Higgs Studies at D0 and the Tevatron

Ken Herner for the CDF and D0 Collaborations

18 July 2013

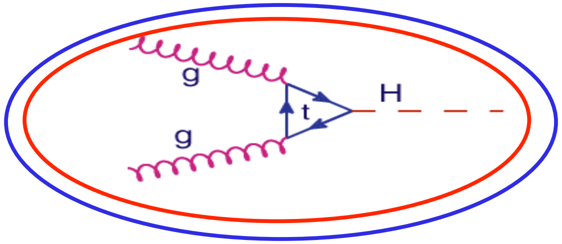
Outline

- Tevatron and LHC Complementarity
- Overview of $H \longrightarrow b\bar{b}$ analyses
- Tevatron cross section and coupling measurements
- D0 spin and parity constraints in $b\bar{b}$ channels

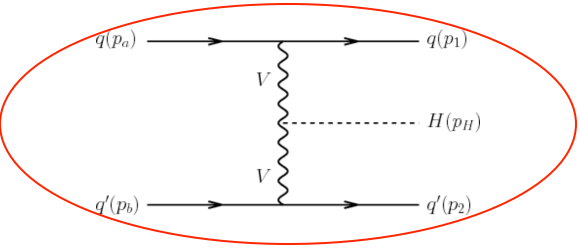
Tevatron-LHC Complementarity

2012 was a momentous year– Discovery of a new boson with mass 125 GeV at the LHC in 4 lepton and $\gamma\gamma$ final states consistent with the SM Higgs; 3σ in $b\bar{b}$ final states at the Tevatron, compatible with LHC

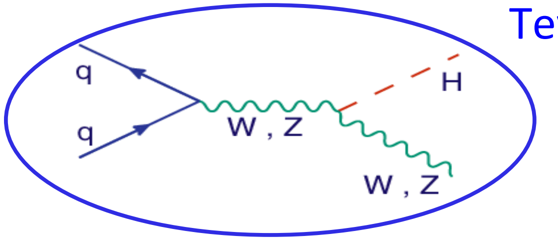
The name of the game now: Probe new particle's properties



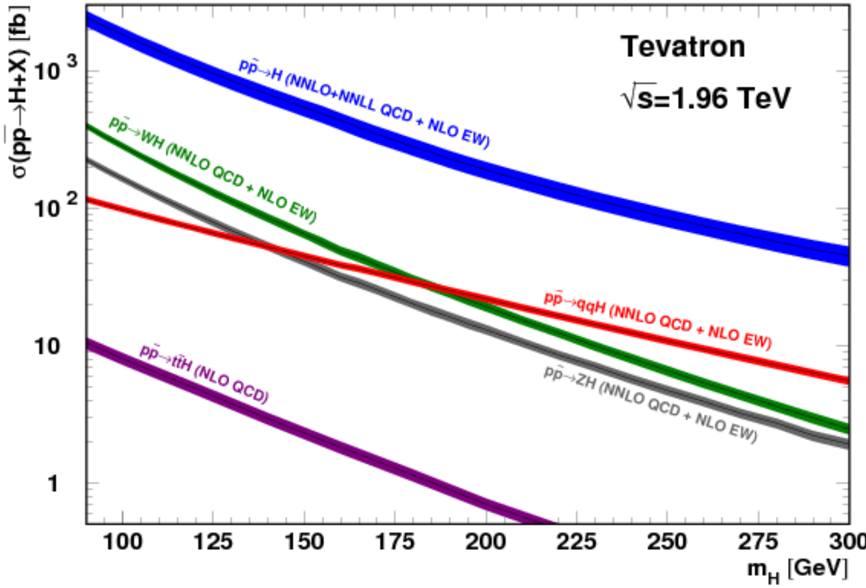
Tev, LHC



LHC



Tev



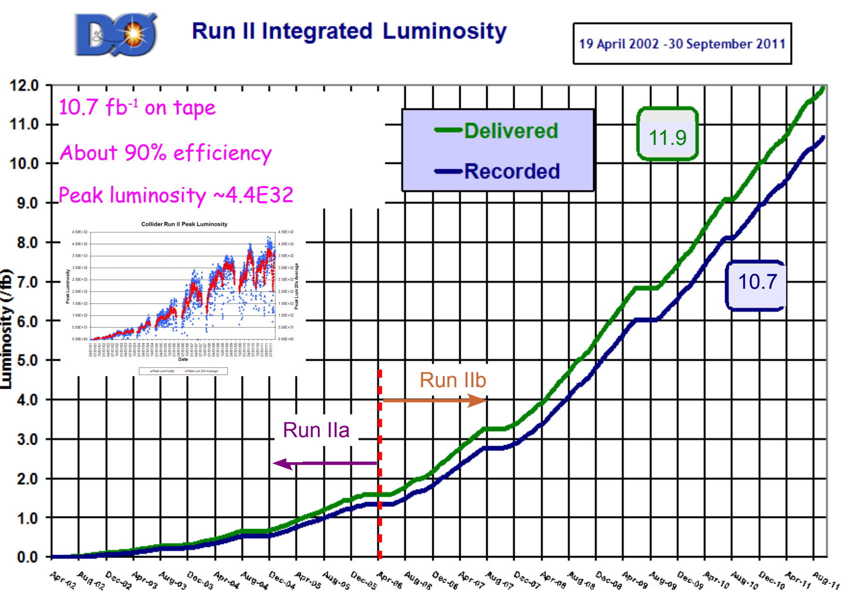
Tevatron main modes: VH→V bb, H → WW*

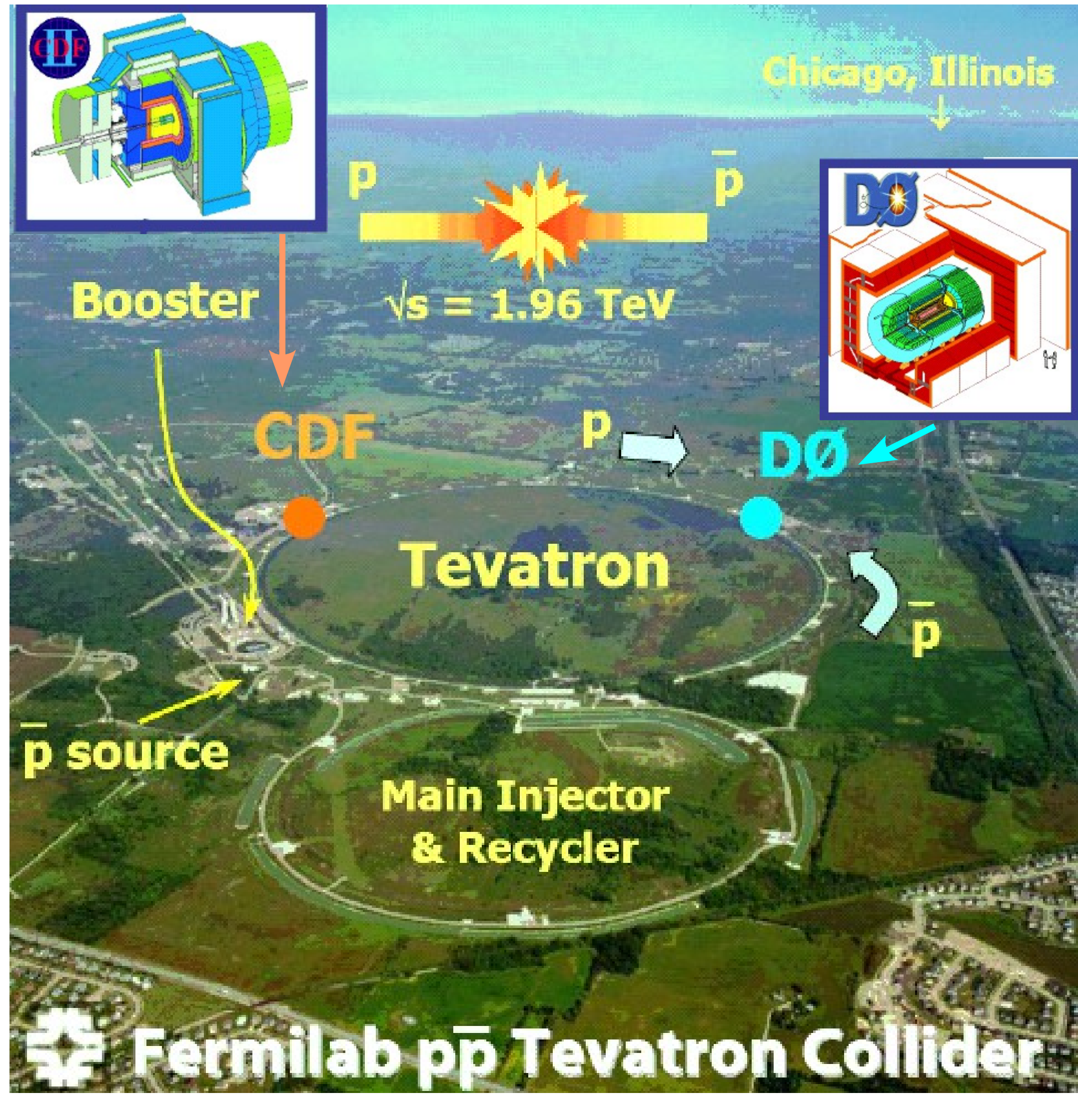
LHC main modes: H → $\gamma\gamma$, H→ZZ, H→WW*

Tevatron can contribute to property measurements, especially in fermionic decay modes

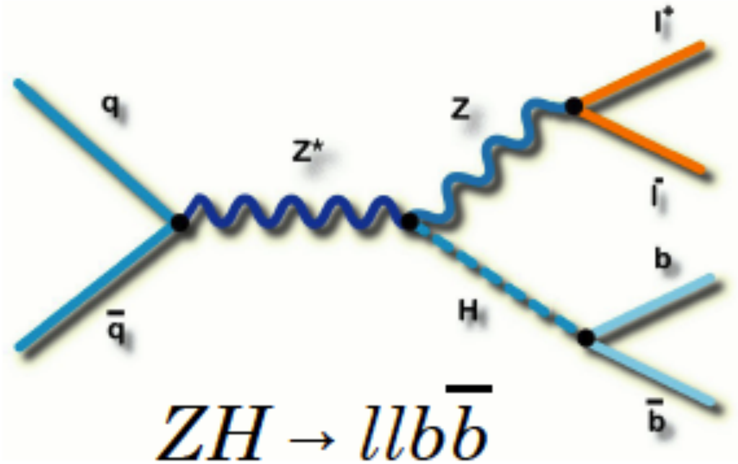
The Tevatron

- 1.96 TeV $p\bar{p}$ collider
- Integrated Luminosities up to 10 fb^{-1}/exp.



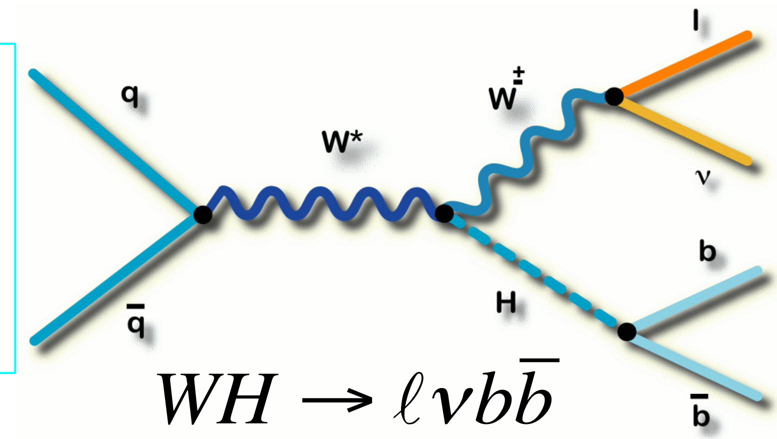


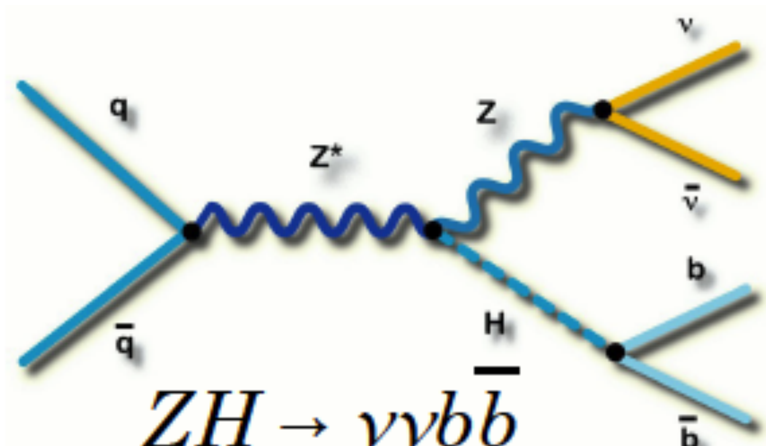
VH⟶ Vb$\bar{b}$ Analyses



- ZH → llbb – 2 leptons + 2 b-jets
  - Fully reconstructed final state
- Modeling of the Z+jets background; rejection of the tt background

- WH → lvbb – 1 lepton + MET + 2 b-jets
- Dominant backgrounds: W+jets, top
- Multijet backgrounds challenging

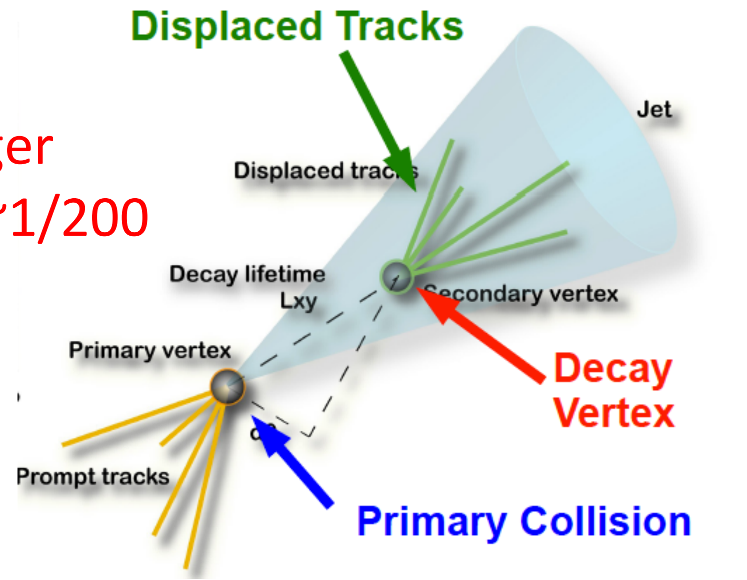


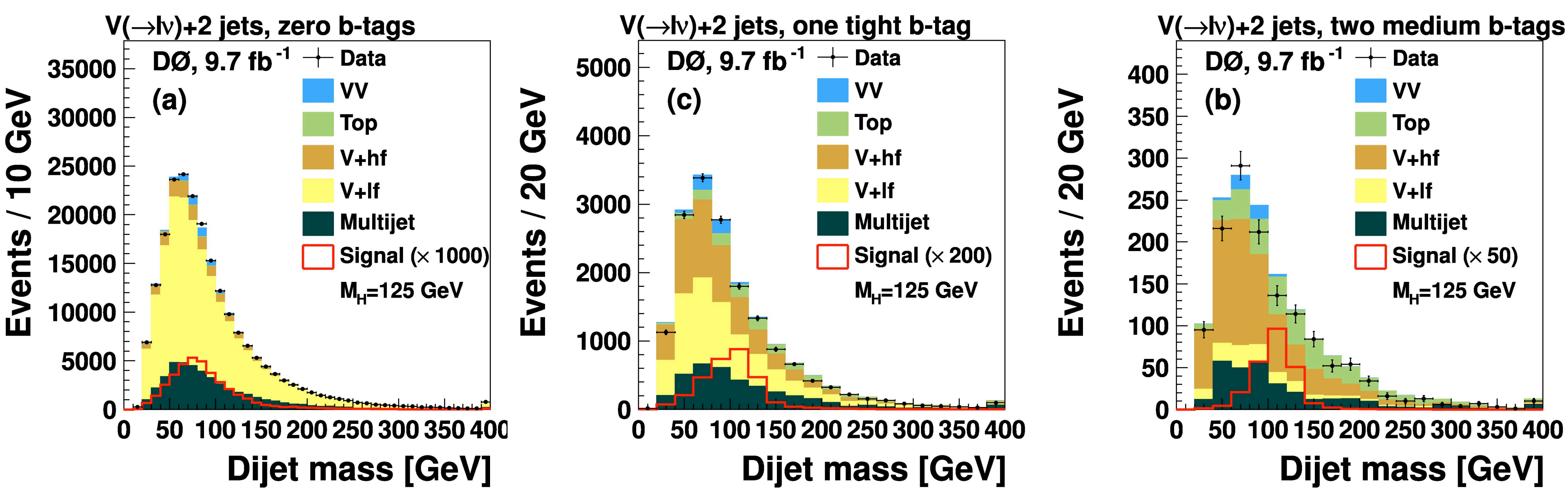


- ZH → vvbb – MET + 2 b-jets (contribution from WH also)
- Accurately model and reject multijet background

