Results on the search for the SM Higgs Boson at CMS

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On behalf of the CMS collaboration

QCD @ work

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Outline

- This talk will be focused on the results from Standard Model (SM) Higgs boson searches at CMS

- Introduction

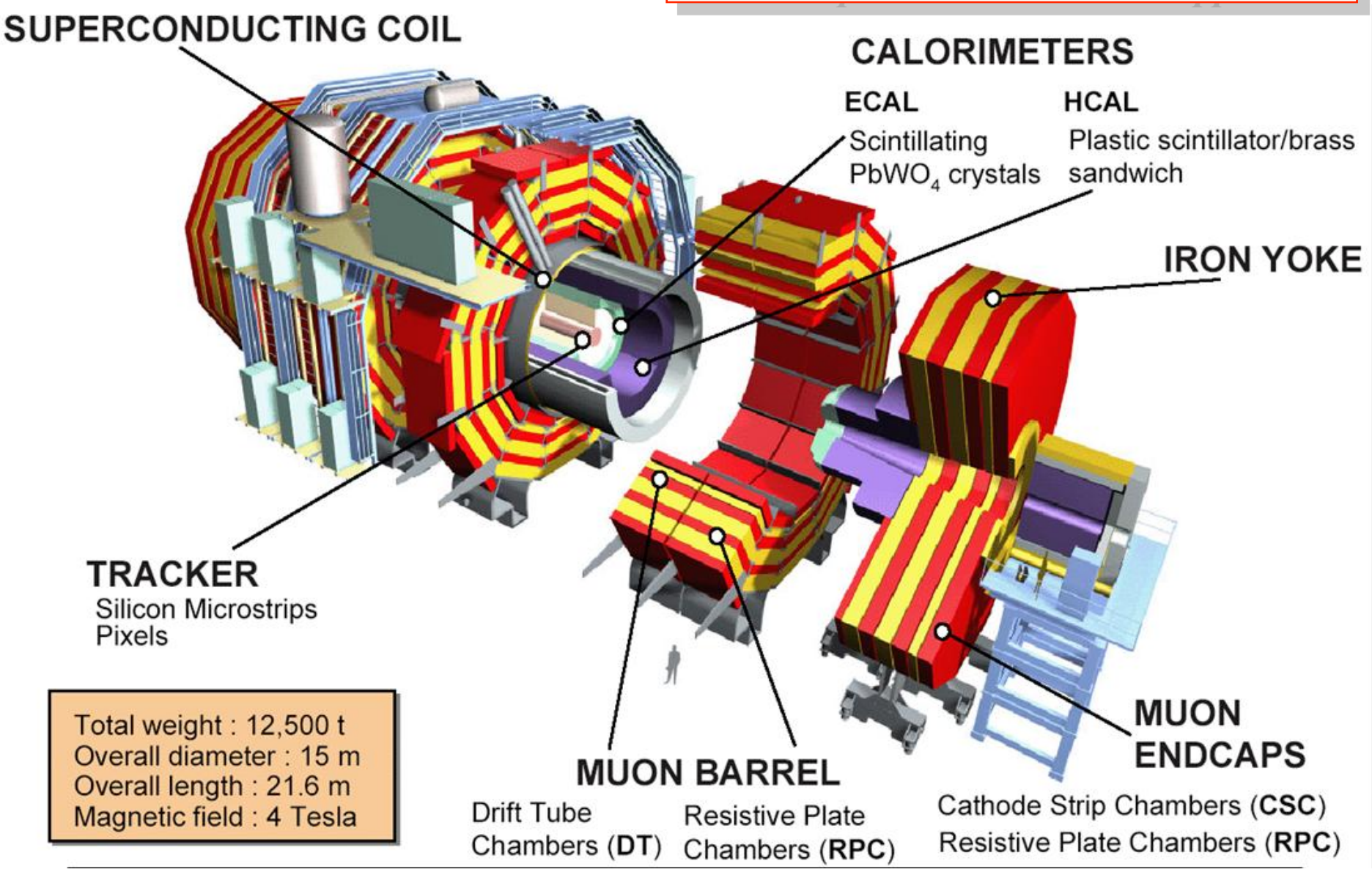
- Search channels of SM Higgs boson

- Analysis strategies and results

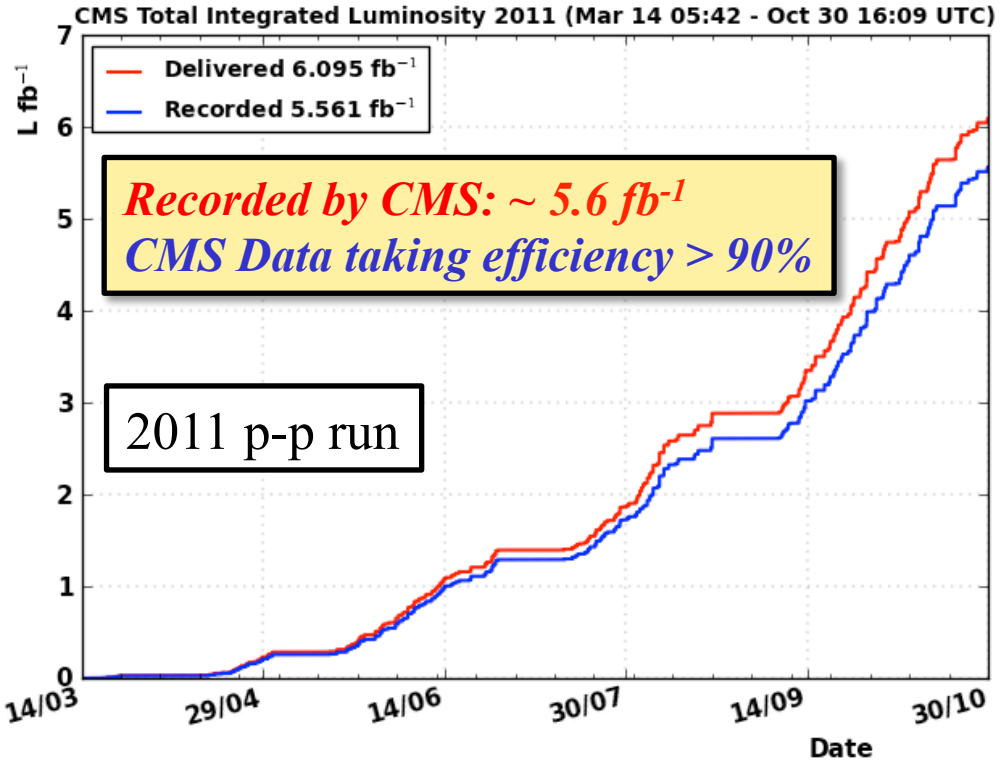
- Combination of channels

The CMS experiment @ LHC

The Compact Muon Solenoid apparatus



The 2011 data sample

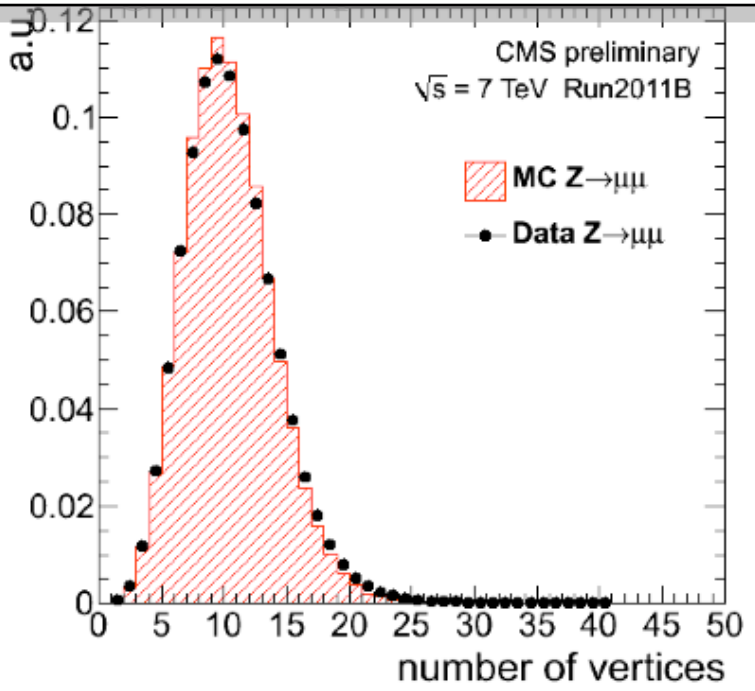


Recorded by CMS: ~ 5.6 fb^{-1}
CMS Data taking efficiency > 90%

2011 p-p run

- ***Centre-of-mass energy*** = 7 TeV
- ***Peak luminosity*** = 3.5 10^{33} cm^{-2} s^{-1}

- ***Multiple p-p interactions in the same bunch crossing ("pile-up")***
- ***Average "pile up" interactions ~ 10***

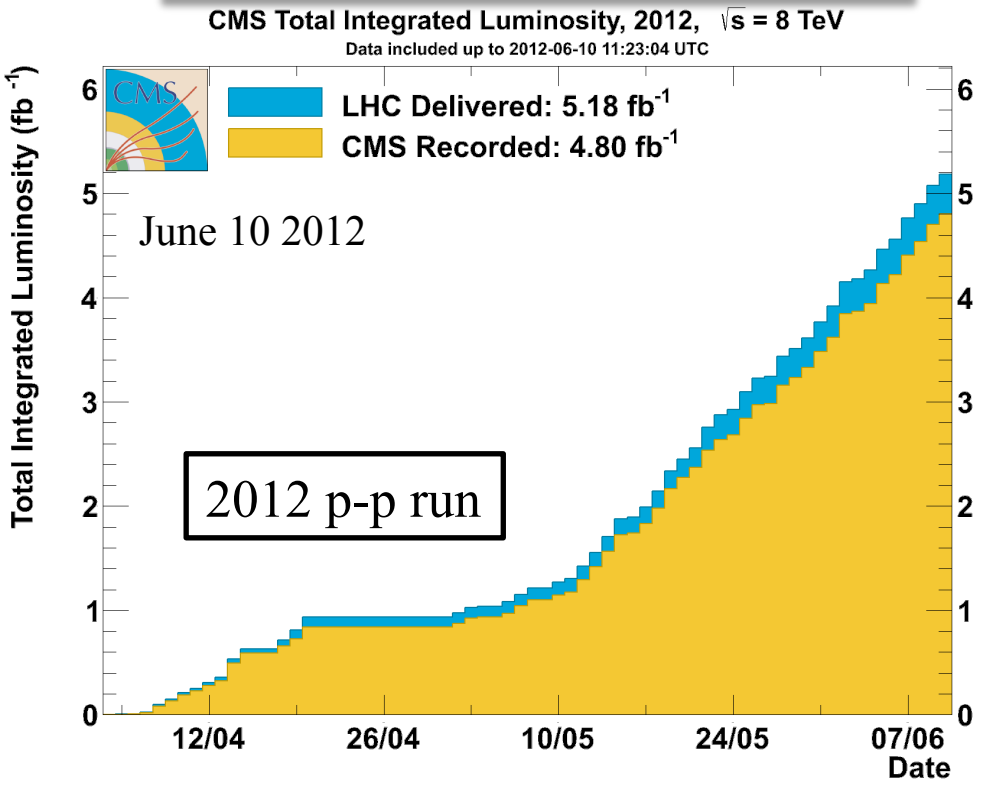


Impressive performance of LHC!

All the results presented in this talk are based on the 2011 data sample

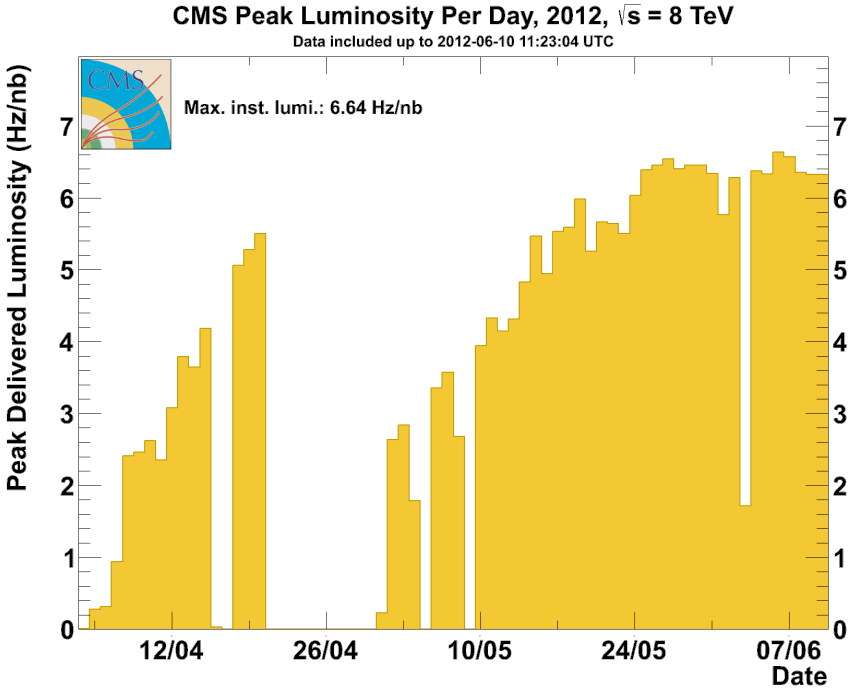
The 2012 p-p run @ 8 TeV

Recorded by CMS: 4.8 fb^{-1}
CMS Data taking efficiency > 90%



Near to collect same integrated luminosity as 2011!!!

