Final Higgs Results from the Tevatron

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University of Glasgow

UCL, 23 March 2012

$$\mathcal{L}_{\text{QED}} = \overline{\psi}(i\gamma_\mu\partial^\mu - m_f)\psi + q\overline{\psi}\gamma_\mu A^\mu\psi - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad + \tfrac{1}{2}m_\gamma^2 A_\mu A^\mu$$

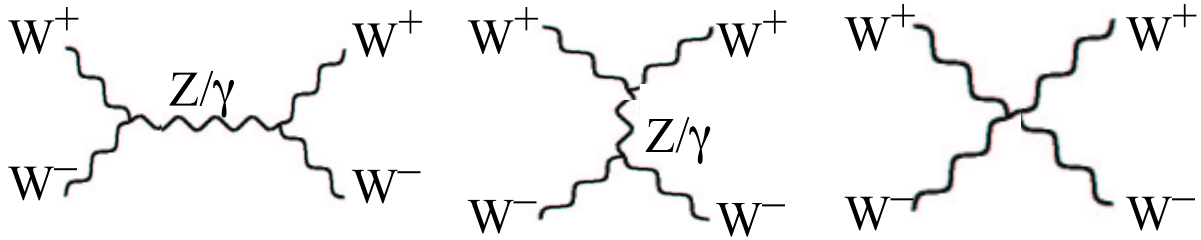
$$\mathcal{L}_{\text{EWK}} = \overline{\psi}\gamma_\mu(i\partial^\mu + g\boldsymbol{\tau}\cdot\mathbf{W} + \tfrac{g'}{2}YB^\mu)\psi - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} - \tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu}$$

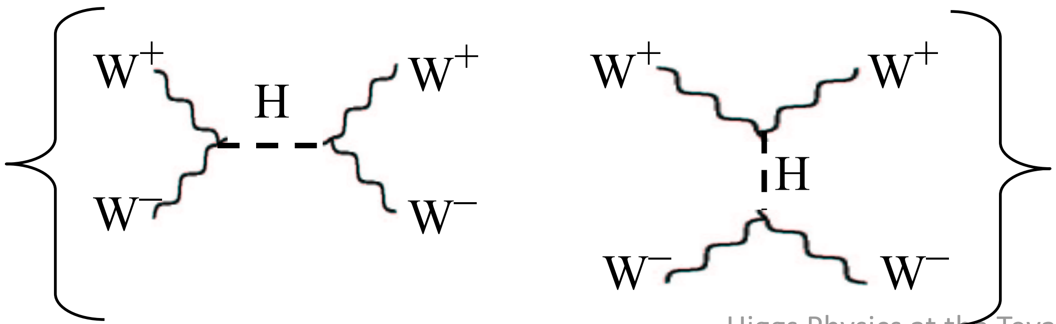
$$+\tfrac{1}{2}m_B^2 B_\mu B^\mu + \tfrac{1}{2}m_W^2 \mathbf{W}_\mu\cdot\mathbf{W}^\mu$$

$$+\tfrac{1}{2}(\partial_\mu H\partial^\mu H + 2\mu^2 H^2) - \tfrac{\lambda}{4}(4vH^3 + H^4)$$

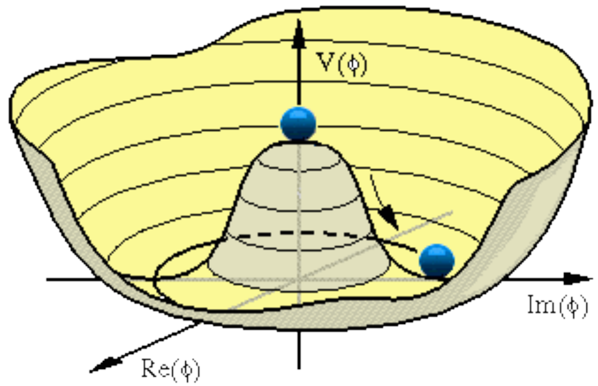
$$+\tfrac{g^2}{4}(v^2 + 2vH + H^2)W_\mu^- W^{+\mu} + \tfrac{g^2+g'^2}{8}(v^2 + 2vH + H^2)Z_\mu Z^\mu$$

$$-\tfrac{g_e}{\sqrt{2}}(v + H)(\overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L)$$

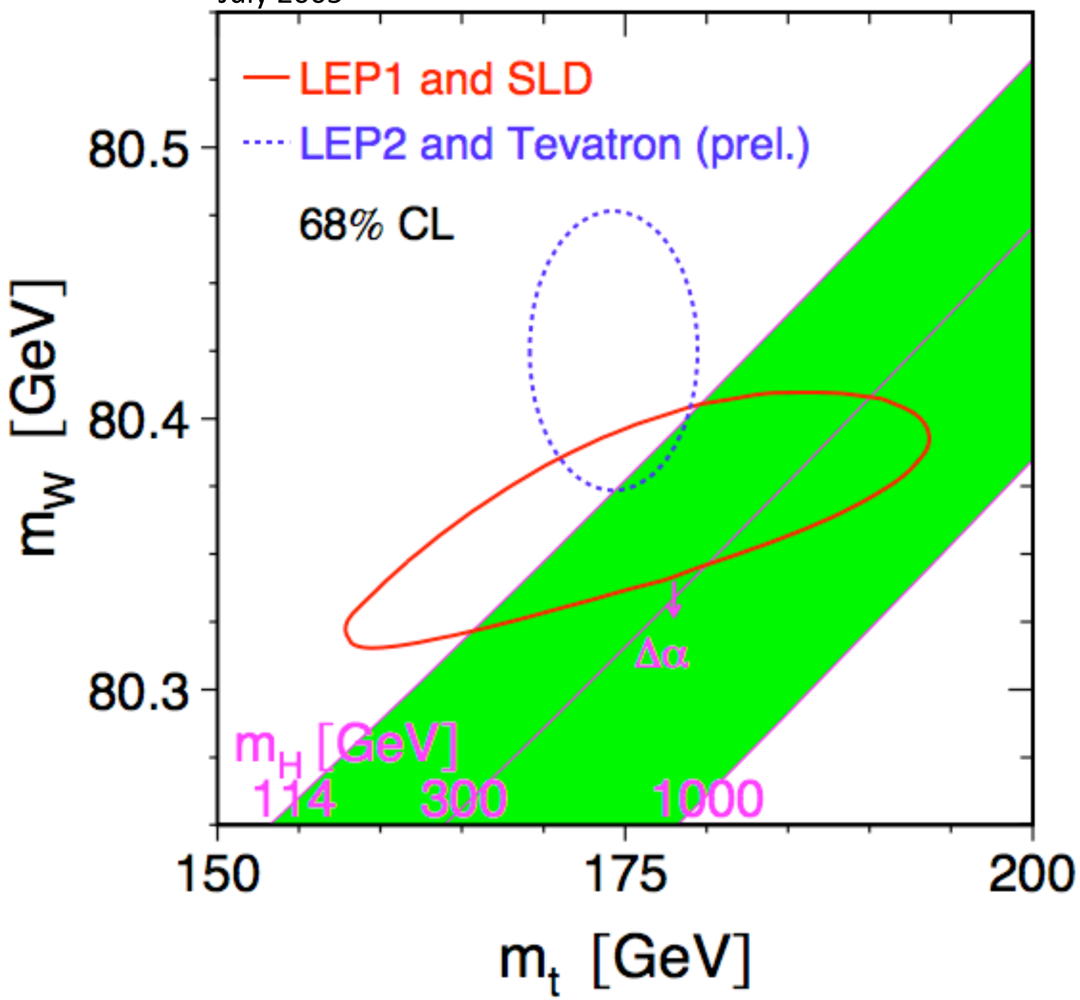




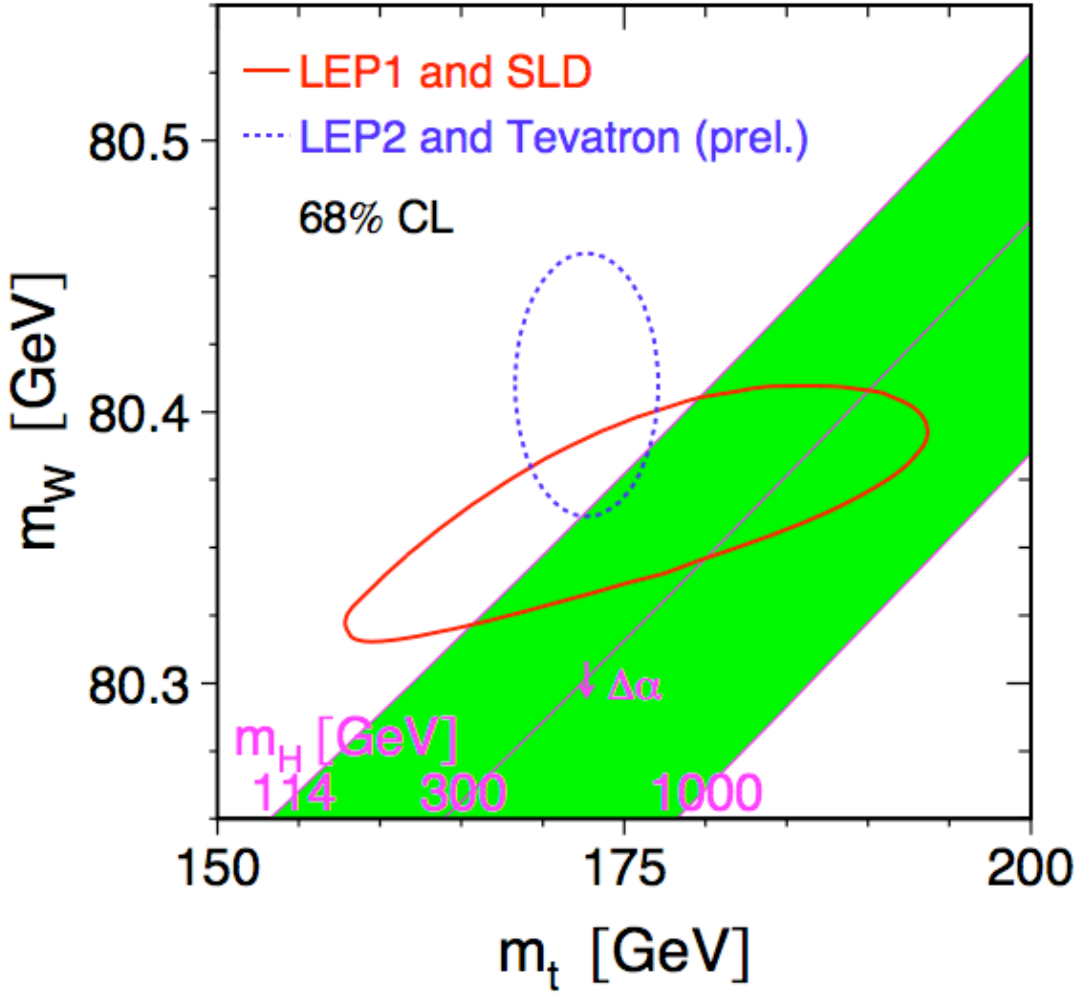
required to cancel high-energy behaviour



July 2005


LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
m_W [GeV]
Δα
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]

March 2006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LEP2 and Tevatron (prel.)
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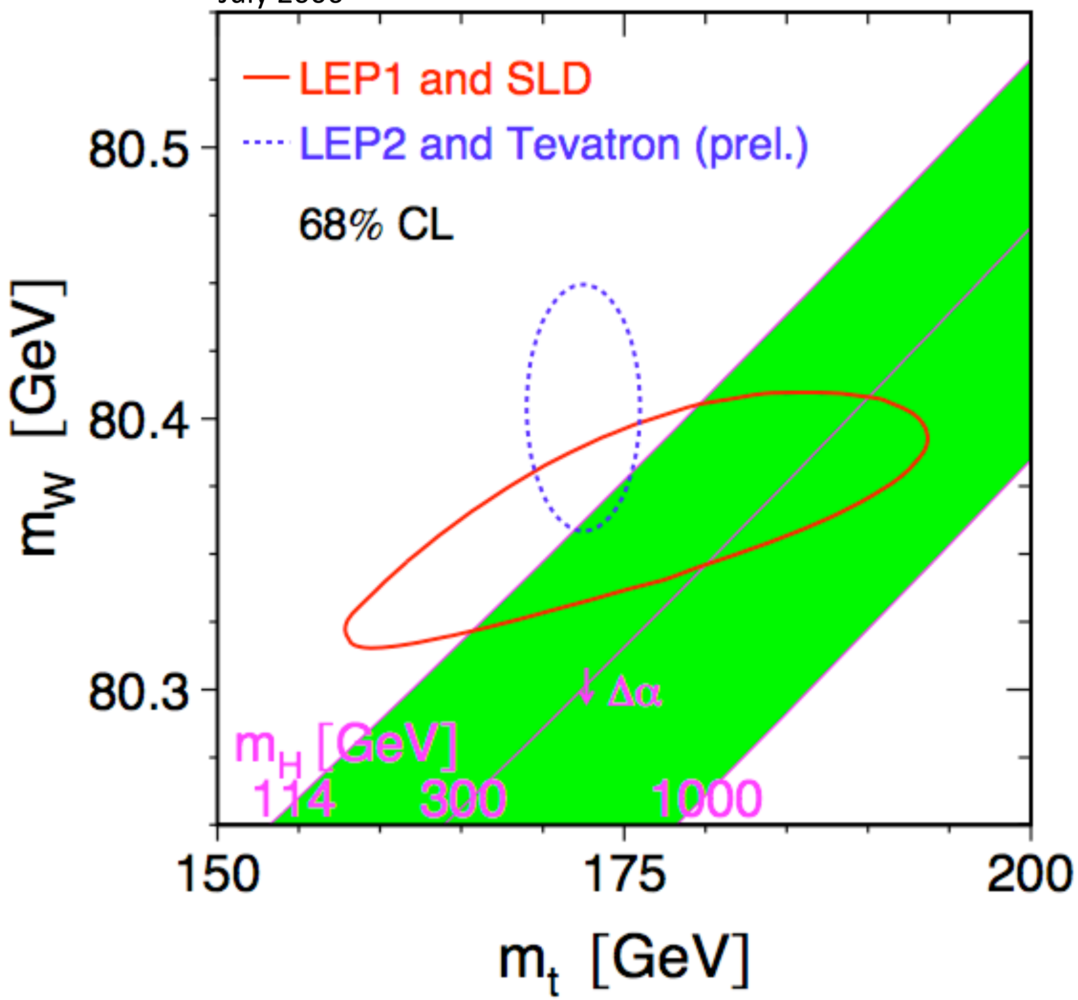
$\Delta\alpha$
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]
m_W [GeV]

