Results on Higgs boson parameters from the Tevatron

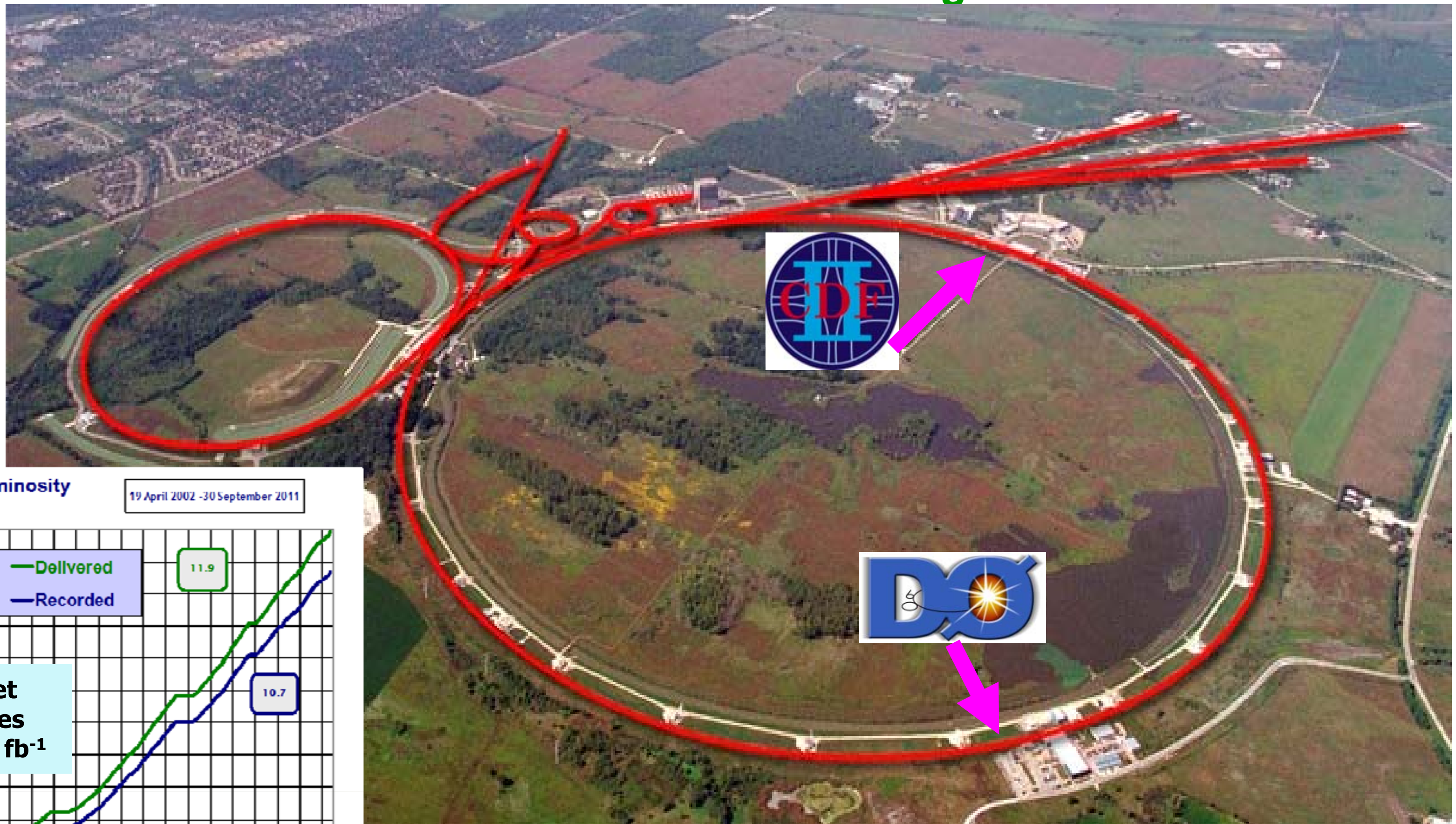
Gregorio Bernardi,

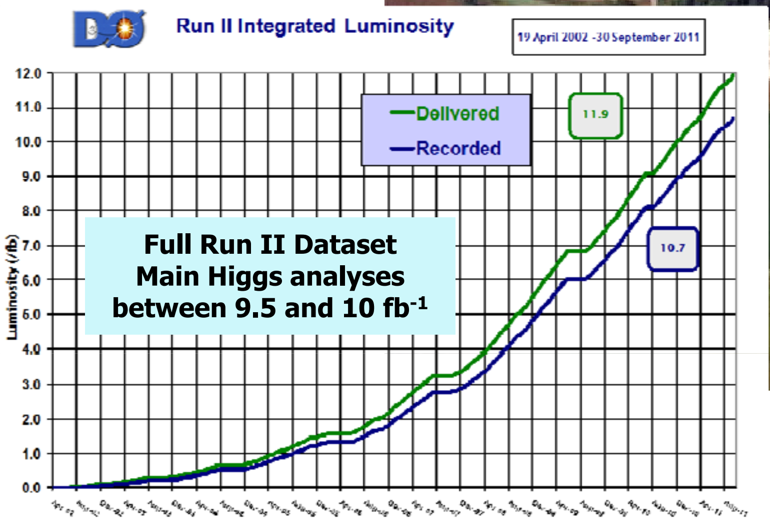
LPNHE Paris

On behalf of CDF and Dzero

Higgs couplings workshop, September 14th, 2013

Thanks to all CDF & DZero colleagues





Outline

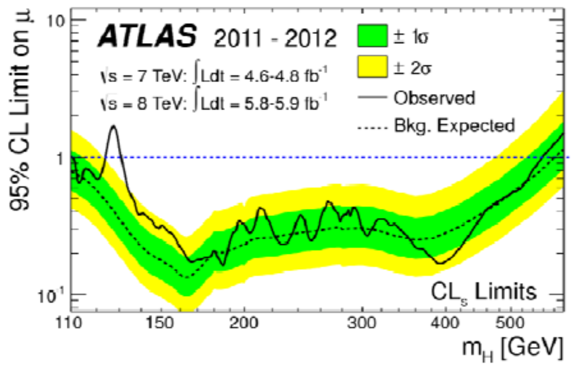
- Historical perspectives/Indirect measurements
- Combinations of Standard Model searches
- Higgs Couplings
- Low mass (H→bb) Higgs searches
- D0 spin and parity constraints in bb channels *New!*
- Prospects

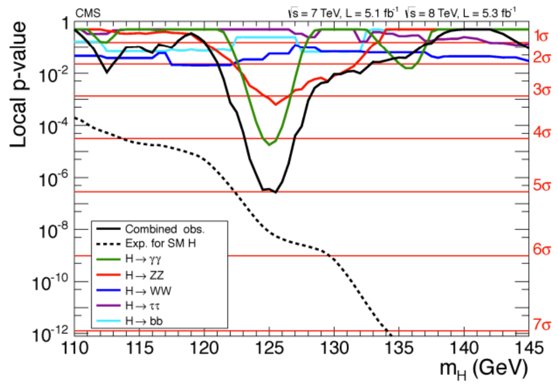
All final individual channels and combinations from CDF and D0 are published.

Higgs: Historical perspective and current Status

- **Tevatron Run II (2002 – 2011, 2 TeV):**
  - First post-LEP 95%CL exclusion (july 2008)
  - First evidence of a Higgs-like particle decaying to a pair of b-quarks (July 2012)

- **LHC (2011 – 2012, 7 - 8 TeV):**
  - Excluded wide mass range (111 – 122 GeV and 127 – 600 GeV)
  - **Discovered a new Higgs-like boson mainly through γγ and ZZ decays (July 2012)**





- **LHC ("full 2011-2012 dataset"):**
  - Since July 2012 progress in each channel, Higgs observation confirmed in bosonic channel
  - ATLAS: m_H = 125.5 ± 0.2 (stat) ± 0.6 (sys) GeV, CMS: m_H = 125.7 ± 0.3 (stat) ± 0.3 (sys) GeV
  - H→bb, with ~23-25 fb^{-1} : compatible with 0 @ Atlas, and ~2.1 σ excess @ CMS
  - strong indications (2.9 σ)of fermionic decays at LHC from CMS H→ττ (full stat) but low ATLAS signal (1.1σ /1.7σ expected, 18fb^{-1})

➔ While it is a Higgs boson, the fermionic decays are not yet firmly established.

Indirect measurement, W-mass

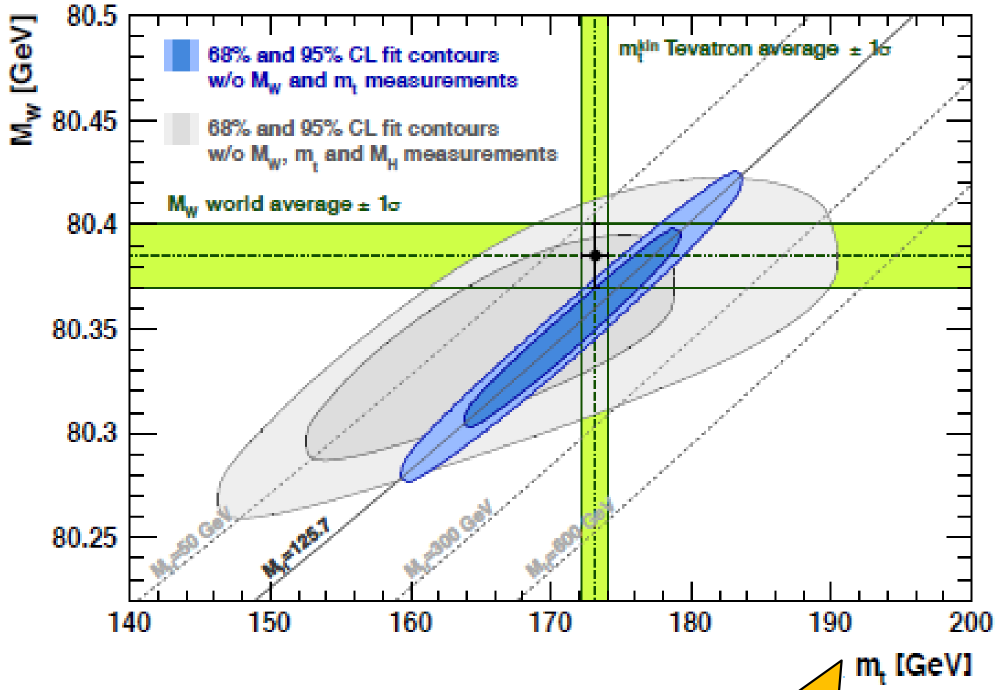
Mw =80385 +/- 15 MeV
Mtop=173.2 +/- 0.9 GeV

If we use the measured mass of the Higgs-like boson to constrain the W boson mass based on SM, we get:

$m_W = 80.359 \pm 0.011$ GeV

Comparing with the current world average directly measured value:

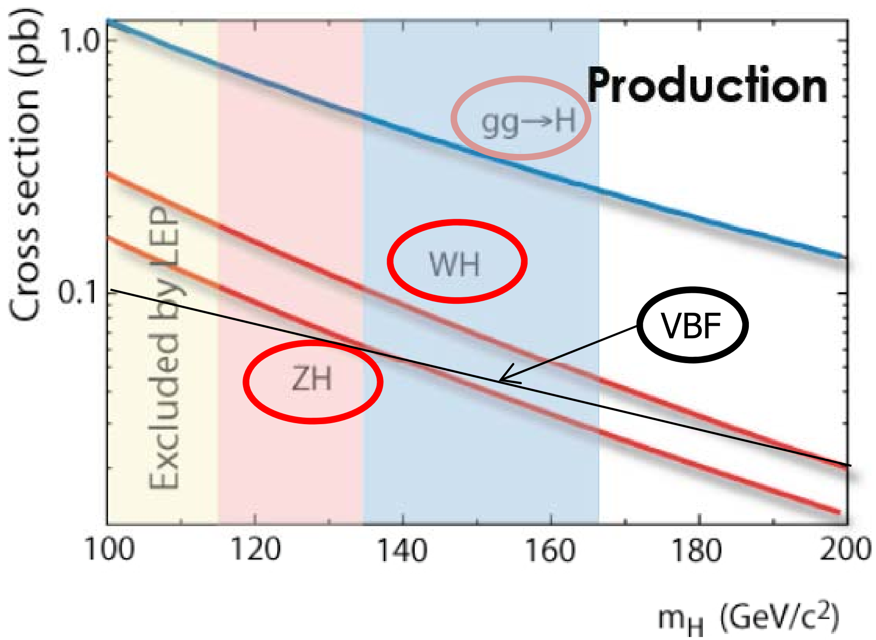
$m_W = 80.385 \pm 0.015$ GeV

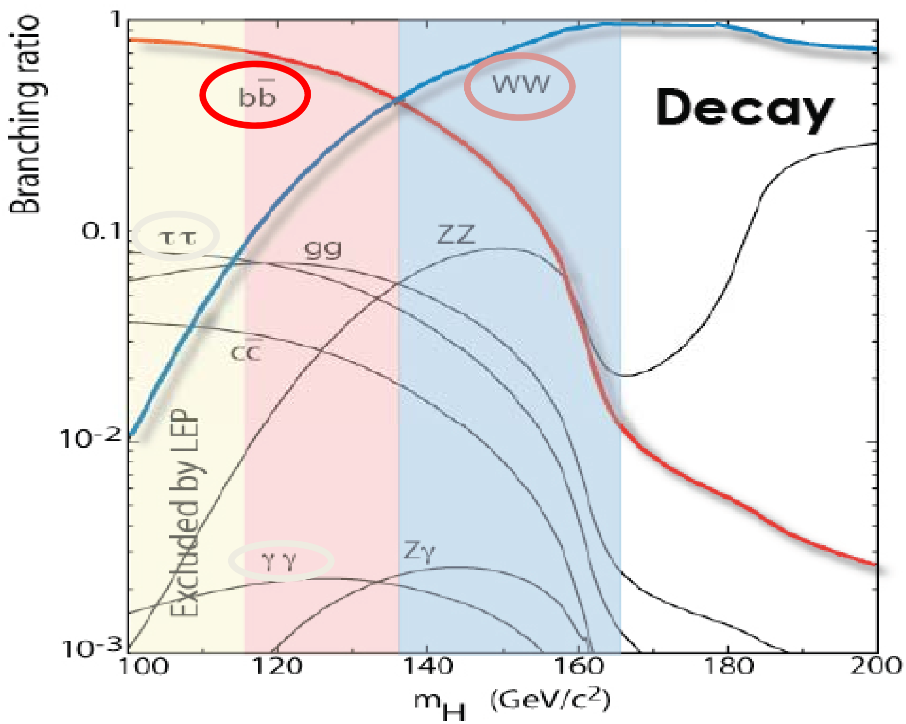


- With a world average around 10 MeV dominated by the Tevatron, and no changes in central values, test direct and indirect Higgs mass values.
- Significant anomaly could be detected if central value would slightly move apart, while reducing uncertainties .
- Currently we have good agreement !!!

test SM consistency with m_W m_{top} m_{Higgs} at > 2 sigma level

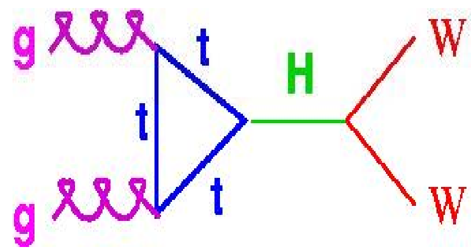
Higgs Production and Decay at the Tevatron