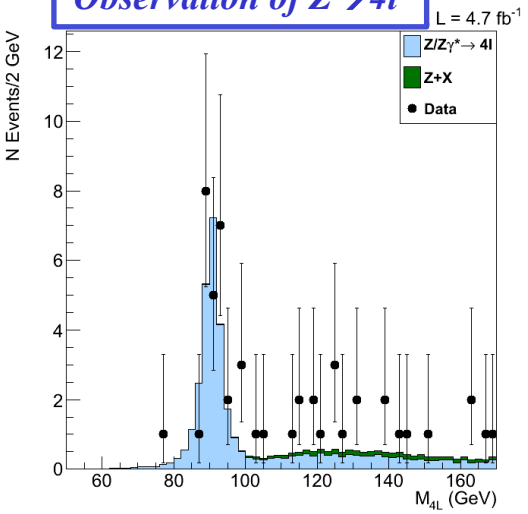
- ***Centre-of-mass energy =*** **8 TeV**
- ***Peak luminosity record =*** **6.64 10^{33} cm^{-2} s^{-1}**



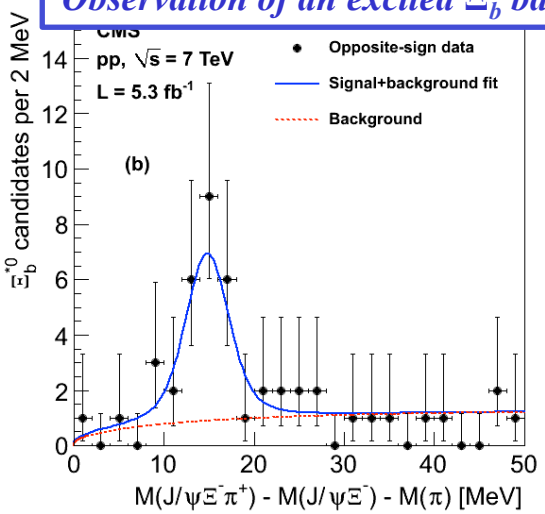
Developing a broad physics program

Establishing competitive measurements in many areas (just a few examples below)

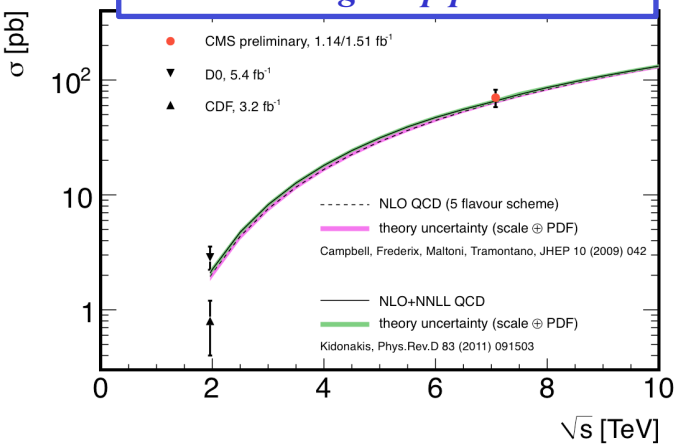
Observation of Z→4l



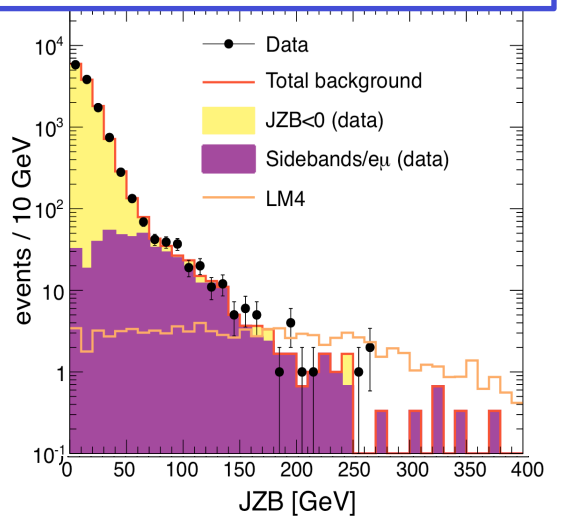
Observation of an excited Ξ_b barion



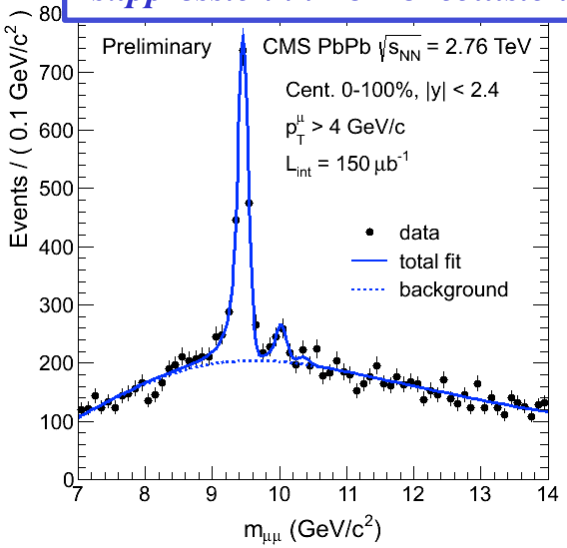
t-channel single top production



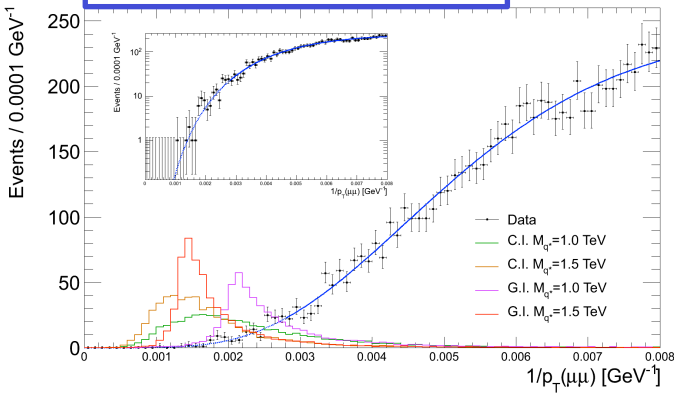
Search for physics beyond SM in events with Z boson, jets and MET



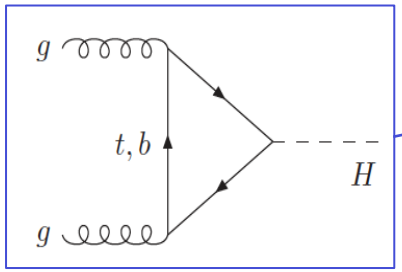
Observation of Y(nS) suppression in Pb-Pb collisions



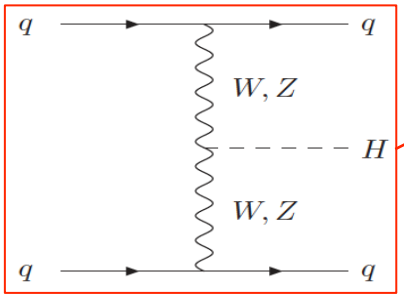
Serch for new physics in highly boosted Z→μμ



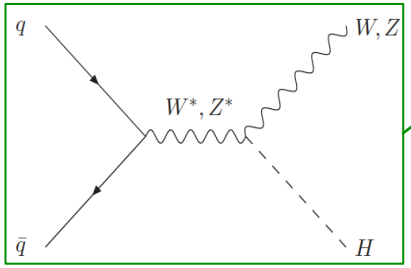
SM Higgs production and decay at LHC



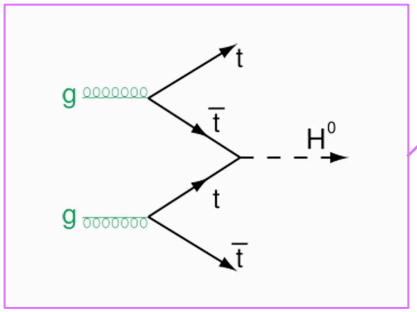
gg fusion



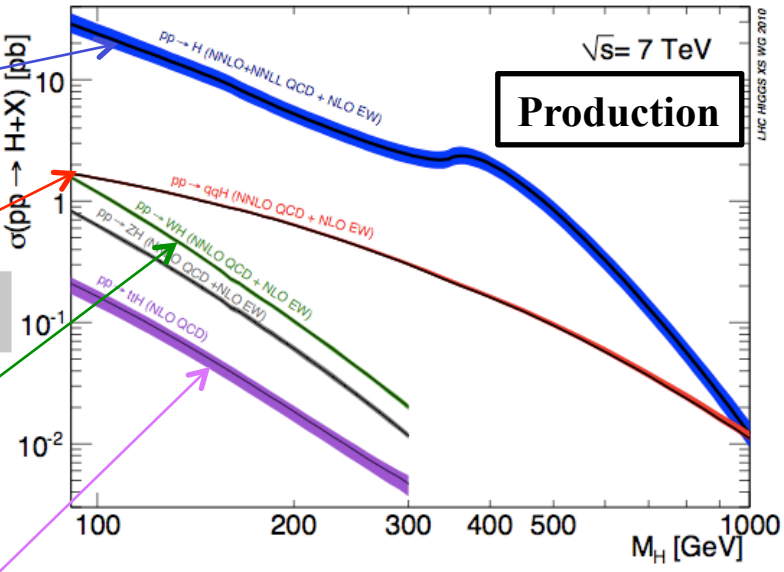
Vector Boson Fusion

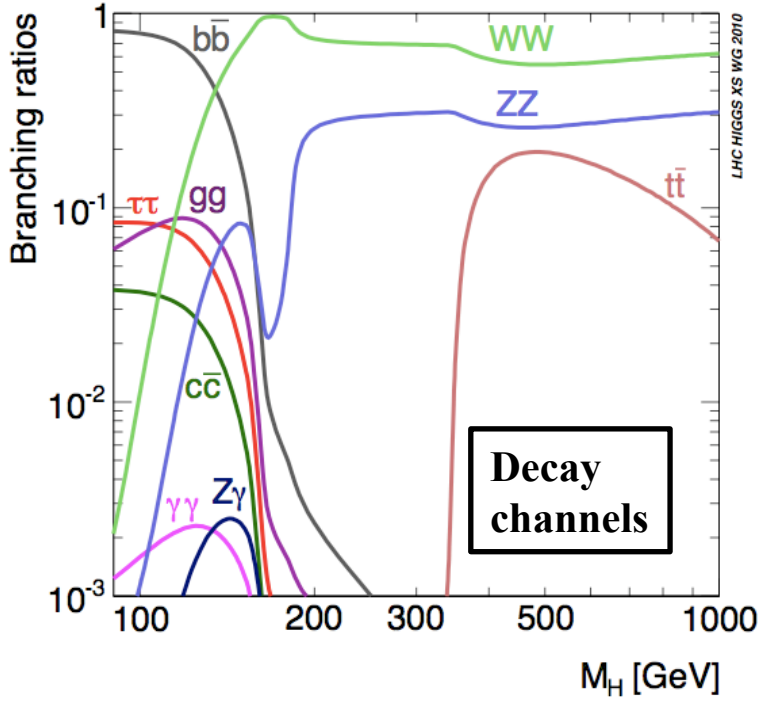


Associated VH production



Associated ttH production





SM Higgs search channels at CMS

11 channels covering search in mass range 110-600 GeV

Channel	m_H range (GeV)	Luminosity (fb^{-1})	Sub-channels	m_H resolution
$H \to \gamma\gamma$	110–150	4.8	2	1–2%
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	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	4.6	6	3%
	200–600			3%
$H \to ZZ \to 2\ell 2\tau$	190–600	4.7	8	10–15%

Highest sensitivity channels

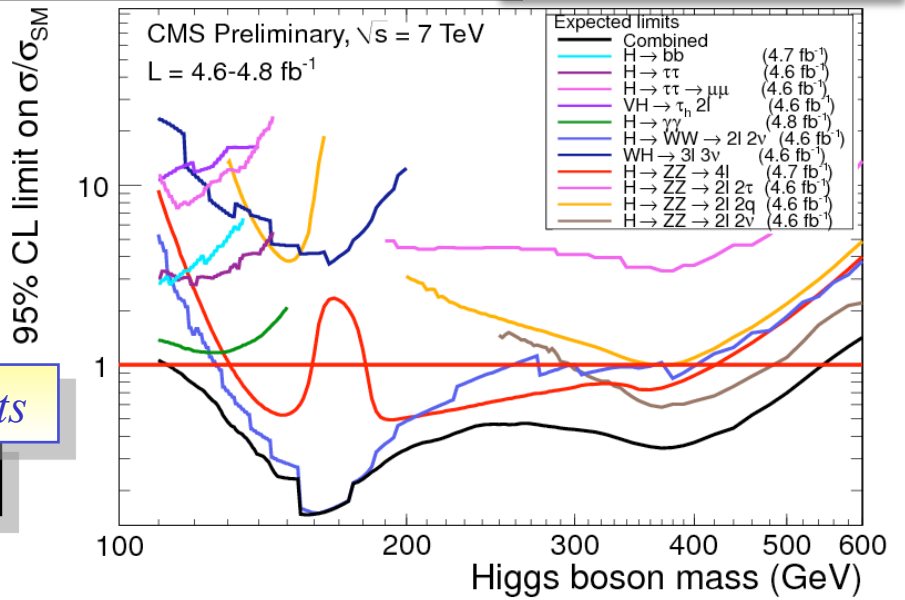
Expected exclusion mass range @ 95% CL: 114.5 – 543 GeV

Direct searches (not LHC)

- $m_H < 114.4$ GeV excluded @95% CL (LEP)
- $156 < m_H < 176$ GeV excluded @ 95% CL (Tevatron)

Indirect constraints from Electroweak measurements

- Preferred range: $m_H < 169$ GeV (Gfitter group)



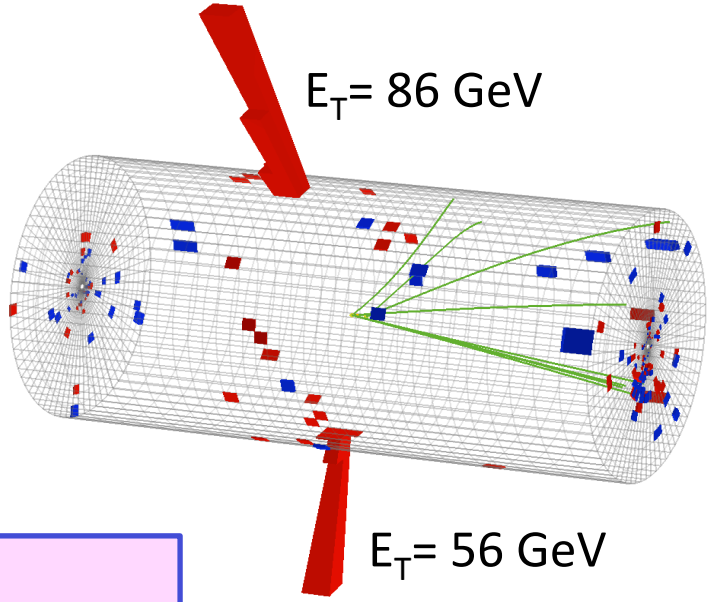
Low-mass channels

- $H \rightarrow \gamma\gamma$
- $H \rightarrow bb$
- $H \rightarrow \tau\tau$
- $WH, H \rightarrow \tau\tau$

H→γγ channel

- *Most recent result: MVA-based analysis*
- *First published version used robust cut-analysis – PLB 710 (2012) 403-425*

PAS HIG-12-001



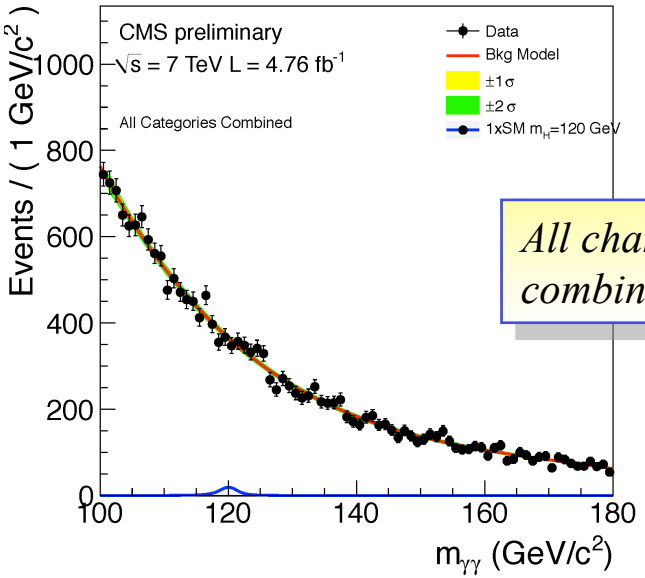
Br ≈ 0.14 -0.23% in search range 110-150 GeV

Clean signature: two isolated, high E_T gamma; narrow peak (1-2% resolution) in $m_{\gamma\gamma}$ over decreasing background

Dominated by ECAL energy resolution (crucial is correct assignement of the di-photon vertex)

Backgrounds: prompt γγ production, γ+jet, jet-jet, Drell-Yan (DY→ee)

