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Overview of the Higgs boson studies at Tevatron

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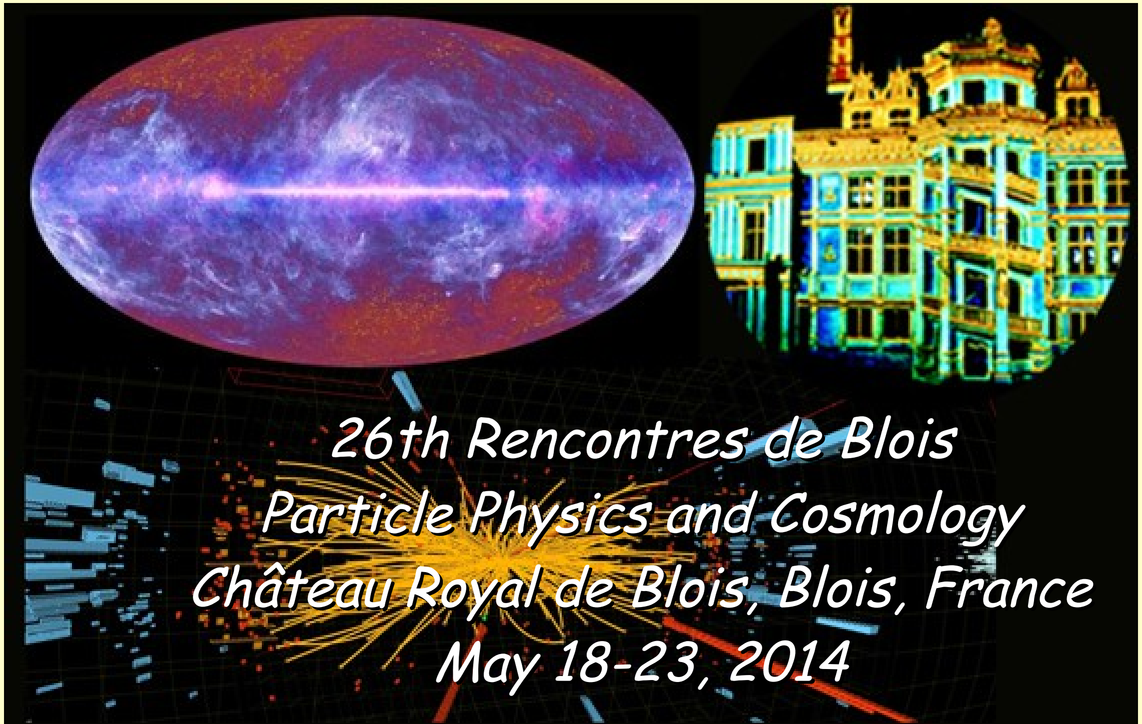
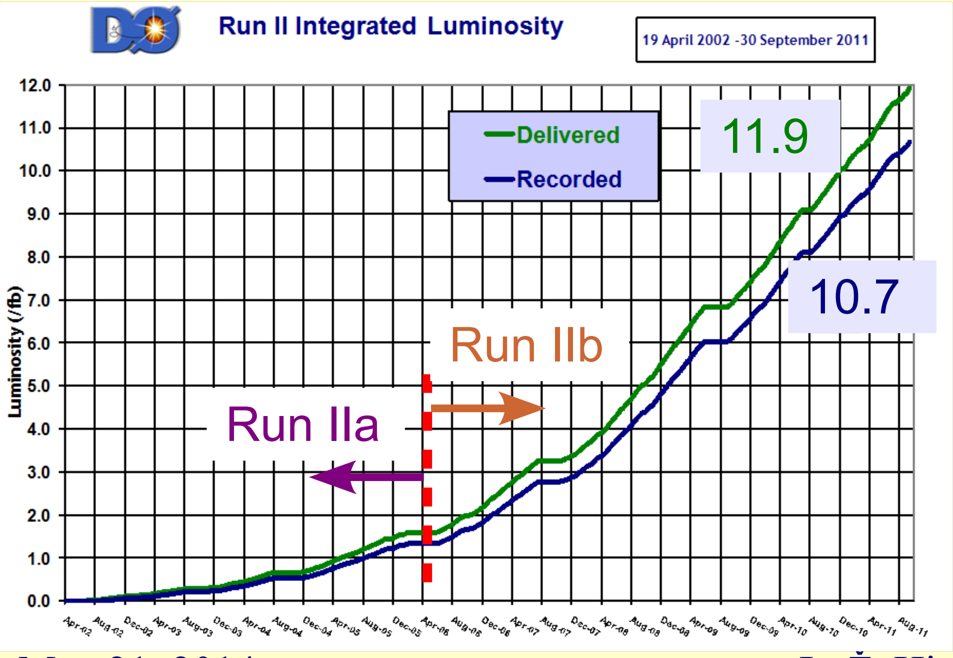
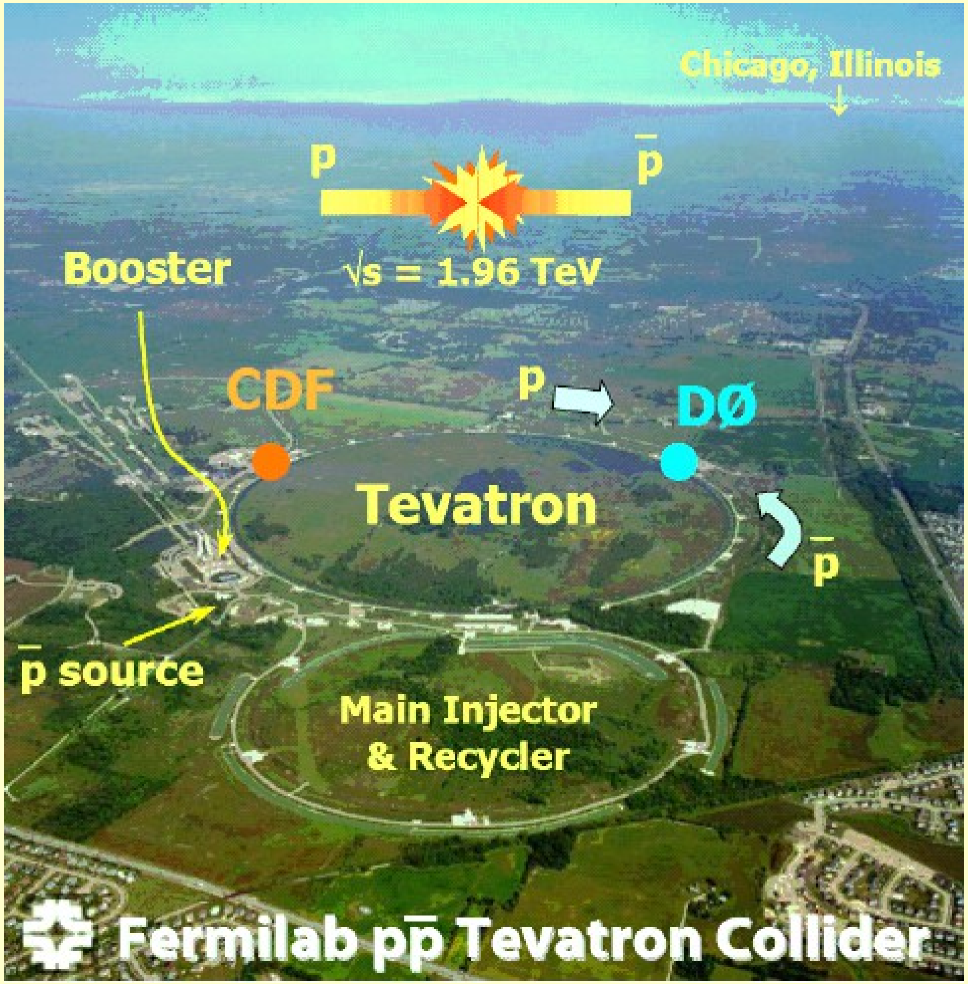
On a behalf of CDF and DØ collaborations



Outline

- Brief analyses overview
- Tevatron results
  - Combined results
  - Constraints on couplings
- Spin/parity studies

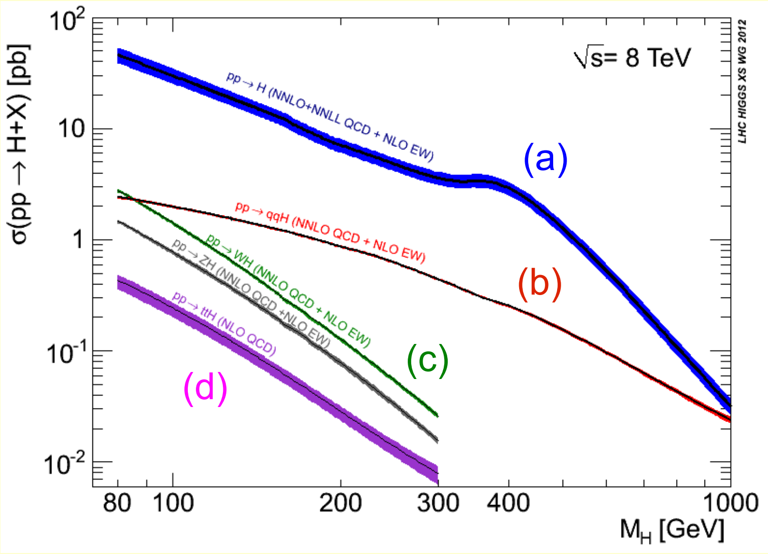


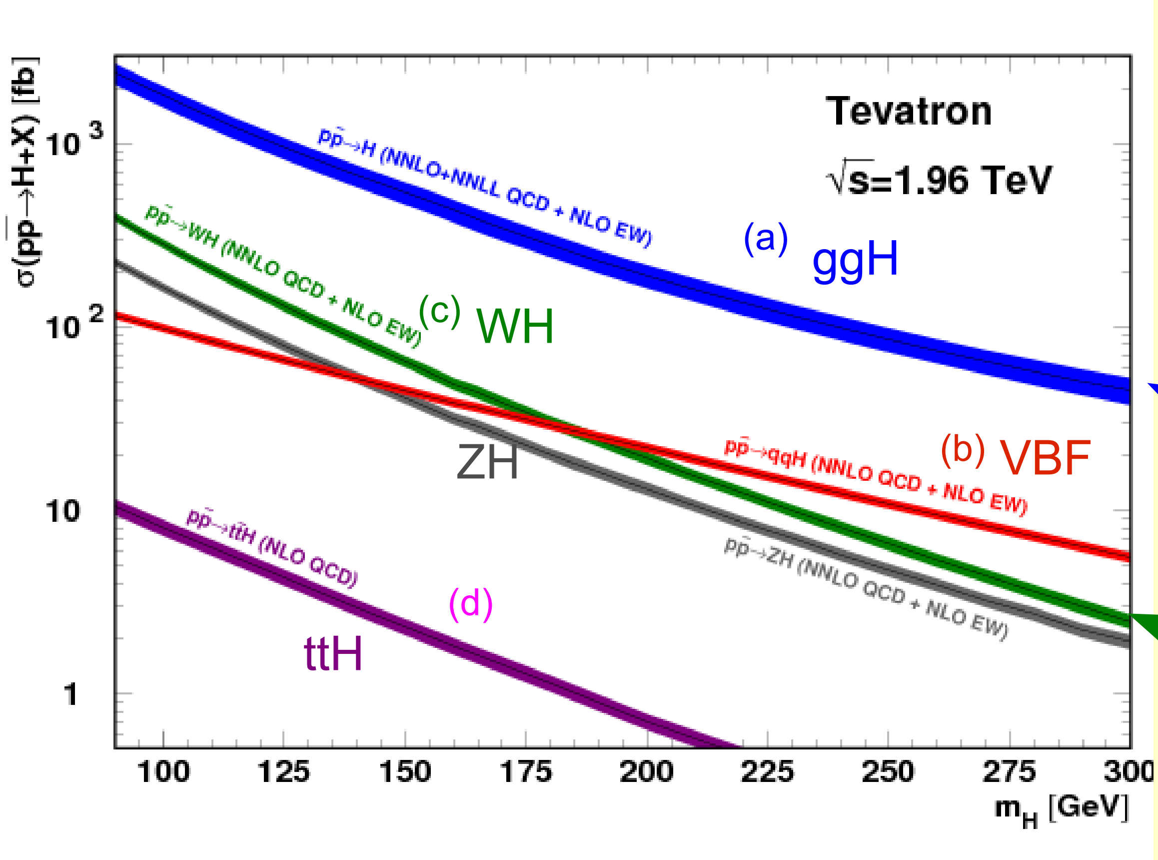


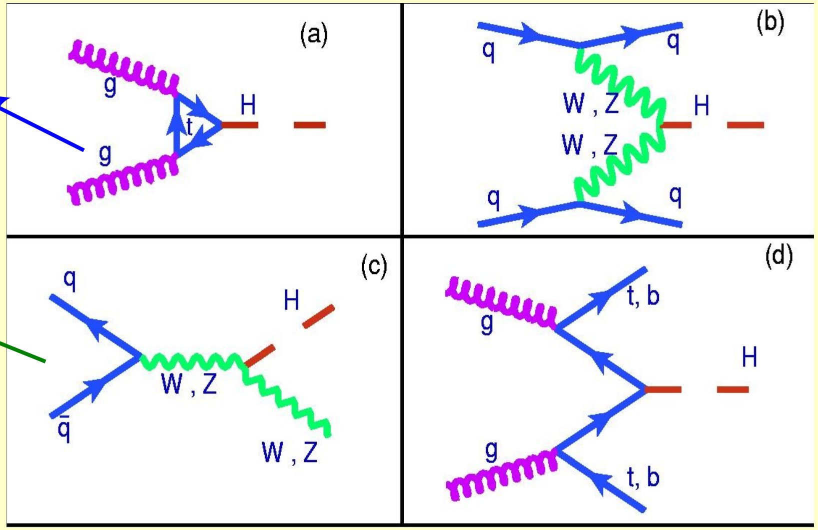
Production at Tevatron ...