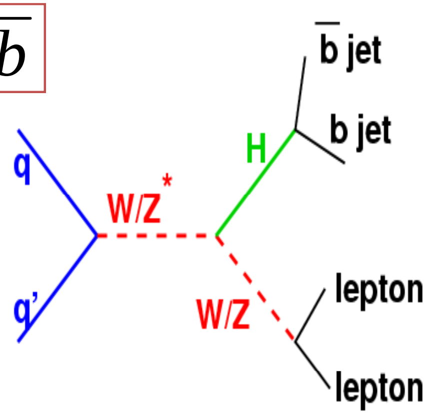
"High" mass ($m_H > 135$ GeV) dominant decay:

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



Low mass ($m_H < 135$ GeV) dominant decay:

$H \rightarrow b\bar{b}$



$WH \rightarrow \ell\nu b\bar{b}$

$ZH \rightarrow \ell^+\ell^- b\bar{b}$

$ZH \rightarrow \nu\bar{\nu} b\bar{b}$

use associated production modes to get better S/B

These are the main search channels, but there has been an extensive program of measurements in all channels to extend the sensitivity to a SM Higgs

Final Higgs combination from Tevatron

All papers now published

All SM channels searched

Full luminosity used in almost all channels

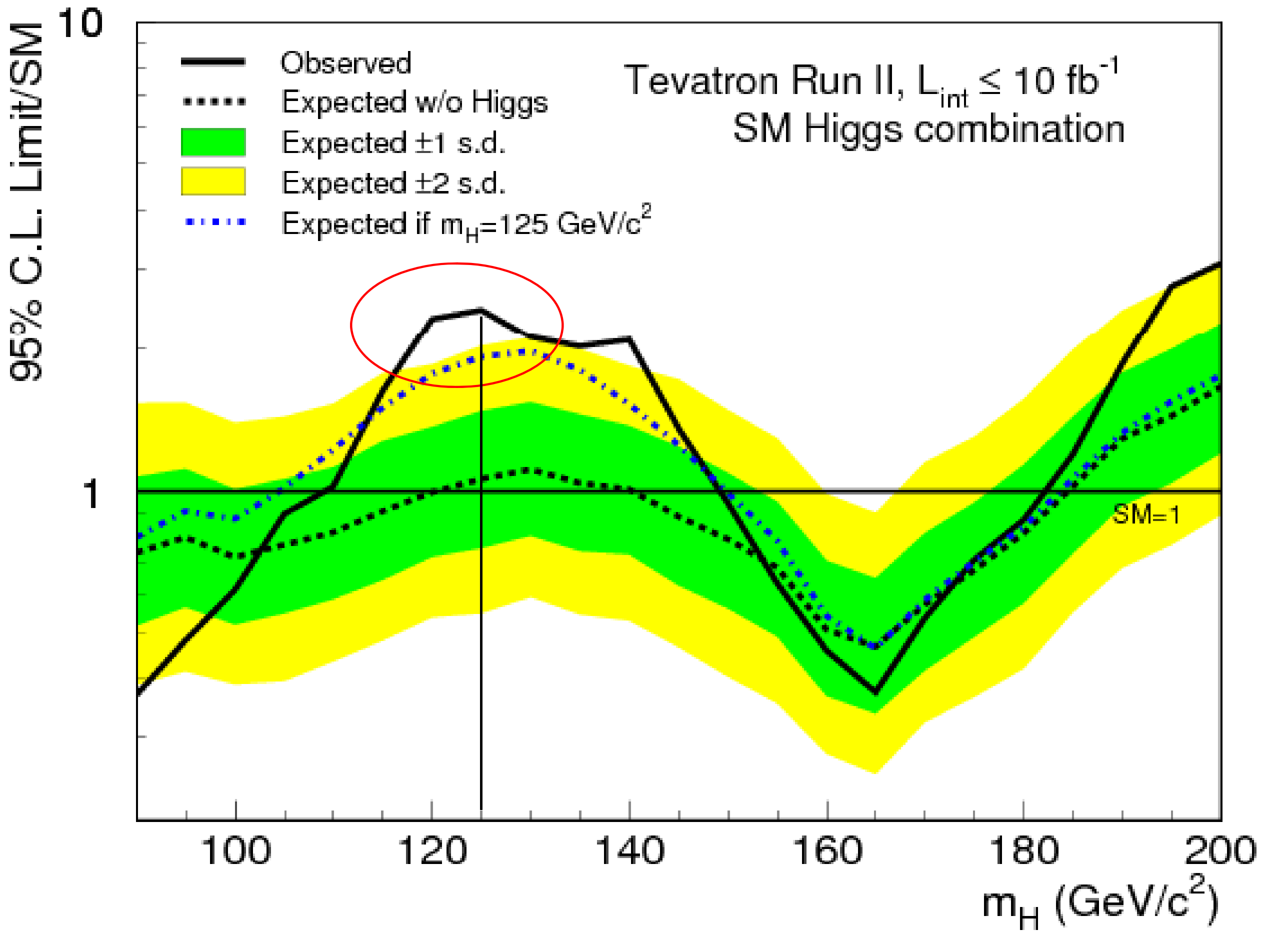
CDF

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

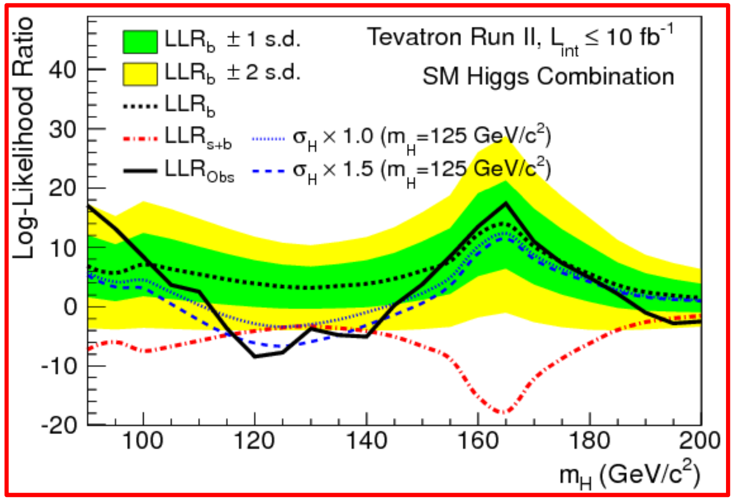
DØ

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

Full Tevatron combination



LLR plot

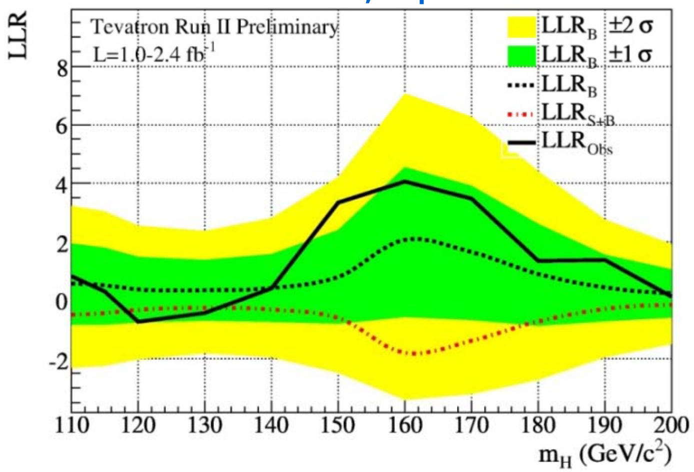


Significant excess, ≥ 3 sigma for 120-125 GeV

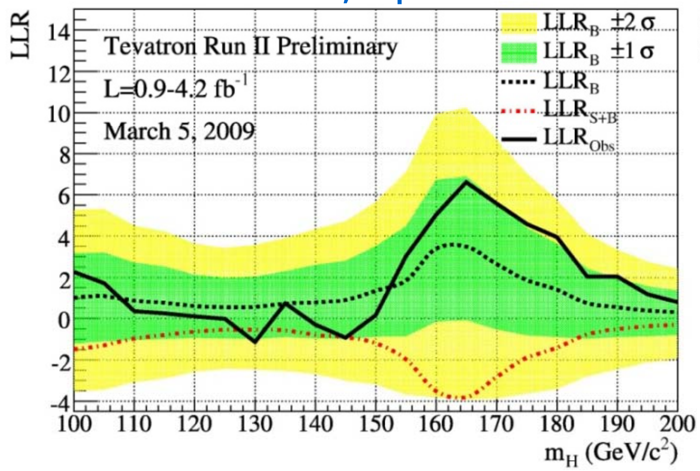
- Expected exclusion: 90 < m_H < 121 GeV, 140< m_H < 184 GeV
  Observed exclusion: 90 < m_H < 107 GeV, 149 < m_H < 182 GeV

