Tevatron Higgs Searches

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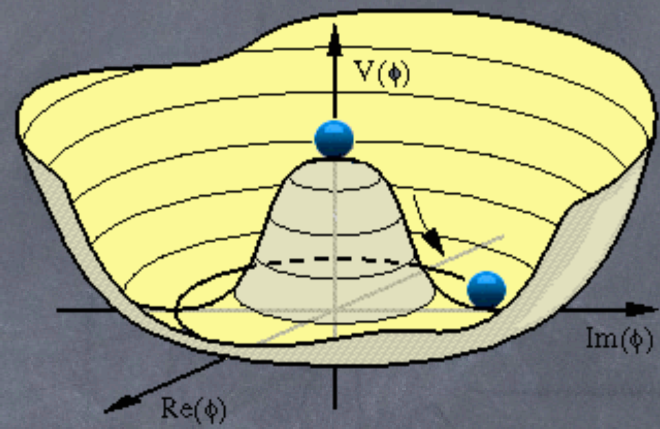
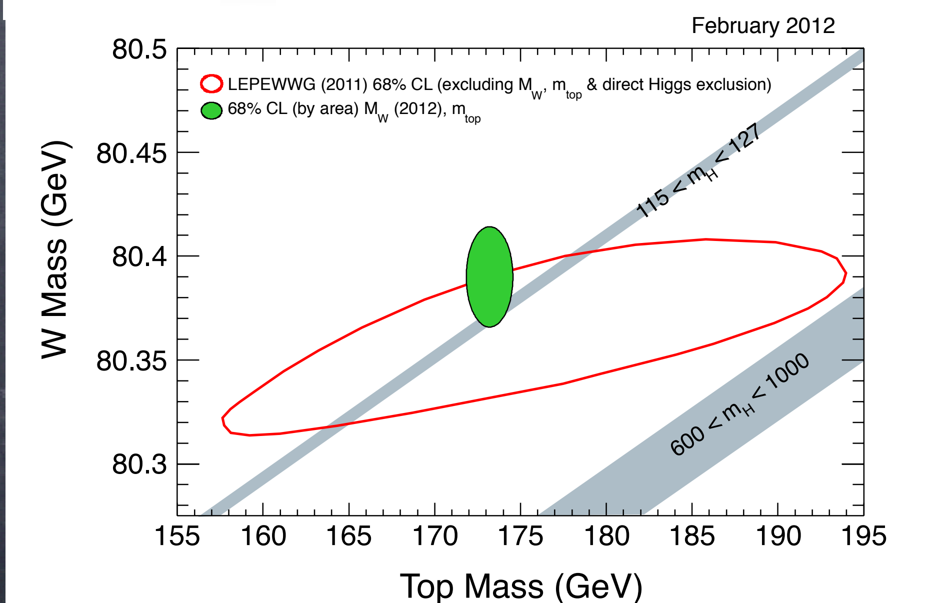
Higgs Mechanism

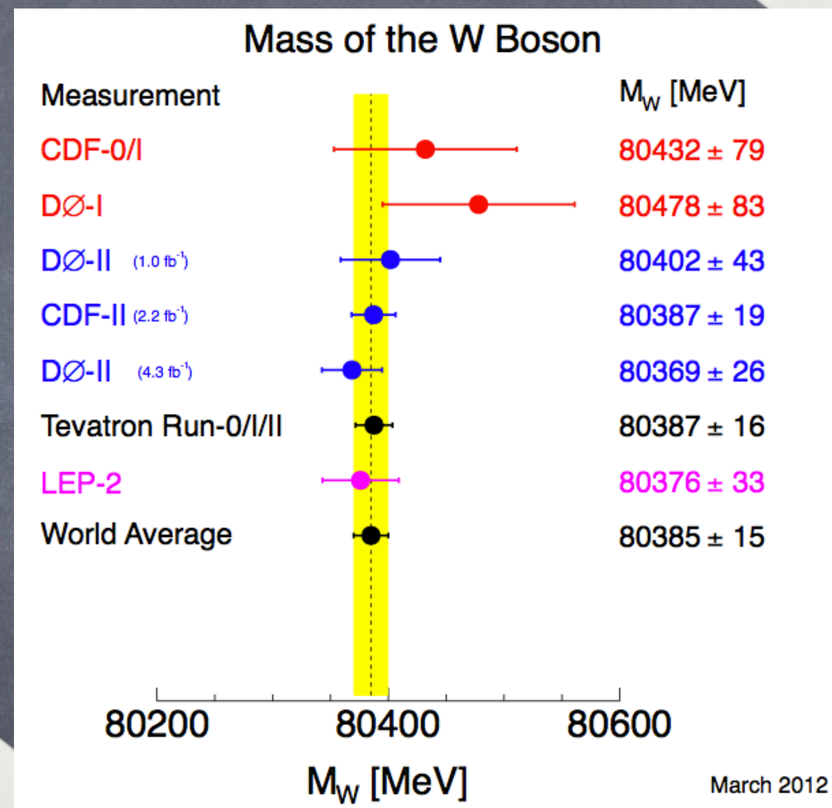
- Standard Model - describes electromagnetic, weak, and strong forces
- need mechanism to give weak gauge bosons mass
- Higgs mechanism adds scalar field throughout the universe
  - symmetric potential with non-zero vacuum expectation
  - ground state breaks the symmetry
  - the W/Z acquire mass, photon still massless



- some nice benefits
  - gauge invariance is maintained
  - masses generated for fermions due to coupling to field
  - predicts presence of a new particle: Higgs boson

limits on SM Higgs mass



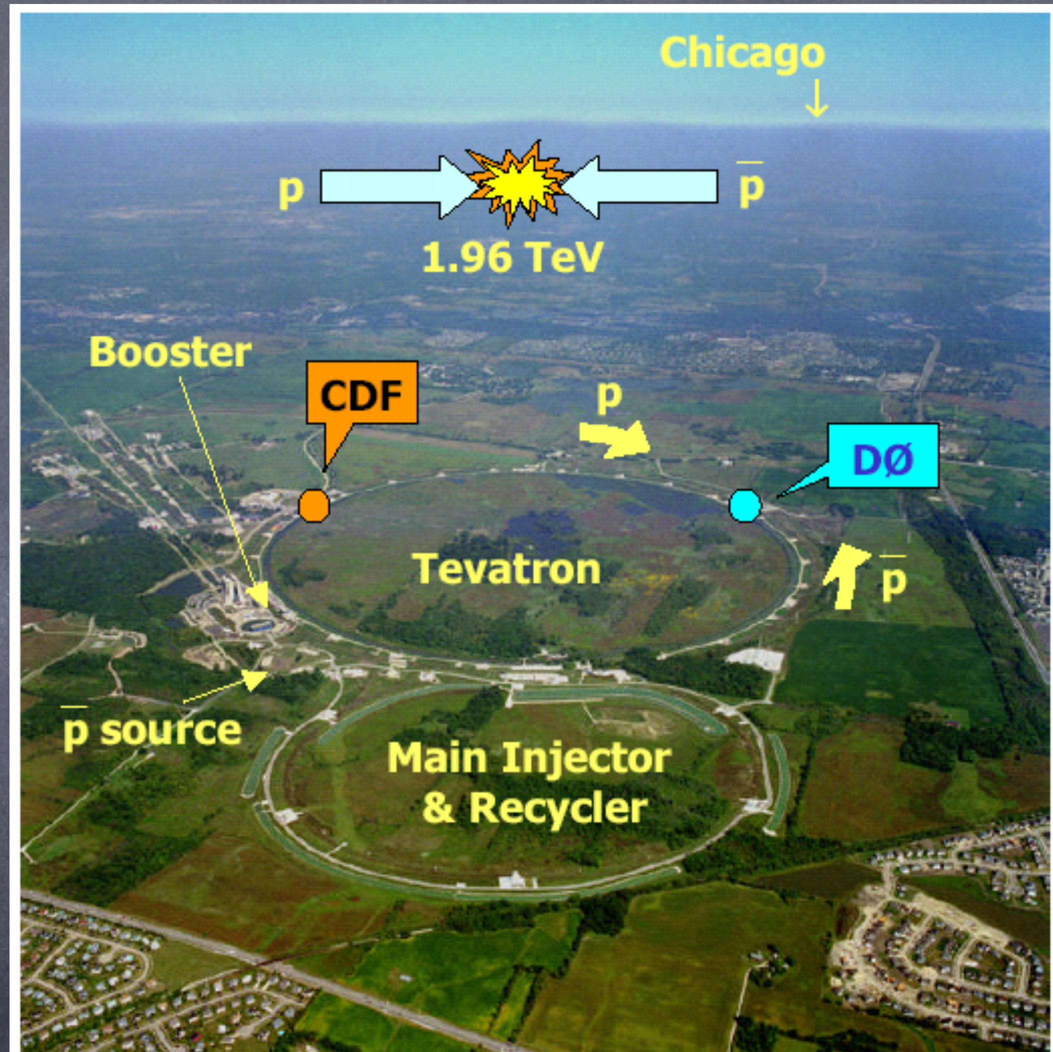


Higgs and top contribute radiative corrections to M_W

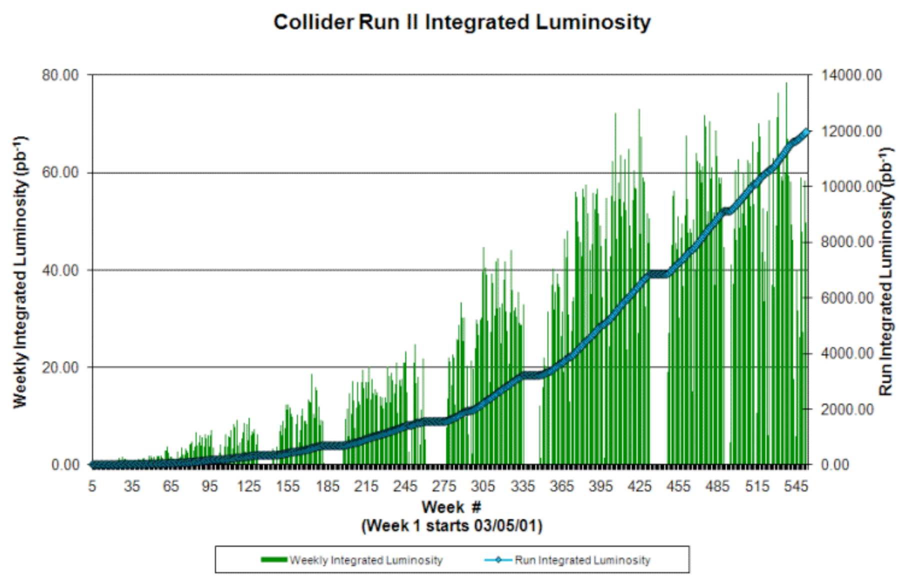
New World Average
$M_W = 80390 \pm 16$ MeV
CDF ± 19, DØ ± 23

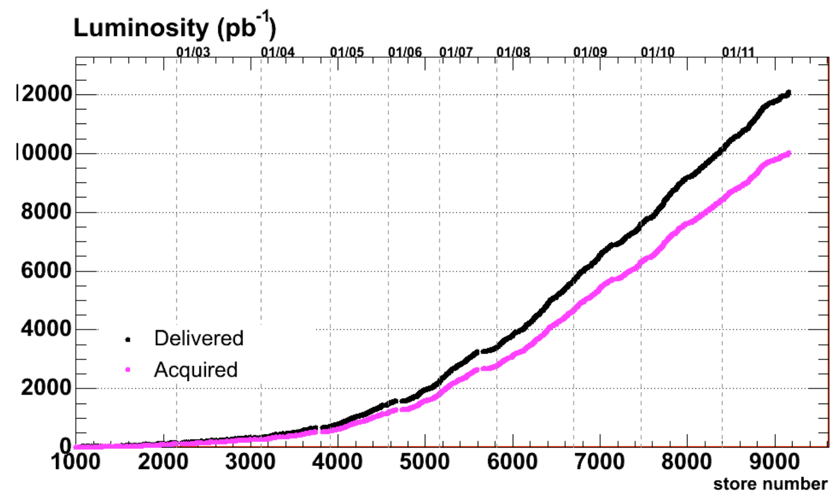
The Tevatron at Fermilab

- Tevatron proton-antiproton collider at Fermilab
- $\sqrt{s}$ = 1.96 TeV
- EWK scale processes probe different region of parton distribution than LHC
- channel sensitivity differs from LHC



Tevatron Integrated Luminosity





- delivered 11.9 fb^{-1}
- exceptionally efficient in final years

- recorded w/ ~90% eff
- final results ~10 fb^{-1}

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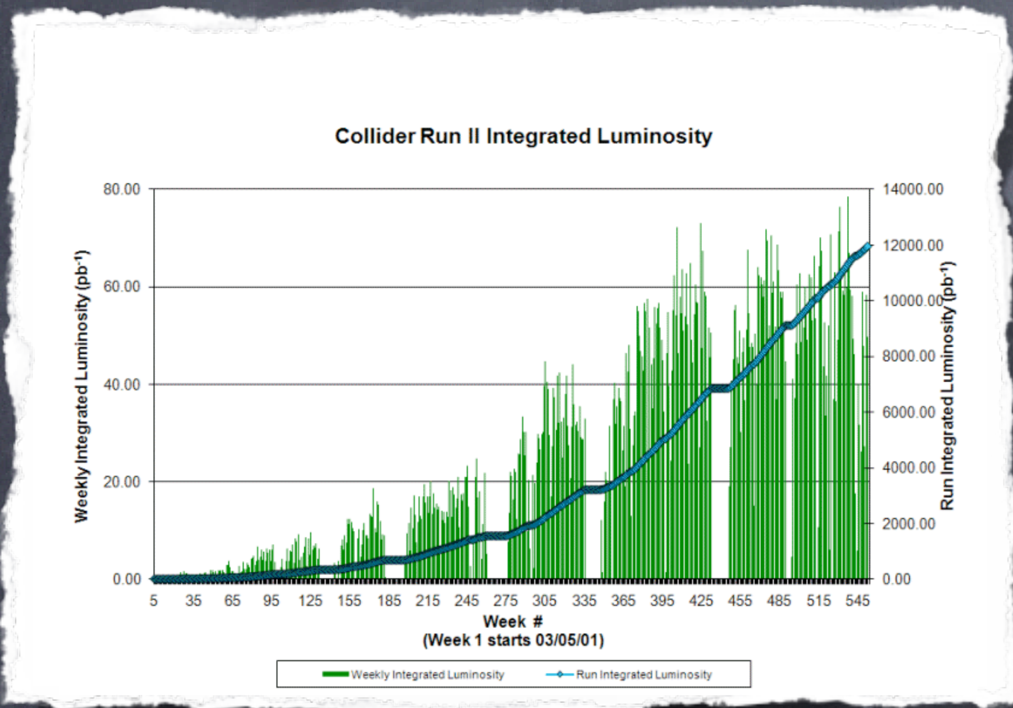

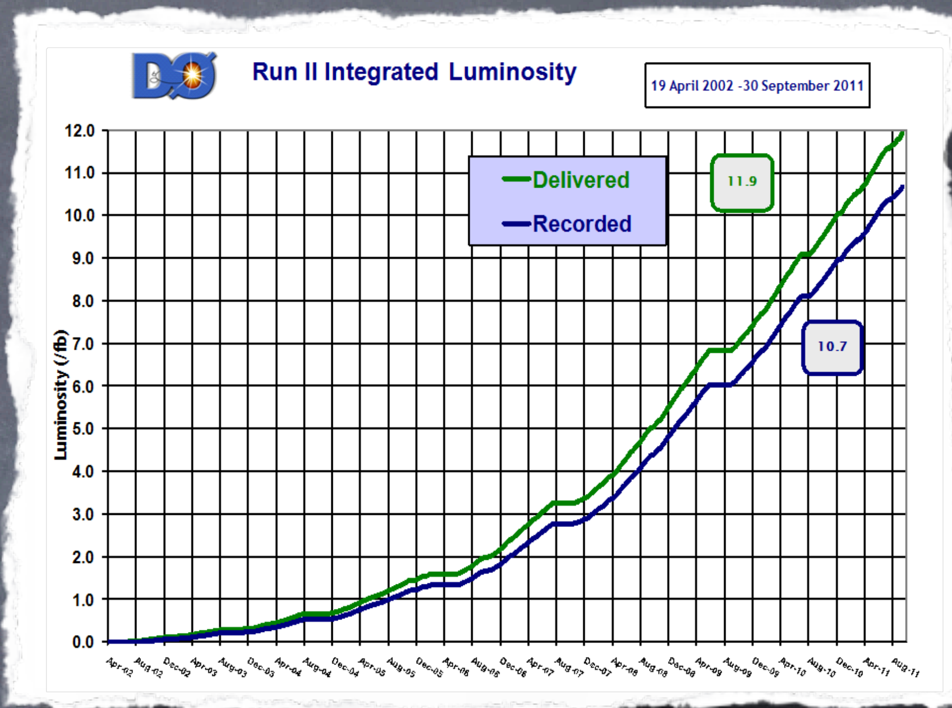

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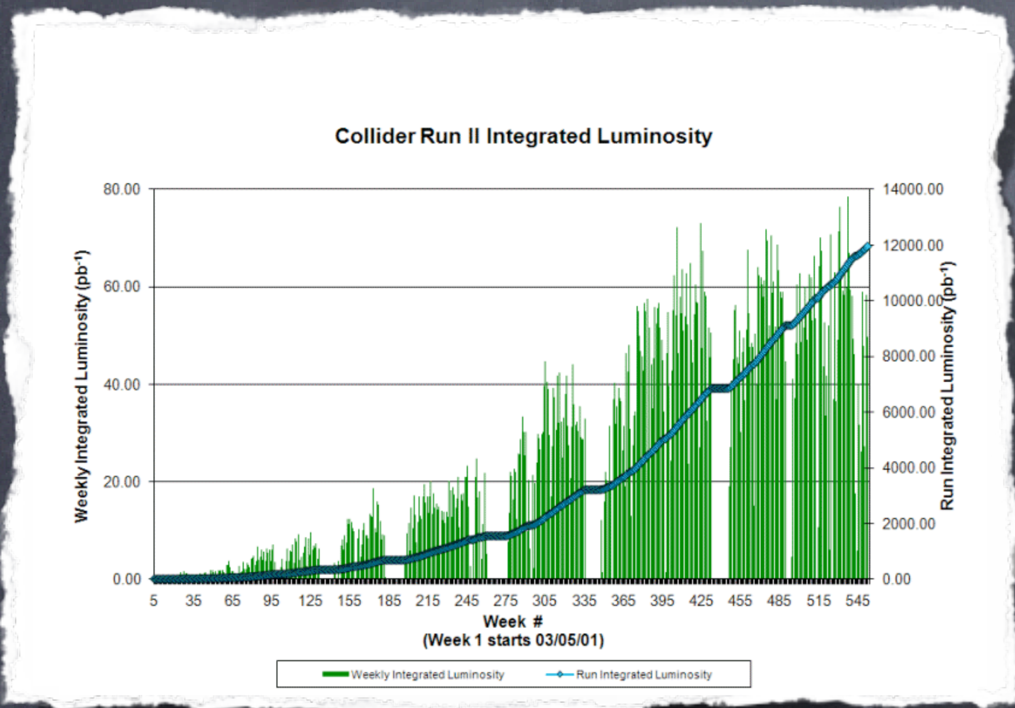
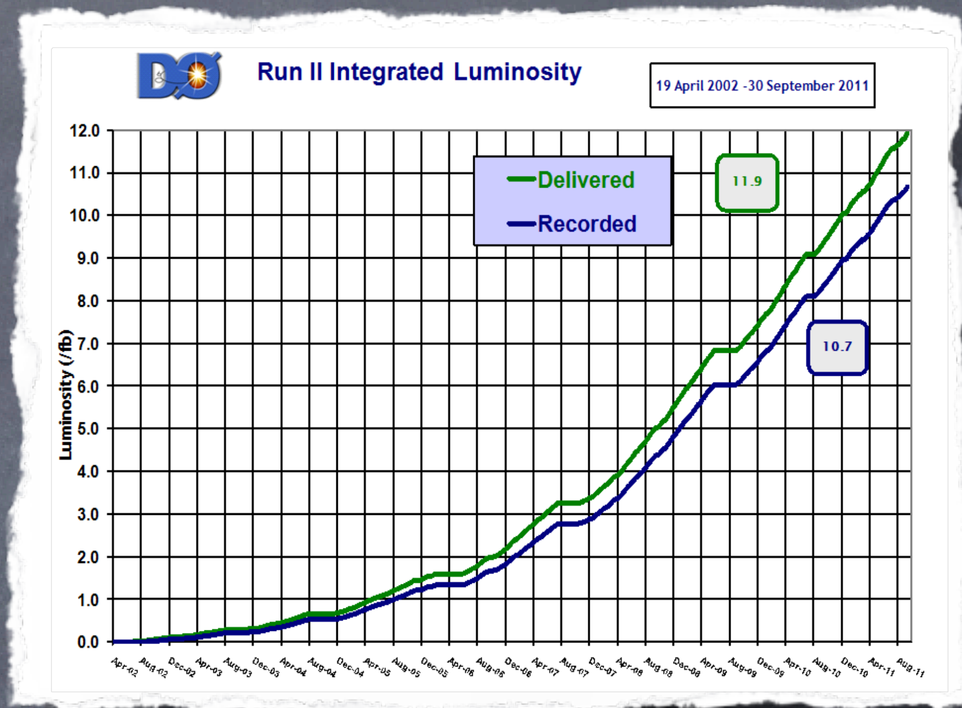
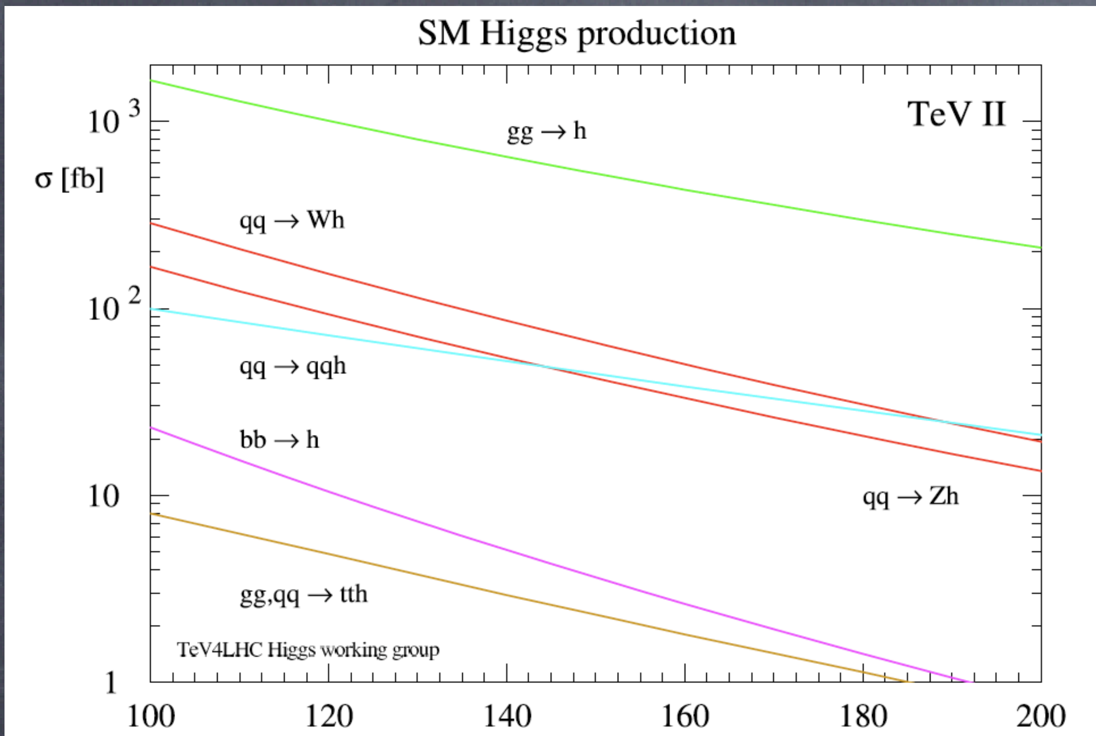
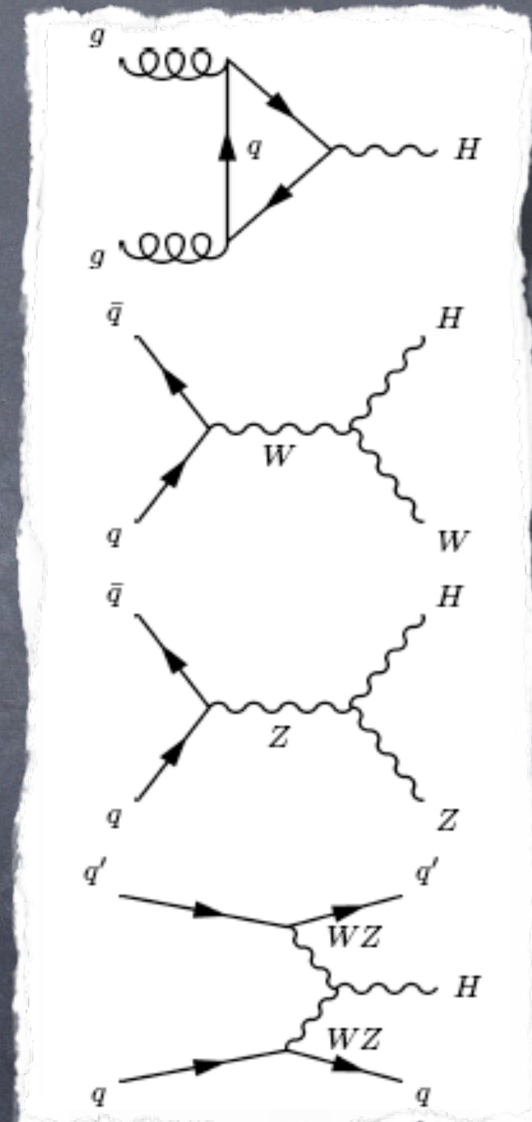




