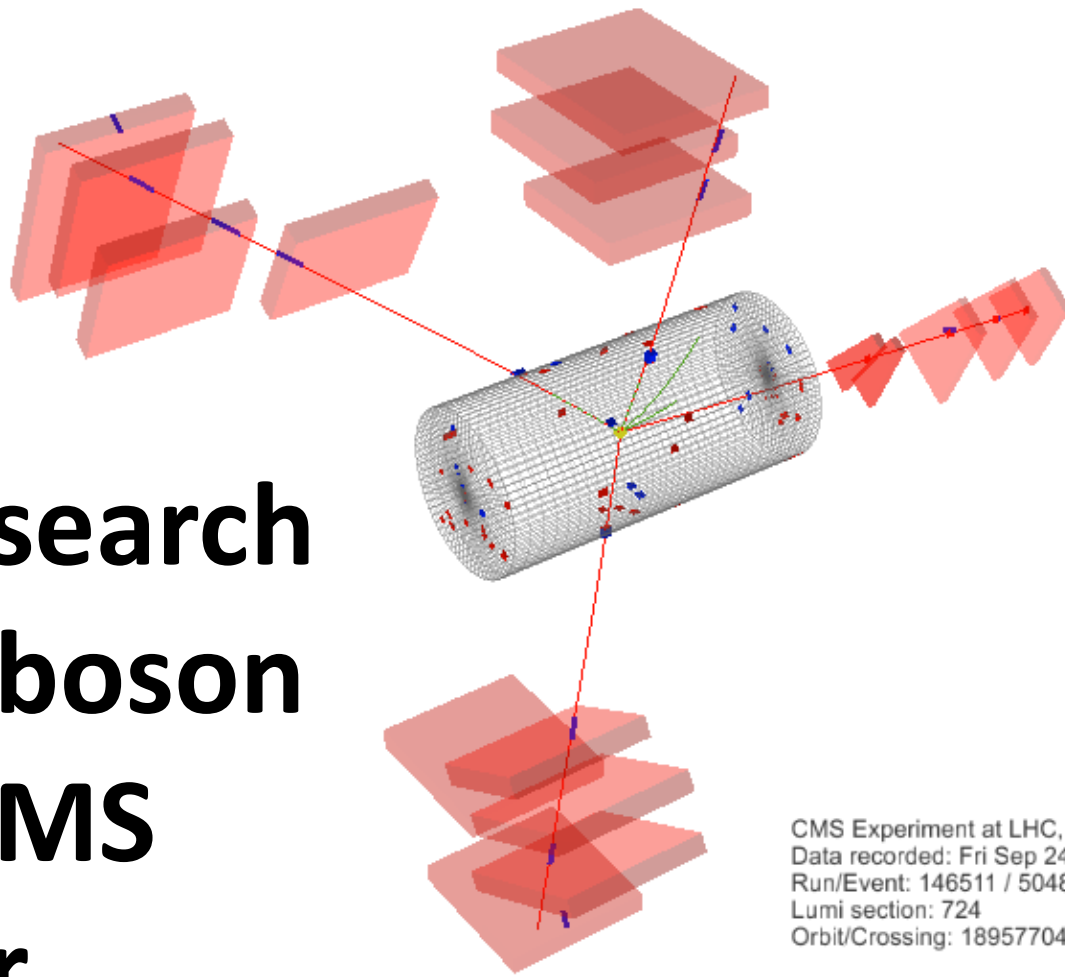


# Status of the search for the Higgs boson with the CMS detector

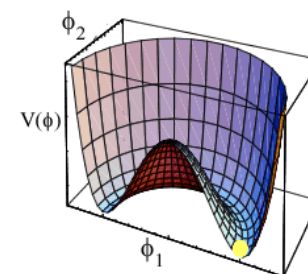
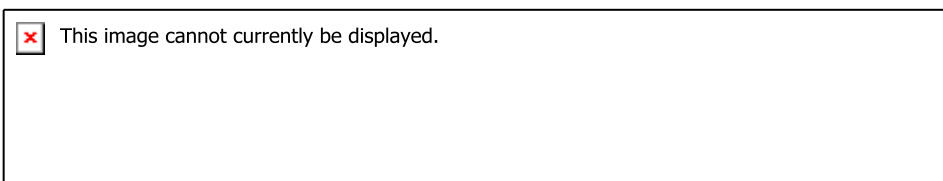
Marco Zanetti, MIT  
for the CMS Collaboration



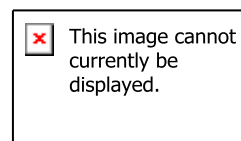
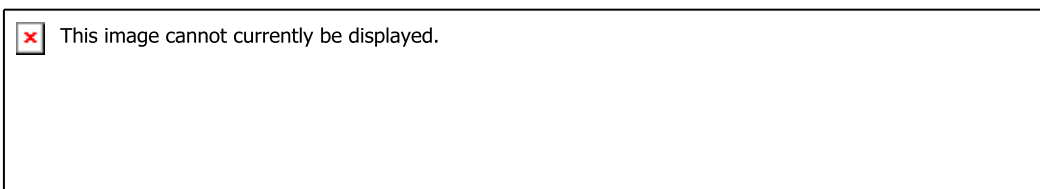
CMS Experiment at LHC, CERN  
Data recorded: Fri Sep 24 02:29:58 2010 CEST  
Run/Event: 146511 / 504867308  
Lumi section: 724  
Orbit/Crossing: 189577049 / 2677



- Tremendous success of the SM, but not yet experimental evidence for the mechanism behind masses of the fields
- Higgs mechanism proposed in 1964 as a way to give masses to gauge Bosons

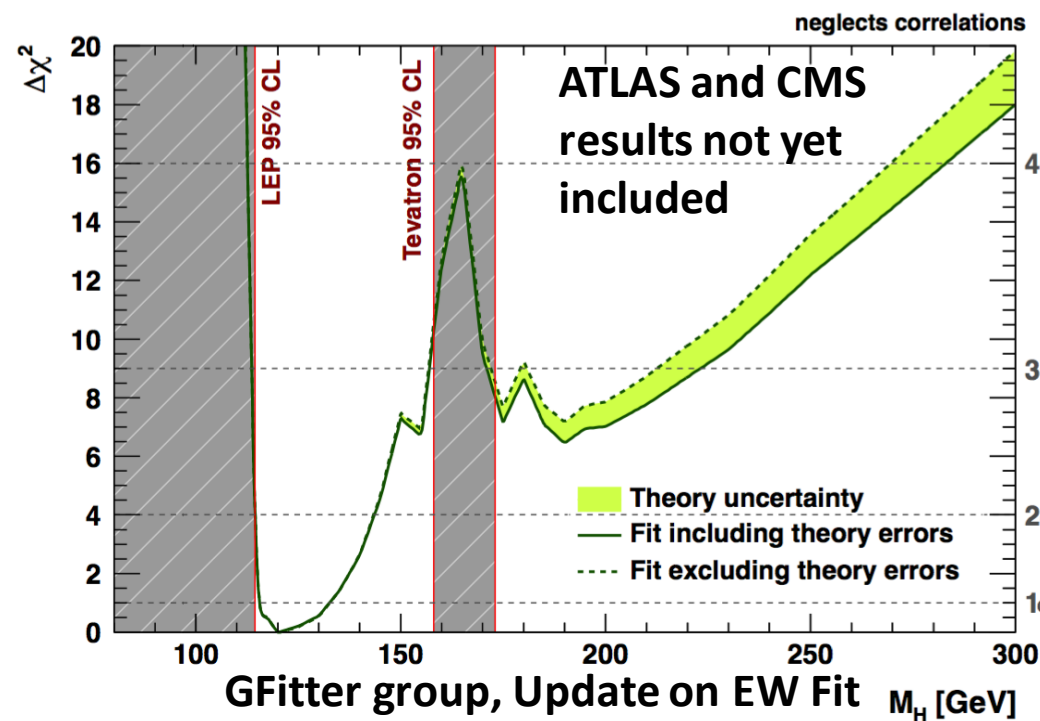
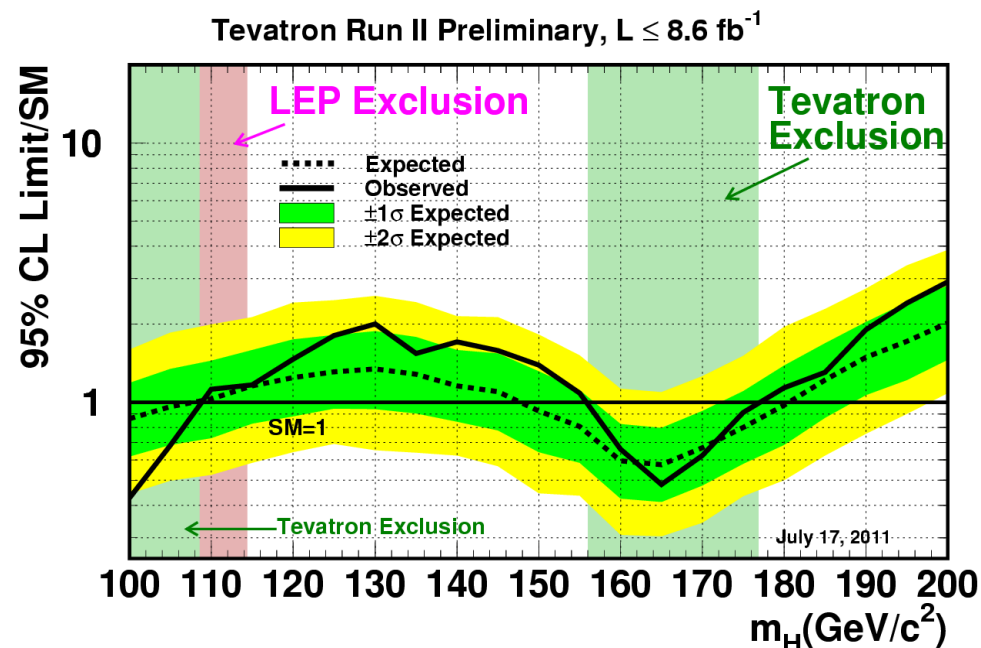


- Incorporated in the SM by Weinberg-Salam to break EW symmetry and give mass to W and Z bosons and fermions:



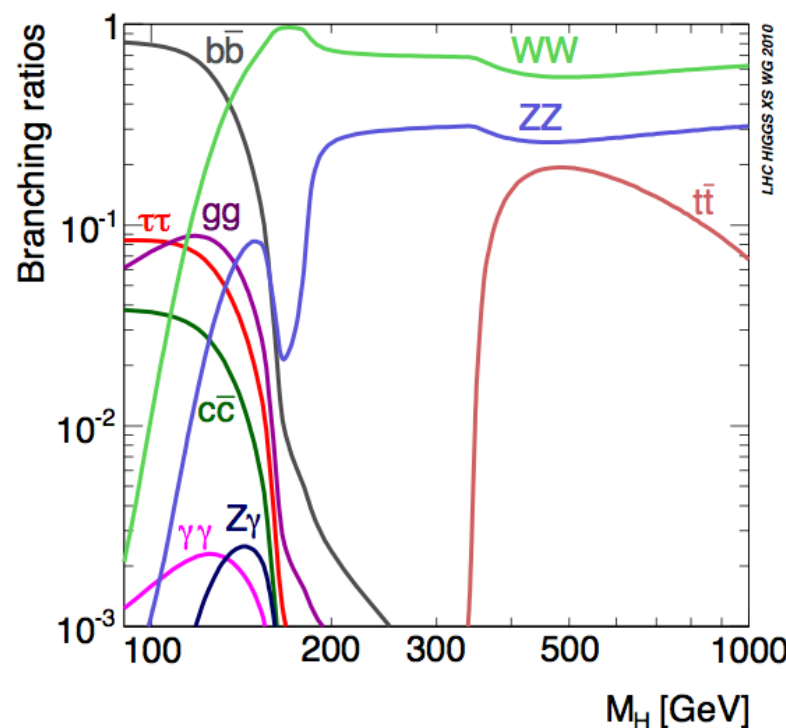
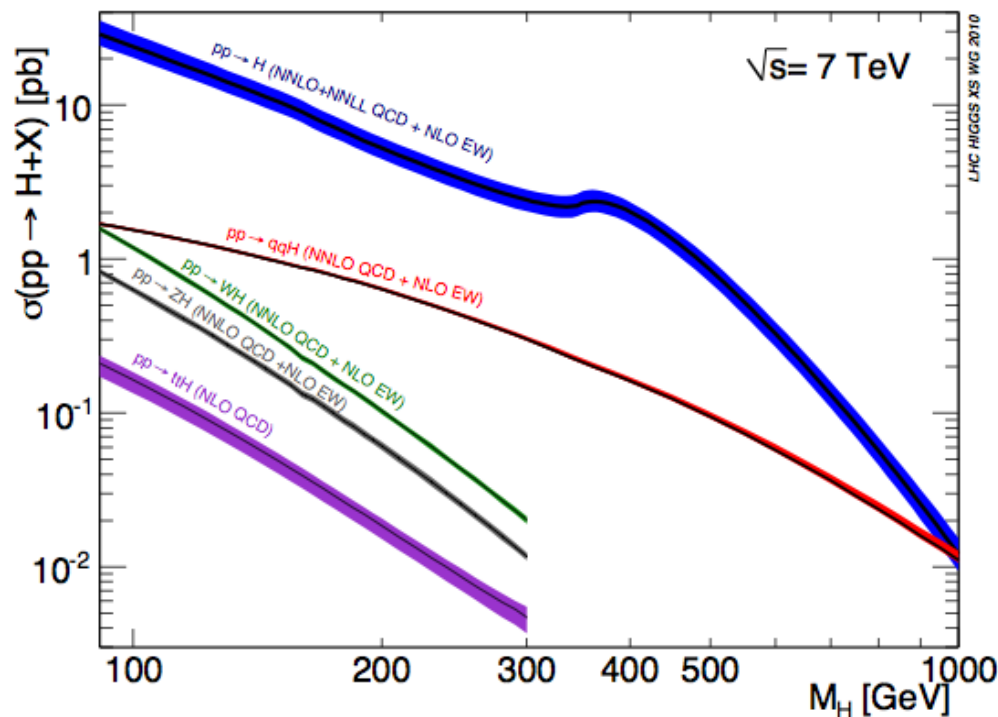
- Key component of the SM, the only fundamental scalar in the theory, but still not discovered
  - Divergences in WW scattering if the Higgs is not there

Disclaimer: what discuss in the following refers to the SM Higgs boson, a few remarks about implications for SM extensions will be given too



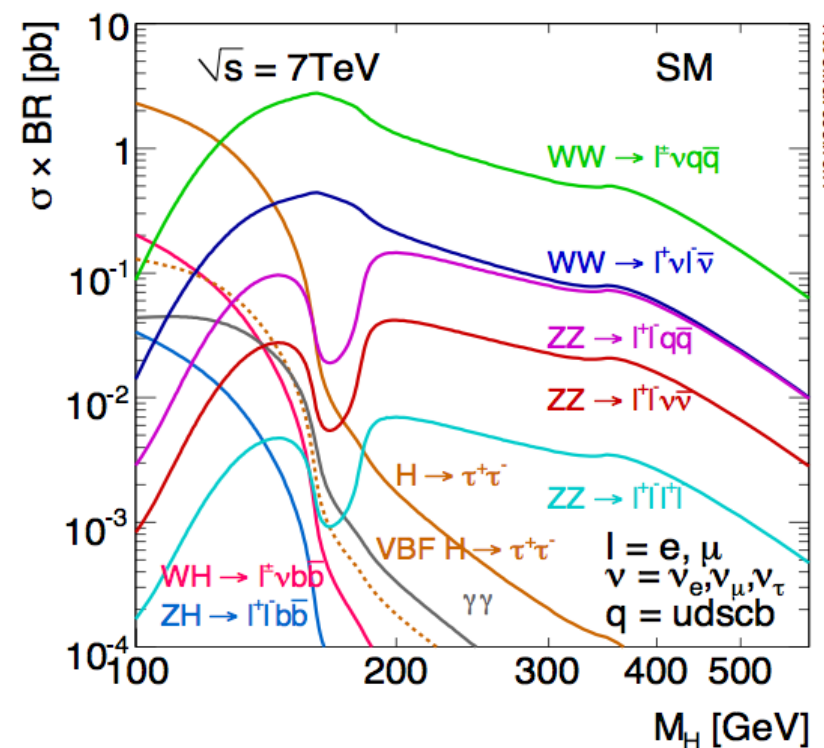
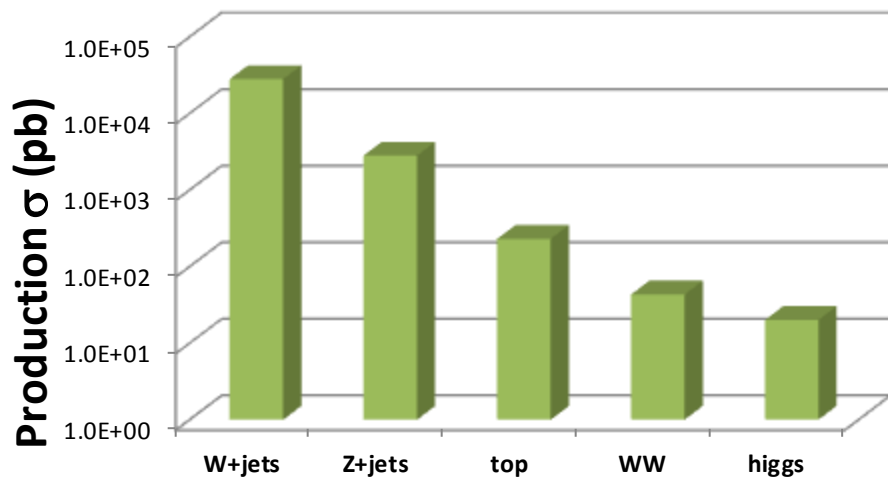
<http://arxiv.org/abs/1107.0975>

- Direct searches
  - LEP:  $M_H > 114.4 \text{ GeV}$
  - Tevatron:  $|M_H - 166| > 10 \text{ GeV}$
- Indirect constraints from precision EW measurements
  - $M_H = 96^{+31}_{-24} \text{ GeV}$ ,  $M_H < 169 \text{ GeV}$  at 95% CL (standard fit)
  - $M_H = 120^{+12}_{-5} \text{ GeV}$ ,  $M_H < 143 \text{ GeV}$  at 95% CL (including direct searches)
- SUSY prefers a light Higgs



- Even at reduced energy (factor 1/3 penalty w.r.t 14 TeV) LHC is a Higgs factory
- $L=5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ , a Higgs boson ( $M_H \sim 120 \text{ GeV}$ ) produced every  $\sim 10$  seconds
- Other production processes important for exclusive final state searches

# Higgs search strategies



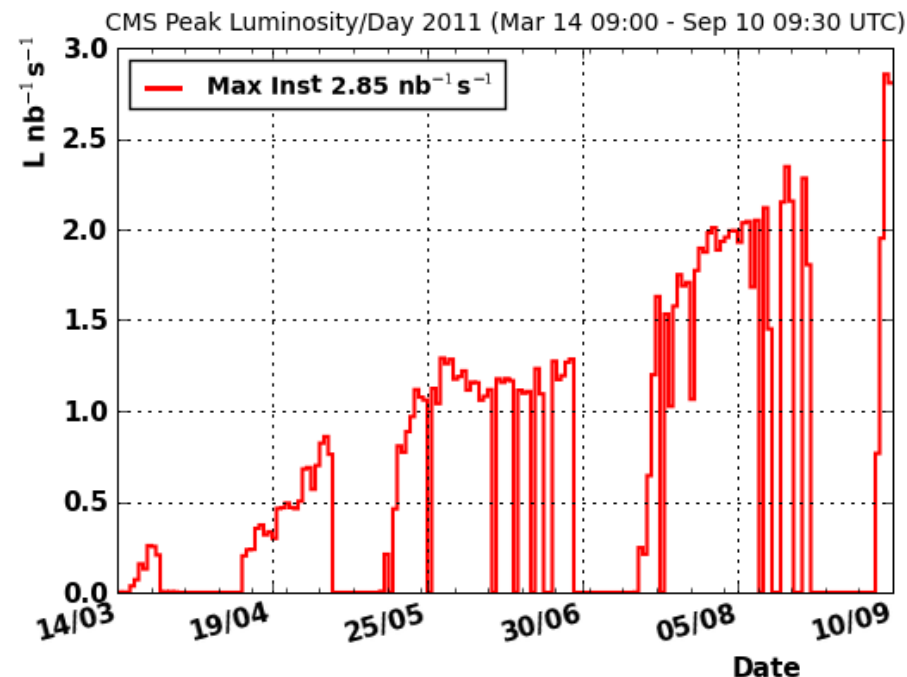
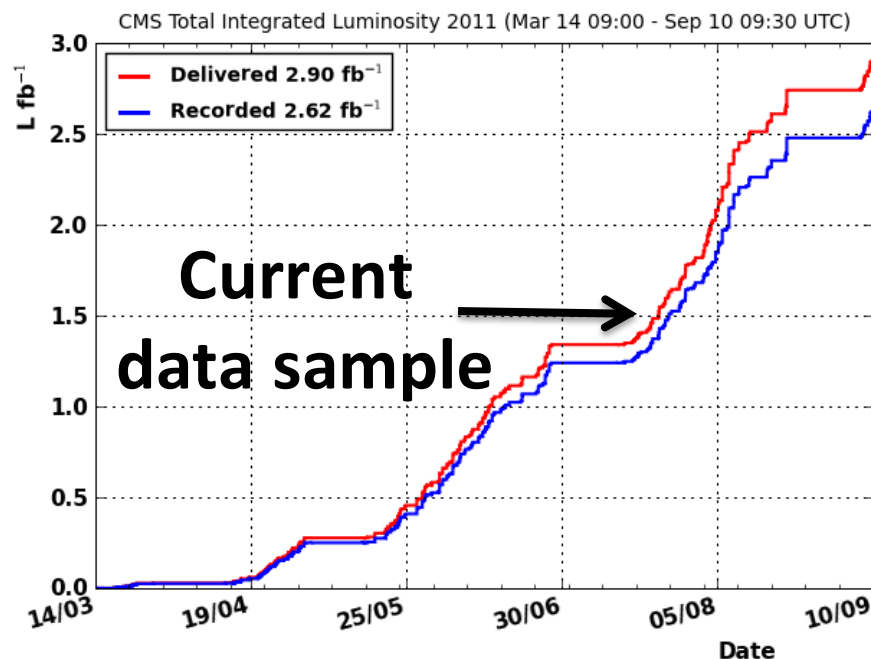
- Higgs production cross section tiny compared to other QCD and EWK processes
- Depending on  $M_H$ , specific exclusive Higgs final states are considered
- Very narrow phase space regions selected to achieve a good S/B ratio

