Higgs Hunting @ CMS

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(On behalf of the CMS Collaboration)

BNL Workshop on SUSY with 5fb^{-1}

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Outline

- **Standard Model**
  - bb
  - WW
  - $\tau\tau$
  - ZZ
  - $\gamma\gamma$
  - Combination
- **BSM**
  - 4^{th} generation
  - Fermiophobic
  - MSSM (neutral & charged)
  - NMSSM
  - Doubly charged Higgs

Summary

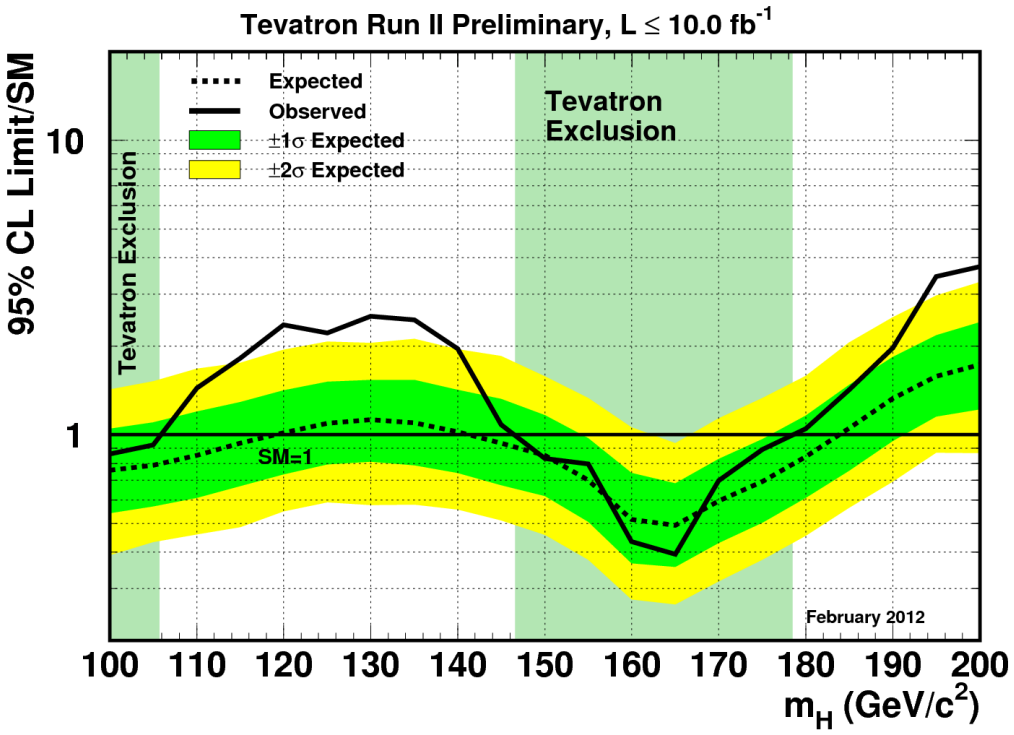
Non-LHC Constraints

Direct exclusions (95% C.L.)

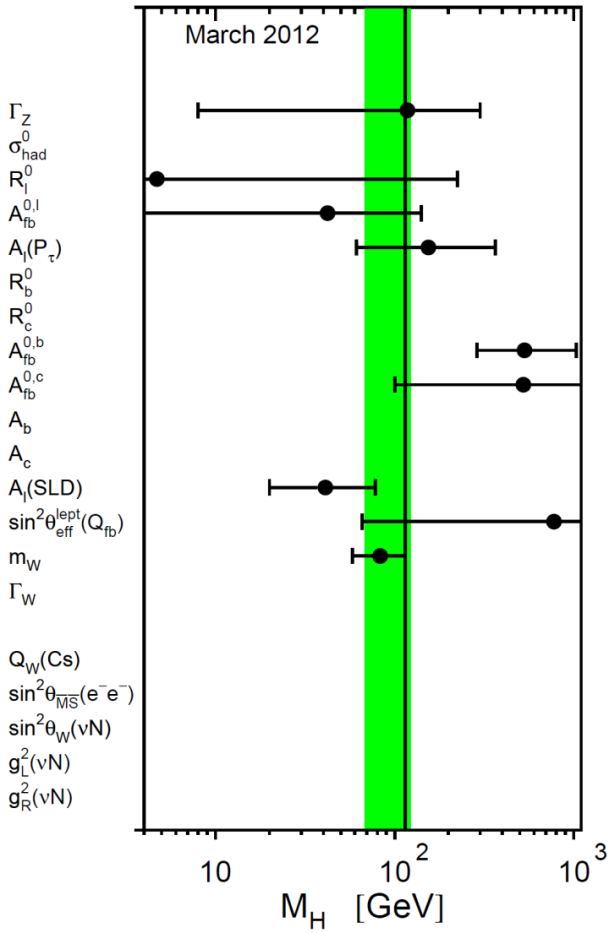
- LEP: $M_H > 114.4$ GeV
- FNAL: $147 < M_H < 179$ GeV

Excess (2.2σ) @ Tevatron

- Consistent with a SM Higgs for 115 – 135 GeV

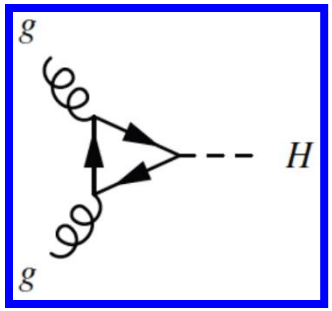


Precision EWK measurements

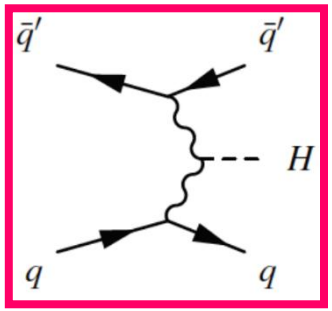


Precision EWK+top: $M_{\mathrm{H}} = 94^{+29}_{-24}$ GeV

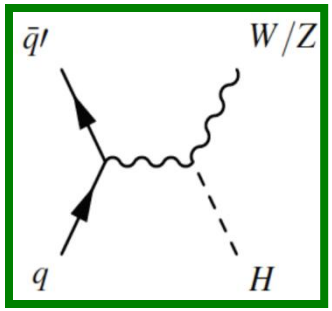
SM Higgs Production at the LHC



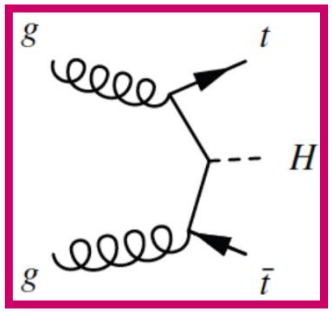
Gluon Fusion



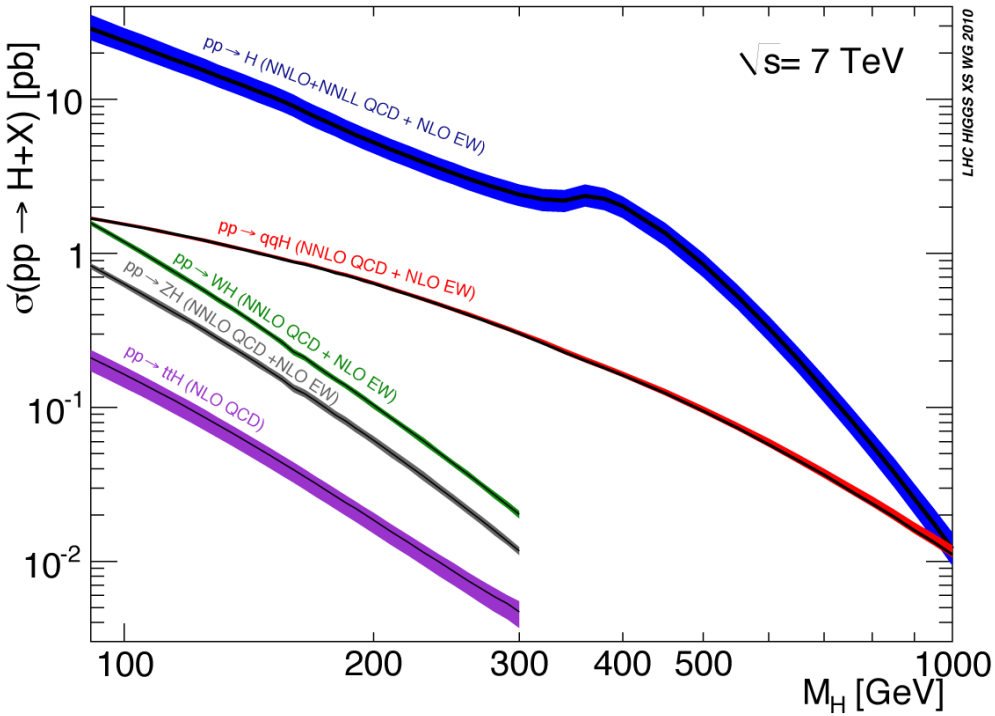
Vector-Boson Fusion



Higgs-strahlung



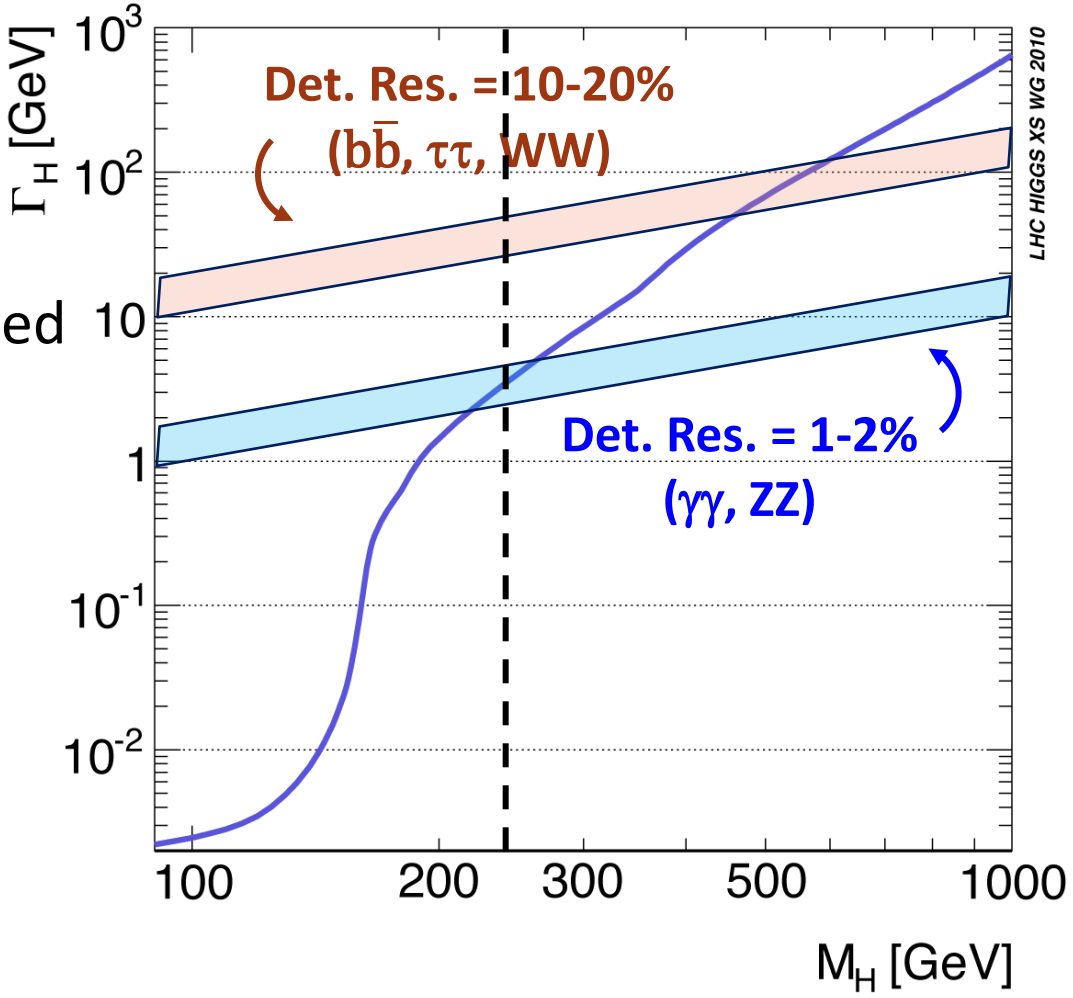
Top Fusion ($t\bar{t}H$)



LHC in 2012, at record luminosity (5.5 x 10^{33} $cm^{-2}s^{-1}$) and energy (8 TeV), is now producing SM Higgs bosons (M_H = 125 GeV) at a rate **~500/hr**

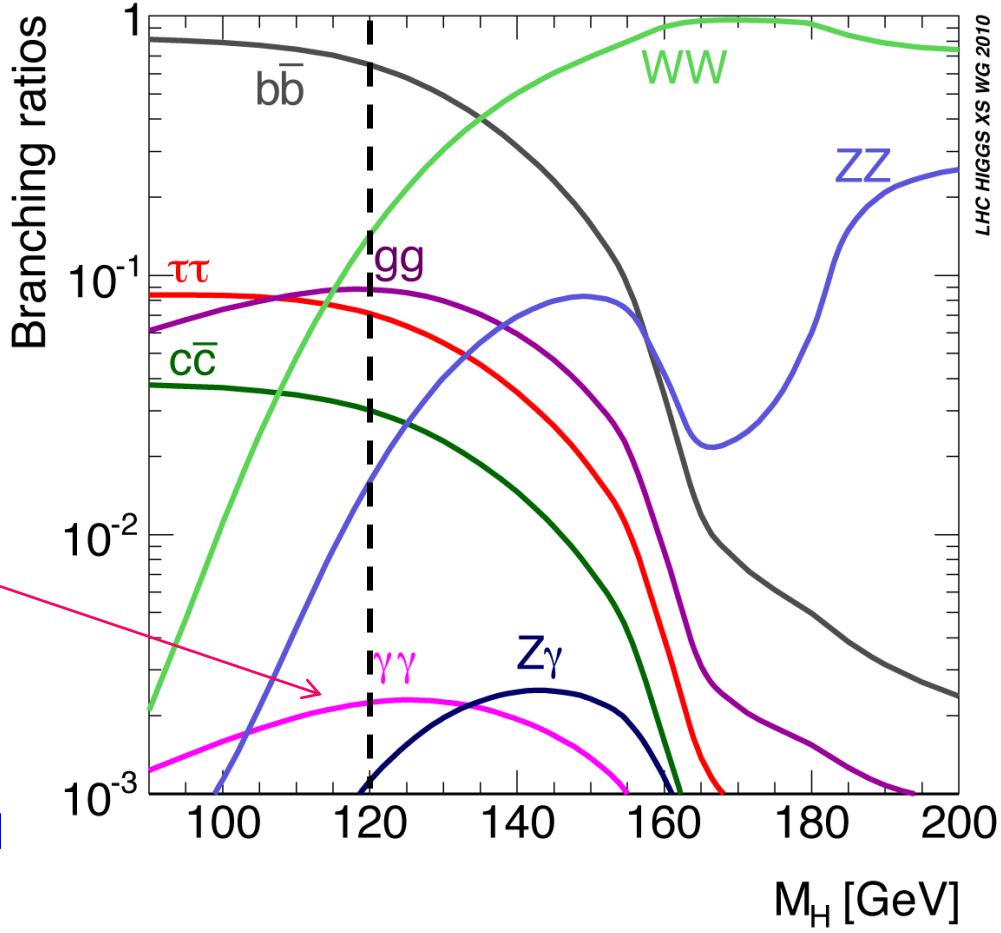
What does the SM Higgs look like?

