Higgs boson searches @CMS

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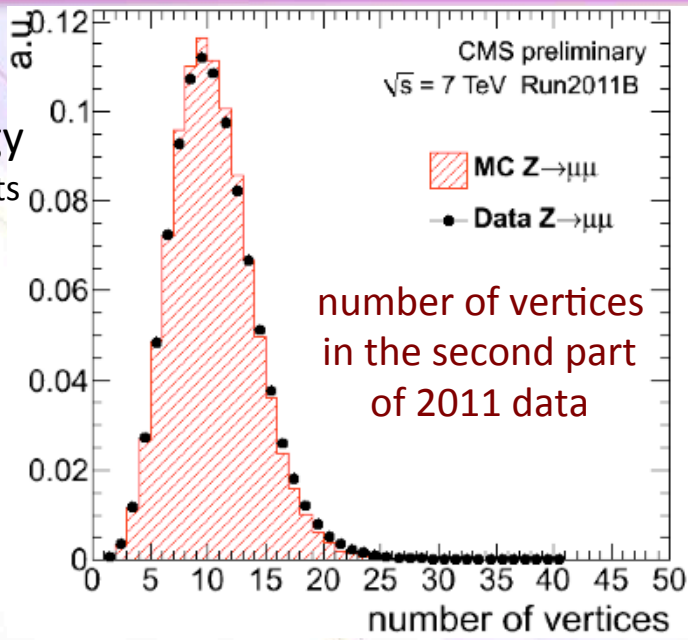
Phenomenology 2012
Symposium
- Pittsburgh 7-9 May 2012-

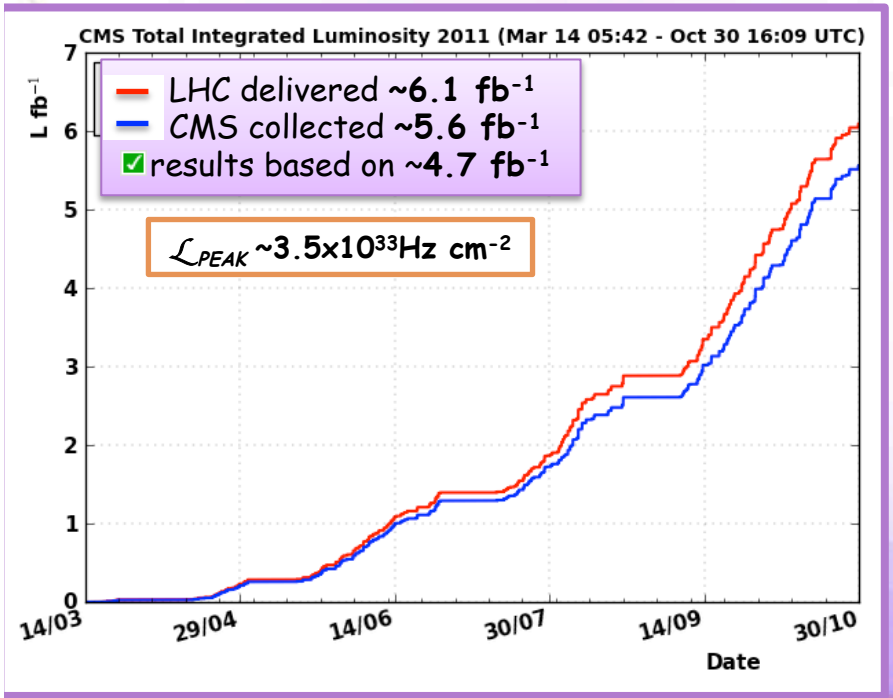
2011 dataset and reconstruction

excellent performance of LHC and CMS in 2011

- more than **5 fb^{-1}** of pp collisions collected @7 TeV CM energy
  surpassed (by x5!) goals for integrated luminosity delivered to experiments
- peak luminosity: $\mathcal{L}_{PEAK}$ ~ 3.5 x 10^{33} Hz cm^{-2}
- data taking efficiency: **~90%**
  average fraction of operational channels per subsystem >98.5%
- ~85-90% of collected data good for all analyses
  Higgs searches based on ~4.7fb^{-1}
- mean pileup: 10 events



number of vertices in the second part of 2011 data



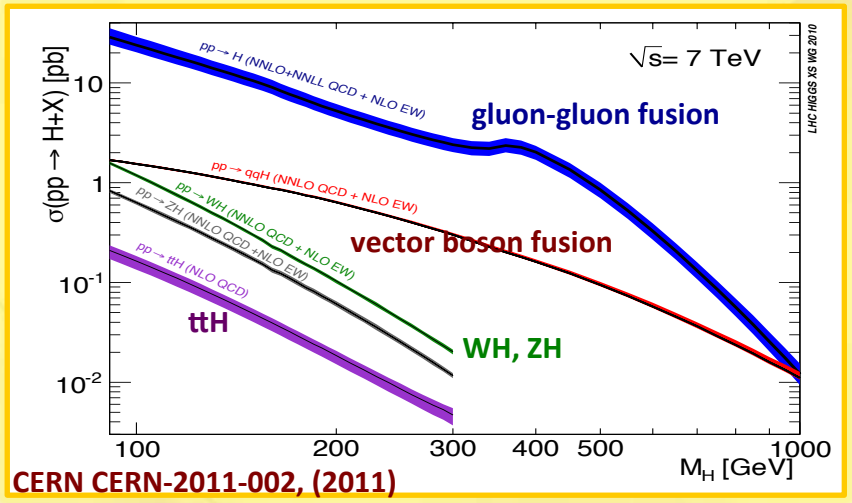
on top of reconstruction of physics objects (mu/e/photons...),
a **Particle Flow algorithm** (PF) has been developed

- ➢ provides a global event description
  in form of a list of particles
- ✅ large improvements in measuring
  - τ
  - jet
  - missing transverse energy (MET)

Higgs hunting: first step

production relative to σ_{tot}:

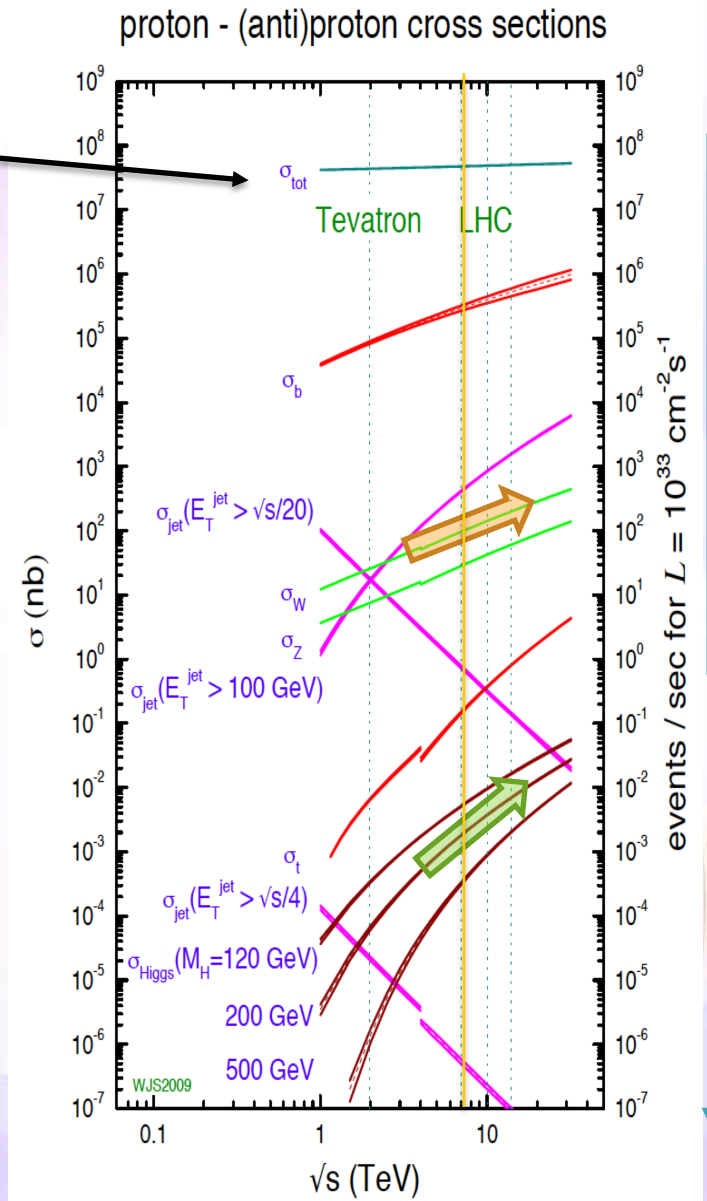
- bb @10^{-3}
- W→lν @10^{-6}
- **Higgs(M_H=110GeV/c^2) @ 10^{-11} !**

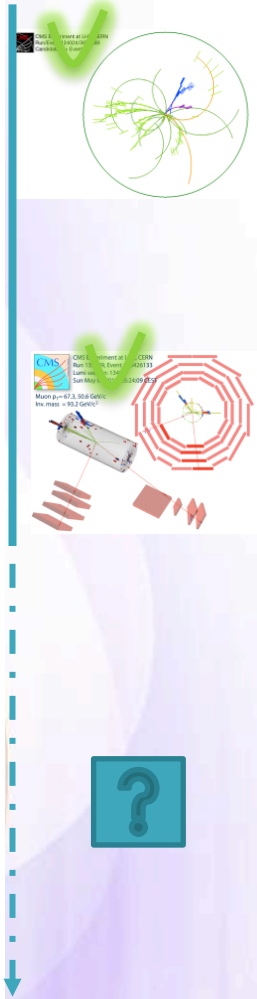


~15 MHz beam crossing,
but only ~300Hz tape writing: 1/10^5

- online fast and sophisticated selection is essential

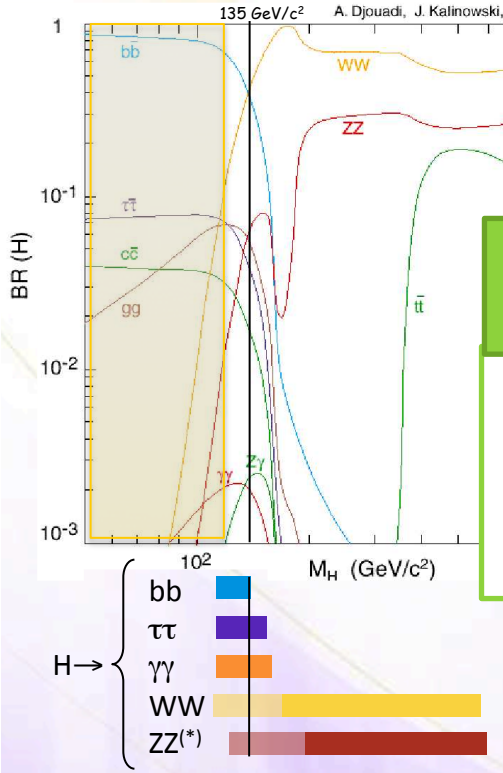
1st & high level trigger algorithms exploit main signatures of physics objects [electron, muon, jet, b-jet, τ, energy]





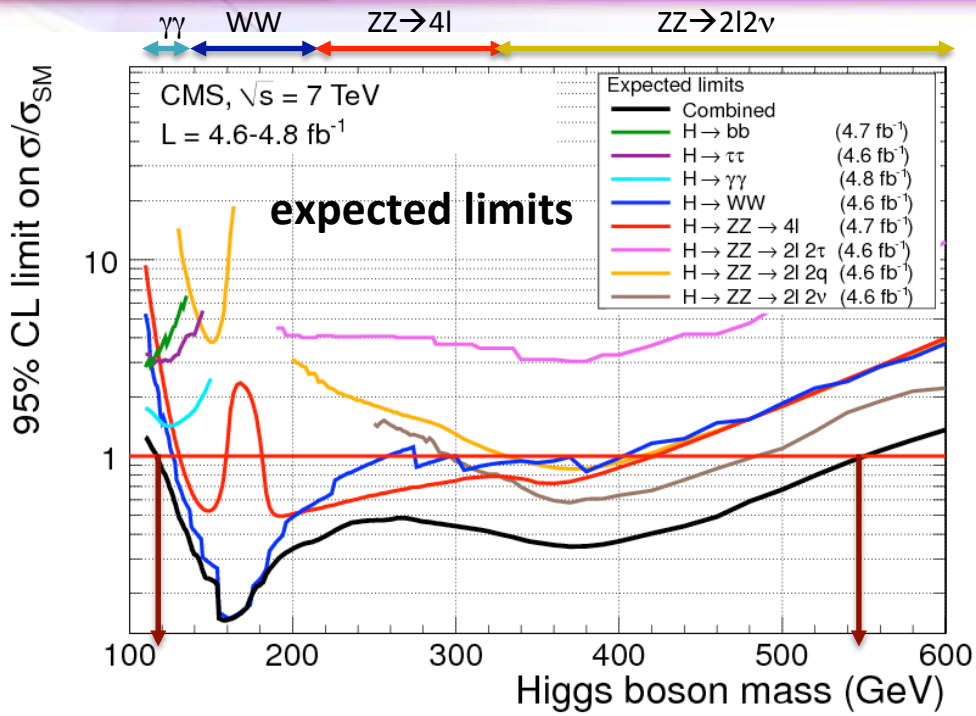
Higgs boson @CMS

different possible
production and decay mechanisms
for both **SM** and **beyond SM** Higgs particle(s)



search mass range
110-600 GeV/c²

95% CL <u>expected</u>
upper limit
on signal strength
114.5-543 GeV/c²



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

- **many different signatures and channels considered in CMS**
- emphasis on SM Higgs searches given today

high-mass Higgs

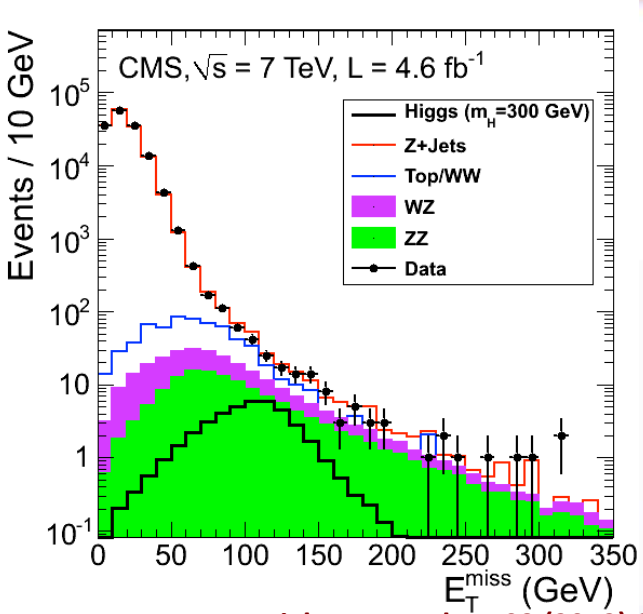
H→ZZ→2l2ν : *most sensitive channel for high mass search*