History of Tevatron results: LLR of all searches

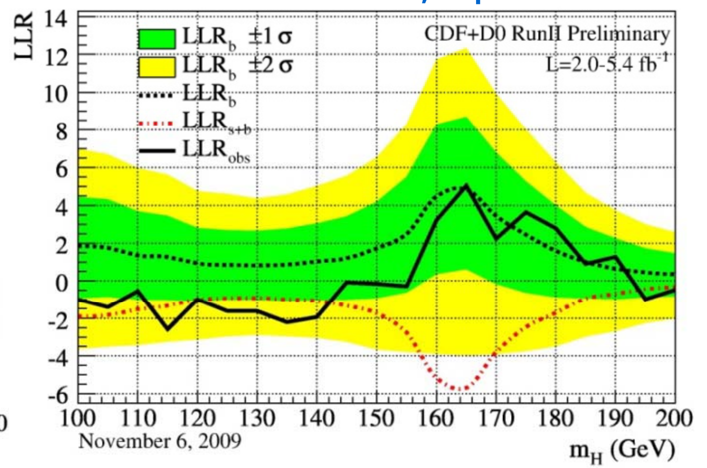
Data of **2007**; up to 2.4 fb^{-1}



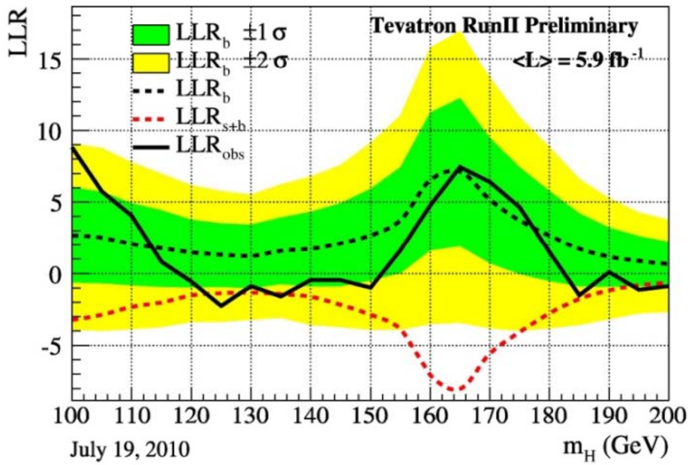
Data of **2008**; up to 4.2 fb^{-1}



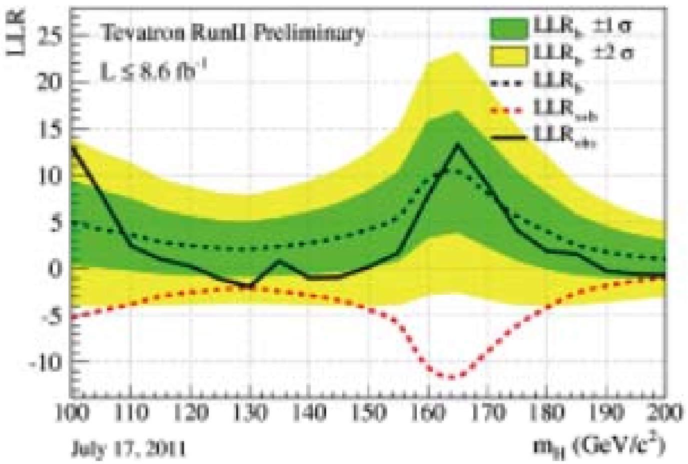
Data of mid **2009**; up to 5.4 fb^{-1}



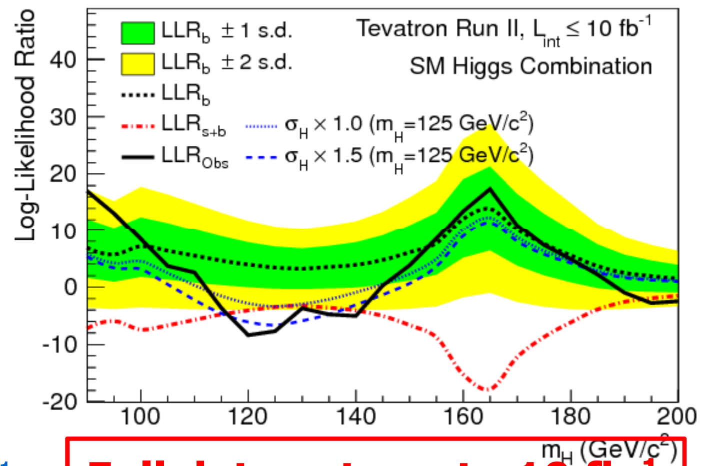
Time



Data of mid **2010**; up to 5.9 fb^{-1}

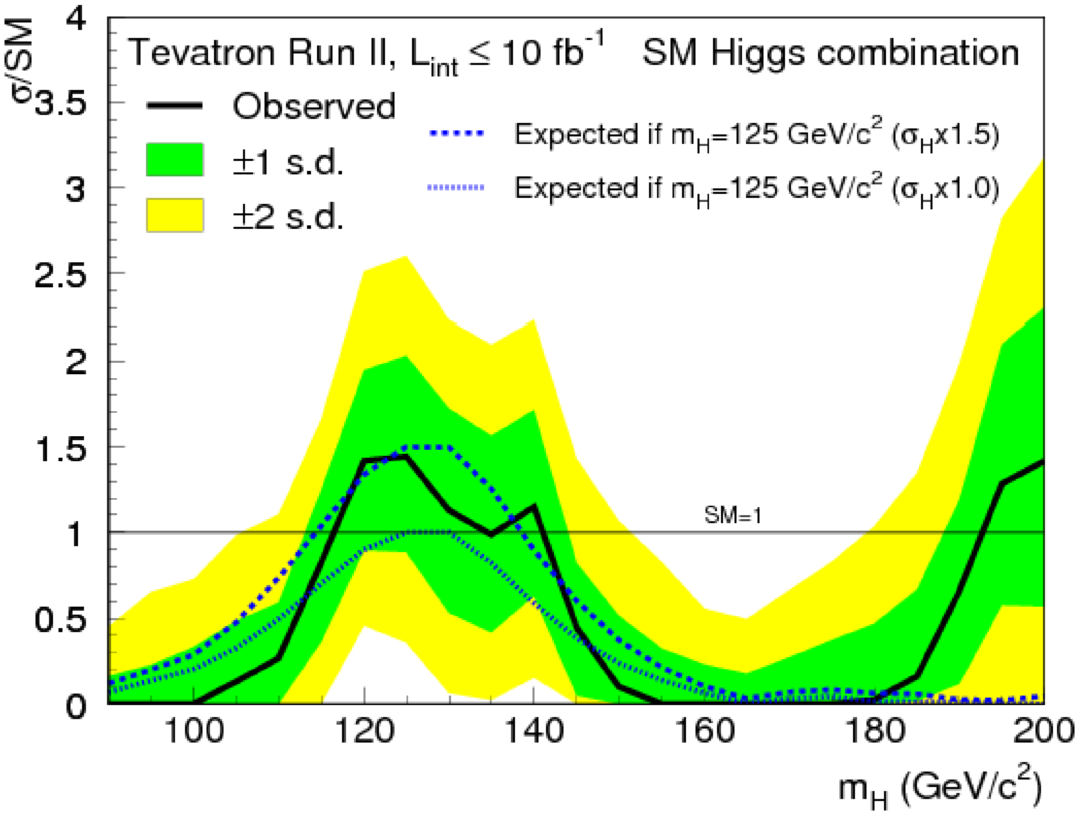


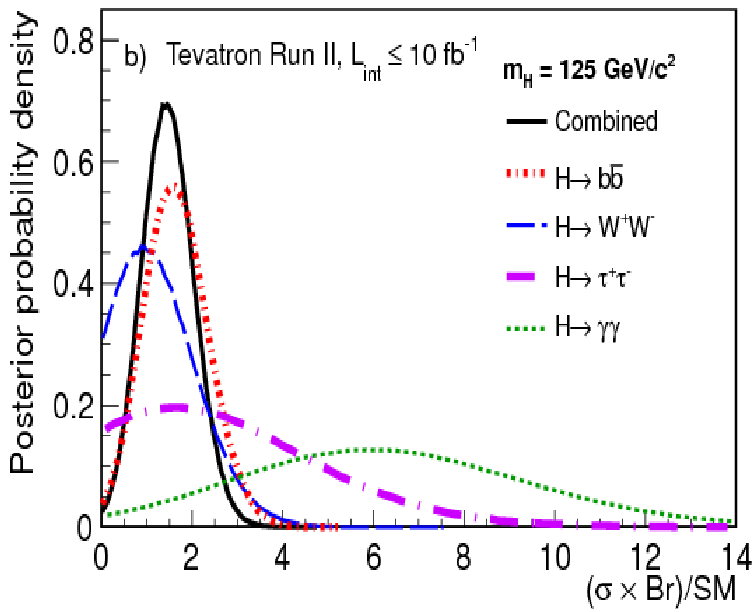
Data of mid **2011**; up to 8.6 fb^{-1}



Full data set; up to 10 fb^{-1}

Quantifying the signal: Best Fit Signal Rate



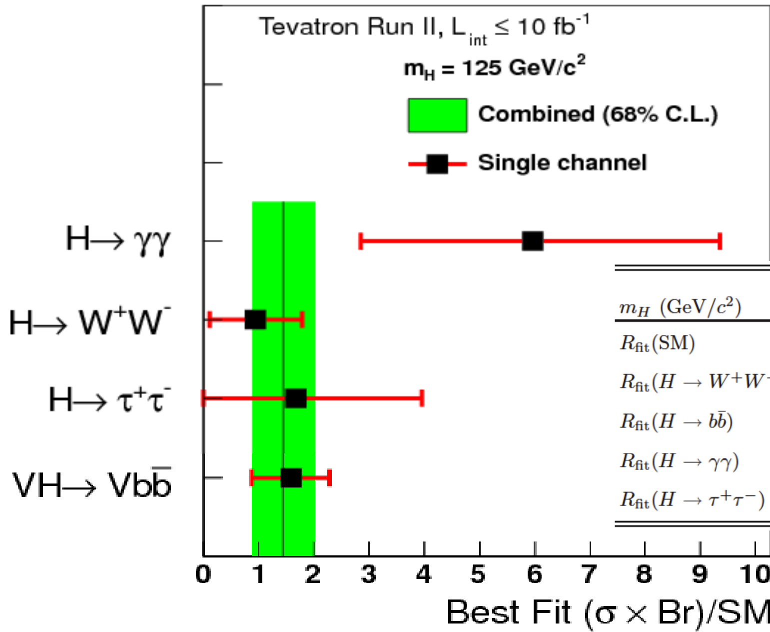


- Maximum likelihood fit to data with signal rate as free parameter.
- Best-fit signal rate at m_H=125 GeV:

$$\sigma_{fit} / \sigma_{SM} = 1.44 \pm 0.59$$

Consistent with SM Higgs.

Reasonably consistent across channels.



m_H (GeV/c^2)	125
R_{fit}(SM)	$1.44^{+0.59}_{-0.56}$
$R_{fit}(H \rightarrow W^+W^-)$	$0.94^{+0.85}_{-0.83}$
$R_{fit}(H \rightarrow b\bar{b})$	$1.59^{+0.69}_{-0.72}$
$R_{fit}(H \rightarrow \gamma\gamma)$	$5.97^{+3.39}_{-3.12}$
$R_{fit}(H \rightarrow \tau^+\tau^-)$	$1.68^{+2.28}_{-1.68}$

Probing Higgs Boson Couplings

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

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

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

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

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

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

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

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

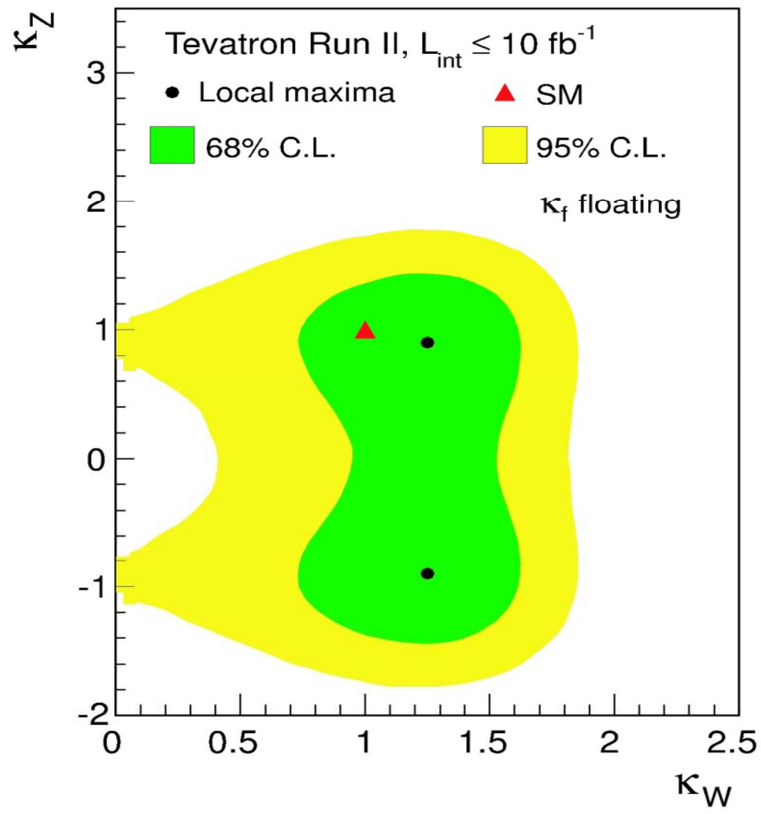
$$\Gamma_{ZZ} \propto \kappa_V^2$$

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

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

Probing Higgs Boson Couplings

- When both κ_W and κ_Z vary independently ➔
  - κ_f integrated over
  - Best fit: $(\kappa_W, \kappa_Z) = (1.25, \pm 0.90)$

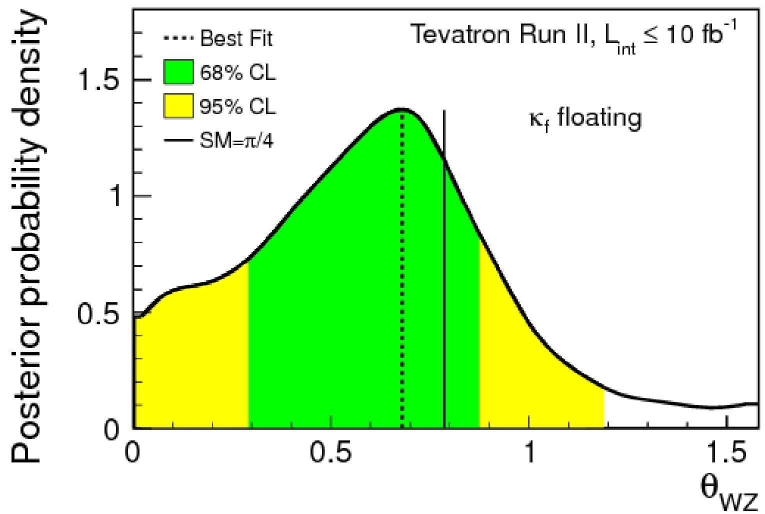


- The point $(\kappa_W, \kappa_Z) = (0, 0)$ corresponds to NO Higgs boson production or decay in the most sensitive search modes at the Tevatron and is not included within the 95% C.L. region due to the significant excess of events in the SM Higgs boson searches @ 125 GeV

Probe $SU(2)_V$ custodial symmetry by measuring the ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$

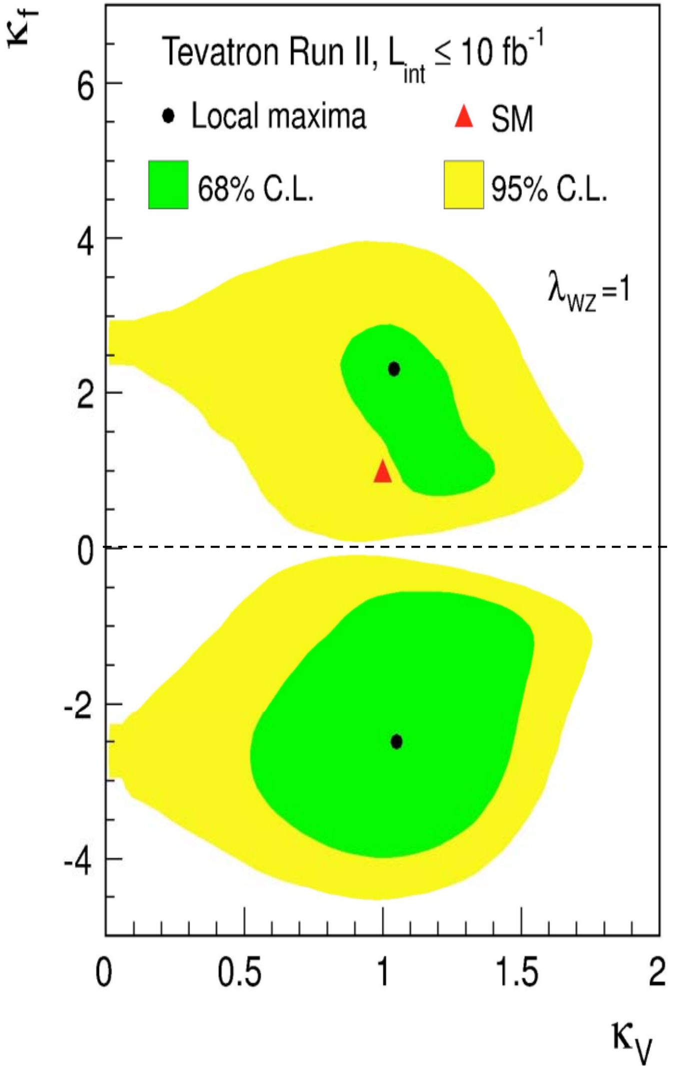
Measure $\theta_{WZ} = \tan^{-1}(\kappa_Z/\kappa_W) = \tan^{-1}(1/\lambda_{WZ})$

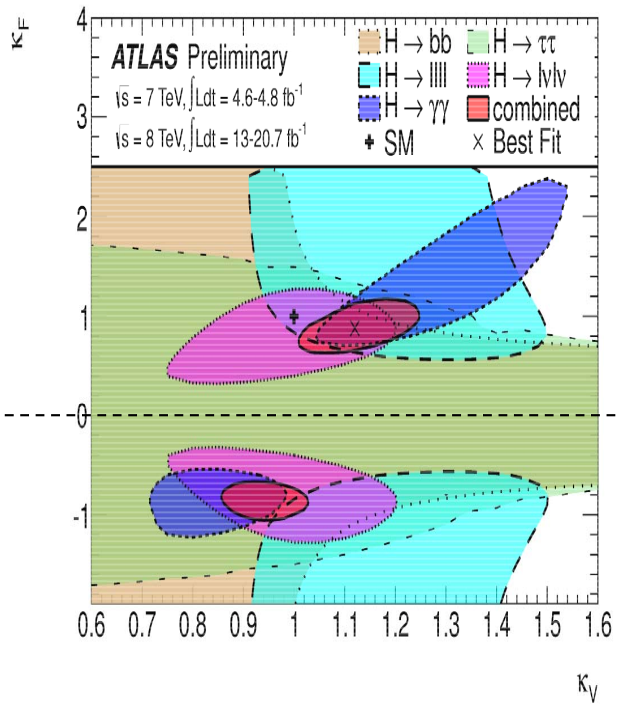
$\theta_{WZ} = 0.68^{+0.21}_{-0.41}$ → $\lambda_{WZ} = 1.24^{+2.34}_{-0.42}$

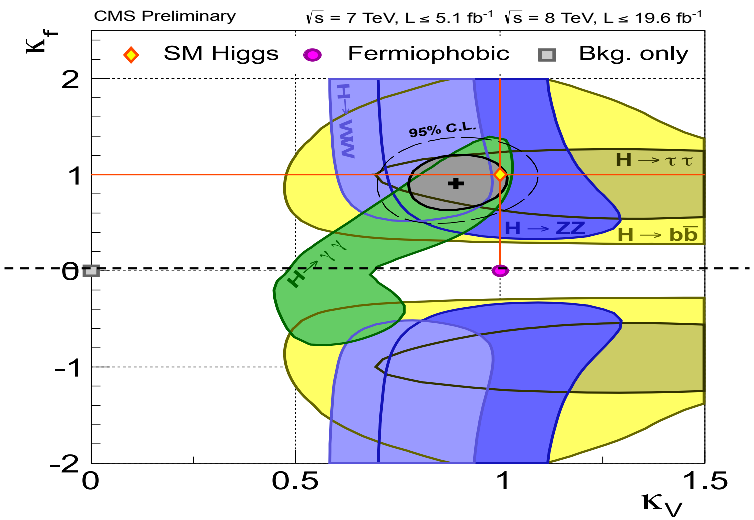


Properties - couplings

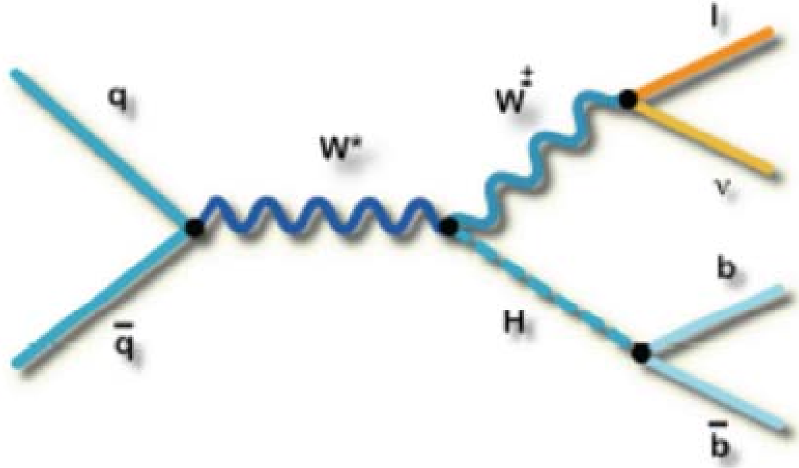
- Measure simultaneously κ_V and κ_f (assuming now λ_{WZ}=1).
- Asymmetry is from the excesses in the $H \rightarrow \gamma\gamma$
- Two minima: (κ_V, κ_f)=(1.05,−2.40) and (κ_V, κ_f) = (1.05, 2.30)
- Good agreement with SM predictions, in agreement with ATLAS/CMS.