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

Different from LHC



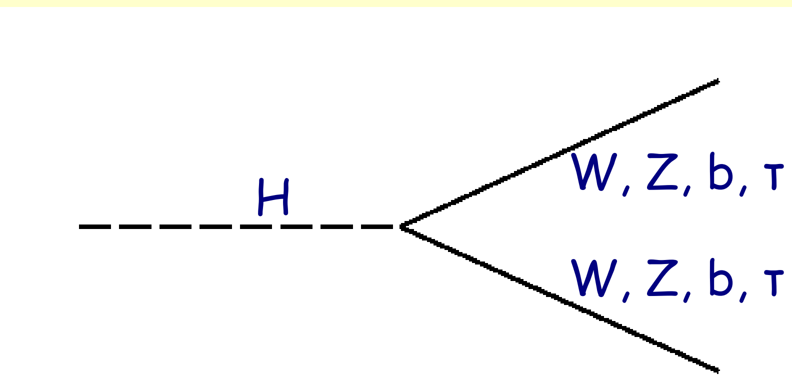


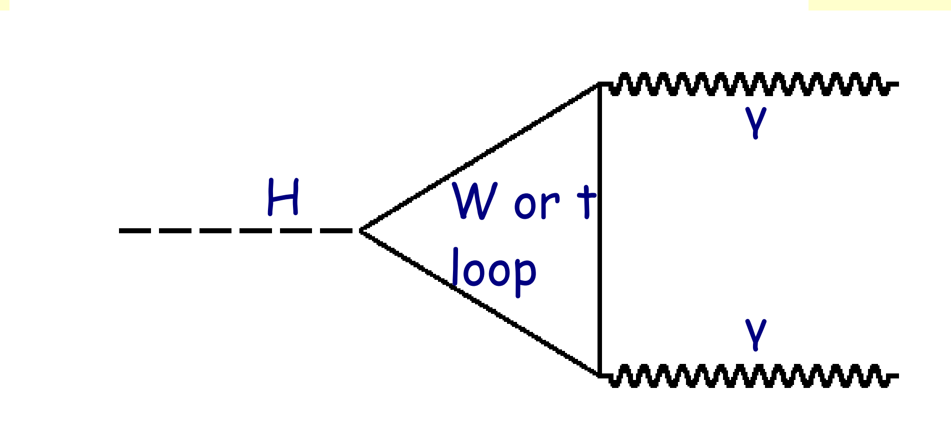


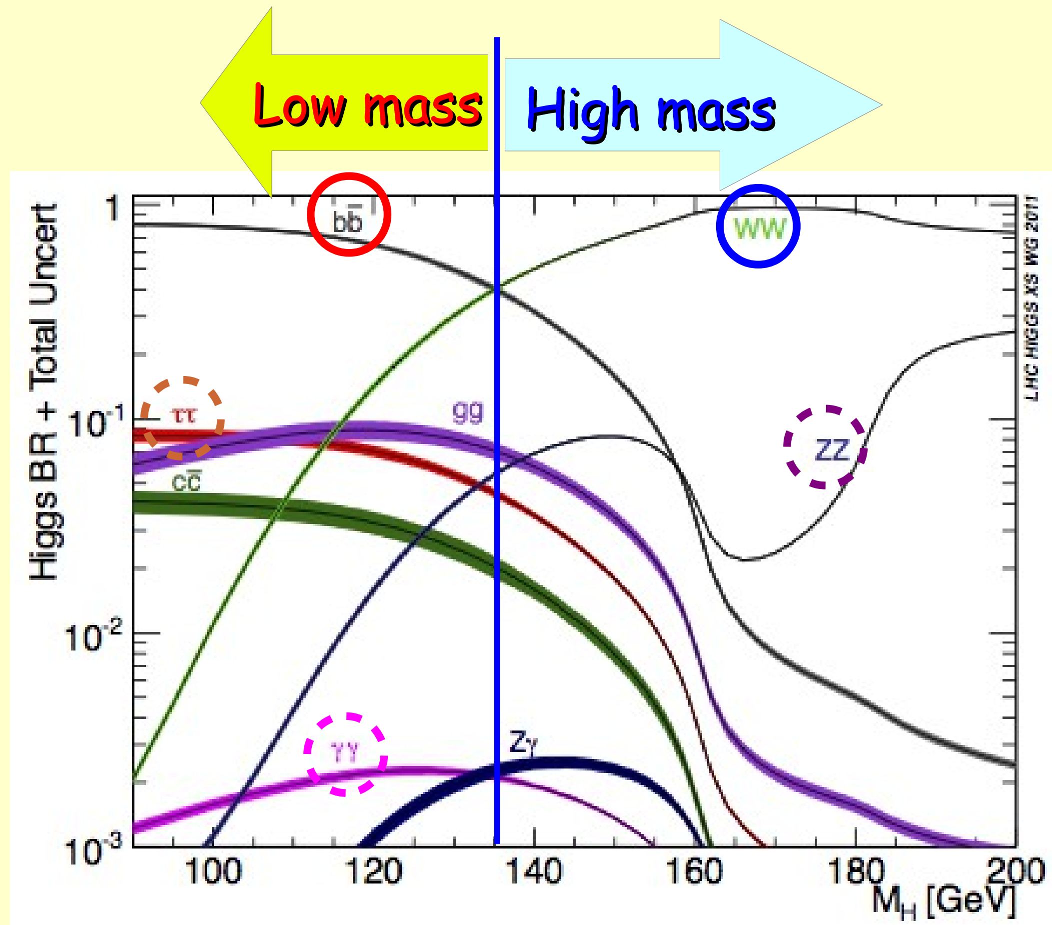
... and Decay

- Dominant decay to:
  - $b\bar{b}$ for $m_H < 135$ GeV (57% @125 GeV)
  - WW for $m_H > 135$ GeV (22% @125 GeV)

γγ and ZZ are discovery channels @LHC







Overview of the searches from Tevatron

DØ	Luminosity (fb^{-1})	M_H (GeV)	Reference
$WH \to \ell\nu bb$	9.7	90–150	Phys. Rev. Lett. 109, 121804 (2012) and Phys. Rev. D 88, 052008 (2013)
$ZH \to \ell\ell b\bar{b}$	9.7	90–150	Phys. Rev. Lett. 109, 121803 (2012) and Phys. Rev. D 88, 052010 (2013)
$ZH \to \nu\bar{\nu}b\bar{b}$	9.5	100–150	Phys. Lett. B 716, 285 (2012)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	9.7	100–200	Phys. Rev. D 88, 052006 (2013)
$H + X \to WW \to \mu^\pm\tau_h^\mp + \leq 1\text{jet}$	7.3	155–200	Phys. Lett. B 714, 237 (2012)
$H \to W^+W^- \to \ell\nu q'\bar{q}$	9.7	100–200	Phys. Rev. D 88, 052008 (2013)
$VH \to ee\mu/\mu\mu e + X$	9.7	100–200	Phys. Rev. D 88, 052009 (2013)
$VH \to e^\pm\mu^\pm + X$	9.7	100–200	Phys. Rev. D 88, 052009 (2013)
$VH \to \ell\nu q'\bar{q}q'\bar{q}$	9.7	100–200	Phys. Rev. D 88, 052008 (2013)
$VH \to \tau_h\tau_h\mu + X$	8.6	100–150	Phys. Rev. D 88, 052009 (2013)
$H + X \to \ell\tau_h jj$	9.7	105–150	Phys. Rev. D 88, 052005 (2013)
$H \to \gamma\gamma$	9.7	100–150	Phys. Rev. D 88, 052007 (2013)
CDF			
$WH \to \ell\nu bb$	9.45	90–150	Phys. Rev. Lett. 109, 111804 (2012)
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$H \to \tau\tau$	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 072012 (2012)
$t\bar{t}H \to WWb\bar{b}b\bar{b}$	9.45	100–150	Phys. Rev. Lett. 109 181802 (2012)
$VH \to jjb\bar{b}$	9.45	100–150	JHEP 1302 004 (2013)

- CDF combination:
  H → bb:
  - Phys. Rev. Lett. 109, 111802 (2012)
  All channels:
  - Phys. Rev. D88 052013 (2013)
- D0 combination:
  H → bb:
  - Phys. Rev. Lett. 109, 121802 (2012)
  All channels:
  - Phys. Rev. D 88, 052011 (2013)

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Tevatron combination: Phys. Rev. D 88, 052014 (2013)

All latest papers are in a single issue of PRD

CDF			
$ZH \to \ell\ell b\bar{b}$	9.45	90–150	Phys. Rev. Lett. 109, 111803 (2012)
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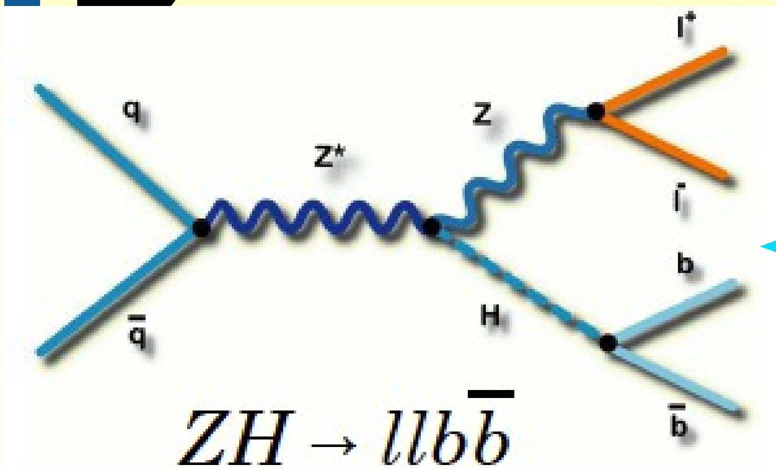
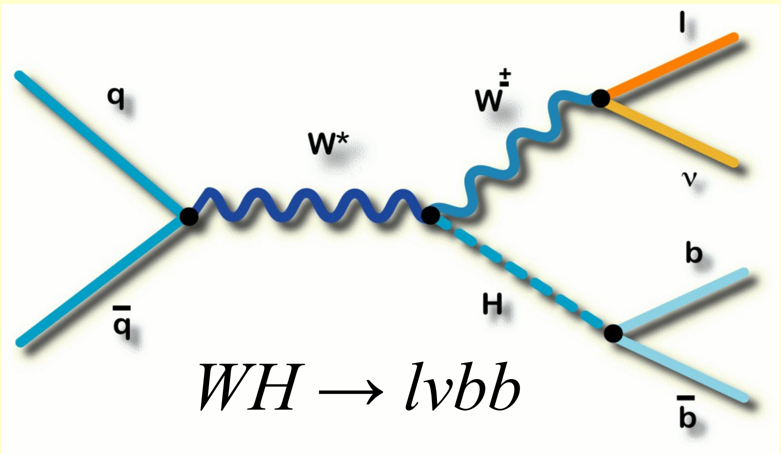
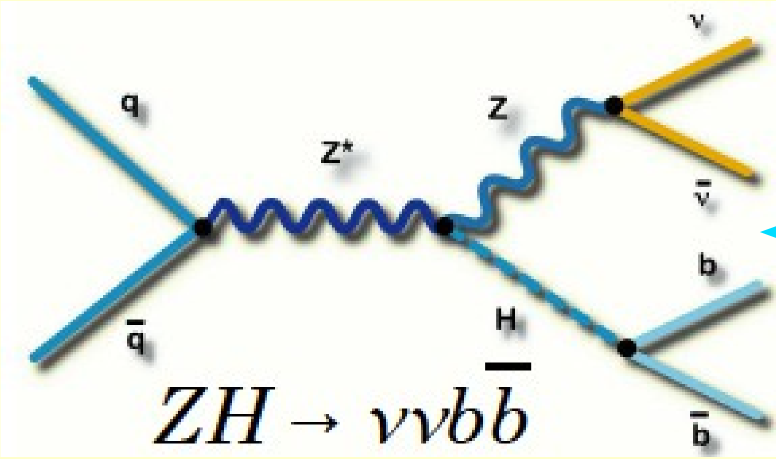
VH → Vbb



- 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

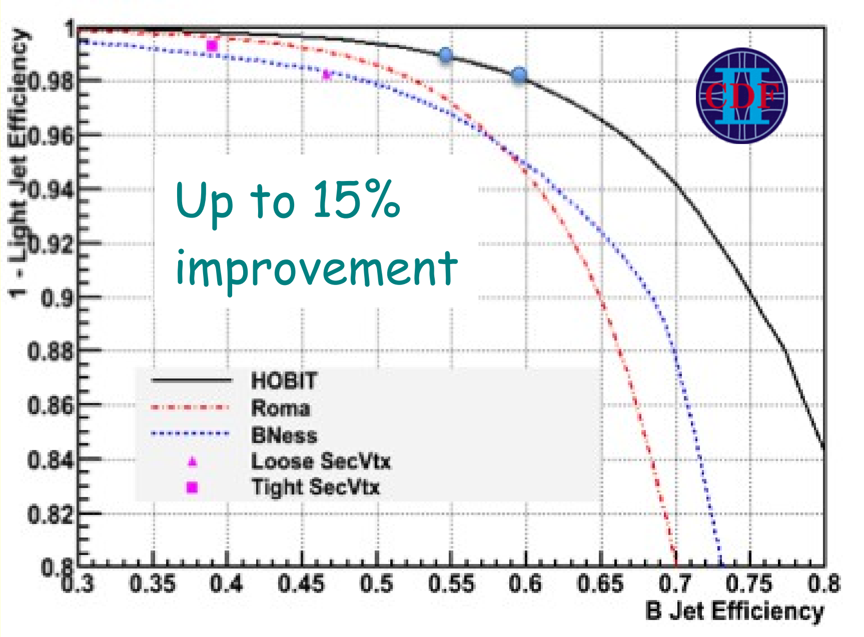


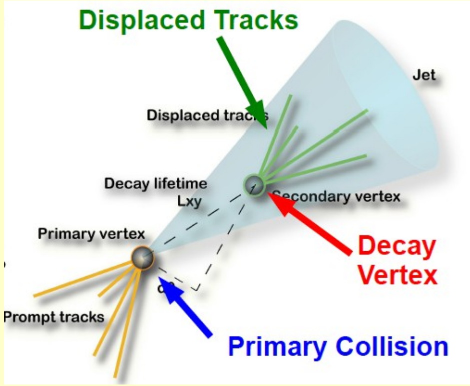


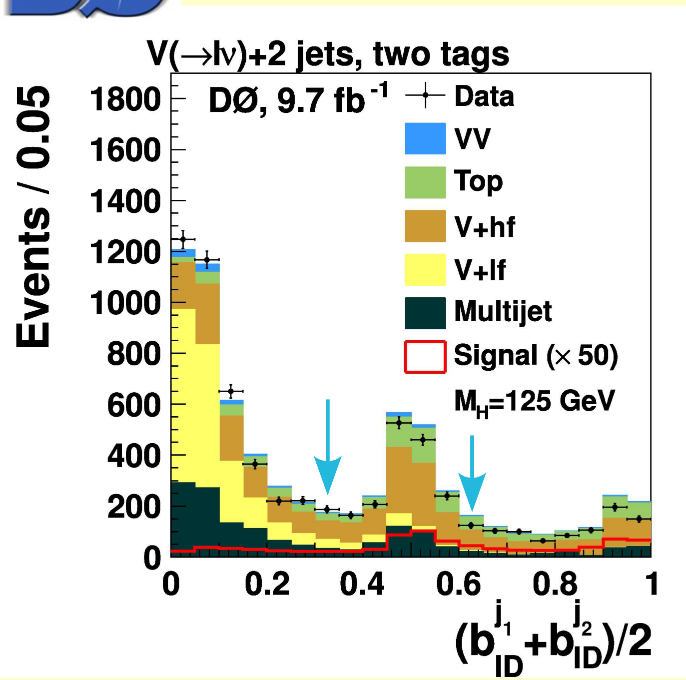
- ZH → ννbb – MET + 2 b-jets (contribution from WH also)
- Background modeling and rejection

VH → Vbb

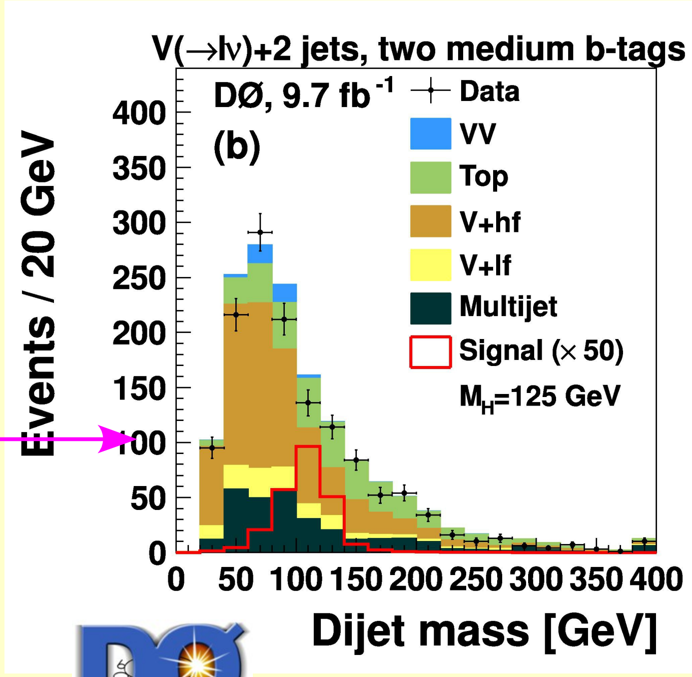
- Key ingredients:
  - Lepton, jet and $\not{E}_T$ reconstruction
  - Jet energy resolution => Δm/m~15%
  - b-tagging
  - Multivariate techniques to reject backgrounds