[BR 6 times larger than ZZ→4l]

neutrinos implies <u>mass resolution 7%</u>

only accessible for high mass ($M_H \geq 250$ GeV/c^2):

- the two Z bosons are boosted
- large MET due to invisible decay

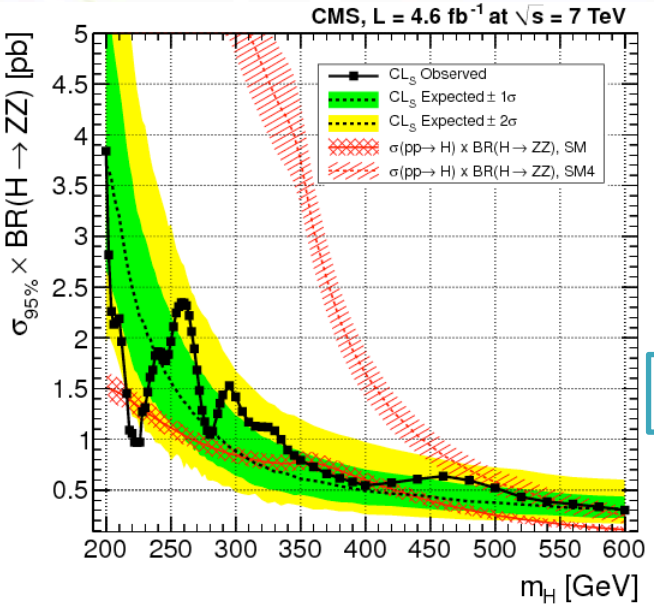


J. High Energy Phys. 03 (2012) 040

no excess observed in data

expected 95% exclusion for M_H in [290;480] GeV/c^2

observed 95% exclusion for M_H in [270;440] GeV/c^2



H→ZZ→2l2q

two opposite-charge, same-flavour leptons consistent w/ M_Z

two jets in Z peak, within tracking acceptance (b-tagging)

- analysis divided in 0/1/2 b-tag event categories
- use of quark-gluon discriminant based on jet shape/constituents
- additional use of angular likelihood discriminant at high mass

sensitivity approaching SM cross-section in high mass region

Higgs masses in the SM4 model w/ the fourth generation are excluded in the range [154;161] and [200; 470] GeV/c2

J. High Energy Physics 04 (2012) 036

searches in the full range (I)

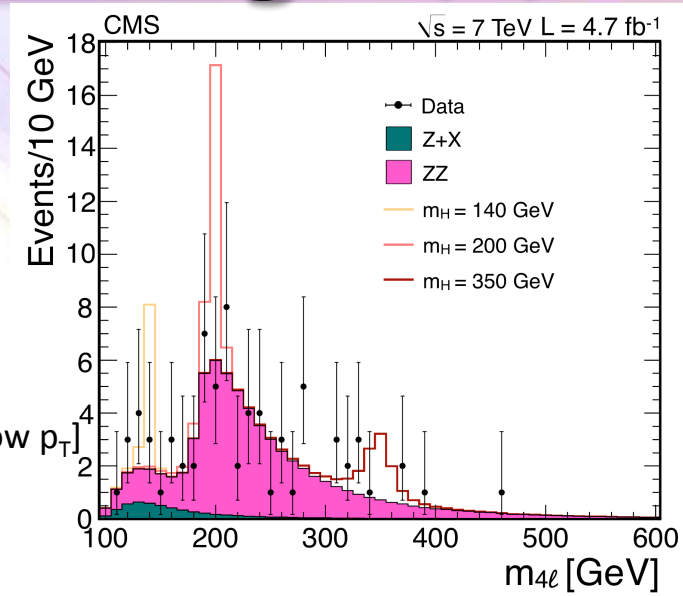
H→ZZ*→4l [golden mode]: *max sensitivity @180 GeV/c²*

4 isolated high p_T leptons → *clean signature, narrow peak*

- consistent with *Z* decays
- from same vertex
- fit mass peak w/ **resolution: 2-4 GeV/c²** [~10-15% in the 2l2τ channel]
- little background, main comes from non-resonant *ZZ* [*Zbb* and top]

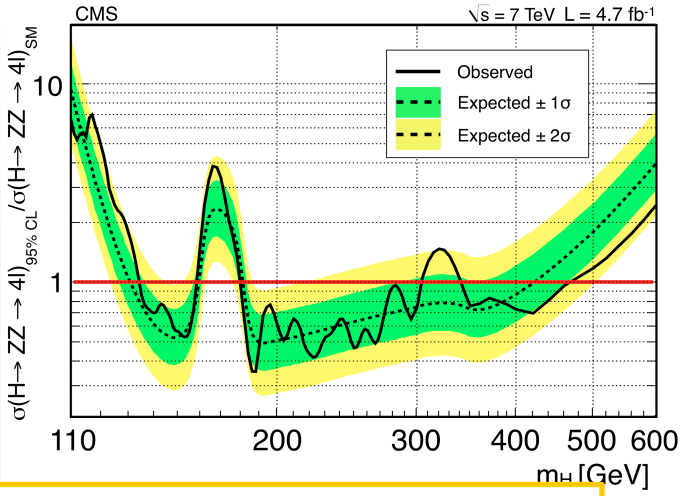
Most important aspect:

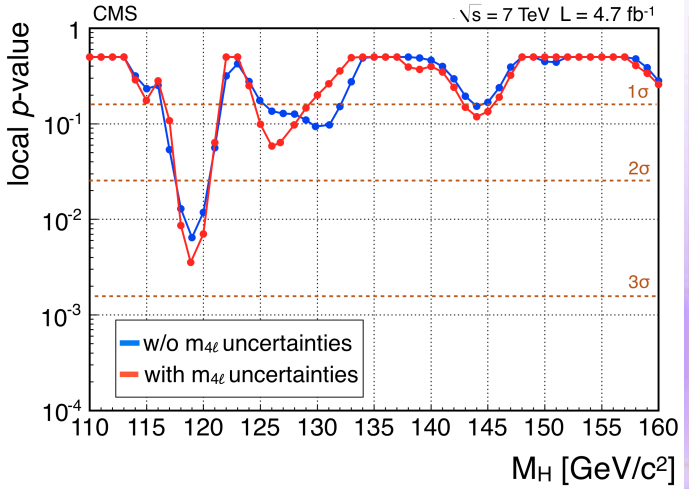
highest possible lepton reconstruction and id efficiency [down to very low p_T]



observed events overall consistent w/ expectations
[100;600]: 72 observed, expected 67.1 ± 6, mild excess

95% C.L. exclusion for M_H in [134;158], [180;305] and [340;465] GeV/c²





[100;160]:
13 observed,
expected 9.5 ± 1.3, excess
some clustering around ~119 and ~125 GeV /c²

p-values (@ 119 GeV/c²)
- local significance is 2.5 reduced to 1.1 after Look Elsewhere Effect (LEE)
- signal strength is about 2 ± 1 times the SM

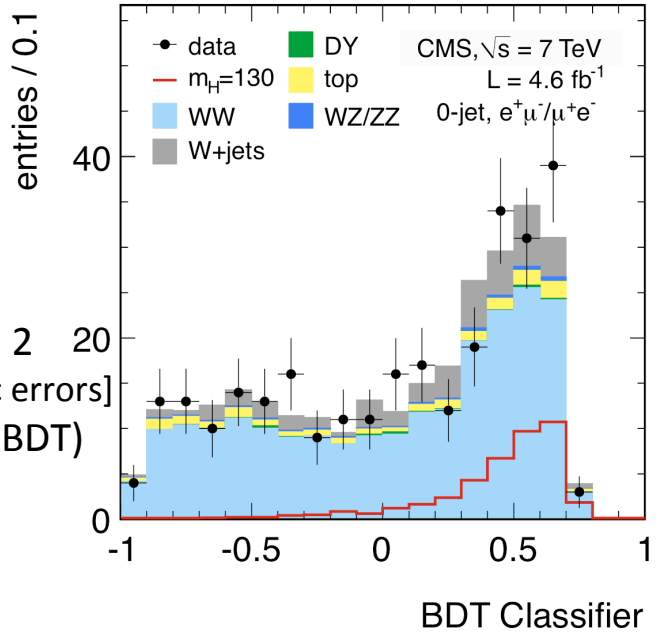
Phys. Rev. Lett. 108, 111804 (2012)

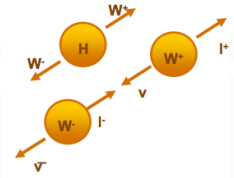
searches in the full range(II)

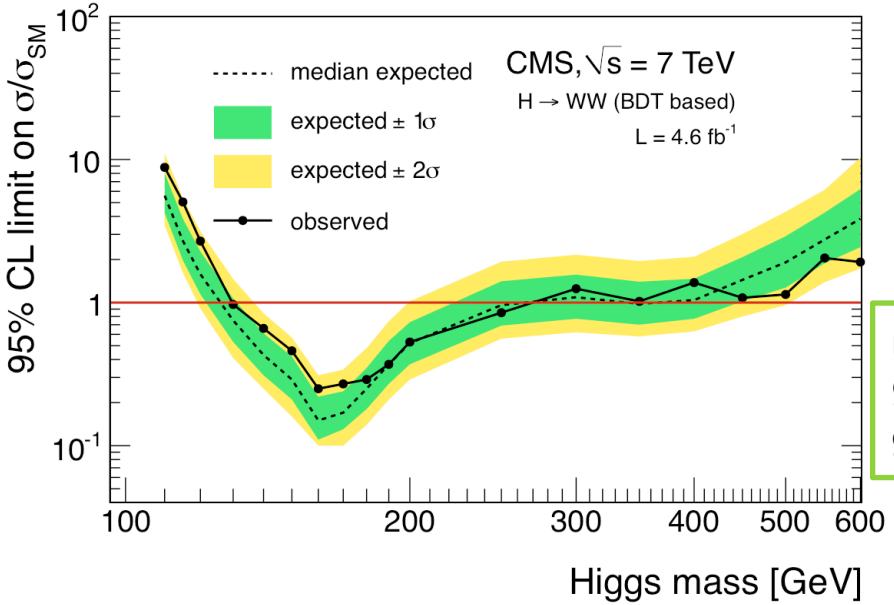
H→WW*→2l2ν : *max sensitivity @160 GeV/c²*

high BR, clean signature, no mass peak

- most sensitive channel around 2xM_W [125 ≤ M_H ≤ 200 GeV/c^2]
- 2 opposite charged, high p_T isolated leptons (leptons only *e, μ)*
  + MET (neutrinos)
- **no narrow mass peak (mass resolution ~20%)**
  -dominant (irreducible) background from pp→WW production
- events are classified according the exclusive jet multiplicity: 0, 1 and 2
  [most sensitive channel is eμ in 0-jet bin higher S/B and smaller systematic errors]
- both a "cut-and-count" and a multivariate (Boosted Decision Tree – BDT) analysis are performed







no evidence of Higgs boson in the full mass range
95% C.L. expected exclusion for M_H in [127-270] GeV/c^2
95% C.L. observed exclusion for M_H in [129-270] GeV/c^2

Phys. Lett. B 710 (2012) 91-113

low-mass Higgs: H→γγ

search-range: [110 - 150] GeV/c²

max sensitivity: < 125 GeV/c² → sensitivity close to 1

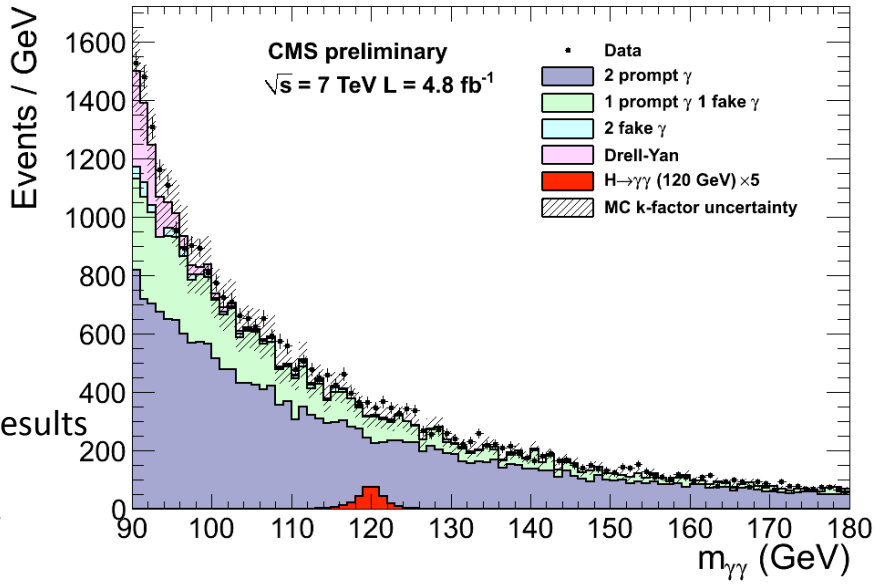
- **narrow peak → very good mass resolution 1-2%**
- small BR: ~2x10^{-3}
- 2 isolated high E_T photons