Huge thanks to Tevatron for the great datasets

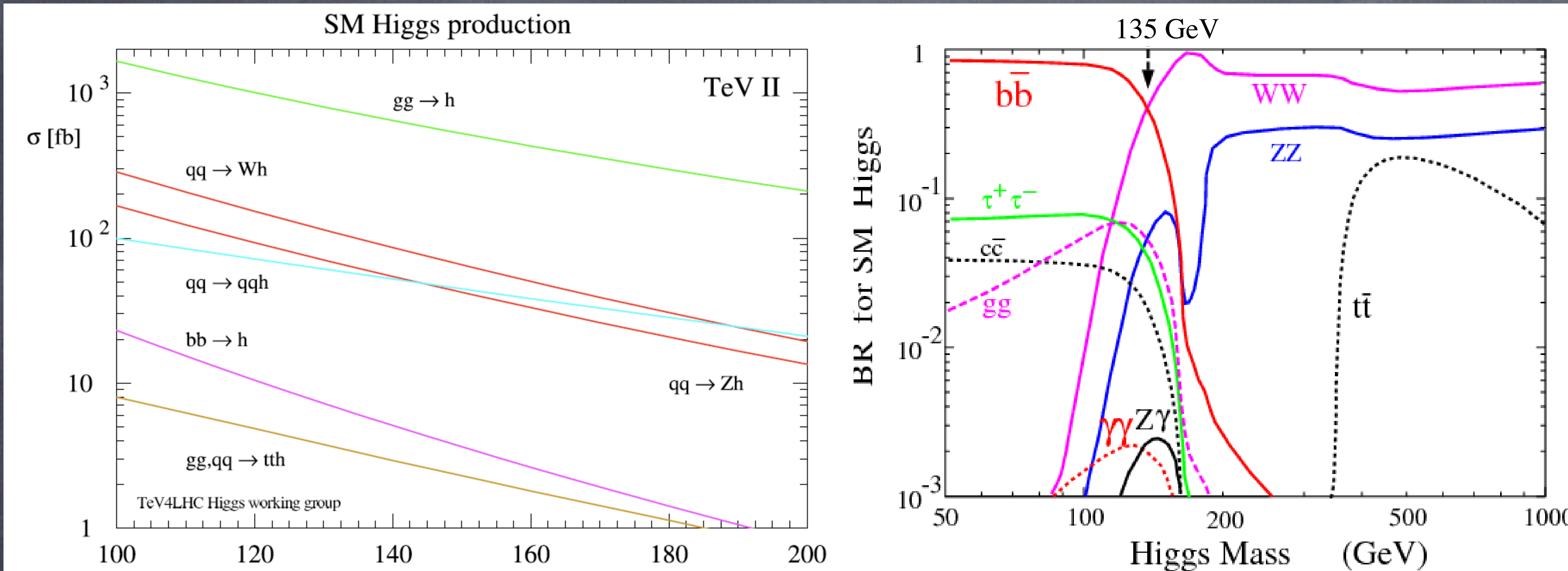
Higgs Production at Tevatron





Gluon fusion dominates
Associated production (WH,ZH)
Vector Boson fusion

Higgs Production at Tevatron



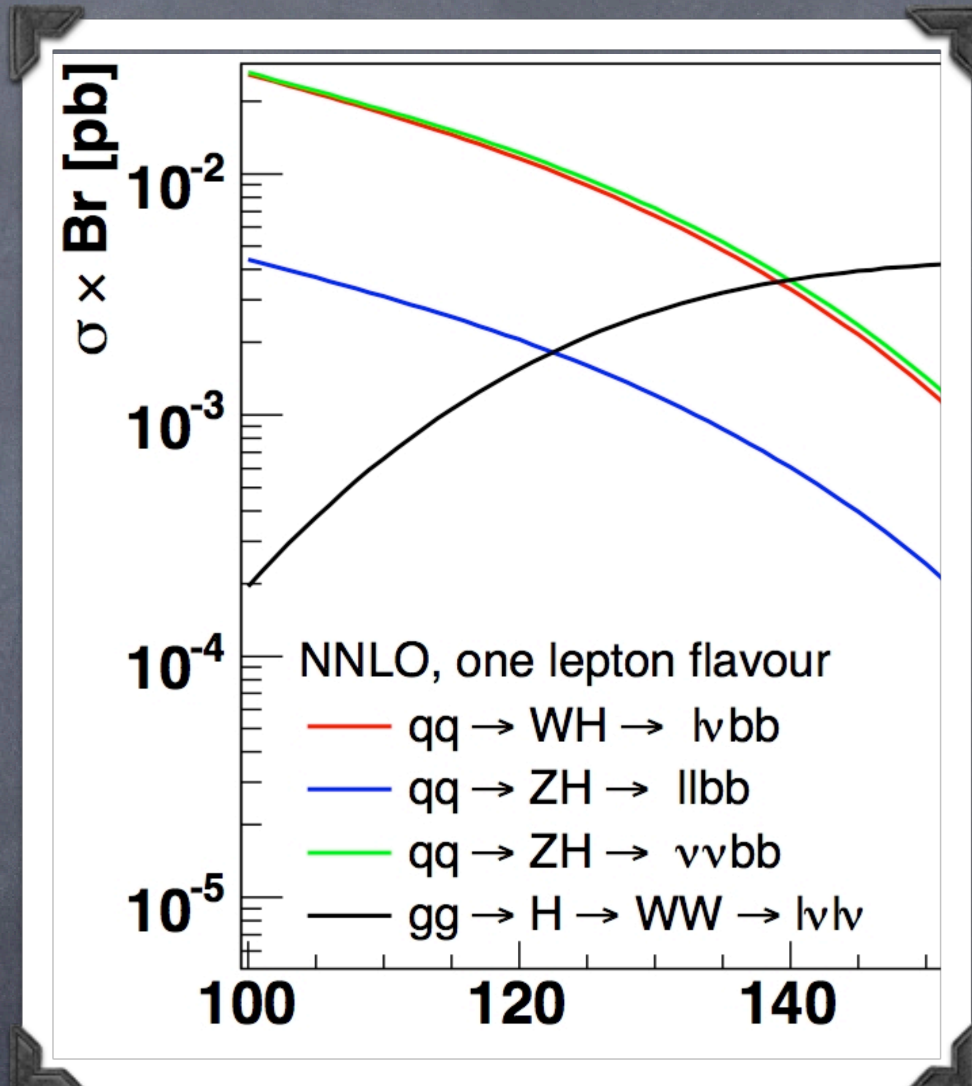
Gluon fusion dominates
Associated production (WH,ZH)
Vector Boson fusion

M_H<135, H→bb

M_H >135, H->WW

SM Higgs at Tevatron

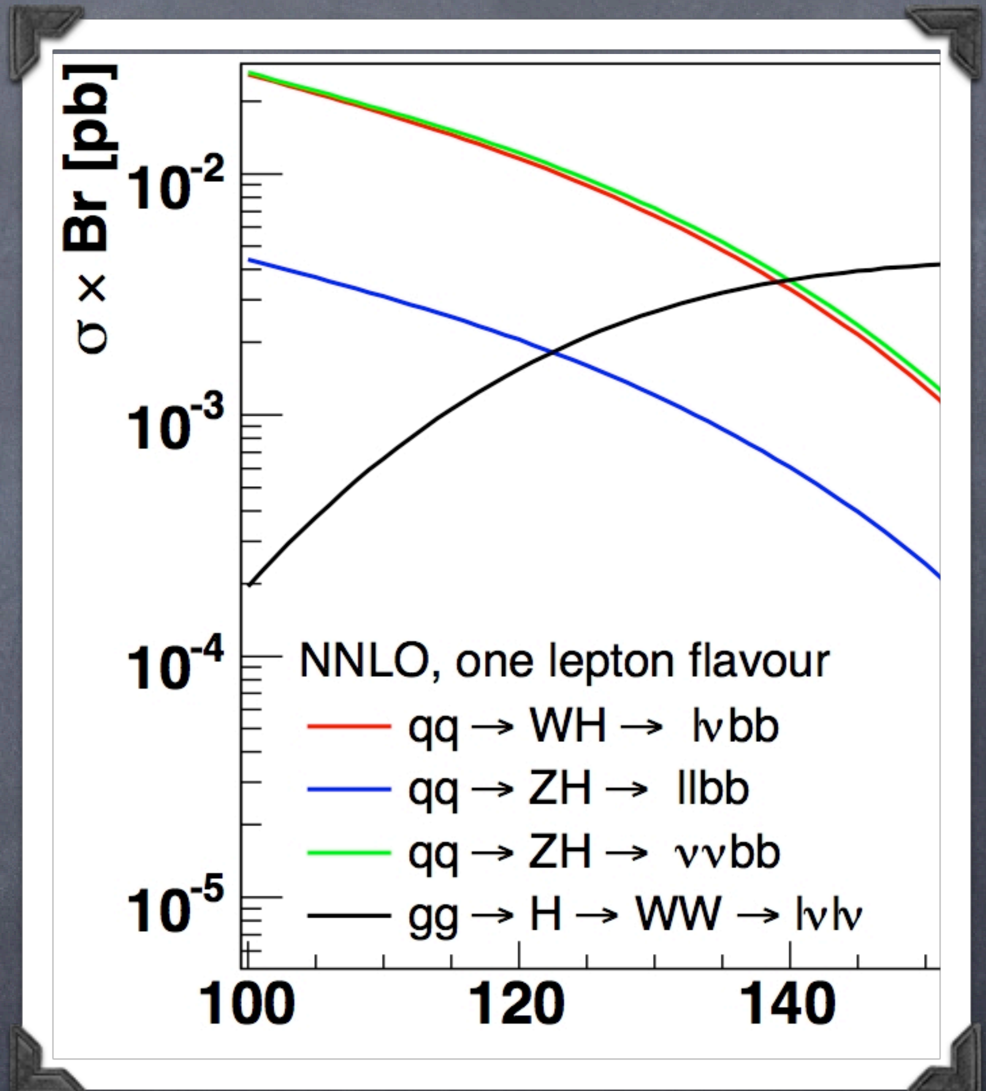
- Winter 2012 focus on the low-mass Higgs region
- low-mass Higgs channels
  - Select: 0,1,2 leptons and/or missing E_T
  - reconstruct high-E_T jets
  - require identification of b-jets for $H \to bb$



http://www-cdf.fnal.gov/physics/new/hdg/Results.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm

SM Higgs at Tevatron

- Winter 2012 focus on the low-mass Higgs region
- re-evaluate current analysis tools to optimize signal sensitivity
  - improve b-tagging strategy
  - jet energy resolution
  - improve MVA discriminants
  - incorporate new channels



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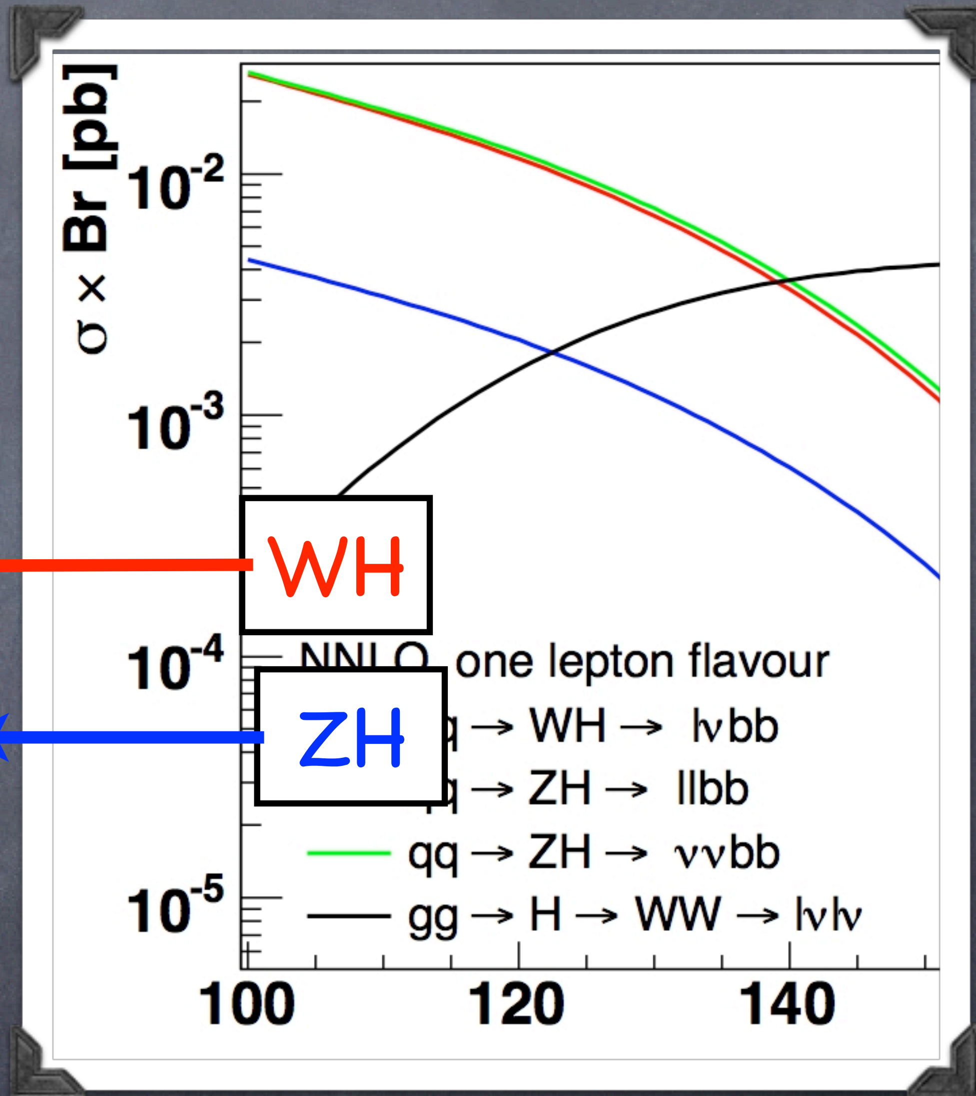

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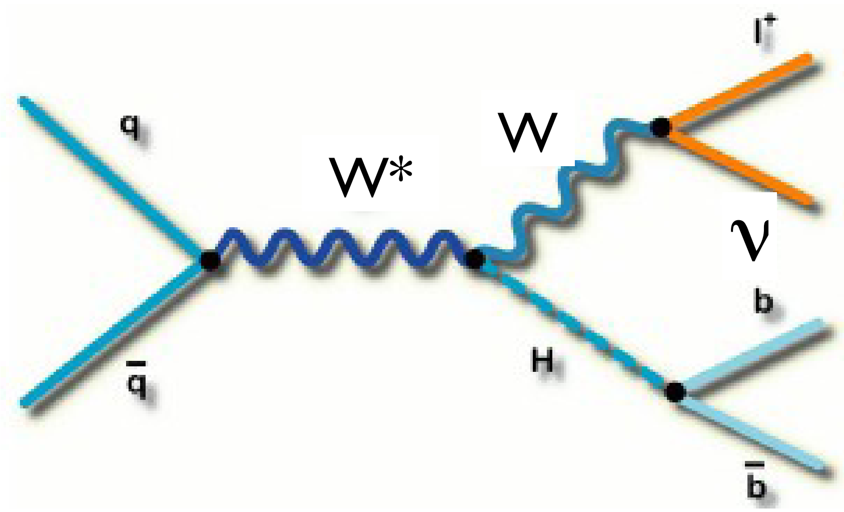
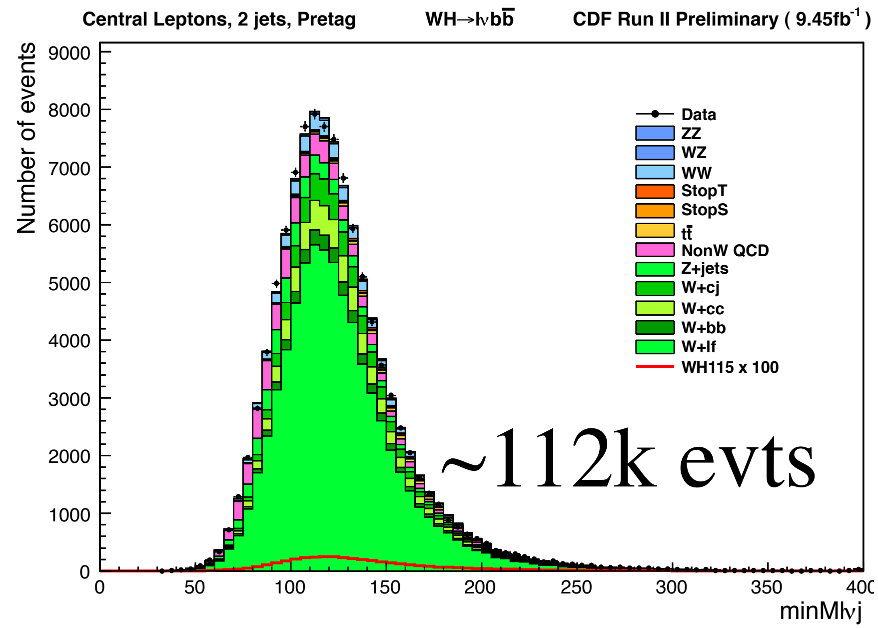
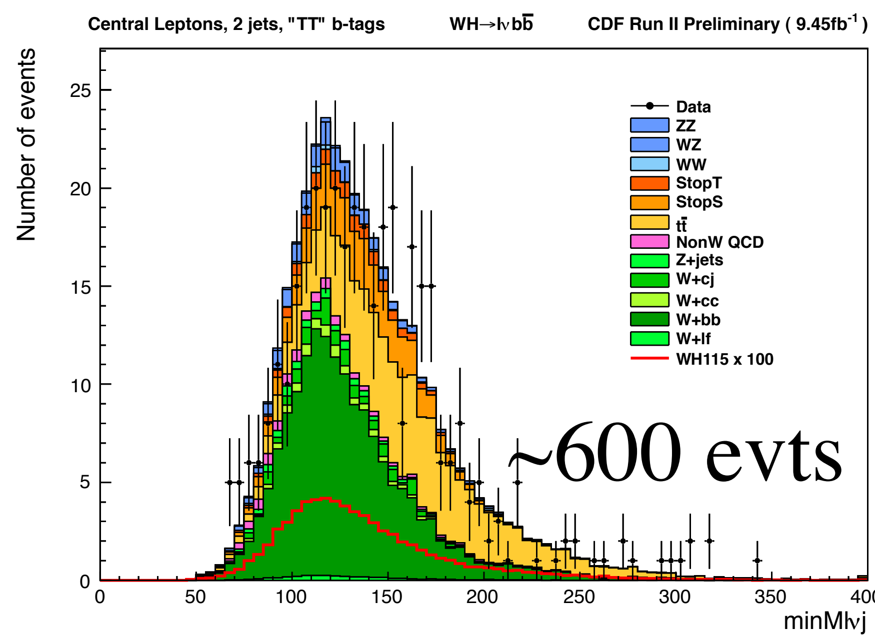
WH → $l\nu$bb Search



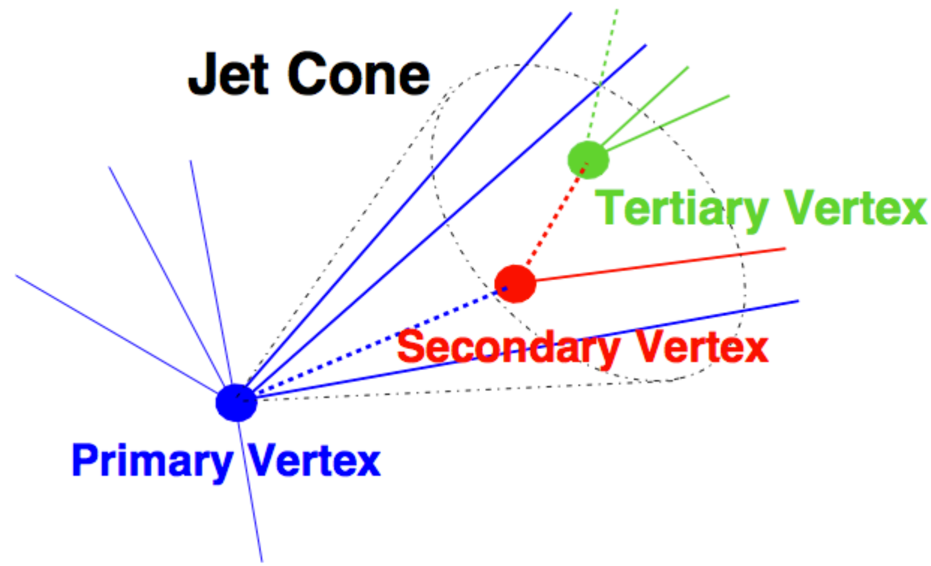


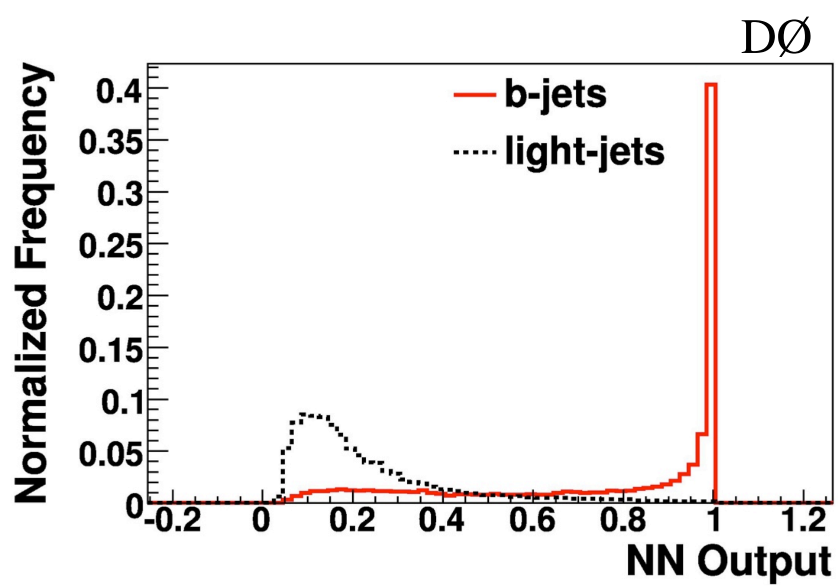


- Identification of b-quarks critical component
- Background rejection
- H→bb reconstruction

identifying b-quark jets

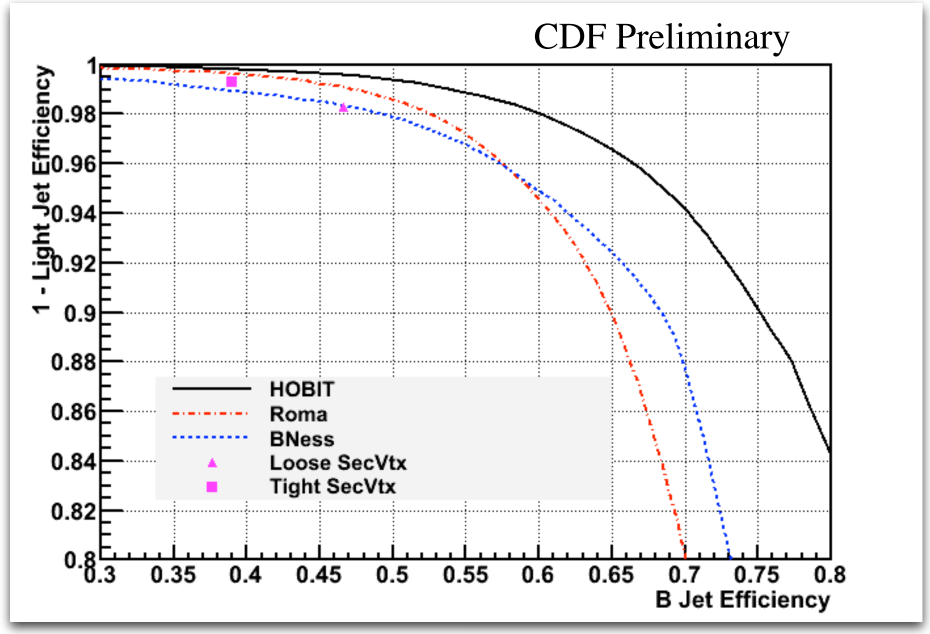
- take advantage of b-quark lifetime
- reconstruct displaced vertices
- soft charge leptons from semi-leptonic decays
- multivariate discriminant based tagger
  - well established for DØ, new tagger for CDF
- optimize thresholds for Higgs signal