- **Low mass**
  - Peak in $\gamma\gamma$, ZZ(4l), also eventually in $b\bar{b}$
  - Observed width dominated by *detector resolution*
- **High mass**
  - Higgs becomes a broad resonance dominated by *natural width*
  - Theory input is critical

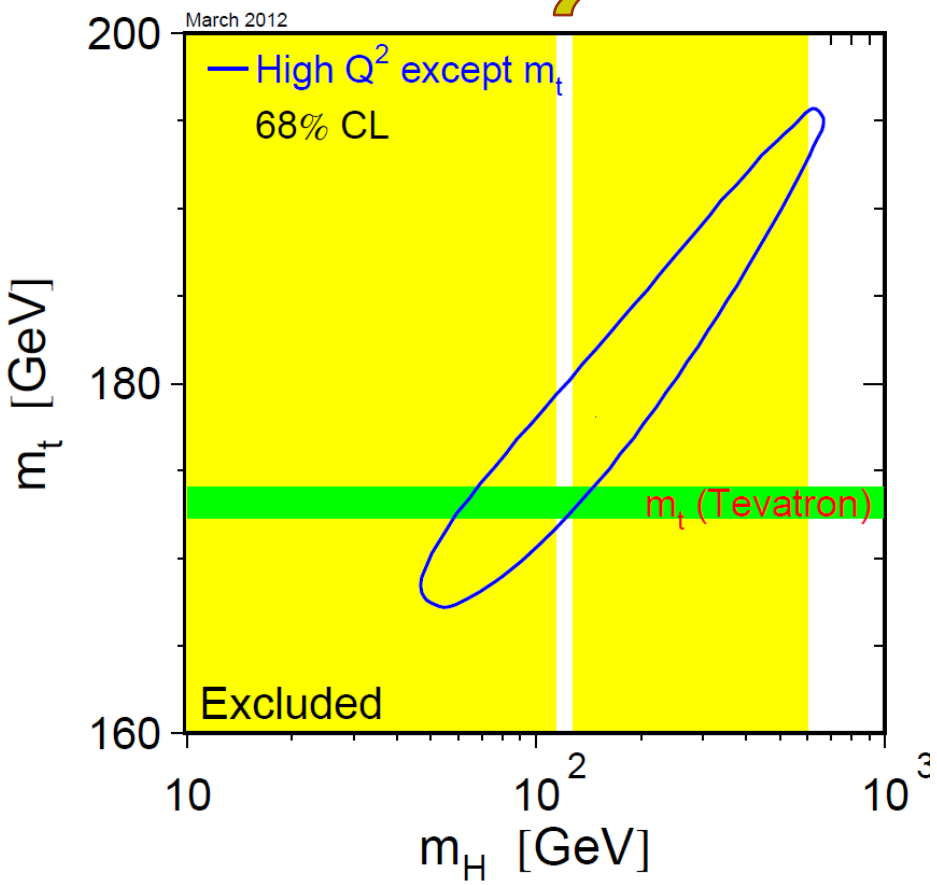


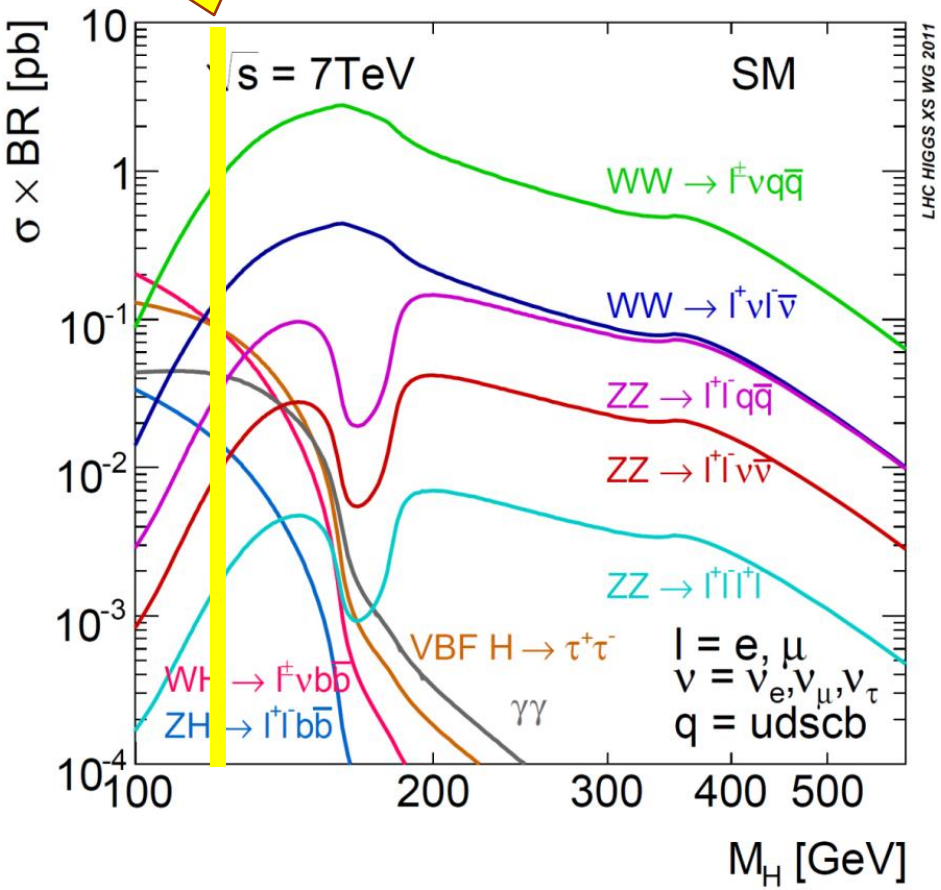
Partial Widths

- **Favorite daughters for $M_H = 120$ GeV:**
  - $b\bar{b} = 65\%$
  - $WW = 14\%$
  - $\tau\tau = 7.0\%$
  - $ZZ = 1.6\%$
  - $\gamma\gamma = 0.2\%$
- **Might discover it in one of its least favorite modes!**
  - Using particles that do not even couple to the Higgs!
  - **$b\bar{b}$ and other modes are critical for establishing the SM Higgs**



Hitting the Sweet Spot





Only region in M_H where

- **Cross sections are large**
- **Fermion final states (bb+ττ) are accessible**
- **Natural width is negligible**

SM Higgs Search at CMS

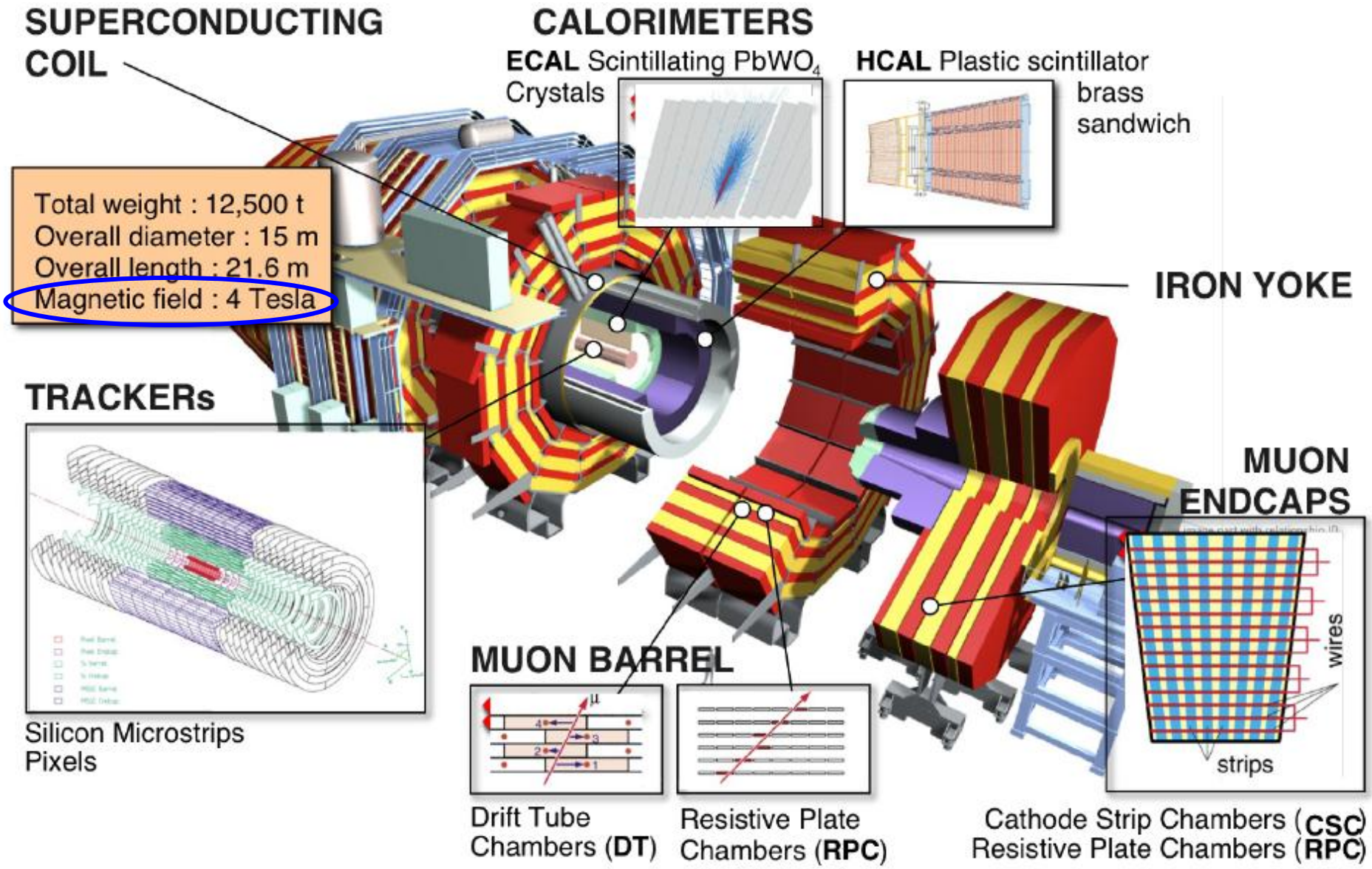
Approved results as of Moriond 2012

	Channel (production)	m_H range	sub-channels	m_H resolution
$\gamma\gamma$	$H \to \gamma\gamma$ (ggH)	110–150	1	1–2%
	$H \to \gamma\gamma$ (VBF)	110–150	1	1–2%
$\tau\tau$	$H \to \tau\tau$ (ggH)	110–140/145	8	20%
	$H \to \tau\tau$ (VBF)	110–140/145	4	20%
	$H \to \tau\tau$ (VH)	100–140	2	20%
$b\bar{b}$	$H \to bb$ (VH)	110–135	5	10%
WW	$H \to WW \to l\nu l\nu$ (ggH)	110–600	5	20%
	$H \to WW \to l\nu l\nu$ (WH)	110–200	1	20%
ZZ	$H \to ZZ \to 4l$ (ggH)	110–600	3	1–2%
	$H \to ZZ \to ll\nu\nu$ (ggH)	250–600	2	7%
	$H \to ZZ \to llqq$ (ggH)	130–164, 200–600	8	3%
	$H \to ZZ \to ll\tau\tau$ (ggH)	190–600	6	10–15%

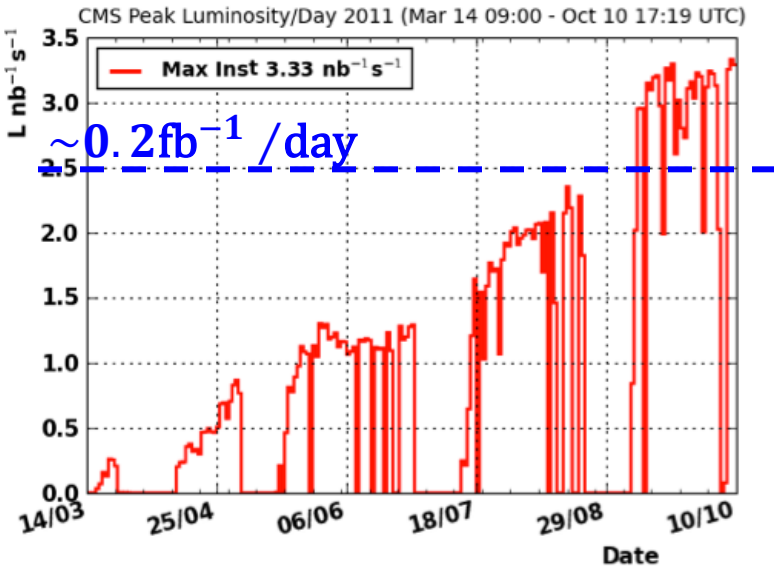
More information available here:

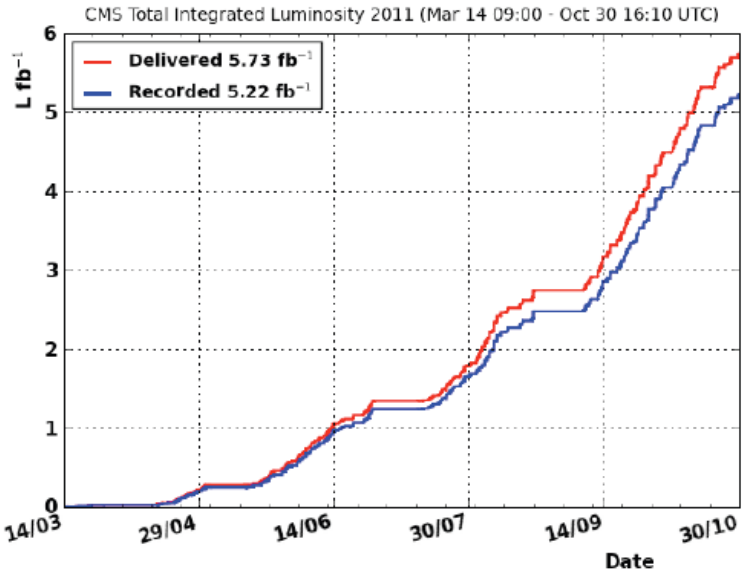
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

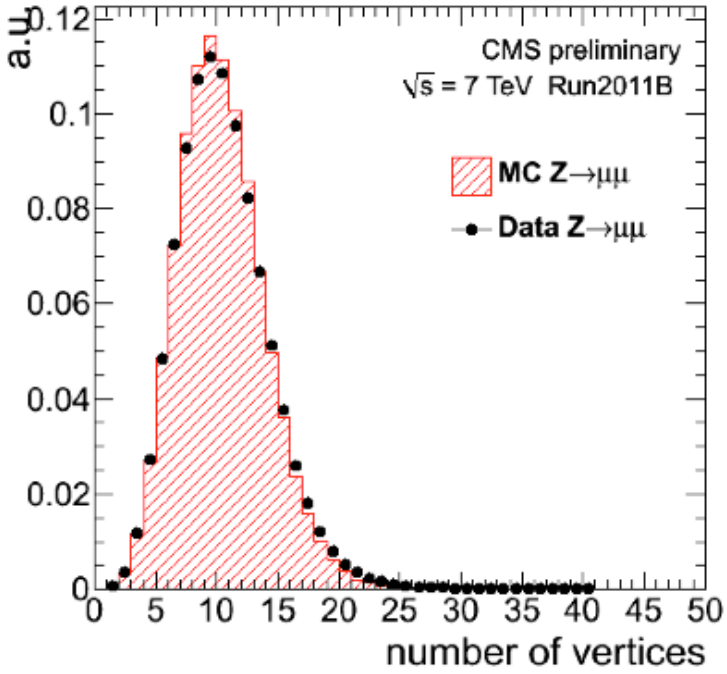
CMS Apparatus



LHC and CMS Performance (2011)







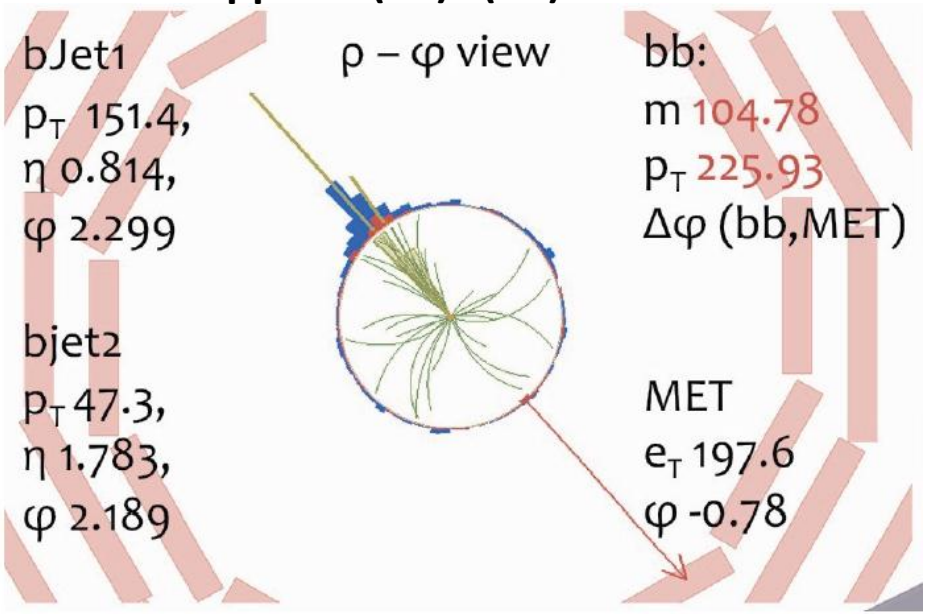
- peak lumi ~ $3.5 \times 10^{-33} cm^{-2} s^{-1}$
- > 5/fb recorded @ > 90% eff
- mean pile-up ~10, not a problem

What do we see at low mass?

(Moving in order of decreasing branching fraction)

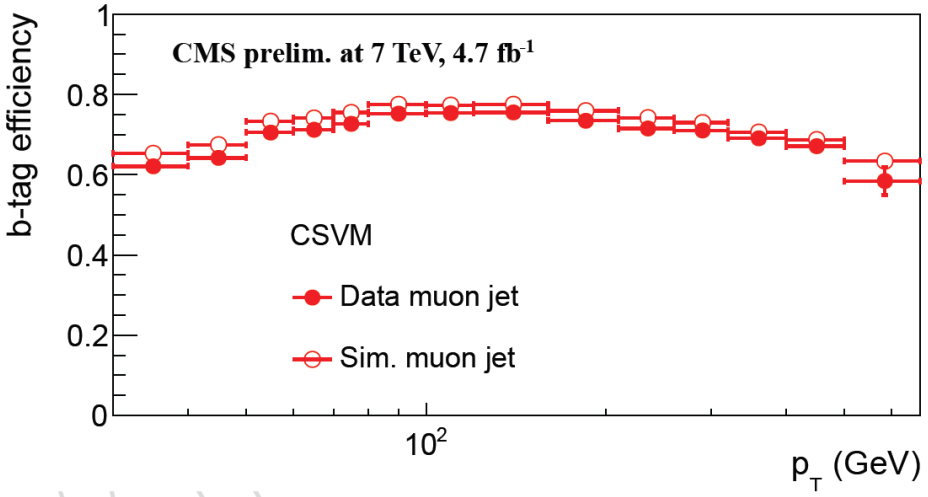
$H \to b\bar{b}$

Candidate pp → Z(νν)H(bb) event

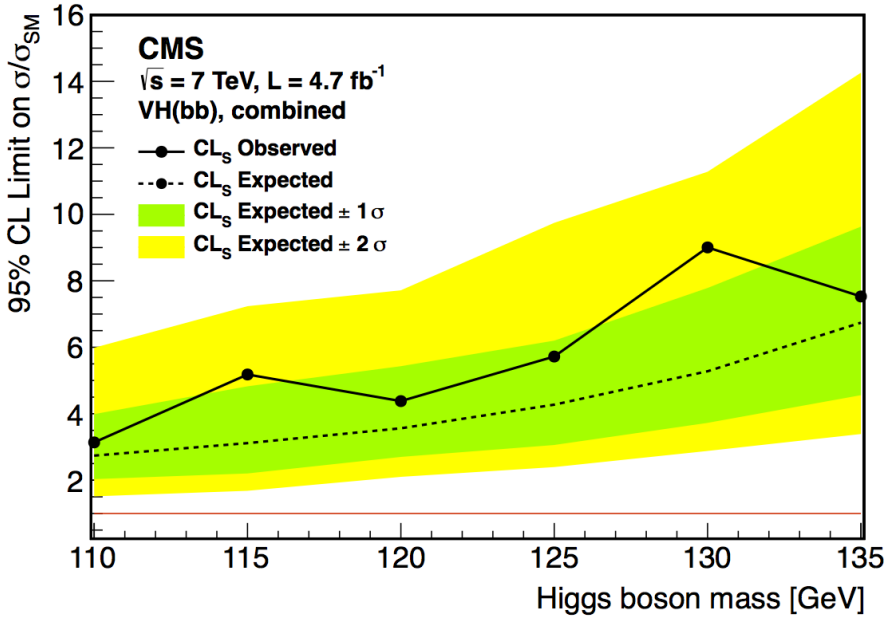


- **Most sensitive in VH channel**
  - V kills QCD and provides trigger
  - p_T spectrum of V+jets is softer
    - boosting V and H increases S/B
    - Standard dijet reconstruction
  - 3 topologies (5 channels):
    - Zℓℓ, Zνν, Wℓν [ℓ = e, μ]
- **Main backgrounds**
  - V+bb, ttbar, single top, VV

