Searches for the Higgs Boson

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For the ATLAS, CDF, CMS & DØ collaborations

Today's Presentation

- Introduction
  - The Higgs mechanism in a nutshell
  - Experimental evidence in the pre-hadron collider era
  - Search strategies at hadron colliders
- Standard Model Higgs boson searches
- Beyond Standard Model Higgs boson searches
- Prospects
- Conclusions

The Case for the Higgs Boson

- Massive weak gauge bosons and fermions implies that there must exist an outside sector of interactions that break the electroweak (EW) symmetry: the "Higgs sector".

- There is no preferred model of the Higgs sector, we just have theories of it.

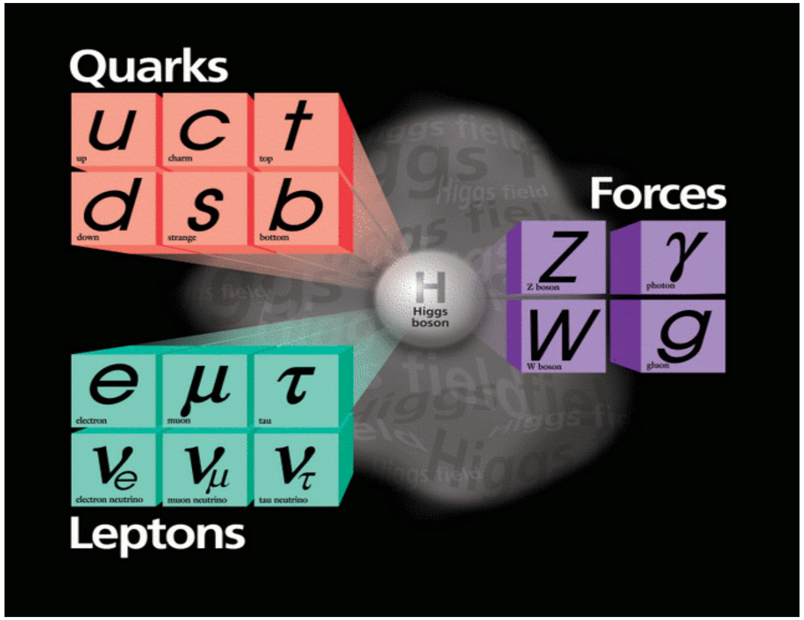
- Simplest realization in the Standard Model:
  - Single scalar doublet field
  - Self interacting; non-zero vacuum expectation value breaks EW symmetry

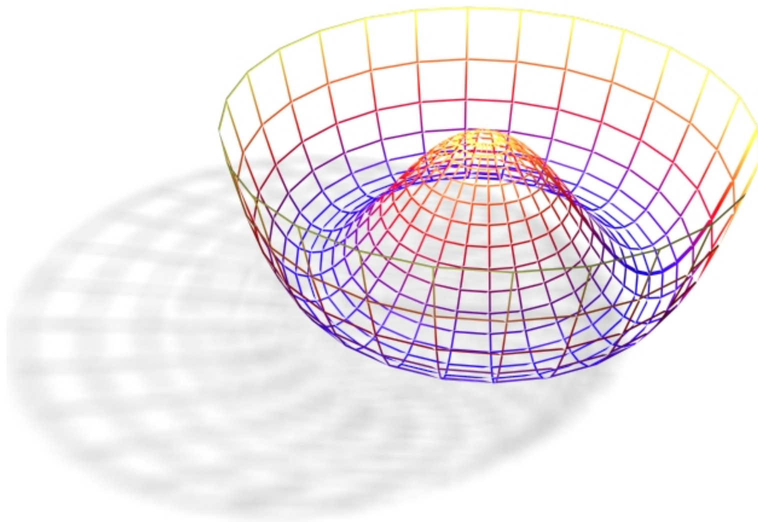
  ➔ gives mass to W/Z bosons

  ➔ gives mass to fermions (through Yukawa interactions)

  ➔ a physical scalar particle remains: the Higgs boson

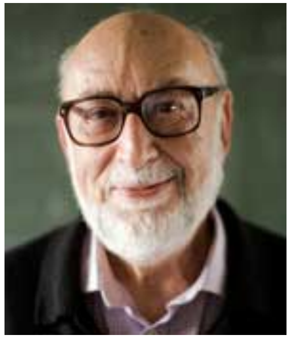
Its mass is not predicted, though!



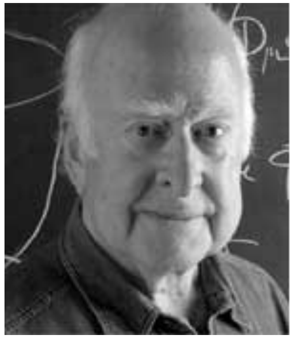


2010 Sakurai Prize for Theoretical Particle Physics

"For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses"

Robert Brout   Francois Englert
Universite Libre de Bruxelles



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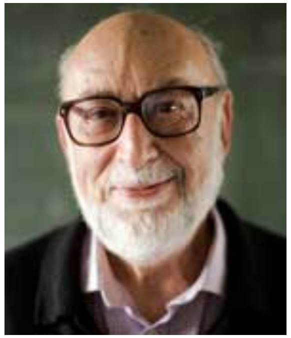

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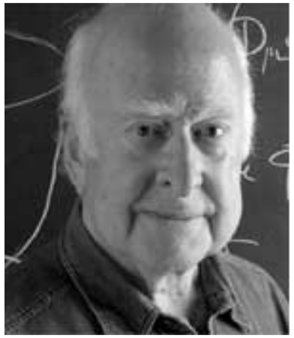

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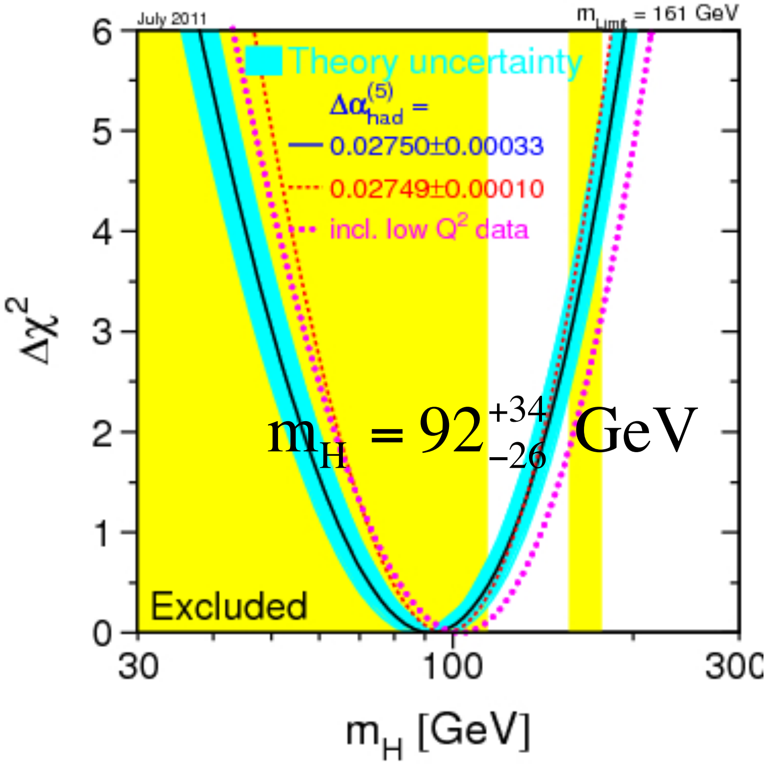
Talk at Wednesday's Higgs Physics session on:

"The Beginnings of Spontaneous Symmetry Breaking in Elementary Particle Theory"

Stalking the Higgs Boson

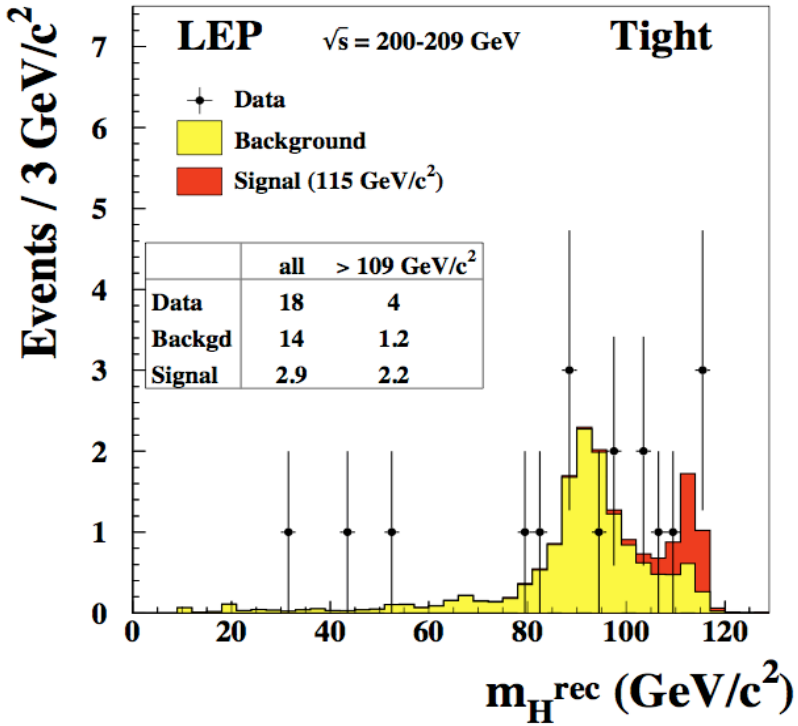
Indirect constraints

- Precision electroweak observables are sensitive to the Higgs boson mass via quantum corrections.



Direct searches at LEP

- Tantalizing hints (~1.7σ) of a SM-like Higgs boson with m_H~115 GeV:



	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

Combining indirect and direct constraints

m_H< 161 GeV (95% CL) m_H> 114.4 GeV (95% CL)

114.4 < m_H< 185 GeV (95% CL)

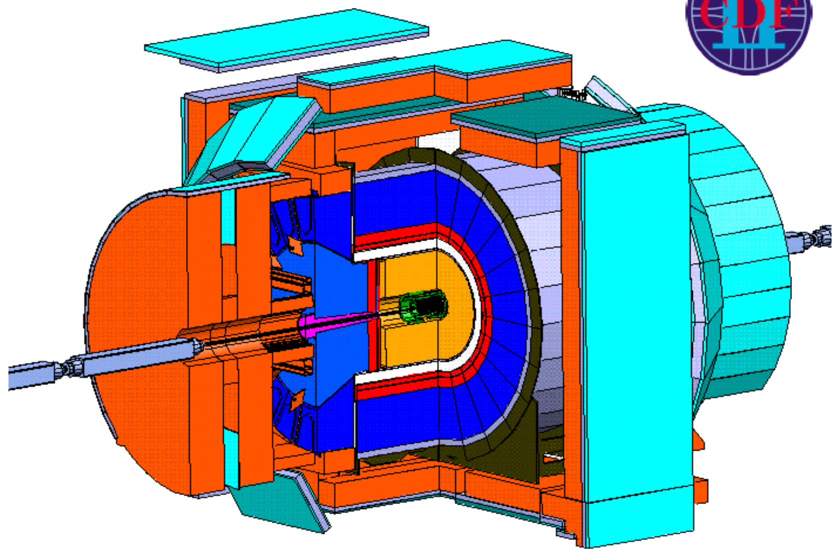
The Hadron Collider Era

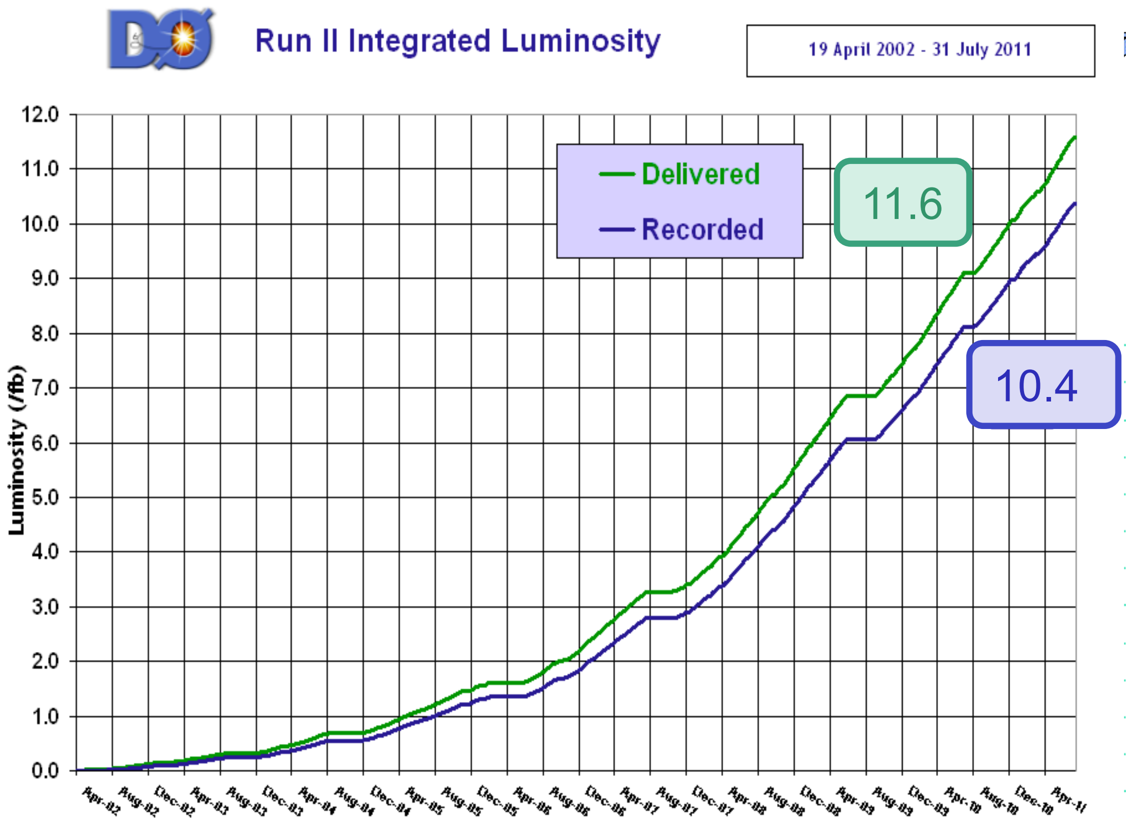
Two machines currently operating:

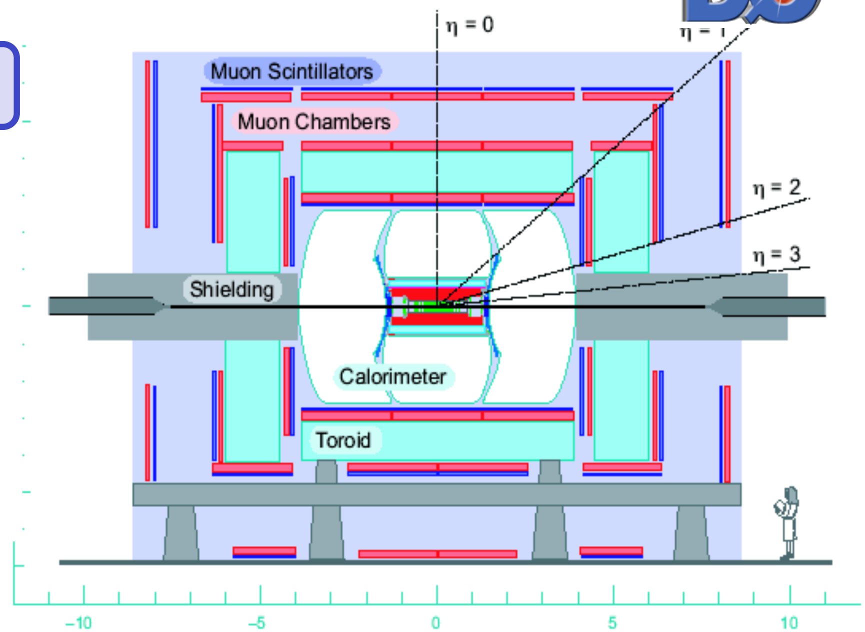
- Fermilab's Tevatron Collider: proton-antiproton collisions at 1.96 TeV.
  ➔ expected to be sensitive to a SM Higgs boson in the EW-preferred mass region.
- CERN's Large Hadron Collider (LHC): proton-proton collisions at 7 TeV (for now)
  ➔ should be able to discover a SM Higgs boson up to at least m_H~600 GeV.

Tevatron Experiments

- Excellent performance by the Tevatron accelerator and CDF and DØ detectors.
  - 10-year long Run II ending Sept. 2011
  - >10 fb^{-1} recorded per experiment to date



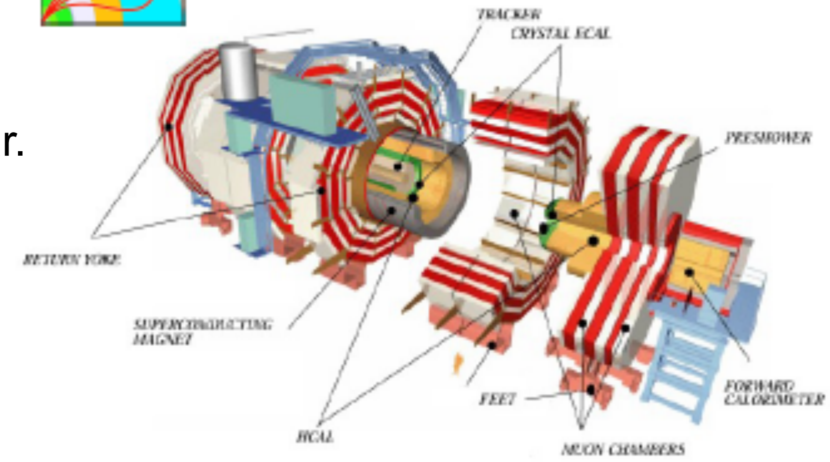


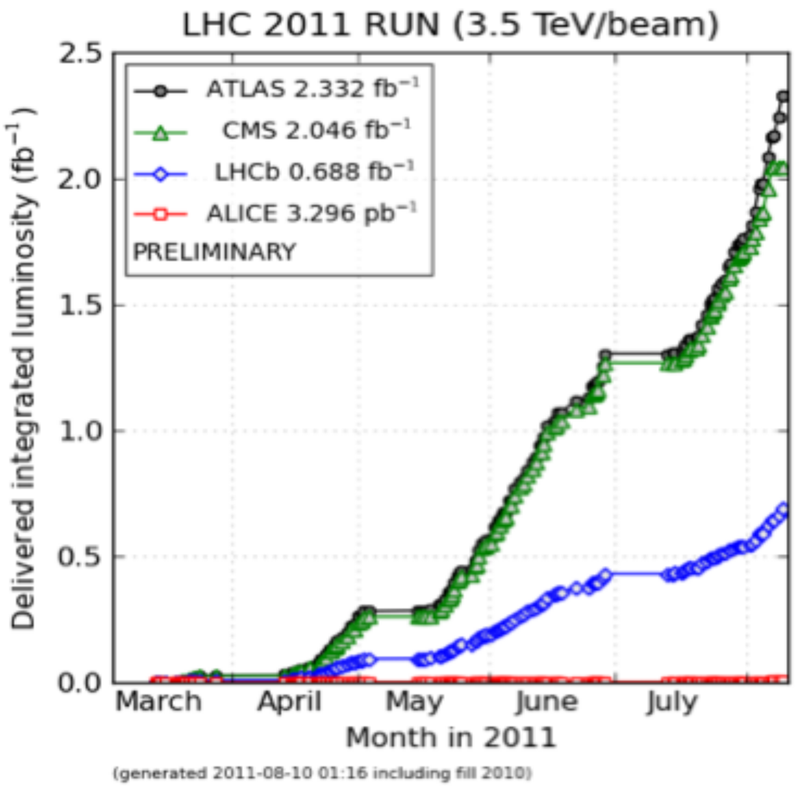


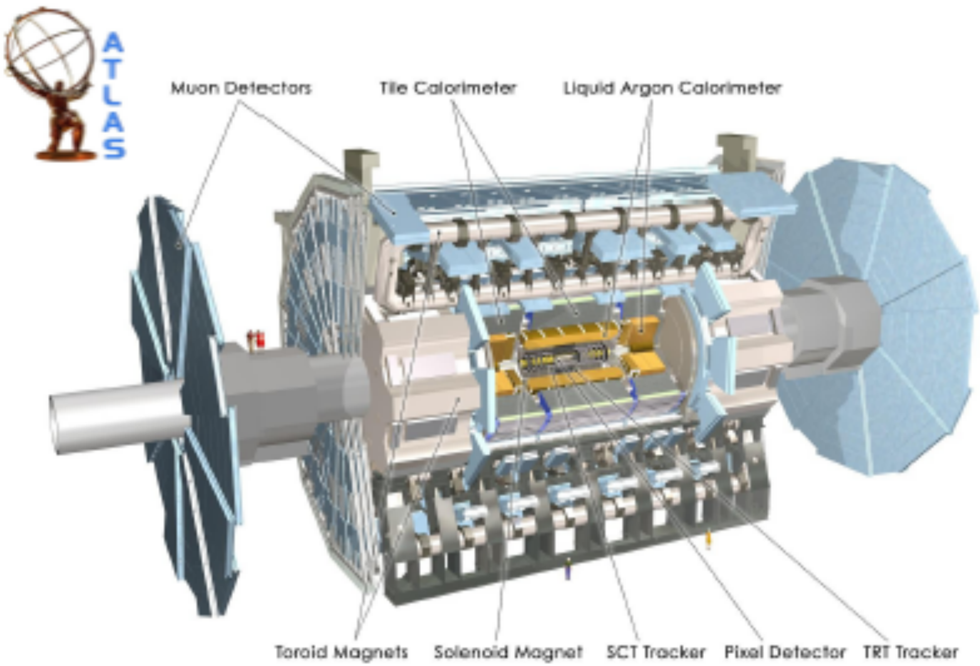
LHC Experiments

- First proton-proton collisions at 7 TeV in 2010.
- Amazing performance by the accelerator and detectors since then:
  - >2 fb^{-1} delivered by the LHC in 2011 so far.
  - High quality physics results with 1.1 fb^{-1} presented at the EPS 2011 conference!

The CMS Experiment

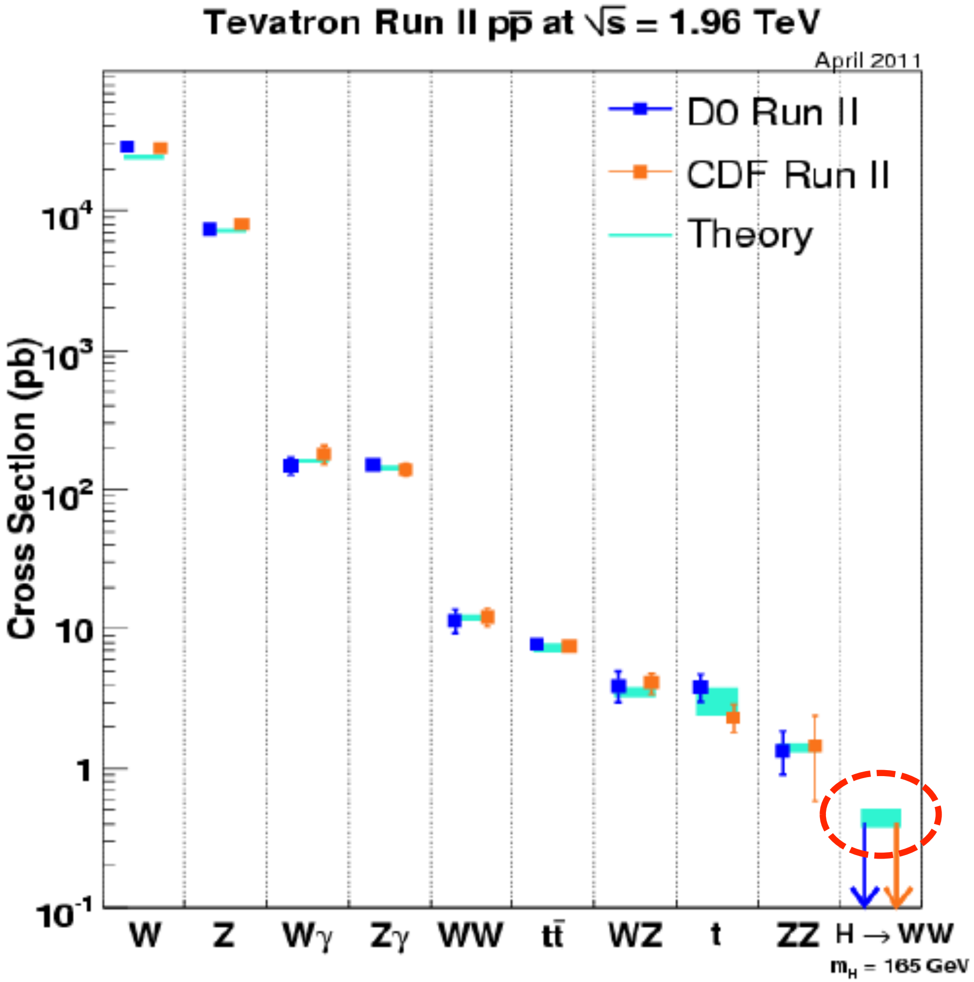


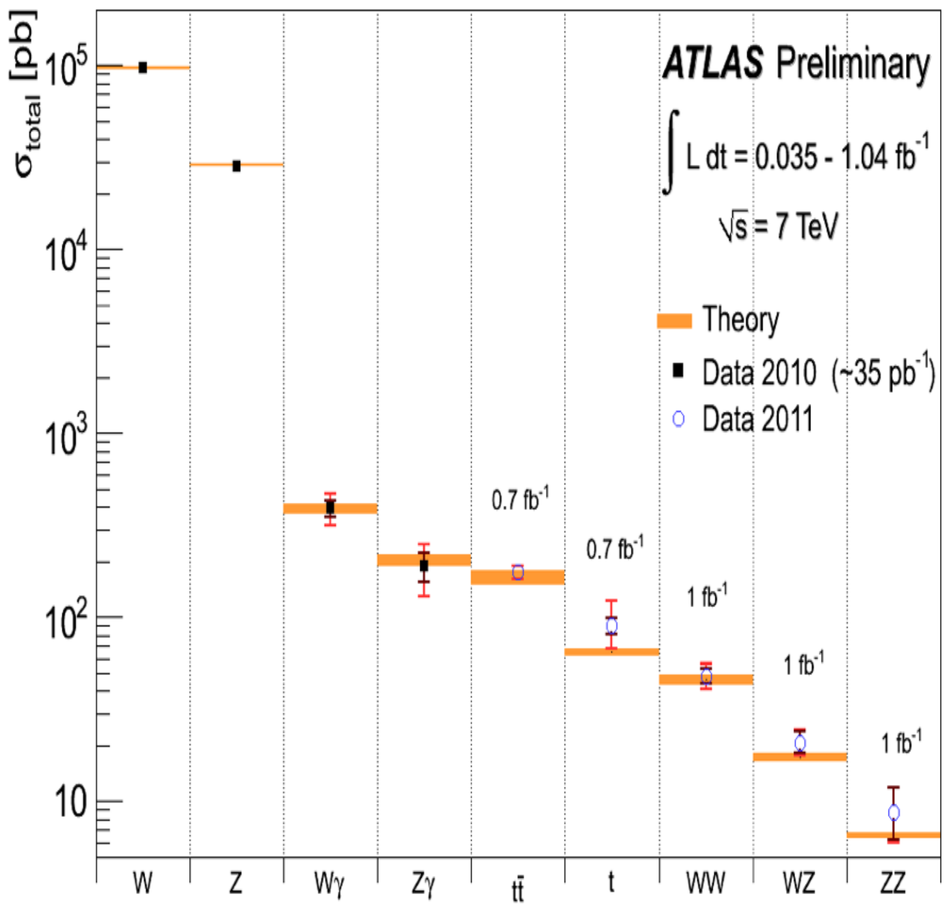




The Stairway to the Higgs

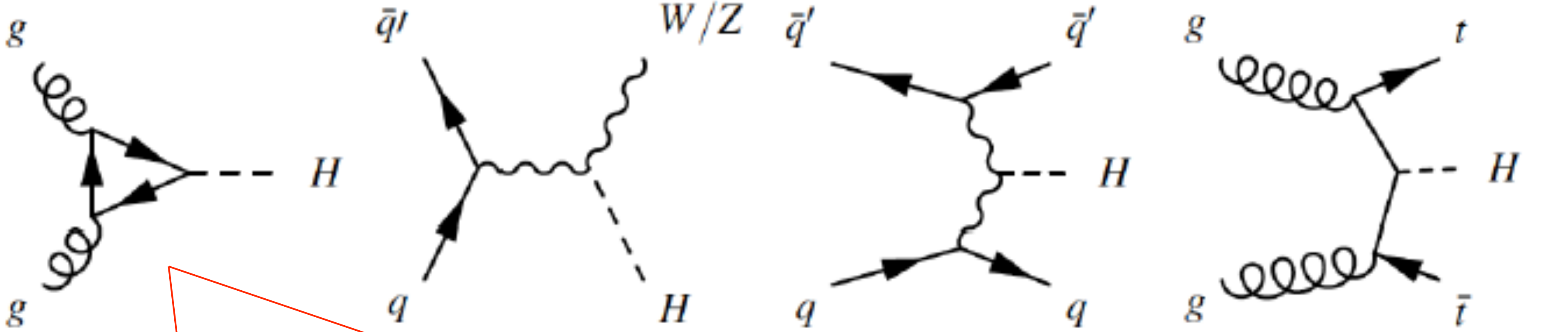
- Higgs boson searches at hadron colliders are background-dominated.





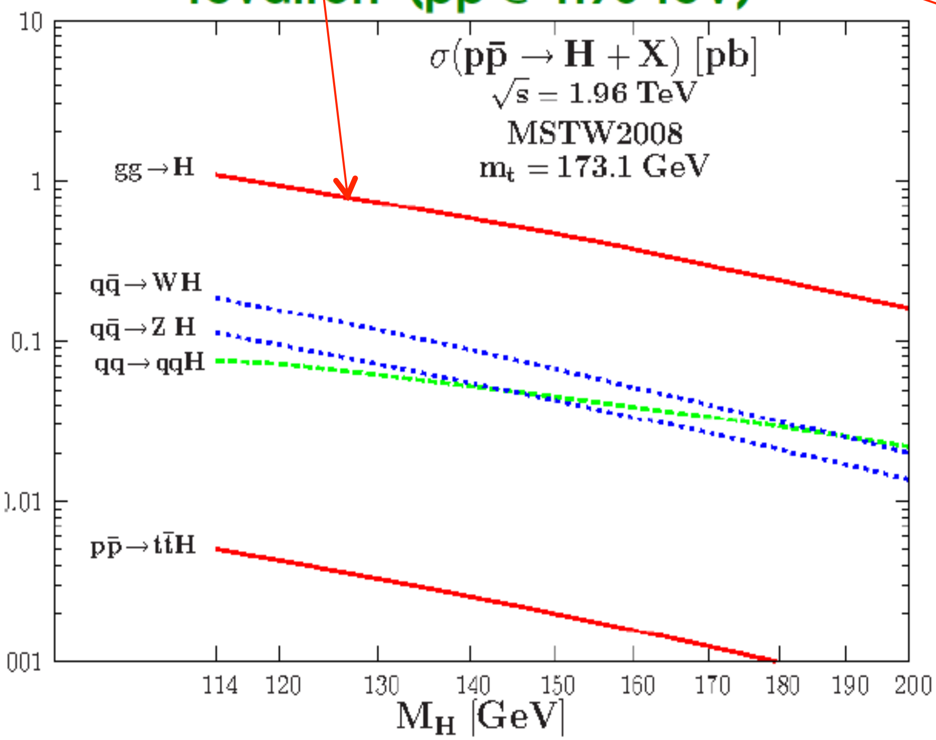
Experiments have established a solid foundation to search for the Higgs boson through precise measurements of SM processes.

SM Higgs Production at Hadron Colliders

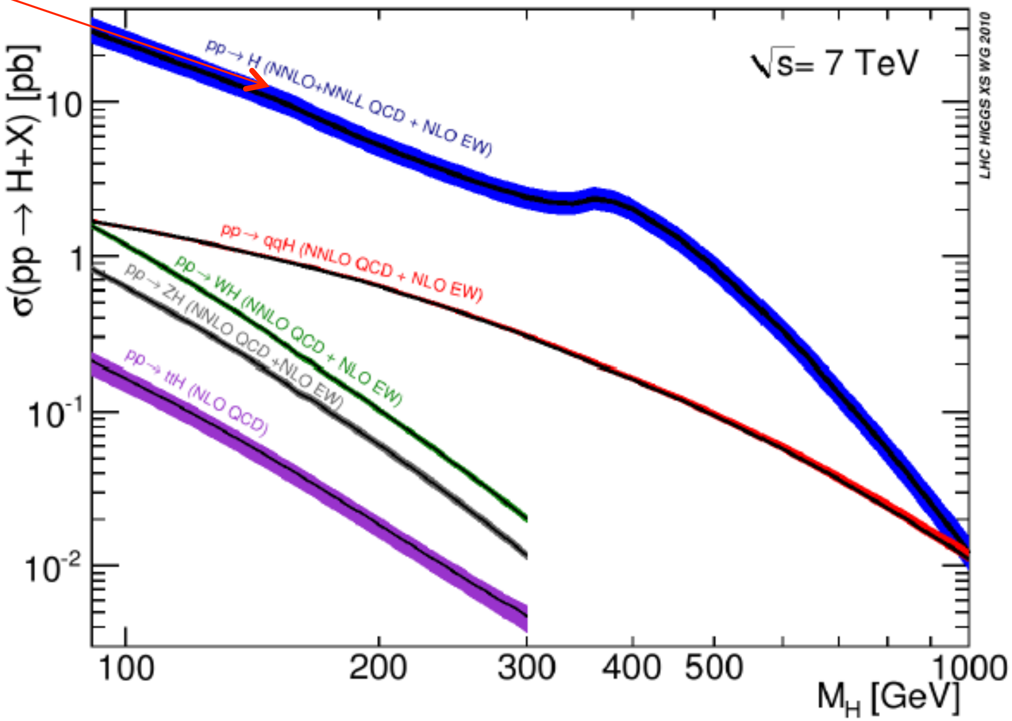


Main production mechanism

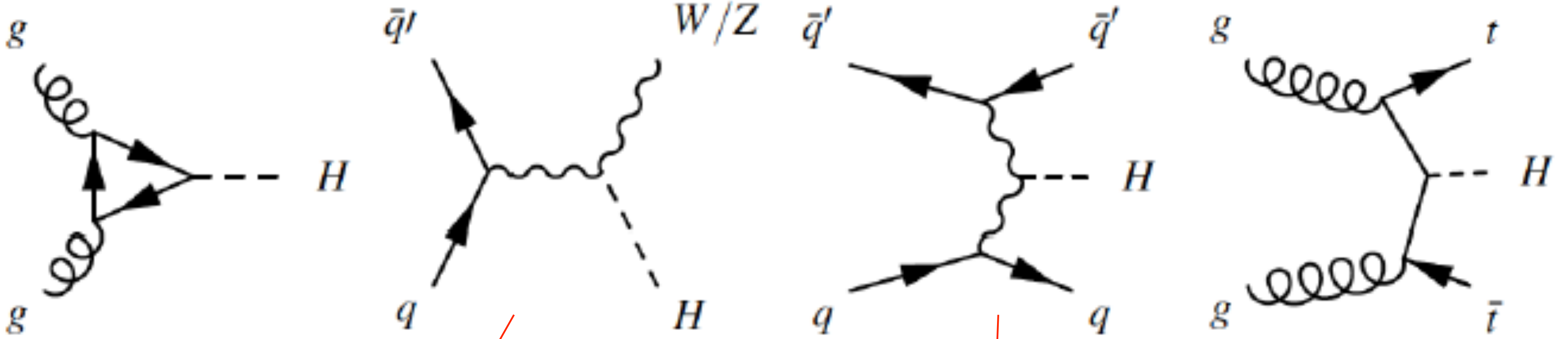
Tevatron ($p\bar{p}$ @ 1.96 TeV)



LHC (pp @ 7 TeV)

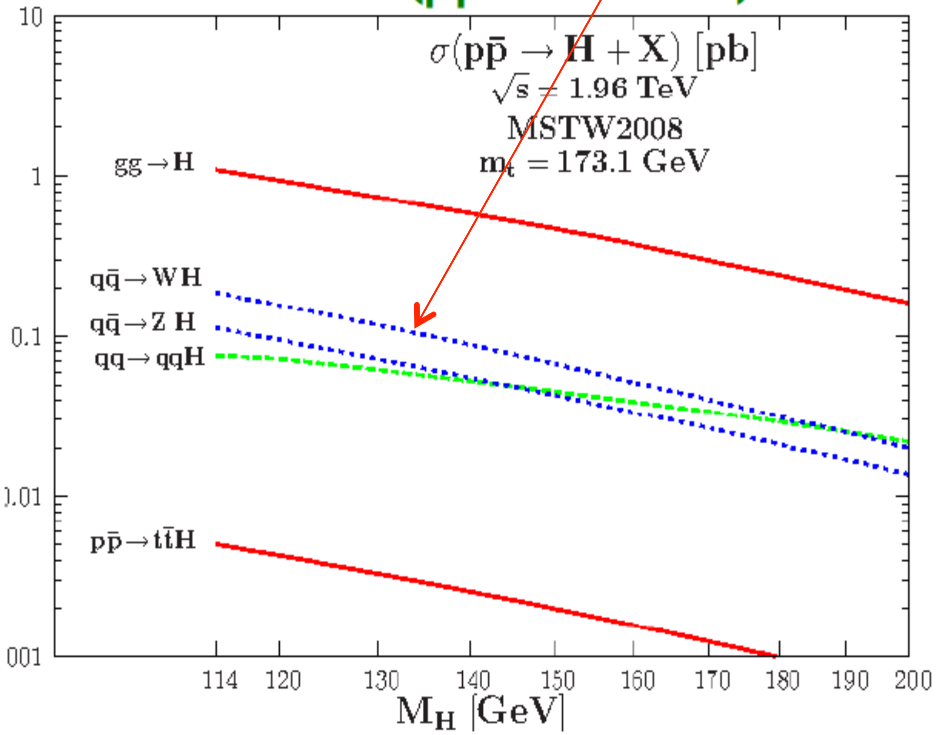


SM Higgs Production at Hadron Colliders



Next most important production mechanism

Tevatron (pp̄ @ 1.96 TeV)



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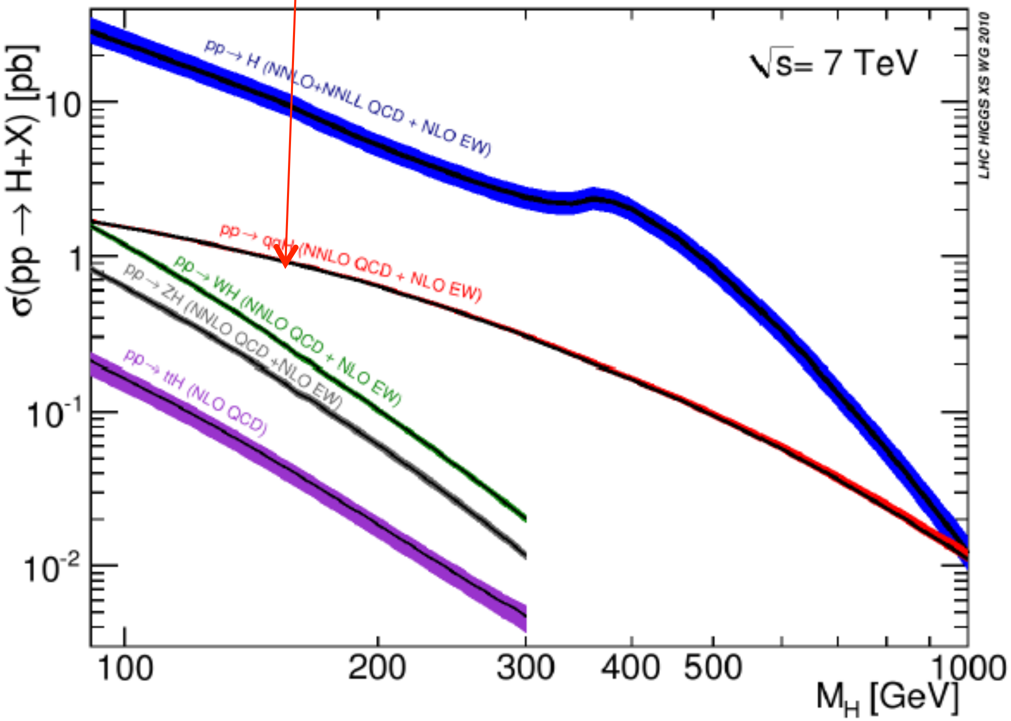
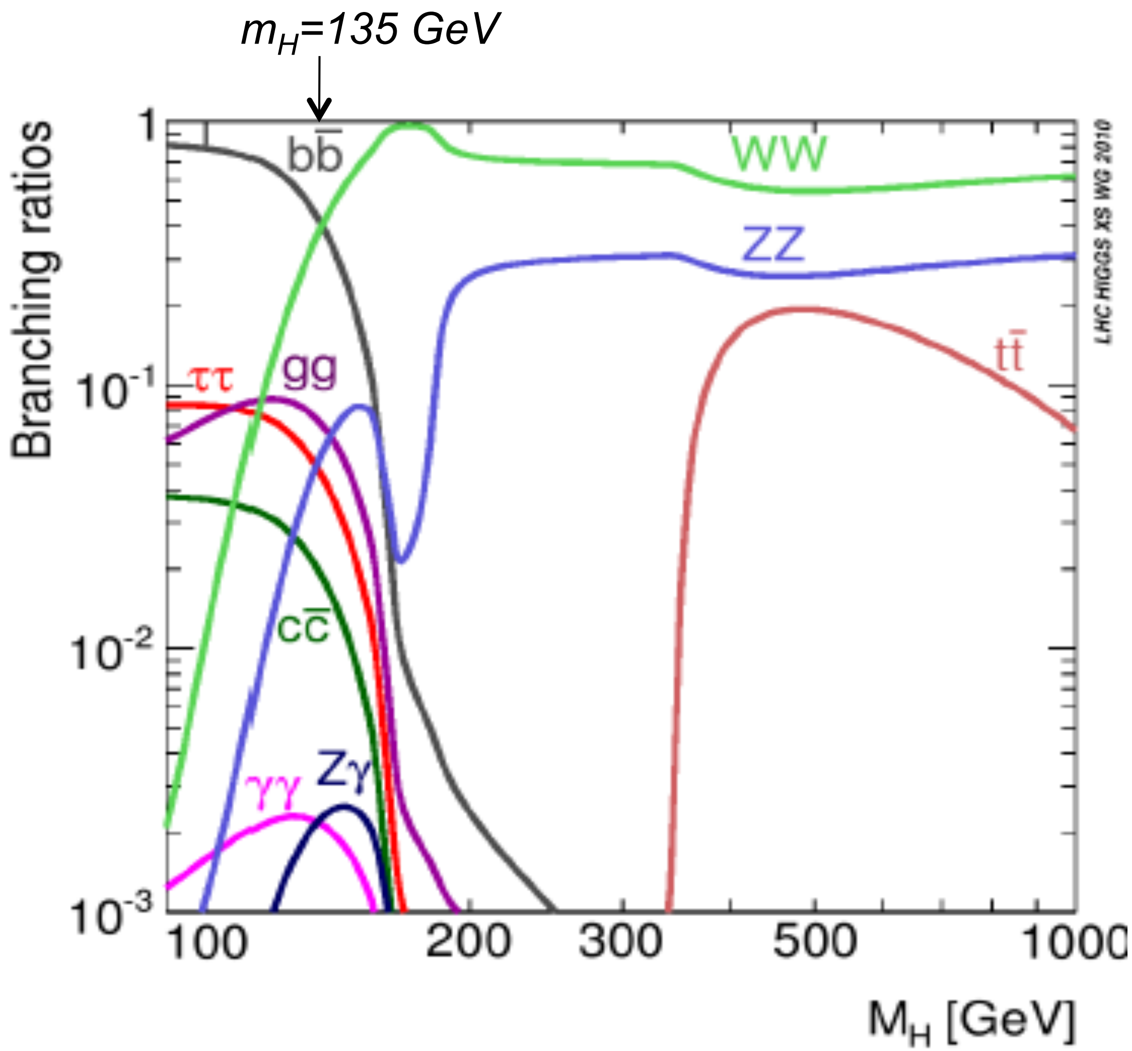


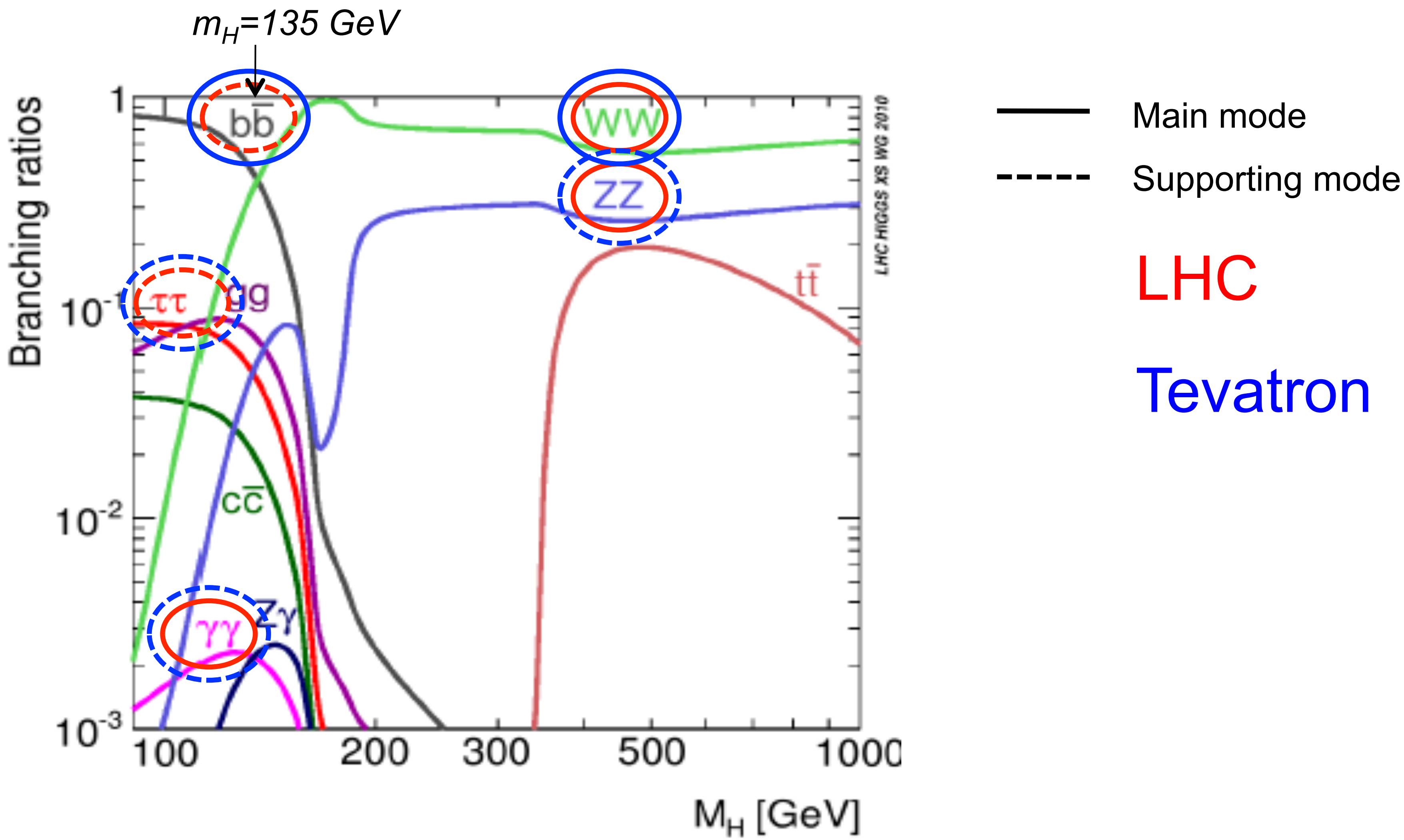
SM Higgs Decay Modes



m_H<135 GeV: H→bb dominates

m_H>135 GeV: H→WW dominates

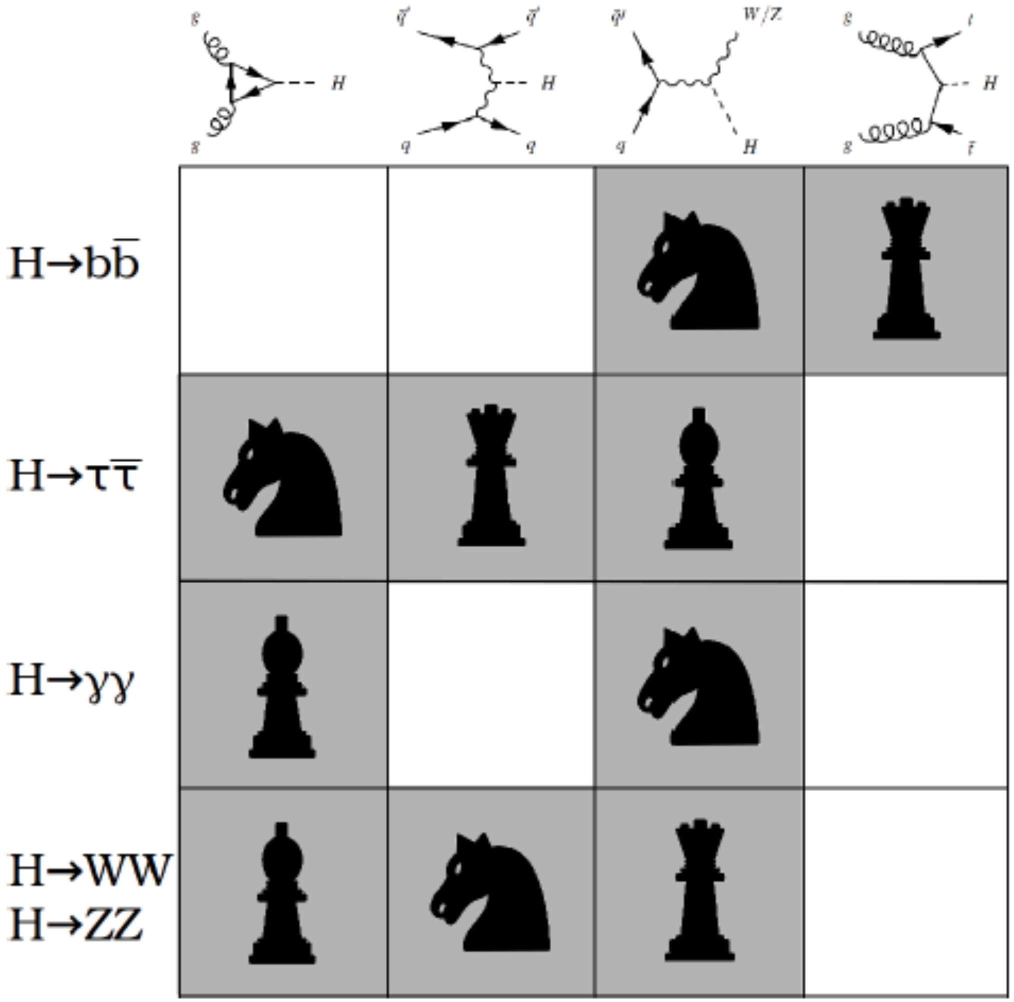
SM Higgs Decay Modes

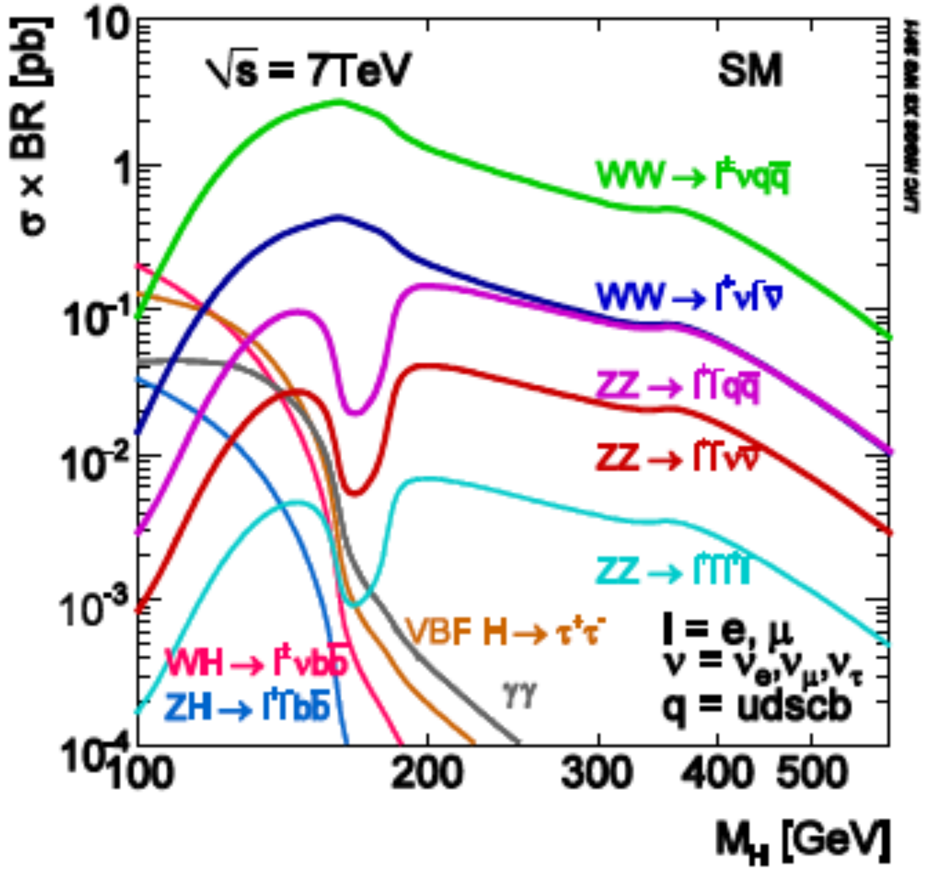


➔ Many decay modes being explored to increase the sensitivity of the search to the SM Higgs boson, but also to a non-SM one!

