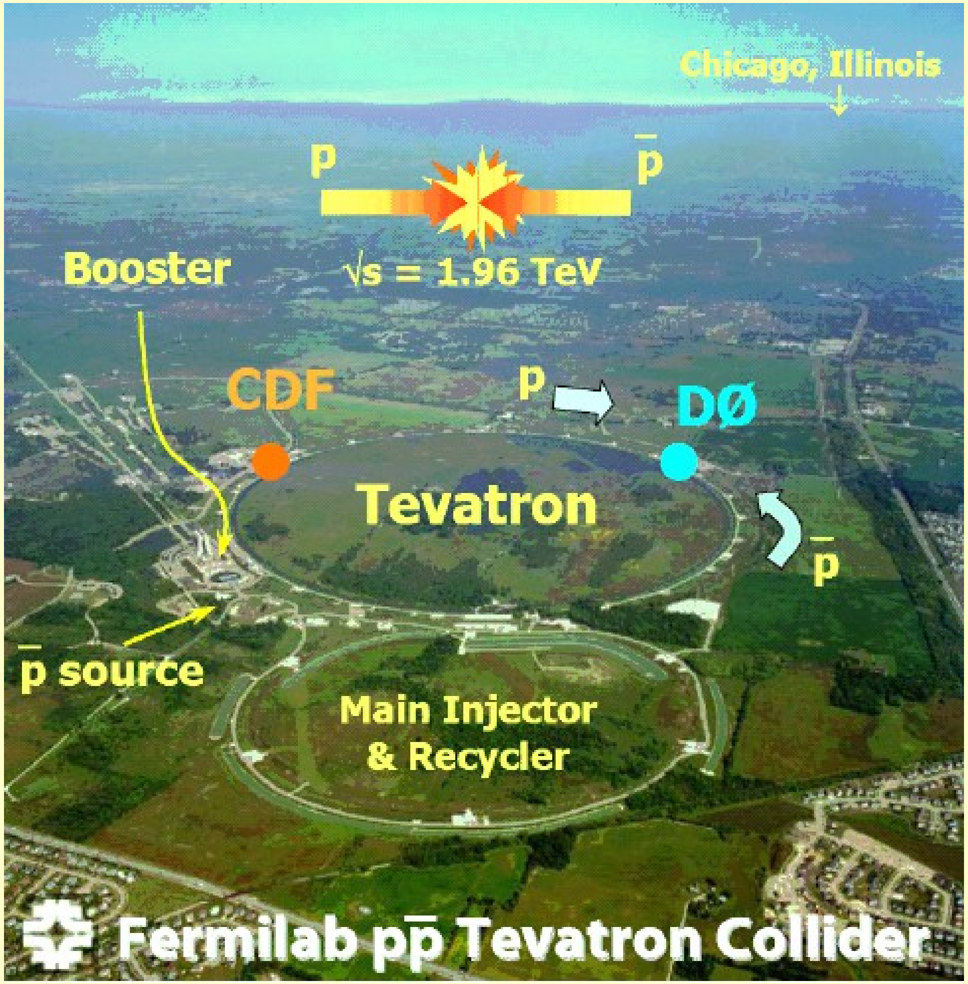
Overview of the Higgs boson studies at Tevatron

Lidija Živković,
LPNHE, Paris VI & VII

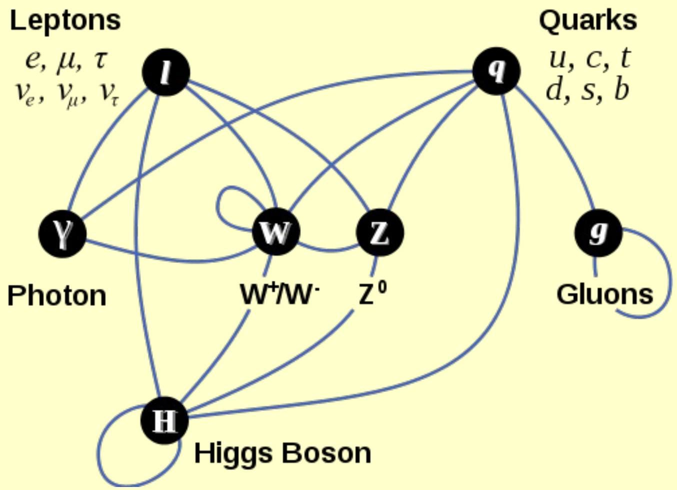
Experimental Seminar at IRFU CEA Saclay,
16 September 2013

Outline

- Current status
- Overview of the main search channels
- Tevatron results
  - Combined results
  - Constraints on couplings
- Spin/parity studies

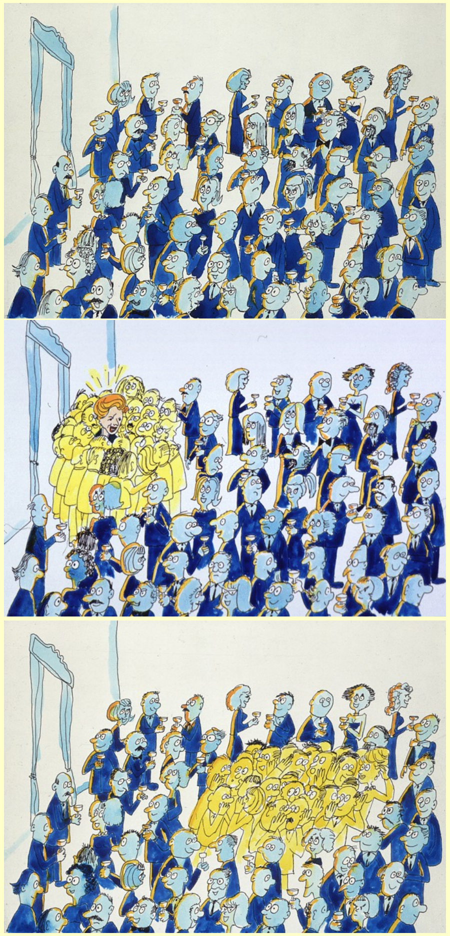


Standard Model



- The Standard Model is defined by the symmetries of the Lagrangian:
  - $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Interactions: strong, weak, and electromagnetic
  - carriers: gluons – g, weak bosons $W^{\pm}$, Z, and photon
- matter particles:
  - leptons and quarks
- and the pattern of spontaneous symmetry breaking
  - complex scalar field
  - breaks $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{EM}$

The Higgs Mechanism



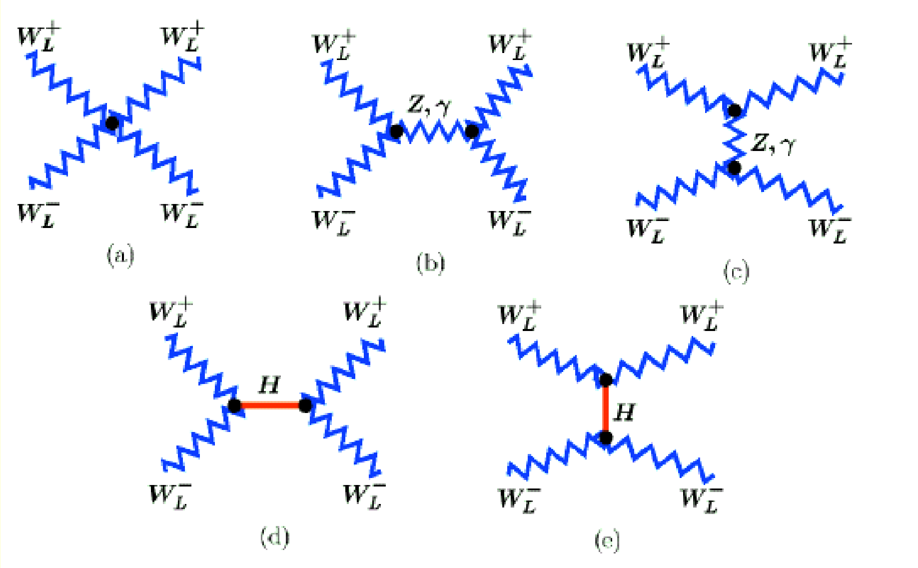
- Essential ingredient of the Standard Model
  - Complex scalar field with potential
- Used to break the el. weak symmetry...

$$M_W = \frac{1}{2} v g \qquad M_Z = \frac{1}{2} v g / \cos\theta_W = M_W / \cos\theta_W$$

- ... and to generate fermion masses:

$$m_f = g_f v / \sqrt{2} \quad \Rightarrow g_f = m_f \sqrt{2} / v$$

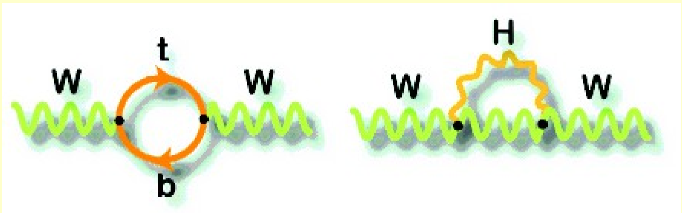
- Unitarity requires a Higgs boson or similar
  - cross section for WW scattering diverges like s/M_W^2
  - scalar Higgs boson cancels divergences

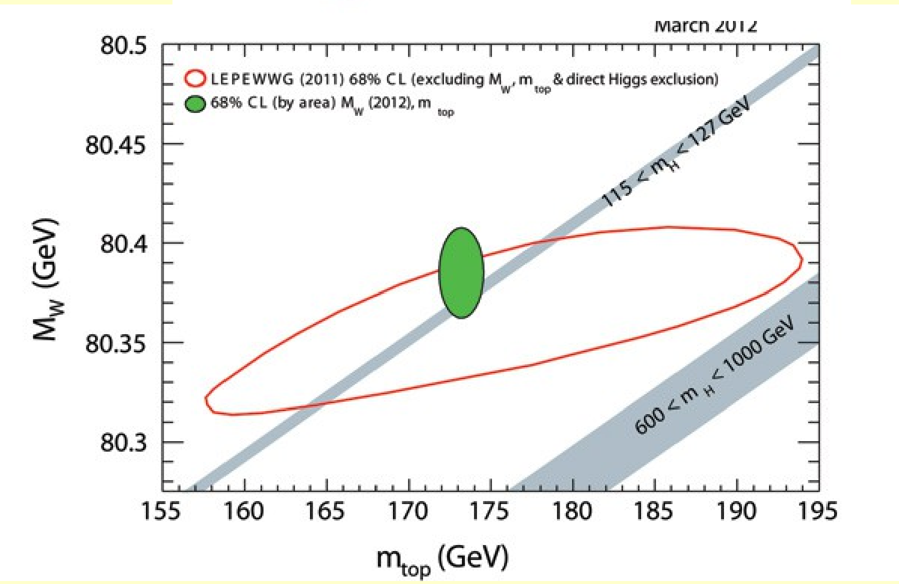


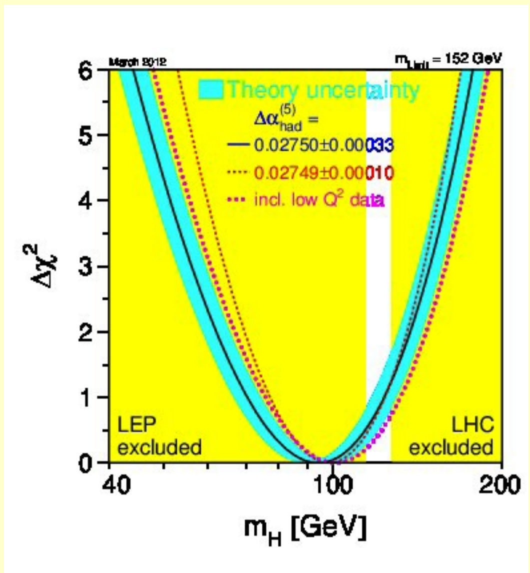
Bounds on mass

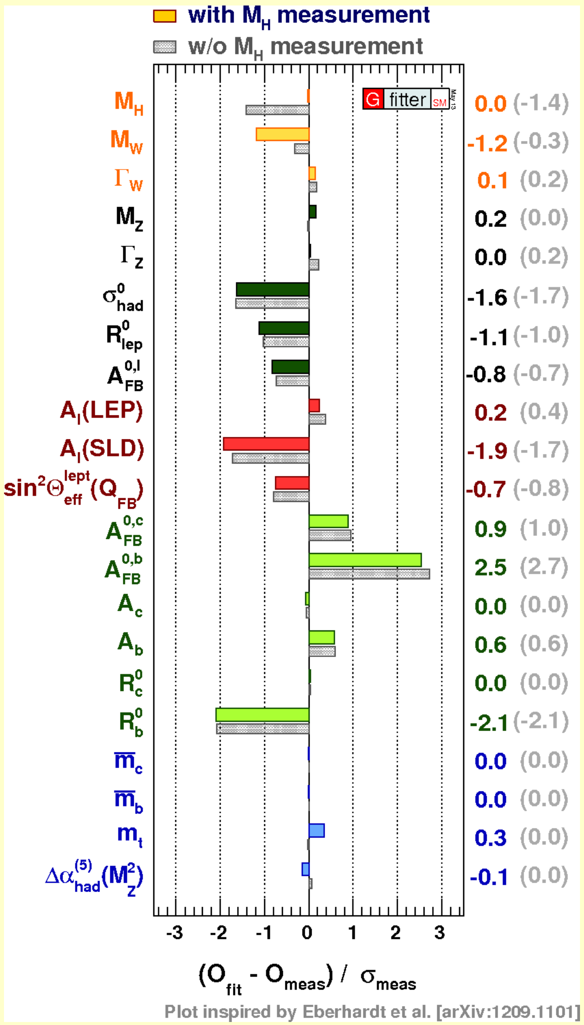
- SM Higgs boson mass is constrained indirectly through precision measurements
  - self-energy corrections to the W mass depend on the mass of the top quark and Higgs boson, ***which are both precisely measured at Tevatron***

- Global SM electroweak fits provide upper limit
  - The best fit gives $m_H = 94^{+29}_{-24}\,GeV$
  - Limit from fit m_H < 152 GeV

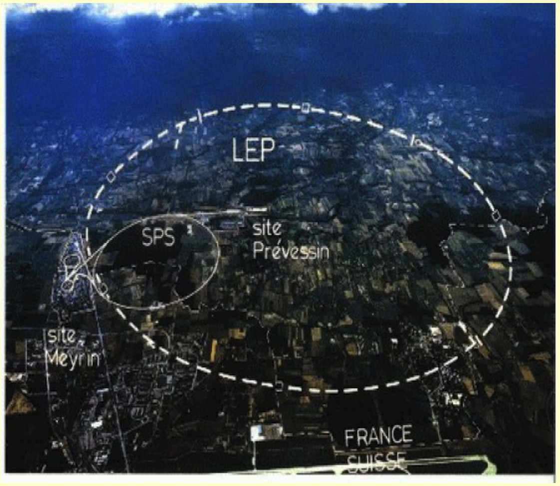








Historical perspective

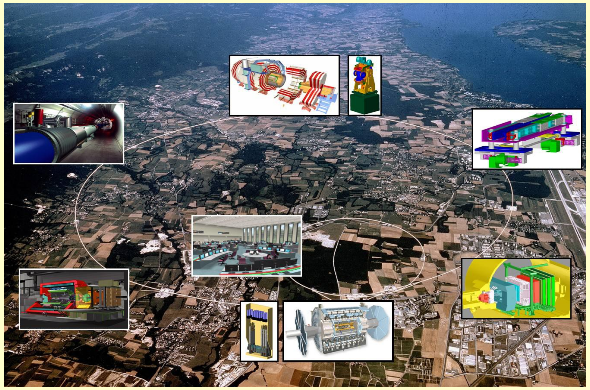


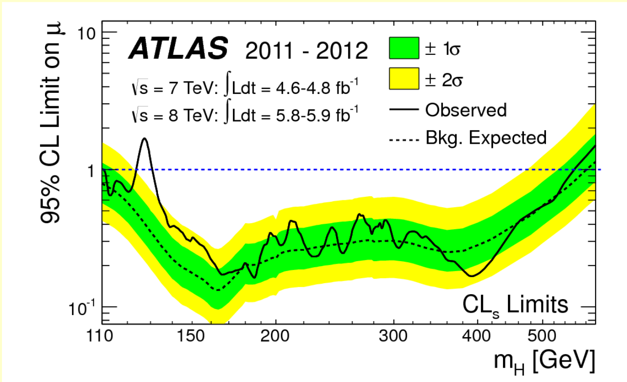
- LEP (1989 – 2000): m_H > 114.4 GeV@95% CL

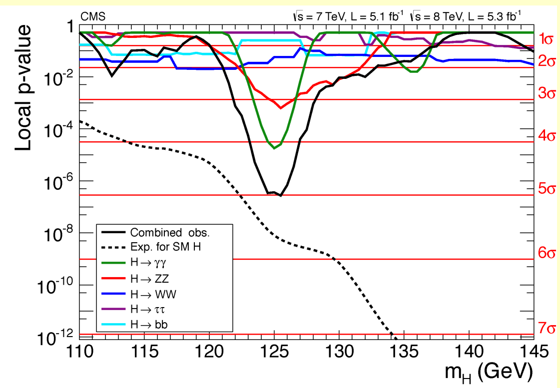
- At hadron colliders:

- Tevatron Run II (2002-2011):
  - First post-LEP exclusion (2009)
  - First evidence of a Higgs-like particle decaying to a pair of b-quarks (July 2012)

- LHC (2009 – 2012):
  - Excluded wide mass range (111 – 122 GeV and 127 – 600 GeV)
  - **Discovered the new Higgs-like boson mainly through γγ and ZZ decays (July 2012)**



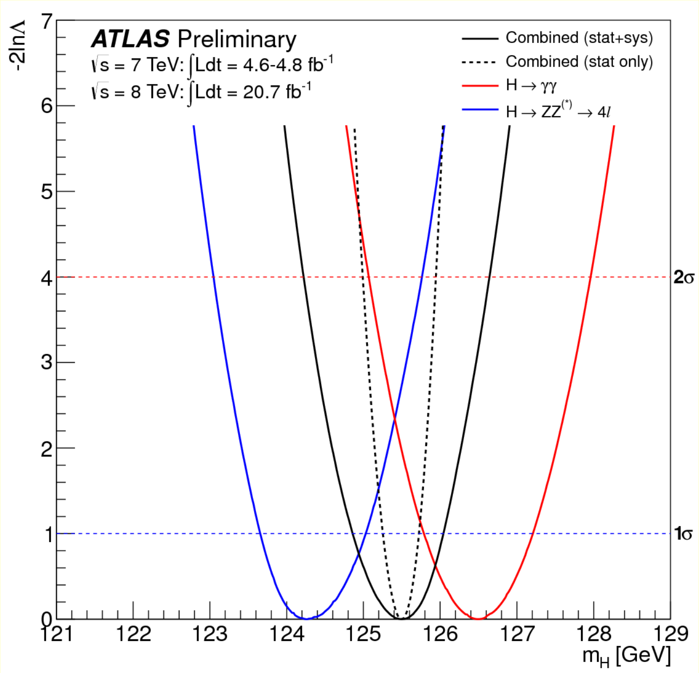


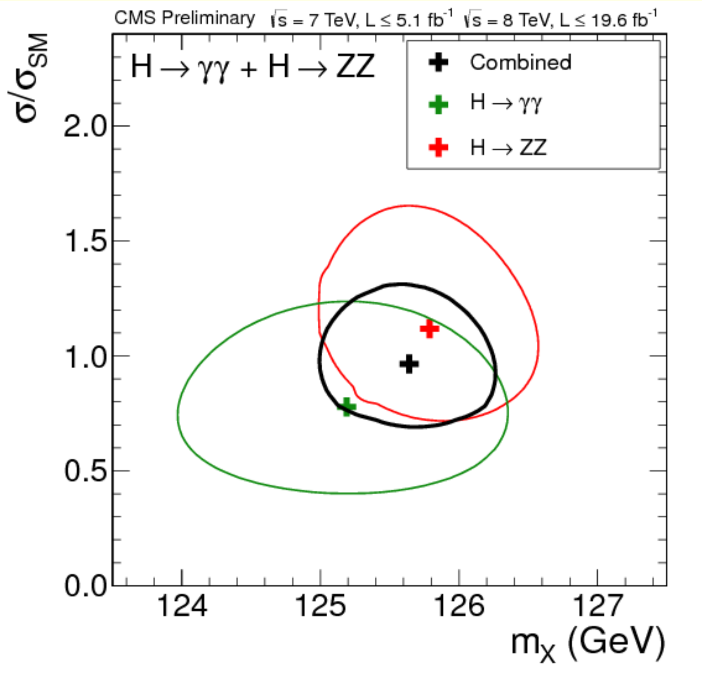


Current situation

As presented at the latest conferences

- LHC (2009 – 2012):
  - Since July 2012 progress in each channel
  - Observation confirmed in bosonic channel
  - ATLAS: m_H = 125.5 ± 0.2 (stat) −0.6+0.5 (sys) GeV
  - CMS: m_H = 125.7 ± 0.3 (stat) ± 0.3 (sys) GeV

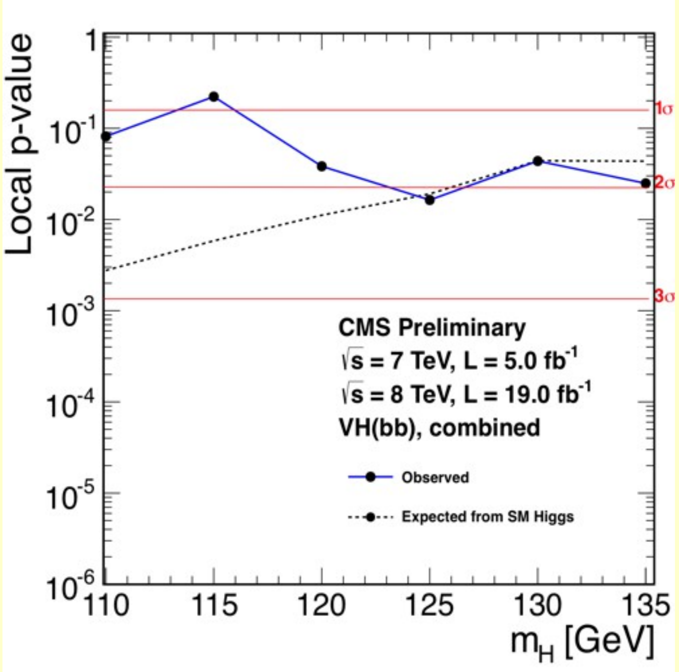


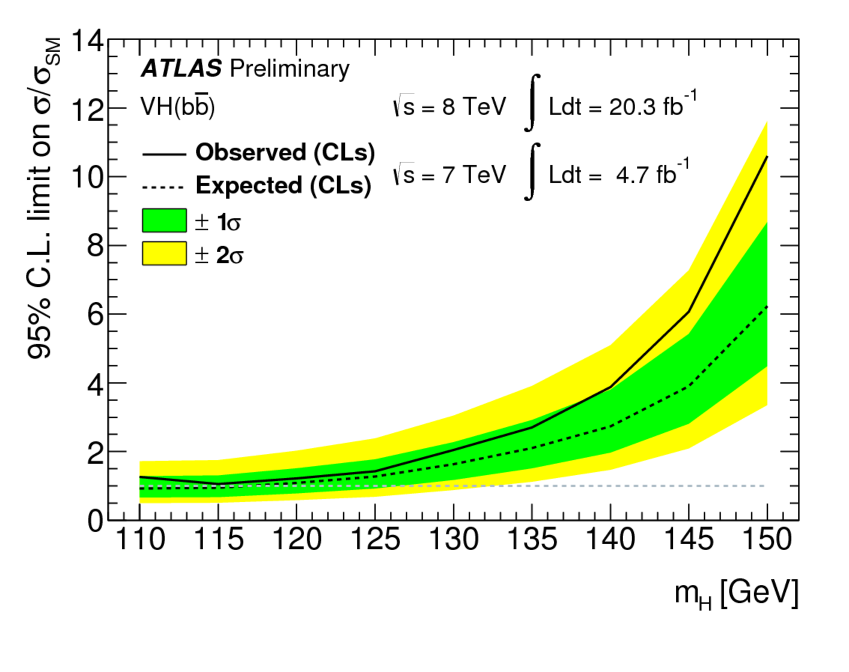


Current situation

As presented at the latest conferences

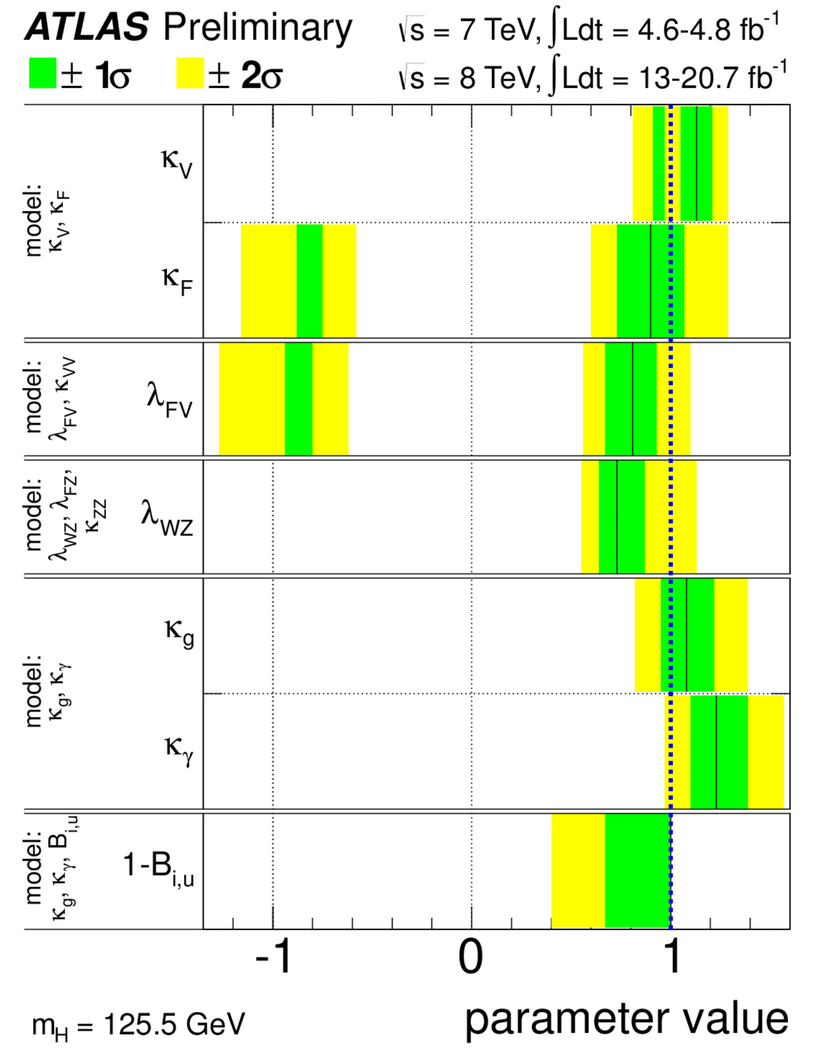
- LHC (2009 – 2012):
  - Fermionic evidence is still weak
  - Strong indication of $H \rightarrow \tau\tau$ at CMS
  - $VH \rightarrow Vbb$ with full data (24 fb^{-1}) shows 2.1 s.d excess at CMS, and there is data deficit at ATLAS

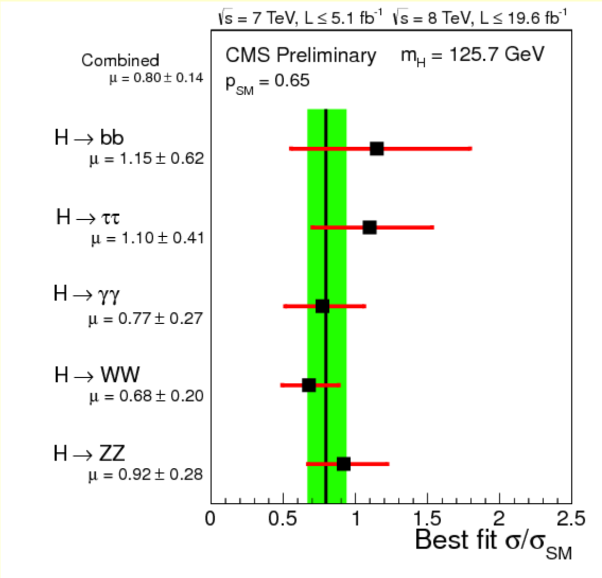


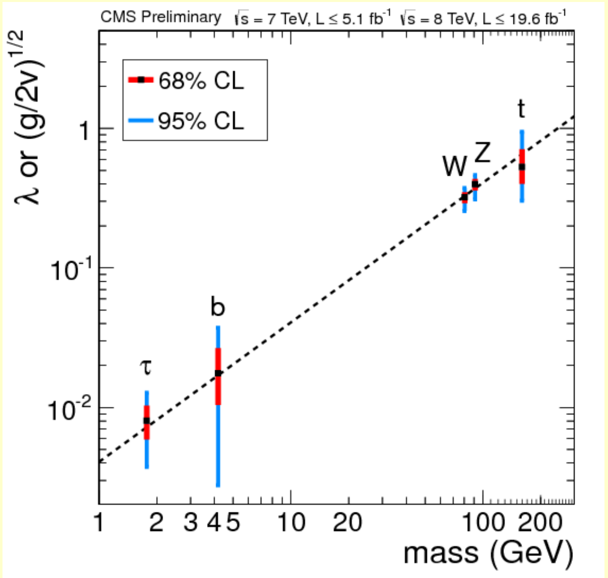


Higgs properties from LHC

- Properties measured so far confirm it is indeed Higgs boson







If it quacks like a

If it walks/swims like a

It's an  *?*

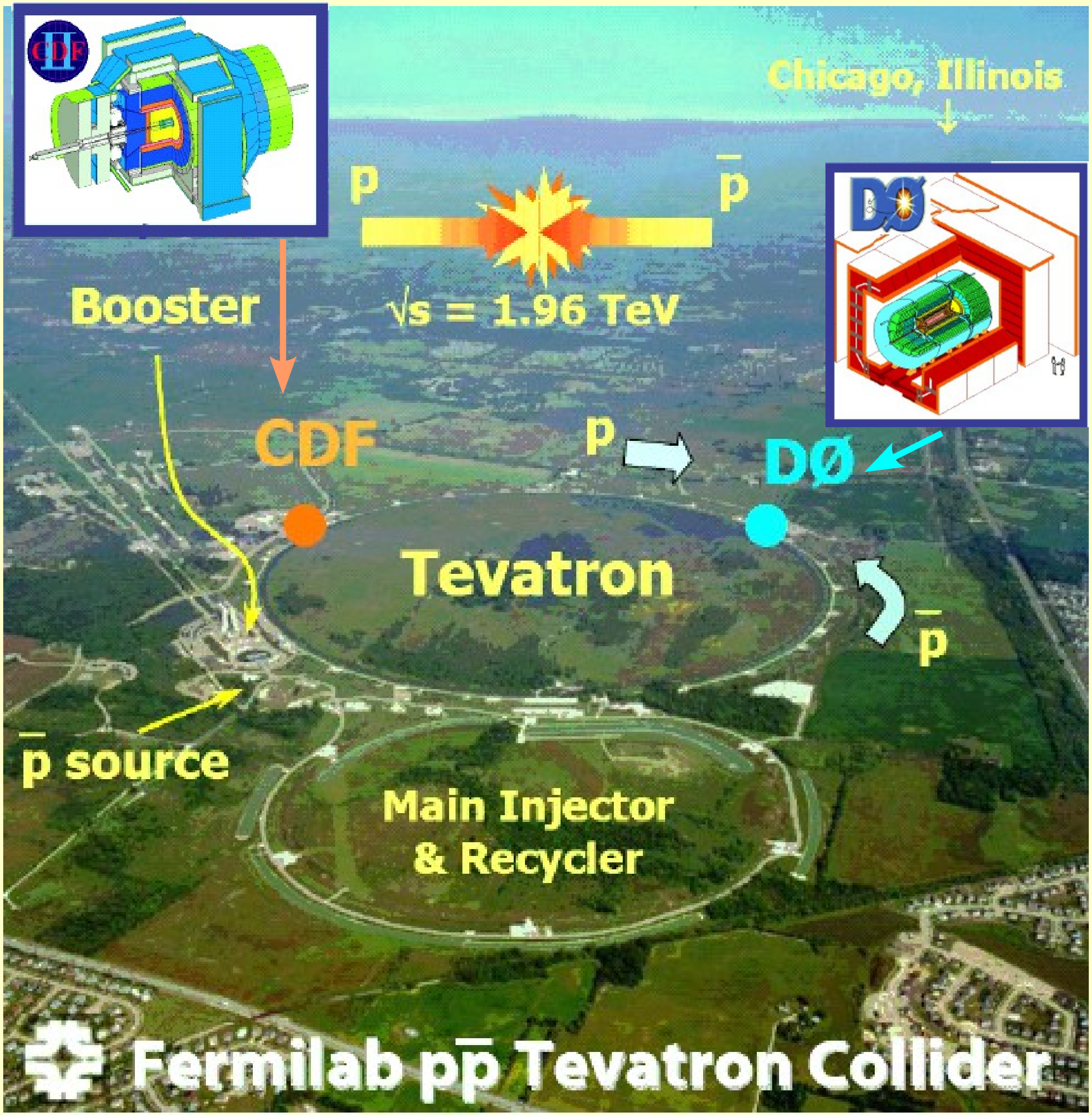
No, it's still a 

Experiments

The Tevatron

$p\bar{p}$ collisions

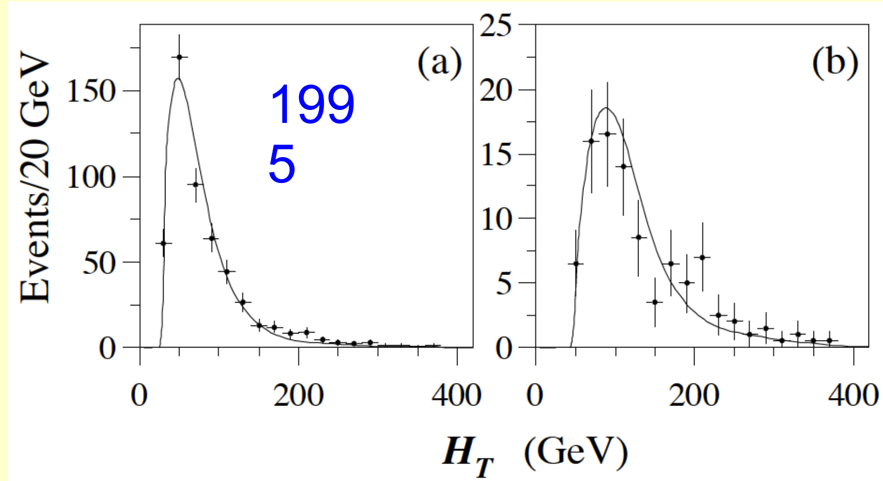
- Ran for 25 years
  - 9 in Run II at center of mass energy $\sqrt{s}$ = 1.96 TeV
- Discovered top quark
- Excluded high mass range of the Higgs boson
- Achieved the most precise measurement of the W and top mass
- Stopped running on September 30th, 2011

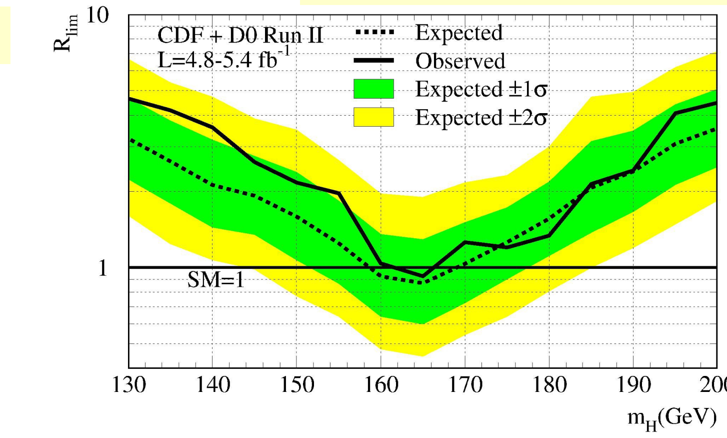


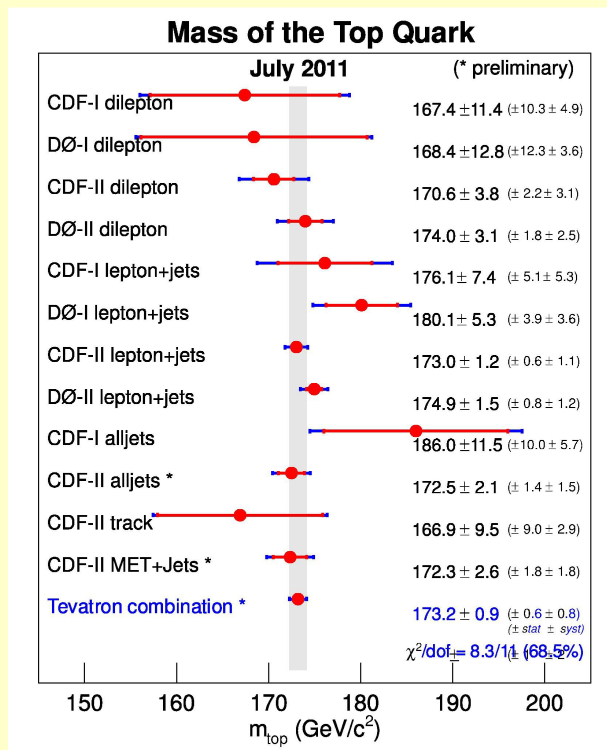
The Tevatron

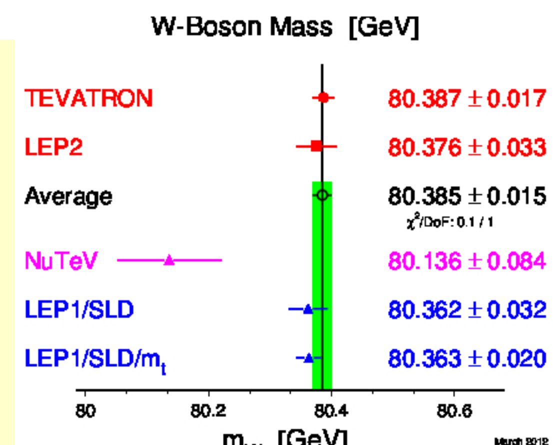
$p\bar{p}$ collisions

- Ran for 25 years
  - 9 in Run II at center of mass energy $\sqrt{s}$ = 1.96 TeV
- Discovered top quark
- Excluded high mass range of the Higgs boson
- Achieved the most precise measurement of the W and top mass
- Stopped running on September 30th, 2011



