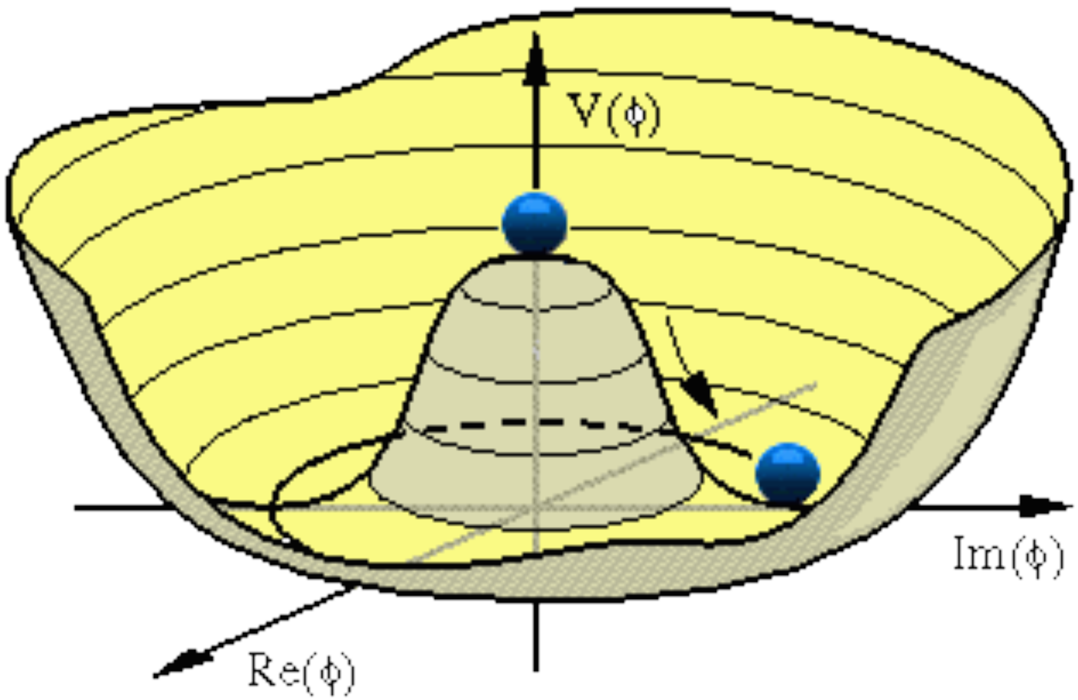
# Searches for the Higgs Boson



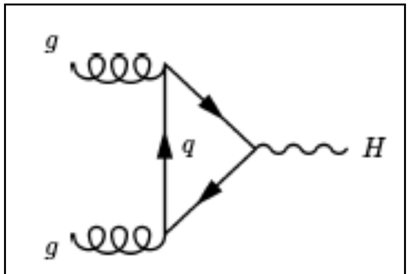


Giovanni Punzi

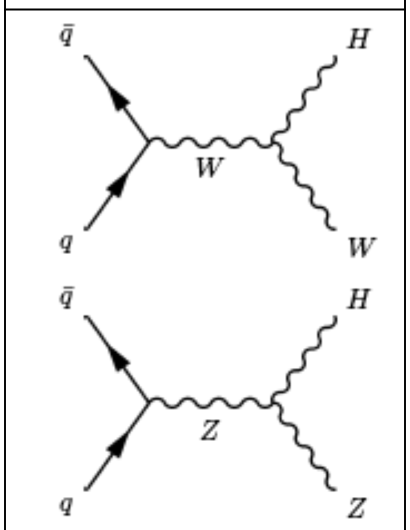

23th Rencontres de Blois

May 30, 2011

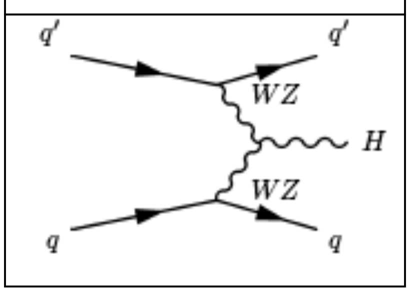
# Producing the SM Higgs at hadron collider



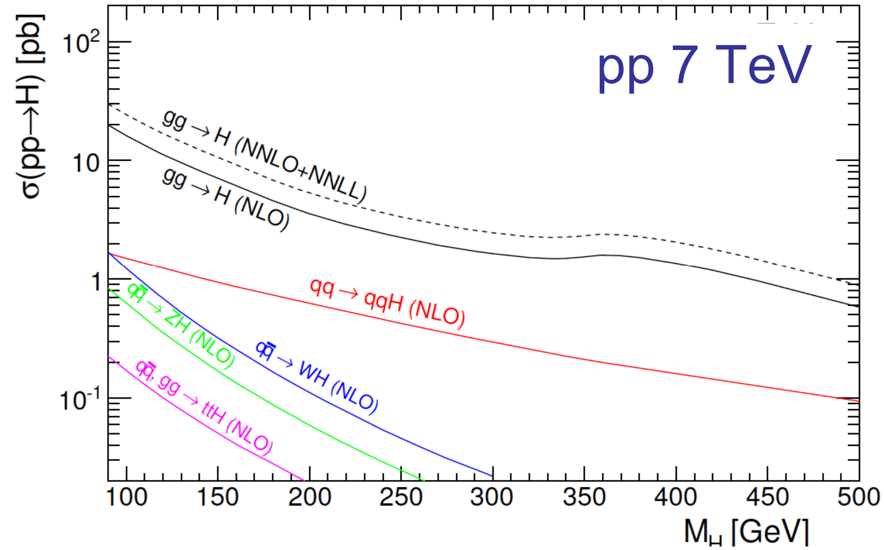

"gluon fusion"
(via fermion loop)

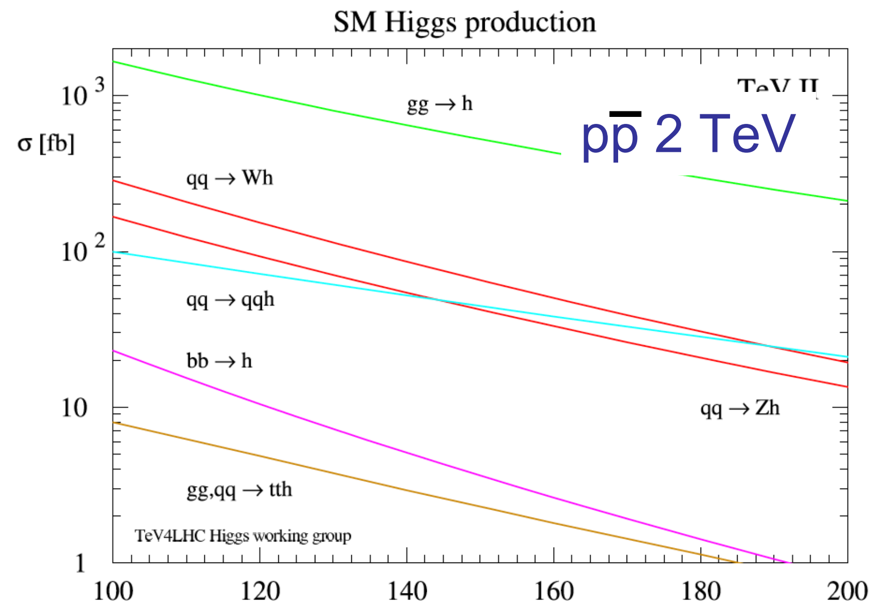



"Higgs-strahlung"
(radiated by a VB)

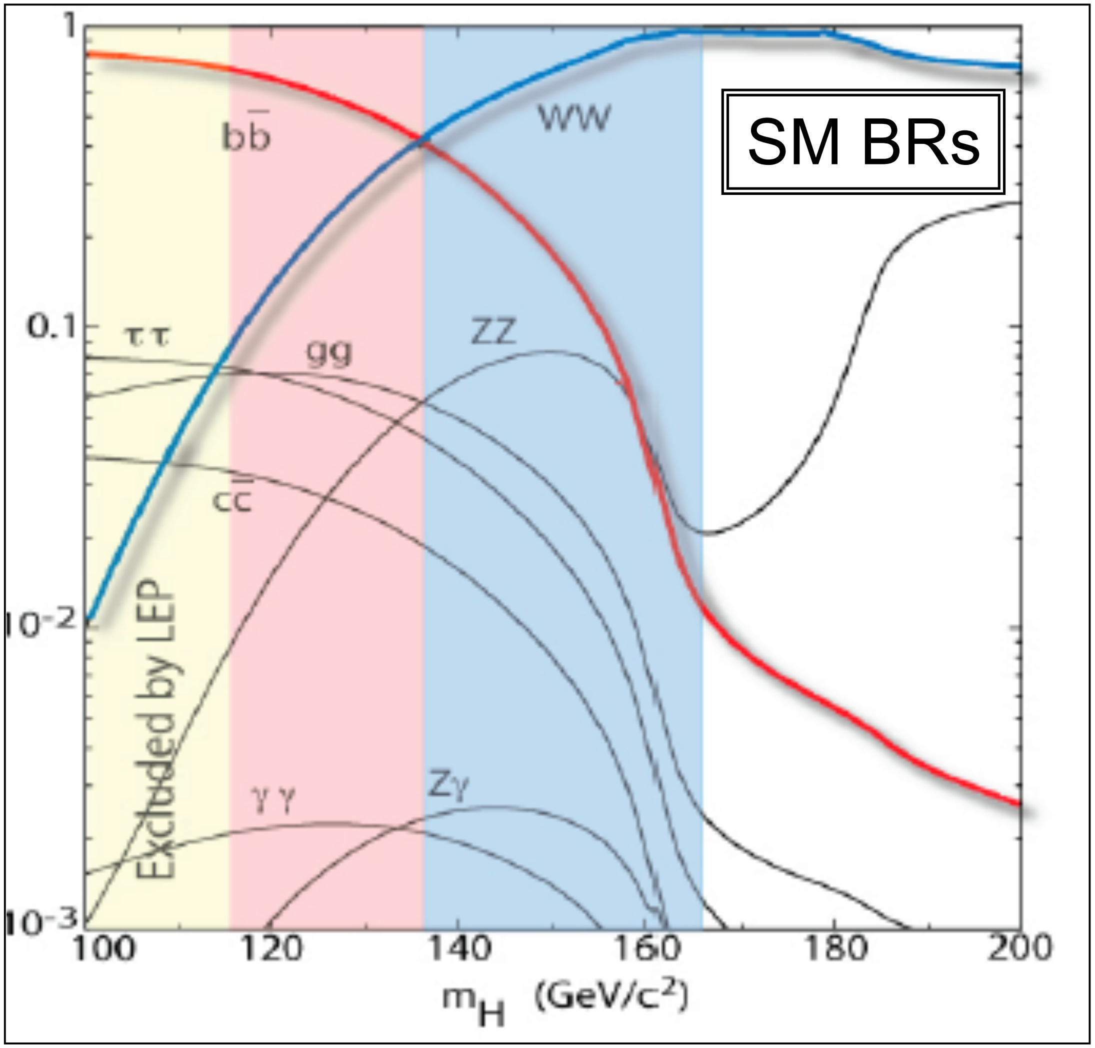



VB-fusion



# Decay modes of the Higgs




<u>In this talk:</u>

- VV searches (Vector coupling)
- bb searches (fermion coupling)
- $\tau\tau$ searches (fermion coupling)
  - SM
  - MSSM
- $\gamma\gamma$ (loop decay)
  - SM
  - fermiophobic
- Other

*<u>See Higgs parallel talks on Wed for much more !</u>*

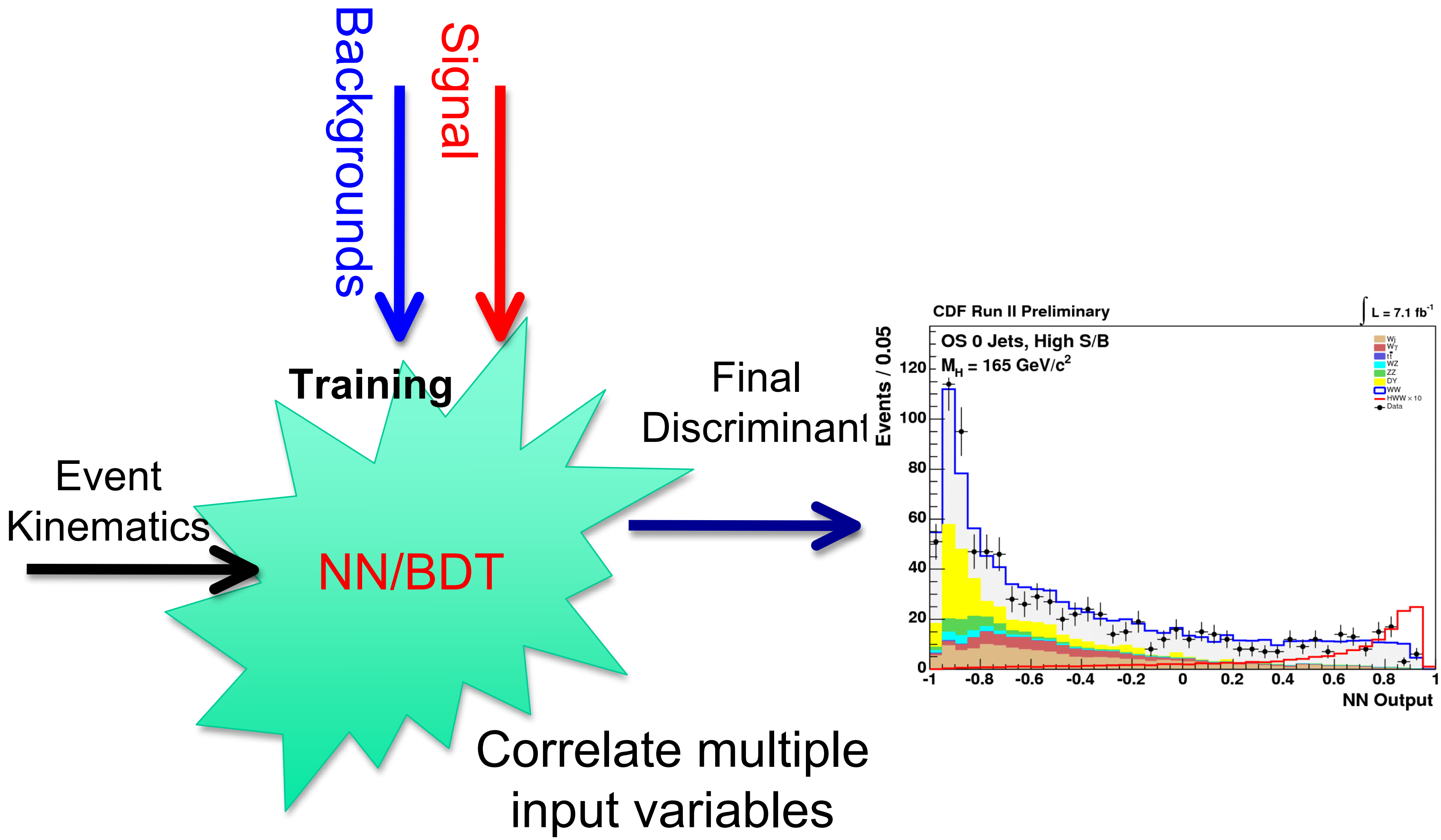
**NB** In most analyses, no attempt is made to exclude contributions from another Higgs decay (e.g. $\tau\tau$ from a WW decay).

# Experimental considerations

- Higgs channels are either rare, or swamped by a much larger background
- S or S/B are small, and often both.
- This led to pushing analysis technology to its limits
  - Using the information in the best possible way - wide cuts and multivariate methodologies
  - Continuous improvements by small steps
- Usually combine several decay modes in a single plot to maximize sensitivity

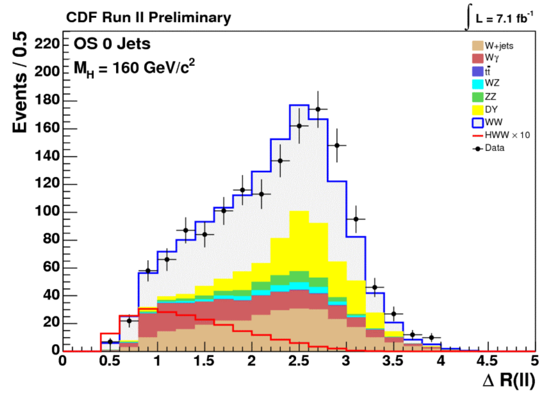
  Also use many sub-channels and combine them.

# Multivariate Discriminants

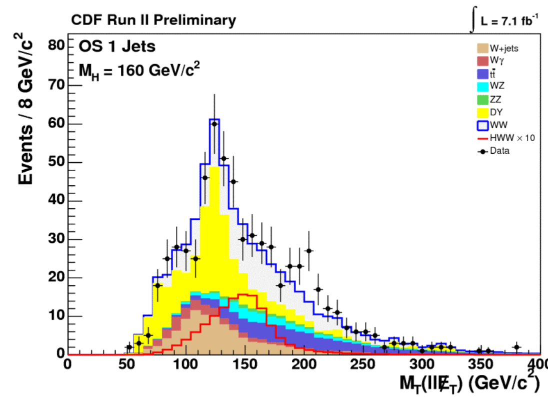


# Divide-and-conquer approach

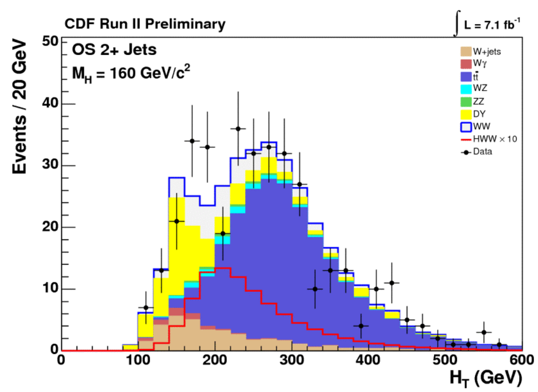
- Separating events into multiple analysis channels and combining the results improves sensitivity.
- Allows to use separate, optimized discriminates for each channel based on:
  - specific signal contributions
  - specific background contributions
  - specific event kinematics




0 jet

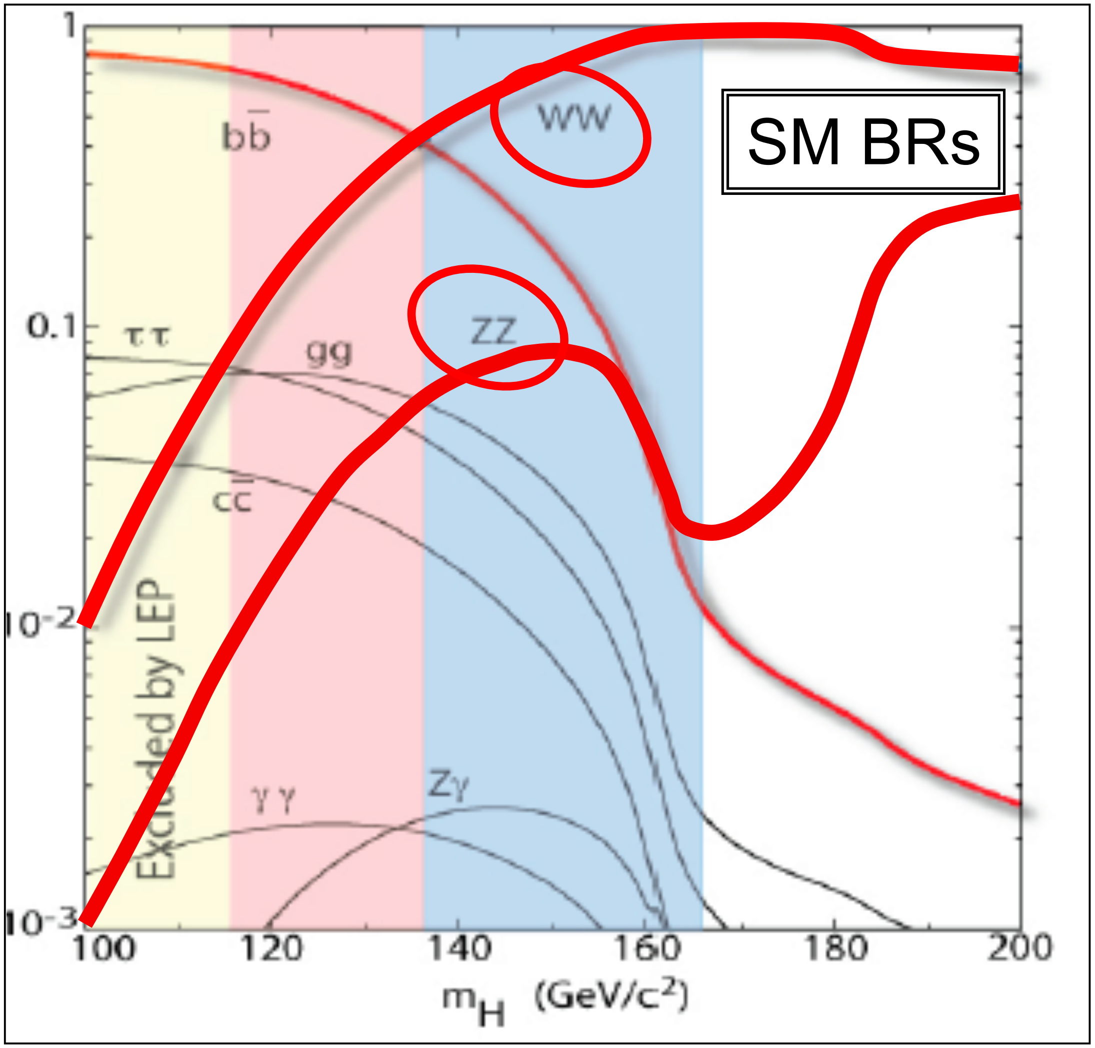



1 jet




2+ jets

# Searches for di-boson modes

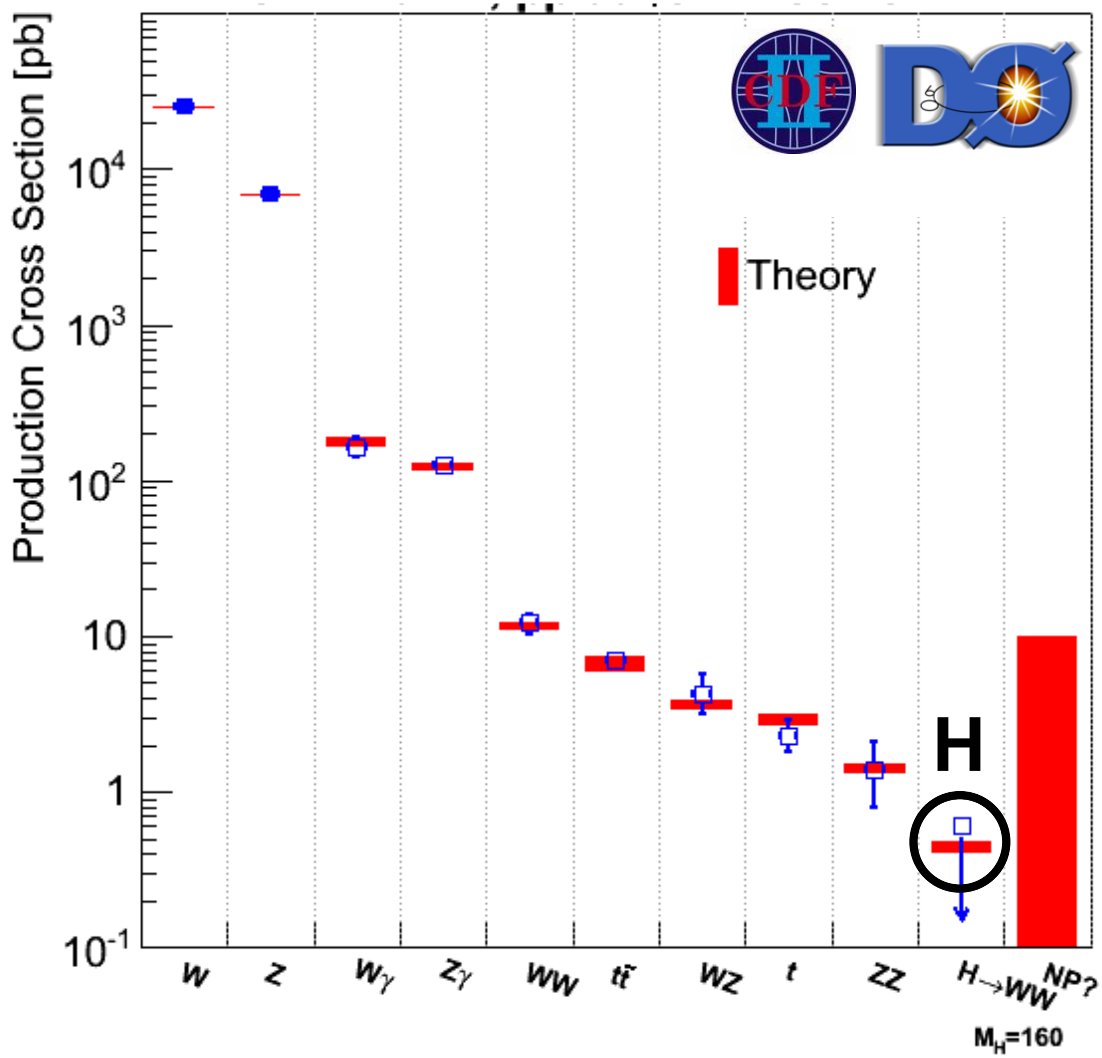



- WW and ZZ crucial modes for Higgs searches above ~140 GeV
- Still useful down to the lower mass region
- Clearest experimental signatures.
- The main workhorse for LHC searches over the whole mass range

