# SM Higgs studies at Tevatron

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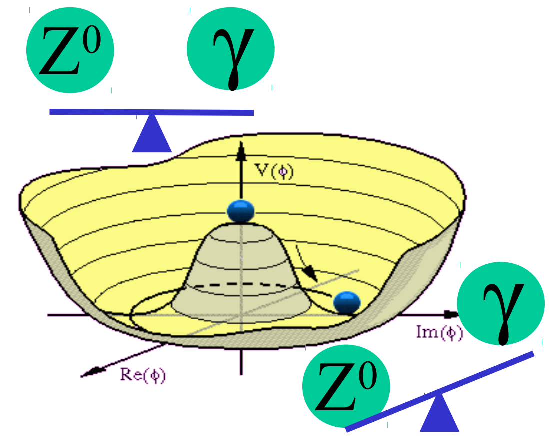
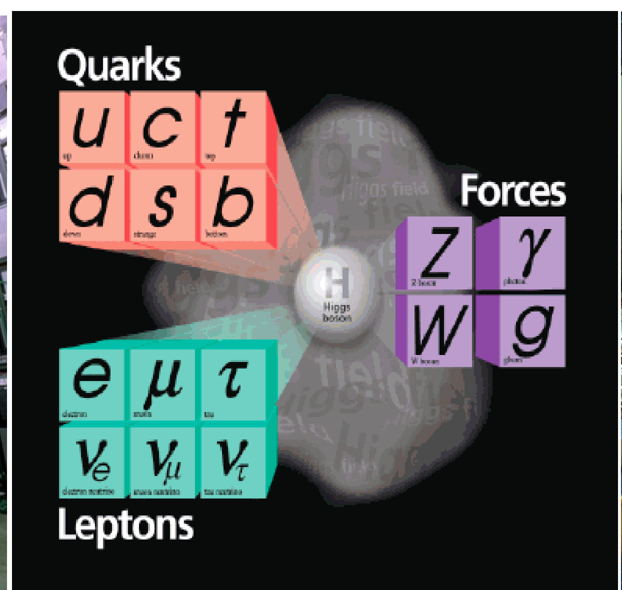
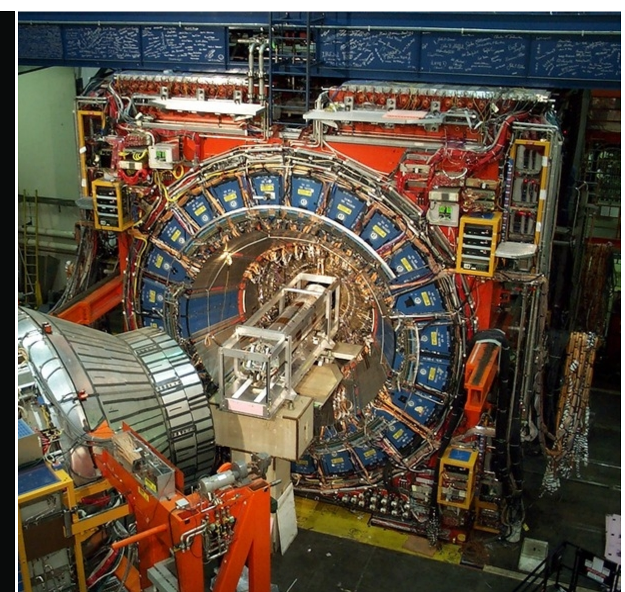
on behalf of the
CDF and DØ collaborations



# Two eras in Higgs physics

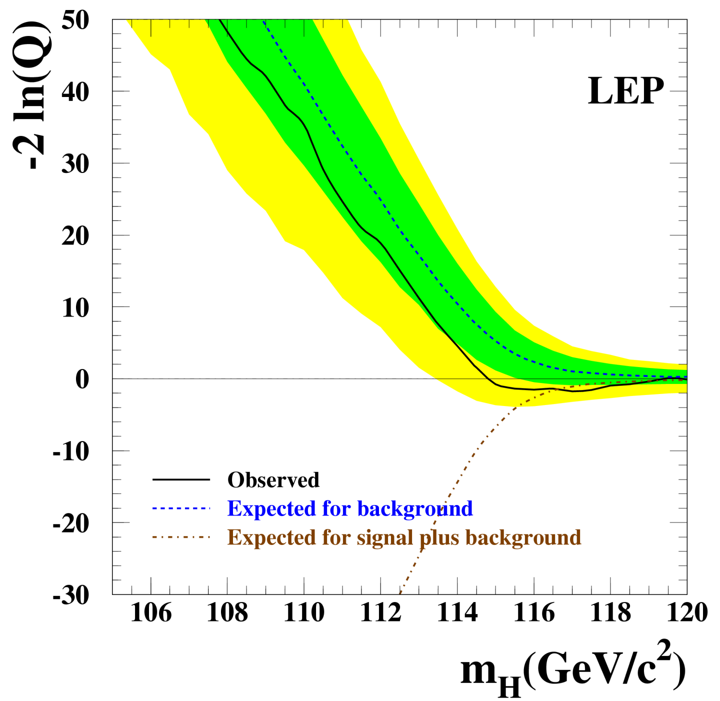
| 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

••• Lep

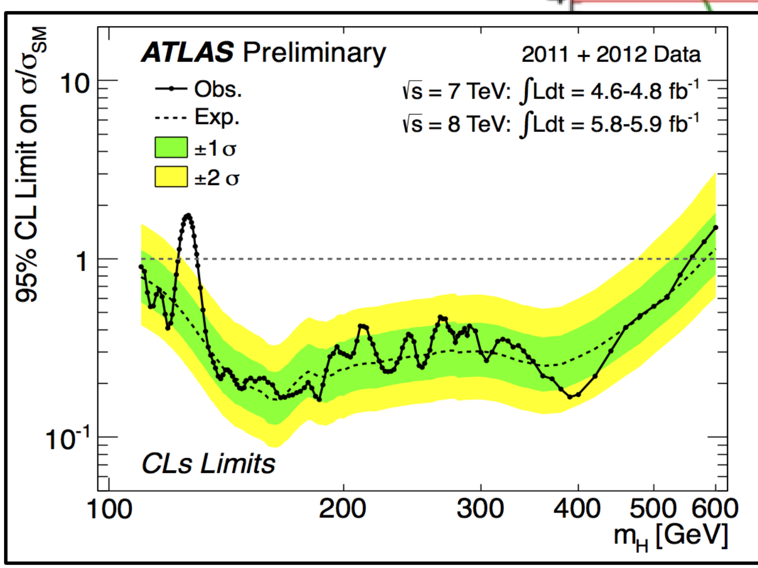
LHC

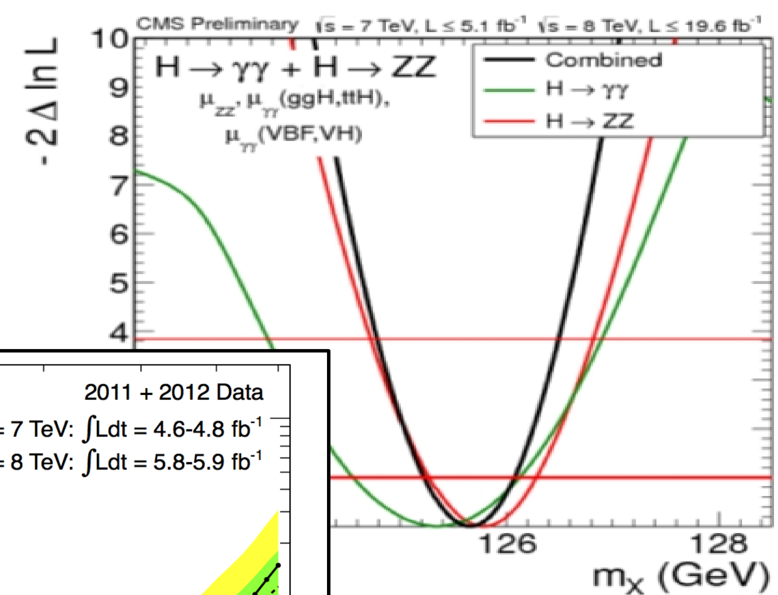
**Search era**

**Measurement era, following the discovery on July 2012**



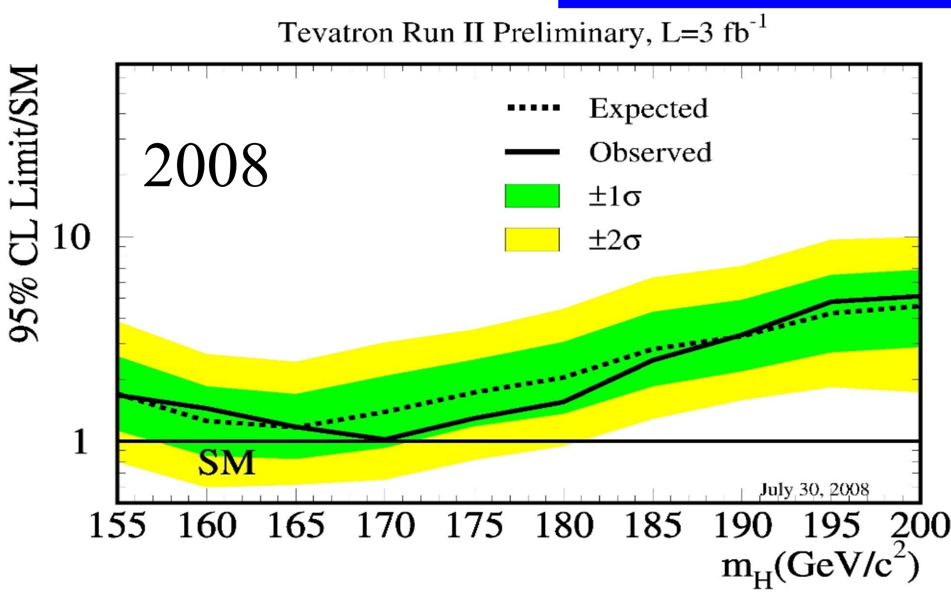

$M_H > 114.4$ GeV @95%

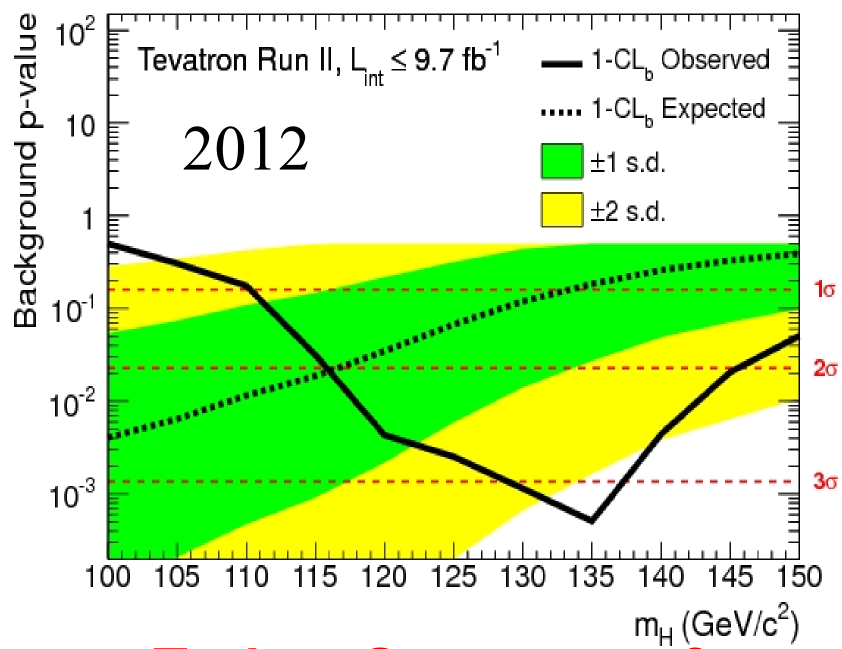



$M_H \sim 126$ GeV

# Tevatron was the bridge between the two eras


First post-LEP constraints on SM Higgs:

- started in 2008, regularly updated

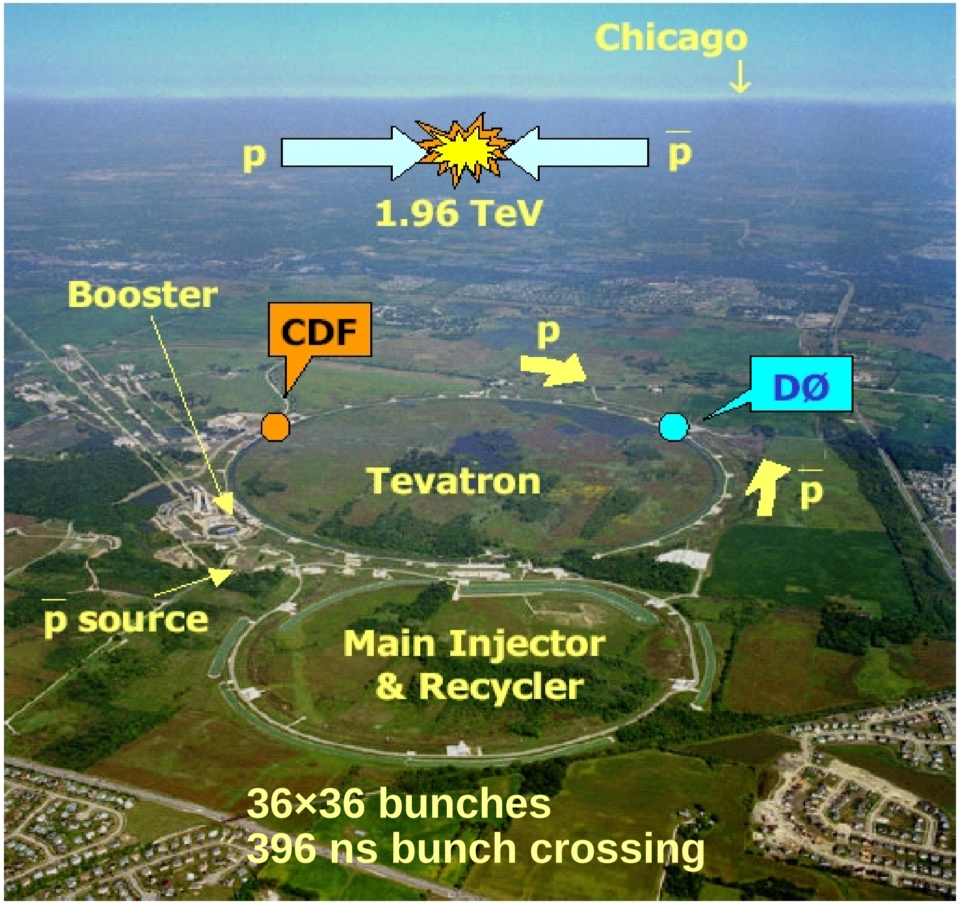
First evidence that Higgs couple to fermions

- evidence for $H \rightarrow b\bar{b}$ in July 2012

PRL 109, 071804 (2012)

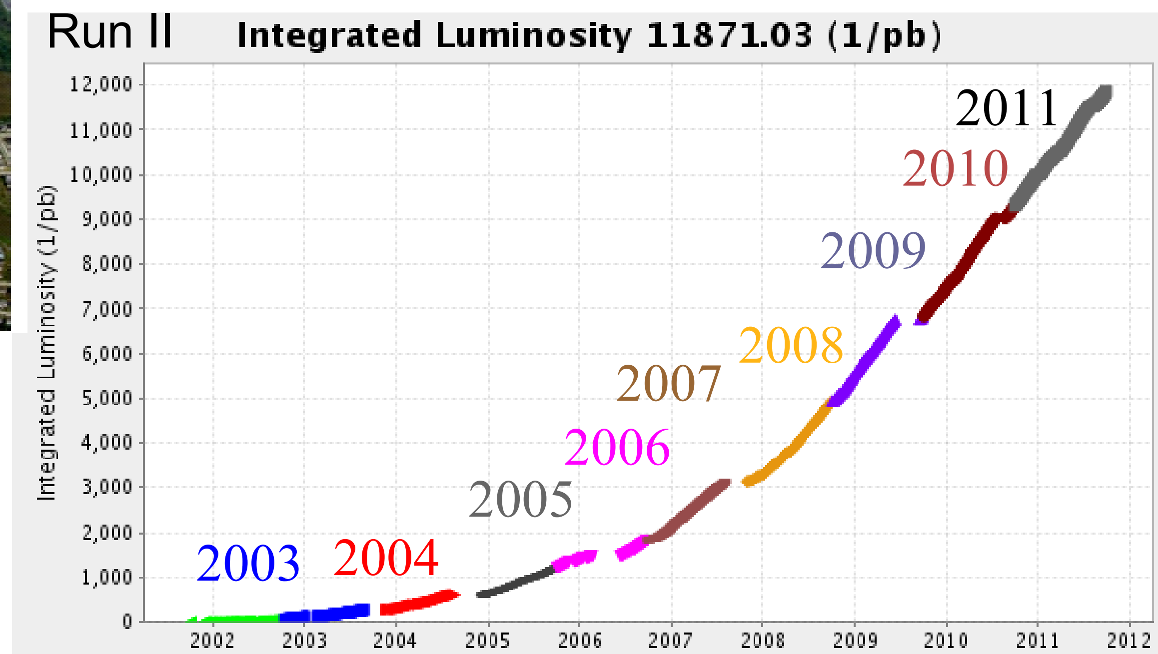
**Today: Summary of SM Higgs studies performed at Tevatron**

# The Tevatron proton-antiproton collider




Tevatron Run II: (2002-2011)

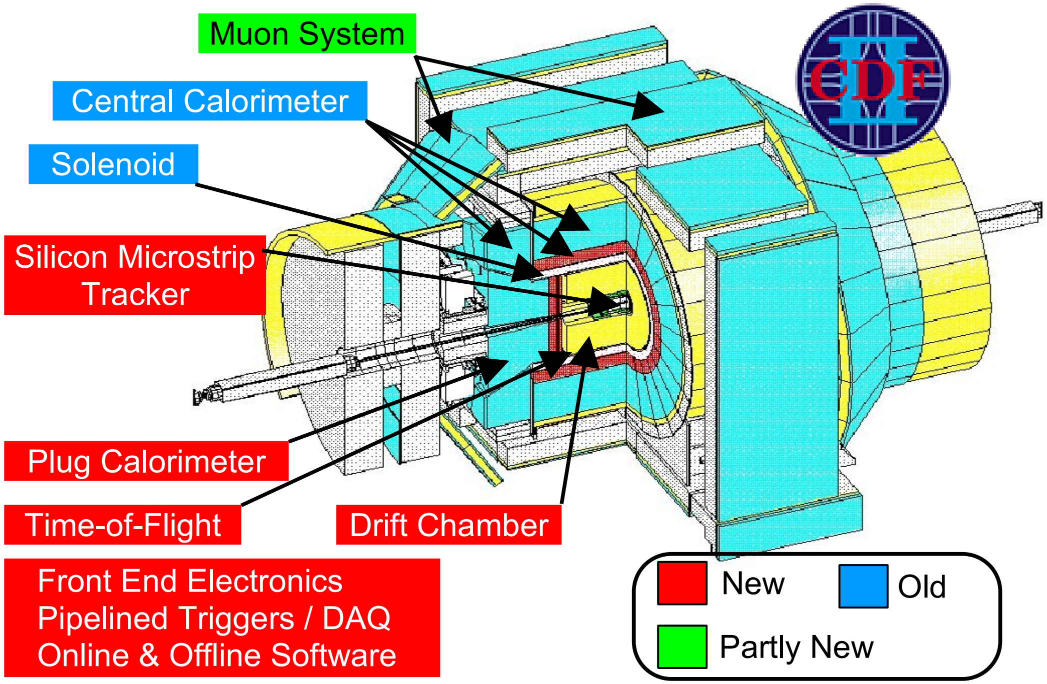
- A decade of successful running
- Improved in performance over time
- ~12 $fb^{-1}$ delivered per experiment
- ~9.5 $fb^{-1}$ for physics analysis

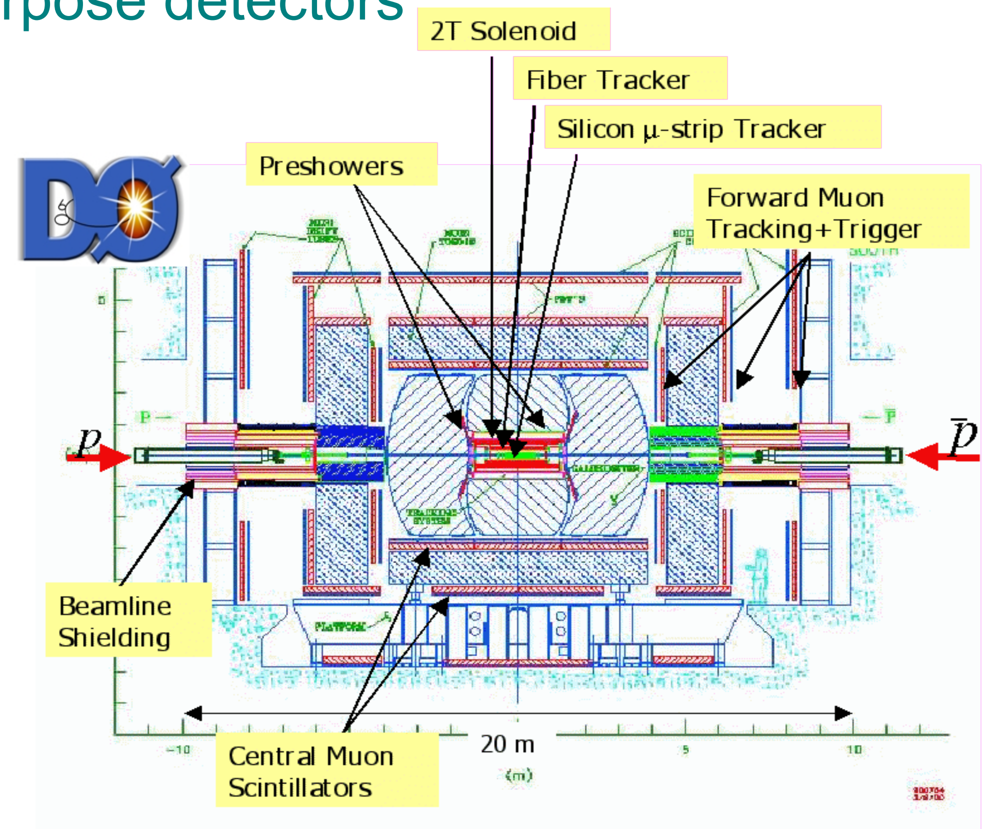



Most of the Higgs results today rely on the full data set

# Tevatron experiments in Run II

## Two multipurpose detectors




Tracking and vertexing:

- Silicon (|η| < 2.5, r~20cm)
- Drift cell (|η| < 1.1, r~130 cm)

Calorimetry

- Pb/Fe/Scintillators (|η|<3.6)

Muons

- Drift chambers/Scintillators (|η|<1.5)

Tracking and vertexing

- Silicon (|η| < 3.0, r~10cm)
- Fiber (|η| < 1.7, r~50 cm)

Calorimetry

- LAr/U (|η|<4.0)

Muons:

- Drift chambers/Scintillators (|η| <2.0)