Search Strategies

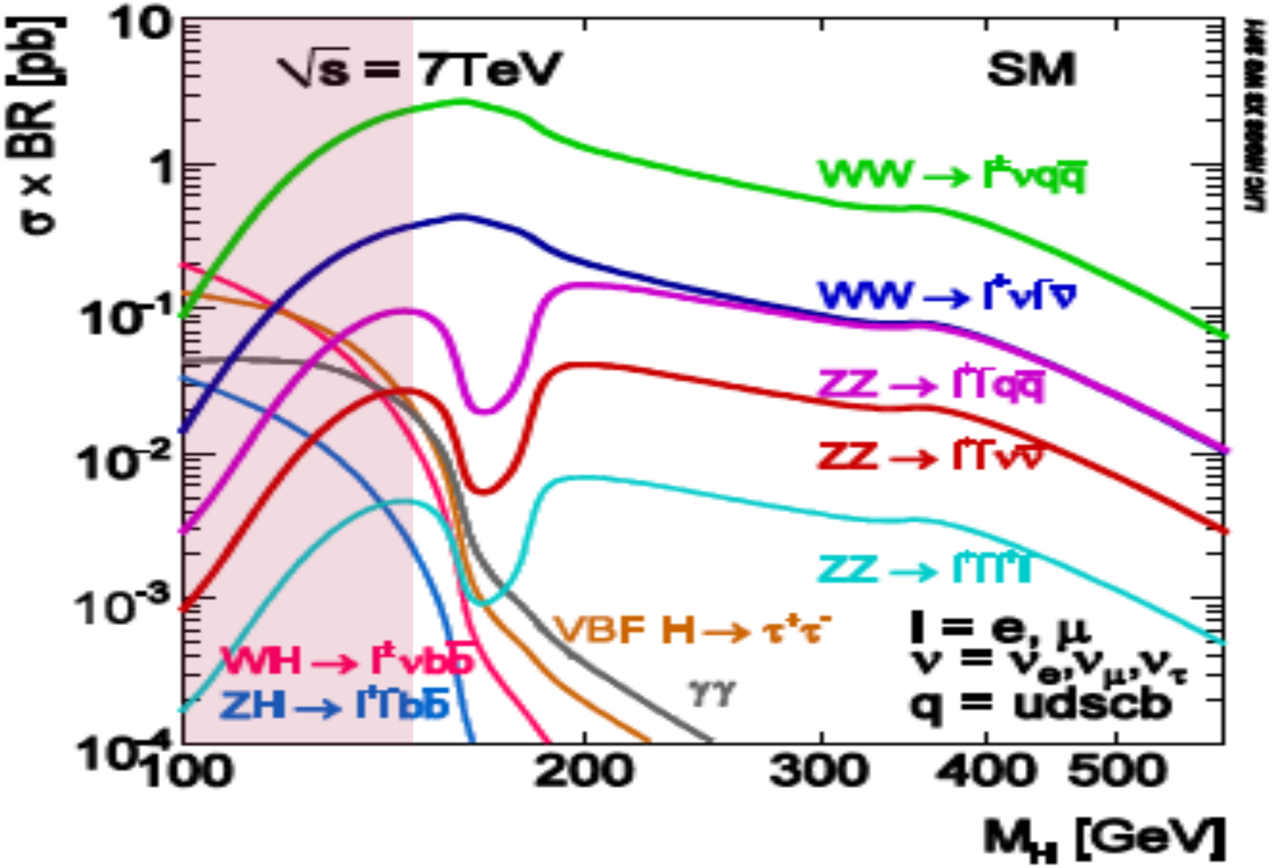
- Defined by a combination of theoretical and experimental considerations (large σxB but experimentally feasible: trigger, backgrounds….)





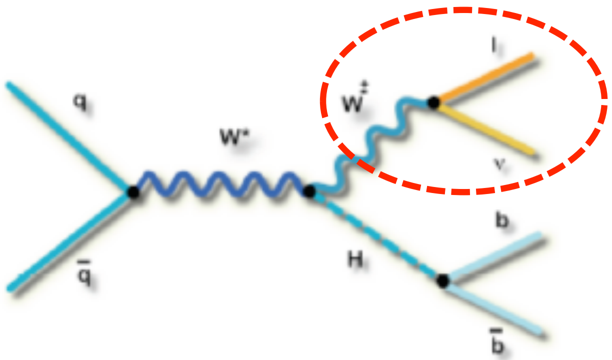
SM Higgs

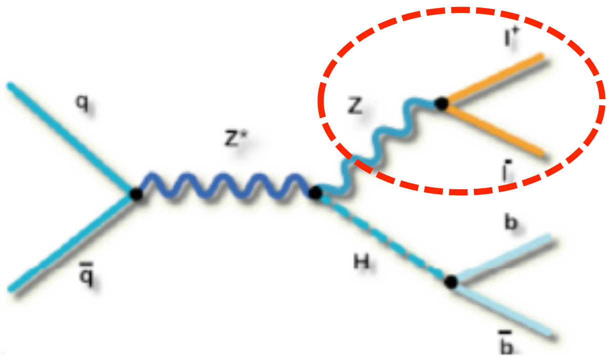
Low Mass (100-140 GeV)

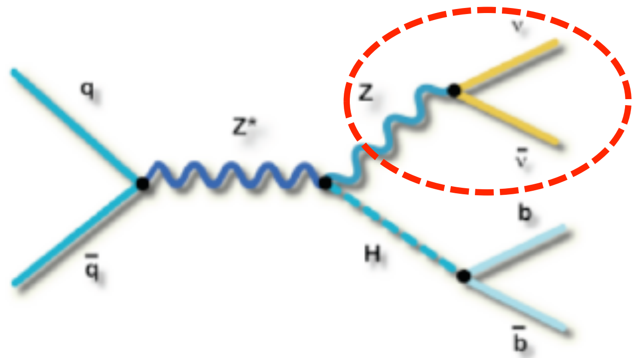


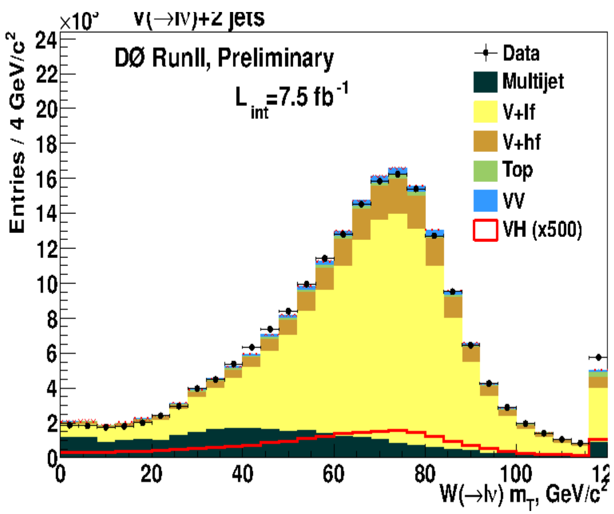
Searching for H→bb

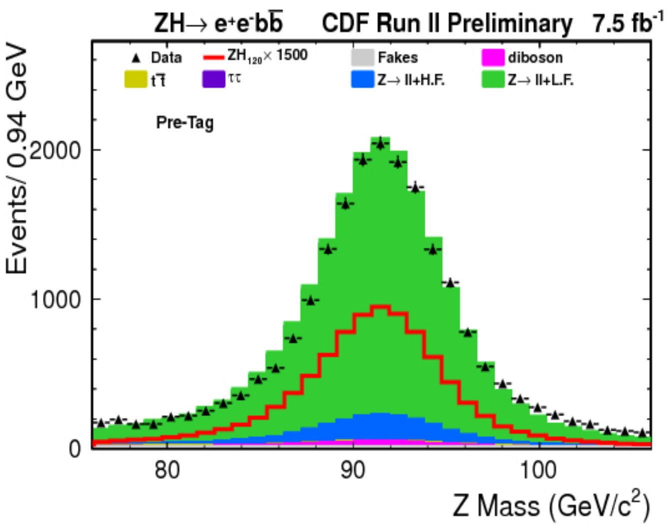
- Highest sensitivity channel at the Tevatron for m_H<130 GeV.
- Identify events consistent with leptonic W/Z decays in association with jets
  - Trigger on high p_T electrons, muons or missing transverse energy ($\not{E}_T$)
  - W→lν: e or μ and high $\not{E}_T$
  - Z→ll: ee or μμ consistent with Z resonance
  - Z→νν: no charged leptons; two acoplanar jets and $\not{E}_T$

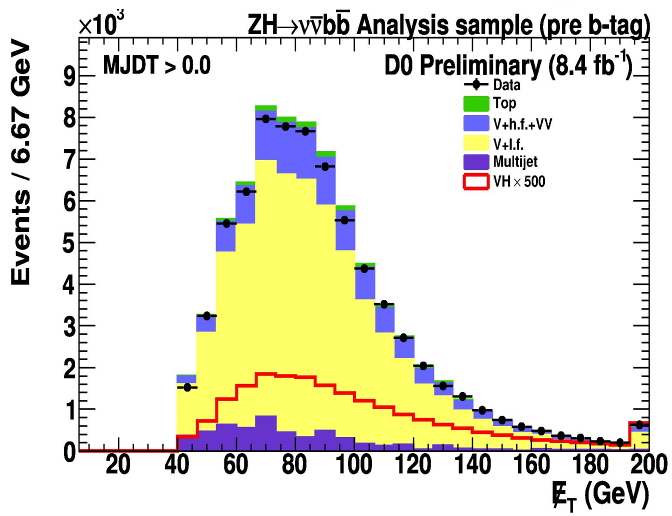






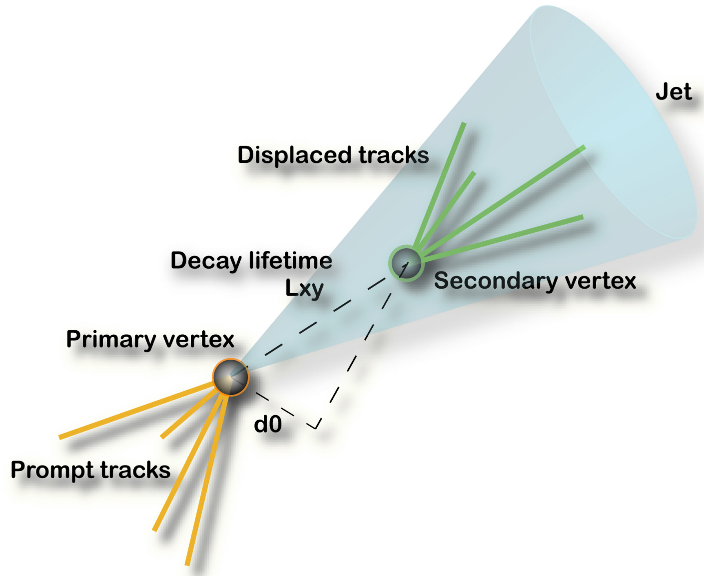




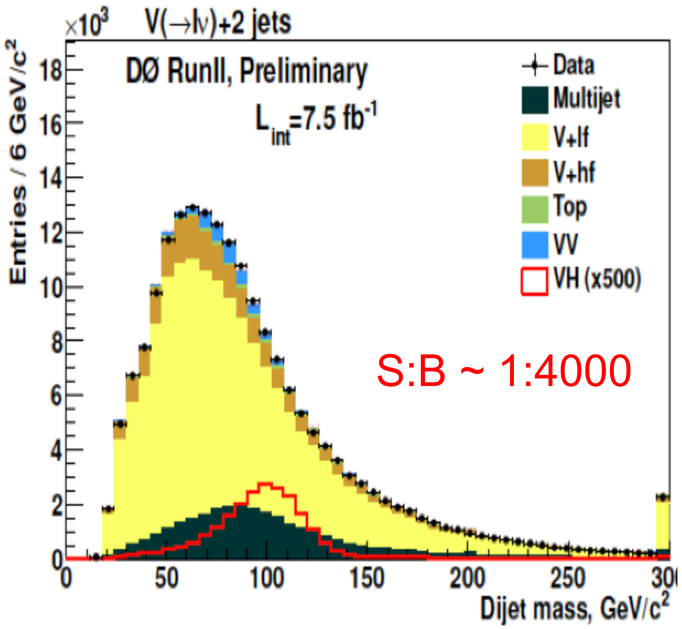


Searching for H→bb

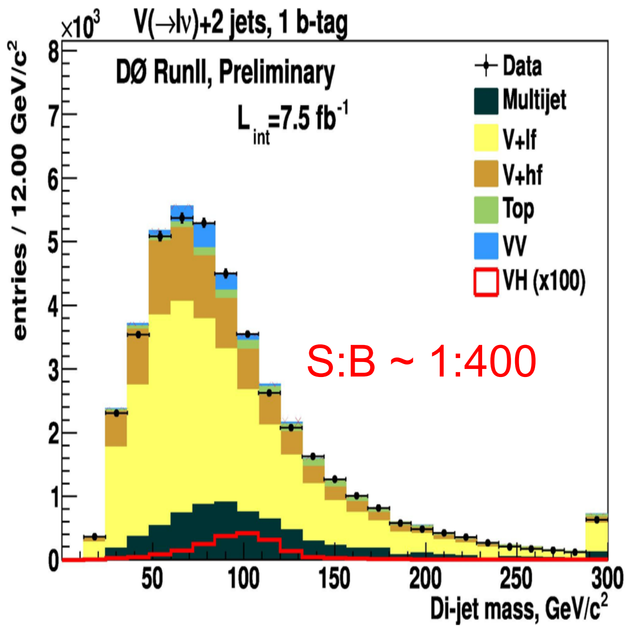
- Heavy-flavor jet identification (b-tagging) key to improve signal-to-background ratio.
- Dijet invariant mass distribution single most discriminant variable.
- Sophisticated multivariate techniques gain ~20-30% additional sensitivity.



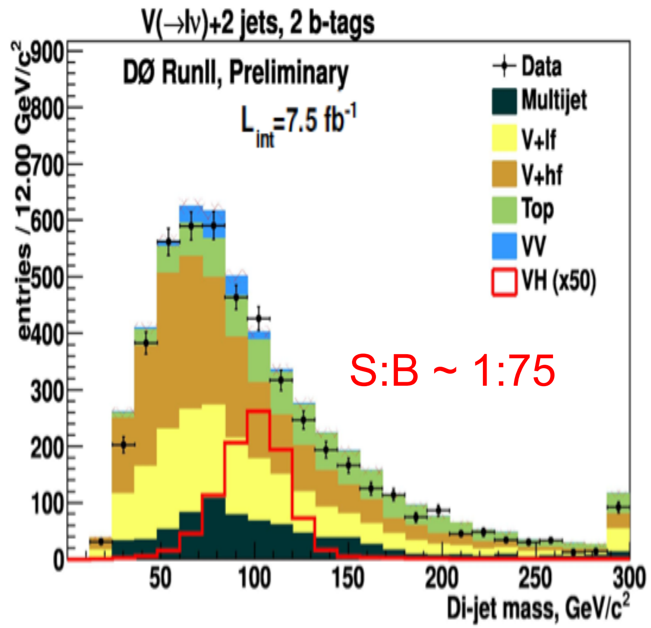
Before b-tagging



=1 b-tag

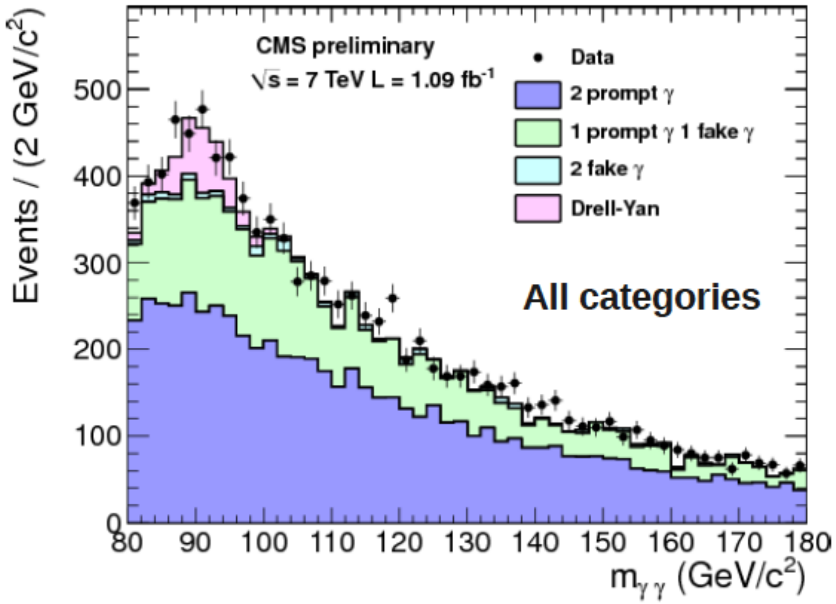


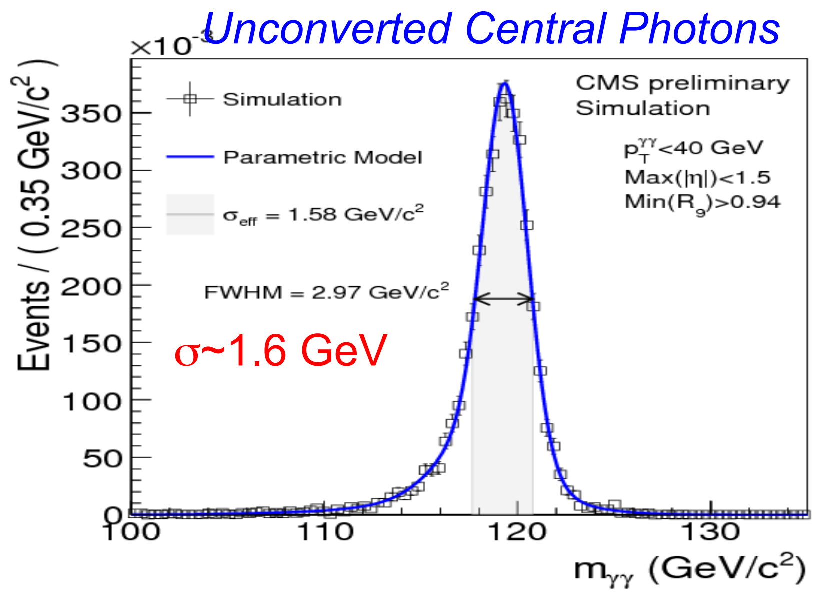
≥2 b-tags



Searching for H→γγ

- Highest sensitivity channel at the LHC for m_H<130 GeV.
- Tiny branching ratio in SM (~0.2%), but clear signature of narrow diphoton resonance on top of smoothly-declining background (dominated by electron and jet fakes).
- Diphoton mass resolution is key:
  - Ranges in ~1.2%-6%.
  - Dedicated corrections for material upstream the calorimeter, vertex position, etc.
  - Categorize events depending on expected mass resolution.





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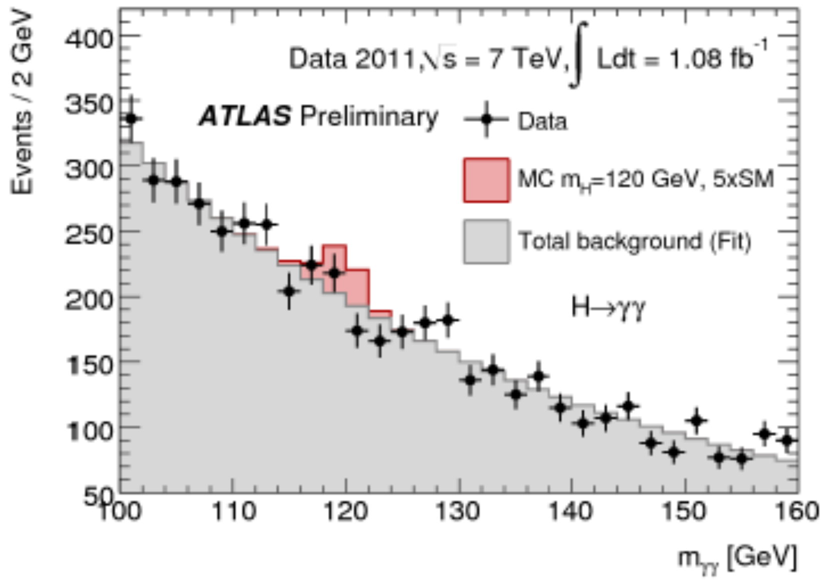
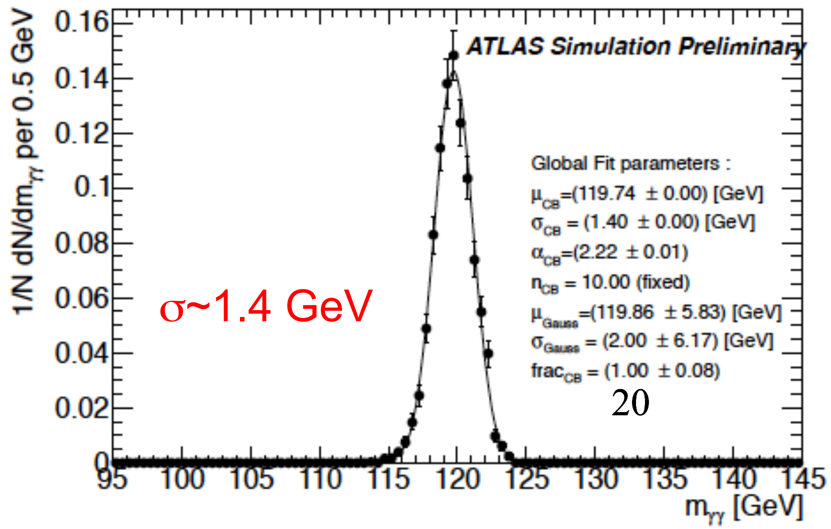
- Diphoton mass resolution is key:
  - Ranges in ~1.2%-6%.
  - Dedicated corrections for material upstream the calorimeter, vertex position, etc.
  - Categorize events depending on expected mass resolution.
- Detailed understanding of background composition achieved via data-driven techniques. Background fitted to exponential model and side-band analysis performed.

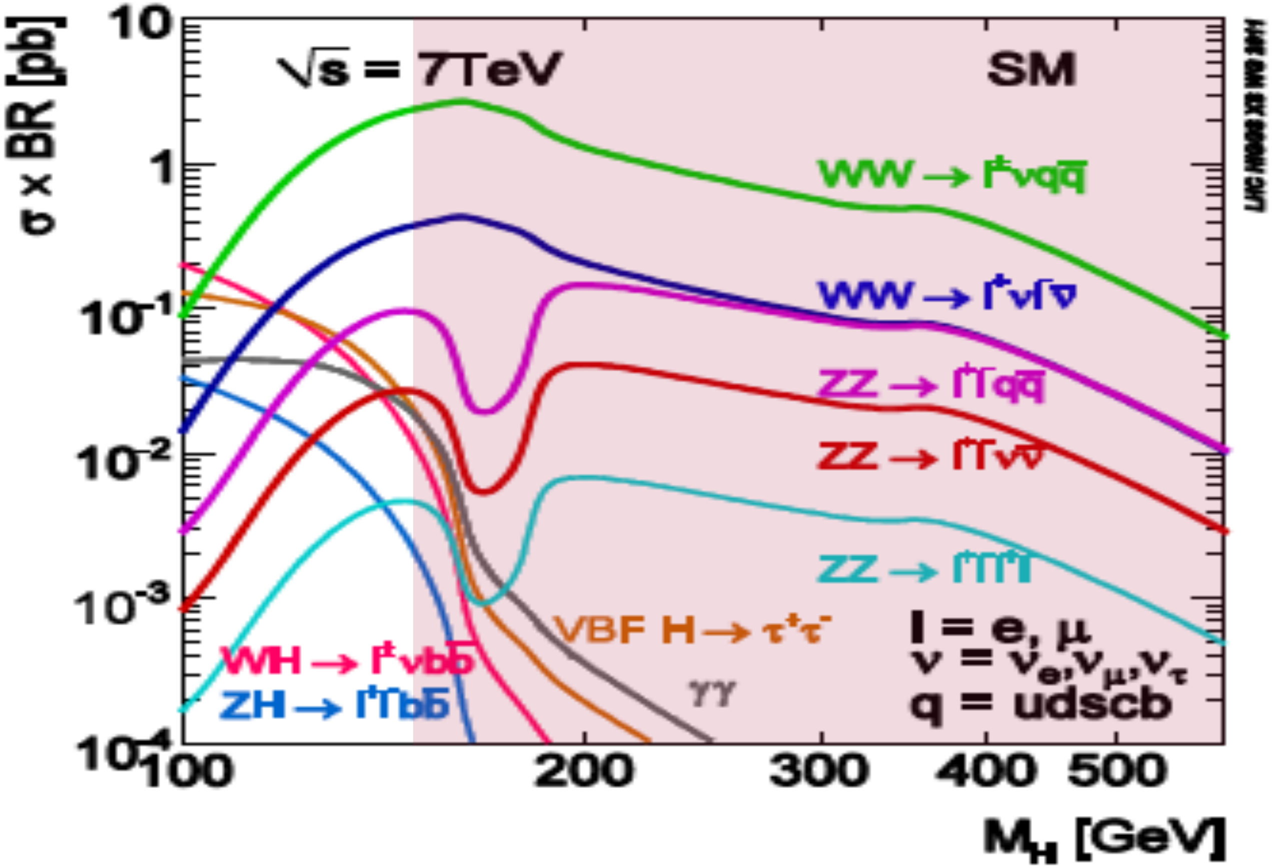


Unconverted Central Photons



SM Higgs

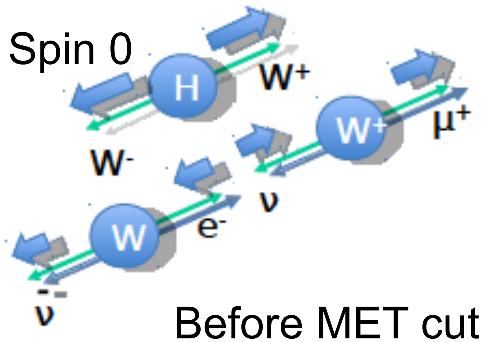
High Mass (140-600 GeV)

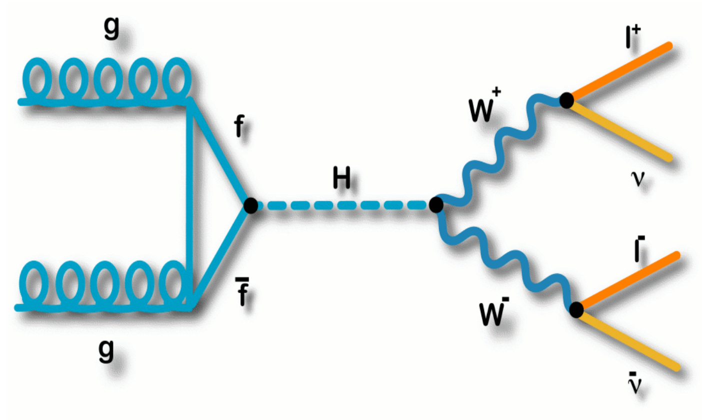


Searching for H→WW

H→WW→lνlν

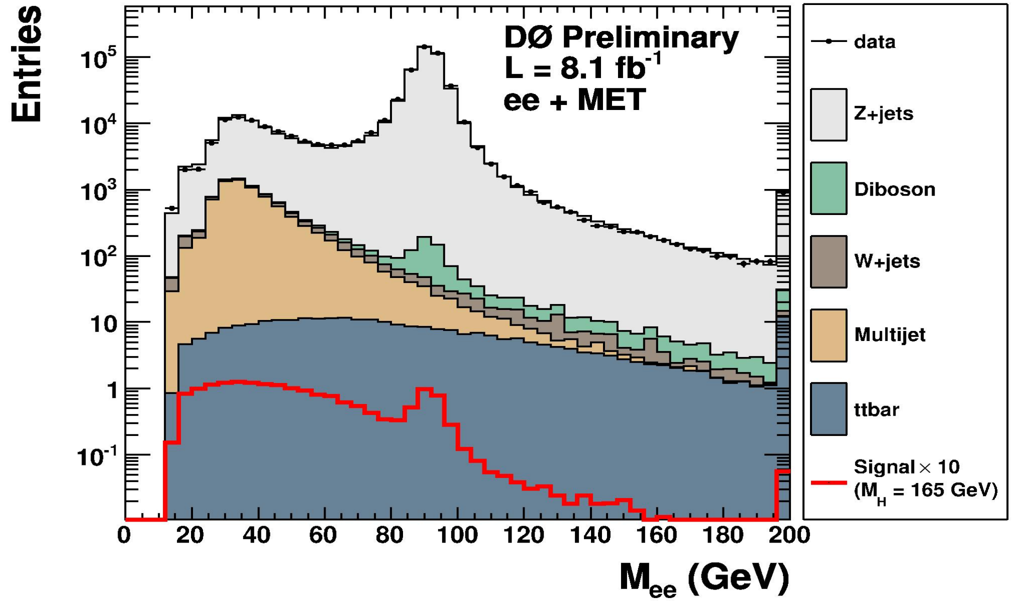
- Highest sensitivity channel in m_H~130-200 GeV range.
- Clean dilepton+$\not{E}_T$ signature.
- Main backgrounds after $\not{E}_T$ cut: WW, W/Z+jets.
- Exploit spin correlation between dibosons:



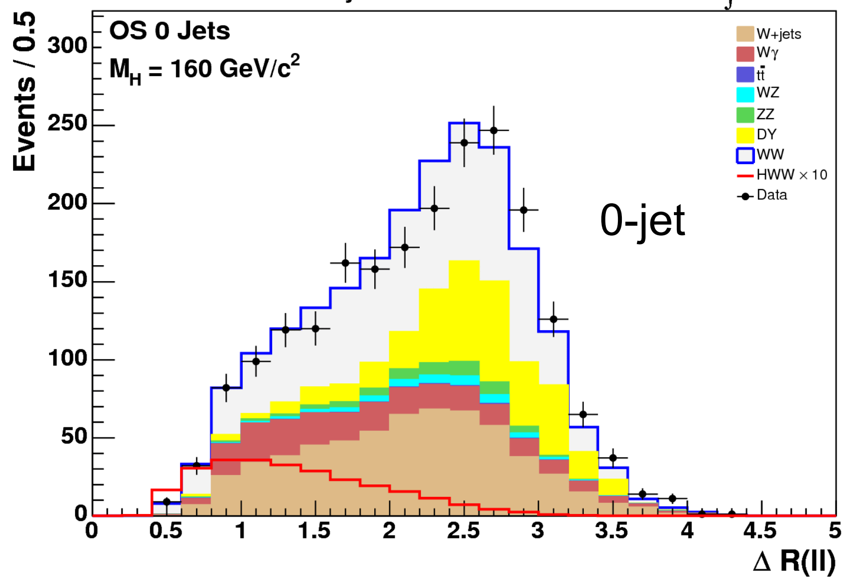


➔ Small angular separation between leptons

Before MET cut



After MET cut



Searching for H→WW

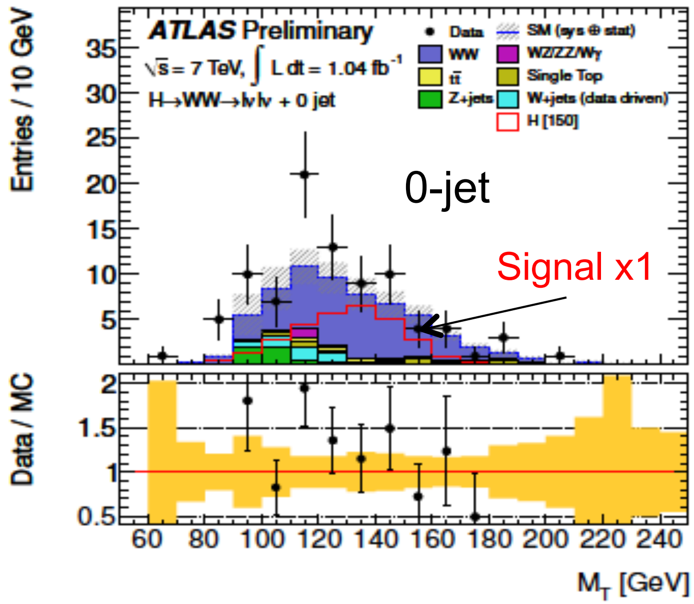
H→WW→lνlν

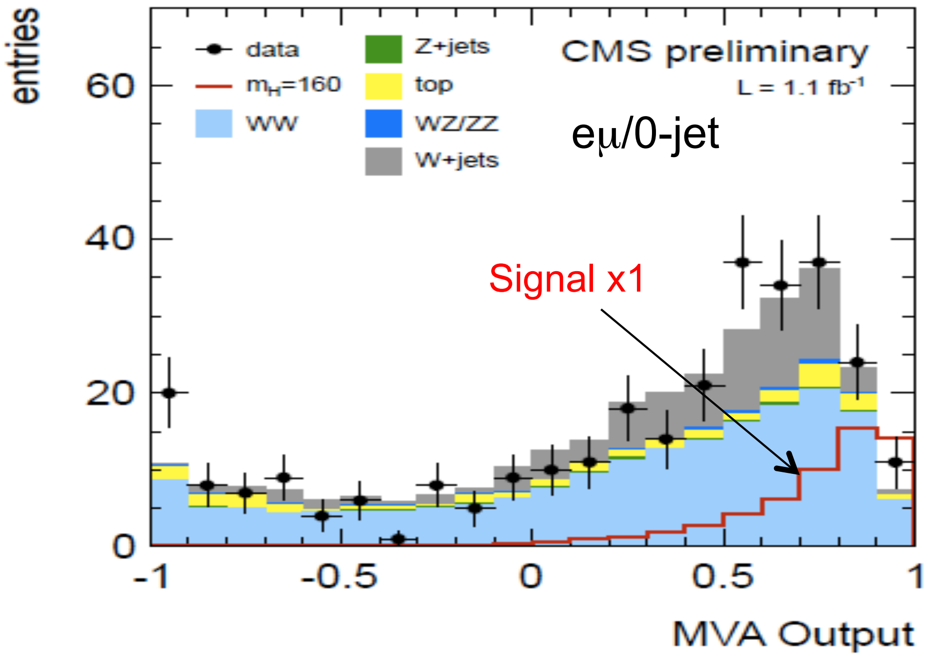
For further signal-to-background discrimination:

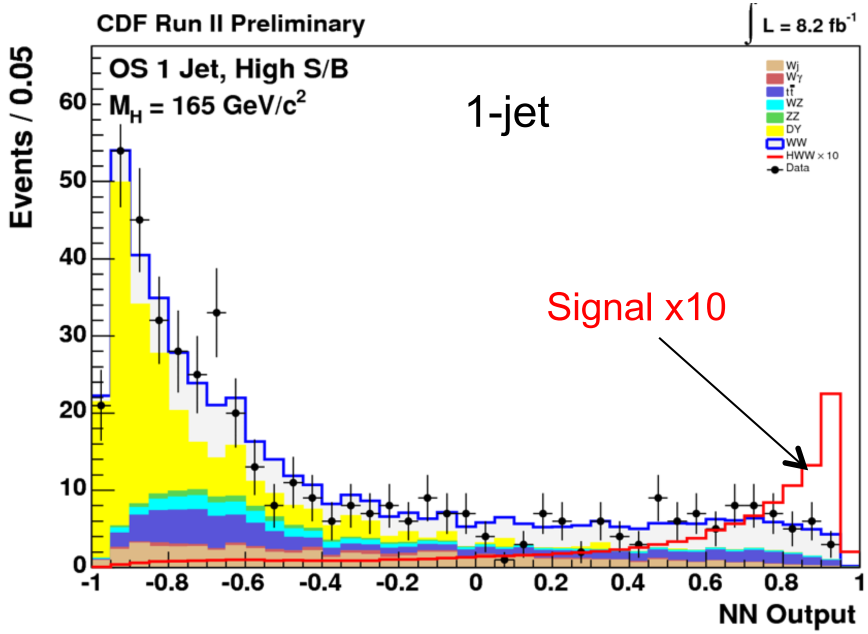
- Categorize events depending on jet multiplicity;
- Optimized selections on discriminant variables e.g. $\Delta\Phi_{ll}$, m_{ll}, $M_T(ll\nu\nu)$, or
- Rely on multivariate techniques.

➔ At the LHC can achieve S:B close to 1 with cut-based analyses.

M_T after all cuts:



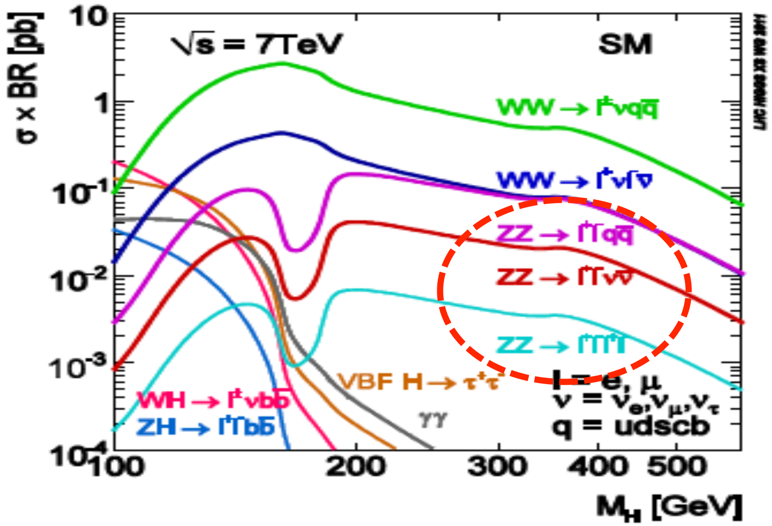




Searching for H→ZZ

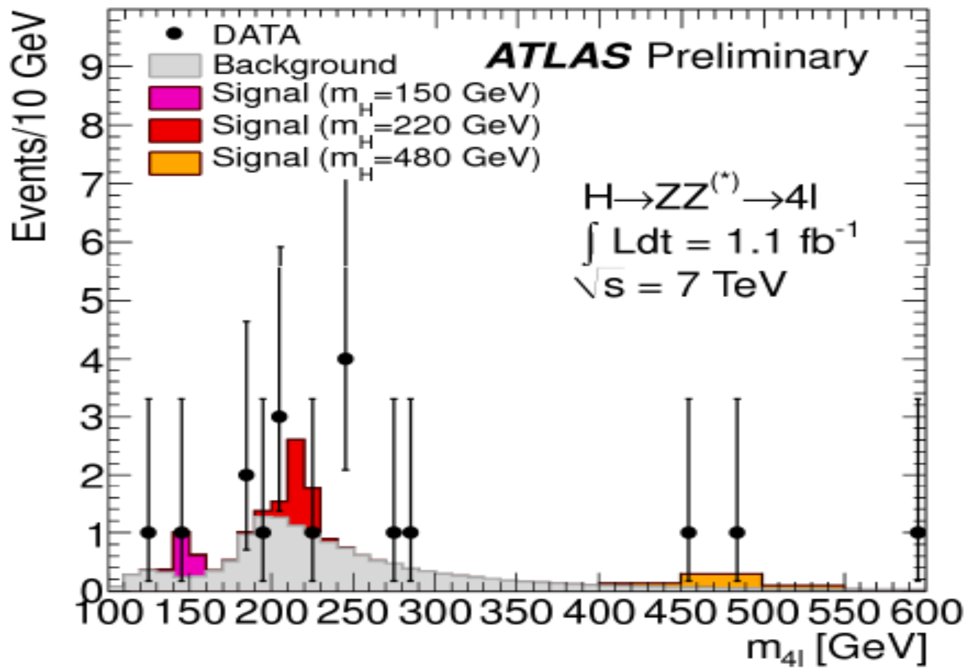
- Highest sensitivity mode for m_H~200-600 GeV.
- Require at least one Z→ll.

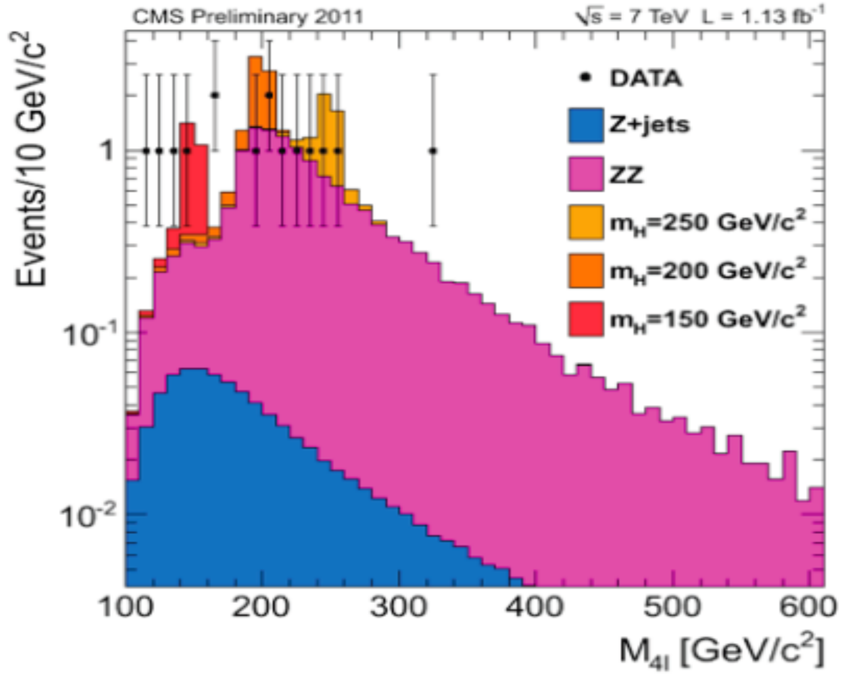
  ➔ Three different final state signatures with comparable sensitivity depending on the other Z boson decay modes.



H→ZZ→4l

- Golden mode owing to clean signature and excellent mass resolution, but limited in rate by small B(Z→ll).
- Main background: non-resonant ZZ production.





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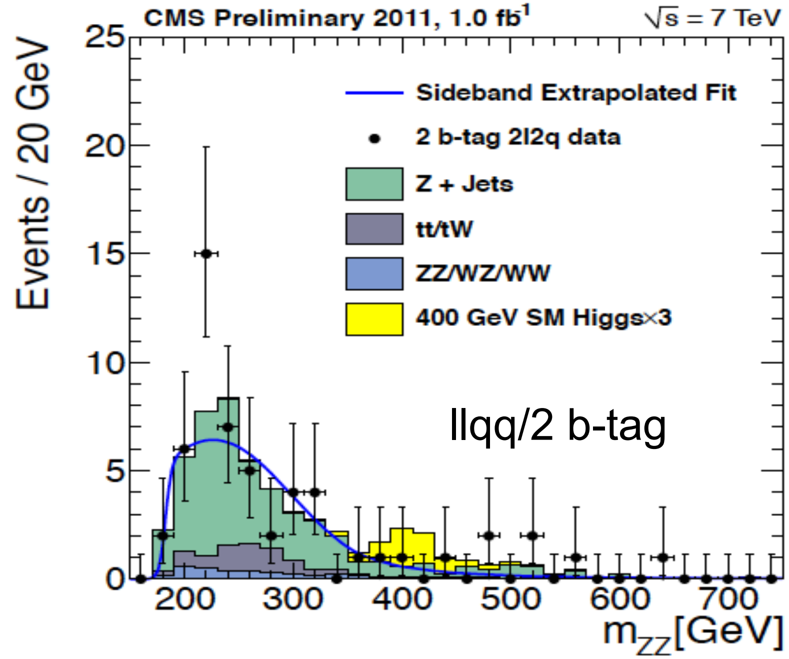
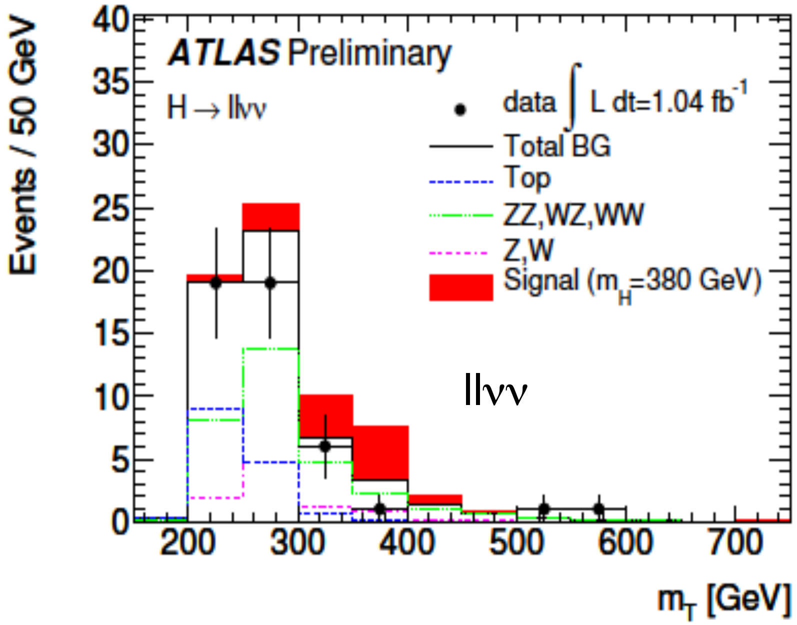


H→ZZ→llqq

- Benefits from high B(Z→qq) (~70%).
- Good mass reconstruction capabilities.
- Dominant background from Z+jets.



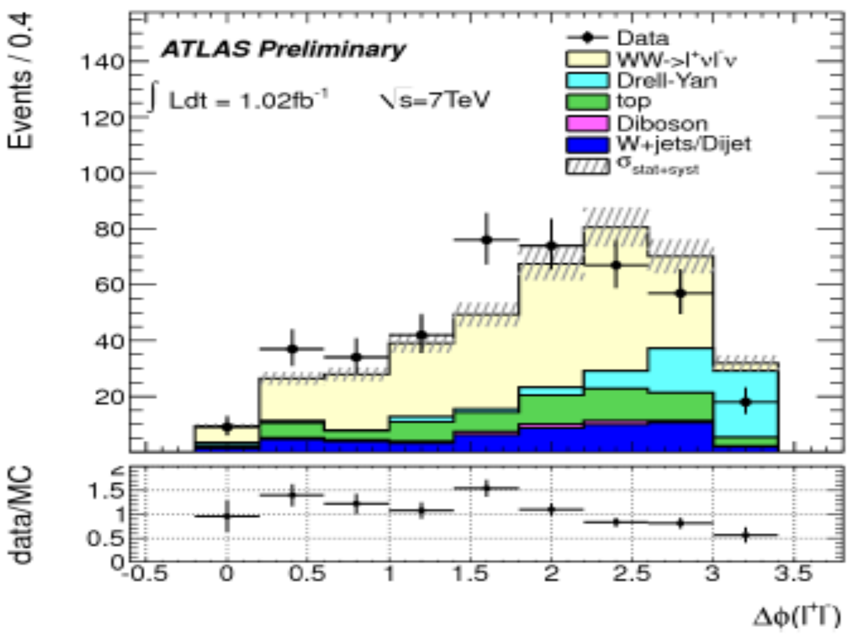
H→ZZ→llνν

- Benefits from sizable B(Z→νν) (~20%).
- Signature: ee/μμ+$\not{E}_T$.
- Main backgrounds dibosons and top suppressed by 3rd lepton and b-tag vetoes.
- Final discriminant: M_T(llνν).

Validation of Search Techniques

- Critical to validate experimental strategy and tools using SM backgrounds that share characteristics with the signal.