# The di-boson path

- Measurements of the various di-boson processes are stepping stones towards H->di-boson reconstruction
- CDF and D0 went through all those steps

Diboson production at Tevatron
(CDF data plotted, D0 similar)



# Some WW Search Channels used at Tevatron

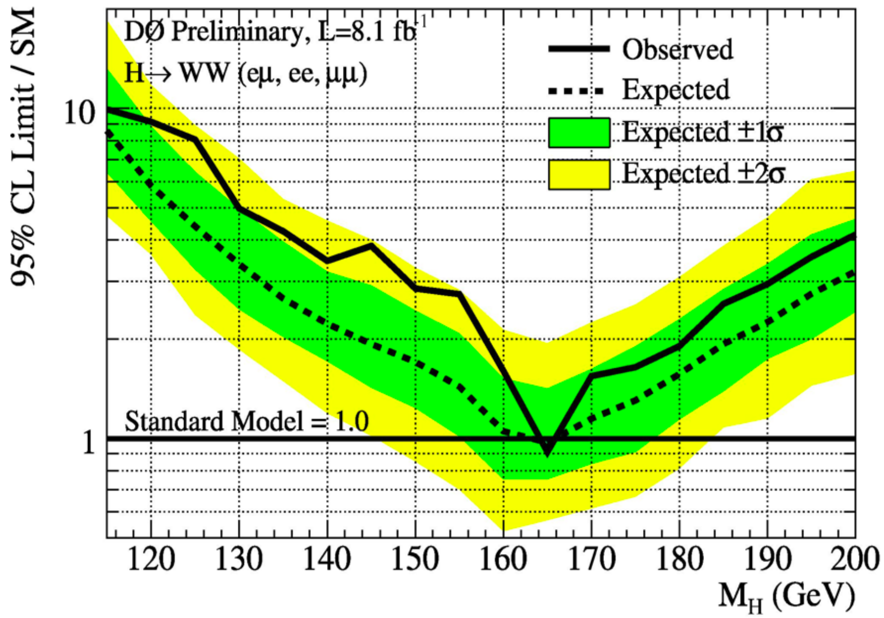
| **Channel** | **Main Signal** | **Main Background** | **Most Important kinematic variables** |
|---|---|---|---|
| OS dileptons, 0 Jets | $gg \to H$ | WW | $LR_{HWW}$, $\Delta R_{ll}$, $H_T$ |
| OS dileptons, 1 Jet | $gg \to H$ | DY | $\Delta R_{ll}$, $m_T(ll, E_T)$, $\not{E}_T$ |
| OS dileptons, 2+ Jets | Mixture | t-tbar | $H_T$, $\Delta R_{ll}$, $M_{ll}$ |
| OS dileptons, low $M_{ll}$, 0 or 1 Jet | $gg \to H$ | $W+\gamma$ | $p_T(l2)$, $p_T(l1)$, $E(l1)$ |
| SS dileptons, 1+ Jet | $WH \to WWW$ | W+Jets | $E_T$, $\Sigma \not{E}_T^{jets}$, $M_{ll}$ |
| Tri-leptons, no Z candidate | $WH \to WWW$ | WZ | $E_T$, $\Delta R_{ll}^{close}$, Type(lll) |
| Tri-leptons, Z candidate, 1 Jet | $ZH \to ZWW$ | WZ | Jet $E_T$, $\Delta R_{lj}$, $\not{E}_T$ |
| Tri-leptons, Z candidate, 2+ Jets | $ZH \to ZWW$ | Z+Jets | $M_{jj}$, $M_T^H$, $\Delta R_{WW}$ |
| OS dilepton, electron + hadronic tau | $gg \to H$ | W+Jets | $\Delta R_{l\tau}$, $\tau$ id variables |
| OS dilepton, muon + hadronic tau | $gg \to H$ | W+Jets | $\Delta R_{l\tau}$, $\tau$ id variables |

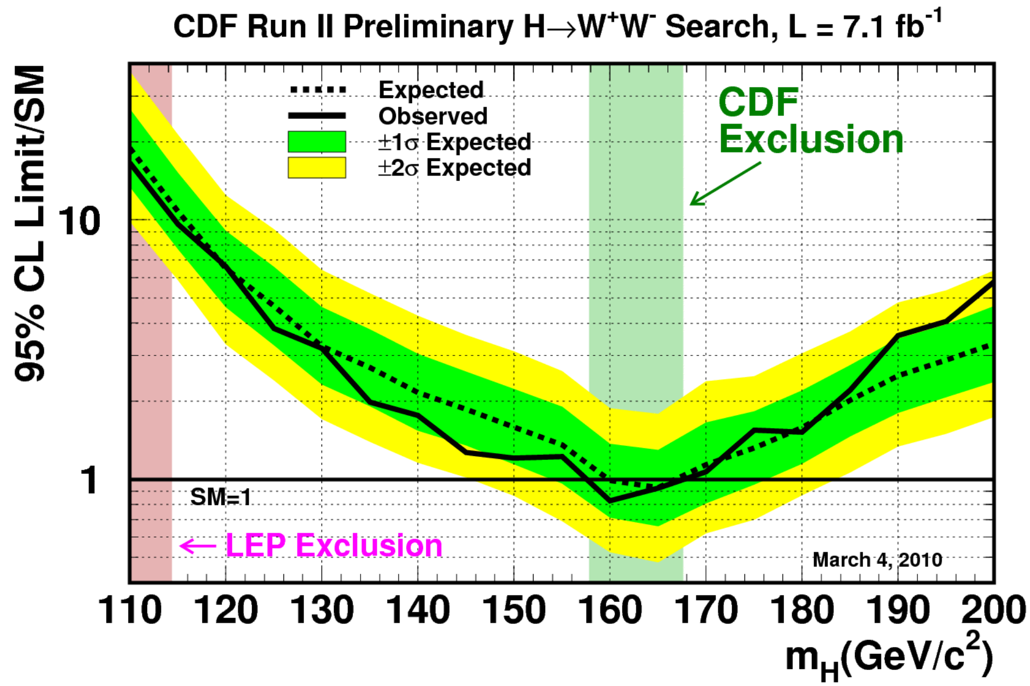
Breakdown by #jets (OS dileptons, 0 Jets; 1 Jet; 2+ Jets)

Associated production (SS dileptons, 1+ Jet; Tri-leptons rows)

$W \to \tau\nu$ (OS dilepton + hadronic tau rows)

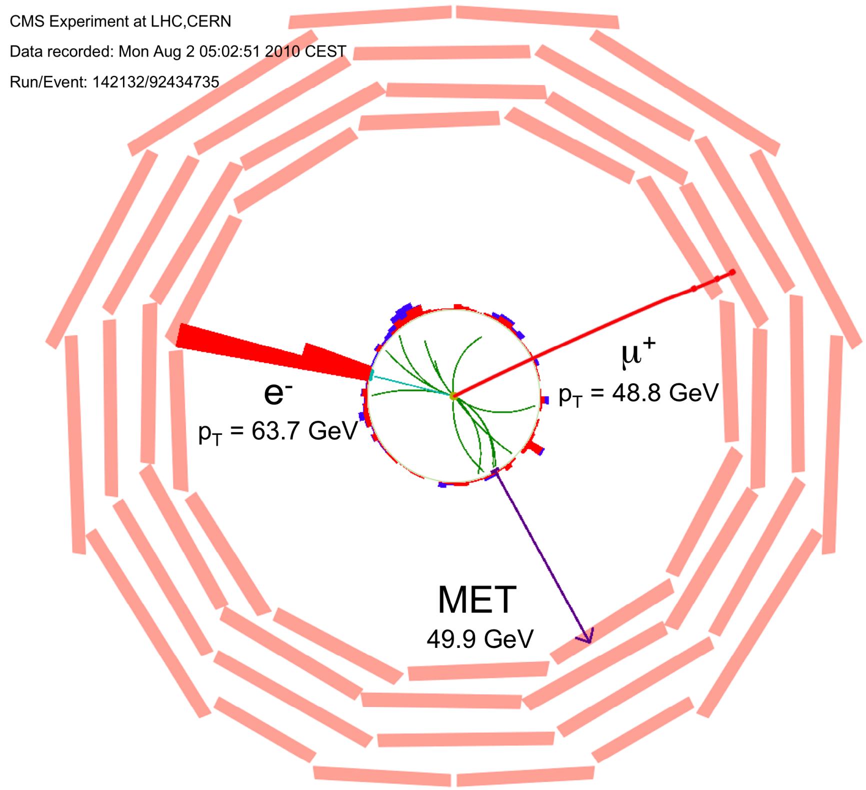
# D0 and CDF limits on H→WW

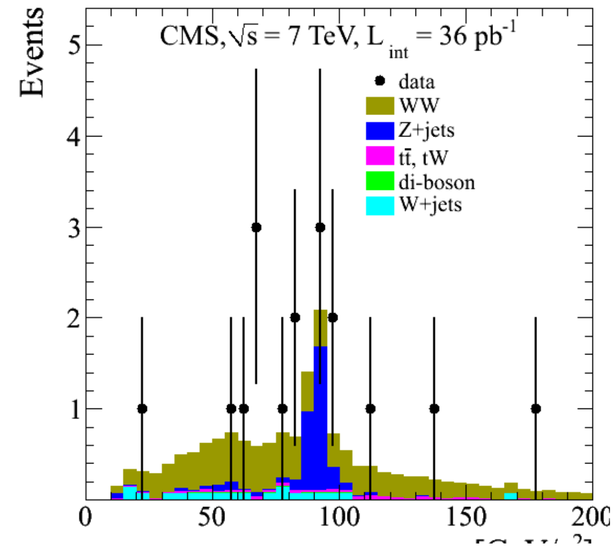


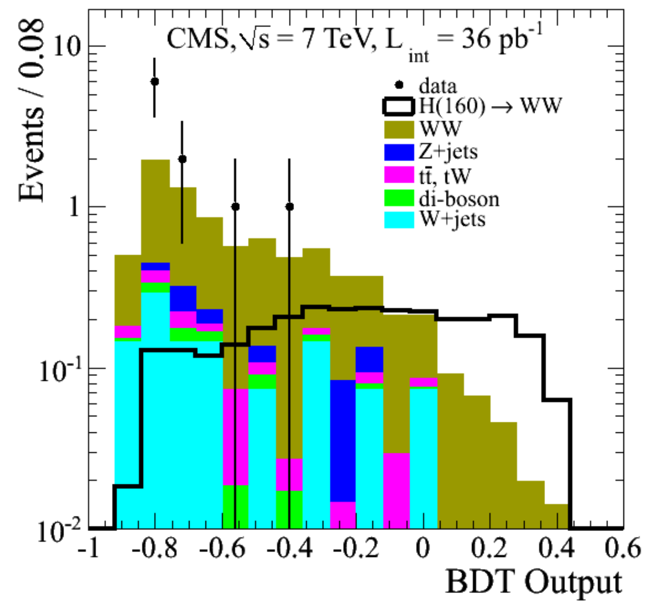




- Updated spring 2011 (7-8 $fb^{-1}$)
- Both CDF and D0 manage to exclude a small region around 165GeV based just on WW mode.

