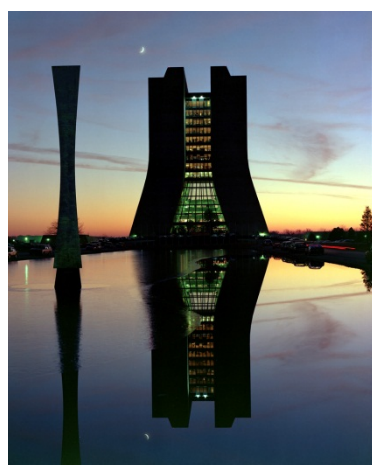
Tevatron Constraints on Models of the Higgs Boson with Exotic Spin and Parity Using Decays to bb Quark Pairs

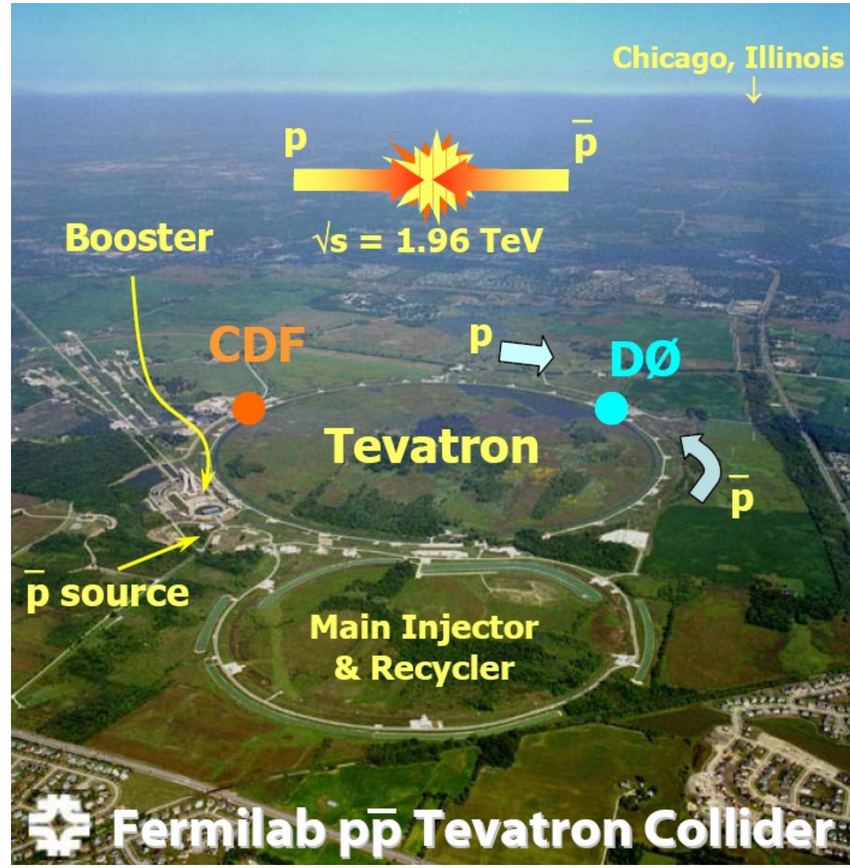
Gavin Davies

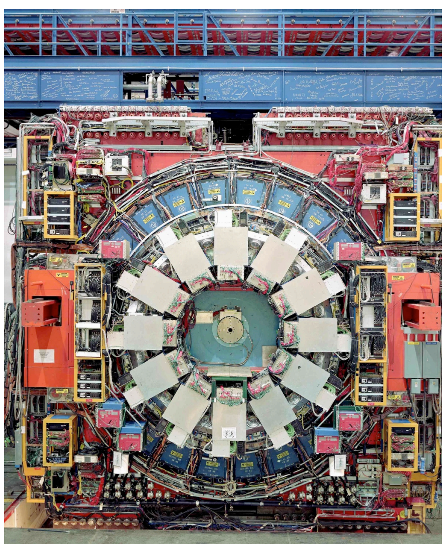
On behalf of the CDF and DØ Collaborations



Outline

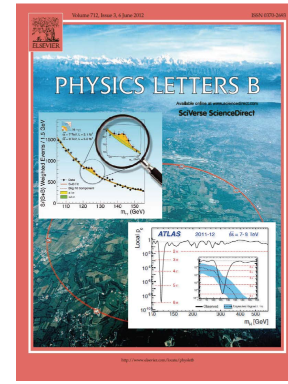
- Introduction
  - Tevatron
  - Higgs searches @ Tevatron
- Higgs Results
  - General
  - Spin-parity
- Conclusions



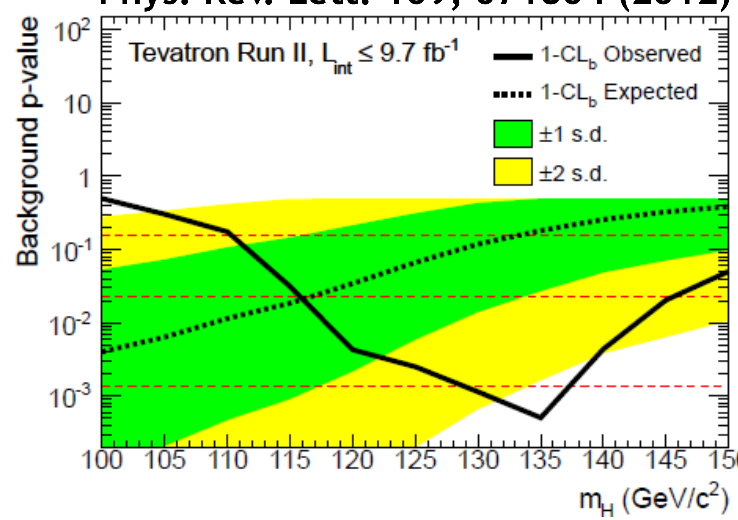


Reminder: Tevatron stopped fall 2011
~ 10fb^{-1} per expt after data quality

- Tevatron
  - Bridge between LEP search & LHC measurement era following discovery
  - 1st exclusion after LEP in 2008
    - And then regularly updated
  - 2012: Evidence for coupling to fermions
  - Complementary as exploiting primarily $H\rightarrow b\bar{b}$ decays
  - ‘Higgs studies at Tevatron’
    - PRD 88, 052014 (2013)
  - ‘Tevatron spin-parity constraints’
    - PRL 114, 151802 (2015)



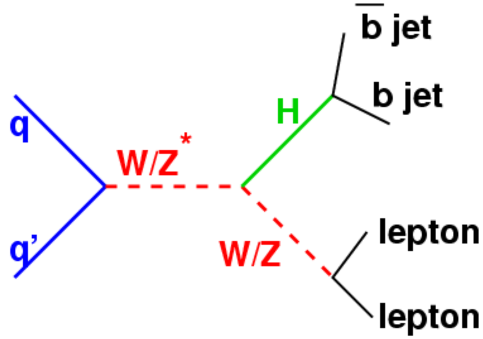
Phys. Rev. Lett. 109, 071804 (2012)

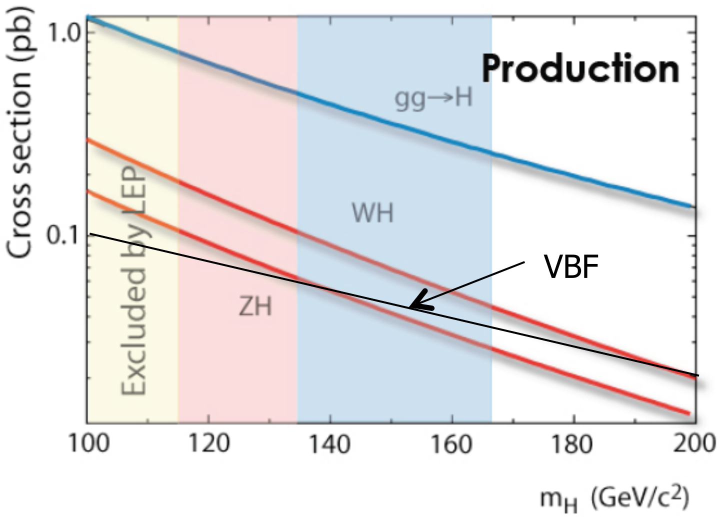


Search Strategy

- 'Low' mass m_H < 135 GeV
  - Dominated by:

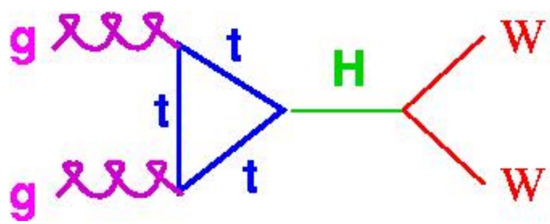
$$q\bar{q}' \rightarrow WH \rightarrow \ell\nu b\bar{b}$$
$$q\bar{q} \rightarrow ZH \rightarrow \ell\ell b\bar{b}$$
$$q\bar{q} \rightarrow ZH \rightarrow \nu\bar{\nu} b\bar{b}$$

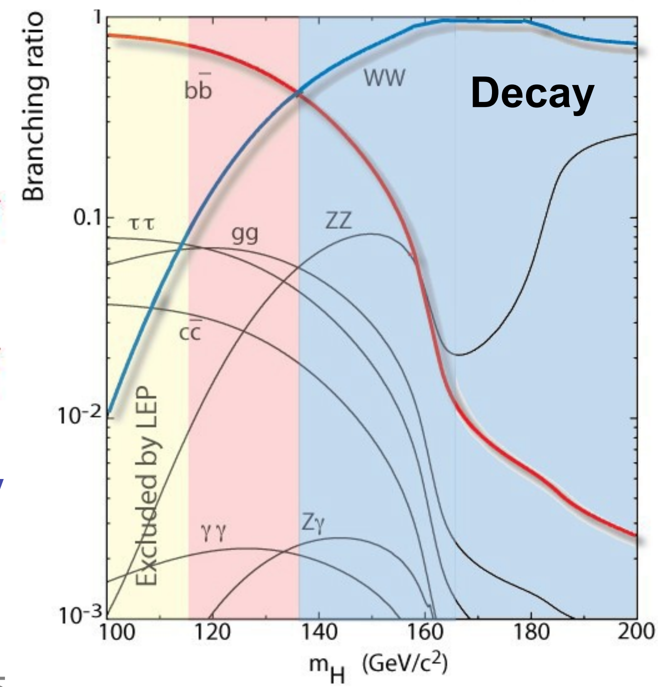




- 'High' mass m_H > 135 GeV
  - Dominated by:

