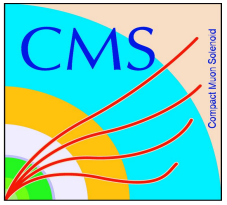
Higgs Results from CMS

Marco Pieri
University of California San Diego
On behalf of the CMS Collaboration



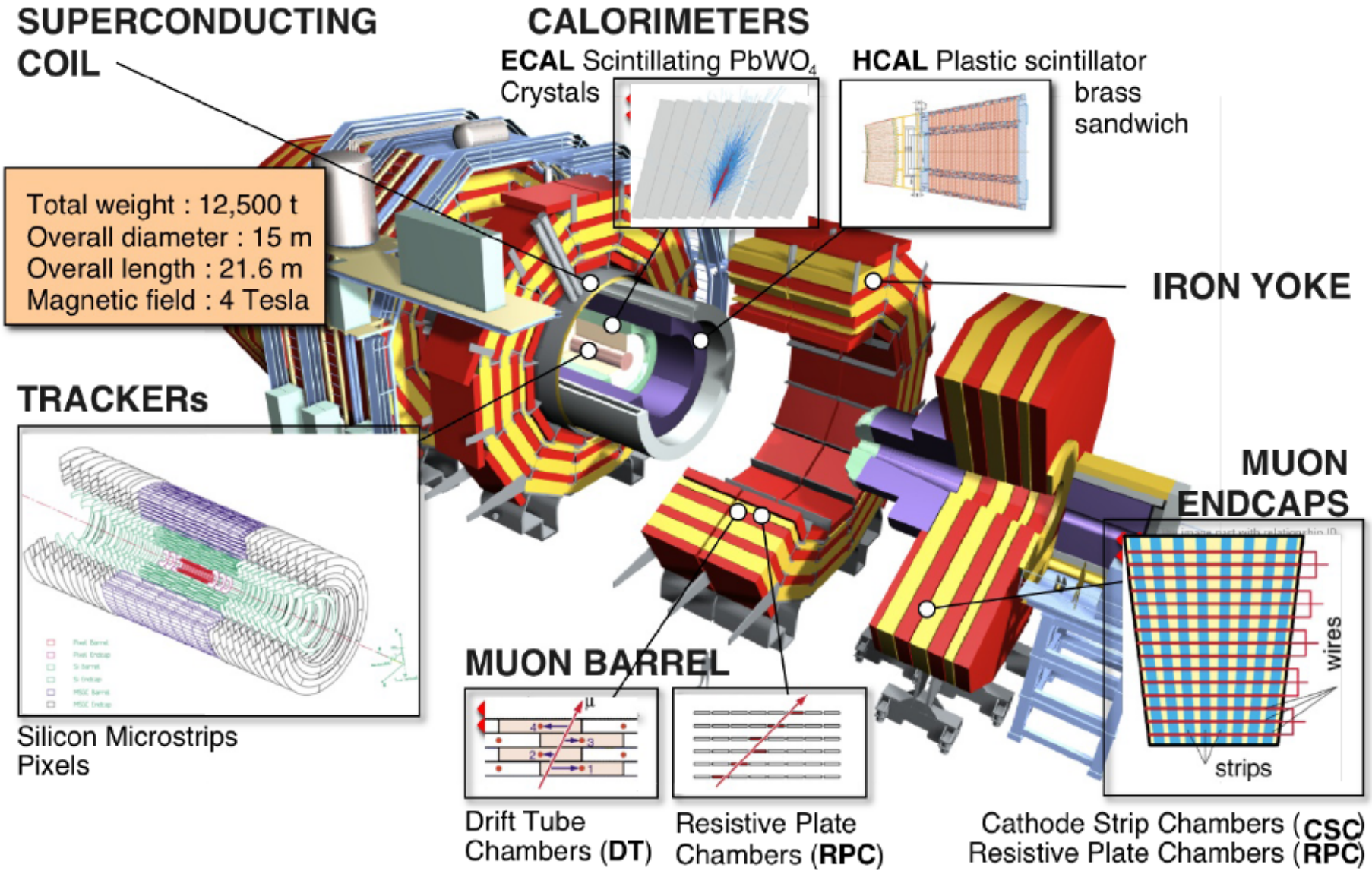
Workshop on Multi Higgs Models,
28-31 August 2012, Lisbon, Portugal

Outline

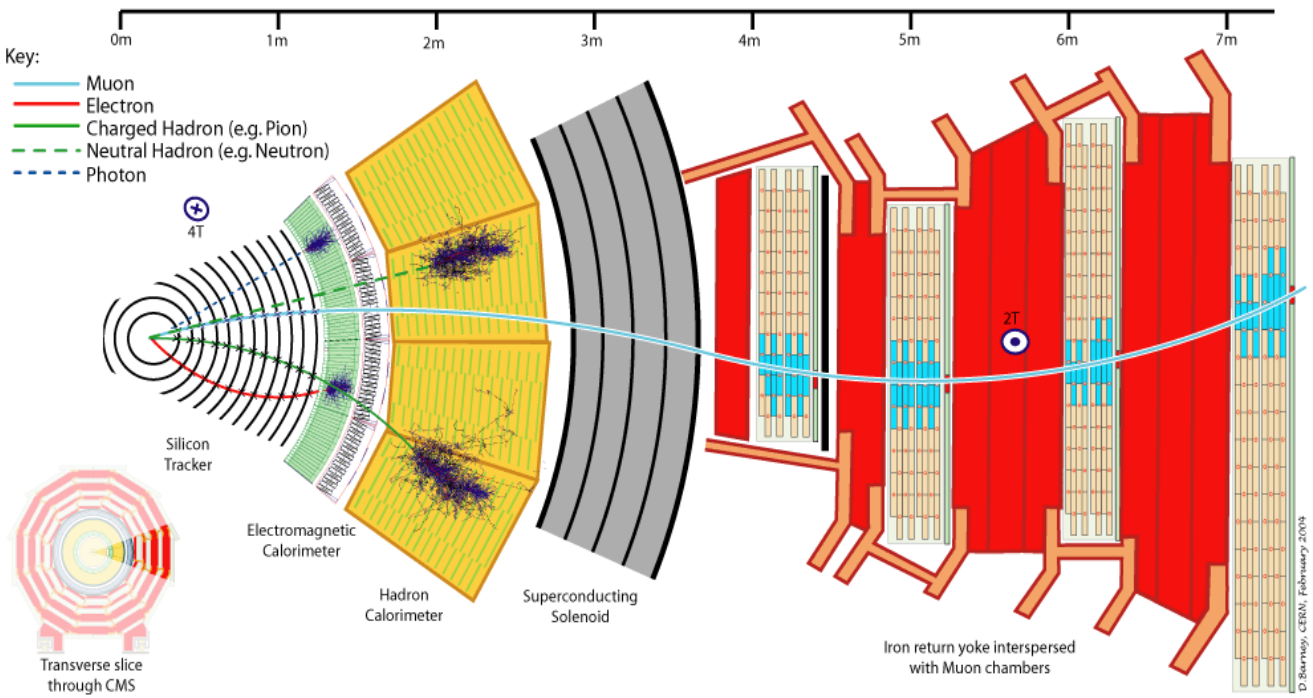
- CMS detector and datasets
- SM Higgs Searches
  - Discovery of a new boson consistent with a Higgs boson
  - Measurement of new boson properties
  - High mass Higgs boson searches
- BSM Searches
  - Fermiophobic Higgs
  - 4 fermion generation
  - MSSM
  - Beyond the MSSM
- Summary

For all CMS public results on Higgs searches see:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

The CMS Detector



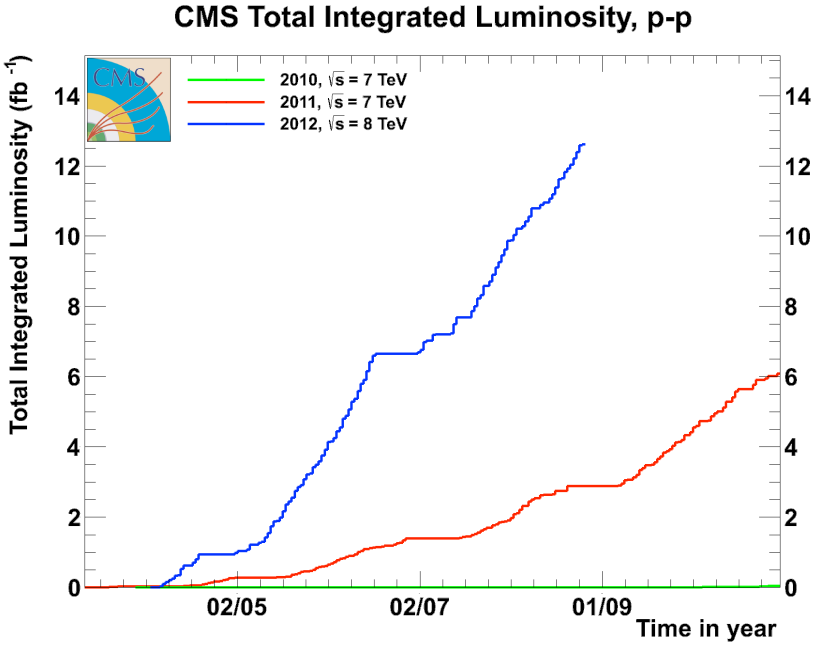
Measurement of particles in CMS

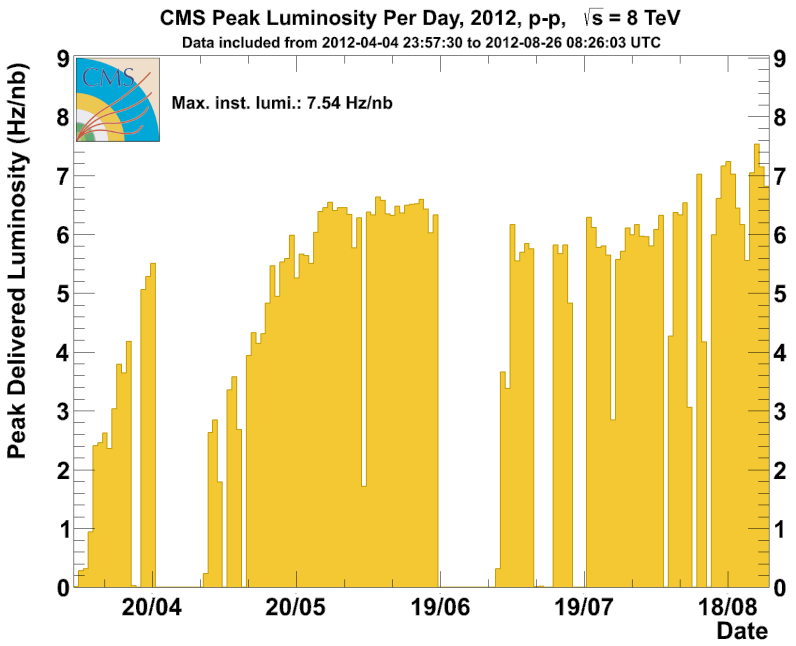


- Global Event Description (GED) - particle flow algorithm
  - combines and links signals from the different sub-detectors
  - provides the optimal event description in form of a list of particles: electron, muons, charged hadrons, photons and neutral hadrons
- τ lepton, jet and MET reconstruction are based on Pflow
- Large improvements obtained w.r.t. simple reconstruction
- Helps a lot in high PU environment

Data: pp collision at 7 and 8 TeV

- Excellent performance of LHC and CMS in 2011 and 2012
- 17 fb^{-1} IntL pp collisions collected until now at 7 and 8 TeV CM energy
  - Analyzed ~10 fb^{-1} until summer conferences 2012
- Peak luminosity 7.5 x 10^{33} $cm^{-2}s^{-1}$
- Data taking efficiency >90%

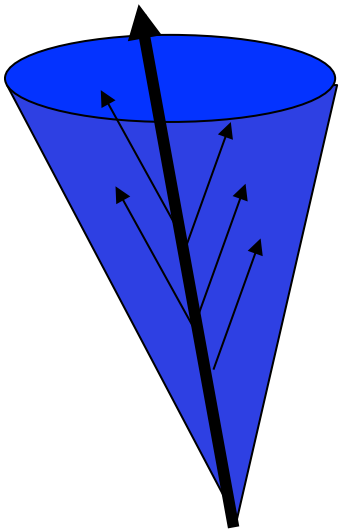




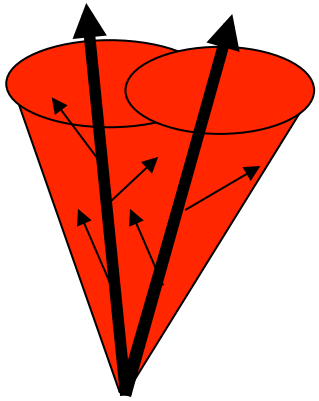
Number of interactions per bunch crossing at the beginning of fills is about 30

Pileup

- Multiple interactions occur for each bunch crossing (in-time and out-of-time pileup)
- Mean PU ~10 events in 2011 and ~20 events in 2012
- Effects of pileup:
  - Slightly deteriorates energy resolution for electrons and photons and jets
    - Apply corrections event by event for photons and jets
  - Adds energy in isolation cones
    - corrected for pileup energy estimated event by event
  - PU jets affect central jet veto and VBF jet tagging
    - Try to reject PU jets (wider and with tracks coming from different PV)

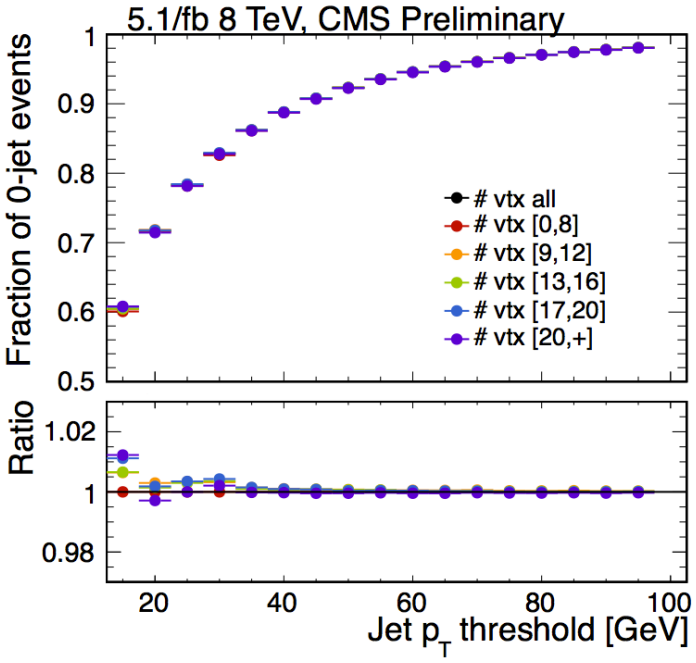


Typical jet

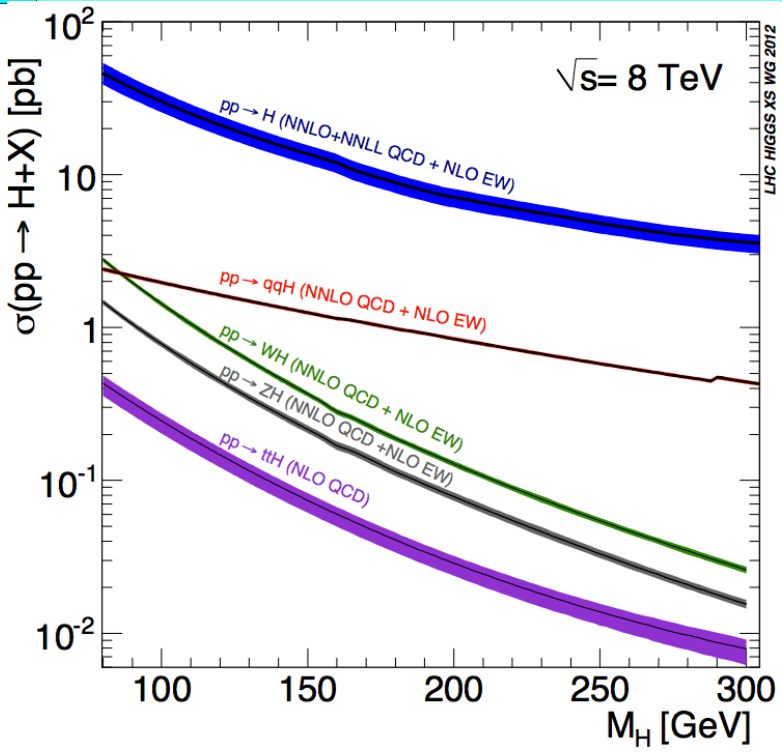


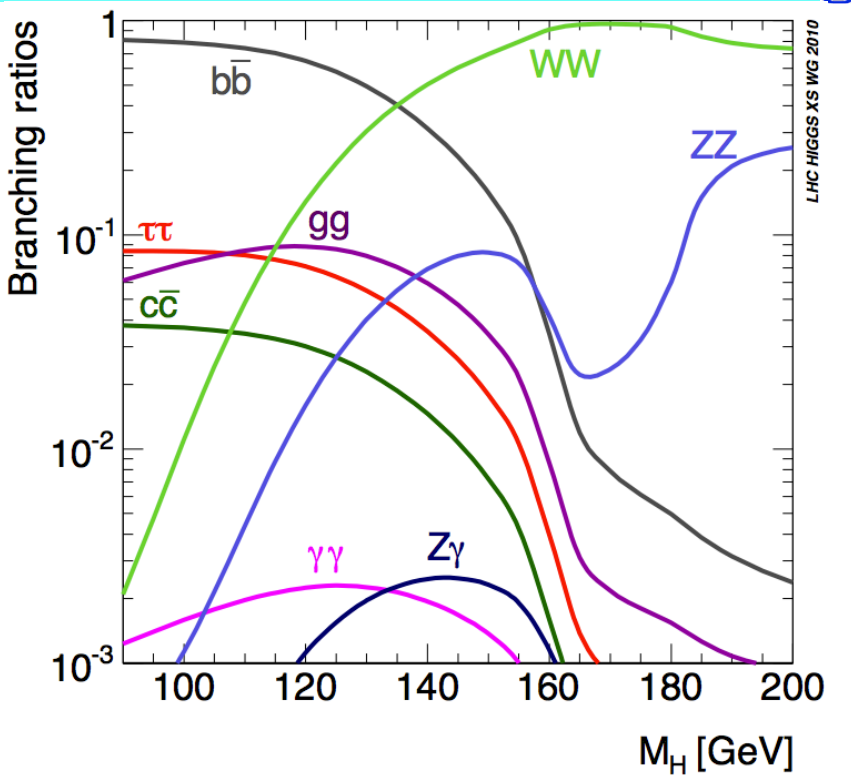
Typical Pileup jet

Constant 0 jet fraction in WW events at different PU levels

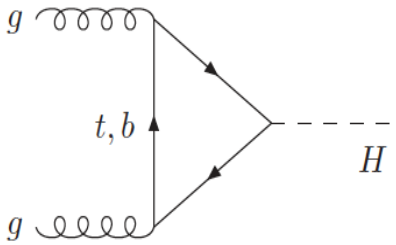


SM Higgs production and decay

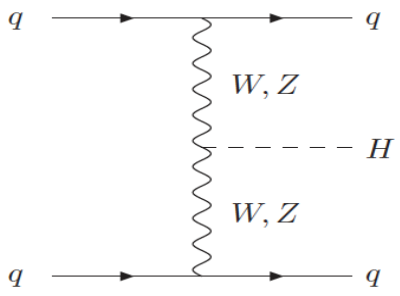




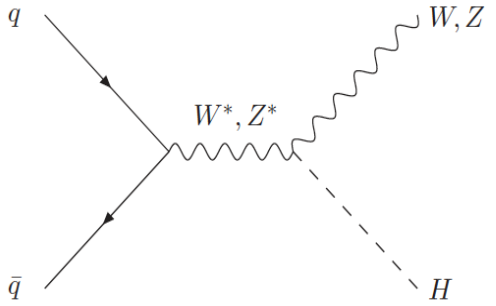
ggH



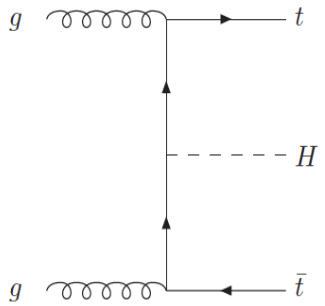
VBF



VH



ttH

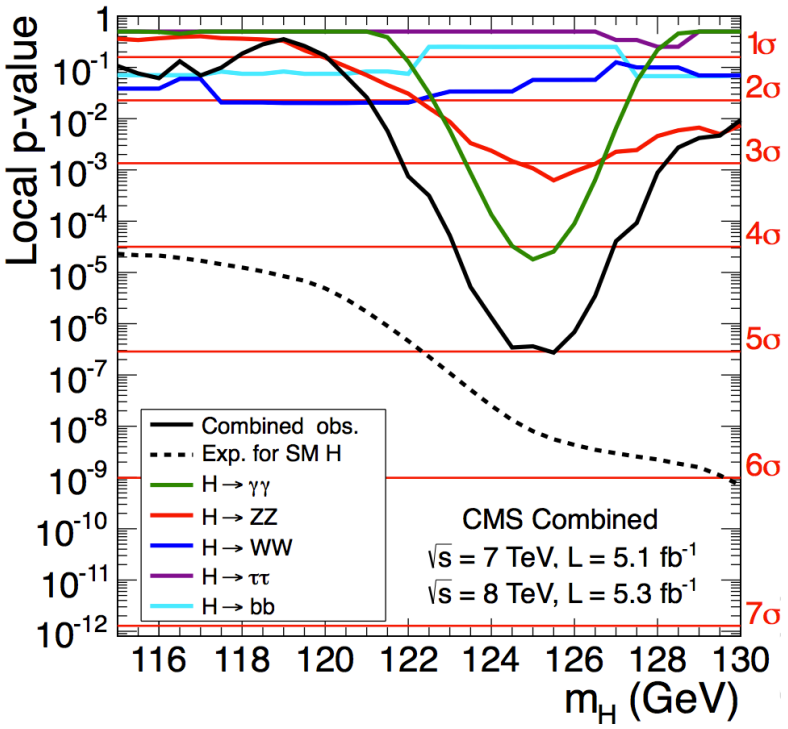


Exploit all four production modes

The discovery

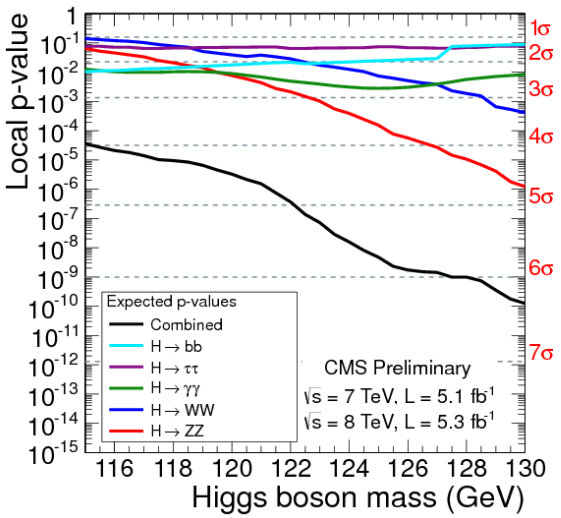
- On July 4th 2012 CMS and ATLAS reported the observation of a new boson with mass about 125 GeV that is consistent with the SM Higgs boson
- 5 main channels in CMS:
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ \rightarrow 4l$
  - $H \rightarrow WW \rightarrow 2l2\nu$
  - $H \rightarrow \tau\tau$
  - $H \rightarrow bb$
- **2012 analysis has been 'blind'**
  - All analyses have been developed before looking at the signal region

arXiv 1207:7235



Most sensitive search channels at 125 GeV

- 2 channels with excellent mass resolution (1-2%)
  - γγ and ZZ -> 4l
  - Search for mass peak over the BG
- 3 channels with worse mass resolution (10-20%)
  - WW -> 2l2ν, ττ and bb
  - Search for excess above estimated BG