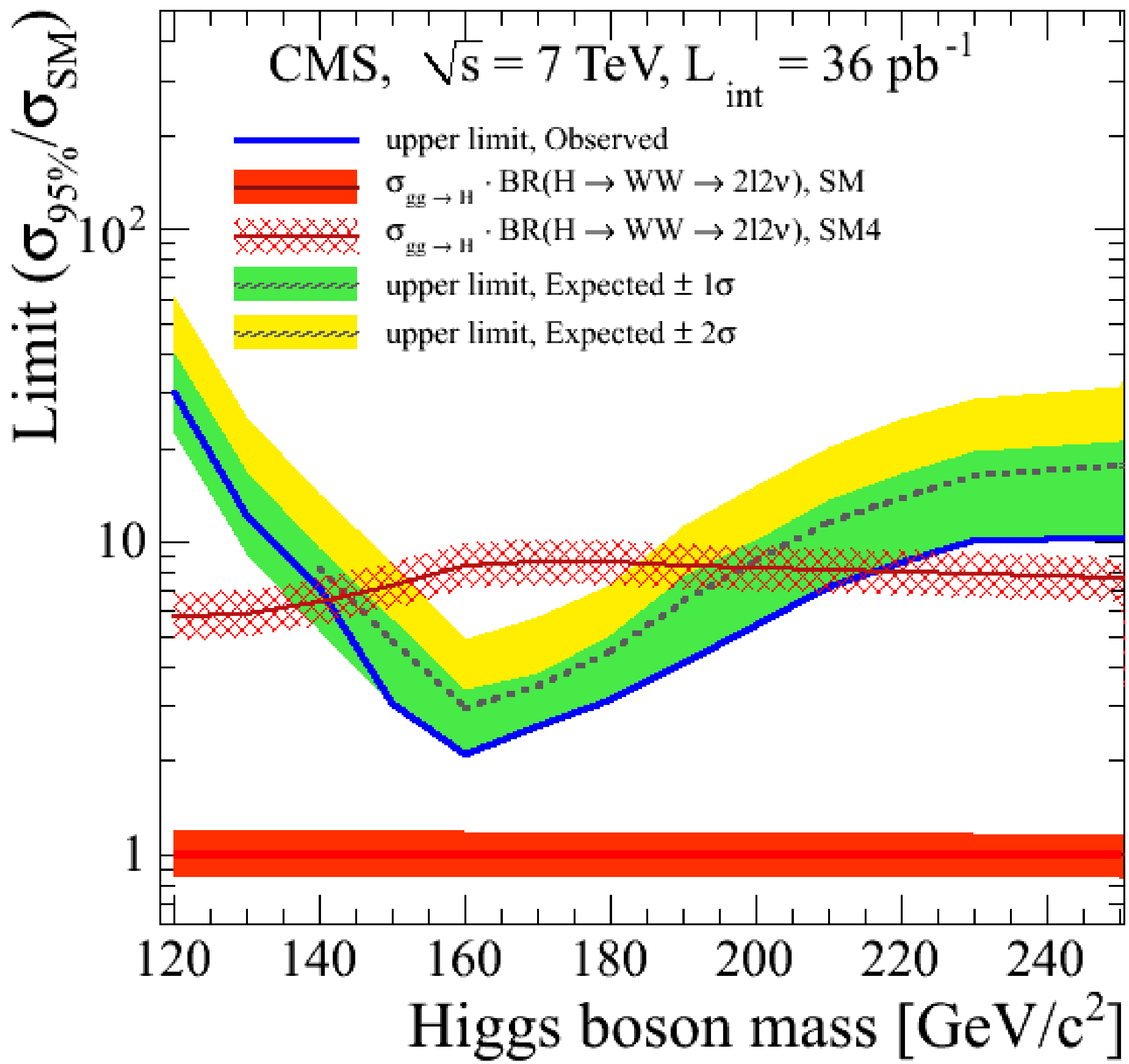
# CMS results on WW mode



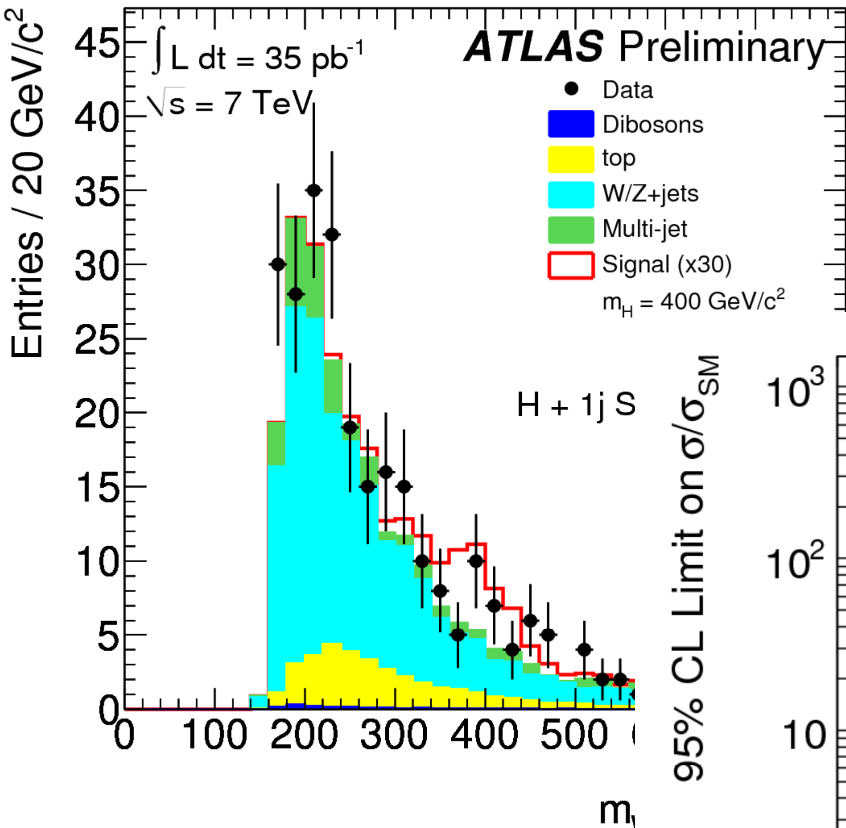



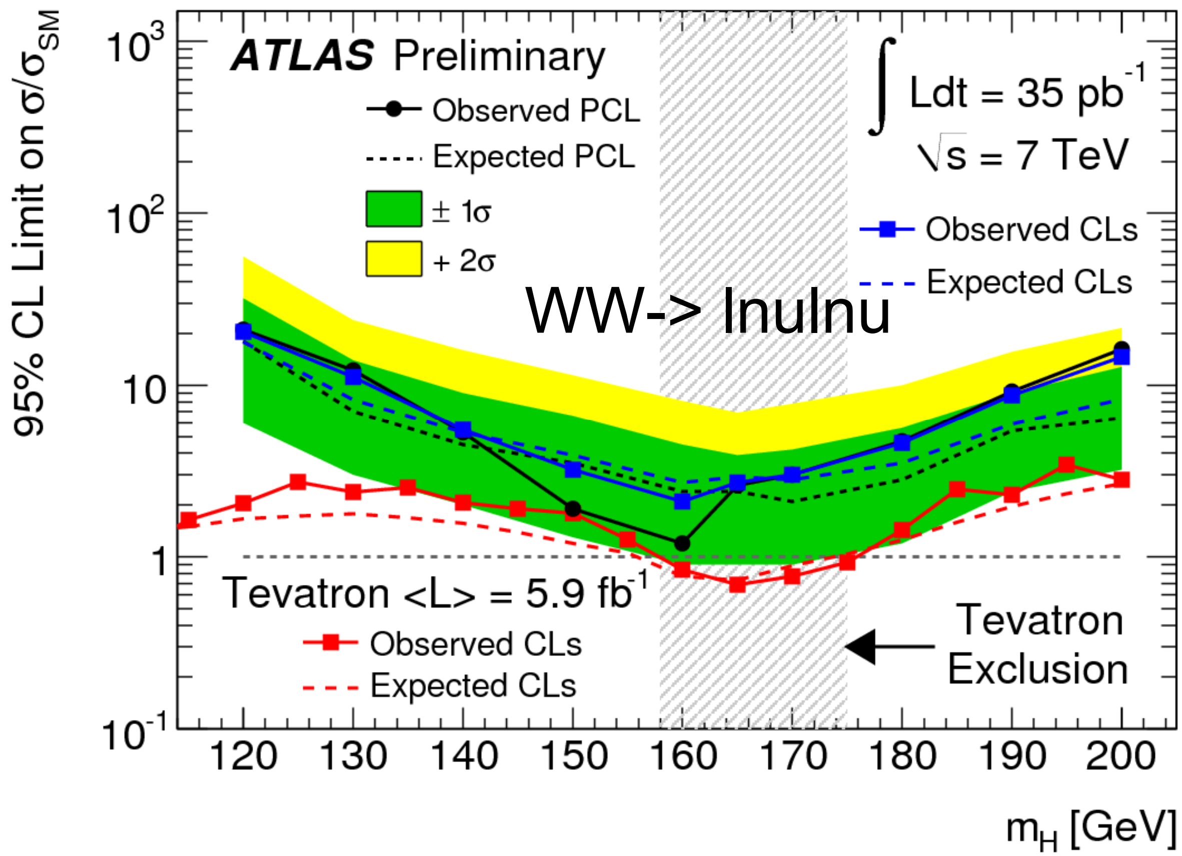
# CMS results on WW mode



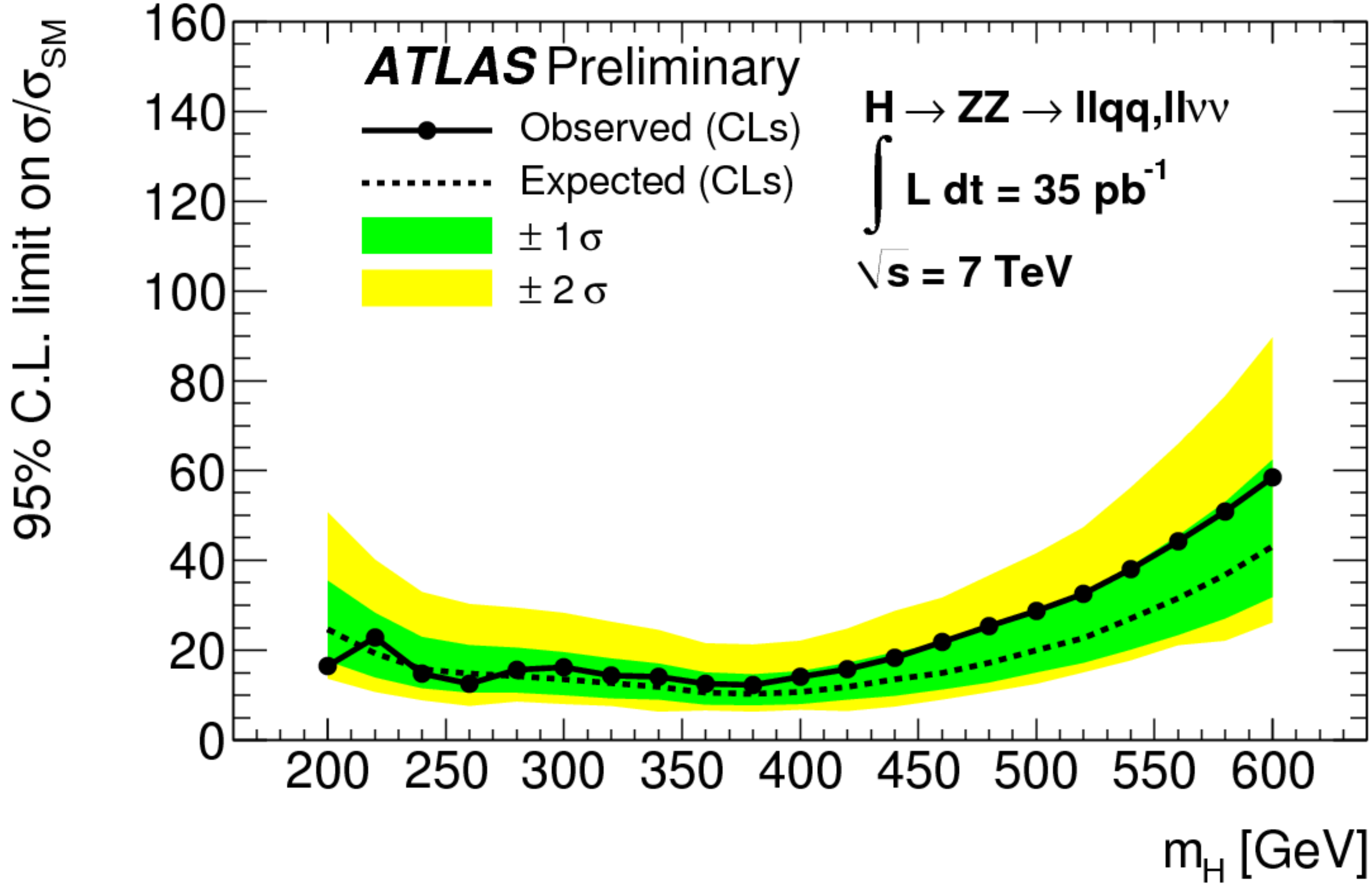
# ATLAS H→WW Analysis



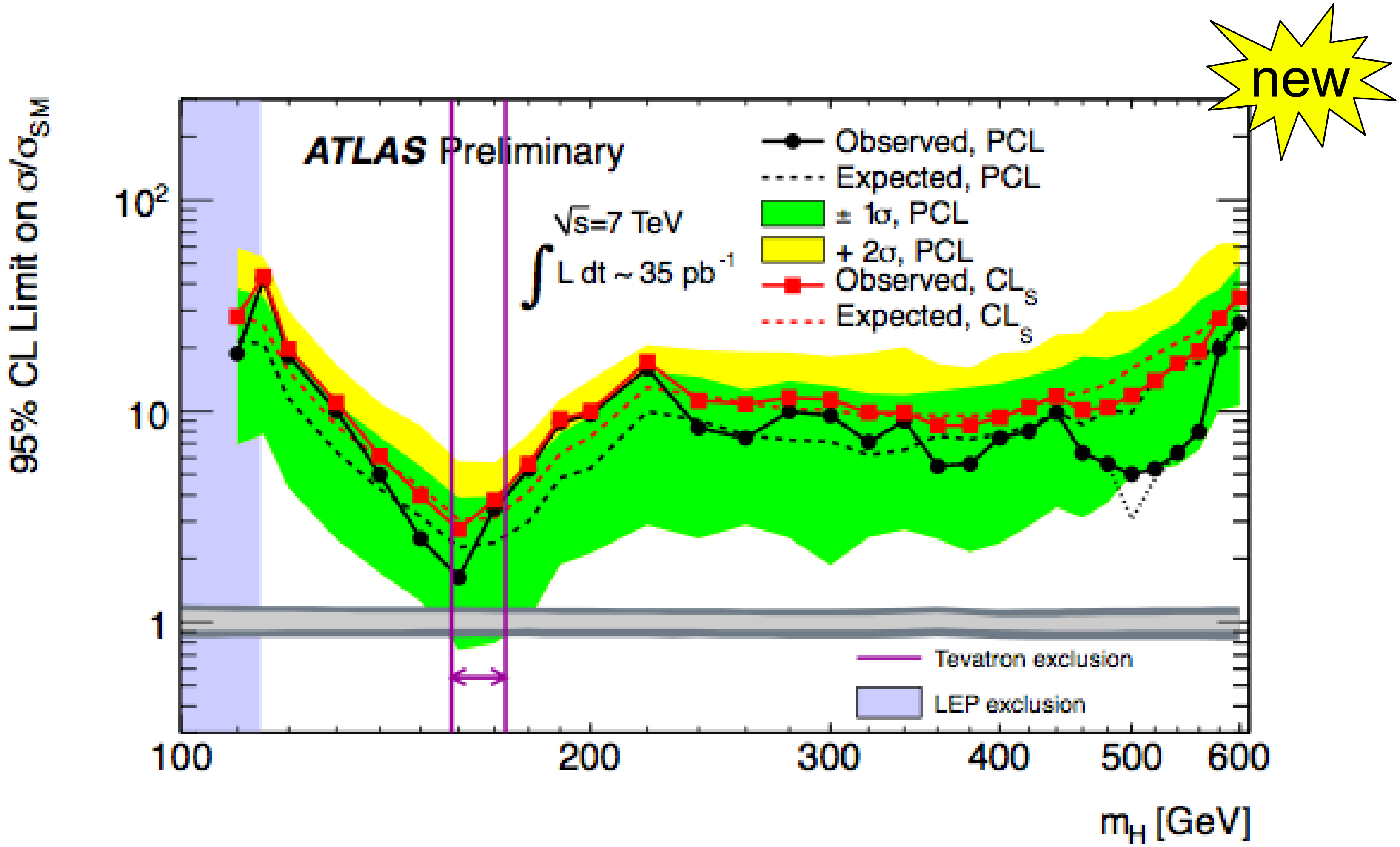

WW mass (1-jet channel as example)



# ATLAS H→ZZ Analysis

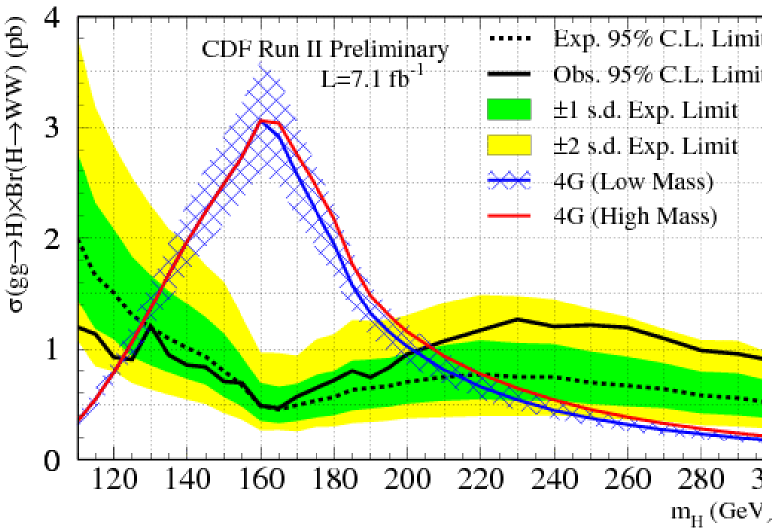


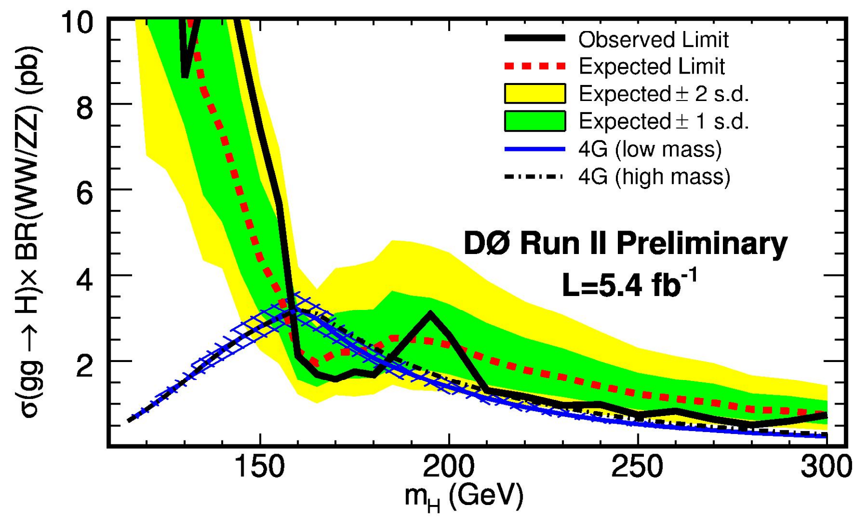
# ATLAS combined limits




- Includes all dibosons + $\gamma\gamma$
- Hot off the press - see talk by J.Elmsheuser on Wed for details

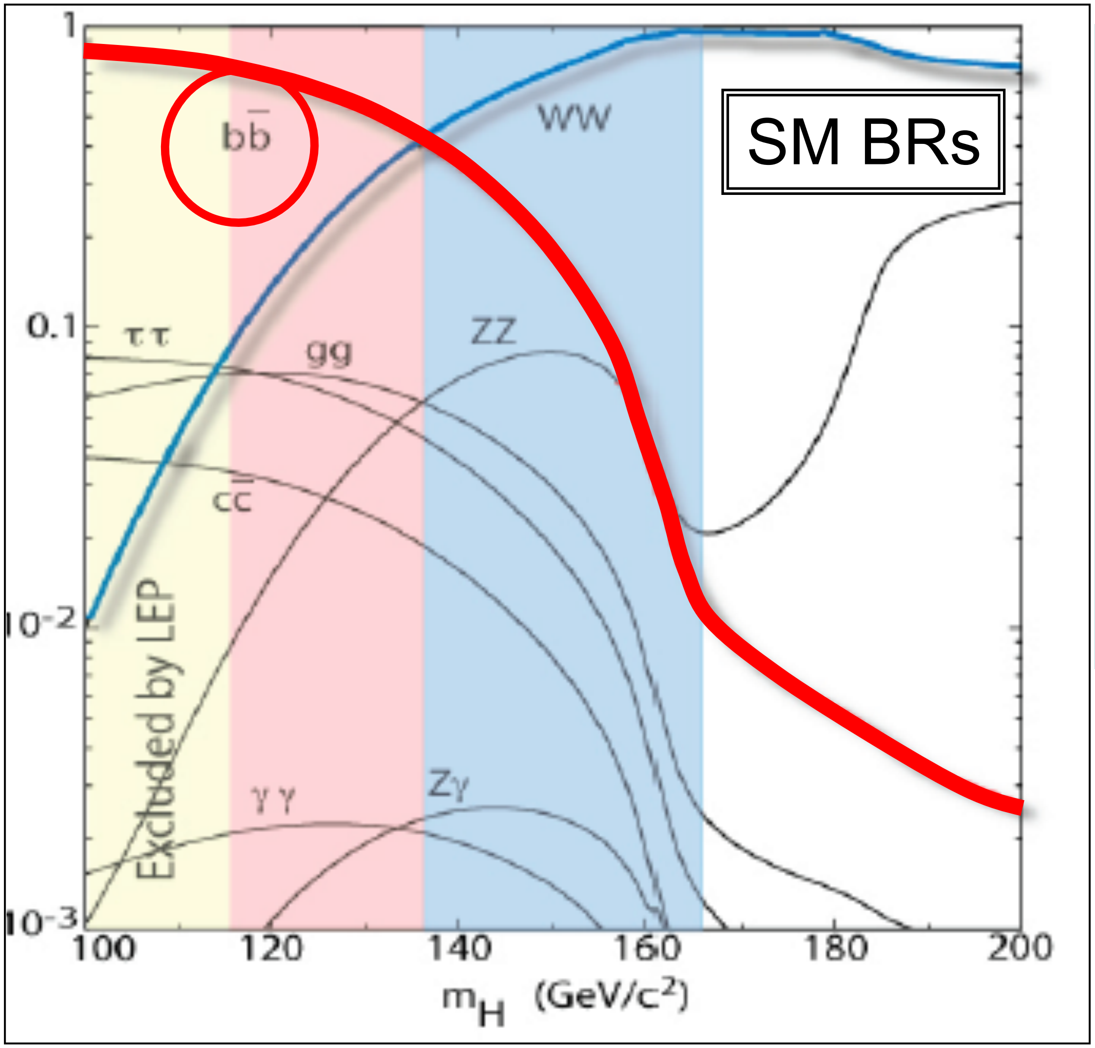
# Application to 4th-Generation Models




- If a 4th generation of quarks exists, it enhanced the process: gg→H by a factor ~9, almost independent of masses involved.
  [Anastasiou, Boughezal, and Furlan, arXiv:1003.4677]
- The WW channel is ideal for this - here select only gg→H→WW processes
- **Strongest limit comes from CDF (7fb$^{-1}$):**
  **Observed exclusion 124 < $m_H$ < 202 GeV**
  (extends a previous result 131-204)
- If a a 4th quark generation exists, the Higgs cannot be in that interval.

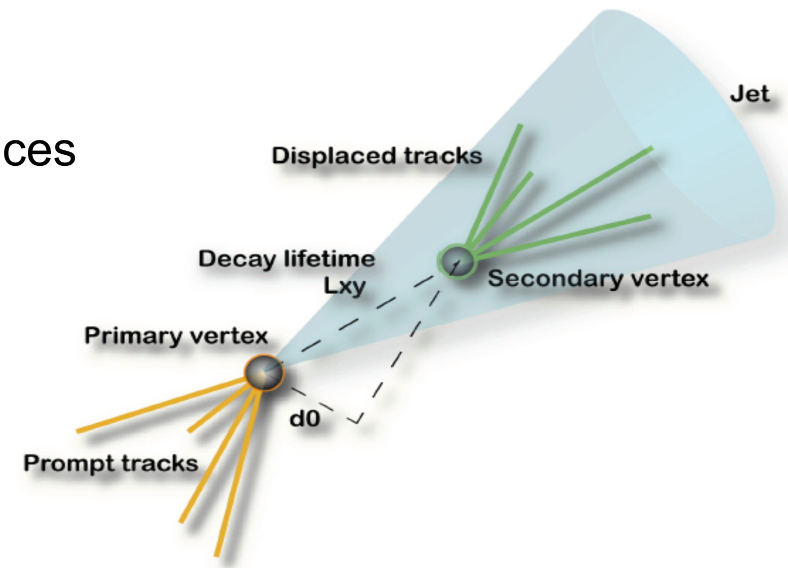
# Searches for b-bbar mode



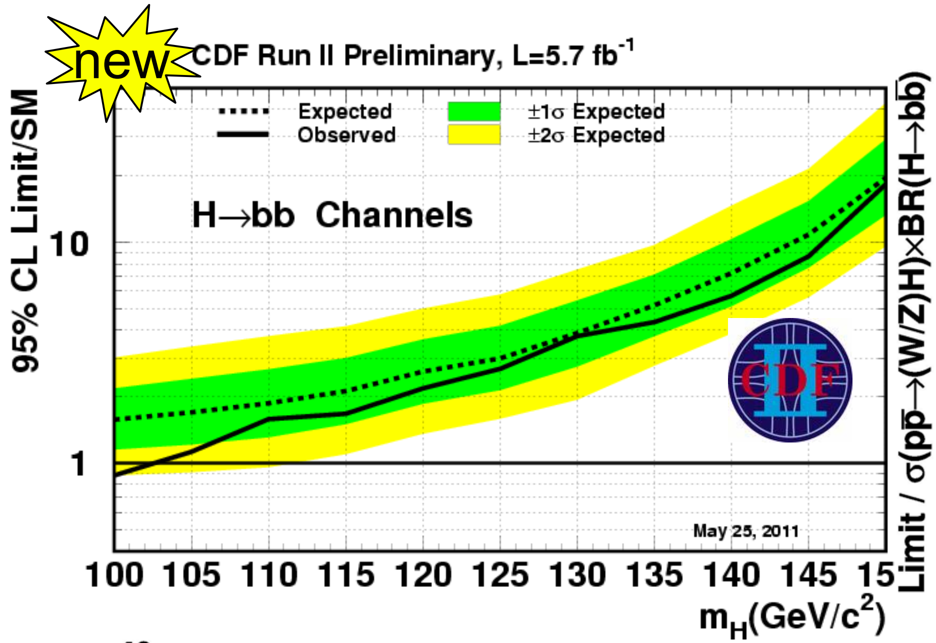

- b-bbar expected to be the most frequent decay below ~140 GeV.
- Most stable in BSM models
- WW results from the Tevatron + EWK fit strongly favor this low mass region if the SM is valid
- Must rely on associated production VH due to high backgrounds.
- More accessible at the Tevatron

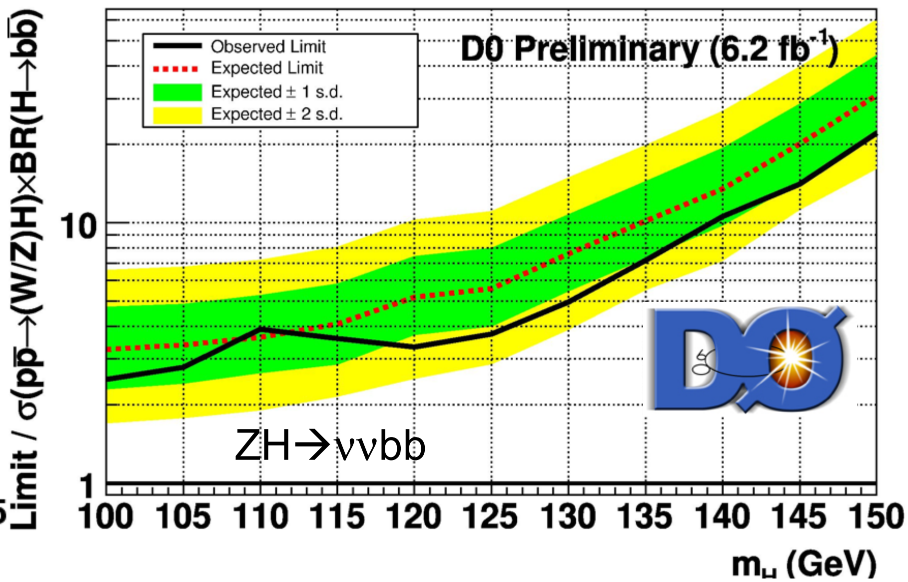
# Heavy Flavor Identification

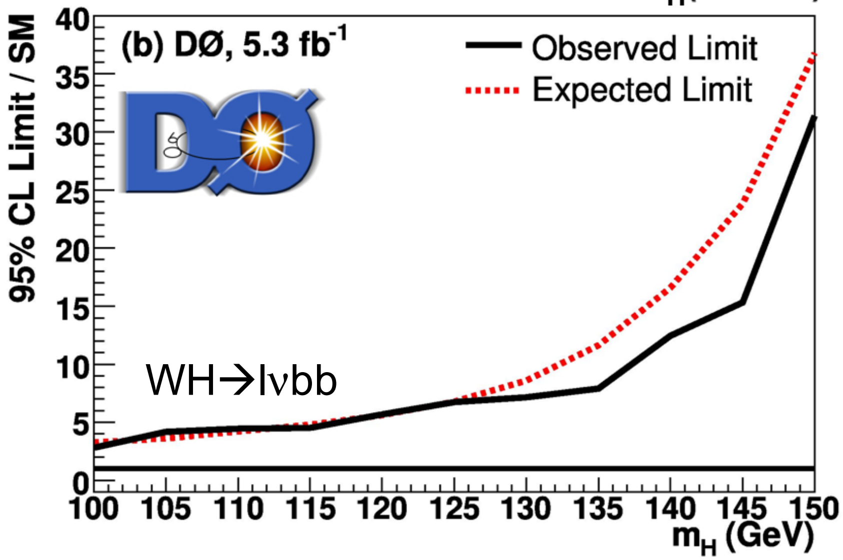
- Critical for searches involving H→bb.
- B-tagging exploits information on:
  - Lifetime: displaced tracks and/or vertices
  - Mass: secondary vertex mass
  - Soft leptons
- Use multivariate techniques for best performance:
  - B-tagging efficiency: ~40-70%
  - Mistag rate: ~0.5-5%
  - Calibrated in data control samples.

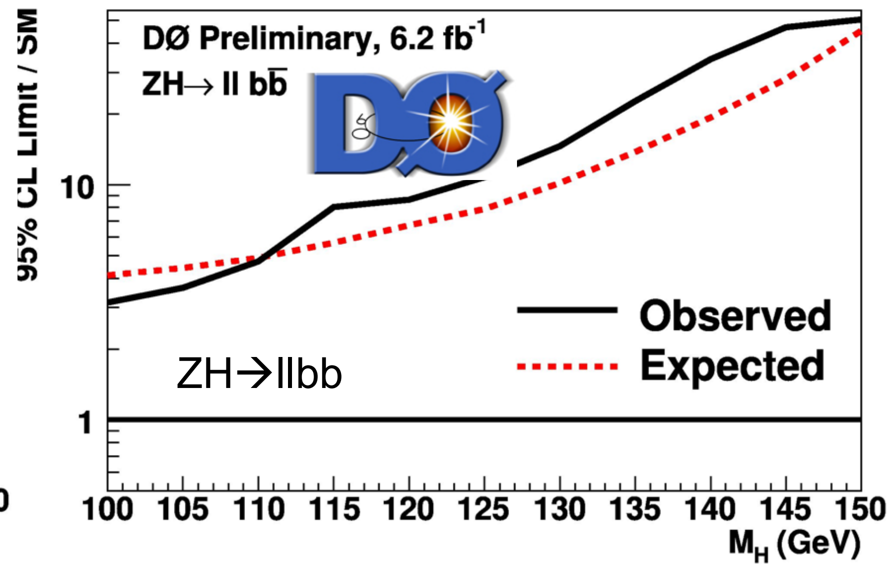


# Current b-bbar results (Tevatron only)



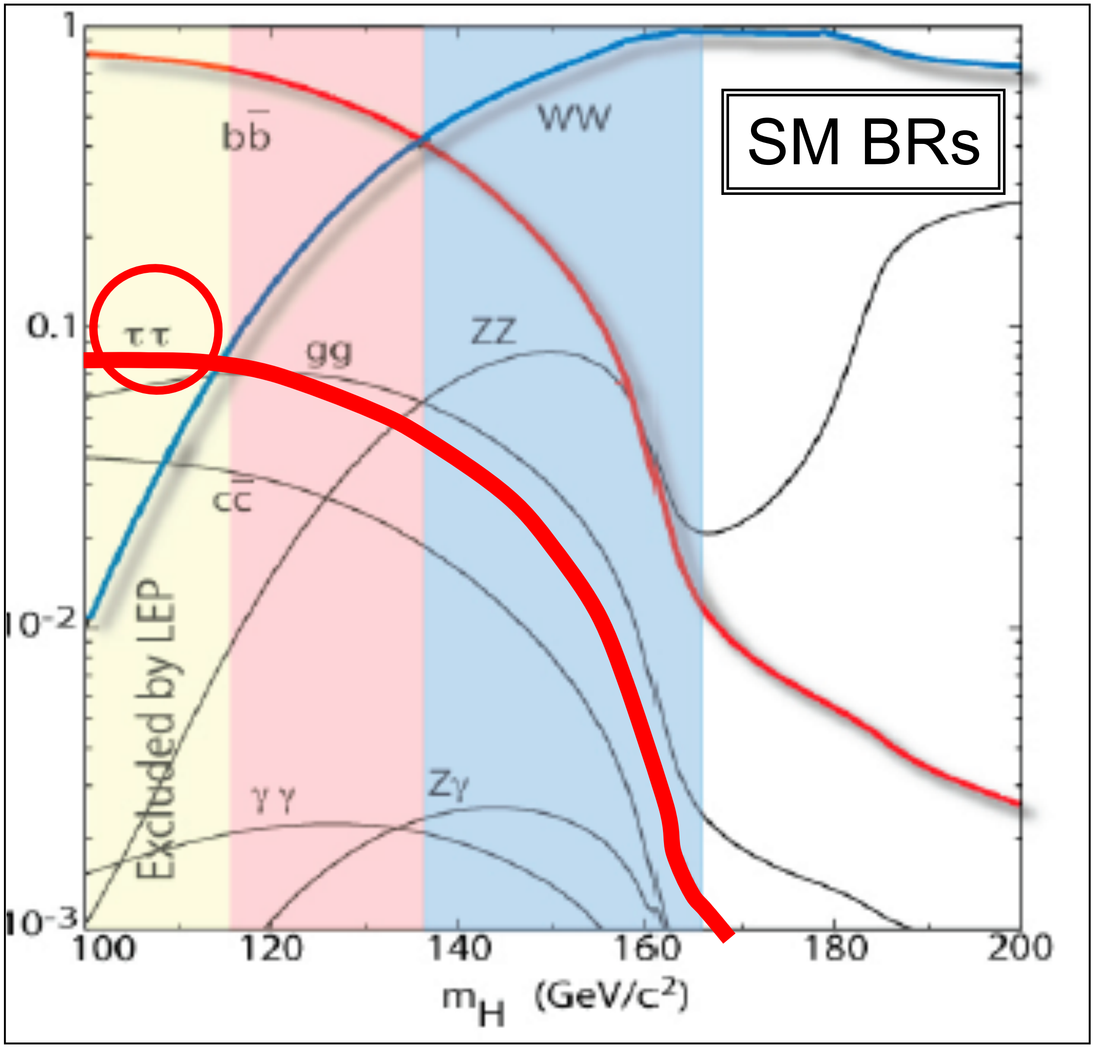




- With 6fb$^{-1}$ the b-bbar channel is already getting below the line at lower masses (summer '10) - big expectations for summer 2011 !

