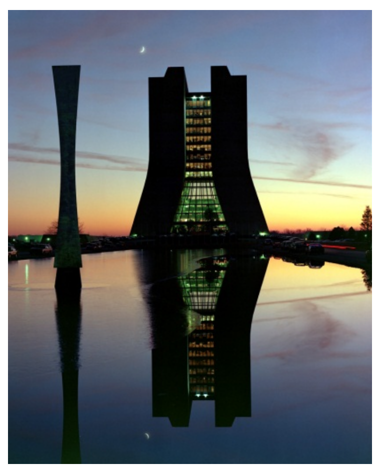
Imperial College London

Higgs Boson Studies at the Tevatron

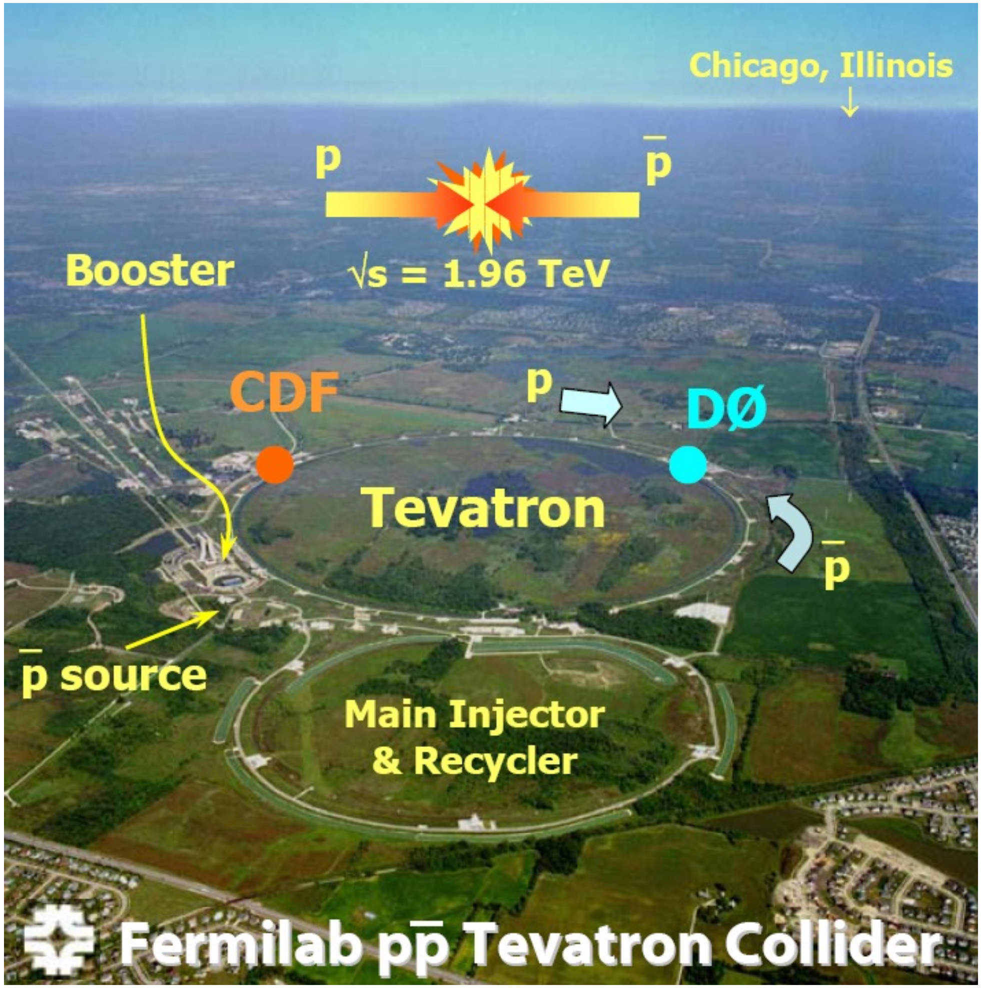
Gavin Davies

On behalf of the CDF and DØ Collaborations



Outline

- Introduction
  - Context
  - Higgs searches @ Tevatron
- SM Higgs results
  - Overall
  - Couplings
  - Spin
- Conclusions



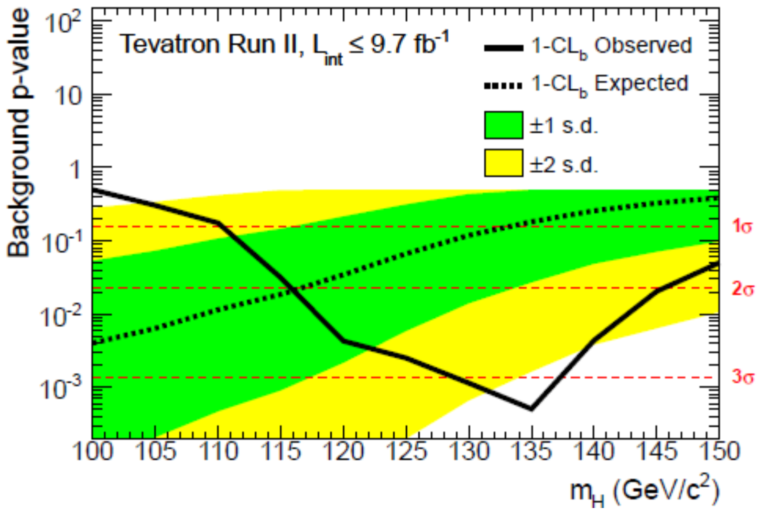
Reminder: Tevatron stopped in fall 2011

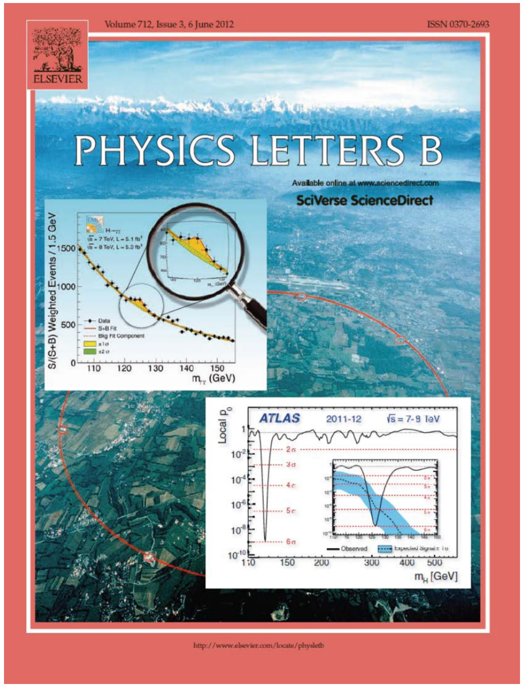
~ 10fb^{-1} per experiment after data quality

Context

- July 12
  - New boson discovered at LHC using bosonic decay modes
  - Evidence for H→bb decay from Tevatron

Phys. Rev. Lett. 109, 071804 (2012)

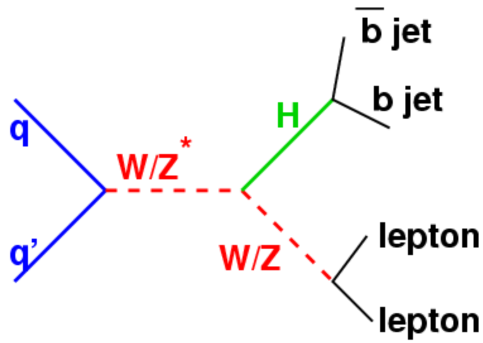


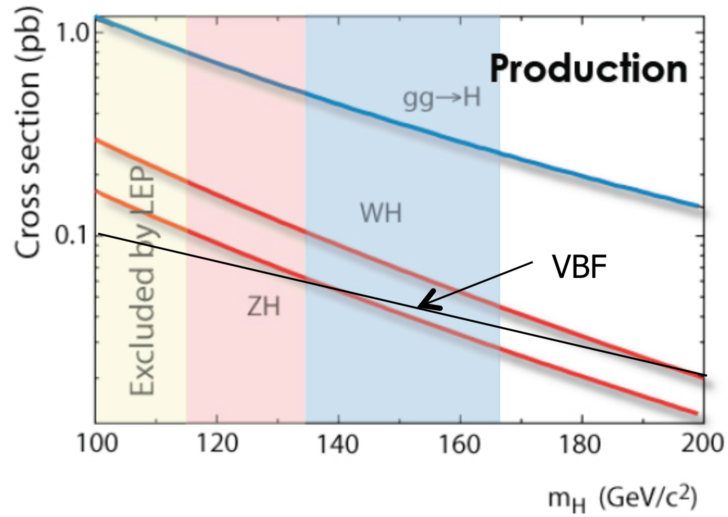


- Since
  - Focus on studying the new boson
  - Tevatron: Complementary as exploiting primarily fermionic (H→bb) decays

- ‘Low’ mass m_H < 135 GeV
  - Dominated by:

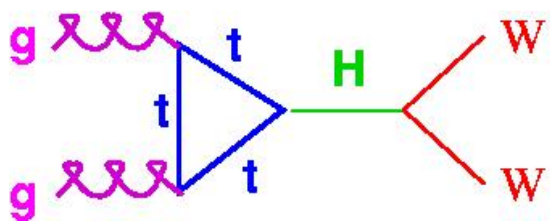
$$q\bar{q}' \rightarrow WH \rightarrow \ell \nu b\bar{b}$$
$$q\bar{q} \rightarrow ZH \rightarrow \ell\ell b\bar{b}$$
$$q\bar{q} \rightarrow ZH \rightarrow \nu\bar{\nu} b\bar{b}$$

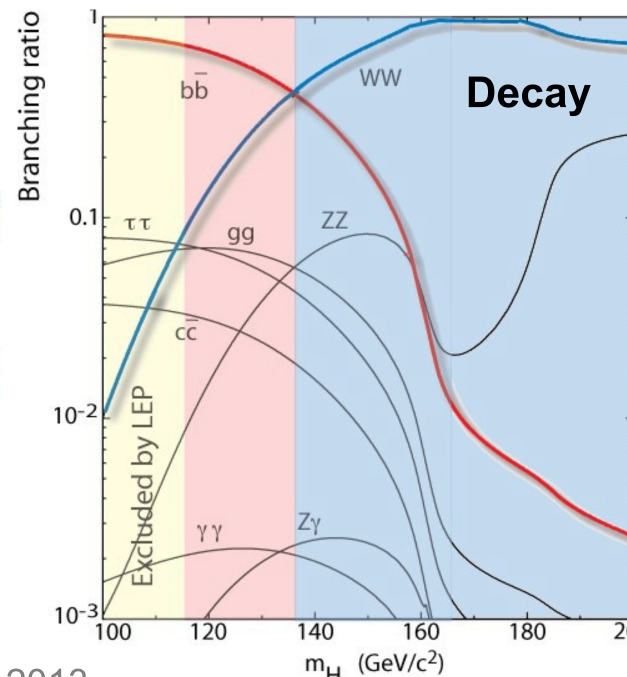




- ‘High’ mass m_H > 135 GeV
  - Dominated by:

$$gg \rightarrow H \rightarrow WW^{(*)} \rightarrow \ell \nu \ell' \nu'$$

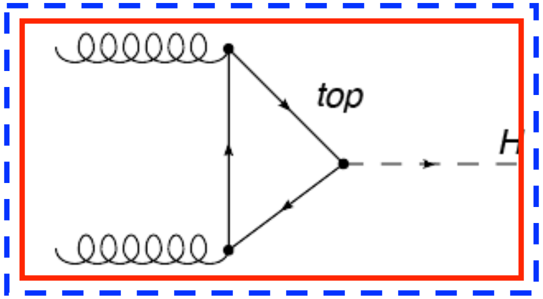


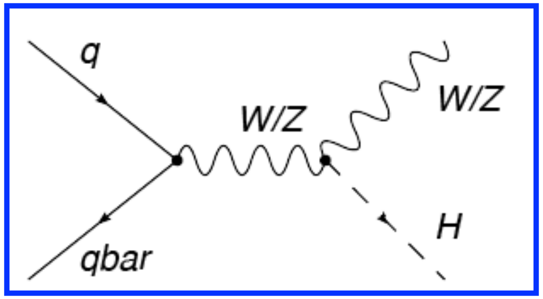


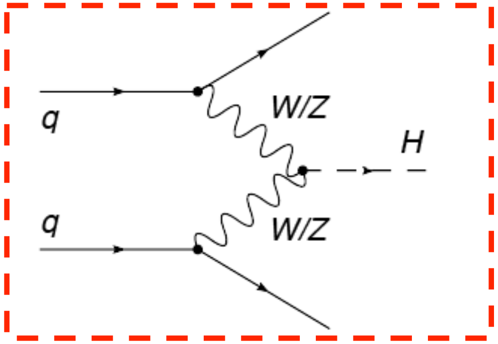
- Less sensitive channels add overall sensitivity

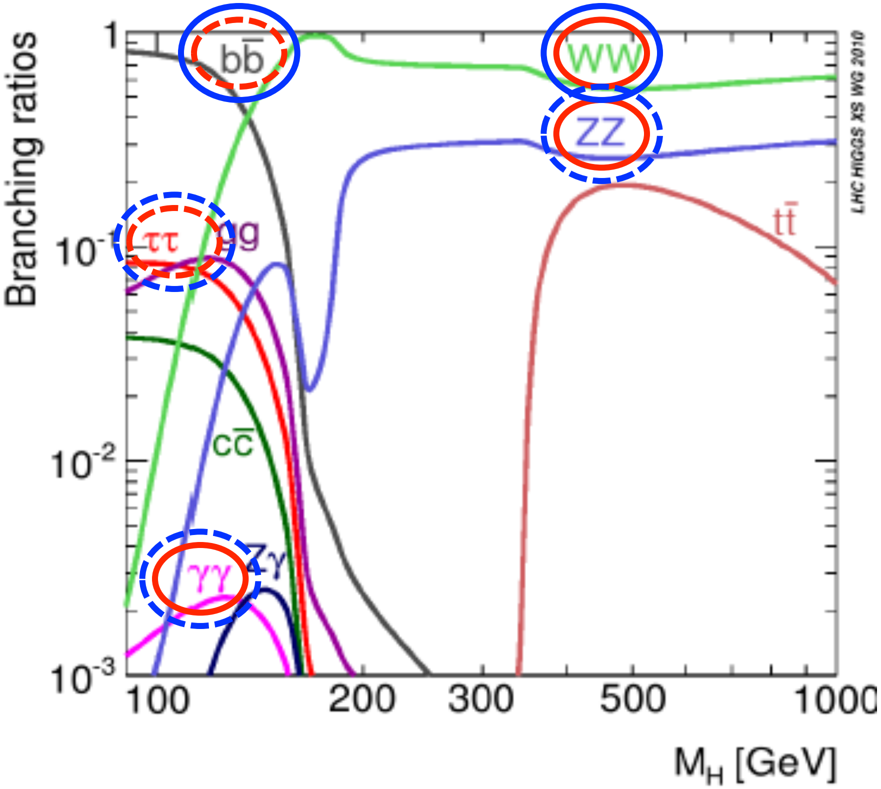
Tevatron -LHC complementarity

@ m_H= 125 GeV





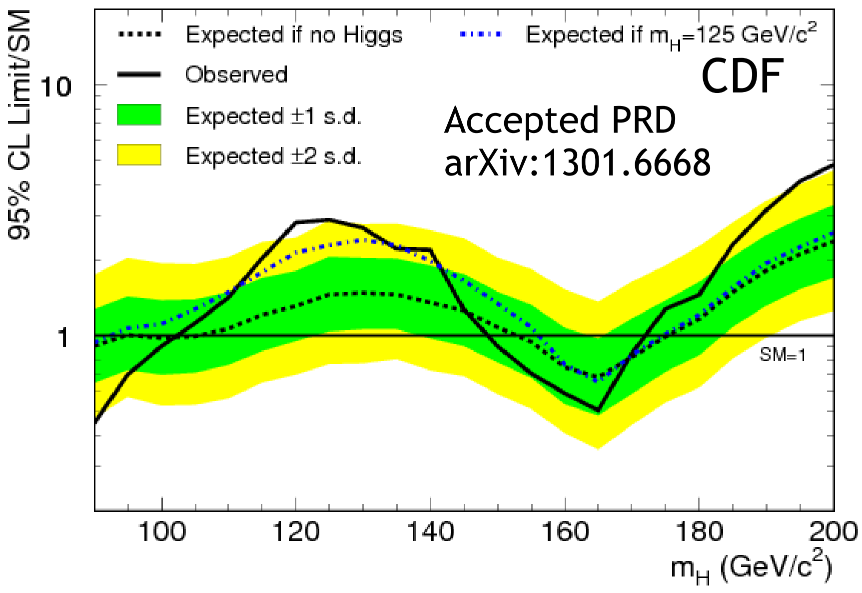


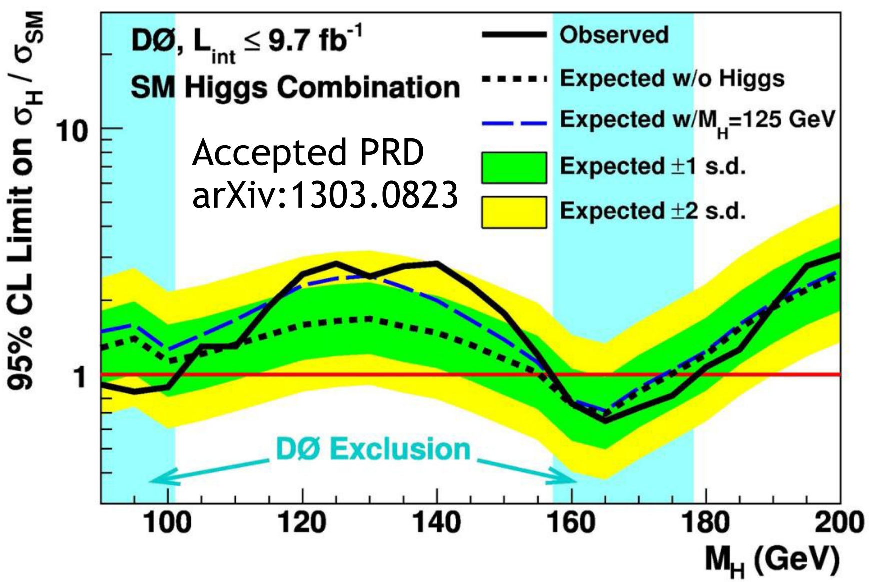


LHC — Main mode

Tevatron - - - - Supporting mode

Individual experiment results





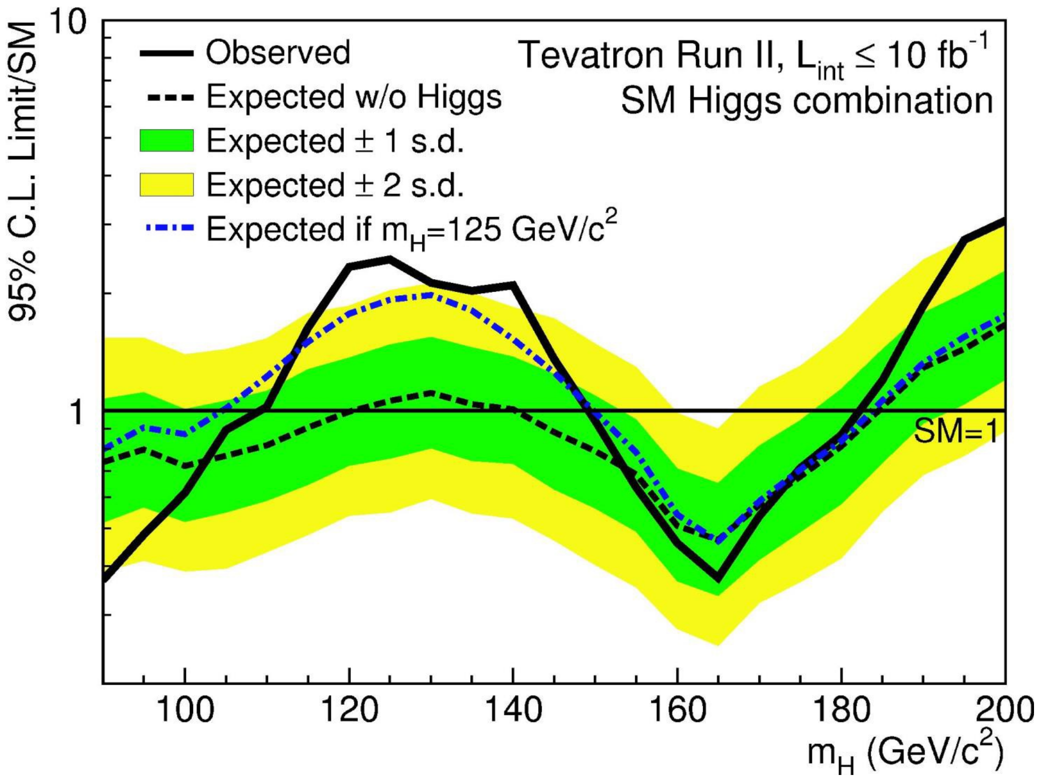
At m_H = 125 GeV
Exp. limit: 1.5 x σ(SM)
Obs. limit: 2.9 x σ(SM)