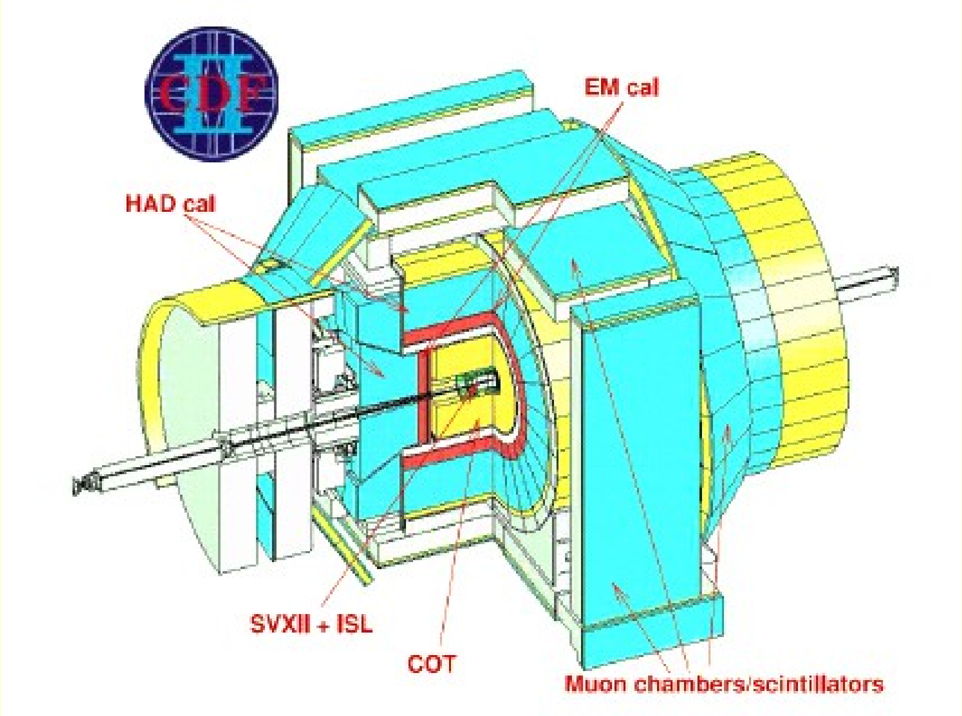


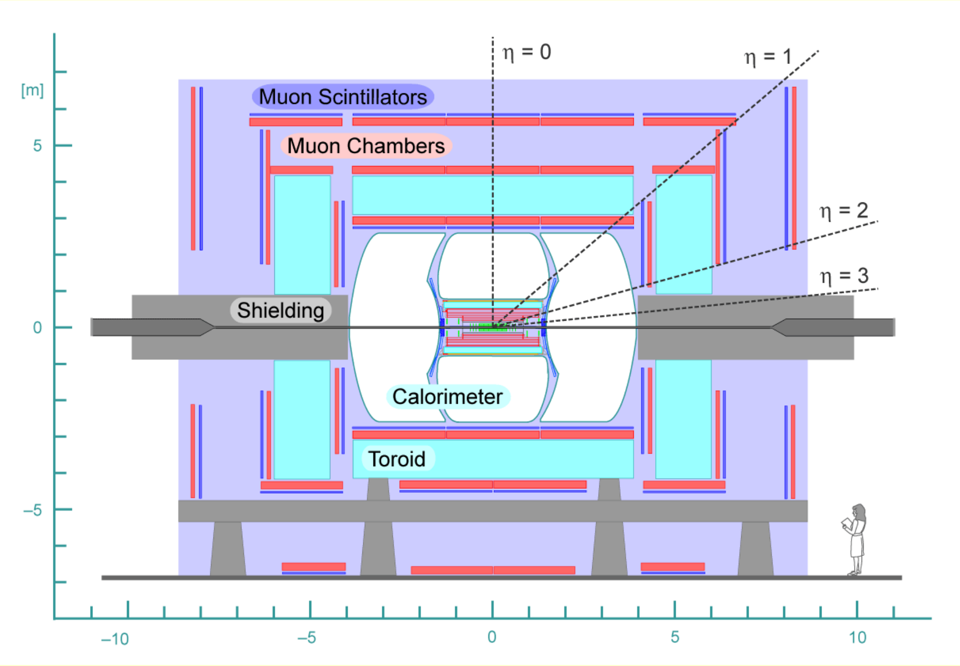




CDF and DØ experiment in Run II

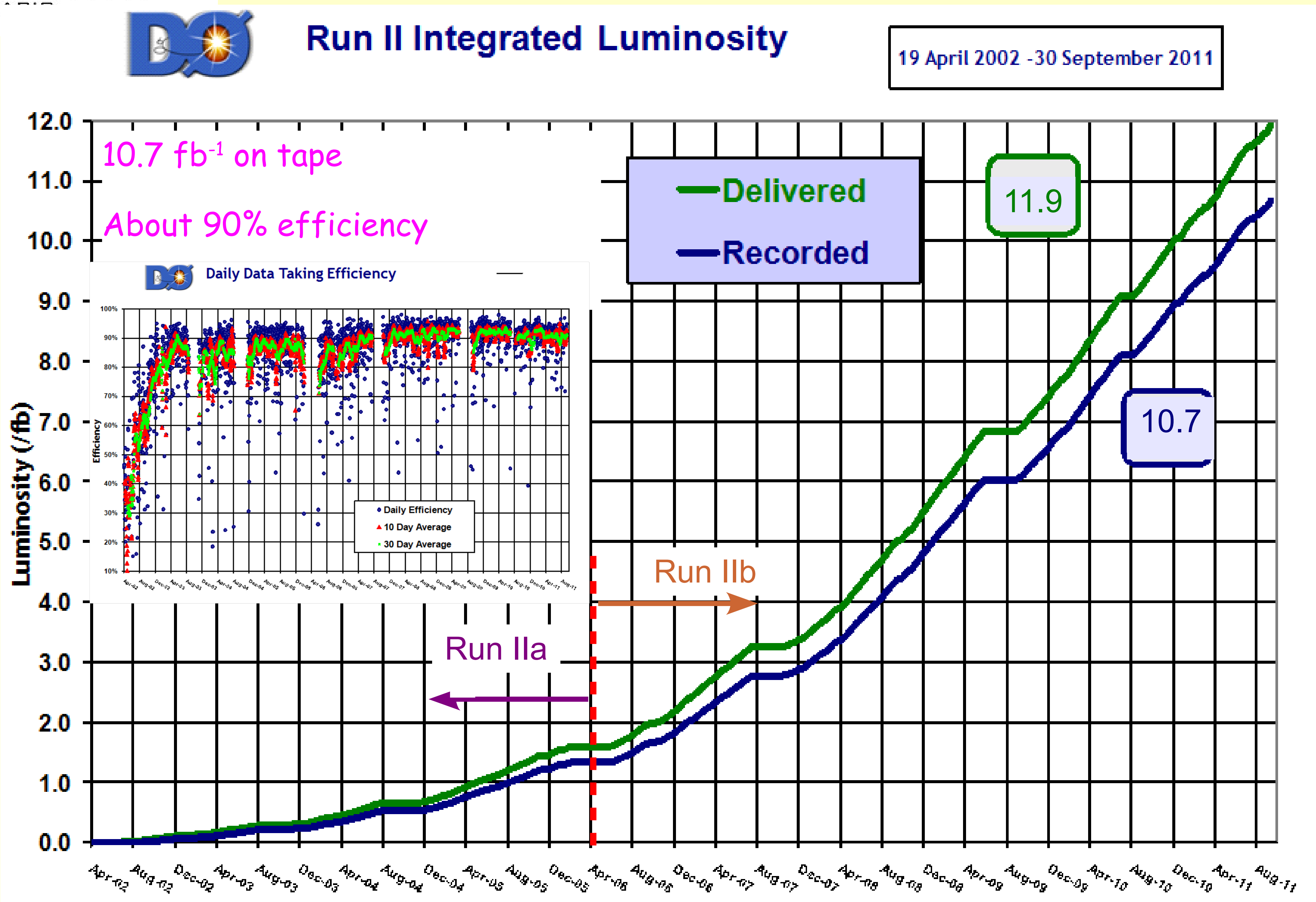
- Both detectors are upgraded in Run II
- New silicon micro-vertex trackers
- New tracking systems
- Upgraded muon chambers





Angular coverage	|η|
Muon ID	~2
Tracking	~2.5
EM / Jet ID	~4

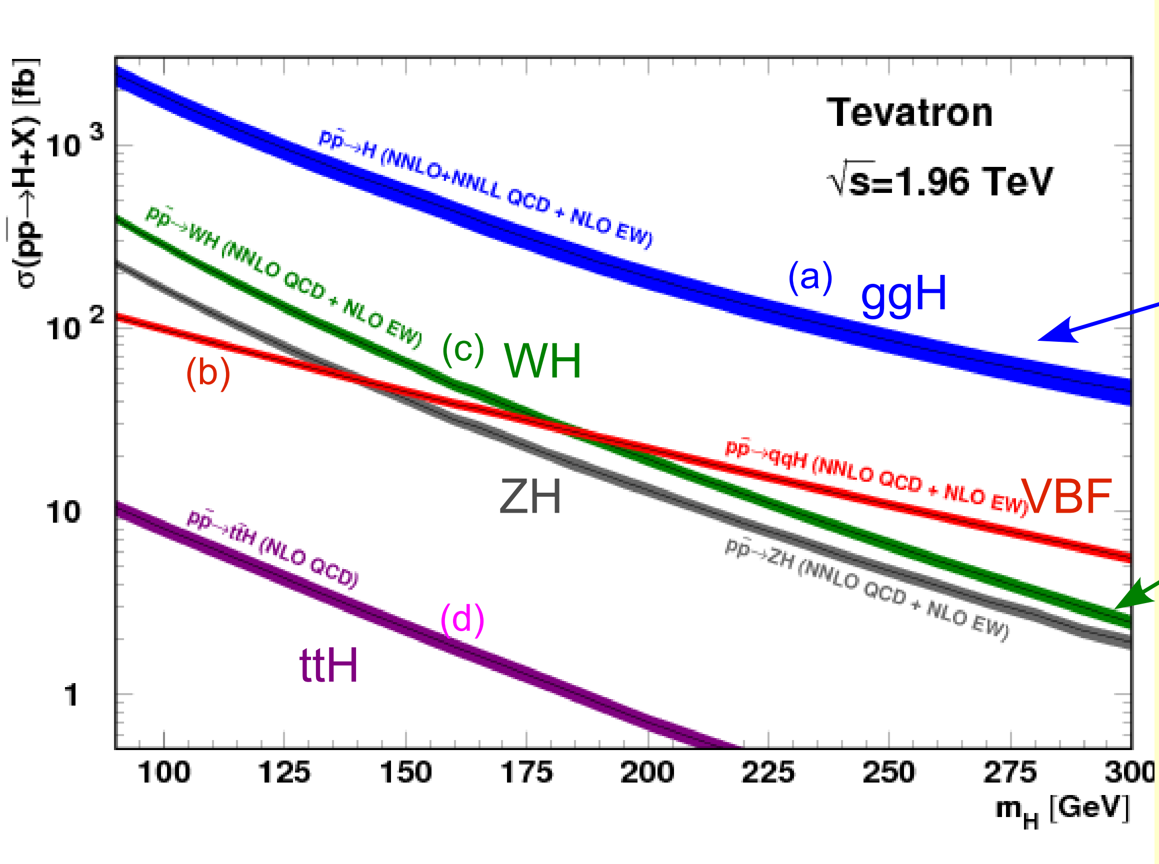
Tevatron Data Taking

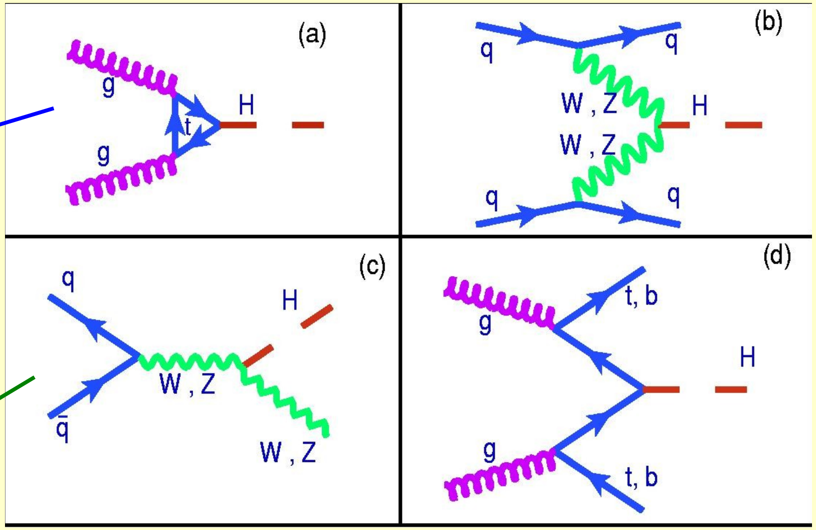


Higgs boson at Tevatron

Production at Tevatron ...

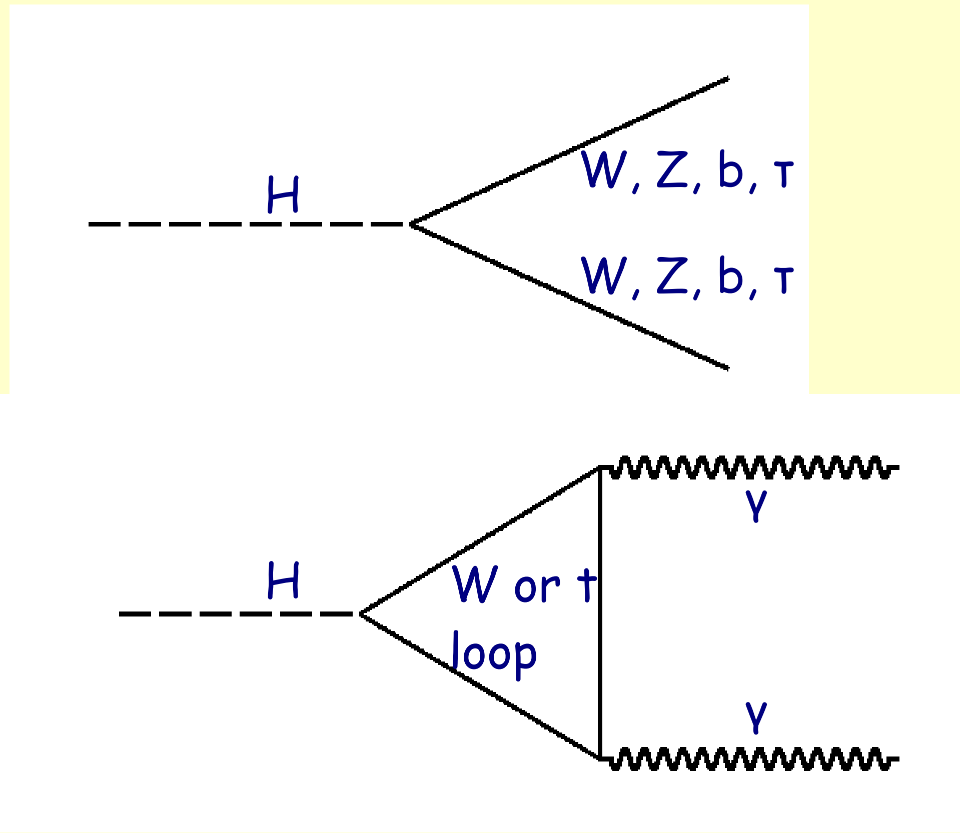
- Dominant production is gluon-gluon fusion (ggH)
- Significant contribution from associated production (VH)

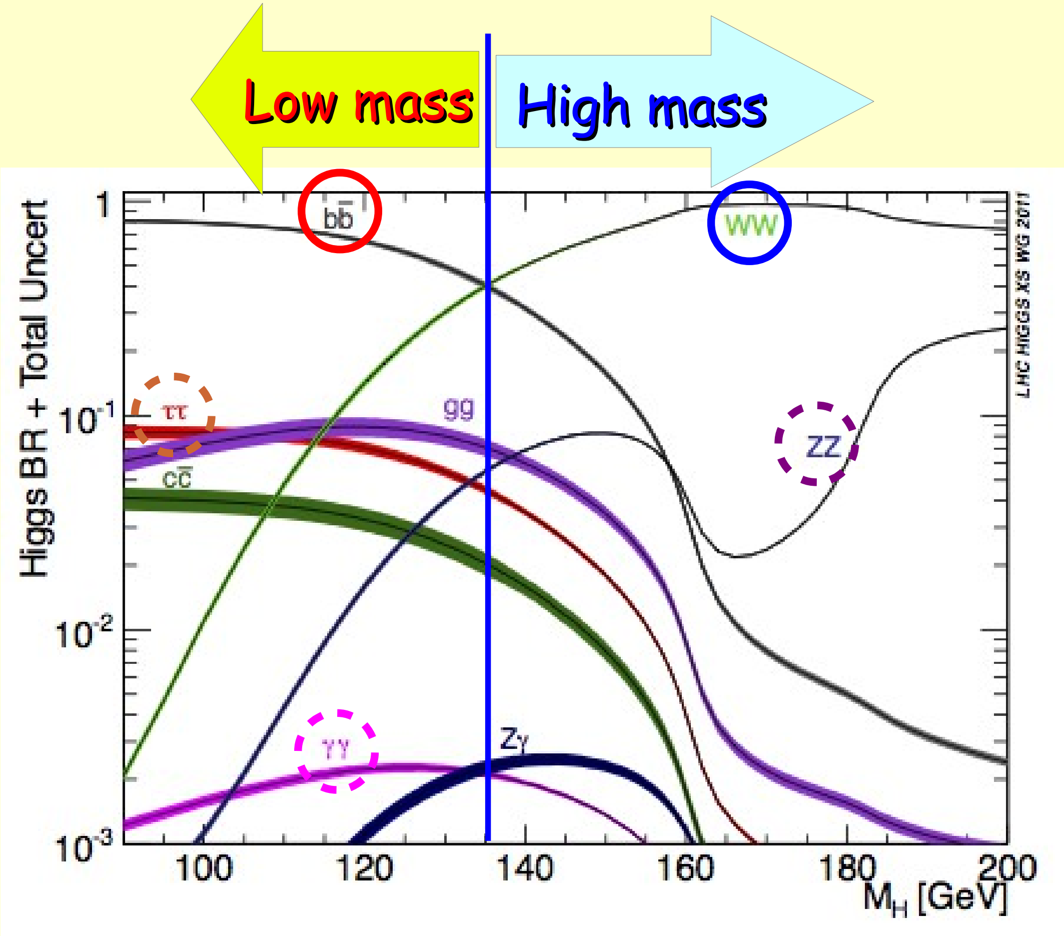




... and Decay

- Dominant decay to:
  - bb for m_H < 135 GeV (57% @125 GeV)
  - WW for m_H > 135 GeV (22% @125 GeV)

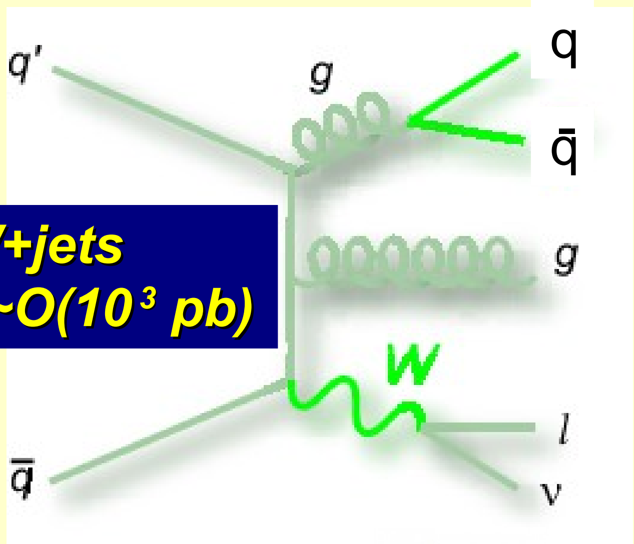




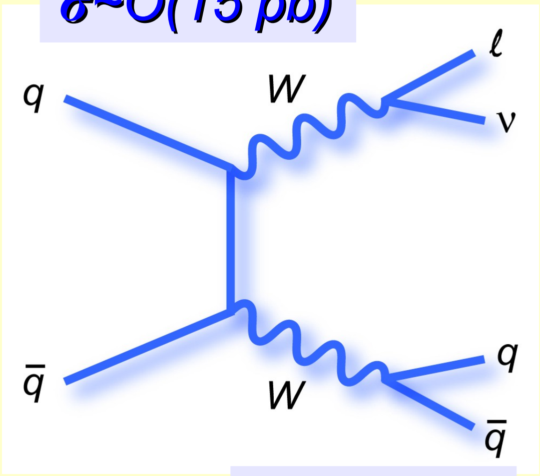
Backgrounds

- We model background processes with Alpgen+Pythia, Pythia and CompHEP
- Normalized with the highest order cross section available (NLO or better)

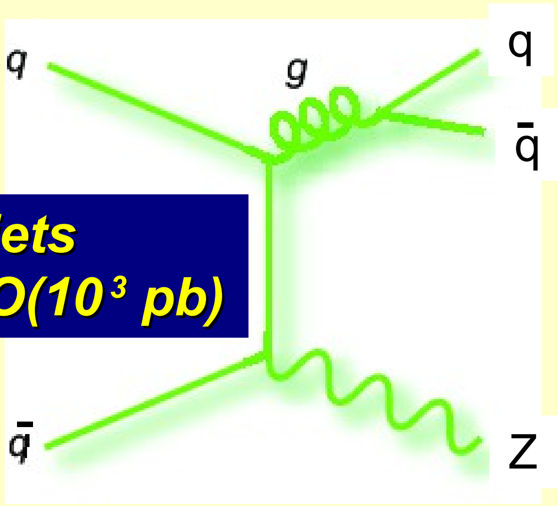
W+jets
σ~O(10³ pb)



diBoson
σ~O(15 pb)

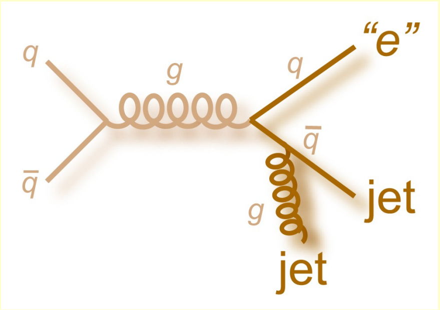


Z+jets
σ~O(10³ pb)

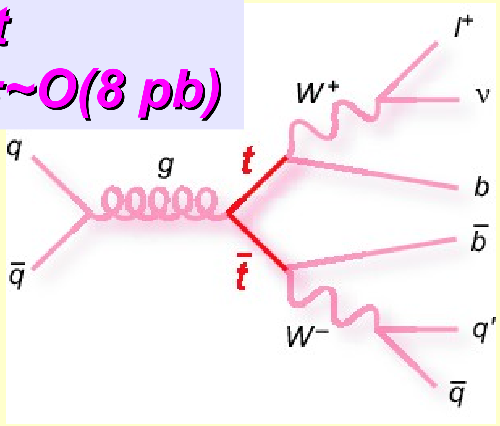


Higgs signal
σ~O(1 pb)

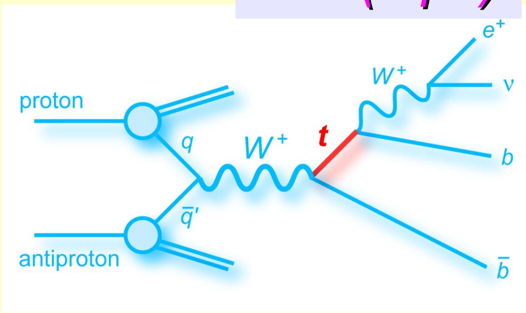
Multijet (QCD) from data



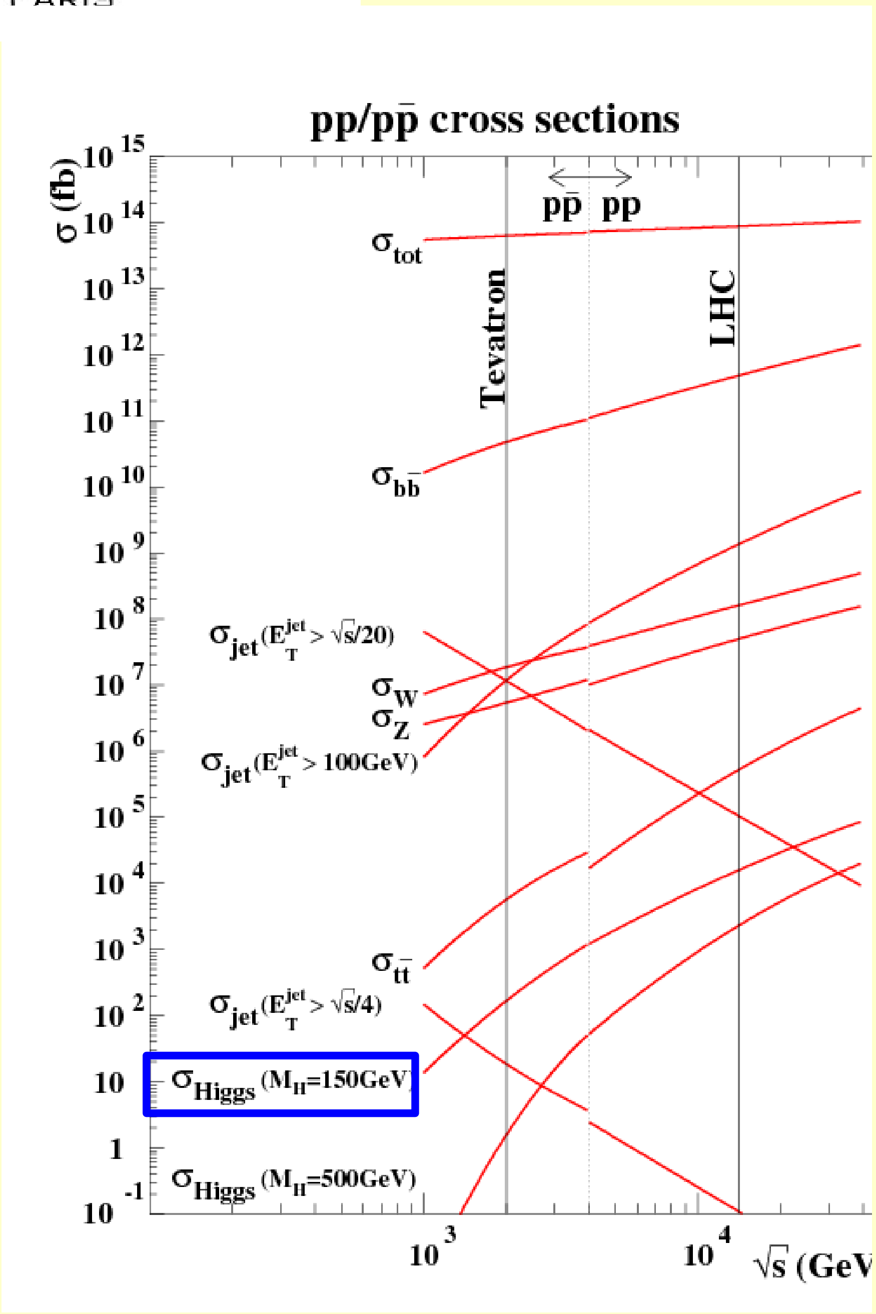
tt
σ~O(8 pb)



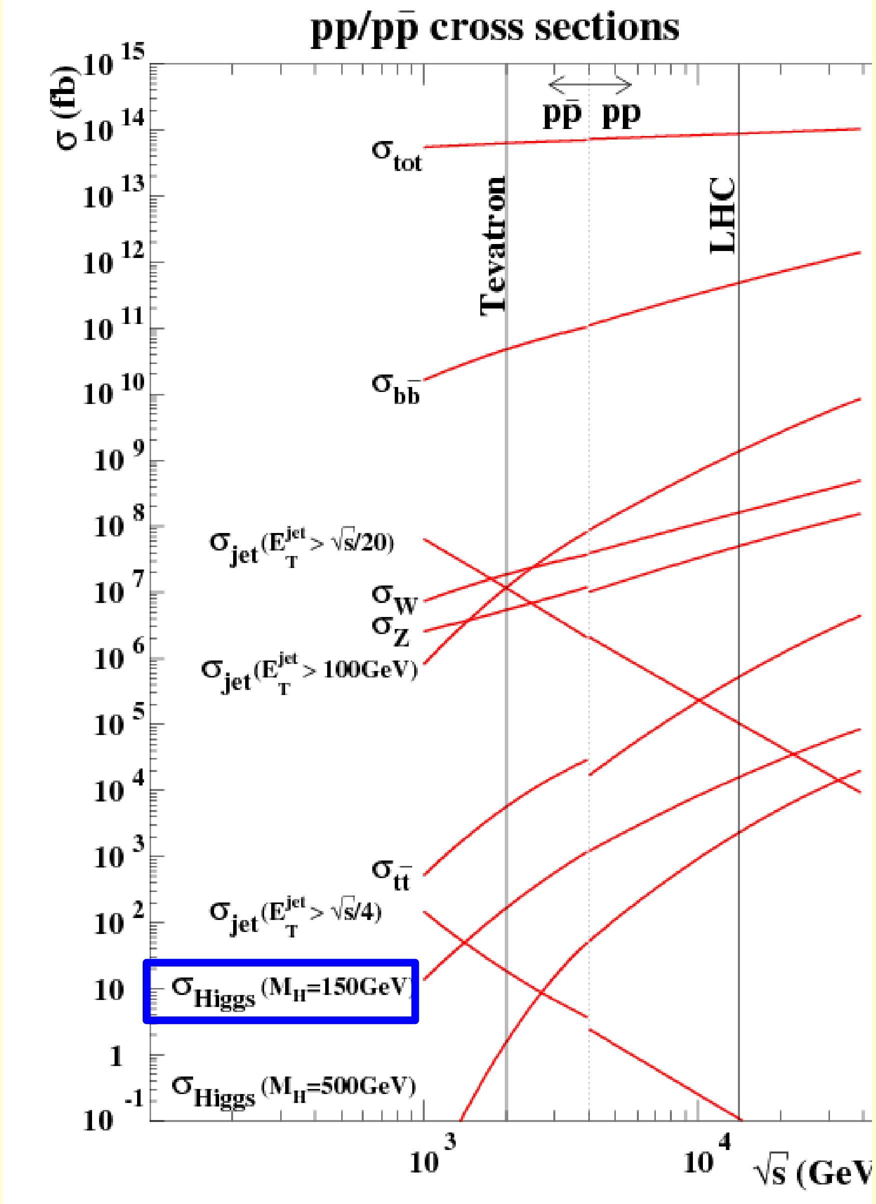
Single top
σ~O(3 pb)



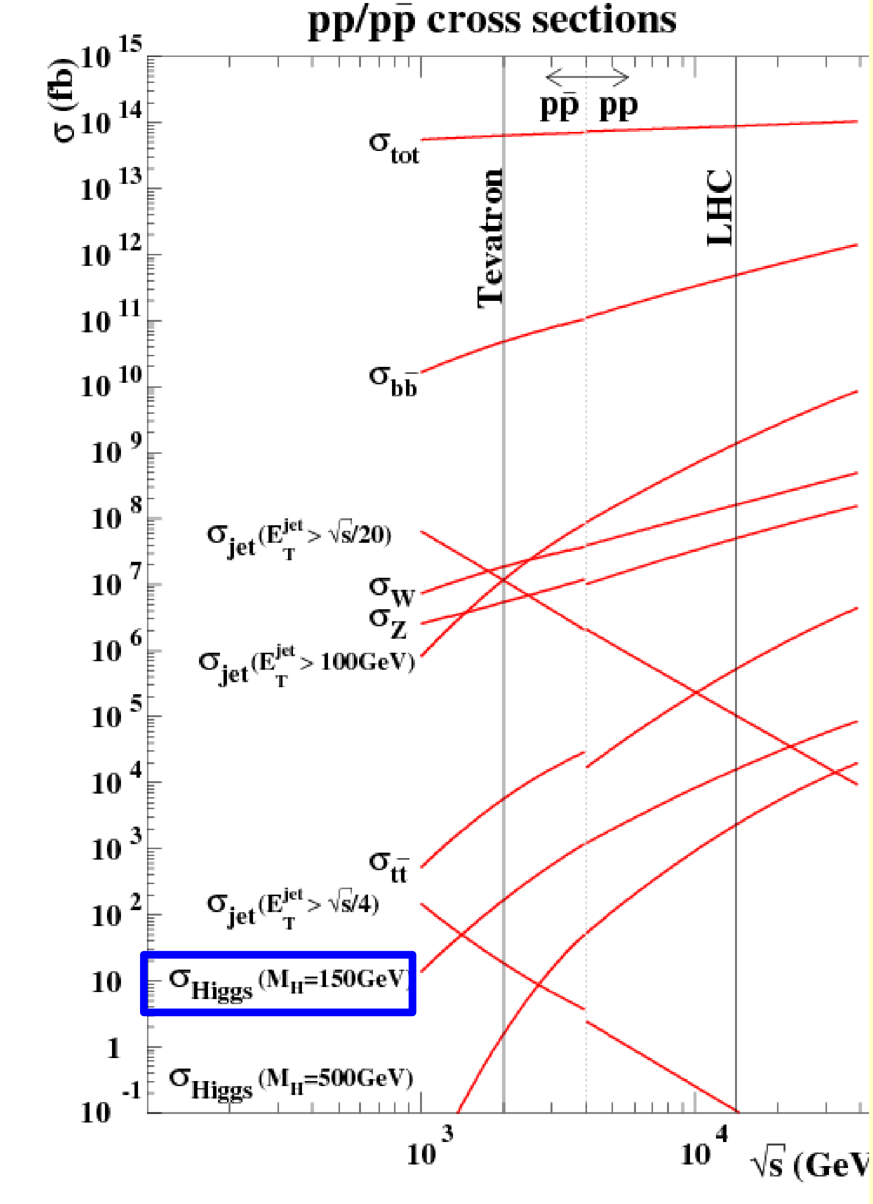
How did we search?



How did we search?



How did we search?



- Extract tiny signal from huge background
- Use efficient and well understood triggers
- Optimize lepton ID, use multivariate techniques (MVA) to identify leptons and various lepton categories
- Optimize b-id, use MVA and multiple b-tagging categories
- Use advanced MVA techniques to further separate signal from background
- Validate search with measurement of known SM processes

Overview of the searches

DØ	Luminosity (fb^{-1})	M_H (GeV)	Reference
$WH \to \ell\nu bb$	9.7	90–150	Phys. Rev. Lett. 109, 121804 (2012) and Acc by PRD arXiv:1301.6122
$ZH \to \ell\ell b\bar{b}$	9.7	90–150	Phys. Rev. Lett. 109, 121803 (2012) and Acc by PRD arXiv:1303.3276
$ZH \to \nu\bar{\nu}b\bar{b}$	9.5	100–150	Phys. Lett. B 716, 285 (2012)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	9.7	100–200	Acc by PRD arXiv:1301.1243
$H + X \to WW \to \mu^{\pm}\tau_h^{\mp} + \leq 1$jet	7.3	155–200	Phys. Lett. B 714, 237 (2012)
$H \to W^+W^- \to \ell\nu q'\bar{q}$	9.7	100–200	Acc by PRD arXiv:1301.6122
$VH \to ee\mu/\mu\mu e + X$	9.7	100–200	Acc by PRD arXiv:1302.5723
$VH \to e^{\pm}\mu^{\pm} + X$	9.7	100–200	Acc by PRD arXiv:1302.5723
$VH \to \ell\nu q'\bar{q}q'\bar{q}$	9.7	100–200	Acc by PRD arXiv:1301.6122
$VH \to \tau_h\tau_h\mu + X$	8.6	100–150	Acc by PRD arXiv:1302.5723
$H + X \to \ell\tau_h jj$	9.7	105–150	Acc by PRD arXiv:1211.6993
$H \to \gamma\gamma$	9.7	100–150	Acc by PRD, arXiv:1301.5358
CDF			
$WH \to \ell\nu bb$	9.45	90–150	Phys. Rev. Lett. 109, 111804 (2012)
$ZH \to \ell\ell b\bar{b}$	9.45	90–150	Phys. Rev. Lett. 109, 111803 (2012)
$ZH \to \nu\bar{\nu}b\bar{b}$	9.45	90–150	Phys. Rev. Lett. 109, 111805 (2012) and Phys. Rev. D 87, 052008 (2013)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	9.7	110–200	Sub to PRD, arXiv: 1306.0023
$H \to WW \to e\tau_h\mu\tau_h$	9.7	130–200	Sub to PRD, arXiv: 1306.0023
$VH \to ee\mu/\mu\mu e + X$	9.7	110–200	Sub to PRD, arXiv: 1306.0023
$H \to \tau\tau$	6.0	100–150	Phys. Rev. Lett. 108, 181804 (2012)
$H \to \gamma\gamma$	10.0	100–150	Phys. Lett. B 717, 173 (2012)
$H \to ZZ \to llll$	9.7	120–200	Phys. Rev. D 86 (2012) 072012
$t\bar{t}H \to WWb\bar{b}b\bar{b}$	9.45	100–150	Phys. Rev. Lett. 109 (2012) 181802
$VH \to jjb\bar{b}$	9.45	100–150	JHEP 1302 (2013) 004

- CDF combination:
  H → bb:
  - Phys. Rev. Lett. 109, 111802 (2012)
  All channels:
  - Accepted to PRD arXiv:1301.6668
- D0 combination:
  H → bb:
  - Phys. Rev. Lett. 109, 121802 (2012)
  All channels:
  - Accepted by PRD arXiv:1303.0823

Overview of the searches

DØ	Luminosity (fb^{-1})	M_H (GeV)	Reference
$WH \to \ell\nu bb$	9.7	90–150	Phys. Rev. Lett. 109, 121804 (2012) and Acc by PRD arXiv:1301.6122
$ZH \to \ell\ell b\bar{b}$	9.7	90–150	Phys. Rev. Lett. 109, 121803 (2012) and Acc by PRD arXiv:1303.3276
$ZH \to \nu\bar{\nu}b\bar{b}$	9.5	100–150	Phys. Lett. B 716, 285 (2012)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	9.7	100–200	Acc by PRD arXiv:1301.1243
$H + X \to WW \to \mu^{\pm}\tau_h^{\mp} + \leq 1$jet	7.3	155–200	Phys. Lett. B 714, 237 (2012)
$H \to W^+W^- \to \ell\nu q'\bar{q}$	9.7	100–200	Acc by PRD arXiv:1301.6122
$VH \to ee\mu/\mu\mu e{+}X$	9.7	100–200	Acc by PRD arXiv:1302.5723
$VH \to e^{\pm}\mu^{\pm}{+}X$	9.7	100–200	Acc by PRD arXiv:1302.5723

Tevatron combination: accepted by PRD, arXiv:1303.6346

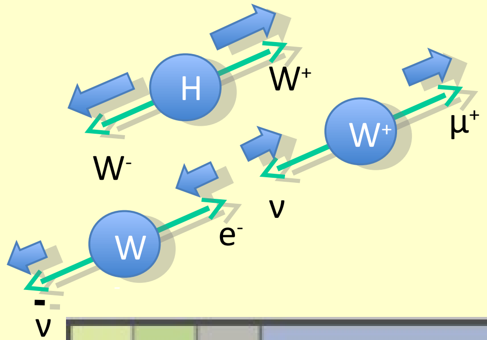
All latest papers will appear in a single issue of PRD

$ZH \to \ell\ell b\bar{b}$	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

- CDF combination:
  H → bb:
  - Phys. Rev. Lett. 109, 111802 (2012)
  All channels:
  - Accepted to PRD arXiv:1301.6668
- D0 combination:
  H → bb:
  - Phys. Rev. Lett. 109, 121802 (2012)
  All channels:
  - Accepted to PRD arXiv:1303.0823

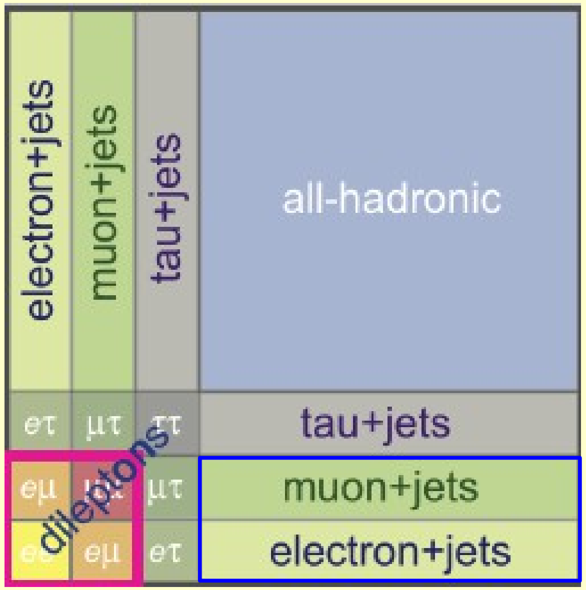
$H \rightarrow WW$

H → WW



- The most sensitive channel for m_H > 135 GeV

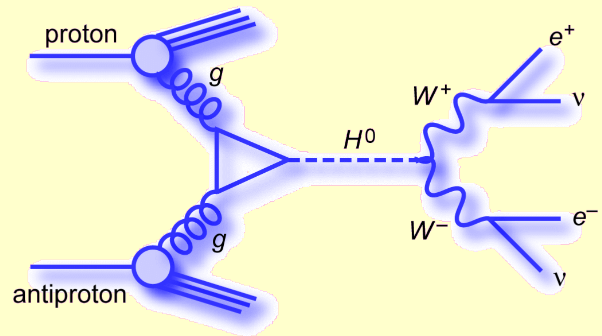
- Split according to the decay mode of the W
  - Dilepton channels have low branching ratios thus low yield, but also low backgrounds
  - Semileptonic channels must contend with large V+jets backgrounds

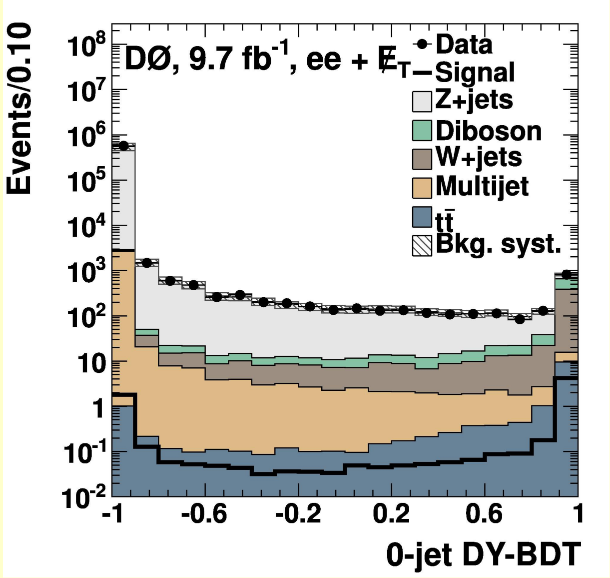


- Split according to the production mode – ggH, VBF and VH
  - Split opposite-sign dilepton and semileptonic channels into different jet multiplicities
  - Include a search for the same-sign leptons, where one originates from associated W
  - Include final states with three leptons

Associated production with W, WH → WWW is important for coupling measurement;
It probes coupling to the W boson only!