# Bunch of legacy papers

Culmination of more than 10 years of hard work at Tevatron

Many results published in a single PRD issue, last September

In particular

CDF+D0 combination PRD 88, 052014 (2013)

| CDF Channel ($V = W, Z$ and $\ell = e, \mu$) | | Luminosity ($fb^{-1}$) | $M_H$ (GeV) | Reference |
|---|---|---|---|---|
| $WH \to \ell\nu b\bar{b}$ | $H \to b\bar{b}$ | 9.45 | 90–150 | PRL **109**, 111804 (2012) |
| $ZH \to \ell\ell b\bar{b}$ | $H \to b\bar{b}$ | 9.45 | 90–150 | PRL **109**, 111803 (2012) |
| $ZH \to \nu\bar{\nu}b\bar{b}$ | $H \to b\bar{b}$ | 9.45 | 90–150 | PRD **87**, 052008 (2013) |
| $WH + ZH \to jjb\bar{b}$ | $H \to b\bar{b}$ | 9.45 | 100–150 | JHEP **02**, 004 (2013) |
| $t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ | $H \to b\bar{b}$ | 9.45 | 100-150 | PRL **109**, 181802 (2012) |
| $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ | $H \to W^+W^-$ | 9.7 | 110–200 | PRD **88**, 052012 (2013) |
| $H \to W^+W^- \to \ell\tau_h$ | $H \to W^+W^-$ | 9.7 | 130–200 | PRD **88**, 052012 (2013) |
| $WH \to WW^+W^- \to \ell\ell\ell, \ell^\pm\ell^\pm$ | $H \to W^+W^-$ | 9.7 | 110–200 | PRD **88**, 052012 (2013) |
| $WH \to WW^+W^- \to \ell\ell\tau_h$ | $H \to W^+W^-$ | 9.7 | 130–200 | PRD **88**, 052012 (2013) |
| $ZH \to ZW^+W^- \to \ell\ell\ell + jet(s)$ | $H \to W^+W^-$ | 9.7 | 110–200 | PRD **88**, 052012 (2013) |
| $H + X \to \tau^+\tau^- + jet(s)$ | $H \to \tau^+\tau^-$ | 6.0 | 100–150 | PRL **108**, 181804 (2012) |
| $H \to \gamma\gamma$ | $H \to \gamma\gamma$ | 10.0 | 100–150 | PLB **717**, 173 (2012) |
| $H \to ZZ$ | $H \to ZZ$ | 9.7 | 120–200 | PRD **86**, 072012 (2012) |
| CDF grand combination | all CDF | 6.0–10.0 | 90–200 | PRD **88**, 052013 (2013) |

| DØ Channel ($V = W, Z$ and $\ell = e, \mu$) | | Luminosity ($fb^{-1}$) | $M_H$ (GeV) | Reference |
|---|---|---|---|---|
| $WH \to \ell\nu b\bar{b}$ | $H \to b\bar{b}$ | 9.7 | 90–150 | PRD **88**, 052008 (2013) |
| $ZH \to \ell\ell b\bar{b}$ | $H \to b\bar{b}$ | 9.7 | 90–150 | PRD **88**, 052010 (2013) |
| $ZH \to \nu\bar{\nu}b\bar{b}$ | $H \to b\bar{b}$ | 9.5 | 100–150 | PLB **716**, 285 (2012) |
| $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ | $H \to W^+W^-$ | 9.7 | 100–200 | PRD **88**, 052006 (2013) |
| $H + X \to W^+W^- \to \mu^\pm\tau_h^\mp + \leq 1$ jet | $H \to W^+W^-$ | 7.3 | 155–200 | PLB **714**, 237 (2012) |
| $H \to W^+W^- \to \ell\nu q'\bar{q}$ | $H \to W^+W^-$ | 9.7 | 100–200 | PRD **88**, 052008 (2013) |
| $VH \to ee\mu/\mu\mu e + X$ | $H \to W^+W^-$ | 9.7 | 100–200 | PRD **88**, 052009 (2013) |
| $VH \to e^\pm\mu^\pm + X$ | $H \to W^+W^-$ | 9.7 | 100–200 | PRD **88**, 052009 (2013) |
| $VH \to \ell\nu q'\bar{q}q'\bar{q}$ | $H \to W^+W^-$ | 9.7 | 100–200 | PRD **88**, 052008 (2013) |
| $VH \to \tau_h\tau_h\mu + X$ | $H \to \tau^+\tau^-$ | 8.6 | 100–150 | PRD **88**, 052009 (2013) |
| $H + X \to \ell\tau_h jj$ | $H \to \tau^+\tau^-$ | 9.7 | 105–150 | PRD **88**, 052005 (2013) |
| $H \to \gamma\gamma$ | $H \to \gamma\gamma$ | 9.7 | 100–150 | PRD **88**, 052007 (2013) |
| DØ grand combination | all DØ | 7.3–9.7 | 90–200 | PRD **88**, 052011 (2013) |

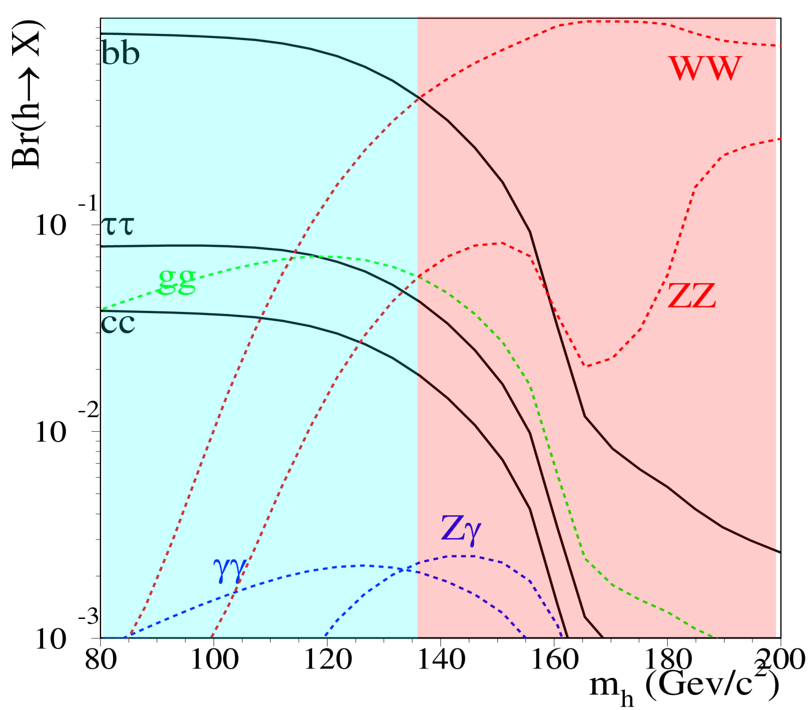
| | | | | |
|---|---|---|---|---|
| CDF+DØ grand combination | all CDF+DØ | 6.0–10.0 | 90–200 | PRD **88**, 052014 (2013) |

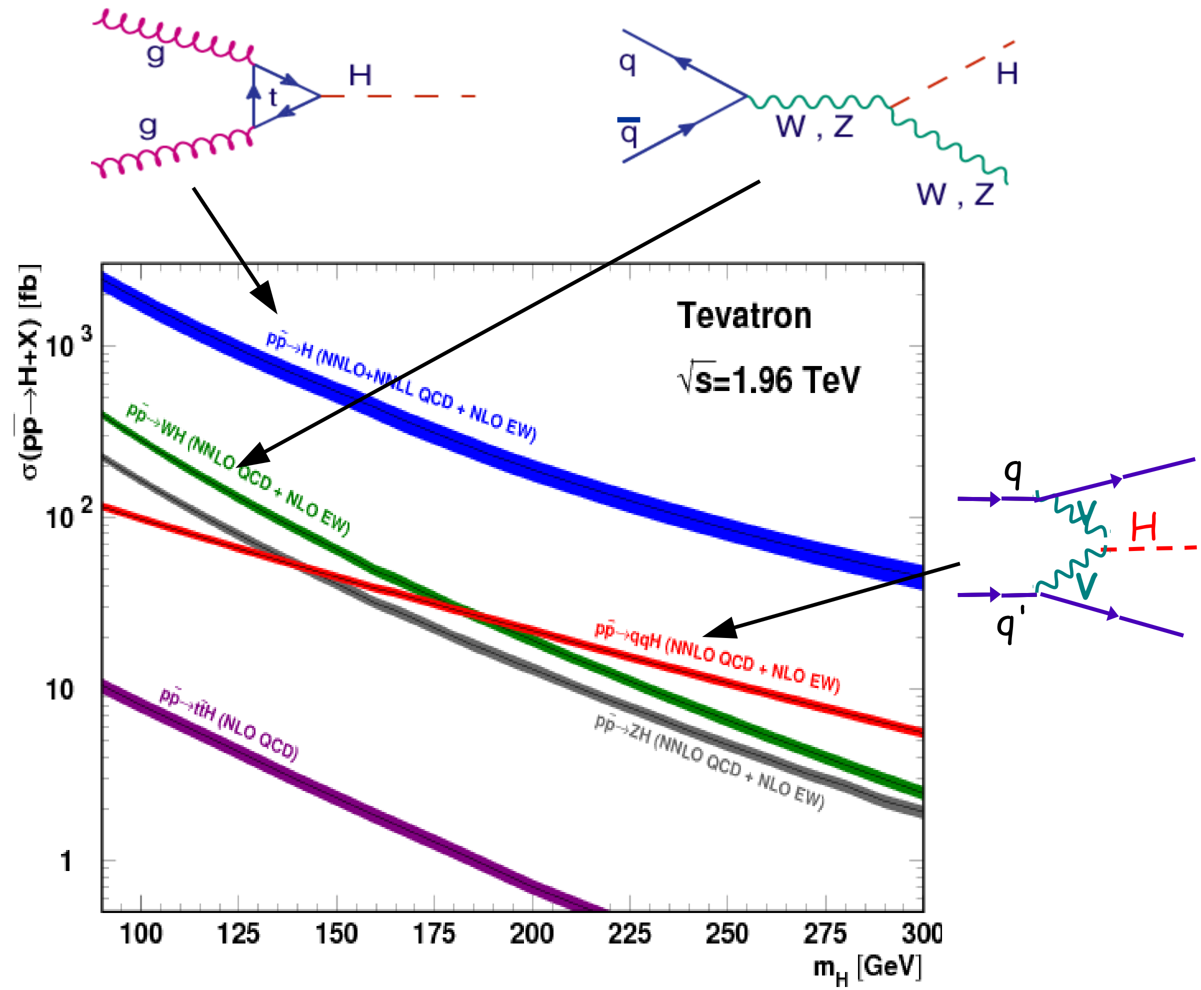
# Low Mass vs High Mass at Tevatron

- The different decay modes define the "low mass" vs "high mass" channels
- Have to account for several production modes
- Tevatron reach in mass range between ~100-200 GeV

$m_H$<135 GeV
$H \rightarrow b\bar{b}$

$m_H$>135 GeV
$H \rightarrow WW^*$

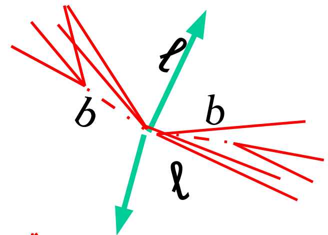


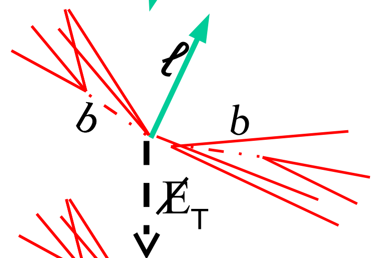
# Most sensitive channels at the Tevatron

## Mostly for $M_H$ < 135 GeV

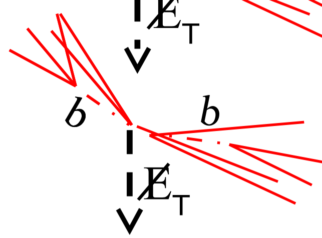
$p\bar{p} \rightarrow ZH \rightarrow \ell\ell b\bar{b}$
- 2 leptons + 2 bjets




$p\bar{p} \rightarrow WH \rightarrow \ell\nu b\bar{b}$
- 1 lepton + $\not\!\!E_T$ + 2 bjets



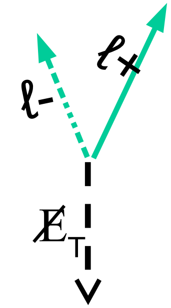

$p\bar{p} \rightarrow ZH \rightarrow \nu\nu b\bar{b}$
- 0 leptons + $\not\!\!E_T$ + 2 bjets




Analysis requirements:
- b-tagging
- Good dijet mass resolution
- Lepton acceptance
- Good modeling of V+jet background

## Mostly for $M_H$ > 135 GeV

$gg \rightarrow H \rightarrow WW^*$
- 2 leptons + $\not\!\!E_T$




Analysis requirements:
- Lepton acceptance
- Good modeling of $\not\!\!E_T$

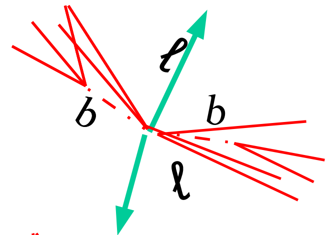
> $VH \rightarrow Vb\bar{b}$ is the most sensitive @125 GeV
> Tevatron can probe $Hb\bar{b}$ coupling

# But also many other channels

| Mostly for $M_H$ < 135 GeV | Mostly for $M_H$ > 135 GeV |
|---|---|

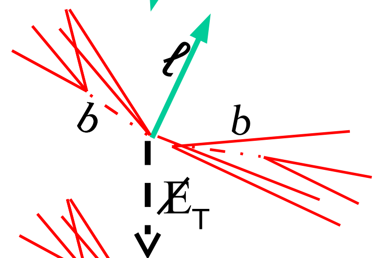
$p\bar{p} \rightarrow ZH \rightarrow \ell\ell b\bar{b}$

- 2 leptons + 2 bjets



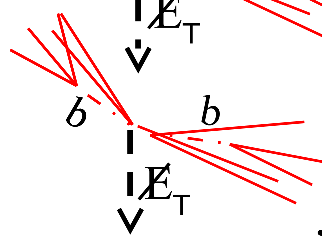

$p\bar{p} \rightarrow WH \rightarrow \ell\nu b\bar{b}$

- 1 lepton + $\not{E}_T$+ 2 bjets




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

- 0 leptons+ $\not{E}_T$+ 2 bjets

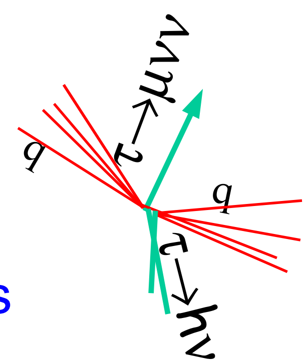



$p\bar{p} \rightarrow$H+ V/X $\rightarrow \tau\tau$ jj

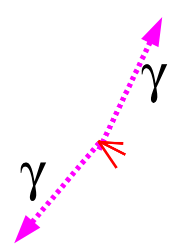
- 1 lepton +1 hadronic tau+jets

$p\bar{p} \rightarrow WH \rightarrow \tau\tau\mu\nu$

- 1 lepton + $\not{E}_T$+ 2 hadronic taus

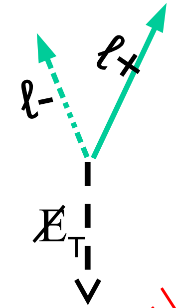



$p\bar{p} \rightarrow H \rightarrow \gamma\gamma$

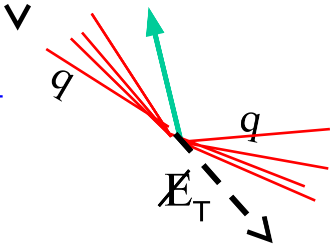



$gg \rightarrow H \rightarrow WW^*$

- 2 leptons + $\not{E}_T$

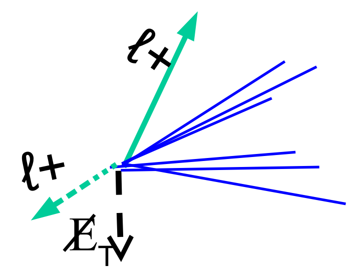



- 1 leptons + jets + $\not{E}_T$



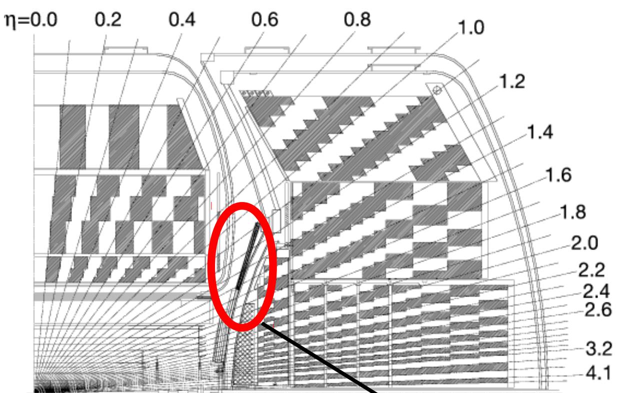

$p\bar{p} \rightarrow VH \rightarrow VWW^*$

- 3 leptons + $\not{E}_T$
- lepton+ $\not{E}_T$ + 4jets
- 2 leptons of same charge + jets

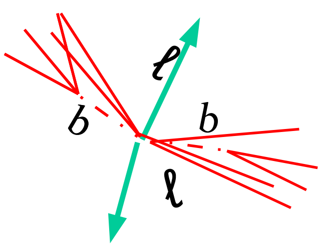


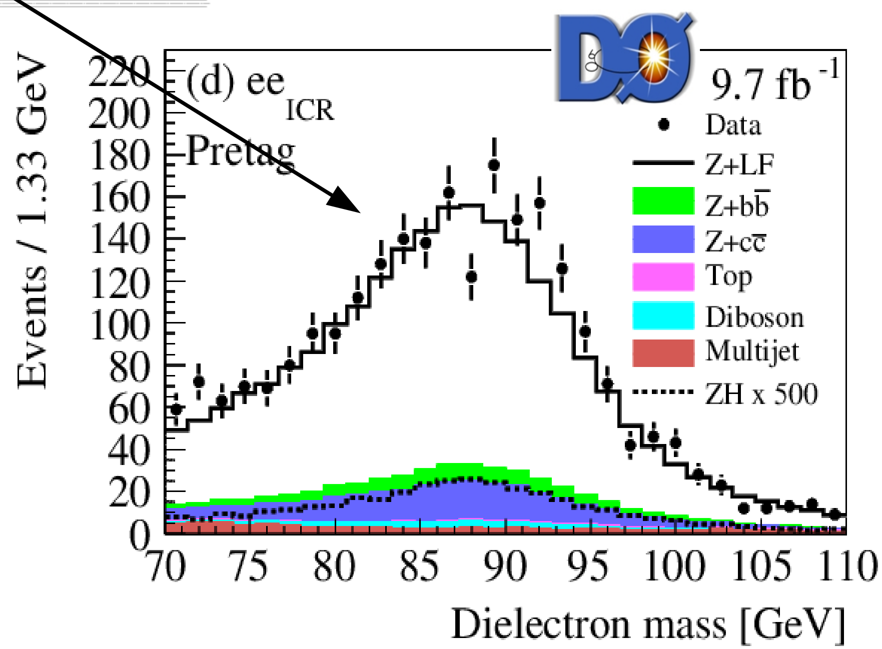
# A taste of Tevatron analyses

- Strategy
  - Try to maximize acceptance, efficiency, and resolution



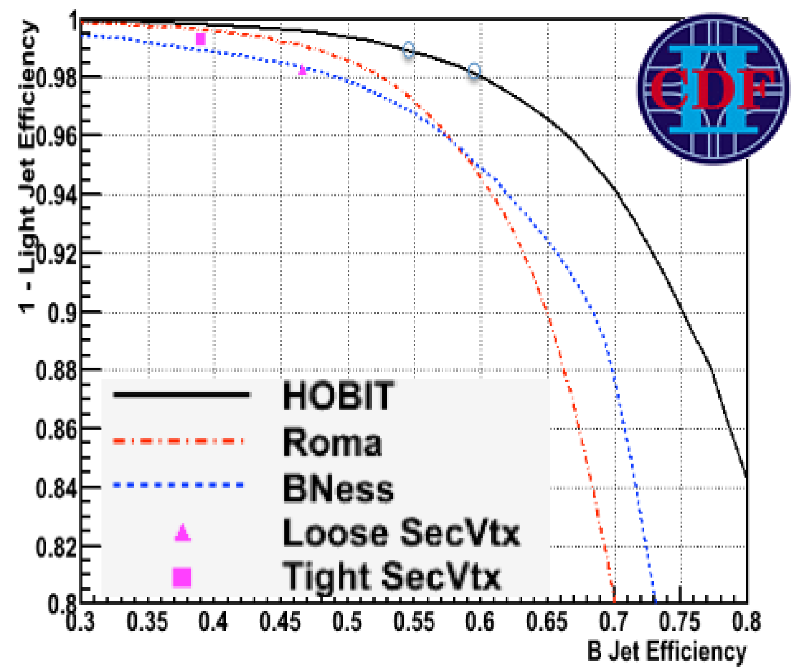

+15% $Z \to ee$ events in $\ell\ell b\bar{b}$ channel



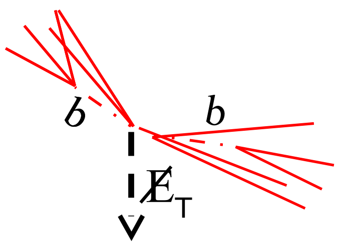

CDF HOBIT b-tagger (2012)

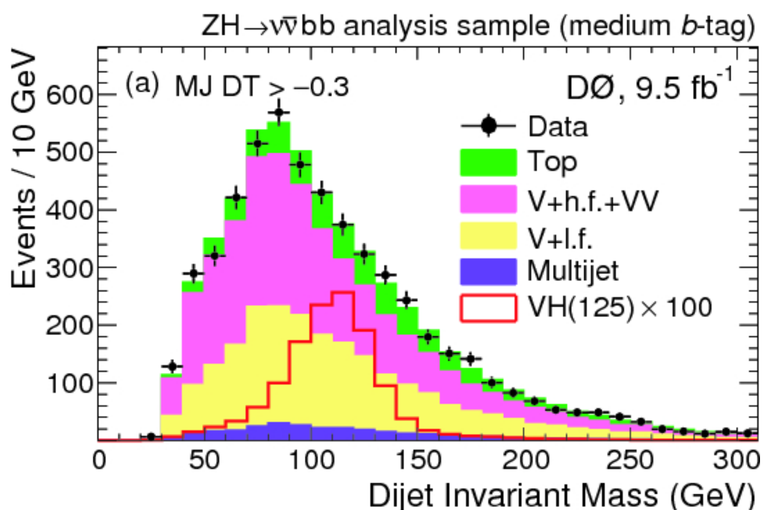
ε~60% for 1.5% mis-tag

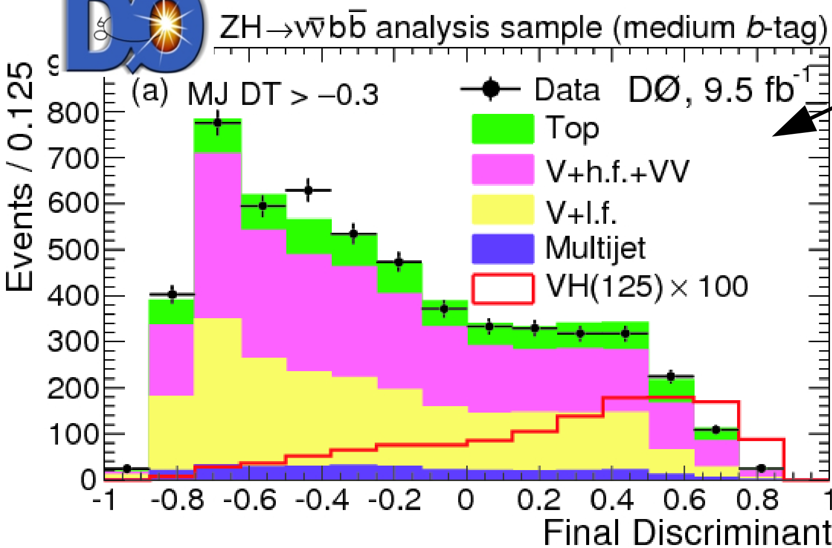


# A taste of Tevatron analyses

- Strategy
  - Try to maximize acceptance, efficiency, and resolution
  - Multivariate techniques (MVA) to maximize use of available information