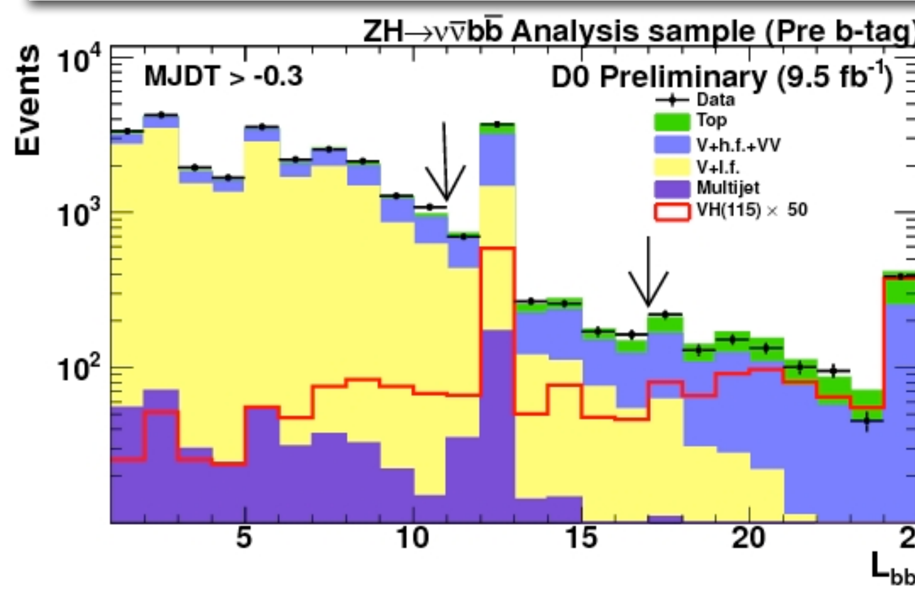




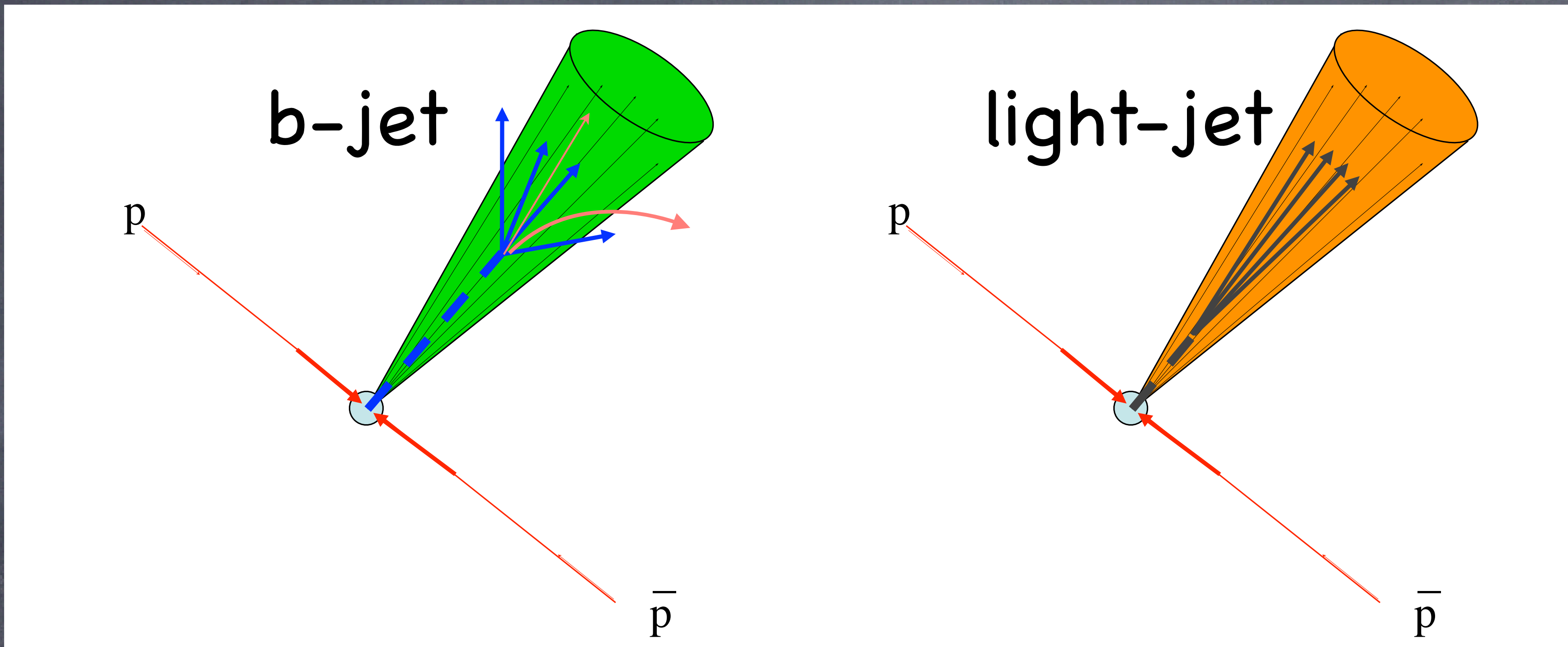
identifying b-quark jets

- b-jet efficiency 40-70%
- light jet mistag 0.5 - 9%
- CDF utilizes 5 tagging regions from tight and loose thresholds
- DØ uses event based tag categories where jet scores are combined
- order 5-15% improvement in Higgs sensitivity



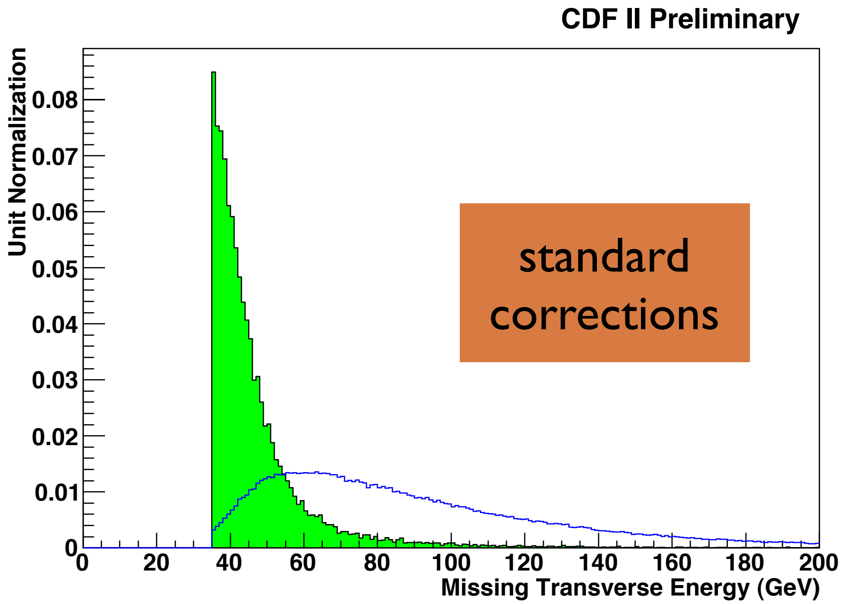


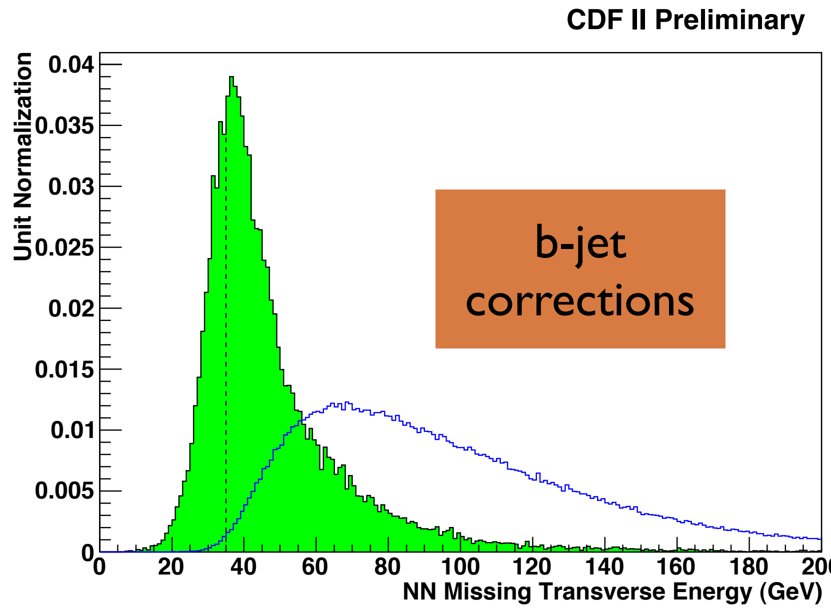
jet energy resolution



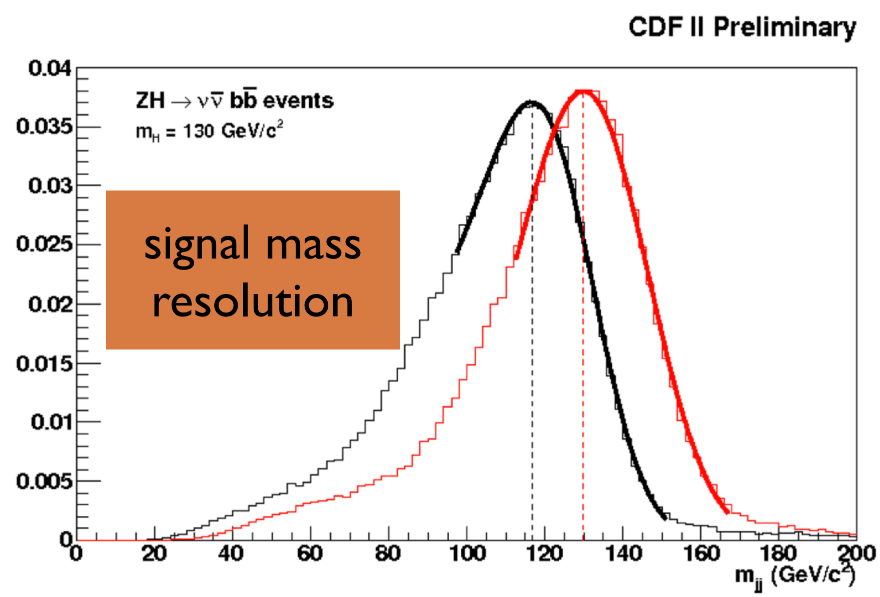
- b-jet calorimeter deposits have sizable differences from light-jets
- develop specialized NN and corrections for b-jets to improve H→bb mass resolution

ZH → $\nu\nu$bb Signature



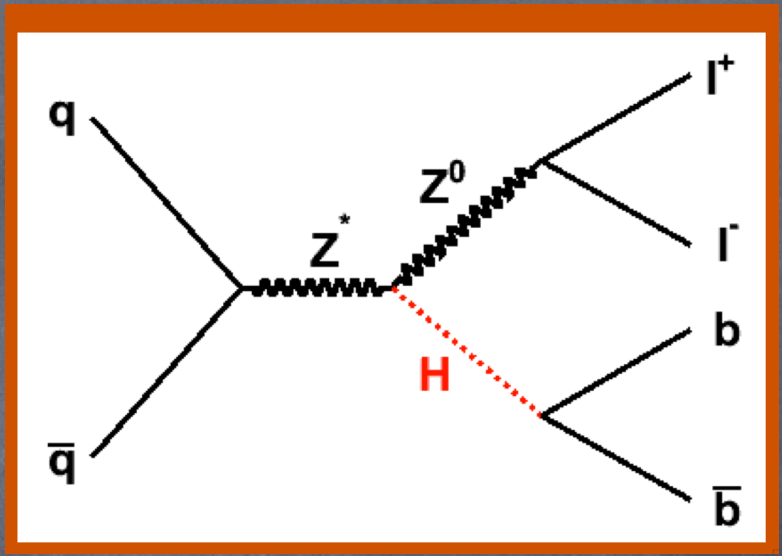


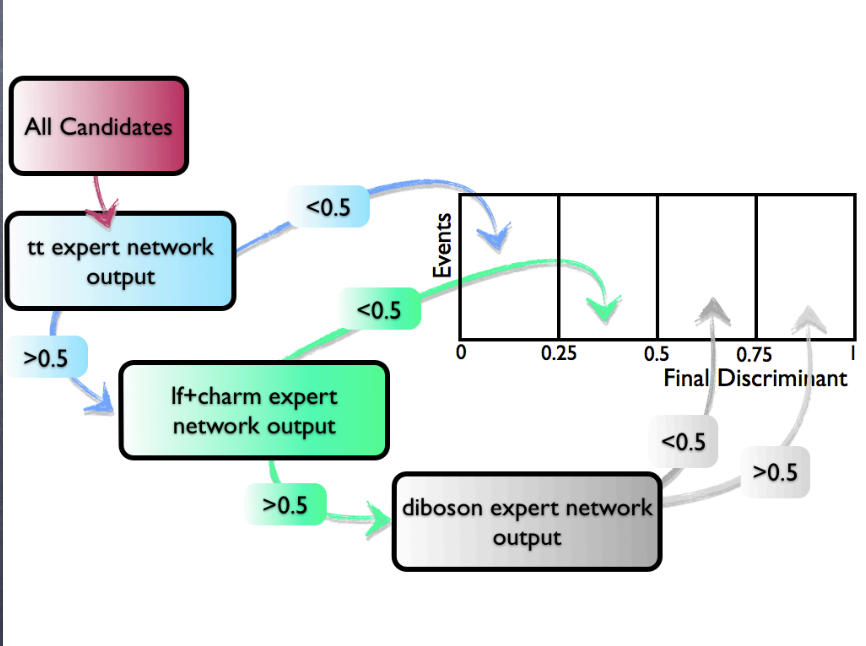
- NN based b-jet corrections
- better signal/background separation
- RMS/mean improves in Met+bb
    - 0.195 -> 0.156
- b-jet corrections now included in all H→bb analysis



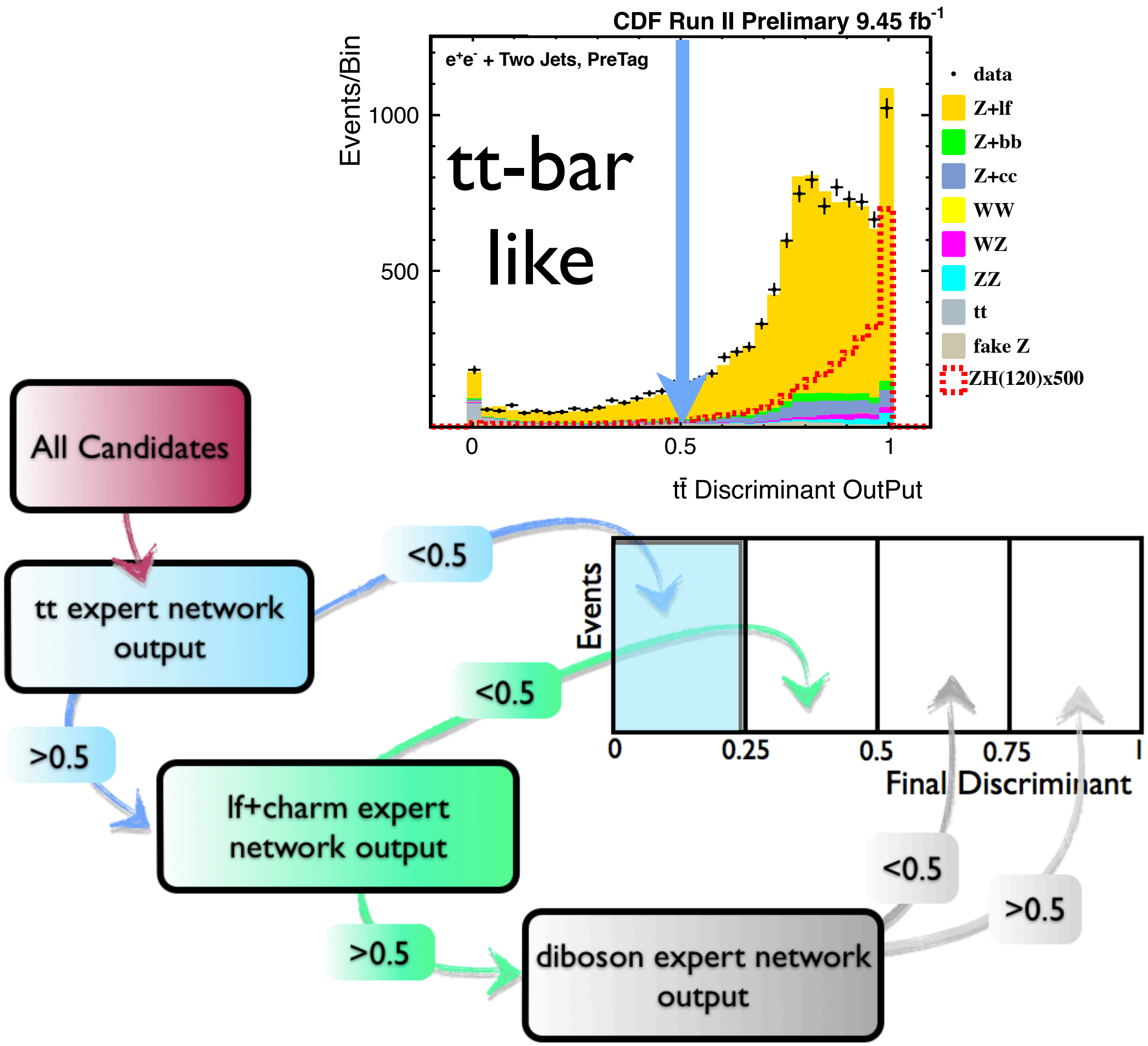
multivariate methods

- going beyond using single MVA to separate signal from all backgrounds
- develop MVA for specific backgrounds
- multi-stage classification of events
- separate easiest background first
- train final discriminant after passing all expert discriminants





CDF ZH→llbb MVA



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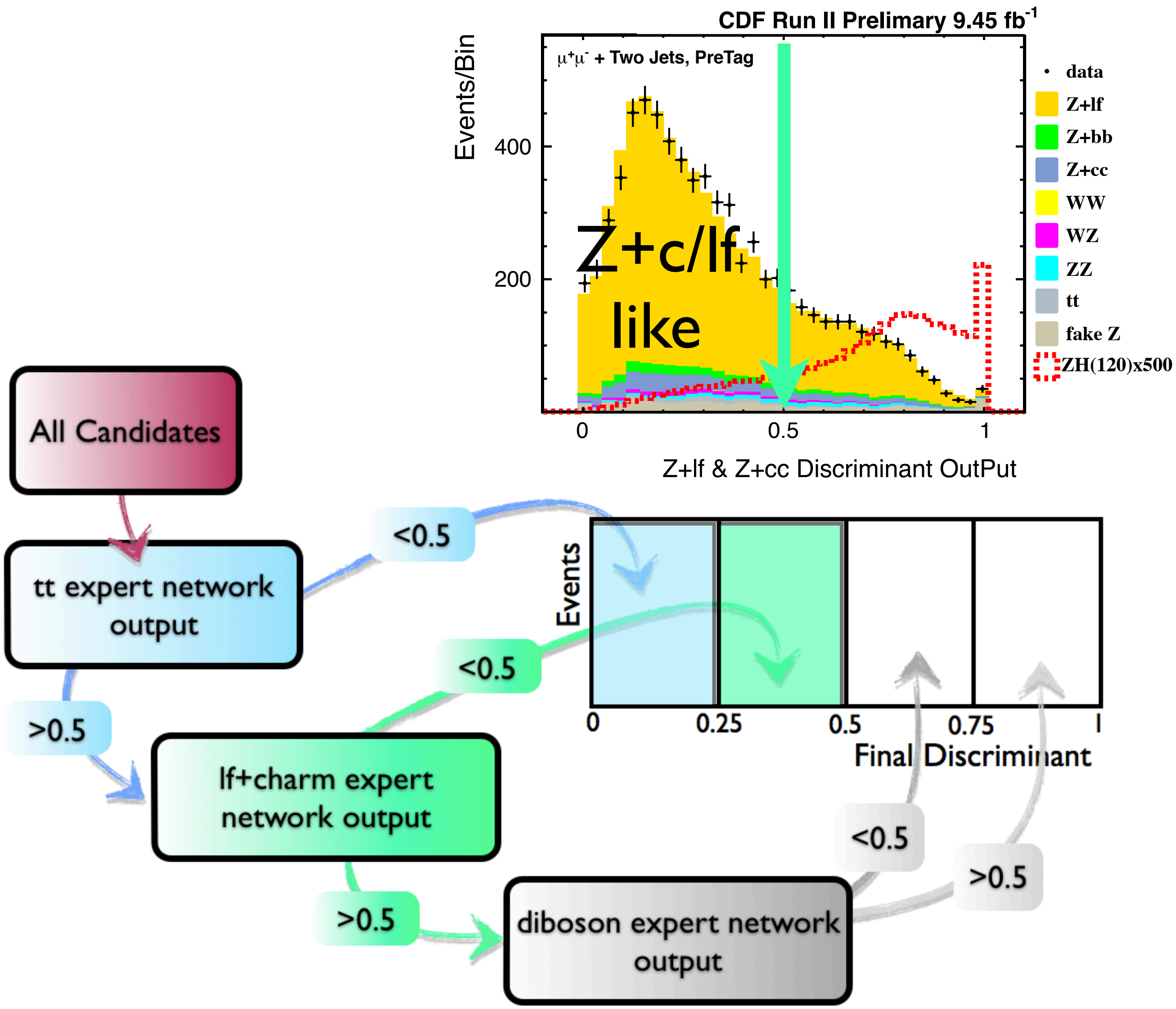