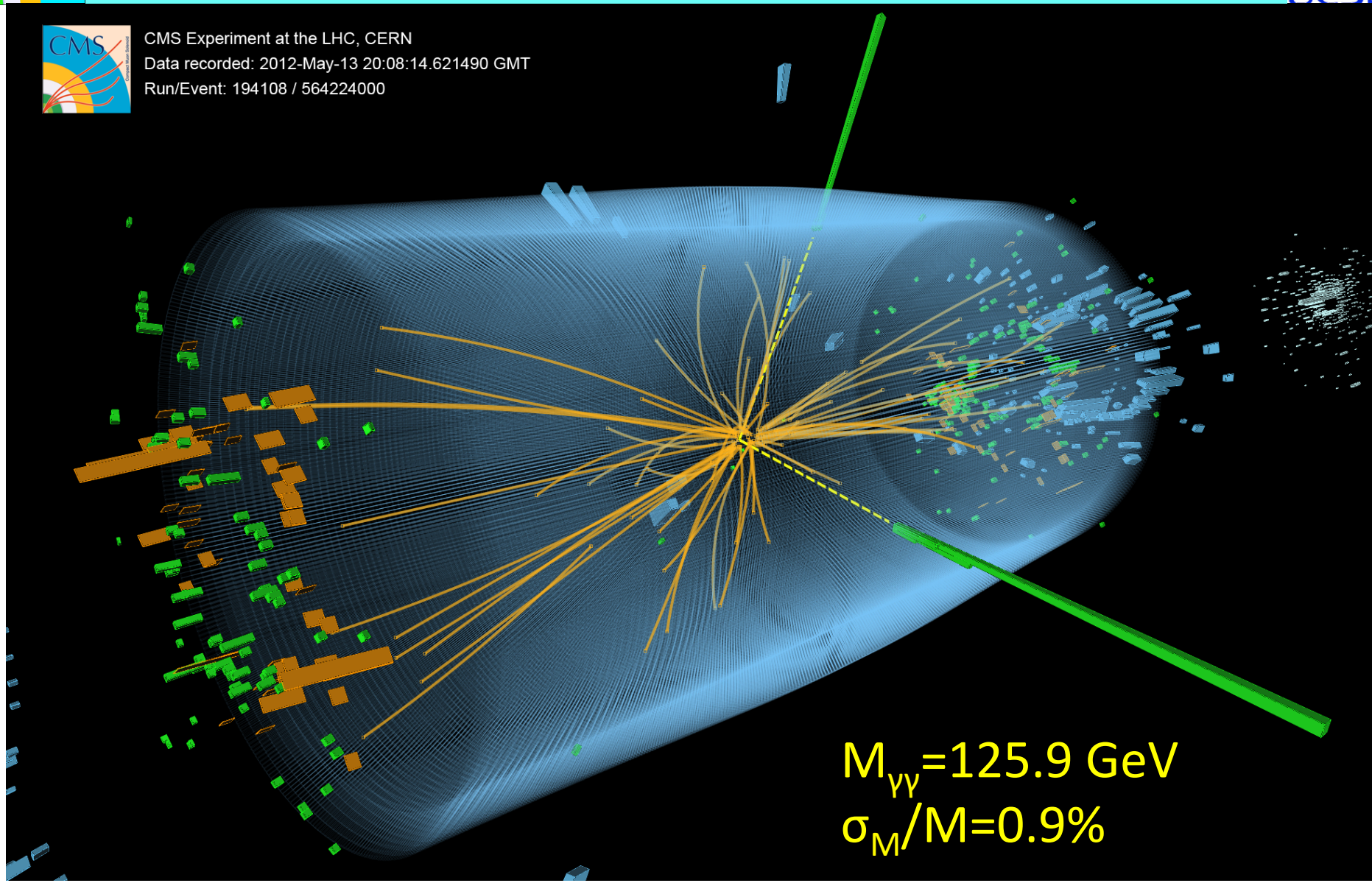


Channel	σ x BR (7-8 TeV) (pb)	Mean Efficiency	Number of signal events	Average s/b	Mass resolution
γγ untagged	0.045	40%	180	3.5%	1%
γγ VBF	0.003	20%	6	20%	1%
ZZ->4l untagged	0.002	30%	8	150%	1.5%
WW->2l2ν untagged	0.2	5%	100	15%	20%
WW VBF	0.015	3%	4	25%	20%
ττ untagged	1.3	2.5%	300	1%	15%
ττ VBF	0.088	2%	15	10%	15%
bb VH	0.13	4%	50	3%	9%

M_H = 125 GeV

Approximate values, only for illustration

H→γγ


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
$M_{\gamma\gamma}$=125.9 GeV
σ_M/M=0.9%

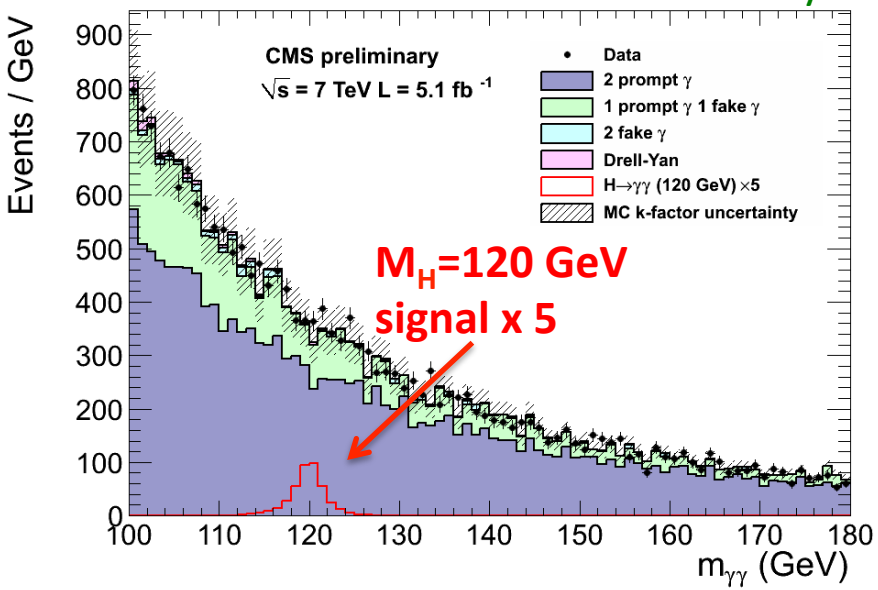
H→γγ

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

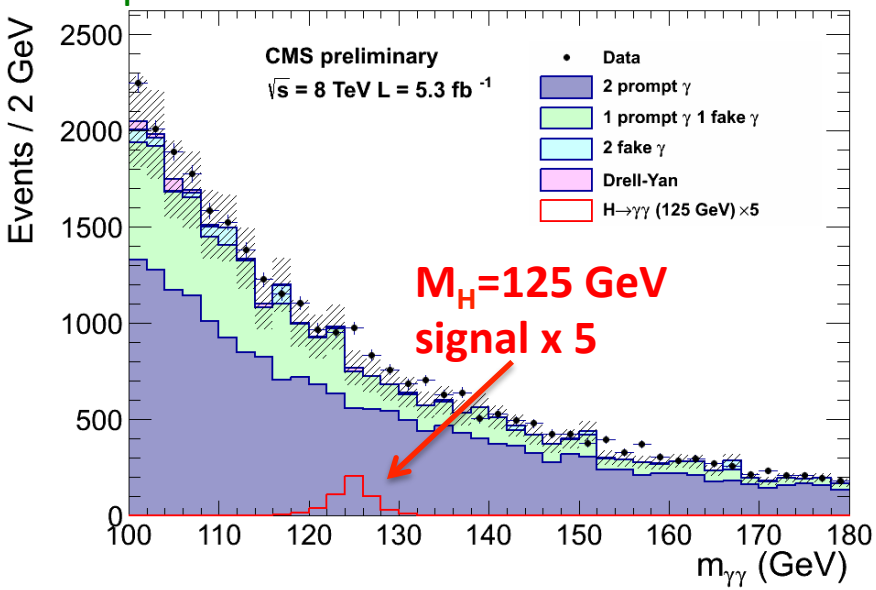
- Signature: small mass peak over **large** smoothly decreasing background
  - Irreducible: 2γ QCD production
  - Reducible: γ+jet with 1 additional fake photon, DY with electrons faking photons
- Studied mass range: 110-150 GeV

BG MC only used for optimization

7 TeV dataset

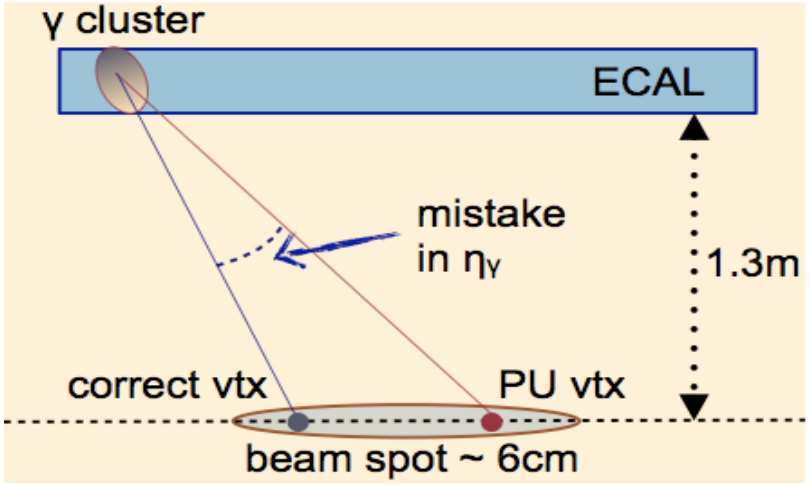


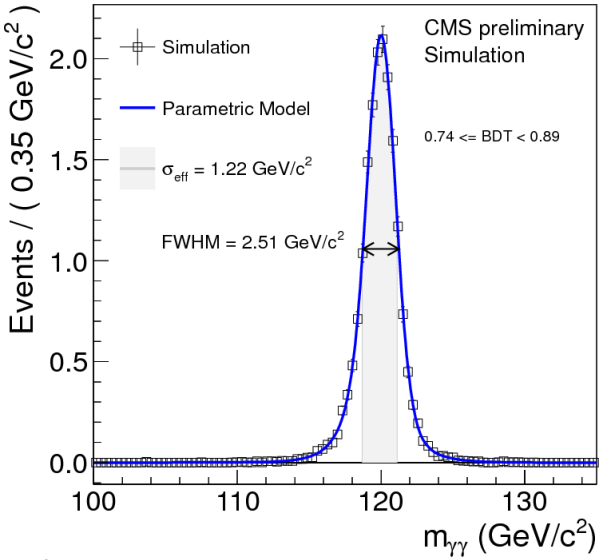
8 TeV dataset



Ingredients of the Analysis

- **Photon Selection**
  - MVA, based on isolation, shower shape and electron rejection
  - Also cut-based optimized in different categories with different BG levels
    - Barrel/endcap
    - Converted/unconverted identified with shower shape in ECAL
- **Primary Vertex Identification**
  - Primary Vertex is identified using tracks from recoiling jets and underlying event + conversion
  - Found correct in ~80% of cases for pileup in analyzed sample
- **Mass resolution**
  - Most important aspect of analysis
  - ECAL response calibrated with $\pi^0 \rightarrow \gamma\gamma$, $W \rightarrow e\nu$ (E/p), $Z \rightarrow ee$
  - Laser corrections measuring transparency loss are applied





σ_M/M ~ 1%

H→γγ analysis

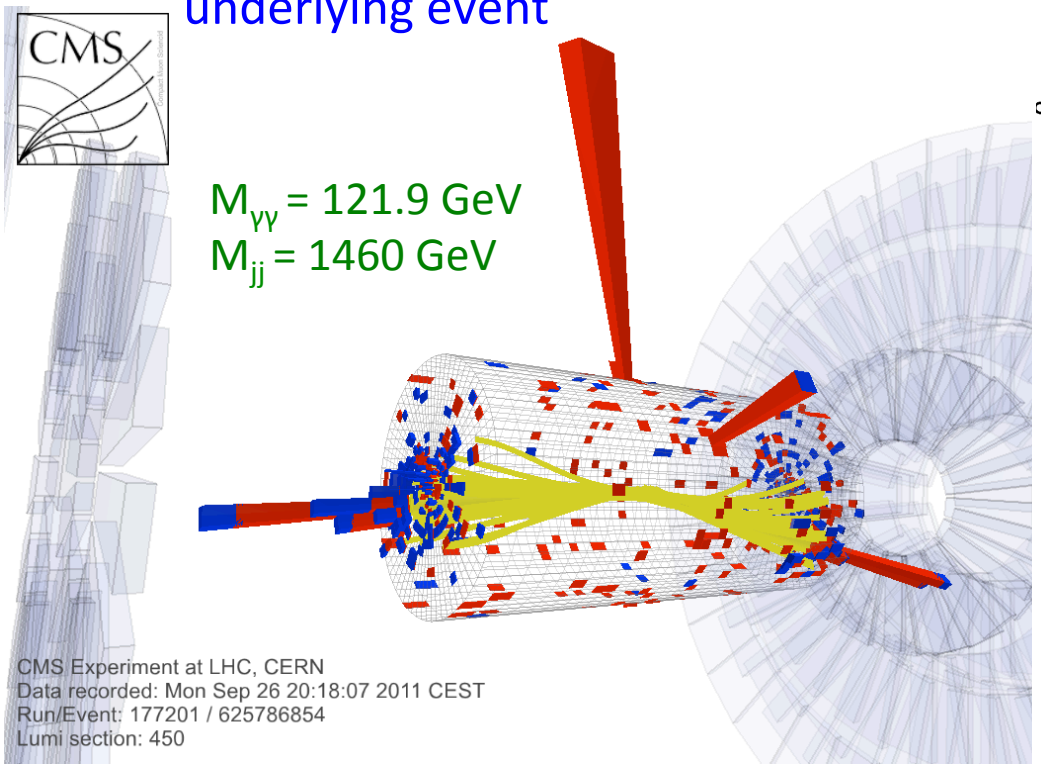
- 4 non-VBF event classes split based on a diphoton Boosted Decision Tree (BDT) classifier output + dijet tag classes
- BG is estimated by fitting to a polynomial in the full mass range (3rd to 5th order)
  - Possible BG bias is always less than 20% of the statistical error
  - Different BG estimation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

Event categories		SM Higgs boson expected signal ($m_H = 125$ GeV)							Background $m_{\gamma\gamma} = 125$ GeV (events/GeV)
		Events	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV, 5.1 fb^{-1}	BDT 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	BDT 1	16.3	88%	6%	6%	–	1.26	1.08	37.5 ± 1.3
	BDT 2	21.5	92%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	BDT 3	32.8	92%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	72%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV, 5.3 fb^{-1}	BDT 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	BDT 1	21.0	87%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	BDT 2	30.2	92%	4%	4%	–	1.94	1.55	115.2 ± 2.3
	BDT 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

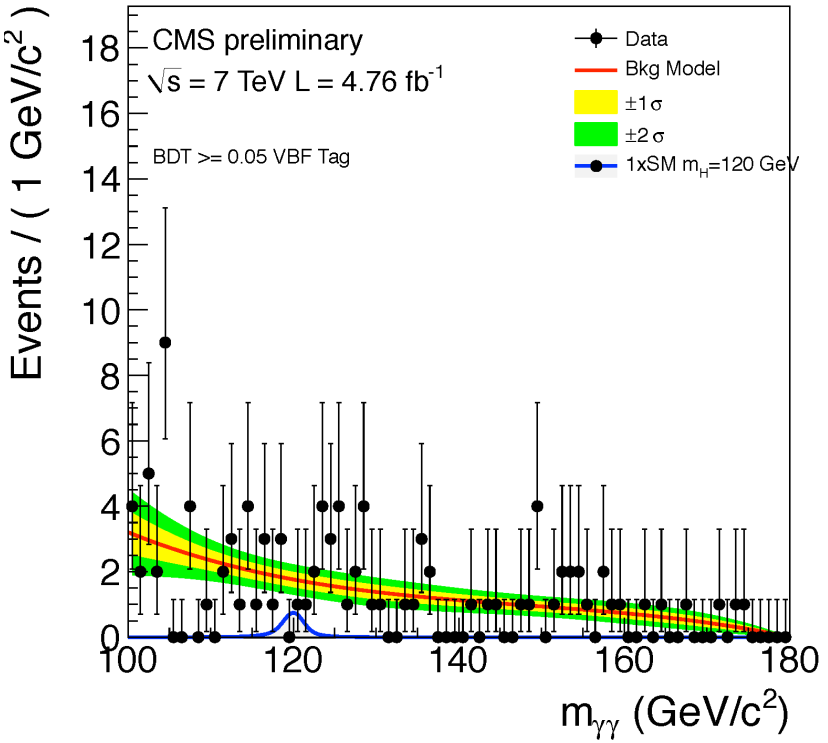
Resolution in 2012 somewhat worse that 2011 because for now used prompt-reco

H→γγ VBF analysis

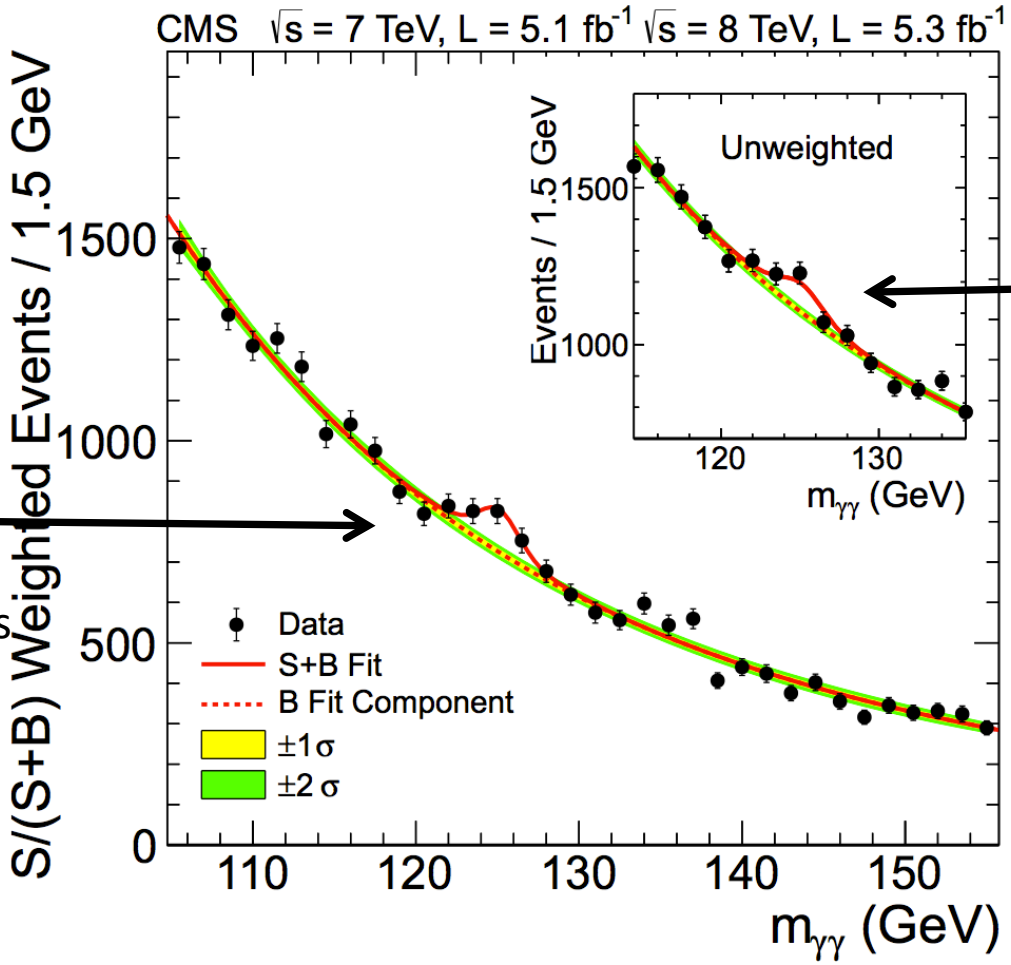
- Exclusive dijet tag improves sensitivity by ~10%
- Photon identification is the same
  - tighter lead photon E_t cut (E_t lead/$M_{\gamma\gamma}$ > 55/120)
- Dijet tag selection on dijet variables
  - exploits two additional VBF high p_T jets at large rapidity
- Contamination of gg-fusion ~25%, syst error 50-70% dominated by underlying event



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



H→γγ combined mass spectrum



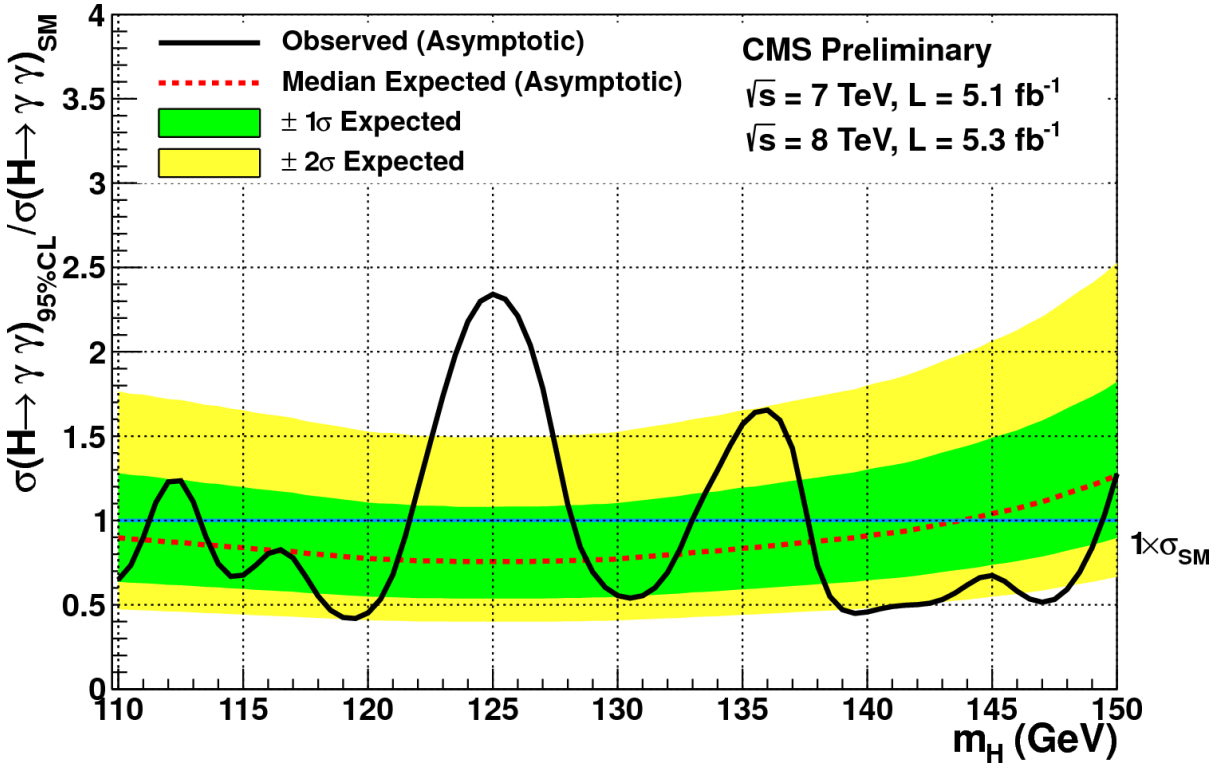
Weighed data events and BG model parametrizations

Unweighed data events and BG model parametrizations

- Sum of mass distributions for each event class, weighted by S/(S+B)
- B is integral of background model over a constant signal fraction interval

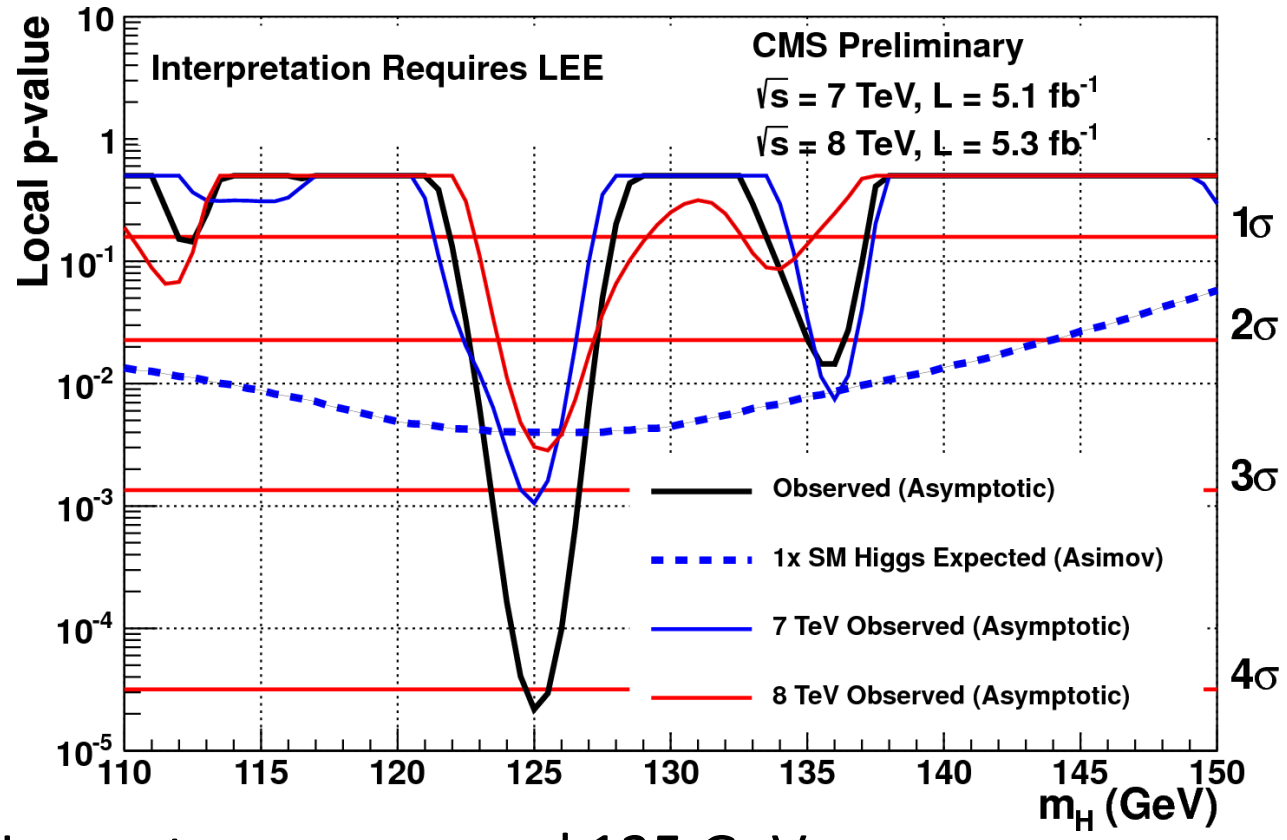
- This plot is not used in the analysis and it is for illustration only, it adds all event classes together