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

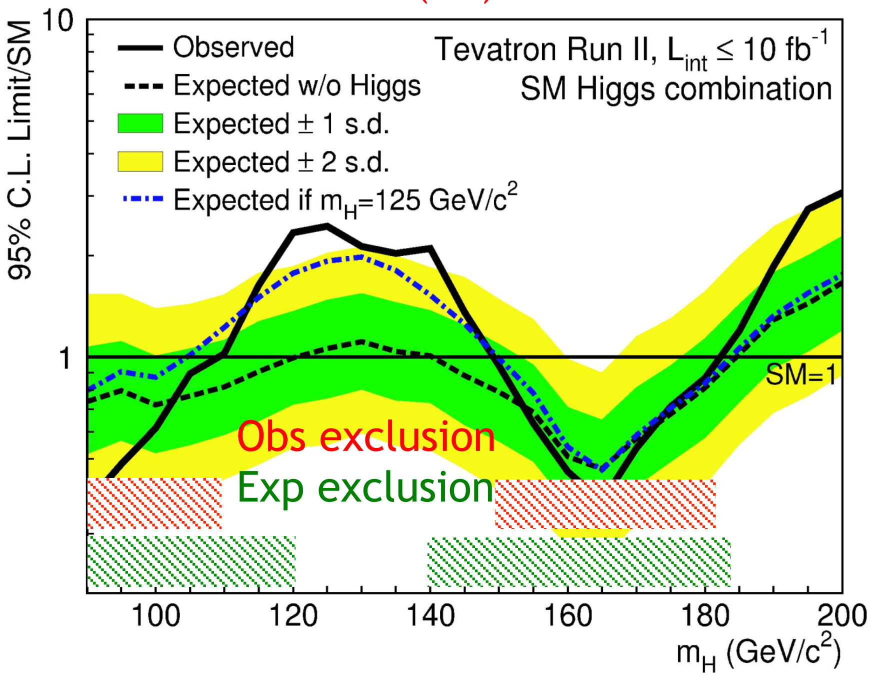




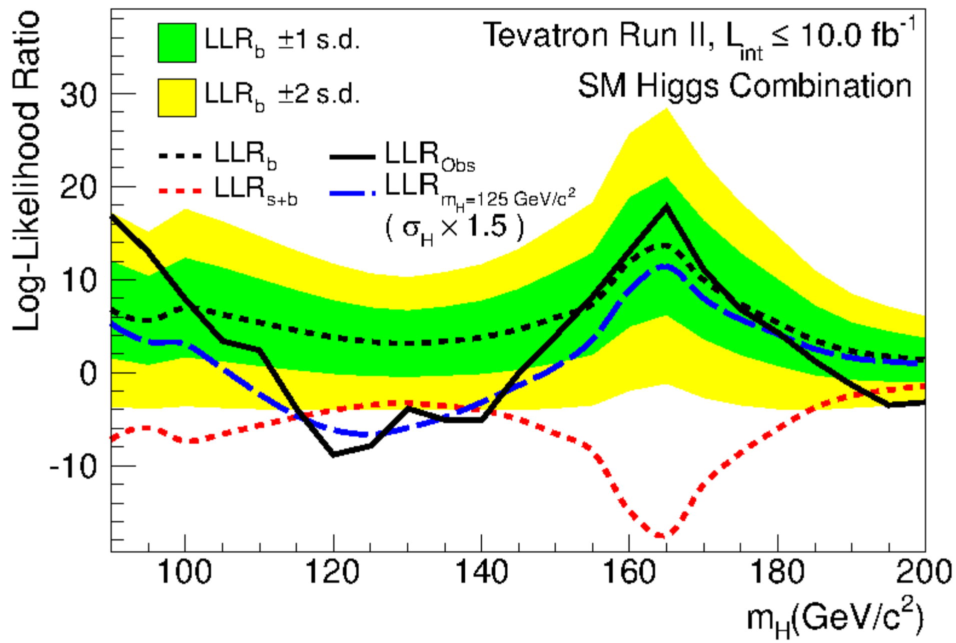
- Less sensitive channels add overall sensitivity
- All channels sub-divided for sensitivity

Tevatron Combination

- Exclusion cross section
  - Sensitivity over ~full mass range
  - 95% CL limit @ m_H = 125 GeV:
    - 1.06 x σ(SM) expected
    - 2.44 x σ(SM) observed



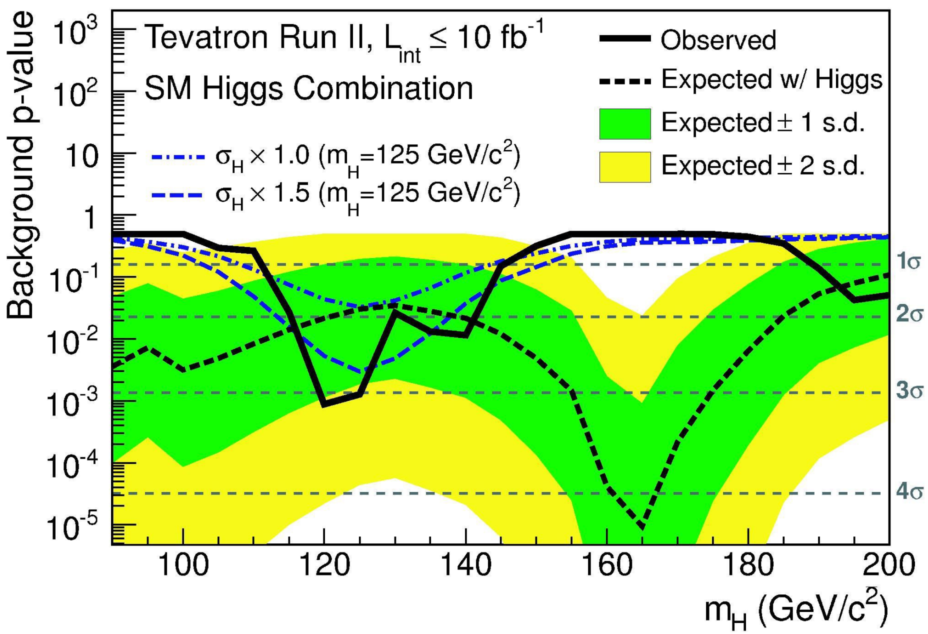
- Log-likelihood ratio (LLR)
  - Relative agreement of B-only and S+B hypotheses
  - Expected S+B shows good sensitivity up to ~185 GeV

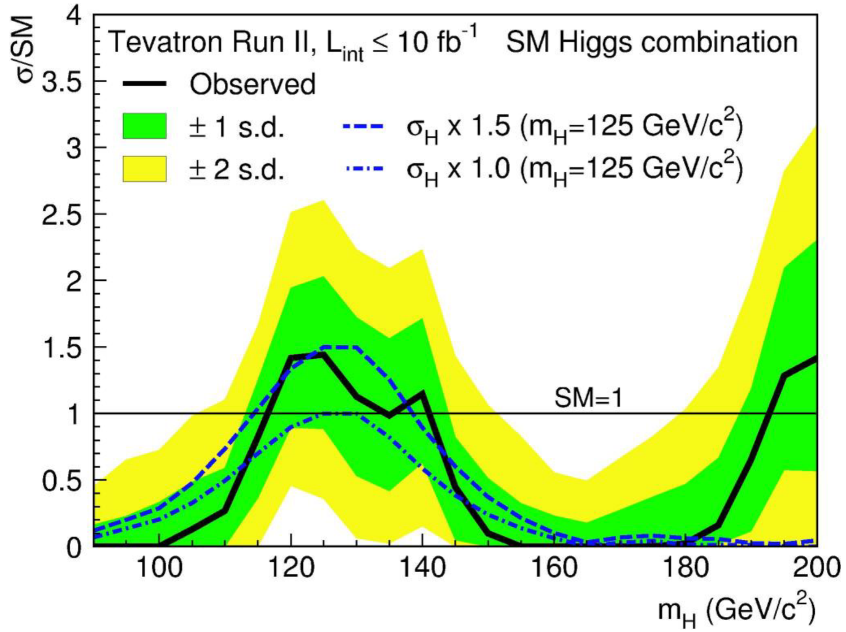


~3σ excess at 120-125 GeV

- Consistent with SM Higgs

Quantifying the Excess

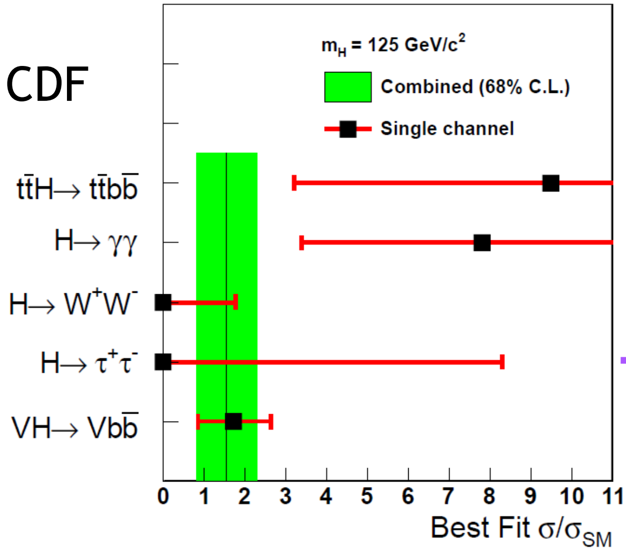




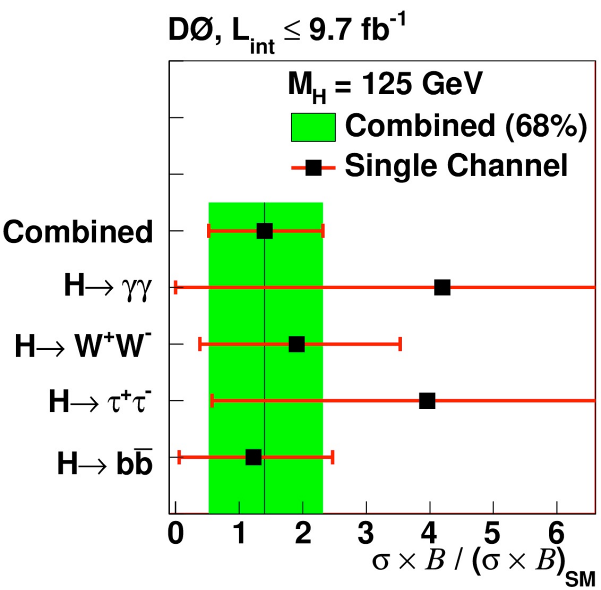
- Compatibility with B-only prediction (left)
  - Minimum local p-value at m_H = 120 GeV: 3.1σ (2.0σ expected)
    p-value at m_H = 125 GeV: 3.0σ (1.9σ expected)
- Compatibility with S+B prediction (right)
  - Maximum likelihood fit with Higgs cross section as a free parameter
    - $\mu = \sigma/\sigma_{SM} = 1.4 \pm 0.6$ @ 125 GeV

Tevatron cross section fits

CDF

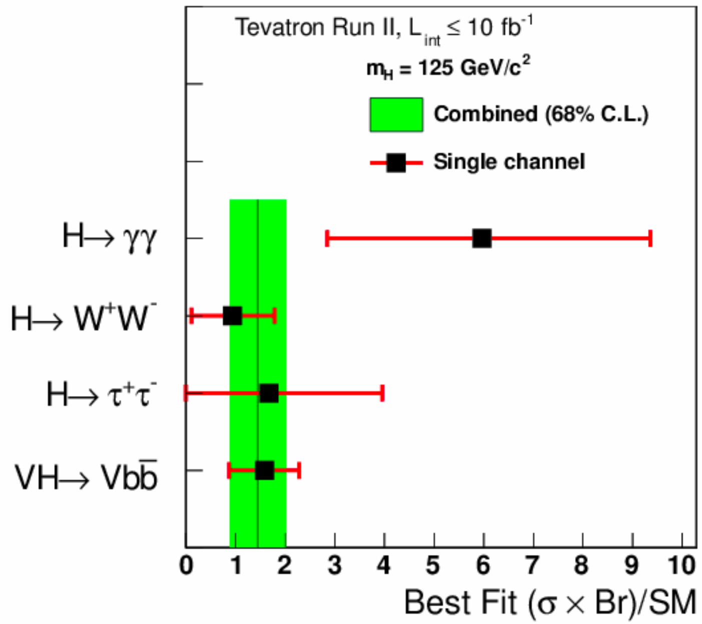


PRD 88, 052013 (2013)



PRD 88, 052011 (2013)

PRD 88, 052014 (2013)



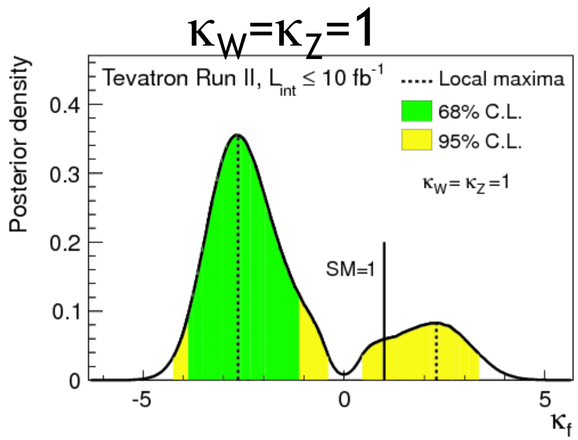
μ
$5.97^{+3.39}_{-3.12}$
$0.94^{+0.85}_{-0.83}$
$1.68^{+2.28}_{-1.68}$
$1.59^{+0.69}_{-0.72}$

