Probing the Spin and Parity of the Higgs using $H \longrightarrow b\bar{b}$ at D0

Ken Herner for the D0 Collaboration

13 September 2013

Outline

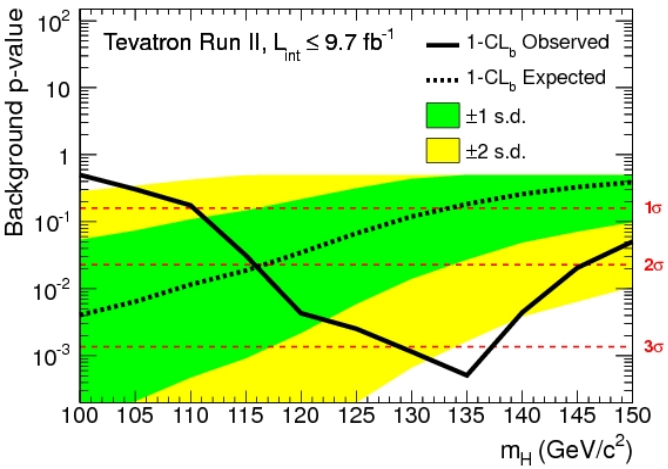
- Higgs Boson properties
  - Latest $H \longrightarrow b\bar{b}$ results
- The Tevatron Higgs program
- Overview of D0 $H \longrightarrow b\bar{b}$ analyses
- D0 spin and parity constraints in $b\bar{b}$ channels

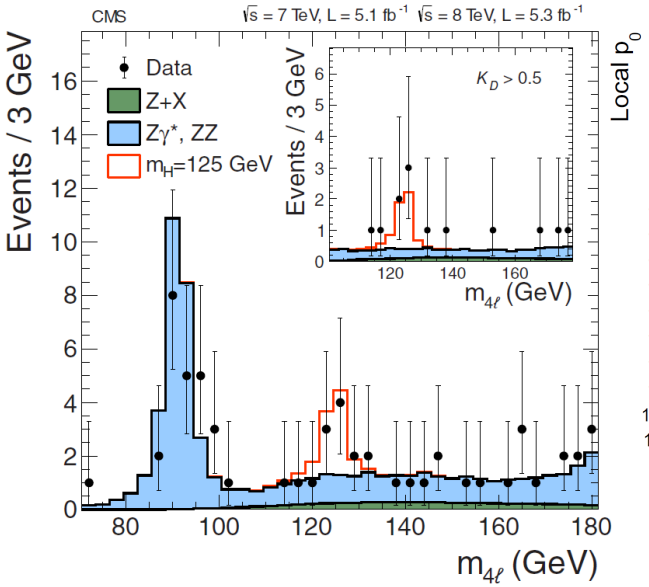
Higgs Boson Knowledge

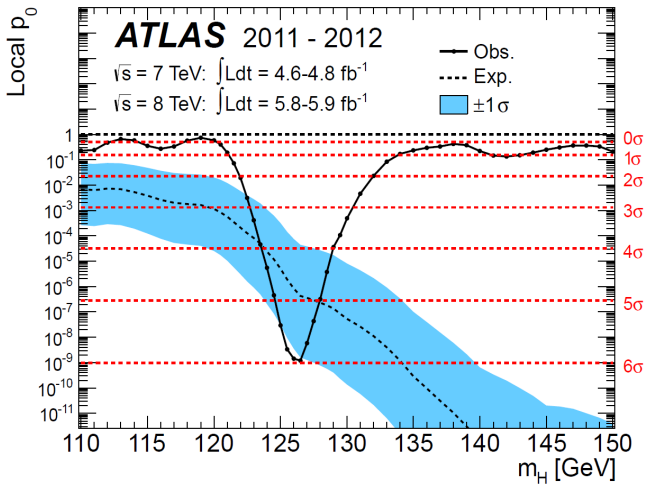
July 2012: LHC discovery of a new boson with mass 125 GeV in 4 lepton and $\gamma\gamma$ final states, consistent with the SM Higgs

3.1σ (global) significance in $b\bar{b}$ final states at the Tevatron

Higgs programs are now about measuring the boson's properties

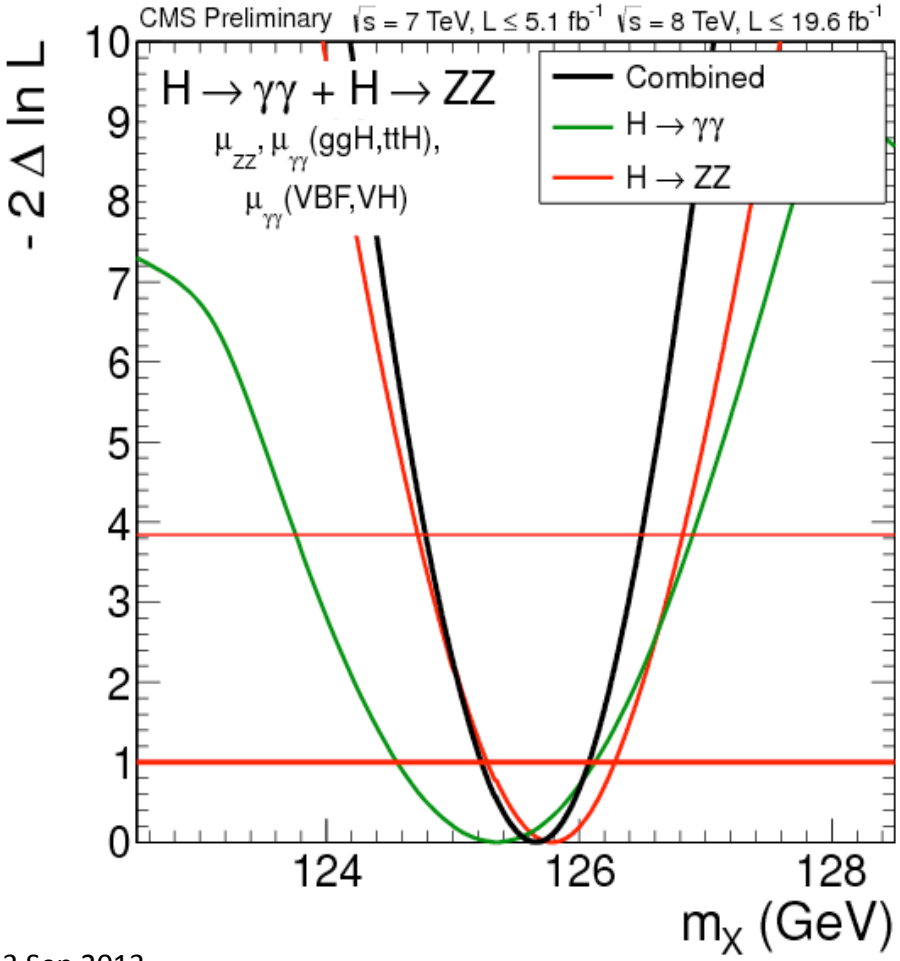


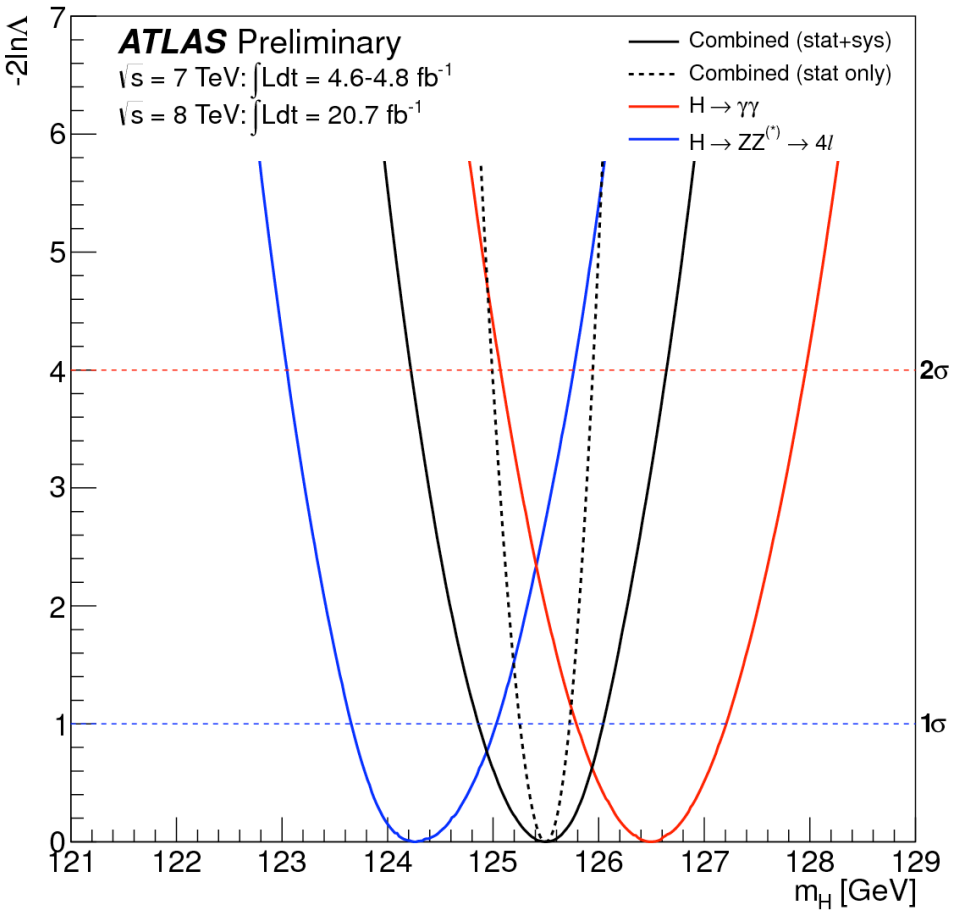




Properties of the new boson - mass

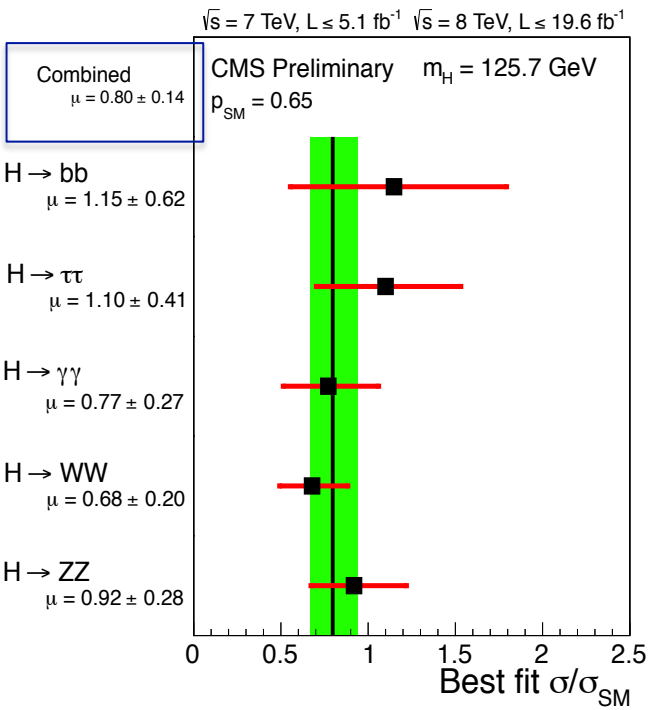
- Mass measurements are from the LHC
  - CMS: 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV
  - ATLAS: 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV

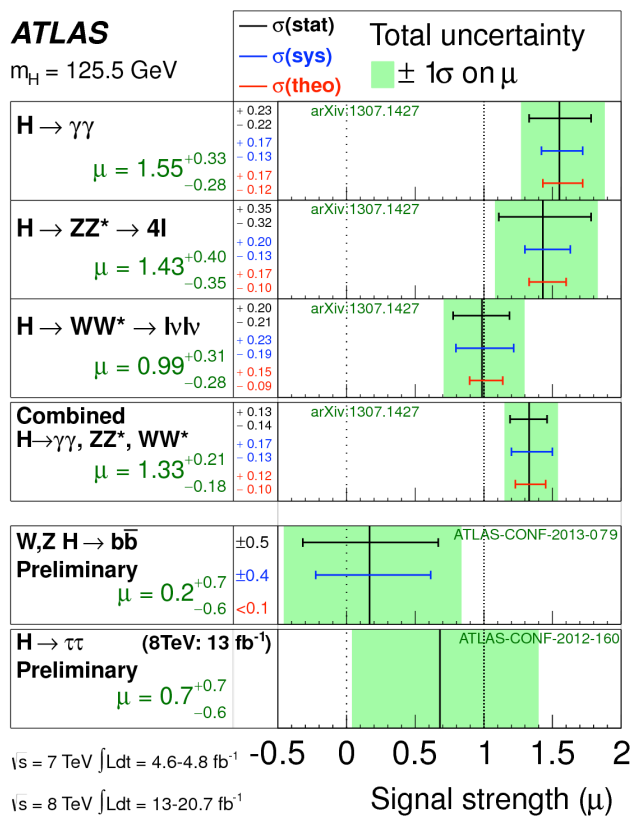


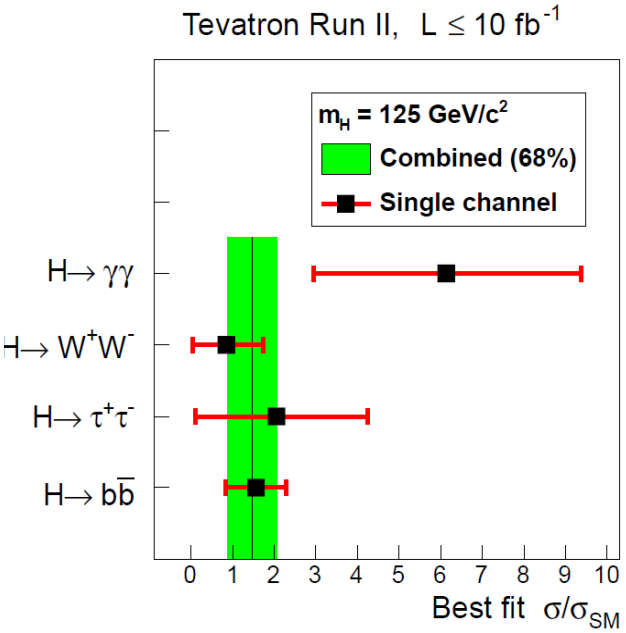


Properties - cross sections

- Measure cross sections and branching fractions using appropriate sub-channels
- Consistent with SM







Properties - couplings

- Fix mass at 125 GeV; perform best fit of 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.)

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

Some examples:

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

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

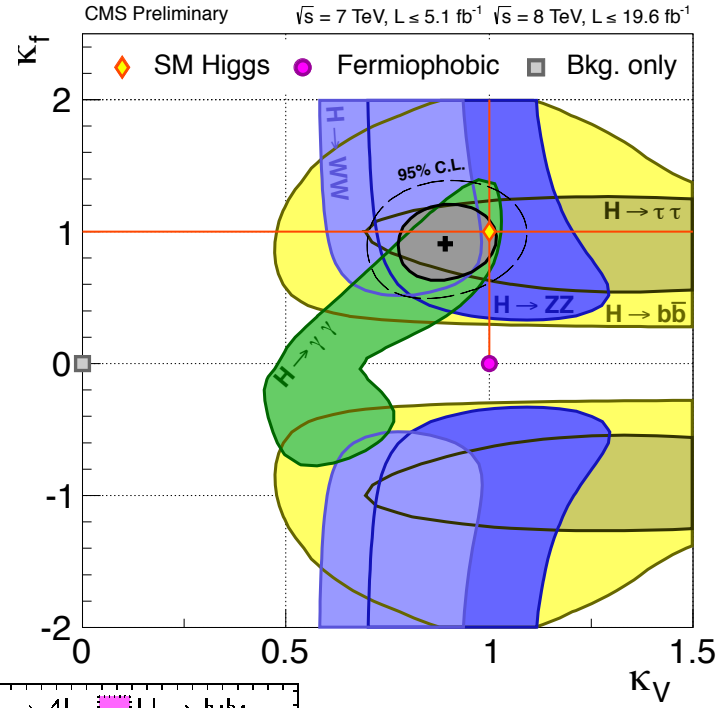
$$\Gamma_{ZZ} \propto \kappa_V^2$$

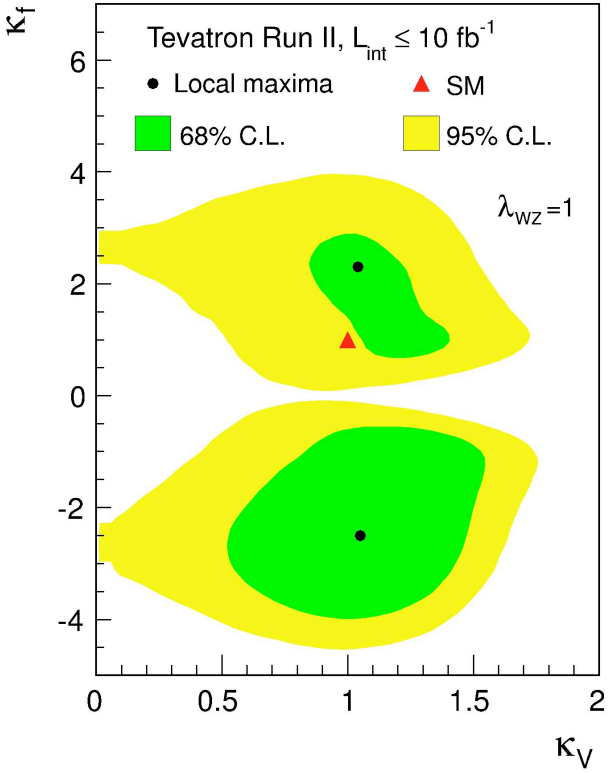
$$\Gamma_{gg} \propto (0.95\kappa_f^2 + 0.05\kappa_V^2)$$

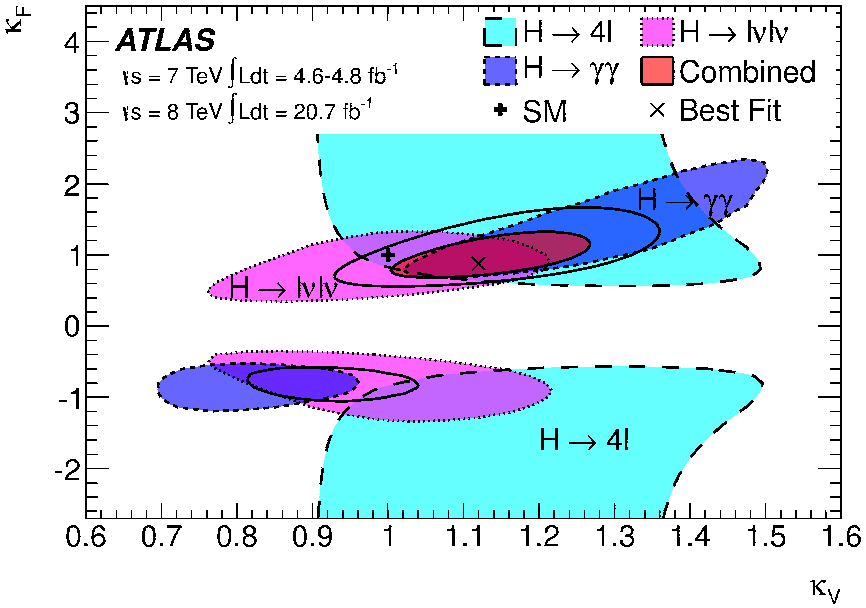
$$\Gamma_{\gamma\gamma} \propto (1.28\kappa_V - 0.28\kappa_f)^2$$