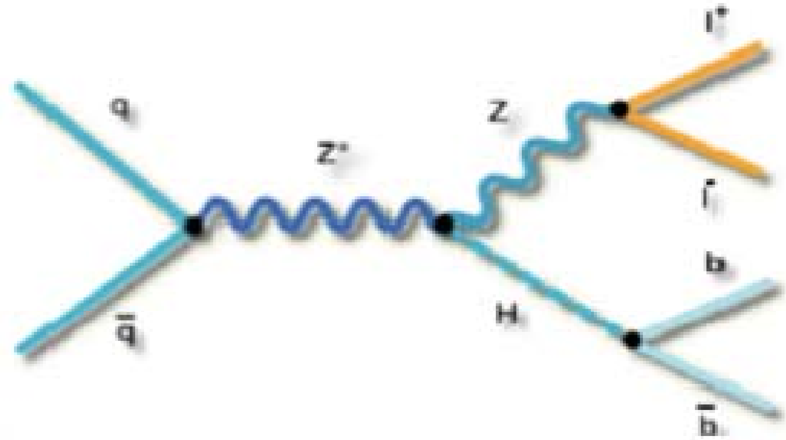
Low Mass Higgs Channels



WH→lνbb: MET+l+bb

Large production cross section

Higher backgrounds than in ZH→llbb

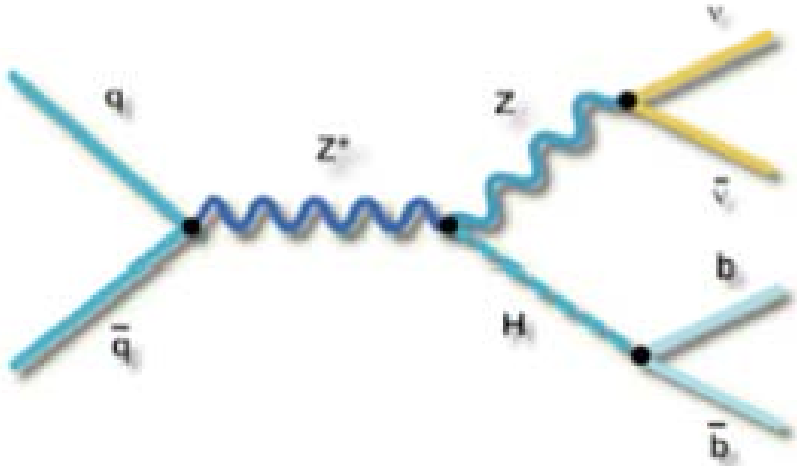


ZH→llbb: ll+bb

Low background

Fully constrained

Small Signal



ZH→ννbb: MET+bb

signal 3x larger than ZH→llbb

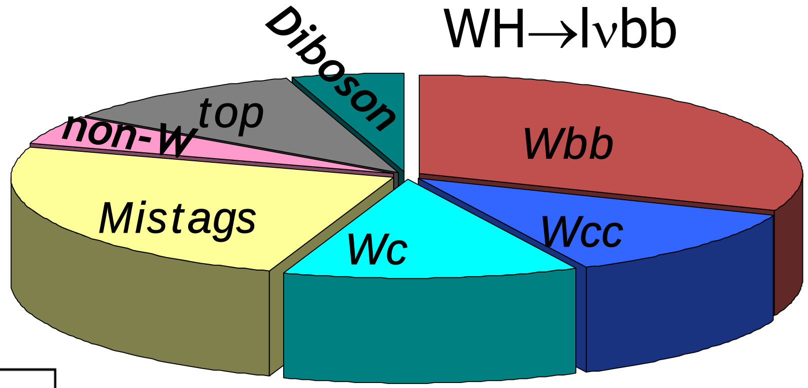
(+ contributions from WH)

difficult backgrounds

Low Mass Higgs Searches

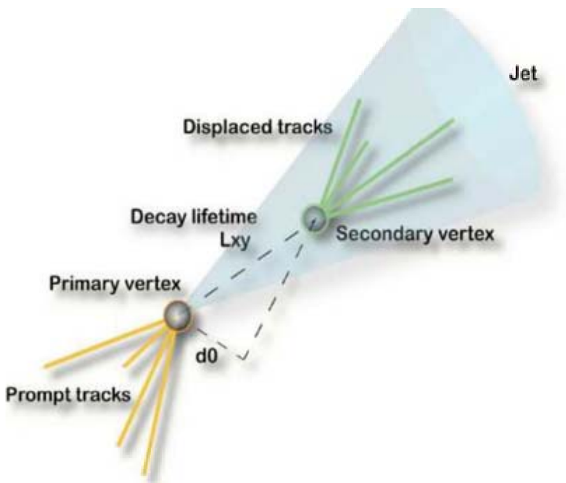
Increase lepton reconstruction and selection efficiencies

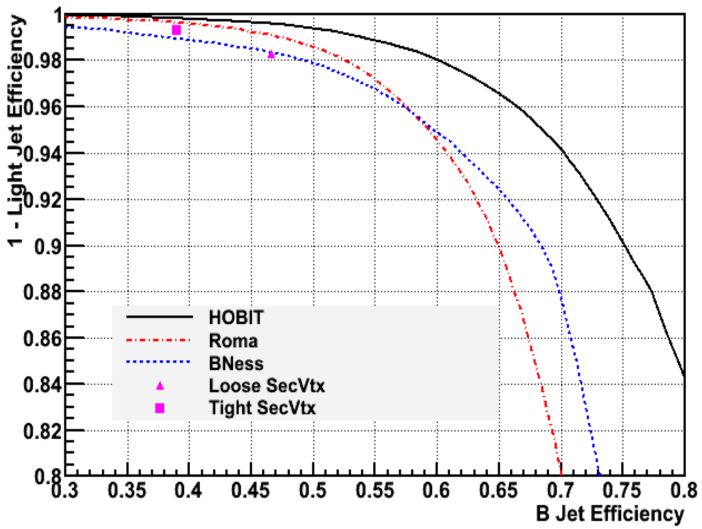
Understand background



Specific to low mass analyses:

B-tagging





Reduce the background by tagging b-quark jets

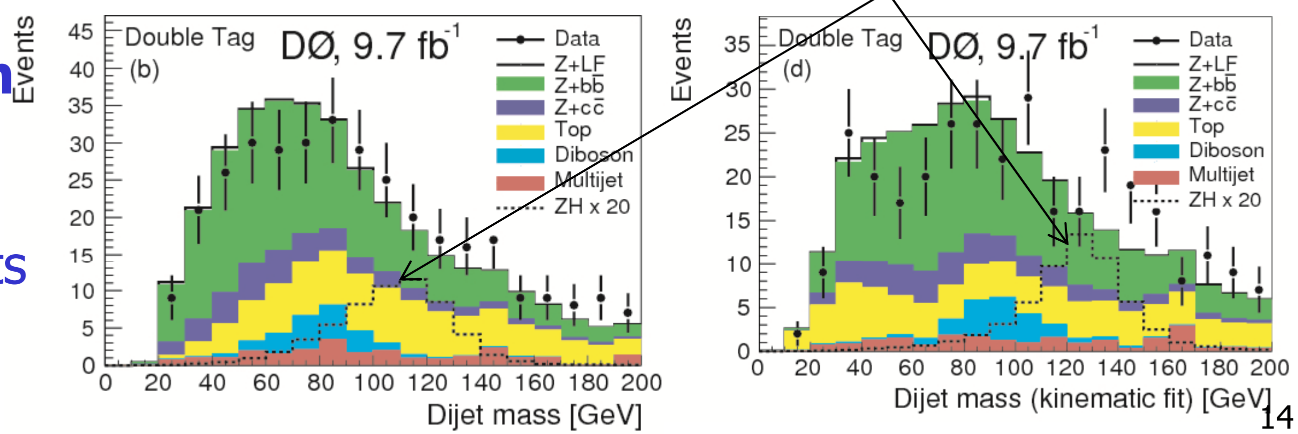
Major step forward with MVA taggers

75% eff. for 10% mistag
42% eff. For 0.9% mistag

Kinematic fit in ZH→llbb (15% sensitivity gain)

Optimize dijet mass resolution

➔ needs precise calibration and resolution for gluon and quark jets separately



From Dijet mass to Multi Variate Analysis

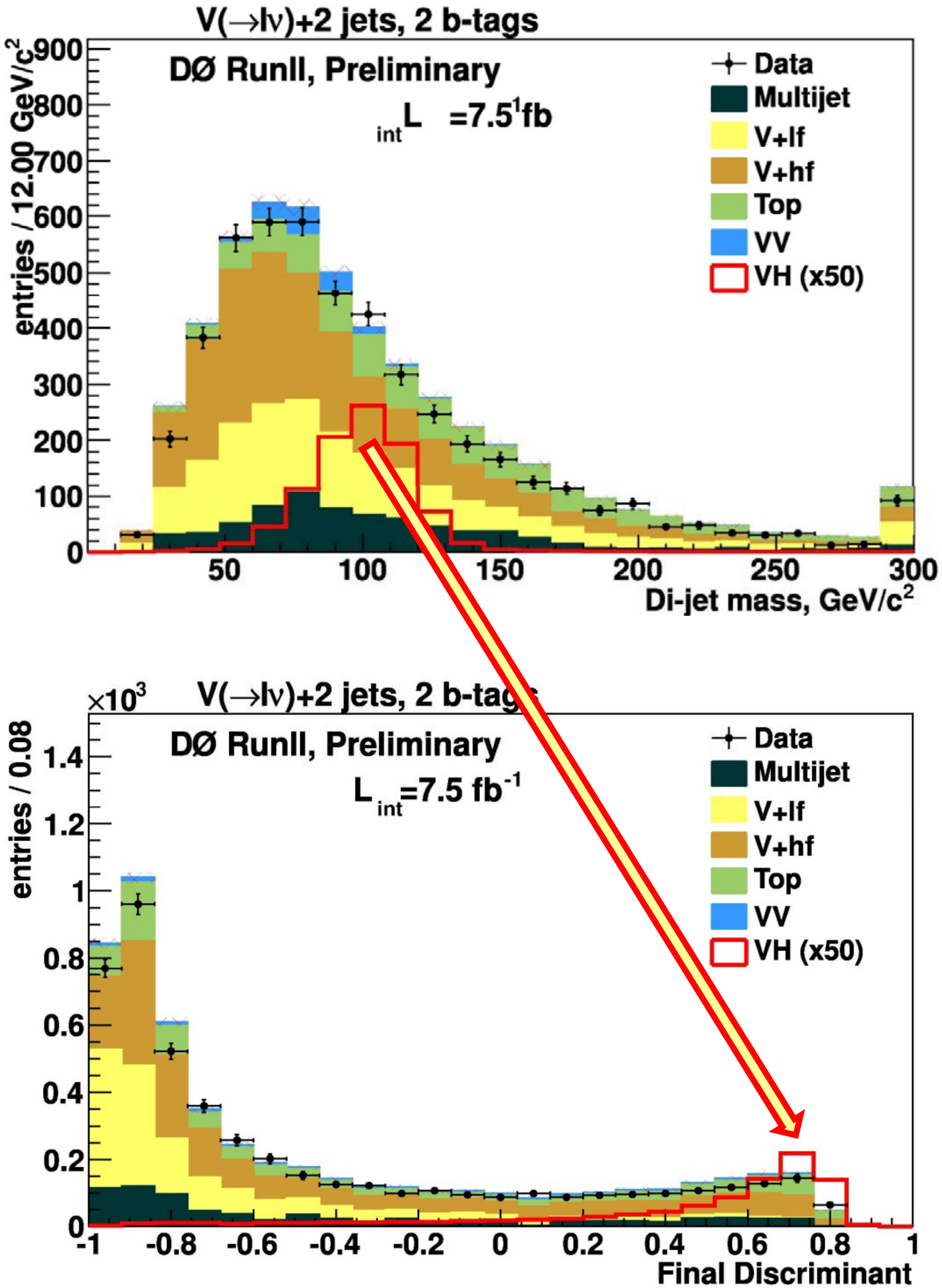
- **To improve S/B ➔ utilize full kinematic event information**

- **Multi Variate Analyses**
  - Neural Networks
  - Boosted Decision Trees

  Or use Matrix Element Calculations to determine probability for an event to be signal or background like

- **Approaches validated in Single Top observation @ Tevatron**
- **Combine these approaches**

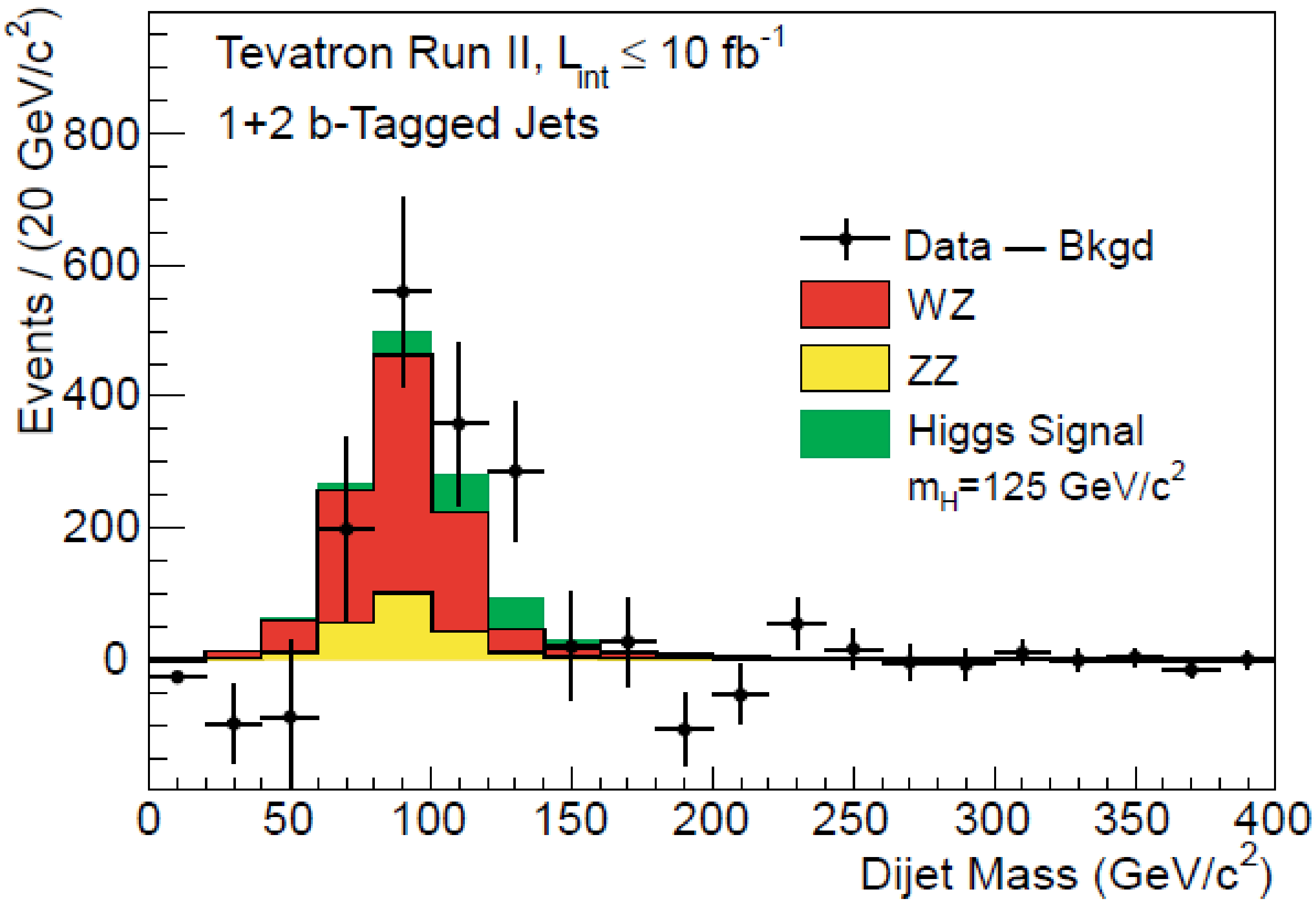
- **Visible gain obtained (~25% in sensitivity)**