$H \rightarrow WW \rightarrow l\nu l\nu$





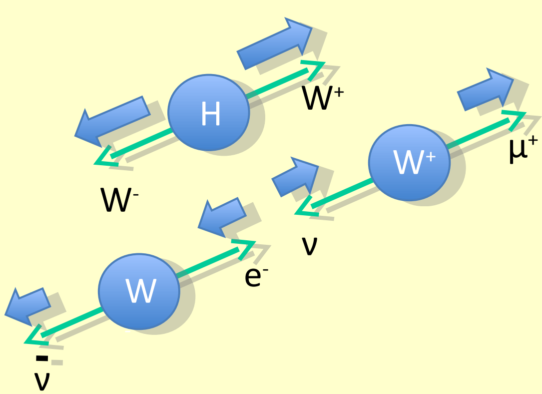
- Signatures:
  - Two isolated high p_T leptons, large $\not{E}_T$, small $\Delta\varphi(ll)$, small $\Delta R(ll)$

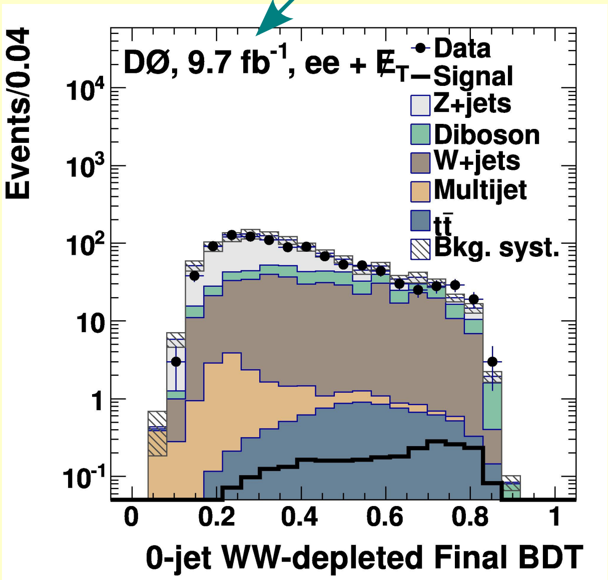
  => Lepton identification improved over years to allow for more efficient selection

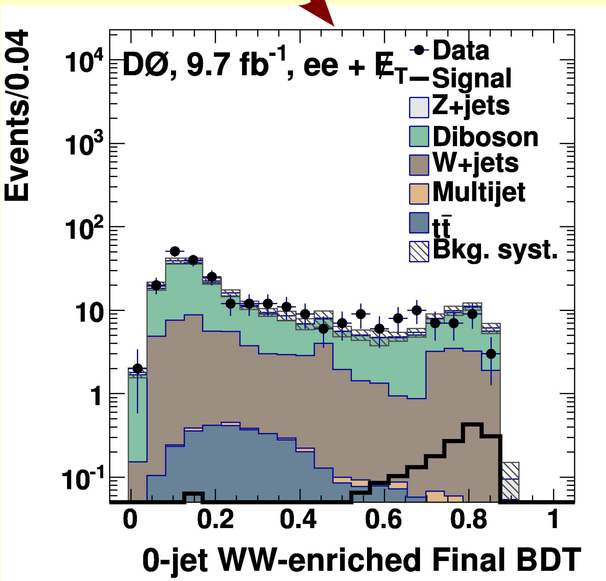
- Use multiple MVA to reject different backgrounds

- Remove most of the Z(+jets) $\rightarrow$ ll

- Use dedicated MVA to separate samples into WW enriched and WW depleted regions

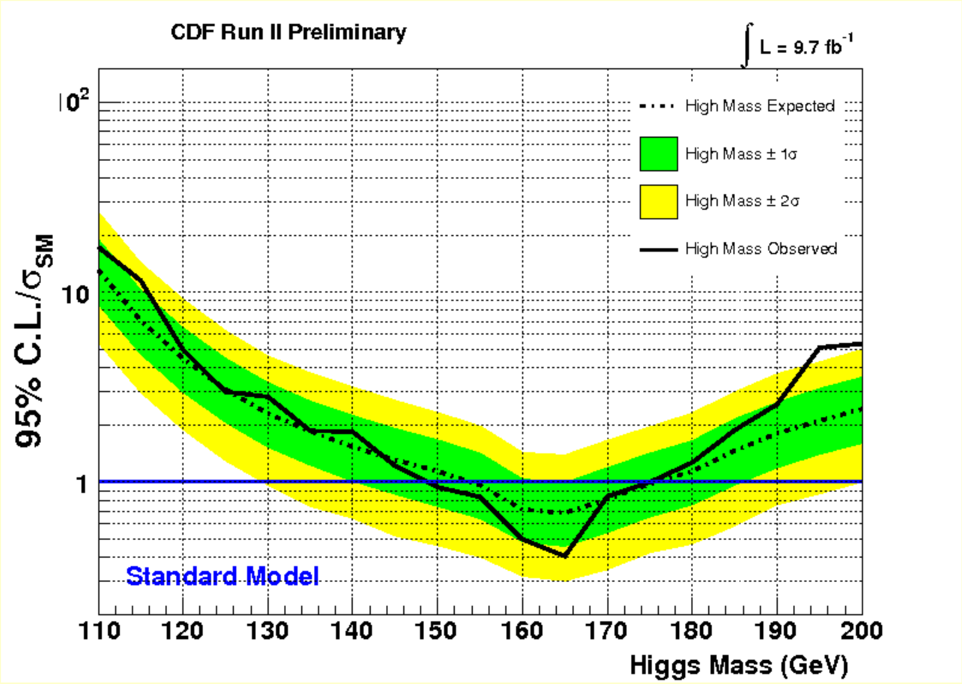


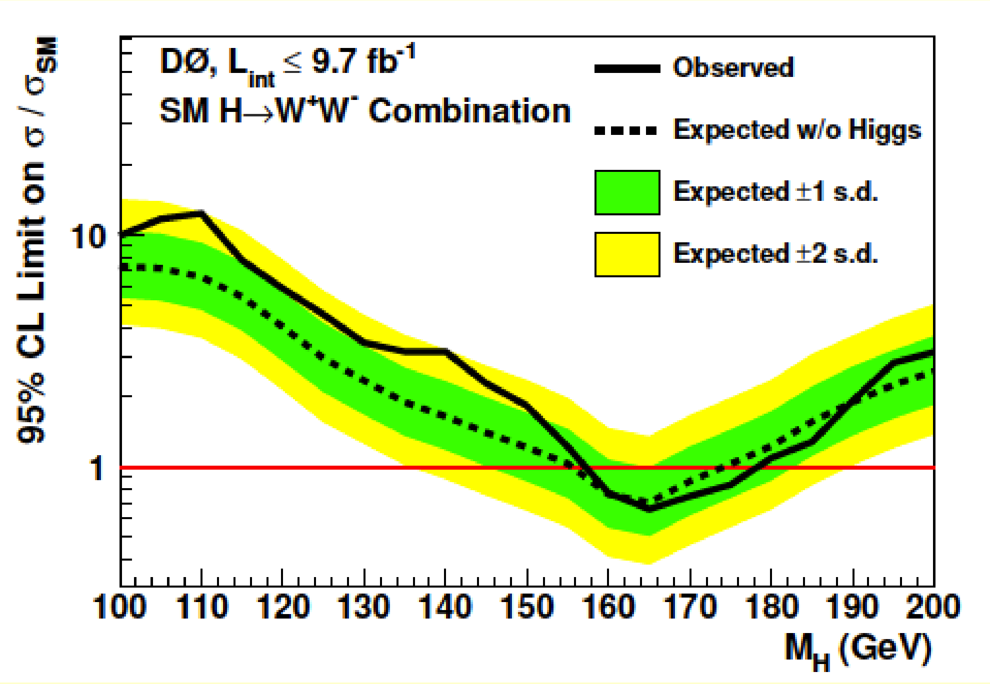




H → WW result

- Both D0 and CDF reached similar sensitivity:
  - Exclusion (expected): 149-172 (153-175) and 157-178 (155-175) GeV @CDF and D0
  - Sensitivity: exp - 3.1; obs – 2.9 and exp – 2.9; obs – 4.6 (@125 GeV)
  - Big gain when additional final states are included (15% at D0)
- Tevatron: Expected sensitivity @125 GeV: 2.04xSM

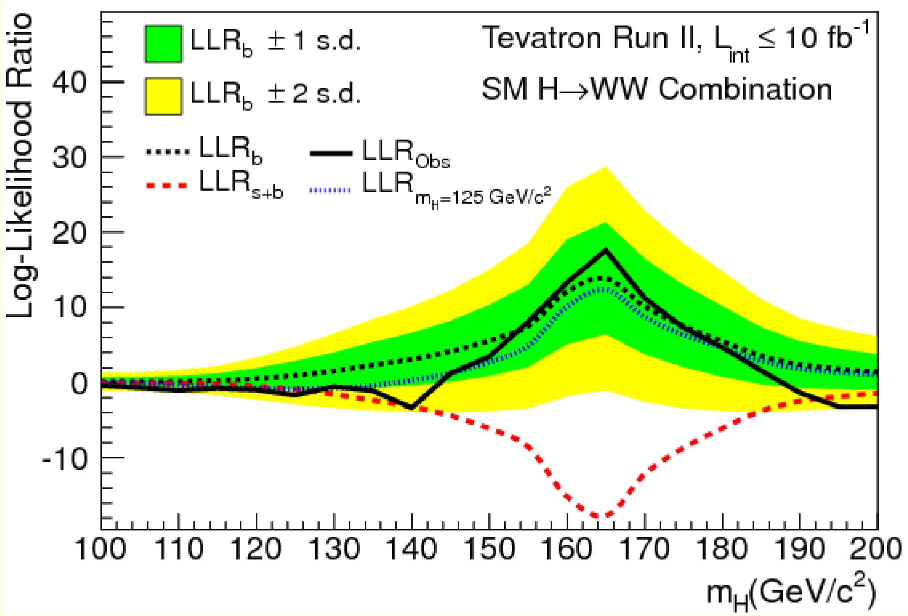




Log Likelihood Ratio (LLR)

Background-like outcomes

Signal-like outcomes



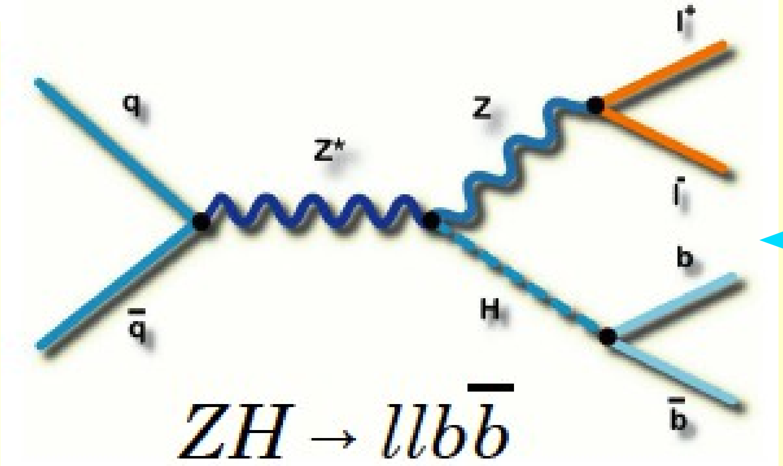
$$LLR = -2\ln\frac{P(s+b)}{P(b)}$$

P - Poisson likelihood of B or S+B hypothesis

- The separation between LLR$_b$ (background-only hypothesis) and LLR$_{s+b}$ (signal-plus-background hypothesis) provides a measure of the discriminating power of the search
- The width of the LLR$_b$, distribution (1 s.d. and 2 s.d. bands) provides an estimate of how sensitive the analysis is to a signal-like background fluctuation in the data, taking account of the presence of systematic uncertainties
- The value of LLR$_{obs}$ relative to LLR$_{s+b}$ and LLR$_b$ indicates whether the data distribution appears to be more like signal-plus-background or background-only.

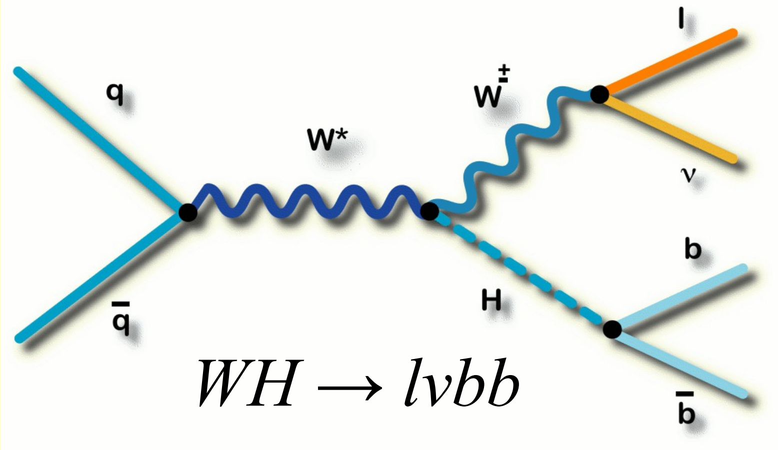
VH → Vbb

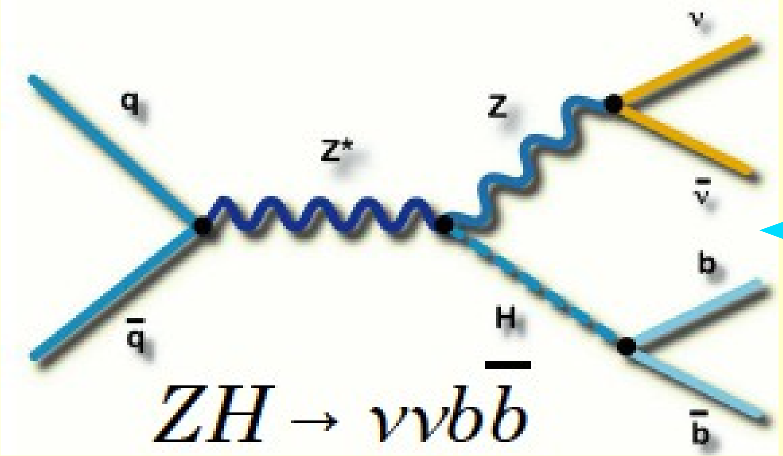
VH → Vbb



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

- WH → lνbb – 1 lepton + MET + 2 b-jets
- Modeling of the W+jets backgrounds
- Modeling and rejection of the multijet backgrounds

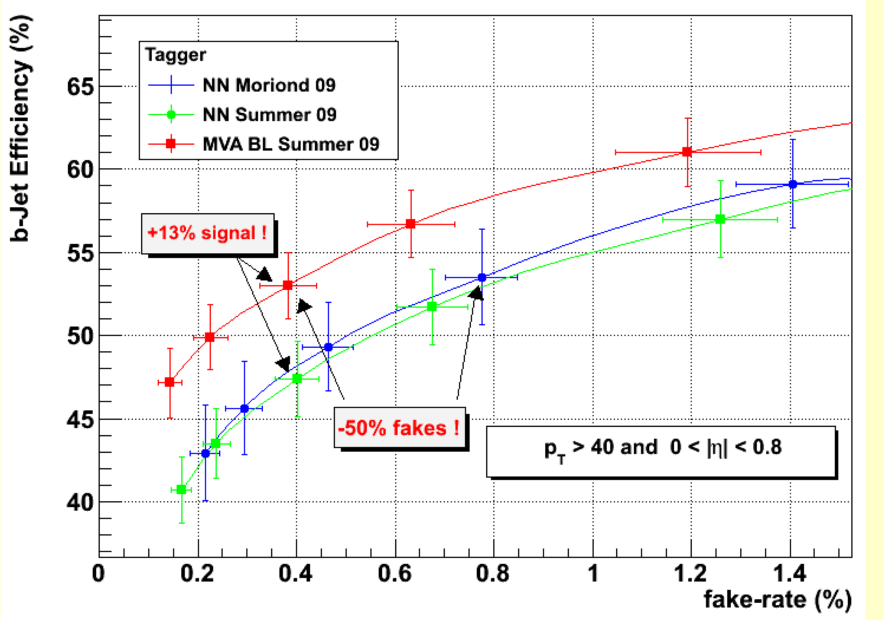


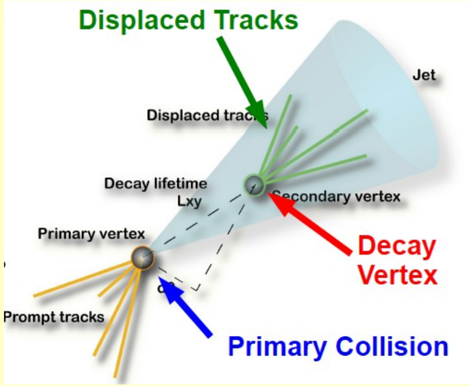


- ZH → ννbb – MET + 2 b-jets (contribution from WH also)
- Background modeling and rejection

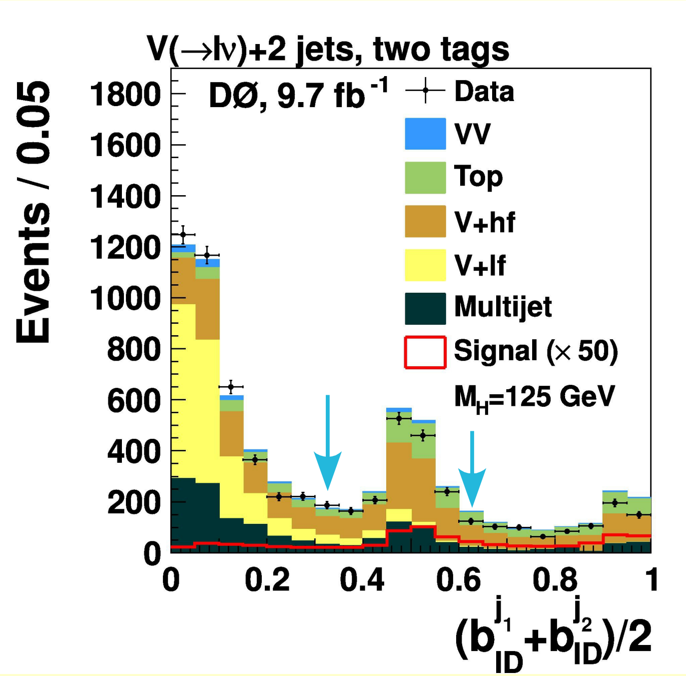
VH → Vbb

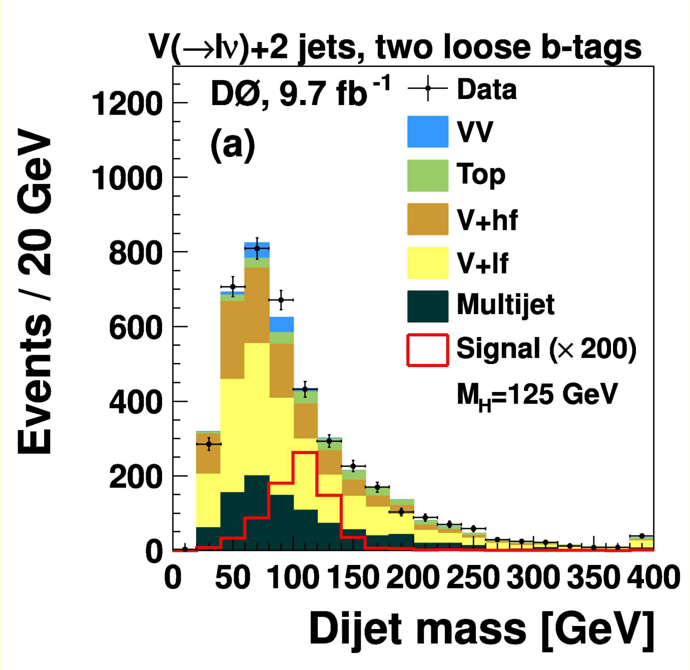
- Key ingredients:
  - Lepton, jet and $\not{E}_T$ reconstruction
  - Jet energy resolution => Δm/m~15%
  - b-tagging
  - Multivariate techniques to reject backgrounds





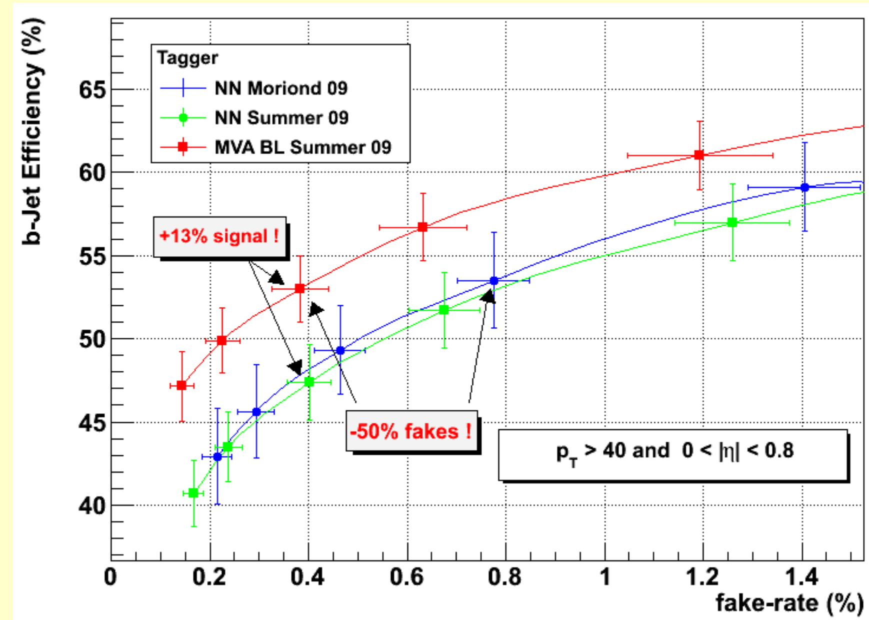
	Before b-tagging	2 loose tags
s/b	1/7000	1/1400

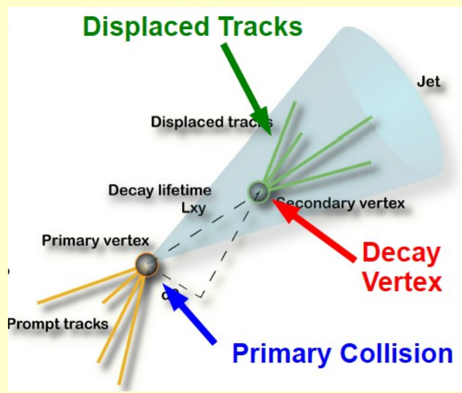




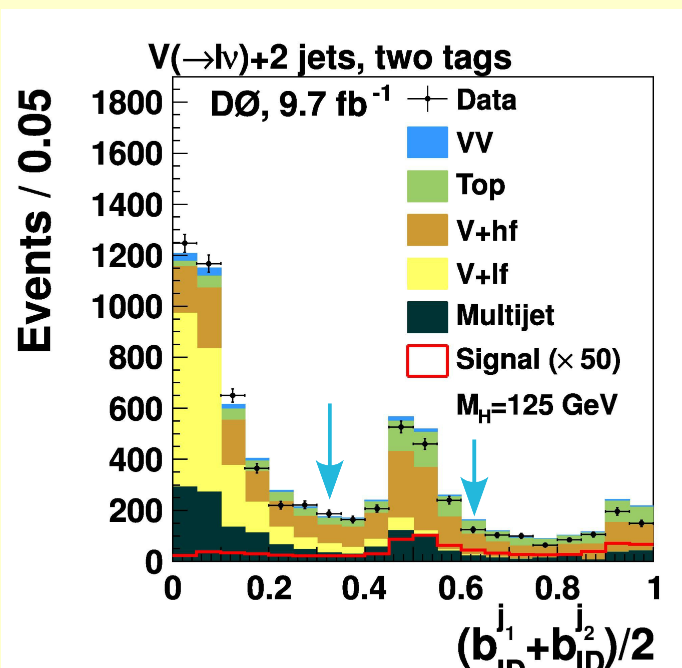
VH → Vbb

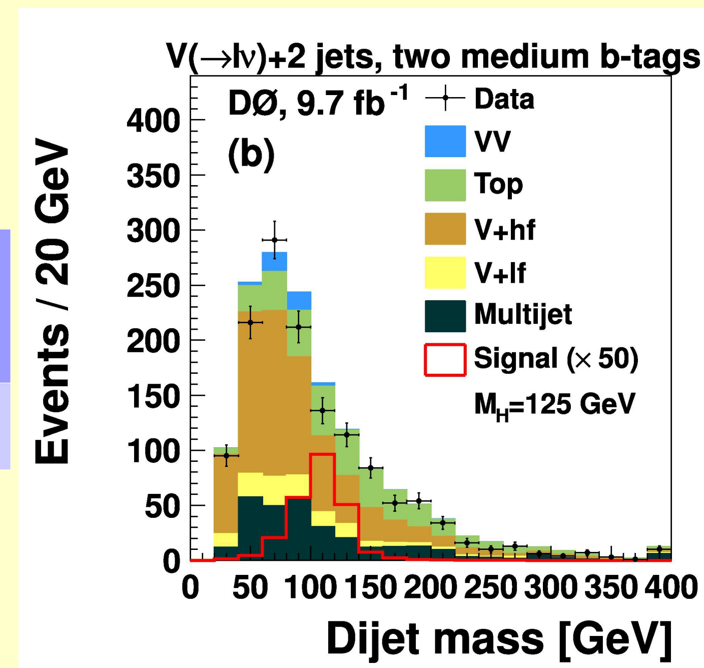
- Key ingredients:
  - Lepton, jet and $\not{E}_T$ reconstruction
  - Jet energy resolution => $\Delta m/m$~15%
  - b-tagging
  - Multivariate techniques to reject backgrounds





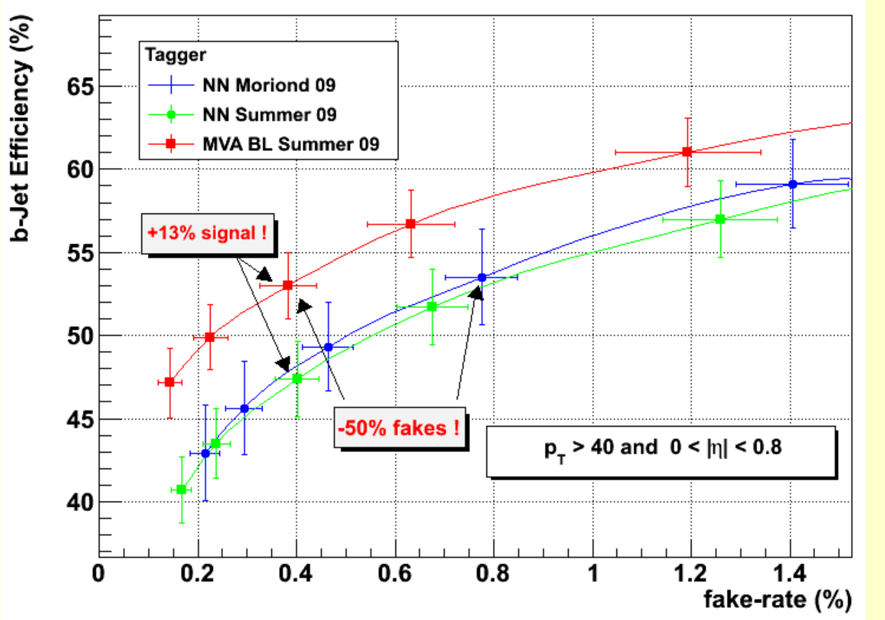
	Before b-tagging	2 med tags
s/b	1/7000	1/400

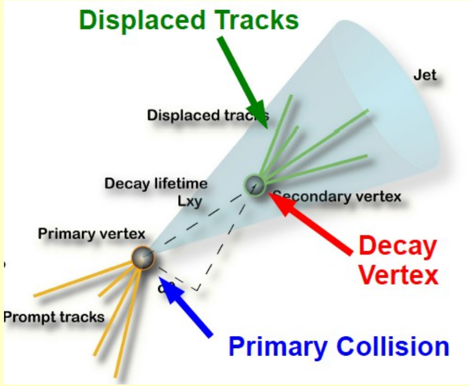




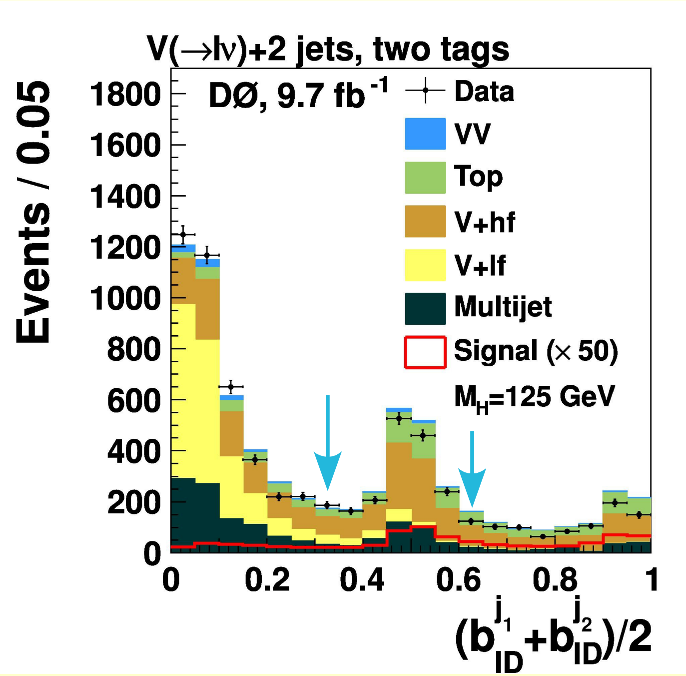
VH → Vbb

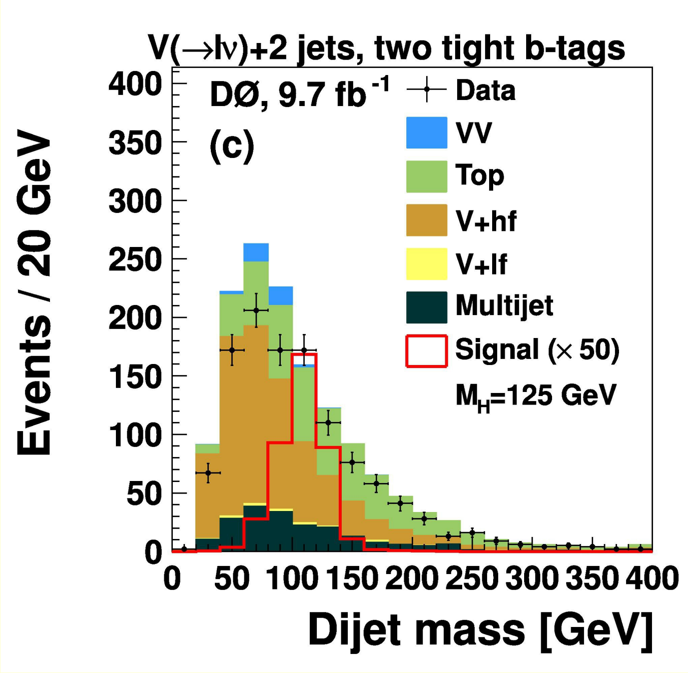
- Key ingredients:
  - Lepton, jet and $\not{E}_T$ reconstruction
  - Jet energy resolution => $\Delta m/m$~15%
  - b-tagging
  - Multivariate techniques to reject backgrounds



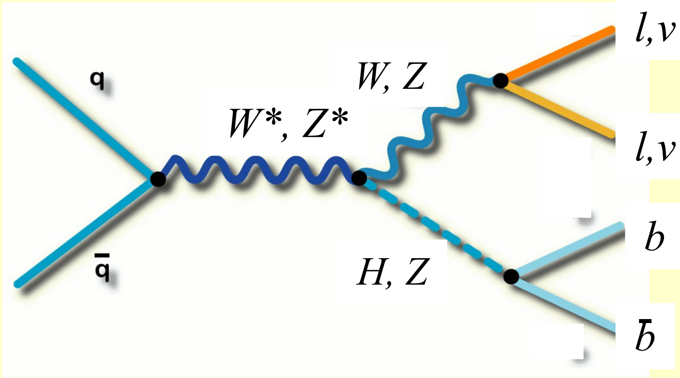


	Before b-tagging	2 tight tags
s/b	1/7000	1/200



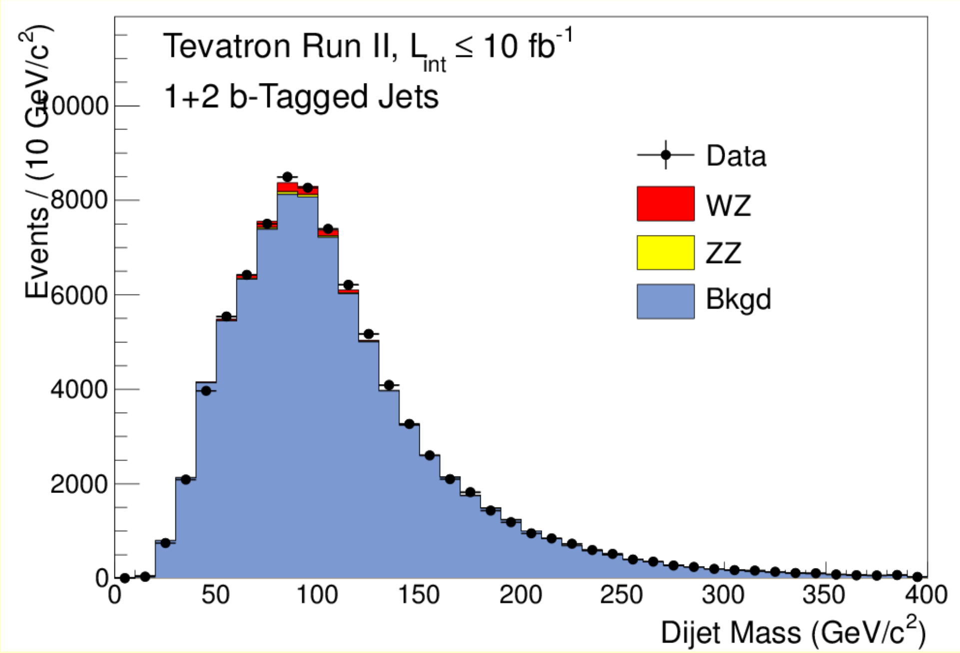


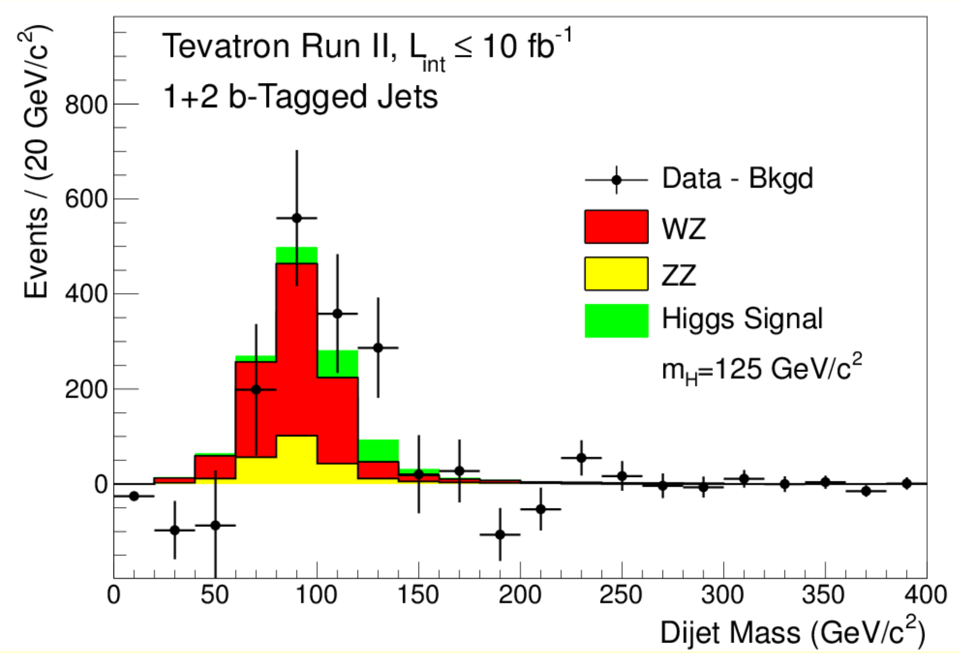
Validation of results



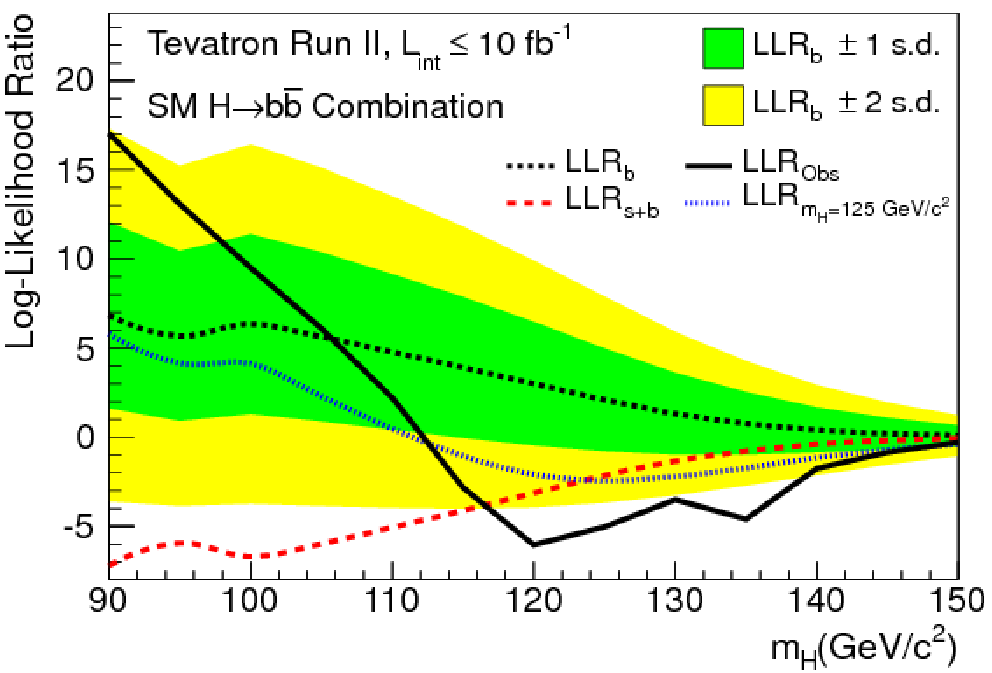
- Measure cross section of the known process with the same final state
  - Smaller cross section for Higgs production (~7 times)
  - Diboson signal peaks at lower masses
- Apply similar analysis
- Measured cross section:(0.68±0.21)*SM