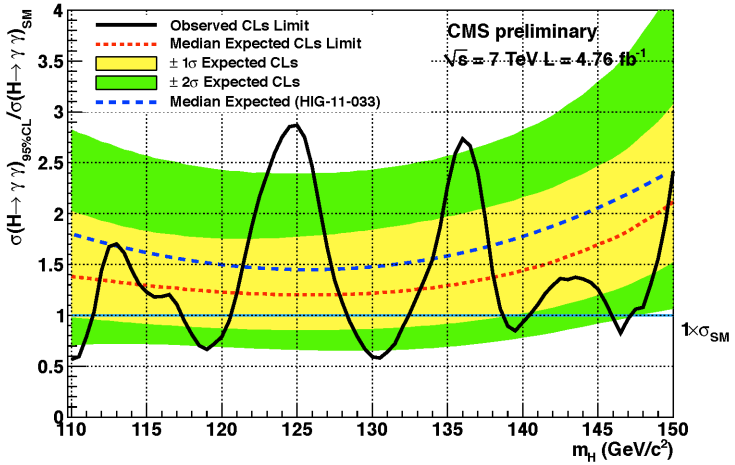
BG is estimated by fitting to a polynomial in the full mass range (3rd to 5th order)

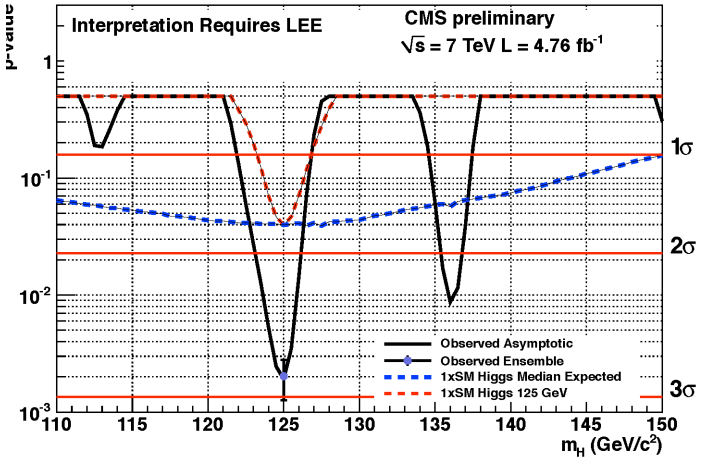
– possible BG bias is always less than 20% of the statistical error

– different BG estimation in cross check analysis gives consistent results

- also search for Vector Boson Fusion production process (→2 additional jets) has lower yield but larger purity







largest excess ~125 GeV/c²

- local significance 2.9 σ
- global significance 1.6 σ

the fermiophobic Higgs excluded in the mass range [110; 124] and [128;136] GeV/c²

excess is larger than SM expectation, but statistically not inconsistent

Phys. Lett. B 710 (2012) 403-425 HIG-12-001 HIG-12-002

low-mass Higgs

H→ττ : *sensitive to both SM and neutral MSSM Higgs boson*

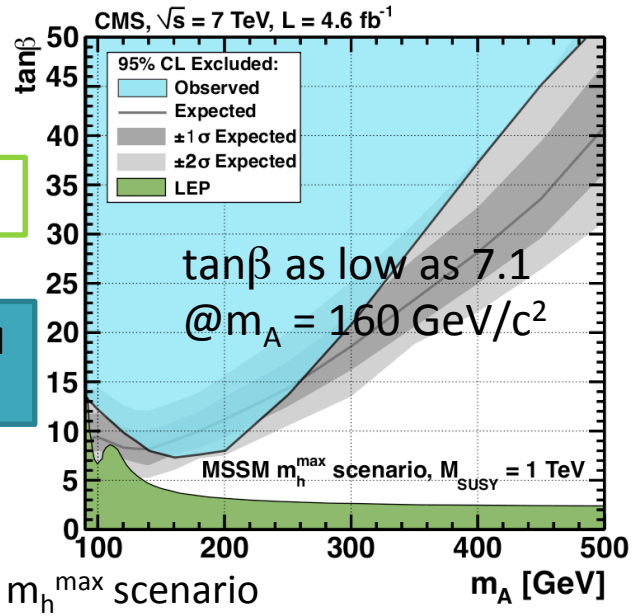
- 4 different SM sub-channels: inclusive / VBF / boosted / WH
  - VBF channel most sensitive
- 1 MSSM channel: b-association

excluded at 95% CL 3-7 x σ_{SM}

- require 2 taus (at least one decaying leptonically) :
  e-μ, μ-τh and *e-τh, μμ*

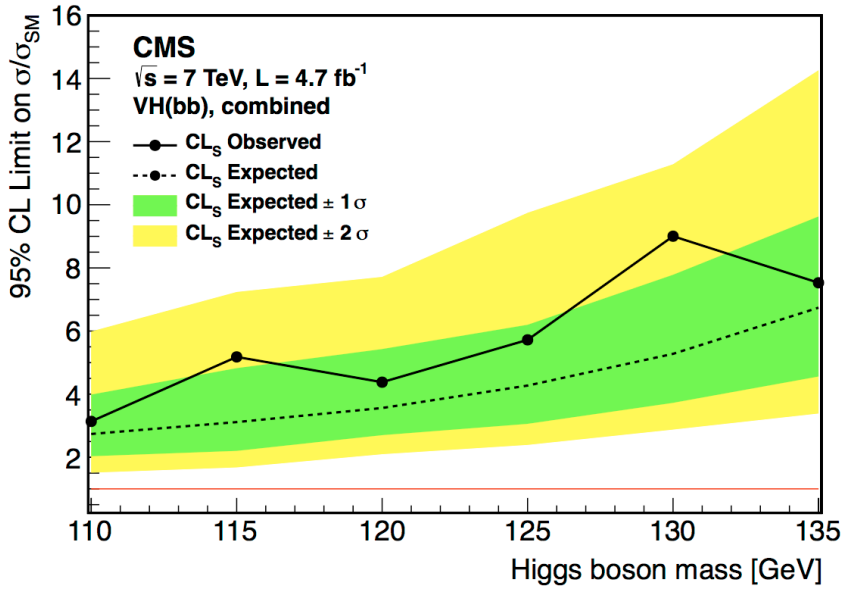
➡ **no narrow mass peak**
(invariant mass resolution **σ_M ~20%**)

stringent new bounds in the MSSM ($\tan\beta$,m_A) parameter space



m_h^{max} scenario

no significant excess of events above the expectation from background is observed



H→bb

- exploit VH associated production (0.66 and 0.36 pb)
  - W->eν,μν
  - Z->ee,μμ, νν
- back-to-back topology: $\Delta\phi_{VH}>3$
- large boost (p_T^V>100-160 GeV)
- tight b-tagging, ME_T cut
- **mass resolution ~10%**

excluded at 95% CL 3-9 x σ_{SM}

The limits are based on the observed event count and background estimate in signal-enriched regions defined by the output discriminant of a multivariate algorithm (BDT)

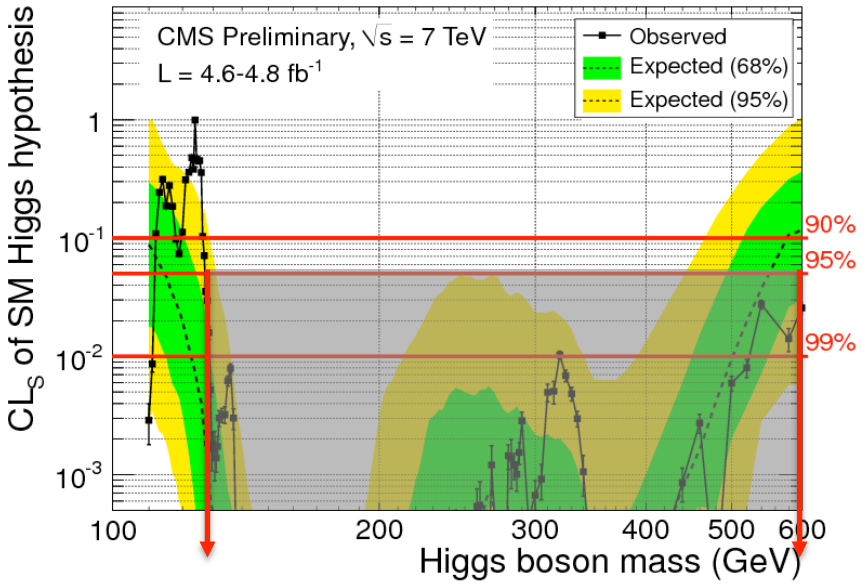
Phys. Lett. B 710 (2012) 284–306

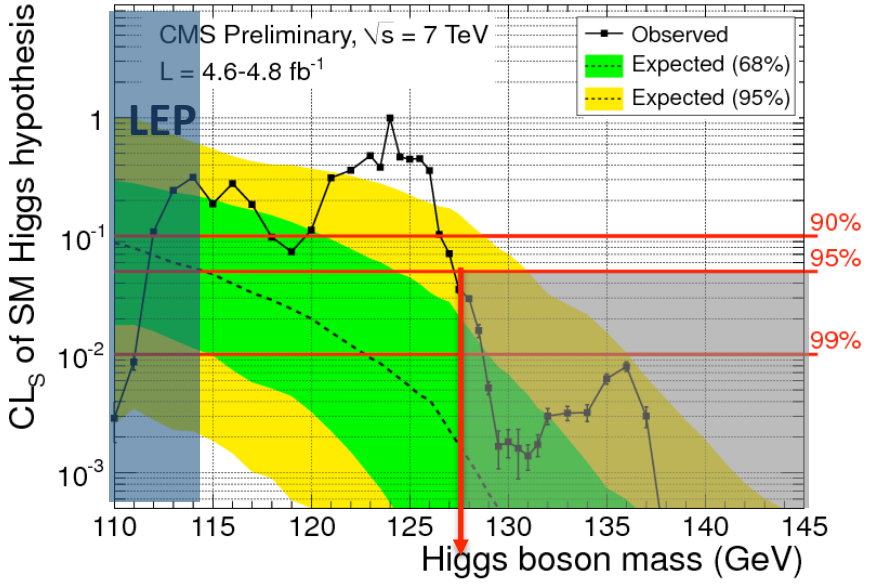
combined exclusion CL_S

search-range: [110 - 600] GeV/c²

all the modes analyzed by CMS with 4.7 fb-1 are included [~50 exclusive sub-channels]

Frequentist CLs with profiled likelihood test statistics and log-normal treatment of nuisance parameters





Expected: 95% exclusion M_H in [114.5;543] GeV/c²

Observed: **95% exclusion** M_H in **[127.5;600] GeV/c²**

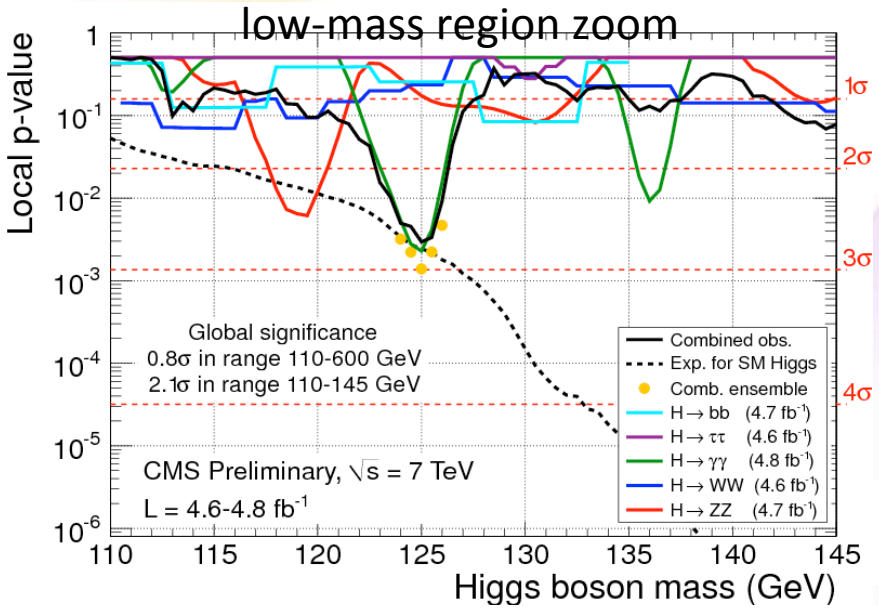
99% exclusion M_H in [129;525] GeV/c²

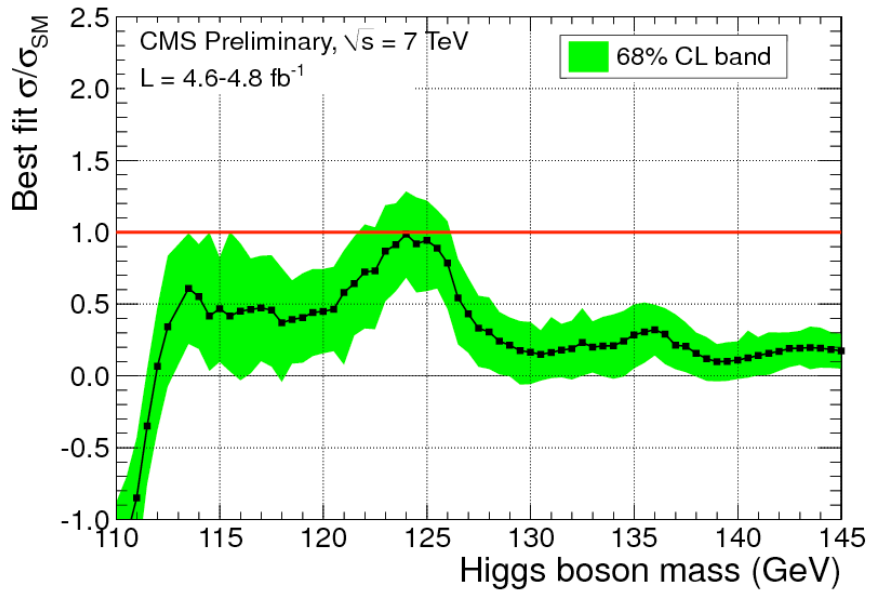
- 95% allowed mass range: **114.4-127.5 GeV/c²**

observed lower limit higher than expected

because of excess in data at low mass [around 125GeV/c²]

combined local p-value





minimum p-value observed at 125 GeV/c² :