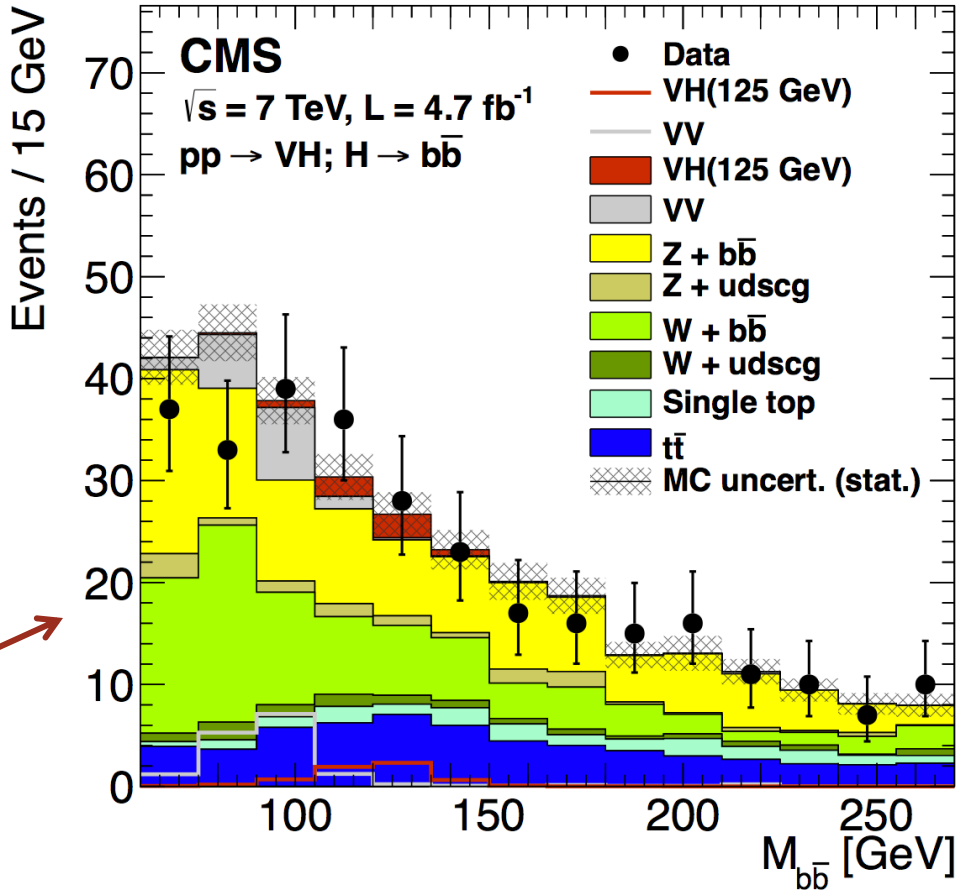
- **b-jet identification is critical**
  - Fake rate < 2% for ε ~ 70%
  - p_T dependence calibrated in data using $t\bar{t}$ events



$H \rightarrow b\bar{b}$: Results

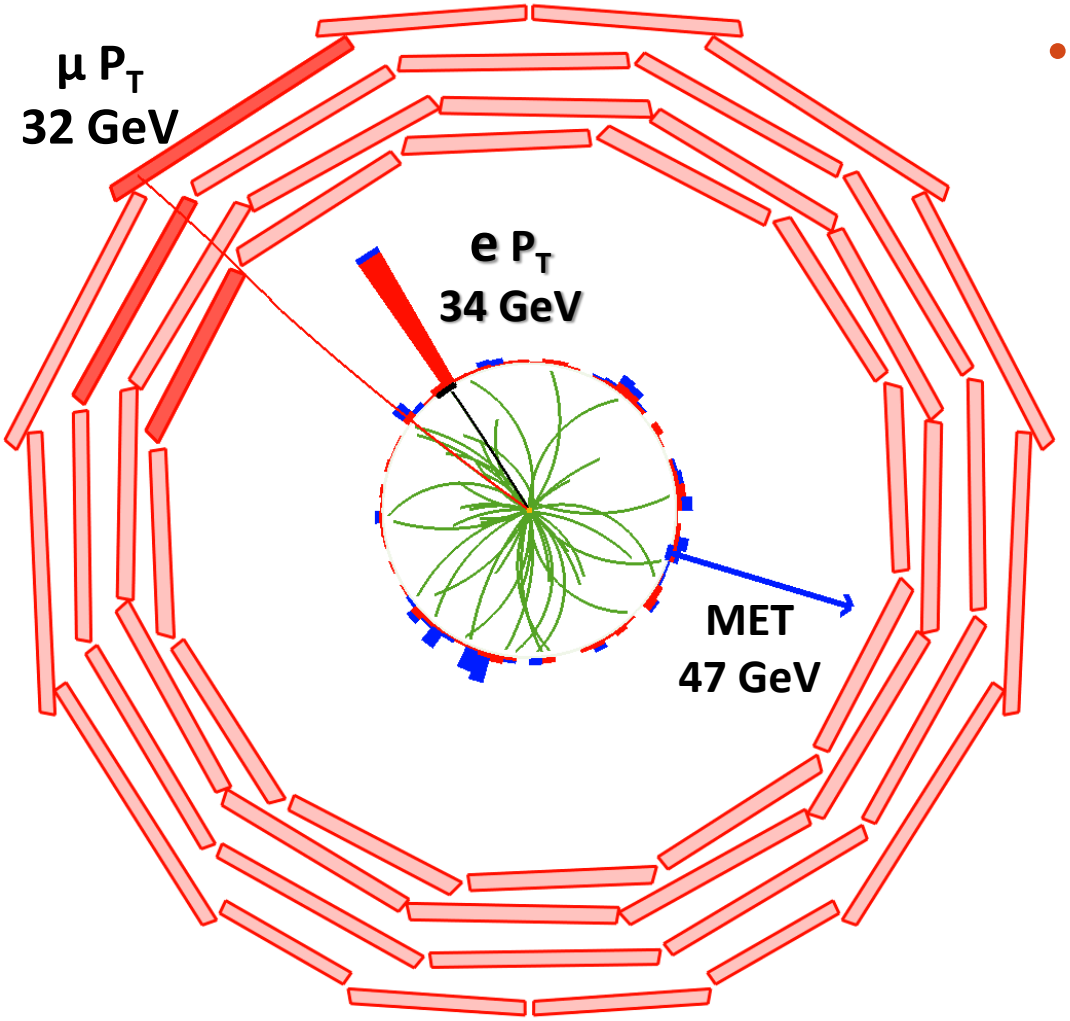


M_{jj} for sum of all five channels



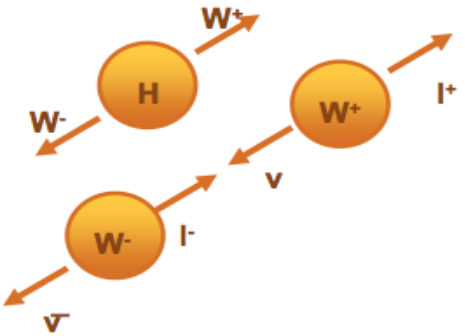
- **Results from MVA analysis**
  - **exclude 3-9 x SM** @ 95% CL_S
  - cross-check analysis on M_{jj}
  - many improvements on the way
- **Coming attractions**
  - $H \rightarrow bb$ using VBF and ttH

$H \rightarrow WW \rightarrow 2\ell 2\nu$



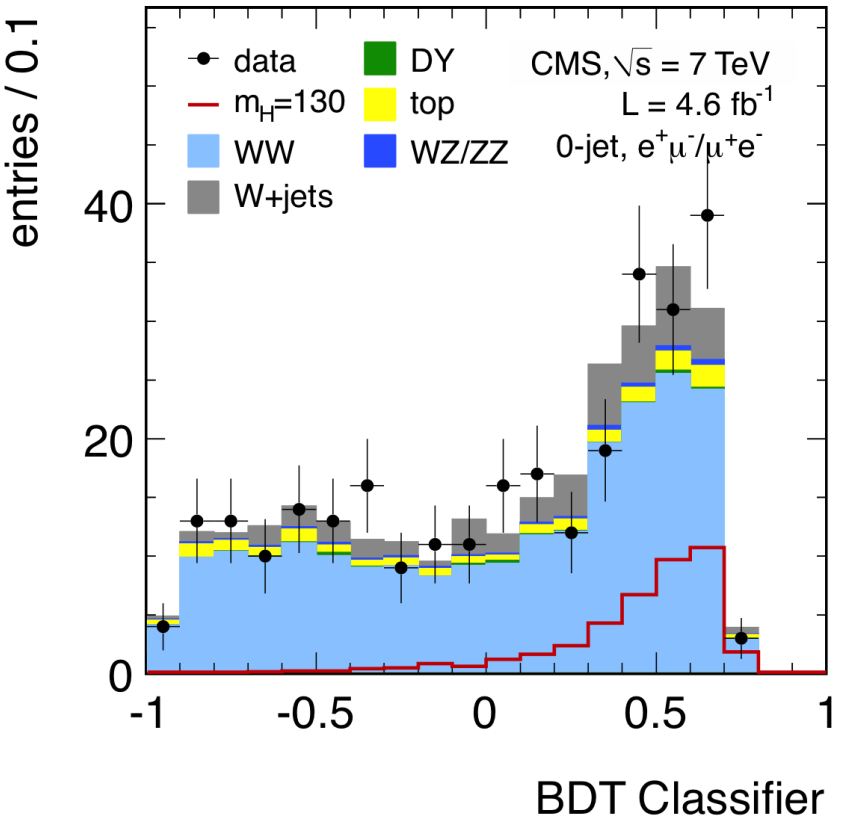
- **364kg Gorilla**
  - 2nd largest σ x BF
  - Charged leptons for trigger
  - Controllable backgrounds
  - Kinematic handles
- **Sensitivity: 115 – 600 GeV**

Spin-0 Higgs + V-A weak int. = small angle between ℓ's, and ν's

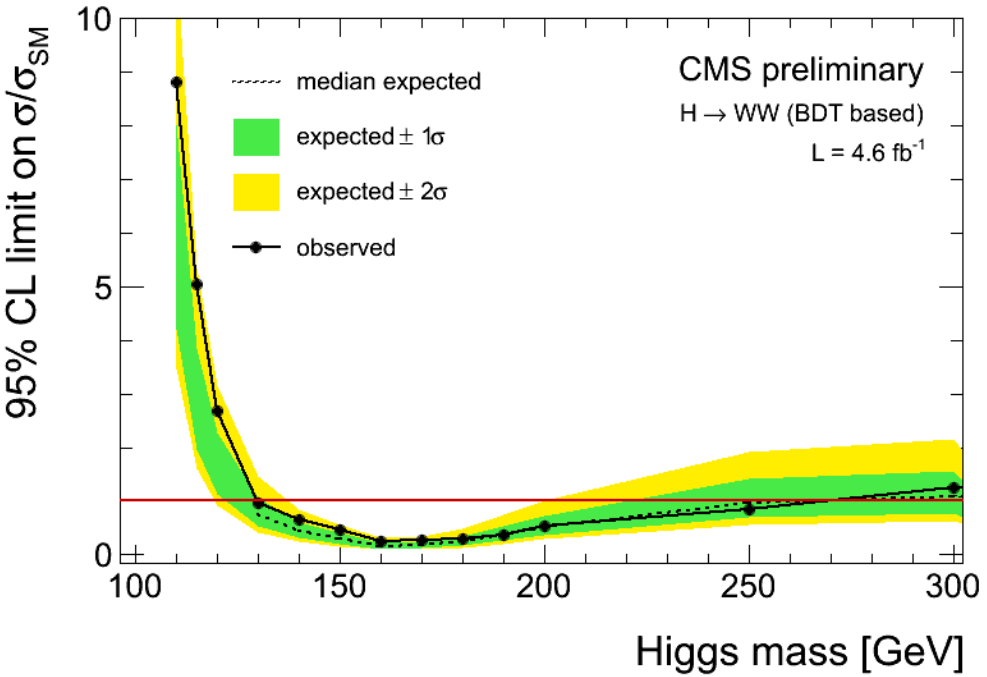


Only real drawback is no sharp mass peak (20% resolution in M_T)

H → WW→2ℓ2ν: Results

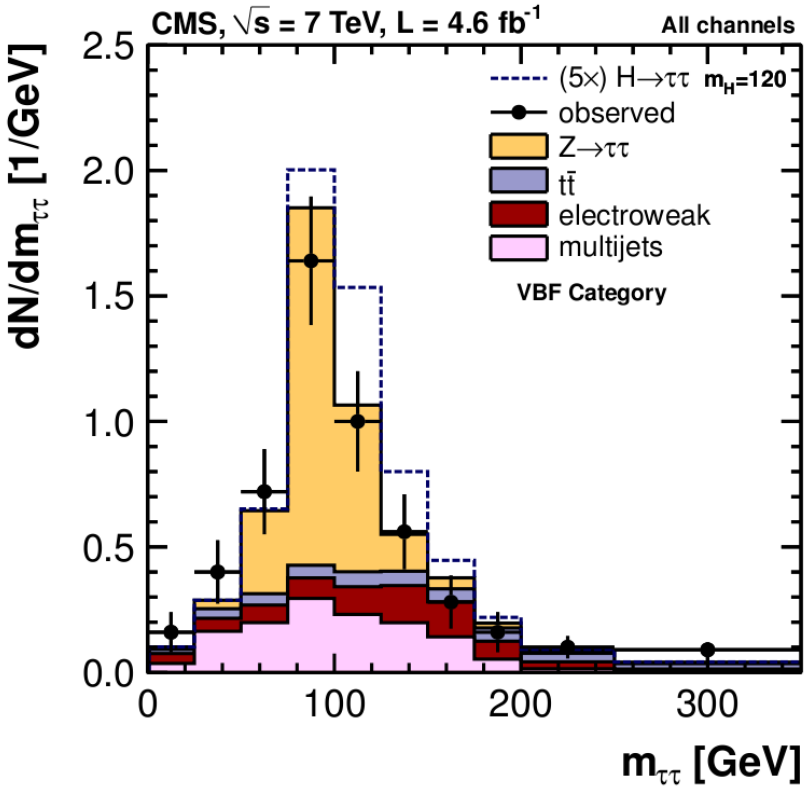


- **Analysis method:**
  - MVA shape analysis with 0/1 jet
    - Cross-check includes VBF (2 jets)
  - Main bkgs obtained from data
  - Not much room left for improvement
    - **Added WH(WW) [HIG-11-034]**
    - adding WW(2ℓ2j)

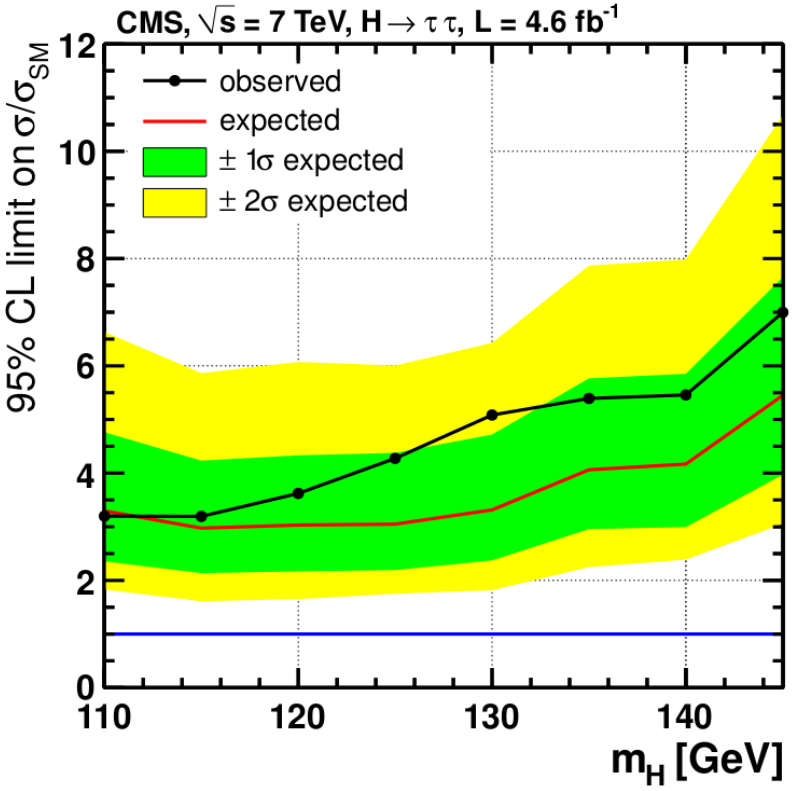


- **Results (95% CL_s)**
  - Exp exclusion: 127-270 GeV
  - Obs exclusion: 129-270 GeV