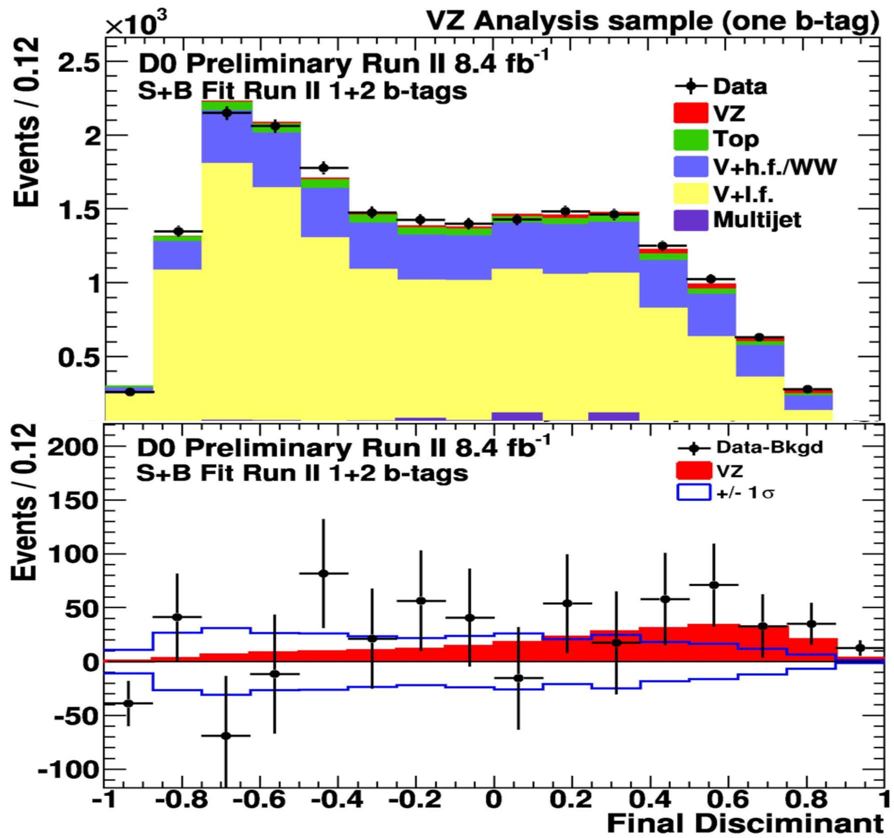
WW→lνlν



$$\sigma_{WW}^{meas} = 48.2 \pm 4.0(\text{stat.}) \pm 6.4(\text{syst.})\ \text{pb}$$

$$\sigma_{WW}^{theo} = 46 \pm 3\ \text{pb}$$

WZ+ZZ→ννbb,ννcc



$$\sigma_{WZ+ZZ}^{meas} = 6.9 \pm 1.3(\text{stat.}) \pm 1.8(\text{syst.})\ \text{pb}$$

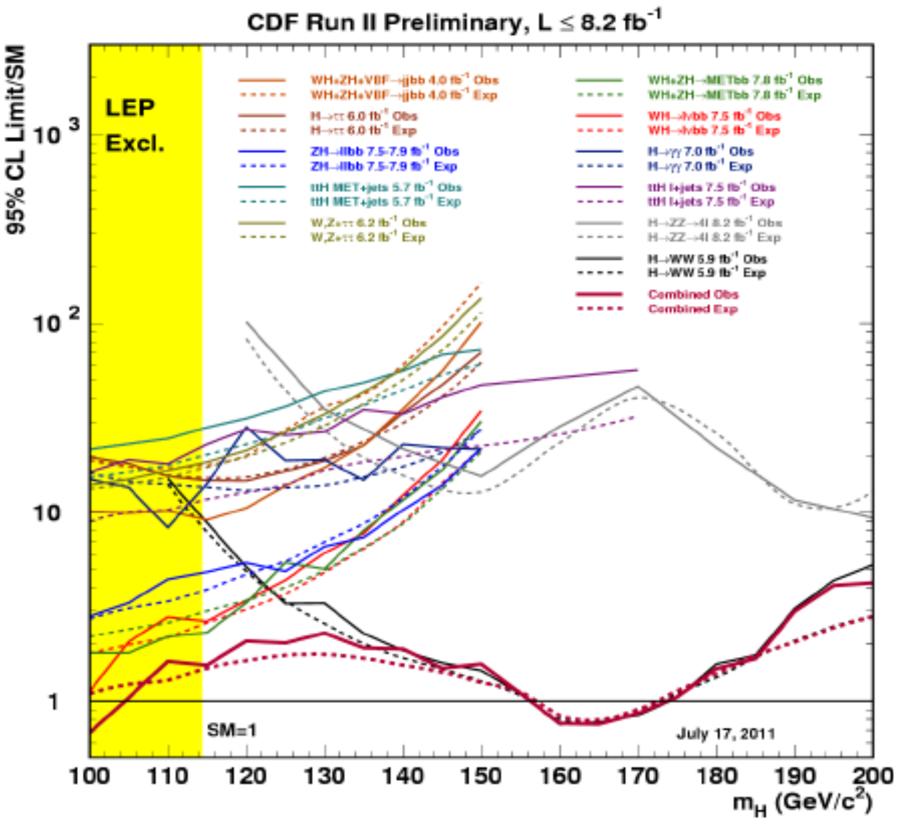
$$\sigma_{WZ+ZZ}^{theo} = 4.6 \pm 0.3\ \text{pb}$$

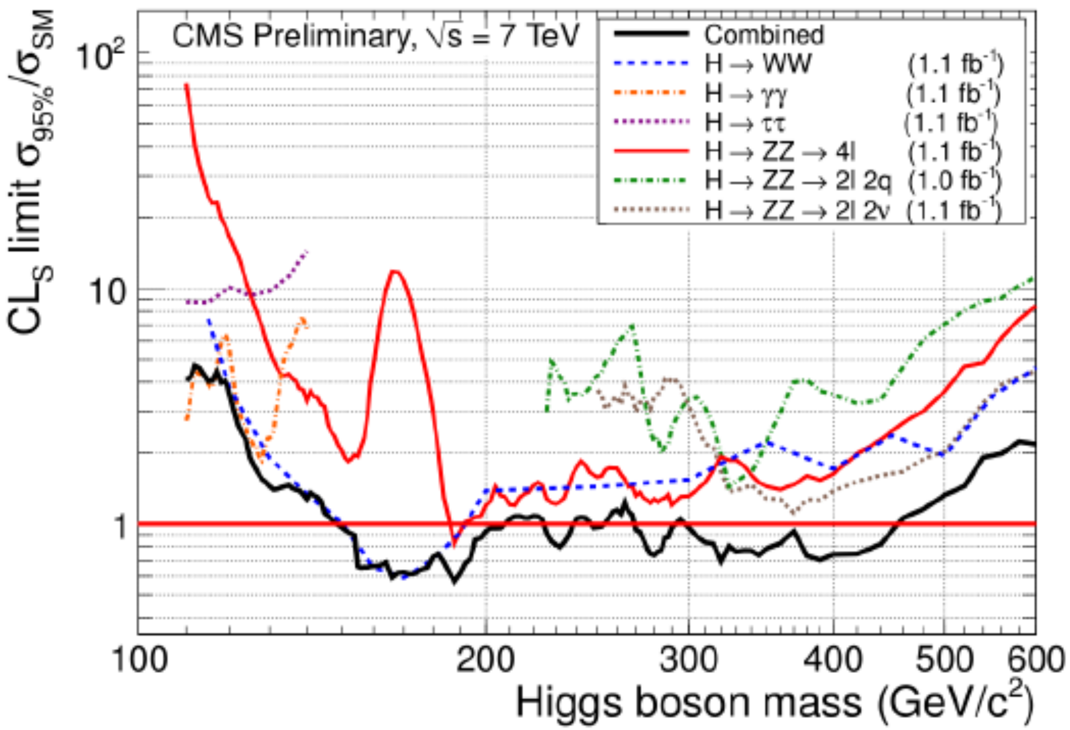
Limits on SM Higgs Production

- Upper limits on Higgs production cross sections derived at 95% C.L. as a function of Higgs boson mass, taking into account experimental and theoretical uncertainties.
- Reported in units of SM cross section: $R_{95\%}=\sigma_{95\%}/\sigma_{SM}$

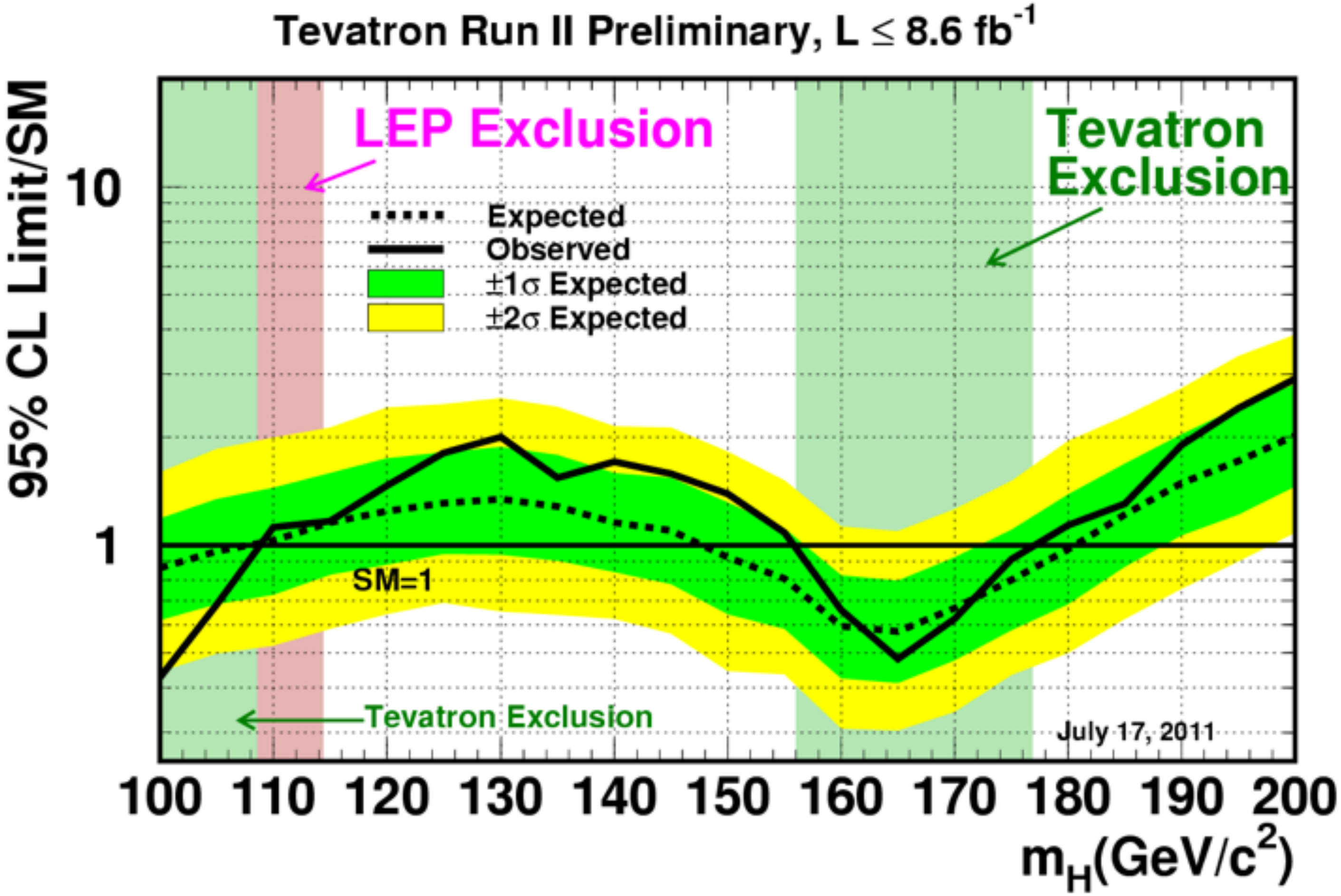
  ➔ exclude m_H range for which $R_{95\%} \leq 1$.

- Combination of multiple channels (and experiments!) yields the greatest sensitivity.
  - Assumes SM prediction for ratio of production cross sections and branching ratios.





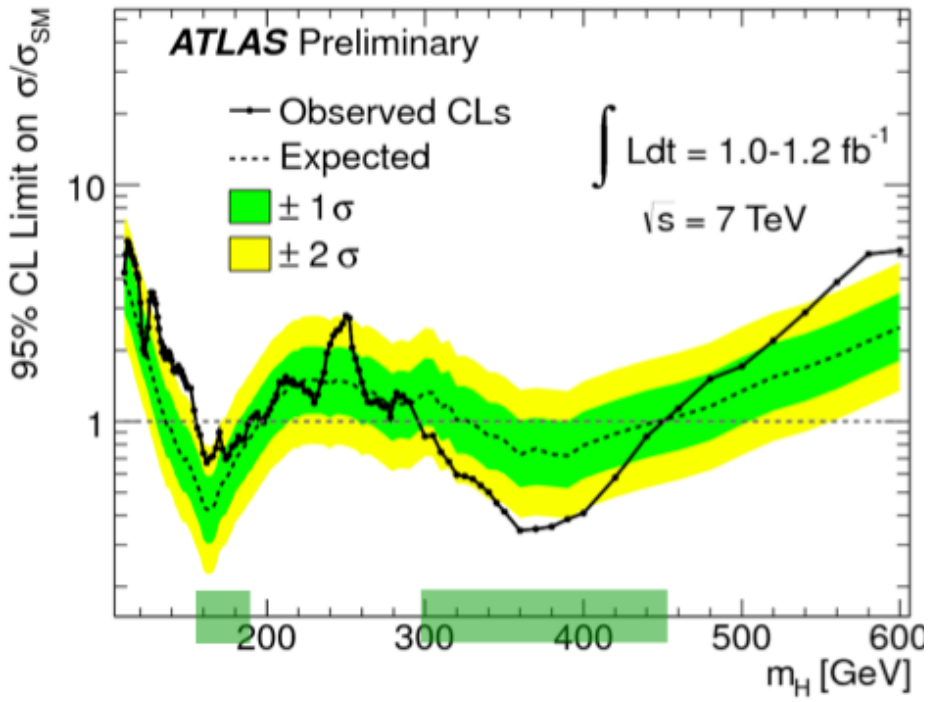
Tevatron Results

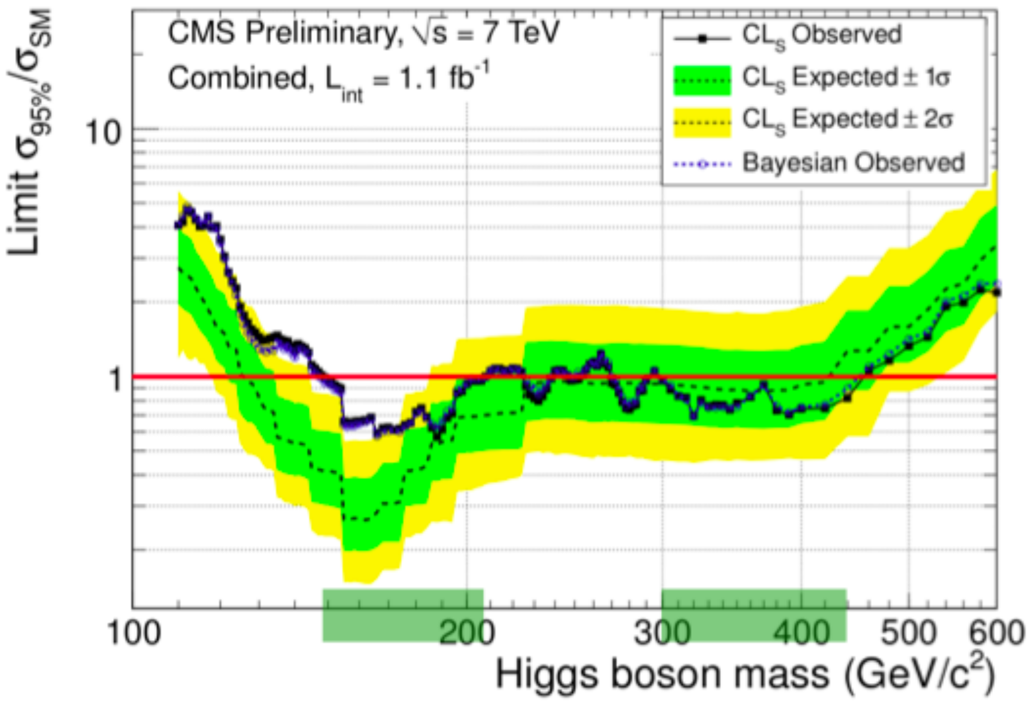


SM Higgs excluded at 95% C.L.

$100 < m_H < 108$ GeV and $156 < m_H < 177$ GeV

LHC Results





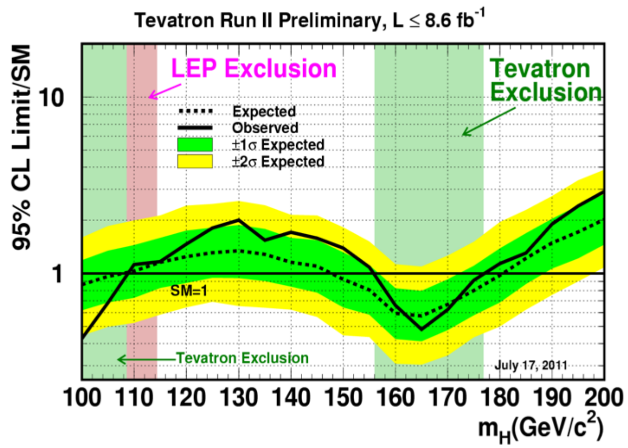
SM Higgs excluded at 95% C.L.

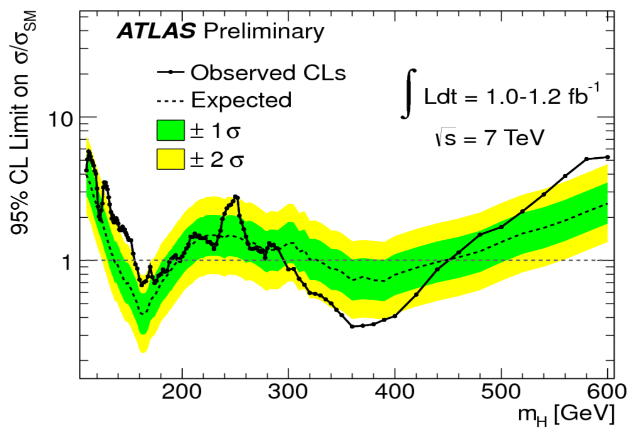
$155 < m_H < 190$ GeV and $295 < m_H < 450$ GeV

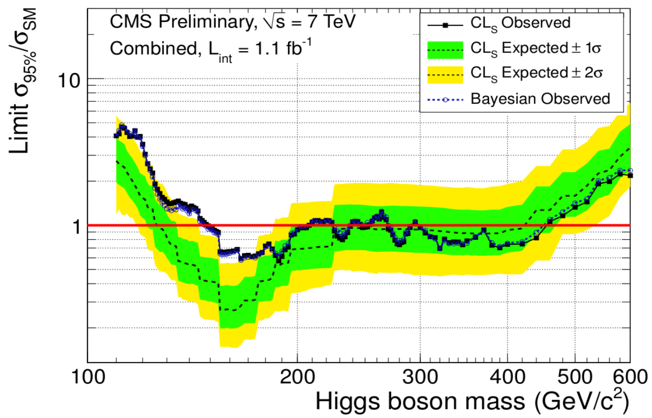
SM Higgs excluded at 95% C.L.

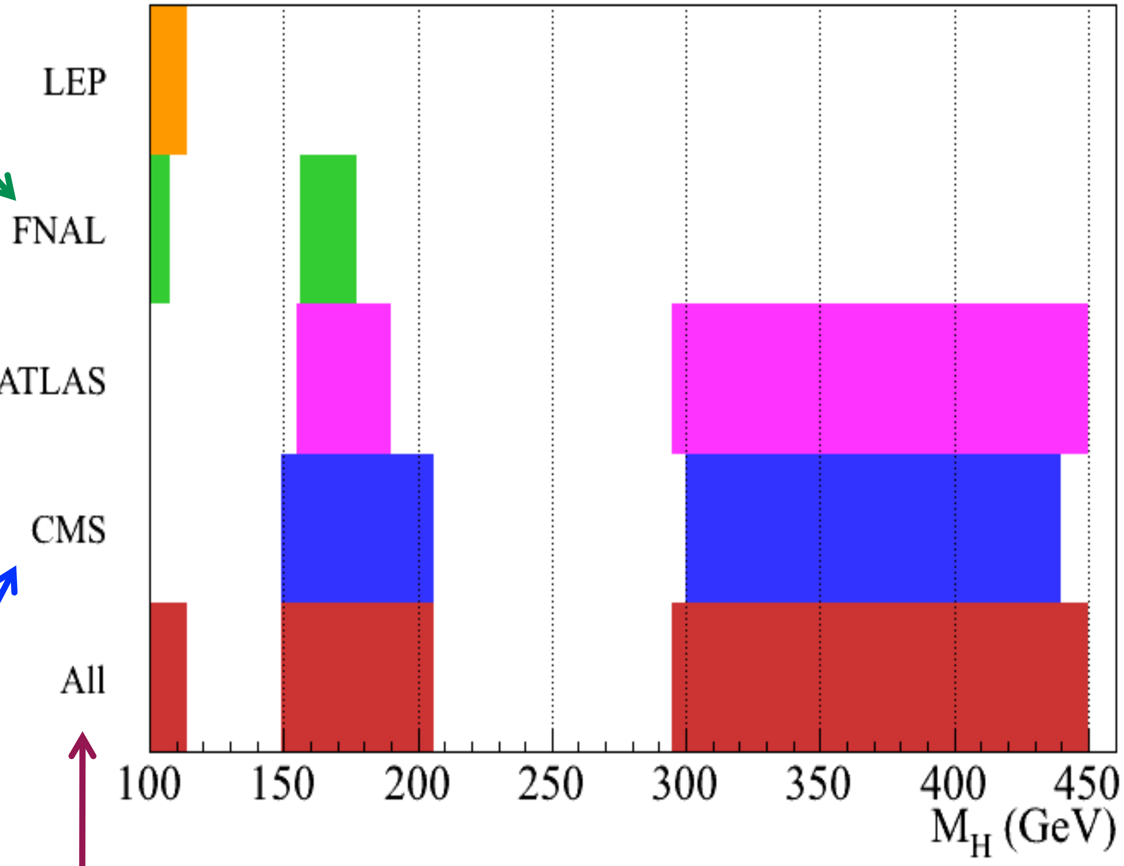
$149 < m_H < 206$ GeV and $300 < m_H < 440$ GeV

Summary of Current Limits









Simple OR of exclusions (*)

(*) Caution, exclusion probability >95%

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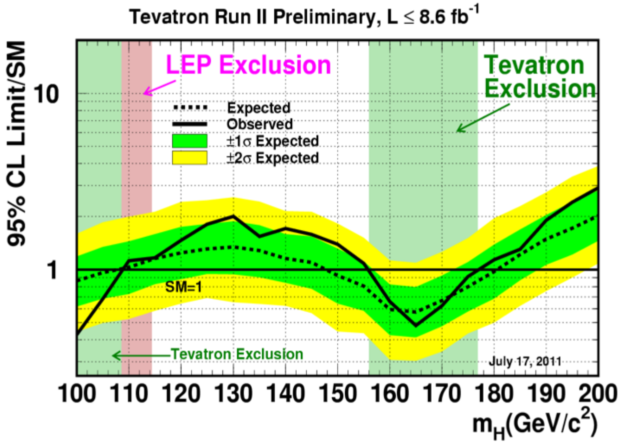
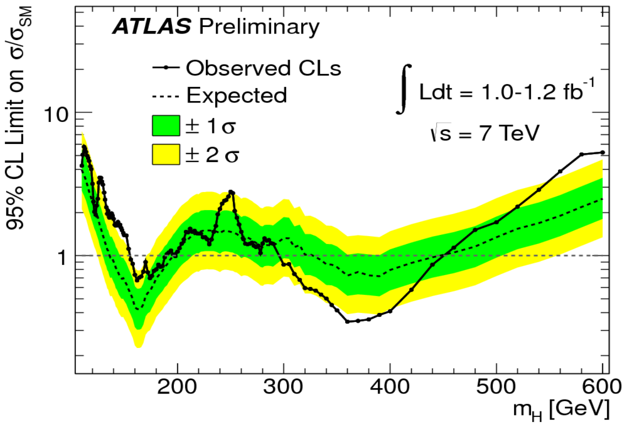
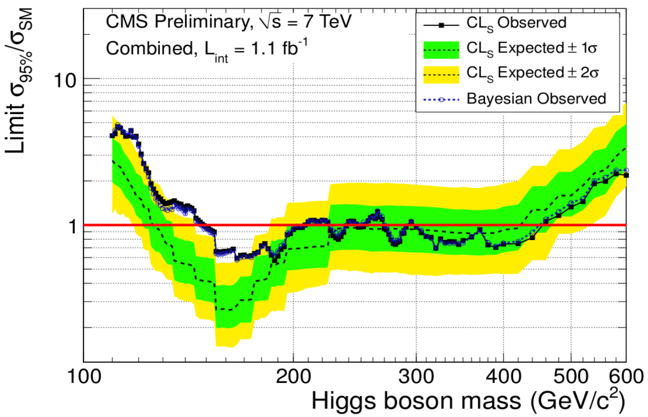
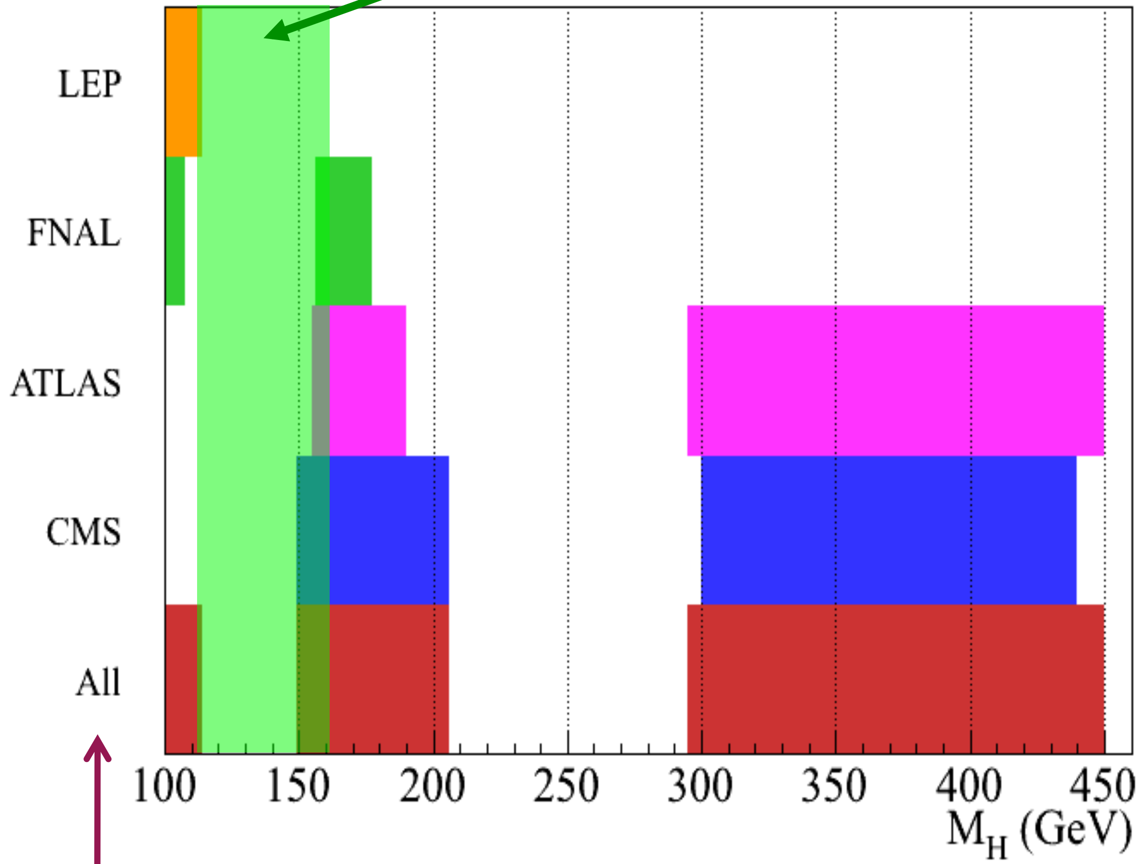






95% C.L. region preferred by fit to precision EW data

NOT EXCLUDED



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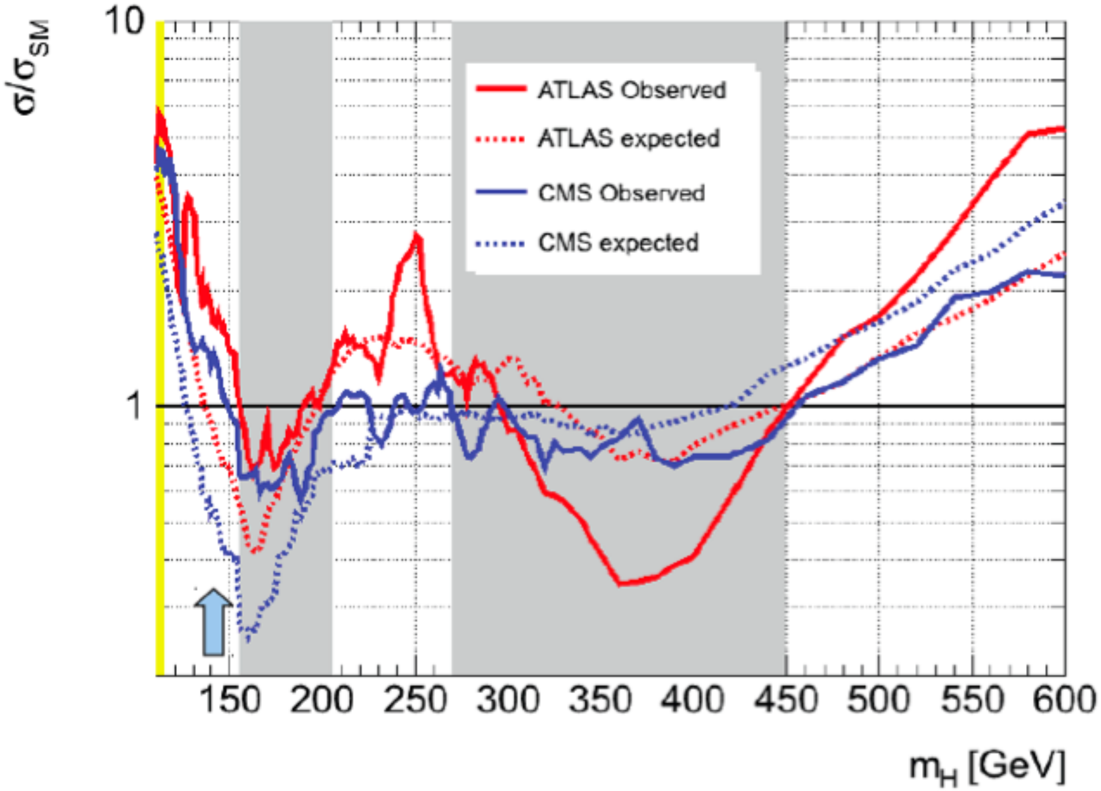
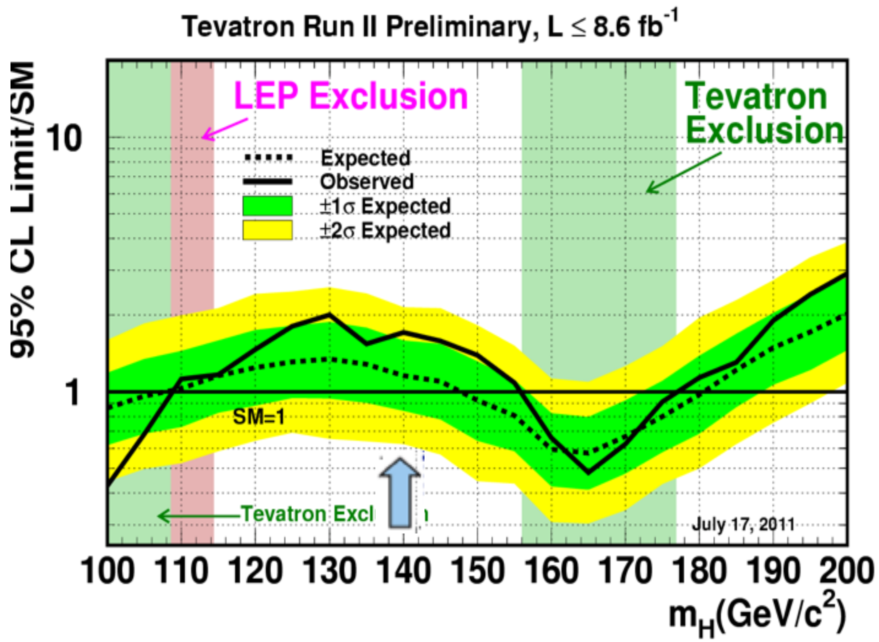
Any Hints of an Excess?

- Searches dominated by gg→H production show interesting common features near m_H~140 GeV (inside region preferred by EW precision data):





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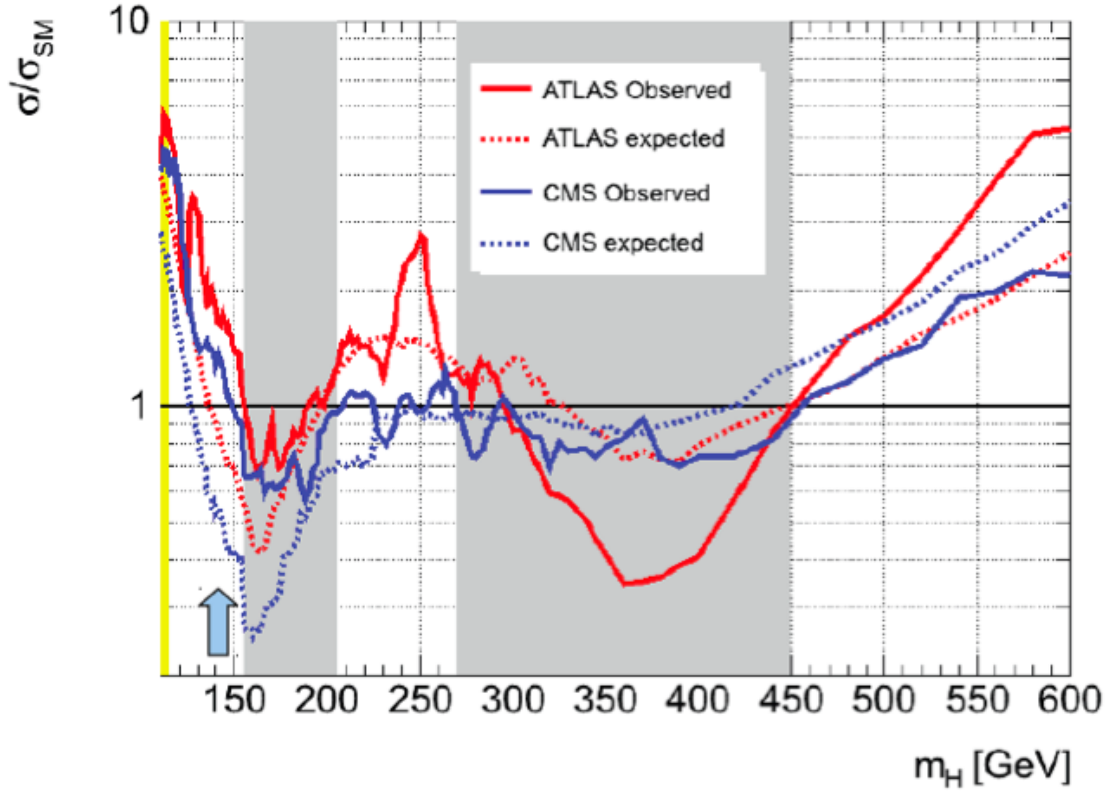
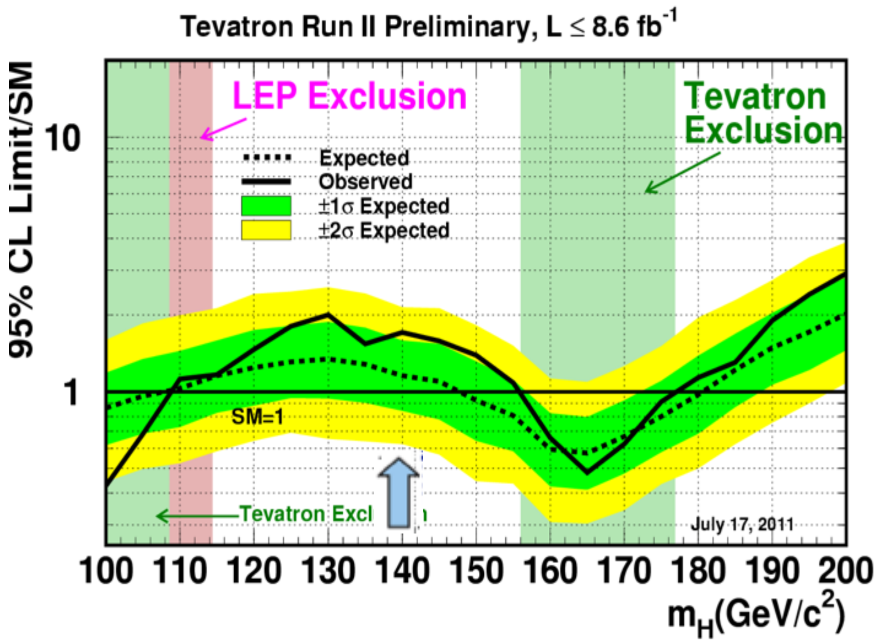
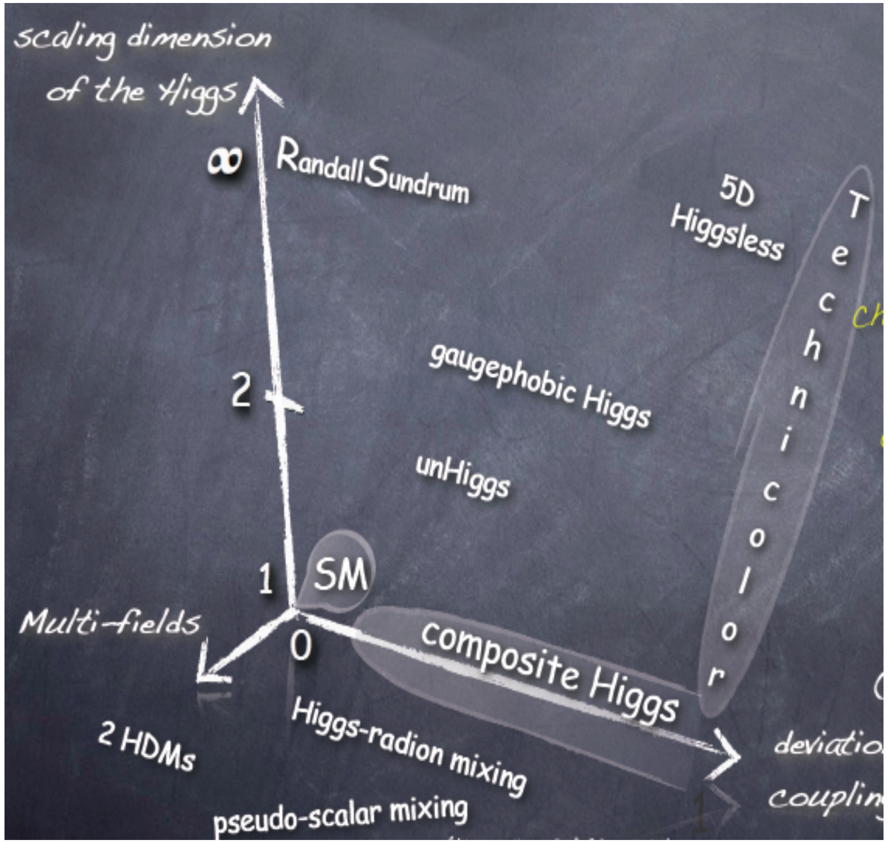




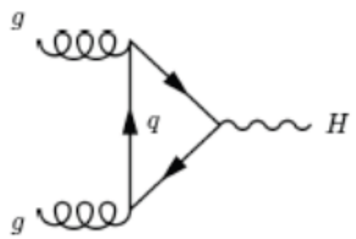
- Local p-values near m_H~140 GeV: ~2.5-3σ for individual results (ATLAS and CMS combinations).
- Individual excesses not significant after taking into account look-elsewhere effect but… …exciting prospects for the upcoming updated results and ATLAS+CMS combination!

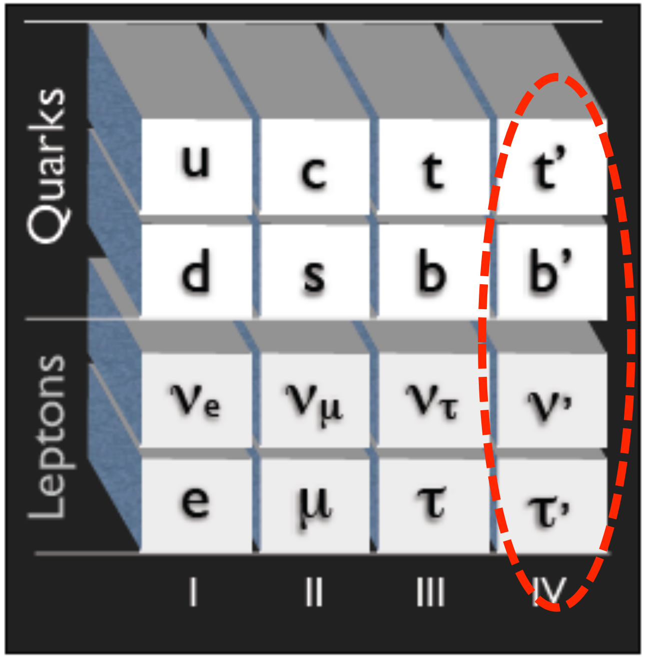
Beyond the SM Higgs



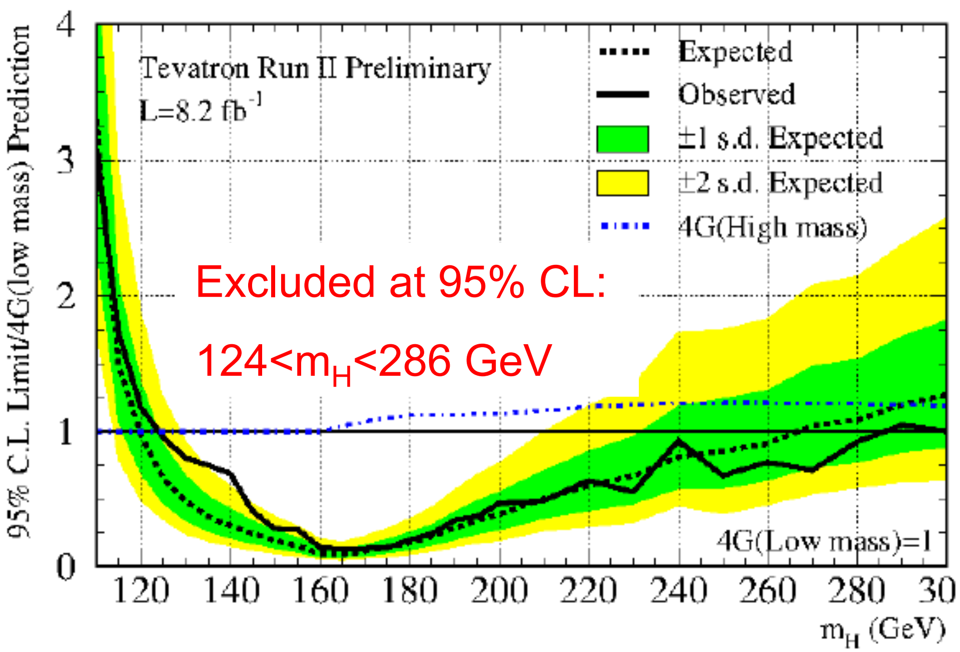
Higgs in 4th Generation Models

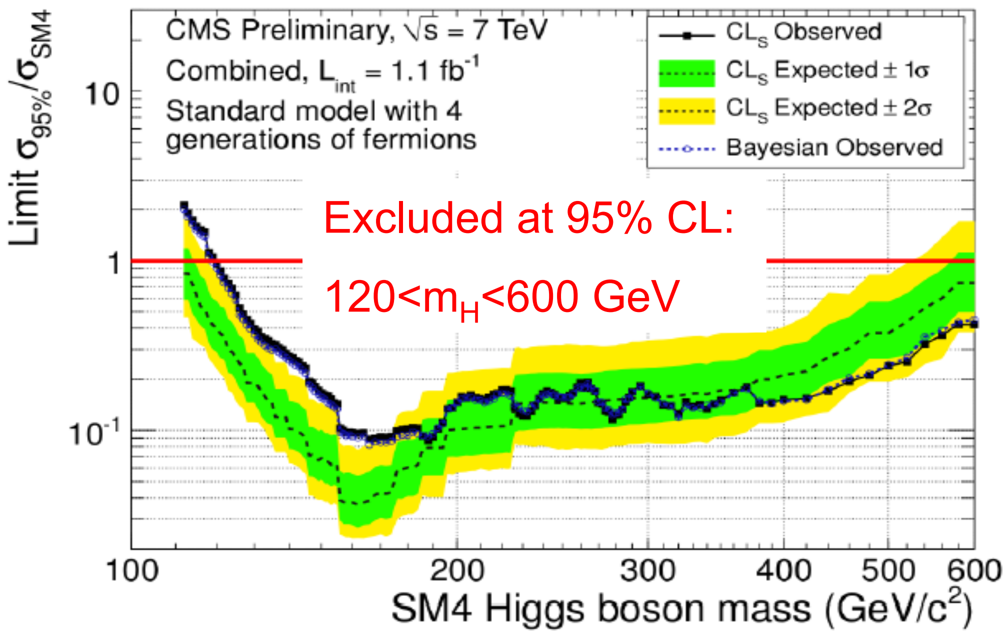
- Sequential 4th generation of fermions consistent with precision EW data. Higgs boson naturally heavy.
- Additional quarks enhance by x3 the ggH coupling.





- Higgs production cross sections:
  - gg→H enhanced by ~x9-7 for m_H~ 100-300 GeV
  - Rest of production modes remain at SM rate.





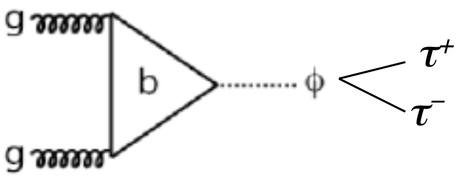
MSSM Higgs Bosons

- MSSM: extended Higgs sector (Type II 2HDM model) $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$
  - After EWSB: four massive scalars (h^0,H^0,$H^\pm$) and one pseudo-scalar (A^0).
  - At tree level: parameterized in terms of M_A and $\tan\beta = v_u/v_d$
    Significant impact from radiative corrections on masses and couplings.

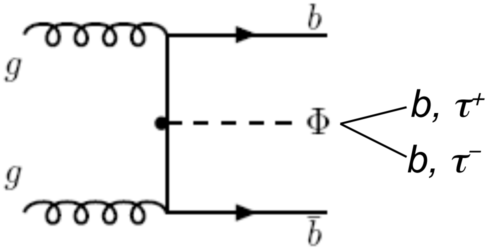
- Neutral Higgs bosons at high $\tan\beta$:
  - $\Phi^0=\{h^0/H^0,A^0\}$ nearly degenerated in mass
  - Coupling to b, τ enhanced ($\propto\tan\beta$)

$\sigma_{\Phi+X} \sim 2 \times \tan^2\beta \times (\sigma_{\Phi+X})_{SM}$
$BR(\Phi^0\to bb)\sim 90\%$, $BR(\Phi^0\to\tau^+\tau^-)\sim 10\%$

- Three complementary channels with comparable sensitivity:

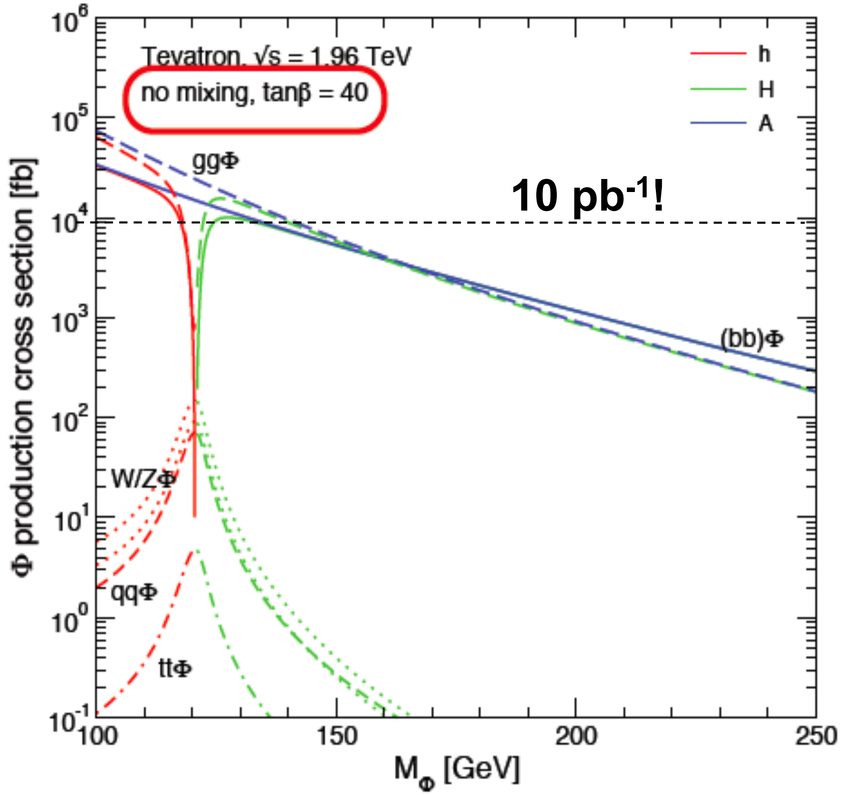


$\Phi^0\to\tau^+\tau^-$

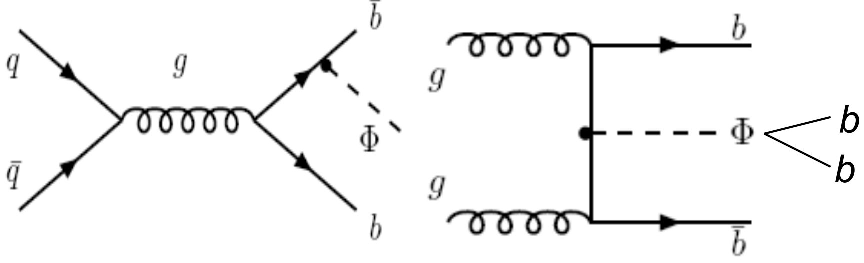


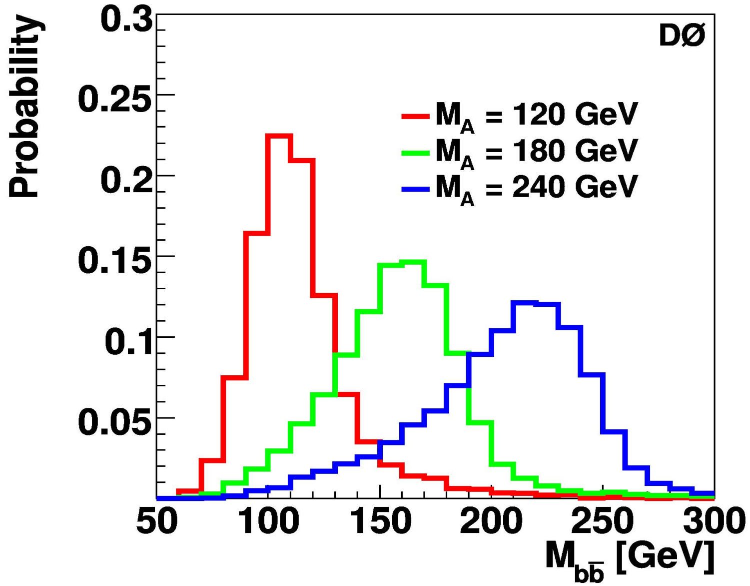
$b(b)+\Phi^0\to bbb(b)$

$b(b)+\Phi^0\to\tau^+\tau^- b(b)$



$b(b)+\Phi^0 \rightarrow bbb(b)$

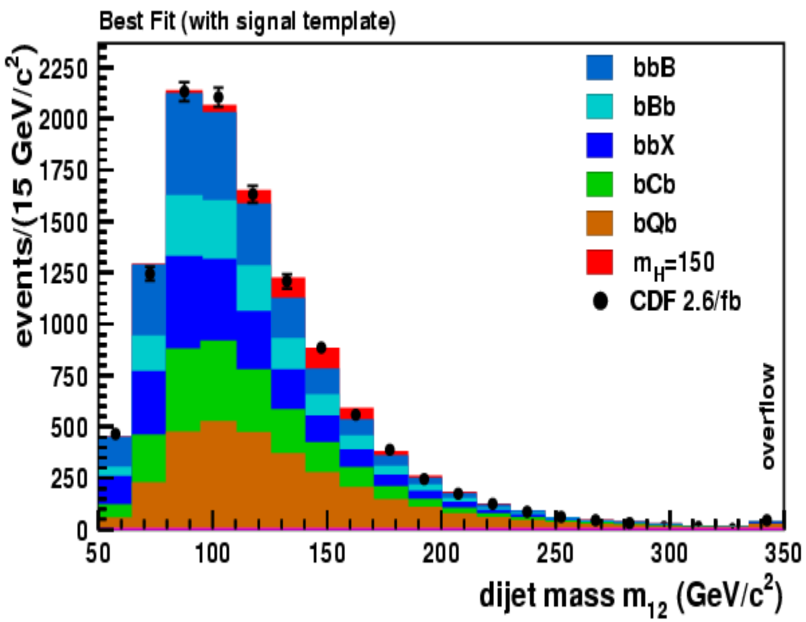




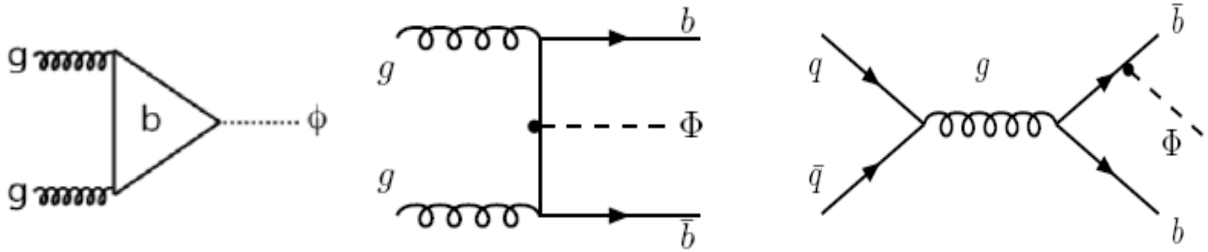
- Searches so far only carried out at the Tevatron.