H→γγ results: exclusion



- Expected 95% CL exclusion: 0.76 x SM at 125 GeV
- Excluded at 95% CL:
  110.0-111.0, 113-123, 129-132, 138-149 GeV
- Cut based and cross check MVA analysis give consistent results

H→γγ results: p-values



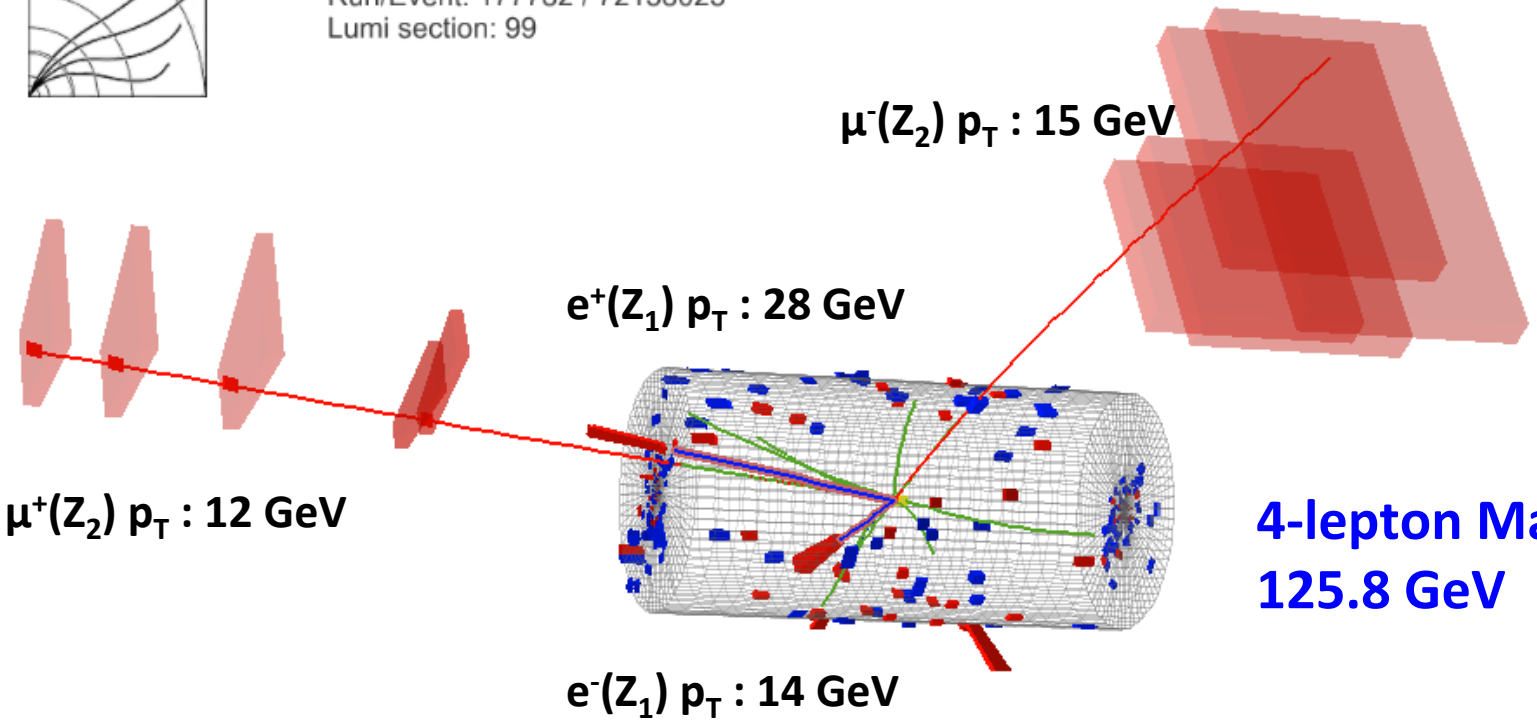
Similar Results from cut based And cross check MVA analysis (3.7 and 4.6 σ)

- Largest excess around 125 GeV
  - Local significance 4.1 σ
  - Global significance in 110-150 GeV 3.2 σ
  - Fitted σ/σ_{SM} at 125: 1.6 ± 0.5

H → ZZ → 4l (4μ, 4e, 2e2μ)

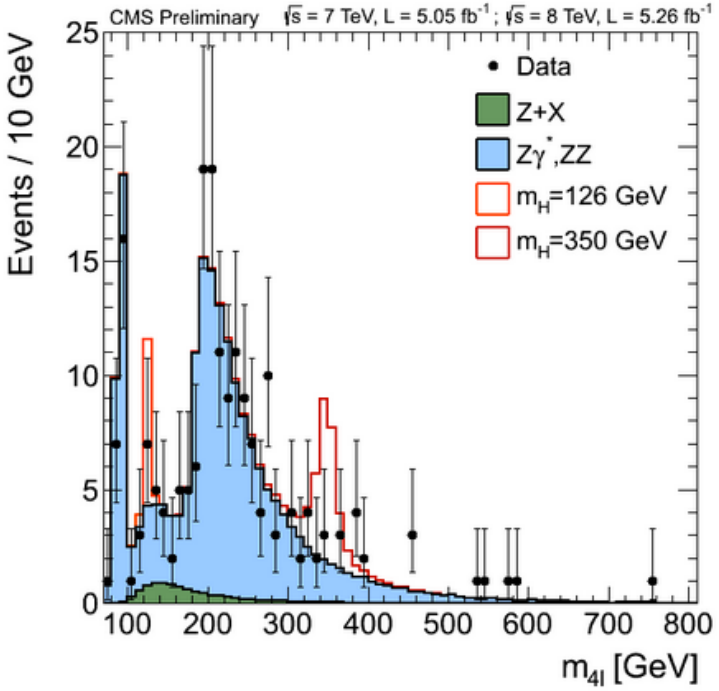
- Clean channel: 2 high mass pairs of opposite sign isolated electrons or muons coming from PV
- **Narrow mass peak**
  - Very good mass resolution 1-2 %
- Background
  - irreducible: ZZ
  - reducible: Z+jets, Zbb, tt, WZ
- Very small BR ~10^{-4} at 125 GeV

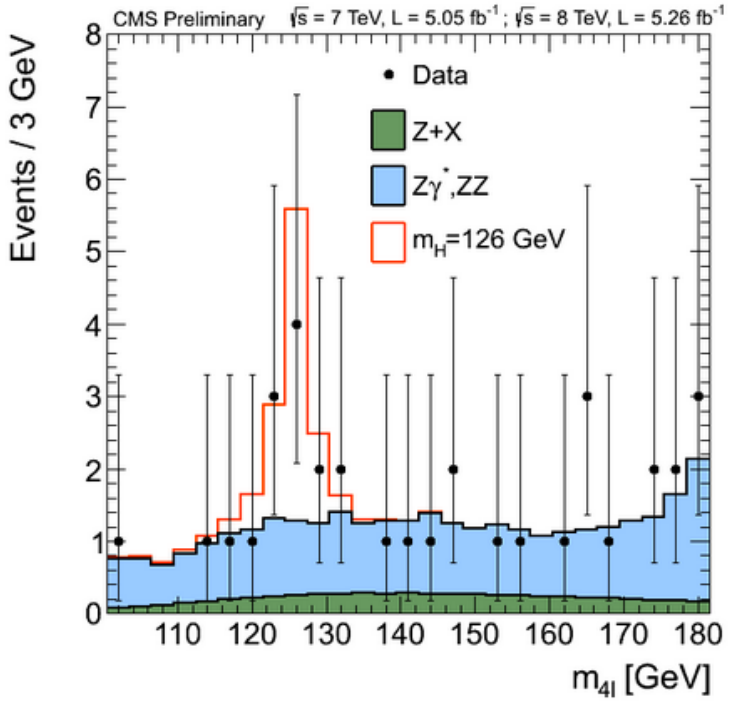
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 4 00:10:13 2011 CEST
Run/Event: 177782 / 72158025
Lumi section: 99



4-lepton Mass : 125.8 GeV

H → ZZ → 4l: candidates

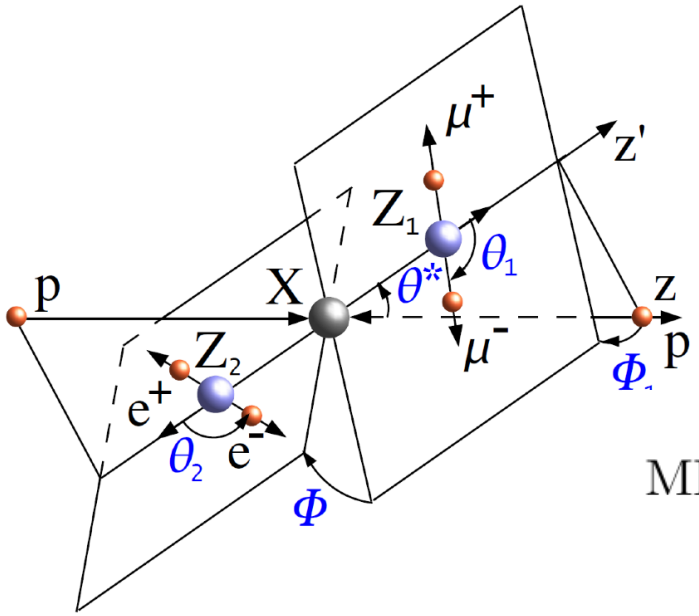




In 110-160 GeV
BG exp.: 20 ± 3
H(125): 7.6 ± 1.1
data: 21

Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
$Z + X$	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160$ GeV)	$3.9^{+1.1}_{-0.8}$	$6.6^{+0.9}_{-0.8}$	$9.5^{+2.0}_{-1.6}$	$20.0^{+3.2}_{-2.6}$
Observed ($110 < m_{4\ell} < 160$ GeV)	6	6	9	21
Signal ($m_H = 125$ GeV)	1.37 ± 0.44	2.75 ± 0.56	3.44 ± 0.81	7.56 ± 1.08
All backgrounds (signal region)	$0.71^{+0.20}_{-0.15}$	$1.25^{+0.15}_{-0.13}$	$1.83^{+0.36}_{-0.28}$	$3.79^{+0.47}_{-0.45}$
Observed (signal region)	1	3	5	9

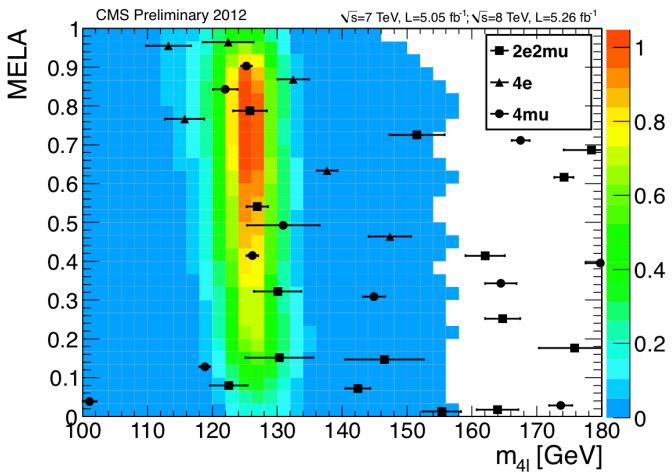
Use other kinematical variables: MELA

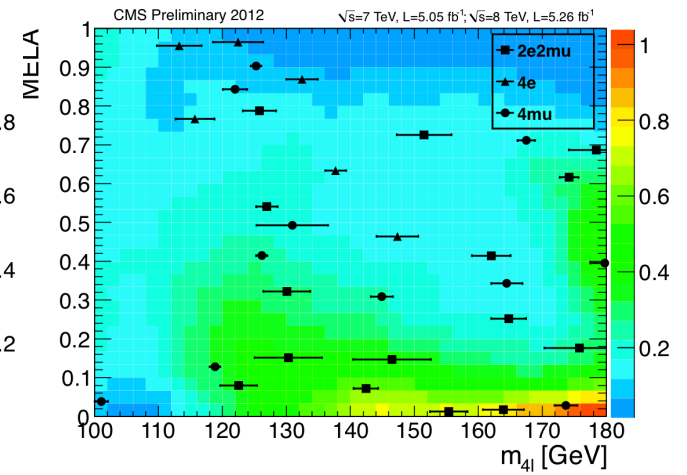


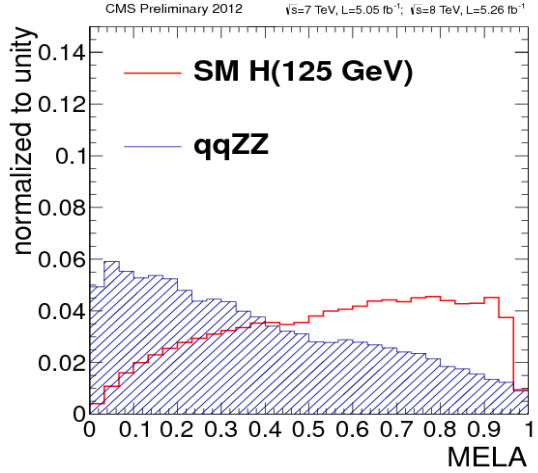
MELA: Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to ZZ background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

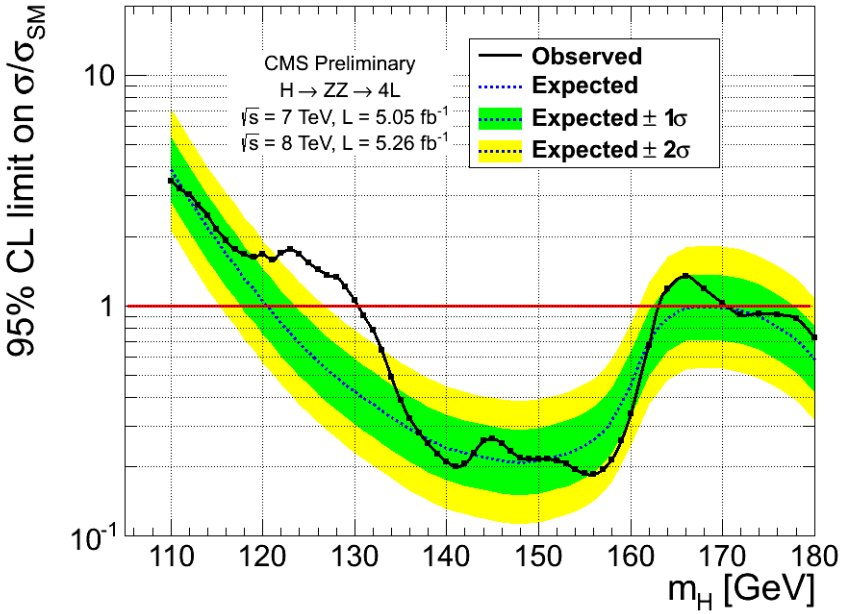
MELA Improves the sensitivity by ~20%
compared to using the mass alone

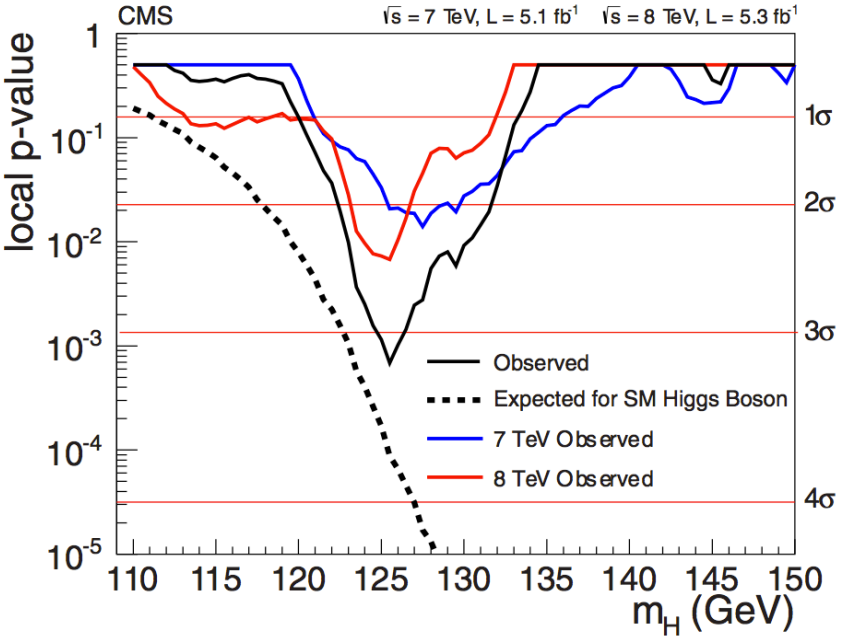






H → ZZ → 4l: exclusion and p-value



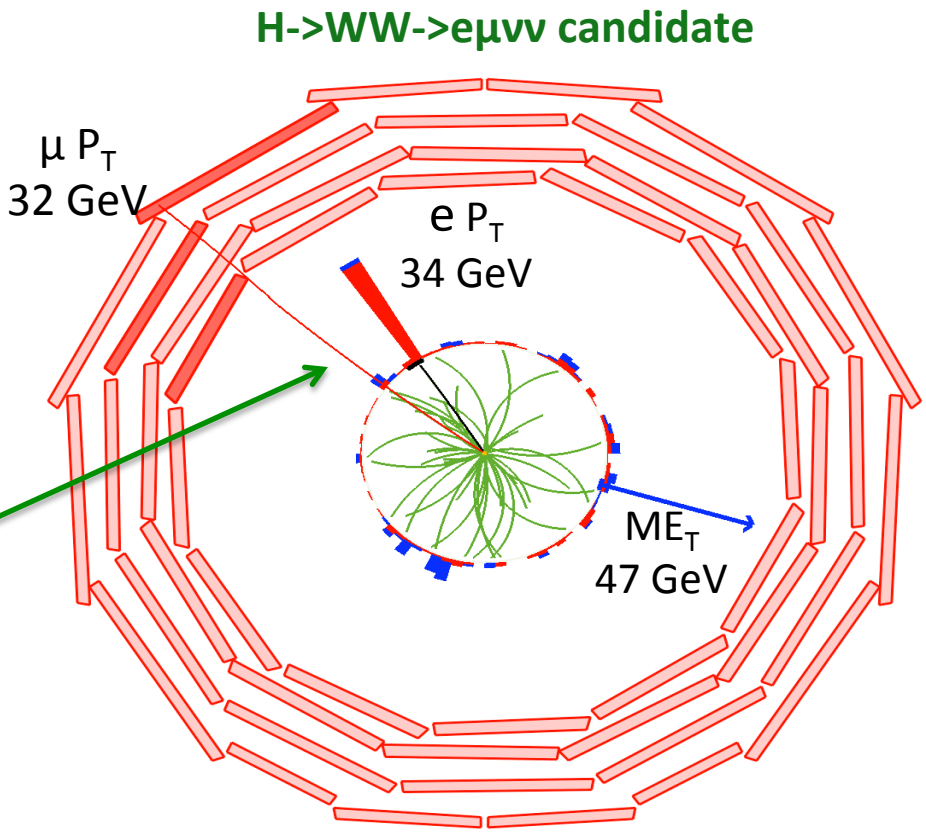


- Excess of events at 125.5 GeV
  - expected significance: 3.8 σ
  - observed significance: 3.2 σ

H→WW→lνlν

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

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



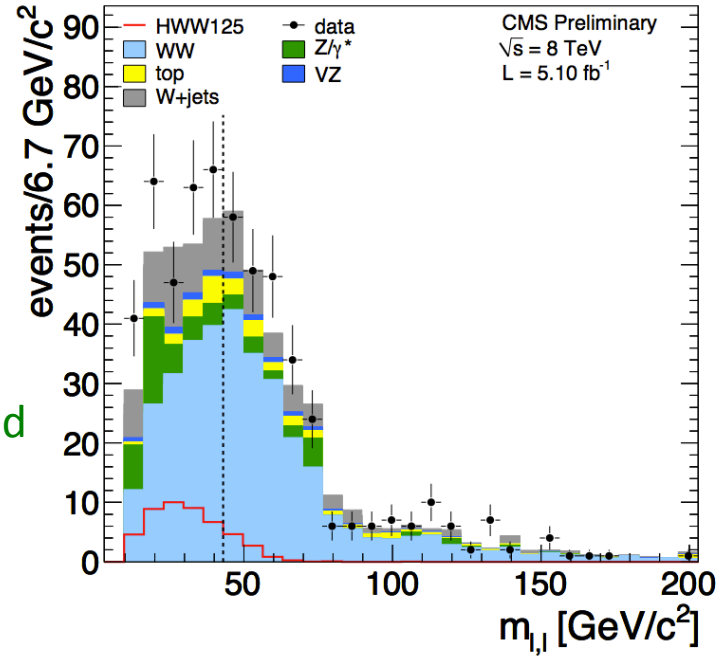
Analysis strategy for H→WW→lνlν

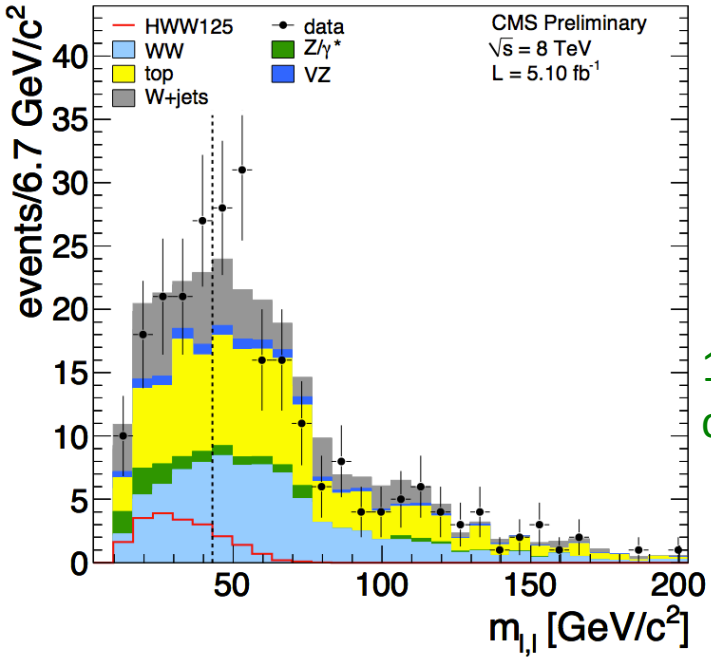
- Analysis is performed in exclusive jet multiplicities (0, 1, 2-jet bins) and flavour (ee, μμ, eμ)
  - Different Backgrounds
    - WW BG contributes more to the 0-jet bin
    - tt BG contributes more to the 1 and 2-jet bins
    - Z+jet and ZZ contribute more to same flavour (ee and μμ)
  - 2 jet bin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

- Two different analyses carried out:
  - Cut and count in 0, 1 and 2-jet bins
  - Multivariate in 0 and 1-jet bin (not yet for 2012 data)
  - Most sensitivity comes from the 0-jet eμ channel

2012 data: cut based analysis at 8 TeV

0-jet bin combined

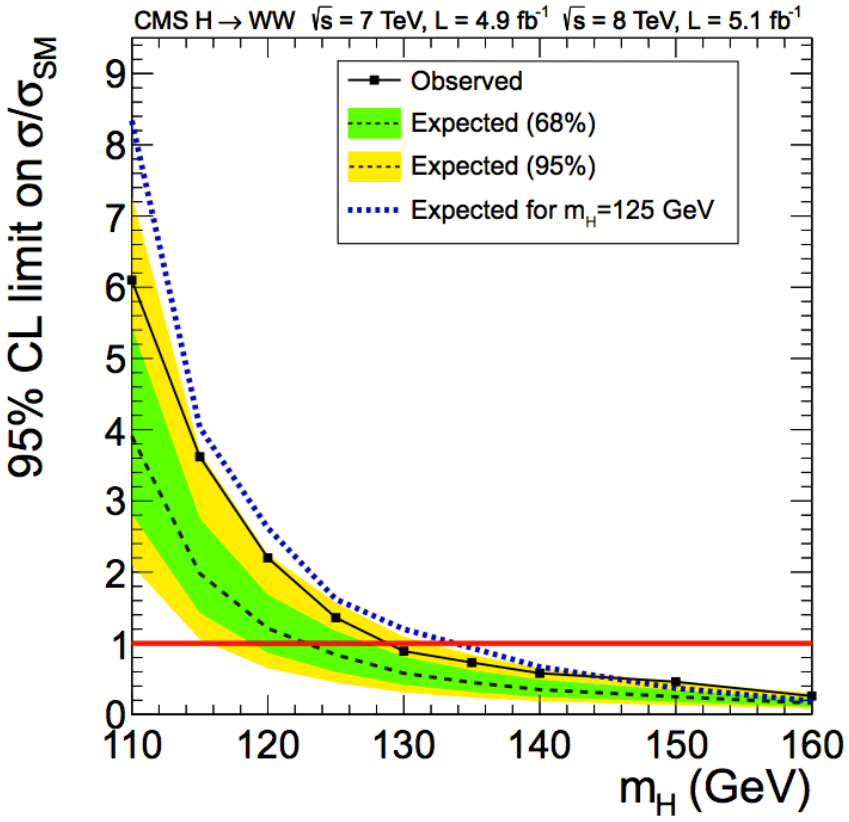




1-jet bin combined

Category:	0-jet eμ	0-jet $\ell\ell$	1-jet eμ	1-jet $\ell\ell$	2-jet eμ	2-jet $\ell\ell$
WW	87.6 ± 9.5	60.4 ± 6.7	19.5 ± 3.7	9.7 ± 1.9	0.4 ± 0.1	0.3 ± 0.1
$WZ + ZZ + Z\gamma$	2.2 ± 0.2	37.7 ± 12.5	2.4 ± 0.3	8.7 ± 4.9	0.1 ± 0.0	3.1 ± 1.8
Top	9.3 ± 2.7	1.9 ± 0.5	22.3 ± 2.0	9.5 ± 1.1	3.4 ± 1.9	2.0 ± 1.2
W + jets	19.1 ± 7.2	10.8 ± 4.3	11.7 ± 4.6	3.9 ± 1.7	0.3 ± 0.3	0.0 ± 0.0
$W\gamma^{(*)}$	6.0 ± 2.3	4.6 ± 2.5	5.9 ± 3.2	1.3 ± 1.2	0.0 ± 0.0	0.0 ± 0.0
All backgrounds	124.2 ± 12.4	115.5 ± 15.0	61.7 ± 7.0	33.1 ± 5.7	4.1 ± 1.9	5.4 ± 2.2
Signal ($m_H = 125$ GeV)	23.9 ± 5.2	14.9 ± 3.3	10.3 ± 3.0	4.4 ± 1.3	1.5 ± 0.2	0.8 ± 0.1
Data	158	123	54	43	6	7