95% CL Exclusion
90 < m_H < 102 GeV
149 < m_H < 172 GeV

At m_H = 125 GeV
Exp. limit: 1.7 x σ(SM)
Obs. limit: 2.9 x σ(SM)

95% CL Exclusion
90 < m_H < 101 GeV
157 < m_H < 178 GeV

Tevatron combination



Accepted PRD
arXiv:1303.6346

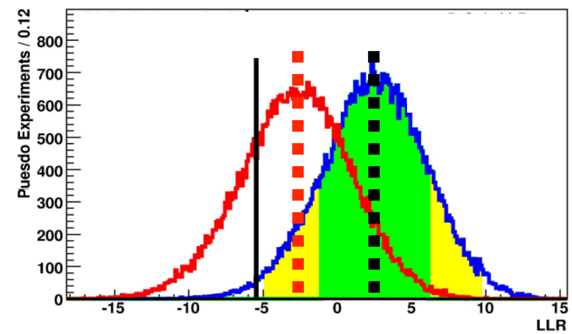
Observed exclusion: $90 < m_H < 109$ GeV, $149 < m_H < 182$ GeV

Expected exclusion: $90 < m_H < 120$ GeV, $140 < m_H < 184$ GeV

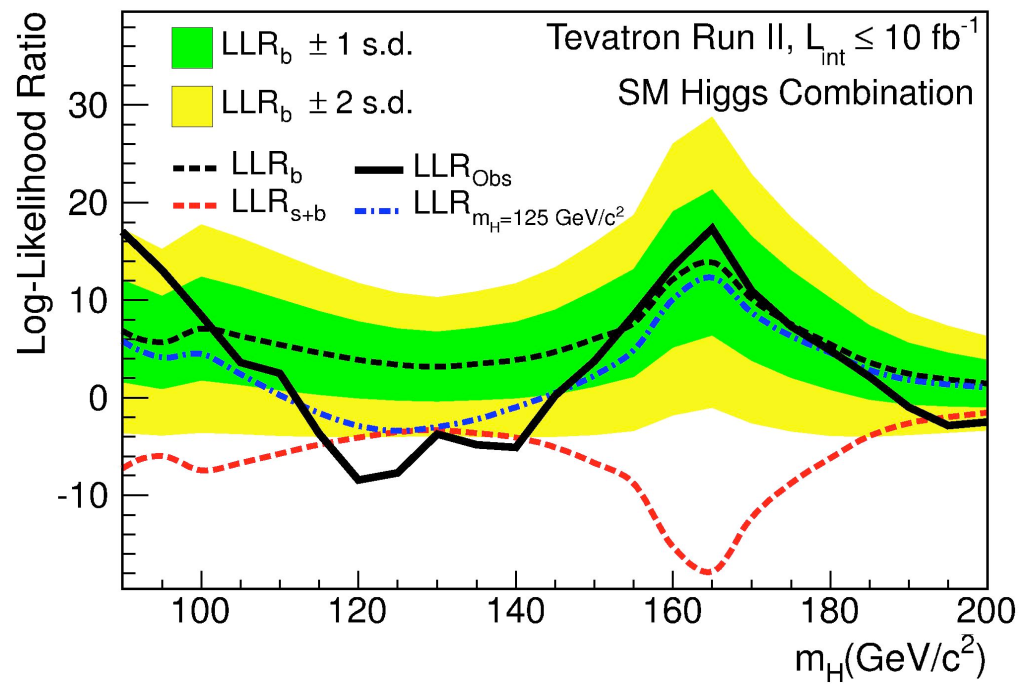
95% CL limit @ m_H = 125 GeV: 1.06 x σ(SM) expected, 2.44 x σ(SM) observed

Quantifying the excess: LLR

- Log-likelihood ratio (LLR)
  - Relative agreement of B-only and S+B hypotheses
  - Throw pseudo-data to populate B-only and S+B models
    - Compare to observed
  - Expected S+B shows good sensitivity up to ~185 GeV
  - ~3σ excess at 120-125 GeV
    - Consistent with SM Higgs

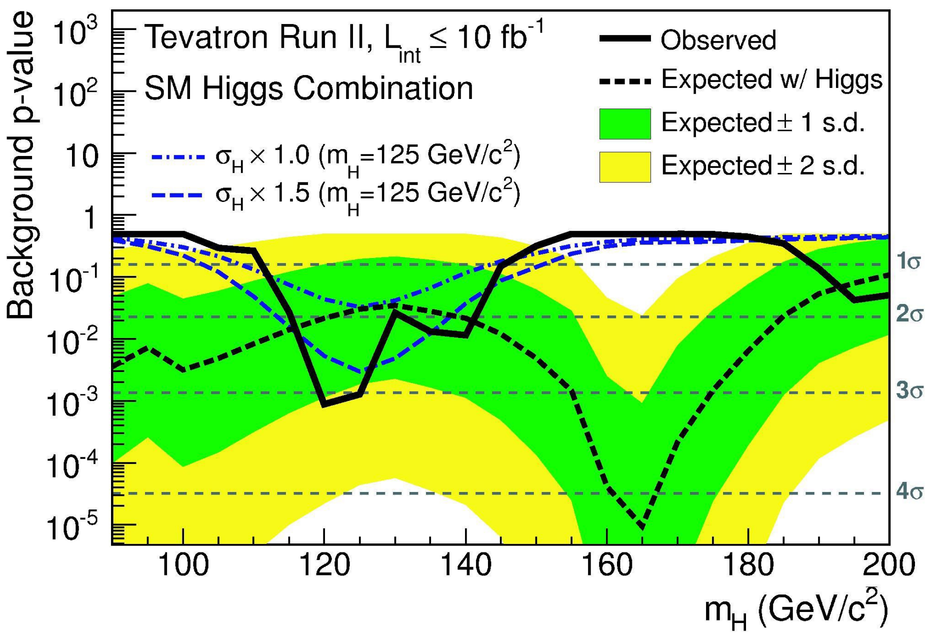


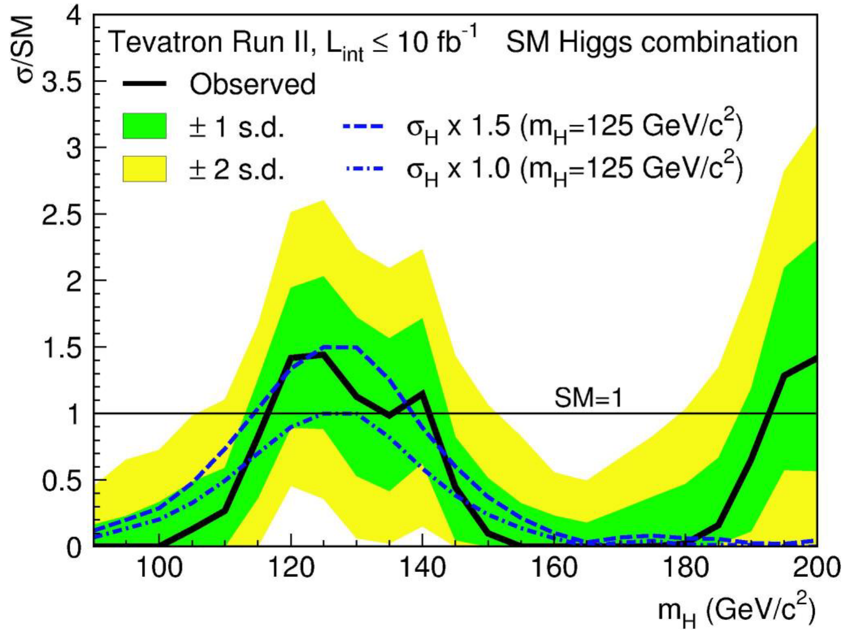
Accepted PRD arXiv:1303.6346



Quantifying the excess

Accepted PRD arXiv:1303.6346

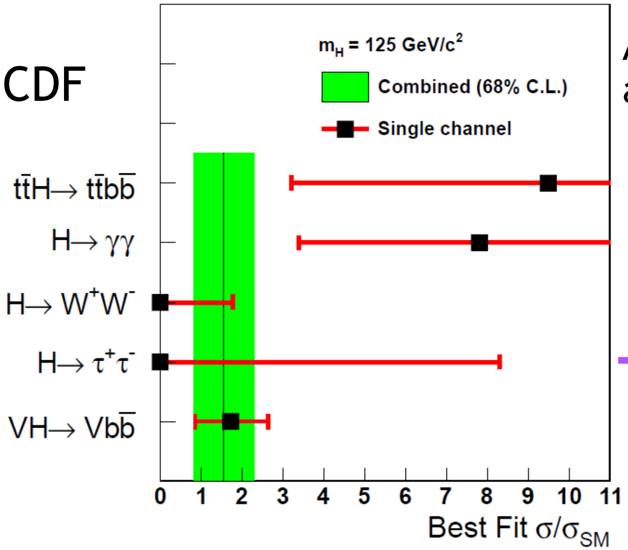




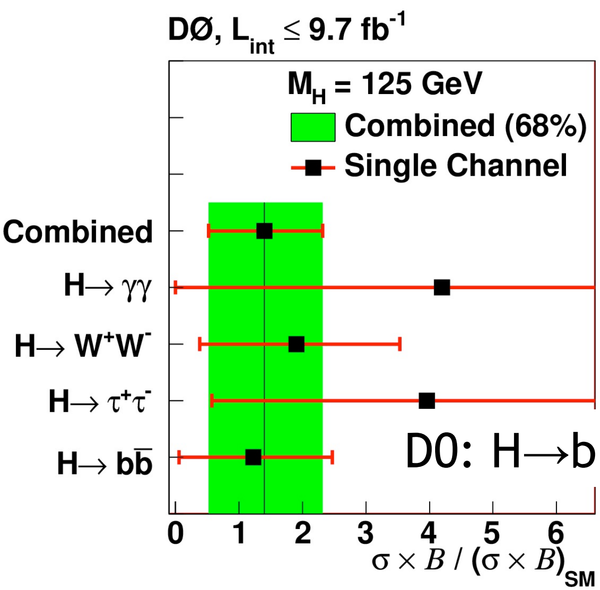
- Compatibility with B-only prediction (left)
  - Minimum local p-value at m_H = 120 GeV: 3.1σ (2.0σ expected)
    p-value at m_H = 125 GeV: 3.0σ (1.9σ expected)
- Compatibility with S+B prediction (right)
  - Maximum likelihood fit with Higgs cross section as a free parameter
    - $\mu = \sigma/\sigma_{SM} = 1.4 \pm 0.6$ @ 125 GeV

Tevatron cross section fits

CDF



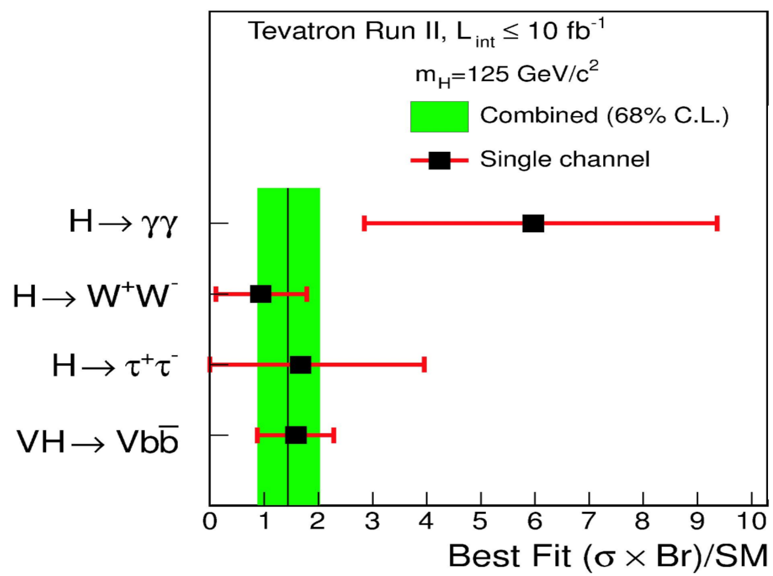
Accepted PRD
arXiv:1301.6668



Accepted PRD
arXiv:1303.0823

D0: H→bb: μ=1.23

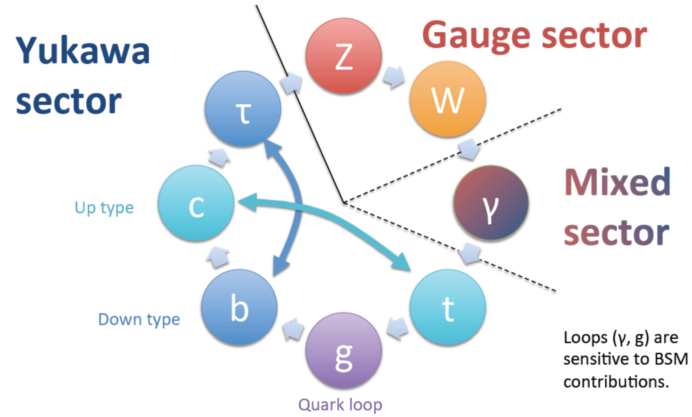
Accepted PRD arXiv:1303.6346



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

Couplings

- Measure deviations of couplings from SM prediction using LHCHXSWG framework (arXiv:1209:0040)



$$\sigma \cdot BR(ii \rightarrow H \rightarrow ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

- Assume all signals near 126 GeV from single resonance of zero width, with SM-like coupling structure
- Additionally: no additional invisible or undetected Higgs decay modes
- e.g.

$$\sigma(WH) \cdot BR(H \rightarrow bb) = \sigma(WH)_{SM} \cdot BR(H \rightarrow bb)_{SM} \frac{\kappa_W^2 \cdot \kappa_b^2}{\kappa_H^2}$$

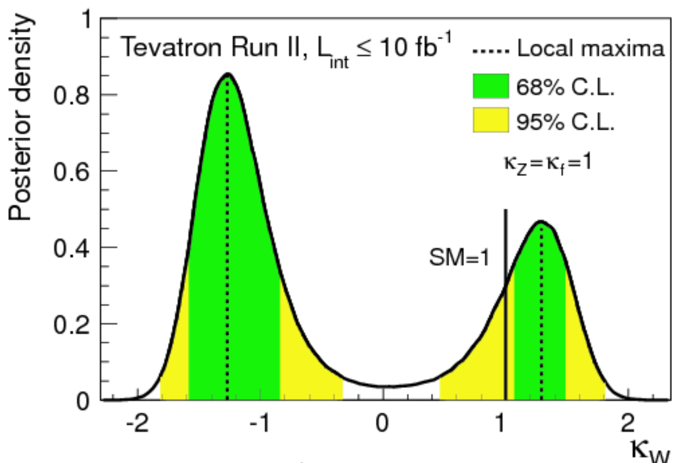
$$\kappa_\gamma = 1.28\kappa_W - 0.28\kappa_f$$