Signal yields for  $1 \text{ fb}^{-1}$

$m_H, \text{ GeV}$	$WW \rightarrow 2l2\nu$	$ZZ \rightarrow 4l$	$\gamma\gamma$
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

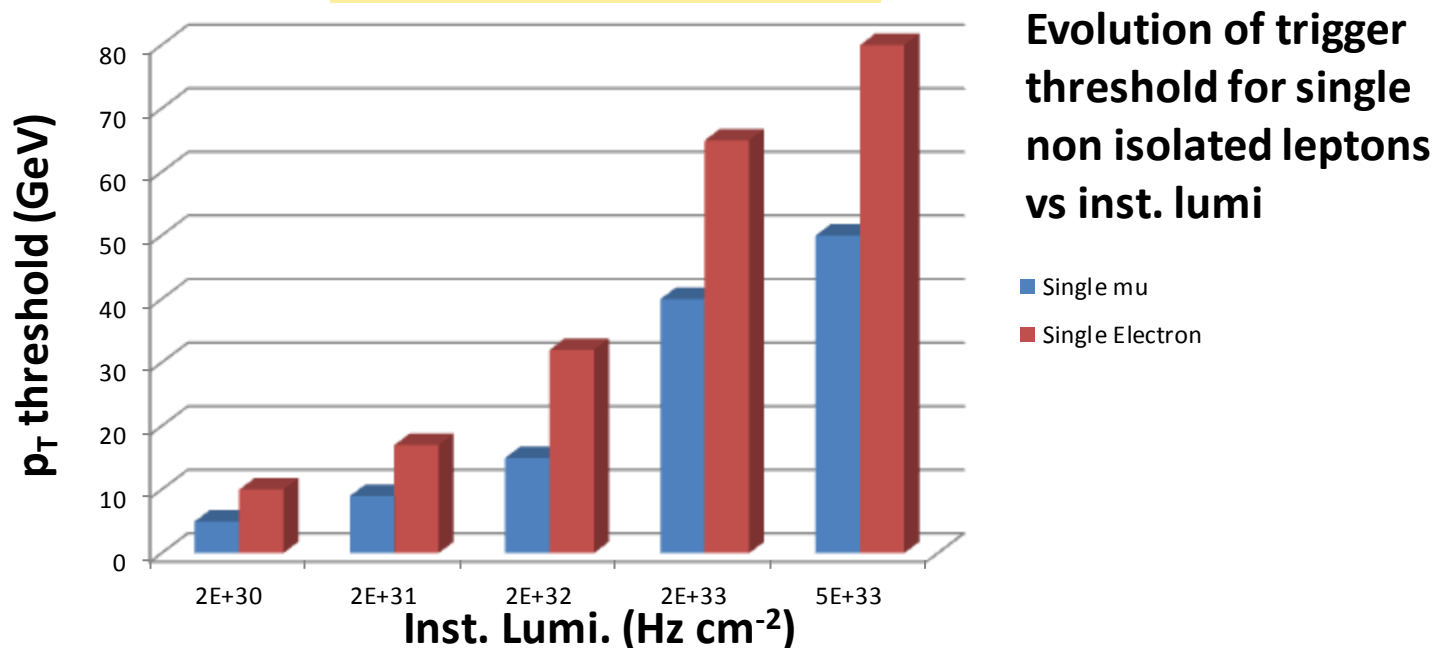
- CMS searched for the Higgs in eight decay modes
- Signature: **Isolated leptons** or **photons** in the final state to suppress background
  - **MET, jets, b-tagging** and **tau identification** play also a crucial role
- most sensitive channels in theoretically favored range [110-200] GeV:
  - **H- $\rightarrow\gamma\gamma$** , **H- $\rightarrow WW\rightarrow l\nu l^+\nu$** , **H- $\rightarrow ZZ\rightarrow l^+l^-l^+l^-$**
- Emphasis on those three, but all eight channels will be discussed

Mode	Mass Range (GeV/c <sup>2</sup> )	Dataset (fb <sup>-1</sup> )	<a href="#">CMS Document</a>
<b>H <math>\rightarrow \gamma\gamma</math></b>	[110-150]	1.7	HIG-11-021
<b>qq-<math>\rightarrow</math>VH; H <math>\rightarrow b\bar{b}</math></b>	[110-135]	1.1	HIG-11-012
<b>H <math>\rightarrow \tau\tau</math></b>	[110-145]	1.6	HIG-11-020
<b>H <math>\rightarrow WW \rightarrow 2l2\nu</math></b>	[110-600]	1.5	HIG-11-014
<b>H <math>\rightarrow ZZ \rightarrow 4l</math></b>	[110-600]	1.7	HIG-11-015
<b>H <math>\rightarrow ZZ \rightarrow 2l2\tau</math></b>	[180-600]	1.1	HIG-11-013
<b>H <math>\rightarrow ZZ \rightarrow 2l2j</math></b>	[226-600]	1.6	HIG-11-017
<b>H <math>\rightarrow ZZ \rightarrow 2l2\nu</math></b>	[250-600]	1.5	HIG-11-016

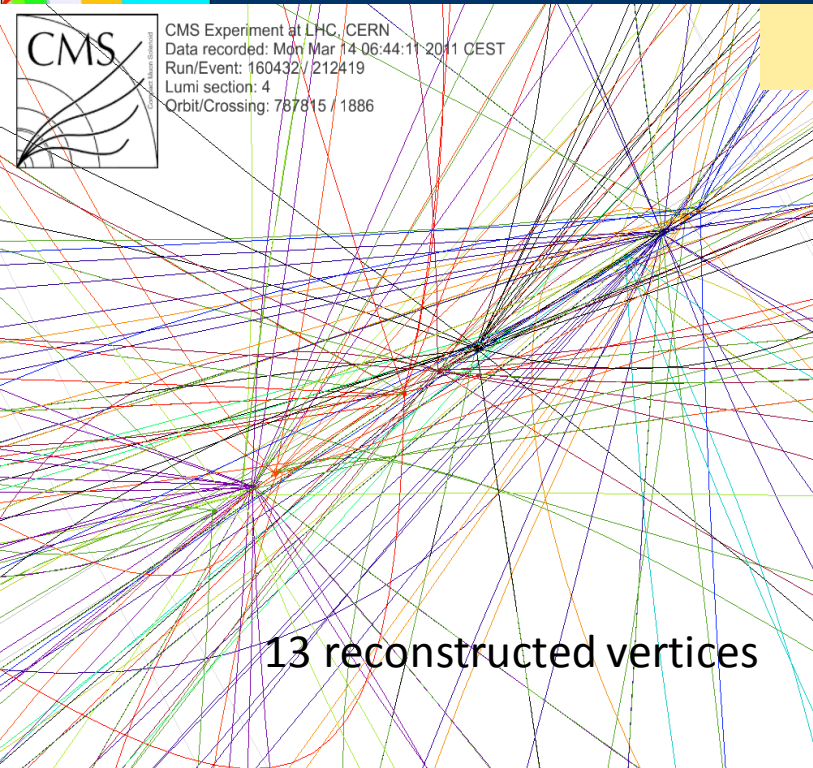


- Results shown in the following correspond to a total integrated luminosity of  $\sim 1.5/\text{fb}$
- Highest instantaneous luminosity  $\sim 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  (in the sample analyzed up to now)

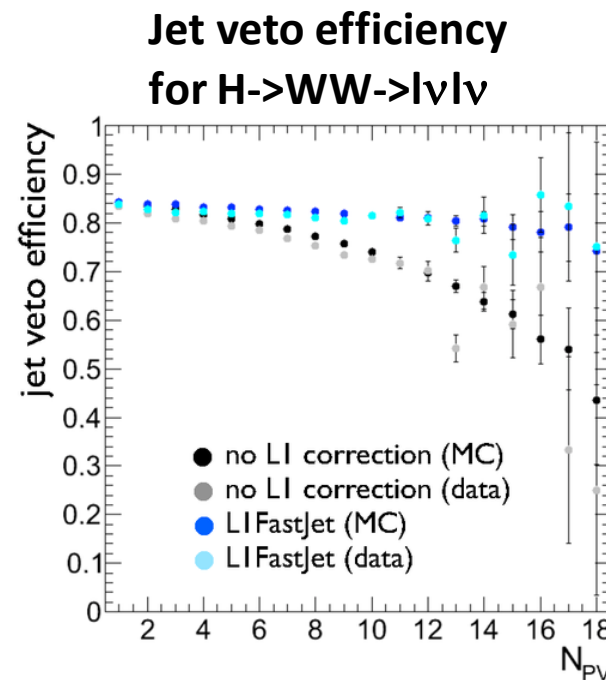
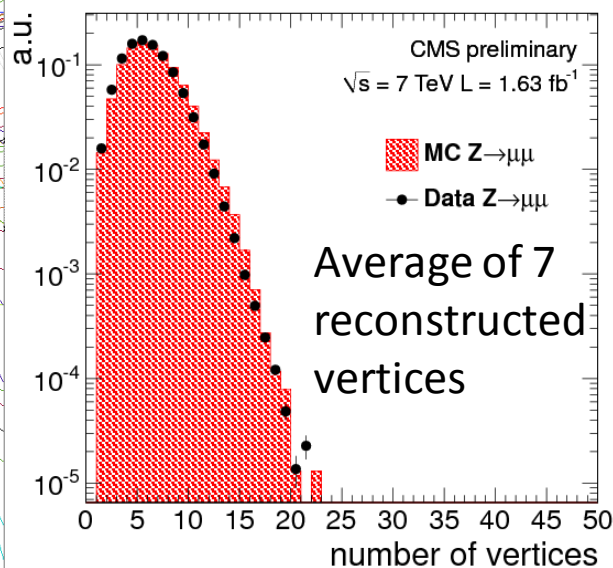
## Trigger



- Inclusive triggers have reached such high thresholds that can not be used anymore for many analyses
- In the context of each analysis dedicated triggers suitable for the specific final state have to be devised:
  - $H \rightarrow WW \rightarrow l\nu l\nu$ : Double mu and double electron thresholds at (17,8) GeV
  - $H \rightarrow \gamma\gamma$ : Double photon (36,18) GeV
- Challenging for the low mass Higgs searches



## Pileup



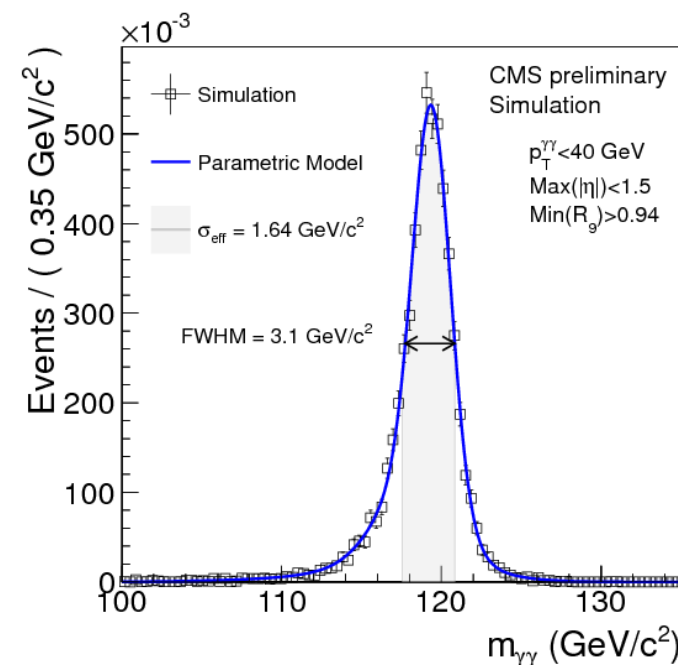
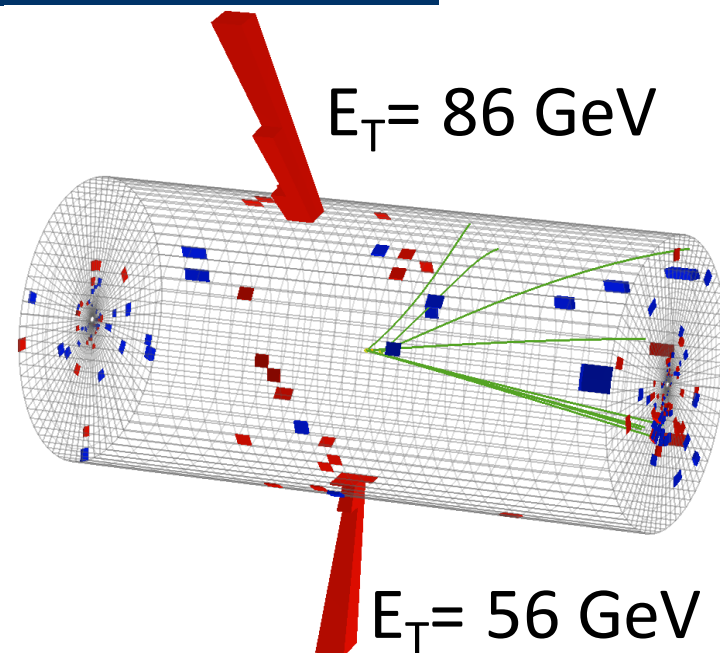
- Additional pileup interactions substantially affects:
  - $ME_T$  resolution, jet energy scale/resolution and multiplicity, lepton isolation, primary vertex identification
- Several techniques have been developed to address the PU effects:
  - FastJet corrections for jets and lepton isolation, track-based  $ME_T$ , etc.

$$H \rightarrow \gamma\gamma$$

- Tiny branching fraction ( $10^{-4}$ ) but still one of the most sensitive channels in the low mass region
- Striking and simple signature:
  - two isolated high pt photons forming a narrow peak in the mass distribution
- Discovery potential driven by di-photon mass resolution: excellent performance of EM calorimeter is necessary
  - *In situ* energy calibration from  $\pi^0 \rightarrow \gamma\gamma$ ,  $E_e/p_e$ ,  $Z \rightarrow e^-e^+$
  - Correction for crystal transparency loss due to radiation exposure (luminosity dependent)

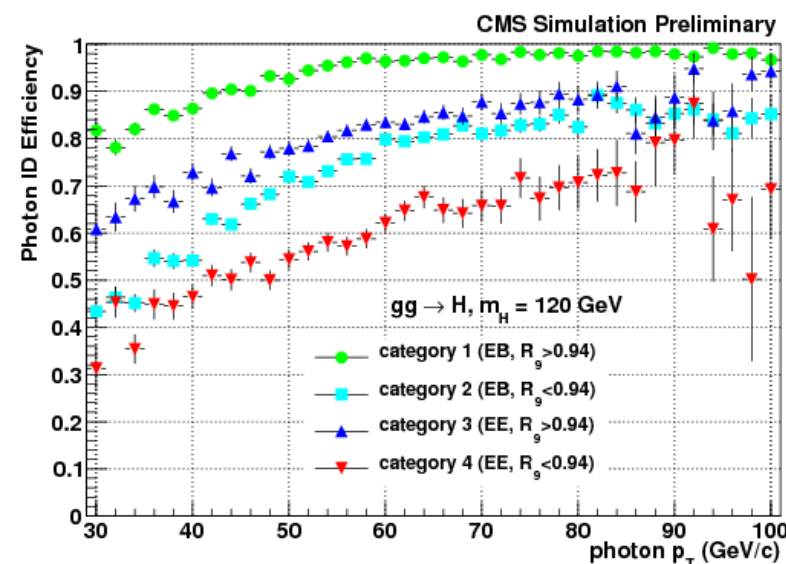
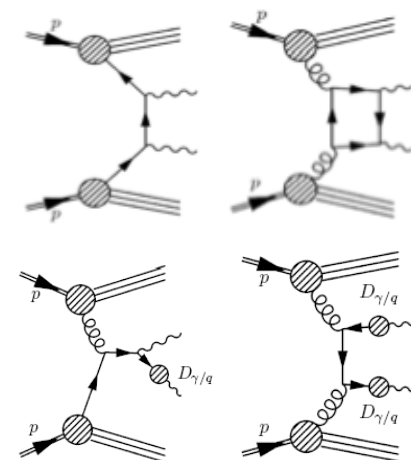
## Analysis Strategy

1. Background rejection and efficiency estimation
2. Di-photon mass reconstruction
3. Signal extraction

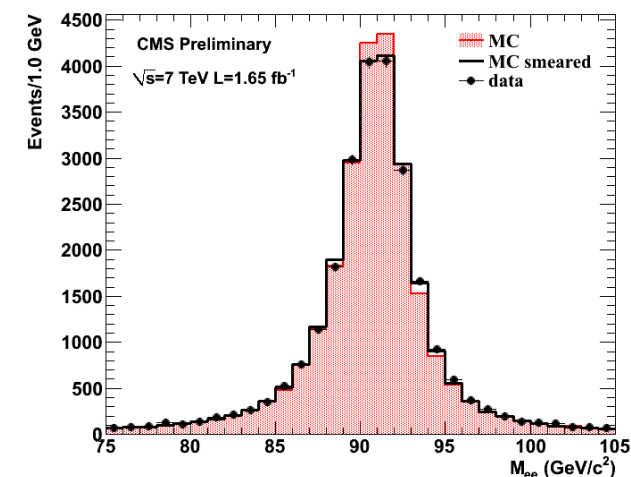
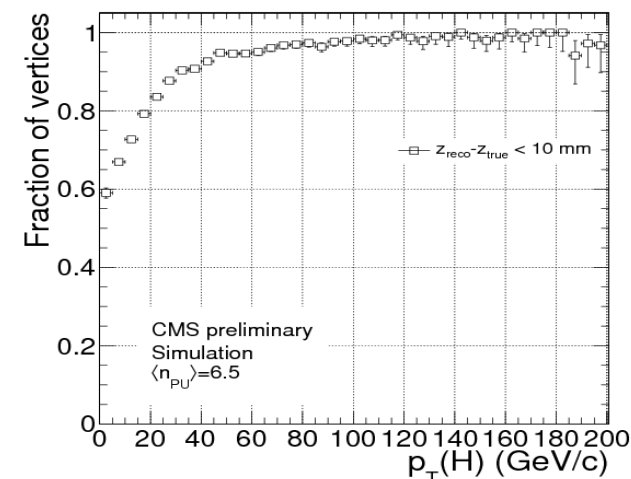
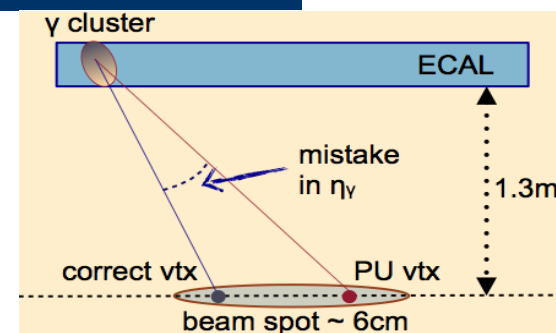