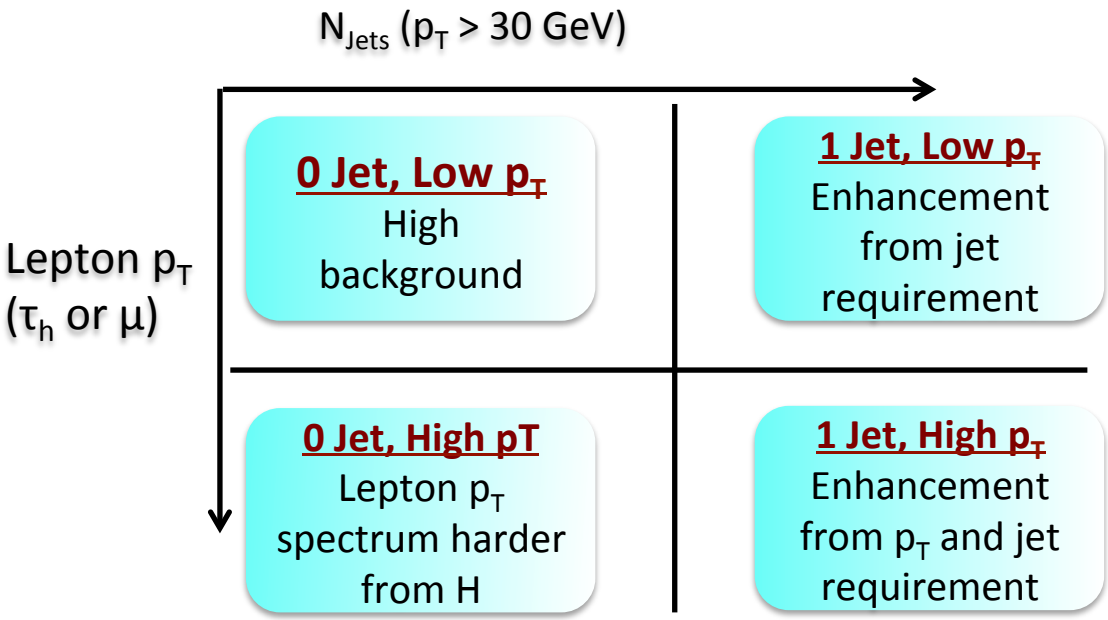
H→WW→lvlv: results



- Broad excess, as expected from resolution, between 110 and 140 GeV
- P-value at 125 GeV
  - expected 2.4 σ
  - observed 1.6 σ

H→ττ

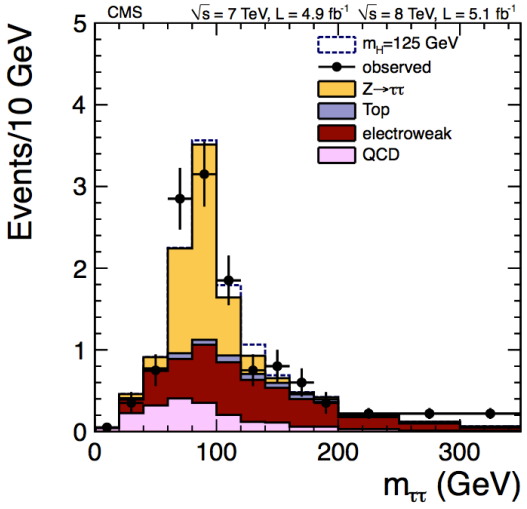
- **No narrow mass peak** (σ_M 15-20%)
- Search performed in τ-pair final states: $\mu\tau_h$, $e\tau_h$, $e\mu$, $\mu\mu$
- For each final state analysis divided into 5 categories: mass resolution, S/B
- All categories are fitted simultaneously
- ττ channel is also important for MSSM



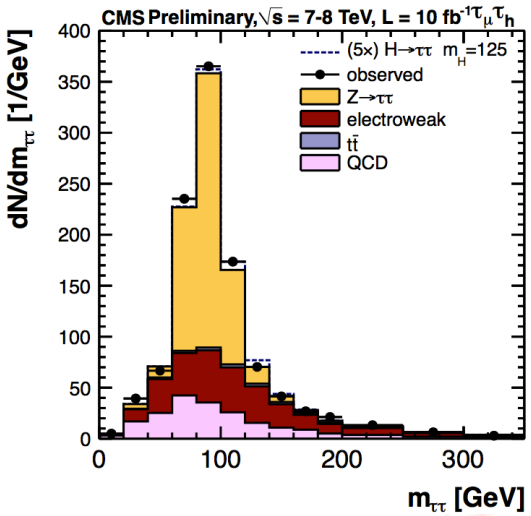
VBF
2 jets, no jets in rapidity gap
MVA based selection

H→ττ: analysis

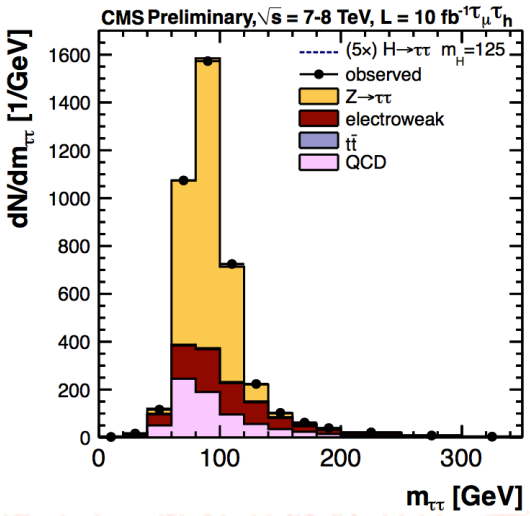
$\mu\tau_h$ VBF



$\mu\tau_h$ 1-jet



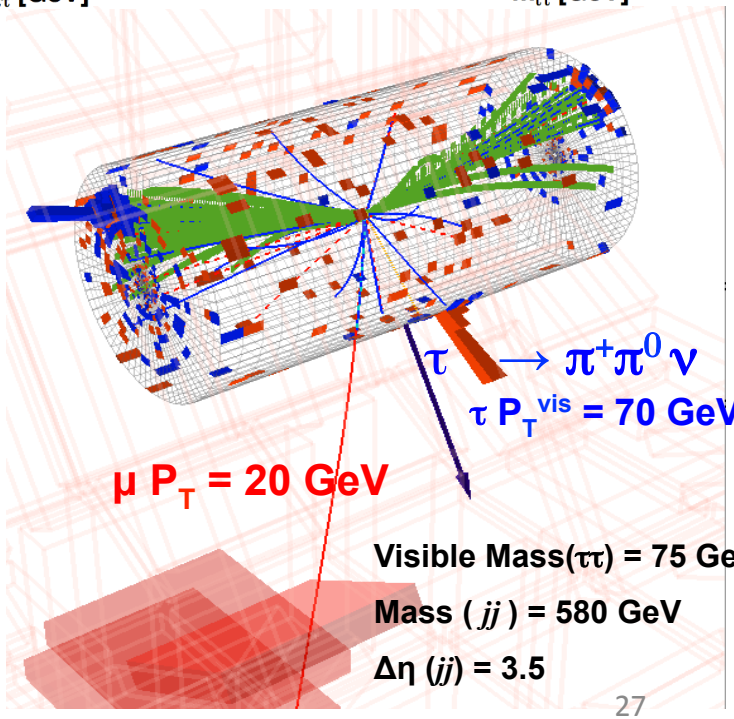
$\mu\tau_h$ 0-jet



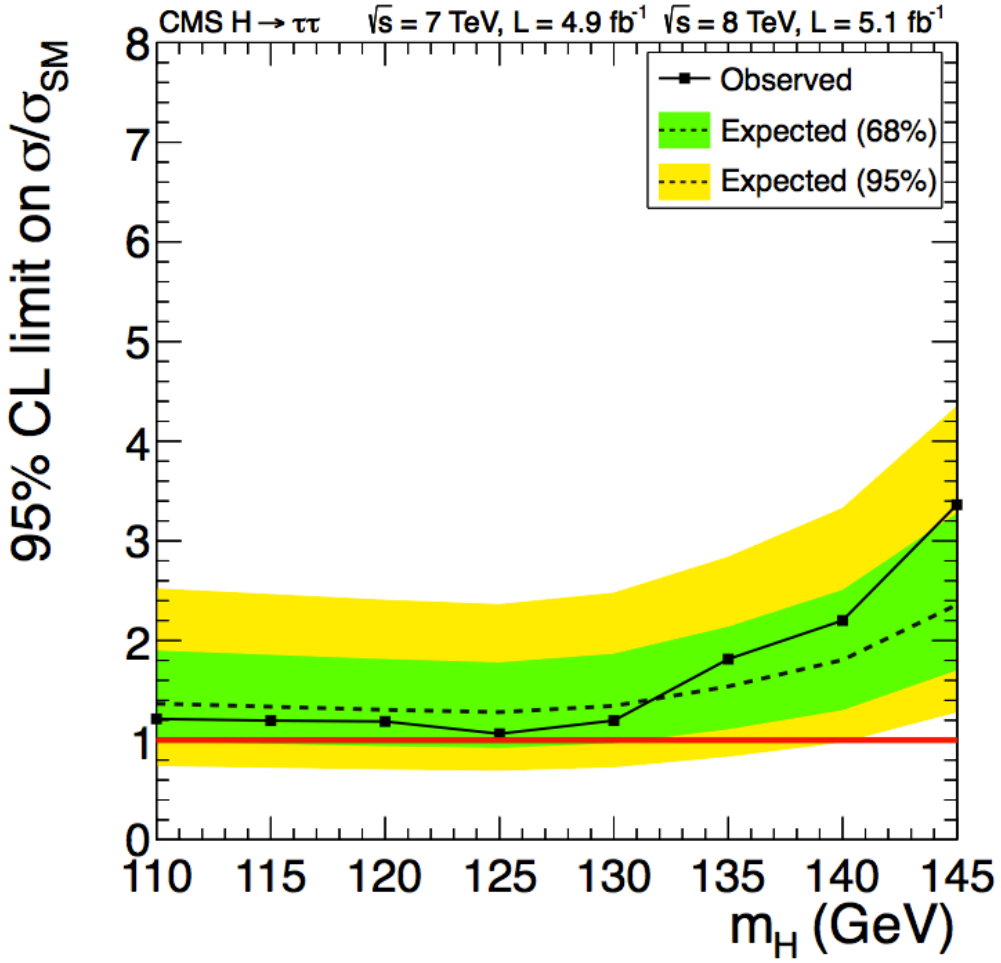
Most sensitive is the VBF channel

Subchannel	$e\tau_h$	$\mu\tau_h$	$e\mu$	$\mu\mu$
$Z \to \tau\tau$	53 ± 5	100 ± 9	56 ± 12	5.3 ± 0.4
QCD	35 ± 7	41 ± 9	7.4 ± 1.4	–
W+jets	46 ± 10	72 ± 15	–	–
Z+jets	13 ± 2	2.5 ± 0.6	–	–
$Z \to \mu\mu$	–	–	–	70 ± 8
$t\bar{t}$	7.0 ± 1.7	14 ± 3	24 ± 2	6.7 ± 1.5
Dibosons	1.2 ± 0.9	2.9 ± 2.1	11 ± 2	2.4 ± 0.9
All backgrounds	156 ± 13	233 ± 20	99 ± 13	85 ± 9
Signal ($m_H = 125$ GeV)	4.3 ± 0.6	7.7 ± 1.1	3.5 ± 0.4	0.8 ± 0.1
Data	142	263	110	83

gg-fusion fraction of signal 30-40%



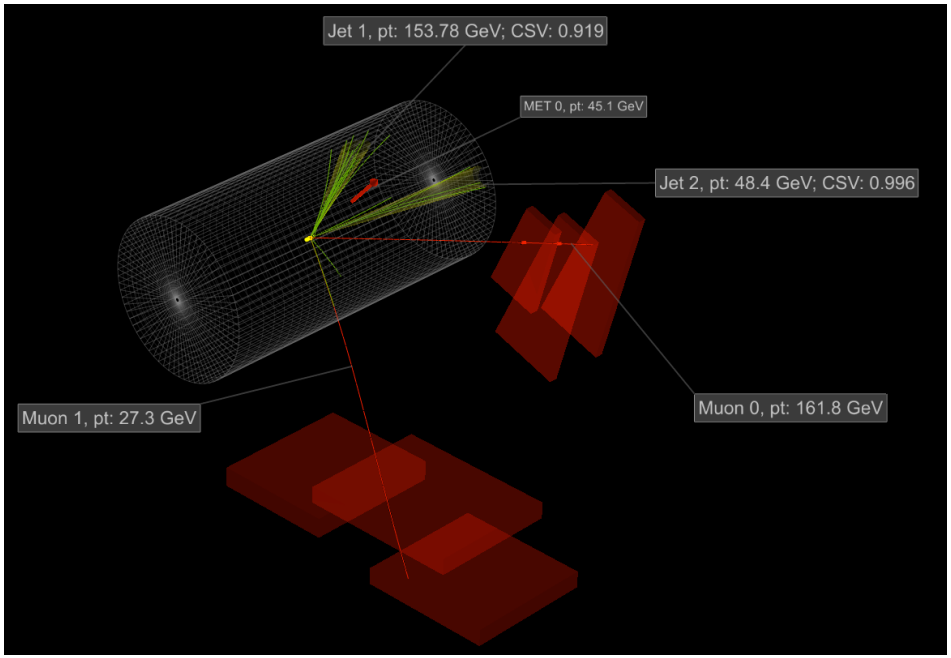
H→ττ: results



- No excess at 125 GeV:
  - Expected 1.4 σ
  - Measured a slightly negative value of μ

H→bb channel (VH)

- QCD BG too large, needs additional tag
- Exploit VH associated production with W and Z decaying leptonically
  - W→e,μ, Z→ee,μμ,νν

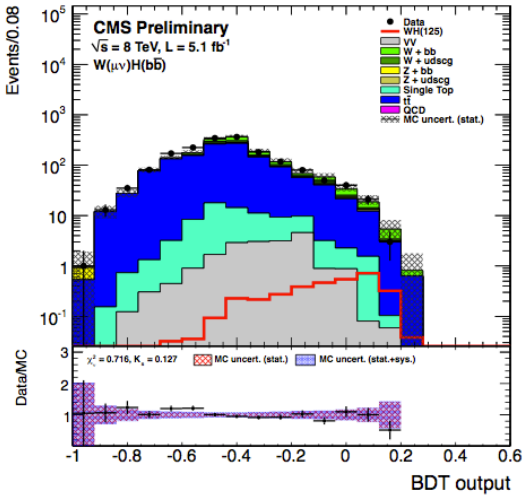


- Require boosted bb system
  - p_T^{bb}>50(120) GeV for ZH with Z→ee,μμ (others)
  - Split into two categories (low and high p_T^{bb})
- Improved mass resolution with regression: 8-9%

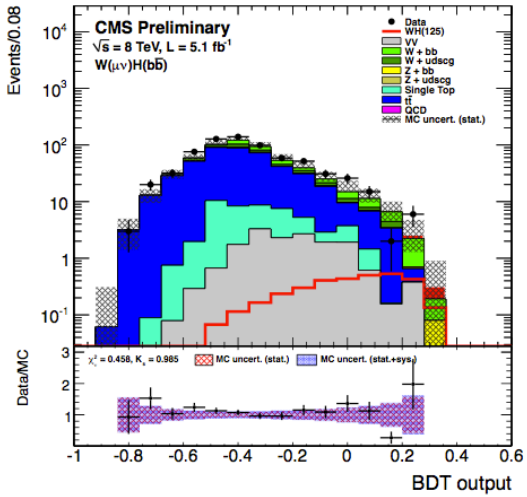
H→bb: MVA shape analysis

- Use shape analysis with MVA discriminator with input variables: jet kinematic variables, b-tag variables, …

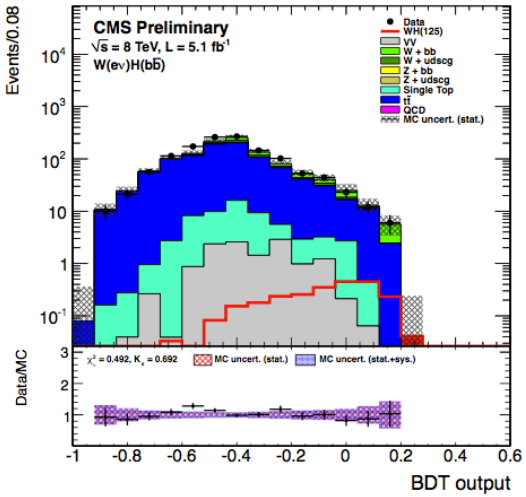
W->μν
Low p_T^{bb}



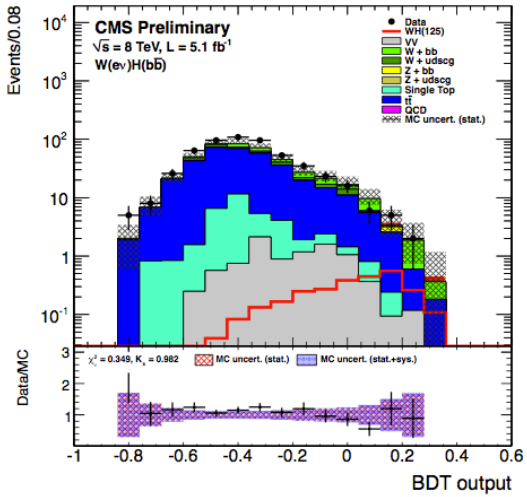
W->μν
High p_T^{bb}



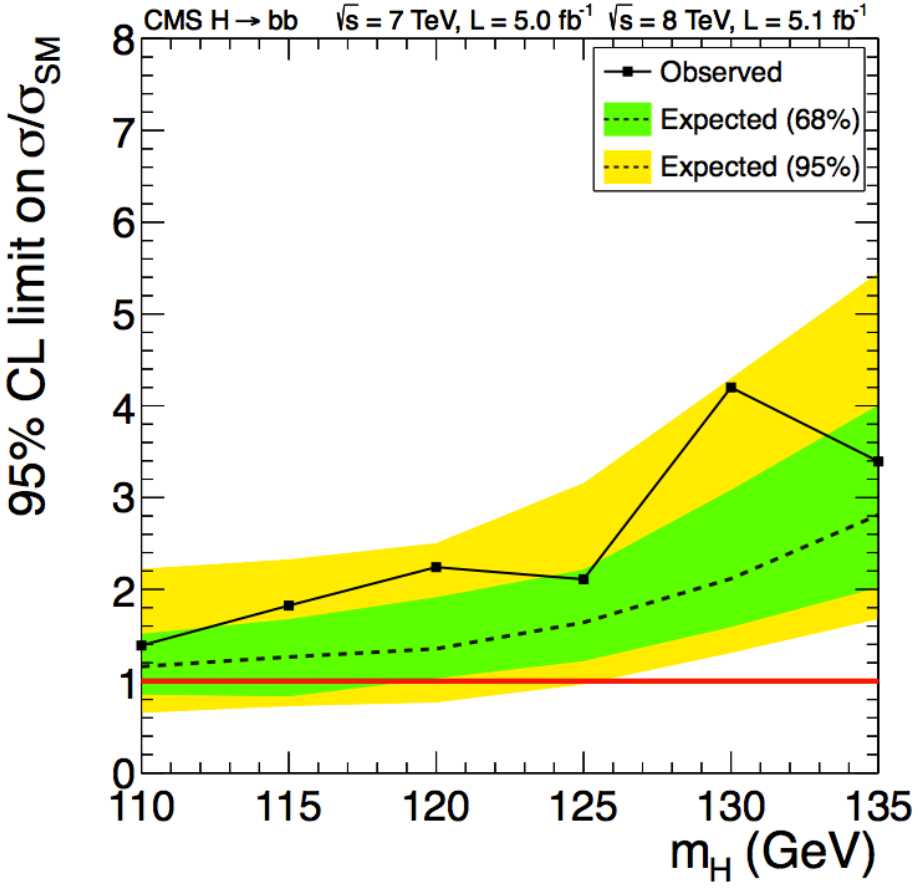
W->ev
Low p_T^{bb}



W->ev
High p_T^{bb}



H→bb: results



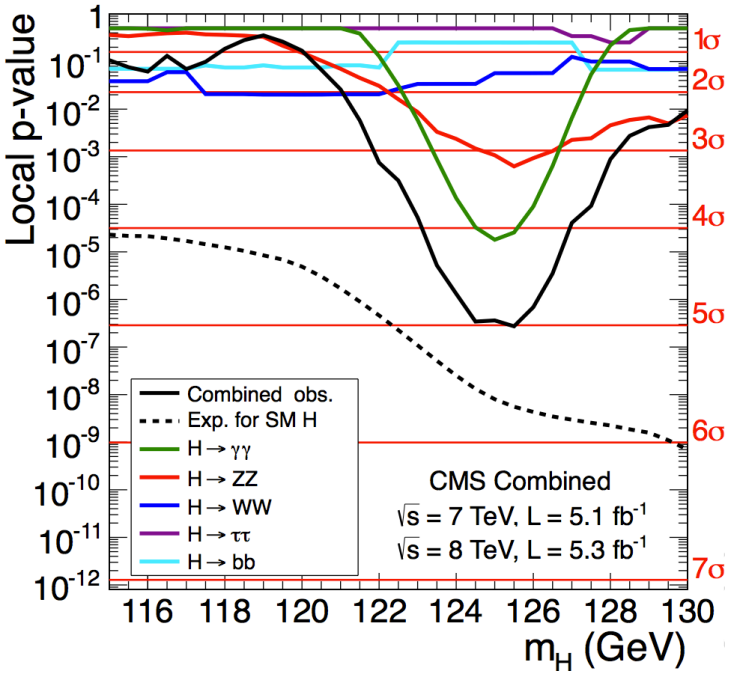
- Very small excess at 125 GeV:
  - Expected 1.9 σ
  - Observed 0.7 σ

Combined results

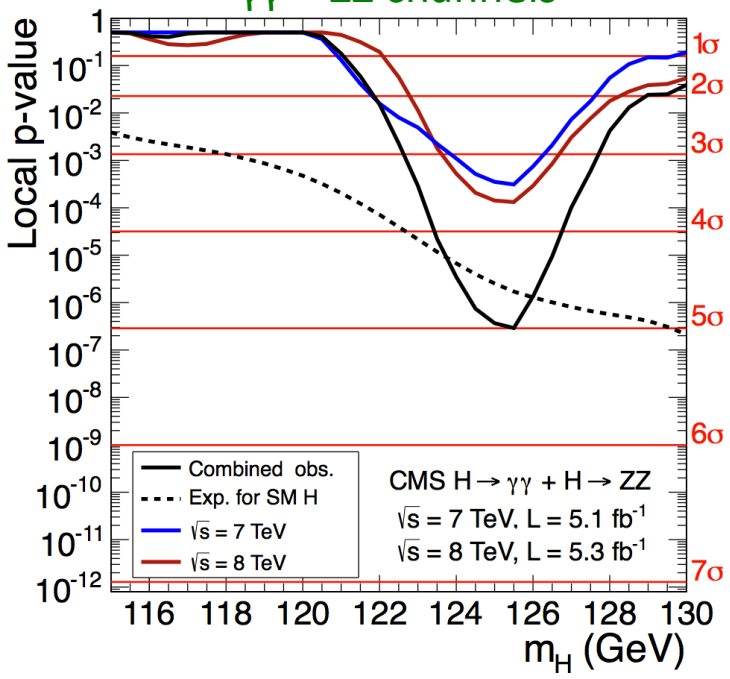
- The 5 channels are combined
- For exclusion and significance, SM cross sections and branching ratios are assumed with their theoretical uncertainties and an overall signal strength multiplier μ is fit
- Method for CL calculation is LHC-type CLs
  - Asymptotic CLs with profiled likelihood test statistics and log-normal treatment of nuisance parameters
  - ATL-PHYS-PUB/CMS NOTE 2011-11, 2011/005, (2011)