Properties - couplings

- Measure cross sections and branching fractions using appropriate sub-channels
- Couplings and expected decay modes consistent with a standard model Higgs boson within uncertainties

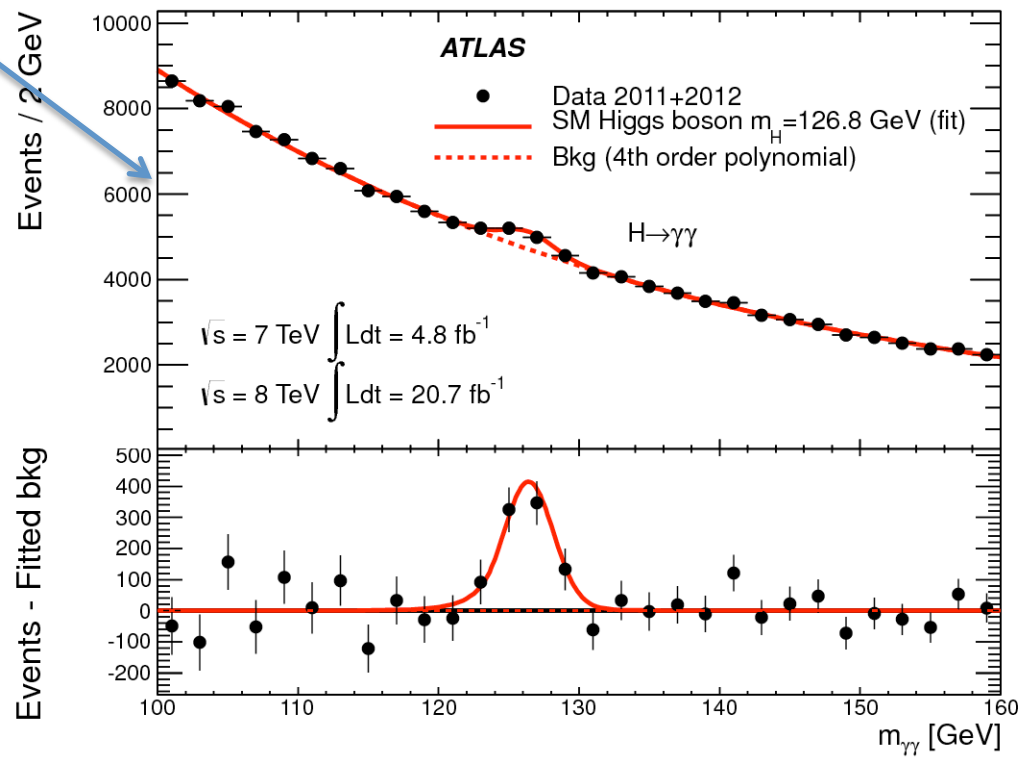






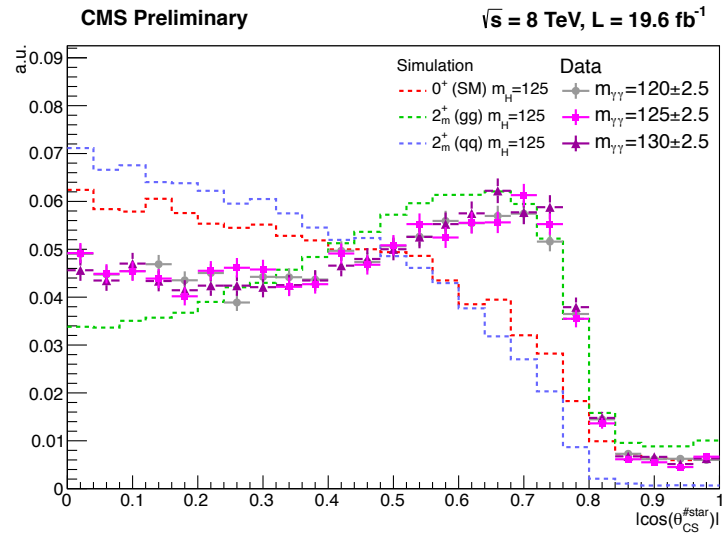
Spin and Parity Introduction

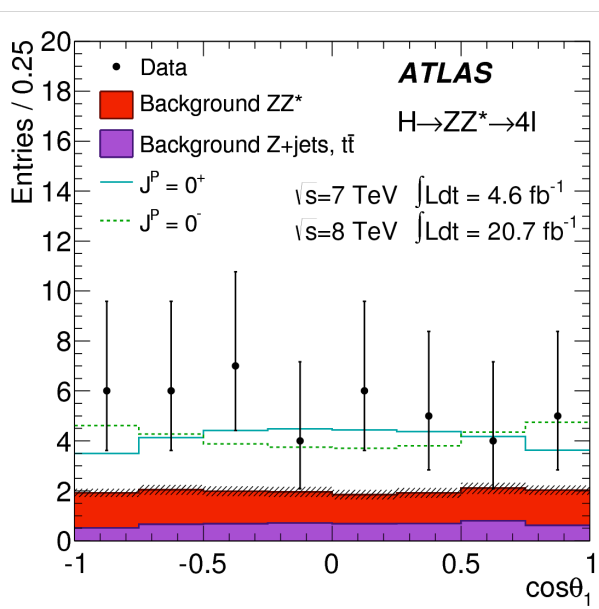
- SM predicts a spin J and parity P combination $J^P = 0^+$
- Other possibilities are 2^+ (graviton-like couplings) and 0^- (a pseudoscalar)
- Spin 1 ruled out via decay to two photons (Landau-Yang Theorem)

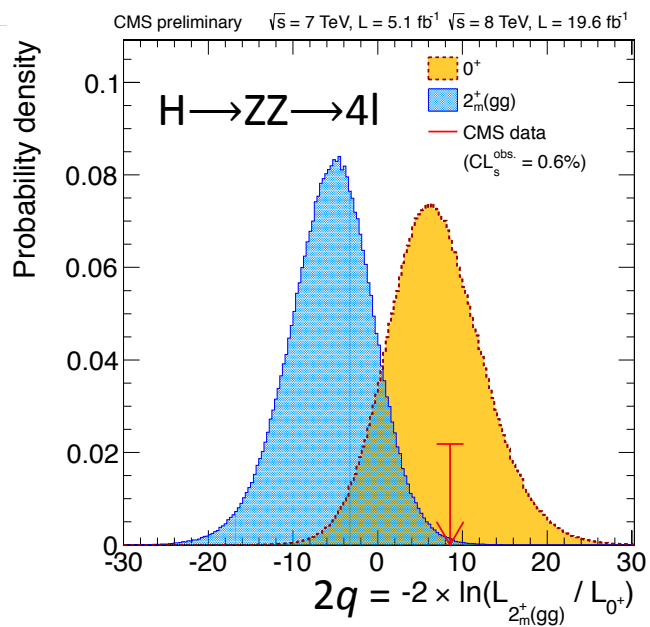


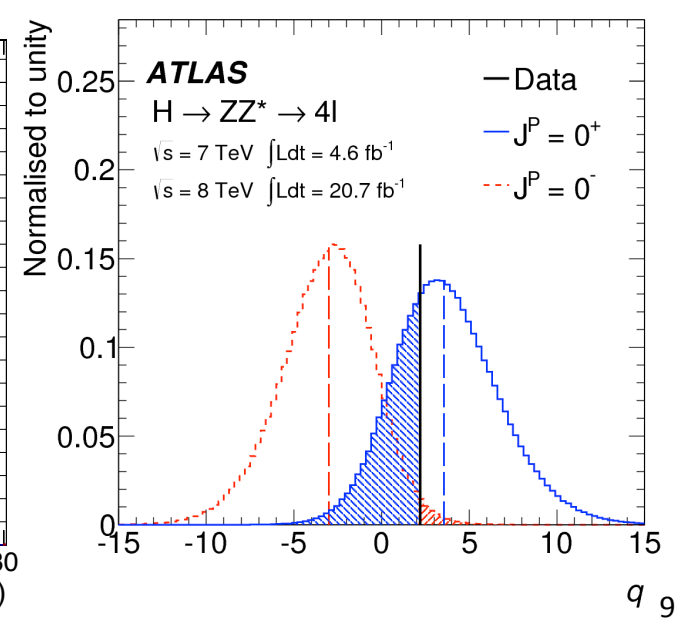
Higgs Spin and Parity at the LHC

- Measurements use bosonic decay modes, take advantage of angular correlations and kinematics of Higgs decay products
- All measurements consistent with $J^P = 0^+$







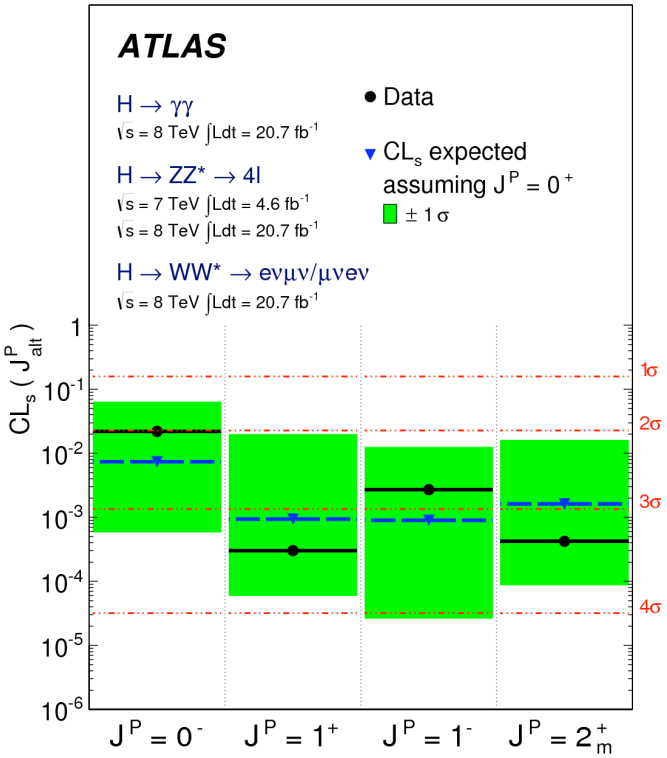


Higgs Spin and Parity at the LHC

- $J^P \neq 0^+$ excluded at 99.9% C.L. (ATLAS 2^+) and 99.8% C.L. (CMS 0^-)
- No measurements using fermionic final states yet
- We need a consistent picture in ALL expected Higgs decay modes
  - The Tevatron has a unique opportunity to study Higgs spin and parity in the bb decay mode

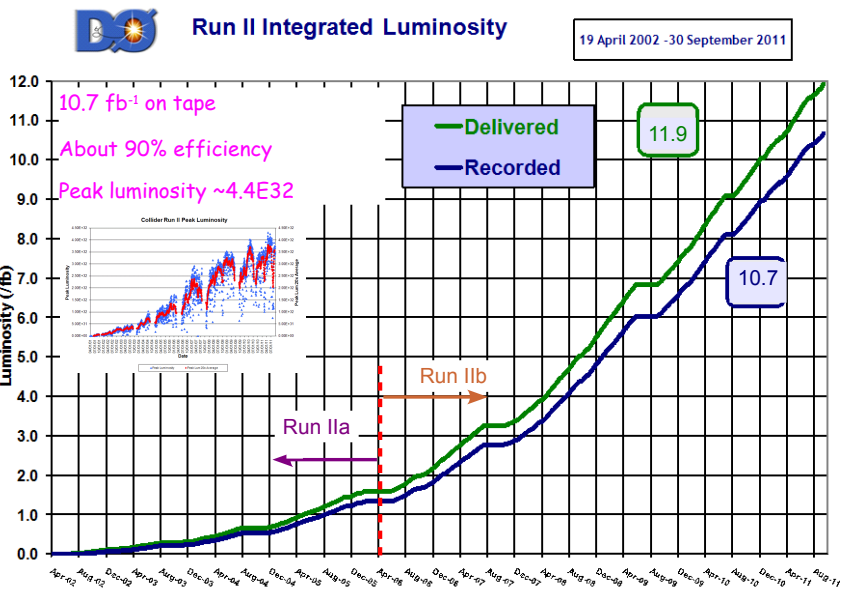
CMS H⟶ZZ⟶4 lepton

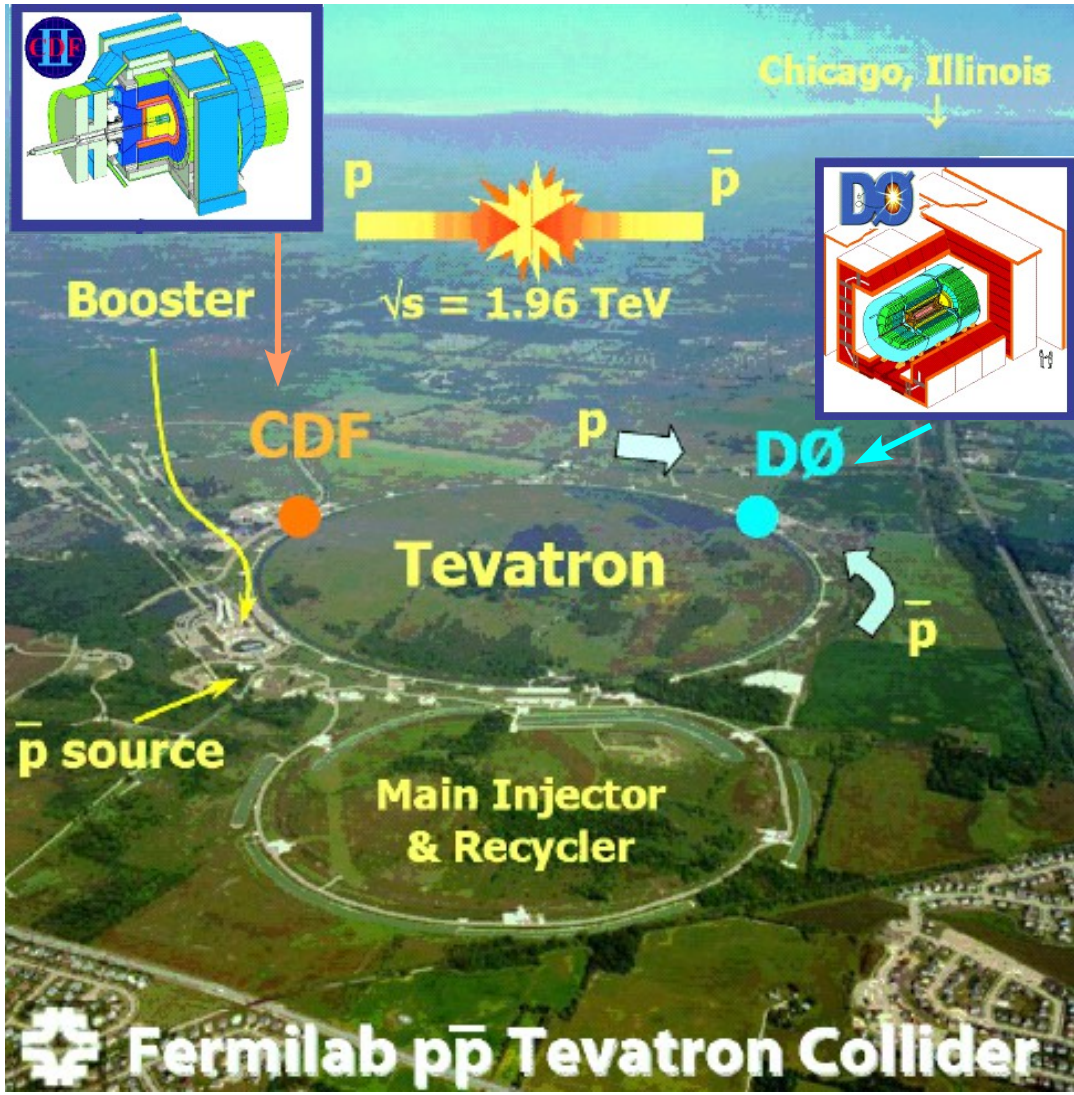
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%



The Tevatron

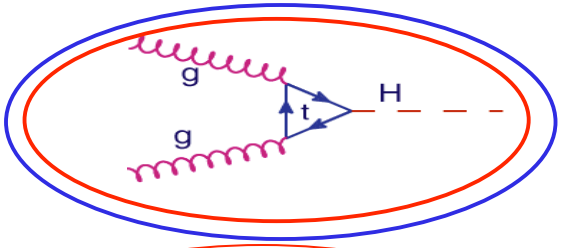
- 1.96 TeV $p\bar{p}$ collider
- Integrated Luminosities up to 10 fb^{-1}/exp.



