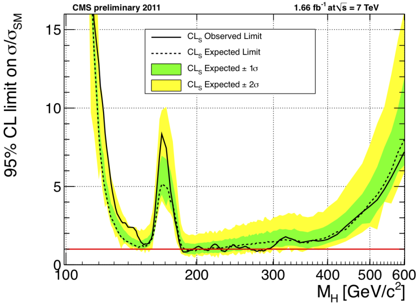
Cut	QCD	$t\bar{t}$	Z+jets	Z $b\bar{b}/c\bar{c}$	Zγ	WZ	ZZ	$m_H = 200\,\mathrm{GeV}/c^2$	Total	Data
Trigger	1.53×10^5	2.18×10^3	4.82×10^5	2.24×10^5	2.64×10^3	221	49.8	10.2	$(8.72\pm0.04)\times10^5$	8.72×10^5
Z_1	1.07×10^4	1.51×10^3	4.43×10^5	2.05×10^5	2.35×10^3	184	43.3	9.29	$(6.65\pm0.01)\times10^5$	6.82×10^5
$Z_1+\ell$	34.6	74.8	1.05×10^3	804	123	51.2	13.9	3.20	$(2.16\pm0.04)\times10^3$	2.52×10^3
$Z_1+\ell^+\ell^-$	0	0.96	0.29	0.89	0.29	0.063	5.21	1.48	7.7 ± 0.5	12
Isolation	0	0	0	0.15	0.29	0.027	4.85	1.31	5.31 ± 0.26	5
IP	0	0	0	0	0.29	0.009	4.48	1.21	4.77 ± 0.21	5
Kinematics	0	0	0	0	0.14	0.009	4.04	1.20	4.19 ± 0.16	5

Results of the shape-based analysis

21 observed events (as expected)



6 events below the on-shell ZZ kinematic threshold (2.8 ± 0.2 events expected)



Also interpretation in framework of fourth-fermion family (SM4): excluded in $110 - 112\,\mathrm{GeV}$ range

Other CMS Higgs analyses

$H \to b\bar{b}$

- important for Higgs couplings
- associated production with W/Z
- 5 final states: $W(\mu\nu)H(bb)$, $W(e\nu)H(bb)$, $Z(\mu\mu)H(bb)$, $Z(ee)H(bb)$, $Z(\nu\nu)H(bb)$

$H \to ZZ^{(*)} \to 2l2\tau$

- 8 final states: $Z(ll) + \tau_{had}\tau_{had}$, $Z(ll) + e\tau_{had}$, $Z(ll) + \mu\tau_{had}$, $Z(ll) + e\mu$ ($ll = ee$ or $\mu\mu$)
- broad signal peak
- data-driven QCD estimation

$H \to ZZ^{(*)} \to 2l2\nu$

- 2 sub-channels: $2e2\nu$ and $2\mu2\nu$
- m_H-dependant cuts on E_T^{miss}, m_T and $\Delta\Phi(E_T^{miss}, \mathrm{jet})$
- Z+jets background estimated from γ+jets in data

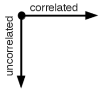
$H \to ZZ^{(*)} \to 2lq\bar{q}$

- categories based on lepton flavour and number of b-tagged jets
- search for a peak in m_{2l2q}
- use Higgs angular distribution
- quark-jet/gluon-jet discriminator

CMS instrumental systematic uncertainties on signal

Simplified overview of typical values:

Systematic Uncertainties		Higgs boson decay channels (mass in GeV/c^2)							
					WW	ZZ			
source	type	$\gamma\gamma$ (120)	bb (120)	$\tau\tau$ (120)	$\ell\nu\ell\nu$ (150)	$\ell\ell\ell\ell$ (200)	$\ell\ell\tau\tau$ (400)	$\ell\ell\nu\nu$ (400)	$\ell\ell qq$ (400)
luminosity	lumi	4.5%							
trigger efficiencies	μ		2%			2%	1%	2%	1%
	e		2%			2%	1%	1%	1%
	γ	1%							
	E_T^{miss}		2%						
reconstruction efficiencies	μ		4%	1%	3%	3%	2%	2%	1%
	e		4%	2%	4%	3%	6%	2%	2%
	γ	1-3%							
	τ_{had}			6%			10%		
	b-tag		20%						20%
p_T scale (event yield)	μ				2%	1%	1%	2%	1%
	e				2%	2%	2%	5%	2%
	jets/E_T^{miss}		2%	4%	2-10%			2%	0.2%
p_T scale (shape)	μ					0.3%			
	e					0.3%			
	γ	0.1-0.3%							
	τ_{had}			3%					
p_T resolution (event yield)	jets/E_T^{miss}		10%						
	jets/E_T^{miss}		2%	4%	2-10%			2%	0.2%
p_T resolution (shape)	μ					10%			
	e					10%			
	γ	20%							