- Study fermion coupling, κ_f and boson couplings κ_W, κ_Z and κ_V

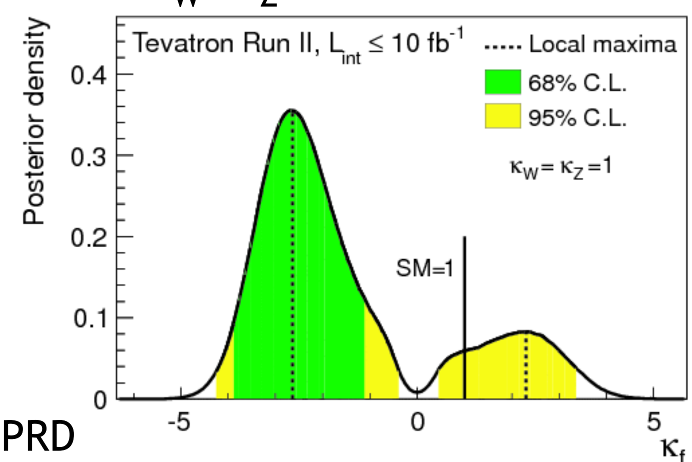
Couplings

- 1D fits: Vary each of κ_W, κ_Z and κ_f independently in turn

$\kappa_Z=\kappa_f=1$



$\kappa_W=\kappa_Z=1$



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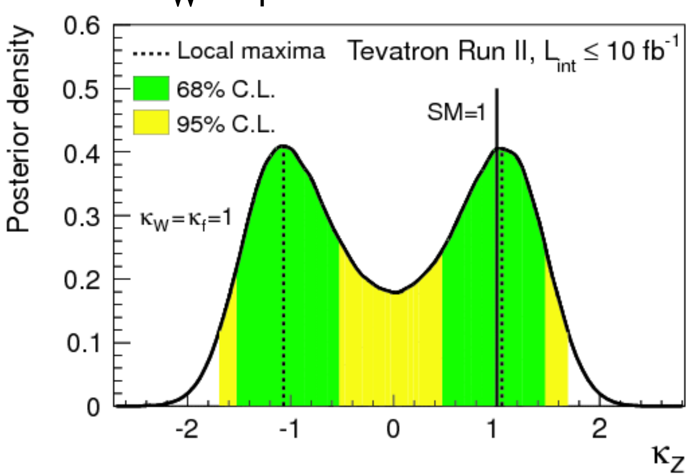
$\kappa_W=\kappa_f=1$



$$k_z = \pm(1.05^{+0.45}_{-0.55})$$

$$k_f = -2.64^{+1.59}_{-1.30}$$

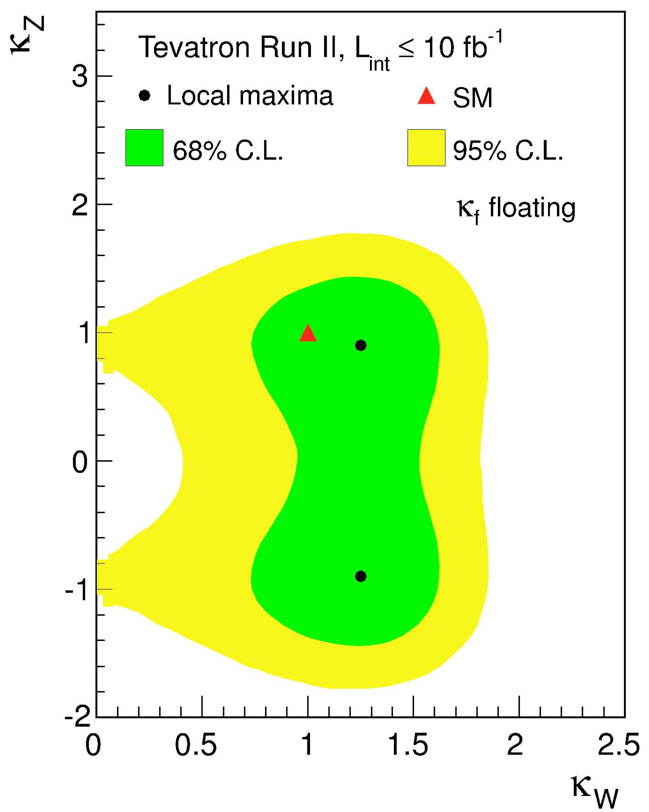
$$k_w = -1.27^{+0.46}_{-0.29} \text{ or } 1.04 < k_w < 1.51$$

Negative values for κ_W and κ_f preferred due to $H\rightarrow\gamma\gamma$ excess

Couplings

- Probe custodial symmetry ie $\lambda_{WZ} = \kappa_W/\kappa_Z \approx 1$(SM)
  - Scale all fermion couplings by a common factor κ_f
  - Measure κ_W and κ_Z independently

Accepted PRD
arXiv:1303.6346

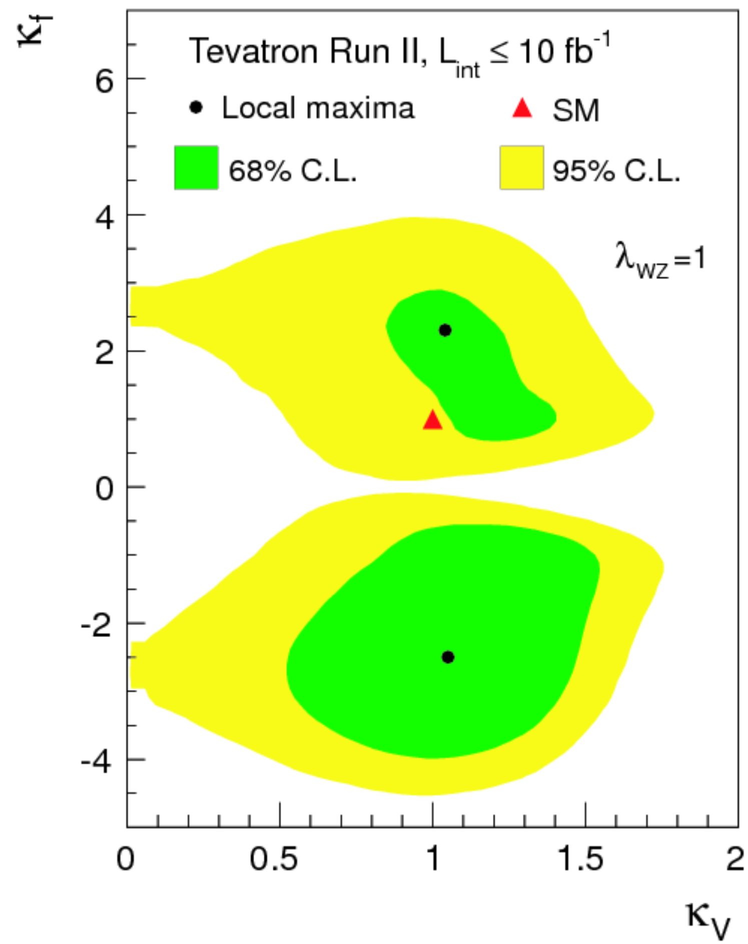


$$Extract : \lambda_{wz} = 1.24^{+2.34}_{-0.42}$$

Couplings

- Independent common vector (κ_V) and fermion (κ_f) couplings

Assume λ_{WZ} = 1



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arXiv:1303.6346

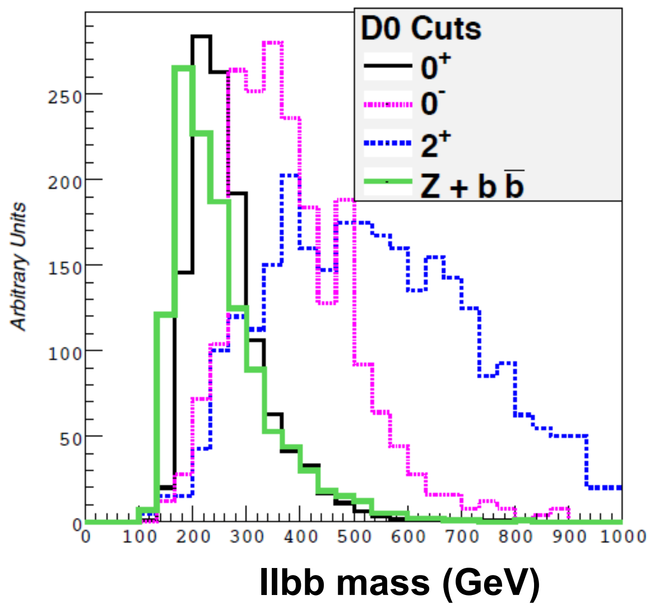
– Again consistent with SM

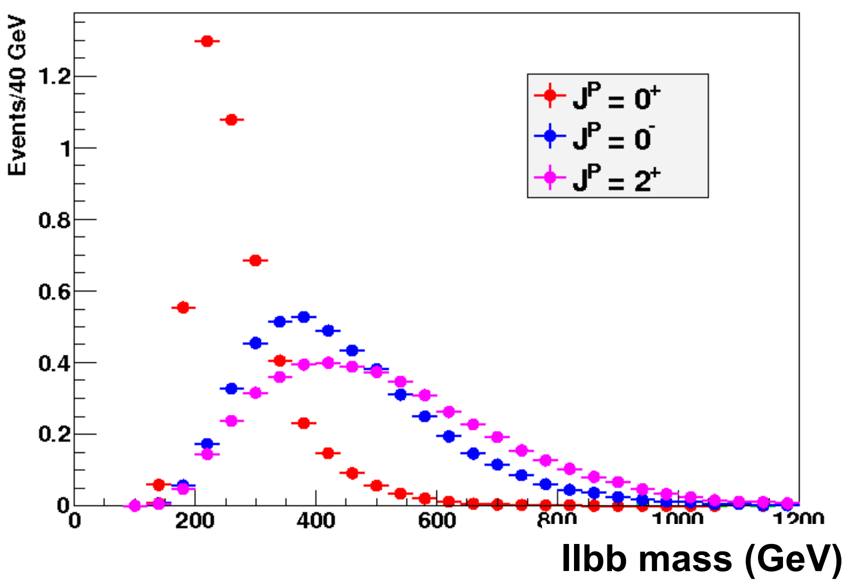
Spin

- SM predicts JP=0^+, but 0^- and 2^+ possible
- LHC confirms 0^+ with bosonic decay modes
- Tevatron sensitive in bb final states
  - Visible mass of Vbb system very sensitive to JP assignment

e.g. Ellis et al., JHEP **1211** 134 (2012)

DØ Note 6387-CONF

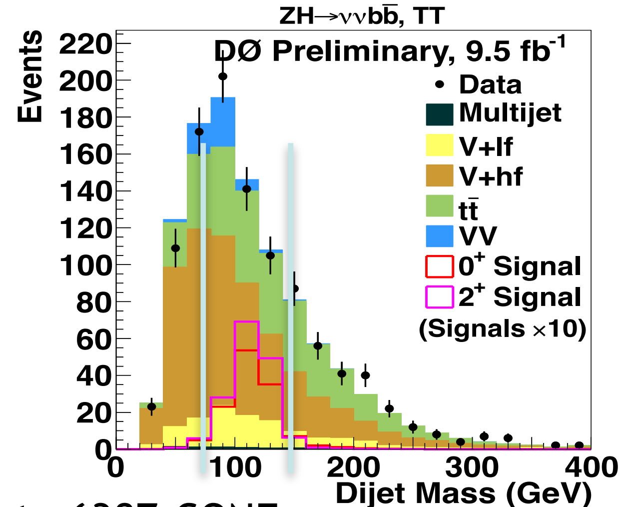




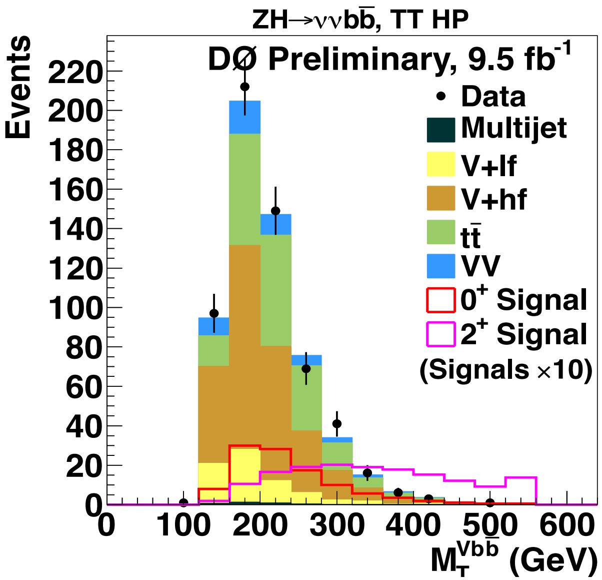
- Today: 2^+ vs 0^+ from DØ. 0^- and combination with CDF to come

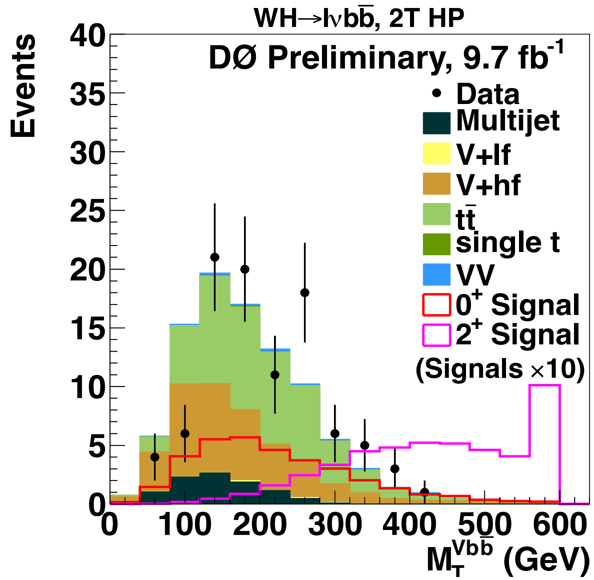
Spin

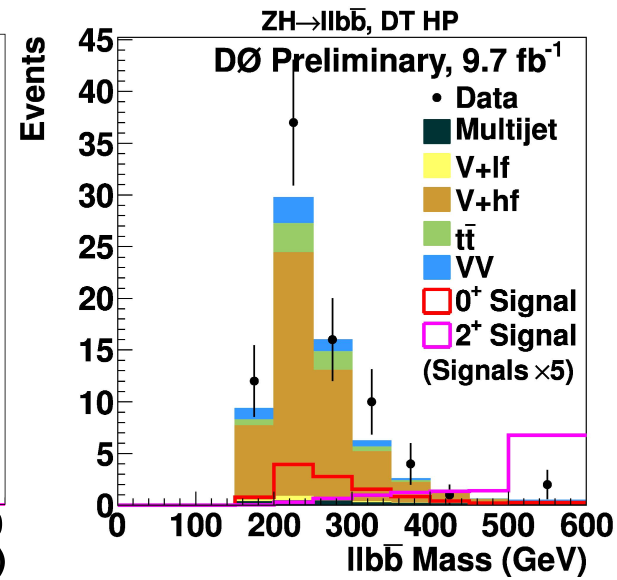
- Strategy
  - Re-use published VH → Vbb analyses
    - With same selections
  - 2^+: RS graviton model from madgraph
    - Normalised to $(\sigma \times Br)_{SM}$
  - Use dijet mass or SM MVA to improve s/b
  - Final discriminant: Visible mass



DØ Note 6387-CONF



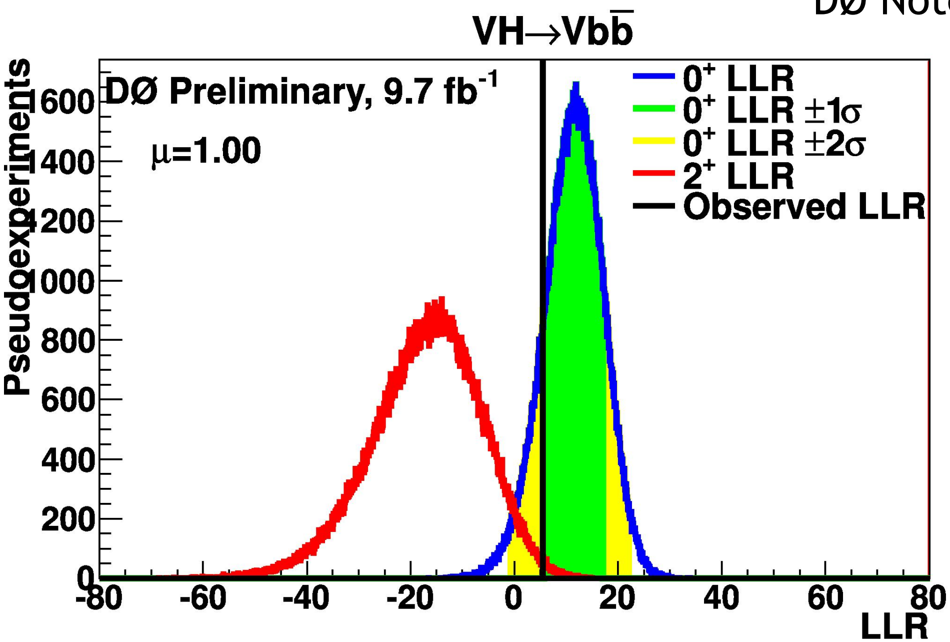


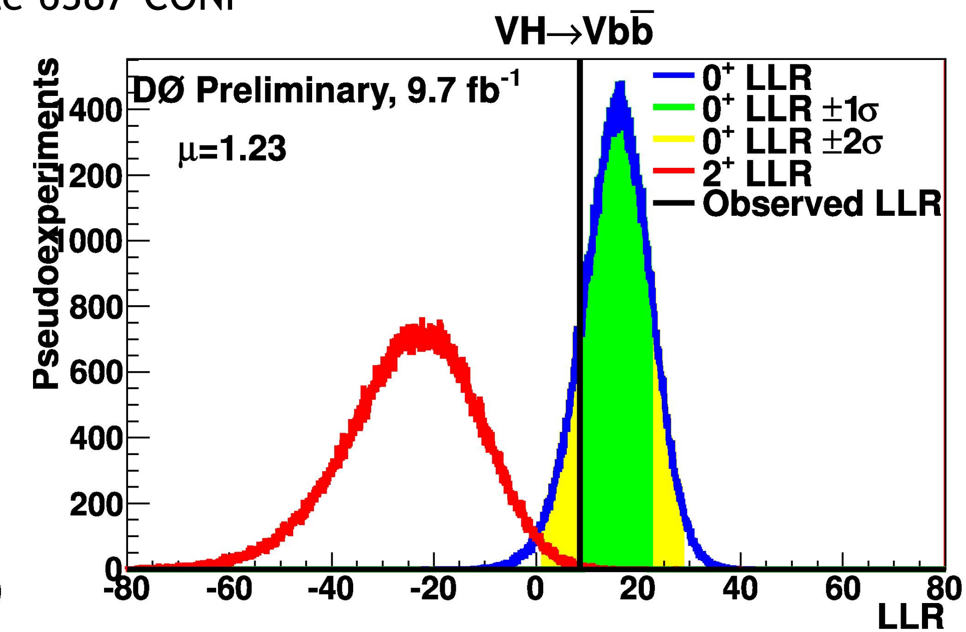


Spin

- Use CLs
  - LLR = -2log[L(H1)/L(H0)] with H1 = (2^+ + bkg) and H0 = (0^+ + bkg)
    - Compute μ x (σ x BR)$_{SM}$ for μ = 1.0 and 1.23 (DØ measured value)