Keys to Success in $b\bar{b}$ Searches

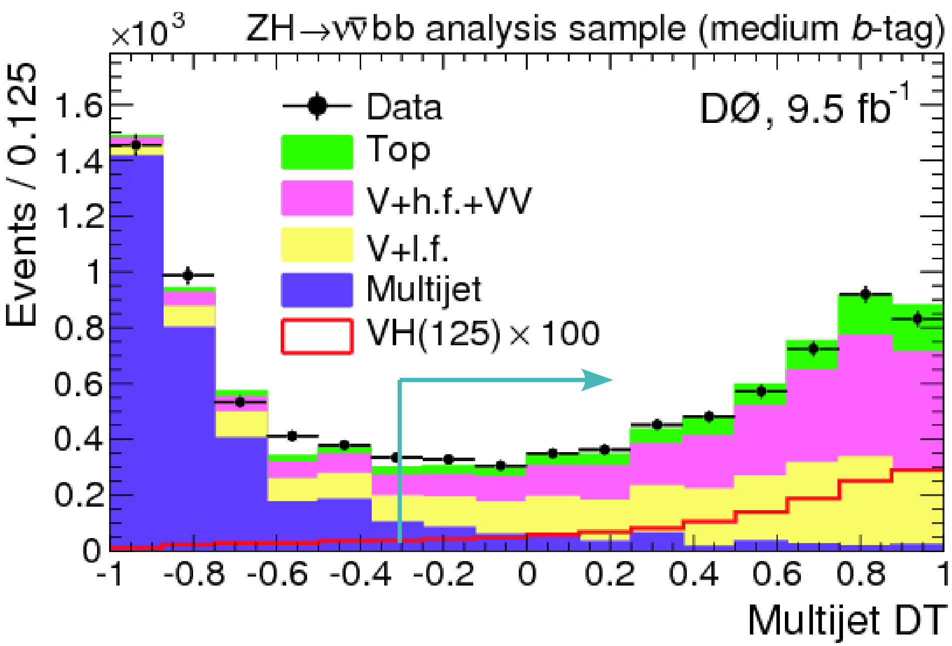
- b-tagging
  - Pick out events with b-jets using tagger
  - Improve s/b ratios from ~1/7000 to ~1/200
- Multivariate techniques

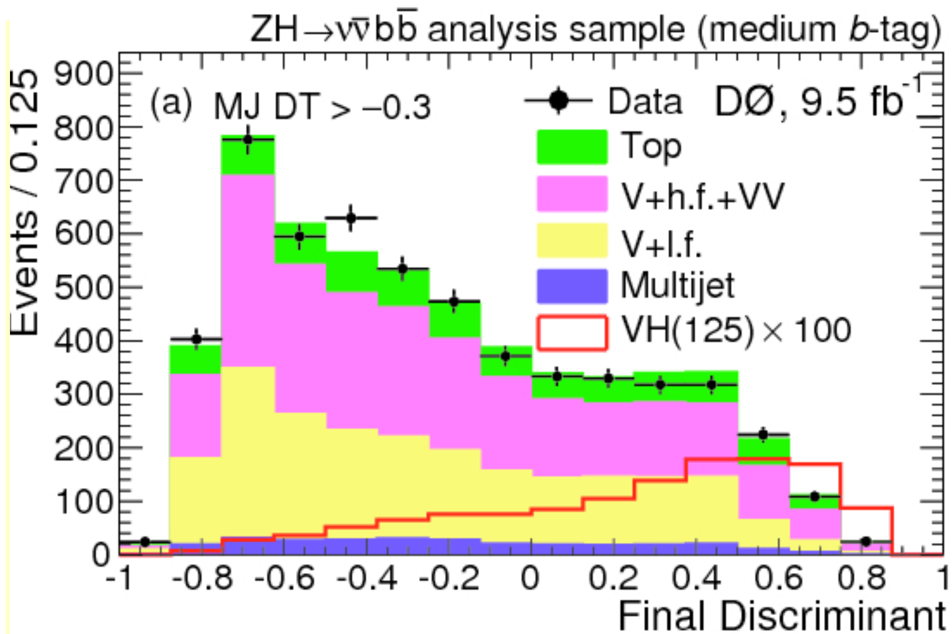




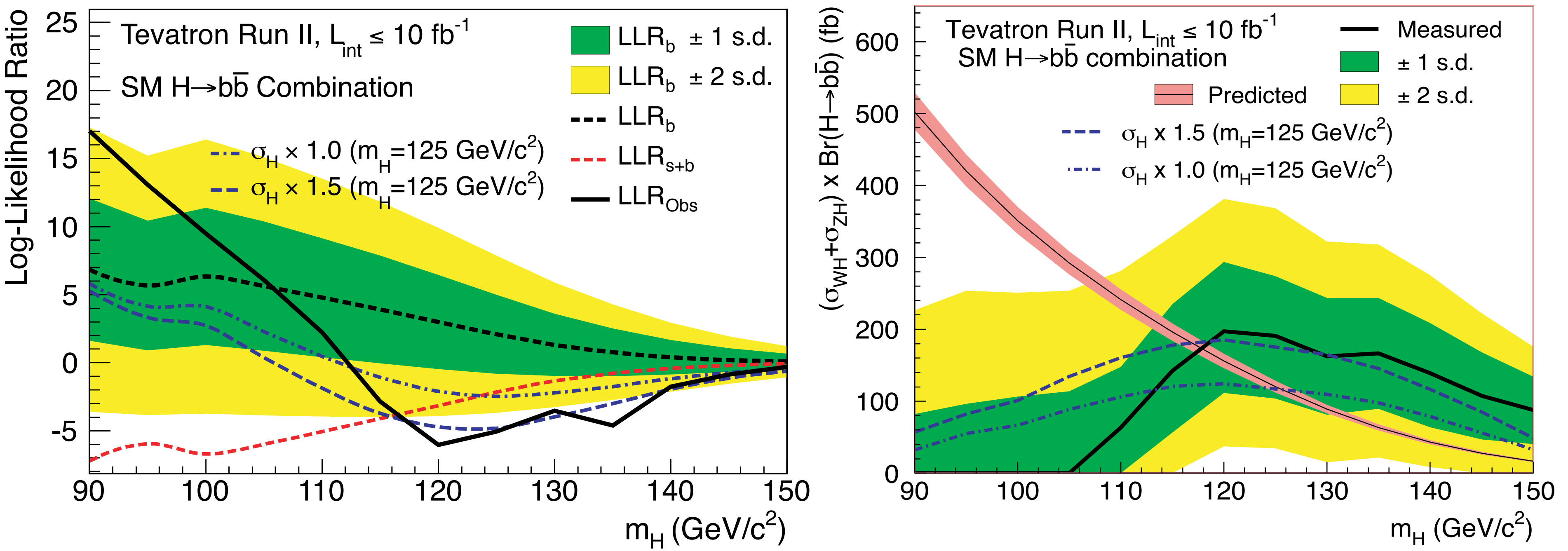
Keys to Success in $b\bar{b}$ Searches

- b-tagging
- Multivariate techniques
  - techniques to discriminate against single backgrounds or against all
  - often chained together





Tevatron VH⟶$b\bar{b}$ Results

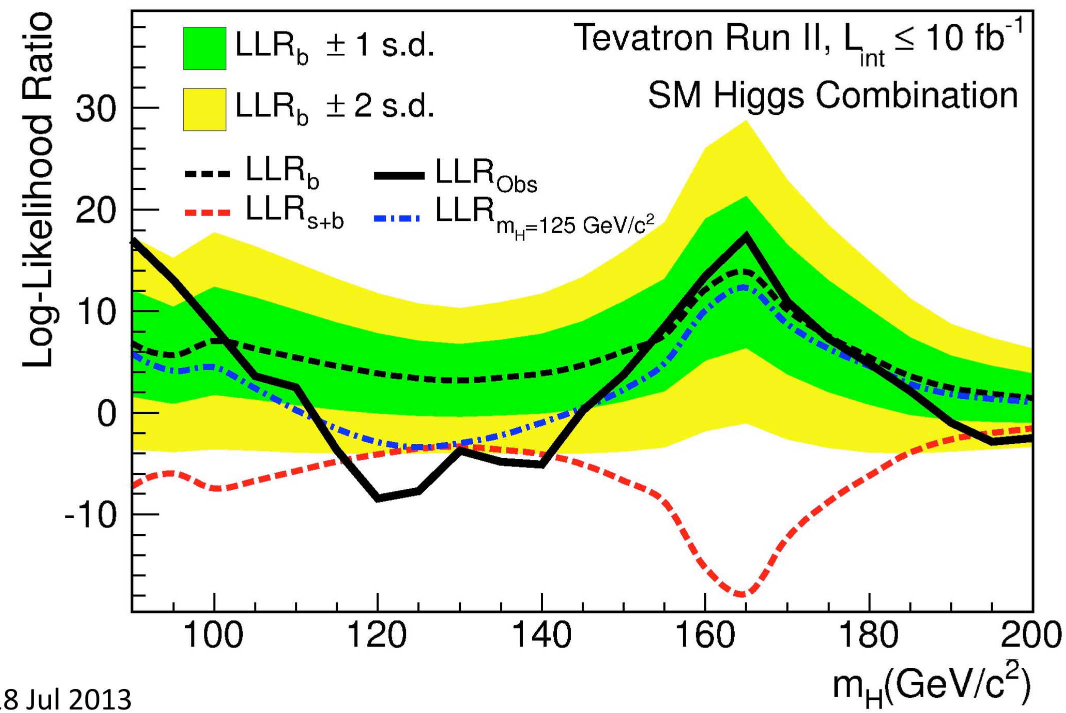


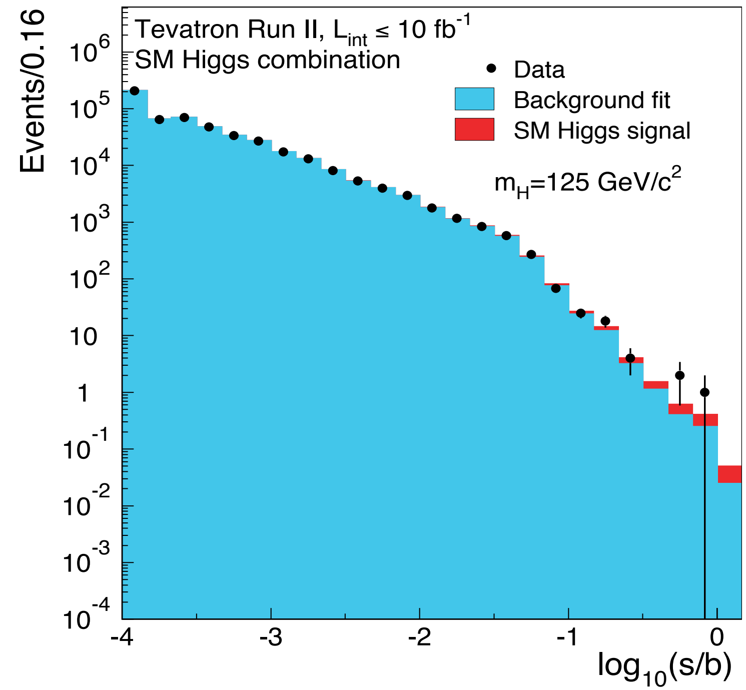
Measured $(\sigma_{WH}+\sigma_{ZH})\times B(H\longrightarrow b\bar{b})$: 0.19 ± 0.09 pb
SM prediction: 0.12 ± 0.01 pb

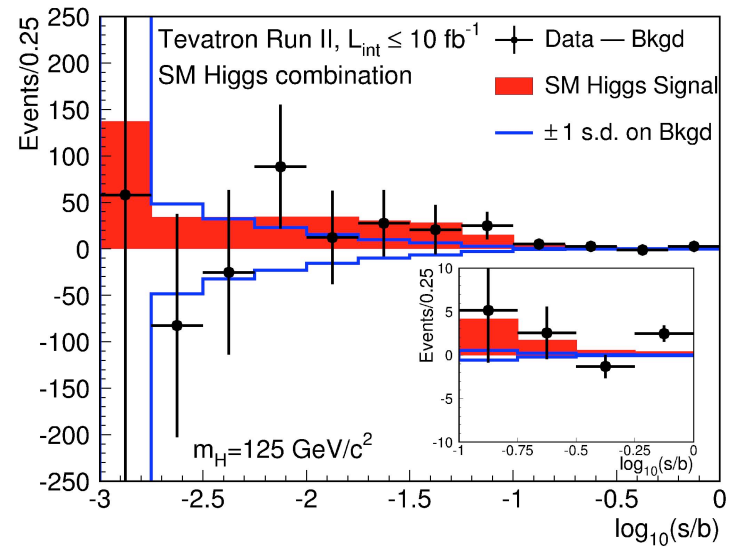
Tevatron + LHC Combination would provide best cross section measurement, and firmly establish H⟶$b\bar{b}$ before 2015 LHC run

Tevatron Combination

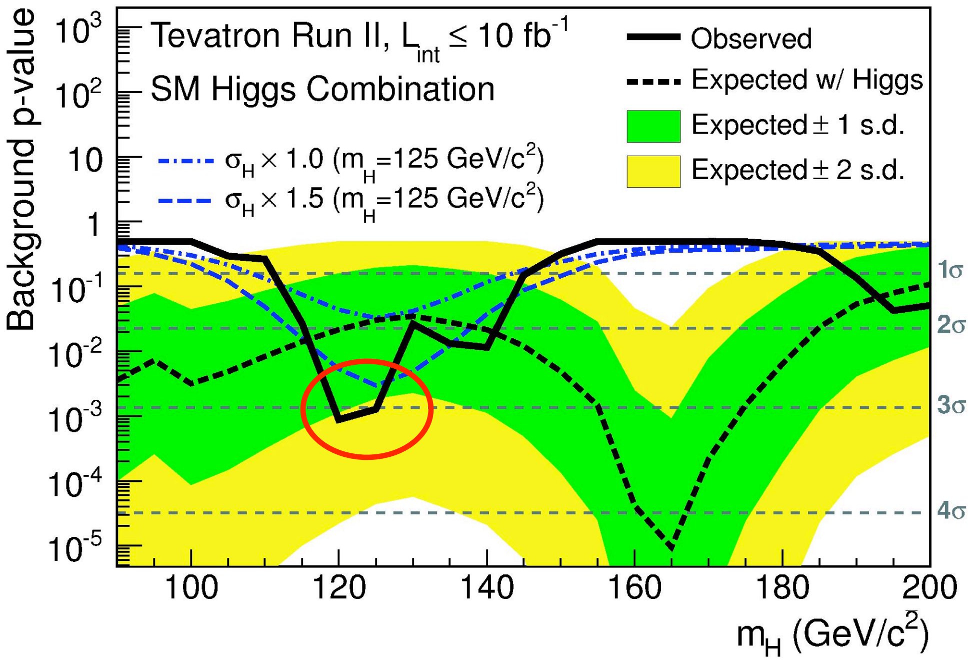
- Combine all search channels from D0 and CDF
  - 17 distinct analyses, over 100 subchannels (WW, ZZ, ττ, γγ decays)
  - Good agreement over many orders of magnitude
- Bayesian and CL_s methods