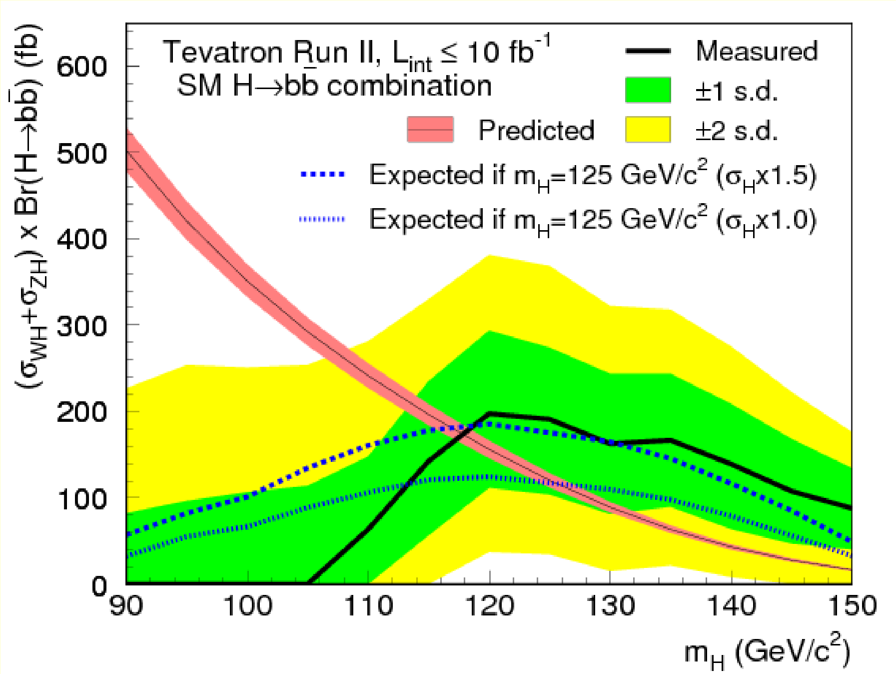
MH = 125 GeV	VH → Vbb [fb]	VZ →Vbb [fb]
vvbb	9	73
lvbb	16	105
llbb	3	24
Total	28	202





Decay mode combinations

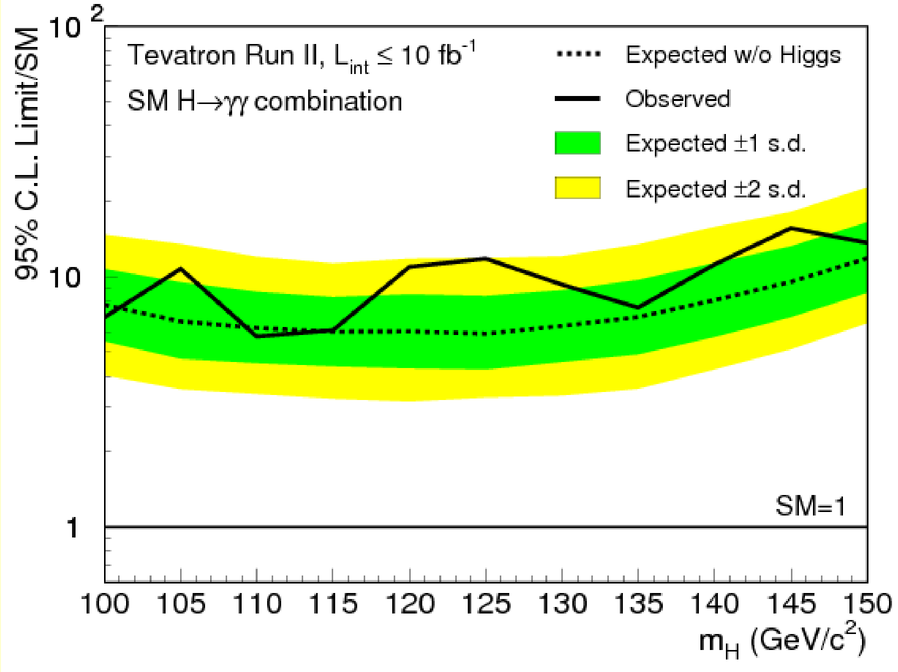


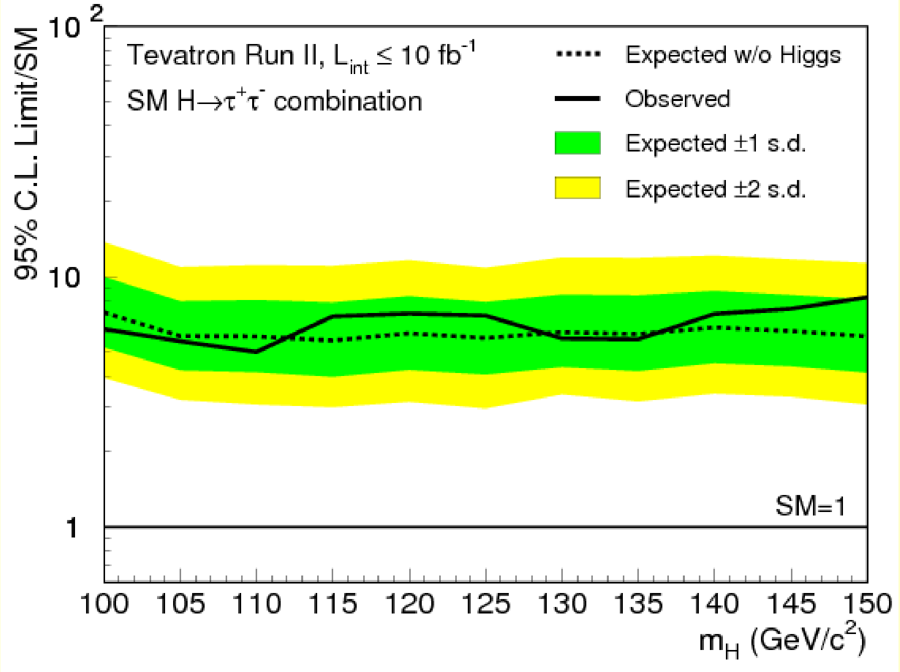


- VH → Vbb:
  - Expected sensitivity at m_H~125 GeV of 1.42xSM.
  - Broad excess consistent with dijet mass resolution
  - Best fit $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \rightarrow bb) = 0.19^{+0.08}_{-0.09}$ pb @125 GeV
  - To be compared with SM: $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \rightarrow bb) = 0.12 \pm 0.01$ pb

$H \rightarrow \gamma\gamma$ and $H \rightarrow \tau\tau$

$H \rightarrow \gamma\gamma$ and $H \rightarrow \tau\tau$

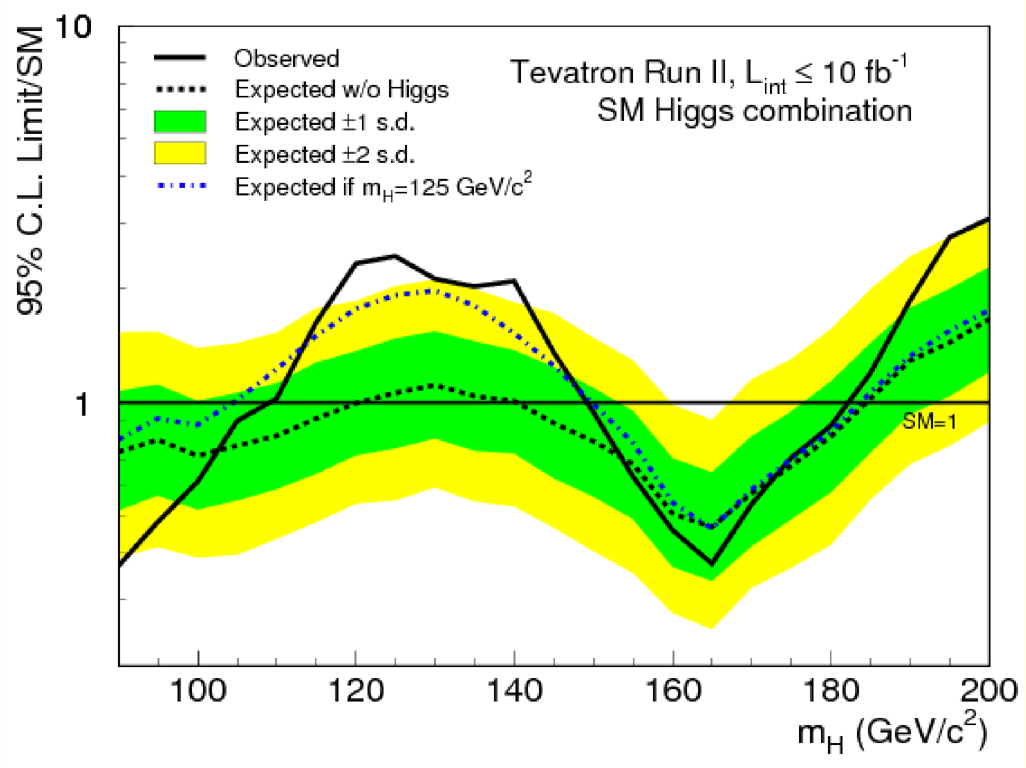




- $H \rightarrow \gamma\gamma$
  - Expected sensitivity @125 GeV of ~5.9*SM
  - ~ 2 s.d. excess in $H \rightarrow \gamma\gamma$
- $H \rightarrow \tau\tau$
  - Expected sensitivity @125 GeV of ~5.7*SM

Combined results from Tevatron

Result of the SM combination



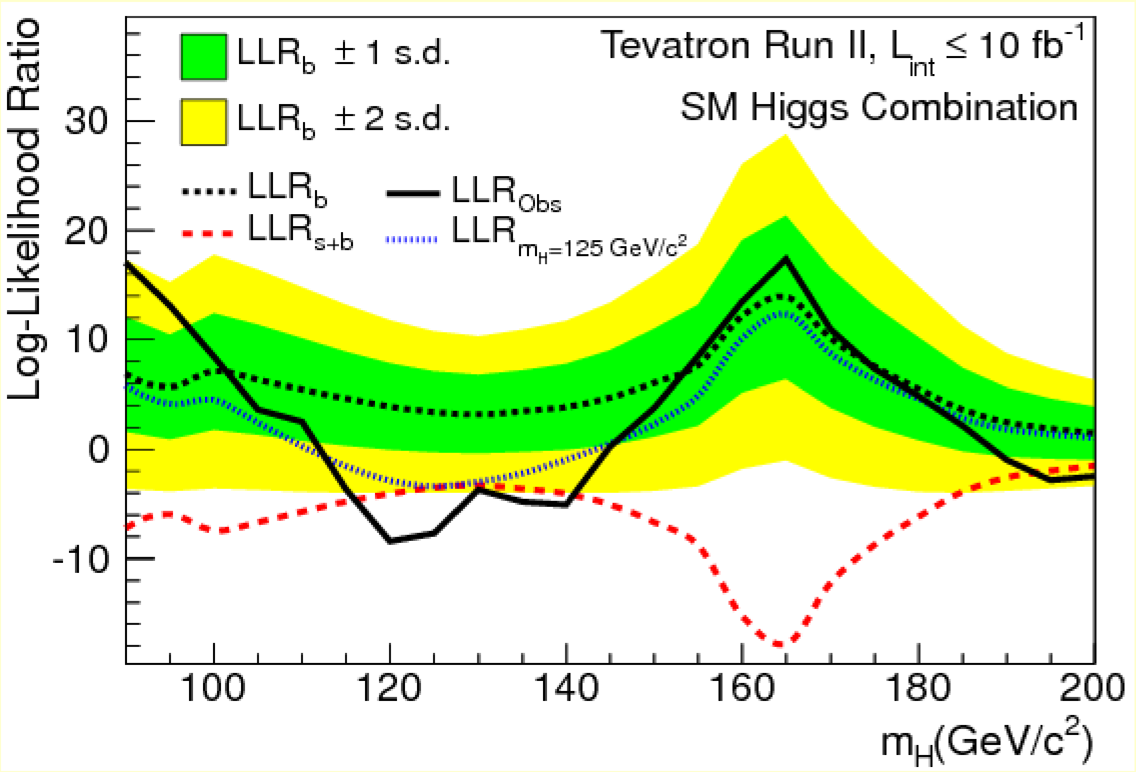
- Tevatron excludes (expect):
  90-109 (90-120) GeV and 149-182 (140-184) GeV @95% C.L.
- Exp. (obs) sensitivity @125 GeV: 1.06 (2.44)*SM

LPNHE PARIS

Sensitivity of the search

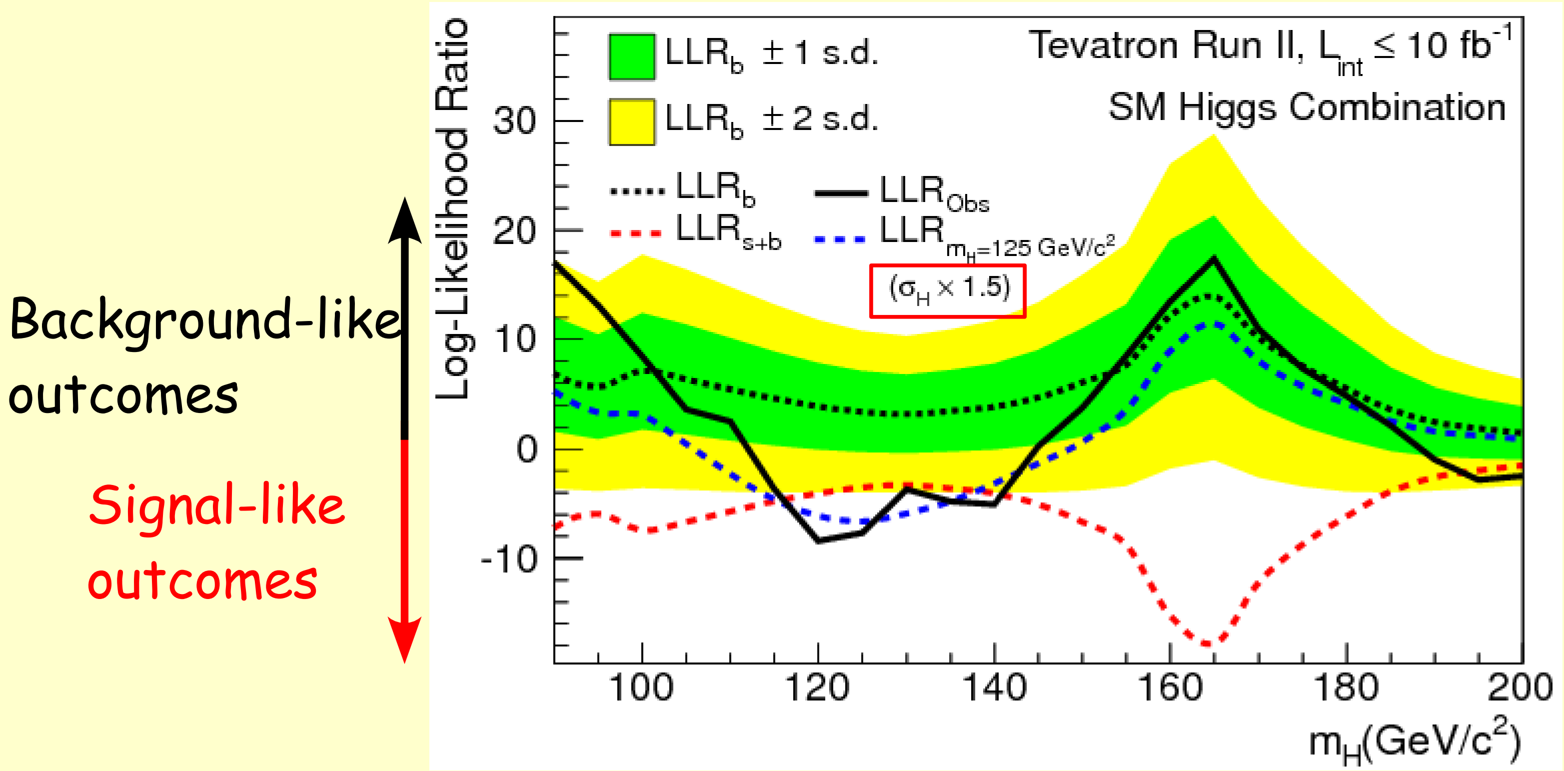
Background-like outcomes

Signal-like outcomes



- Observed broad excess in data

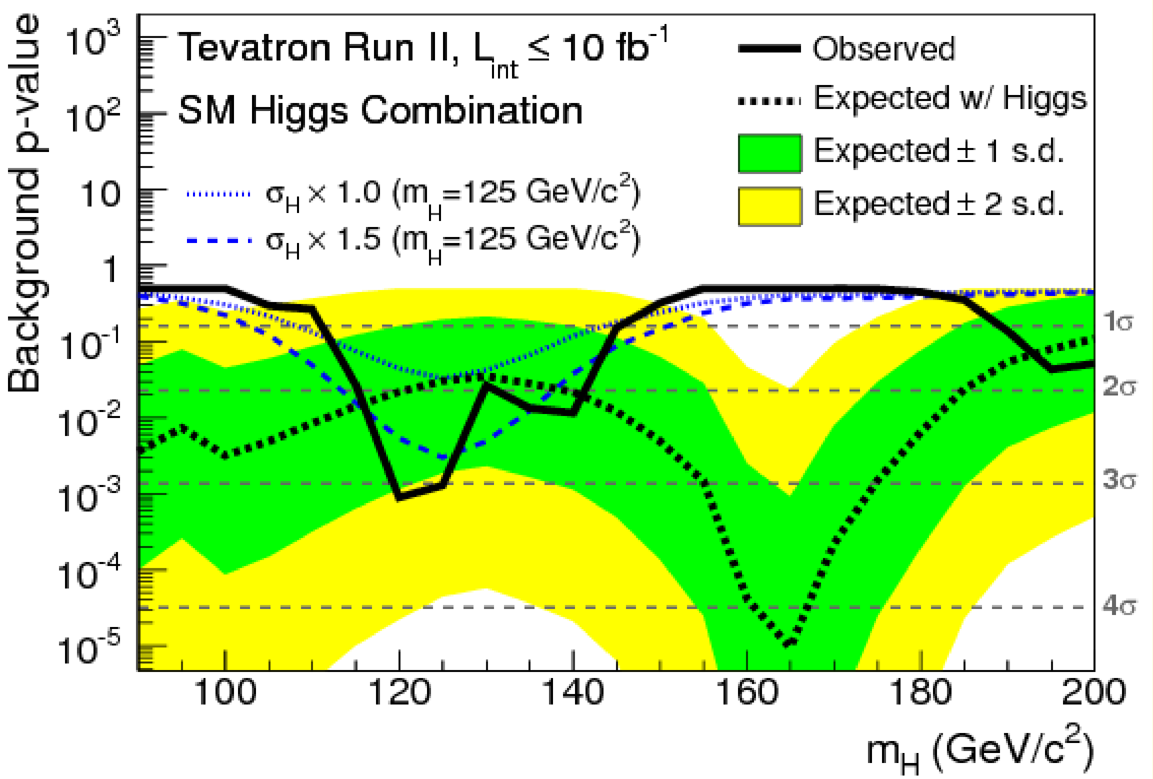
Sensitivity of the search



- Observed broad excess in data
  - Consistent with the assumption of the presence of the Higgs boson with a m_H=125 GeV and a cross section of ~1.5(±0.6)*SM

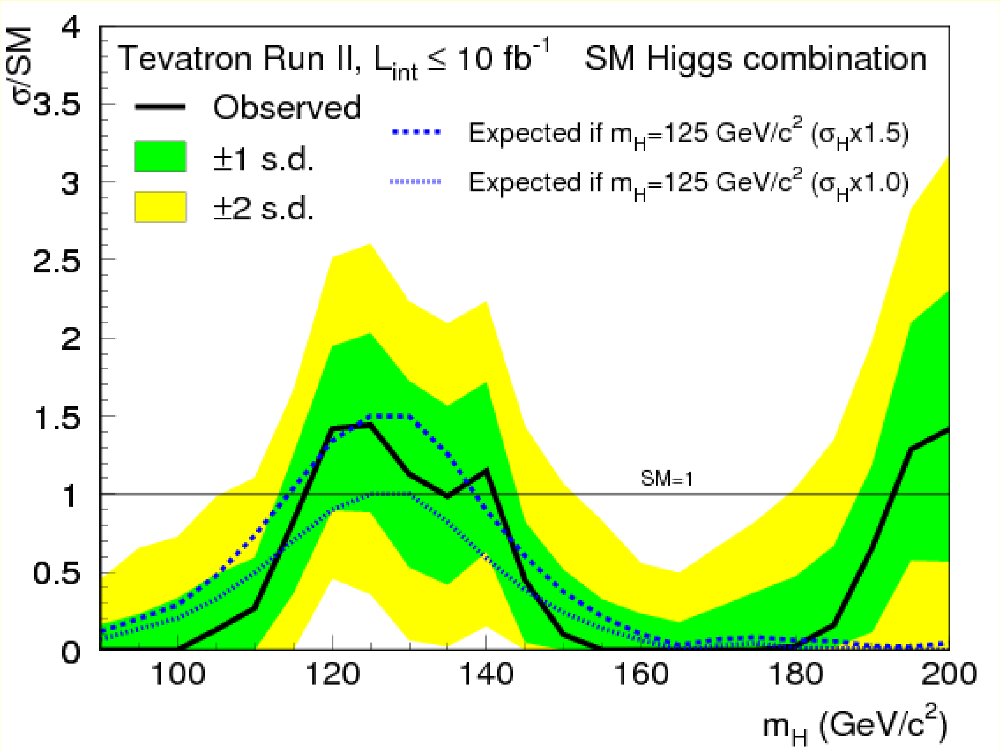
p-value for background hypothesis

- p-value for background hypothesis provides information about the consistency with the observed data
- Local p-value distribution for background only expectation:
  - 3 s.d. (@125 GeV)



Signal Strength

- Best fit for the signal, signal strength, is consistent with SM within 1 s.d.
- @125 GeV: $1.44^{+0.59}_{-0.56}$



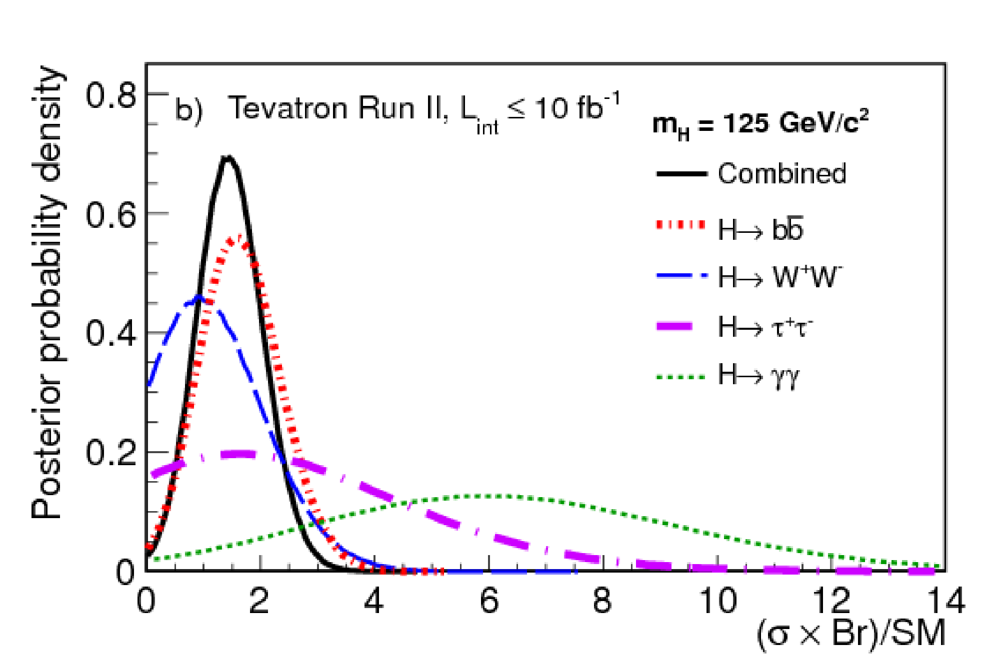
Signal strengths for various decays

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

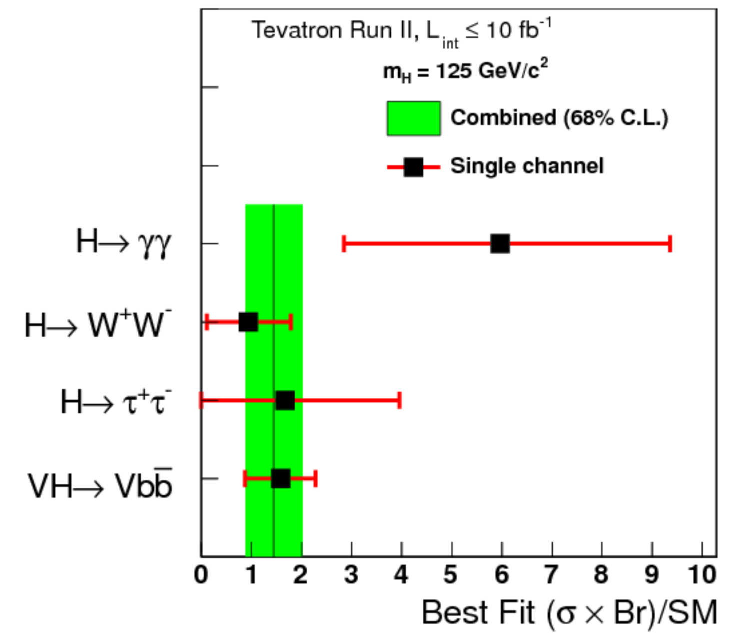
- $VH \to Vbb$; $H \to WW$; $H \to \tau\tau$; $H \to \gamma\gamma$;

Signal strength for various decays

- Posterior probability densities for R = (σ × $\mathcal{B}$)/SM from the combinations of all search channels

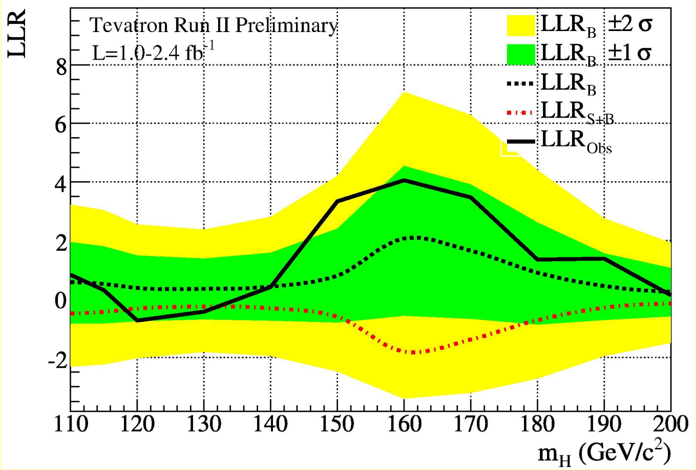


m_H (GeV/c^2)	125
$R_{\rm fit}$(SM)	$1.44^{+0.59}_{-0.56}$
$R_{\rm fit}(H \to W^+W^-)$	$0.94^{+0.85}_{-0.83}$
$R_{\rm fit}(H \to b\bar{b})$	$1.59^{+0.69}_{-0.72}$
$R_{\rm fit}(H \to \gamma\gamma)$	$5.97^{+3.39}_{-3.12}$
$R_{\rm fit}(H \to \tau^+\tau^-)$	$1.68^{+2.28}_{-1.68}$

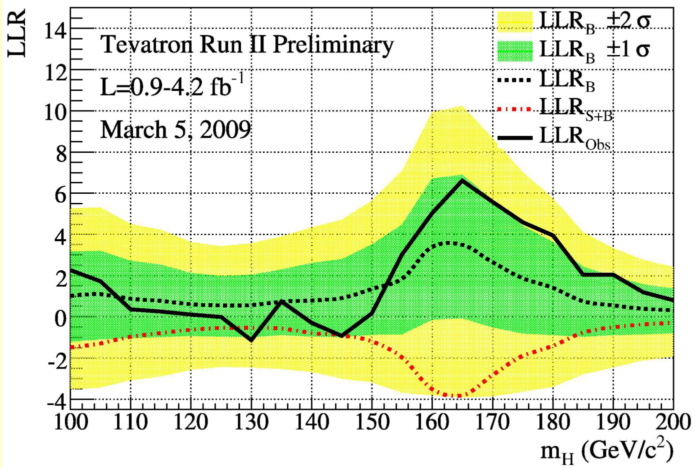


History of Tevatron results

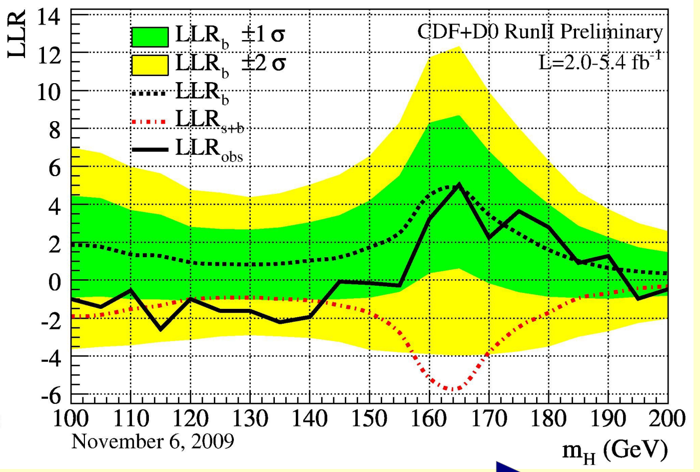
Data of 2007; up to 2.4 fb^{-1}



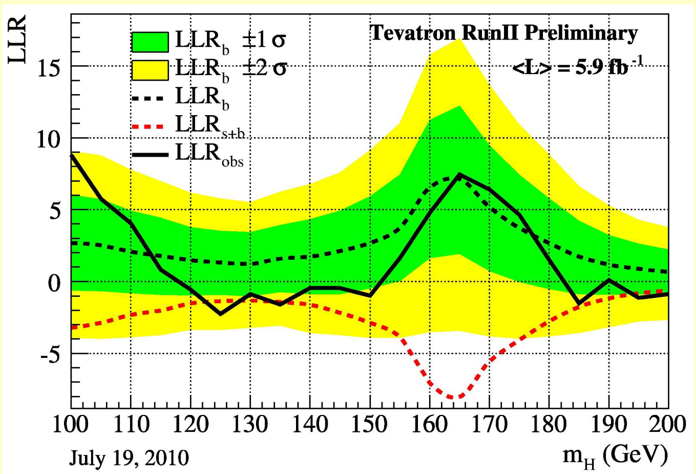
Data of 2008; up to 4.2 fb^{-1}



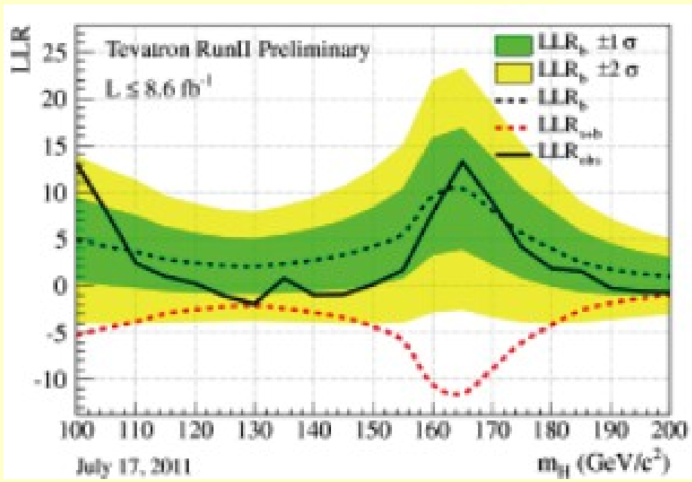
Data of mid 2009; up to 5.4 fb^{-1}



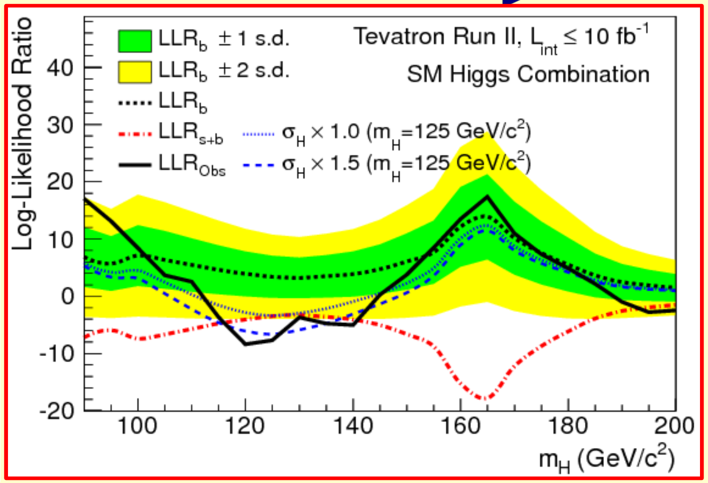
Time



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}

Couplings

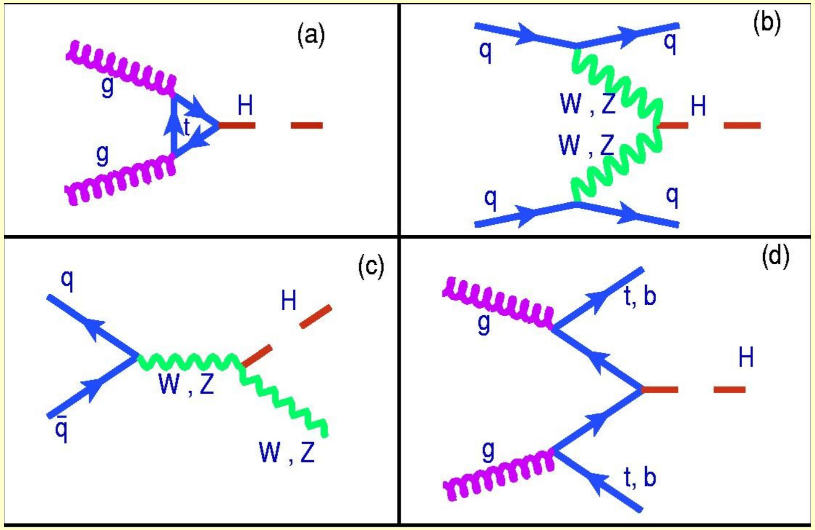
Higgs boson couplings to bosons and fermions

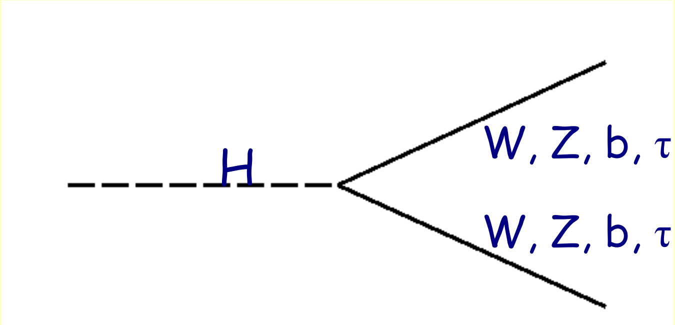
- Several production and decay mechanisms contribute to signal rates per channel => interpretation is difficult

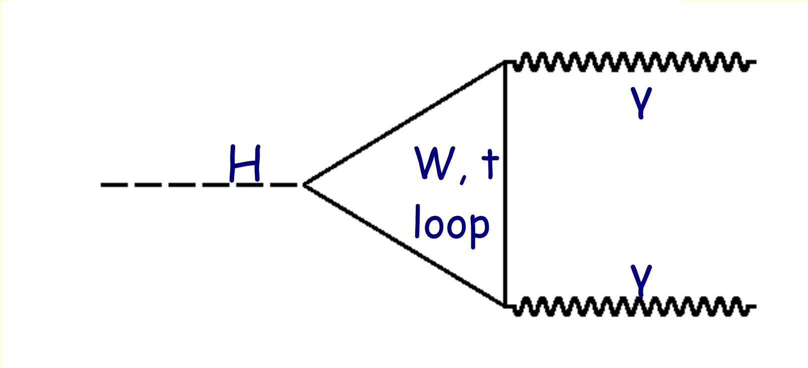
- Simplified model, SM-like with the following:
  - Hff couplings are scaled together by κ_f
  - HWW coupling is scaled by κ_W
  - HZZ coupling is scaled by κ_Z

- For some studies, we scale the HWW and HZZ couplings by $\kappa_W = \kappa_Z = \kappa_V$

- Standard Model is recovered if $\kappa_f = \kappa_W = \kappa_Z = 1$







Higgs boson couplings to bosons and fermions

- Follow the prescription from LHC Higgs cross section working group: arXiv:1209.0040
- Basic assumptions:
  - There is only one underlying state at m_H~125 GeV
  - It has negligible width
  - It is a CP even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched)
  - No additional invisible or undetected Higgs decay modes

Constraining couplings

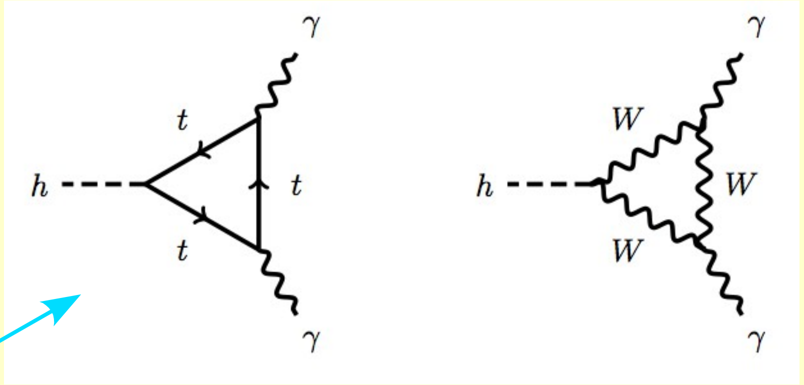
- Scale cross sections for each process according to couplings

$$\sigma(gg \to H) = \sigma_{SM}(gg \to H)(0.95\kappa_f^2 + 0.05\kappa_f\kappa_V)$$
$$\sigma(VH, VBF) = \sigma_{SM}(VH, VBF)\kappa_V^2$$