Imperial College London

Couplings

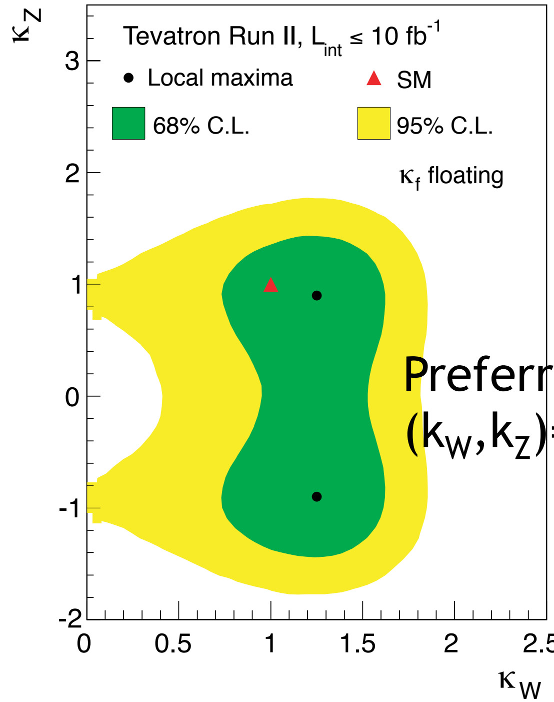
- Use LHCHXSWG framework (arXiv:1209:0040)

- 1D fits: Vary each of κ_W, κ_Z or κ_f independently in turn
  - Negative values for κ_f (κ_W) preferred due to $H\rightarrow\gamma\gamma$ excess



- 2D fits: Probe custodial symmetry i.e. $\lambda_{WZ} = \kappa_W/\kappa_Z \approx 1$(SM) or assume $\lambda_{WZ} = 1$

- All consistent with SM

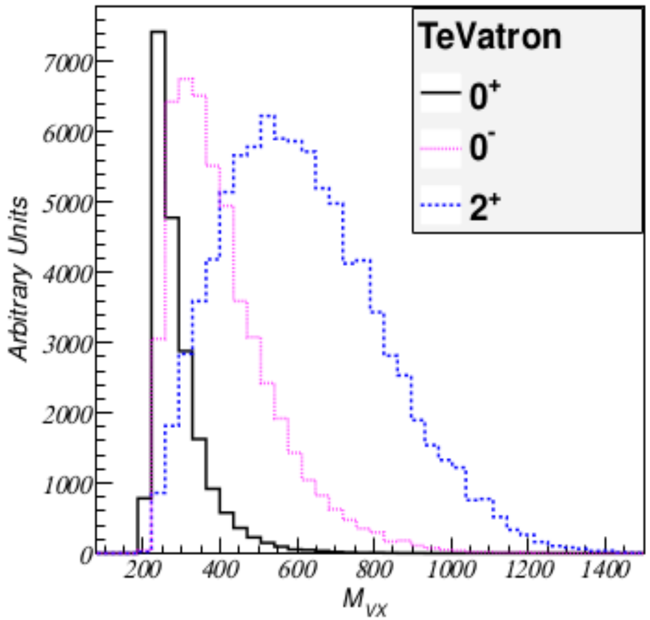


Preferred region $(k_W,k_Z)= (1.25,\pm0.90)$

Spin / Parity

- Tevatron sensitive in $b\bar{b}$ final states
  - VH cross section at threshold sensitive to β, & hence J^P assignment
    e.g. Ellis et al., JHEP 1211 134 (2012)

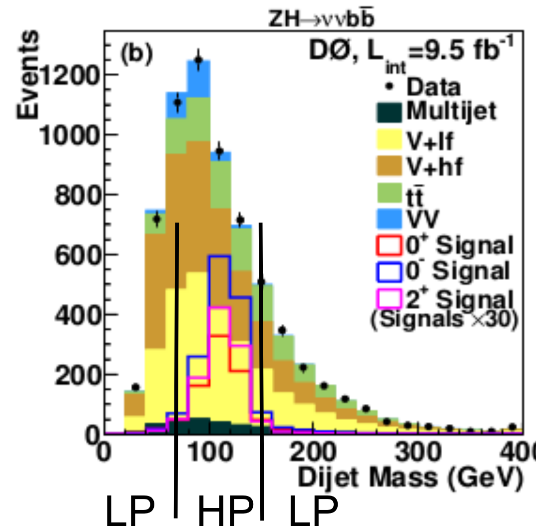
$J^P=0^+$; $\sigma \sim \beta$
$J^P=0^-$; $\sigma \sim \beta^3$
$J^P=2^+$; $\sigma \sim \beta^5$

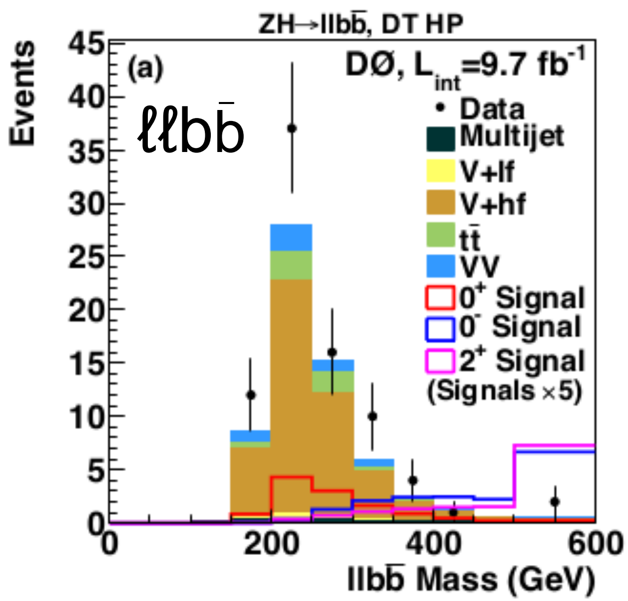


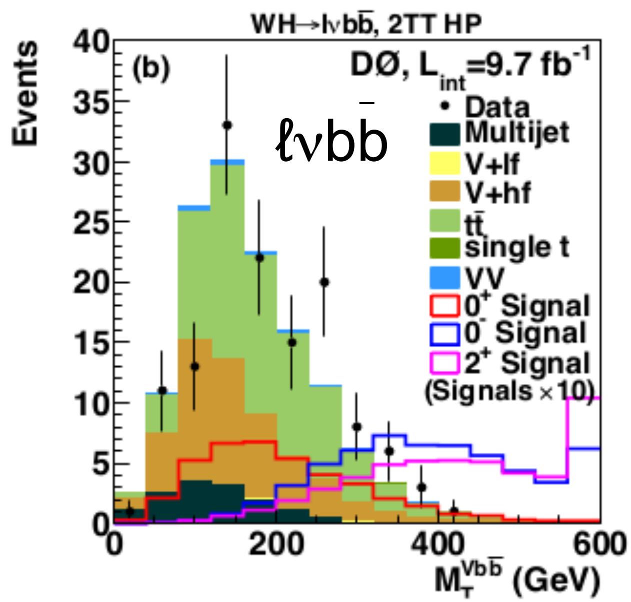
- Strategy
  - Models tested
    - 0^-: Model of Ellis et al.
      i.e. Basic dim. 5 effective coupling
    - 2^+: Standard RS graviton model
  - Re-use published VH → $Vb\bar{b}$ analyses, assume m_X = 125GeV
  - Main discriminating variable
    - Invariant or transverse mass

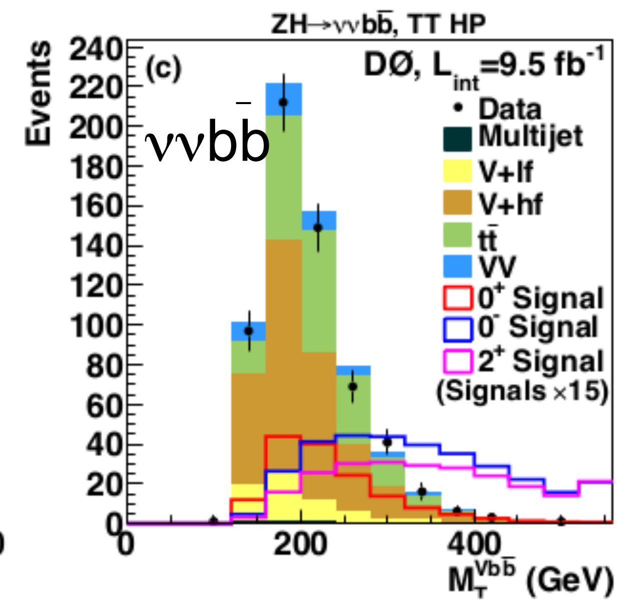
Spin / Parity

- Published event selection, b-tag, jet multiplicity & lepton categories
- DØ [Phys. Rev. Lett. **113**, 161802 (2014)]
  - Split into high (HP) & low purity (LP) samples
  - Final discriminant: invariant or transverse mass



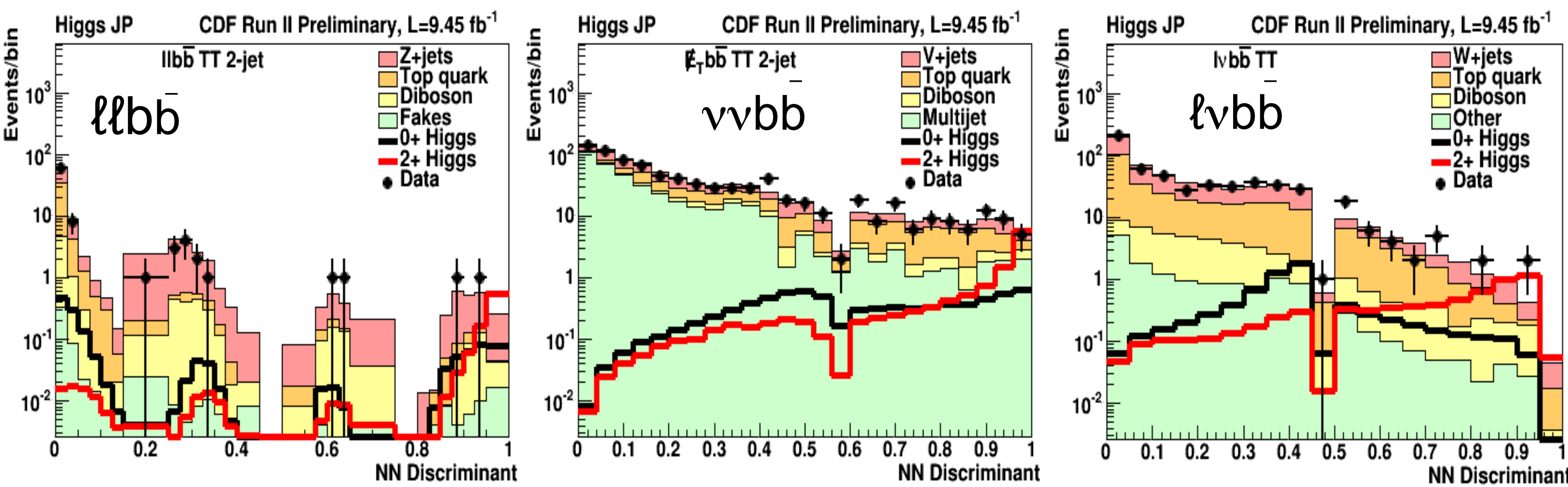






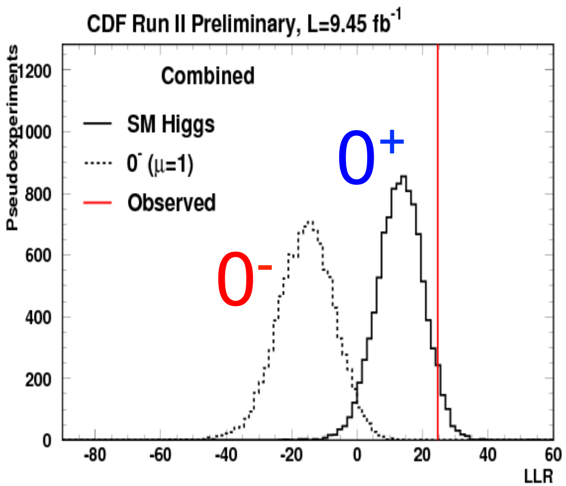
Spin / Parity

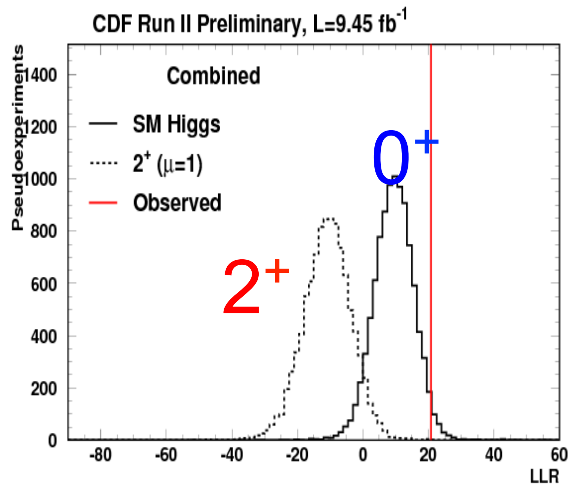
- Published event selection, b-tag, jet multiplicity & lepton categories
- CDF [Phys. Rev. Lett. **114**, 141802 (2015)]
  - Final discriminant:
    - MVA approach, combination of NNs trained against SM and BSM signals
    - Information on mass of VX system included