Benchmarks : Dibosons to Heavy Flavor

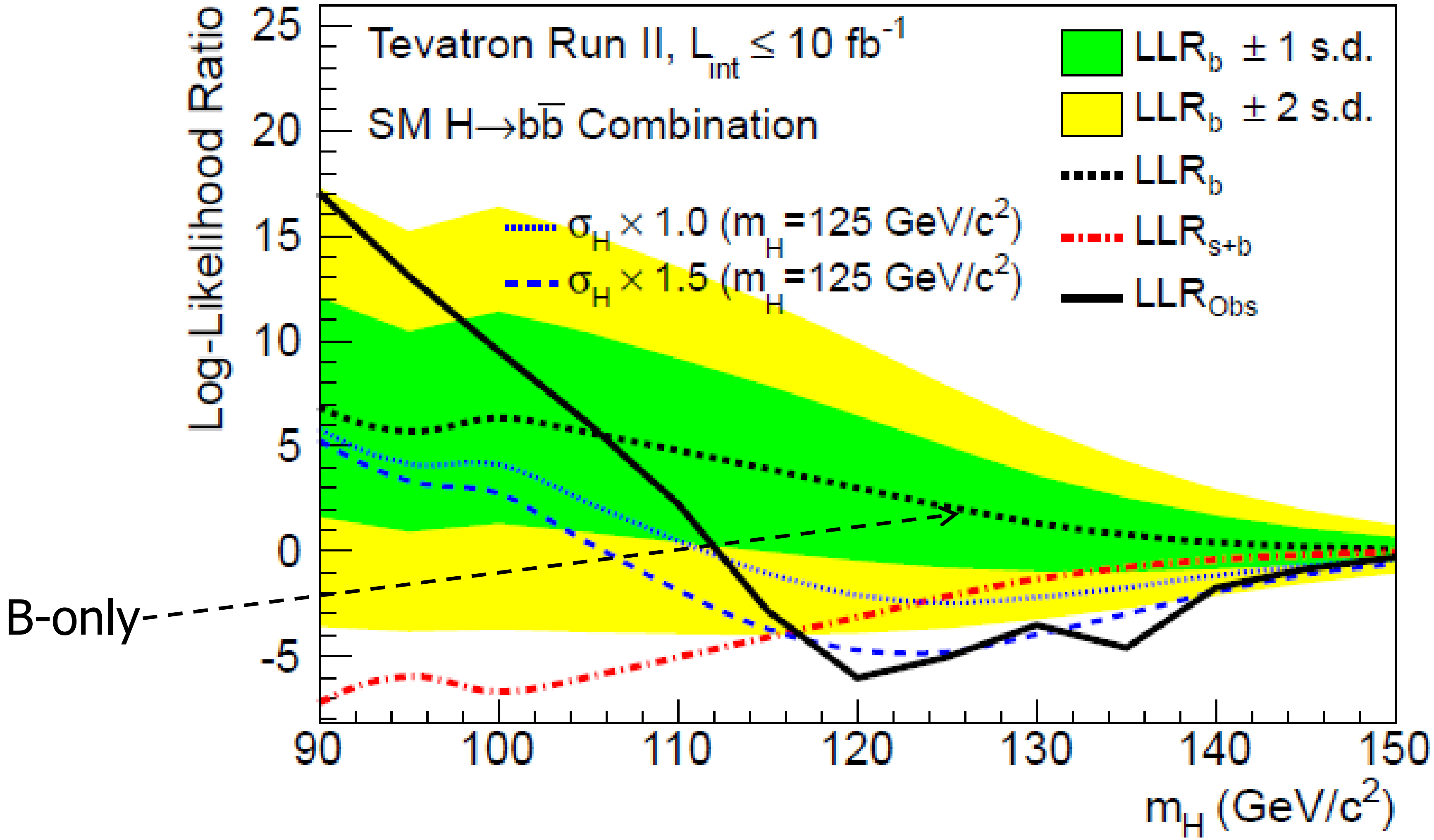
CDF- D0 combination on the same dataset/techniques as for H→bb, i.e. WZ, ZZ with Z→bb, same 3 final states, same b-tagging categorizations

→ **cross-section: 3.0 +/- 0.9 pb (NLO: 4.4 +/- 0.3 pb)**



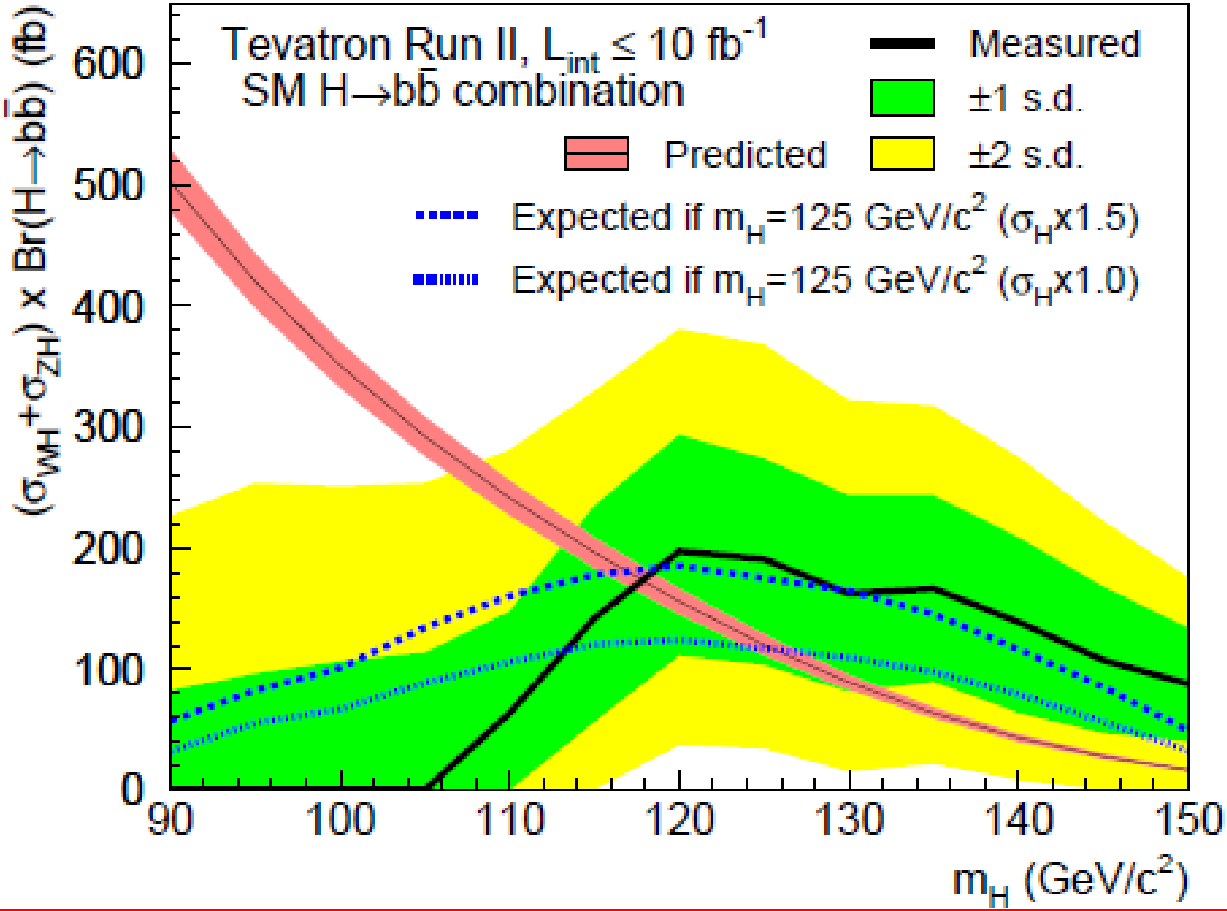
→ **Since there is a light Higgs, we should see it also in H→bb if it's SM-like!**

Combined Log-Likelihood Ratio for H→bb



Shape consistent with LLR expected in presence of 125 GeV Higgs, prefers slightly stronger strength than SM

Combined Cross section * BR measurement



$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \rightarrow b\bar{b})$ = 0.19 ± 0.09 (stat + syst) pb

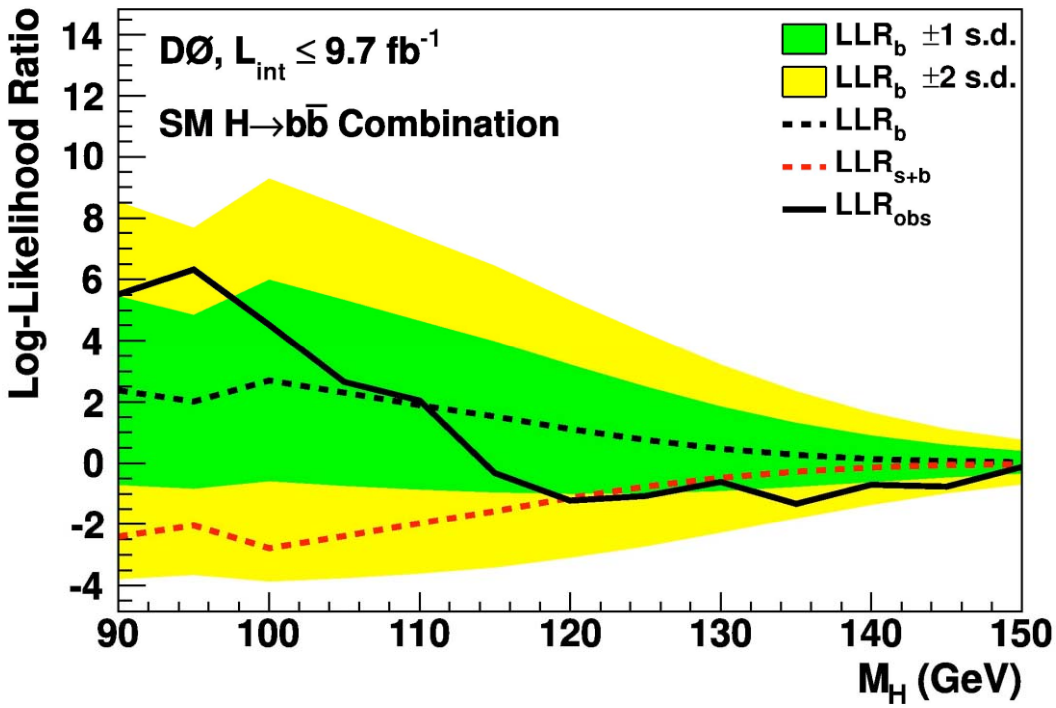
SM Higgs @ 125 GeV: 0.12 ± 0.01 pb

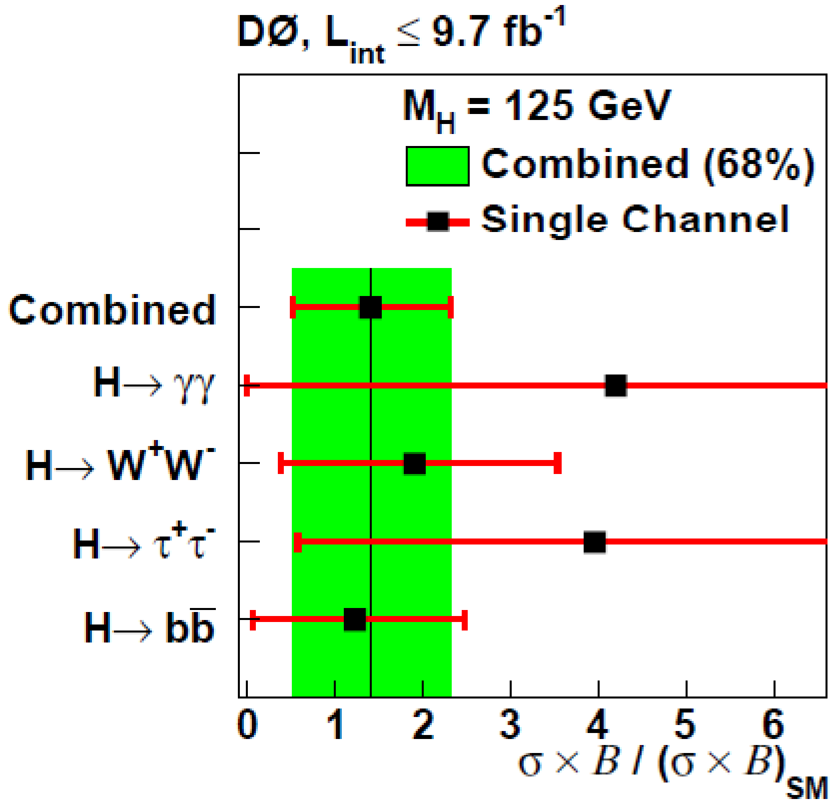
Tevatron: σ(VH) = 1.6 ± 0.7 (stat. + syst.) × SM
CMS: σ(VH) = 1.0 ± 0.5 (stat. + syst.) × SM
ATLAS: σ(VH) = 0.2 ± 0.6 (stat. + syst.) × SM

Spin@ D0 Starting from VH→Vb$\bar{b}$ Results

- 3 Analyses: WH->lvbb, ZH->llbb, ZH->vvbb
- Same inputs as for final Tevatron and D0 Higgs combination.
  → excess compatible with SM Higgs