Significance at 125 GeV

All five channels



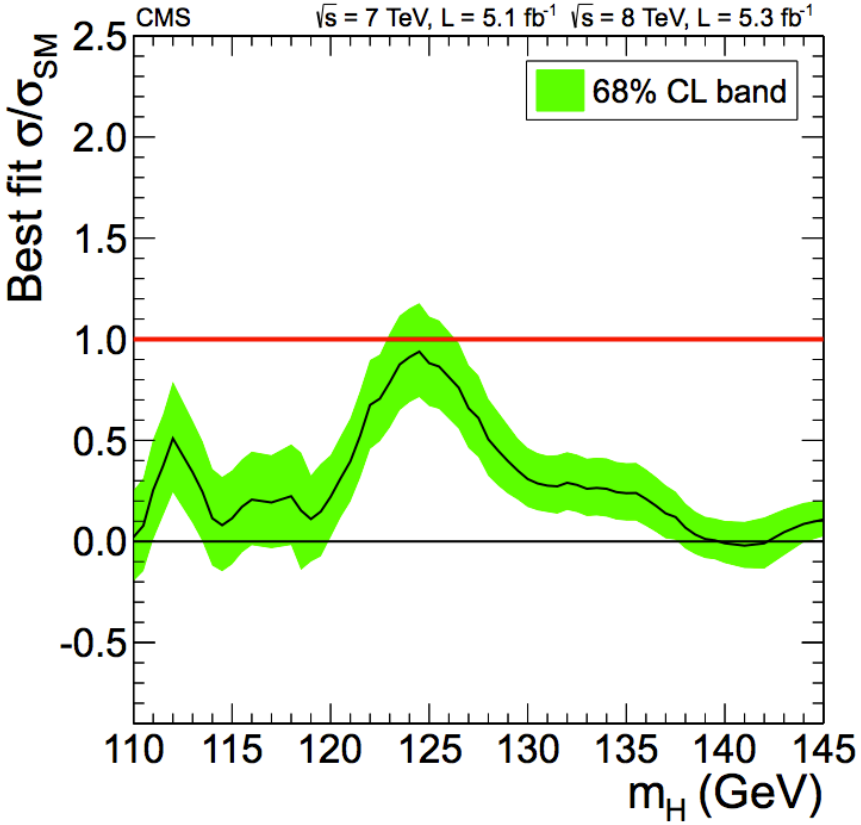
γγ + ZZ channels



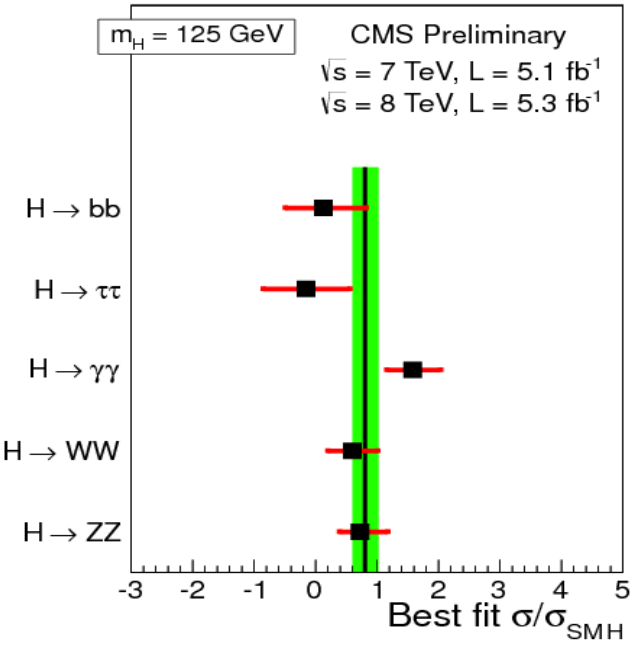
Local excess significance of different combinations

Decay mode or Combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau$ + bb	2.4	0.4
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

Combined signal strength



Comparison of channels for M_H=125 GeV



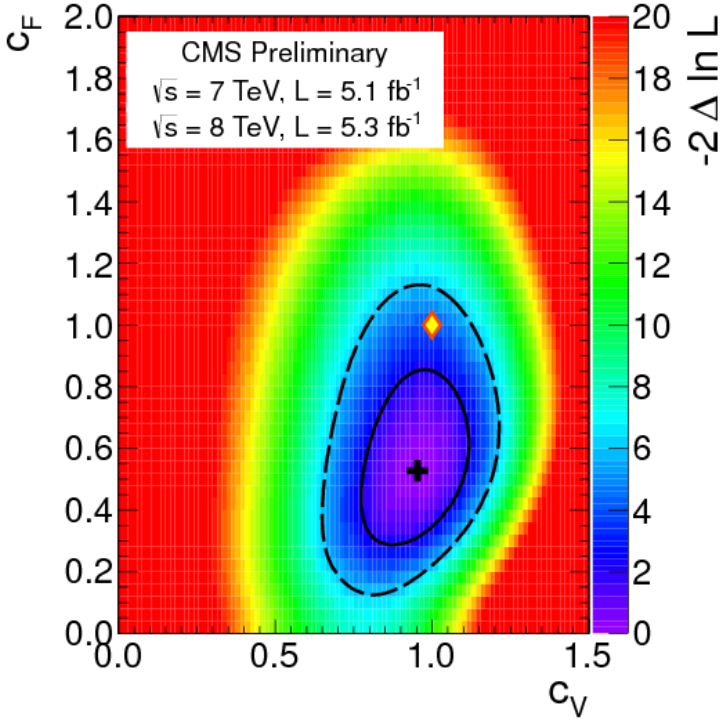
- The fitted σ of the excess near 125 GeV is consistent with the SM scalar boson expectation:
  - $\sigma/\sigma_{SM} = 0.87 \pm 0.23$
- Signal strengths in different channels are consistent
- Common cross section theoretical errors contribute to all measurements
  - Dominated by 15% error on gg-fusion where applicable

Couplings

- First measurement of new boson couplings when interpreted as a Higgs boson
- Scale vectorial and fermionic couplings by C_V and C_F (use LO)

Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4/C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^4/C_F^2$

HIG-12-020

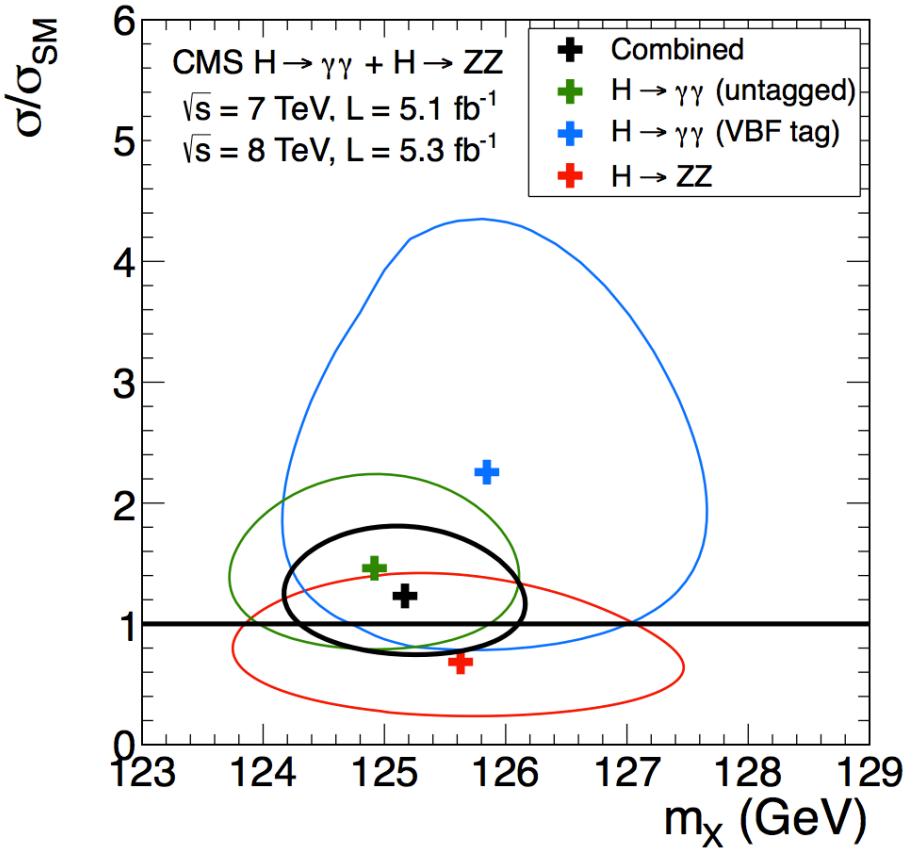


- Best fit: $(C_V, C_F) = (1, 0.5)$
- Consistent within 2σ with the SM Higgs boson

Solid contour: 68% CL
Dashed contour: 95% CL

- From inclusive ZZ→4l and WW→2l2v
  - $R_{WW/ZZ} = 0.9^{+1.1}_{-0.6}$

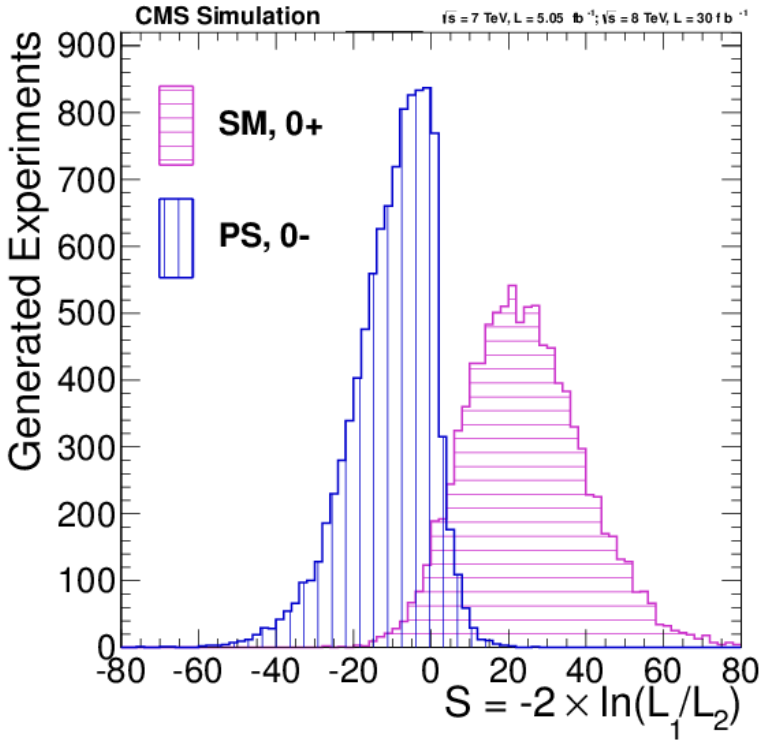
Mass of the observed new boson



- $M_X = 125.3 \pm 0.4$ (stat.) $\pm$ 0.5 (syst.) GeV
  - To reduce model dependence, allow for free cross section in three channels and fit for the common mass:
  - Measurement dominated by H→γγ

Spin-parity measurements

- Not yet sensitive with the analyzed dataset
- Only result is that the observation of γγ decay, excludes the spin 1 hypothesis
- Spin 2 and CP can be probed using angular distributions
- No public results yet using data



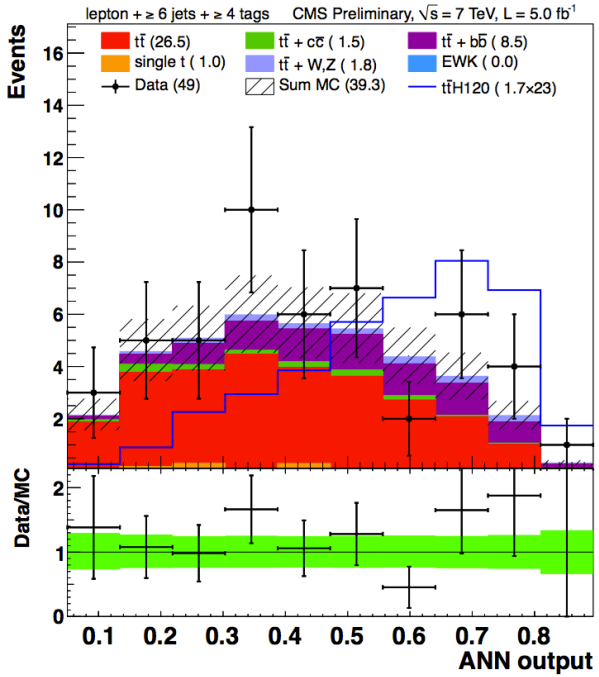
- **H->ZZ** projections
- Using discriminator similar to MELA we can distinguish between scalar and pseudo-scalar at 3 σ level with 30 fb^{-1} at 8 TeV, assuming SM cross section
- Other channels being studied

H→bb channel (ttH)

- First results on ttH with H→bb – directly probes ttH coupling
- Use semileptonic and dilepton tt decays
  - ttH→lvjjbb and ttH→lvlvbb
- Shape analysis using MVA (Neural Network) with simultaneous fit of different jet and b-tag multiplicities

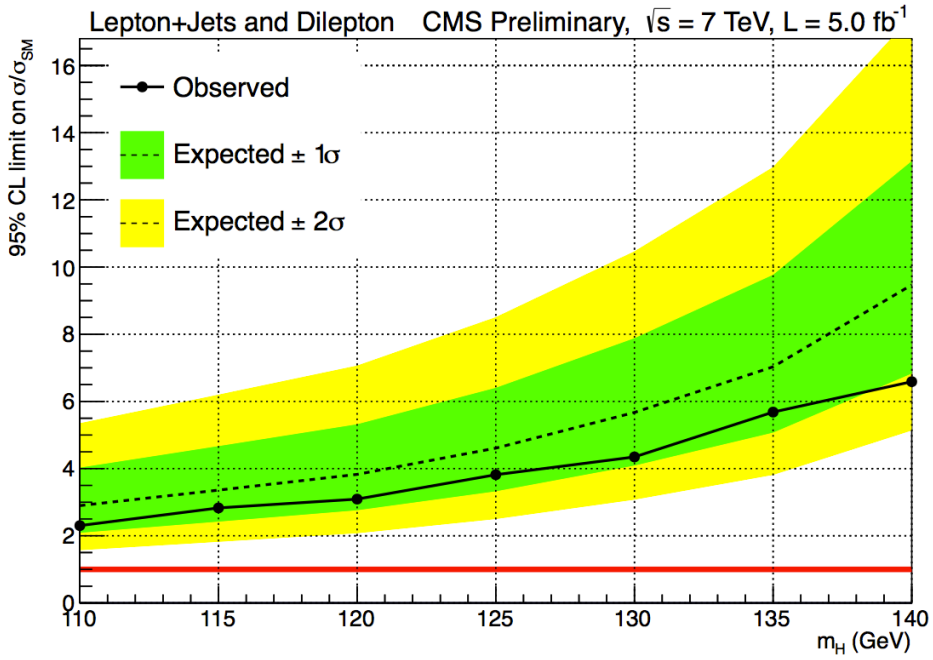
HIG-12-025

6 jet, ≥4 b-tag



Exclusion using 2011 dataset at 7 TeV

No excess: exp(obs) limit at $M_H(125) = 4.6(3.8)$

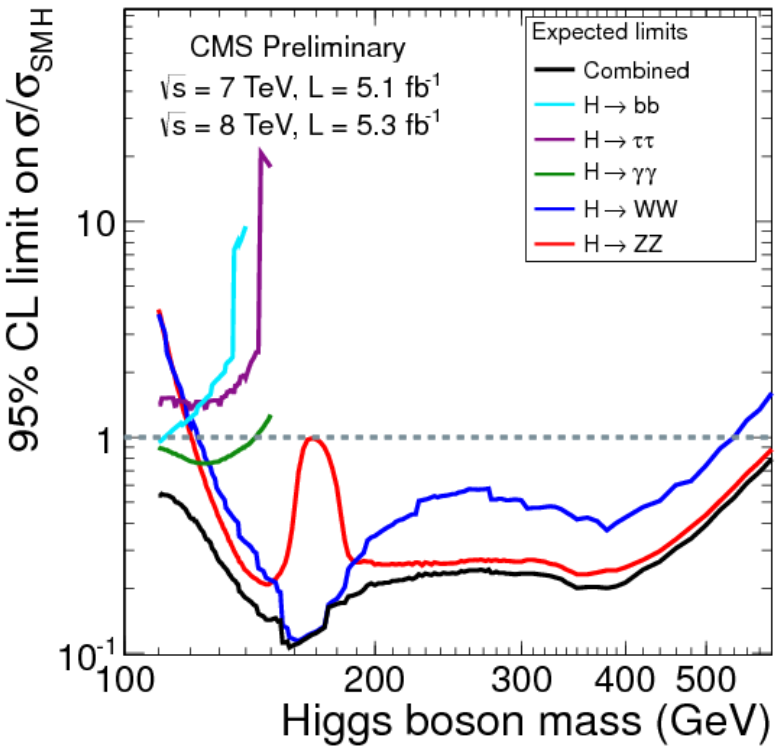


High mass: exclusion in 110 - 600 GeV

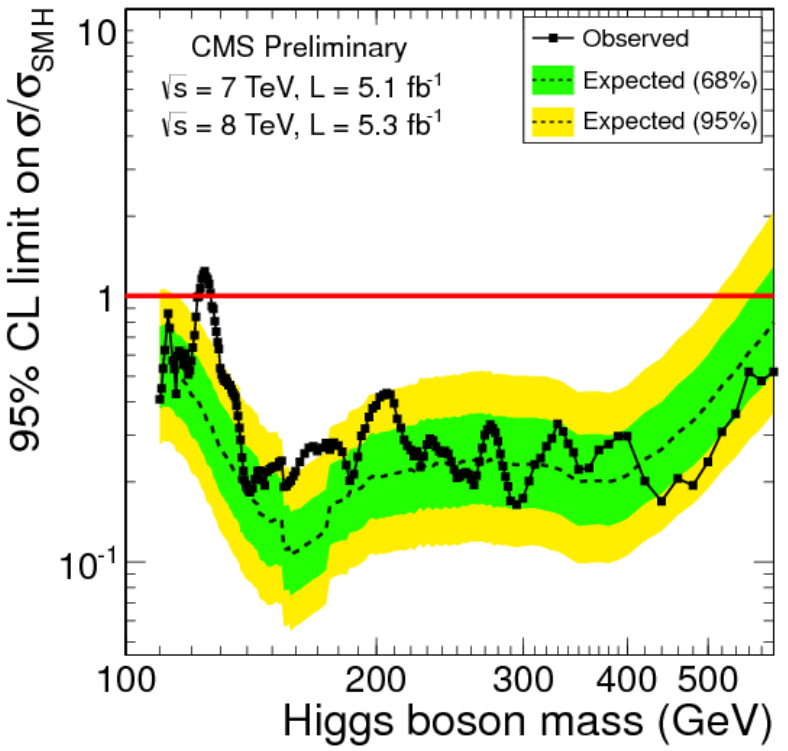
HIG-12-020

- High mass: WW and ZZ decays
  - add WW→lνqq, ZZ→2l2ν, ZZ→2l2q, ...

Expected in different channels



Expected and observed combined



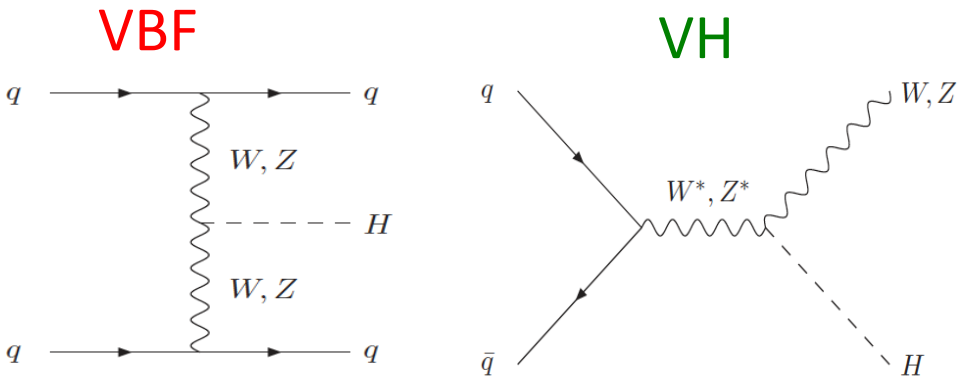
- SM Higgs boson excluded
  - at 95% CL in the mass range: 110 -122.5, 127 – 600 GeV
  - at 99% CL in: 110-112, 113-121.5, 128 – 600 GeV

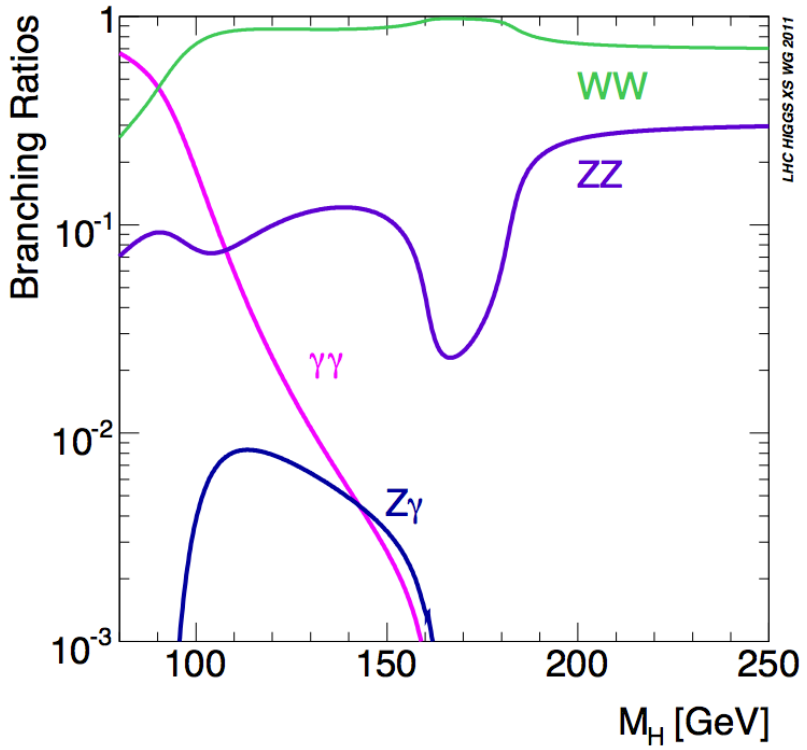
BSM Higgs

- Modified SM
  - Fermiophobic Higgs
  - SM4 – SM with 4^{th} fermion generation
- MSSM
  - neutral Higgs bosons - decays into μμ, ττ and bb
  - charged Higgs bosons – decays into τν
- NMSSM
  - low mass pseudo-scalar – decays into μμ
- See-saw models
  - doubly charged Higgs

Search for a Fermiophobic Higgs boson

- Fermiophobic (FP) Higgs boson only couples to vector bosons
- gg-fusion and tt-fusion not allowed at tree level
- FP Higgs only produced in VBF and VH
- No bb and ττ decays. WW, ZZ and γγ BR enhanced at low mass
- Exclusive VBF searches and VH searches

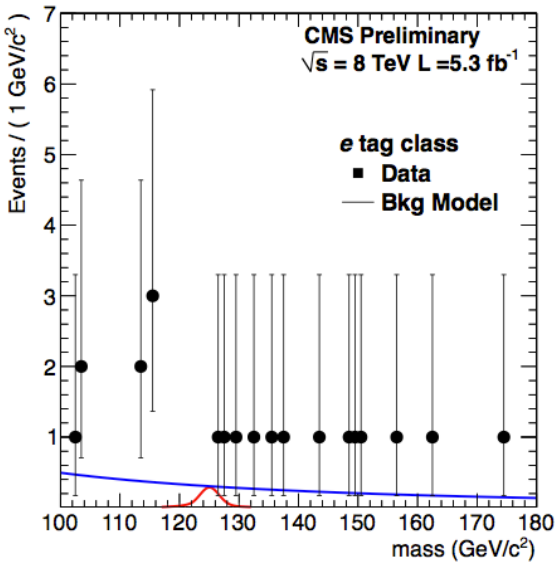




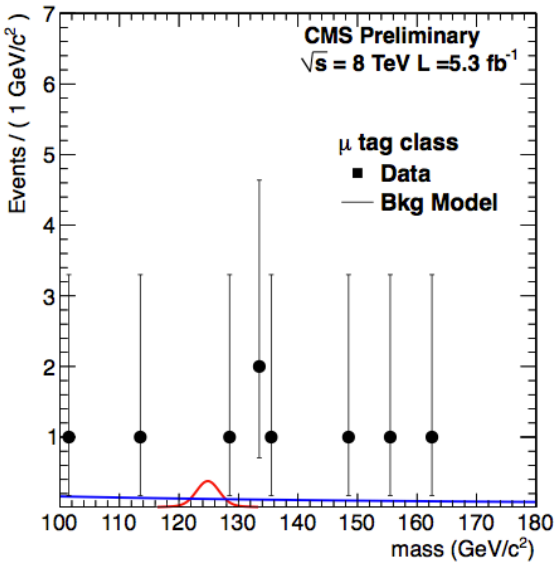
H→γγ FP analysis

- VBF as in SM search
- Also search for VH: two photons plus e or μ or MET (not yet included in SM search)