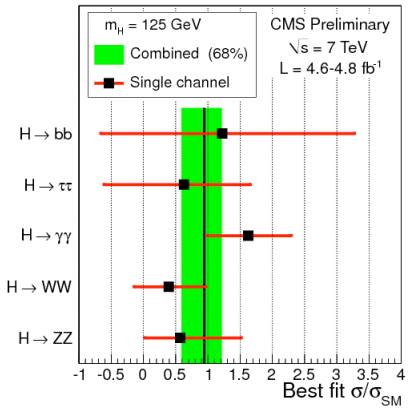
- **local significance 2.8 σ**
  similar significance expected from signal
- estimated **global significance**:
  0.8 σ in [110-600] GeV/c²
  2.1 σ in [110-145] GeV/c²

the fitted σ of the excess near 125 GeV/c²
is consistent w/ the SM Higgs boson expectation

previously reported excess ~119.5GeV/c² in the H→ZZ*→4l channel washed out by the gg one

at low mass several channels show modest excess

- at 125 GeV/c²
  the mass-sensitive channels show an excess consistent w/
  - ❑ signal expectations
  - ❑ signal and background-only hypothesis

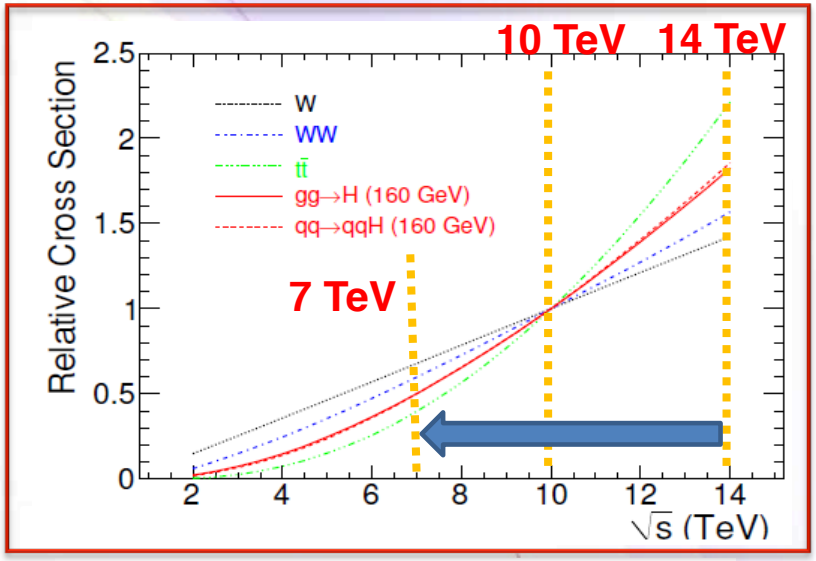


more data needed

conclusions

SM scalar boson search in >10 independent channels w/ the full 2011 dataset

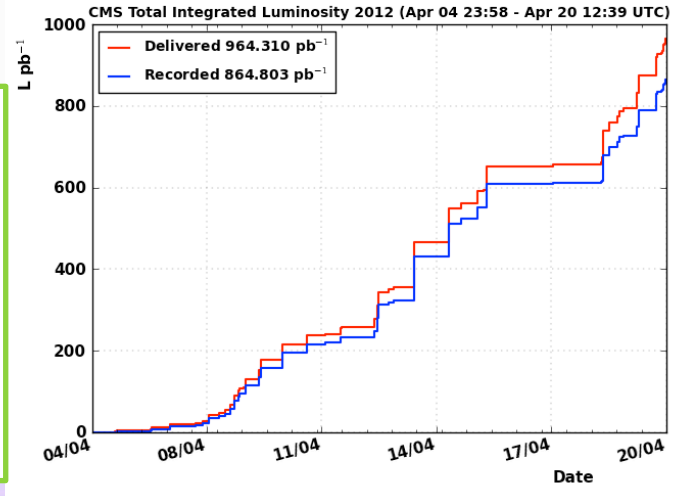
- ☑ **excluded the most part of the Higgs mass range in [127.5;600] GeV/c² at 95% CL**
- ☑ **observe a modest excess around 125 GeV/c²**
  - local significance 2.8 σ
  - global significance 0.8 σ (in the full search range)
    and 2.1 σ (in 110-145 GeV/c²)
  - the excess is consistent both w/
    - ❑ background fluctuation
    - ❑ a Higgs boson with mass ~125 GeV/c²
- if the Higgs exists,
  limited between 114.5 and 127.5 GeV/c²



- **more data are needed to come to a conclusion**
- **2012 data are the decisive one !**

In 2012 LHC is running

- ☑ @√s = 8TeV CM energy
  - Higgs cross section rises by a factor 2 at √s = 8 TeV ☺
- ☑ high luminosity [~1fb^{-1}/week]
  - should collect ~15fb^{-1}
- **should be able to discover or exclude the SM scalar boson down to the LEP limit**



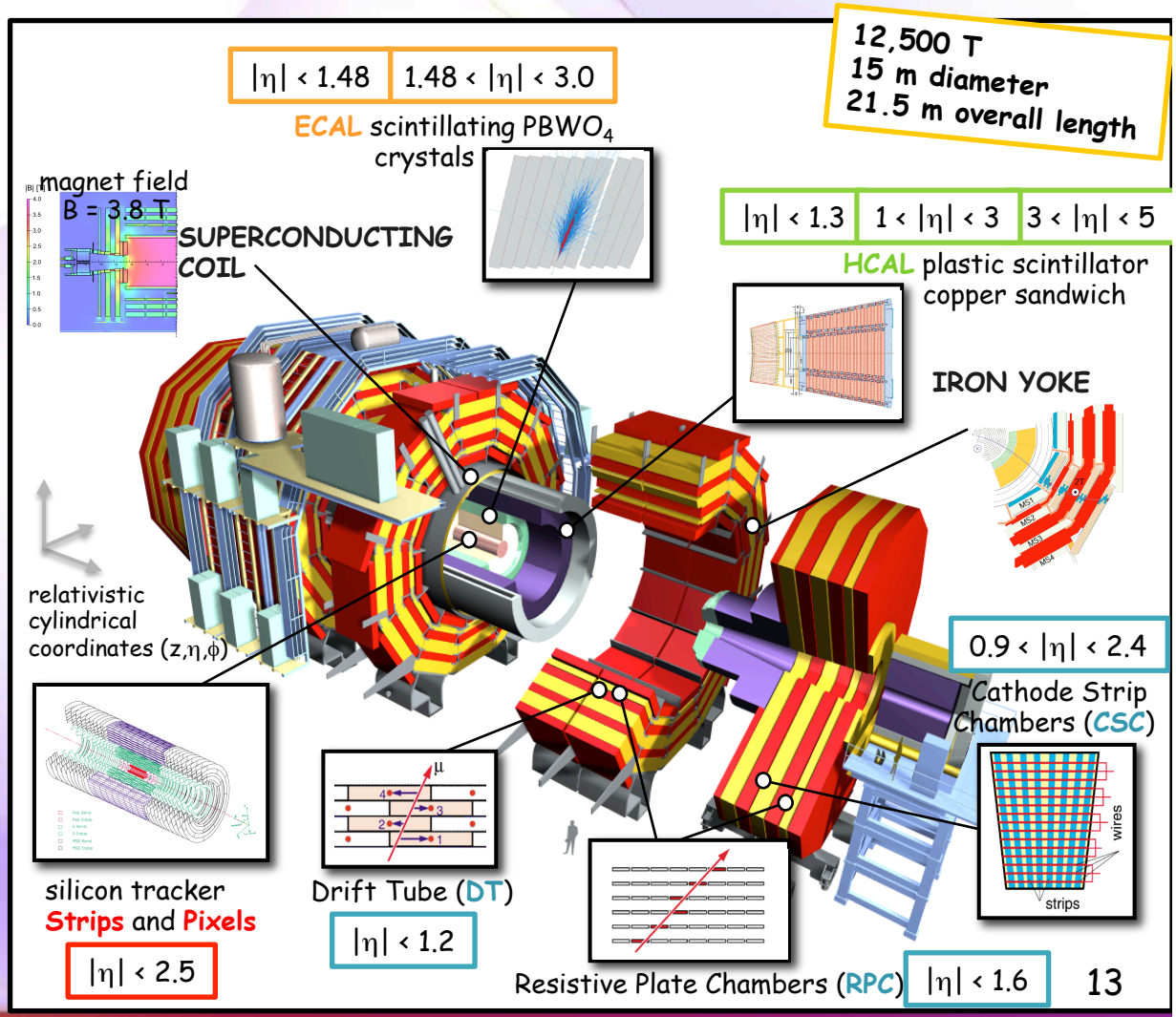
BACKUP

the CMS detector

Compact **M**uon **S**olenoid [compact 4π experiment]

→ design based on:

- high intensity B field
  3.8T superconducting solenoid
- high precision
  silicon tracker
  ($\sigma/p_T \approx 1.5 \bullet 10^{-4}\ p_T \oplus 0.005$)
- high precision homogeneous
  EM calorimeter
  $\sigma/E \approx 2.8\%/\sqrt{E} \oplus 12\%/E \oplus 0.3\%$
- hermetic calorimeter
  $\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$
- redundant
  muon spectrometer (B=2T)
  $\sigma/p_T \approx 1\%$ @ 40 GeV



Fall 2010 forecasts

In 2010, CMS predicted that

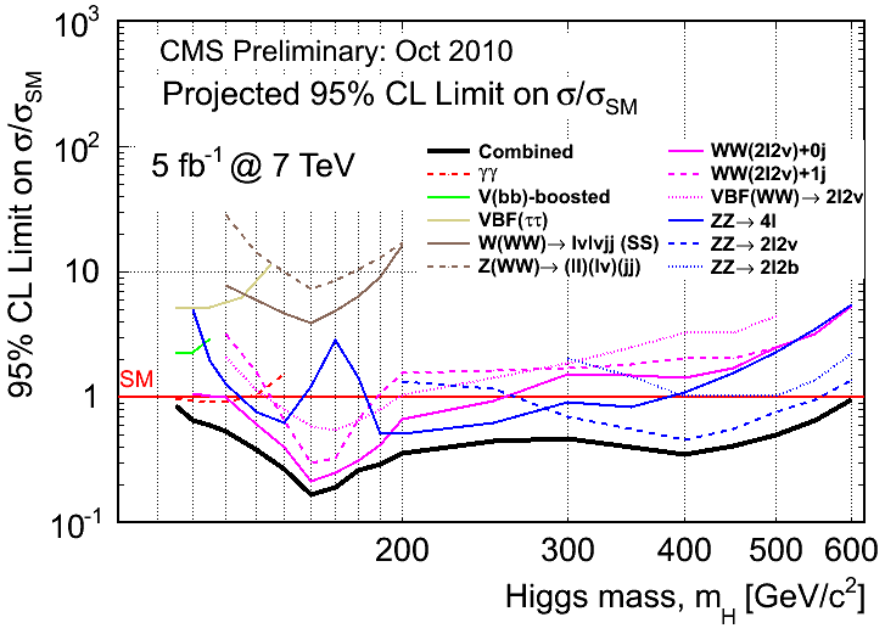
5fb^{-1} of 7 TeV data

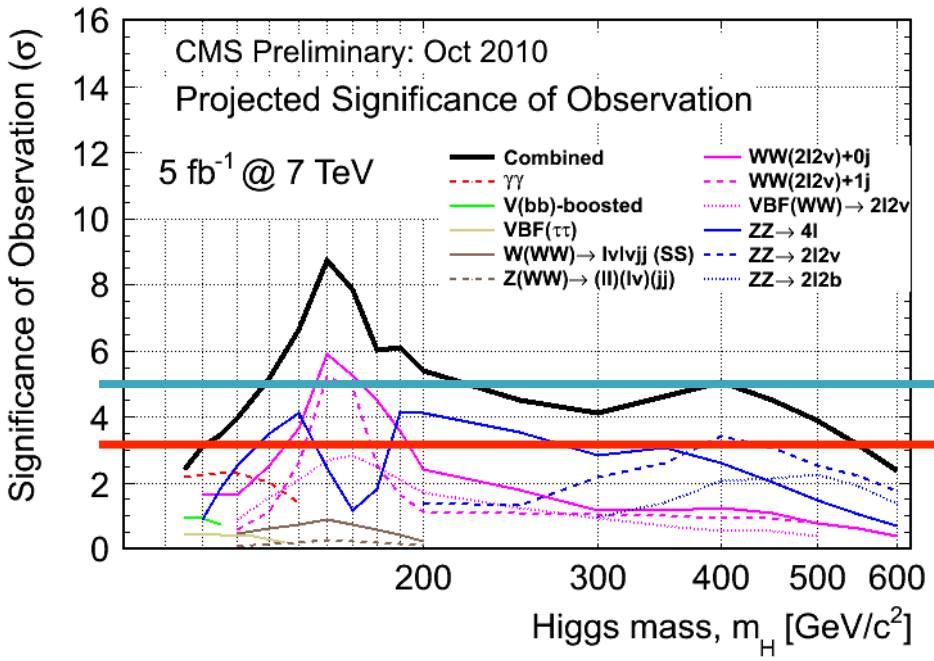
would provide a 95% exclusion

across the full mass range, if the Higgs is not there

➢ at low mass,

reliance on γγ decay mode found crucial for this





or a discovery, for 137<M_H<220 GeV

➢ at low mass, γγ and ZZ decay modes both necessary to achieve that goal

or at least firm (>3σ) evidence,

for all other mass values below 600 GeV…

Nuts and Bolts of Higgs results

All Higgs searches from CMS follow the recipe of a joint working group with ATLAS.
The method is CL_s and the test statistics is a profile log-likelihood ratio. The recipe is as follows:

1) One writes a global likelihood function, whose parameter of interest is the "signal strength modifier" $\mu=\sigma/\sigma_{SM}$. If **s** and **b** denote signal and background, and **θ** is a vector of systematic uncertainties, one can generically write for a single channel:

$$\mathcal{L}(\text{data}\,|\,\mu,\theta) = \text{Poisson}\,(\,\text{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,)\cdot p(\tilde{\theta}|\theta)$$

Note that θ has a "prior" coming from (sometimes hypothetical) auxiliary measurements.

In L one may combine many different search channels; e.g., where counting experiments are performed one includes the product of the Poisson factors:

$$\prod_i \frac{(\mu s_i+b_i)^{n_i}}{n_i!}\,e^{-\mu s_i-b_i}$$

Nuts and Bolts of Higgs results

2) A profile likelihood test statistics q_μ is defined as $\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}$

A constraint is posed on the MLE $\mu^$ to be confined in $0<=\mu^<=\mu$, which avoids negative solutions and ensures that best-fit values *above* the signal hypothesis μ are not counted as evidence against it.

3) ML estimates θ_μ for H_1 and θ_0 for H_0 are then computed, given the data

4) Pseudo-data is then generated for the two hypotheses, using the above MLE of the nuisance parameters. With the pseudo-data, one constructs the pdf of the test statistics given a signal of strength $\mu(H_1)$ and $\mu=0$ (H_0).

5) One can then compute the integrals defining p-values for the two hypotheses:

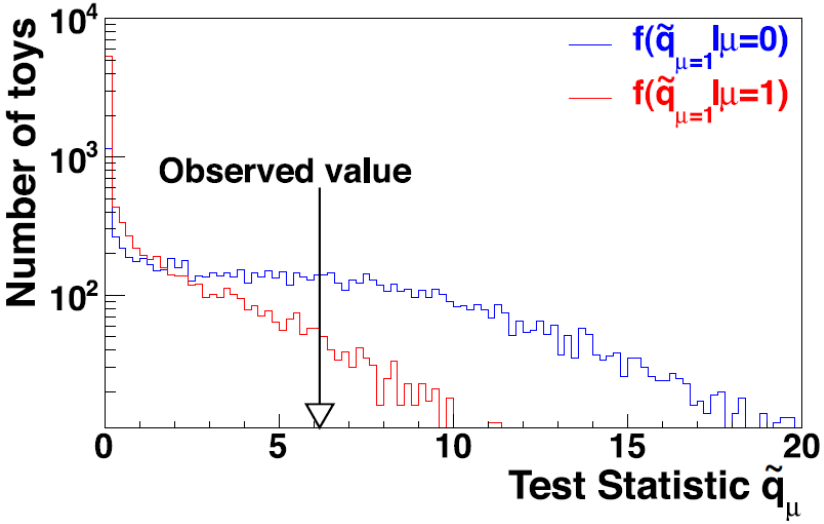
$$p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \,|\, \text{signal+background}) = \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|\mu, \hat{\theta}_\mu^{\text{obs}})\, d\tilde{q}_\mu$$

$$1 - p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \,|\, \text{background-only}) = \int_{q_0^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|0, \hat{\theta}_0^{\text{obs}})\, d\tilde{q}_\mu$$

6) Finally one obtains:

$CL_s = p_\mu/(1-p_b)$

→Mass hypotheses are excluded if $CL_s < 0.05$



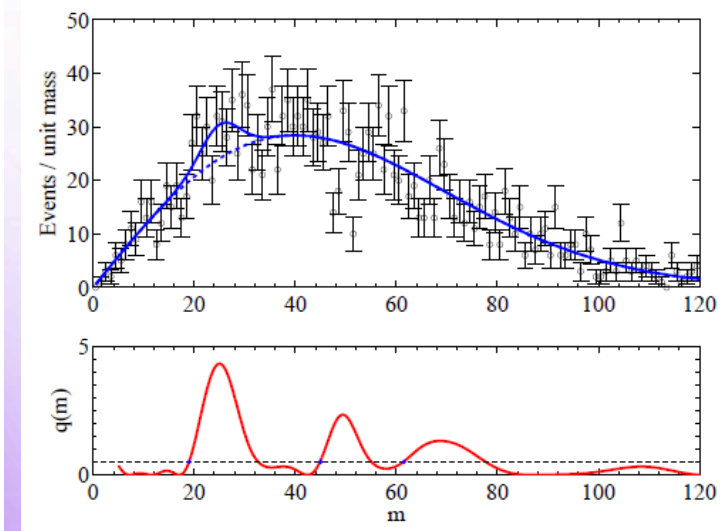
Significance: LEE and upcrossings

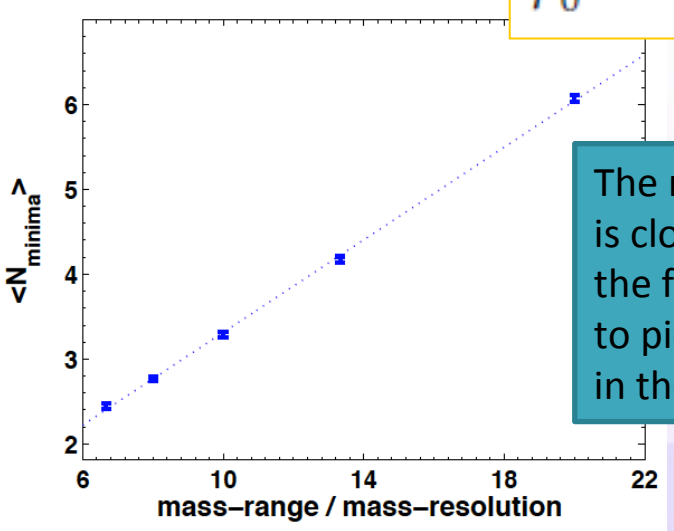
The look-elsewhere effect is well-known and rules of thumb or toys are often used to "rescale" the significance of a background fluctuation.

In complex cases such as the Higgs combination the above are insufficient measures. One instead counts the number of "upcrossings" of the distribution of p-values (or the value of the test statistics itself) above some reference value, as a function of mass. Its wiggling tells one how many places one has been searching in

The number of times that the test statistics crosses some reference point is a measure of the trials factor. One estimates the global p-value with the number N_0 of upcrossings from a minimal value of the q_0 test statistics (for which $p=p_0$) by the formula

$$p_0^{\text{global}} \sim p_0^{\text{min}} + N_0\, e^{-\frac{1}{2} Z^2_{\text{max}}}$$

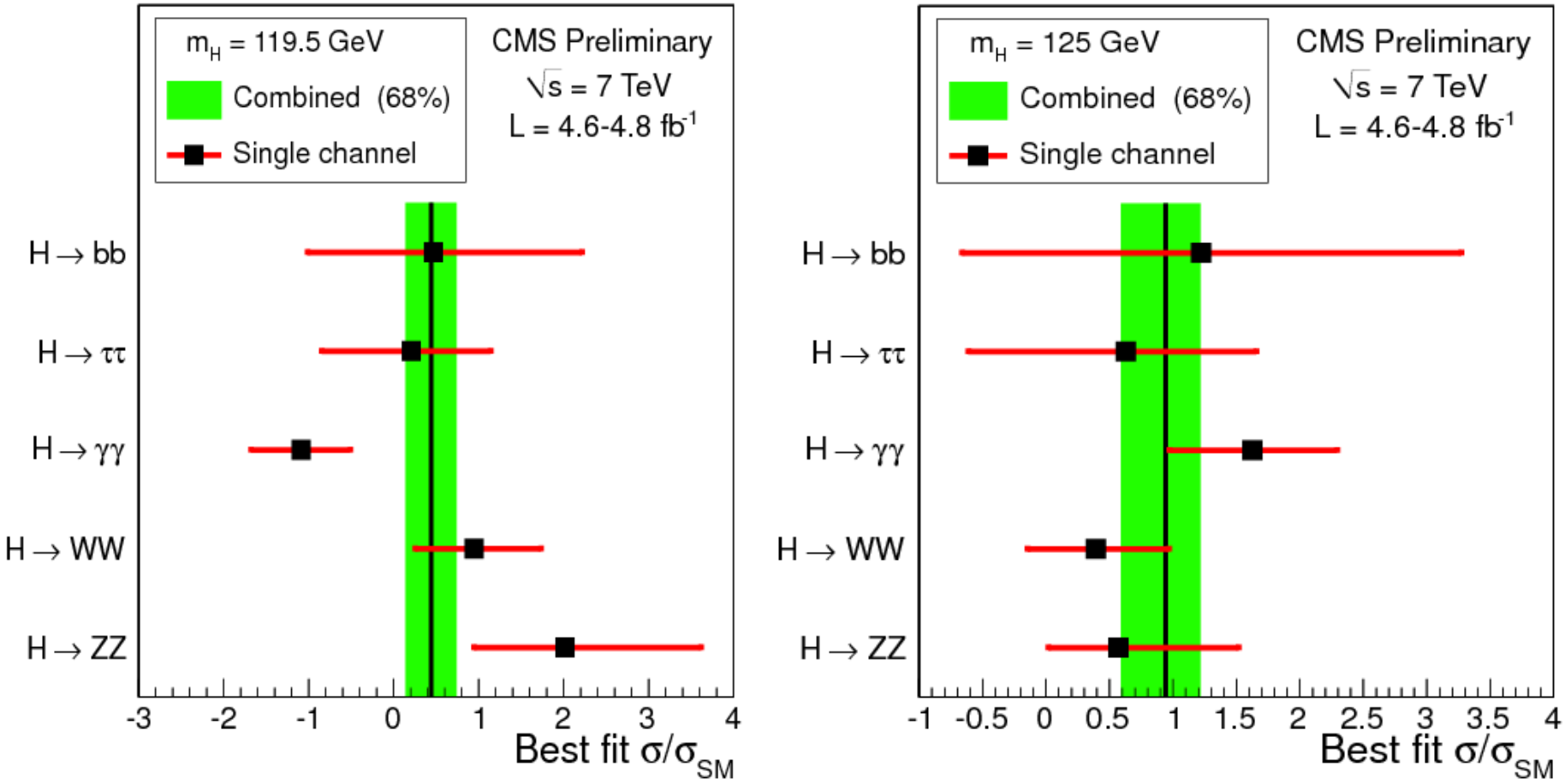




The number of local minima is closely connected to the freedom of the fit to pick signal-like fluctuations in the investigated range

E. Gross and O. Vitells, "Trials factors for the look elsewhere effects in High-Energy Physics", Eur.Phys.J.C70:525-530 (2010)