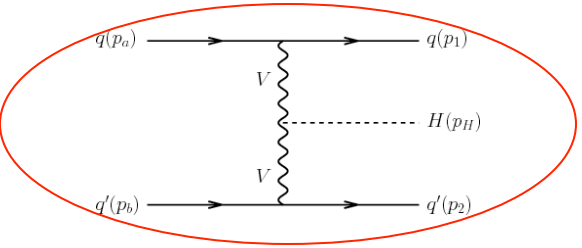


Tevatron-LHC Complementarity

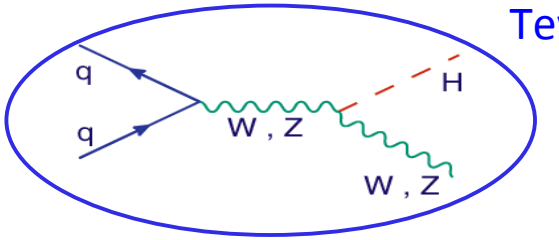
Tevatron contributes to property measurements, especially in fermionic decay modes



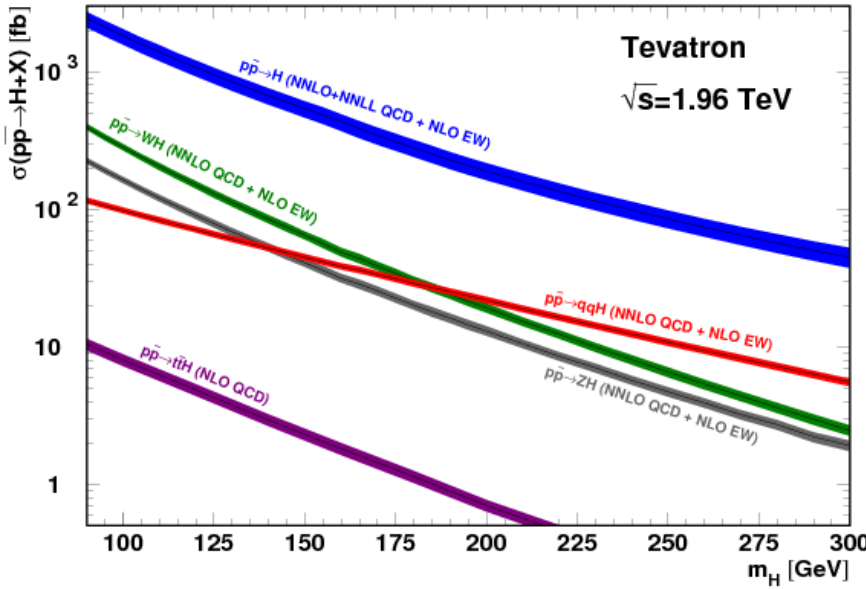
Tev, LHC



LHC



Tev



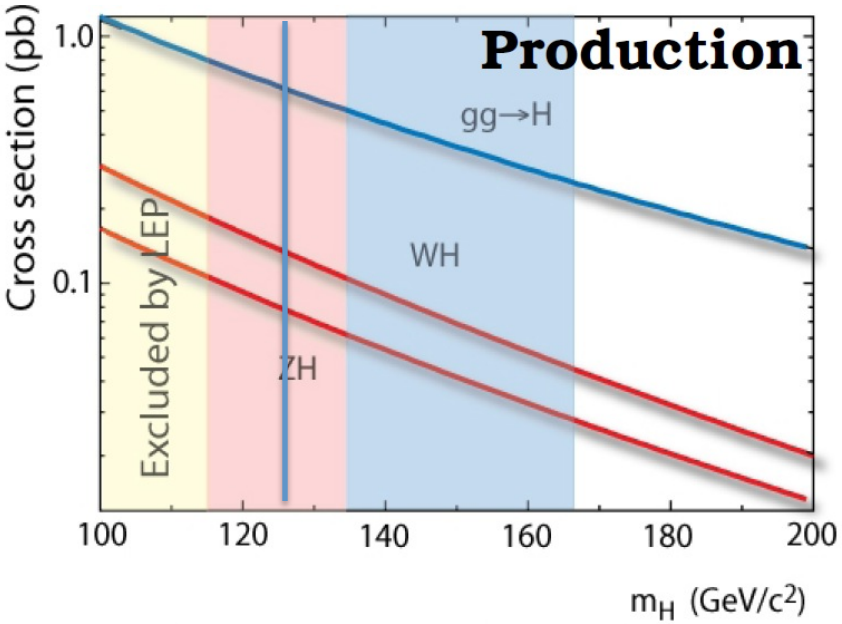
Tevatron main modes: VH→V bb, H → WW*

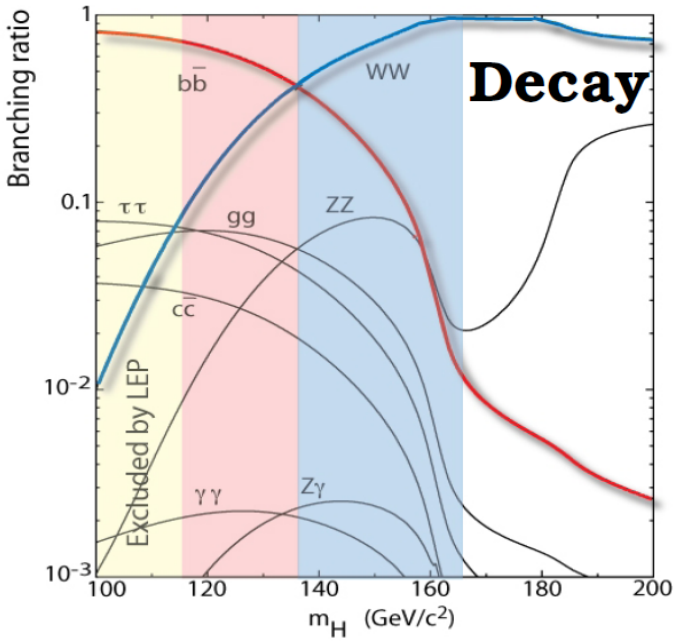
LHC main modes: H → γγ, H→ZZ, H→WW*

Higgs Analyses at the Tevatron

- Analyses divided into "Low-mass" and "High-mass" based on production and decay mode
- Low-mass: associated production $VH \rightarrow Vb\bar{b}$
- High-mass: H→*WW* decays (mostly gg prod.; also VH, VBF)
- Also contributions in secondary (ττ, γγ) channels

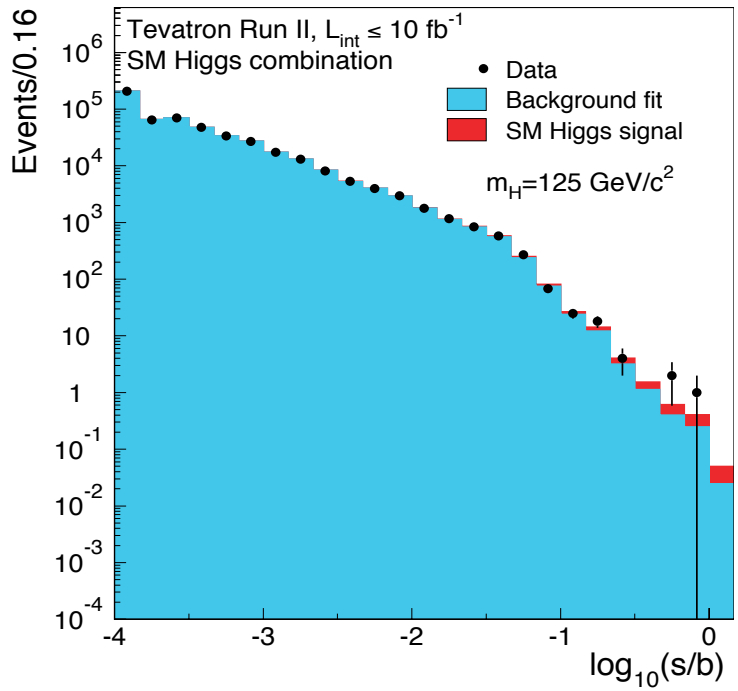
More details in the Mar. 22 W&C by Lidija Zivkovic

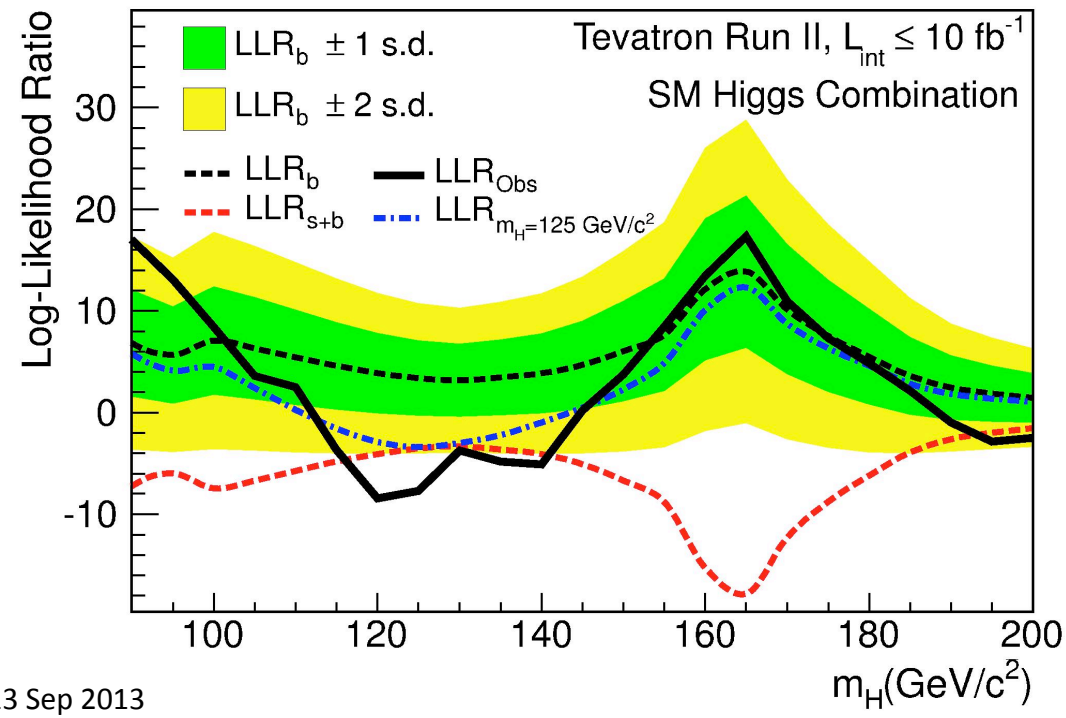


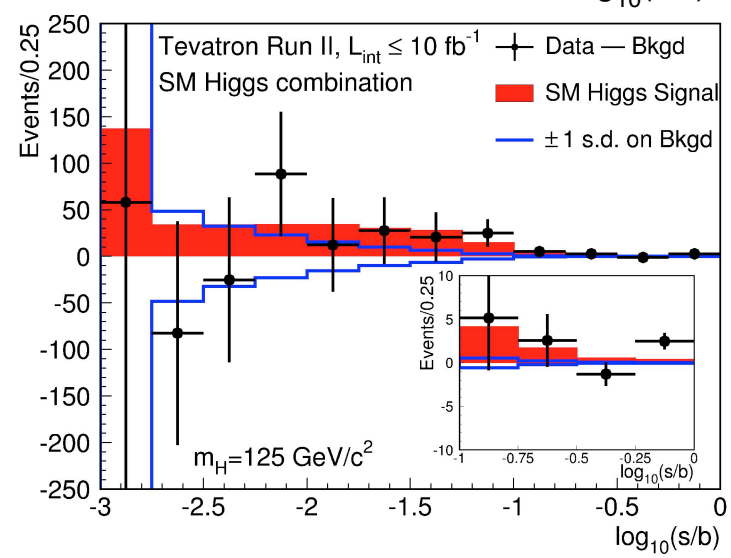


Tevatron Combination

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







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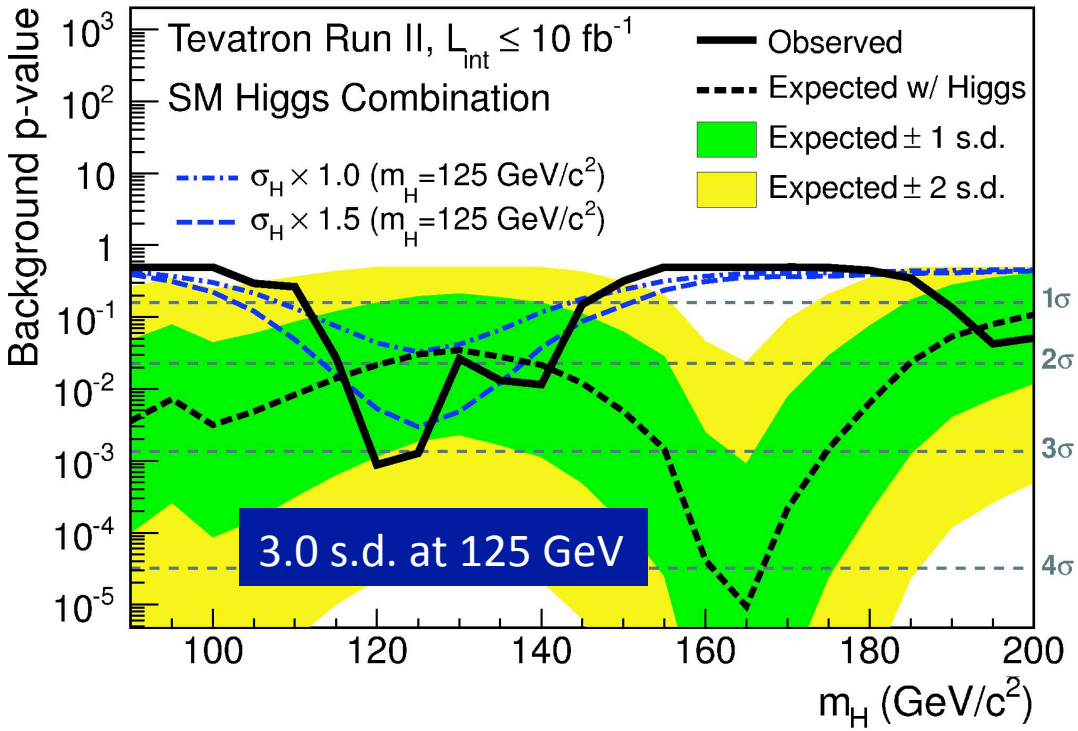
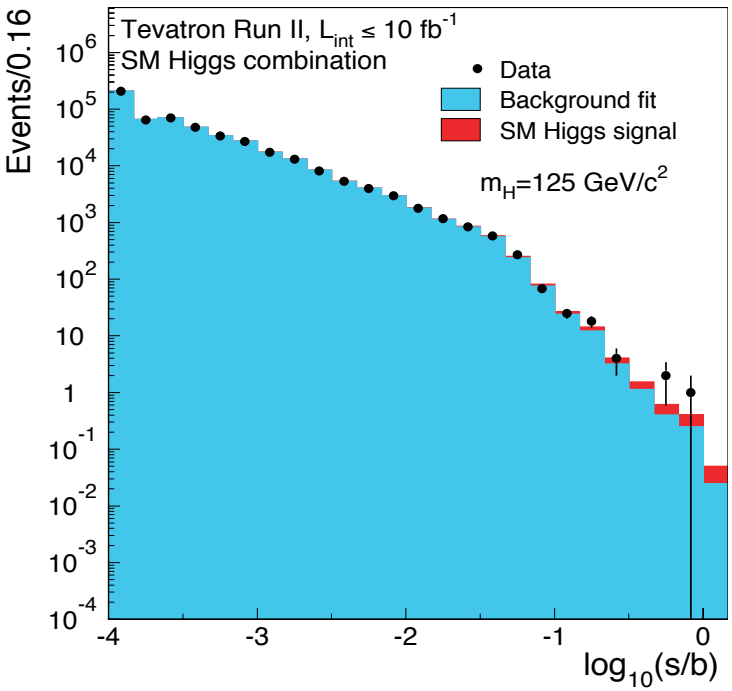
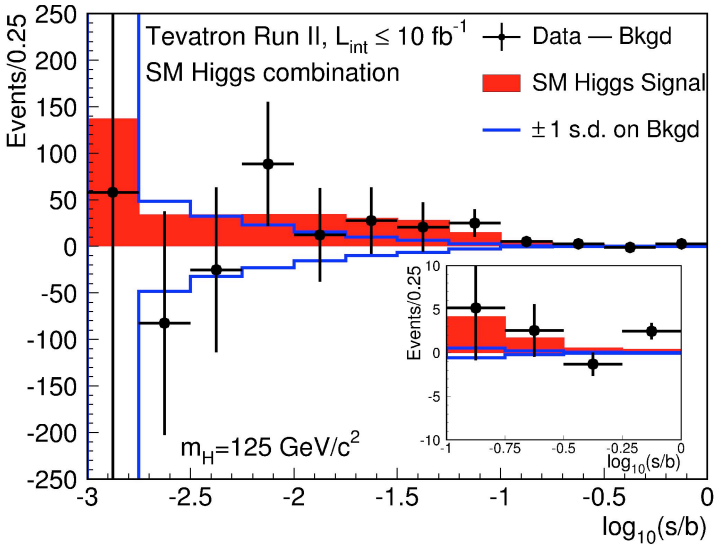
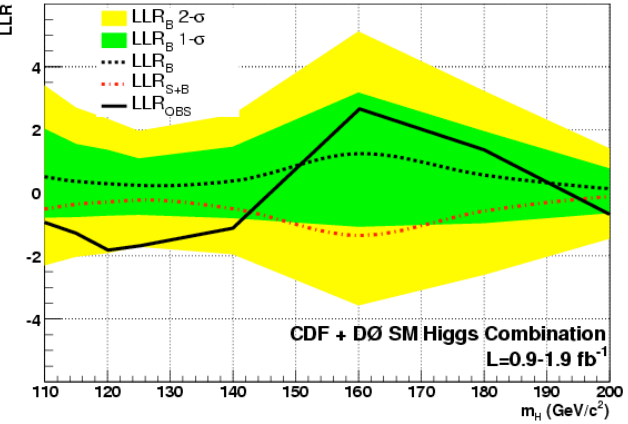