- Best fit H->bb cross section: 1.23 $^{+1.24}_{-1.17}$ × SM



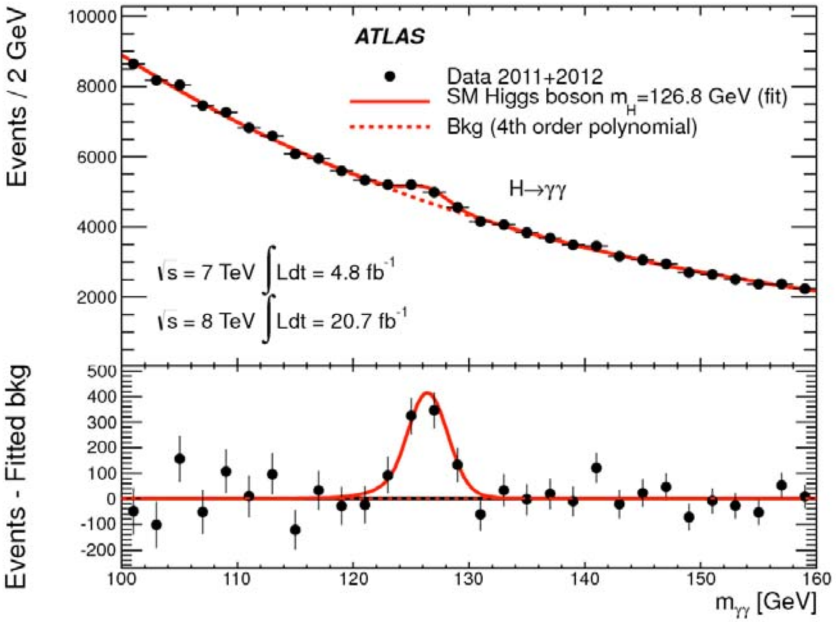


Higgs Spin and Parity: introduction

SM predicts a spin J and parity P combination $J^P = 0^+$

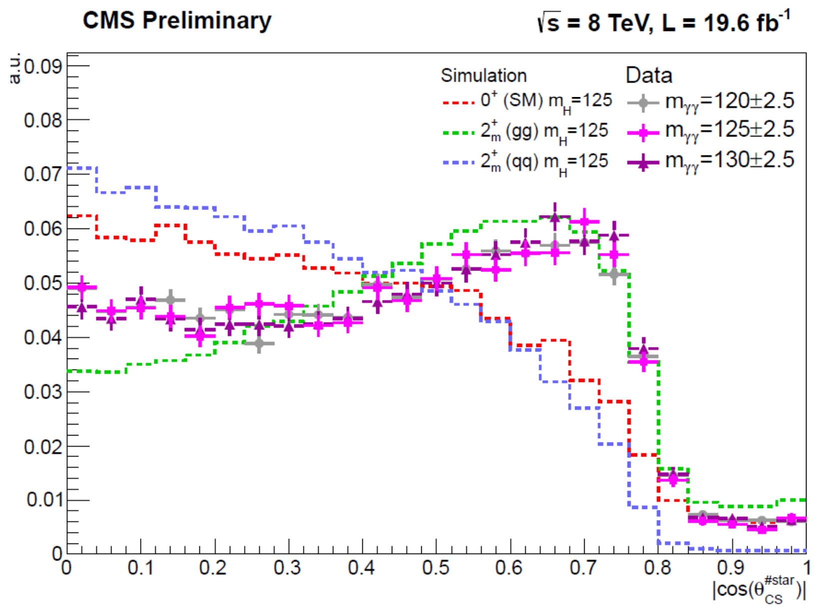
Other possibilities are 2^+ (graviton-like couplings) and 0^- (pseudoscalar)

Spin 1 ruled out with observation of decay $H \to \gamma\gamma$ (Landau-Yang Theorem)



- at ATLAS and CMS, all measurements are consistent with $J^P = 0^+$

- Measurements use bosonic decay modes, take advantage of angular correlations and kinematics of Higgs decay products



Spin and Parity at the Tevatron

- **In associated production, production processes are different depending on J^P assignment**
  - **For 0^+, production is S-wave; cross section ~β near threshold**
  - **For 0^-, production is P-wave; cross section ~β^3 near threshold**
  - **For 2^+, mostly D-wave contribution for graviton-like couplings; cross section ~β^5**

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

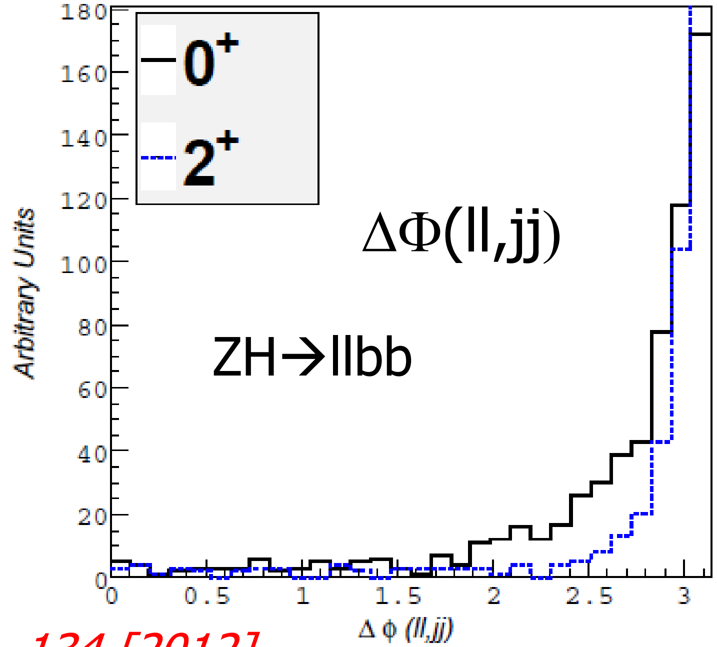
- **At the Tevatron we expect the kinematic differences to come from different behaviors at the production threshold**

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

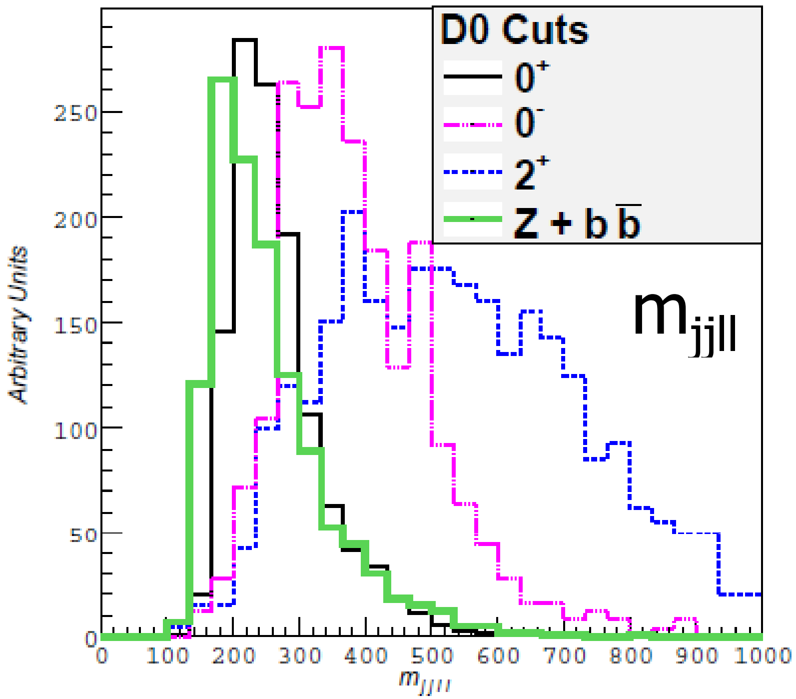
Testing Spin and Parity

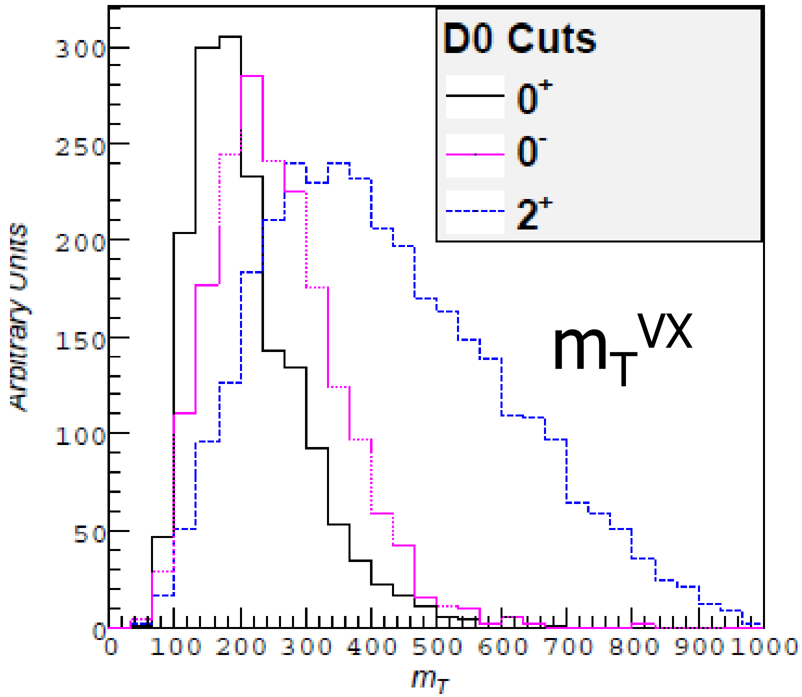
Visible mass of Vbb system very sensitive to J^P assignment,

good separation from backgrounds for 2+ and 0- as well, much better than for SM Higgs!



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





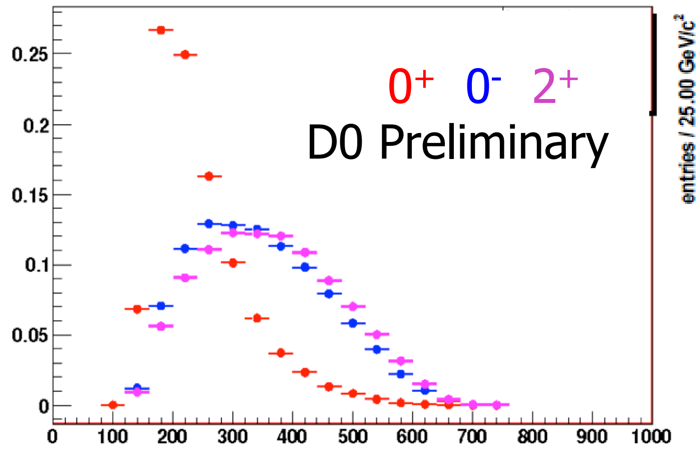
Generating signals

- **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**

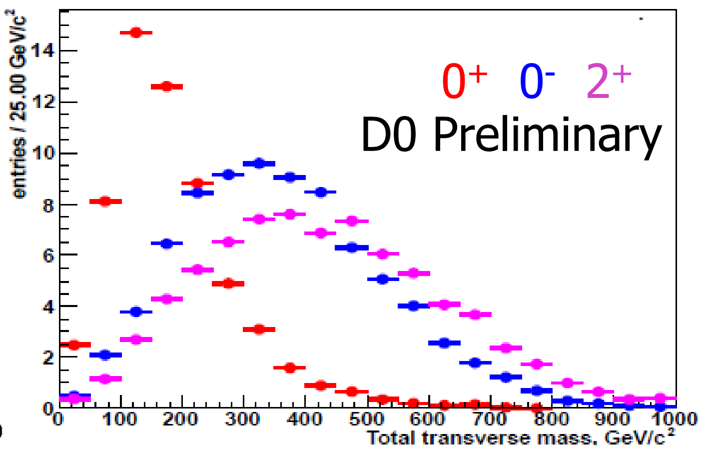
- **Observe similar separation to that predicted**

