Searches for the SM Scalar Boson at CMS

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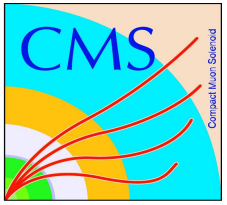
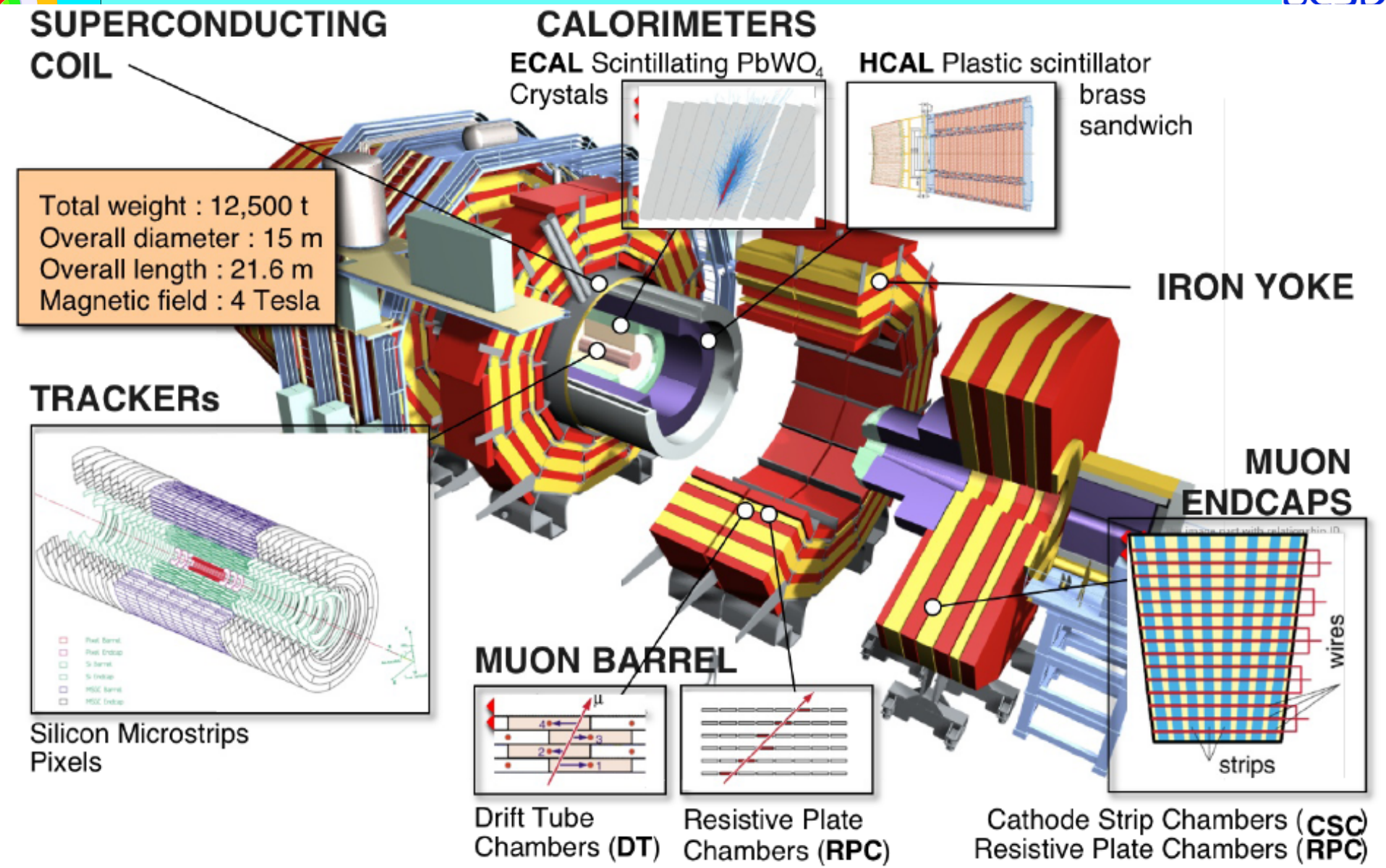
On behalf of the CMS Collaboration



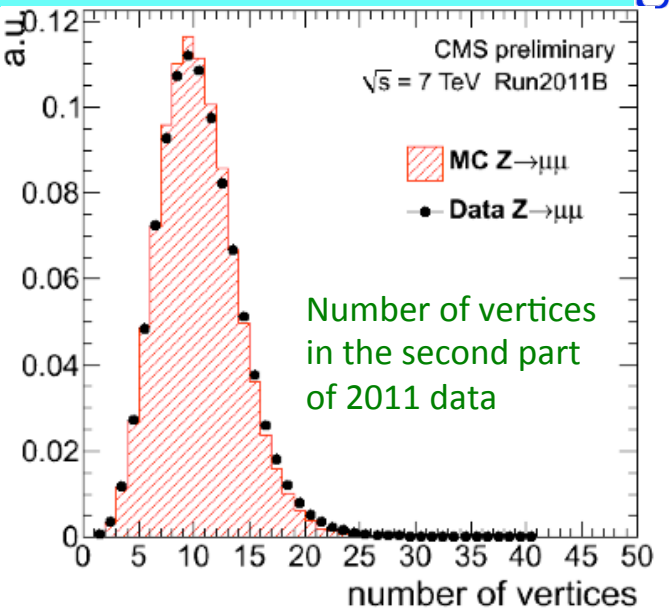
Moriond EW, La Thuile, 3-10 March 2012

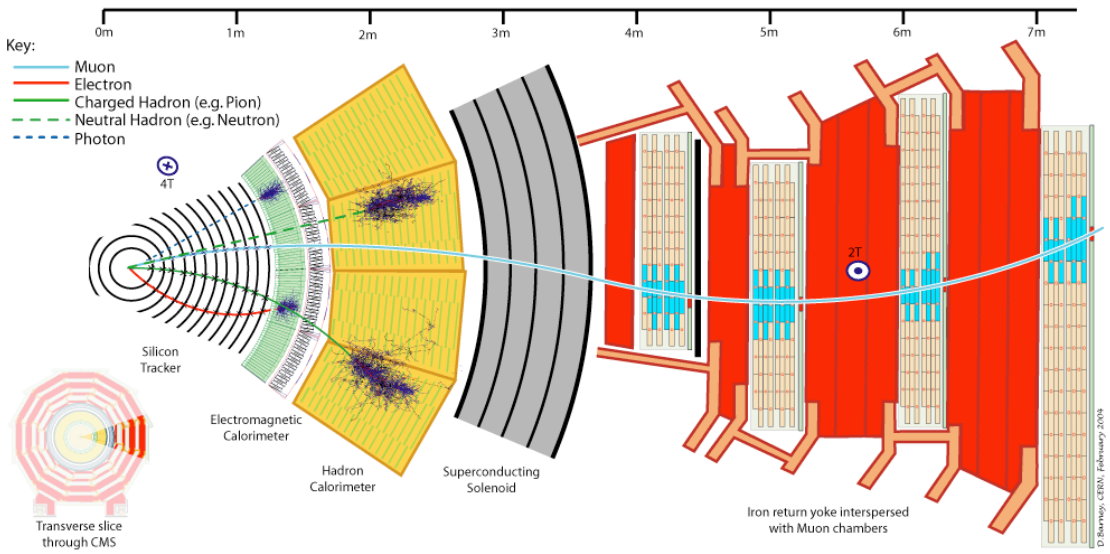
CMS detector



Dataset and reconstruction

- Excellent performance of LHC and CMS in 2011
  - More than 5 fb^{-1} of pp collisions collected at 7 TeV CM energy
  - Peak luminosity 3.5 x 10^{33} $cm^{-2}s^{-1}$
  - Data taking efficiency 90%
  - 90% of collected data good for all analyses
  - Mean pileup 10 events





A Particle Flow algorithm (PF) has been developed

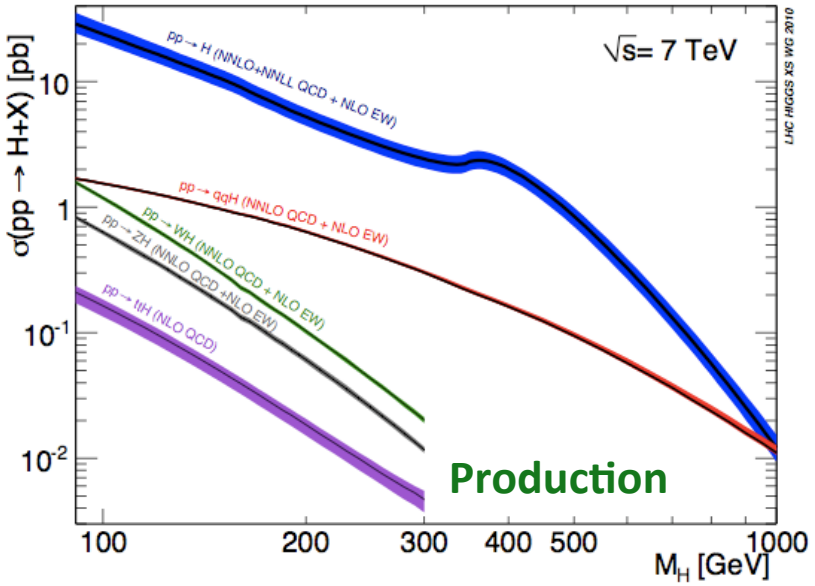
- Provides a global event description in form of a list of particles and avoids double-counting

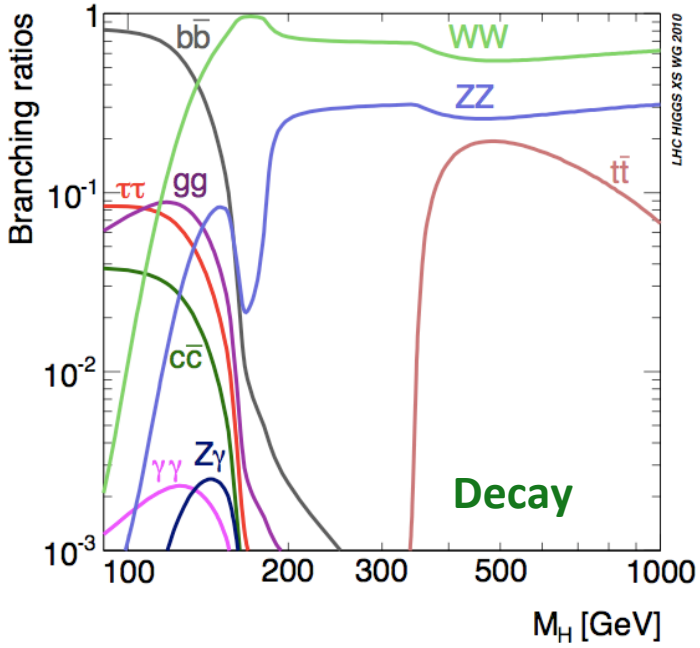
Large improvements in τ, jet and missing transverse energy (MET) measurement

The SM Scalar boson at LHC

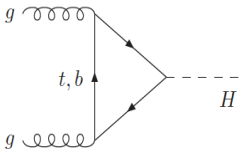
- Indirect constraints from precision EW measurements
  - $M_H < 169$ GeV at 95% CL (standard fit)
  - $M_H < 143$ GeV at 95% CL (including direct searches, before LHC)
- Direct searches
  - LEP: $M_H < 114.4$ GeV excluded at 95% CL
  - Tevatron: latest results in previous talks
- SM scalar boson favored at low mass, above the LEP limit

Gfitter group
M. Baak et al.
arXiv:1107.0975

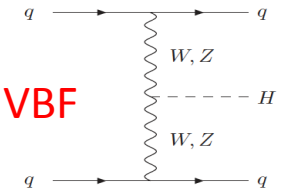




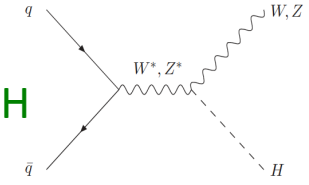
ggH



VBF



VH



Cross sections and BR
from the LHC cross section working group:

SM scalar boson channels at CMS

Low mass

High mass

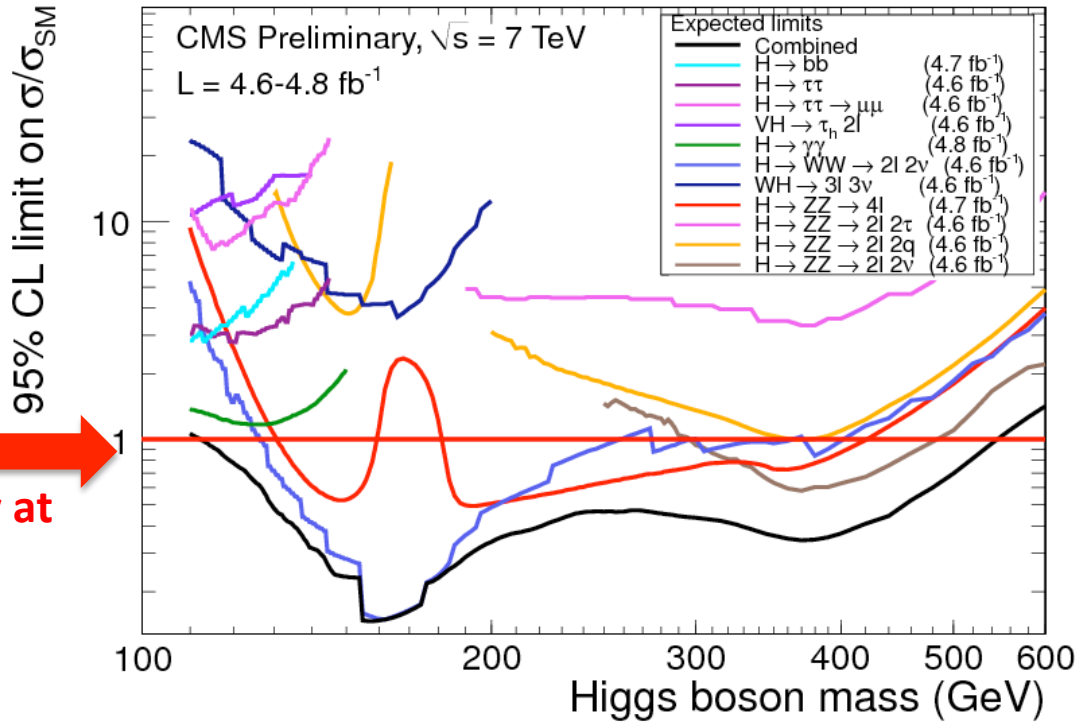
	Channel	m_H range (GeV)	Luminosity (fb^{-1})	Sub-channels	m_H resolution
new	$H \to \gamma\gamma$	110–150	4.8	2	1–2%
	$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	110–145	4.6	9	20%
new	$H \to \tau\tau \to \mu\mu + X$	110–140	4.5	3	20%
new	$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu$'s	100–140	4.7	2	20%
	$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu)(bb)$	110–135	4.7	5	10%
	$H \to WW^* \to 2\ell 2\nu$	110–600	4.6	5	20%
new	$WH \to W(WW^*) \to 3\ell 3\nu$	110–200	4.6	1	20%
	$H \to ZZ^{(*)} \to 4\ell$	110–600	4.7	3	1–2%
	$H \to ZZ^{(*)} \to 2\ell 2q$	130–164 200–600	4.6	6	3% 3%
	$H \to ZZ \to 2\ell 2\tau$	190–600	4.7	8	10–15%
	$H \to ZZ \to 2\ell 2\nu$	250–600	4.6	2	7%

11 independent channels

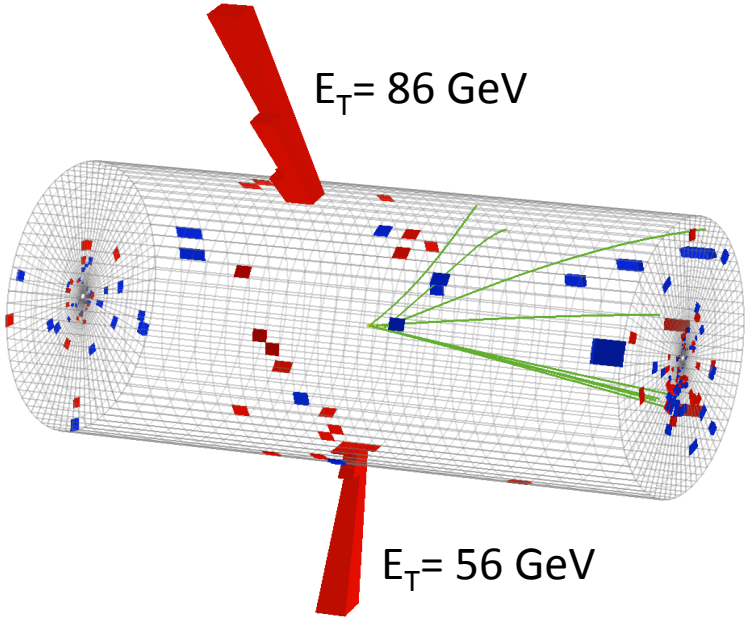
Search mass range 110-600 GeV

Expected combined 95% exclusion 114.5-543 GeV

Exclusion sensitivity at LEP lower limit



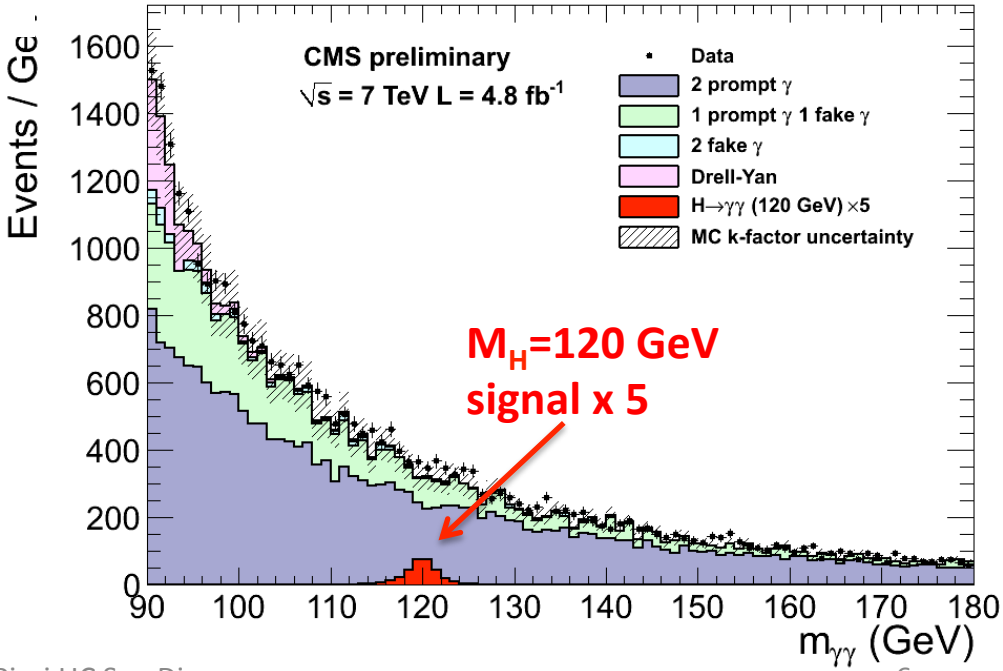
Low mass: H→γγ



- Small BR: ~2×10^{-3}
- Two isolated high E_t photons
- VBF channel has two additional jets from outgoing quarks
- **Narrow mass peak**
  - very good mass resolution 1-2%

- Signature: small mass peak over large smoothly decreasing background
  - Irreducible: 2γ QCD production
  - Reducible: γ+jet with 1 additional fake photon, DY with electrons faking photons
- Studied mass range: 110-150 GeV

BG MC only used for optimization



H→γγ analysis strategy

- Cut based analysis in categories
  - VBF channel
  - 4 event classes based on photons pseudorapidity/shower shape for the remaining events

arXiv:1202.1487
Accepted by PLB

- Multivariate (MVA) analysis (shown here)
  - Event-by event mass resolution, photon id discriminant, di-photon kinematic variables and vertex probability combined using with boosted decision tree (BDT)
  - Sensitivity improvement corresponds to about 50% increase in integrated luminosity

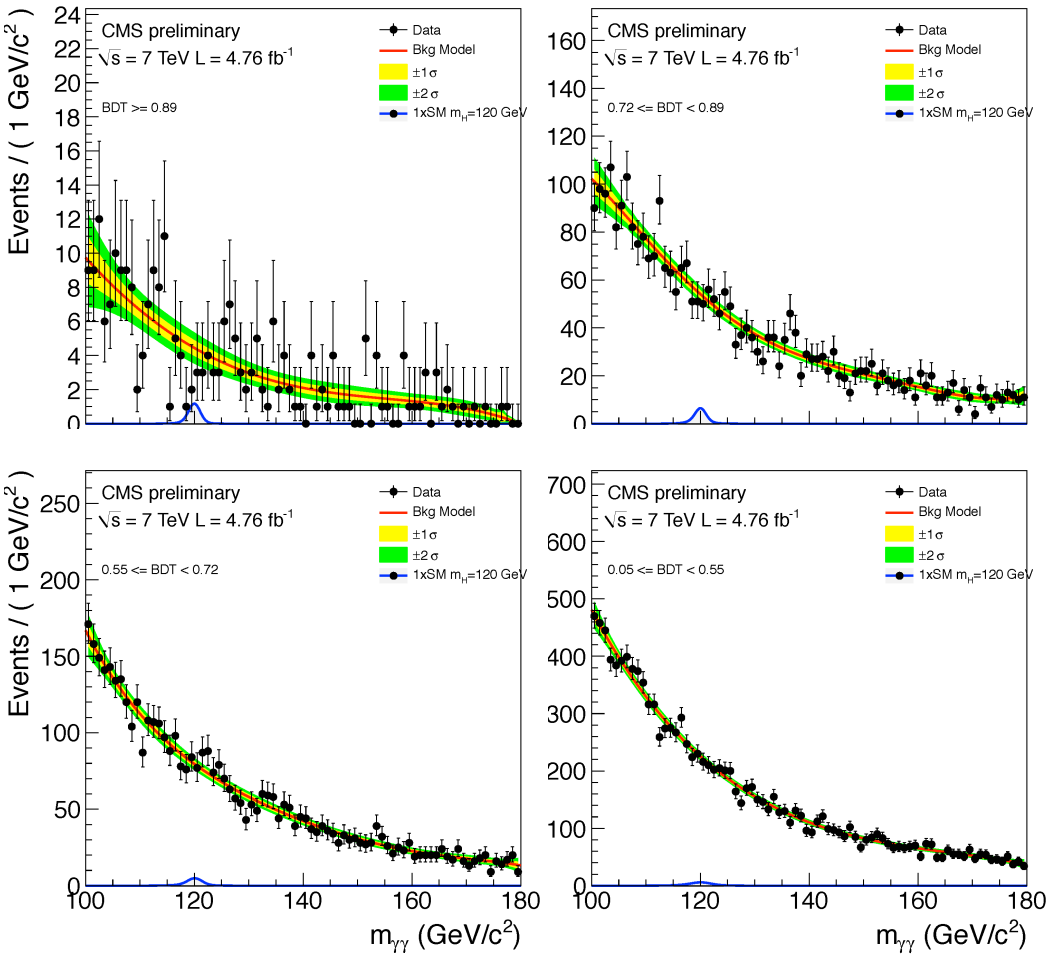
NEW

CMS document
HIG-12-001

H→γγ non-VBF MVA analysis

- 4 non-VBF event classes split based on the diphoton BDT classifier output
- BG is estimated by fitting to a polynomial in the full mass range (3rd to 5th order)
  - Possible BG bias is always less than 20% of the statistical error
  - Different BG estimation in cross check analysis gives consistent results