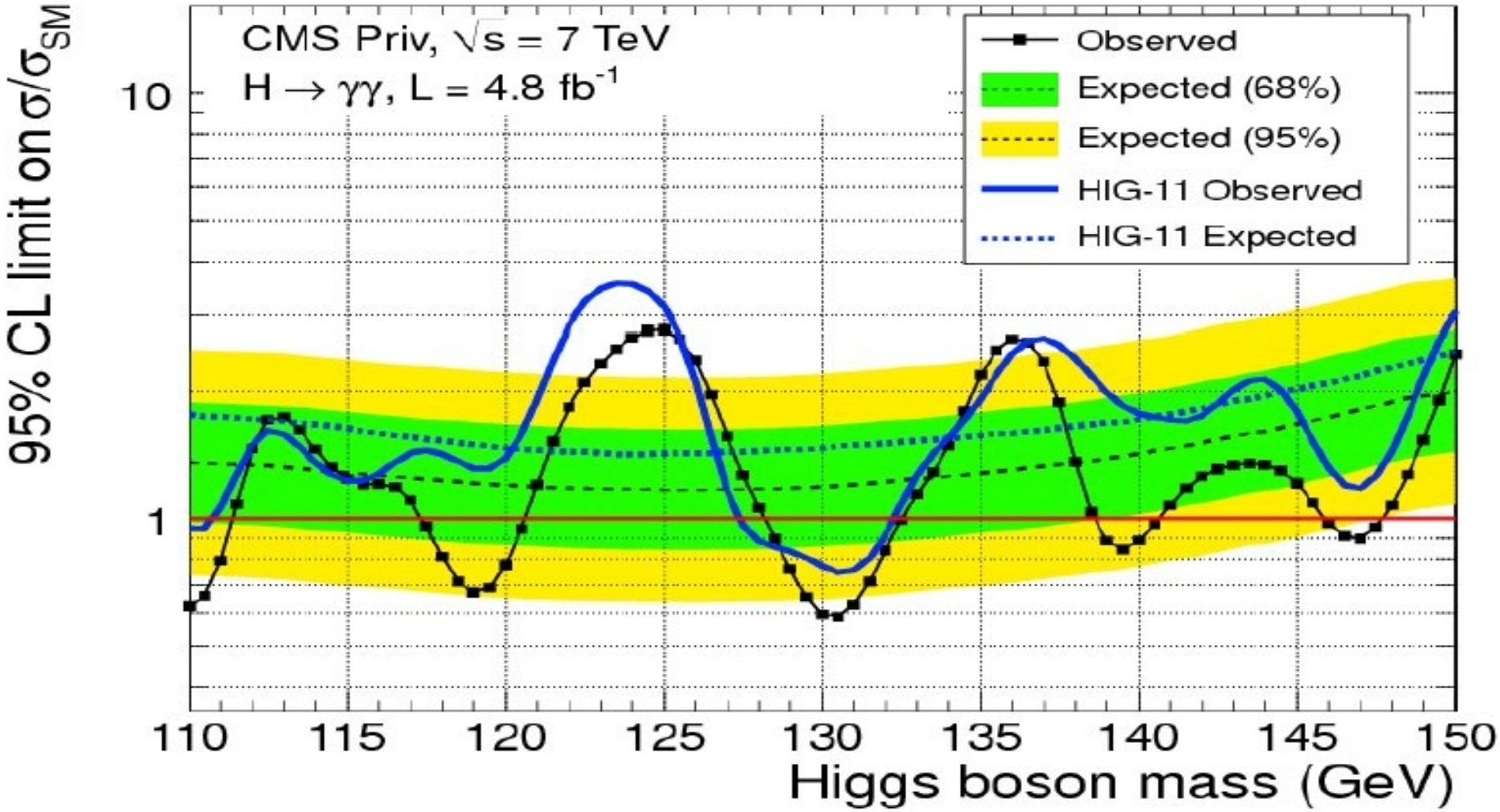
Compare Channel by Channel



Comments

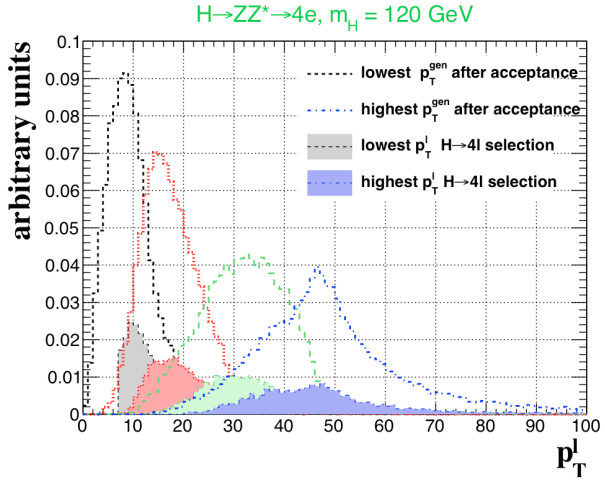
- previously reported 119.5 GeV 4l excess canceled by $\gamma\gamma$
- 125 GeV excess: cross sections consistent, driver is $\gamma\gamma$

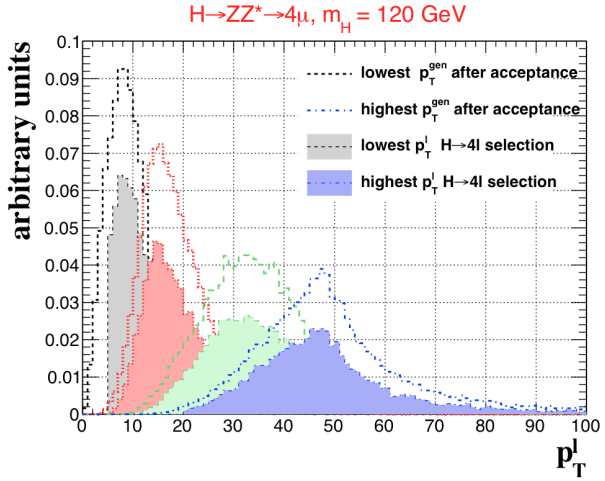
Comparison: Published vs New

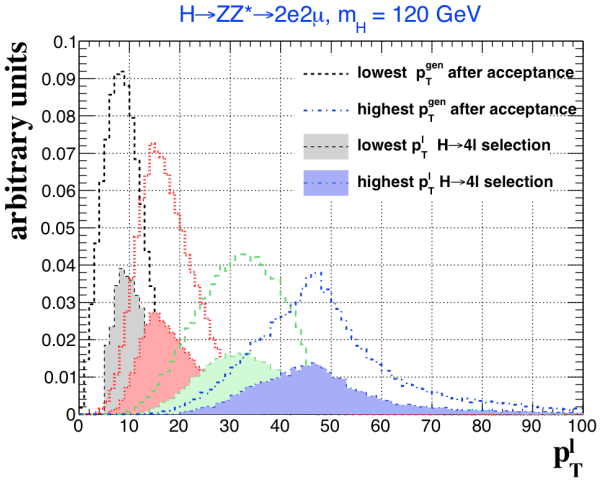


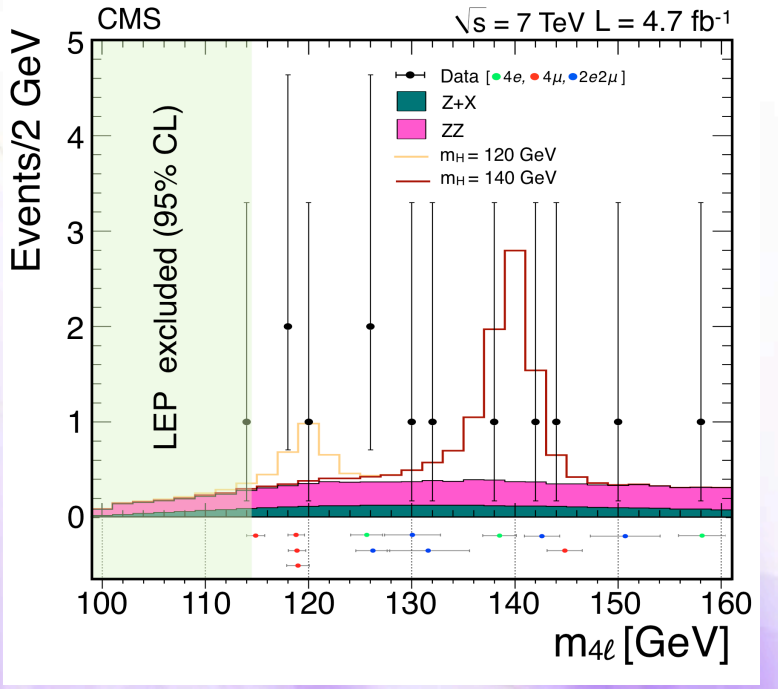
sensitivity improves by 20%, peak shifts upwards by ~ 1 GeV
significance decreased (local: 3.1 std -> 2.9 std)
compatible with statistical effects of the new analysis

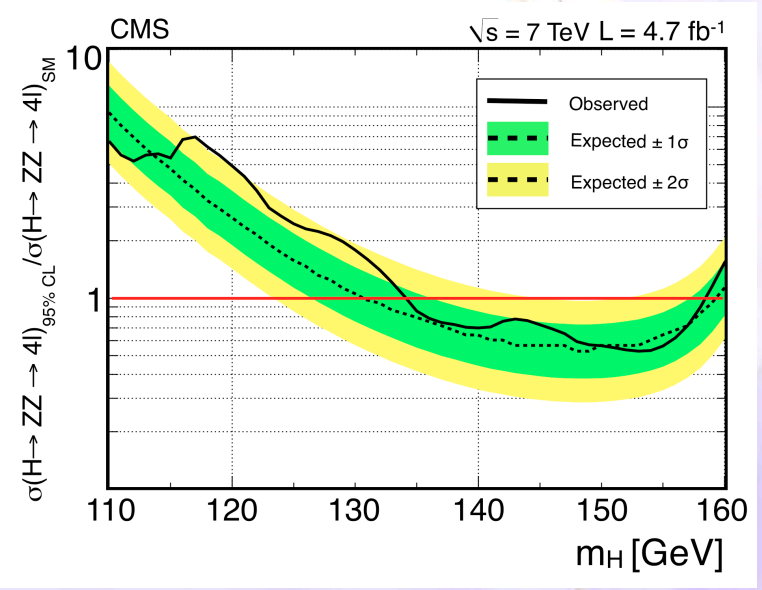
SM H→ZZ*→4l: zoom @low mass







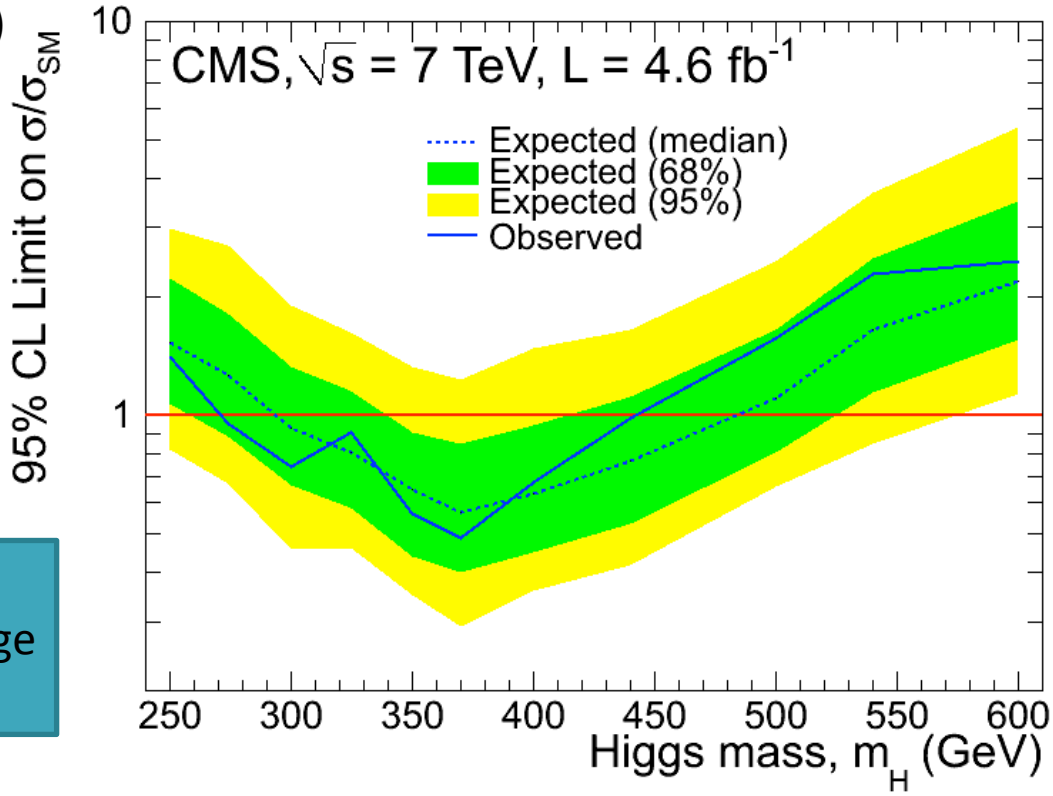




SM H→ZZ→2l2ν

H→ ZZ → 2l2nu decay channel (l= e or μ)

- ✓ no significant excess is observed above the background expectation
- upper limits are set on the Higgs boson production cross section



the presence of the SM Higgs boson w/ a mass in the 270-440 GeV/c² range is excluded at 95% confidence level

m_H (GeV)	ZZ	WZ	Top/WW/ W+jets/Z→ ττ	Z+Jets	Total Background	Expected Signal	Data
250	$36.0 \pm 0.2 \pm 2.6$	$24.0 \pm 0.3 \pm 2.0$	$65.0 \pm 3.8 \pm 5.8$	15.0 ± 15.0	$140.0 \pm 3.8 \pm 16.0$	22.0 ± 2.2	142
300	$23.0 \pm 0.2 \pm 1.7$	$13.0 \pm 0.2 \pm 1.1$	$18.0 \pm 1.1 \pm 3.0$	6.3 ± 6.3	$60.0 \pm 1.1 \pm 7.3$	21.0 ± 2.1	64
350	$16.0 \pm 0.1 \pm 1.1$	$7.0 \pm 0.2 \pm 0.6$	$2.0 \pm 0.1 \pm 1.0$	4.1 ± 4.1	$29.0 \pm 0.3 \pm 4.4$	21.0 ± 2.5	26
400	$12.0 \pm 0.1 \pm 0.9$	$4.6 \pm 0.1 \pm 0.4$	< 1.1	2.7 ± 2.7	$19.0 \pm 0.2 \pm 2.9$	17.0 ± 2.0	18
500	$7.5 \pm 0.1 \pm 0.5$	$2.0 \pm 0.1 \pm 0.2$	< 1.1	1.4 ± 1.4	$11.0 \pm 0.1 \pm 1.5$	7.4 ± 1.3	14
600	$3.9 \pm 0.1 \pm 0.3$	$0.8 \pm 0.1 \pm 0.1$	< 1.1	0.6 ± 0.6	$5.3 \pm 0.1 \pm 0.7$	2.9 ± 0.7	5