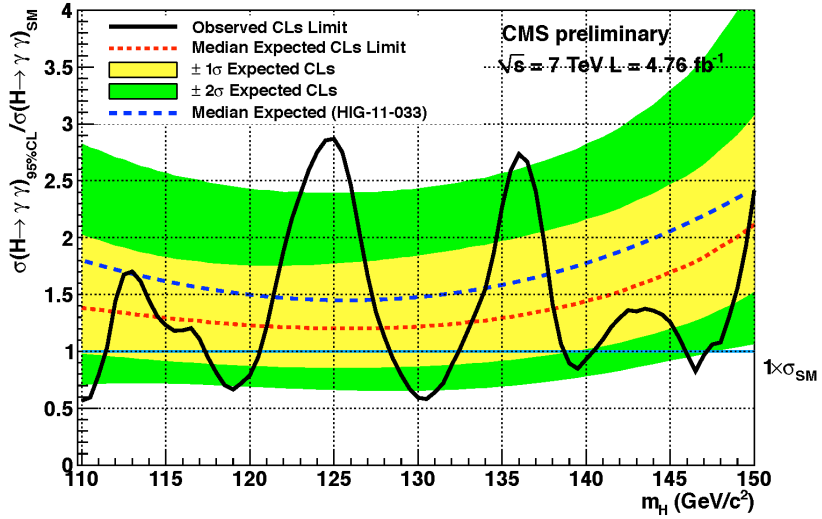
H→γγ results

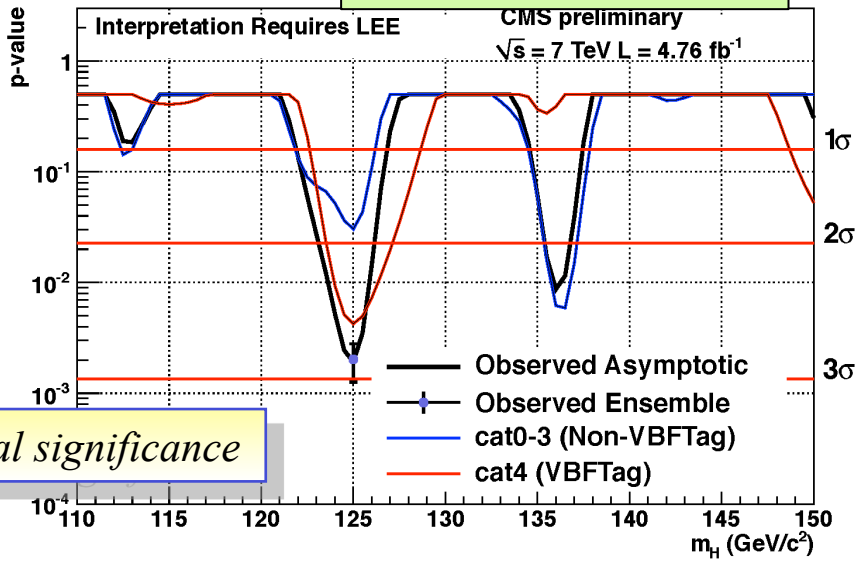


All channels combined

Background evaluated from polynomial fit to m_{jj} data distribution

Most significant excess at ~ 125 GeV





Local significance

Observed limit →5 exclusion intervals @95%CL:
110.0-111.0, 117.5-120.5, 128.5-132.0,
139.0-140.0, 146.0-147.0 GeV

Local significance of the excess: 2.9 σ
Global significance ("Look-Elsewhere Effect") in the search mass range: 1.6 σ

H→ττ channel

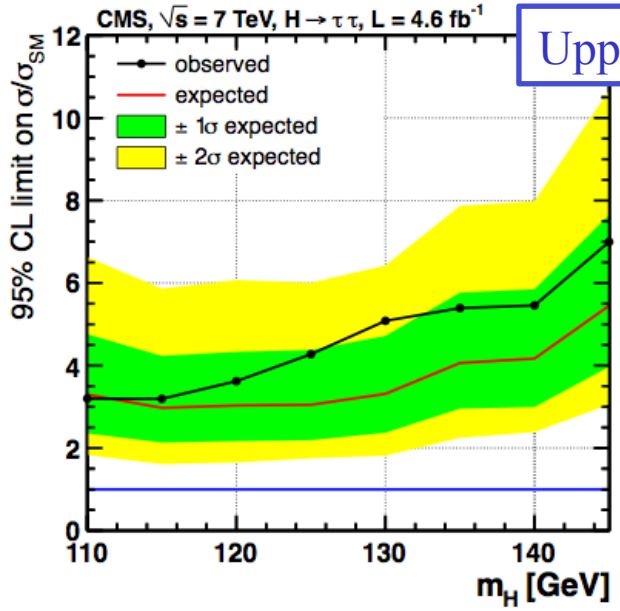
- *Channels considered: $e\tau_h$, $\mu\tau_h$, $e\mu$*
- *Required large Missing E_T (MET) in the final state*
- *Sensitivity for low-mass Higgs*
- *Also sensitive to neutral MSSM Higgs bosons*

PLB 713 (2012) 68-90

Main backgrounds: DY→ττ, W+jets

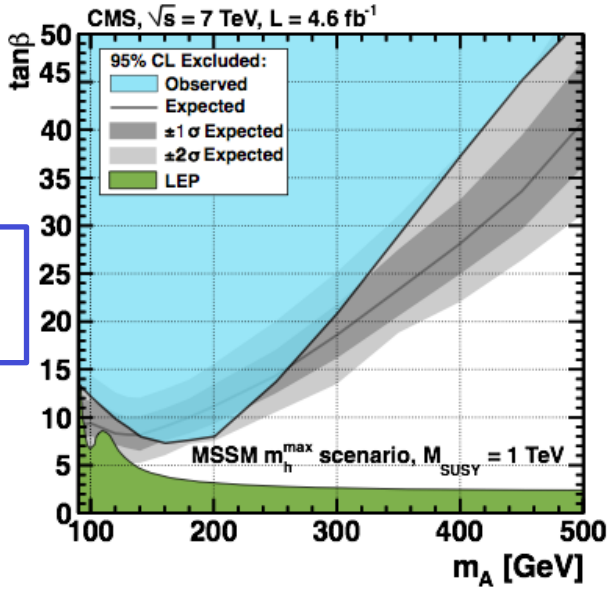
W+jets rejection: MET direction w.r.t. direction of visible decay products ~ collinear in signal

Signal extraction: binned likelihood fit to the $m_{\tau\tau}$ invariant mass distribution



Upper limits vary from 3 to 7 σ_{SM}

Excluded large region of the MSSM parameter space



WH, H→ττ channel

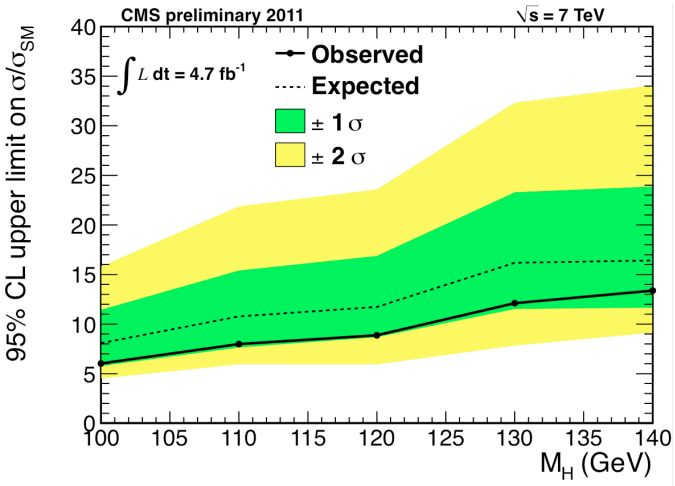
- *Channels considered: $e\mu\tau_h$, $\mu\mu\tau_h$*

PAS HIG-12-006

Dominant background: DY+jets
Rejected by requiring leptons to have same charge

Limit derived by counting events after full selection

Upper limits vary from 6 to 13 σ_{SM}



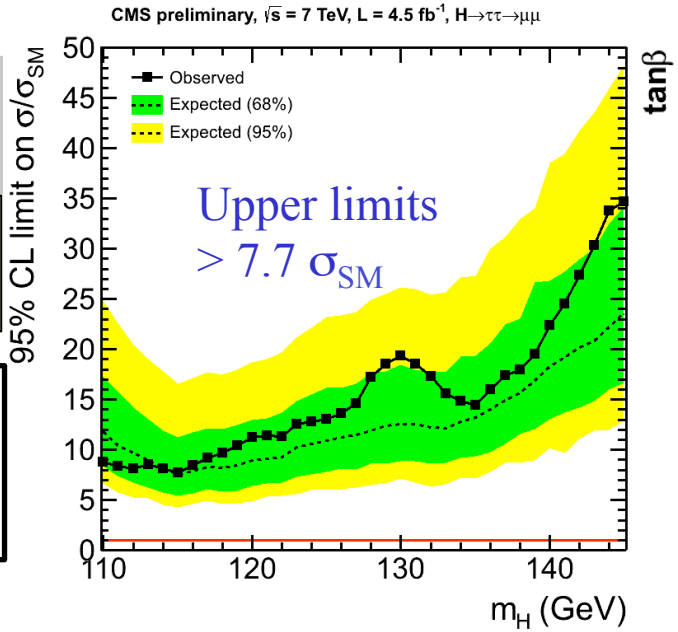
H→τ(μ)τ(μ) channel

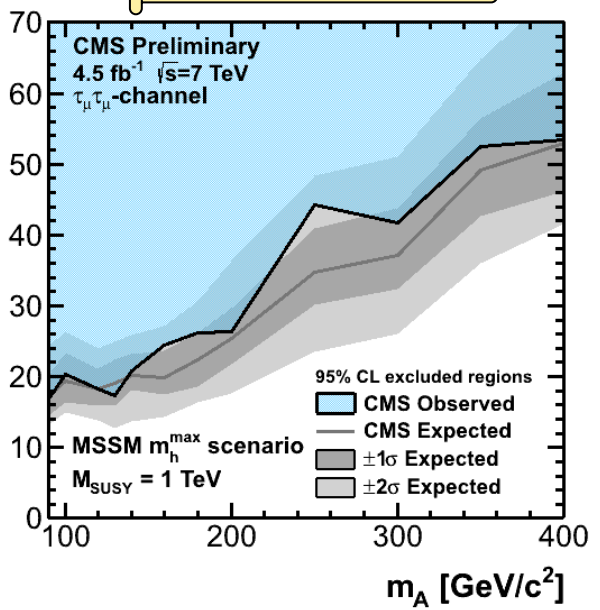
PAS HIG-12-007

- *Complementary to the main H→ττ analysis*

Main backgrounds:
DY→μμ, DY→ττ

Signal extraction by binned likelihood fit to 2D ($m_{\mu\mu}$, $m_{\tau\tau}$) distribution





H→bb channel

- *Favoured BR at low mass, but huge bkg in inclusive channel (di-jet QCD production)*
- *Associated VH production channel must be exploited*
- *Channels considered: VH, with V=Z, W; Z→μμ, ee, νν; W→μν, eν*

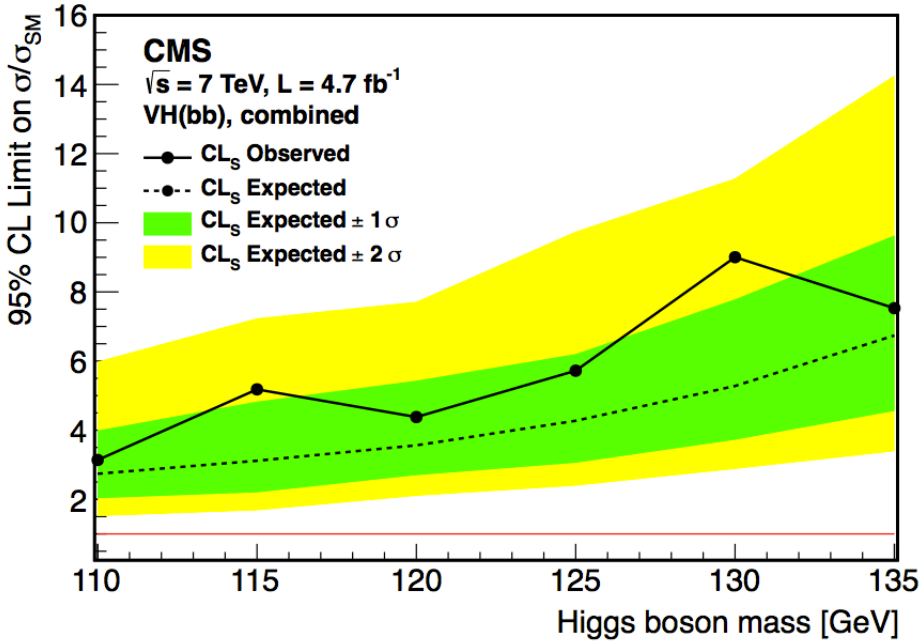
PLB 710 (2012) 284-306

Main backgrounds: W/Z+jets, top, diboson, multijet

Signal selection: two high E_T jets passing b-tagging Requirements + leptons/MET from Z/W bosons

Exploited kinematics of the jj system and of V boson for bkg rejection

Limit extraction: counting events in the signal-region of a BDT discriminant Improves sensitivity w.r.t. signal region based on cut on m_{jj} only



Upper limits vary from 3.4 to 7.5 σ_{SM}

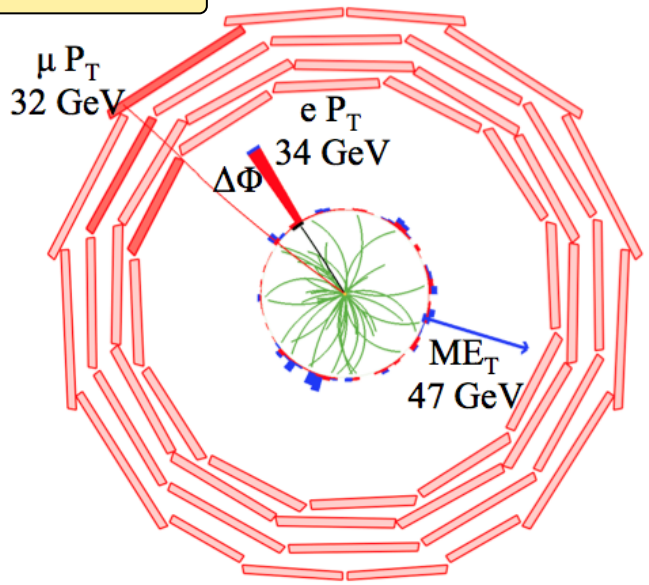
H→WW channels

- H→WW→2l2ν
- H→WW→lνjj
- WH →W(WW)→3l3ν
- V→2j, H→WW

H→WW→2l2ν channel

PLB 710(2012) 91-113

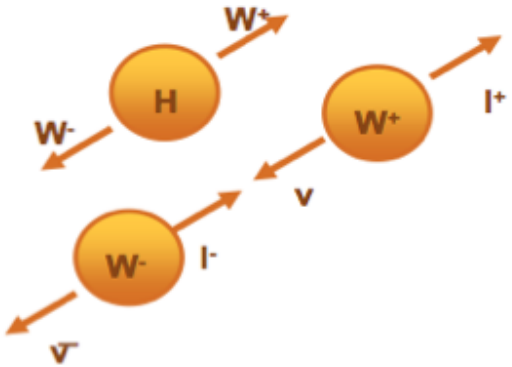
- *MVA-based and cut-based analyses*
- *Three channels:* μμ, ee, eμ
- *Best sensitivity for* $m_H \approx 2m_W$



Signature: two isolated, high p_T leptons of opposite sign; large missing transverse energy (MET) in the event

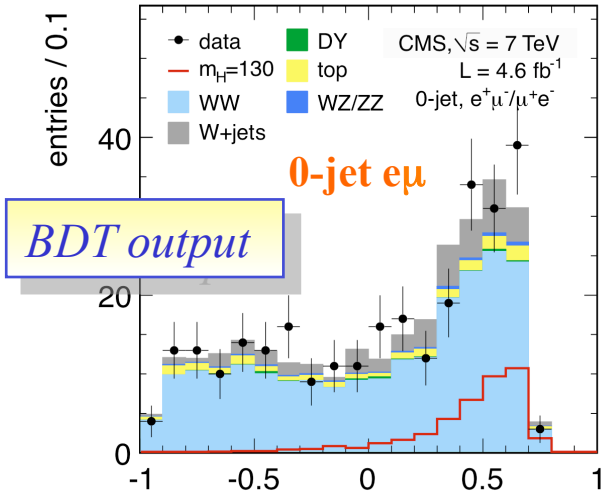
Backgrounds: non resonant WW, W+jets, DY, top, other diboson channels