ZH⟶ννbb



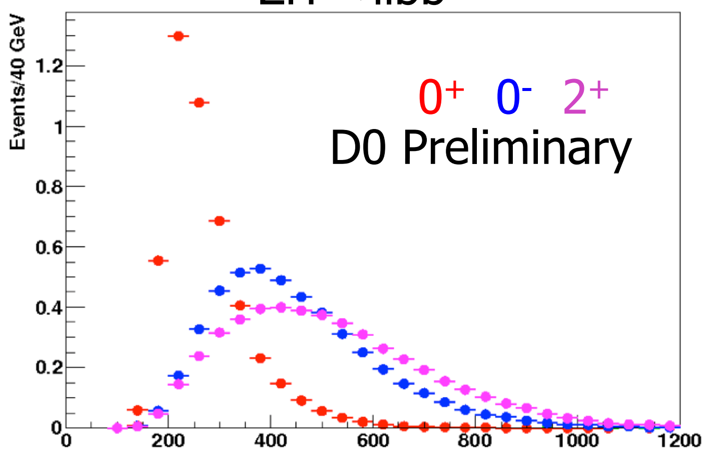
V+X m_T

WH⟶lνbb



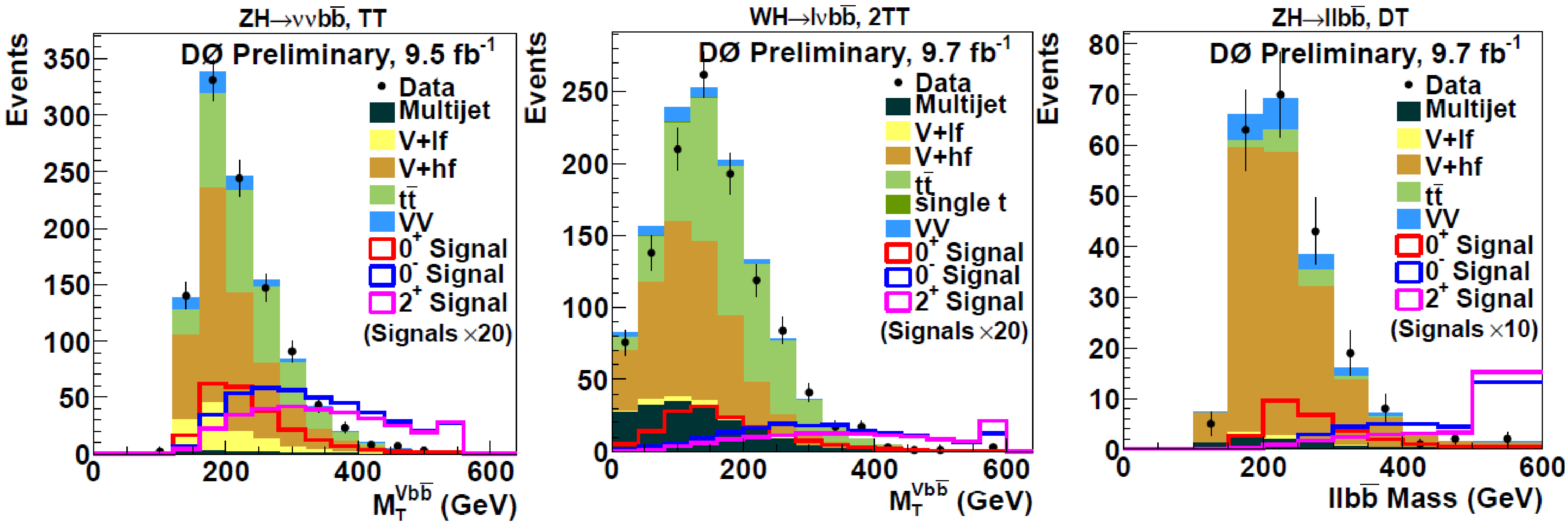
V+X m_T

ZH⟶llbb



V+X mass

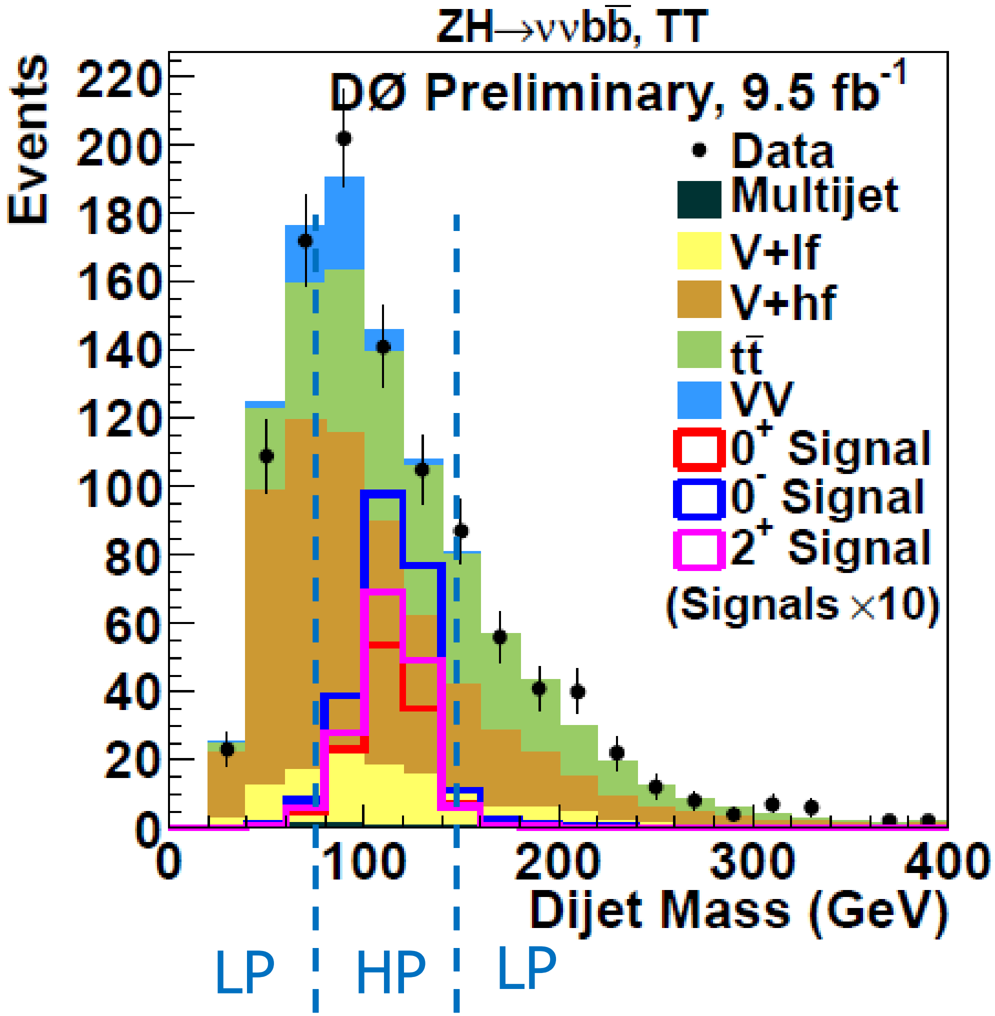
Visible Mass in VH Channels

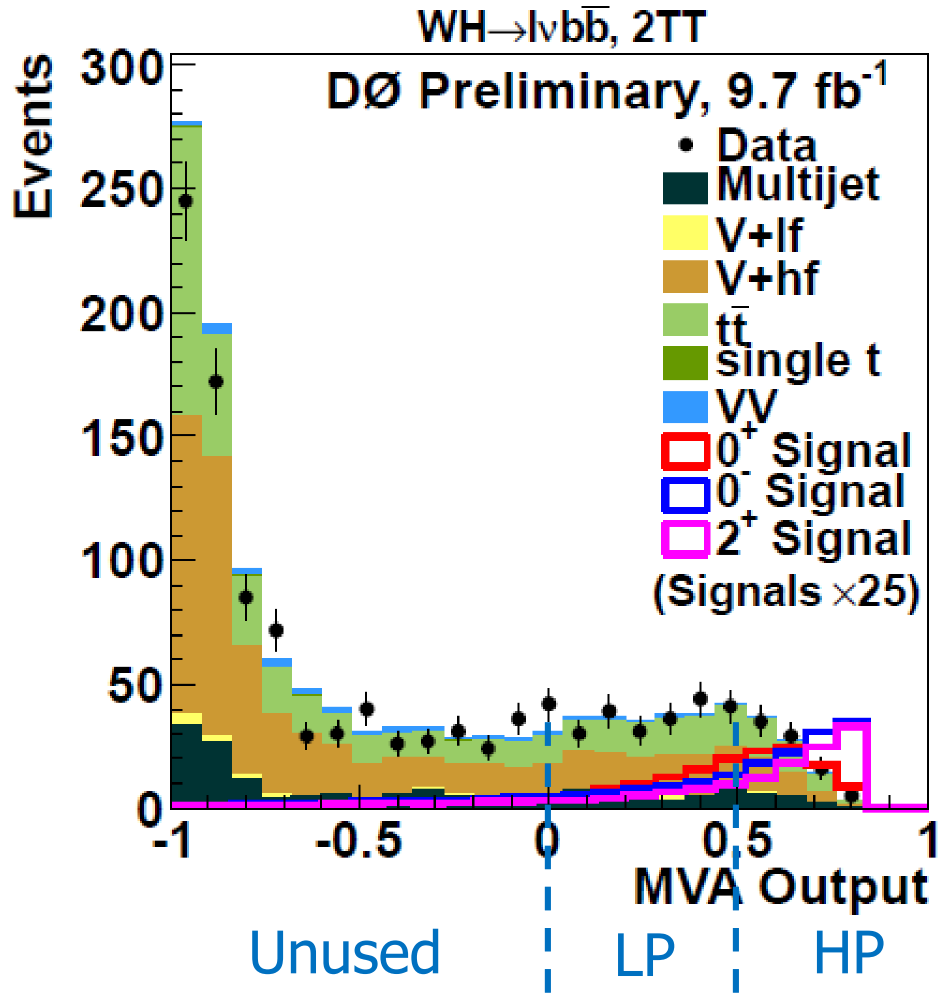


- Tightest b-tag sub-channel shown (upper edge bins combined due to statistics)
- Good separation between different signals
- Can we do better on the backgrounds?

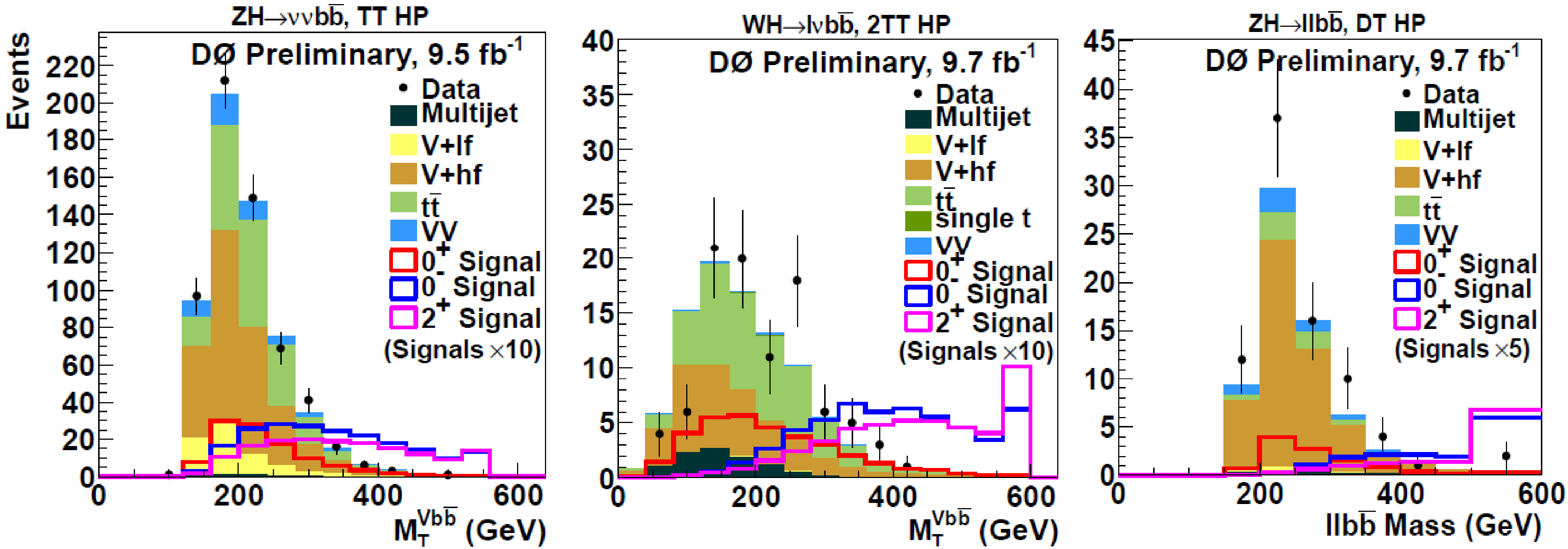
Additional Discrimination

- **Take advantage of known mass**
  - **- vvbb, llbb → use M_{bb} to define High/Low Purity (HP/LP) regions**
  - **- lvbb → MVA output to make HP/LP regions**
- **Separate channels for statistical analysis**





Final Variables



Tightest High Purity b-tag channel shown for each analysis

Large separation between **SM/0^+** and **0^-** or **2^+**

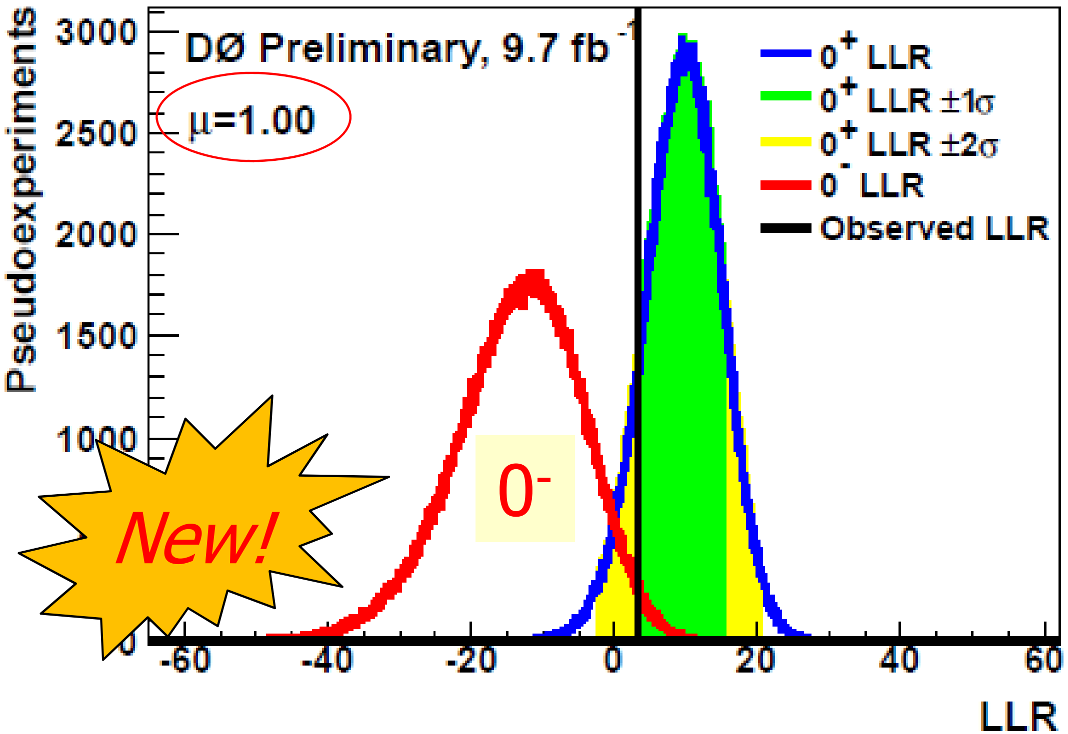
Higgs Spin Results

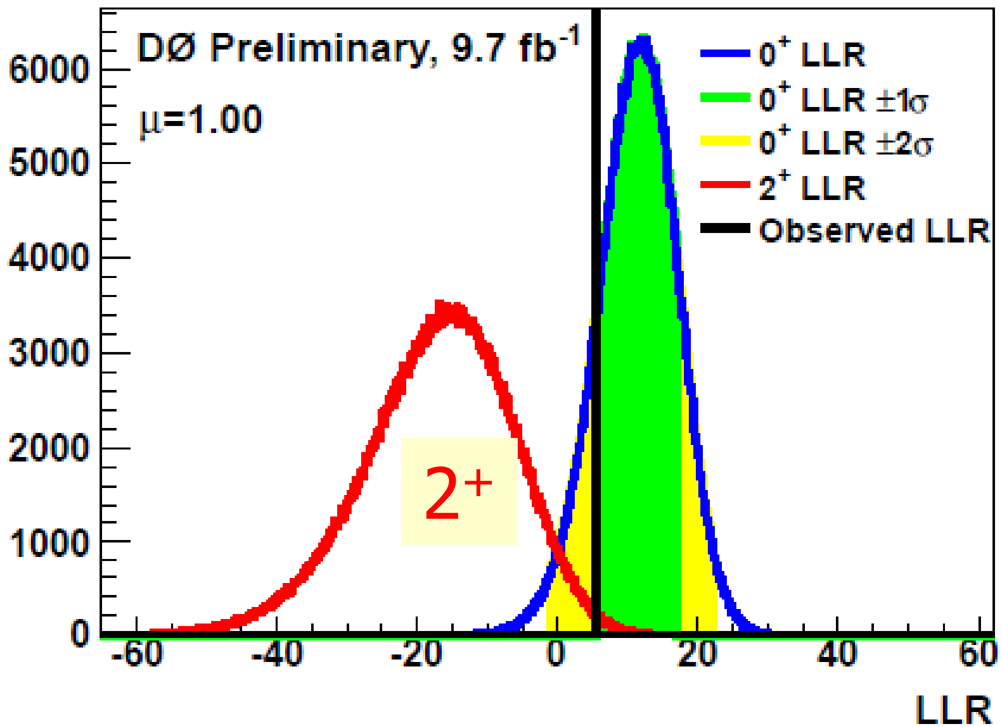
- Use CL_s to quantify model preference, log-likelihood ratio (LLR) as test statistic

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

  - H1: 0^- signal + Background or 2^+ signal + Background
  - H0: 0^+ signal + Background

- Compute for 2 different signal scale factors μ on SM $\sigma(VH) \times Br(bb)$
  - 1.00 (SM-like, shown) and 1.23 (D0 measured rate)