- A table of theory-related systematics will follow in a few slides

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   - Low mass: $H \to \gamma\gamma$, $H \to \tau\tau$, $(H \to b\bar{b})$
   - Intermediate and high mass: $H \to WW \to 2l2\nu$, $H \to ZZ \to 4l$, $(H \to ZZ \to 2l2\tau$, $H \to ZZ \to 2l2q$, $H \to ZZ \to 2l2\mu)$
2. Combination of Higgs searches (CMS and ATLAS+CMS)
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Statistical combination: procedure *(CMS-NOTE-2011-005)*

Convergence on statistical procedure and on correlated systematics with ATLAS (LHC Higgs Combination Group)

- Upper limits on $\mu = \sigma/\sigma_{SM}$ in a modified-frequentist approach:
  - MC sampling of the test statistic q_μ for B-only and $S+B$ hypotheses

$$q_\mu = -2 \ln \frac{L(data; \mu, \hat{\theta}_\mu)}{L(data; \hat{\mu}, \hat{\theta}_\mu)} \quad (0 \leq \hat{\mu} \leq \mu)$$

- *different from LEP and Tevatron*
- *has good asymptotic behaviour*

  - nuisance parameters profiled in q_μ (toys generated around $\hat{\theta}_\mu$)
  - uncertainties modeled with log-normal pdfs (probability density functions)
  - compare the p-values to the value of q_μ in data and compute ratio:

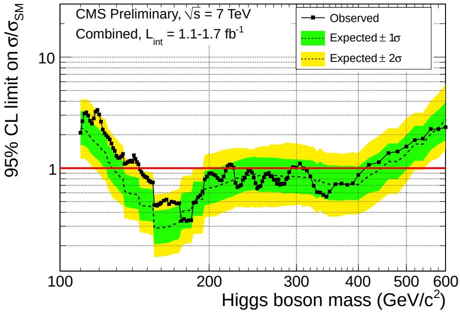
$$CL_S = \frac{CL_{SB}}{CL_B} = \frac{p_\mu}{1 - p_0}$$

- *protects against downward fluctuations of background*

  - vary hypothesis (value of μ tested) until reach exclusion with $CL_S < 0.05$
- Correlations seriously taken into account in the combination

→ Combination and statistical analysis with the RooStats software package

Statistical combination CMS: results (PAS-HIG-11-022)

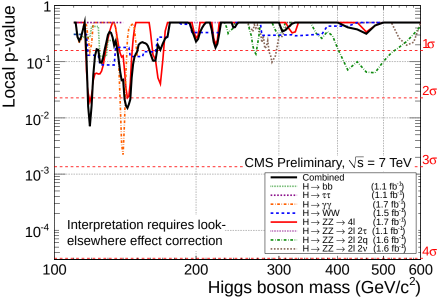


Expectation: SM exclusion range $130 - 440\,\mathrm{GeV}$ (median $\sigma/\sigma_{SM} < 1$)

Data: 95% CL exclusions in ranges: $145 - 216, 226 - 288, 310 - 400\,\mathrm{GeV}$

p-value: probability of an excess from the B-only hypothesis at least as large as the one observed. $Z = \sqrt{q_0^{obs}}$

- the combination is not the product of individual *p*-values!

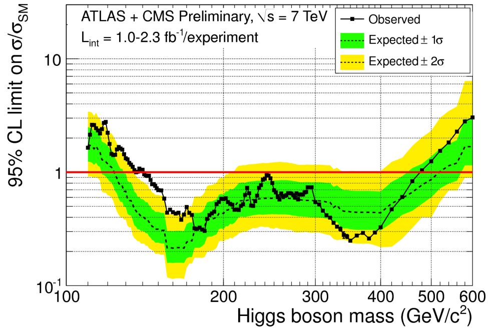


- taking into account the look-elsewhere effect: $p_0^{global} \sim 0.4$

Combination ATLAS-CMS *(CMS-PAS-HIG-11-023, ATL-CONF-2011-157)* $1.0 - 2.3\,\mathrm{fb}^{-1}$