- *MET is crucial for DY rejection*
- *Use of projected MET to nearest lepton direction improves DY→ττ rejection*



Scalar boson + V-A decay
=> Small leptons opening angle

H→WW→2l2ν results



BDT output

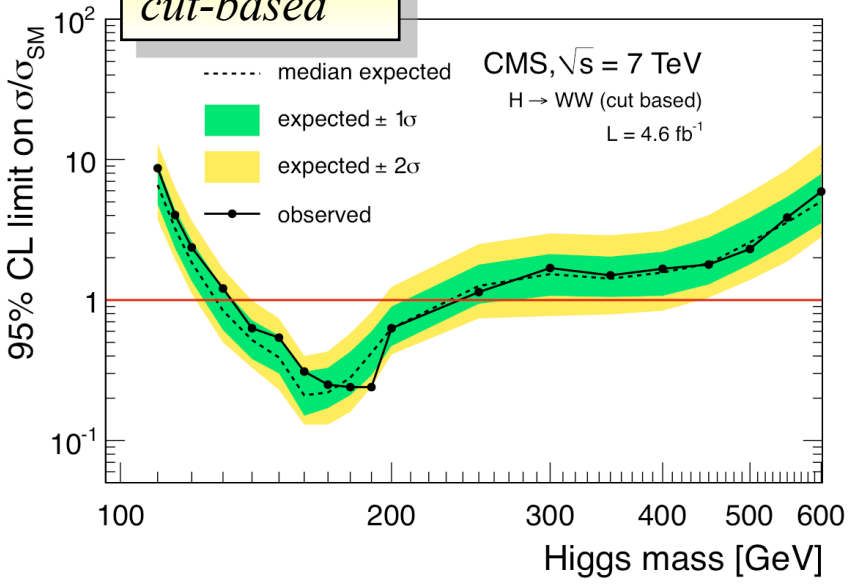
Several input variables to BDT

- *leptons p_T, m_{ll}, $\Delta\Phi_{ll}$, transverse mass of (ll, MET), transverse mass of (l, MET), ΔR_{ll}*

Shape analysis of BDT output for limit extraction

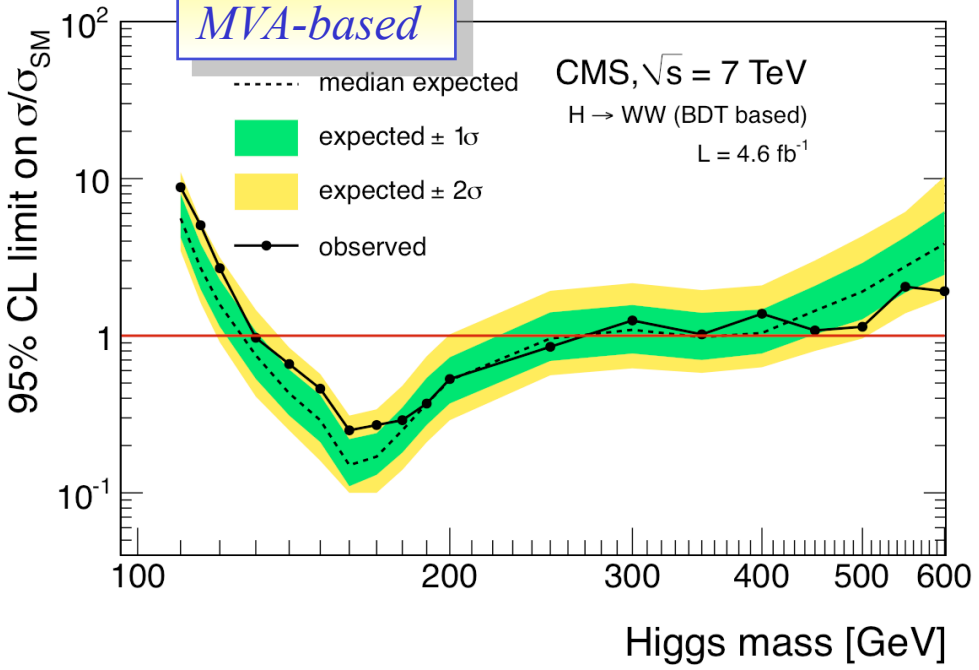
MVA-analysis has better sensitivity -> used for final result

cut-based



Observed limit → exclusion interval: 132-238 GeV

MVA-based



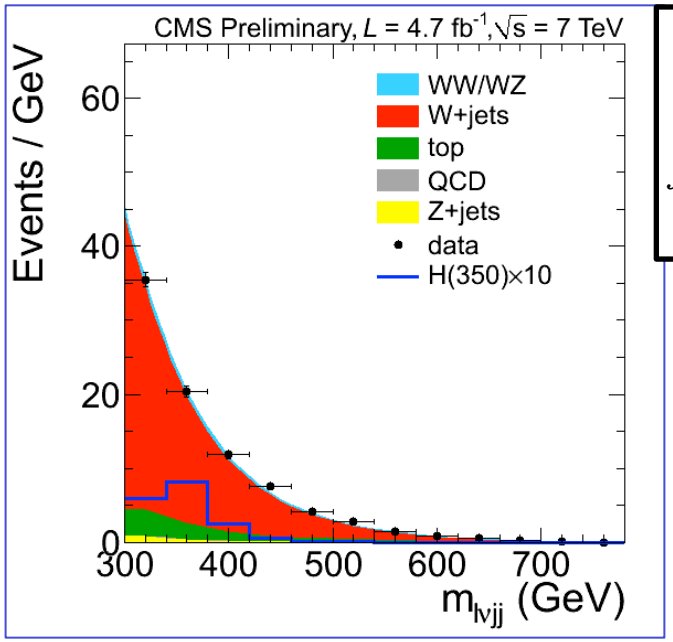
Observed limit → exclusion interval: 129-270 GeV

The H→WW→lνjj channel

Signature: one isolated, high p_T lepton (l=e,μ); missing transverse energy (MET) in the event; two or three high E_T jets
m_{jj} of leading jets consistent with W mass

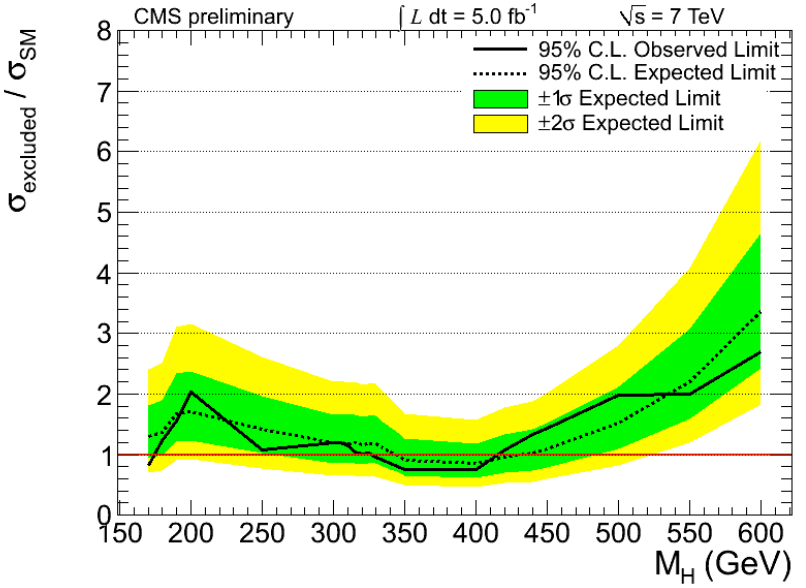
New!
PAS HIG-12-003

Longitudinal component of neutrino momentum reconstructed from W mass constraint of the (l, ν) system



Dominant W+jets bkg normalization from a fit to the m_{jj} sidebands

Signal extraction by shape analysis of the $m_{lνjj}$ distribution in signal region (65< m_{jj} < 95 GeV)

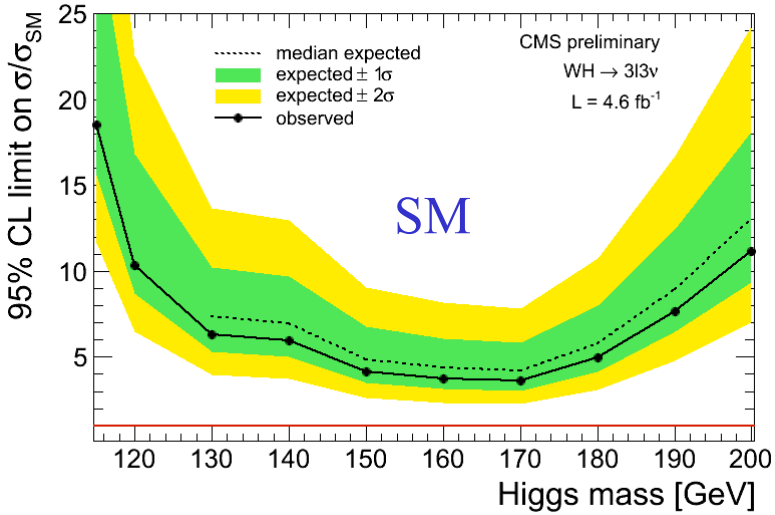


Observed limit → exclusion interval: 327-415 GeV

The WH →W(WW)→3l3ν channel

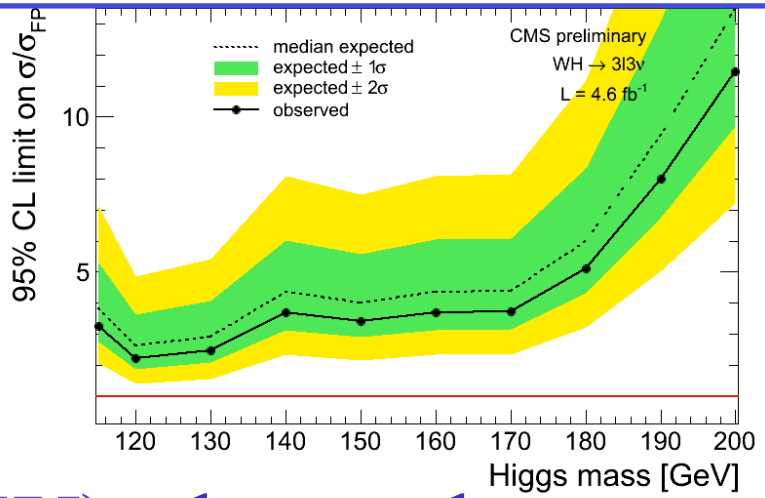
Select events with 3 leptons (l=e,μ), large MET, low hadronic activity
Main bkg: WZ events, top

PAS HIG-11-034

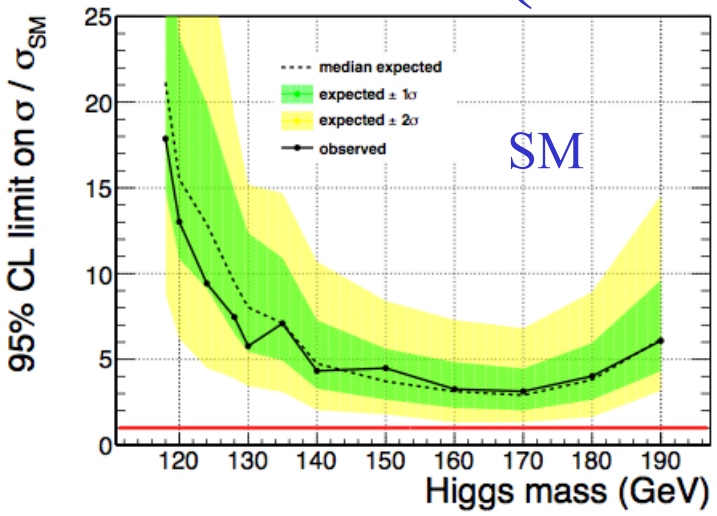


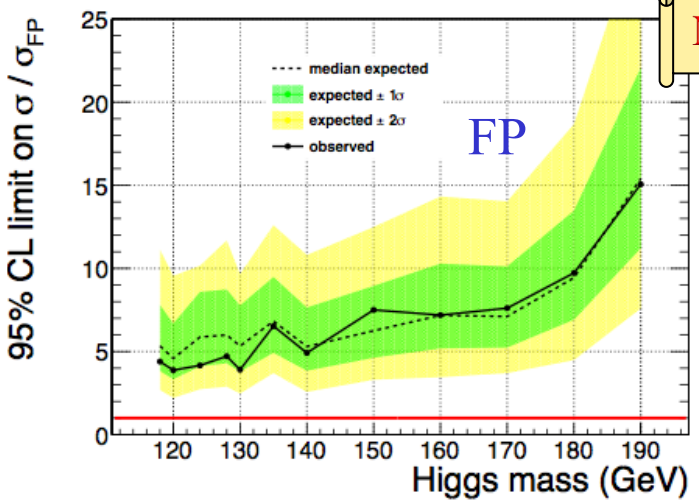
Robust cut &count analysis

Also Fermiophobic (FP) Higgs scenario



VH (V→2j, H→WW) channel

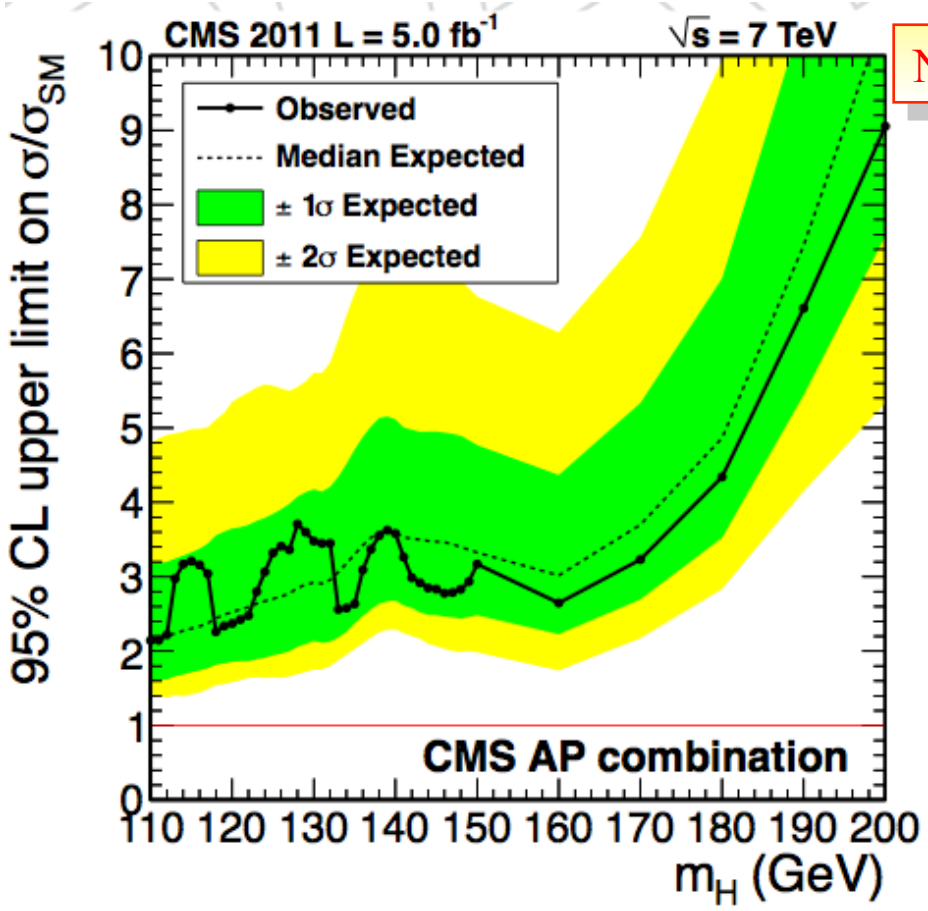




New!PAS HIG-12-014

Same selection as the H→WW→2l2ν plus two central jets from a vector boson (V) resonance

Combination of the VH channels



NEW!