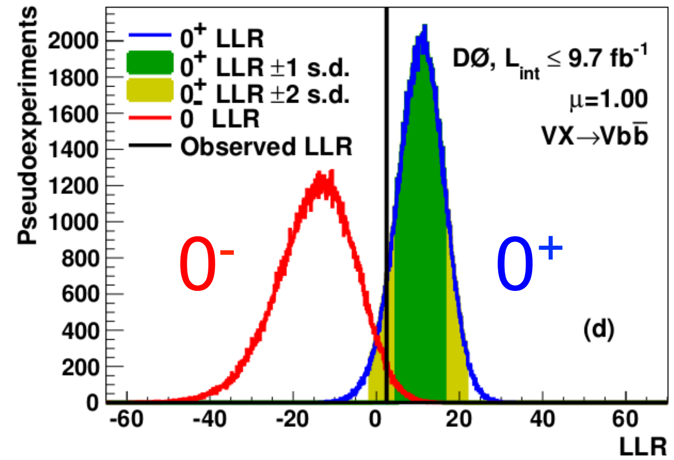


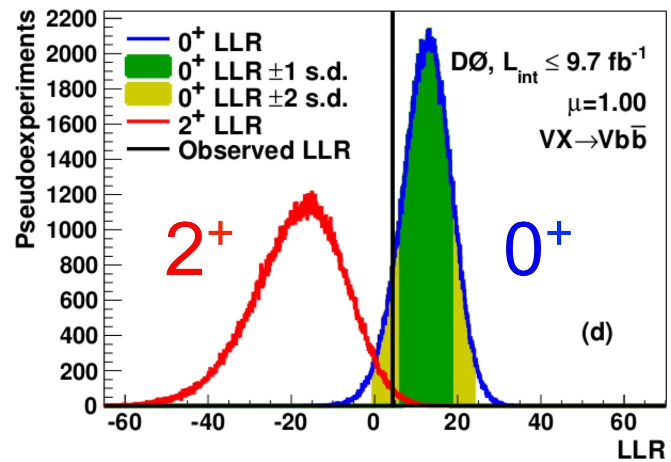
Spin / Parity

- LLR = -2log[L(H1)/L(H0)] with H1=(2^++bkg) or (0^-+bkg) & H0=(0^++bkg)
  - $CL_s = CL_{H1}/CL_{H0}$





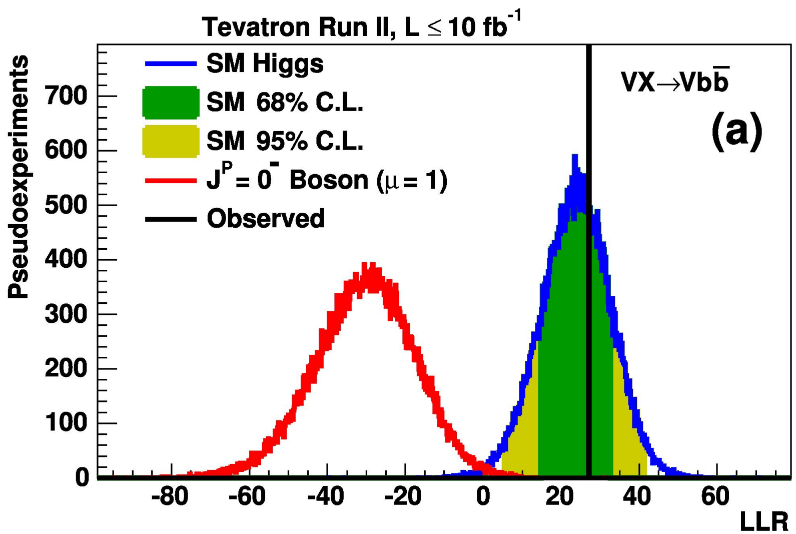


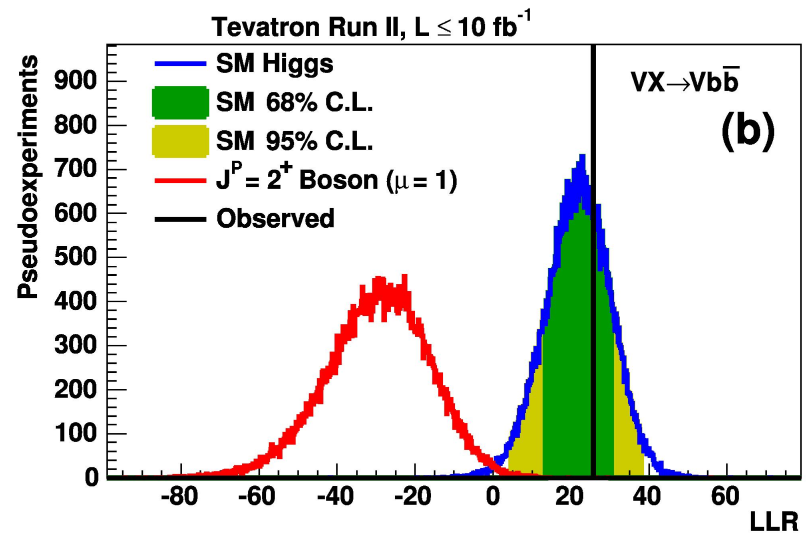


- CDF
  - 0^- signal excluded at 99.99% CL (99.92% exp)
  - 2^+ signal excluded at 99.1% CL (99.3% exp)
- DØ
  - 0^- signal excluded at 97.6% CL (99.9% exp)
  - 2^+ signal excluded at 99.0% CL (99.9% exp)

Spin / Parity

- Tevatron Combination [Phys. Rev. Lett. **114**, 151802 (2015]

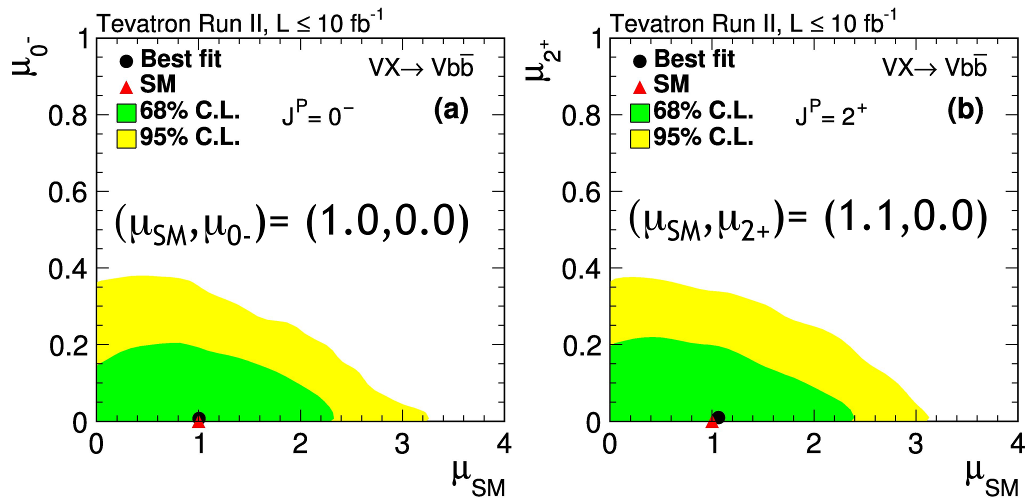




- Assuming production rate x BR of X same as for SM (i.e. μ = 1)
  - 0^- signal excluded at 5.0σ (4.8σ exp)
  - 2^+ signal excluded at 4.9σ (4.6σ exp)
- Other values of μ tested

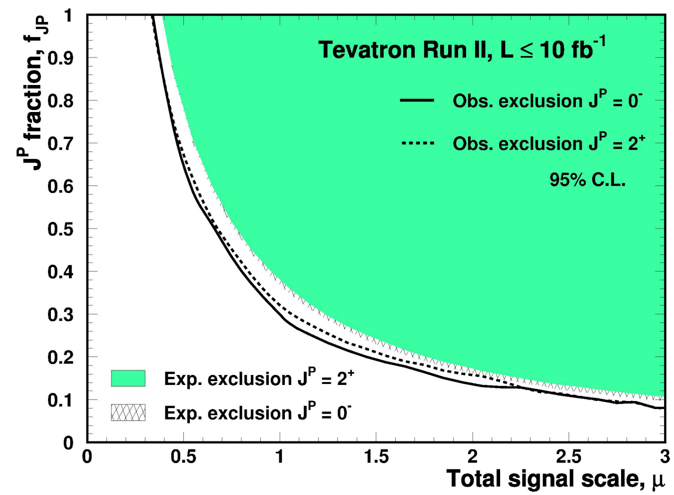
Spin / Parity

- Consider admixture of 0^+ & 0^- (or 2^+)
- Limits on 0^- (or 2^+) fraction
  - μ_{SM}=0,exclude at 95%CL
    - f_{0-} > 0.36 (0.32 exp)
    - f_{2+} > 0.36 (0.33 exp)



'Exotic fraction' vs total rate

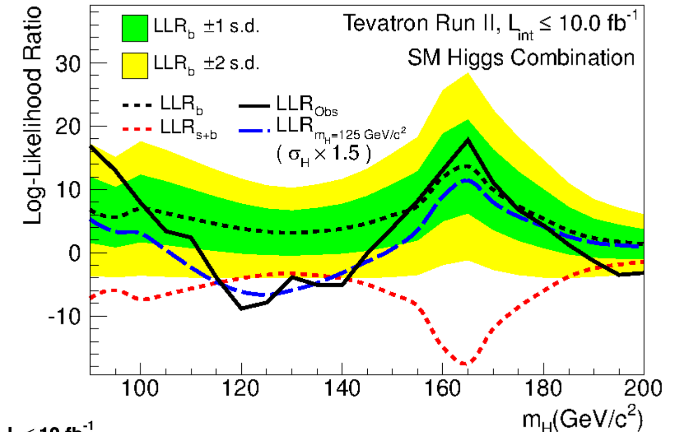
$f_{JP} = \mu_{exotic} / \mu_{exotic}+\mu_{SM}$