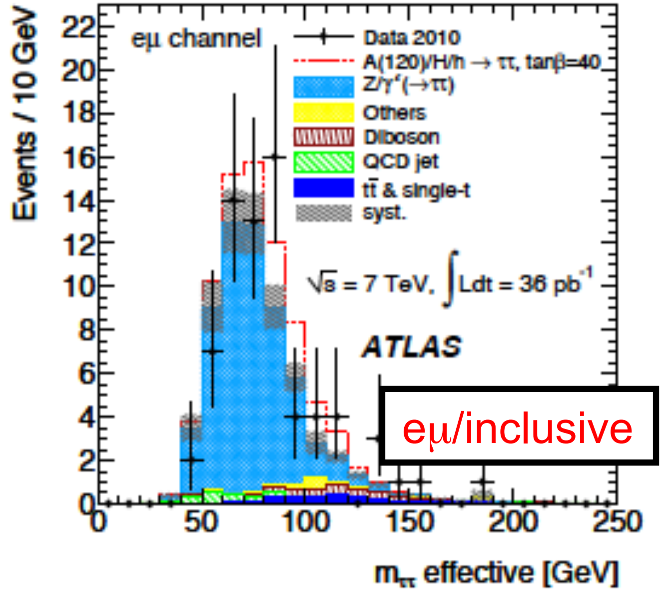
- Experimental signature:
  - 3, 4 or ≥5 jets; ≥3 b-tags
  - Invariant mass of leading two jets peaks at M_Φ

- Backgrounds dominated by heavy flavor-enriched QCD multijets:
  - Composition estimated from data
  - Shape extracted from 2-tag sample or MC simulation
  - Rate normalized outside the "signal region"

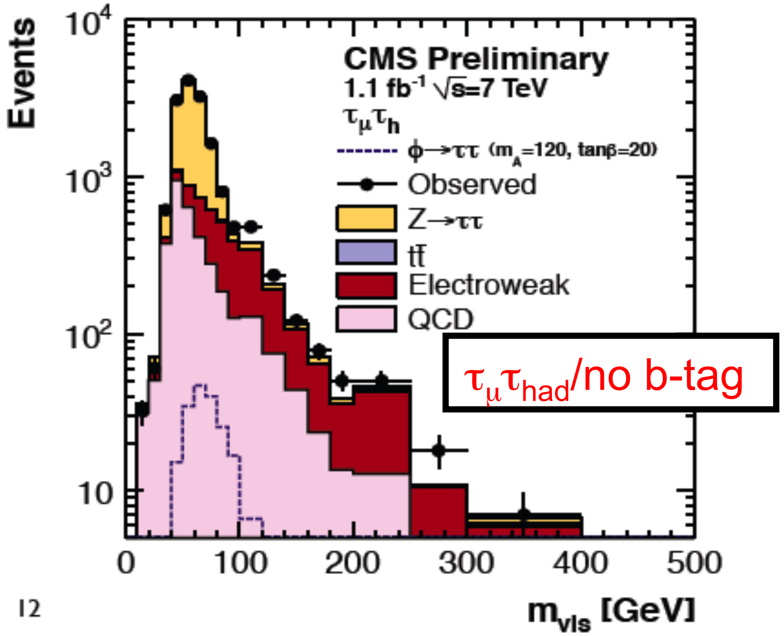


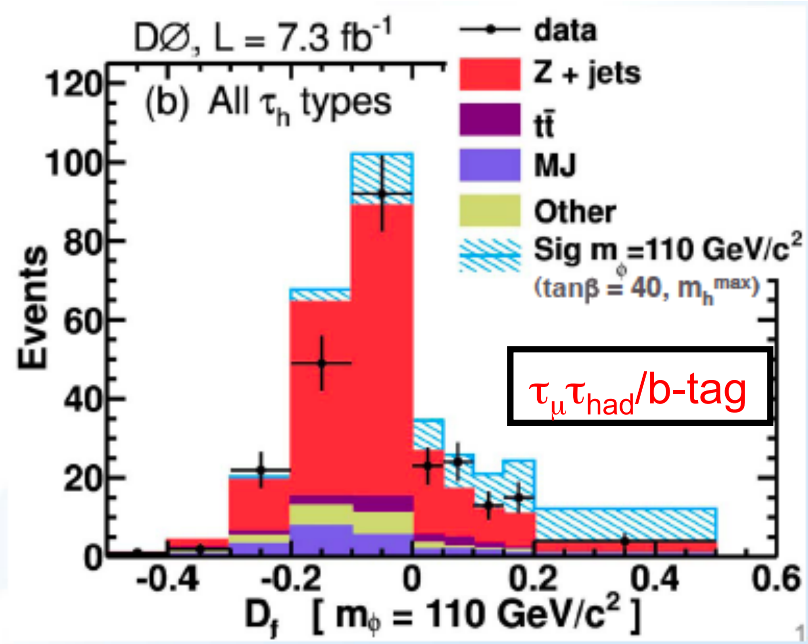
$(b)+\Phi^0 \rightarrow (b)\tau^+\tau^-$





- Require ≥1 leptonic tau decays: $\tau_\mu\tau_{had.}$ $\tau_e\tau_{had,}$ $\tau_e\tau_{\mu,}$ $\tau_\mu\tau_{\mu.}$
- Inclusive and exclusive (assoc. production) analyses involve different diagrams.
- Also differently sensitive to backgrounds:
  - No b-tag: $Z \rightarrow \tau\tau$ dominates
  - B-tagged: ttbar dominates

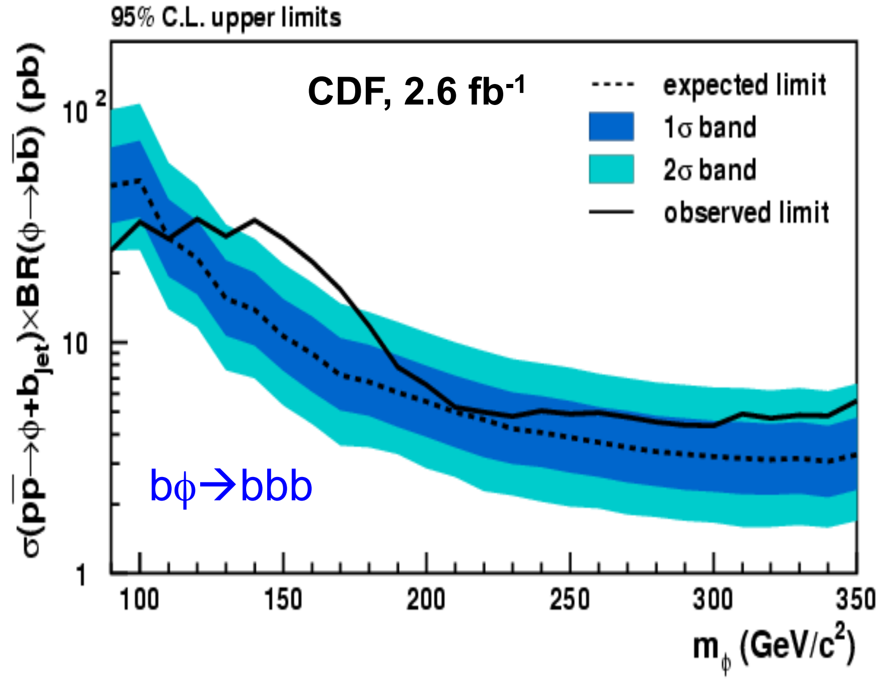


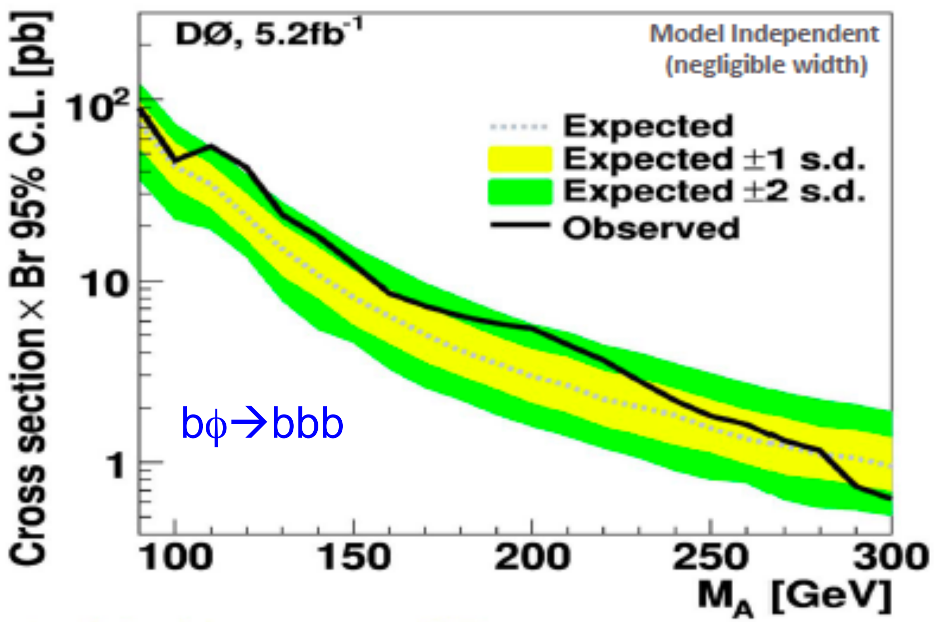


Any Hints of an Excess?

$\phi \rightarrow bb$

- Both CDF and DØ see ~2σ excesses around m_A~120-150 GeV.
- Updated analyses and Tevatron combination underway.





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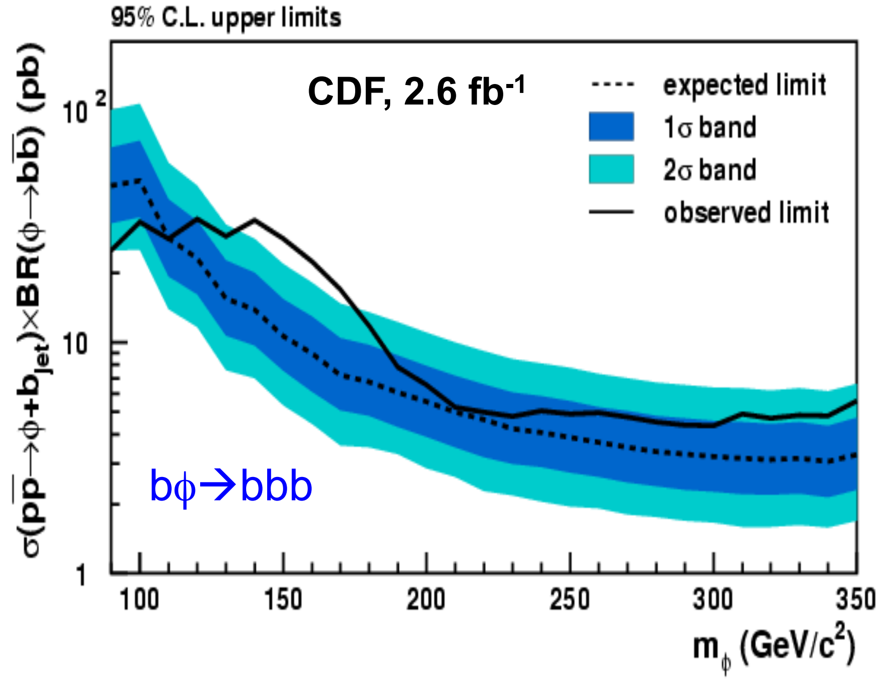
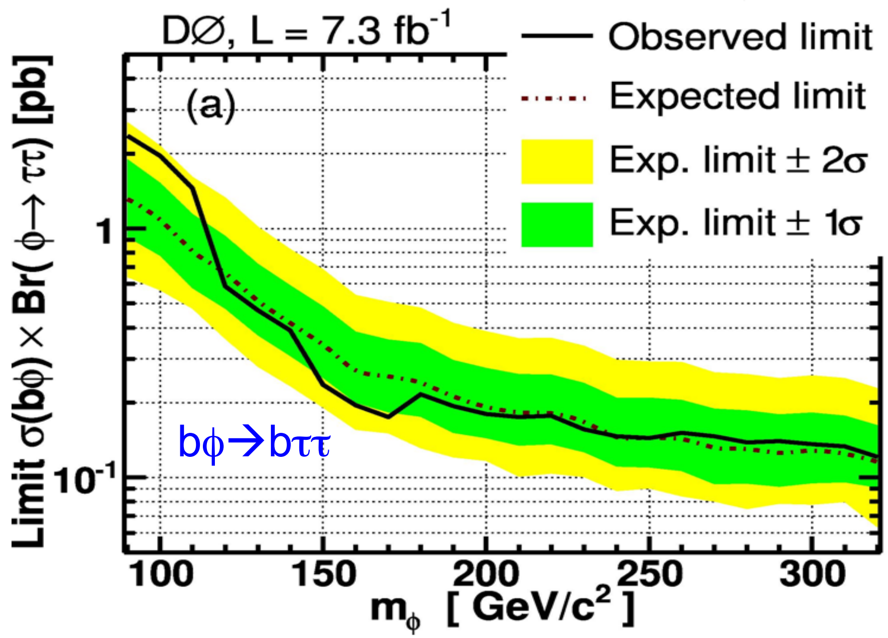
- Tevatron searches don't observe any significant excess.





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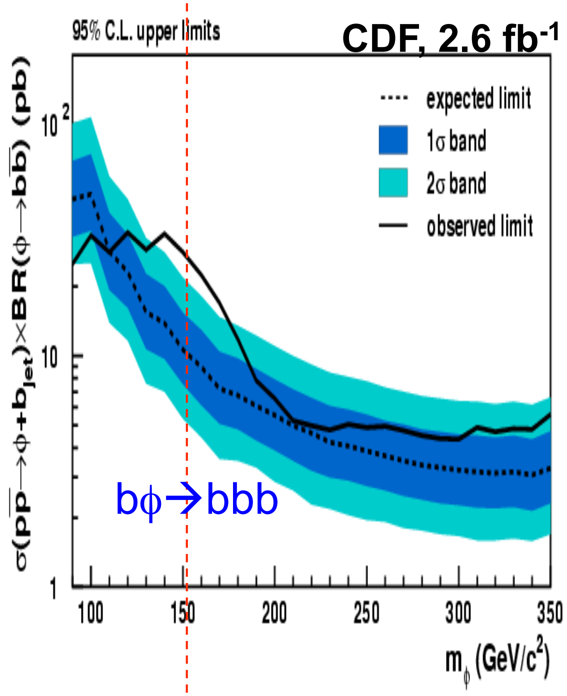
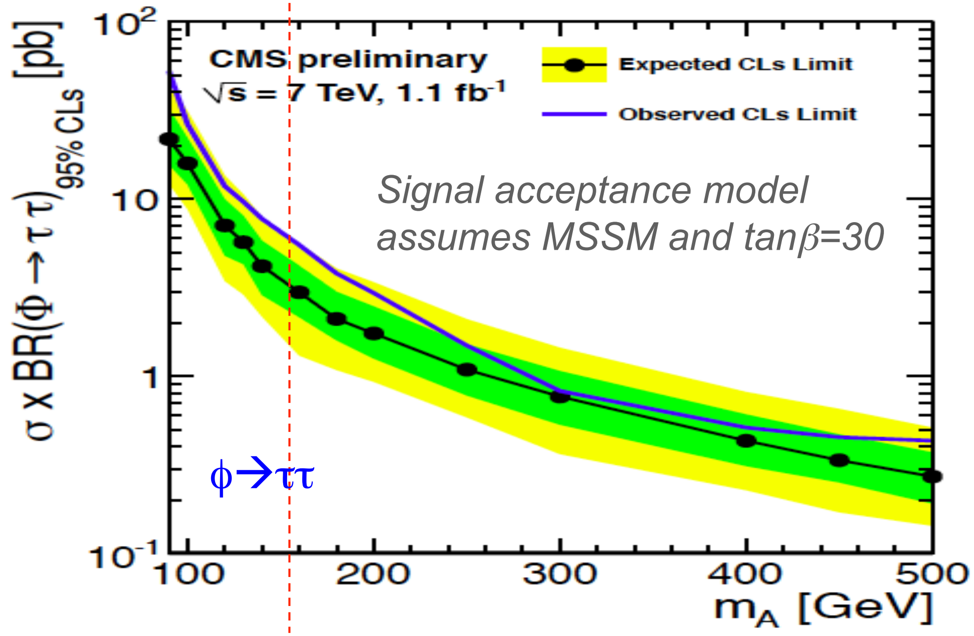
$\phi \rightarrow \tau\tau$

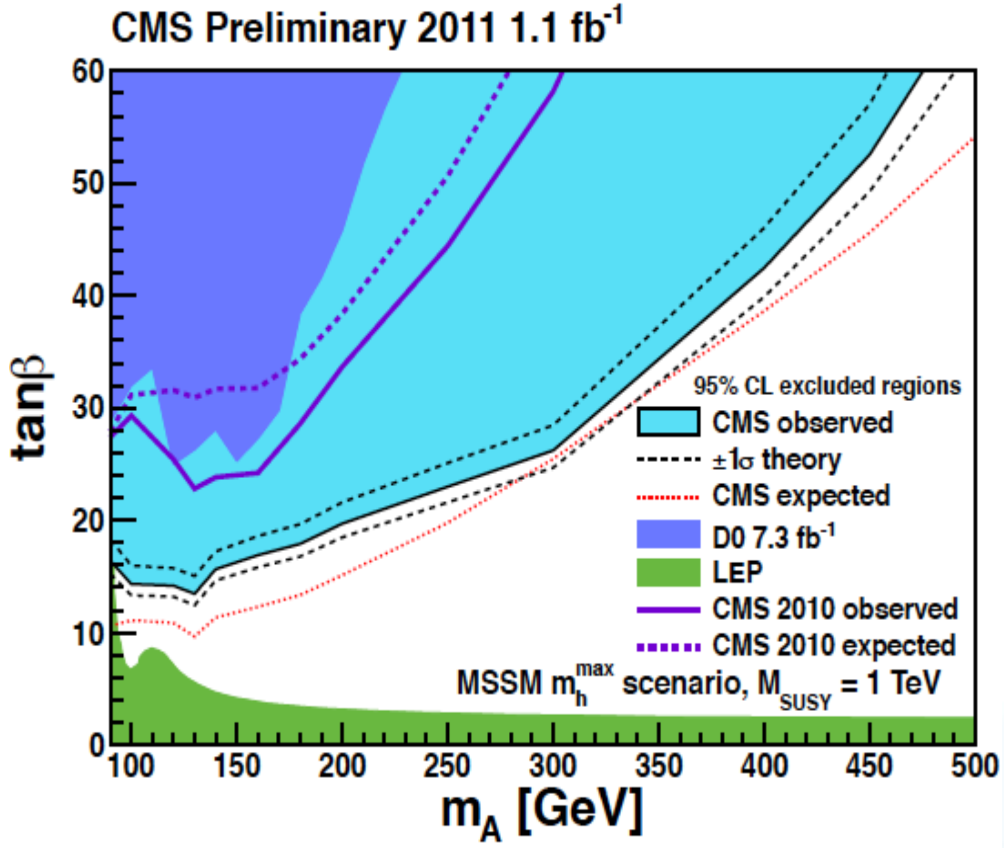
- Tevatron searches don't observe any significant excess.
- However, the highest sensitivity result available at the LHC observes broad excess in m_A~100-300 GeV, with a ~2σ deviation at m_A~150 GeV.

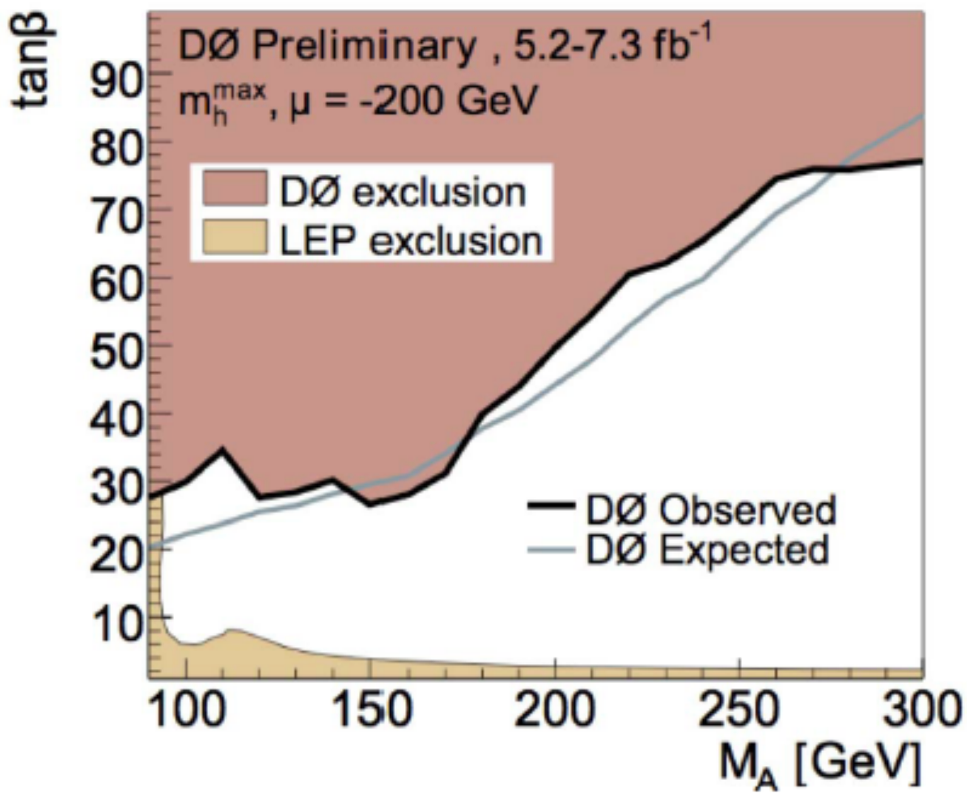
Combination of Tevatron and LHC results will be eventually required to start assembling a consistent picture.





Interpretations within the MSSM





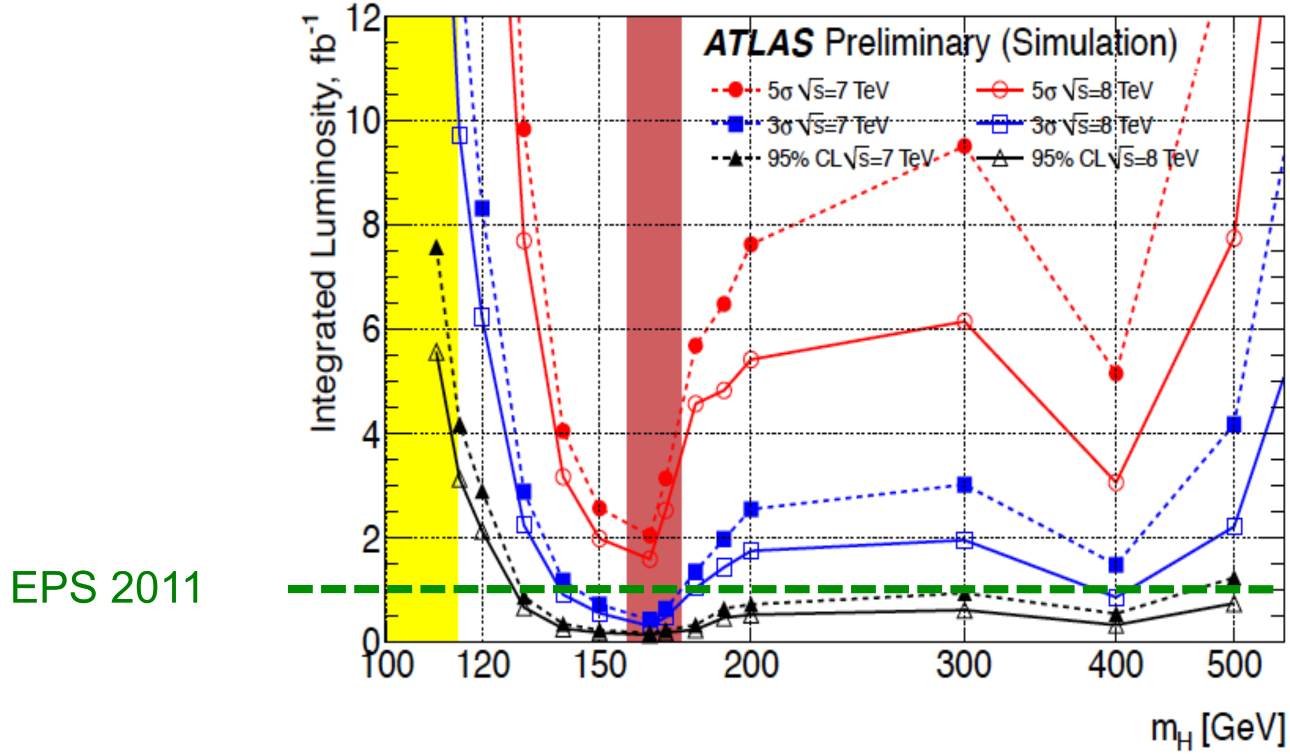
Combination of $H^{\pm}$ and $(b)\Phi^0 \rightarrow (b)\tau^+\tau$

Combination of $b\Phi^0 \rightarrow b\tau\tau$ and $b\Phi^0 \rightarrow bbb$

Already probing below “interesting” tanβ~30 region over wide mass range!

Prospects

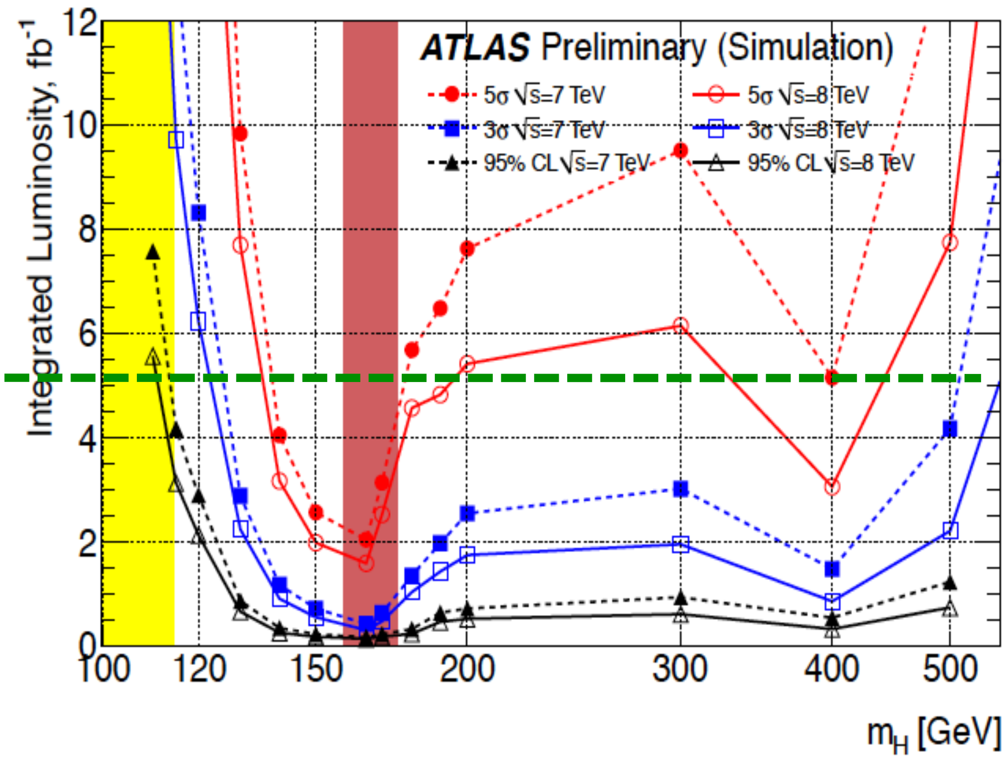
LHC Prospects



- LHC experiments have made an impressive start and have a great future.
- Largest gain in the short term will come from increased luminosity:
  - Combination of ATLAS and CMS in the near future.

LHC Prospects

End of 2011?



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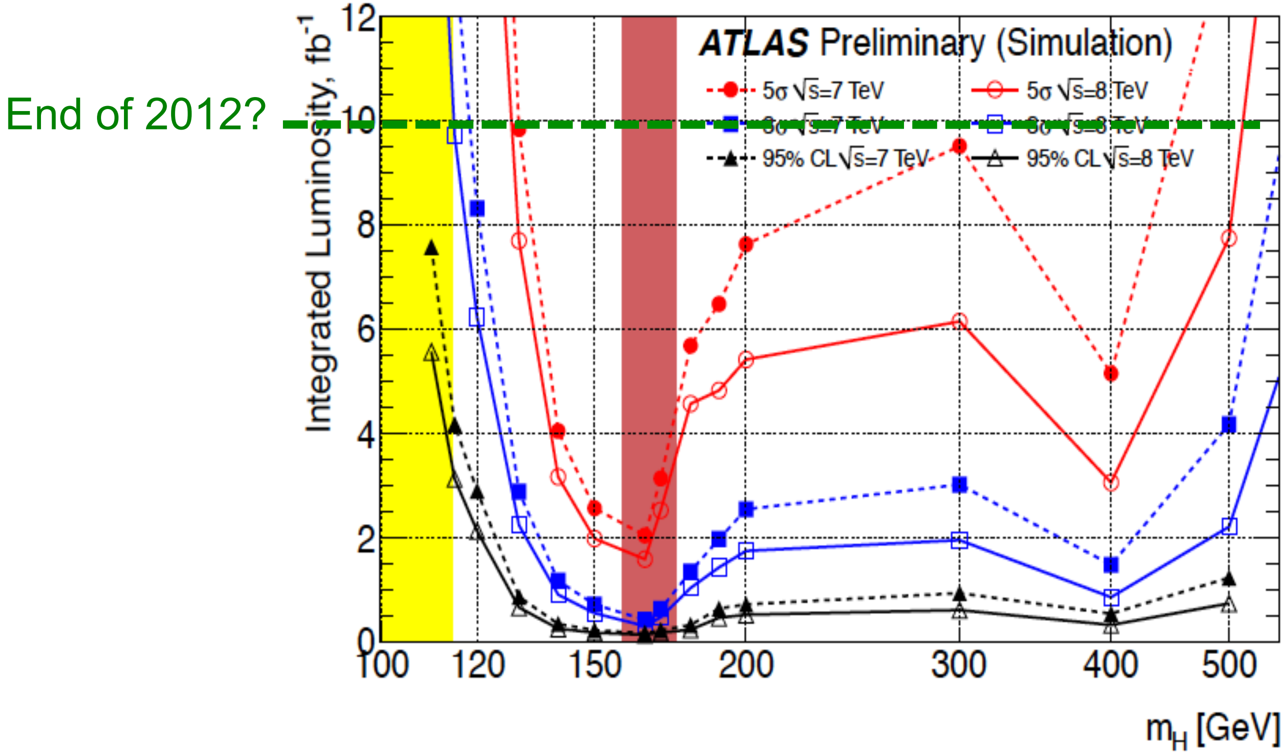
LHC Prospects



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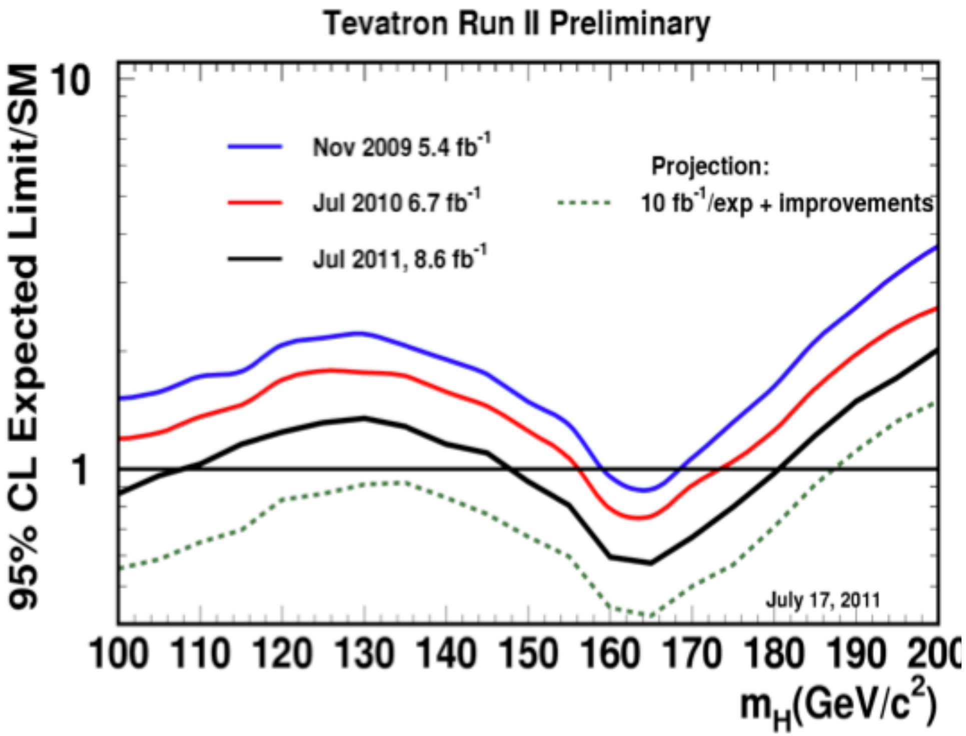
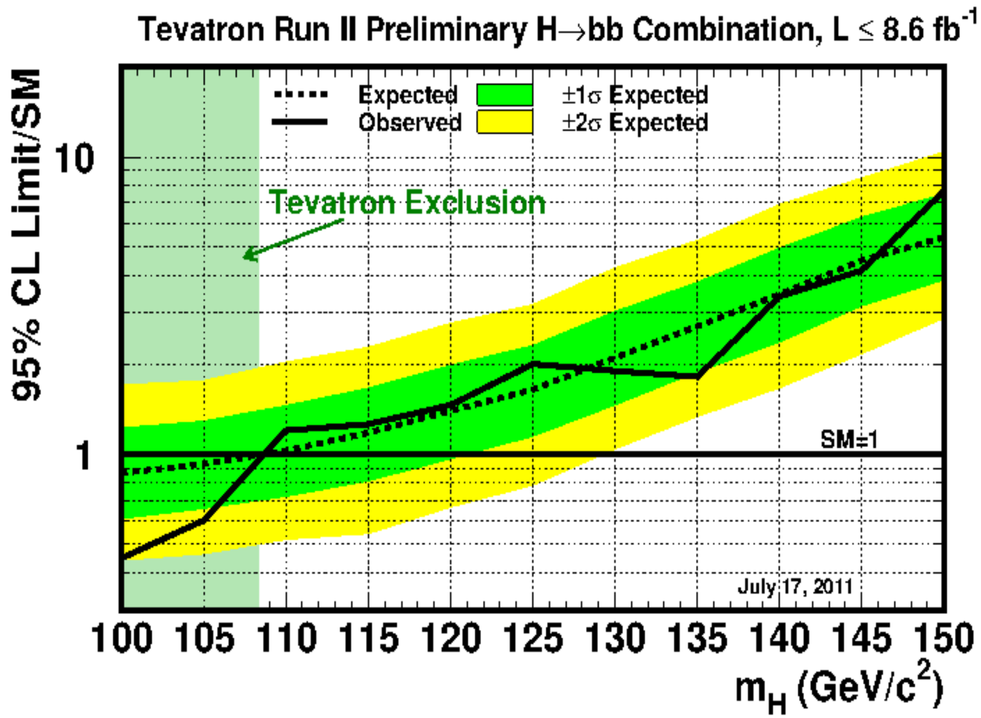
  - ~5 fb^{-1}/exp by end of 2011: exclusion potential over entire mass range or 5σ observation if m_H=140 GeV, per experiment!
  - ~10 fb^{-1}/exp by end of 2012?: discovery potential for m_H>130 GeV, per experiment!
- Sensitivity at low mass reliant largely upon $H\rightarrow\gamma\gamma$ and $H\rightarrow WW$.

Tevatron Prospects





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  - Best current limits for m_H<130 GeV and a unique window into H→bb.

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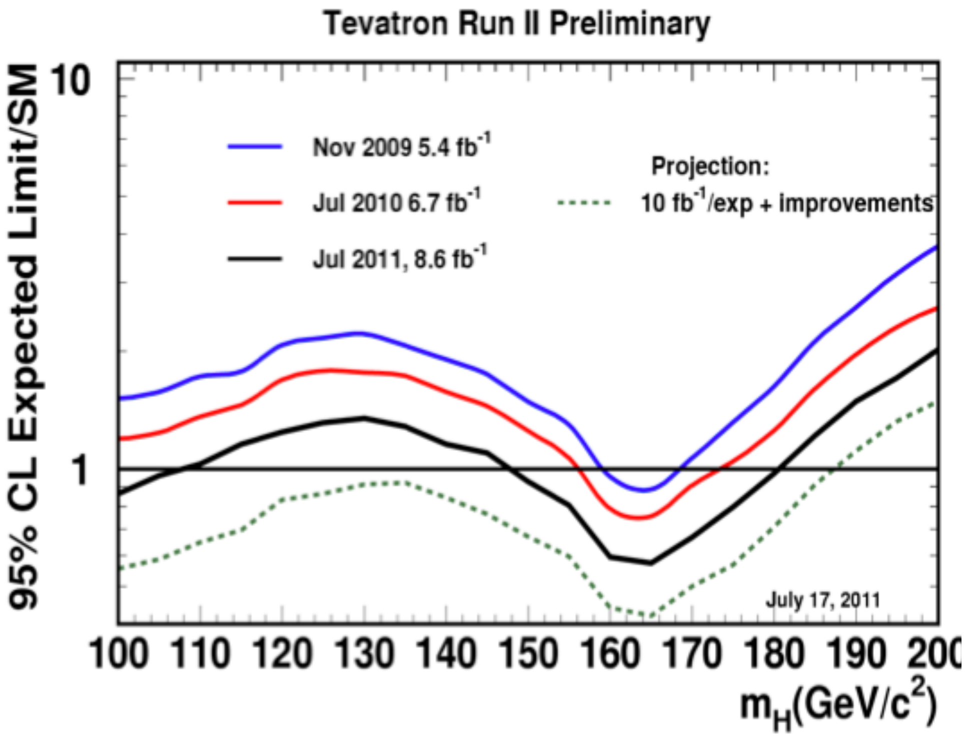
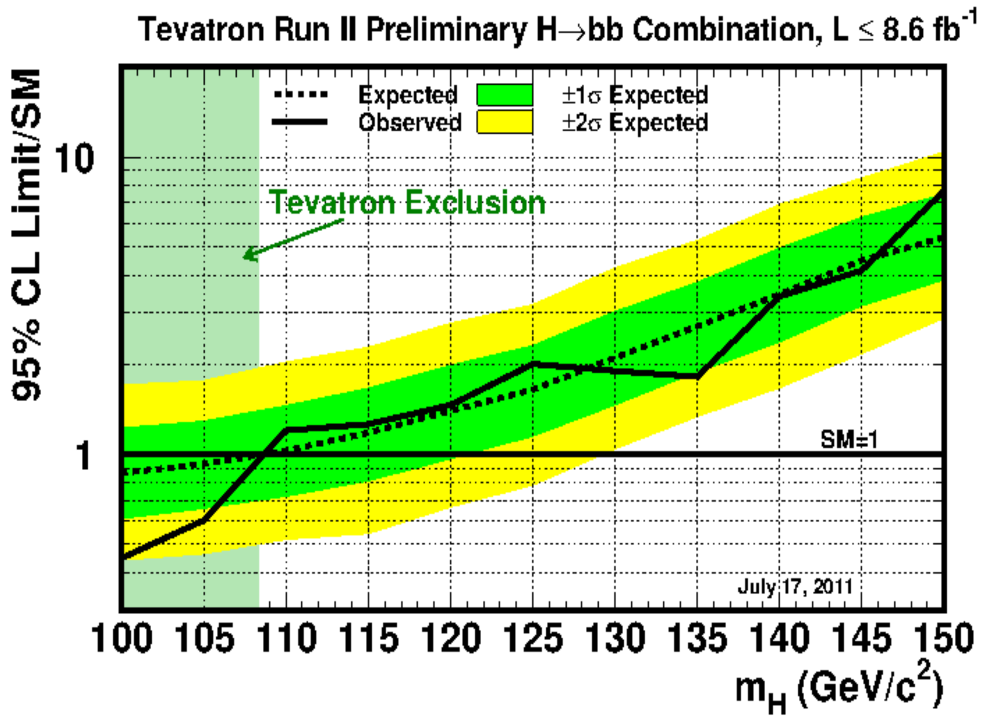
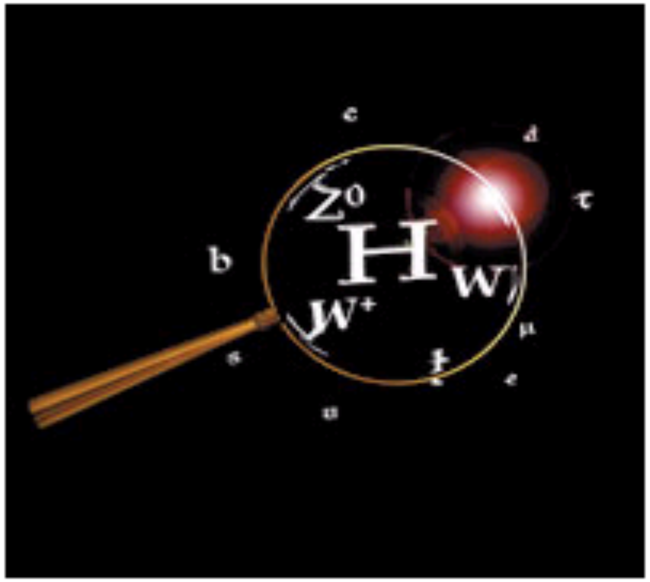




- Tevatron experiments will help complete the picture.
  - Best current limits for m_H<130 GeV and a unique window into H→bb.
- Tevatron experiments will collect data through Sept. 30, 2011.
  - Current results based on ~8 fb^{-1} on average. Expect ~10 fb^{-1} by Winter 2012.
  - Including ongoing analysis improvements: exclusion potential for m_H<190 GeV and ~2.5-3σ sensitivity for m_H~115-150 GeV.

Conclusions



- Over the last year we have made major progress in our exploration of the Higgs sector:
  - Large regions of mass are excluded for the SM Higgs.

    An excess at m_H~140 GeV is observed, so far consistent with both, a background fluctuation, or an emerging signal.
  - Searches for non-SM Higgs also show interesting features.

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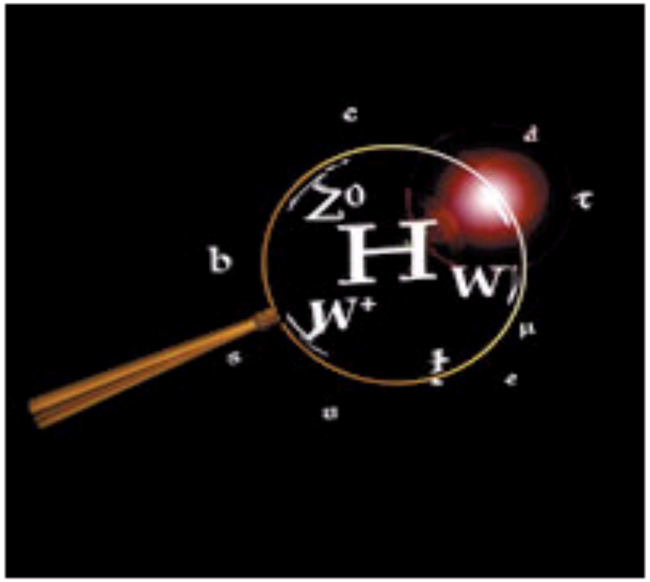

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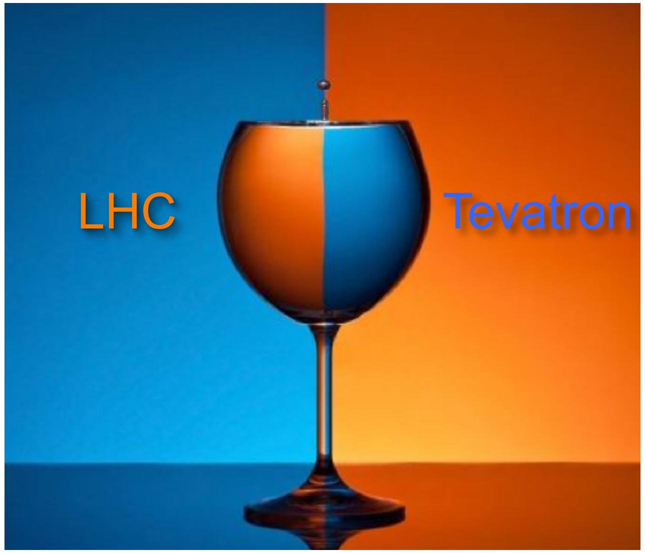
  - Both machines are sensitively probing the Higgs sector in complementary ways.



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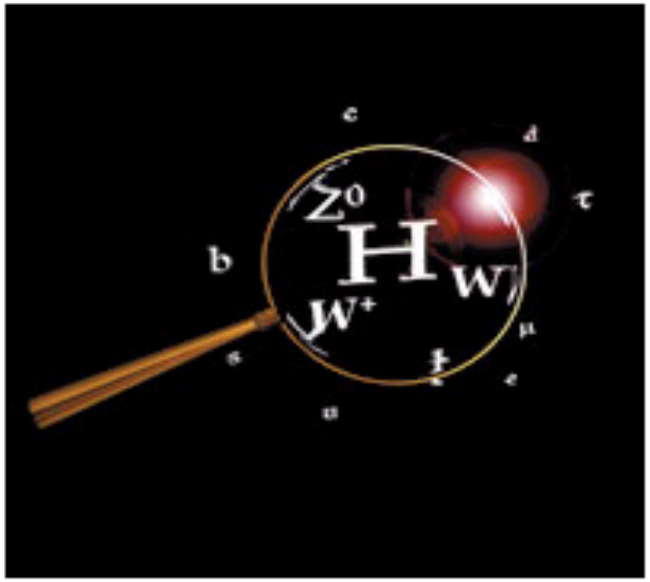

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Exciting times ahead!
Please stay tuned!

Disclaimer

- There is a large number of exciting results that could not be covered in this talk due to time limitations.