July 2006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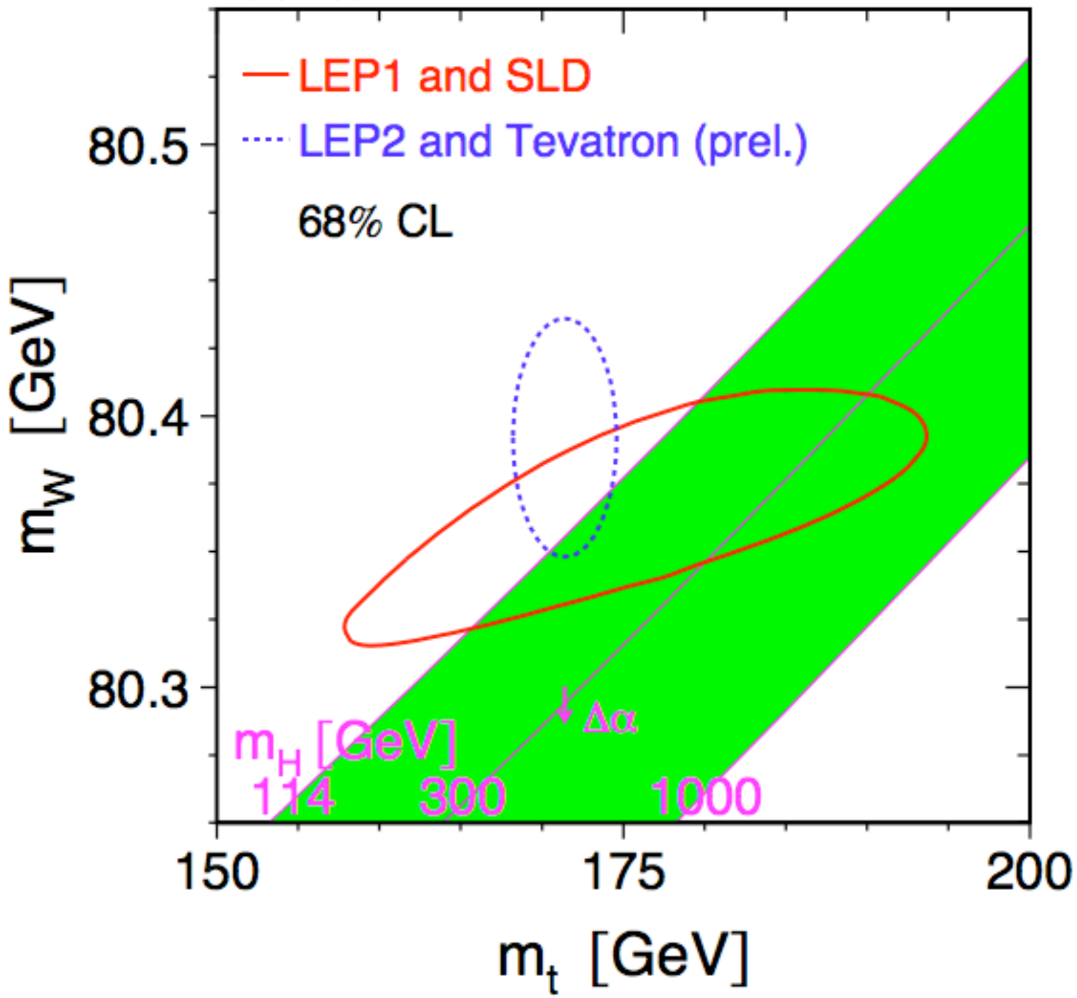
March 2007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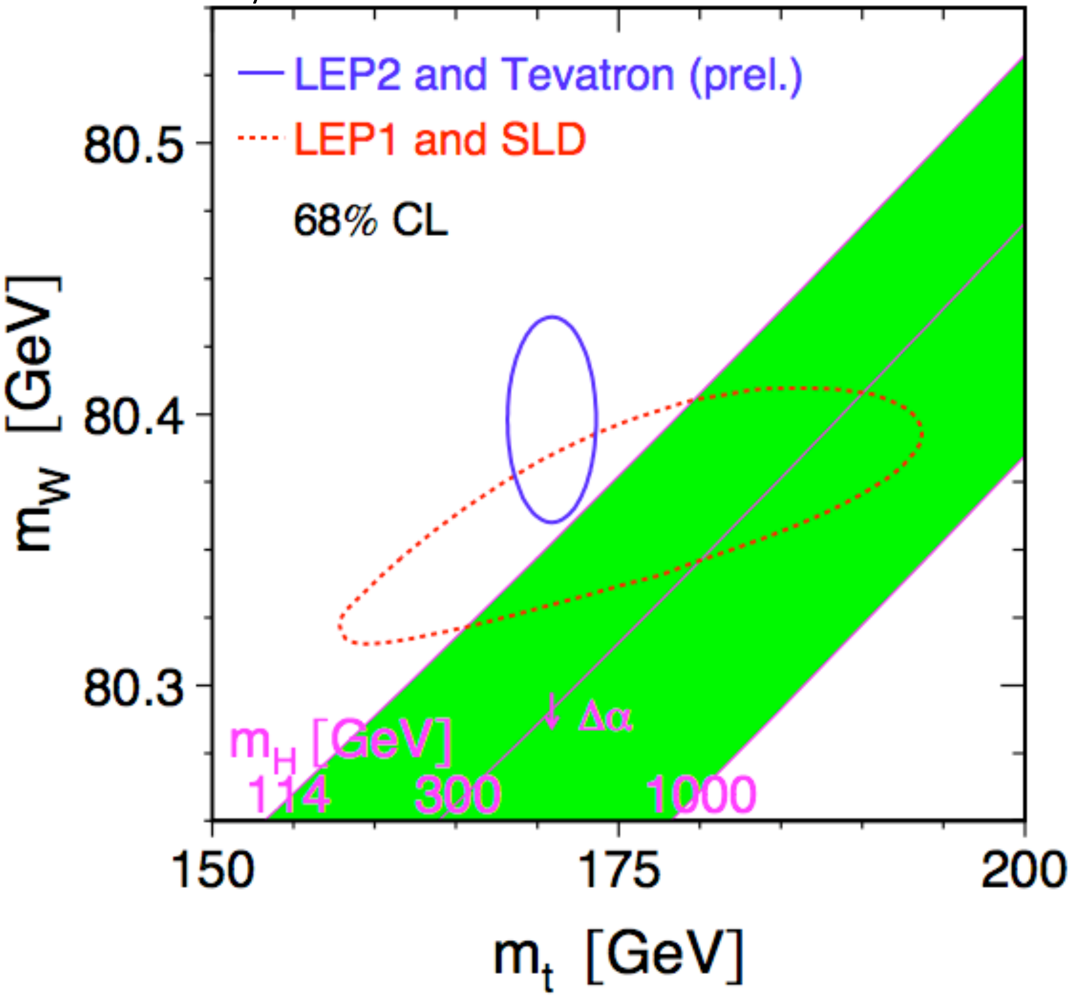
LEP2 and Tevatron (prel.)
LEP1 and SLD
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m_W [GeV]
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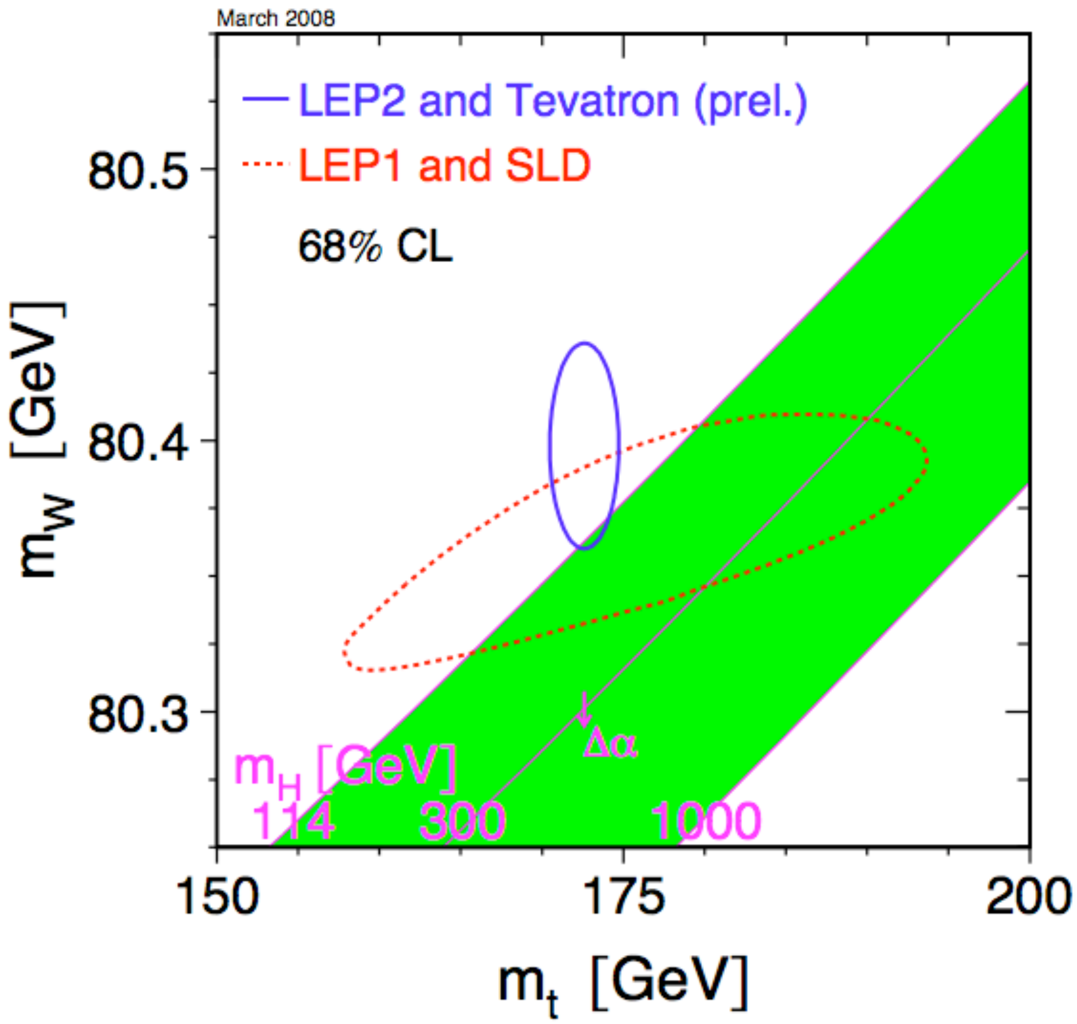