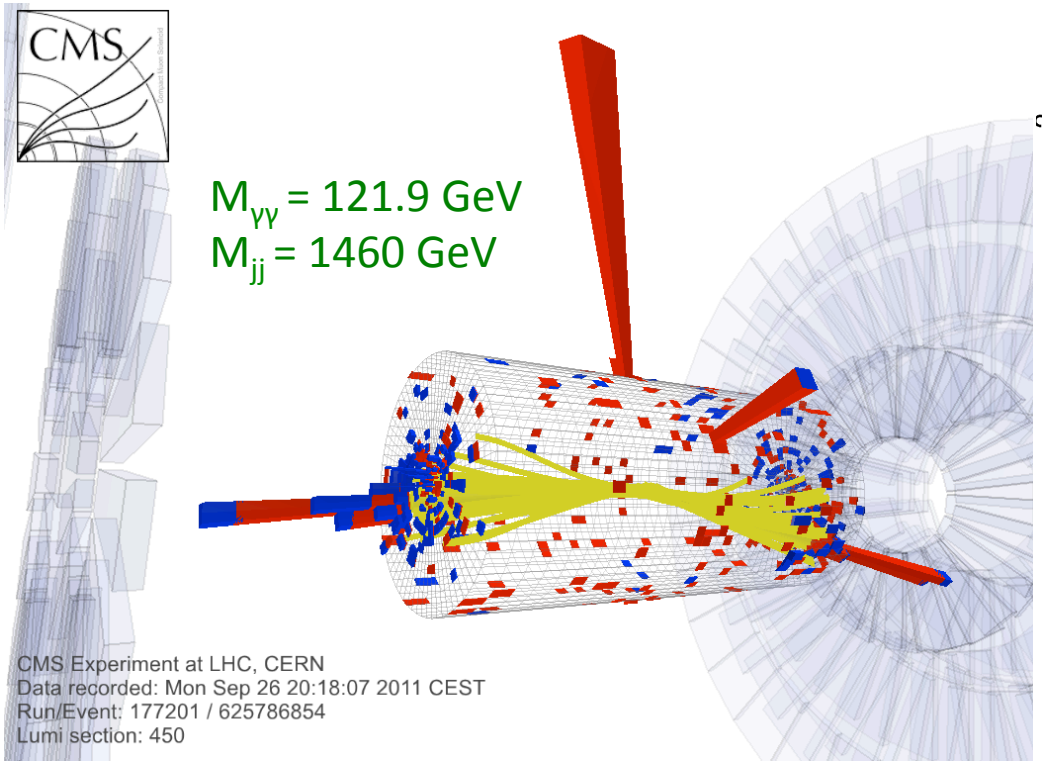
Events passing VBF selection removed



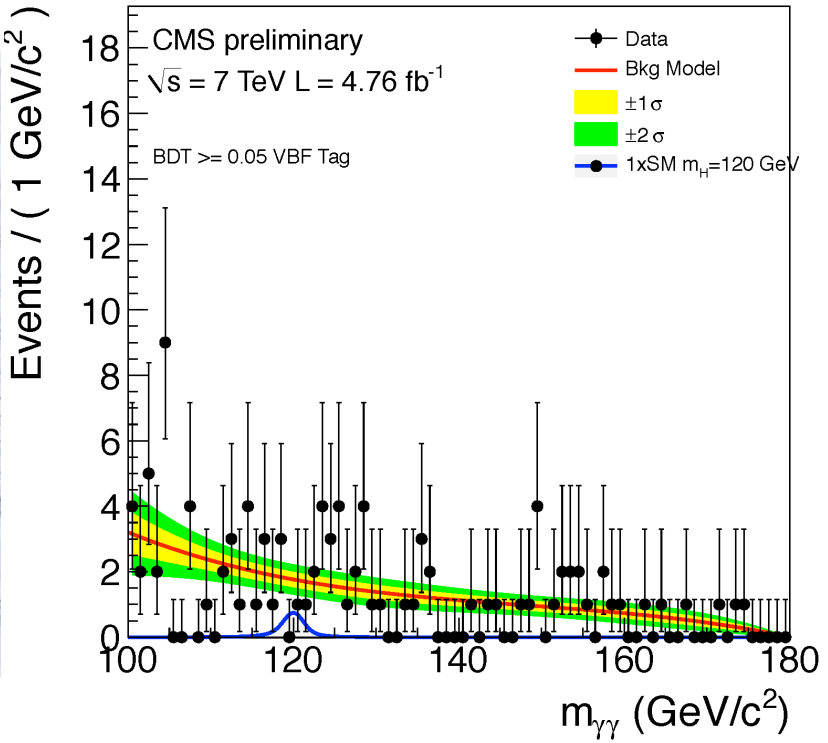
m_H=120 GeV	class 0	class 1	class 2	class 3	Dijet class
Total signal expected events	3.4	19.3	18.7	33.0	2.8
Data (events/GeV)	4.5	55.1	81.3	229.1	2.1
resolution FWHM/2.35 (%)	0.9	0.9	1.2	1.7	1.1

H→γγ VBF analysis

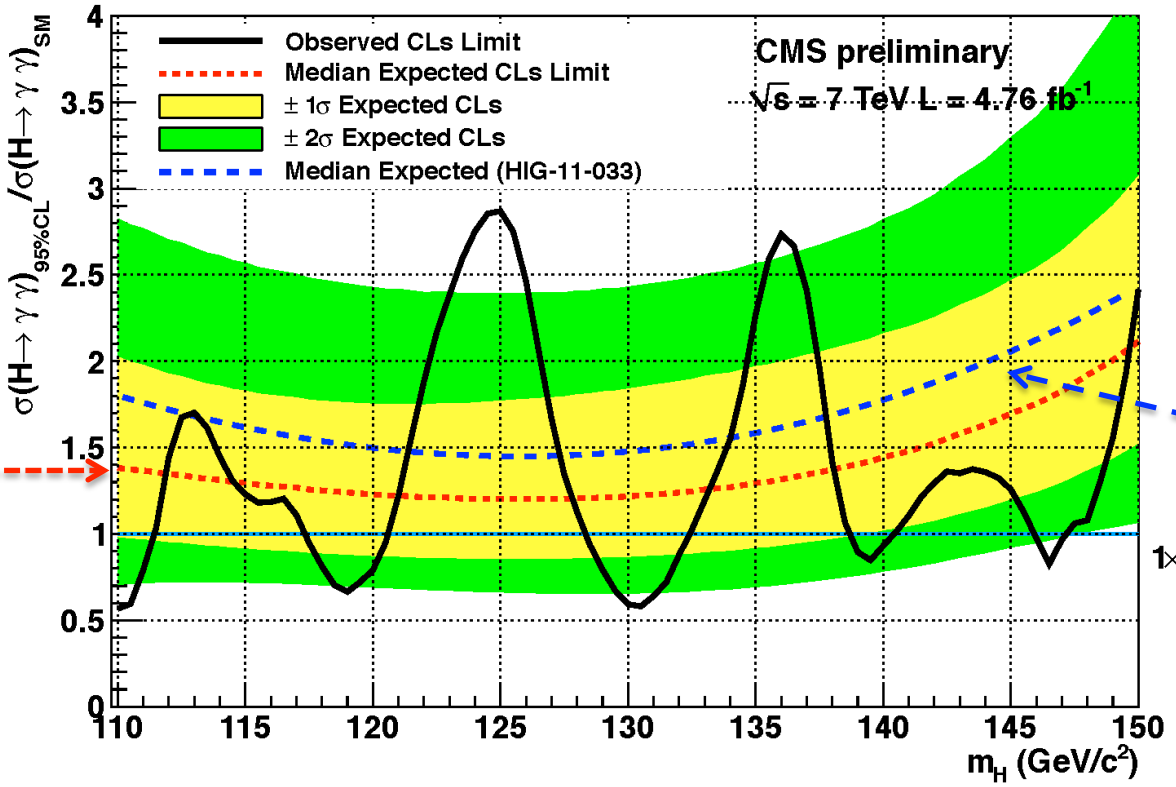
- Exclusive dijet tag improves sensitivity by ~10%
- Photon identification is the same
  - tighter lead photon E_t cut (E_t lead/$M_{\gamma\gamma}$ > 55/120)
- Dijet tag selection on dijet variables
  - exploits two additional VBF high p_T jets at large rapidity



Dijet tag selection has high s/b, ~1/3



H→γγ results: exclusion



CMS document HIG-12-001

NEW

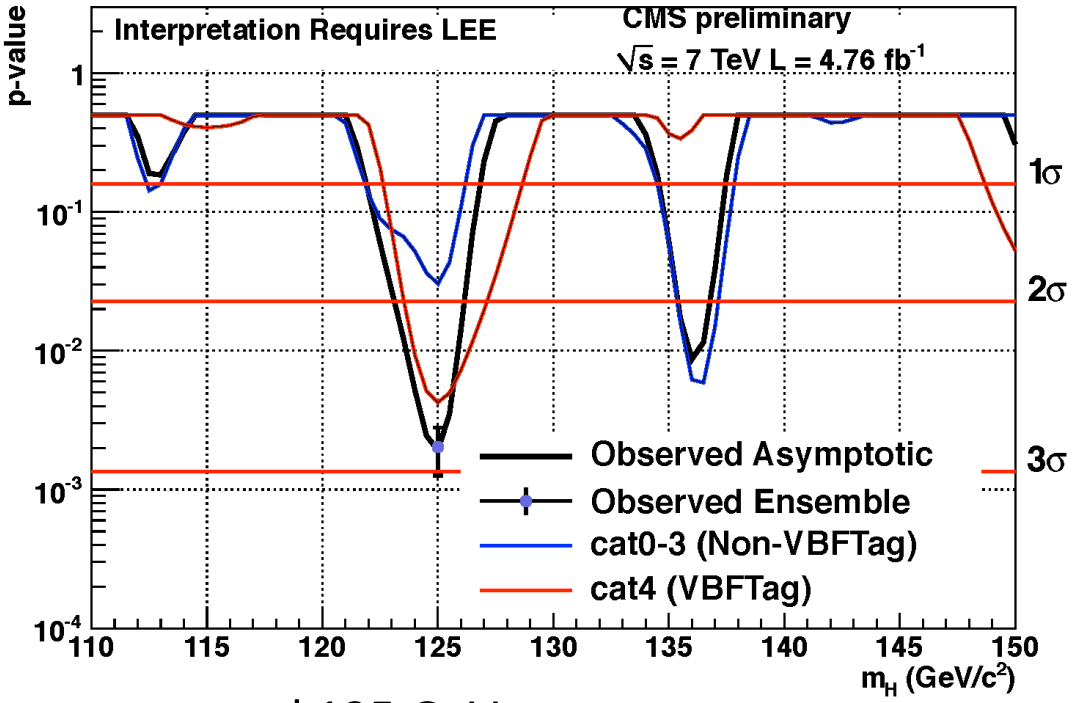
Expected from MVA analysis Improvement ~20%

Expected from cut based analysis

- Expected 95% CL exclusion: 1.2-2 x SM
- Excluded at 95% CL: 110.0-111.0, 117.5-120.5, 128.5-132.0, 139.0-140.0, 146.0-147.0 GeV
- Cut based analysis gives consistent results
  - arXiv:1202.1487
- Cross check MVA analysis also gives consistent results

H→γγ results: p-values

- P-value: probability that a BG only fluctuation is more signal-like than observation



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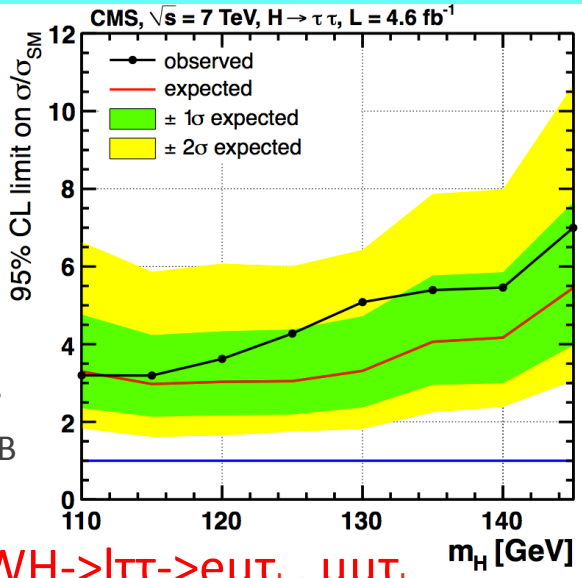
Similar results as cut based

- Largest excess around 125 GeV
  - Local significance 2.9 σ
  - Global significance 1.6 σ
- Look elsewhere effect (LEE) estimated in the mass range 110-150 GeV with toy experiments

Low mass: H→ττ

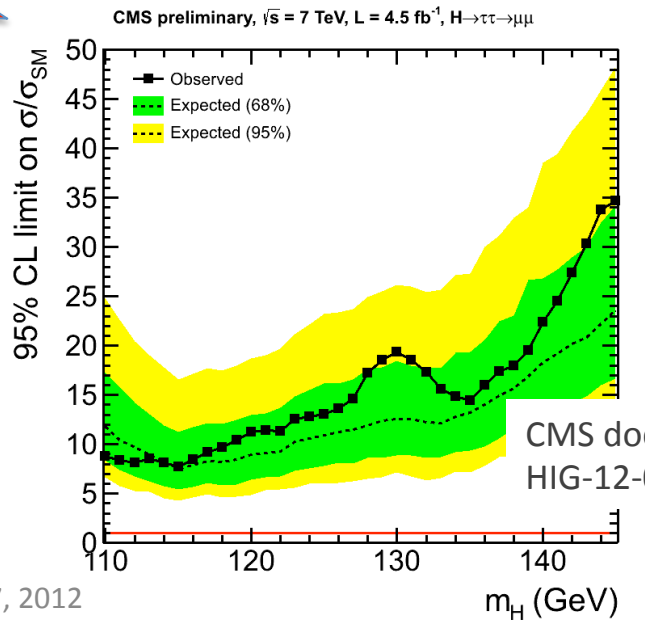
- **No narrow mass peak** (σ_M ~20%)
- Also important for MSSM
- Three different sub-channels for SM:
  - VBF production, two additional forward jets
  - Boosted: one jet with P_t>150 GeV
  - gg-fusion 0 or 1 additional jets
- Two new channels added



arXiv:1202.3697
Submitted to PLB

- H->ττ->μμ
  - Large BG from Z->μμ

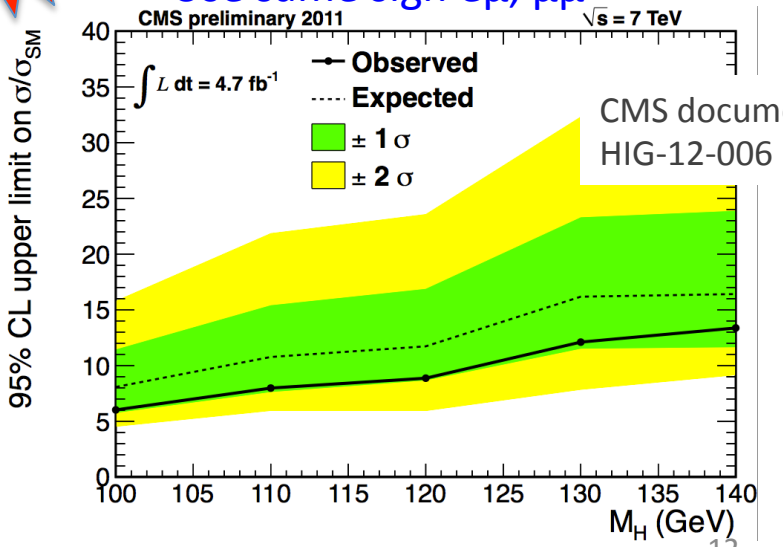
NEW



CMS document
HIG-12-007

- WH->lττ->eμτ_h, μμτ_h
  - Also sensitive to WH->WWW
  - Use same sign eμ, μμ

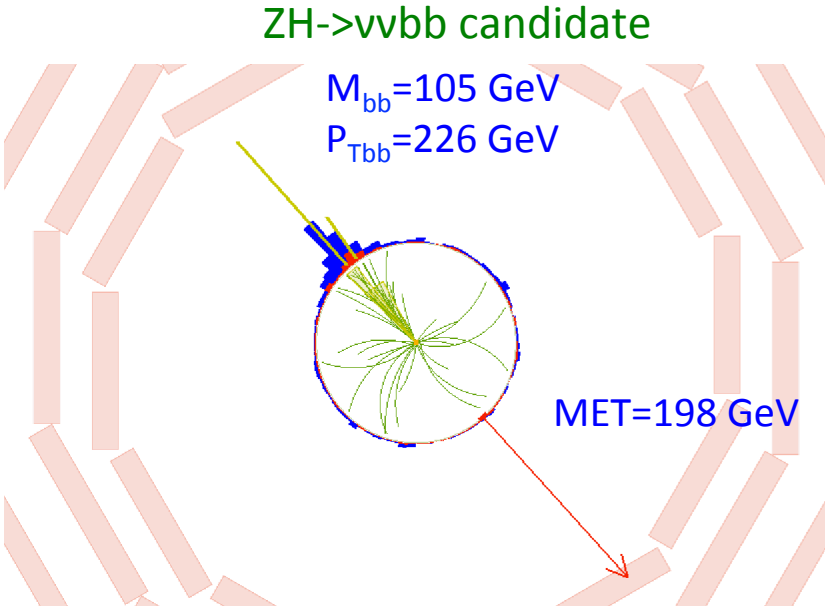
NEW

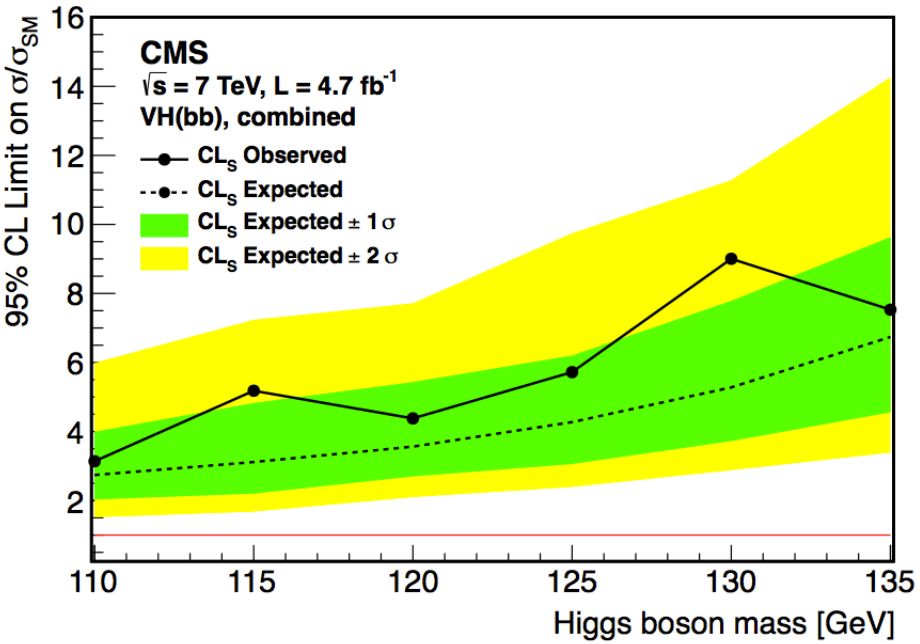


CMS document
HIG-12-006

Low mass: H→bb channel

- BG too large, needs additional tag
- Exploit VH associated production with W and Z decaying leptonically
  - W->e,μ
  - Z->ee,μμ, νν
- Require boosted bb system
- Mass resolution ~10%





