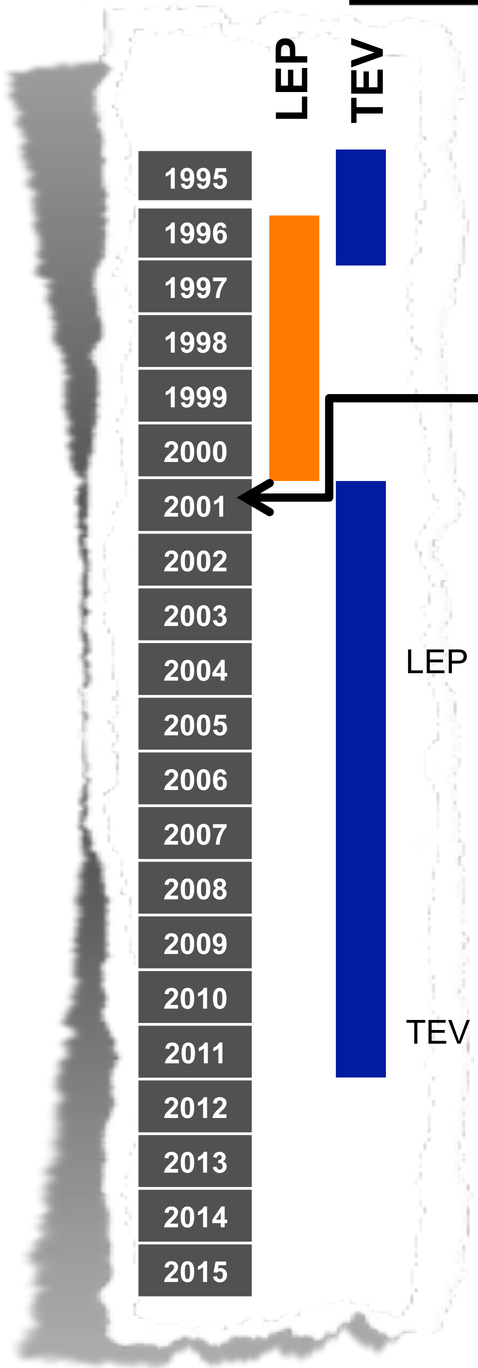
D0 Special Collaboration Meeting, Fermilab, June 9-10, 2014

From Limits to Evidence: Road to the Higgs

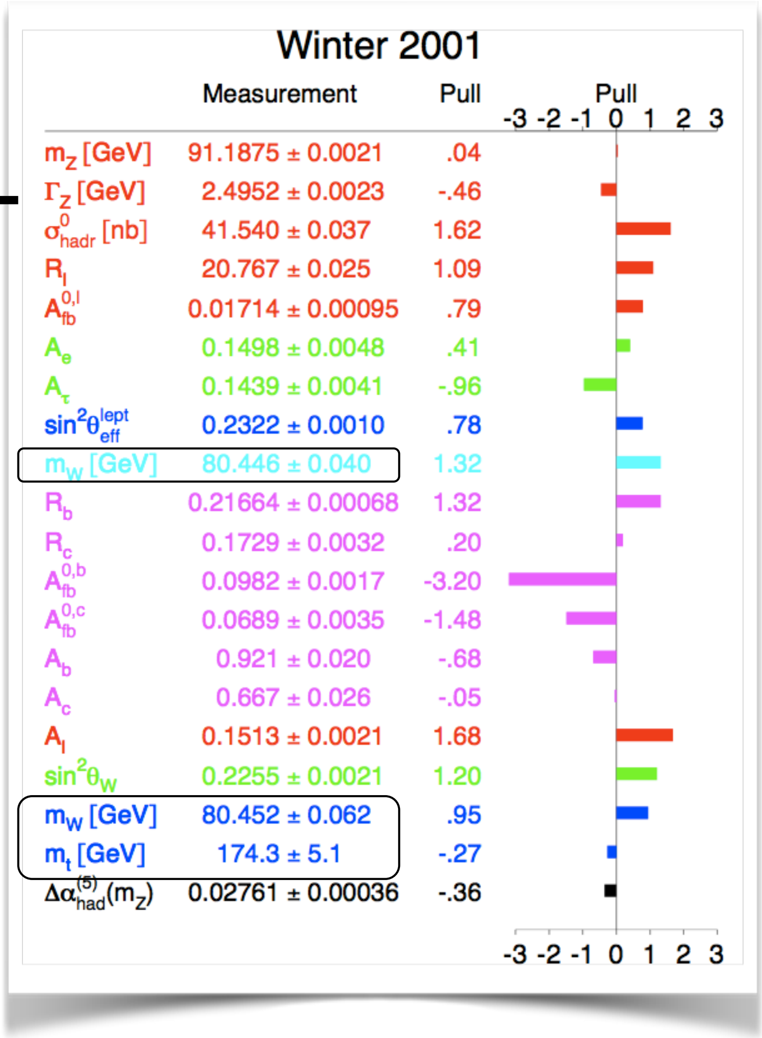
Aurelio Juste

ICREA/IFAE, Barcelona

Historical Perspective

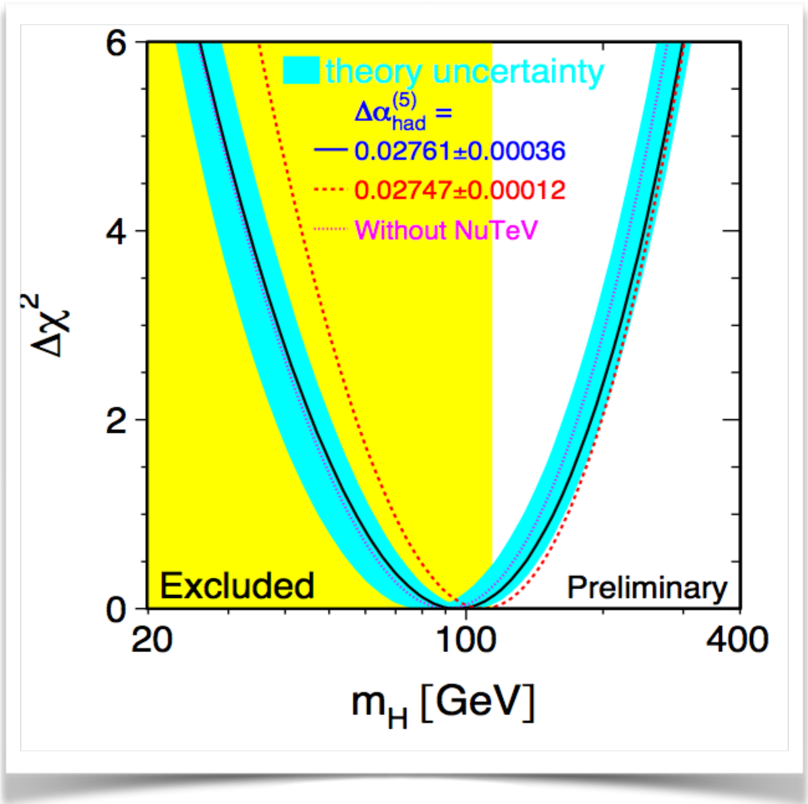


What was known about the Higgs boson at the beginning of Run 2:



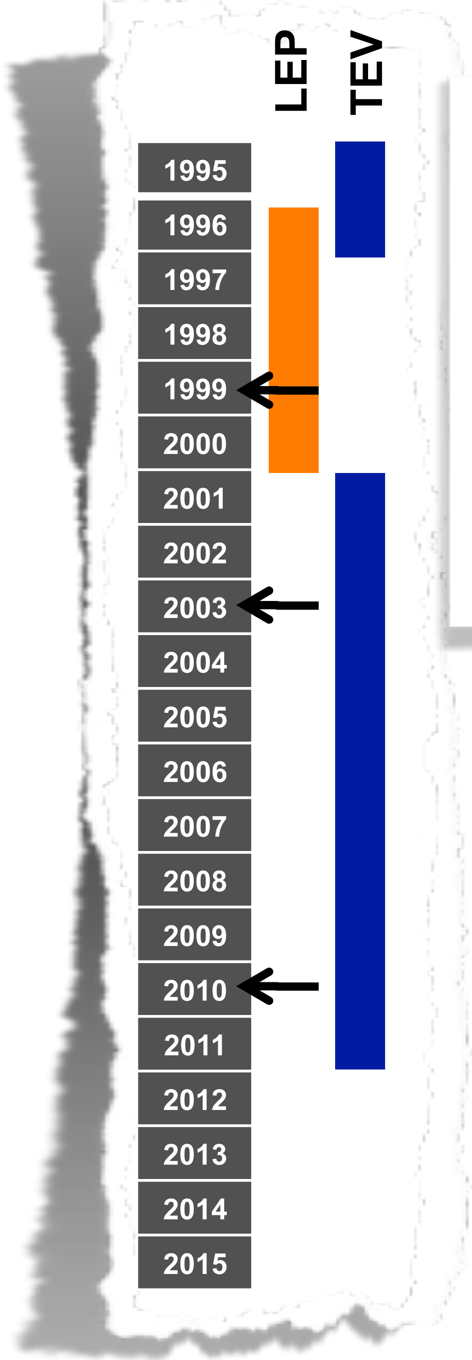
Winter 2001

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.04
Γ_Z [GeV]	2.4952 ± 0.0023	-.46
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.09
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.79
A_e	0.1498 ± 0.0048	.41
A_τ	0.1439 ± 0.0041	-.96
$\sin^2\theta^{lept}_{eff}$	0.2322 ± 0.0010	.78
m_W [GeV]	80.446 ± 0.040	1.32
R_b	0.21664 ± 0.00068	1.32
R_c	0.1729 ± 0.0032	.20
$A^{0,b}_{fb}$	0.0982 ± 0.0017	-3.20
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.48
A_b	0.921 ± 0.020	-.68
A_c	0.667 ± 0.026	-.05
A_l	0.1513 ± 0.0021	1.68
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.95
m_t [GeV]	174.3 ± 5.1	-.27
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.36

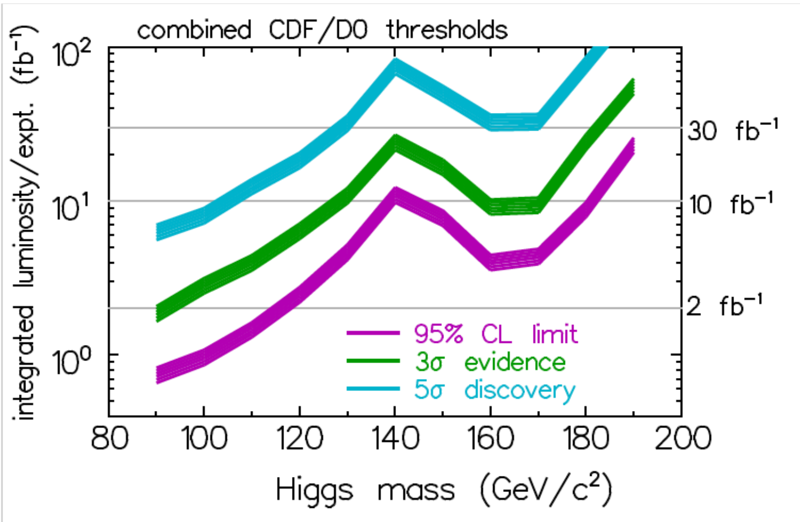


- Direct searches at LEP
  m_H>114.4 GeV @ 95% CL
- Indirect constraints from precision electroweak observables
  m_H<200 GeV @ 95% CL

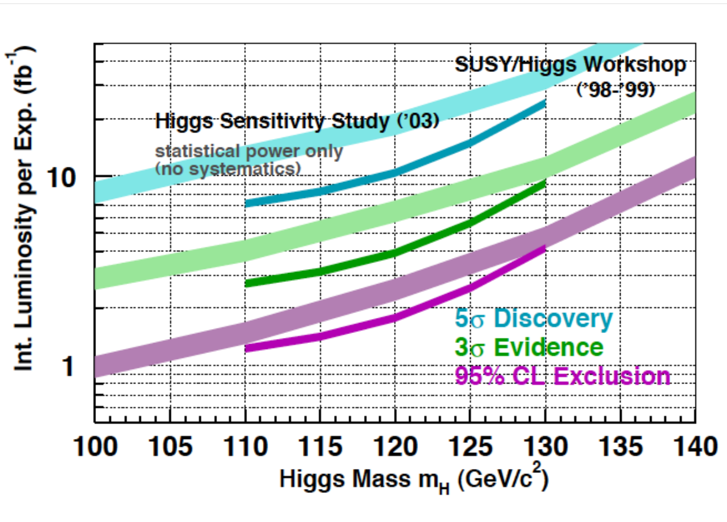
Historical Perspective

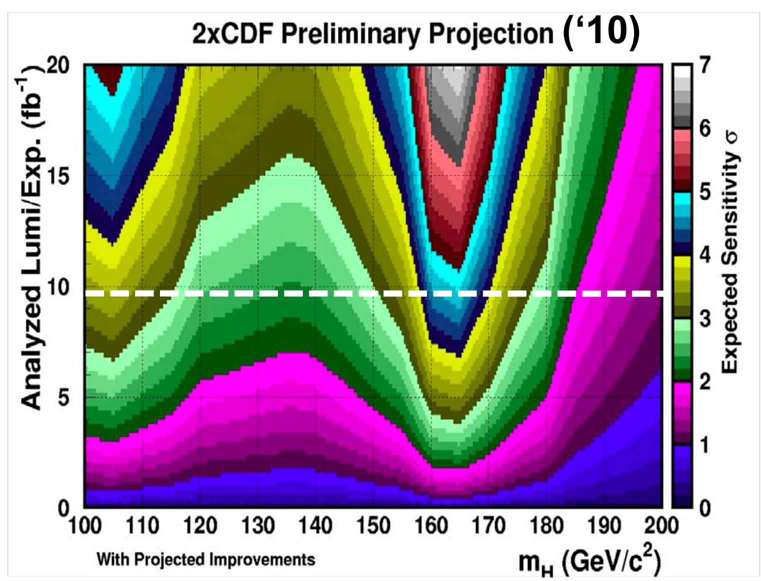


SUSY-Higgs Working Group ('99)



Higgs Sensitivity Study ('03)

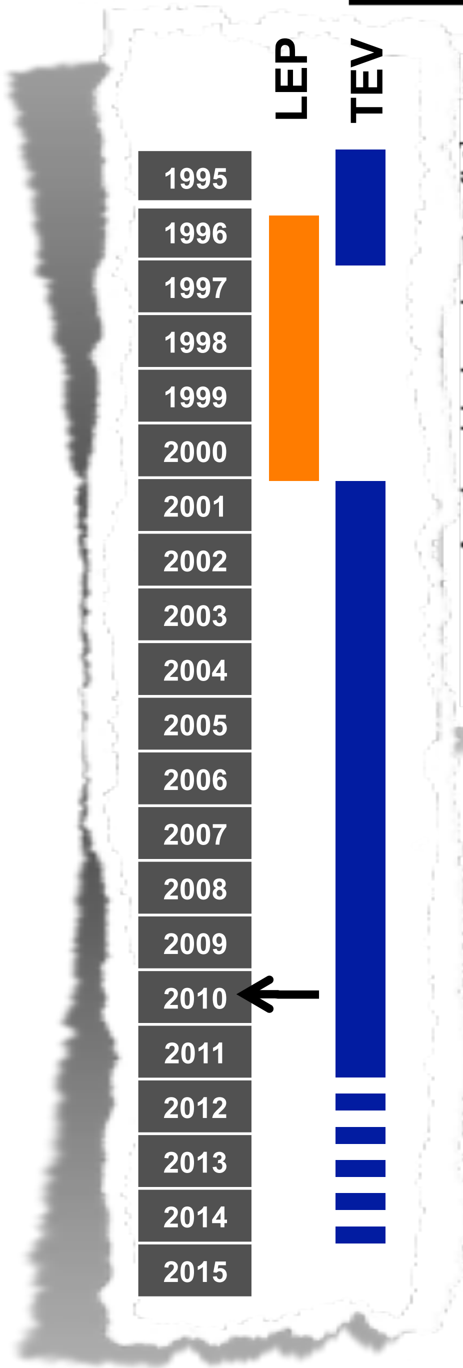




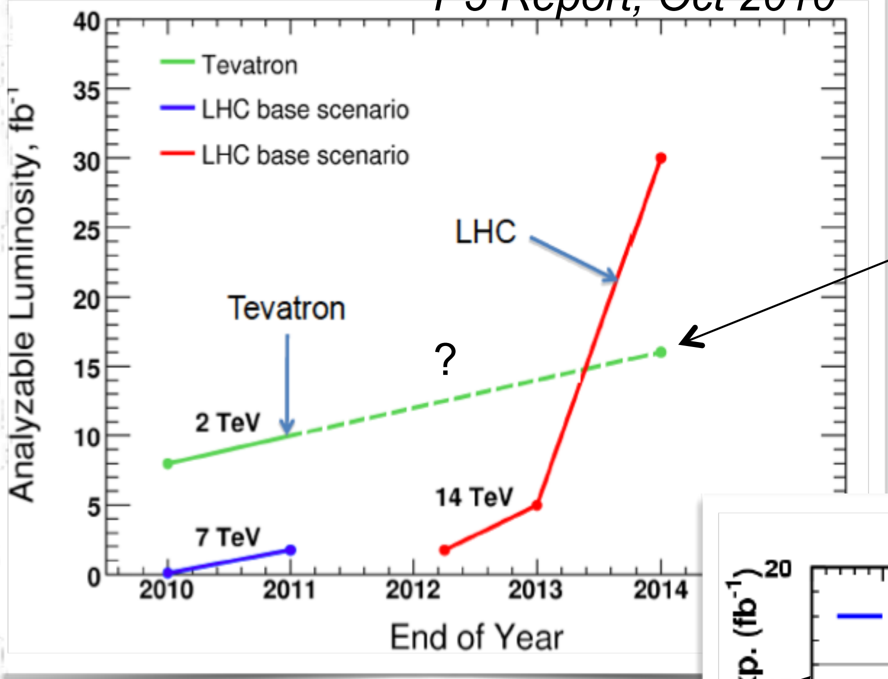
Over the years Higgs sensitivity projections were produced with increased degree of sophistication and realism.

The Tevatron was expected to be sensitive precisely in this mass range!

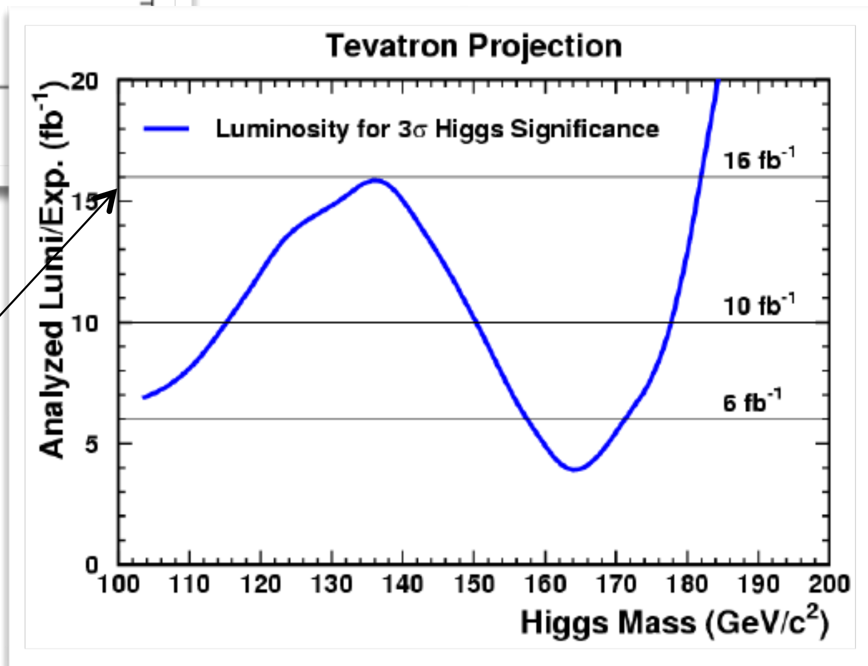
Historical Perspective



P5 Report, Oct 2010



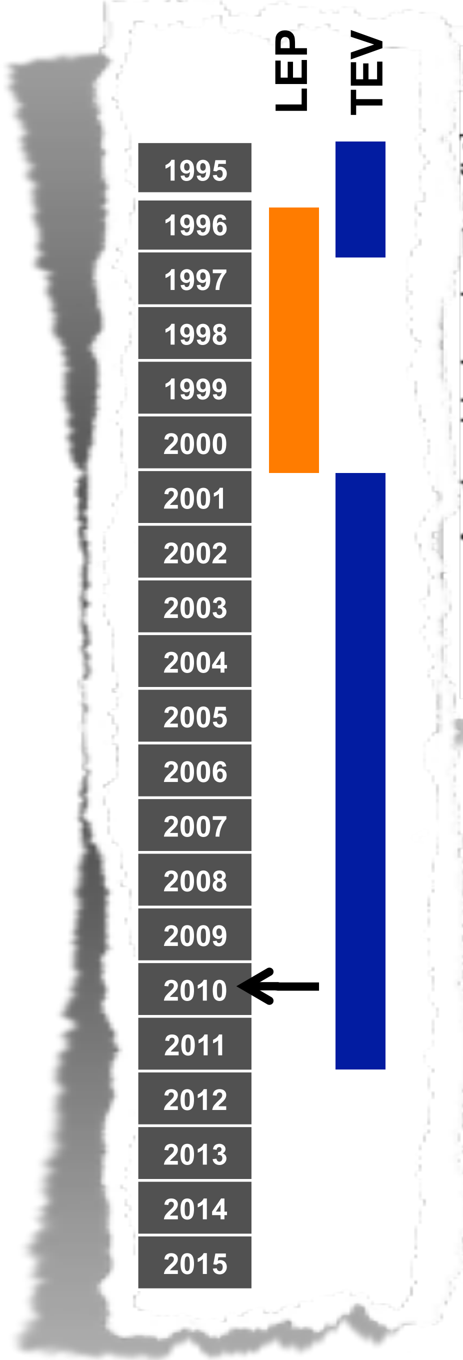
Strong support by HEP community, Fermilab PAC and P5 for Tevatron run extension till 2014



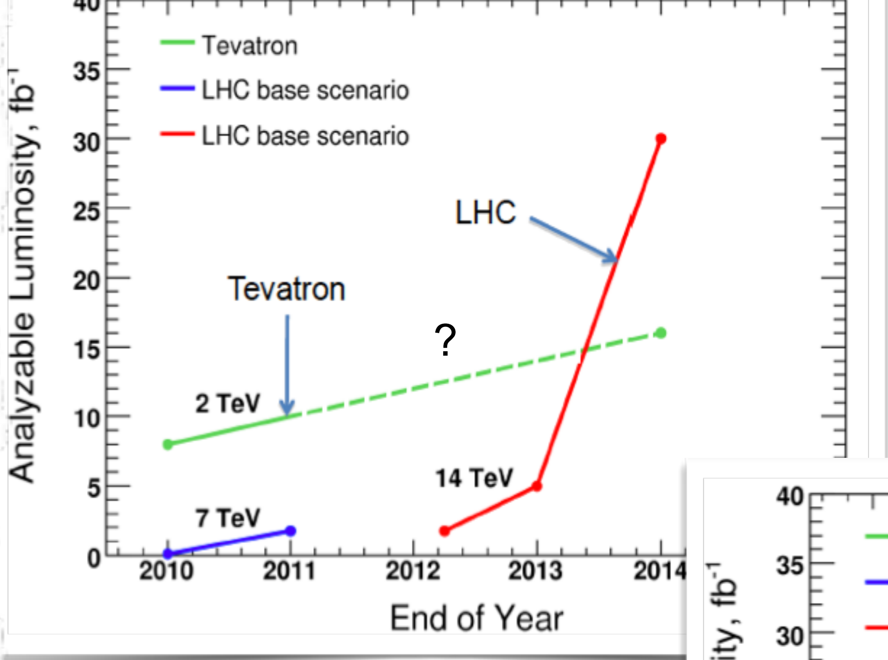
Expect ≥3σ sensitivity over interesting mass range with 16 fb^{-1} analyzed/exp and a number of improvements.