- Recompute all Higgs boson decay branching ratios from scaled partial widths

$$\Gamma(H \to VV) = \Gamma(H \to VV)_{SM}\kappa_V^2; (V = W, Z)$$
$$\Gamma(H \to ff) = \Gamma(H \to ff)_{SM}\kappa_f^2$$
$$\Gamma(H \to gg) = \Gamma(H \to gg)_{SM}(0.95\kappa_f^2 + 0.05\kappa_f\kappa_V)$$
$$\Gamma(H \to \gamma\gamma) = \Gamma(H \to \gamma\gamma)_{SM}|\alpha\kappa_V + \beta\kappa_f|^2$$

$$\mathcal{BR}(H \to XX) = \frac{\Gamma(H \to XX)}{\Gamma_{TOT}}$$



α=1.28; β=-0.28;

from Spira et al. arXiv:hep-ph/9504378

=> $H \to \gamma\gamma$ from destructive interference between the two contributions

- If any of the couplings is negative, interference becomes constructive

=> Larger rate of the $H \to \gamma\gamma$

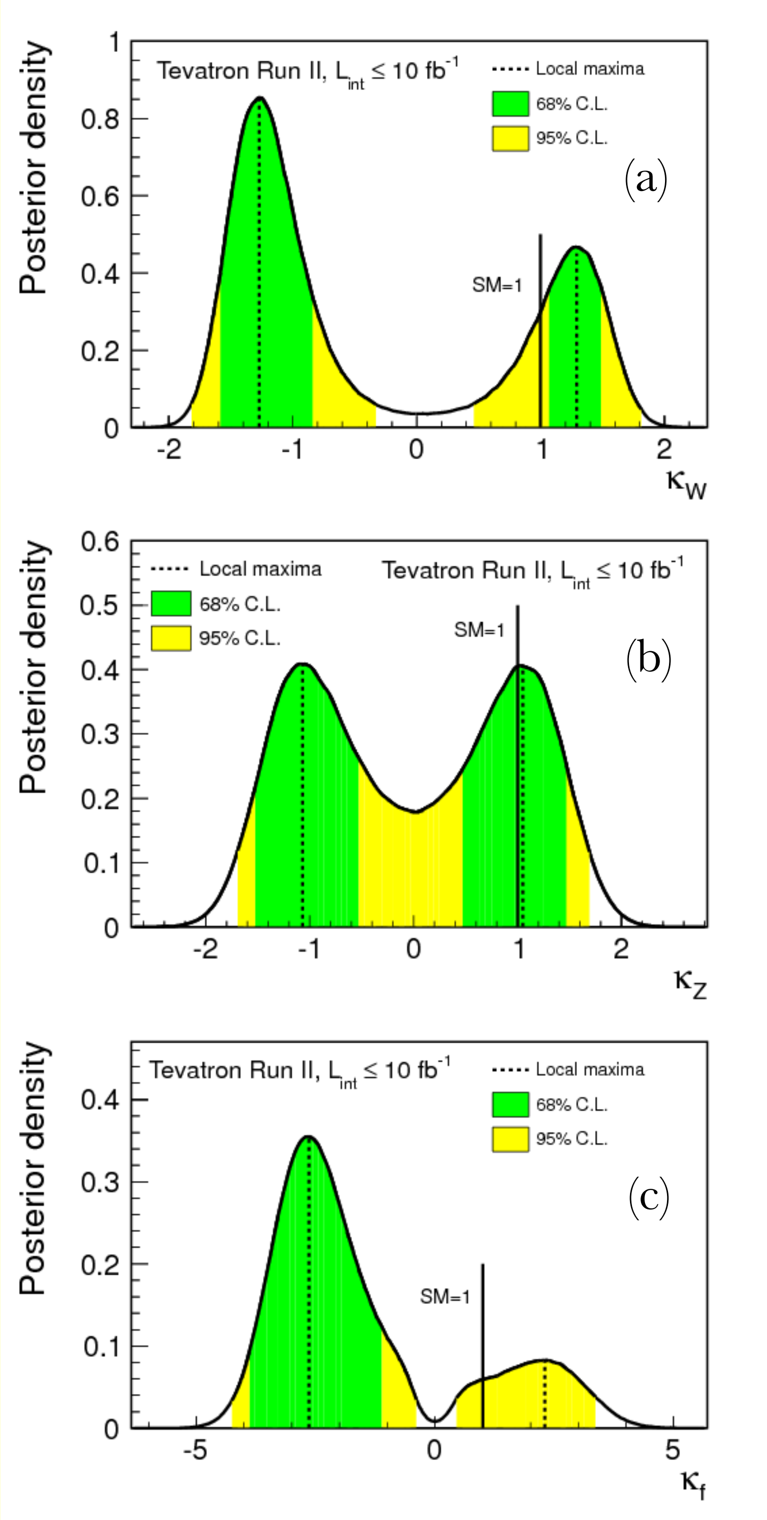
Couplings

- Posterior probability distributions

  (a) vary κ_W ($\kappa_Z = \kappa_f = 1$)
  - A negative sign of κ_W is preferred by the Tevatron data due to the excess in $H \to \gamma\gamma$
  - Best fit: $\kappa_W = -1.27$

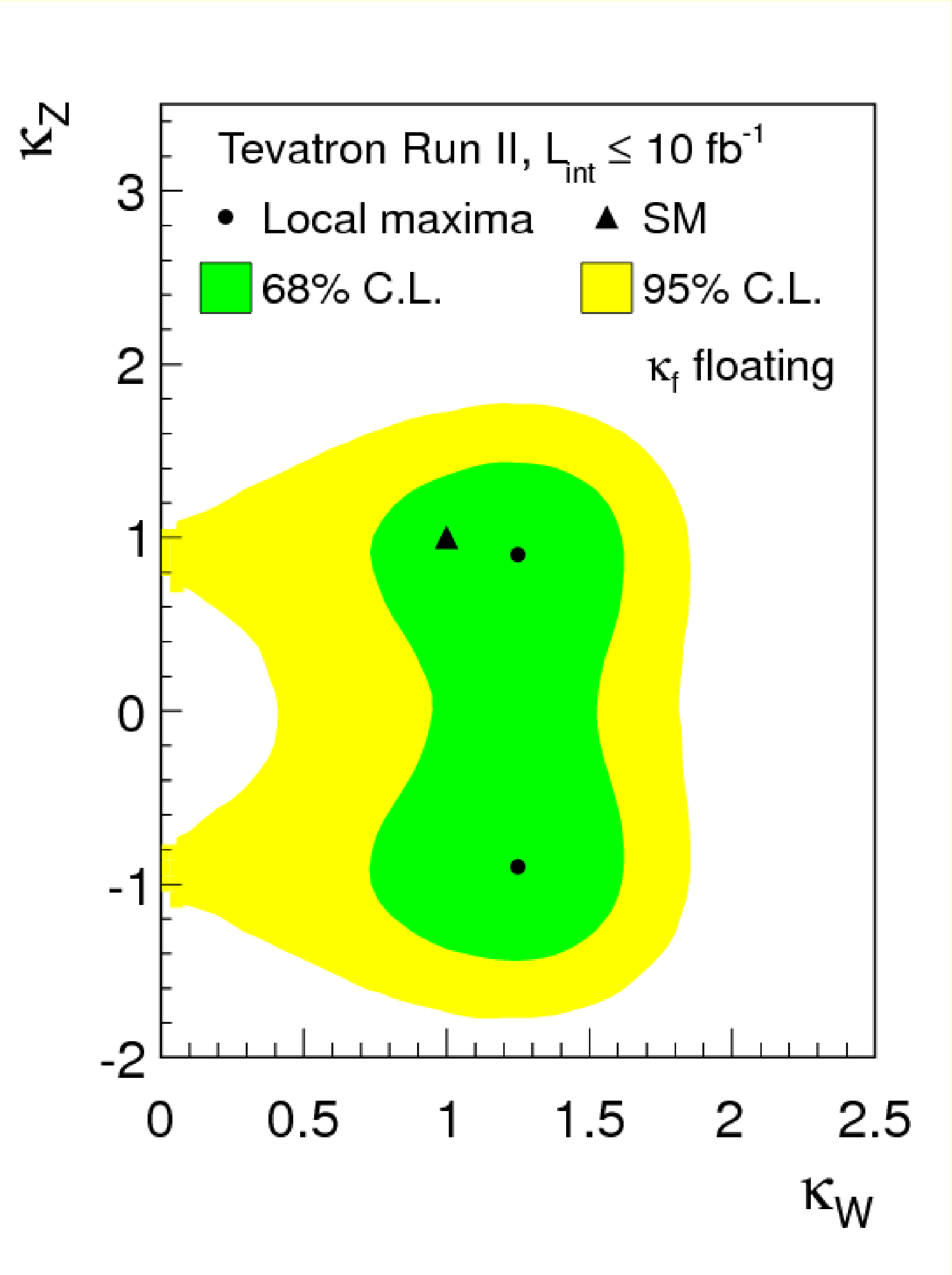
  (b) vary κ_Z ($\kappa_W = \kappa_f = 1$)
  - Searches at the Tevatron are sensitive almost exclusively to $(\kappa_Z)^2$ so the posterior density is nearly symmetric
  - Best fit: $\kappa_Z = \pm 1.05$

  (c) vary κ_f ($\kappa_W = \kappa_Z = 1$)
  - Asymmetry due to $H \to \gamma\gamma$
  - Best fit: $\kappa_f = -2.64$ (large due to the excesses in $H \to \gamma\gamma$ and $VH \to Vbb$)



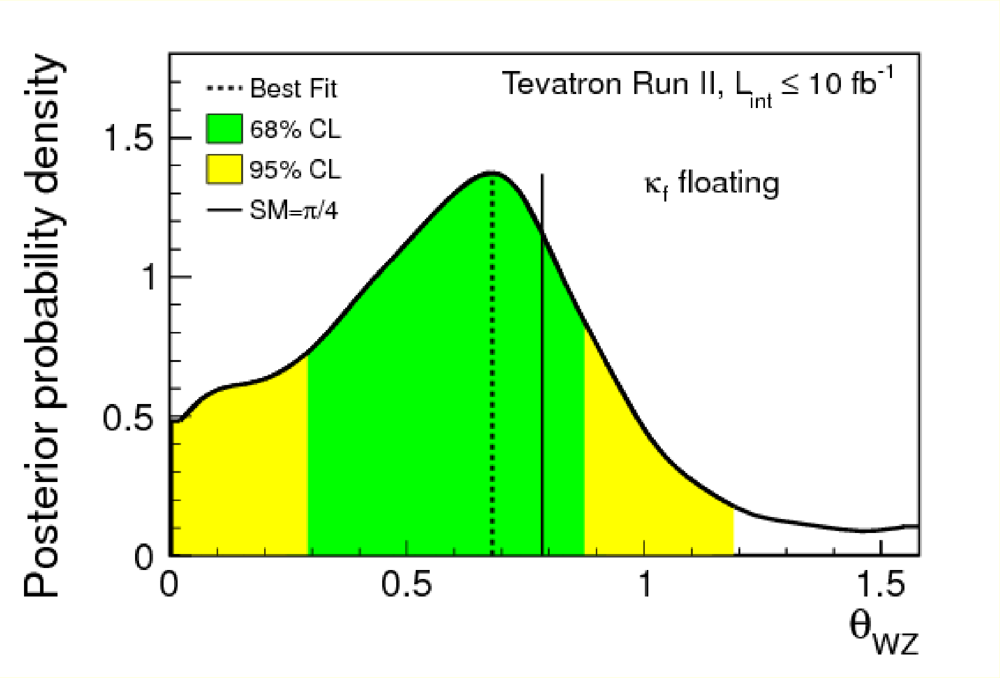
Couplings

- 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 excluded at more than 95% C.L. region due to the significant excess of events in the SM Higgs boson searches @ 125 GeV



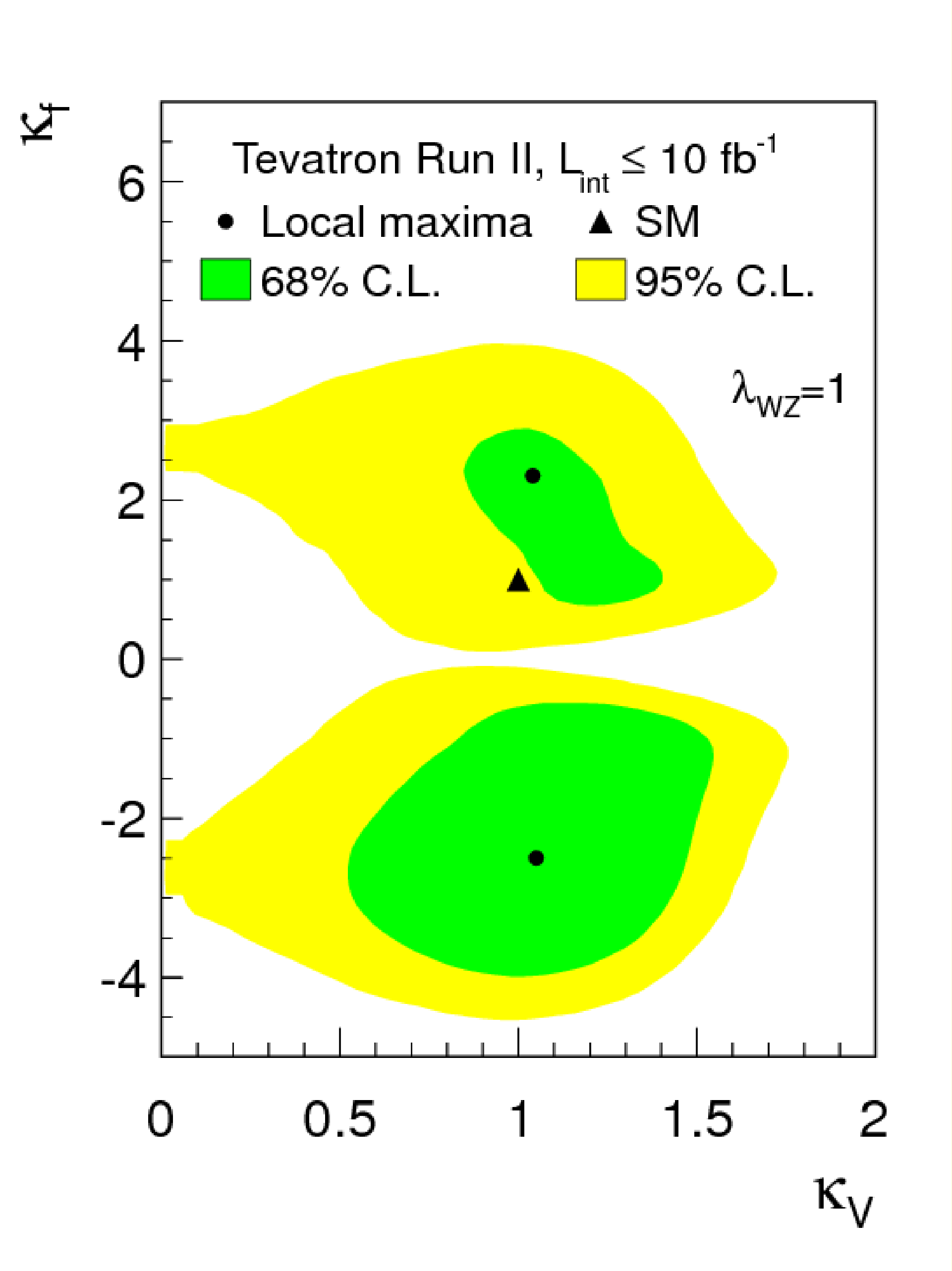
Couplings

- Probe $SU(2)_V$ custodial symmetry by measuring the ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$
  - Measure $\theta_{WZ} = \tan^{-1}(\kappa_Z/\kappa_W) = \tan^{-1}(1/\lambda_{WZ})$
  - Measure: $|\theta_{WZ}| = 0.68^{+0.21}_{-0.41} \rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$
- Consistent with Standard model and with LHC measurements:
  95% CL interval for λ_{WZ}: [0.62,1.19] (CMS)
  68% CL interval for λ_{WZ}: [0.61, 1.04] (ATLAS)



Couplings

- Assuming that custodial symmetry holds, $\lambda_{WZ} = 1$, allow both κ_V and κ_f to vary
- Asymmetry is from the excesses in the $H \to \gamma\gamma$
- Two minima:
  $(\kappa_V, \kappa_f)=(1.05,-2.40)$ and
  $(\kappa_V, \kappa_f) = (1.05, 2.30)$
- The integral of the posterior density in the (+,+) quadrant is 26% of the total, while the remaining 74% of the integral of the posterior density is contained within the (+,−) quadrant



Summary on couplings

- Couplings to fermions: $\kappa_f = -2.64^{+1.59}_{-1.30}$
- Couplings to bosons:

  $\kappa_W = -1.27^{+0.46}_{-0.29}$; *second interval* $1.04 < \kappa_W < 1.51$

  $\kappa_Z = \pm 1.05^{+0.45}_{-0.55}$

  - if varied together: $(\kappa_W, \kappa_Z) = (1.25, \pm 0.90)$

- For custodial symmetry: $|\theta_{WZ}| = 0.68^{+0.21}_{-0.41} \rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$

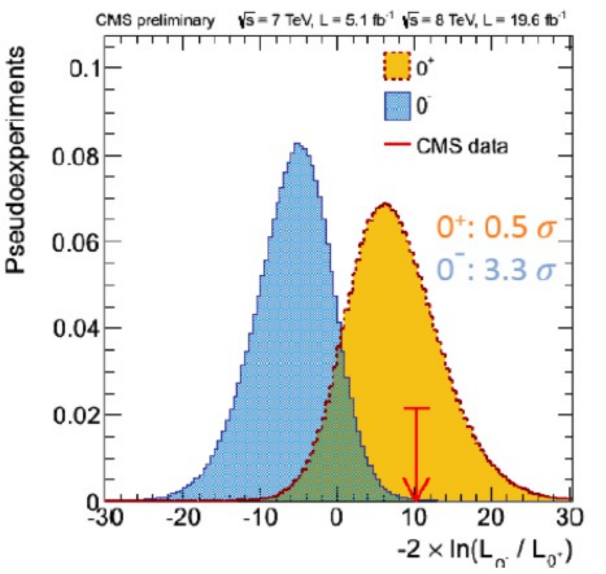
- If custodial symmetry is preserved:

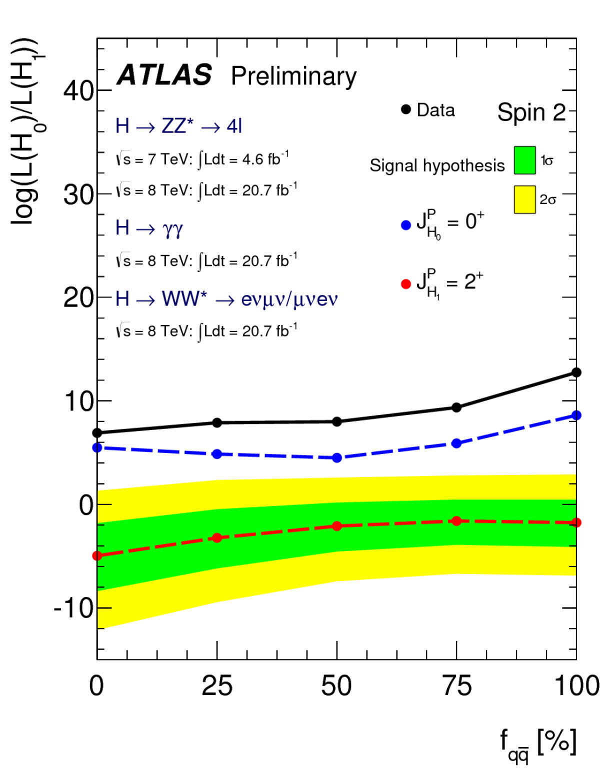
  $(\kappa_V, \kappa_f) = (1.05, -2.40)$ and $(\kappa_V, \kappa_f) = (1.05, 2.30)$

Spin (J) and Parity (P)

Motivation

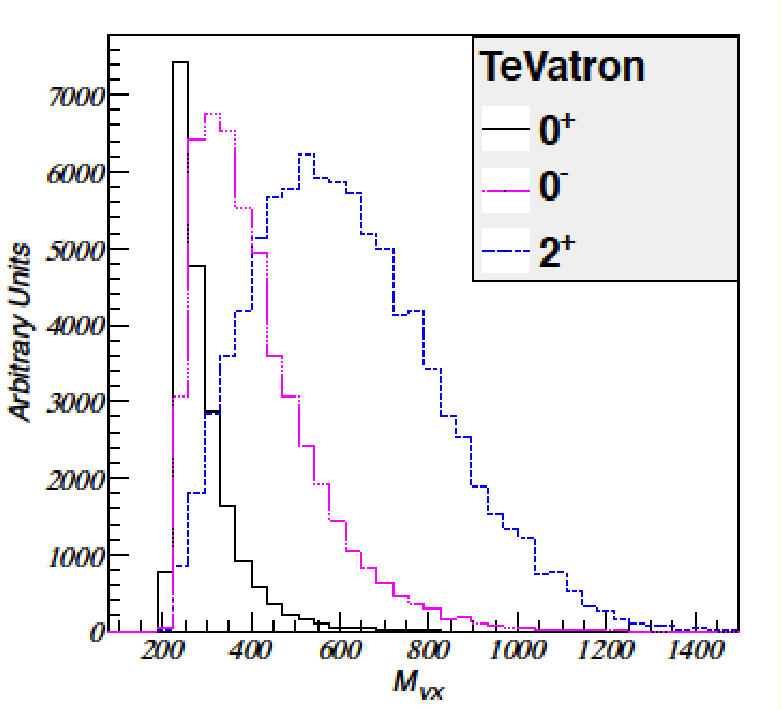
- Standard Model predicts Higgs boson with $J^P = 0^+$
  - The $H \to \gamma\gamma$ excludes J=1 (Landau-Yang theorem)
- J^P are studied at LHC
  - Results favor $J^P=0^+$ over $2^+, 0^-$, ... in $H \to ZZ$, $H \to WW$, $H \to \gamma\gamma$ under various hypotheses for production
  - No results yet for the bb decay mode
- Important to build a consistent picture in all expected Higgs boson decay modes





Spin and Parity at Tevatron

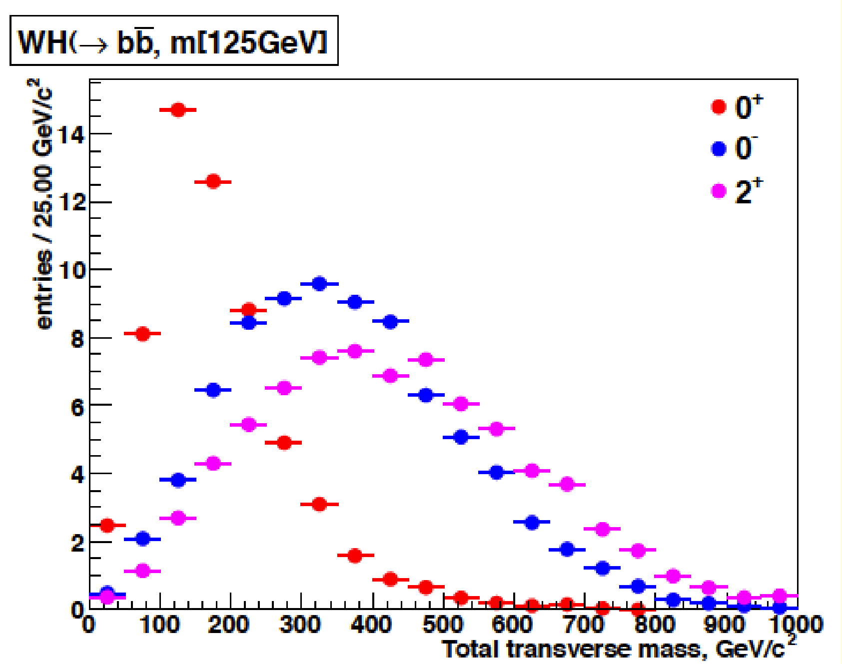
- Different spin and parity states manifest in various ways
  - Angles of decay products
  - Cross section behavior at threshold:
    - s-wave for 0^+: $\sigma \sim \beta$
    - p-wave for 0^-: $\sigma \sim \beta^3$
    - d-wave for 2^+: $\sigma \sim \beta^5$



- VH production at Tevatron is sensitive to threshold effects
  - Paper by Ellis et al. http://arxiv.org/abs/1208.6002
  - Differential cross-sections depend strongly on J^P of the new particle

Spin and Parity at Tevatron

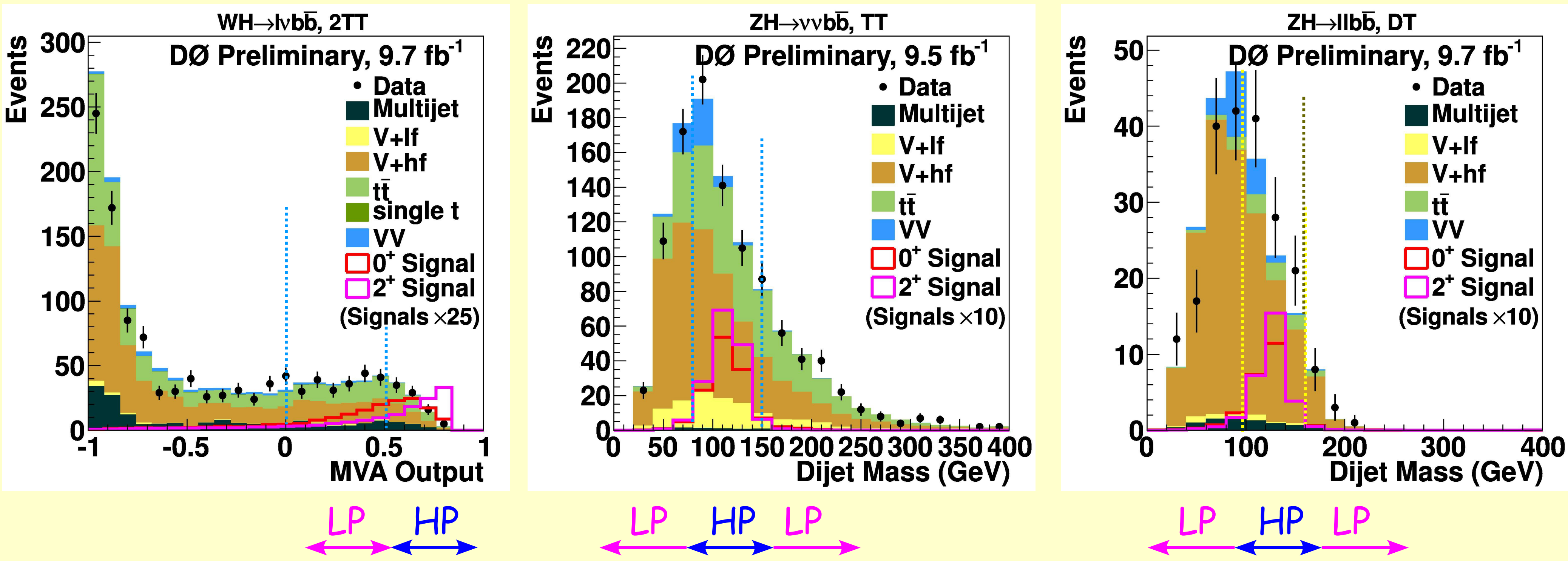
- Use published VH → Vbb analyses and compare SM process with the new hypothesis
- Main discrimination variable: total mass of the V+X system (X is 0^+, 0^- or 2^+)
  - In a case of V → lν or V → νν total transverse mass is a better choice



- Assume σ×ℬ of SM Higgs boson in a first step
  - 2^+: Standard RS graviton in Madgraph
  - 0^-: Model by Ellis et al. implemented in Madgraph

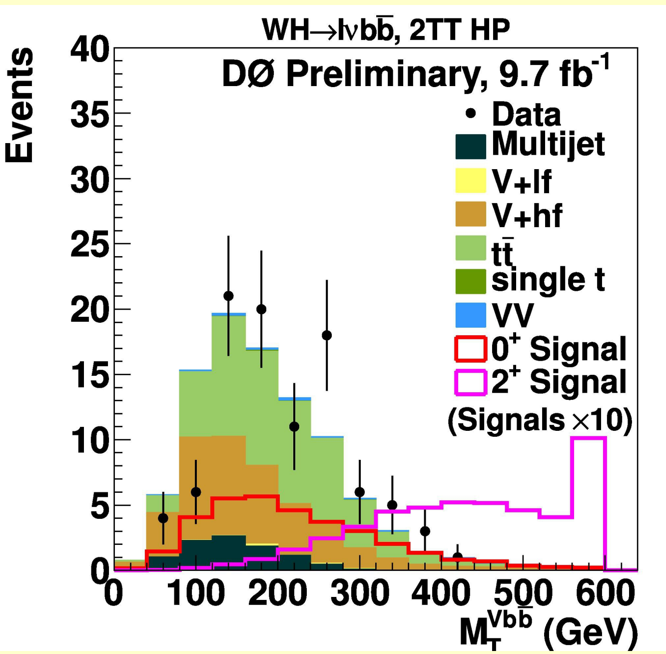
Background rejection

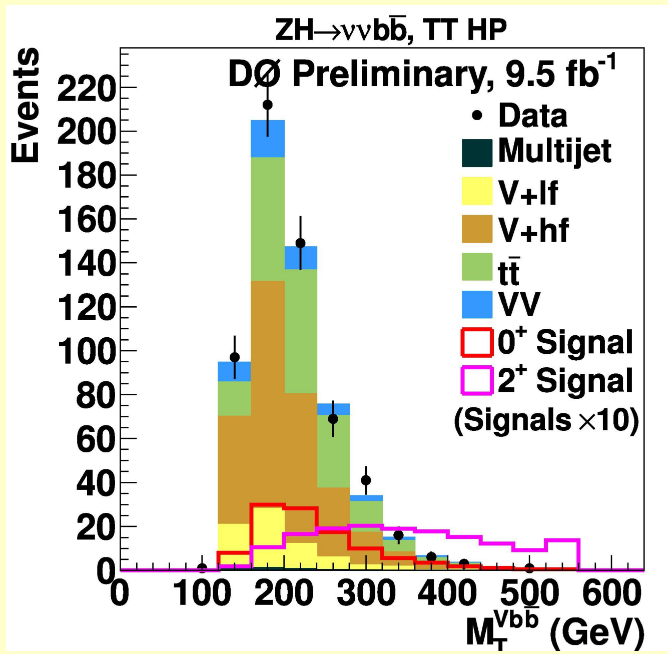
- Divide samples into low and high purity based on dijet invariant mass or MVA output from the published analysis

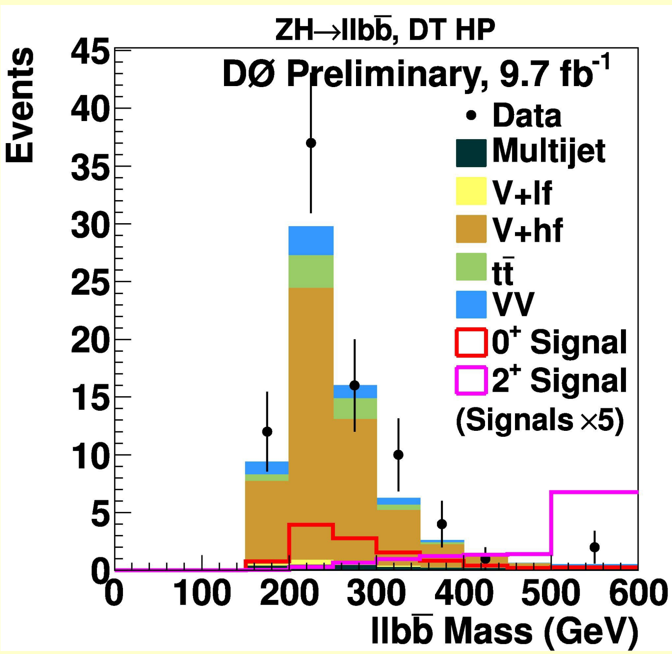


Final variable

- Total (transverse) mass as final discriminating variable

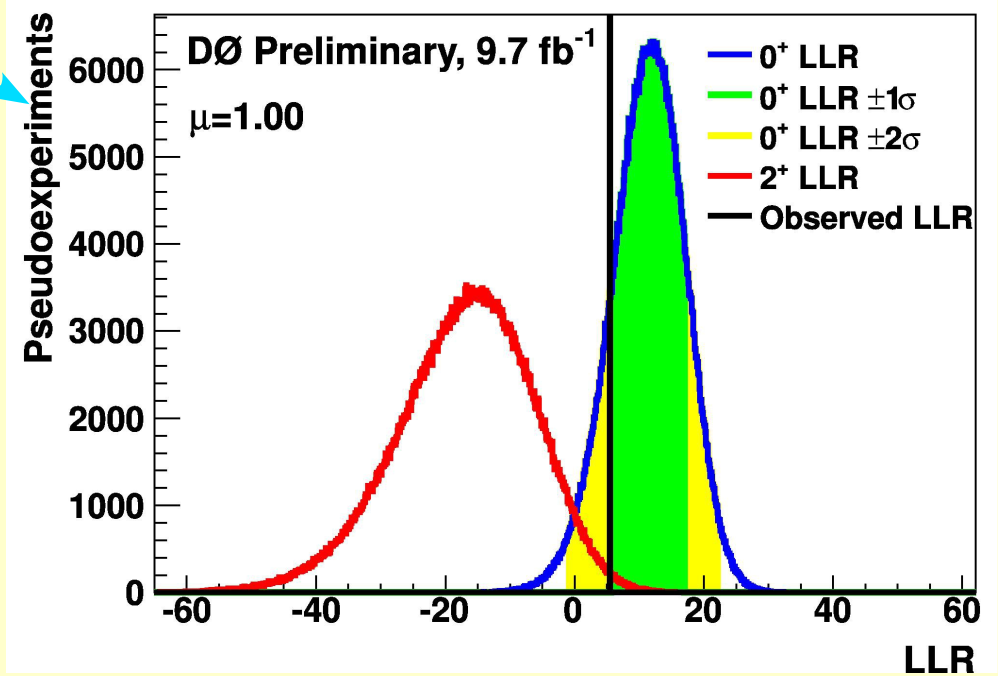






Results

- Build log-likelihood ratio test: LLR= -2 log(H_1/H_0)
  - H_0 is the SM Higgs (0^+) + Bkg
  - H_1 is either 2^+ + Bkg or 0^- + Bkg
- Compute for 2 different signal scale factors μ on SM σ×ℬ
  - 1.00 (SM – shown here)
  - 1.23 (D0 measured rate)



LPNHE PARIS

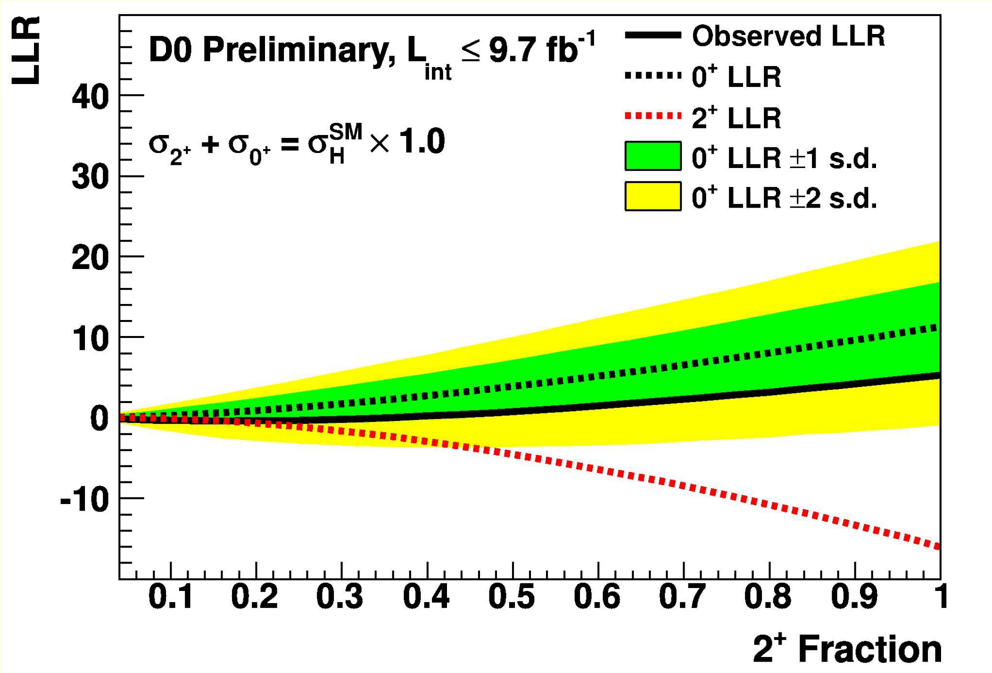
Results

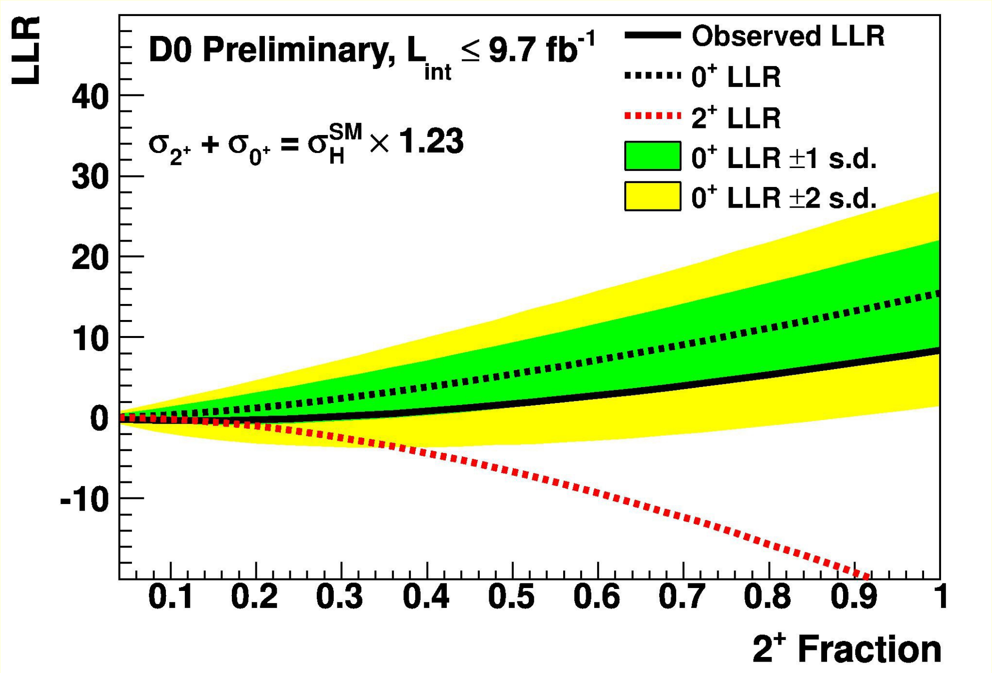
- $CL_s = CL_{H1}/CL_{H0}$
- $Cl_x = P(LLR \geq LLR^{obs}|x)$
- Interpret 1-CLs as C.L. for exclusion of 2^+ in favor of 0^+
- Exclude 2^+ model at >99.2% C.L.
- Expected exclusion is 3.2σ (μ=1.0)
- Competitive with LHC single-channel measurements