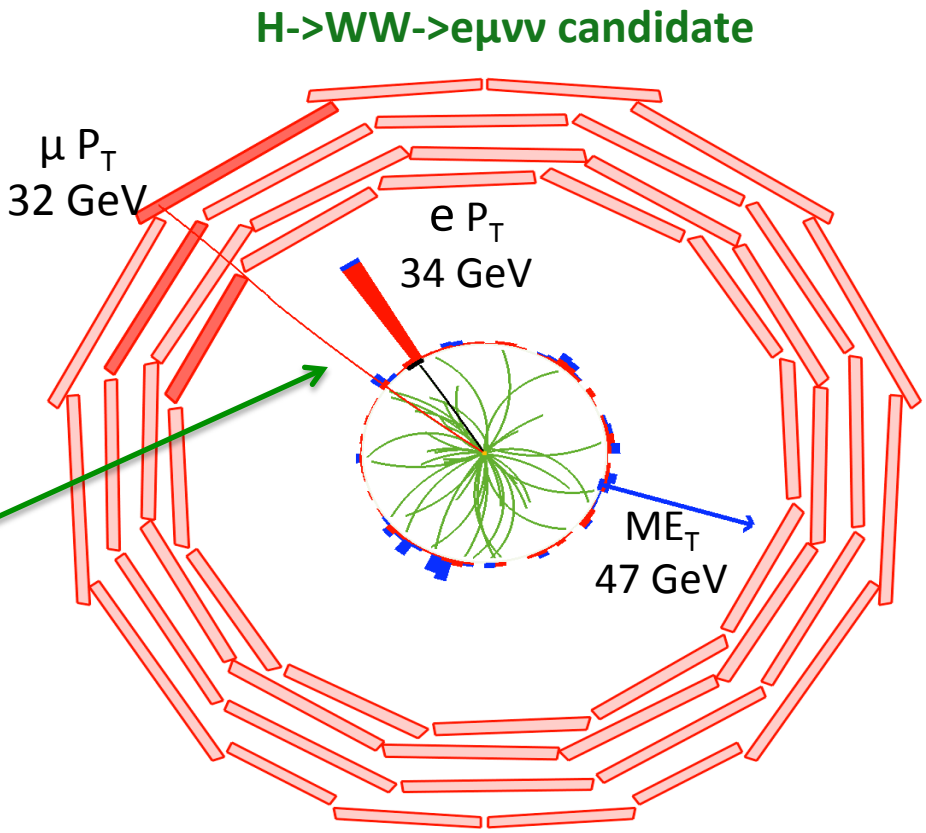
Excluded at 95% CL
3-9xSM

arXiv:1202.4083
Submitted to JHEP

Full mass range: H→WW→lνlν

- Most sensitive channel around $2xM_W$
  (125 <~ M_H <~ 200 GeV)
- **No narrow mass peak (mass resolution ~20%)**
- Two high p_T isolated leptons + MET
- Main backgrounds
  - WW (irreducible)
  - Z+jets, WZ, ZZ, tt, W + jets
- BG estimation crucial
  - Main BG estimated from data

Scalar BEH boson +
V-A structure of W decay
favors small opening angle
between the 2 charged
leptons
(tend to have small Δϕ)



Analysis strategy for H→WW→lvlv

- Analysis is performed in exclusive jet multiplicities (0, 1, 2-jet bins) and flavour (ee, μμ, eμ)
  - WW BG contributes more to the 0-jet bin
  - tt BG contributes more to the 1 and 2-jet bins
  - Z+jet and ZZ contribute more to same flavour (ee and μμ)
  - 2 jet bin corresponds to VBF dijet tag

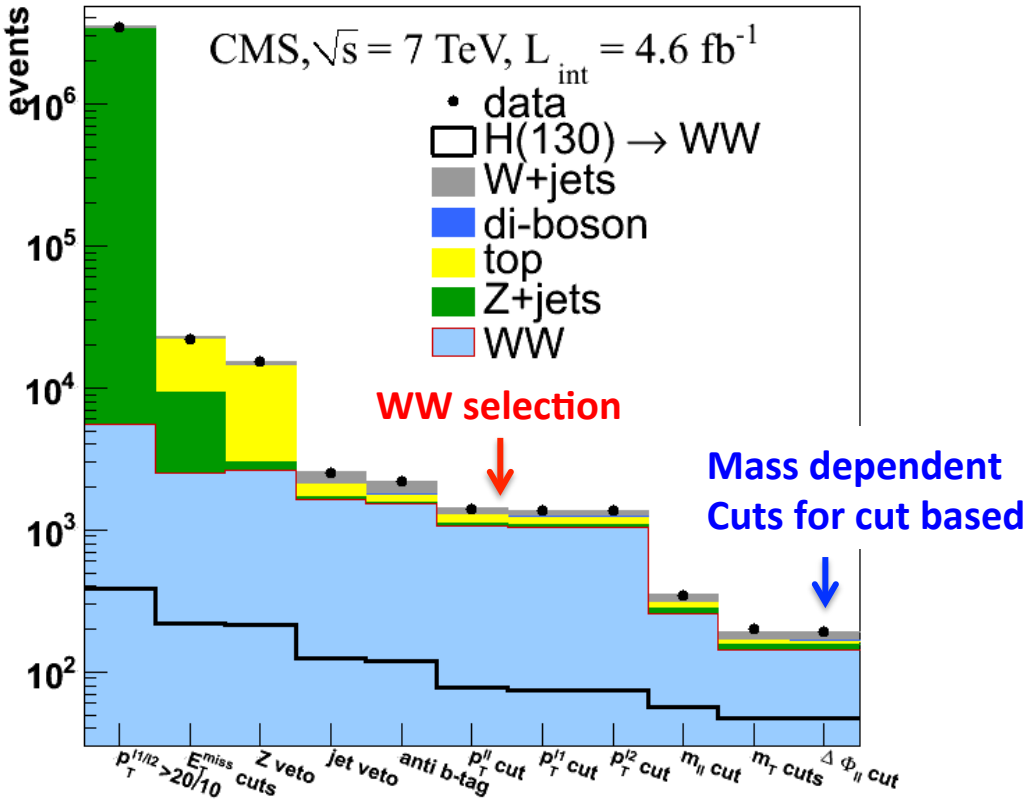
- Two different analyses carried out:
  - Cut and count in 0, 1 and 2-jet bins
  - Multivariate in 0 and 1-jet bin

H→WW→lvlv selection

- **MET affected by pileup, special treatment**
  - Use projected MET: transverse to nearest lepton if angle <90°, full MET otherwise
  - Use minimum between MET with all particles and charged MET only from charged particles identified primary vertex to reduce effect of pileup
- Tighter cuts + Z mass veto for ee and μμ due to Z background

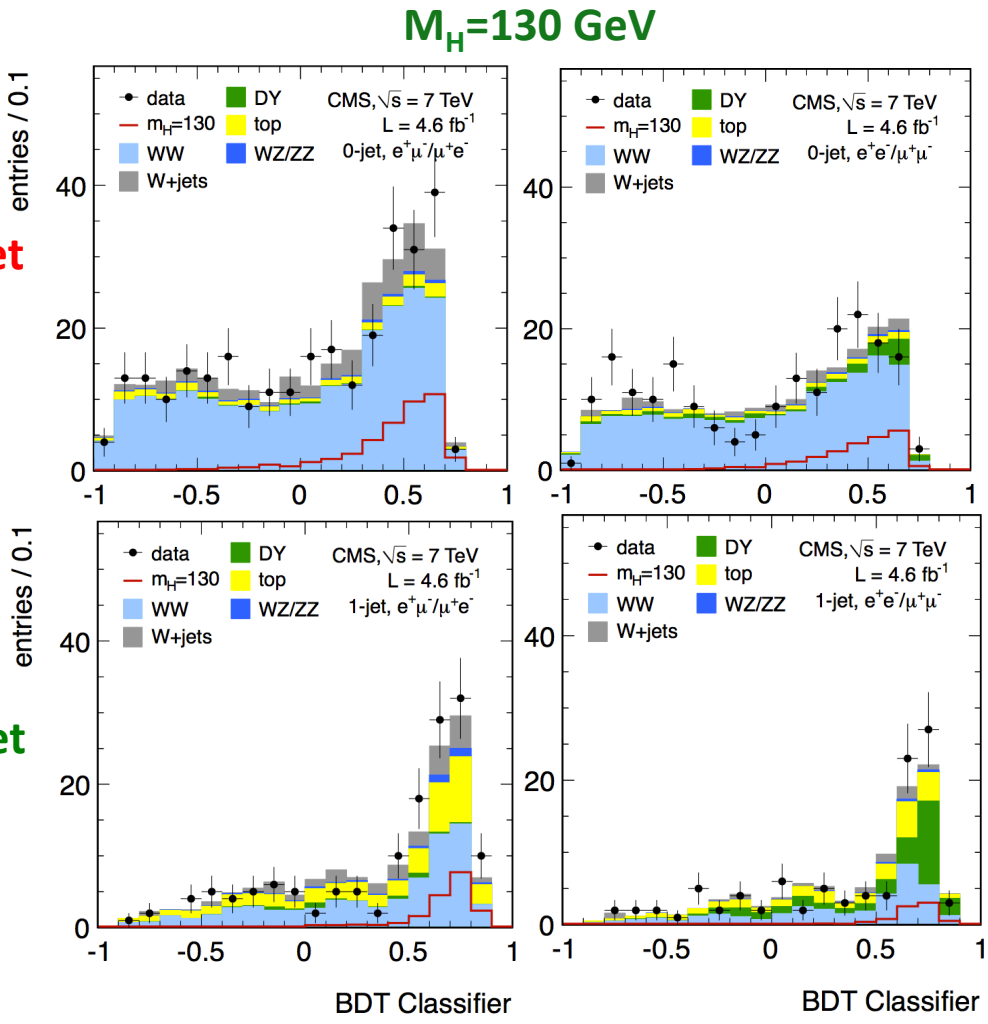
0-jet bin
M_H=130 GeV

Data-BG comparison after sequential cuts



MVA analysis: 0 and 1-jet bins

- BDT trained at different masses, input variables:
  - $P_{tleptons}$, M_{ll}, $\Delta\phi_{ll}$, ΔR_{ll}, M_t (for dilepton system and each lepton)
- Overall uncertainties:
  - signal efficiency ~20%
  - background ~15%
- Use BDT output classifier distribution for CL estimation
- Many cross checks made, using Matrix Element method, using shape method with only M_{ll} variable



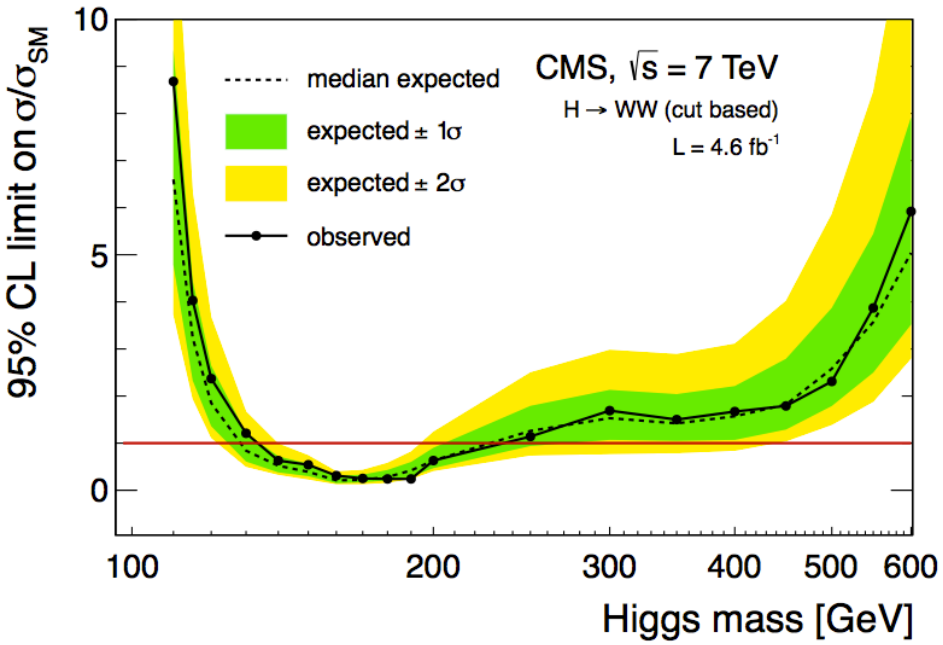
Most sensitive channel is eμ in 0-jet bin
higher s/b and smaller systematic errors

H→WW results

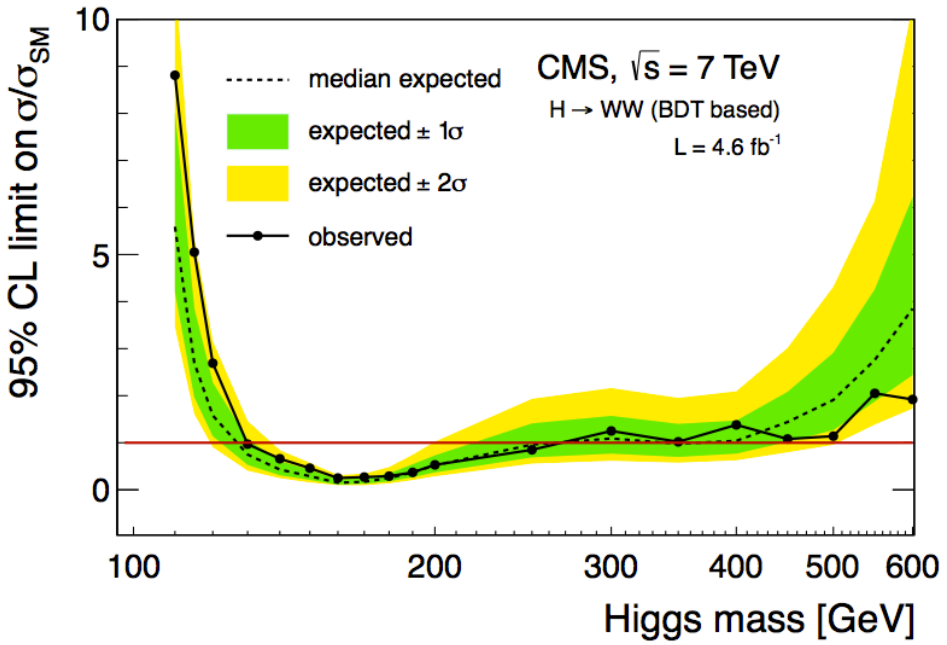
- No significant excess in the full mass range

arXiv:1202.1489
Accepted by PLB

Cut based



MVA based

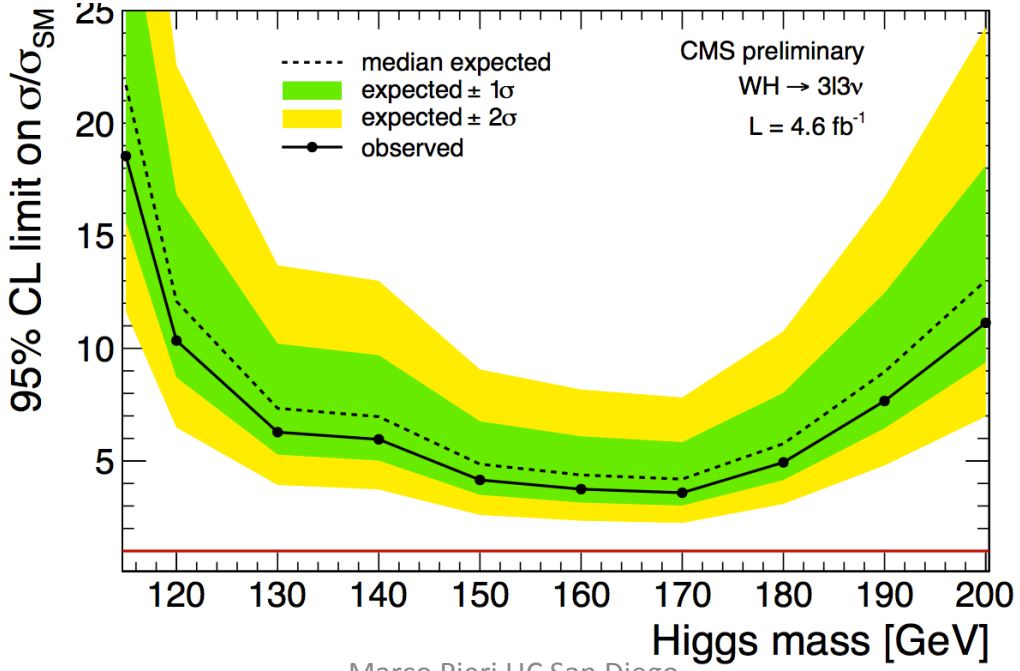


- Multivariate analysis more sensitive, especially at low mass
  - 95% C.L. expected exclusion for M_H in [127-270] GeV
  - 95% C.L. observed exclusion for M_H in [129-270] GeV
- Slight excess at low mass in BDT analysis

WH→WWW→3l3v

- Similar to WW analysis
- Cut and count analysis with mass independent selection
- Main backgrounds estimated from data

stage	WH (120) $H \to \tau\tau$	WH (120) $H \to WW$	data	all bkg.	WZ $\to 3\ell\nu$	ZZ $\to 4\ell$	top+Z/γ^*
3-lepton preselection	2.1 ± 0.0	3.5 ± 0.1	950	968.3 ± 11.9	482.9 ± 1.8	78.4 ± 0.9	348.0 ± 9.7
min-MET > 40 GeV	1.0 ± 0.0	1.8 ± 0.1	244	270.5 ± 4.4	208.2 ± 1.1	7.9 ± 0.3	54.5 ± 4.3
Z removal	0.4 ± 0.0	1.0 ± 0.1	40	47.9 ± 3.1	15.9 ± 0.4	0.7 ± 0.1	31.3 ± 3.1
top veto	0.1 ± 0.0	0.6 ± 0.1	12	14.2 ± 1.3	8.8 ± 0.4	0.4 ± 0.1	4.9 ± 1.3
$\Delta R_{\ell^+\ell^-}$ & $m_{\ell\ell}$	0.1 ± 0.0	0.5 ± 0.1	7	8.4 ± 0.9	5.7 ± 0.2	0.3 ± 0.1	2.6 ± 0.9



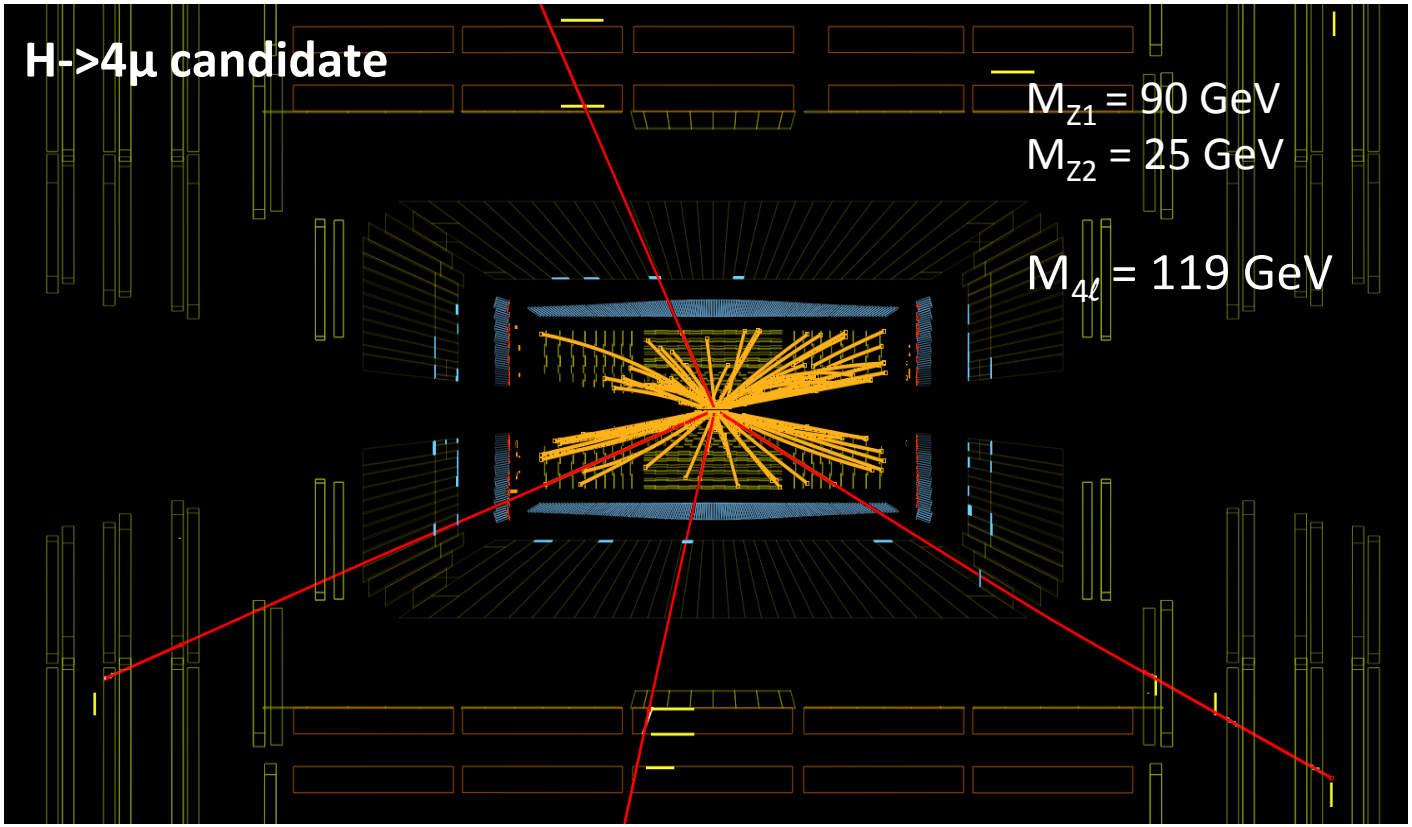
NEW

CMS document
HIG-11-034

Full mass range: H → ZZ → 4l (4μ, 4e, 2e2μ)

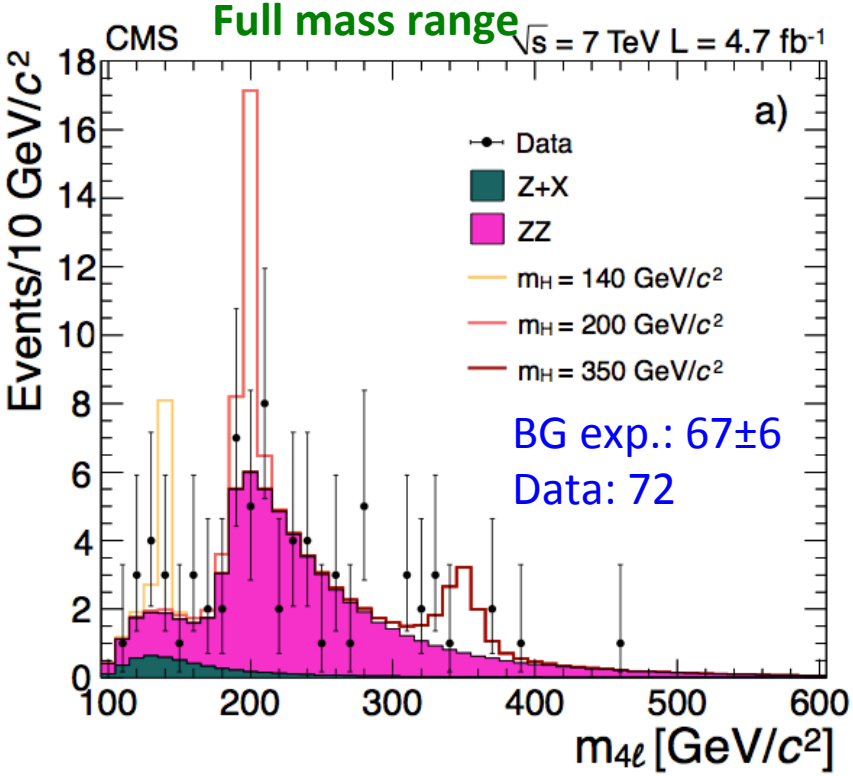
- Clean channel: 2 high mass pairs of isolated electrons or muons
- **Narrow mass peak**
  - Very good mass resolution 1-2 %
- Small BR ~1E-3 at high mass