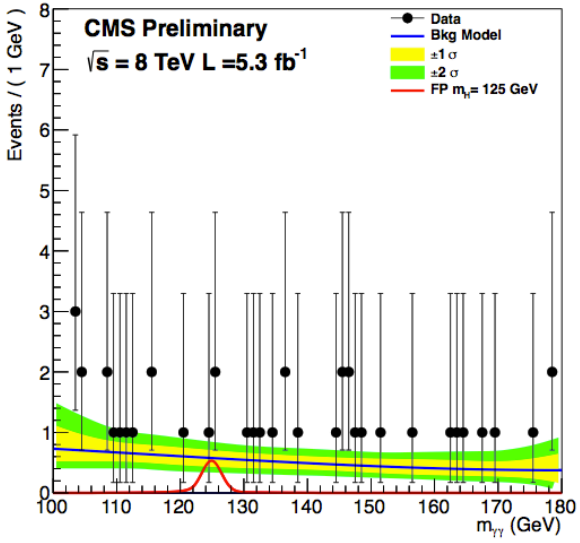
Electron tag 8 TeV data



Muon tag 8 TeV data



MET tag 8 TeV data



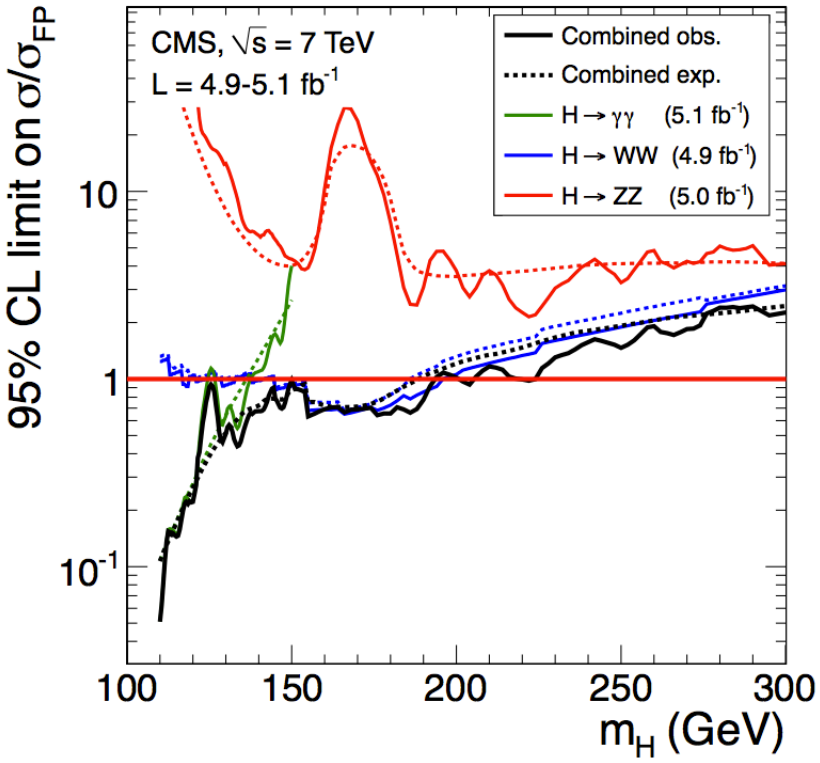
- Sensitivity is further increased in the untagged class taking advantage of the $P_{t\gamma\gamma}$ spectrum that is harder for the signal than for the BG

FP results

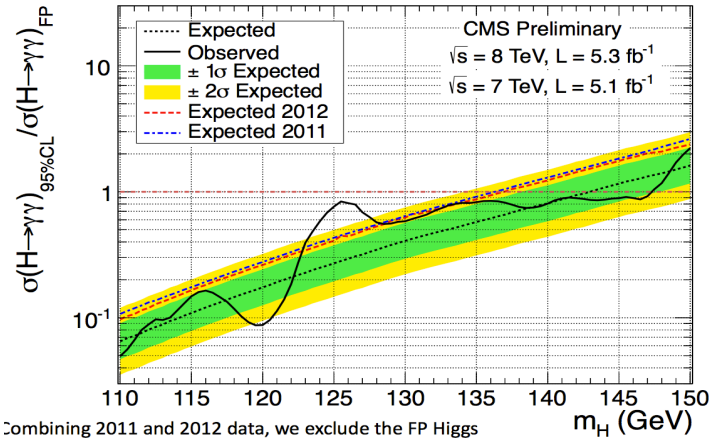
- Some excess at 125 GeV consistent with the new observed boson
- Excluded in a pure FP model
  - At 95% CL 110-194 GeV from combination of 2011 data
  - At 99% CL 110-134 GeV from γγ channel 2011+2012 data

HIG-12-022

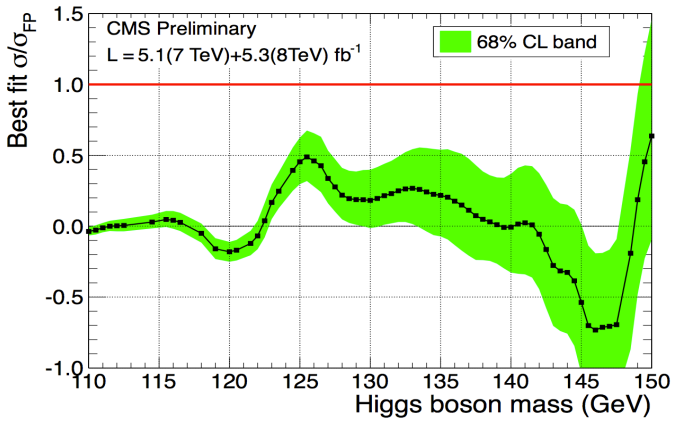
2011 7 TeV data: combined channels



7+8 TeV data: γγ channel



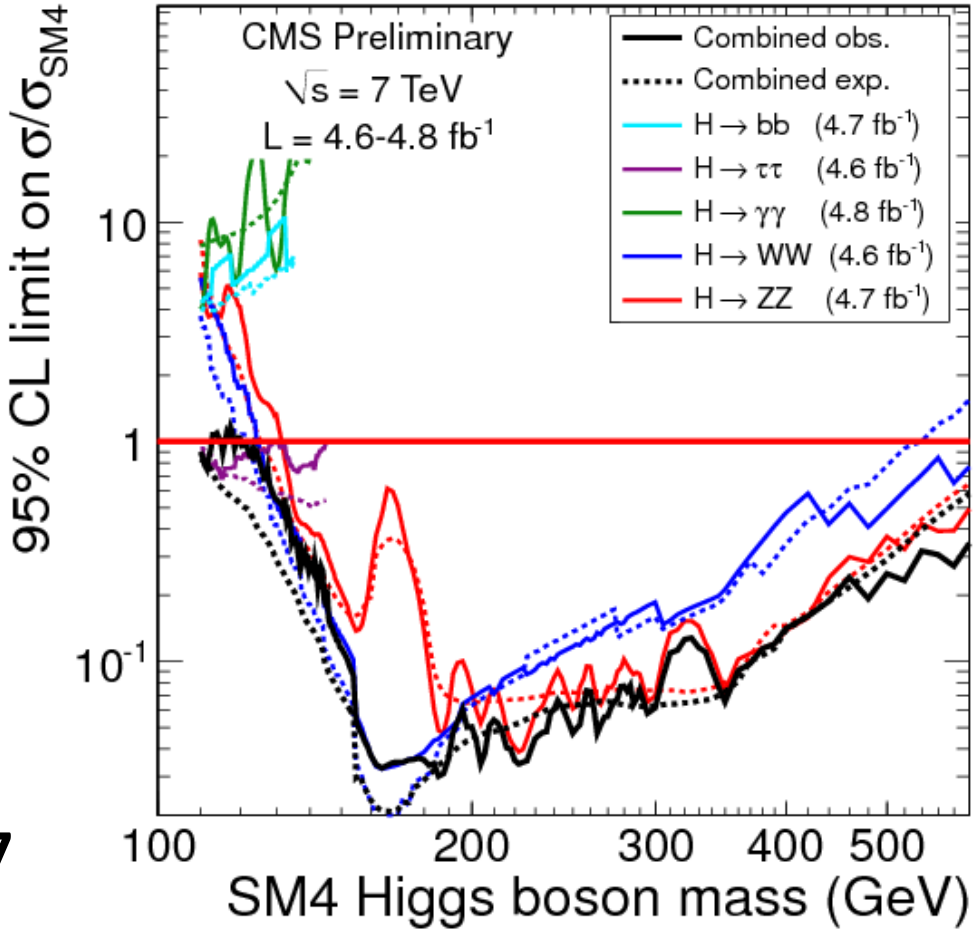
Combining 2011 and 2012 data, we exclude the FP Higgs



4 fermion generations model

HIG-12-008

- A 4th generation of fermions mainly increases the gg-fusion cross section
- Assume:
  - $M_{D4}=M_{L4}=600$ GeV
  - $M_{U4} - M_{D4} = [\ 1 + 1/5*\ln(M_H/115)\ ] * 50$ GeV
- Reinterpretation of SM Higgs searches
- **Excluded at 95% CL M_H in [120-600] GeV using 7 TeV data**

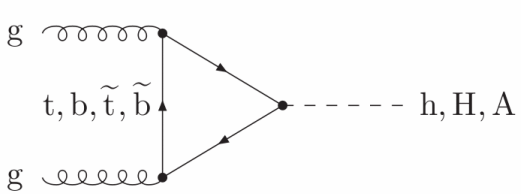


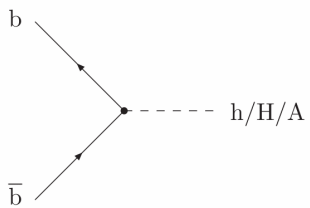
MSSM Higgs bosons

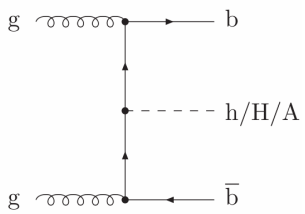
- Minimal SuperSymmetric Model requires at least 2 Higgs doublets and predicts 5 Higgs bosons:
  - 3 Neutral bosons Φ = h, H, A
  - 2 Charged bosons $H^{\pm}$
- All masses and couplings at tree level are determined by 2 independent parameters: for example M_A, tanβ
  - For large tanβ main decays of neutral Higgs bosons are to bb and ττ
  - Production in association with b-quarks becomes important

Φ (h,H,A), Φ→ττ,bb,μμ

- In MSSM Φ can be produced by gg fusion or bb annihilation



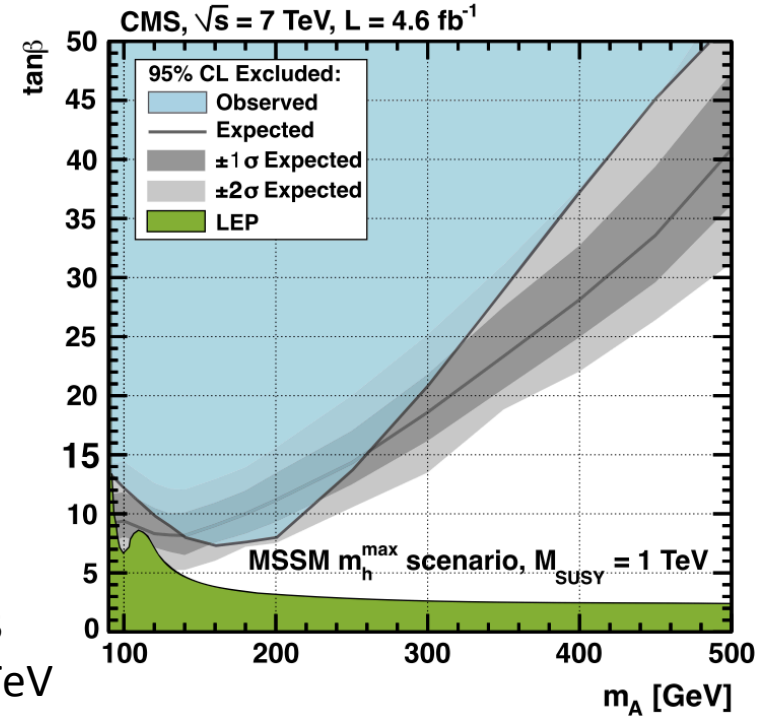




Often at least one b jet produced in the central detector

- Φ→ττ is the most sensitive
  - Search similar to SM + tag b-jet
- Search channels are μ-τ_{had}, e-τ_{had}, e-μ
- No significant excess observed

Excluded region at large tanβ



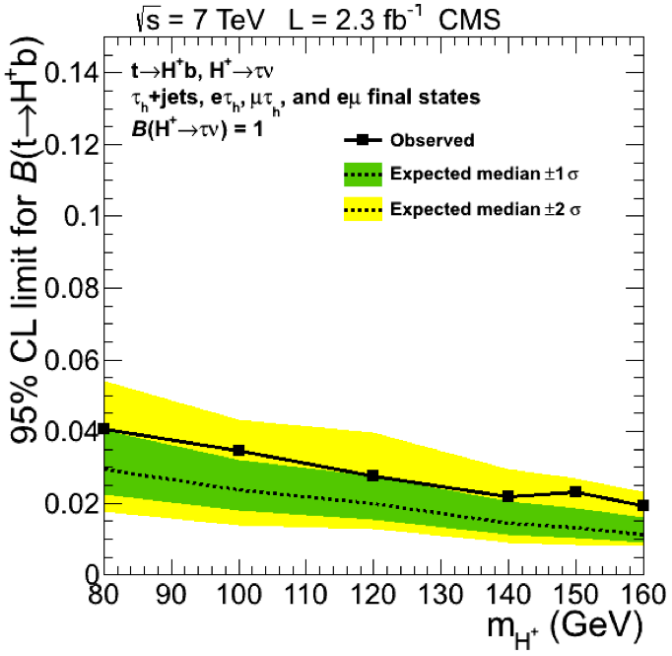
- Also search in the bb channel with the request of an additional b-tagged jet and in the μμ channel
  - No signal observed, limits less stringent than those from ττ channel

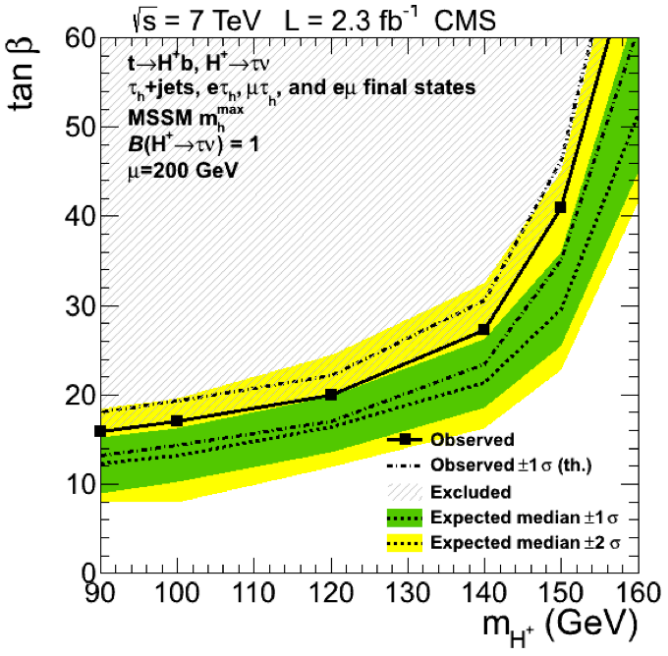
arXiv:1202.4083
2011 data at 7 TeV

$H^{\pm}$ of MSSM

- Charged Higgs are searched for in top decays for M_{H^+} in the range 80-160 GeV ($M_{H^+} < M_{top}$)
  - $t\bar{t} \rightarrow H^{\pm}W^{\mp}b\bar{b}$, $t\bar{t} \rightarrow H^{\pm}H^{\mp}b\bar{b}$
- Search for $H^{\pm} \rightarrow \tau\nu$ (favoured for large tanβ)
- No signal observed
- 95% CL limit on BR($t \rightarrow bH^+$) of 2-4% assuming BR ($H^+ \rightarrow \tau\nu$) =1
- Extended limits in tanβ vs M_{H^+} plane in MSSM

arXiv:1205.5736





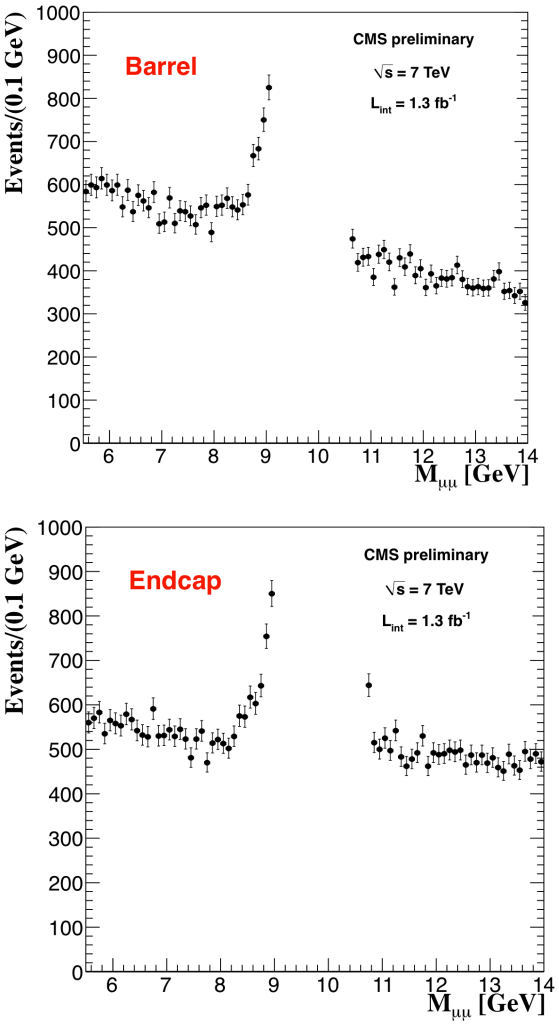
NMSSM: $a_1 \rightarrow \mu^+\mu^-$

- MSSM + one additional scalar singlet
- One more scalar and one more pseudo-scalar:

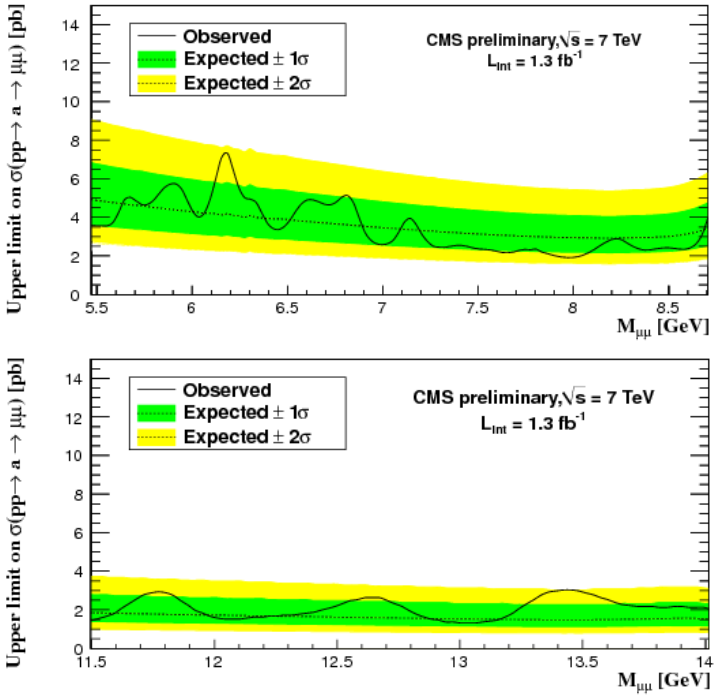
  $a_1 = a_{MSSM}\cos(\theta_A) + a_S \sin(\theta_A)$ (could be at low mass)
- Search in the dimuon mass spectrum around the ϒ

HIG-12-004

Dimuon mass spectrum

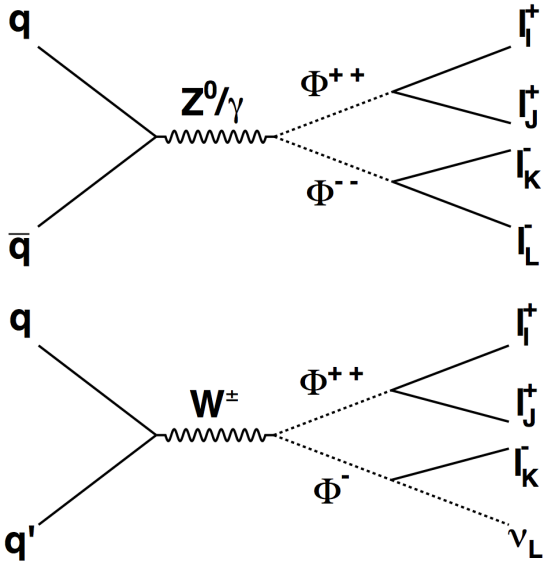


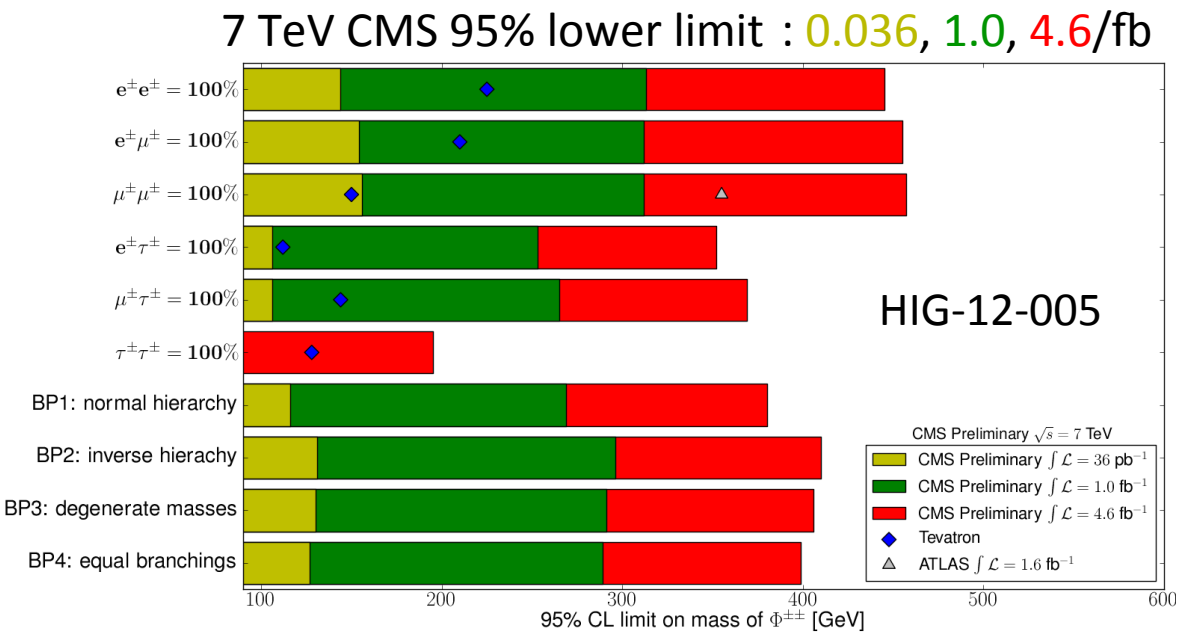
σ x BR upper limits (pb)



Doubly charged Higgs

- Minimal Type II See-Saw Models with an additional triplet predict additional Higgs particles: Φ±±, Φ±, Φ0
- Possible explanation for neutrino masses
- Search for pair production or associated production with Φ++Φ-
- Φ±±, Φ± are assumed to be degenerate in mass
- Signature is 3 or 4 charged leptons
  - Search for resonant same sign leptons from Φ±± in all possible flavours



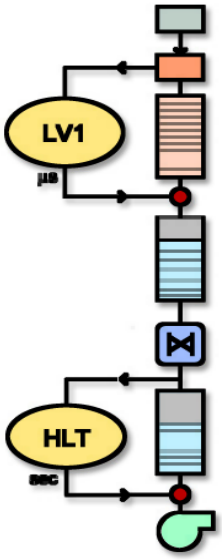


Summary

- We observed a new boson consistent with a SM-like Higgs boson
  - larger excess in H→γγ and H→ZZ
  - smaller or no excess in H→WW, H→bb and H→ττ
  - **M_X = 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV**
  - couplings consistent within 2σ with the SM Higgs boson
  - a new era starts for the measurements of its properties
- Remaining mass range from 113 to 600 GeV is excluded at 99% CL
- No evidence of BSM Higgs bosons, improved limits are obtained in different scenarios
- CMS and LHC are on track to get a total of more than 25 fb^{-1} by the end of the year
  - more precise measurements of the new bosons's properties soon