DØ Note 6387-CONF





  - Clear preference for 0^+

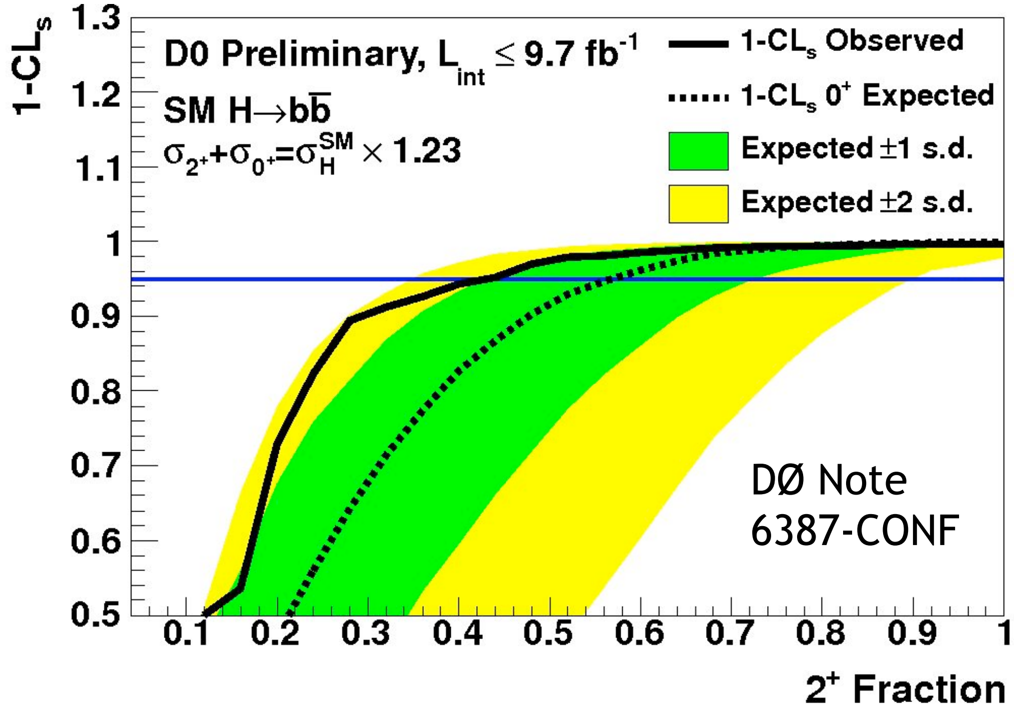
Spin

- Use CLs
  - LLR = -2log[L(H1)/L(H0)] with H1 = (2^+ + bkg) and H0 = (0^+ + bkg)
    - Compute μ x (σ x BR)$_{SM}$ for μ = 1.0 and 1.23 (DØ measured value)
  - $CL_s = CL_{H1}/CL_{H0}$
  - $CL_x = P(LLR \geq LLR_{obs}|x)$
  - 1-CL_s: Exclusion of 2^+ in favour of 0^+
  - Exclude 2^+
    - At 99.9% CL obs (μ=1.23)
    - At 99.9% CL exp (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

Spin

- Consider both 2^+ and 0^+ signal in data
  - Vary fraction, f_{2+}, of 2^+ from $0 \to 1$
  - $H1 = \mu \times (\sigma \times BR)_{SM} \times ([2^+ \times f_{2+}] + [0^+ \times (1-f_{2+})])$ + background
  - $H0 = \mu \times (\sigma \times BR)_{SM} \times 0^+$ (pure 0^+) + background

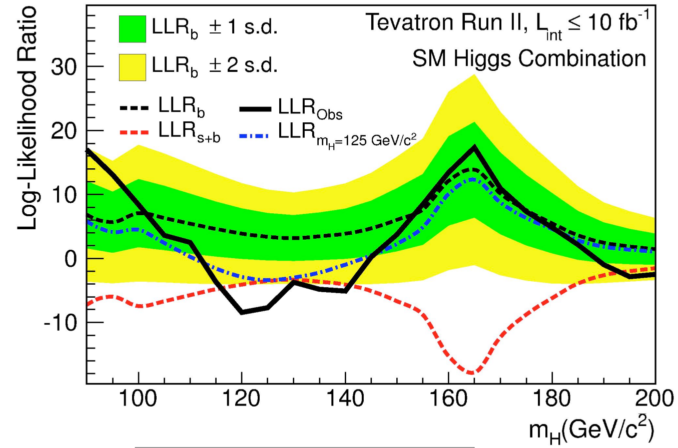


Exclude at 95% CL

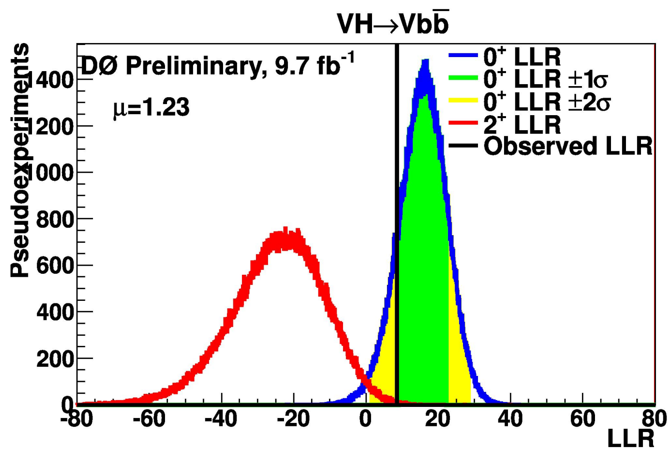
$f_{2+} > 0.42$ (μ=1.23)

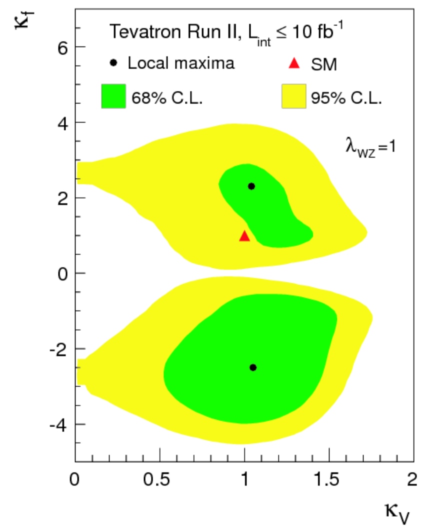
Conclusions & forward look

- Tevatron
  - SM sensitivity over most of accessible mass range
  - Excess from 115 < m_H < 140 GeV
    - 3σ significance at 125 GeV
  - Coupling & DØ spin results consistent with SM



Exclude 2^+ at 99.9% CL





- Consistent Higgs boson picture forming

- Tevatron: continue to provide valuable information on nature of the observed boson despite rapid progress on H → bb at LHC
  - Look forward to combination


The
CDF and DØ
Collaborations

Final 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
$H + X \to WW \to \mu^{\pm}\tau_h^{\mp} + \leq 1\text{jet}$	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 publications

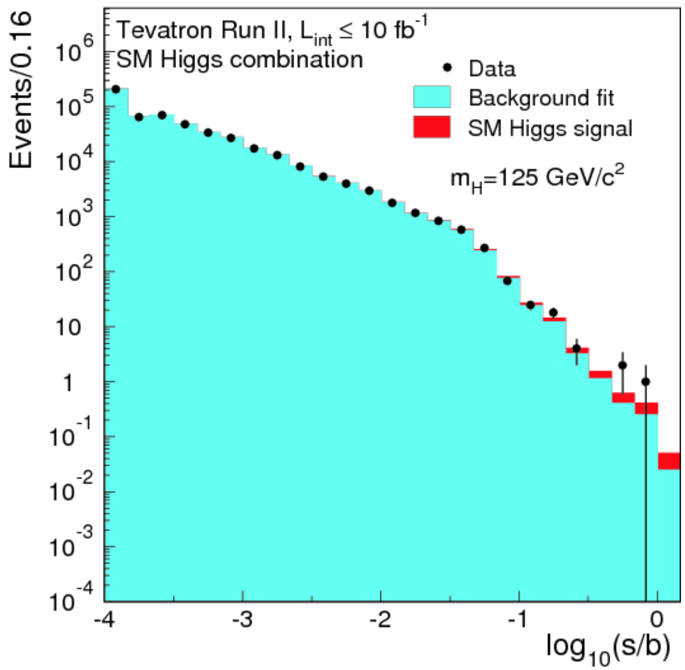
DØ Combination:
Acc. by PRD arXiv:1303.0823

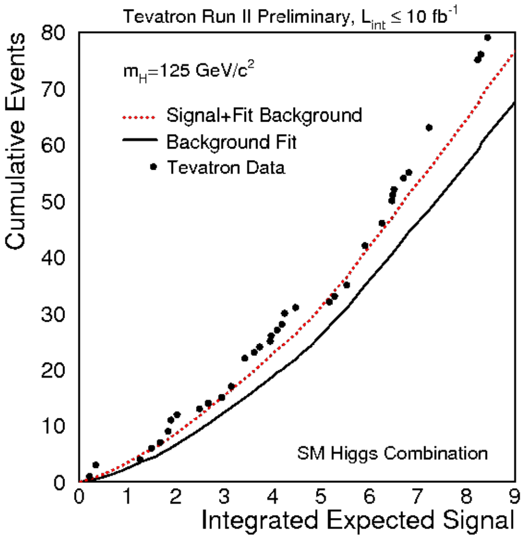
CDF Combination:
Acc. by PRD arXiv:1301.6668

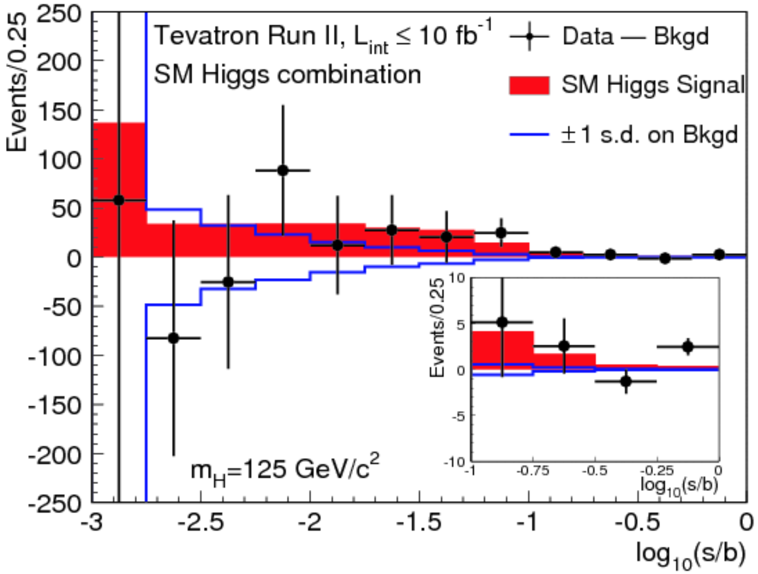
Tevatron Combination:
Acc. by PRD arXiv:1303.6346

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
$ZH \to \ell\ell b\bar{b}$	9.7	90–150	Phys. Rev. Lett. 109, 121803 (2012) and Acc by PRD arXiv:1303.3276
$ZH \to \nu\bar{\nu}$			(2012)
$H \to W^+W$			01.1243
$H + X \to$			(2012)
$H \to W^+W$			01.6122
$VH \to ee$			02.5723
$VH \to e^{\pm}$			02.5723
$VH \to \ell\nu$			01.6122
$VH \to \tau_h\tau$			02.5723
$H + X \to$			1.6993
$H \to \gamma\gamma$			01.5358
CDF			
$WH \to \ell\nu$			804 (2012)
$ZH \to \ell\ell b$			803 (2012)
$ZH \to \nu\bar{\nu}$			805 (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
$VH \to e e\mu/\mu\mu e + X$	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

Visualising the excess

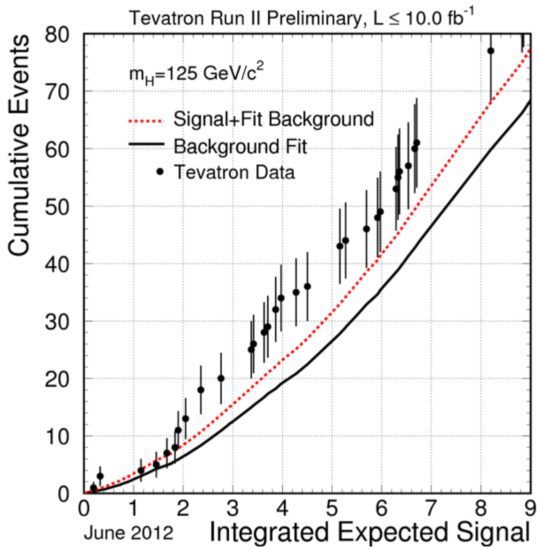




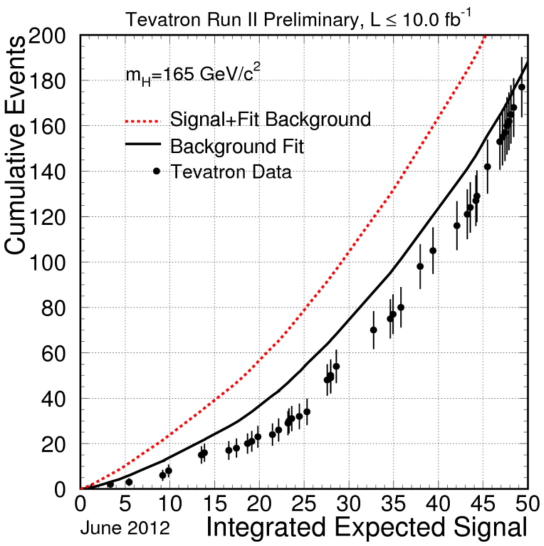


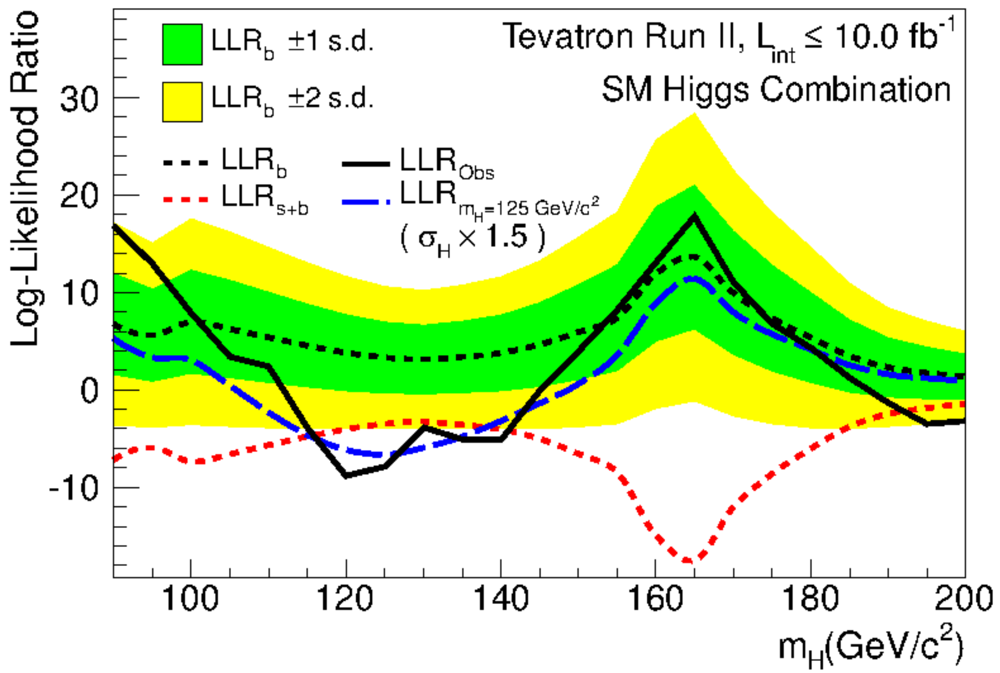
- Display all input histogram bins ordered according to S/B in one plot
  - Background model constrained by the data