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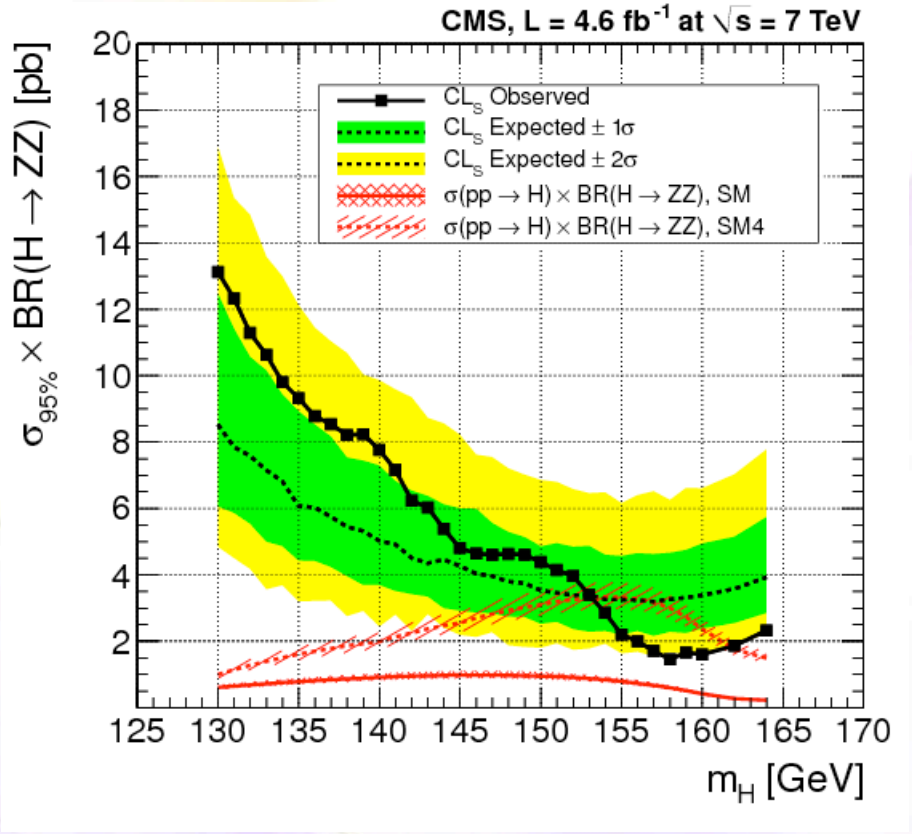
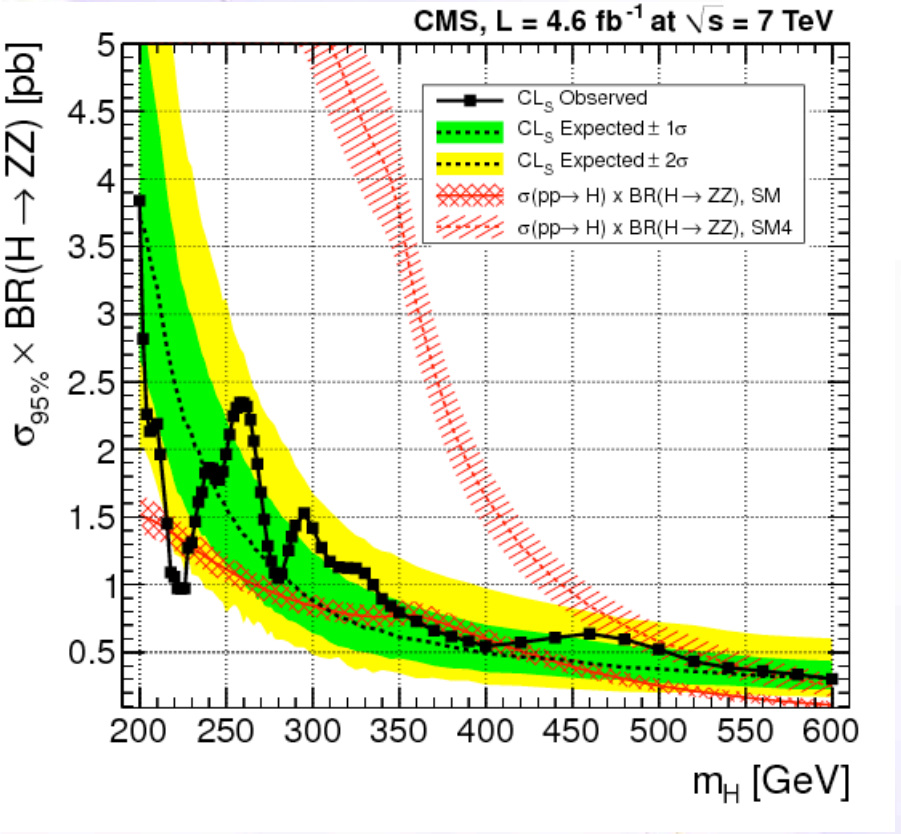
SM H→ZZ→2l2q





- ☑ the exclusion limits of the SM Higgs boson are approaching those of the SM expectation [compatible with other results from different channels]
- ☑ Higgs masses hypotheses in the SM4 model w/ the fourth generation are excluded in the range [154;161] and [200; 470] GeV/c^2

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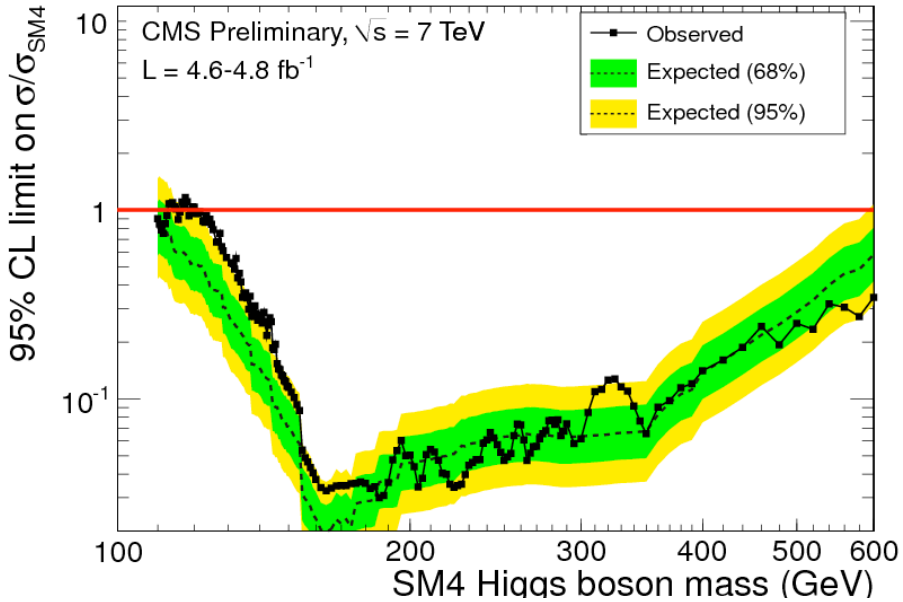
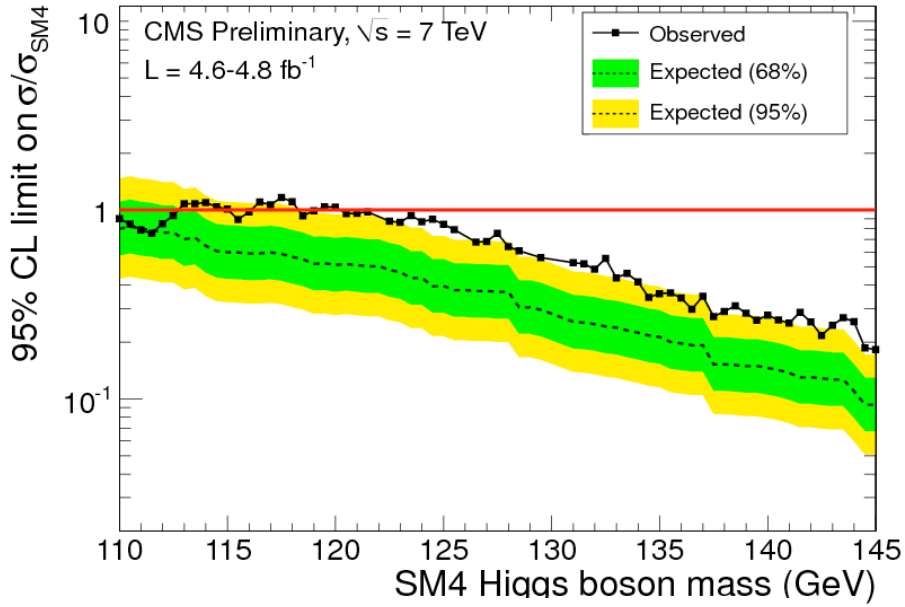
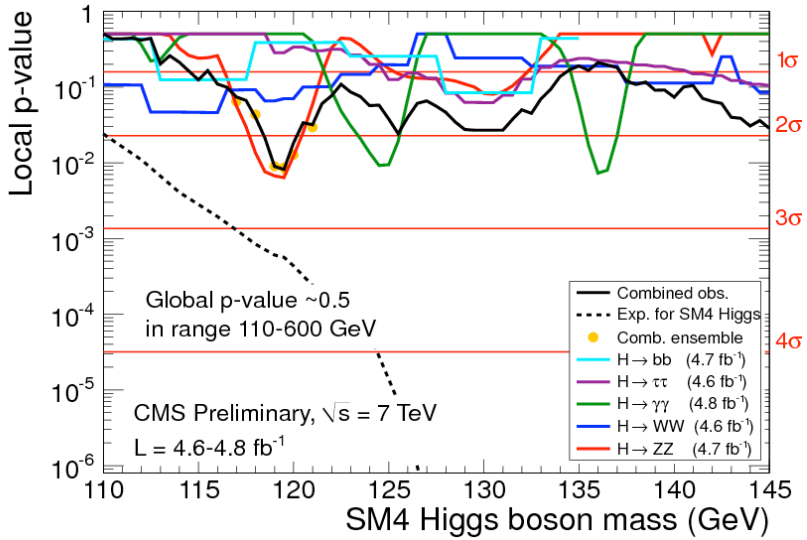
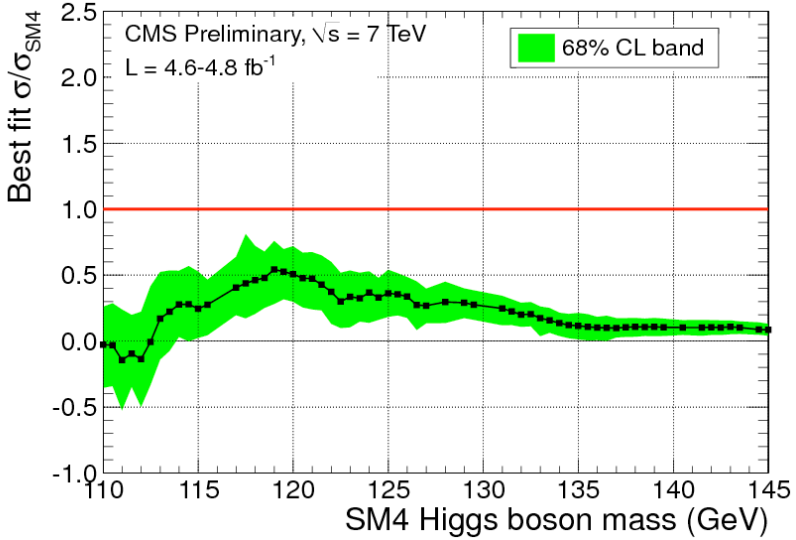
SM4 Higgs boson