Upper limits ~ 2-3 σ_{SM} for $m_H < 135$ GeV

$H \rightarrow ZZ$ channels

- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow ZZ \rightarrow 2l2\nu$
- $H \rightarrow ZZ \rightarrow 2l2q$
- $H \rightarrow ZZ \rightarrow 2l2\tau$

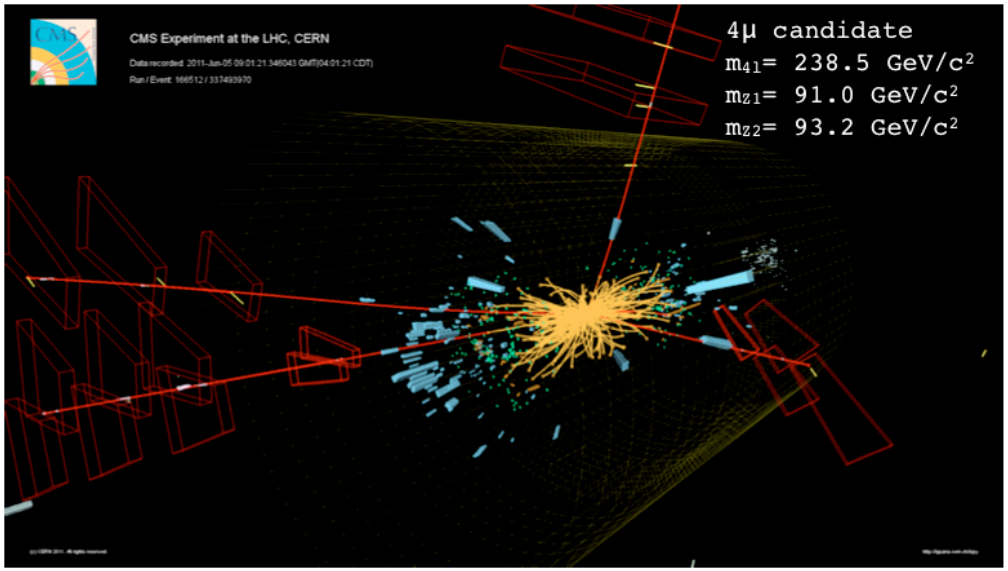
H→ZZ→4l channel

- *Three channels:* 4μ, 4e, 2e2μ
- *Search performed in the 110-600 GeV mass range*

PRL 108 (2012) 111804

Signature: two pairs of isolated, high p_T leptons of opposite sign; one Z bosons can be off-mass shell

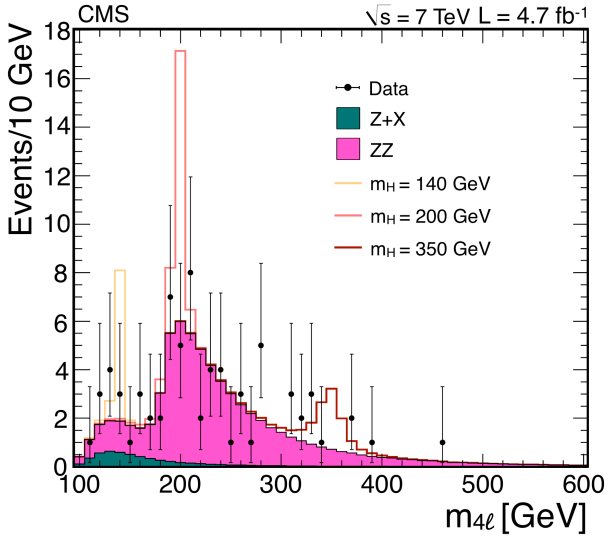
Needs high lepton efficiency through all p_T range

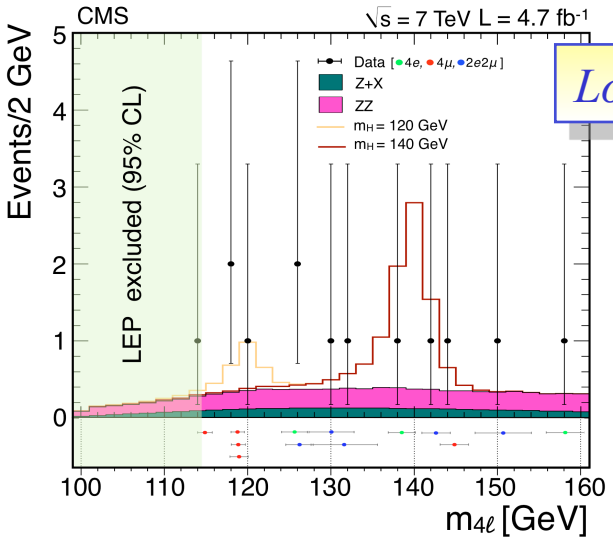


Dominant backgrounds: non resonant ZZ, Z+jets

Signal extraction by shape analysis to m_{4l} distribution

H→ZZ→4l results

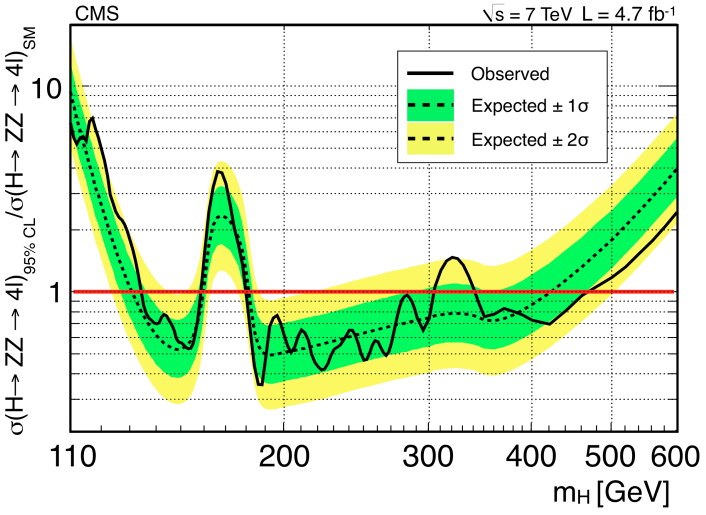


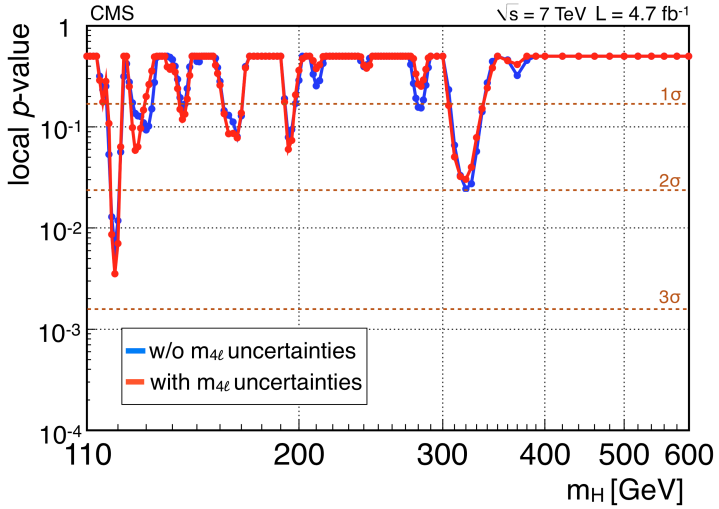


Low mass range

Overall:
BKG exp.: 67±6
Data: 72

Low mass:
BKG exp.: 9.5±1.3
Data: 13





Max significance of the local fluctuations: 2.5 σ @ ~ 119 GeV

Observed limit →3 exclusion intervals @95%CL:
134-158, 180-305, 340-465 GeV

Global significance in the search mass range: 1.0 σ
(1.5σ in 100-160 GeV)

H→ZZ→2l2ν channel

- *2 lepton channels: l = e, μ*
- *BR ≈ 6 BR(H→4l)*
- *Most sensitive channel for m_H > ~ 300 GeV*

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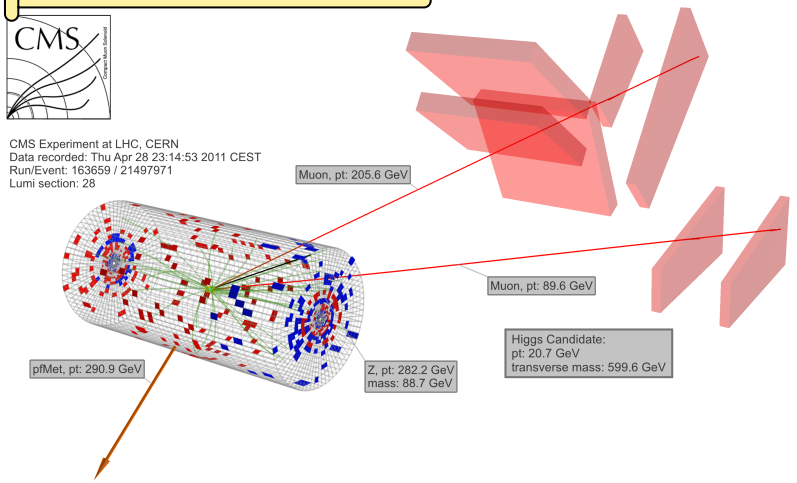
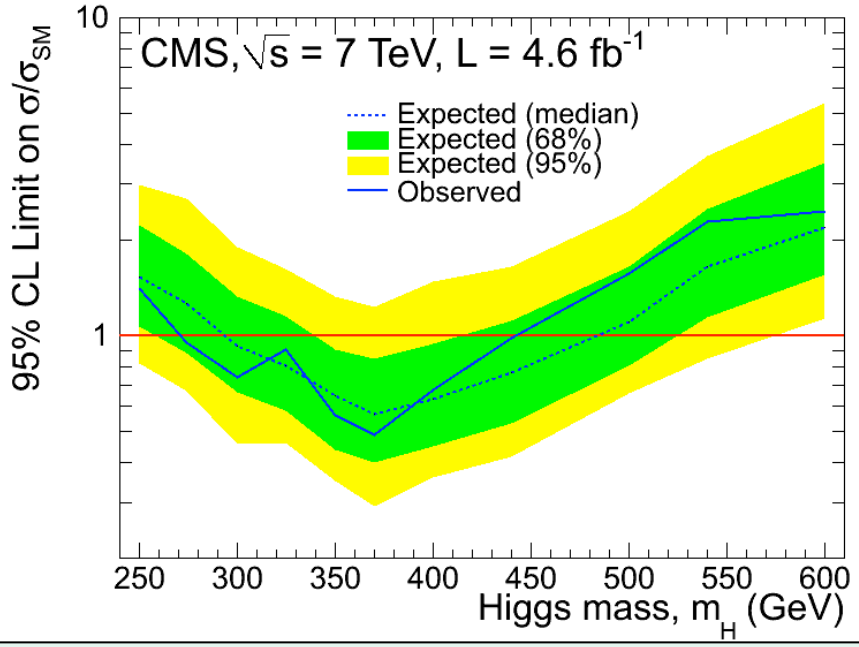


Signature: two isolated, high p_T leptons of opposite sign; m_{ll} compatible with Z boson; large missing transverse energy (MET) in the event

Backgrounds: ZZ, DY+jets, top, other diboson

Boosted Z kinematics exploited to reject ZZ bkg

Signal extraction by binned likelihood fit to the transverse mass of the (MET, dilepton) system



Observed exclusion intervals @95%CL: 270-440 GeV

H→ZZ→2l2q channel

- *2 lepton channels: l = e, μ*
- *BR ≈ 20 BR(H->4l),*
- *130-164, 200-600 GeV ranges explored*

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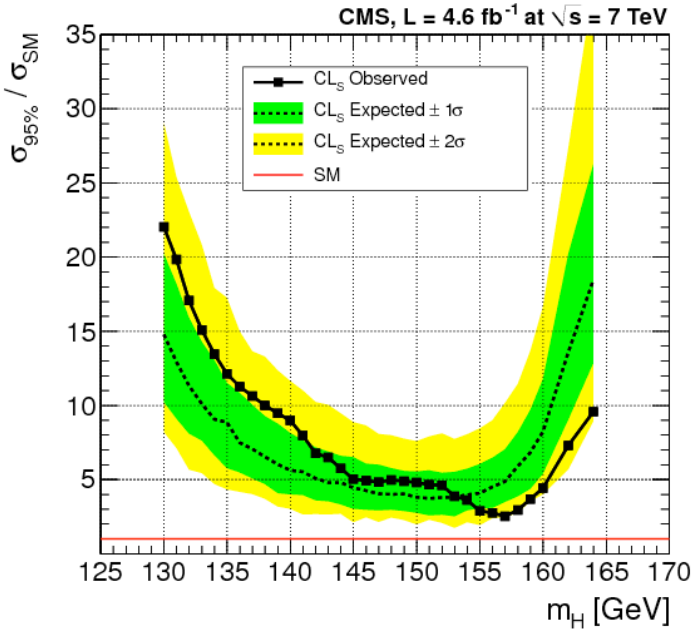
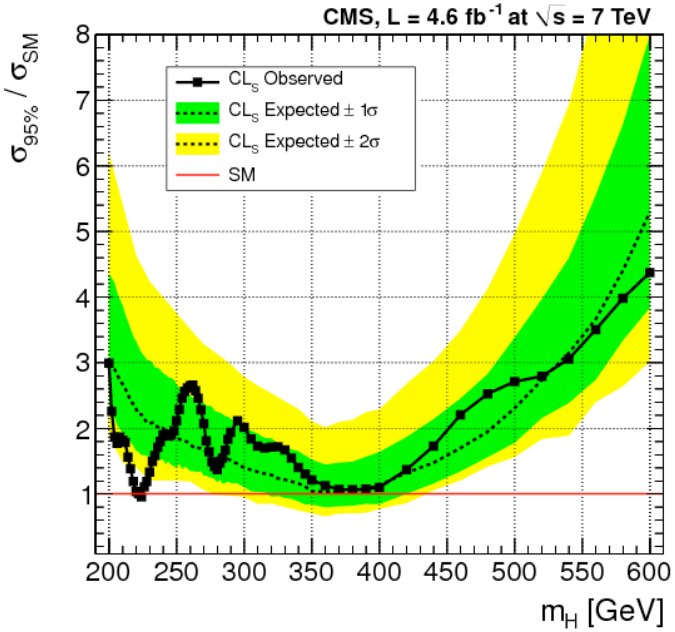
Signature: two isolated, high p_T leptons of opposite sign; m_{ll} compatible with Z boson (high-mass search); two high E_T jets, m_{jj} mass compatible with Z boson

Signal extraction: shape analysis of m_{lljj} invariant mass distribution

Backgrounds: DY+jets, top, ZZ





Exclusion limits approaching SM expectations

The H→ZZ→2l2τ channel

- *Search complementary to H→4l channel*
- *Mass range 200-600 GeV*
- *l = e,μ; 2τ = $\tau_h\tau_h$, $\tau_\mu\tau_h$,$\tau_e\tau_h$, $\tau_e\tau_\mu$*