# H- $\gamma\gamma$ selections

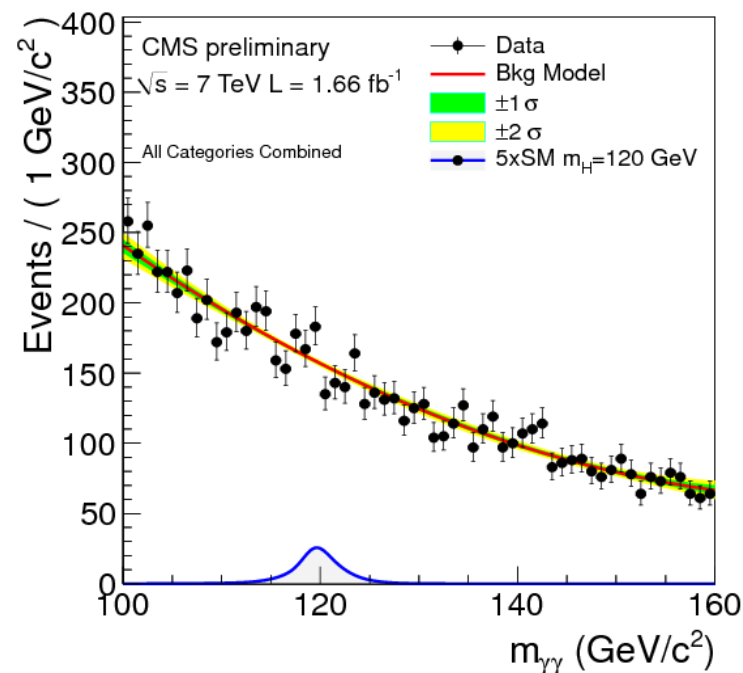
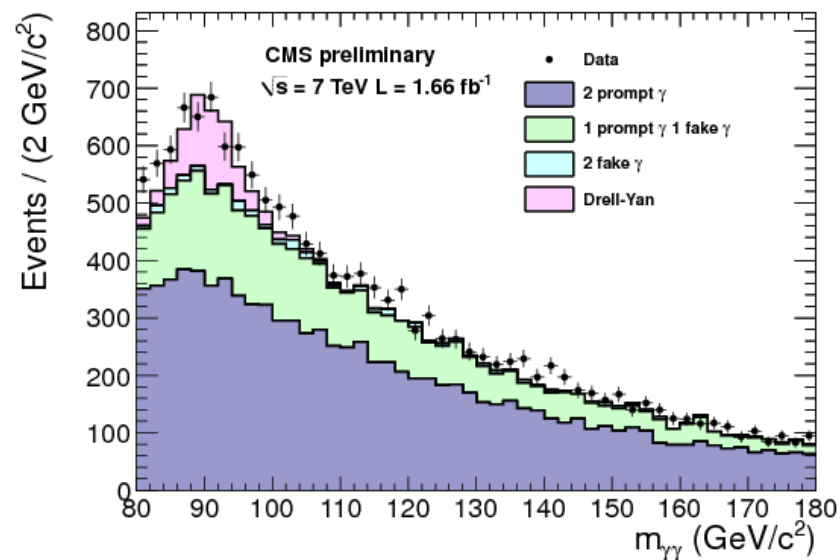
- Background: prompt QCD photons and fakes from jets
- $p_T > (40, 30)$  GeV for the two photon candidates
- Photon ID performed in categories based on  $\eta_\gamma$  and conversion probability:
  - Isolation (corrected for pileup contamination)
  - EM cluster shape to reject  $\pi^0 \rightarrow \gamma\gamma$
  - Electron veto
- Trigger and selection efficiency estimated directly from data:
  - Tag&Probe from  $Z \rightarrow e^-e^+$  events
  - Electron veto efficiency computed on the photon from  $Z \rightarrow \mu^-\mu^+\gamma$  events



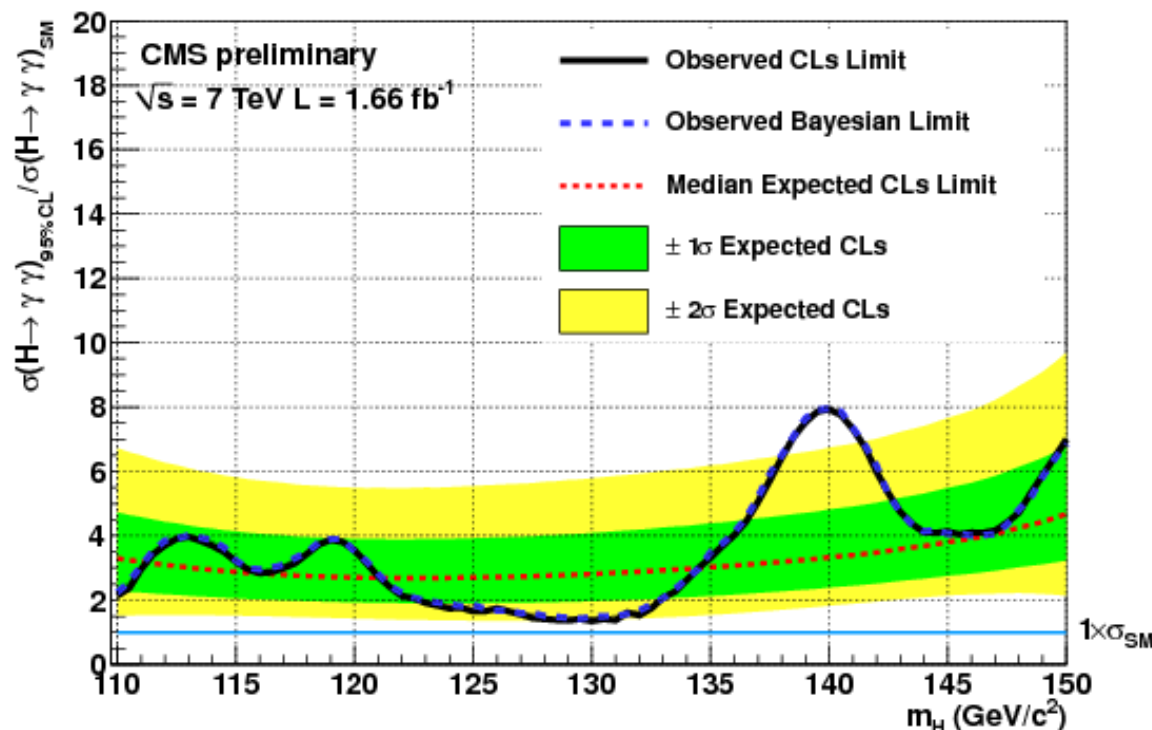
- Di-photon mass resolution affected by the collision vertex choice
  - High pileup,  $\sigma_z \sim 6$  cm
  - Negligible if within 1 cm
- Vertex assignment relies on:
  - Comparison (balancing) of di-photon kinematics and tracks associated to the vertex
  - Tracks from converted photons
- Photon energy scale and resolution measured in data using  $Z \rightarrow e^-e^+$  events
- MC Photon energy smeared to match  $Z \rightarrow e^-e^+$  data
  - Resolution overestimated in MC due to suboptimal crystal transparency correction
  - Improvements expected soon



- Events classified in 8 categories:
  - $(\eta_\gamma, \text{conversion probability}, p_T^{\gamma\gamma})$  featuring different mass resolution
  - Maximizes statistical power
- Overall good agreement data-MC, but background is determined by data
- $M_{\gamma\gamma}$  is fit in each category using
  - 2<sup>nd</sup> order polynomial for bkgr shape
  - Signal shape from MC smeared to match data resolution
- No striking structure observed

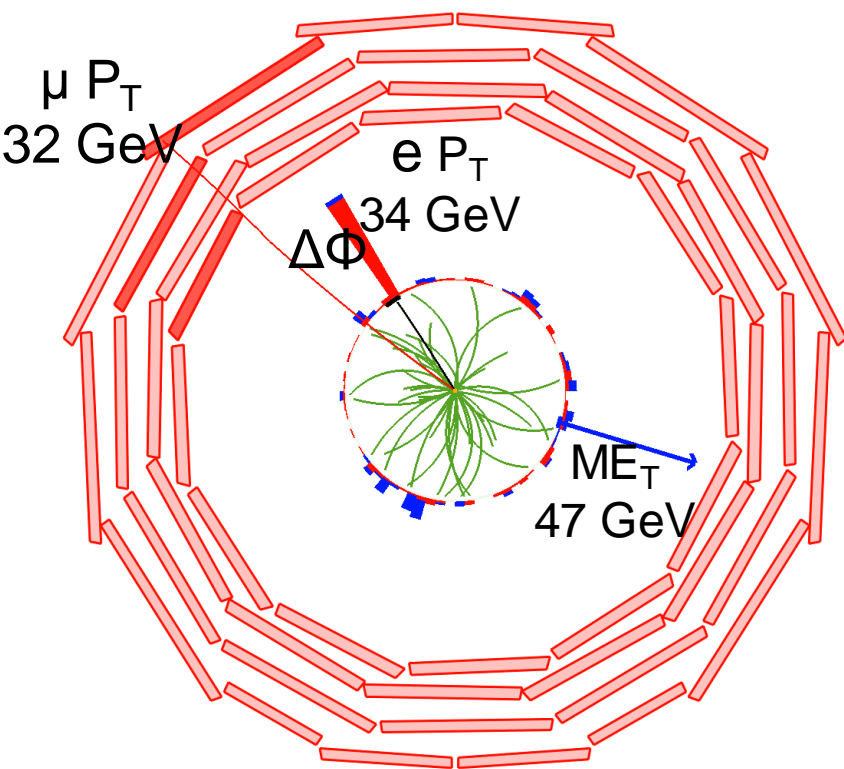


- All limits plots shown hereafter are computed accordingly to the “**Modified Frequentist**” (CLs) method (details [here](#) )
- standard for ATLAS-CMS
- Results cross checked with the bayesian flat prior approach



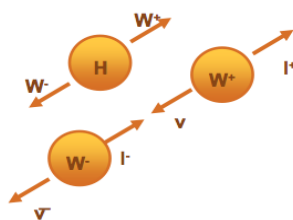
- 2-4  $\sigma_{\text{SM}}$  excluded at 95% CL in the [110-150] range
- Fermiophobic Higgs excluded between [110-112]  $\text{GeV}/c^2$

$$H \rightarrow WW \rightarrow l^- \nu l^+ \nu$$



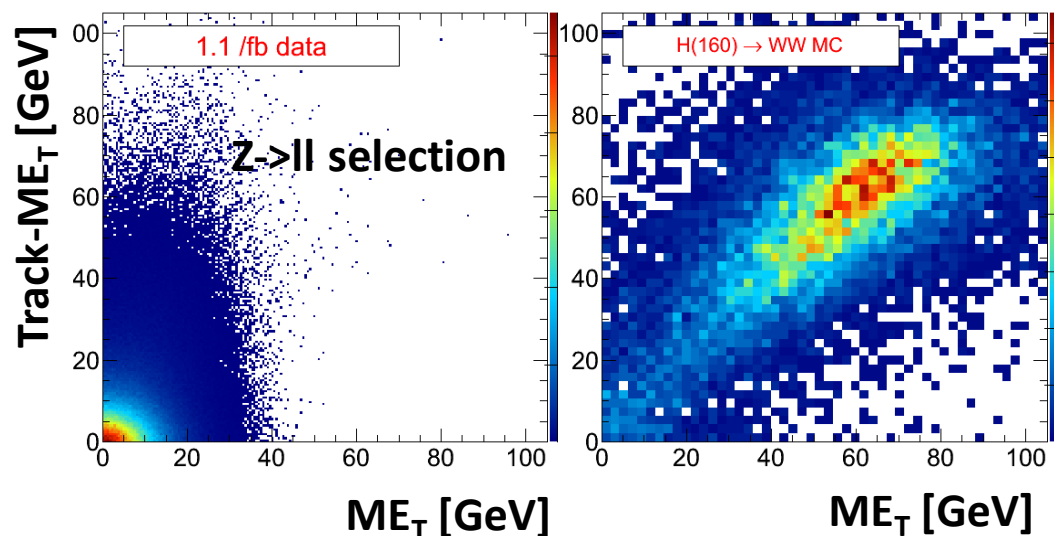
- Channel with best S/B after final selections in a wide mass range
- Clean signature:
  - 2 isolated, high  $p_T$  leptons with small opening angle
  - High  $ME_T$
  - Analysis performed on exclusive jet multiplicities (0, 1, 2-jet bins)
- No mass peak, signal extraction from event counting
- Analysis optimized depending on the Higgs mass hypothesis
  - $p_T^l$ ,  $M_{ll}$ ,  $M_T$ ,  $\Delta\phi$  as discriminating variables
  - VBF selections for the 2-jet case

Vectors from the decay of a scalar and V-A structure of W decay lead to small leptons opening angle (especially true for on-shell Ws)



- Drell-Yan

- Suppressed by  $M_{ll}$  and  $ME_T$  cuts
- Pileup enhances significantly the  $ME_T$  tails. MC simulation not describing the effect completely.
- Construct a variable insensitive to pileup:  $\min(\text{track-}ME_T, ME_T)$



- W+jets (with one jet faking a lepton)

- Low  $p_T$  cut on trailing lepton (10 GeV) to recover efficiency for low Higgs masses
- Optimize lepton ID (isolation, quality cuts) to keep fakes rate under control

- Top (tt and single top)

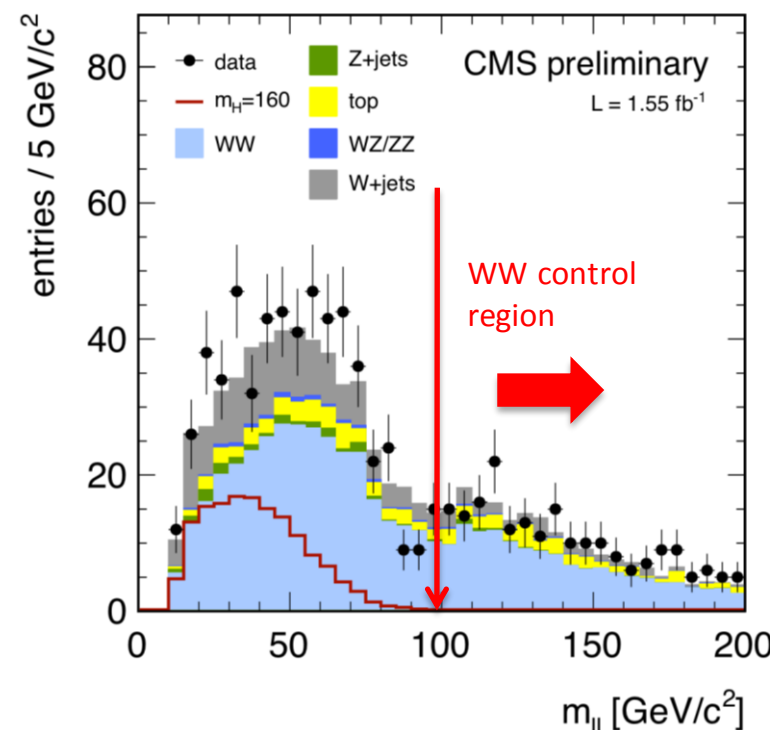
- Veto events with a b-tagged jet or an additional soft muon

- WW


- Exploit the signal kinematic features ( $M_{ll}$ ,  $M_T$ ,  $\Delta\phi$ )

Main backgrounds estimated from data

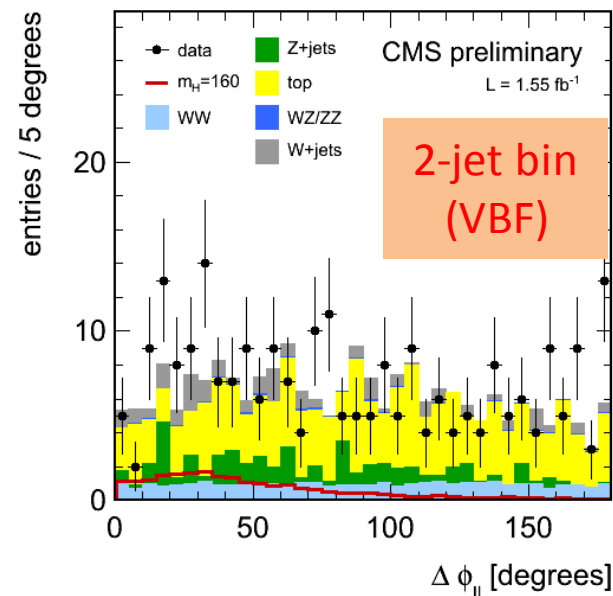
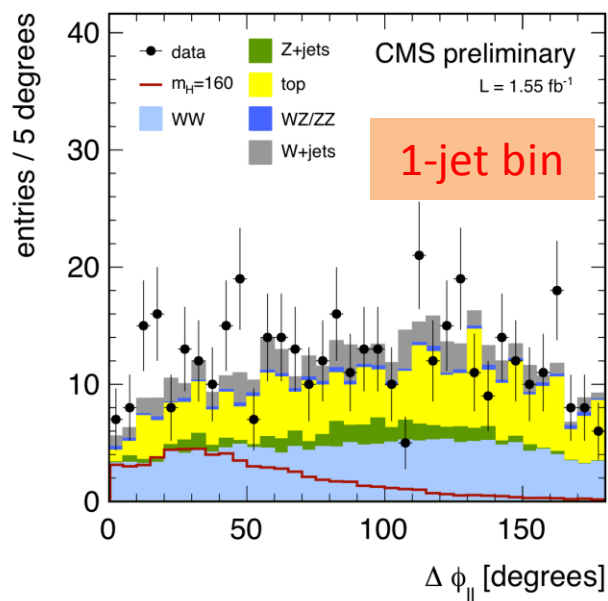
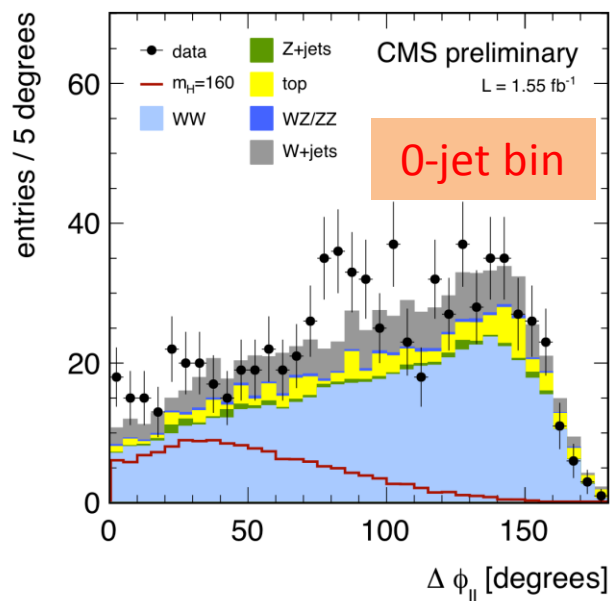
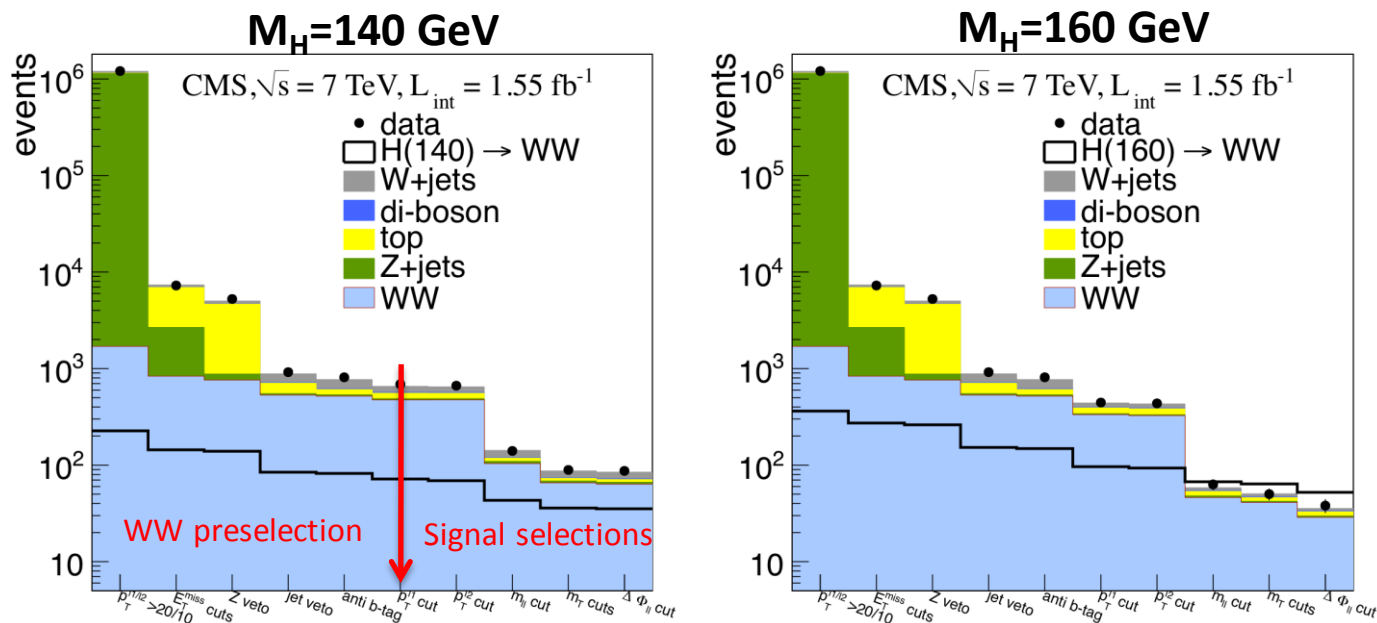
- **Drell-Yan** and **WW** are estimated from  $M_{ll}$  control regions
- Data events are counted in the control region. Expected number of non-DY/WW background events is subtracted
- Number of events in signal region (low  $M_{ll}$ ) estimated using MC predicted ratio
- **Drell-Yan**:
  - Control region is the Z peak
  - Normalization performed after  $ME_T$  cut
- **WW**:
  - Control region is  $M_{ll} > 100$  GeV
  - $M_H$  dependent  $p_T$  cuts applied in addition
  - For  $M_H > 200$  GeV signal contamination in control region no longer negligible => directly use WW MC instead



## Main backgrounds estimated from data

- **Top and fake-induced background (W+jets)** normalizations use the same approach
  - From the efficiency of a cut ( $\varepsilon$ ) and the number of events that fail that cut ( $N_{\text{fail}}$ ), the number of events that passed ( $N_{\text{pass}}$ ) can be deduced:
    - Measure (in)efficiency in a background enriched sample
    - Extrapolate into signal region from rejected phase space
-  This image cannot currently be displayed.
- **Top:**
    - top-tagging efficiency is measured in a top enriched sample (b-tag)
    - Extrapolate from a sample of top-tagged events
  - **W+jets**
    - In a QCD dominated (di-jet) sample measure the efficiency of events with loosely identified leptons to pass the analysis selections
    - Extrapolate from a sample where one lepton fails ID