	Before b-tagging	2 med tags
s/b	1/7000	1/400
	Before b-tagging	2 tight tags
s/b	1/7000	1/200



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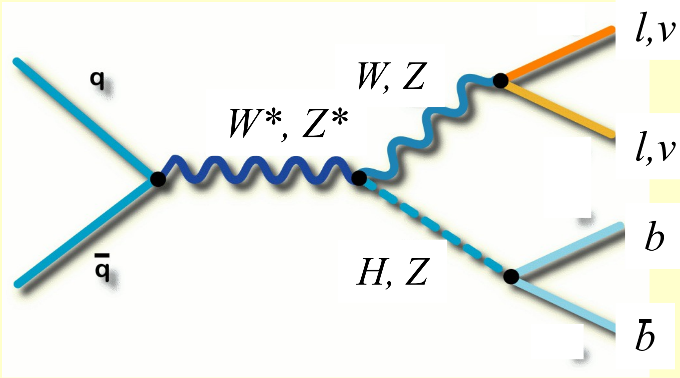
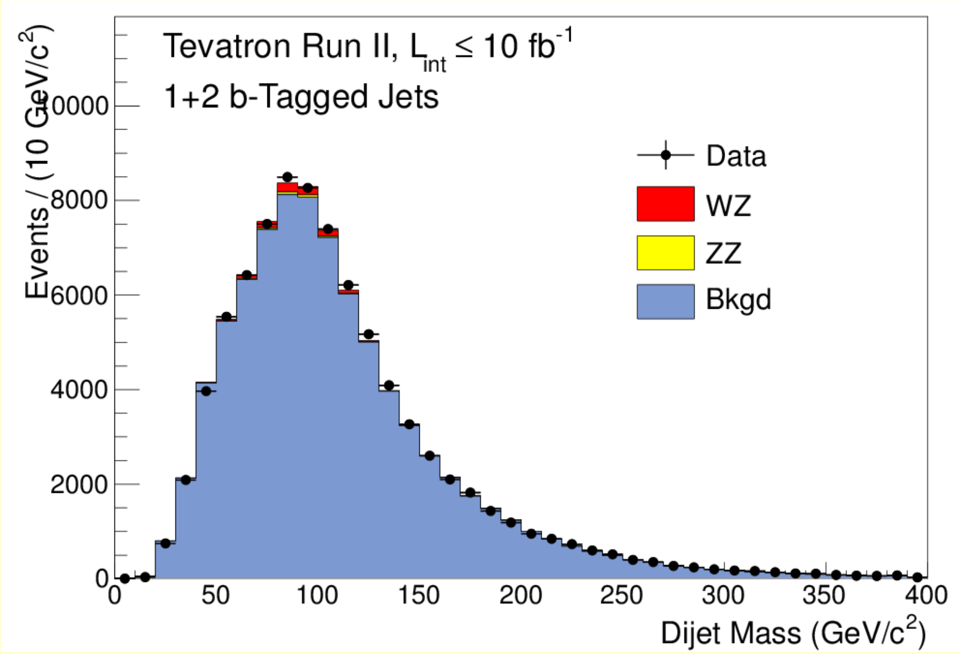
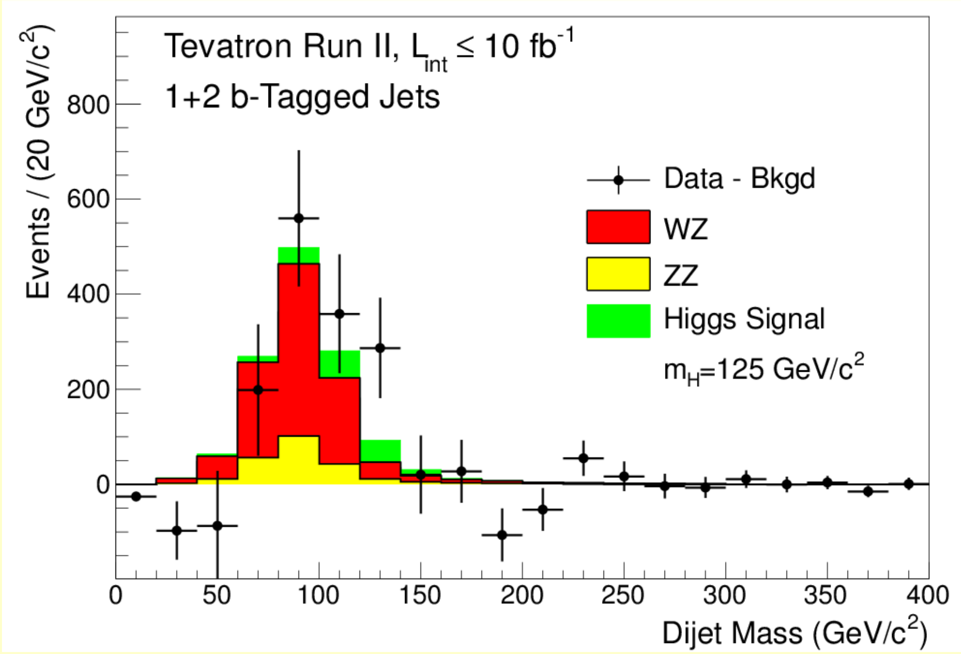
Validation of results



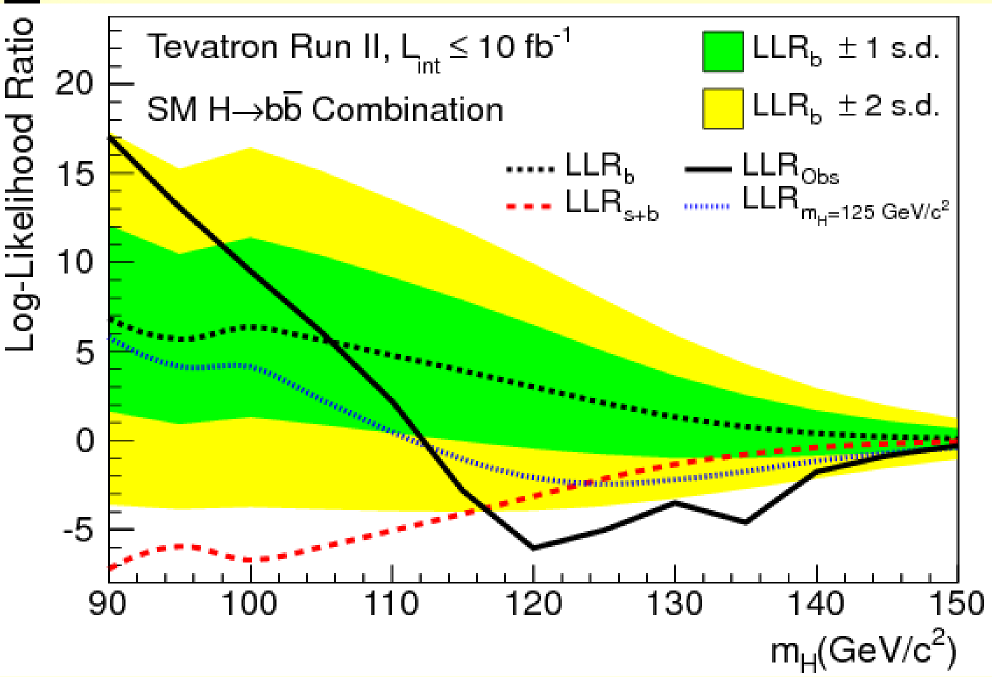
- Measure cross section of the known process with the same final state
  - Smaller cross section for Higgs production (~7 times)
  - Diboson signal peaks at lower masses
- Apply similar analysis
- Measured cross section: (0.68±0.21)*SM

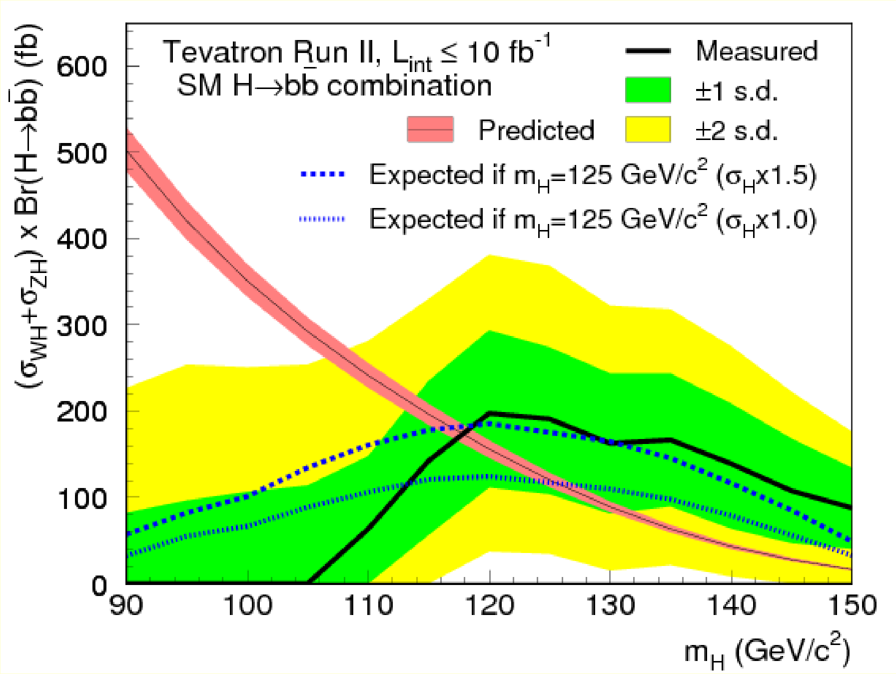
MH = 125 GeV	VH → Vbb [fb]	VZ → Vbb [fb]
vvbb	9	73
lvbb	16	105
llbb	3	24
Total	28	202





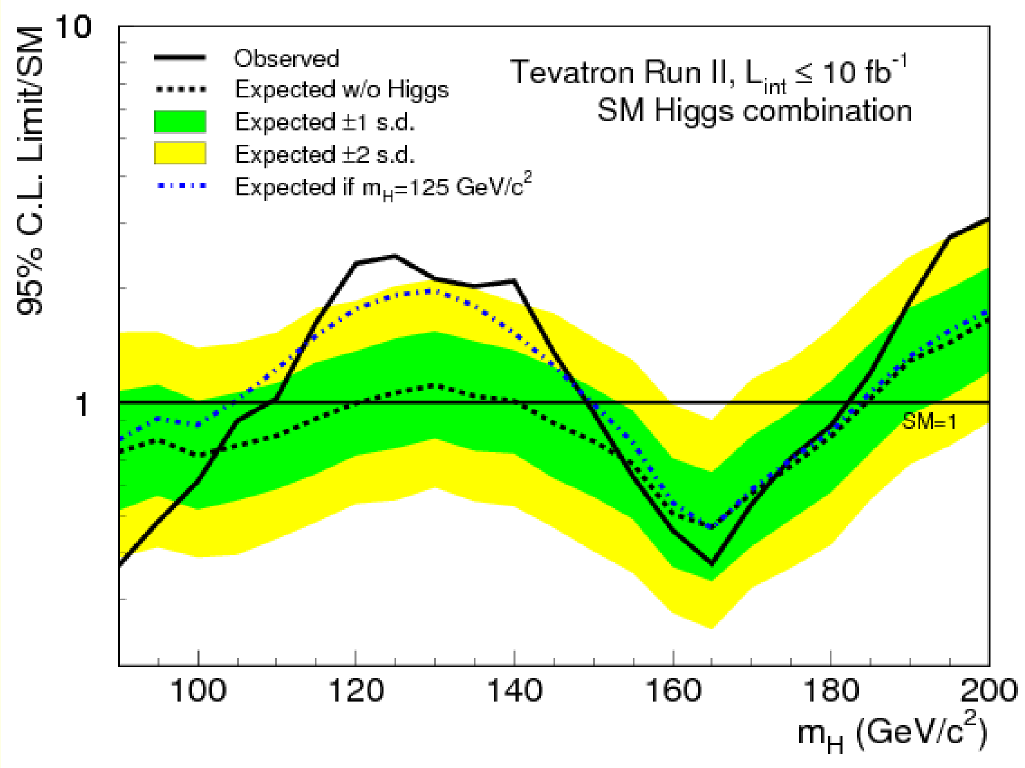
H → bb combination





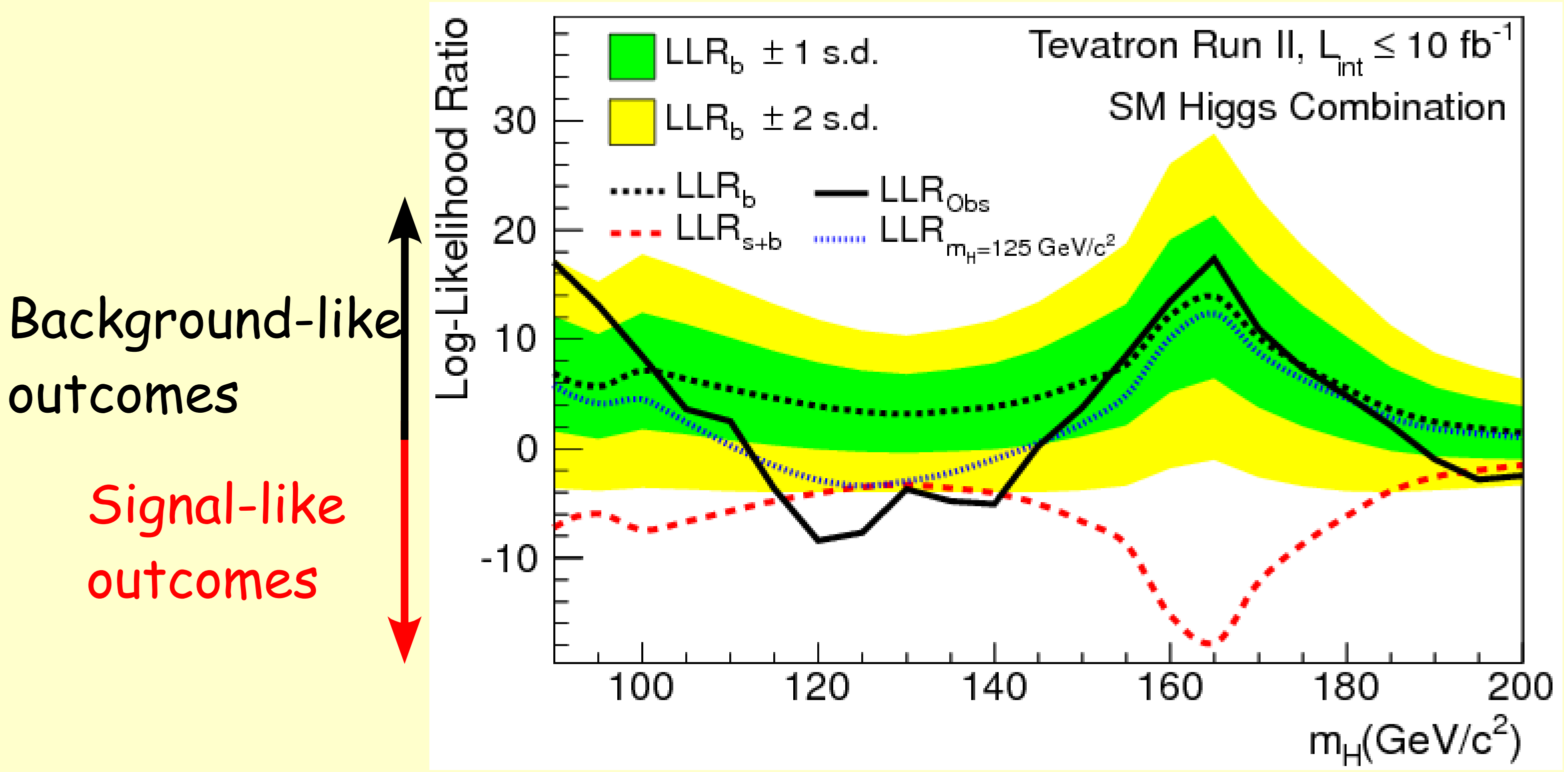
- VH → Vbb:
  - Expected sensitivity at m_H~125 GeV of 1.42xSM.
  - Broad excess consistent with dijet mass resolution
  - Best fit $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to bb) = 0.19^{+0.08}_{-0.09}$ pb @125 GeV
  - To be compared with SM: $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H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