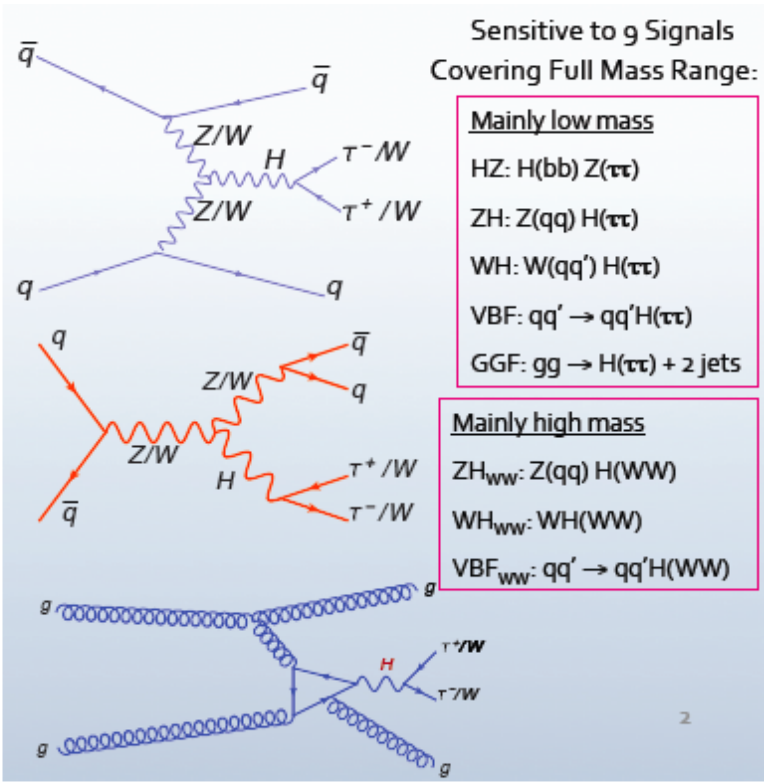
# Searches for ττ



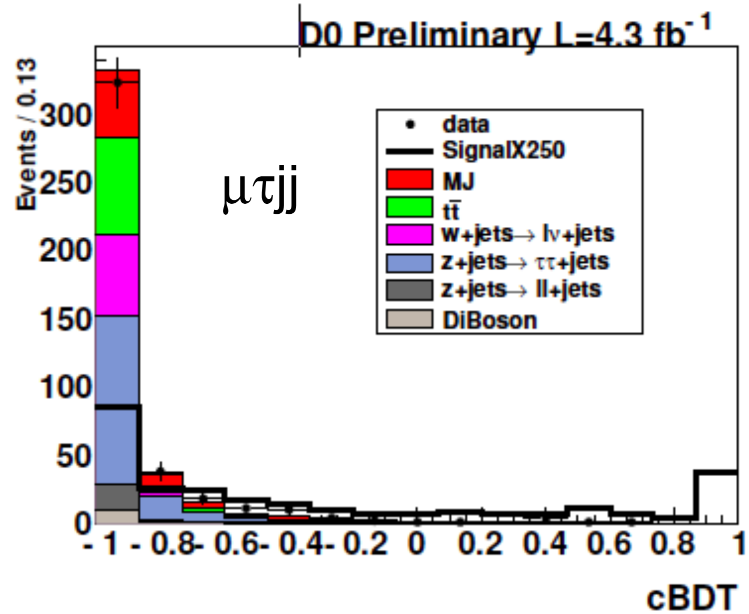

- Next fermion after b-bbar - no more than 8% though
- As for b-bbar need to look for associated production to reject high backgrounds
- Might be enhanced in SUSY

# H+X→ττjj

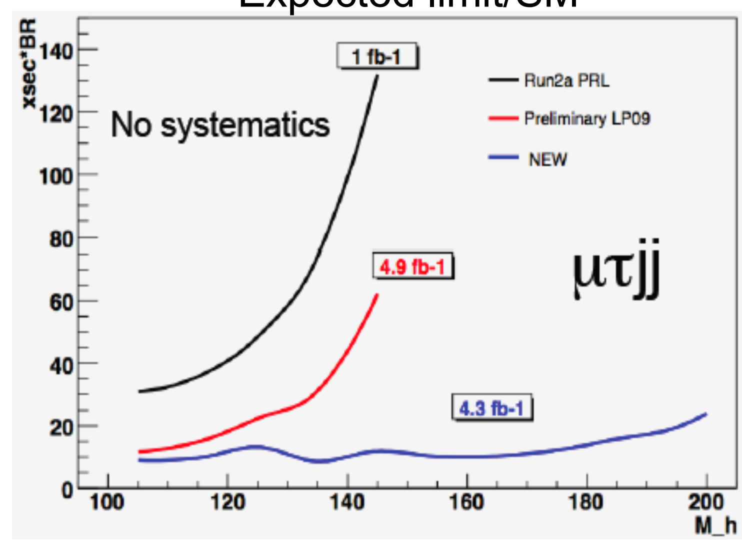
- H→ττ: second largest BR(~8%) at low mass.
- Select events with $\tau_l\tau_h$+2j (l=e,μ) final states.
- Challenges:
  - Efficient categorization of 9 signal processes!



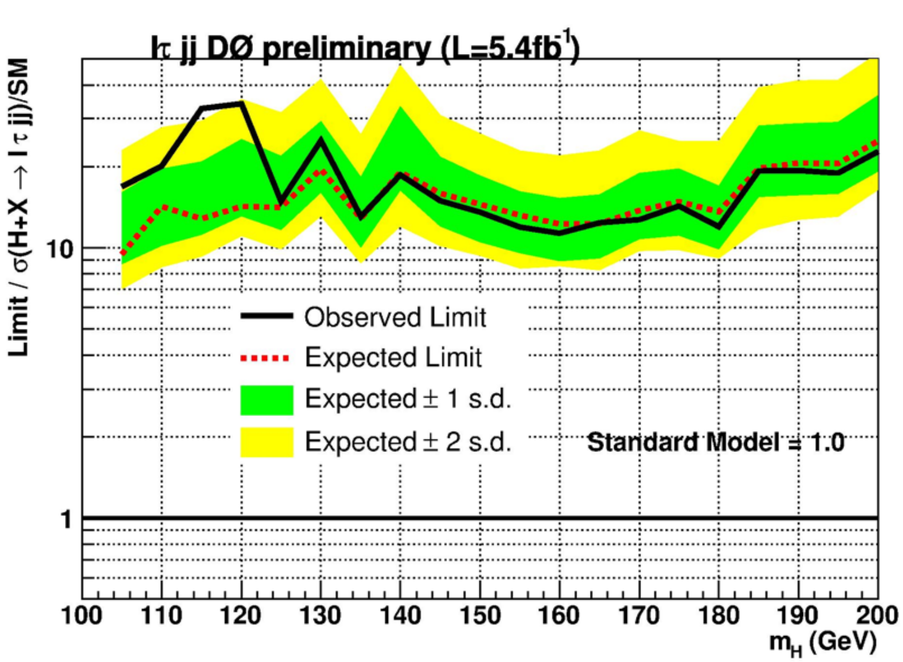

  - Multijet and V+jets background modeling.
- Extra signals + sophisticated MVA approach yield major improvement in sensitivity wrt previous results!

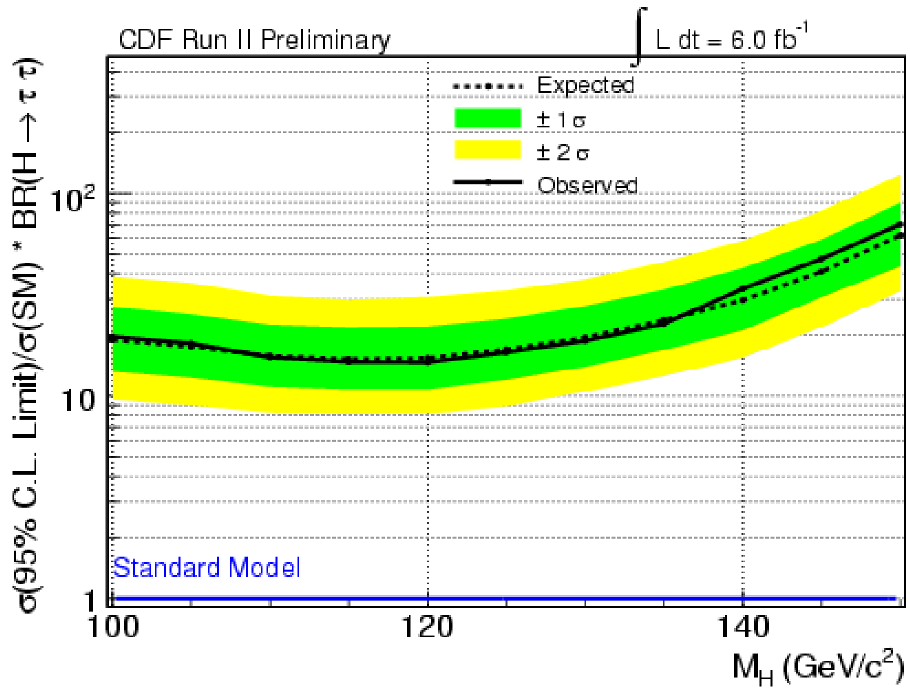



Expected limit/SM



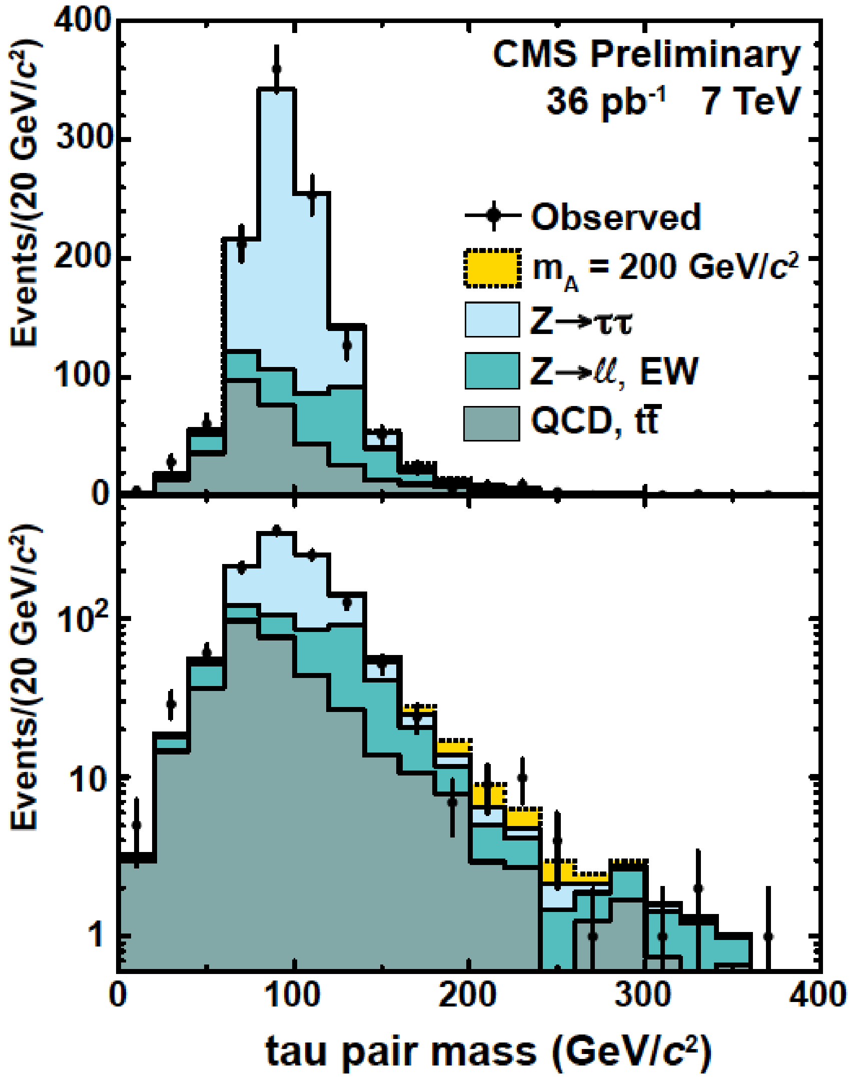
# Recent Tevatron results on $H+X \rightarrow \tau\tau jj$ (~6$fb^{-1}$)