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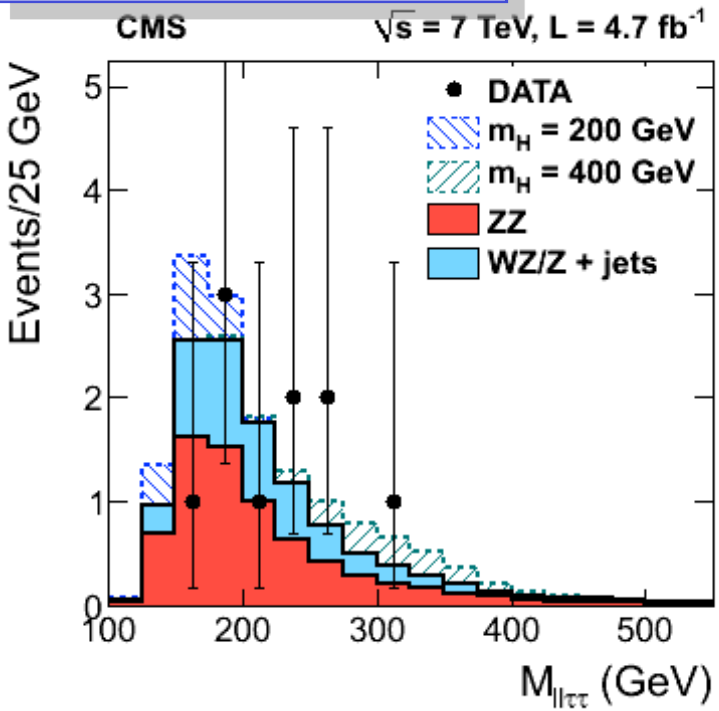
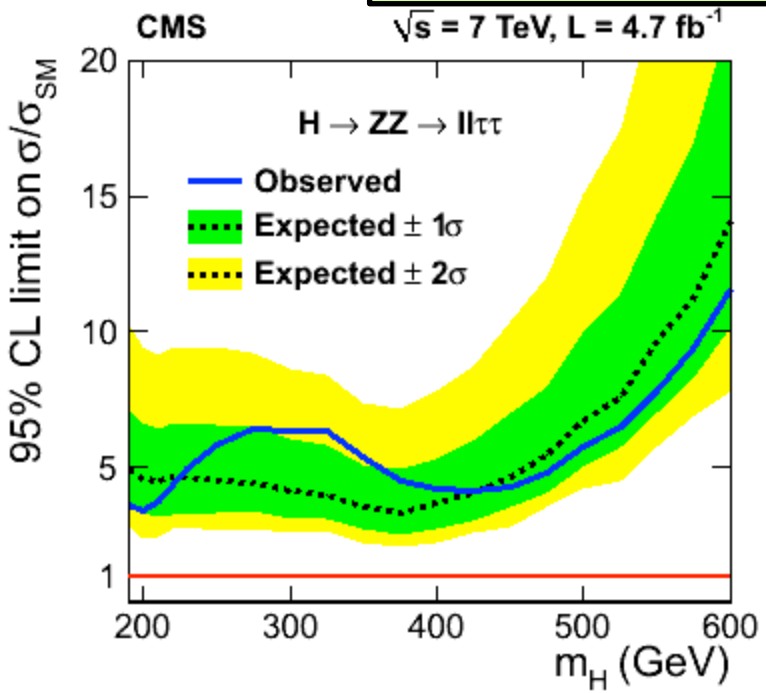
Bkg. expected: 11.60 ± 0.54 (stat) ± 1.62 (syst)
Signal expected: ~ 1.5 events for m_H in 200-400 GeV range

Limits extracted by shape analysis of $m_{ll\tau\tau}$ invariant mass distribution

All channels combined



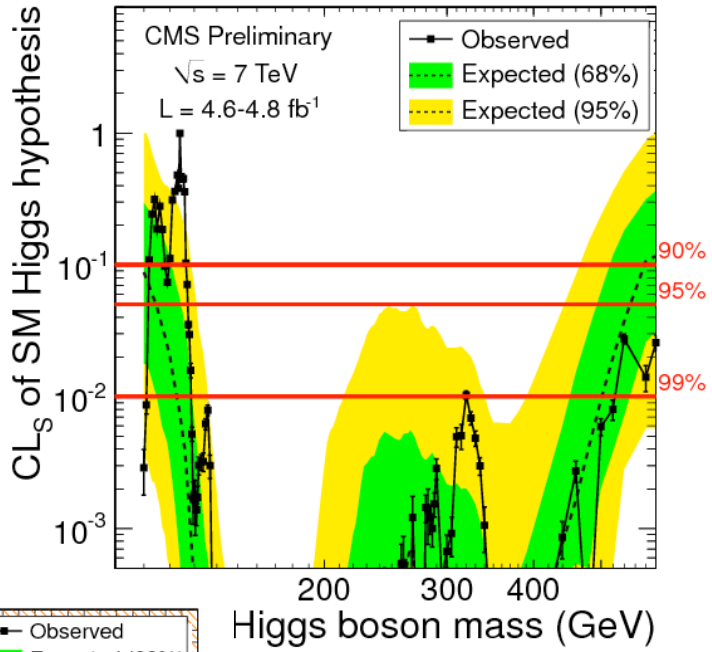


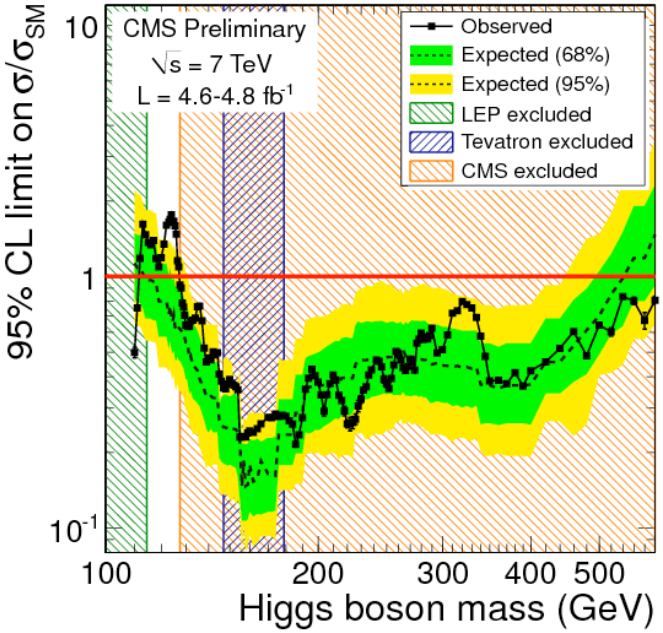
Observed upper limits vary from 4 to 12 σ_{SM}

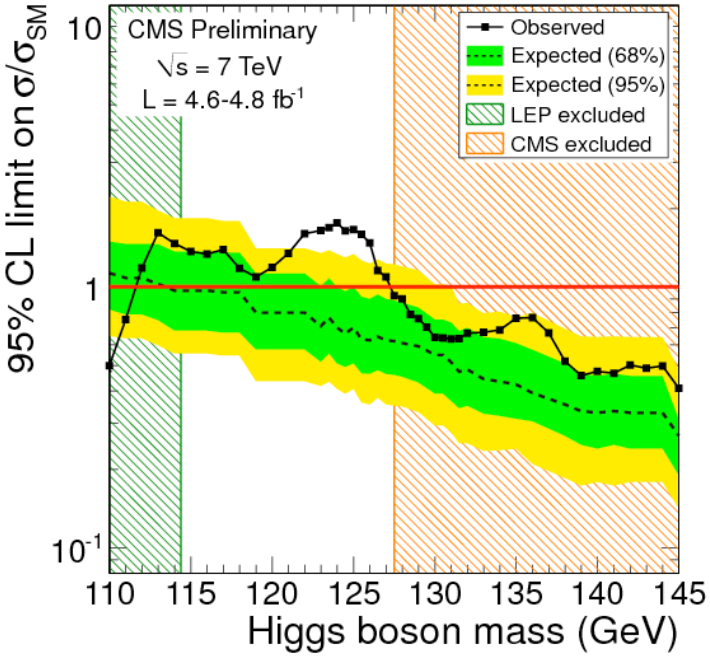
Combination of SM Higgs searches

Modified frequentist CLs construction

Observed, expected limits and bands by generating ensambles of pseudo-datasets





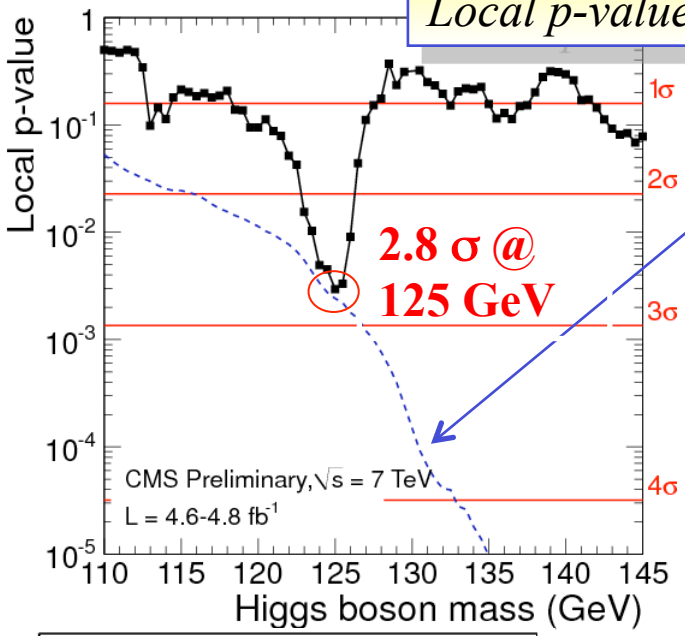


Expected exclusion @ 95%CL: 114.5-543
Excluded 127.5 – 600 GeV @ 95%CL
Excluded 129 – 525 GeV @ 99%CL

Weaker limit than expected around 125 GeV due to excess of events w.r.t. bkg expectation

Combination of SM Higgs searches

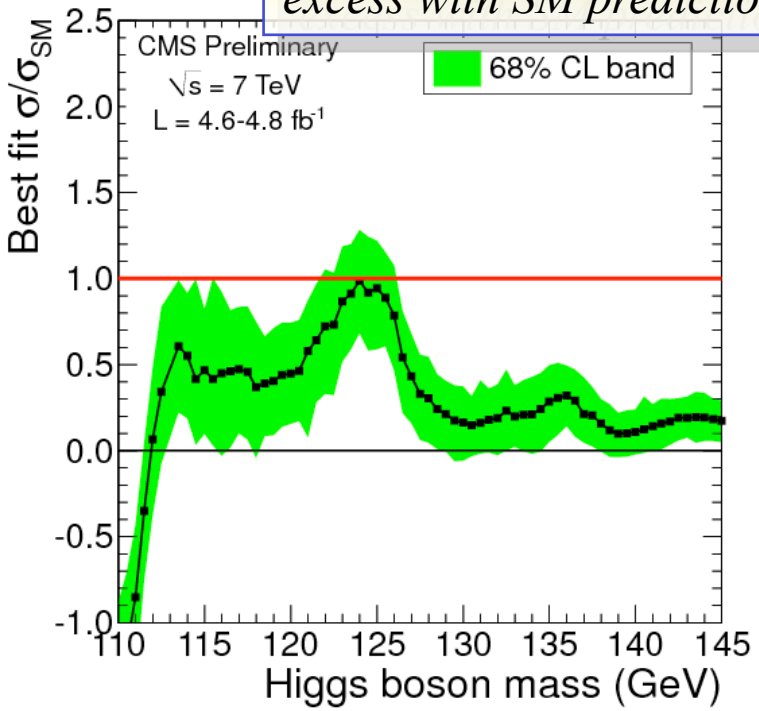
Local p-value

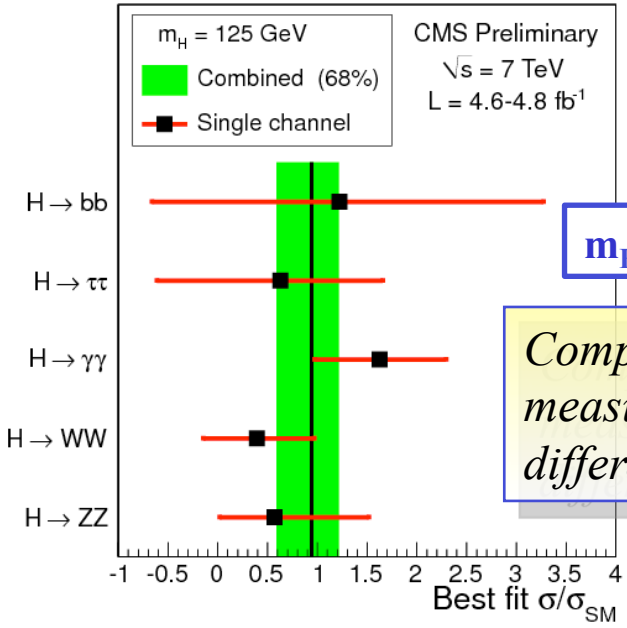


Expected p-value if SM Higgs boson exists

Global significance ("Look-Elsewhere Effect"):
0.8 σ in the range 110-600GeV
2.1 σ in the range 110-145GeV

Compatibility of observed excess with SM prediction





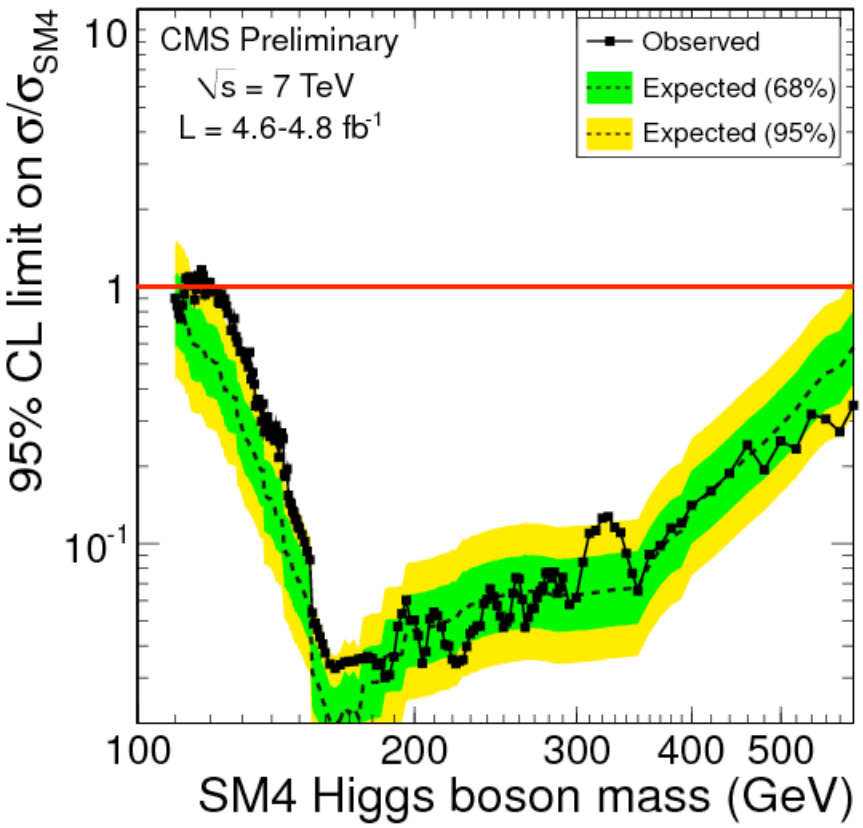
m$_H$ = 125 GeV

Compatibility of measurements in different channels

Combination: other scenarios

SM with 4 fermions generations (SM4)