Visualising the excess



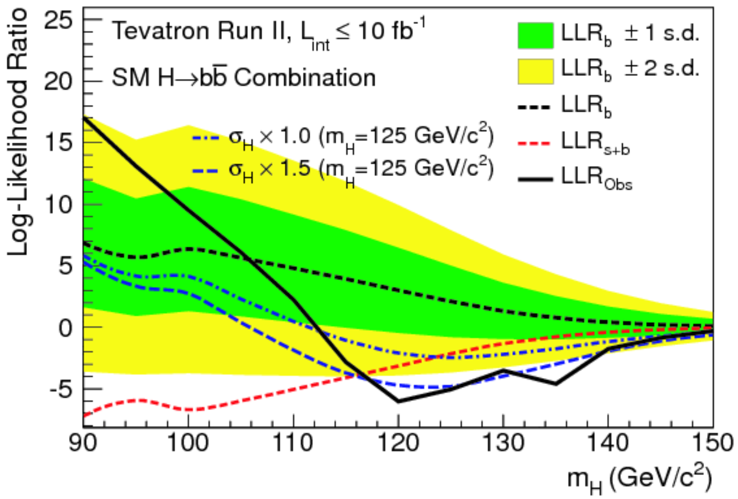
Comparison to m_H = 165GeV

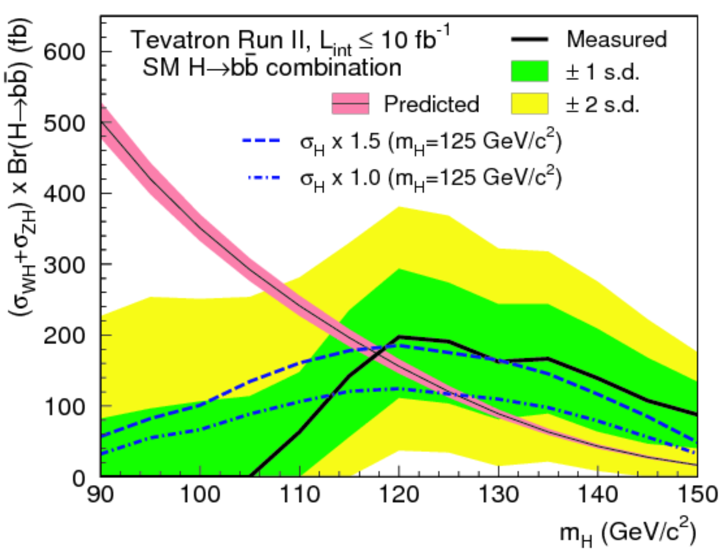




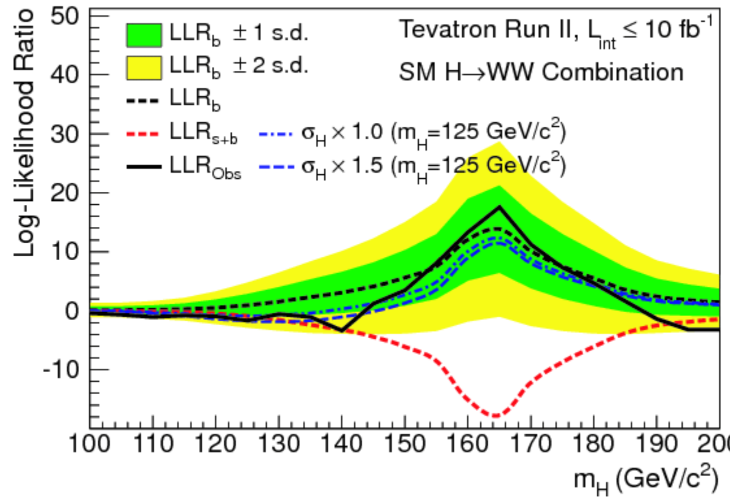
Quantifying the excess: sub-channels

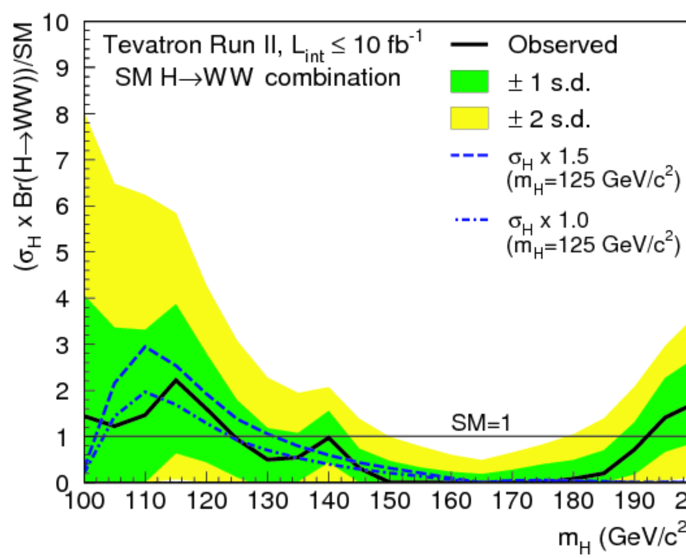
H→bb combination



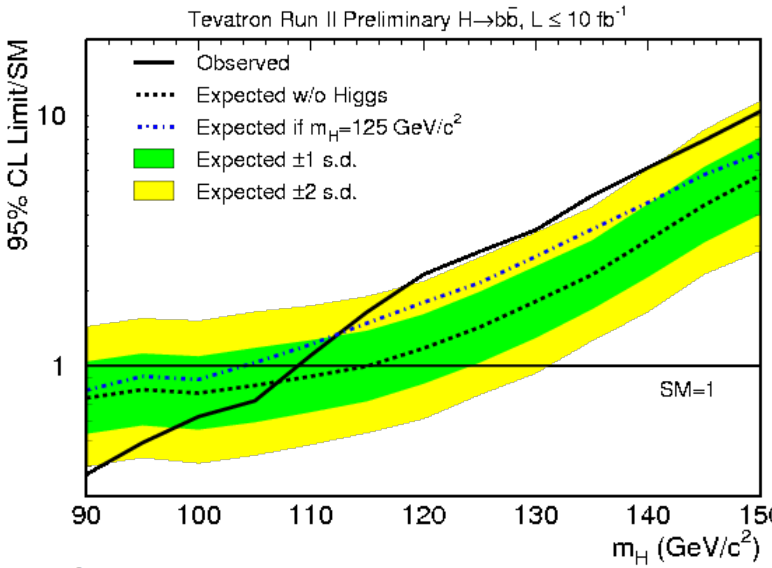


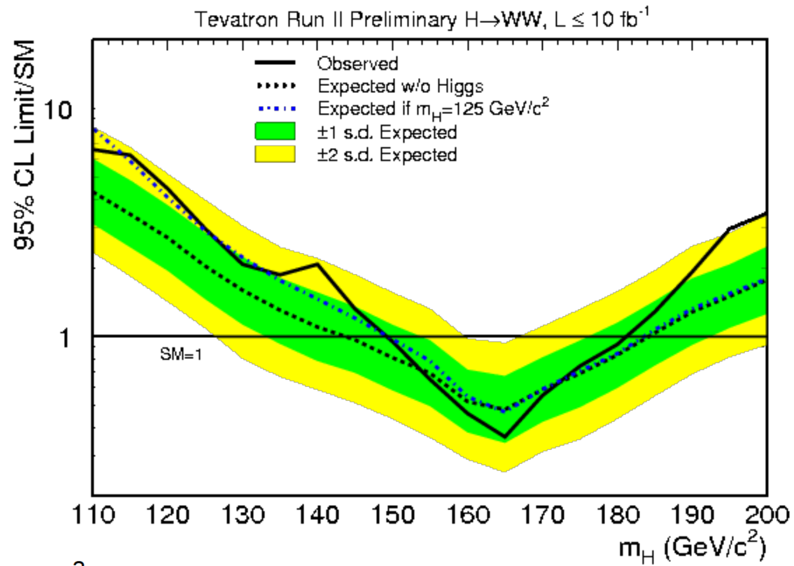
H→WW combination

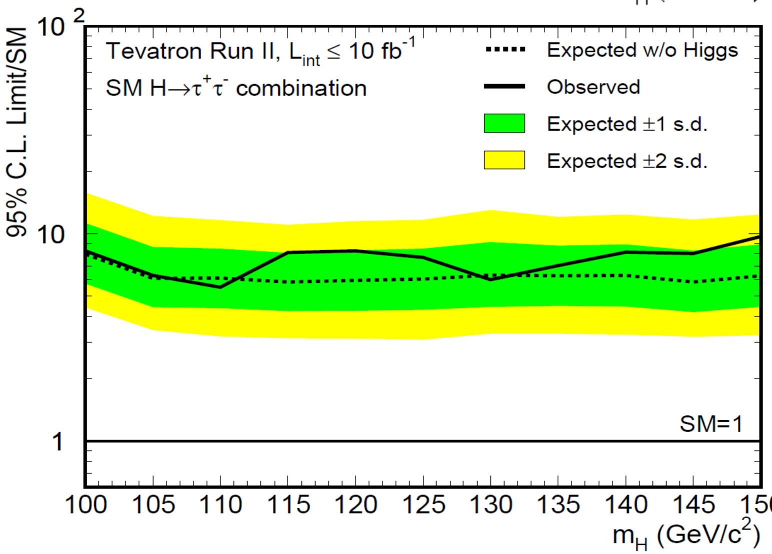


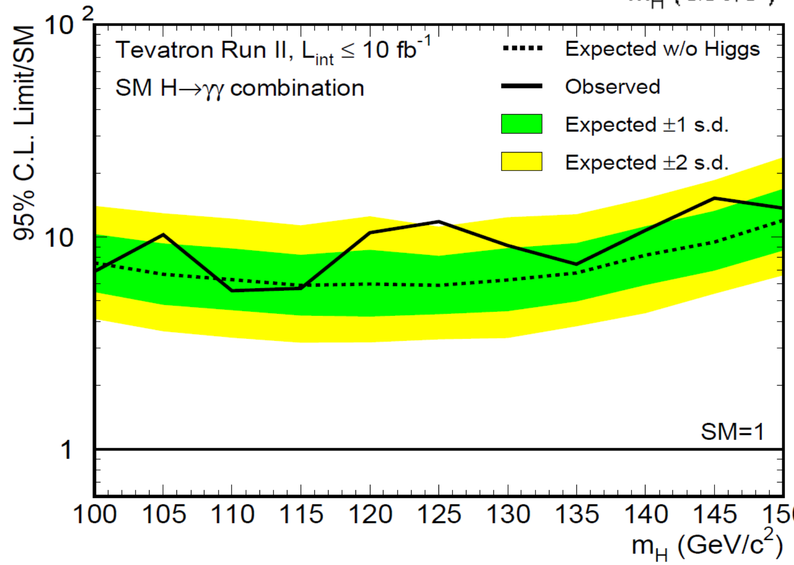


Limits: By channel

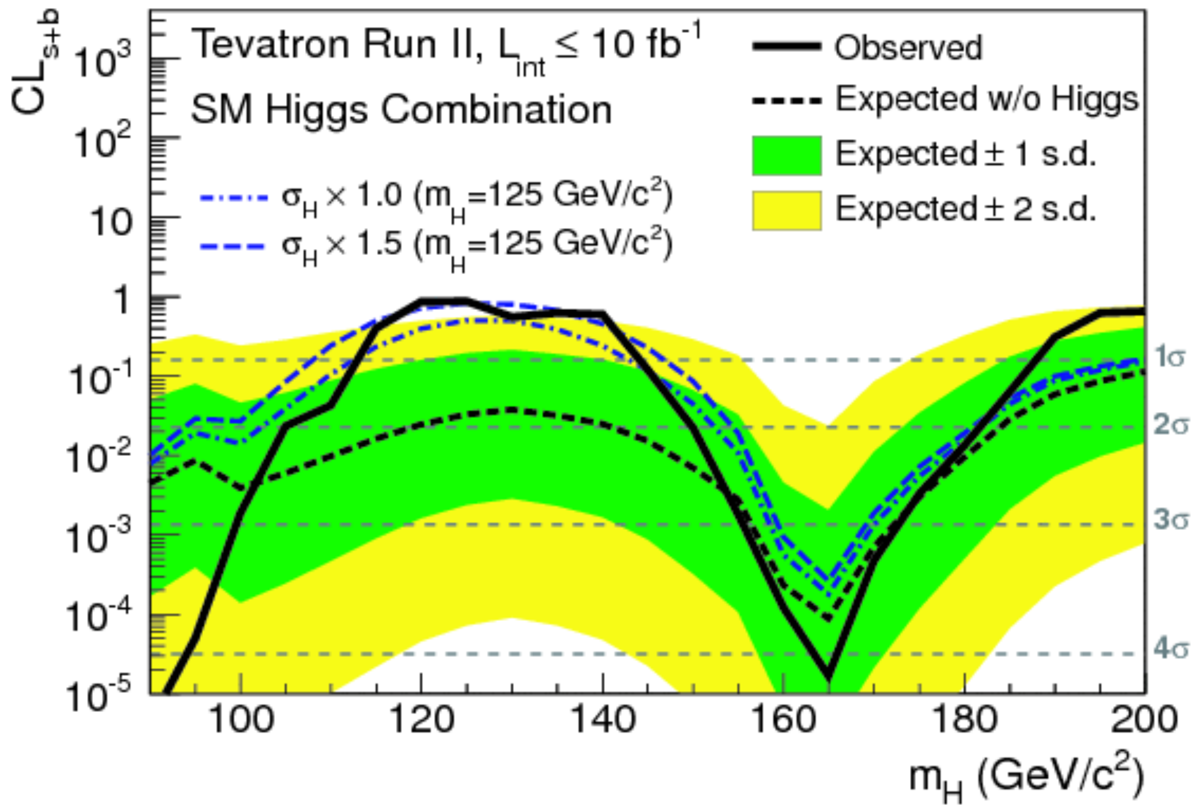








Tevatron combination: CL_{s+b}

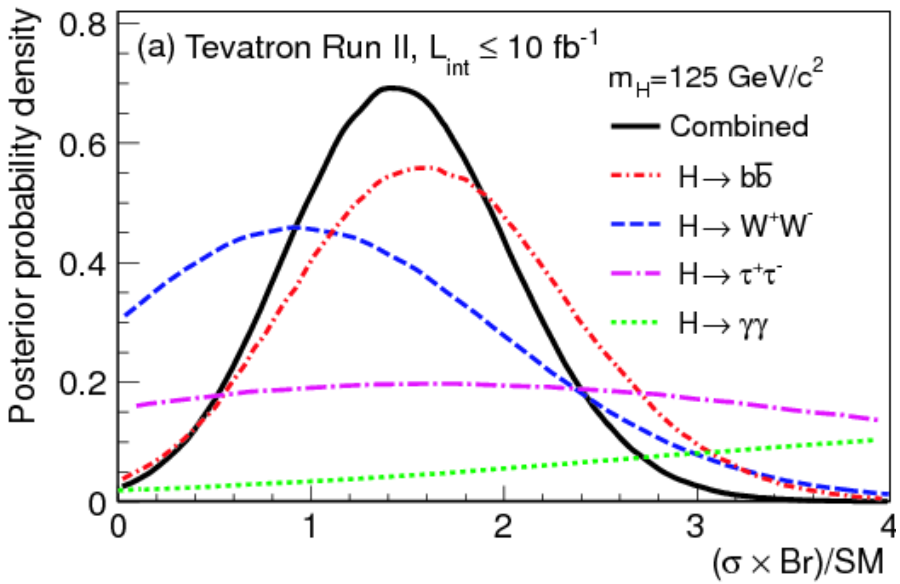


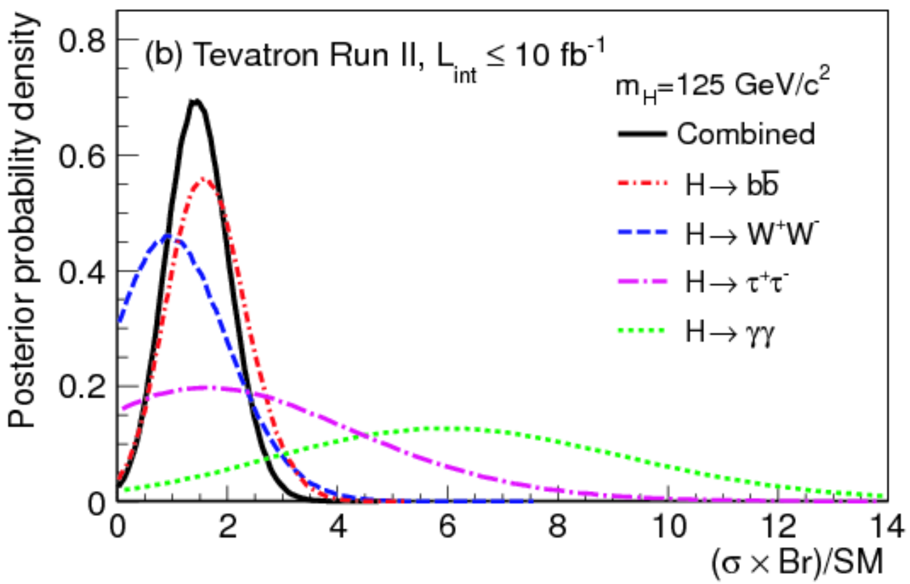
Cross section fits

TABLE VII: Best-fit values of $R = (\sigma \times \mathcal{B})/\mathrm{SM}$ using the Bayesian method for all SM Higgs boson decay modes combined and the combinations of CDF and D0's Higgs boson search channels focusing on the $H \to W^+W^-$, $H \to b\bar{b}$, $H \to \gamma\gamma$, and $H \to \tau^+\tau^-$ decay modes as a function of Higgs boson mass over the range $115 < m_H < 140$ GeV/c^2. The quoted uncertainties bound the smallest interval containing 68% of the integral of the posterior probability density.

m_H (GeV/c^2)	115	120	125	130	135	140
$R_{\mathrm{fit}}(\mathrm{SM})$	$0.82^{+0.43}_{-0.46}$	$1.42^{+0.53}_{-0.52}$	$1.44^{+0.59}_{-0.56}$	$1.13^{+0.60}_{-0.60}$	$0.99^{+0.58}_{-0.57}$	$1.15^{+0.57}_{-0.52}$
$R_{\mathrm{fit}}(H \to W^+W^-)$	$2.22^{+1.65}_{-1.59}$	$1.59^{+1.20}_{-1.15}$	$0.94^{+0.85}_{-0.83}$	$0.49^{+0.69}_{-0.63}$	$0.54^{+0.53}_{-0.52}$	$0.97^{+0.58}_{-0.53}$
$R_{\mathrm{fit}}(H \to b\bar{b})$	$0.72^{+0.47}_{-0.44}$	$1.26^{+0.62}_{-0.55}$	$1.59^{+0.69}_{-0.72}$	$1.82^{+0.91}_{-0.91}$	$2.62^{+1.22}_{-1.21}$	$3.23^{+1.61}_{-1.74}$
$R_{\mathrm{fit}}(H \to \gamma\gamma)$	$0.65^{+2.66}_{-0.54}$	$5.34^{+3.20}_{-2.76}$	$5.97^{+3.39}_{-3.12}$	$3.17^{+2.69}_{-2.81}$	$0.00^{+4.04}_{-0.00}$	$3.31^{+3.30}_{-3.13}$
$R_{\mathrm{fit}}(H \to \tau^+\tau^-)$	$1.70^{+2.20}_{-1.70}$	$2.00^{+2.22}_{-1.90}$	$1.68^{+2.28}_{-1.68}$	$0.00^{+2.88}_{-0.00}$	$0.00^{+2.83}_{-0.00}$	$1.25^{+2.62}_{-1.15}$