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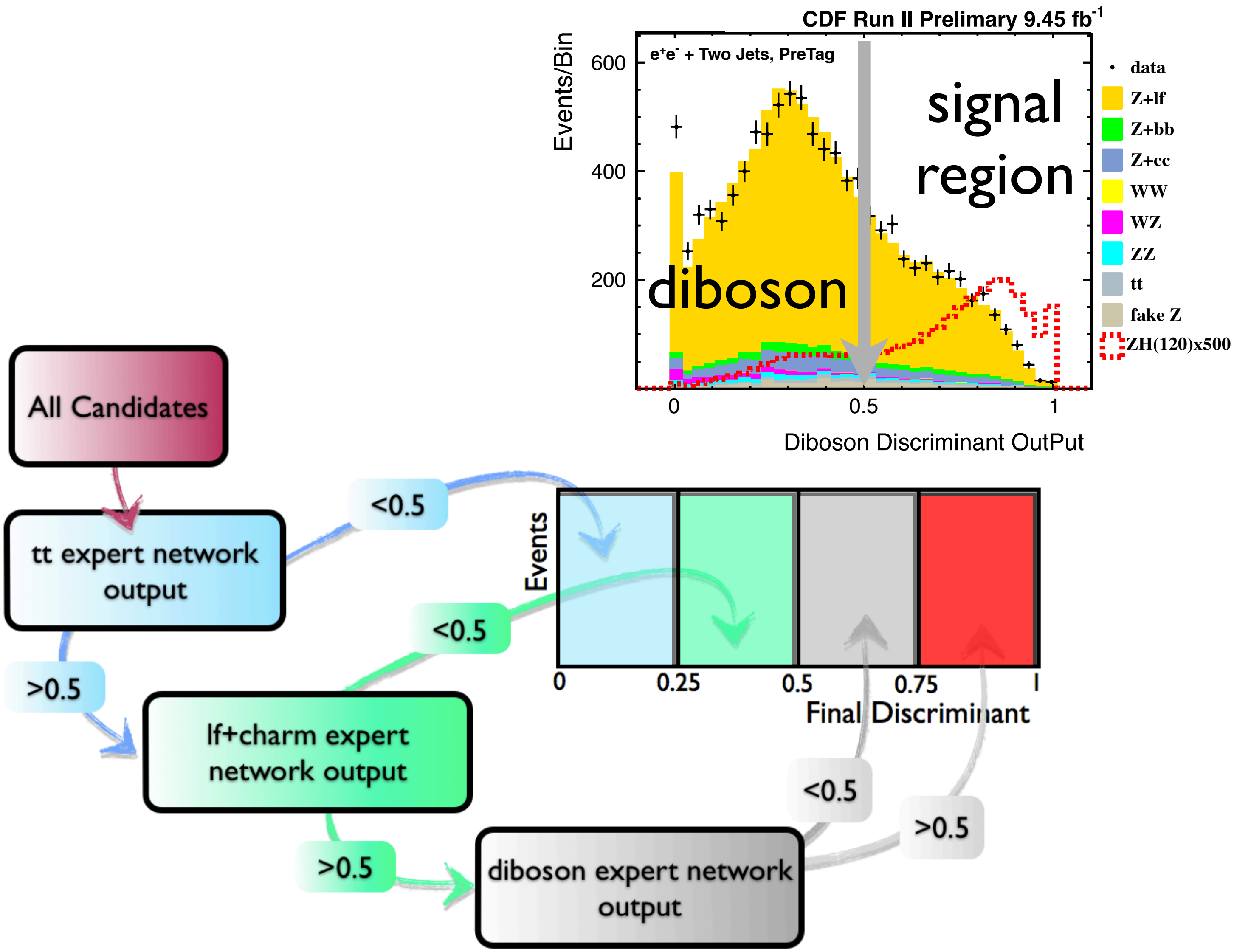
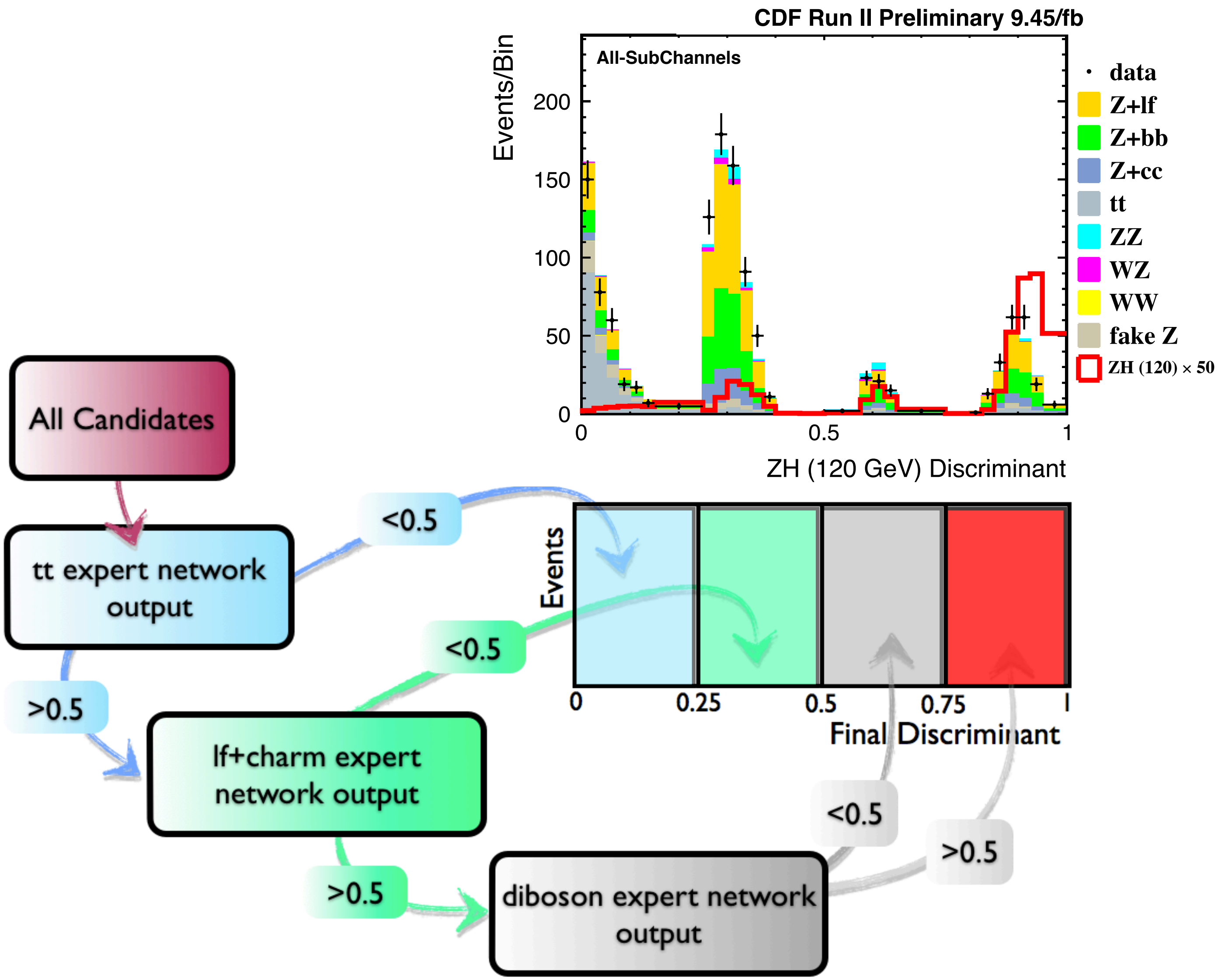
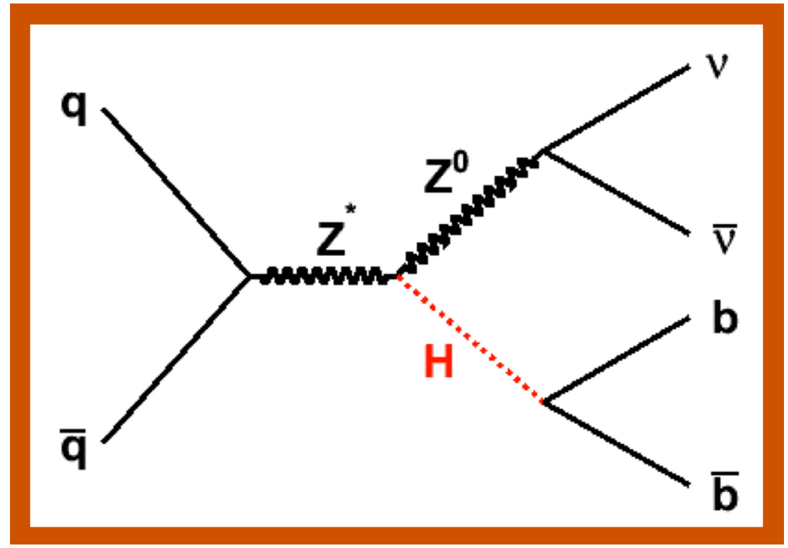


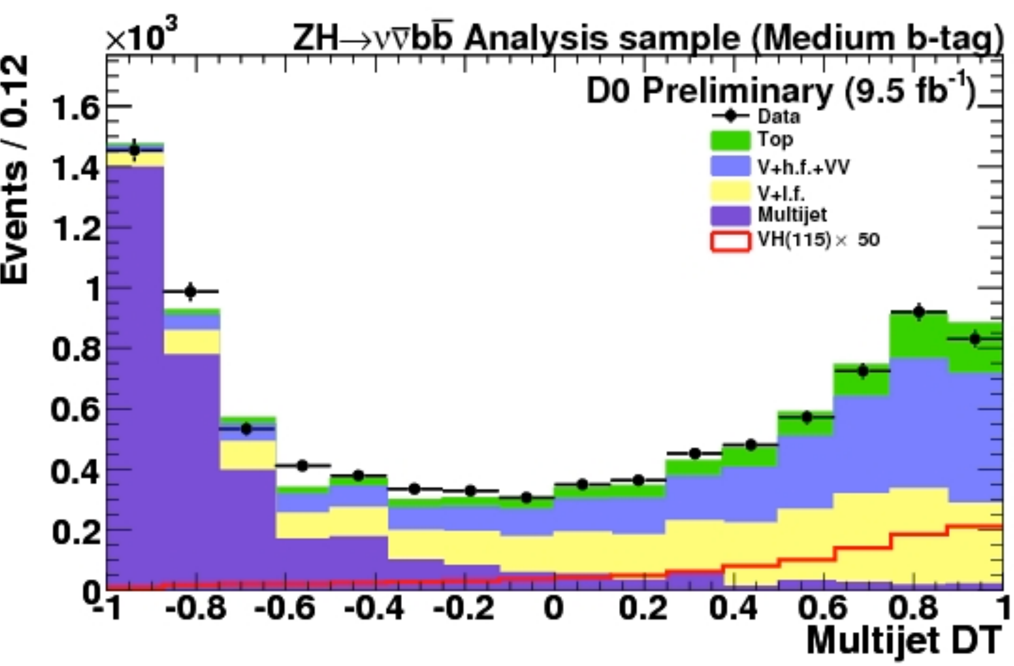
CDF ZH→llbb MVA

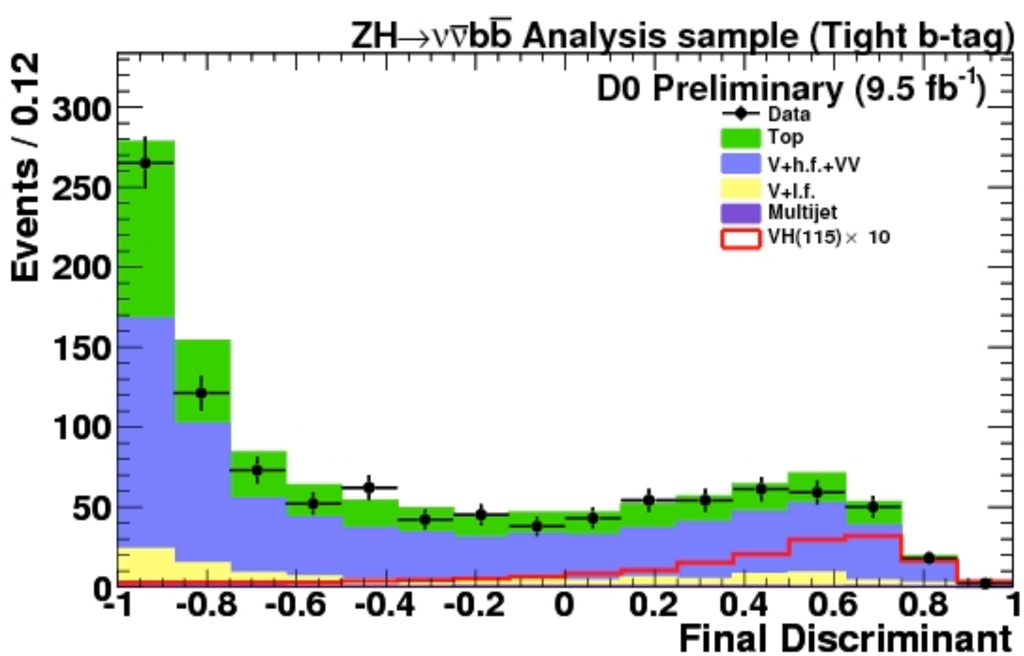


DØ ZH→ννbb MVA

- develop MVA for rejecting multijet background first
- validate in the EWK control sample region



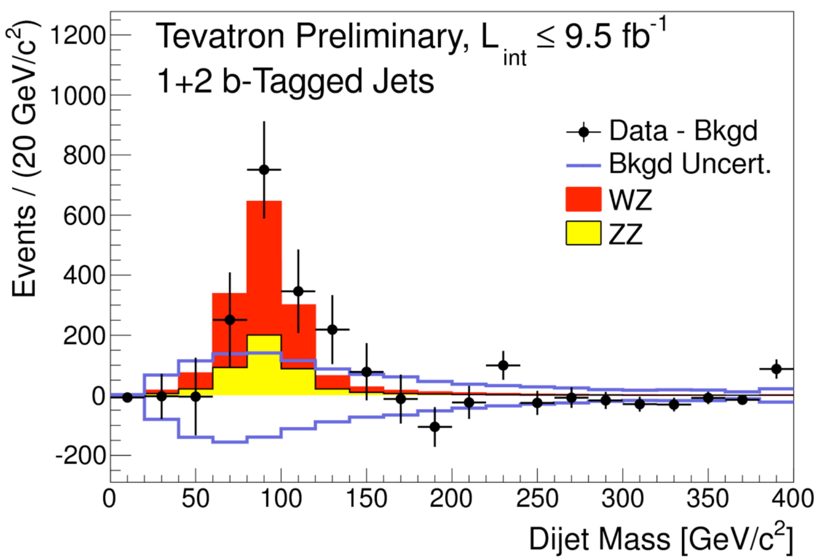


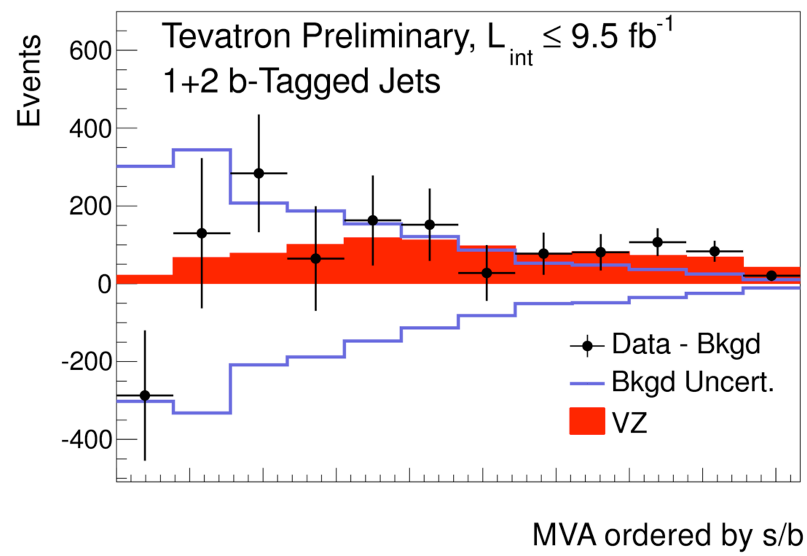


WZ/ZZ→X+bb validation

- identical final state as WH/ZH→X+bb
- σ(WZ/ZZ) ≈5x σ_{SM}(WH/ZH)

- same event selection
- utilize Higgs techniques
- critical test of analysis





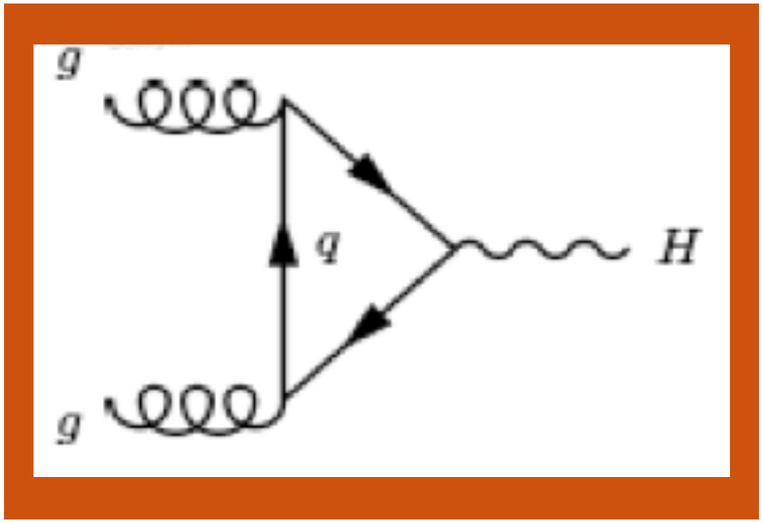
σ(WZ/ZZ)=4.47±0.64(stat)±0.73(syst) pb

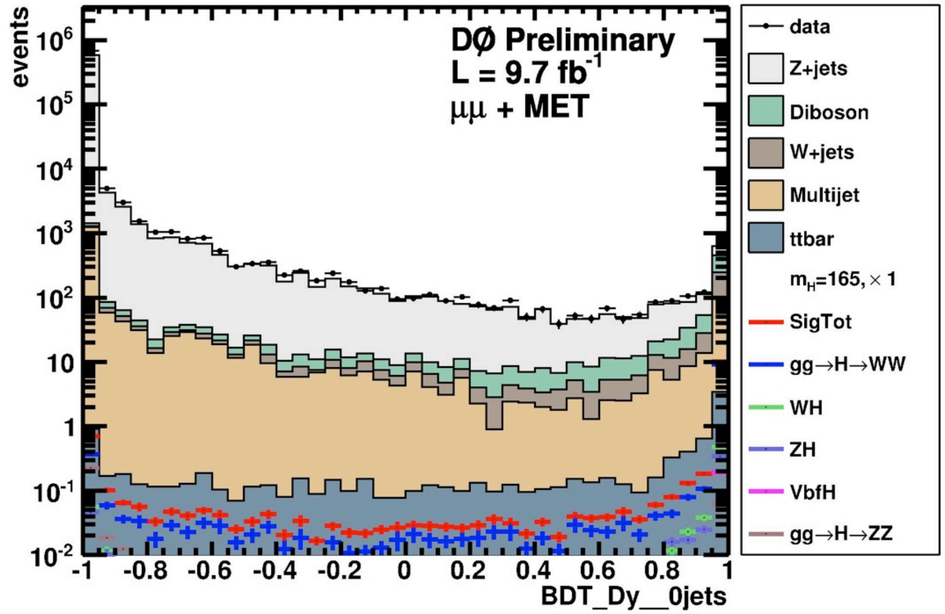
approximately 4.6σ significance

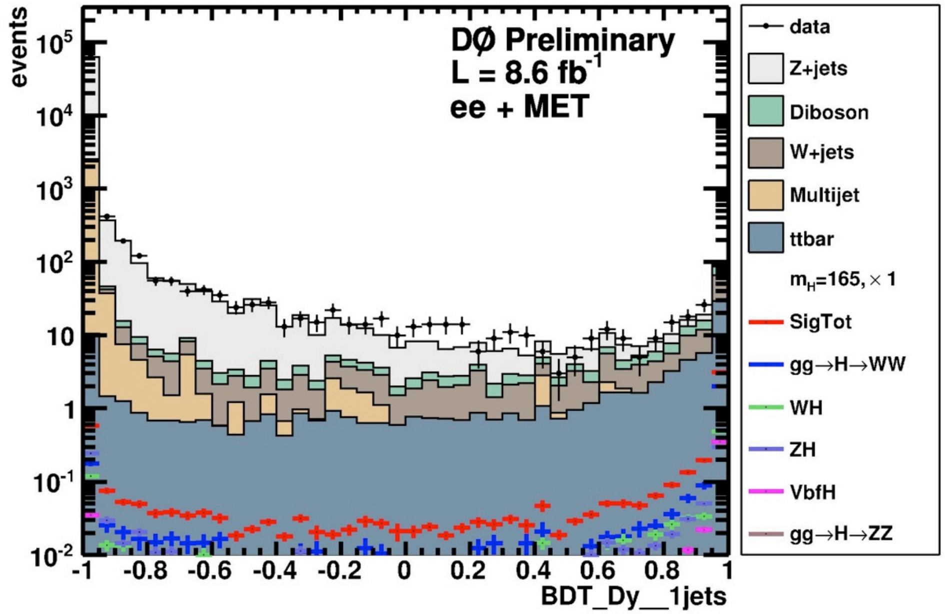
σ_{SM}(WZ/ZZ) = 4.4±0.3 pb

H→WW MVA

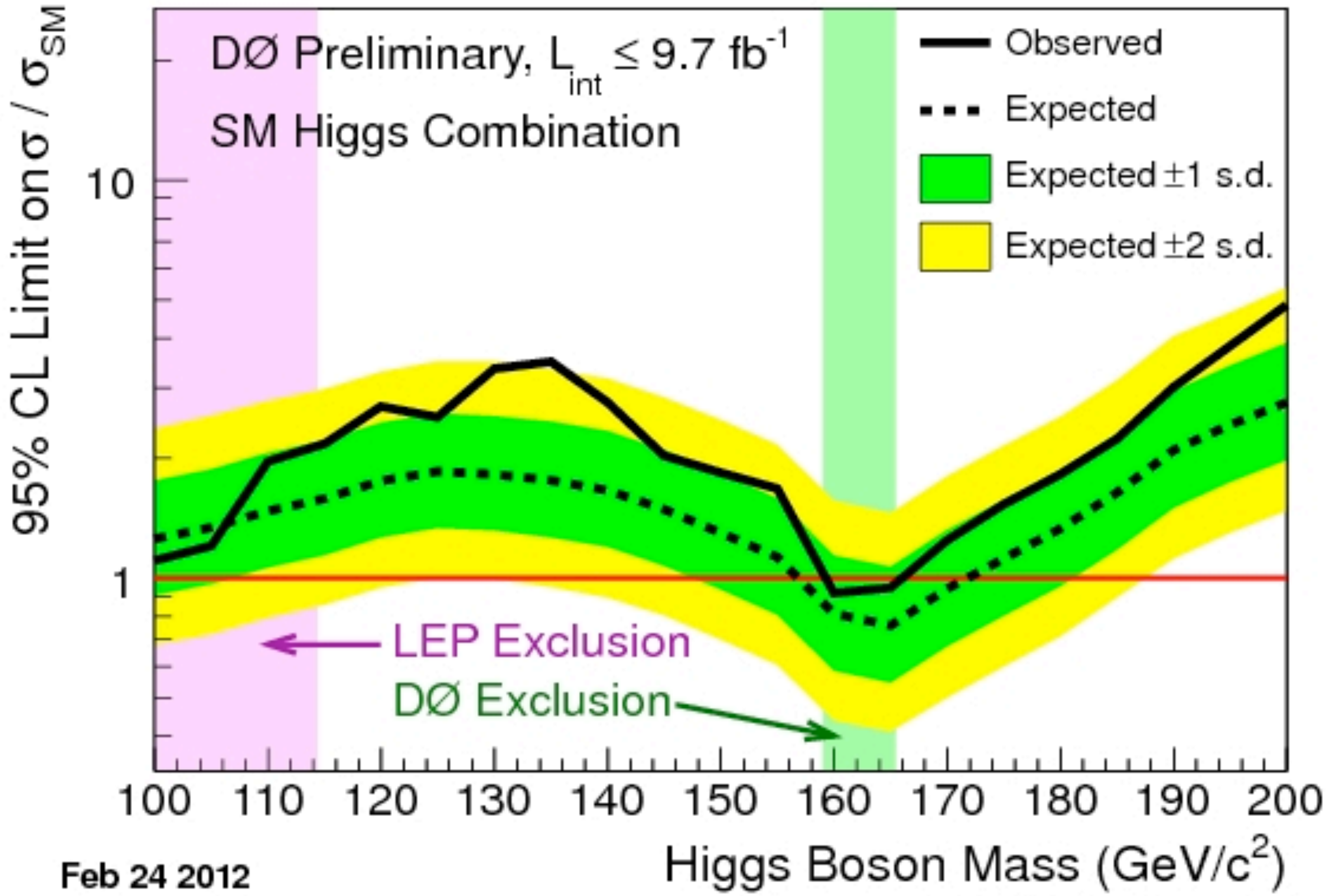
- also continuing to work on H→WW sensitivity beyond just adding luminosity
- improved the background rejection
- increase the acceptance through trilepton and same-sign selections