Exploit complementarity between Tevatron and LHC to gain further insight

Historical Perspective

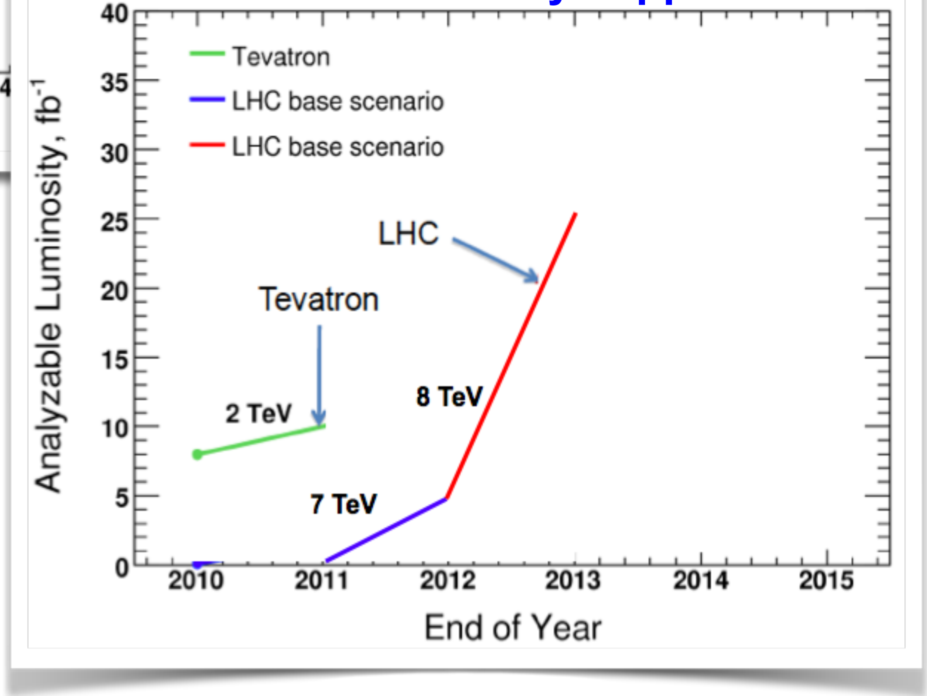


P5 Report, Oct 2010



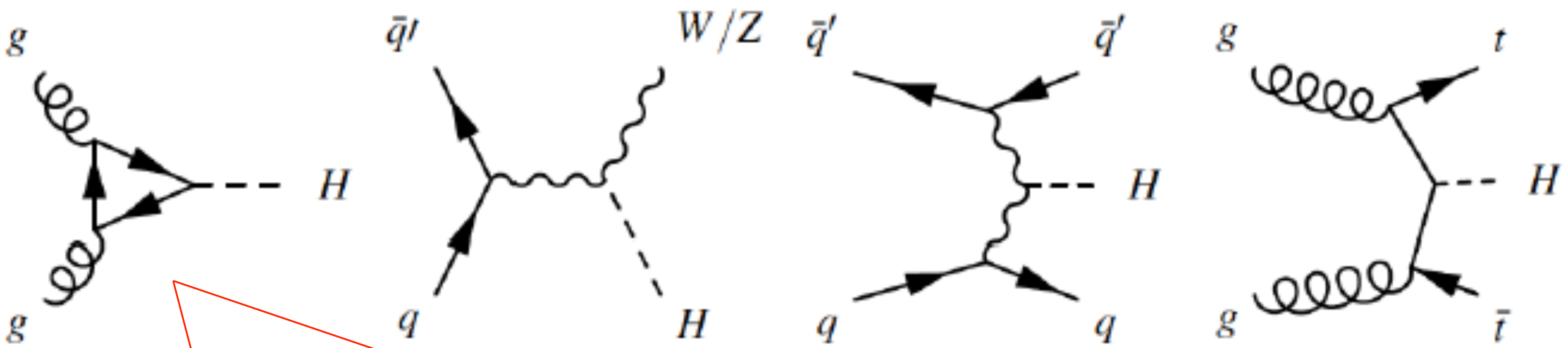
Tevatron ended in Sep 2011.
LHC adjusted the schedule.

What actually happened

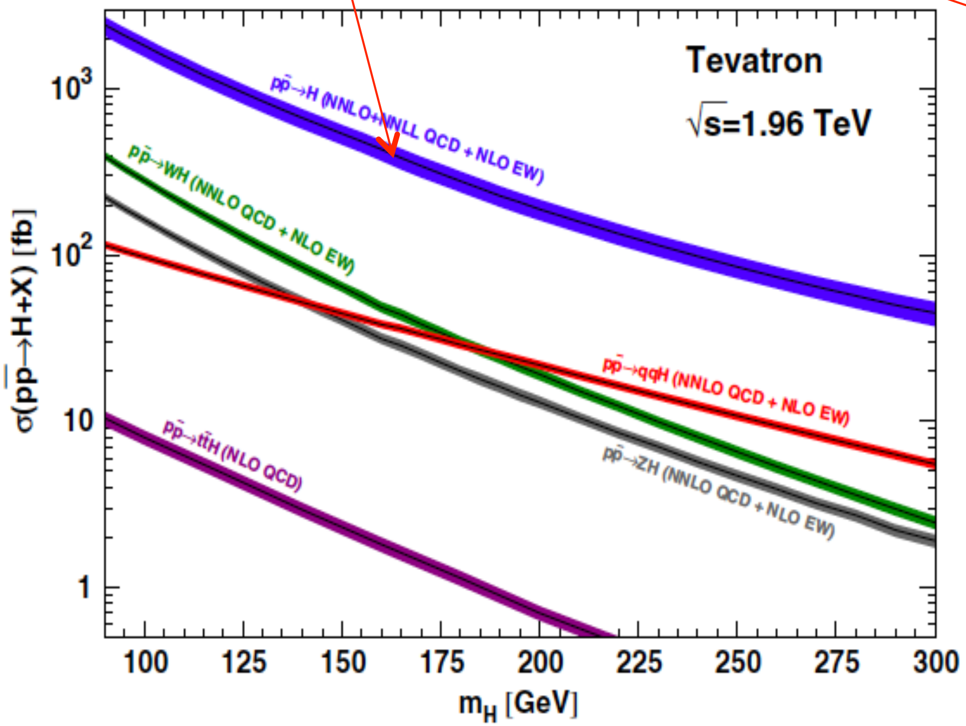


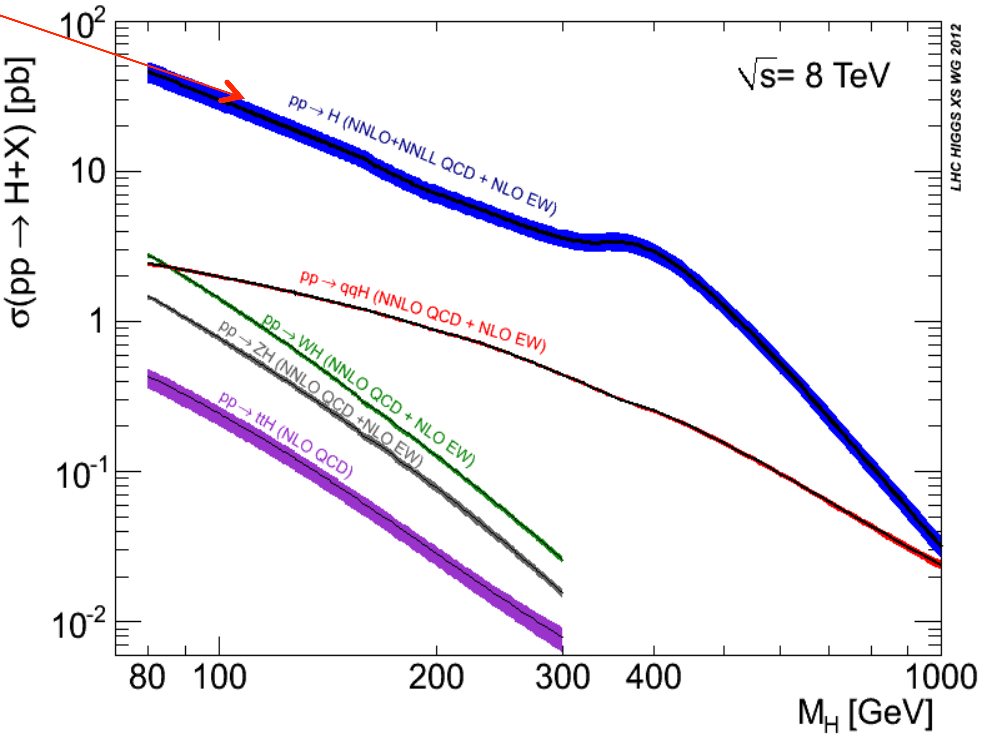
Renewed efforts at Tevatron to try to leave the strongest possible legacy!