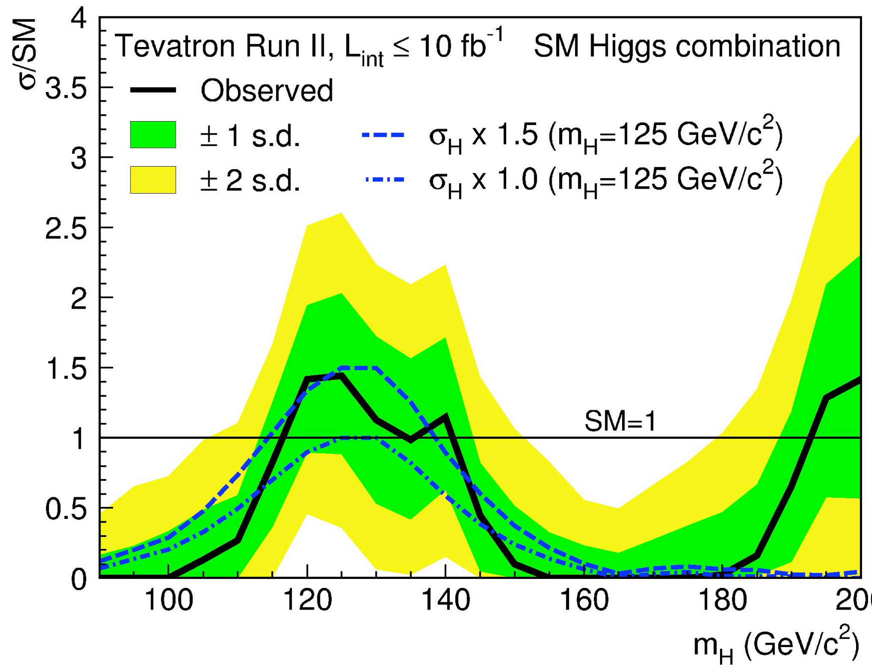






Tevatron Cross Section & p-values

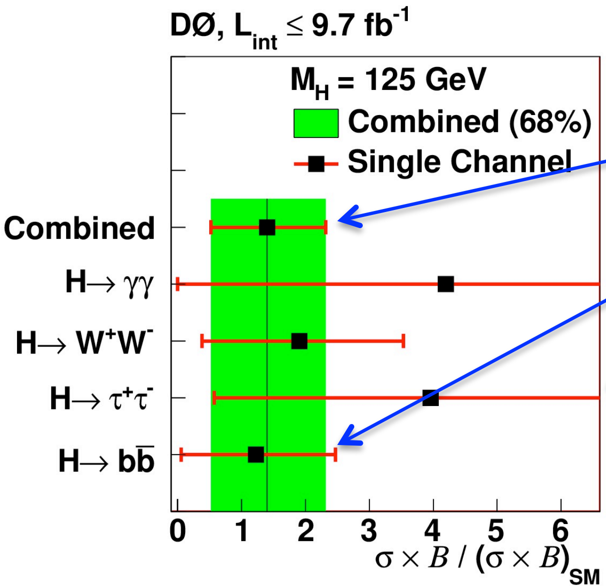




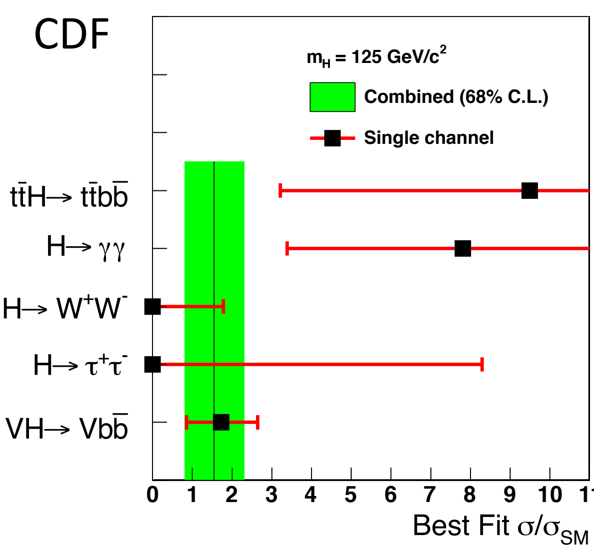
3.0 s.d. (local) at M_H=125 GeV

$\sigma/SM=1.44^{+0.59}_{-0.56}$ at M_H=125 GeV

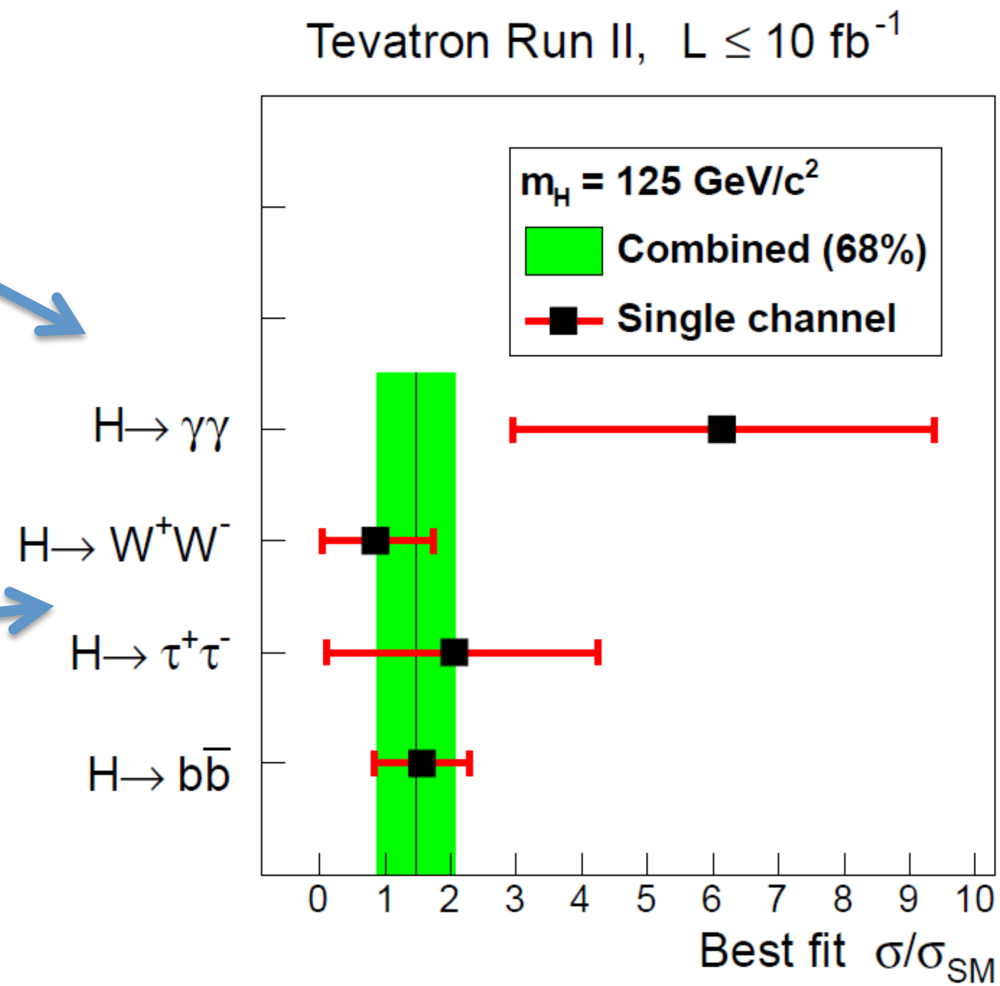
Tevatron Cross Sections



D0 combined rate: 1.40 x SM
D0 H⟶bb rate: 1.23 x SM



CDf combined rate: 1.54 x SM



Coupling Measurements

- Fix mass at 125, perform best fit to all x-secs/branching fractions
- Scale all fermion couplings by κ_F and all boson couplings by κ_V
  - Need to preserve unitarity in branching fractions
- Also compare κ_W and κ_Z (custodial sym.)

Some examples:

$$\Gamma_{b\bar{b}}, \Gamma_{c\bar{c}}, \Gamma_{\tau\tau} \propto \kappa_f^2$$

$$\Gamma_{WW} \propto R^2 \kappa_V^2, \quad R = \kappa_W / \kappa_Z$$

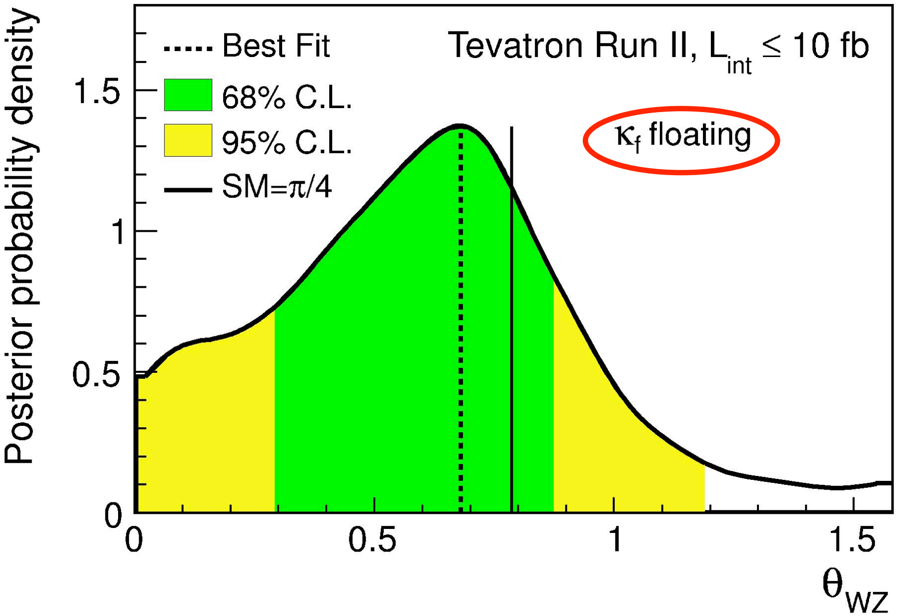
$$\Gamma_{ZZ} \propto \kappa_V^2$$

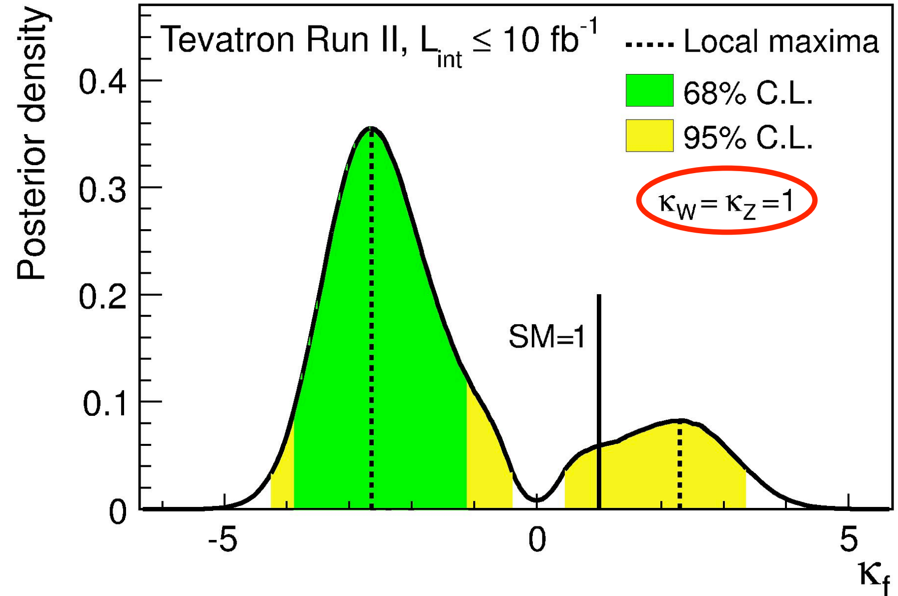
$$\Gamma_{gg} \propto (0.95\kappa_f^2 + 0.05\kappa_V^2)$$

$$\Gamma_{\gamma\gamma} \propto (1.28\kappa_V - 0.28\kappa_f)^2$$

$$B_i' = \frac{B_i s_i}{\sum_j B_j s_j}$$

1D Coupling Measurements



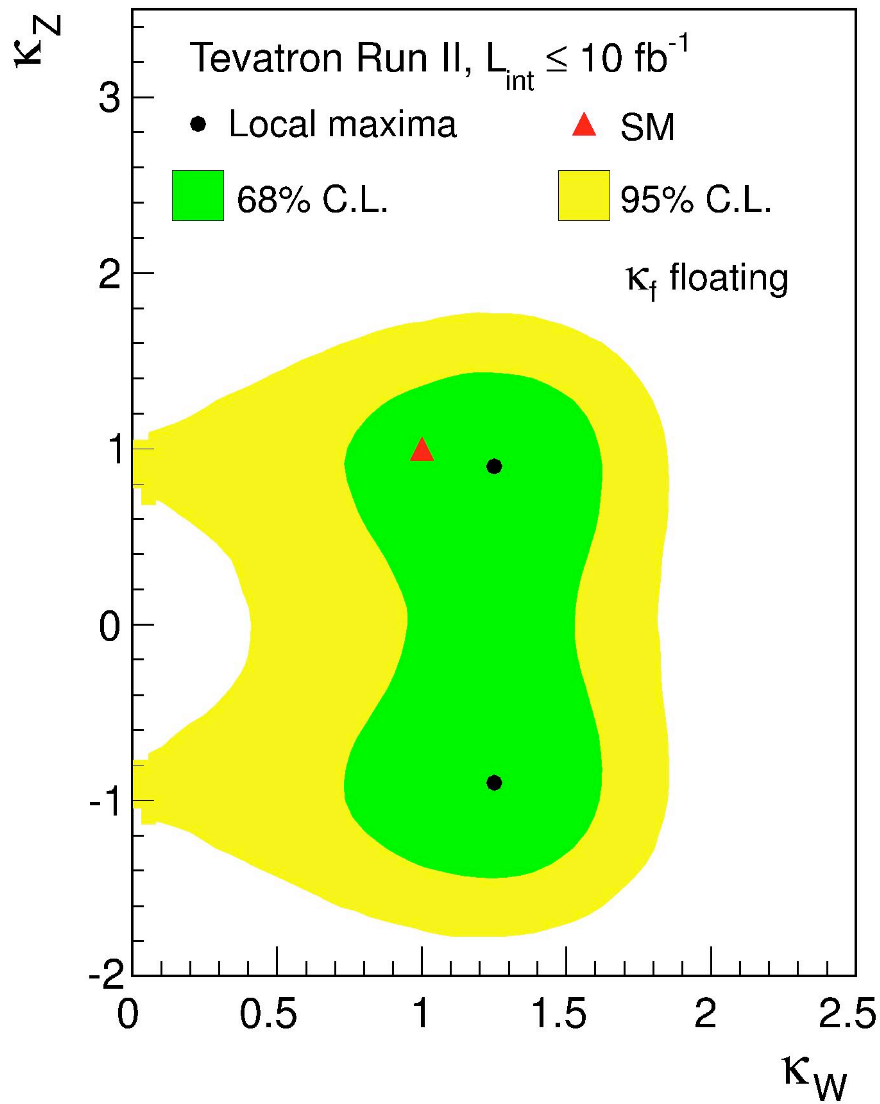


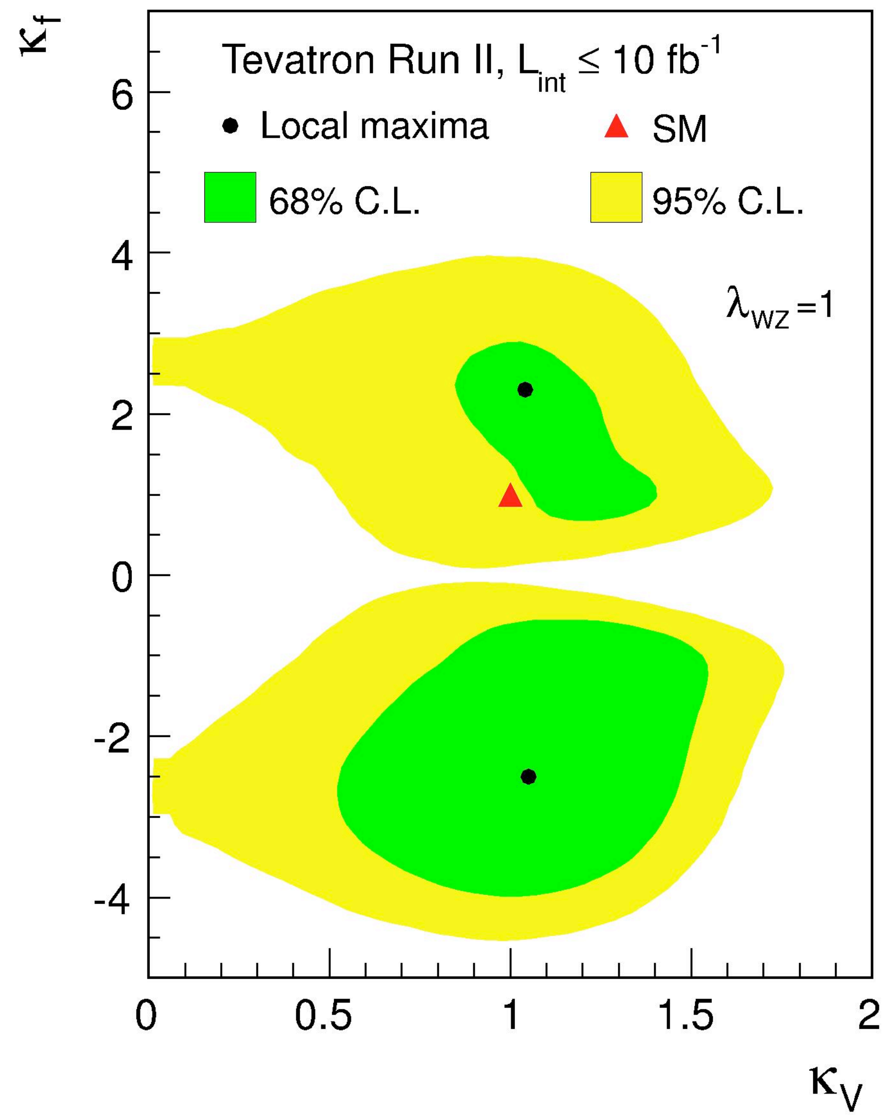
$$\theta_{WZ} = \mathrm{Tan}^{-1}(\kappa_Z / \kappa_W)$$

$$\kappa_W / \kappa_Z = 1.24^{+2.34}_{-0.42}$$

κ_W, κ_Z = coupling ratios to SM for W and Z

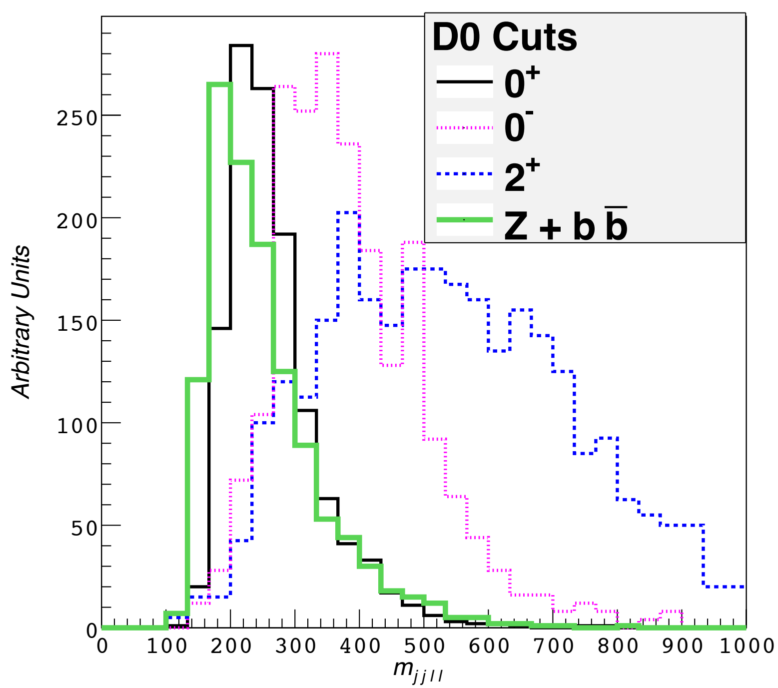
κ_W vs. κ_Z κ_f vs. κ_V

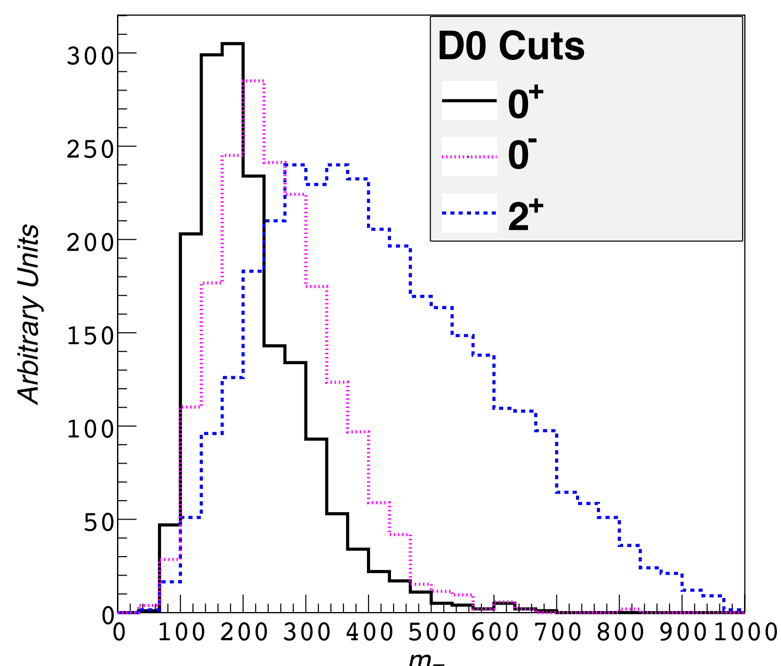




Testing Spin and Parity

- Standard Model predicts $J^P = 0^+$; 2^+, 0^- also possible
- LHC tests confirm 0^+ at 3σ level in combined bosonic final states
- Tevatron has sensitivity in bb final states
  - We need a consistent picture in **all** expected decay modes!
- Visible mass of Vbb system very sensitive to J^P assignment (e.g. Ellis, Hwang, Sanz, You, JHEP **1211**, 134 [2012])





