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Searches for the Standard Model Higgs Boson at the Tevatron

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Today's Presentation

- Introduction
  - The Higgs mechanism in a nutshell
  - Experimental indications in the pre-hadron collider era
  - Search strategies at hadron colliders

- Standard Model Higgs boson searches at the Tevatron

- Summary and outlook

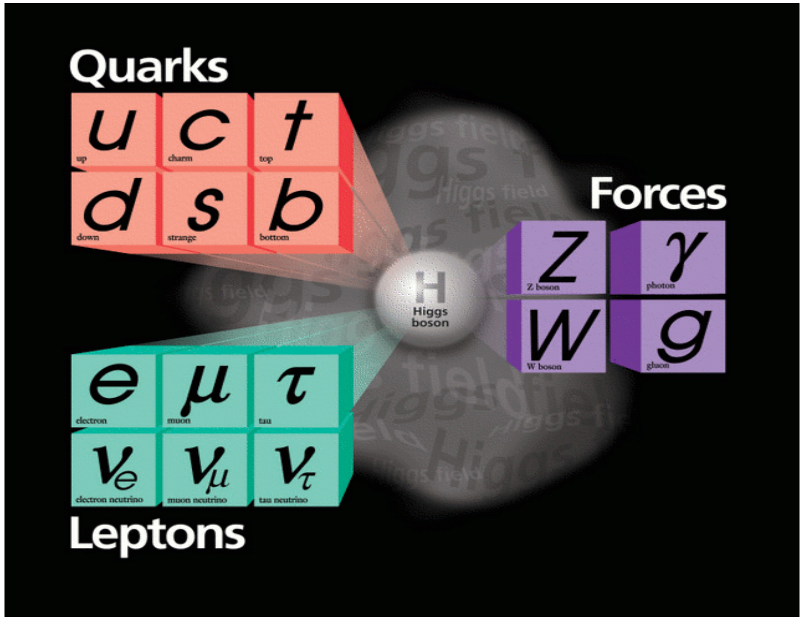
The Case for the Higgs Boson

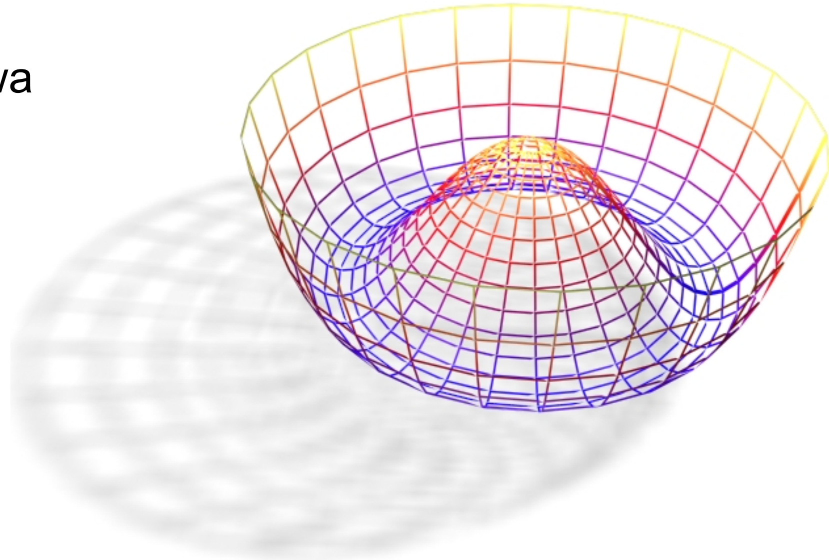
- Massive weak gauge bosons and fermions implies that there must exist an outside sector of interactions that break the electroweak (EW) symmetry: the “Higgs sector”.

- 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!

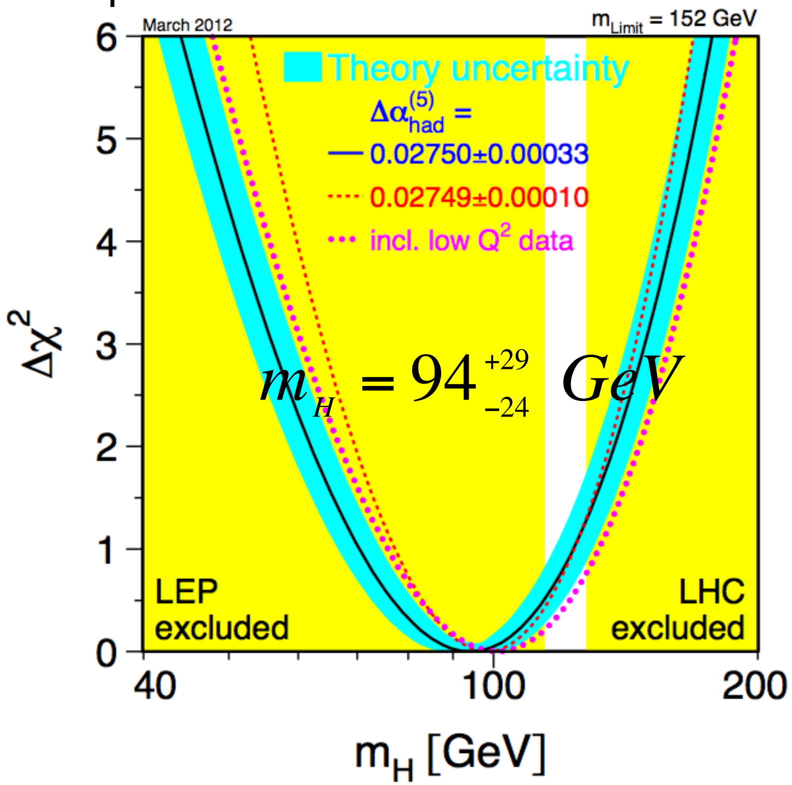




Stalking the Higgs Boson

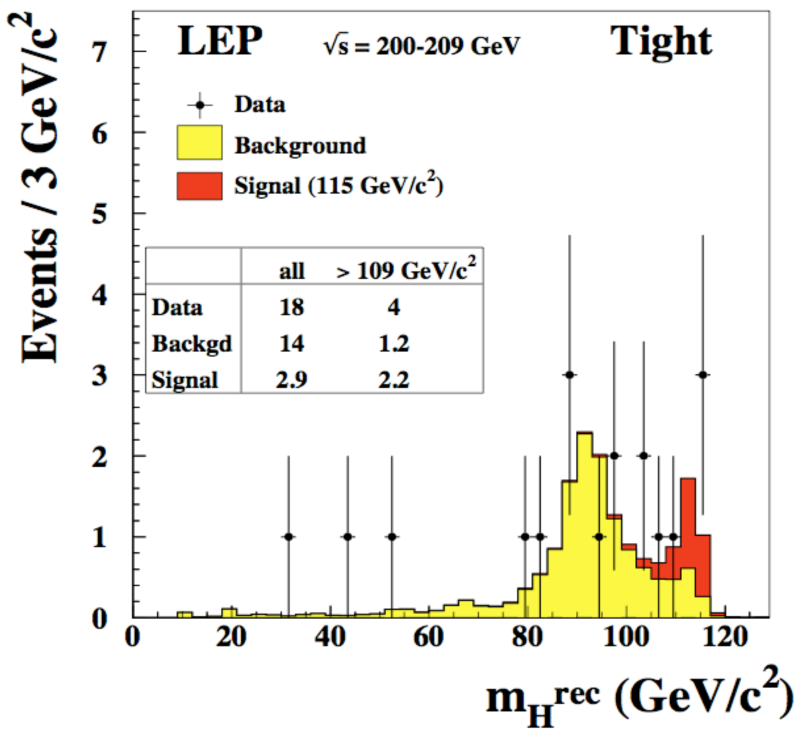
Indirect constraints

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



Direct searches at LEP

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



Combining indirect and LEP direct constraints

m_H< 152 GeV (95% CL) m_H> 114.4 GeV (95% CL)

114.4 < m_H< 171 GeV (95% CL)

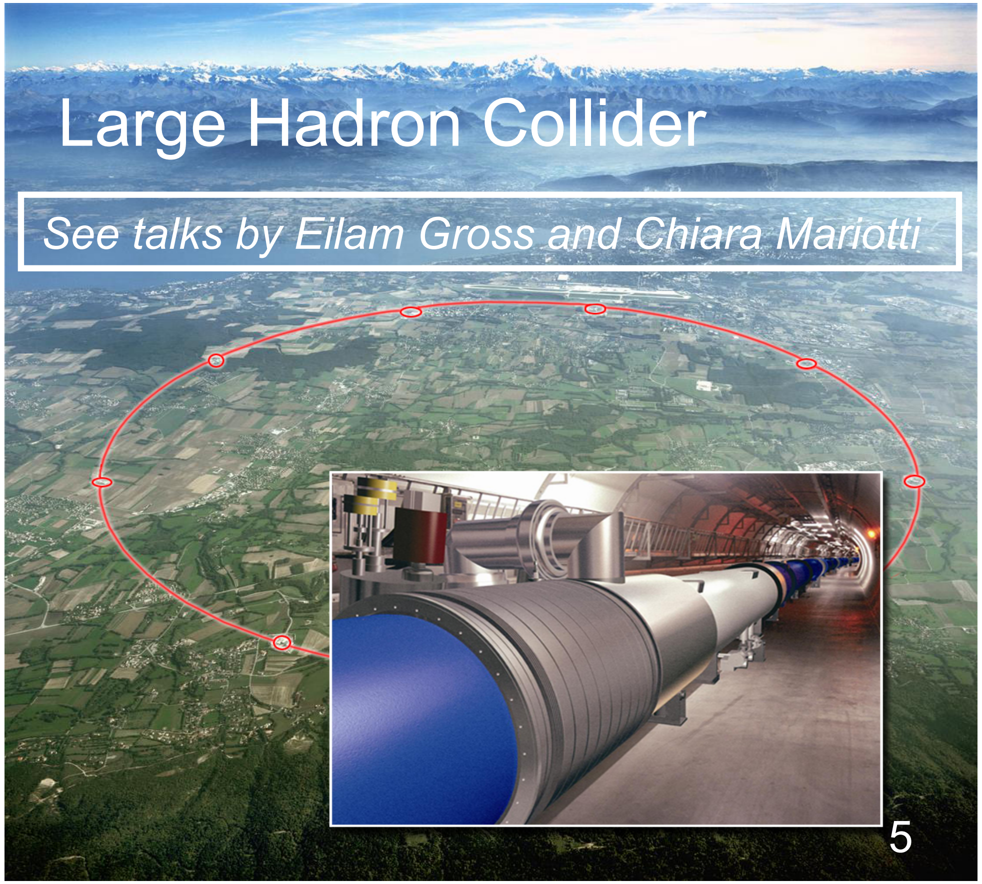
This is precisely the range where the Tevatron is sensitive!

The Hadron Collider Era

- Fermilab's Tevatron Collider: 10-year long Run II ended Sept. 30th, 2011.
  - proton-antiproton collisions at 1.96 TeV.

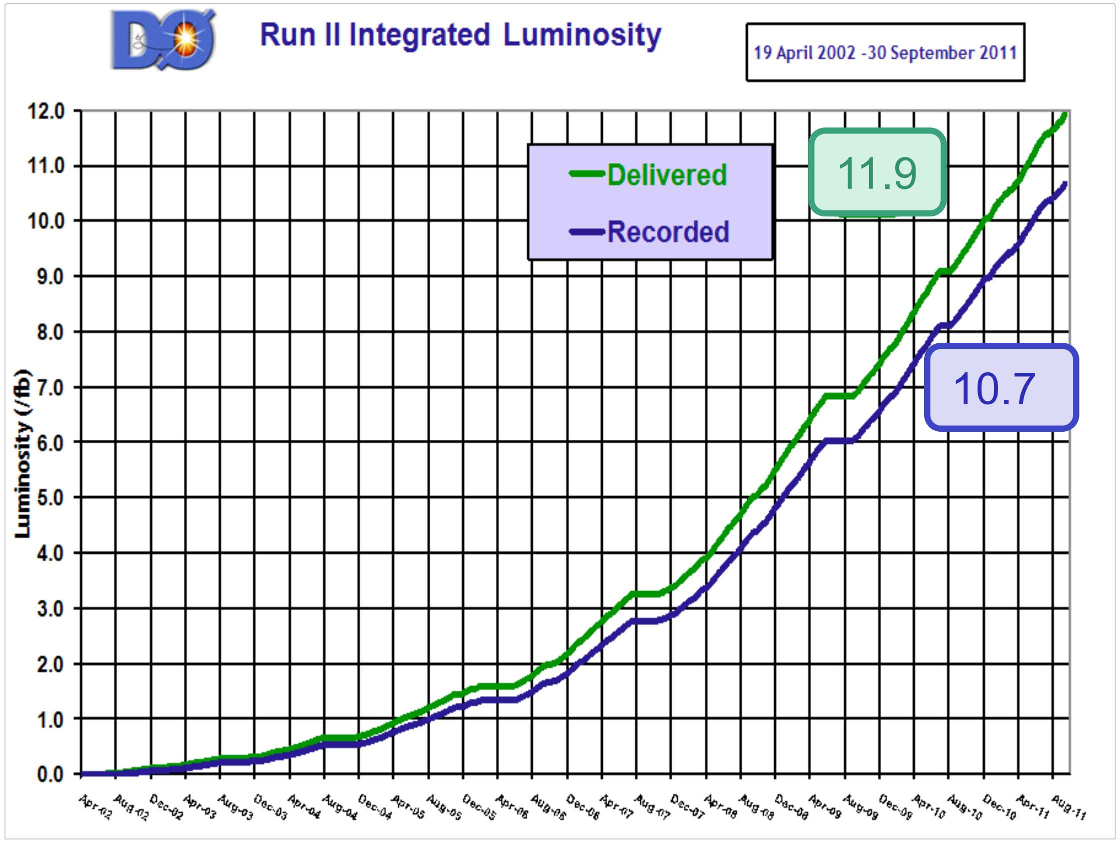
  ➔ expected to be sensitive to a SM Higgs boson in the EW-preferred mass region.
- CERN's Large Hadron Collider (LHC): only hadron collider in operation today.
  - proton-proton collisions at 8 TeV (for now).

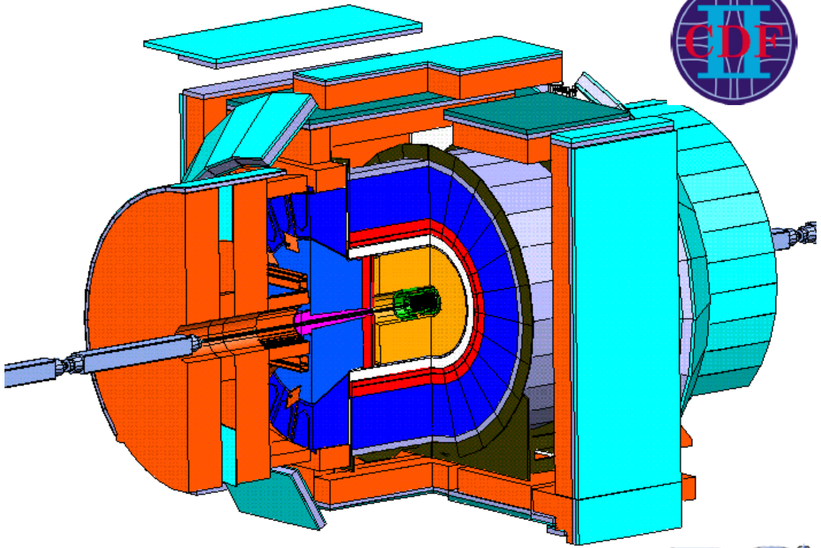
  ➔ should be able to discover a SM Higgs boson up to at least m_H~600 GeV.

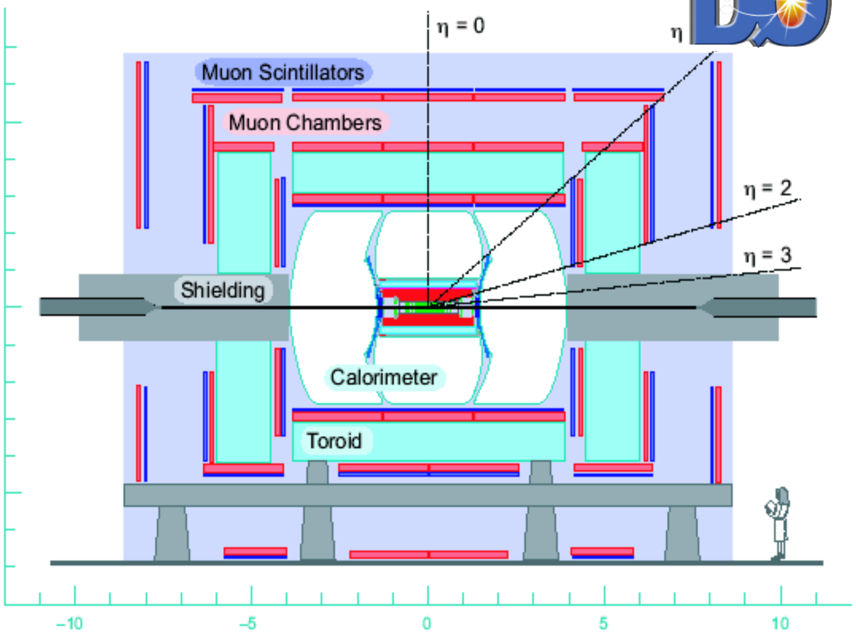


Tevatron Experiments

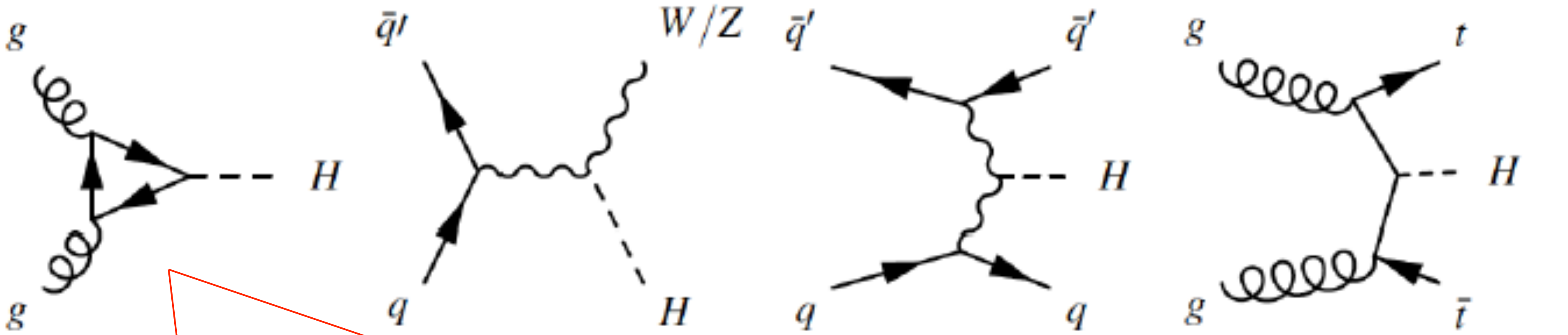
- Excellent performance by the Tevatron accelerator and CDF and DØ detectors.
  - Almost 12 fb^{-1} delivered
  - Up to 10 fb^{-1} in analysis





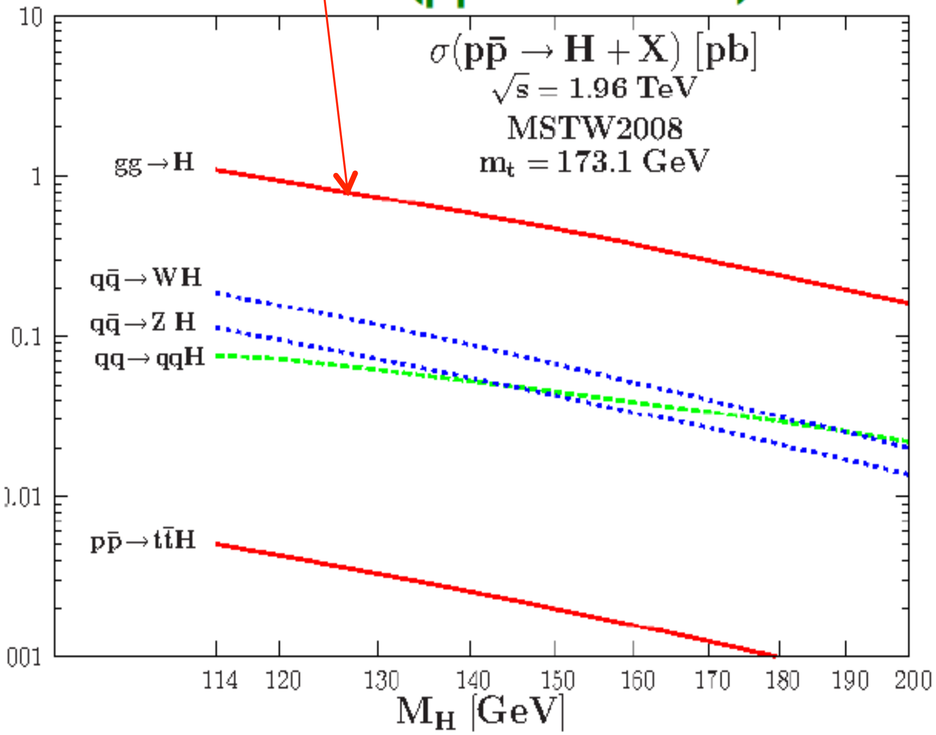


SM Higgs Production at Hadron Colliders

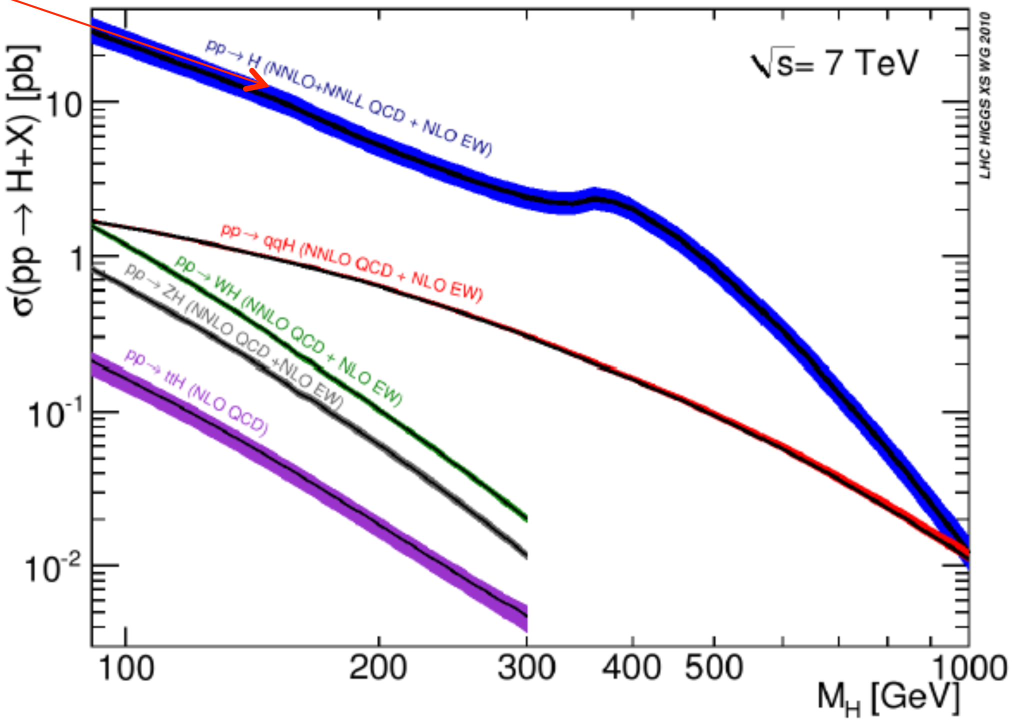


Main production mechanism

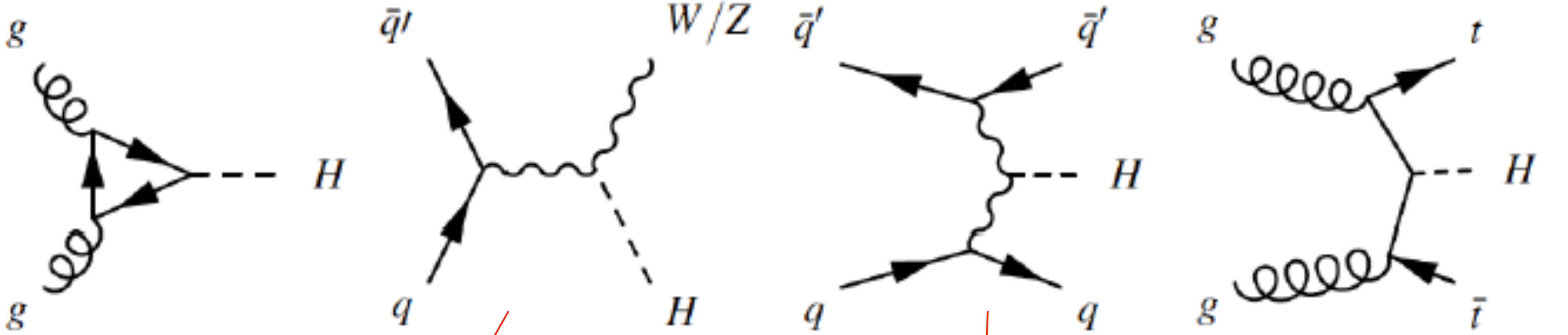
Tevatron ($p\bar{p}$ @ 1.96 TeV)



LHC (pp @ 7 TeV)

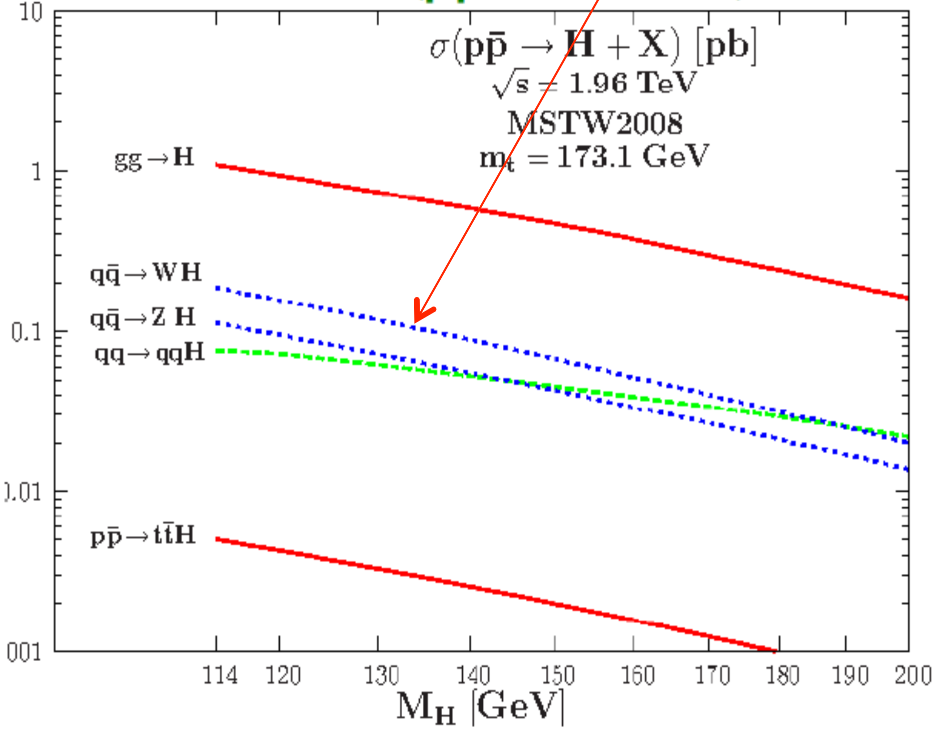


SM Higgs Production at Hadron Colliders

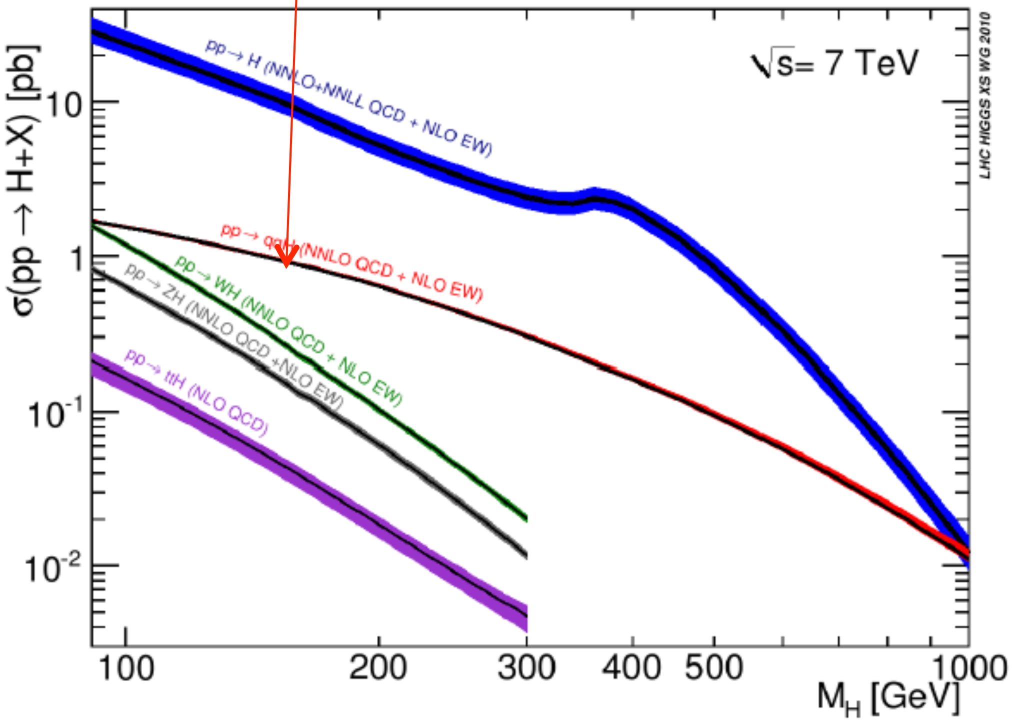


Next most important production mechanism

Tevatron (pp̄ @ 1.96 TeV)

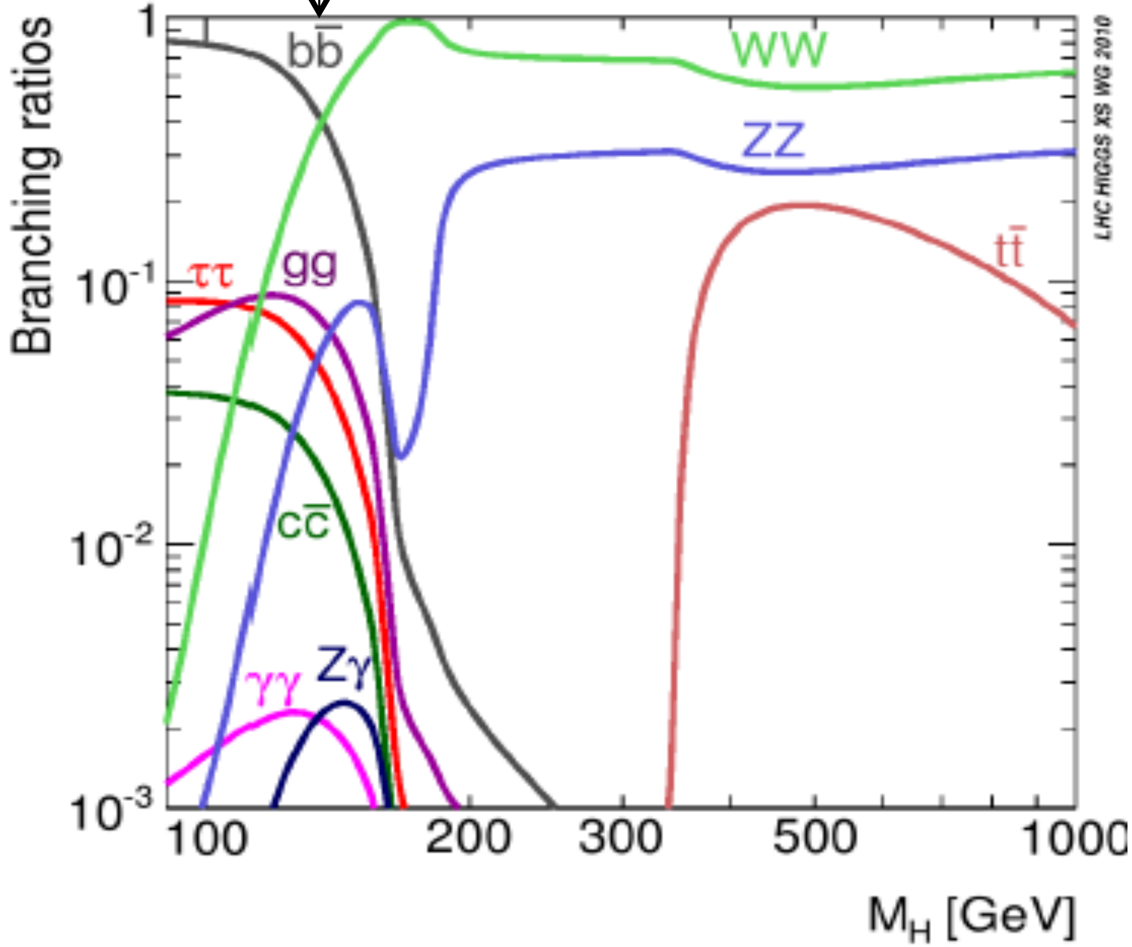


LHC (pp @ 7 TeV)