- Background
  - irreducible: ZZ, Reducible: Z+jets, Zbb, tt, WZ
- Most important aspect:
  - highest possible lepton id efficiency down to very low P_t



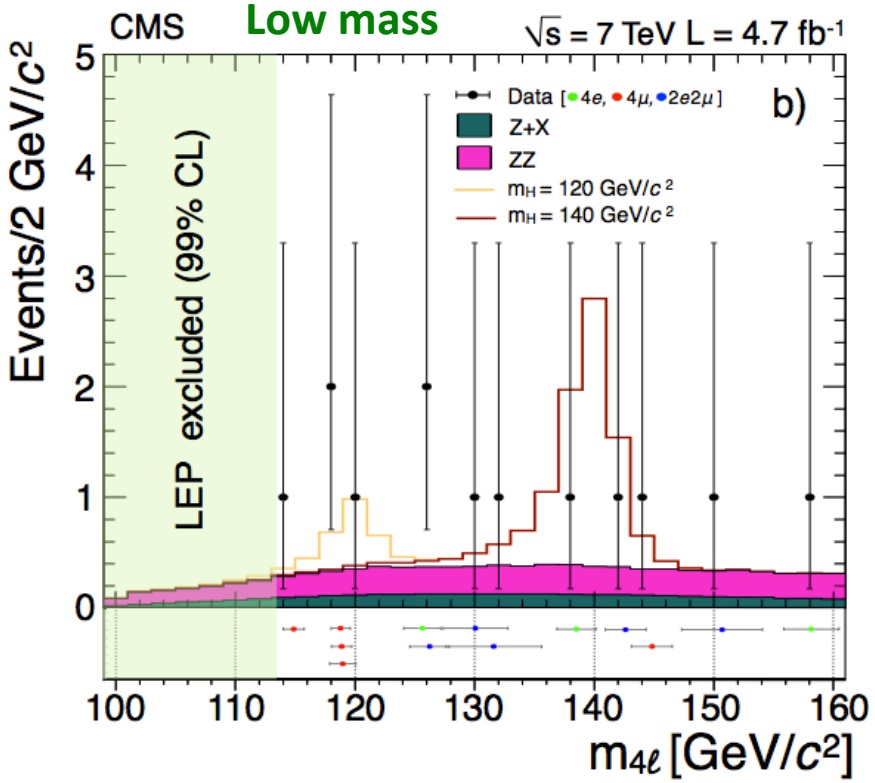
H→ZZ→4l: invariant mass spectrum

Full mass range



BG exp.: 67±6
Data: 72

Low mass



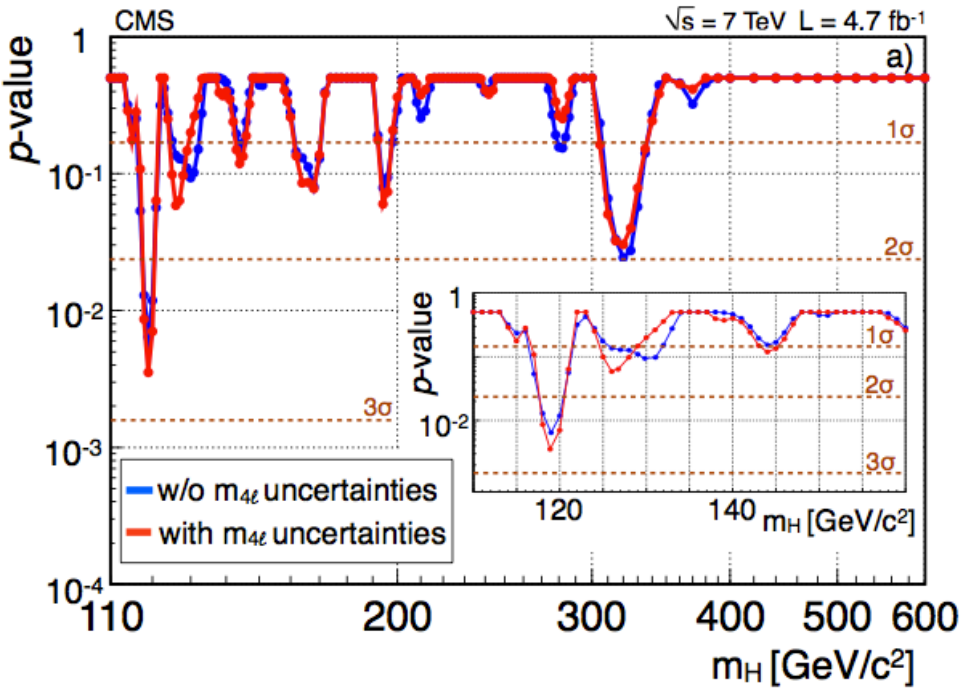
Channel	$4e$	4μ	$2e2\mu$
ZZ continuum	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
$m_H = 120\,\mathrm{GeV}/c^2$	0.25	0.62	0.68
$m_H = 140\,\mathrm{GeV}/c^2$	1.32	2.48	3.37
$m_H = 350\,\mathrm{GeV}/c^2$	1.95	2.61	4.64
Observed	12	23	37

BG exp.: 9.5±1.3
Data: 13
In 100-160 GeV

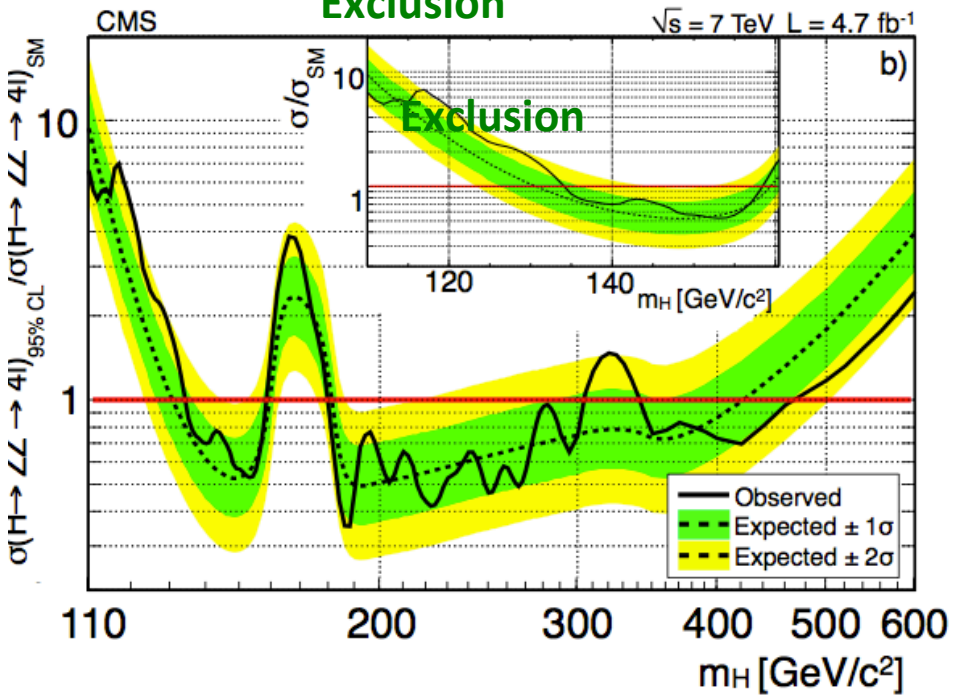
H→ZZ→4l results

arXiv:1202.1997
Accepted by PRL

P-values



Exclusion



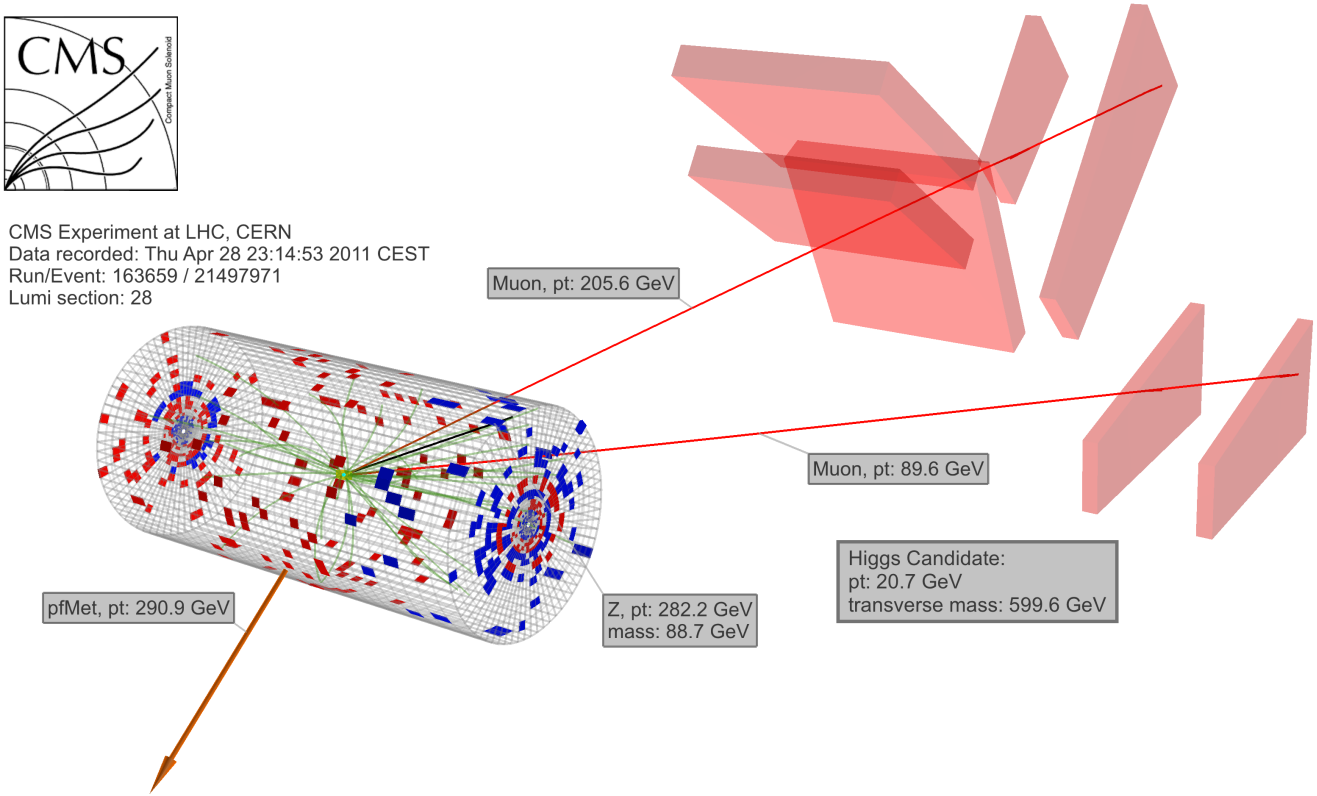
- Largest excess observed at 119.5 GeV
  - local significance 2.5 σ
  - global significance 1.0 σ in the full mass range, 1.6 in the mass range 100-160 GeV

SM scalar boson excluded at 95% CL for M_H in [134-158], [180-305] and [340-465] GeV

High mass: H→ZZ→llvv channel

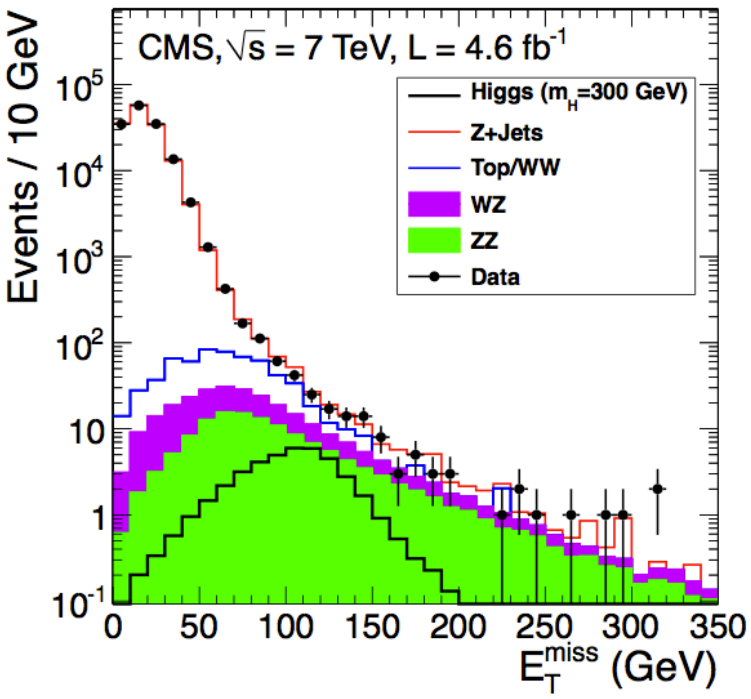
- Most sensitive channel for high mass search
  - BR 6 times larger than ZZ→4l
- **Missing neutrinos implies mass resolution 7%**
- Only accessible for high mass (M_H >~ 250 GeV):
  - the two Z bosons are boosted
  - large MET due to invisible decay
- Main backgrounds
  - ZZ (irreducible)
  - Z+jets, tt, WZ

H->ZZ->llvv candidate



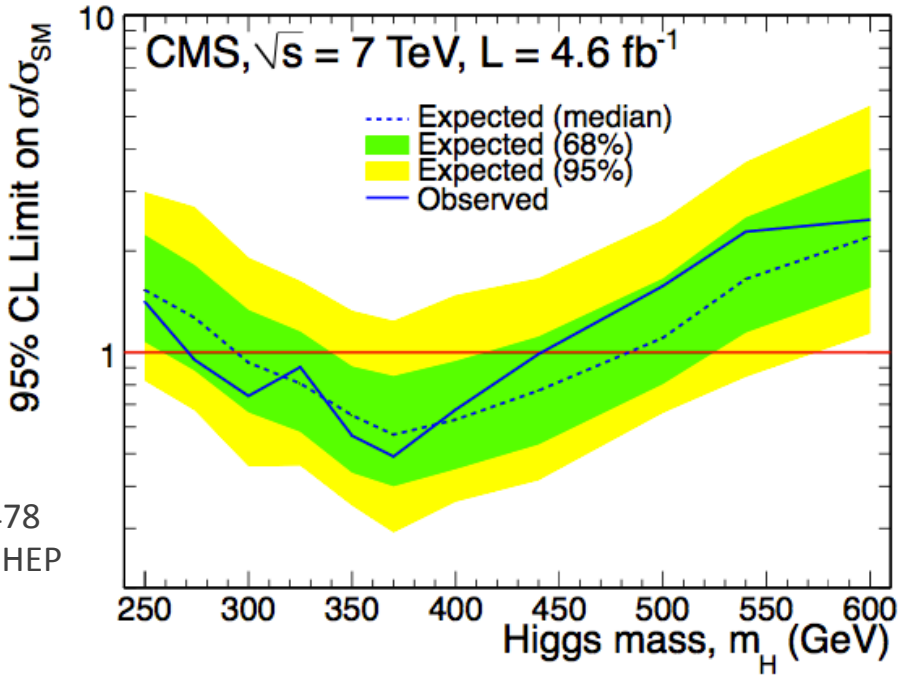
H→ZZ→llνν results

MET after preselection



- Two analyses: cut and count and mass shape
- Discriminating variable for shape analysis transverse mass:

$$M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss\,2} + M(\ell\ell)^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{miss})^2$$



arXiv:1202.3478
Accepted by JHEP

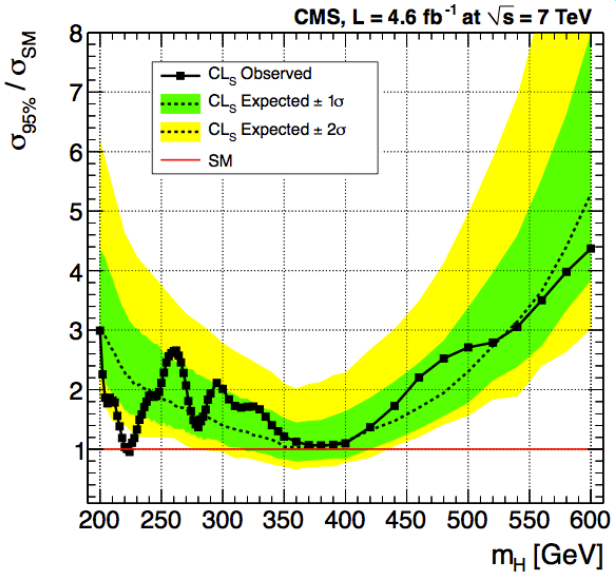
- BG estimation
  - Z+jets estimated using γ+jet to model the MET distribution
  - Non resonant BG normalization from eμ events
  - ZZ and WZ from MC

- No excess observed in data
- Expected 95% exclusion for M_H in [290-480] GeV
- Observed 95% CL exclusion for M_H [270-440] GeV

Other SM channels

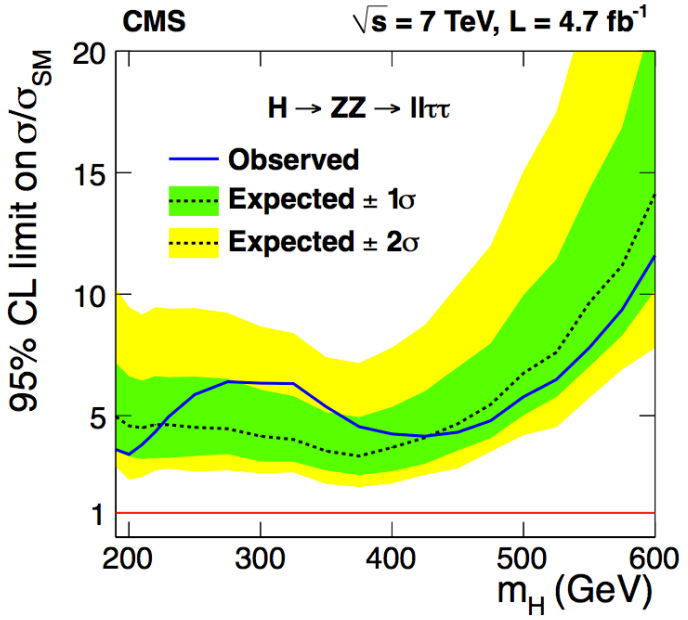
- H → ZZ → llqq (high mass)
  - Sensitivity similar to other ZZ decays

arXiv:1202.1416
Submitted to JHEP



- H → ZZ → llττ (high mass)
  - All τ decay channels searched for
  - Lower sensitivity (~4xSM)

arXiv:1202.3617
Accepted by JHEP



Combination of all channels

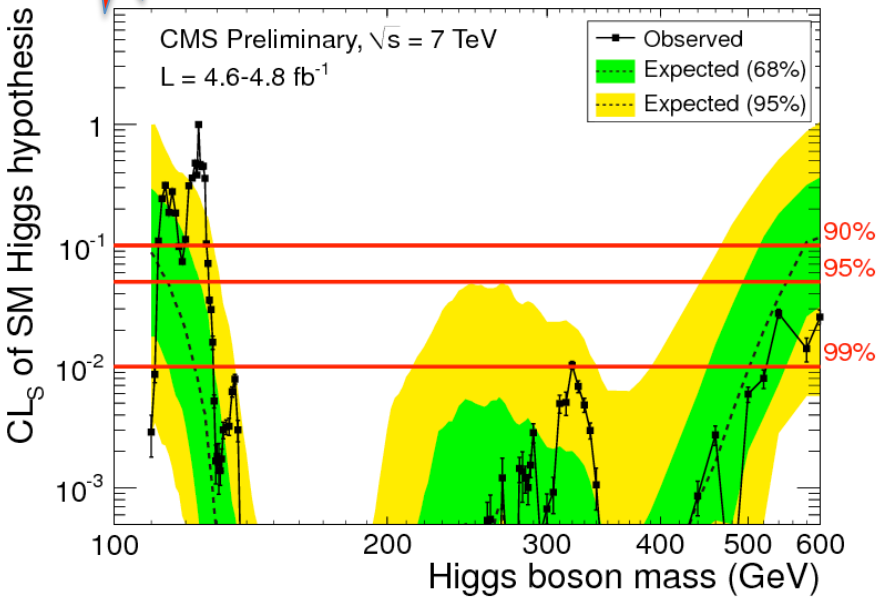
- SM cross sections and branching ratios are assumed with their theoretical uncertainties and an overall signal strength multiplier is fit
- Method for CL calculation is LHC-type CLs
  - Frequentist CLs with profiled likelihood test statistics and log-normal treatment of nuisance parameters
  - ATL-PHYS-PUB/CMS NOTE 2011-11, 2011/005, (2011)
- Here we show the latest results that include the new analyses presented here
- Results based on 2011 data have been recently submitted for publication
  - arXiv:1202.1488, accepted by PLB

Exclusion C.L.