$H \rightarrow \tau\tau$



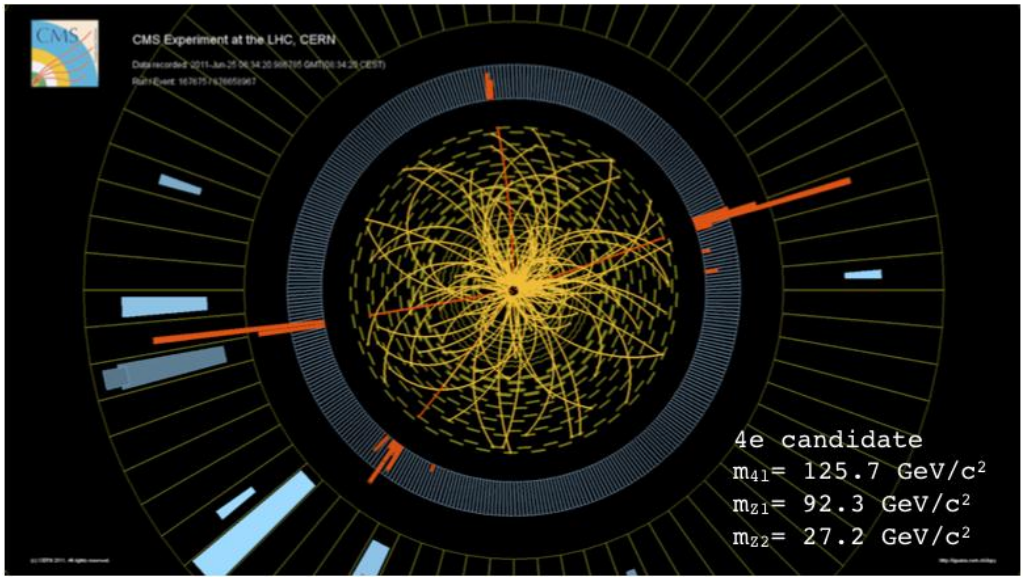
- **Analysis method:**
  - Binned ML fit to $M_{\tau\tau}$ in categories
    - 0/1 jet, boosted, VBF
  - Use $e\mu$, $e\text{-}\tau_h$, and $\mu\text{-}\tau_h$



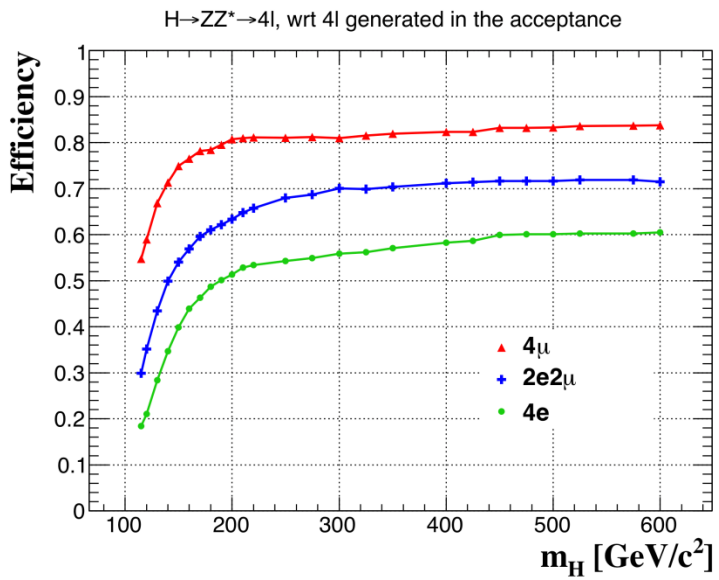
- **Results from SM analysis**
  - **exclude 3-7 x SM** @ 95%CL_S
  - New SM results (Moriond 2012)
    - $\mu\mu$ mode [HIG-12-007]
    - WH($\tau\tau$) [HIG-12-006]

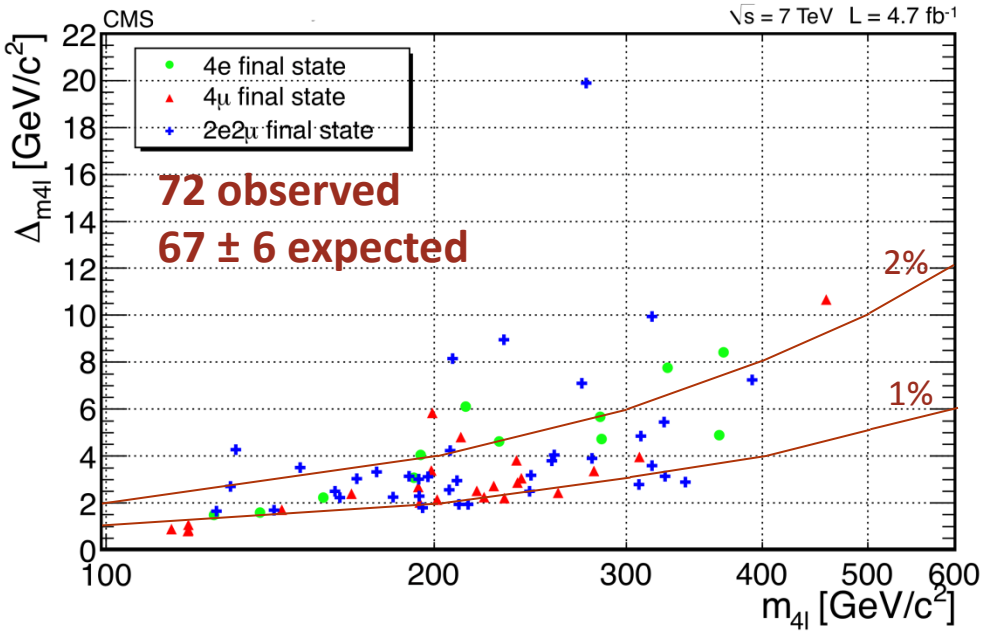
HIG-11-029 (arXiv.1202.4083)

$H \rightarrow ZZ \rightarrow 4\ell$

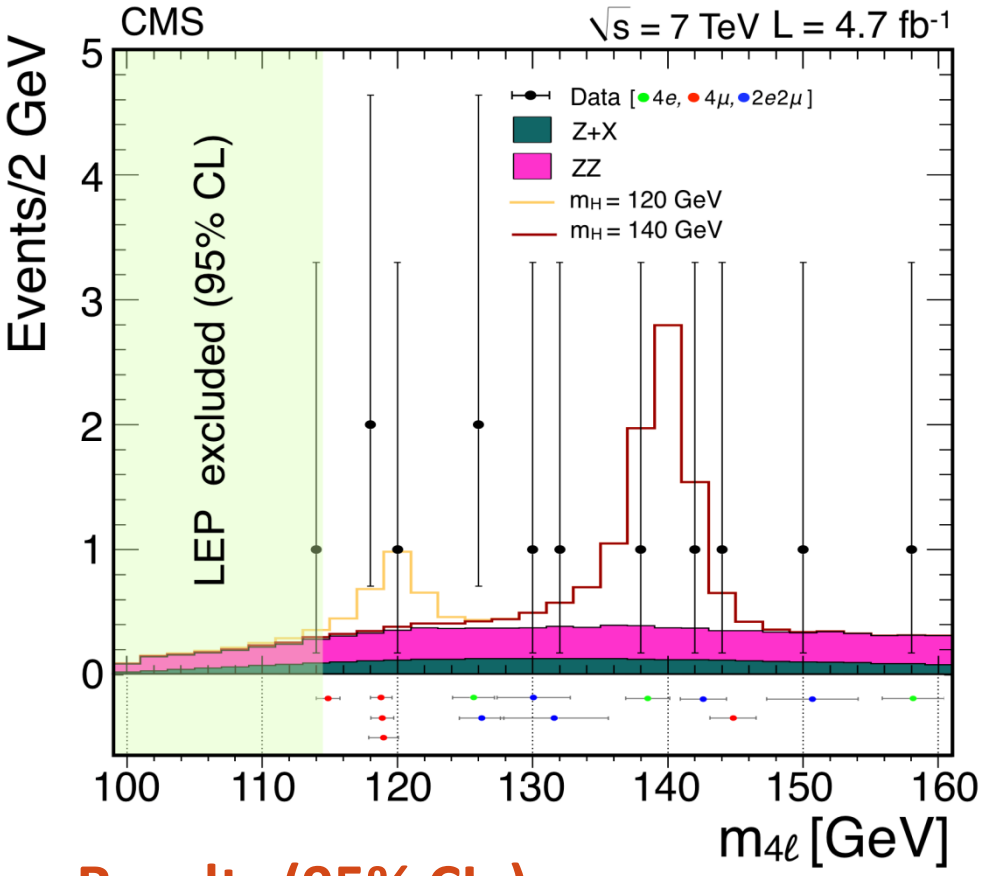


- **High purity**
  - Small signal, smaller bkg
- **4 charged tracks**
  - > 97% trigger efficiency
  - Excellent resolution (1-2%)
  - Robust against pile-up

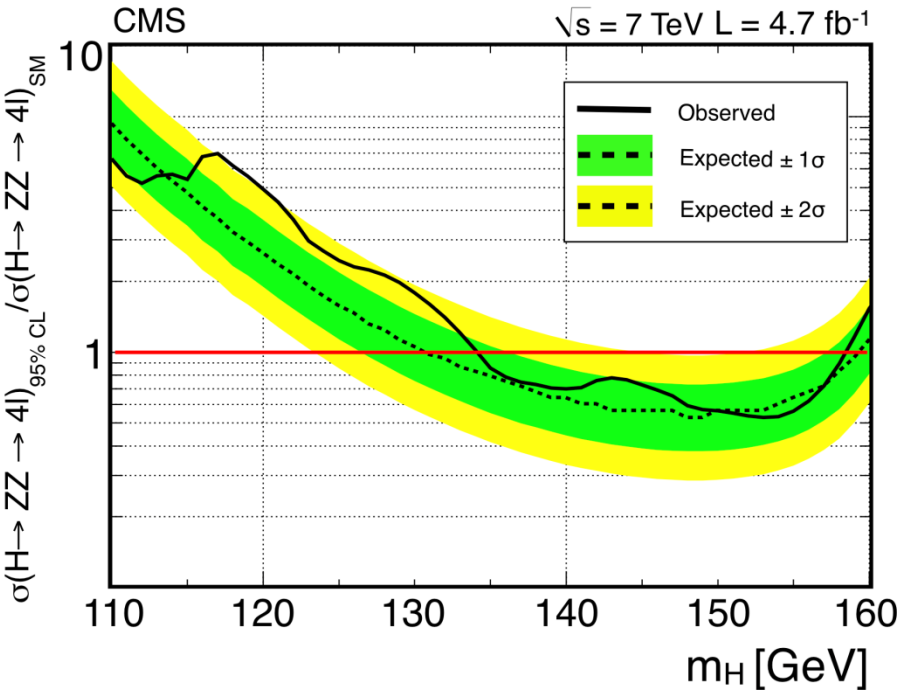




$H \rightarrow ZZ \rightarrow 4\ell$: Results

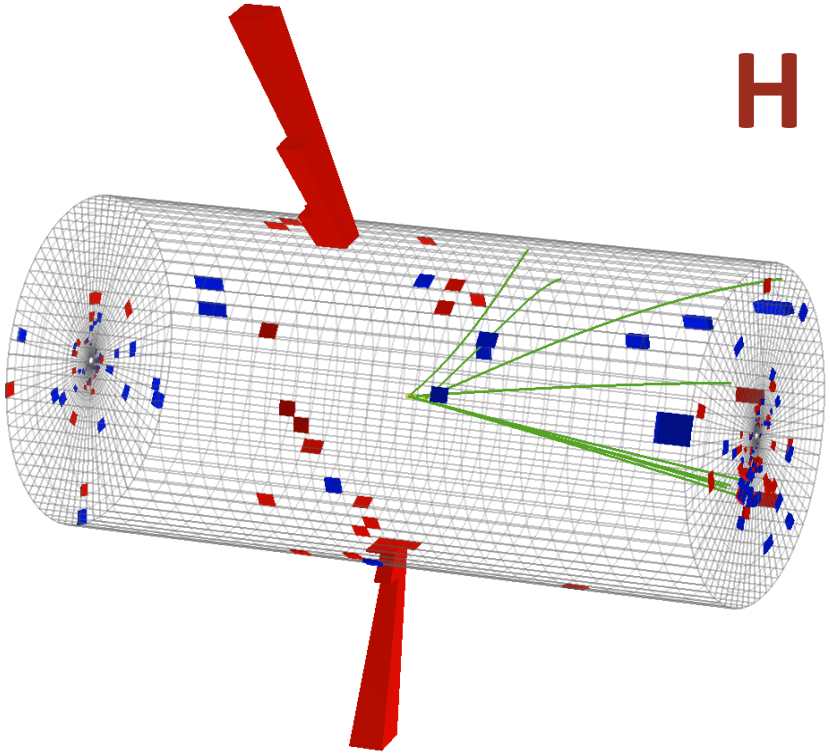


- **In the region 100 – 160 GeV:**
  - 13 events observed
    - 5 μμ, 5, eμ, 2 ee
  - 9.5 ± 1.3 expected
- **Some clustering near 119 GeV**
  - But only in μμ

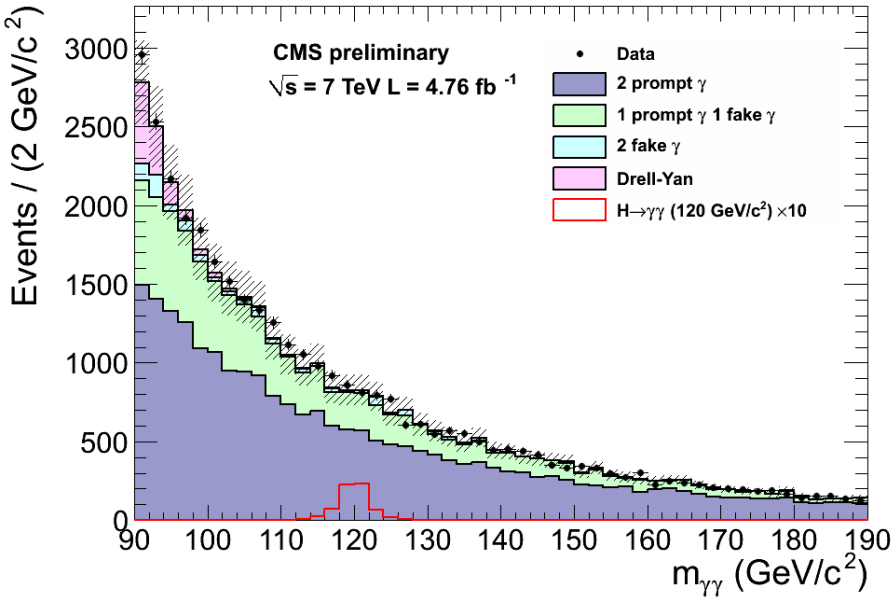


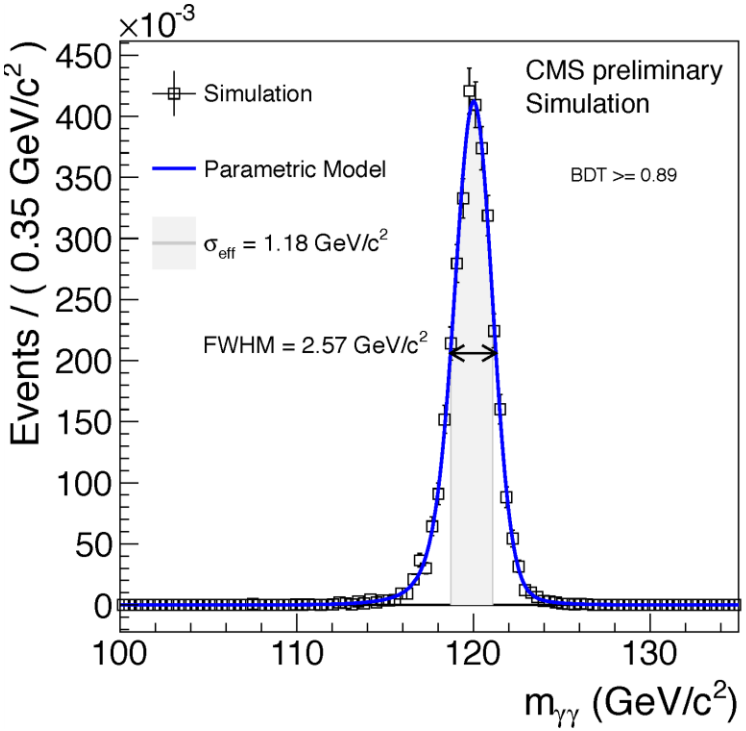
- **Results (95% CL_s)**
  - **Observed exclusion: 134-158 GeV**
  - Broad excess in obs limit 115-135 GeV, expect narrow excess if Higgs

$H \rightarrow \gamma\gamma$

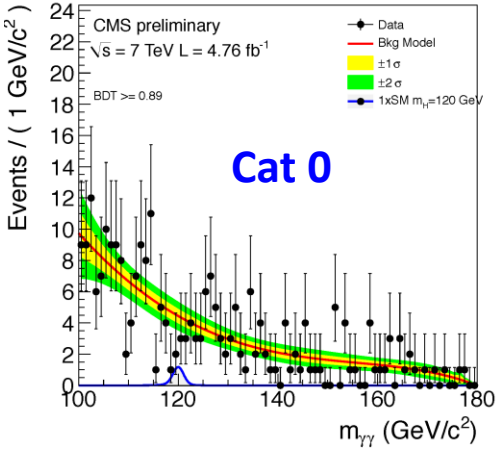


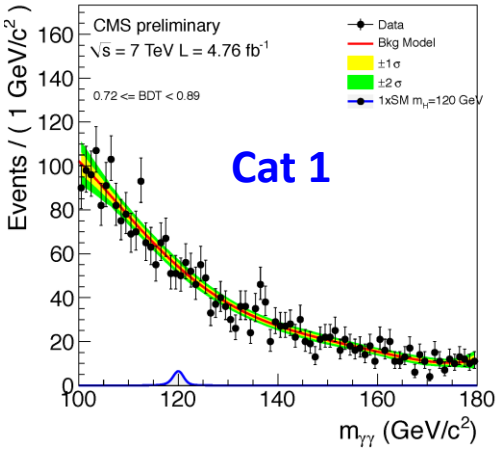
- **Resolution is critical**
  - Smallest BF in searched channels
  - Large irreducible diphoton bkg
  - Challenging trigger with pile-up
  - Few event-level handles
- **Search for narrow peak on large smoothly falling background**