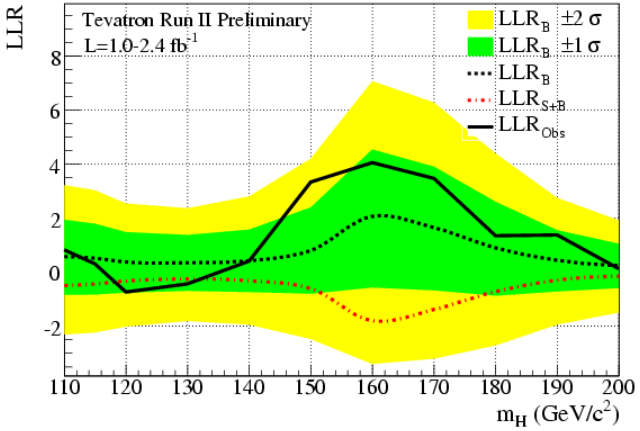


Tevatron Higgs Through the Years

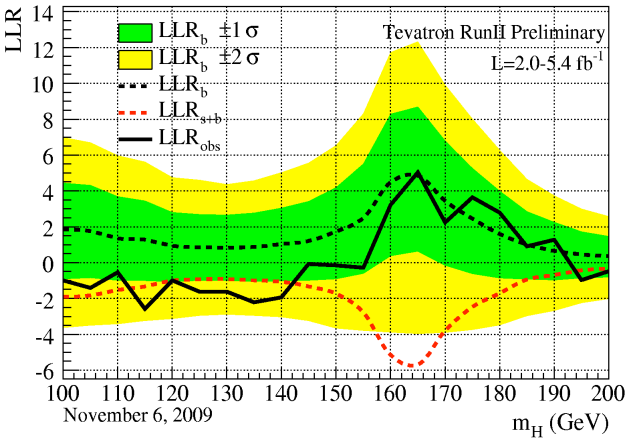
2007



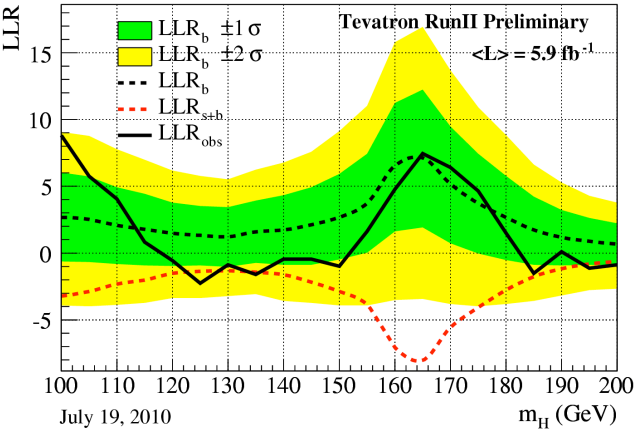
2008



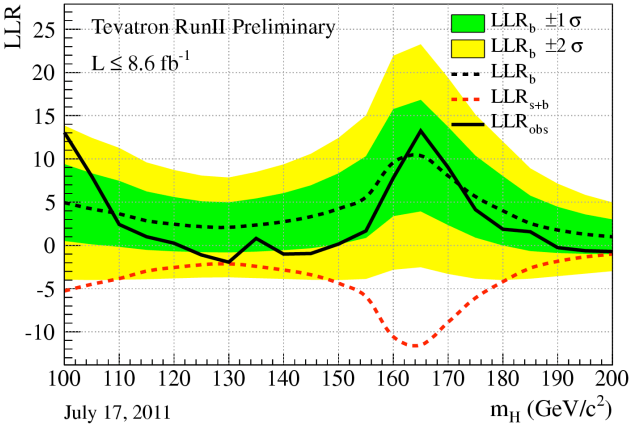
2009



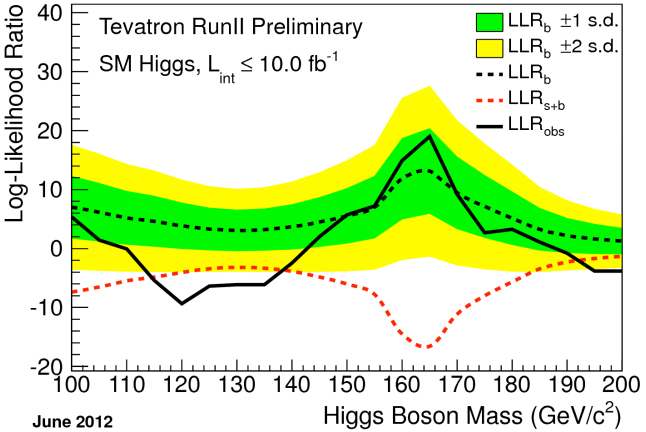
2010



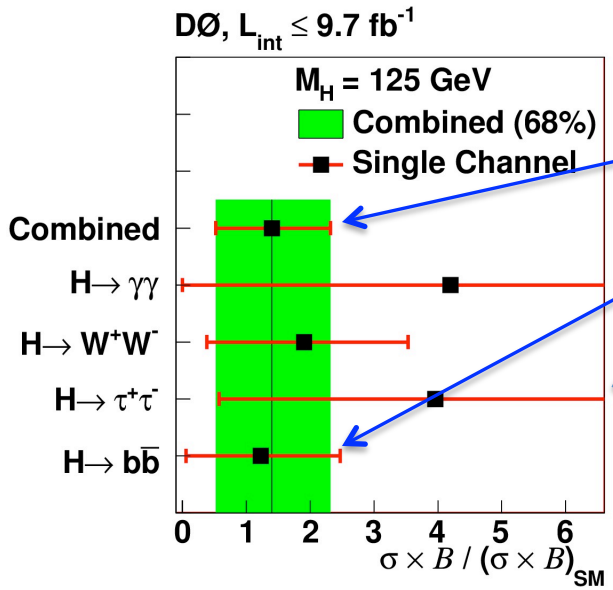
2011



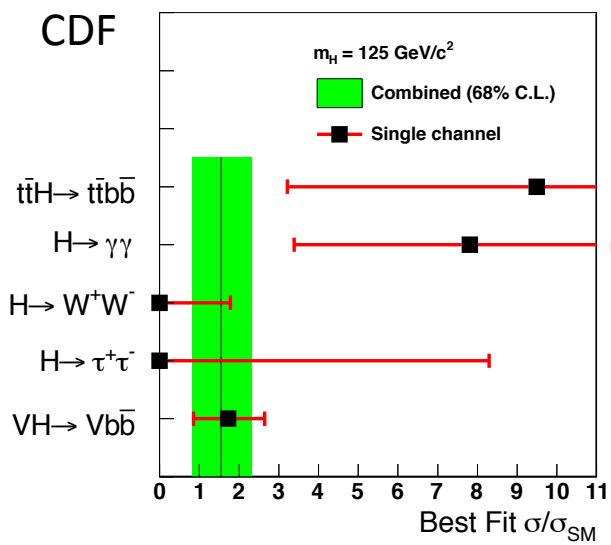
2012



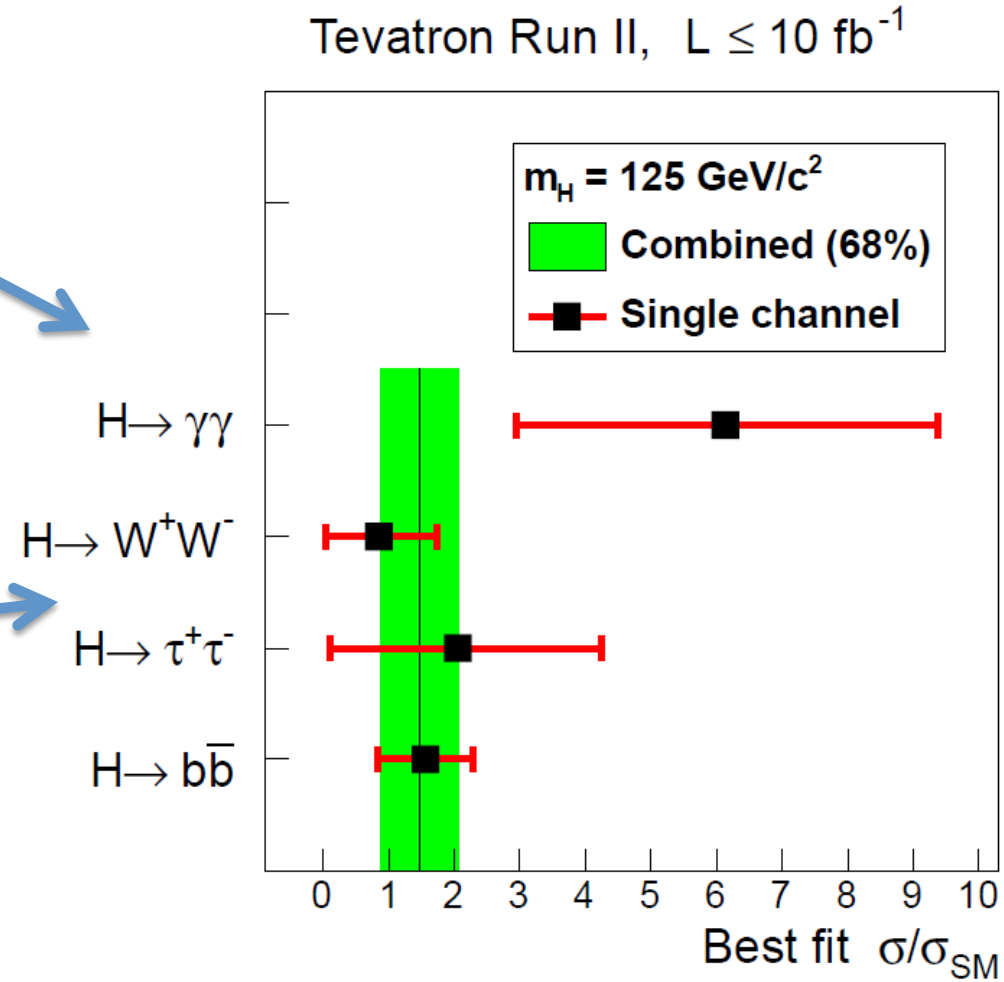
Tevatron σ × Br



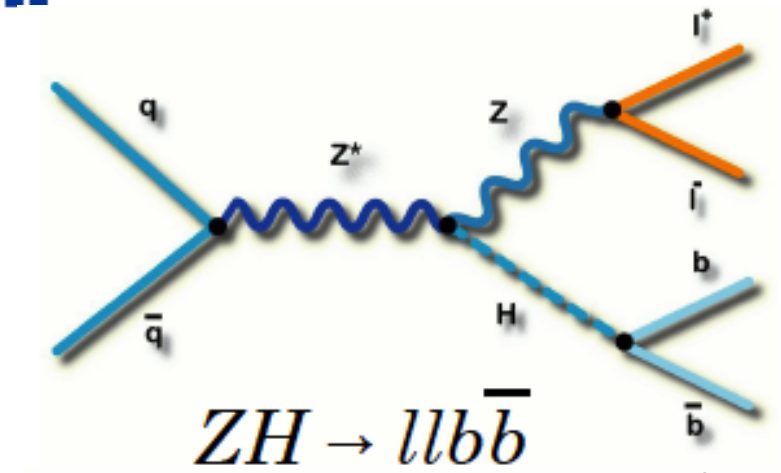
D0 combined rate: 1.40 x SM
D0 H⟶bb rate: 1.23 x SM



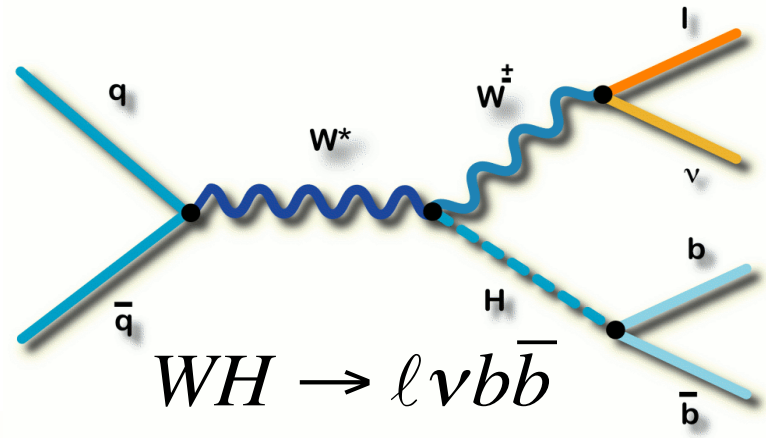
CDF combined rate: 1.54 x SM



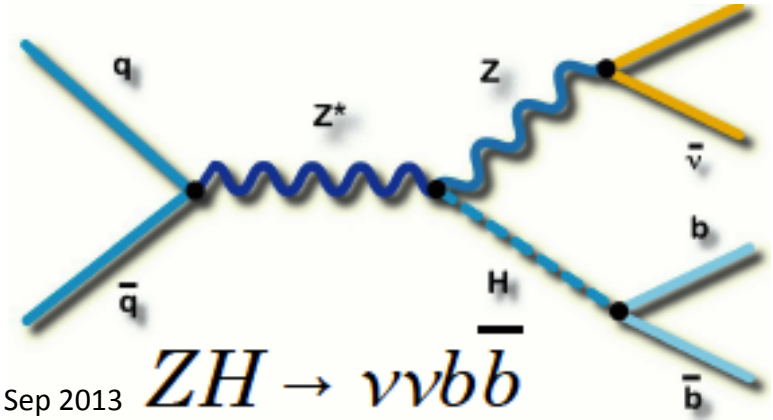
VH⟶ Vb$\bar{b}$ Analyses



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



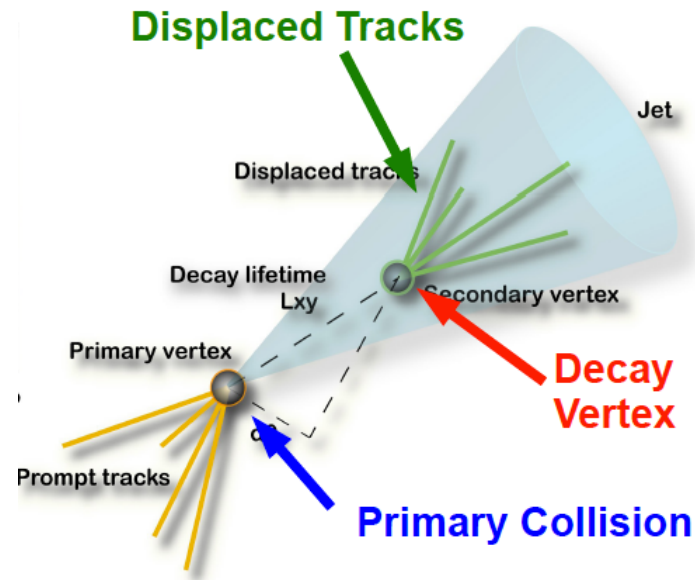
- WH → lνbb – 1 lepton + MET + 2 b-jets
- Dominant backgrounds: W+jets, top
- Multijet backgrounds challenging

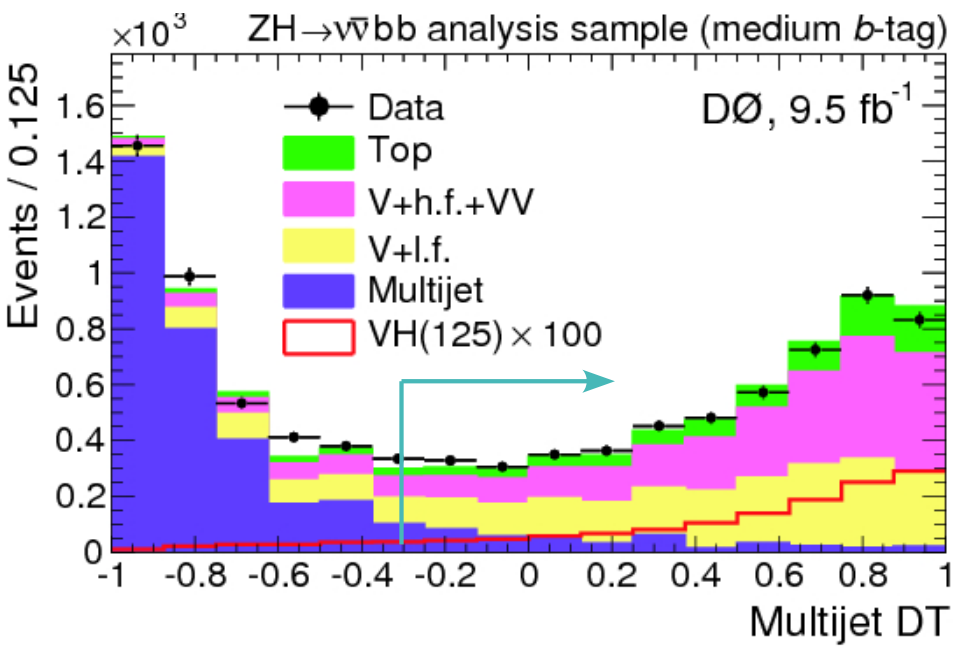


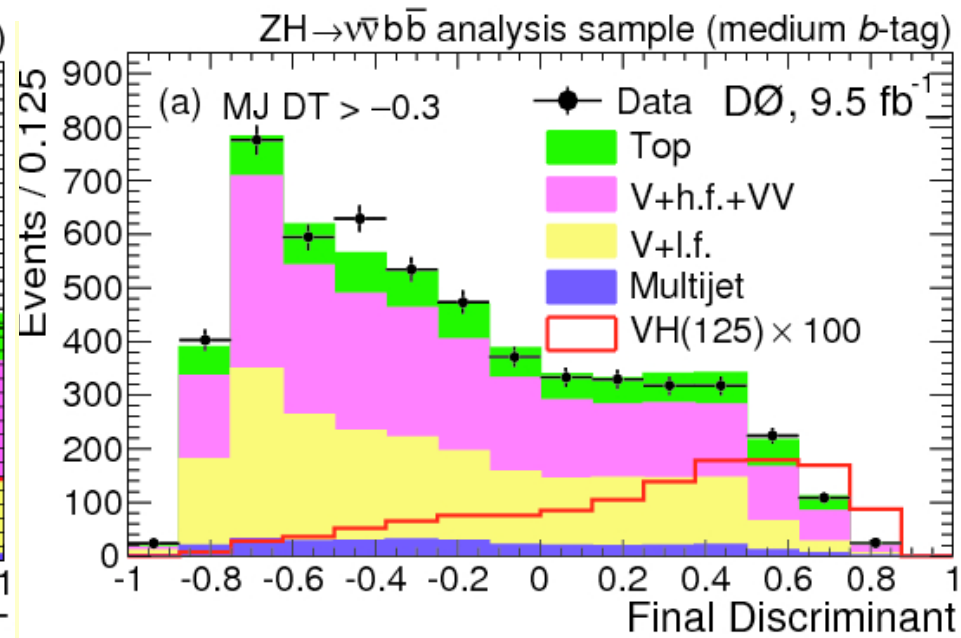
- ZH → ννbb – MET + 2 b-jets (contribution from WH also)
- Accurately model and reject multijet background

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
  - Discriminate against single backgrounds or against all
  - Multiple MVA techniques per analysis