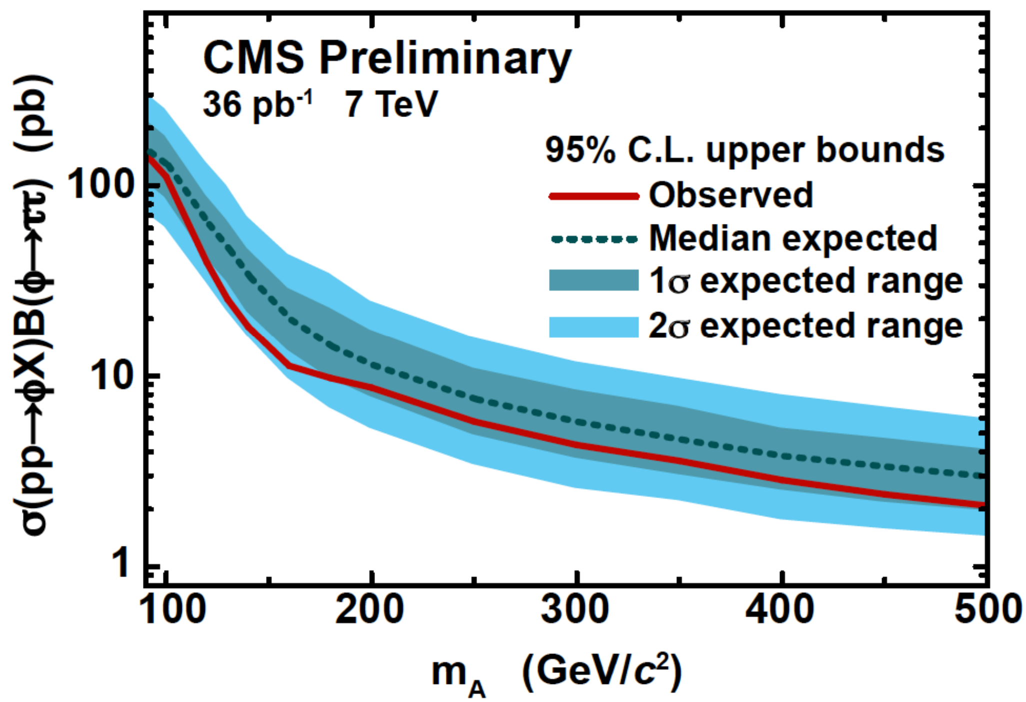


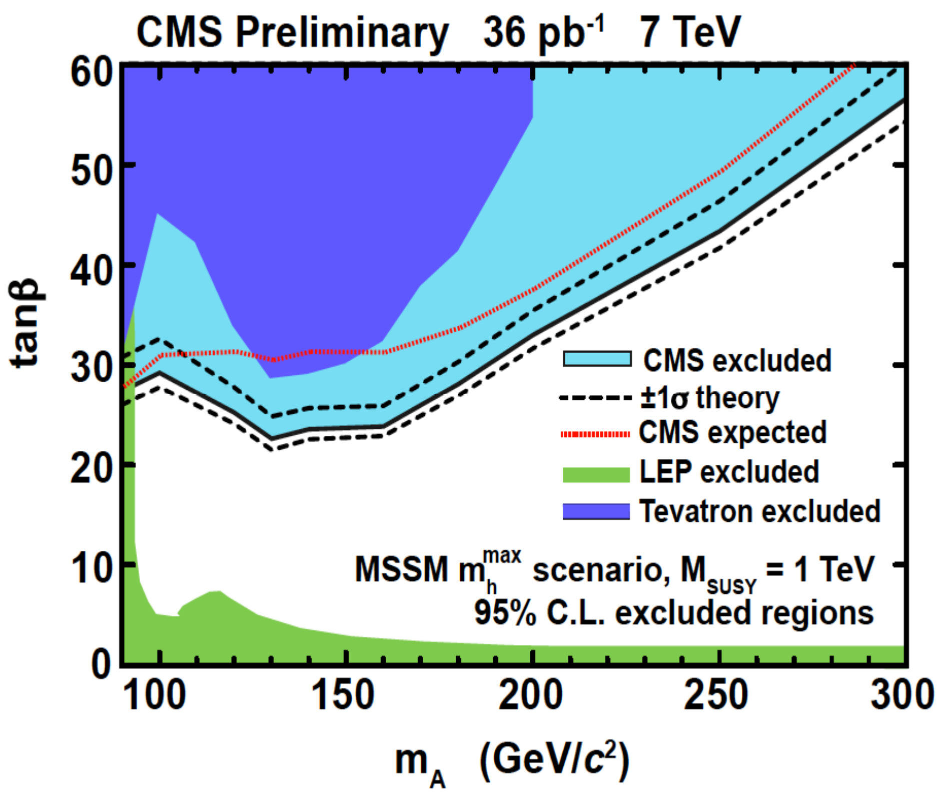

- Use $\tau\tau$ + 1,2 jets
- Contribute to global SM combination

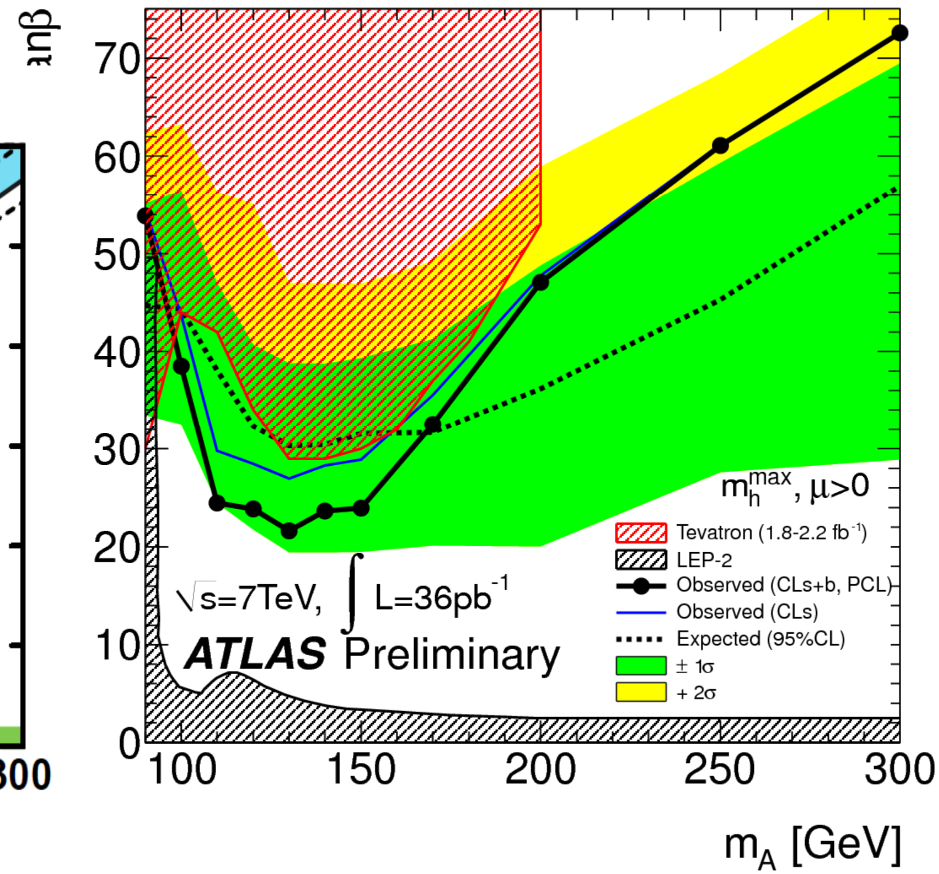
# Search for H→ττ at CMS



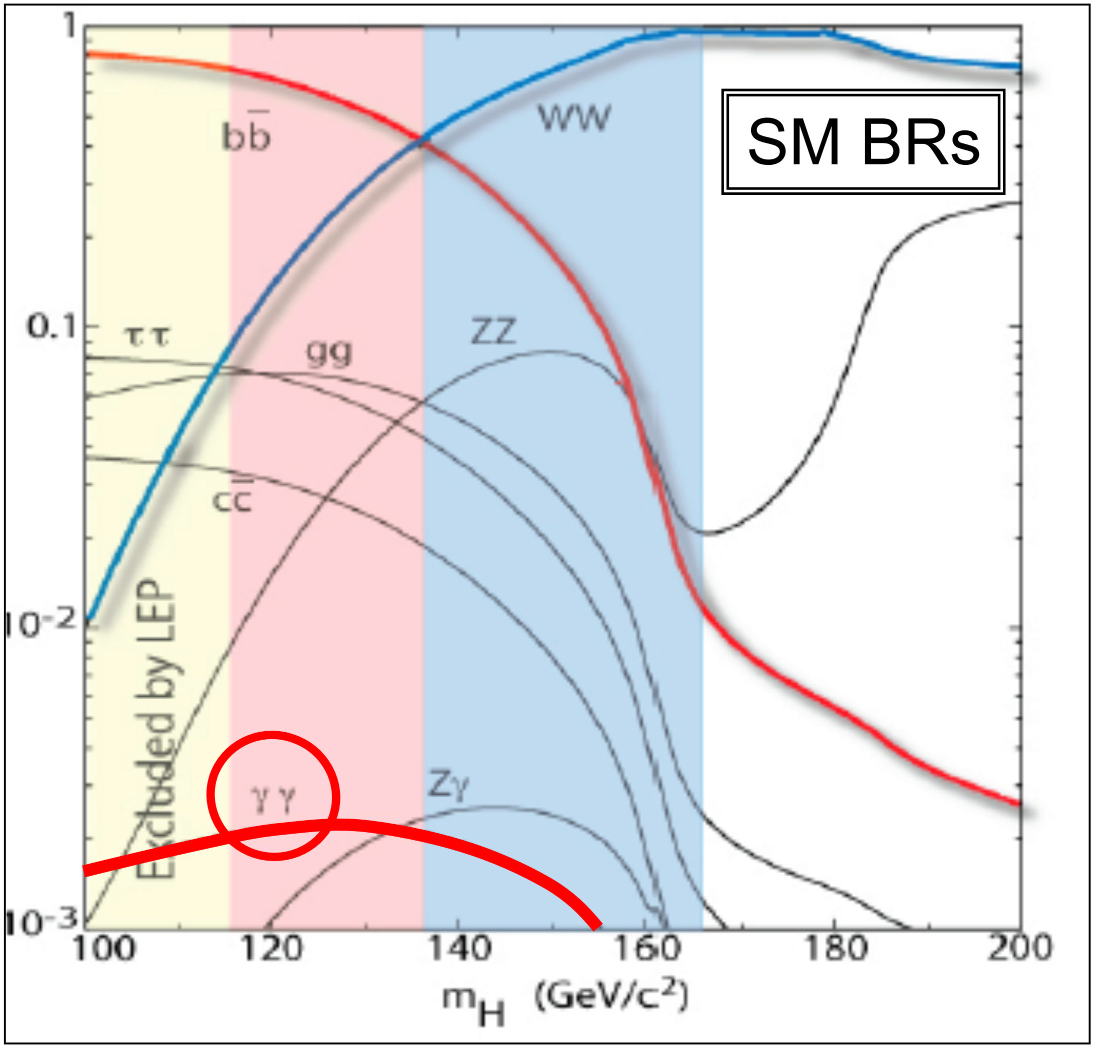
# SUSY constraints from H→ττ searches

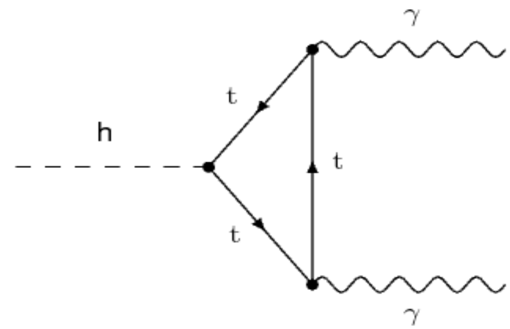


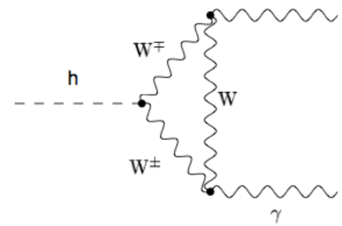



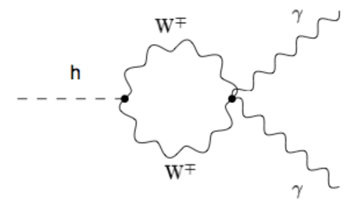

- The first results from ATLAS and CMS extend beyond the previous Tevatron results with $2fb^{-1}$

# Searches for γγ



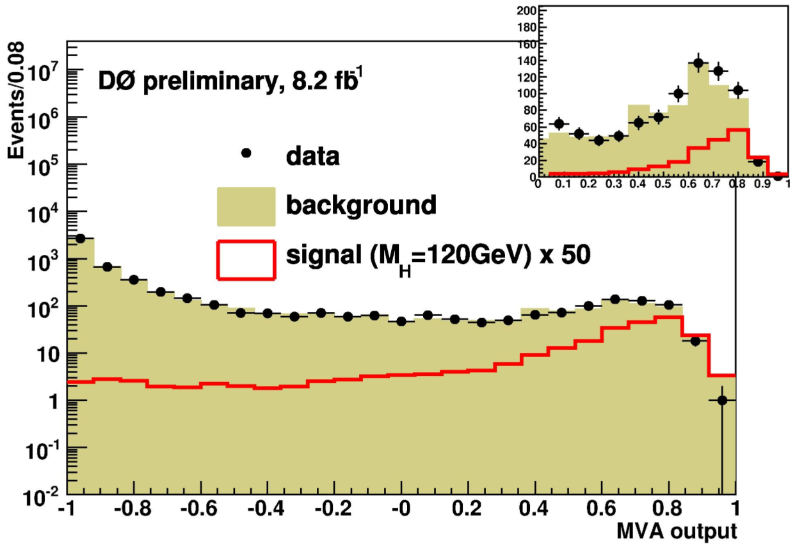



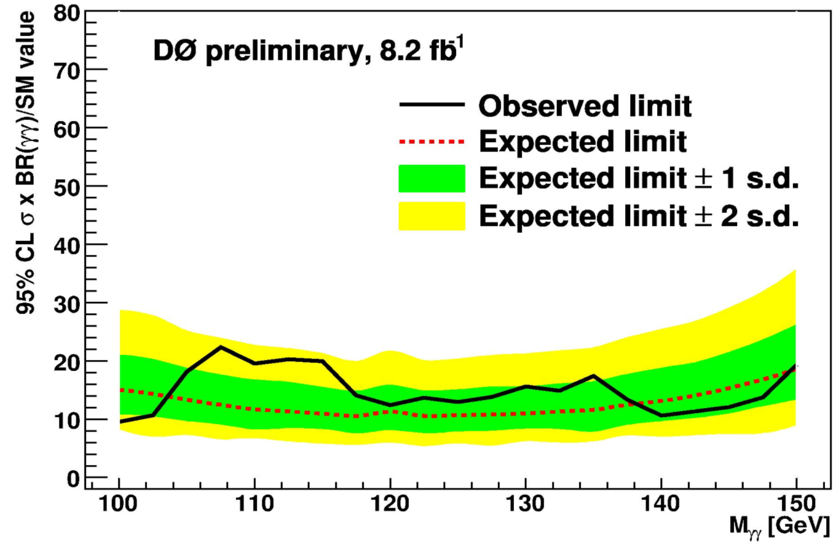



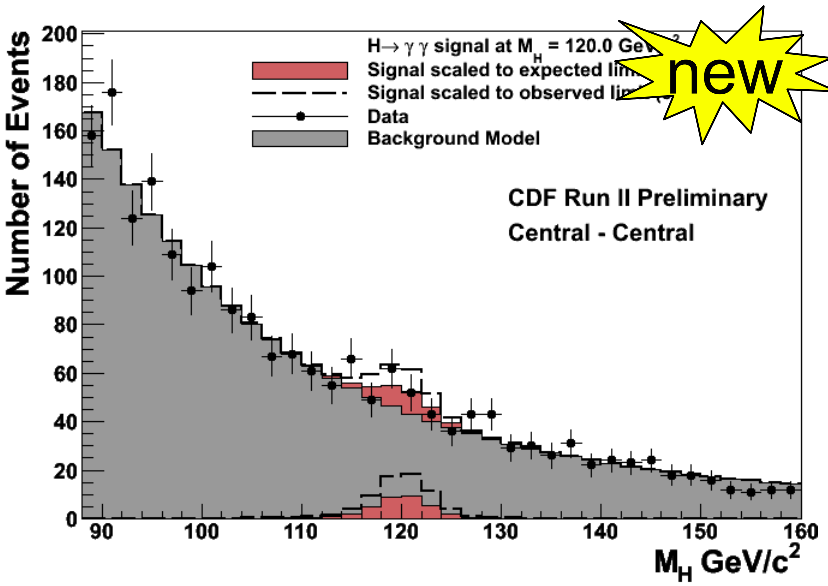



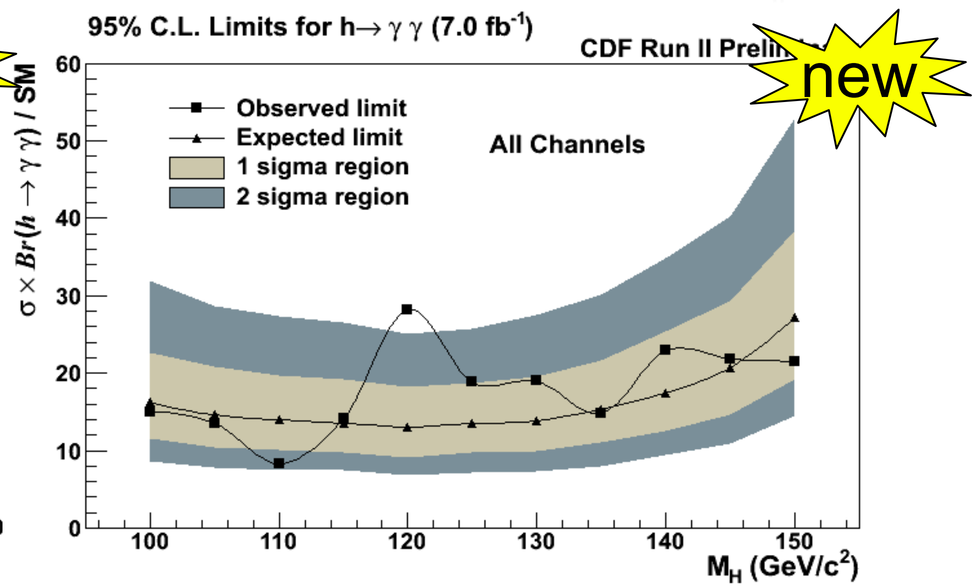

- Proceeds via quark or V loops. Sensitive to new heavy particles or deviations from SM.
- Rare in SM, but good mass resolution.
- Can be enhanced in "fermiophobic" models

# Tevatron H→γγ searches



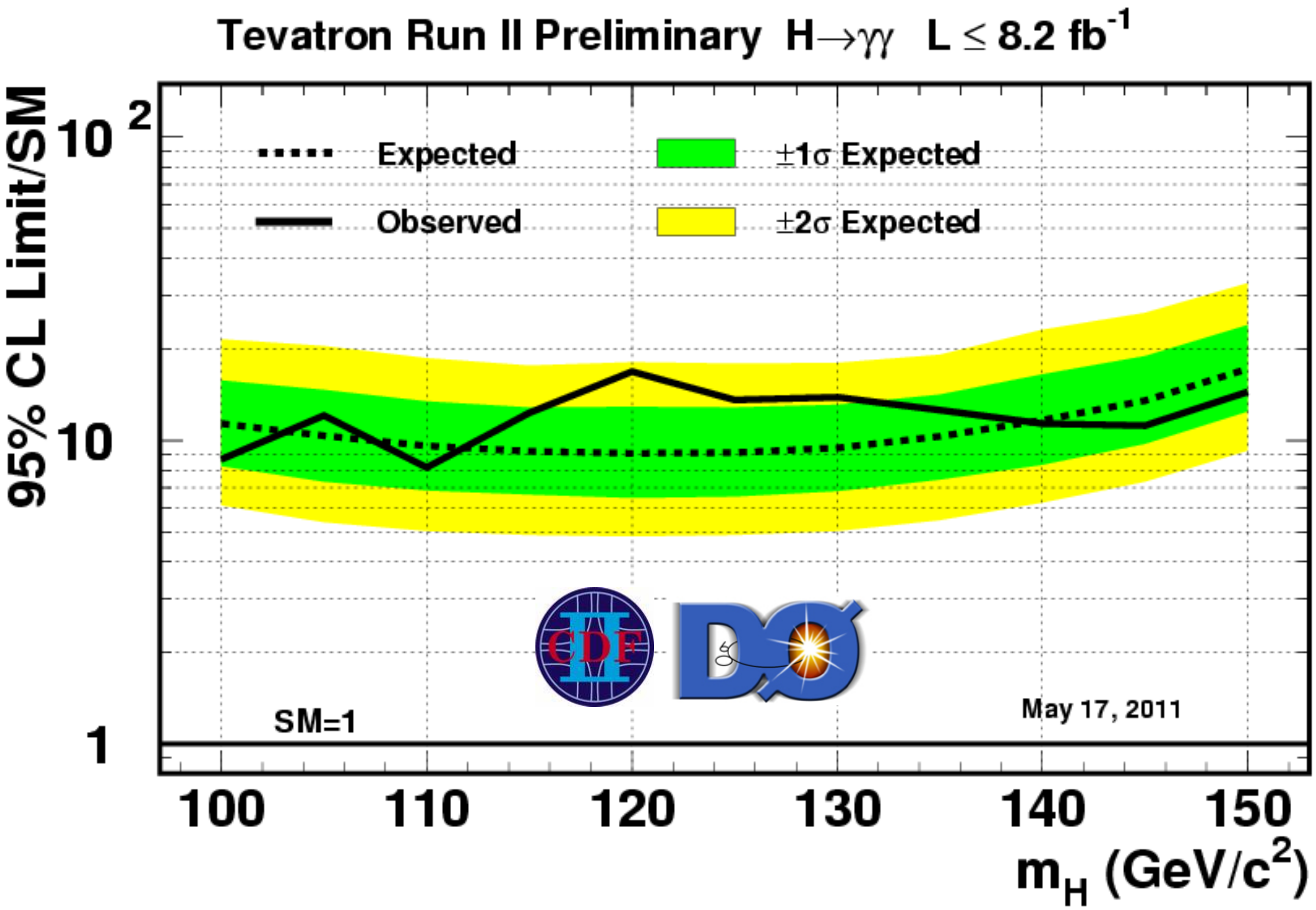




- New CDF results - no MVA yet
- Slight excess at 120GeV, but <2σ after trial factor

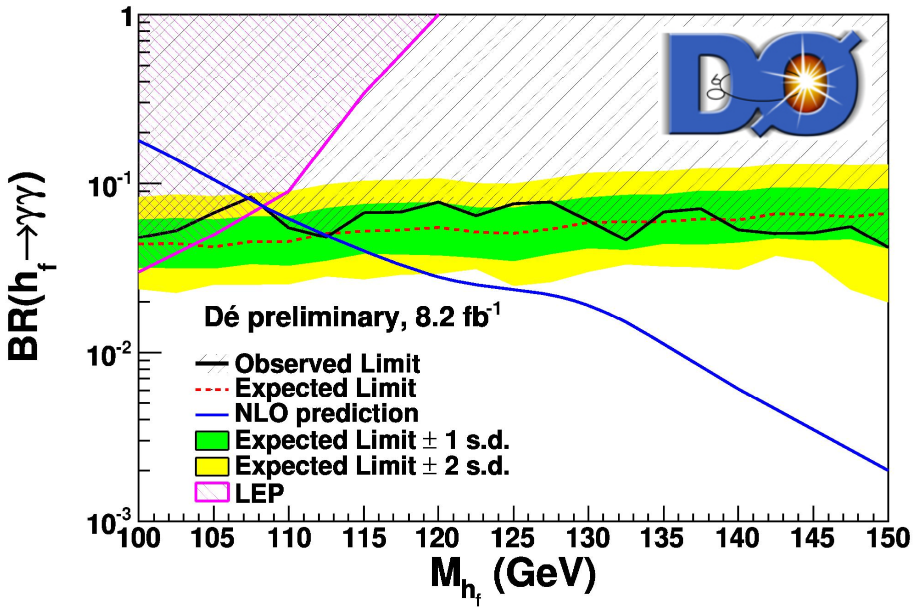
# Tevatron SM H→γγ Combination

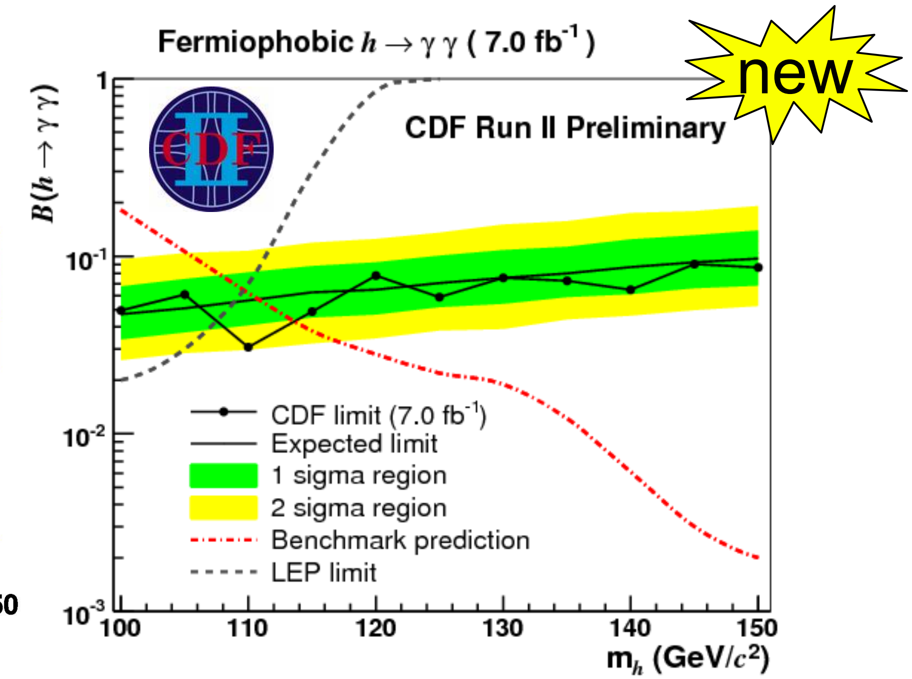
new




- Expected @ 120: 9.1xSM   Observed : 16.9xSM
- Reaching within one order of magnitude of SM prediction - an analysis that was not planned to happen at the Tevatron.

# Fermiophobic $h_f \rightarrow \gamma\gamma$ (Tevatron)




Fermiophobic = zero fermion coupling

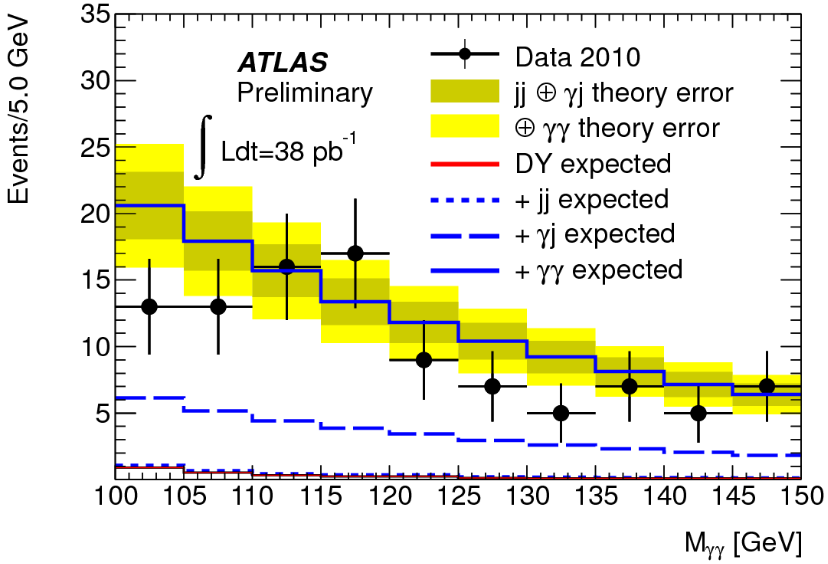
- no gg production
- q-qbar modes suppressed (only via loops)
- net effect:enhanced $\gamma\gamma$ production (x30 @ 100GeV)

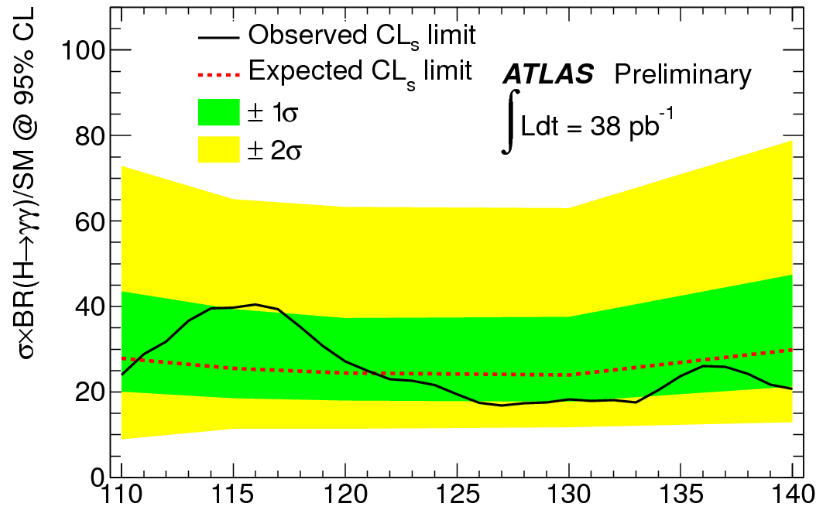
•LEP Limit: >109.7 GeV

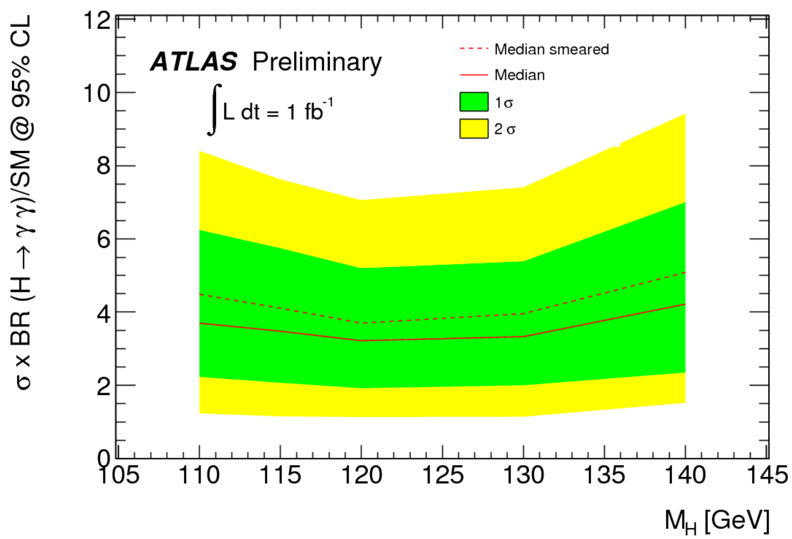
•DØ's recent (8.2/fb): >112 GeV

•CDF new (7/fb): >114 GeV  (not yet combined)

# H→γγ at ATLAS



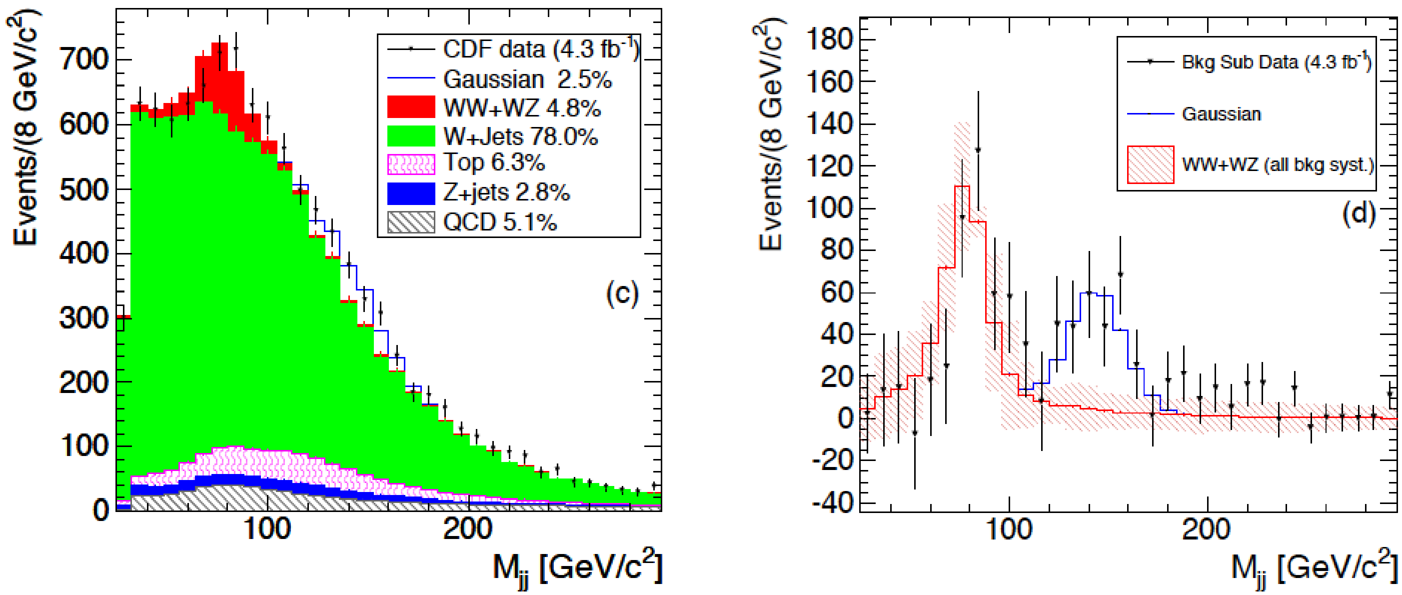




- First preliminary result uses 38pb$^{-1}$
- 95% upper C.L. limits @ ~25xSM
- Projected ~4xSM with 1 fb$^{-1}$

When in search for the unknown, you don't know what you are going to find.