SM Higgs Production at Hadron Colliders

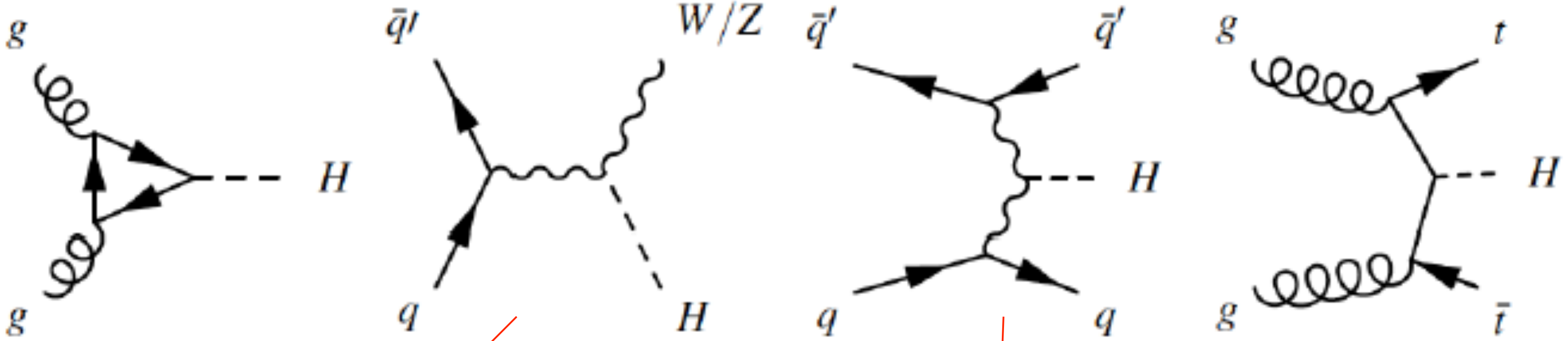


Main production mechanism

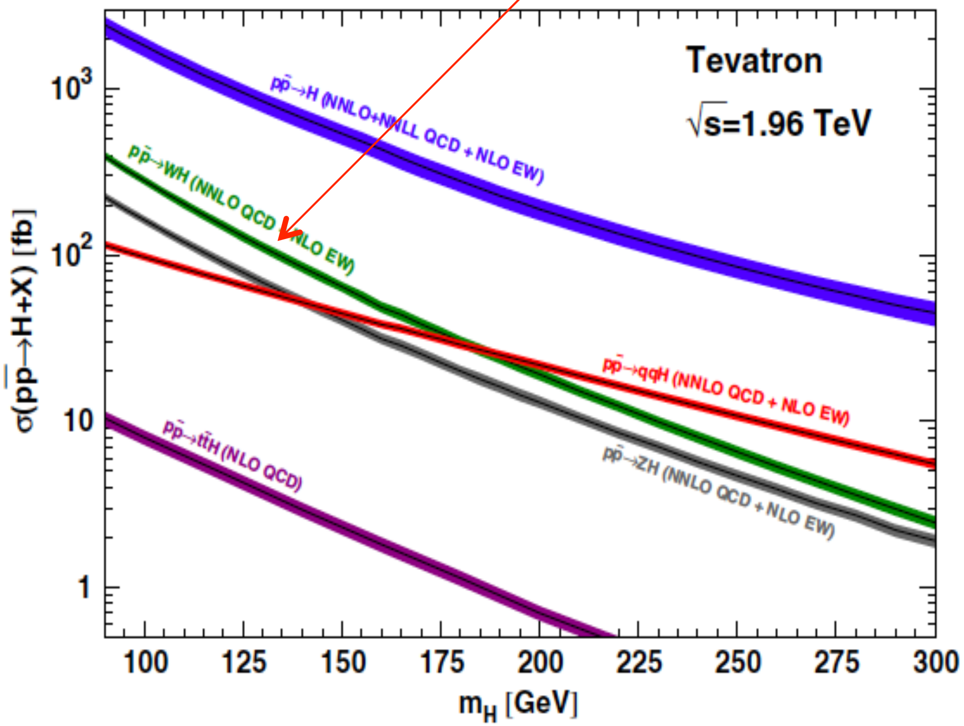


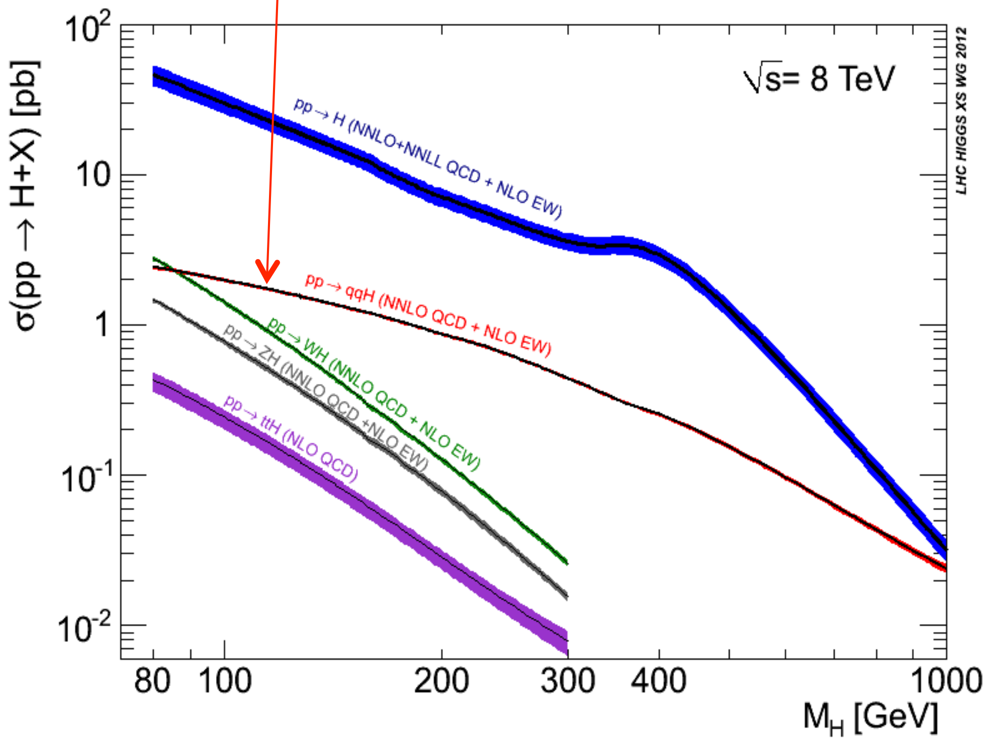


SM Higgs Production at Hadron Colliders

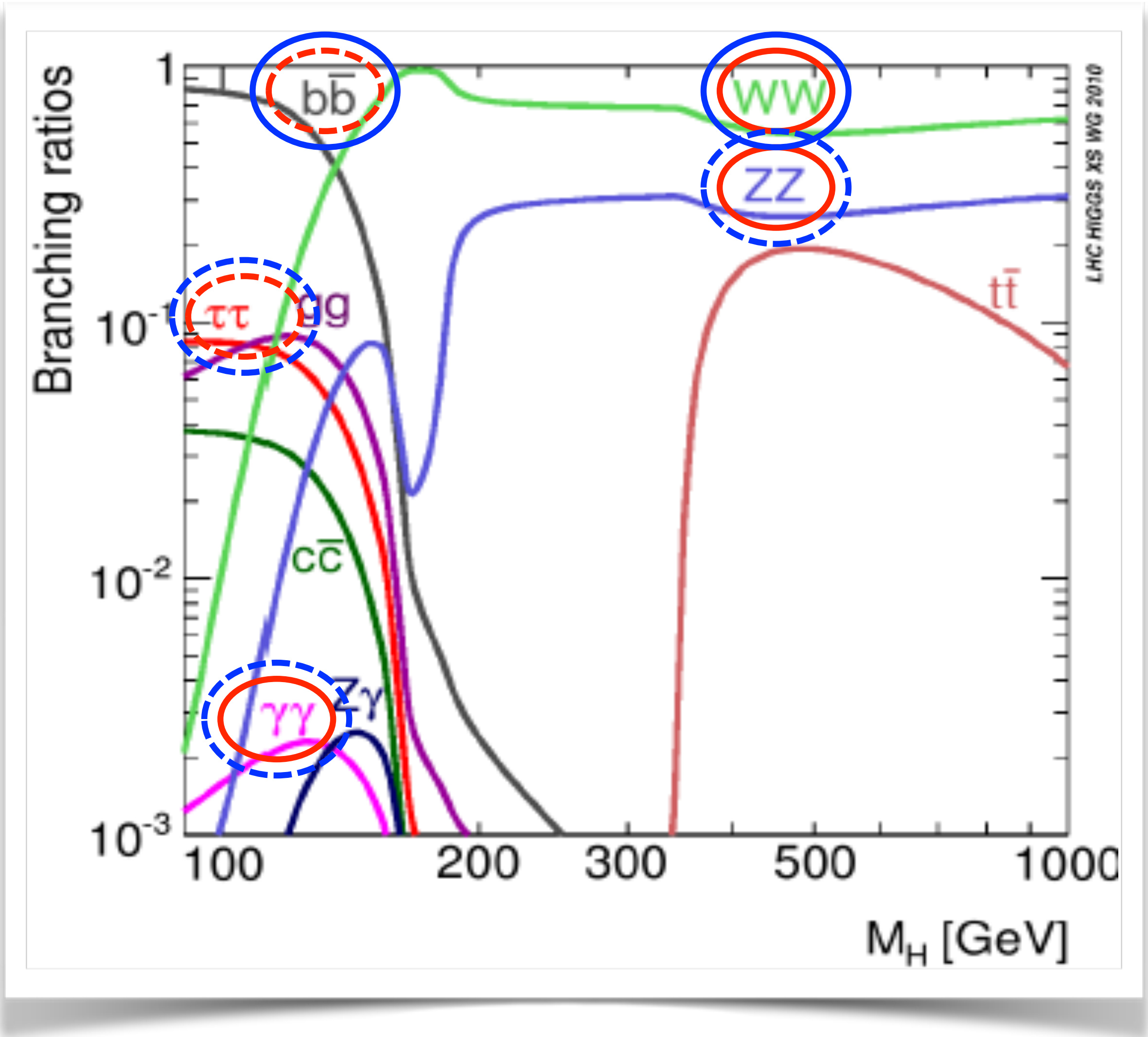


Next most important production mechanism





SM Higgs Decay Modes



m_H<135 GeV: H→bb̄ dominates

m_H>135 GeV: H→W^+W^- dominates

Main mode

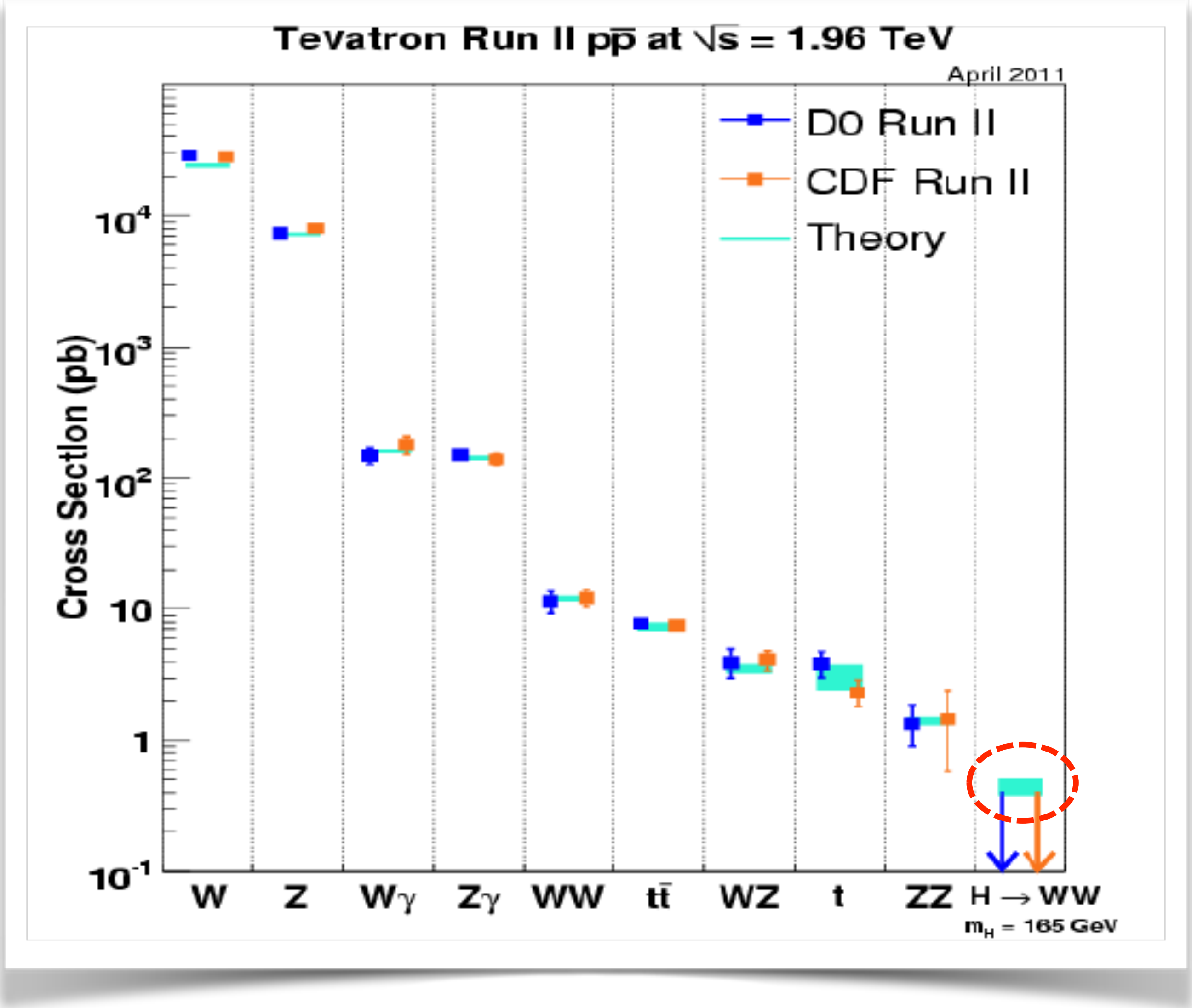
Supporting mode

LHC

Tevatron

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

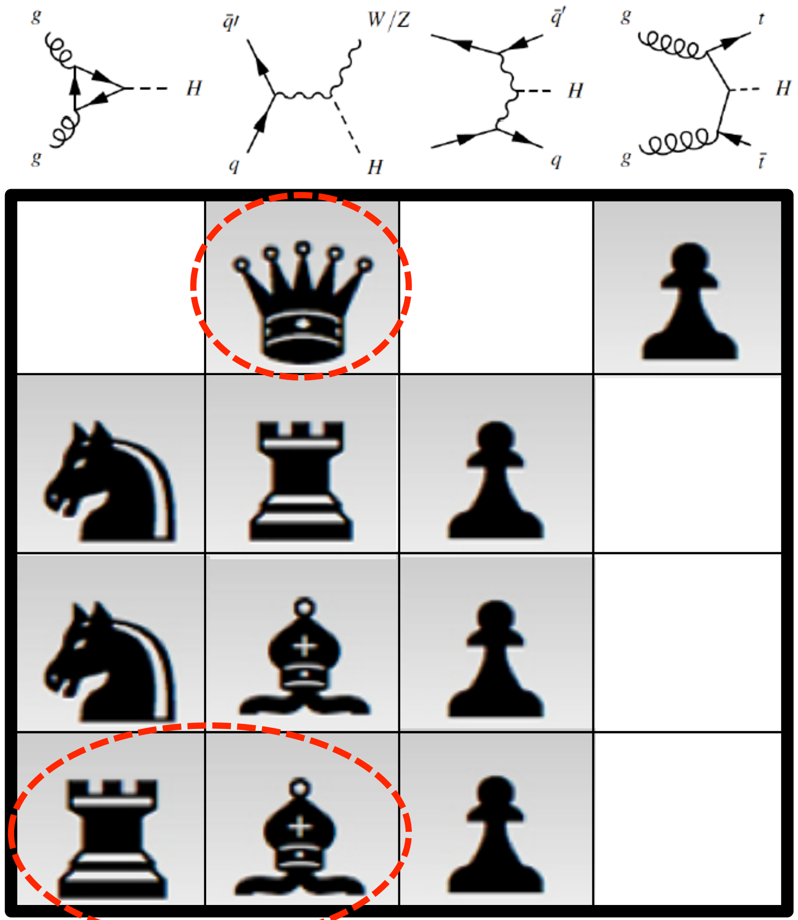
The Stairway to the Higgs



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

Search Strategies

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

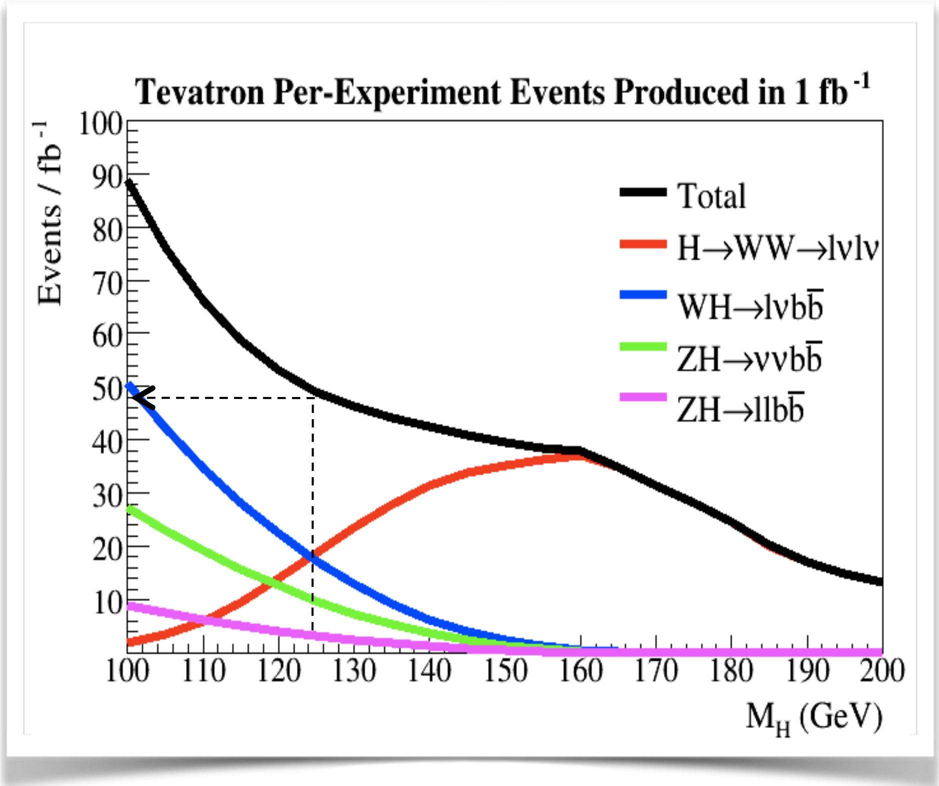


$H \rightarrow b\bar{b}$

$H \rightarrow \tau^+\tau^-$

$H \rightarrow \gamma\gamma$

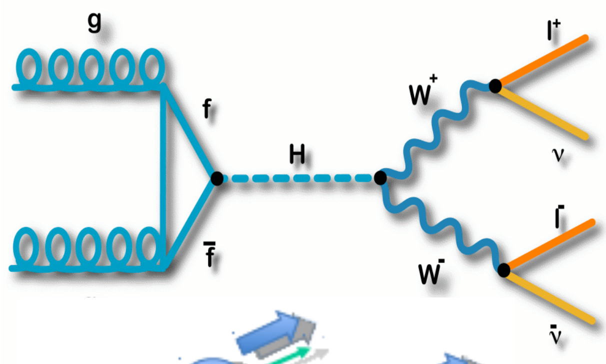
$H \rightarrow W^+W^-$

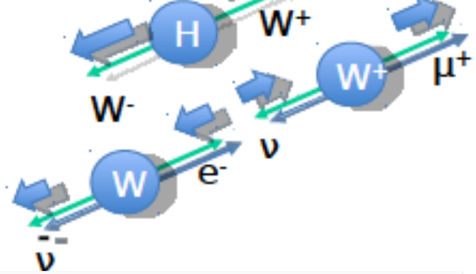


For m_H=125 GeV, ~1000 Higgs events produced at the Tevatron in the main search channels with 10 fb^{-1}!

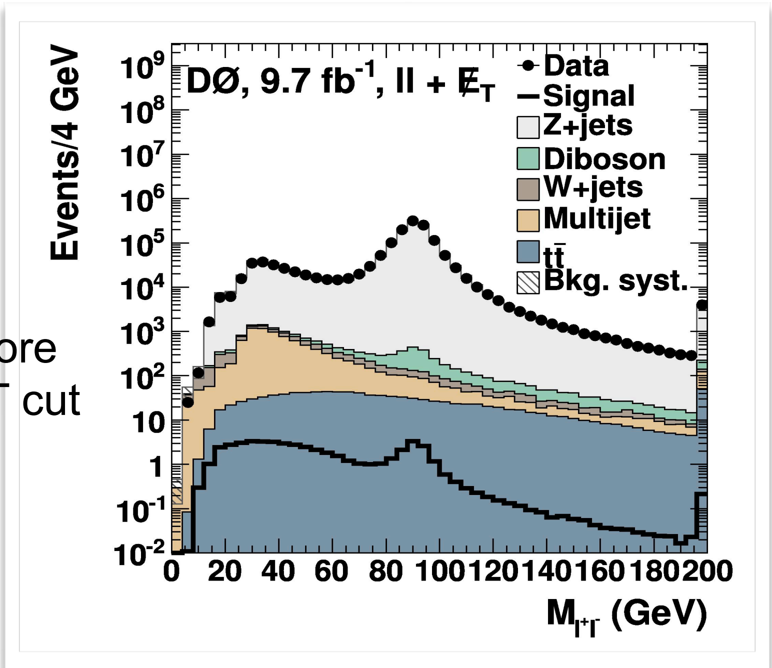
Searching for H→WW→lνlν

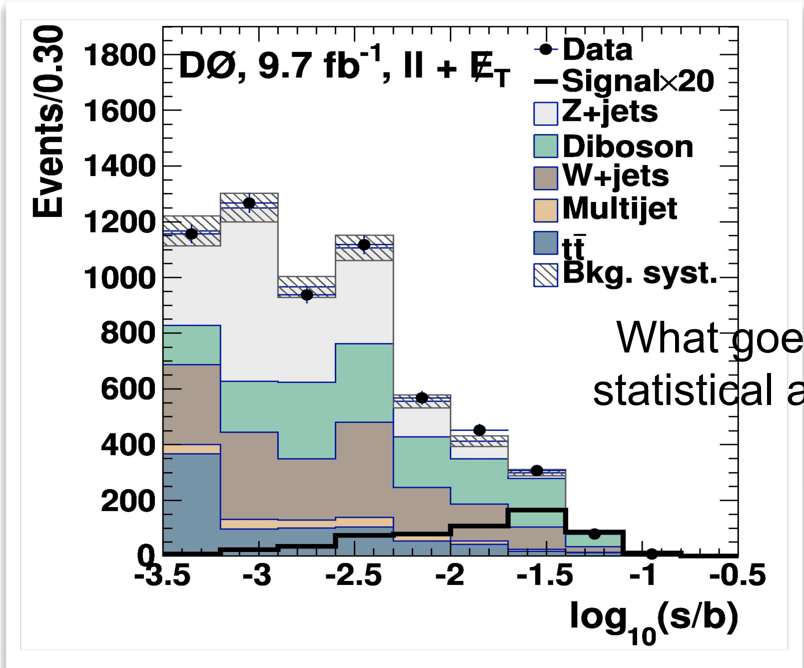
- Highest sensitivity channel in m_H~130-200 GeV range.
- Signature: opposite-sign dileptons+MET
- Main backgrounds after MET cut: WW, W/Z+jets,Wγ
- After final selection expect (m_H=165 GeV):
  ~7 signal events/fb^{-1}/experiment with S:B~1:50-1:100
- Aggressive program of improvements over the years to improve sensitivity:
  - Lepton ID/trigger, event selection optimization
  - Multivariate techniques





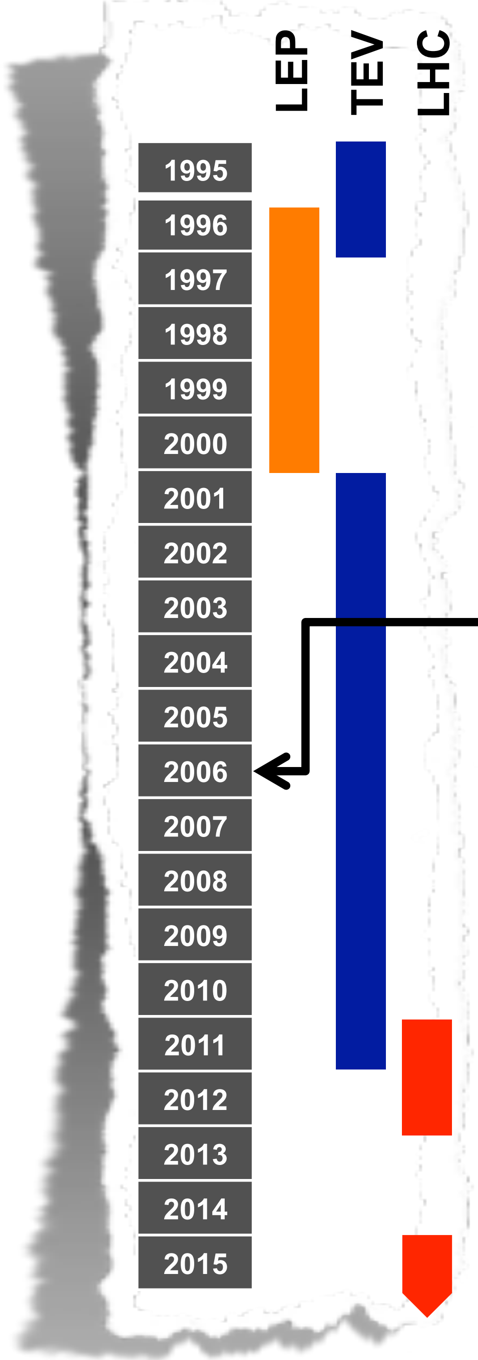
Before MET cut

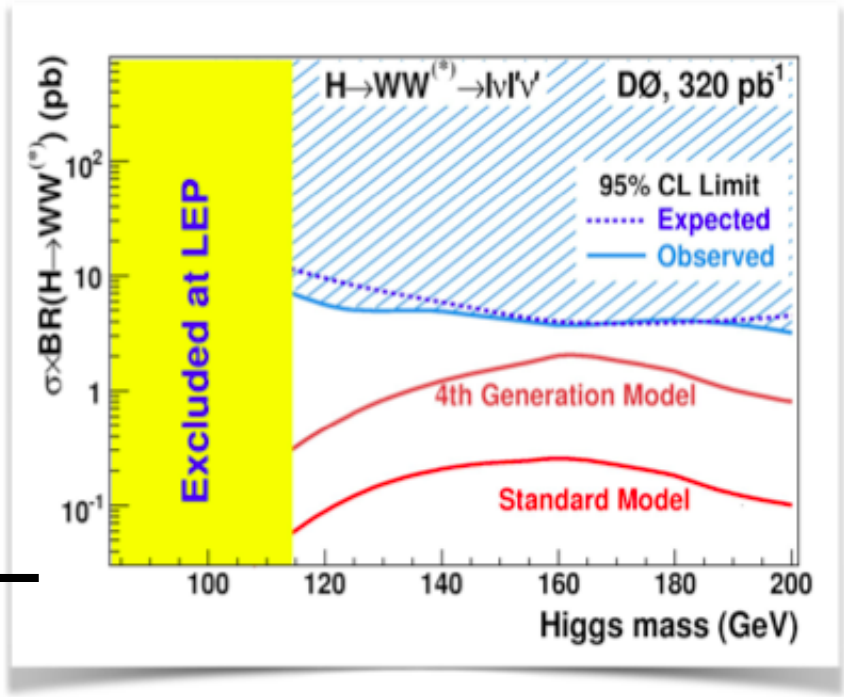




What goes into statistical analysis

Some H→WW Highlights



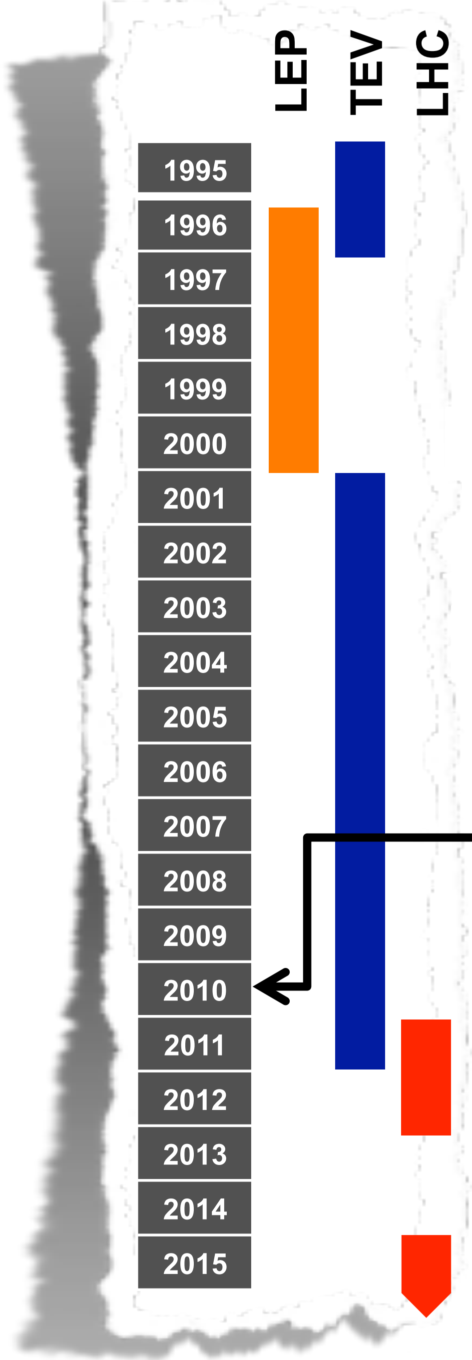


Expected sensitivity:

~10xSM at m_H=165 GeV

~100xSM at m_H=125 GeV

Some H→WW Highlights



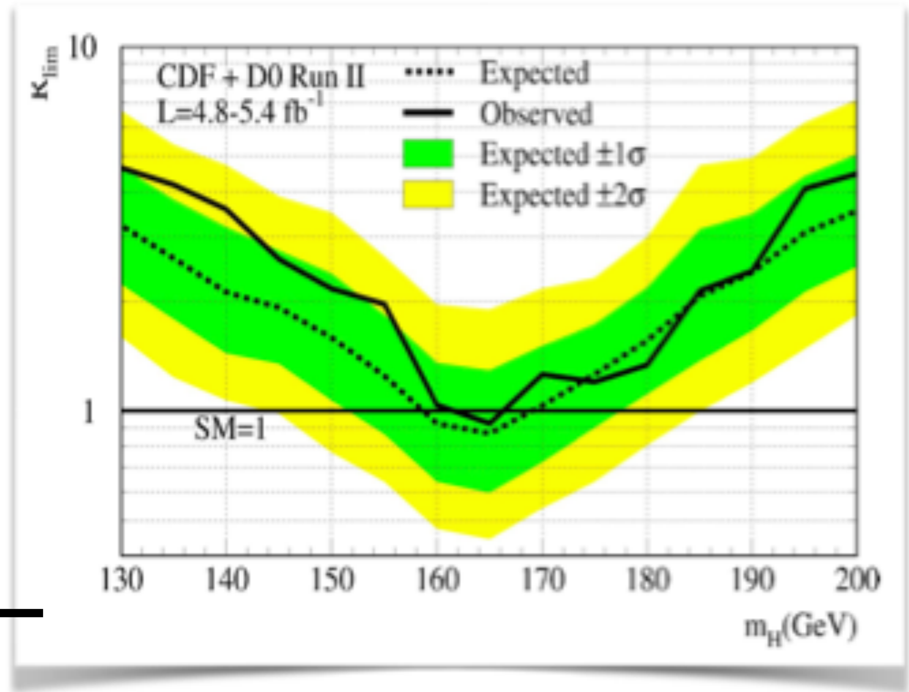
TOPCITE = 100+

PRL Editors' Suggestion

PRL Cover

"Physics" Viewpoint article

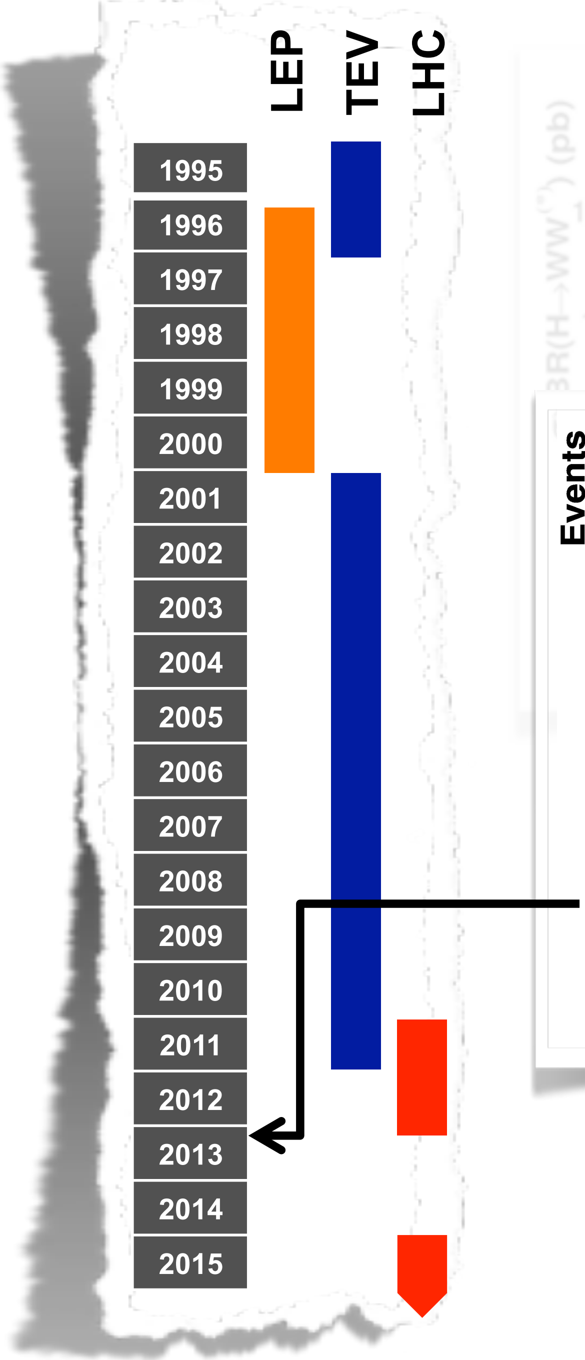
4 years later….