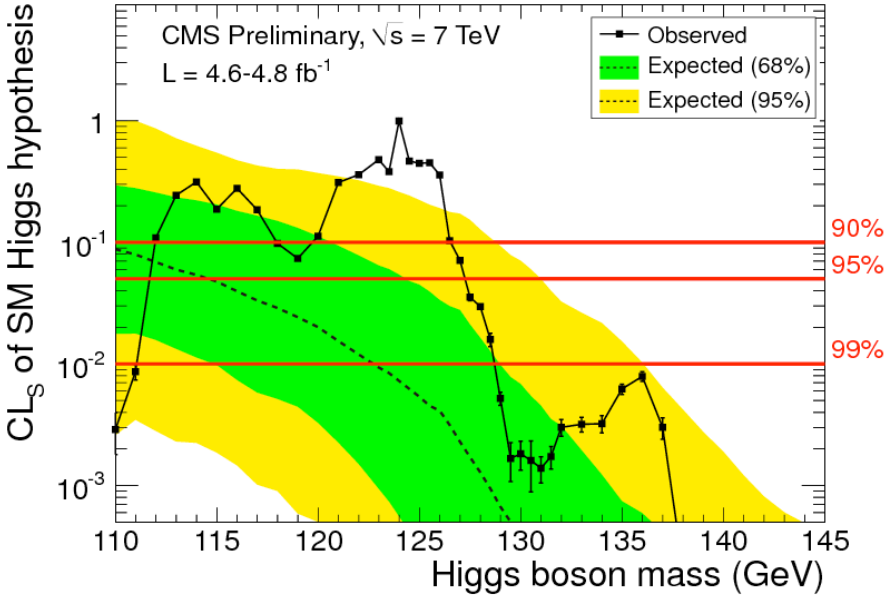
NEW

CMS document HIG-12-008

Full mass range

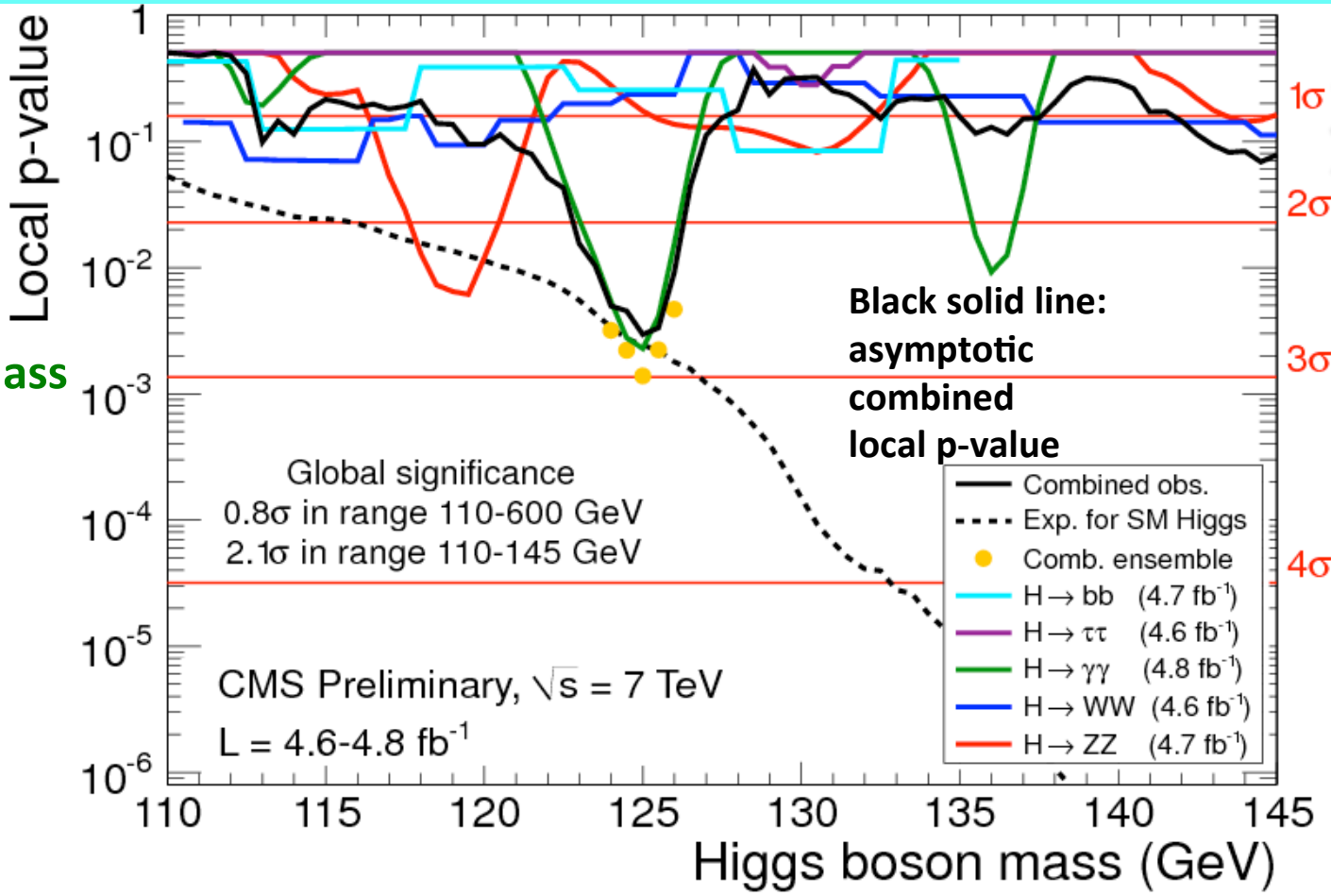


Low mass region



- Expected: 95% exclusion M_H in [114.5-543] GeV
- Observed: 95% exclusion M_H in [127.5-600] GeV
  99% exclusion M_H in [129-525] GeV
- 95% allowed mass range: 114.4-127.5 GeV
- Observed lower limit higher than expected because of excess in data at low mass

P-values

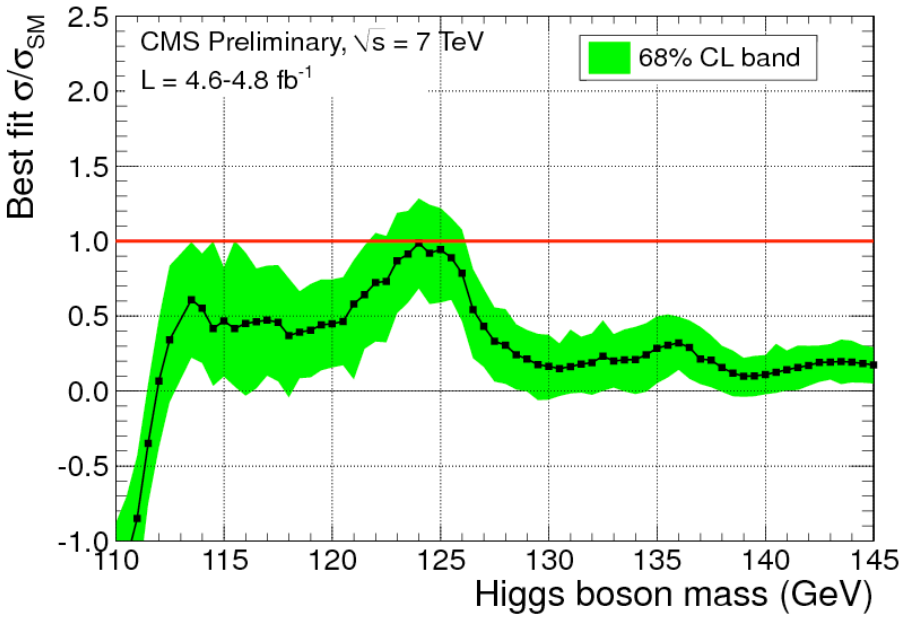


Low mass region

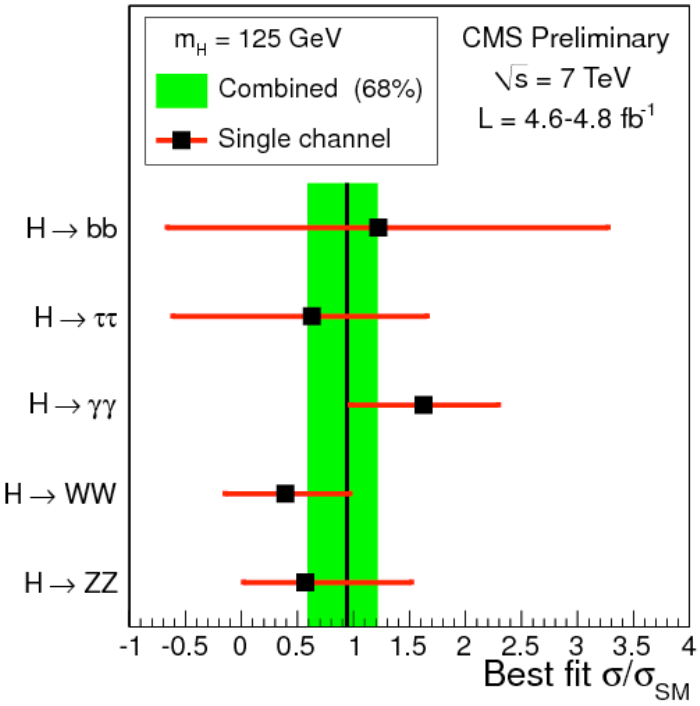
- Minimum p-value observed at 125 GeV with local significance: 2.8 σ
  - Similar significance expected from signal
- Estimated global significance:
  - 0.8 σ in [110-600] GeV, 2.1 σ in [110-145] GeV,

Fitted signal strength σ/σ_{SM}

NEW



Comparison of channels for M_H=125 GeV



- The fitted σ of the excess near 125 GeV is consistent with the SM scalar boson expectation
- At low mass several channels show some excess
  - At 125 GeV all sensitive channels show an excess consistent with signal expectations
- More data are needed to investigate this excess

Summary and outlook

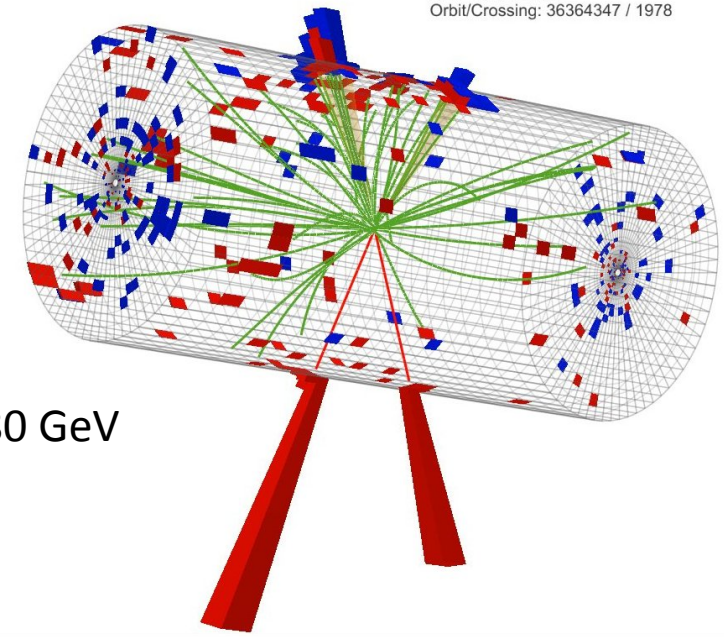
- SM scalar boson search in 11 independent channels
- Expected 95% CL exclusion: M_H in [114.5-543] GeV
- Observed 95% CL exclusion: M_H in [127.5-600] GeV
- SM scalar boson if it exists, is limited at 95% CL in the range [114.4-127.5] GeV
- Observe an excess around 125 GeV in the unexcluded region
  - Local significance 2.8 σ, global significance 0.8 σ (in the full search range) and 2.1 σ (in 110-145 GeV)
  - The excess is consistent both with background fluctuation and also with a BEH scalar boson with mass about 125 GeV
  - More data are needed to investigate the origin of the excess
- In 2012 LHC will run at 8 TeV CM energy
  - should be able to discover or exclude the SM scalar boson

Backup

H→ZZ→llqq channel

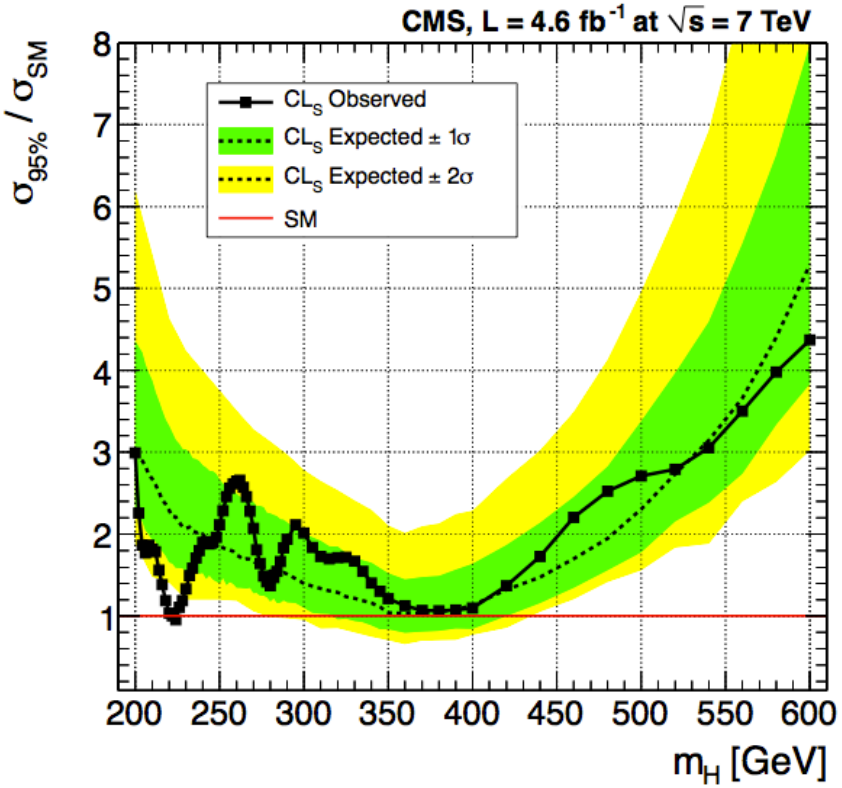
- Search optimized in two mass ranges:
  - 125-170 GeV
  - 183-800 GeV
- Kinematical fit imposing that the jj mass is consistent with the Z
  - For low mass cut M_{ll}<80 GeV applied to select on-shell Z->qq

arXiv:1202.1416
Submitted to JHEP



M_{eejj}=580 GeV

95% exclusion from H→ZZ→llqq

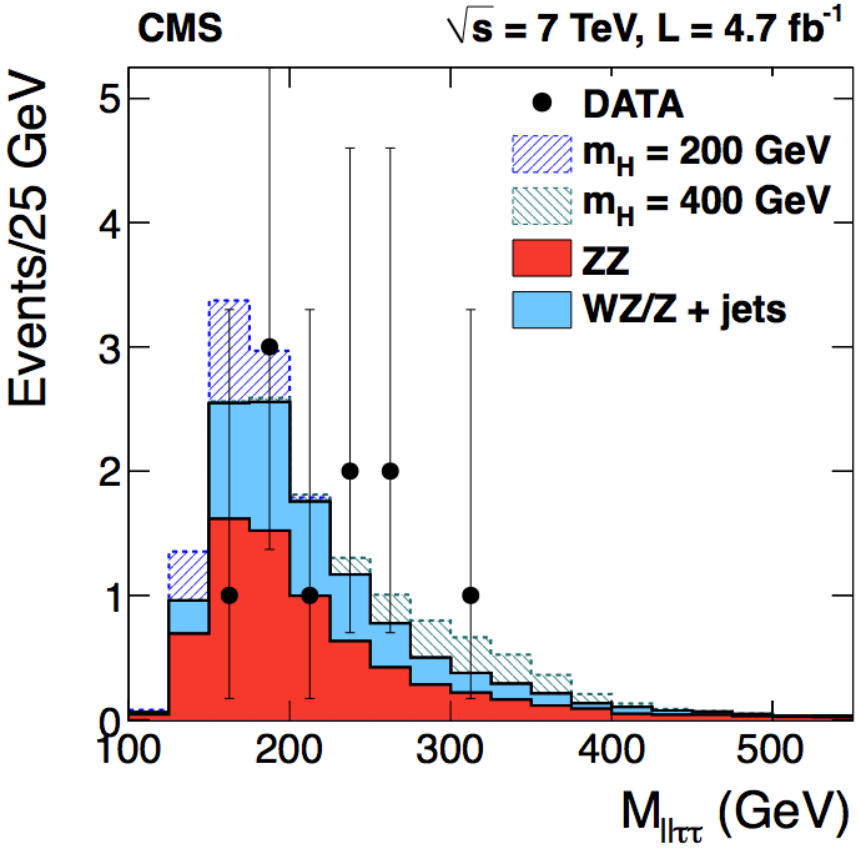


Mass resolution after kinematical fit ~ 3%

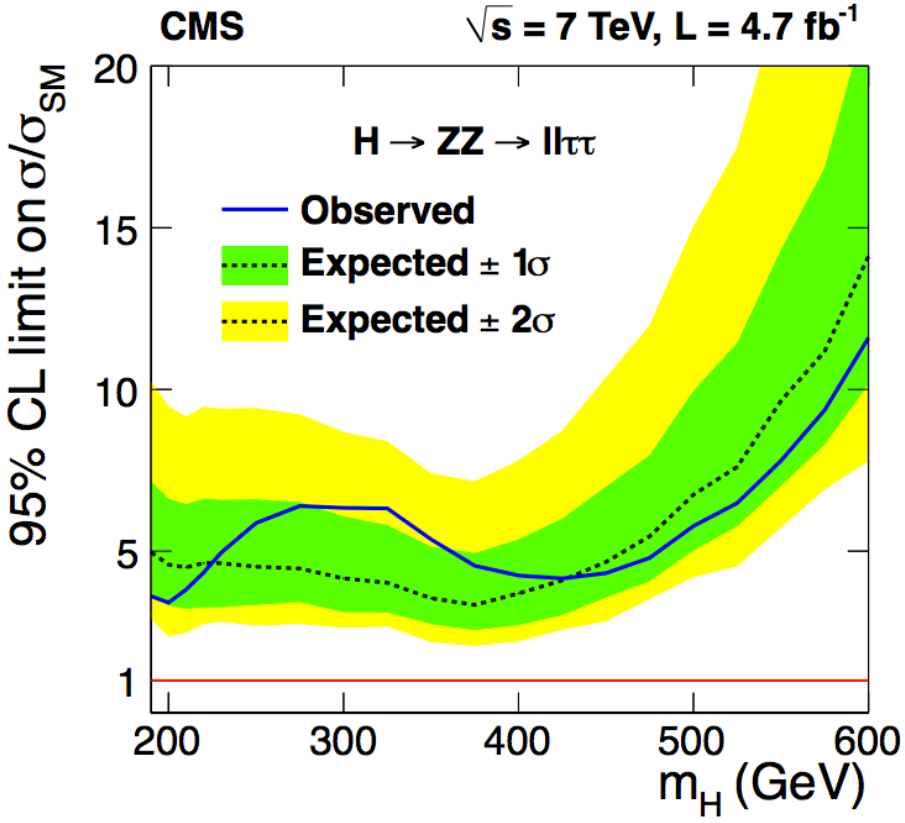
H→llττ channel

- All τ decays used
- Sensitivity about 4xSM
- Expect 10.2 events from BG
- Observe 10 events in data