Backup

Trigger



40 MHz

100 KHz

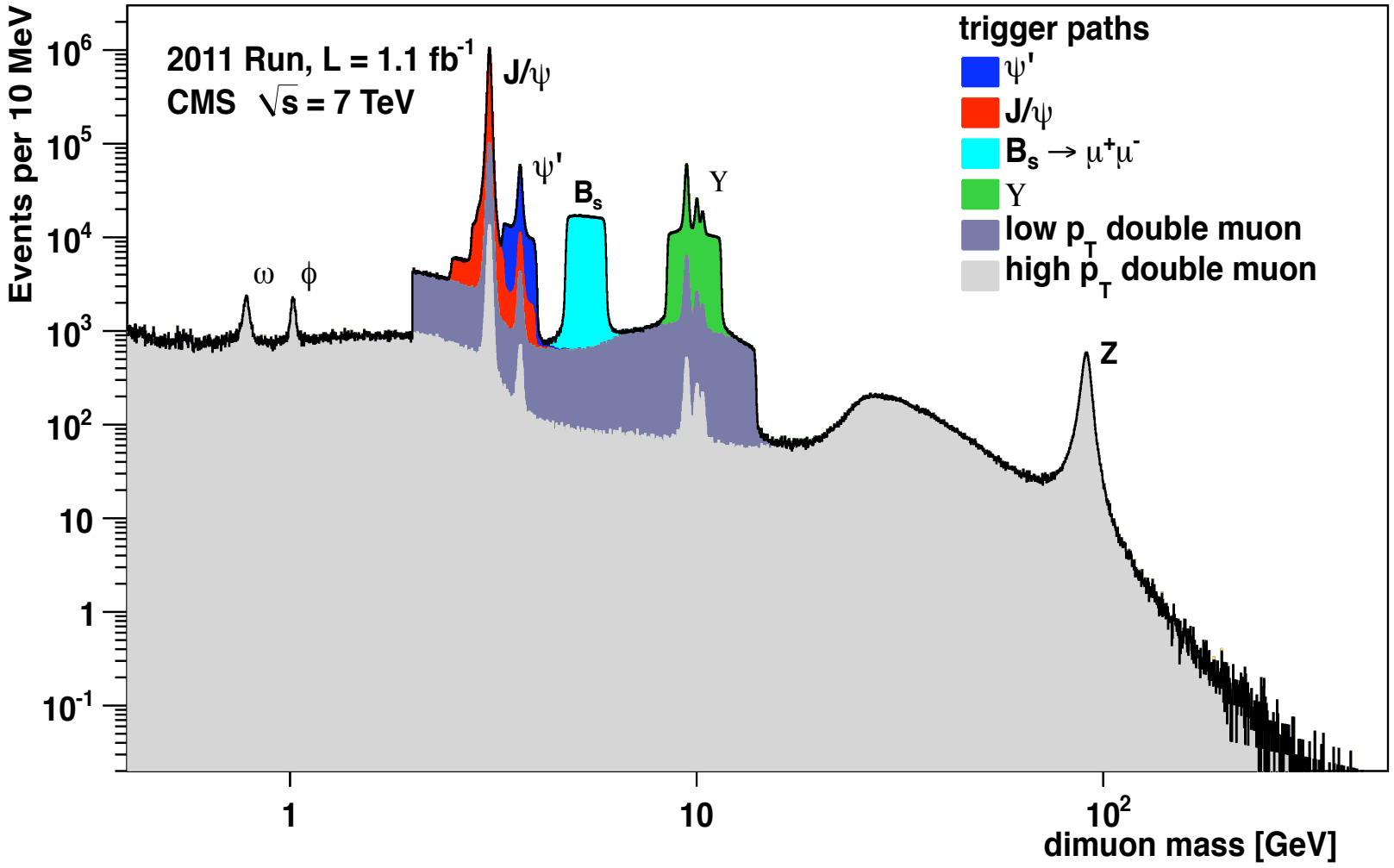
~300 Hz

- 2-level trigger system
  - Input: 40 MHz (20 MHz until now)
  - Level1 Trigger output 100 KHz
  - All events fully built and sent to the online Filter Farm
  - High Level Trigger (HLT)output ~500 Hz (saved for physics analysis)

- The HLT has access to the full event information and runs the offline reconstruction only optimized for speed
- ~300 HLT paths select events for all analyses
  - Single object triggers: e, γ, μ, MET, …
  - Multi object triggers: ee, γγ, μμ, ee+MET, …
  - Prescaled triggers used for control samples and to measure efficiencies, including trigger efficiency

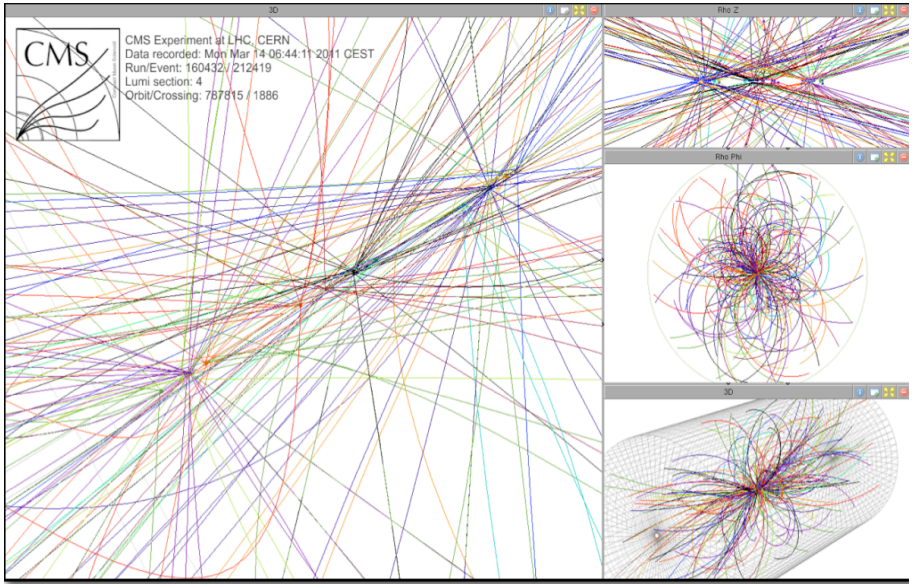
Dimuon Mass Spectrum

- Di-muon mass distribution from several trigger paths

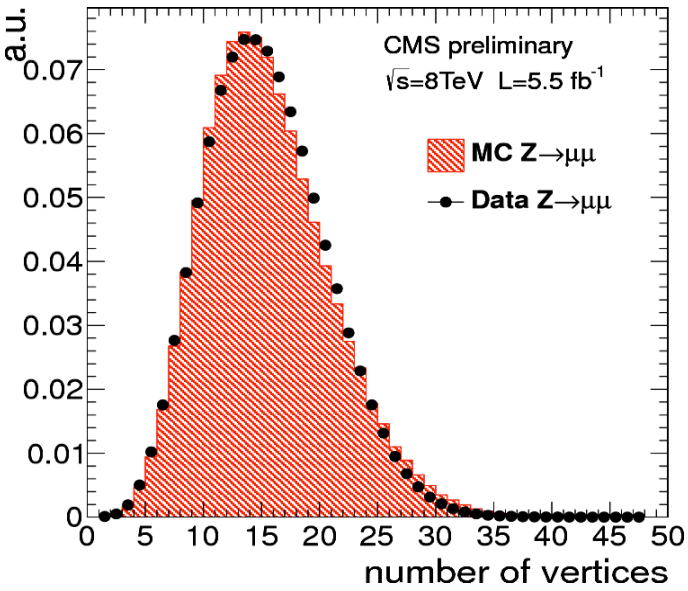


Pileup

- Multiple interactions occur for each bunch crossing (in-time and out-of-time pileup)



8 TeV dataset

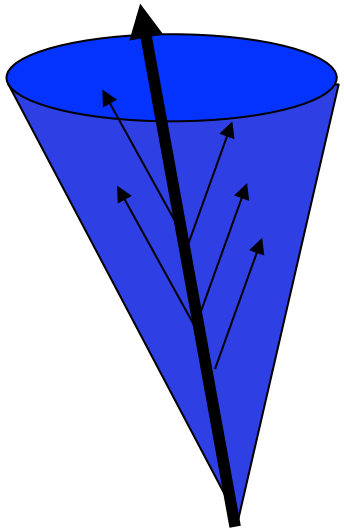


- Effects of pileup:

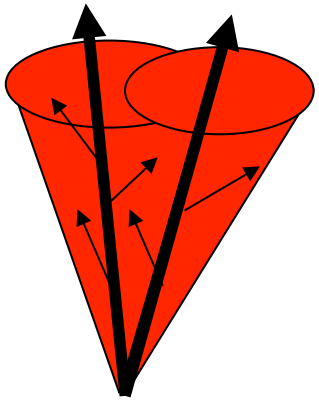
Mean pileup ~20 events in 2012

  - Slightly deteriorates energy resolution for electrons and photons and jets
    - Apply corrections event by event for photons
  - Adds energy in isolation cones
    - corrected for pileup energy estimated event by event
  - PU jets affect central jet veto and VBF jet tagging
    - Try to reject PU jets (wider and with tracks coming from different PV)

2012 high PU



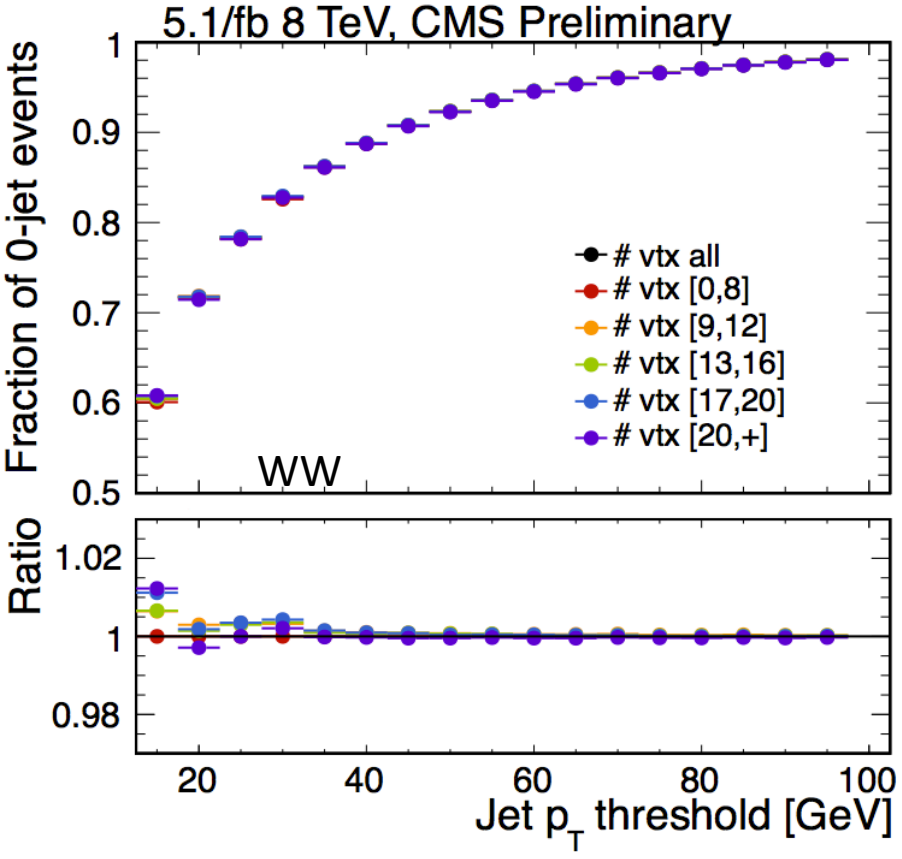
Typical jet



Typical Pileup jet

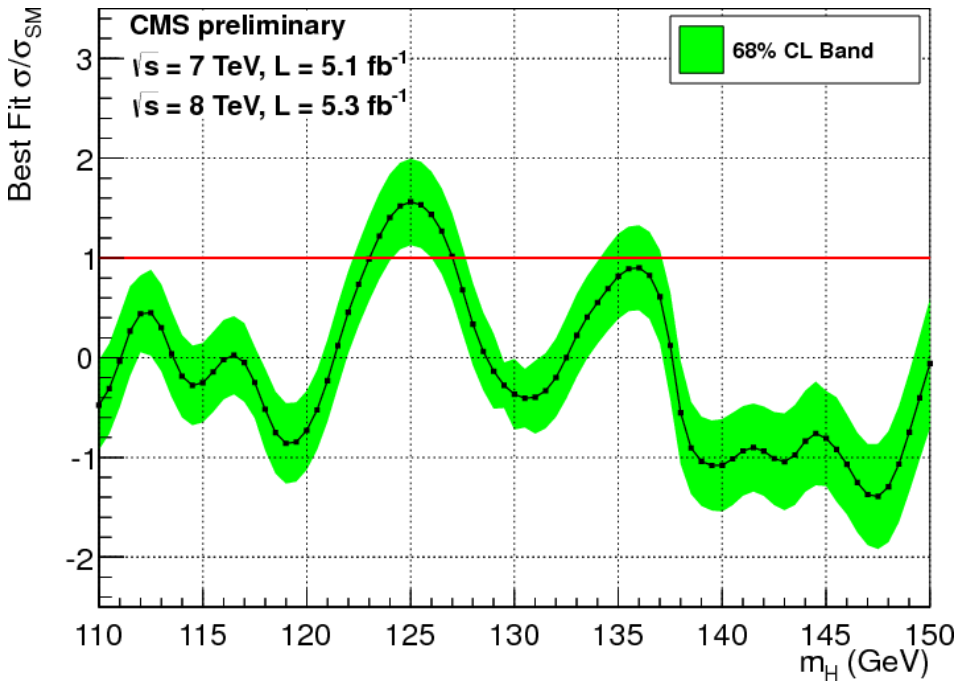
- Pileup jets structure differs w.r.t. regular jets:
  - pileup jets tend to originate from several overlapping jets which merge together
  - jets are wider
  - tracks come from a different PV
- Multivariate discriminant exploits jet shape and tracking variables
  - discrimination both inside and outside tracker acceptance

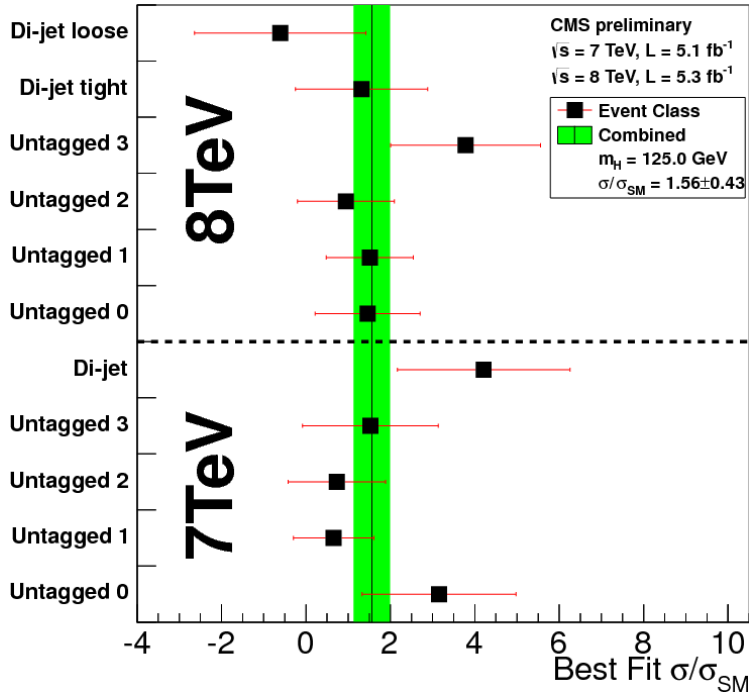
Constant 0 jet fraction in WW events with different PU levels



Signal strength in H→γγ

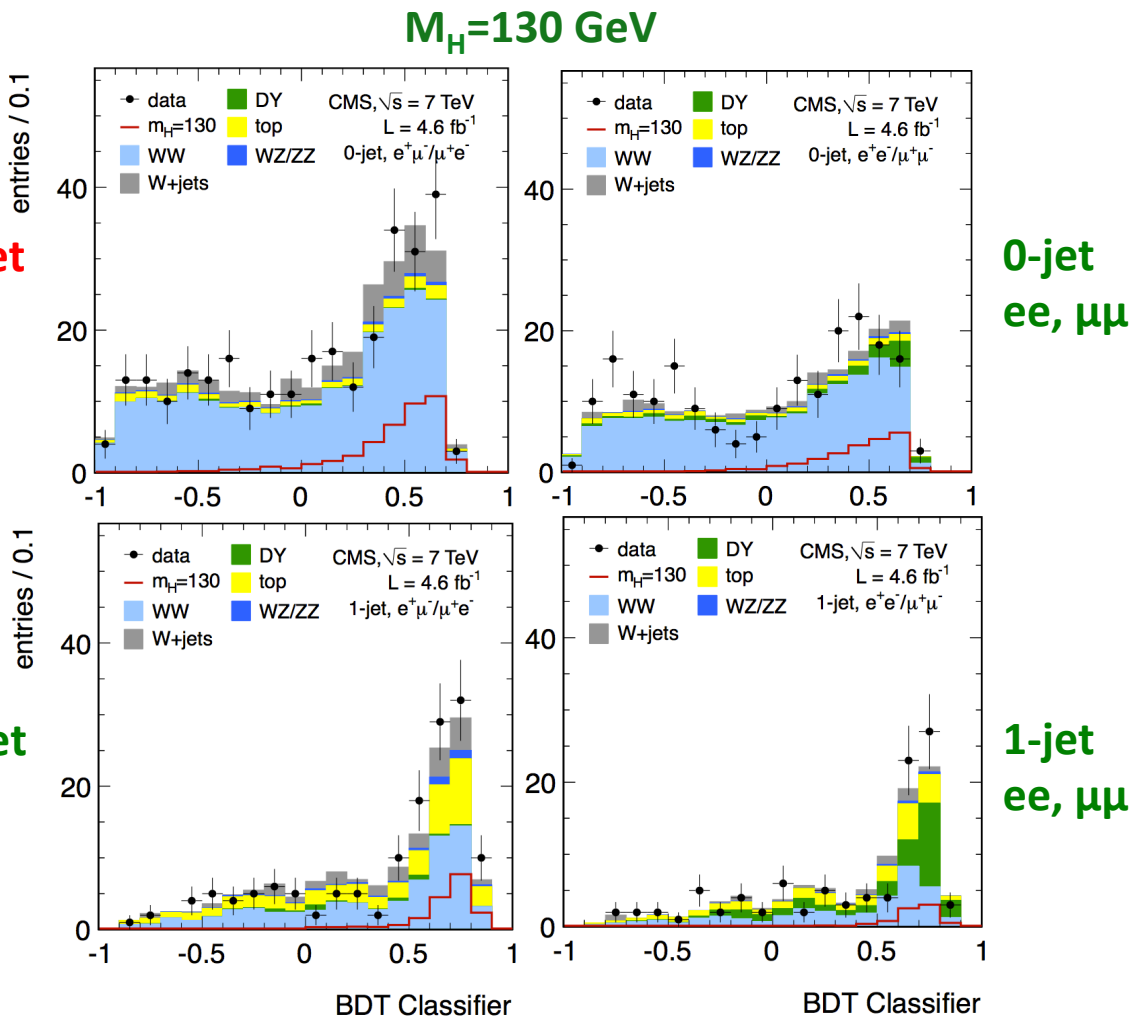
- μ = 1.6 ± 0.5
- All classes give consistent results





H→ WW with 2011 data: MVA analysis: 0 and 1-jet bins

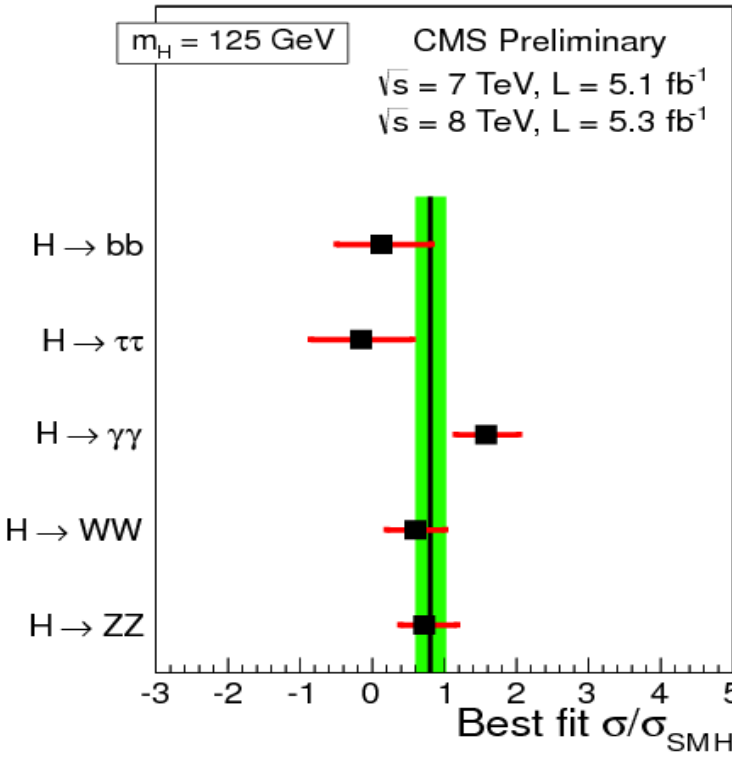
- BDT trained at different masses, input variables:
  - $P_{tleptons}$, M_{ll}, $\Delta\phi_{ll}$, ΔR_{ll}, M_t (for dilepton system and each lepton)
- Overall uncertainties:
  - signal efficiency ~20%
  - background ~15%
- Use BDT output classifier distribution for CL estimation
- Many cross checks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



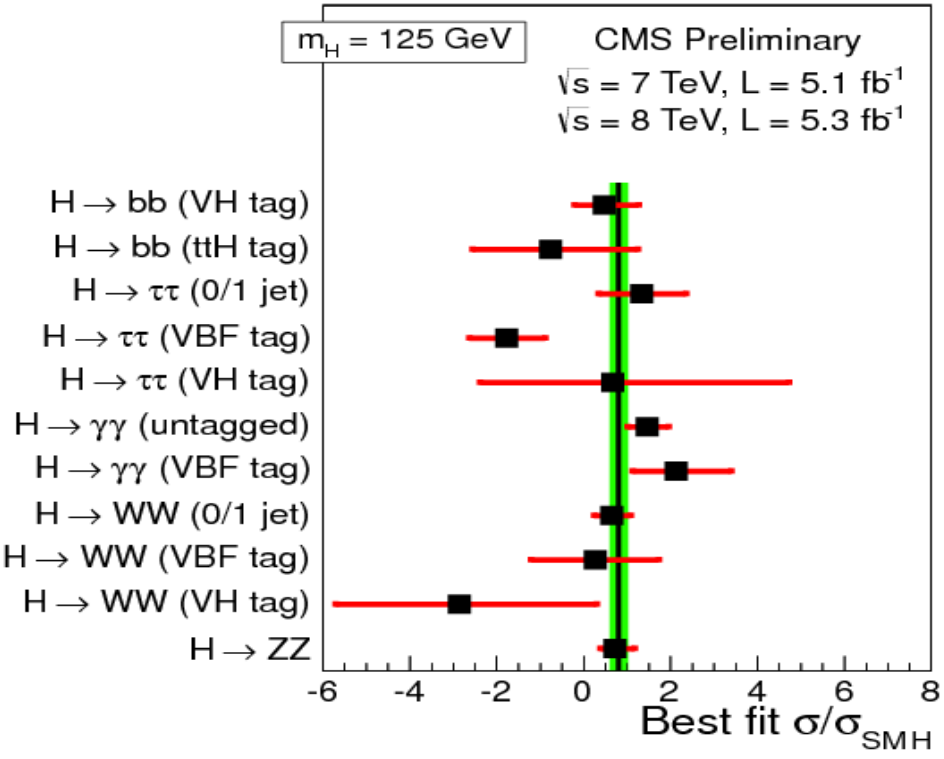
Most sensitive channel is eμ in 0-jet bin higher s/b and smaller systematic errors

Combination: signal strength in individual channels

Comparison of channels for M_H=125 GeV



Comparison of channels for M_H=125 GeV

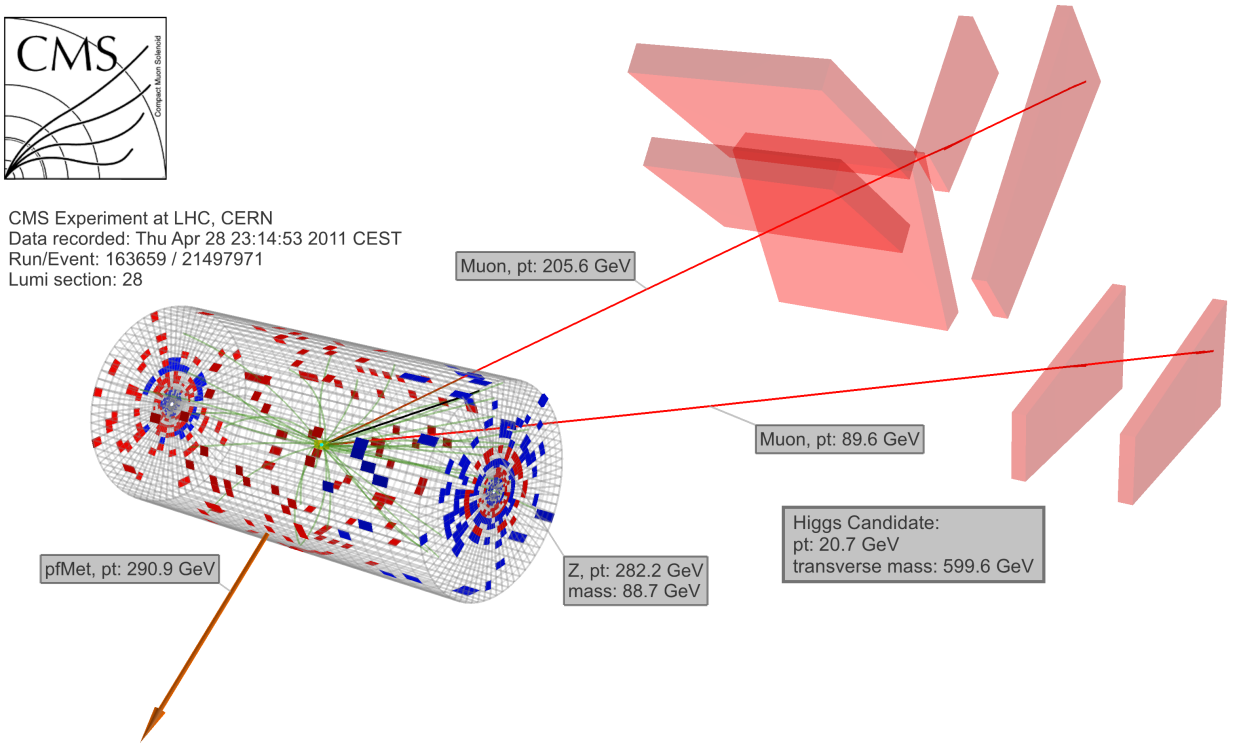


- Common cross section theoretical errors contribute to all measurements
  - Dominated by 15% error on gg-fusion where applicable