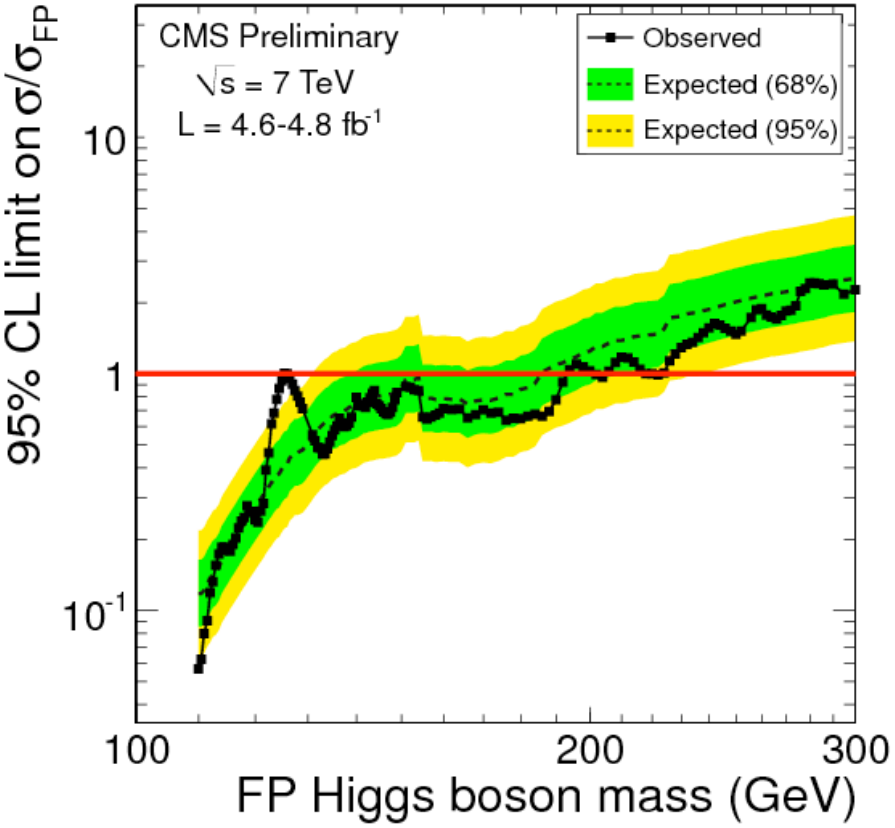
- SM extension with fourth fermion generation (SM4)
- Enhanced gg fusion production
- Also decay rates affected



Excluded: 120-600 GeV @95% CL

Fermiophobic (FB) Higgs boson

- Suppressed coupling with fermions
- No gg fusion, no ttH production
- Enhancement of H→ γγ / WW / ZZ



Excluded: 110-192GeV @95% CL

Conclusions

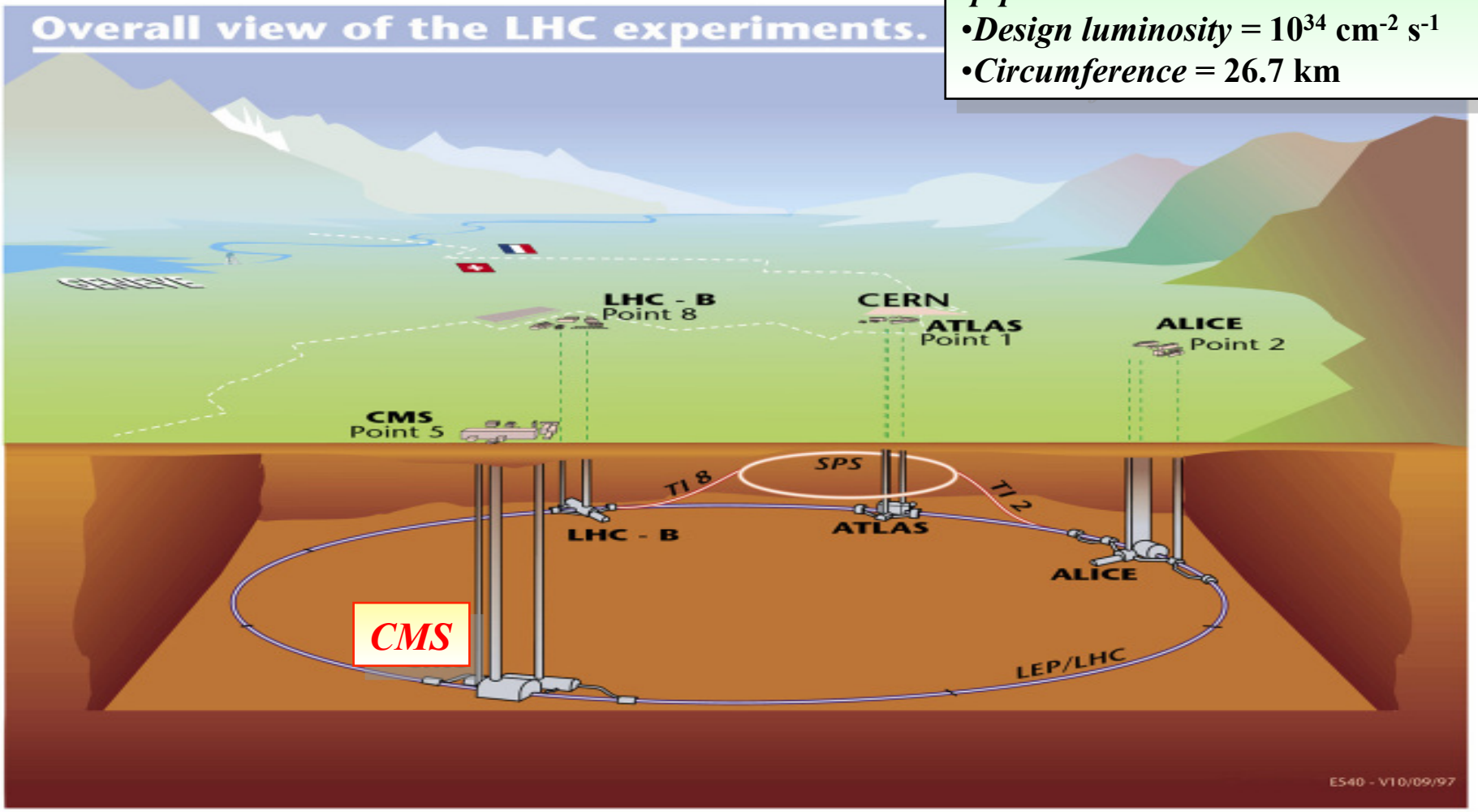
- Status of SM Higgs boson searches based on 2011 data sample reviewed
  - Almost 5 fb^{-1} of data collected at 7 TeV
  - 11 search channels (total of 50 exclusive sub-channels)
  - Explored 110 – 600 GeV m_H mass range
- Combination of channels gives SM Higgs excluded in the range 127.5 – 600 GeV @ 95% CL
- Small excess of events at ~ 125 GeV
  - Local significance of 2.8σ
  - Global significance is lower (2.1σ in the range 110-145 GeV)
- Adding new 2012 data at 8 TeV should clarify the origin of the excess

Backup slides

The CMS experiment @ LHC

The Large Hadron Collider

- ***p-p collider***
- ***Design luminosity*** **= 10^{34} cm^{-2} s^{-1}**
- ***Circumference*** **= 26.7 km**

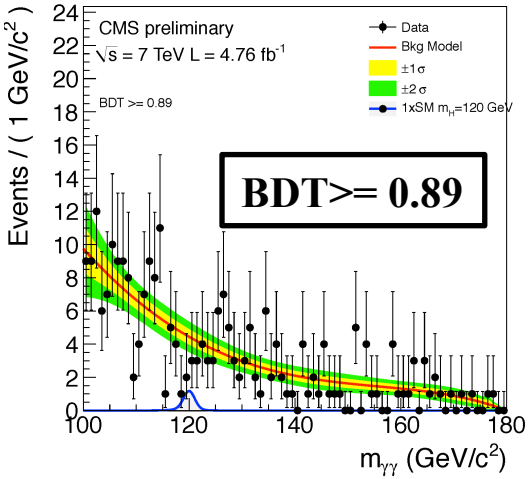


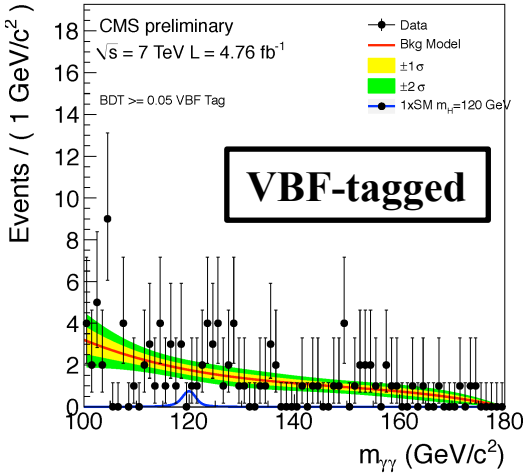
H→γγ

Signal mass region: [m_H-10, m_H+10 GeV]

Expected signal and data events in m_H=120 GeV signal region

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



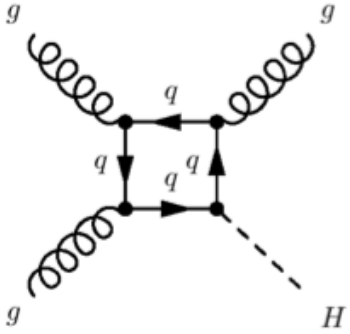


- Events classification in independent 4+1 categories of different sensitivities
- 4 categories based on output of di-photon BDT discriminant + 1 VBF-category (S/B ~ 1/3)
- Di-photon BDT exploits signal-like kinematics, di-photon mass resolution, photon BDT identification

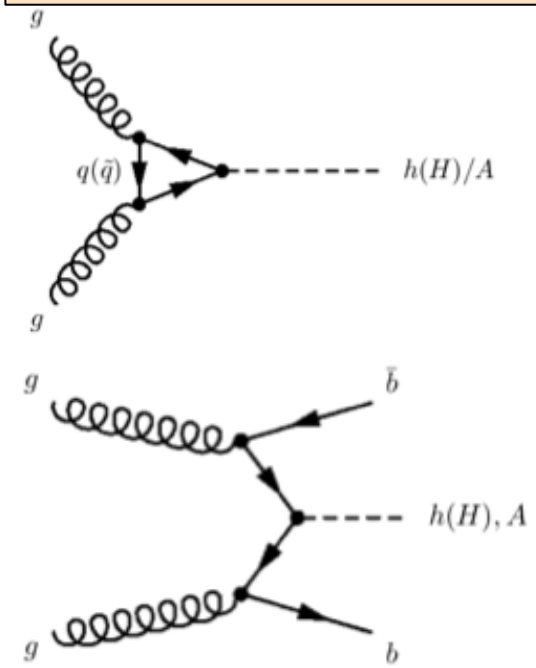
MVA Analysis improvement
~ 20 % w.r.t. cut analysis

H→ττ

Production of SM H + high-p_T jet



Production of MSSM neutral Higgs bosons



Event classification for final analysis

SM search

- VBF (2 forward jets, VBF-tagged)
- Boosted (1 jet p_T >150)
- 0/1 jet (not more than 1 non-boosted jet)

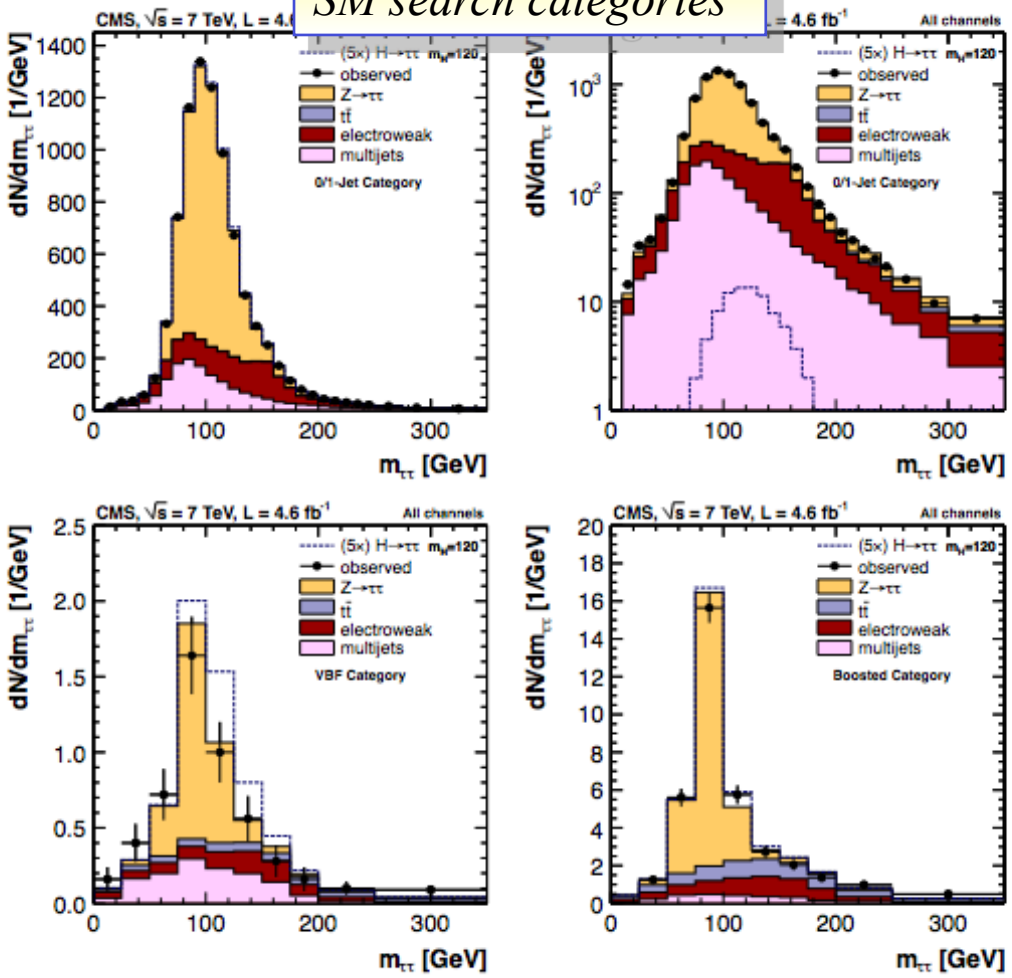
MSSM search

- b-Tag (at least 1 b-tagged jet)
- non b-tag

H→ττ

ML technique for reconstruction of ττ invariant mass:
achieved resolution ~ 20%

SM search categories



WH, H→ττ

Final yields and bkg expectations after full selection

Channel	$\mu\mu\tau$	$e\mu\tau$
Fakes	3.09 ± 1.03	5.64 ± 1.80
WZ	2.13 ± 0.35	2.12 ± 0.35
ZZ	0.17 ± 0.07	0.18 ± 0.07
Triboson	0.20 ± 0.20	0.20 ± 0.20
Backgrounds	5.60 ± 1.11	8.15 ± 1.84
Observed	5	4
VH ($m_H = 120$ GeV)	0.40	0.38

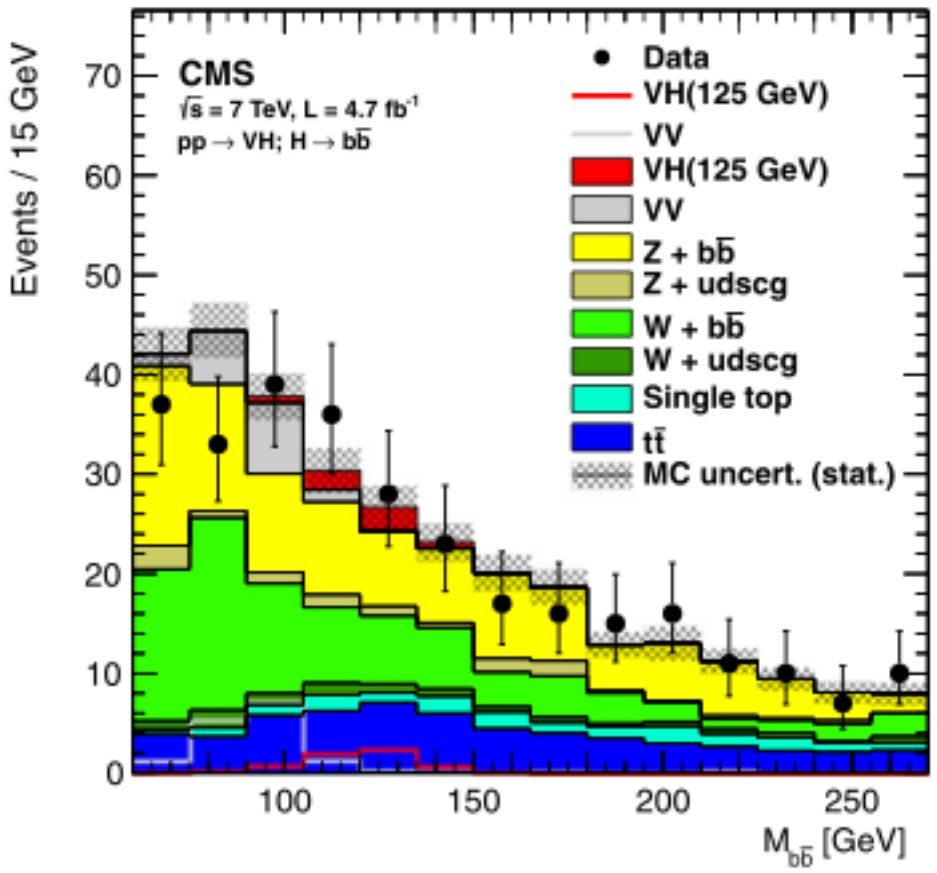
H→τ(μ)τ(μ)