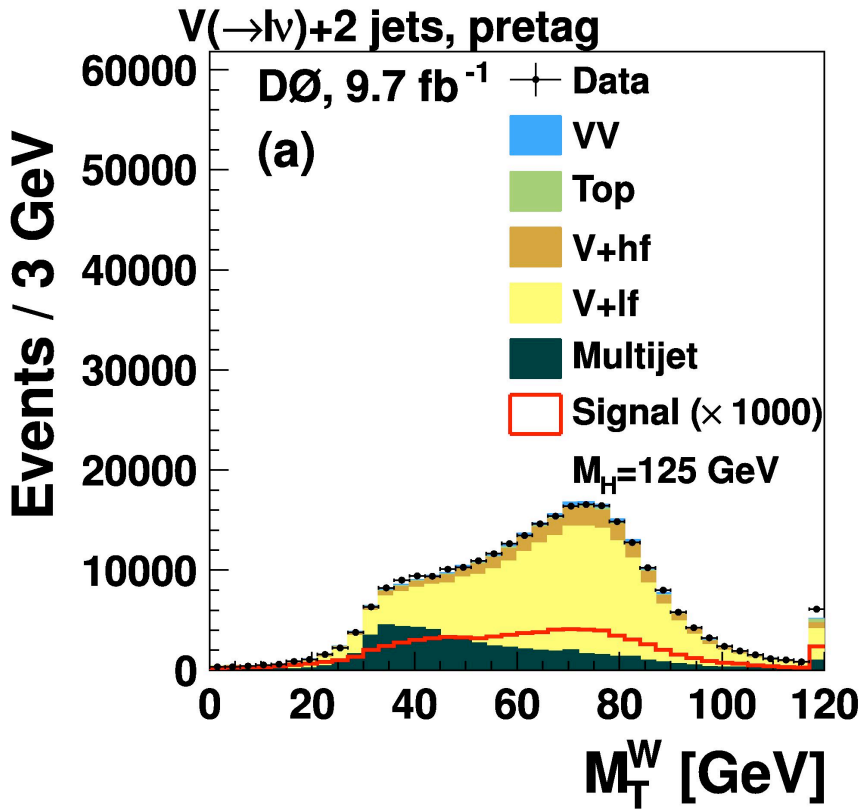


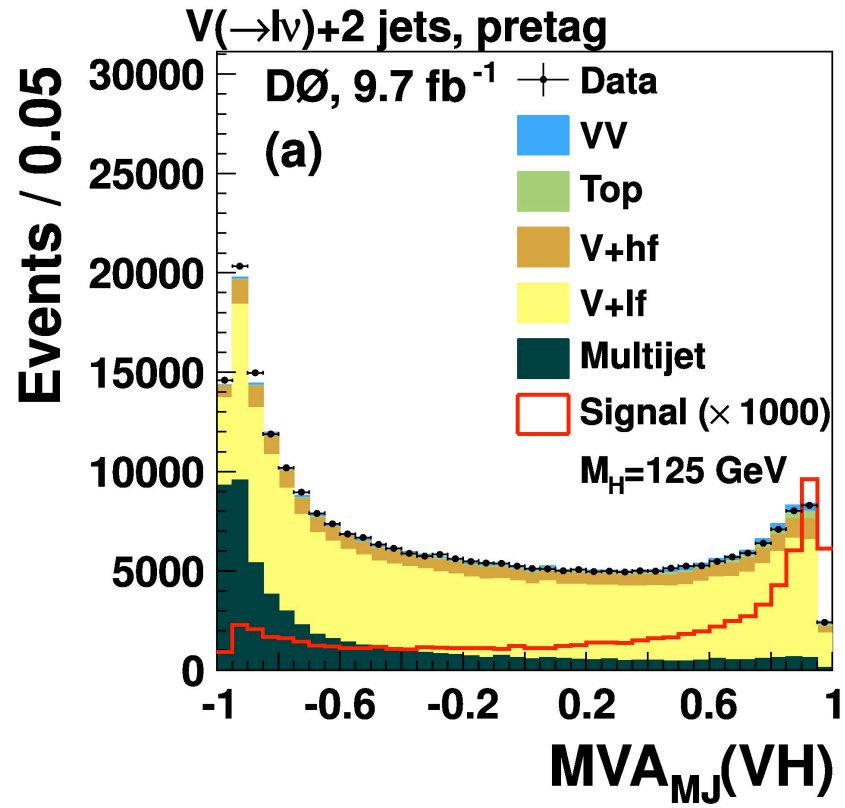




WH→lνbb̄ Search

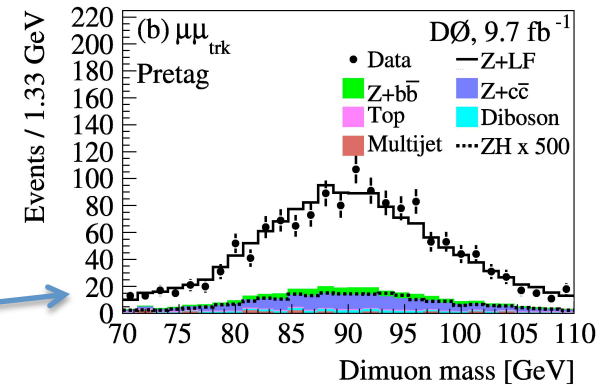
- Large *W*+jets background
- Also contributions from multijet background
  - Develop specialized decision tree to reject multijet events

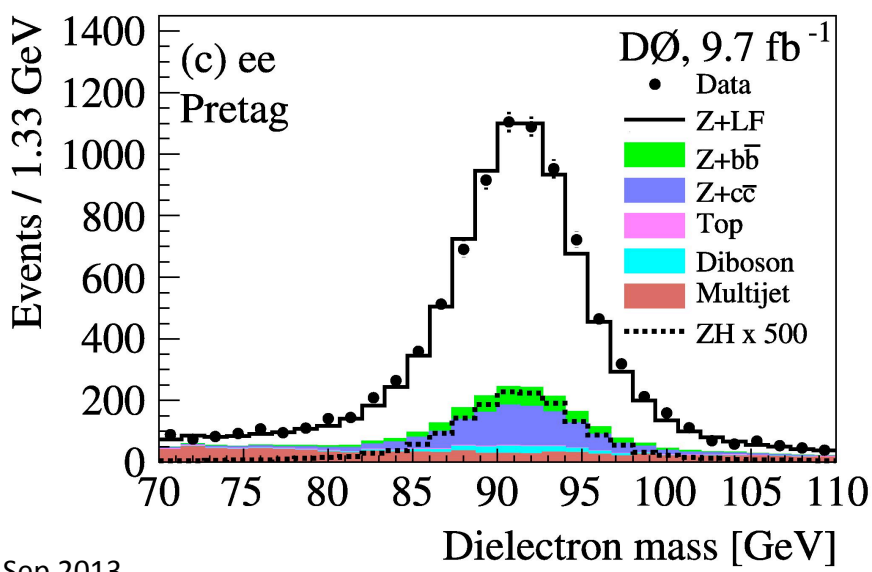


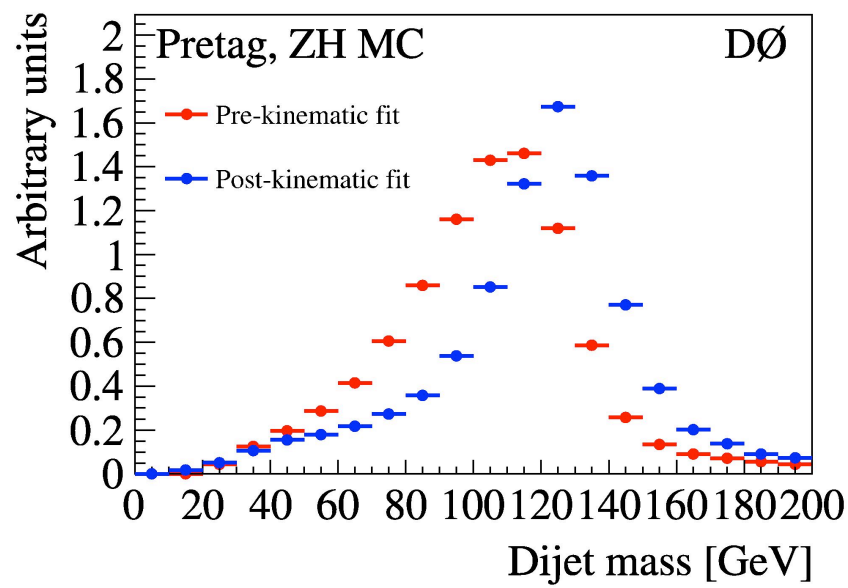


ZH⟶llb$\bar{b}$ Search

- Can derive MC normalizations from *Z* peak; reduces luminosity uncertainty
- Fully Reconstructed Final State
  - Able to use "kinematic fit" to correct physics objects to improve mass resolution
- Recover inefficiency with secondary channels where second lepton is not identified (mu+track, e+ICR electron)

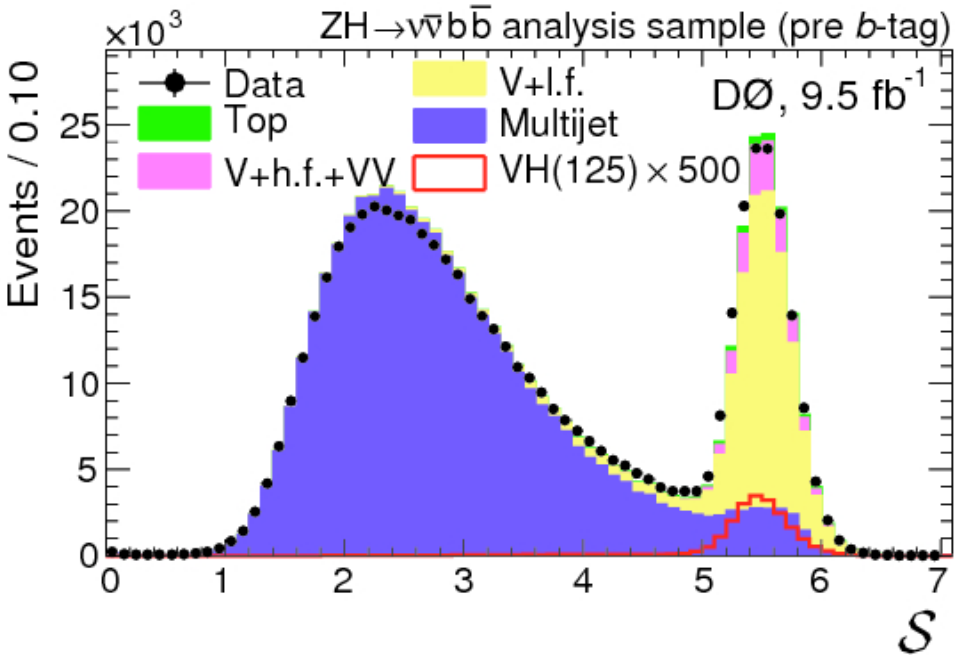


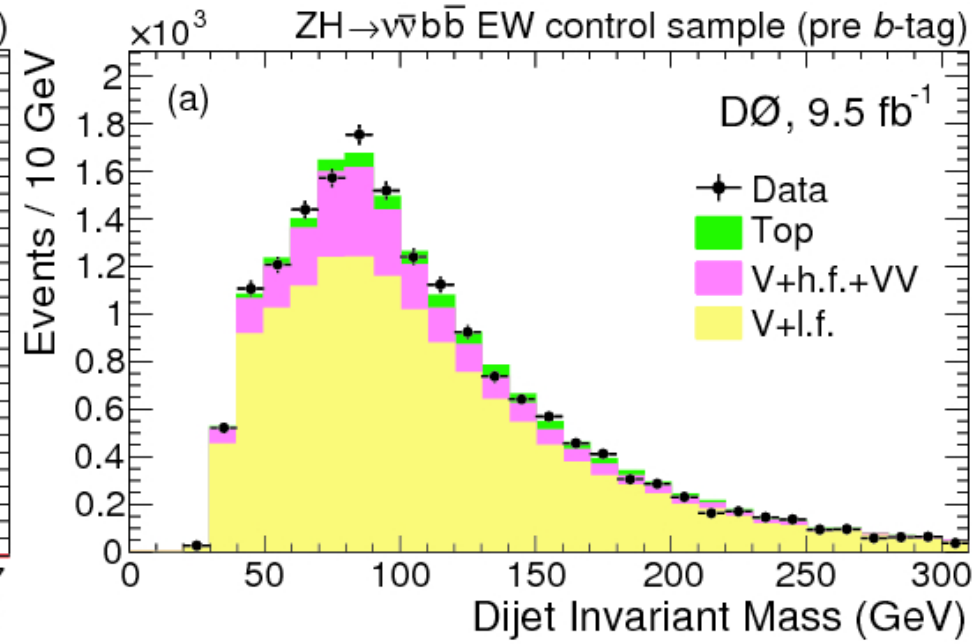




ZH→$\nu\nu b\bar{b}$ Search

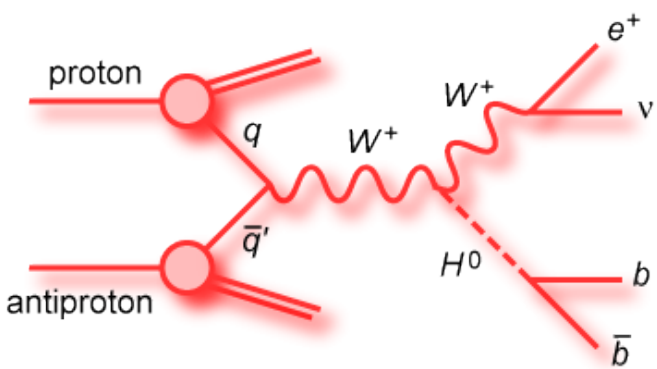
- Challenging multijet background
- Use variables such as MET significance (*S*) for discrimination; develop decision tree to reject multijet backgrounds
- Use sideband regions for electroweak and multijet background estimation

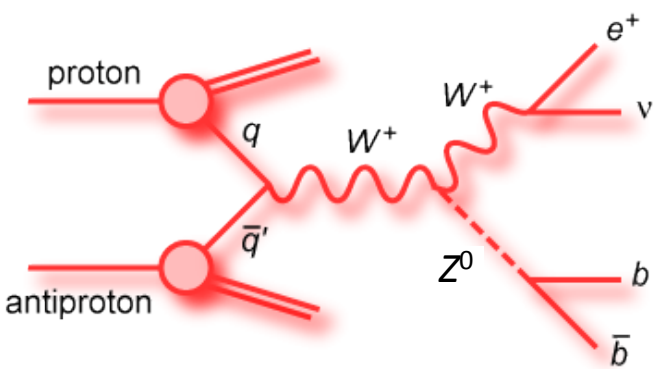




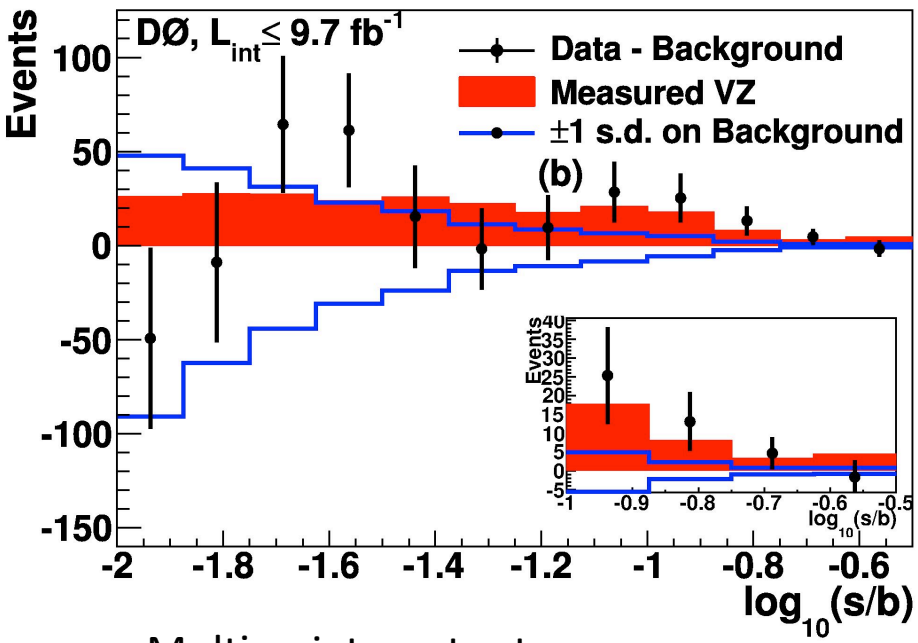
$H \rightarrow b\bar{b}$ Search Validation

- WZ and ZZ (with $Z \rightarrow b\bar{b}$): same final states as WH/ZH
  - 4-5 times larger cross section
- Remove WZ and ZZ from SM backgrounds, treat them as a potential signal, WW is a background
  - Do NOT change basic selection criteria from the WH/ZH analyses
- Perform WZ+ZZ (VZ) cross section measurement (also done by CDF)
- Also evaluates quality of background modeling

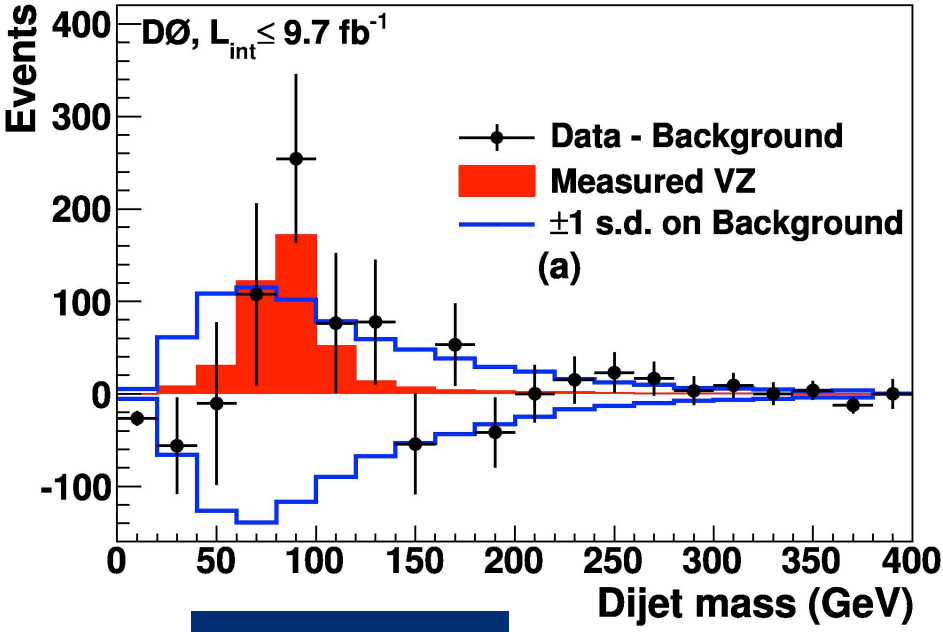




Benchmark results



Multivariate output

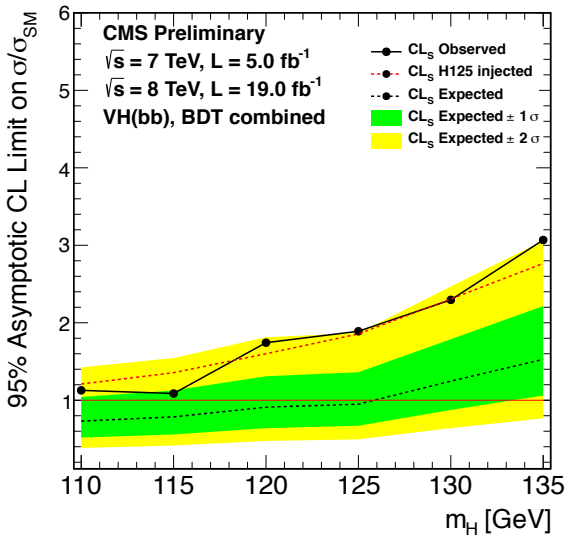


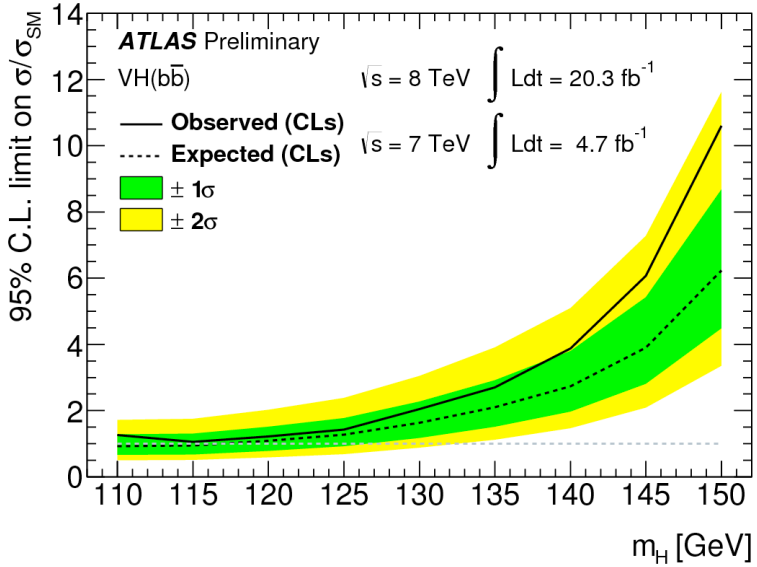
M_Z = 91.1 GeV

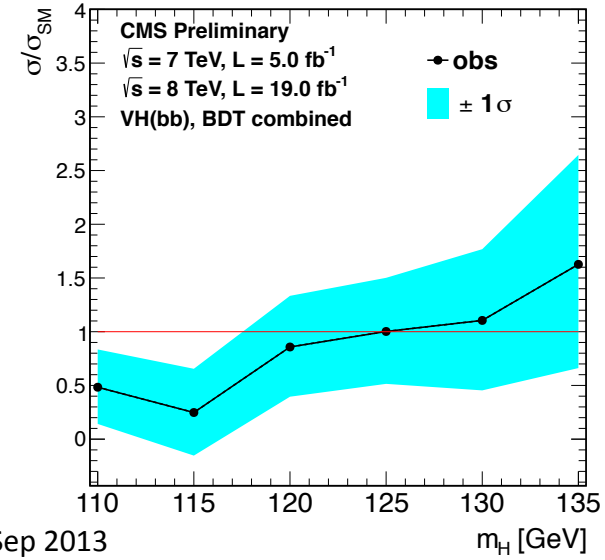
D0 measured VZ cross section: (0.73 ± 0.32) x SM prediction of 4.4 pb
3.4 σ expected sensitivity