March 2008
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
Δα
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175
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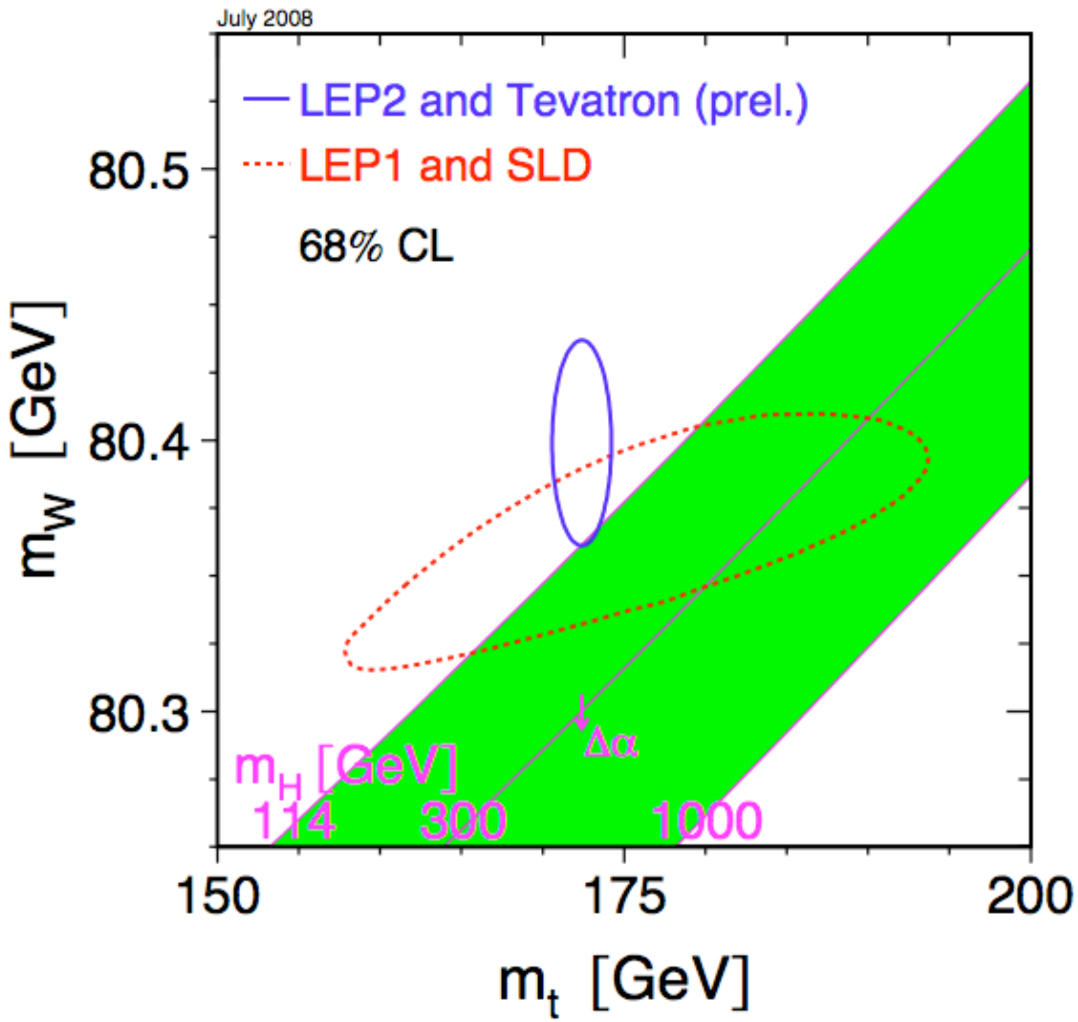
m_t [GeV]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m_W [GeV]
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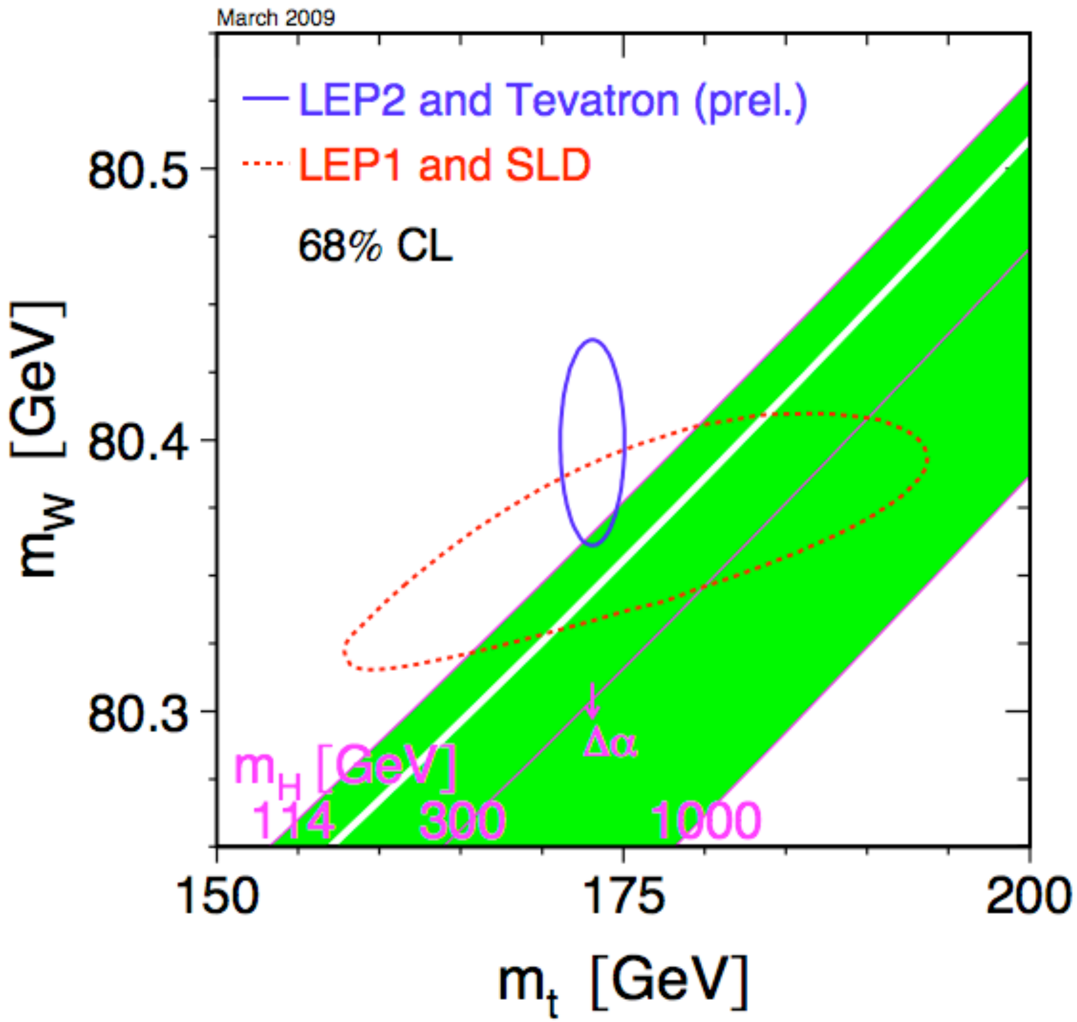
March 2009
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
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1000
Δα
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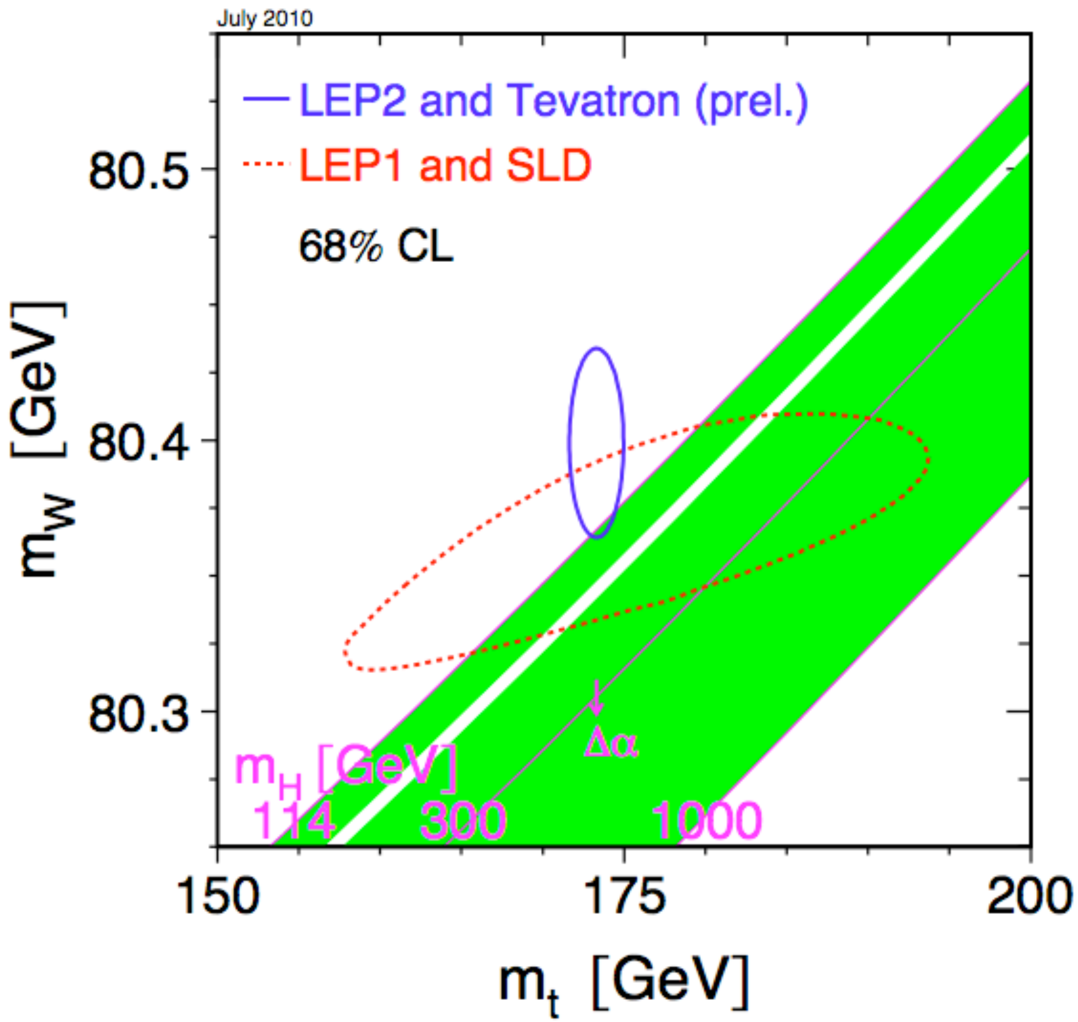
m_t [GeV]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LEP2 and Tevatron (prel.)
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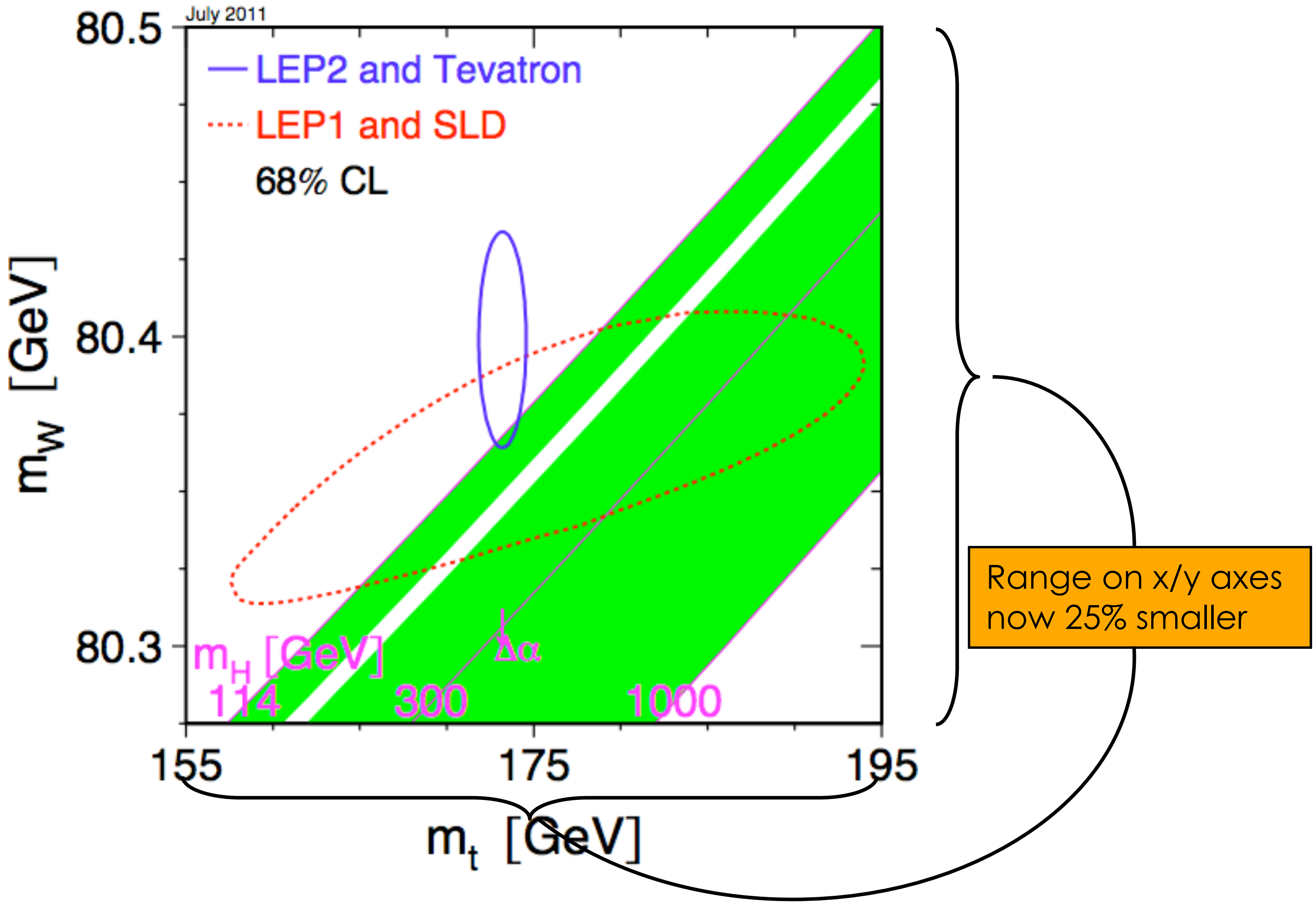
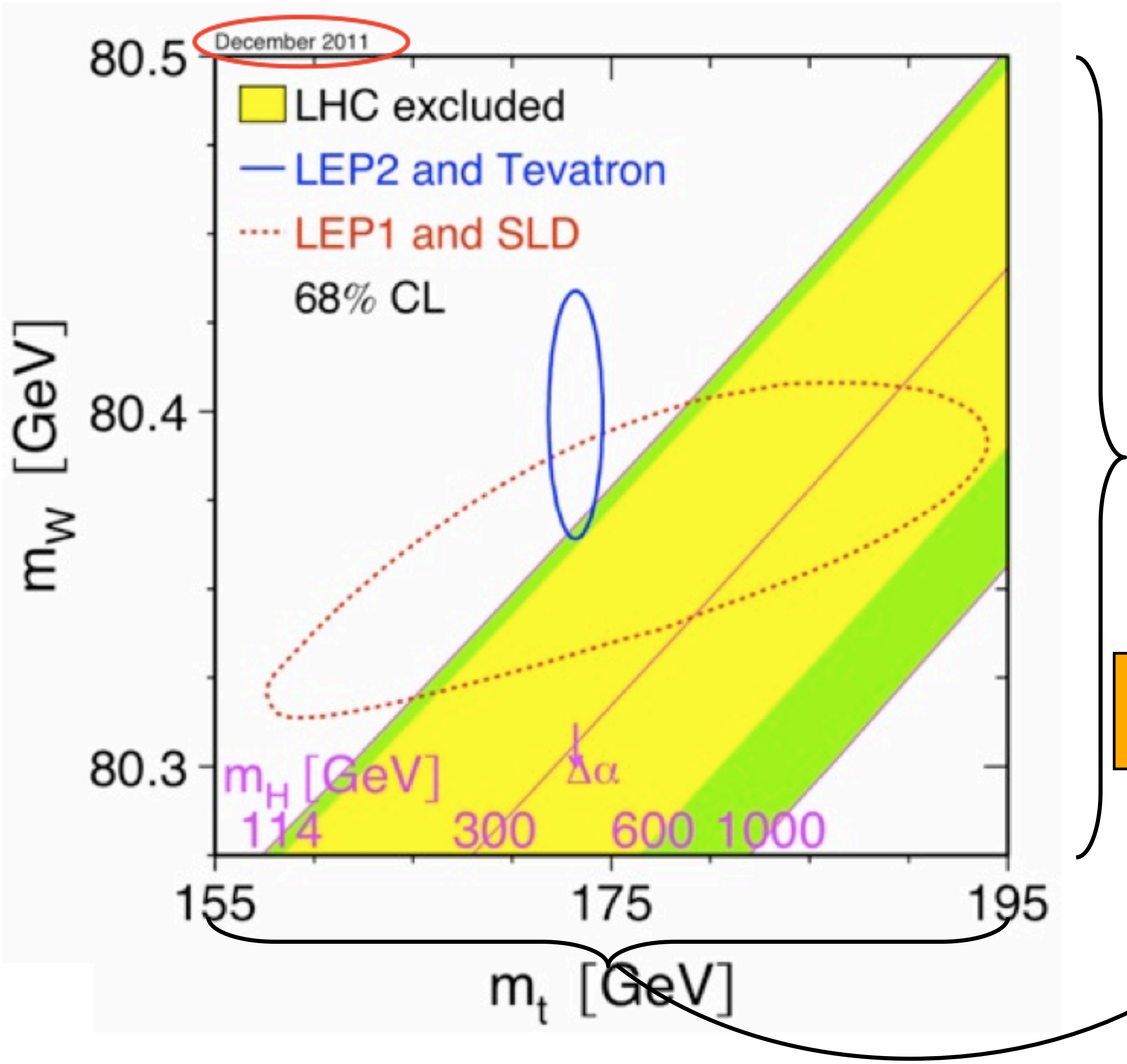
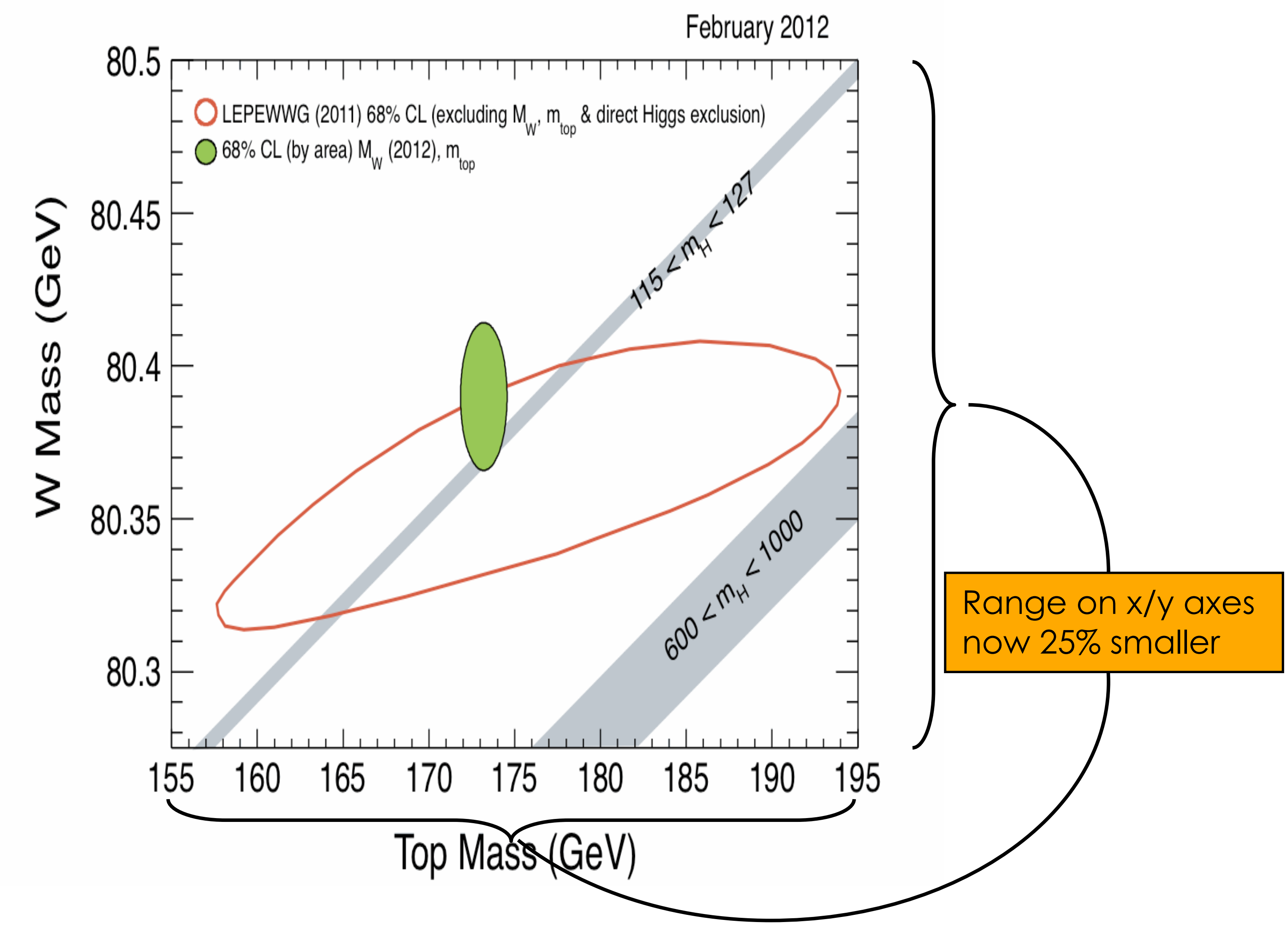
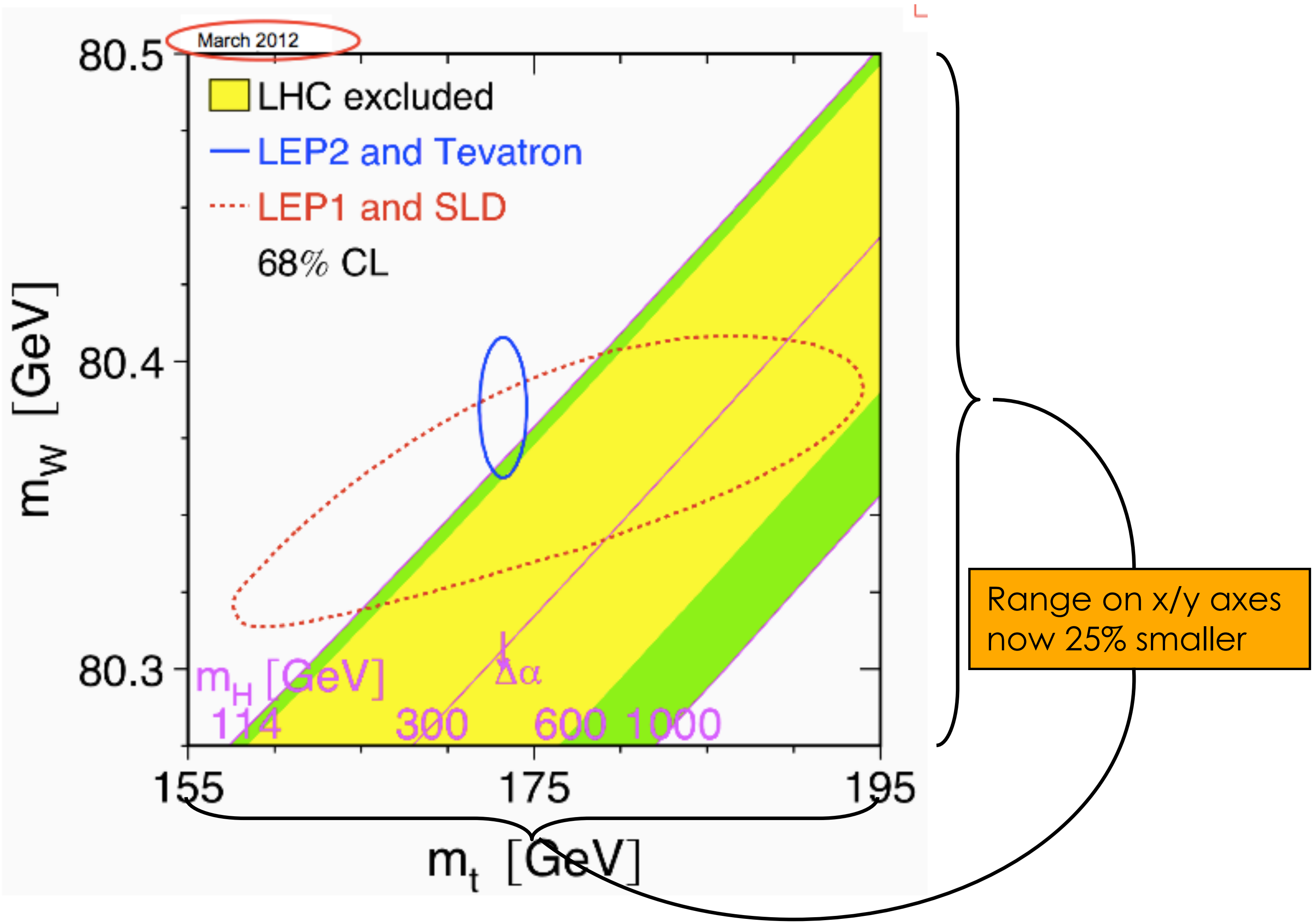

July 2011
LEP2 and Tevatron
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
Δα
155
175
195
m_t [GeV]
Range on x/y axes
now 25% smaller

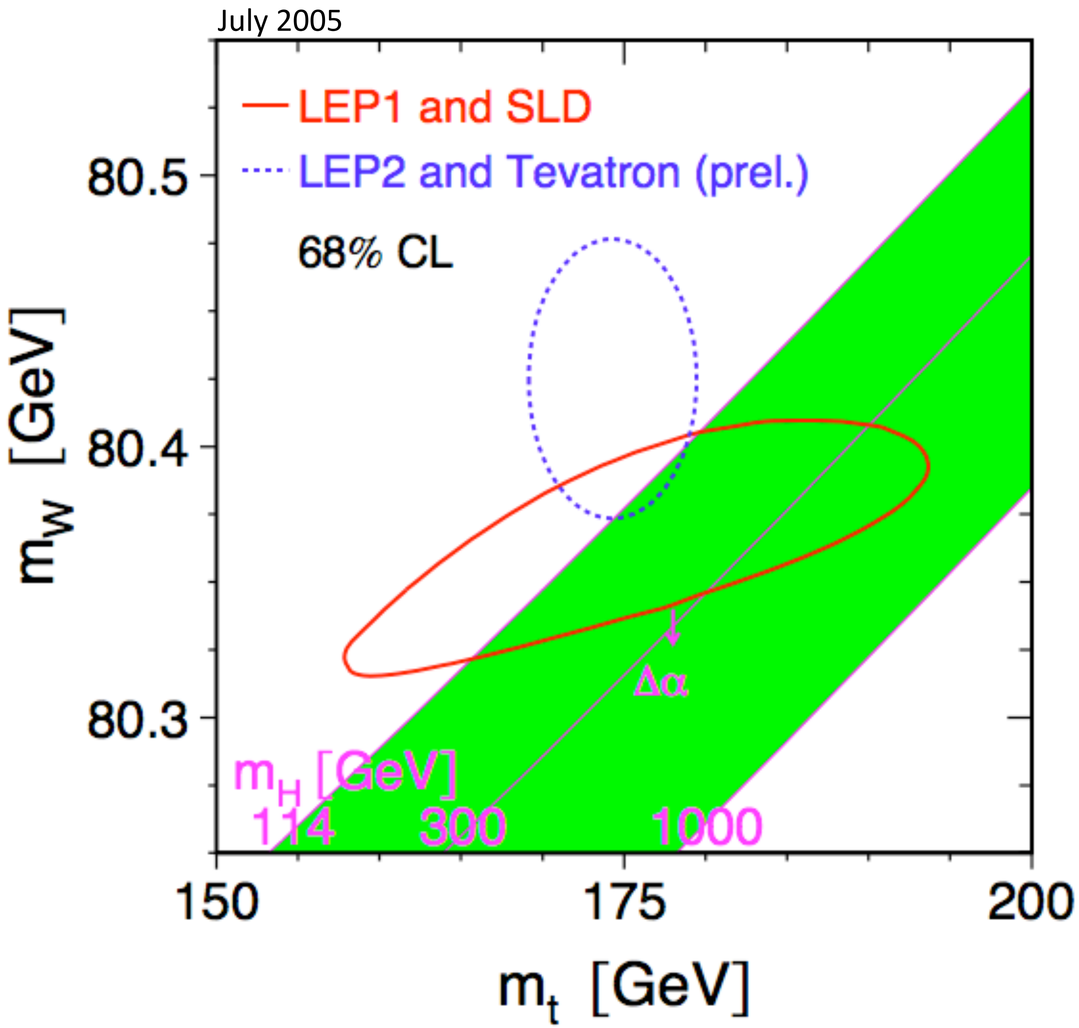


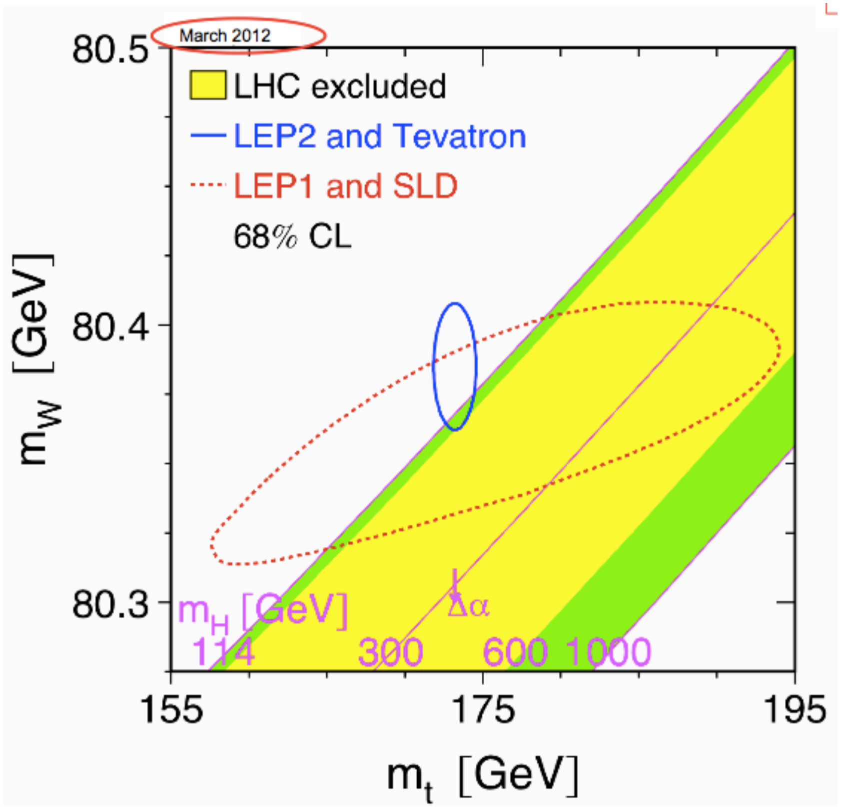
Range on x/y axes now 25% smaller


February 2012
LEPEWWG (2011) 68% CL (excluding M_W, m_{top} & direct Higgs exclusion)
68% CL (by area) M_W (2012), m_{top}
$115 < m_H < 127$
$600 < m_H < 1000$
W Mass (GeV)
80.5
80.45
80.4
80.35
80.3
155
160
165
170
175
180
185
190
195
Top Mass (GeV)
Range on x/y axes now 25% smaller