Result of the SM combination



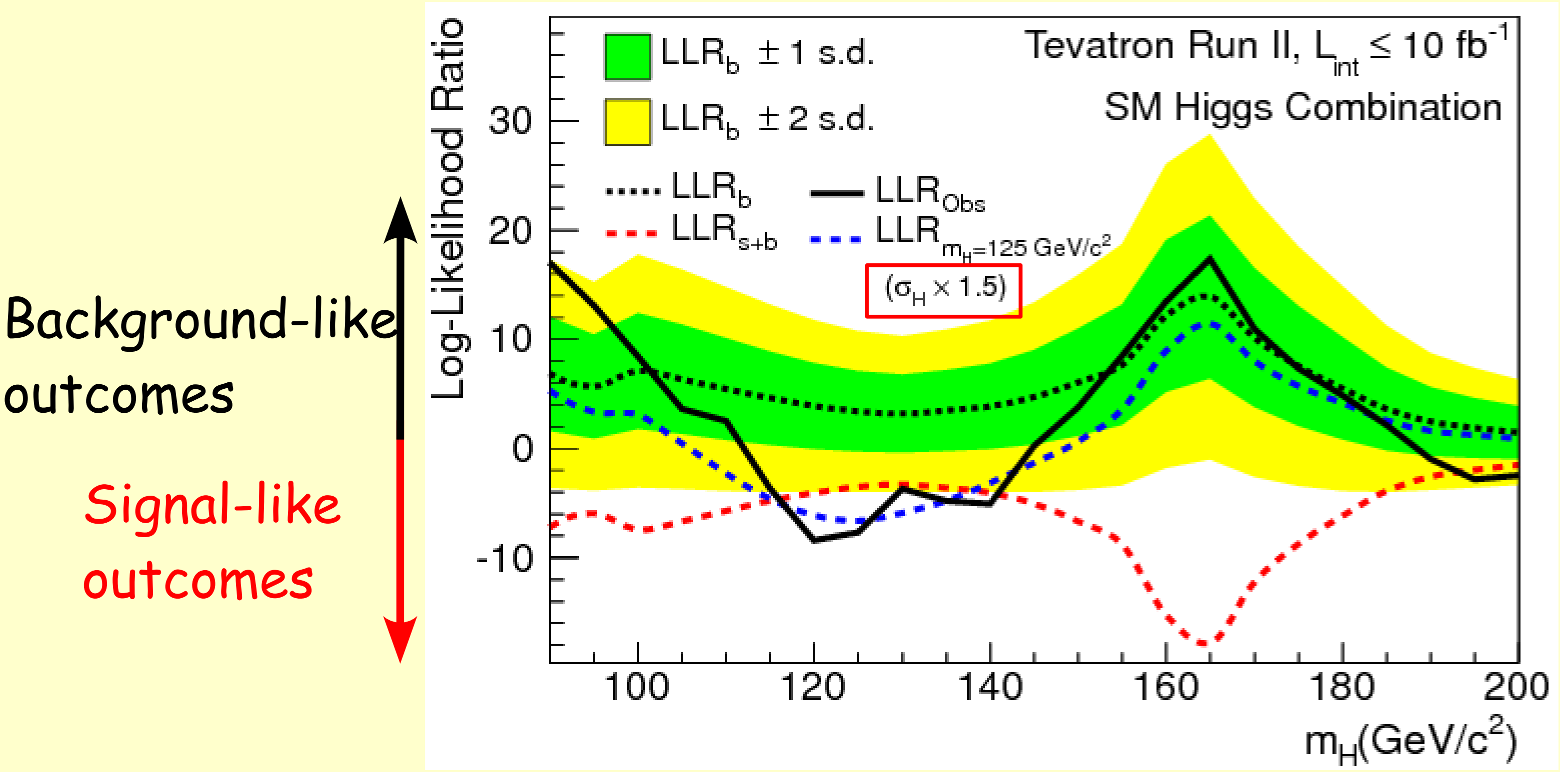
- Tevatron excludes (expect):
  90-109 (90-120) GeV and 149-182 (140-184) GeV @95% C.L.
- Exp. (obs) sensitivity @125 GeV: 1.06 (2.44)*SM

Sensitivity of the search



- Observed broad excess in data

Sensitivity of the search

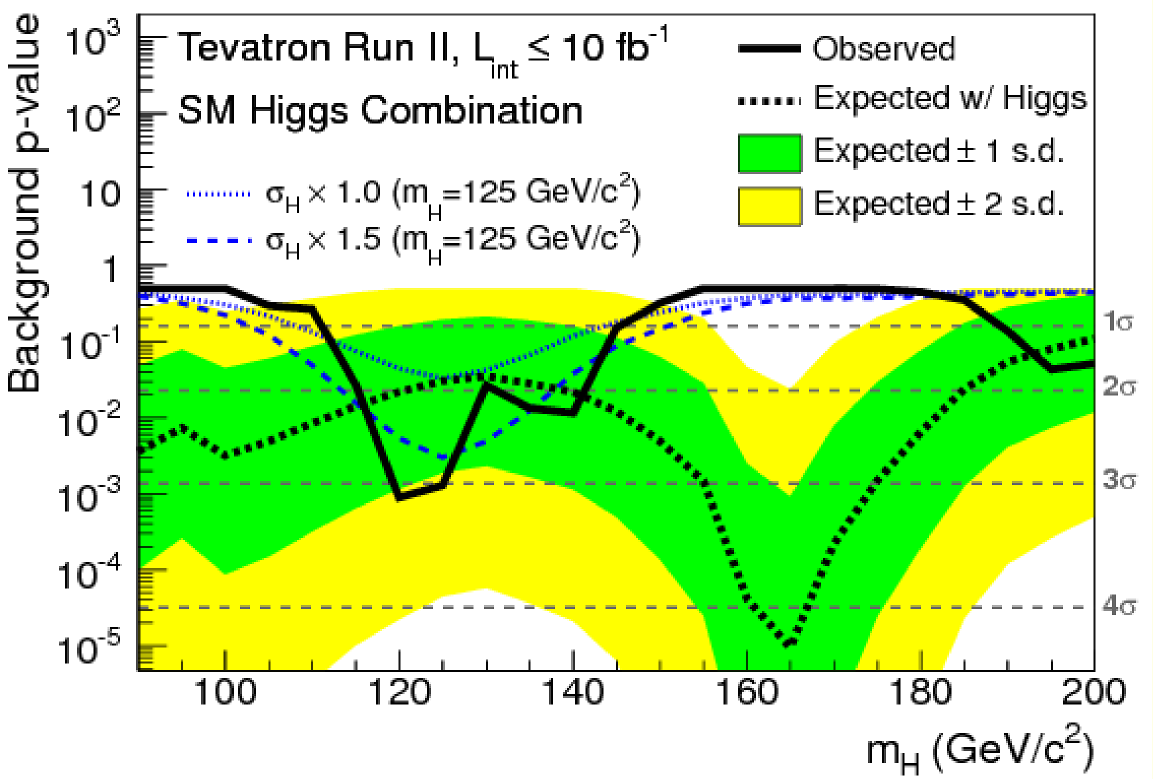


- Observed broad excess in data

  - 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

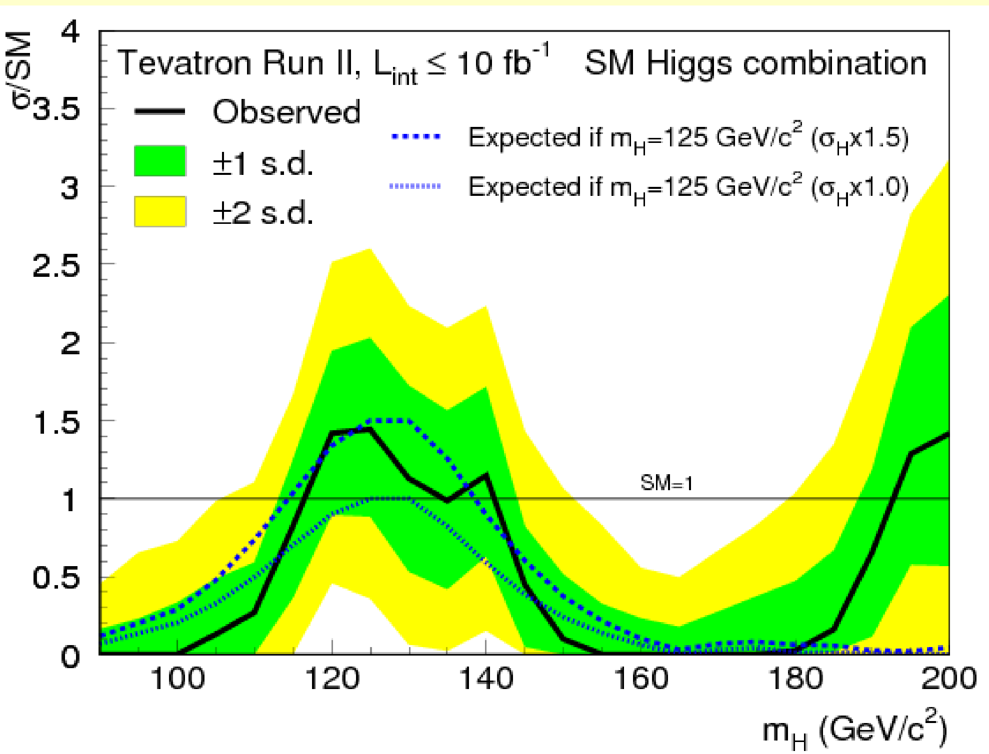
p-value for background hypothesis

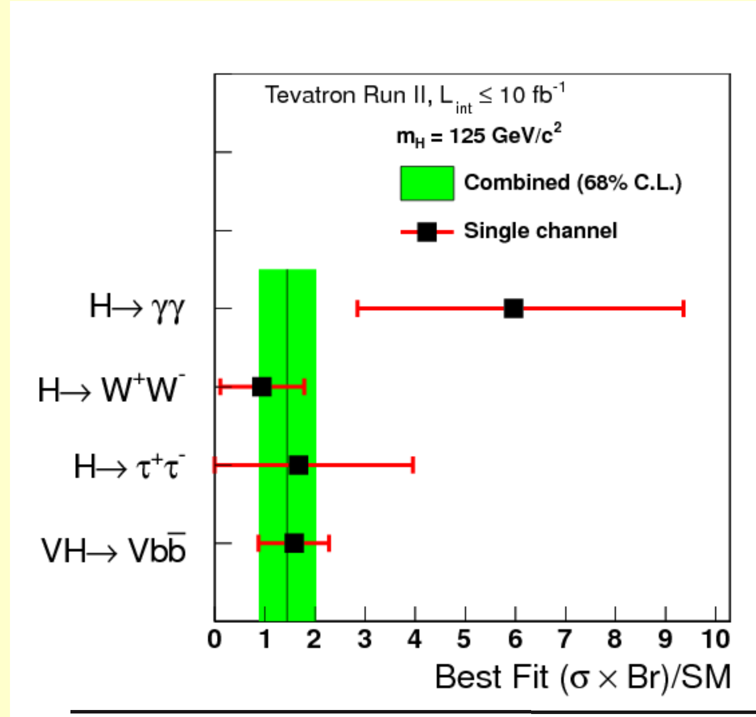
- p-value for background hypothesis provides information about the consistency with the observed data
- Local p-value distribution for background only expectation:
  - 3 s.d. (@125 GeV)



Signal Strength

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





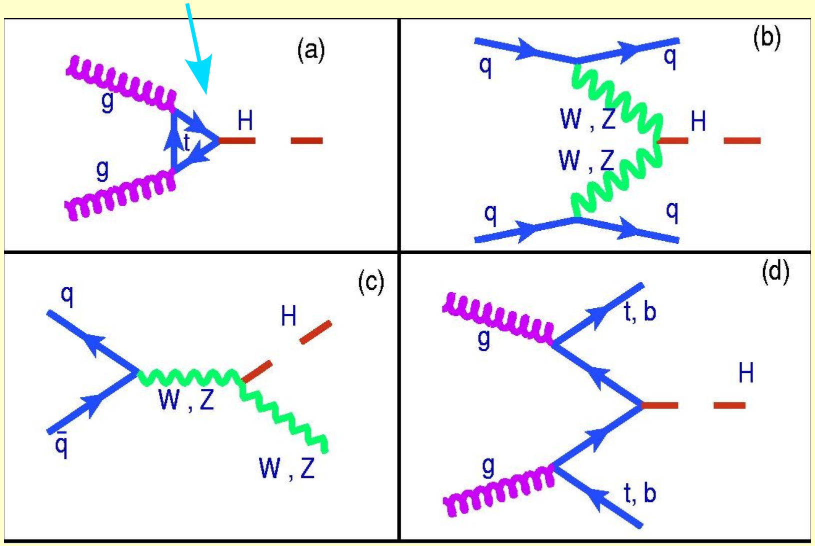
m_H (GeV/c^2)	125
$R_{\rm fit}$(SM)	$1.44^{+0.59}_{-0.56}$
$R_{\rm fit}(H \to W^+W^-)$	$0.94^{+0.85}_{-0.83}$
$R_{\rm fit}(H \to b\bar{b})$	$1.59^{+0.69}_{-0.72}$
$R_{\rm fit}(H \to \gamma\gamma)$	$5.97^{+3.39}_{-3.12}$
$R_{\rm fit}(H \to \tau^+\tau^-)$	$1.68^{+2.28}_{-1.68}$

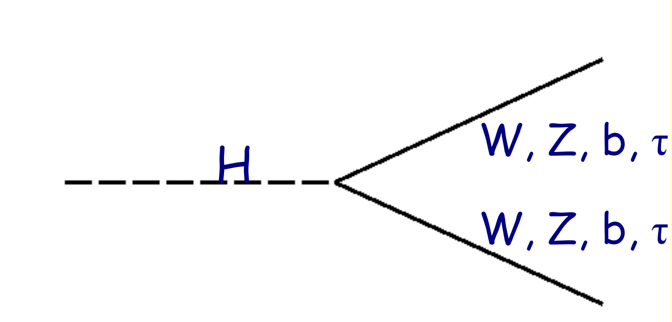
Couplings

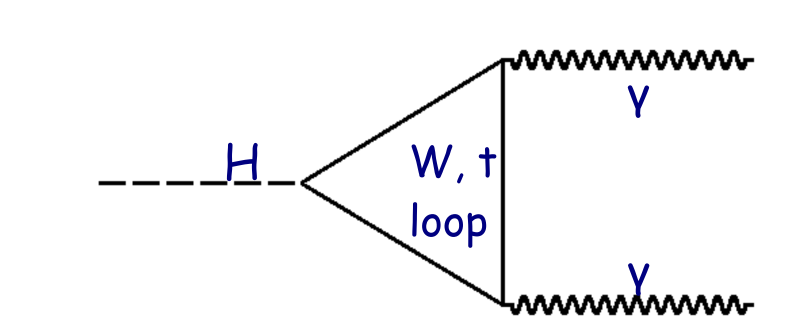
Higgs boson couplings to bosons and fermions