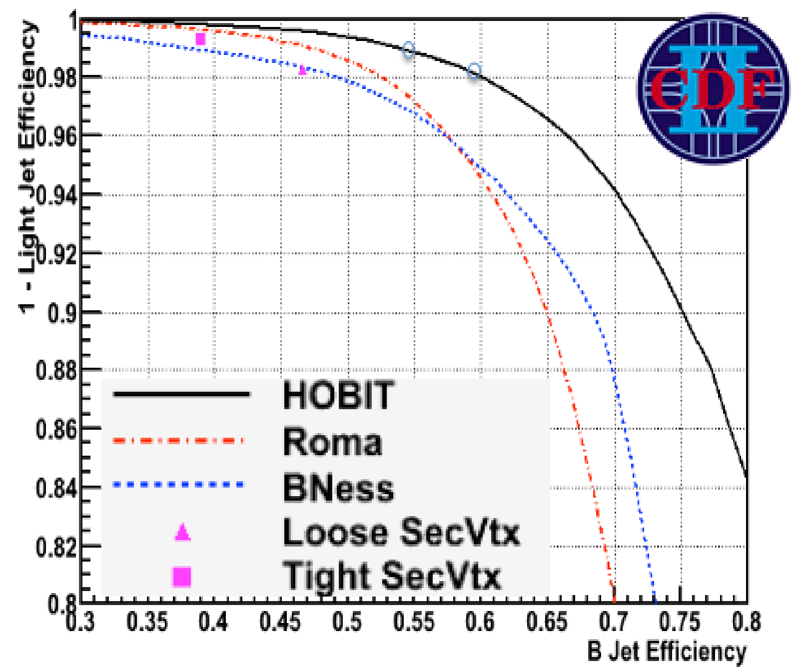




~25% better S/√B than $M_{b\bar{b}}$

CDF HOBIT b-tagger (2012)

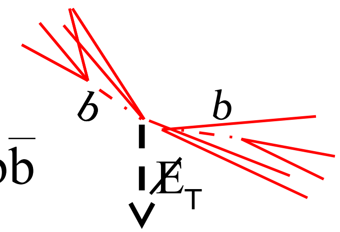
ε~60% for 1.5% mis-tag



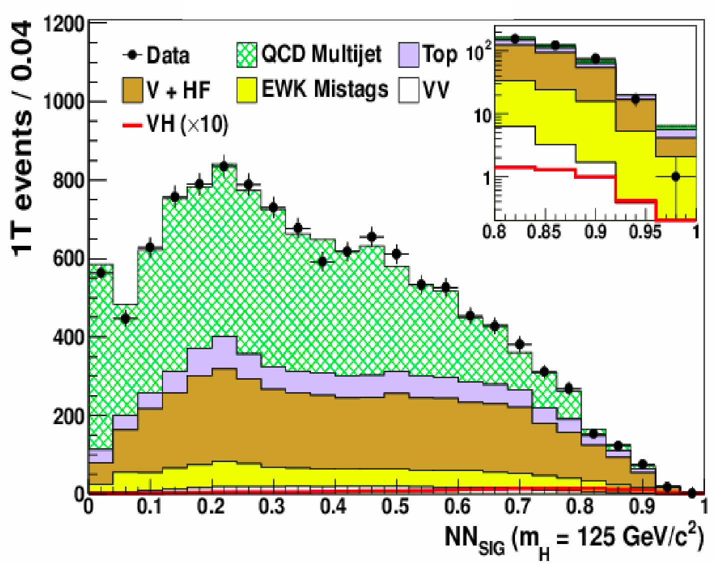
# A taste of Tevatron analyses

- Strategy
  - Try to maximize acceptance, efficiency, and resolution
  - Multivariate techniques (MVA) to maximize use of available information
  - Split analyses into subchannels with different S/B

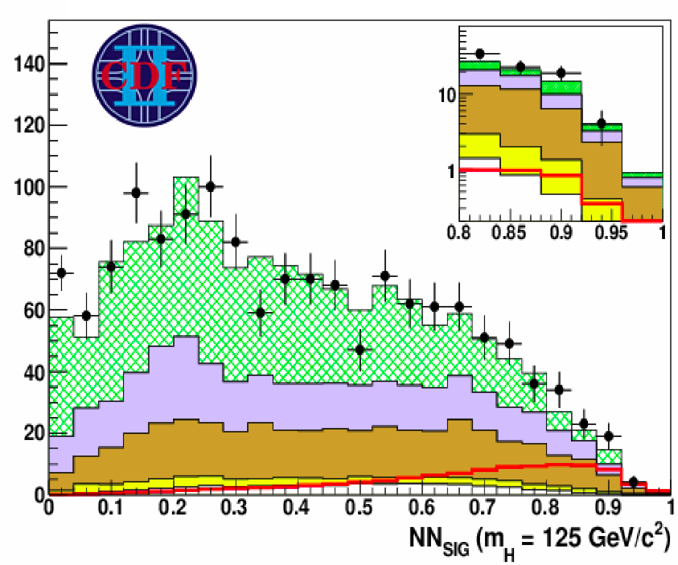
$ZH \rightarrow \nu\nu b\bar{b}$



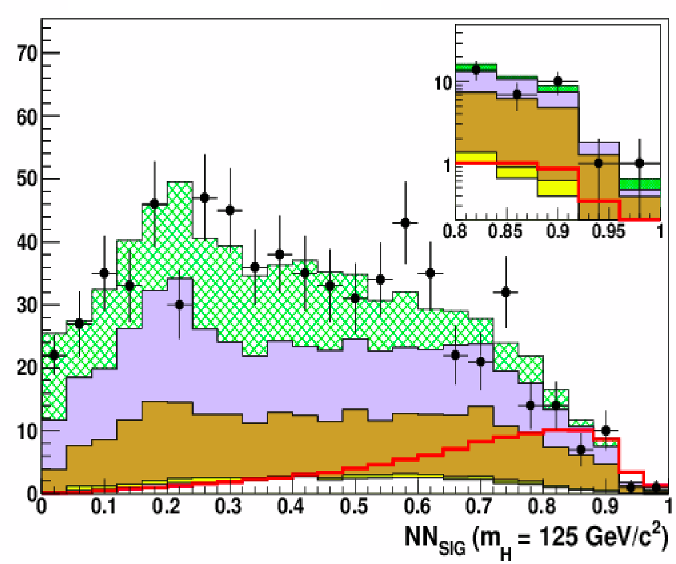

1 loose b-tag




1 loose+1 tight b-tag

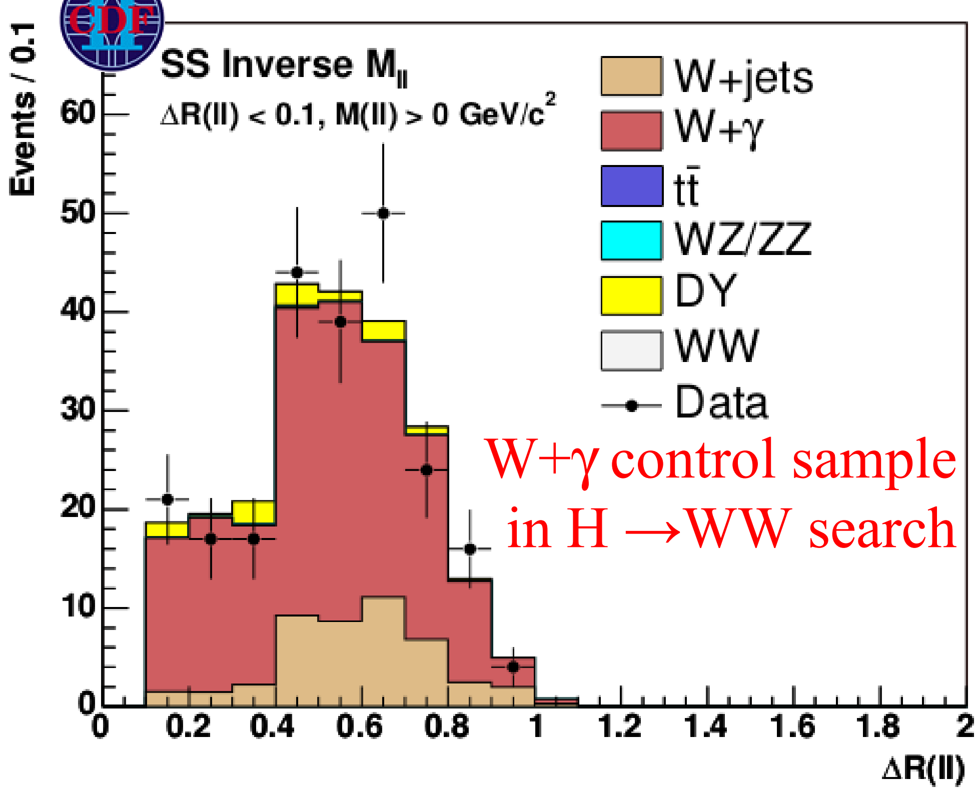


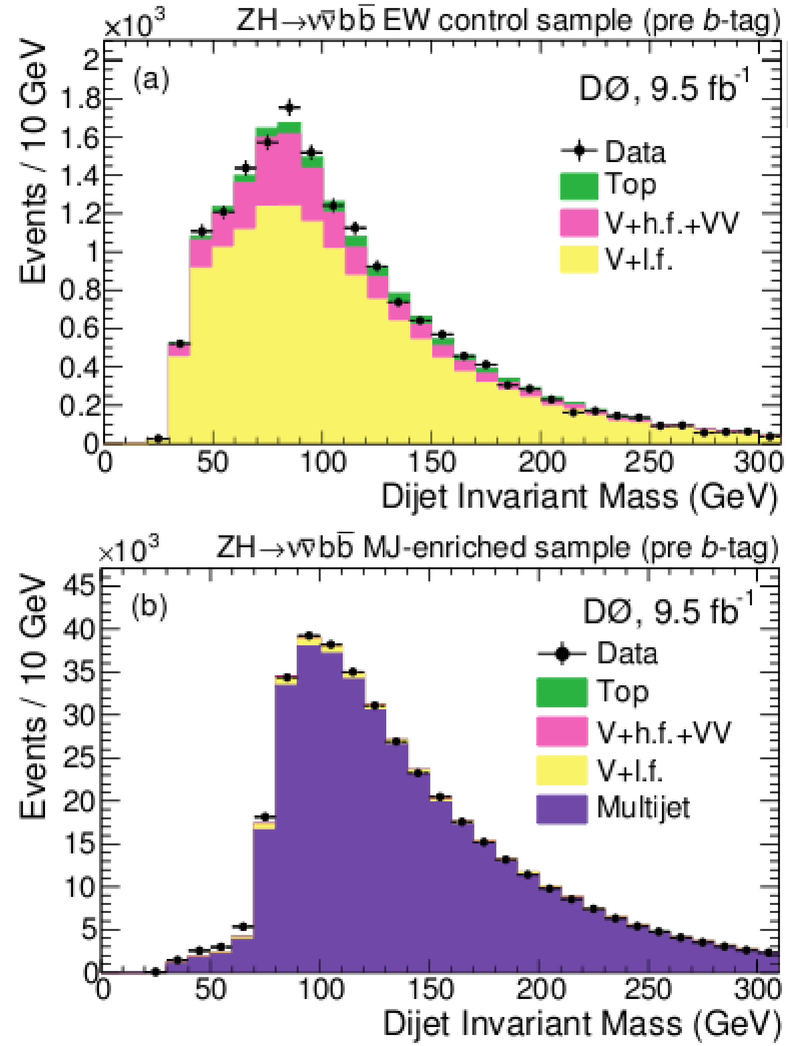

2 tight b-tag



# A taste of Tevatron analyses

- Strategy
  - Try to maximize acceptance, efficiency, and resolution
  - Multivariate techniques (MVA) to maximize use of available information
  - Split analyses into subchannels with different S/B
  - Use data to control background



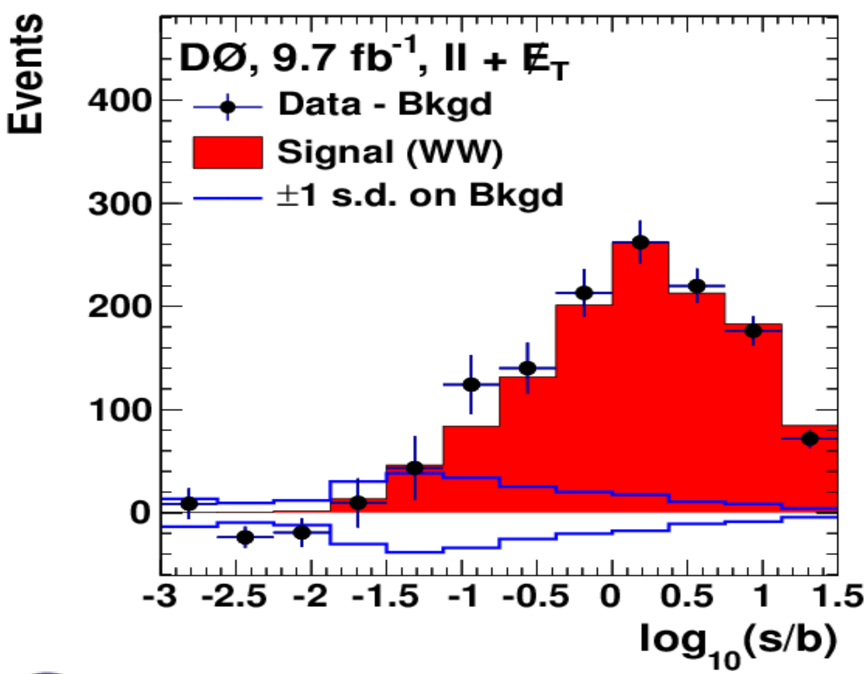
# A taste of Tevatron analyses

- Strategy
  - Try to maximize acceptance, efficiency, and resolution
  - Multivariate techniques (MVA) to maximize use of available information
  - Split analyses into subchannels with different S/B
  - Use data to control background
  - Use SM candles to validate the methods

$p\bar{p} \rightarrow WW \rightarrow \ell\ell\nu\nu$

Measurement σ=11.6±0.7 pb

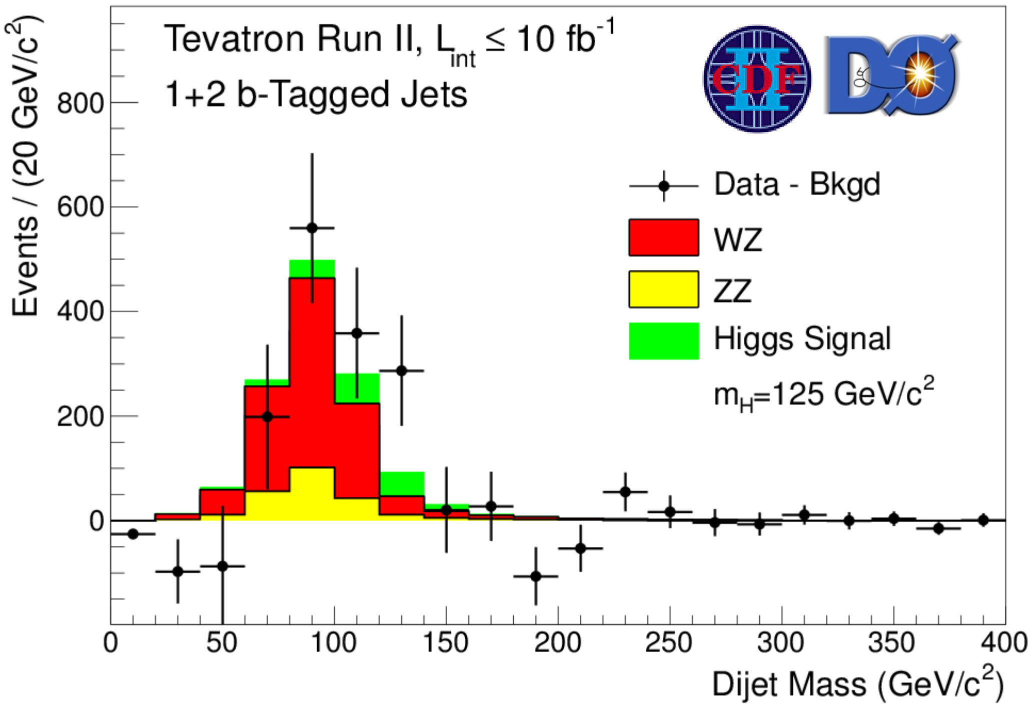
Agreement with prediction: σ=11.3±0.7 pb




$p\bar{p} \rightarrow VZ \rightarrow Vb\bar{b}$

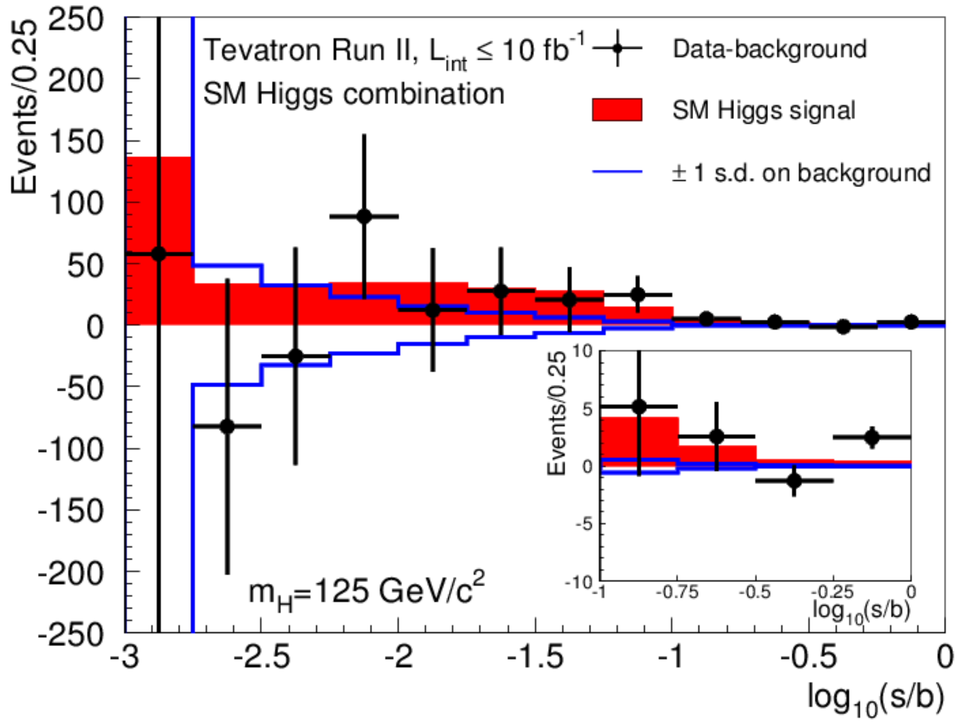
Measurement σ=3.0±0.6(stat)±0.7(syst) pb

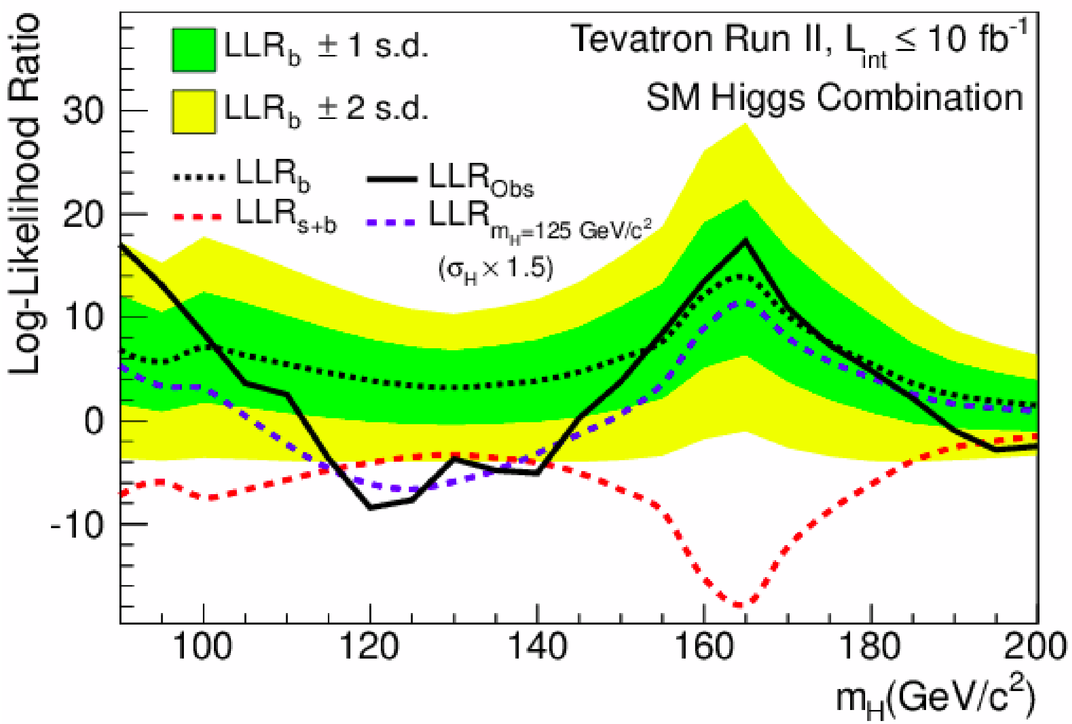
Agreement with prediction: σ=4.4±0.3 pb



# Combined SM Higgs results

- Build Likelihood based on all multivariate discriminant distributions to test S and S+B hypotheses
- Combine ~300 sub-channels