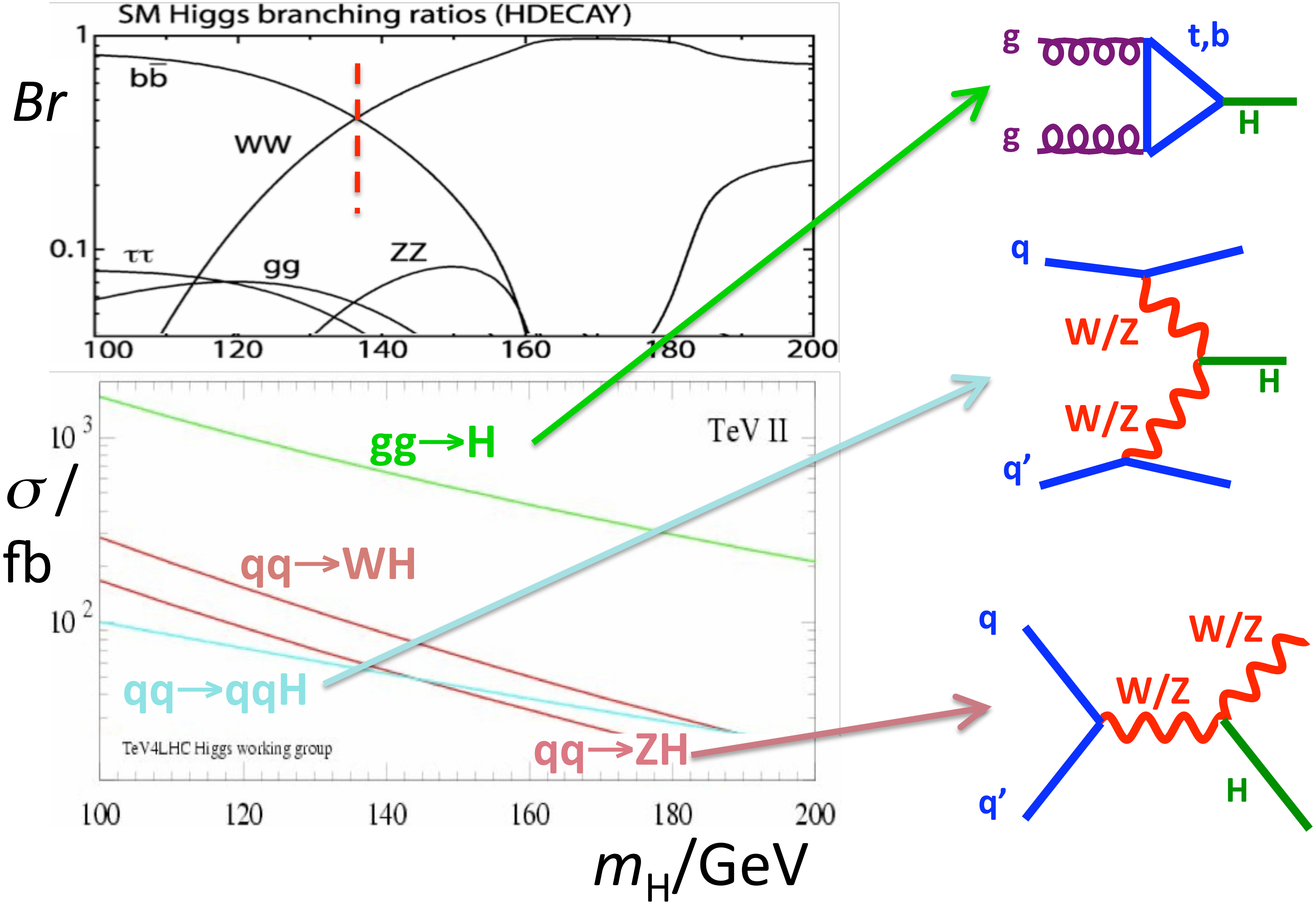
March 2012
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
600 1000
Δα
155
175
195
m_t [GeV]
Range on x/y axes now 25% smaller





m_H<152 GeV at 95% CL (indirect)

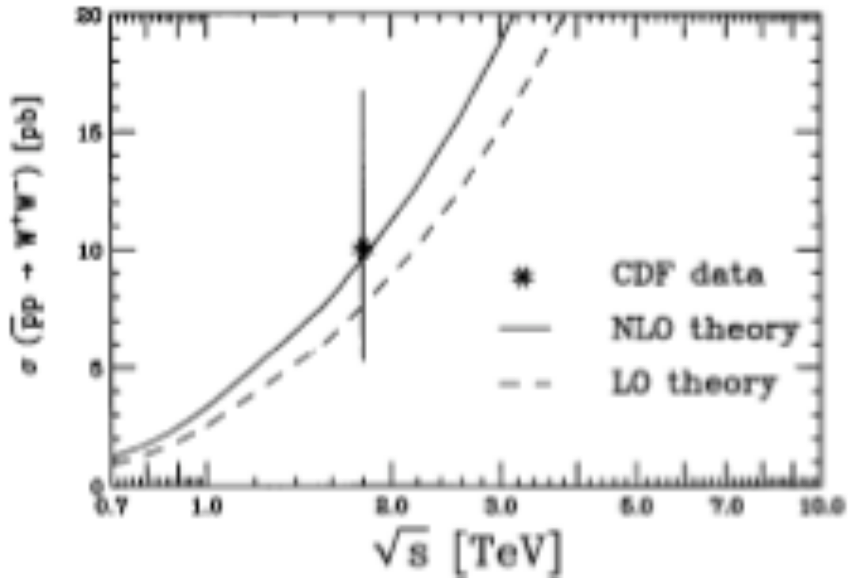
SM Higgs searches

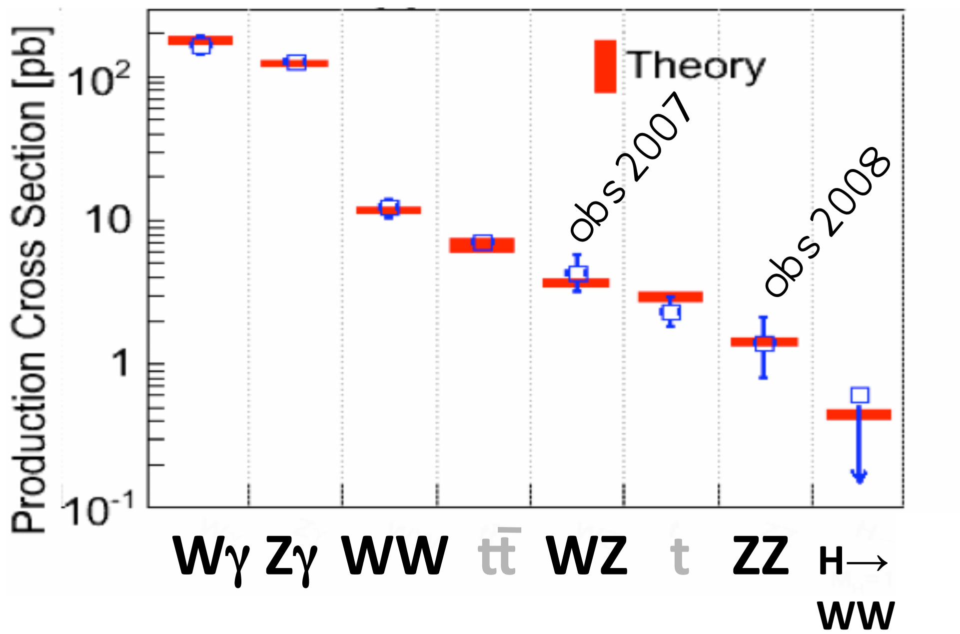


Single experiment sensitivity
Feb 2012, M_H=125 GeV

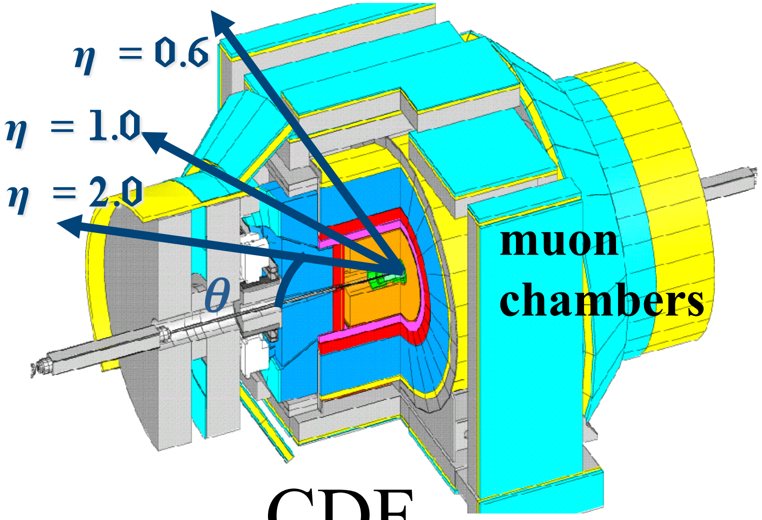
	CDF, D0	Atlas, CMS
$H \to \gamma\gamma$	10-13xSM	1.5-2xSM
$H \to WW$	~3.5xSM	1-2xSM
$H \to bb$	~2xSM	~3.5xSM

Tevatron Run 1:
Heavy diboson production:
only WW observed,
5 events above 1.2 expected bck