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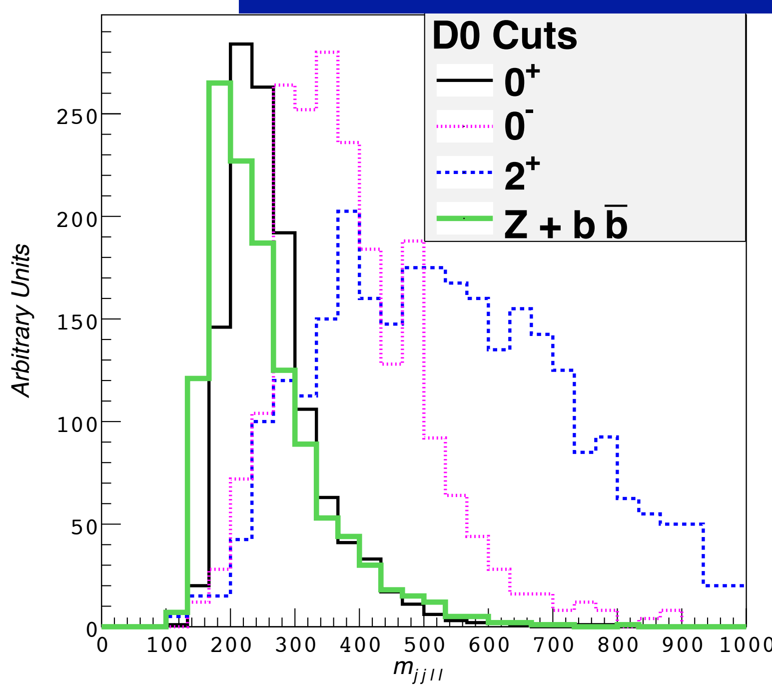
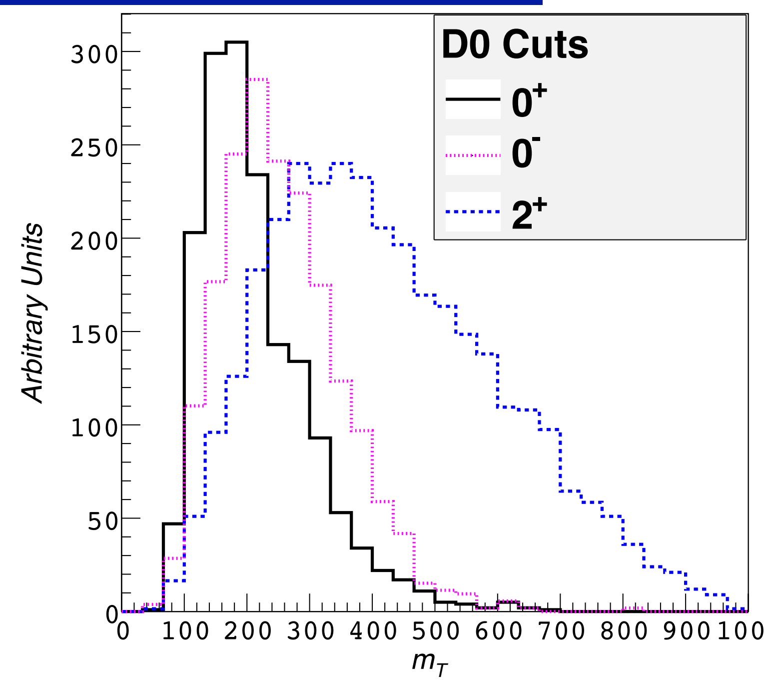
- Visible ma ment (e.g. Ellis,

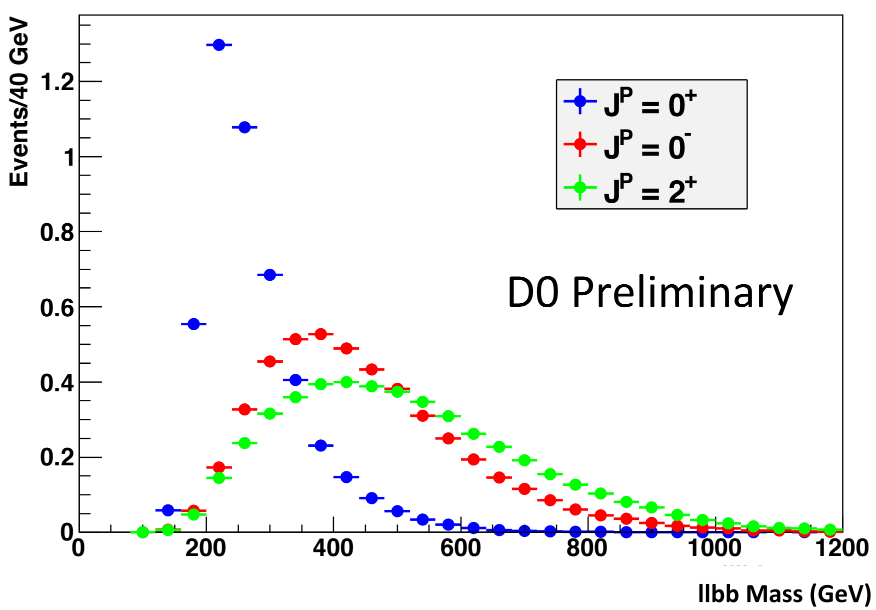
Today's results only cover 0^+ vs. 2+
0^- vs. 0^+ studies are ongoing





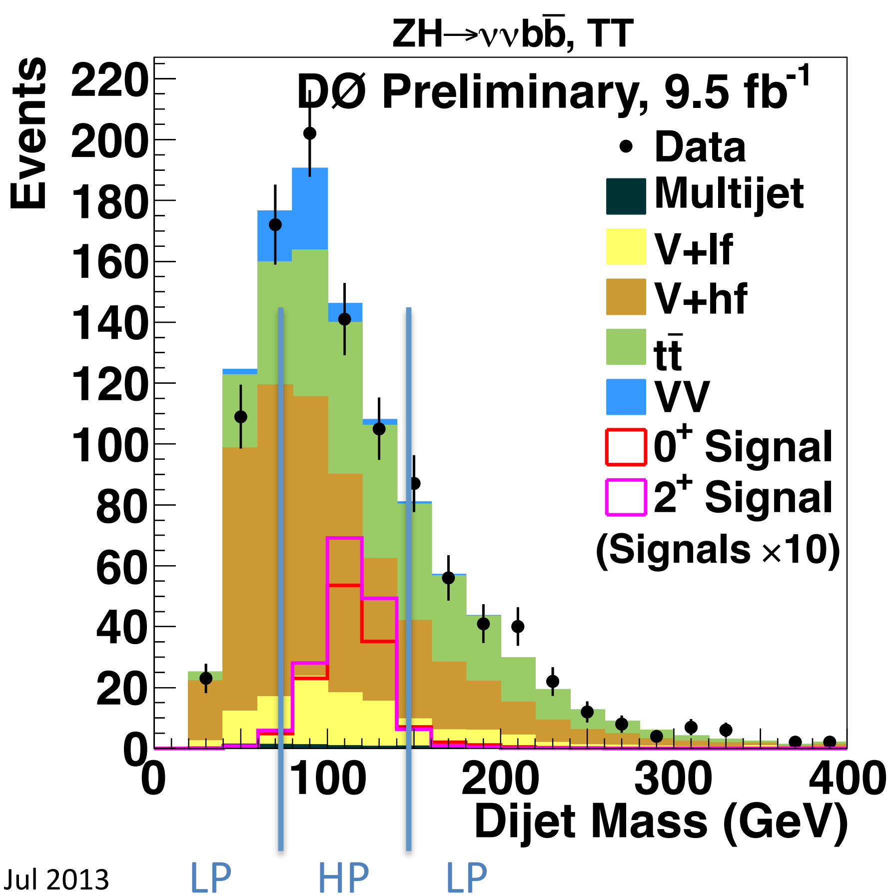
Generating signals

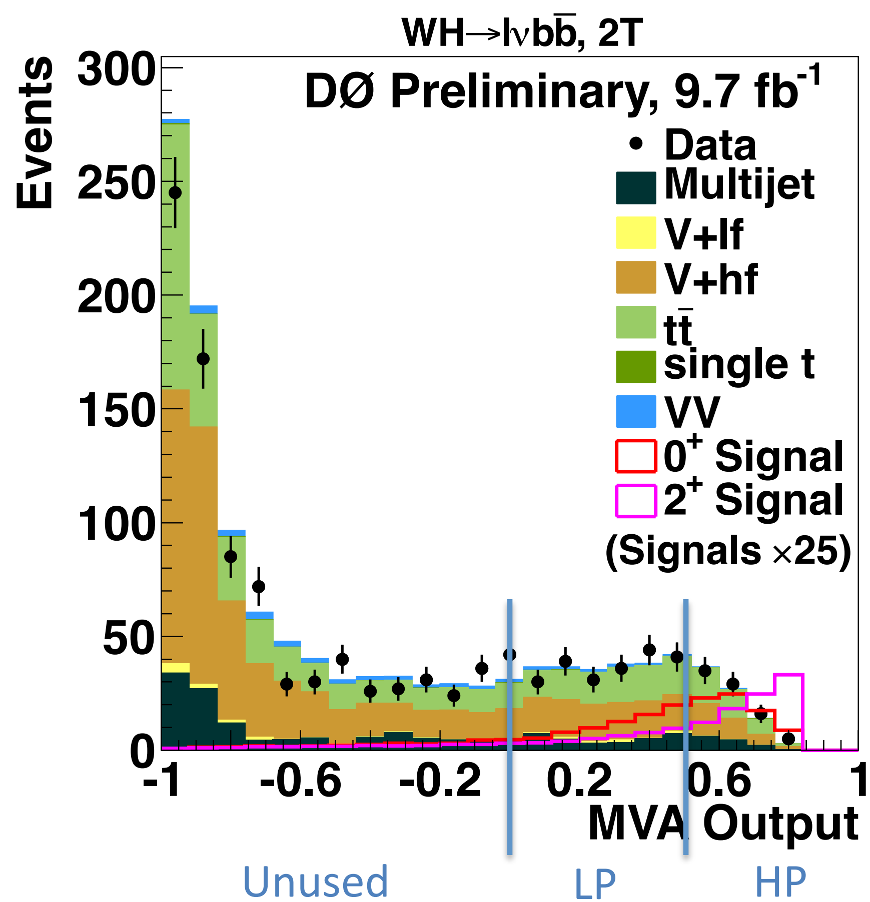
- Generate 2^+ signal with MADGRAPH5; interfaced to PYTHIA for showering
  - Use RS graviton model, initial normalization to SM xsec x Br
  - Note: no generic Spin-2 model
  - Only considering VH processes (no e.g. gg or VBF)
- MADGRAPH 0^+ VH checked against PYTHIA VH; good agreement
- Observe similar separation to that predicted



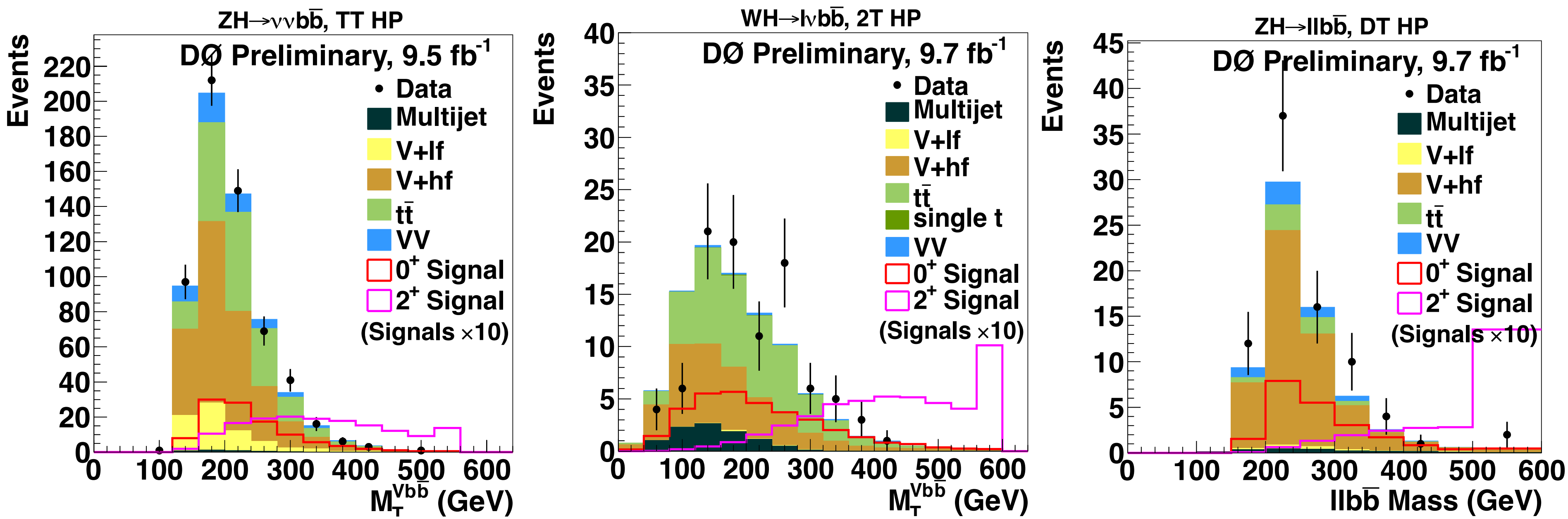
Additional Discrimination

- Take advantage of known mass
  - vvbb, llbb: create high/low purity regions using Mbb
- lvbb uses MVA output to make HP/LP regions
- Separate channels in statistical analysis





Final Variables



Tightest HP b-tag channel per analysis shown

Results

- Use CL_s to quantify model preference, LLR as test statistic
  - H1: $J^P = 2^+$ + BG
  - H0: $J^P = 0^+$ + BG

$$LLR = -2\log(L(H1)/L(H0))$$

- Compute for 2 different signal scale factors on SM $\sigma \times Br\ (bb)$
  - 1.00 (SM)
  - 1.23 (D0 measured rate)

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  - 1.00 (SM; shown)
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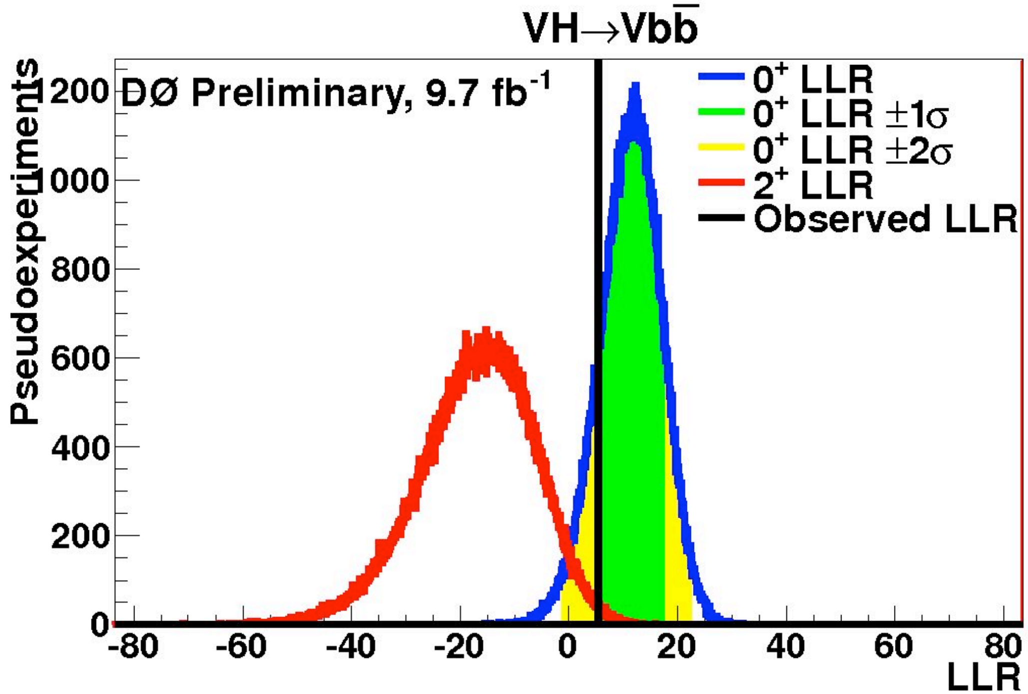