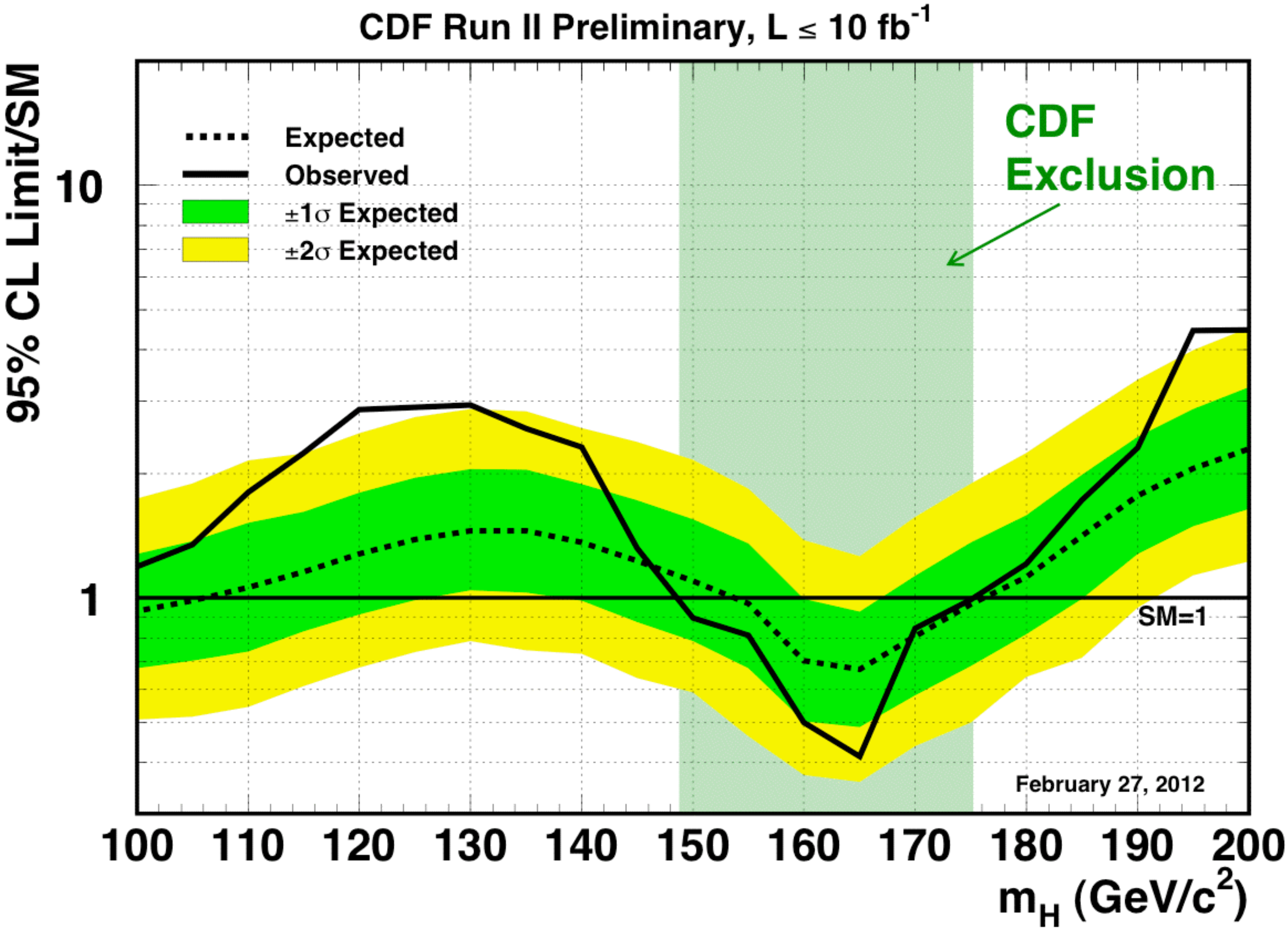
DØ full combination



Exclude SM Higgs at 95% C.L. : $159 < m_H < 166\ GeV/c^2$

Expect to exclude: $157 < m_H < 172\ GeV/c^2$

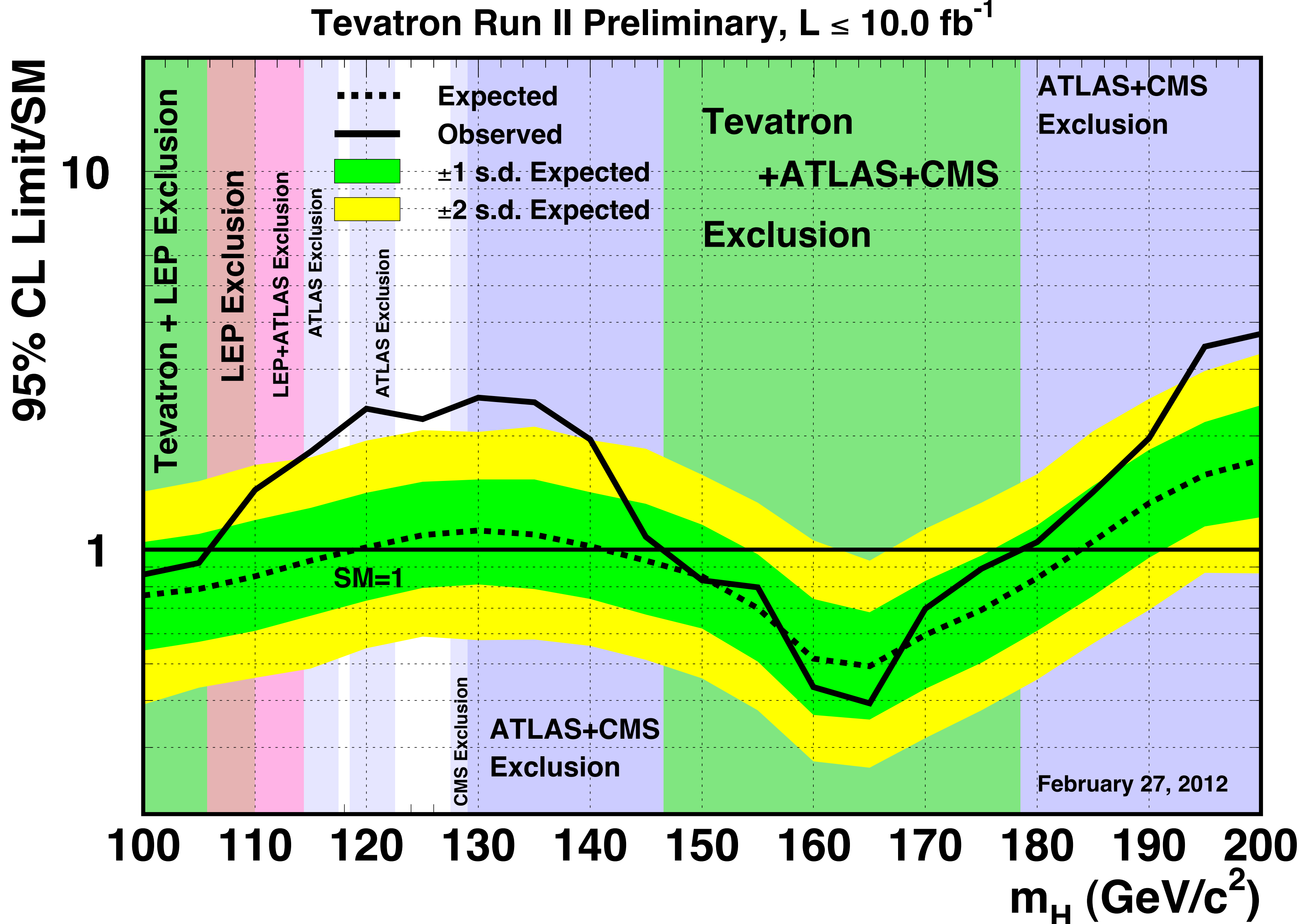
CDF full combination



Exclude SM Higgs at 95% C.L. : $147 < m_H < 175$ GeV/c^2

Expect to exclude: $100 < m_H < 106$ GeV/c^2 & $154 < m_H < 176$ GeV/c^2

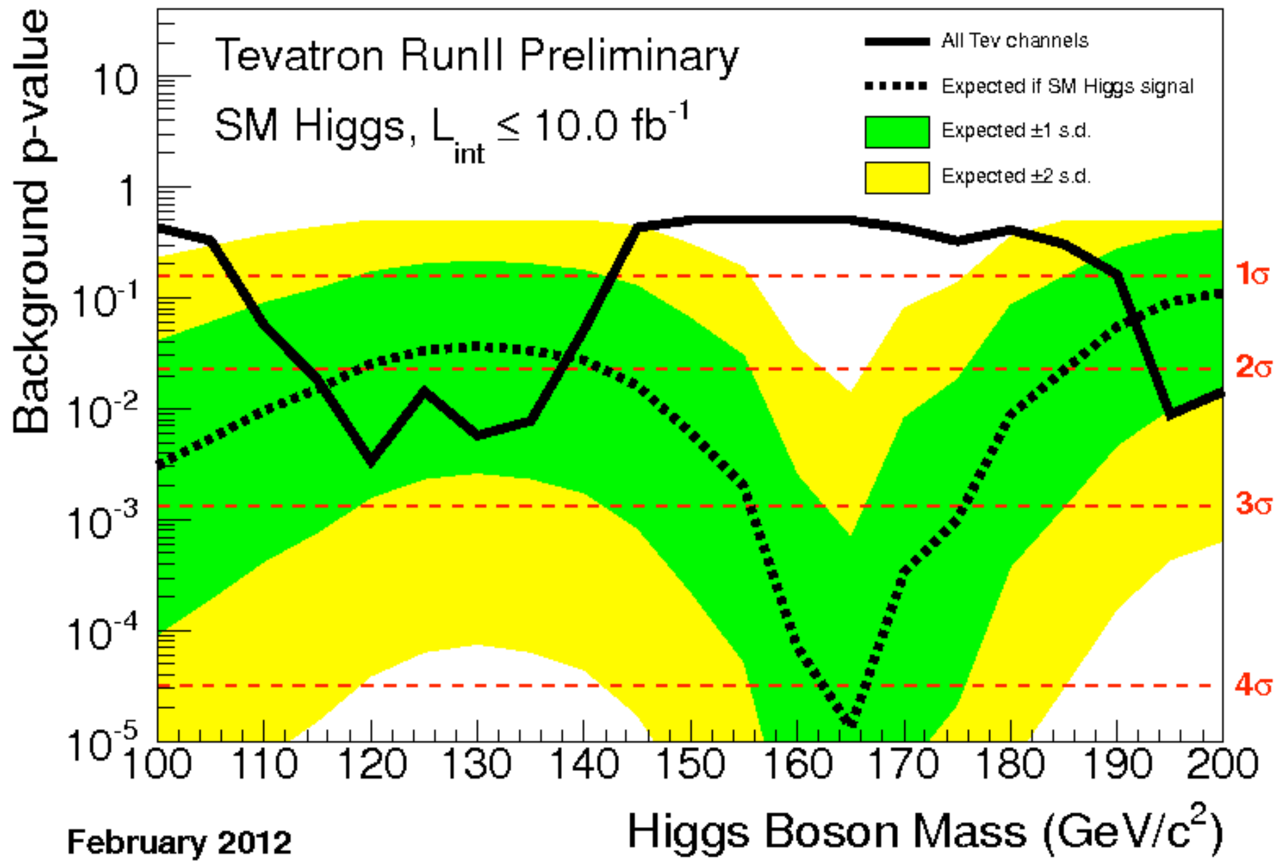
Tevatron combination



Exclude SM Higgs @ 95% C.L.

$100 < m_H < 106$ GeV/c^2 & $147 < m_H < 179$ GeV/c^2

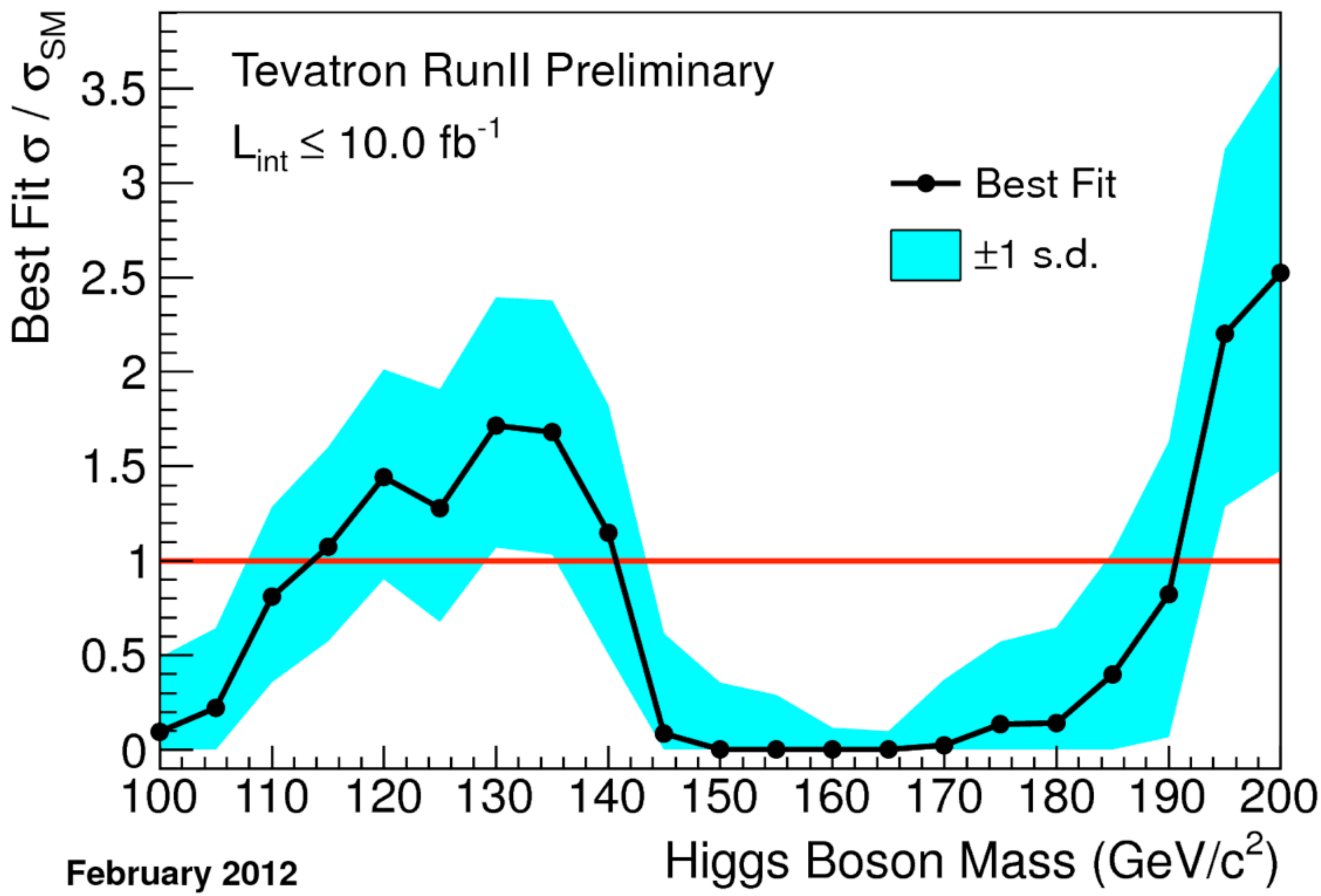
compatible with background



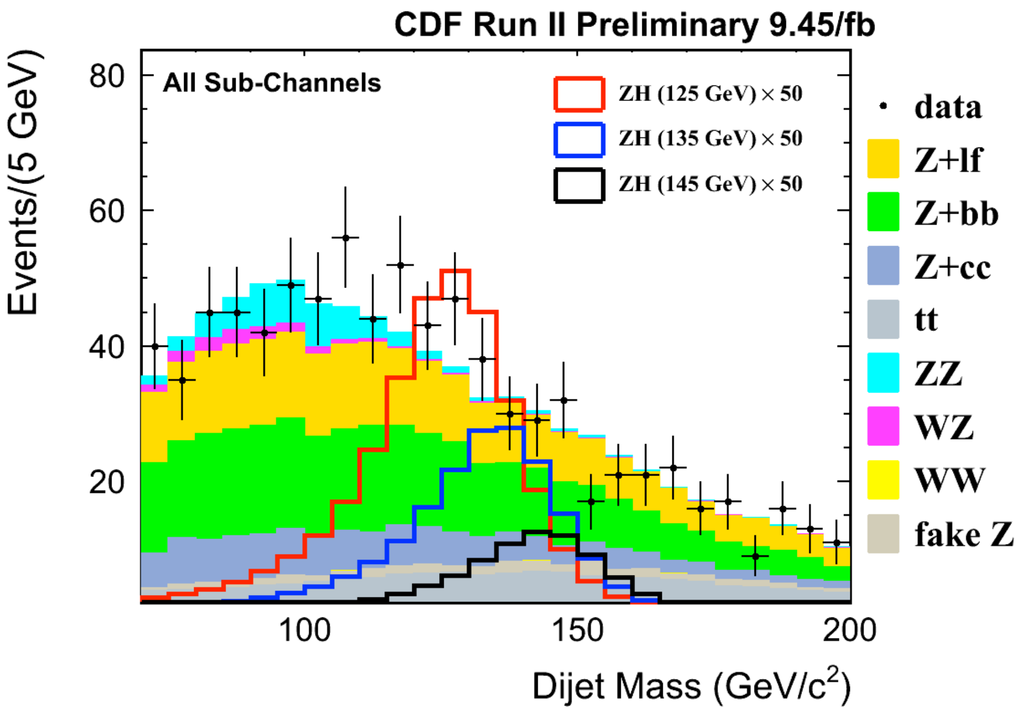
- Highest local p-value (2.8σ) is found at m_H = 120 GeV/c^2
- Same LEE of 4 for entire SM search range 100 to 200 GeV/c^2

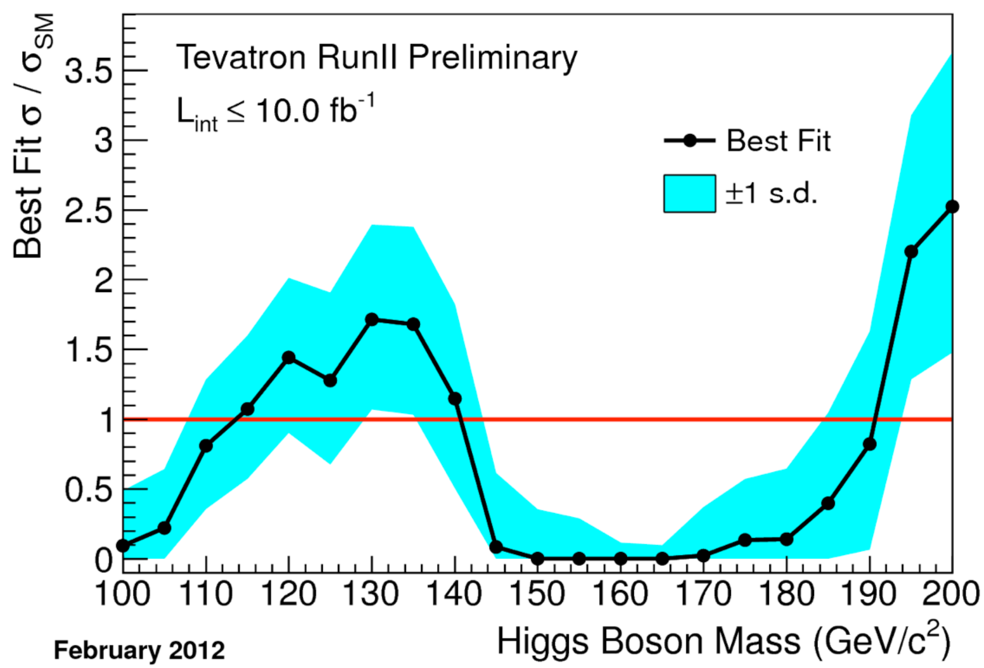
SM Higgs Searches		
Experiment	Local P-value	Global P-value
CDF+D0	2.8σ	2.2σ

fitted Higgs cross section



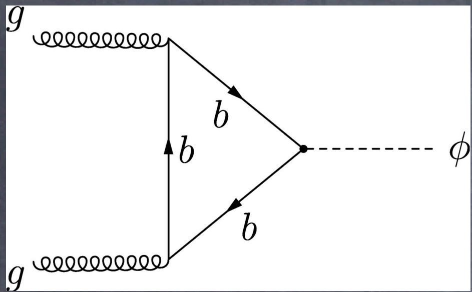
compatible with SM Higgs

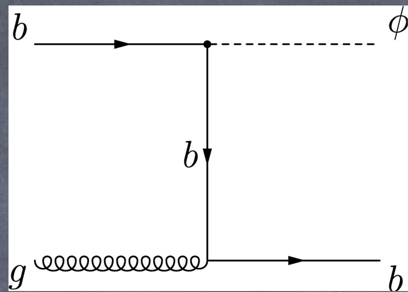




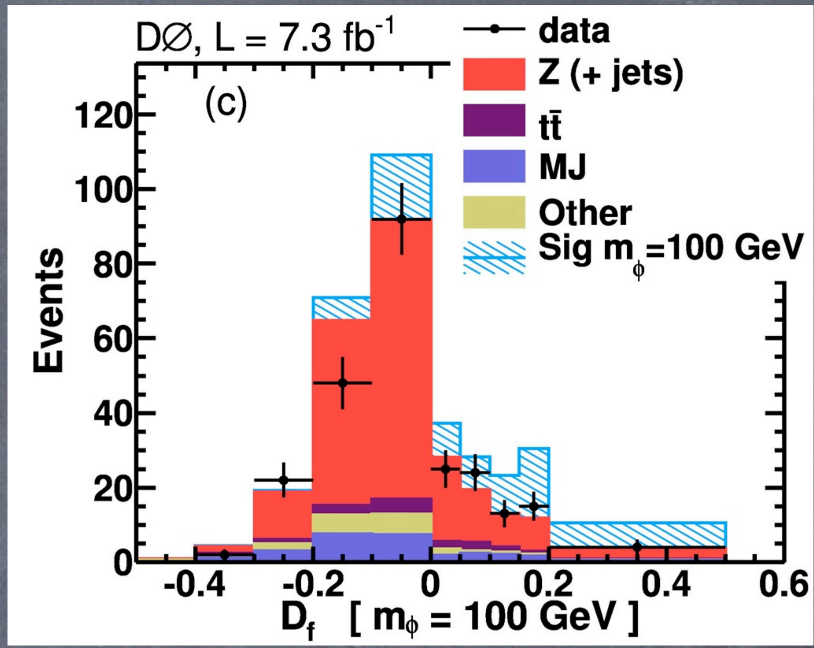
- Behavior at higher m_H values is consistent with the expectation from a lower mass Higgs
- Data are most consistent with SM in mass range from 110 $< m_H <$ 125 GeV/c^2

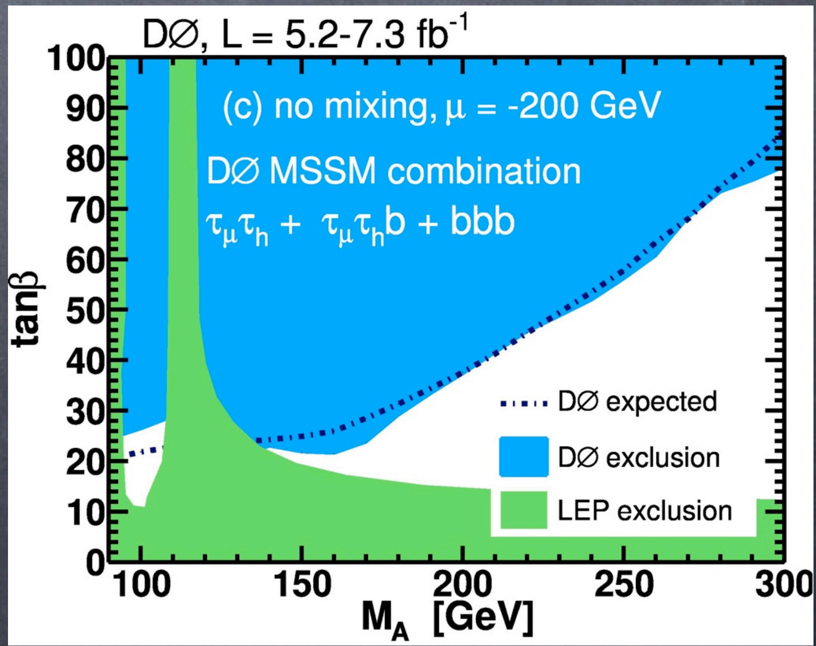
SUSY Higgs searches





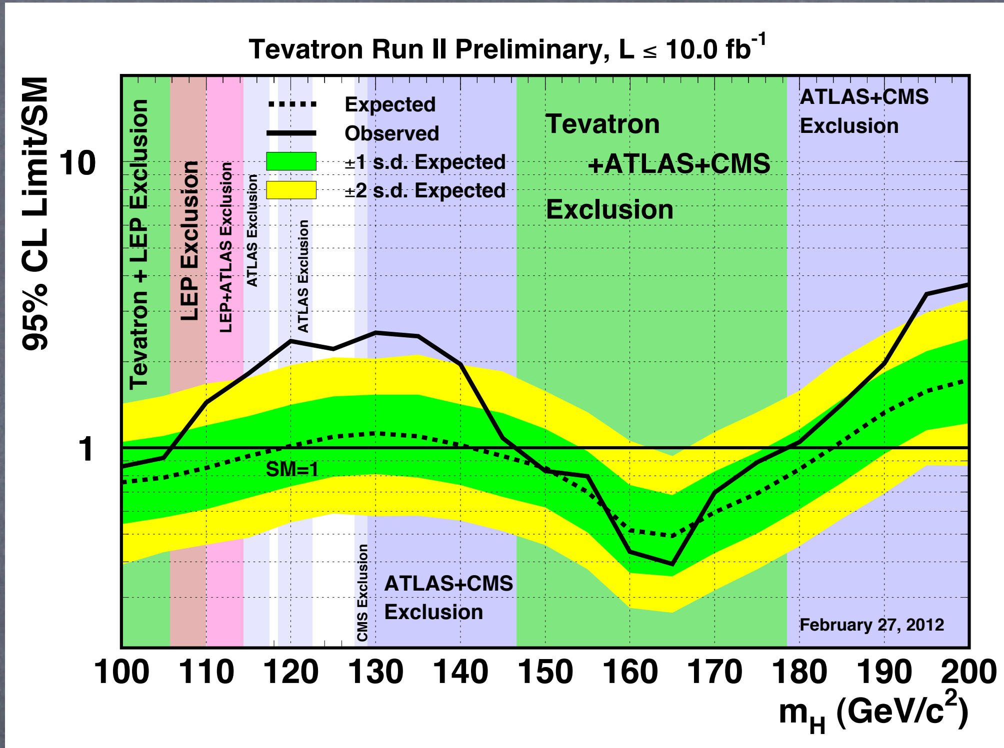
- MSSM introduces two Higgs doublet fields
  - couple to up/down separately
  - ratio of vacuum is $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
  - Higgs coupling to b and tau enhanced at high tanβ
- combined $b\phi \rightarrow bbb$ & $b\phi \rightarrow b\tau\tau$ & $\phi \rightarrow \tau\tau$
- identification of b-jets and τ reconstruction critical
- able to exclude the "natural" region of tanβ





Tevatron Higgs Summary

- Tevatron delivered a spectacular dataset
- CDF and D0 incorporated full dataset into Higgs searches
- added considerable improvements beyond luminosity
- measure WZ/ZZ $\rightarrow$X+bb at 4.6σ significance, consistent with SM
- Observe an excess of Higgs like event consistent with SM Higgs production around 125 GeV/c^2
- global significance of excess 2.2σ