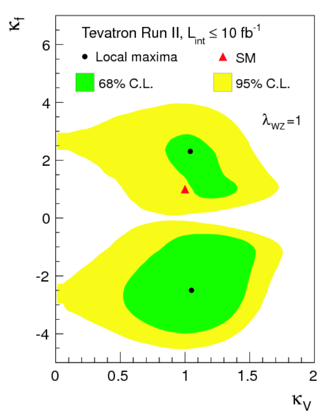


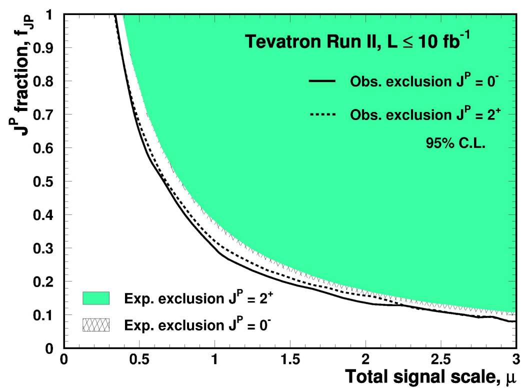
$\mu = \mu_{exotic}+\mu_{SM}$

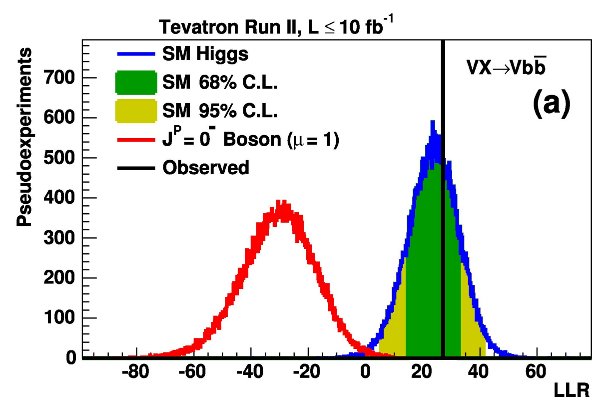
Conclusions

- Tevatron
  - Sensitivity over most of accessible mass range
  - Excess from $115 < m_H < 140$ GeV
    - ~3σ significance at 125 GeV
  - Coupling & spin results consistent with SM Higgs









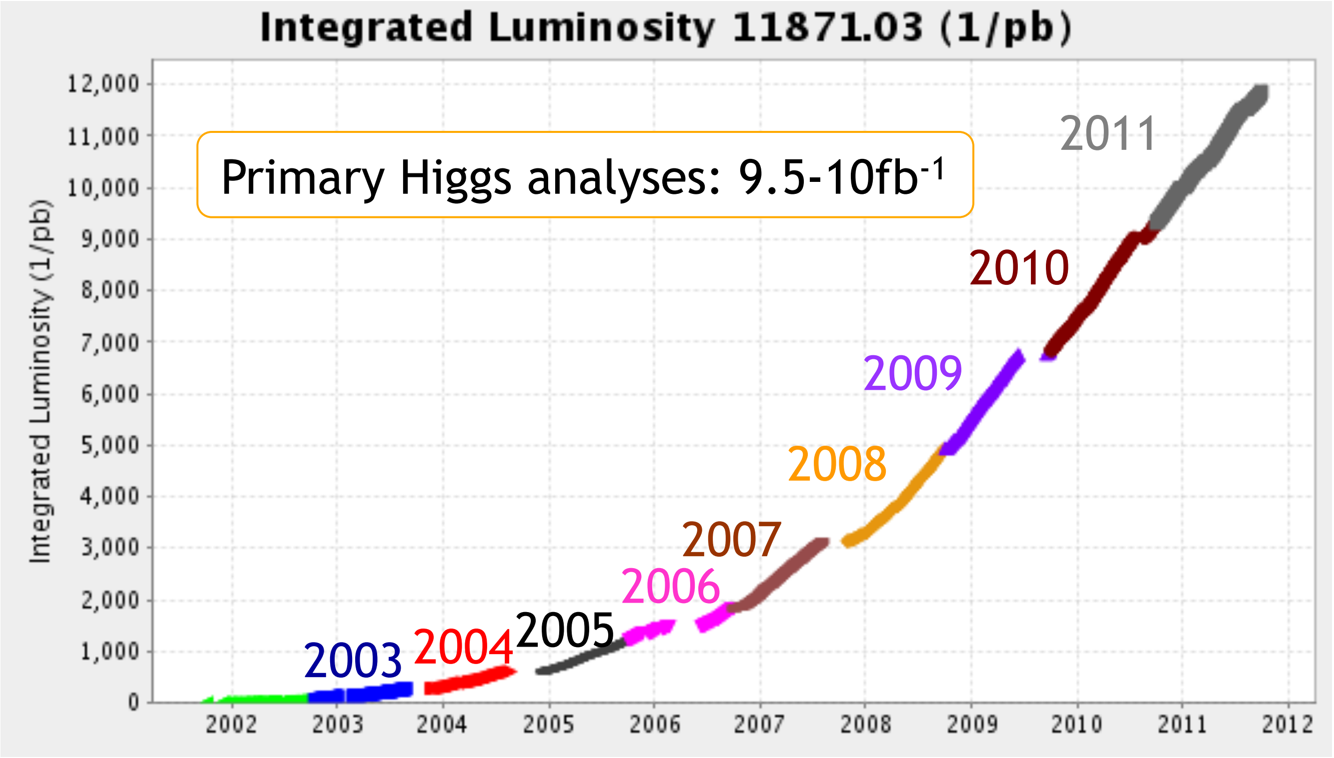
Exclude:
0^- and 2^+ at 5σ

- Tevatron: Continued to provide valuable information on nature of observed boson
  - Look forward to Tevatron + LHC $H \rightarrow b\bar{b}$ combination
- Testament to Tevatron's legacy: Making of a new generation of physicists
  - Many moved to LHC

The
CDF and DØ
Collaborations

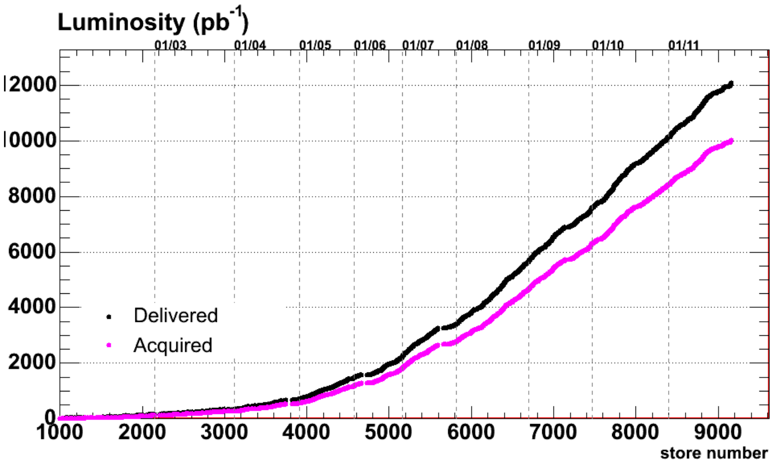
Tevatron

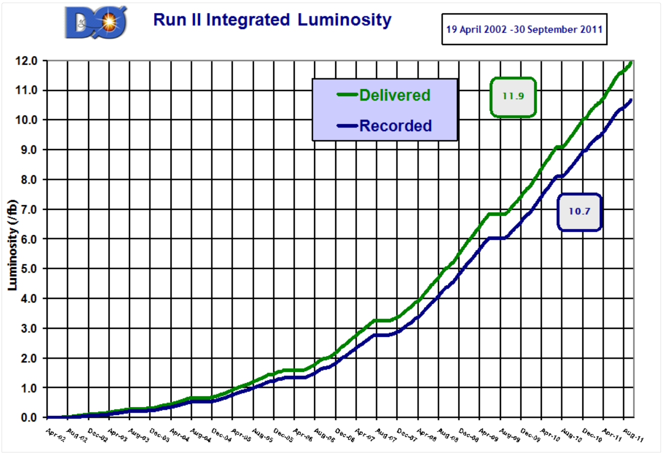
- ~12fb^{-1} delivered, ~11fb^{-1} recorded, ~10fb^{-1} after data quality per expt
  - with $L_{inst} \leq 4 \times 10^{32}$



Many thanks to Accelerator Division

Tevatron





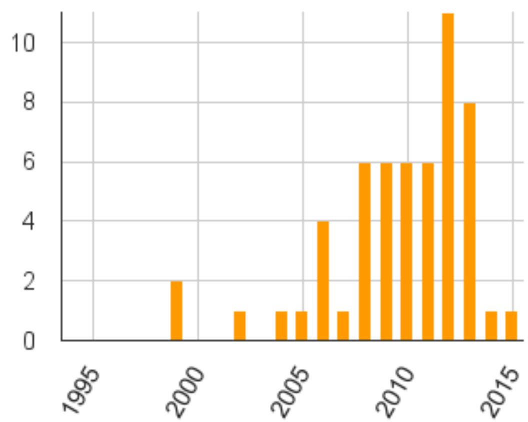
- Proton-antiproton
  - Unlikely to be repeated
  - Dominantly $q\bar{q}$ collisions not gg as at LHC
    - Gives enhanced xsect for some processes eg VH
  - Initial CP eigenstate (and DØ’S ability to reverse magnetic field)
    - Enable incisive asymmetry and CP measurements eg A_{fb} in $t\bar{t}$
- Relative cleanliness (low pileup) facilitates precision measurements
  - e.g. W mass, top quark mass