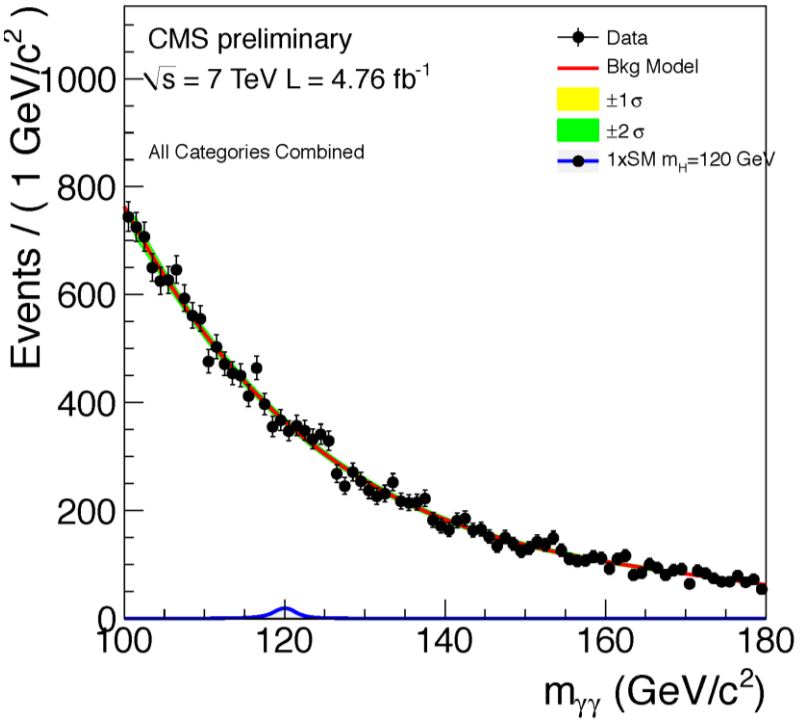




$H \rightarrow \gamma\gamma$: MVA Analysis





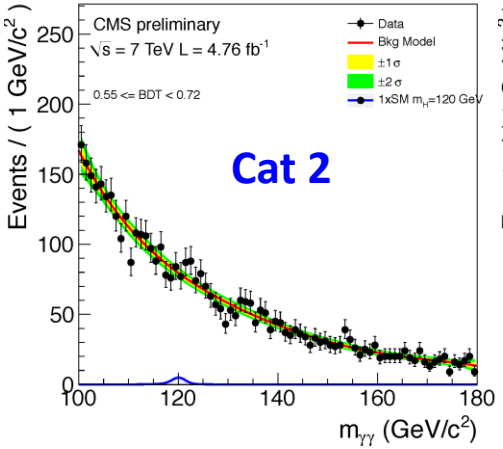


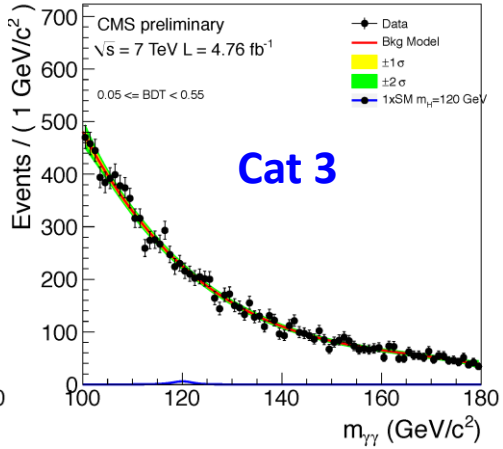
Strategy

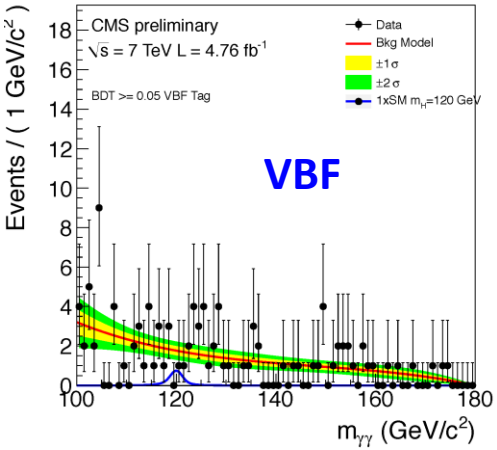
- Categorize events based on diphoton
  - "diphoton BDT"
- Add VBF events
- Fit $M_{\gamma\gamma}$ in categories

Background shape

- Obtained from data
- Different functions tried
- Additional cross-checks

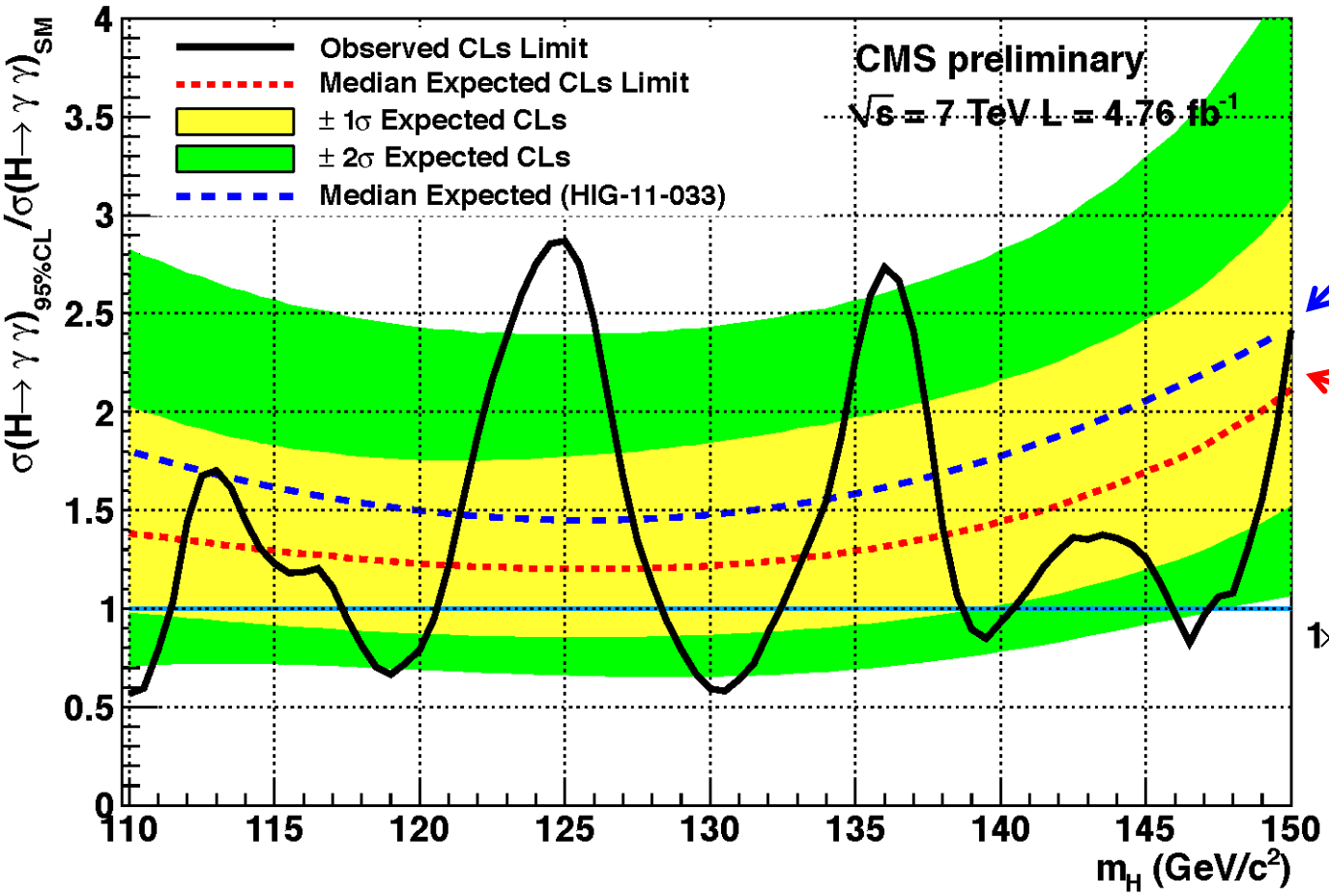






20% improvement in expected limit over published result

$H \rightarrow \gamma\gamma$: Results



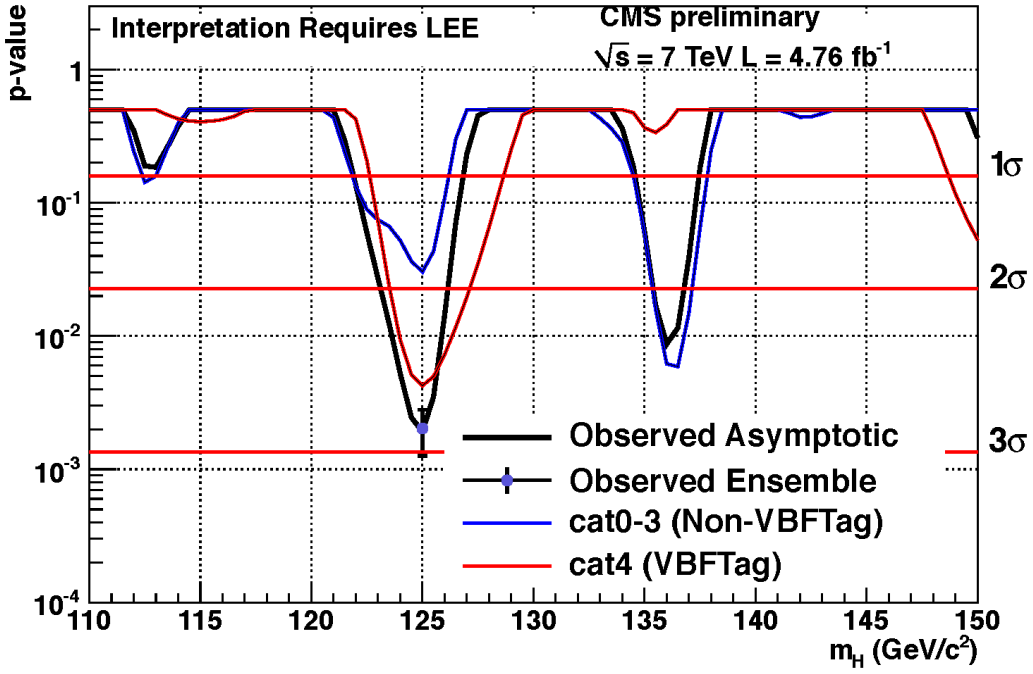
arXiv.1202.1487 (published)

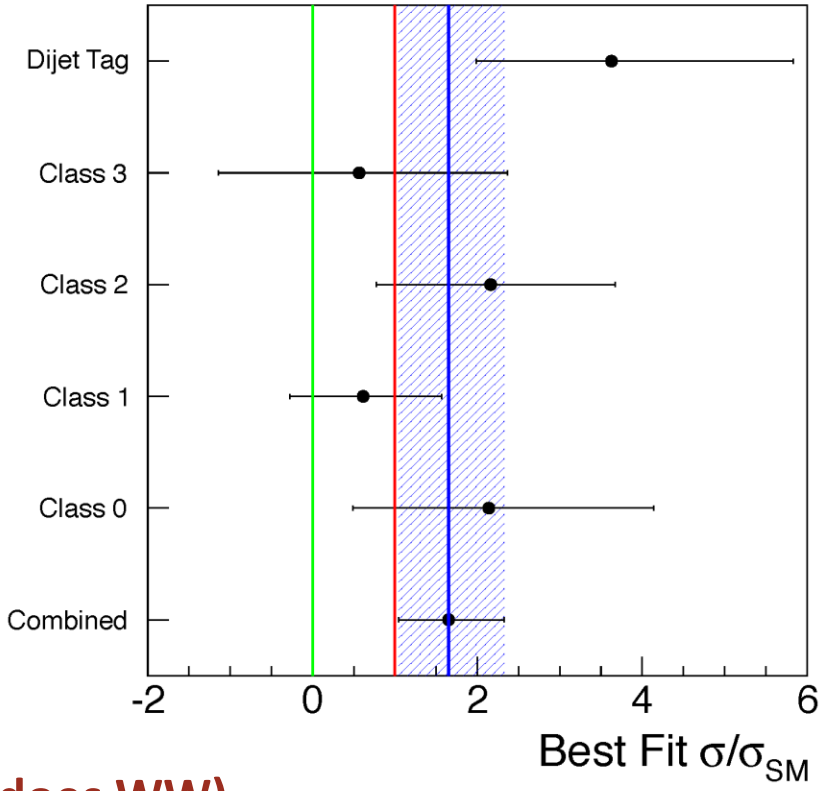
CMS PAS HIG-12-001

Expected limits from 1.2 – 2.1 for 110-150 GeV (95% CL_S)

Two regions of large excess: 125 GeV and 136 GeV

$H \rightarrow \gamma\gamma$: p-values and signal strength





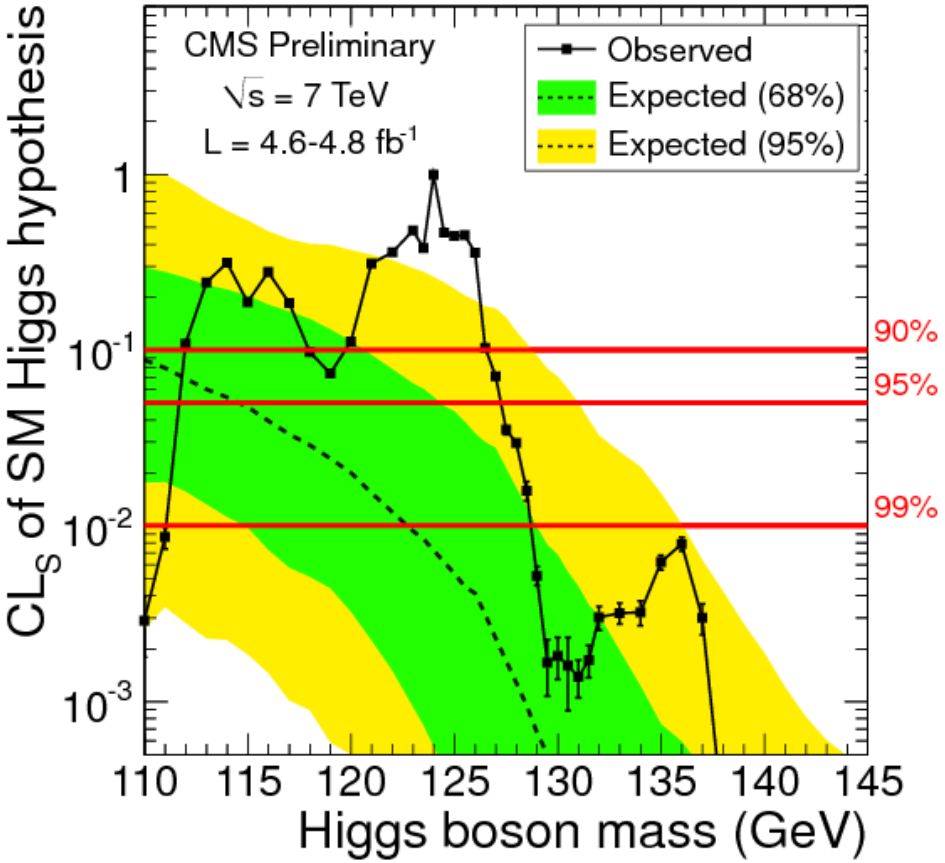
VBF does not like a 136 GeV Higgs (neither does WW)

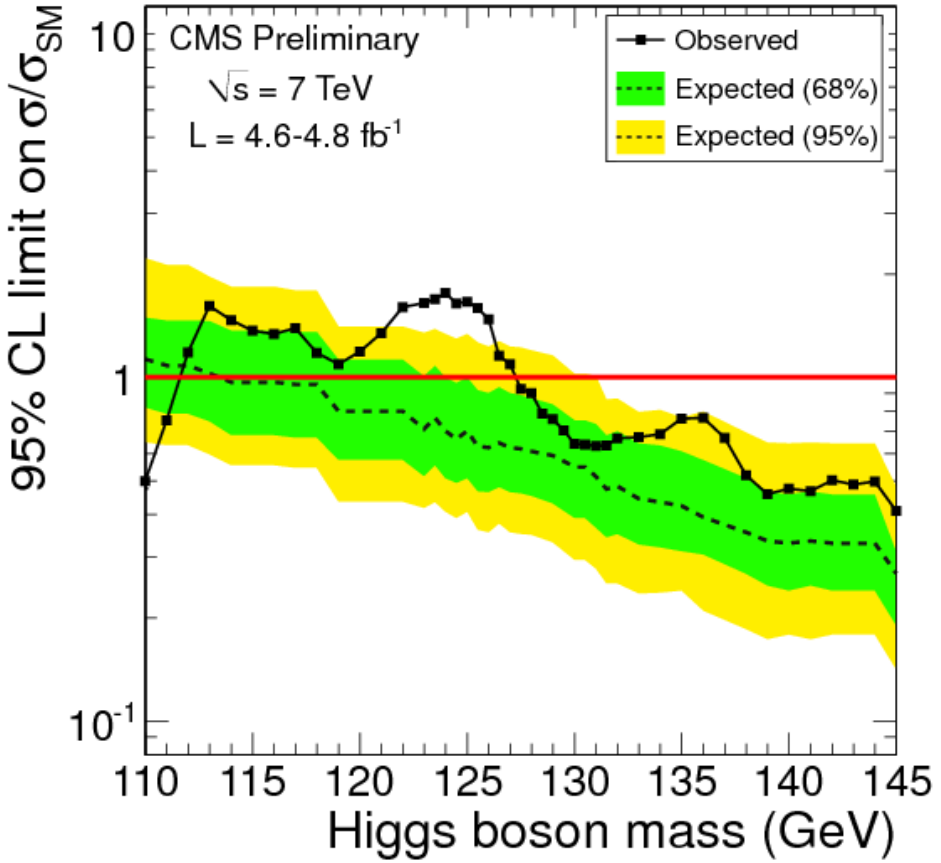
@ 125 GeV: local p-value = 2.9σ, global p-value = 1.6σ

LHC will provide the conclusion (maybe soon!)