# H $\rightarrow$ WW $\rightarrow$ $l^- \nu l^+ \nu$ cut flow



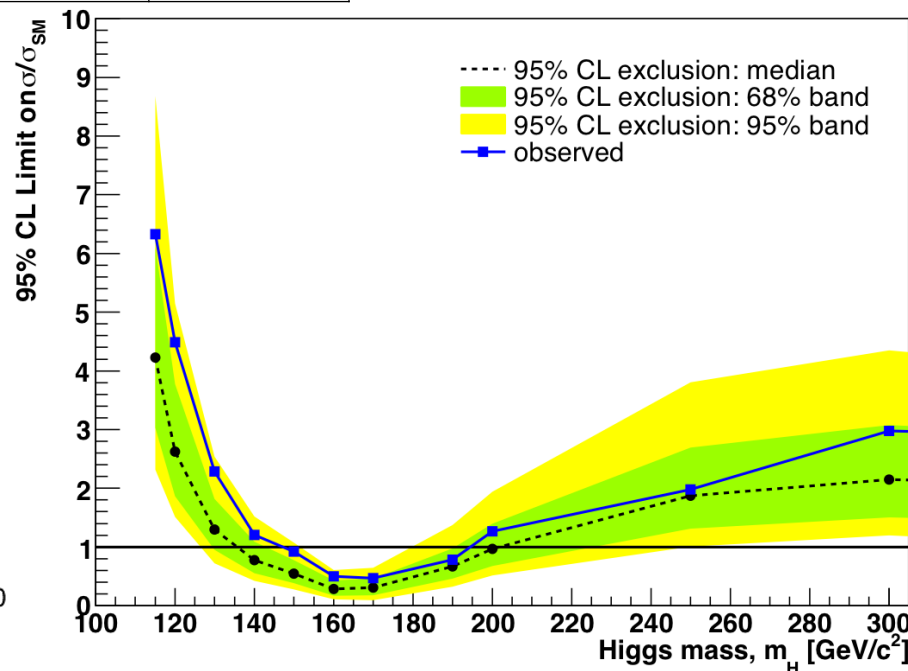
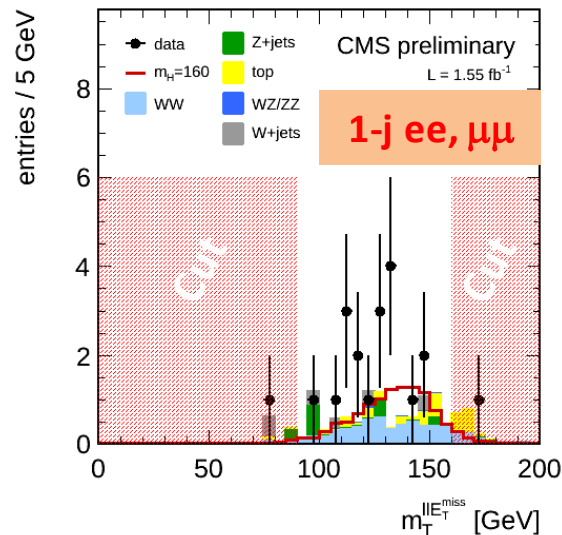
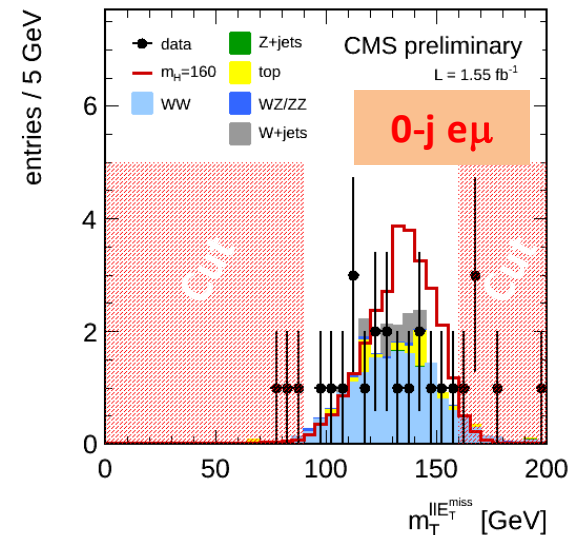
# H $\rightarrow$ WW $\rightarrow$ l $\nu$ l $^+\nu$ results

Final yields for M<sub>H</sub>=140 GeV hypothesis

	0-j ee, $\mu\mu$	0-j e $\mu$	1-j ee, $\mu\mu$	1-j e $\mu$	2-j
<b>Background</b>	44.0 $\pm$ 6.2	40.6 $\pm$ 7.0	12.6 $\pm$ 3.7	17.8 $\pm$ 3.5	5.3 $\pm$ 1.7
<b>Signal (m<sub>h</sub>=140)</b>	19.1 $\pm$ 4.3	16.1 $\pm$ 3.6	5.3 $\pm$ 1.8	7.7 $\pm$ 2.6	2.5 $\pm$ 0.3
<b>Data</b>	46	41	23	23	7

H  $\rightarrow$  WW  $\rightarrow$  2l2 $\nu$  + 0/1/2 jets (CLs)

Final M<sub>T</sub> plots for M<sub>H</sub>=160 GeV hypothesis

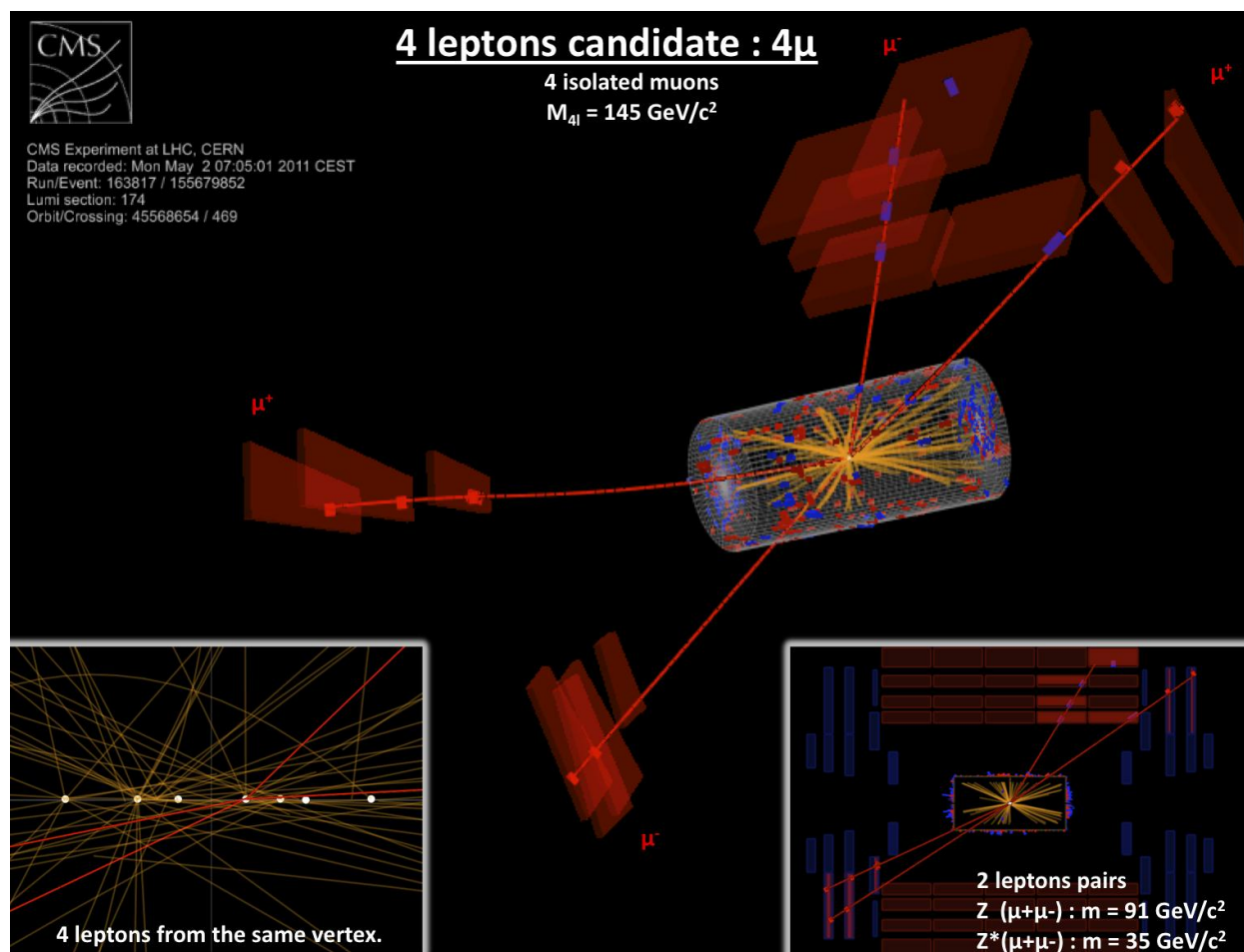


- No evidence of signal
- Expected exclusion at 95% CL for M<sub>H</sub> in [136-200] GeV
- Observed exclusion at 95% CL for M<sub>H</sub> in [147-193] GeV

$H \rightarrow ZZ \rightarrow l^- l^+ l^- l^+$

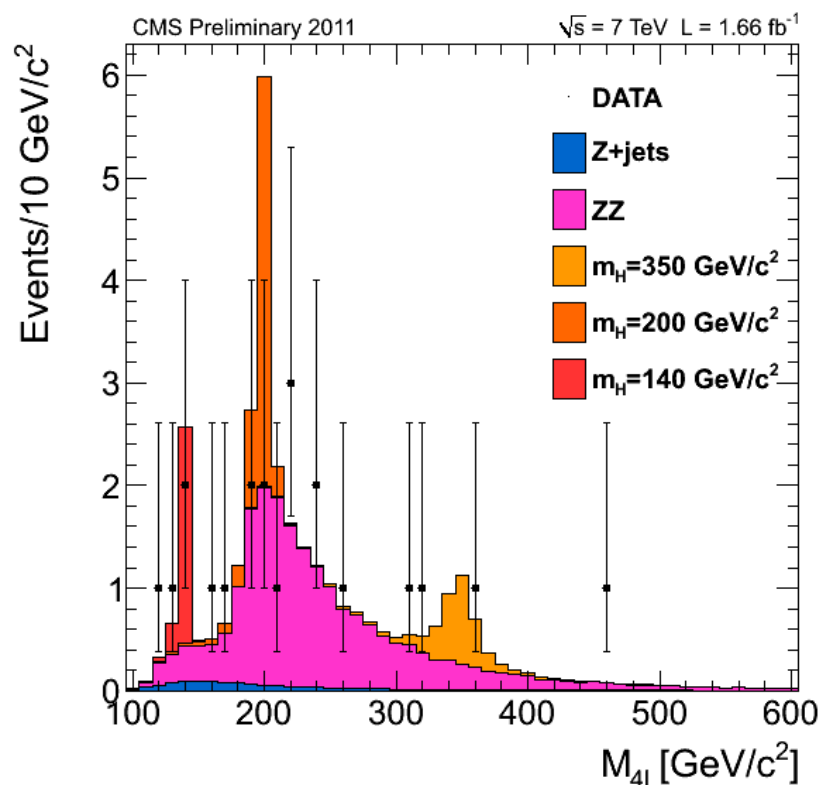
# $H \rightarrow ZZ \rightarrow \ell\ell^+\ell\ell^+$

- The golden channel: clean signature, narrow mass peak
- Main challenge is the efficiency for low  $p_T$  leptons
- Background from continuous ZZ, Z+jets and Zbb/tt/WZ

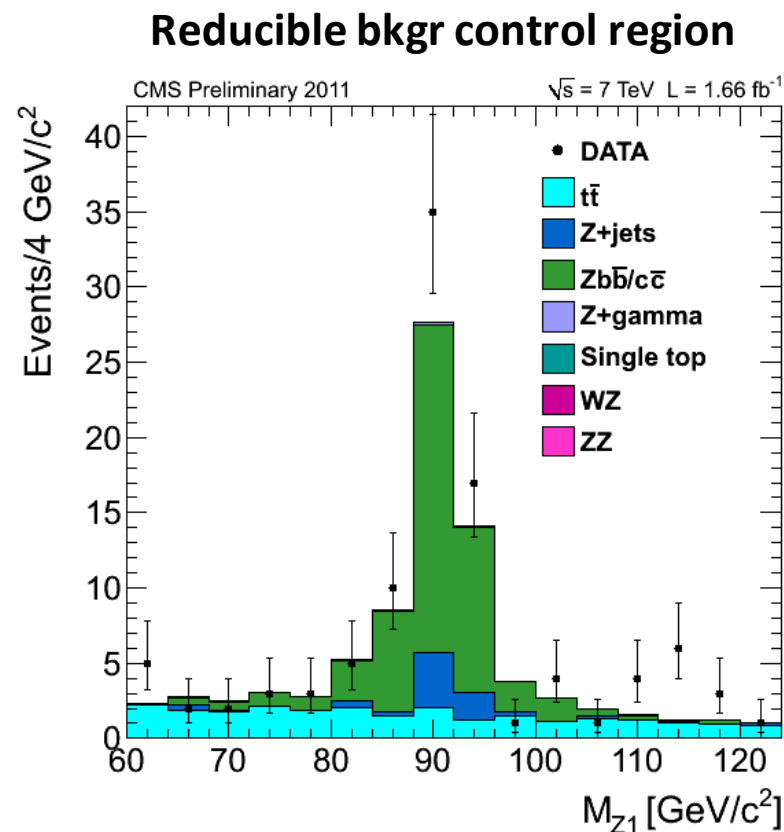


# H $\rightarrow$ ZZ $\rightarrow$ l $^+$ l $^-$ l $^+$ l $^-$ event

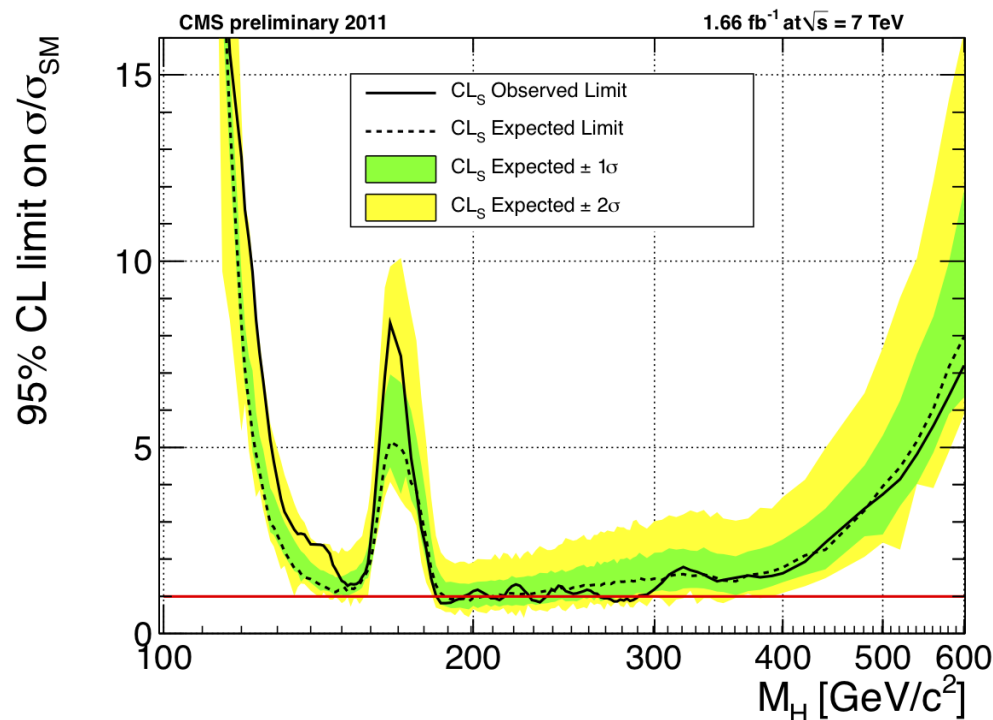
- Best 4l candidate choice
  - Two pairs of opposite charge identified leptons,  $p_T > 20, 10, 7, 5$  GeV
  - Z hypothesis for at least one pair
  - $M_{4l} > 100$  GeV
- Rejection of reducible background (isolation, impact parameter)
- $M_{ll} > 20$  GeV selections for the second Z candidate



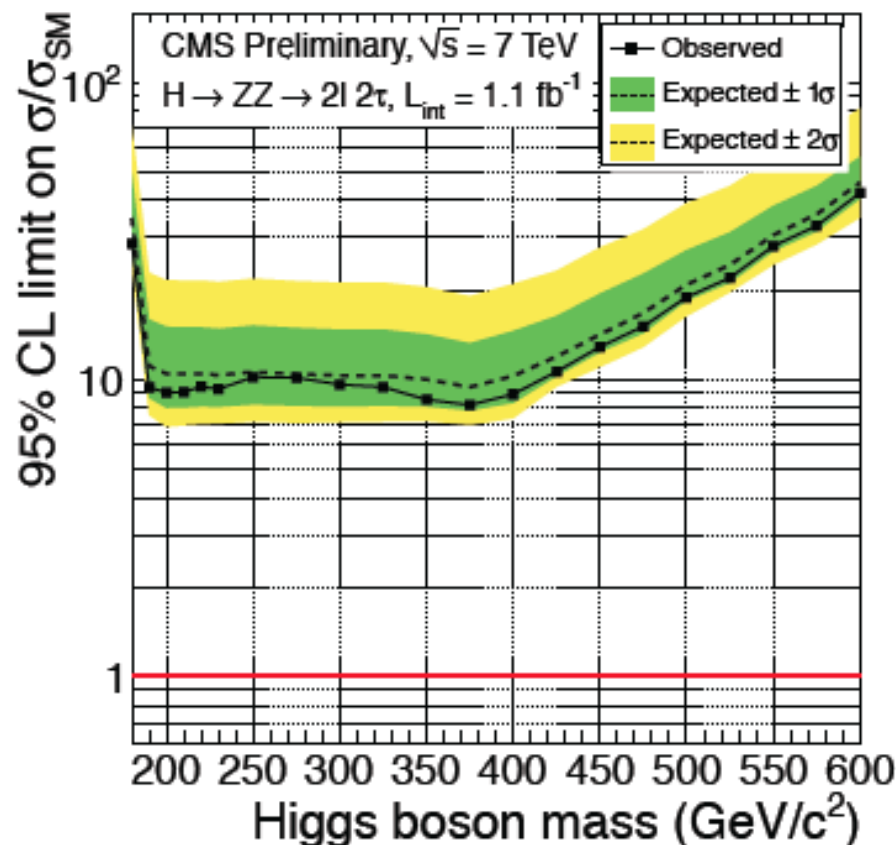
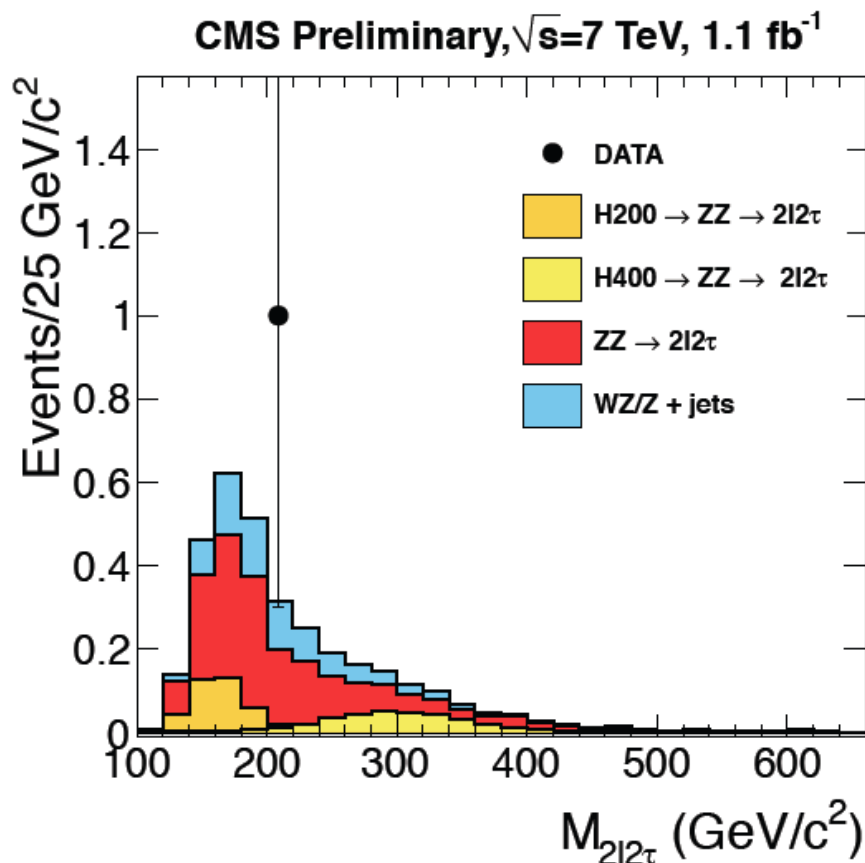
- Non resonant ZZ is estimated from the rate of Z->ll events in data
- Z+jets from fake rate method estimated from data
- Reducible backgrounds (Zbb/tt) is measured in a dedicated control region:
  - Same requirements for the on-shell Z candidate
  - Relaxed selections on charge, flavor and isolation for the other candidate pair plus inverted impact parameter cut



- Events counts:
  - **data: 21, expected bkgr:  $21.2 \pm 0.8$**
  - 6 events below  $M_H=180$ ,  $2.8 \pm 0.2$  expected
- Shape analysis:
  - Signal from convolution of Breit-Wigner with Crystal-Ball
  - Background from an empirical function