excluded in the mass range
[120;600] GeV/c² at 95% CL
[125;600] GeV/c² at 99% CL



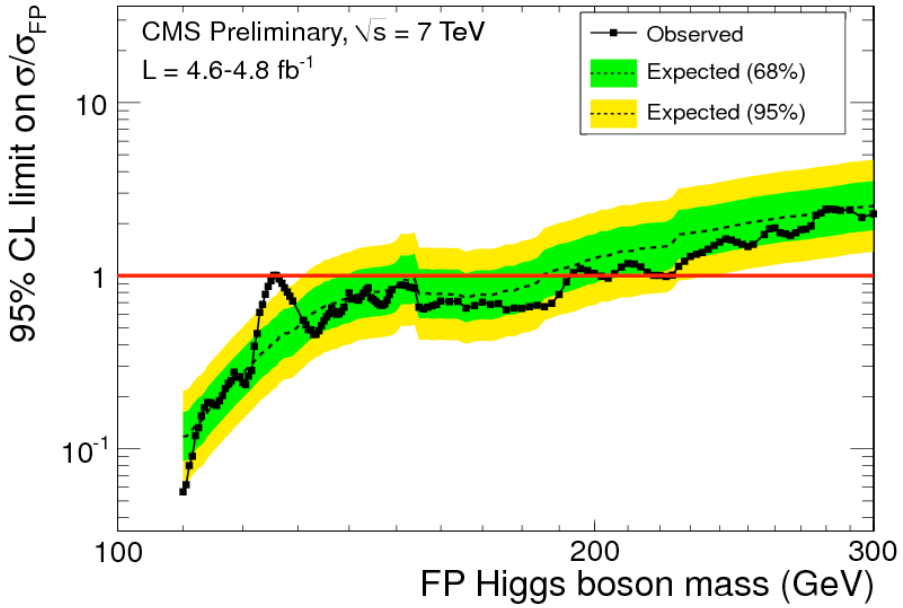


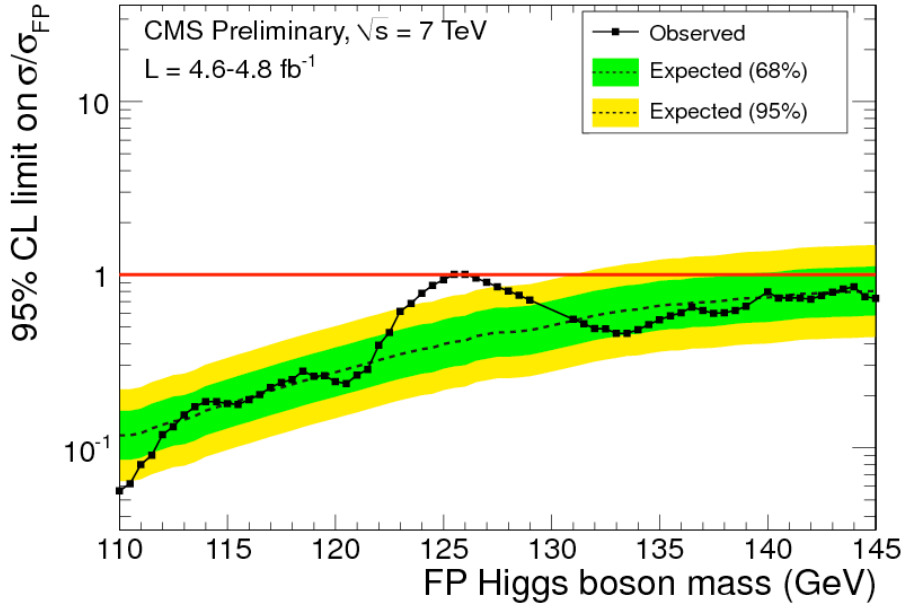




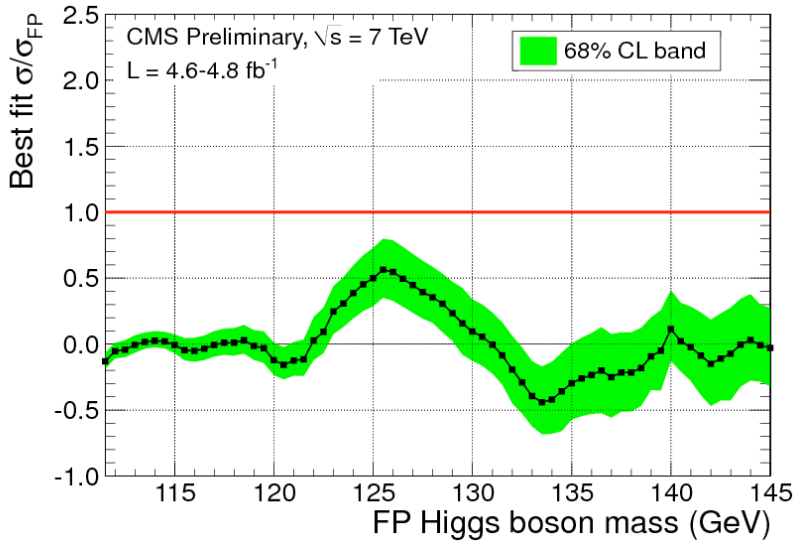
CMS-HIG-12-008

fermiophobic Higgs boson





excluded in the mass range
[110;192] GeV @ 95% CL
[110–188] GeV @ 99% CL
with the exception of two gaps:
124.5– 128 and 148–154 GeV



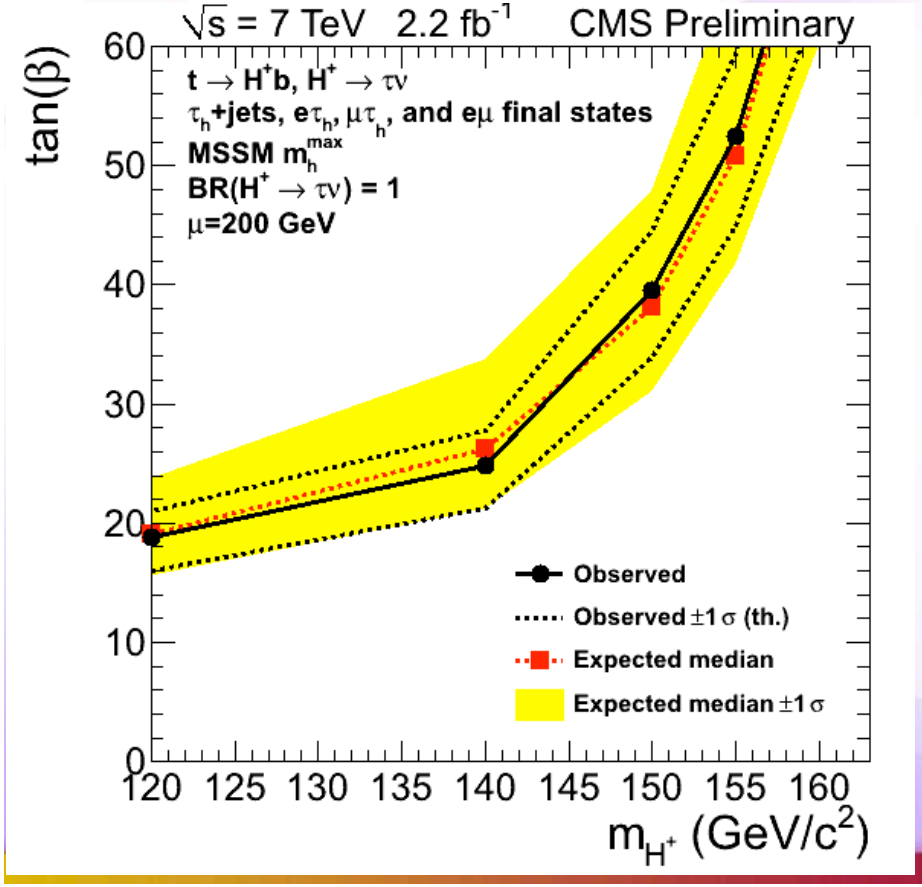
charged MSSM Higgs boson

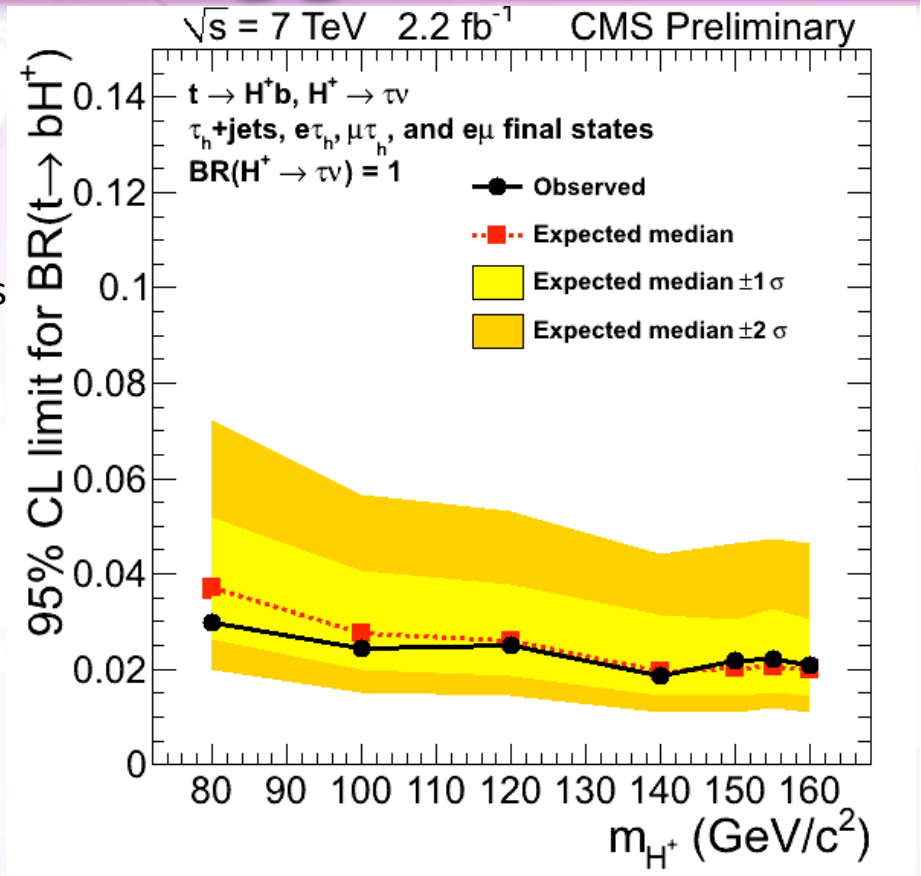
the search for the light charged Higgs boson

($m_{H+} < m_{top}$)

- produced from the top quark decay $t \rightarrow H^+b$
- decaying into $\tau^+\nu$

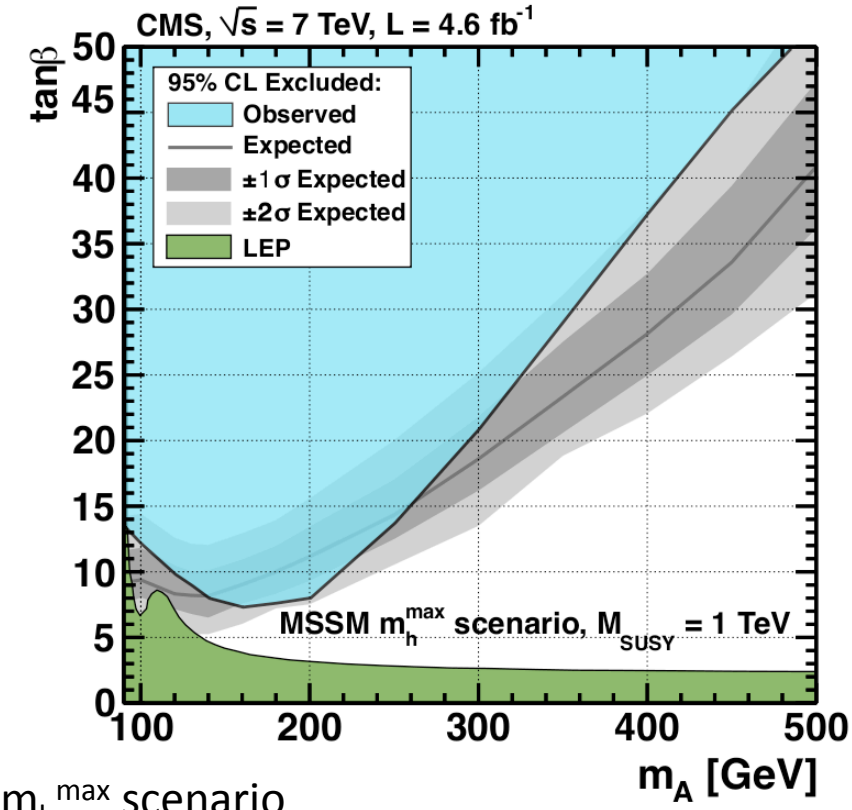
fully hadronic, lepton-tau and e-mu final state topologies





the upper limit 2-3 % on the BR($t \rightarrow H^+b$) has been obtained for the Higgs boson mass interval $80 < m_{H+} < 160$ GeV/c^2 assuming BR($H^+ \rightarrow \tau^+\nu$)=1

neutral MSSM Higgs boson



m_h^{max} scenario

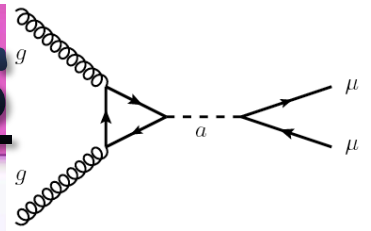
stringent new bounds in the parameter space, excluding at 95% CL values of tanβ as low as 7.1 at m_A = 160 GeV/c^2

Search for doubly charged H^{++}

Model assumption	Combined limit on all production mechanisms	Limit on pair-production only
BR(Φ++ -> e+e+) = 100%	445 GeV	387 GeV
BR(Φ++ -> e+μ+) = 100%	455 GeV	389 GeV
BR(Φ++ -> e+τ+) = 100%	352 GeV	300 GeV
BR(Φ++ -> μ+μ+) = 100%	457 GeV	391 GeV
BR(Φ++ -> μ+τ+) = 100%	369 GeV	313 GeV
BR(Φ++ -> τ+τ+) = 100%	198 GeV	165 GeV
Benchmark point 1 (Normal hierarchy)	380 GeV	326 GeV
Benchmark point 2 (Inverse hierarchy)	410 GeV	361 GeV
Benchmark point 3 (Degenerate masses)	406 GeV	350 GeV
Benchmark point 4 (Equal branching ratios)	399 GeV	353 GeV

The doubly charged Higgs is a member of $SU(2)_L$ scalar triplet Φ
in extensions of the Standard Model which include the seesaw mechanism of type II.
The search is inclusive and is performed in events with three or more isolated charged leptons of all flavors originating from the decays of pair produced triplet components $\Phi^{++}\Phi^{--}$ and $\Phi^{++}\Phi^{-}$.
No signal is observed
and new lower limits at the 95% CL are set on the $\Phi^{\pm\pm}$ mass,
under specific assumption on the Φ^{++} branching fraction

light pseudoscalar Higgs



The dimuon invariant mass spectrum is investigated
in the mass range between 5.5 GeV and 14 GeV using 1.3 fb^{-1} of pp collision data
to search for a light pseudoscalar Higgs boson.
Such a light Higgs boson is predicted in many models,
including the Next-to-Minimal Supersymmetric Standard Model (NMSSM)
which avoids the m-term problem of the MSSM.