Cross section fits

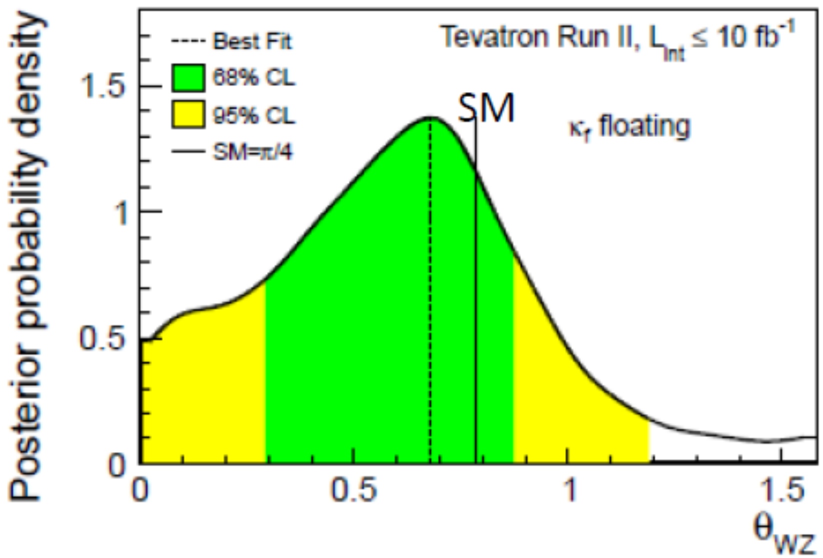




Couplings

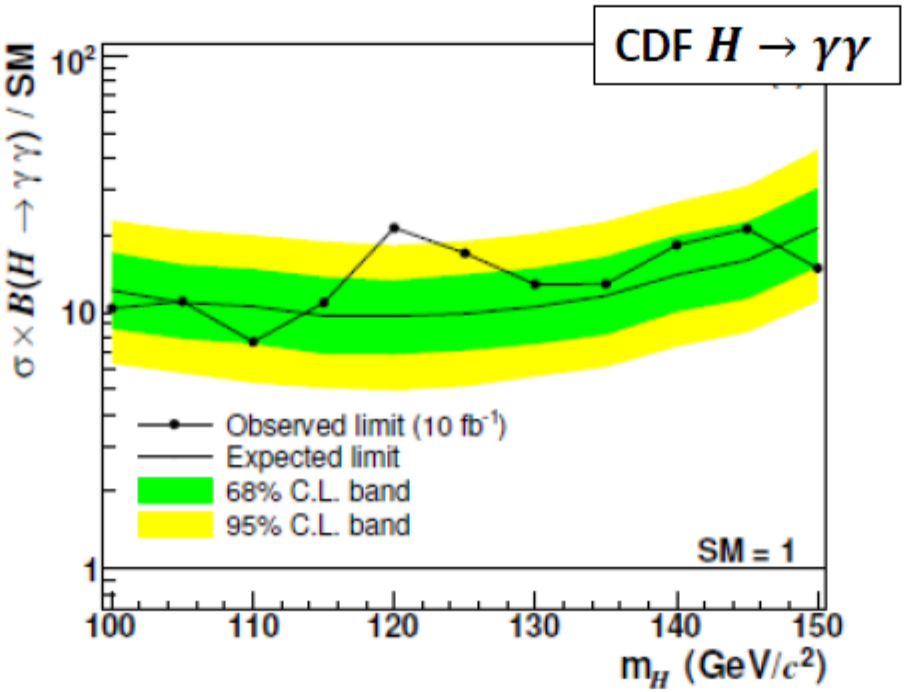
- Probe custodial symmetry ie $\lambda_{WZ} = k_W/k_Z \approx 1$(SM)
  - Scale all fermion couplings by a common factor k_f
  - Compute posterior probability for

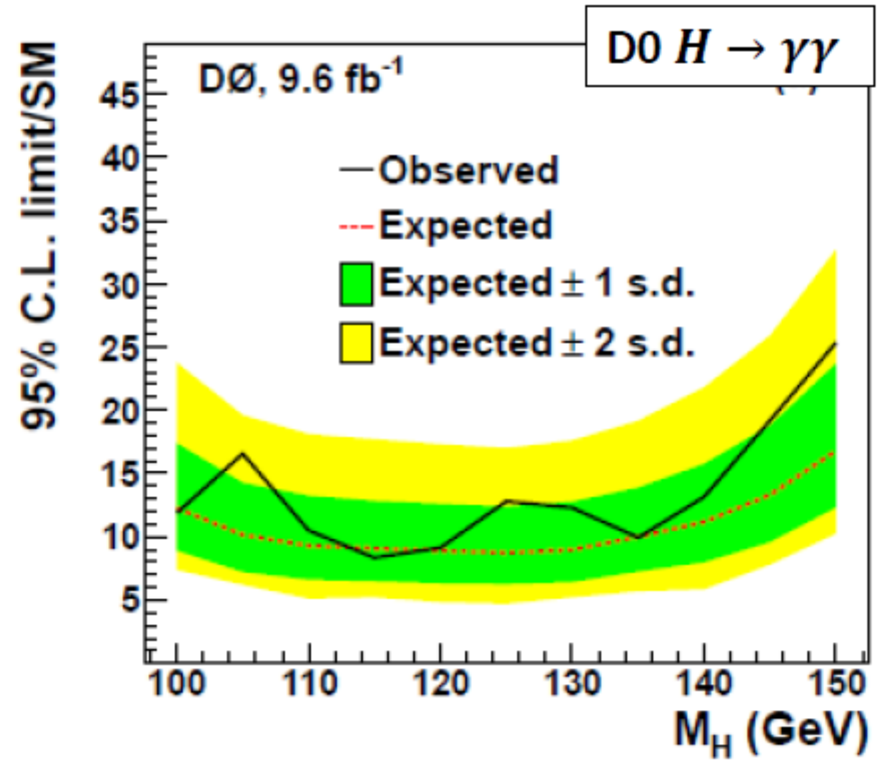
$$\theta_{WZ} = \tan^{-1}(K_Z/K_W).$$



$$|\theta_{WZ}| = 0.68^{+0.21}_{-0.41}$$
$$\boldsymbol{K_W/K_Z = 1.24^{+2.32}_{-0.42}}$$

$H \rightarrow \gamma\gamma$





Spin

- Use CLs
  - LLR = -2log[L(H1)/L(H0)] with H1 = (2^+ + bkg) and H0 = (0^+ + bkg)

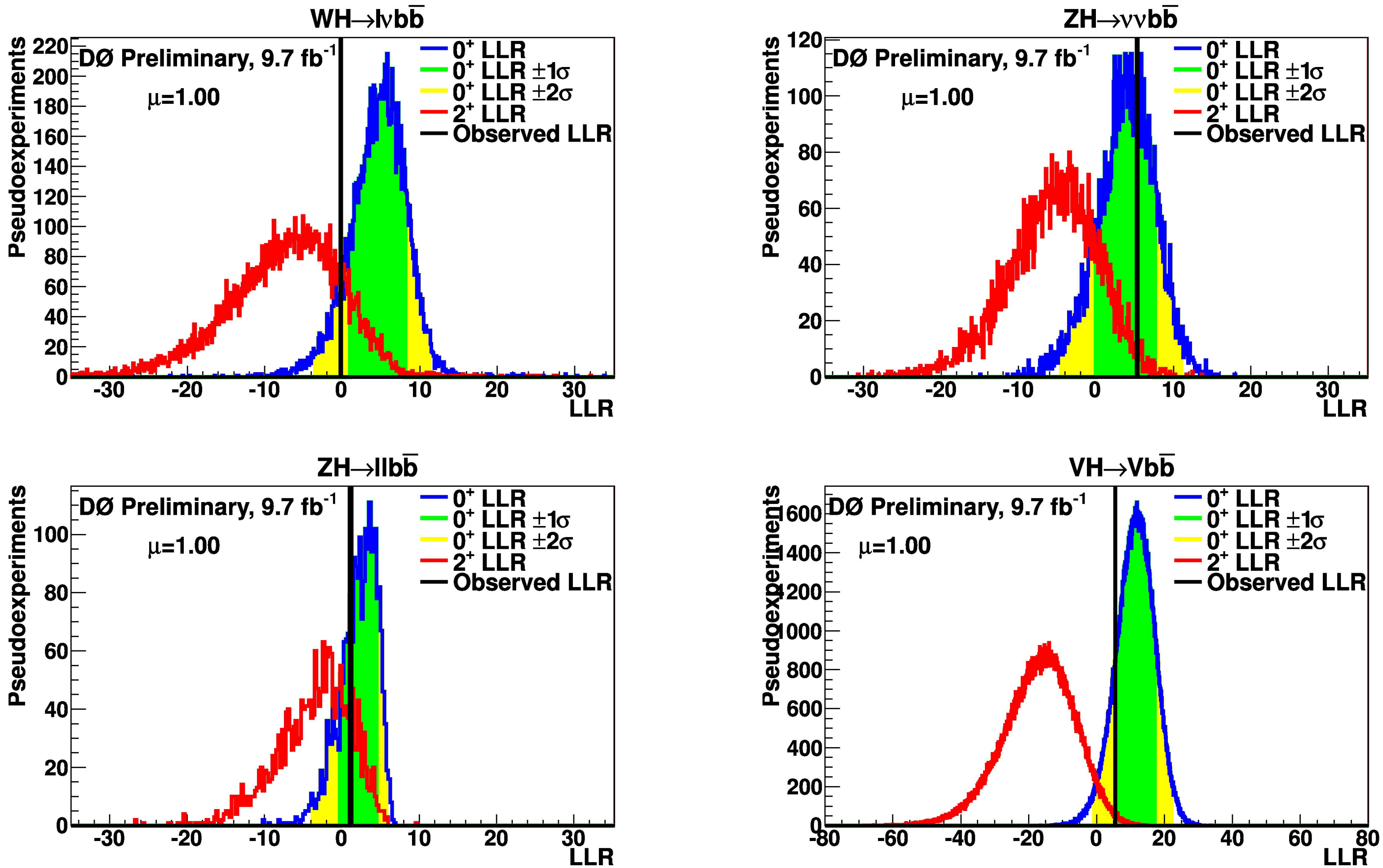
Channel	$WH \to \ell\nu bb$	$ZH \to \ell\ell bb$	$ZH \to \nu\nu bb$	Combined
	$J^P = 2^+$ vs. $J^P = 0^+$			
Exp. Lim. σ^{2+}/σ_{SM}	1.01	1.59	1.15	0.49
Obs. Lim. σ^{2+}/σ_{SM}	1.56	1.76	1.02	0.73

TABLE I: 95% C.L. upper limits on $J^P = 2^+$ associated production as a ratio to the SM Higgs associated production cross section times $H \to b\bar{b}$ branching fraction, taking the null hypothesis H_0 to be SM Higgs boson signal plus background, and test hypothesis H_1 to be $J^P = 2^+$ signal plus background.

  - Exclude at 95% CL
    - $\sigma_{2+} / \sigma_{SM} =$ 0.73 obs
    - $\sigma_{2+} / \sigma_{SM} =$ 0.49 exp

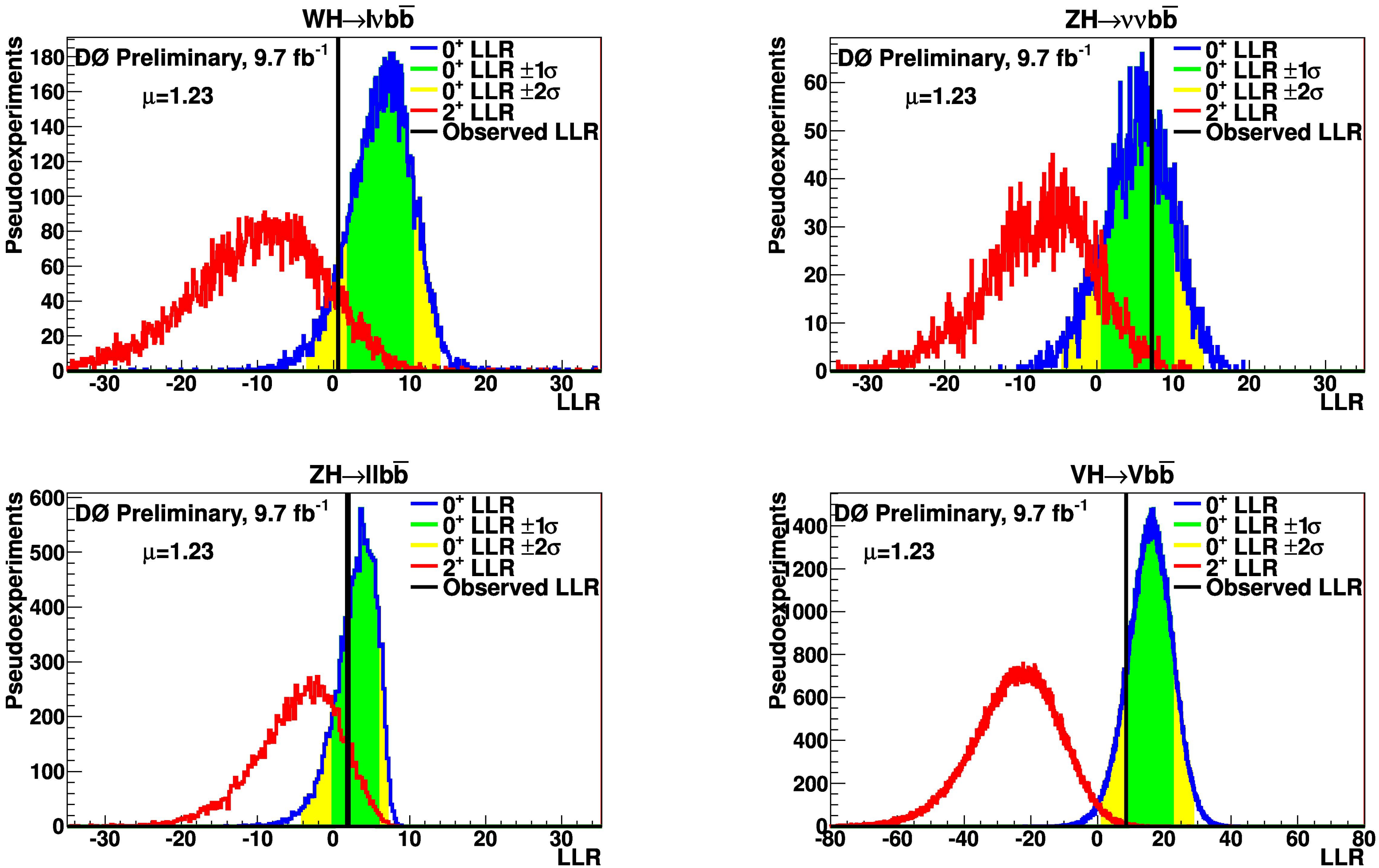
Spin

- Use CLs: LLR = -2log[L(H1)/L(H0)] with H1 = (2^+ + bkg) and H0 = (0^+ + bkg)



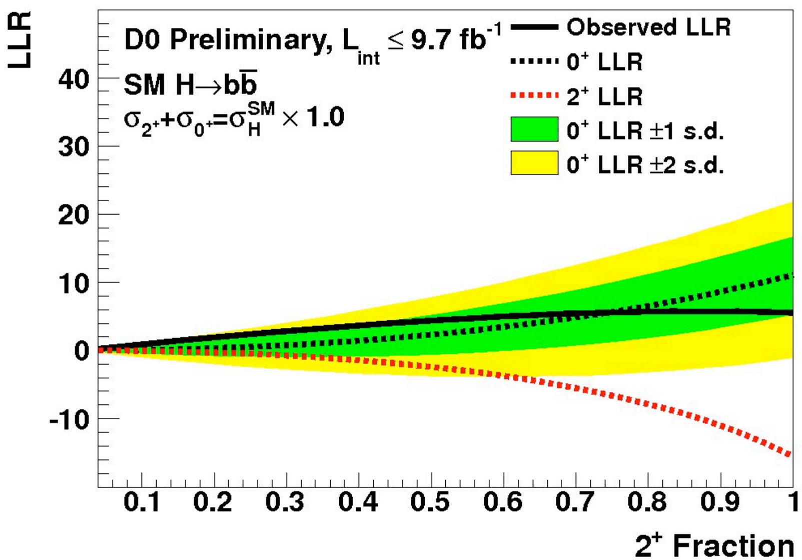
Spin

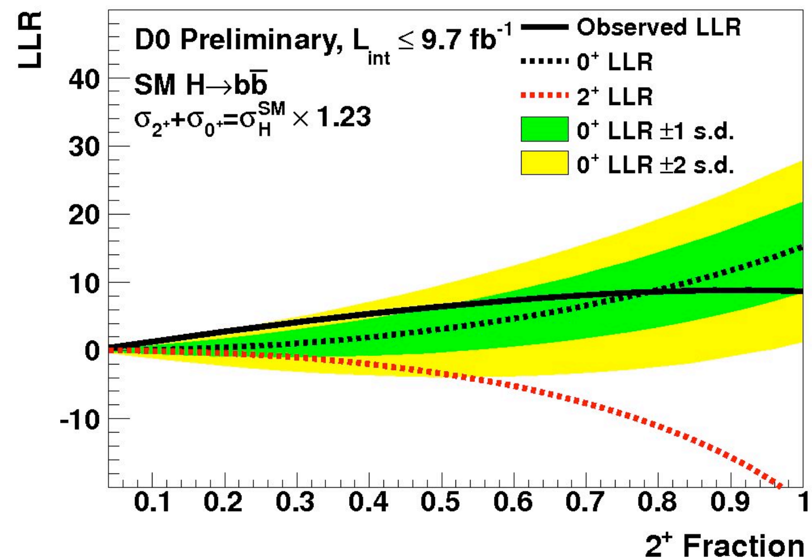
- Use CLs: LLR = -2log[L(H1)/L(H0)] with H1 = (2^+ + bkg) and H0 = (0^+ + bkg)



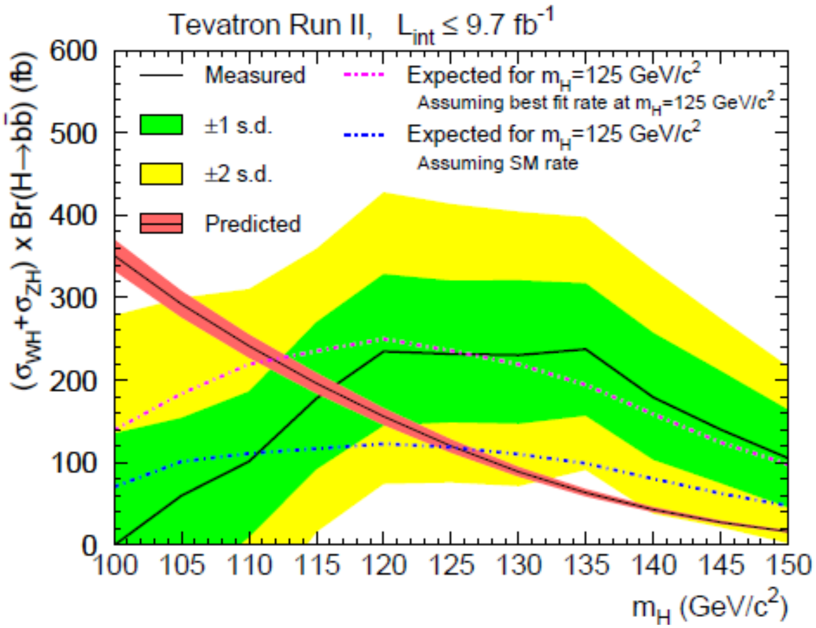
Spin

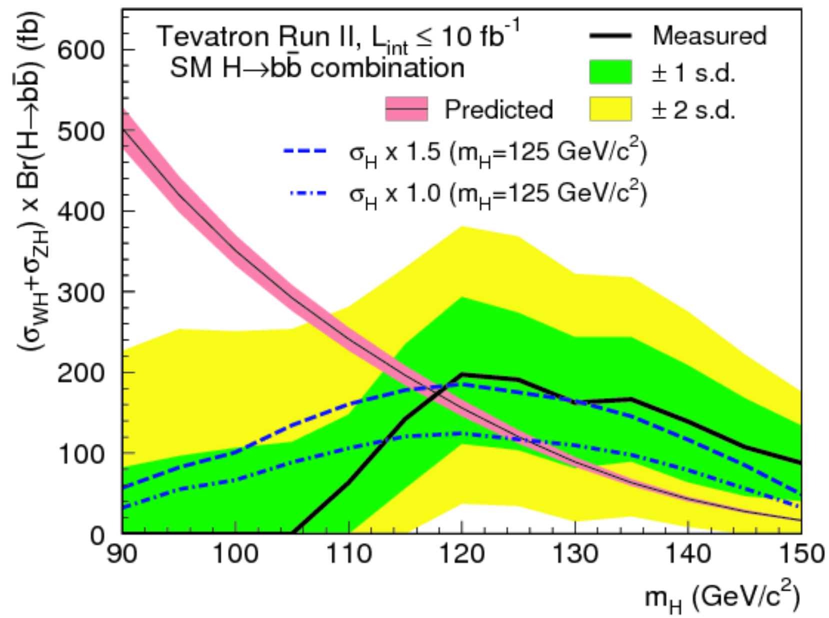
- Consider both 2^+ and 0^+ signal in data
  - Vary fraction, f_{2+}, of 2^+ from $0 \rightarrow 1$
  - H1 = μ x $(\sigma \times BR)_{SM}$ x $([2^+ \times f_{2+}] + [0^+ \times (1-f_{2+})])$ + background
  - H0 = μ x $(\sigma \times BR)_{SM}$ x 0^+ (pure 0^+) + background