- For more detailed information see the set of excellent talks presented at the Higgs Physics parallel sessions:

http://indico.cern.ch/sessionDisplay.py?sessionId=17&confId=129980#all

and the experiments' public webpages:

ATLAS EXPERIMENT https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

CDF II http://www-cdf.fnal.gov/physics/new/hdg/Results.html

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

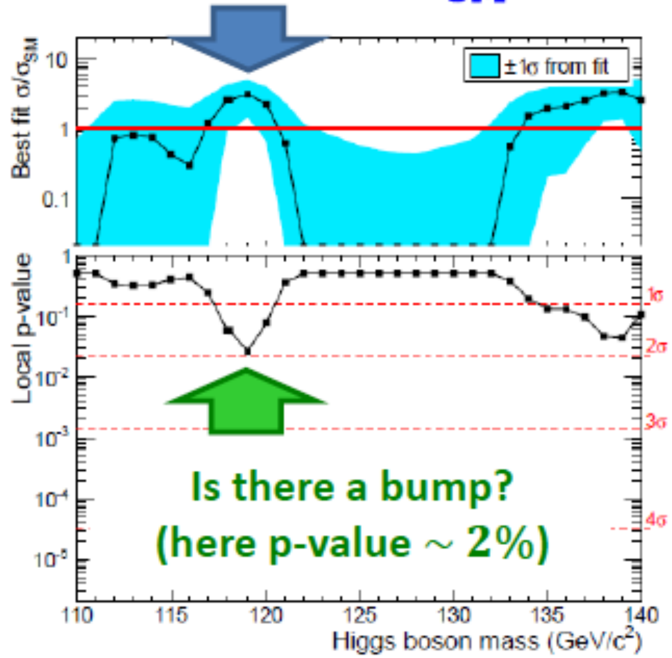
DØ http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm

Backup

- **The look-elsewhere effect (LEE) is significant in Higgs searches**
  - Higgs mass is unknown a priori
  - Each channel can represent many effective measurements (Trial Factor)
  - If errors are correctly estimated, ~2% of measurements will fluctuate up by 2σ or more → expect to see bumps!
- **Resolution is the key parameter**
  - For a given search window: higher resolution → larger LEE
  - Local p-value plot will show features with frequency driven by resolution

P-value plot: roadmap

Is it consistent with the SM Higgs?
(here $\sigma \sim 3 \times \sigma_{SM}$)

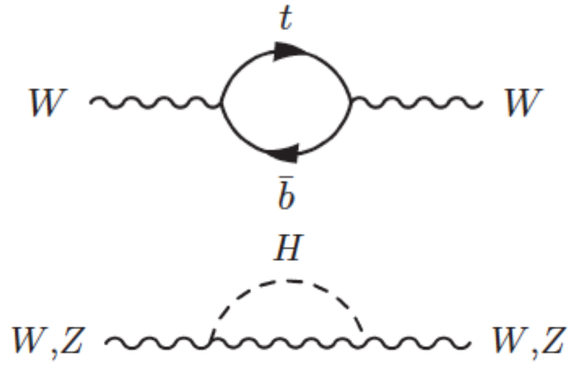


LEE in modes with high resolution gives trial factors O(20-100)

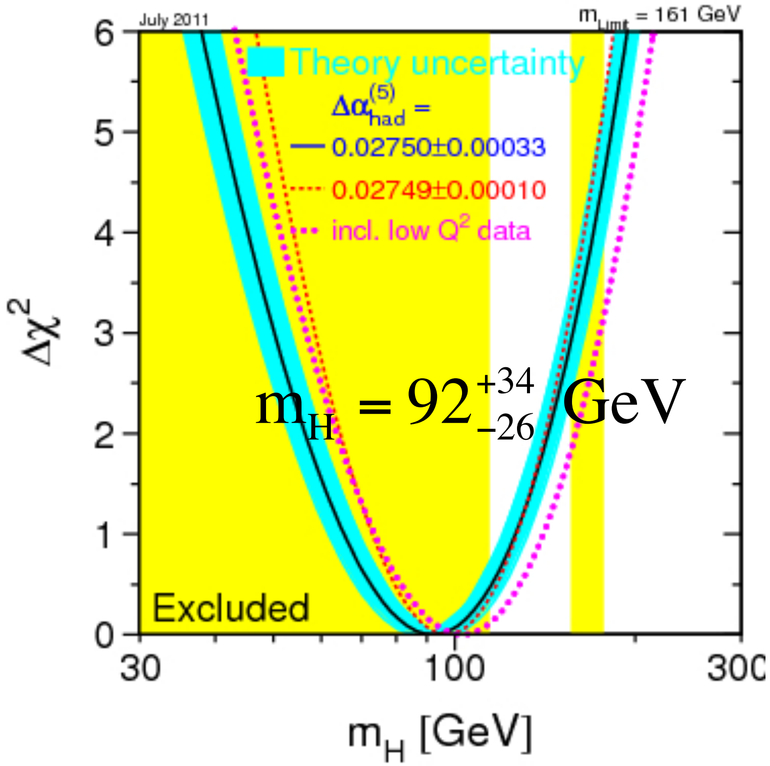
Stalking the Higgs Boson

Indirect constraints

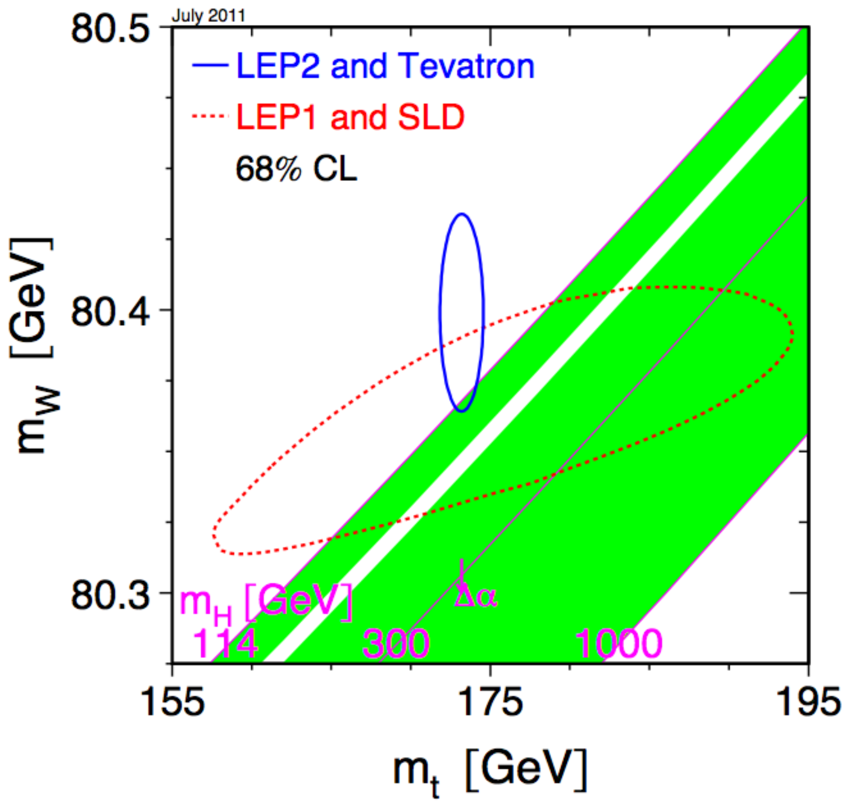
- Precision electroweak observables are sensitive to the Higgs boson mass via quantum corrections.



$$\Delta M_W \propto m_t^2,\ \log m_H$$

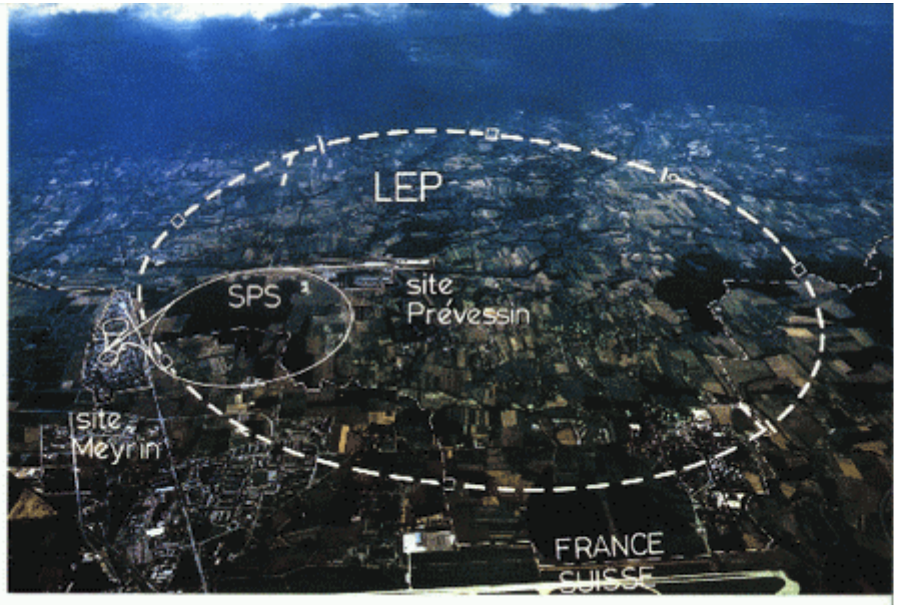


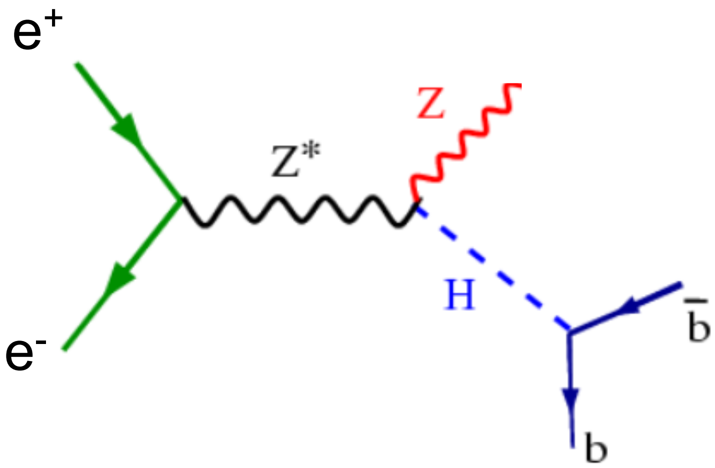
$m_H < 161$ GeV (95% CL)



Stalking the Higgs Boson

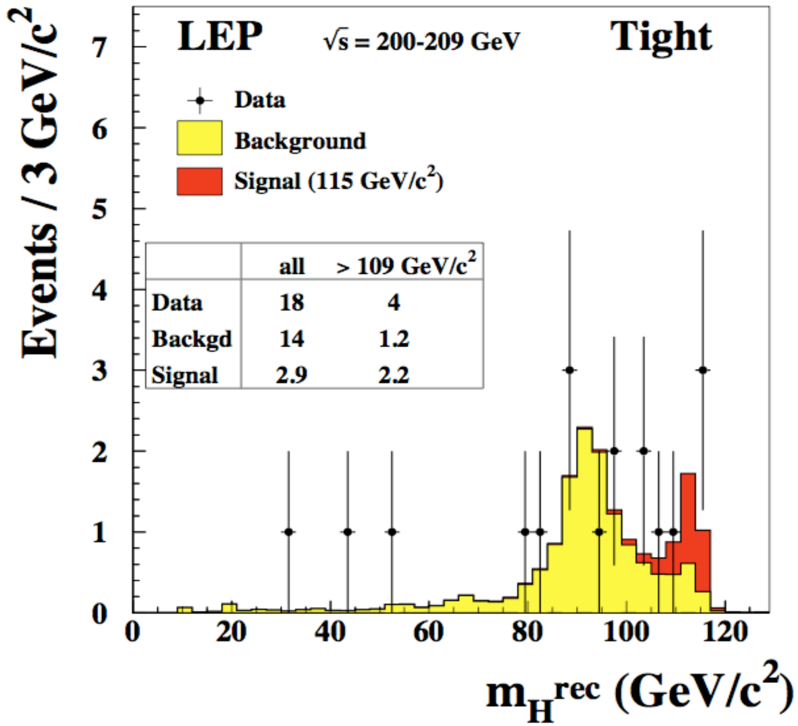
LEP 1989-2000





Direct searches at LEP

- Tantalizing hints (~1.7σ) of a SM-like Higgs boson with m_H~115 GeV:



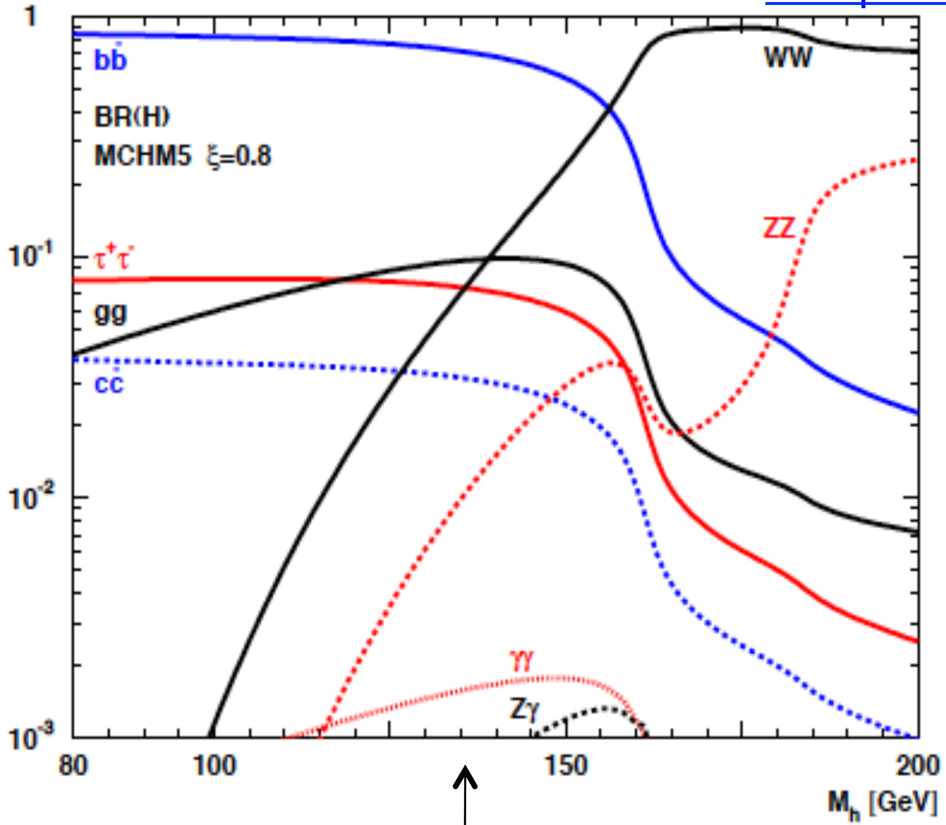
m_H> 114.4 GeV (95% CL)

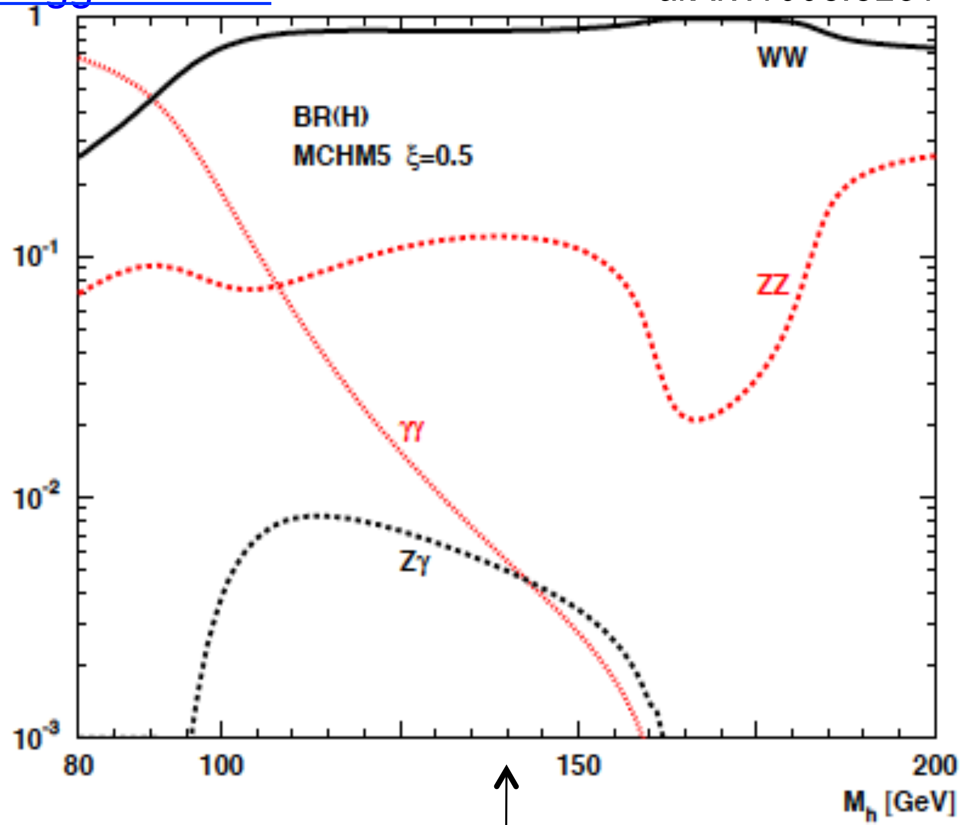
Nature May Just Be More Complicated…

➔ Probing multiple production and decay modes critical for model discrimination

Composite Higgs Models

arXiv:1003.3251





↑ m_H=135 GeV

↑ m_H=135 GeV

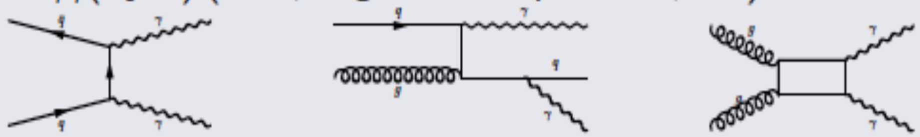
Enhanced B(H→bb)

Suppressed couplings to fermions
(also means no gg→H production!)

Searching for H→γγ

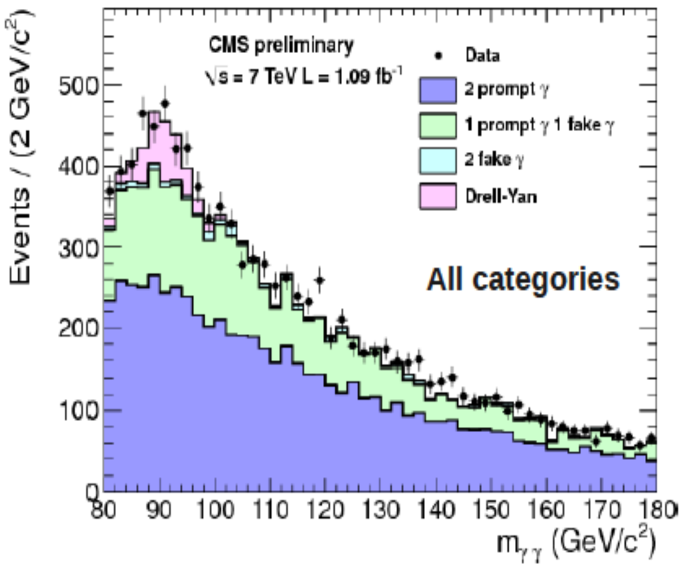
Background

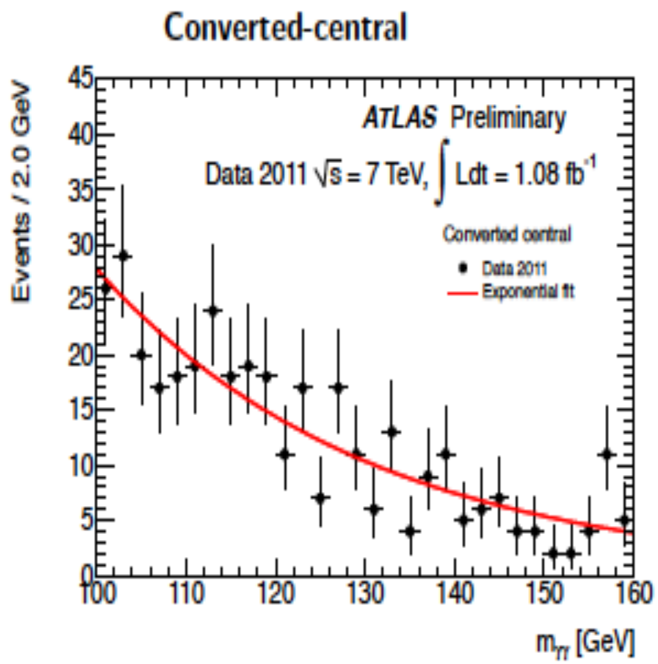
- Irreducible : $\gamma\gamma$(+jets) (Born, fragmentation processes, box)



- Reducible : γ/jet(s), jet(s)/jet(s)
- Drell-Yan events : both e misidentified as γ

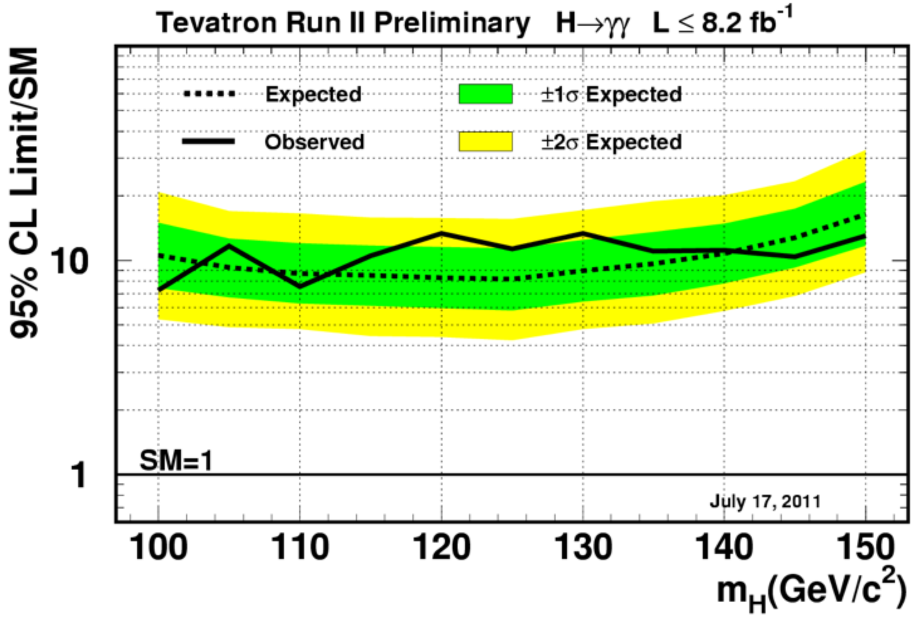
- Detailed understanding of background composition achieved via data-driven techniques.
- Background fitted to exponential model and side-band analysis performed in different categories



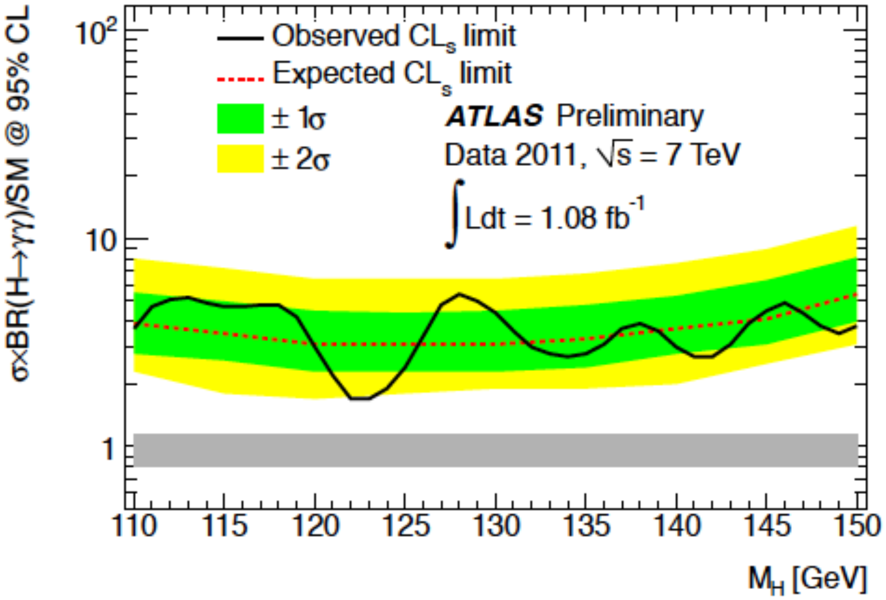


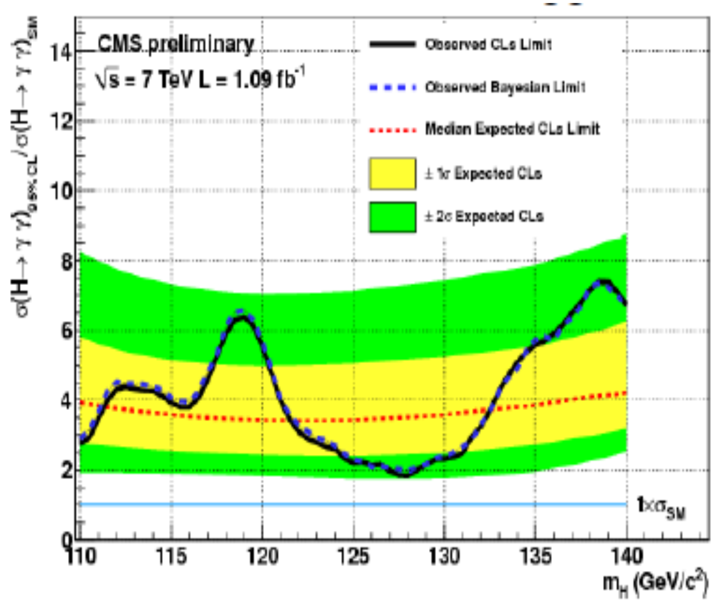
Searching for H→γγ

- Tevatron (7-8.2 fb^{-1}): expected limit ~8.5xSM



- LHC: Large dataset and refinements to analysis has lead to big jump in sensitivity:
  - Expected limits ~4xSM
  - No significant excess seen
  - Observed limit consistent with statistical fluctuations around the background-only hypothesis





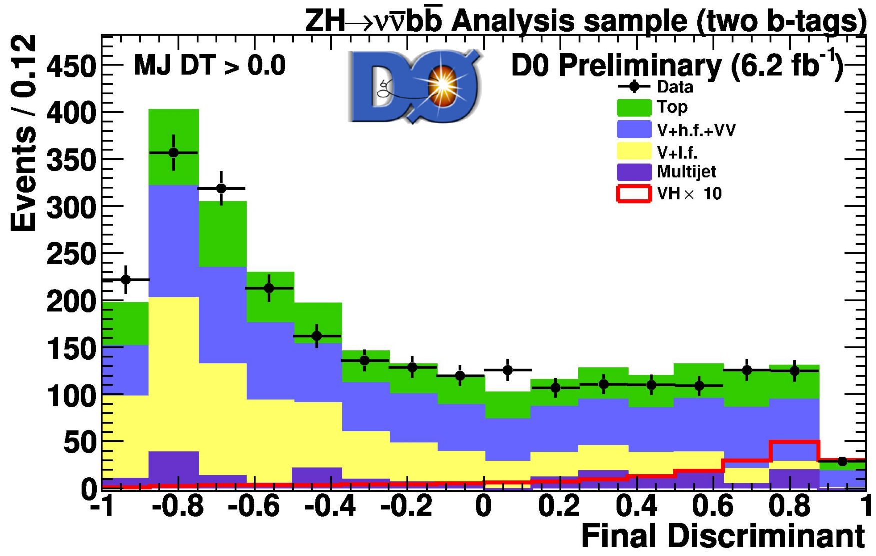
H→bb: Multivariate Techniques

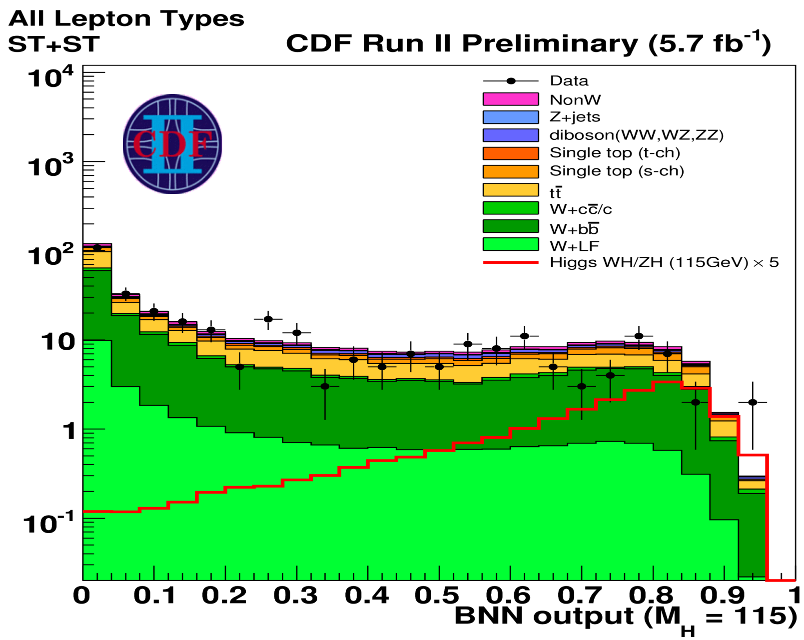
Multivariate techniques are used to improve signal-to-background ratios

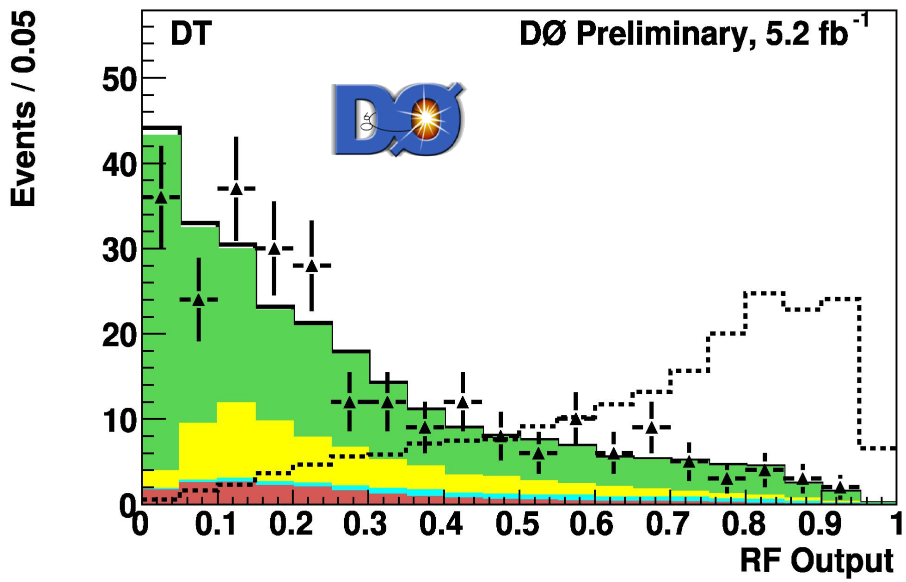
- Boosted Decision Trees
- Neural Networks
- Matrix Element Discriminants

➔ Typically achieve S/B of ~1/5-1/25

S/B ~1/100 for dijet mass alone



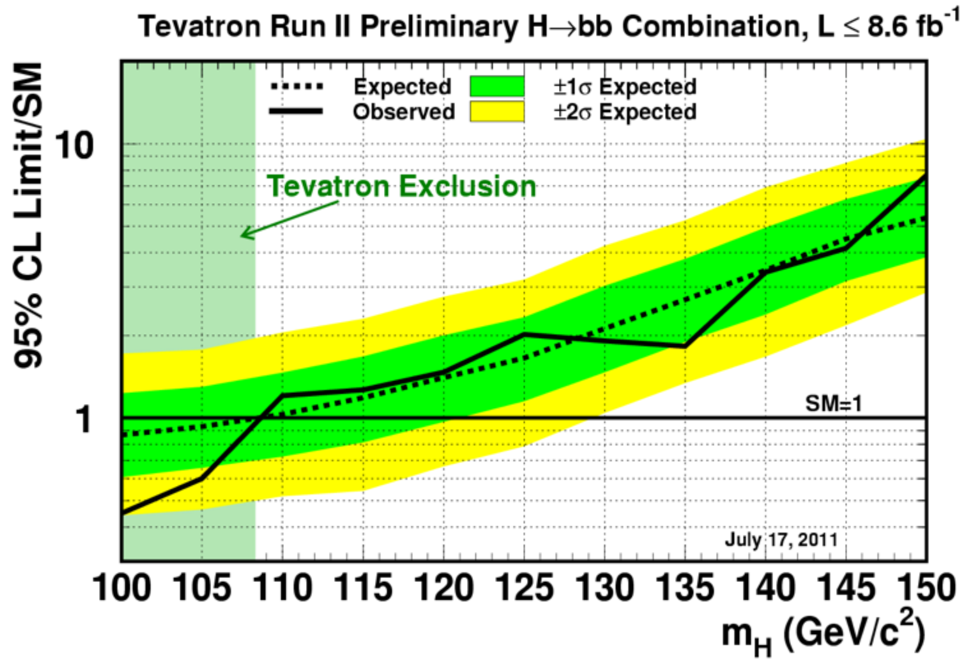




Searching for H→bb

95% CL Limits at m_H = 115 GeV

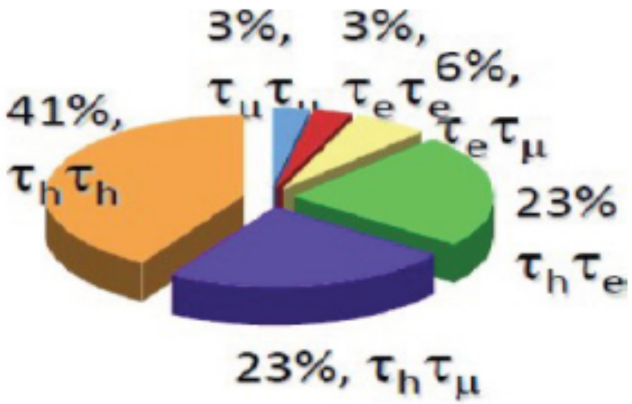
Channel	Exp/obs Limit (σ/SM)
WH→lνbb (7.5 fb^{-1})	2.7/2.6
ZH→ννbb (7.8 fb^{-1})	2.9/2.3
ZH→l^+l^-bb (7.9 fb^{-1})	3.9/4.8
WH→lνbb (8.5 fb^{-1})	3.5/4.6
ZH→ννbb (8.4 fb^{-1})	4.0/3.2
ZH→l^+l^-bb (8.6 fb^{-1})	4.8/4.9
WH→lνbb (1.0 fb^{-1})	~25/20
ZH→l^+l^-bb (1.0 fb^{-1})	~25/20
VH/VBF→jjbb (4.0 fb^{-1})	17.8/9.1
ttH→l+jets (7.5 fb^{-1})	11.722.9
ttH→jets (5.7 fb^{-1})	20.2/28.1

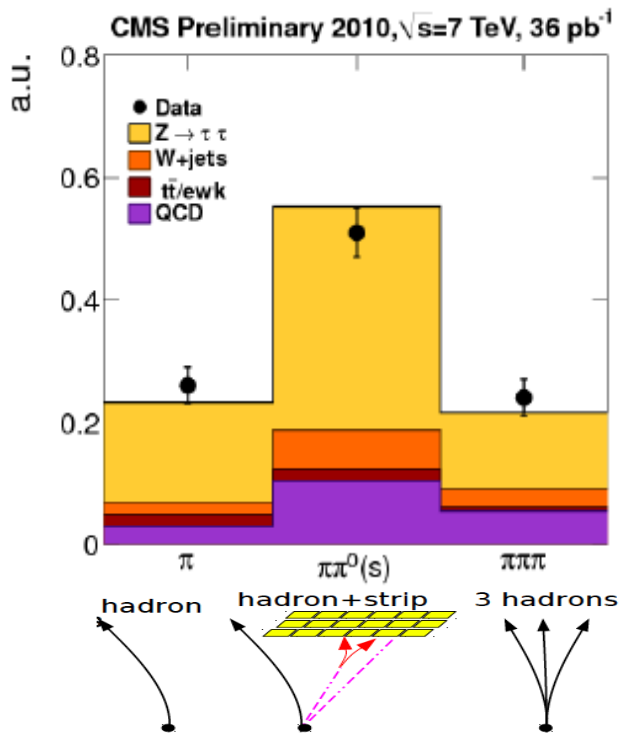


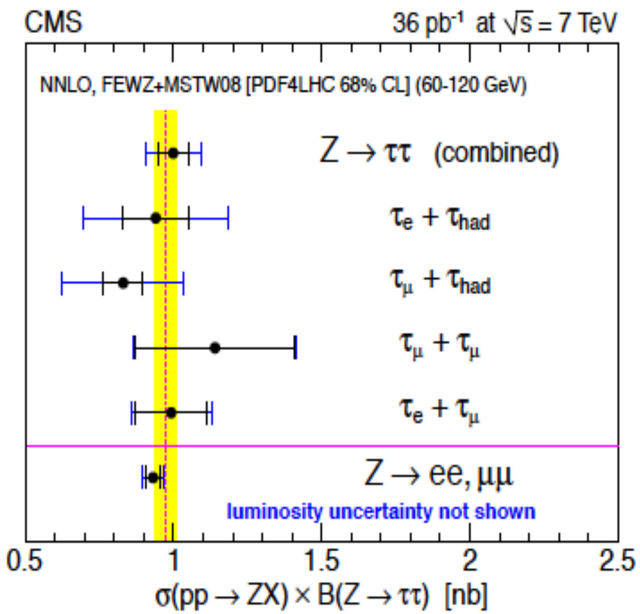
- At 115-120 GeV
  - Almost at 1*SM sensitivity
  - No excess seen
  - Inconsistent with CMS & ATLAS
- At 130-140 GeV
  - 2*SM – 3*SM sensitivity
  - No excess seen – would expect observed limit to be 1*SM high

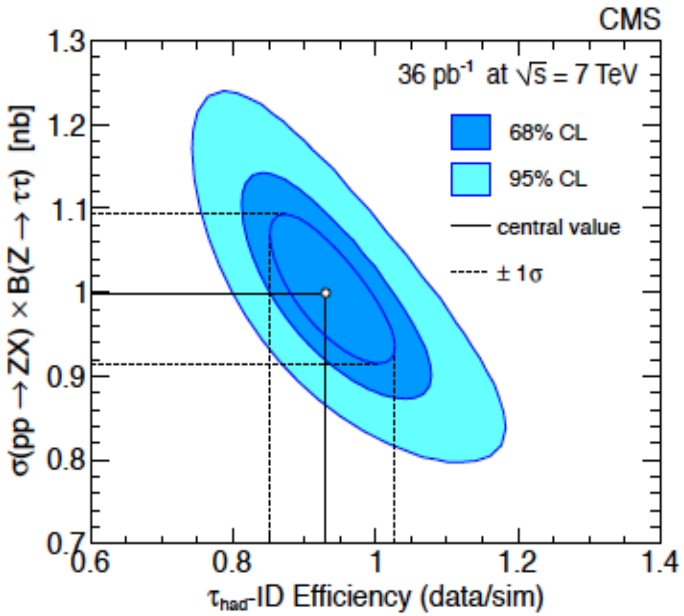
Searching for H→ττ

- $H \rightarrow \tau\tau$: second largest BR(~8%) at low mass!
- Large hadronic tau branching ratio requires to achieve excellent tau identification performance: efficiency: ~50-65%, jet fake rate: ~1-2%
- $Z \rightarrow \tau\tau$ standard candle useful for calibration purposes.



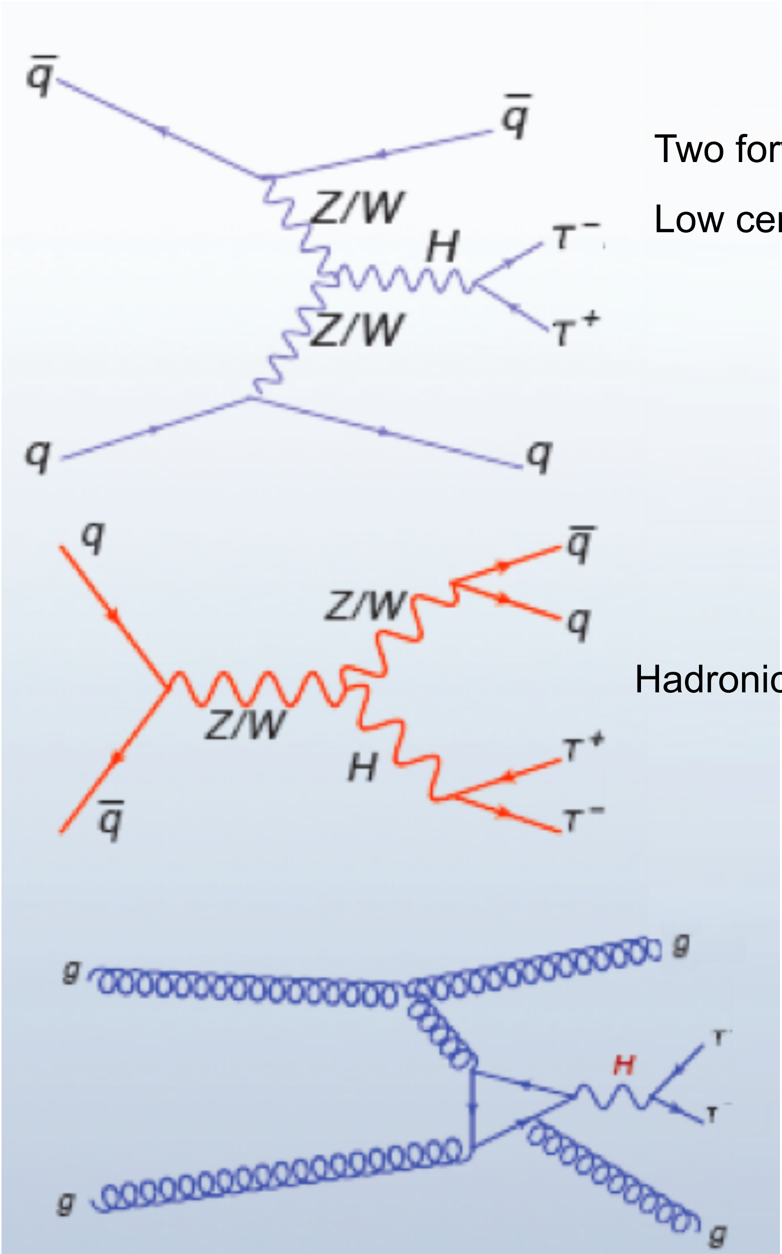






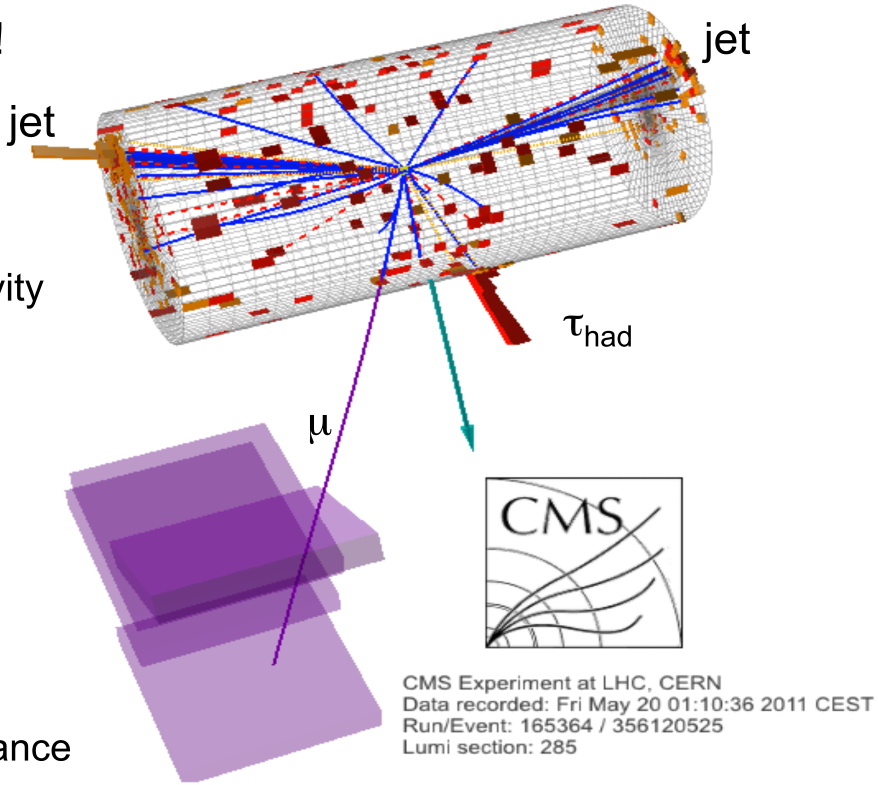
Searching for H→ττ

- Many possible signal topologies to be explored!

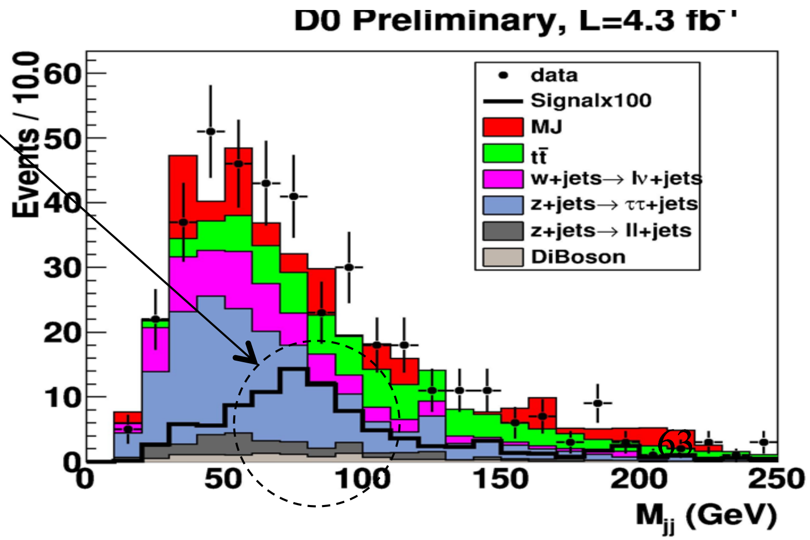


Two forward jets

Low central-jet activity

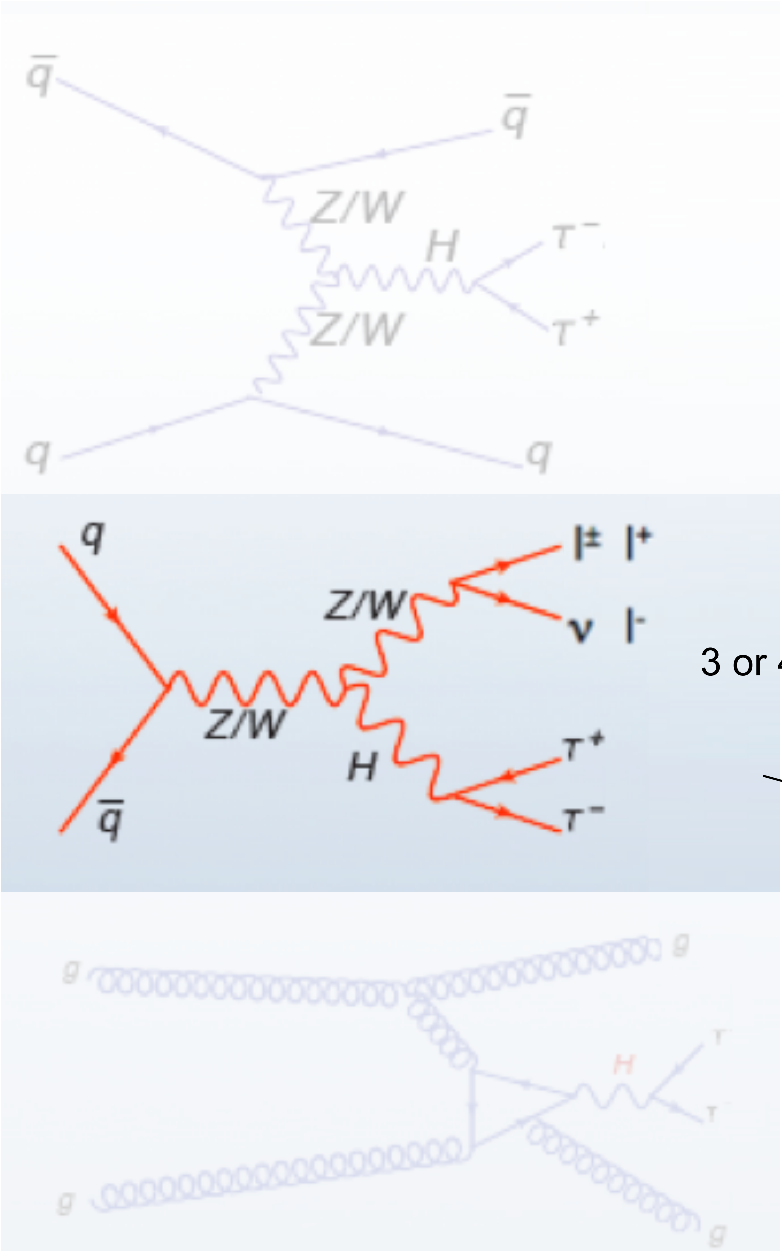


Hadronic W/Z resonance

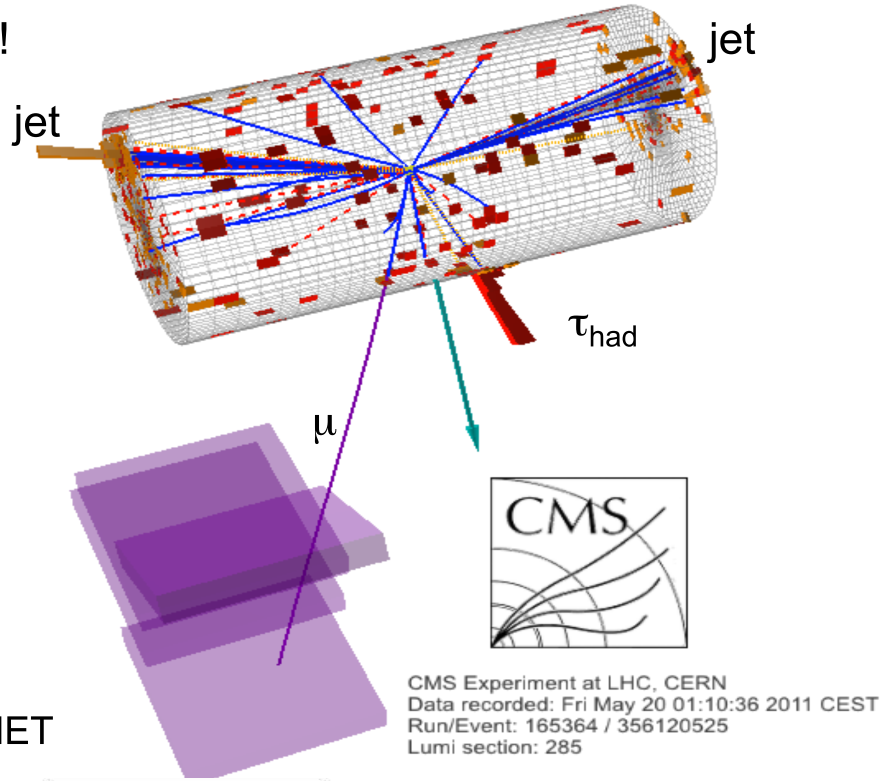


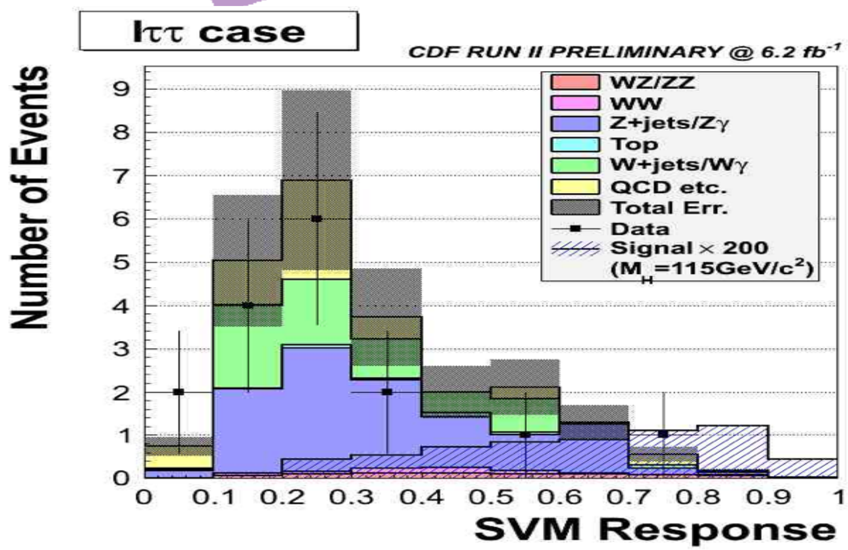
Searching for H→ττ

- Many possible signal topologies to be explored!



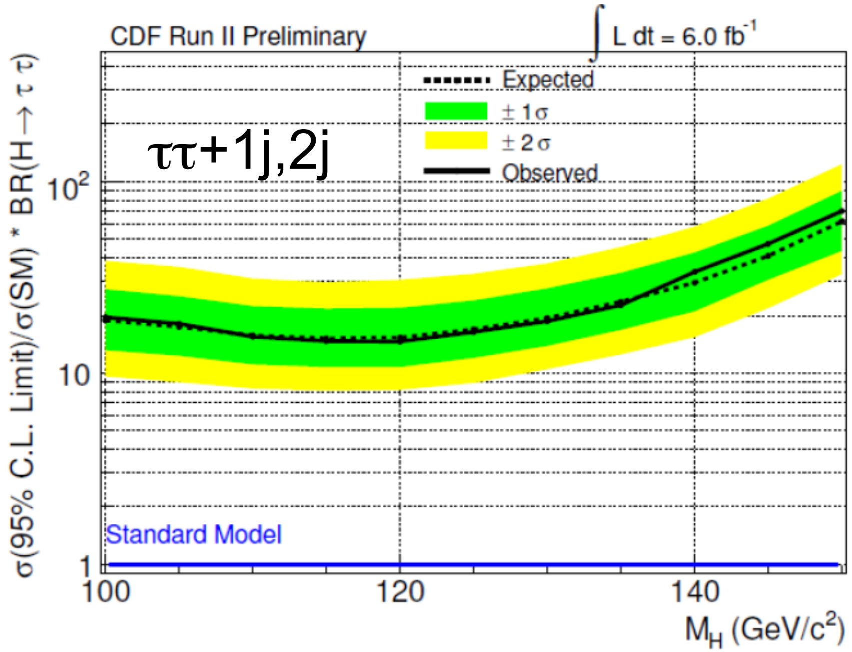
3 or 4 leptons+MET





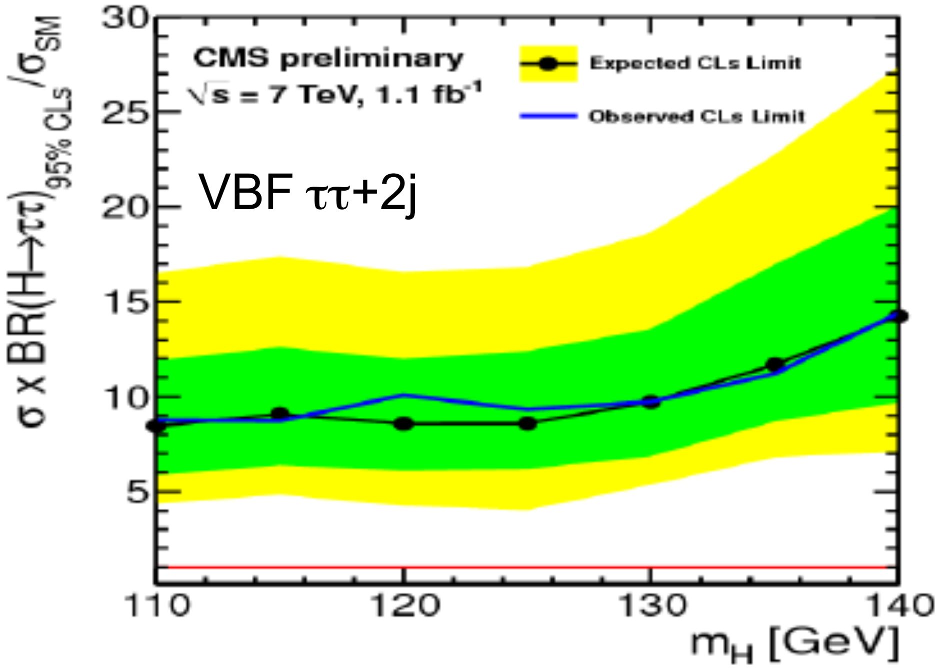
Searching for H→ττ

- Comparable sensitivity for different searches.
- Large potential for improvement in the near future:
  - More data to analyze.
  - Further refinements to analysis possible.