Snapshot of Recent Activity

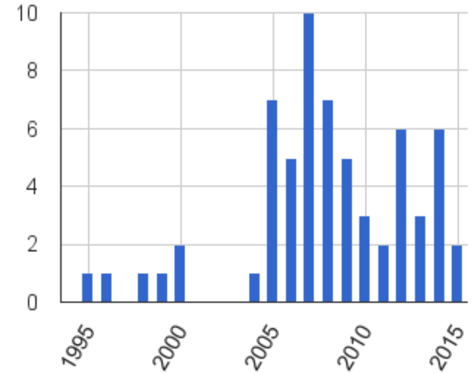
- e.g. looking at DØ publications

Focus here: Higgs

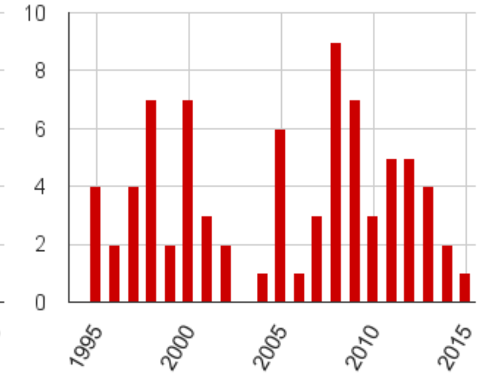
DØ Higgs Publications



DØ Heavy Flavor Publications

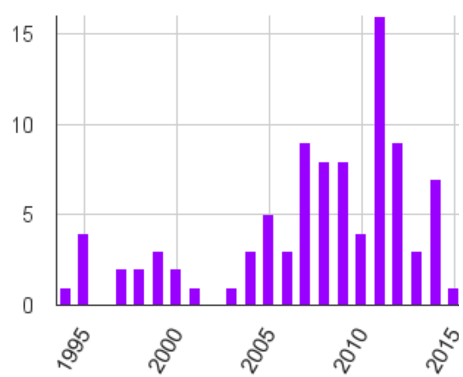


DØ EW Publications

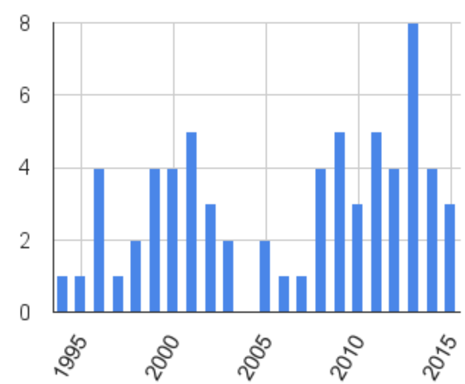


Wealth of other results reported elsewhere

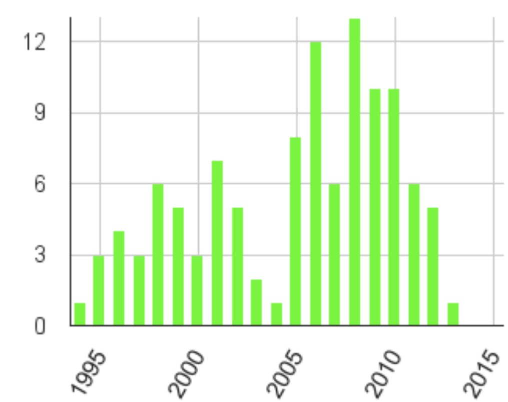
DØ Top Publications



DØ QCD Publications

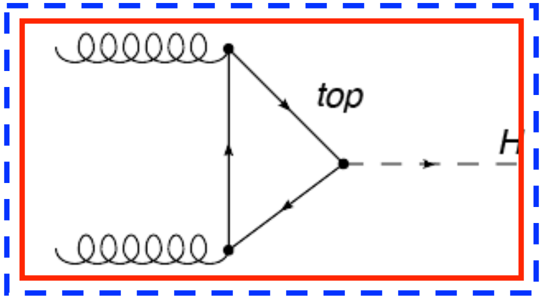


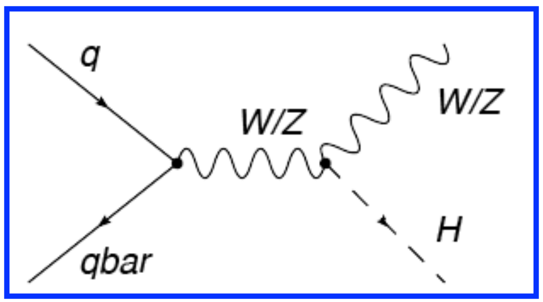
DØ NP Publications

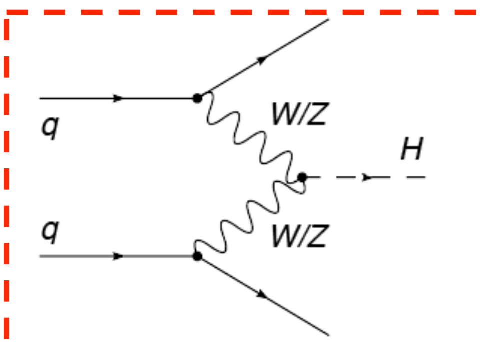


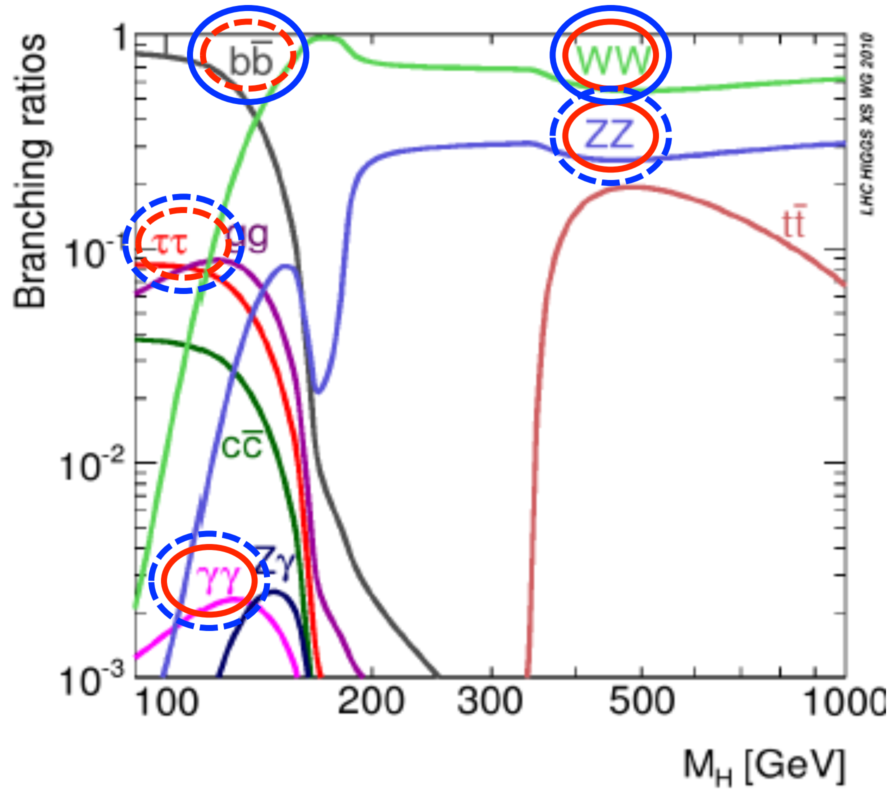
Tevatron -LHC Complementarity

@ m_H= 125 GeV









LHC

Tevatron

Main mode

Supporting mode

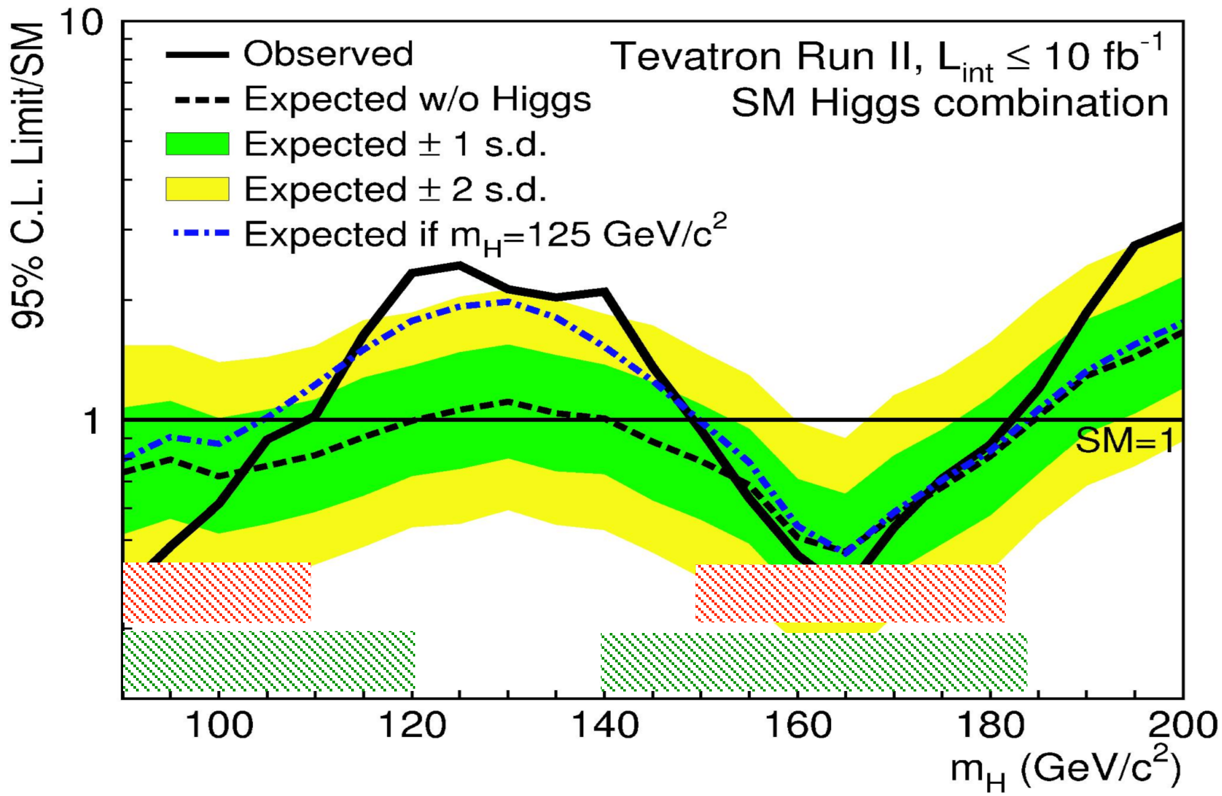
Details: Final Full Combination

CDF Channel ($V = W, Z$ and $\ell = e, \mu$)		Luminosity (fb^{-1})	M_H (GeV)	Reference
$WH \to \ell\nu b\bar{b}$		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)
$ZH \to \nu\bar{\nu}b\bar{b}$		9.45	90–150	PRD **87**, 052008 (2013)
$WH + ZH \to jjb\bar{b}$		9.45	100–150	JHEP **02**, 004 (2013)
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$		9.45	100-150	PRL **109**, 181802 (2012)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$		9.7	110–200	PRD **88**, 052012 (2013)
$H \to W^+W^- \to \ell\tau_h$		9.7	130–200	PRD **88**, 052012 (2013)
$WH \to WW^+W^- \to \ell\ell\ell, \ell^\pm\ell^\pm$		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)
$ZH \to ZW^+W^- \to \ell\ell\ell + jet(s)$		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
$WH \to \ell\nu b\bar{b}$		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)
$ZH \to \nu\bar{\nu}b\bar{b}$		9.5	100–150	PLB **716**, 285 (2012)
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$		9.7	100–200	PRD **88**, 052006 (2013)
$H + X \to W^+W^- \to \mu^\pm\tau_h^\mp + \leq 1$ jet		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)
$VH \to ee\mu/\mu\mu e + X$		9.7	100–200	PRD **88**, 052009 (2013)
$VH \to e^\pm\mu^\pm + X$		9.7	100–200	PRD **88**, 052009 (2013)
$VH \to \ell\nu q'\bar{q}q'\bar{q}$		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)
$H + X \to \ell\tau_h jj$		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)

Tevatron Combination



Observed exclusion
Expected exclusion

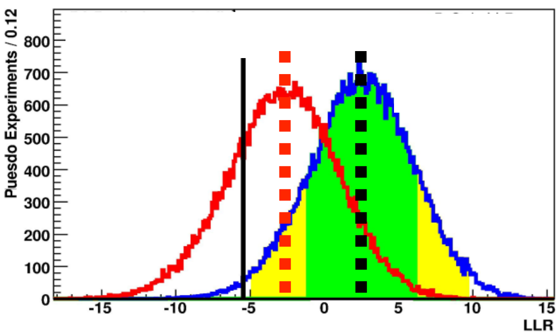
Observed exclusion: 90 < m_H < 109 GeV, 149 < m_H < 182 GeV

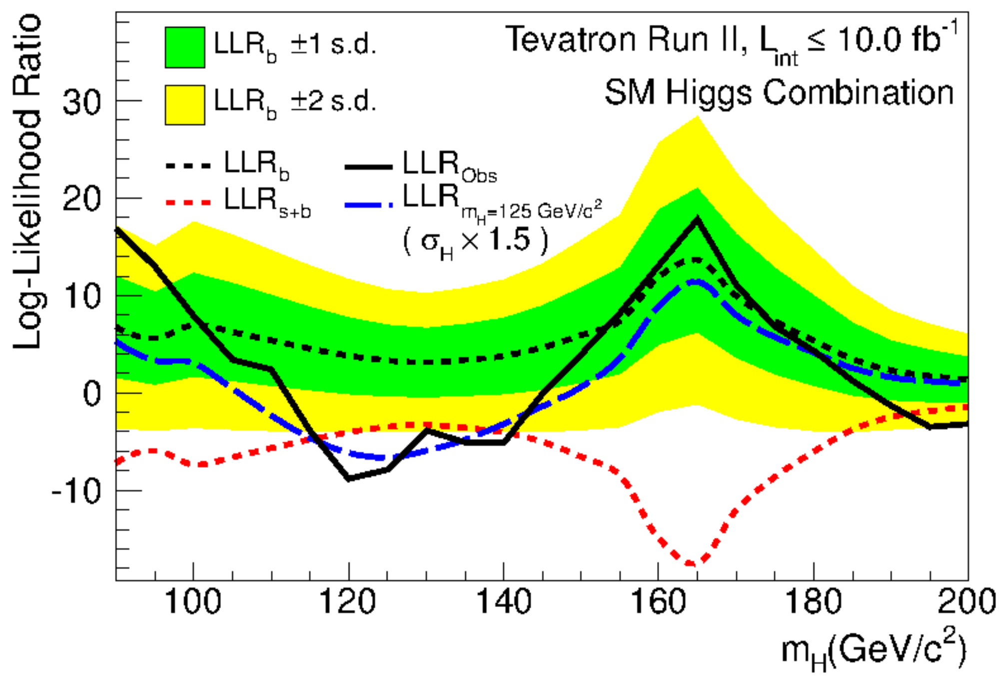
Expected exclusion: 90 < m_H < 120 GeV, 140 < m_H < 184 GeV