H→bb: PRL 109, 071084 (2012)





$$\sigma_{VH} = 0.23 \pm 0.09\ \mathrm{pb}$$

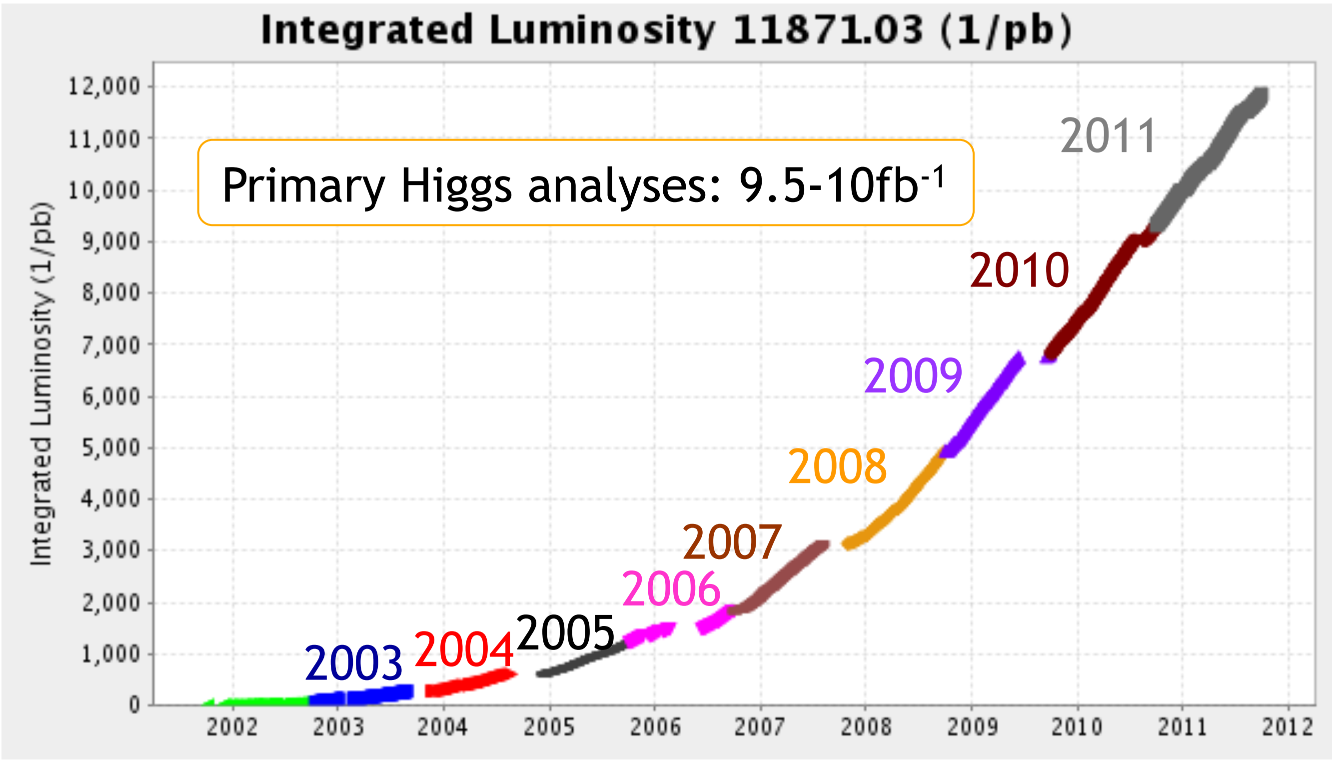
$$\sigma_{VH} = 0.19 \pm 0.09\ \mathrm{pb}$$

$$SM : \sigma_{VH} = 0.12 \pm 0.01\ \mathrm{pb}$$

– Results consistent

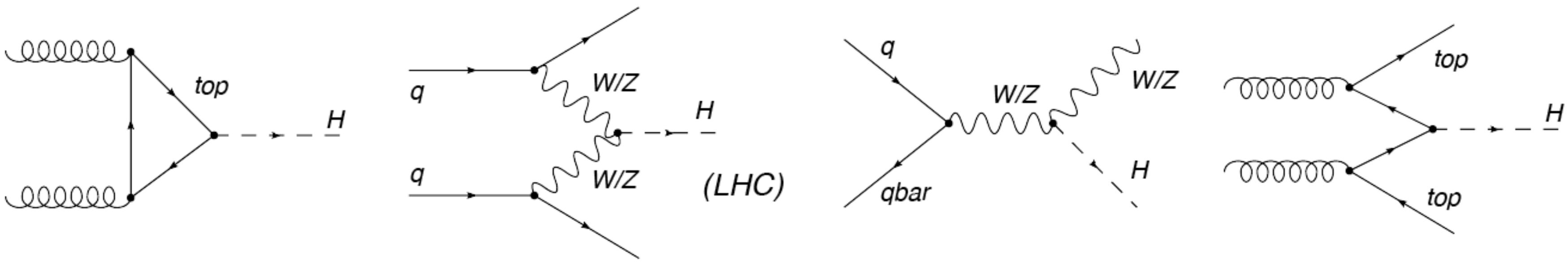
Tevatron

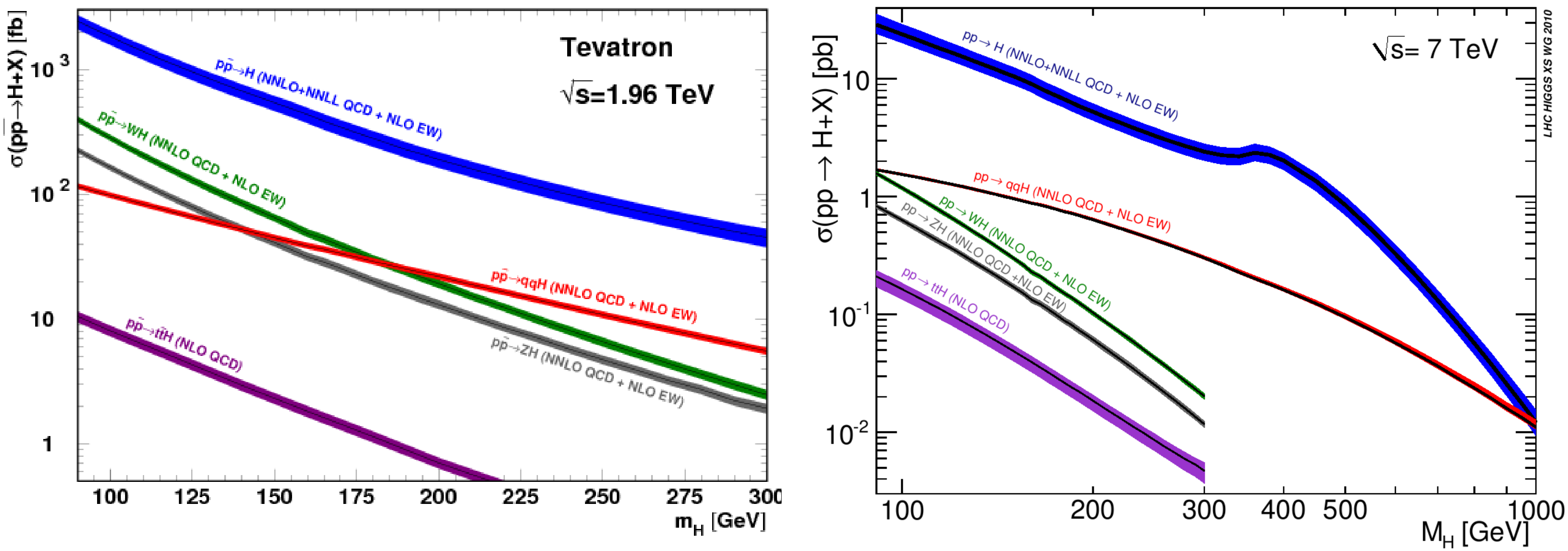
- ~12fb^{-1} delivered, ~11fb^{-1} recorded, ~10fb^{-1} after data quality per expt



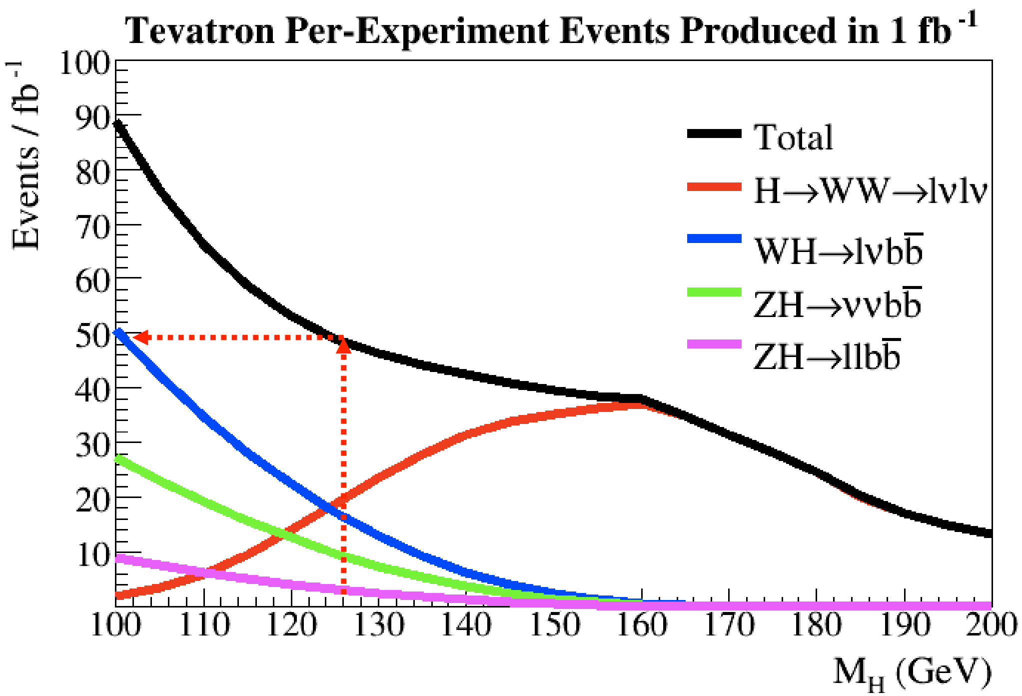
Many thanks to Accelerator Division

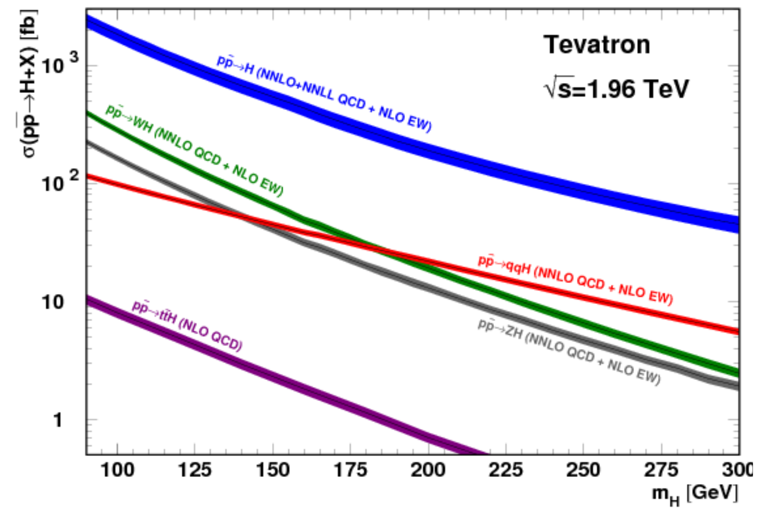
Higgs production

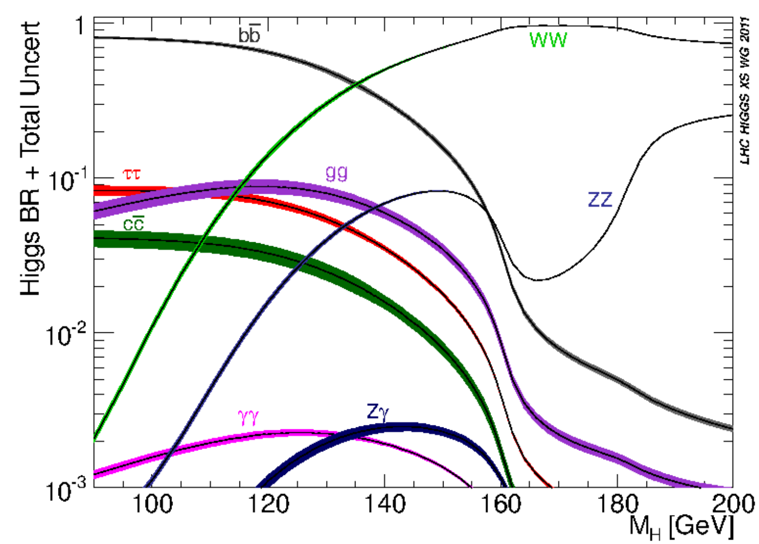




Higgs production





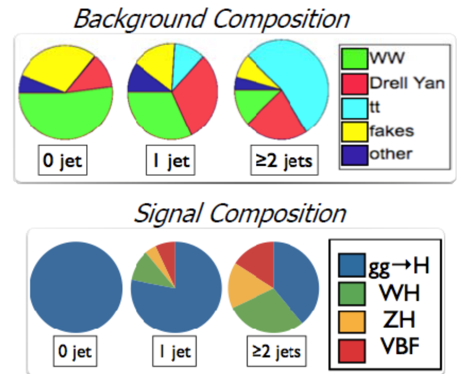


- More than 50 Higgs events / fb^{-1}
  - With 10/fb per experiment, over 1000 total Higgs events to find!

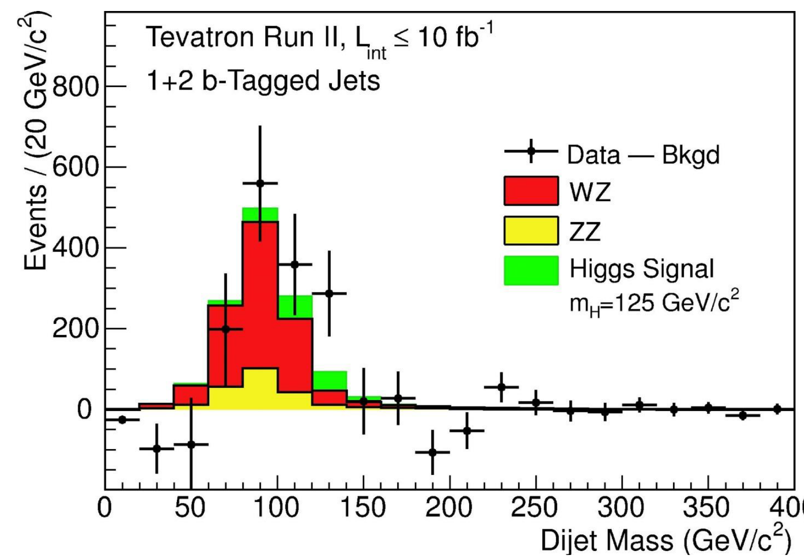
Search strategy

- Leave no stone unturned
  - Maximise ‘inclusive’ acceptance
  - Separate into sub-channels with different s/b
  - Use multivariate techniques

e.g. H→WW



- Modeling
  - Check modeling in control regions & validate analyses by measuring SM diboson signals
  - Derive systematics on both normalisation & shape from independent measurements

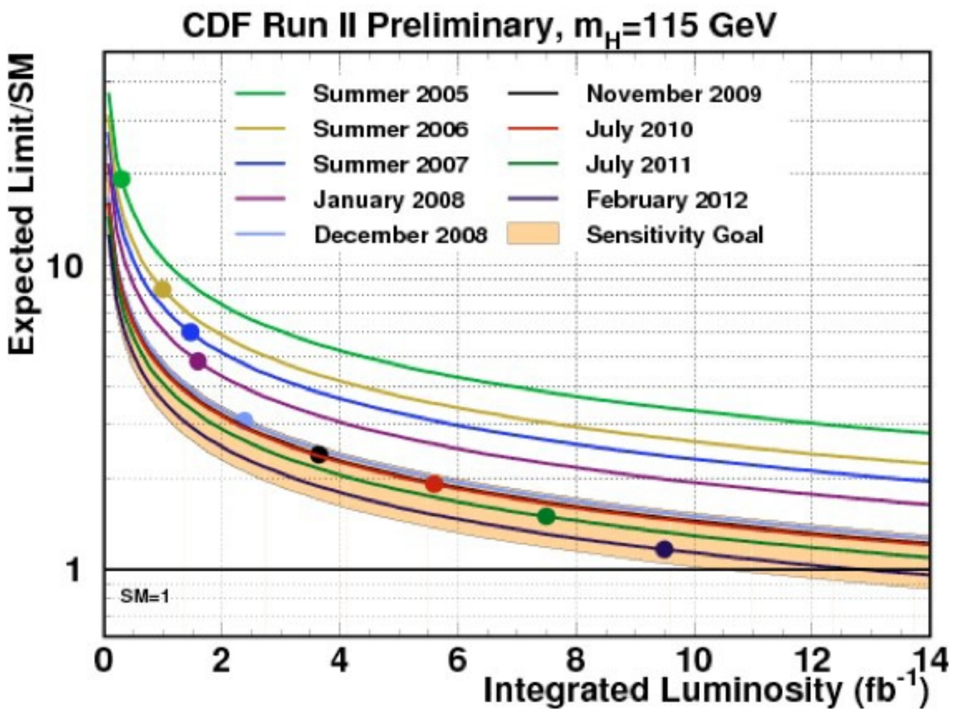


$\sigma(VZ) = (0.7 \pm 0.2)\ \sigma(SM)$

- Combination
  - Bayesian and CL_S techniques used
  - Systematics introduced as nuisance parameters
    - Impact of these mitigated with constraints from data