Higgs Combination at Low Mass

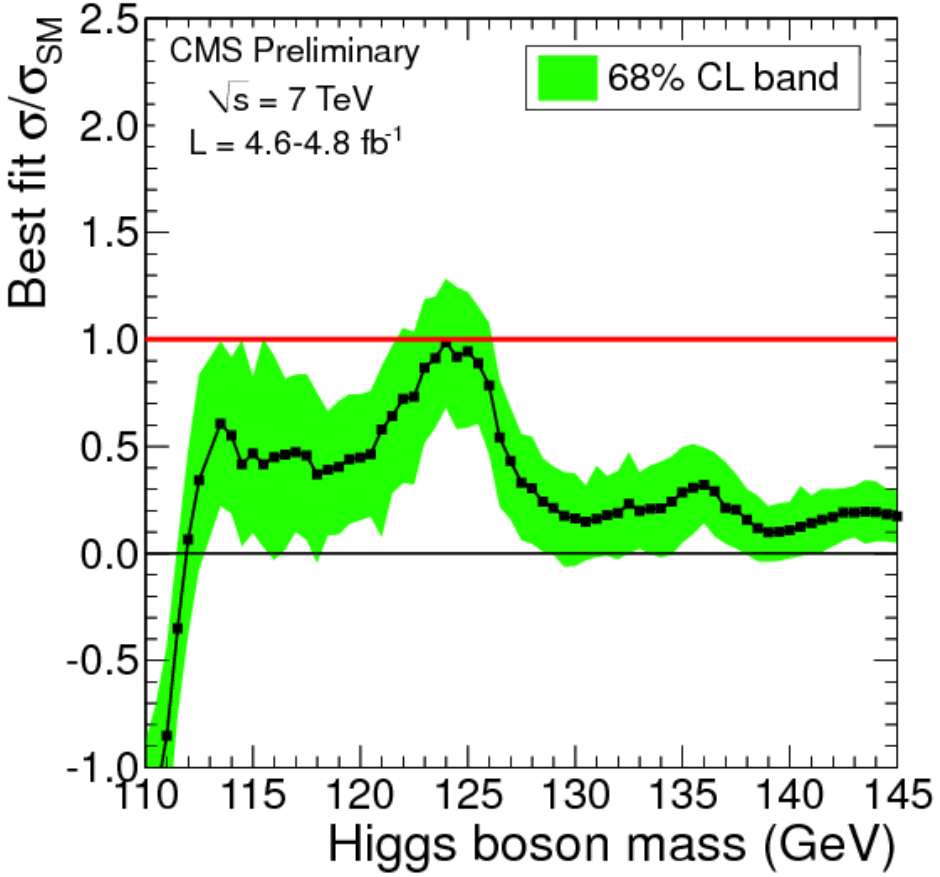
CMS Winter 2012 Combination

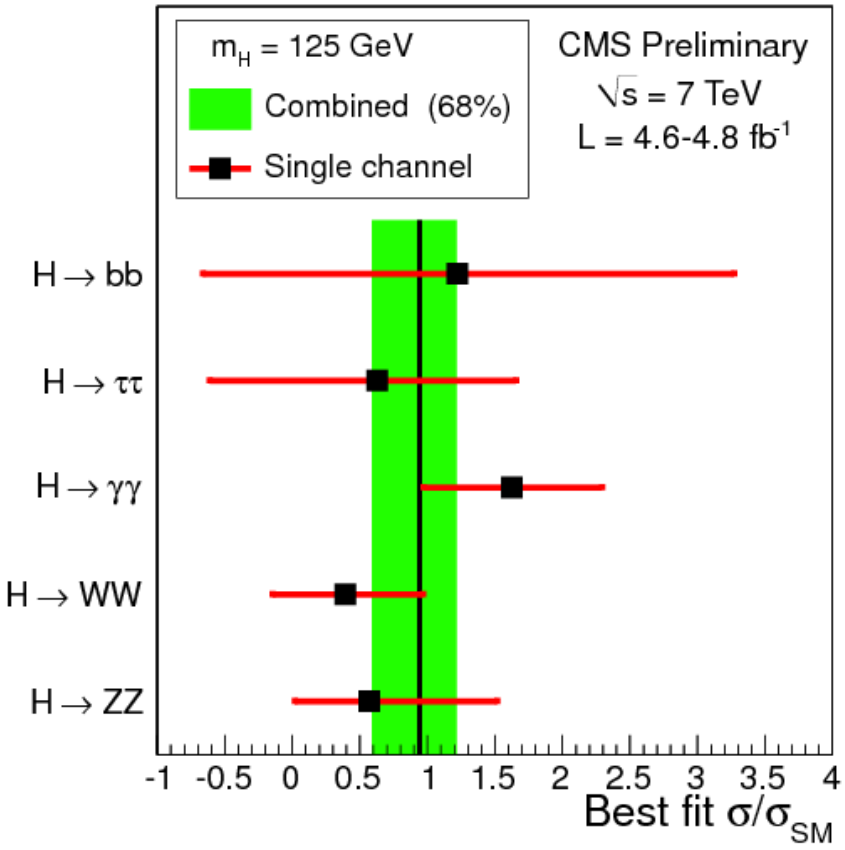




@95% CL_S { **Expected exclusion: 114.5 – 543 GeV**
Observed exclusion: 127.5 – 600 GeV

Is it the SM Higgs?

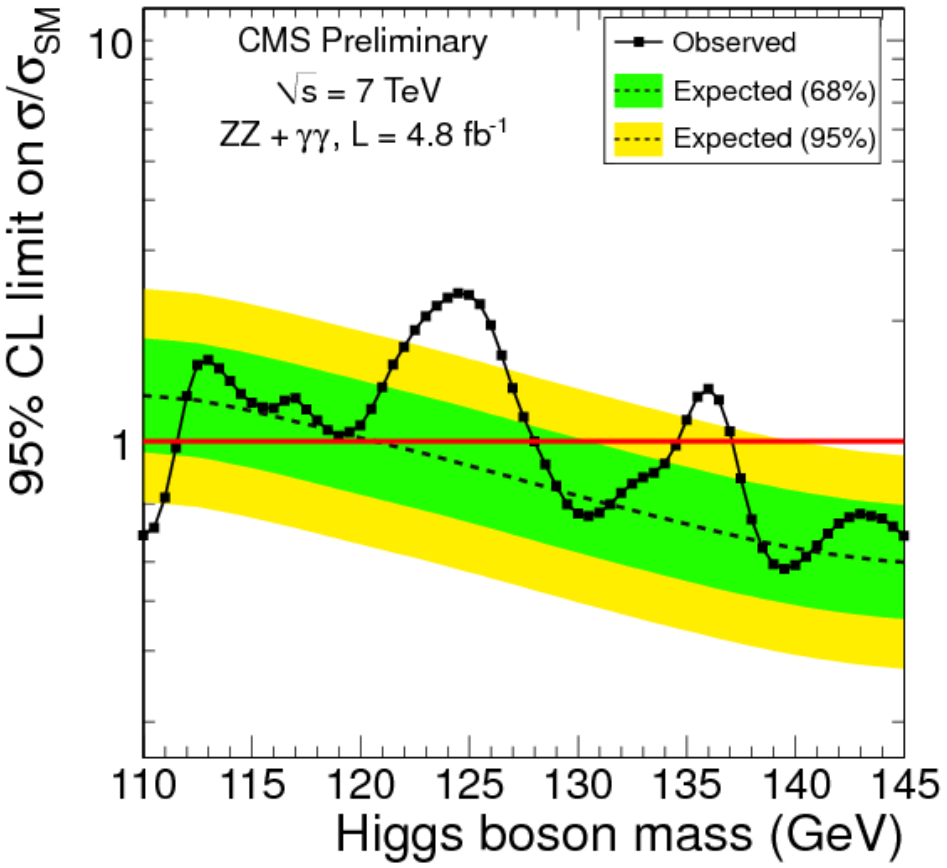




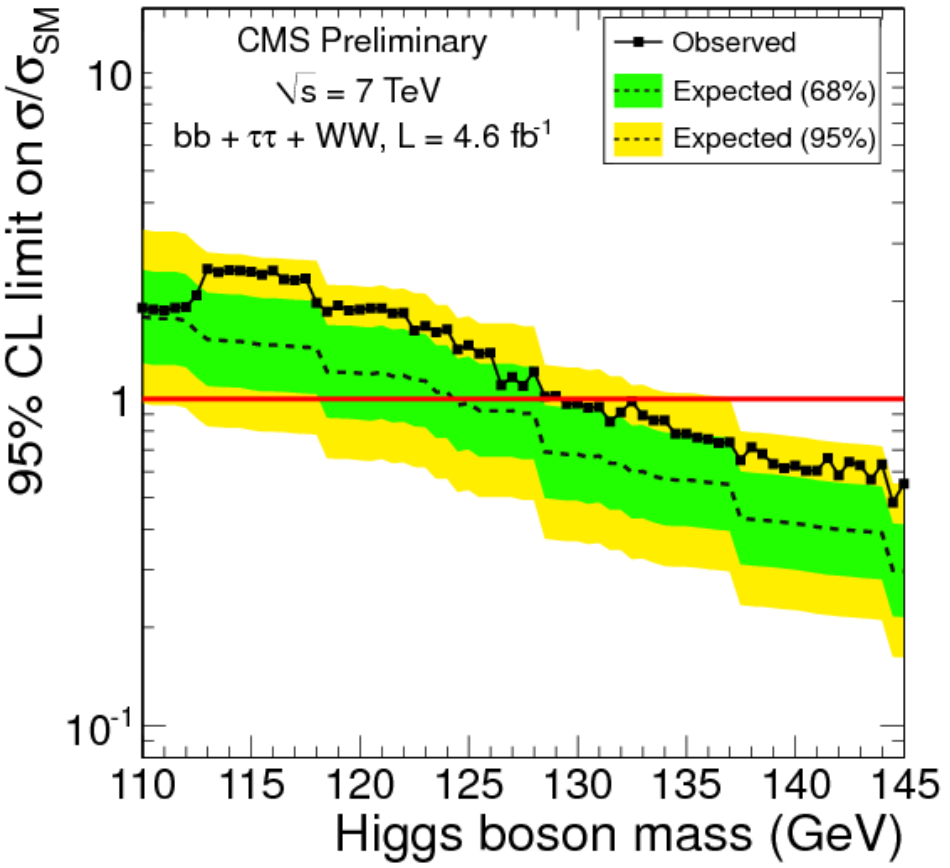
All channels are consistent with a SM Higgs @ 125 GeV

γγ + ZZ vs. bb + ττ + WW

1-2% mass resolution



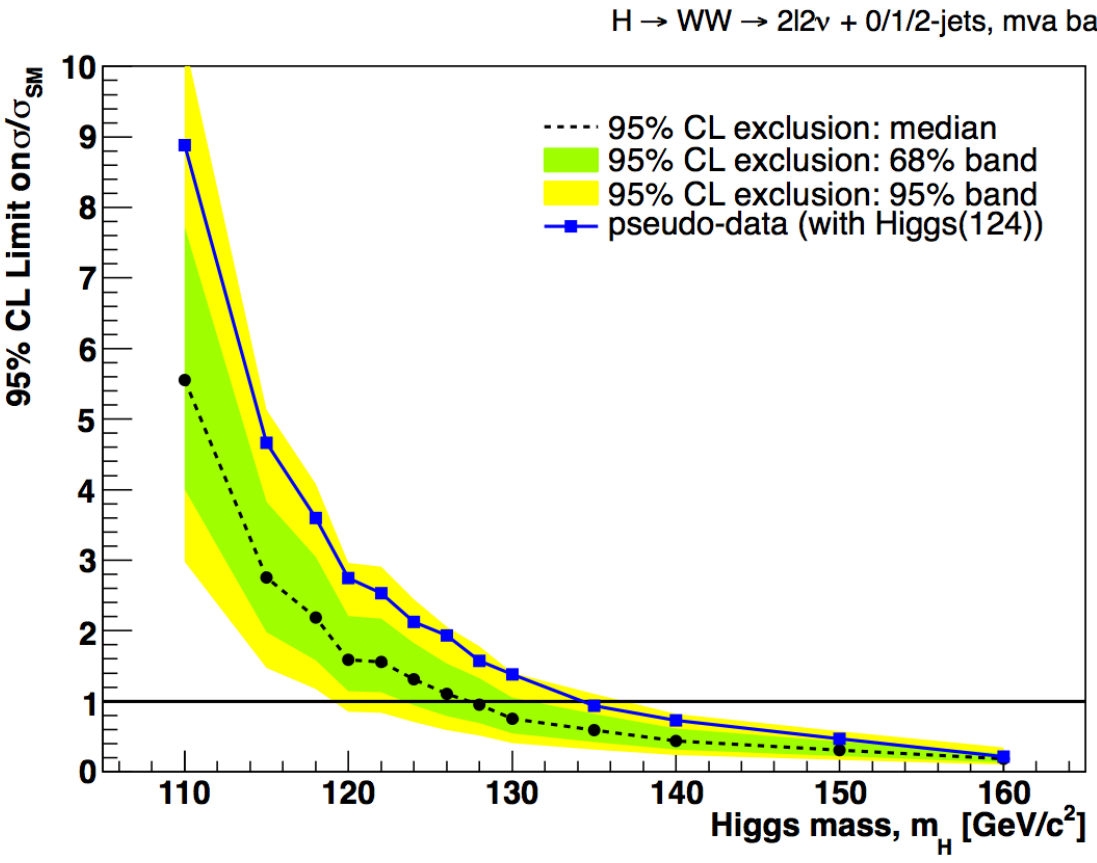
10-20% mass resolution



ZZ does not remove excesses

Broad 1σ excess 112 – 145 GeV

What Would Signal Look Like in WW?



Run pseudo-experiments injecting WW signal @ 124 GeV

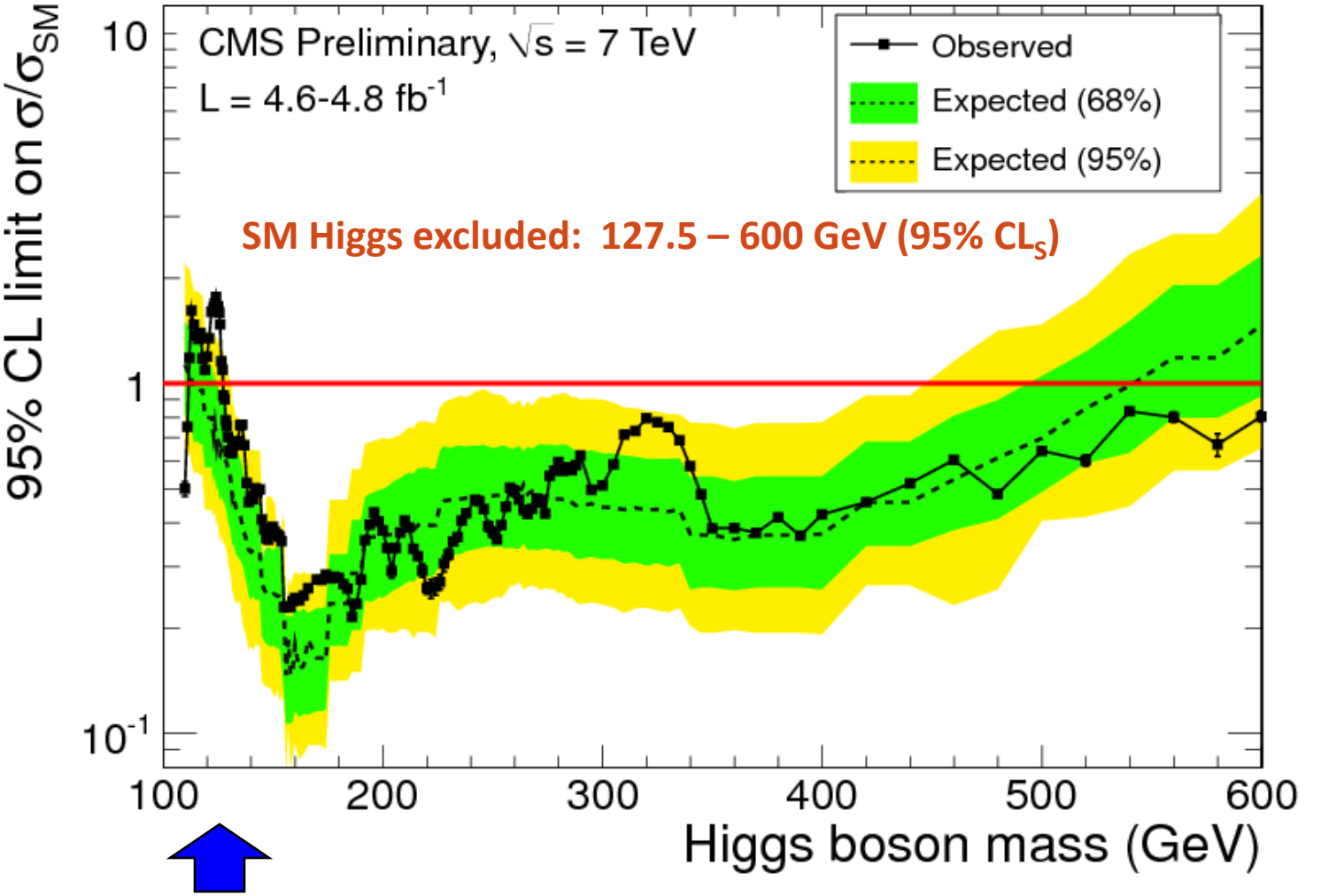
Reproduce the analysis and recalculate "observed" limits

Results look very similar to actual data result

Demonstrates that observed excess in WW is compatible with a SM Higgs near 125 GeV

What if no SM Higgs at Low Mass?