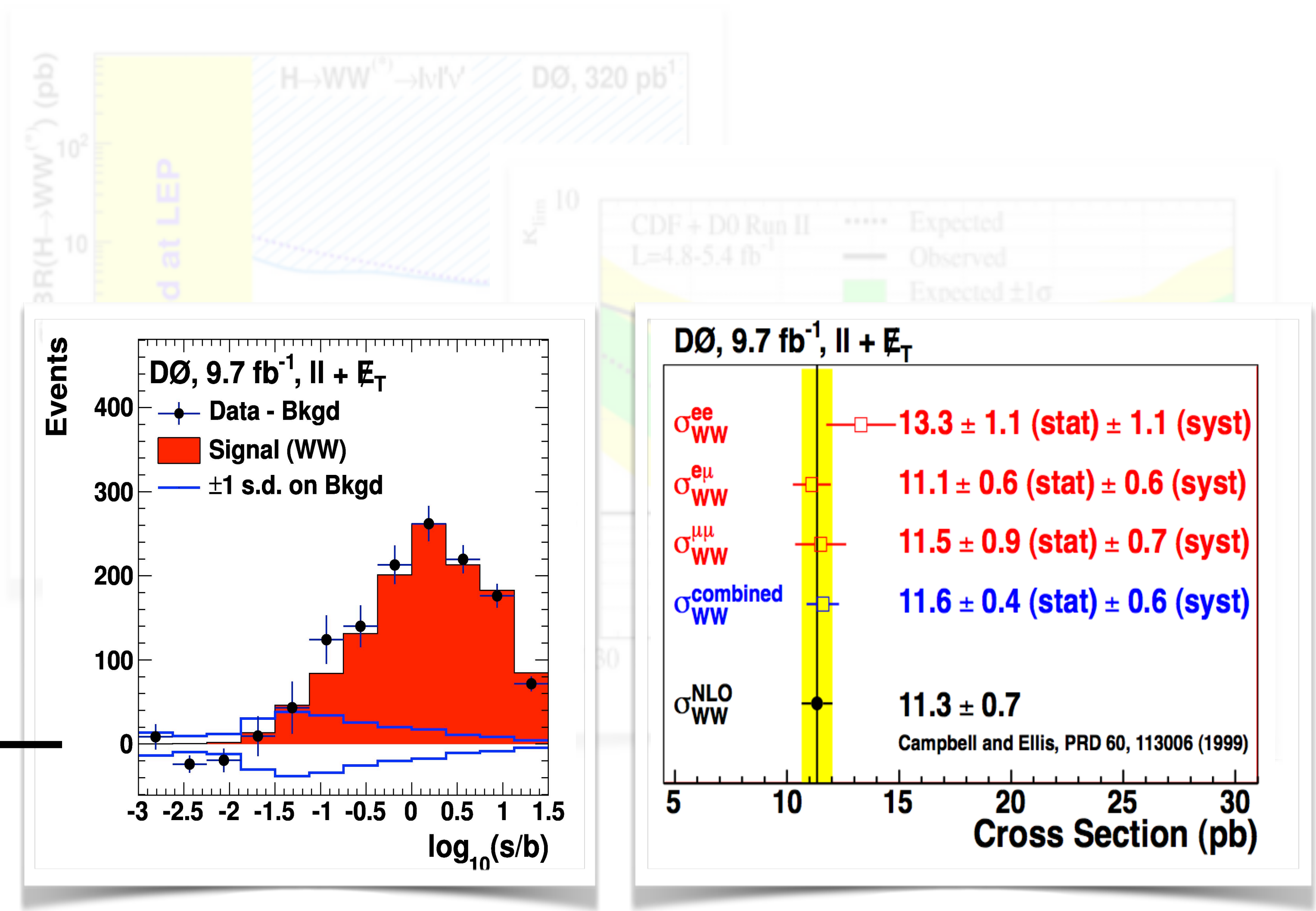


The Tevatron brings new information about the Higgs

First Higgs exclusion beyond LEP

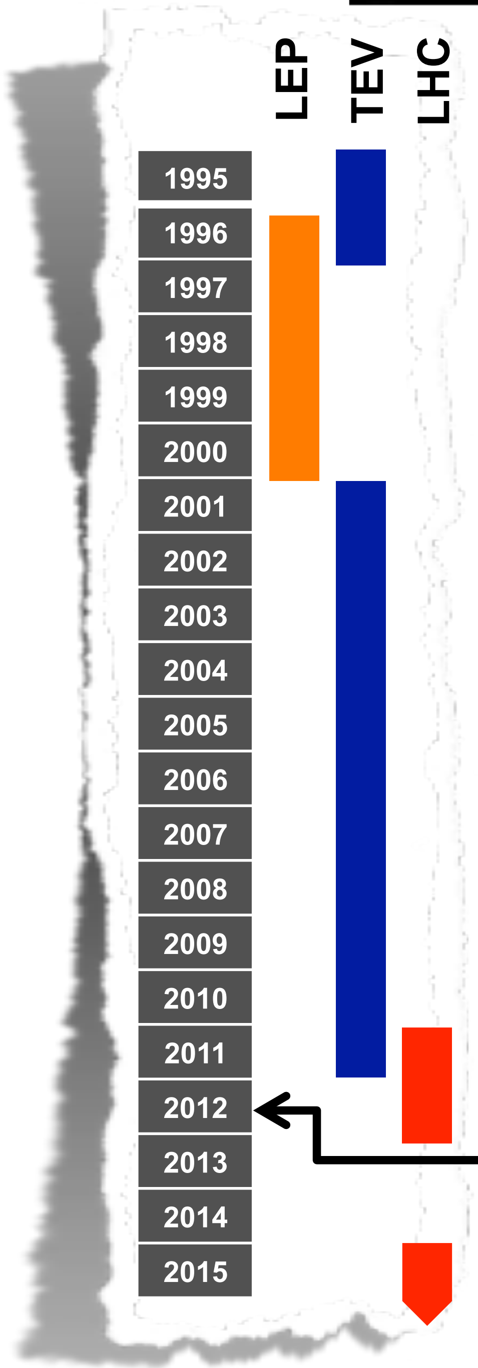
Some H→WW Highlights

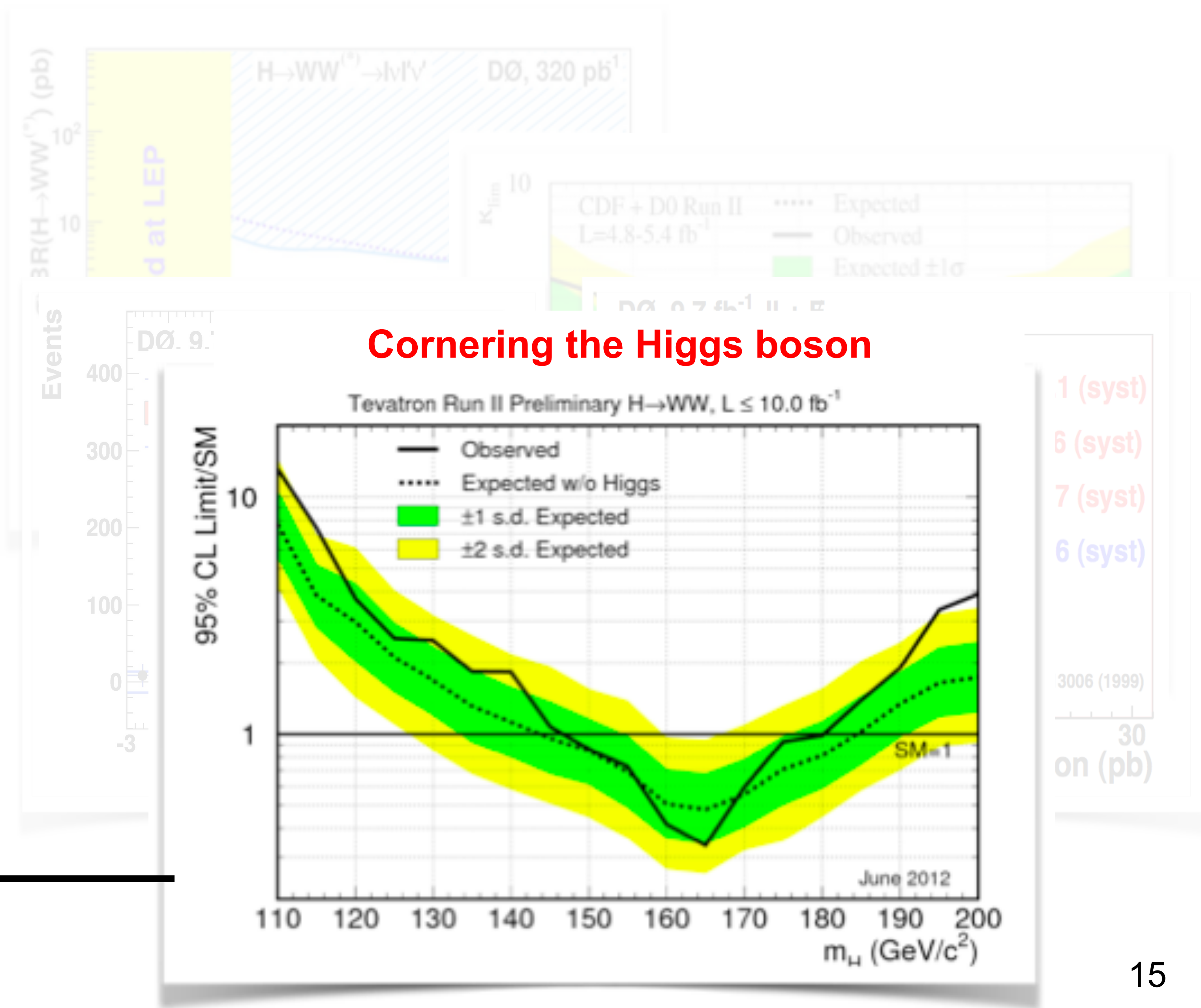




Validation of H→WW search strategy by
measuring correct cross section for WW

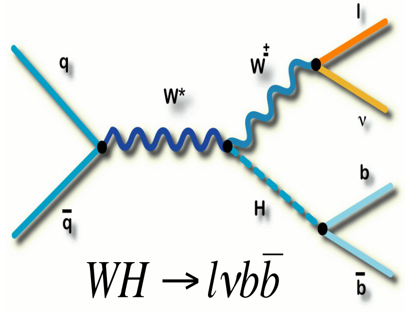
Some H→WW Highlights

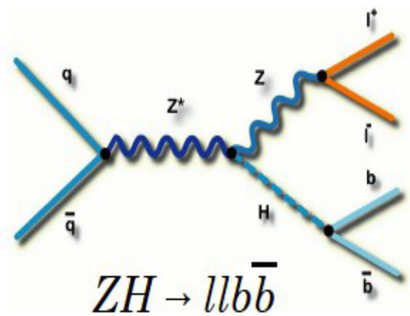


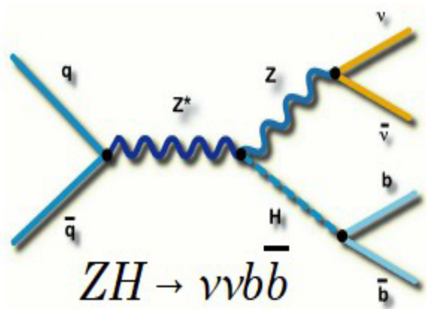


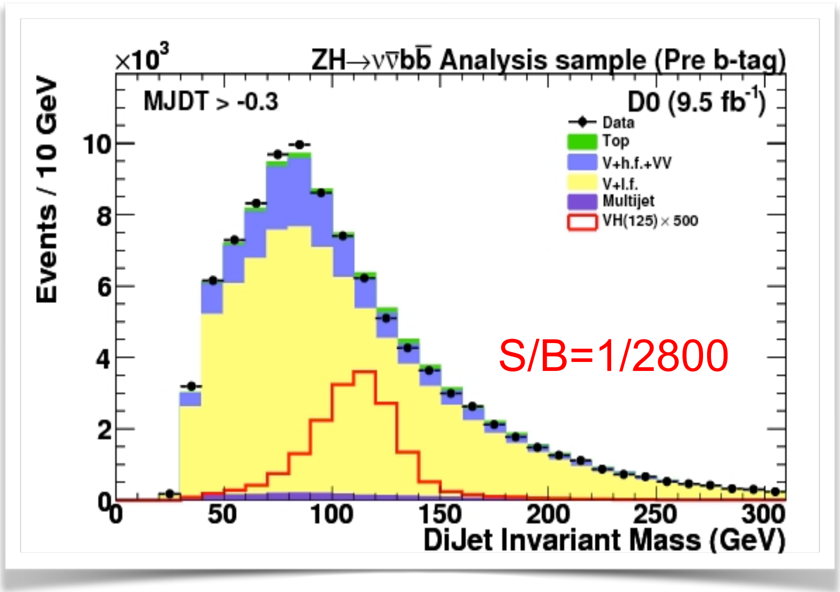
Searching for H→b$\bar{b}$

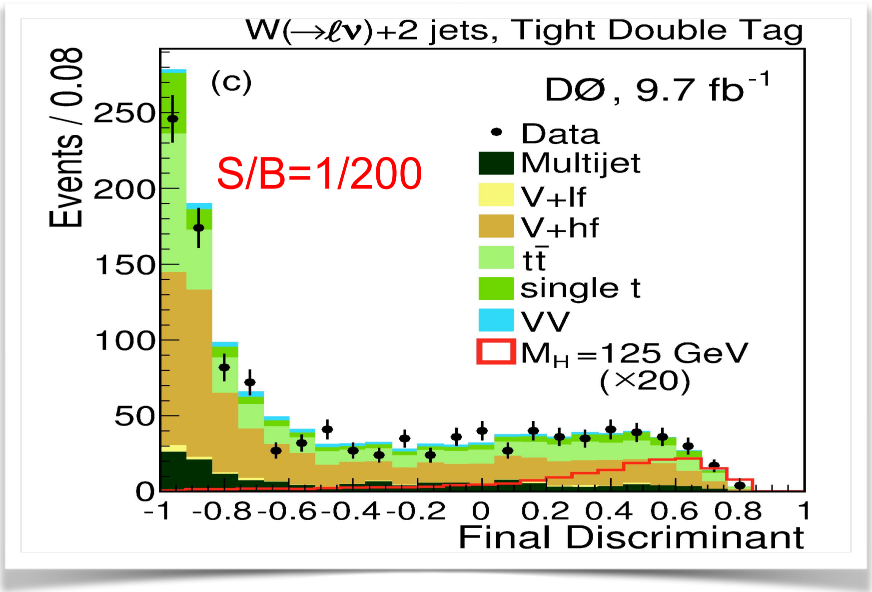
- Highest sensitivity channel at the Tevatron for m_H<130 GeV.
- Signature: leptonic W/Z decays+jets
- Main challenge: understand/suppress background (eventually dominated by W/Z+heavy-flavor).
- Key aspects:
  - Lepton, jet, MET trigger/reconstruction
  - B-tagging
  - Dijet mass resolution
  - Multivariate techniques
  - Minimize background uncertainties



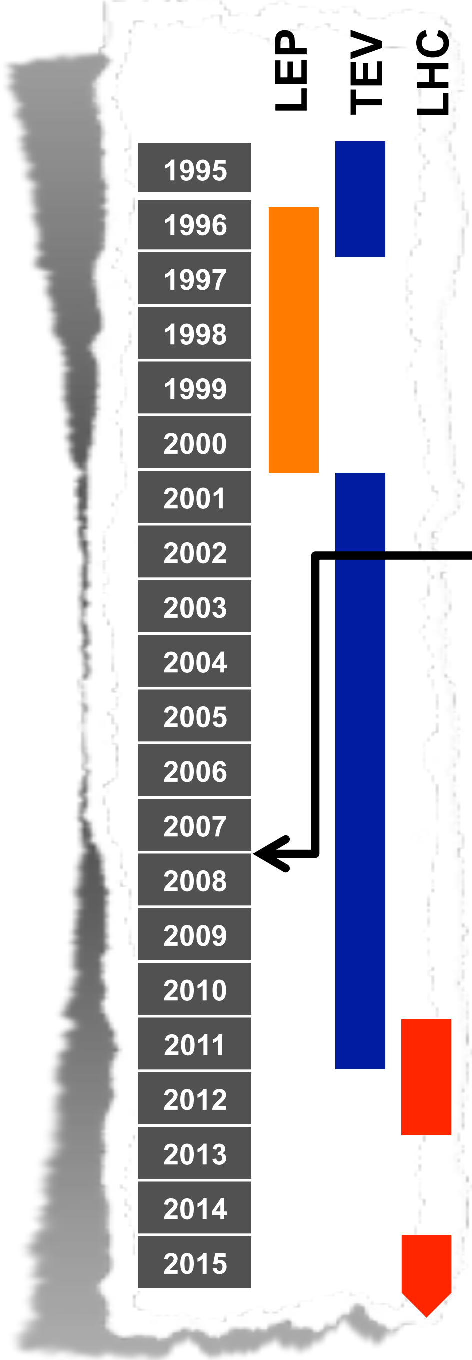


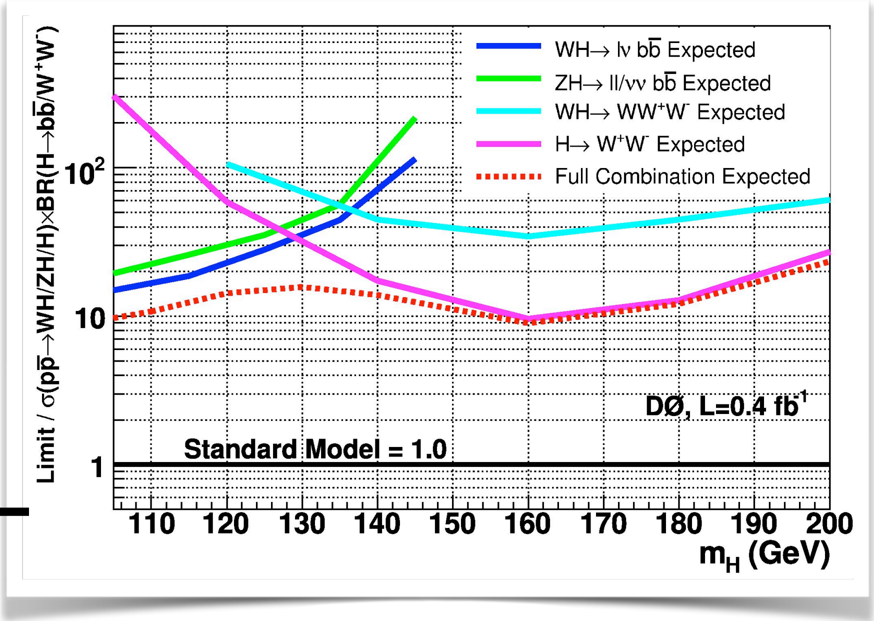






Some H→bb Highlights



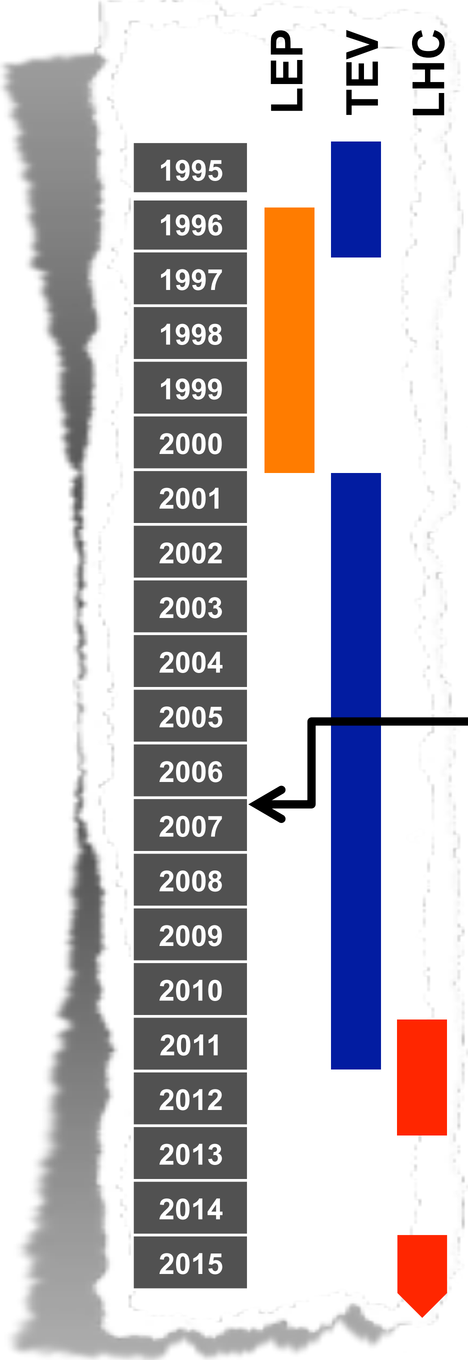


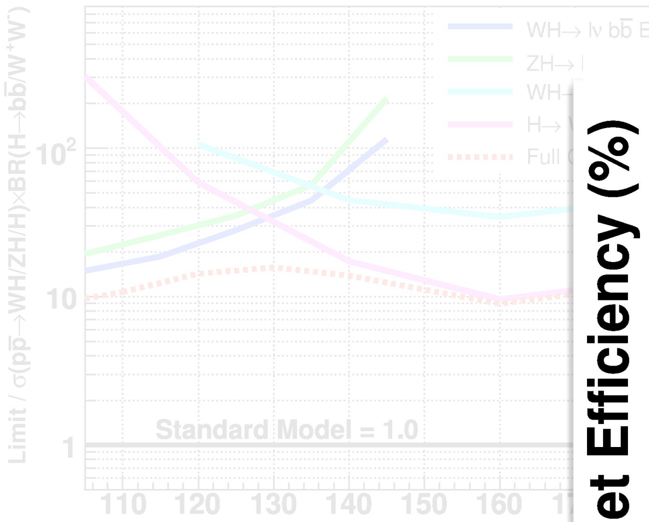
Expected sensitivity:

~20xSM at m_H=115 GeV

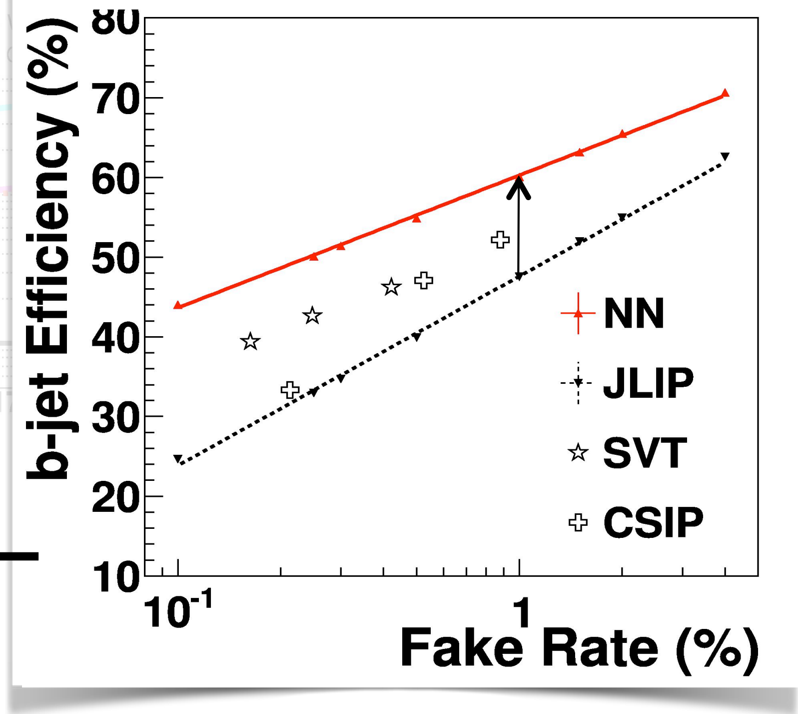
(using JLIP b-tagger)

Some H→bb Highlights





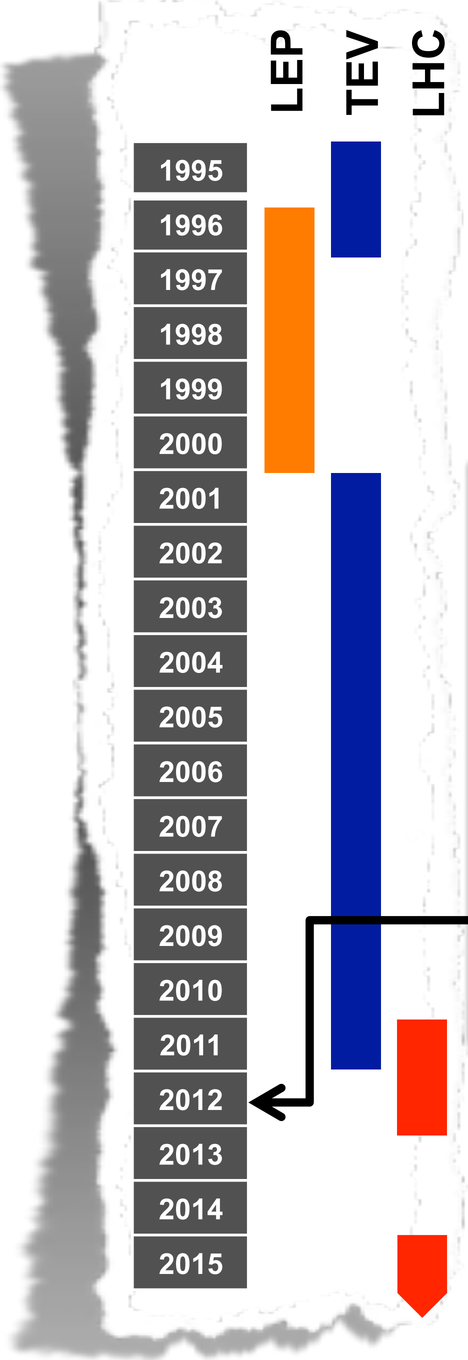
Multivariate b-tagging for the first time at a hadron collider

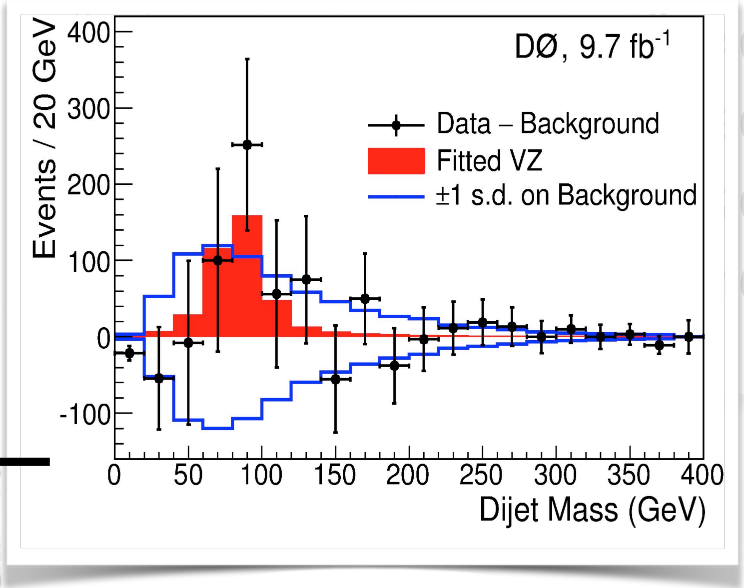


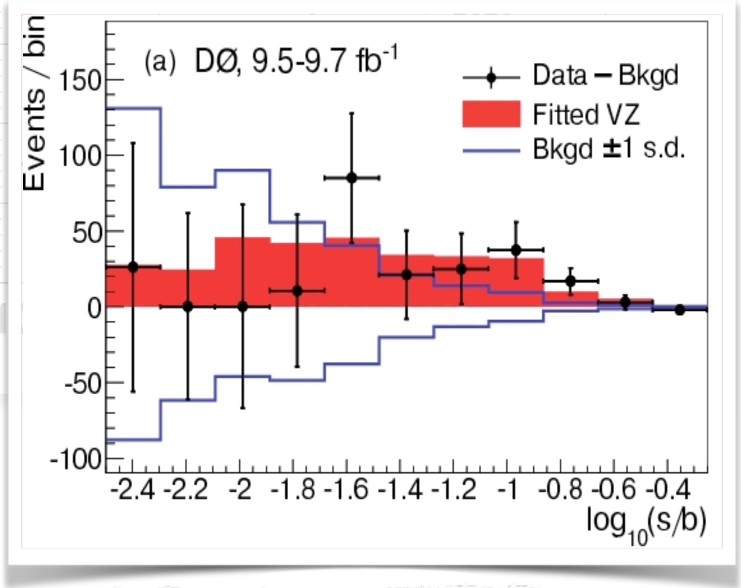
Significant impact on H→bb search

Further improved over the years (MVA_{bl}, MVA_{bl}*)

Some H→bb Highlights





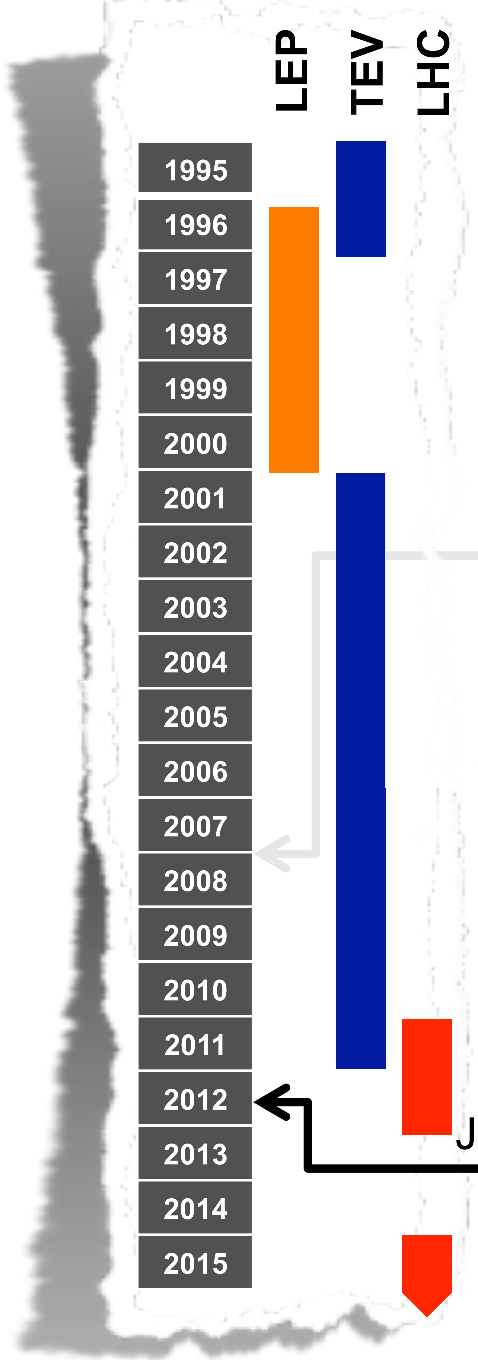


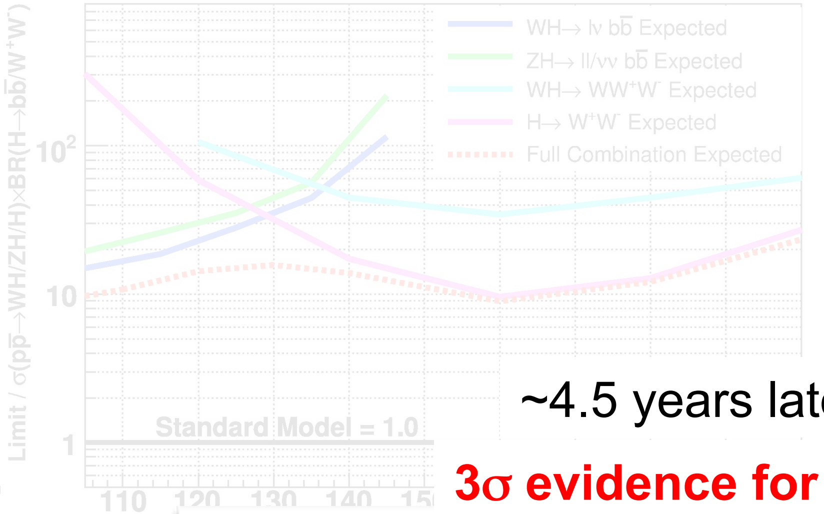
Validation of VH, H→bb search strategy by measuring correct cross section for VZ, Z→bb

$$\sigma_{VZ}^{meas} = 3.3 \pm 1.4 \text{ pb}$$

$$\sigma_{VZ}^{SM} = 4.4 \pm 0.3 \text{ pb}$$

Some H→bb Highlights





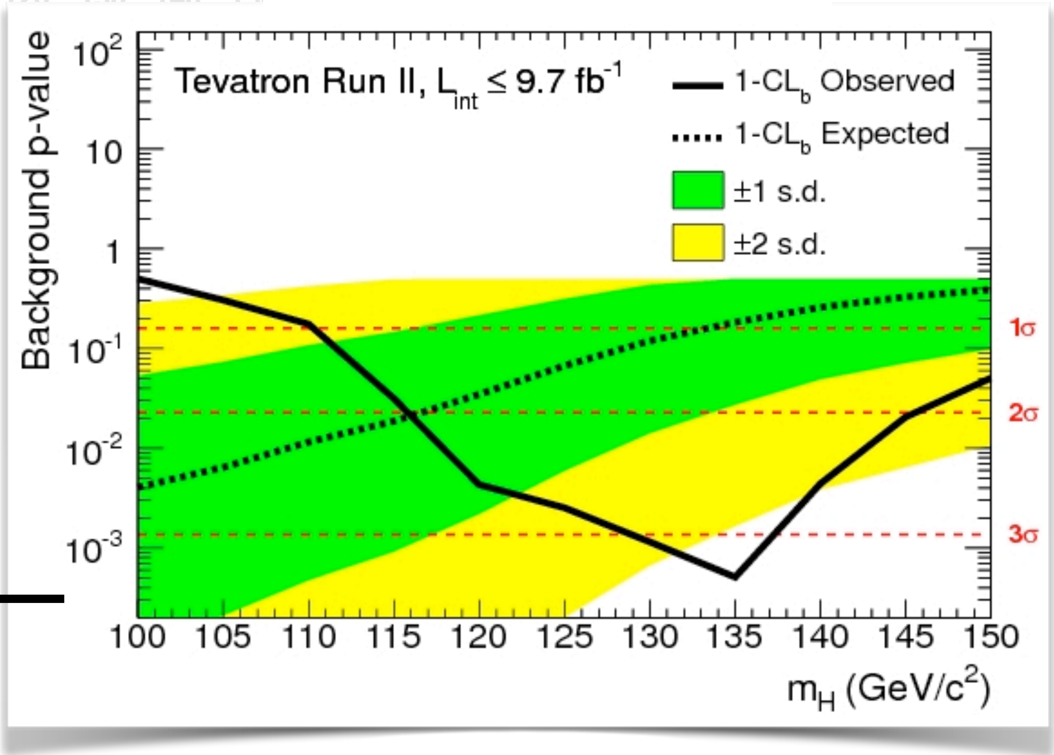
TOPCITE = 100+

PRL Editors' Suggestion

"Physics" Viewpoint article

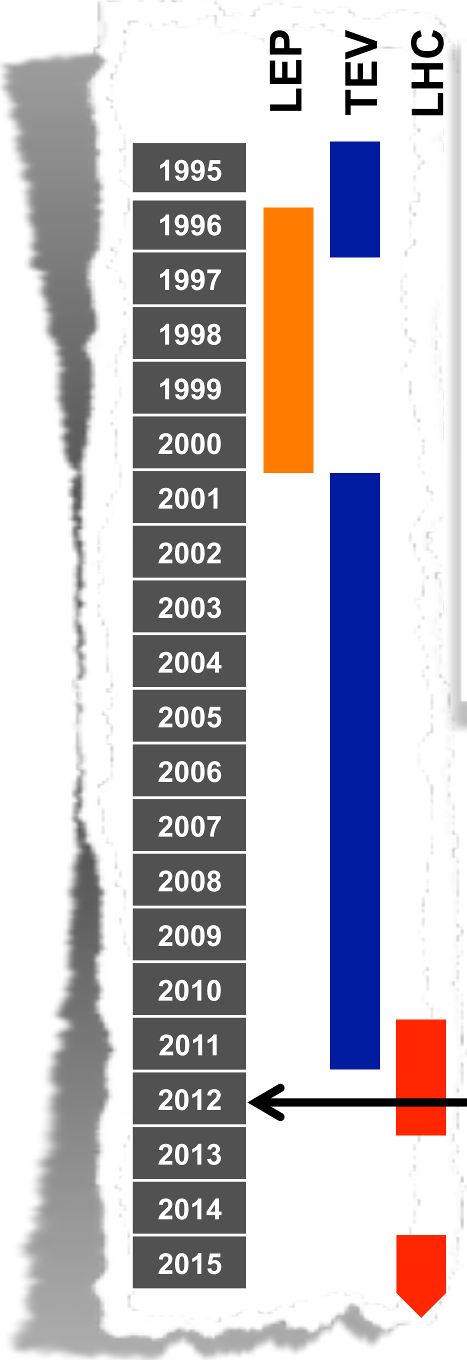
~4.5 years later….

3σ evidence for H→bb



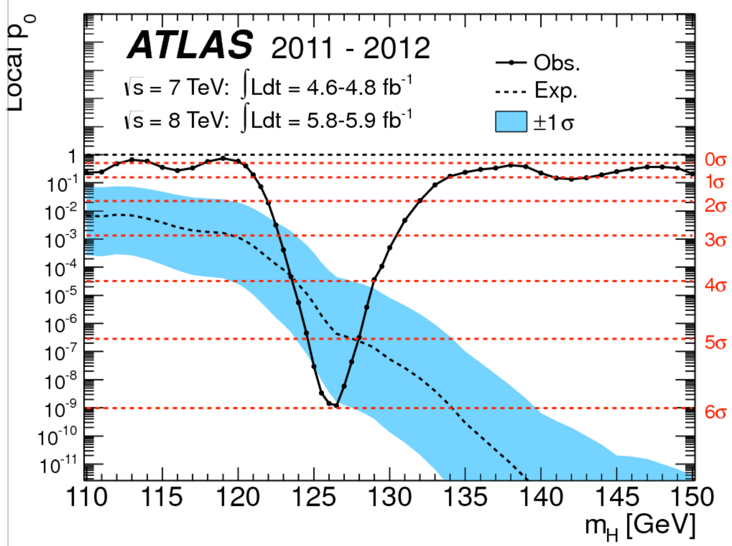
July 3, 2012

July 4, 2012: “Higgsdependence Day”

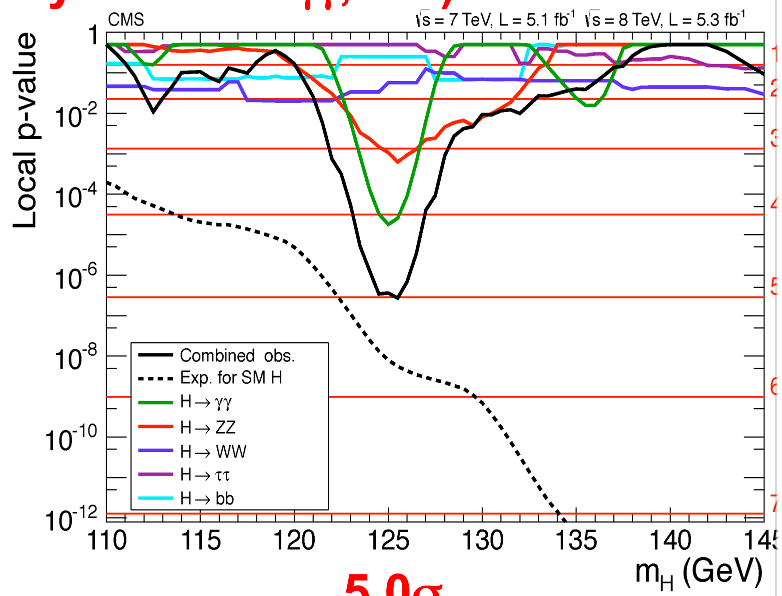


July 4, 2012

Observation (mainly from H→γγ, ZZ*)