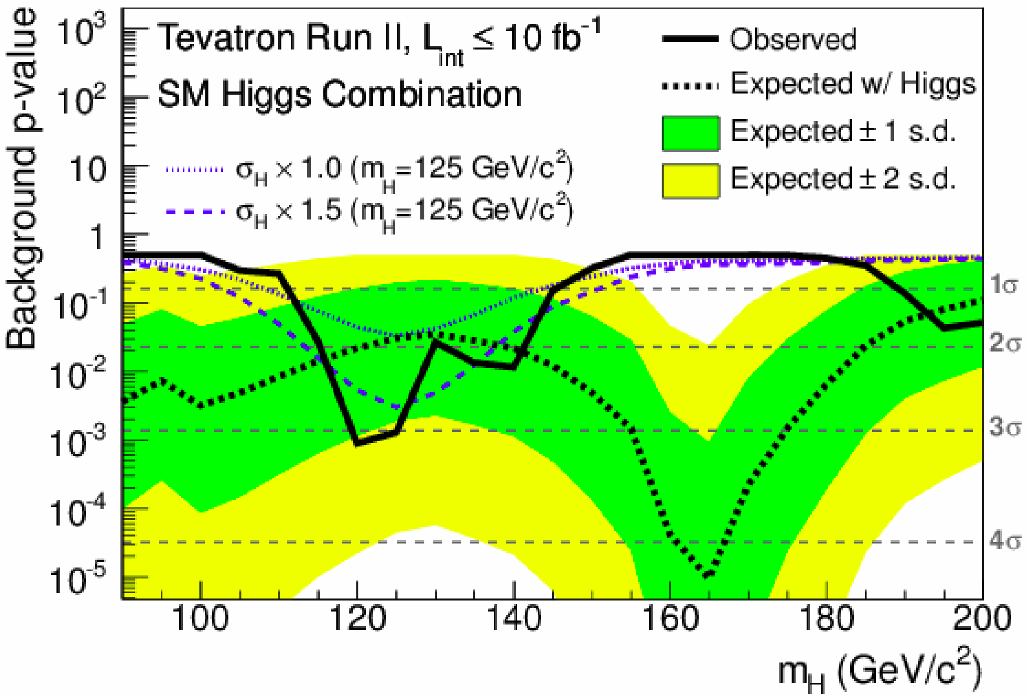


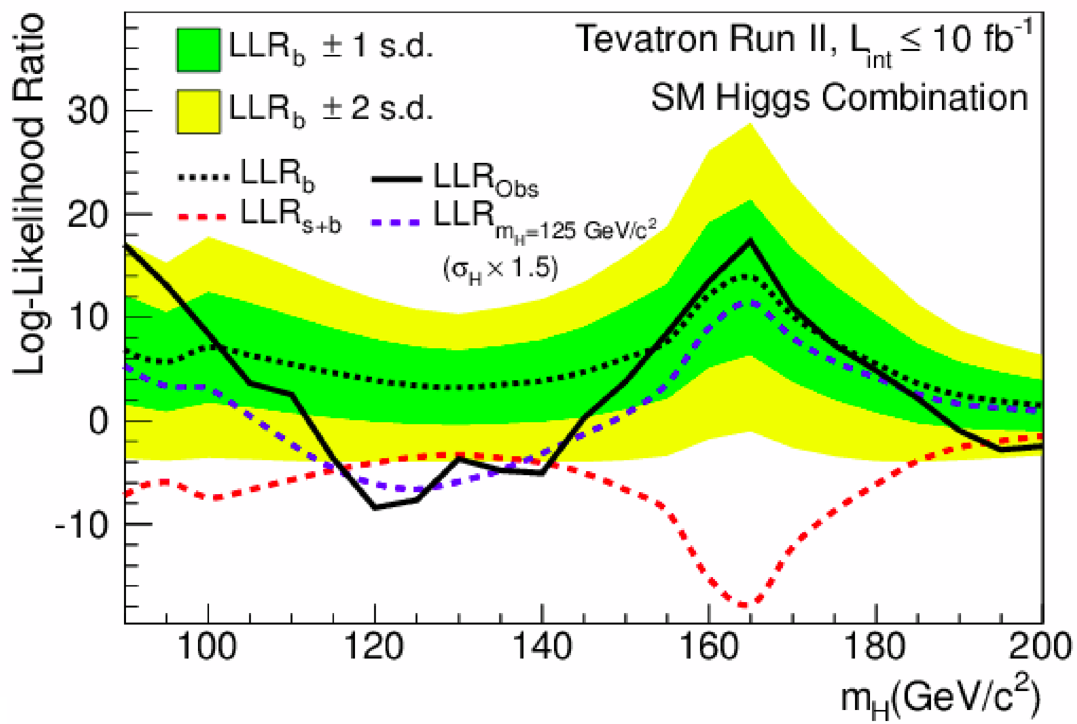




- Broad excess in the low mass range around 115-140 GeV

# Combined SM Higgs results

- Build Likelihood based on all multivariate discriminant distributions to test S and S+B hypotheses
- Combine ~300 sub-channels

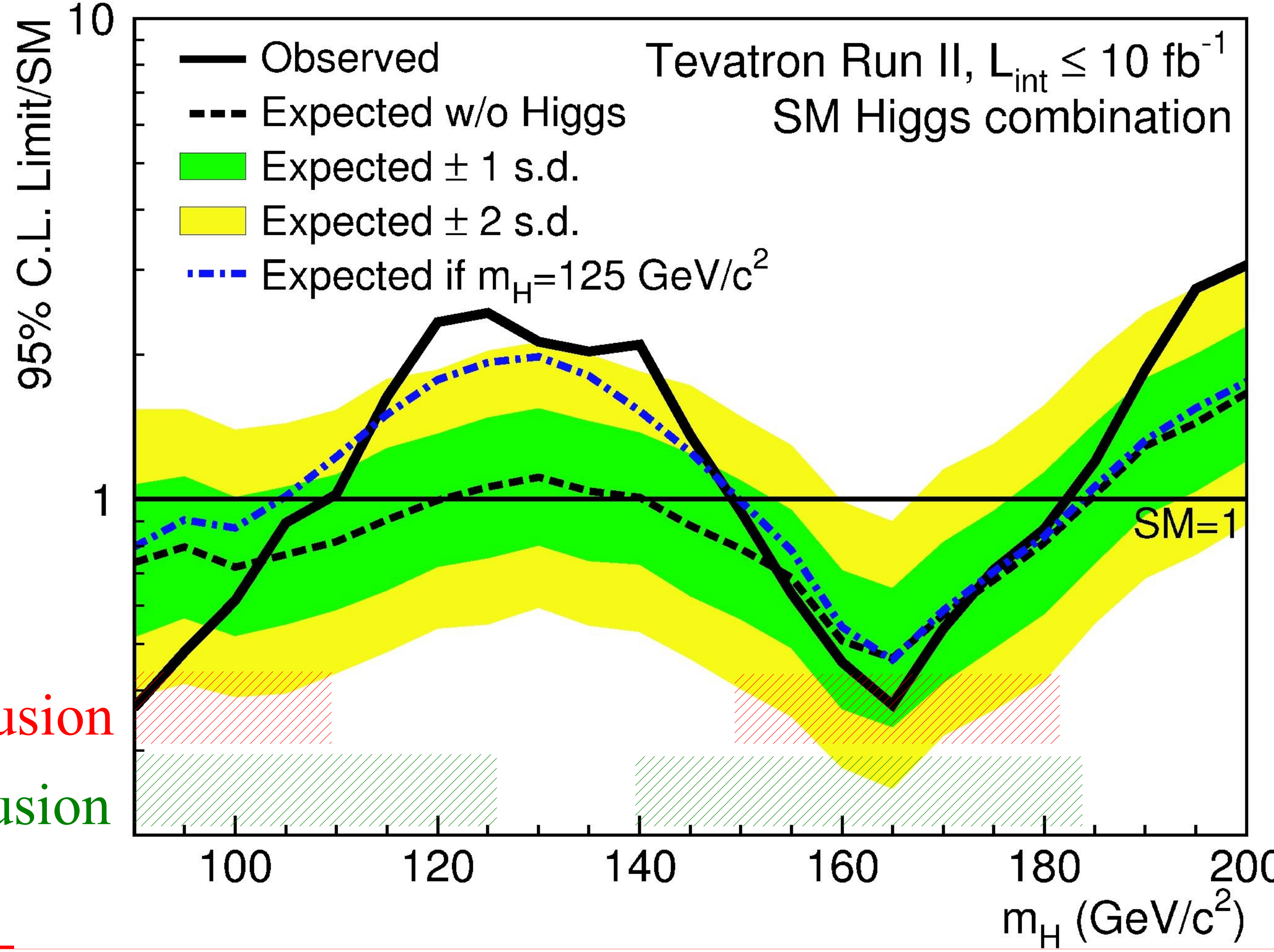



- Broad excess in the low mass range around 115-140 GeV
- Local p-value corresponding to 3.0 sigma for $M_H$=125 GeV
  - D0 1.7 sigma @ 125 GeV
  - CDF 2.0 sigma @ 125 GeV
- Consistent with a Higgs boson of 125 GeV at x1.5 SM rate

# Exclusion limits at 95% CL

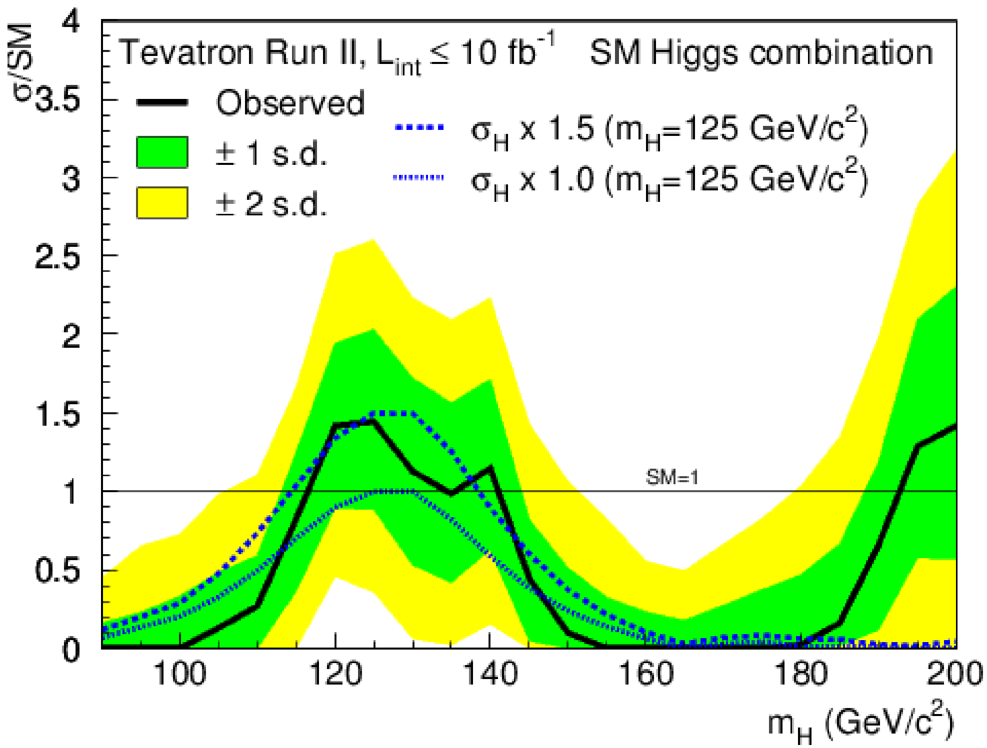
- Expected sensitivity almost covering the full range [90-185] GeV
  - 90< $M_H$<120 GeV and 140<$M_H$<184 GeV
- Observed excluded region is smaller because of the excess
  - 90<$M_H$<109 GeV and 149 < $M_H$<182 GeV

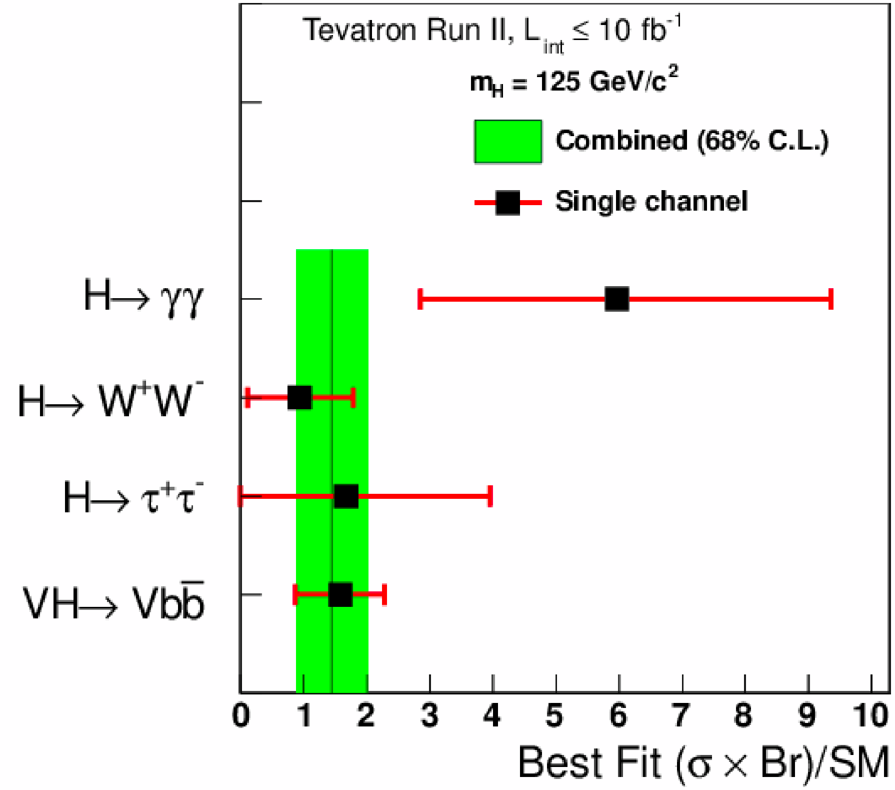



observed exclusion

expected exclusion

# Quantifying excess: signal strength




- Best fit of overall signal strength
  R = 1.4 ± 0.6 for $M_H$=125 GeV
  - Consistent with SM Higgs
  - Fairly consistent across channels
- H → b$\bar{b}$ results: R=1.6 ± 0.7
  - Atlas R= 0.2±0.6
  - CMS R= 1.0±0.5

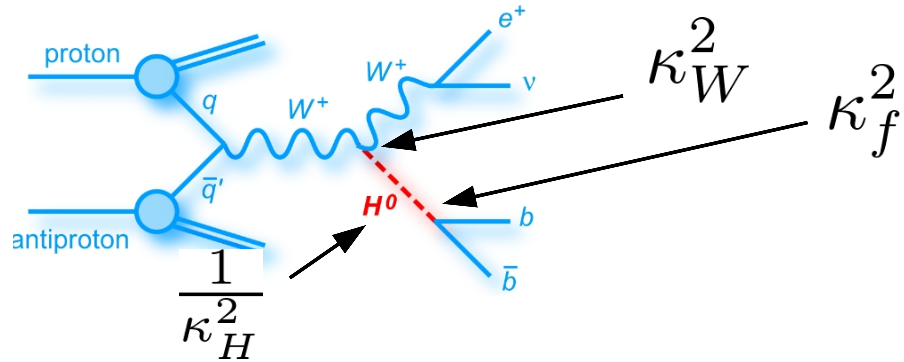
| | CDF | DØ | CDF+DØ |
|---|---|---|---|
| $R_{\rm fit}$(SM) | $1.54^{+0.77}_{-0.73}$ | $1.40^{+0.92}_{-0.88}$ | $1.44^{+0.59}_{-0.56}$ |
| $R_{\rm fit}(H \to W^+W^-)$ | $0.00^{+1.78}_{-0.00}$ | $1.90^{+1.63}_{-1.52}$ | $0.94^{+0.85}_{-0.83}$ |
| $R_{\rm fit}(VH \to Vb\bar{b})$ | $1.72^{+0.92}_{-0.87}$ | $1.23^{+1.24}_{-1.17}$ | $1.59^{+0.69}_{-0.72}$ |
| $R_{\rm fit}(H \to \gamma\gamma)$ | $7.81^{+4.61}_{-4.42}$ | $4.20^{+4.60}_{-4.20}$ | $5.97^{+3.39}_{-3.12}$ |
| $R_{\rm fit}(H \to \tau^+\tau^-)$ | $0.00^{+8.44}_{-0.00}$ | $3.96^{+4.11}_{-3.38}$ | $1.68^{+2.28}_{-1.68}$ |
| $R_{\rm fit}(t\bar{t}H \to t\bar{t}b\bar{b})$ | $9.49^{+6.60}_{-6.28}$ | – | – |

# Probing the Higgs couplings

- Follow prescription of LHC Higgs working group Arxiv:1209.0040
  - Assume a SM-like Higgs particle of 125 GeV
    - no invisible decay, no extra particle in loops
- Multiply SM coupling to fermions and bosons by
  - $\kappa_f$ for Hbb, Hcc, Htt, H$\tau\tau$ vertices
  - $\kappa_W$, $\kappa_Z$ for HWW, HZZ vertices
- Propagate modification to production ($\sigma$) and Branching ratios (BR)
    - eg for $p\bar{p} \rightarrow WH \rightarrow Wb\bar{b}$ :

$$\sigma.\mathcal{B}R = [\sigma \cdot .\mathcal{B}R]_{SM} \times \frac{\kappa_f^2 \kappa_W^2}{\kappa_H^2}$$

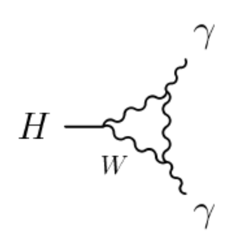
total width scaling factor

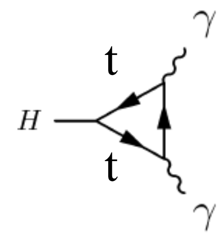



NB: Sign disambiguation in loop interference terms

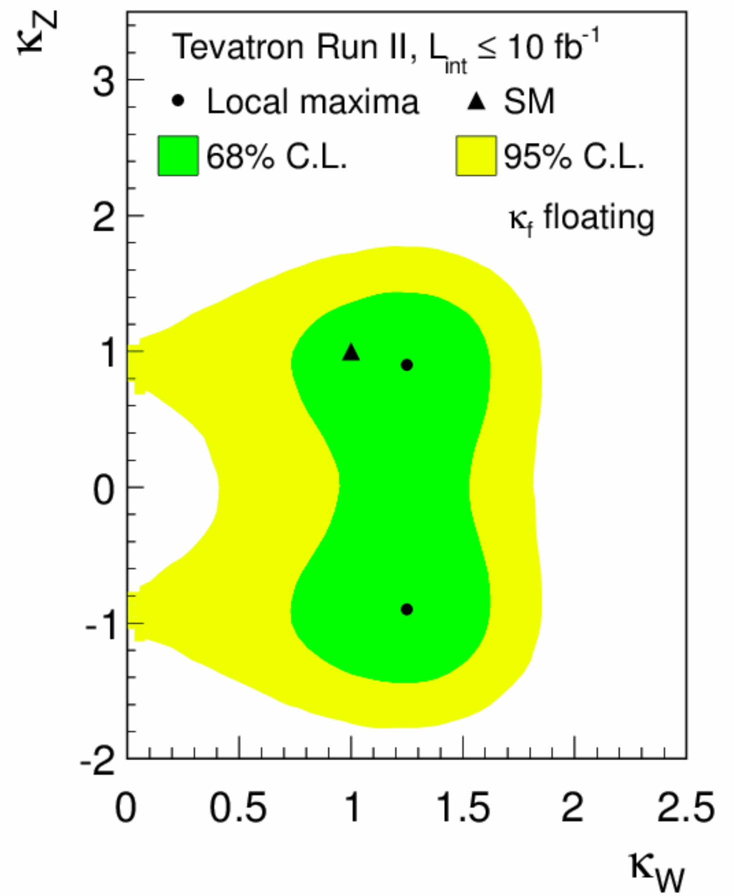
- in particular $H \rightarrow \gamma\gamma$ :

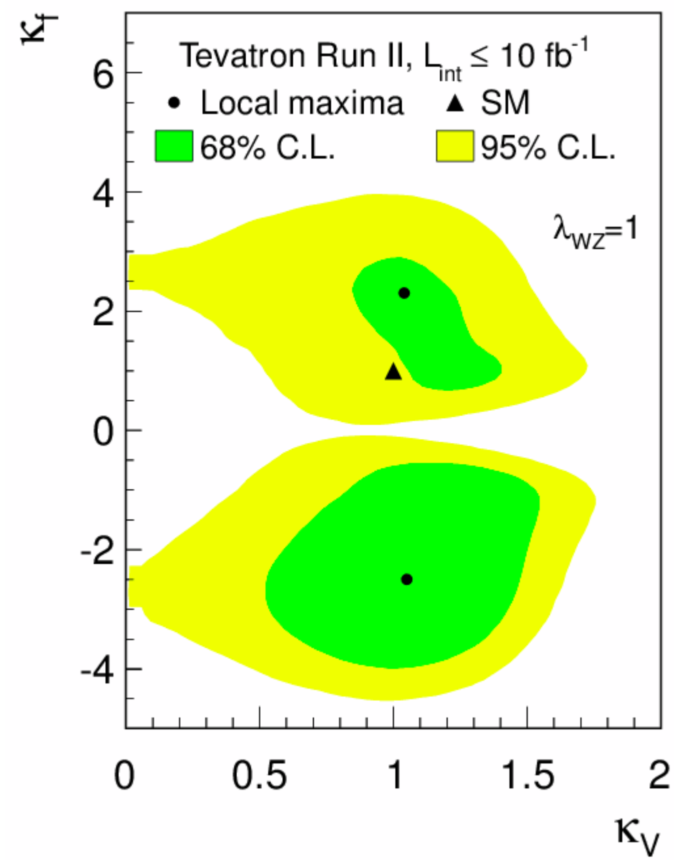
$$\Gamma(H \rightarrow \gamma\gamma) = \Gamma(H \rightarrow \gamma\gamma)_{SM}(1.28\kappa_W - 0.28\kappa_f)^2$$