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

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







$$\Gamma(H \to \gamma\gamma) = \Gamma(H \to \gamma\gamma)_{SM}|\alpha\kappa_V + \beta\kappa_f|^2$$

Couplings

- Couplings to fermions (κ_W=κ_Z=1): $\kappa_f = -2.64^{+1.59}_{-1.30}$
- Couplings to bosons (κ_f=$\kappa_{Z \text{ or } W}$=1):

$$\kappa_W = -1.27^{+0.46}_{-0.29}$$

$$\textit{second interval } 1.04 < \kappa_W < 1.51$$

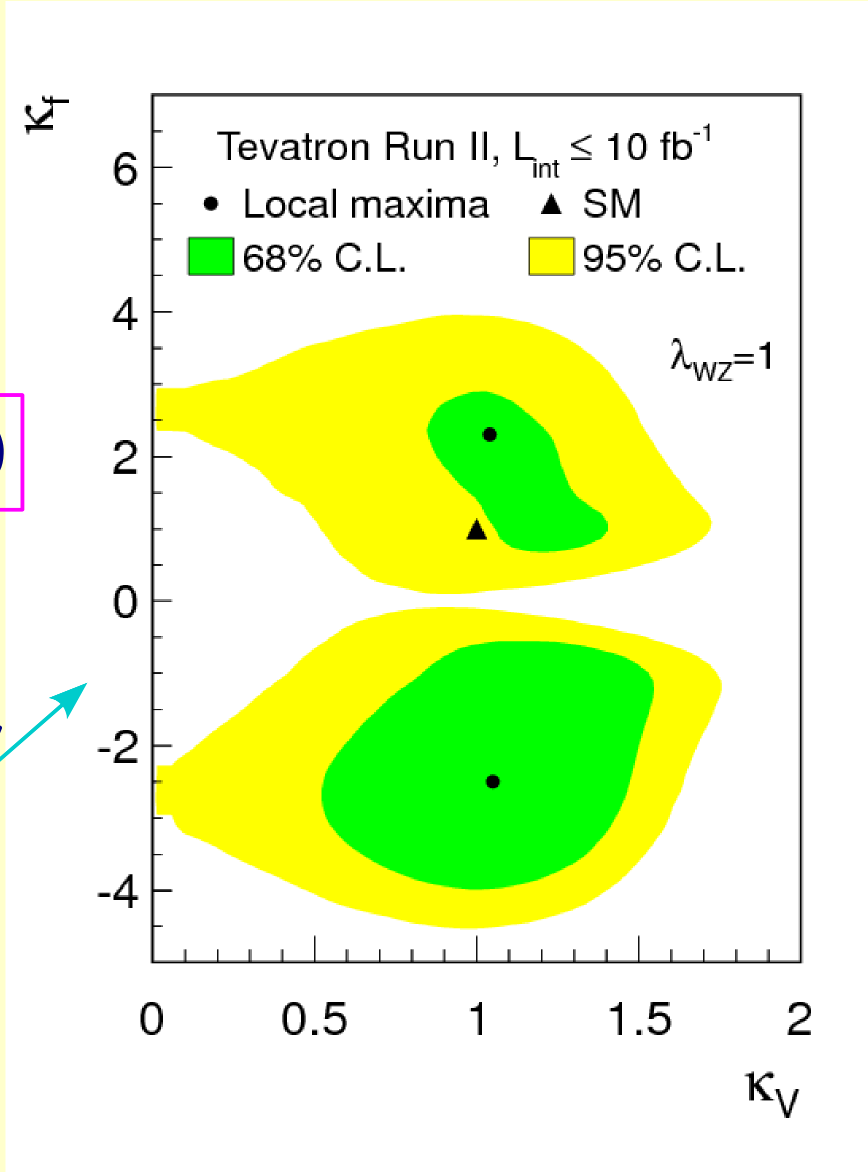
$$\kappa_Z = \pm 1.05^{+0.45}_{-0.55}$$

if varied together: (κ_W, κ_Z) = (1.25,±0.90)

- For custodial symmetry:

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

- Assuming that custodial symmetry holds, λ_{WZ} = 1, allow both κ_V and κ_f to vary
  - Asymmetry is from the excesses in the H → γγ
- Two minima: (κ_V, κ_f)=(1.05,-2.40) and (κ_V, κ_f) = (1.05, 2.30)



Spin (J) and Parity (P)

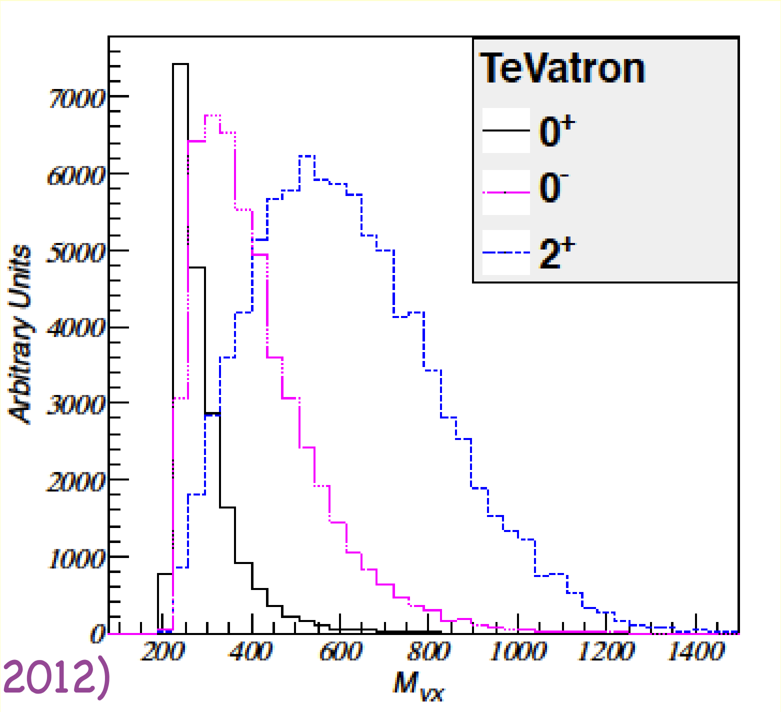
Motivation

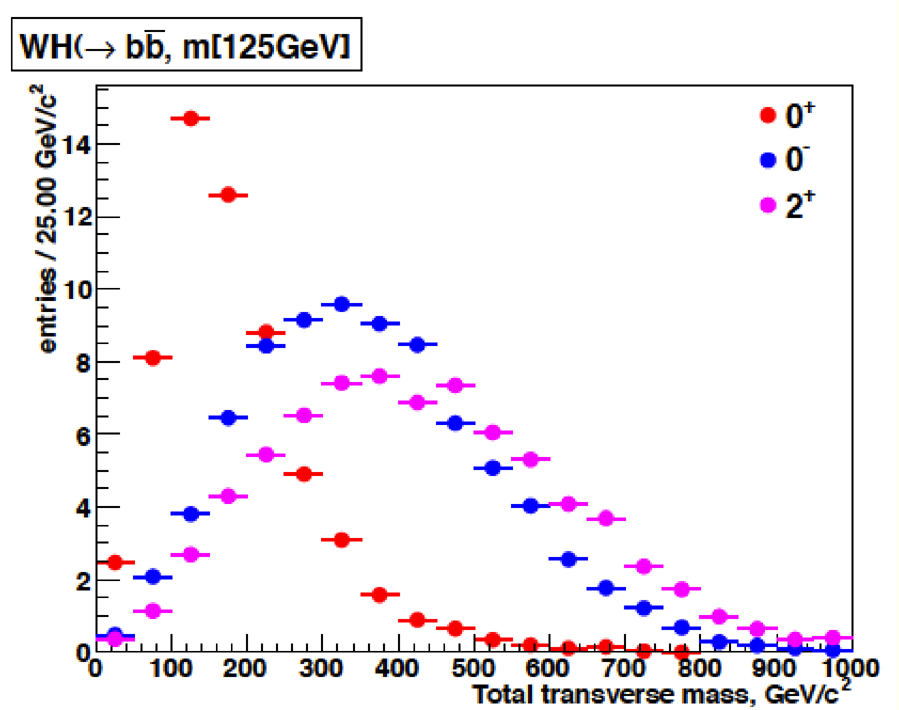
- Standard Model predicts Higgs boson with $J^P = 0^+$
  - The $H \rightarrow \gamma\gamma$ excludes J=1 (Landau-Yang theorem)
- Studied:
  - $J^P = 0^-$ – pseudoscalar from 2HDM, SUSY, etc
  - $J^P = 2^+$ – graviton, RS model assumed
- Different spin and parity states manifest in various ways
  - Angles 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

Spin and Parity at Tevatron

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

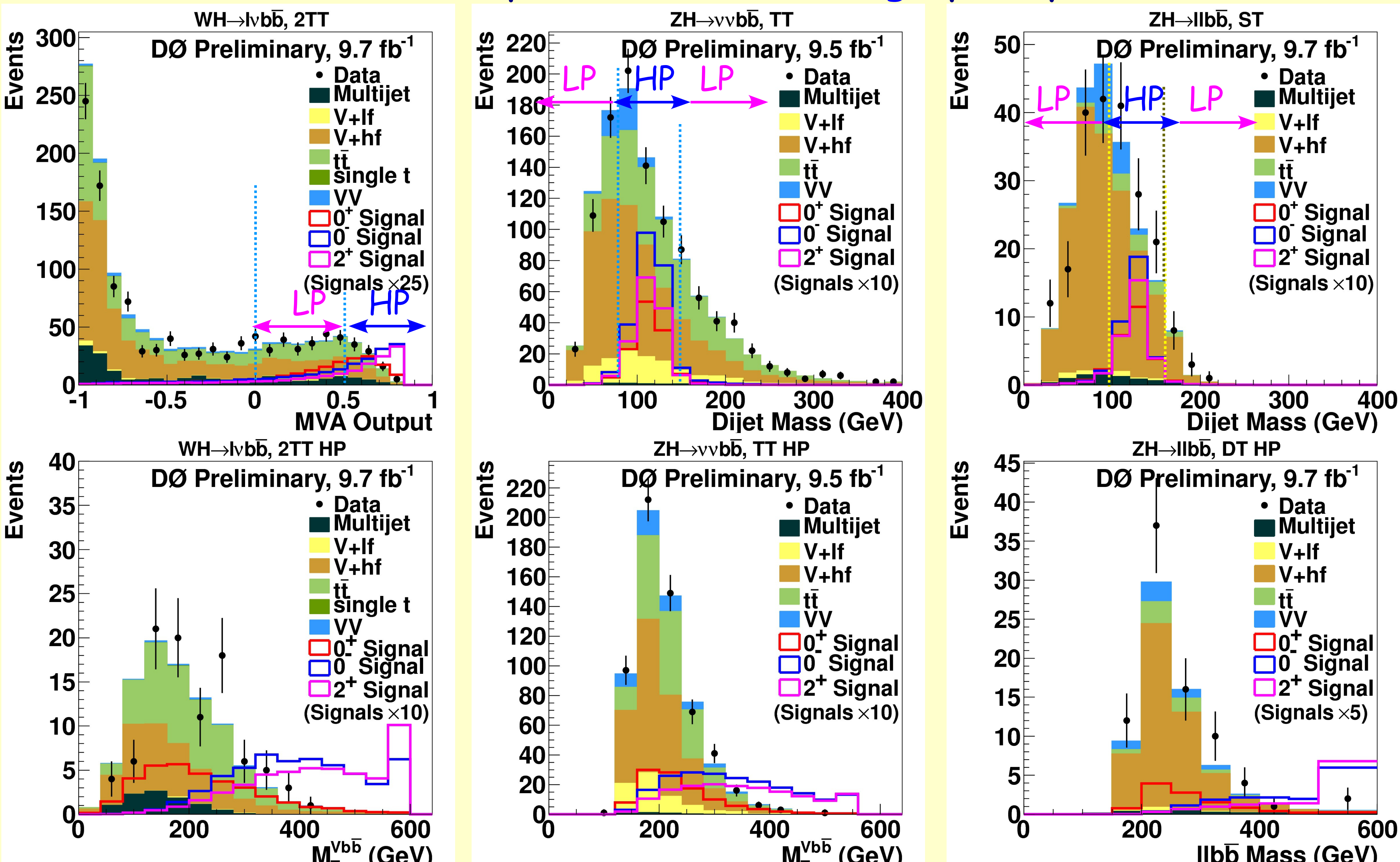
Ellis, et al., JHEP 1211, 134 (2012)





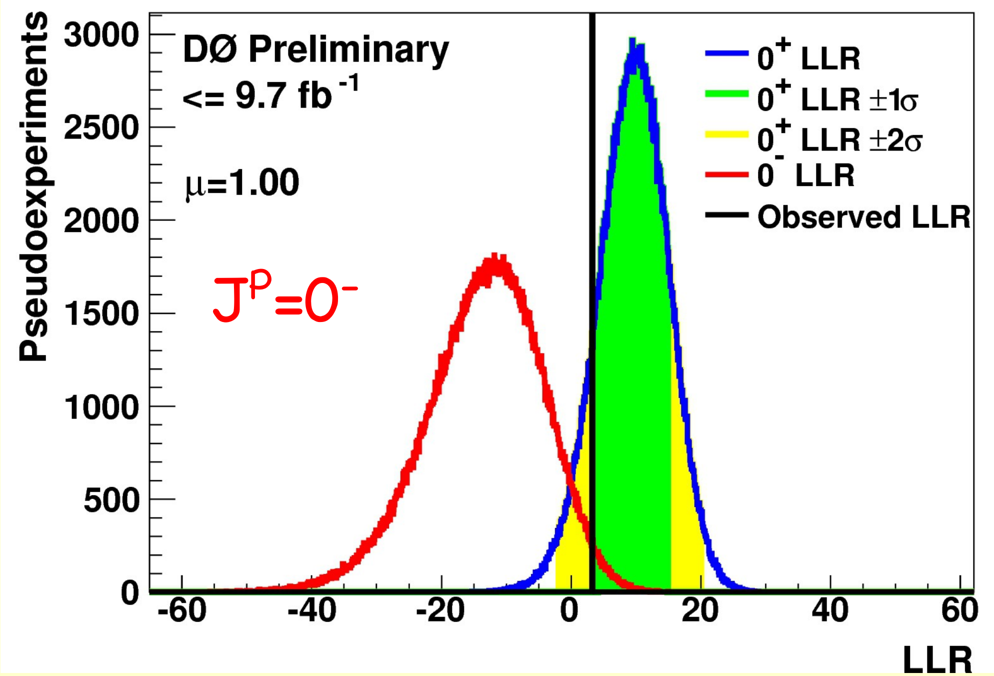
Selection

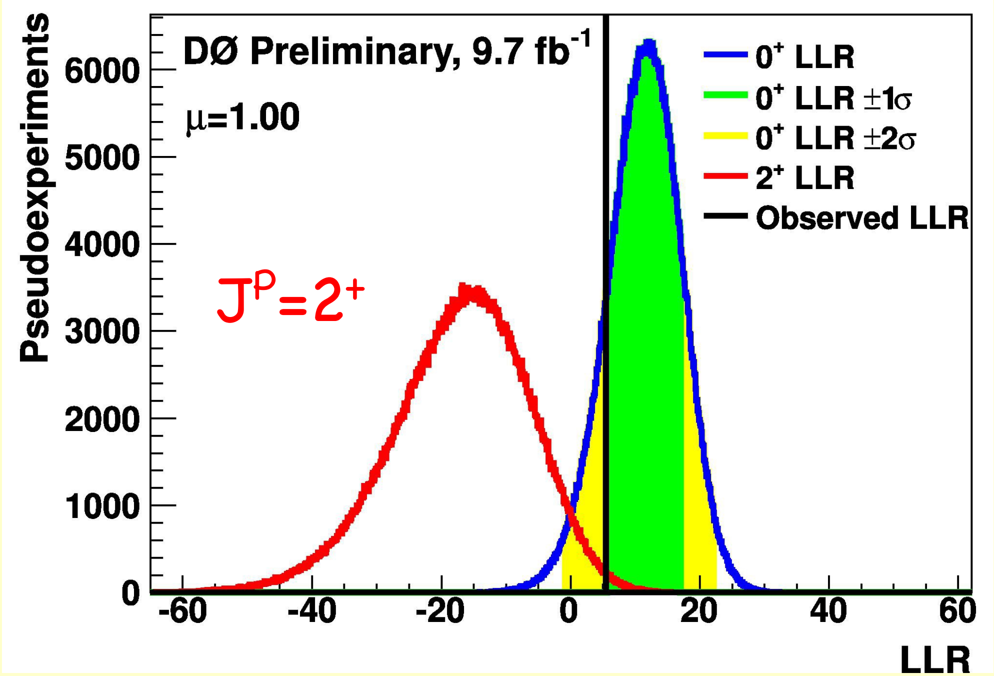
- Divide samples into low and high purity