SM Higgs Decay Modes

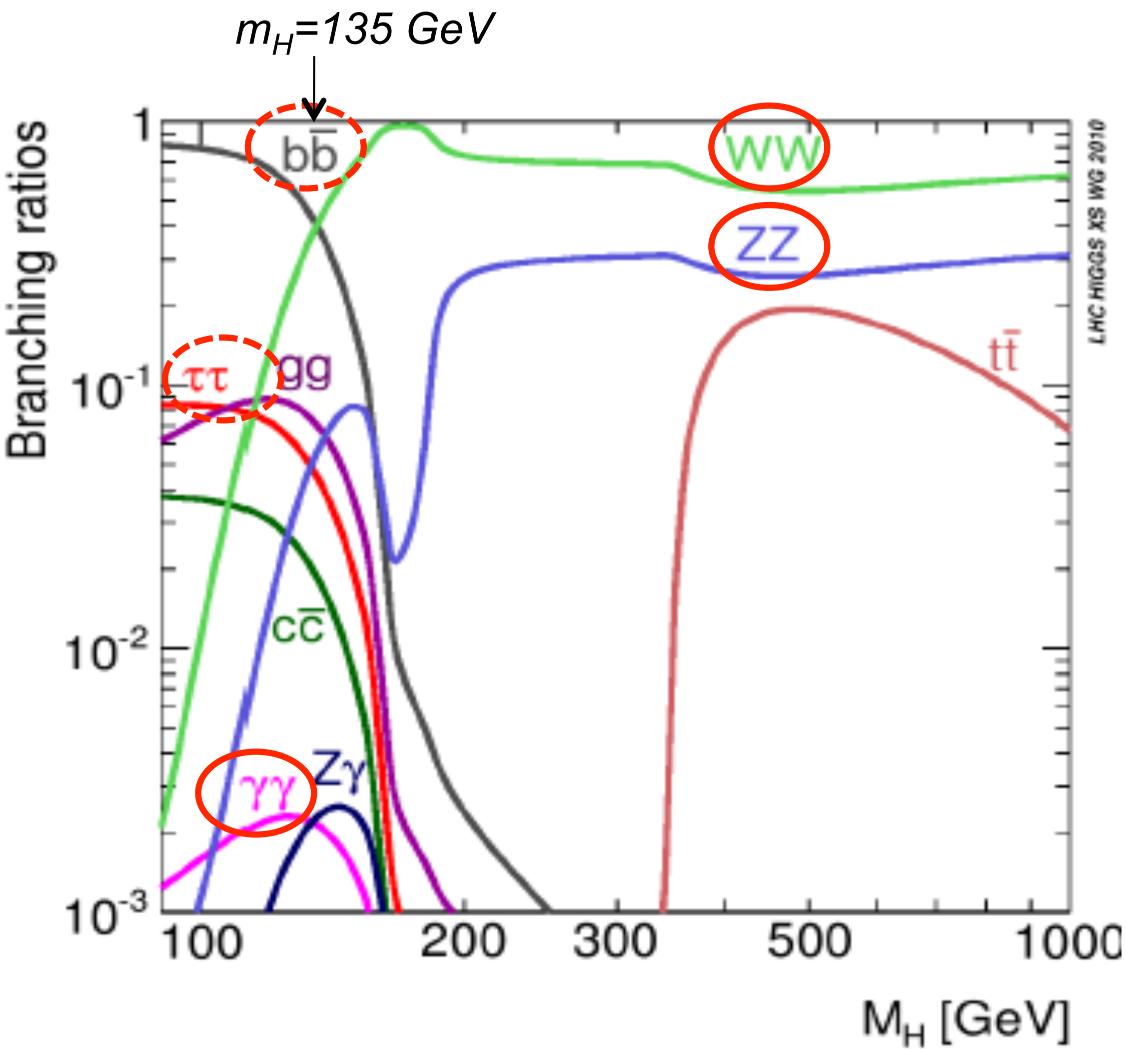
m_H=135 GeV



m_H<135 GeV: H→bb dominates

m_H>135 GeV: H→WW dominates

SM Higgs Decay Modes



m_H<135 GeV: H→bb dominates

m_H>135 GeV: H→WW dominates

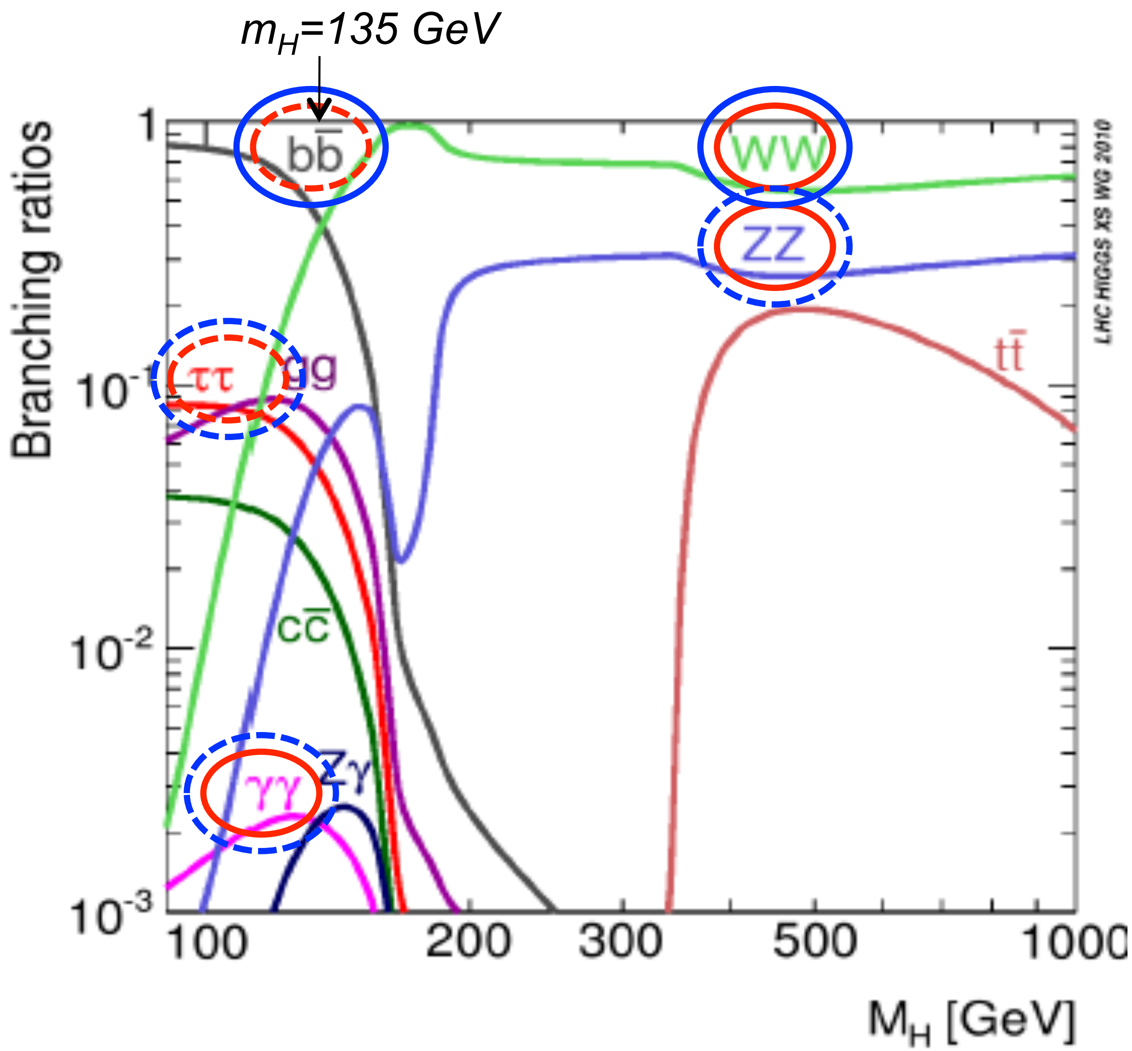
Main mode

Supporting mode

LHC

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

SM Higgs Decay Modes



m_H<135 GeV: H→bb dominates

m_H>135 GeV: H→WW dominates

Main mode

Supporting mode

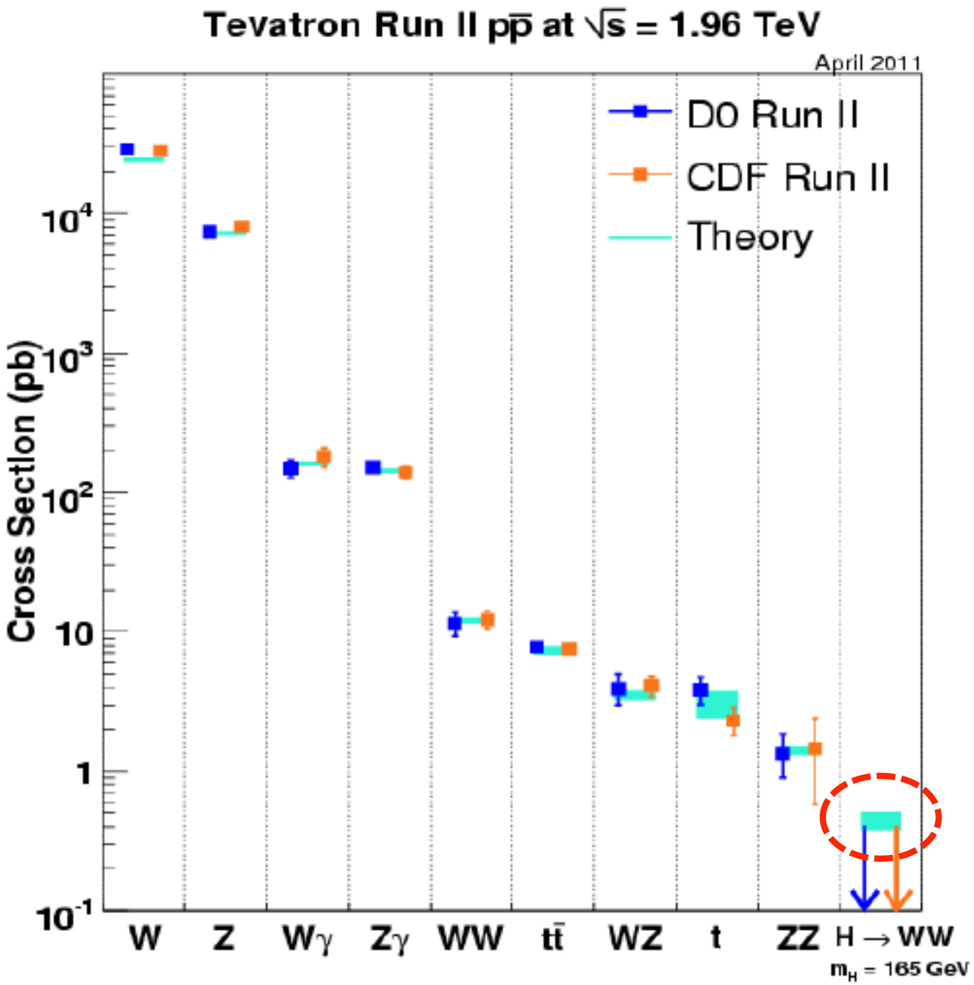
LHC

Tevatron

➔ Many decay modes being 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

- Higgs boson searches at the Tevatron are background-dominated.

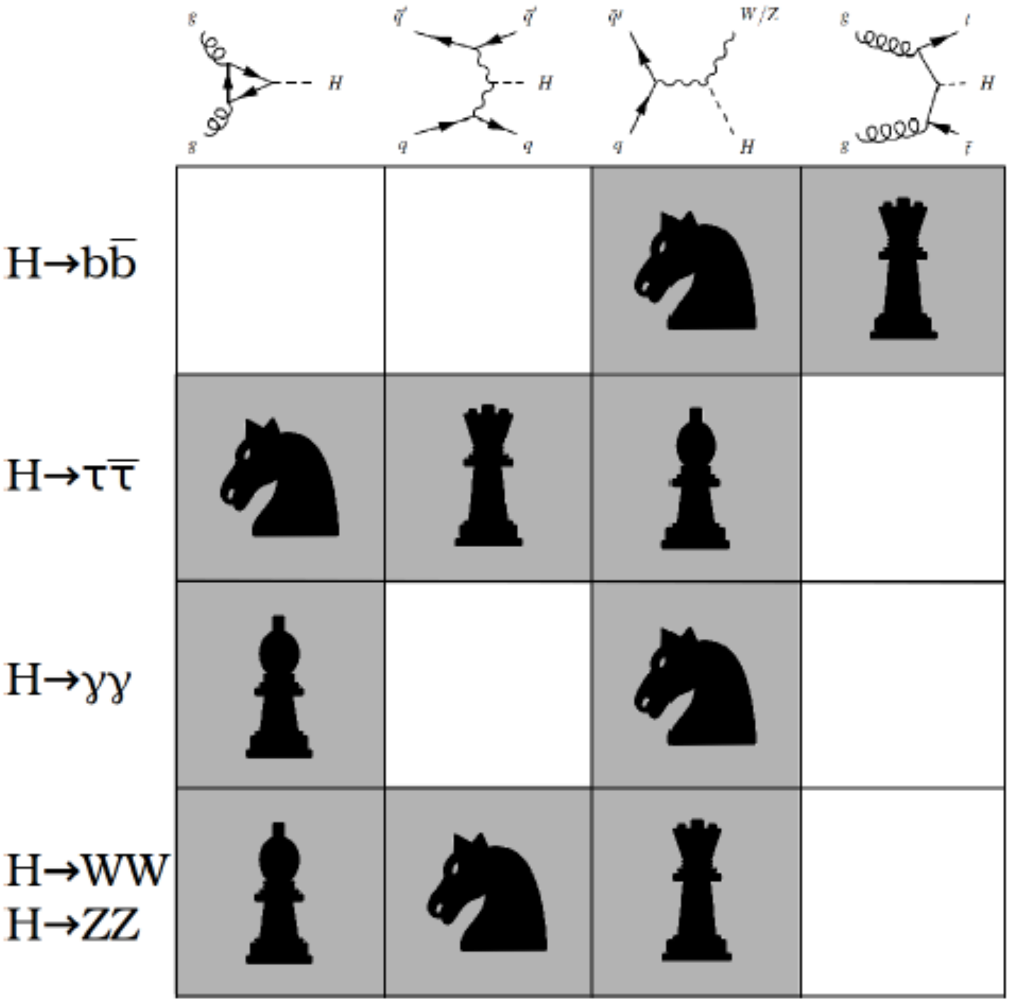


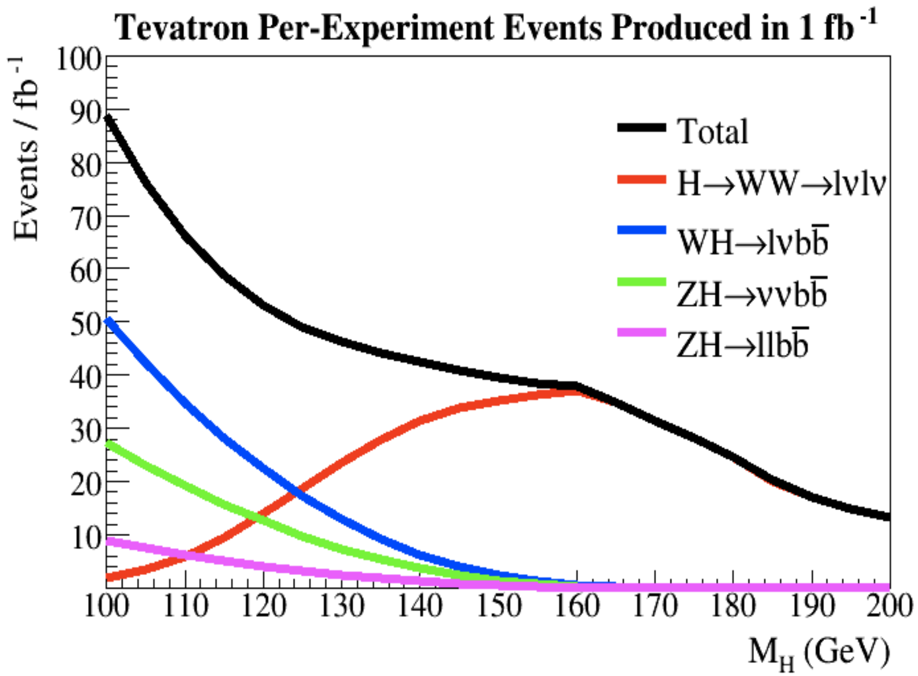
- **Instrumental backgrounds**: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.
- **Physics backgrounds**: estimated using simulation and state-of-art theoretical predictions, and further calibrated to data whenever possible
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)
  - Diboson production
  - Double and single top quark production

Experiments have 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 $\sigma x B$ but experimentally feasible: trigger, backgrounds….).

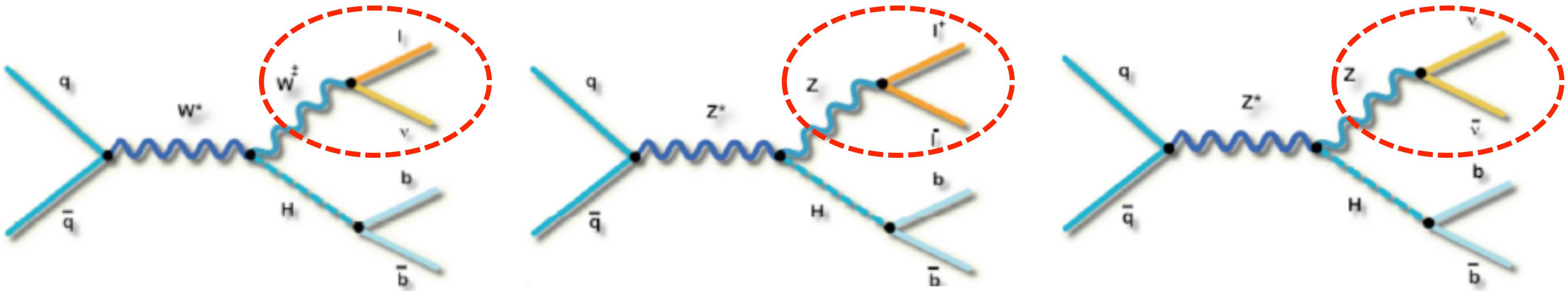


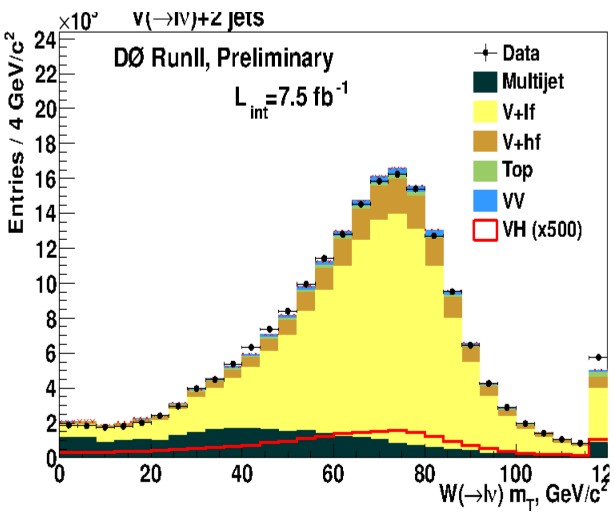


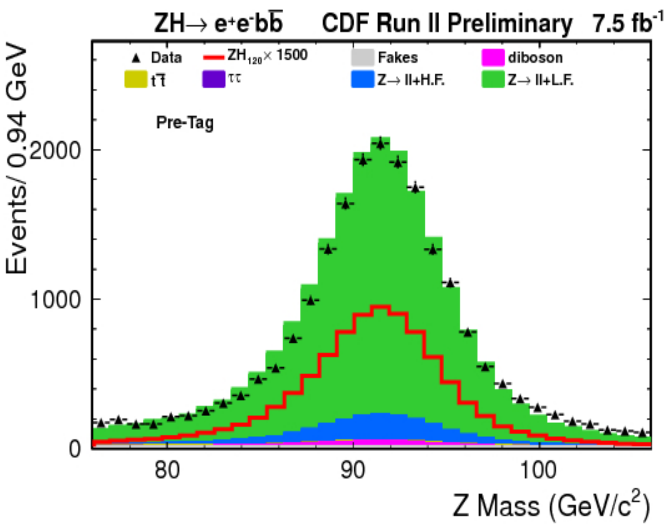
~600-1200 Higgs events produced at the Tevatron in the main search channels with 10 fb^{-1}!

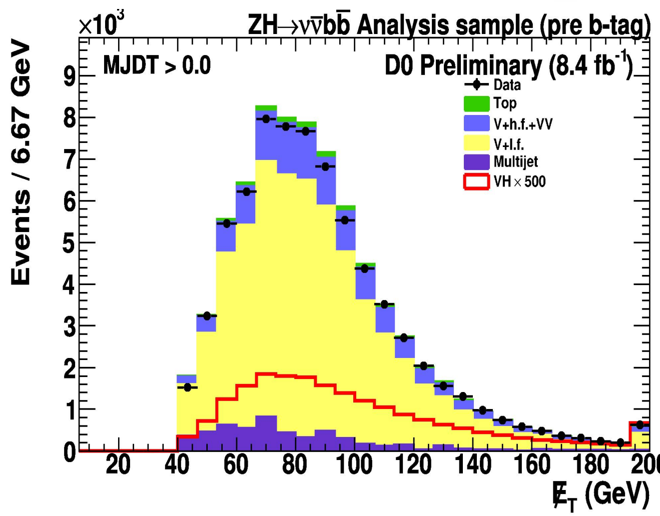
Searching for H→bb

- 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 $\not{E}_T$





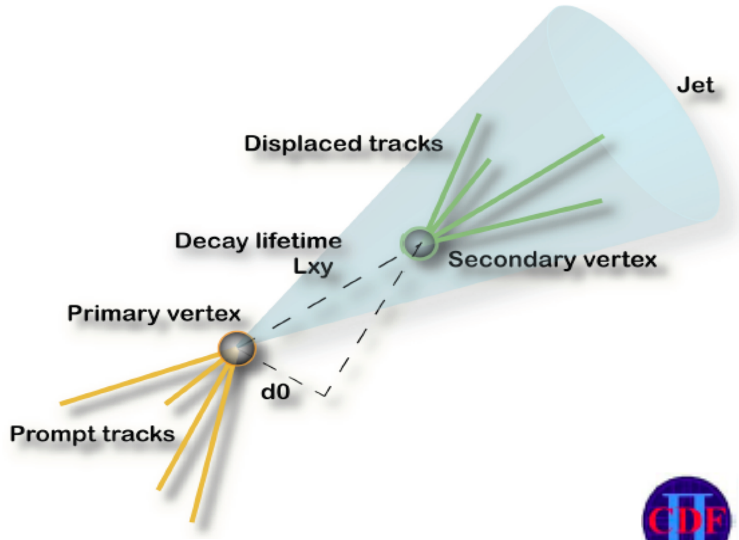


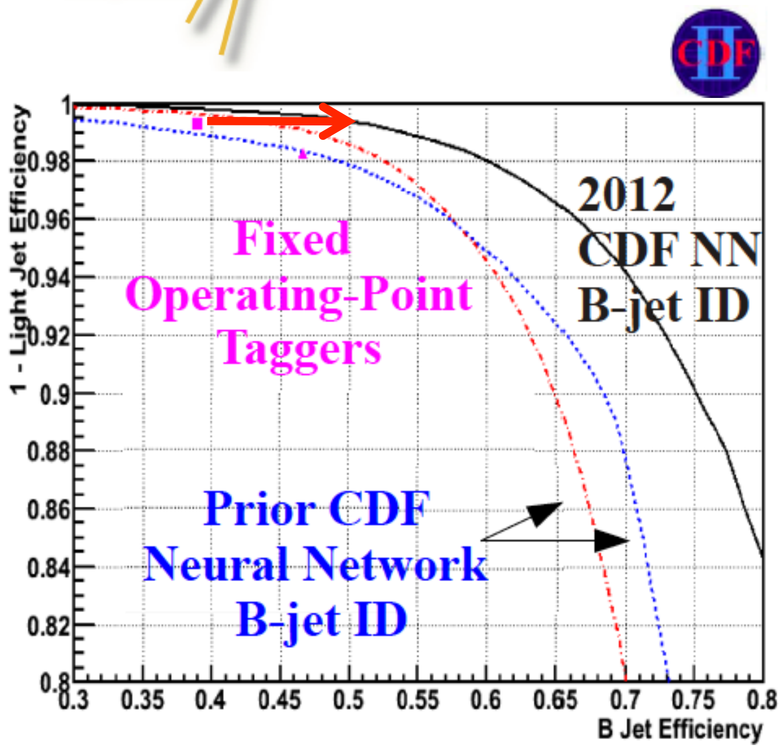


Heavy Flavor Identification

- Critical for searches involving H→bb.
- B-tagging exploits information on:
  - Lifetime: displaced tracks and/or vertices
  - Mass: secondary vertex mass
- Both experiments use multivariate techniques for improved performance:
  - b-to-light discrimination: continuous tagger (multiple operating points)
  - b-to-c discrimination
- Typical performance:
  - B-tagging efficiency: ~50-80%
  - Mistag rate: ~0.5-10%
  - Calibrated in data control samples.
- Winter 2012: major progress at CDF by using new NN b-tagger.
  E.g. ε_b~39%→54% @ 1.4% fake rate

38% increase in per-jet b-tagging efficiency!





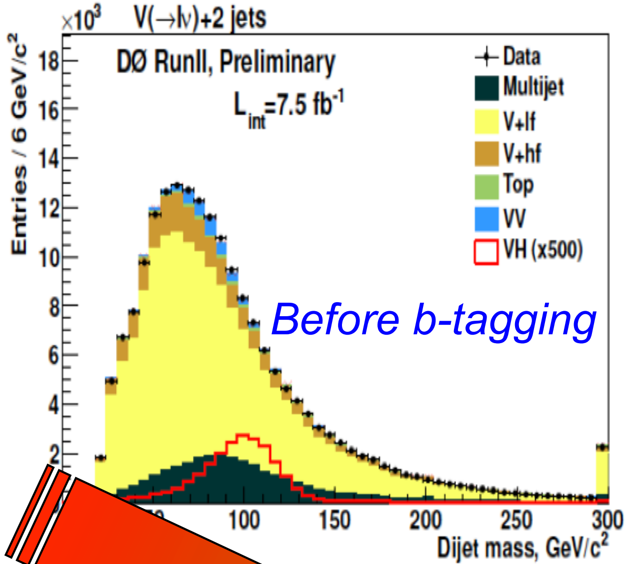
Searching for H→bb: After B-Tagging

B-tagging brings significant improvement to S:B

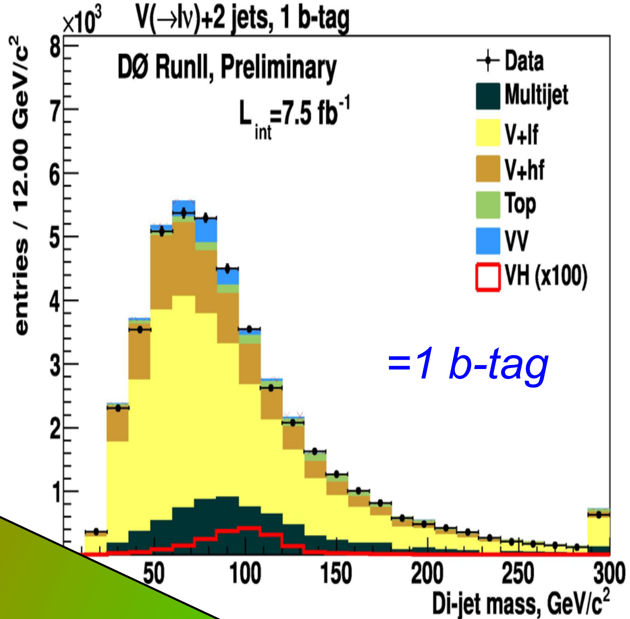
WH→lνbb

Dijet invariant mass

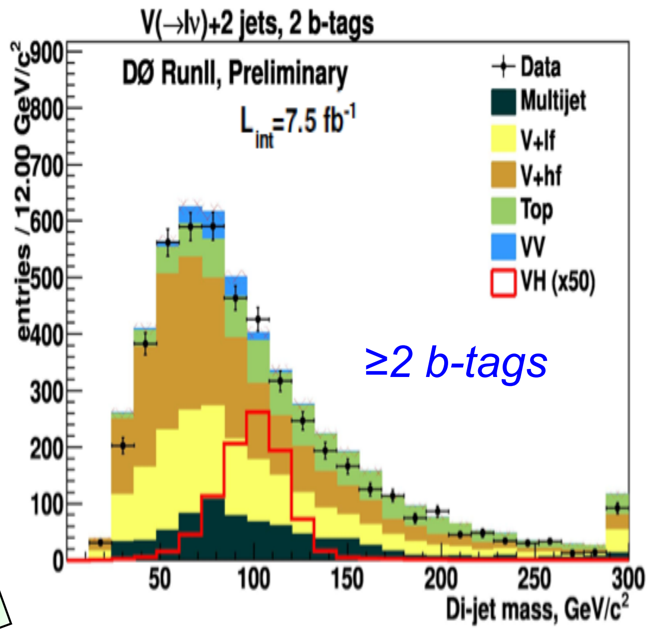
➔ single most discriminant variable



S:B ~ 1:4000



S:B ~ 1:400



S:B ~ 1:75

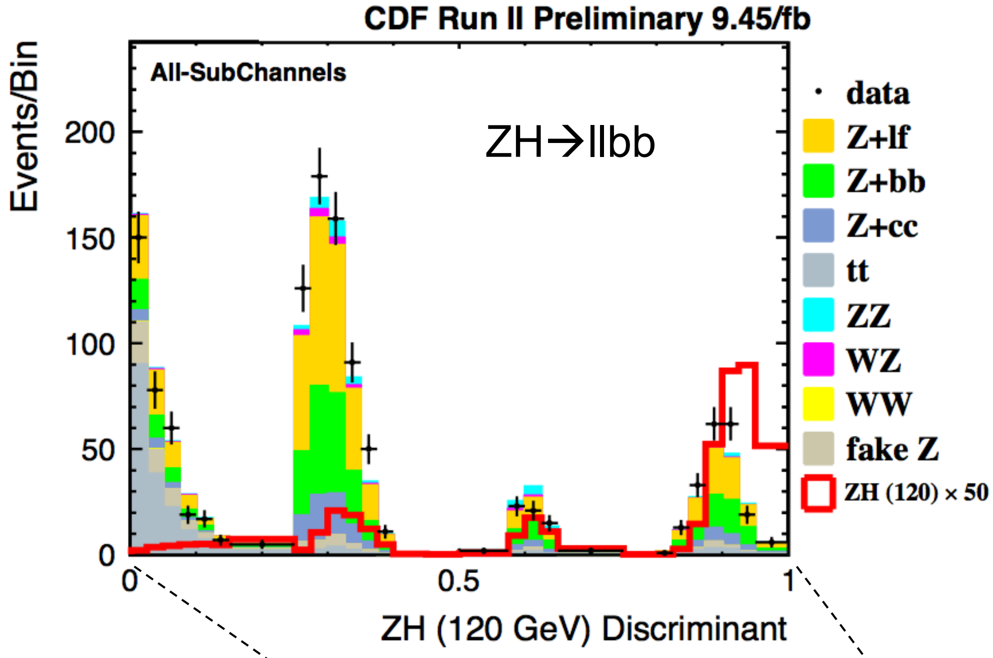
Signal-to-Background Discrimination

Most Higgs analyses use multivariate analysis (MVA) techniques:

- Used against:
  - **Instrumental backgrounds**: increase signal acceptance in event selection
  - **Physics backgrounds**: as final discriminant. Typical sensitivity gain compared to single variable ~15-20%.

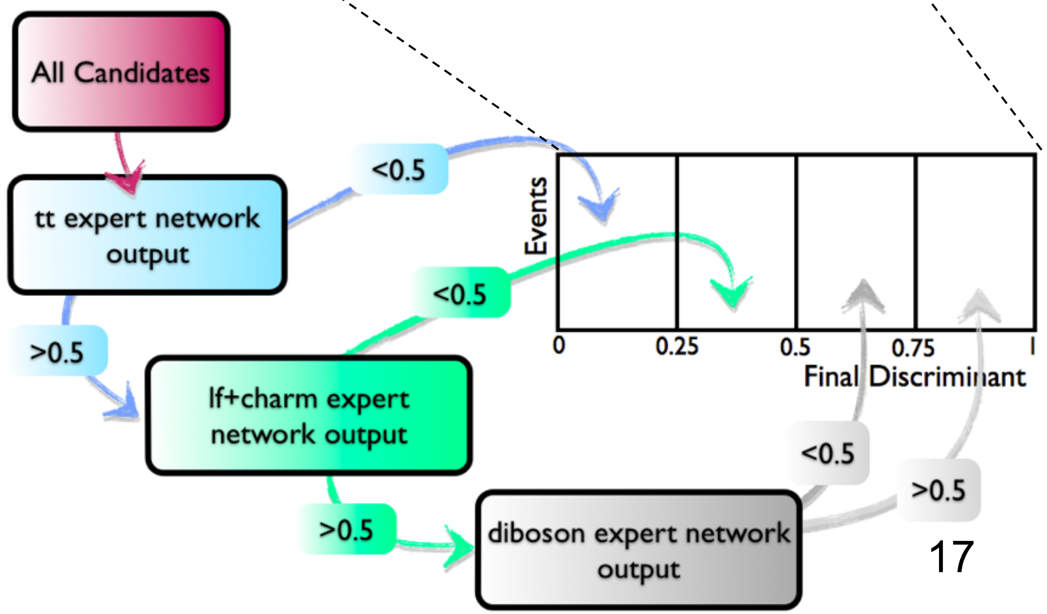
➔ Typically achieve S/B of ~1/1-1/25

S/B ~1/100 for dijet mass alone



Increase sensitivity by splitting analysis into subchannels with different S:B

(e.g. by lepton quality, number of jets,..) and combine at the end.