95% CL Limits at m_H = 115 GeV

Channel	Exp/obs Limit (σ/SM)
ττ+1j,2j (6.0 fb^{-1})	15.2/14.7
llττ/lνττ (6.2 fb^{-1})	17.3/18.5
ττ+2j (5.4 fb^{-1})	12.8/32.8
VBF ττ+2j (1.1 fb^{-1})	9.0/9.0

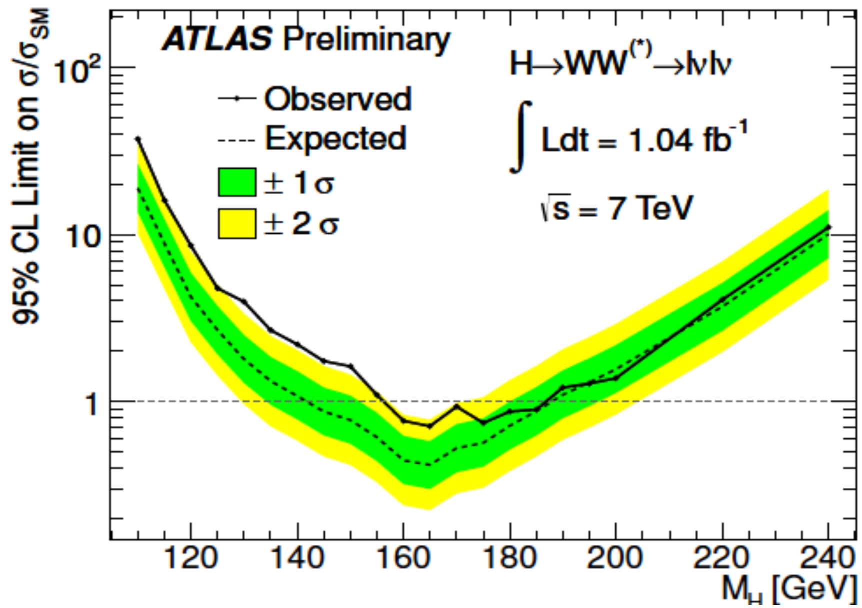


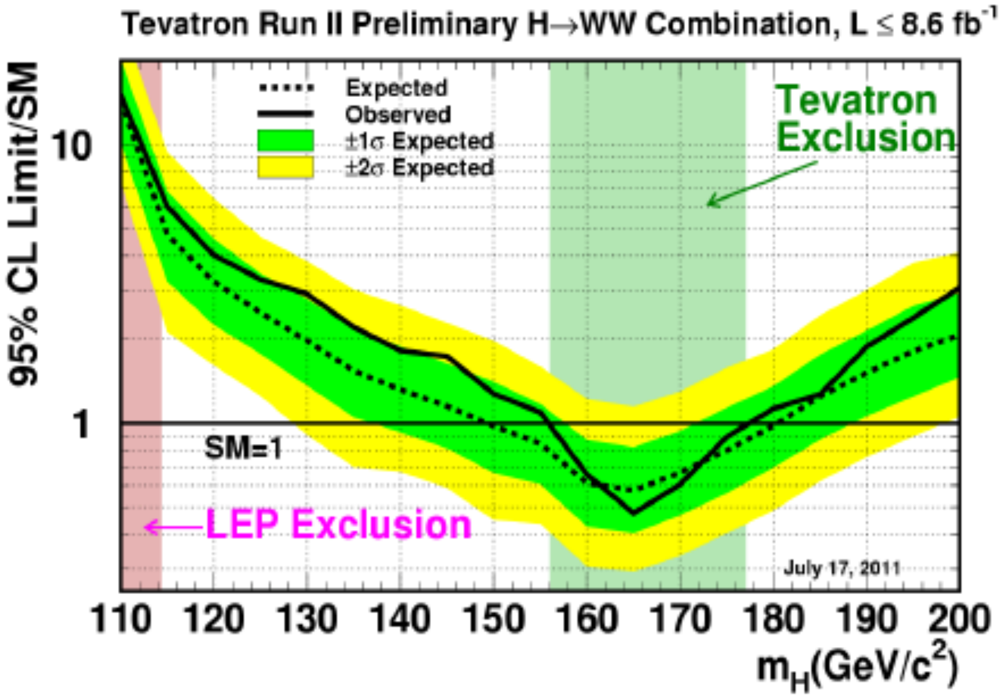
H→WW→lνlν

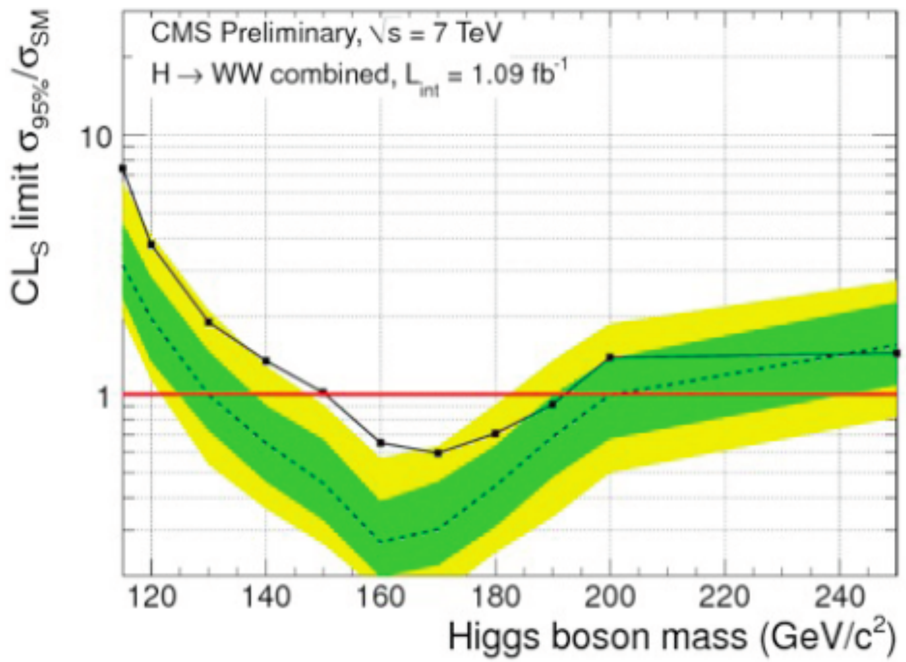
- Consistent exclusions by four experiments:
  - Tevatron: 156-177 GeV (obs)
  - ATLAS: 158-186 GeV (obs)
  - CMS: 150-193 GeV (obs)

but also tantalizing broad excesses in ~120-160 GeV mass region….

(Mass resolution ~20%).

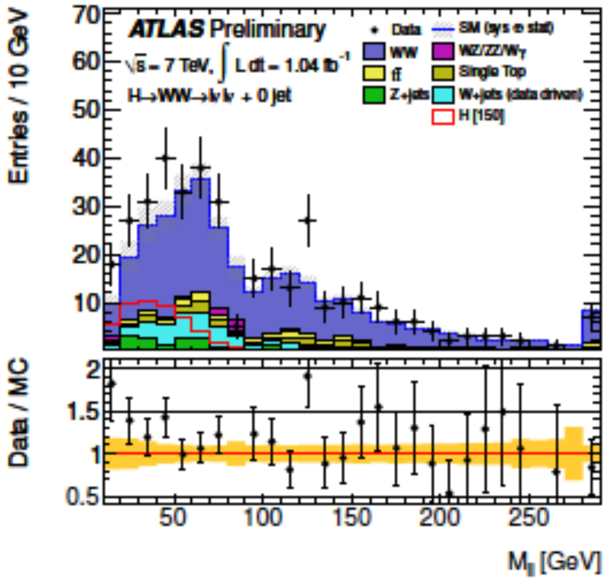




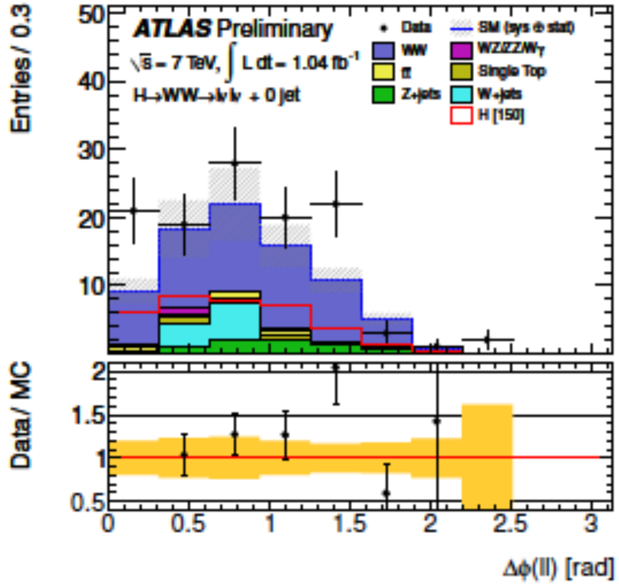


H→WW→lνlν/0-jet @ ATLAS

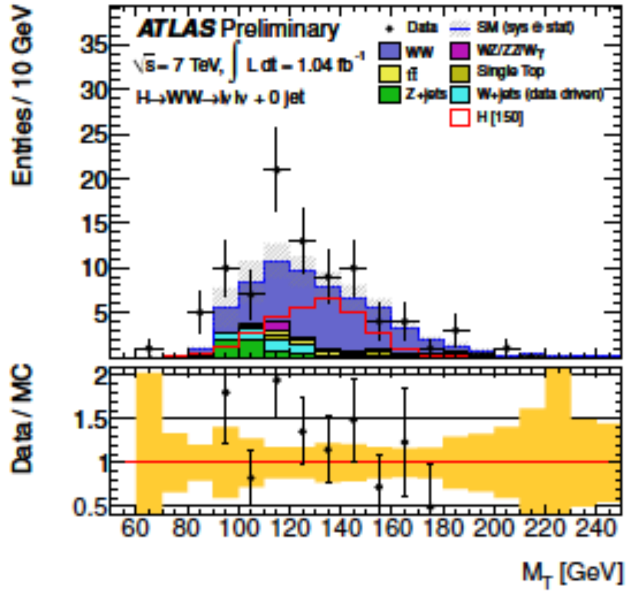
M_{ll} after p_T^{ll} cut:



$\Delta\phi_{ll}$ after m_{ll} cut:



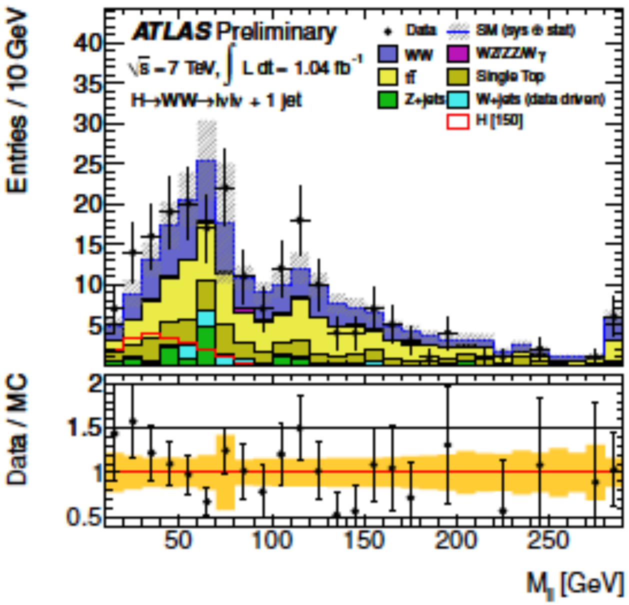
M_T after all cuts:



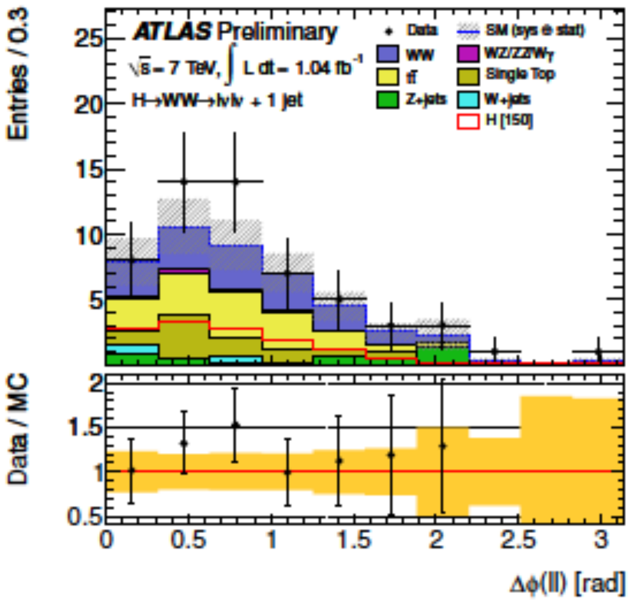
Selection	Signal	WW	W+jets	Z/γ^*+jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
Jet Veto	50 ± 11	260 ± 30	46 ± 17	80 ± 70	22 ± 8	17 ± 4	7.8 ± 1.5	430 ± 100	453
$\lvert\mathbf{P}_T^{\ell\ell}\rvert > 30$ GeV	48 ± 10	230 ± 20	38 ± 14	15 ± 6	19 ± 7	16 ± 4	7.3 ± 1.4	330 ± 50	371
$m_{\ell\ell} < 50$ GeV	34 ± 7	59 ± 8	11 ± 3	7 ± 4	2.7 ± 1.8	2.8 ± 0.8	0.9 ± 0.3	83 ± 11	116
$\Delta\phi_{\ell\ell} < 1.3$	30 ± 7	46 ± 6	5.8 ± 1.8	5 ± 3	2.8 ± 1.7	2.8 ± 0.8	0.8 ± 0.2	63 ± 9	89
$0.75 \times m_H < m_T < m_H$	21 ± 4	26 ± 3	2.9 ± 0.9	1 ± 2	1.6 ± 1.2	0.7 ± 0.4	0.6 ± 0.2	33 ± 5	49
ee	3.1 ± 0.7	3.7 ± 0.7	0.5 ± 0.2	0.4 ± 0.6	0.0 ± 0.6	0.0 ± 0.2	0.05 ± 0.19	4.7 ± 1.2	7
$e\mu$	11 ± 2	13.4 ± 1.9	1.7 ± 0.7	0 ± 0	1.1 ± 0.8	0.4 ± 0.3	0.4 ± 0.3	17 ± 2	21
$\mu\mu$	6.9 ± 1.5	8.8 ± 1.3	0.7 ± 0.5	0.5 ± 2.0	0.4 ± 0.8	0.3 ± 0.3	0.18 ± 0.19	11 ± 3	21

H→WW→lνlν/1-jet @ ATLAS

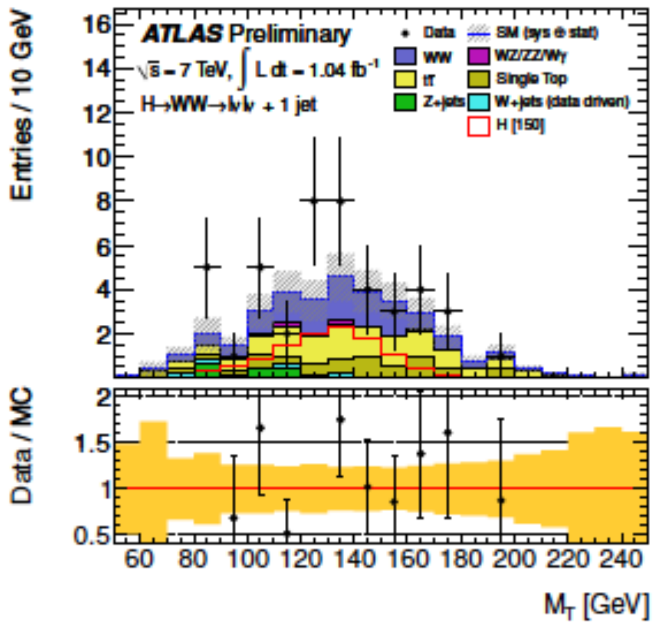
M_{ll} after Z->ττ veto:



$\Delta\phi_{ll}$ after m_{ll} cut:

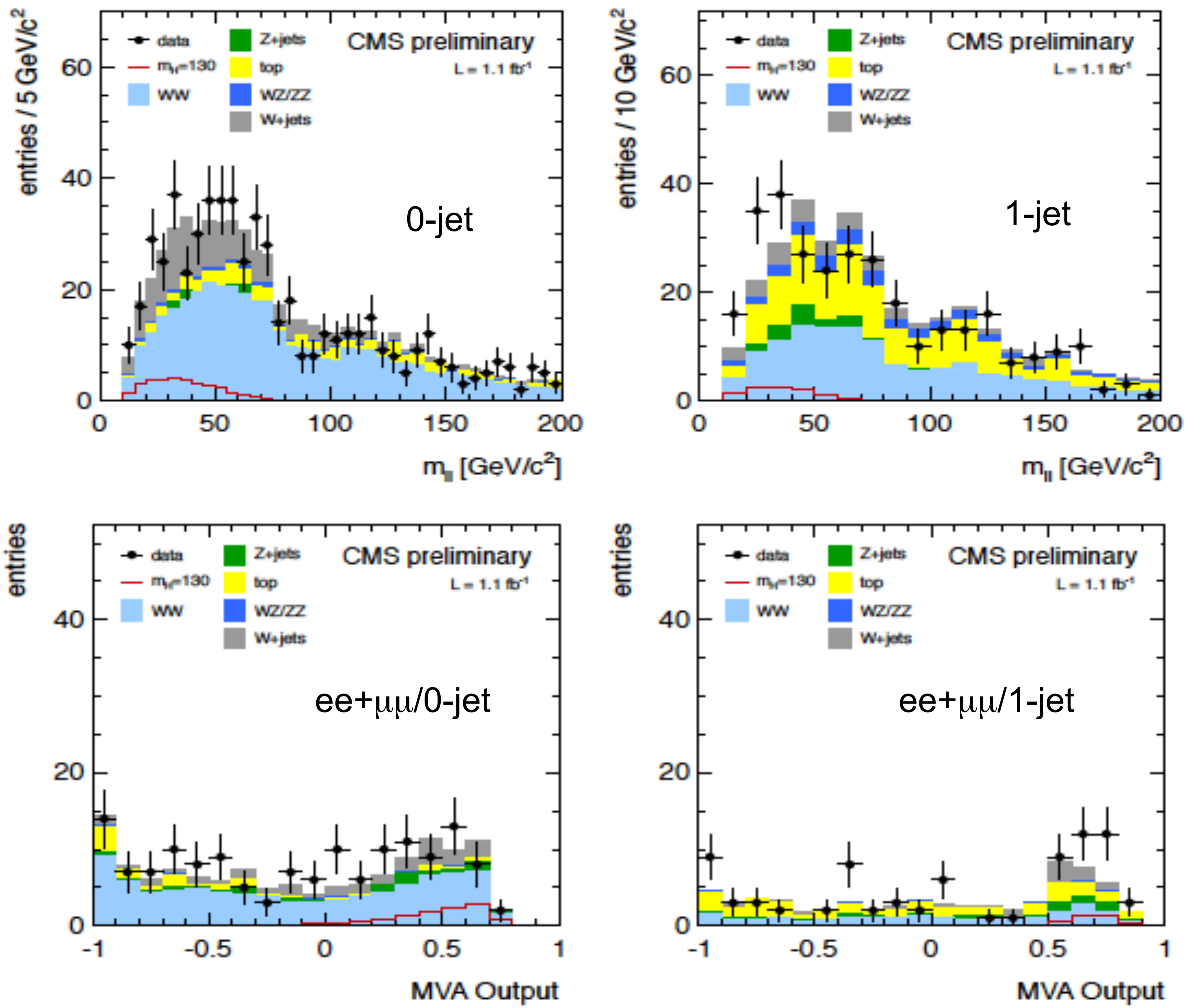


M_T after all cuts:



Selection	Signal	WW	W+jets	Z/γ^*+jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
1 jet	23 ± 4	92 ± 9	20 ± 10	40 ± 30	240 ± 60	88 ± 13	6.2 ± 0.8	490 ± 70	465
b-jet veto	23 ± 4	91 ± 9	19 ± 10	40 ± 30	140 ± 40	45 ± 7	6.1 ± 0.8	340 ± 50	333
$\lvert \mathbf{P}_T^{\text{tot}} \rvert < 30$ GeV	19 ± 3	76 ± 8	9 ± 5	25 ± 19	80 ± 20	35 ± 6	4.1 ± 0.5	230 ± 40	221
$Z \to \tau\tau$ veto	19 ± 4	74 ± 8	10 ± 5	20 ± 10	80 ± 19	33 ± 5	4.0 ± 0.7	220 ± 17	212
$m_{\ell\ell} < 50$ GeV	13 ± 3	16 ± 3	1.2 ± 0.5	3.4 ± 1.6	12 ± 4	7.2 ± 1.7	0.9 ± 0.2	41 ± 5	56
$\Delta\phi_{\ell\ell} < 1.3$	11 ± 2	13 ± 2	1.0 ± 0.5	1.5 ± 1.2	11 ± 4	6.3 ± 1.5	0.74 ± 0.20	33 ± 5	44
$0.75 \times m_H < m_T < m_H$	7.2 ± 1.6	6.2 ± 1.3	0.5 ± 0.9	0.4 ± 0.6	4.9 ± 1.7	2.3 ± 0.7	0.34 ± 0.16	15 ± 3	21
ee	0.9 ± 0.3	0.8 ± 0.3	0.08 ± 0.04	0.0 ± 0.4	0.8 ± 1.0	0.2 ± 0.4	0.06 ± 0.08	2.0 ± 1.2	4
$e\mu$	4.0 ± 0.9	3.5 ± 0.8	0.4 ± 0.2	0.4 ± 0.7	3.1 ± 1.3	1.2 ± 0.6	0.24 ± 0.13	8.8 ± 1.9	8
$\mu\mu$	2.3 ± 0.5	1.9 ± 0.4	0.0 ± 0.8	0.0 ± 0.4	1.1 ± 1.1	0.8 ± 0.7	0.04 ± 0.07	3.9 ± 1.7	9

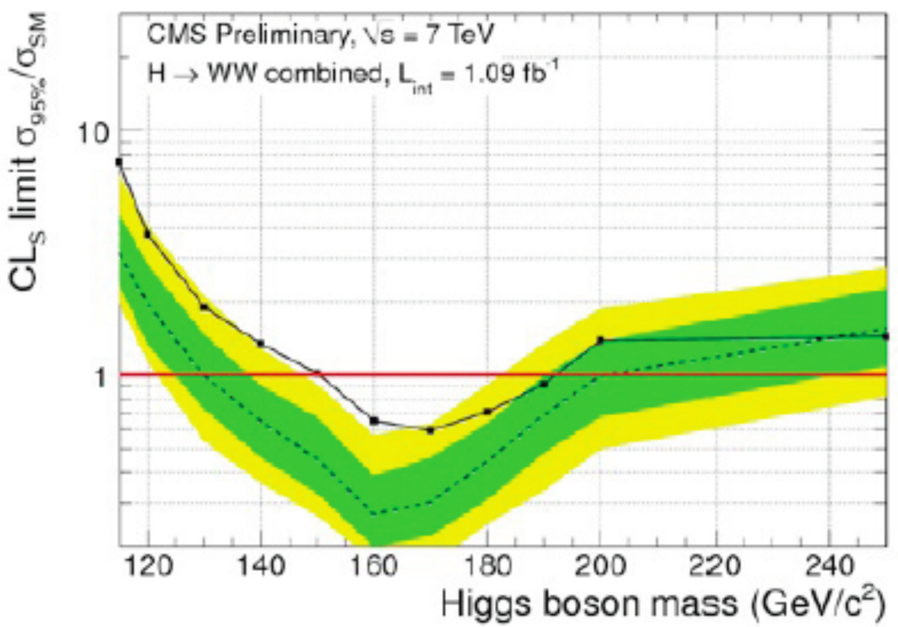
H→WW→lνlν @ CMS



CMS preliminary
L = 1.1 fb⁻¹
data
m_H=130
WW
Z+jets
top
WZ/ZZ
W+jets
0-jet
1-jet
ee+μμ/0-jet
ee+μμ/1-jet
entries / 5 GeV/c²
entries / 10 GeV/c²
entries
m_{ll} [GeV/c²]
MVA Output

H→WW→lνlν @ CMS

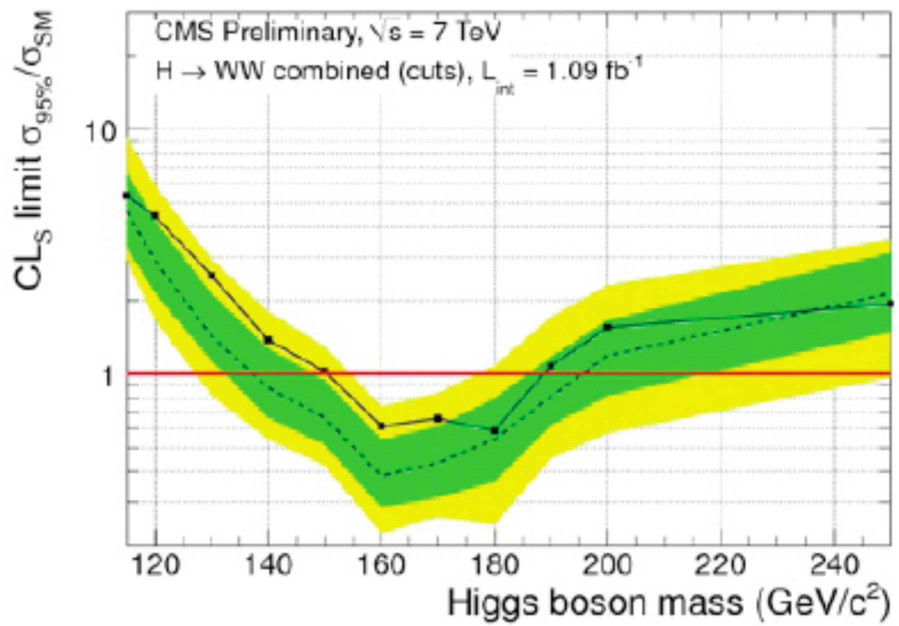
MVA analysis



Exp.: [130 - 200] GeV

Obs.: [150 - 193] GeV

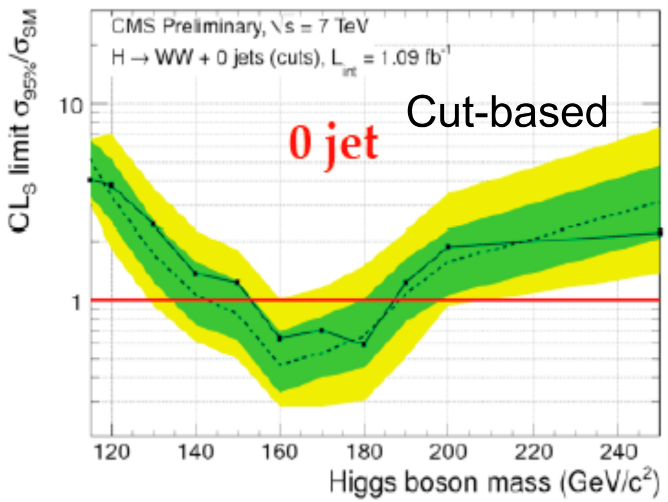
cut-based analysis



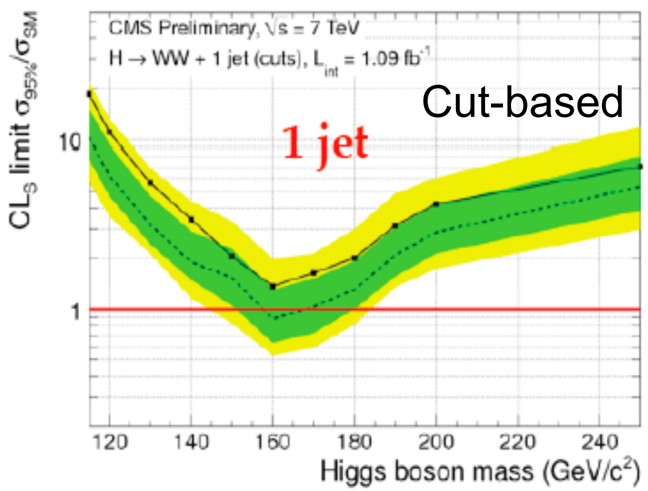
Exp.: [135 - 190] GeV

Obs.: [150 - 190] GeV

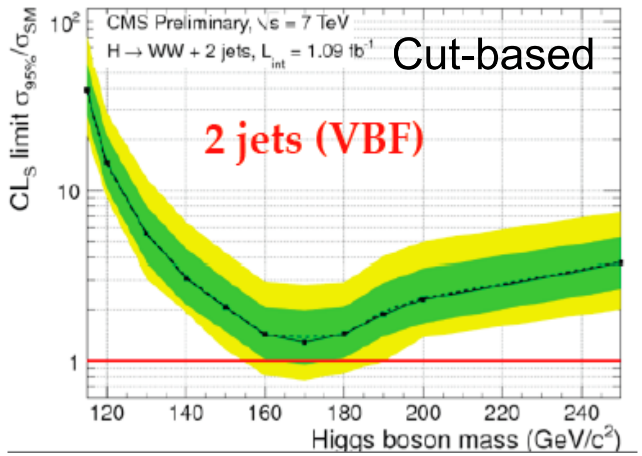
H→WW→lνlν @ CMS



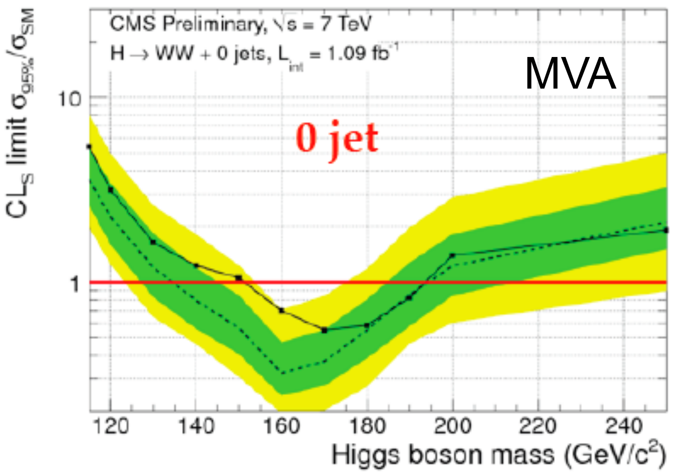
CMS Preliminary, √s = 7 TeV
H → WW + 0 jets (cuts), L_int = 1.09 fb⁻¹
Cut-based
0 jet
CL_S limit σ_95%/σ_SM
Higgs boson mass (GeV/c²)



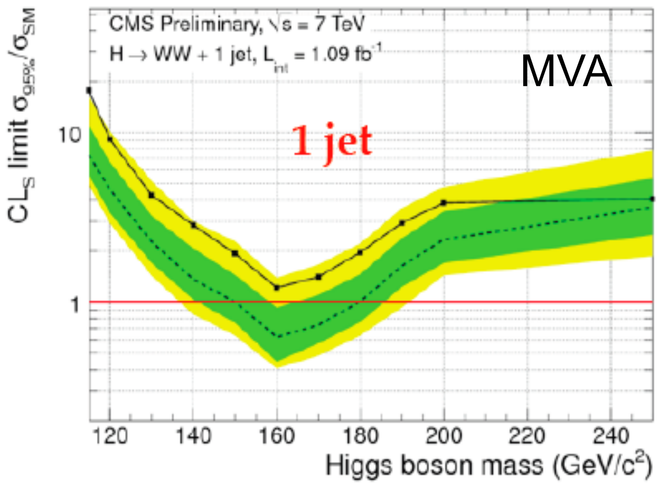
CMS Preliminary, √s = 7 TeV
H → WW + 1 jet (cuts), L_int = 1.09 fb⁻¹
Cut-based
1 jet
CL_S limit σ_95%/σ_SM
Higgs boson mass (GeV/c²)



CMS Preliminary, √s = 7 TeV
H → WW + 2 jets, L_int = 1.09 fb⁻¹
Cut-based
2 jets (VBF)
CL_S limit σ_95%/σ_SM
Higgs boson mass (GeV/c²)



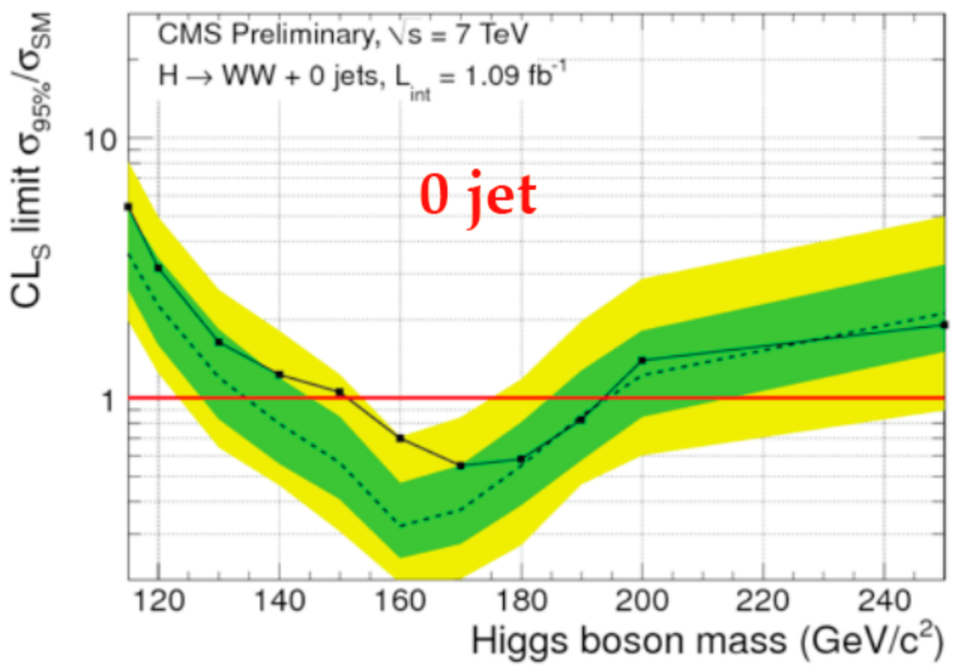
CMS Preliminary, √s = 7 TeV
H → WW + 0 jets, L_int = 1.09 fb⁻¹
MVA
0 jet
CL_S limit σ_95%/σ_SM
Higgs boson mass (GeV/c²)



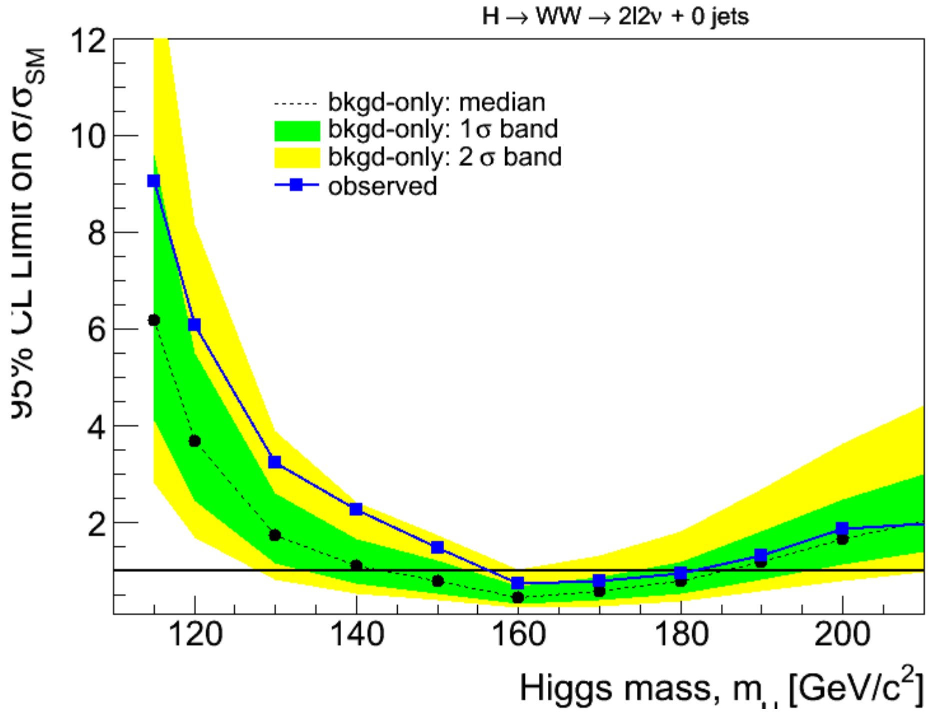
CMS Preliminary, √s = 7 TeV
H → WW + 1 jet, L_int = 1.09 fb⁻¹
MVA
1 jet
CL_S limit σ_95%/σ_SM
Higgs boson mass (GeV/c²)

H→WW→lνlν Signal Injection Test @ CMS

Data

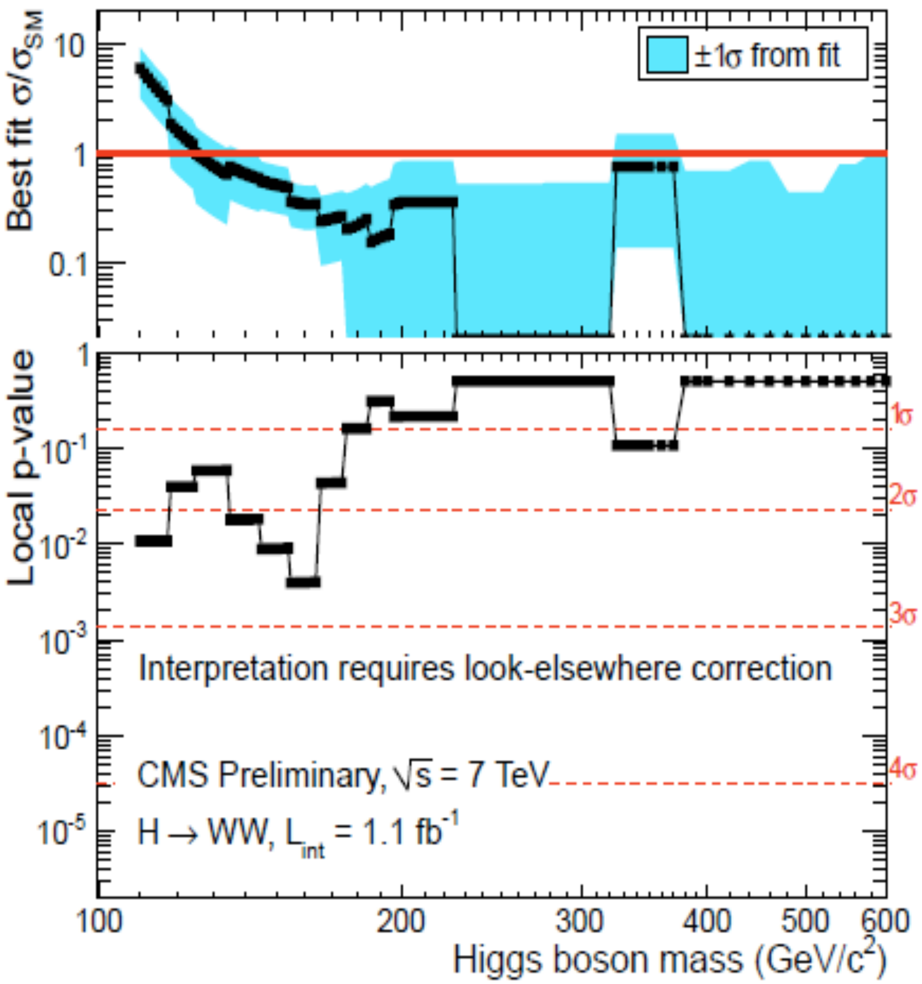


Signal (m_H=140 GeV) injected into background MC



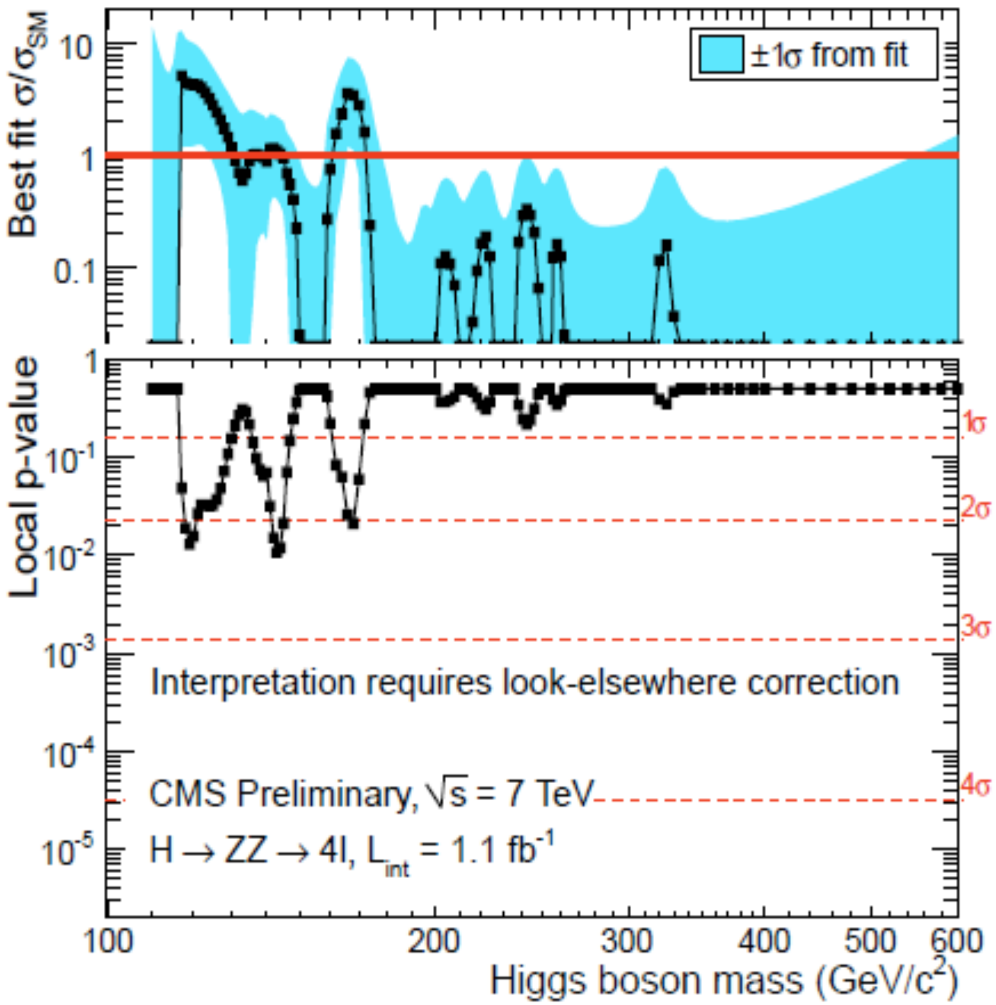
Local p-values @ CMS

H→WW→lνlν



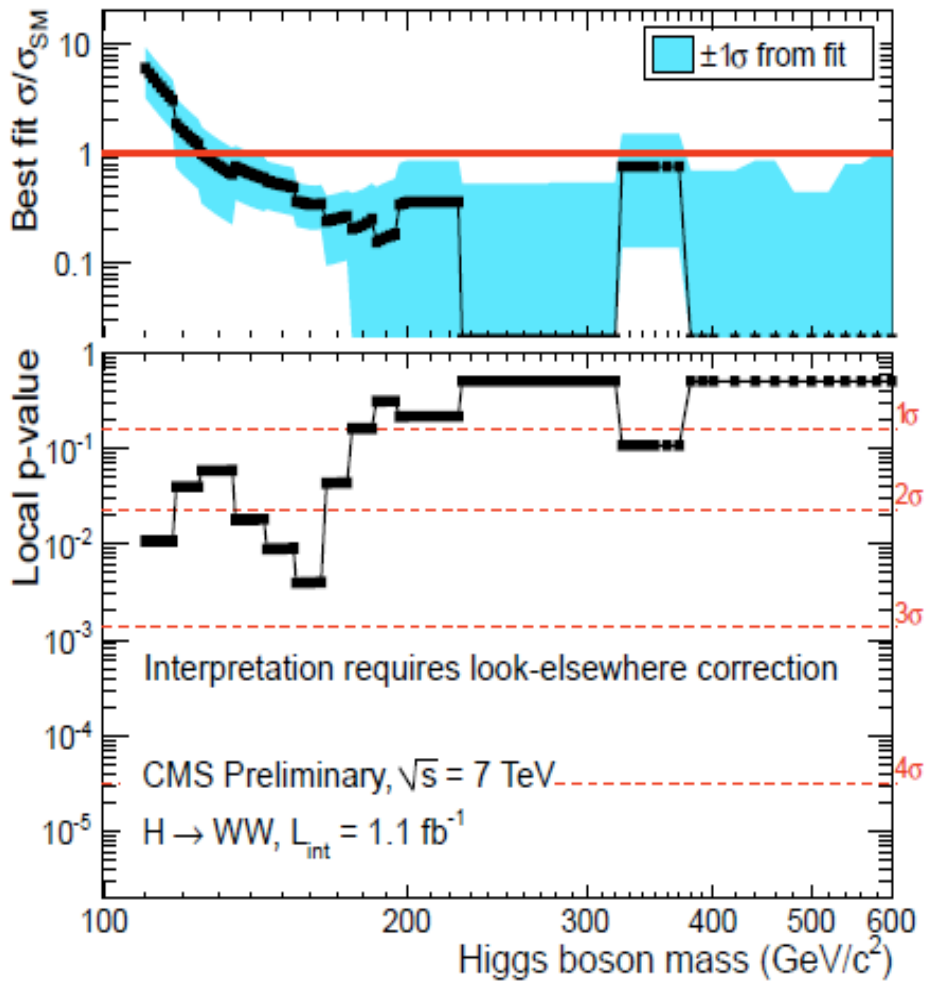
Low resolution (~20%) ➔ trial factor ~3

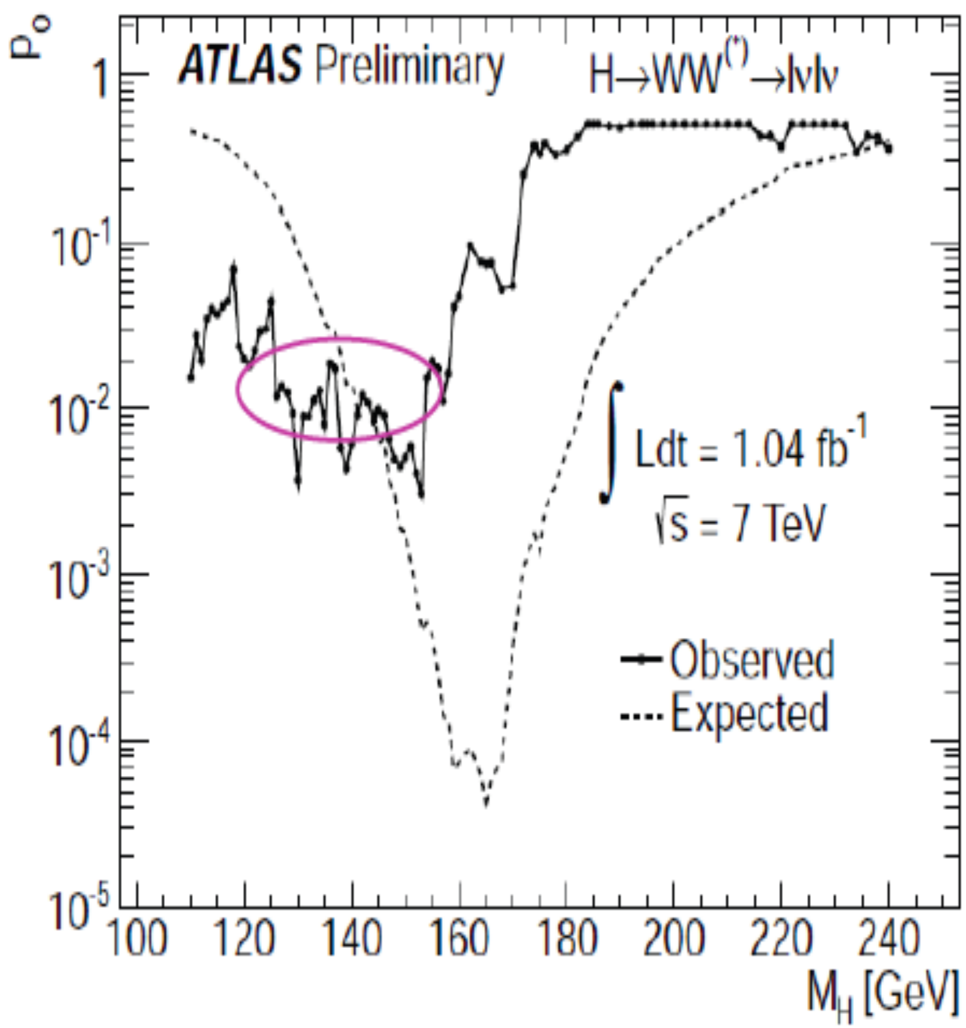
H→ZZ→4l



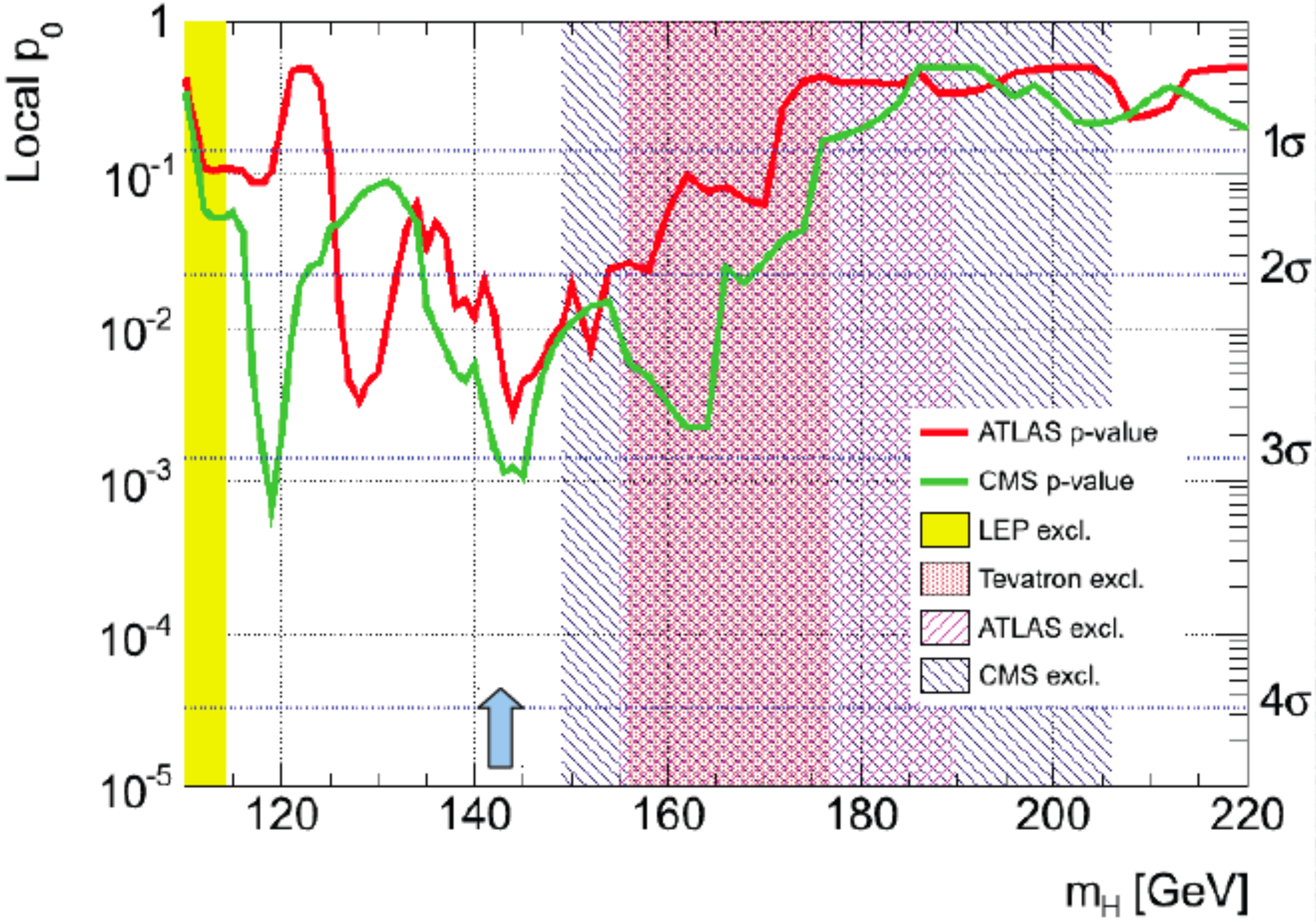
Low resolution (~1-2%) ➔ trial factor ~O(100)

$H \to WW \to \to l\nu l\nu$ Local p-values @ ATLAS and CMS



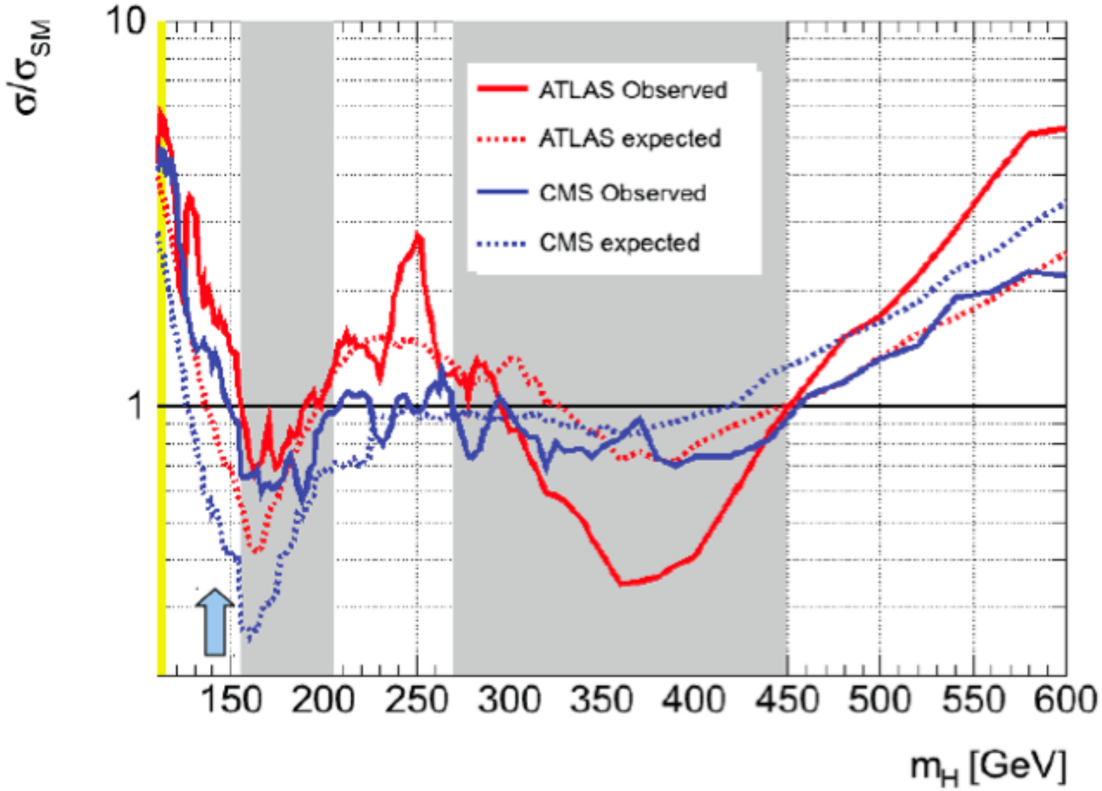


Combined Local p-values @ ATLAS and CMS

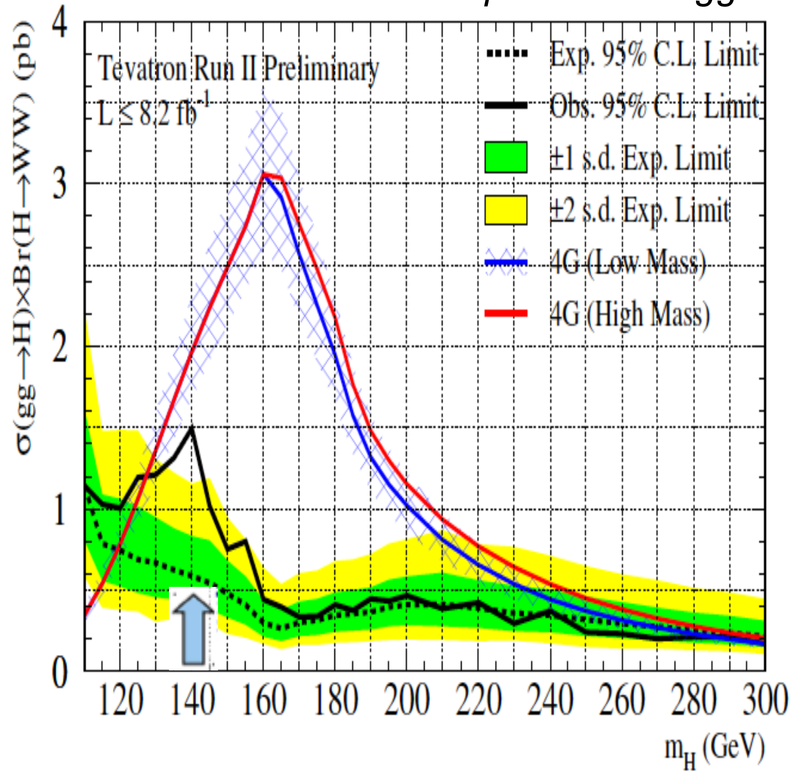


Any Hints of an Excess?