Combination of:

- CMS: CMS-PAS-HIG-11-022 + update of $H \to \tau^+\tau^-$ analysis
- ATLAS: ATL-CONF-2011-135 + update of $H \to ZZ \to 2l2\nu$ analysis
    - 67 signal sub-channels (varies with m_H)
    - nuisance parameters: 268 ($m_H \leq 135$) or 191 ($m_H \geq 250$)



SM Higgs exclusion ranges:
95% CL upper limits below $r = 1$:

- expected: $124 - 520\,\mathrm{GeV}/c^2$
- observed: $141 - 476\,\mathrm{GeV}/c^2$

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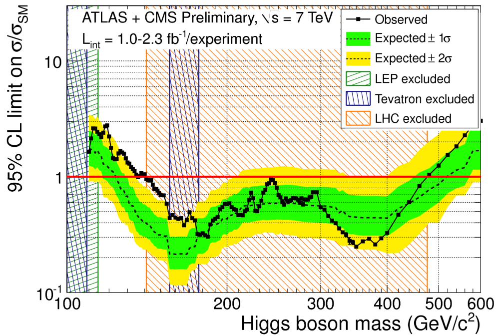
- ATLAS: ATL-CONF-2011-135 + update of $H \to ZZ \to 2l2\nu$ analysis
  - 67 signal sub-channels (varies with m_H)
  - nuisance parameters: 268 ($m_H \leq 135$) or 191 ($m_H \geq 250$)



SM Higgs exclusion ranges:

95% CL upper limits below $r = 1$:

- expected: $124 - 520\,\mathrm{GeV}/c^2$
- observed: $141 - 476\,\mathrm{GeV}/c^2$

Theory uncertainties (1/3)

Theory-related uncertainties:

- for Higgs: provided by LHC Higgs Cross Section and PDF4LHC groups
- for SM backgrounds: calculated separately by ATLAS and CMS (taking into account analysis-specific acceptances)

- associated with partonic luminosities, or PDFs, and α_S
- associated with missing higher-order theory corrections
  - assessed by varying QCD renormalisation and hadronisation scales
  - assumed uncorrelated among processes; except for those with W/Z (eg. $pp \rightarrow WH$ and $pp \rightarrow ZH$)
- on branching ratios: assumed mostly negligible

Theory uncertainties (2/3)

- on acceptance of analysis cuts (QCD scales and PDFs) assumed negligible (in comparision to σ_{total})
  - except for exclusive production modes with 0, 1 and 2 jets
  - $H \rightarrow WW$ acceptance uncertainty small but included
- further possible WW modeling uncertainties (Drell-Yan, $W\gamma$ with asymmetric γ conversion, etc.): not considered at present
- jets-splitting in $H \rightarrow WW$ analysis makes it sensitive to underlying event and parton showering modelling
  - signal simulated with POWHEG/PYTHIA in both experiments $\rightarrow$correlated
- probability of a loosely defined lepton faking a lepton passing the final high quality selection assessed with same methods
  - difference between W-associated jets and generic di-jet and γ-jet $\rightarrow$correlated

Theory uncertainties (3/3)

Source	Affected Processes	Typical uncertainty
PDFs+α_s (cross sections)	$gg \to H$, $t\bar{t}H$, $gg \to VV$	$\pm 8\,\%$
	VBF H, VH, VV@NLO	$\pm 4\,\%$
Higher-order uncertainties on cross sections	total inclusive $gg \to H$	$^{+12\,\%}_{-7\,\%}$
	inclusive "gg" $\to H + \geq 1$ jets	$\pm 20\,\%$
	inclusive "gg" $\to H + \geq 2$ jets	$\pm 20\%$ (NLO), $\pm 70\%$ (LO)
	VBF H	$\pm 1\,\%$
	associated VH	$\pm 1\,\%$
	$t\bar{t}H$	$^{+4\,\%}_{-10\,\%}$
	uncertainties specific to high mass Higgs boson, see Section 2.1	$\pm 30\%$
	V	$\pm 1\,\%$
	VV up to NLO	$\pm 5\,\%$
	$gg \to VV$	$\pm 30\,\%$
	$t\bar{t}$, incl. single top productions for simplicity	$\pm 6\,\%$
acceptance	acceptance for $H \to WW \to \ell\nu\ell\nu$ events	$\pm 2\%$
phenomenology	modelling of underlying event and parton showering	$\pm 10\,\%$
	fake lepton probability (W + jets $\to \ell\ell^{fake}$)	$\pm 40\%$
luminosities	ATLAS and CMS uncertainties on their luminosity measurements	$\pm 3.7\,\%$, $\pm 4.5\,\%$