- Overall the distribution of events is consistent with the SM ZZ\*
- 1-2 x SM Higgs cross sections are excluded in [150-420] GeV

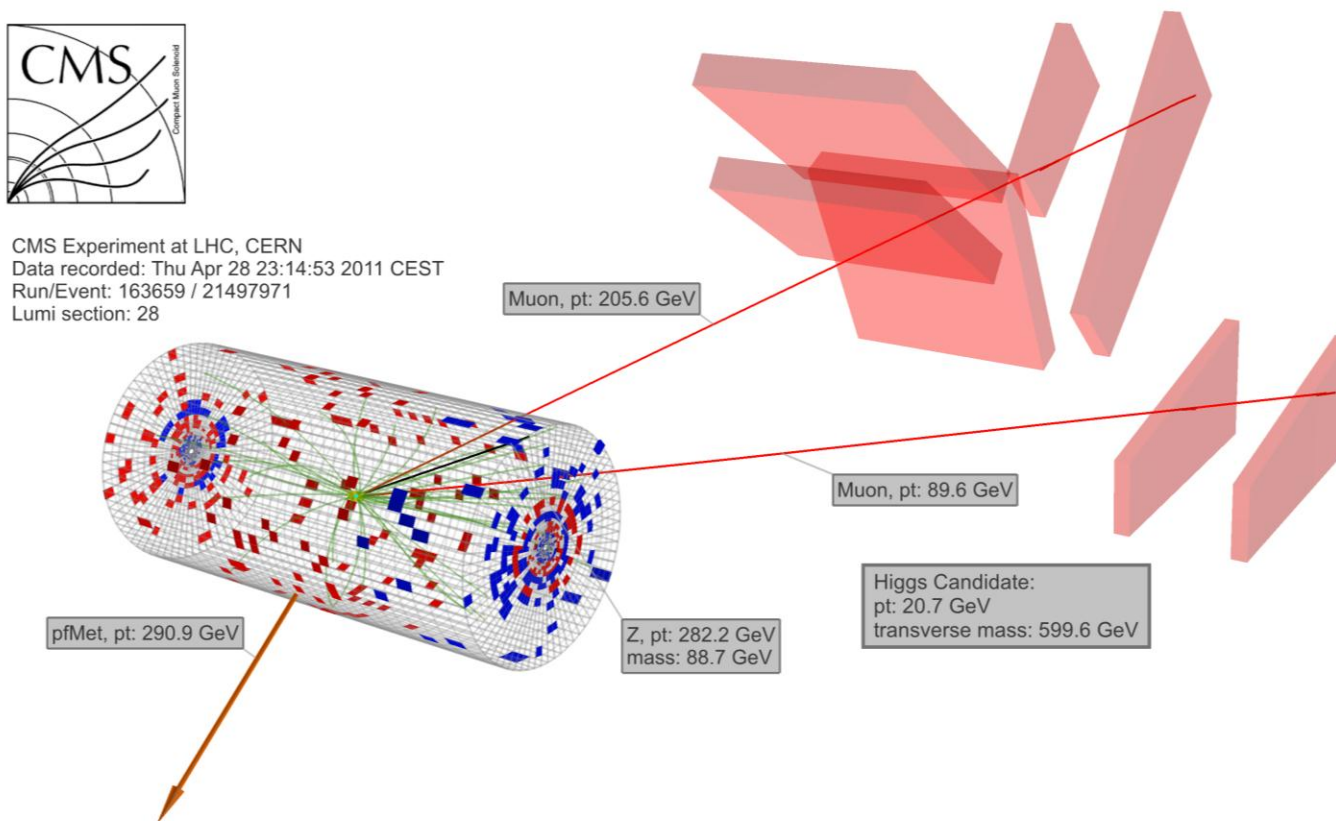


- Using both  $\tau_{\text{had}}\tau_{\text{had}}$  and  $\tau_{\text{had}}\tau_l$  final states
- Requires  $30 < M_\tau < 80$  GeV
- Definitely needs more data..

$H \rightarrow ZZ \rightarrow l^- l^+ \nu \nu$  and  $H \rightarrow ZZ \rightarrow l^- l^+ q q$   
(high  $M_H$  searches)

# $H \rightarrow ZZ \rightarrow l l^+ \nu \nu$

- Six times larger branching fraction than  $4l$  final state, but no mass peak
- Suitable for high  $M_H$ , where  $Z \rightarrow \nu \nu$  has a large boost  $\Rightarrow$  high  $ME_T$
- Backgrounds from  $Z$ +jets,  $t\bar{t}$ ,  $WZ$  and  $ZZ$

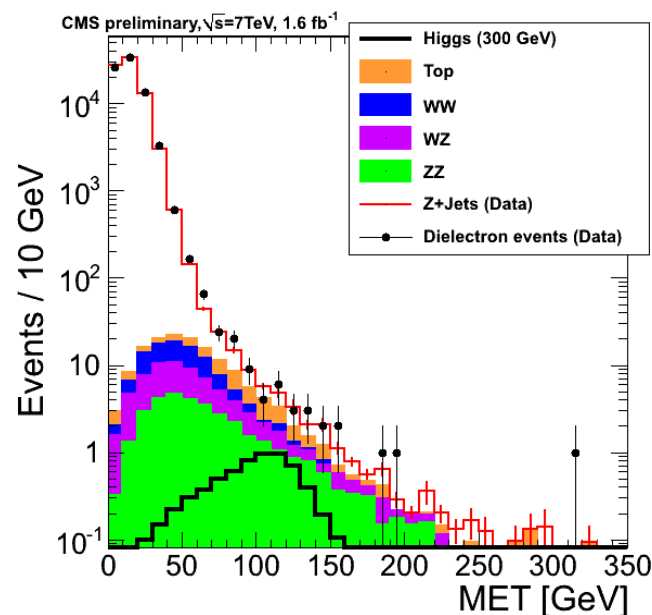
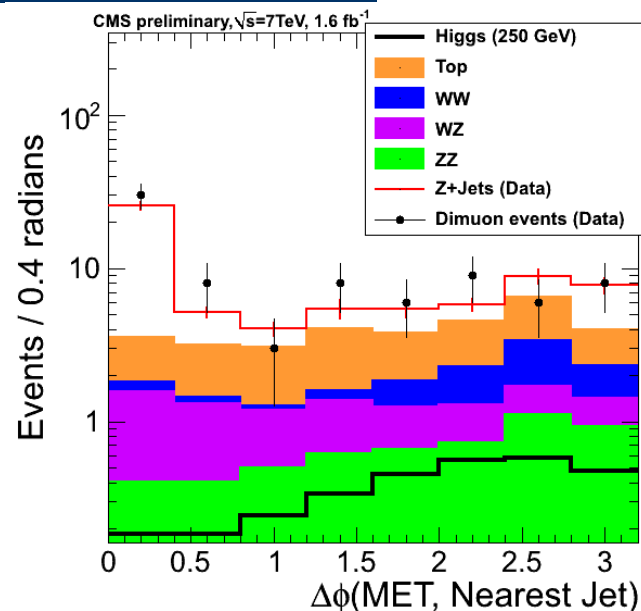


## Rejection

- Lepton  $p_T > 20$  GeV, Z hypothesis,  $p_T^Z > 25$  GeV
- Anti-btag and soft muon veto for top bkgr
- $M_H$  hypothesis-specific cuts:
  - Large  $ME_T$  ( $> 70$  GeV for  $M_H = 250$  GeV)
  - $\Delta\phi(ME_T, \text{jet})$
  - Transverse mass

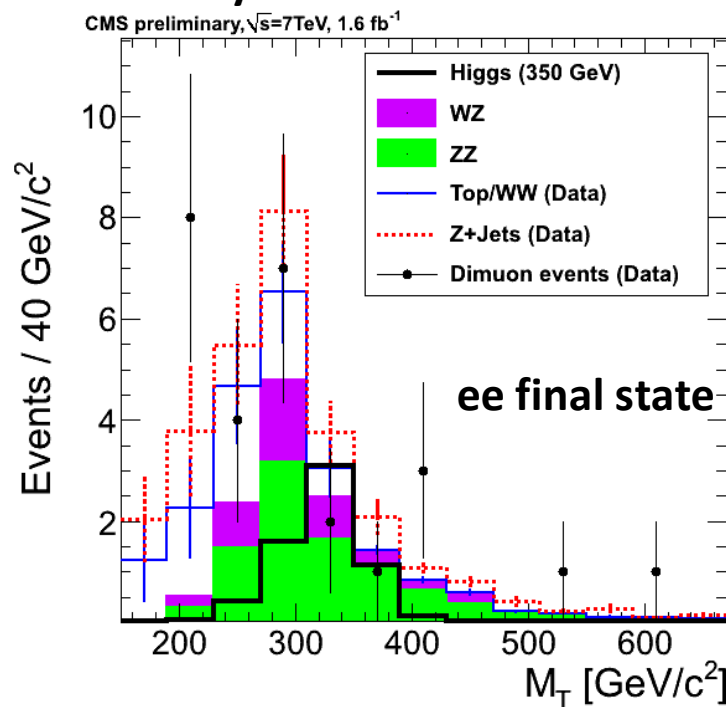
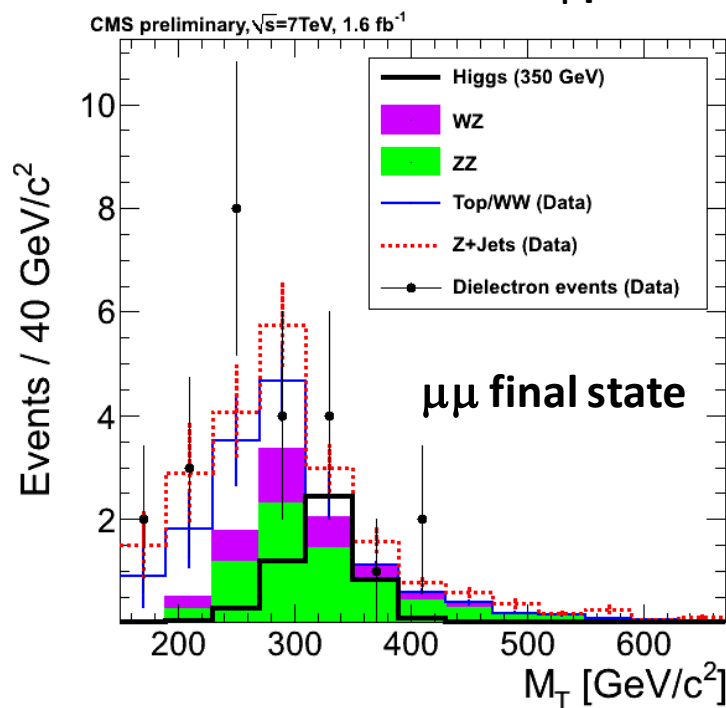
## Normalization


- Z+jets estimated by using  $\gamma$ +jets as template for  $ME_T$  distribution
- Non-resonant background from events with opposite flavor leptons passing selections
- Resonant background (ZZ, ZW) from MC



# H $\rightarrow$ ZZ $\rightarrow$ l $^+$ l $^-$ $\nu\nu$ Yields

## M<sub>T</sub> plot for M<sub>H</sub>=350 GeV analysis



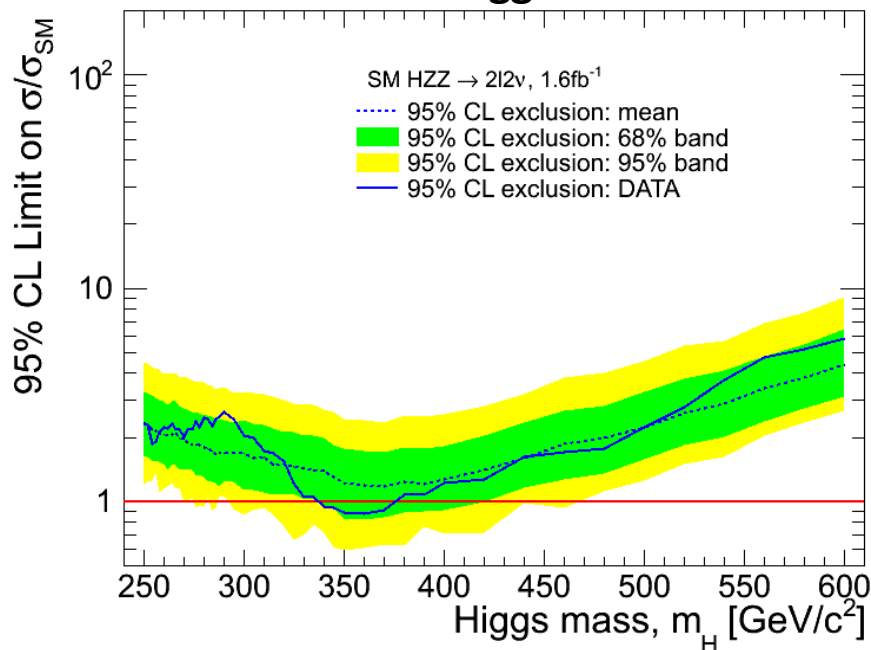
 This image cannot currently be displayed.

## Examples of final yields for two M<sub>H</sub> hypotheses

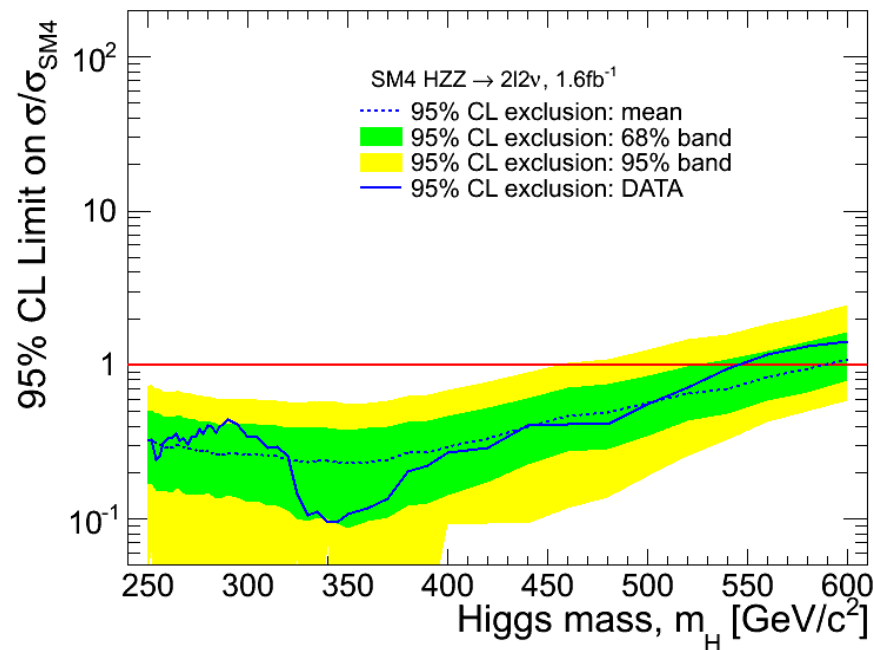
		M <sub>H</sub> =250 GeV		M <sub>H</sub> =350 GeV
	μμ	ee	μμ	ee
Background	39±4.3	29±3.5	14±1.7	10±1.3
Signal (m <sub>h</sub> =140)	5.5±0.73	4.2±0.59	5.6±0.85	4.4±0.7
Data	35	32	10	9

# H $\rightarrow$ ZZ $\rightarrow$ l $l^+\nu\nu$ limits

SM Higgs

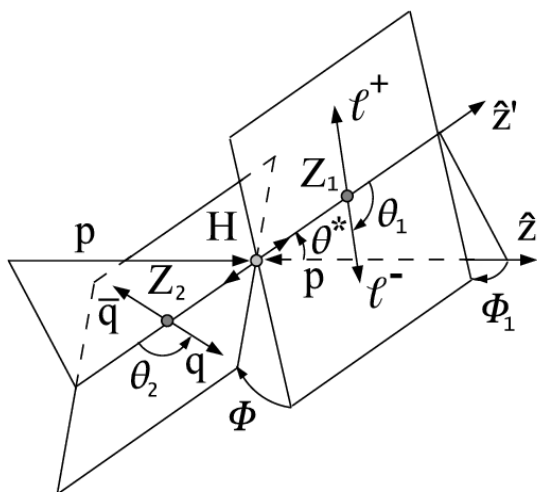
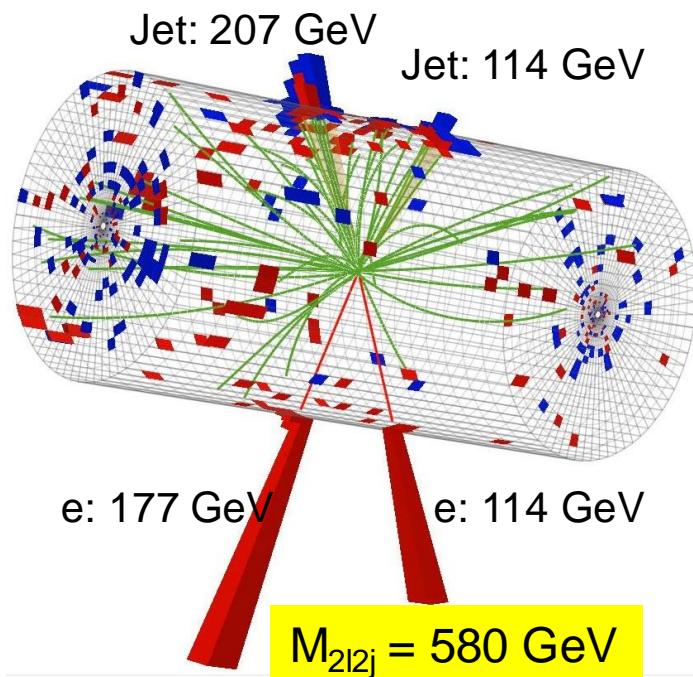


SM4 Higgs



- The analysis is performed in [250-600] GeV
- SM Higgs excluded at 95% CL in [340-375] GeV
- The hypothesis of 4<sup>th</sup> fermion generation coupling to Higgs is excluded in [250-550] GeV

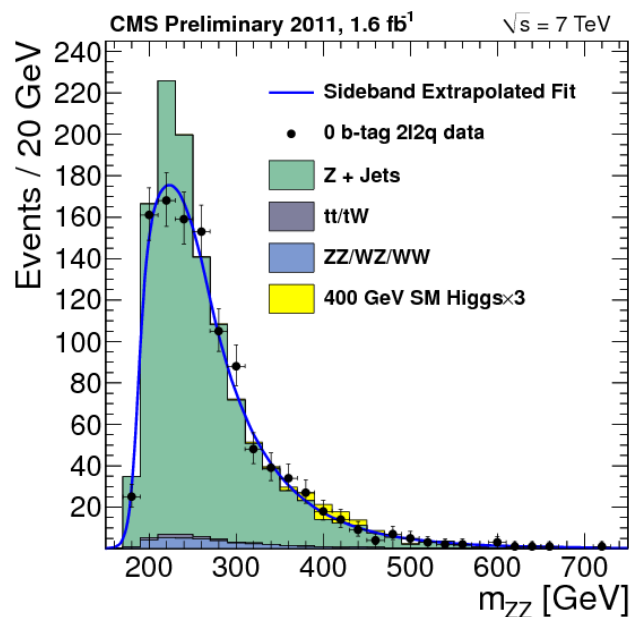
# $H \rightarrow ZZ \rightarrow \ell\ell^+ qq$



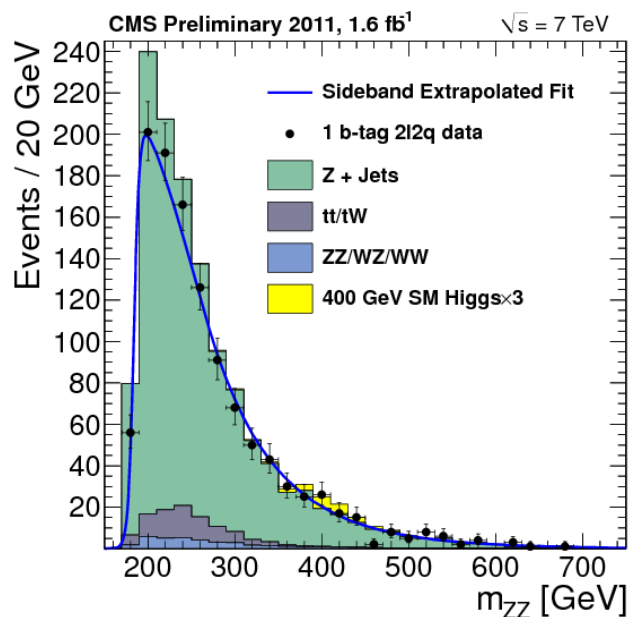
- Pros:
  - Highest branching ratio among ZZ modes
  - Final state fully reconstructed
- Contra:
  - Very large background from Z+jets and
  - Limited resolution of the di-jet mass
- Both Z candidates required to be on-shell  
=> high  $M_H$  range is probed
- The five angles involved in the decay chain are employed as signal discriminator
- Backgrounds from Z+jets, top and di-bosons+jets
- Analysis performed in bins of b-jet multiplicity
  - In 0-bjet bin, quark-gluon discrimination is used

- Background normalization extrapolated from sidebands
  - SB defined as  $60 < M_{jj} < 75$  &  $105 < M_{jj} < 130$  GeV
- Additional handles on top background from  $e\mu jj$  final state where Z+jets background is absent