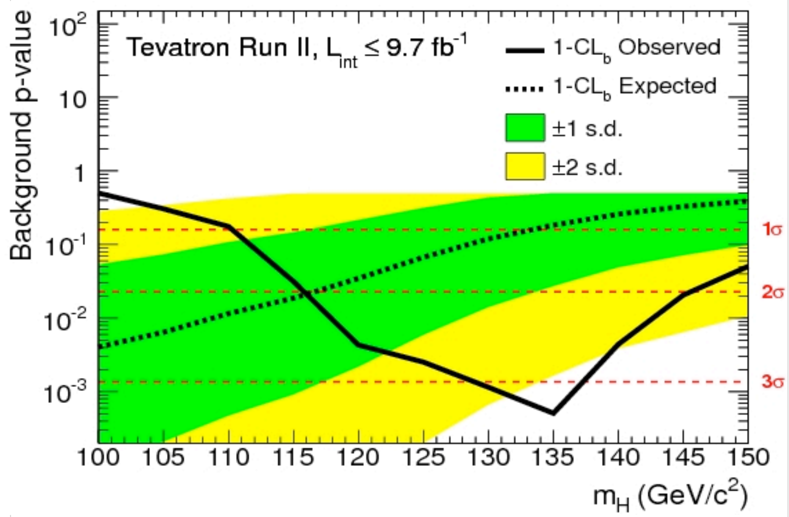


5.9σ

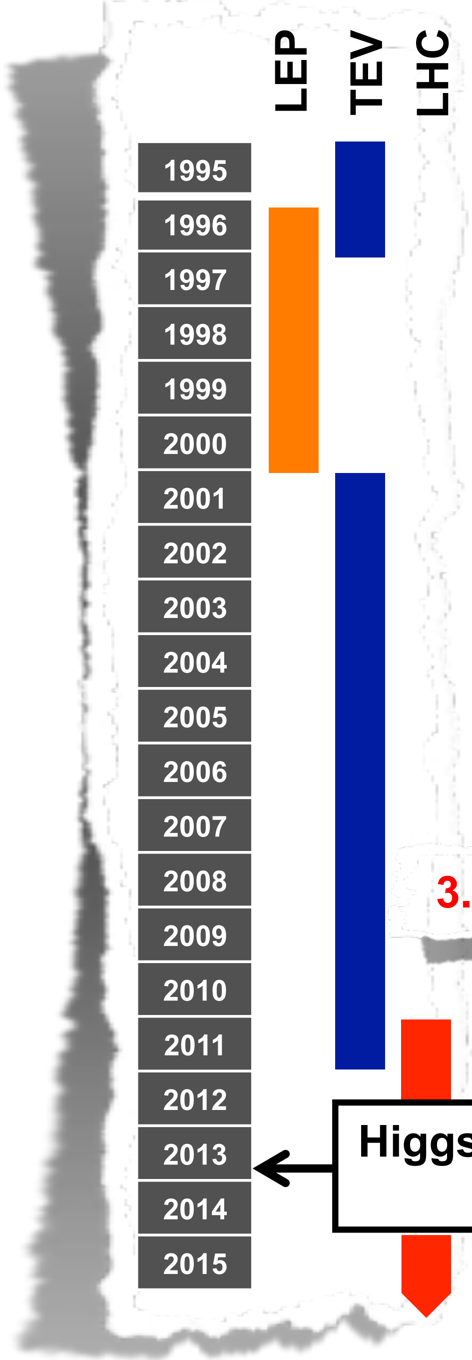


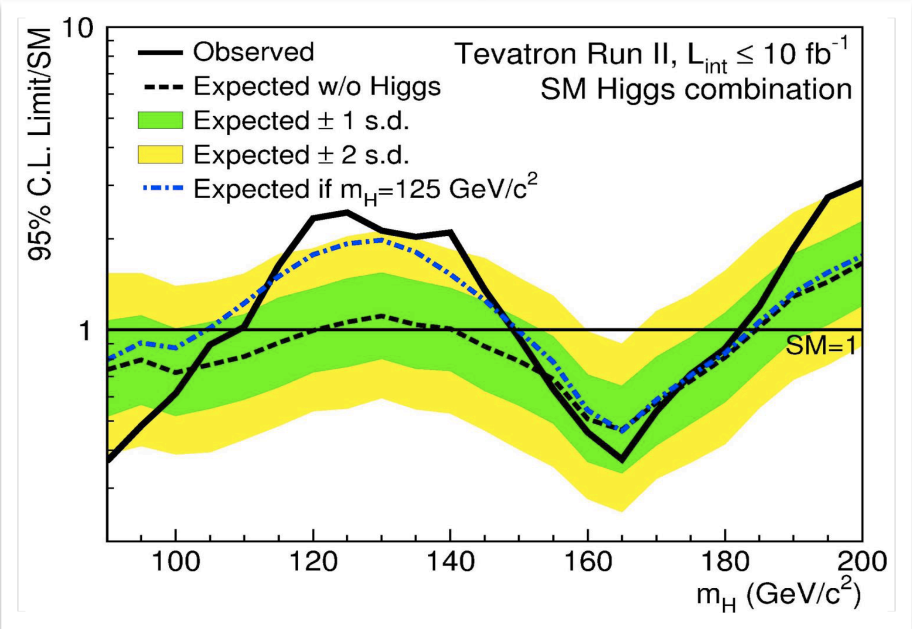
5.0σ

3σ evidence for H→bb



Final Tevatron Combined Results





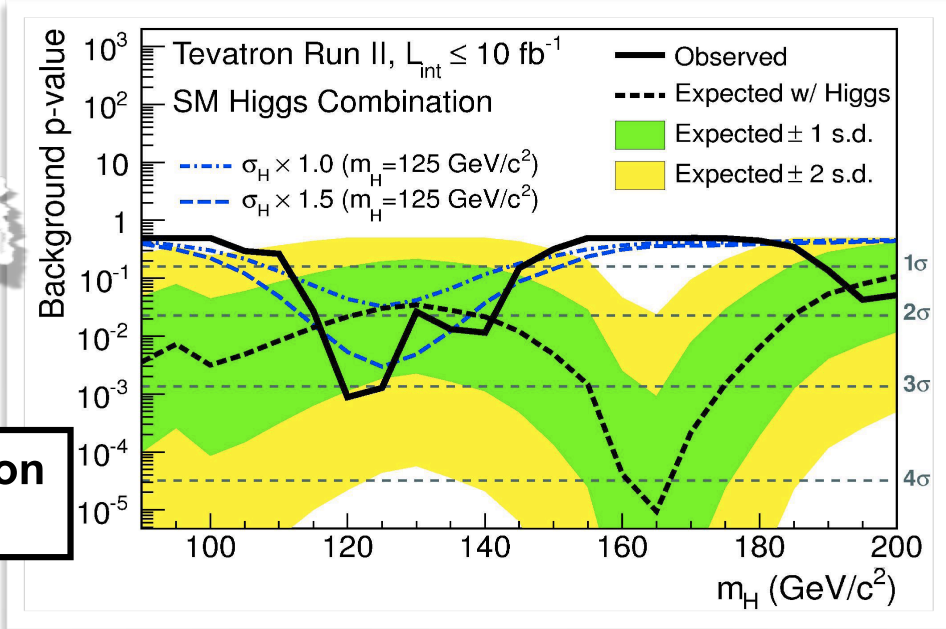
Achieved SM sensitivity over most of mass range accessible

Observed exclusion:

$90 < m_H < 109$ GeV

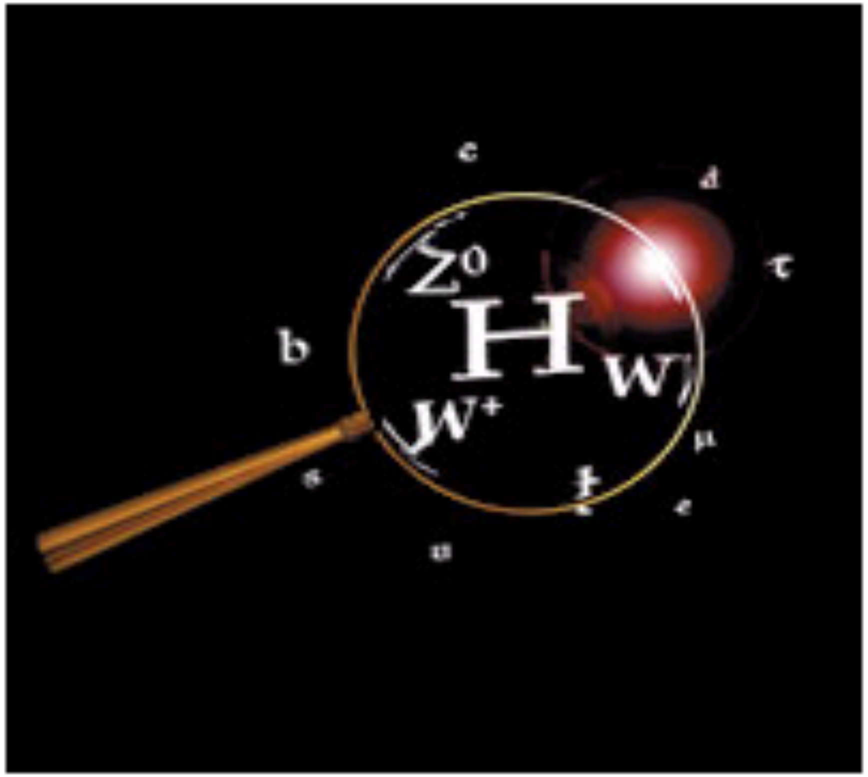
$149 < m_H < 182$ GeV

3.0σ (1.9σ exp) at m_H=125 GeV

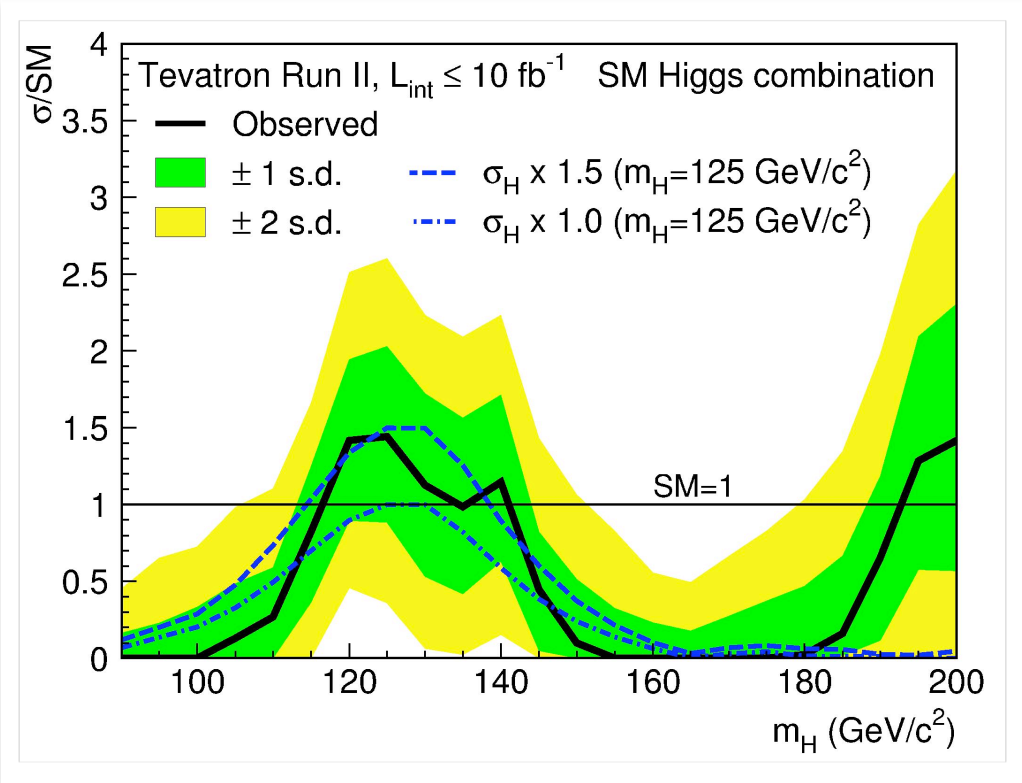


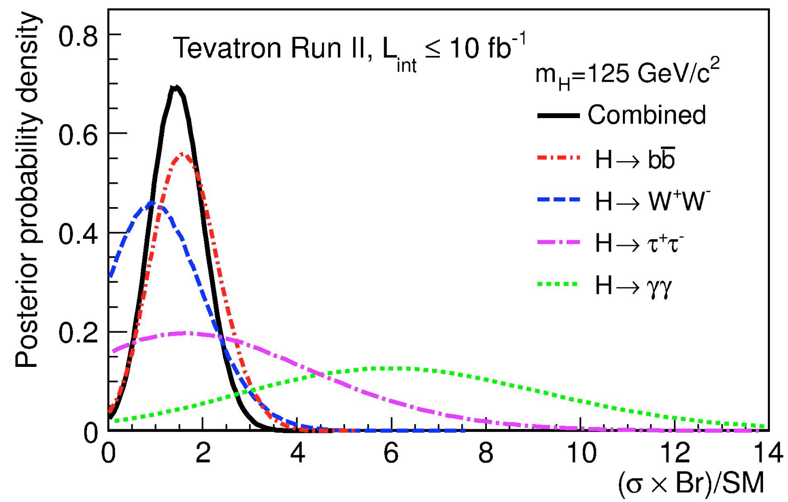
Higgs Boson Studies at the Tevatron
PRD 88, 052014 (2013)

Fingerprinting X(125)



Production Rate



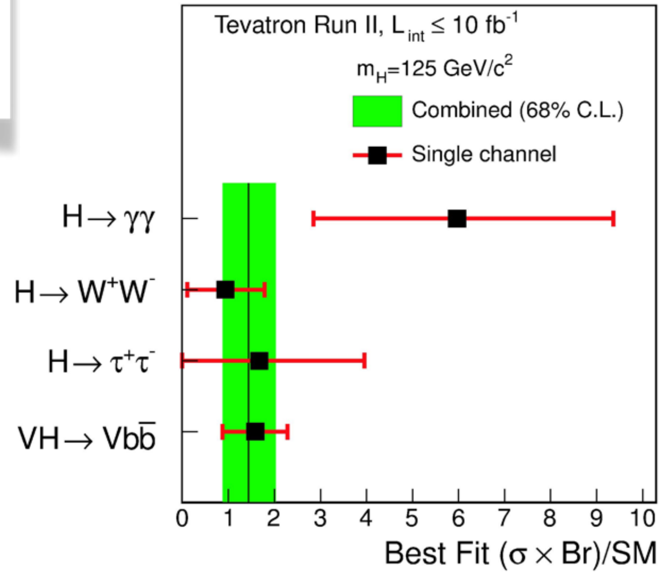


- Maximum likelihood fit to data with signal rate as free parameter.
- Best-fit signal rate at m_H=125 GeV:

$$\mu = 1.44^{+0.59}_{-0.56}$$

Consistent with SM Higgs.

Reasonably consistent across channels.

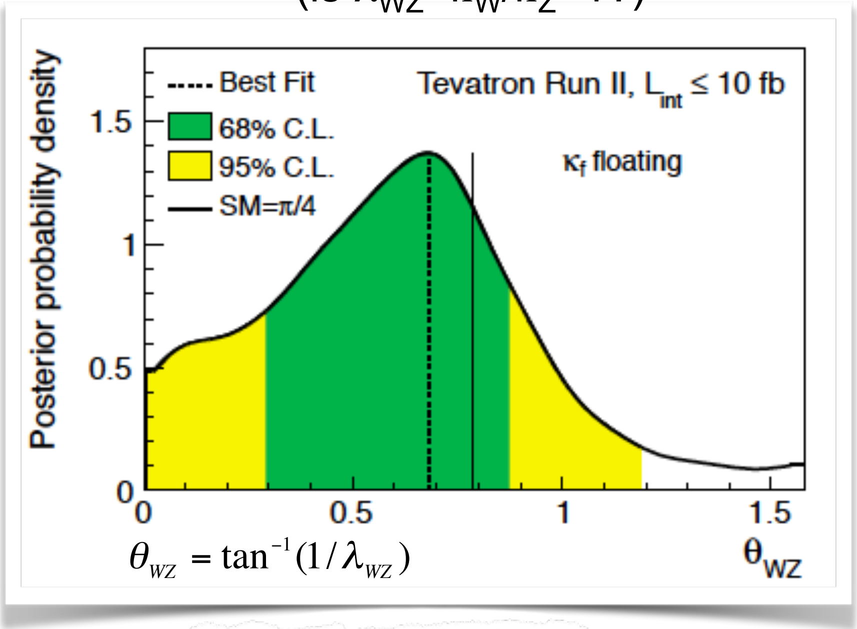


μ
$5.97^{+3.39}_{-3.12}$
$0.94^{+0.85}_{-0.83}$
$1.68^{+2.28}_{-1.68}$
$1.59^{+0.69}_{-0.72}$

Probing Higgs Boson Couplings

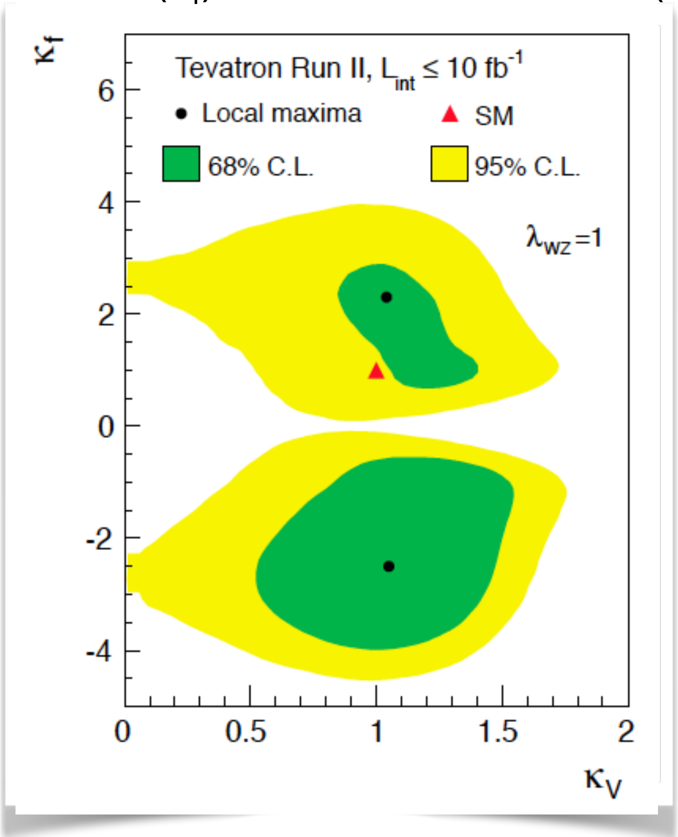
- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult
- Under some assumptions, all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors (κ) to the SM Higgs couplings.

Probe $SU(2)_V$ custodial symmetry
(is $\lambda_{WZ}=\kappa_W/\kappa_Z=1$?)



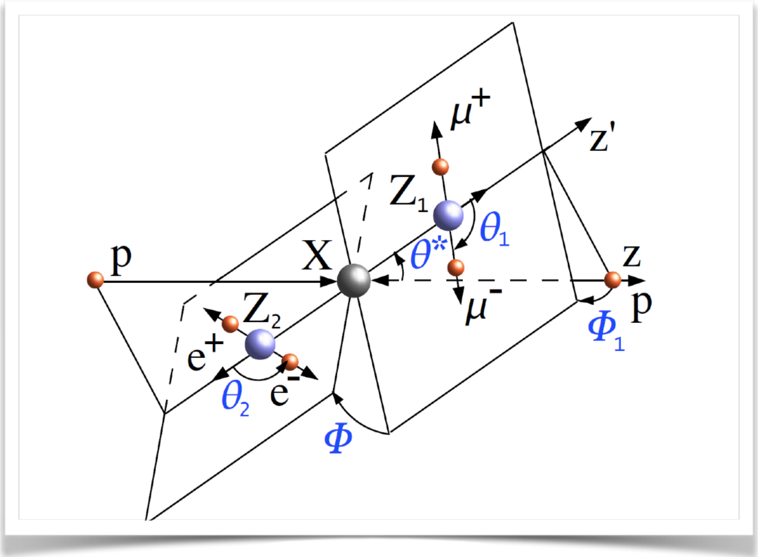
$$\lambda_{WZ} = 1.24^{+2.34}_{-0.42}$$

Measure simultaneously coupling to fermions (κ_f) and to vector bosons (κ_V)

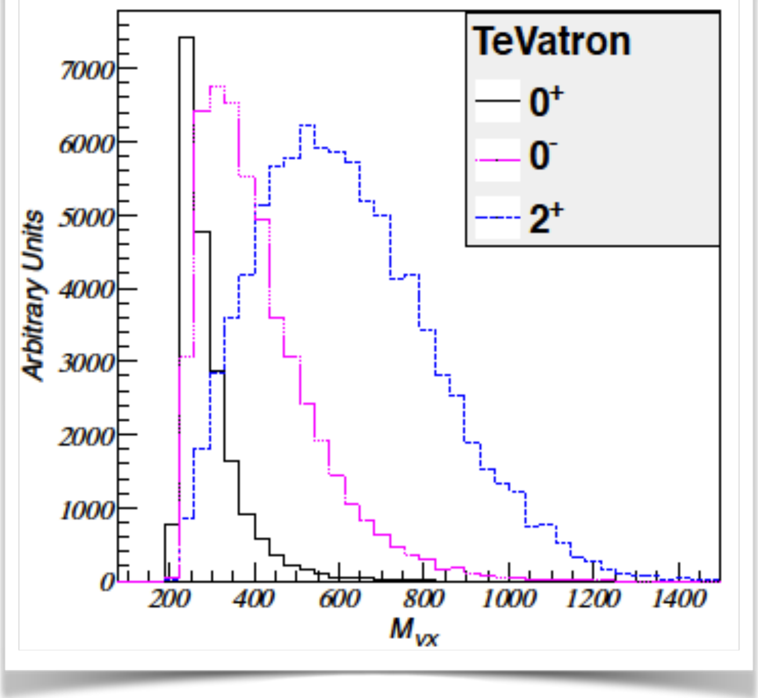


Measurements consistent with the SM prediction (but limited precision)

Spin/Parity



JHEP 1211, 134 (2012)

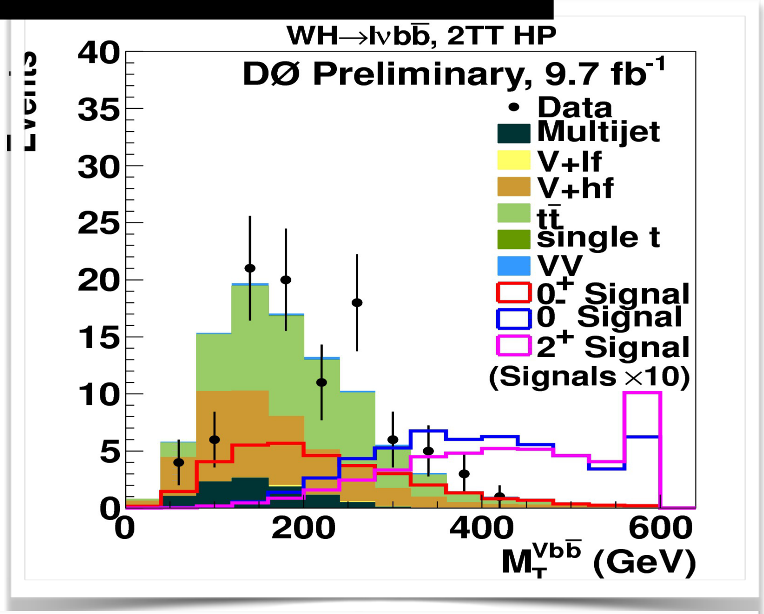


J^P	Class	Comments
0^+	SM Higgs	P = C = +
0^-	Pseudo-scalar	2HDMs, SUSY, etc
1^- 1^+	Composite Higgs. KK modes of ED. Strong SB (rho analog – QCD).	Quark production only. Forbidden by Landau-Yang? No!
2^+ 2^-	Graviton-like tensor, tensor, or pseudo-tensor	Many assumptions to be made, depending on the model constructed

- Main sensitivity at the LHC through angular distributions of decay products in H→ZZ→4l, H→$\gamma\gamma$ and H→WW→lνlν.
- Main sensitivity at the Tevatron from the threshold behavior of the VH cross section:
  - s-wave for 0^+: $\sigma \sim \beta$
  - p-wave for 0^-: $\sigma \sim \beta^3$
  - d-wave for 2^+: $\sigma \sim \beta^5$

Spin/Parity

- Main discriminating variable: mass of the V+X system (with X being $J^P=0^+$, 0^-, 2^+)
- Using publication results for VH, H→bb.