- Searches dominated by gg→H production show tantalizing common features near m_H~140 GeV (inside region preferred by EW precision data):



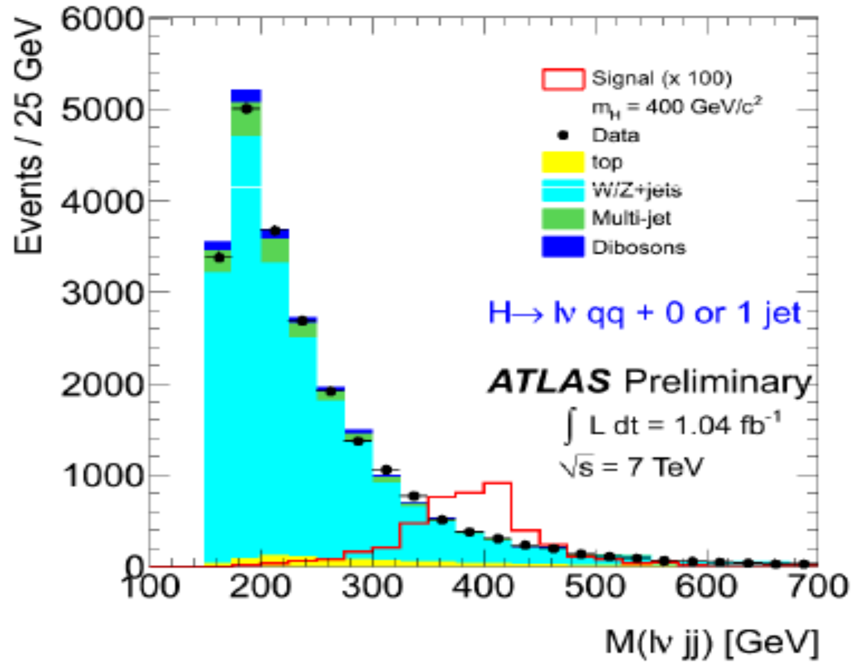
Combination of searches optimized for gg→H

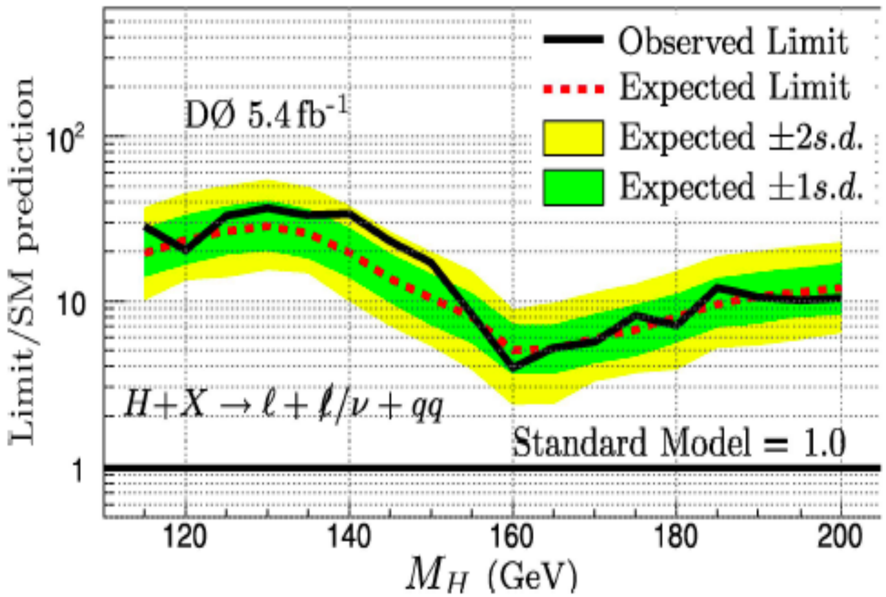


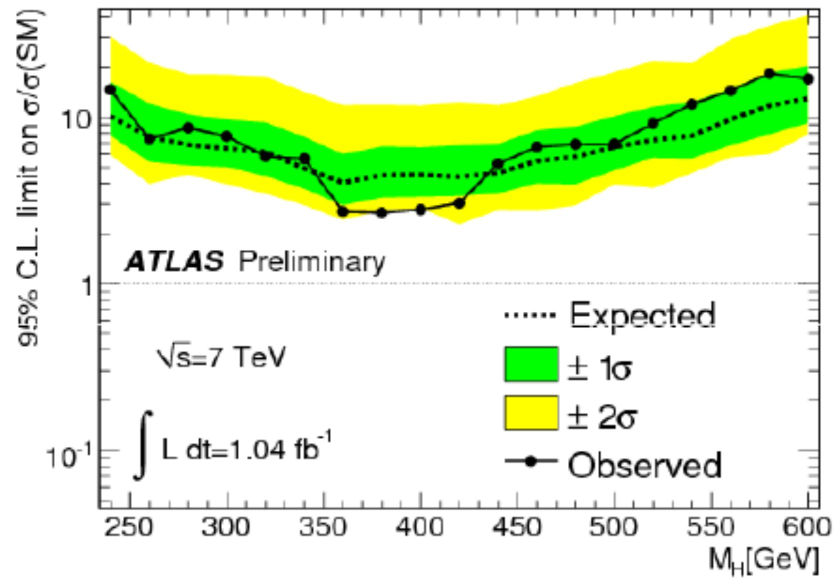
- Local p-values near m_H~140 GeV: ~2.5-3σ for individual results (ATLAS, CMS and Tevatron combinations).
- Individual excesses not significant after taking into account look-elsewhere effect but…

H→WW→lνjj

- Largest σxB at high mass.
- Possibility to reconstruct Higgs mass imposing W mass constraint but worse resolution than for H→ZZ→lljj.
- Worse S:B from large W+jets background.
- Tevatron and LHC searches have comparable sensitivity in different mass regions.

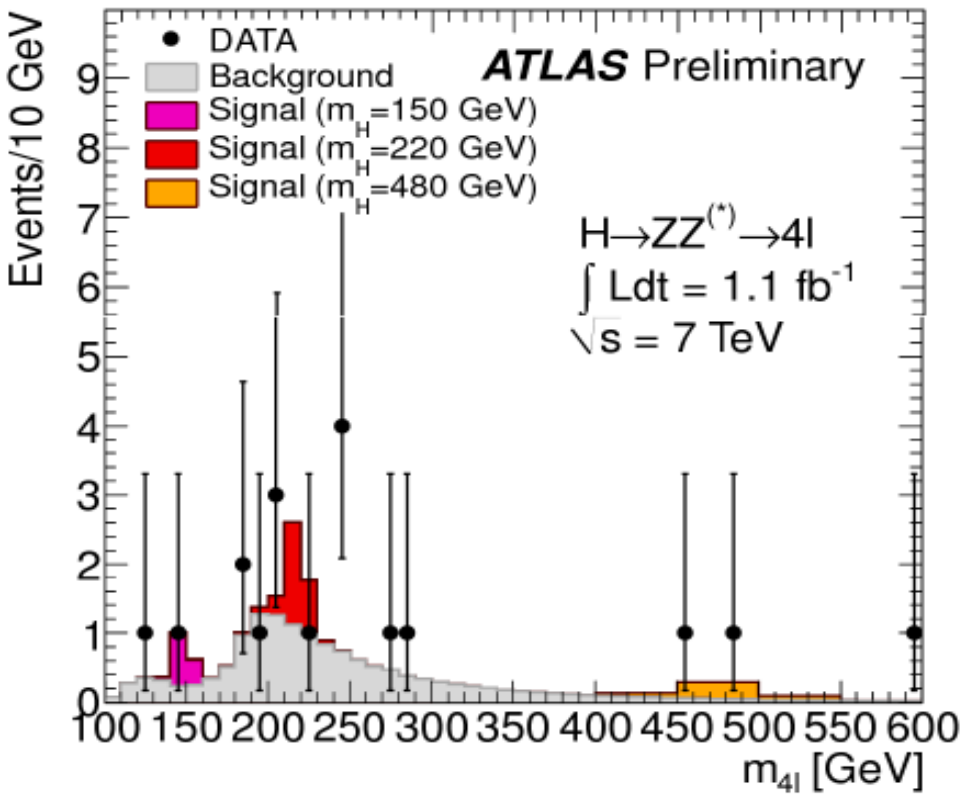


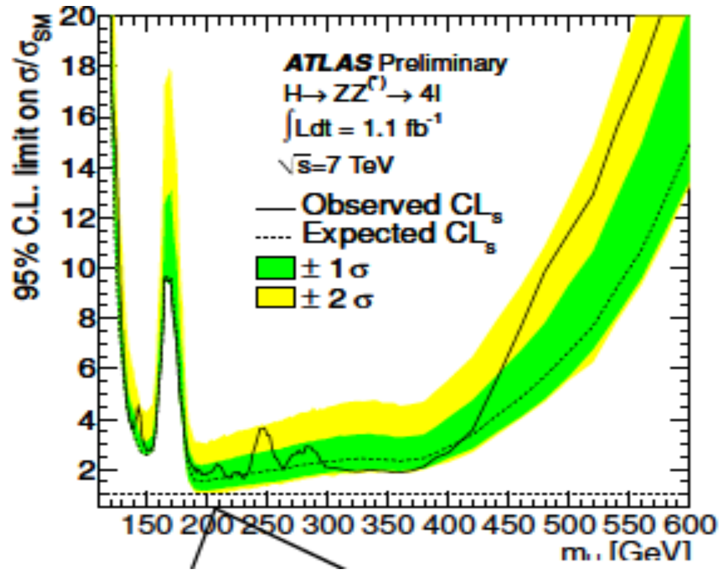


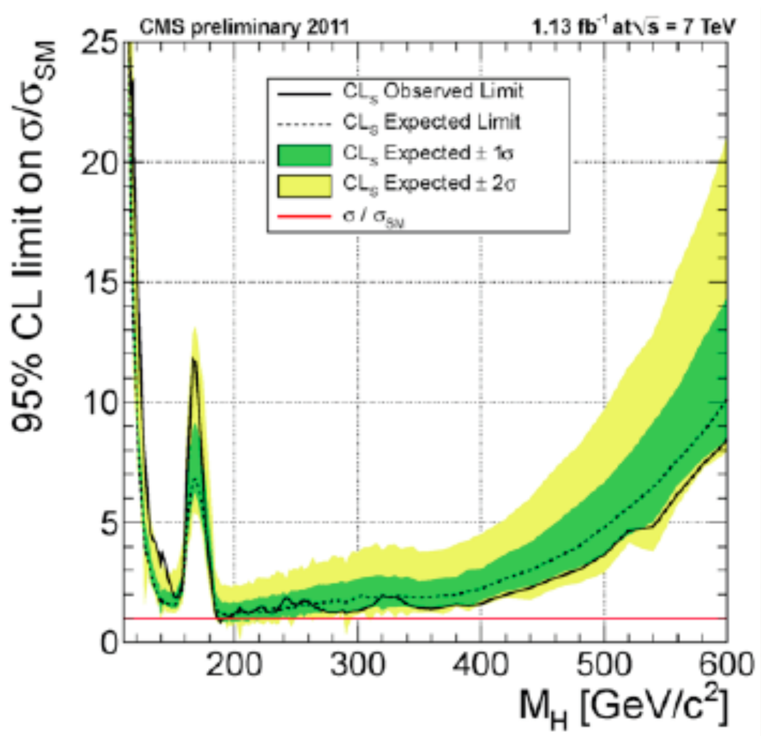


H→ZZ→4l

- Cleanest channel at high mass but small statistics.
- Main background ZZ production.
- Higgs mass reconstruction with good resolution!

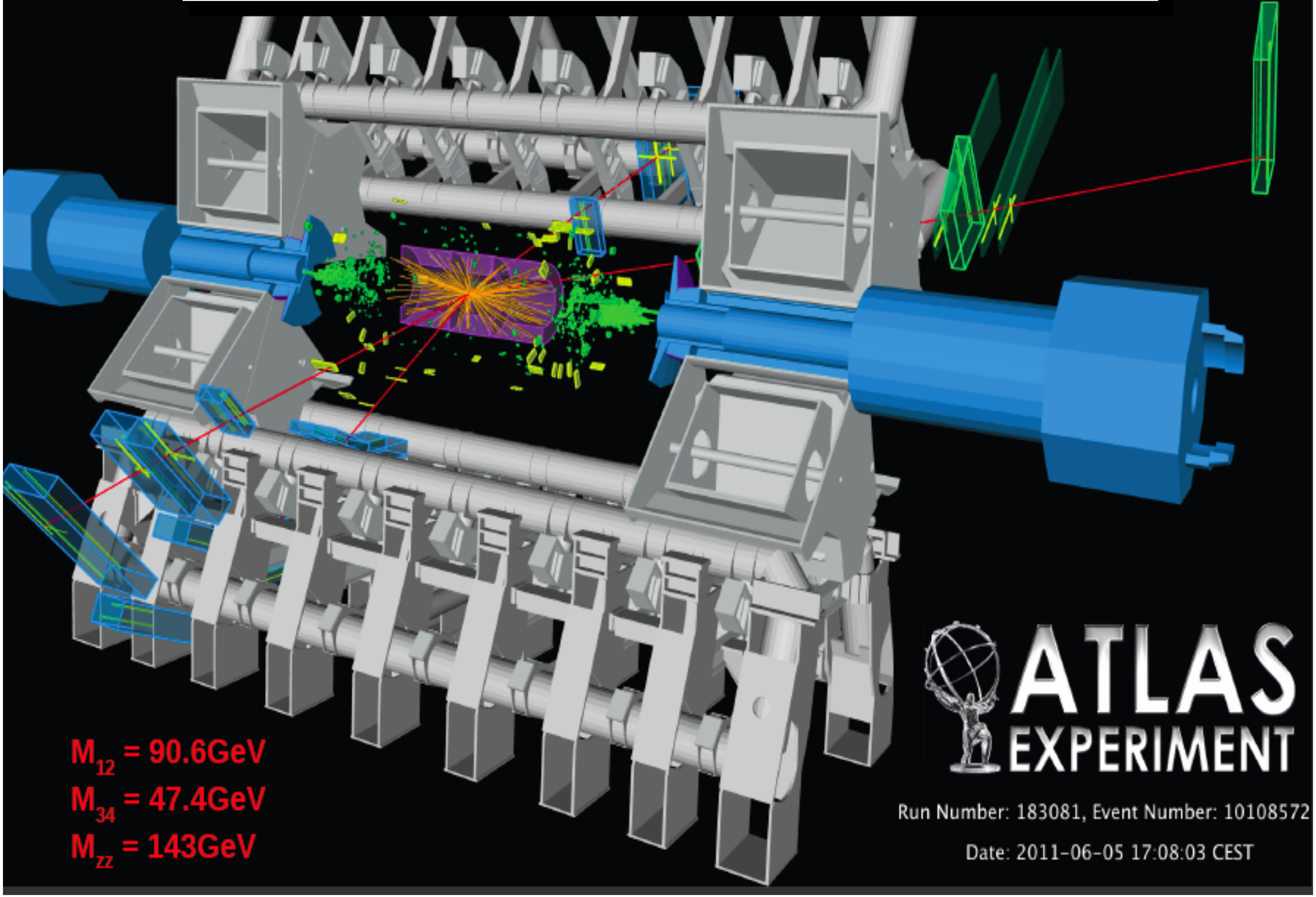






- No excess observed.
- Expected limit: ~2xSM in M_H~200-350 GeV

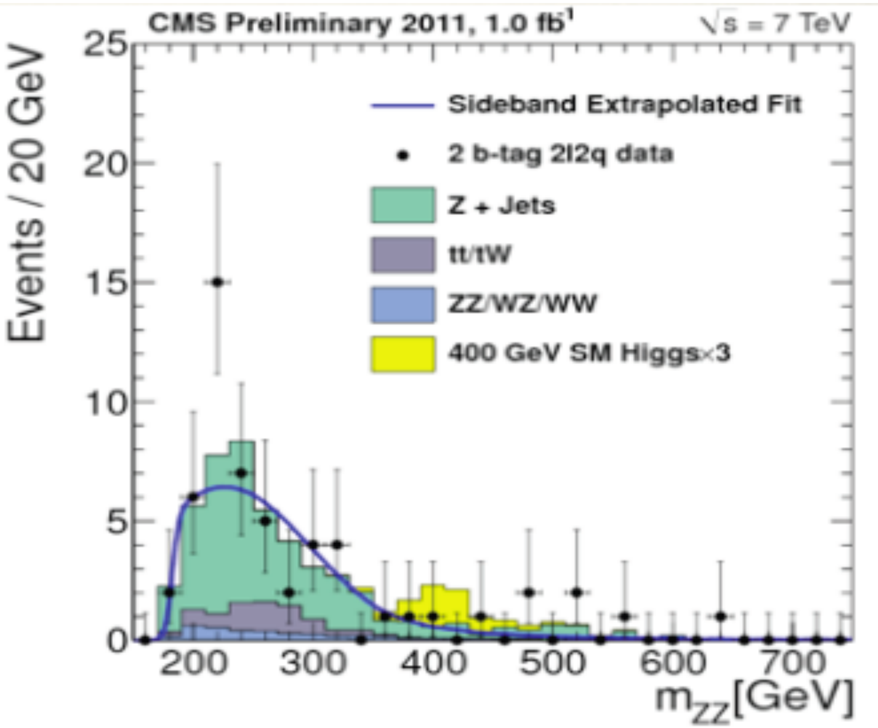
ZZ*→4μ Candidate Event

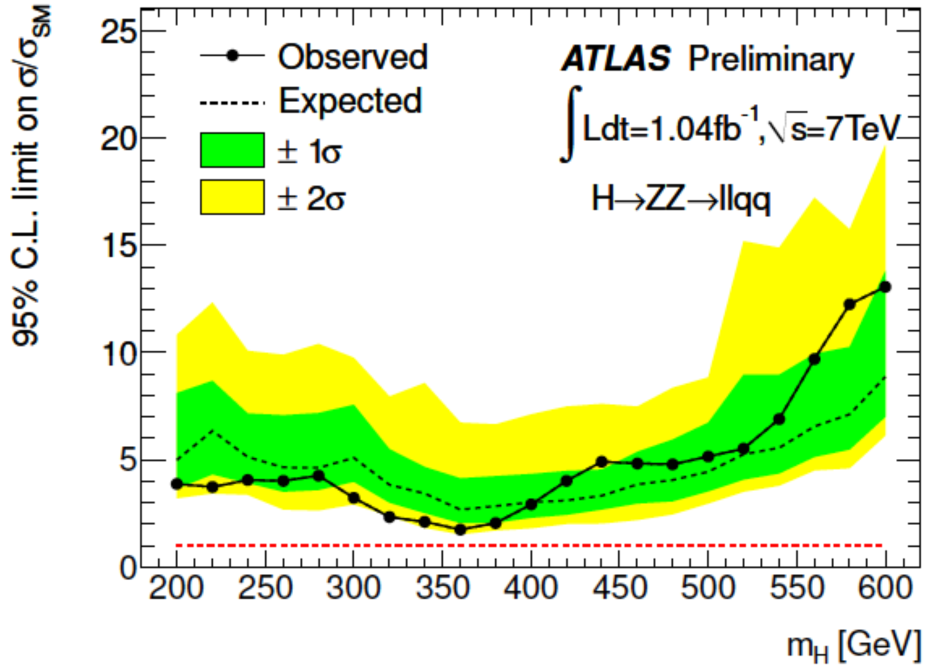


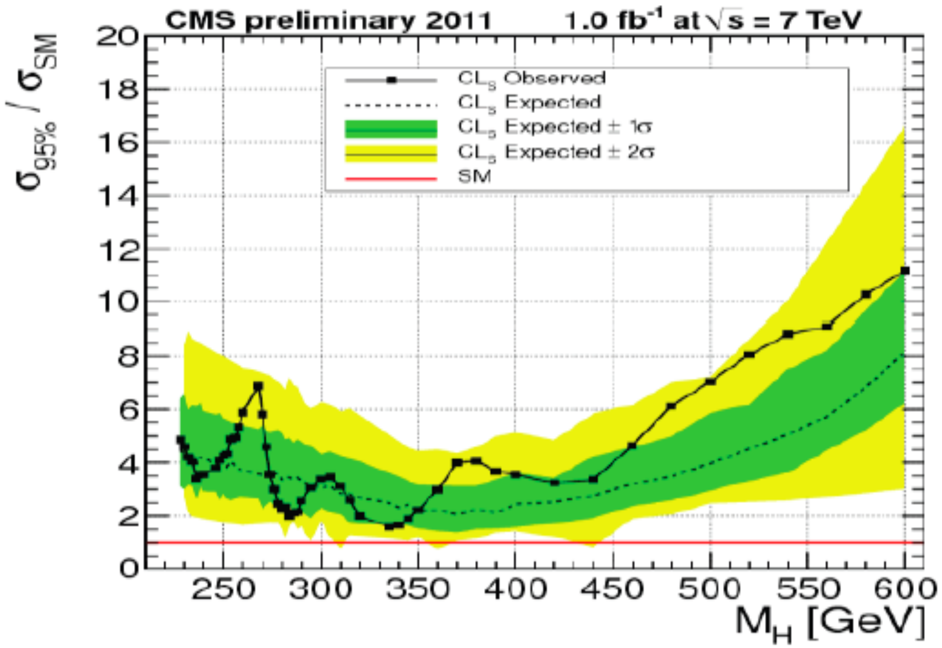
M_{12} = 90.6GeV
M_{34} = 47.4GeV
M_{ZZ} = 143GeV

H→ZZ→lljj

- Benefits from high B(Z→jj).
- Still good mass reconstruction capabilities.
- Dominant background from Z+jets.
- Improved S:B by split sample in <2 b-tag and =2 b-tag.



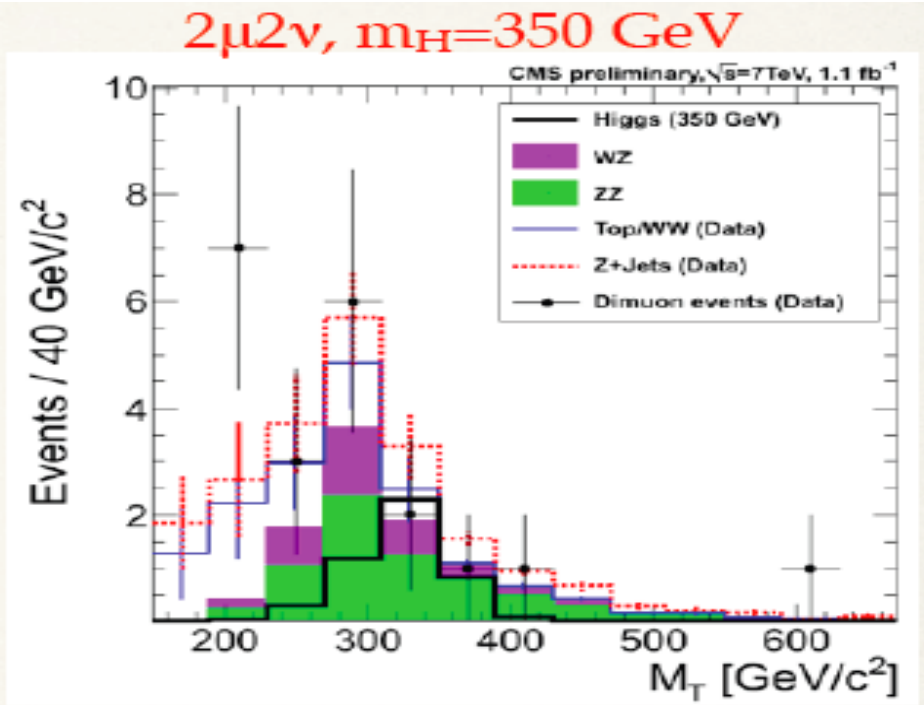


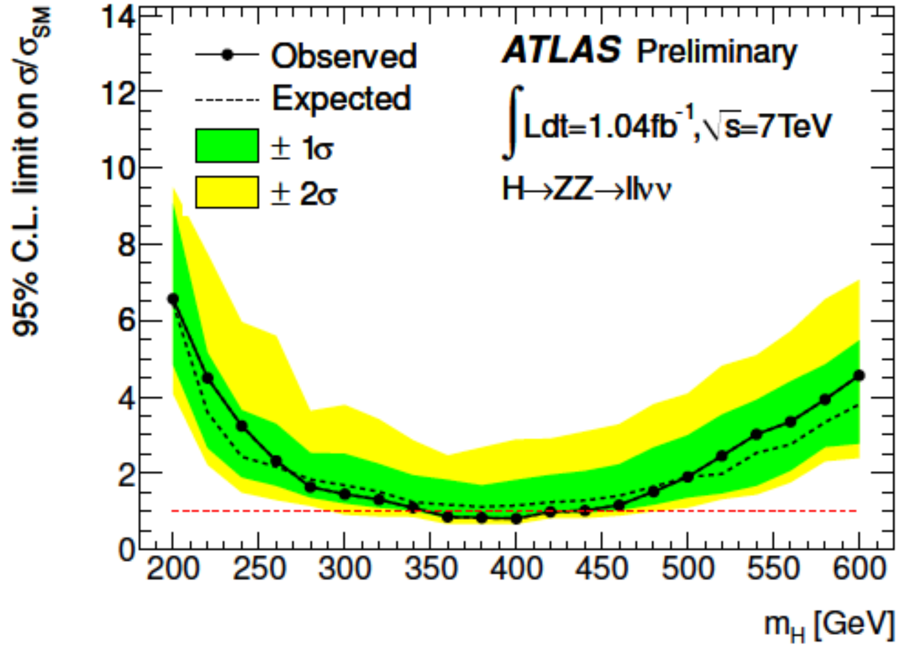


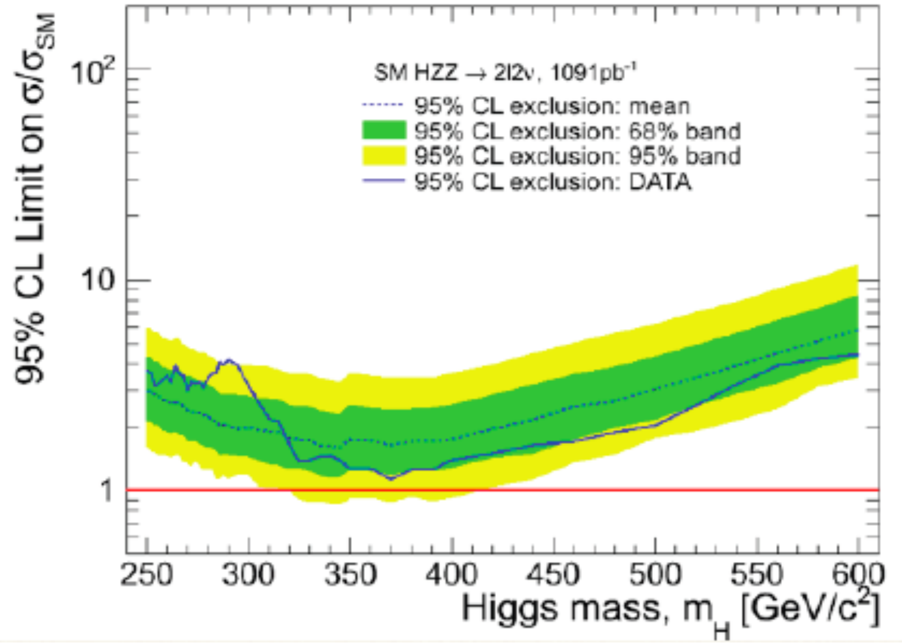
- No excess observed.
- Expected limit: ~2xSM at M_H~350 GeV

H→ZZ→llνν

- Benefits from sizable B(Z→νν).
- Signature: ee/μμ+MET
- Main backgrounds dibosons and top suppressed by 3rd lepton and b-tag vetoes
- Final discriminant: $M_T(ll\nu\nu)$





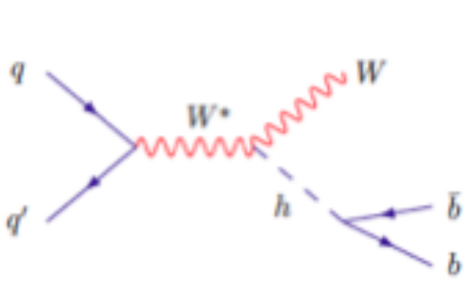


- No excess observed.
- Expected limit: <2xSM in M_H~300-500 GeV

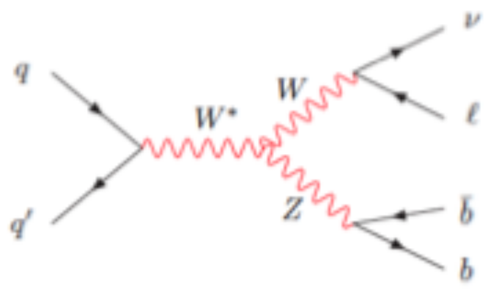
ATLAS: excludes M_H~360-420 GeV

Validation of Search Techniques

- Critical to validate experimental strategy and tools using SM backgrounds that share characteristics with the signal.



VS

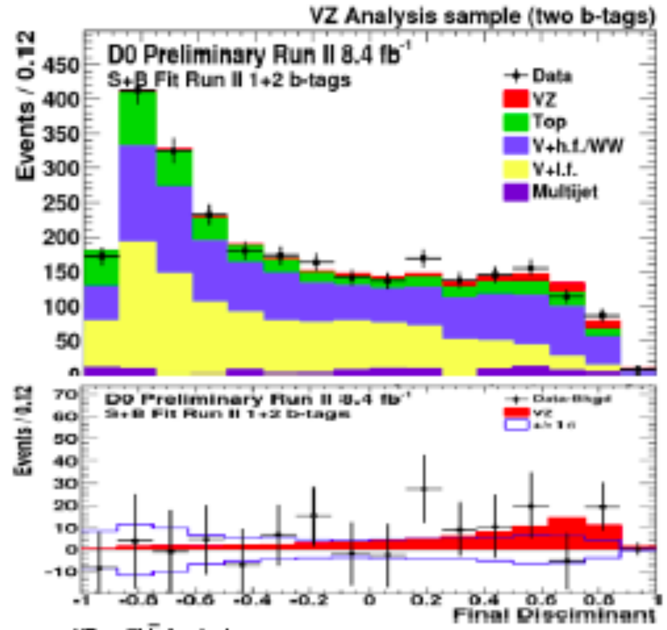


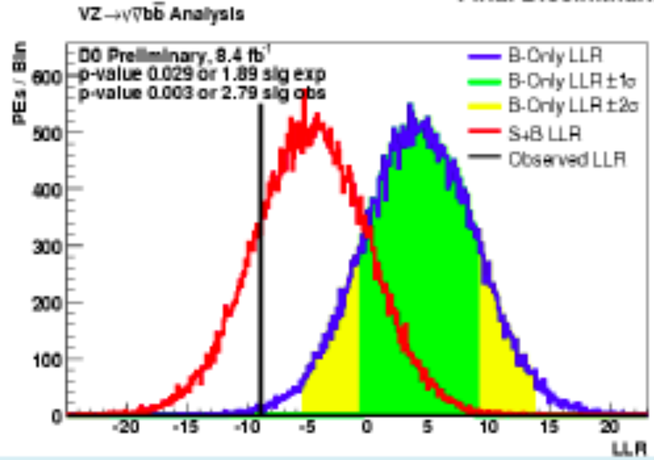
For m_H=115 GeV
$WH \rightarrow l\nu bb$: σ = 26 fb

$WZ \rightarrow l\nu bb$: σ = 105 fb

➔ x5 larger σxB but sits at lower mass and has peaking WW background.

- Low mass Higgs analyses will be used to measure WZ/ZZ (Z→bb) cross section.
  ➔ Tevatron combination upcoming!



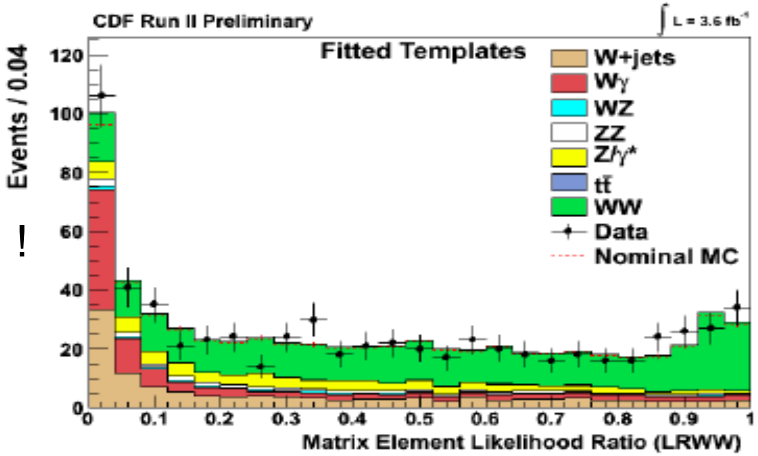


Cross-section measurement:
$\sigma(WZ+ZZ)_{mes}/\sigma_{SM}$ = **1.5 ± 0.5**
2.8 s.d. from BG only hypo.

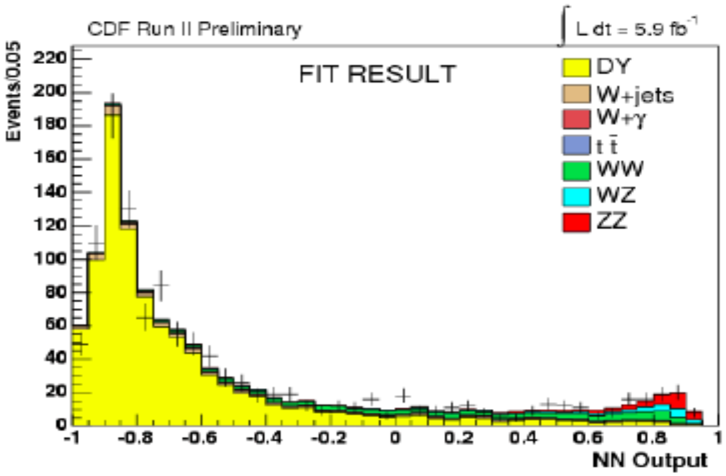
Validation of Search Techniques

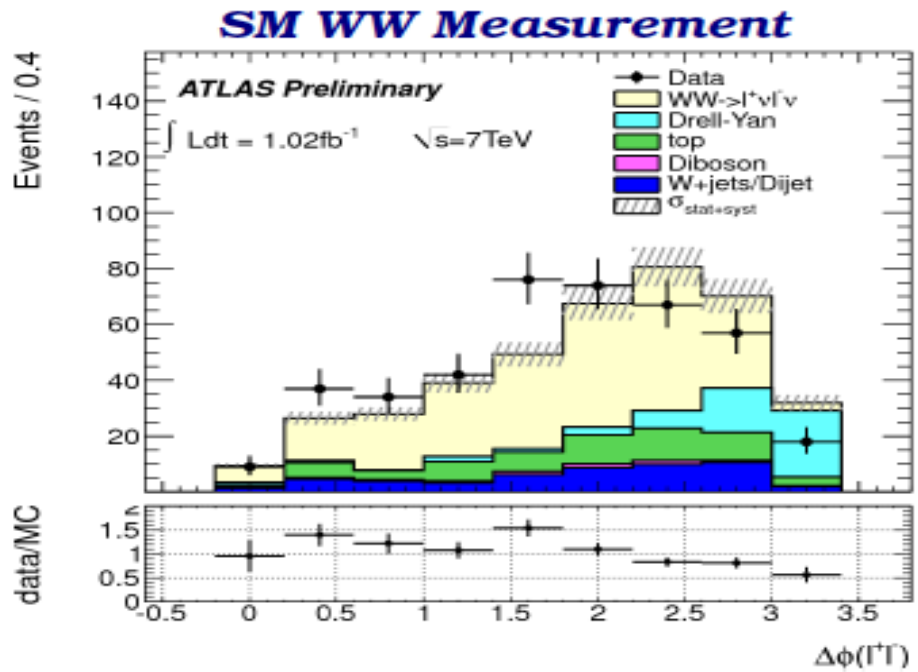
- Critical to validate experimental strategy and tools using SM backgrounds that share characteristics with the signal.

$WW \rightarrow l\nu l\nu : \sigma(WW) = 12.1\ ^{+1.8}_{-1.7}\ \text{pb}$



$ZZ \rightarrow ll\nu\nu : \sigma(ZZ) = 1.45\ ^{+0.60}_{-0.51}\ \text{pb}$

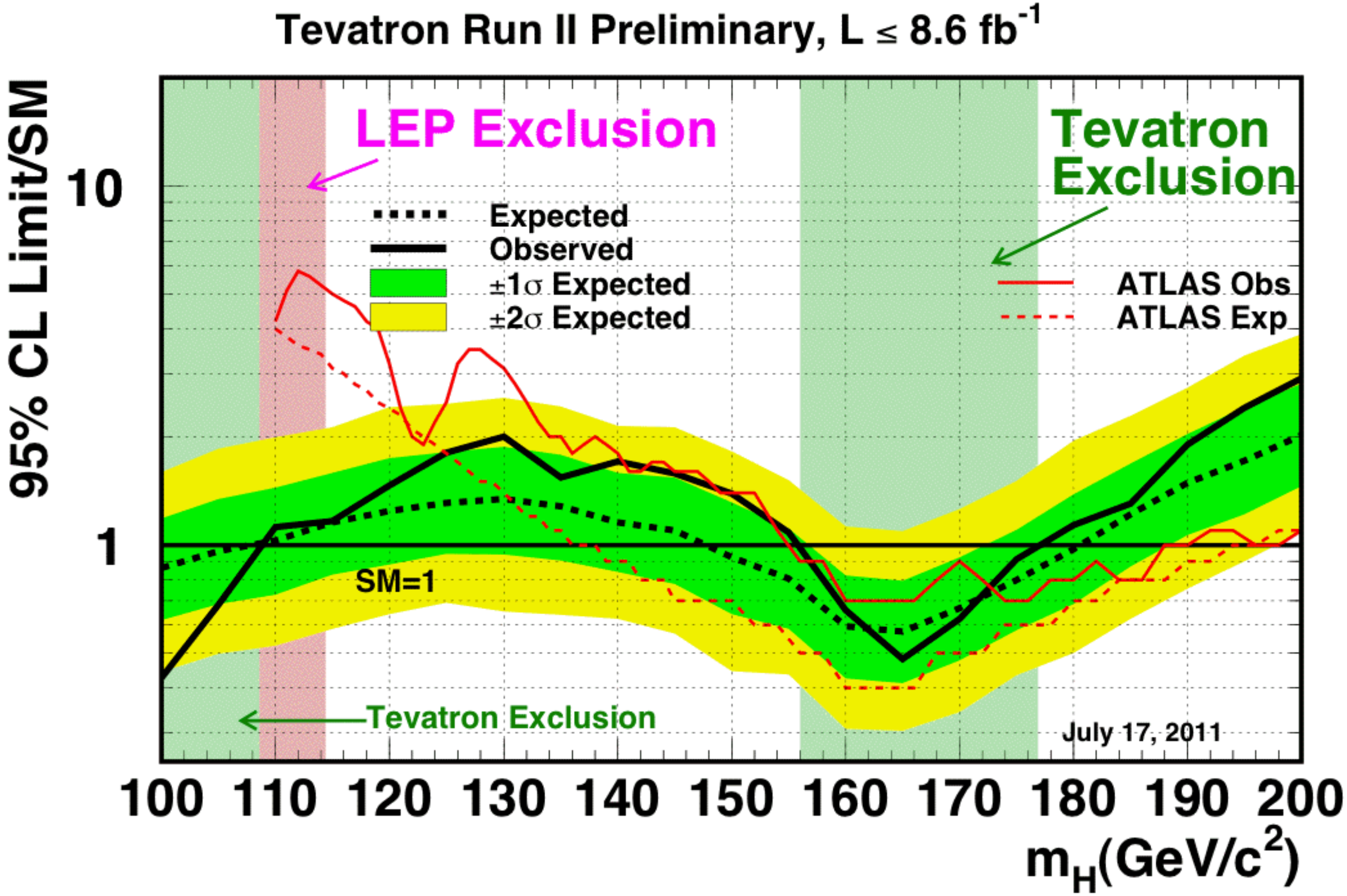




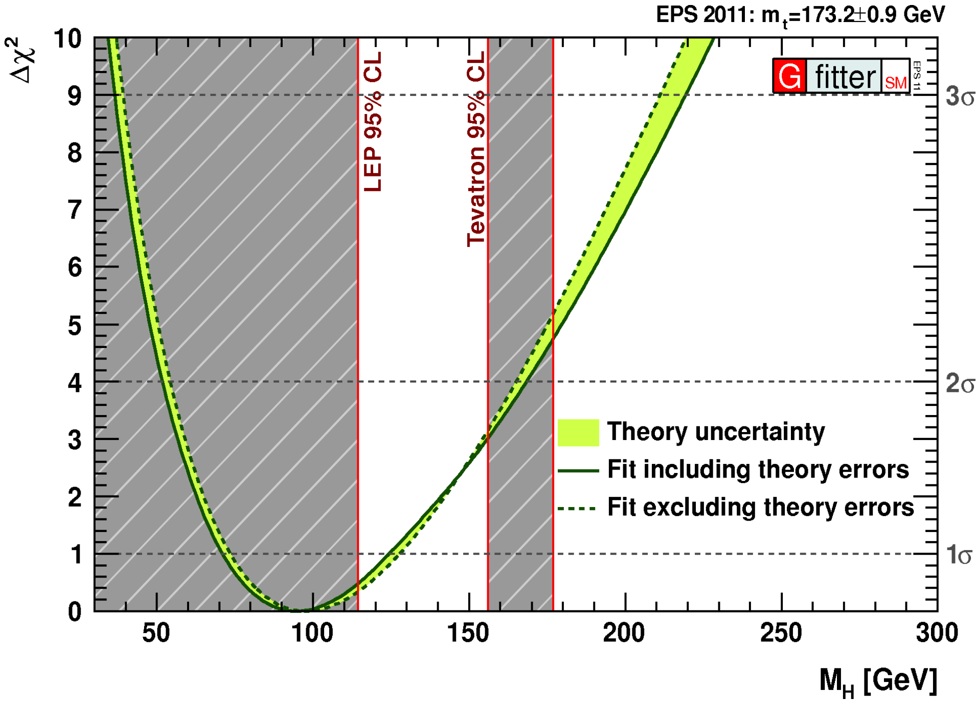
$$\sigma\left(p\bar{p}\rightarrow WW\right)^{EXPT} = 48.2 \pm 4.0\left(stat\right) \pm 6.4\left(syst\right)\ [pb]$$

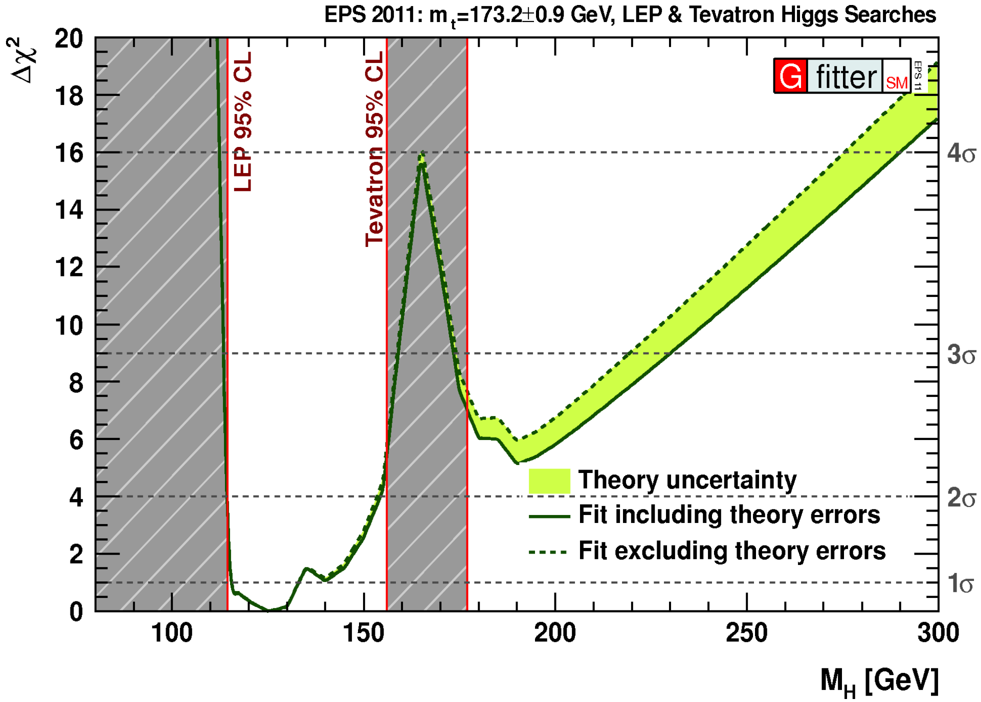
$$\sigma\left(p\bar{p}\rightarrow WW\right)^{THEORY} = 46 \pm 3\ [pb]$$