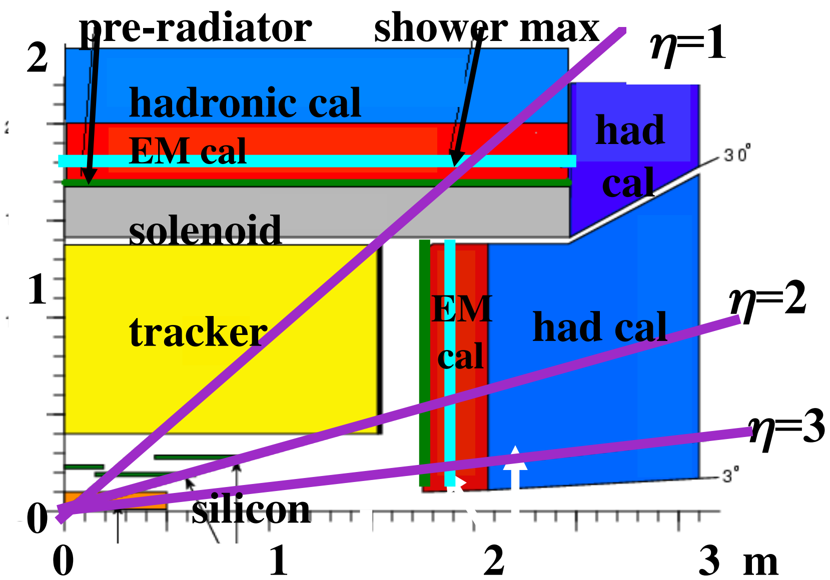


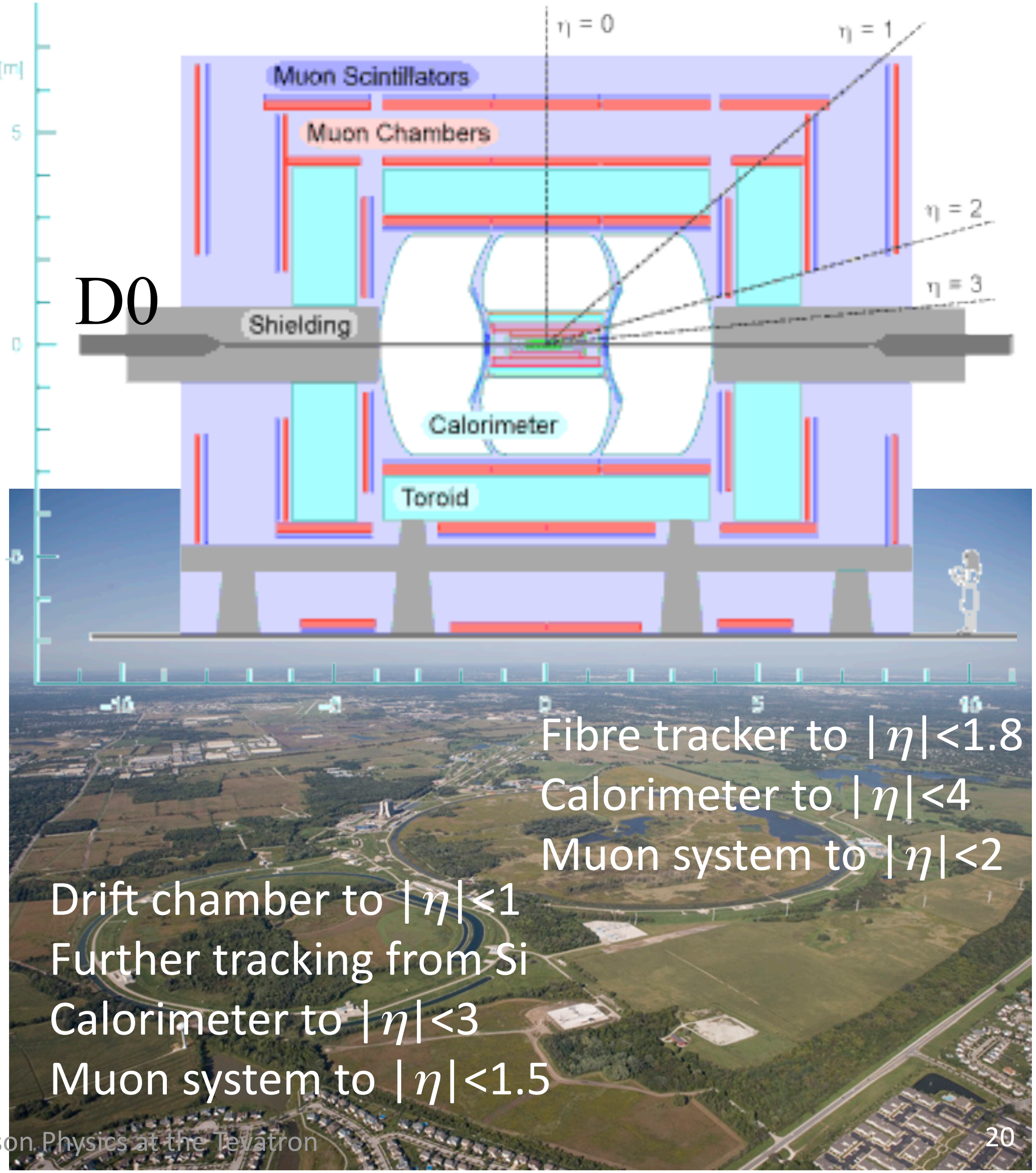


Tevatron



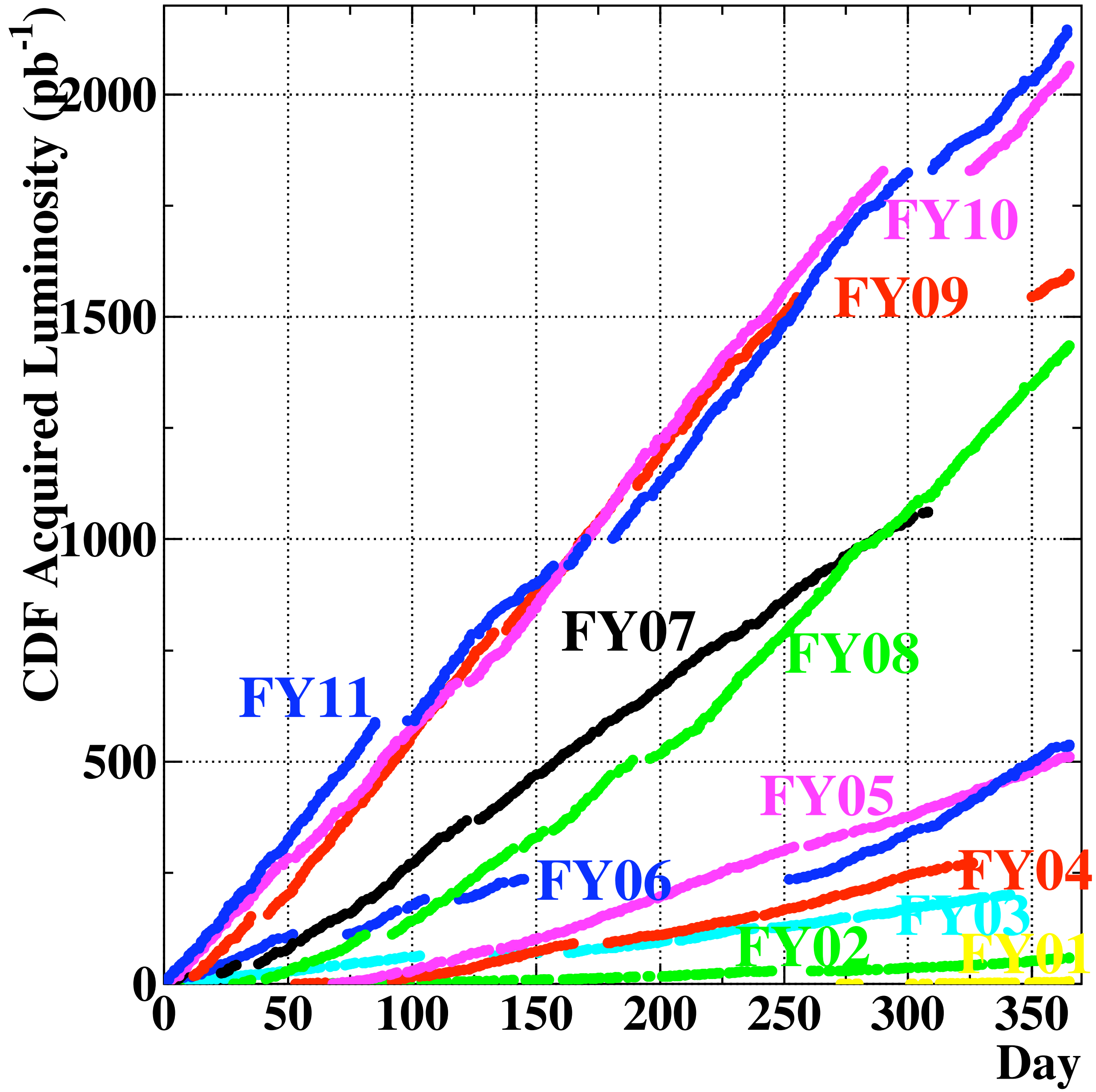
CDF



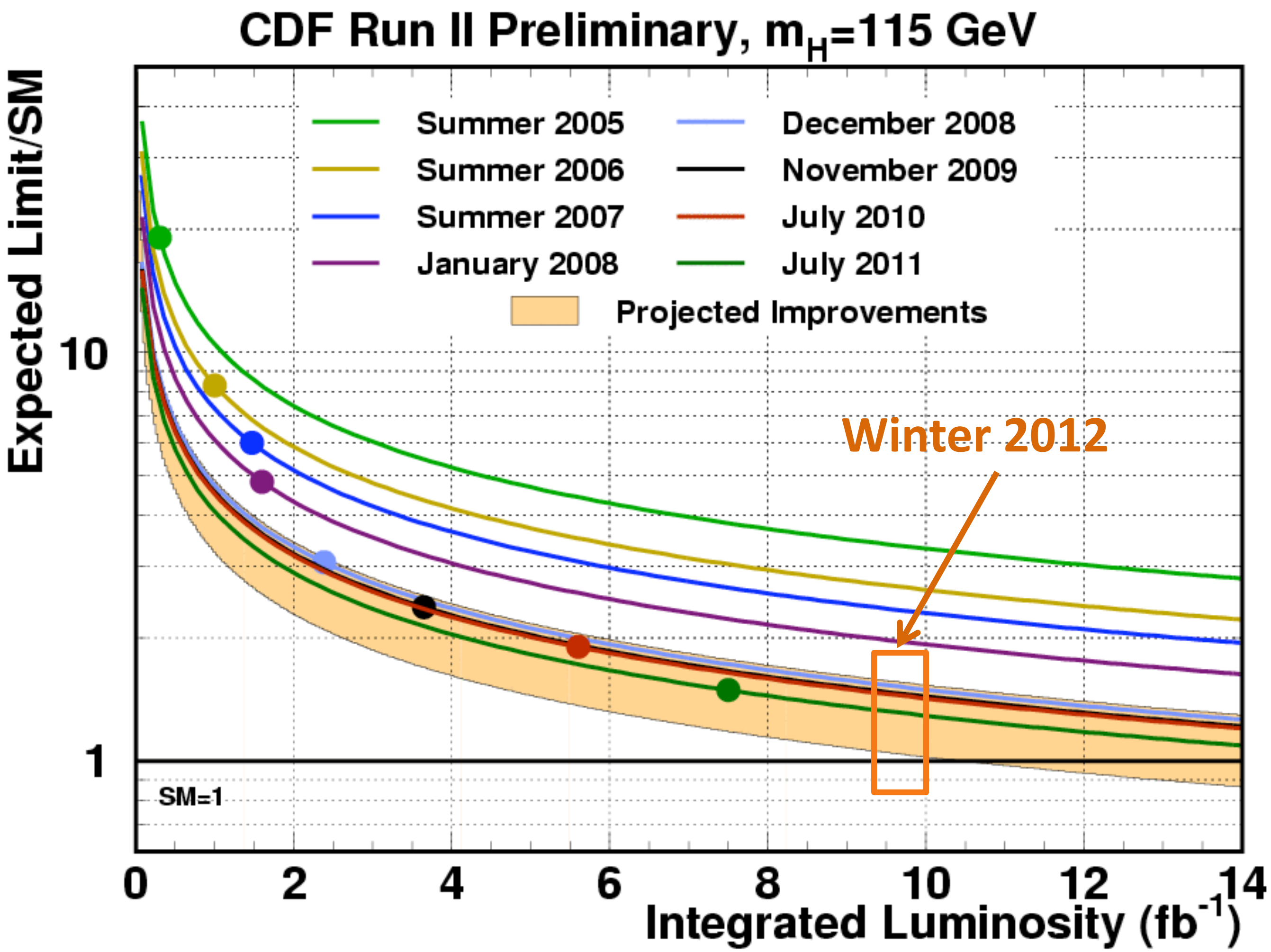


Fibre tracker to $|\eta|<1.8$
Calorimeter to $|\eta|<4$
Muon system to $|\eta|<2$

Drift chamber to $|\eta|<1$
Further tracking from Si
Calorimeter to $|\eta|<3$
Muon system to $|\eta|<1.5$


CDF Acquired Luminosity (pb^{-1})
0
500
1000
1500
2000
0
50
100
150
200
250
300
350
Day
FY11
FY10
FY09
FY08
FY07
FY06
FY05
FY04
FY03
FY02
FY01

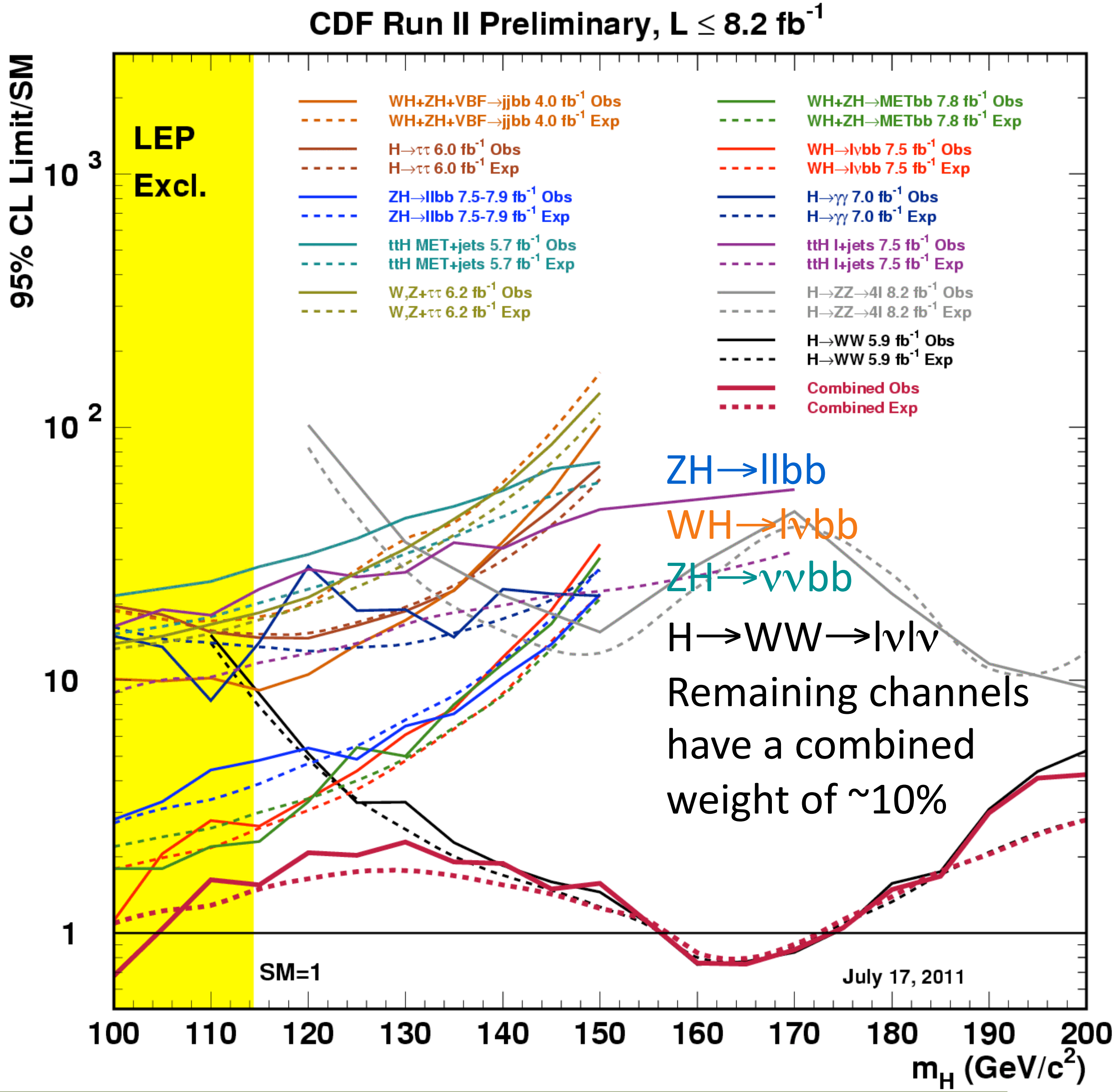
Sensitivity Projections



Maximize signal acceptance

Model all signal and background processes well

Use multivariate analysis (MVA) to exploit all kinematic differences



Expect 167 SM Higgs events (reconstructed and selected) and ~200,000 events from SM backgrounds for m_H=125 GeV/c^2

Improvements since summer 2011

25% more luminosity

- Most recent data
- Use every last pb^{-1} of data with component specific quality requirements

New multivariate b-tagger optimized for $H \rightarrow bb$ jets

- ~20% more acceptance

Additional triggers and leptons

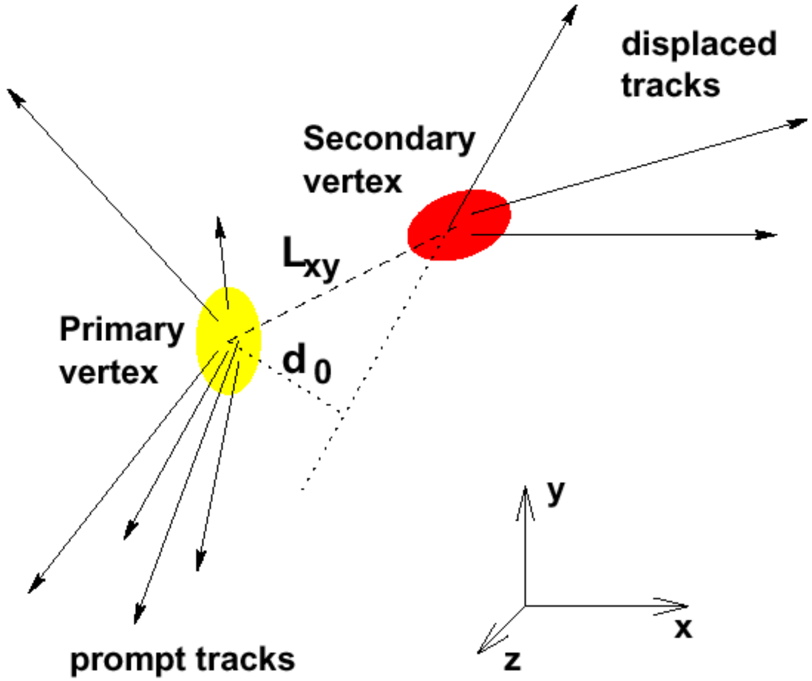
Improved dijet invariant mass resolution

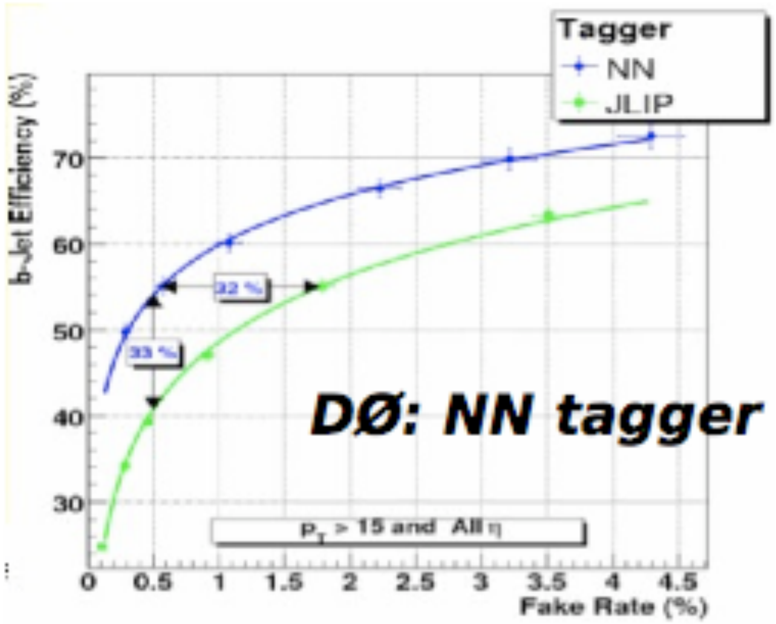
Improved MVA

Improved modeling

b-tagging

UK!





Secondary vertex-finding algorithm

Attempt to fit tracks to decay vertex

Jet probability

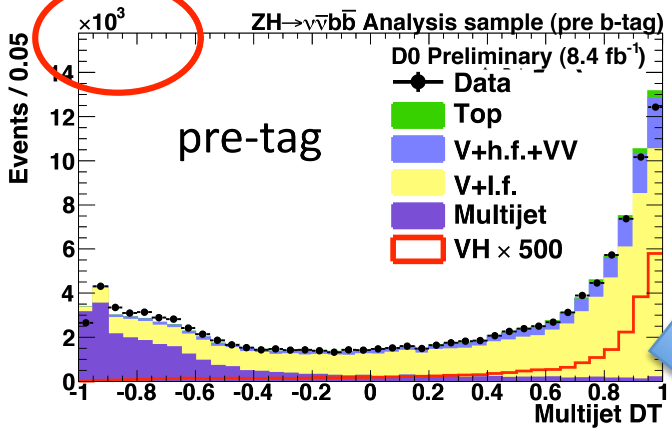
Compares track impact parameters to measured resolution functions

Neural network filters

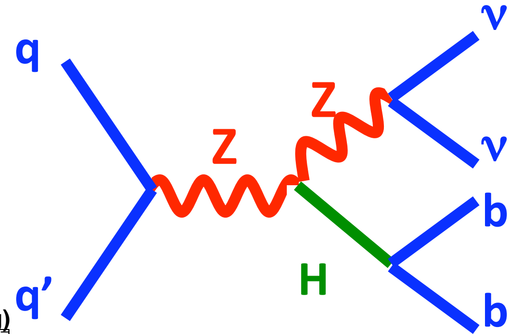
- n_{tracks} in secondary vertex
- p_T fraction carried by those tracks
- goodness of vertex fit
- vertex mass
- transverse decay length & significance
- …

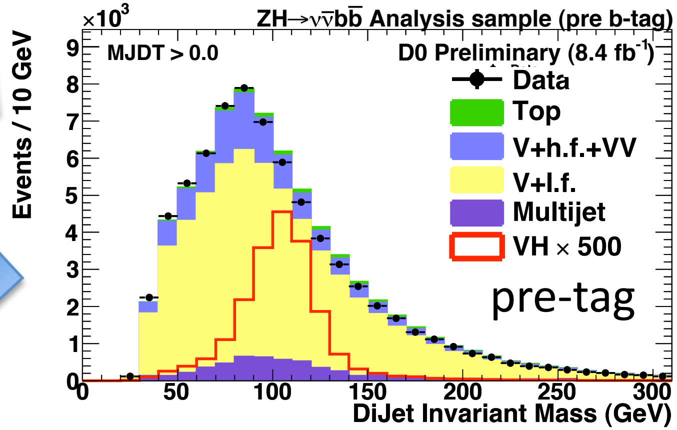
ZH → ννbb

UK!