Clear preference for 0^+

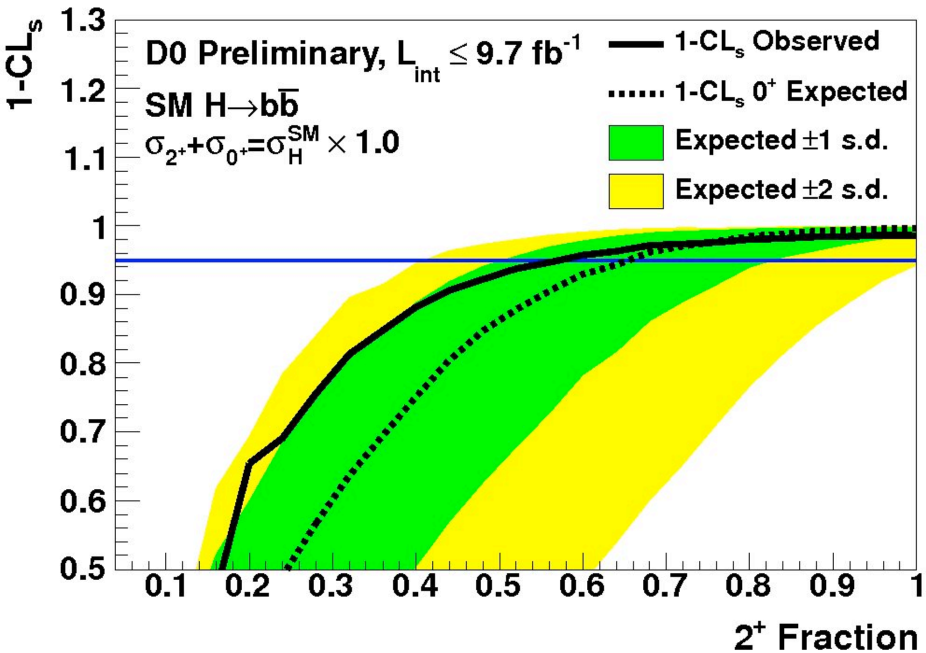
Results

- $CL_s = CL_{H1}/CL_{H0}$
- $CL_x = P(LLR \geq LLR^{obs} | x)$
- Interpret 1-CL_s as C.L. for exclusion of 2^+ in favor of 0^+
- Exclude 2^+ model at > 99.2% C.L.
- Expected exclusion is 3.1σ (μ=1.0)

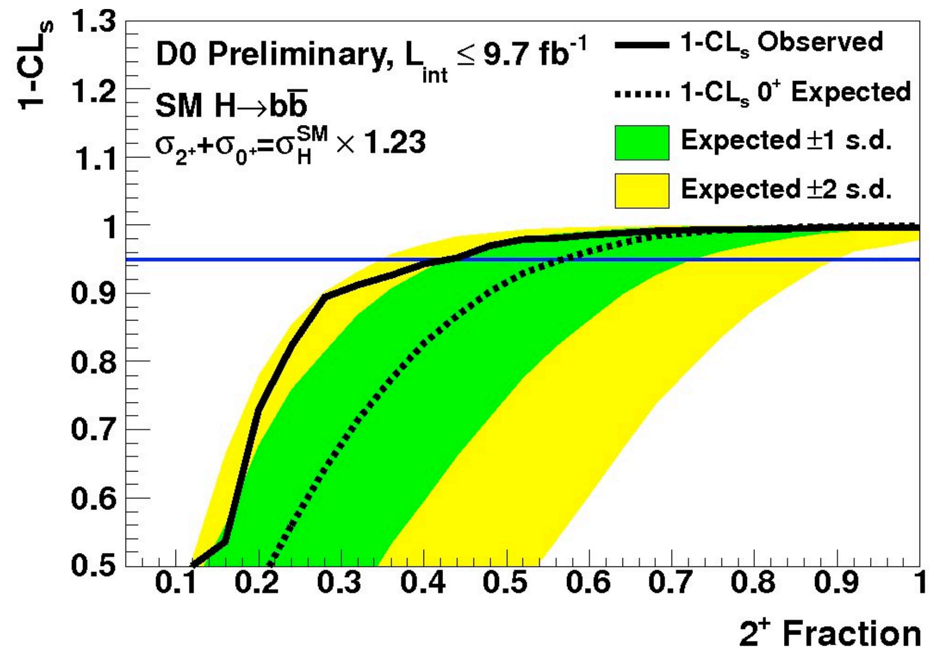
	Combined Result
1 – CL_s Exp. (μ=1.00)	0.9995
1 – CL_s Obs. (μ=1.00)	0.992
1 – CL_s Exp. (μ=1.23)	0.9999
1 – CL_s Obs. (μ=1.23)	0.999

Signal Admixtures

- Allow possibility of both a 2^+ and 0^+ signal in data
  - Vary 2^+ fraction f_{2+} from 0 to 1
  - H1: $\mu \times (\sigma \bullet Br(\to bb))_{SM} \times [2^+ \times f_{2+} + 0^+ \times (1 - f_{2+})]$ + Background
  - H0: $\mu \times (\sigma \bullet Br(\to bb))_{SM} \times 0^+$ (i.e. pure 0^+) + Background
- Fix μ to 1.00 or 1.23, compute LLR, CLs, etc.



Exclude f_{2+} > 0.56 at 95% C.L.

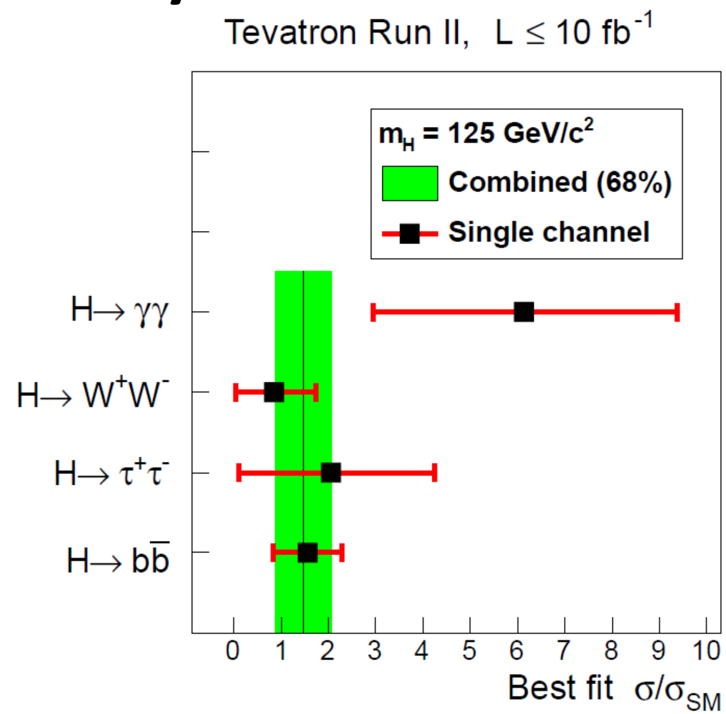


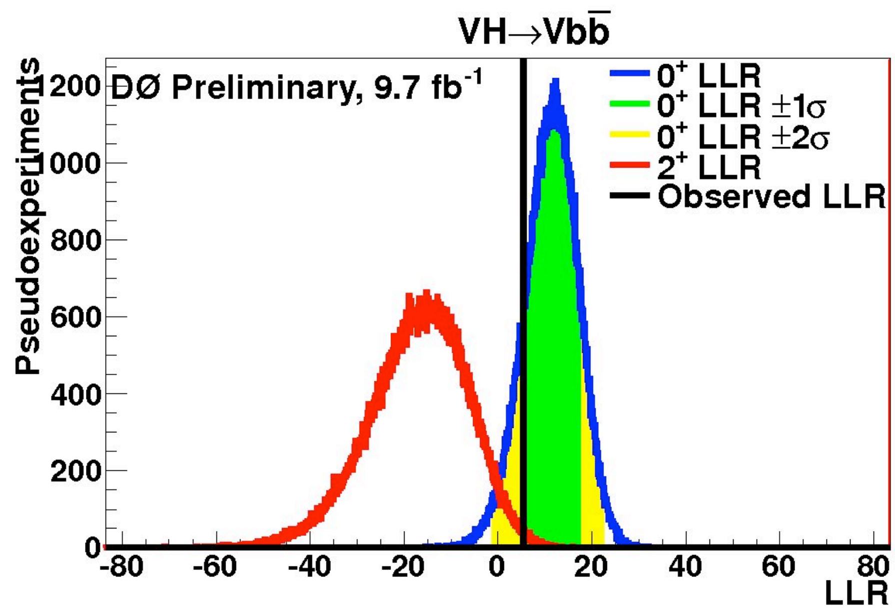
Exclude f_{2+} > 0.42 at 95% C.L.

Summary

- A broadly consistent Higgs boson picture is forming; Tevatron provides complementary info in $b\bar{b}$ channels
- All final Tevatron Higgs combinations accepted in Phys. Rev. D
- Cross section and coupling measurements consistent with the SM predictions
- D0 spin and parity tests in $b\bar{b}$ final states favor $J^P=0^+$; reject $J^P=2^+$ (graviton-like couplings) at >99.2% C.L.

  Exclude $f_{2+} > 0.42$ at 95% C.L.
- Still to come: $J^P=0^-$ tests, combination with CDF





Backup

Final Tevatron Publications

DØ	Luminosity (fb^{-1})	M_H (GeV)	Reference
$WH \to \ell\nu bb$	9.7	90–150	Phys. Rev. Lett. 109, 121804 (2012) and Acc by PRD arXiv:1301.6122
$ZH \to \ell\ell b\bar{b}$	9.7	90–150	Phys. Rev. Lett. 109, 121803 (2012) and Acc by PRD arXiv:1303.3276
$ZH \to \nu\bar{\nu}b\bar{b}$	9.5	100–150	Phys. Lett. B 716, 285 (2012)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	9.7	100–200	Acc by PRD arXiv:1301.1243
$H + X \to WW \to \mu^\pm\tau_h^\mp + \leq 1$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	Acc by PRD arXiv:1301.6122
$VH \to ee\mu/\mu\mu e+X$	9.7	100–200	Acc by PRD arXiv:1302.5723
$VH \to e^\pm\mu^\pm+X$	9.7	100–200	Acc by PRD arXiv:1302.5723
$VH \to \ell\nu q'\bar{q}q'\bar{q}$	9.7	100–200	Acc by PRD arXiv:1301.6122
$VH \to \tau_h\tau_h\mu + X$	8.6	100–150	Acc by PRD arXiv:1302.5723
$H + X \to \ell\tau_h jj$	9.7	105–150	Acc by PRD arXiv:1211.6993
$H \to \gamma\gamma$	9.7	100–150	Acc by PRD, arXiv:1301.5358
CDF			
$WH \to \ell\nu bb$	9.45	90–150	Phys. Rev. Lett. 109, 111804 (2012)
$ZH \to \ell\ell b\bar{b}$	9.45	90–150	Phys. Rev. Lett. 109, 111803 (2012)
$ZH \to \nu\bar{\nu}b\bar{b}$	9.45	90–150	Phys. Rev. Lett. 109, 111805 (2012) and Phys. Rev. D 87, 052008 (2013)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	9.7	110–200	Sub to PRD, arXiv: 1306.0023
$H \to WW \to e\tau_h\mu\tau_h$	9.7	130–200	Sub to PRD, arXiv: 1306.0023
$VH \to ee\mu/\mu\mu e+X$	9.7	110–200	Sub to PRD, arXiv: 1306.0023
$H \to \tau\tau$	6.0	100–150	Phys. Rev. Lett. 108, 181804 (2012)
$H \to \gamma\gamma$	10.0	100–150	Phys. Lett. B 717, 173 (2012)
$H \to ZZ \to llll$	9.7	120–200	Phys. Rev. D 86 (2012) 072012
$t\bar{t}H \to WWb\bar{b}b\bar{b}$	9.45	100–150	Phys. Rev. Lett. 109 (2012) 181802
$VH \to jjb\bar{b}$	9.45	100–150	JHEP 1302 (2013) 004

Final Tevatron Publications

D0 Combination:
Acc. by PRD arXiv:1303.0823

CDF Combination:
Acc. by PRD arXiv:1301.6668

Tevatron Combination:
Acc. by PRD arXiv:1303.6346

DØ	Luminosity (fb^{-1})	M_H (GeV)	Reference
$WH \to \ell\nu bb$	9.7	90–150	Phys. Rev. Lett. 109, 121804 (2012) and Acc by PRD arXiv:1301.6122
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$H \to W^+W^- \to$			v:1301.1243
$H + X \to WW$			237 (2012)
$H \to W^+W^- \to$			v:1301.6122
$VH \to ee\mu/\mu\mu e$			v:1302.5723
$VH \to e^{\pm}\mu^{\pm}+X$			v:1302.5723
$VH \to \ell\nu q'\bar{q}'q\bar{q}$			v:1301.6122
$VH \to \tau_h\tau_h\mu +$			v:1302.5723
$H + X \to \ell\tau_h jj$			v:1211.6993
$H \to \gamma\gamma$			v:1301.5358
CDF			
$WH \to \ell\nu bb$			111804 (2012)
$ZH \to \ell\ell b\bar{b}$			111803 (2012)
$ZH \to \nu\bar{\nu}b\bar{b}$			111805 (2012)
			052008 (2013)
$H \to W^+W^- \to$			: 1306.0023
$H \to WW \to e$			: 1306.0023
$VH \to ee\mu/\mu\mu e+X$	9.7	110–200	Sub to PRD, arXiv: 1306.0023
$H \to \tau\tau$	6.0	100–150	Phys. Rev. Lett. 108, 181804 (2012)
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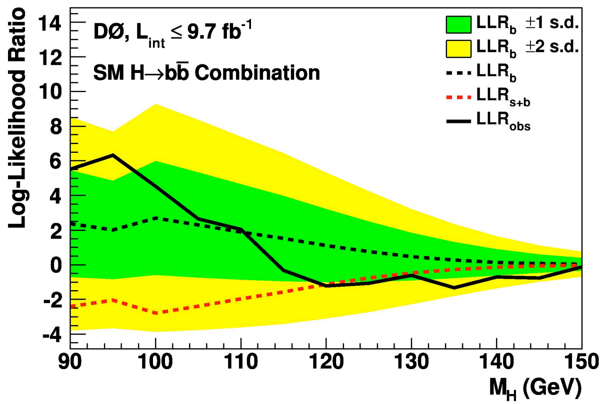
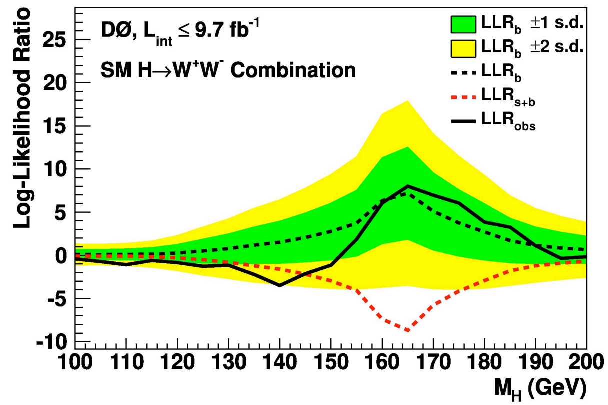
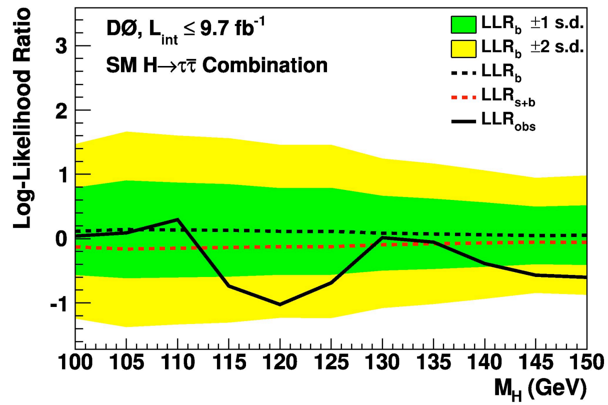
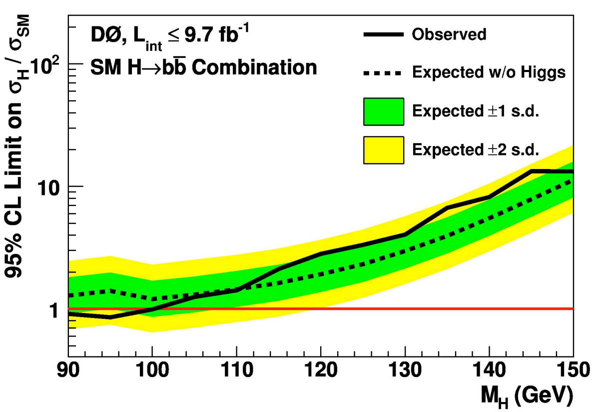
$VH \to jjb\bar{b}$	9.45	100–150	JHEP 1302 (2013) 004