	Combined result	Result in σ
1 – Cls Exp. (μ=1.00)	0.9992	3.16
1 – Cls Obs. (μ=1.00)	0.9922	2.42
1 – Cls Exp. (μ=1.23)	0.9999	3.72
1 – Cls Obs. (μ=1.23)	0.9988	3.04

Signal Admixtures

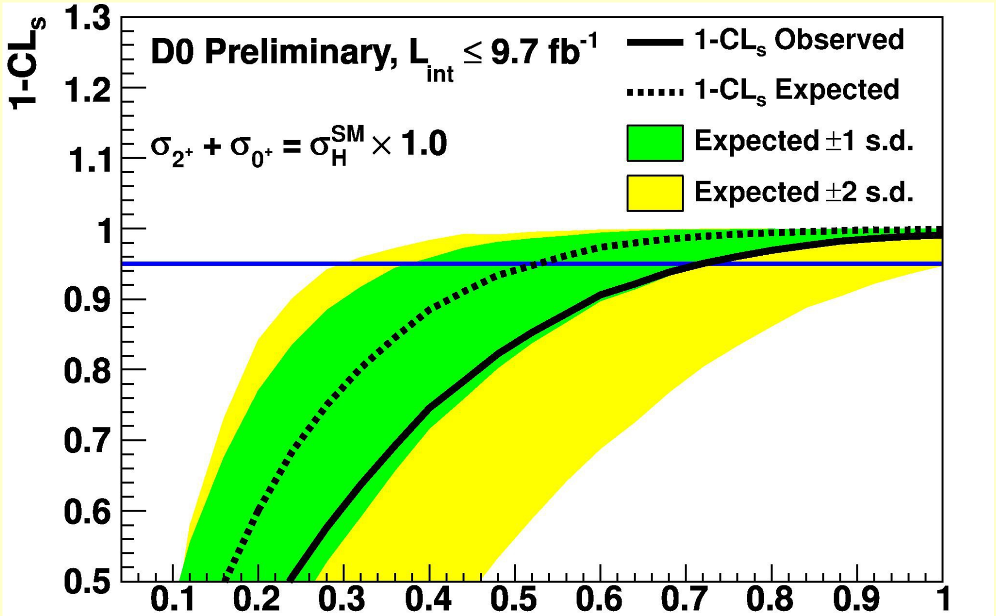
- Allow possibility of both a 2^+ and 0^+ signal in data
- Vary 2^+ fraction f_{2+} from 0 to 1
  - H1: $\mu \times (\sigma \times \mathcal{B})_{SM} \times [2^+ \times f_{2+} + 0^+ \times (1-f_{2+})]$ + Background
  - H0: $\mu \times (\sigma \times \mathcal{B})_{SM} \times 0$ + Background (pure 0^+)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



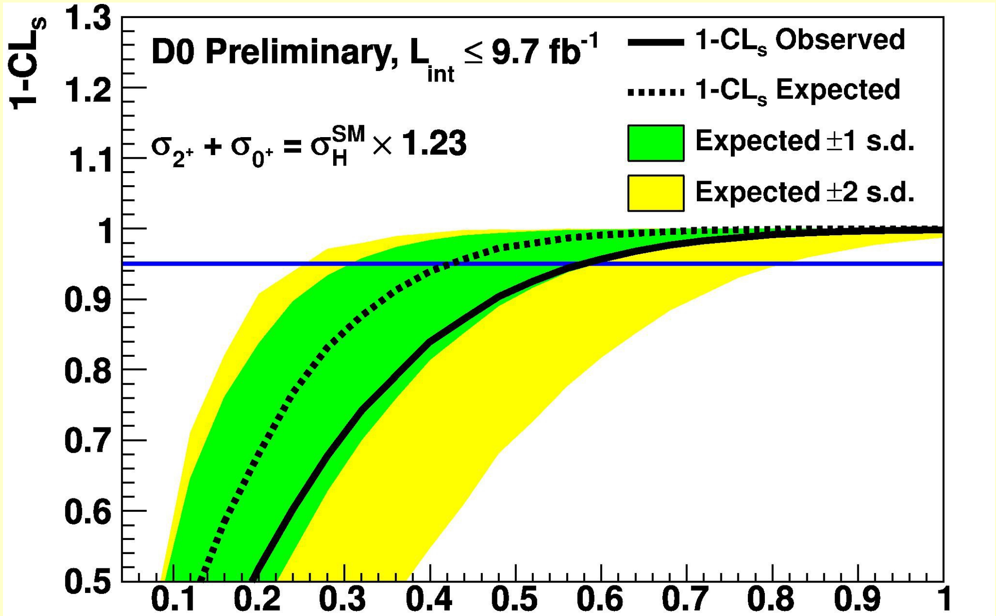


Signal Admixtures

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



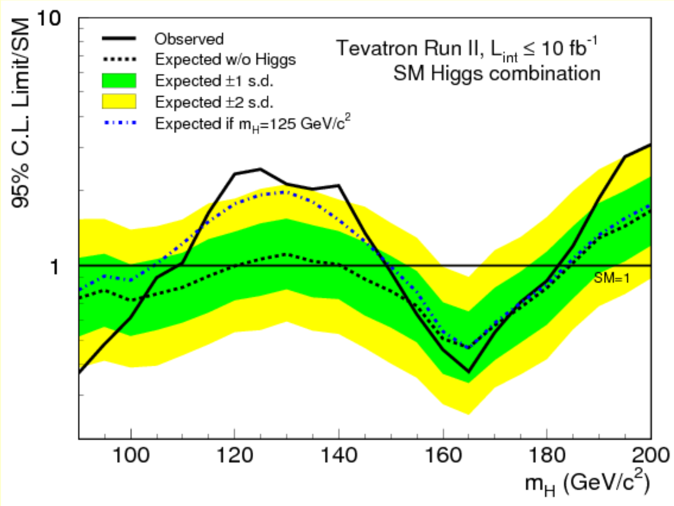
Exclude $f_{2+} > 0.71$ at 95% C.L.



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

Summary

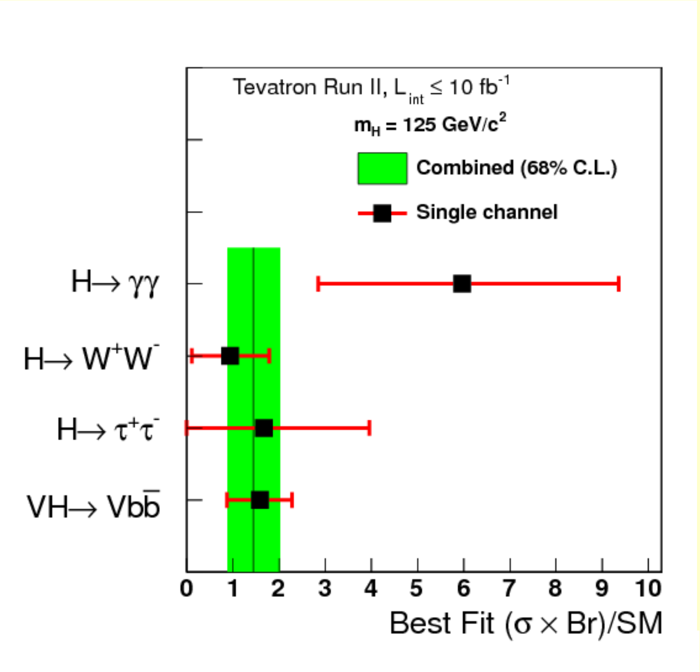
- Tevatron has ended its 25 years' run on September 30th 2011
  - It ran more than 9 years at $\sqrt{s}$ = 1.96 TeV
  - It delivered almost 12 fb^{-1} during that period
  - We are grateful for all these data
- In 2009, Tevatron published first exclusion since LEP, pointing to a low mass Higgs (115-140 GeV) , when combined with the indirect limits.
- In July 2012, Tevavatron published first (so far only) evidence for fermionic decay of the Higgs (H->bb)

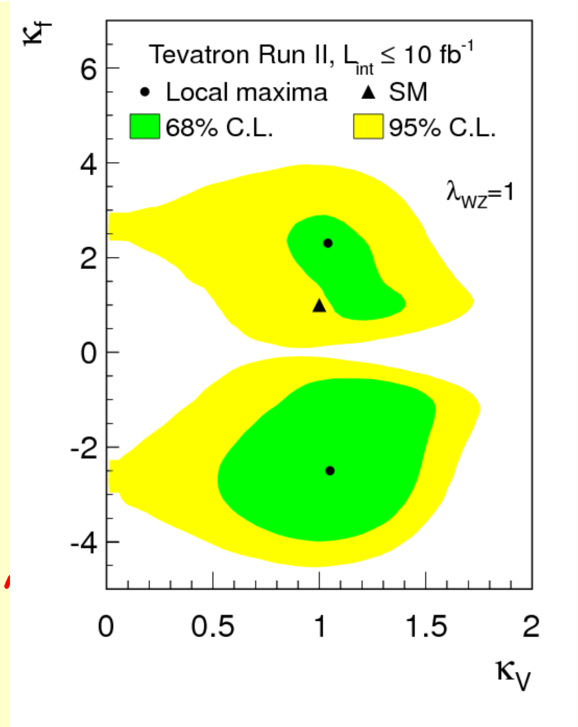


- D0 and CDF finalized publications of all search channels in 2013
- Both experiments performed very well
  - Improvements over the years led to the 95% C.L. exclusion sensitivity <~1.0xSM for m_H < 185 GeV when combining two experiments

Summary

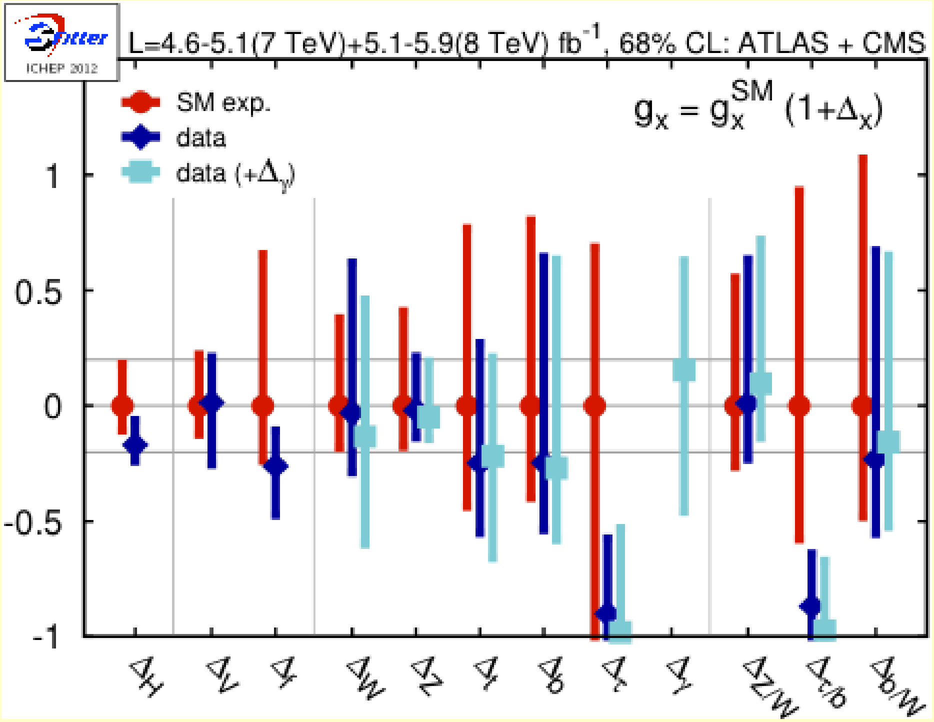
- 3 s.d. excess @125 GeV observed in data when combining from both experiments, consistent with LHC observation
- Signal strengths in all analyzed decay channels are consistent with SM Higgs expectation
- Results on Higgs couplings are also consistent with the SM predictions
- Spin and parity studies in VH → Vbb are underway
  - Exclude 2^+ model at >99.2% C.L.
- It is unlikely that H→bb is established before 2015, except if the results from all experiments are combined

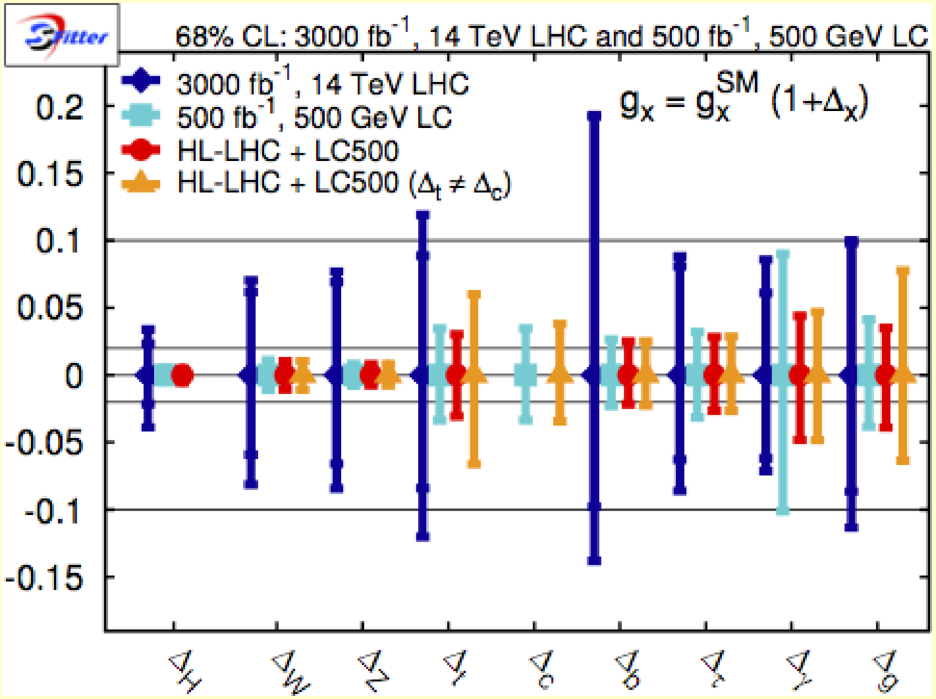




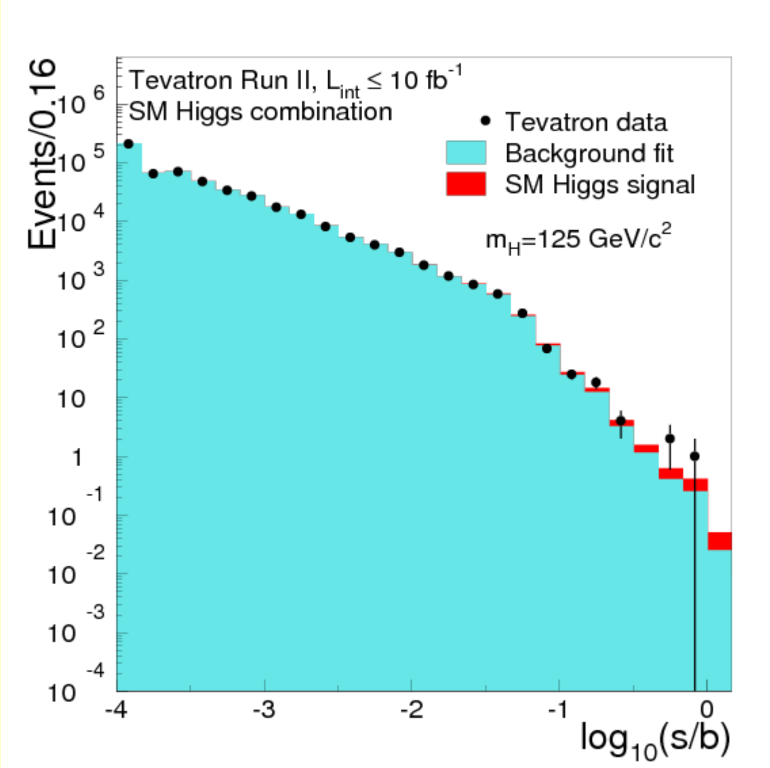
Backup

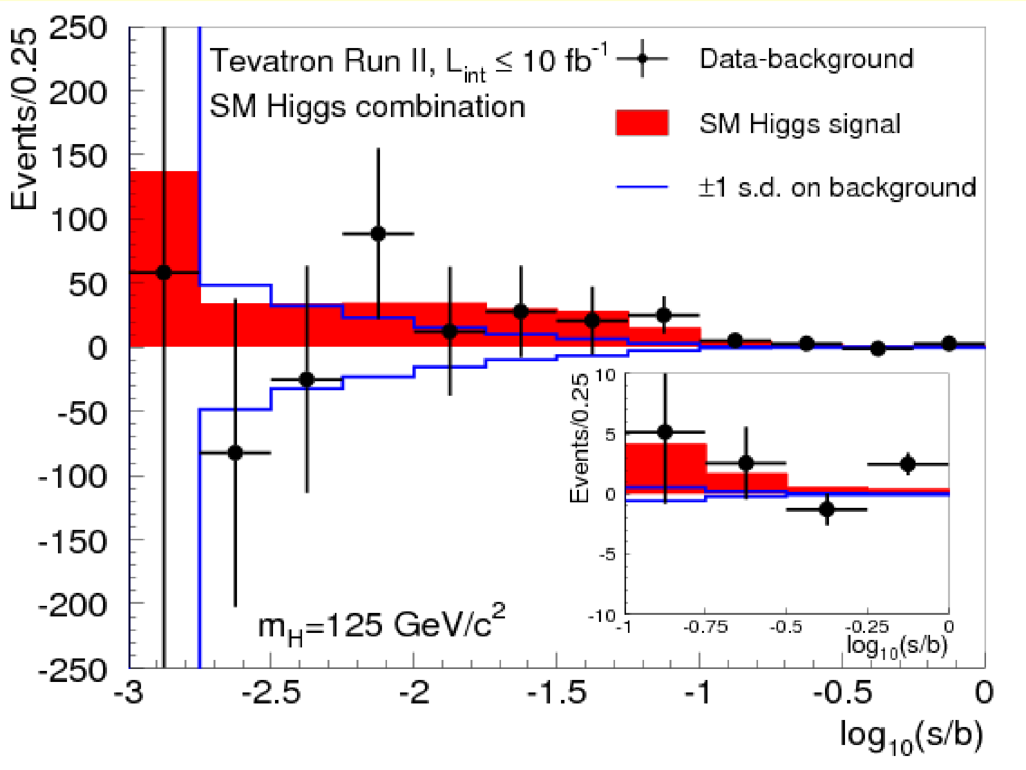
Couplings prospects





Combining all CDF and D0 channels: What does combined signal look like?

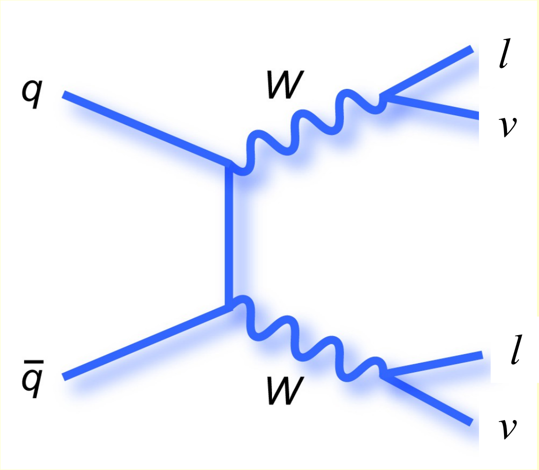


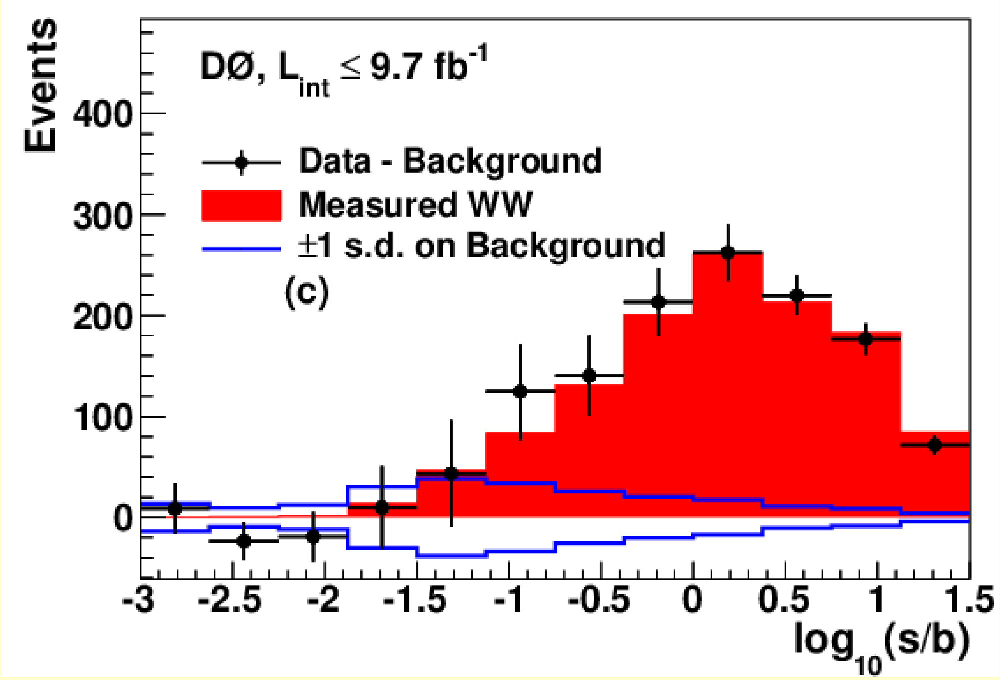


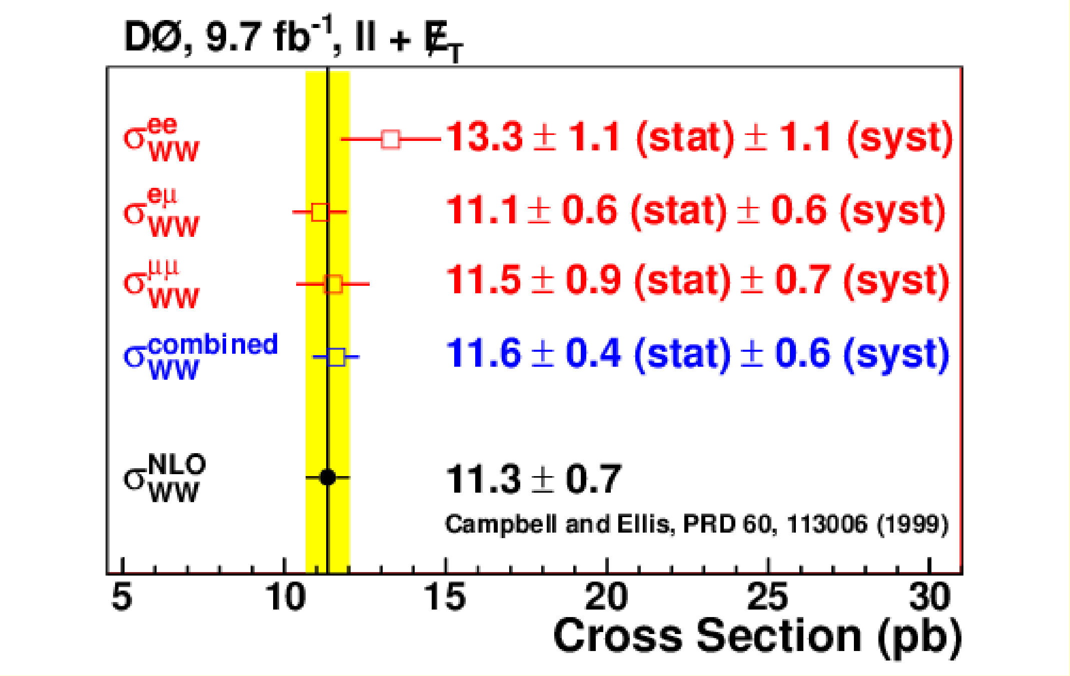
- Distribution of $\log_{10}(s/b)$, for the data from all combining Higgs boson decay channels

Validation with diboson measurement

- Use identical selection and similar MVA
  - Use WW process as a signal in training
- Measured cross section: (1.02±0.06)*SM



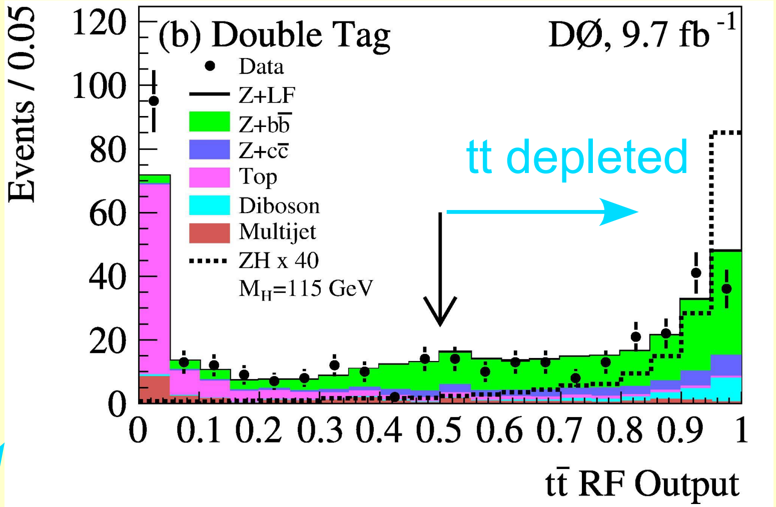


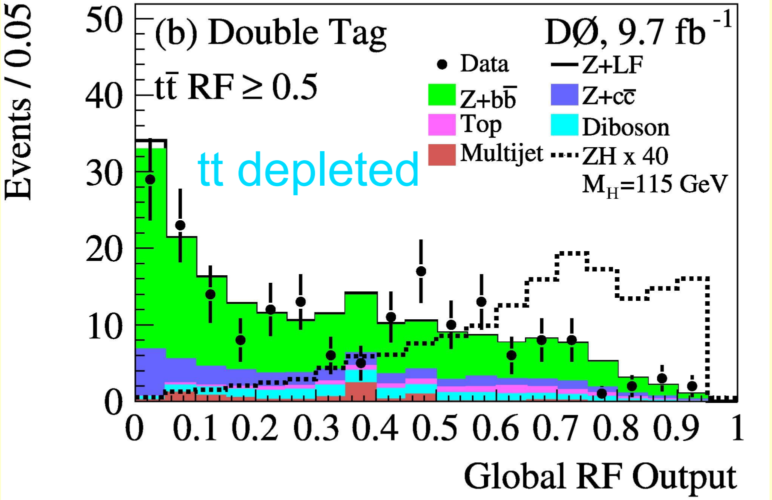


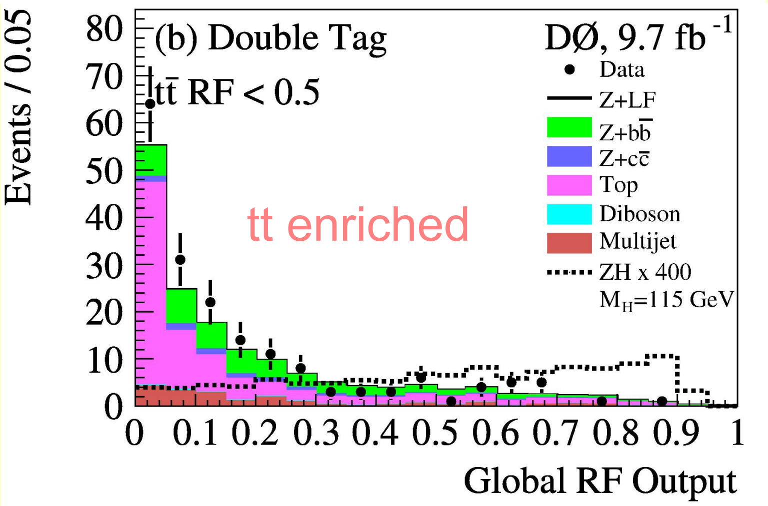
LPNHE PARIS

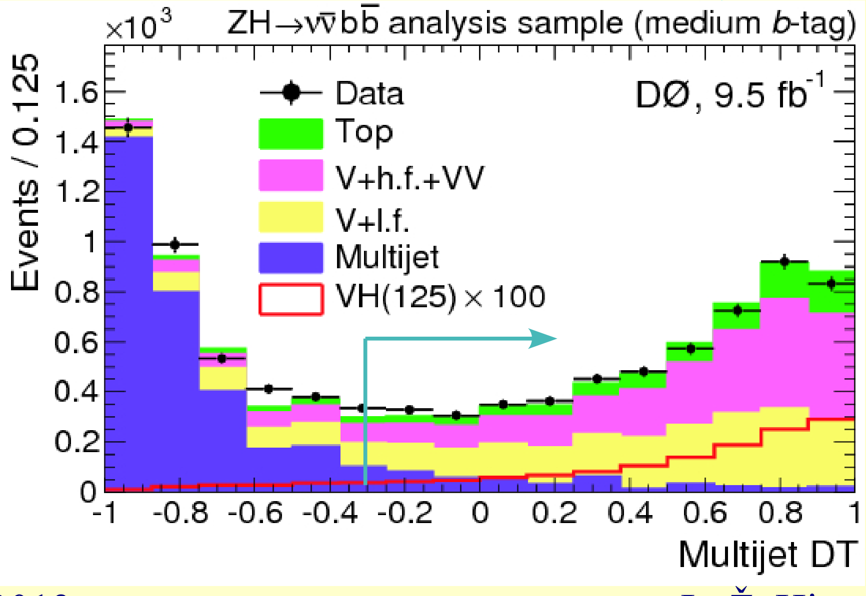
VH → Vbb

- Key ingredients:
  - Lepton, jet and $\not{E}_T$ reconstruction
  - Jet energy resolution (15%)
  - b-tagging: eff 50-80%; mis id 1-10%
  - Multivariate techniques to reject backgrounds
    - Either to split into two regions or to remove background



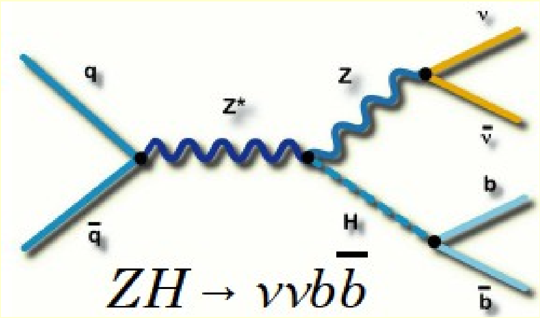


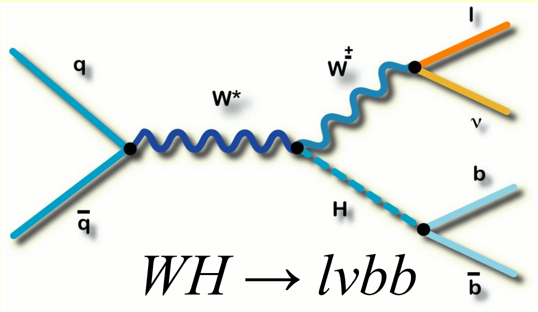


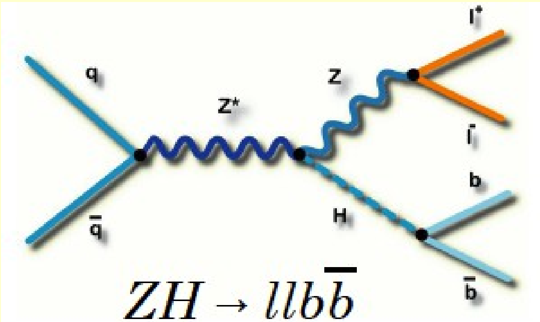


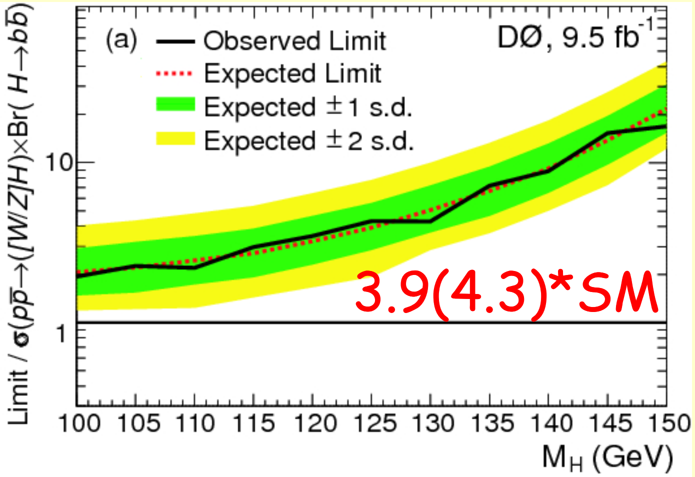
VH → Vbb results

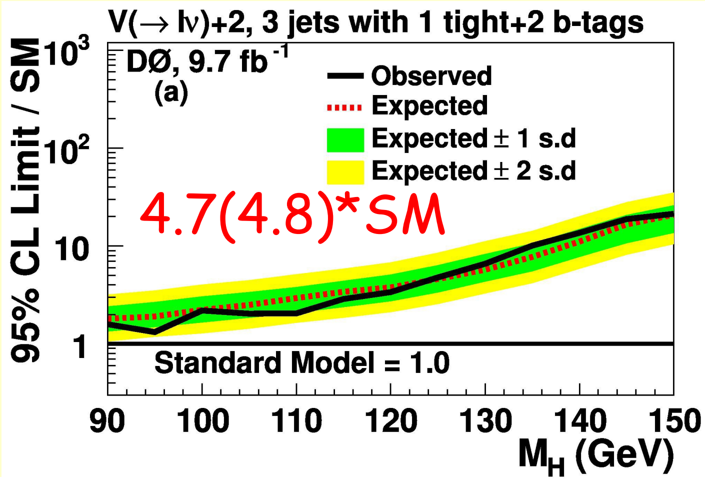
- Exp (obs) @125 GeV at D0 and CDF:

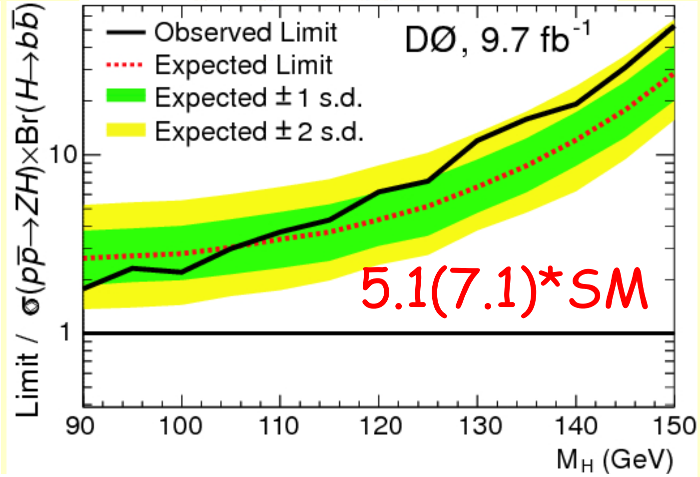


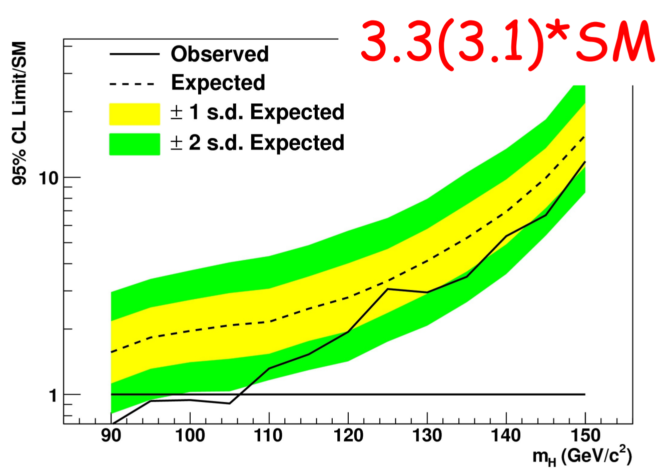


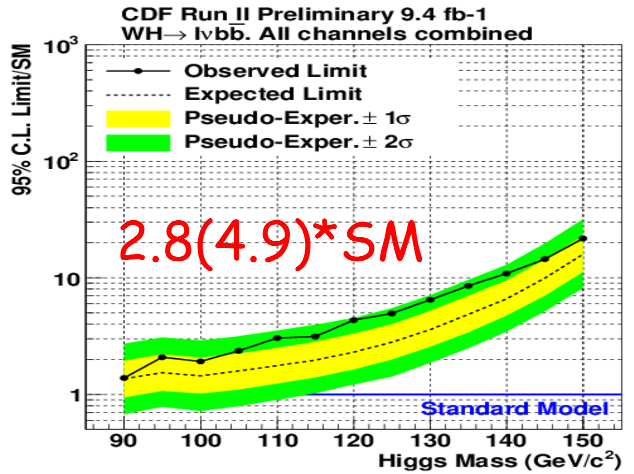


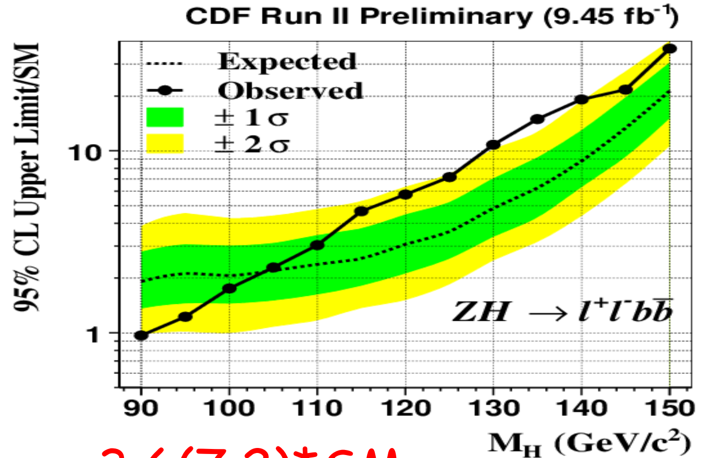








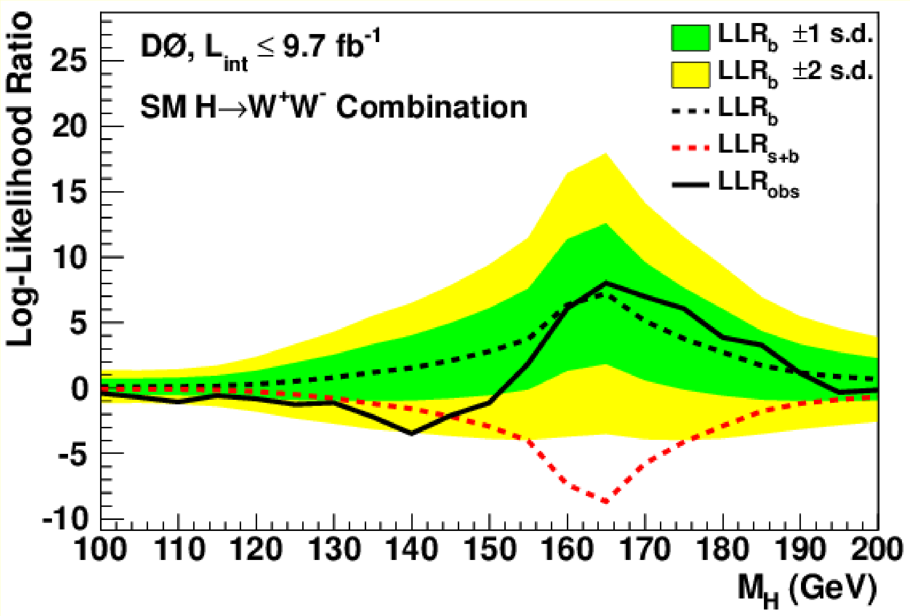




3.6(7.2)*SM

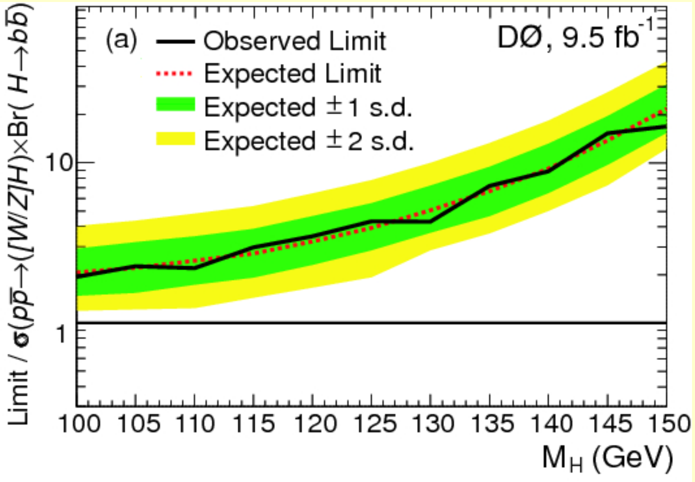
D0 combination

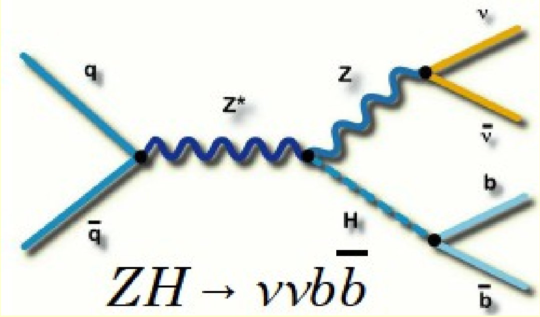
D0 H → WW


DØ, $L_{int} \leq 9.7\ fb^{-1}$
SM $H \rightarrow W^+W^-$ Combination
LLR_b ±1 s.d.
LLR_b ±2 s.d.
LLR_b
LLR_{s+b}
LLR_{obs}
Log-Likelihood Ratio
M_H (GeV)