95% CL limit @ m_H = 125 GeV: 1.06 x σ(SM) expected, 2.44 x σ(SM) observed

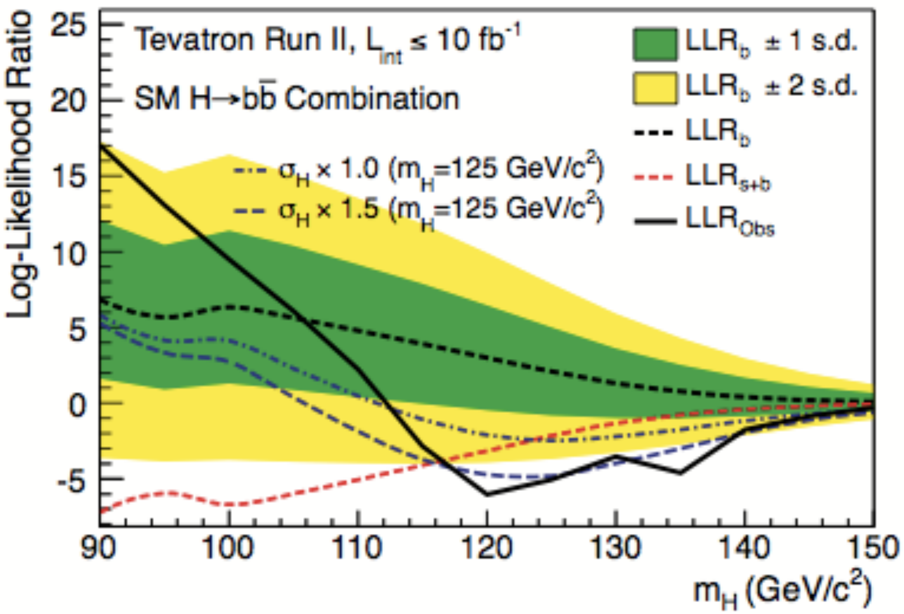
Quantifying the Excess: LLR

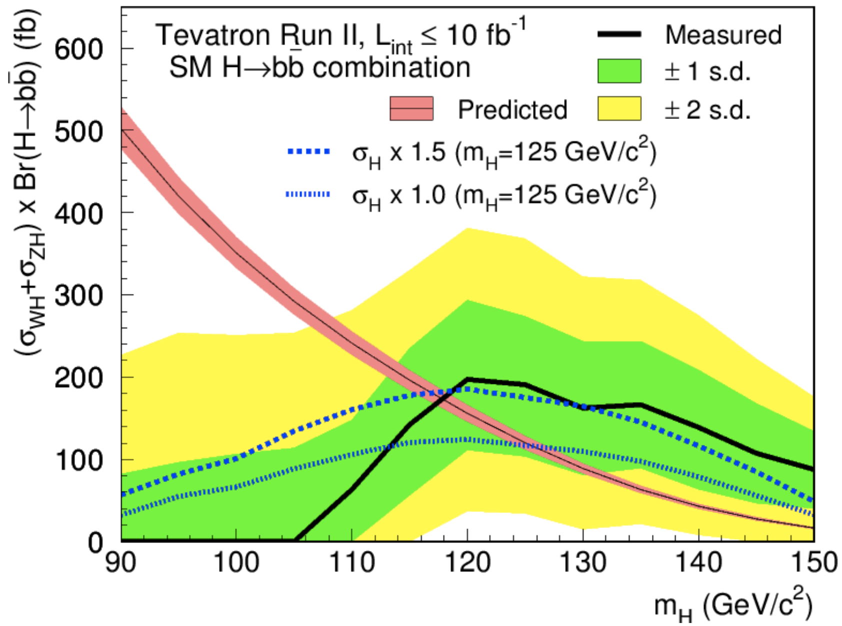
- Log-likelihood ratio (LLR)
  - Relative agreement of B-only and S+B hypotheses
  - Throw pseudo-data to populate B-only and S+B models
    - Compare to observed
  - Expected S+B shows good sensitivity up to ~185 GeV
  - ~3σ excess at 120-125 GeV
    - Consistent with SM Higgs





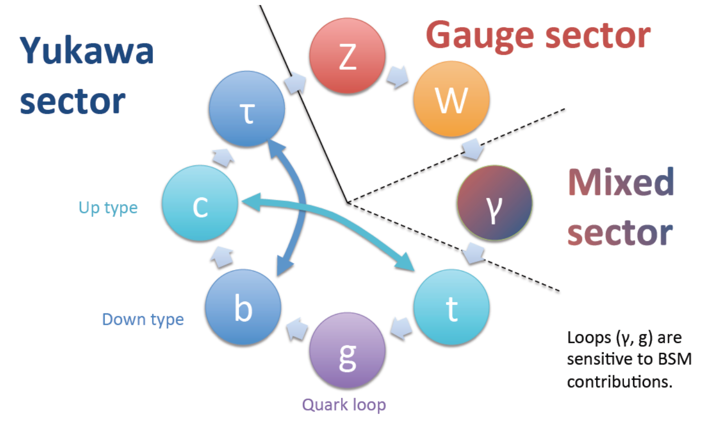
Tevatron: H → bb Results





Couplings

- Measure deviations of couplings from SM prediction using LHCHXSWG framework (arXiv:1209:0040)



$$\sigma \cdot BR(ii \to H \to ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

– Assume all signals near 126 GeV from single resonance of zero width, with SM-like coupling structure

– Additionally: no additional invisible or undetected Higgs decay modes

– e.g.

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

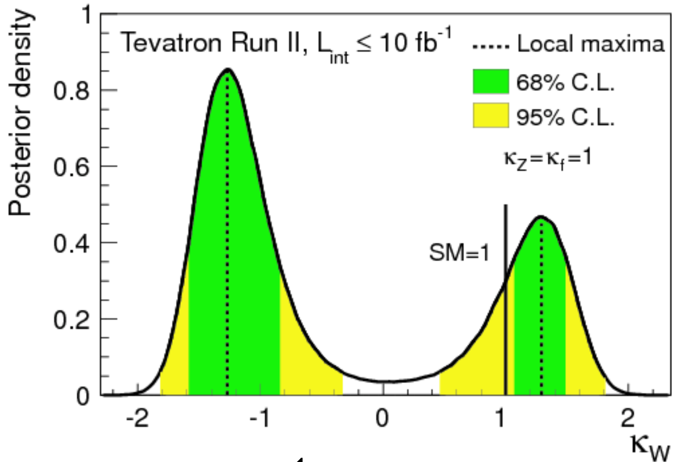
$$\kappa_\gamma = 1.28\kappa_W - 0.28\kappa_f$$

– Study fermion coupling, κ_f and boson couplings κ_W, κ_Z and κ_V

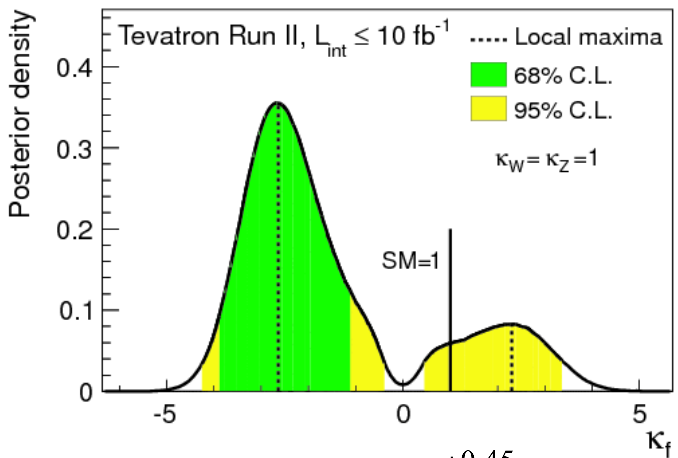
Couplings: 1D

- 1D fits: Vary each of κ_W, κ_Z and κ_f independently in turn

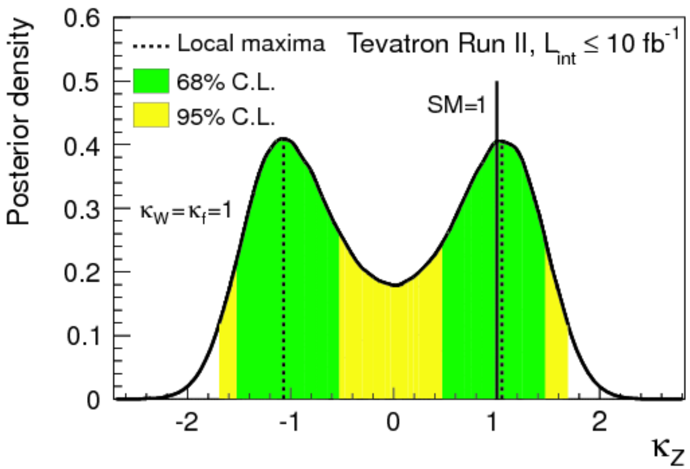
$\kappa_Z=\kappa_f=1$



$\kappa_W=\kappa_Z=1$



$\kappa_W=\kappa_f=1$



$$k_z = \pm(1.05^{+0.45}_{-0.55})$$

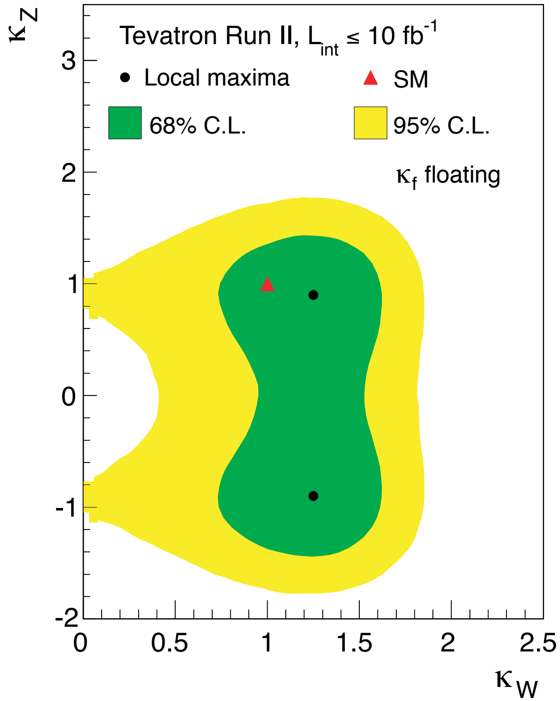
$$k_f = -2.64^{+1.59}_{-1.30}$$

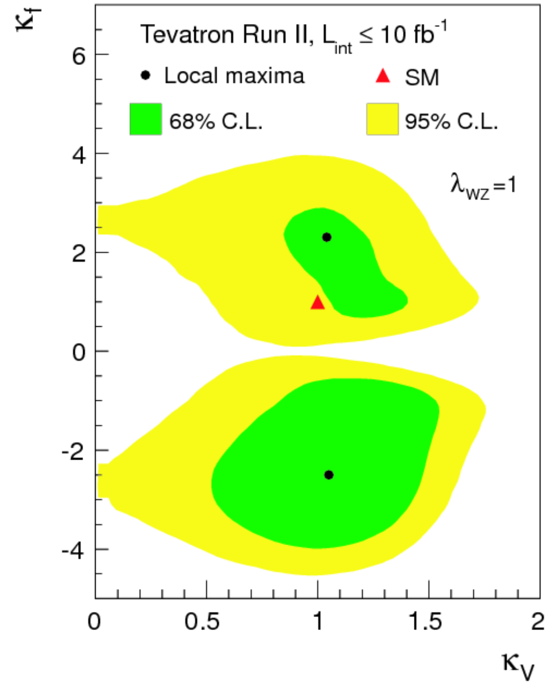
$$k_w = -1.27^{+0.46}_{-0.29} \text{ or } 1.04 < k_w < 1.51$$