arXiv:1202.3617
Accepted by JHEP

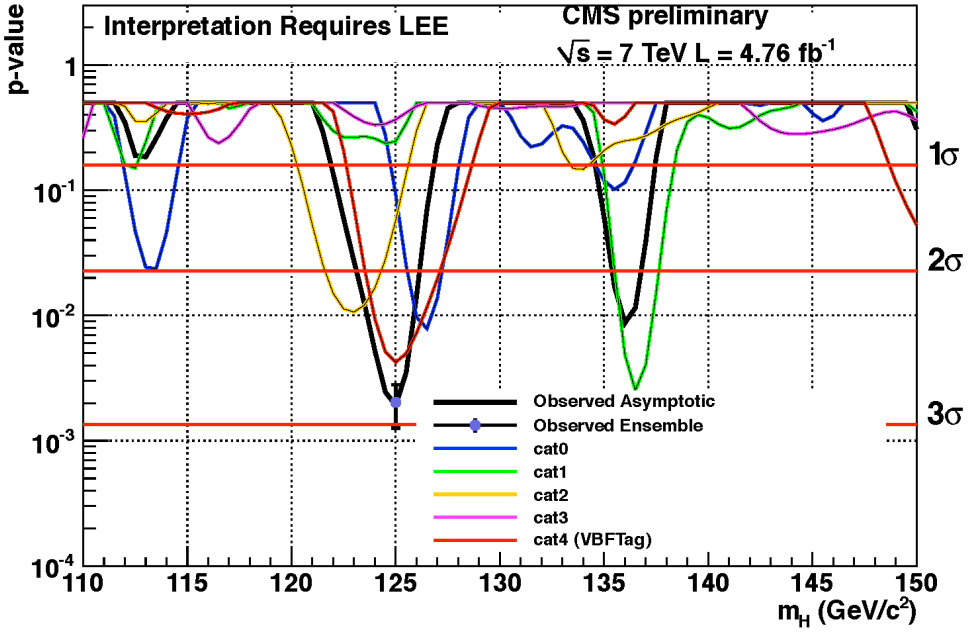


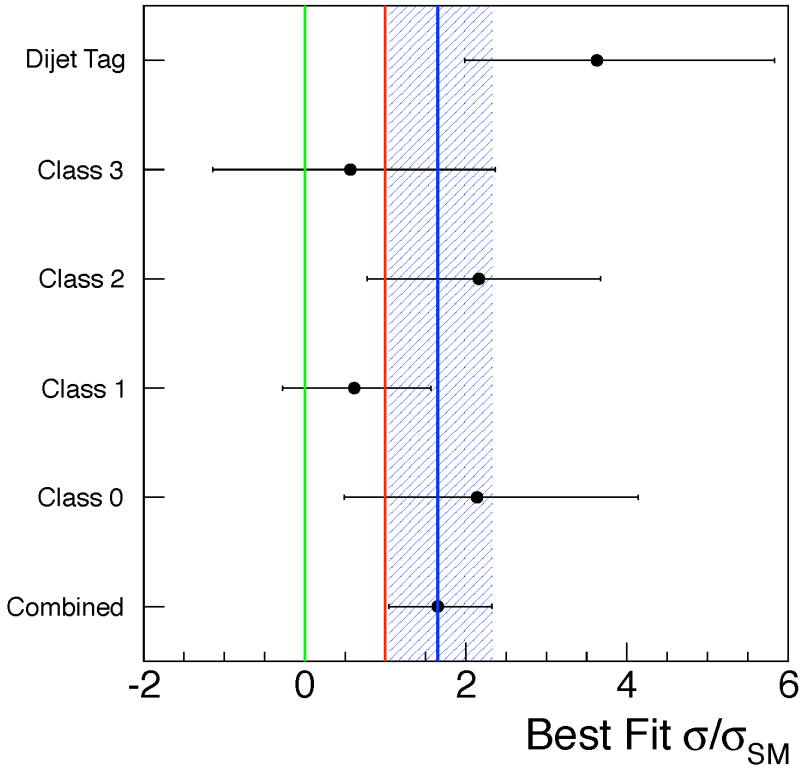
95% Exclusion



H→γγ: p-value and fitted signal strength in classes

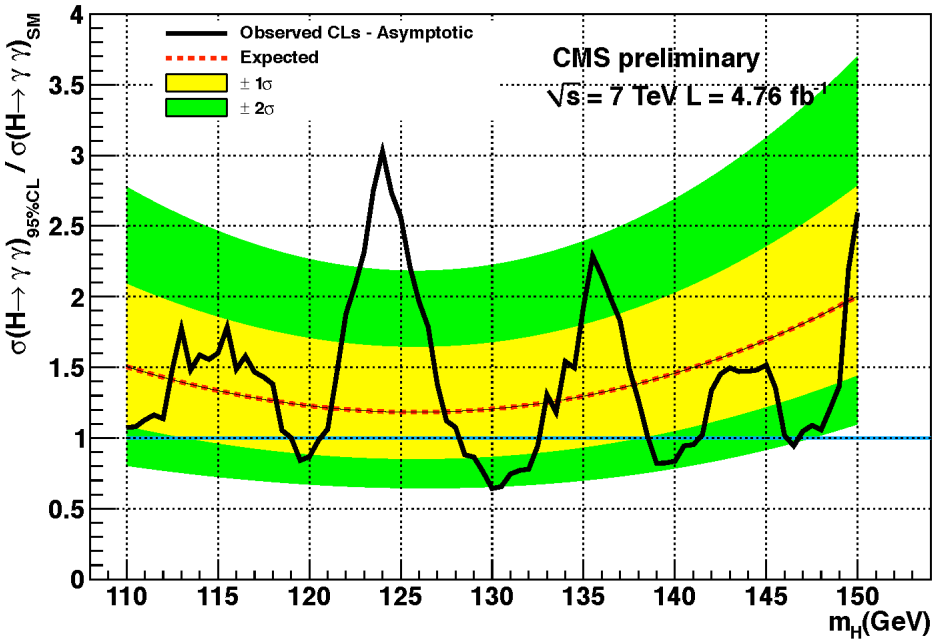
CMS document
HIG-12-001

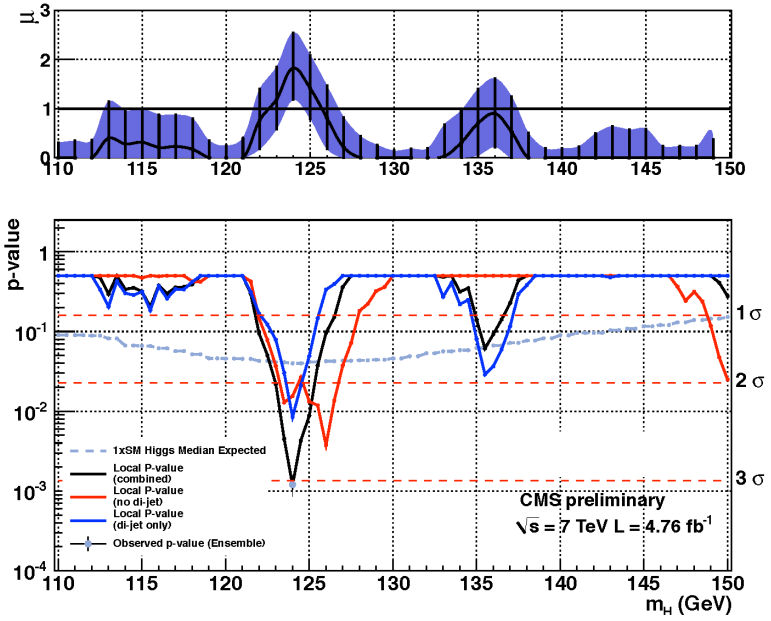




H→γγ: results of cross check MVA analysis

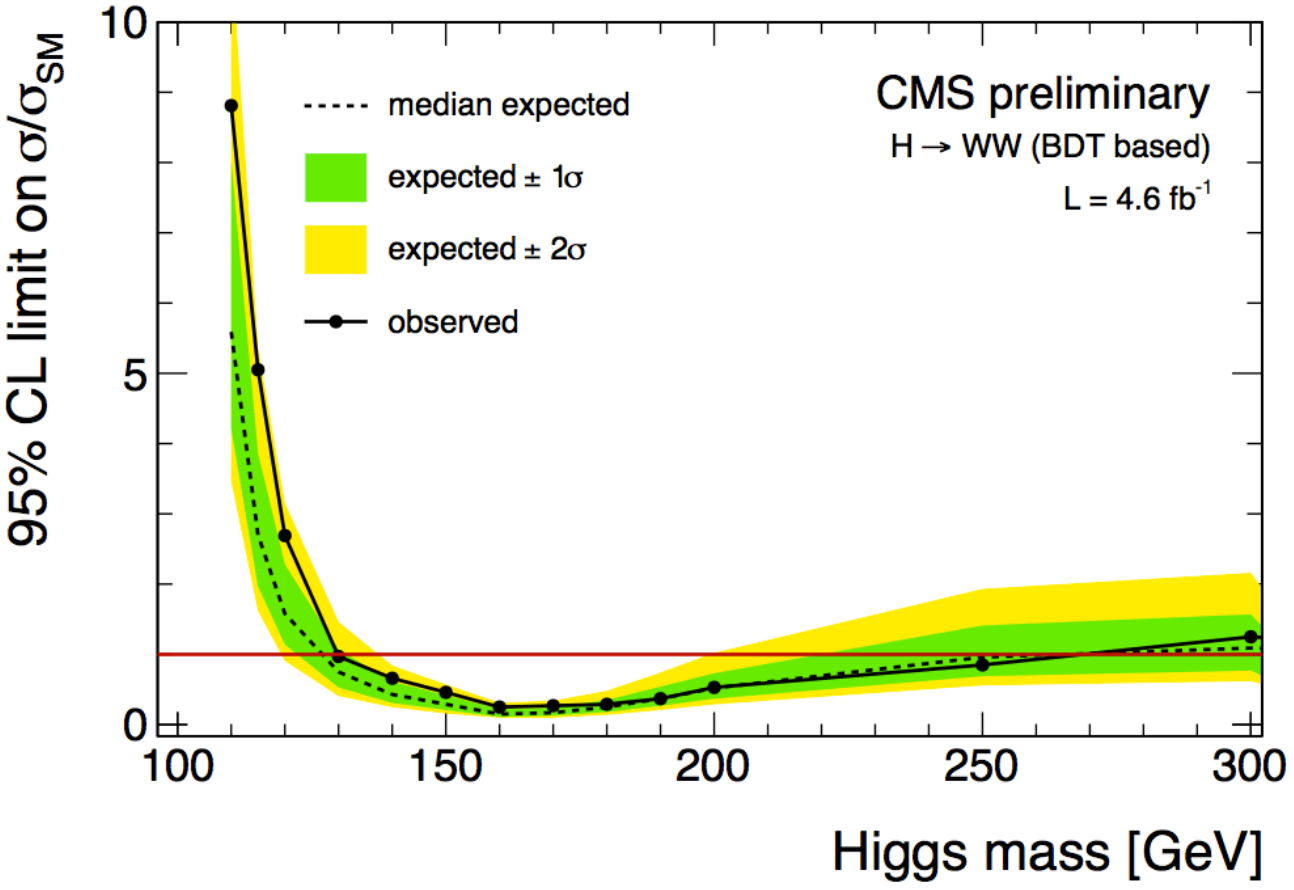
CMS document
HIG-12-001





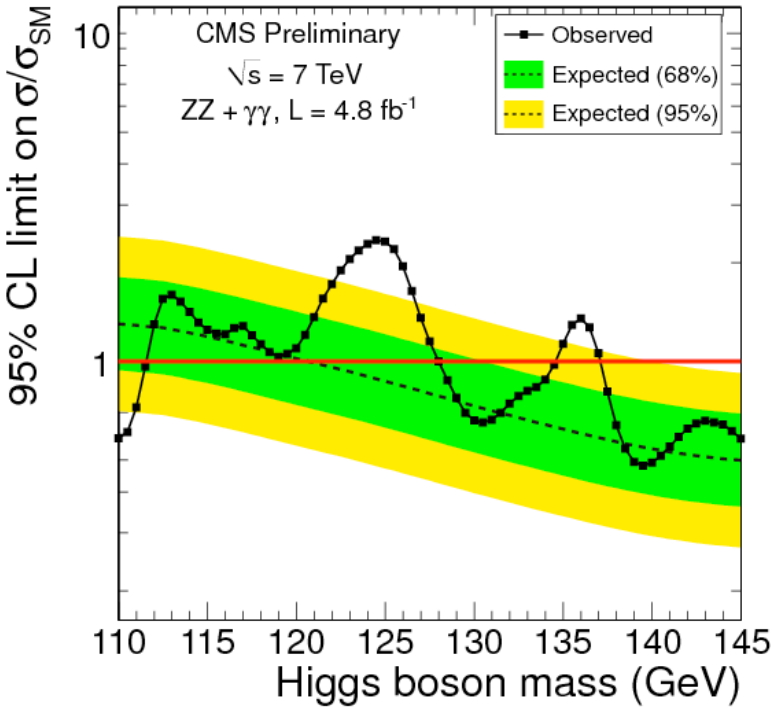
H→WW→lvlv: exclusion 100-300 GeV

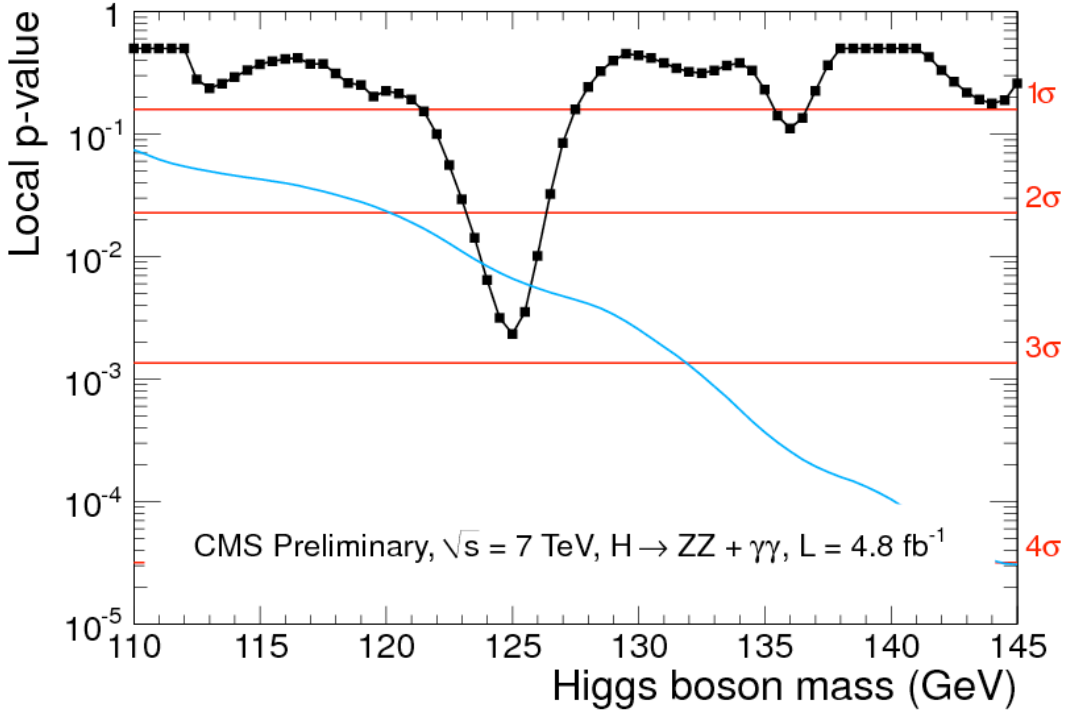
arXiv:1202.1489
Accepted by PLB



Partial combinations (ZZ+γγ)

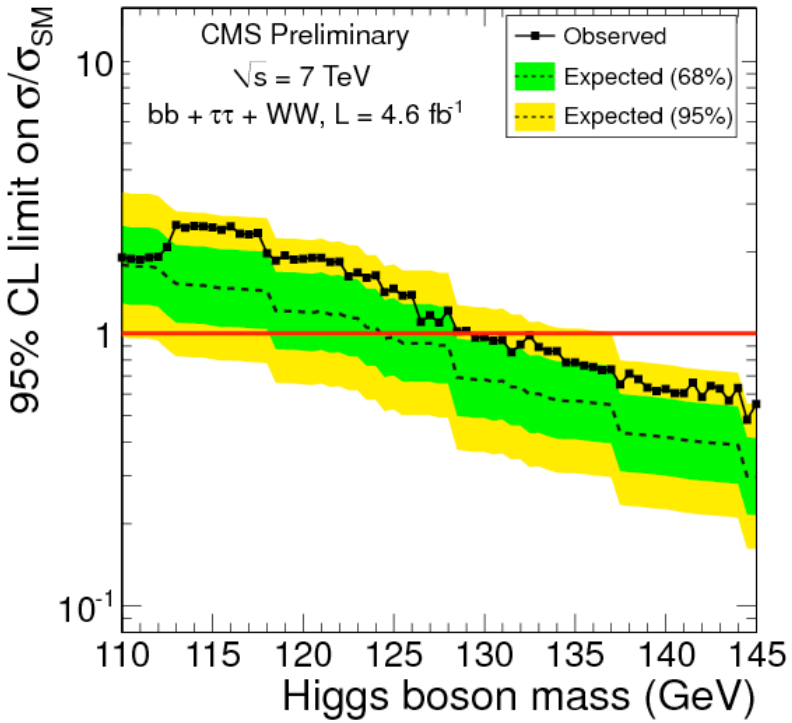
CMS document
HIG-12-008

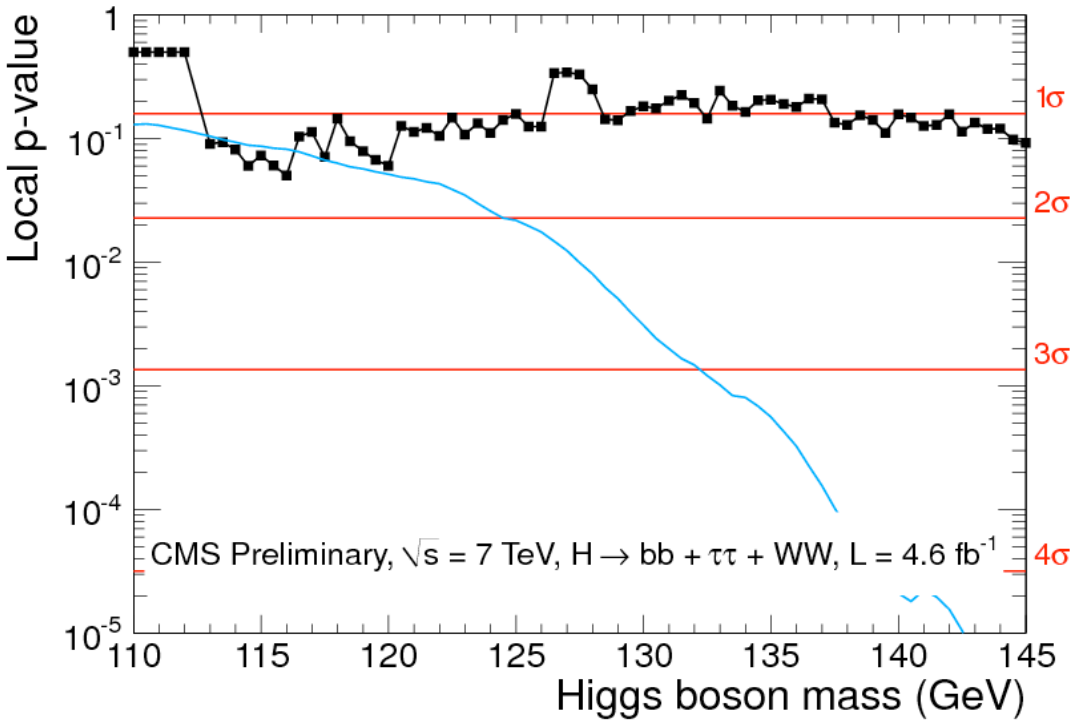




Partial combinations (WW+bb+ττ)