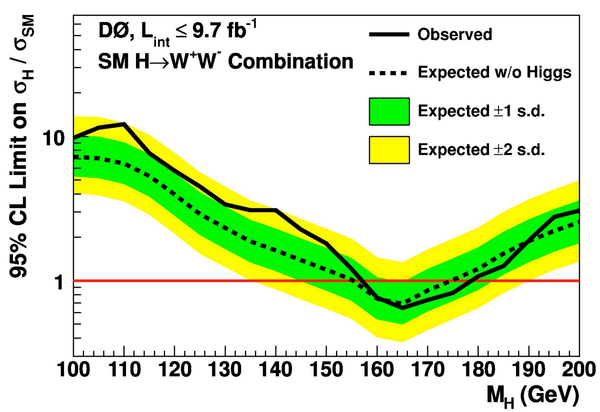
Final D0 SM Combination

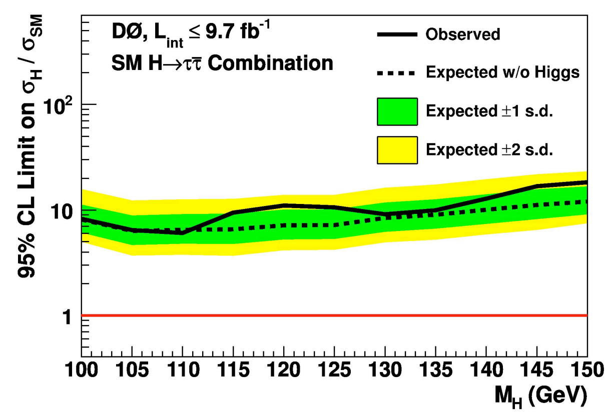




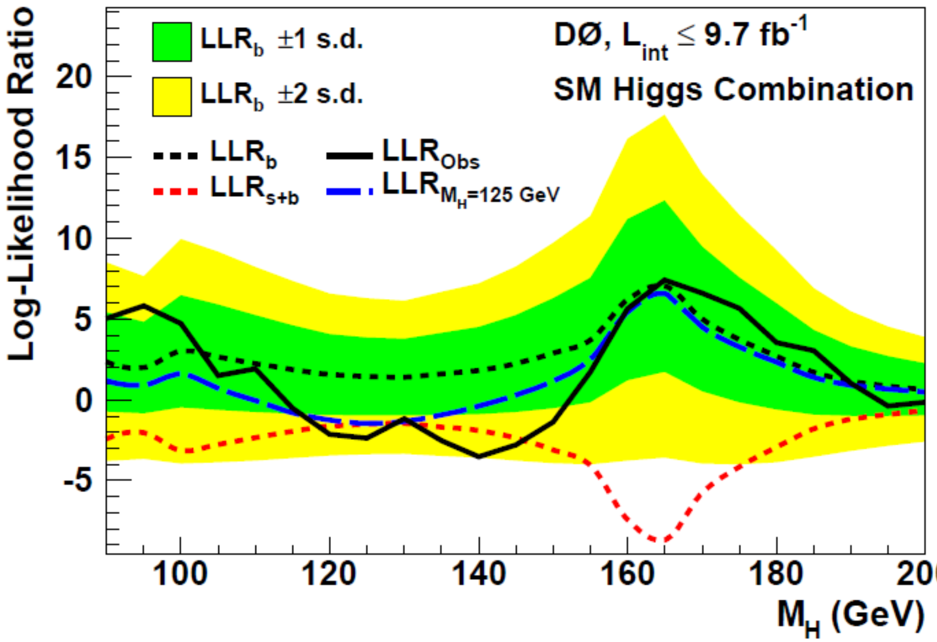


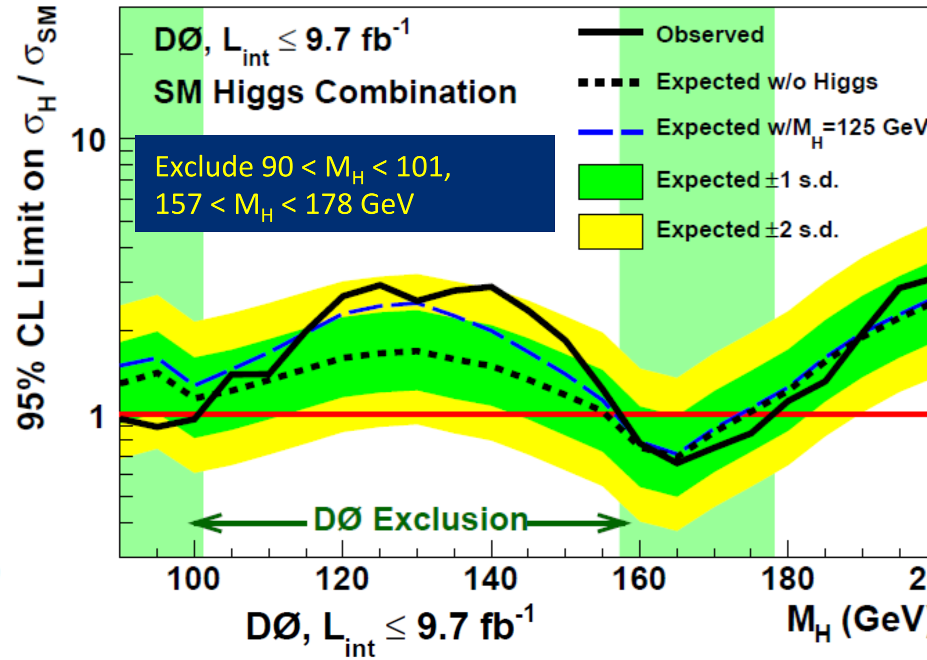


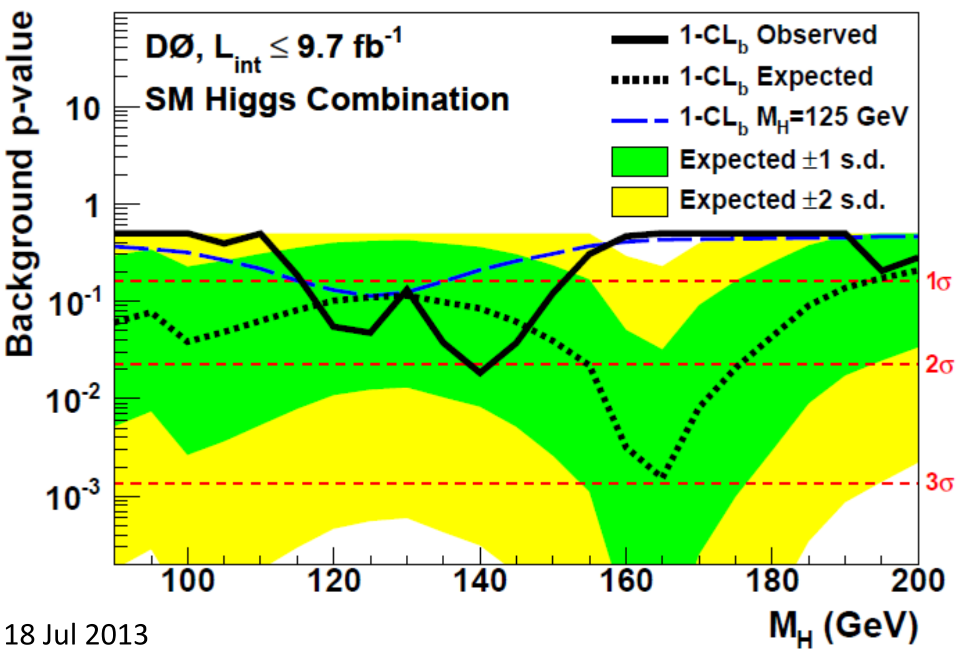


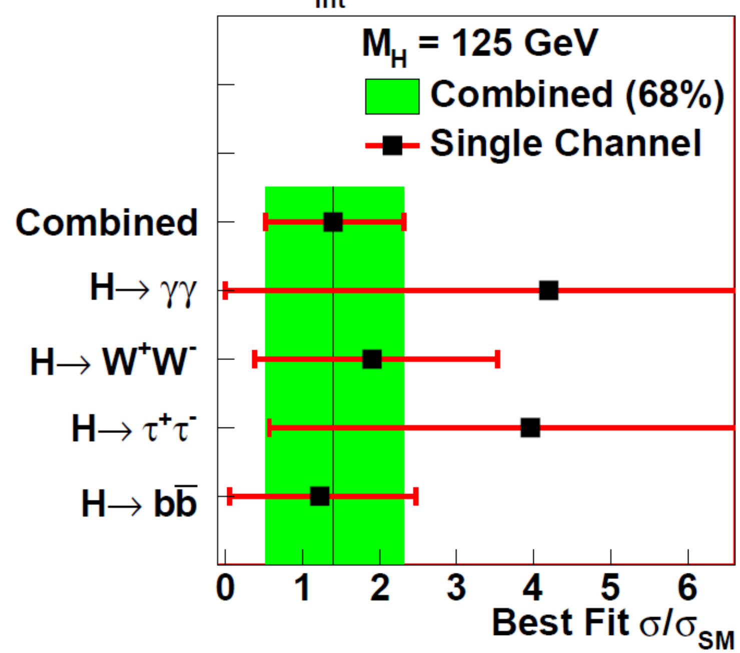


Final D0 SM Combination

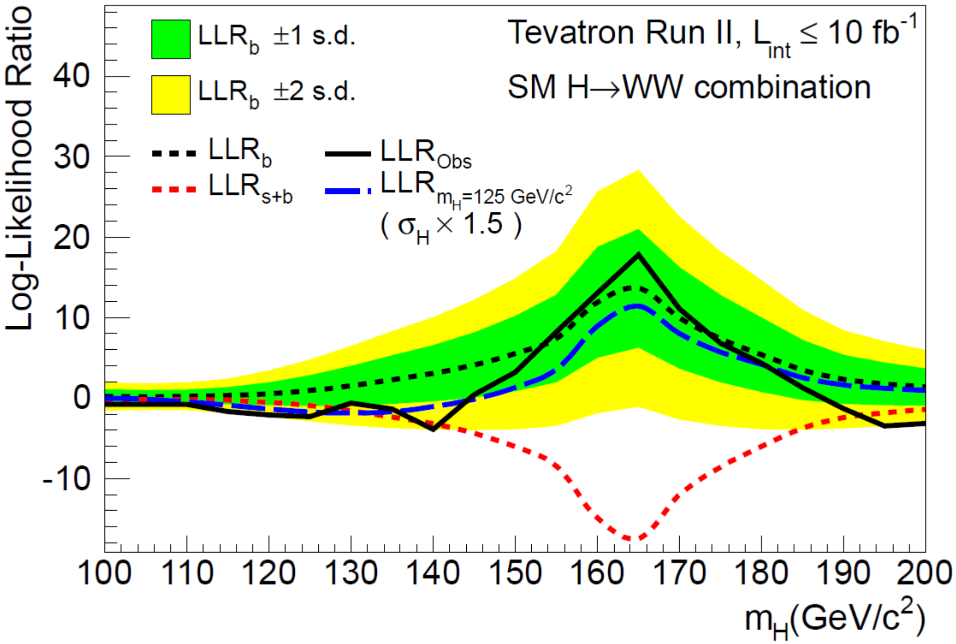


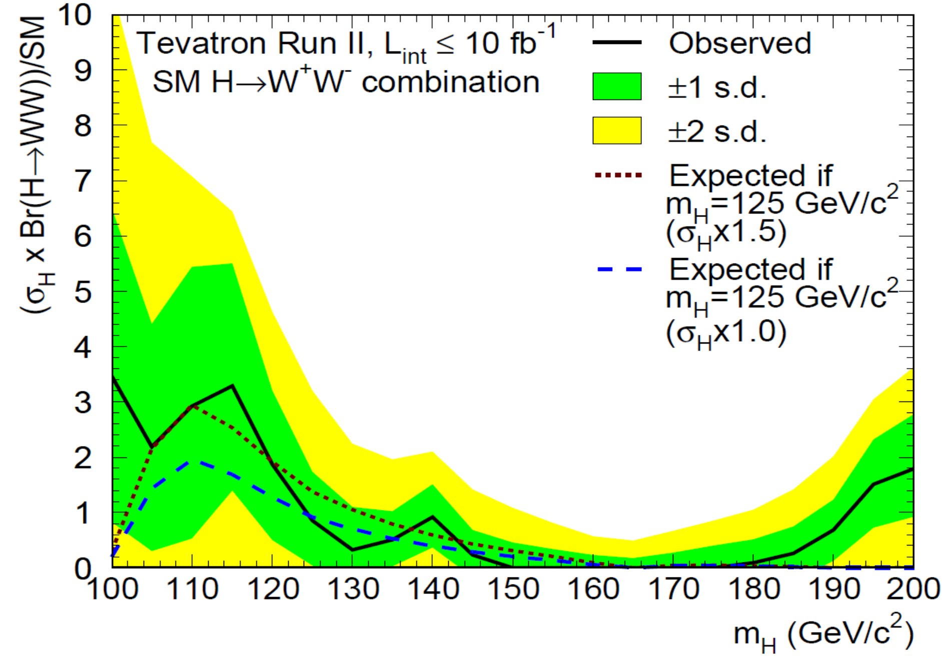


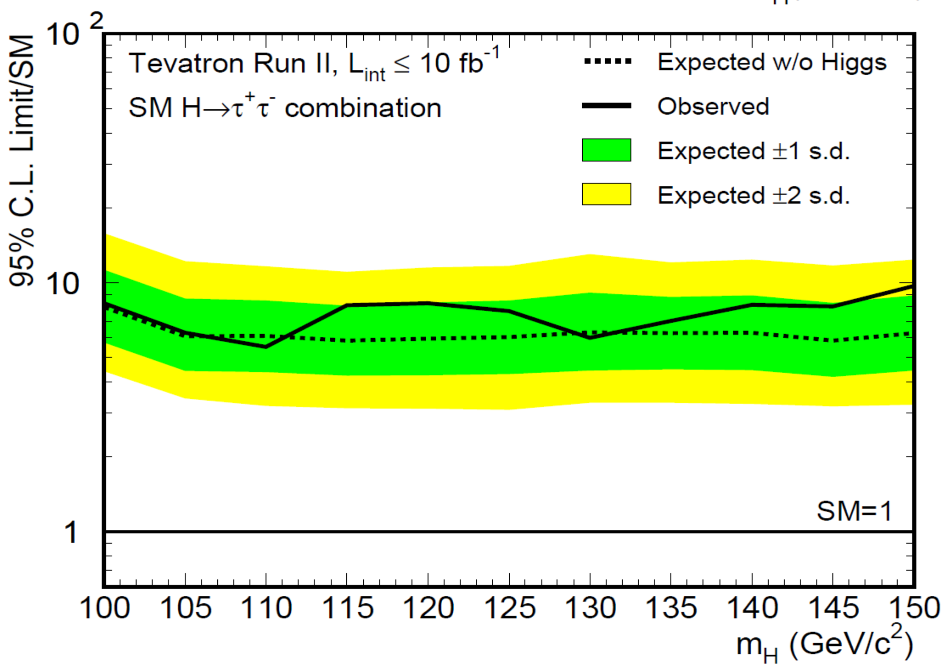


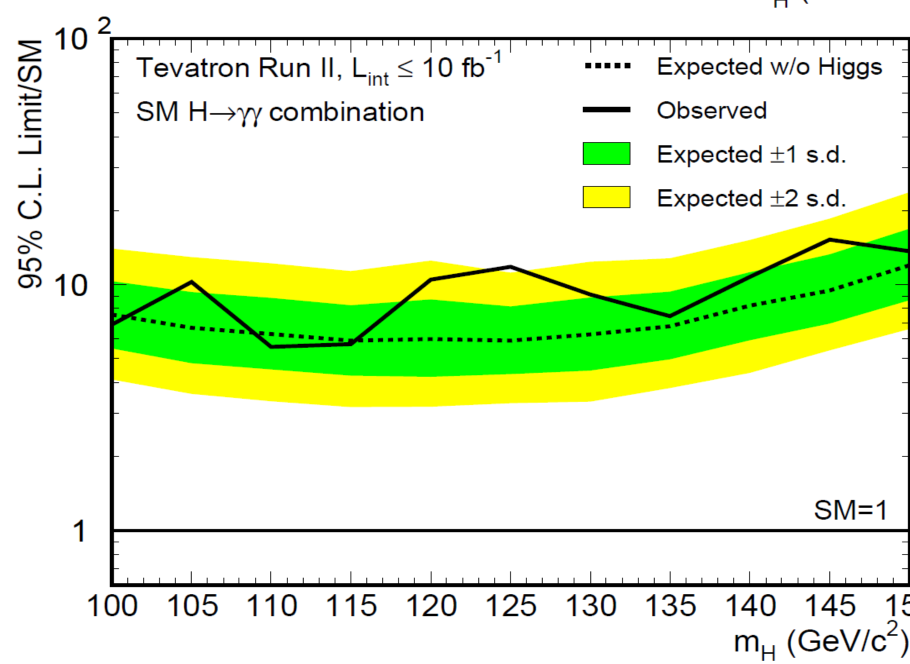


Tevatron Sub-combinations



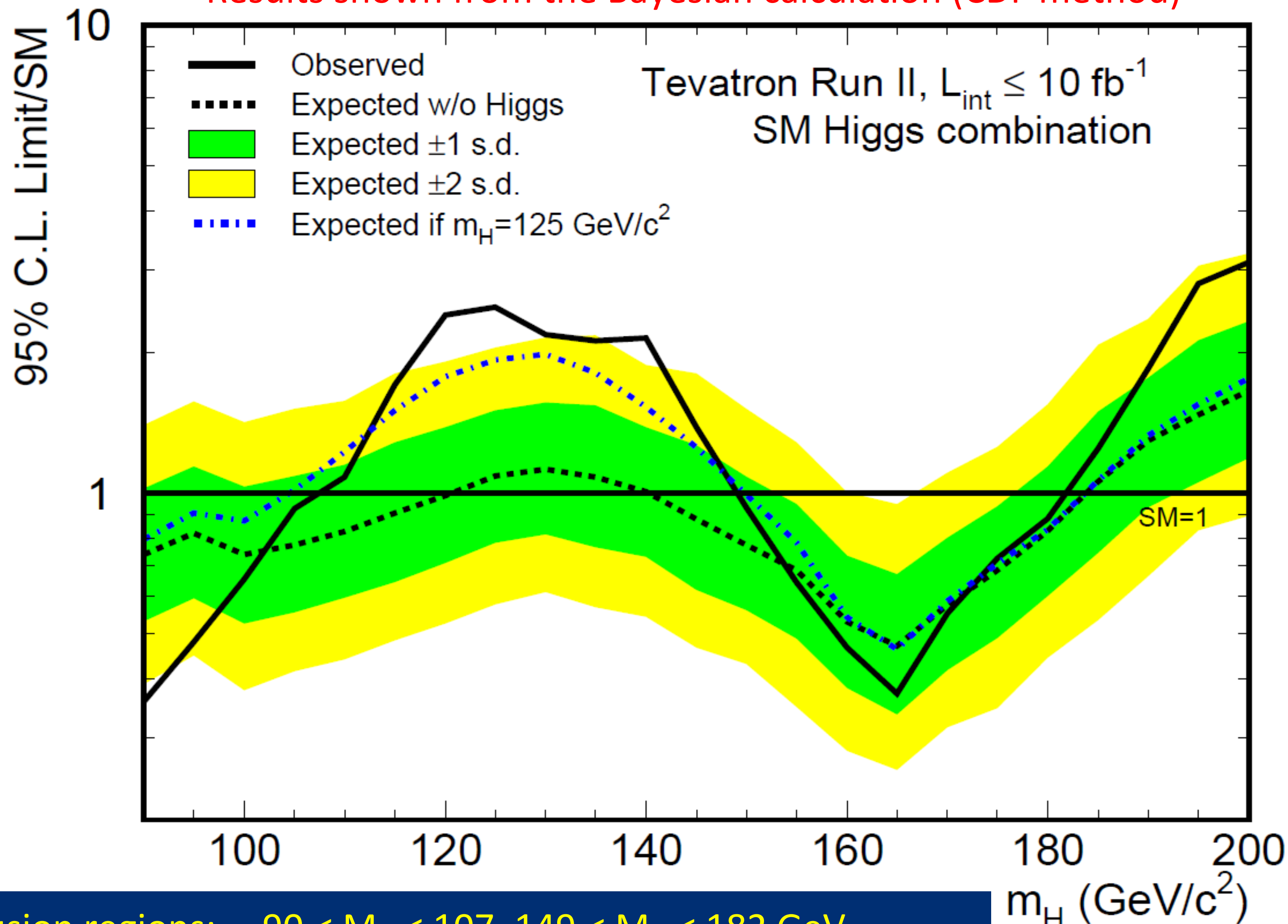






Tevatron Limits

Results shown from the Bayesian calculation (CDF method)



Exclusion regions: 90 < M_H < 107, 149 < M_H < 182 GeV
Expected exclusion: 90 < M_H < 121, 140 < M_H < 184 GeV

Tevatron Cross Section Posteriors

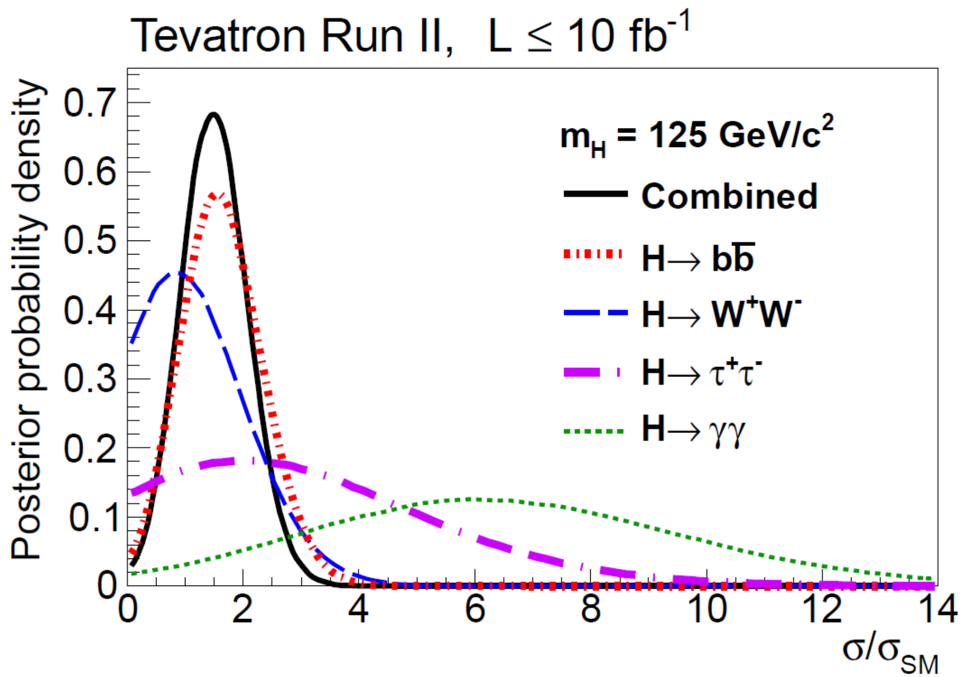


TABLE VII: Measurements of the best-fit values of $R = \sigma \times \mathcal{B}/\mathrm{SM}$ using the Bayesian method, for the combined SM, $H \to W^+W^-$, $H \to b\bar{b}$, $H \to \gamma\gamma$, and $H \to \tau^+\tau^-$ searches, for 115 GeV/$c^2 \le m_H \le$ 140 GeV/c^2. The quoted uncertainties bound the smallest interval containing 68% of the integral of the posterior probability densities.

	115	120	125	130	135	140
$R_{\rm fit}(\mathrm{SM})$	$0.87^{+0.48}_{-0.45}$	$1.46^{+0.55}_{-0.51}$	$1.48^{+0.58}_{-0.60}$	$1.12^{+0.62}_{-0.57}$	$1.07^{+0.60}_{-0.57}$	$1.16^{+0.57}_{-0.53}$
$R_{\rm fit}(H \to W^+W^-)$	$3.29^{+2.21}_{-1.89}$	$1.87^{+1.33}_{-1.36}$	$0.85^{+0.88}_{-0.81}$	$0.33^{+0.78}_{-0.33}$	$0.51^{+0.52}_{-0.48}$	$0.92^{+0.59}_{-0.54}$
$R_{\rm fit}(H \to b\bar{b})$	$0.73^{+0.46}_{-0.46}$	$1.29^{+0.59}_{-0.56}$	$1.56^{+0.72}_{-0.73}$	$1.84^{+0.96}_{-0.88}$	$2.61^{+1.21}_{-1.25}$	$3.21^{+1.64}_{-1.64}$
$R_{\rm fit}(H \to \gamma\gamma)$	$0.10^{+3.13}_{-0.10}$	$5.03^{+3.03}_{-2.75}$	$6.13^{+3.25}_{-3.19}$	$3.05^{+2.76}_{-2.72}$	$0.00^{+4.10}_{-0.00}$	$2.89^{+3.38}_{-2.89}$
$R_{\rm fit}(H \to \tau^+\tau^-)$	$2.61^{+2.39}_{-2.26}$	$2.86^{+2.57}_{-2.08}$	$2.12^{+2.25}_{-2.12}$	$0^{+3.16}_{-0}$	$0.95^{+2.86}_{-0.95}$	$2.46^{+2.40}_{-2.13}$