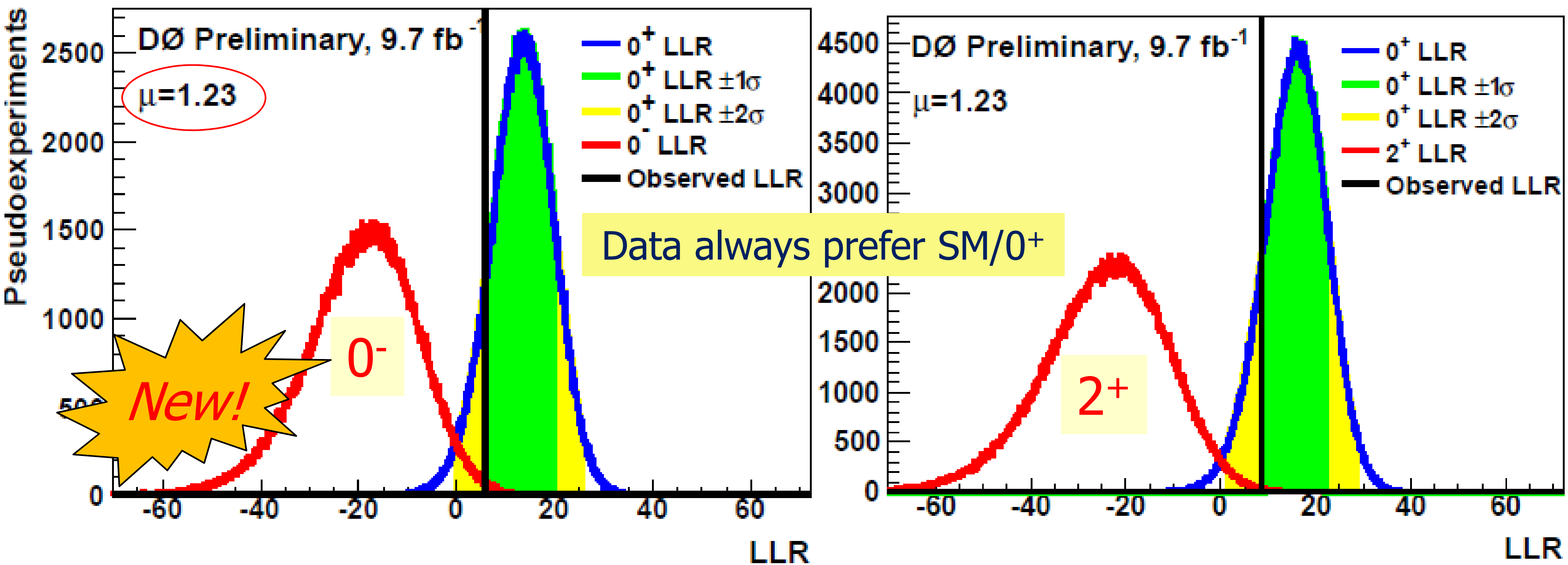
Higgs Spin Results

- Use CL_s to quantify model preference, log-likelihood ratio (LLR) as test statistic

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

  - H1: 0^- signal + Background or 2^+ signal + Background
  - H0: 0^+ signal + Background

- Compute for 2 different signal scale factors μ on SM $\sigma(VH) \times Br(bb)$
  - 1.00 (SM-like) and 1.23 (D0 measured rate, shown)



Higgs Spin 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 0^- or 2^+
- in favor of 0^+

- We exclude 0^- model at > 97.9% C.L.
- Expected exclusion is 3.1 s.d. (μ=1.0)

- We exclude 2^+ model at > 99.2% C.L.
- Expected exclusion is 3.2 s.d. (μ=1.0)

New!

	Results 0^-	Result in s.d. 0^-	Results 2^+	Result in s.d. 2^+
$1 - CL_s$ Exp. (μ=1.00)	0.998	3.1	0.9992	3.2
$1 - CL_s$ Obs. (μ=1.00)	0.979	2.3	0.992	2.4
$1 - CL_s$ Exp. (μ=1.23)	0.9997	3.5	0.9999	3.7
$1 - CL_s$ Obs. (μ=1.23)	0.995	2.5	0.999	3.0

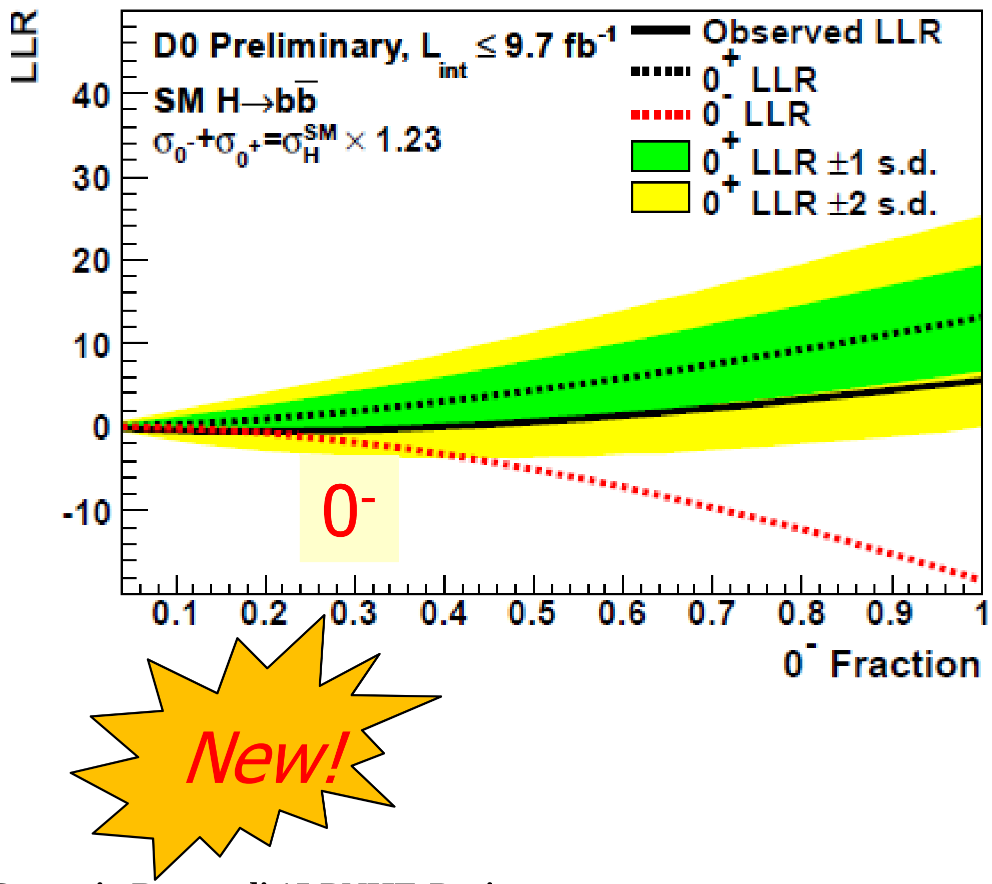
Single Tevatron experiment has sensitivity competitive with LHC experiments

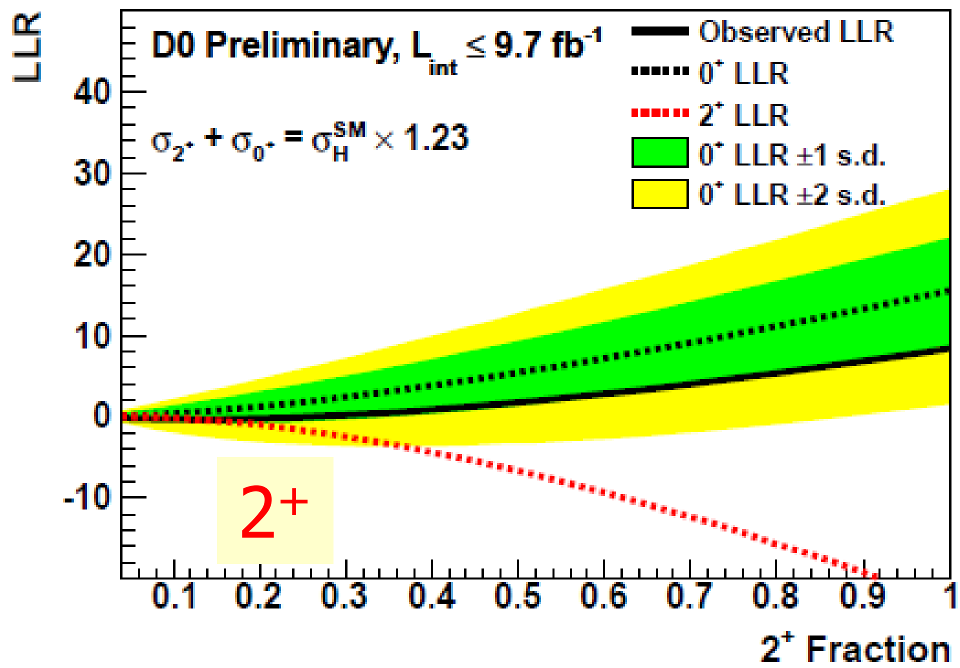
(example: ATLAS WW/ZZ/$\gamma\gamma$ combination expected exclusion for 0- & 2+: 2.3σ & 3.0σ)

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

Signal Admixtures

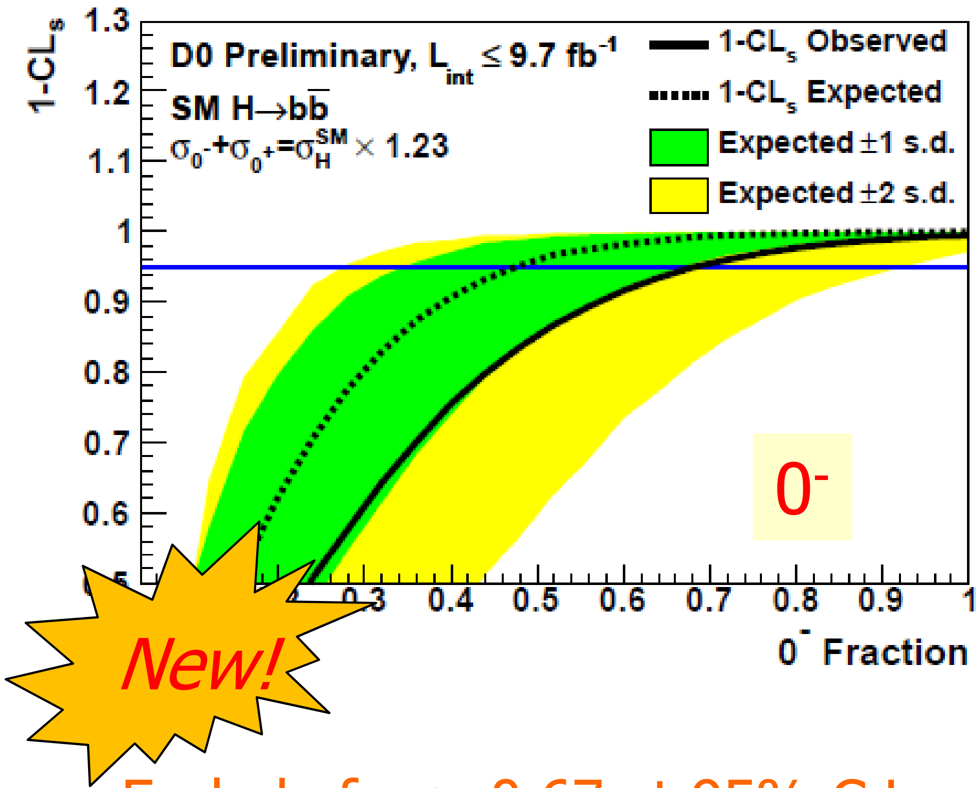
- **Allow possibility of both a 0^- (or 2^+) and 0^+ signal in data**
  - Vary 0^- (or 2^+) Fraction f_x from 0 to 1
  - H1: $\mu \times (\sigma \bullet Br(\text{->}bb))_{SM} \times [0^- \times f_x + 0^+ \times (1 - f_x)]$ + Background
  - H0: $\mu \times (\sigma \bullet Br(\text{->}bb))_{SM} \times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

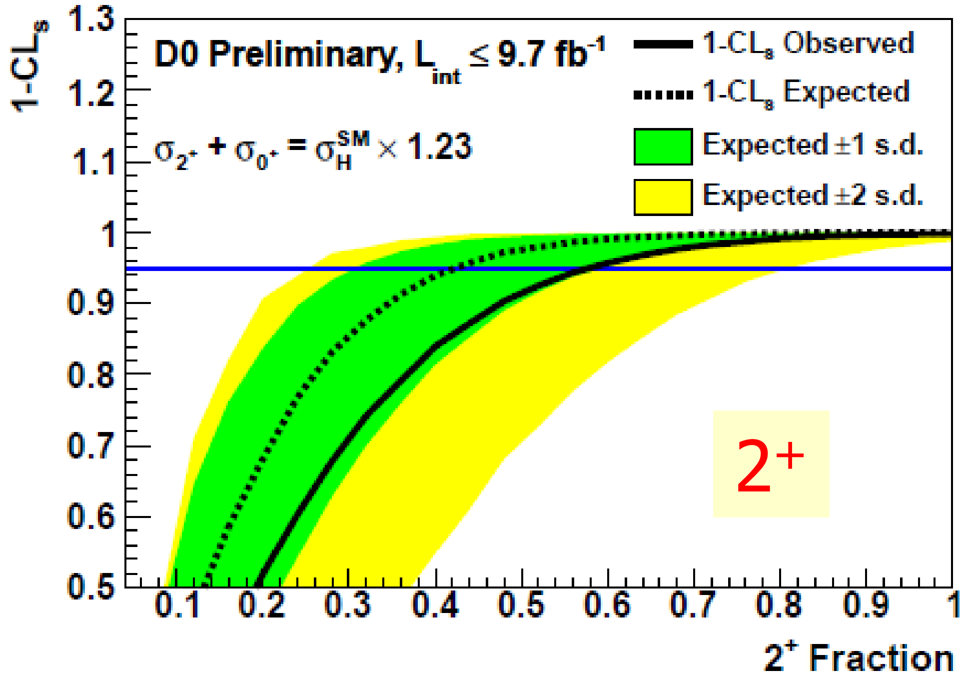




Signal Admixtures

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





Exclude $f_{0-} > 0.67$ at 95% C.L. Exclude $f_{2+} > 0.57$ at 95% C.L.

Summary and Outlook

- Latest Tevatron results based on full Run II dataset in all major search channels are all now published in PRD.
- Signal strengths in 4 decay channels (bb,$\tau\tau$,$\gamma\gamma$,WW), and results on Higgs couplings to fermions, W, Z, are consistent with the SM.
- Published evidence for WH/ZH production with H→bb (7/2012), where H is consistent with a SM Higgs boson of 125 GeV, as the boson discovered by ATLAS & CMS is so far the only evidence in a single fermionic decay channel of the Higgs.
- The H→bb channel could be seen at >4 sigma level before the 2015-18 LHC Run, through combination of all H→bb results. Combining all fermionic channels may establish fermionic decay of the Higgs boson at 5 sigma level now, a milestone result!

.

- D0 spin and parity tests (first in bb final states) favor $J^P=0^+$; reject $J^P=0^-$ and 2^+ (graviton-like couplings) at >97.9% and 99.2% C.L, assuming SM strength. Higgs signal at D0 cannot contain (at 95%CL) more than 67% or 57% of 0^- or 2^+.
- Final publications on Higgs are approaching for Tevatron: ➔ these results, and possibly combination with CDF which could reach 5 sigmas exclusion of JP 0^- and 2^+ hypotheses.