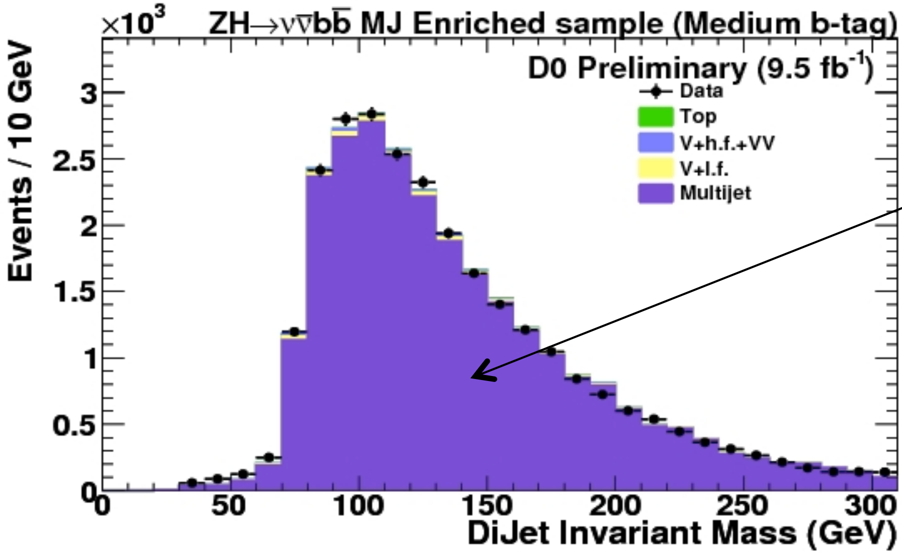


Control Regions

Validate background modeling in signal depleted “side-bands”

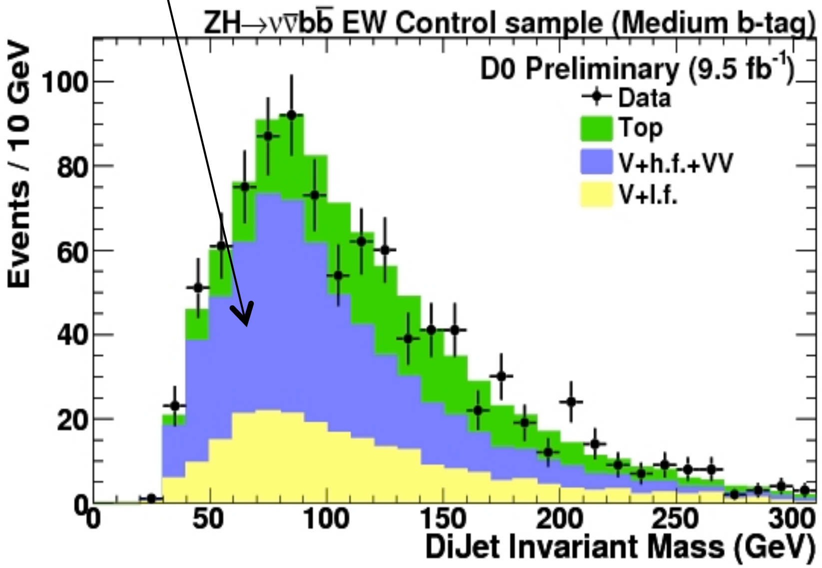
Example: $\not\!\!E_T$+2 b-jets

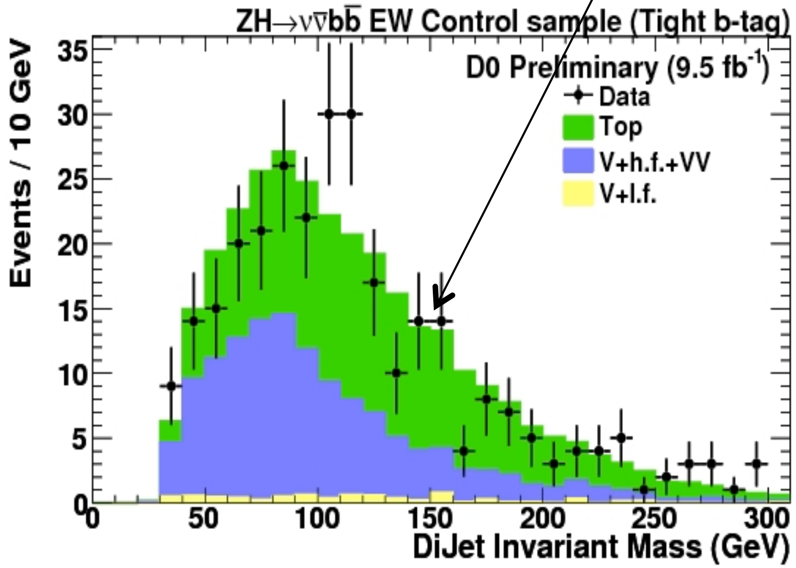
Multijet-enriched



W+jets-enriched

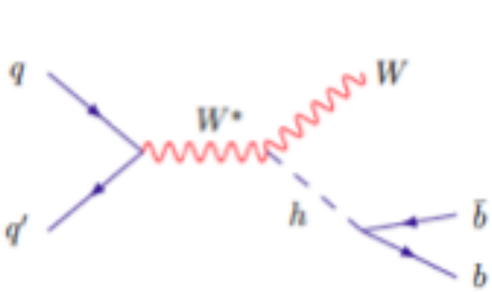
Top-enriched



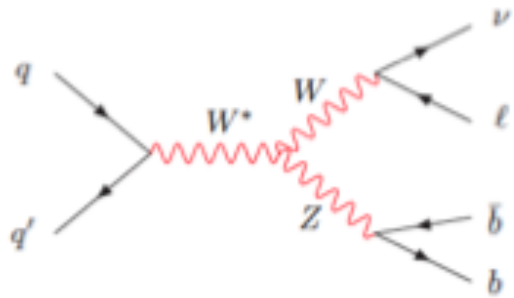


Validation of H→bb Search Techniques

Validate search strategy by looking for a known SM signal with similar signature



VS



For (W/Z)H with mH = 115 GeV:

WH → lνbb:	27 fb (l=e,μ)
ZH → llbb:	5 fb (ll=ee,μμ)
ZH → ννbb:	15 fb
Total:	46 fb

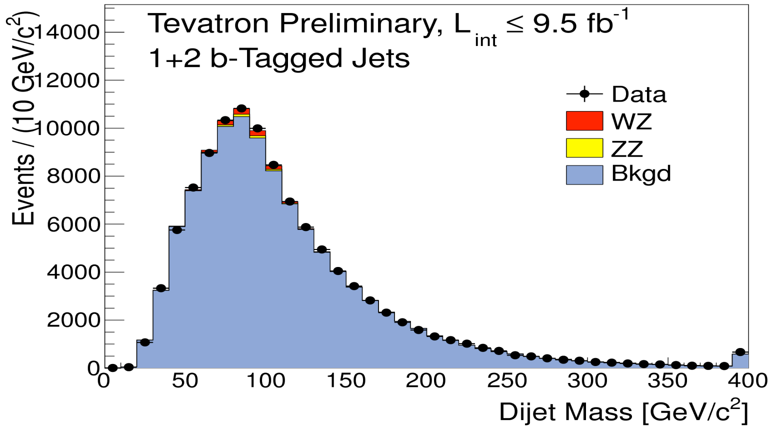
For (W/Z)Z:

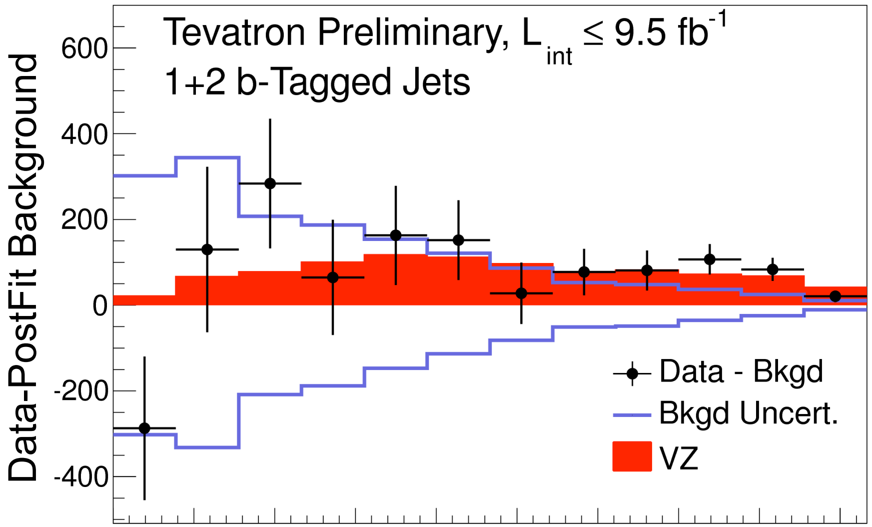
WZ → lνbb:	105 fb (l=e,μ)
ZZ → llbb :	24 fb (ll=ee,μμ)
ZZ → ννbb:	73 fb
Total:	202 fb

- Differences:
  - Cross section for diboson production is x4.5 larger than for W/ZH.
  - There is relatively more signal contribution from Z→cc than from H→cc.
  - Diboson signal sits at low mass where there is a significant peaking background from WW→lνcs and systematic uncertainties are larger.

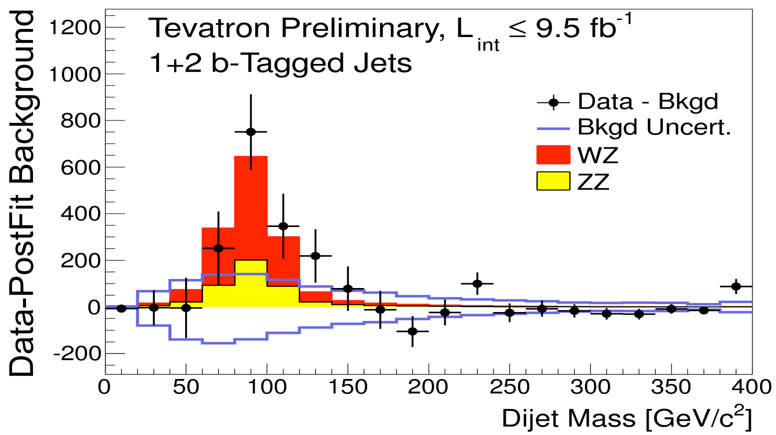
Validation of H→bb Search Techniques

- Combination of CDF and DØ searches for WZ/ZZ in lνbb, llbb, ννbb
  - Exact copies of the corresponding Higgs analysis.
  - Global fit to the final discriminant distributions in all subchannels.





MVA ordered by s/b



Measured cross section in good agreement with the SM:

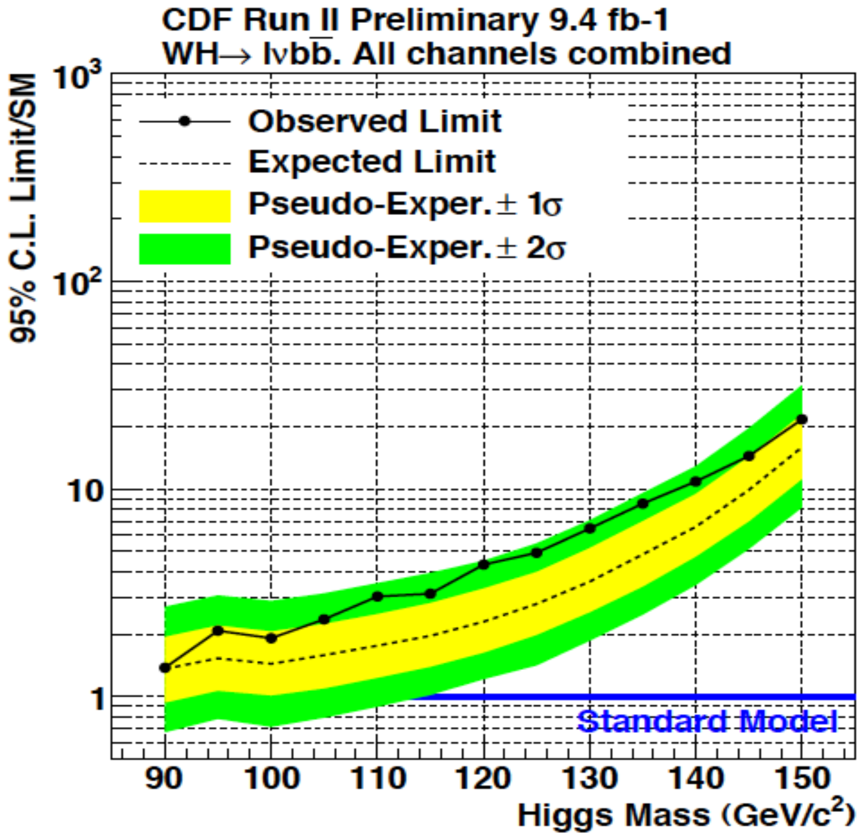
$\sigma_{WZ+ZZ} = (1.01 \pm 0.21)\, \sigma_{SM}$

Obs. significance of 4.6 s.d (4.8 s.d. exp.).

Summary of H→bb Results

95% CL Limits at m_H = 115 GeV

Channel	Exp/obs Limit (σ/SM)
WH→lνbb (9.4 fb^{-1})	2.0/3.1
ZH→ννbb (9.4 fb^{-1})	2.7/2.7
ZH→l^+l^-bb (9.4 fb^{-1})	2.6/4.7
WH→lνbb (9.7 fb^{-1})	3.2/4.0
ZH→ννbb (9.5 fb^{-1})	3.0/2.5
ZH→l^+l^-bb (9.7 fb^{-1})	4.2/3.7
VH/VBF→jjbb (9.4 fb^{-1})	8.3/7.2
ttH→l+jets (9.4 fb^{-1})	10.1/14.5
ttH→jets (5.7 fb^{-1})	20.2/28.1



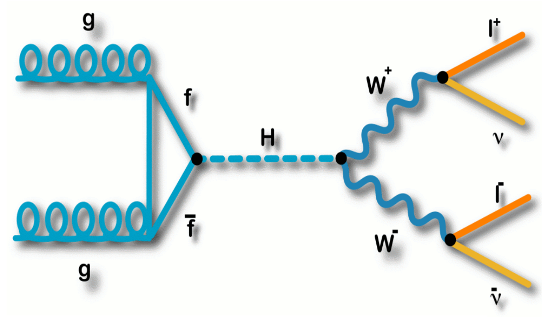
- Limits from individual VH, H→bb channels at ~2-3xSM at m_H=115 GeV and quickly degrading towards high mass.
- Important to consider additional channels with different mass dependence.

See talk by Elisabetta Pianori at Higgs Parallel Session

Searching for H→WW→lνlν

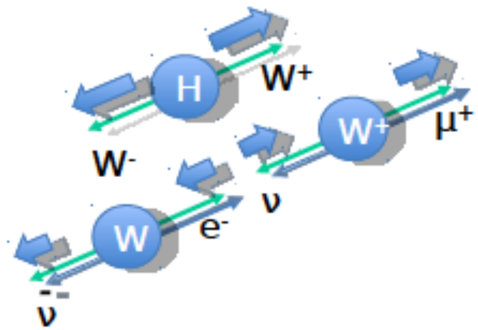
- Highest sensitivity channel in m_H~130-200 GeV range.
- Clean dilepton+$\not{E}_T$ signature.
- Main backgrounds after $\not{E}_T$ cut: WW, W/Z+jets.
- After final selection expect (m_H=165 GeV):

  ~7 signal events/fb^{-1}/experiment with S:B~1:50-1:100

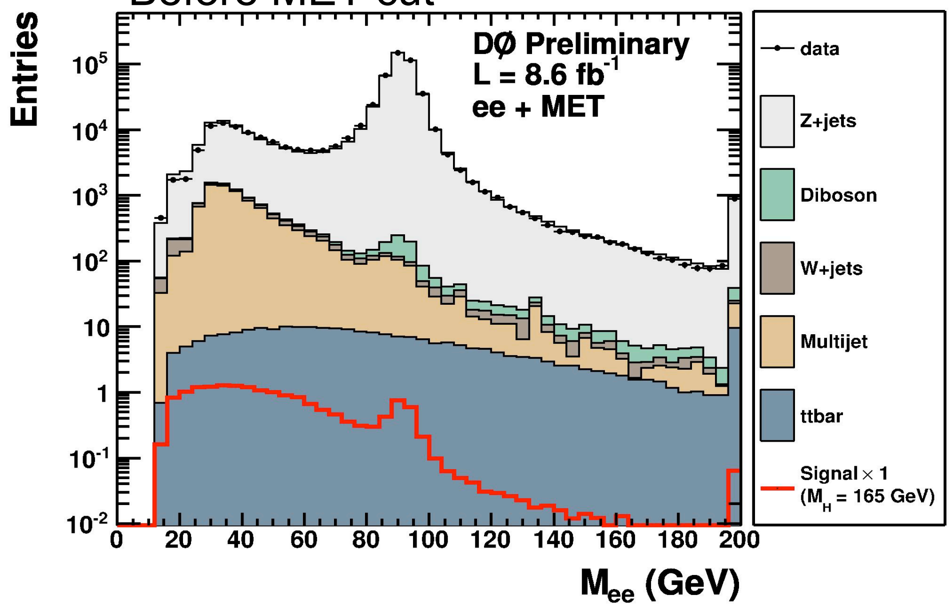


- Exploit spin correlation between dibosons.

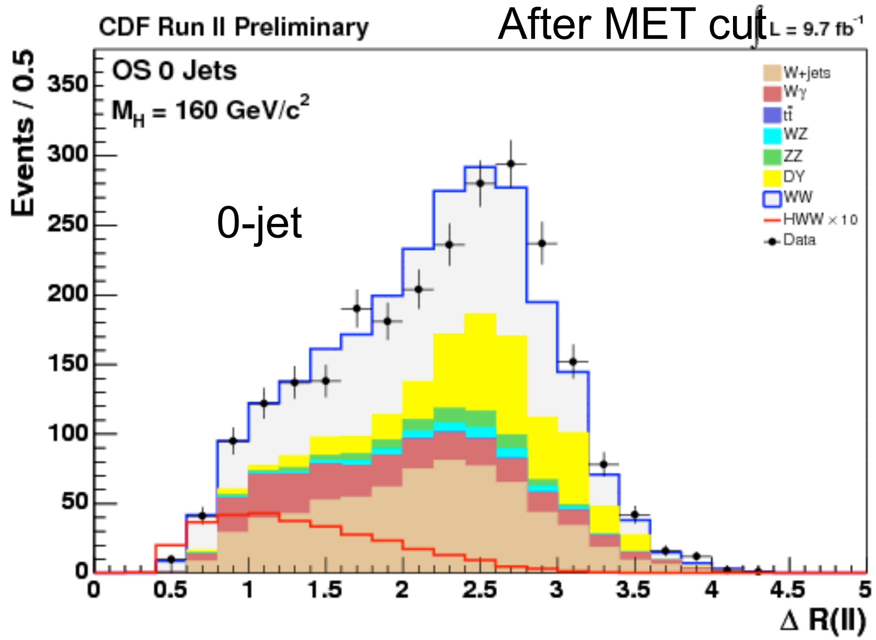
  ➔ Small angular separation between leptons



Before MET cut



After MET cut



Searching for H→WW→lνlν

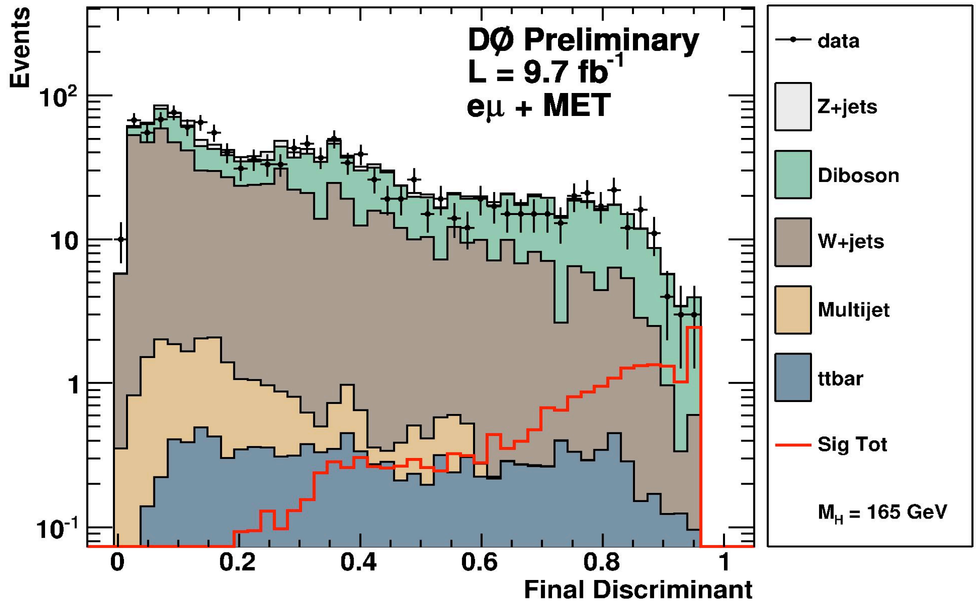
To increase the sensitivity:

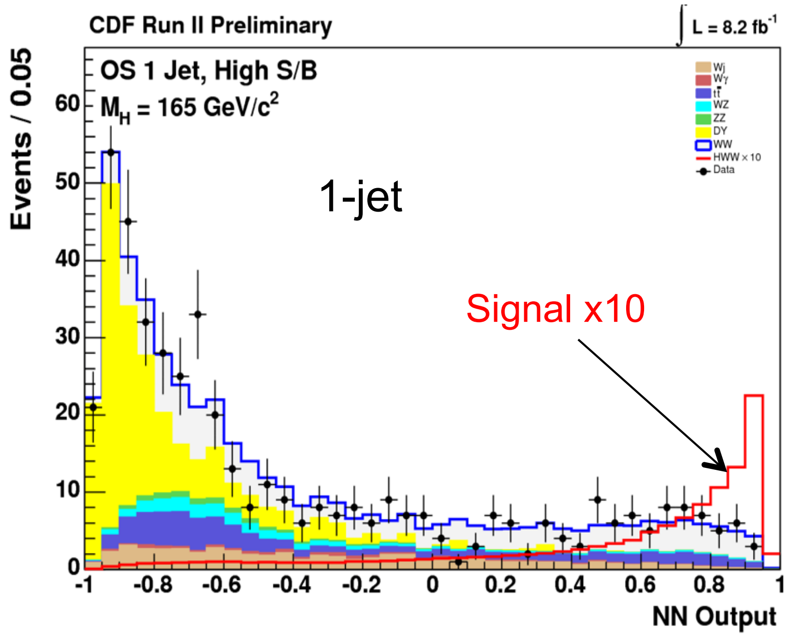
- Build multivariate discriminants combining several variables

- Split samples with different S:B and combine at the end:
  - by lepton flavor (DØ) or quality (CDF)
  - by jet multiplicity

- Add additional requirements for particular subsamples:
  - Suppress $Z/\gamma^* \to e^+e^-, \mu^+\mu^-$ by cutting on dedicated MVA variable (DØ)
  - Suppress top quark pairs by vetoing b-tag in 2-jet events (CDF)

eμ/0-jet

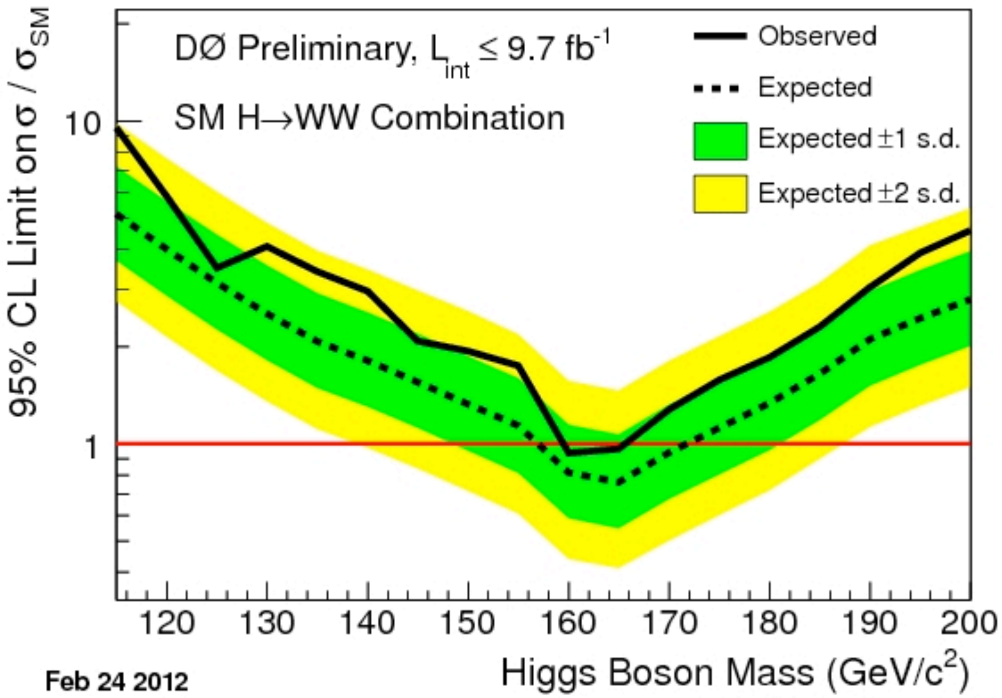




Low Mass Results from H→WW,ττ,γγ

95% CL Limits at m_H = 115 GeV

	Channel	Exp/obs Limit (σ/SM)
CDF	H→WW→lνlν (9.7 fb^{-1})	7.1/11.5
DØ	H→WW→lνlν (9.7 fb^{-1})	7.7/11.8
CDF	H+X→ττ+jets (8.3 fb^{-1})	12.6/12.2
CDF	VH→ττl(l) (6.2 fb^{-1})	17.3/18.5
DØ	H+X→ττjj (6.2 fb^{-1})	14.3/21.8
DØ	VH→ττμ (7.0 fb^{-1})	14.2/10.7
CDF	H→γγ (10.0 fb^{-1})	10.6/12.7
DØ	H→γγ (9.7 fb^{-1})	11.5/8.4



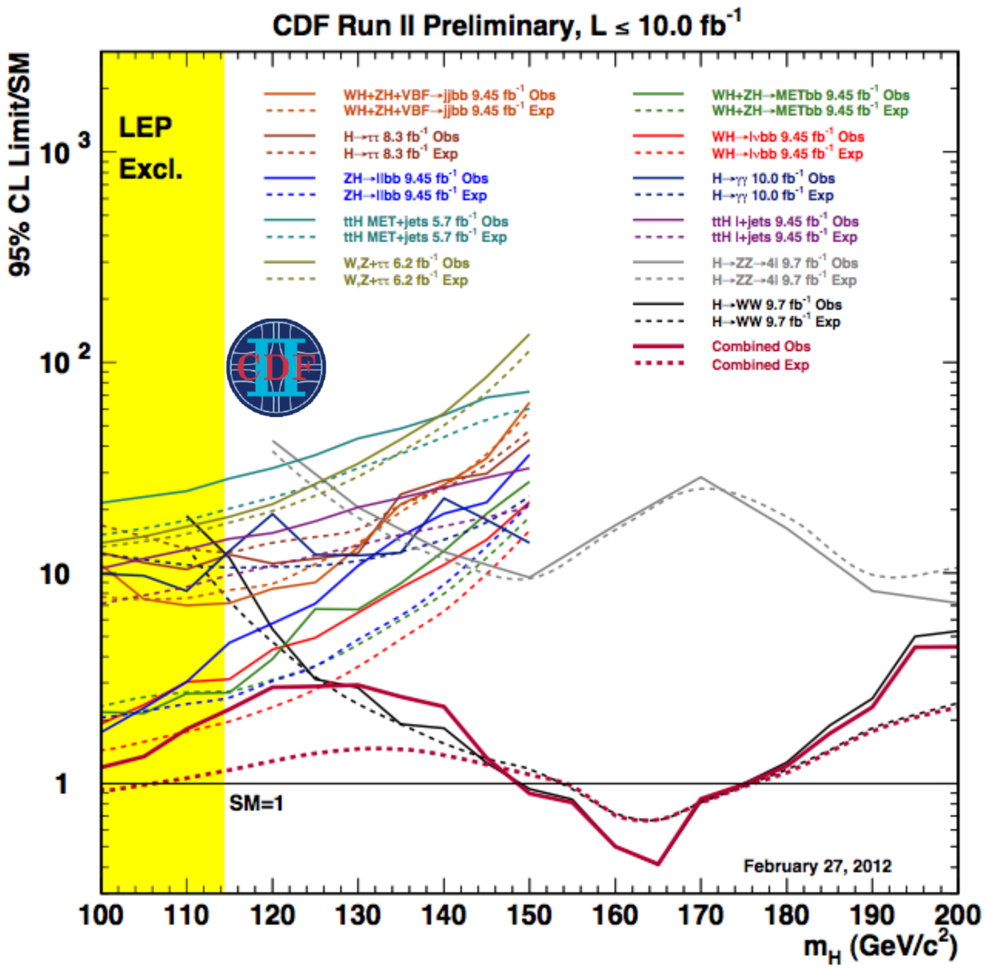
Additional channels contribute useful sensitivity at low/intermediate m_H:

- H→WW→lνlν: improving towards high m_H.
- H+X→ττjj, H→γγ : ~flat vs m_H.

→ Combination of all contributing channels crucial

Combined Limits on SM Higgs Production

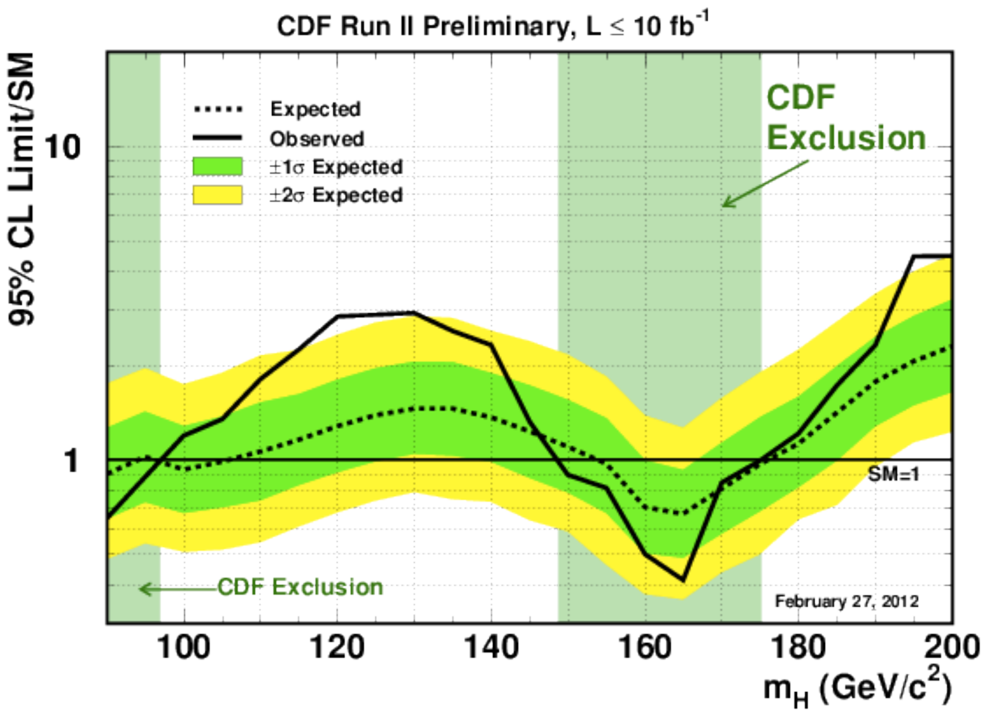
- Combination of multiple channels (and experiments!) yields the greatest sensitivity.

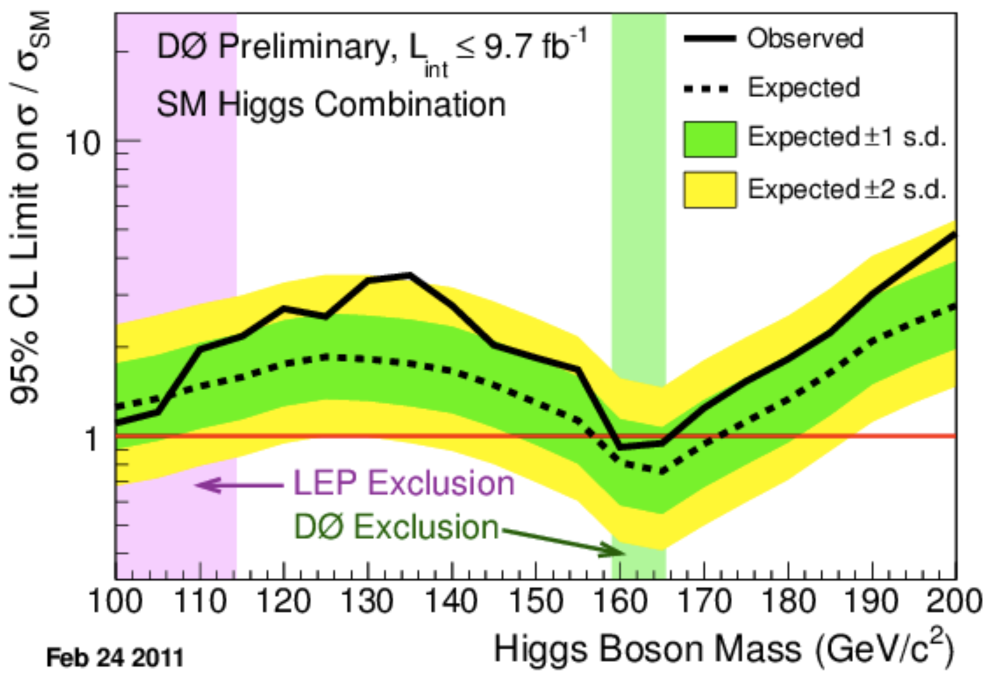


- Assumes SM prediction for ratio of production cross sections and branching ratios.
- More than 50 different sources of systematic uncertainties are considered (including correlations among channels and experiments), and constrained in sidebands.
- Use different techniques to cross check calculations (Bayesian, modified frequentist)

  ➔ results agree within ≤5%.