Tevatron Excl @ 95% C.L
$100 < m_H < 106$ GeV/c^2
$147 < m_H < 179$ GeV/c^2

Backup

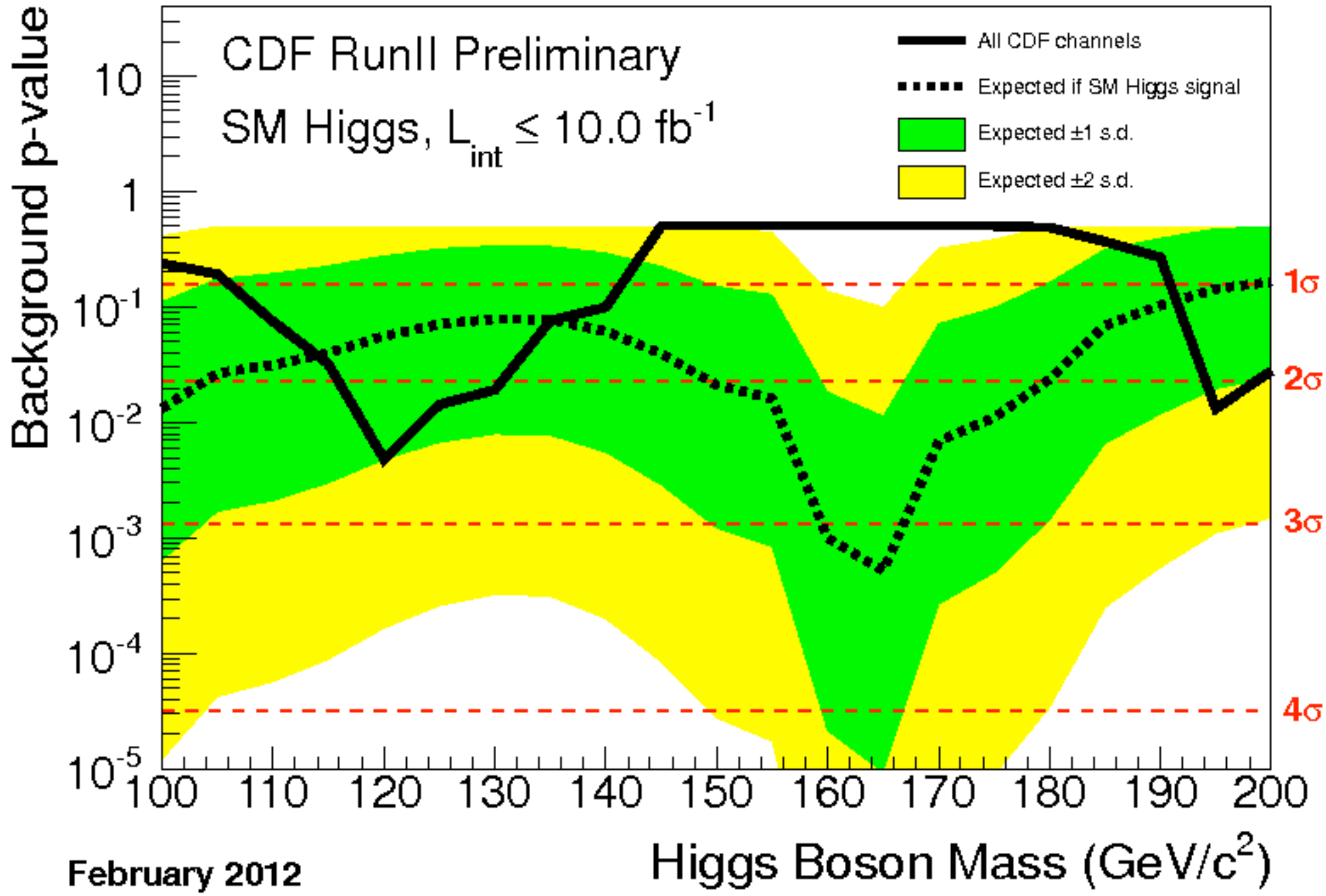
CDF only limits

CDF combination channels

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(TT,TL,Tx,LL,Lx)	9.45	100-150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(TT,TL)	9.45	100-150
$ZH \to \nu\bar{\nu}b\bar{b}$ (SS,SJ,1S)	9.45	100-150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(TT,TL,Tx,LL)	9.45	100-150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2×(TT,TL,Tx,LL)	9.45	100-150
$H \to W^+W^-$ 2×(0 jets,1 jet)+(2 or more jets)+(low-$m_{\ell\ell}$)	9.7	110-200
$H \to W^+W^-$ (e-τ_{had})+(μ-τ_{had})	9.7	130-200
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)	9.7	110-200
$WH \to WW^+W^-$ tri-leptons with 1 τ_{had}	9.7	130-200
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet)+(tri-leptons with 2 or more jets)	9.7	110-200
$H \to ZZ$ four leptons	9.7	120-200
$H + X \to \tau^+\tau^-$ (1 jet)+(2 jets)	8.3	100-150
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ ℓ-τ_{had}-τ_{had}	6.2	100-150
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ (ℓ-ℓ-τ_{had})+(e-μ-τ_{had})	6.2	100-125
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ ℓ-ℓ-ℓ	6.2	100-105
$ZH \to \ell^+\ell^-\tau^+\tau^-$ four leptons including τ_{had} candidates	6.2	100-115
$WH + ZH \to jjb\bar{b}$ (SS,SJ)	9.45	100-150
$H \to \gamma\gamma$ (CC,CP,CC-Conv,PC-Conv)	10.0	100-150
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (lepton) (4jet,5jet,≥6jet)×(SSS,SSJ,SJJ,SS,SJ)	9.45	100-150
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (no lepton) (low met,high met)×(2 tags,3 or more tags)	5.7	100-150

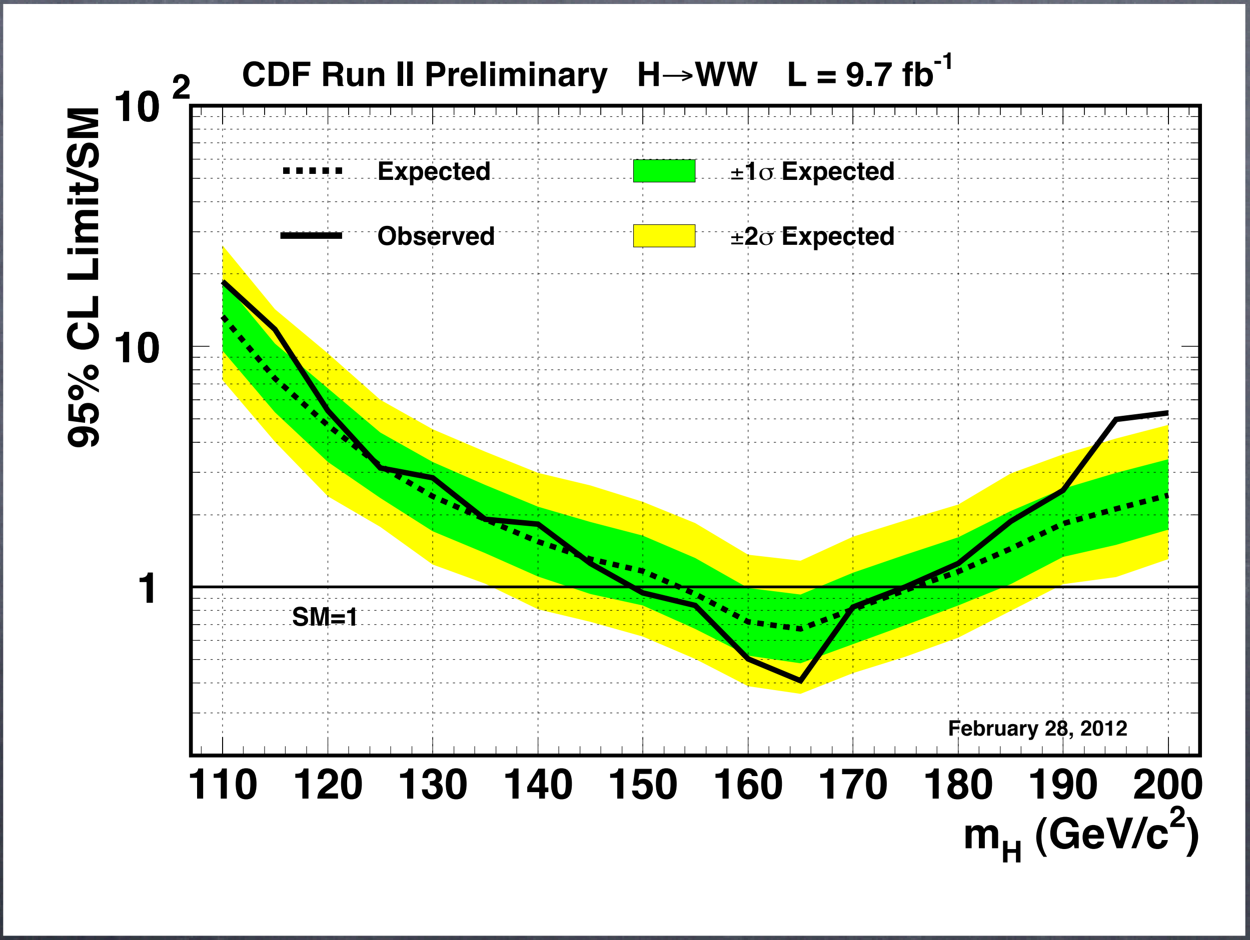
l = e or μ

compatibility with background

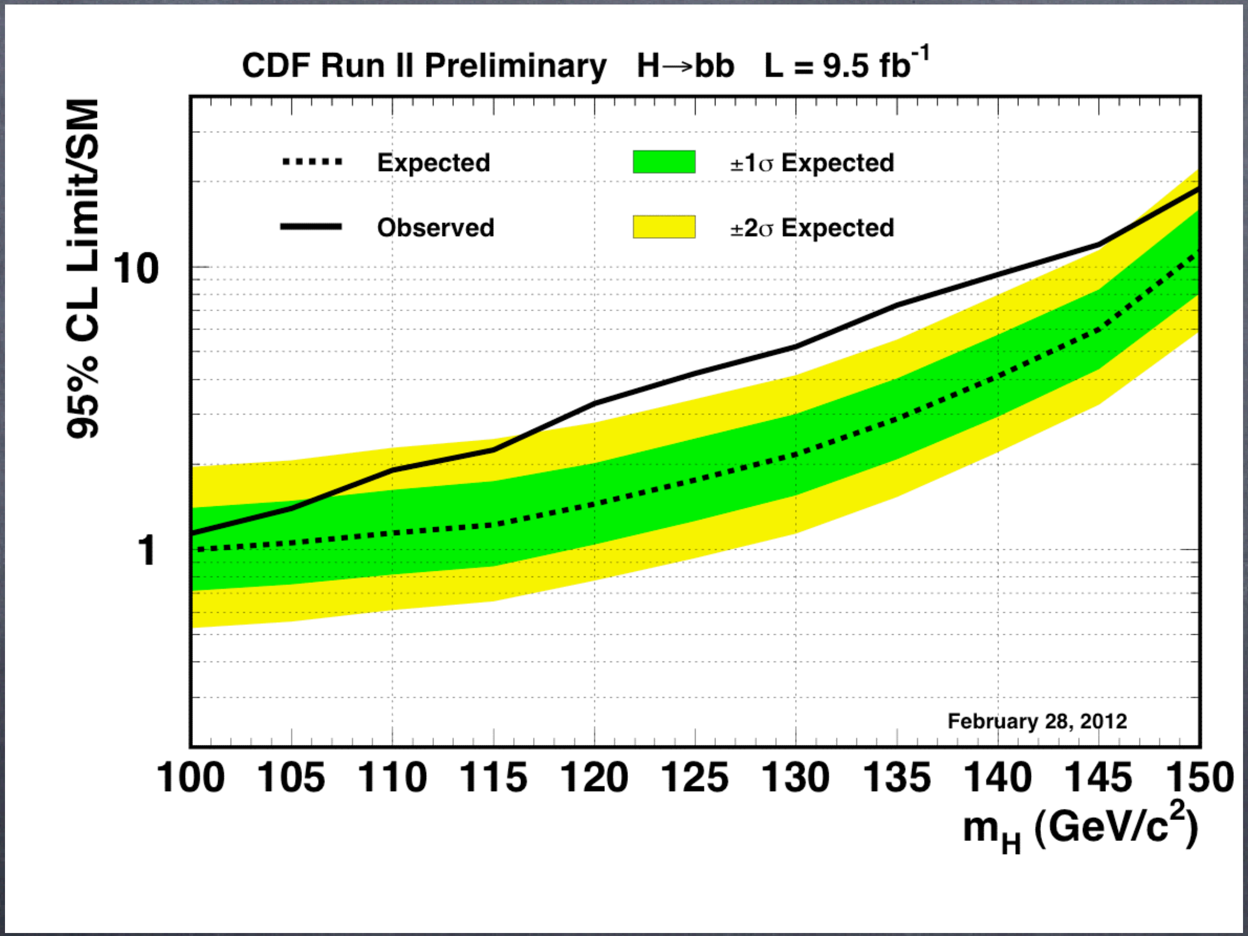


Highest local p-value, 2.6σ, is found at m_H = 120 GeV/c^2

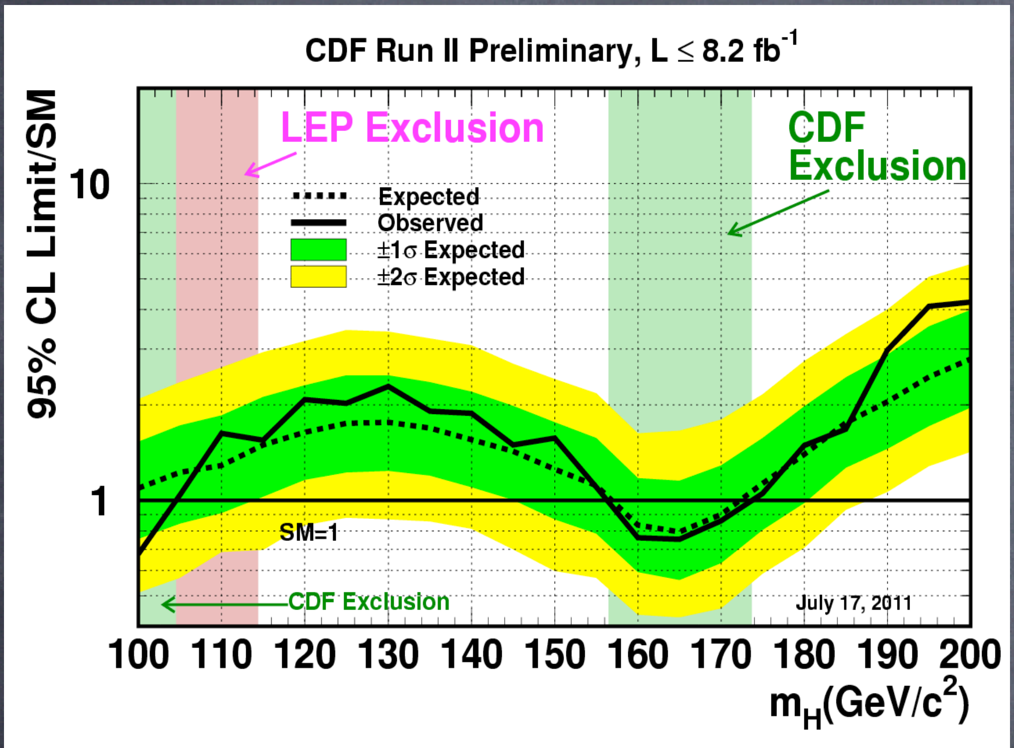
CDF H→WW Combination

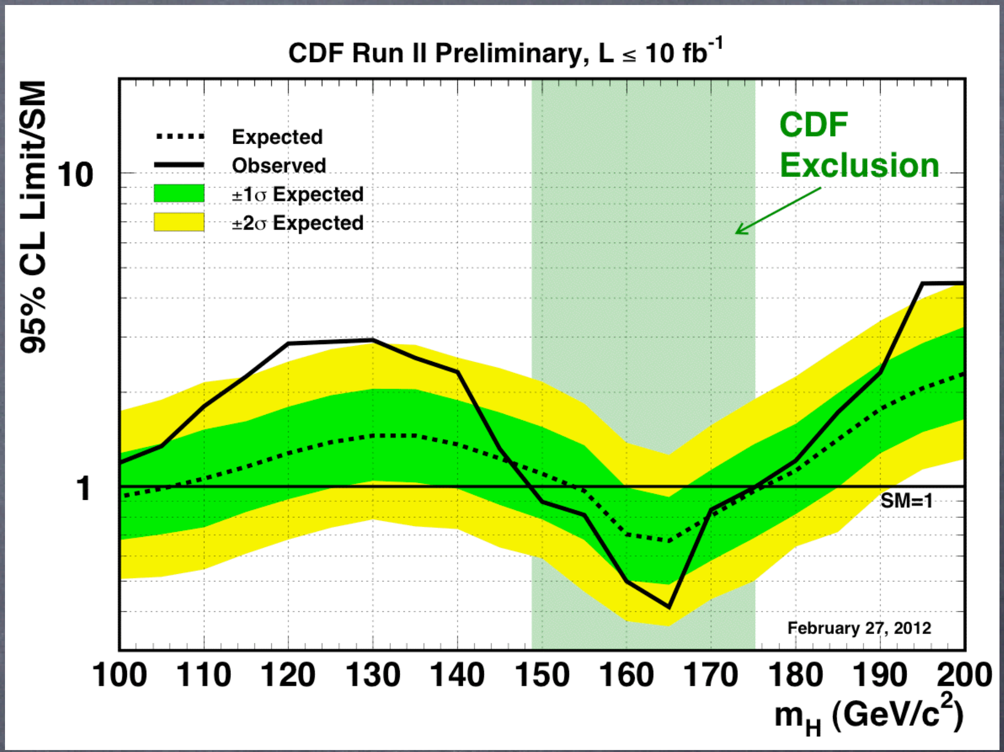


CDF H→bb Combination



how much did things change?



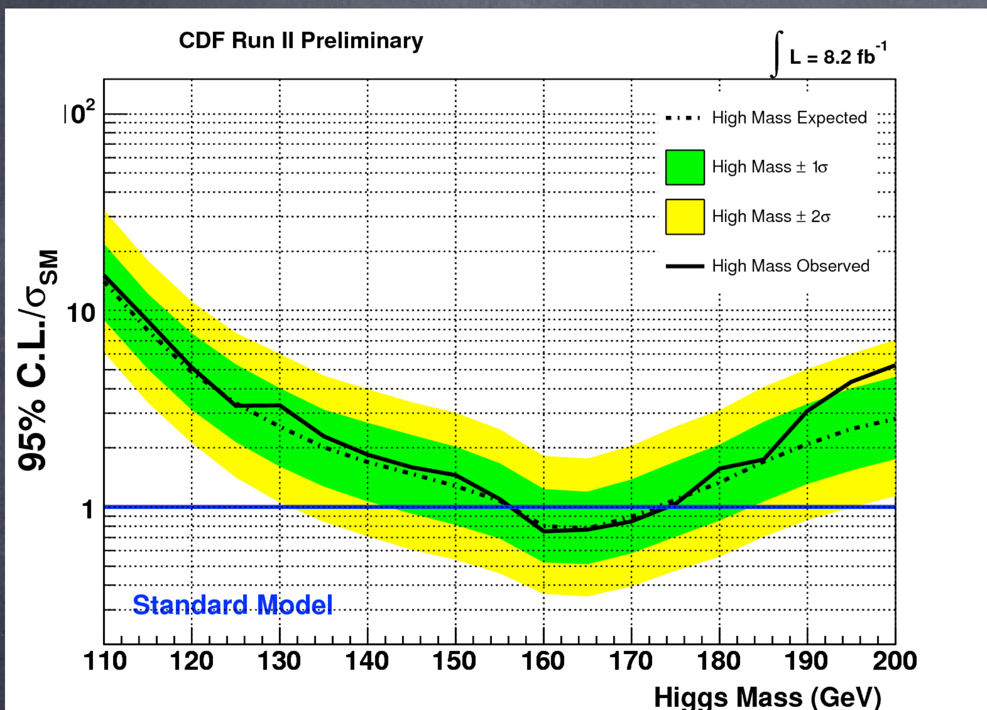


Summer 2011

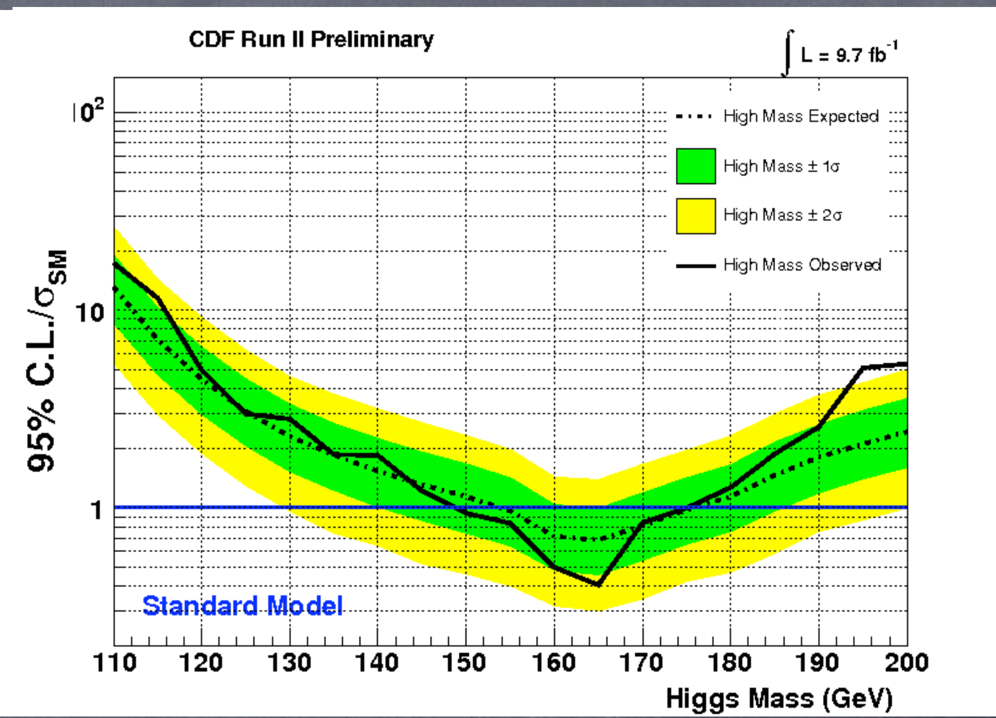
Winter 2012

A ~0.5σ excess in mass range from 115 to 135 GeV/c^2 has become a ~2σ excess. How can this happen?

H→WW



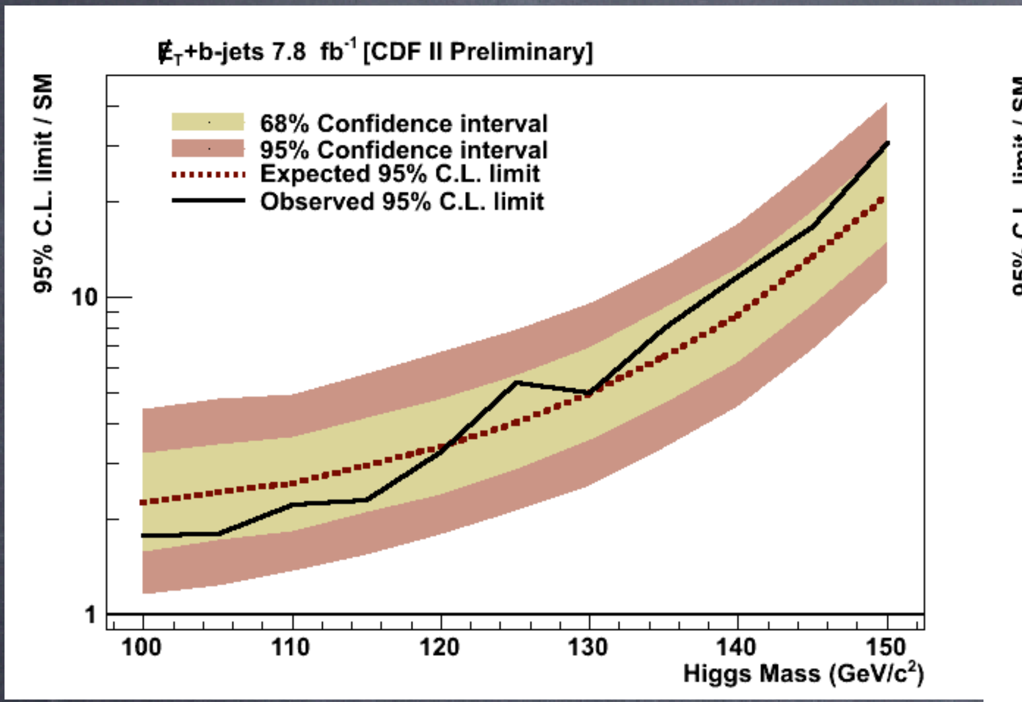
Summer 2011

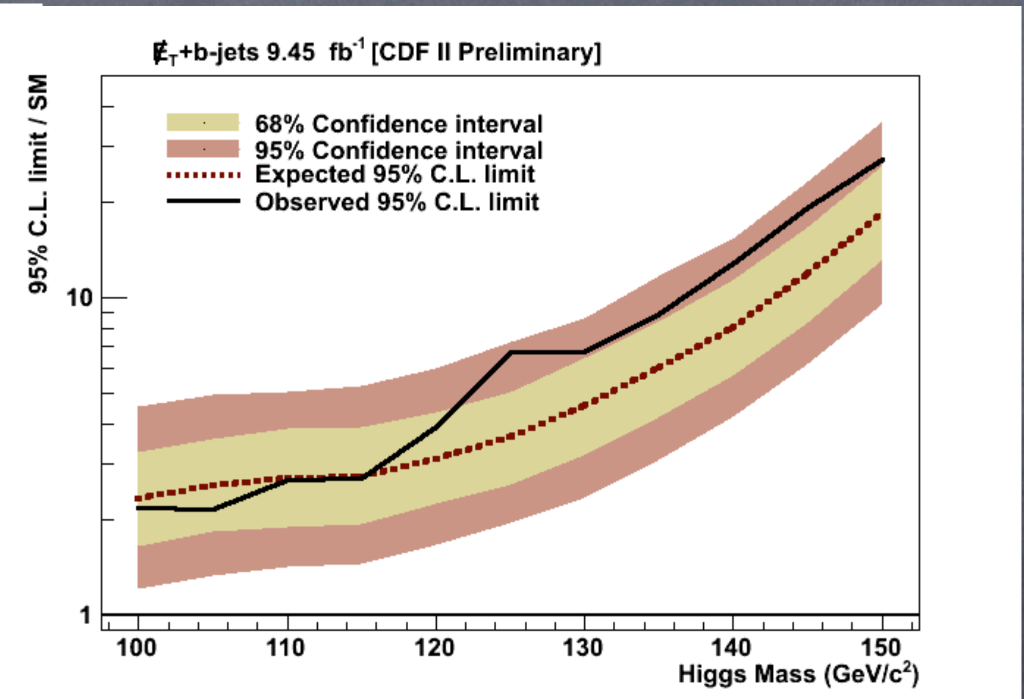


Winter 2012

- 18% additional data
- Small signal acceptance improvements ($0.1 < \Delta R_{ll} < 0.2$)
- No appreciable change in behavior of limits