CMS document
HIG-12-008

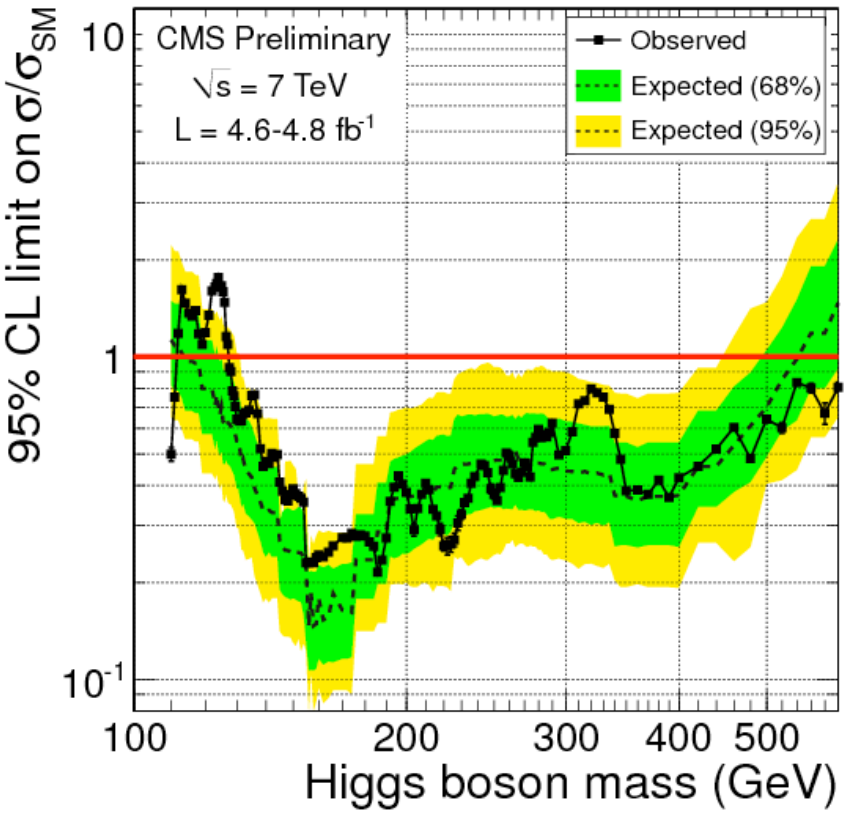




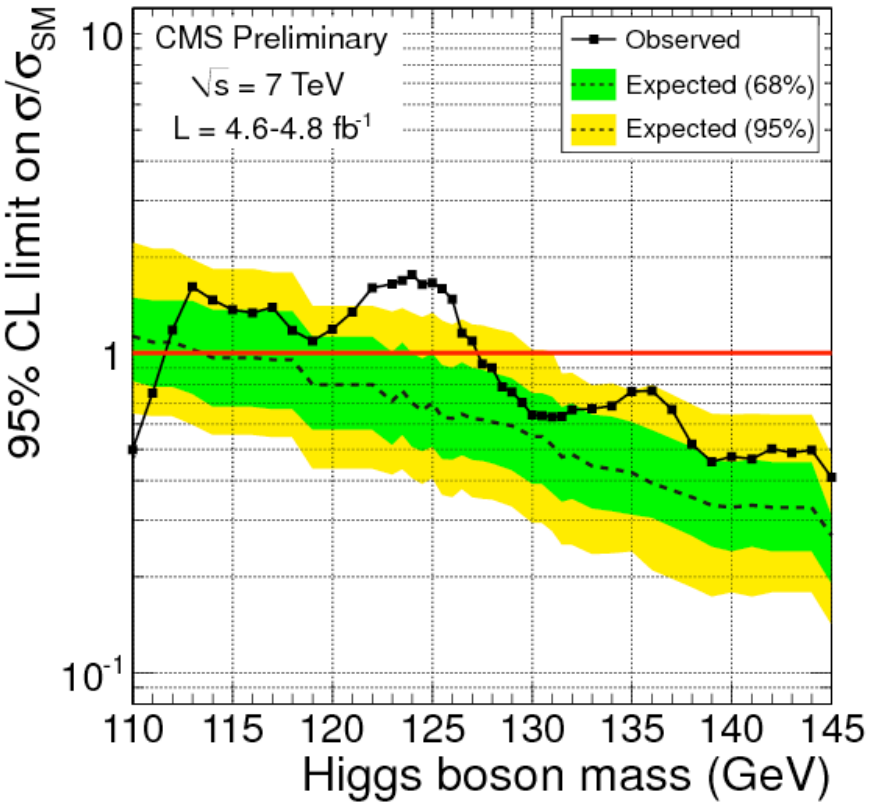
95% CL exclusion on the signal strength

CMS document
HIG-12-008

Full mass range

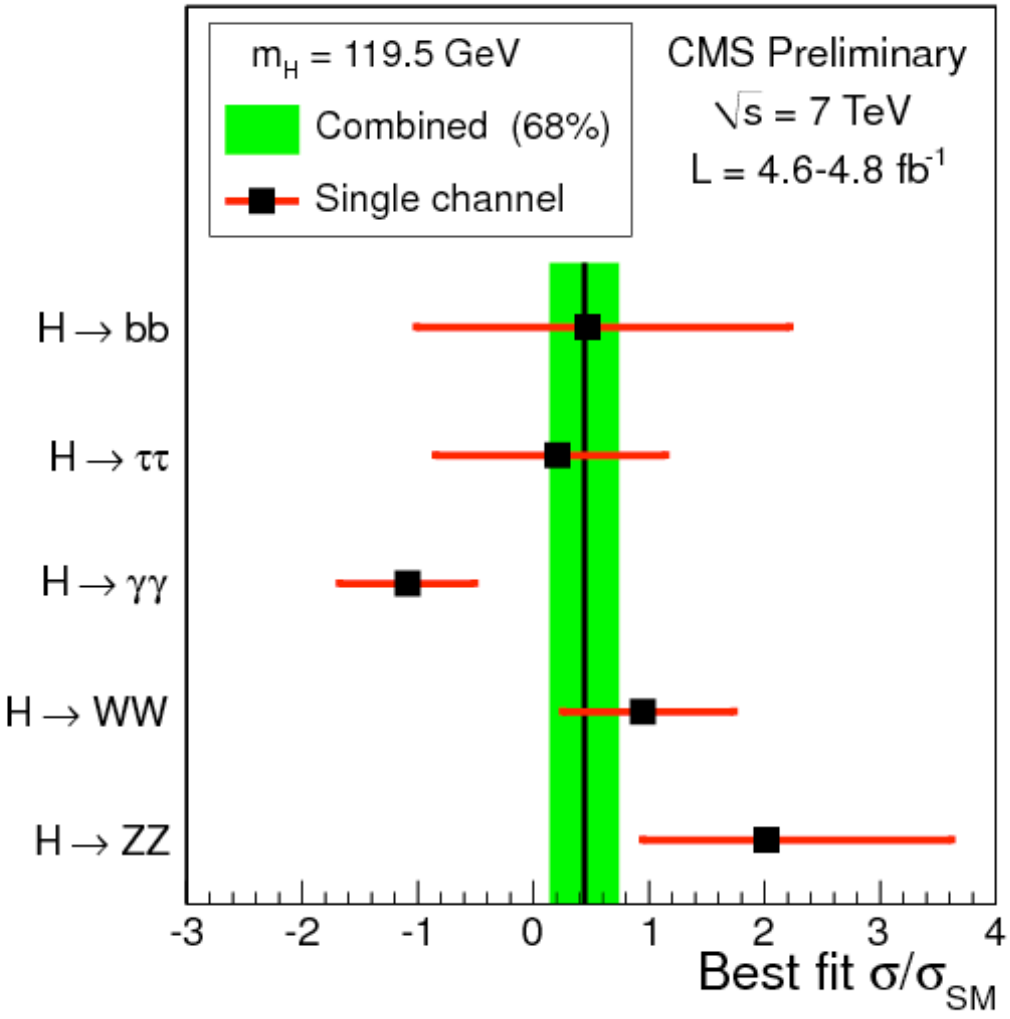


Low mass region



Fitted signal strengths σ/σ_{SM} at 119.5 GeV

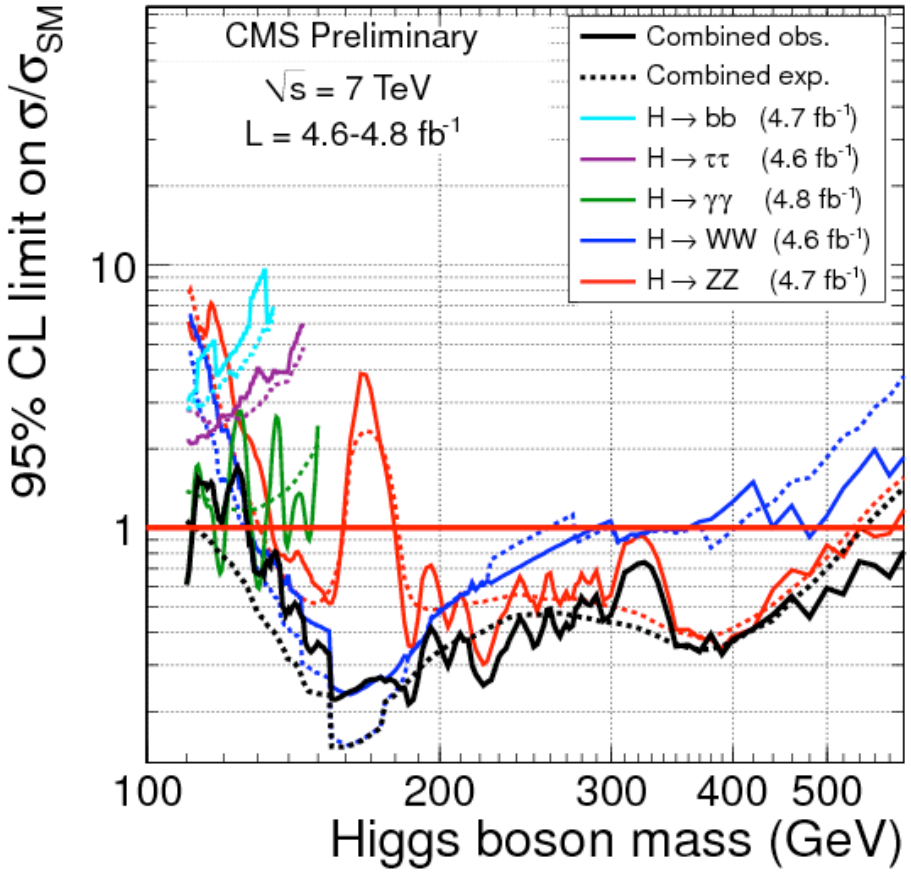
CMS document
HIG-12-008



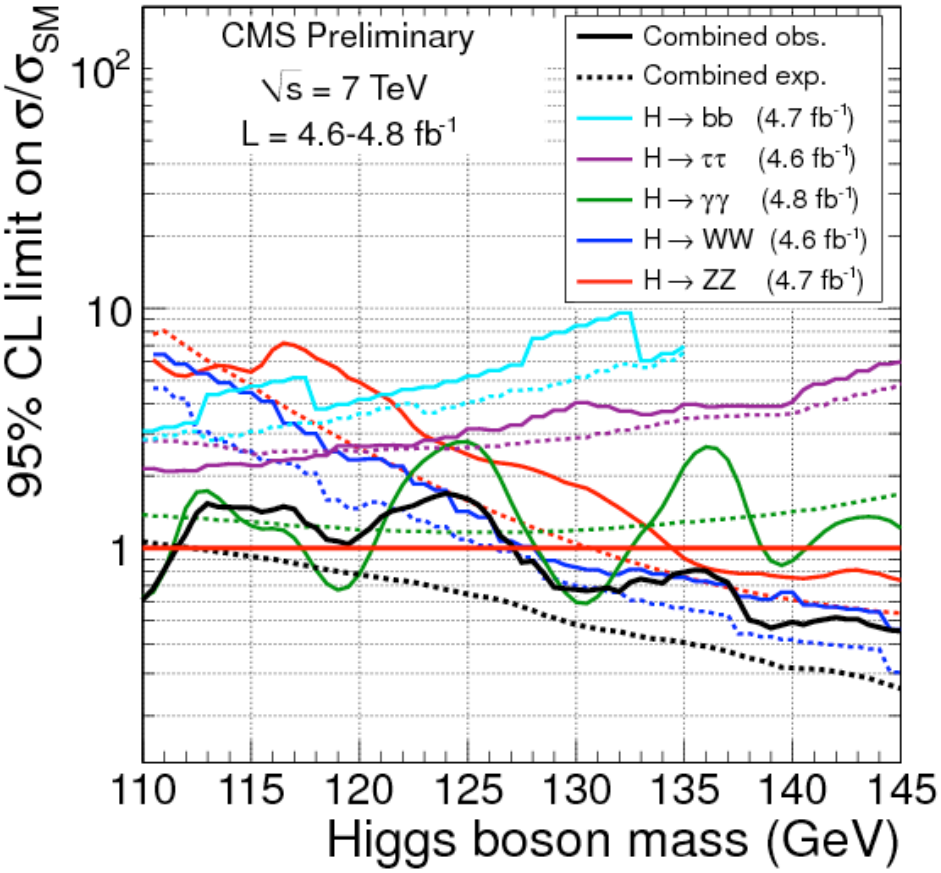
95% CL exclusion for different channels

CMS document
HIG-12-008

Full mass range

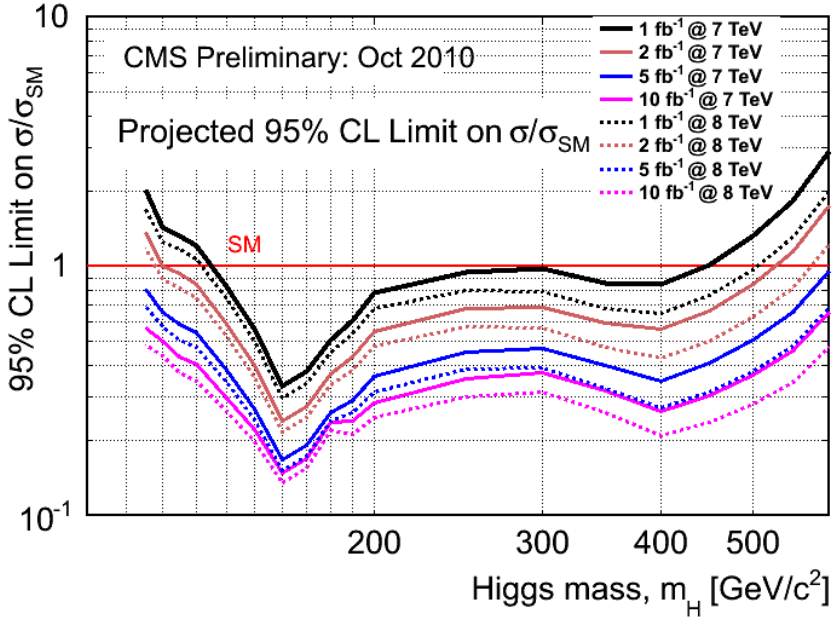


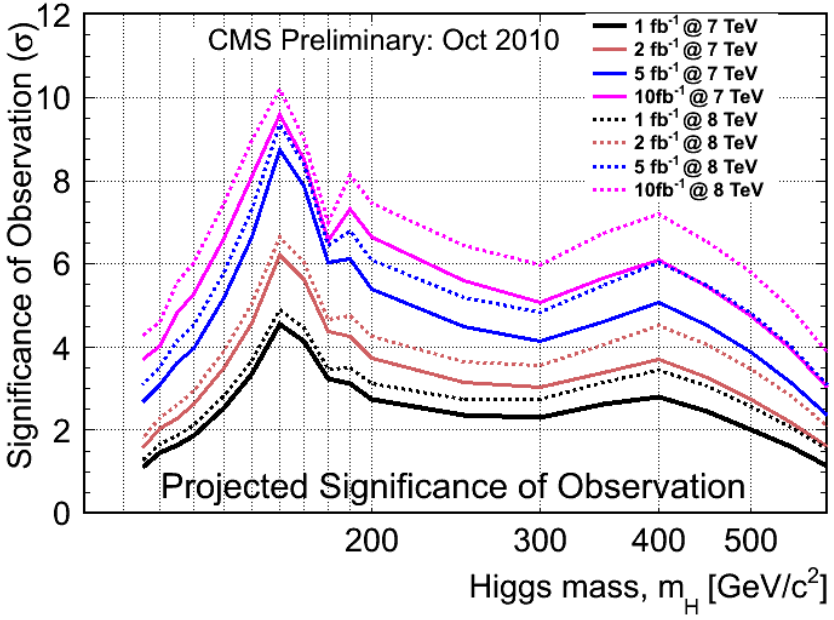
Low mass region



Projections for 2012 run

- 8 TeV vs 7 TeV is expected to increase the sensitivity by 10-20%





H→γγ: results for cut based

arXiv:1202.1487
Accepted by PLB

All together

Dijet tag

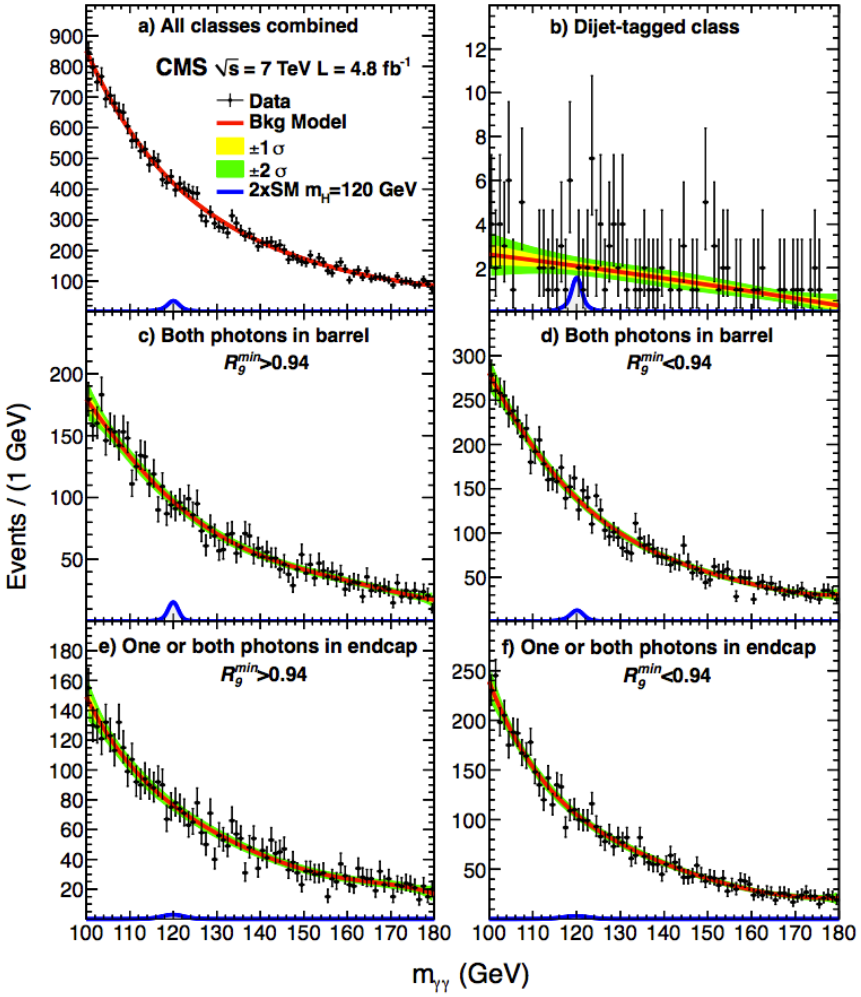
The 5 classes are exclusive

Barrel unconverted

Barrel converted

Endcap unconverted

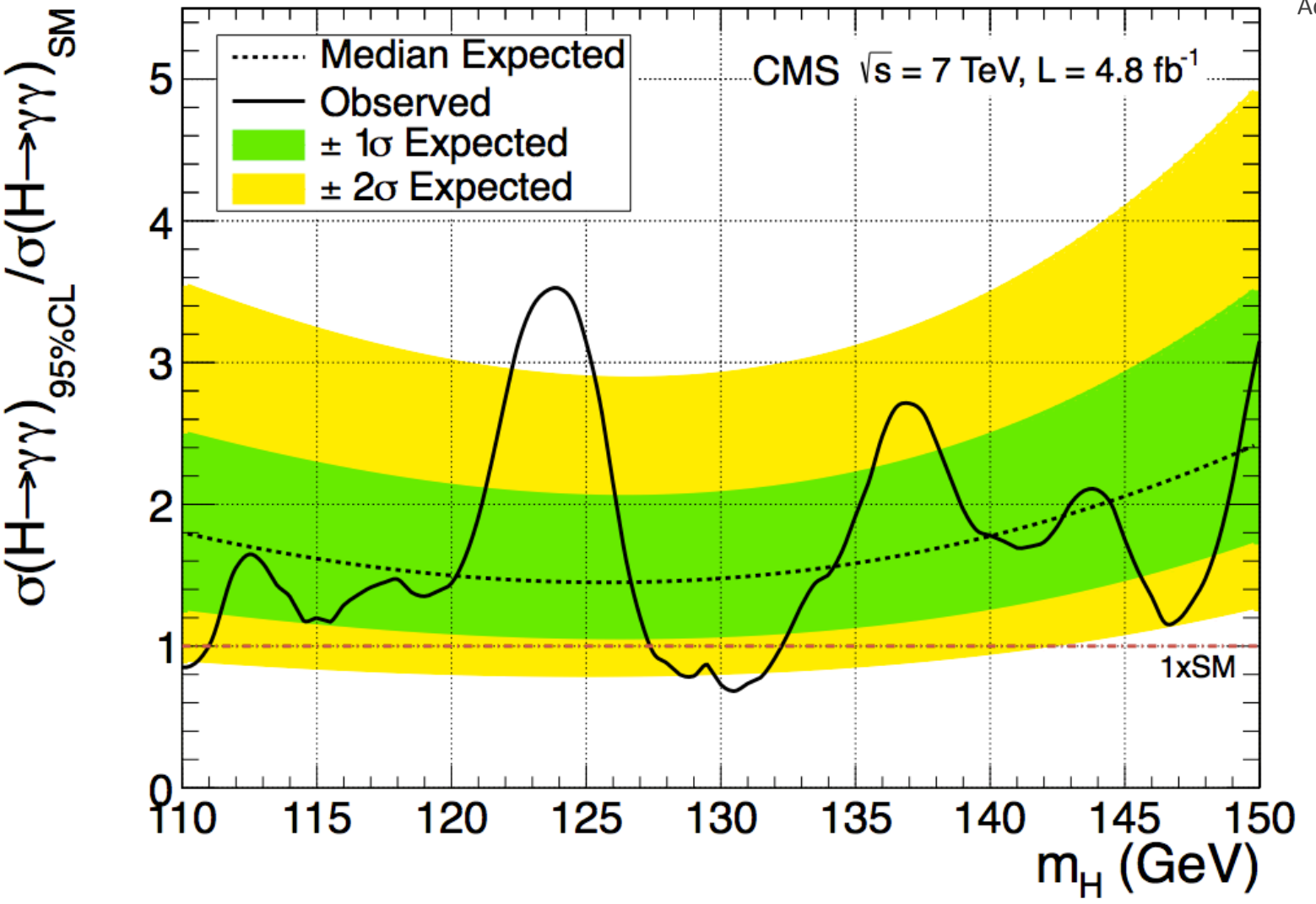
Endcap converted



	Both photons in barrel		One or both in endcap		Dijet
	R_9^{min} >0.94	R_9^{min} <0.94	R_9^{min} >0.94	R_9^{min} <0.94	tag
SM signal expected	25.2 (33.5%)	26.6 (35.3%)	9.5 (12.6%)	11.4 (14.9%)	2.8 (3.7%)
Data (events/GeV)	97.5 (22.8%)	143.4 (33.6%)	76.7 (17.9%)	107.4 (25.1%)	2.3 (0.5%)
σ_{eff} (GeV)	1.39	1.84	2.76	3.19	1.71
FWHM/2.35 (GeV)	1.19	1.53	2.81	3.18	1.37