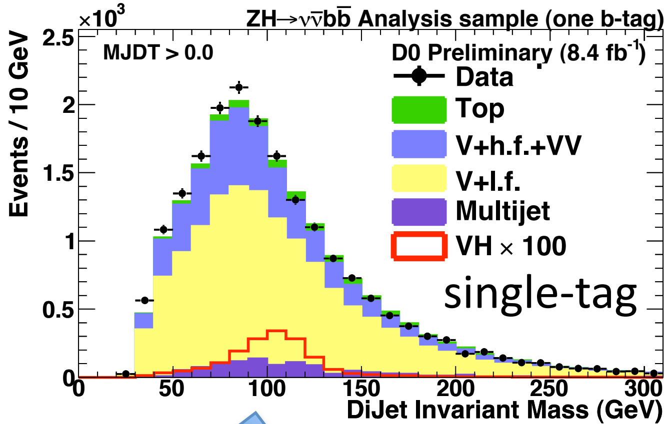


cut >0 removes 95% of the QCD background, 65% of the non-QCD background, and keeps 70% of signal

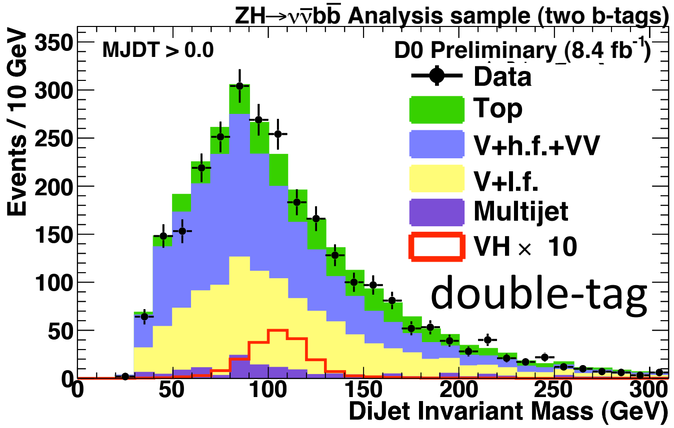


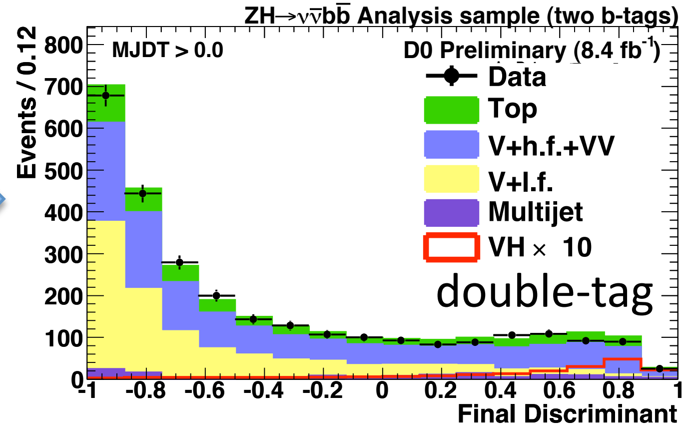


Data
Top
V+h.f.+VV
V+l.f.
Multijet
VH ×

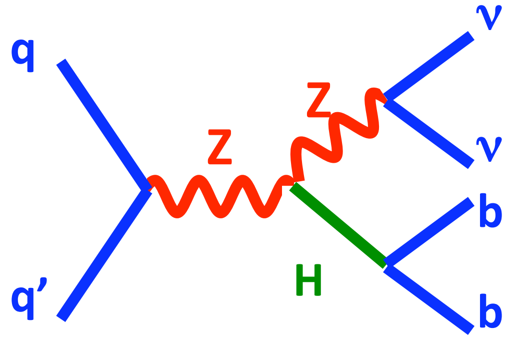


most difficult final state among most sensitive channels

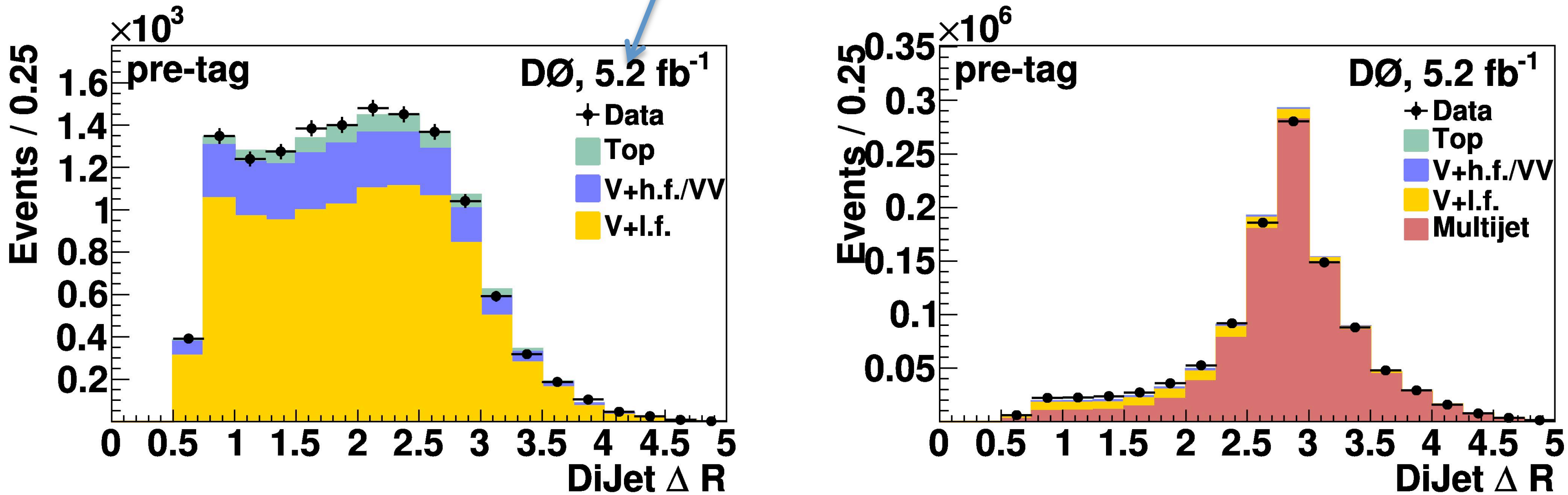




ZH → ννbb

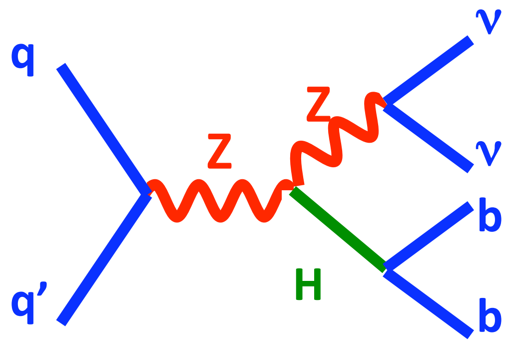


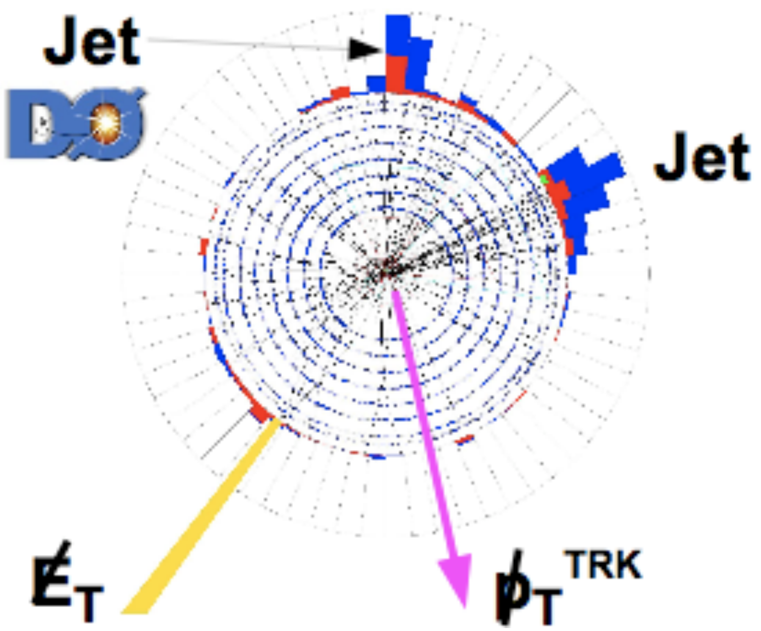
(an earlier iteration)

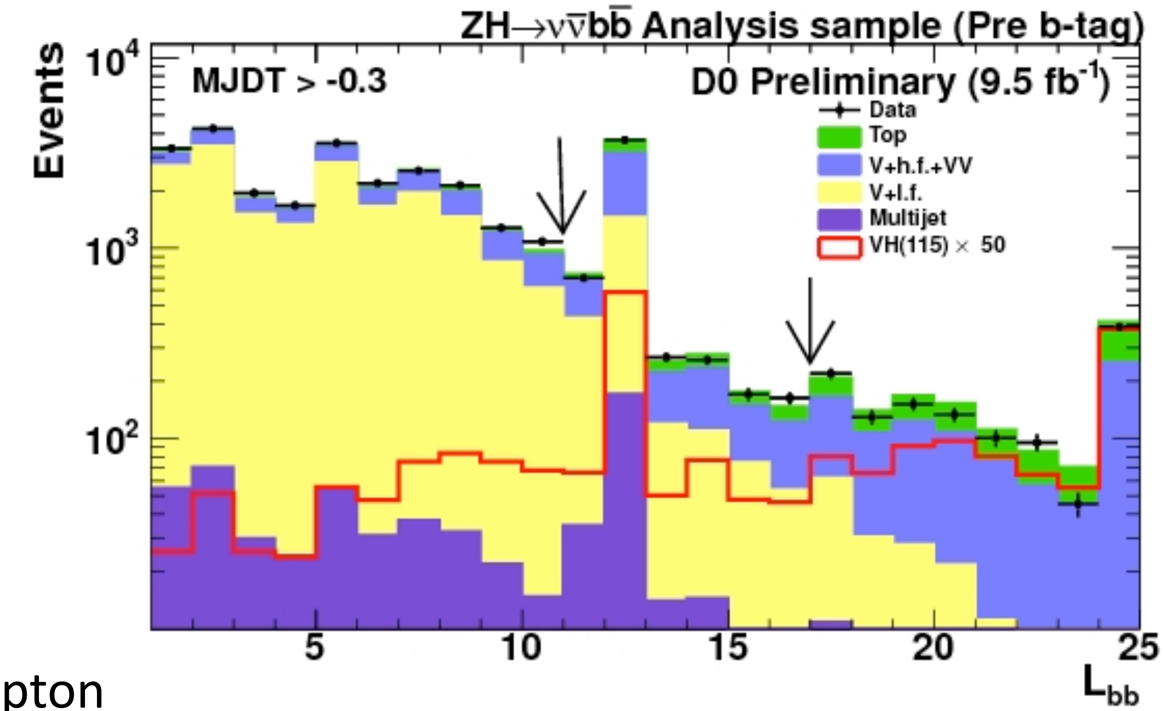


EWK and jets control regions

ZH → ννbb







50% signal is from WH with lost lepton

$\not{p}_T^{trk}$ suppresses multijet background

Now exclude isolated tracks from $\not{p}_T^{trk}$

Improves WH acceptance by 10%

Event-level b-tagging

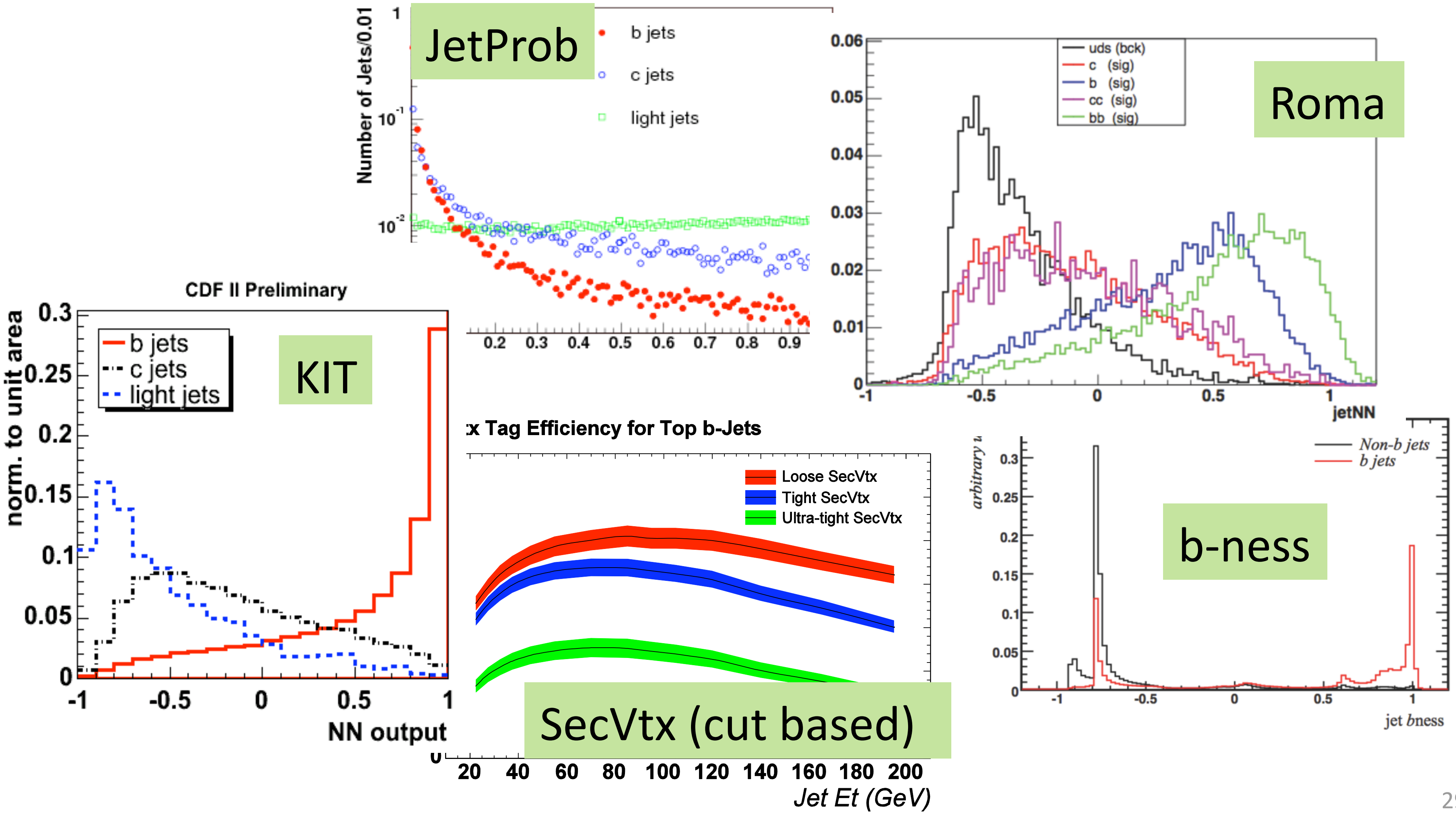
Sum b-tagger outputs for both jets

Classify according to sum

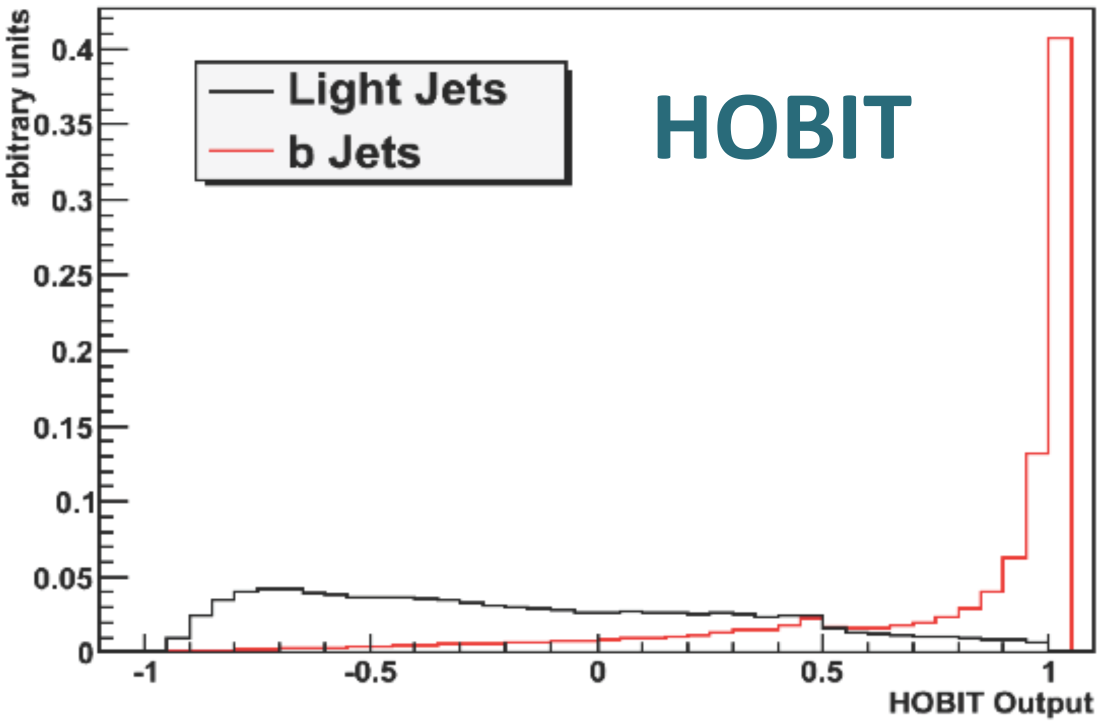
25% improvement in sensitivity (6% expected from luminosity)

Improved b-tagging

In 2010, CDF had 5 b-tagging algorithms with different strengths, weaknesses and applications

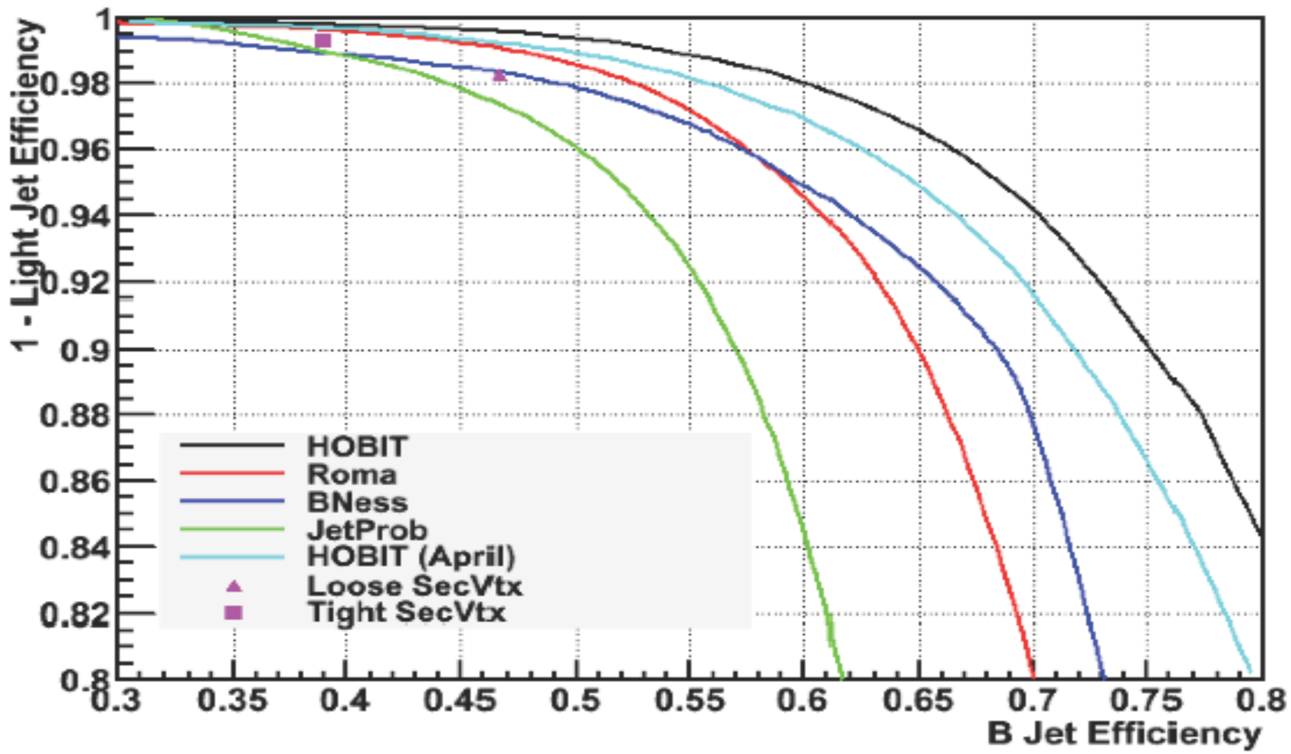


- Study of tagger performance says that we . . .
  - Need maximum acceptance
  - Can afford an increase in fake rates
- Need multiple operating points
  - allows separation of high S/B data (two “tight” tagged jets) and low S/B data (two “loose” tagged jets) into independent analysis channels