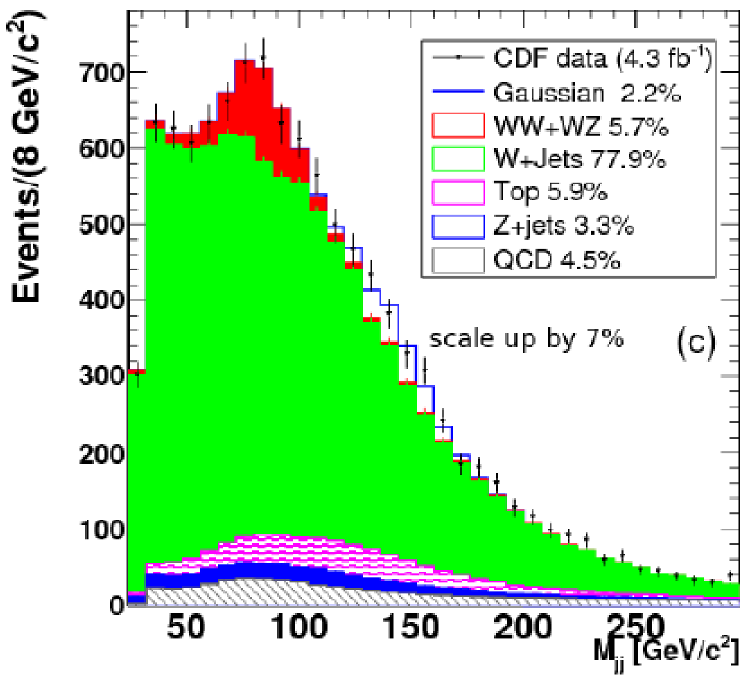
# Update on W-jj excess

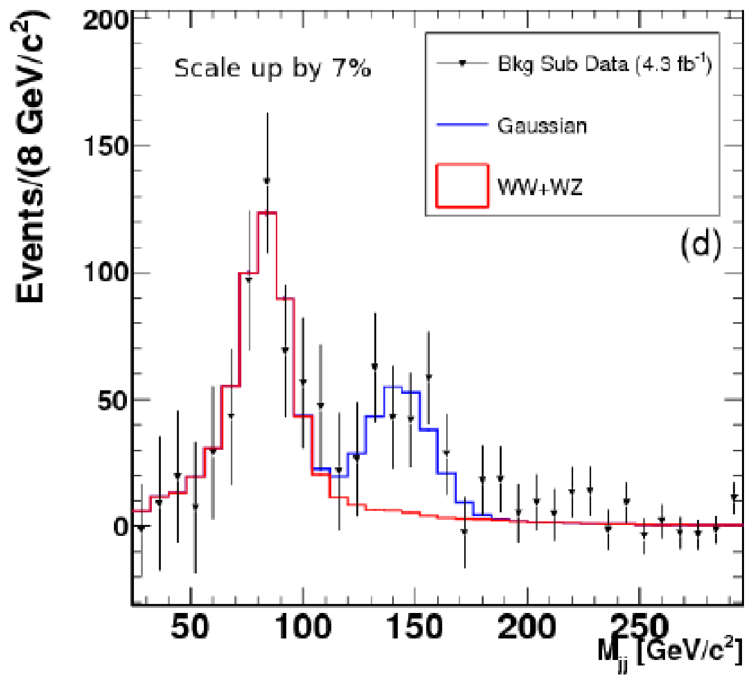



- 3.2σ excess (w/ trial factor) in Mjj spectrum in W+2jets events
  [PRL 106,171801 (2011)]
- Since publication, many papers cited this result and proposed possible interpretations, mostly based on NP
- Interesting SM suggestion: could this be top background ?
  [arXiv:1104.4087, arXiv:1104.3790]
- Would imply a huge error in previous top cross section measurements - however, when one has an unknown peak with the shape of one of his background, one needs to consider the possibility seriously.

# *What happens if we change the Jet Energy scale?*

Result of the fit scaling JES up by 7%



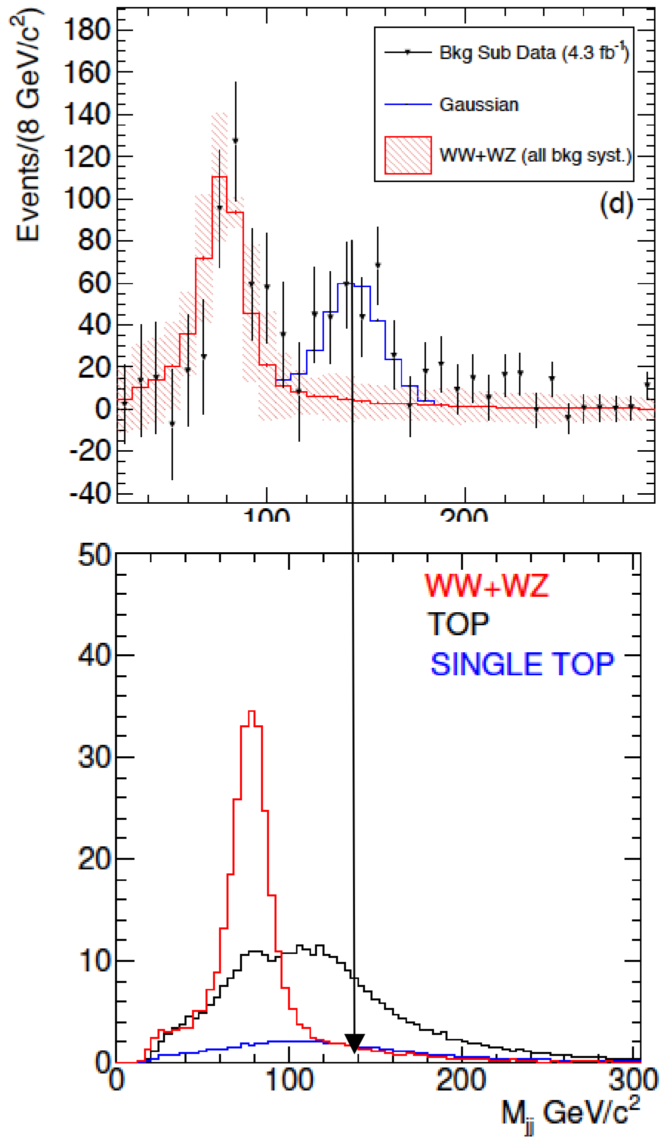




Si

always above $3\sigma$

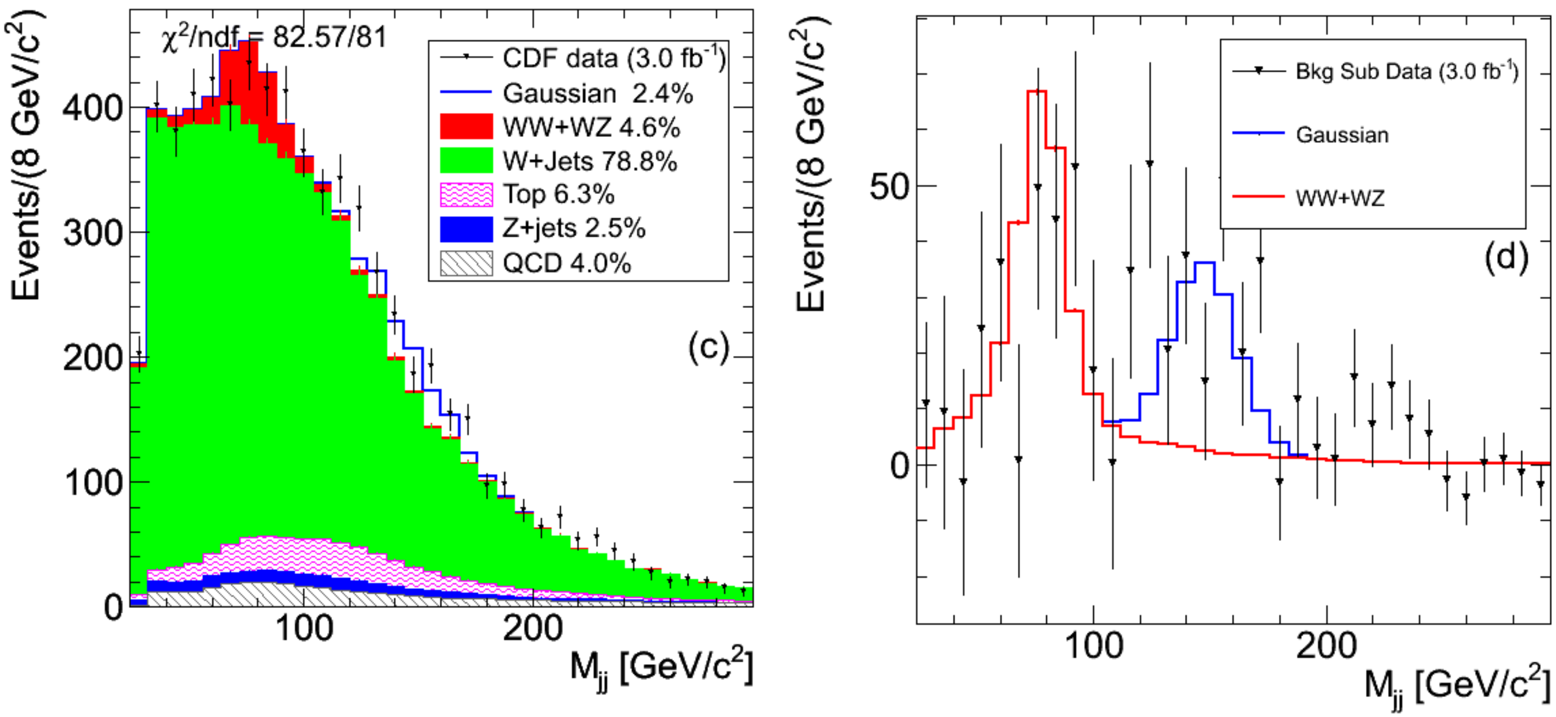
# Update on W-jj excess

- But, the answer is NO - this cannot possibly be top background
  - There is no significant tagged component
  - Top-enriched control samples show perfect agreement with simulation
  - When using actual detector simulation, the top background does not peak at the right place



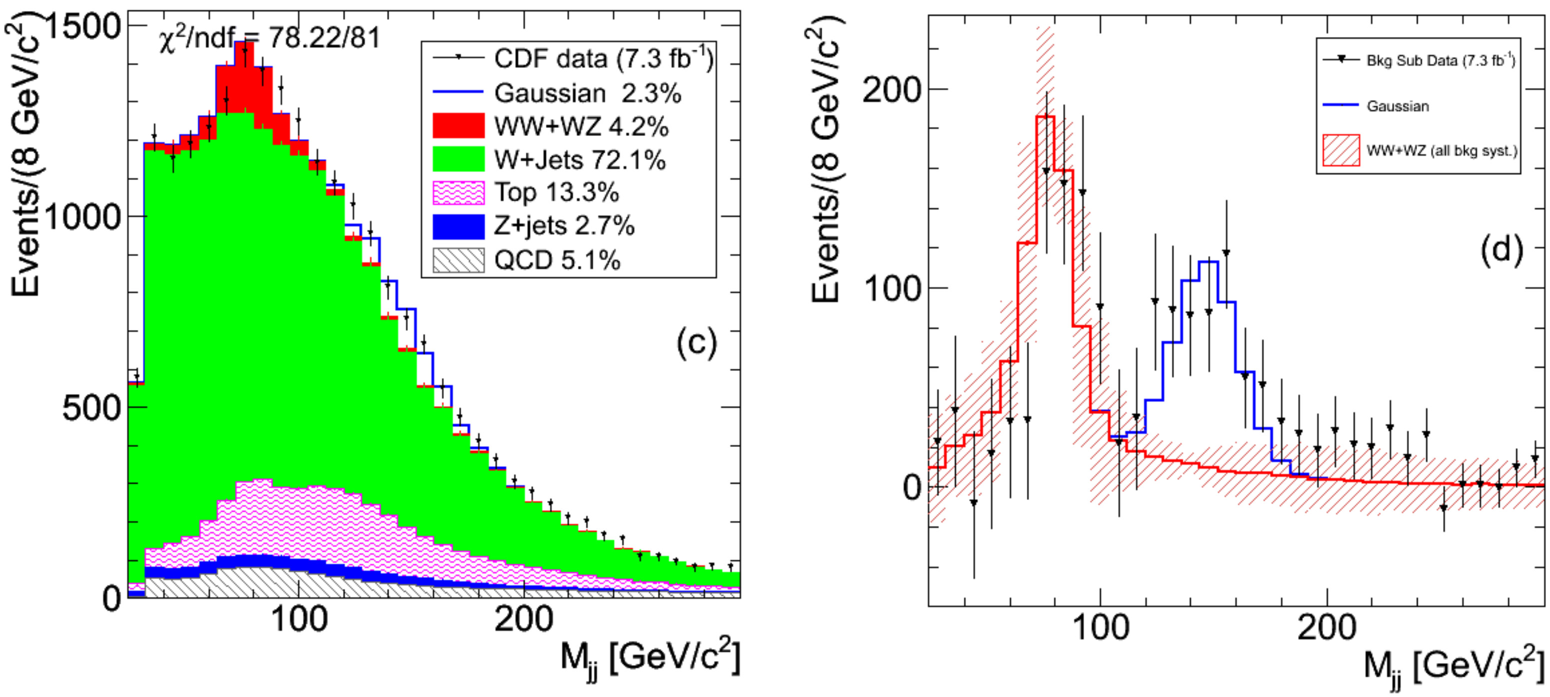

FAQ: Maybe it’s just statistics - why aren’t you showing the full sample anyway ?

# Additional sample of 3fb$^{-1}$ of data




- Looks just the same as the initial 4.3fb-1
- 2.85$\sigma$ excess including (unneeded) trial factor
- Fitted mass of the excess 147$\pm$ 5 GeV compatible with first sample

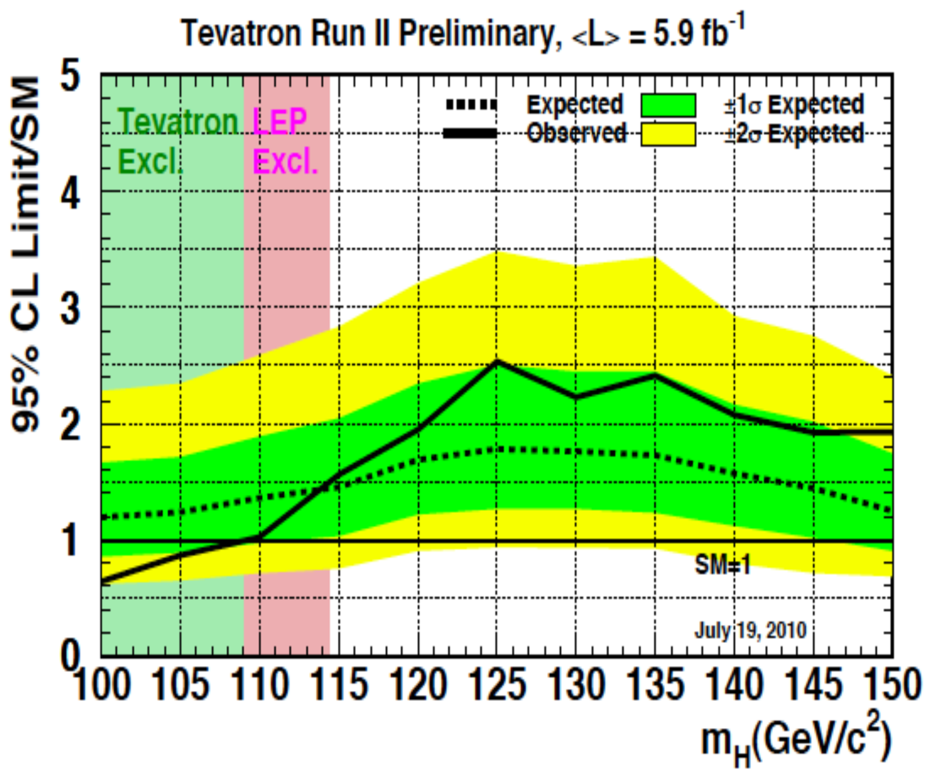
# Updated W-jj with 7.3fb$^{-1}$

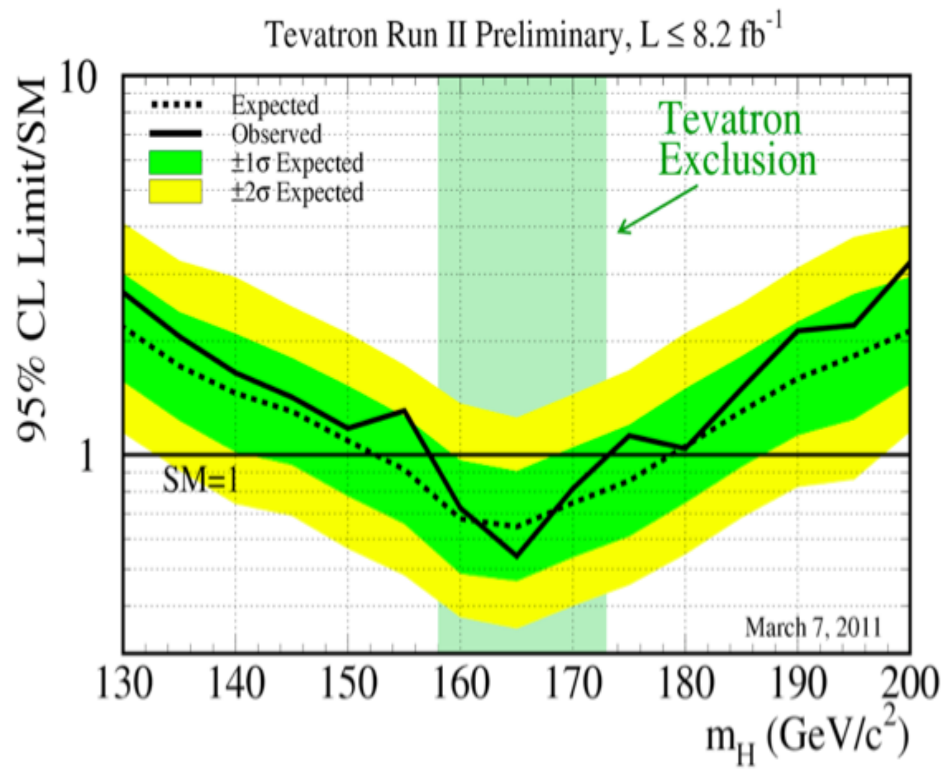



- Now closer to 5 sigma
- It was not just a statistical fluctuation
- Serious issue for CDF to understand this.
- Larger sample now allows for more detailed studies
  - stay tuned for updates.

# Combined Tevatron Limits

**"Low Mass" combination (ICHEP 2010)** **"High Mass" combination (Moriond 2011)**




- Better than ~2xSM sensitivity for all mass points below 200 GeV
- At $m_H$=115 GeV expected limit 1.45xSM
- New exclusion at 95% C.L.: 158-173 GeV (expected: 153-179 GeV).
  - Expected exclusion as of ICHEP 2010 was 156-173 GeV.