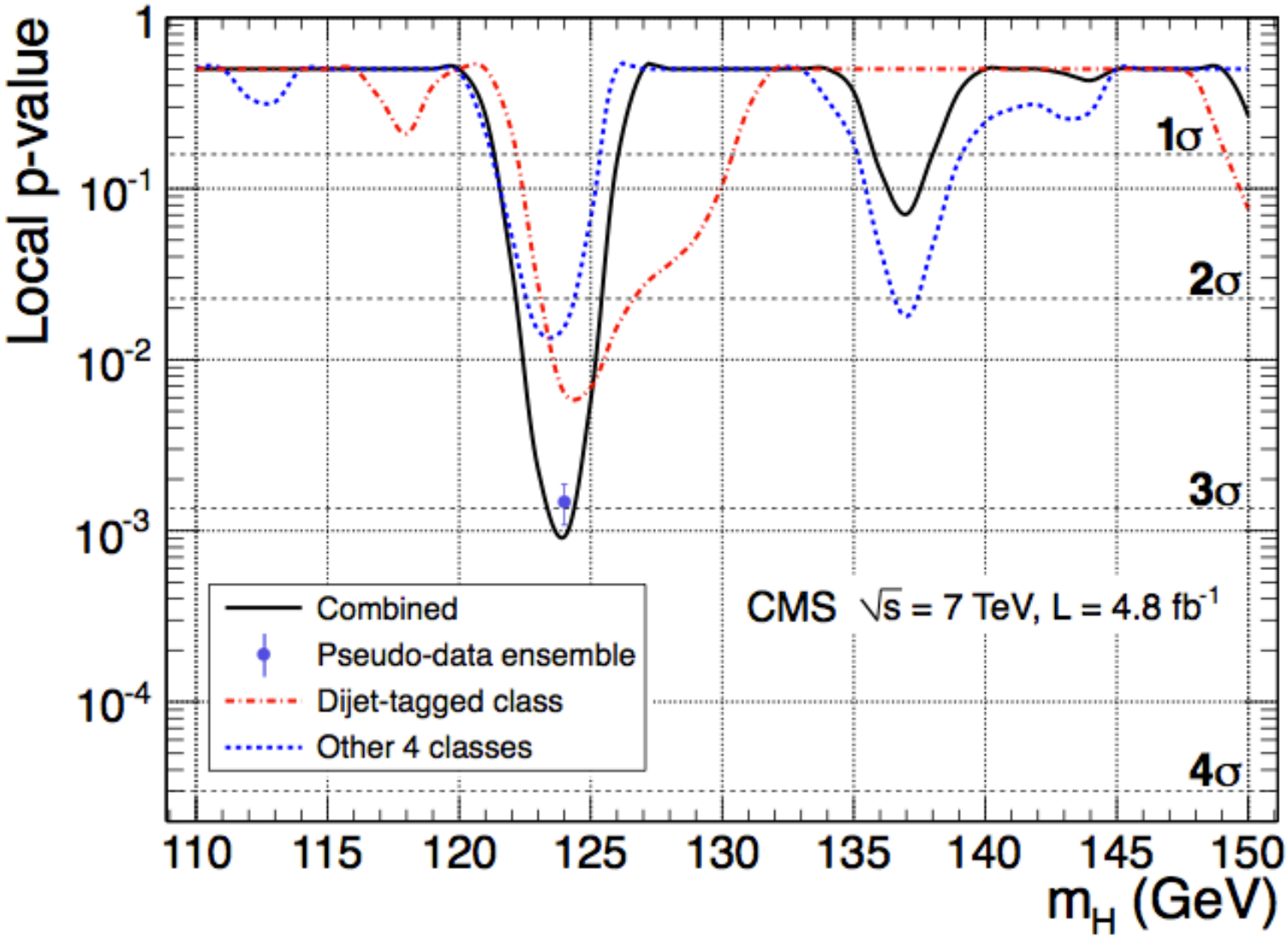
H→γγ: exclusion

arXiv:1202.1487
Accepted by PLB



H→γγ: p-value

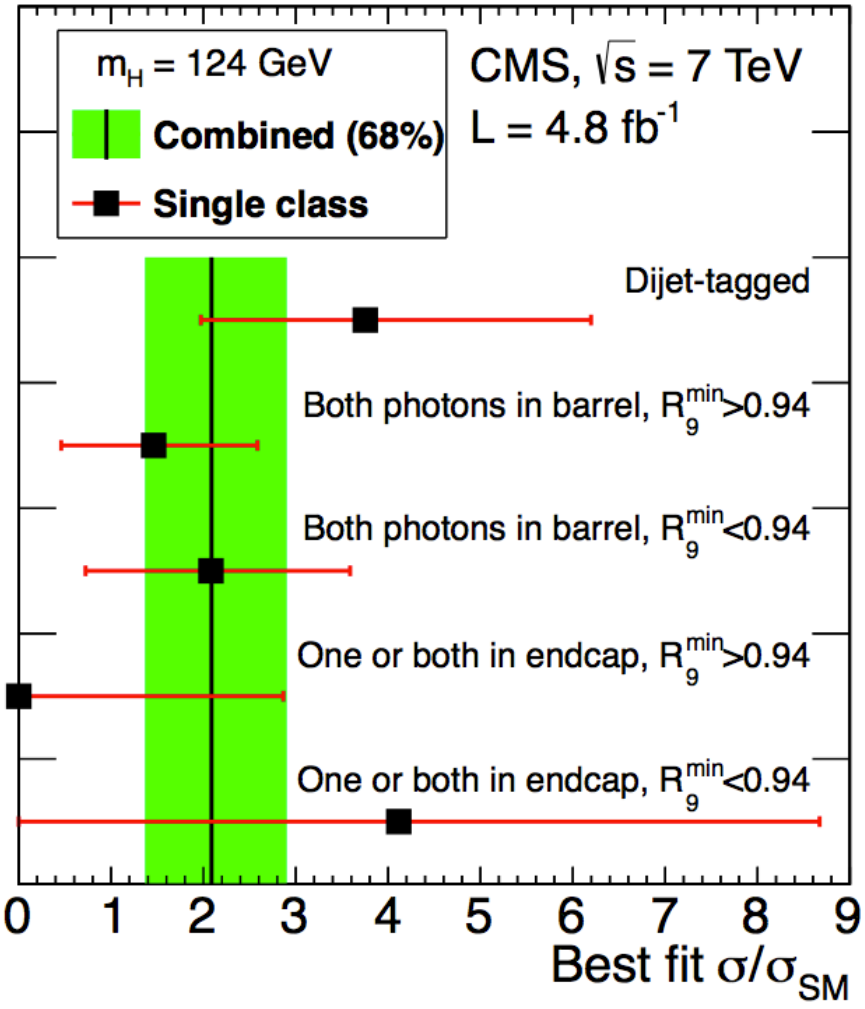
arXiv:1202.1487
Accepted by PLB



H→γγ fit of the signal strength in different channels

arXiv:1202.1487
Accepted by PLB

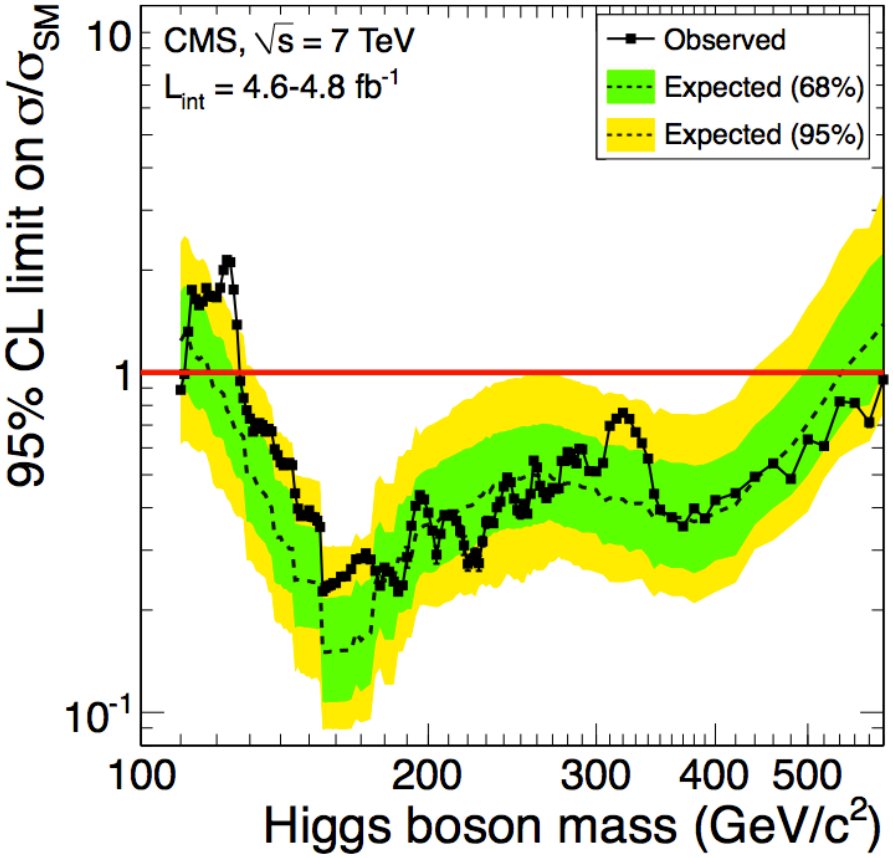
Fit of the signal strength
$\mu=\sigma/\sigma_{SM}$



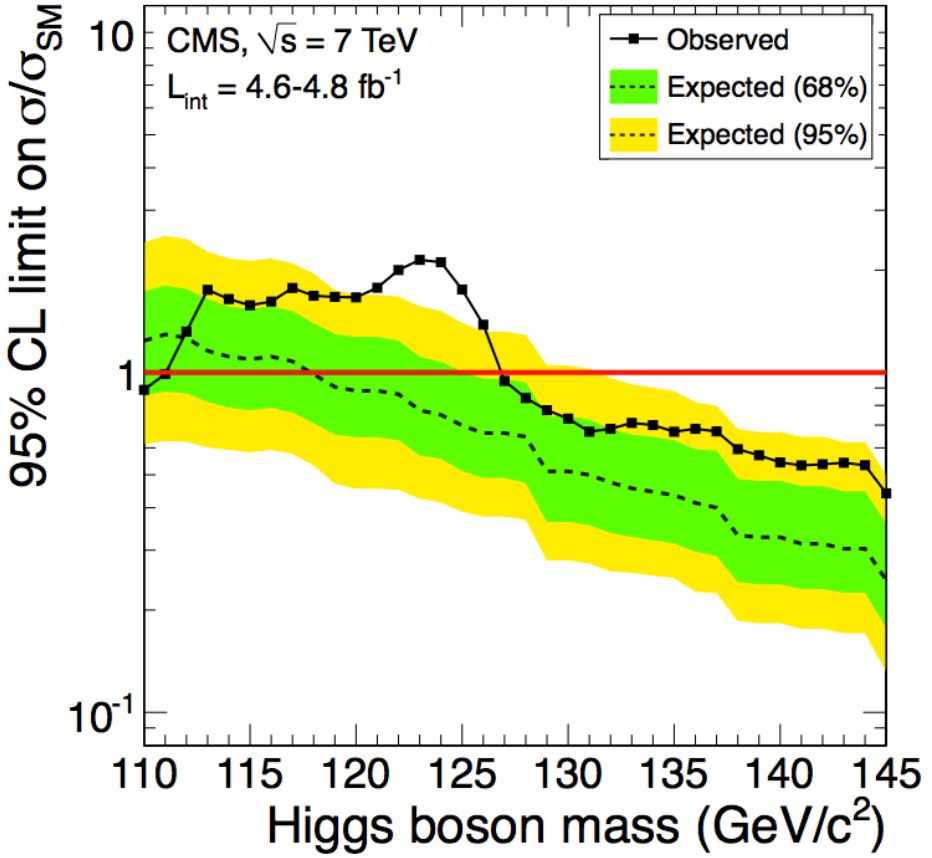
95% excluded cross section ratio to SM

arXiv:1202.1488
Accepted by PLB

Full mass range



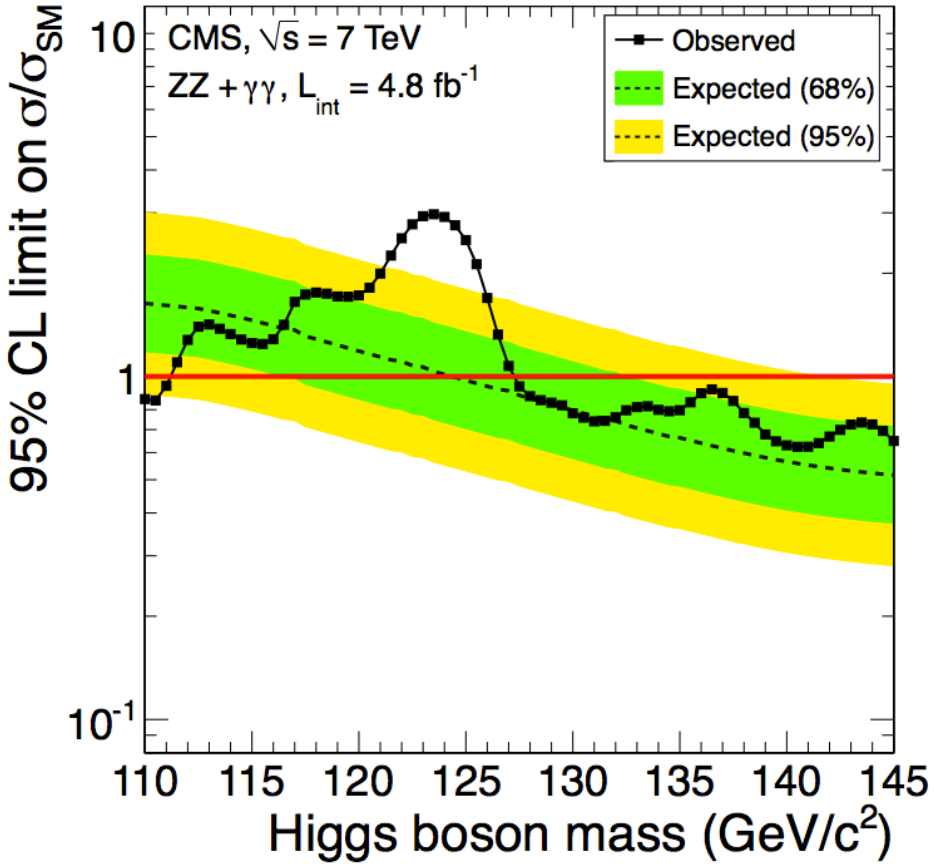
Low mass region



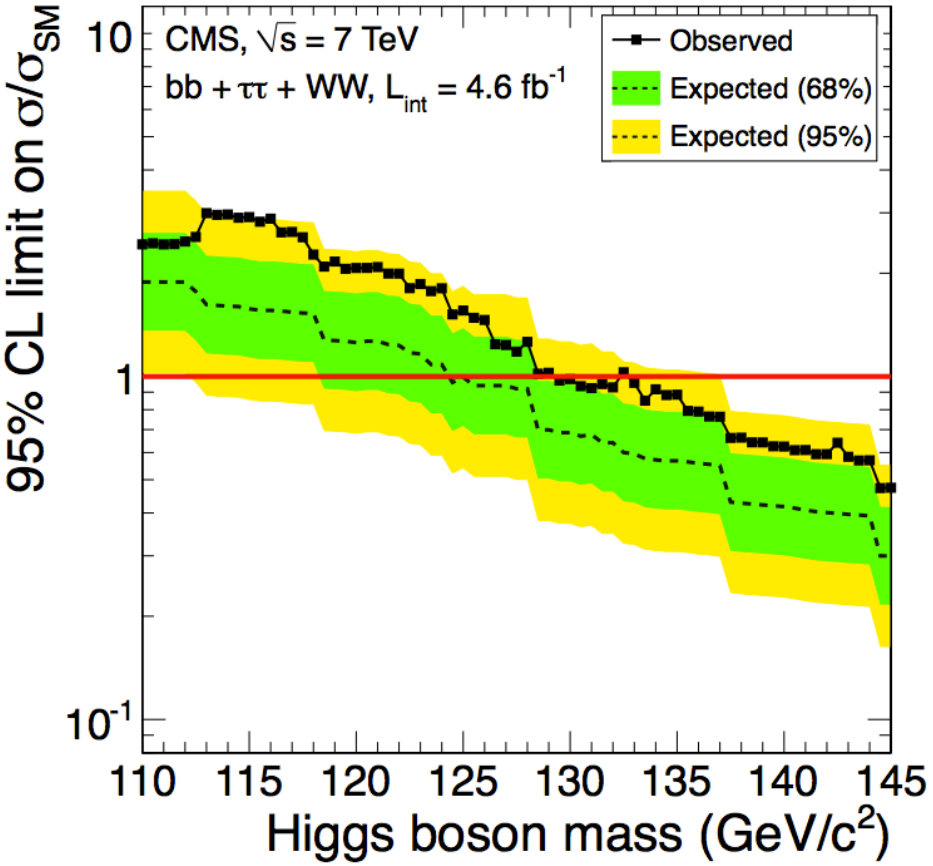
Partial combinations

arXiv:1202.1488
Accepted by PLB

ZZ+γγ

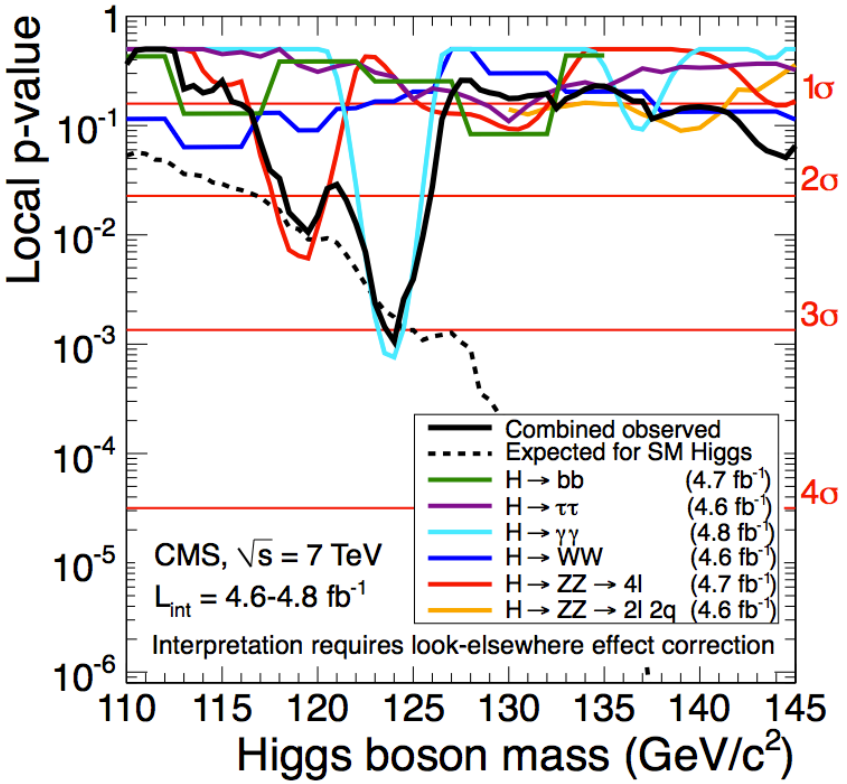


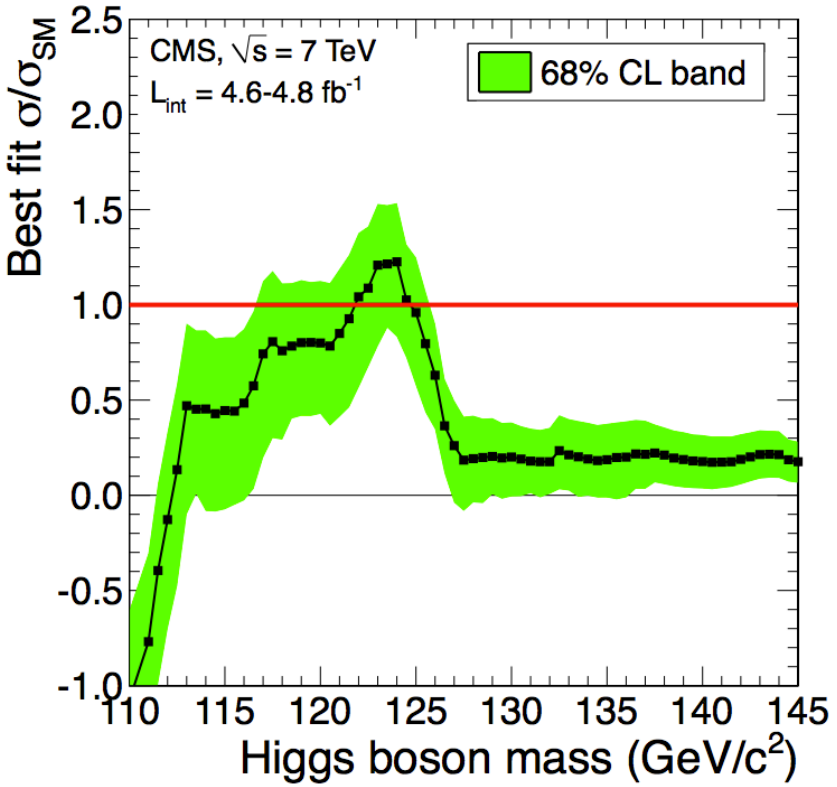
bb+tautau+WW



P-value and fitted μ

arXiv:1202.1488
Accepted by PLB





Local significance: 3.1 σ

Global p-value significance:

2.1 σ in [110-145] GeV

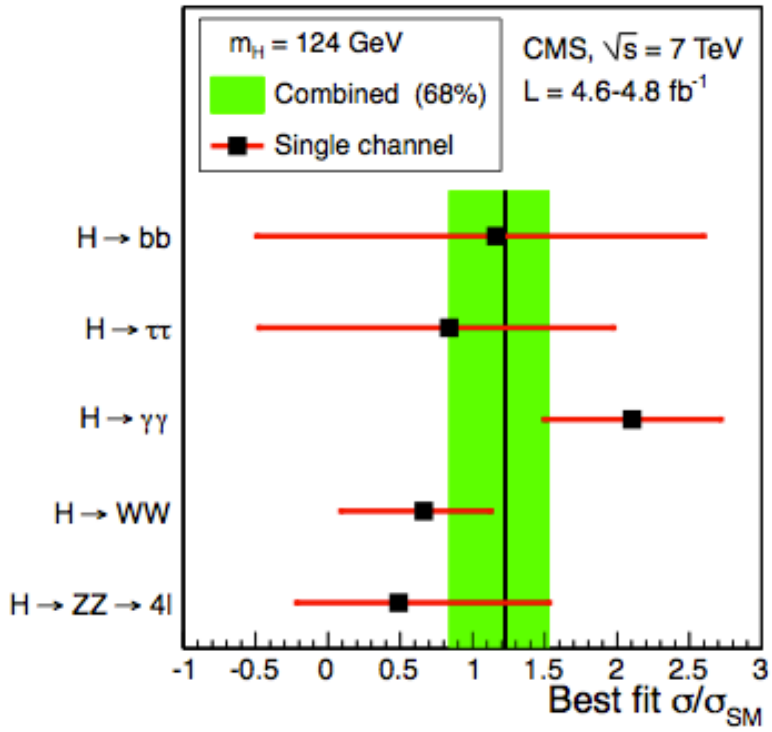
1.5 σ in [110-600] GeV

Largest excesses observed

- Fitted signal strength in the different channels and in combination

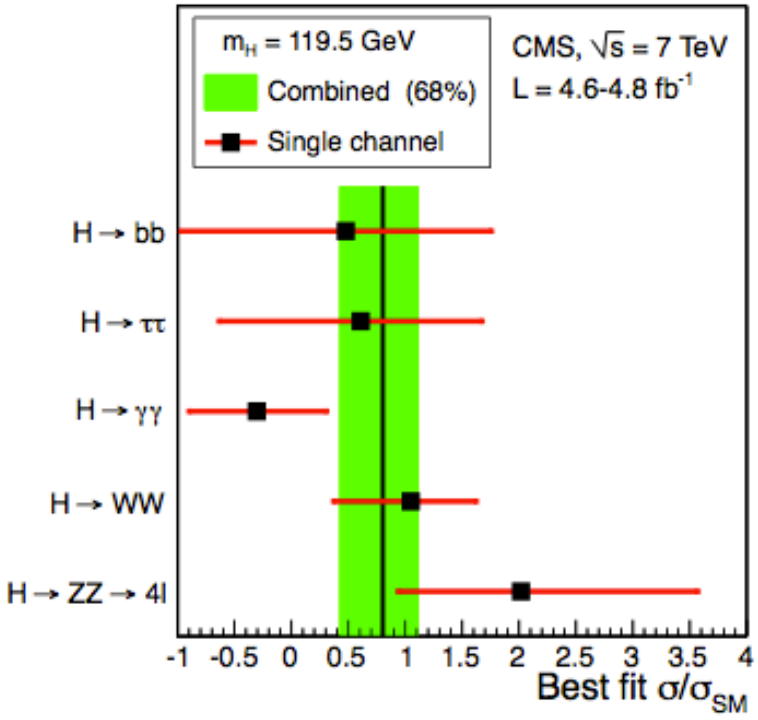
arXiv:1202.1488
Accepted by PLB

Highest excess at 124 GeV



- All investigated channels show consistent excess but the observed excess is also consistent with BG only

2nd highest excess at 119.5 GeV



- Local p-value significance ~2.3 σ
- Excess mainly coming from the 3 ZZ->4l events
- Deficit in that region in H->γγ