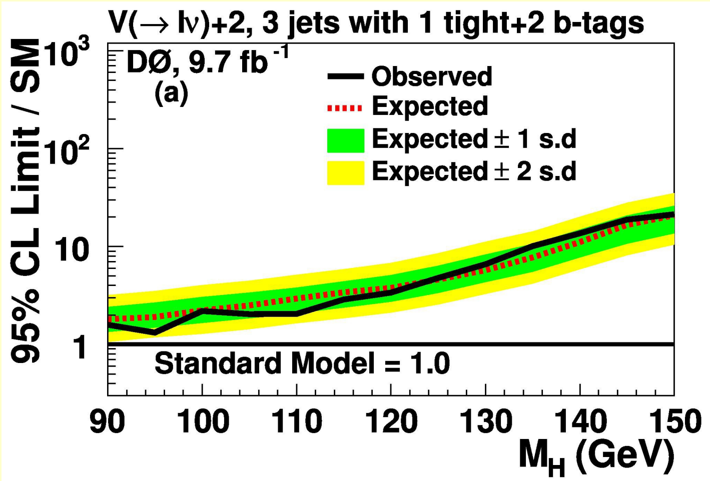
VH → Vbb results

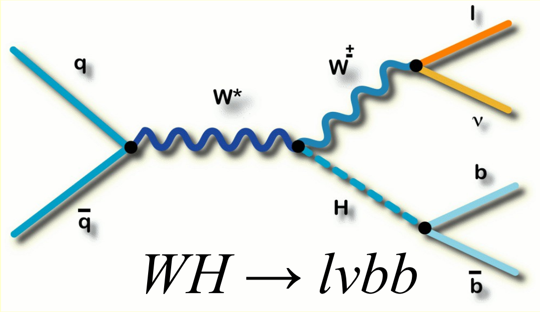
- Exp (obs) @125 GeV:
  - 3.9(4.3)*SM



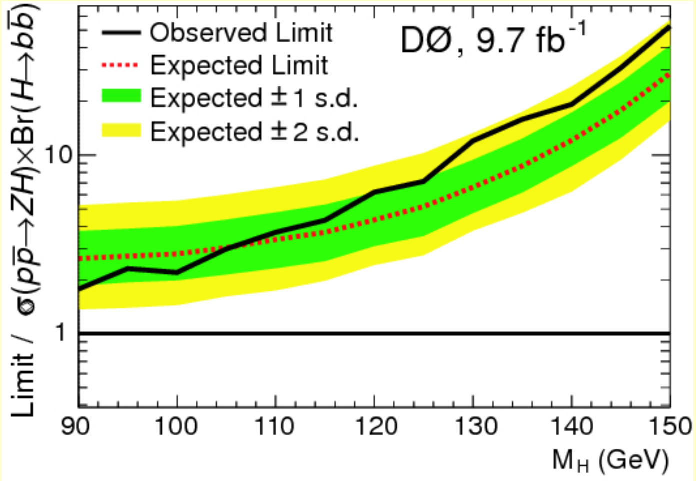


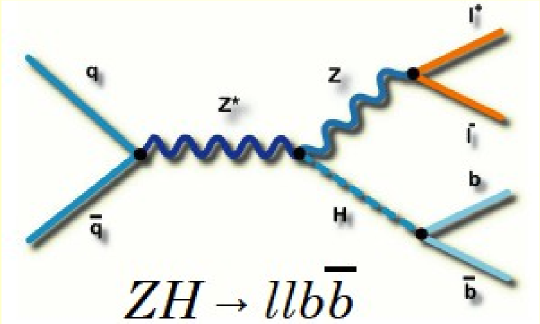
- Exp (obs) @125 GeV:
  - 4.7(4.8)*SM



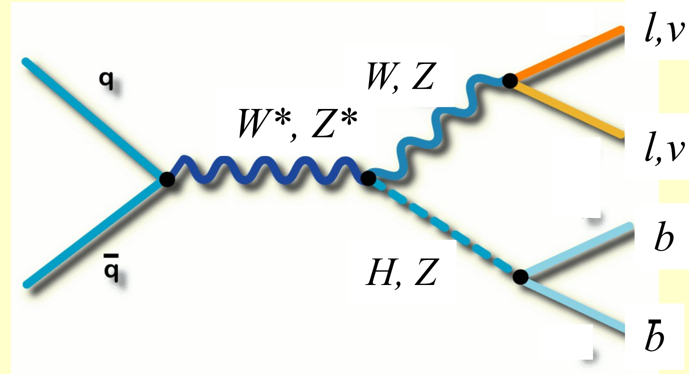


- Exp (obs) @125 GeV:
  - 5.1(7.1)*SM



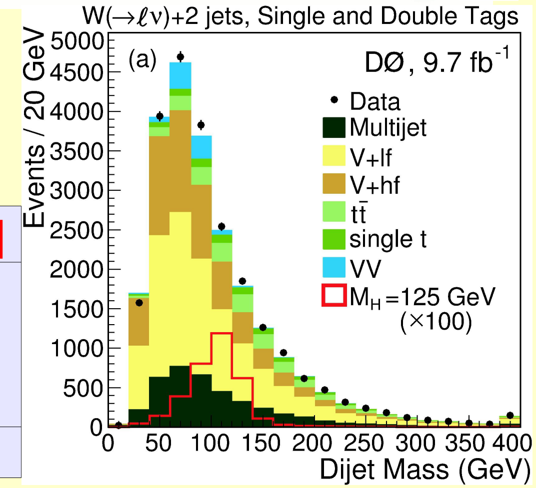


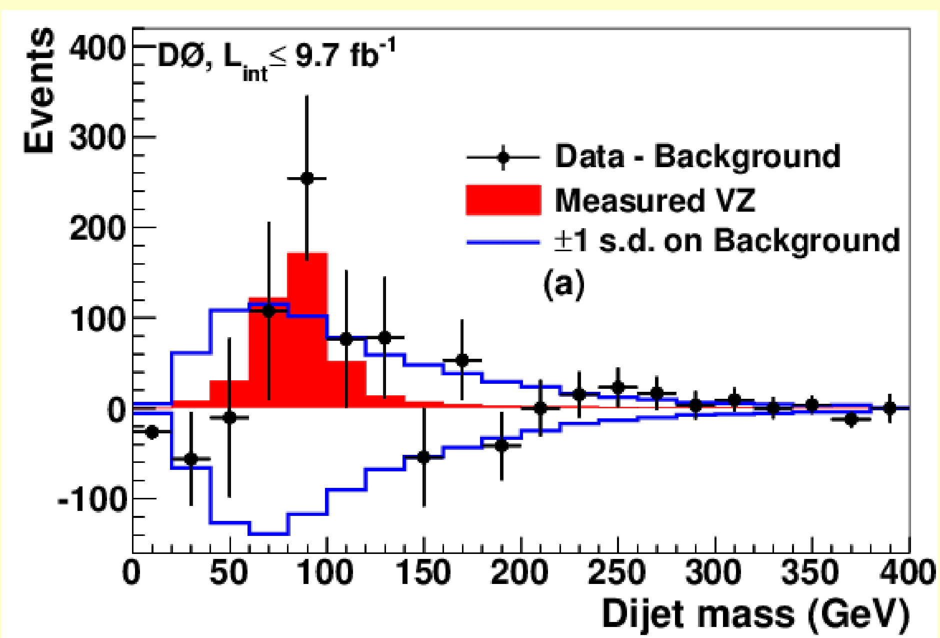
Validation of results

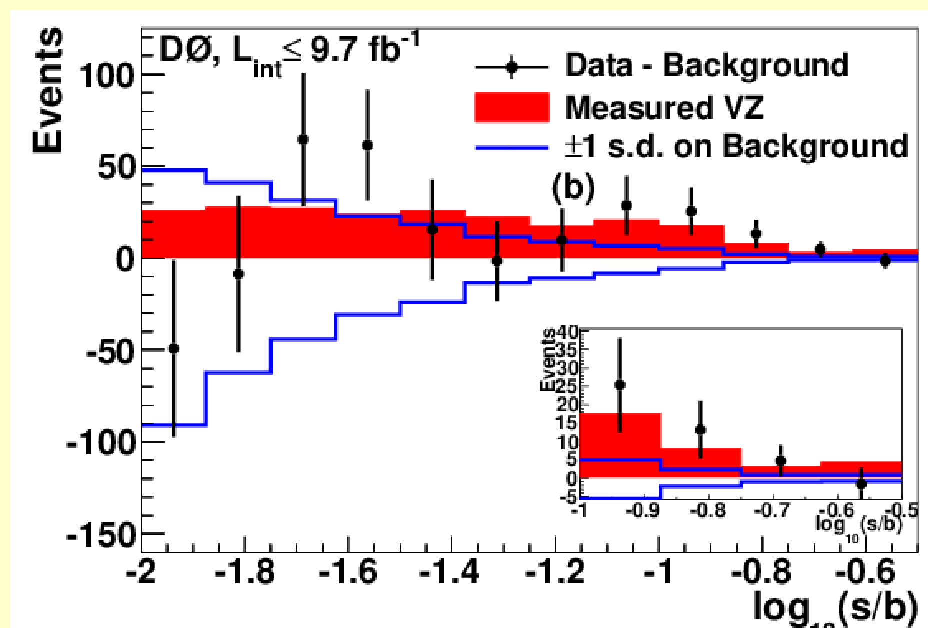


- Measure cross section of the known process with the same final state
  - Smaller cross section for Higgs production (~7 times)
  - Diboson signal peaks at lower masses
- Apply similar analysis
- Measured cross section: (0.73±0.32)*SM

MH = 125 GeV	VH → Vbb [fb]	VZ →Vbb [fb]
vvbb	9	73
lvbb	16	105
llbb	3	24
Total	28	202



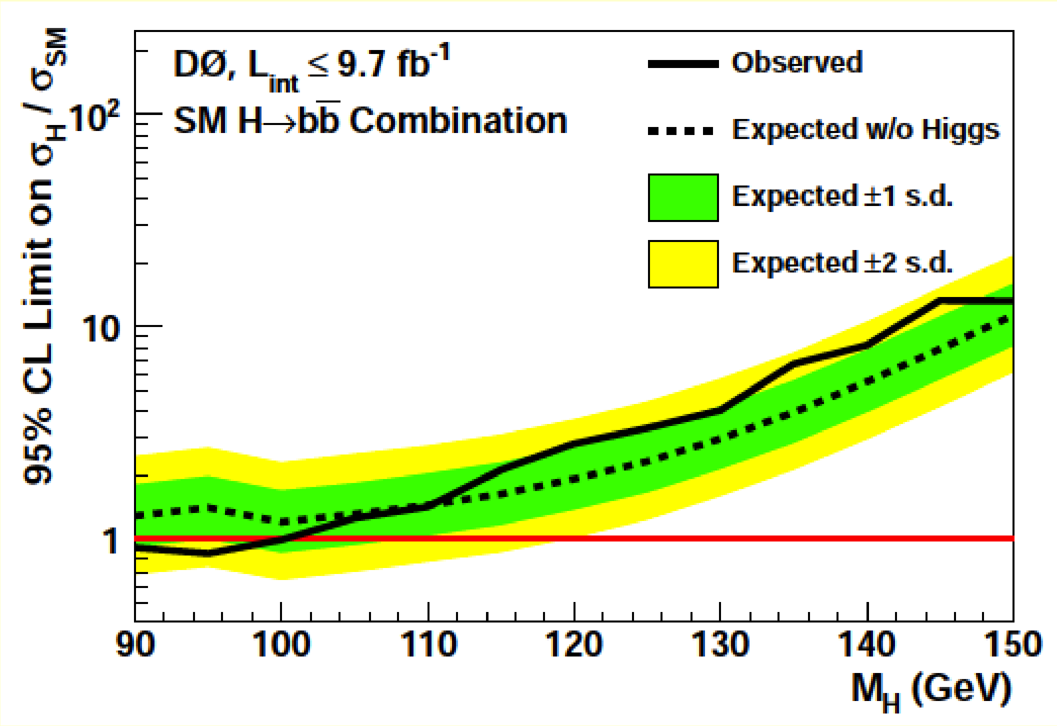


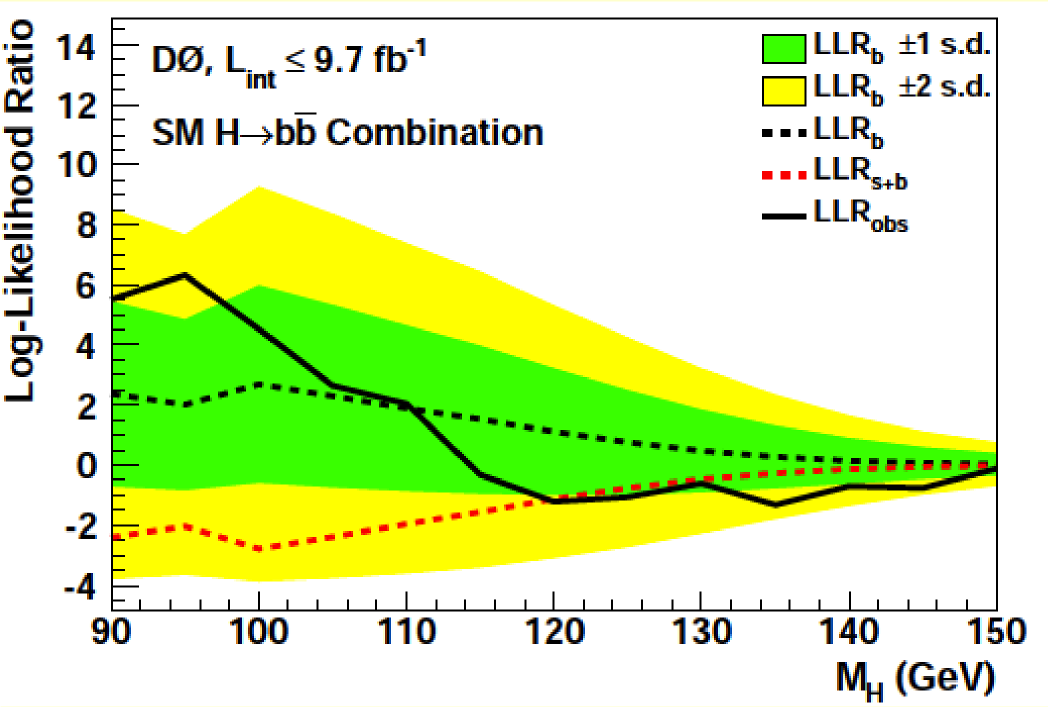


LPNHE PARIS

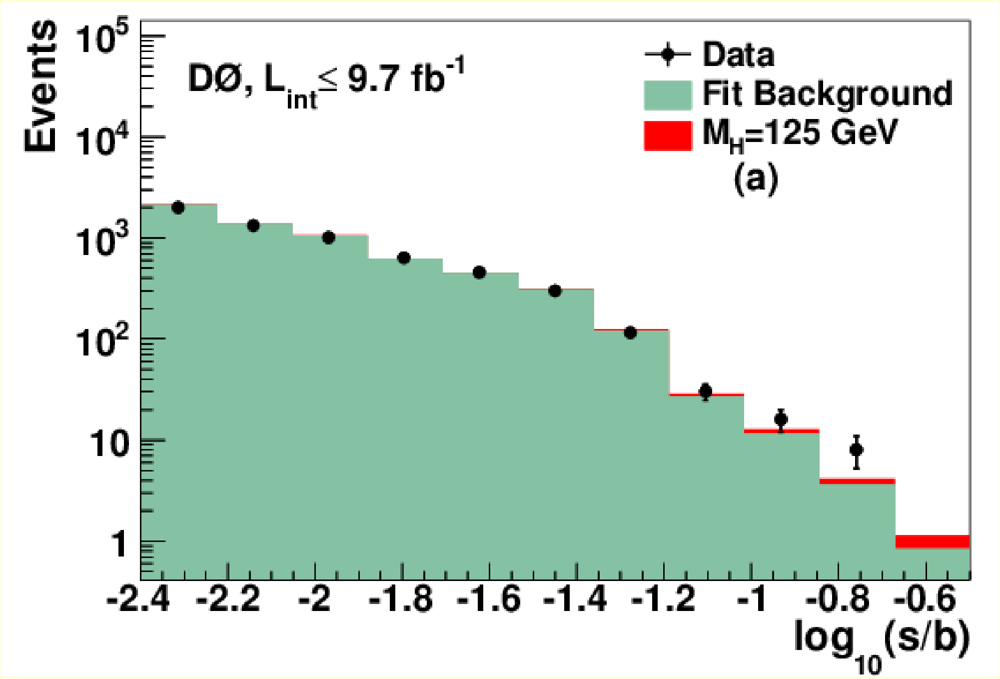
VH → Vbb results

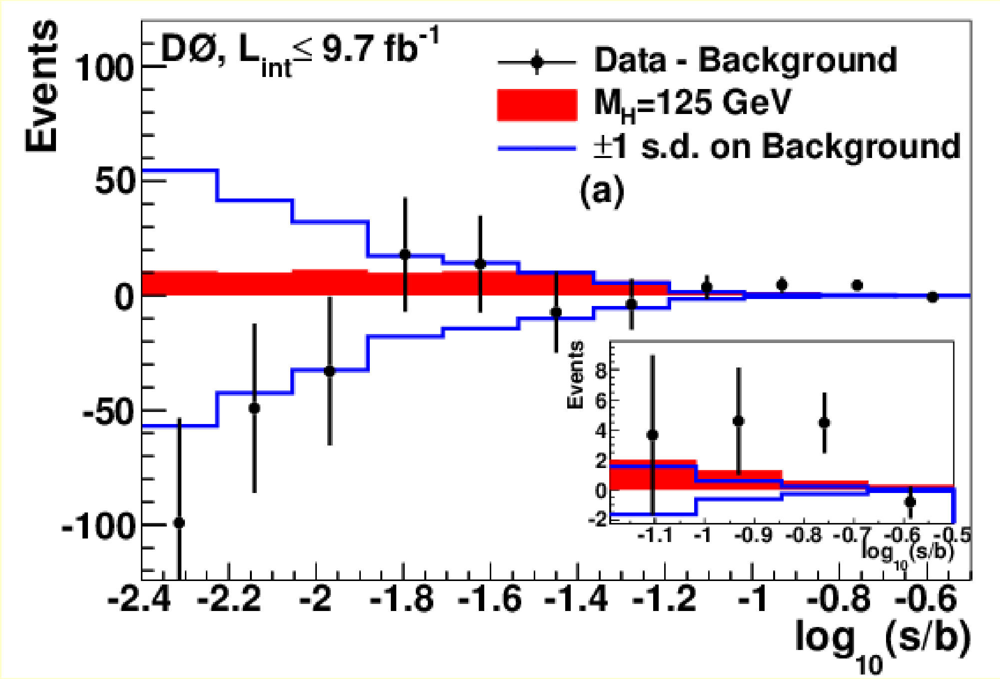
- Expected sensitivity @125 GeV: 2.3*SM; observed 3.5*SM





Combining all D0 channels: What does combined signal look like?



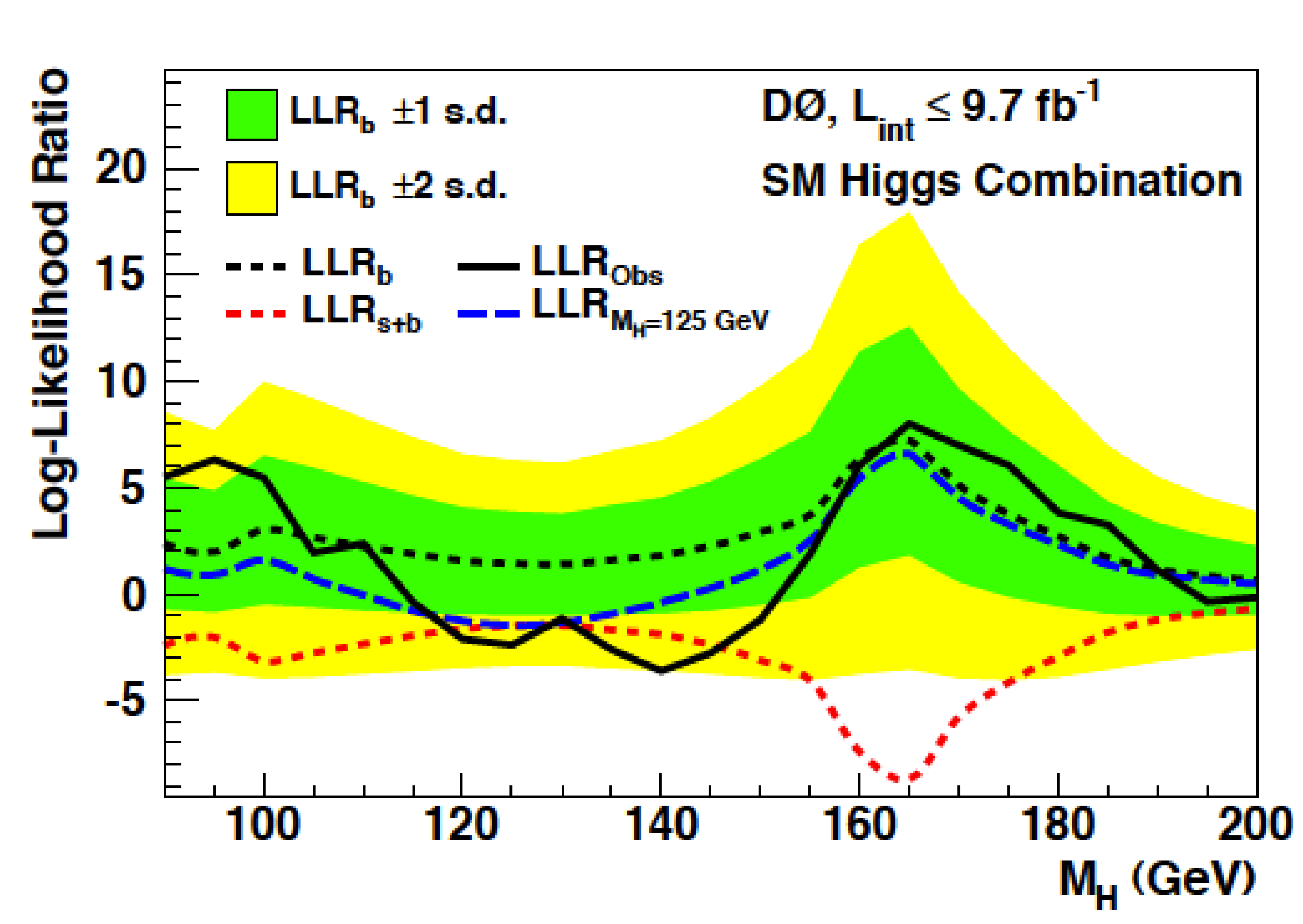


- Distribution of $\log_{10}$(s/b), for the data from all contributing Higgs boson search channels

Sensitivity of the search

Background-like outcomes

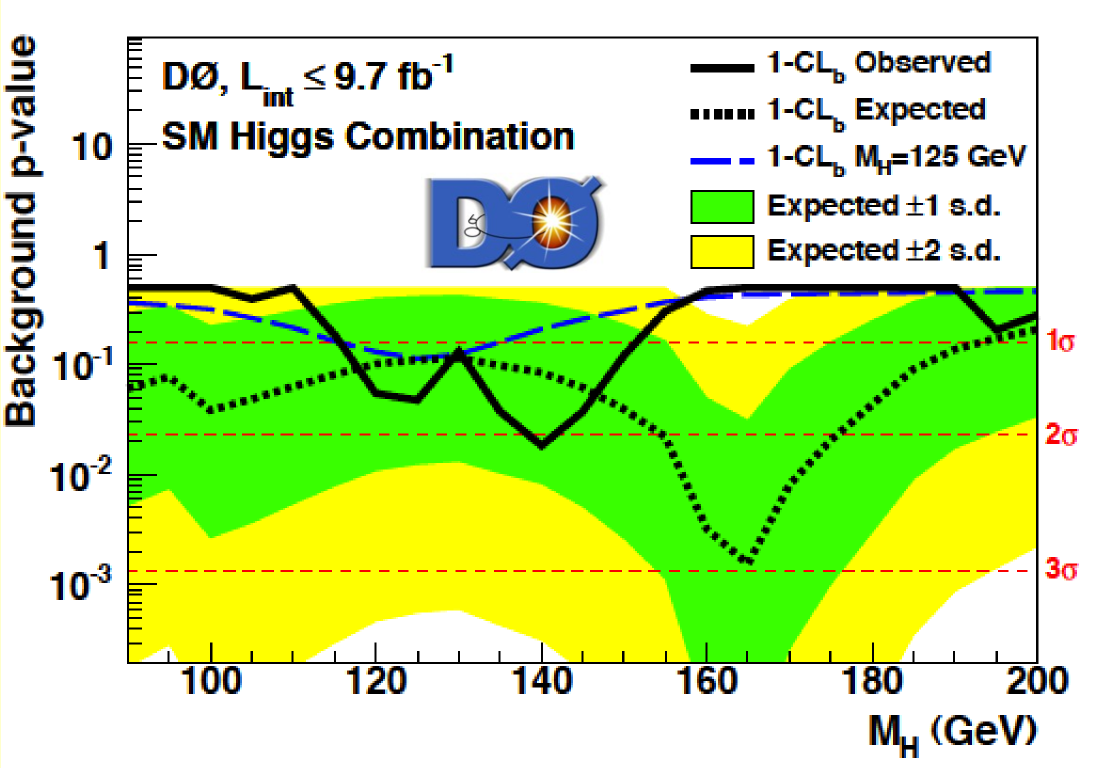
Signal-like outcomes



- Observe a broad excess between ~115 GeV and ~145 GeV consistent with a SM Higgs expectation

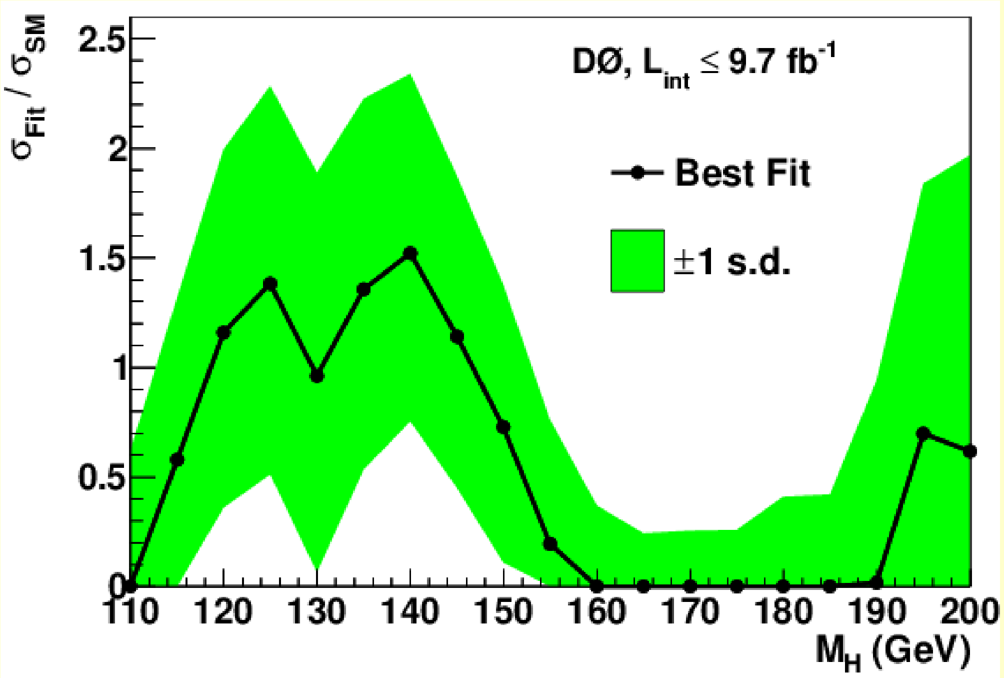
p-value for background hypothesis

- p-value for background hypothesis provides information about the consistency with the observed data
- Local p-value distribution for background only expectation:
  - D0: 1.7 s.d. (@125 GeV)



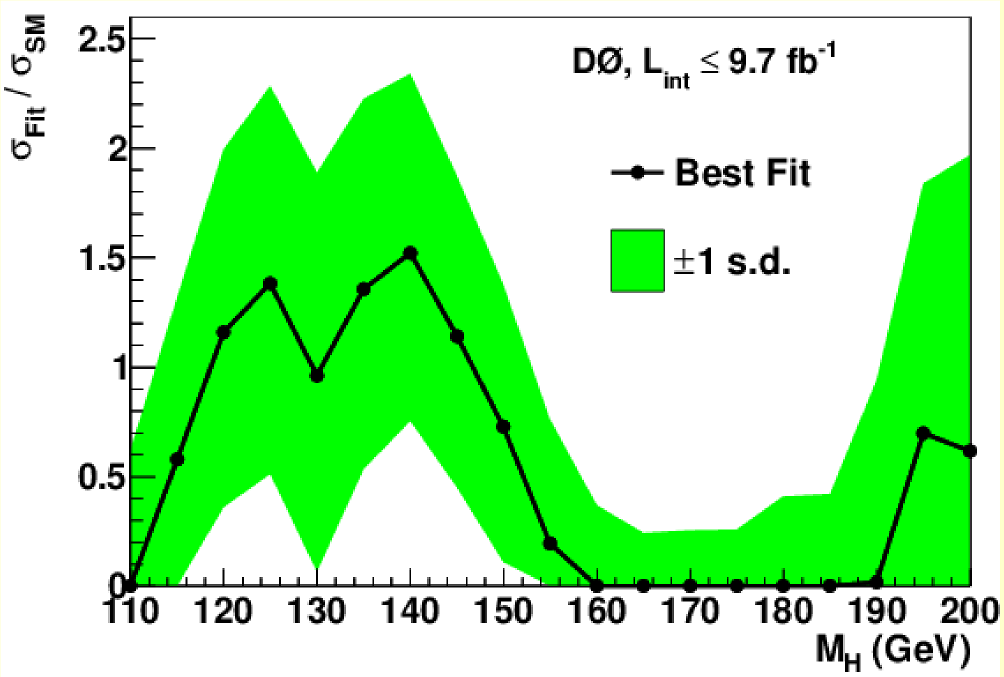
Signal Strength

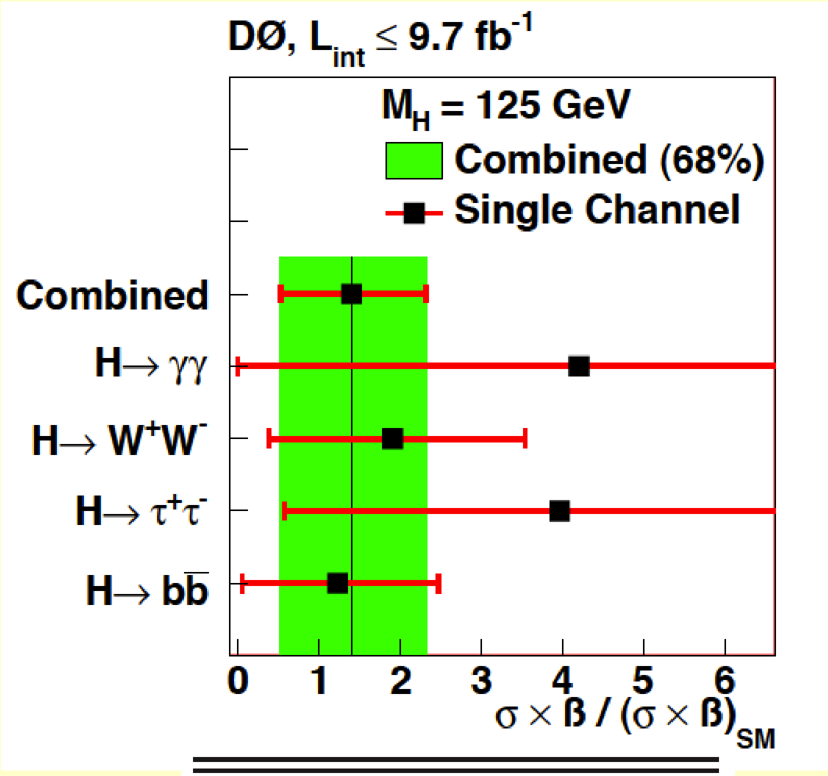
- Best fit for the signal, signal strength, is consistent with SM within 1 s.d.
- @125 GeV: $1.40^{+0.92}_{-0.88}$



Signal Strength

- Best fit for the signal, signal strength, is consistent with SM within 1 s.d.
- @125 GeV: $1.40^{+0.92}_{-0.88}$





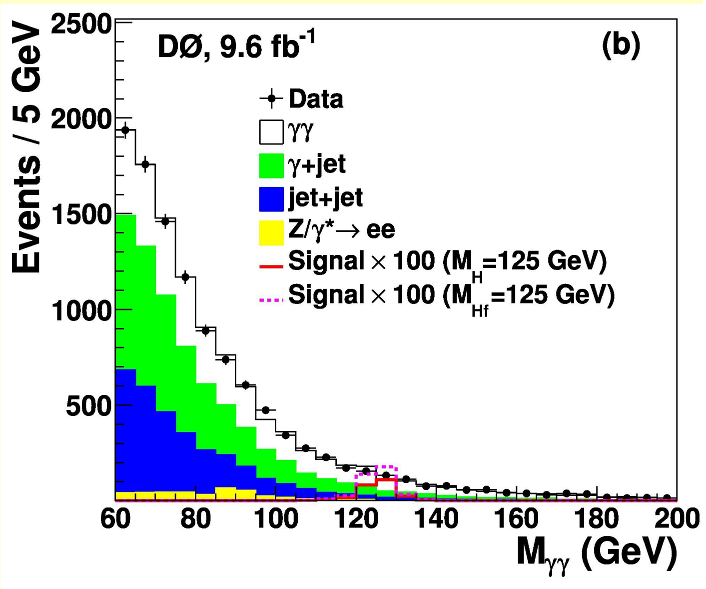
Combined	$1.40^{+0.92}_{-0.88}$
$H \to \gamma\gamma$	$4.20^{+4.60}_{-4.20}$
$H \to W^+W^-$	$1.90^{+1.63}_{-1.52}$
$H \to \tau^+\tau^-$	$3.96^{+4.11}_{-3.38}$
$H \to b\bar{b}$	$1.23^{+1.24}_{-1.17}$

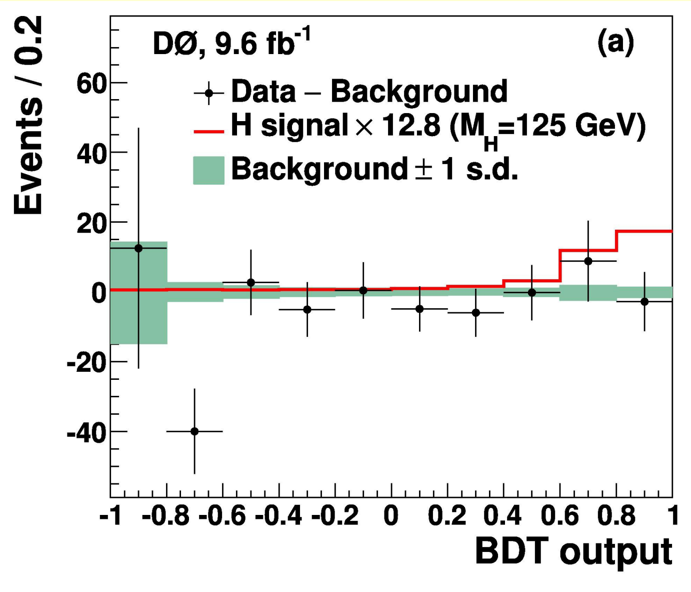
$H \rightarrow \gamma\gamma$

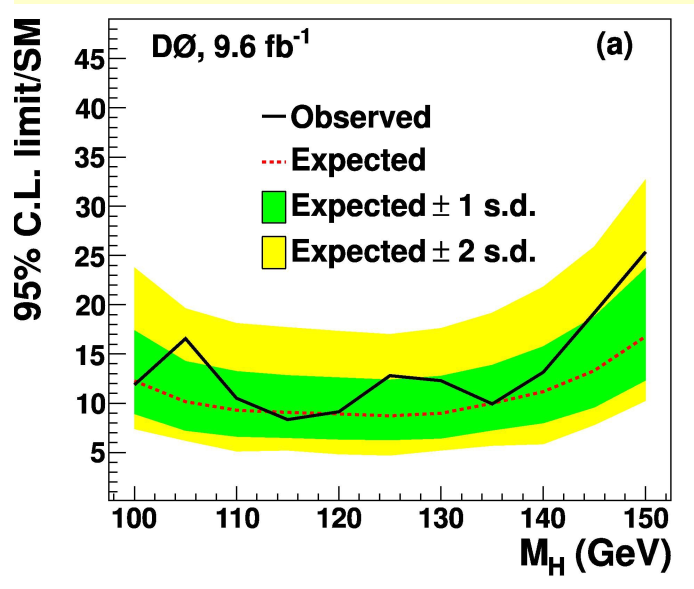
$H \rightarrow \gamma\gamma$

New since ICHEP'12

- Updated data quality requirement
- Narrow resonance on top of a smoothly falling background in the $m_{\gamma\gamma}$ spectrum: Measured mass resolution 3.1 GeV @ m_H=125 GeV
- Multiple stages of MVA:
  - Neural Network to select loose photons, and then to define two independent samples, γ-enriched and jet-enriched
  - Boosted Decision Trees to further separate signal from backgrounds
- Exp. (obs.) sensitivity @125 GeV: 8.7*SM (12.8*SM)