Results

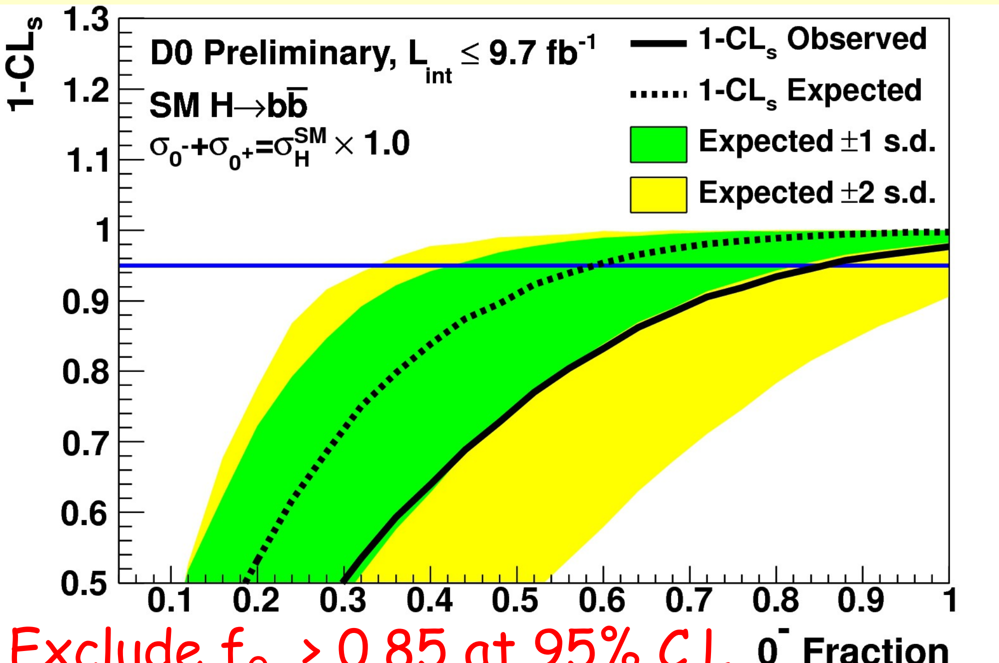
- Build log-likelihood ratio test: $LLR = -2 \log(H_1/H_0)$
  - H_0 is the SM Higgs (0^+) + Bkg
  - H_1 is either 0^- + Bkg or 2^+ + Bkg
- $J^P=0^-$ excluded at the 97.9% C.L.
- $J^P=2^+$ excluded at the 99.2% C.L.



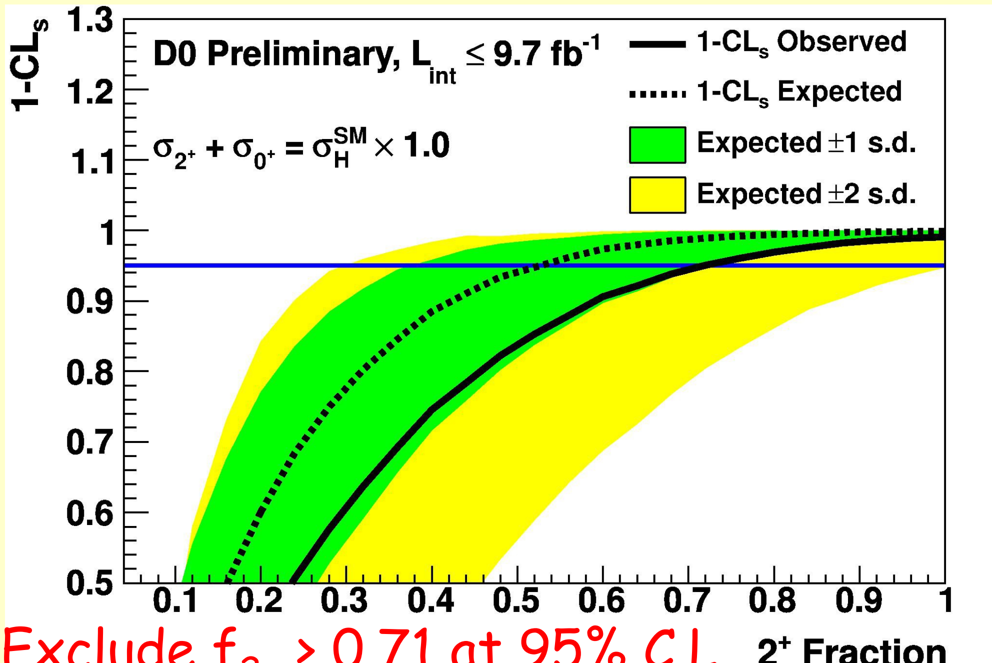


Signal Admixtures

- Allow possibility of both a $0^-(2^+)$ and 0^+ signal in data
- Vary fraction f_x from 0 to 1 $$f_X = \frac{\sigma_X}{\sigma_X + \sigma_{0+}}$$
  - 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^+)



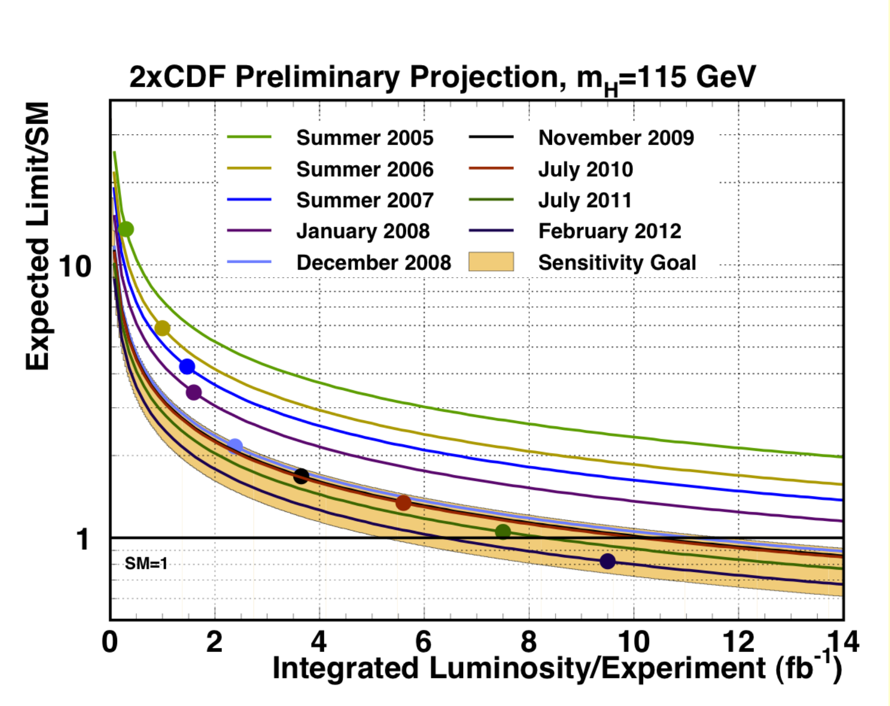
Exclude $f_{0-} > 0.85$ at 95% C.L.



Exclude $f_{2+} > 0.71$ 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 and delivered almost 12 fb^{-1} during that period



- Achievements:
  - First post-LEP exclusion
  - First evidence for H->bb
  - Almost 1xSM exclusion sensitivity over the full range (110-185 GeV)
- With final results observed broad excess in low mass range
- 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 – D0 is close to publication, CDF and Tevatron still to come

Backup

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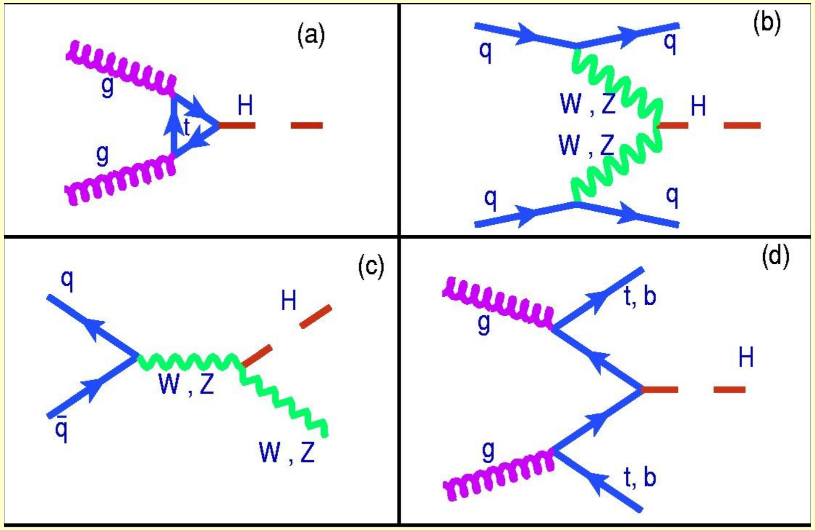
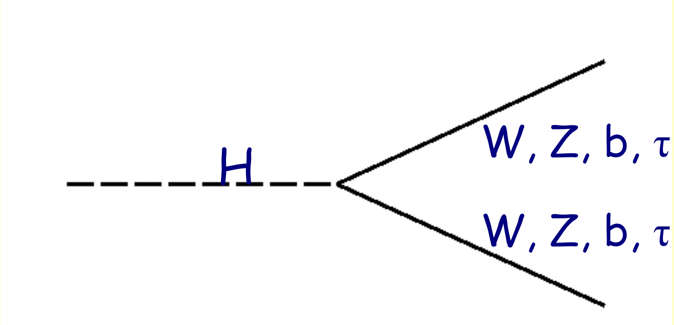
Higgs boson couplings to bosons and fermions

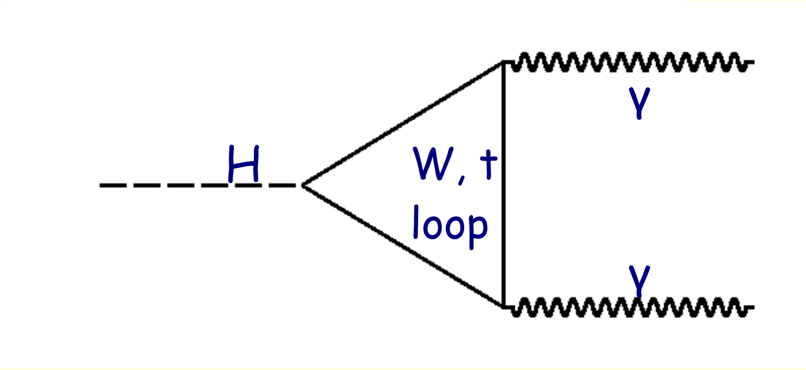
- Follow the prescription from LHC Higgs cross section working group: arXiv:1209.0040
- Basic assumptions:
  - There is only one underlying state at m_H~125 GeV
  - It has negligible width
  - It is a CP even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of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

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 $\kappa_f = \kappa_W = \kappa_Z = 1$







Constraining couplings

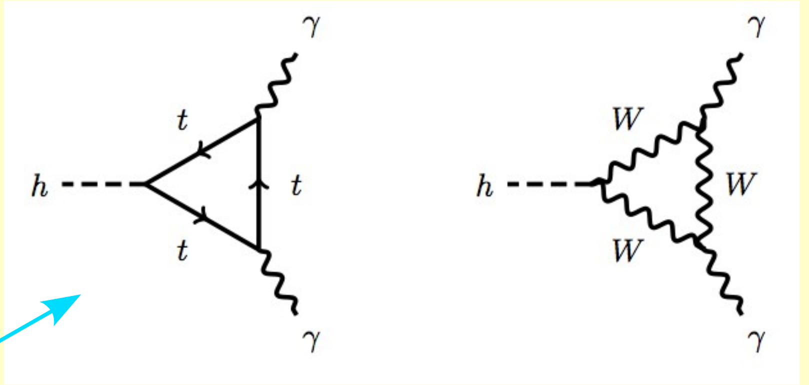
- Scale cross sections for each process according to couplings

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

- 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 $H \to \gamma\gamma$

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Couplings

- Posterior probability distributions

  (a) vary κ_W ($\kappa_Z = \kappa_f = 1$)