- Alternative J^P hypothesis rejected in favor of 0^+:

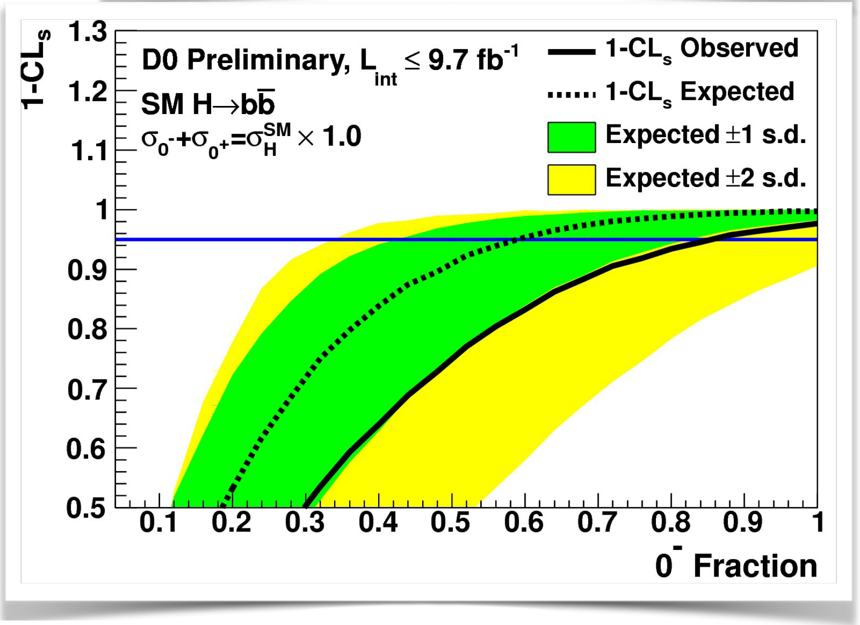
Assuming μ=1:

- Exclude $J^P=0^-$ (vs. 0^+) with 97.6% CL
- Exclude $J^P=2^+$ (vs. 0^+) with 99.2% CL

- In addition, assume the observed X(125) is an admixture of two J^P eigenstates:

$$\phi = \cos\alpha\, H + \sin\alpha\, A$$

CP-even CP-odd

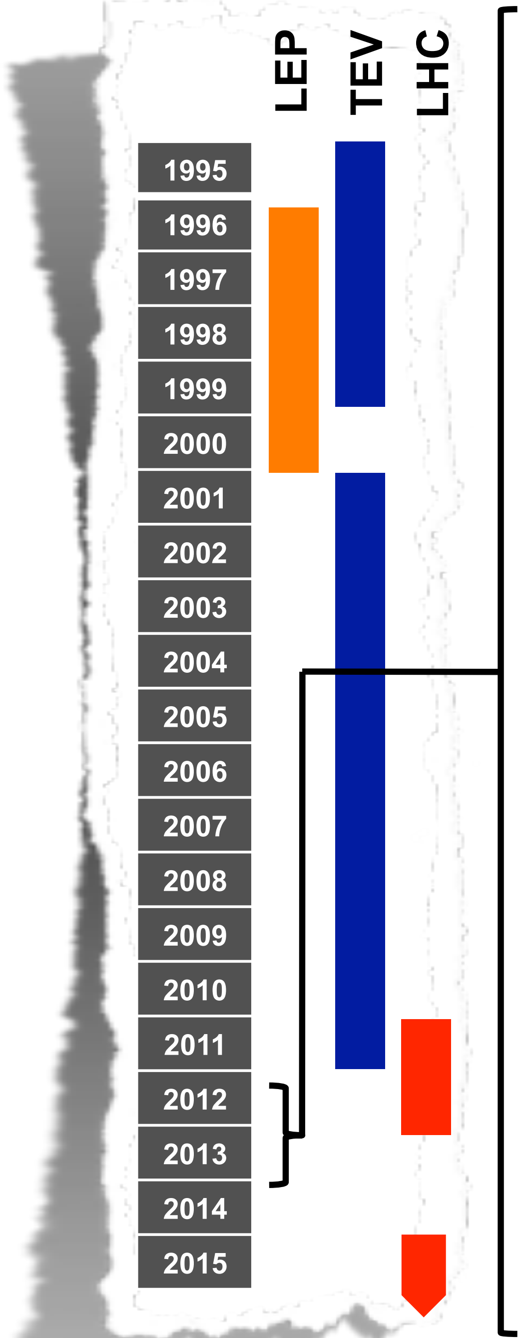


Assuming μ=1:

- Exclude $f_{0-}>0.85$ @ 95% CL
- Exclude $f_{2+}>0.71$ @ 95% CL

First exclusion in a fermionic decay channel of the $J^P=0^-$ and $J^P=2^+$ hypotheses for X(125)

An Impressive Legacy



DØ	Luminosity (fb^{-1})	M_H (GeV)	Reference
$WH \to \ell\nu bb$	9.7	90–150	Phys. Rev. Lett. 109, 121804 (2012) and Phys. Rev. D 88, 052008 (2013)
$ZH \to \ell\ell b\bar{b}$	9.7	90–150	Phys. Rev. Lett. 109, 121803 (2012) and Phys. Rev. D 88, 052010 (2013)
$ZH \to \nu\bar{\nu}b\bar{b}$	9.5	100–150	Phys. Lett. B 716, 285 (2012)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	9.7	100–200	Phys. Rev. D 88, 052006 (2013)
$H + X \to WW \to \mu^\pm\tau_h^\mp + \leq 1$jet	7.3	155–200	Phys. Lett. B 714, 237 (2012)
$H \to W^+W^- \to \ell\nu q'\bar{q}$	9.7	100–200	Phys. Rev. D 88, 052008 (2013)
$VH \to ee\mu/\mu\mu e + X$	9.7	100–200	Phys. Rev. D 88, 052009 (2013)
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$VH \to \tau_h\tau_h\mu + X$	8.6	100–150	Phys. Rev. D 88, 052009 (2013)
$H + X \to \ell\tau_h jj$	9.7	105–150	Phys. Rev. D 88, 052005 (2013)
$H \to \gamma\gamma$	9.7	100–150	Phys. Rev. D 88, 052007 (2013)
CDF			
$WH \to \ell\nu bb$	9.45	90–150	Phys. Rev. Lett. 109, 111804 (2012)
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$H \to WW \to e\tau_h\mu\tau_h$	9.7	130–200	Phys. Rev. D88, 052012 (2013)
$VH \to ee\mu/\mu\mu e + X$	9.7	110–200	Phys. Rev. D88, 052012 (2013)
$H \to \tau\tau$	6.0	100–150	Phys. Rev. Lett. 108, 181804 (2012)
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$H \to ZZ \to llll$	9.7	120–200	Phys. Rev. D 86 072012 (2012)
$t\bar{t}H \to WWb\bar{b}b\bar{b}$	9.45	100–150	Phys. Rev. Lett. 109 181802 (2012)
$VH \to jjb\bar{b}$	9.45	100–150	JHEP 1302 004 (2013)

CDF Combinations

H→bb: PRL 109, 111802 (2012)

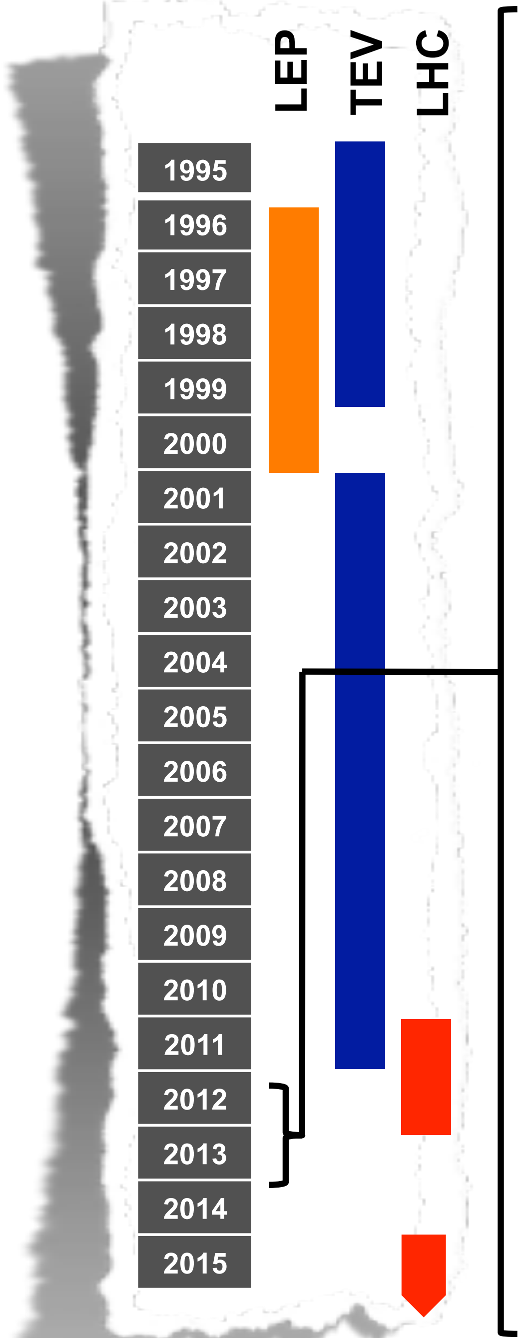
All channels: PRD 88, 052013 (2013)

D0 Combinations

H→bb: : PRL 109, 121802 (2012)

All channels: PRD 88, 052011 (2013)

An Impressive Legacy



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Tevatron combination: PRD 88, 052014 (2013)

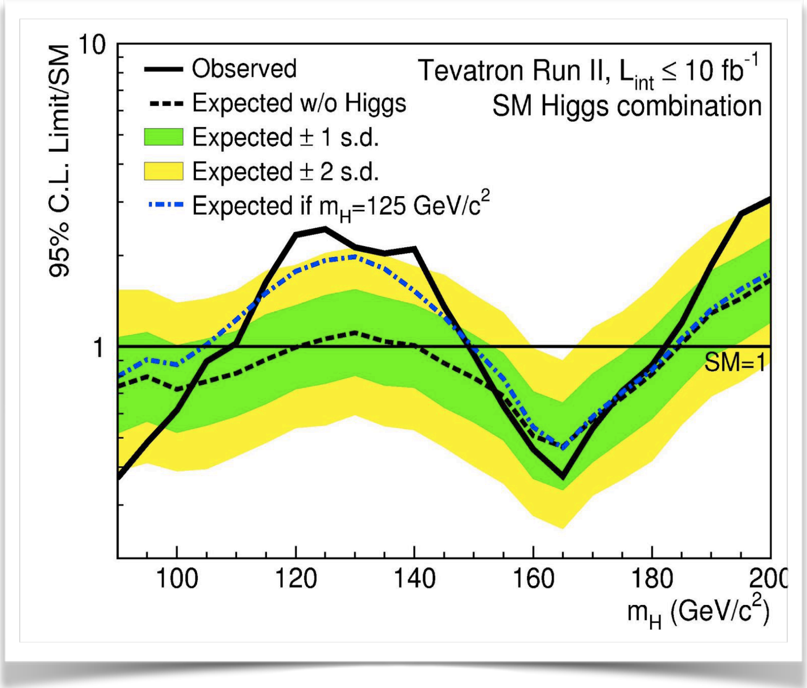
All latest papers are in a single issue of PRD

Publications on spin/parity upcoming

Conclusions

Delivering on a promise:

- Higgs program published with the full dataset.
- Achieved SM sensitivity over most of the accessible mass range.
- 3σ excess near m_H=125 GeV, compatible with the LHC observation.
- Valuable measurements of couplings.
  Probing spin/CP quantum numbers.



- The Higgs race at the Tevatron turned out to be a marathon requiring everybody in the machine and the experiments to run the extra mile to make these results possible.

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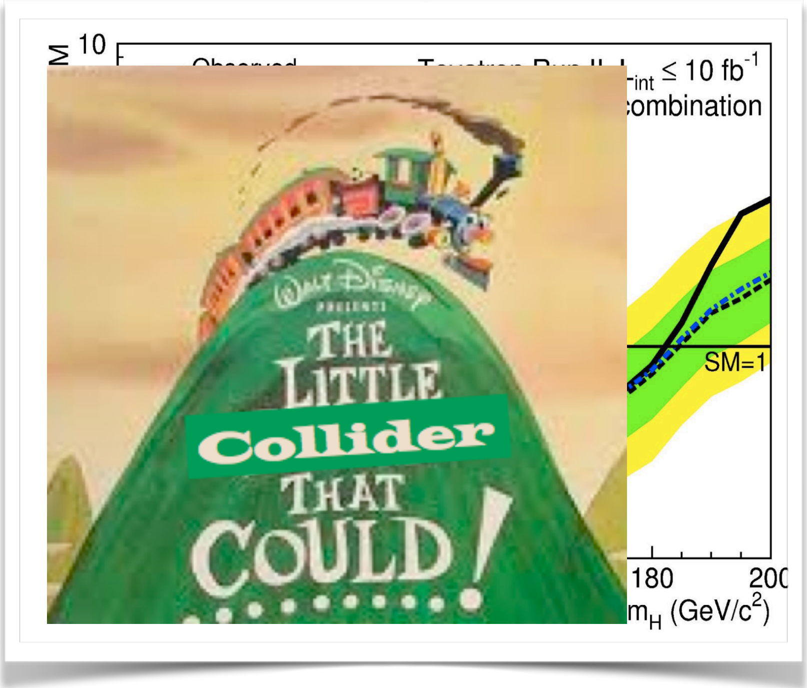

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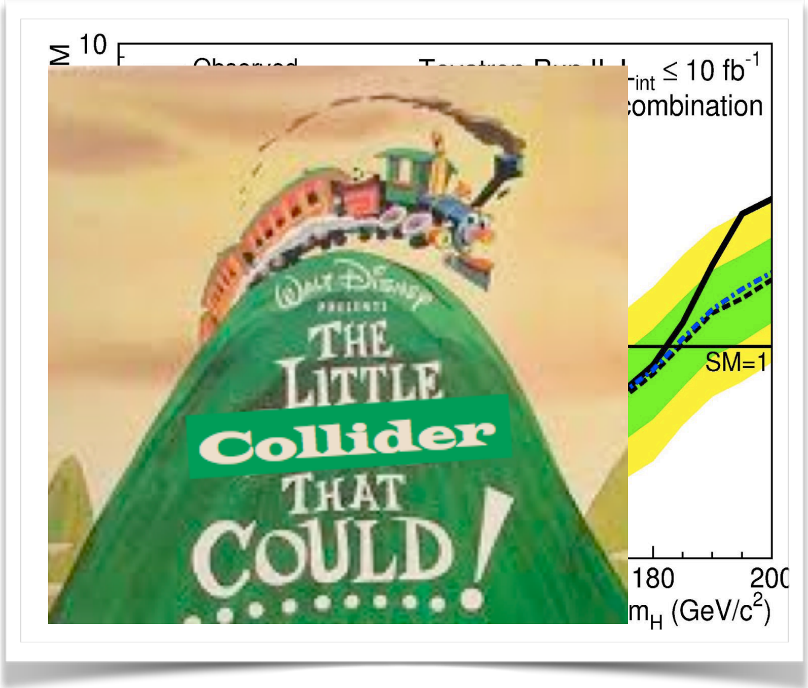


- The Higgs race at the Tevatron turned out to be a marathon requiring everybody in the machine and the experiments to run the extra mile to make these results possible.

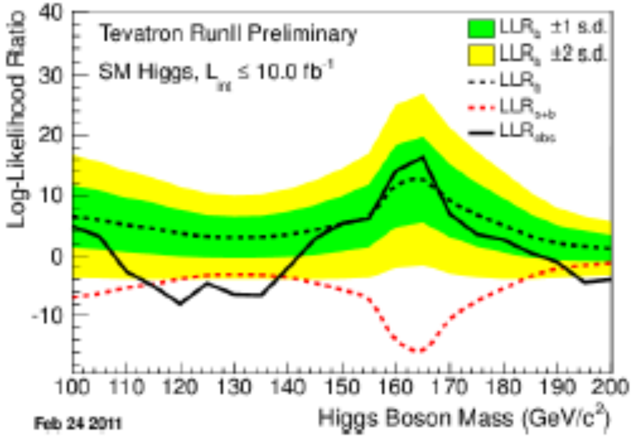
The Tevatron legacy will live onto the LHC Run 2:

- Complementarity on physics capabilities.
- Development of novel experimental techniques, now in use at the LHC.
- Training of generations of physicists that are now helping materialize successes at the LHC.