VH⟶Vb$\bar{b}$ @ LHC status

- Higgs decay to b$\bar{b}$ not yet observed
- Hints consistent with SM

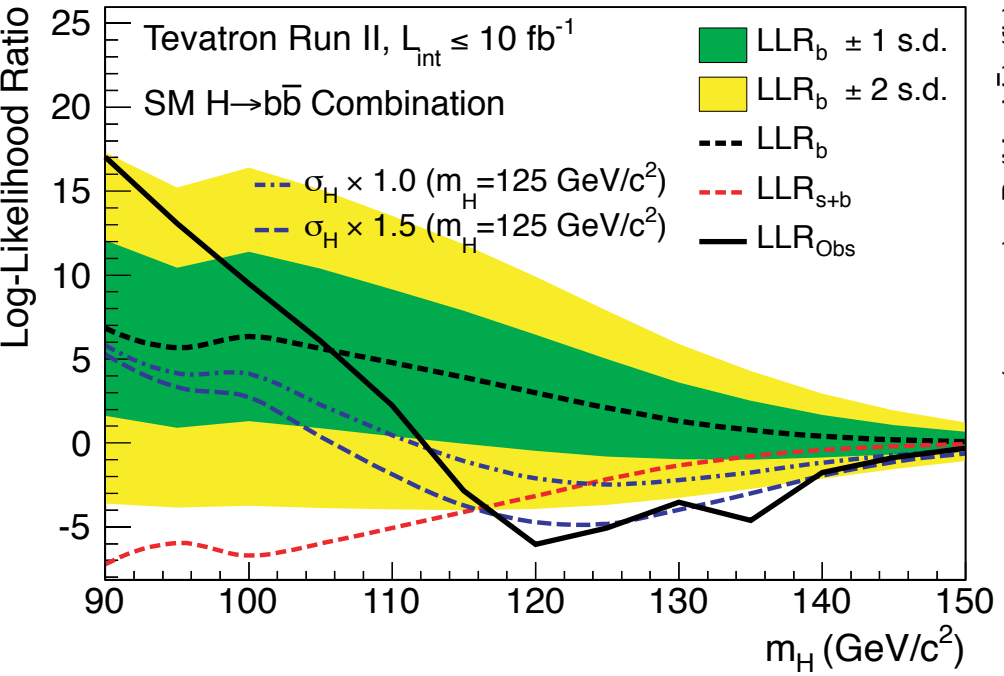


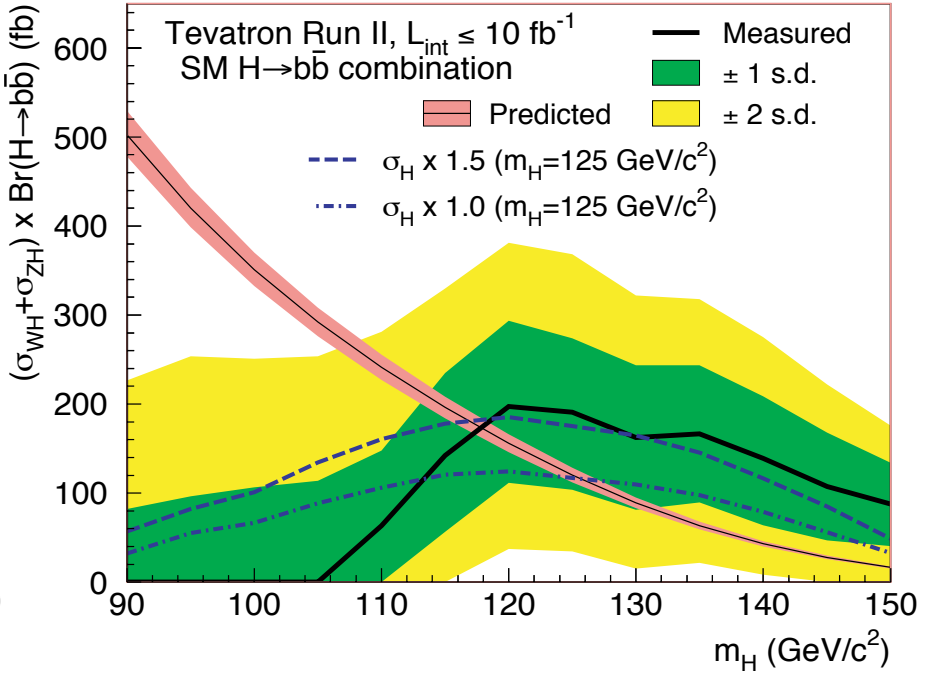




CMS: σ(VH) = 1.0 ± 0.5 (stat. + syst.) × SM (2.1 σ signif.)
ATLAS: σ(VH) = 0.2 ± 0.5 (stat.) ± 0.4 (syst.) × SM

Tevatron VH⟶Vb$\bar{b}$ Results

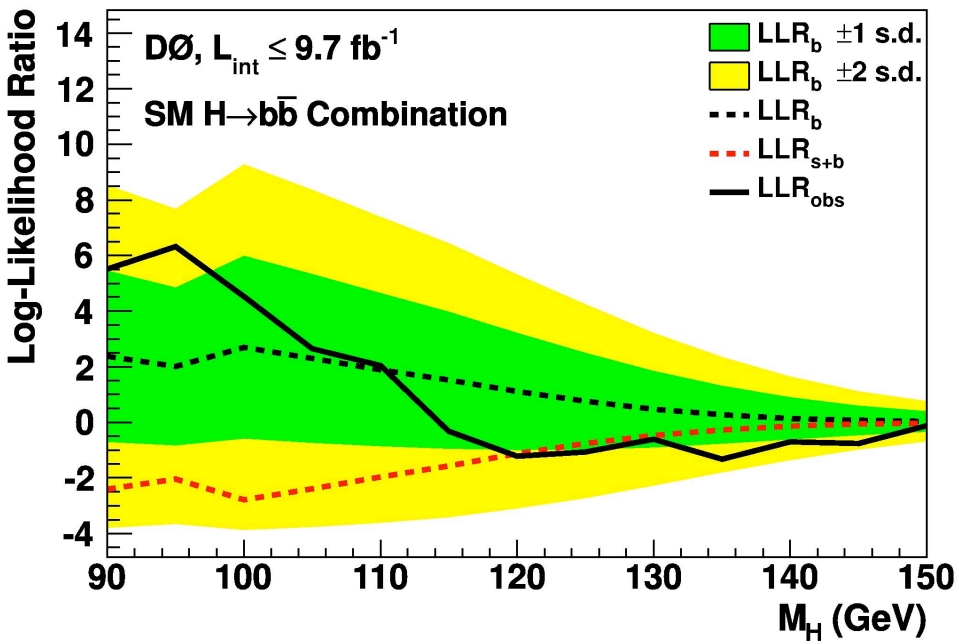


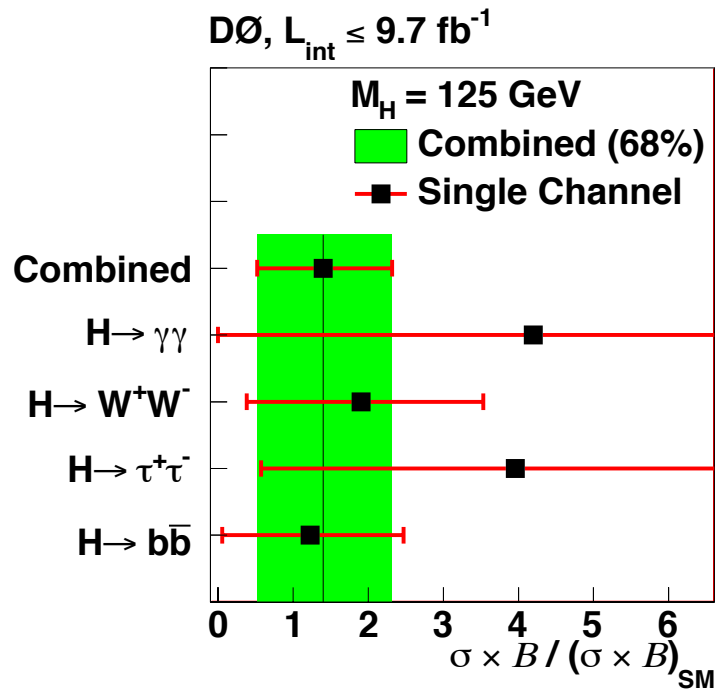


Measured $(\sigma_{WH}+\sigma_{ZH})\times B(H\longrightarrow b\bar{b})$: 0.19 ± 0.09 pb
SM prediction: 0.12 ± 0.01 pb
σ/σ_{SM} = 1.6 ± 0.7

D0 VH⟶Vb$\bar{b}$ Results

- 3 Analyses: WH->lvb$\bar{b}$, ZH->llb$\bar{b}$, ZH->vvb$\bar{b}$
- Inputs to final D0 Higgs combination; excess compatible with SM Higgs
- Best fit H->bb cross section: $1.23^{+1.24}_{-1.17} \times$ SM





Spin and Parity at the Tevatron

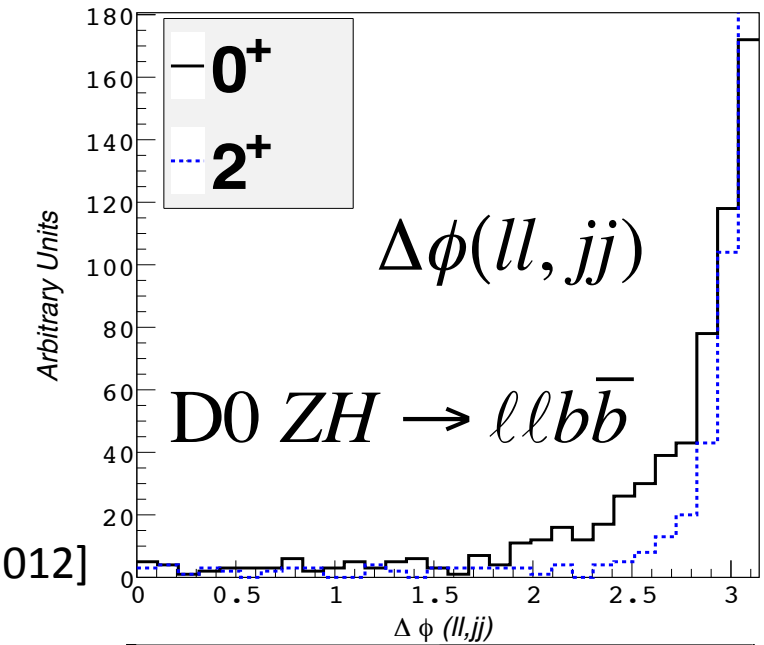
- LHC uses decay product and angular information in bosonic decays (mostly gg + VBF production modes)
- In associated production, production processes are different depending on J^P assignment
  - For 0^+, production is S-wave; cross section $\sim\beta$ near threshold
  - For 0^-, production is P-wave; cross section $\sim\beta^3$ near threshold
  - For 2^+, D-wave contribution dominate for graviton-like couplings; cross section $\sim\beta^5$
- Thus at the Tevatron we expect the kinematic differences to come from different behaviors at the production threshold

Details in
Miller, Choi, Eberle, Muhlleitner, and Zerwas, PLB **505**, 149 (2001)
Ellis, Hwang, Sanz, You, JHEP **1211**, 134 (2012)

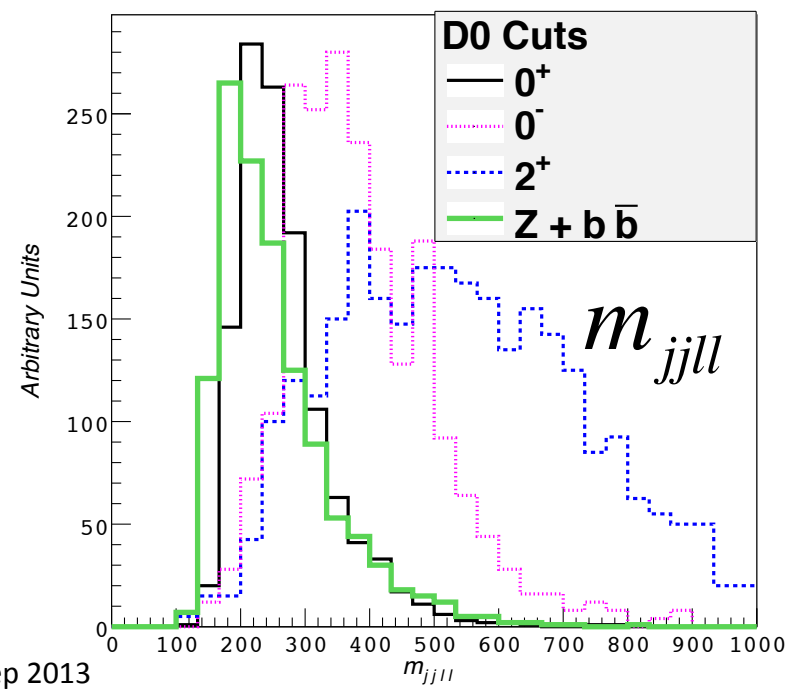
$$\beta = 2p/\sqrt{s}$$

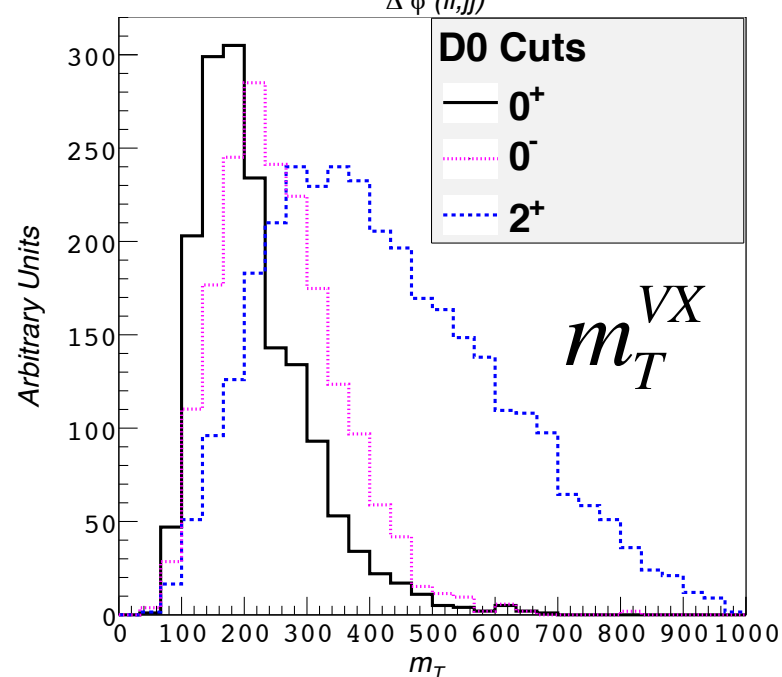
Testing Spin and Parity

Visible mass of Vbb system very sensitive to J^P assignment, good separation with backgrounds for 2+ and 0- as well



plots from Ellis, Hwang, Sanz, You, JHEP **1211**, 134 [2012]