# Global SM Electroweak Fit

- In the assumption of SM Higgs, one should keep into account indirect contraints as well
- LEP + Tevatron (Fall 2010) :
  - 2σ interval: [115,152] GeV

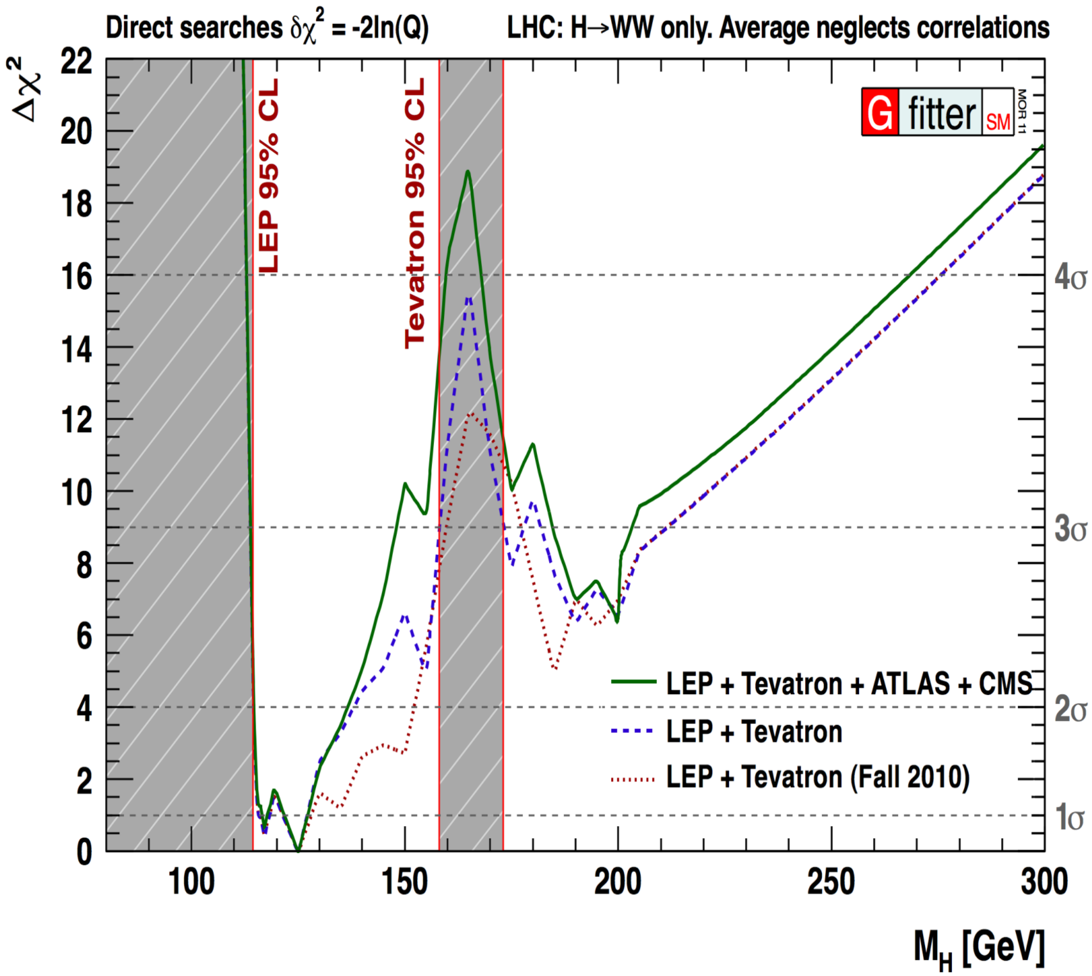
$$M_H = 120.2^{+17.9}_{-5.2}\ \text{GeV}$$

- LEP + Tevatron (Moriond 2011):
  - 2σ interval: [115,138] GeV

$$M_H = 120.2^{+12.3}_{-4.7}\ \text{GeV}$$

- Fit with LEP + Tevatron + LHC (H➔WW) searches (Moriond 2011) :
  - 2σ interval: [115,137] GeV

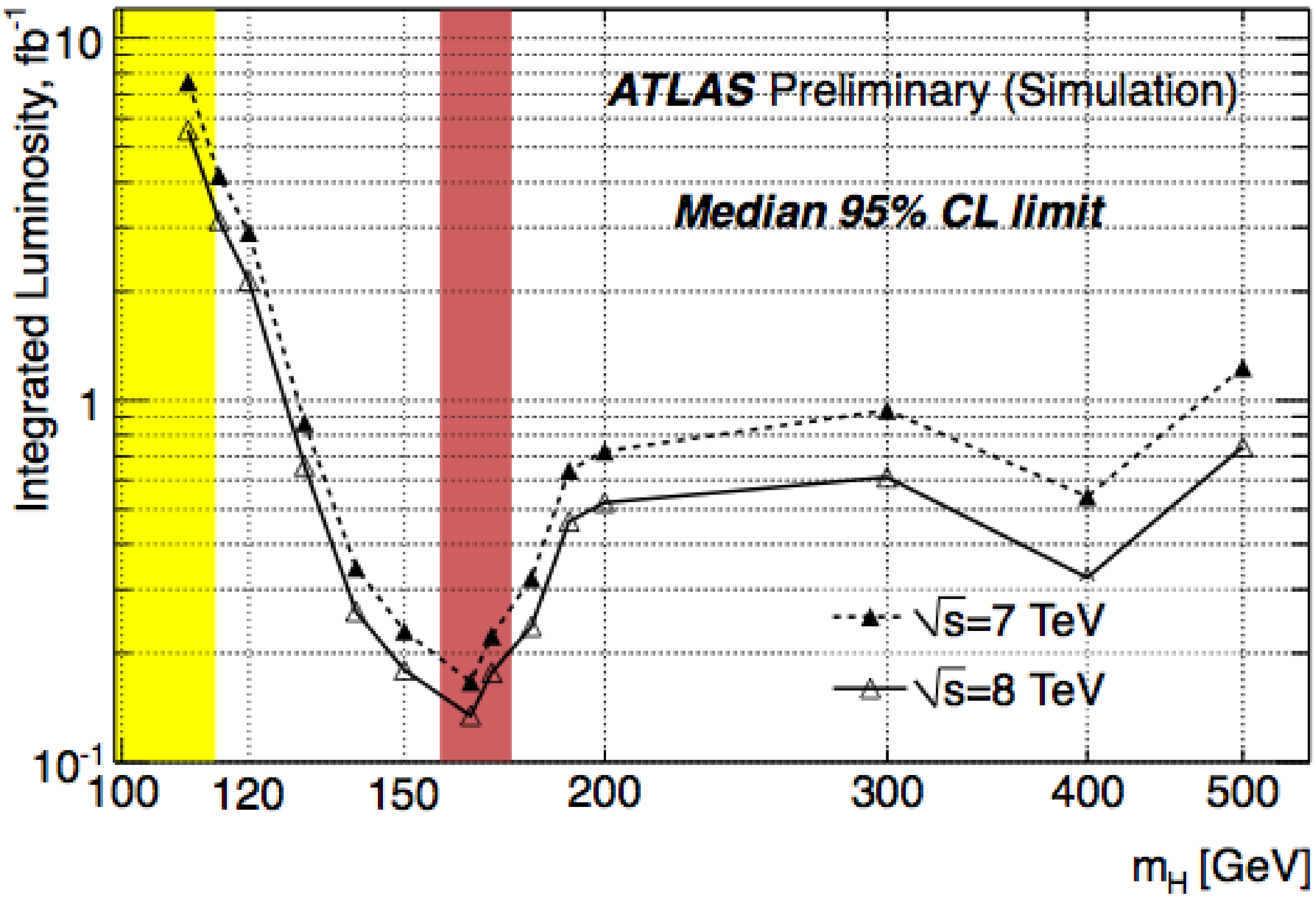
$$M_H = 120.2^{+12.3}_{-4.7}\ \text{GeV}$$




If SM is correct, Higgs mass is determined to <10%

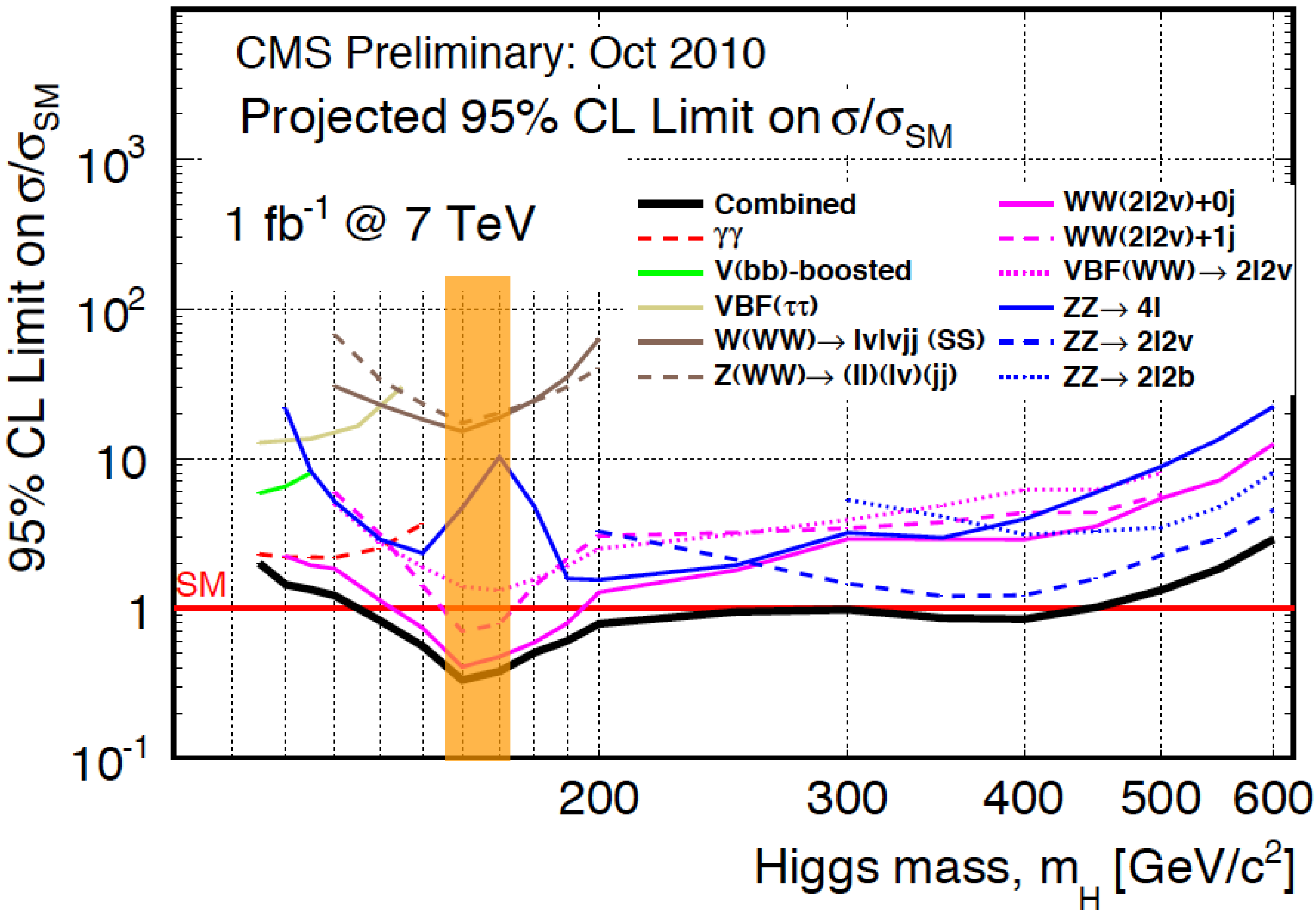
Indirect constraints are going to improve as well - see M. Verzocchi talk

# ATLAS prospects



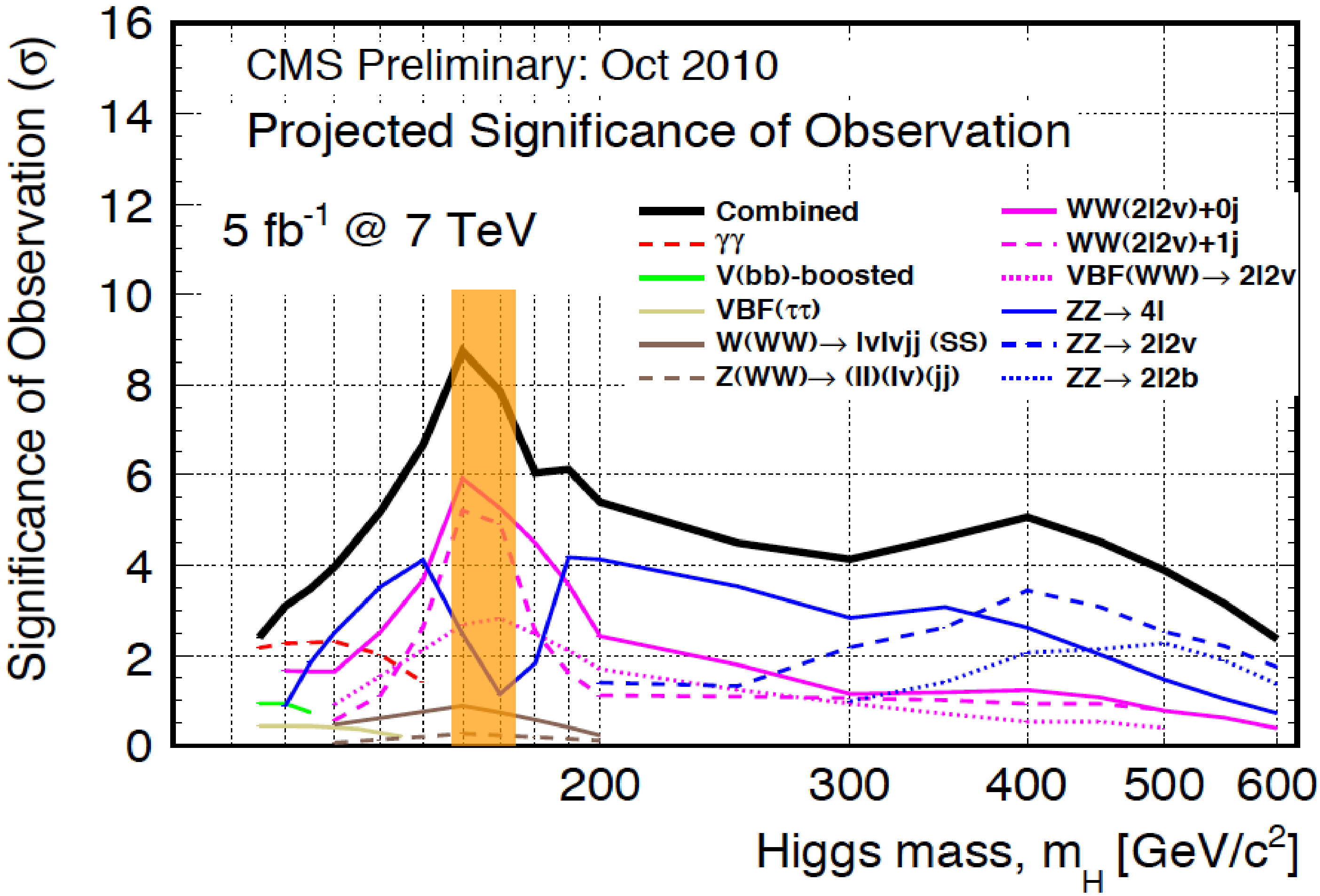

- 1fb-1 cover the full range above ~130, driven by VV modes

# CMS prospects



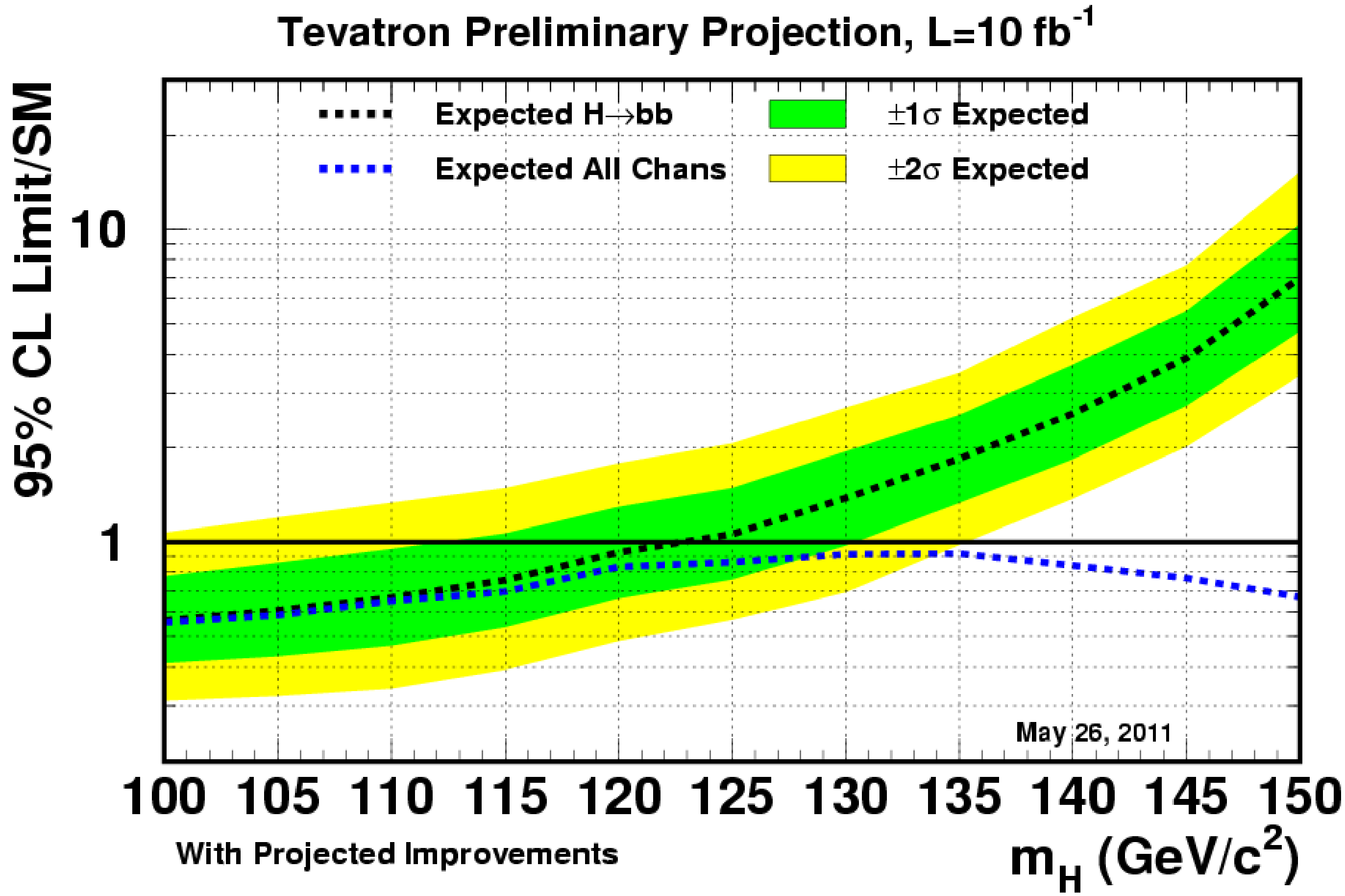

- 1fb-1 cover the full range above ~130, driven by VV modes

# CMS prospects




- 5 fb-1 yield 4σ the full range >130 GeV, driven by VV modes

# Tevatron prospects 2011

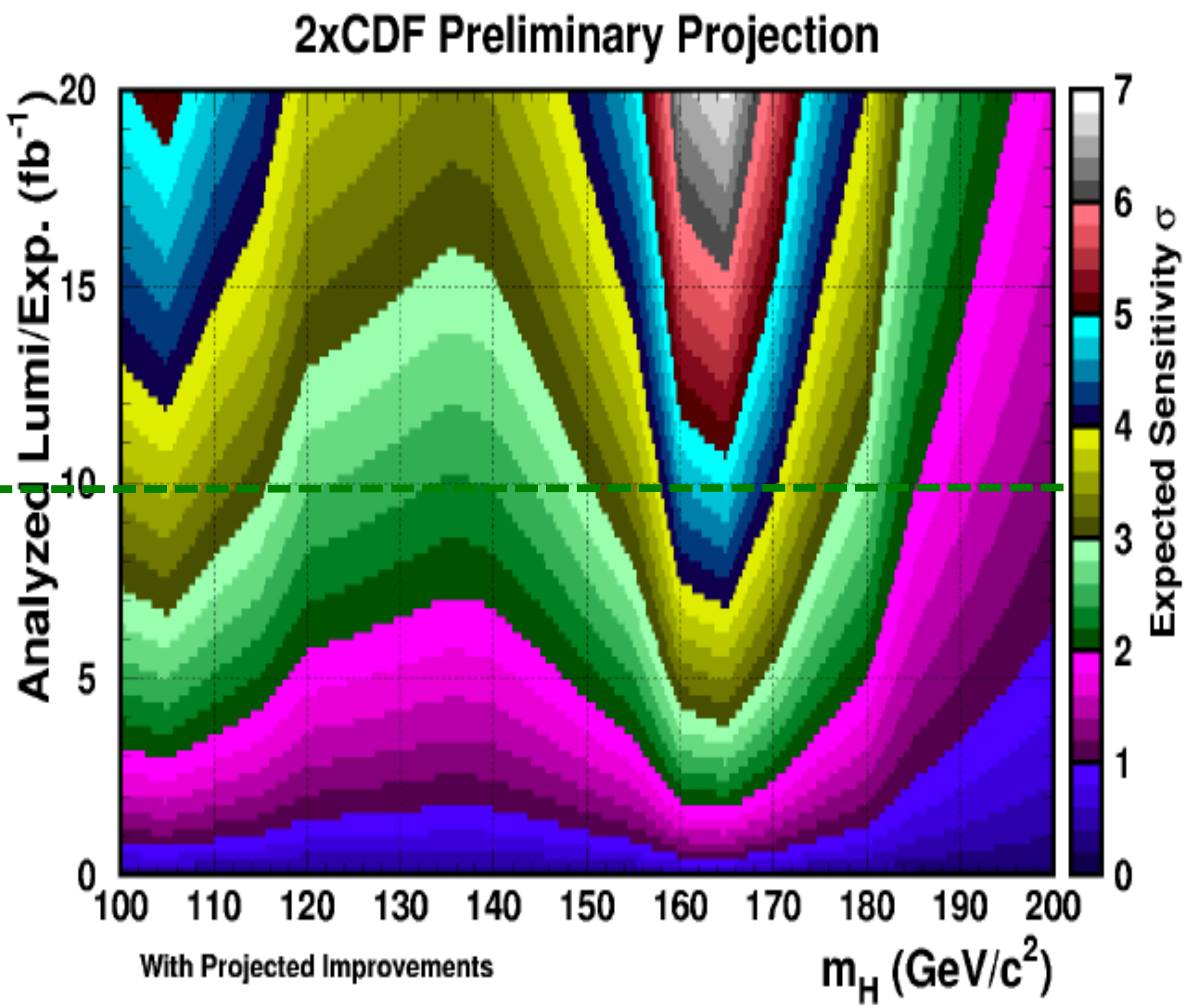



- Below the line for the whole range
- Better at low masses - driven by VH, H->bb
- Complementary information to LHC

# Tevatron prospects 2011

>2.4σ for $m_H$<185 GeV

3σ for $m_H$~115 GeV

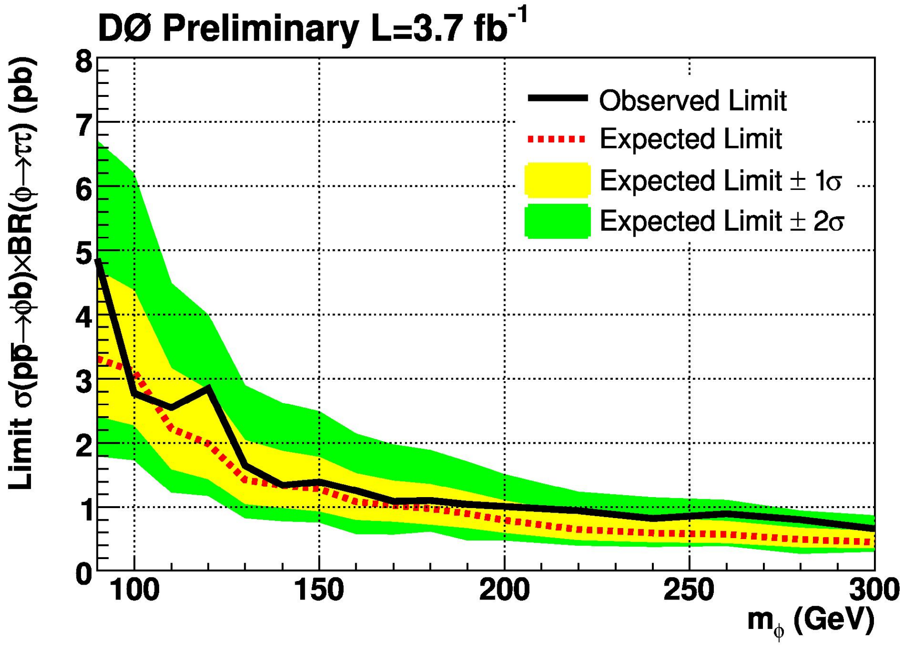


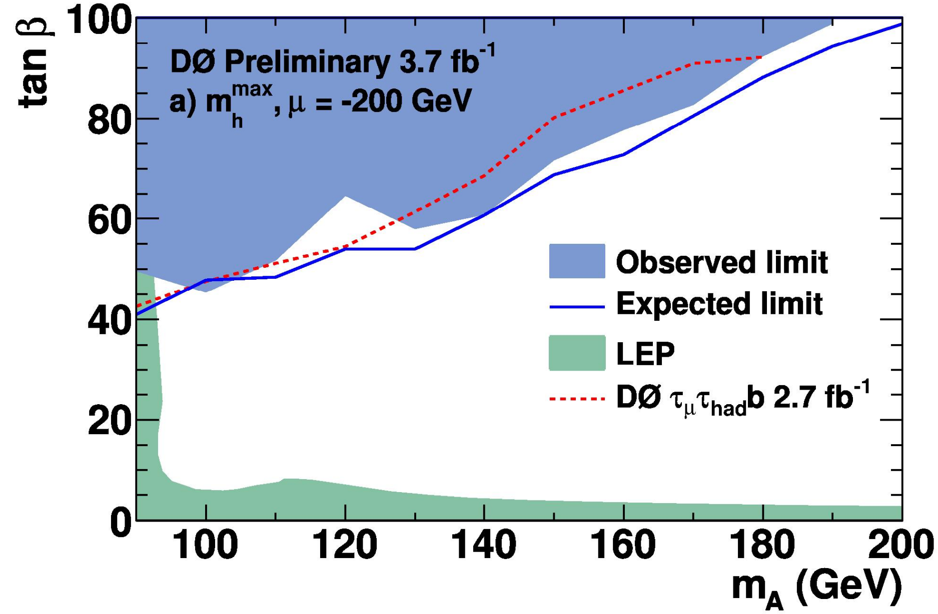
# We live in the Higgs era

- Coming to terms with EW symmetry breaking.
- We know quite a lot already about the Higgs
  - The SM Higgs mass is very constrained
  - No model with a rate >> SM is viable.
  - Coexistence of a SM-like Higgs and a 4-th quark generation is very nearly excluded
- The next step is finding out whether SM is right or wrong. Should not take long. Surprises might come up.
- A new era will follow - we don’t know its name.
- We should enjoy this special time we are so lucky to live in.