CDF and DØ Individual Results



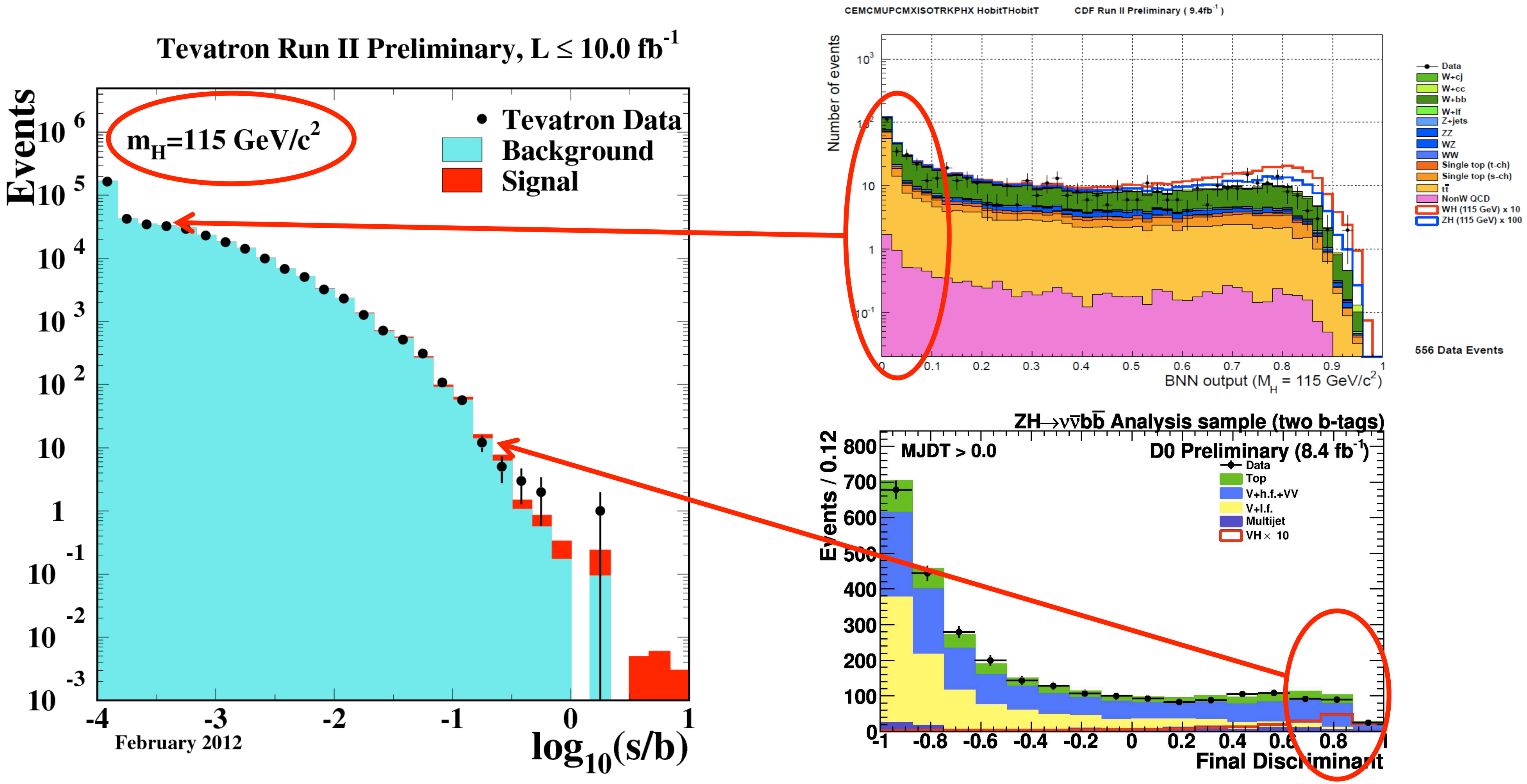


At m_H = 115 GeV:	At m_H = 125 GeV:	At m_H = 115 GeV:	At m_H = 125 GeV:
Exp. limit: 1.16 x SM	Exp. limit: 1.39 x SM	Exp. limit: 1.58 x SM	Exp. limit: 1.85 x SM
Obs. limit: 2.25 x SM	Obs. limit: 2.89 x SM	Obs. limit: 2.17 x SM	Obs. limit: 2.53 x SM

95% CL exclusion: 147 < m_H < 175 GeV

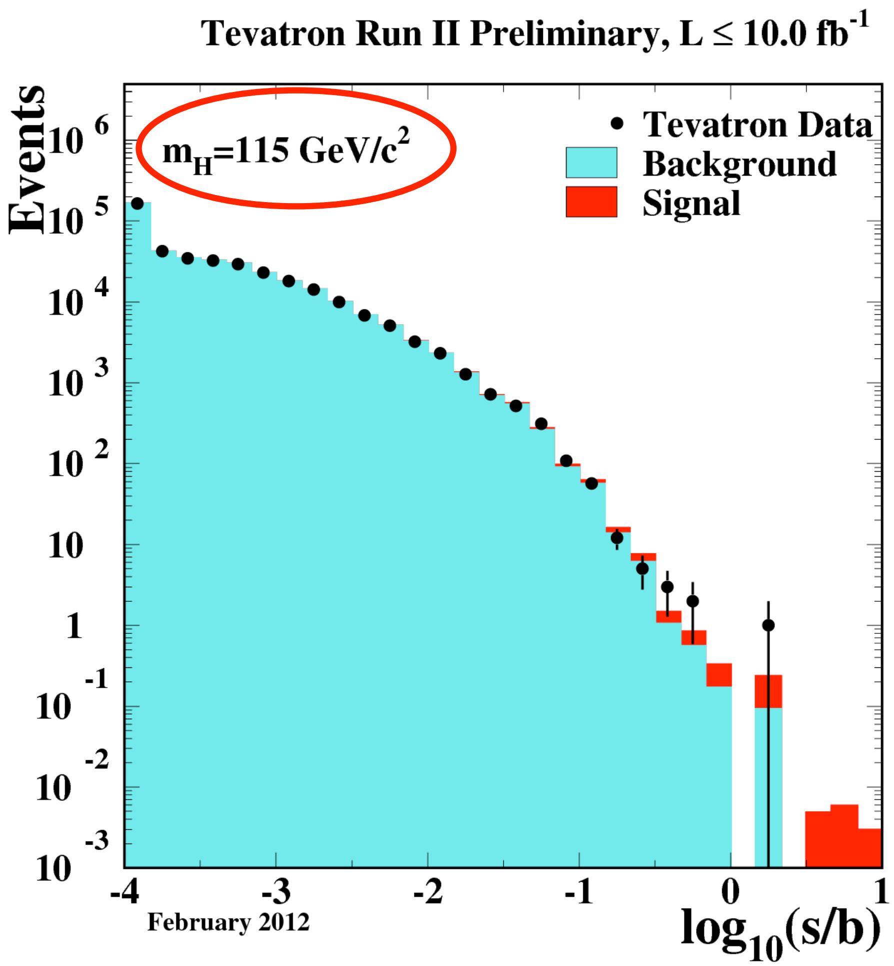
95% CL exclusion: 159 < m_H < 166 GeV

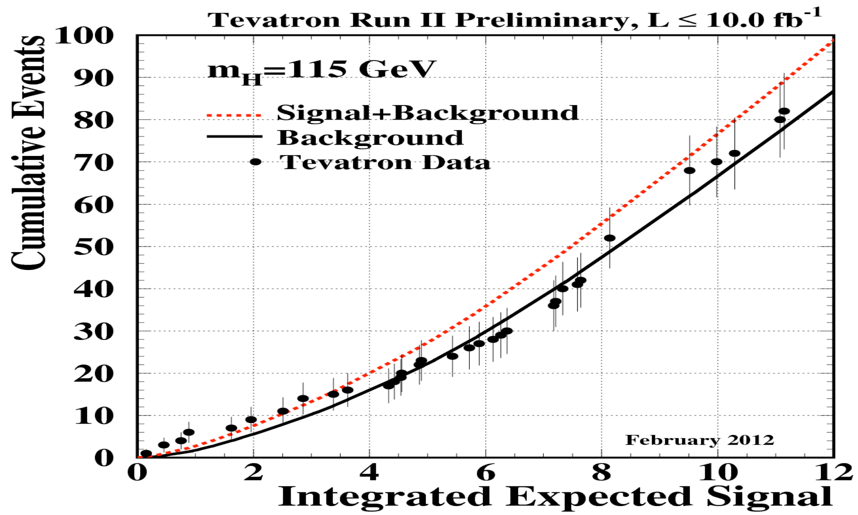
Visualizing the Tevatron Data

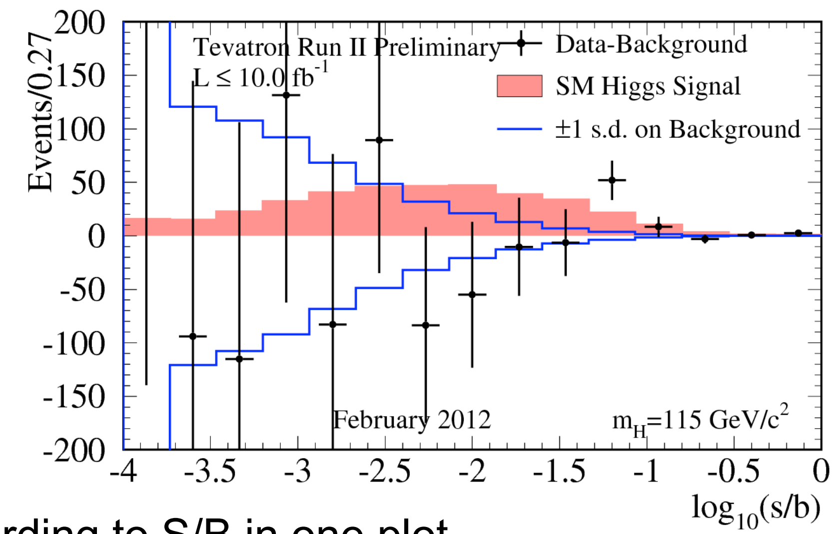


- Display all input histogram bins ordered according to S/B in one plot.
- The background model has been constrained by the data.

Visualizing the Tevatron Data

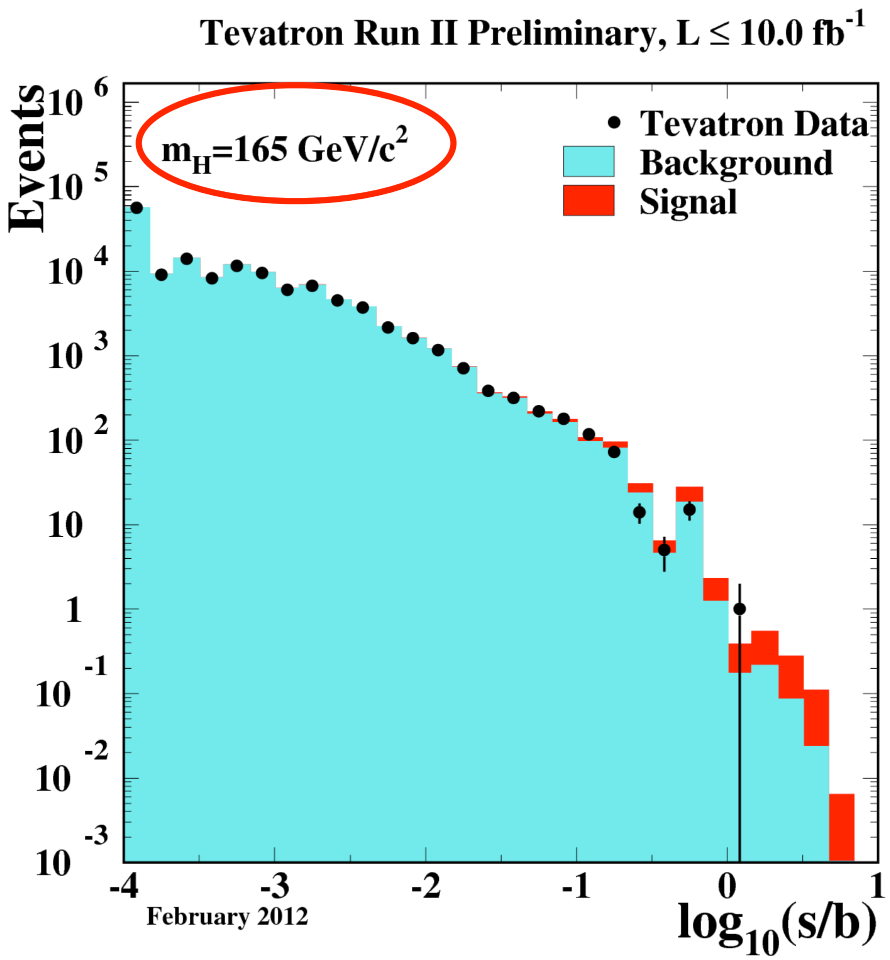


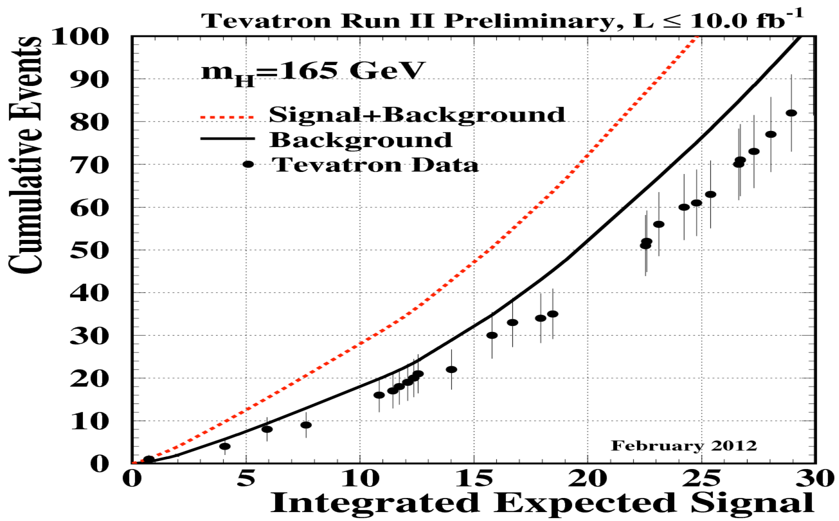


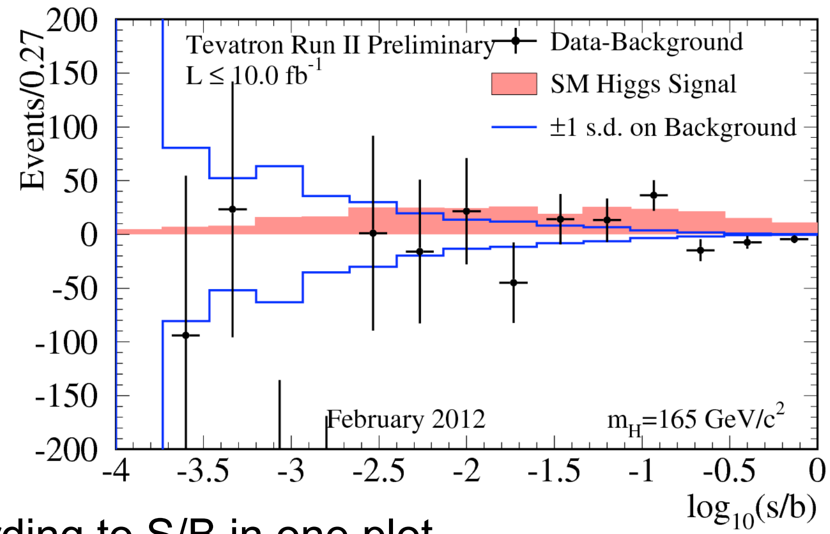


- Display all input histogram bins ordered according to S/B in one plot.
- The background model has been constrained by the data.
- Data consistent with the B-only hypothesis within the systematic uncertainties.

Visualizing the Tevatron Data







- Display all input histogram bins ordered according to S/B in one plot.
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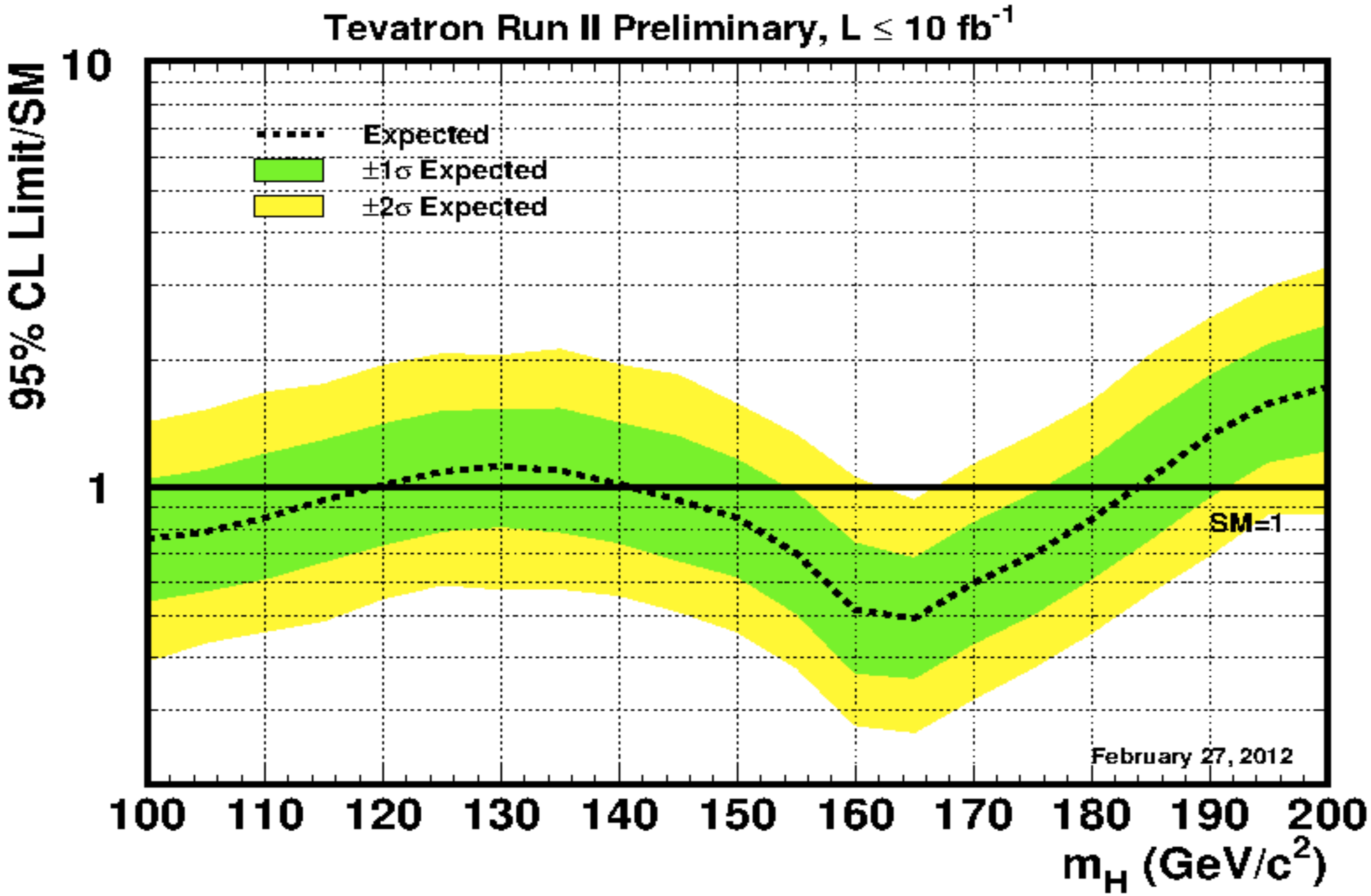
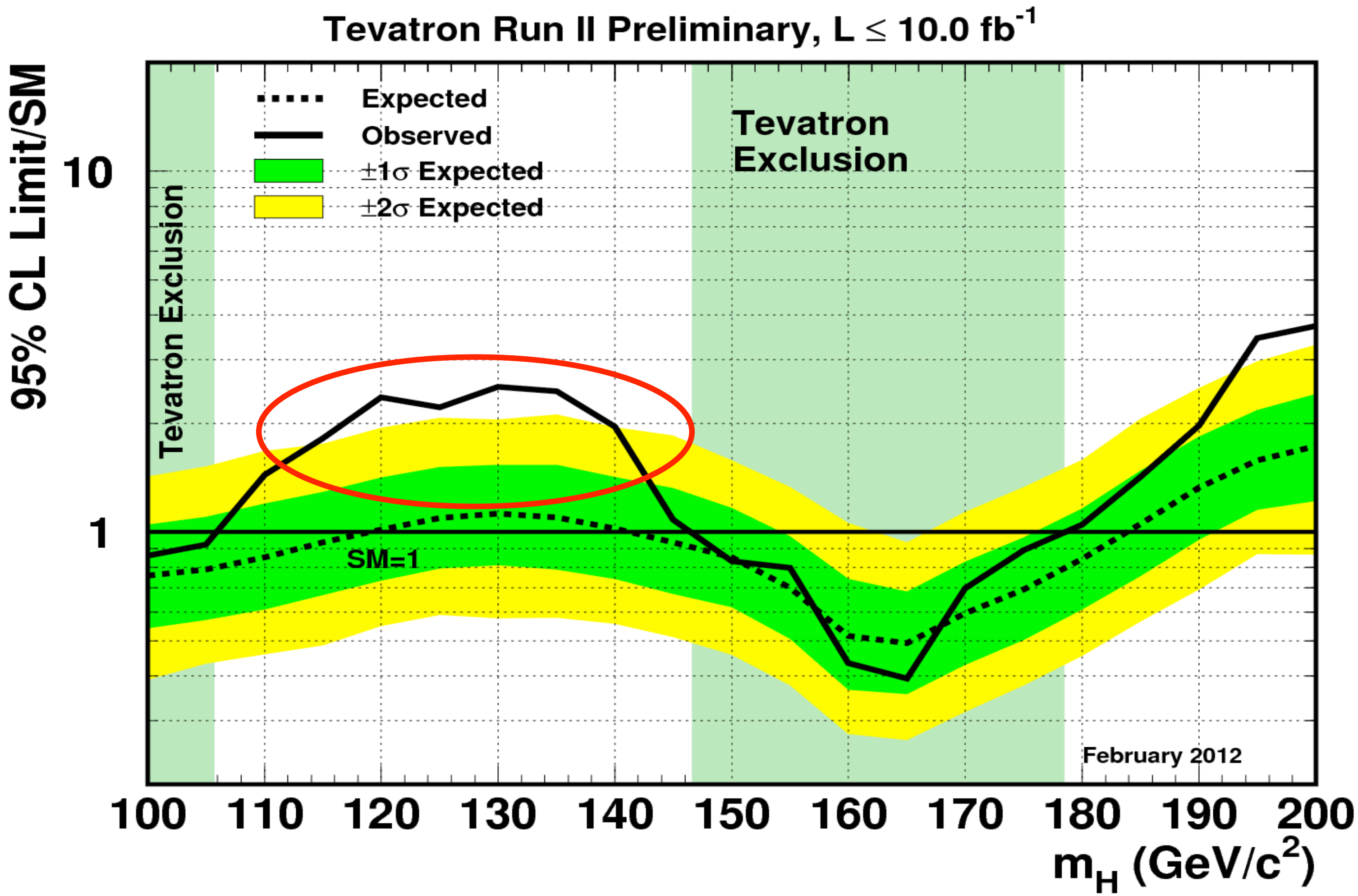
Combined Tevatron Expected Limits



- Expected exclusion: $100 < m_H < 120$ GeV, $141 < m_H < 184$ GeV
- 95% CL limit at m_H=125 GeV: 1.10xSM (expected)

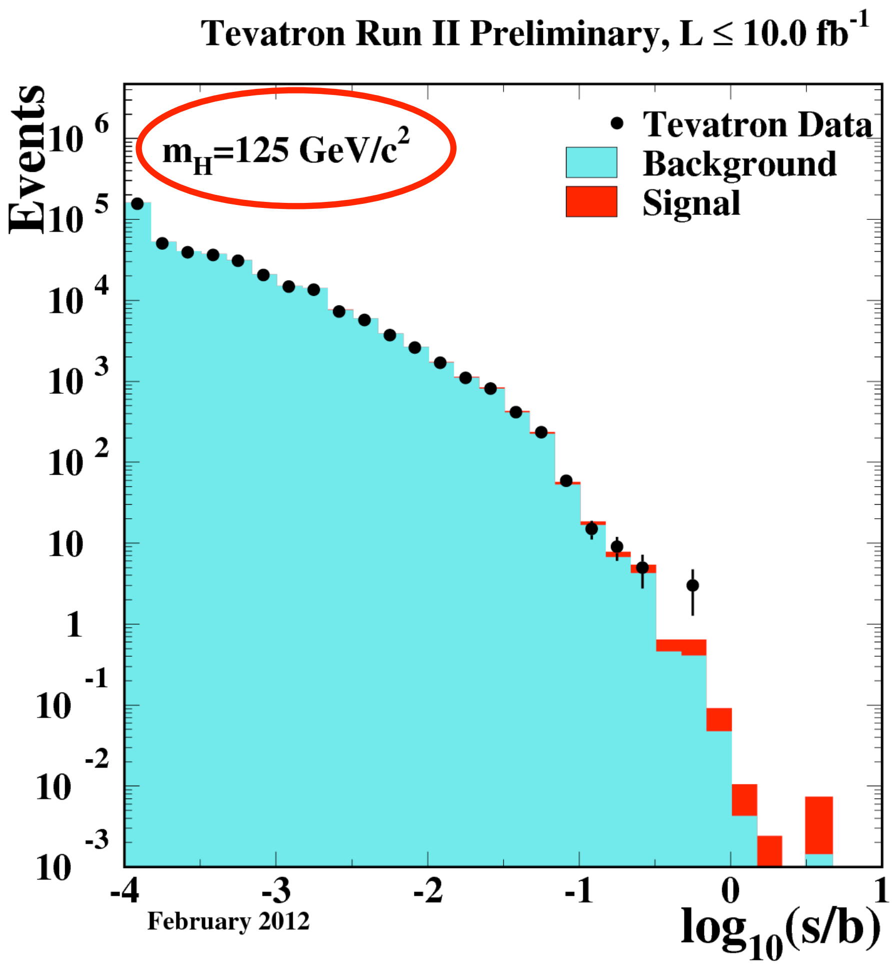
Combined Tevatron Observed Limits

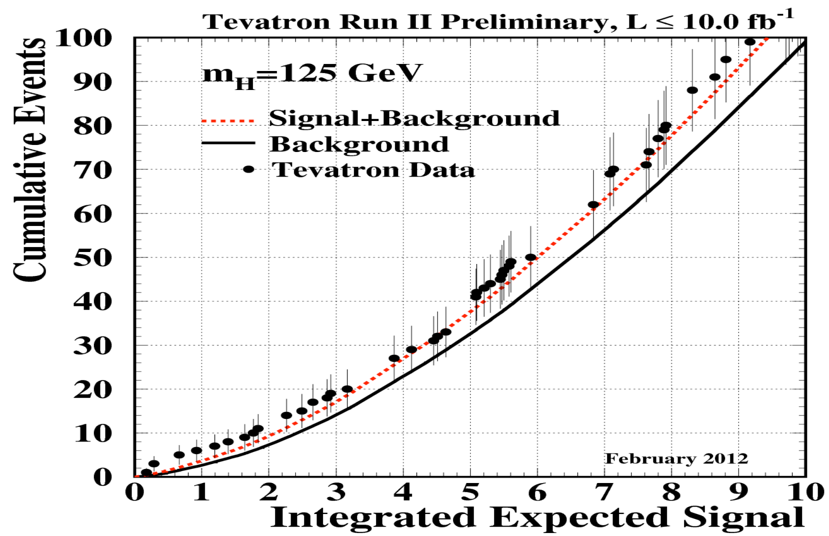


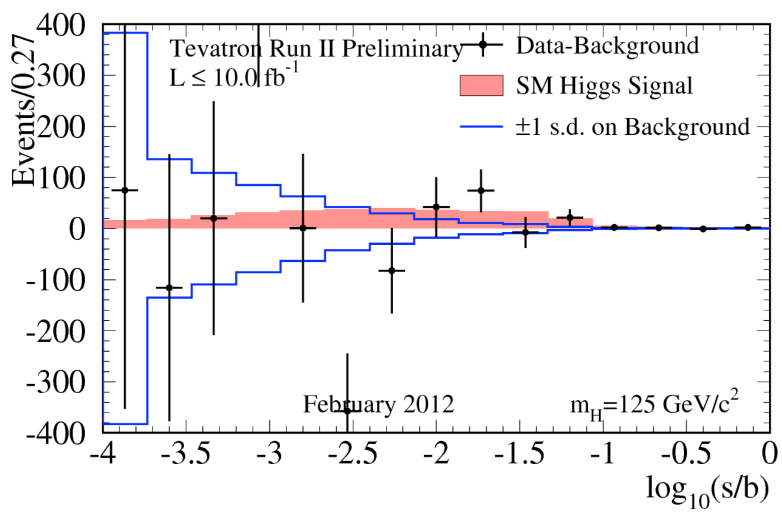
- Expected exclusion: $100 < m_H < 120$ GeV, $141 < m_H < 184$ GeV

  Observed exclusion: $100 < m_H < 106$ GeV, $147 < m_H < 179$ GeV
- 95% CL limit at m_H=125 GeV: 1.10xSM (expected), 2.22xSM (observed)

Visualizing the Excess



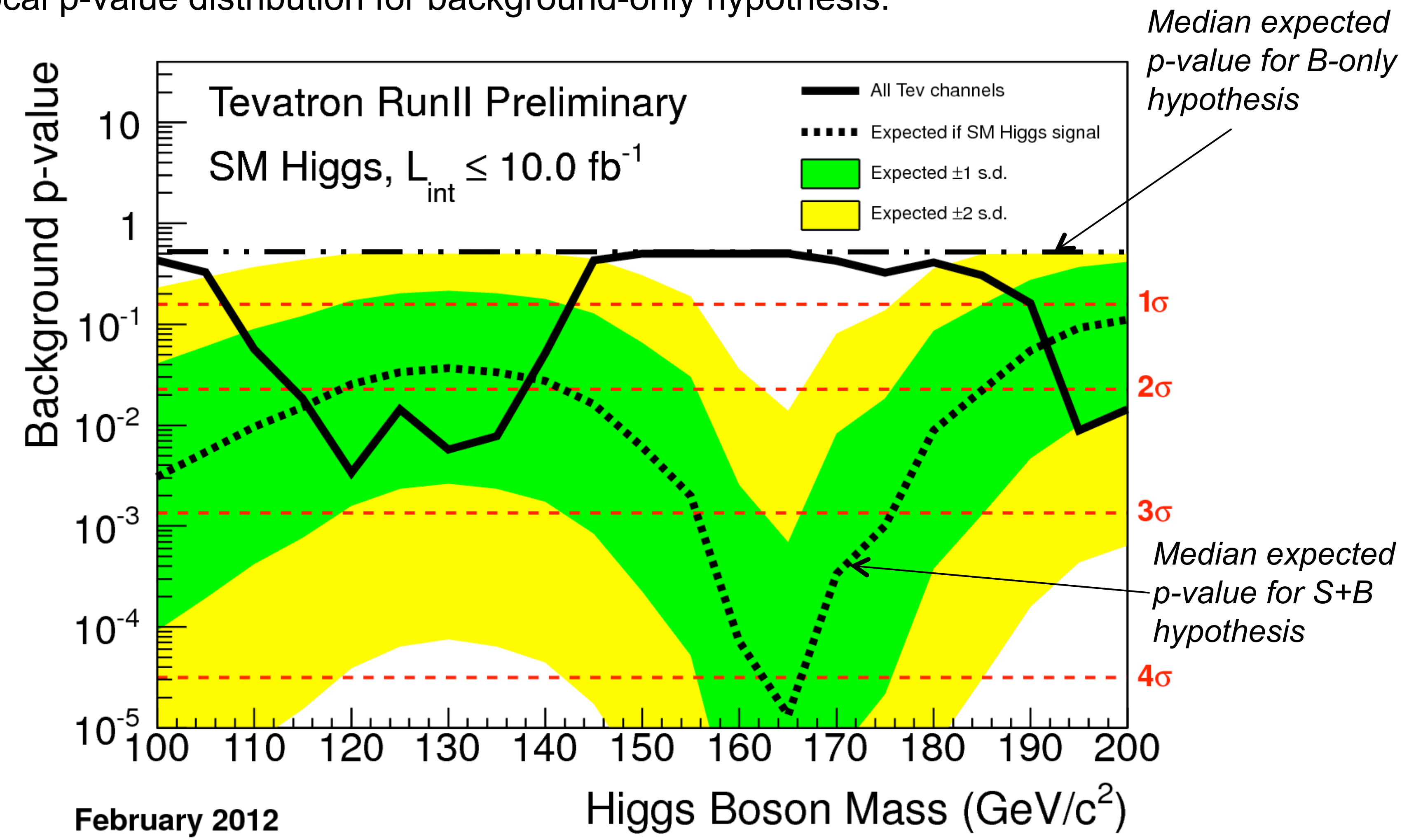




- Display all input histogram bins ordered according to S/B in one plot.
- The background model has been constrained by the data.