From T. Junk:

Coupling Determination: Production Cross Sections

Scalings for:

WH: $R^2 C_V^2$
ZH: C_V^2
VBF: $C_V^2(0.79R^2 + 0.21)$ -- Coefficients gotten from the HAWK program, turning on and off the W and Z contributions at Born level These do not interfere as the initial and final states are different for W and Z exchange.

ggH: $(0.95C_f^2+0.05C_V C_f)$ -- Coefficients from the mixture of 2-loop light-quark EW contribution – interferes constructively with the triangle diagram. These 2-loop contributions are not included in VBF, even our NNLO calculations.

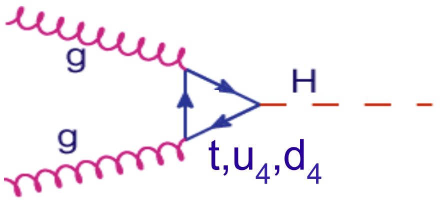
What's the right R dependence here?

ttH: C_f^2

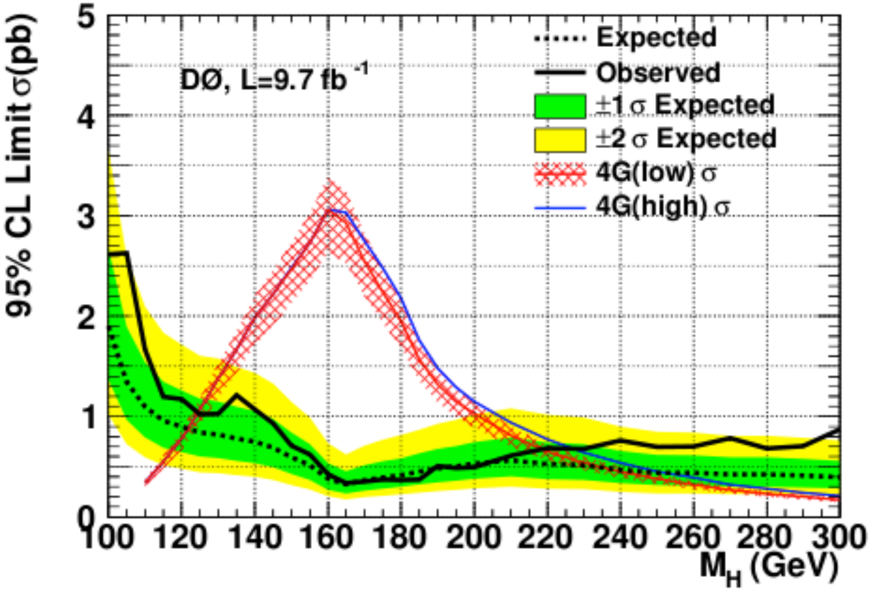
All signal predictions: Scale by the production and decay scalings

Higgs searches in 4th generation models

- New heavy generation of quarks
  - ggH coupling is multiplied by 3 compared to SM
  - Production is enhanced by 9
- OS dilepton, lνjj(jj) searches can be recycled
  - For these channels in SM gg → H is the dominant SM signal
  - → No need for dedicated BDT training within 4th gen context
  - Extend mass range with
  - MC at 200 <M_H < 300 GeV



Today's D0 exclusion:
observed 125<m_H<218 GeV
expected 122<m_H<232 GeV

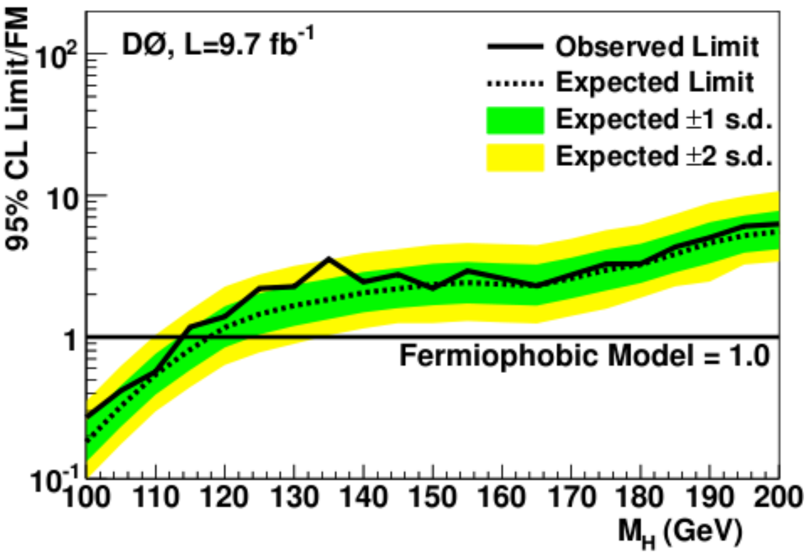


Former publication: PRD 82, 011102 (2010), DO+CDF 4.8-5.2 fb-1 :

131 < m_H<208 GeV excluded (125<m_H<227 GeV expected sensitivity)

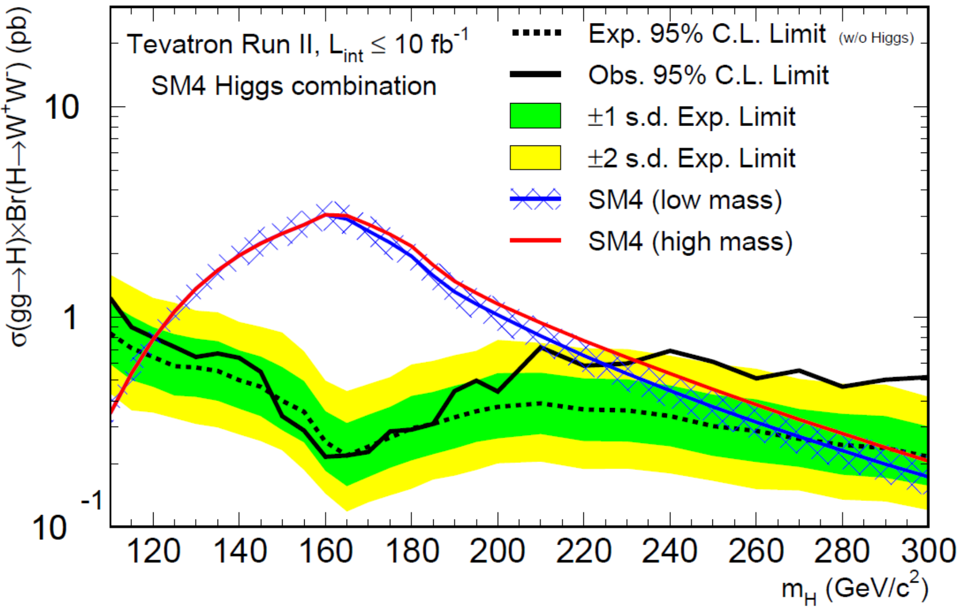
Fermiophobic Higgs searches

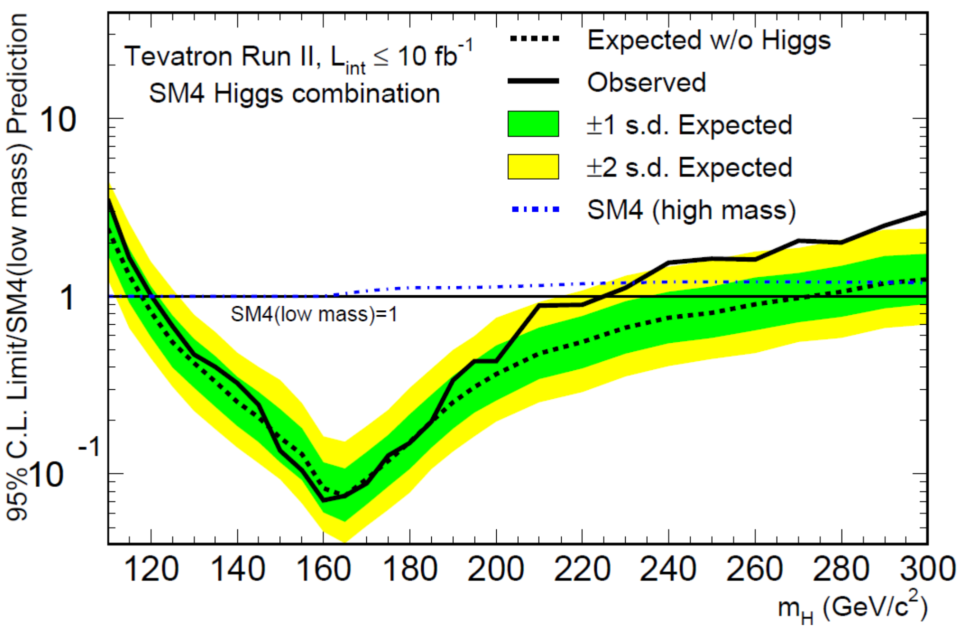
- Models where H → ff couplings do not occur
  - Also means no gg → H production
- So we consider channels with H →γγ , WW
  - H → γγ (VH and VBF)
  - OS dilepton (VH and VBF)
  - SS dilepton (VH)
  - trilepton (VH)
- Benefits from SM search refinements
  - Employ same subchannels and BDT techniques
  - Retrain BDTs in channels where gg → H provides dominant signal in SM
    - OS dilepton, H → γγ