# 2d constraints on coupling



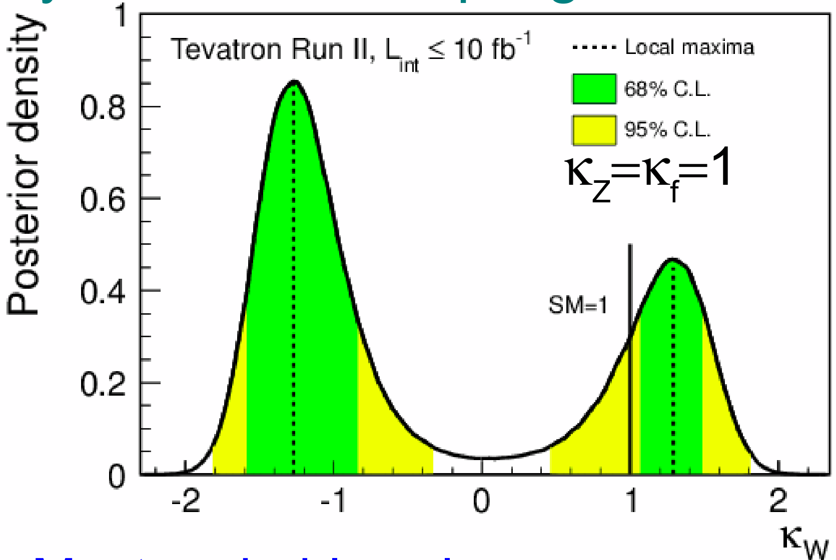



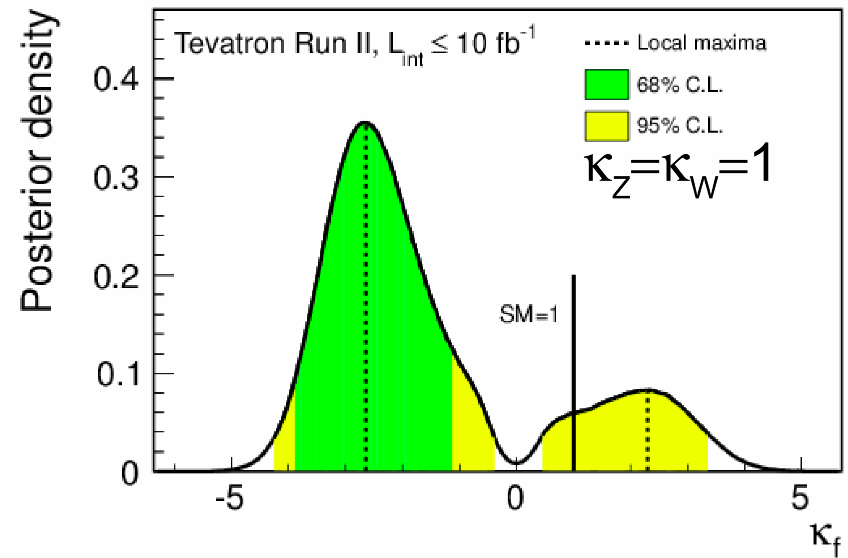

- $\kappa_f$ floating
  - Preferred region around $(\kappa_W,\kappa_Z)=(1.25\ ,\ \pm0.90)$
- Assuming custodial symmetry $\kappa_W=\kappa_Z=\kappa_V$
  - Preferred regions around $(\kappa_V,\kappa_f)=(1.05\ ,\ -2.40)$ and $(\kappa_V,\kappa_f)=(1.05\ ,\ 2.30)$

NB: Negative values for $\kappa_f$ are preferred because of slight $H\rightarrow\gamma\gamma$ excess

# 1d constraints on couplings

- Vary one of the coupling, let the 2 other fixed to SM value of 1




  - Most probable values:

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

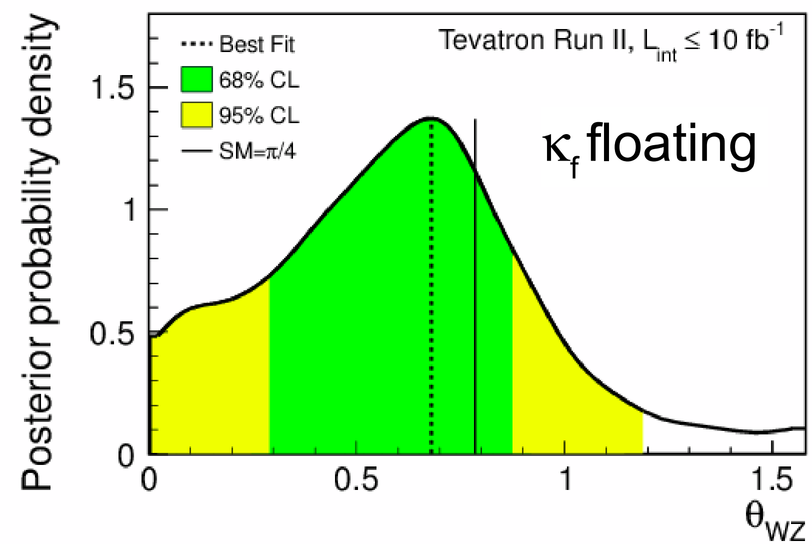
$$\kappa_Z = \pm 1.05^{+0.45}_{-0.55}$$

$$\kappa_f = -2.64^{+1.59}_{-1.30}$$

- Test custodial symmetry ($\kappa_f$ floating)

$$|\theta_{WZ}| = 0.68^{+0.21}_{-0.41}$$

with $\theta_{WZ} = \tan^{-1}(\frac{\kappa_Z}{\kappa_W})$



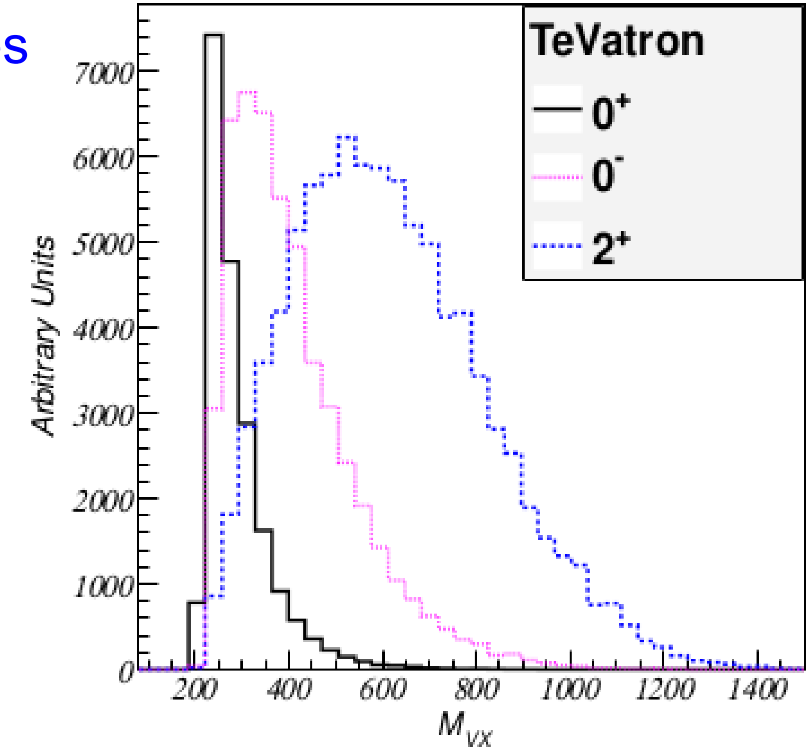
# More properties: Testing spin/parity

- Spin/parity of particle affects excitation curve near production threshold
  - $p\bar{p} \rightarrow Z/W+X$ sensitive to "threshold" effects (convoluted with proton PDF) (see Ellis et al JHEP 1211, 134 (2012) )
    - s-wave for $0^+$: $\sigma \sim \beta$;
    - p-wave for $0^-$: $\sigma \sim \beta^3$
    - d-wave for $2^+$: $\sigma \sim \beta^5$

$$\text{with } \beta = \sqrt{\frac{\hat{s}-(M_H+M_Z)^2}{\hat{s}-(M_H-M_Z)^2}}$$

  - Differential cross-sections depend strongly on $J^{PC}$ of new particle

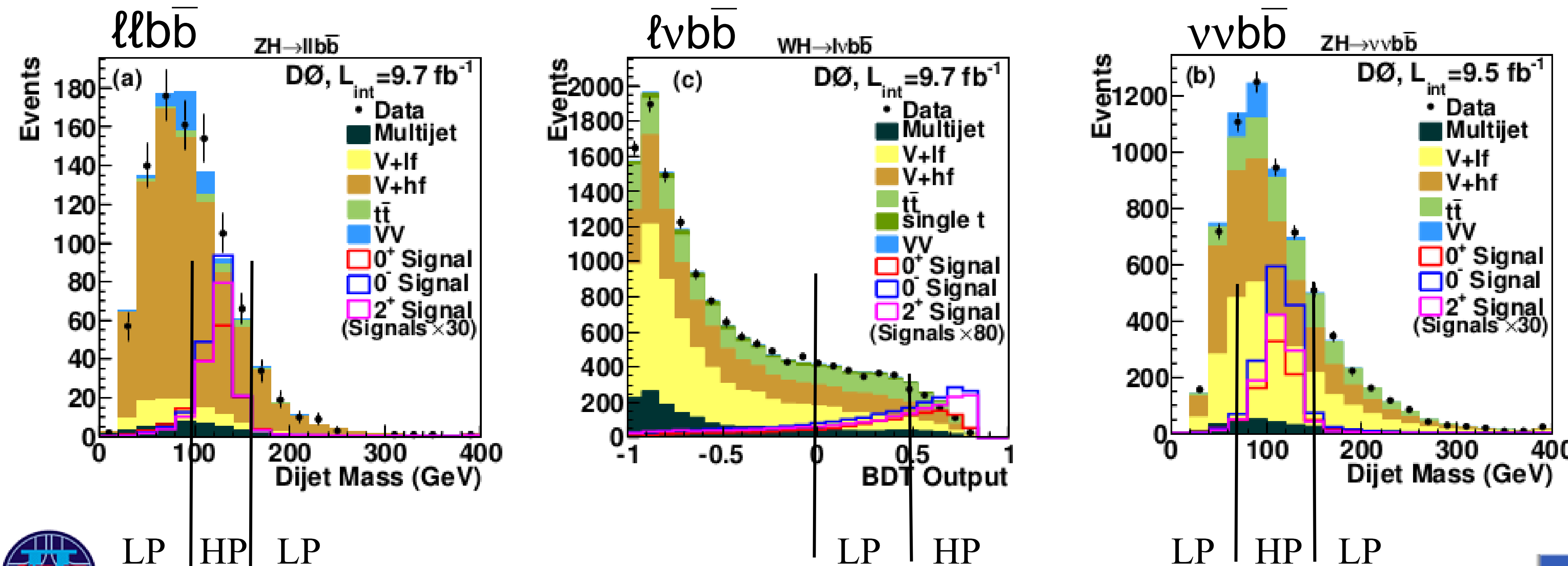
- Strategy
  - Re-use $VH \rightarrow Vb\bar{b}$ (published) search analyses with $M_X$=125 GeV
  - Main discriminating variables at the end
    - Overall mass
    - Or overall transverse mass
  - Assume $\sigma \times Br = \mu \times [\sigma \times Br]_{SM}$
  - Test two models
    - $2^+$: Standard RS graviton $\mathcal{L}_{2^+} = \frac{c_V^G}{\Lambda} G^{\mu\nu} T_{\mu\nu}$
    - $0^-$: Model by Ellis et al. $\mathcal{L}_{0^-} = \frac{c_V^A}{\Lambda} A F_{\mu\nu} \tilde{F}^{\mu\nu}$



# Spin/parity analyses at D0

## D0 re-employ VH → Vb$\bar{b}$ search analyses at $M_H$=125 GeV

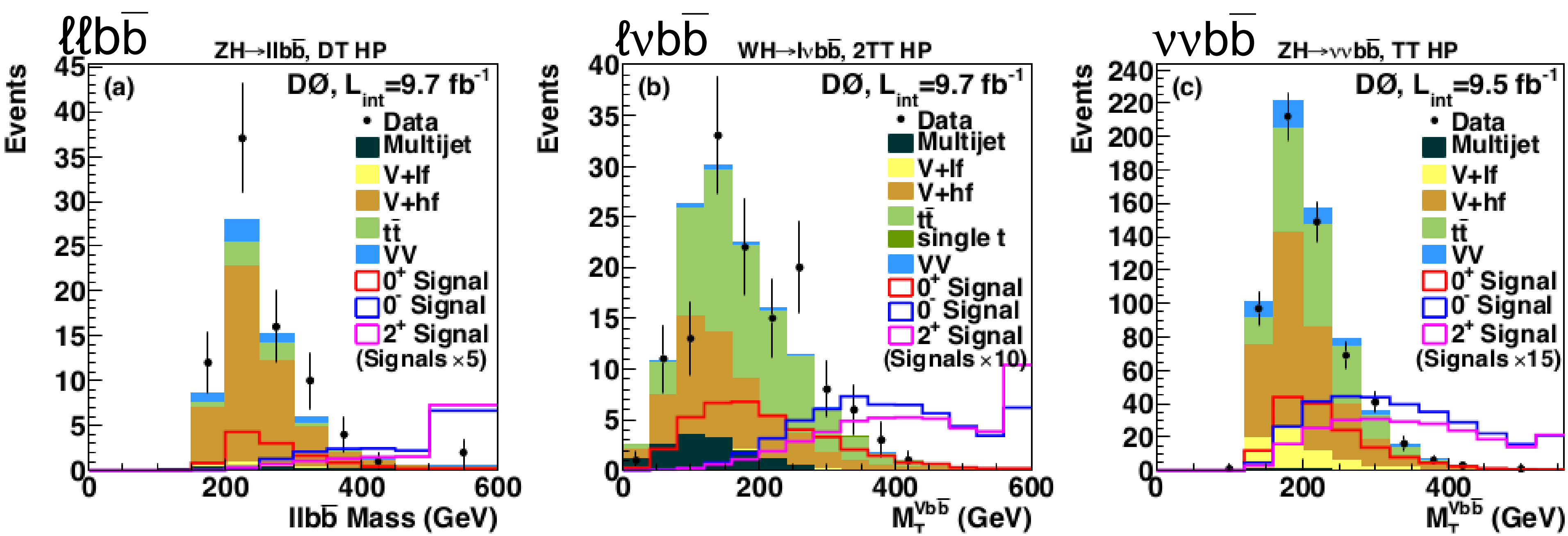
- Same event selection, same b-tag, jet multiplicity, and lepton categories.
- Split samples into High Purity (HP) and Low Purity (LP) regions according to dijet invariant mass or MVA output
  - Lower-purity regions provide additional constraints on systematics
  - Include all regions in confidence level calculations



# Spin/parity analyses at D0

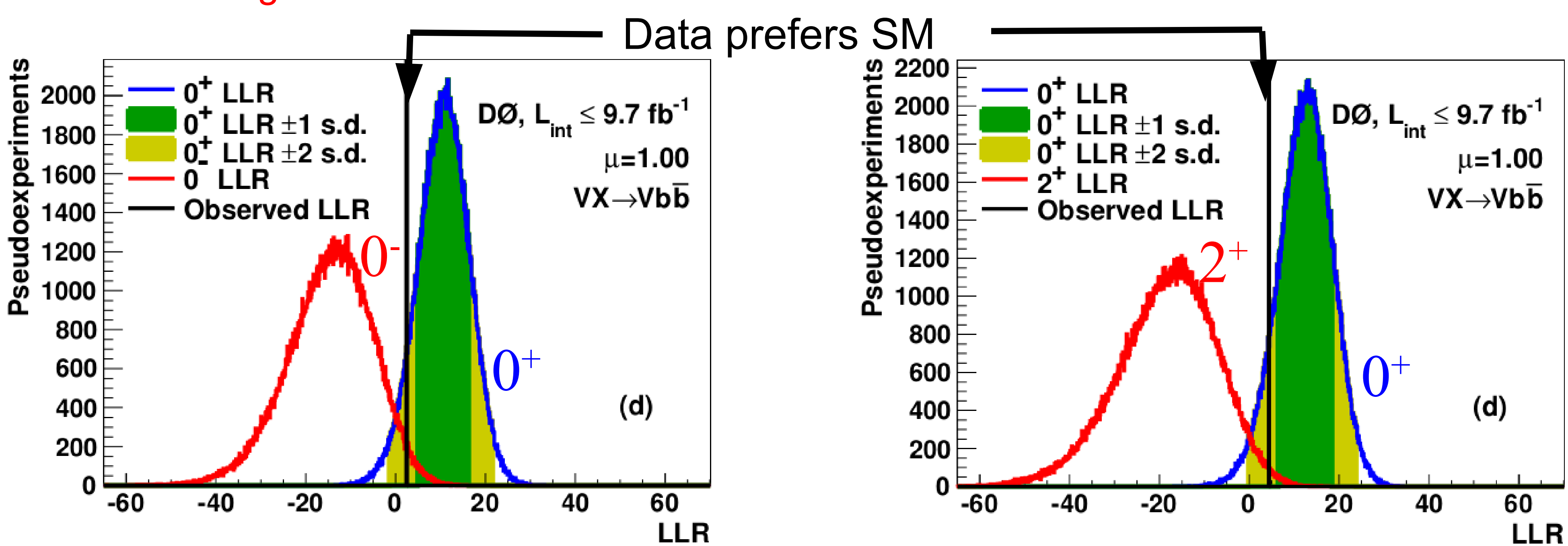
D0 re-employ VH → $Vb\bar{b}$ search analyses at $M_H$=125 GeV

- Same event selection, same b-tag, jet multiplicity, and lepton categories.
- Split samples into High Purity (HP) and Low Purity (LP) regions according to dijet invariant mass or MVA output
  - Lower-purity regions provide additional constraints on systematics
  - Include all regions in confidence level calculations
- Overall mass or overall transverse mass used as final discriminant



# Spin/parity results from D0

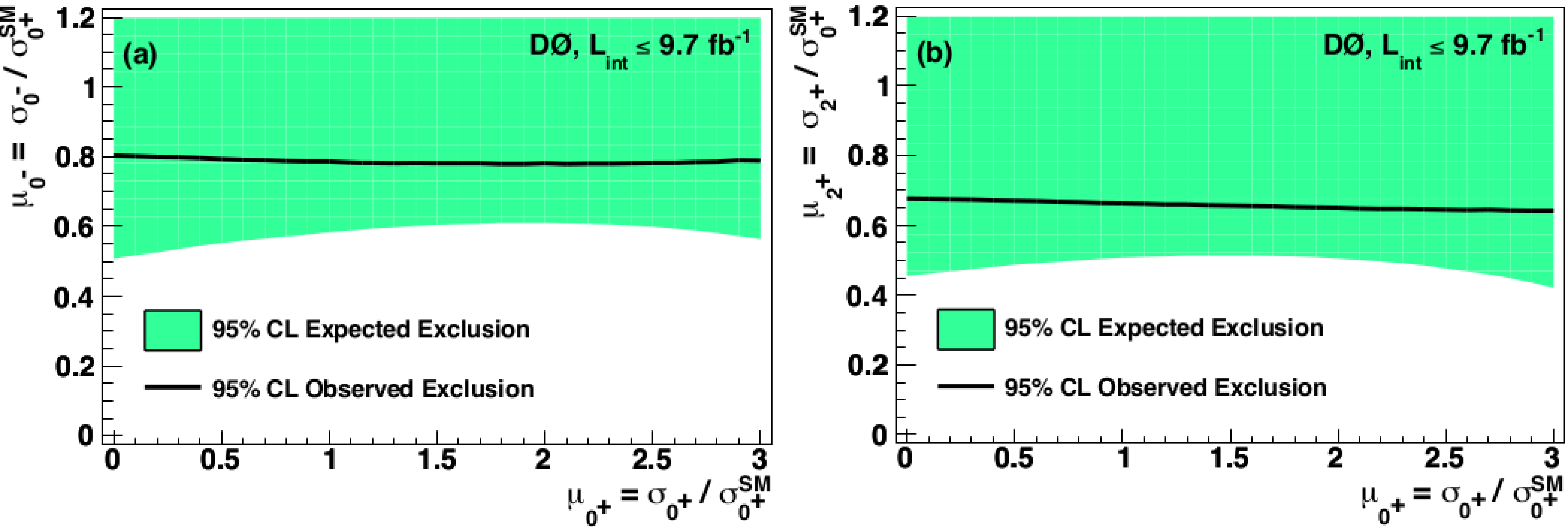
- Build log-likelihood ratio test: LLR= -2 log(H1/H0)
  - H1 is BSM signals: either $2^+$ + Bkg or $0^-$ + Bkg
  - H0 is the SM Higgs ($0^+$) + Bkg
  - Exclusion confidence level a la CLs method: CLs= $CL_{H1}/CL_{H0}$
- Assuming σ x Br = 1 x SM Higgs boson
  - $2^+$ signal excluded at 99.0% CL in favor of $0^+$ (expectation 99.9x%)
  - $0^-$ signal excluded at 97.6% CL in favor of $0^+$ (expectation 99.9x%)
- Assuming σ x Br = 1.23 x SM Higgs boson (D0 measured rate)
  - $2^+$ signal excluded at 99.9% CL
  - $0^-$ signal excluded at 99.5% CL



# Test different rate of production

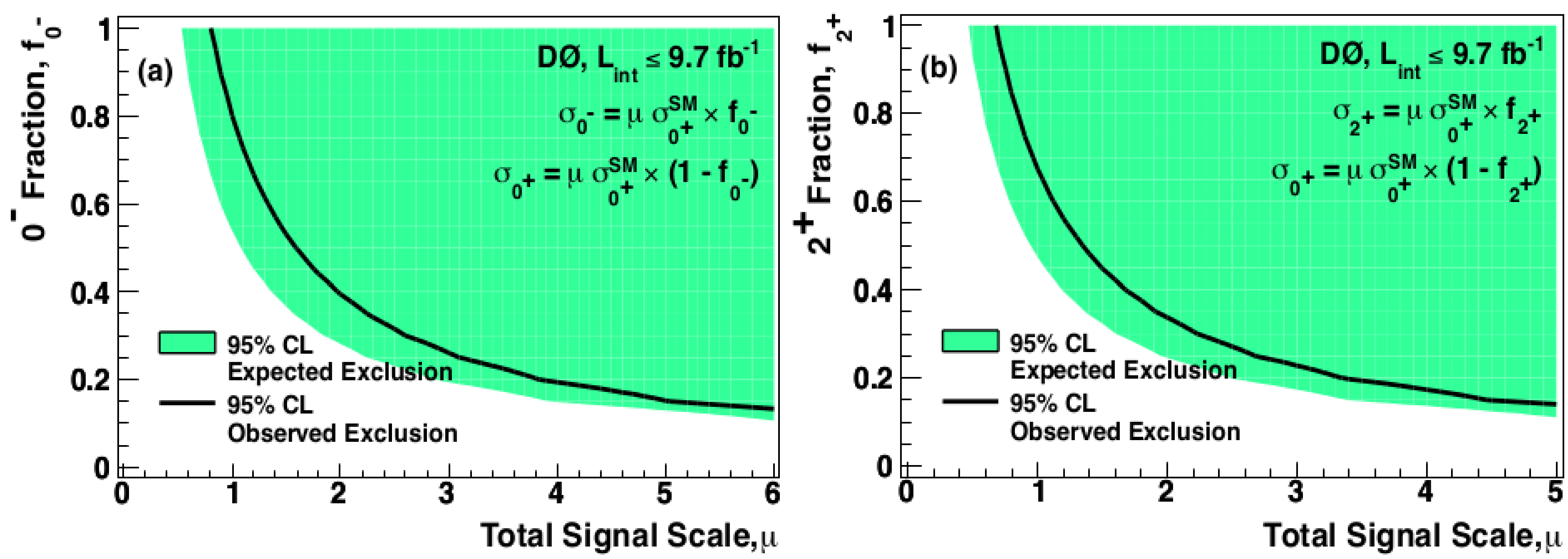
- Scan over different possibility for SM rate vs BSM rate
- Exclude region in this parameter space at 95% CL using $CLs = CL_{H1}/CL_{H0}$

- Eg Assuming $\mu_{0+}=1$ , exclude $\mu_{0-}>0.77$ and $\mu_{2+}>0.65$ in favor of 0+