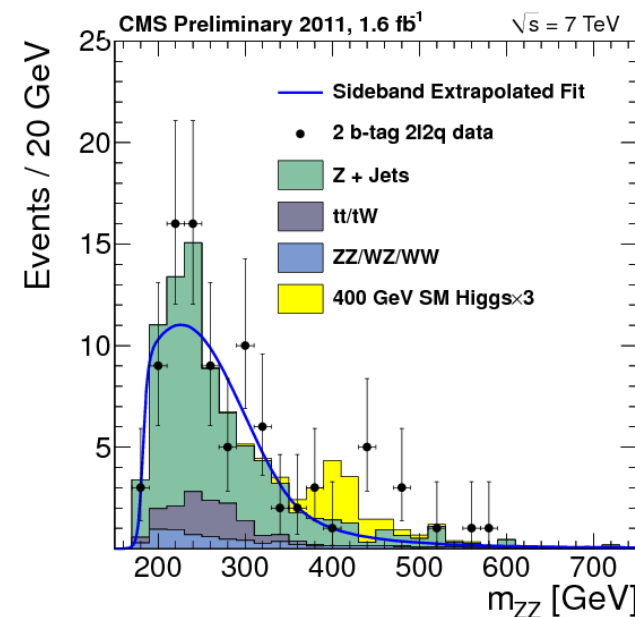
## 0 b-jet



## 1 b-jet



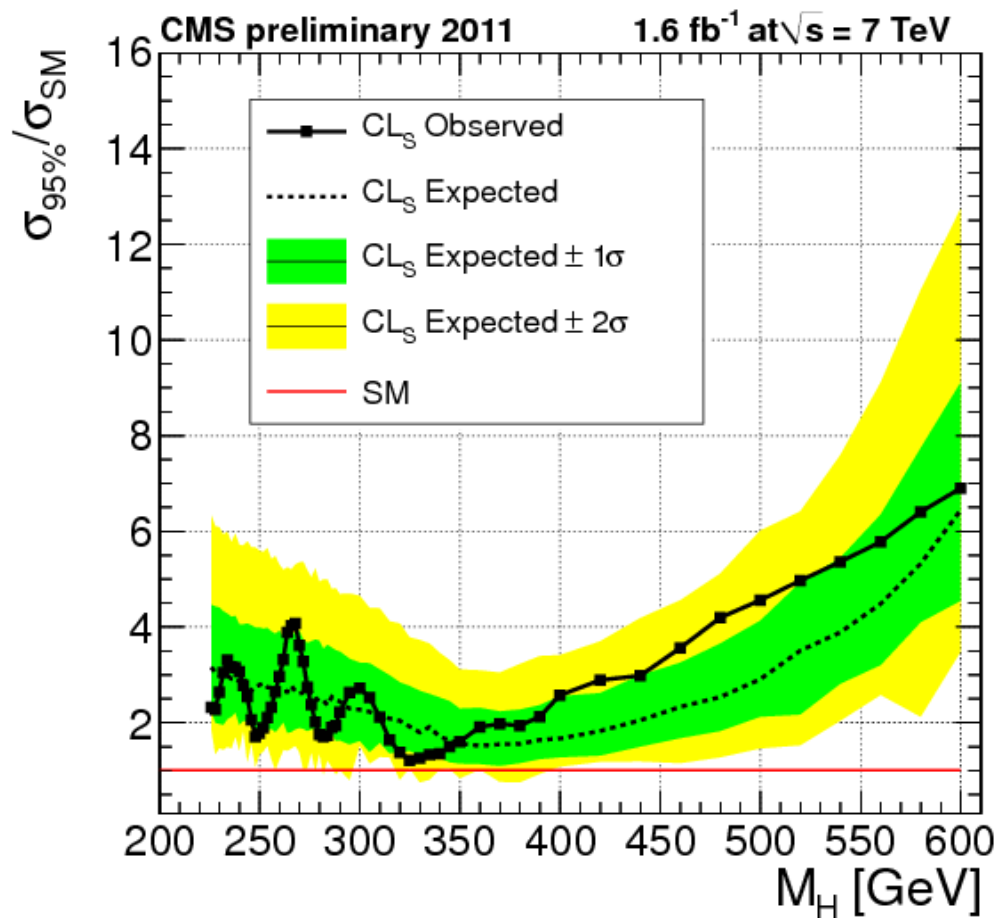
## 2 b-jet



# H $\rightarrow$ ZZ $\rightarrow$ l $^+$ l $^-$ qq Results

	selection		
	0 <i>b</i> -tag	1 <i>b</i> -tag	2 <i>b</i> -tag
$\mu^- \mu^+ jj$			
observed yield	586	627	48
exp. background (data)	$575.9 \pm 23.1$	$606.8 \pm 24.5$	$41.2 \pm 4.7$
exp. background (MC)	$634.7 \pm 10.1$	$681.4 \pm 10.7$	$43.1 \pm 2.8$
$e^- e^+ jj$			
observed yield	492	518	45
exp. background (data)	$490.5 \pm 21.3$	$526.9 \pm 22.8$	$35.4 \pm 4.1$
exp. background (MC)	$501.4 \pm 8.8$	$542.8 \pm 9.4$	$37.5 \pm 2.6$

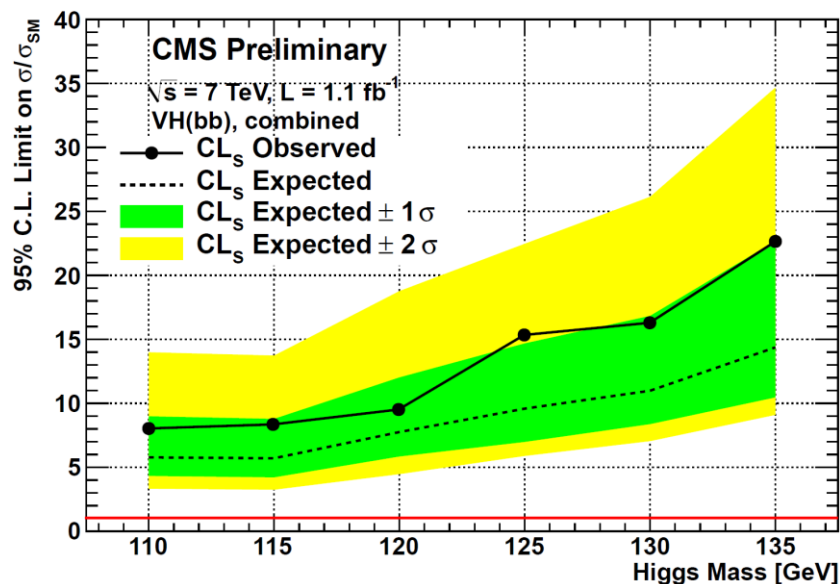
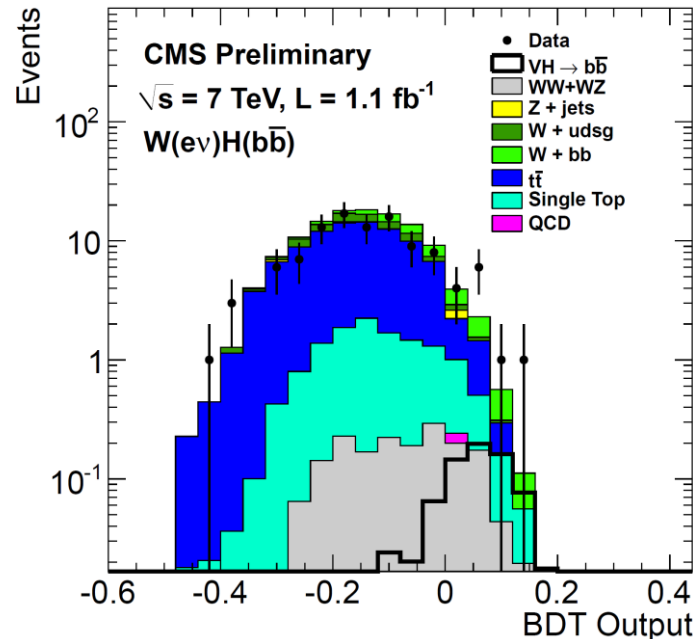
- Observed yields compatible with SM background
  - Signal yields  $\sim < 10$  events
  - Best S/B in ll2b final state
- $M_H$  shape analysis
  - Signal from Breit-Wigner convoluted with Crystal-Ball
  - Empirical shape for background (normalized in data)
- No excess observed in data, SM Higgs cross section limits set in [226-600] GeV



$qq \rightarrow VH; H \rightarrow bb$

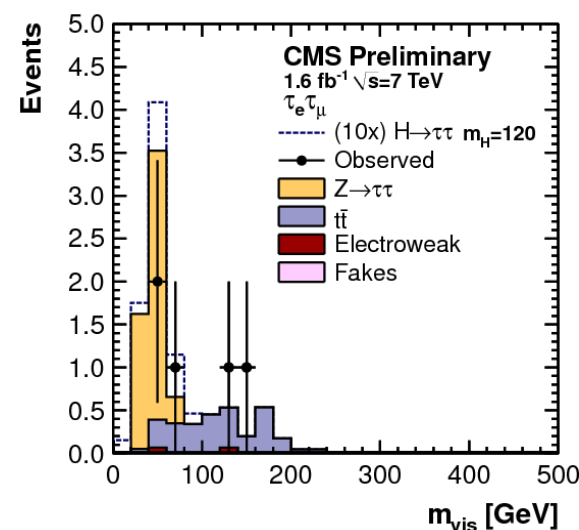
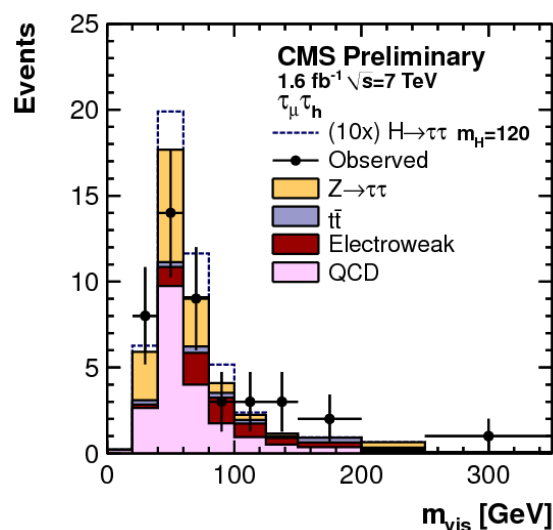
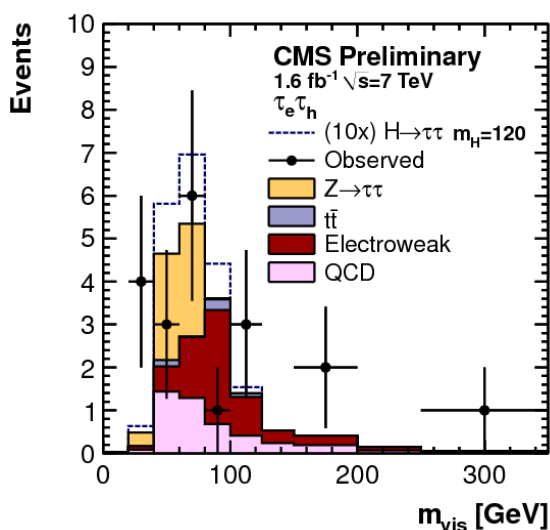
# $qq \rightarrow VH; H \rightarrow bb$

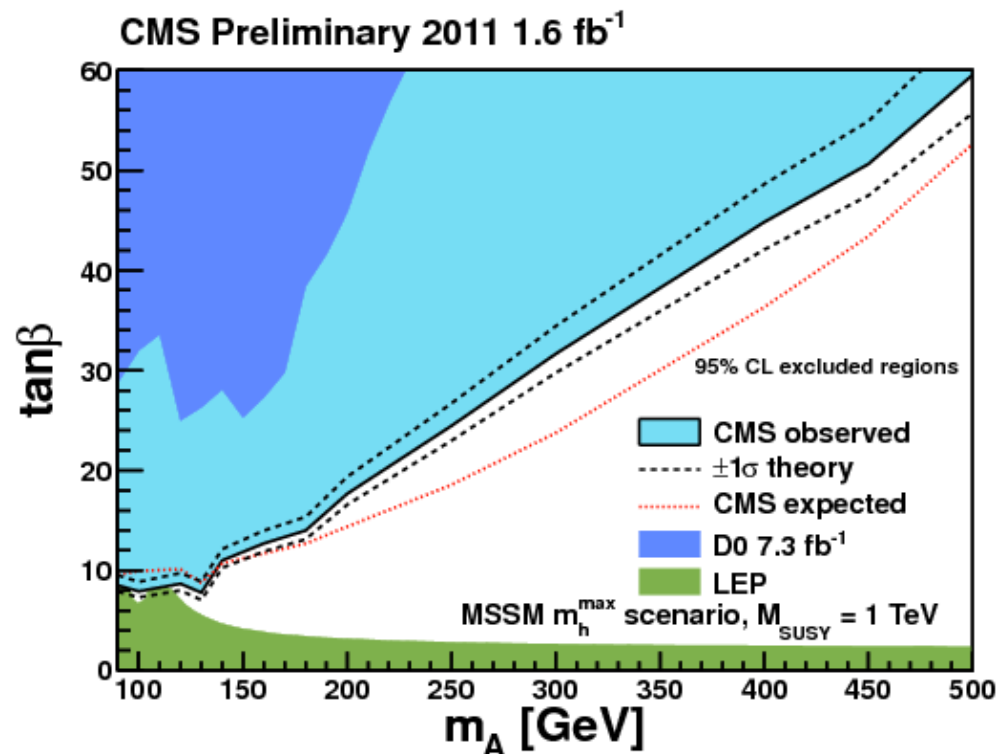
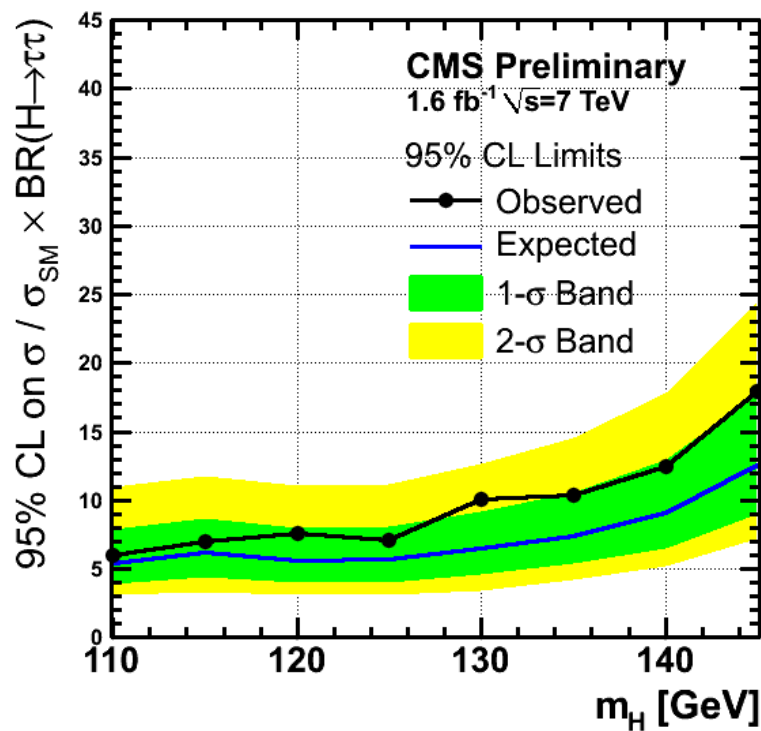
- The inclusive  $bb$  final state is overwhelmed by QCD background
- The idea is to exploit the  $W/Z+H$  associate production with the Higgs heavily boosted
  - Require  $p_T^{bb} > 100$  (150) GeV for  $ZH$  ( $WH$ )
- Topology is very clear, several final states considered:
  - $l\nu bb, llbb, \nu\nu bb$
  - $\Delta\phi(V,H)$ , tight  $b$ -tagging
- Still non negligible background from  $V$ +jets, top and di-boson. Background normalized in data control regions
- Results based on the shape of multivariate analysis output (BDT)



$H \rightarrow \tau\tau$

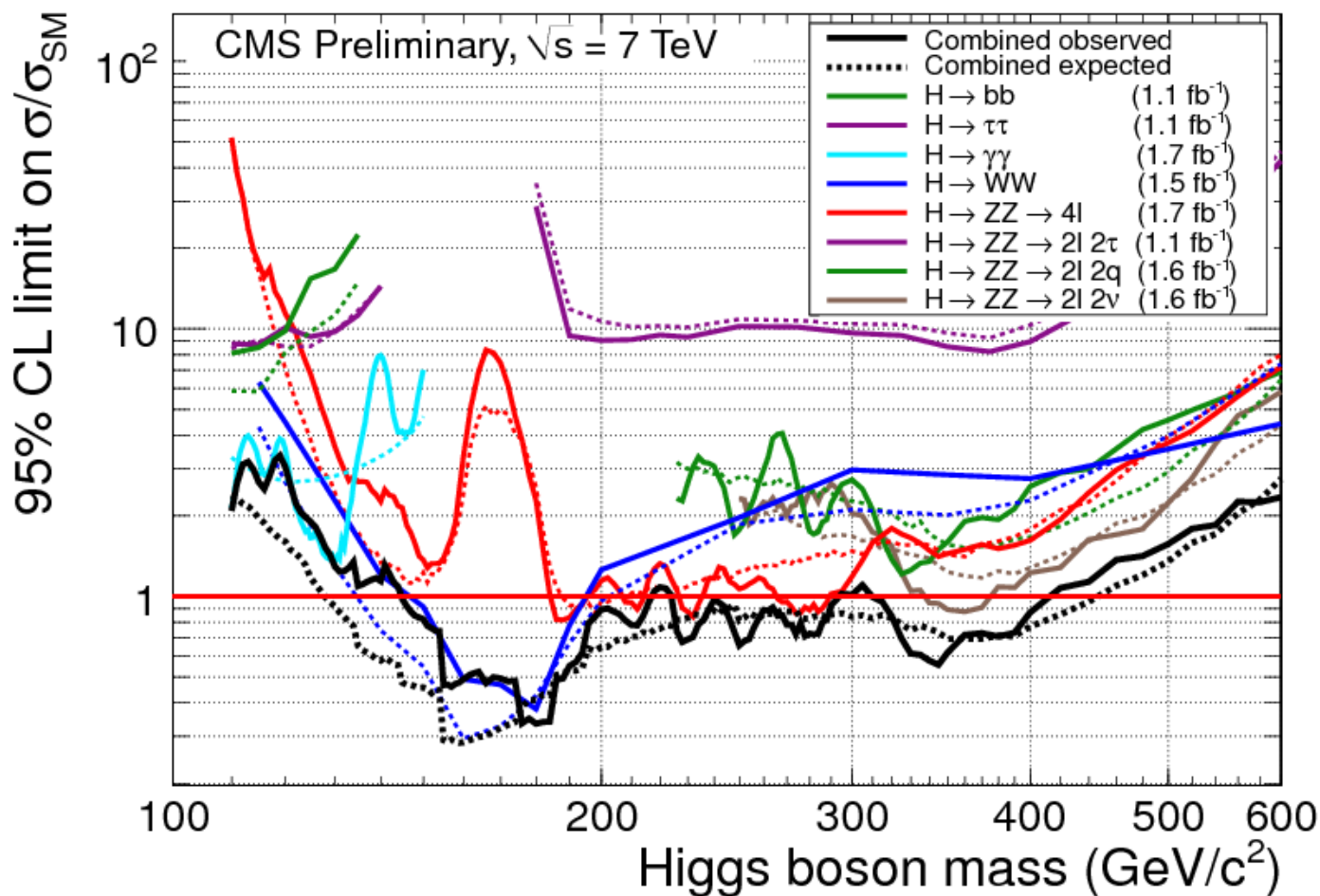
- $\tau_{\text{had}}\tau_{\mu}$ ,  $\tau_{\text{had}}\tau_e$ ,  $\tau_{\mu}\tau_e$  used as possible final states
- Visible mass (combination of visible tau decay products) exploited to extract the Higgs signal
- Main backgrounds are Z  $\rightarrow$   $\tau\tau$ , V+jets, top and QCD, all normalized from data
- VBF production is the most sensitive process in the context of SM Higgs searches.
- Non-VBF (orthogonal) sample to enhance statistical power.
- For MSSM Higgs searches final states with at least 1 b-tagged jet are considered