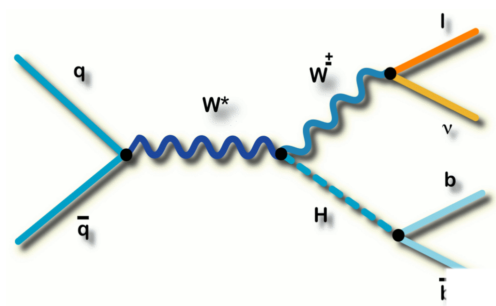
Track record of improvement

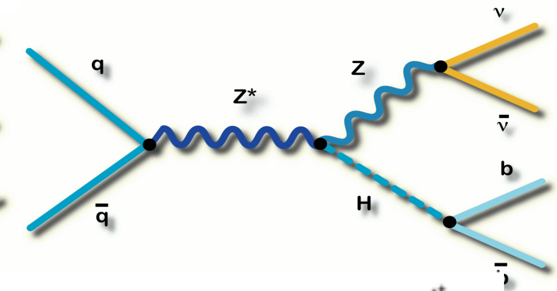
- eg CDF

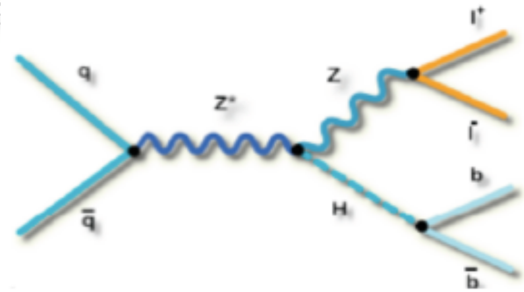


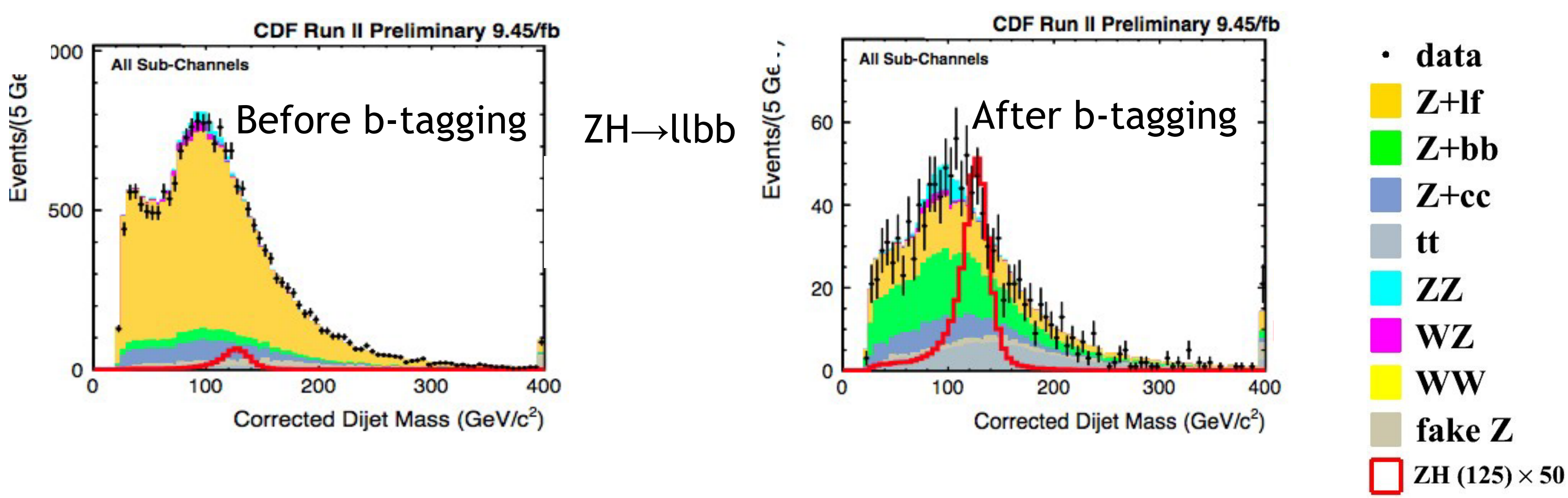
Low mass: H → bb

- Lepton from W/Z, MET, b-tagged jets
  - Dominant bkgds: Multijet, W/Z+jets, diboson, top
- Mass resoln & b-tagging critical
- Use MVA b-tag classifiers
  - 50-80% b-tag efficiency, 0.5-10% mis-tag rate



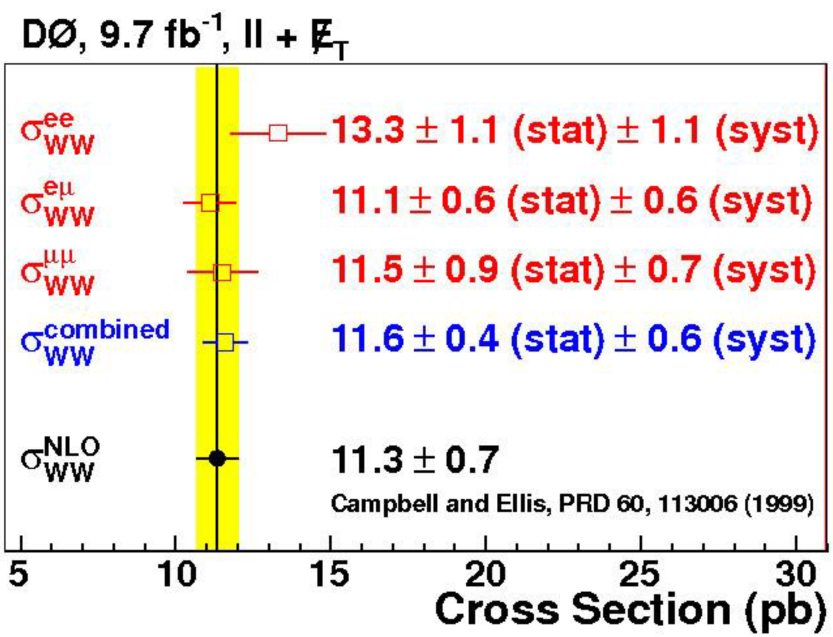


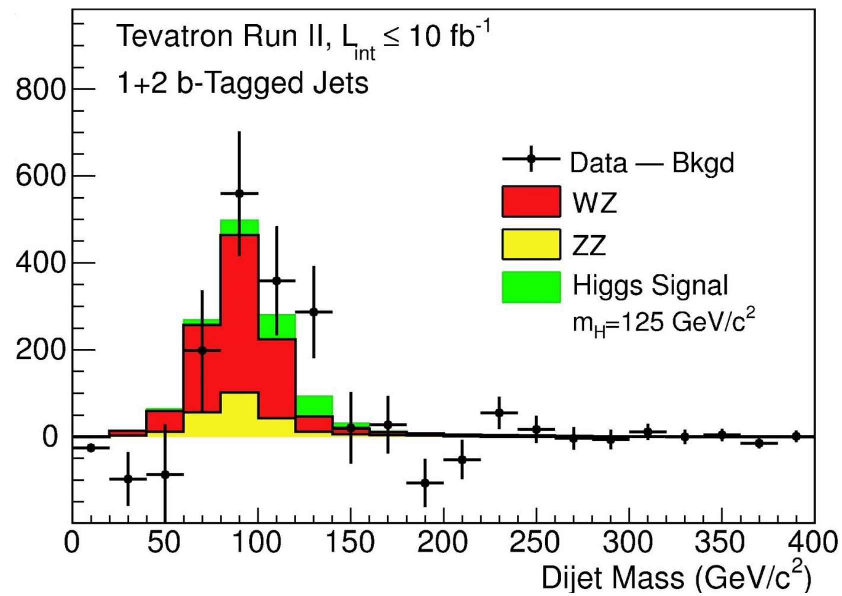




Search validation

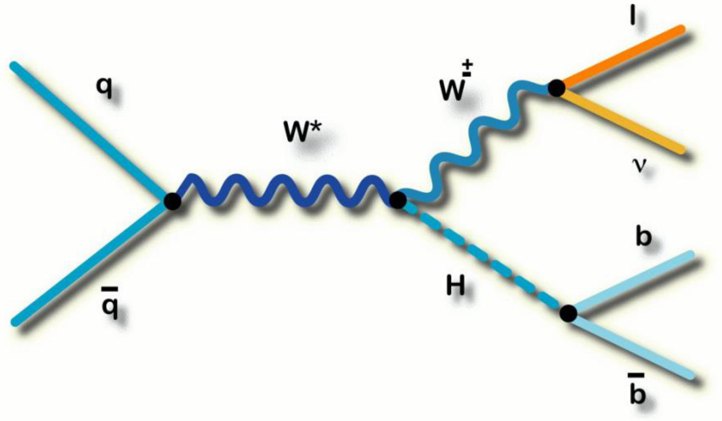
- Validate analyses by measuring SM diboson signal
  - Train MVAs with diboson signal rather than Higgs
    - Performed with same sub-division of channels as H search
  - H→ WW → lνlν: Measure WW → lνlν production
  - VH → Vbb analyses: Measure WZ/ZZ with Z → bb





$\sigma(VZ) = (0.7 \pm 0.2)\ \sigma(SM)$

Search validation: VH → Vbb



M_H = 125 GeV	VH→Vbb [fb]	VZ→Vbb [fb]
ZX→ννbb	9	73
WX→lνbb	16	105
ZX→llbb	3	24
Total:	28	202

Differences:

– Cross section for diboson production is 7x 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.

All the detail..

CDF

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ 2-jet channels 4×(5 b-tag categories)	$H \to b\bar{b}$	9.45	90–150	[48]
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)		9.45	90–150	[48]
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		9.45	90–150	[49]
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(4 b-tag categories)		9.45	90–150	[50]
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2×(4 b-tag categories)		9.45	90–150	[50]
$WH + ZH \to jjb\bar{b}$ (2 b-tag categories)		9.45	100–150	[51]
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ (4 jets,5 jets,≥6 jets)×(5 b-tag categories)		9.45	100-150	[52]
$H \to W^+W^-$ 2×(0 jets)+2×(1 jet)+1×(≥2 jets)+1×(low-$m_{\ell\ell}$)	$H \to W^+W^-$	9.7	110–200	[53]
$H \to W^+W^-$ (e-$\tau_{\rm had}$)+(μ-$\tau_{\rm had}$)		9.7	130–200	[53]
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)		9.7	110–200	[53]
$WH \to WW^+W^-$ (tri-leptons with 1 $\tau_{\rm had}$)		9.7	130–200	[53]
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet,≥2 jets)		9.7	110–200	[53]
$H \to \tau^+\tau^-$ (1 jet)+(≥2 jets)	$H \to \tau^+\tau^-$	6.0	100–150	[54]
$H \to \gamma\gamma$ 1×(0 jet)+1×(≥1 jet)+3×(all jets)	$H \to \gamma\gamma$	10.0	100–150	[55]
$H \to ZZ$ (four leptons)	$H \to ZZ$	9.7	120–200	[56]

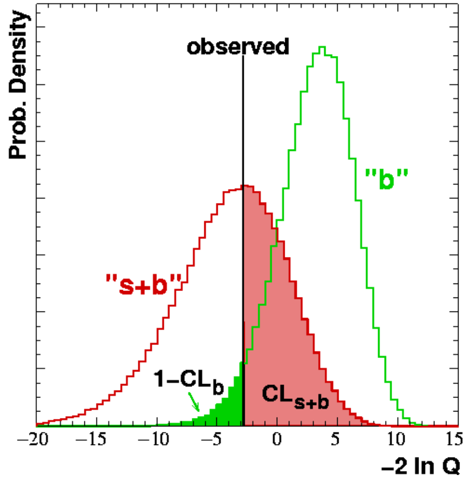
DØ

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ 2-jet channels 2×(4 b-tag categories)	$H \to b\bar{b}$	9.7	90–150	[57, 58]
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(4 b-tag categories)		9.7	90–150	[57, 58]
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)		9.5	100–150	[45]
$ZH \to \ell^+\ell^- b\bar{b}$ 2×(2 b-tag)×(4 lepton categories)		9.7	90–150	[59, 60]
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ 2×(0 jets,1 jet,≥2 jets)	$H \to W^+W^-$	9.7	115–200	[61]
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{\rm had}\nu$ (3 τ categories)		7.3	115–200	[62]
$H \to W^+W^- \to \ell\bar{\nu}jj$ 2×(2 b-tag categories)×(2 jets, 3 jets)		9.7	100–200	[58]
$VH \to e^\pm\mu^\pm + X$		9.7	100–200	[63]
$VH \to \ell\ell\ell + X$ ($\mu\mu e$, 3 × $e\mu\mu$)		9.7	100–200	[63]
$VH \to \ell\bar{\nu}jjjj$ 2×(≥4 jets)		9.7	100-200	[58]
$VH \to \tau_{\rm had}\tau_{\rm had}\mu + X$ (3 τ categories)	$H \to \tau^+\tau^-$	8.6	100-150	[63]
$H+X \to \ell^\pm\tau^\mp_{\rm had}jj$ 2×(3 τ categories)		9.7	105–150	[64]
$H \to \gamma\gamma$ (4 categories)	$H \to \gamma\gamma$	9.6	100-150	[65]

Statistical techniques

- Two statistical approaches used
  - Better than 10% agreement over whole mass range (~2% on average)
- Bayesian
  - Flat signal prior, credibility intervals
- Modified frequentist
  - Log-likelihood test statistic, $CL_s = CL_{s+b}/CL_b$

$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\,|\,s+b,\hat{\theta})}{L(\text{data}\,|\,b,\hat{\hat{\theta}})}\right)$$



- Operate on binned, final discriminants
  - Poisson statistics assumed for each bin
- Systematics introduced as nuisance parameters
  - Impact of these mitigated with constraints from data

Cross Section & BR

m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$\sigma_{t\bar{t}H}$ (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to\tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to\gamma\gamma)$ (%)
100	1821.8	281.1	162.7	97.3	8.000	79.1	3.68	8.36	1.11	0.113	0.159
105	1584.7	238.7	139.5	89.8	7.062	77.3	3.59	8.25	2.43	0.215	0.178
110	1385.0	203.7	120.2	82.8	6.233	74.5	3.46	8.03	4.82	0.439	0.197
115	1215.9	174.5	103.9	76.5	5.502	70.5	3.27	7.65	8.67	0.873	0.213
120	1072.3	150.1	90.2	70.7	4.857	64.9	3.01	7.11	14.3	1.60	0.225
125	949.3	129.5	78.5	65.3	4.279	57.8	2.68	6.37	21.6	2.67	0.230
130	842.9	112.0	68.5	60.5	3.769	49.4	2.29	5.49	30.5	4.02	0.226
135	750.8	97.2	60.0	56.0	3.320	40.4	1.87	4.52	40.3	5.51	0.214
140	670.6	84.6	52.7	51.9	2.925	31.4	1.46	3.54	50.4	6.92	0.194
145	600.6	73.7	46.3	48.0	2.593	23.1	1.07	2.62	60.3	7.96	0.168
150	539.1	64.4	40.8	44.5	2.298	15.7	0.725	1.79	69.9	8.28	0.137
155	484.0	56.2	35.9	41.3	2.037	9.18	0.425	1.06	79.6	7.36	0.100
160	432.3	48.5	31.4	38.2	1.806	3.44	0.159	0.397	90.9	4.16	0.0533
165	383.7	43.6	28.4	36.0	1.607	1.19	0.0549	0.138	96.0	2.22	0.0230
170	344.0	38.5	25.3	33.4	1.430	0.787	0.0364	0.0920	96.5	2.36	0.0158
175	309.7	34.0	22.5	31.0	1.272	0.612	0.0283	0.0719	95.8	3.23	0.0123
180	279.2	30.1	20.0	28.7	1.132	0.497	0.0230	0.0587	93.2	6.02	0.0102
185	252.1	26.9	17.9	26.9	1.004	0.385	0.0178	0.0457	84.4	15.0	0.00809
190	228.0	24.0	16.1	25.1	0.890	0.315	0.0146	0.0376	78.6	20.9	0.00674
195	207.2	21.4	14.4	23.3	0.789	0.270	0.0125	0.0324	75.7	23.9	0.00589
200	189.1	19.1	13.0	21.7	0.700	0.238	0.0110	0.0287	74.1	25.6	0.00526

Cross section & BR

We use the following references for our cross sections and branching ratios. The citations below include only those papers which contain numbers that we use. Further citations are available in our conference note.

- The WH and ZH cross sections are from Baglio and Djouadi: arXiv:1003.4266v2, which is published as JHEP 1010:064 (2010). We have obtained from the authors an extension of Table 3 to include test mass range down to 100 GeV and predictions with more digits. The VBF production cross sections were computed with VBF@NNLO, and we multiply these by $(1+\delta_{EW})$ from the HAWK program, which amounts to a roughly 2% to 3% downward correction.
- The $gg \rightarrow H$ production cross section is calculated at NNLL in QCD and also includes two-loop electroweak effects. For details, see C. Anastasiou, R. Boughezal and F. Petriello, "Mixed QCD-electroweak corrections to Higgs boson production in gluon fusion", arXiv:0811.3458 [hep-ph] (2008), which is published as JHEP 0904:003 (2009), and D. de Florian and M. Grazzini, "Higgs production through gluon fusion: updated cross sections at the Tevatron and the LHC", arXiv:0901.2427v1 [hep-ph] (2009), which is published as Phys.Lett.B674:291-294 (2009). These cross were updated with the full m_{top} dependence in the calculation.
- We follow the BNL Accord to assign scale uncertainties separately in the 0, 1, and 2 or more jet bins. Details can be found in arXiv:1107.2117.
- PDF uncertainties follow the prescription of the PDF4LHC working group.
- The Higgs boson decay branching ratios are those reported in the Handbook of LHC Cross Sections: 1. Inclusive observables, arXiv:1101.0593v2.
- Higgs boson decay branching ratio uncertainties from m_b, m_c, and α_s are computed by Baglio and Djouadi in arXiv:1012.0530, which is published as JHEP 1103:055 (2011).