Quantifying the Excess: p-values

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

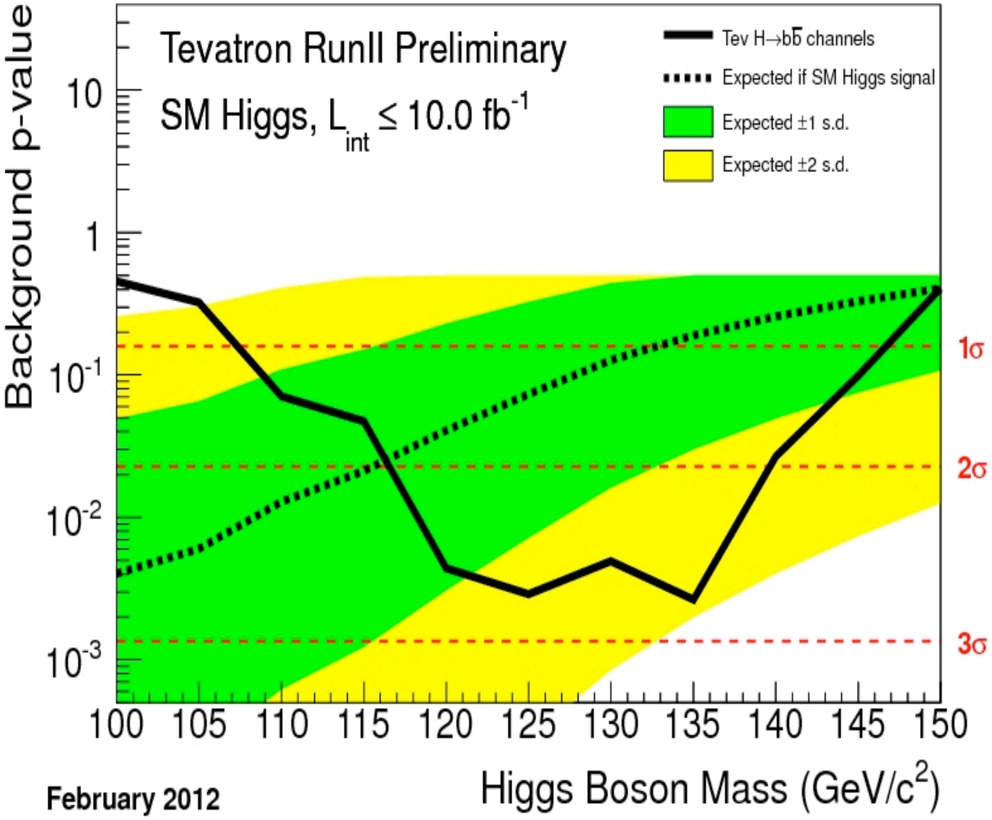


- Minimum local p-value: 2.7 standard deviations
- Minimum global p-value with look-elsewhere factor of 4: 2.2 standard deviations

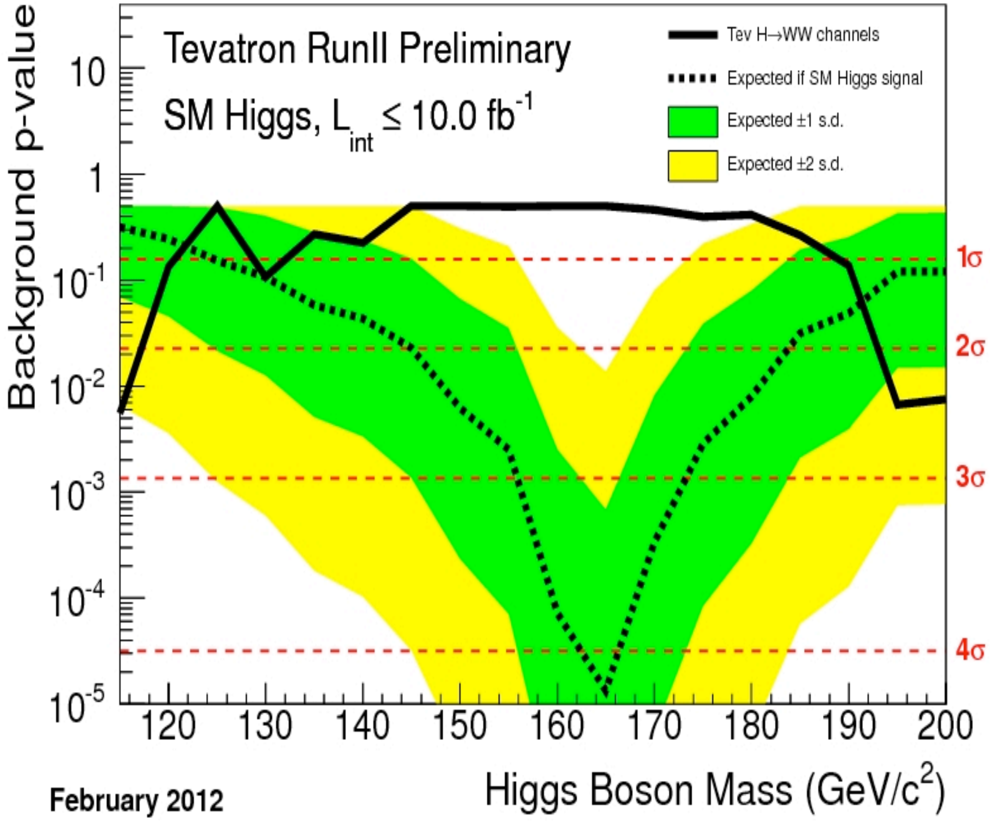
Quantifying the Excess: p-values

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

H→bb channels



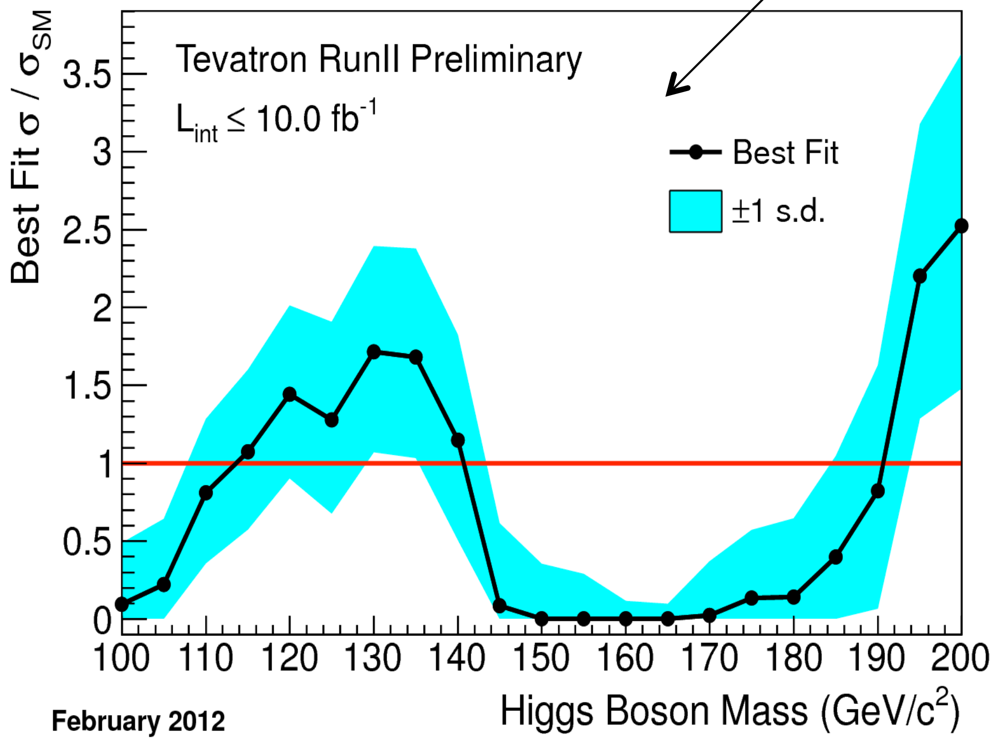
H→WW channels

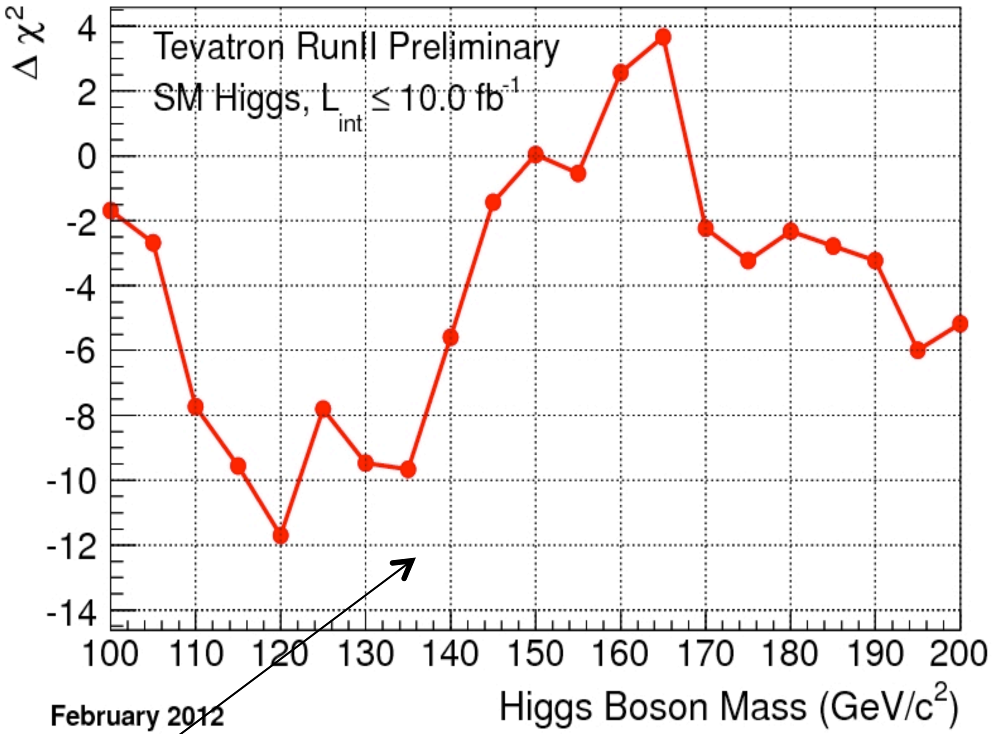


- **H→bb channels**: main contribution to excess in $115<m_H<135$ GeV region
  - Minimum local p-value: 2.8 standard deviations
  - Minimum global p-value with look-elsewhere factor of 2: 2.6 standard deviations
- **H→WW channels**: no significant excess in $115<m_H<135$ GeV region

Quantifying the Excess: Best Fit Signal Rate

- Maximum likelihood fit to data with signal rate as free parameter.



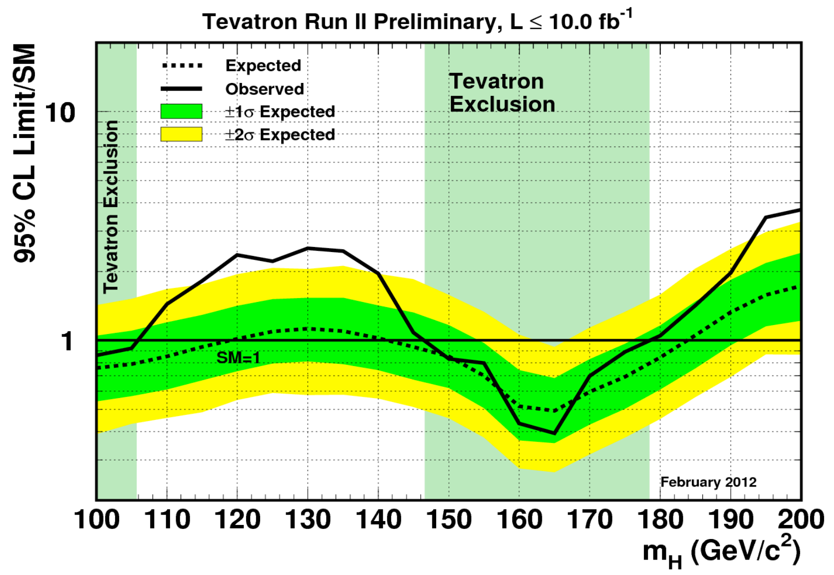


- $\Delta\chi^2$ test with fixed signal prediction from SM theory agrees well with freely floating signal rate estimation:
  - $\Delta\chi^2$ minimum in $115 < m_H < 135$ GeV range.

Summary and Outlook

- Tevatron program now analyzing full dataset in most search channels.
- Tevatron combination has reached SM sensitivity over most of $100<m_H<185$ GeV range.
- Tantalizing excess in $115<m_H<135$ GeV region with global p-value of 2.2 s.d. (2.7 s.d. local) .

  H→bb only: 2.6 s.d. global (2.8 s.d. local).



Summary and Outlook

- Tevatron program now analyzing full dataset in most search channels.
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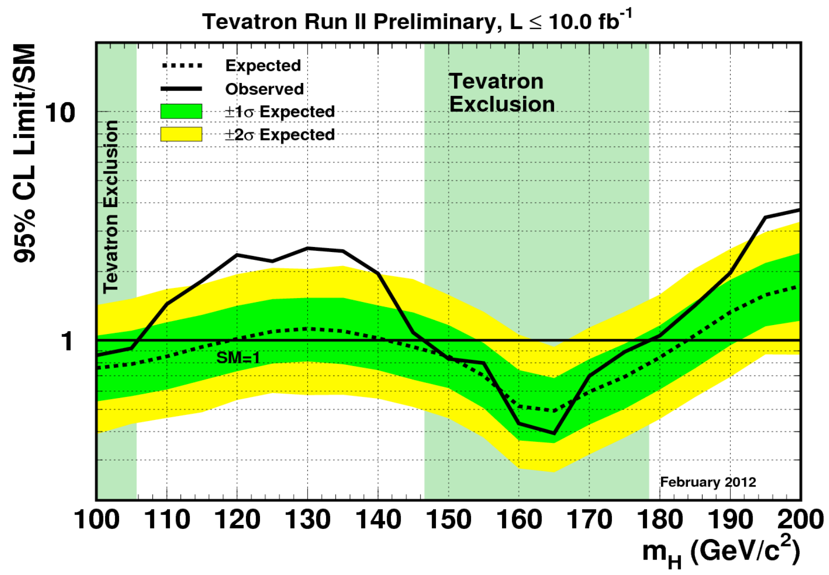


- These are by no means the final Tevatron results!
- Further improvements expected in the near future, particularly in searches targeting the $115<m_H<135$ GeV region.

- Tevatron and LHC are sensitively probing the Higgs sector in complementary ways.

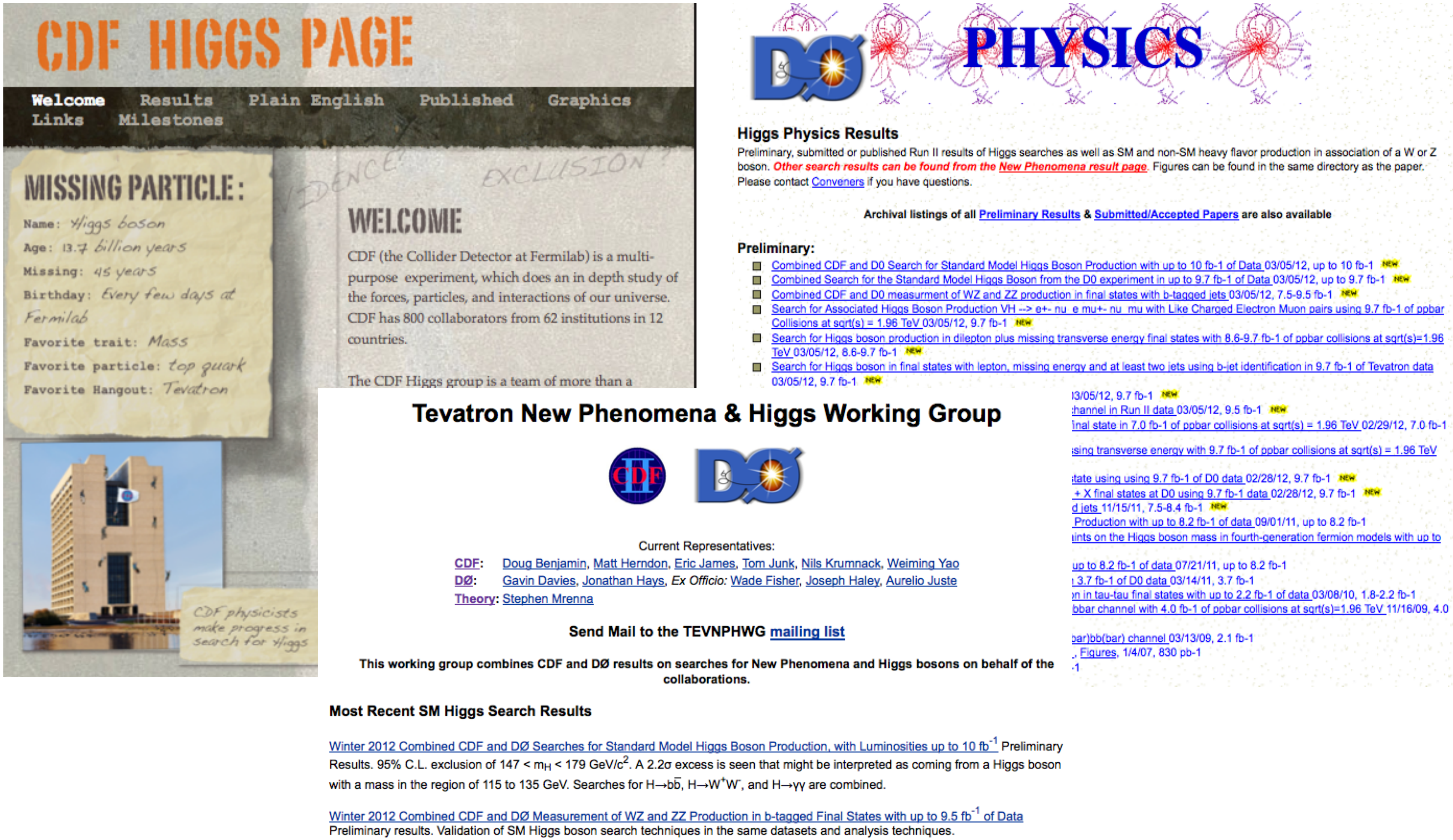
  In particular, Tevatron currently provides a unique window into the H→bb mode.

  Looking forward to a LHC-Tevatron combination!

Further Information

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

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



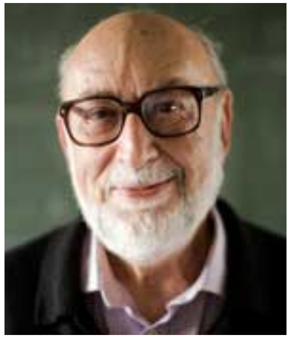
http://tevnphwg.fnal.gov/

Backup

2010 Sakurai Prize for Theoretical Particle Physics

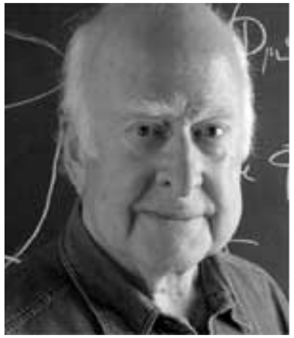
"For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses"

Robert Brout



Francois Englert

Universite Libre de Bruxelles



Peter W. Higgs

Univ. of Edinburgh

Gerald S. Guralnik

Brown University

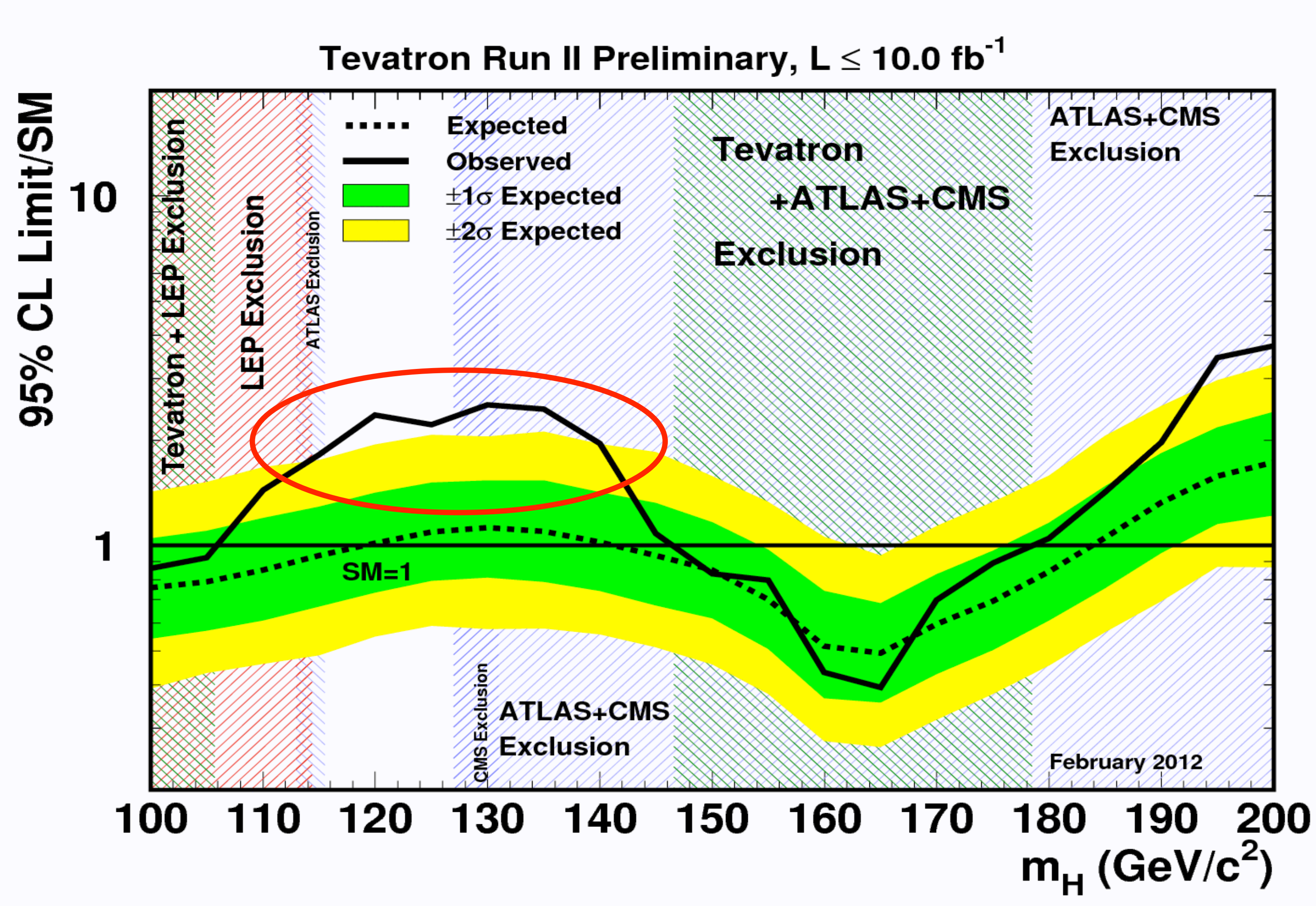
Carl R. Hagen

Univ. of Rochester

T.W.B. Kibble

Imperial College

Combined Tevatron Observed Limits

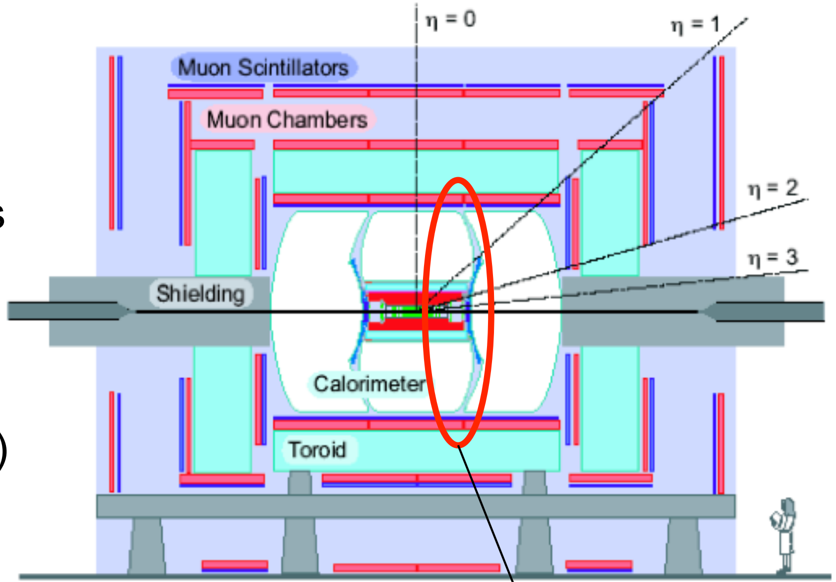


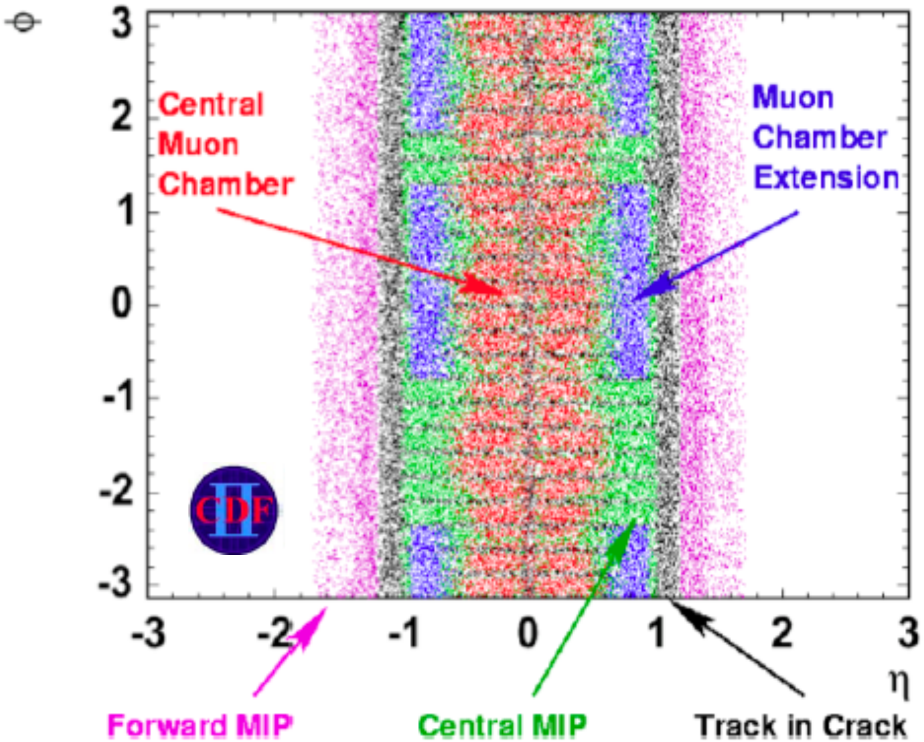
- Expected exclusion: 100 < m_H < 120 GeV, 141< m_H < 184 GeV
  Observed exclusion: 100 < m_H < 106 GeV, 147 < m_H < 179 GeV
- 95% CL limit at m_H=125 GeV: 1.10xSM (expected), 2.22xSM (observed)

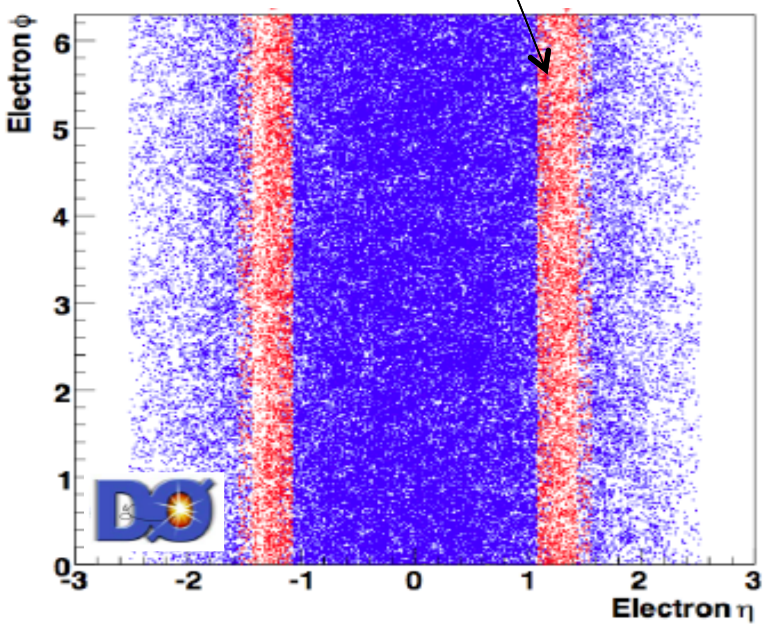
Lepton Identification

Major effort to improve lepton acceptance:

- Electrons in inter-cryostat region (DØ): ~+10%
- Isolated tracks pointing to un-instrumented regions in the muon system (CDF, DØ): ~+10%
- Not all these lepton categories fire the trigger!
  ➔ collect events through e.g. $\not{E}_T$+jets trigger (>+20% signal acceptance in CDF's ZH→$\mu\mu$bb)



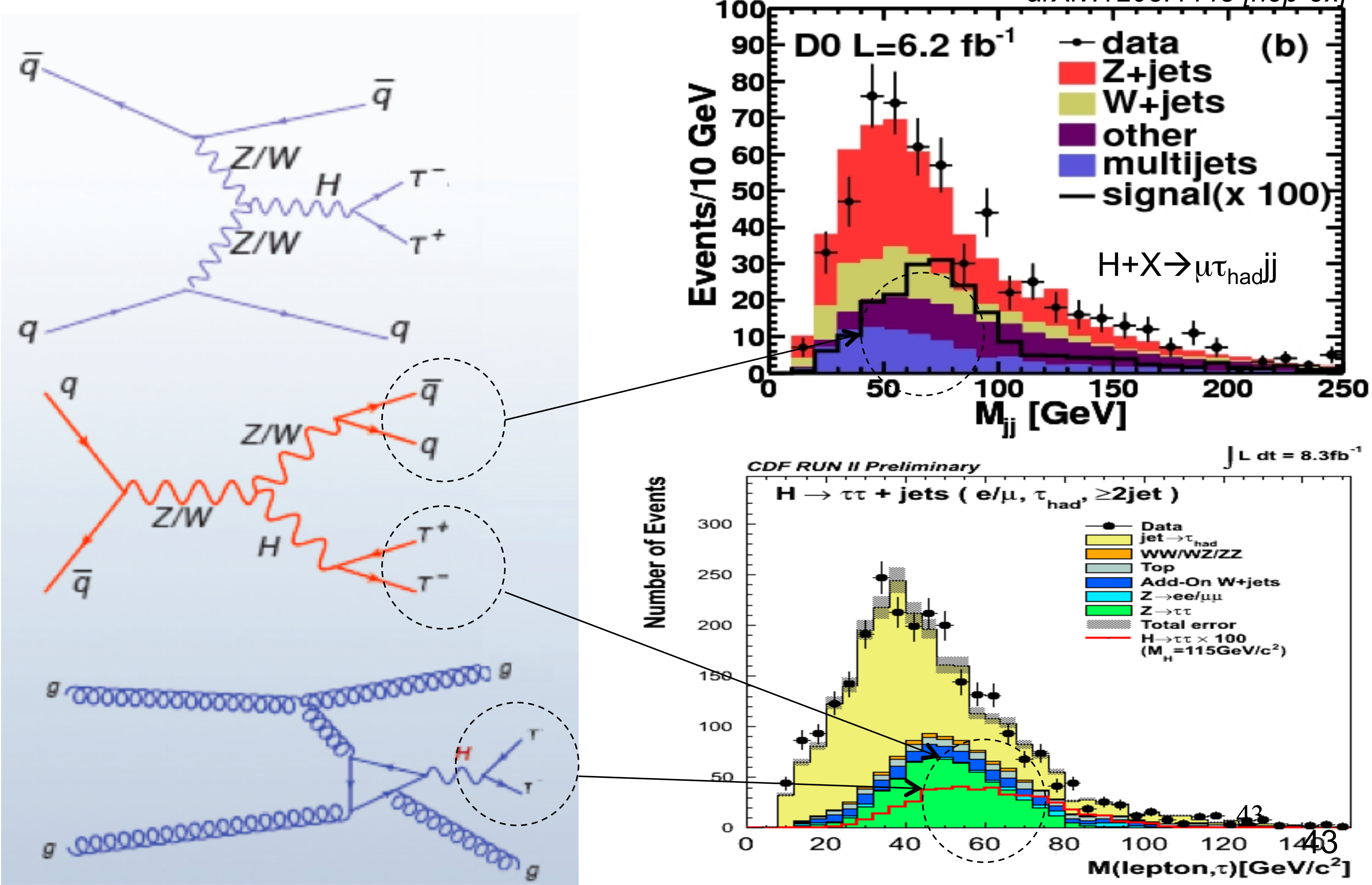




Searching for H(→ττ)+X

- $H \to \tau\tau$: second largest BR(~8%) at low mass.
- Many possible signal topologies to be explored!

arXiv:1203.4443 [hep-ex]



Searching for H(→ττ)+X

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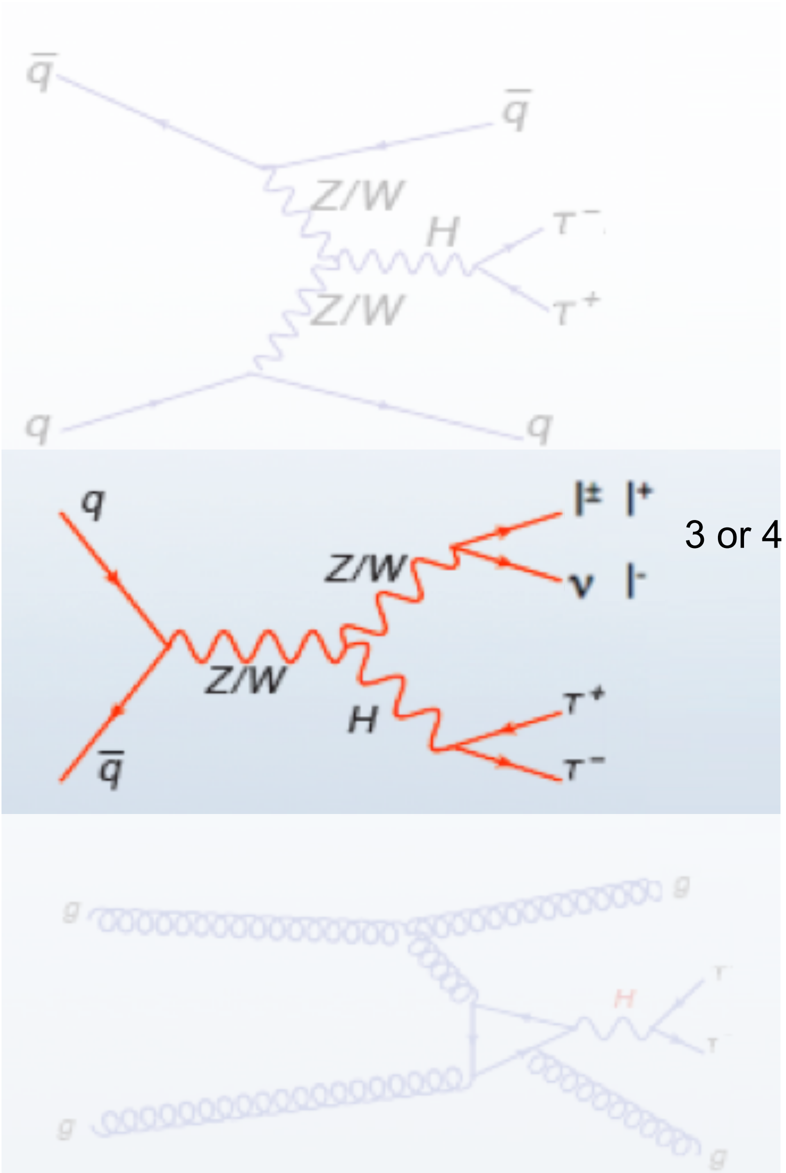
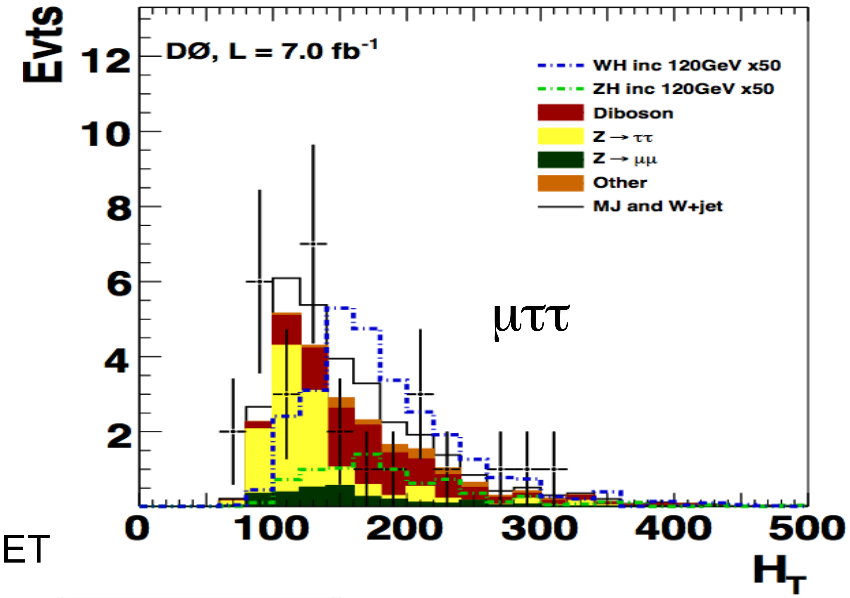
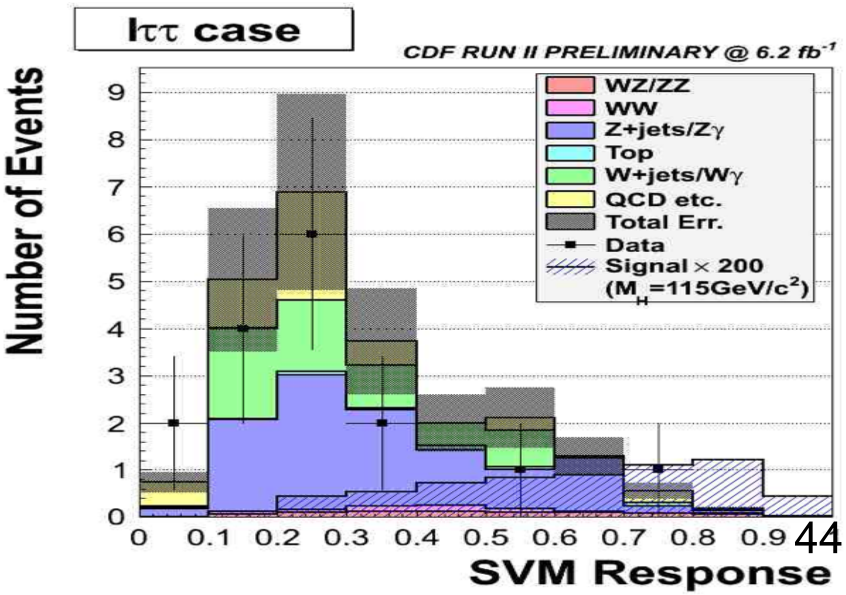