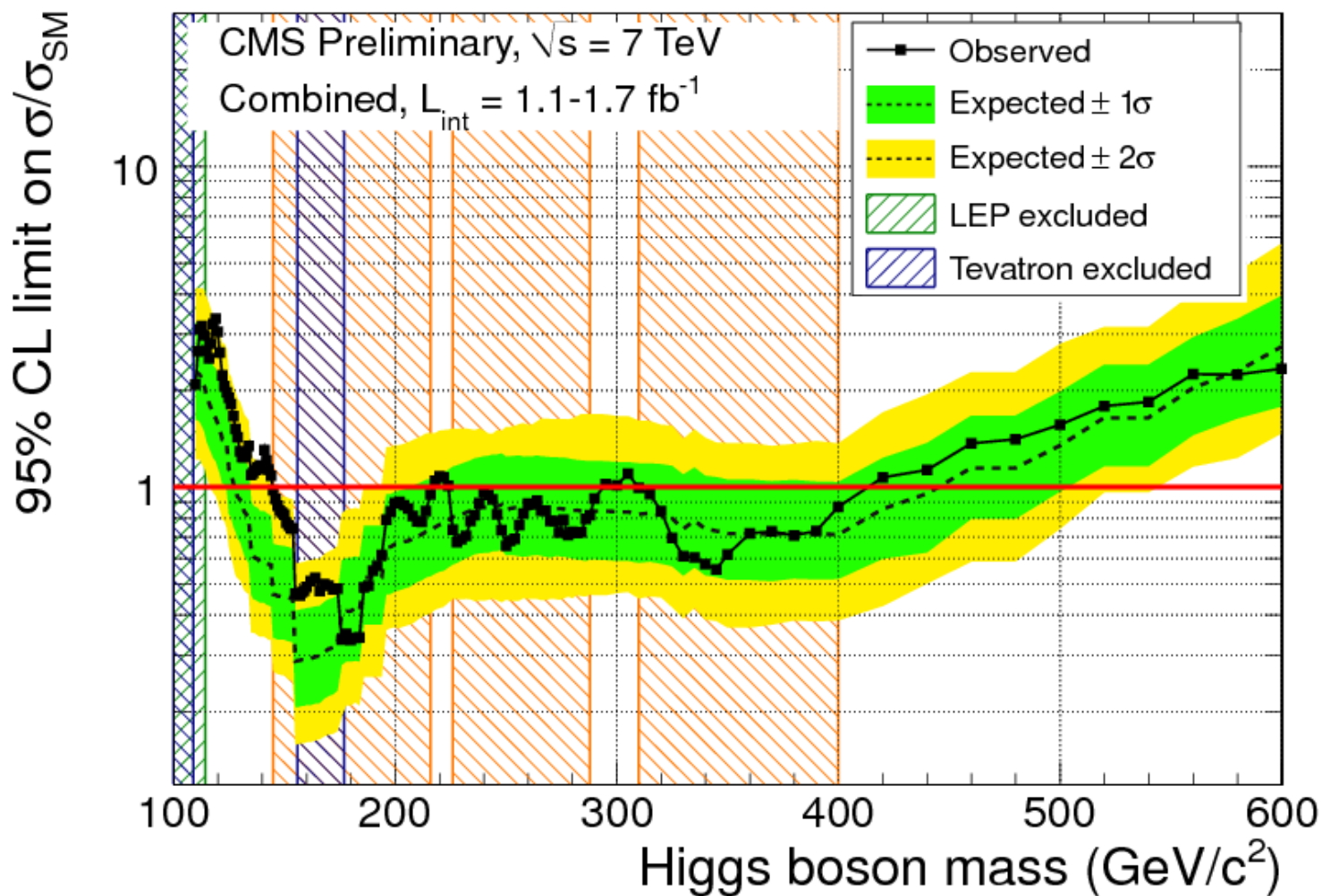


- Important contribution in the low SM  $M_H$  range
- Most sensitive channel for neutral Higgs searches in the context of SUSY models
  - Large portion of  $\tan\beta$ - $M_A$  plane excluded

# Grand Combination



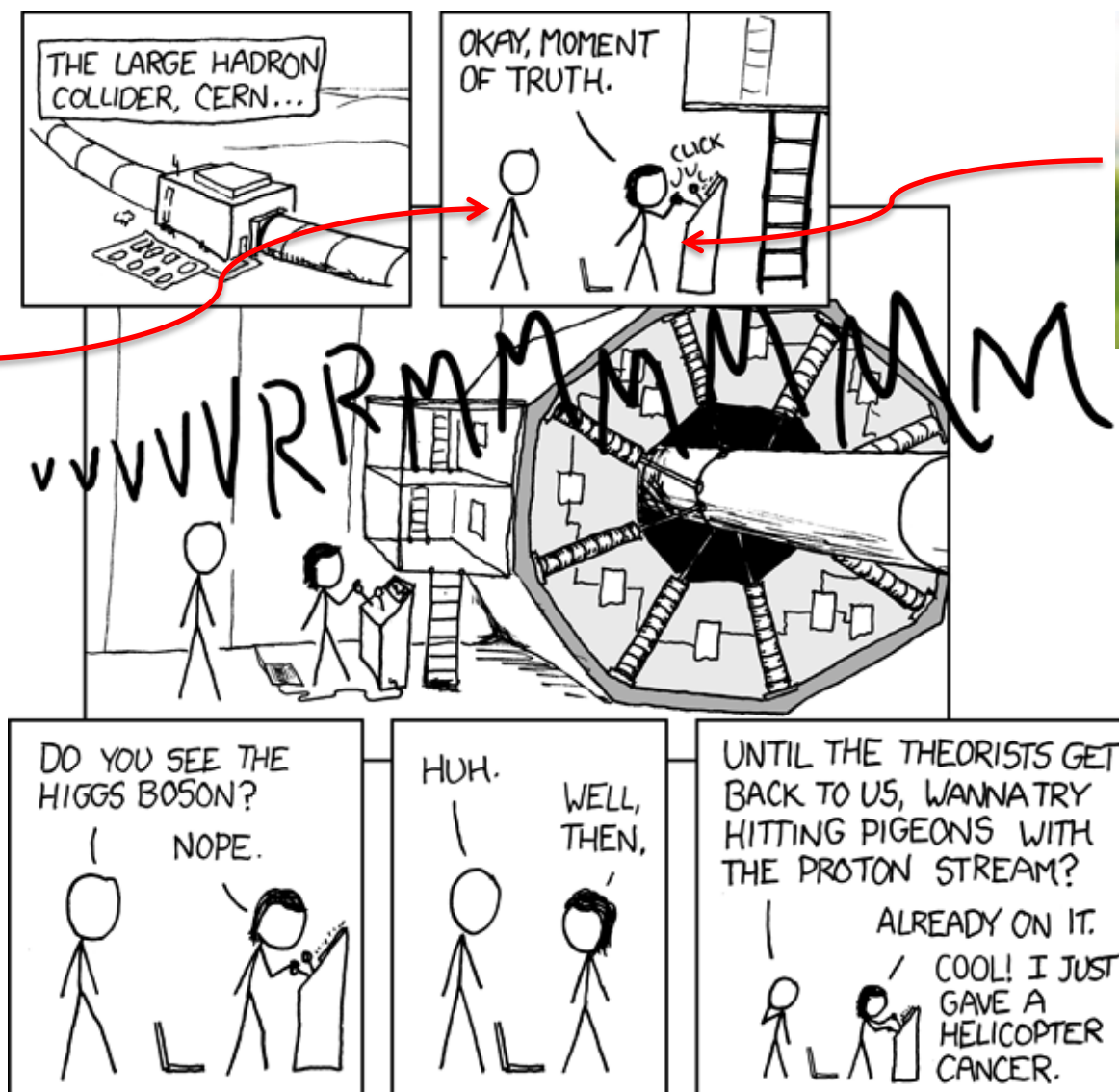
\* Not yet updated for  $H \rightarrow \tau\tau$



\* Not yet updated for  $H \rightarrow \tau\tau$

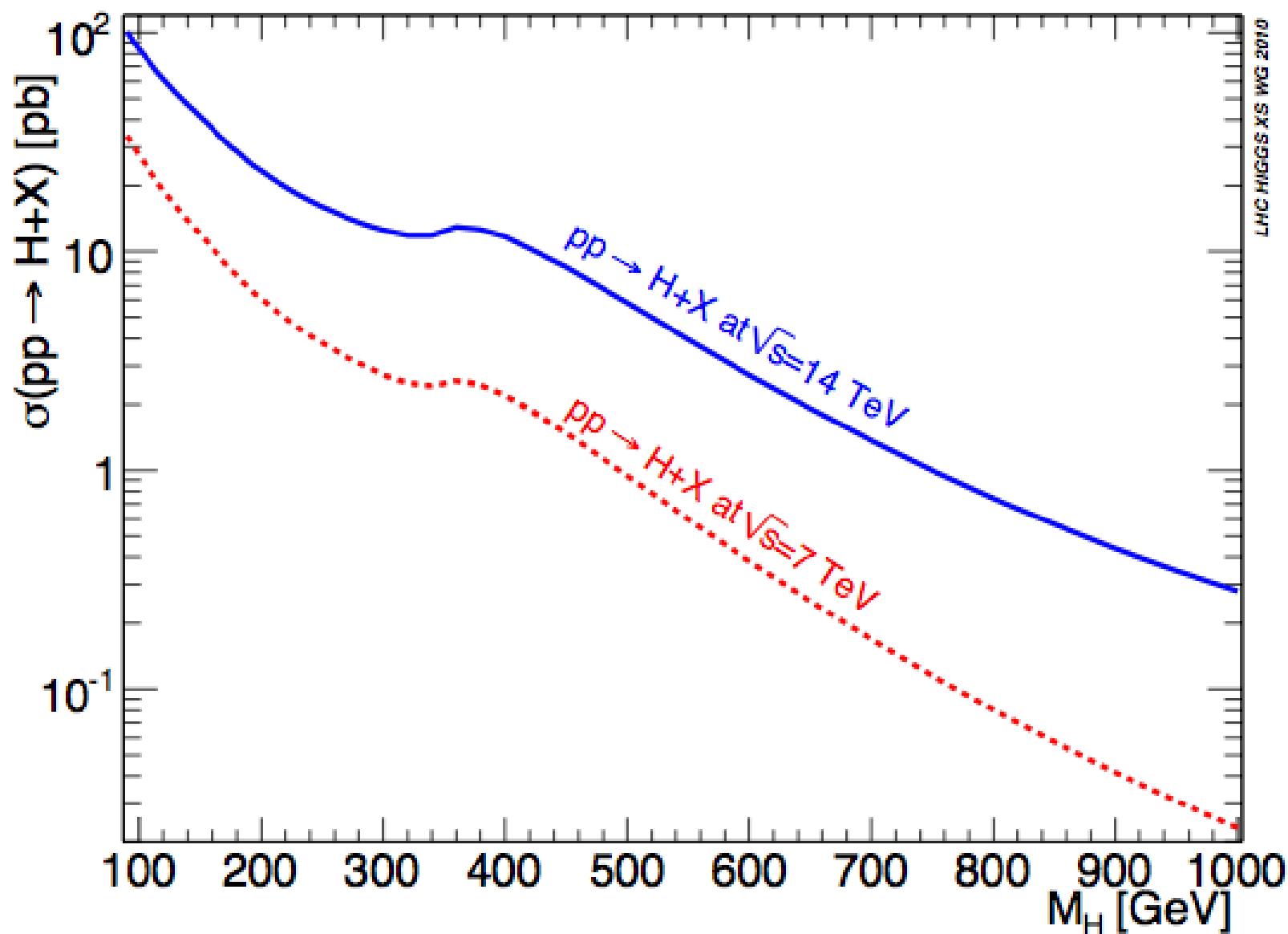
- The result of the CMS searches for the SM Higgs in 8 Higgs boson decay channels with  $1.5 \text{ fb}^{-1}$  data have been presented
- No SM Higgs signal observed in the [110-600] GeV mass range
- A wide range of mass has been excluded at 95% CL:
  - SM: [145-216], [226-288] & [310-340] GeV
  - Fermiophobic: [110-112] GeV
  - 4<sup>th</sup> generation SM: [250-550] GeV
- The expected SM exclusion range is [130-440] GeV
- The most theoretically interesting but experimentally difficult low mass region has still to be fully probed
- With data collected so far we were not expected to unveil the full range, a few more  $\text{fb}^{-1}$  are needed!

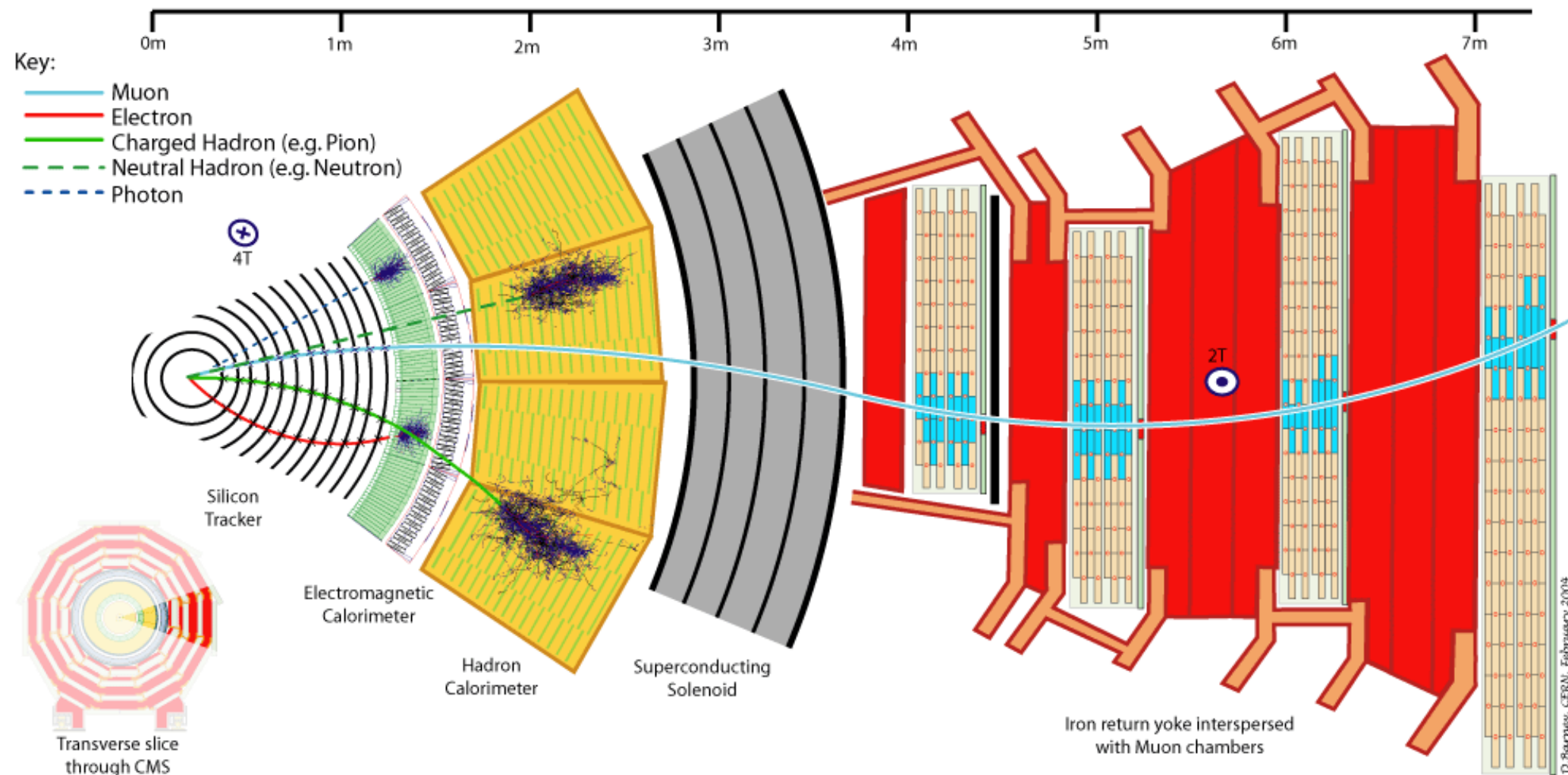
## A portrait photograph of Prof. Dr. Gert H. W. van Erp. He is a middle-aged man with dark hair, smiling at the camera. He is wearing a light blue collared shirt under a grey sweater. The background is slightly blurred, showing what appears to be a poster or chart on a wall.



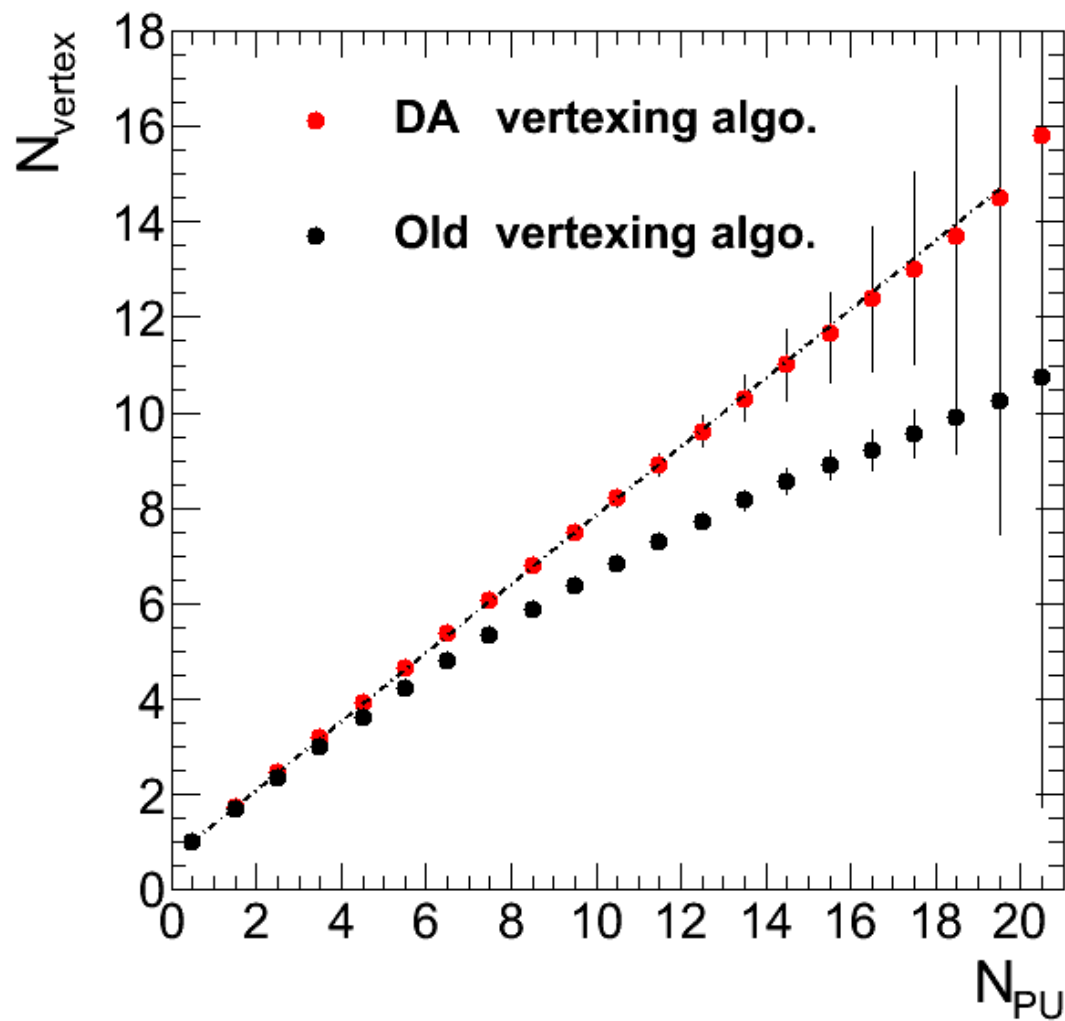
# BACKUP

# 7-14 TeV comparison





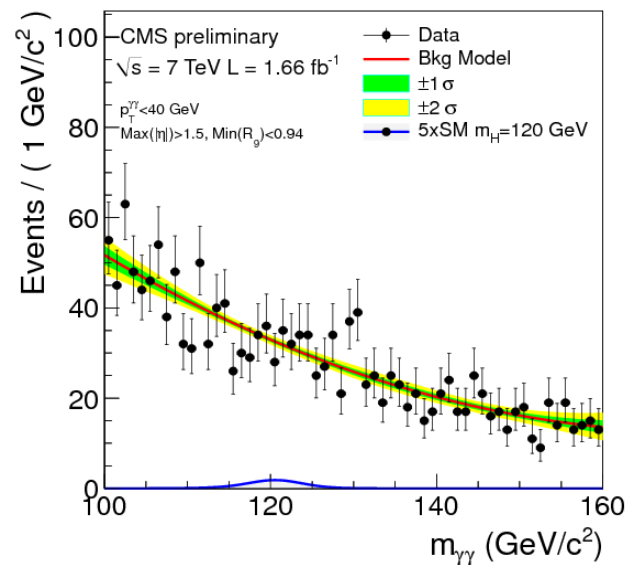
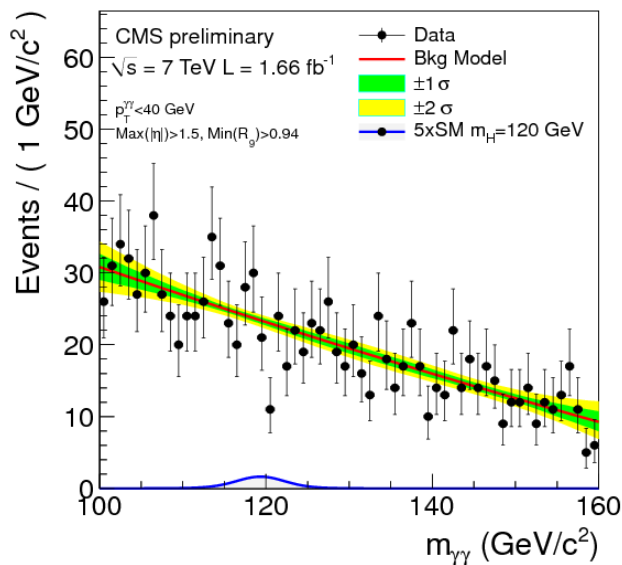
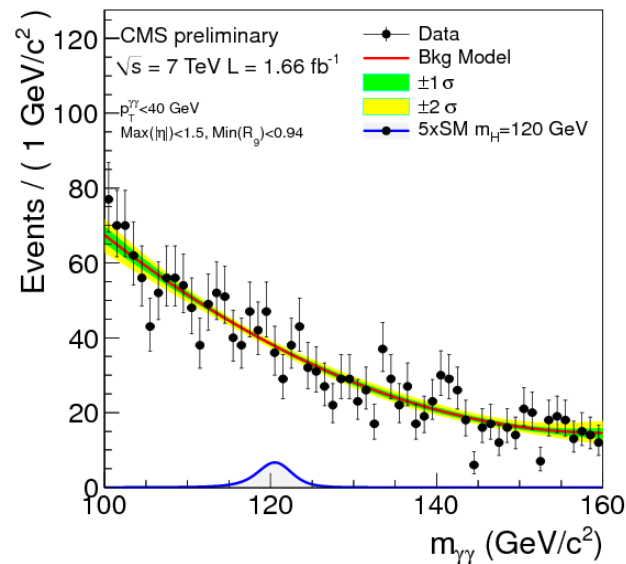
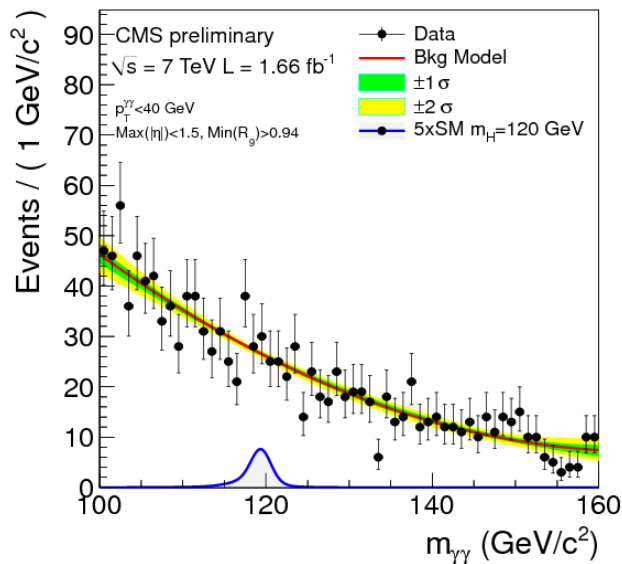
# Vertex reconstruction