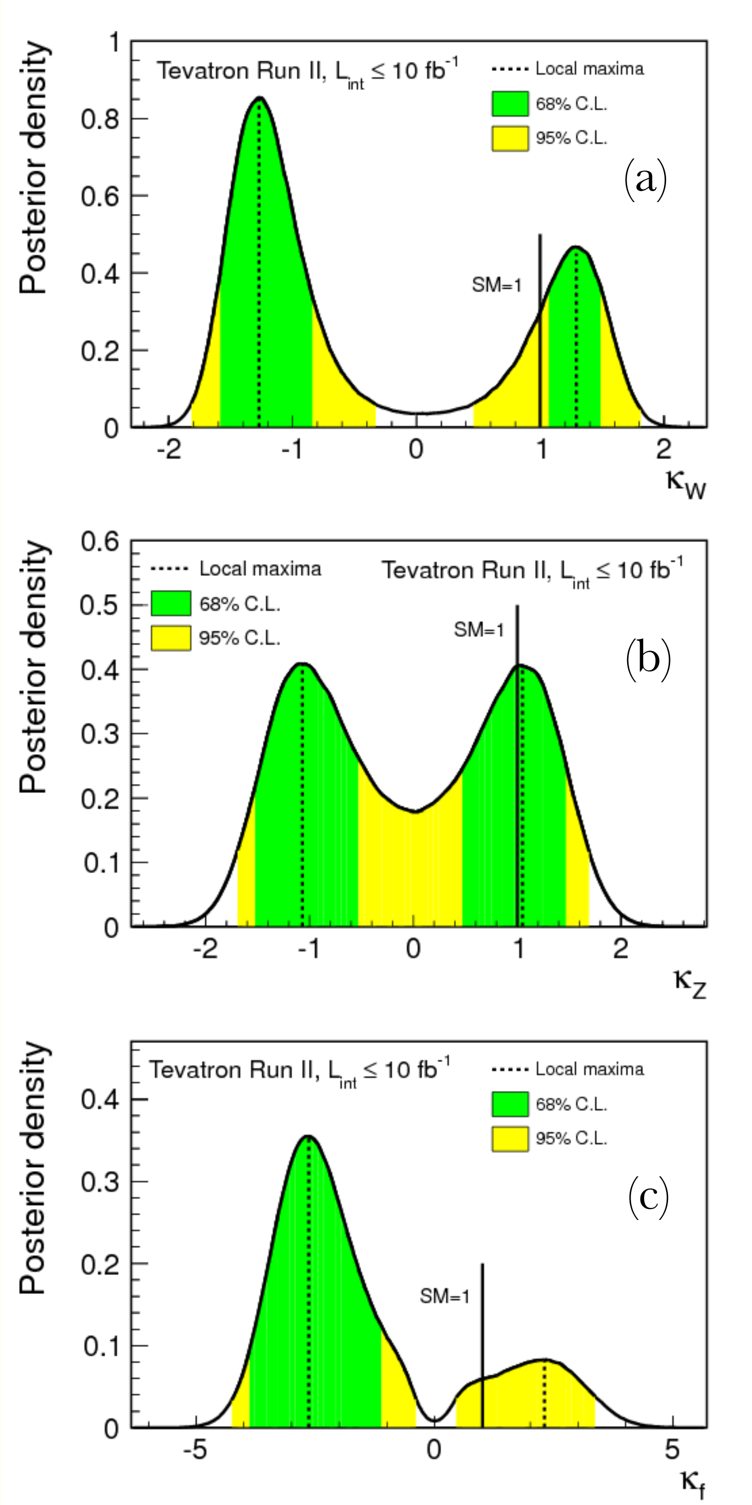
  - A negative sign of κ_W is preferred by the Tevatron data due to the excess in $H \rightarrow \gamma\gamma$
  - Best fit: $\kappa_W = -1.27$

  (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: $\kappa_Z = \pm 1.05$

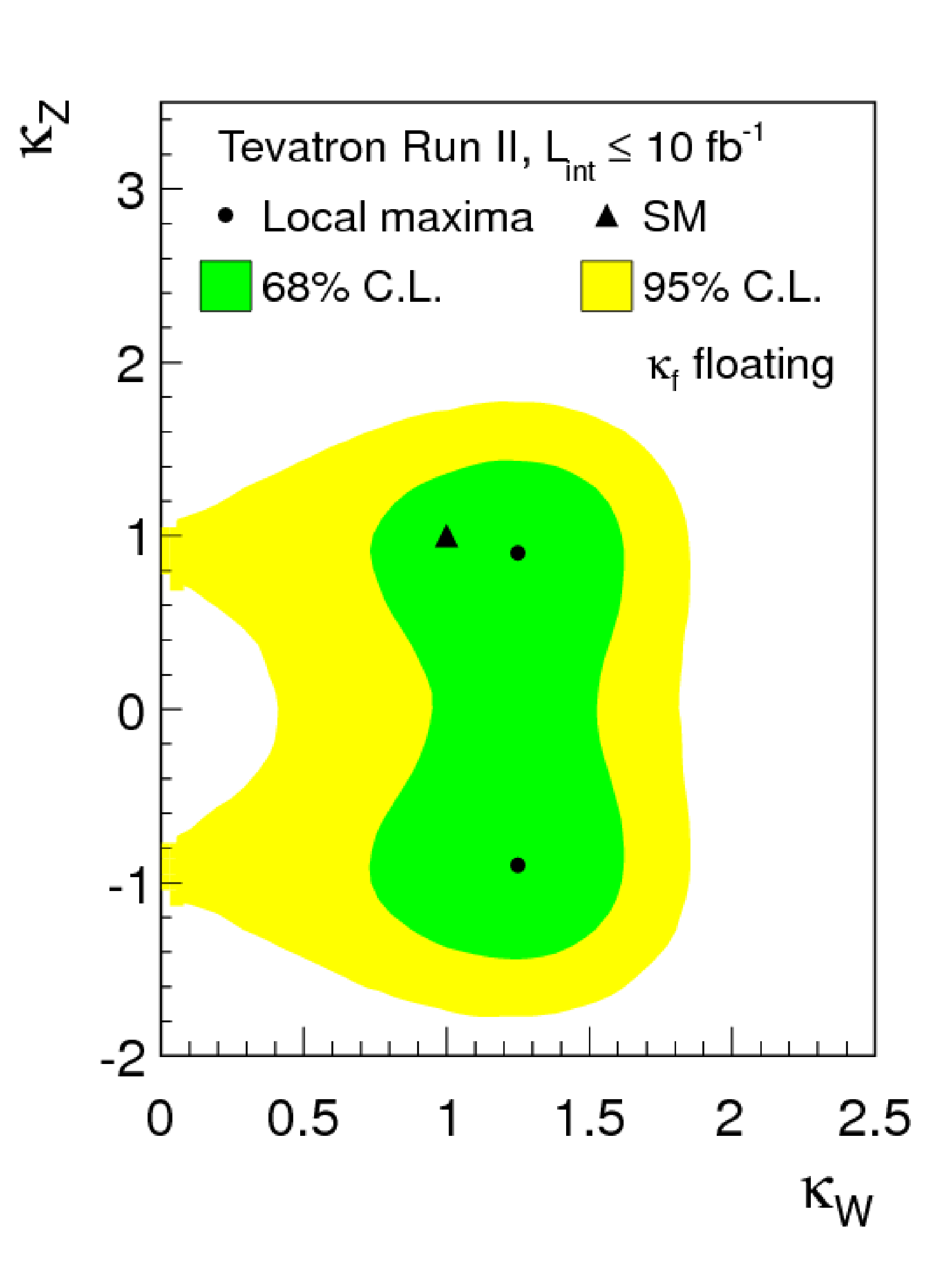
  (c) vary κ_f ($\kappa_W = \kappa_Z = 1$)

  - Asymmetry due to $H \rightarrow \gamma\gamma$
  - Best fit: $\kappa_f = -2.64$ (large due to the excesses in $H \rightarrow \gamma\gamma$ and $VH \rightarrow Vbb$)



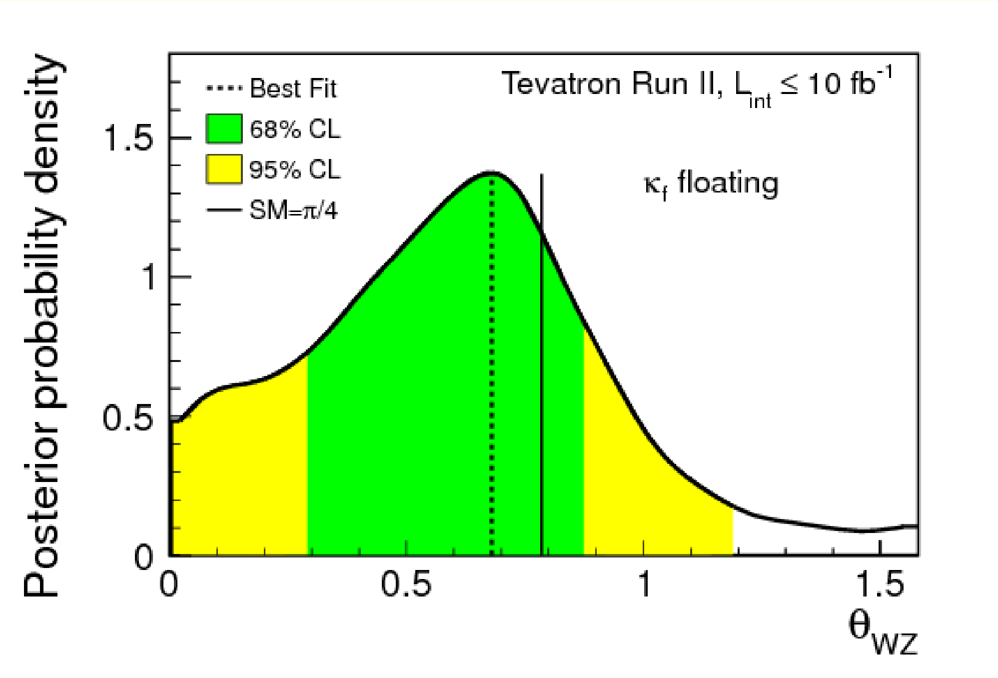
Couplings

- 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



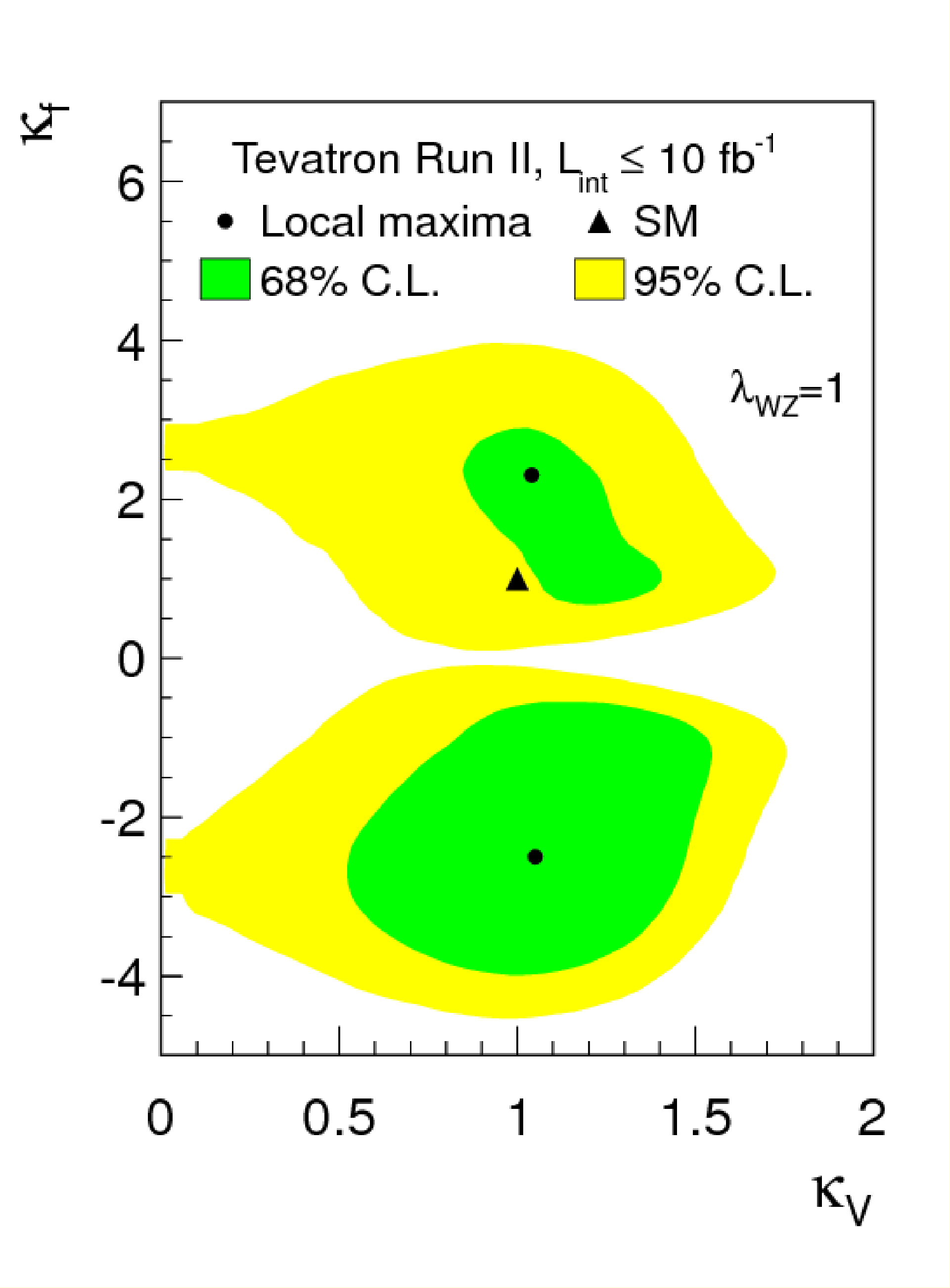
Couplings

- 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)



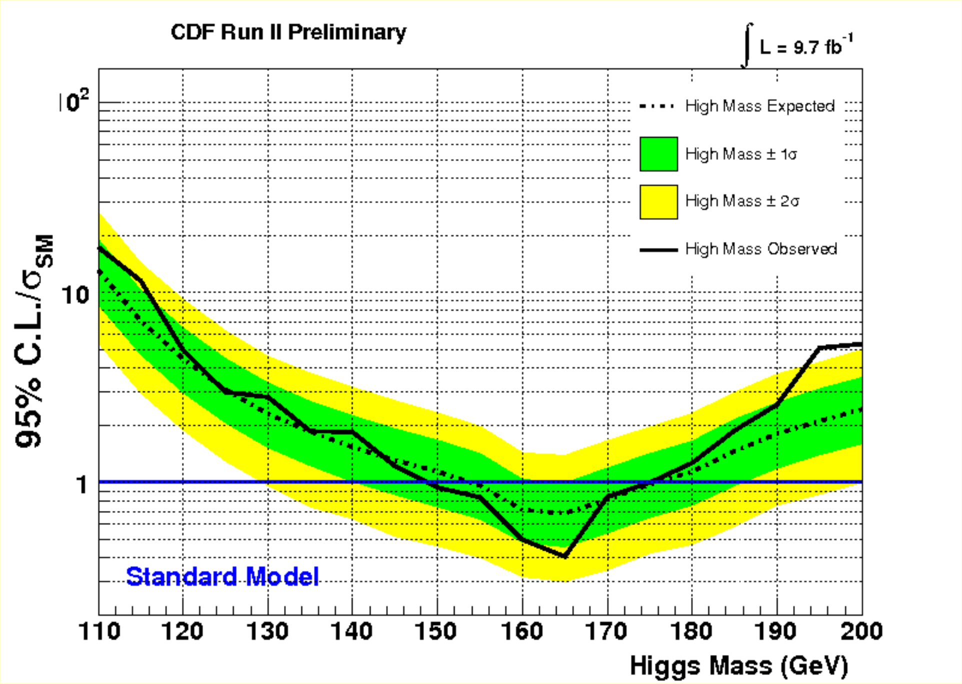
Couplings

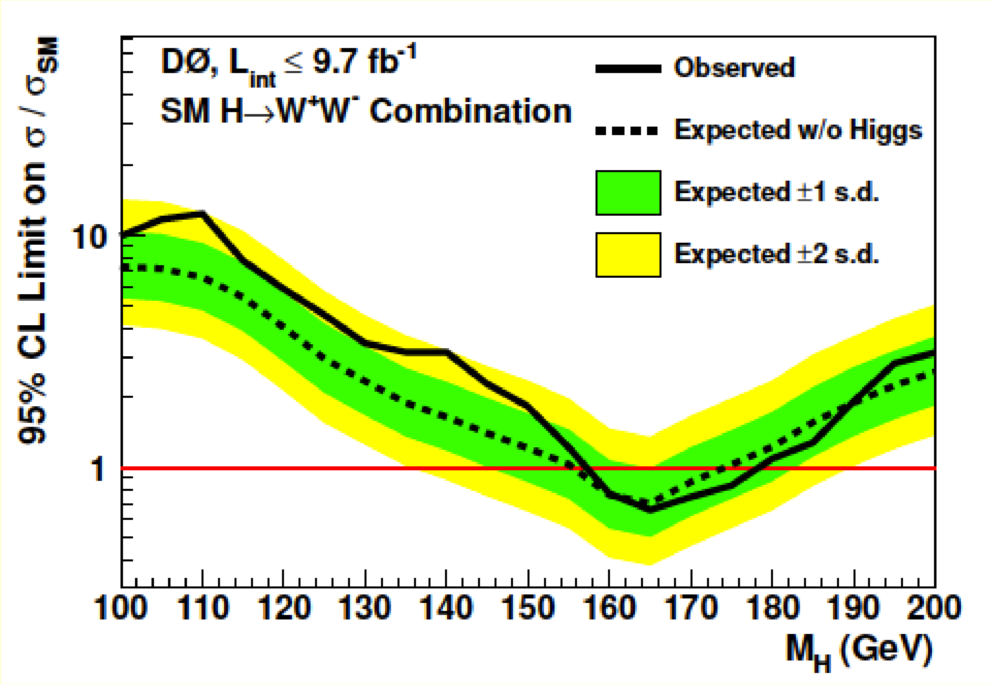
- Assuming that custodial symmetry holds, $\lambda_{WZ} = 1$, allow both κ_V and κ_f to vary
- Asymmetry is from the excesses in the $H \rightarrow \gamma\gamma$
- Two minima:
  $(\kappa_V, \kappa_f) = (1.05, -2.40)$ and
  $(\kappa_V, \kappa_f) = (1.05, 2.30)$
- The integral of the posterior density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