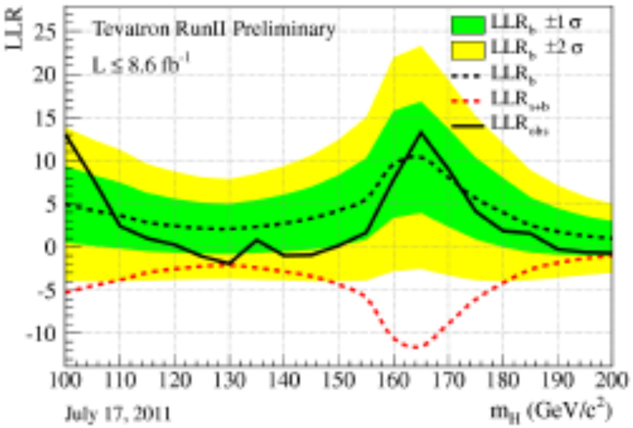
Backup

Log-Likelihood Ratio Distributions

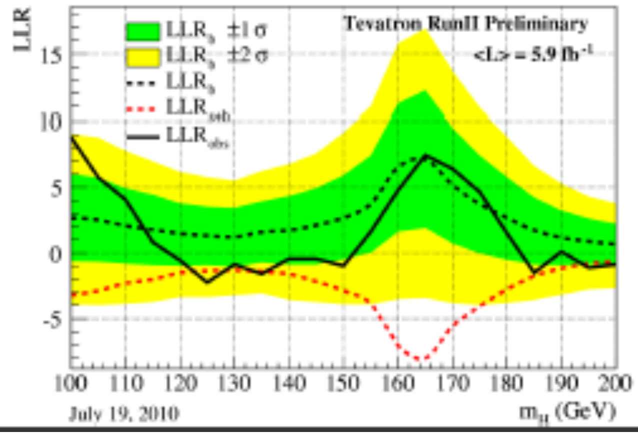
2012



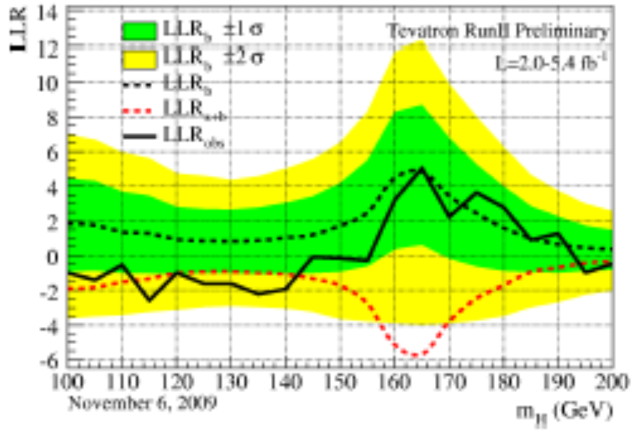
2011



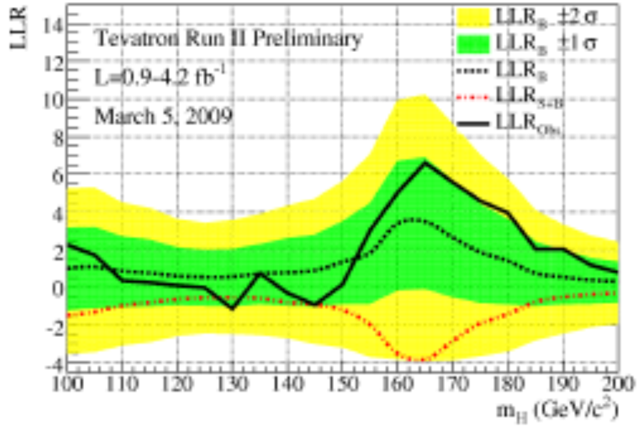
2010



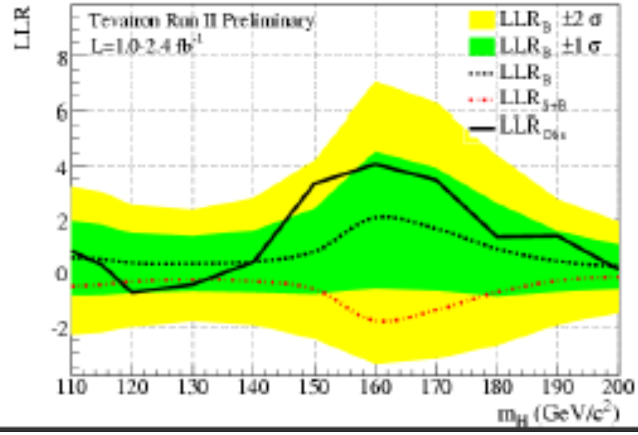
2009



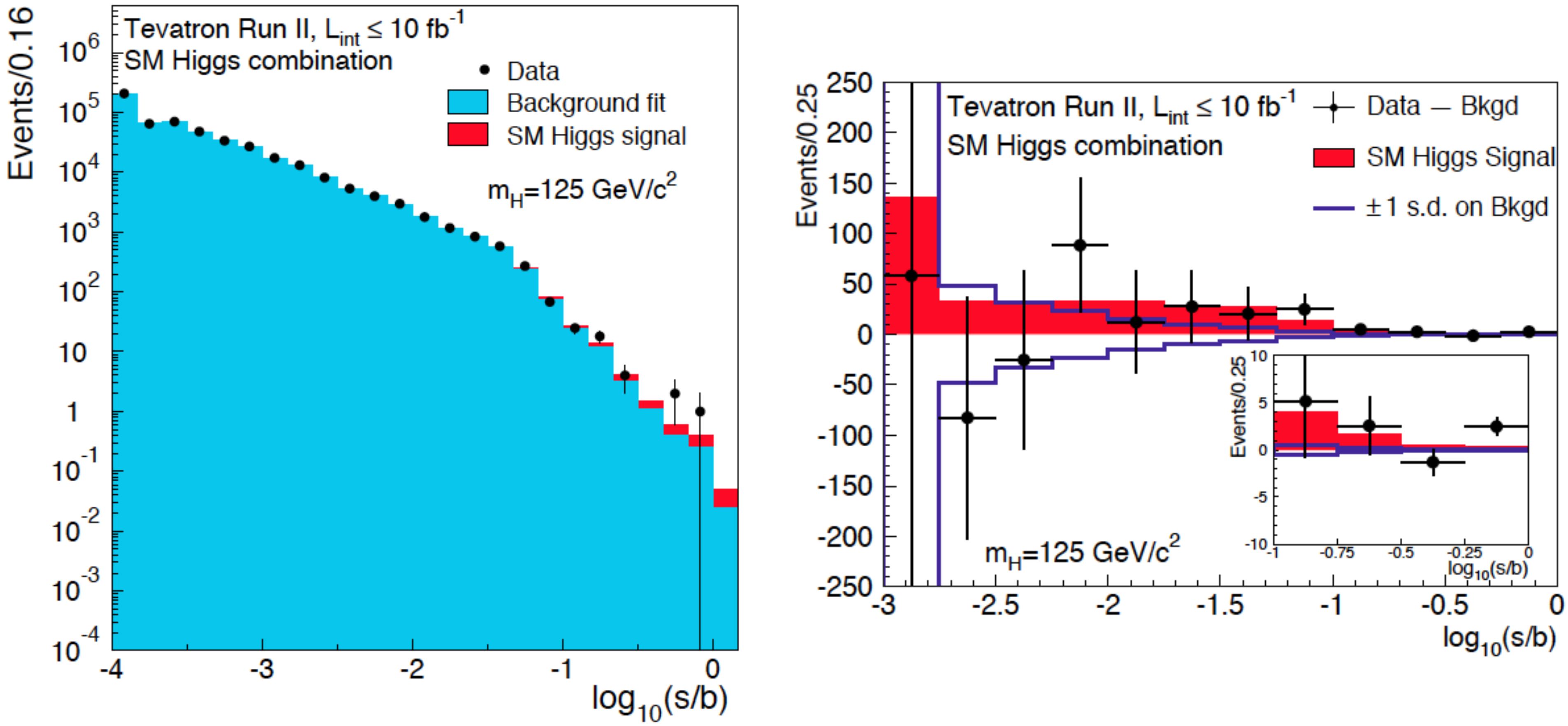
2008



2007

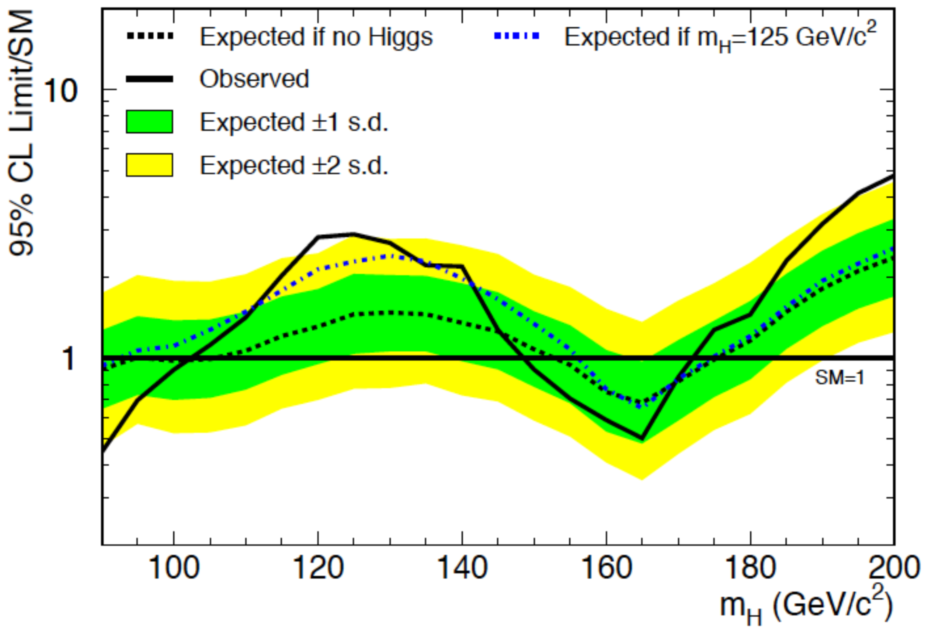


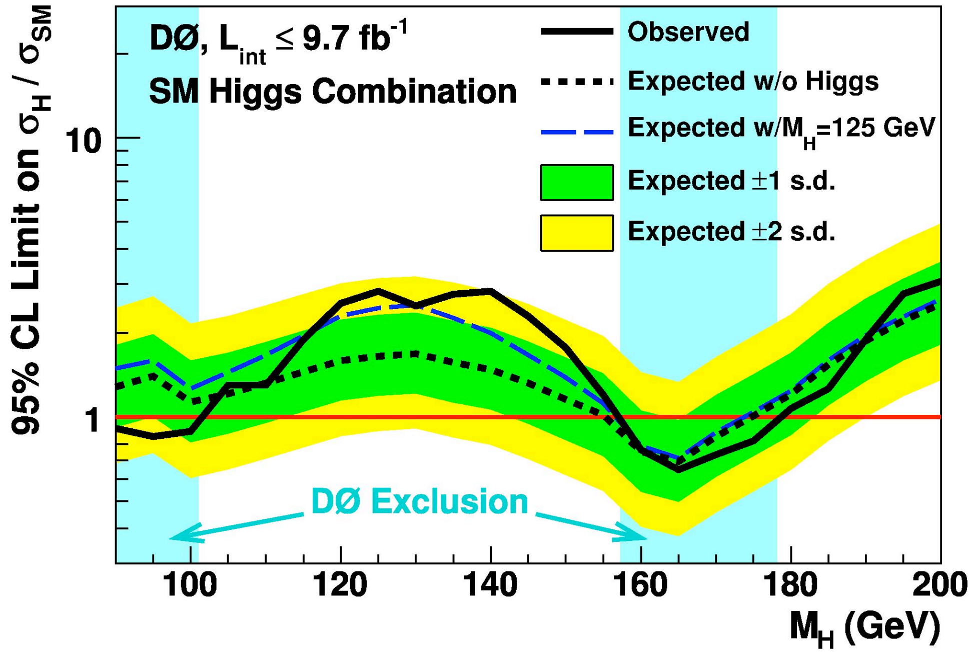
Visualizing the Excess



- Display all input histogram bins ordered according to S/B in one plot.
- The background model has been constrained by the data.

CDF and DØ Individual Results





Observed 95% CL exclusion:

$90 < m_H < 102$ GeV, $149 < m_H < 172$ GeV

At m_H = 125 GeV:

Exp. limit: 1.46 x SM
Obs. limit: 2.89 x SM

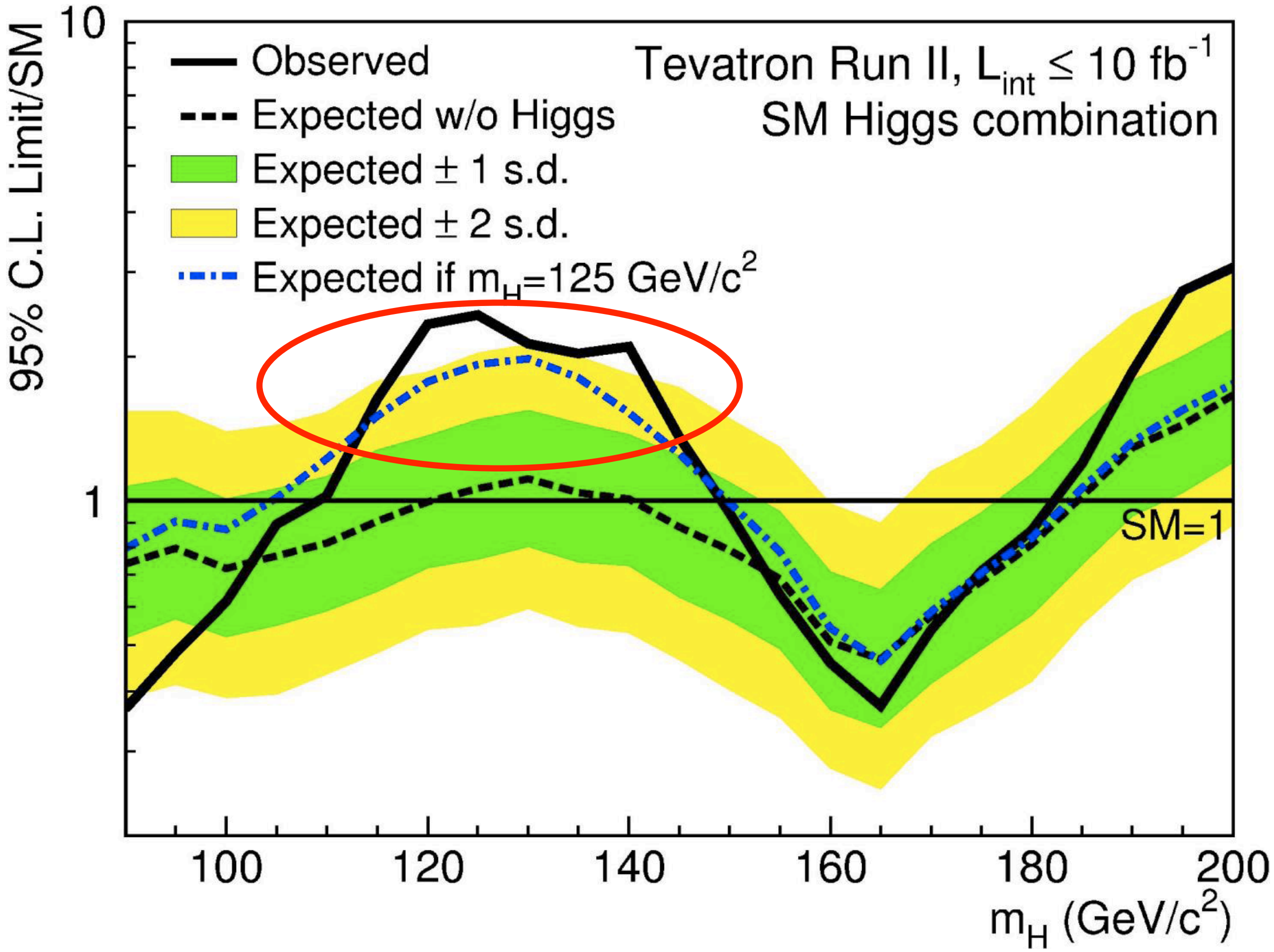
Observed 95% CL exclusion:

$90 < m_H < 101$ GeV, $157 < m_H < 178$ GeV

At m_H = 125 GeV:

Exp. limit: 1.68 x SM
Obs. limit: 2.92 x SM

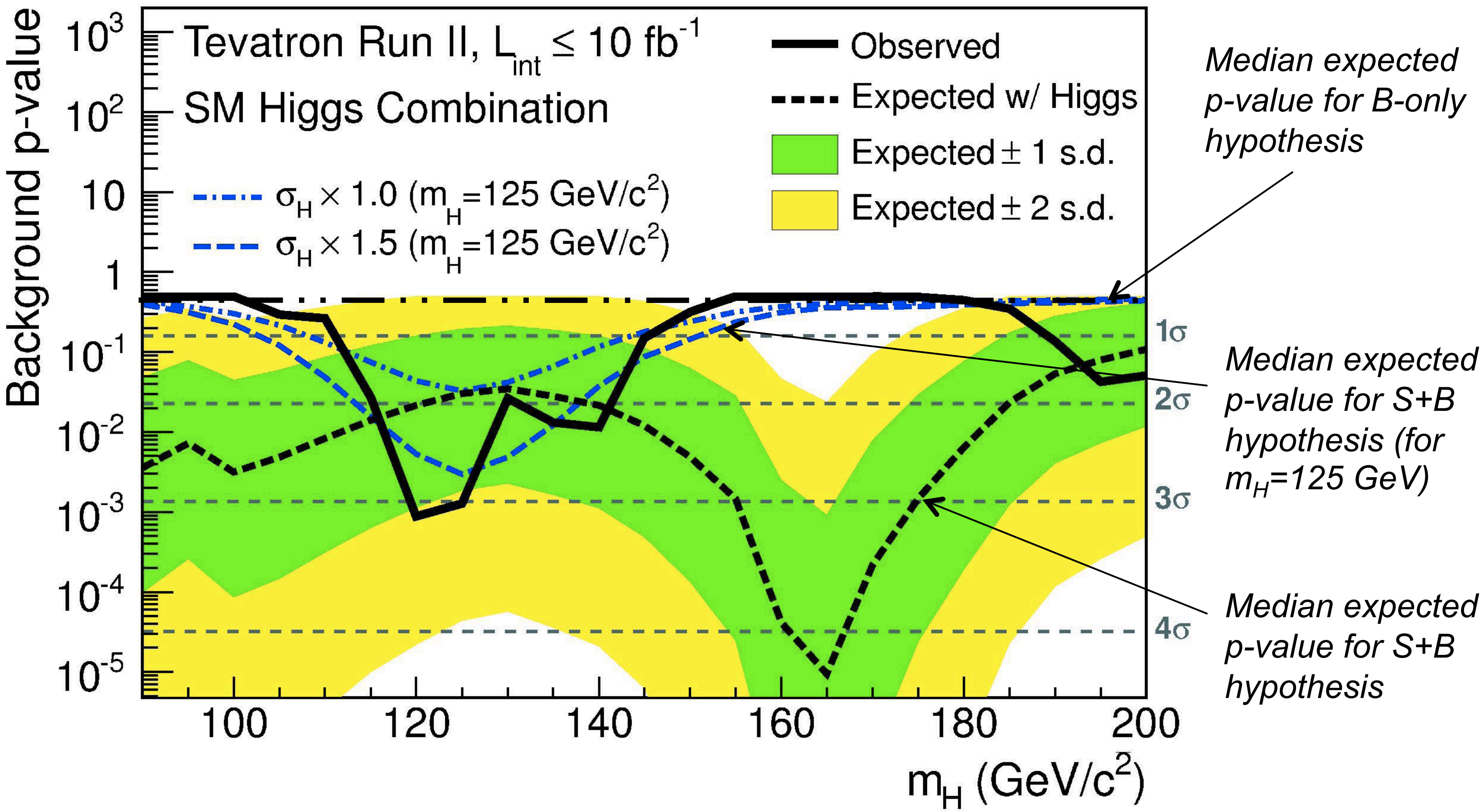
Final Tevatron Combined Results



- Expected exclusion: 90 < m_H < 120 GeV, 140< m_H < 184 GeV
  Observed exclusion: 90 < m_H < 109 GeV, 149 < m_H < 182 GeV
- 95% CL limit at m_H=125 GeV: 1.06xSM (expected), 2.44xSM (observed)

Quantifying the Excess: p-values

- Local p-value distribution for background-only hypothesis:



- Minimum local p-value at m_H=120 GeV: 3.1σ (2.0σ expected)

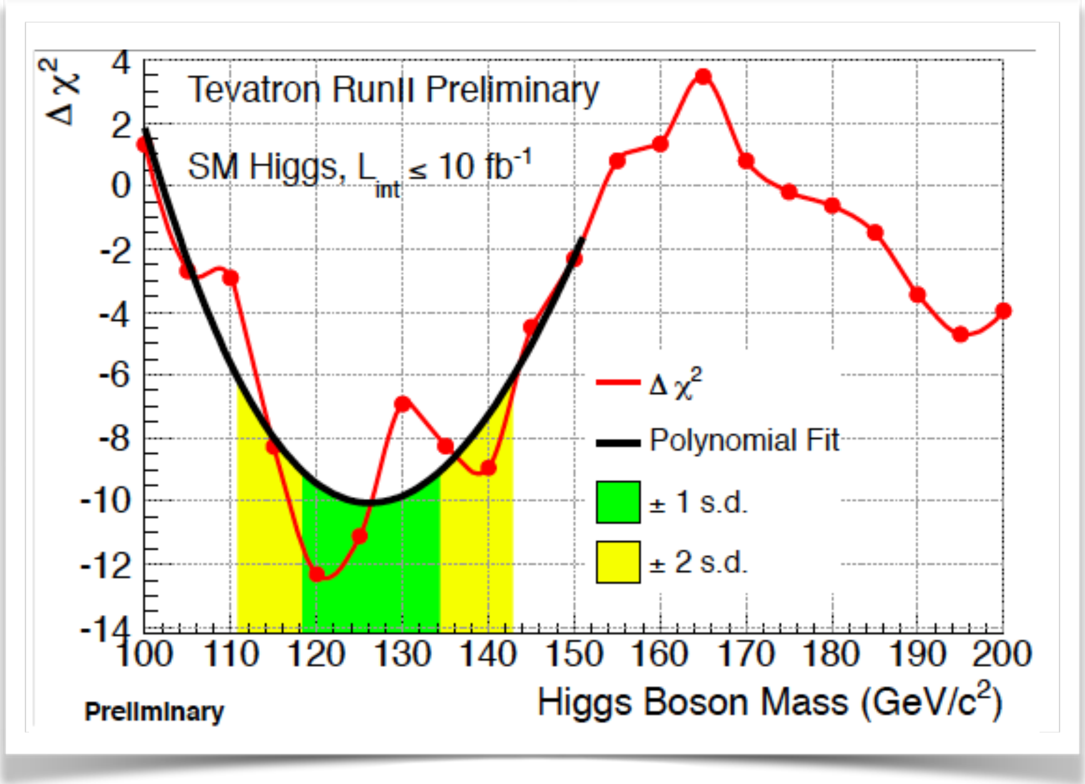
  p-value at m_H=125 GeV: 3.0σ (1.9σ expected)

Mass

- Mass has already been measured to better than 0.5%.

ATLAS: $m_H = 125.5 \pm 0.2(stat.) + 0.5/-0.6(syst)$ GeV

CMS: $m_H = 125.3 \pm 0.4(stat.) \pm 0.5(syst)$ GeV



$$M_H^{fit} = 126.2^{+8.1}_{-7.8}\ \text{GeV}$$

Probing Higgs Boson Couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult
- A better option: measure deviations of couplings from the SM prediction (*arXiv:1209.0040*).
  Basic assumptions:
  - there is only one underlying state at m_H~125 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).

  Additional assumption made in this study:
  - no additional invisible or undetected Higgs decay modes.
- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.
  Examples:

$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2\kappa_W^2}{\kappa_H^2}$$

$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2\kappa_b^2}{\kappa_H^2}$$

$$\kappa_g = f(\kappa_t, \kappa_b, M_H)$$

$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, M_H)$$