ZH→ννbb



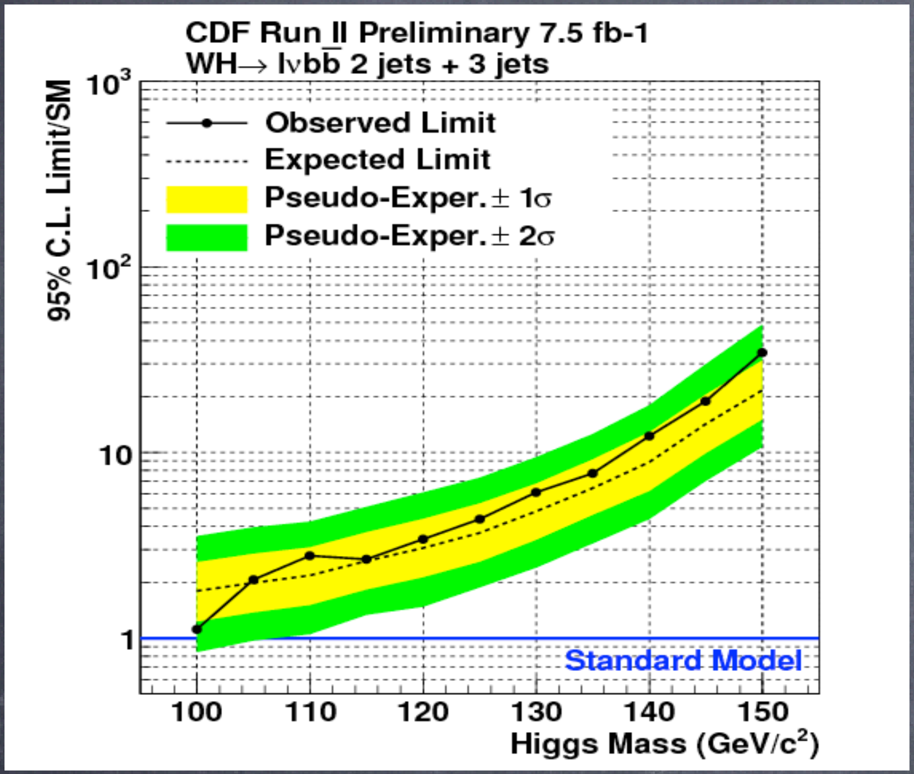


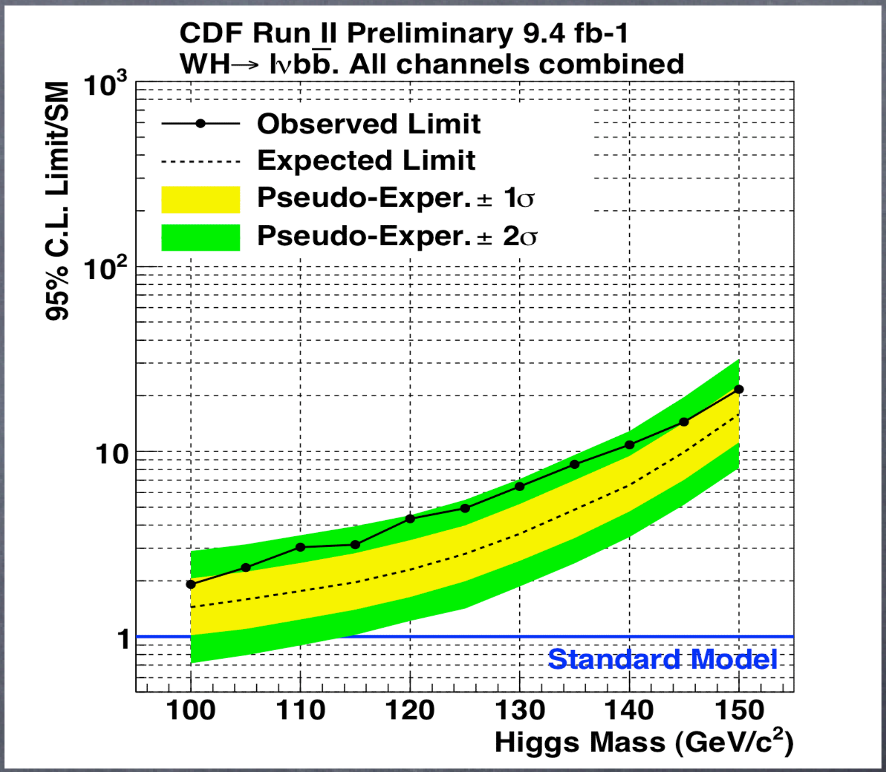
Summer 2011

Winter 2012

- 21% additional luminosity
- Small improvements in background rejection
- same basic behavior w/ 0.5 to 1.0σ increases in significance of excess

WH→lνbb



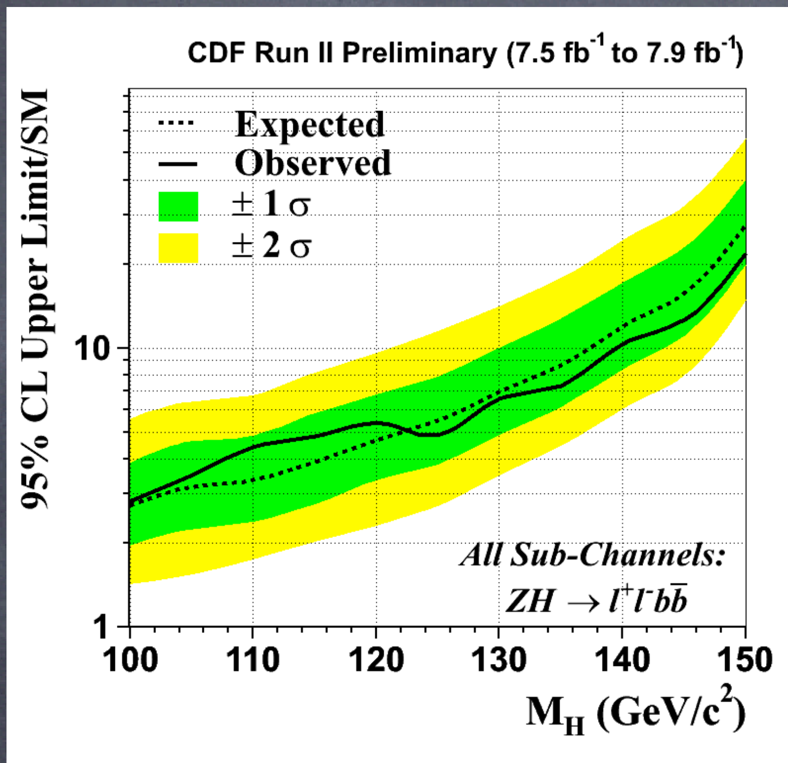


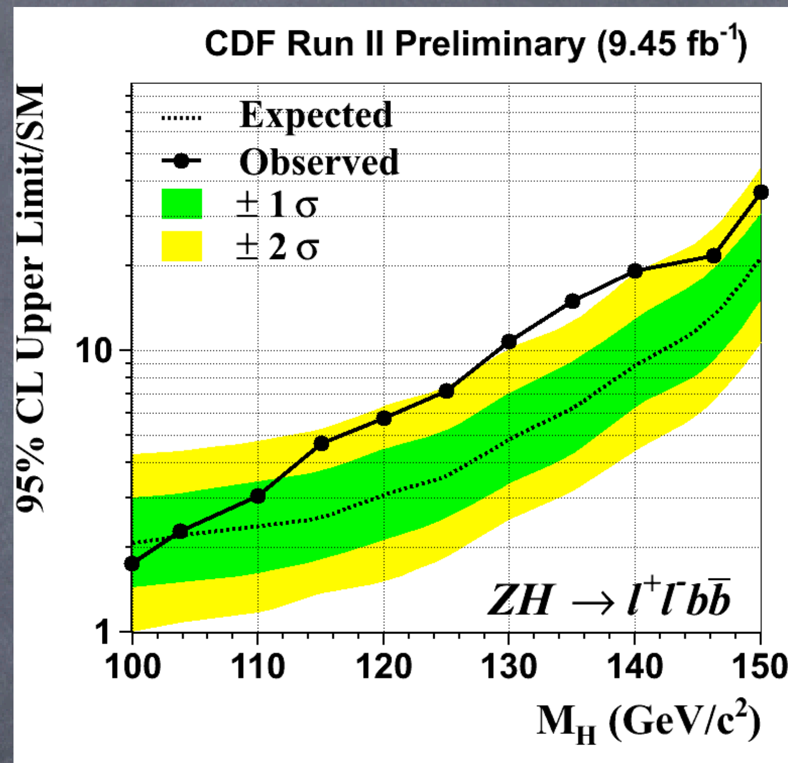
Summer 2011

Winter 2012

- 26% (69%) additional luminosity for 2-jet (3-jet) channels
- 5-10% level lepton acceptance/trigger efficiency improvements
- New HOBIT b-tagger equivalent to adding another 20% in additional luminosity
- Limits show same basic behavior with 1.0 to 1.5σ increases in significance of excess

ZH→llbb





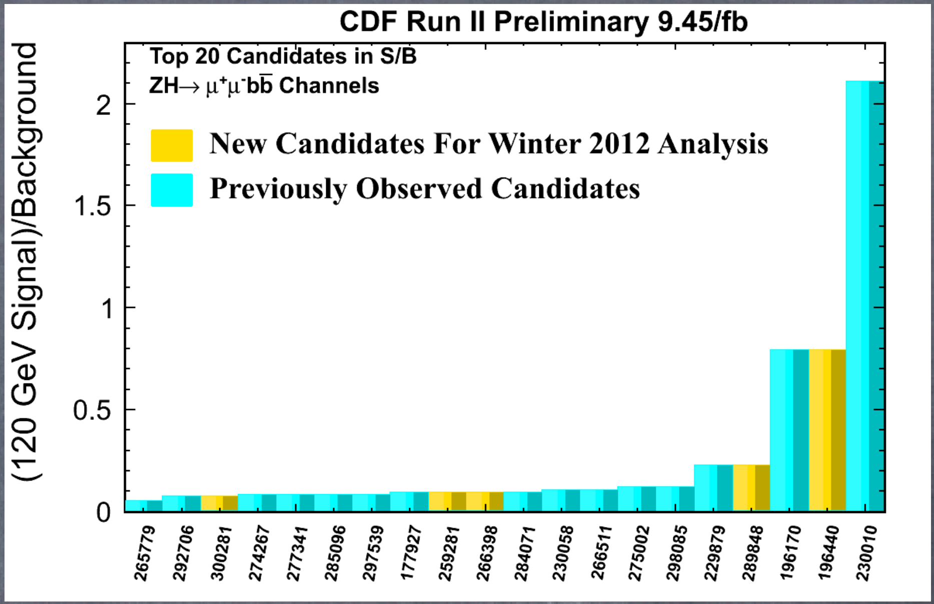
Summer 2011

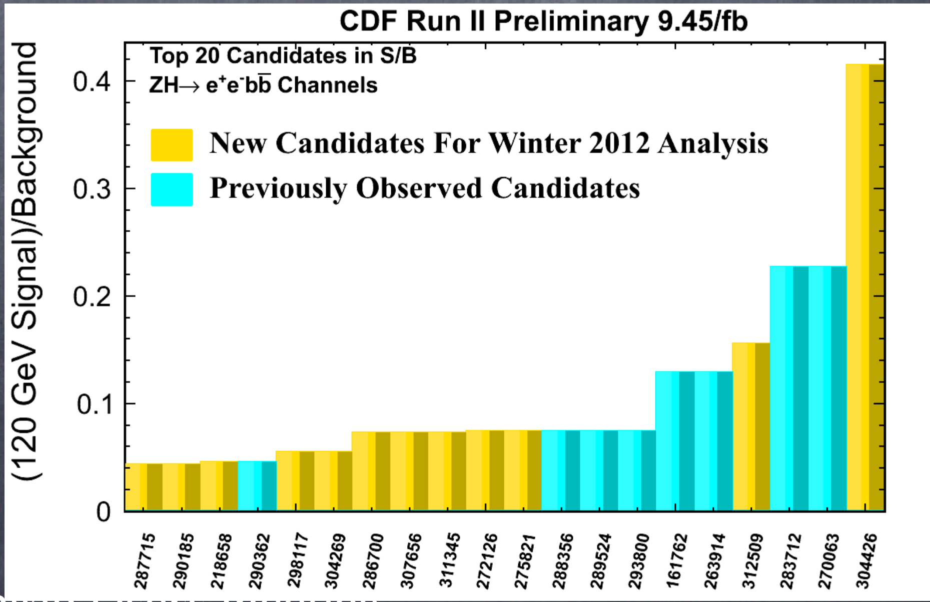
Winter 2012

- 23% additional luminosity
- More gain from HOBIT in this analysis than WH (original tagging not as sophisticated)
- 56% of data events in current analysis were not included in previous analysis!
- 37% sensitivity improvement (4.67® 2.95 at m_H=120 GeV/c^2)

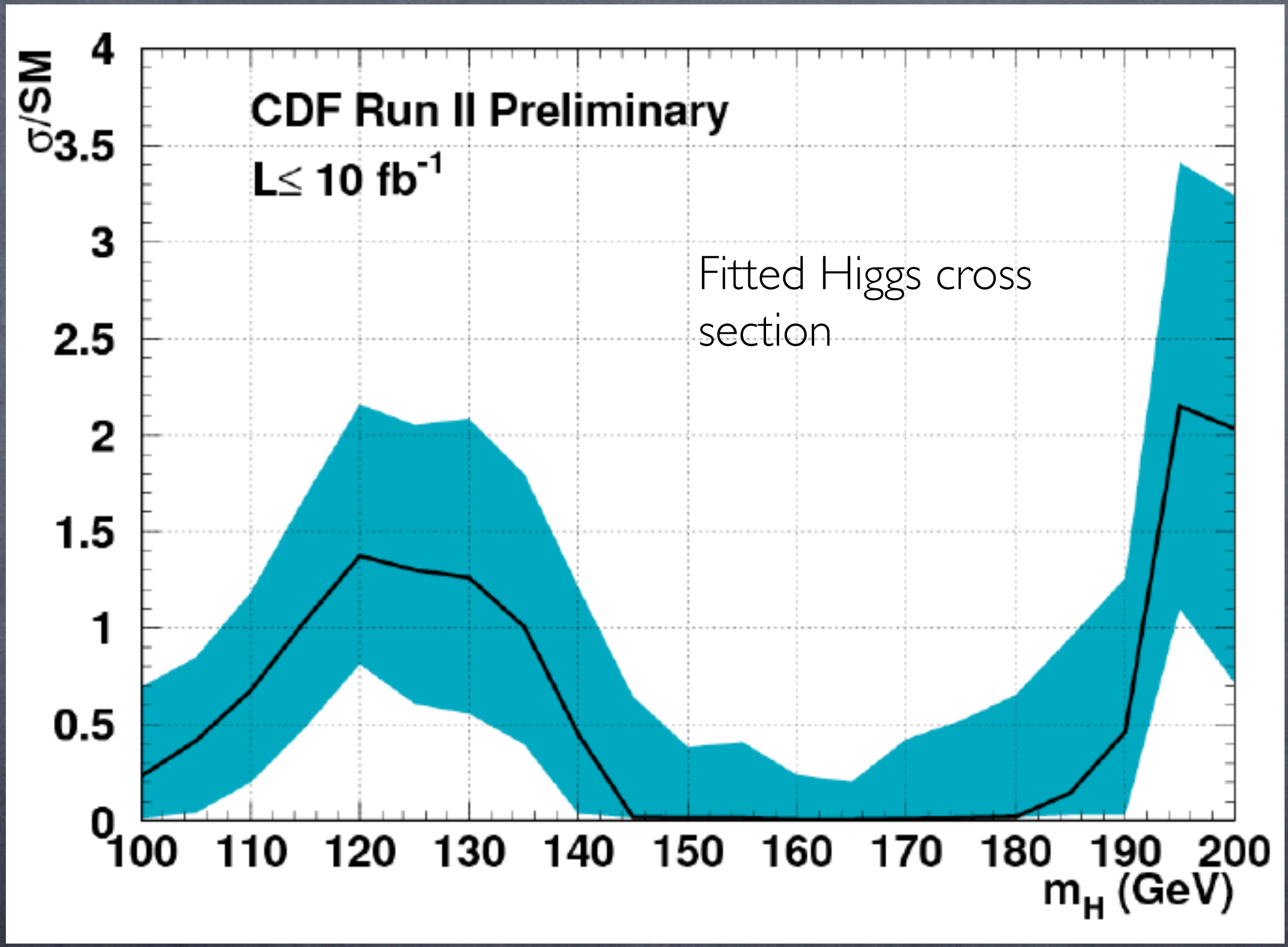
ZH→llbb

- Examine top 20 events in both channels based on S/B of the discriminant bin in which it's located
- The electron channel contains 12 new candidates within this high score region, while muon channel has 5



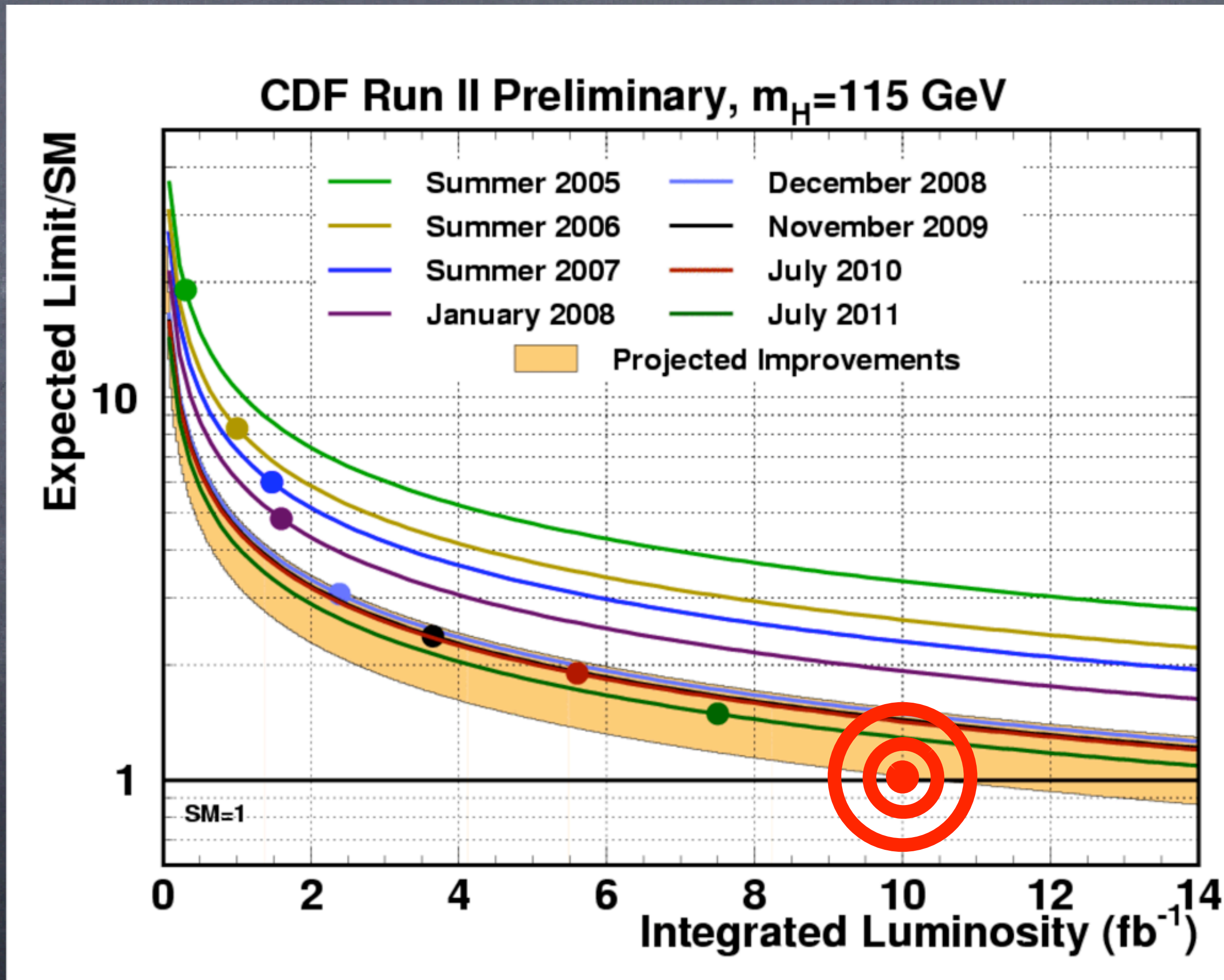


compatible with SM Higgs?