# Test admixture of BSM particles with SM Higgs

- Admixture of BSM + SM Higgs tested for different production rate:
  - For $0^-$: f=fraction of $0^-$, tested signal = f x $0^-$ + (1-f)x $0^+$
  - For $2^+$: f=fraction of $2^+$, tested signal = f x $2^+$ + (1-f)x $0^+$



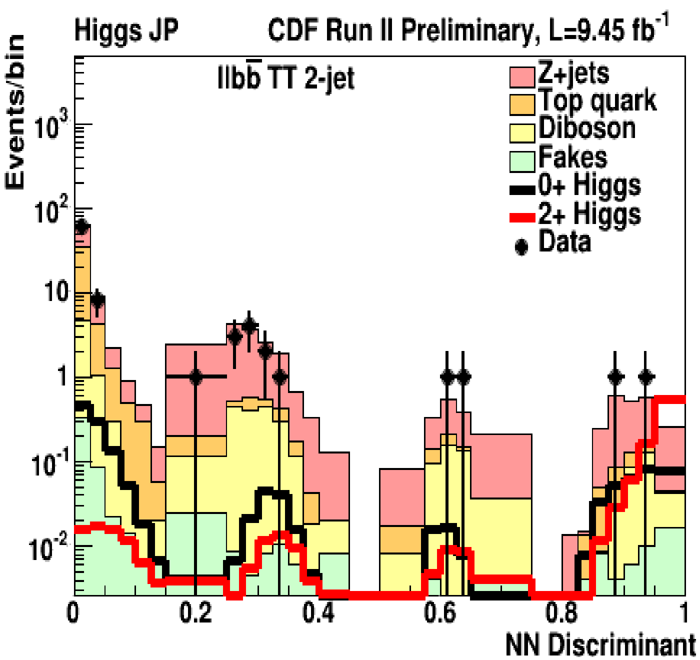

- Assuming overall production: σ x Br = SM Higgs boson
  - for mixing with $0^-$:exclude f > 0.80 at 95% CL in favor of $0^+$ production
  - for mixing with $2^+$:exclude f > 0.67 at 95% CL in favor of $0^+$ production

# Spin/parity analyses at CDF (brand new)

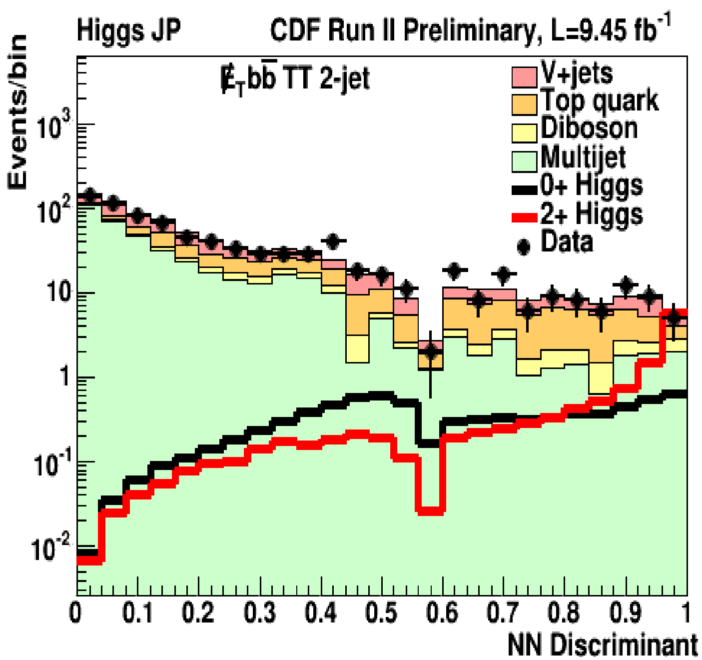
Re-employ VH → Vb$\bar{b}$ search analyses at $M_H$=125 GeV

- Same event selection, same use of MVA trained against specific backgrounds
- Same events categories (lepton quality, jet multiplicity, b-tag categories)
- Final discriminant:
  - NN trained against the BSM signal if >0.5
  - NN trained against the SM signal otherwise

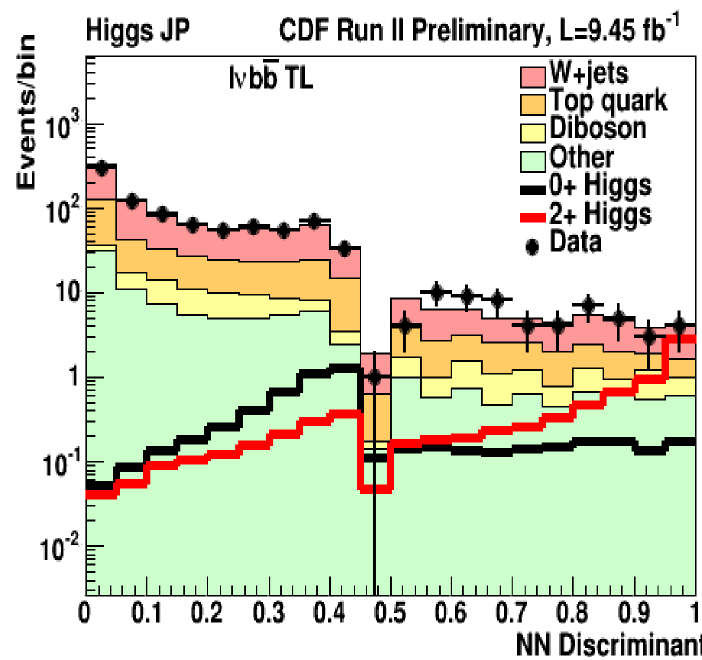
$\ell\ell b\bar{b}$




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



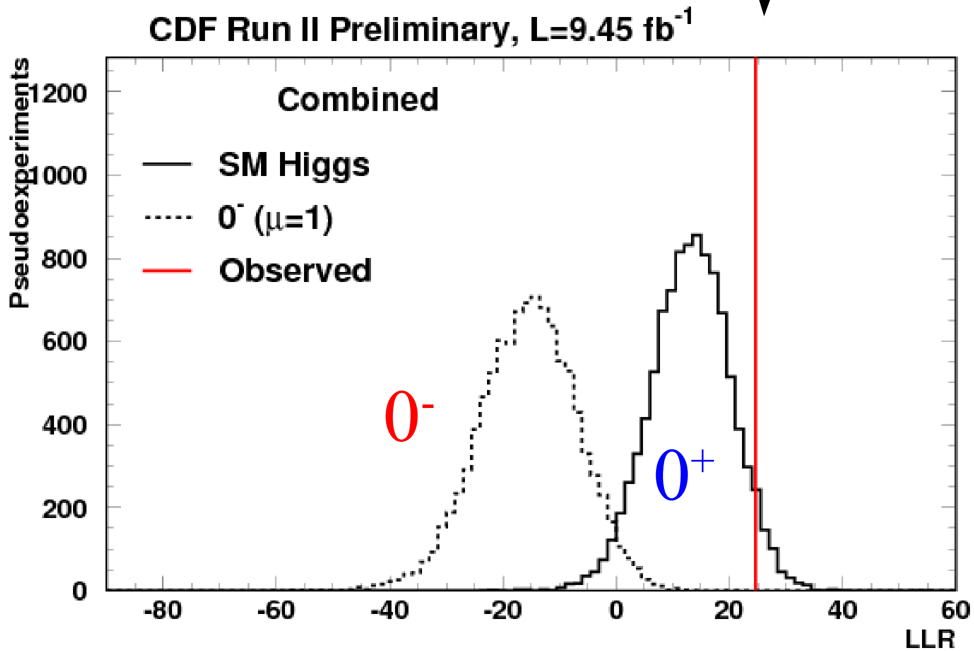

$\nu\nu b\bar{b}$

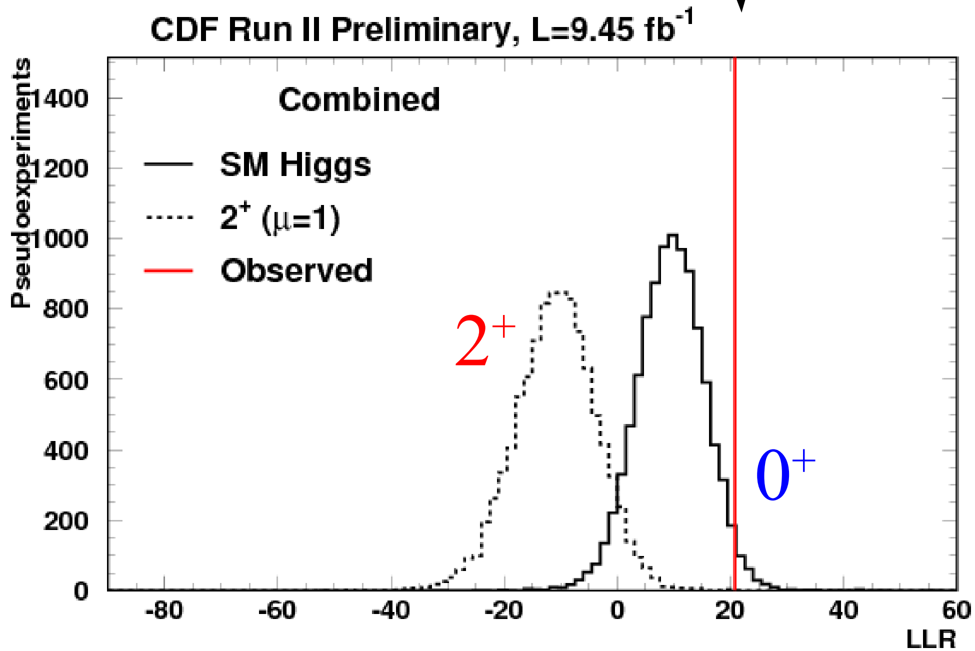


# Spin/parity results from CDF

- Build likelihood test: LLR= -2 log(H1/H0)
  - H1 is BSM signals: either $2^+$ + Bkg or $0^-$ + Bkg
  - H0 is the SM Higgs ($0^+$) + Bkg
- Assuming σ x Br = 1 x SM Higgs boson
  - Using exclusion confidence level a la CLs method: $CLs = CL_{H1}/CL_{H0}$
    - $2^+$ signal excluded at 99.14% CL in favor of $0^+$ (99.3 % expected)
    - $0^-$ signal excluded at 99.99% CL in favor of $0^+$ (99.92 % expected)

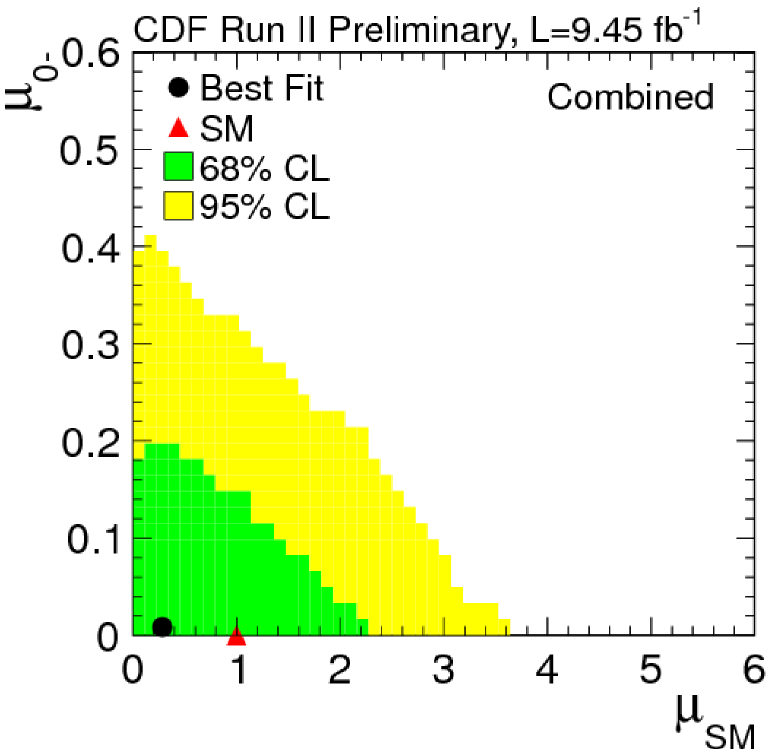
Data prefers SM

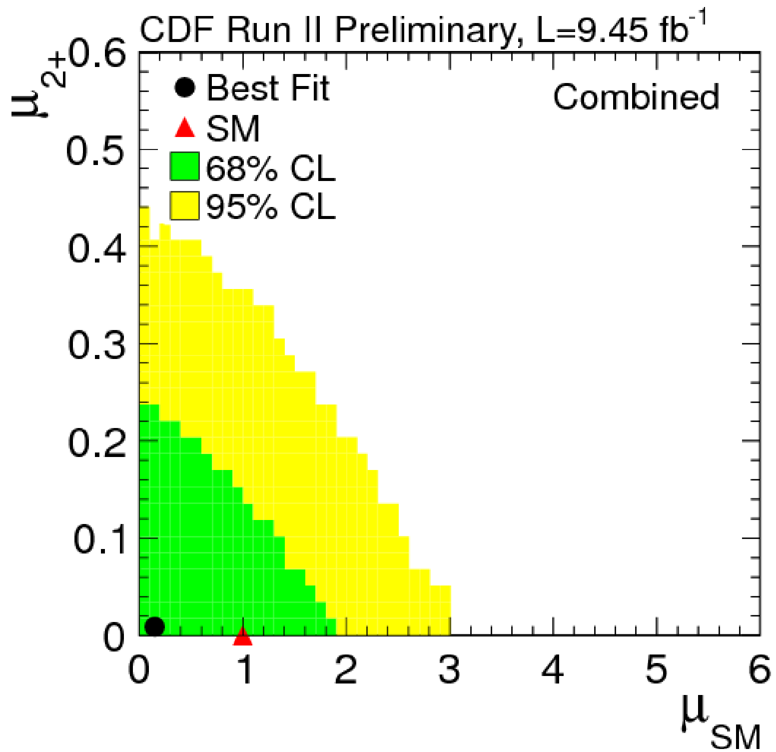


# Test admixture of BSM particles with SM Higgs

- Compute Bayesian posterior probability as a function of $\mu_{SM}$ and $\mu_{BSM}$

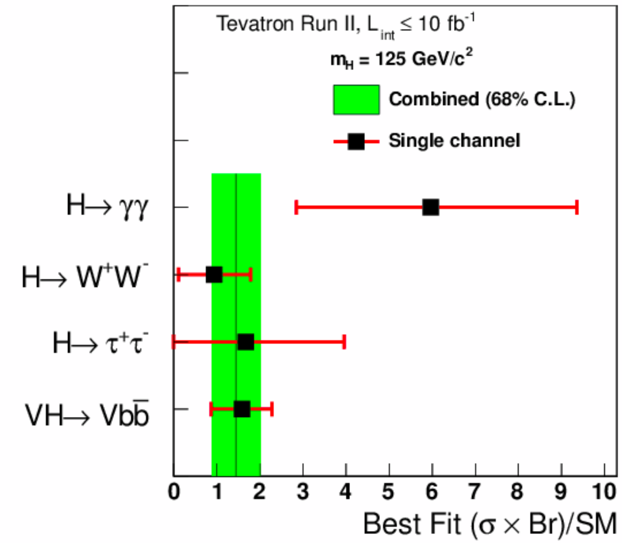


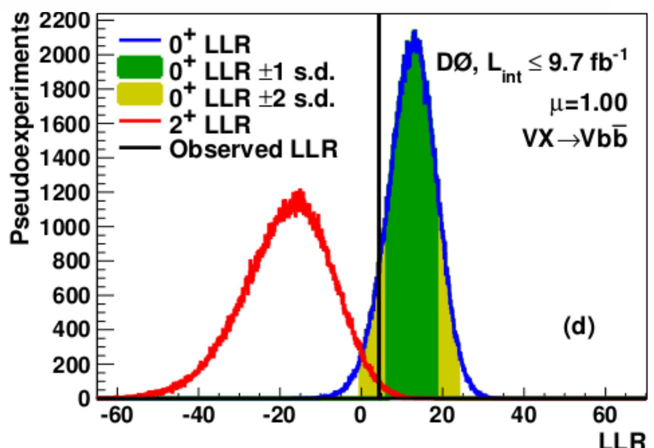

- Derive 95% CL exclusion:
  - Assuming no SM Higgs is present: $\mu_{0-}>0.32$ and $\mu_{2+}>0.35$ excluded
  - Assuming SM Higgs is present: $\mu_{0-}>0.28$ and $\mu_{2+}>0.31$ excluded

# Summary

- Ten years of excellent performances for Tevatron, CDF and D0
- Extensive search for SM Higgs at CDF and D0
  - Achieved almost 1xSM exclusion sensitivity over the full range [90-185] GeV
  - Excluded @95% CL : $90<M_H<109$ GeV and $149 < M_H<182$ GeV
- Observed broad excess in low mass range
  - Significance of 3 sigma for $M_H$=125 GeV
  - Compatible with experimental resolution
  - Compatible with SM Higgs expectation



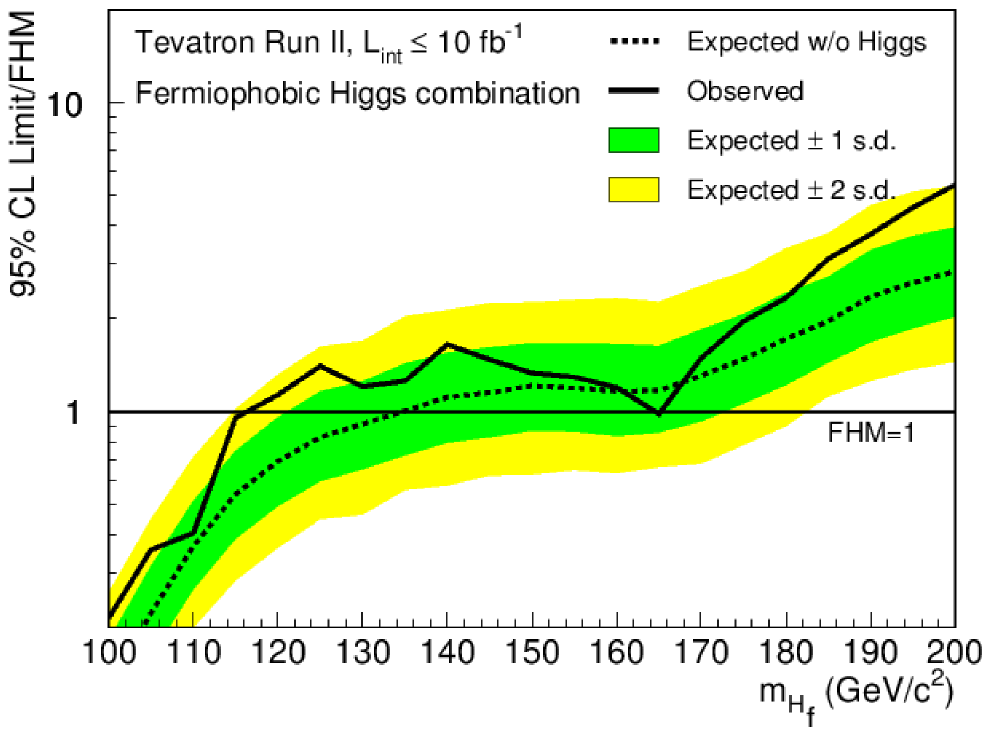

- Probed properties of Higgs-like particle
  - Overall Yield: (1.4 ± 0.6) x SM for $m_H$=125 GeV
  - $H\rightarrow b\bar{b}$ Yield: (1.6 ± 0.7) x SM for $m_H$=125 GeV
  - Probe couplings to bosons and fermions:
    - Data are compatible with SM
  - Test of spin/parity in $H \rightarrow b\bar{b}$ channels
    - Exclusion of exotic signals over various hypotheses
      - CDF: public-note 11103 (this week)
      - D0: to appear on Arxiv this week.
      - CDF+D0 combination to appear soon



# Support slides

# Fermiophobic Higgs search

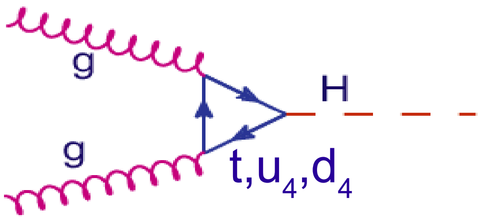
- Recycle SM analysis accounting for suppression of gg → H
  - Look for H → γγ decay
    - Reoptimize H → γγ analysis
      - $P_T(H)$ harder than in SM because of WH, ZH production mode
  - Look for H → WW decay signatures

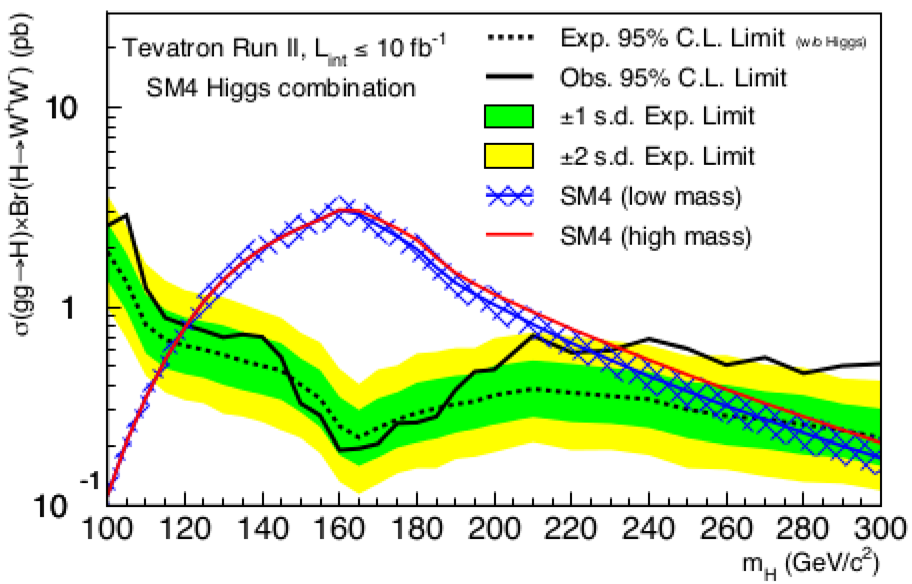


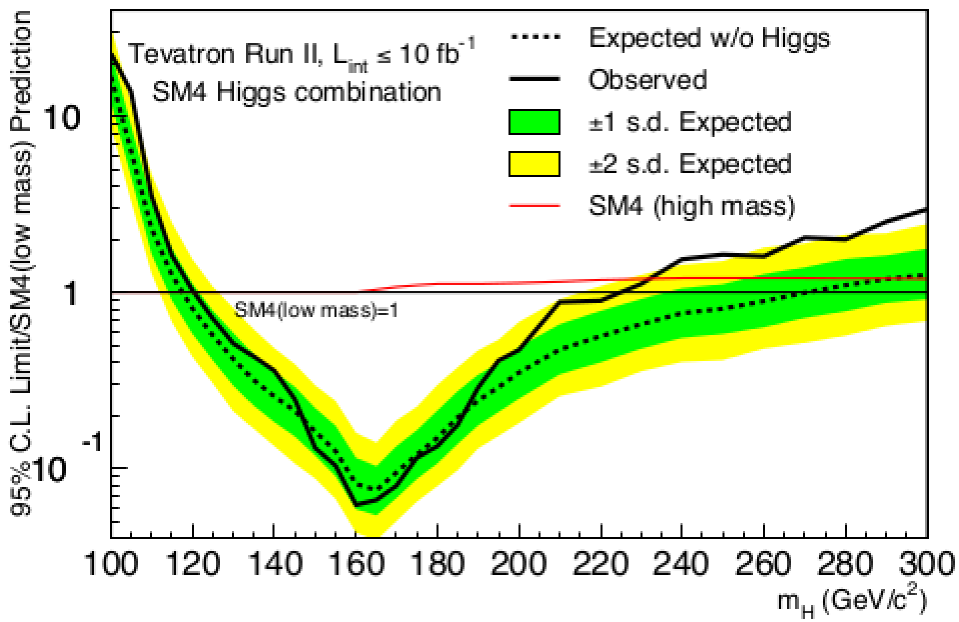

**Exclude: $m_H$<116 GeV @95%CL**
**Expected exclusion: $m_H$<135 GeV**

# Higgs search within $4^{th}$ generation model

- New heavy generation of quarks
  - ggH coupling is multiplied by 3 compared to SM
  - Production is enhanced by 9
- Search in $gg \rightarrow H \rightarrow WW$ channels can be recycled
  - Dilepton + MET, lepton+MET+ jets