Testing Spin and Parity

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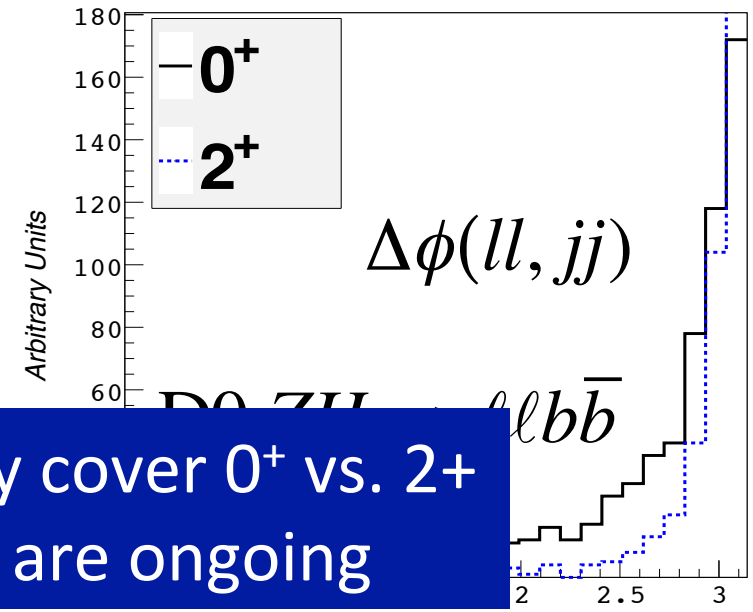
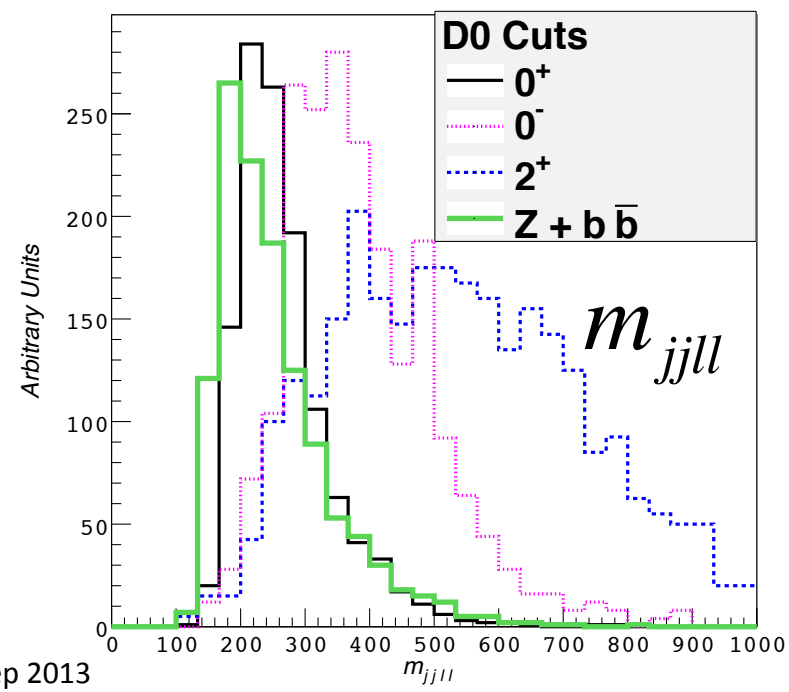
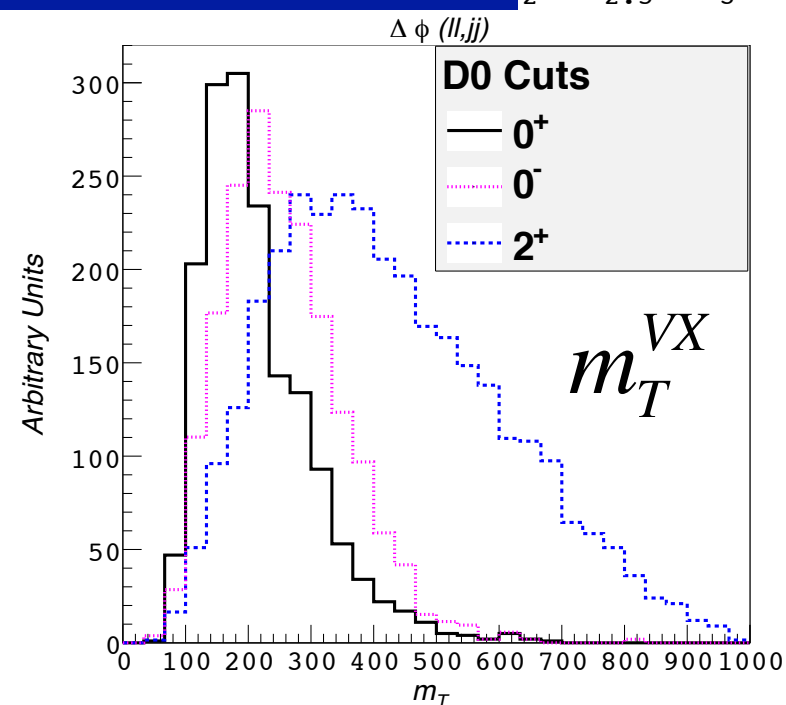


Today's results only cover 0^+ vs. 2+
0^- vs. 0^+ studies are ongoing

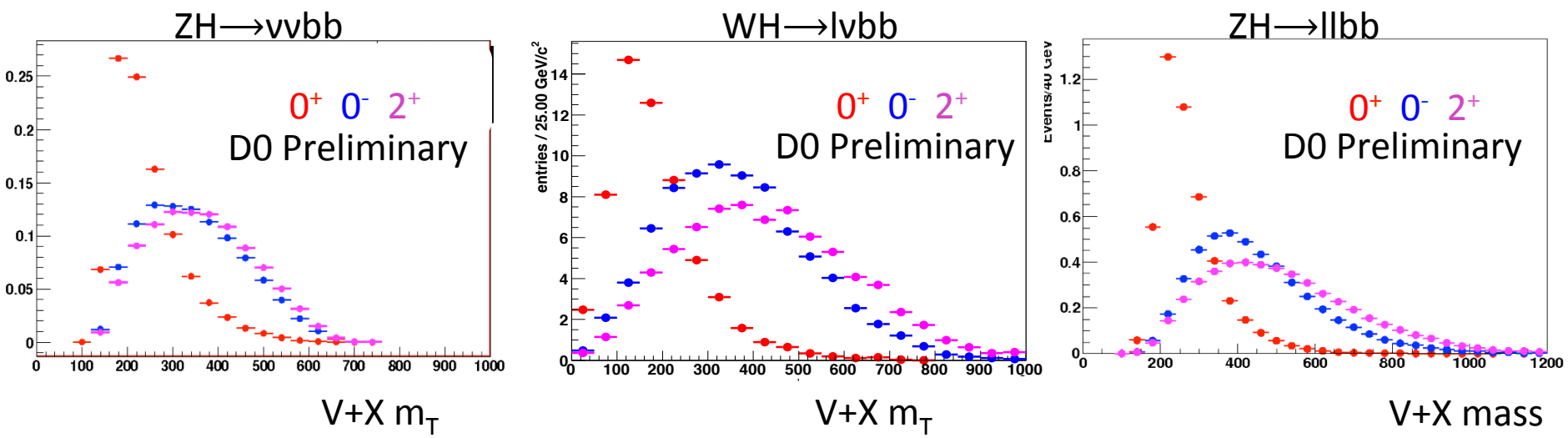
plots from Ellis, Hwang



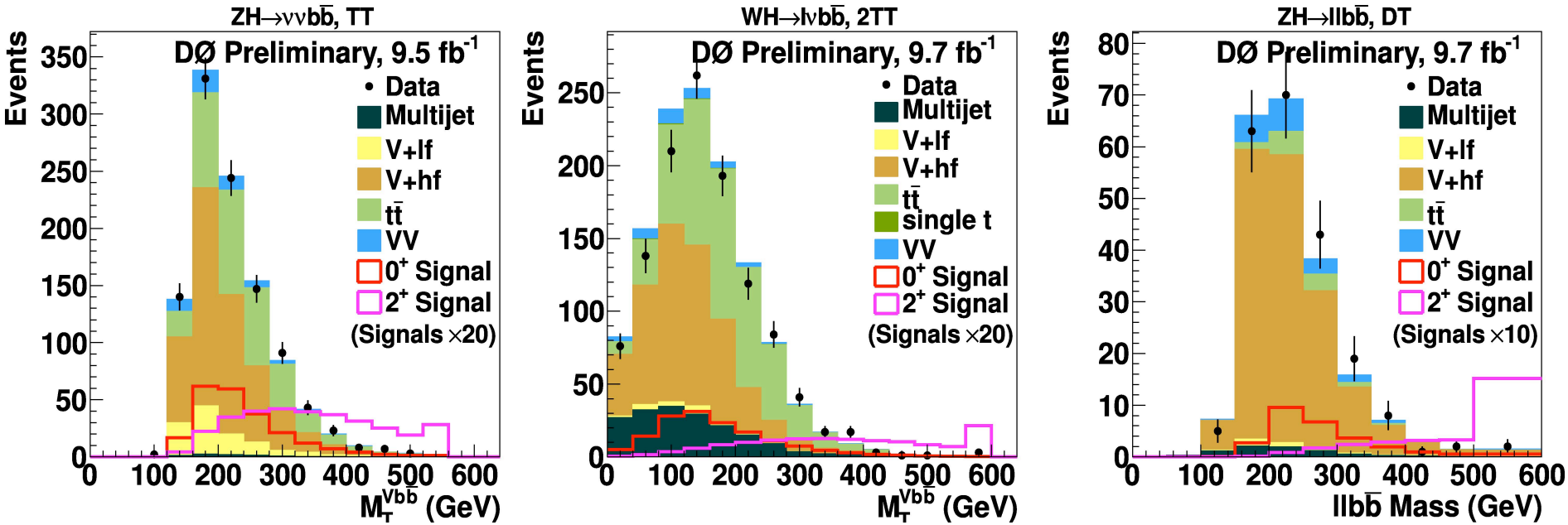


Generating signals

- Generate 2^+ signal with MADGRAPH5; interfaced to PYTHIA for showering
  - Use RS graviton model, initial normalization to SM σ 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



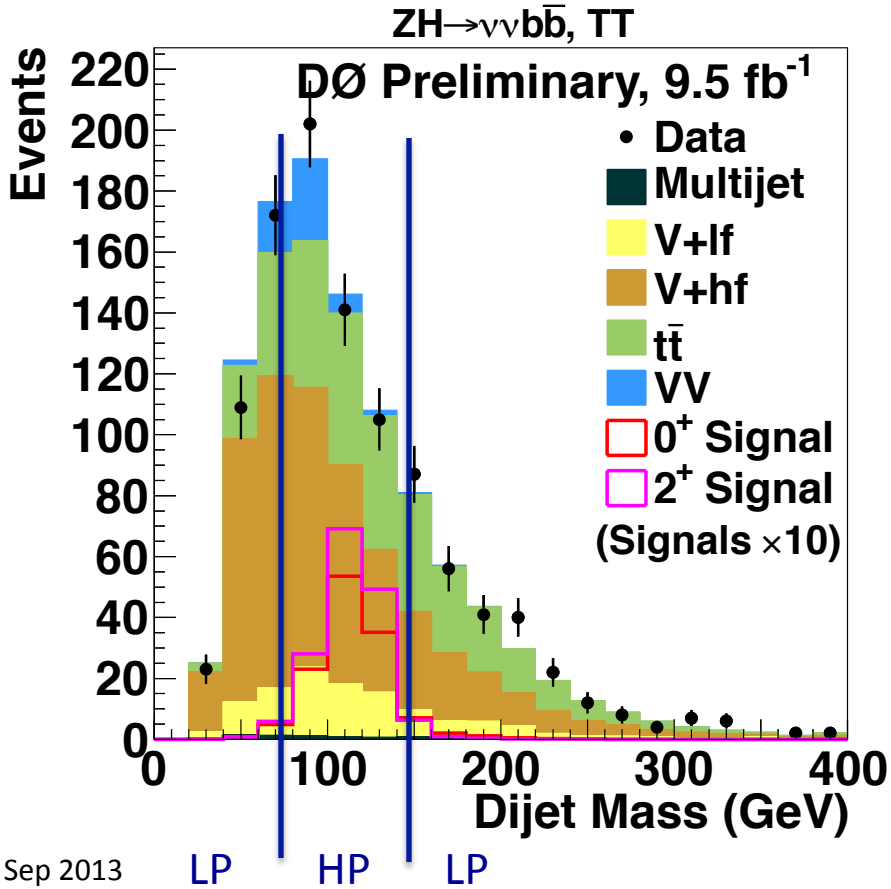
Visible Mass in VH Channels

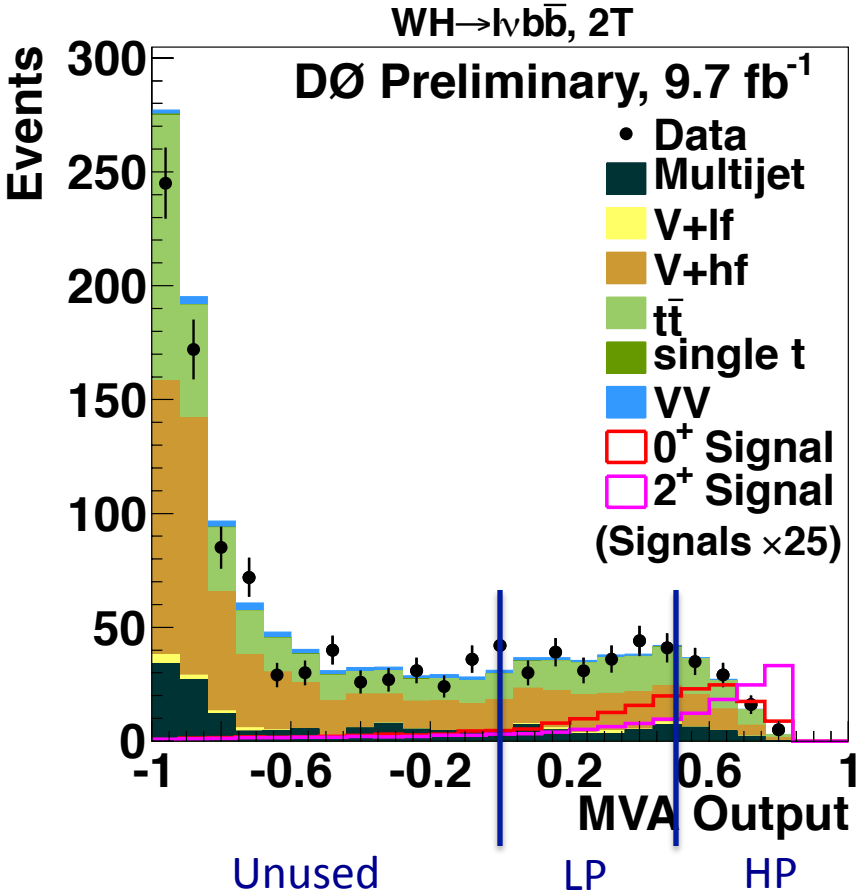


- Tightest b-tag sub-channel shown (upper edge bins combined due to statistics)
- Good separation between different signals
- Can we do better on the backgrounds?

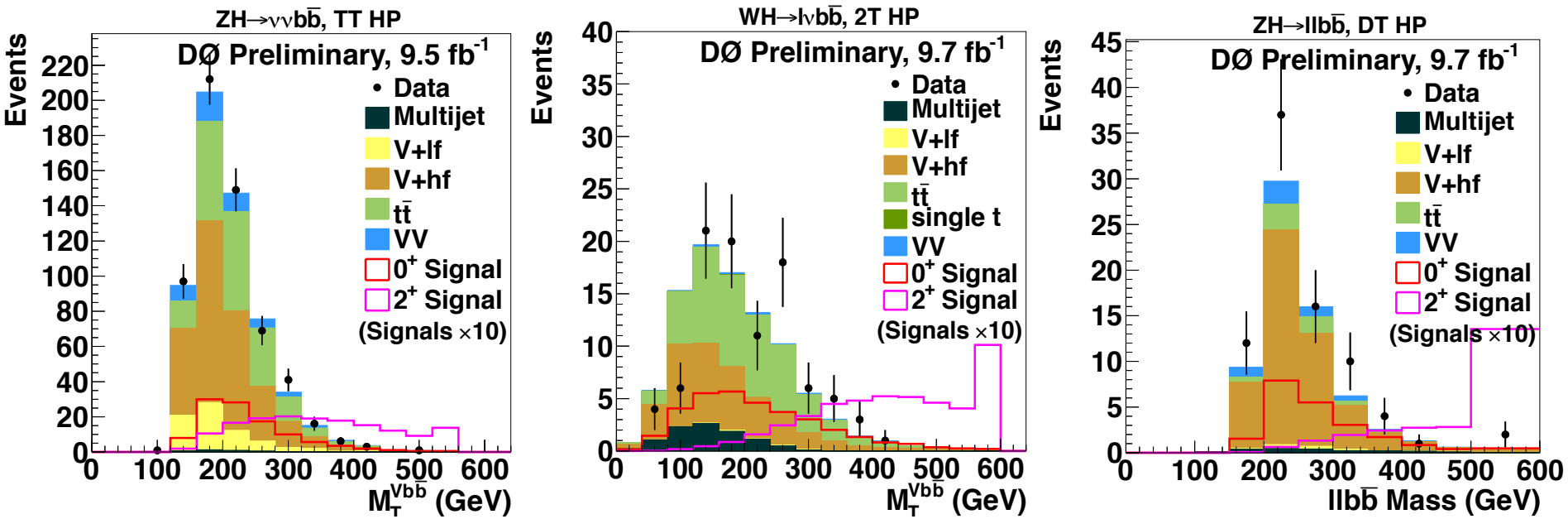
Additional Discrimination

- Take advantage of known mass
  - $\nu\nu bb$, $llbb$: create High/Low Purity (HP/LP) regions using M_{bb}
- $l\nu bb$ uses MVA output to make HP/LP regions
- Separate channels in statistical analysis





Final Variables



Tightest High Purity b-tag channel per analysis shown

Results

- Use CL_s to quantify model preference, log-likelihood ratio (LLR) as test statistic
  - H1: 2^+ signal + Background
  - H0: 0^+ signal + Background

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

- Compute for 2 different signal scale factors μ on SM σ(VH) × Br(bb)
  - 1.00 (SM)
  - 1.23 (D0 measured rate)
- Allow systematic uncertainties to vary in pseudoexperiments (LHC first fits signals to data for normalization, thereby constraining systematics)

Results

- Use CL_s to quantify model preference, log-likelihood ratio (LLR) as test statistic
  - H1: 2^+ signal + Background
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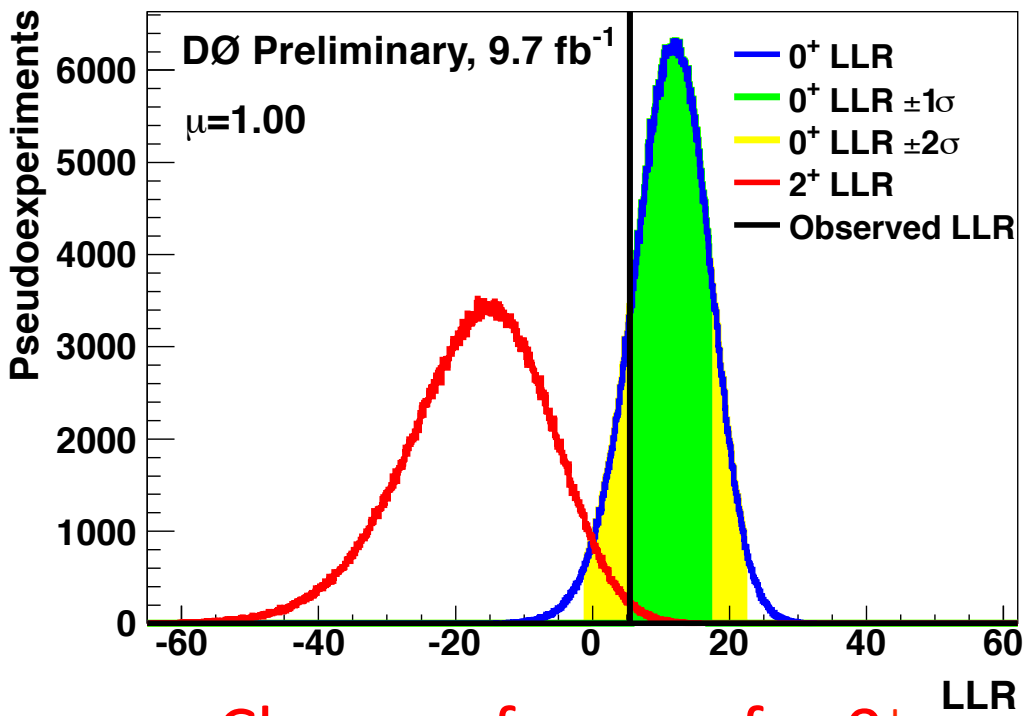
$$LLR = -2\log(L(H1)/L(H0))$$