3 or 4 leptons+MET

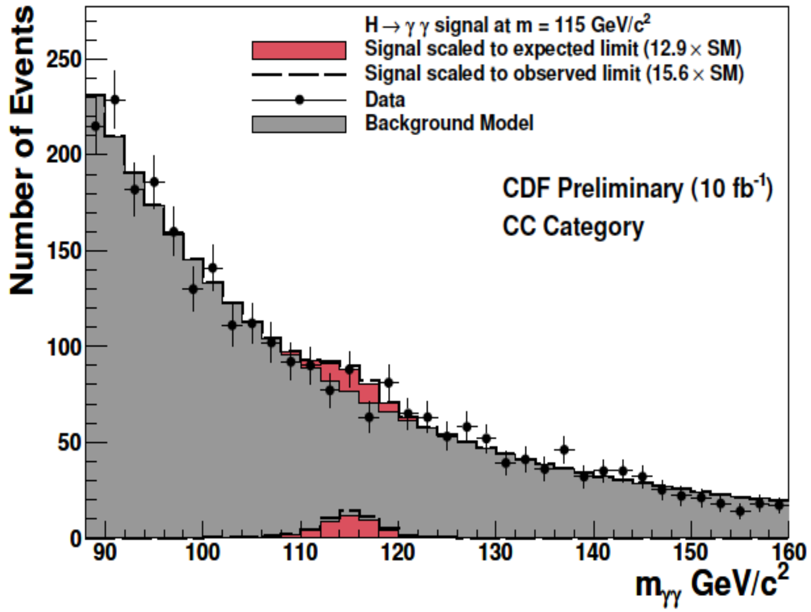


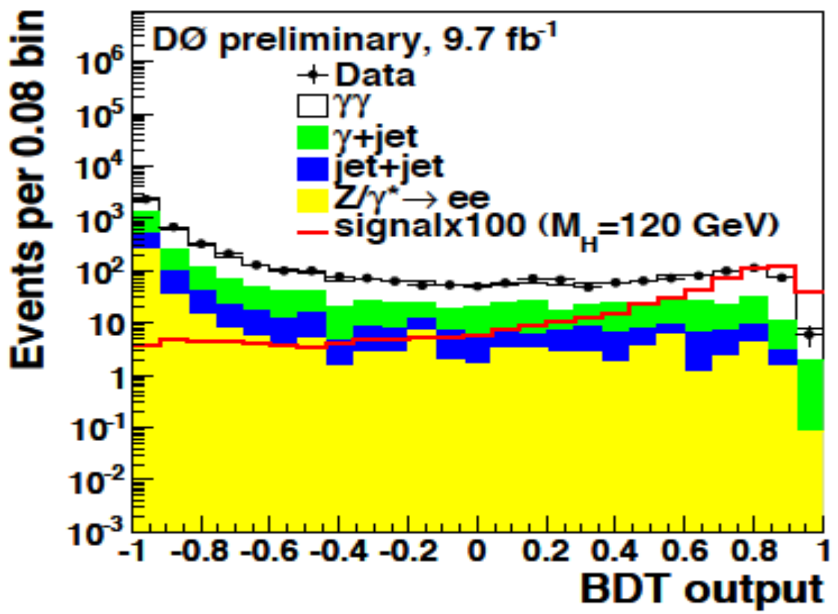


Searching for H(→γγ)+X

- Tiny BR in SM (~0.2%) but large enhancements possible in some beyond-SM scenarios (e.g. fermiophobic Higgs).
- Typical event selection:
  2 photons with p_T>25 GeV in central calorimeter
  NN-based photon ID.
- Main backgrounds estimated from data:
  - Sideband fitting (CDF)
  - Full background breakdown (DØ):
    - Direct QCD γγ (~50%): normalization from data, shape from SHERPA MC
    - γ+j and dijet (jet →γ): both norm and shape from data
- Recent improvements:
  - Additional categories (CDF): converted central photon, central-forward, etc
  - MVA analysis (DØ): 10 variables

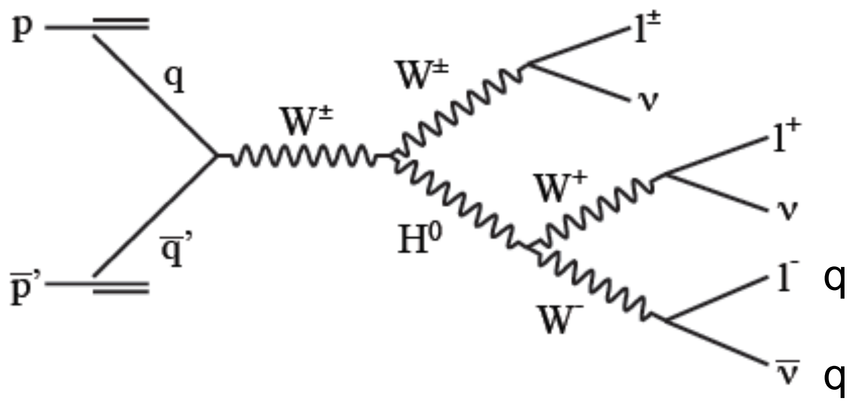
➔ ~20% improvement in sensitivity

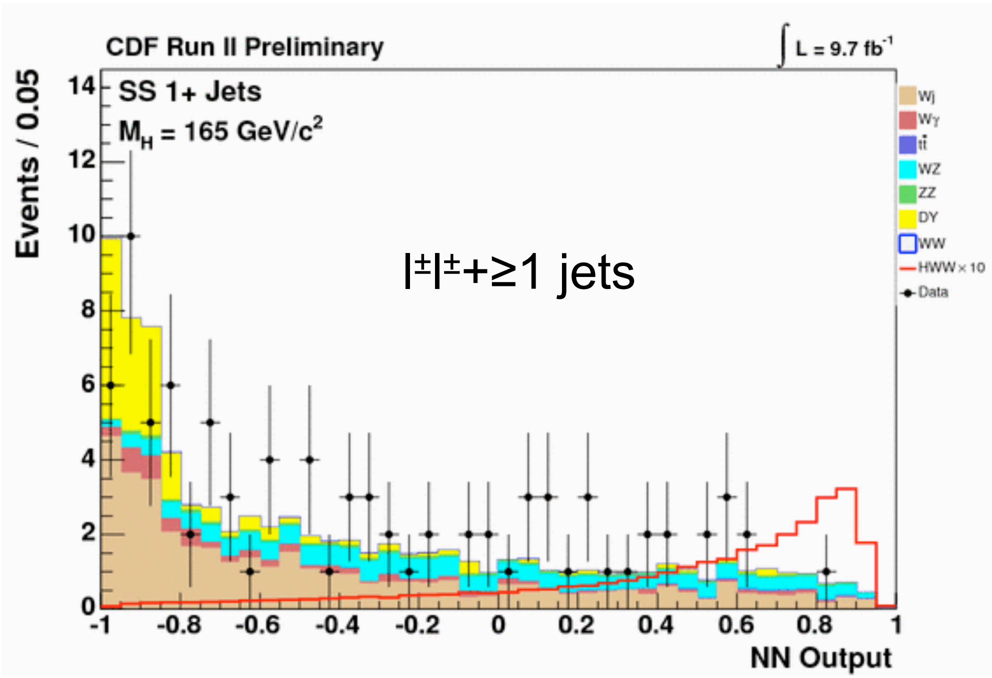


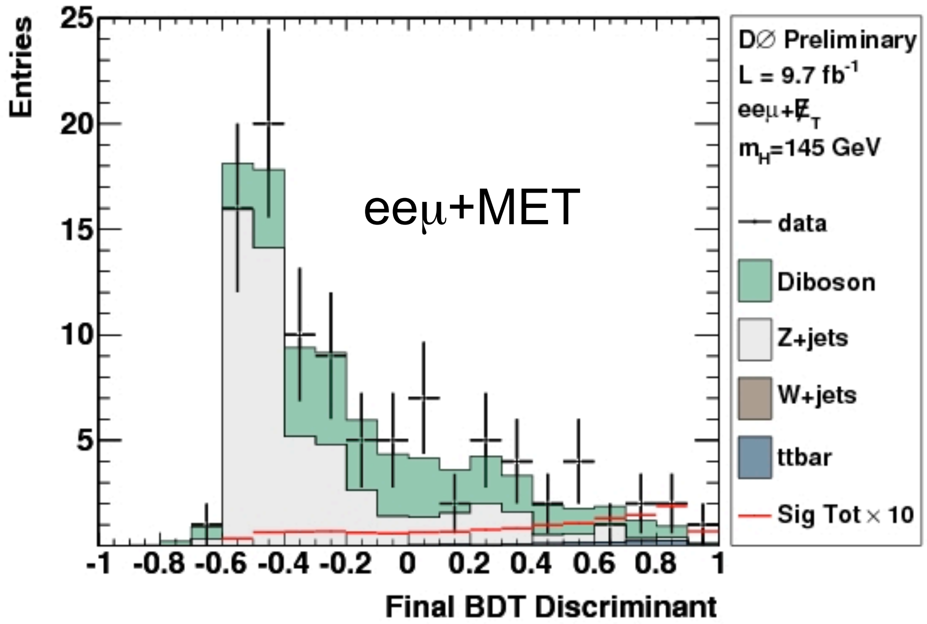


Searching for VH, H→WW

- Additional sensitivity at intermediate/high mass from VH production with H→WW.
- Control backgrounds via:
    - Same-sign leptons: main backgrounds are instrumental ($Z/\gamma^* \to l^+l^-$ with charge mismeasurement, multijet, W+jet/γ)
    - Trileptons: main backgrounds are WZ/ZZ and Z+jets/γ
- Small signal rate but good S:B: ~1:15-1:70 depending on channel.

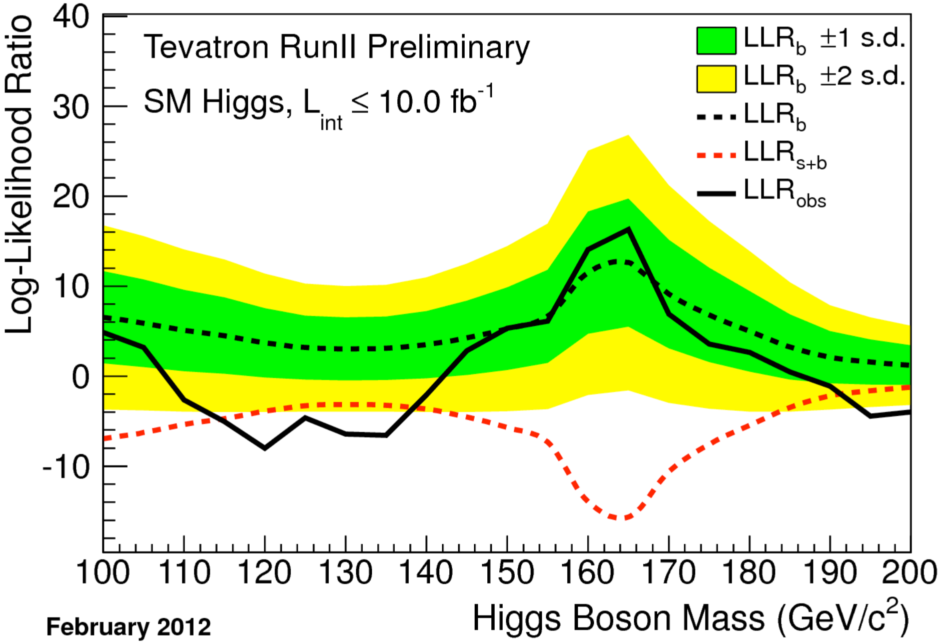




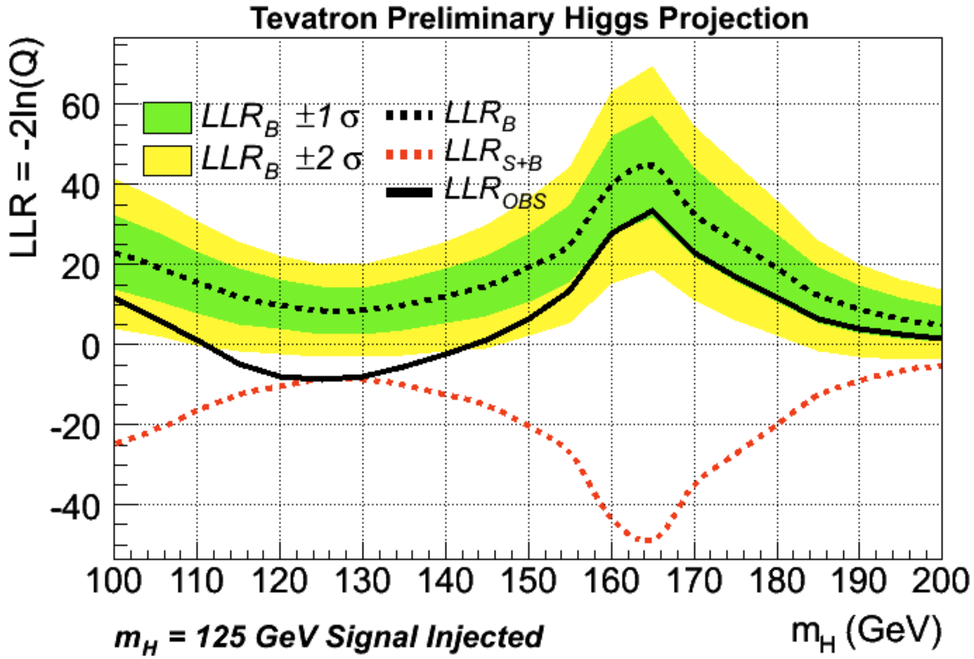


Log-Likelihood Ratio Distributions: Signal Injection

Data



3 s.d. Signal Injection Study

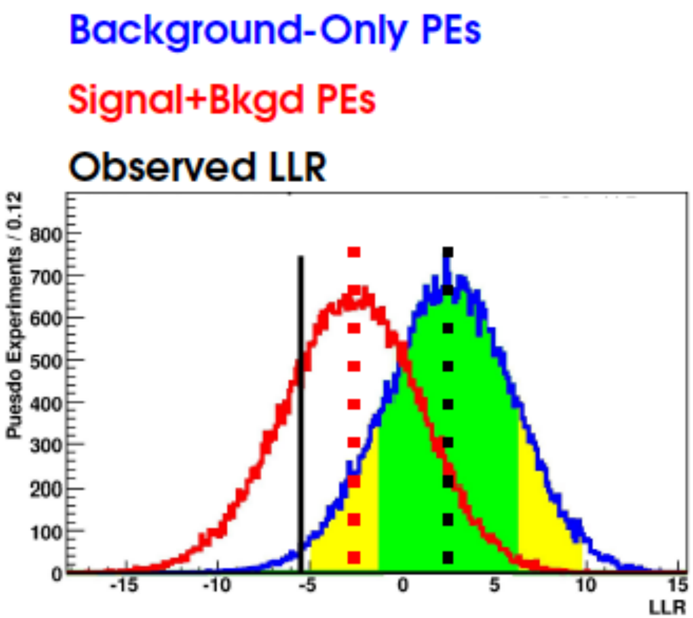


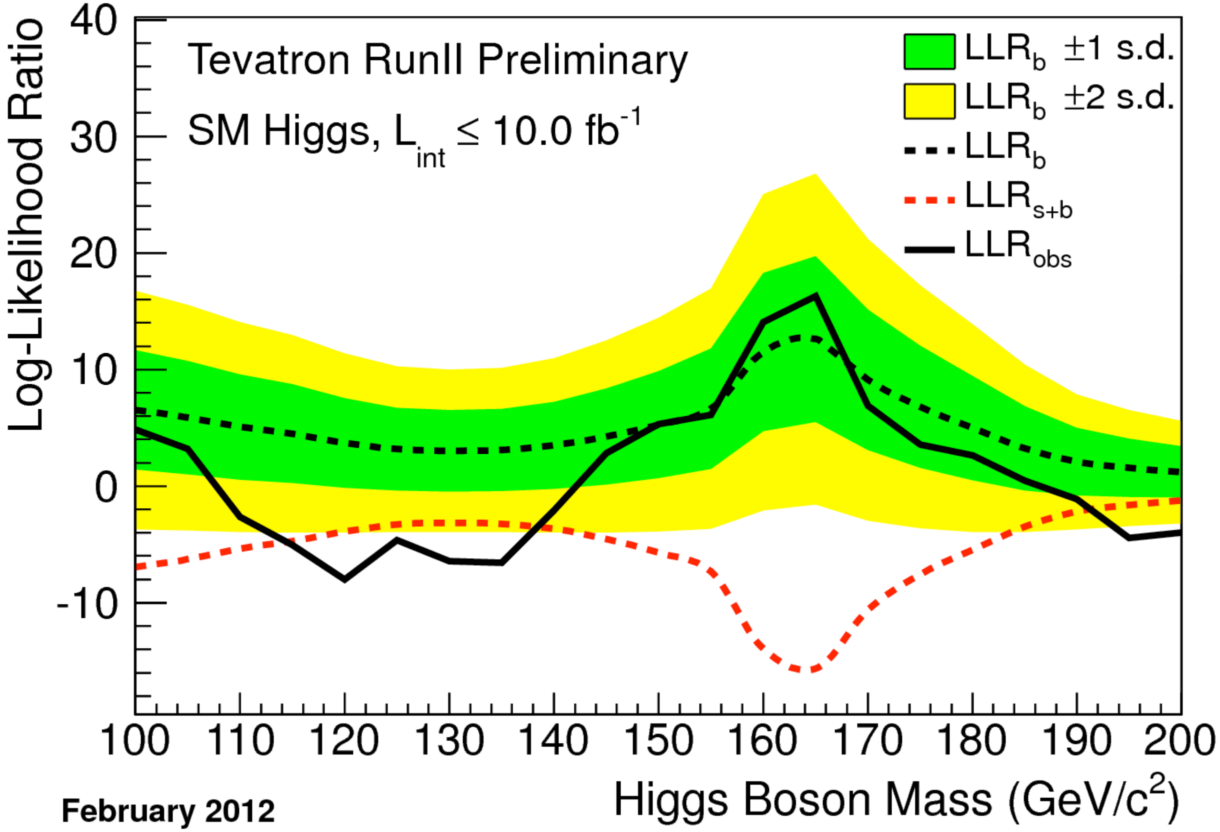
Question: is the global signature observed consistent with a SM Higgs signal?

- Evaluate expected LLR after injecting a SM Higgs signal at m_H=125 GeV; integrated luminosity scaled so that excess is 3 s.d. above background expectation.
- Expect broad excess over whole mass range.
- Observed LLR consistent with what would be expected from signal+background.

Log-Likelihood Ratio Distributions

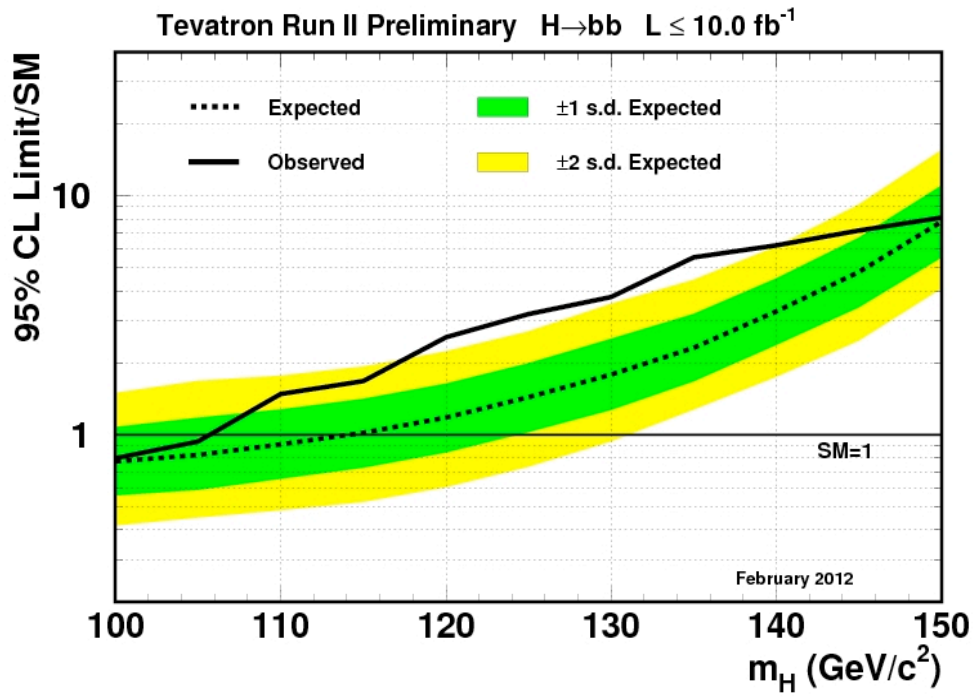
- The log-likelihood ratio test-statistic helps to gauge the relative agreement of the data with the background or signal-plus-background hypotheses.
- Pseudo-experiments are drawn according to both hypotheses taking into account both statistical (Poisson fluctuations) and systematic uncertainties (Gaussian fluctuations).



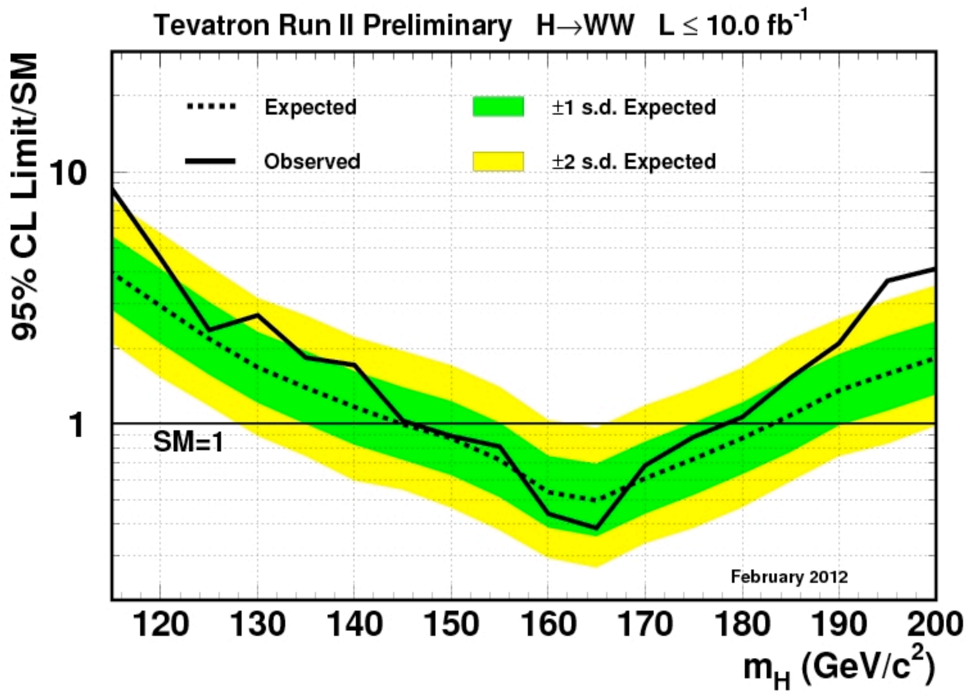


Combined Tevatron Observed Limits

H→bb channels



H→WW channels

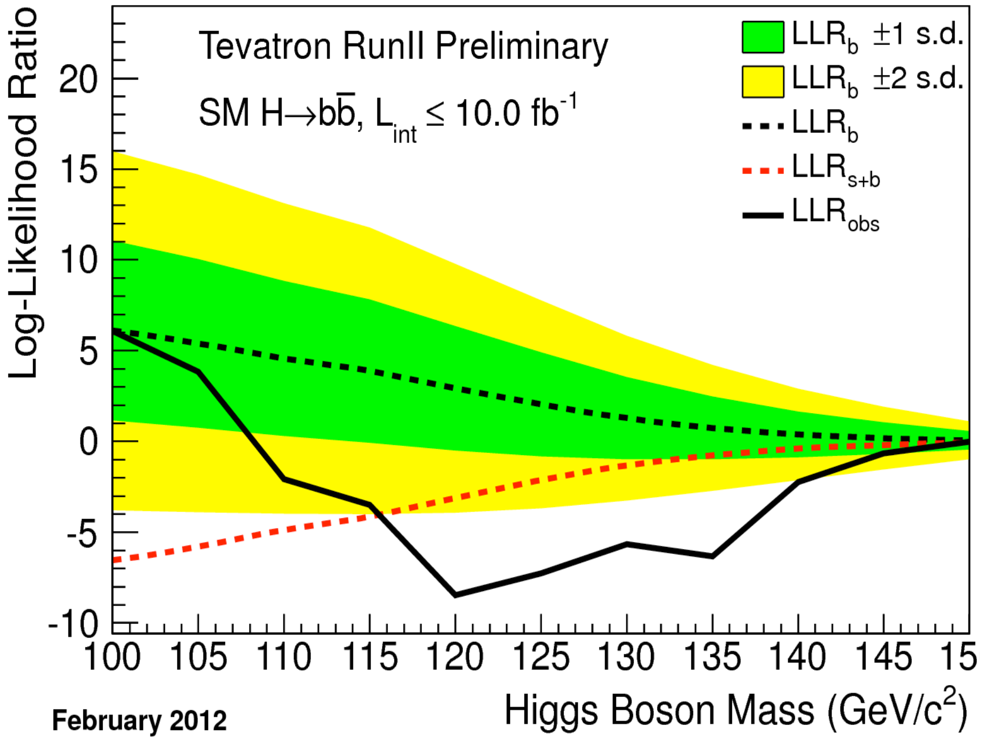


- H→bb and H→WW channels have comparable sensitivity (<2xSM) at m_H=130 GeV.
- Excess most prominent in H→bb channels.

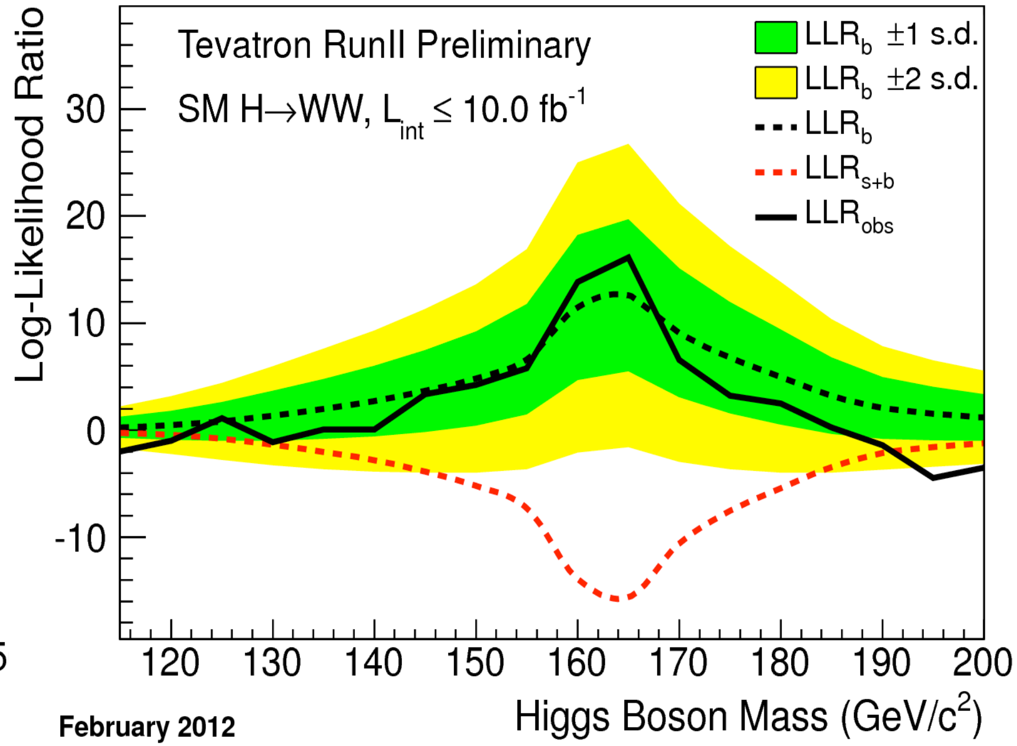
Log-Likelihood Ratio Distributions

- The log-likelihood ratio test-statistic helps to gauge the relative agreement of the data with the background or signal-plus-background hypotheses.
- Pseudo-experiments are drawn according to both hypotheses taking into account both statistical (Poisson fluctuations) and systematic uncertainties (Gaussian fluctuations).