Final yields and bkg expectations in ($m_{\mu\mu}$, $m_{\tau\tau}$) bins for m_H = 120 GeV

VBF					*Boosted*				
$m_{\mu\mu}$	$m_{\tau\tau}$	S×10	B	Data	$m_{\mu\mu}$	$m_{\tau\tau}$	S×10	B	Data
0 – 75	0 – 100	0.26	4.11	4	0 – 80	0 – 105	1.24	23.7	21
0 – 75	100 – 120	1.84	1.04	0	0 – 80	105 – 125	1.76	8.12	4
0 – 75	120 – 150	2.13	1.88	5	0 – 80	125 – 150	1.71	2.13	1
75 – 105	100 – 120	0.06	2.69	4	0 – 80	150 – 200	0.07	1.08	2
75 – 105	120 – 150	0.05	4.89	1	80 – 100	0 – 105	0.05	1.81	0

H→bb

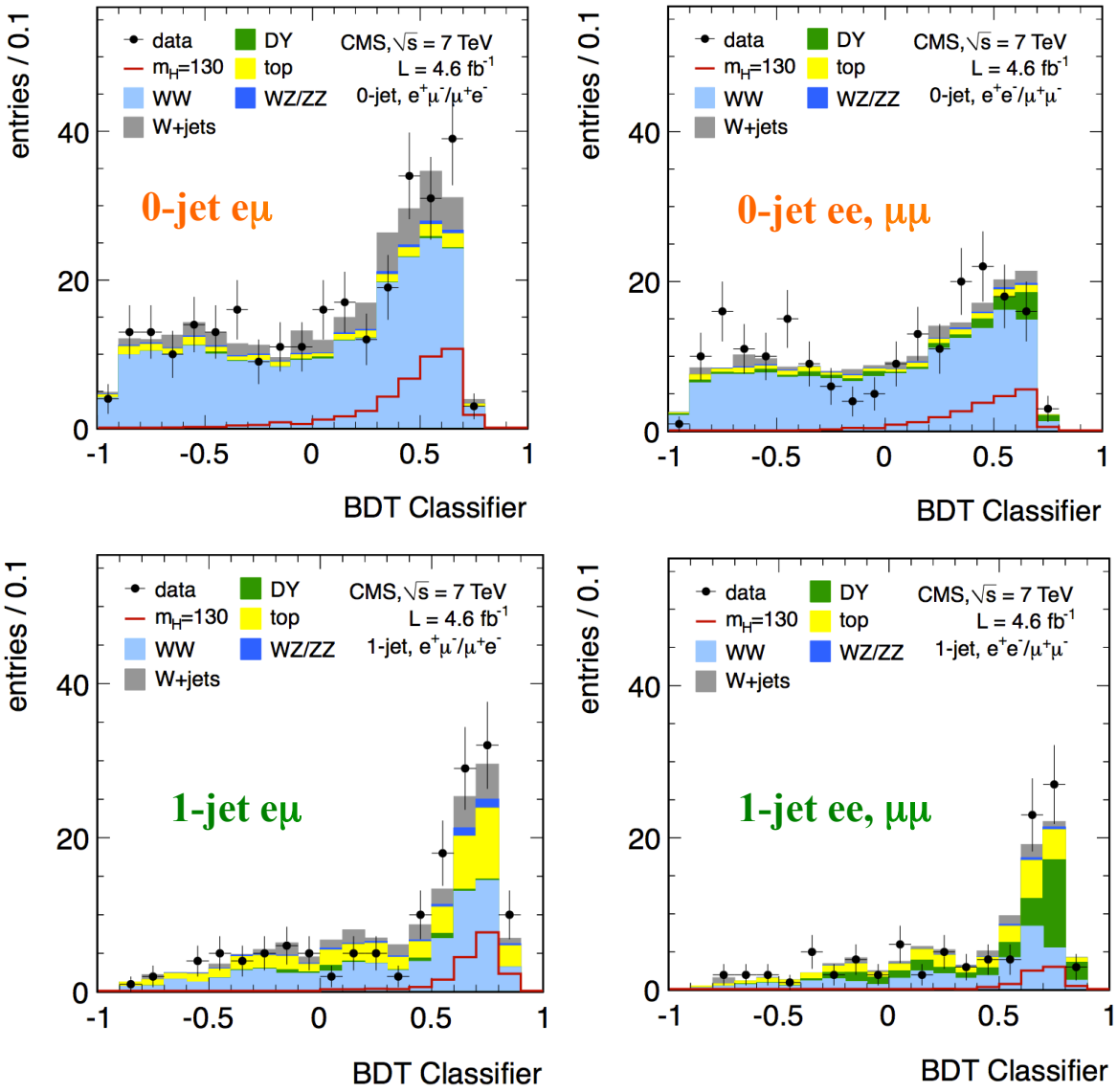
Dijet invariant mass distribution, all channels combined



Data-driven estimates of the dominant bkg yields (V+jets, top)

H→WW→2l2ν

BDT output for different event categories



Events classification in independent 0-, 1-, 2-jet (VBF) exclusive categories

Selection optimized for the different categories

H→ZZ→4l channel

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

- *DY+jets bkg extrapolated from sideband sample*
- *ZZ bkg determined from simulation (small statistics available in data); estimate cross-checked by extrapolation from measured inclusive Z rate in data*

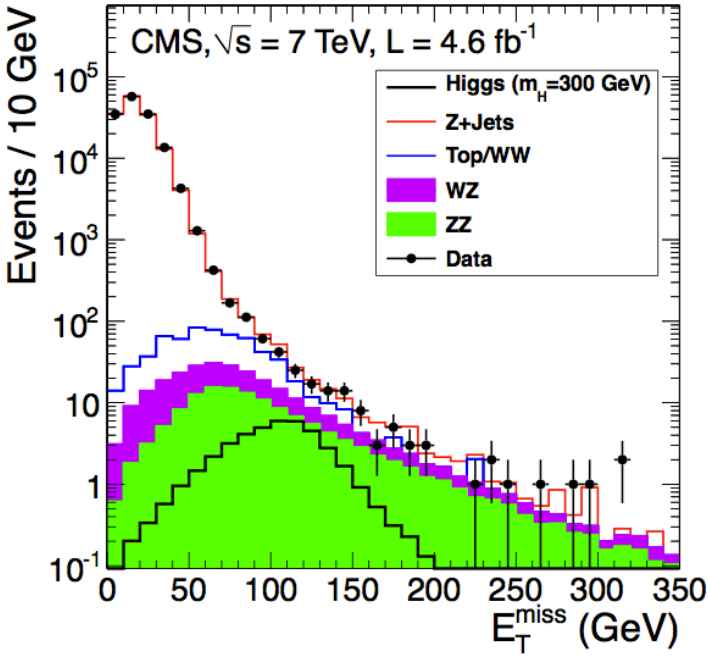
Main systematics:
- Luminosity determination, lepton ID
- theoretical uncertainty on Higgs cross section

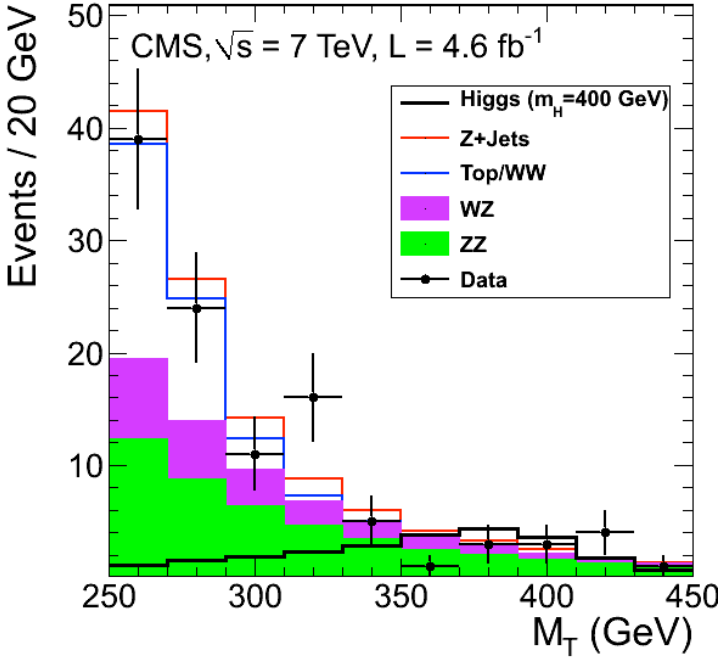
H→ZZ→2l2ν

Both counting analysis and shape analysis (better sensitivity -> used for final result)
Shape analysis: Signal extraction by binned likelihood fit to the transverse mass of the (MET, dilepton) system

$$M_{\mathrm{T}}^2 = \left(\sqrt{p_{\mathrm{T}}(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_{\mathrm{T}}^{\mathrm{miss}\,2} + M(\ell\ell)^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{\mathrm{miss}})^2$$

- *DY+jets MET distribution from γ+jets control sample*
- *Non-resonant bkg normalization from eμ control sample*
- *Diboson bkg determined from simulation (small statistics available in data)*

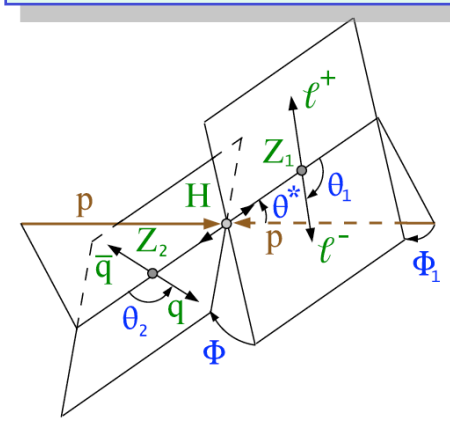




H→ZZ→2l2q

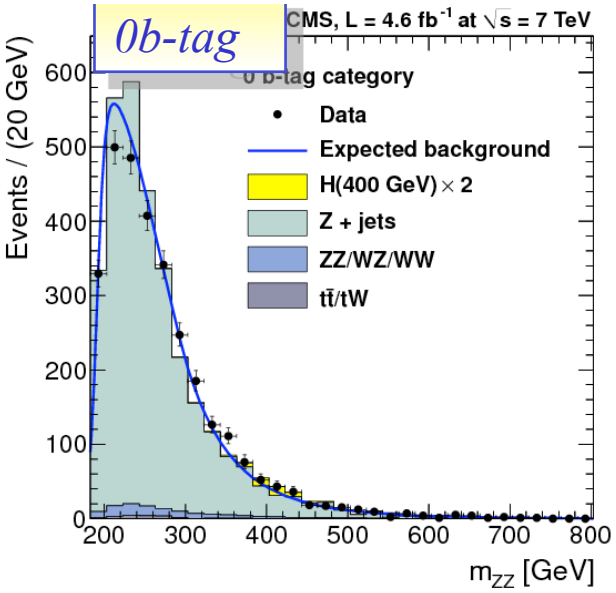
- *Kinematics described in terms of 5 angles with known distributions*
- *Angular variables are combined in a likelihood discriminant*

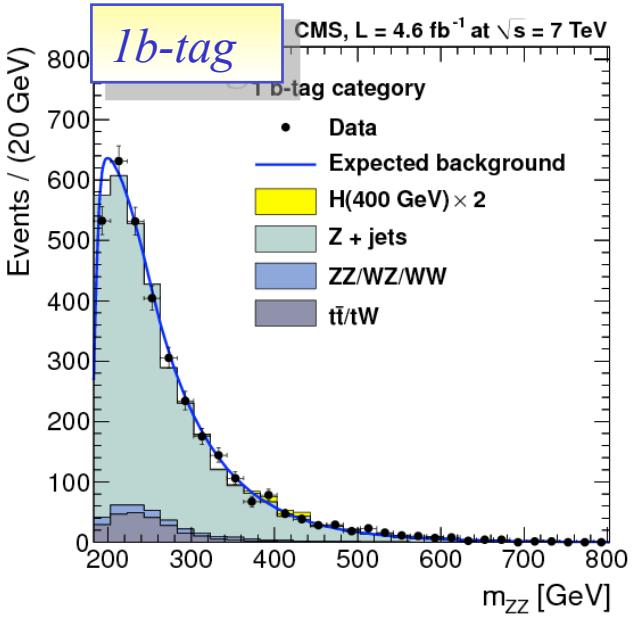
Events classification in exclusive categories (2 b-jet, 1 b-jet, 0 b-jet)

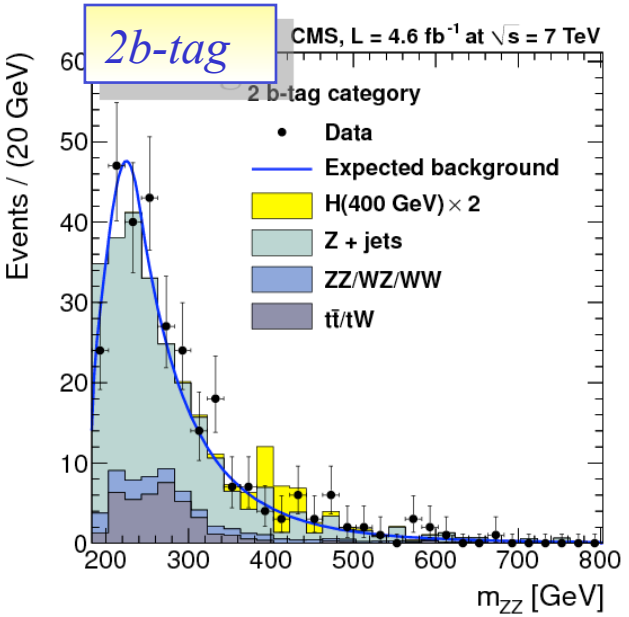


m_{lljj} resolution ~3% after kinematic fit constraining jj invariant mass to Z boson mass

Shape analysis of m_{lljj} invariant mass distribution







Example of systematics uncertainties

Systematics are, of course, channel and analysis dependent

The following table summarizes sources and uncertainties in a typical search analysis

Table from H→bb analysis

Source	Range
Luminosity	4.5%
Lepton efficiency and trigger (per lepton)	3%
Z($\nu\nu$)H triggers	2%
Jet energy scale	2–3%
Jet energy resolution	3–6%
Missing transverse energy	3%
b-Tagging	3–15%
Signal cross section (scale and PDF)	4%
Signal cross section (p_T boost, EWK/QCD)	5–10%/10%
Signal Monte Carlo statistics	1–5%
Backgrounds (data estimate)	10–35%
Diboson and single-top (simulation estimate)	30%

Now improved to 2.2 %

Limited statistics of the control samples