Tevatron Comparison with ATLAS

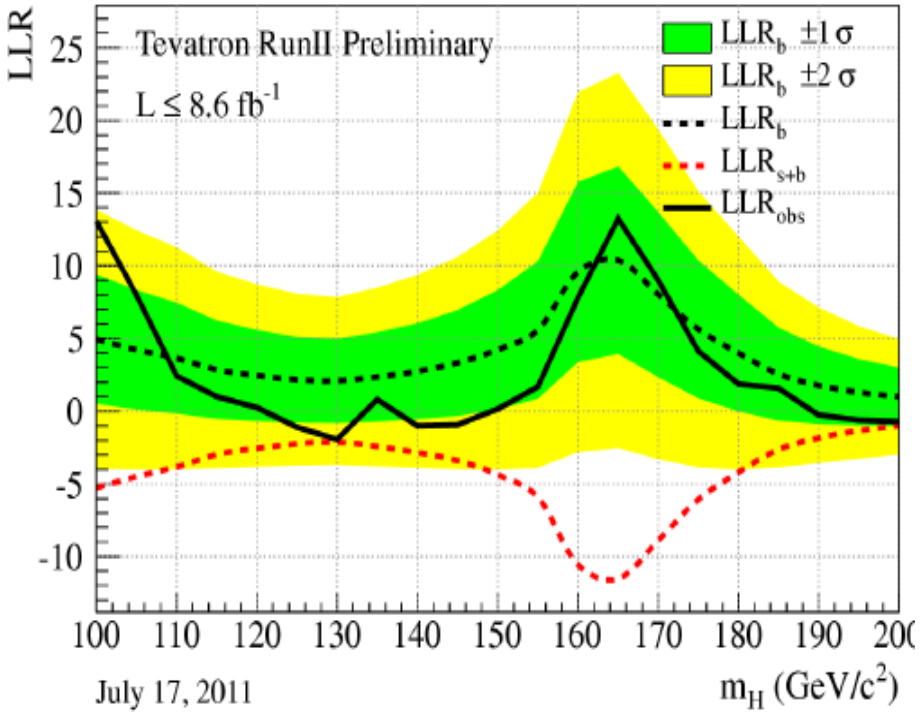


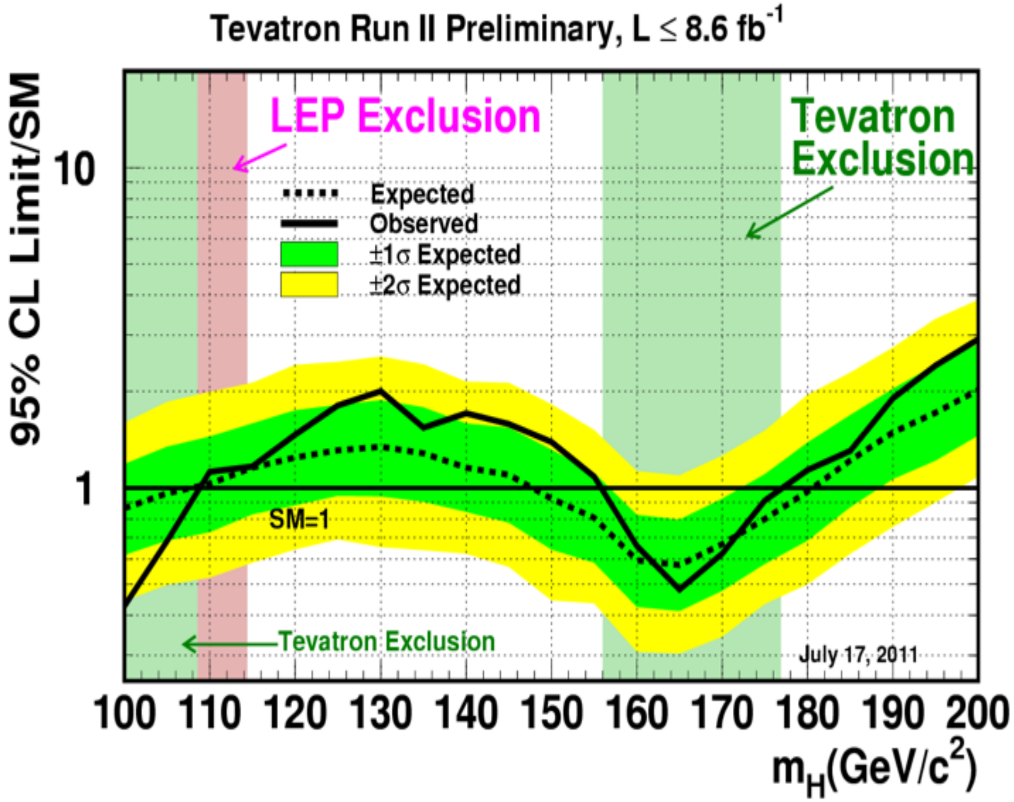
Tevatron Impact to Global Fit





Tevatron Combination





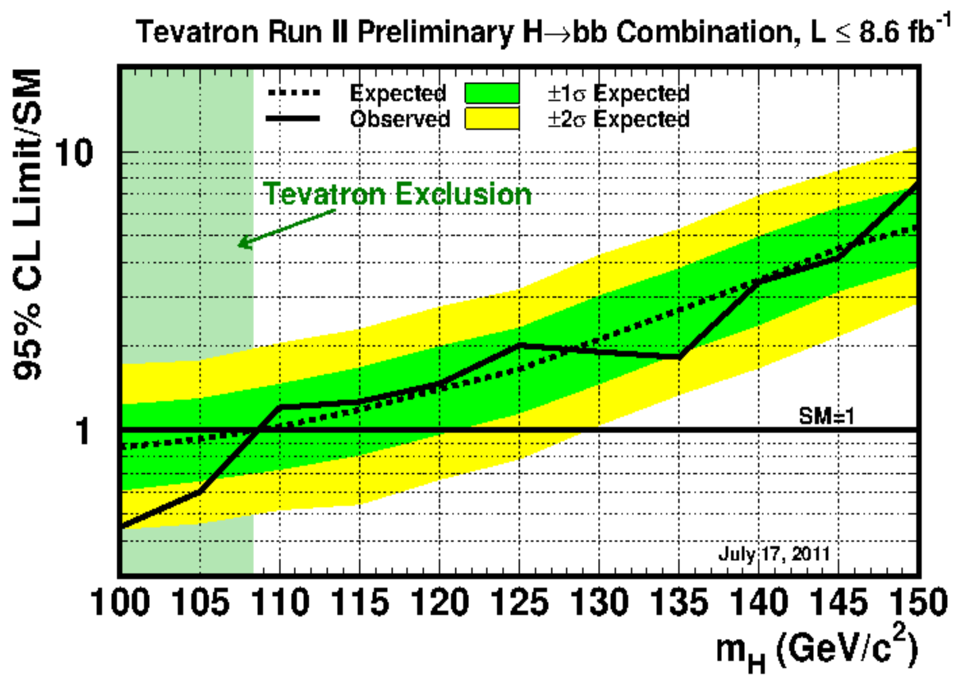
- Most signal-like excess
  - Consistent with 130 GeV Higgs

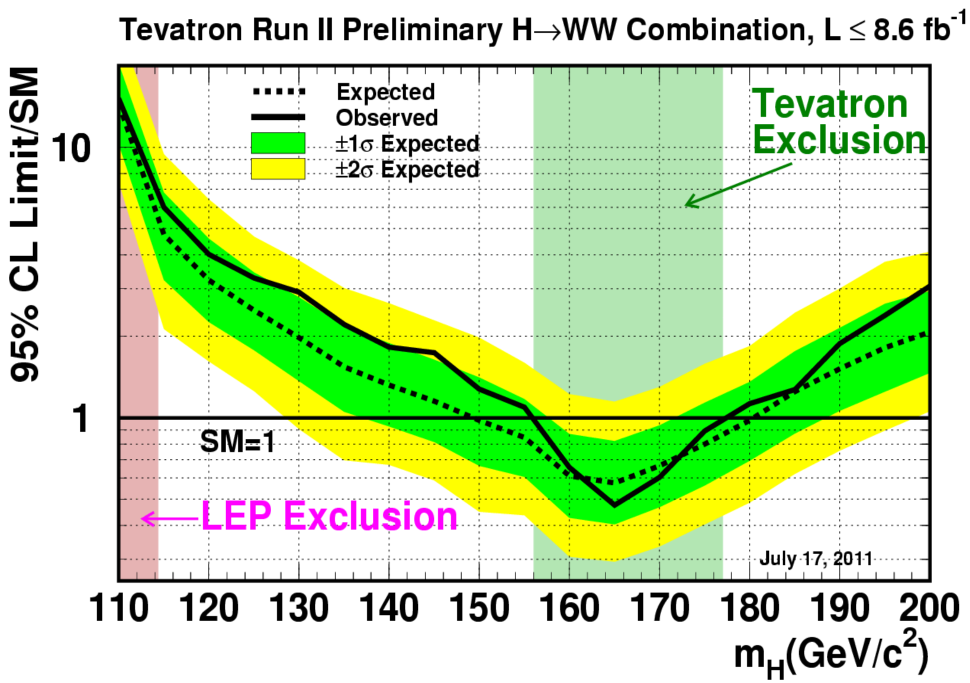
SM Higgs excluded @ 95% C.L.

$156 < m_H < 177$ GeV obs ($148 < m_H < 180$ GeV exp)

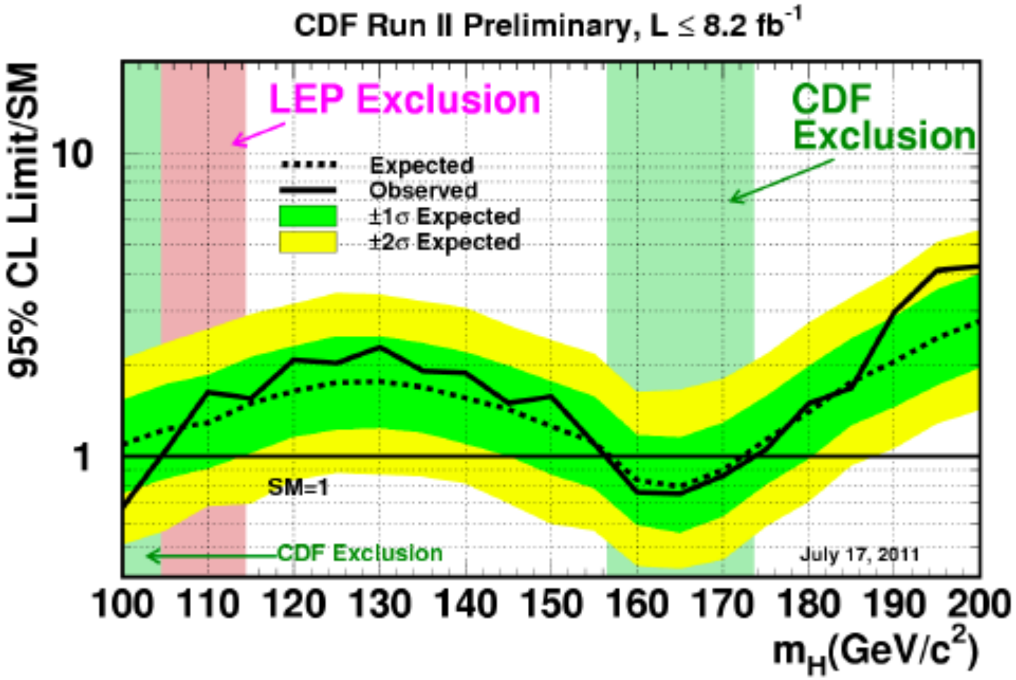
$100 < m_H < 108$ GeV obs ($100 < m_H < 109$ GeV exp)

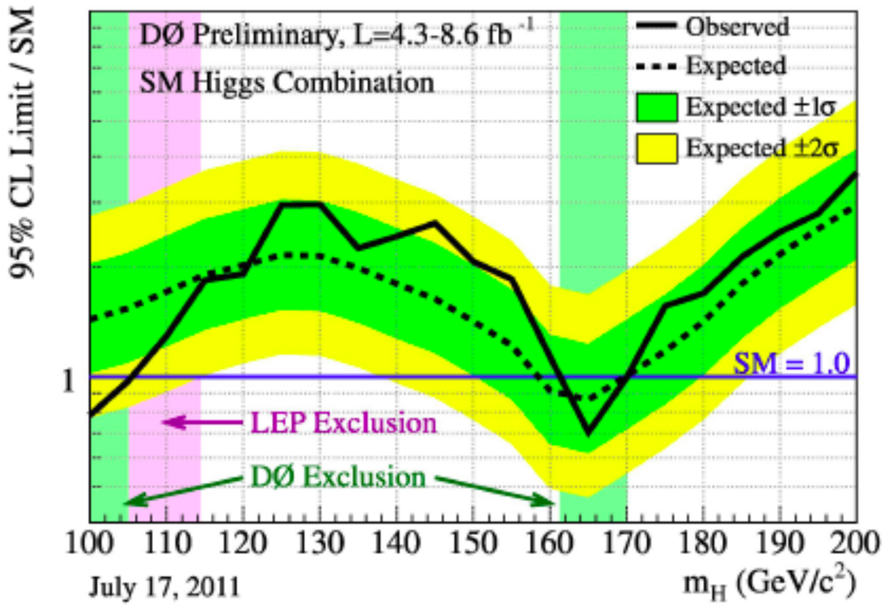
Tevatron H→bb vs H→WW



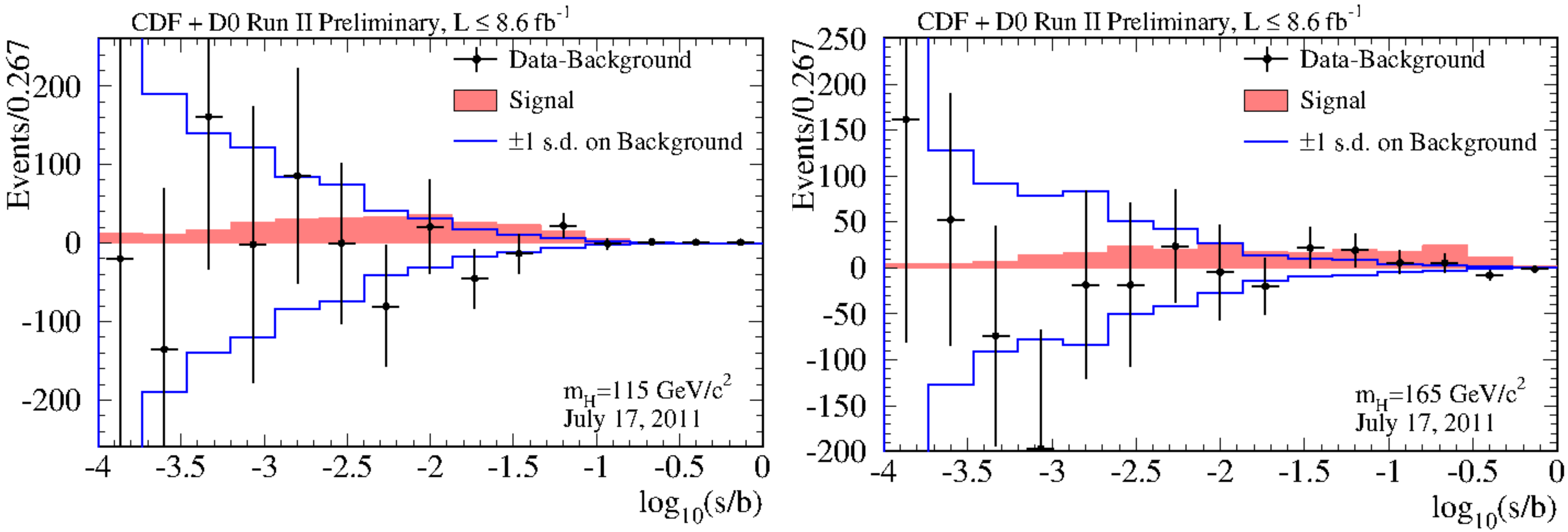


CDF and D0 Limits

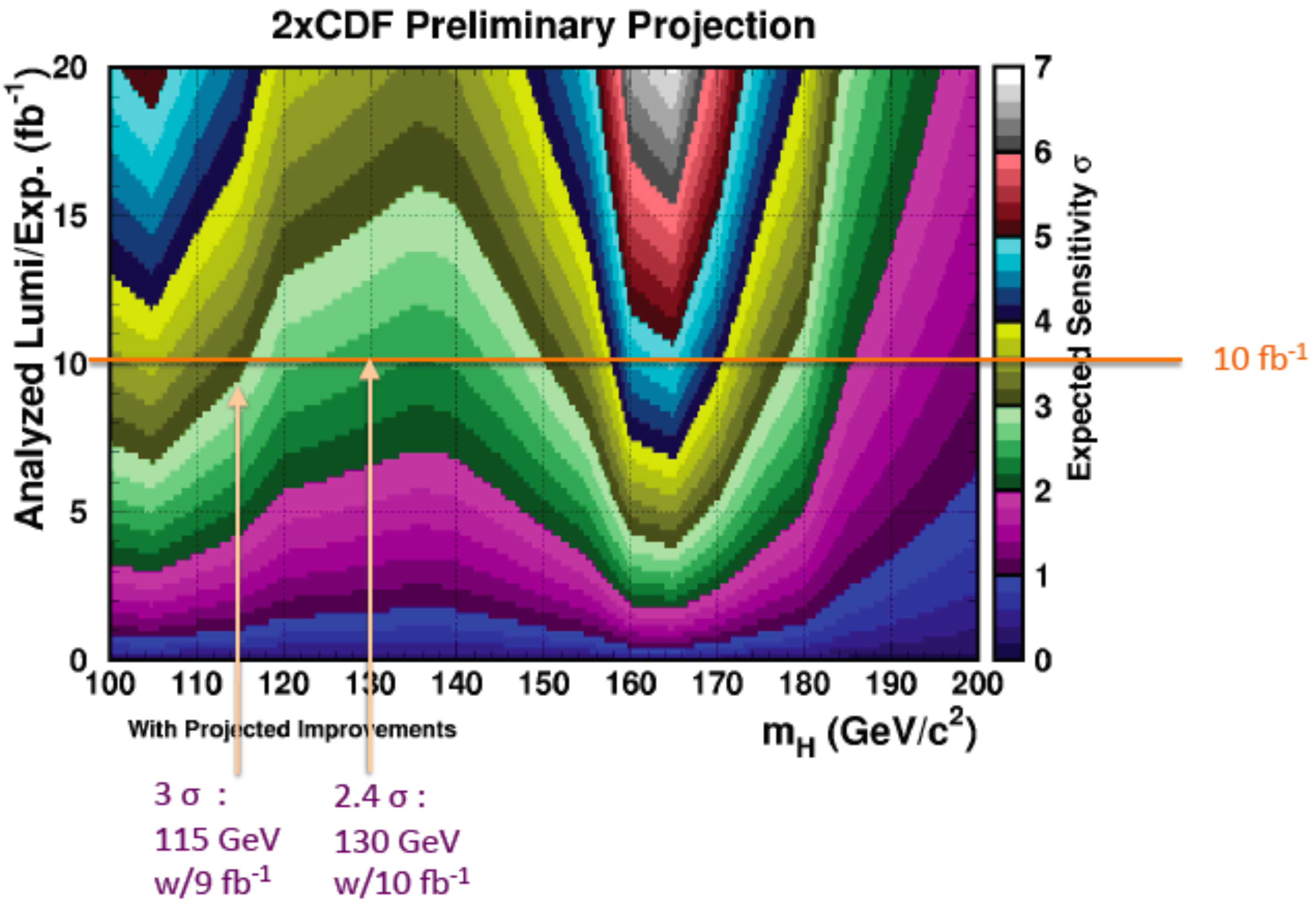




Tevatron Signal-to-Background

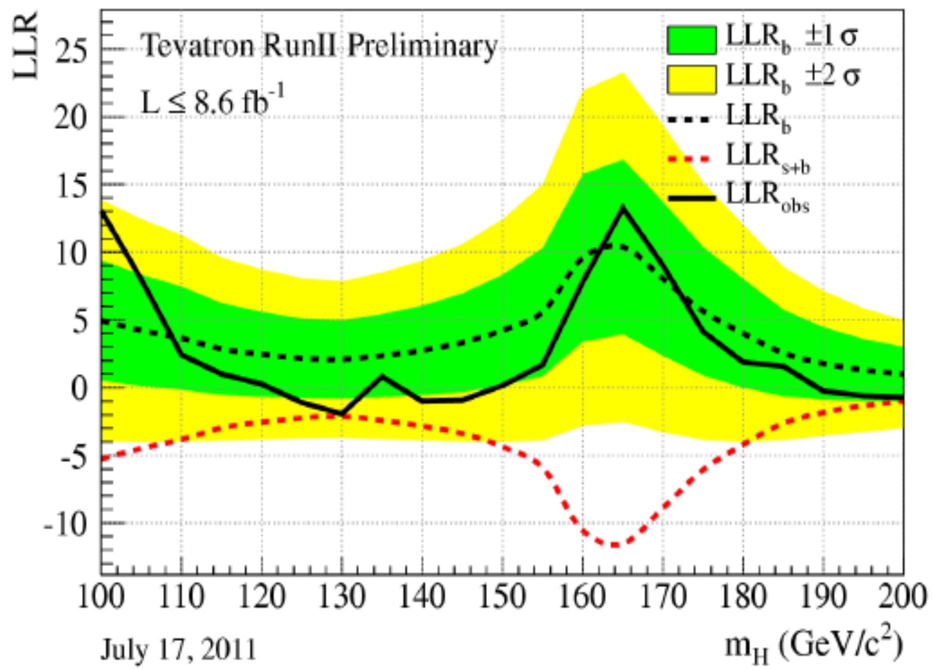


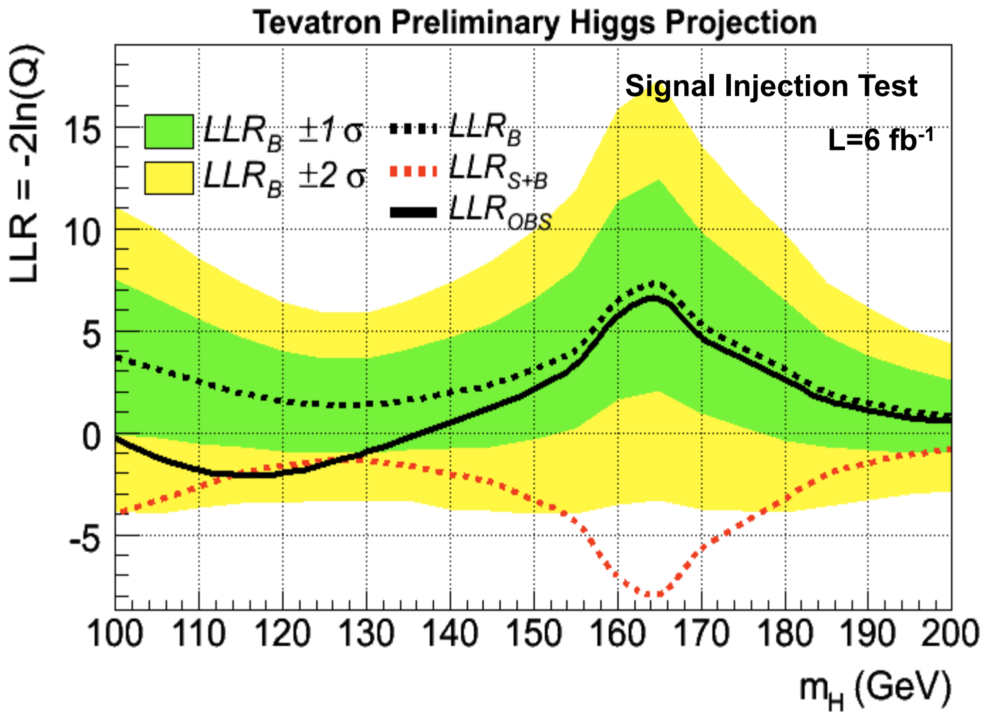
Tevatron Prospects



What Would a Signal Look Like?

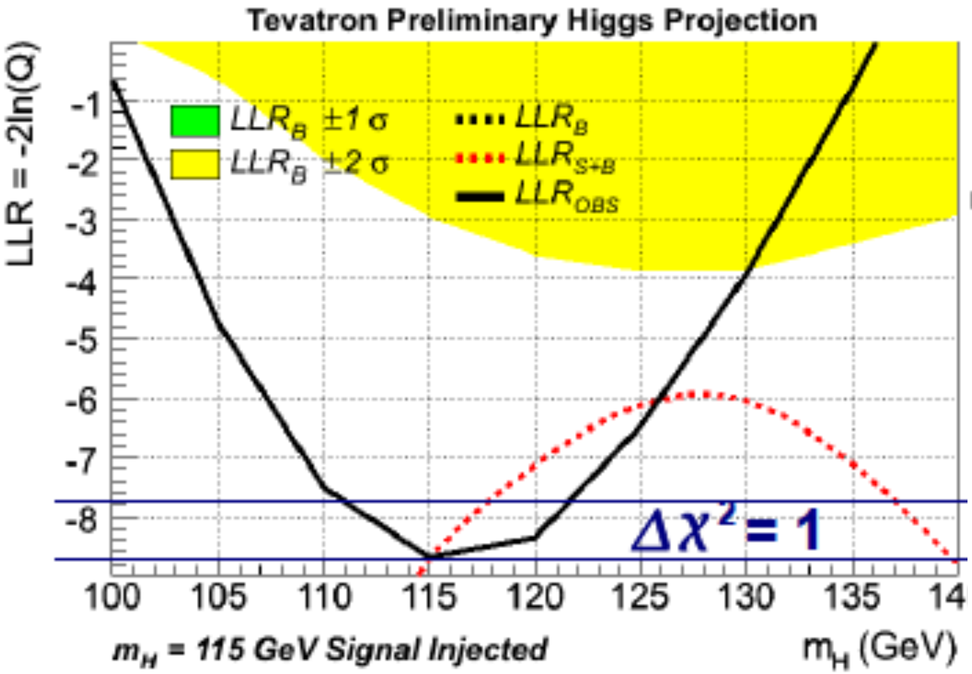
Observed

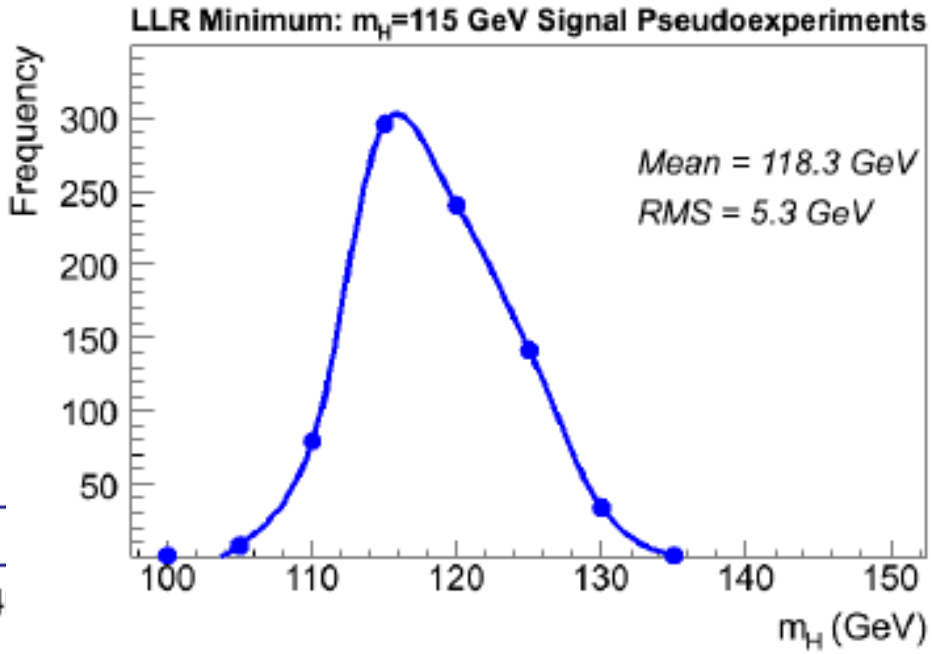




- Consider main low mass analyses (WH→lνbb, ZH→ννbb, ZH→llbb) at 6 fb^{-1} and evaluate expected LLR after injecting a SM-like signal at m_H=115 GeV
  ➔ observed limit consistent with a what would be expected from signal +background (but also consistent with background-only)

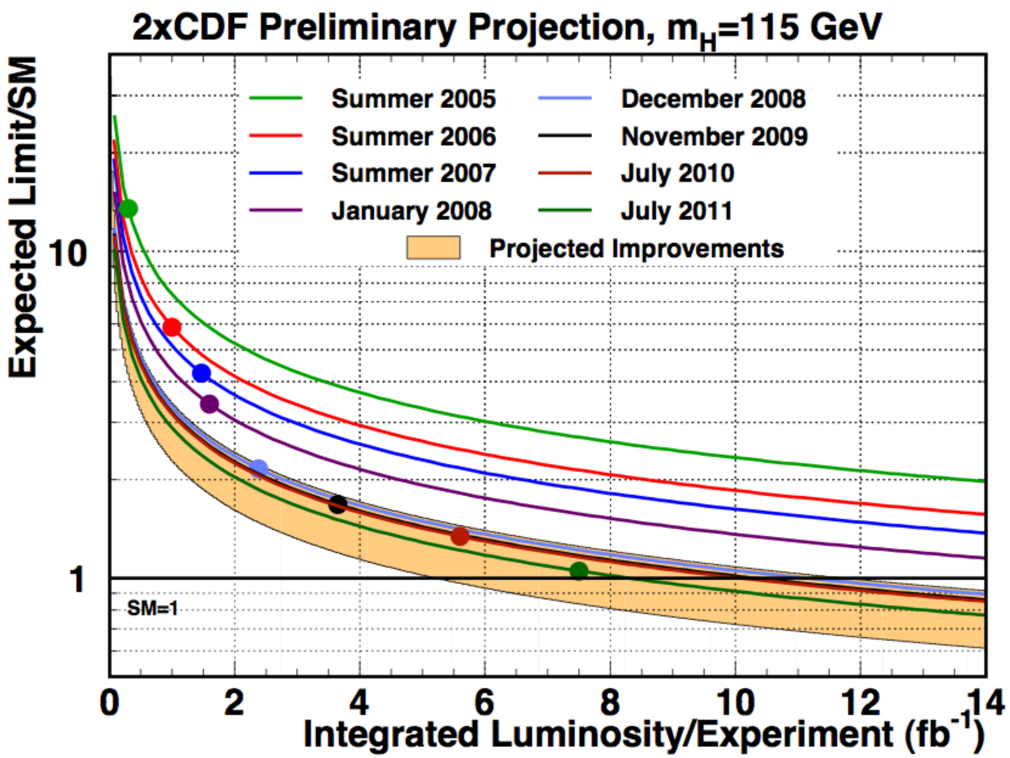
What's the Expected Mass Resolution?

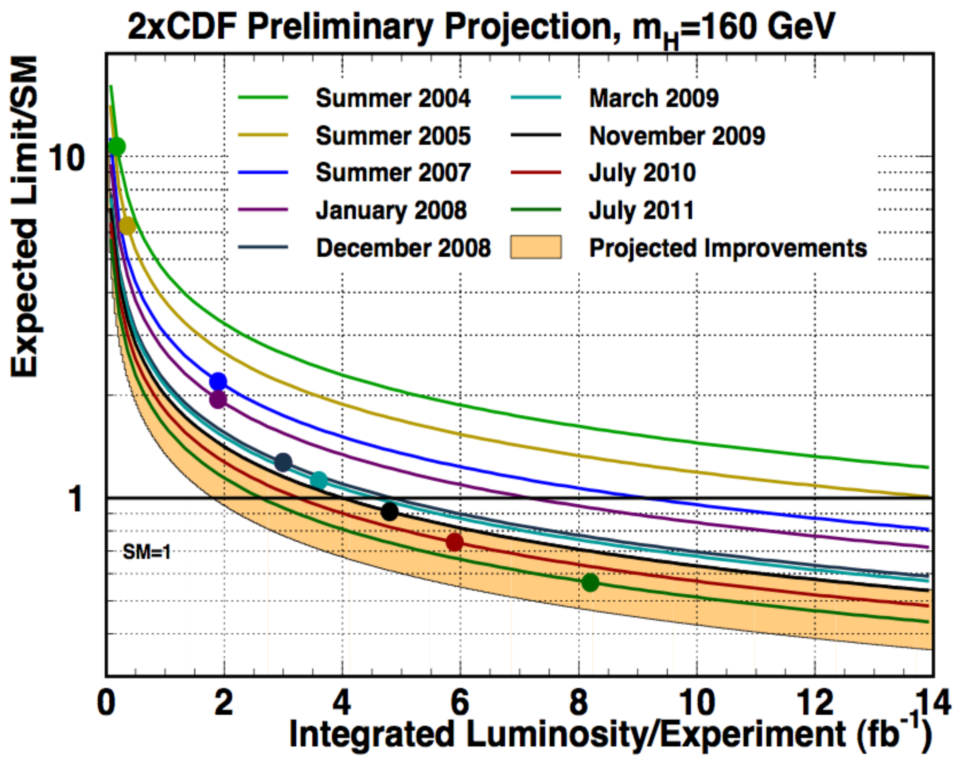




- Steeply falling cross section provides opportunity to determine mass with good resolution.
- Curvature of the observed LLR vs m_H is the most accurate estimate of such resolution.
- Ensemble testing assuming signal at 3σ level yields a mass resolution of ~5-6 GeV below m_H~135 GeV. Resolution degrades at higher masses.

SM Higgs Projections



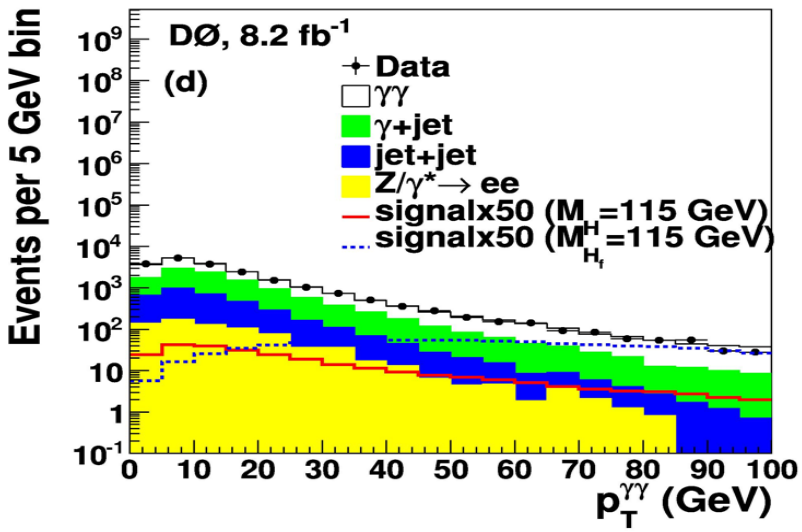


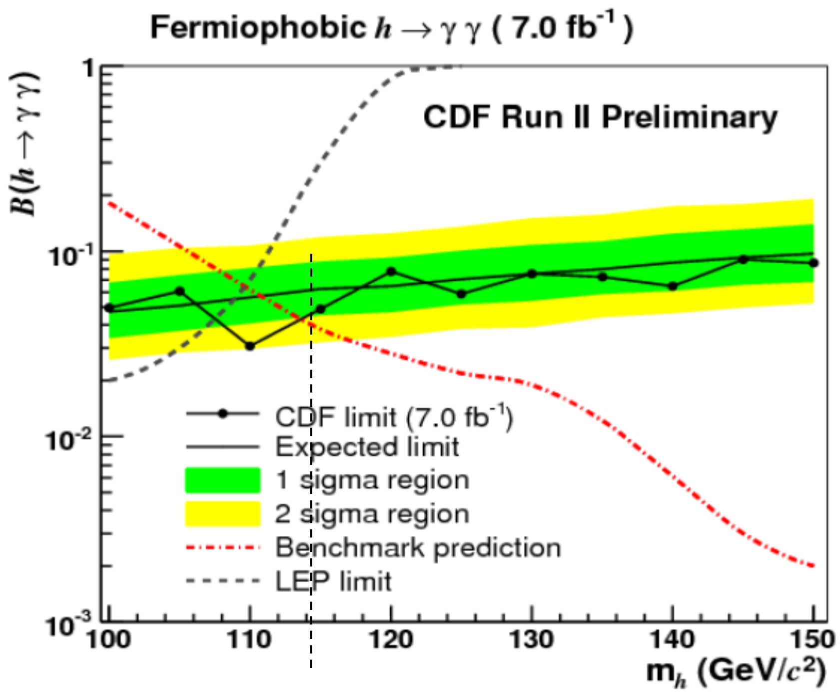
Orange band: assumed analysis improvements wrt 2007 analysis (x1.5 and x2.25)

- Limits have improved faster than $1/\sqrt{L}$ 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…

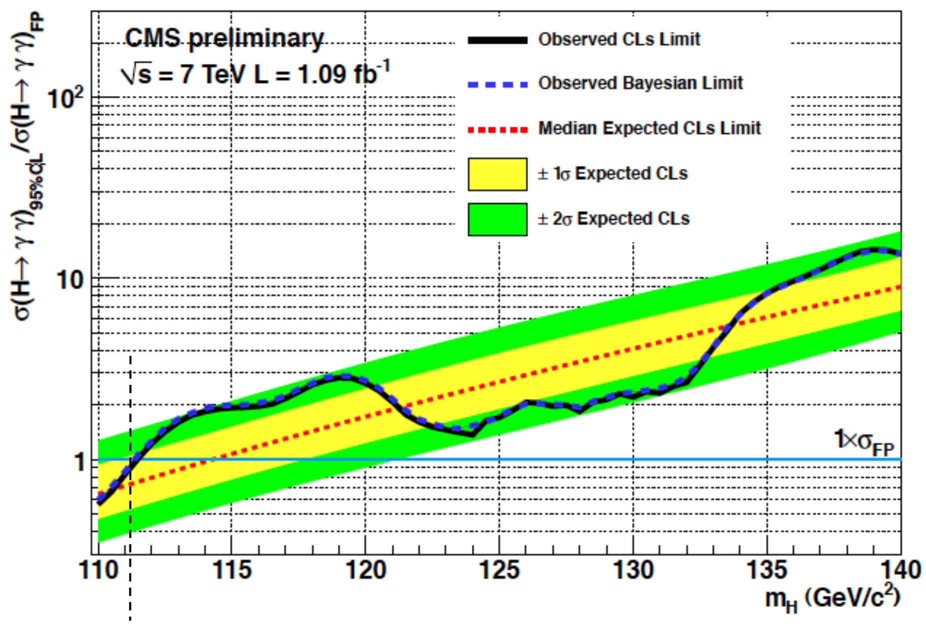
Fermiophobic Higgs ($H\rightarrow\gamma\gamma$)

- Couplings to fermions highly suppressed:
  - Only VH and VBF production
  - Large enhancement in $B(H\rightarrow\gamma\gamma)$: ~x100(10) at m_H=100(130) Gev
- Single experiments already exceeding LEP combined limit (m_H>109.7 GeV @ 95% CL).





m_H>114 GeV @ 95% C.L.

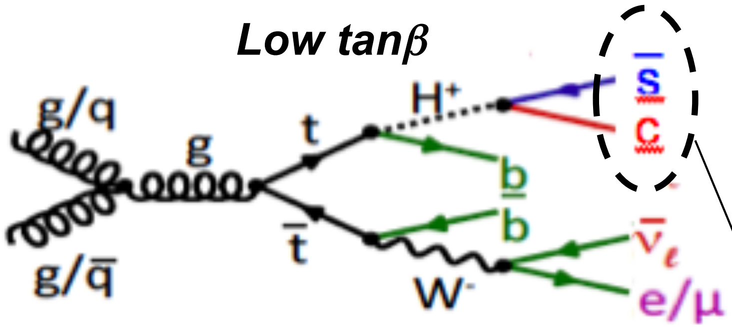


m_H>111 GeV @ 95% C.L.

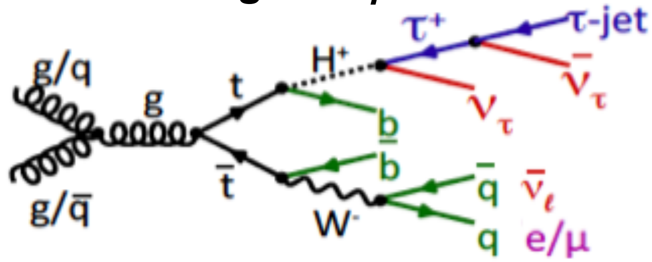
Charged Higgs

- For $m_{H^\pm} < m_t - m_b$, can have significant $B(t \rightarrow H^\pm b)$
  ➔ study kinematics and branching ratios in tt events.

Low tanβ

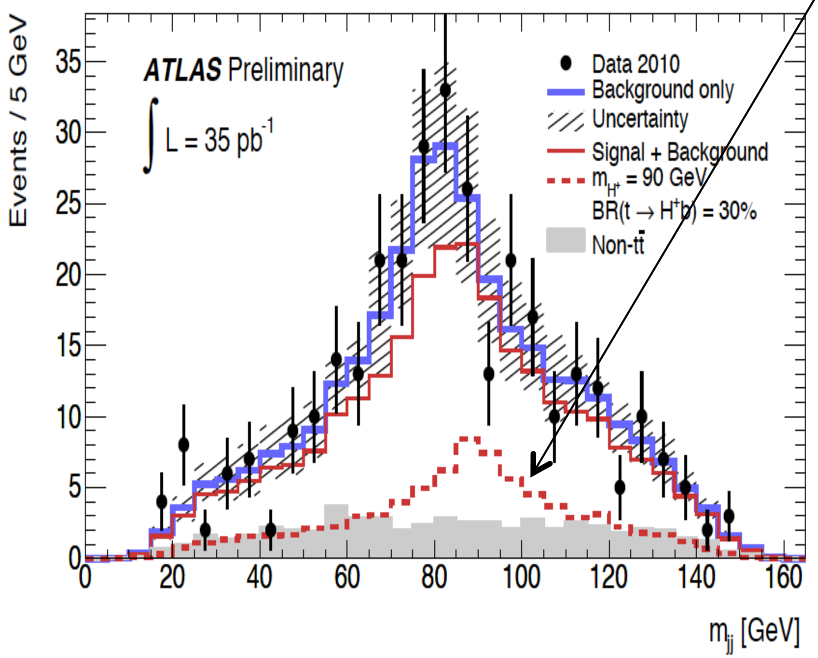


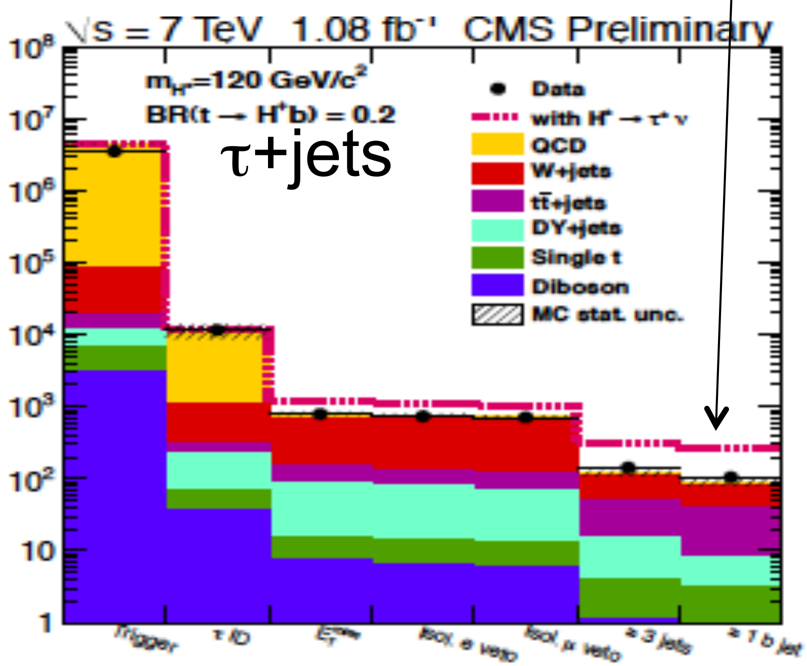
High tanβ



H+→cs resonance

Increased τ+jets rate

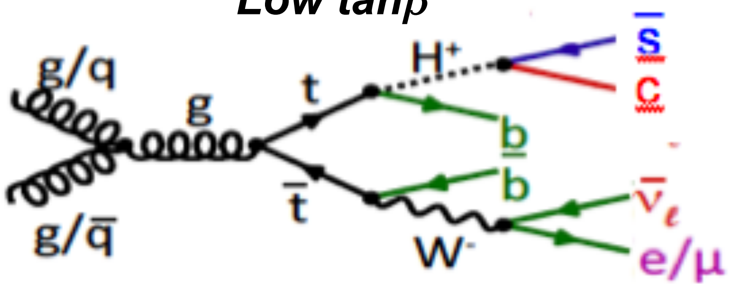




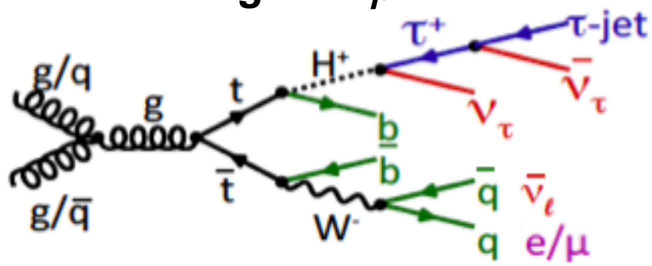
Charged Higgs

- For $m_{H^\pm} < m_t - m_b$, can have significant $B(t \to H^\pm b)$
  ➔ study kinematics and branching ratios in tt events.

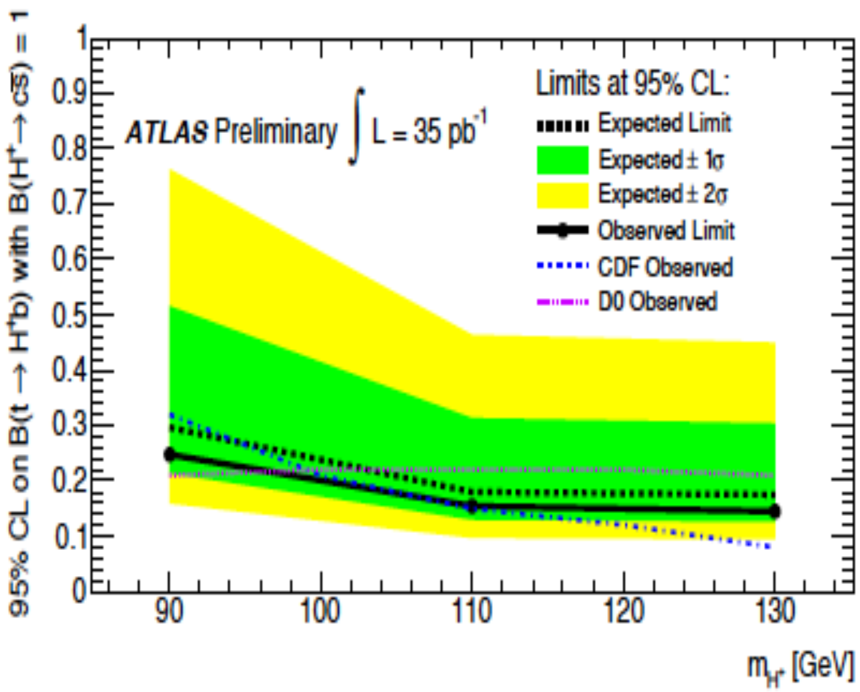
Low tanβ

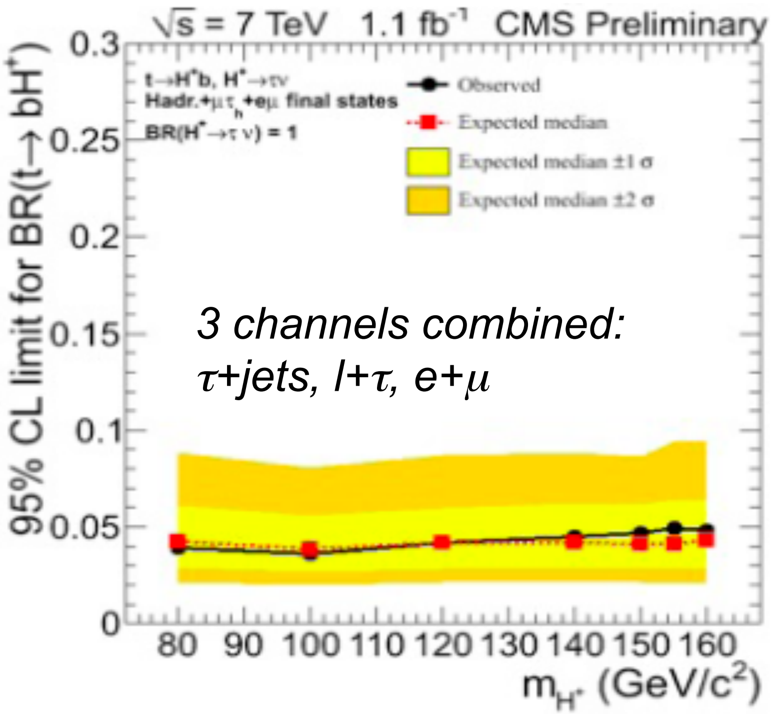


High tanβ



Results at Tevatron/LHC so far consistent with the Standard Model

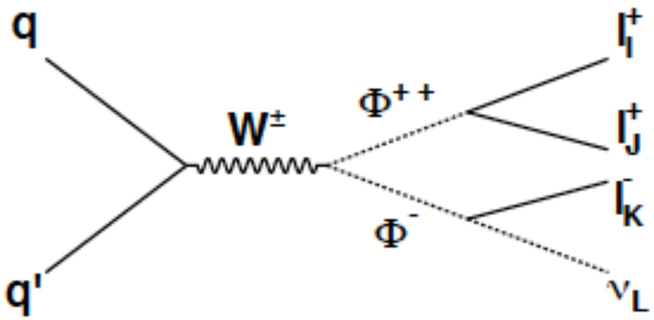


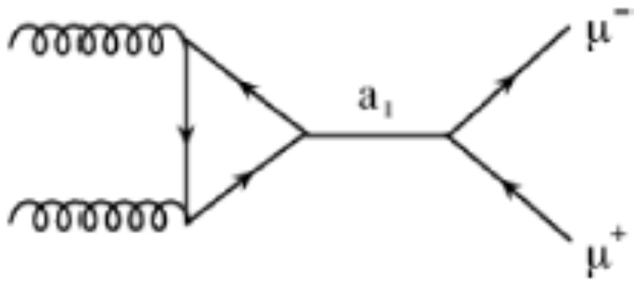


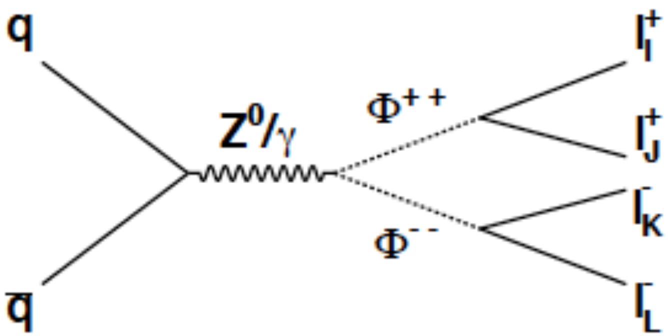
And Beyond the MSSM…

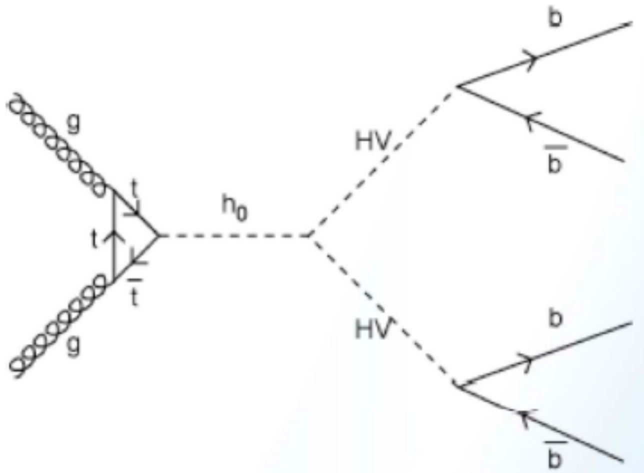
More exotic scenarios being probed ("leaving no stone unturned"):

- Doubly-charged Higgs (from Higgs triplet)
- Light CP-odd scalar (e.g. NMSSM)
- Higgs decaying to Hidden Valley pions
- …









And Beyond the MSSM…

More exotic scenarios being probed ("leaving no stone unturned"):

- Doubly-charged Higgs (from Higgs triplet)
- Light CP-odd scalar (e.g. NMSSM)
- Higgs decaying to Hidden Valley pions
- …