# BACKUP

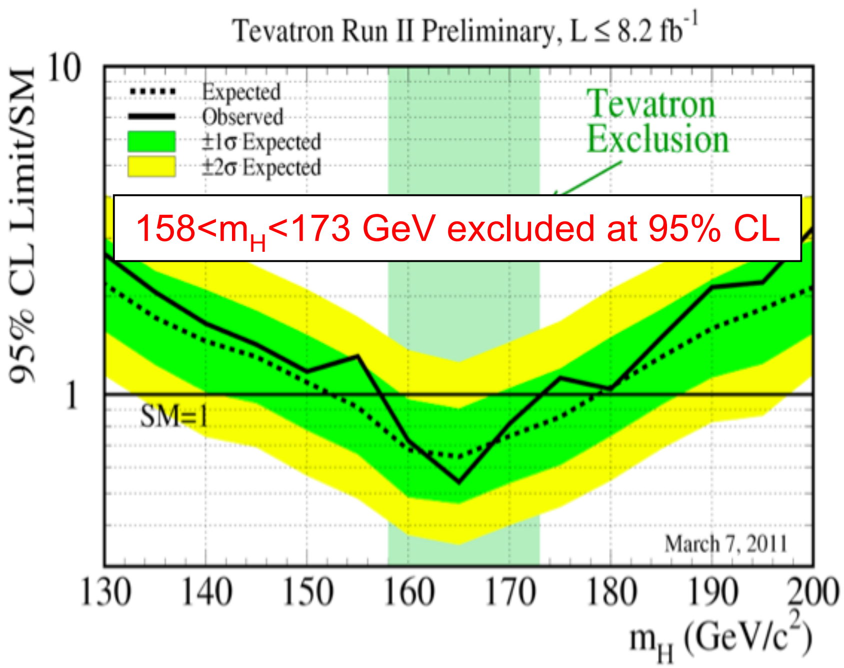
# Tau tau + b

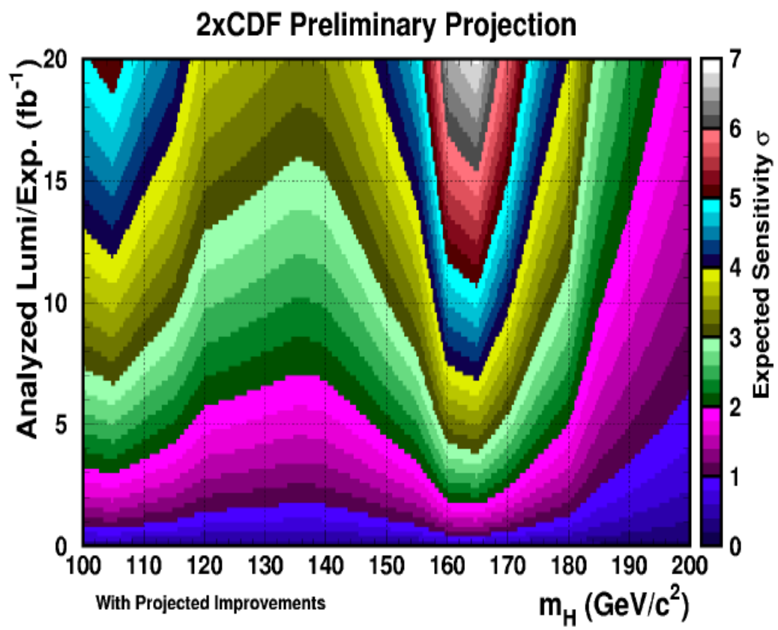

DØ Preliminary L=3.7 fb$^{-1}$
Observed Limit
Expected Limit
Expected Limit ± 1σ
Expected Limit ± 2σ
Limit σ(pp̄→φb)×BR(φ→ττ) (pb)
$m_\phi$ (GeV)


DØ Preliminary 3.7 fb$^{-1}$
a) $m_h^{max}$, μ = -200 GeV
Observed limit
Expected limit
LEP
DØ $\tau_\mu\tau_{had}$b 2.7 fb$^{-1}$
tan β
$m_A$ (GeV)

# Conclusions

- The Tevatron Higgs program continues to make steady progress in sensitivity and starting to corner the SM Higgs boson:



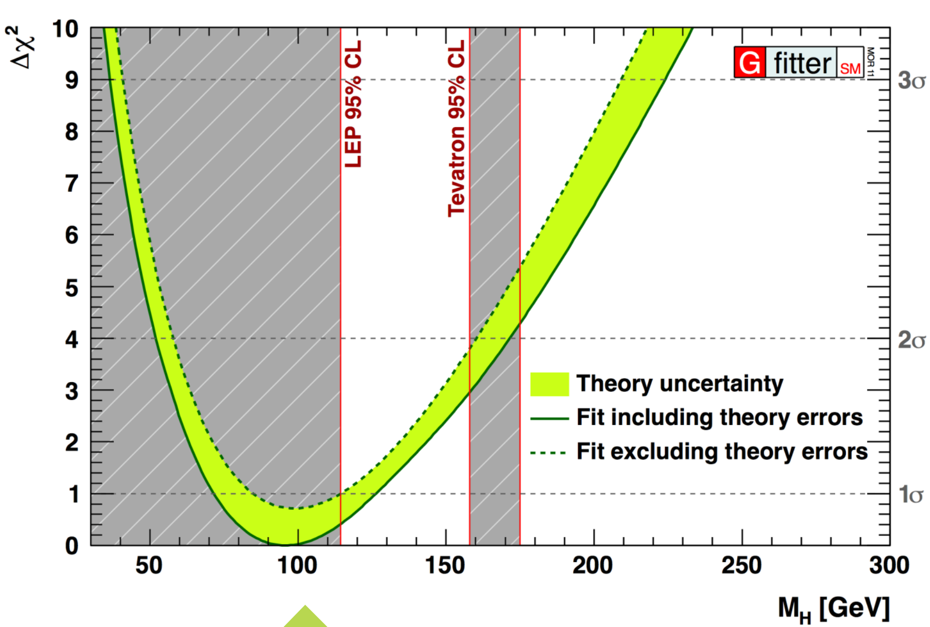



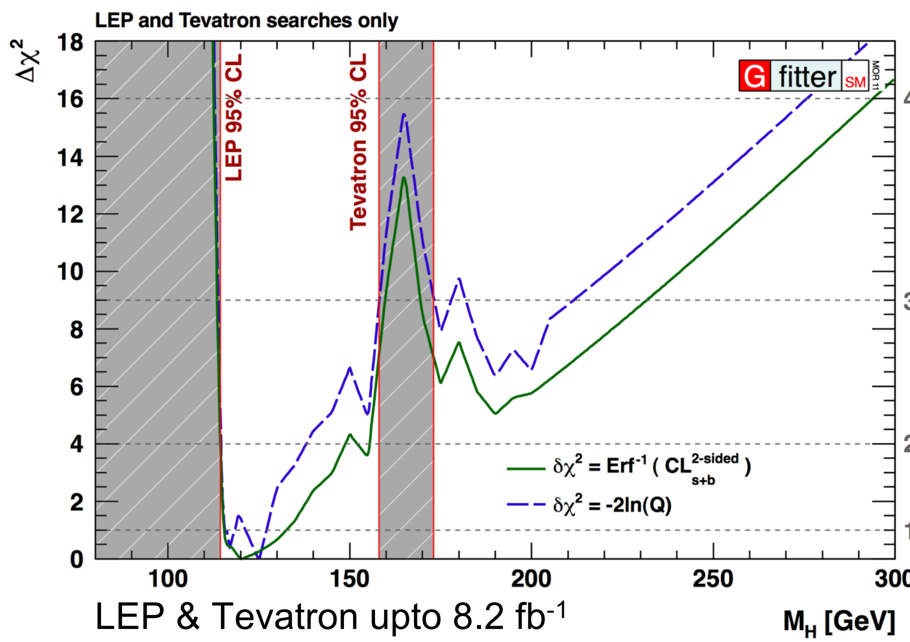

- With the dataset collected by end of 2011 plus additional improvements underway expect a-priori exclusion at 95% C.L. (if the Higgs doesn't exist) or >2.5σ sensitivity for $m_H$<185 GeV.
- Large dataset and refined analysis techniques hold a lot of promise for BSM Higgs searches, with the potential for surprises around the corner. Expect significantly improved results in coming months.
- Exciting times ahead. Stay tuned!

# Electroweak Fit – Tevatron Higgs Constraints

- $M_H$ from fit w/o Higgs searches:
  - Central value $\pm 1\sigma$: $M_H = 95.7^{+30.3}_{-24.2}$ GeV
  - $2\sigma$ interval: $[52,171]$ GeV

- **Fit with LEP & latest Tevatron searches:**
  - $CL_{s+b}^{2s}$ central value $\pm 1\sigma$: $M_H = 120.2^{+12.3}_{-4.7}$ GeV
  - $2\sigma$ interval:
    - $CL_{s+b}^{2-sided}$ : $[114,149] \cup [152,155]$ GeV
    - $-2\ln Q$ : $[115,138]$ GeV

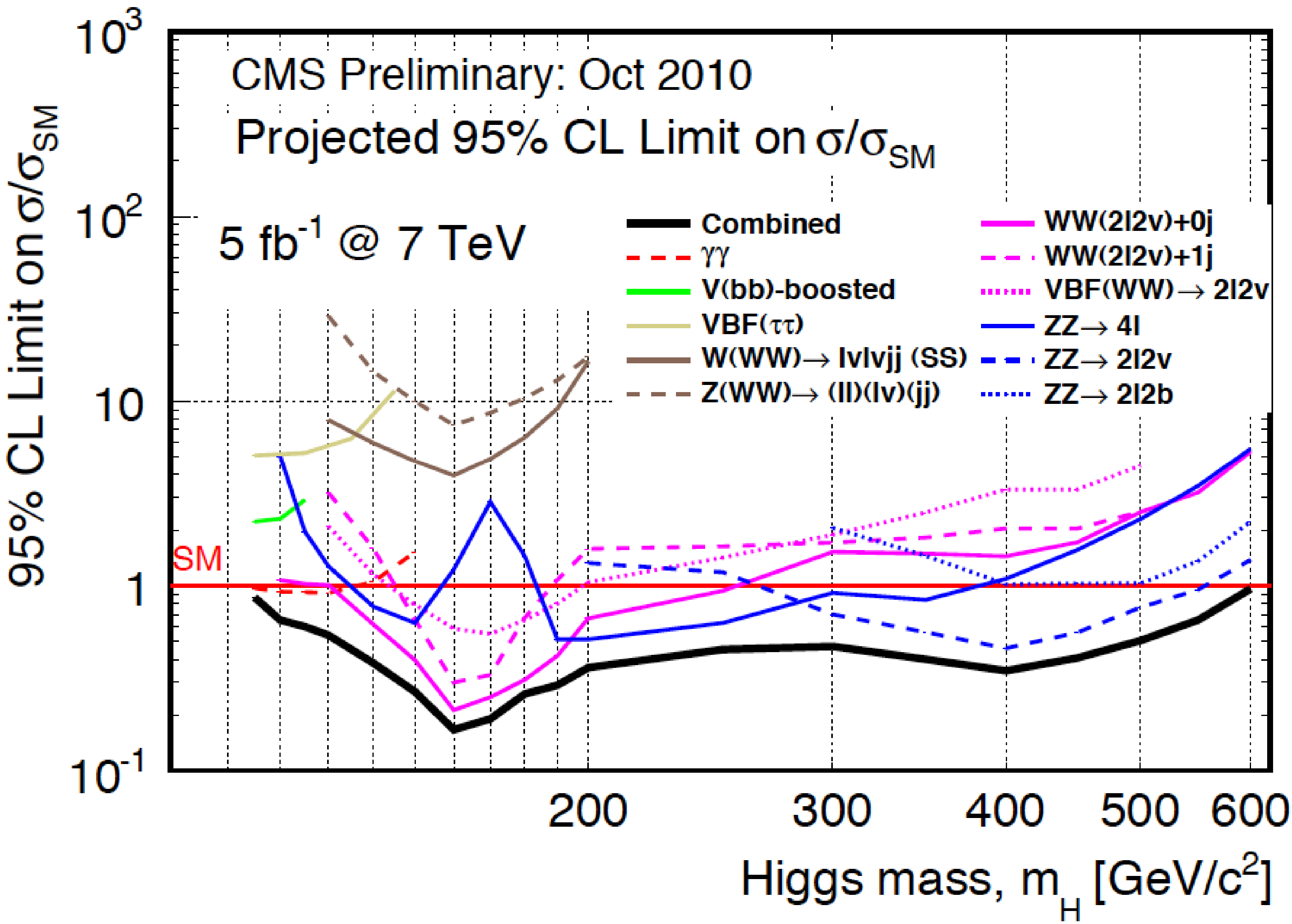



LEP & Tevatron upto 8.2 $fb^{-1}$

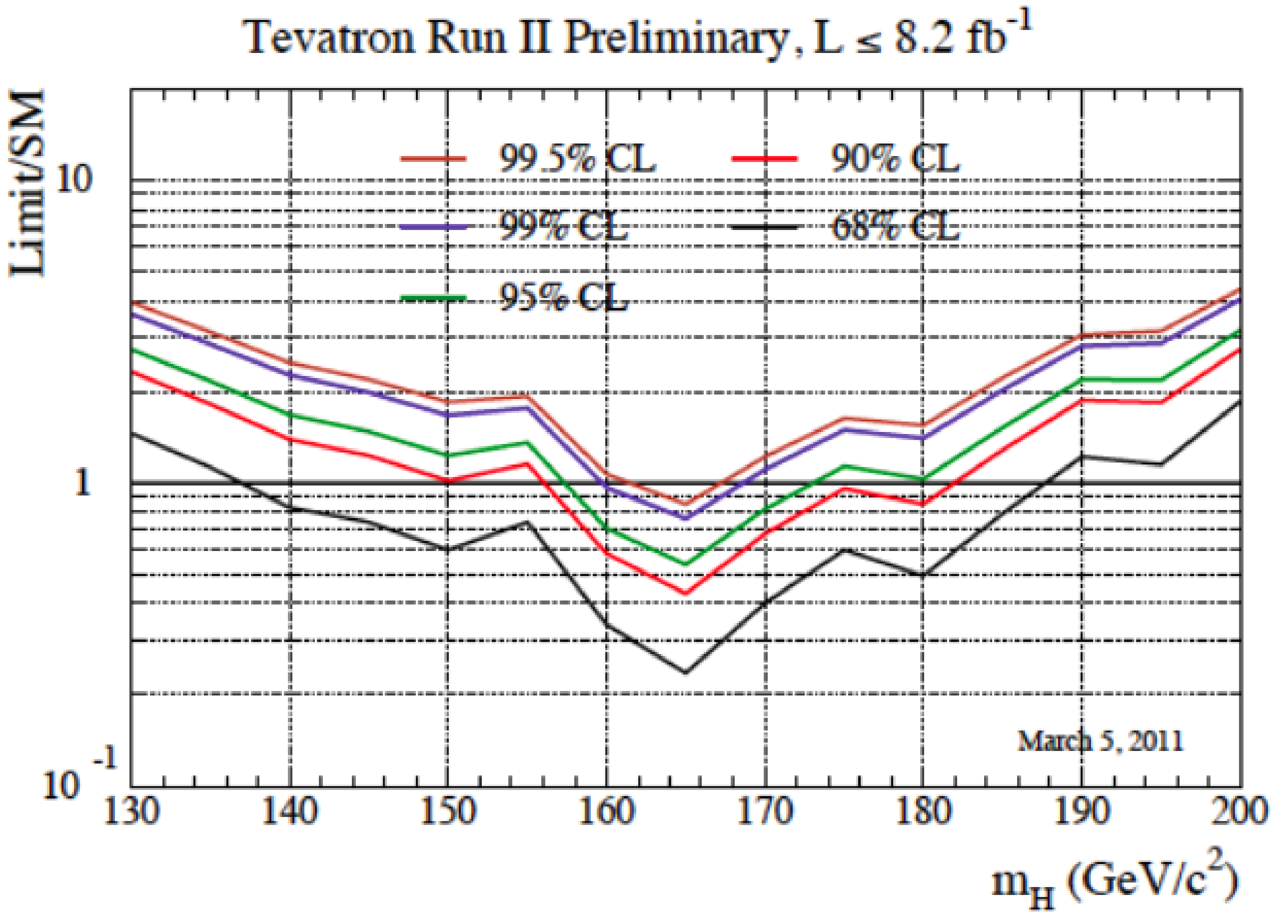
- Green error band from including / excluding theoretical errors in fit
  - Theoretical errors included in $\chi^2$ with "flat likelihood term"

# CMS outlook



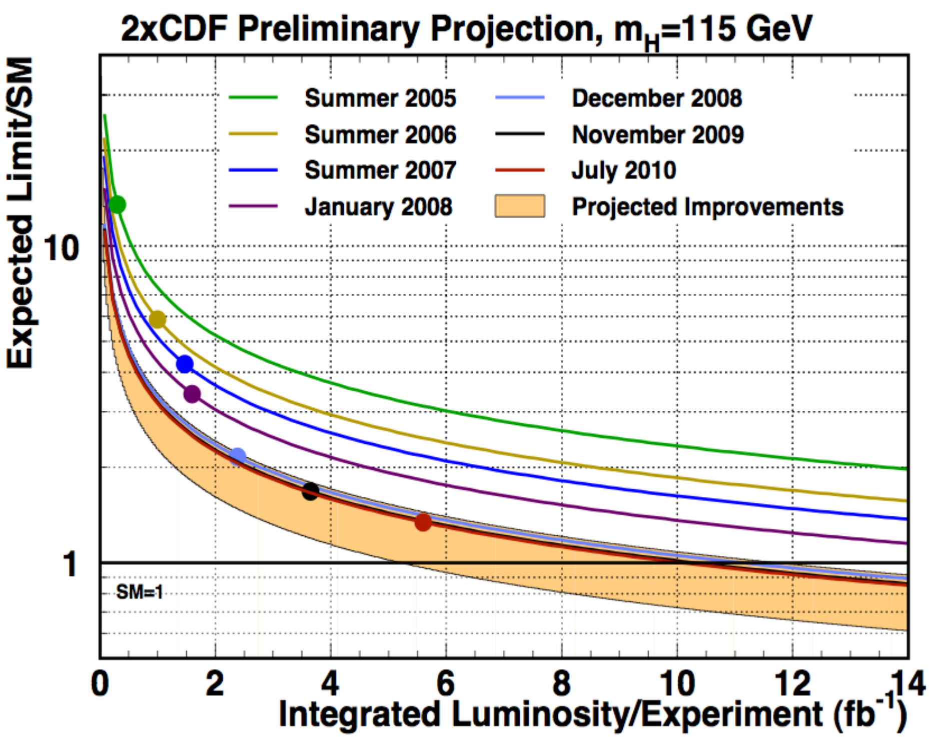
CMS Preliminary: Oct 2010
Projected 95% CL Limit on σ/σ_SM
5 fb^-1 @ 7 TeV
Combined
γγ
V(bb)-boosted
VBF(ττ)
W(WW)→ lνlνjj (SS)
Z(WW)→ (ll)(lν)(jj)
WW(2l2ν)+0j
WW(2l2ν)+1j
VBF(WW)→ 2l2ν
ZZ→ 4l
ZZ→ 2l2ν
ZZ→ 2l2b
SM
95% CL Limit on σ/σ_SM
10^3
10^2
10
1
10^-1
200
300
400
500
600
Higgs mass, m_H [GeV/c^2]

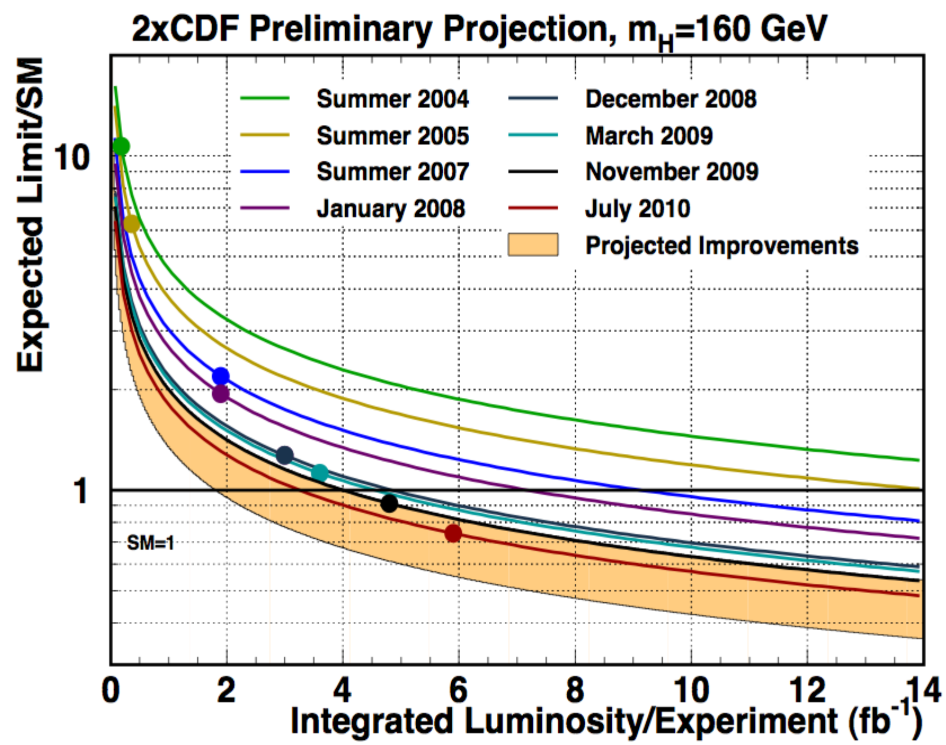
# Just how excluded is it?




- SM Higgs of 162 < $m_H$ < 166 GeV excluded **@99.5% CL**

# SM Higgs Prospects




Orange band: assumed analysis improvements wrt 2007 analysis (x1.5 and x2.25)

- Limits have improved faster than 1/√L due to analysis improvements.
- Major effort underway to continue to improve intrinsic sensitivity:
  - Optimized object identification/resolution
  - Optimized selections and signal-to-bckg discrimination
  - Reduced systematic uncertainties
  - Adding new channels…