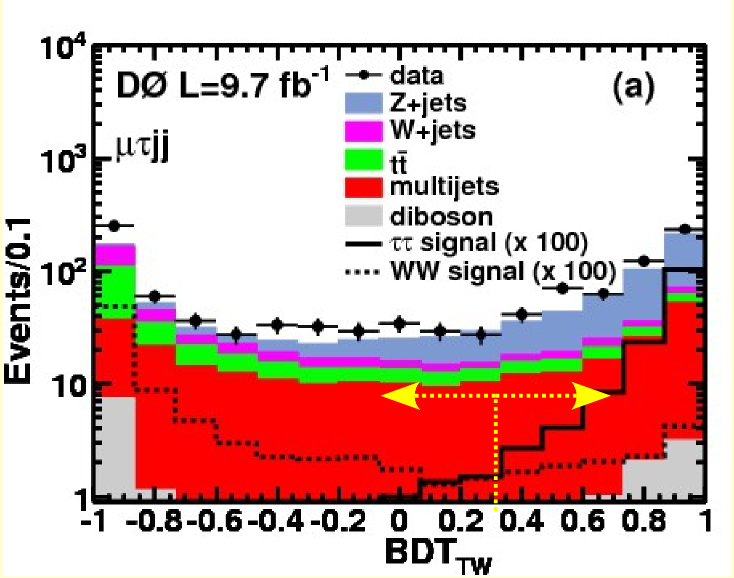


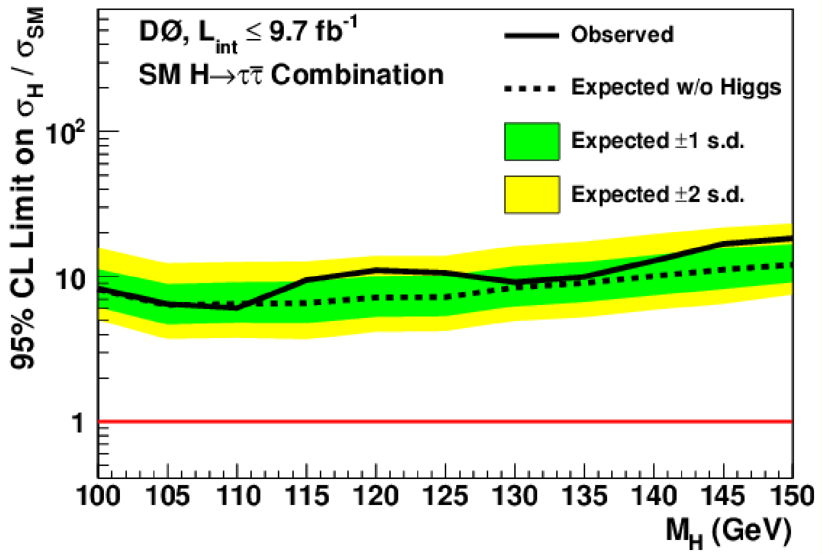
$H \rightarrow \tau\tau$

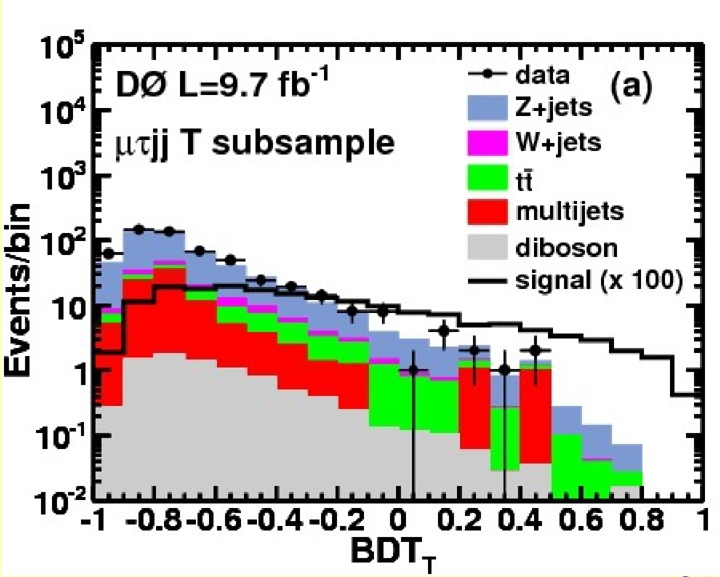
$H \to \tau\tau$

New since ICHEP'12

- Combine analyses with $H \to \tau\tau$:
  - VH → μττ – added ~20% more data, optimized
  - H+X → lτ + 2 jets – added
- They include some contribution from $H \to WW$
  - Use dedicated MVA to separate different contributions
- Exp. (obs.) @125 GeV: 7.25 (10.84)*SM (~60% improvement from ICHEP'12)



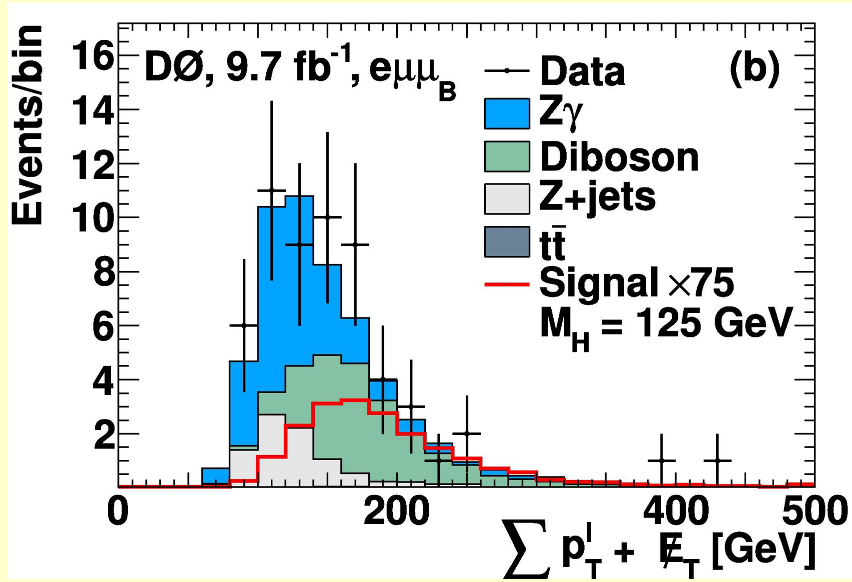


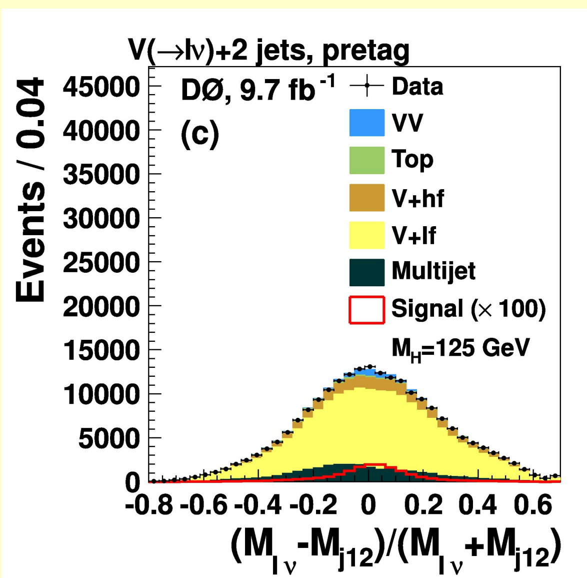


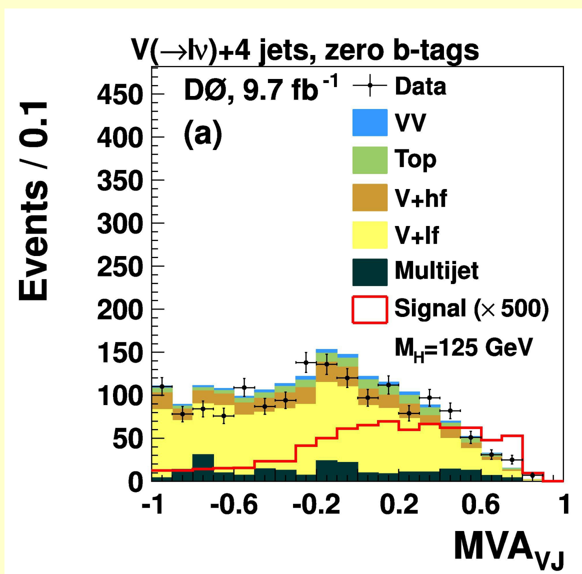
Other H → WW searches

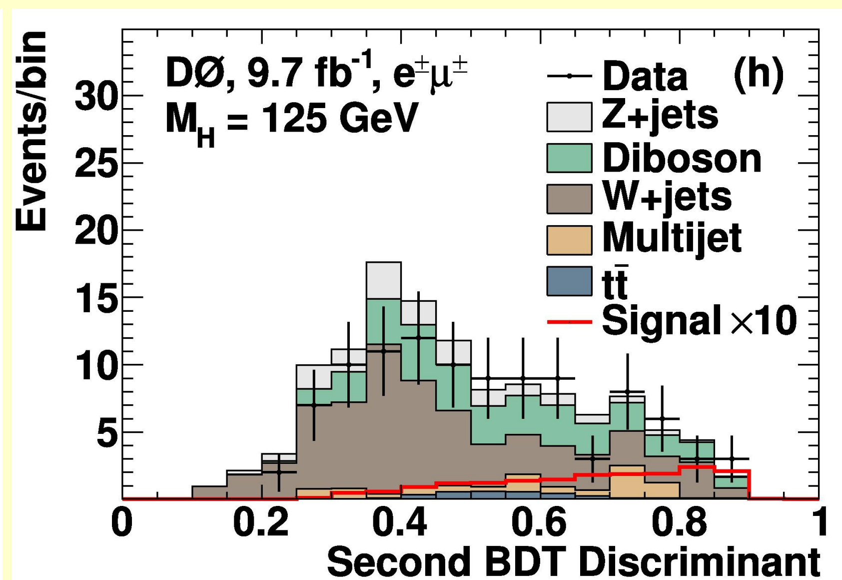
New since ICHEP'12

- Included semileptonic decays of W, and also associated production:
  - $H \to WW \to l\nu jj$ – added ~80% of data
  - $VH \to VWW \to l\nu$+4 jets - optimized
  - $VH \to VVV \to lll$+X – added ~12% of data
  - $VH \to VWW \to e^{\pm}\mu^{\pm}$+X - optimized

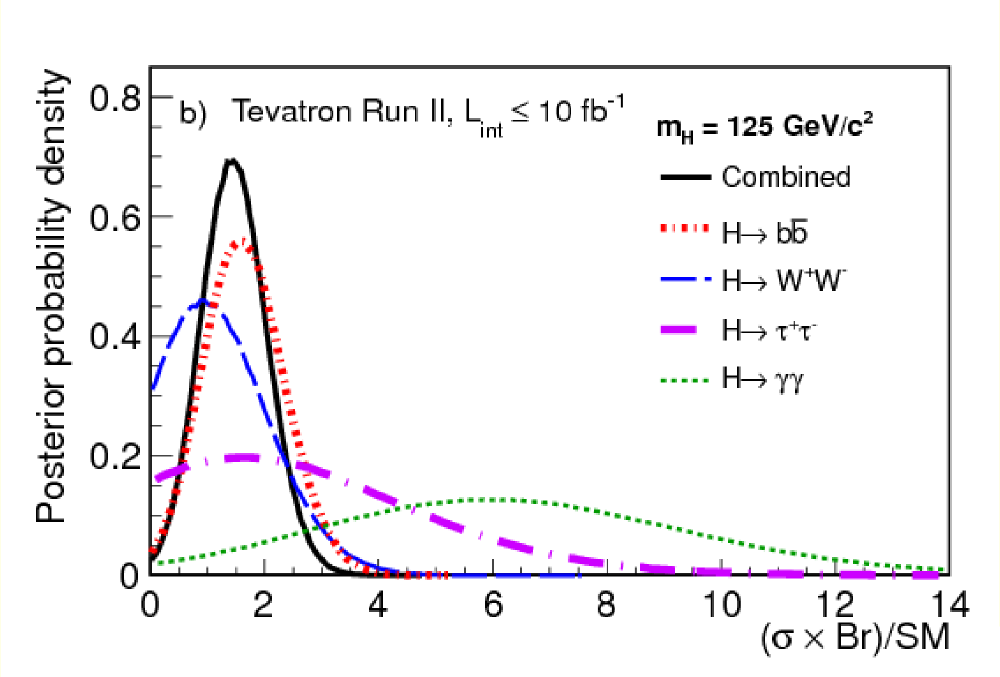


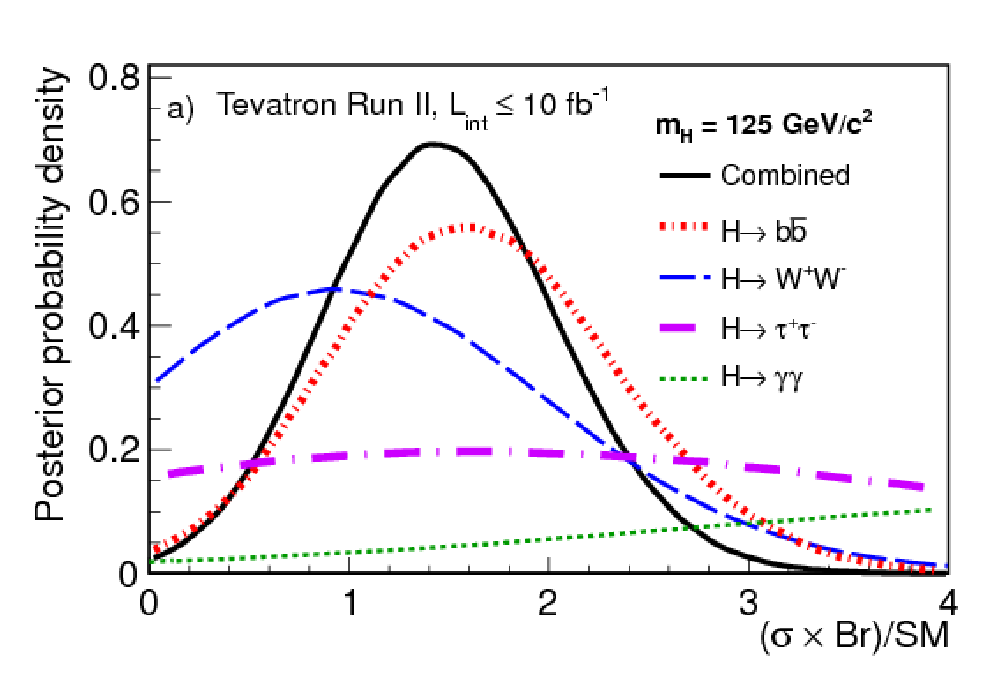


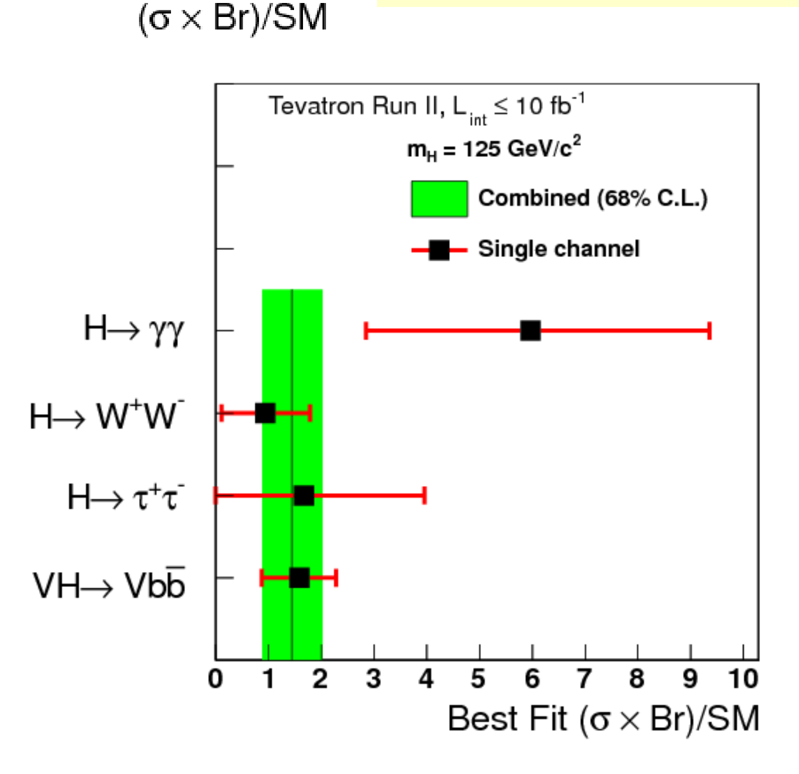




Signal strength for various decays







Comparison of Tev and LHC Methods

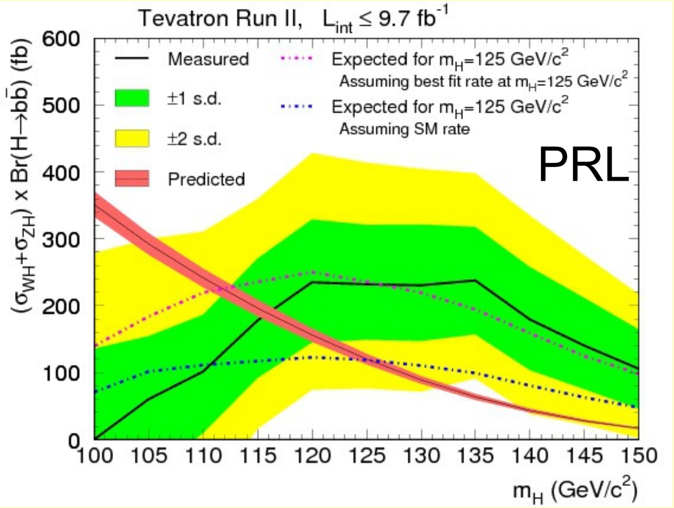
- Signal scaling
  - Tevatron: signals fixed in both hypotheses
    - 2+ normalization does vary when setting 95% C.L. upper limits
    - Exclude $\mu > 0.73$ at 95% C.L. in this case
  - LHC: signals fixed to best fit values in each hypothesis (need not be equal)
- Systematic uncertainties
  - Tevatron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

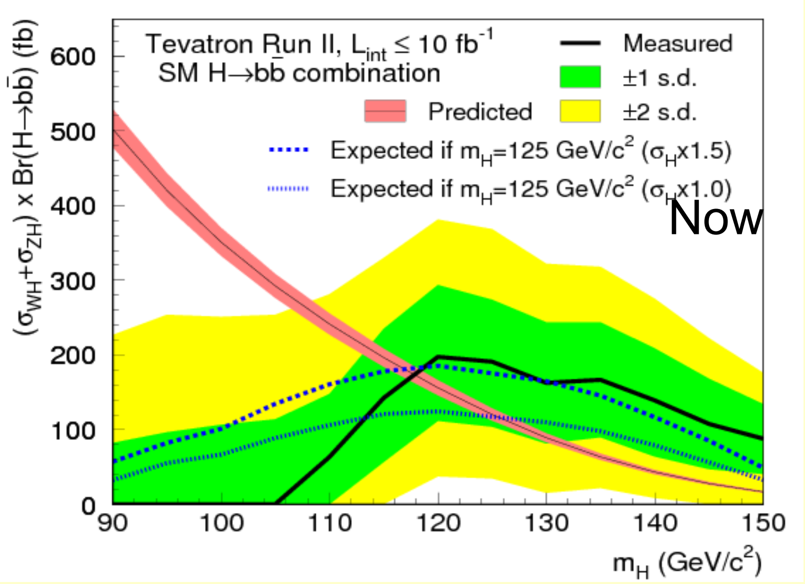
- Allow systematic uncertainties to vary in pseudoexperiments
- (LHC first fits signals to data for normalization, thereby constraining systematics)

Tevatron H→bb Results
PRL 109,071804(2012)

- Last Summer:
  - σ_{VH}=0.23±0.09 pb (SM: 0.12±0.01pb) @125 GeV

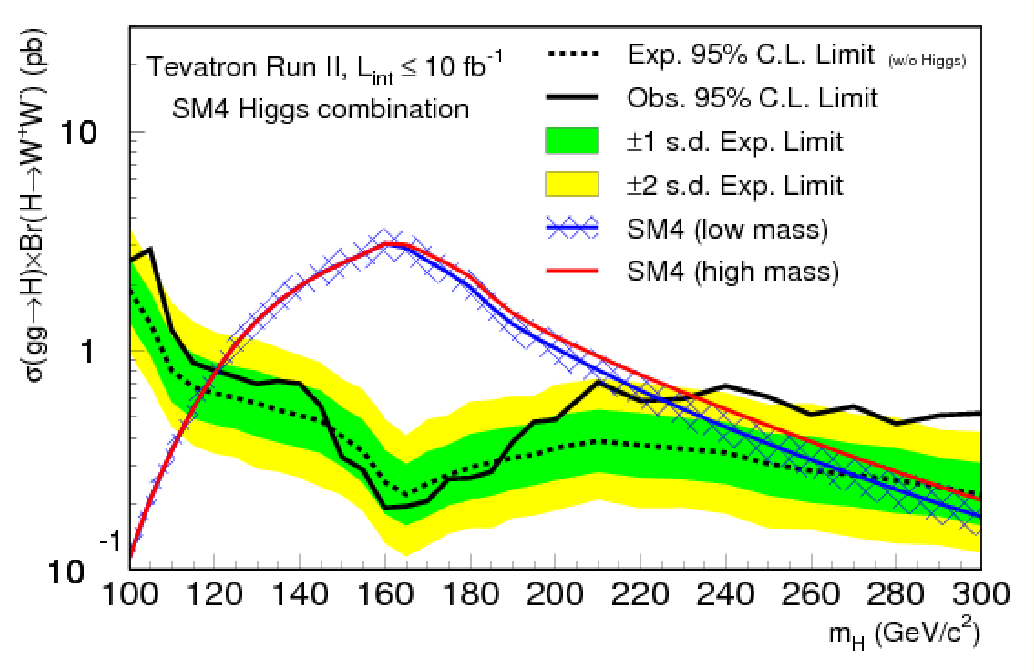
- Now:
  - σ_{VH}=0.19+-0.09 pb, consistent with the summer results
  - The shift in this result is due to the updated ZH → vvbb analysis from CDF and corresponds to a change in the central value of 0.6 times the total uncertainty, consistent with the difference expected given the observed changes in the CDF ZH → vvbb

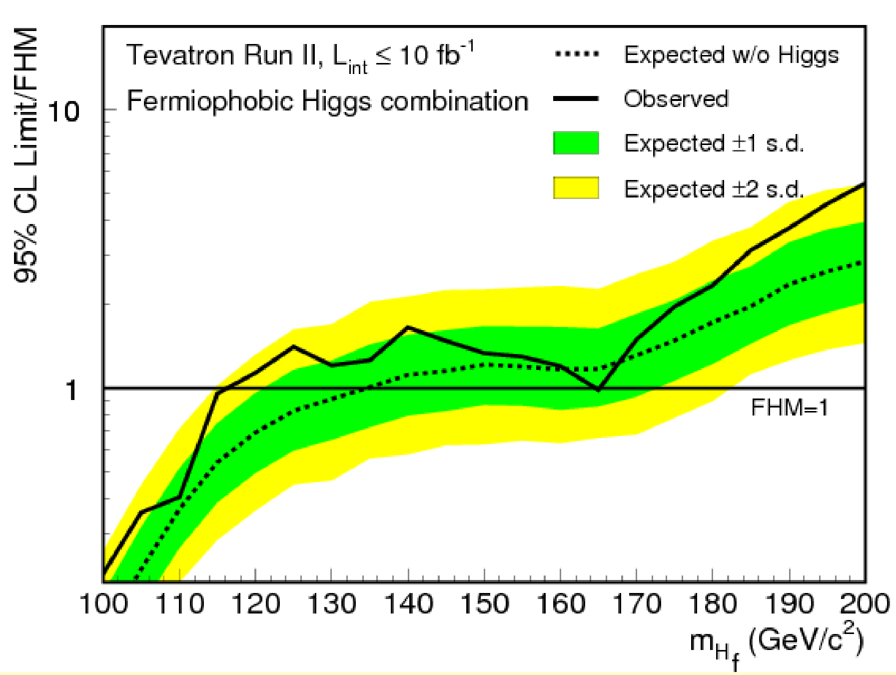




Interpretation in non SM

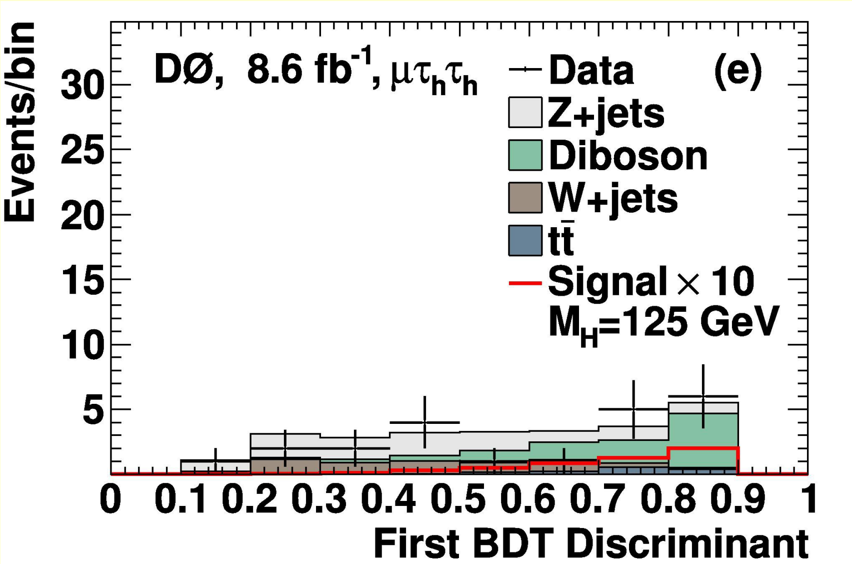
- a
- a

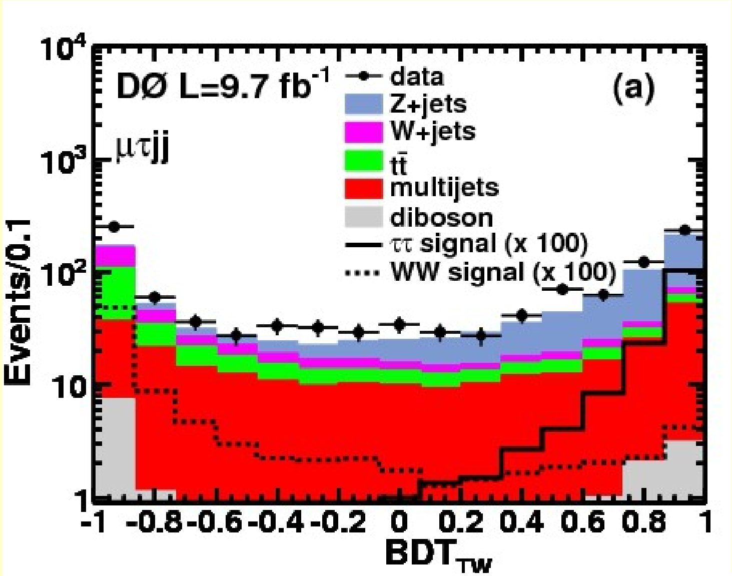


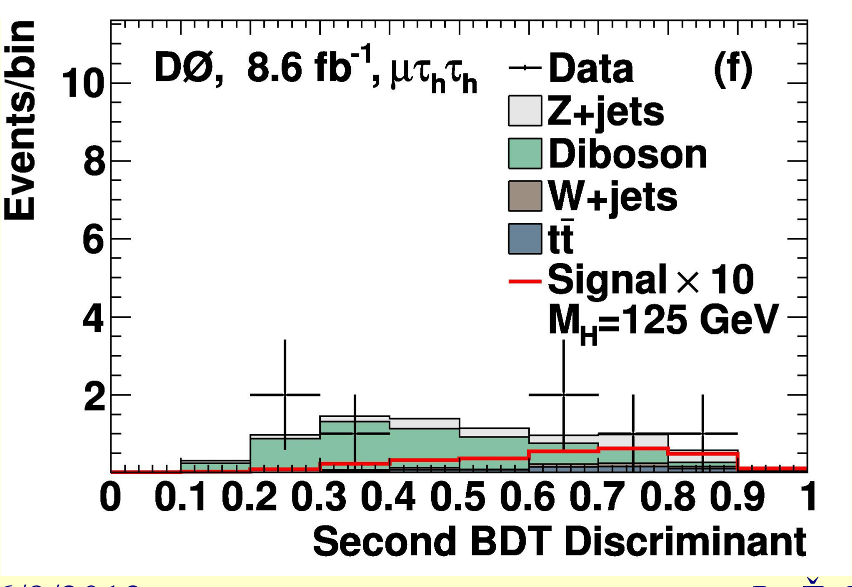


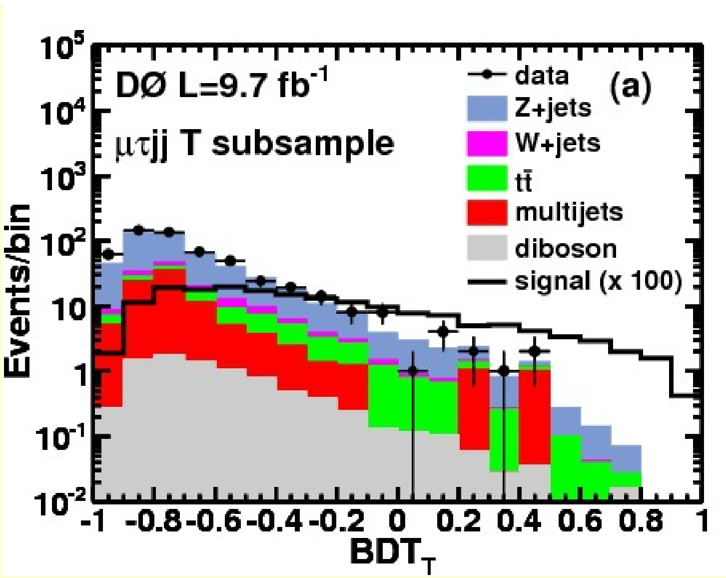
H->tautau

- a


DØ, 8.6 fb^{-1}, $\mu\tau_h\tau_h$
(e)
Data
Z+jets
Diboson
W+jets
$t\bar{t}$
Signal × 10
M_H=125 GeV
Events/bin
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
First BDT Discriminant


DØ L=9.7 fb^{-1}
(a)
$\mu\tau jj$
data
Z+jets
W+jets
$t\bar{t}$
multijets
diboson
$\tau\tau$ signal (x 100)
WW signal (x 100)
Events/0.1
BDT_{TW}


DØ, 8.6 fb^{-1}, $\mu\tau_h\tau_h$
(f)
Data
Z+jets
Diboson
W+jets
$t\bar{t}$
Signal × 10
M_H=125 GeV
Events/bin
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Second BDT Discriminant


DØ L=9.7 fb^{-1}
(a)
$\mu\tau jj$ T subsample
data
Z+jets
W+jets
$t\bar{t}$
multijets
diboson
signal (x 100)
Events/bin
BDT_T

Systematics

- Luminosity: 6.1%
- b-tagging rate: 1-10%
- JES and JER ~7%
- Lepton id and similar: 1-9%
- Simulated backgrounds cross sections 4-30%
- MJ background 10-30%

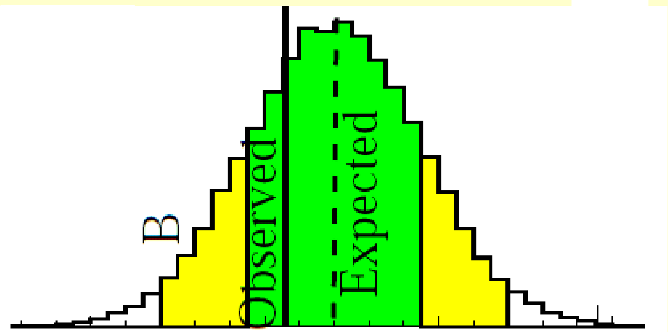
An example of limits settings

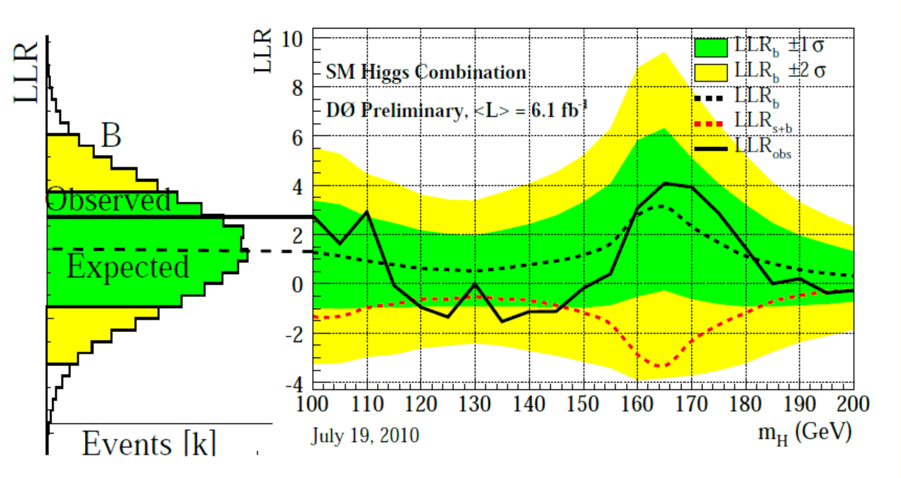
- Compare Poisson likelihood of B hypothesis to S+B hypothesis, and calculate their negative log likelihood ratio (LLR):

$L(B)$	$L(S+B)$	LLR
$\prod_i \frac{b_i^{d_i} \exp(b_i)}{d_i!}$	$\prod_i \frac{(s_i+b_i)^{d_i} \exp(s_i+b_i)}{d_i!}$	$2 \cdot \sum_i s_i - d_i \cdot \log(1+s_i/b_i)$

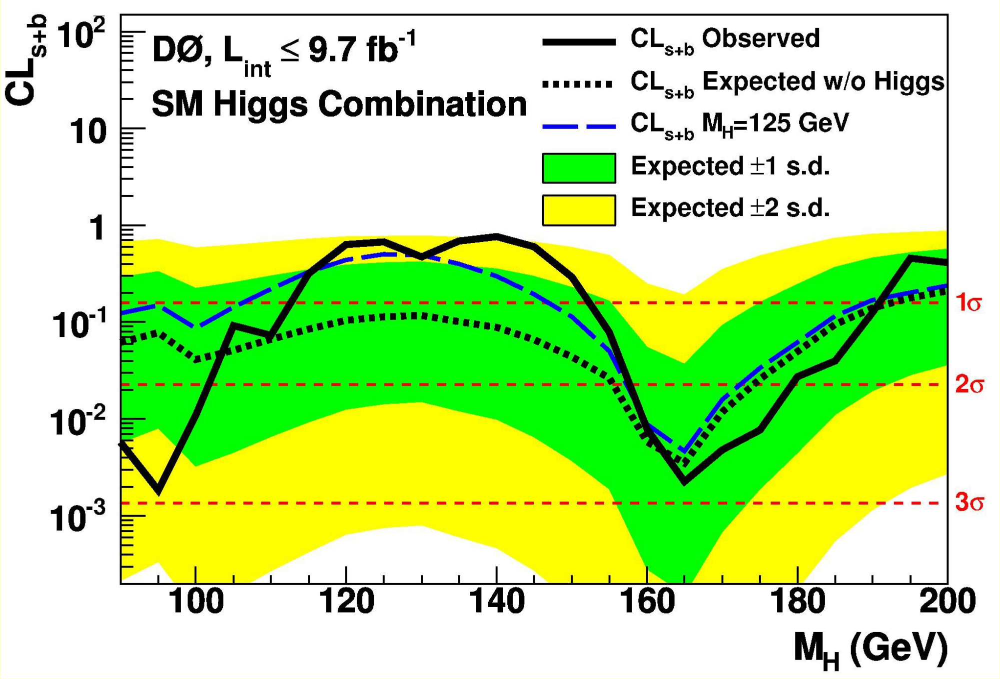
d_i events observed in bin i with S and B expectations s_i and b_i.

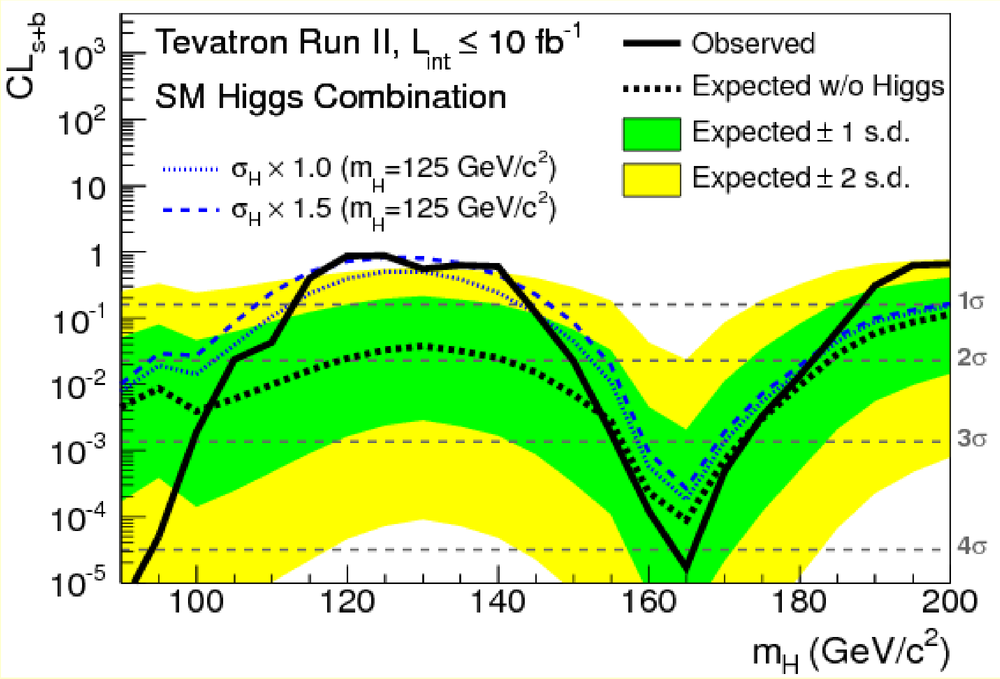
- Sum over all bins gives observed LLR
- Repeat calculation but with pseudo-data obtained by a Poisson fluctuation of b_i in each bin (B) or s_i+b_i in each bin (S+B)
- Repeat many times to obtain LLR distribution: median is Expected LLR





S+B p-values


DØ, $L_{int} \leq 9.7\ fb^{-1}$
SM Higgs Combination
CL_{s+b} Observed
CL_{s+b} Expected w/o Higgs
CL_{s+b} M_H=125 GeV
Expected ±1 s.d.
Expected ±2 s.d.
CL_{s+b}
M_H (GeV)
1σ
2σ
3σ


Tevatron Run II, $L_{int} \leq 10\ fb^{-1}$
SM Higgs Combination
$\sigma_H \times 1.0$ (m_H=125 GeV/c^2)
$\sigma_H \times 1.5$ (m_H=125 GeV/c^2)
Observed
Expected w/o Higgs
Expected ± 1 s.d.
Expected ± 2 s.d.
CL_{s+b}
m_H (GeV/c^2)
1σ
2σ
3σ
4σ