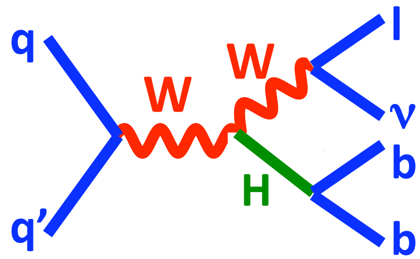
- Multivariate, continuous output
- 25 input variables
- Trained with jets from H→bb MC
- Validated with ttbar and soft electron samples

ron



mistag rate	SecVtx efficiency	HOBIT efficiency
~1%	39%	54%
~2%	47%	59%

$WH \rightarrow l\nu bb$



OLD – Multiple Taggers

Tagging Category	S/√B
SecVtx+SecVtx	0.228
SecVtx+JetProb	0.160
SecVtx+Roma	0.103
Single SecVtx	0.146
Sum	0.331

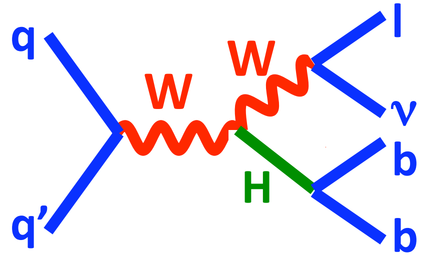
NEW - HOBIT

Tagging Category	S/√B
Tight-Tight	0.266
Tight-Loose	0.200
Single Tight	0.143
Loose-Loose	0.053
Single Loose	0.044
Sum	0.369

Significant effort to optimize tagging categories and thresholds for loose/tight HOBIT selections

11% gain in S/√B translates directly into increase in overall search sensitivity

WW/WZ → ℓνjj

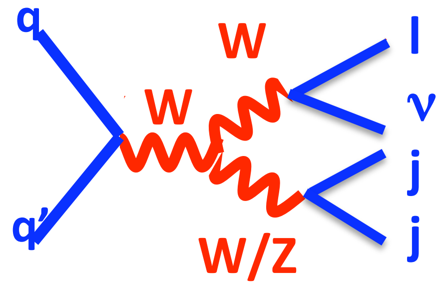


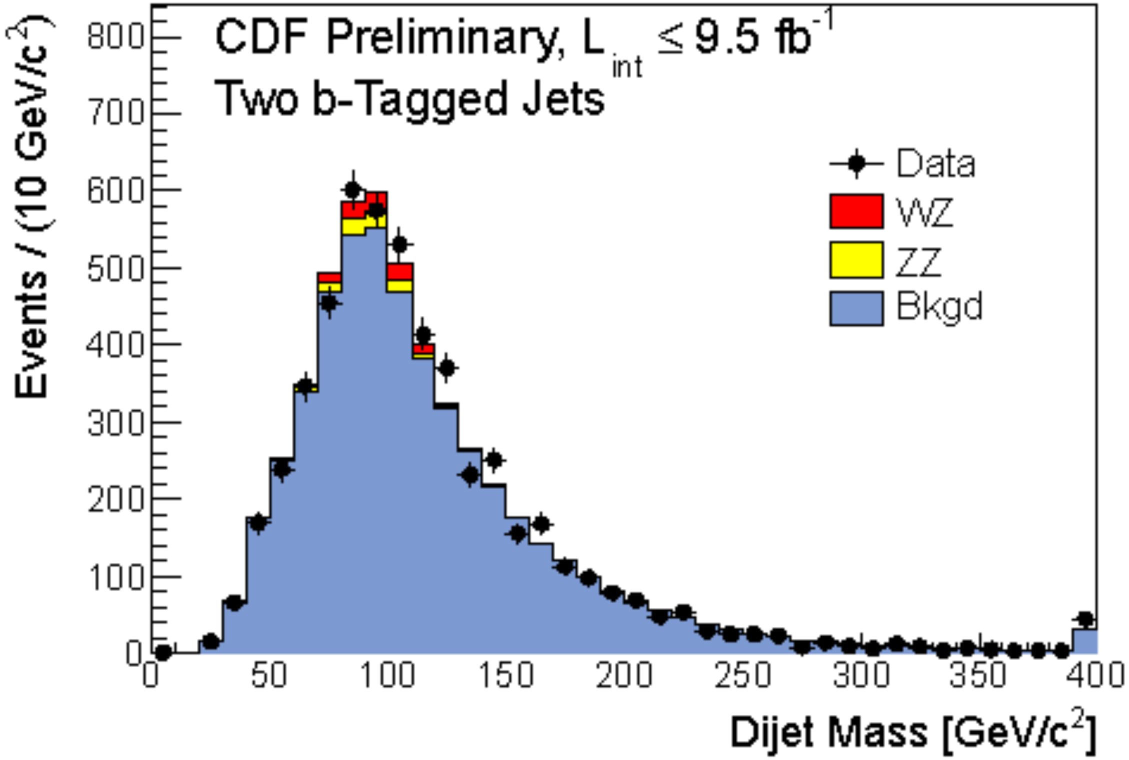
<u>Do we see WZ and ZZ events ?</u>

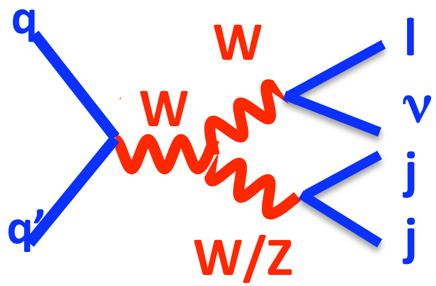
same final state

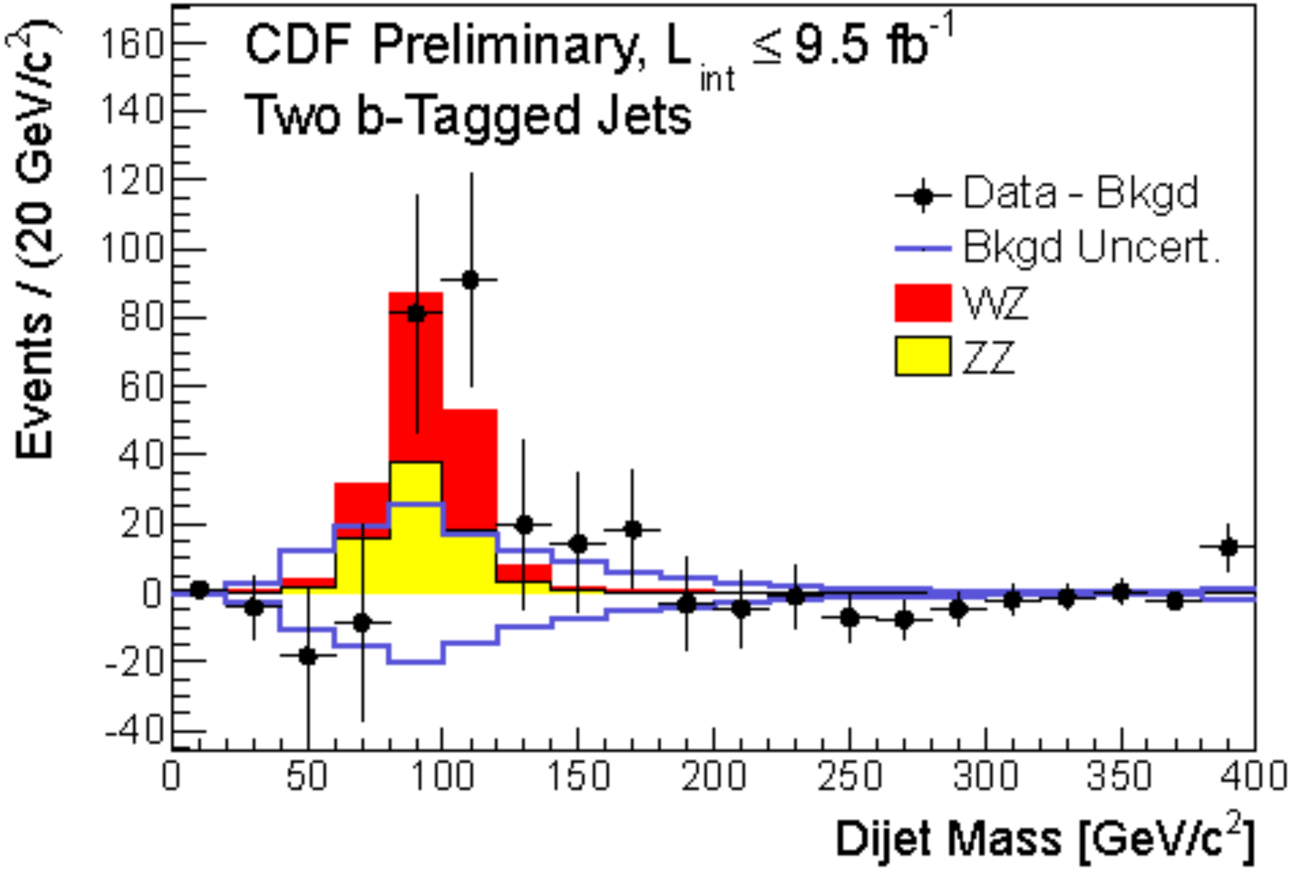
same set of tagged events

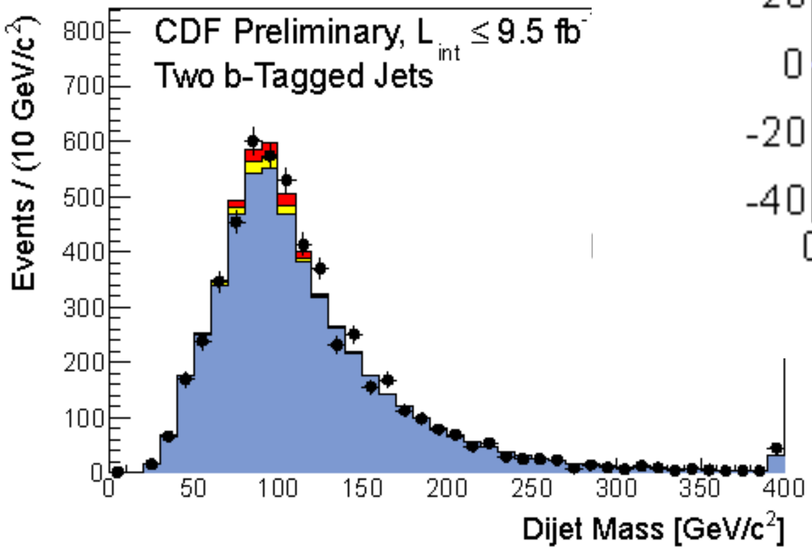
different MVA optimized for WZ and ZZ events



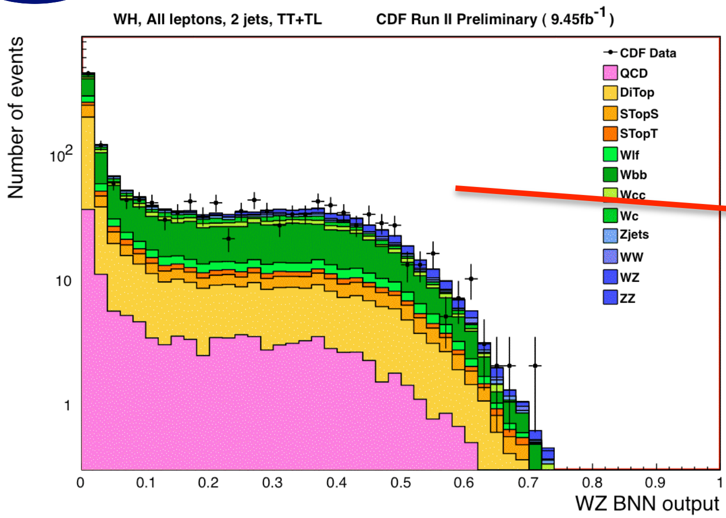



q
q'
W
W
W/Z
l
ν
j
j

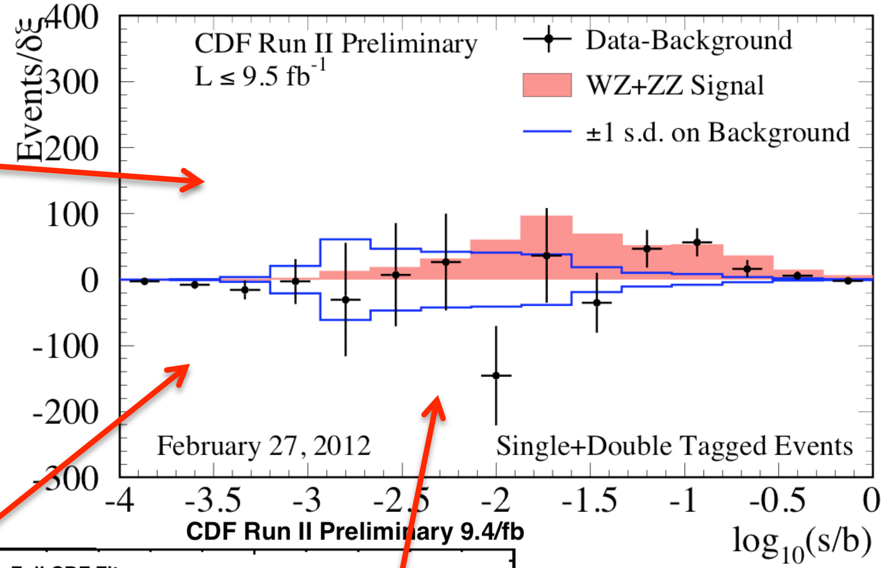

CDF Preliminary, L_int ≤ 9.5 fb^-1
Two b-Tagged Jets
Data - Bkgd
Bkgd Uncert.
WZ
ZZ
Events / (20 GeV/c^2)
Dijet Mass [GeV/c^2]

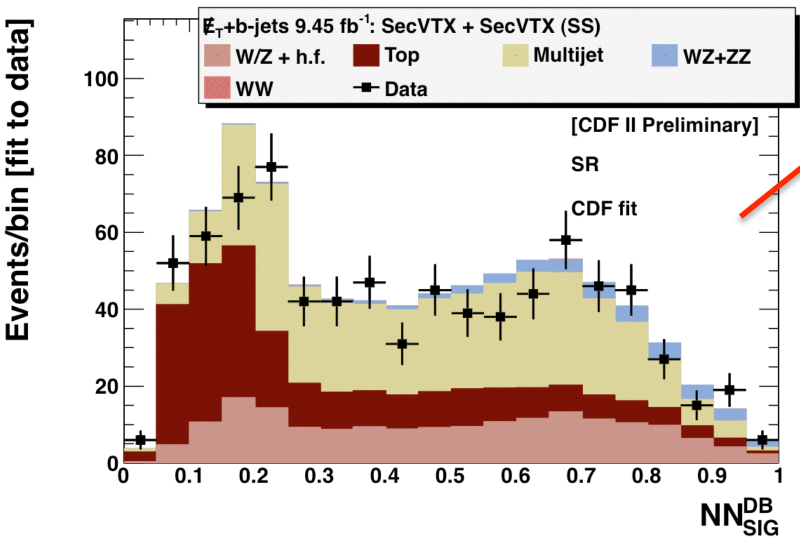

CDF Preliminary, L_int ≤ 9.5 fb
Two b-Tagged Jets
Events / (10 GeV/c^2)
Dijet Mass [GeV/c^2]