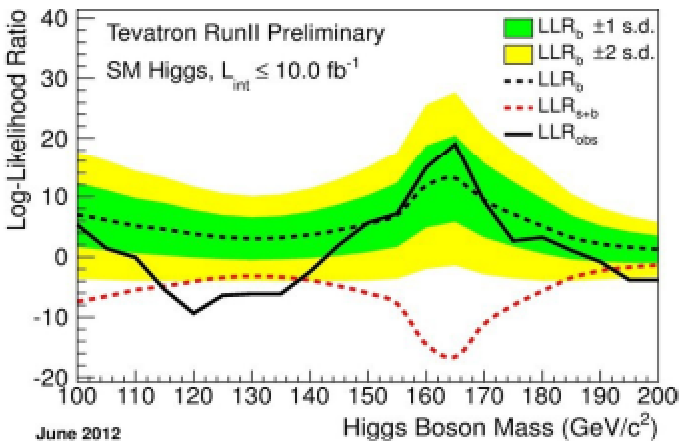



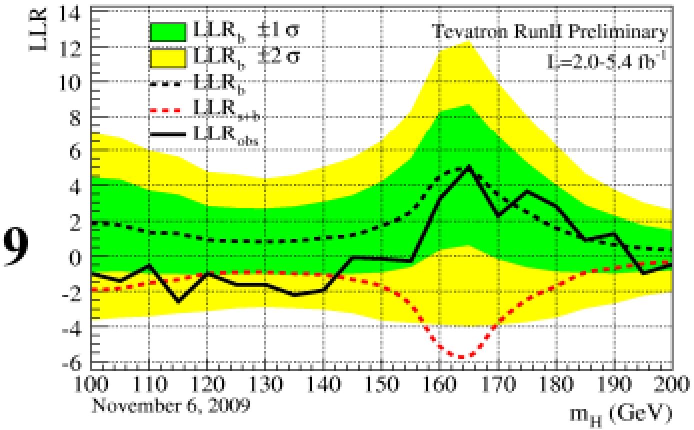

**CDF+D0 combined exclusion: $121 < m_H < 225$ GeV @95%CL**

**expected exclusion: $118 < m_H < 270$ GeV**

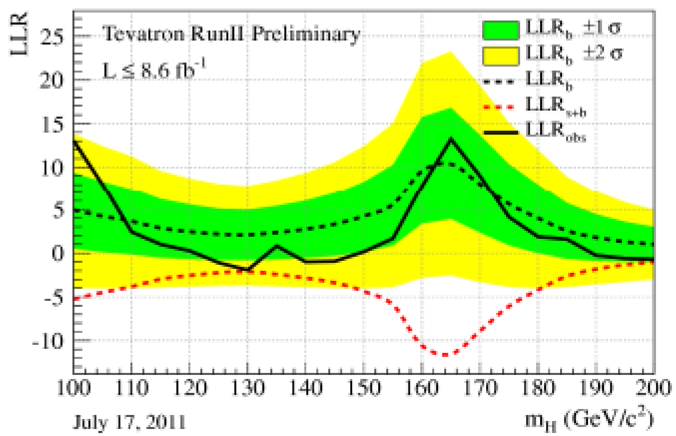
# Historical Look at Tevatron Higgs Combination



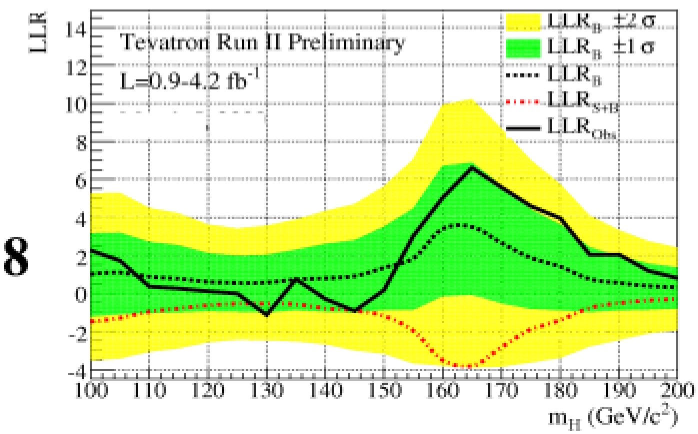

2012



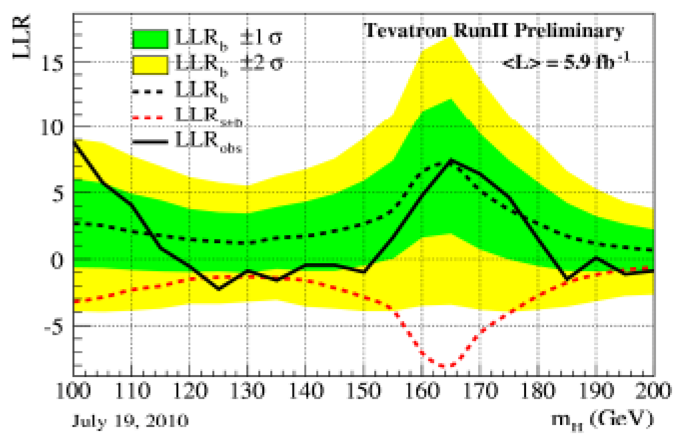

2009



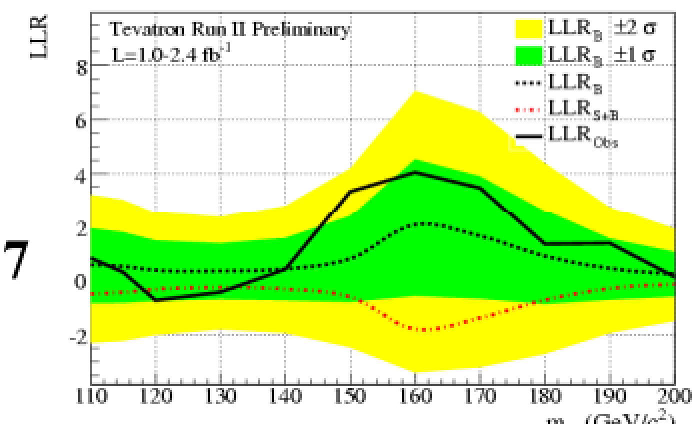

2011




2008

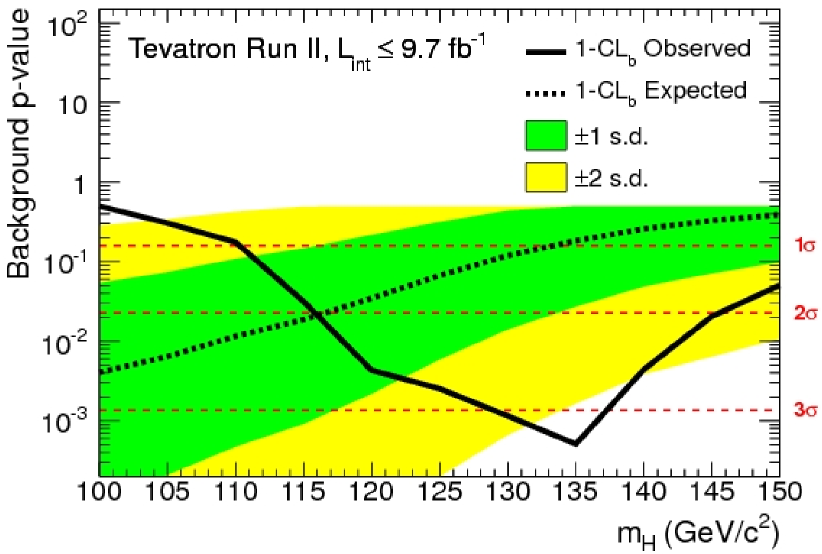


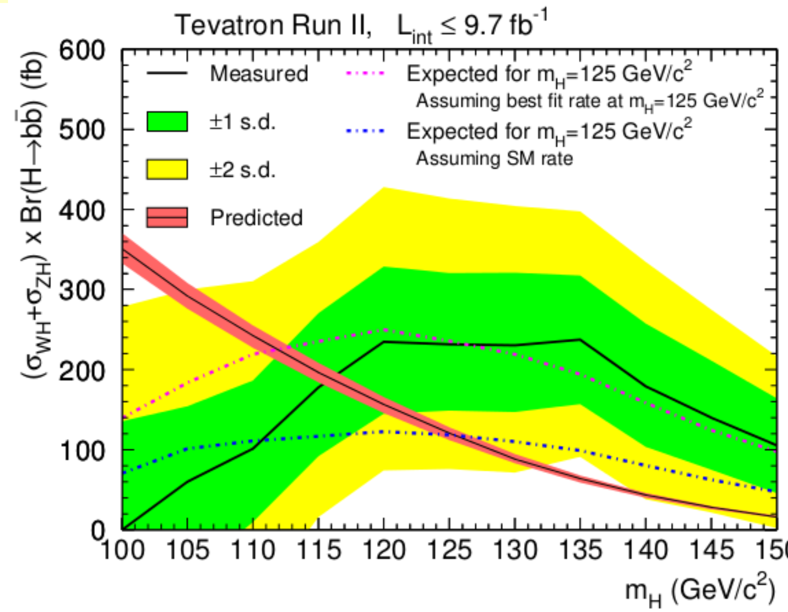

2010




2007

# H → b$\bar{b}$ results




July 2012 combination (PRL 109, 071804)

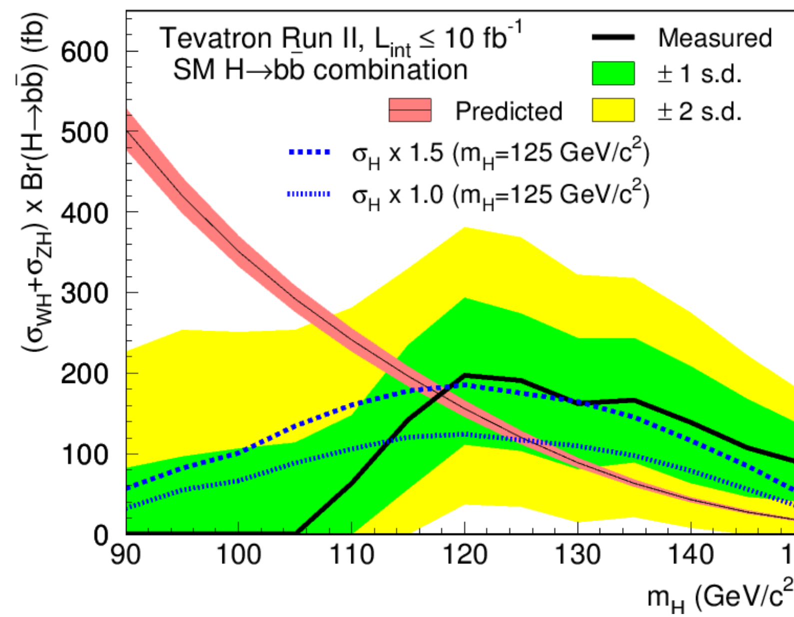
- 3.3 sigma @135 GeV (2.8sigma @ 125)
- 3.1 sigma accounting for LEE
- Measure VH → Vb$\bar{b}$ yield:
  - σ=0.23±0.09 pb for $M_H$=125 GeV

SM prediction for VH → Vb$\bar{b}$

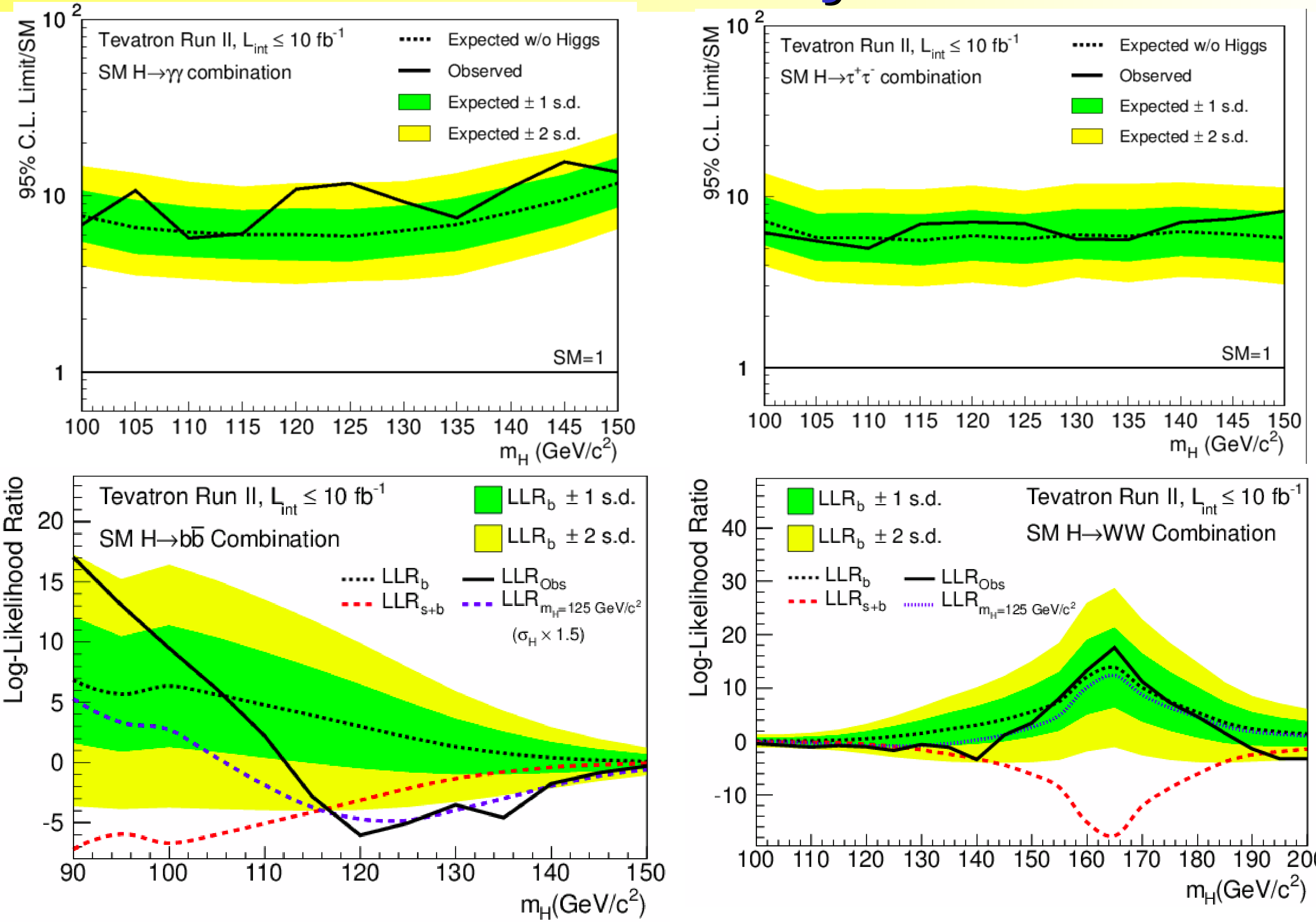
- σ=0.12±0.01 pb for $M_H$=125 GeV

Final Tevatron combination (arxiv:1303.6346)

- σ =0.19±0.09 pb for $M_H$=125 GeV
- Change mostly driven by newest CDF Met+bb analysis

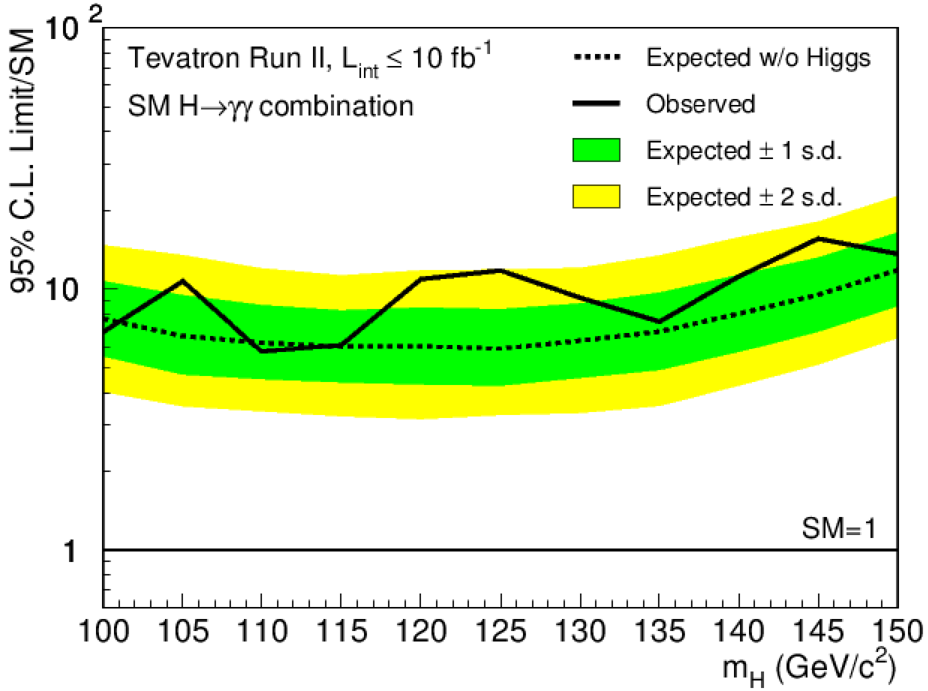


# Breakdown into decay modes



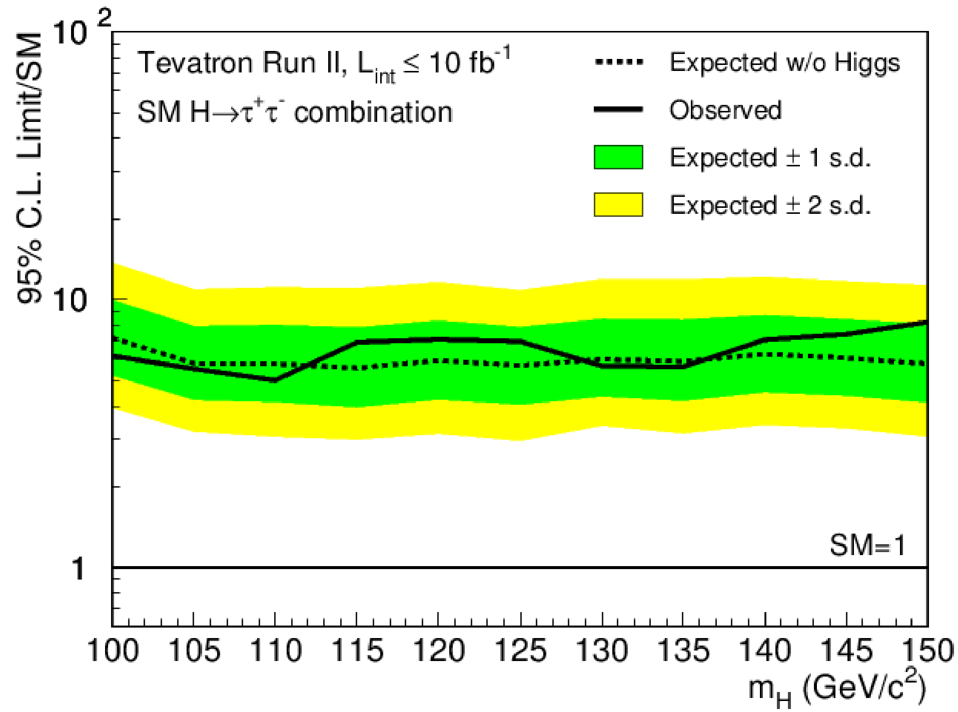

- Excess consistent with a Higgs seen in the most sensitive channels: H → bb̄, H → WW