H→bb channels

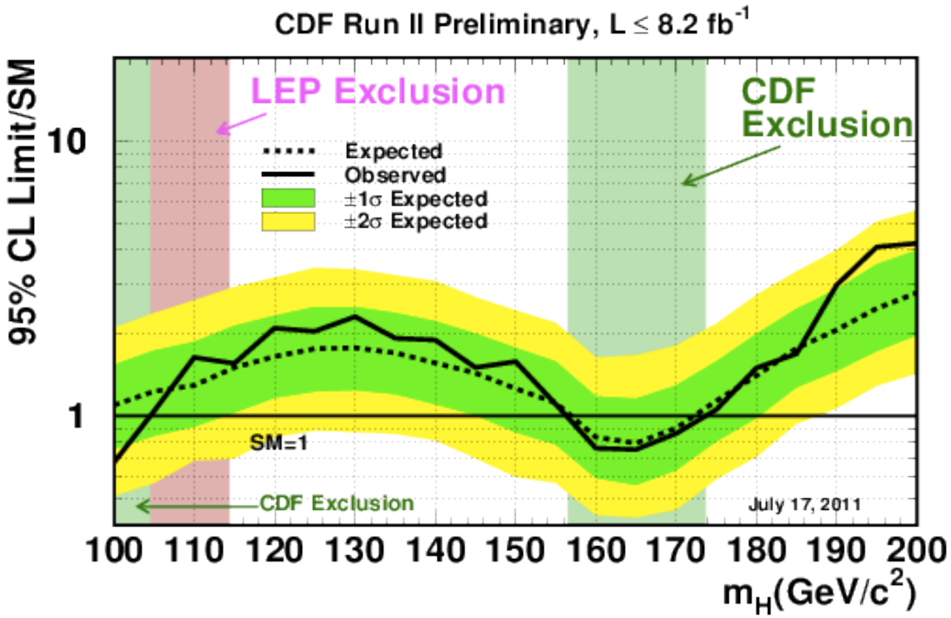


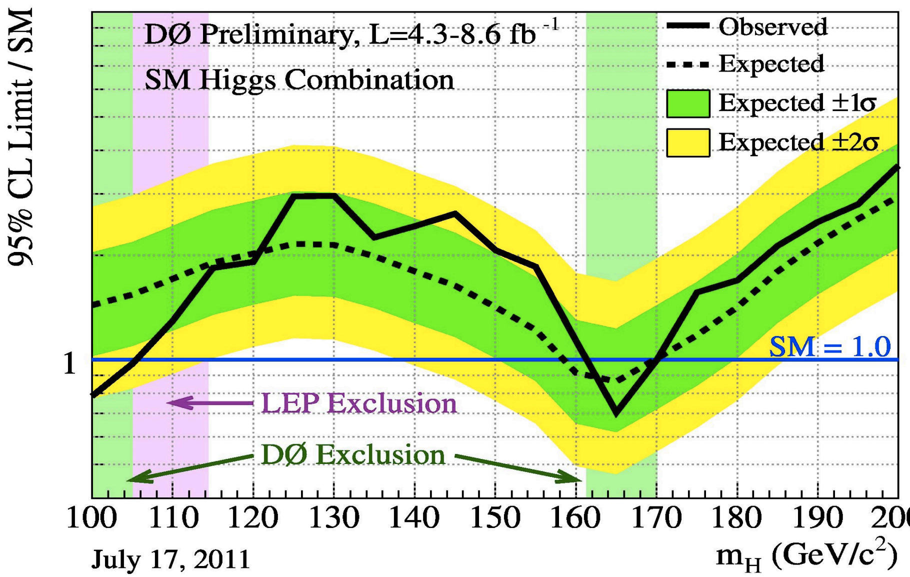
H→WW channels



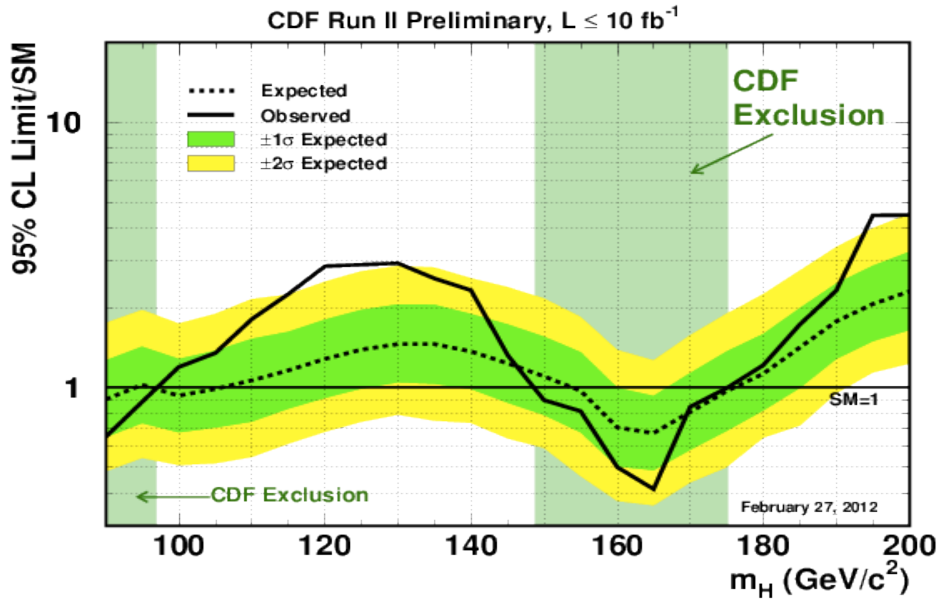
CDF and DØ Individual Results

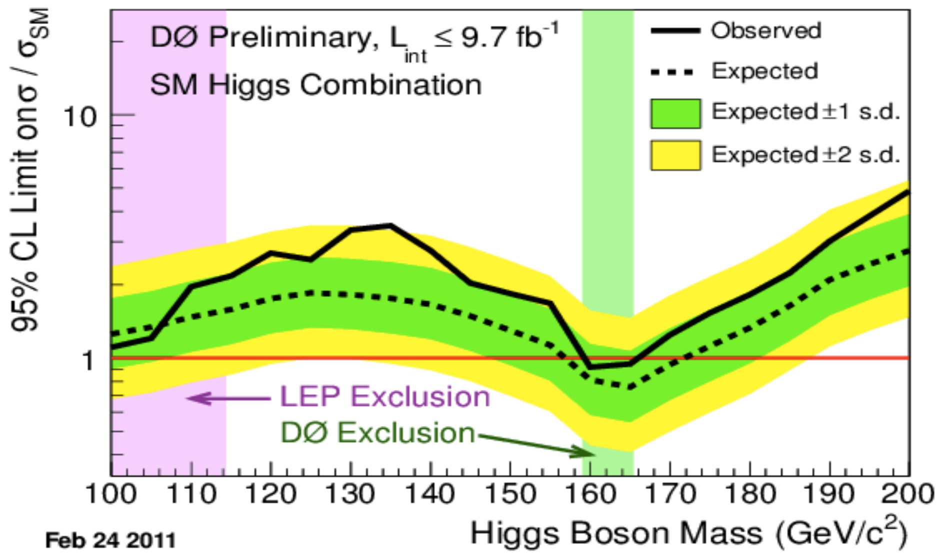
Summer 2011





Winter 2012

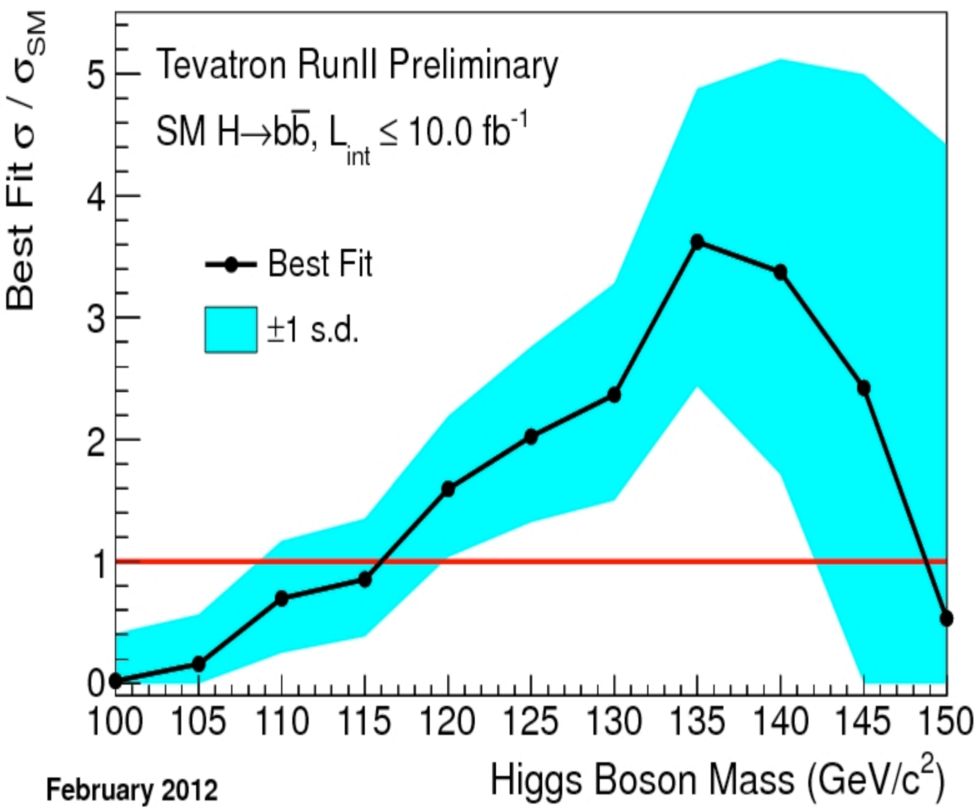




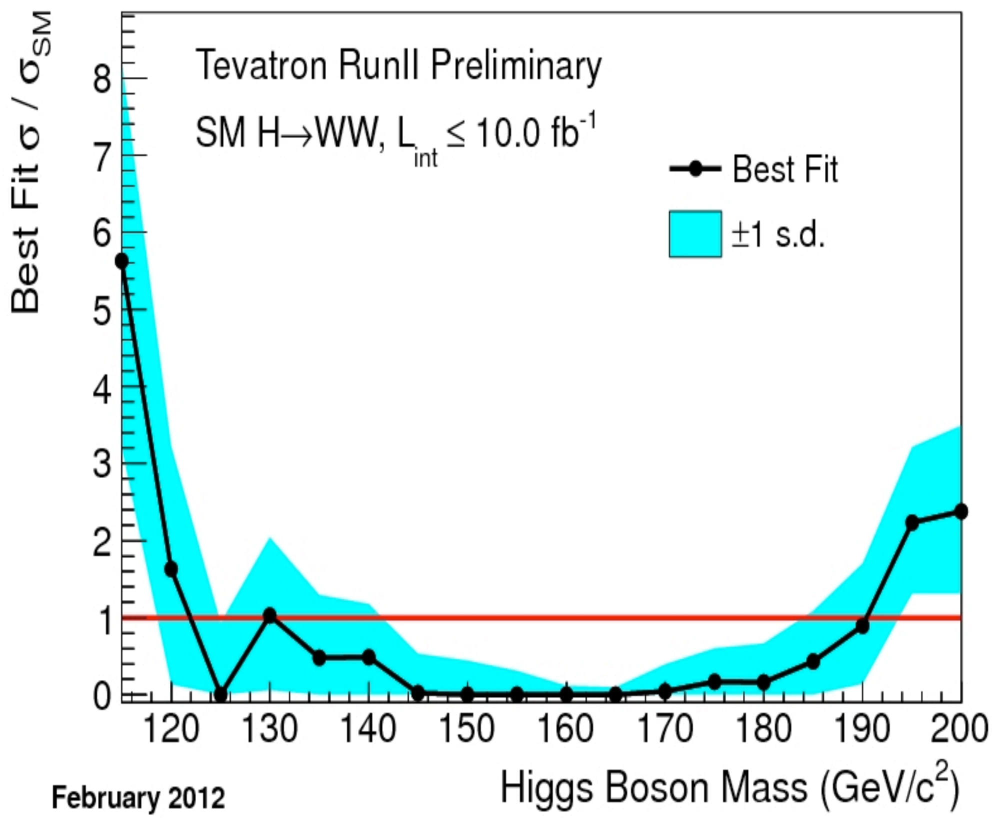
Quantifying the Excess: Best Fit Signal Strength

- Maximum likelihood fit to data with signal strength as free parameter:

H→bb channels

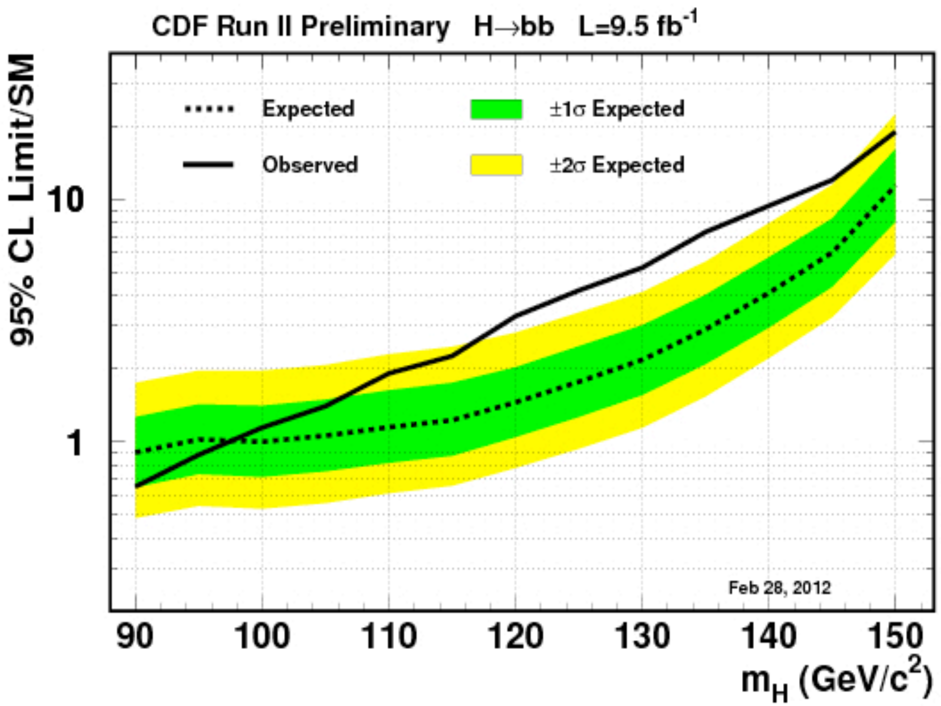


H→WW channels

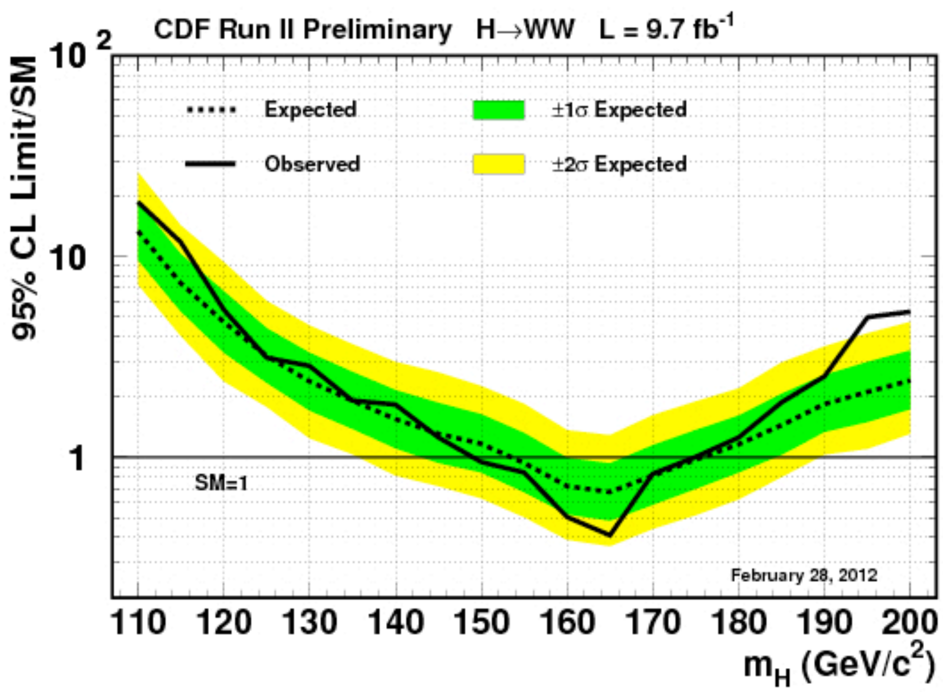


CDF Observed Limits

H→bb channels

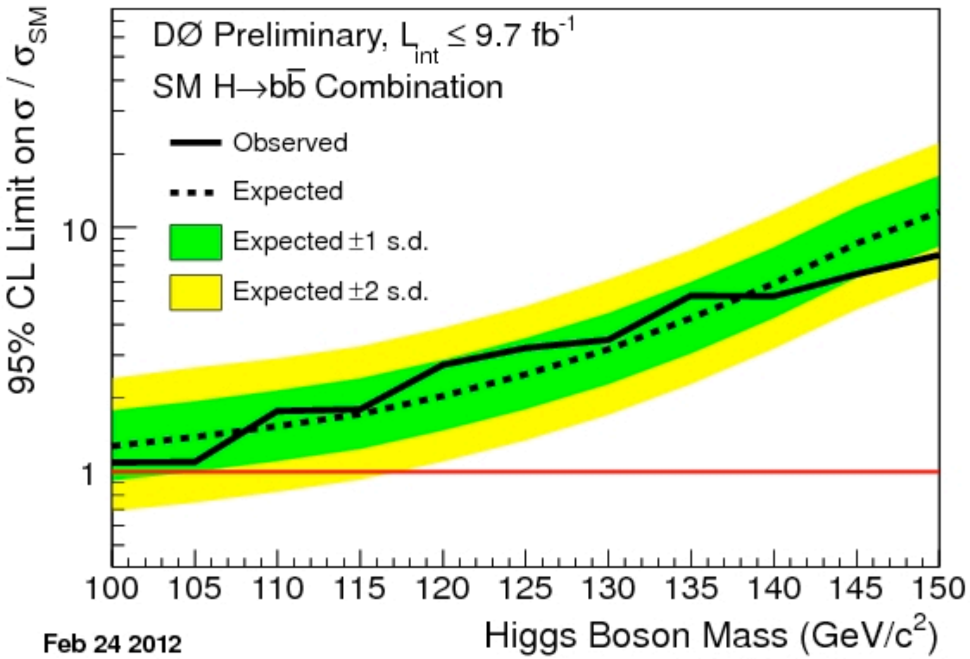


H→WW channels

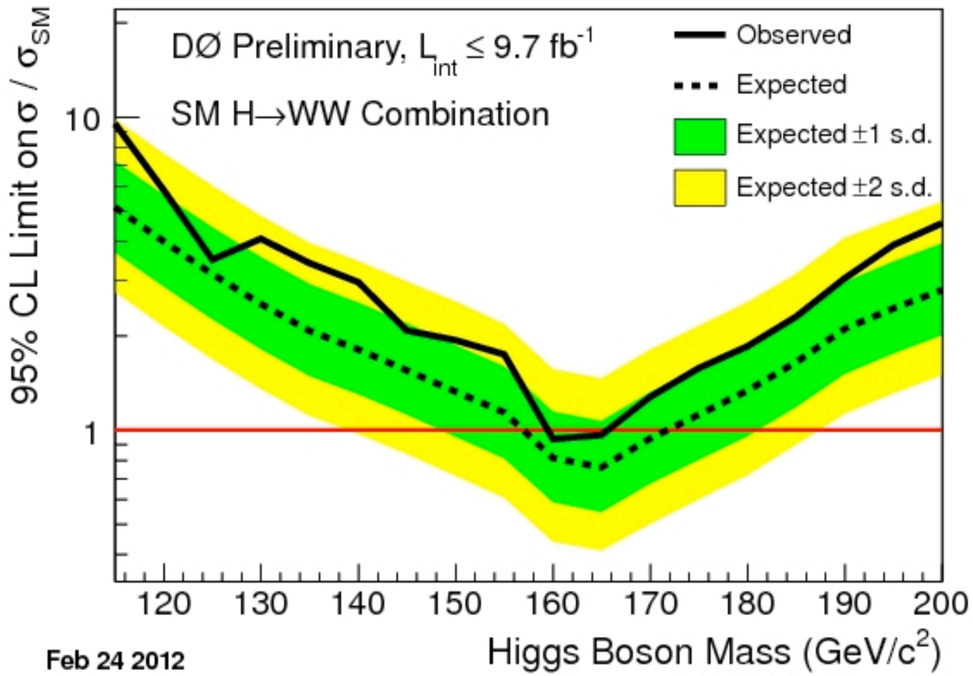


DØ Observed Limits

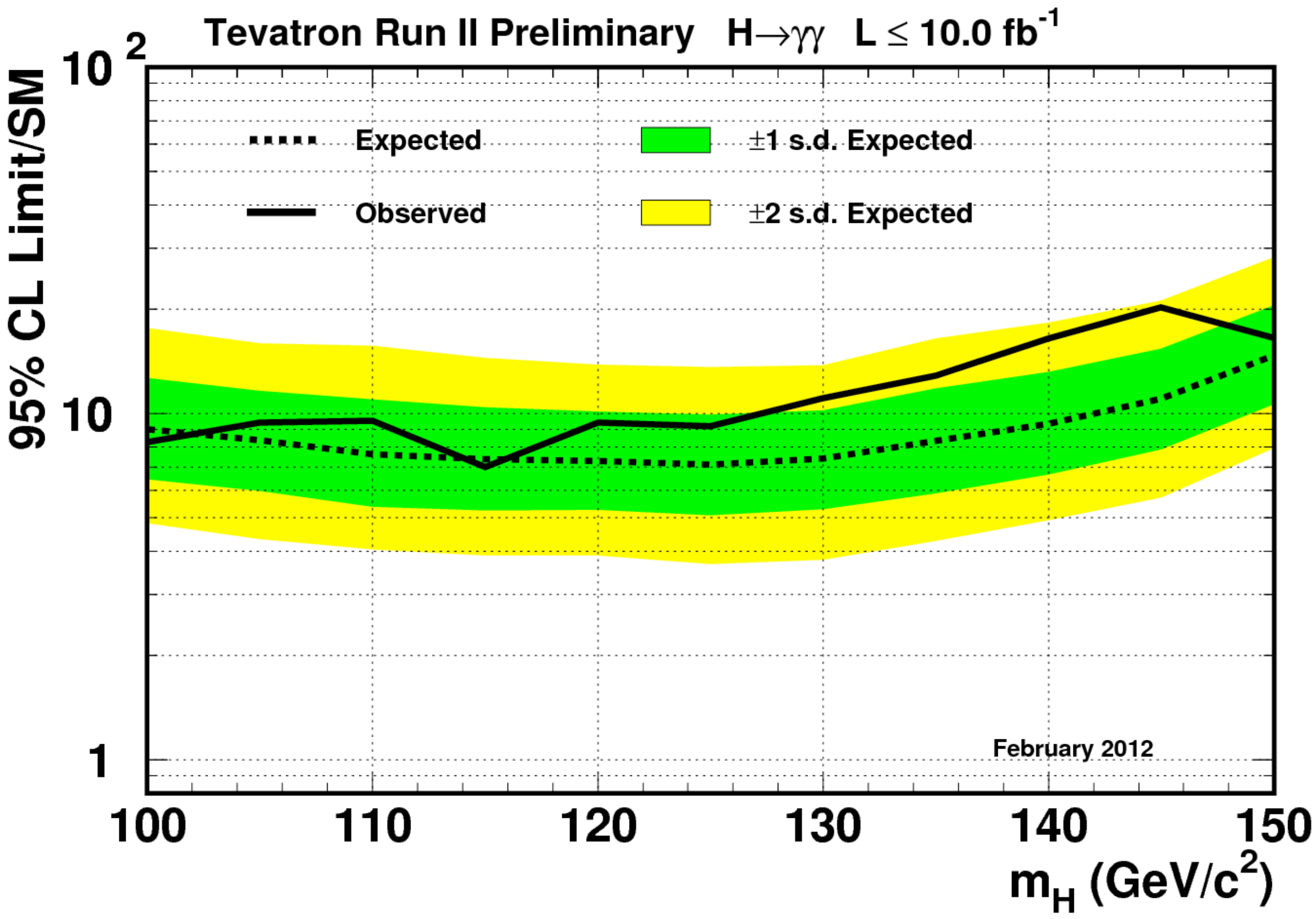
H→bb channels



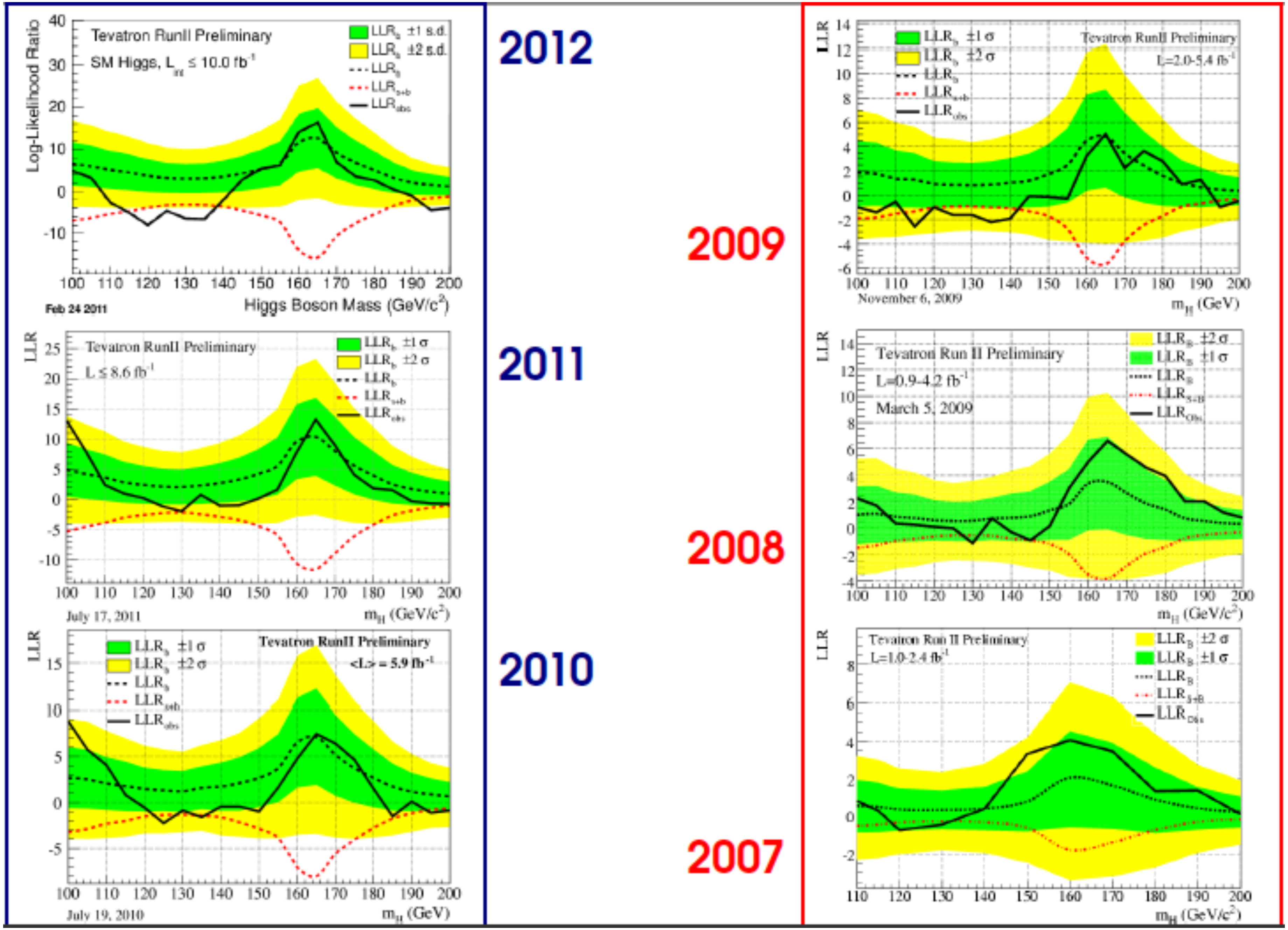
H→WW channels



H→γγ Combined Tevatron Observed Limits

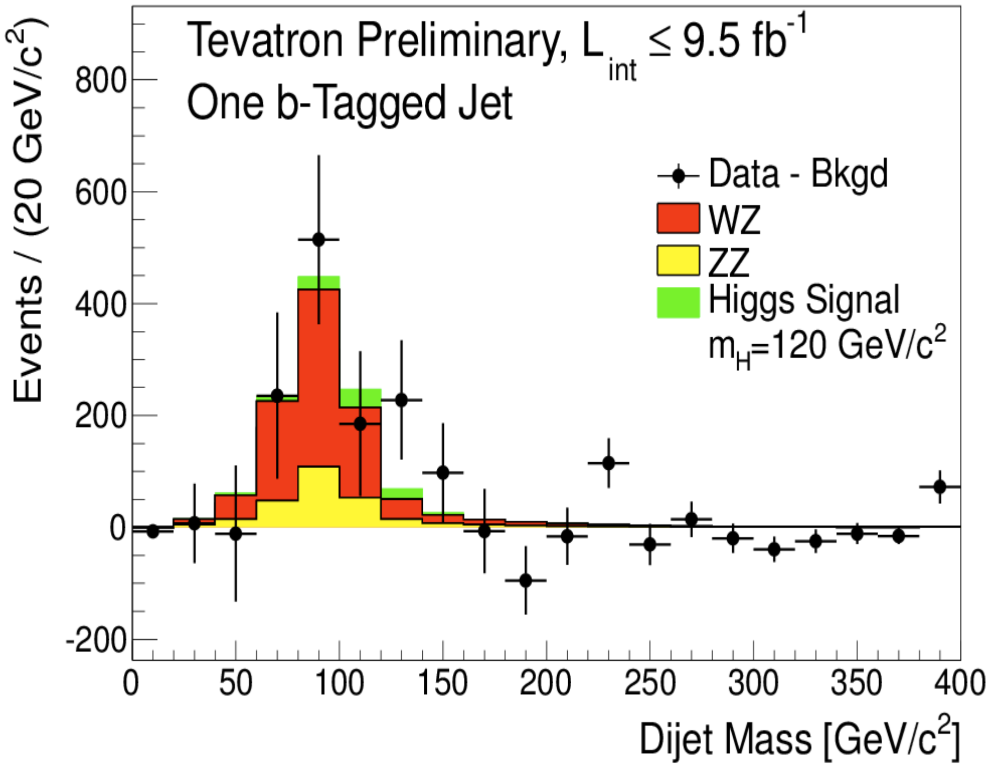


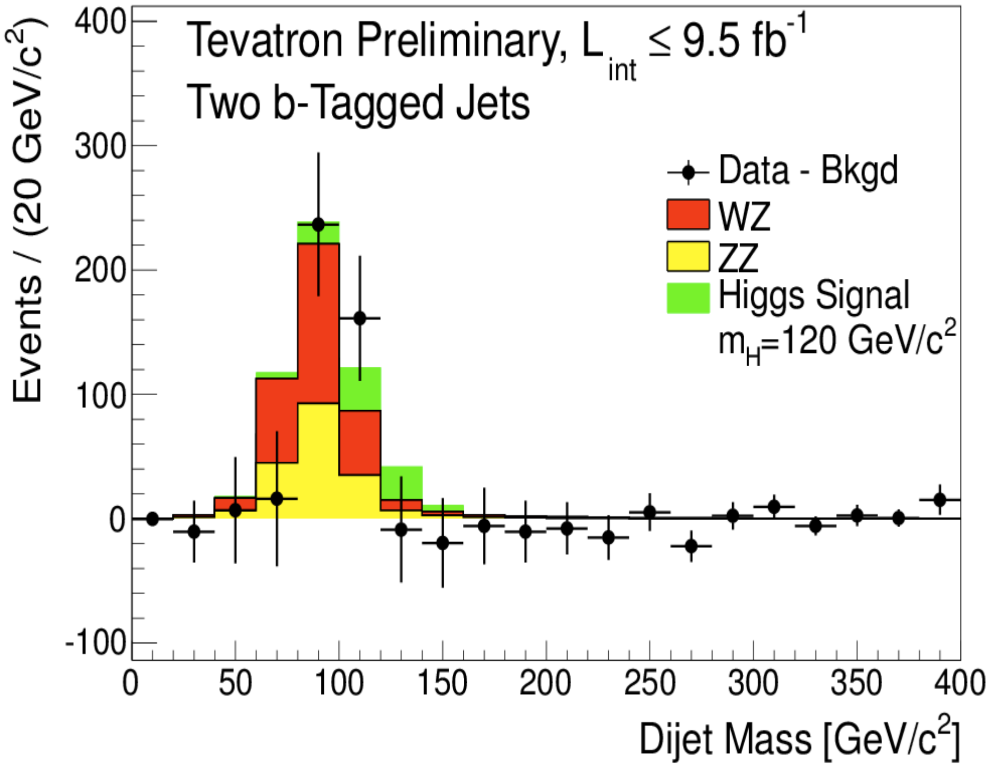
Log-Likelihood Ratio Distributions



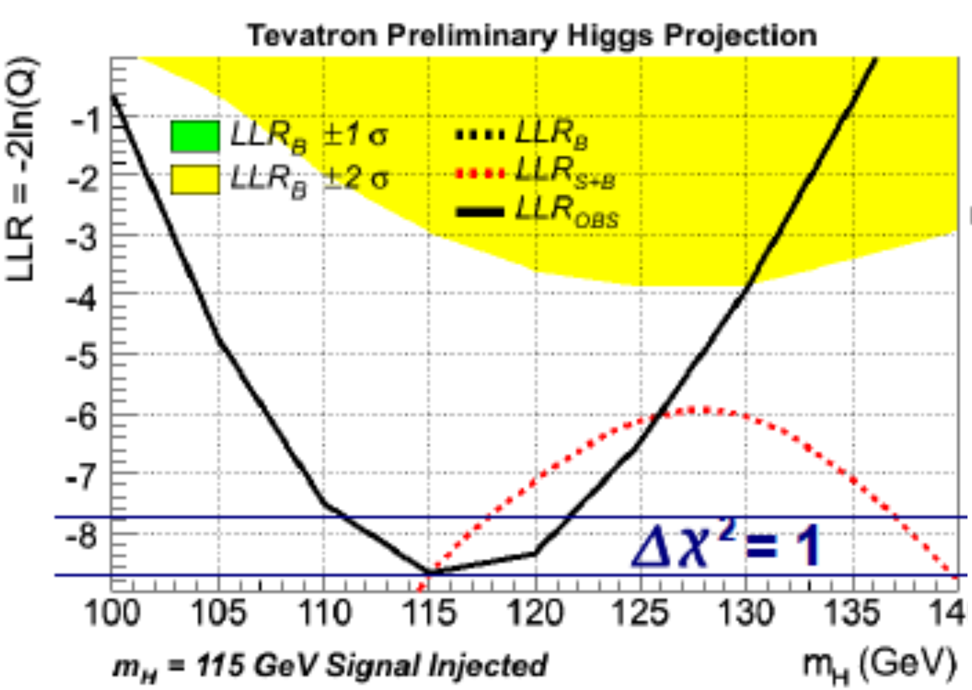
Visualizing the Excess

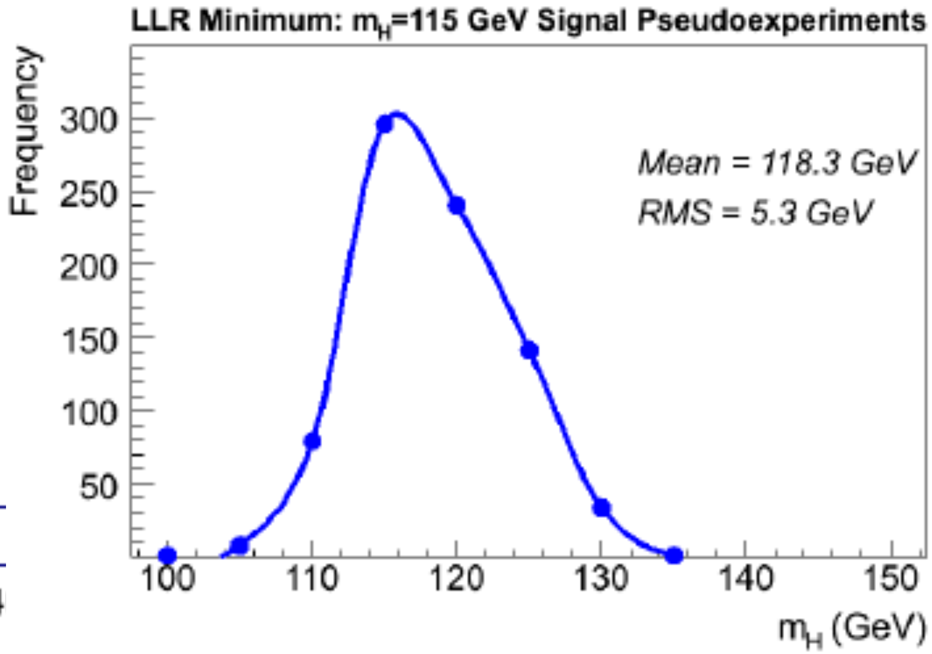
- Simple overlay of H→bb signal prediction (m_H=120 GeV) on dijet mass spectrum.
  - Use Tevatron low mass inputs for WZ/ZZ, Z→bb combination.
  - Data not inconsistent with containing a signal.