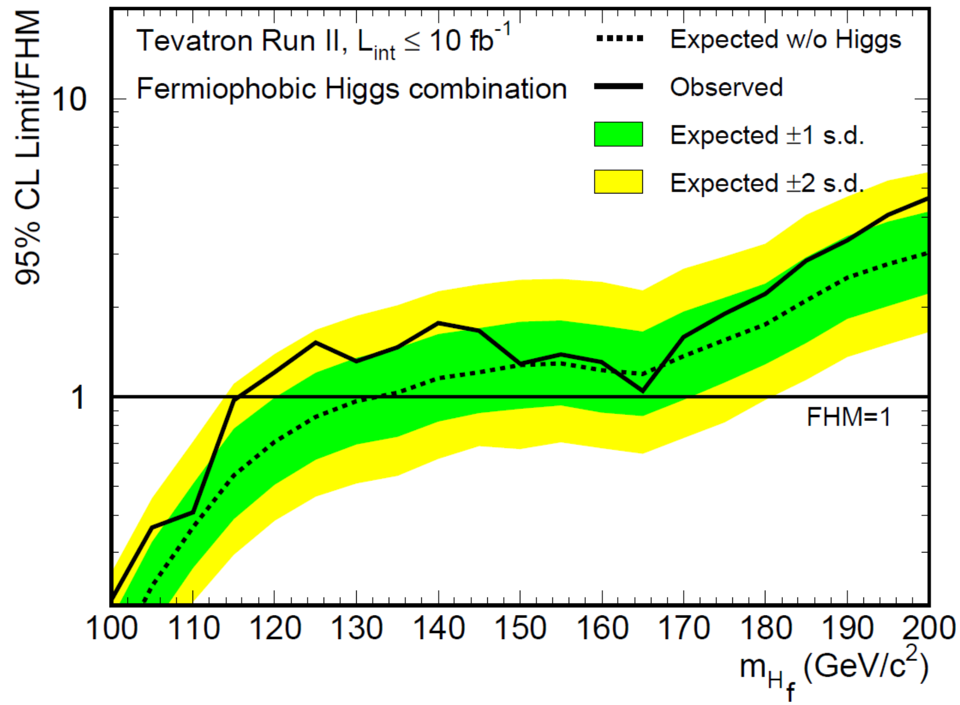


exclusion @95%CL
observed m_H<114 GeV
expected m_H<117 GeV

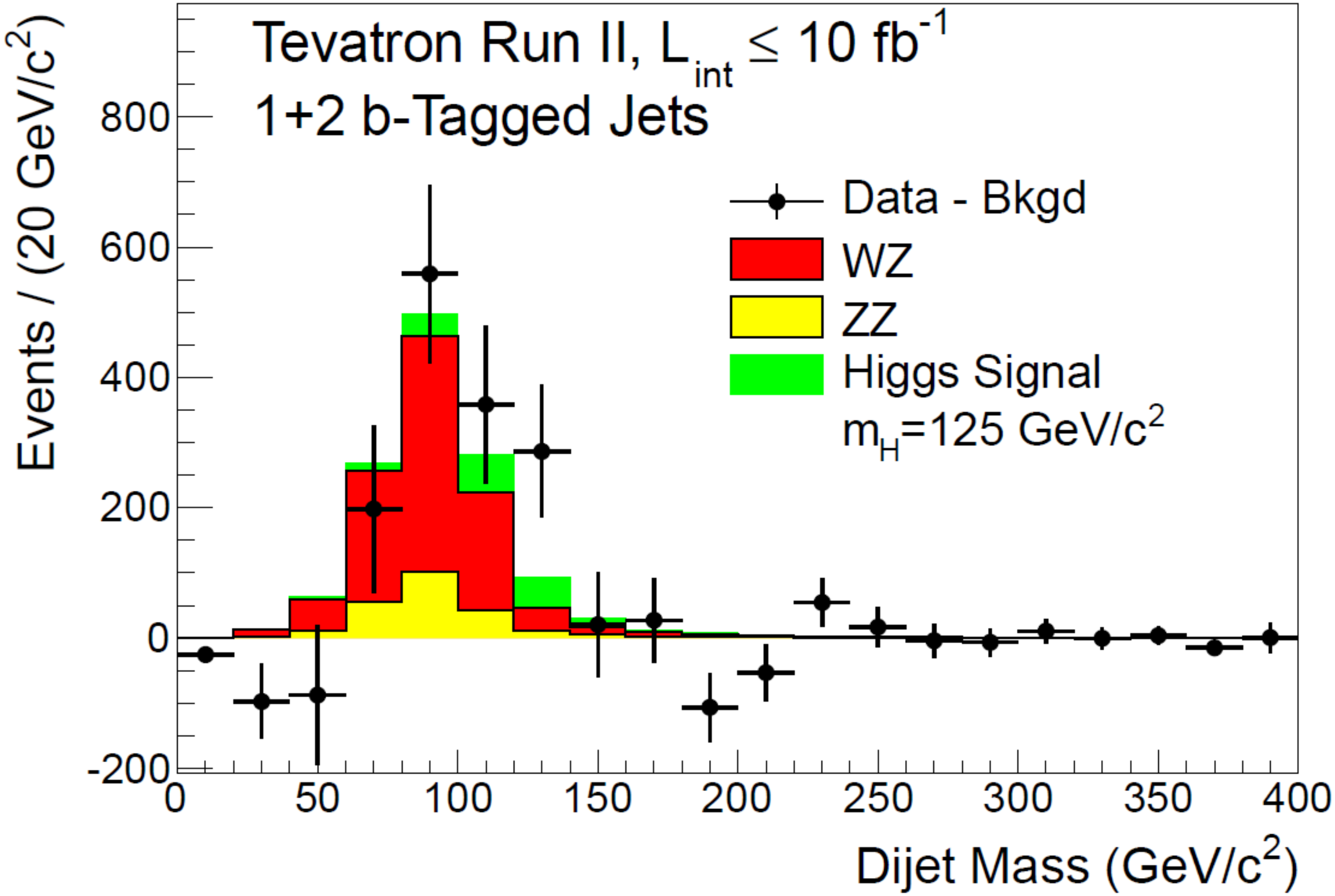
Tevatron BSM Results





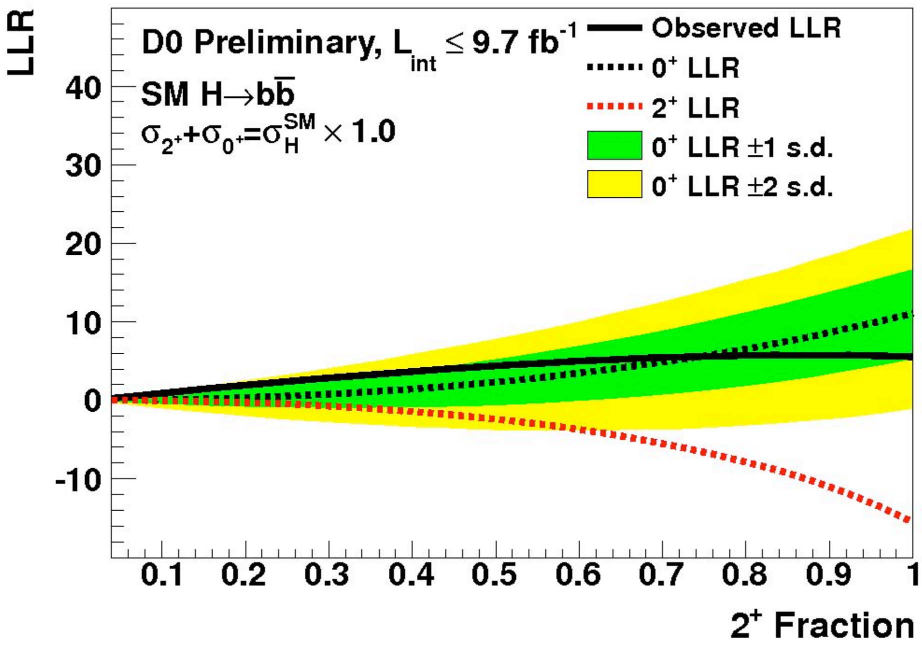


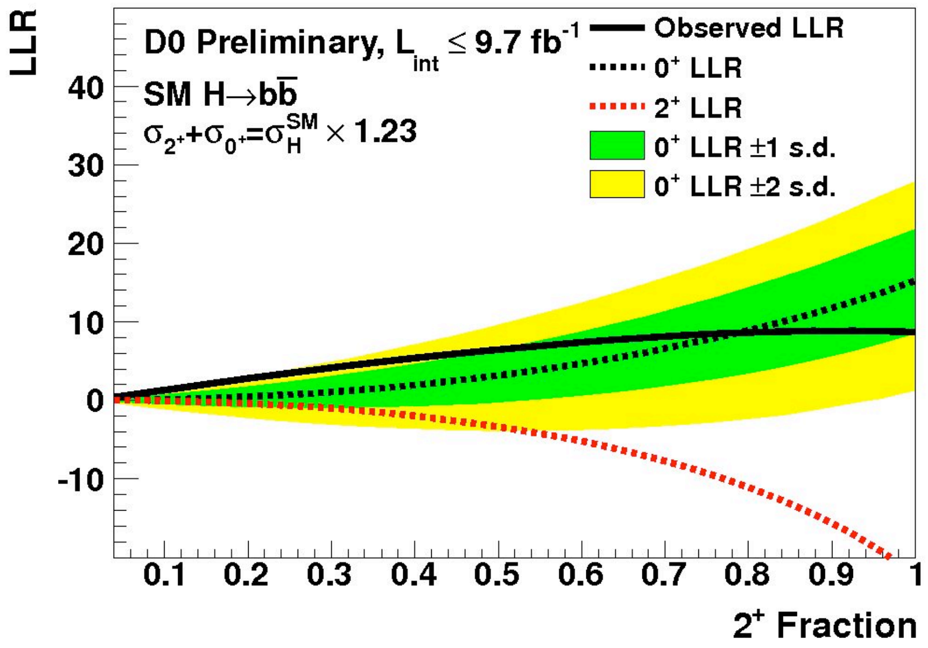
bb Diboson Combination



Measured value: 3.0 +/- 0.6 (stat.) +/- 0.7 (syst.) pb
SM Value : 4.4 +/- 0.3 pb

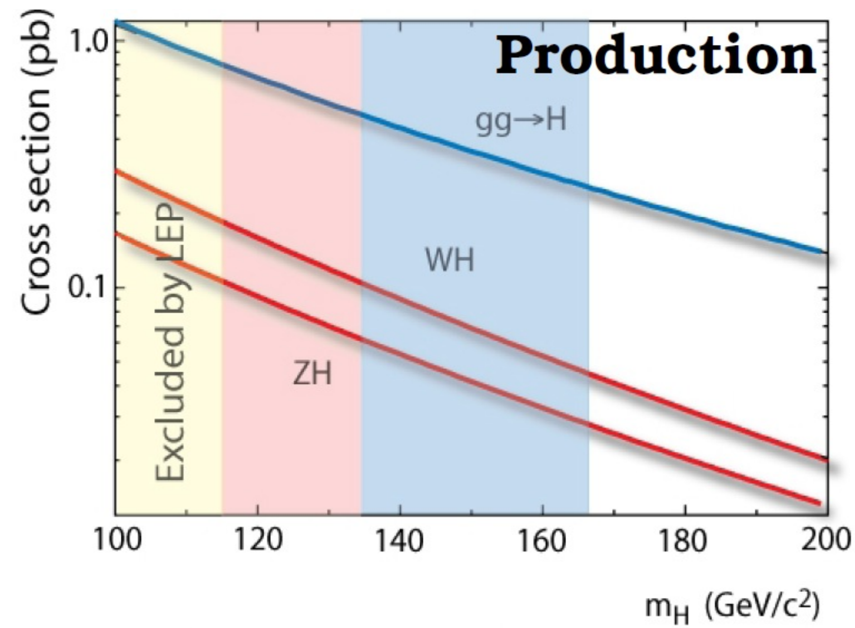
LLR vs. 2+ Fraction

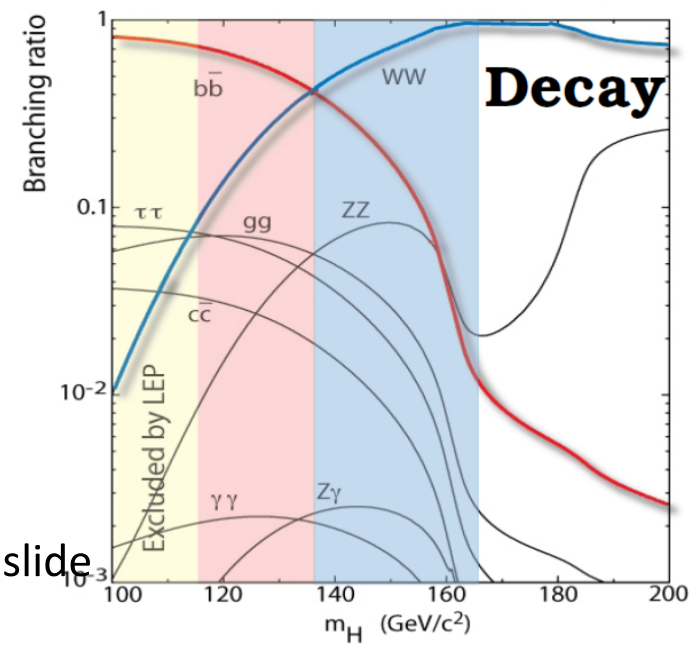




Suite of Higgs Analyses

- Traditionally analyses divided into "Low-mass" and "High-mass"
- Low-mass: associated production $VH \to Vb\bar{b}$
- High-mass: H→WW decays (mostly gg prod.; also VH, VBF)
- Also contributions in secondary (tau, γγ) channels

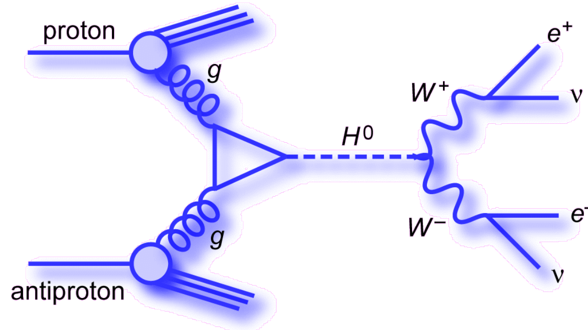


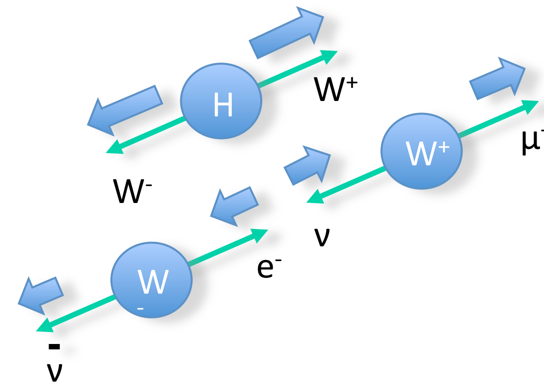


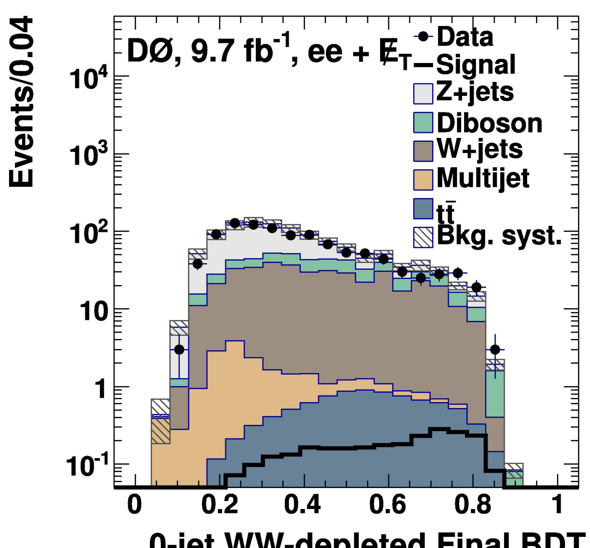
more work to do on this slide

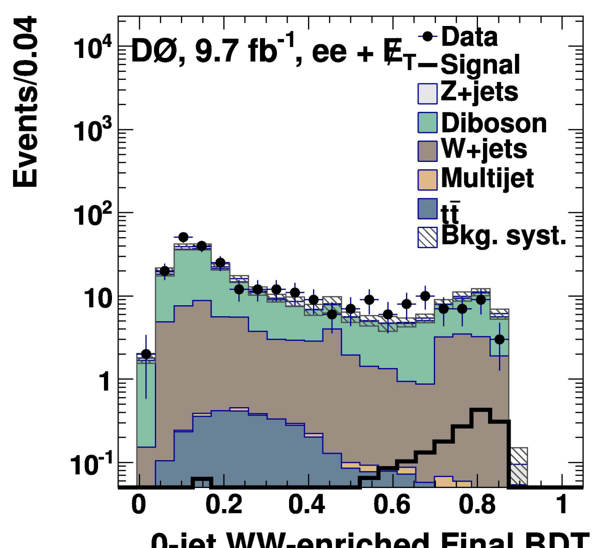
H->WW Analyses

- Signatures:
  - Two isolated high p_T leptons, large $\not{E}_T$, small $\Delta\phi(ll)$, small $\Delta R(ll)$
- Use multiple MVAs to reject different backgrounds
  - Reduce Z(+jets) → ll w/ dedicated BDT
  - Use dedicated MVA to separate samples into WW enriched and WW depleted regions









Comparison of Tev and LHC Methods

- Signal scaling
  - Tevatron: signals fixed in both hypotheses
    - 2+ normalization does vary when setting 95% C.L. upper limits
    - Exclude $\mu > 0.73$ at 95% C.L. in this case
  - LHC: signals fixed to best fit values in each hypothesis (need not be equal)
- Systematic uncertainties
  - Tevatron varies systs. in pseudoexperiments
  - LHC does not vary systs. in PEs