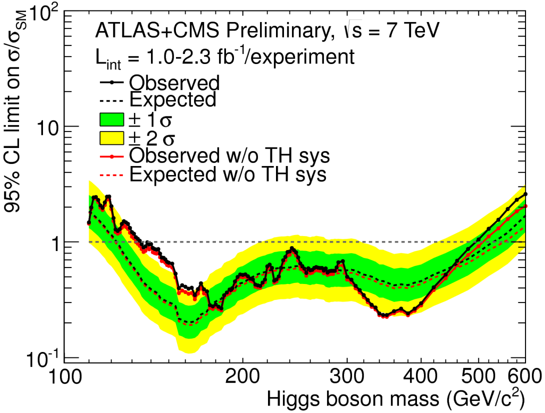
Each uncertainty source is usually correlated among affected channels:

- but the size of an uncertainty may still vary from one channel to another
- some effects, even if mostly uncorrelated, are assumed 100% correlated (simplification) $\to$ limits are then slightly more conservative

Impact of theory uncertainties

Combined limits with and without theoretical systematic uncertainties:

- at this stage: differences of $3 - 6\%$ except for the very high mass range: $\sim 20\%$ at $600\,\mathrm{GeV}/c^2$ (from σ_H and m_H shape)



Choice of data-driven methods to constrain uncertainties: how much "data-driven" are they?

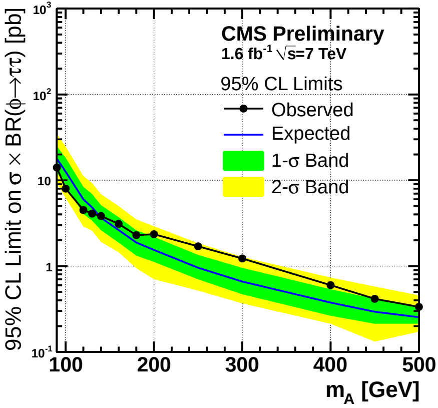
Theory uncertainties will relatively play a bigger role as statistics will increase!

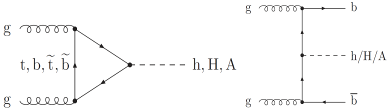
Outline

1. Standard Model Higgs searches at CMS
   - Low mass: $H \to \gamma\gamma$, $H \to \tau\tau$, $(H \to b\bar{b})$
   - Intermediate and high mass: $H \to WW \to 2l2\nu$, $H \to ZZ \to 4l$, $(H \to ZZ \to 2l2\tau$, $H \to ZZ \to 2l2q$, $H \to ZZ \to 2l2\mu)$
2. Combination of Higgs searches (CMS and ATLAS+CMS)
   - Statistical combination procedure
   - Combination with ATLAS
   - Overview of theory uncertainties
3. Non Standard Model Higgses
   - MSSM $A, h \to \tau\tau$
   - Charged Higgses

5 Higgs bosons expected in MSSM:

- 3 neutral (h, H: CP-even; A: CP-odd) and 2 charged (H^+, H^-)

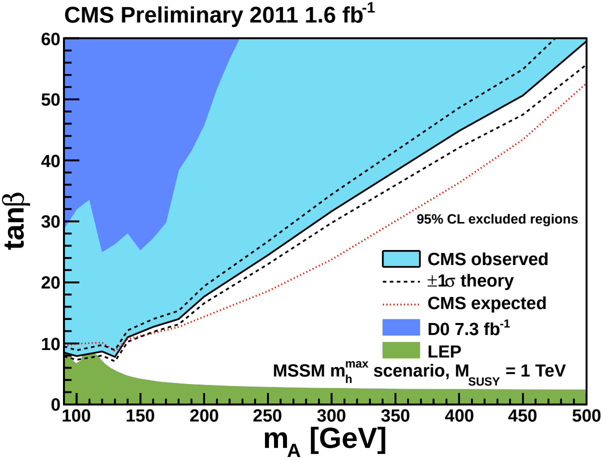




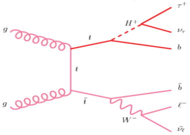
- *B* category: ≥ 1 b-jet with $p_T > 20\,\mathrm{GeV}/c$; < 2 jets with $p_T > 30\,\mathrm{GeV}/c$
- non-*B* category: 0 b-jet with $p_T > 20\,\mathrm{GeV}/c$; < 2 jets with $p_T > 30\,\mathrm{GeV}/c$