# Breakdown of the results

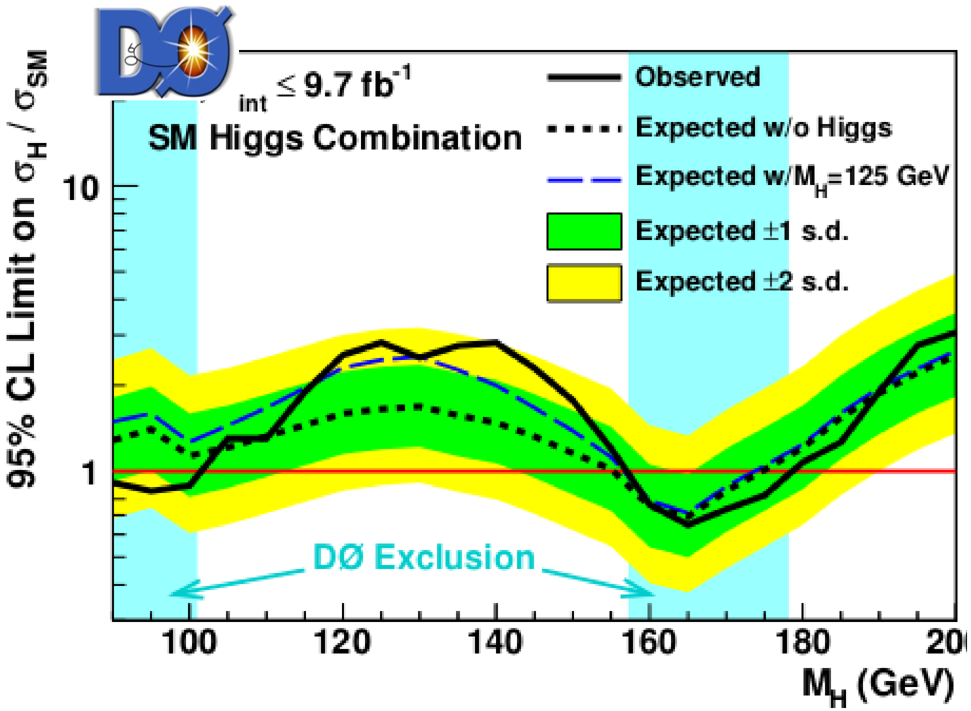


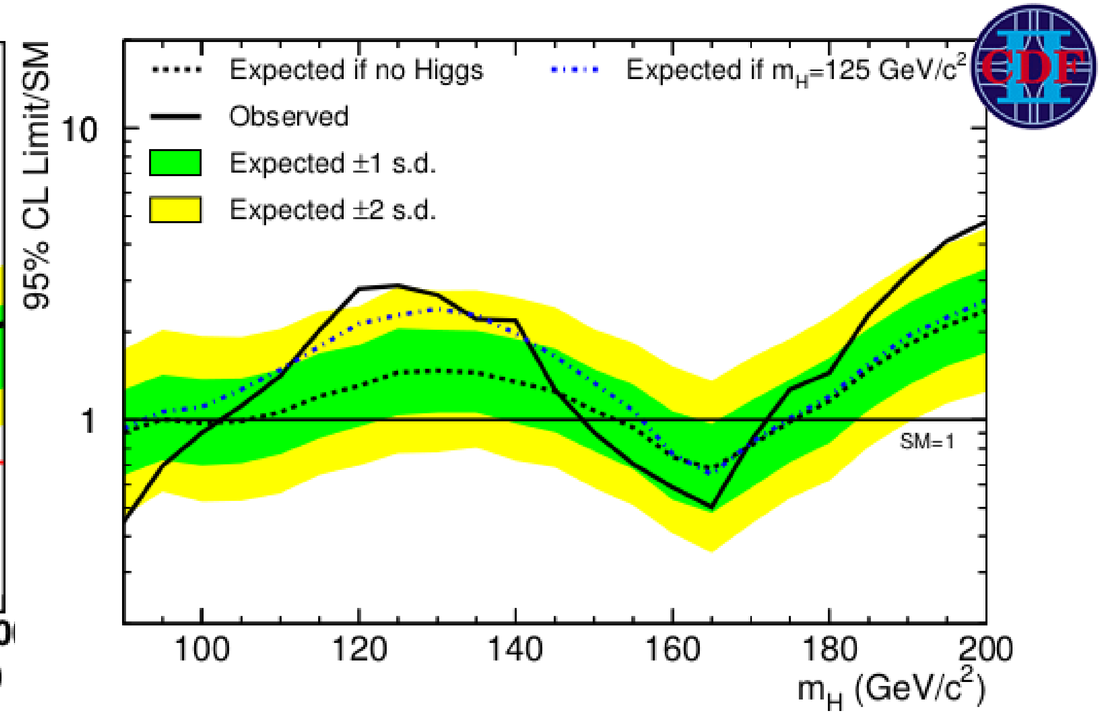

- $H \to \gamma\gamma$ limits
  - Sensitivity : 5.9*SM @ 125 GeV
  - ~2 sigma excess @125 GeV

- $H \to \tau\tau$ limits
  - Sensitivity : 5.7*SM @ 125 GeV



# Breakdown of results: limits

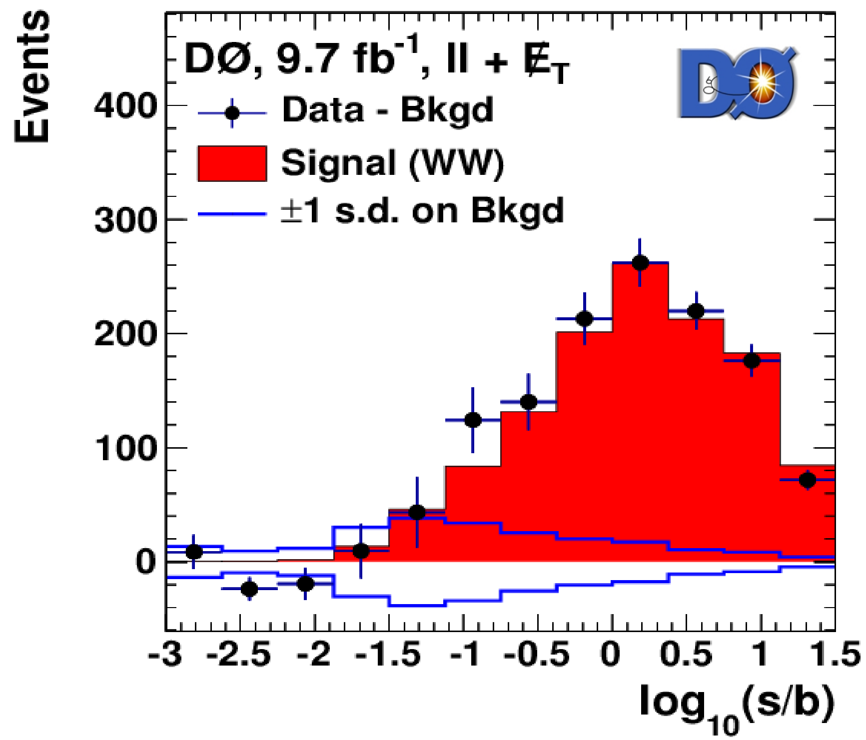


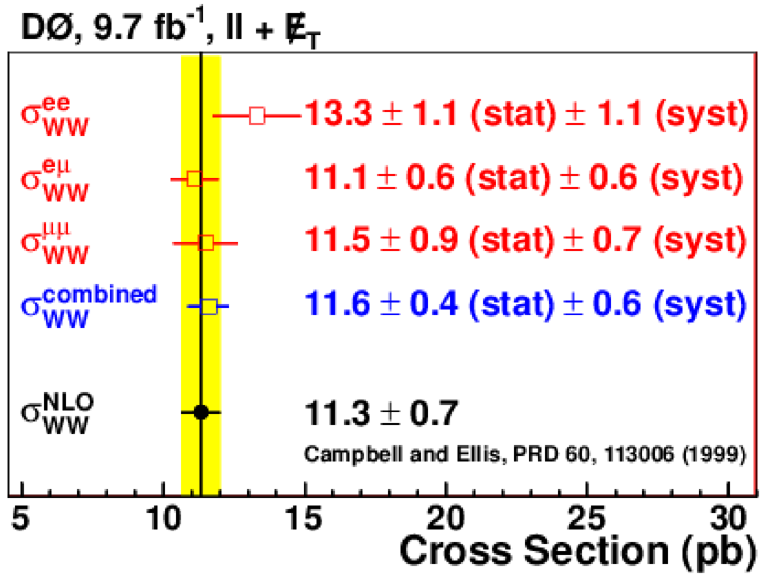




- Similar feature in both experiments:
- Deviation from background-only hypothesis in the low mass region
  - D0 1.7 sigma @ 125 GeV
  - CDF 2.0 sigma @ 125 GeV

# Validate methods with data : WW yield

- Measure $p\bar{p} \to WW \to \ell\nu\ell\nu$ cross-section
  - Employ same analysis technique as in searches for $H \to WW \to \ell\nu\ell\nu$
    - Same subchannels
    - Same inputs to MVA
    - Train MVA to discriminate WW production
    - Similar treatment of systematic uncertainties

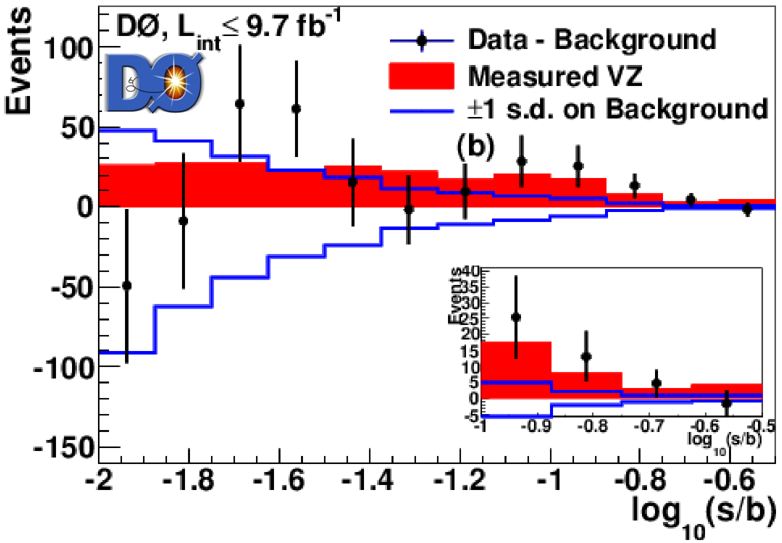


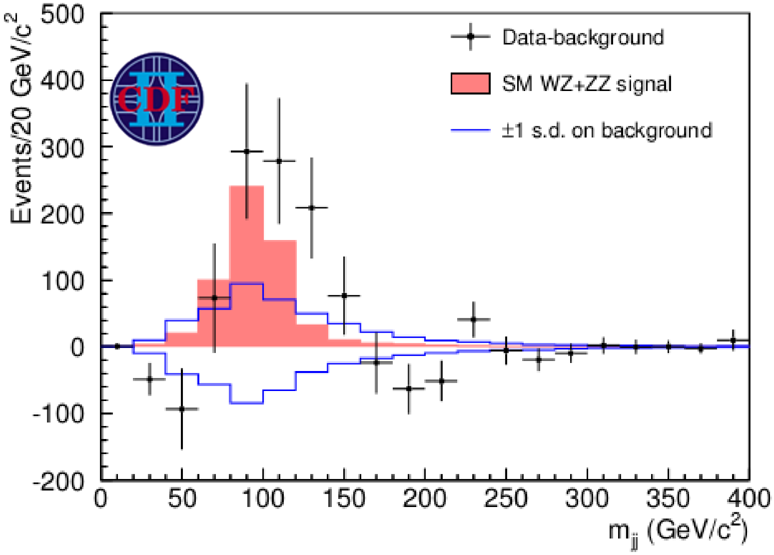




Measured cross-section: 11.6±0.7 pb

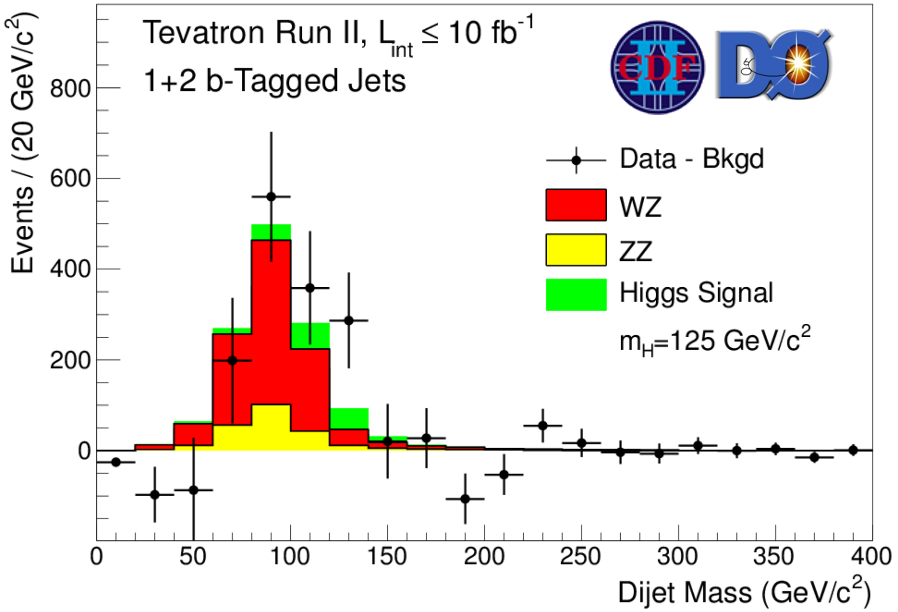
in agreement with NNLO prediction: $\sigma$=11.3 ± 0.7 pb

# Validate methods with data : VZ ($Z \to b\bar{b}$) yield

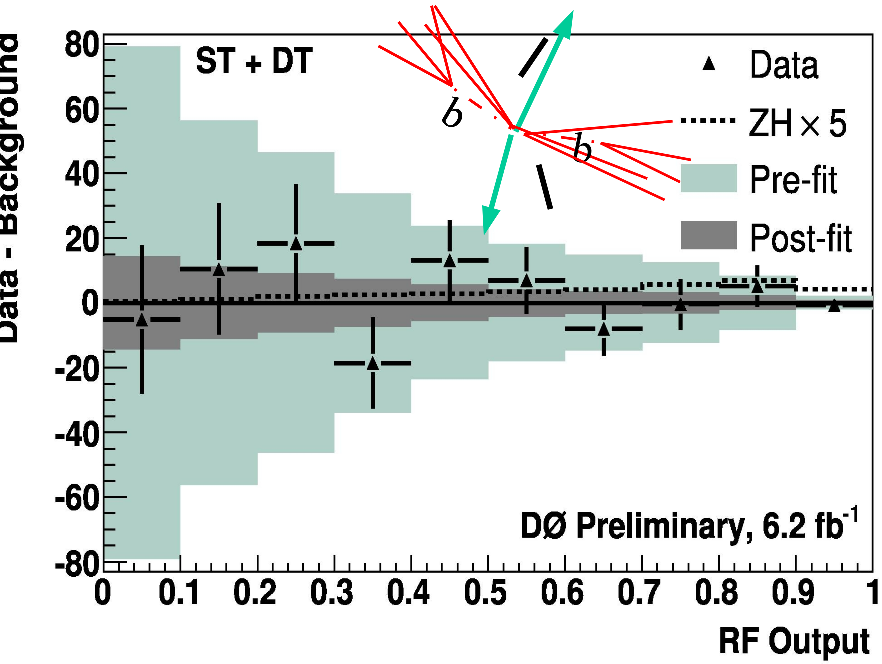



- Measure $p\bar{p} \to VZ \to Vb\bar{b}$
  - Same techniques as for search in $VH \to Vb\bar{b}$ channel
- Results (MVA discriminant):
  $\sigma = 3.0 \pm 0.6\ (stat) \pm 0.7\ (syst)$ pb
- In agreement with SM prediction
  - 4.4±0.3 pb



# Systematics



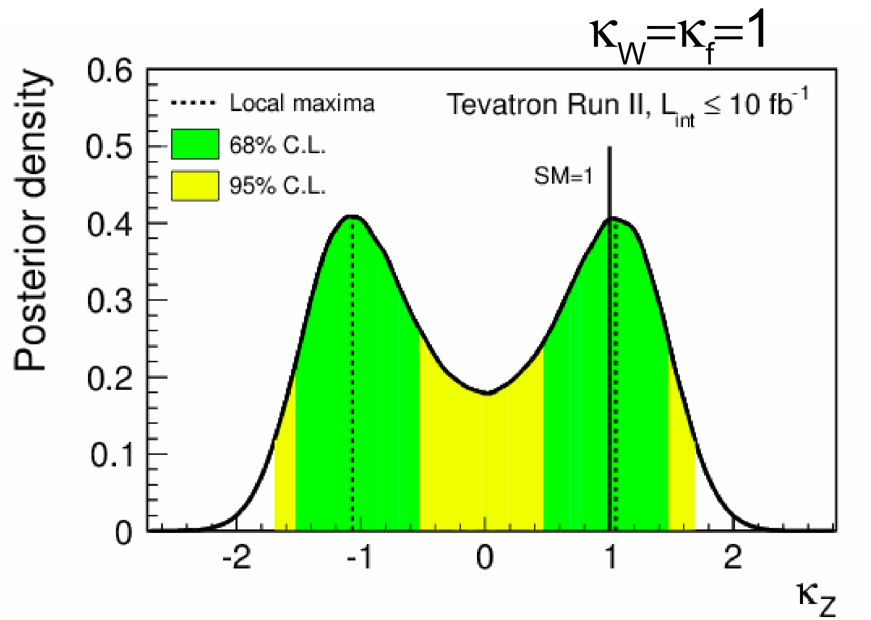

Systematics are channel dependent

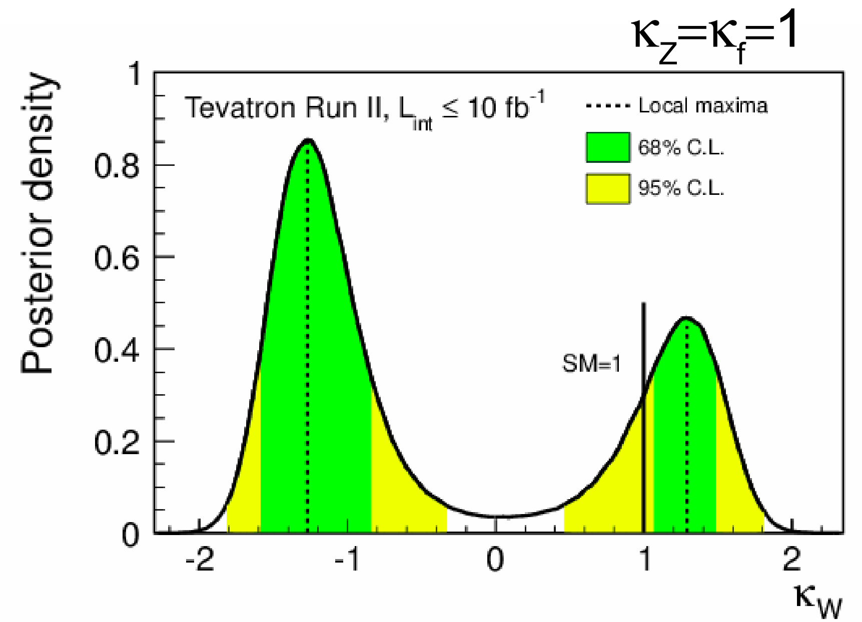
- Flat systematics: affect overall normalization
- Shape systematics: modify output of final discriminant
- Impact of systematics is reduced thanks to statistical method (~fit procedure in background dominated region)
- Have to account of correlations among channels
- Degrade sensitivity by ~15-25%

Main sources are:

- Luminosity and normalization
- Multijet background estimates
- Background cross-sections, K-factors for W/Z+ Heavy flavor
- Modeling of background differential distributions (shape)
- B-tagging efficiency
- Jet energy calibration
- Lepton identification

# 1d constraints on couplings



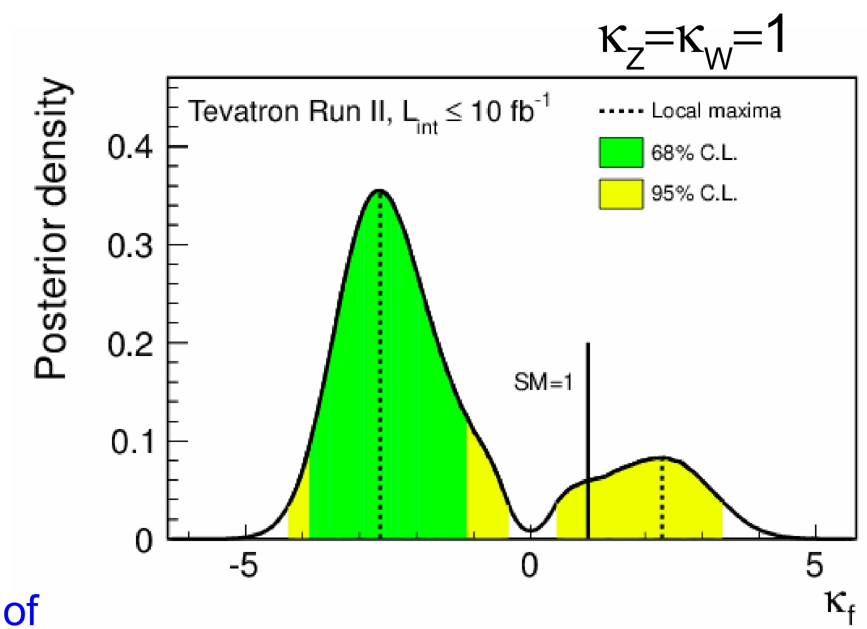




- Vary one of the coupling, let the 2 other fixed to SM value of 1
- Compute posterior probability
- Most probable values:

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

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

$$\kappa_f = -2.64^{+1.59}_{-1.30}$$

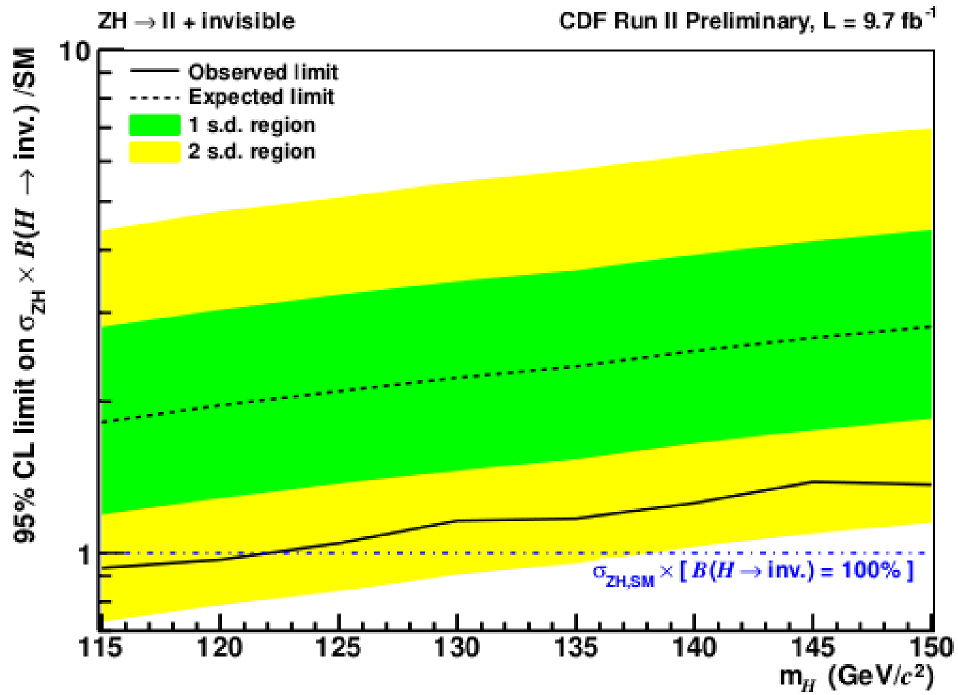


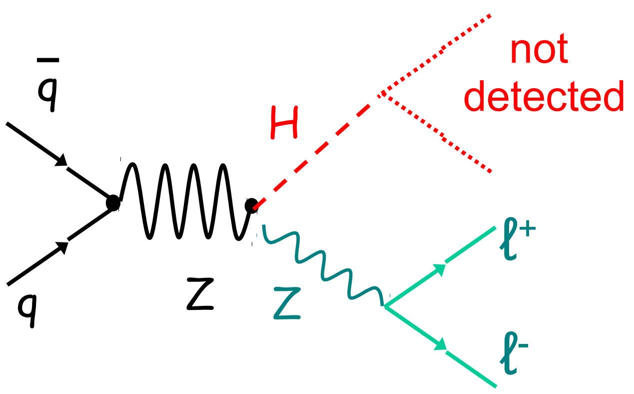

Negative values for $\kappa_f$ and $\kappa_W$ are preferred because of $H \to \gamma\gamma$ excess

# New(Winter 14): CDF search for invisible Higgs

First search for H → invisible at Tevatron.

- Look for events with large missing momentum in the ZH channel
- Use the clean Z $\rightarrow \ell^+\ell^-$ signal to select events




- Results:
  - Exclude σ x BR > 90 fb for $M_H$=125 GeV at 95% CL
  - Exclude 100% BR (invisible), for $M_H$<120 GeV at 95% CL

more details CDF Note 11068