High mass: H→ZZ→llvv channel

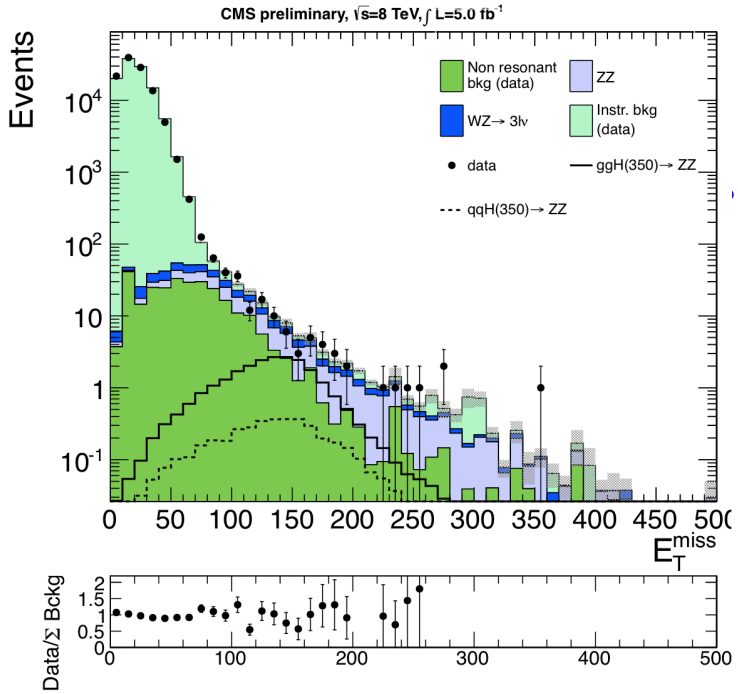
- Most sensitive channel for high mass search
  - BR 6 times larger than ZZ→4l
- **Missing neutrinos implies mass resolution 7%**
- Only accessible for high mass (M_H > 200 GeV):
  - the two Z bosons are boosted
  - large MET due to invisible decay
- Main backgrounds
  - ZZ (irreducible)
  - Z+jets, tt, WZ

H->ZZ->llvv candidate



H→ZZ→llνν results

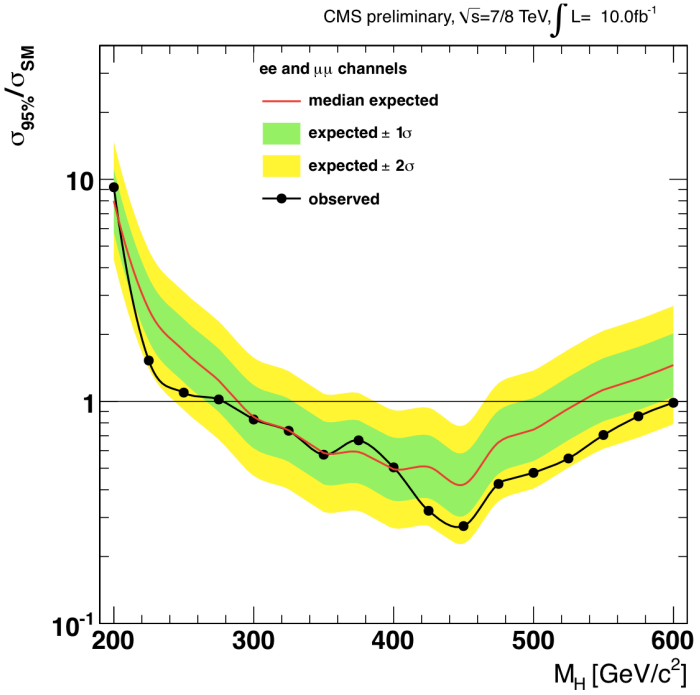
MET after preselection



- Cut and count analysis with cuts on E_t^{miss} and transverse mass optimized in different mass ranges

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

VBF and gg-fusion treated separately

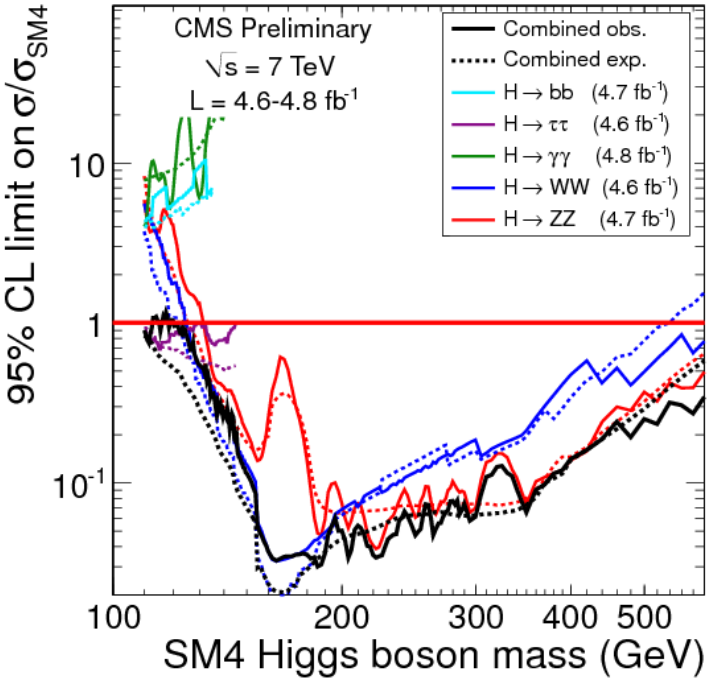


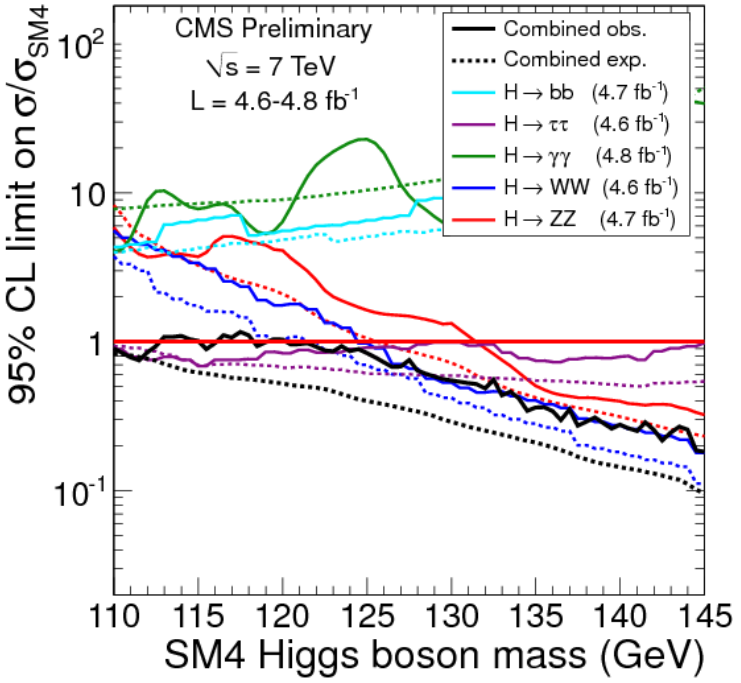
- BG estimation
  - Z+jets estimated using γ+jet to model the MET distribution
  - Non resonant BG normalization from eμ events
  - ZZ and WZ from MC

- No excess observed in data
- Expected 95% exclusion for M_H in [291 - 534] GeV
- Observed 95% CL exclusion for M_H [278 – 600] GeV

4 fermion generation model

- A 4th generation of fermions mainly increases the gg-fusion cross section
- Assume:
  - $M_{D4}=M_{L4}=600GeV$
  - $M_{U4} - M_{D4} = [\ 1 + 1/5*\ln(M_H/115)\ ] * 50\ GeV$
- Reinterpretation of SM Higgs searches



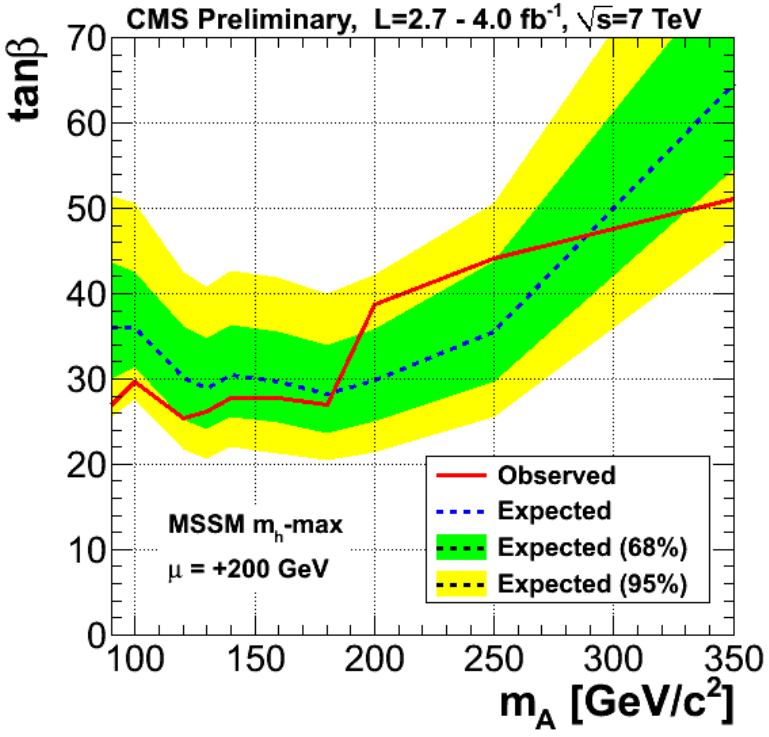


- Excluded at 95% CL M_H in [120-600] GeV using 7 TeV data

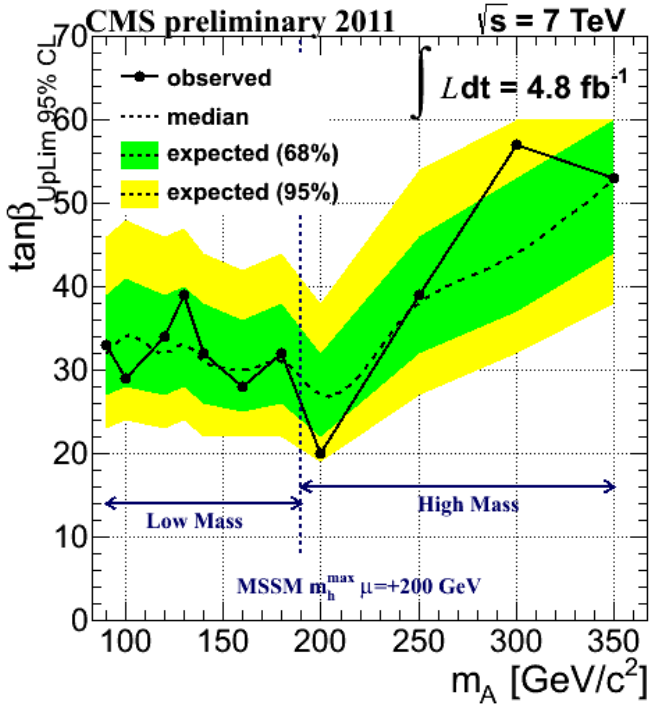
Φ (h,H,A), Φ→bb

- Search in the bb channel with the request of an additional b-tagged jet
- Upper limits on the pp → bH + X, H → $b\bar{b}$ cross section are derived, and interpreted in the MSSM

All hadronic – trigger on jets



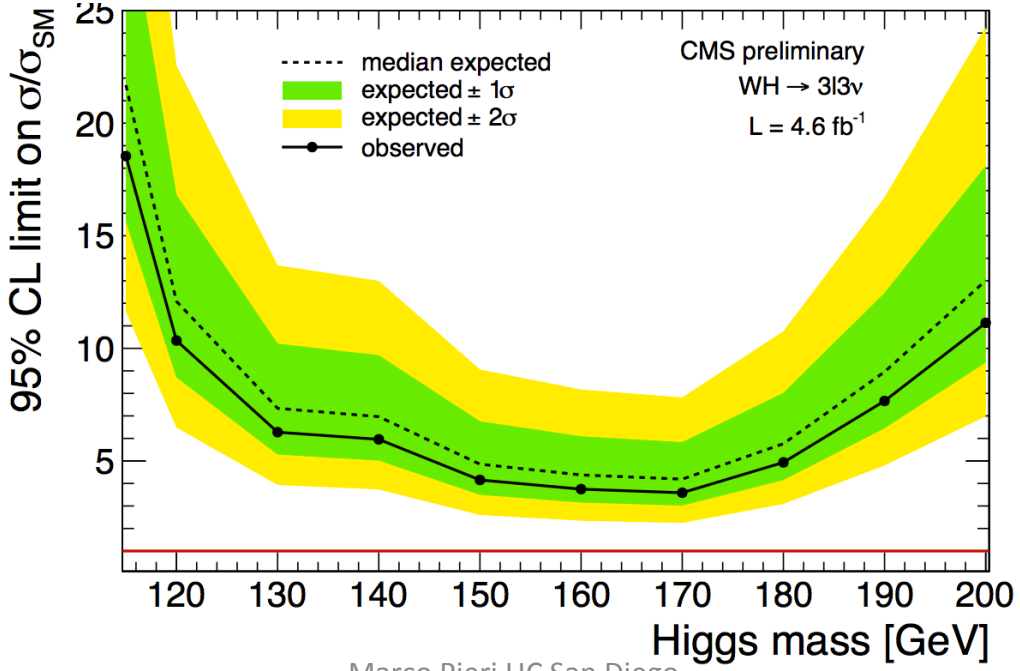
Semi-leptonic – trigger on μ



WH→WWW→3l3v

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

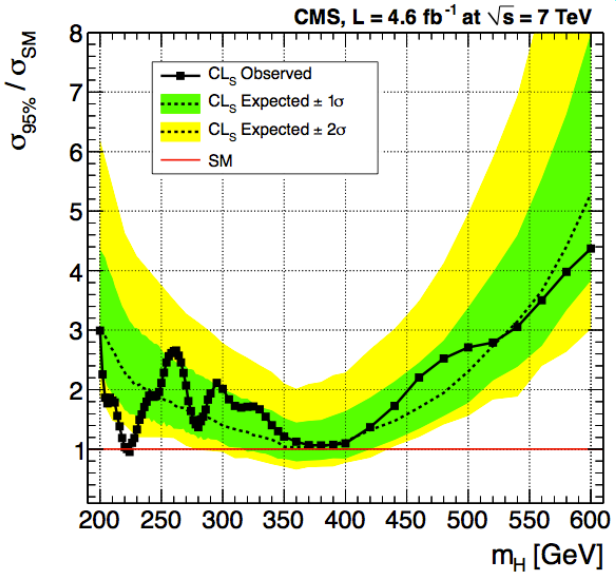
stage	WH (120) $H \to \tau\tau$	WH (120) $H \to WW$	data	all bkg.	WZ $\to 3\ell\nu$	ZZ $\to 4\ell$	top+Z/γ^*
3-lepton preselection	2.1 ± 0.0	3.5 ± 0.1	950	968.3 ± 11.9	482.9 ± 1.8	78.4 ± 0.9	348.0 ± 9.7
min-MET > 40 GeV	1.0 ± 0.0	1.8 ± 0.1	244	270.5 ± 4.4	208.2 ± 1.1	7.9 ± 0.3	54.5 ± 4.3
Z removal	0.4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



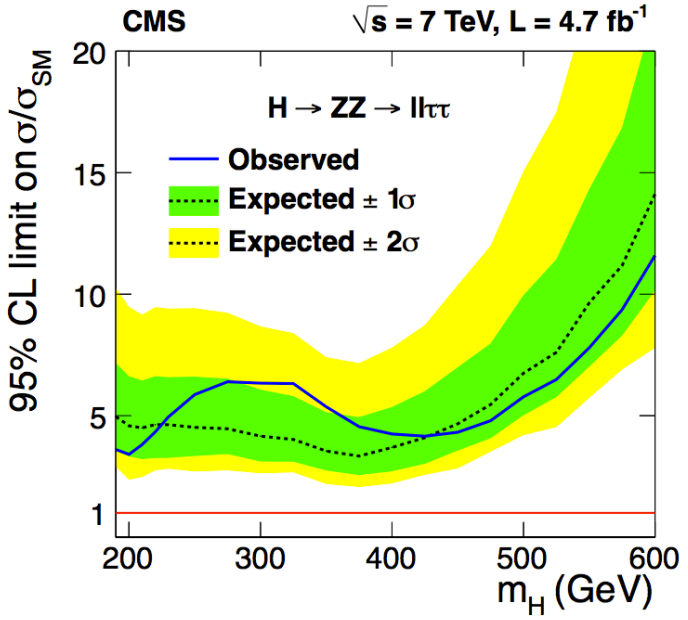
HIG-11-034

Other high mass SM channels

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



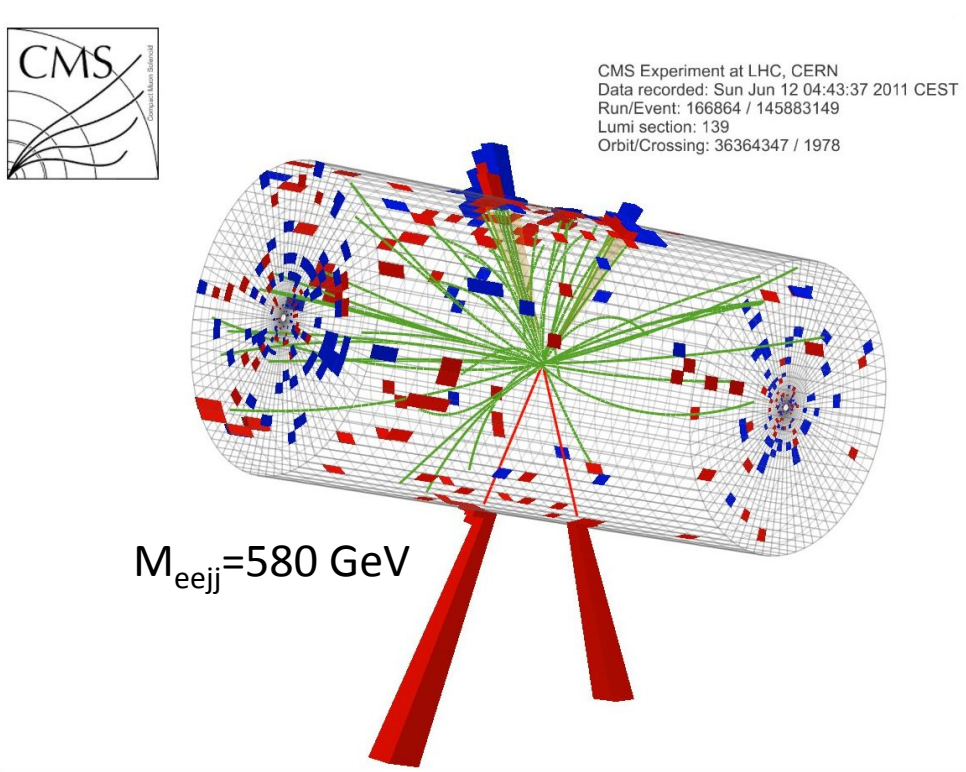
- H → ZZ → llττ (high mass)
  - All τ decay channels searched for
  - Lower sensitivity (~4xSM)



H→ZZ→llqq channel

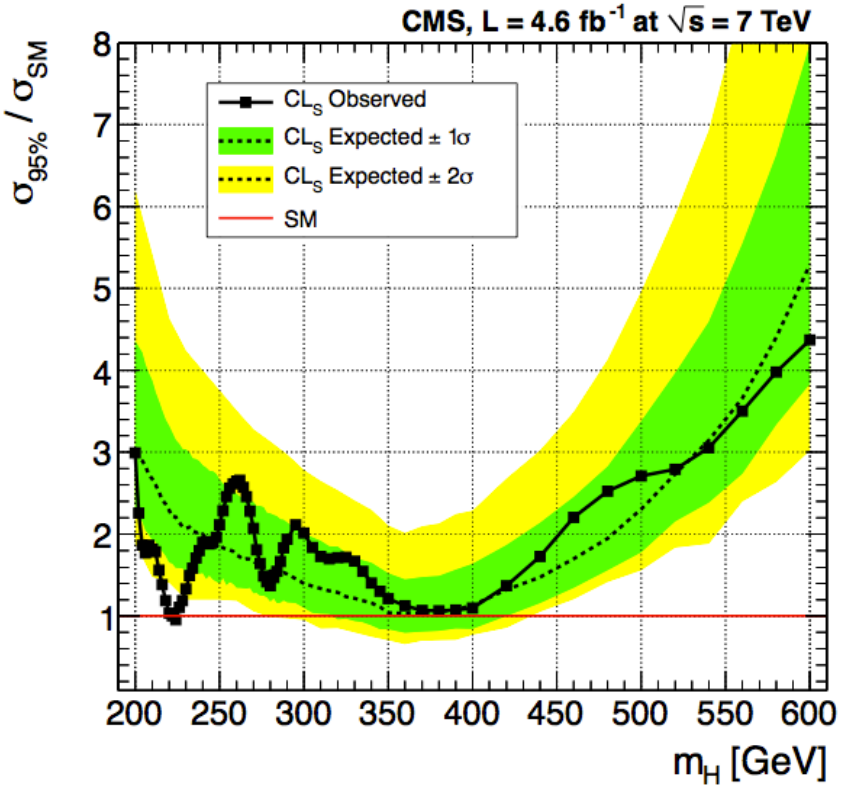
arXiv:1202.1416

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



M_{eejj}=580 GeV

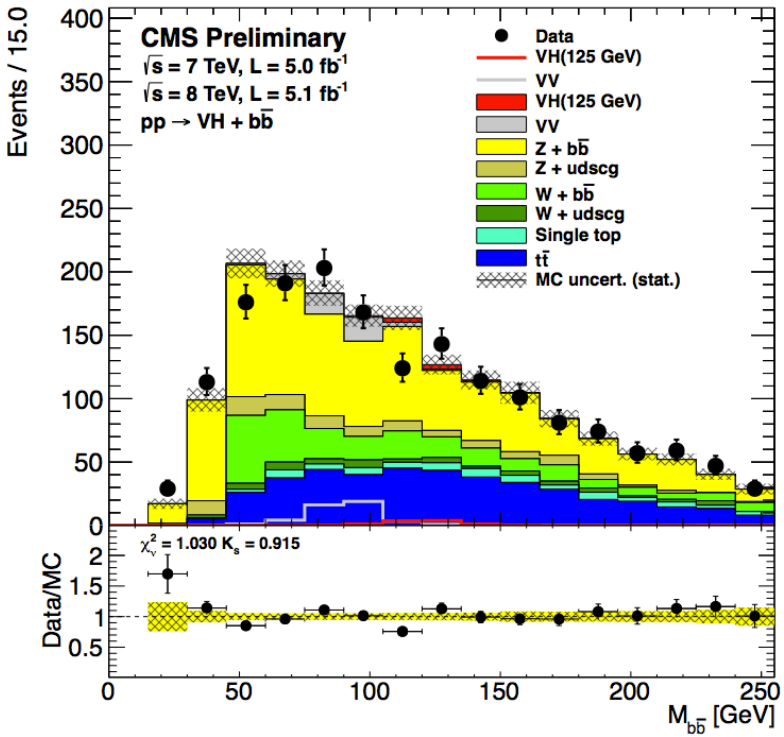
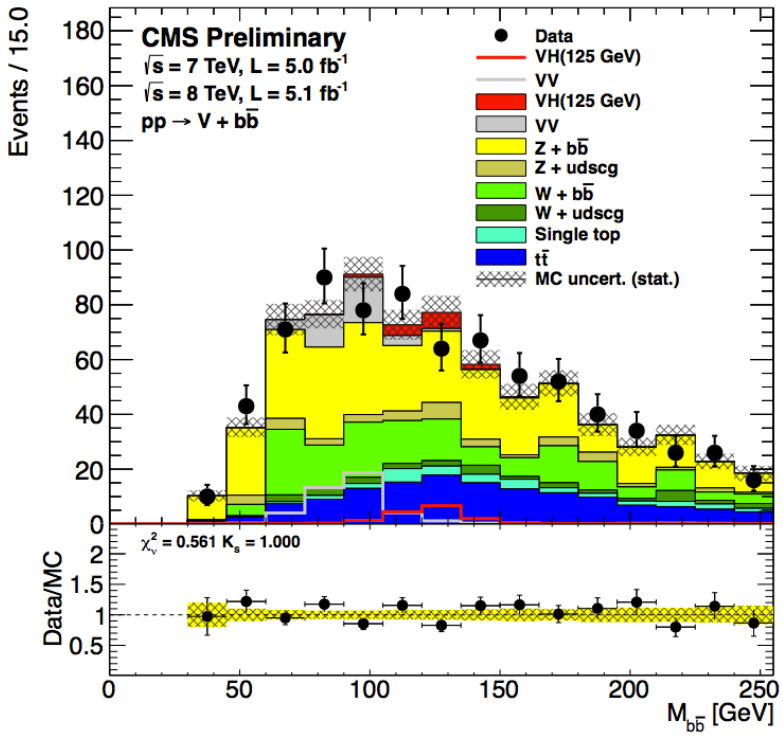
95% exclusion from H→ZZ→llqq



Mass resolution after kinematical fit ~ 3%

H→bb: mass distribution

Low Pt bin



High Pt bin