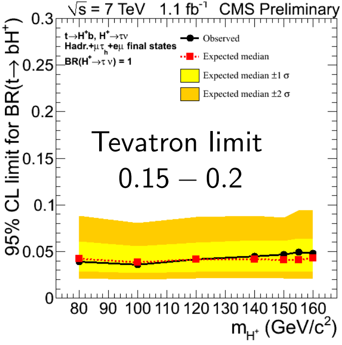
Cross-section limits translated into ($\tan\beta - m_A$) constraints

- Production cross section increases with $\tan\beta^2$
- Stringent new bounds in the MSSM parameter space

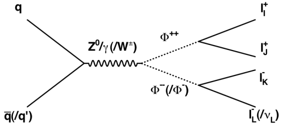


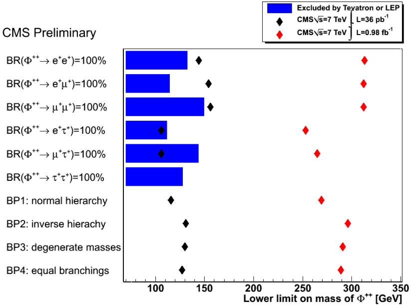
Search for $H^+ \to \tau^+\nu$ in:
$t\bar{t} \to H^+W^-b\bar{b} \to \tau\nu_\tau l\nu_l b\bar{b}$





Also search for an exotic doubly-charged Higgs (related to m_ν in type II see-saw models)





Conclusion

With the first inverse femtobarns a very rich program opened up:

- CMS physics results available at: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Detailled selection of early CMS SM Higgs results:

- wide 95% exclusion range(s) disfavouring a high-mass Higgs
- excess at low mass requires further studies and increased statistics
- recent combination of ATLAS-CMS analyses
  $\rightarrow$ hardest region to reach at low mass; every channel counts

Also searched for the Higgs beyond Standard Model:

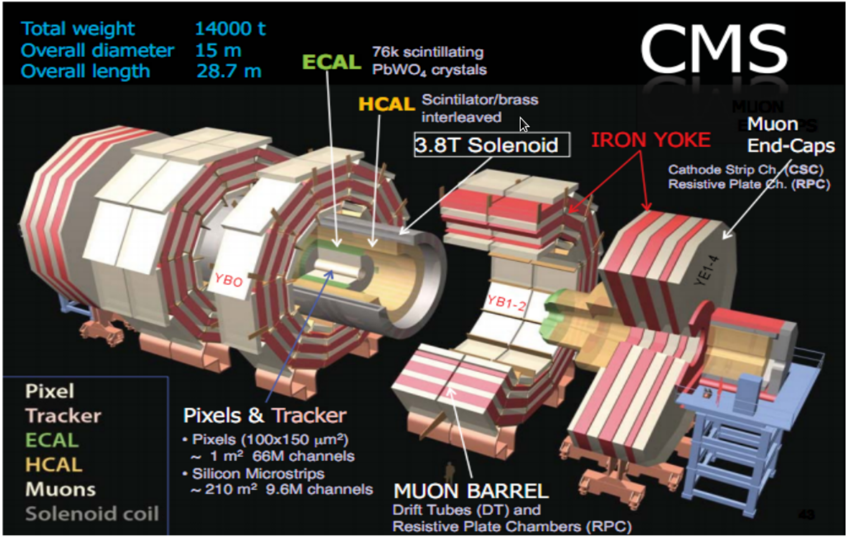
- constraints on MSSM Higgs, fermiophobic Higgs and 4^{th} generation

Larger dataset already available:

- their analysis is on-going; will allow to improve our Higgs constraints

BACKUP SLIDES

The CMS detector



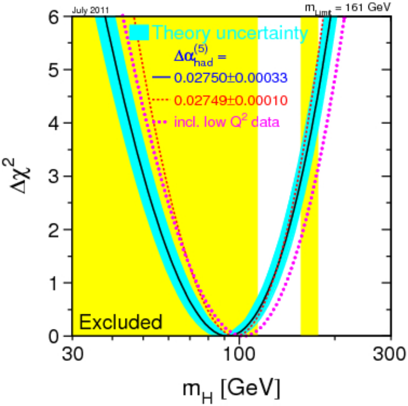
Experimental constraints on the Higgs boson