Negative values for κ_W and κ_f preferred due to $H \rightarrow \gamma\gamma$ excess

All consistent with SM

Couplings: 2D





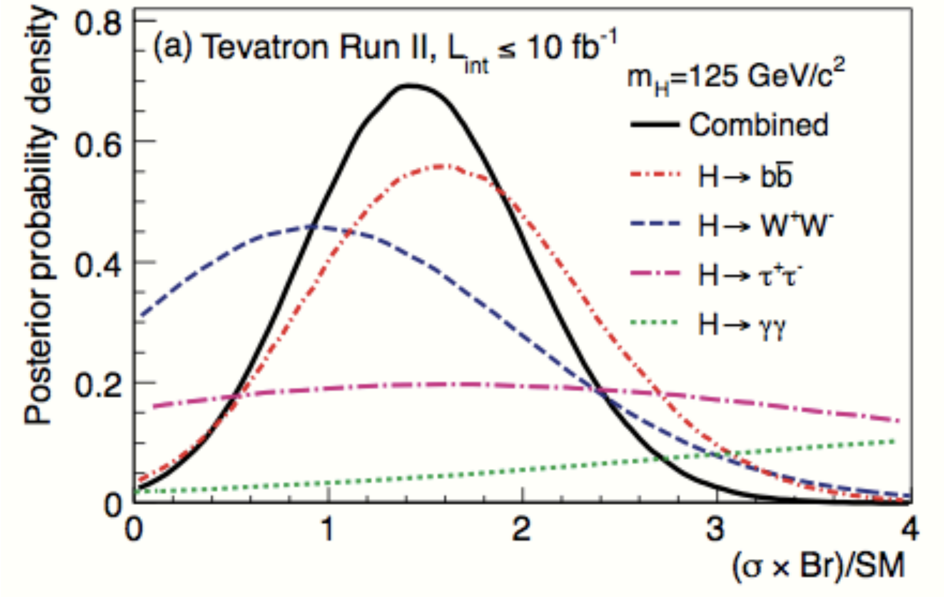
- Probe custodial symmetry
  ie $\lambda_{WZ} = \kappa_W/\kappa_Z \approx 1$(SM)
  - Preferred region
    $(\kappa_W,\kappa_Z)= (1.25,\pm 0.90)$

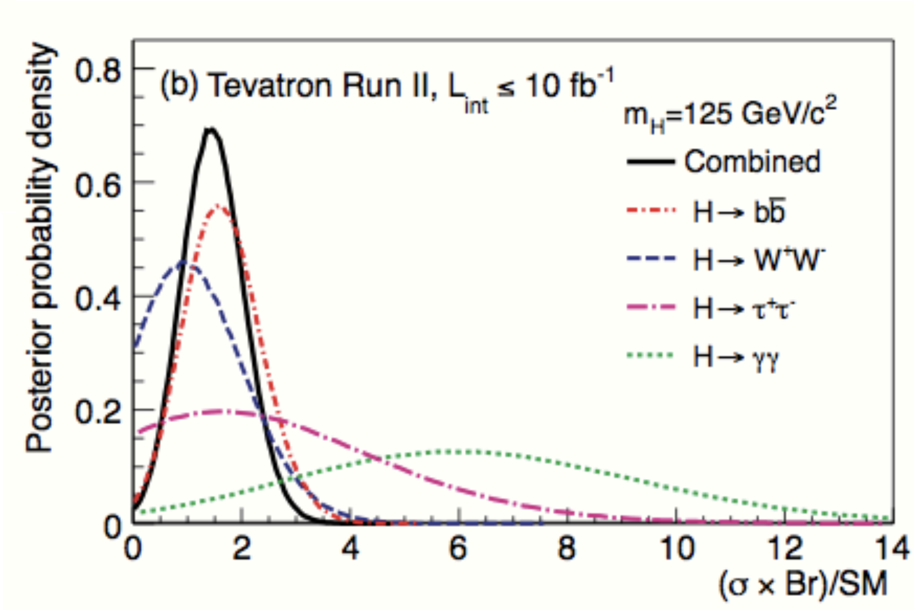
- Assume $\lambda_{WZ} = 1$
  - Preferred regions
    $(\kappa_V,\kappa_f)= (1.05,-2.40)$ &
    $(\kappa_V,\kappa_f)= (1.05, 2.30)$

All consistent with SM

Tevatron: Couplings

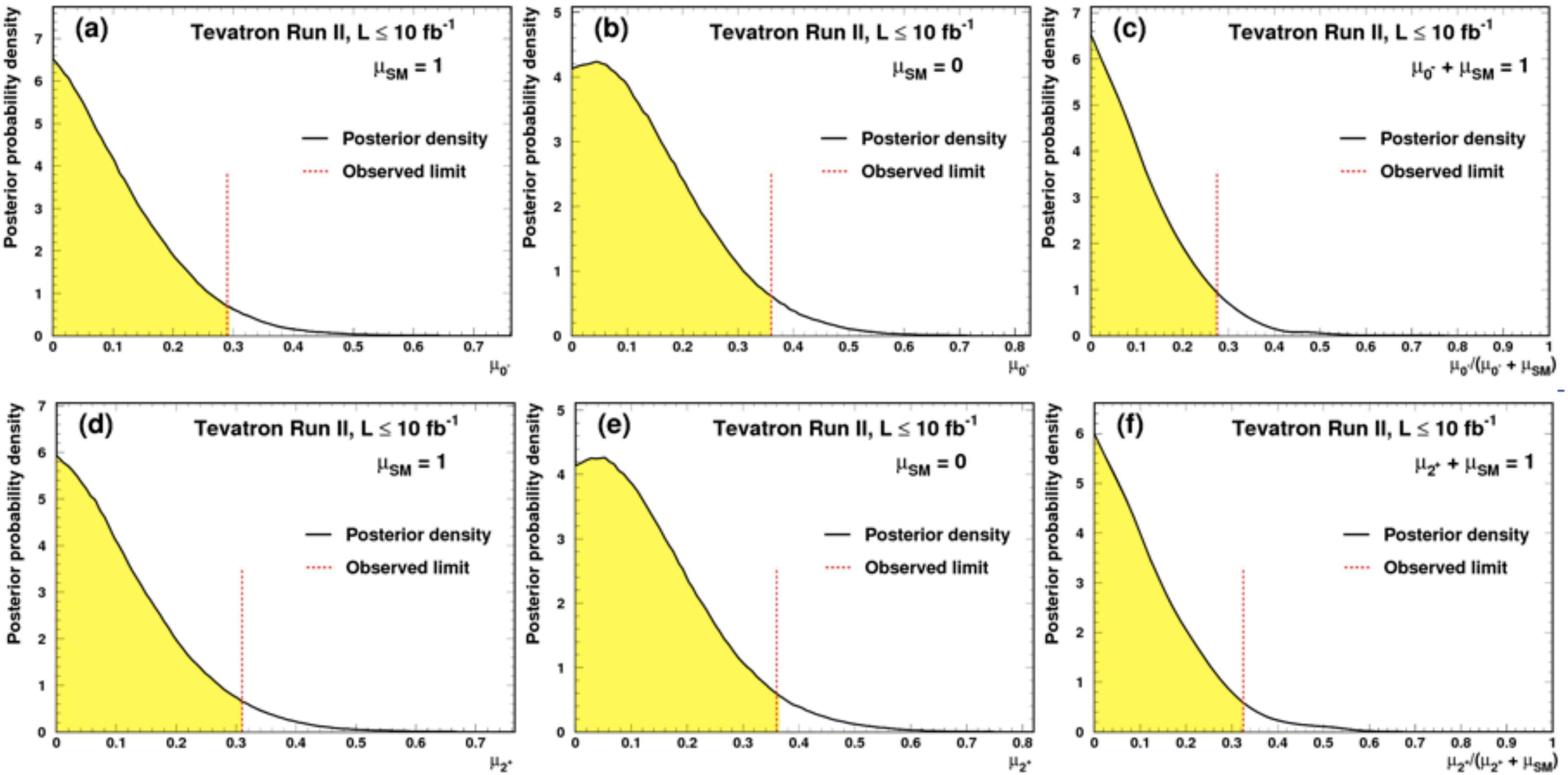
- Posterior probability densities





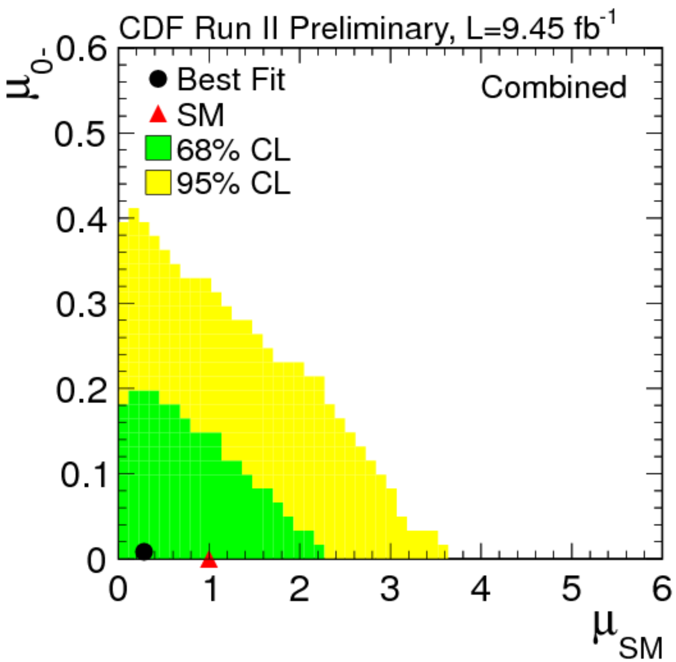
Spin / Parity

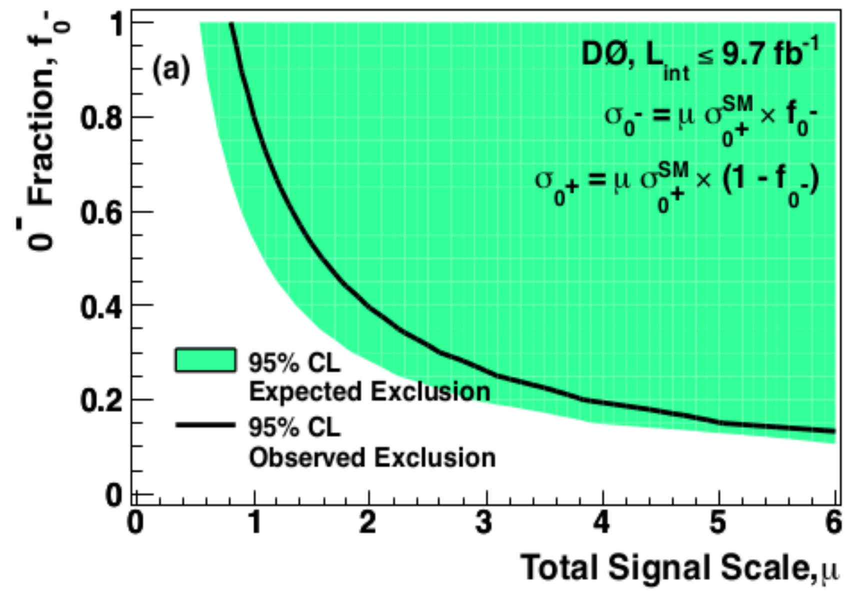
- Posterior probability density functions



Spin / Parity

- Consider admixture of 0^+ & 0^- (or 2^+), set limits on 0^- (or 2^+) fraction





Exclude at 95% CL

$f_{0-} > 0.32$ & $f_{2+} > 0.35$ (no SM Higgs present)

$f_{2+} > 0.28$ & $f_{2+} > 0.31$ (SM Higgs present)

Exclude at 95% CL

$f_{0-} > 0.80$

$f_{2+} > 0.67$

Spin / Parity

- Consider admixture of 0^+ & 0^- (or 2^+), set limits on 0^- (or 2^+) fraction