- Compute for 2 different signal scale factors μ on SM σ(VH) × Br(bb)
  - 1.00 (SM; shown)
  - 1.23 (D0 measured rate)



Clear preference for 0^+

Results

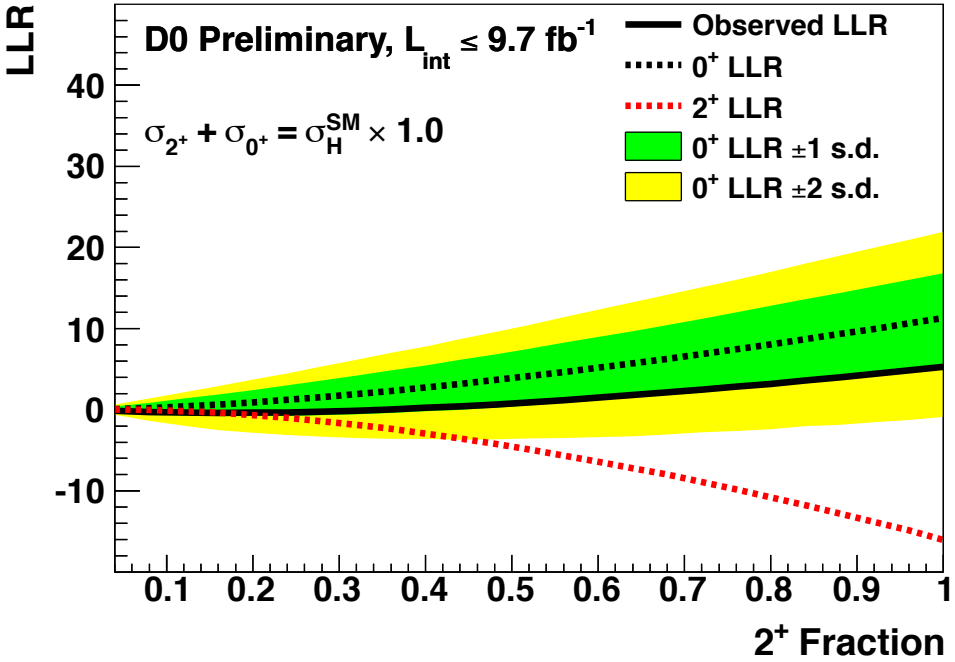
- $CL_s = CL_{H1}/CL_{H0}$
- $CL_x = P(LLR \geq LLR^{obs} | x)$
- Interpret 1-CL_s as C.L. for exclusion of 2^+ in favor of 0^+
- Exclude 2^+ model at > 99.2% C.L.
- Expected exclusion is 3.2 s.d. (μ=1.0)
- Competitive with LHC single-channel measurements

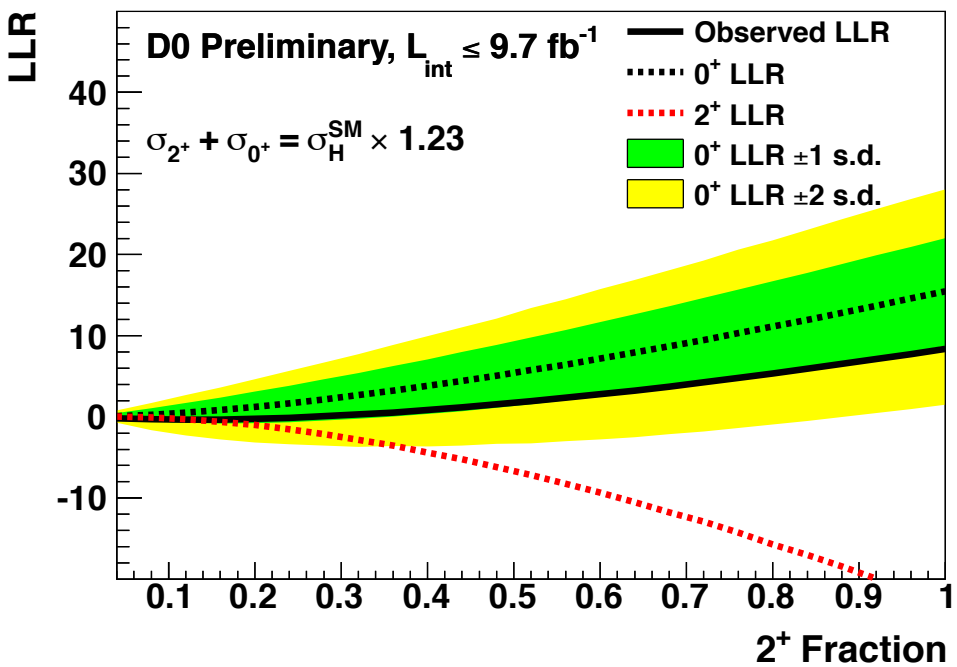
	Combined Result	Result in s.d.
1 – CL_s Exp. (μ=1.00)	0.9992	3.16
1 – CL_s Obs. (μ=1.00)	0.9922	2.42
1 – CL_s Exp. (μ=1.23)	0.9999	3.72
1 – CL_s Obs. (μ=1.23)	0.9988	3.04

http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H138/

Signal Admixtures

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





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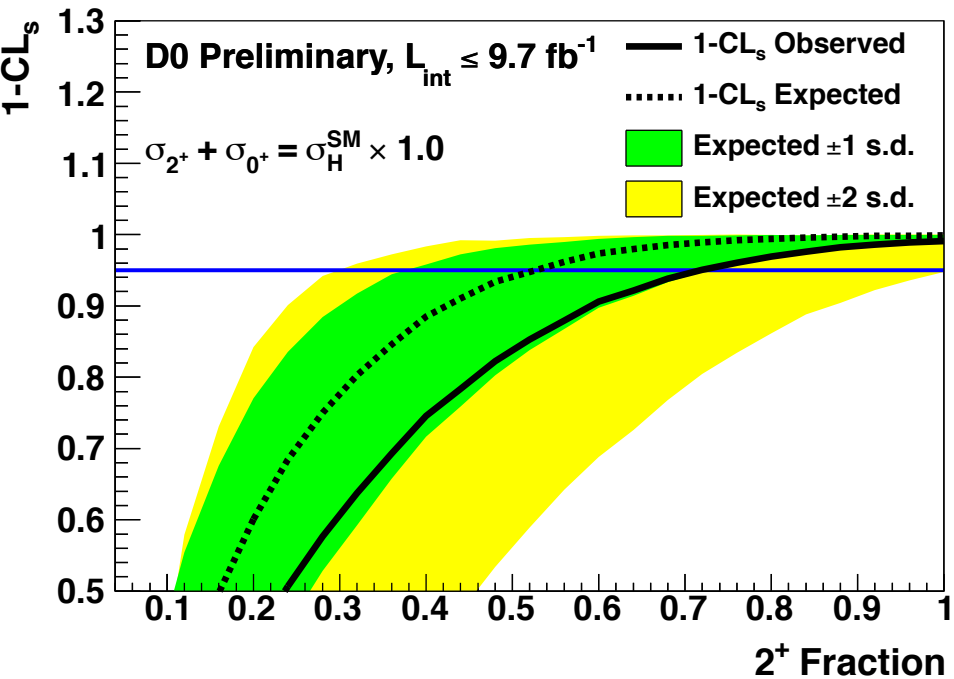
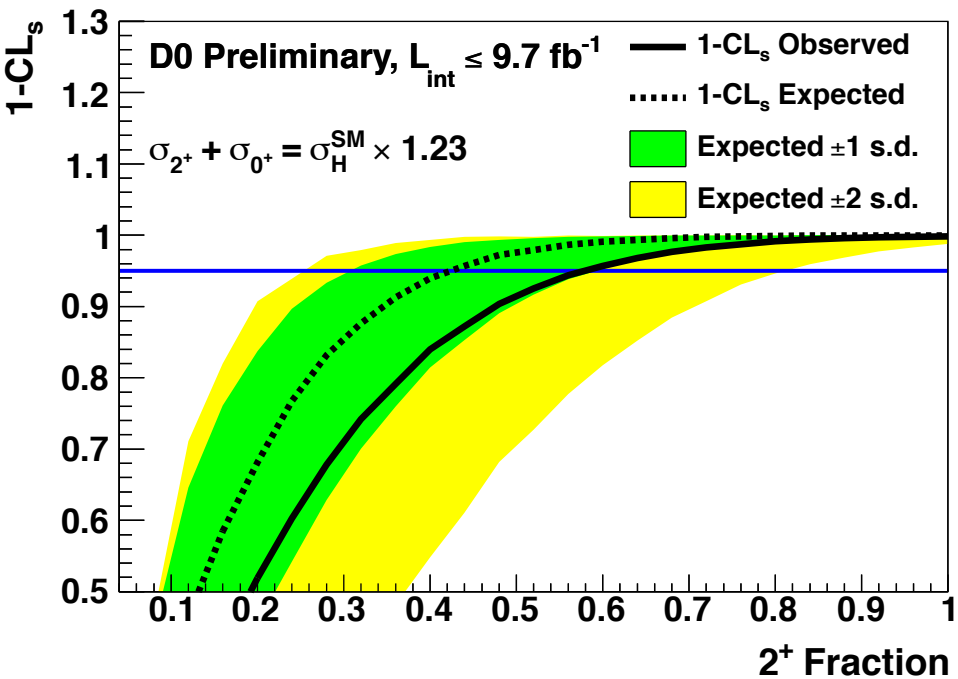


Exclude f_{2+} > 0.71 at 95% C.L.

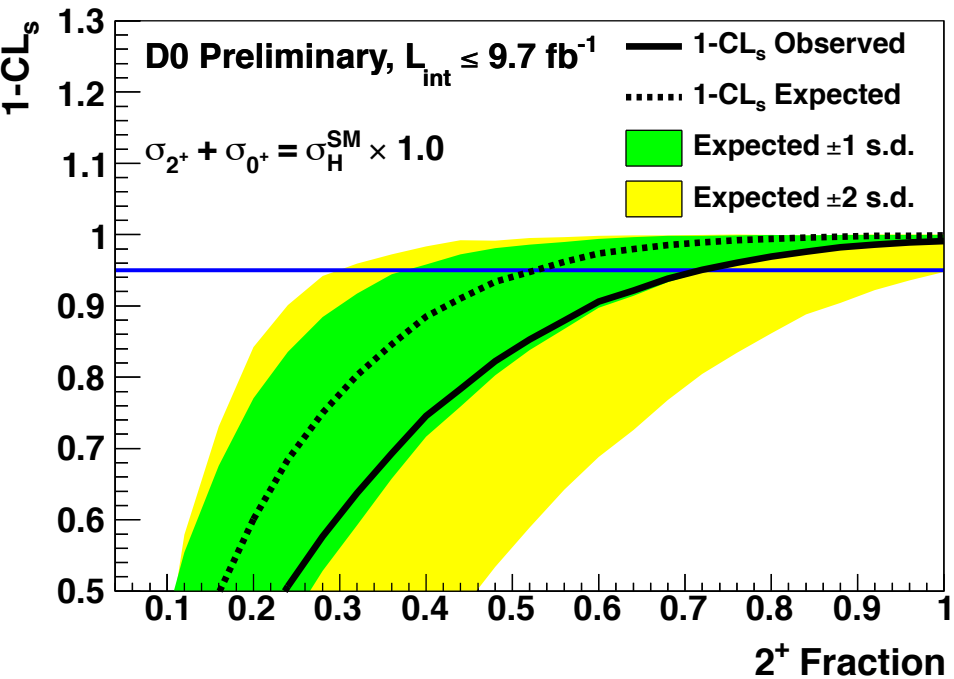


Exclude f_{2+} > 0.57 at 95% C.L.

Signal Admixtures

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

Will be repeated for 0^+ vs. 0^-



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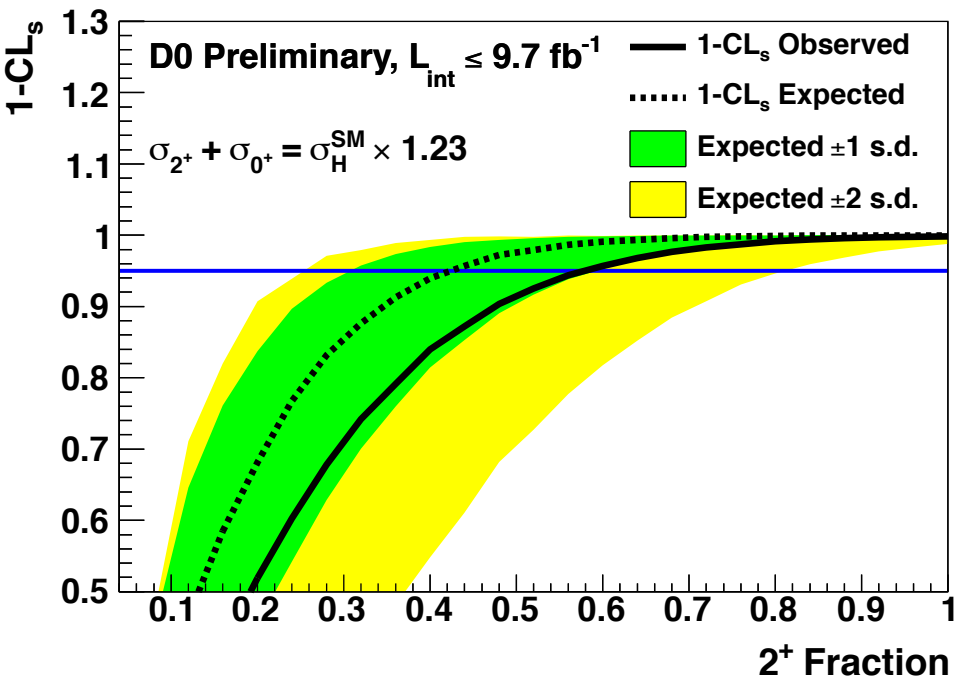

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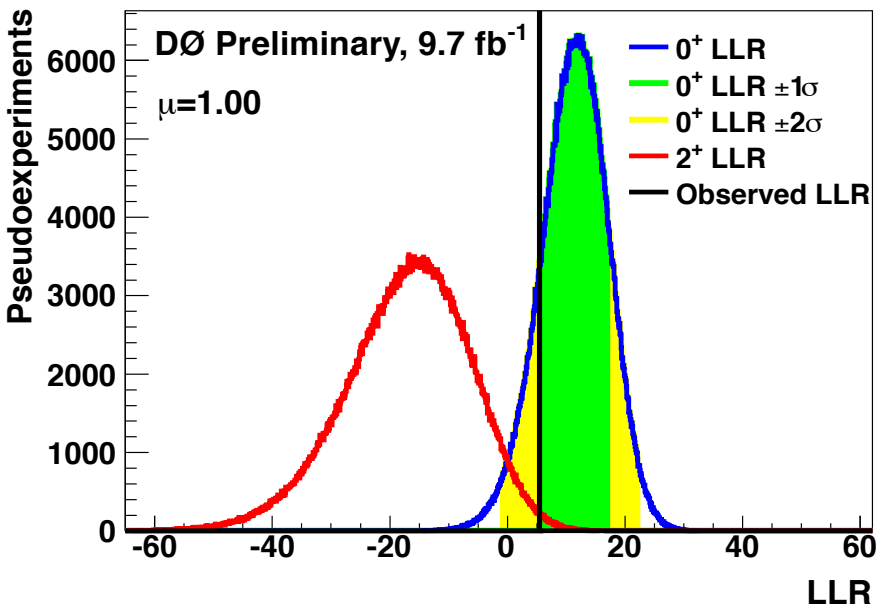
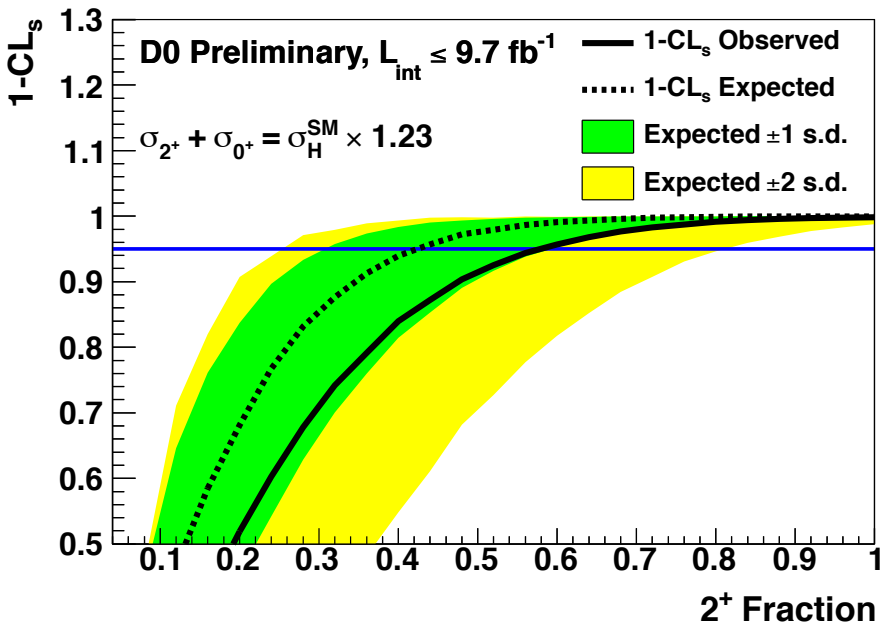
Summary

- D0 spin and parity tests (first in $b\bar{b}$ final states) favor $J^P=0^+$; reject $J^P=2^+$ (graviton-like couplings) at > 99.2% C.L.
- A consistent Higgs boson picture is forming; Tevatron provides complementary info in $b\bar{b}$ channels
  - Cross sections, couplings, spin, and parity all consistent with SM Higgs
- Still to come: $J^P=0^-$ tests