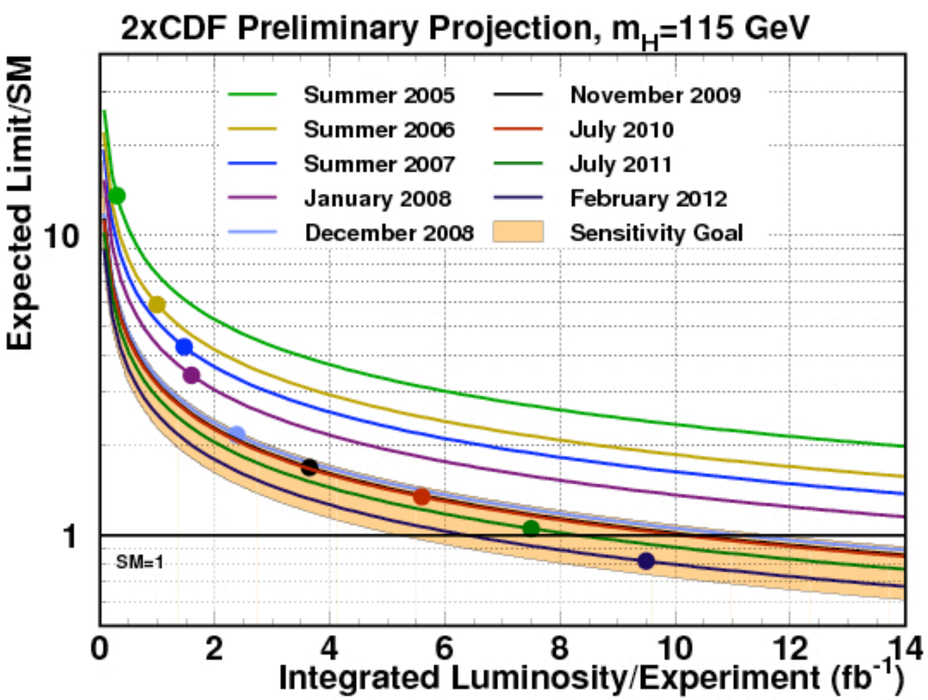
What's the Expected Mass Resolution?

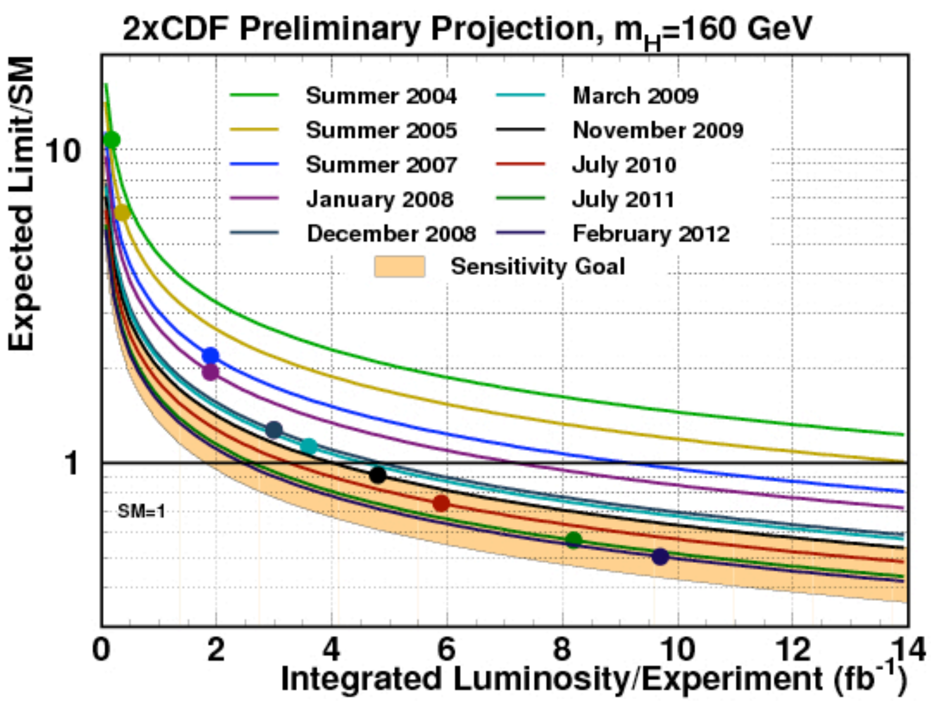




- Steeply falling cross section provides opportunity to determine mass with good resolution.
- Curvature of the observed LLR vs m_H is the most accurate estimate of such resolution.
- Ensemble testing assuming signal at 3σ level yields a mass resolution of ~5-6 GeV below m_H~135 GeV. Resolution degrades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

Tevatron SM Higgs Prospects





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

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

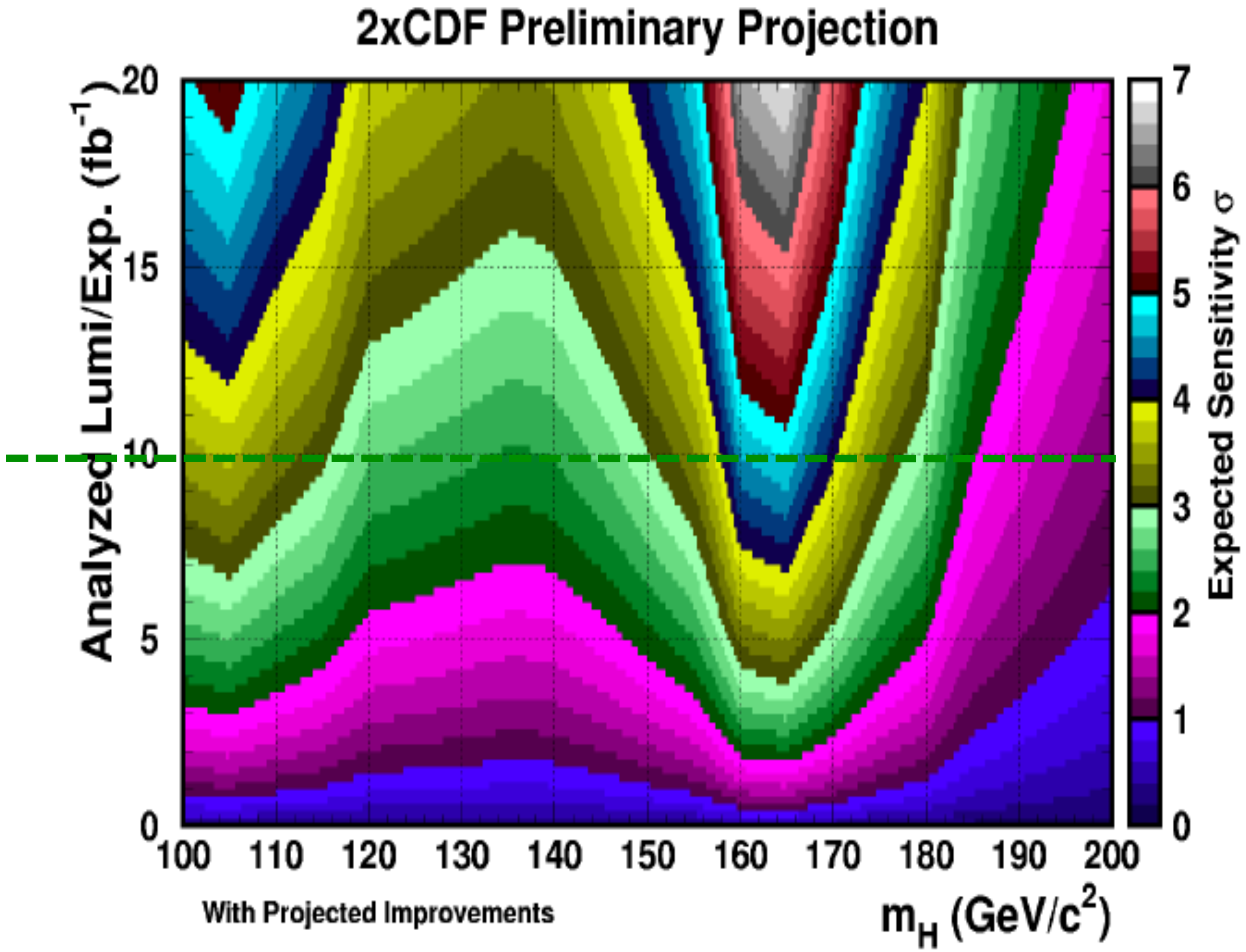
SM Higgs Prospects

- Median projected reach assuming improvements. These are "a-priori sensitivities" (i.e. not taking into account current observed limits).
- There is a band of possibilities around these lines.

End of 2011: 10 fb^{-1}/exp

>2.4σ for m_H<185 GeV

3σ for m_H~115 GeV



Theoretical Uncertainties

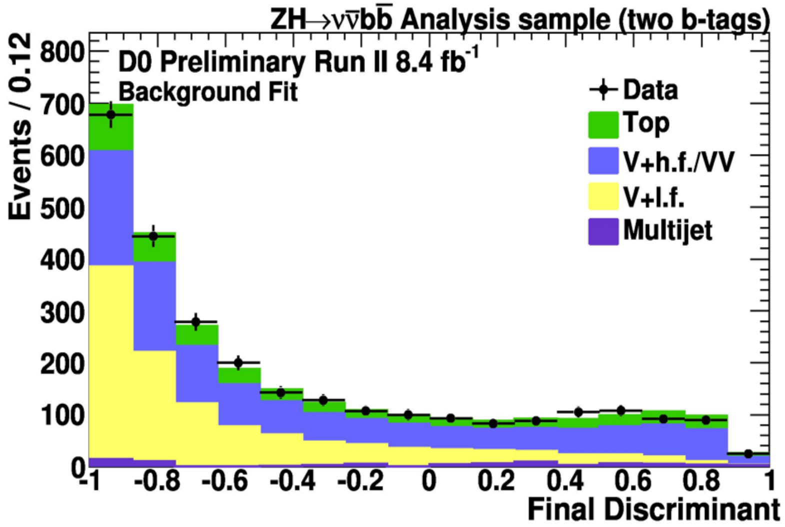
- Progress in Higgs searches at the Tevatron has relied on advances in theory and development of MC generators over the years.

- Since we combined searches in different production/decay modes:
  - Cross section limits given relative to the SM prediction
  - Need to incorporate theoretical uncertainties for cross sections and branching ratios.
  - Following the prescriptions of the LHC Higgs cross section WG.

- Recent theoretical developments:
  - Effect of splitting H→WW search in jet multiplicity bins (Berger at al.): currently using BNL accord
  - Interference between H→WW and non-resonant WW production: not implemented yet.

Interpreting the Data

- Use the final discriminant distribution to perform hypothesis testing (S+B vs B-only).
- In absence of an excess, set limits using:
  - The CL_s method or
  - A Bayesian method



CL_s method

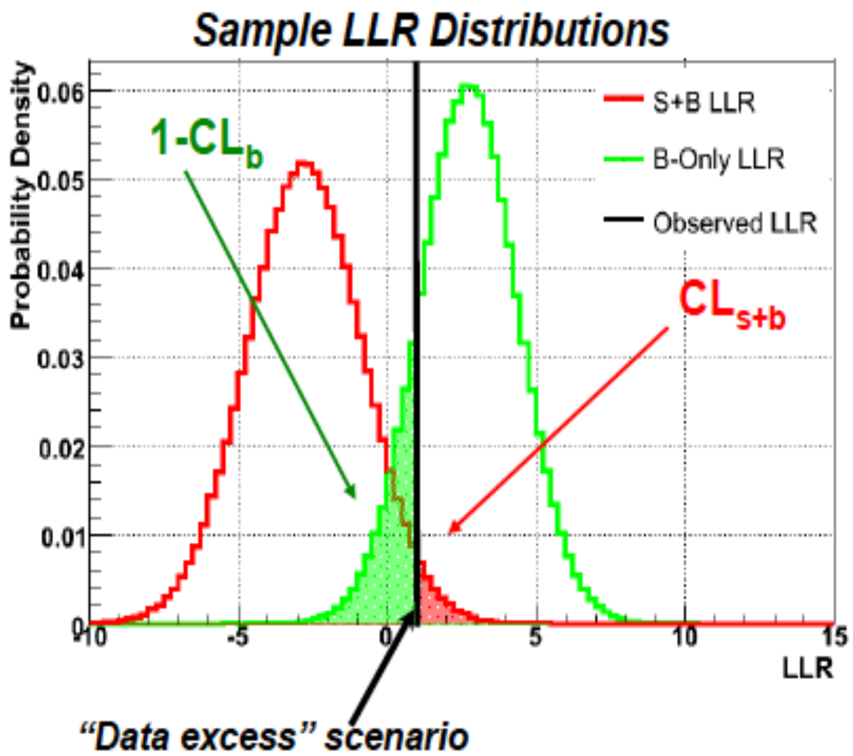
1. Compute the likelihood ratio for S+B vs B-only hypothesis using Poisson statistics:

$$Q(\vec{d};\vec{s},\vec{b}) = \prod_{i=1}^{N_{chan}} \prod_{j=1}^{N_{bins}} \frac{(s+b)_{ij}^{d_{ij}} e^{-(s+b)_{ij}}}{d_{ij}!} / \frac{b_{ij}^{d_{ij}} e^{-b_{ij}}}{d_{ij}!}$$

$$LLR = -2\ln Q$$

2. Generate pseudo-experiments for S+B and B-only hypotheses via Poisson trial.
   - Systematics are folded in via Gaussian marginalization
   - Correlations held amongst signals and backgrounds
3. Define CL_s:

$$CL_s = \frac{CL_{s+b}}{CL_b}$$



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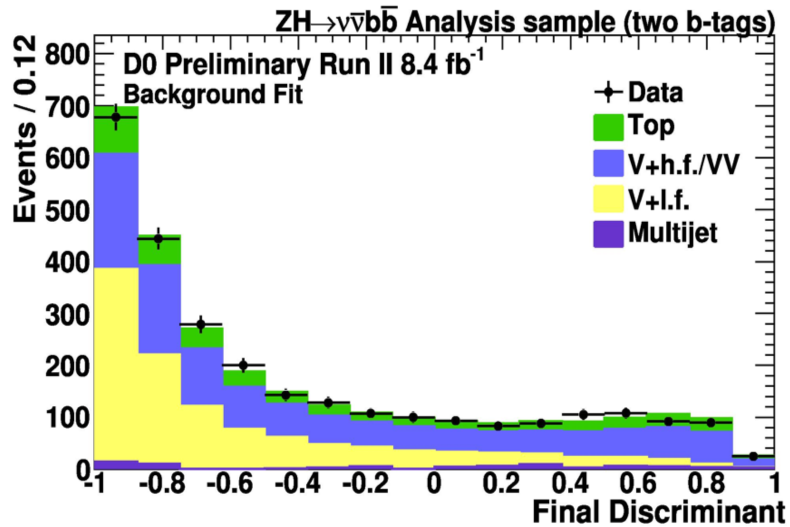

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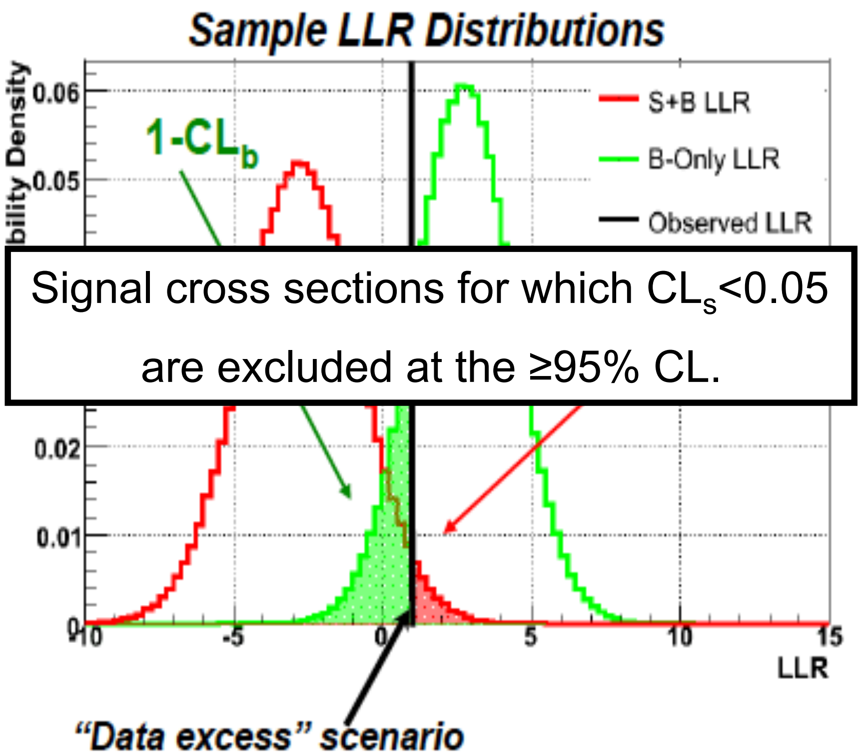
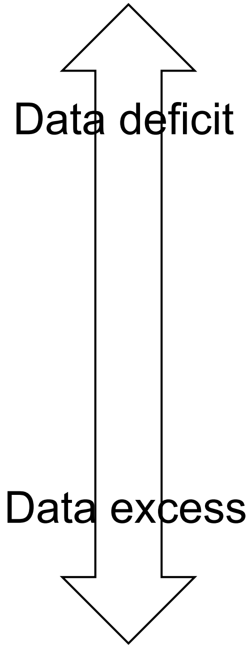
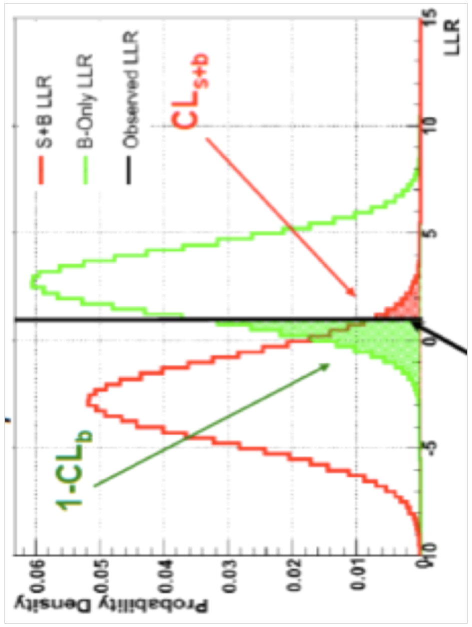


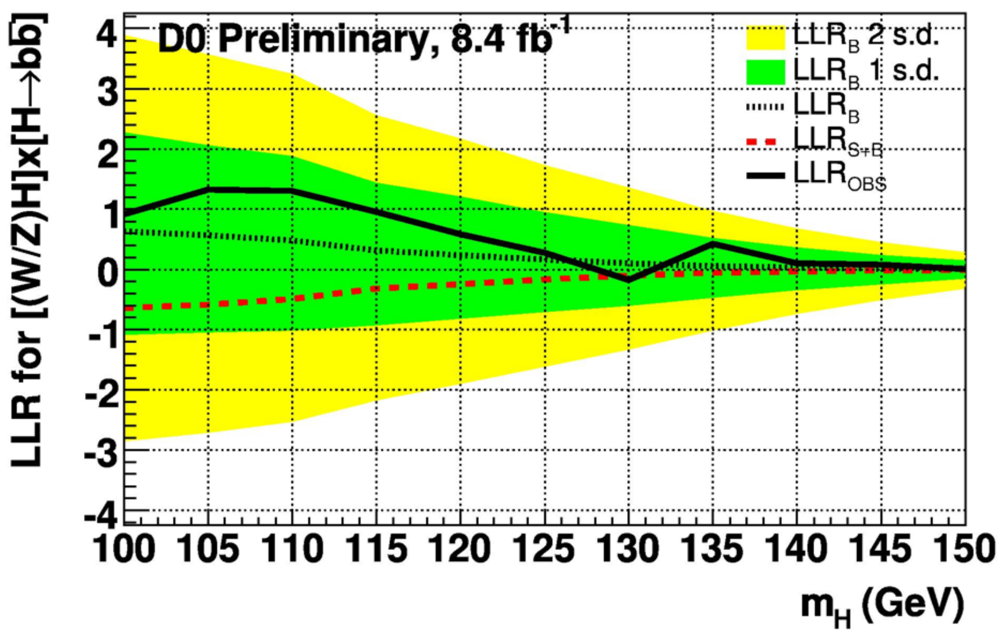
Signal cross sections for which CL_s<0.05 are excluded at the ≥95% CL.

Interpreting the Data





ZH→ννbb



- Dashed lines show S+B and B-only mean value.
- Shaded bands indicate 1 and 2σ variation of B-only distribution
- Solid black line indicates **data observation**

Constraining Systematic Uncertainties

LEP: small background, small systematic uncertainties

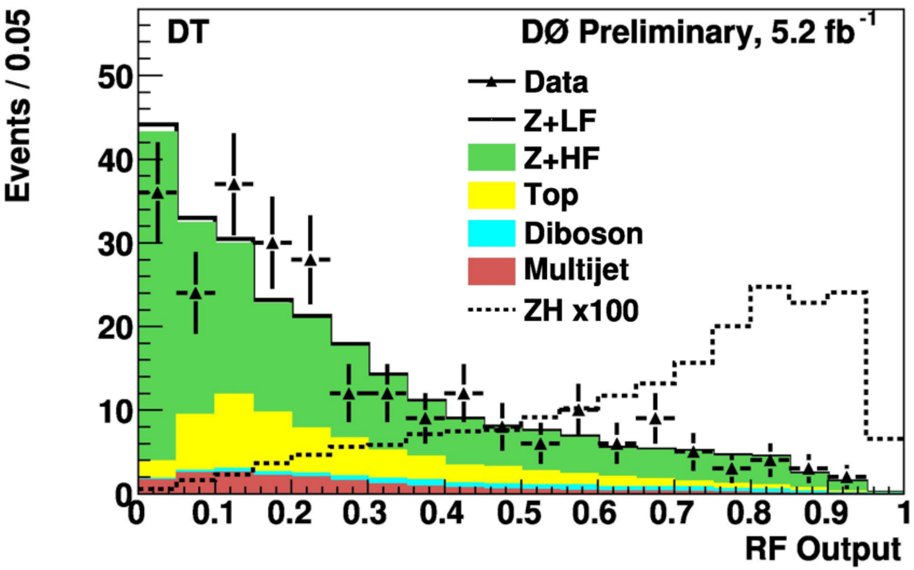
Tevatron: large background, large systematic uncertainties (particularly at low mass)

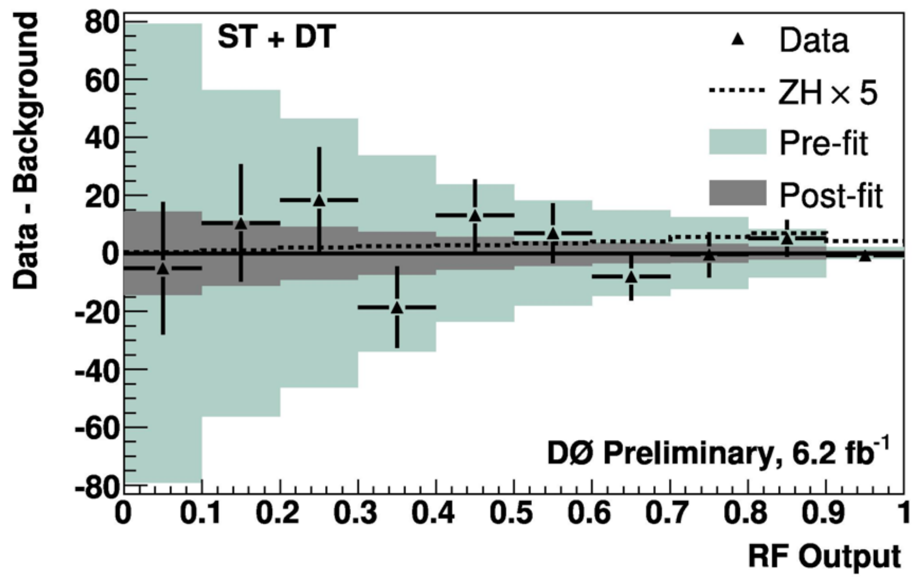
NEW wrt LEP: to counteract the degrading effects of systematic uncertainties, we use a “profile likelihood”, obtained by fitting MC expectations to data for each outcome (analogous to “side-band fitting”).

$$LLR = -2\ln Q = -2\ln\left(\frac{L(data \mid s+b;\ \hat{\theta})}{L(data \mid b;\ \hat{\theta})}\right)$$

- Capitalizes on shape and statistics of data to constrain background uncertainties.

ZH→llbb





Systematic Uncertainties

Example: ZH→ννbb

Systematic Uncertainty	Signal (%)	Background (%)
Single Tag		
Jet EC - Jet ER	1.0	2.5
Jet R&T	2.6	2.6
b Tagging	3.2	1.3
Trigger	2	1.9
Lepton Identification	1.1	0.8
Heavy Flavor Fractions	–	4.1
Cross Sections	6	9.8
Luminosity	6.1	5.8
Multijet Normalilzation	–	1.3
Total	9.8	12.3
Double Tag		
Jet EC - Jet ER	0.7	2.3
Jet R&T	3.5	2.6
b Tagging	5.8	3.6
Trigger	2	1.9
Lepton Identification	1.1	1.0
Heavy Flavor Fractions	0	8.0
Cross Sections	6	9.8
Luminosity	6.1	5.8
Multijet Normalilzation	–	1.1
Total	10.9	13.9

Systematic uncertainties can affect both shape and normalization of signal and background.

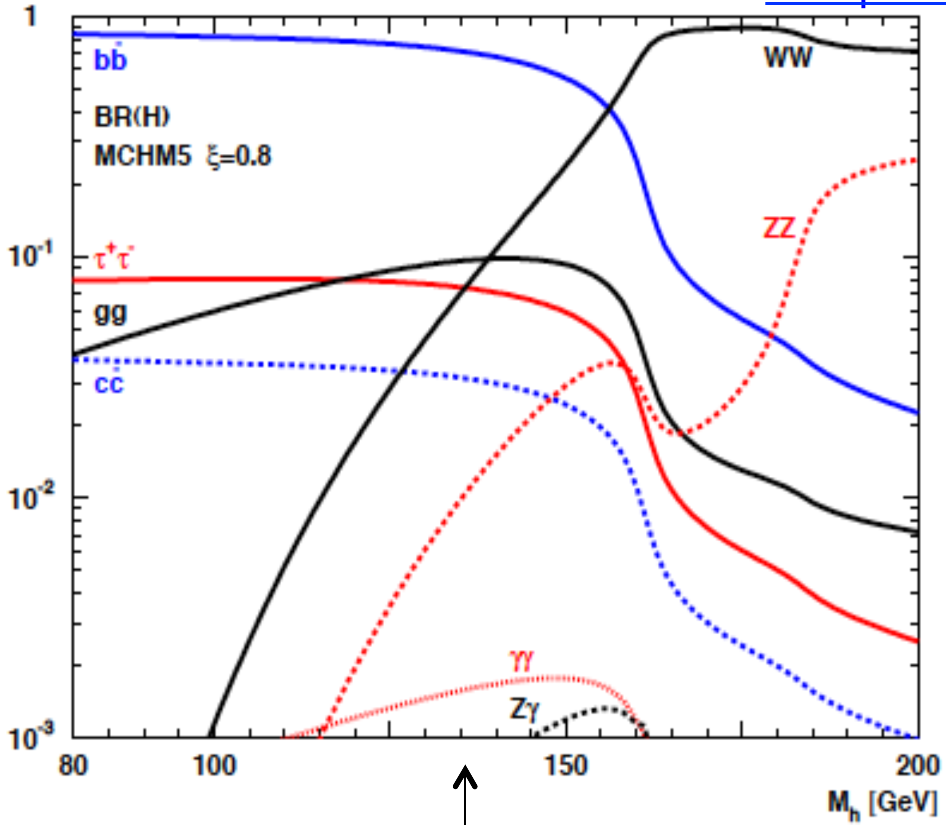
→ Main systematic uncertainties from b-tagging and background modeling.

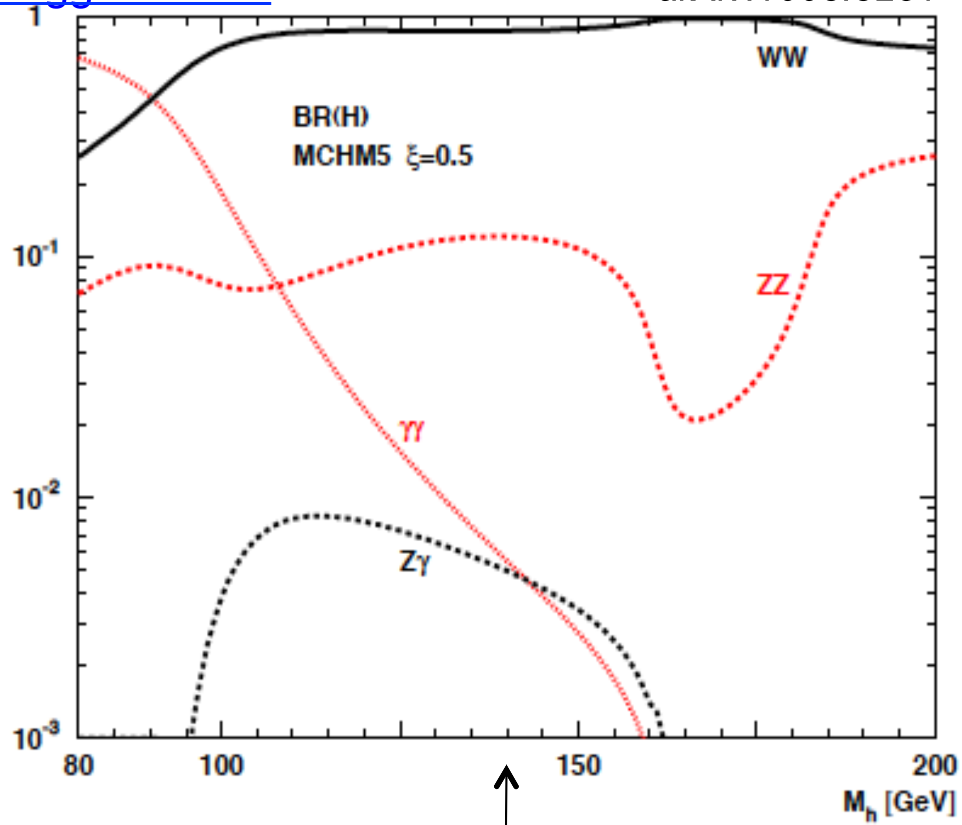
Nature May Just Be More Complicated…

➔ Probing multiple production and decay modes critical for model discrimination

Composite Higgs Models

arXiv:1003.3251





m_H=135 GeV

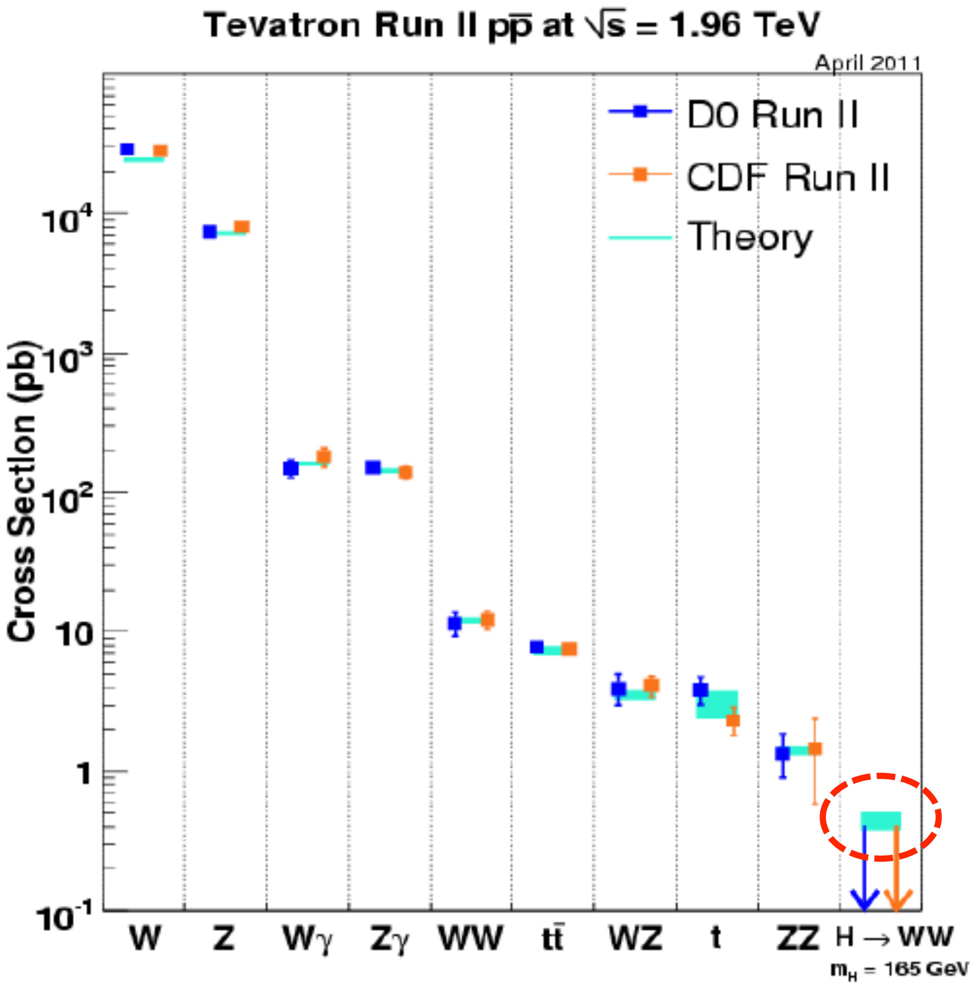
m_H=135 GeV

Enhanced B(H→bb)

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

The Stairway to the Higgs

- Higgs boson searches at the Tevatron are background-dominated.



- Instrumental backgrounds: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.
- Physics backgrounds: estimated using simulation and state-of-art theoretical predictions, and further calibrated to data whenever possible
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)
  - Diboson production
  - Double and single top quark production

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