CMS Winter Combination: Full Range



If not here…

It must be way out here

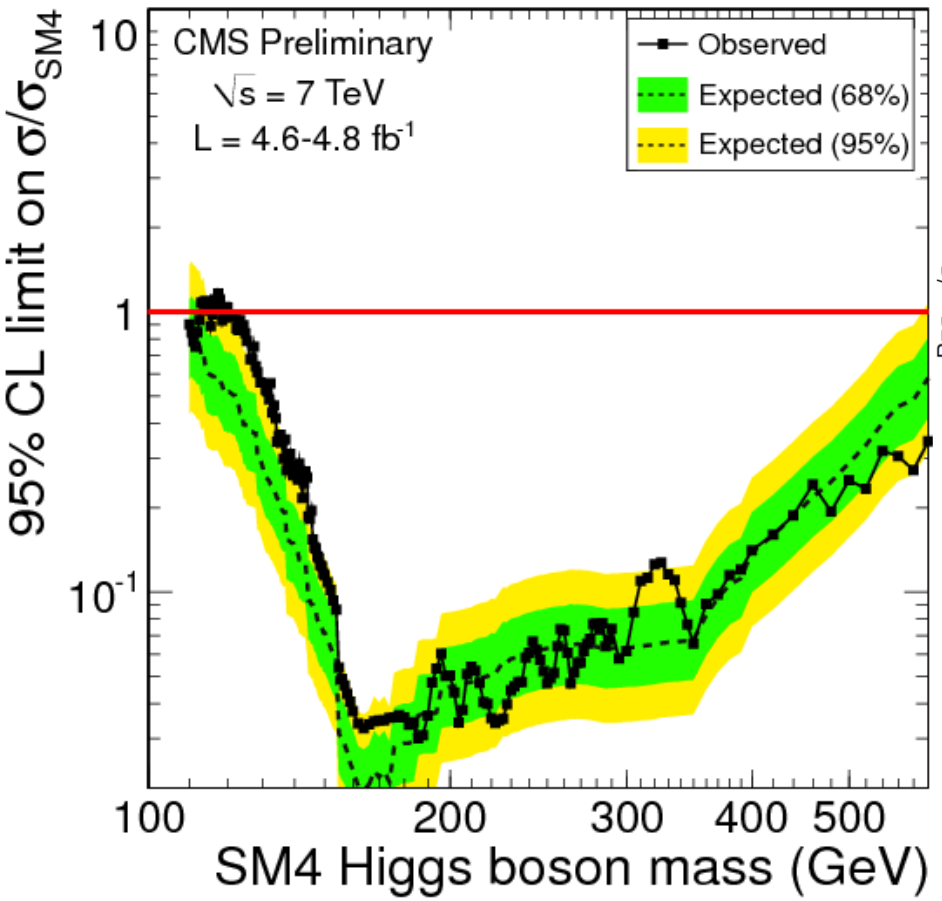
BSM Higgs Searches

BSM Overview

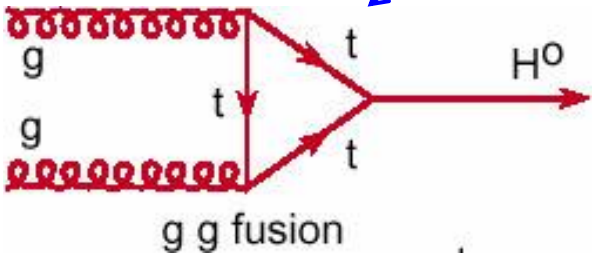
- **Extensions to the SM**
  - 4^{th} generation of heavy fermions
  - Fermiophobic Higgs sector
- **Supersymmetric**
  - MSSM with two Higgs doublets
  - NMSSM with additional scalar field
- **Triple your fun**
  - Minimal seesaw model of type II
  - Triplet scalar field $\rightarrow$ doubly charged Higgs

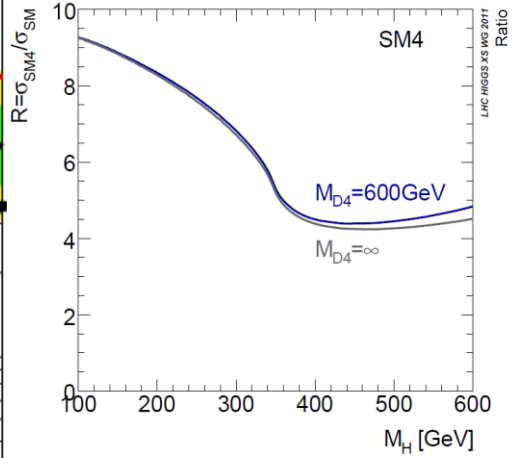
Limits on SM4 Higgs

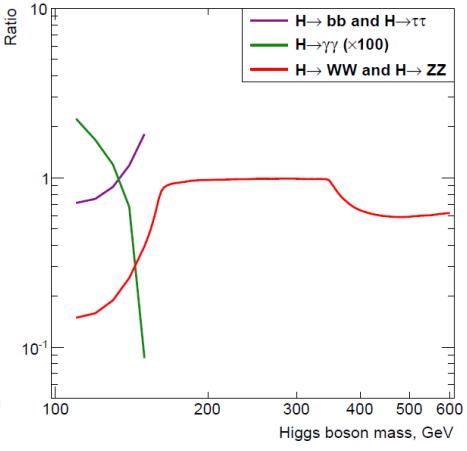
SM4 Higgs excluded for M_H > 120 GeV



Add b' and t'



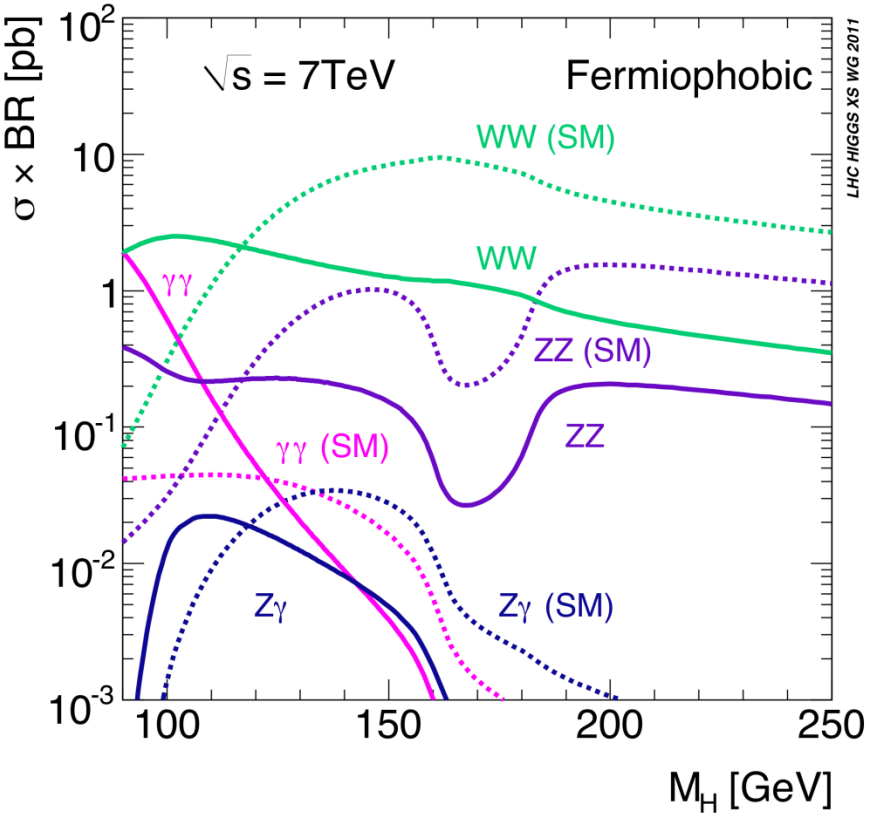


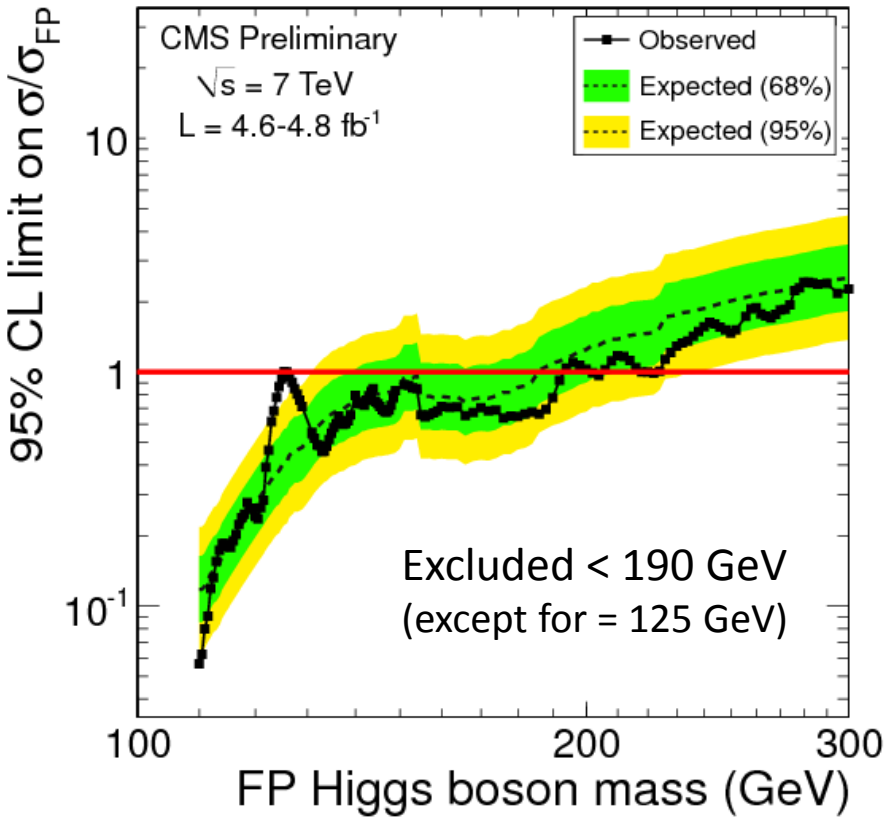


Cross sections and branching fractions modified significantly

Fermiophobic Higgs

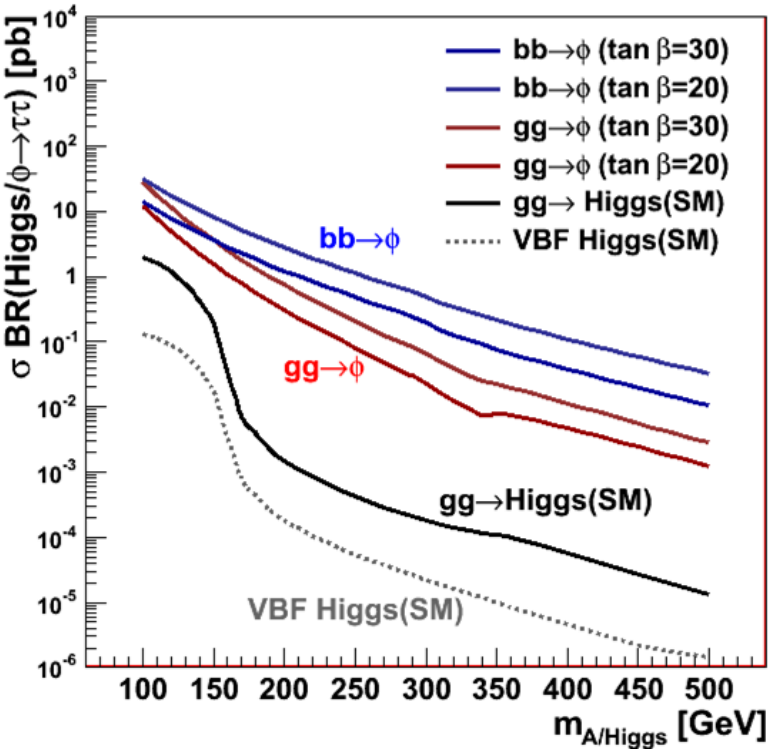
- **Assume no coupling to fermions**
  - Gluon fusion and ttH production forbidden (no change to VBF and VH)
  - Big enhancement (10x) to $\gamma\gamma$ branching fraction
  - Reinterpretation of existing analyses (VH added for $\gamma\gamma$)





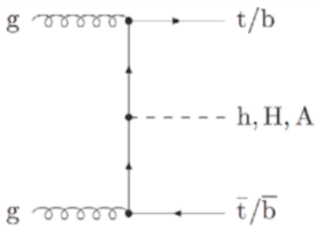
MSSM Higgs

- **Two Higgs doublets**
  - Five Higgs particles
    - Three neutral (h, H, A)
    - Two charged ($H^{\pm}$)
  - Two free parameters
    - Search in m_A – tanβ plane
- **Searches @ CMS**
  - Neutral: $\tau\tau$ (and bb)
  - Charged: look in top decays

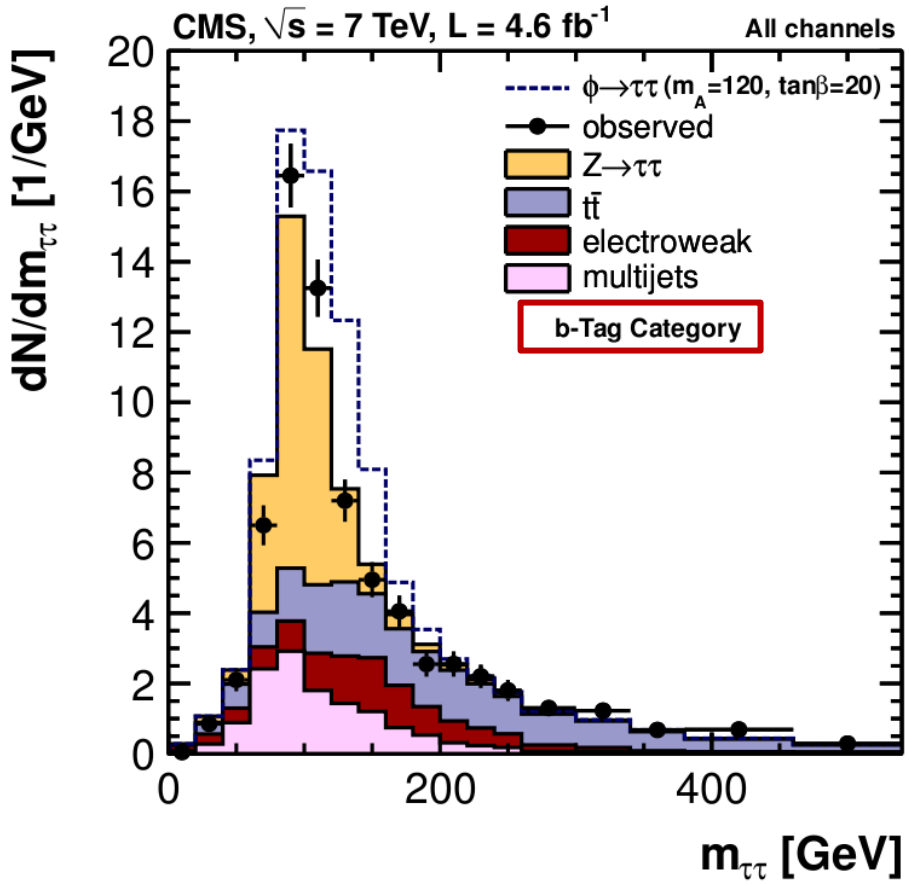


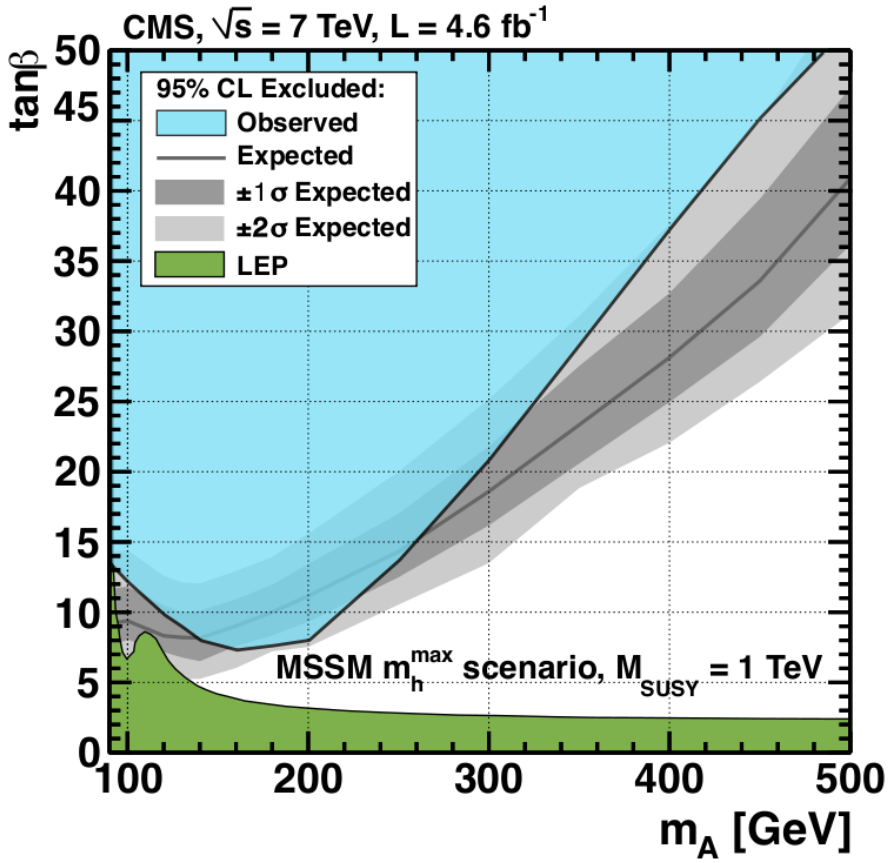
MSSM ϕ(h, H, A)