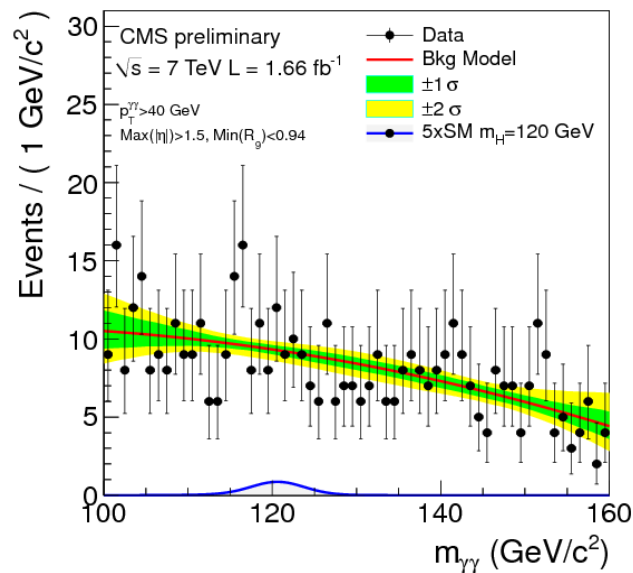
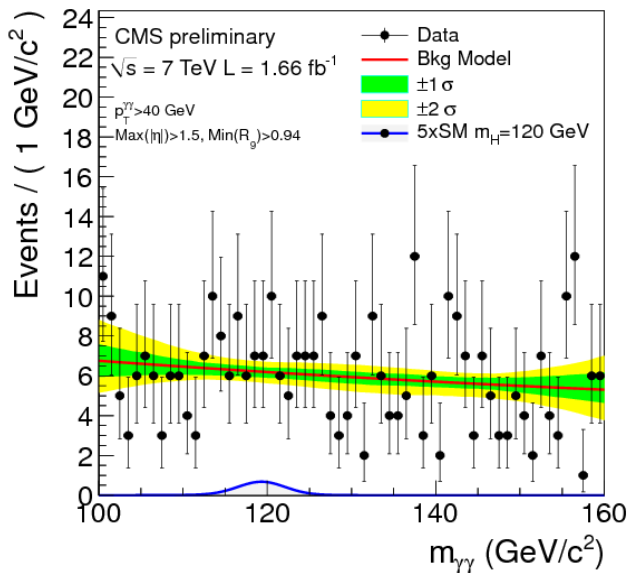
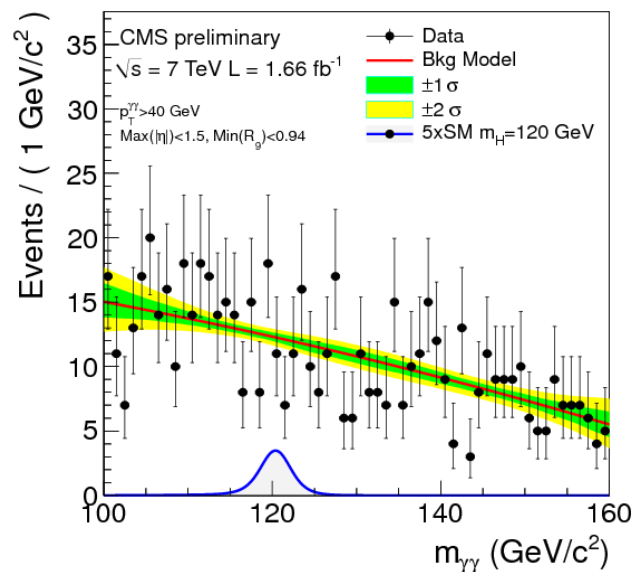
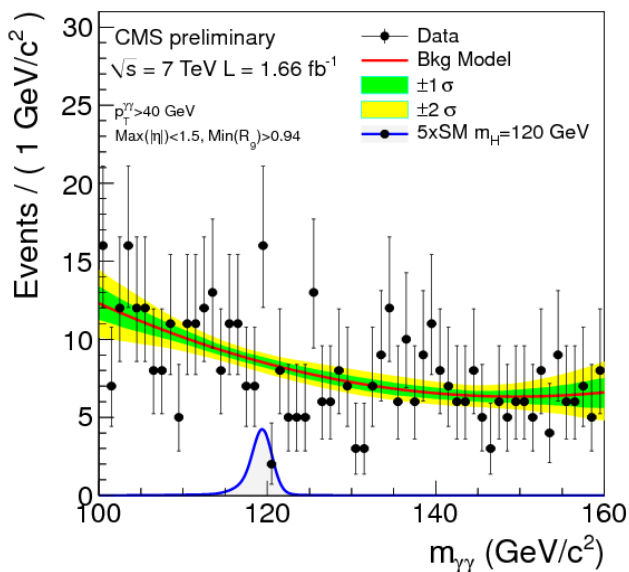
# H- $\rightarrow\gamma\gamma$ Systematics

Source	Systematics
<i>applicable to individual photons</i>	
Photon identification efficiency	1.0% $\div$ 4.0%
R9 cut efficiency	4.0% $\div$ 6.5%
Energy resolution	0.2% $\div$ 0.5%
Energy scale	0.05% $\div$ 0.34%
<i>applicable to di-photons</i>	
Integrated luminosity	6.0%
Trigger efficiency	1.0%
Vertex finding efficiency	0.5%
pT>40GeV cut efficiency	6.0%
<i>cross sections and branching ratios</i>	
Gluon-gluon cross section	12.5%(scale) 7.9%(PDF)
Fermiophobic: scale	0.5%(VBF) 0.8%(WH) 1.6%(ZH)
Fermiophobic: PDF	3.1%
Fermiophobic: BR	5.0%

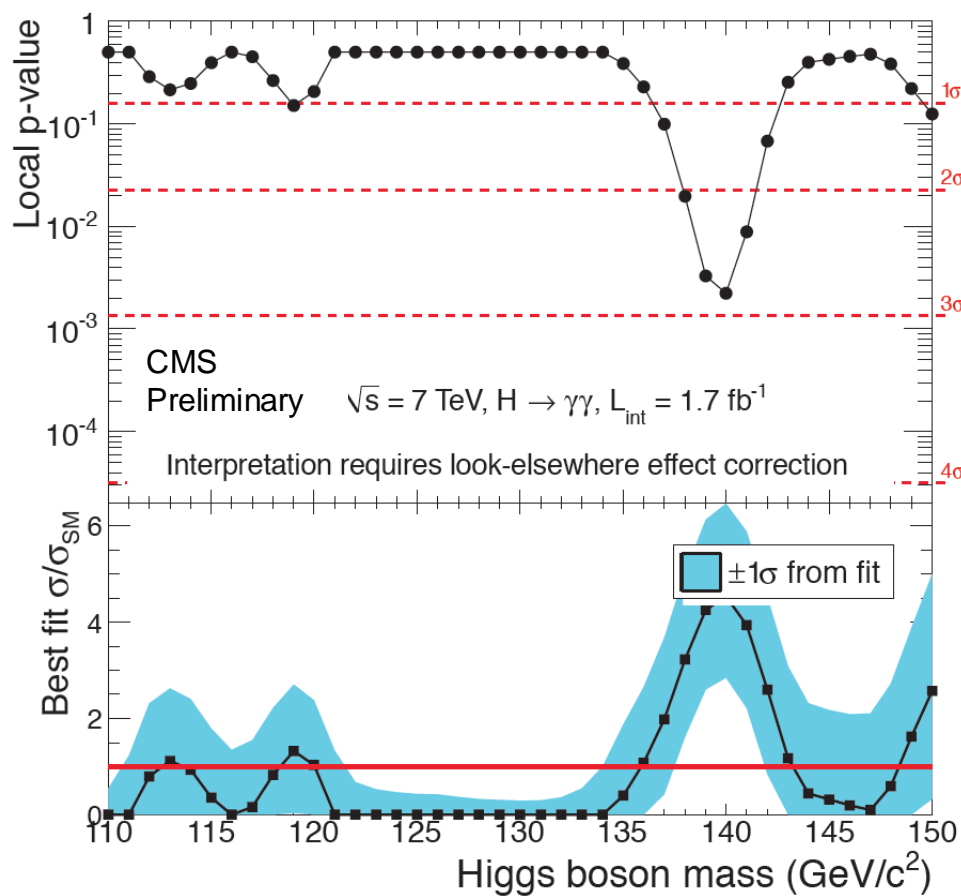
# H- $\gamma\gamma$ fits



# H- $\gamma\gamma$ fits



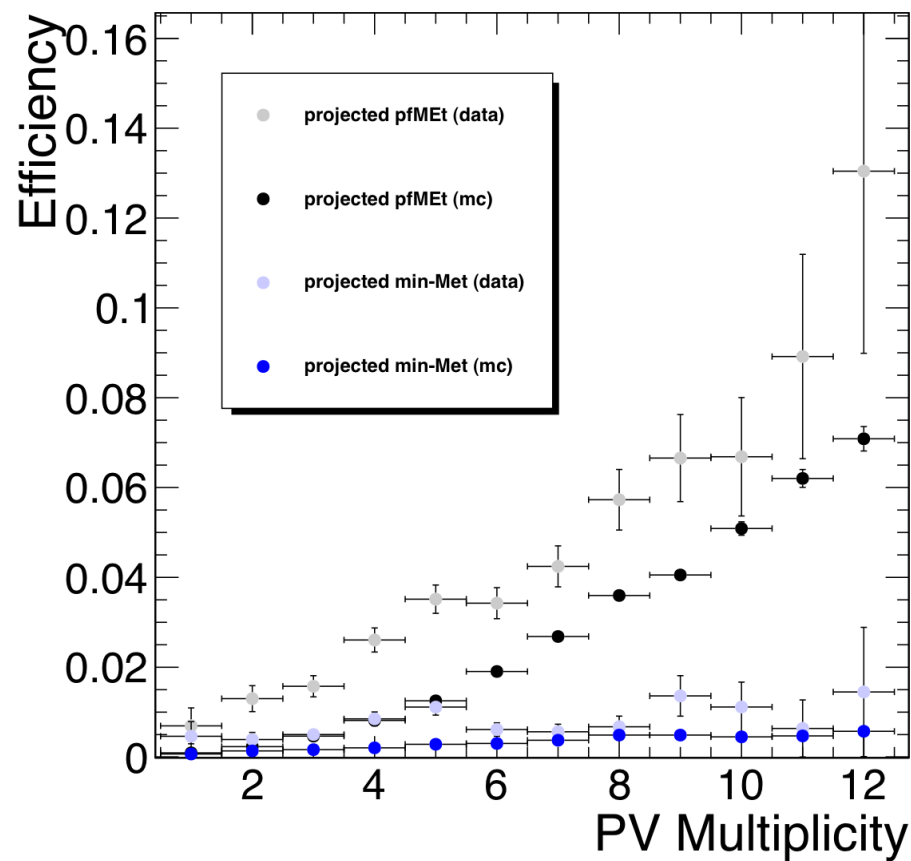
# H- $\rightarrow\gamma\gamma$ p-value



Efficiency for Z- $\rightarrow$ ll events to pass  
 $ME_T > 30$  cut

$$N_{out}^{\ell\ell,exp} = R_{out/in}^{\ell\ell} (N_{in}^{\ell\ell} - N_{in}^{non-Z} - N_{in}^{ZV})$$

Z-peak to signal region ratio from MC, verified in data  
 opposite-flavor events in Z peak  
 same-flavor events in Z peak  
 WZ, ZZ contribution from MC



- Theoretical uncertainties  $\sim 5 \div 20\%$
- Systematic uncertainties on backgrounds estimated from data are mostly statistical in nature and will decrease with more integrated luminosity

Uncertainties relative to the  $M_H=130$  GeV analysis for  $L=1\text{fb}^{-1}$

Process	Relative Systematic Uncertainty	0-jet Yield
Drell-Yan ( $ee/\mu\mu$ )	60%	$1.48 \pm 0.26$ (stat) $\pm 0.89$ (syst)
$W$ +jets	36%	$18.74 \pm 2.40$ (stat) $\pm 6.75$ (syst)
Top	25%	$3.66 \pm 0.82$ (stat) $\pm 0.92$ (syst)
$WW$	15%	$52.56 \pm 0.71$ (stat) $\pm 7.88$ (syst)

# H- $\rightarrow$ ZZ- $\rightarrow$ 4l Systematics

Table 4: Summary of the magnitude of systematic uncertainties in percent. The uncertainties assigned for the lepton reconstruction, identification and isolation apply to the event yields. The uncertainty assigned to the electron energy scale is further propagated through the shape of the expected signal and background reconstructed mass distributions.

Luminosity	4.5
Trigger efficiency	1.5
Higgs cross section	17-20
Higgs B.R.	2
Lepton reco/ID eff.	2-3
Lepton isolation eff.	2
Electron energy scale	3

# H- $\rightarrow$ ZZ- $\rightarrow$ 2l2 $\nu$ Systematics

Table 5: Systematic uncertainties on the final event yields for both electron and muon final states. Ranges indicate different uncertainty values for different processes — for example QCD Scale uncertainties differ from one Higgs mass point to another.

Uncertainty	value, %
Luminosity	4.5
pdf, gluon-gluon initial state	6-11
pdf, quark-quark initial state	3.3-7.6
QCD scale, gluon-gluon initial state (ggH)	7.6-11
QCD scale, quark-quark initial state (VBF)	0.2-2
QCD scale, gluon-gluon initial state (ggZZ)	20
QCD scale, quark-quark initial state (qqVV)	5.8-8.5
Anti b-tagging	1-1.2
Lepton ID+Isolation	2
Lepton momentum scale	5 (for 2e), 2 (for 2 $\mu$ )
Jet energy scale	1-1.5
PU effects	1-3
Trigger	1 (for 2e), 2 (for 2 $\mu$ )
non-resonant backgrounds estimation from data	7% ( $\alpha$ )
Z + jets estimation from data	19-57%

# H- $\rightarrow$ ZZ- $\rightarrow$ 2l2q Systematics

Table 3: Summary of systematic uncertainties on signal normalization. Most sources give multiplicative errors on the cross-section measurement, except for the expected Higgs boson production cross section, which is relevant for the measurement of the ratio to the SM expectation.

source	0 $b$ -tag	1 $b$ -tag	2 $b$ -tag
muon reco	2.7%		
electron reco	4.5%		
jet reco	1-5%		
pileup	2%		
$b$ -tagging	3-7%	3%	+13% / - 18%
gluon-tagging	4.6%	-	-
$\cancel{E}_T$	-	-	3%
acceptance (PDF)	3%		
acceptance (HQT)	2%	5%	3%
acceptance (WBF)	1-2%		
luminosity	4.5%		
Higgs cross section	13-18%		

**Frequentist:** test values of  $\mu = \sigma/\sigma_{SM}$  by running pseudo-experiments and evaluating how often they are more signal-like than the real data observation

For each value of the signal strength  $\mu = \sigma/\sigma_{SM}$

- Evaluate the test statistics (profile likelihood)

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

$\hat{\theta}_\mu$ : value of  $\theta$  which maximizes likelihood given  $\mu$

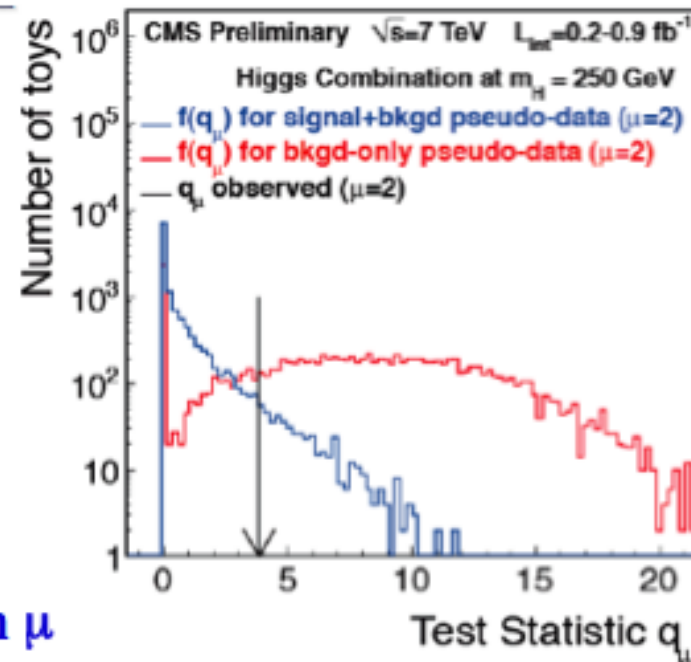
- Determine the value of  $\theta$  which give the best global fit of the data and measured  $\theta_0$ . Do it separately for the case of no signal and for the tested
- Use values to generate pseudo-experiments for background-only and signal+background  
In each pseudo-experiment generate also values of the external measurements  $\theta_0$
- Evaluate test statistics for pseudo-experiments comparing with the data building  $CL_s$

$$CL_s = \frac{CL_{S+B}}{CL_B} = \frac{p_\mu}{p_0} = \frac{P(q_\mu \geq q_\mu^{obs} | \mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs}))}{P(q_\mu \geq q_\mu^{obs} | b(\hat{\theta}_\mu^{obs}))}$$

signal+background hypothesis

background-only hypothesis

If  $CL_s < 0.05$ : value  $\mu$  is excluded at 95% CL



Courtesy of  
Monica Vazquez Acosta

- Excesses are quantified using p-values: probability for a background pseudo-experiment to look more signal-like than the observed data.
- In the definition of the p-value, the  $\sigma/\sigma_{\text{SM}}$  is freely floating, but required to be consistently among the channels

- Using the method defined in the LHC Higgs Combination document [AN 11/298](#).
- The probability of observing an excess ( $p_{\text{global}}$ ) is computed from the local p-value ( $p_{\text{local}}$ ) and local significance ( $Z_{\text{max}} = \mu/\Delta\mu$ ), and from the number of times the data crosses from excess to deficit ( $N_0$ ):

$$p_{\text{global}} = p_{\text{local}} + N_0 \exp(-\frac{1}{2} Z_{\text{max}}^2)$$

- The test statistics is profiled, so that all information from the data is used to constrain the nuisance parameters (was done at TeV.)
- In the pseudo-experiments, the external measurements are randomized, not the nuisances: purely Frequentist approach
- In the denominator, we profile also the signal strength  $\mu = \sigma/\sigma_{\text{SM}}$  (gives better asymptotics)
- The two methods were compared on some test models, and found to give very similar results.

# Combination summary

channel	mass range (GeV/ $c^2$ )	luminosity (fb $^{-1}$ )	number of sub-channels	type of analysis	number of nuisances
$H \rightarrow \gamma\gamma$	110-150	1.7	8	mass shape (unbinned)	3+40=43
$H \rightarrow \tau\tau$	110-140	1.1	6	mass shape (binned)	10+25=35
$H \rightarrow b\bar{b}$	110-135	1.1	5	cut&count	10+59 = 69
$H \rightarrow WW \rightarrow 2\ell 2\nu$	110-600	1.5	5	cut&count	15 +79 =94
$H \rightarrow ZZ \rightarrow 4\ell$	110-600	1.7	3	mass shape (unbinned)	14+20=34
$H \rightarrow ZZ \rightarrow 2\ell 2\tau$	180-600	1.1	8	mass shape (unbinned)	13+10=23
$H \rightarrow ZZ \rightarrow 2\ell 2\nu$	250-600	1.6	2	cut&count	14+4=18
$H \rightarrow ZZ \rightarrow 2\ell 2q$	226-600	1.6	6	mass shape (unbinned)	12+15=27
TOTAL (8)	110-600	1.1-1.7	27 for low $m_H$ 24 for high $m_H$		241 for low $m_H$ 146 for high $m_H$