One free parameter in the SM Higgs sector: can choose it as m_H

Indirect constraints: Higgs present in virtual loops (of W/Z propagators, ...): $m_H < 161\,\mathrm{GeV}/c^2$ at 95% CL
http://lepewwg.web.cern.ch/LEPEWWG/

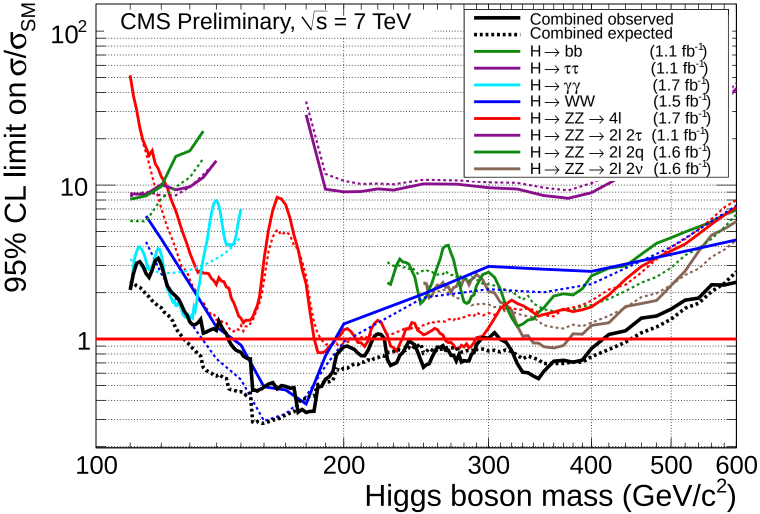
Direct searches (yellow regions on plot):

- at LEP-2: [PLB 565,61 (2003)]: $m_H > 114.4\,\mathrm{GeV}/c^2$ at 95% CL
- at Tevatron [arXiv:1107.5518]: 95% CL exclusions in range $156 - 177\,\mathrm{GeV}/c^2$



Report here on first analysis results at CMS/LHC (Summer 2011)