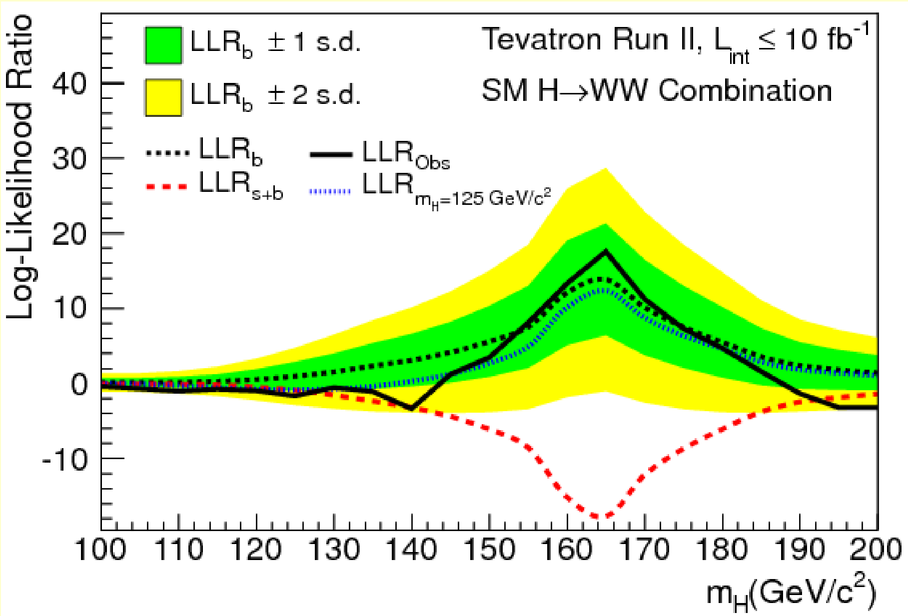
H → WW result

- 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)

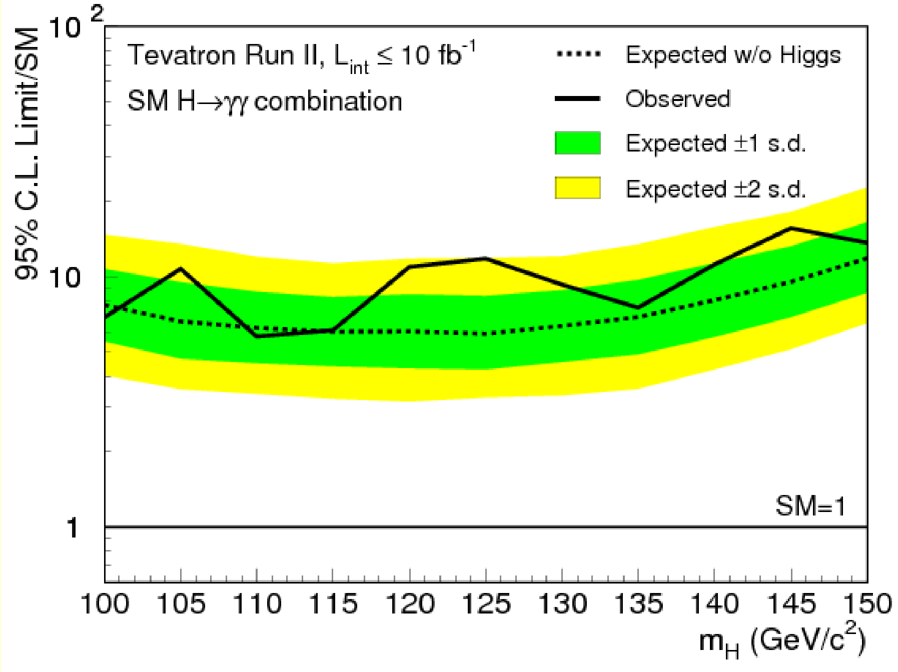


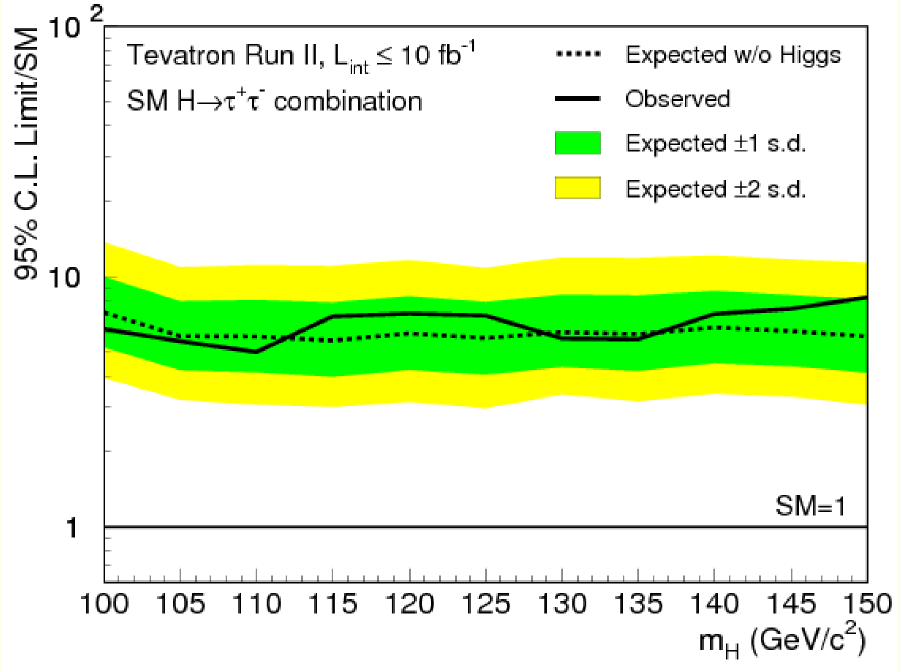
$$LLR = -2\ln\frac{P(s+b)}{P(b)}$$

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.

$H \to \gamma\gamma$ and $H \to \tau\tau$





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

- $H \to \tau\tau$
  - Expected sensitivity @125 GeV of ~5.7*SM

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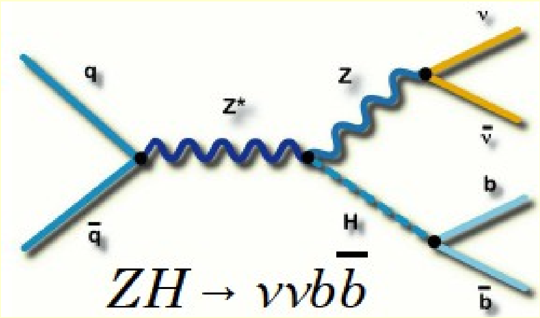
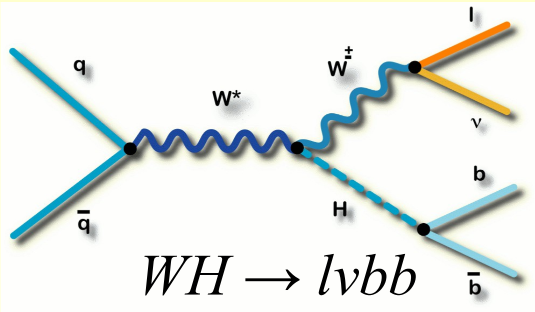
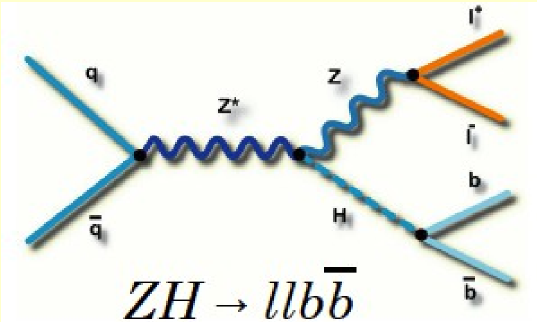
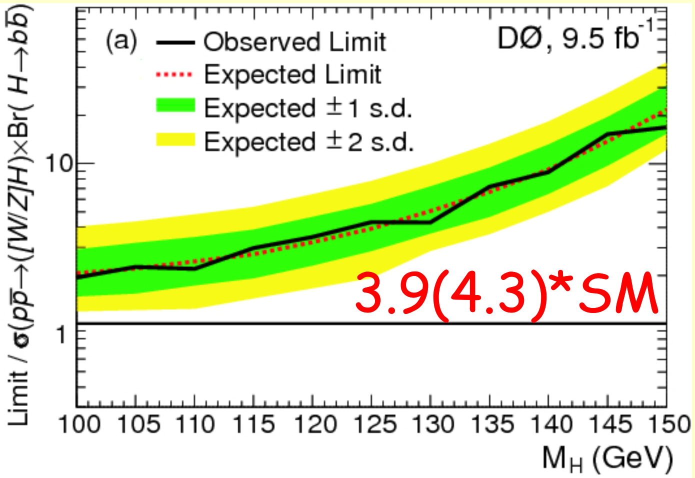
VH → Vbb results

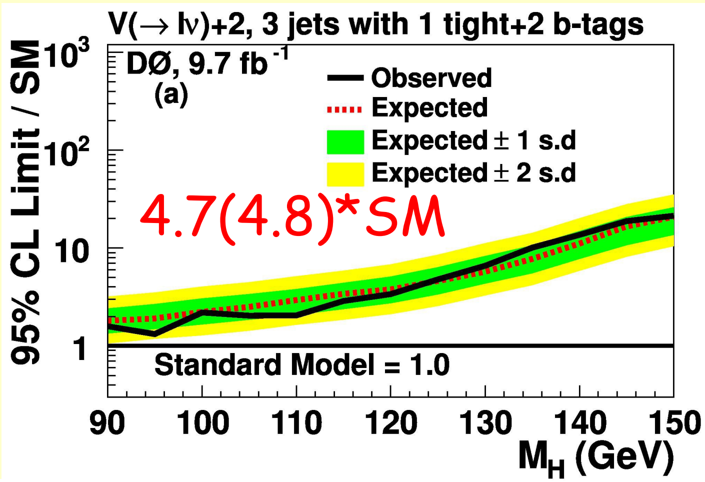
- Exp (obs) @125 GeV at D0 and CDF:

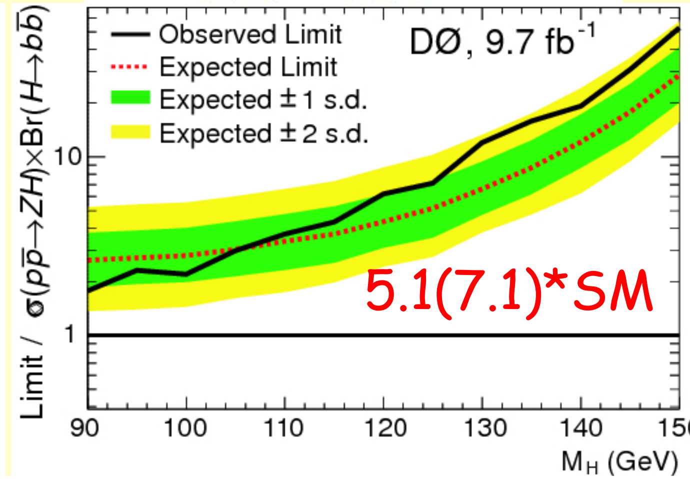


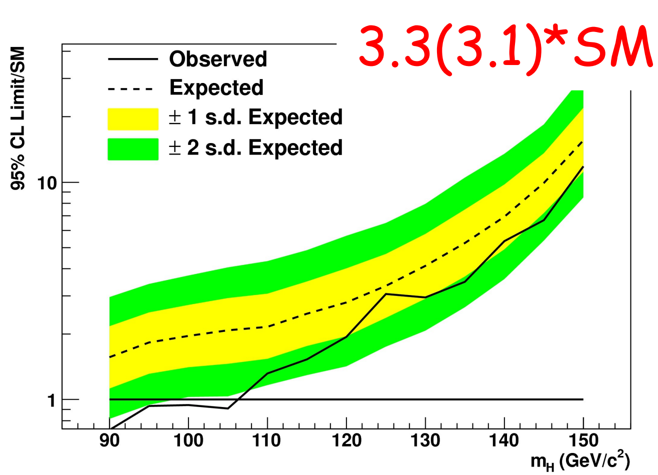


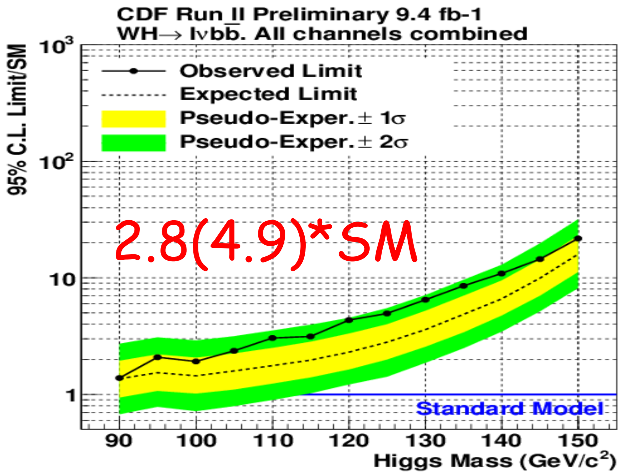


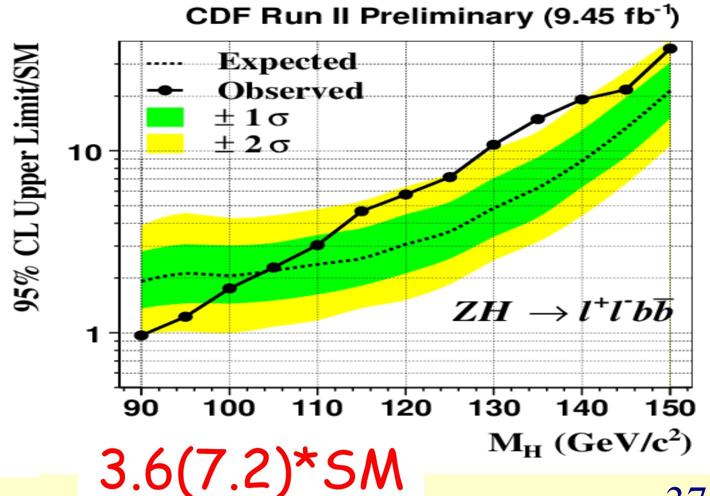












Comparison of Tev and LHC Methods

- 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 → ννbb 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 → ννbb