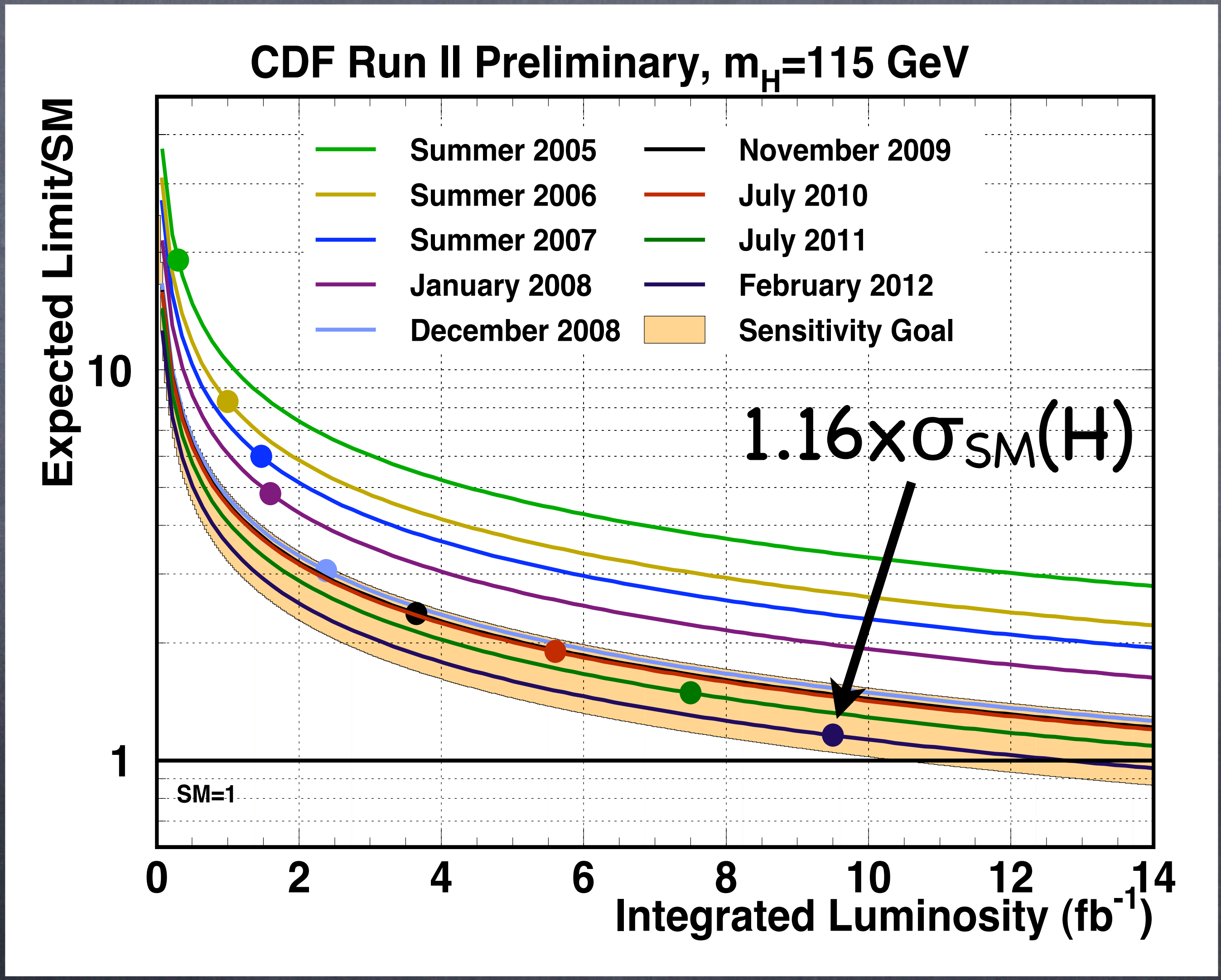


Consistent with SM Higgs at 1σ level for mass range between 107 and 142 GeV/c^2

Projected Sensitivity



Achieved Sensitivity



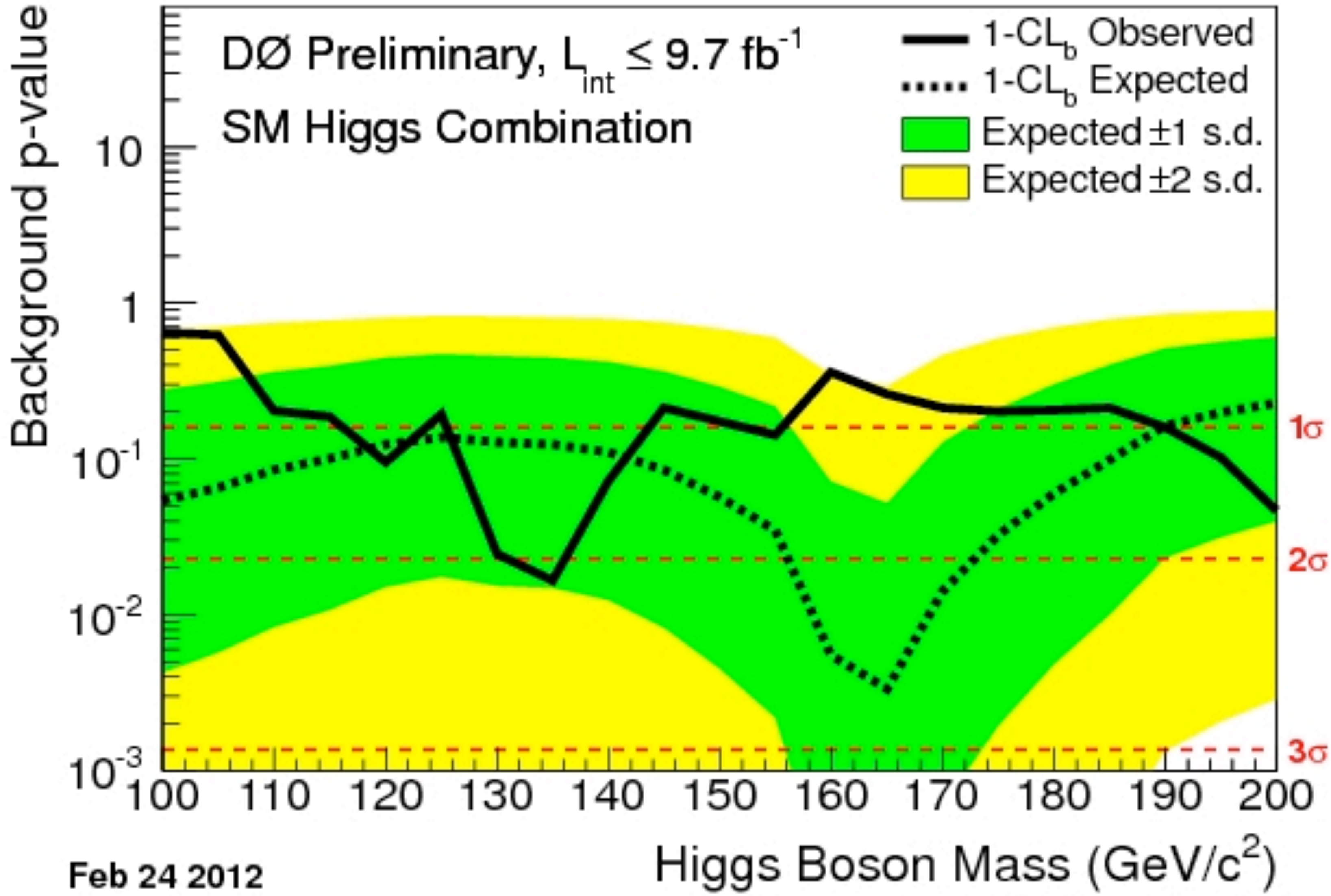
DØ only limits

DØ combination channels

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$	(TST,LDT,TDT)×(2,3 jet)	9.7	100-150
$ZH \to \nu\bar{\nu}b\bar{b}$	(MS,TS)	9.5	100-150
$ZH \to \ell^+\ell^- b\bar{b}$	(TST,TLDT)×(ee,$\mu\mu$,ee_{ICR},$\mu\mu_{trk}$)	9.7	100-150
$H{+}X \to \ell^\pm\tau^\mp_{\rm had}jj$		4.3-6.2	105-200
$VH \to e^\pm\mu^\pm + X$		9.7	115-200
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$	(0,1,2+ jet)	8.6-9.7	115-200
$H \to W^+W^- \to \mu\nu\tau_{\rm had}\nu$		7.3	115-200
$H \to W^+W^- \to \ell\bar{\nu}jj$		5.4	130-200
$VH \to \ell\ell\ell + X$		9.7	100-200
$VH \to \tau\tau\mu + X$		7.0	115-200
$H \to \gamma\gamma$		9.7	100-150

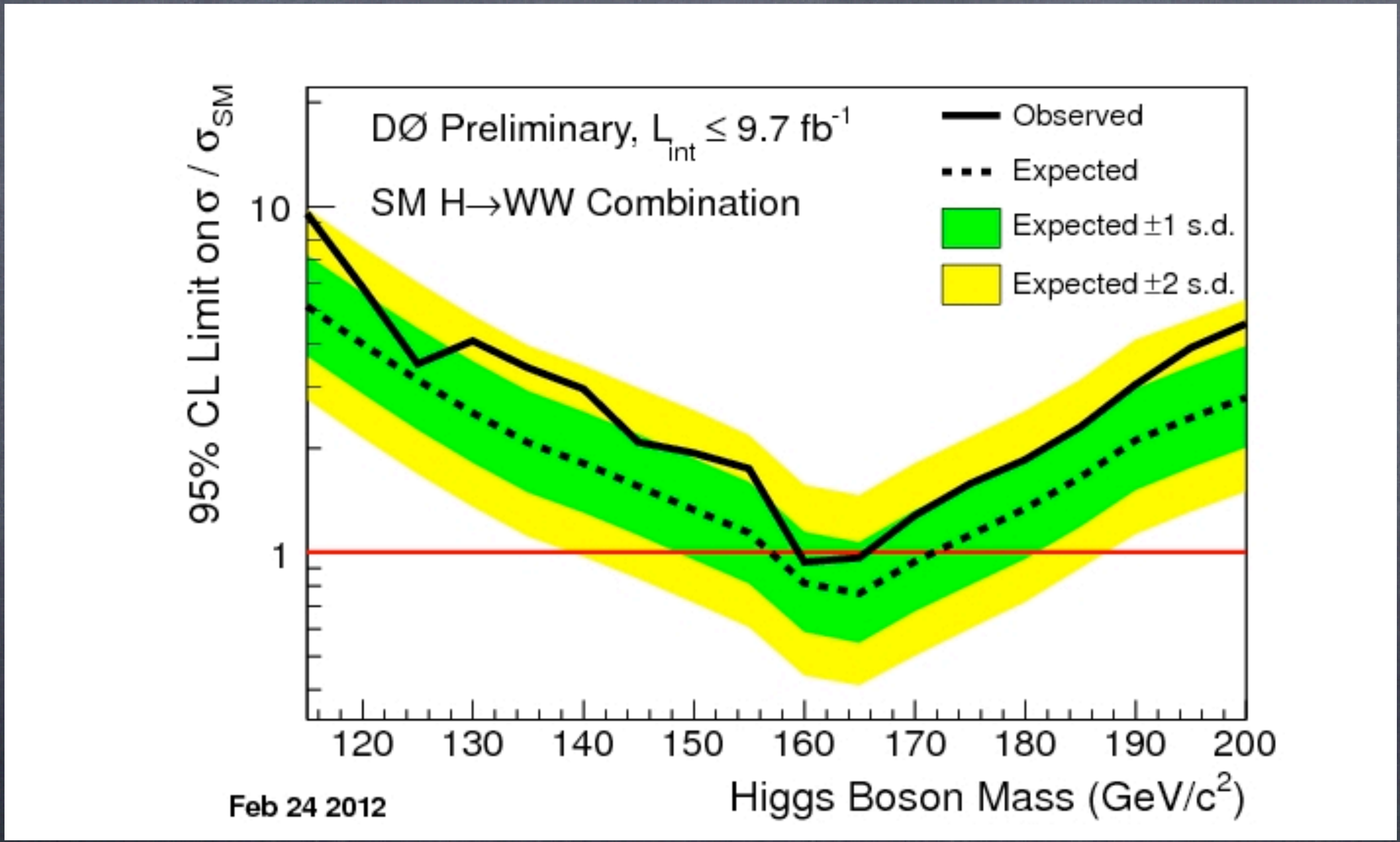
l = e or μ

compatibility with background

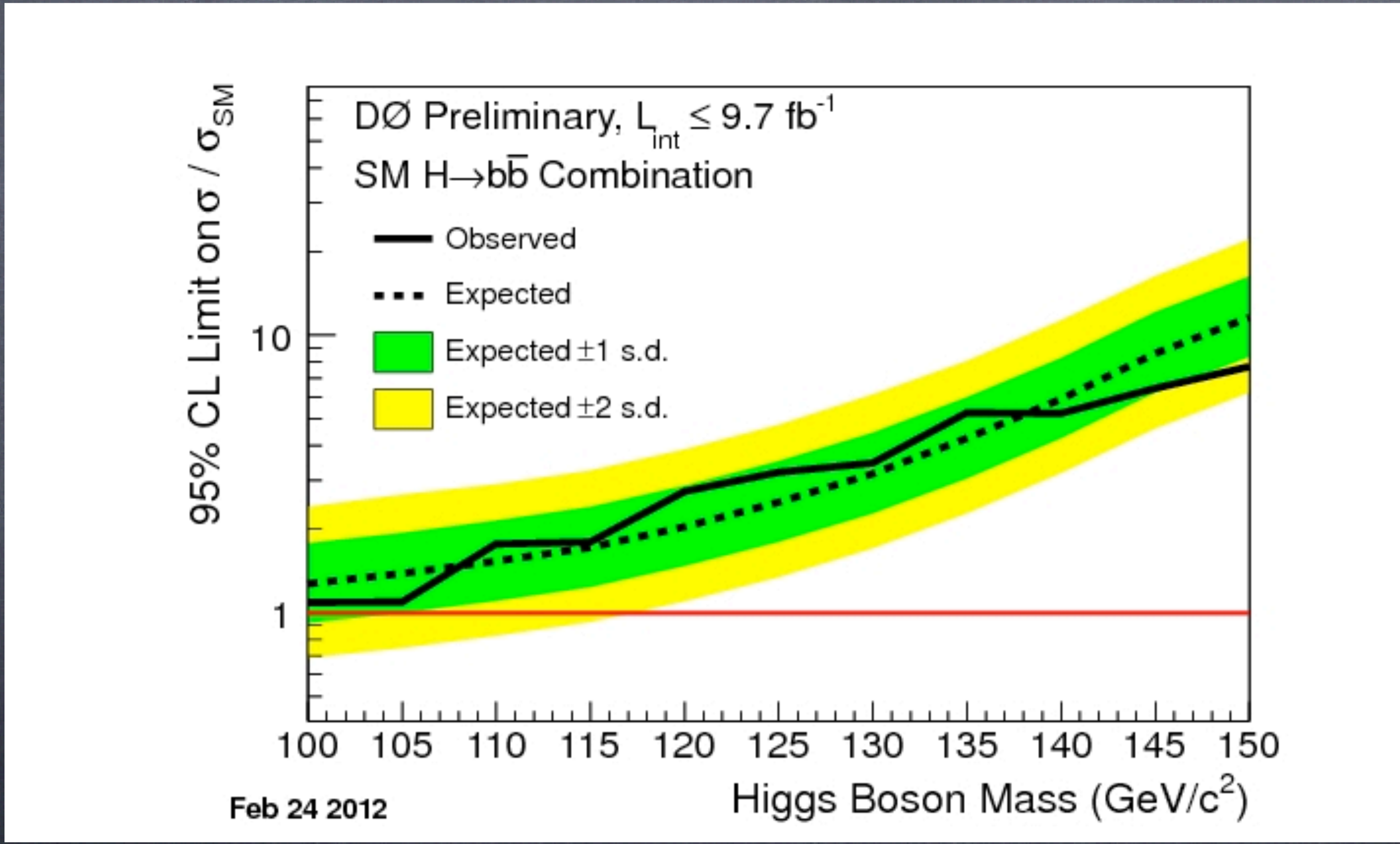


Highest local p-value, 2.14σ, is found at m_H = 135 GeV/c^2

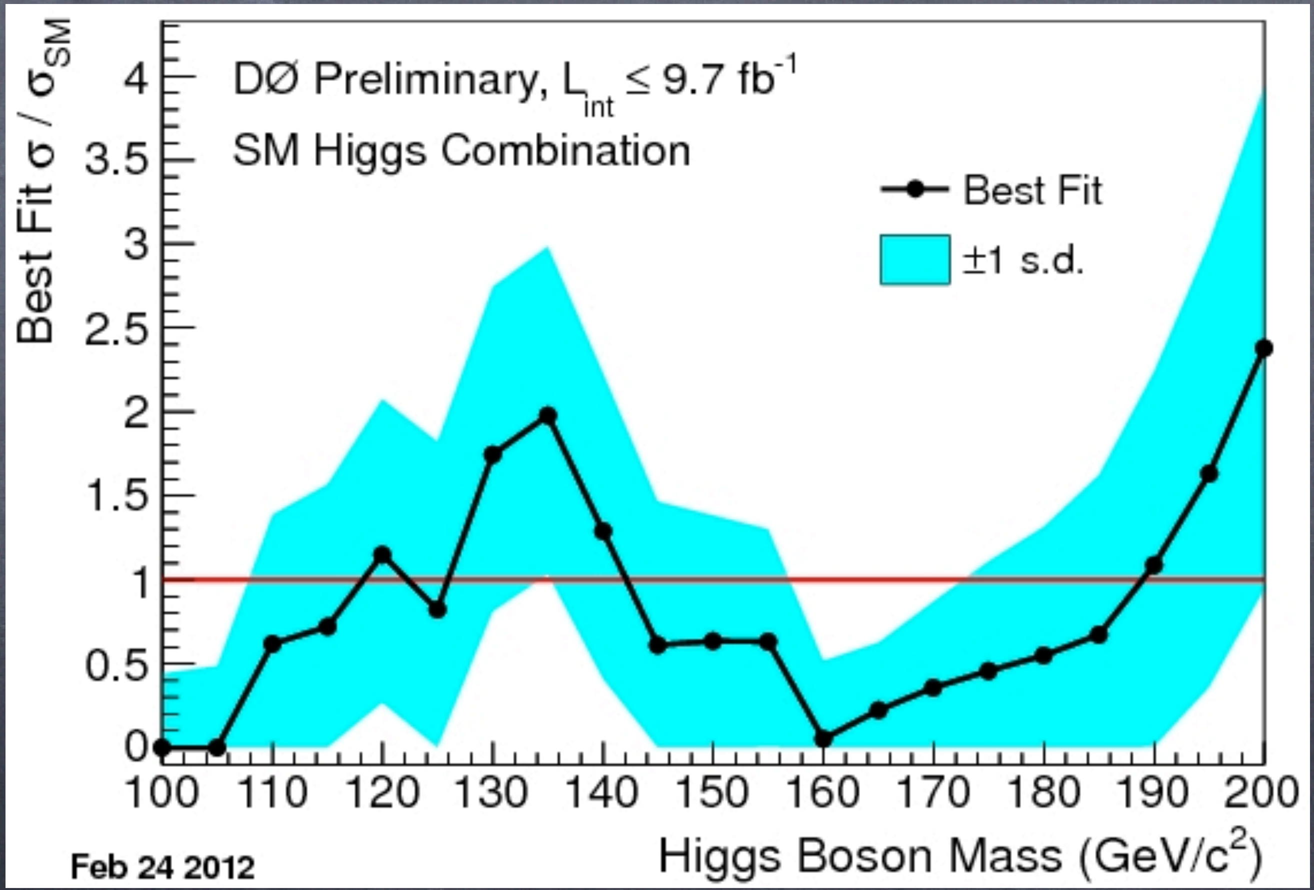
DØ H→WW Combination



DØ H→bb Combination

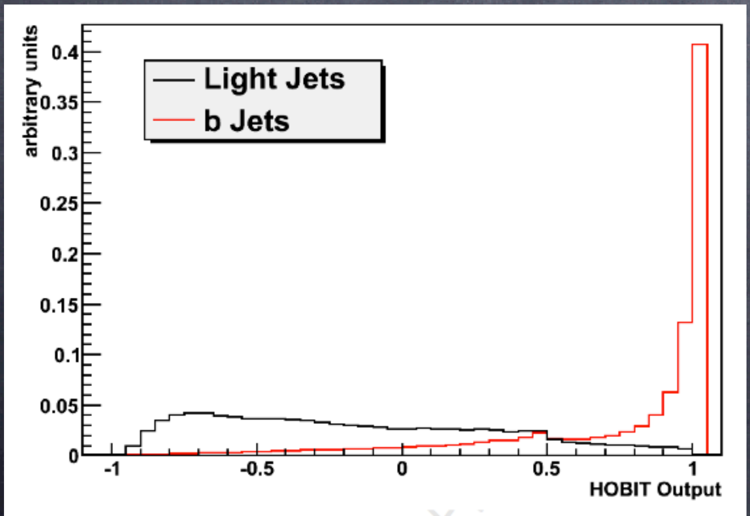


fitted Higgs cross section



Higgs optimized b identification tagger

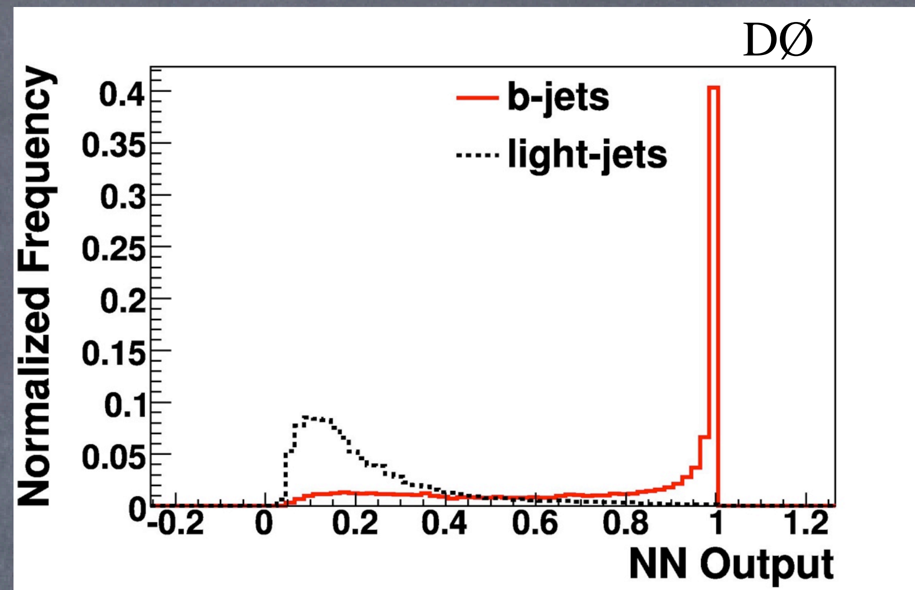
- 25 input variables
- 8 operating points
- validated in tt-bar and soft-electron samples

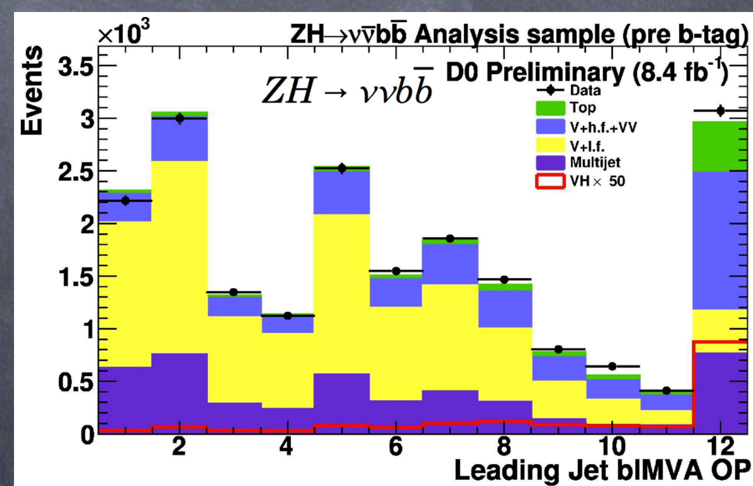


tagger	eff	HOBIT	increase
SV T	0.38	0.50	30%
SV L	0.47	0.60	27%
Roma	0.50	0.58	16%

identifying b-quark jets

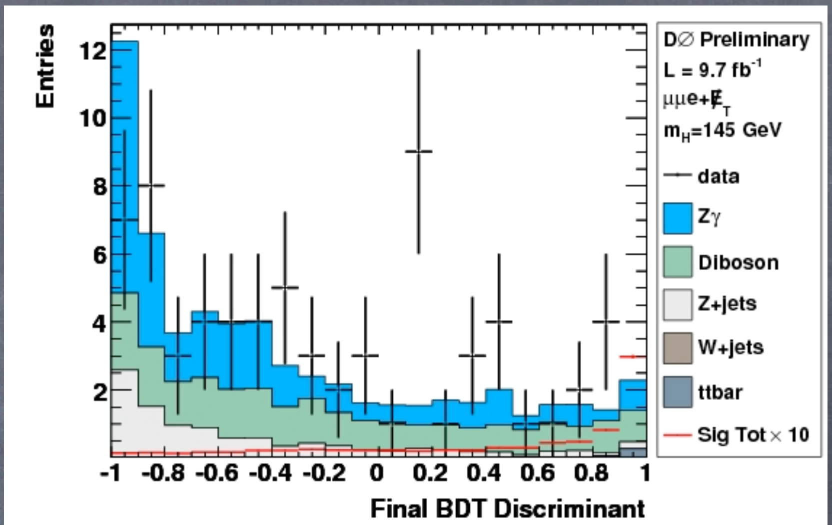
- CDF utilizes 4/5 tagging regions from tight and loose thresholds
- DØ uses event based tag categories where jet scores are combined
- efficiency 50-70%
- light jet mistag 0.5 - 5%
- order 5-15% improvement in Higgs sensitivity

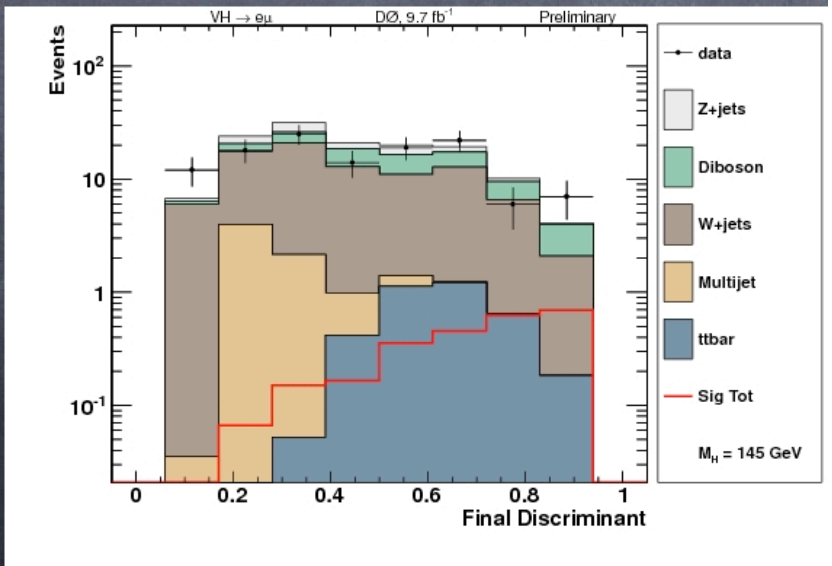


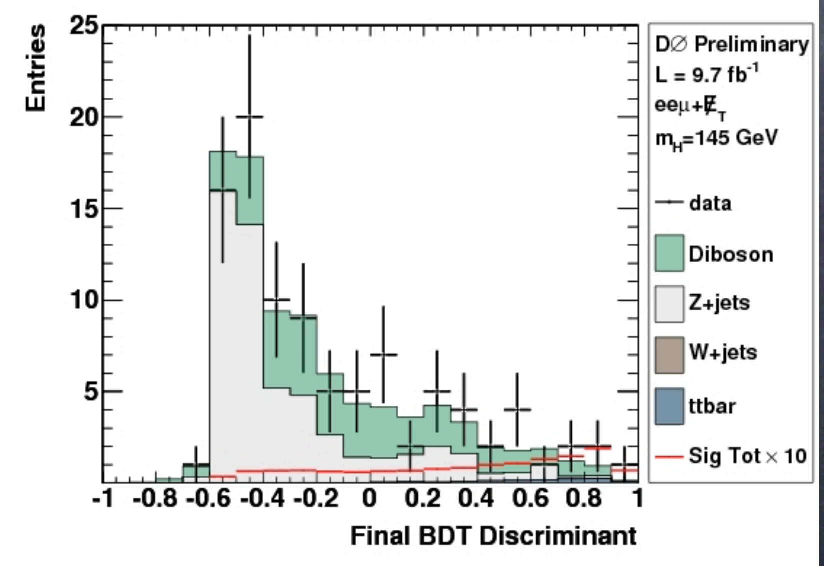


extending the search

- VH → VVV Search
- final states with same sign dilepton or trileptons
- low signal rate, but small background







H→γγ Search

- Neural Network photon-ID
- new event based discriminant
- low-mass Higgs discovery channel at LHC
- extends to Fermiophobic higgs search