Enhanced coupling to b quarks, add associated production via b-tags



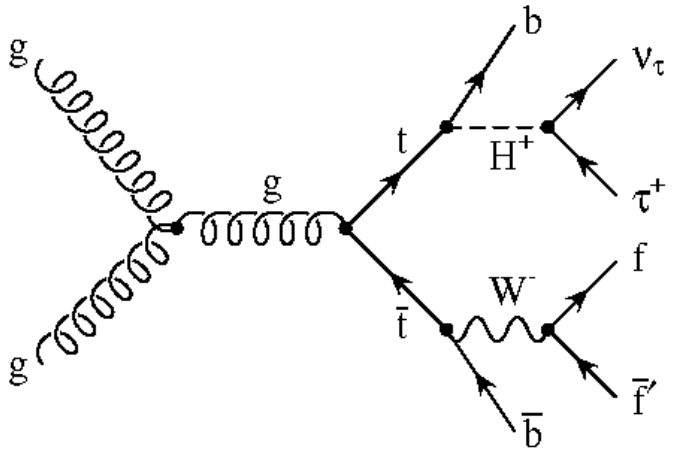
$\propto \tan^2 \beta$

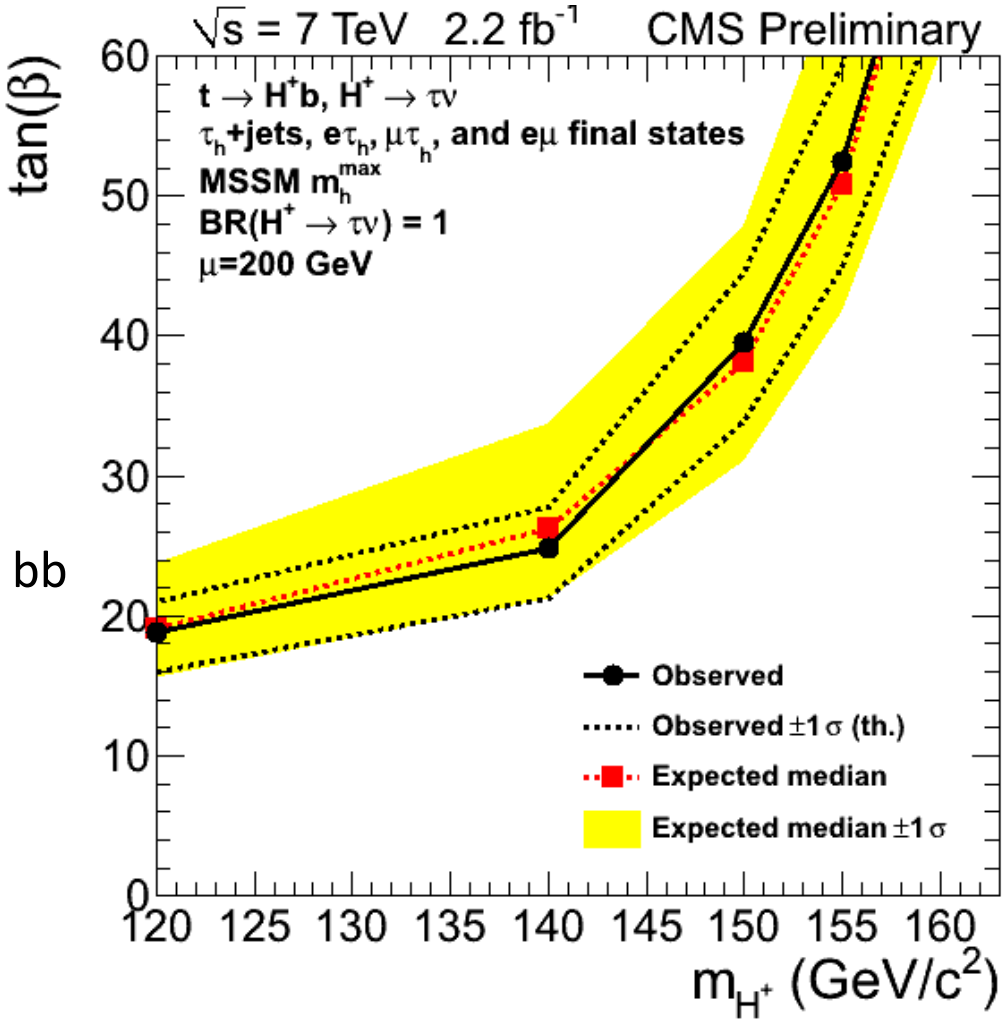




Charged Higgs

For $m_H < m_t$

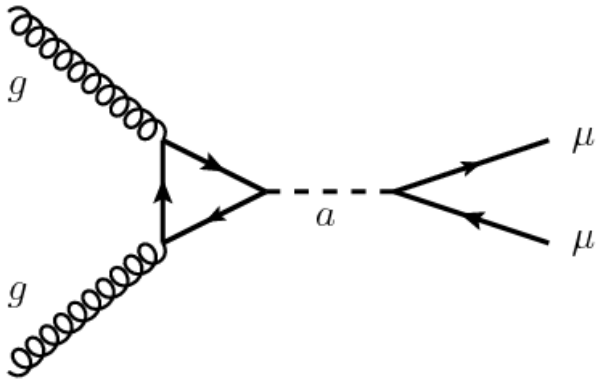


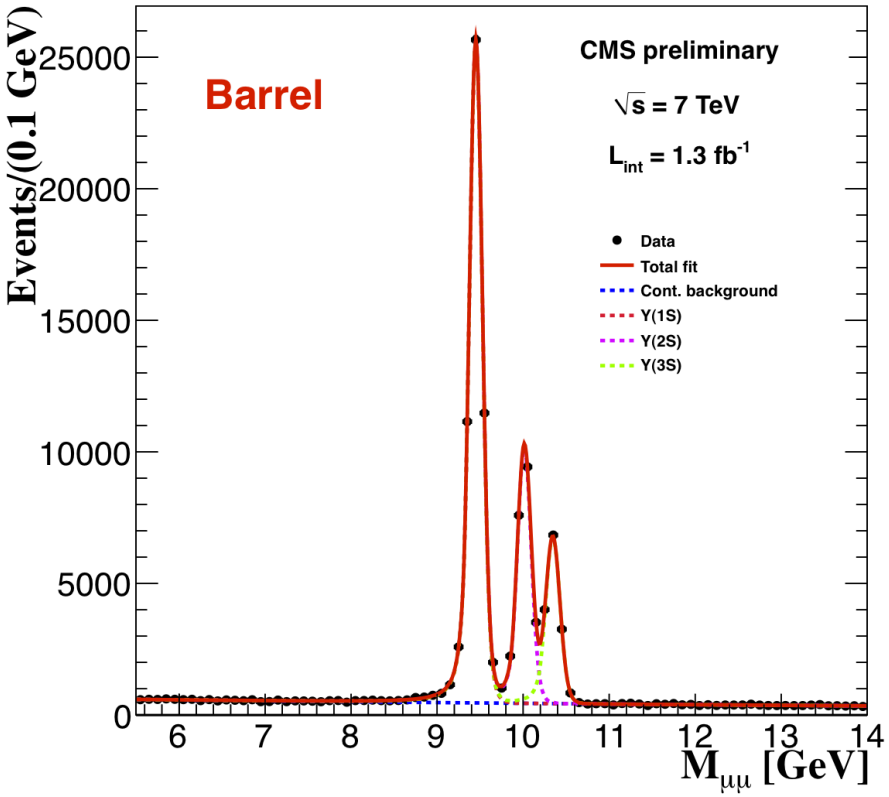


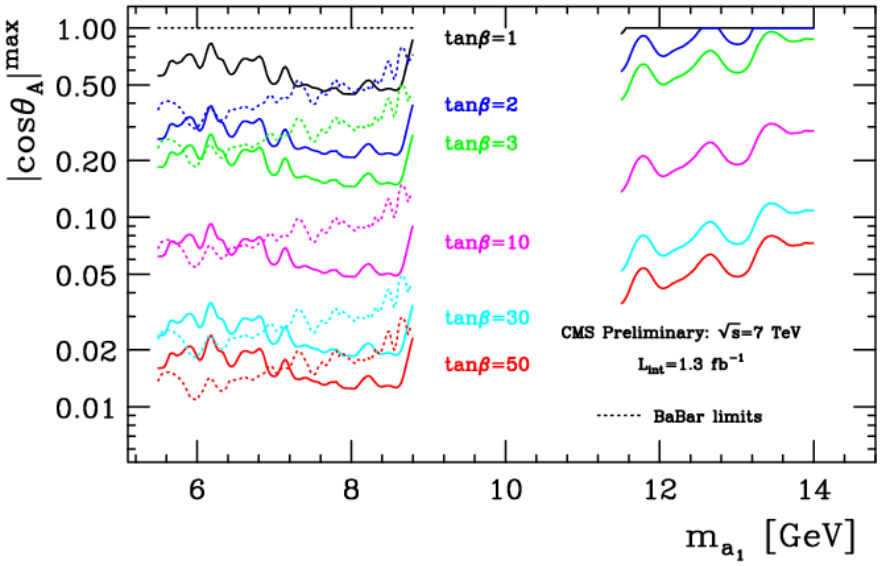
- **Strategy**
  - Look for $tt \rightarrow H^+W^-bb$ or H^+H^- bb with $H \rightarrow \tau\nu$
  - Three classed of events:
    - All hadronic with jets + $\tau \rightarrow$ had
    - Lepton + jets with $\tau \rightarrow$ had
    - Dilepton in the $e\mu$ channel
- **Constrain BF($t \rightarrow Hb$) < 3%**

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

- **Add a scalar singlet**
  - 3 CP even (h_1, h_2, h_3) , 2 CP odd (a_1, a_2), $H^{\pm}$
  - Out pops a ~10 GeV boson
  - Search for $a_1 = \mathrm{a} \cdot \cos\theta_A + a_S \sin\theta_A$

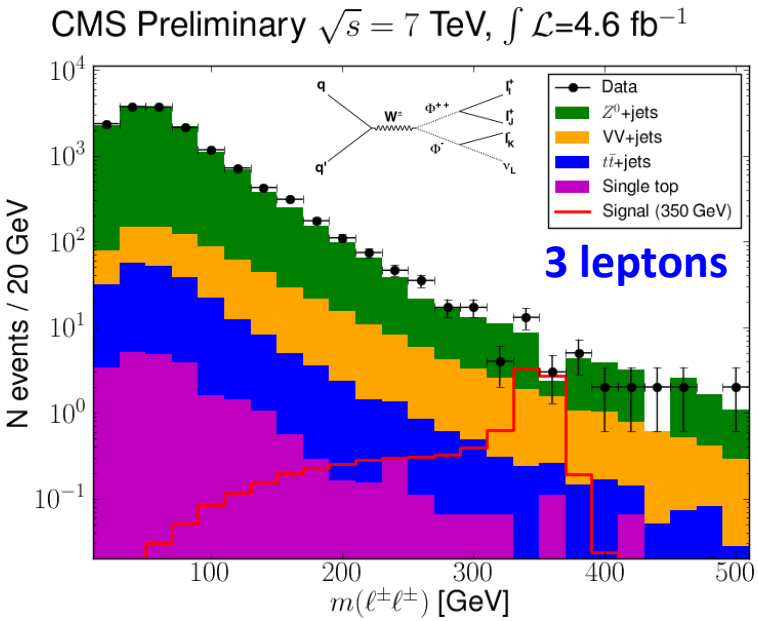


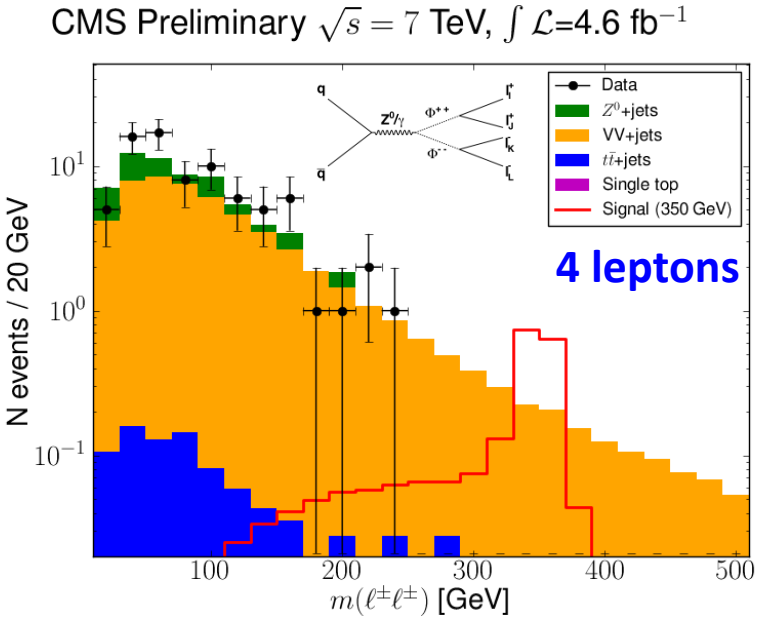




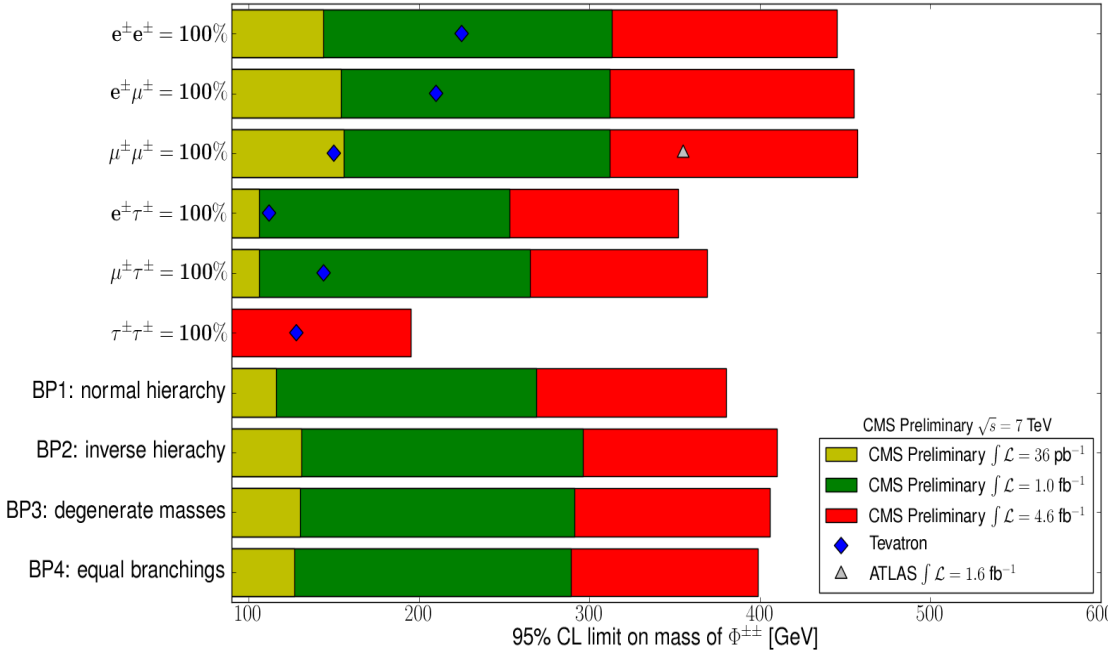
BaBar searches in $\Upsilon(3s) \rightarrow \gamma a_1$

Doubly Charged Higgs Φ^{++}



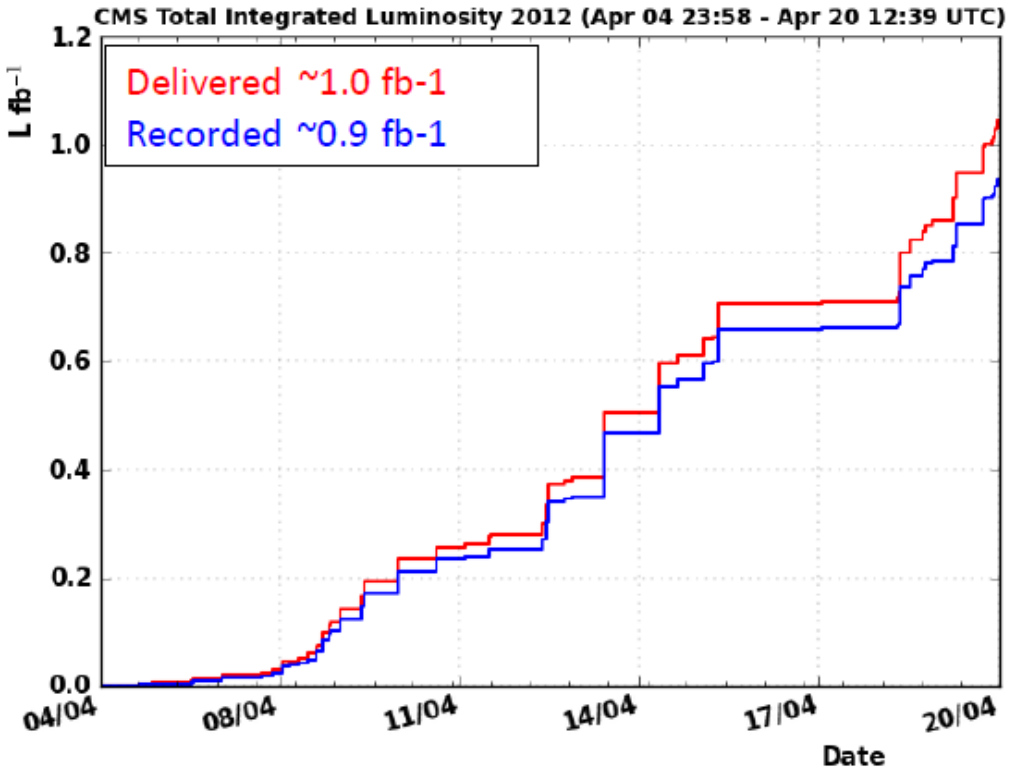


- **Triplet Higgs field in see-saw models**
  - Produced in association with singly charged Higgs or in pairs
    - Unique signature
    - No SM background with real leptons
  - Search with all lepton flavors



LHC in 2012

Higher energy (4 TeV per beam) and higher luminosity (> 7e33)



- **Phenomenal performance**
  - Record luminosity (> 5e33) achieved shortly after startup
  - $1fb^{-1}$ delivered in a few weeks
  - Sustained rate of $1.5fb^{-1}$ /wk
- **Challenging conditions**
  - Average pile-up ~ 30
  - Triggers are working!
    - Extensive development over the break, rates are less than expected (feared)
  - CMS is in great shape
    - > 90% data-taking efficiency, as usual

Summary

- **LHC continues its outstanding performance**
  - On track to deliver promised samples in 2012
- **No evidence for SM or BSM Higgs in 2011 data**
  - But hints at low mass (125 GeV)
- **CMS is searching far and wide**
  - Adding channels to SM search
  - Expanding search for BSM Higgs-like objects
- **2012 should be the definitive year**