CMS Statistical combination: results *(PAS-HIG-11-022)*



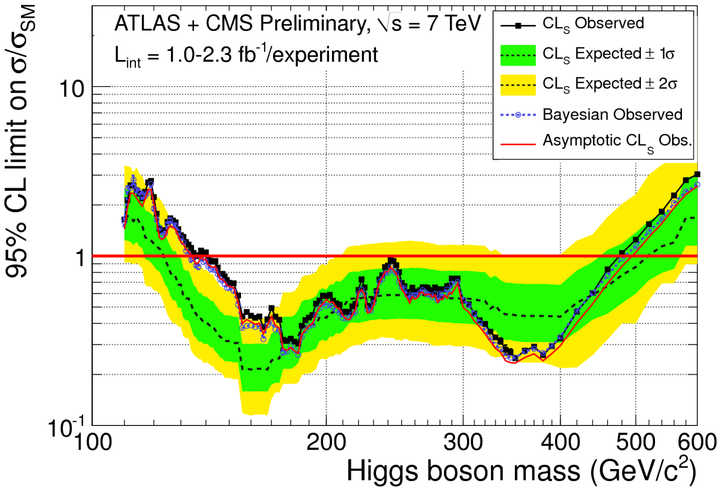
Analyses included in the combination

Channel	Experiment	m_H range (GeV/c^2)	Lumi (fb^{-1})	Number of sub-channels	Type of analysis	Reference
$H \to \gamma\gamma$	ATLAS	110–150	1.1	5	mass shape (unbinned)	[82]
	CMS	110–150	1.7	8	mass shape (unbinned)	[91]
$H \to \tau\tau$	ATLAS	110–150	1.1	5	mass shape (binned)	[83, 84]
	CMS	110–140	1.6	6	mass shape (binned)	[14]
$H \to bb$	ATLAS	110–130	1.0	2	mass shape (binned)	[85]
	CMS	110–135	1.1	5	cutting and counting	[92]
$H \to WW \to \ell\nu\ell\nu$	ATLAS	110–300	1.7	6	cutting and counting	[86]
	CMS	110–600	1.5	4	cutting and counting	[93]
$H \to ZZ \to \ell\ell\ell\ell$	ATLAS	110–600	2.0-2.3	3	mass shape (binned)	[88]
	CMS	110–600	1.7	3	mass shape (unbinned)	[94]
$H \to ZZ \to 2\ell 2\tau$						
	CMS	180–600	1.1	8	mass shape (unbinned)	[95]
$H \to ZZ \to 2\ell 2\nu$	ATLAS	200–600	2.0	2	m_T shape (binned)	[15, 89]
	CMS	250–600	1.6	2	cut&count	[96]
$H \to ZZ \to 2\ell 2q$	ATLAS	200-600	1.0	2	mass shape (binned)	[90]
	CMS	225–600	1.6	6	mass shape (unbinned)	[97]

ATLAS instrumental systematic uncertainties on signal

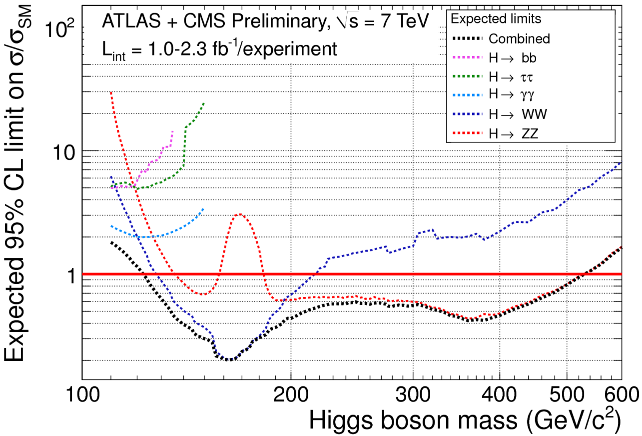
Systematic uncertainties		Higgs boson decay channels (mass in GeV/c^2)						
					WW	ZZ		
source	type	$\gamma\gamma$ (120)	bb (120)	$\tau\tau$ (120)	$\ell\nu\ell\nu$ (150)	$\ell\ell\ell\ell$ (200)	$\ell\ell\nu\nu$ (400)	$\ell\ell qq$ (400)
luminosity	lumi	3.7%						
reconstruction efficiencies	μ		1%	1.1%	0.6%	1.2%	0.7%	0.5%
	e		1%	3.4%	2%	1.9%	1.2%	1.1%
	γ	11%						
	τ_{had}			8.3%				
	b-tag		16%				0.7%	4.9%
p_T scale (event yield)	jets/E_T^{miss}		2-8%	16%	6%		1.4%	1.3 %
	e		1%	$^{+1.2}_{-0.1}$%	0.2%	0.1%	0.2%	0.3%
p_T resolution	μ		2%		1.5%	0.1%	1%	1.2%
	e		1%		0.1%	0.1%	0.2%	0.2%
	γ							
	jets		1%	0.2%	2%		0.2%	2.2%
	E_T^{miss}		2%	0.4%	0.6%			

CLs versus Bayesian and PL limits



- checked self-consistency of Bayesian and CL_s limits at the 10-20% level

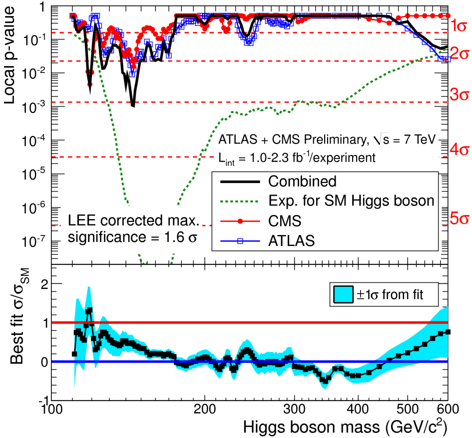
Impact of the Higgs channels individually:



Significance

To quantify an excess use the test statistic: $q_0 = -2\ln\frac{\mathcal{L}(\text{data}|0,\hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}$ if $\hat{\mu} \geq 0$

and $q_0 = 0$ otherwise. $Z = \sqrt{q_0^{\text{obs}}}$



- largest excess has a local significance of 3.1 (limit less restrictive than in the B-only hypothesis)
- after estimation of LEE correction $Z \sim 1.6\sigma$