MVA-based search

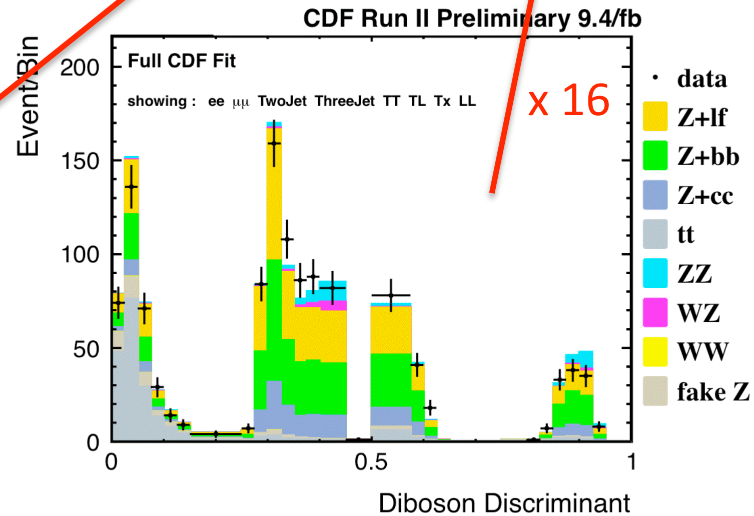


x 20





x 3

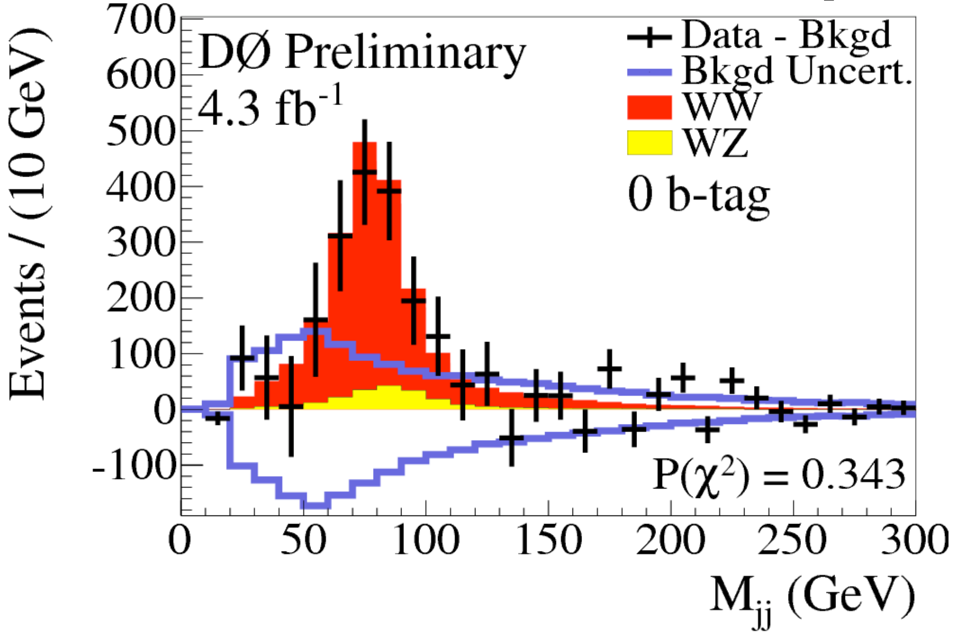


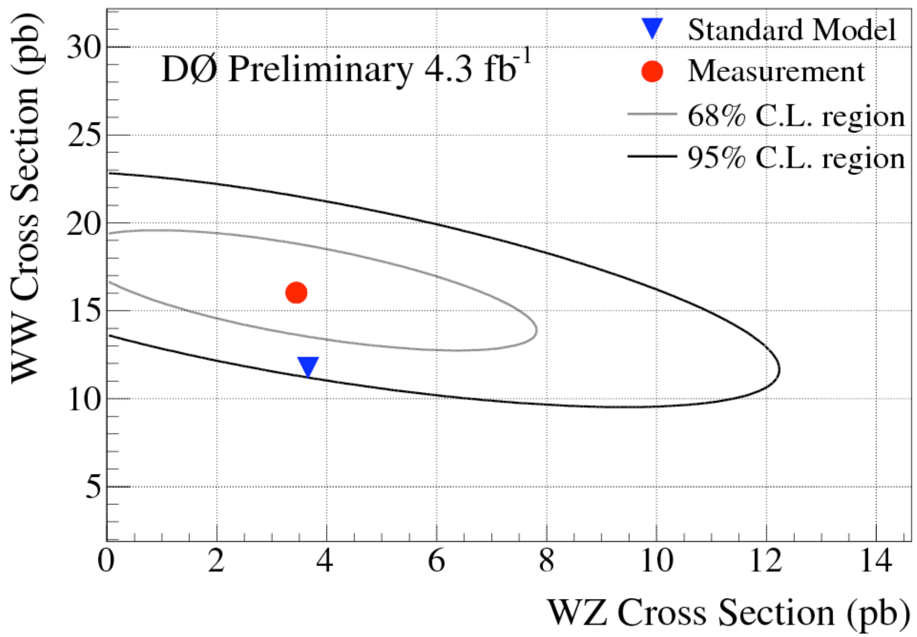
x 16

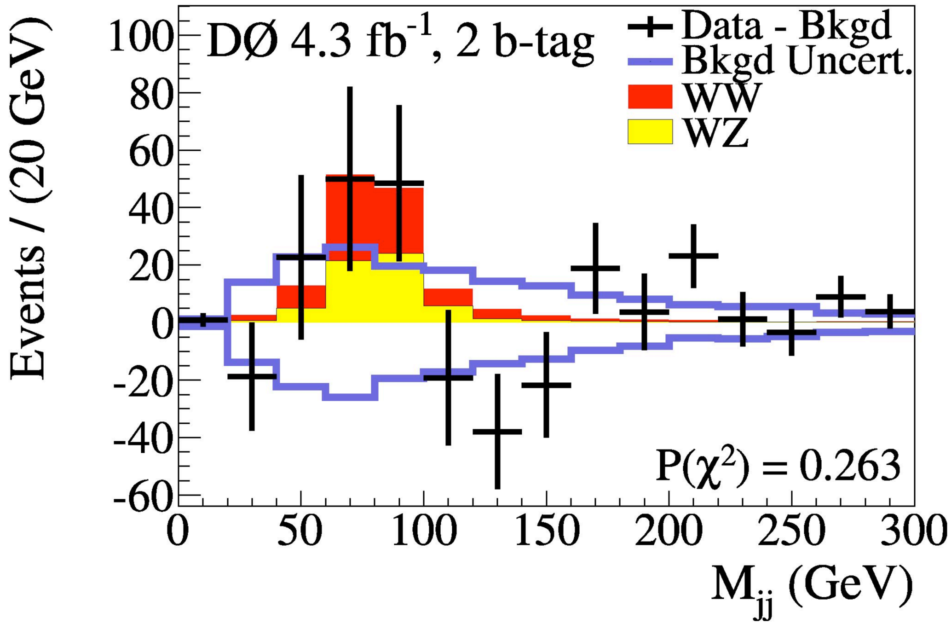
440 signal events and ~35,000 background

σ(WZ+ZZ)= 4.08 +/- 1.32 pb; ~3.2σ significance
SM Prediction = 4.4 +/- 0.3 pb

WW/WZ → ℓνjj



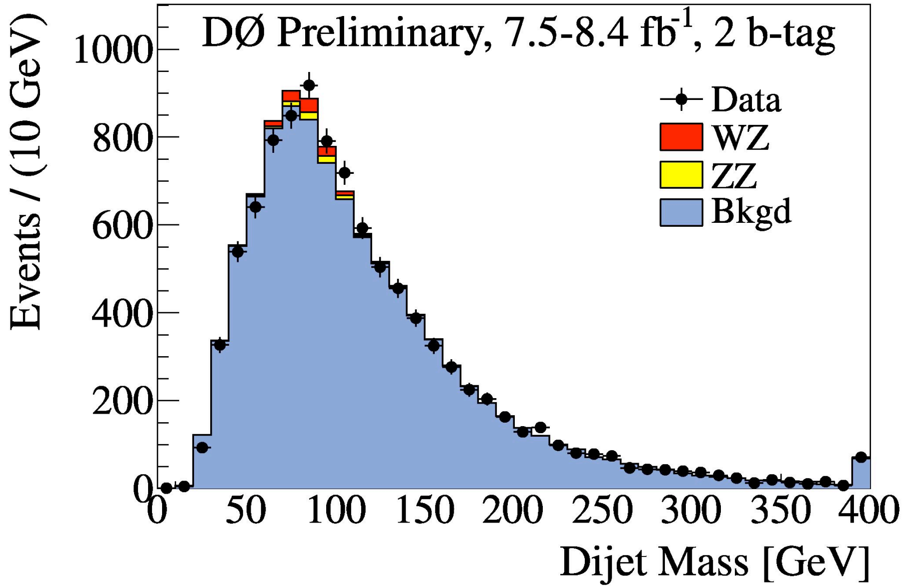


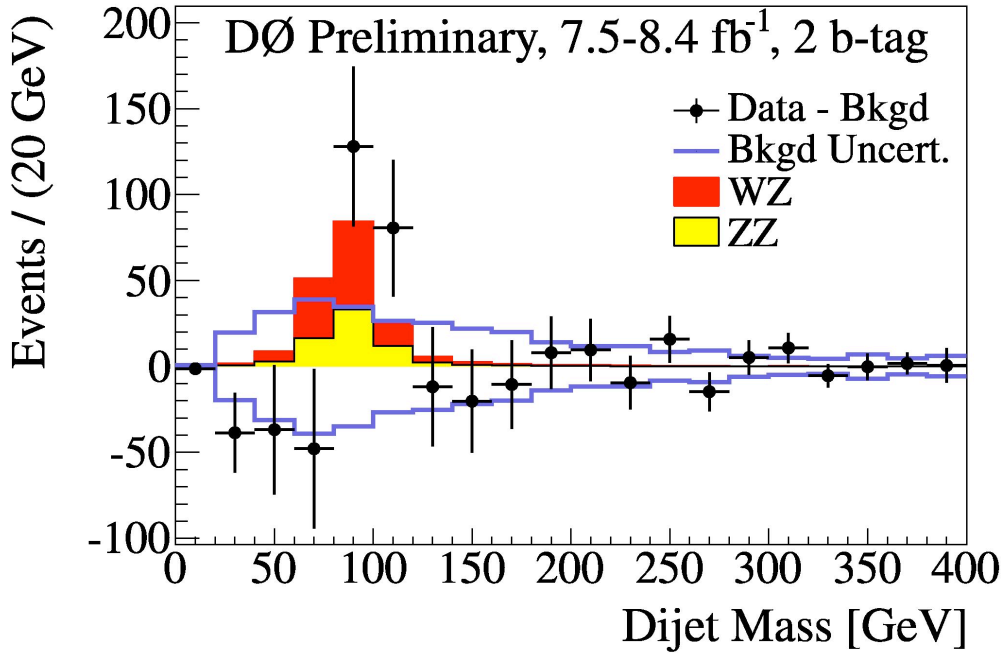


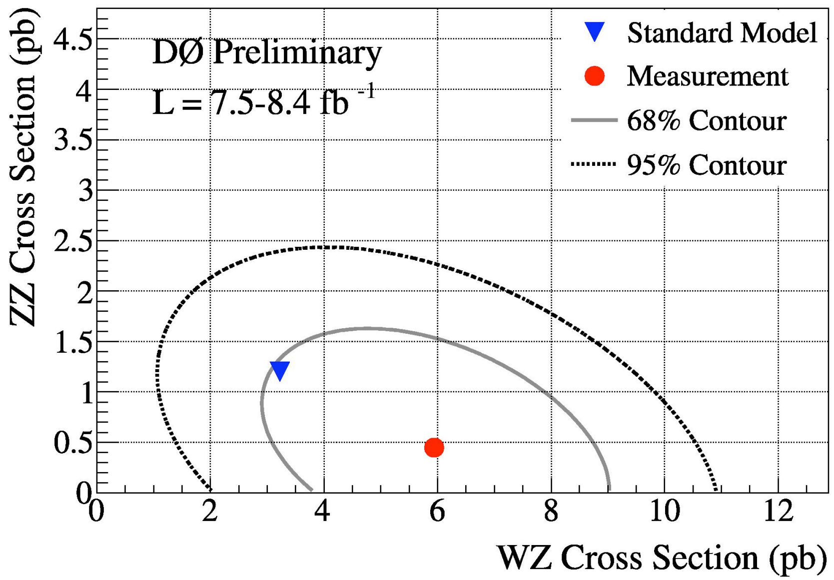
σ(WW+WZ)
= 19.6 $^{+3.1}_{-3.0}$ pb

8σ significance

WZ/ZZ → Xbb







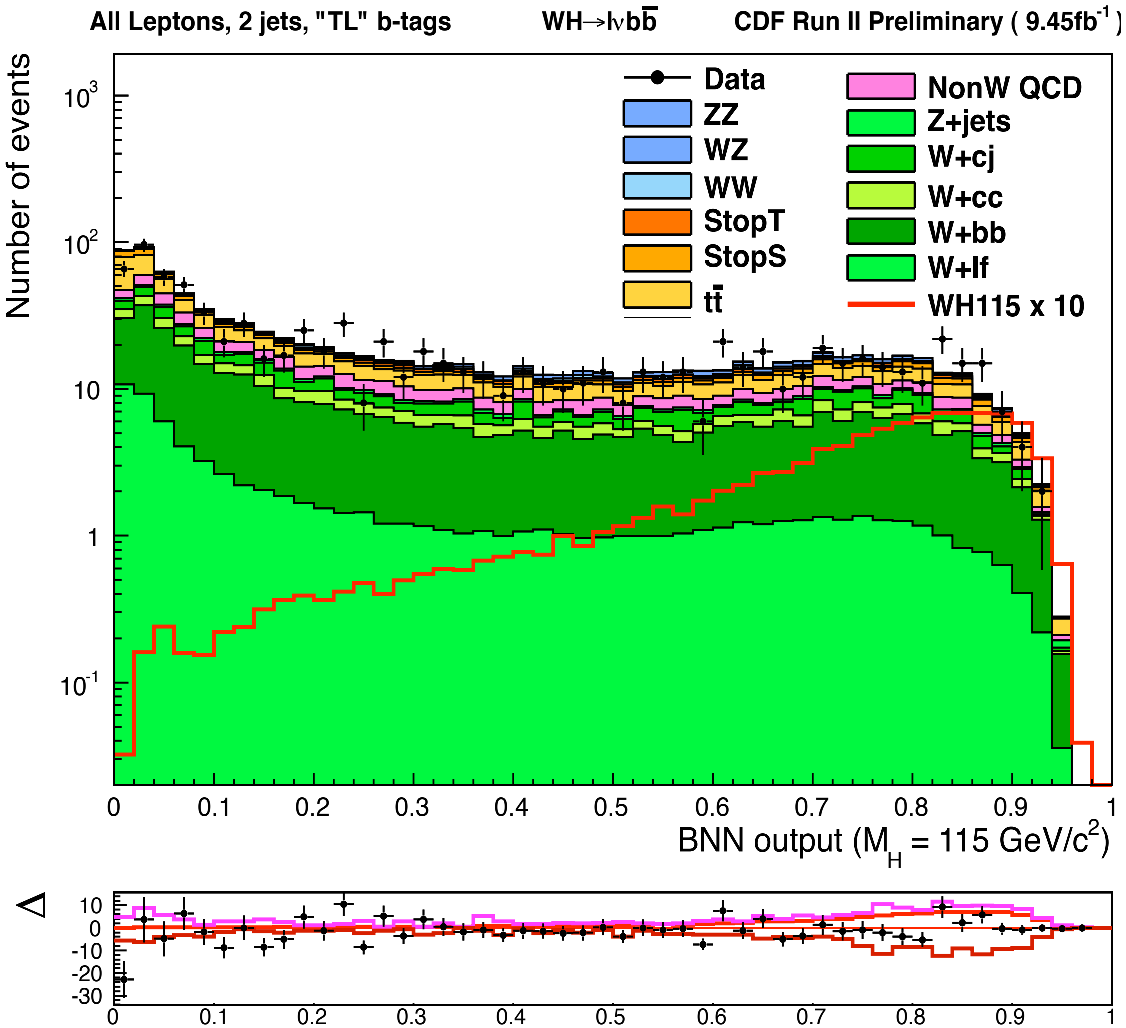
σ(WZ+ZZ)
= 5.0 ± 1.0 ± 1.3 pb

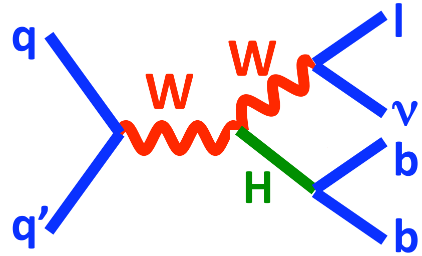
3.3σ significance

Theory: 4.4 ± 0.3 pb

WH → $l\nu bb$

Key issue: estimating W+bb background
Fraction from MC applied to data. Mistags from inclusive jets.



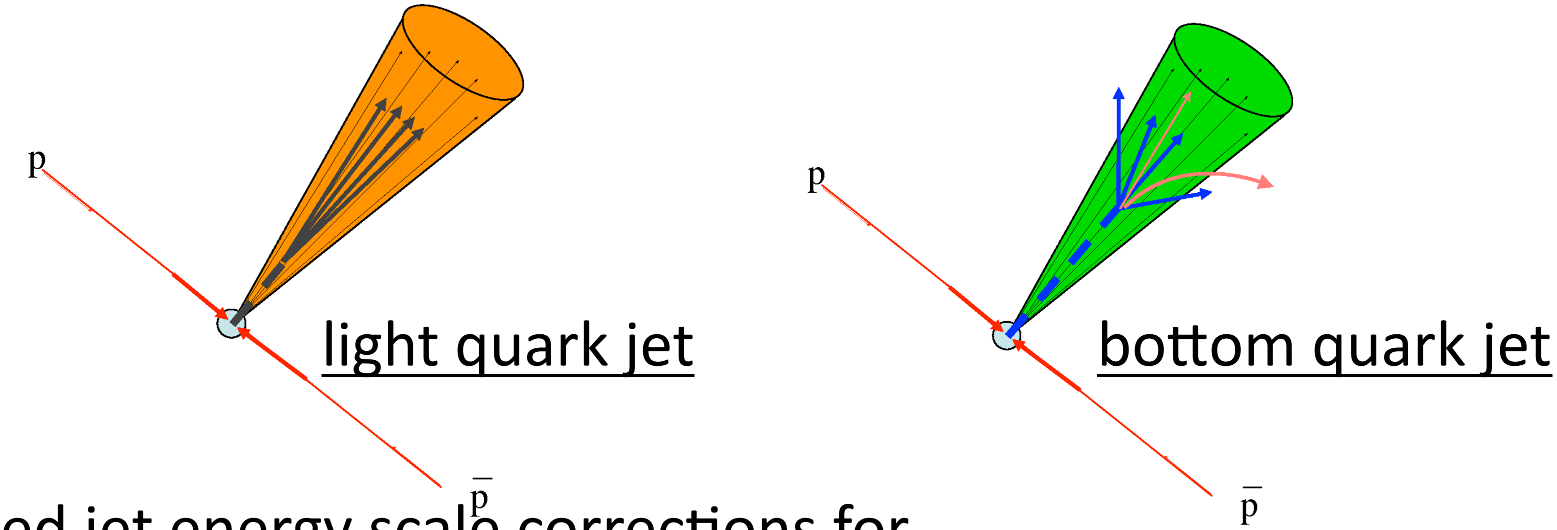


Results at mH = 115GeV: 95%CL Limits/SM

Higgs Events	Exp. Limit	Obs. Limit
31	1.97	3.13

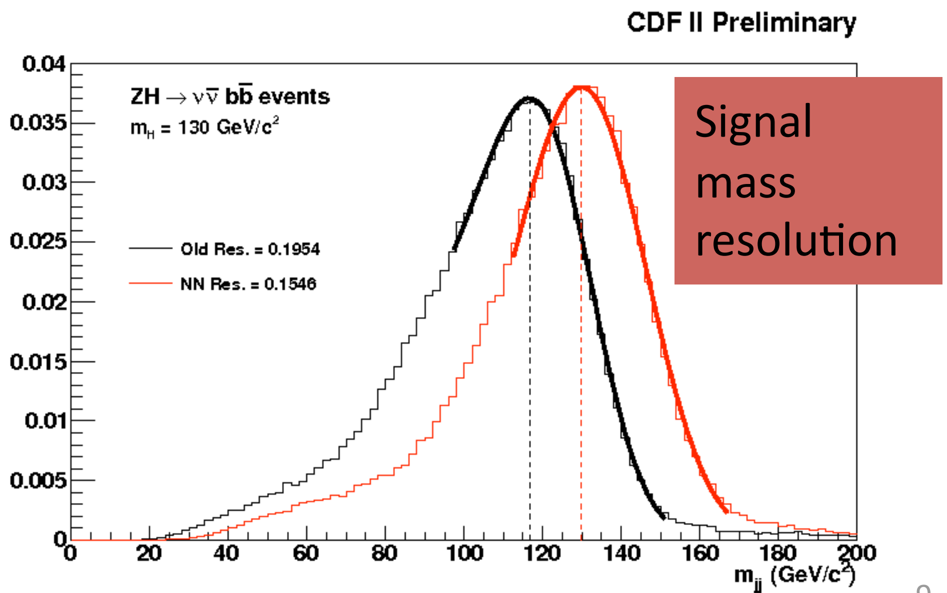
World's most sensitive low-mass Higgs search

Jet resolution improvements

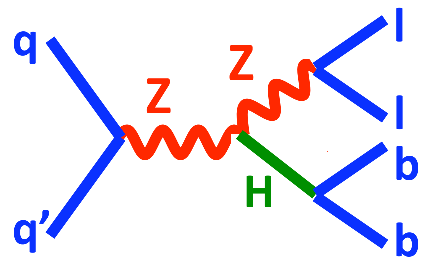


Specialized jet energy scale corrections for bottom quark jets improve dijet invariant mass and MET measurements

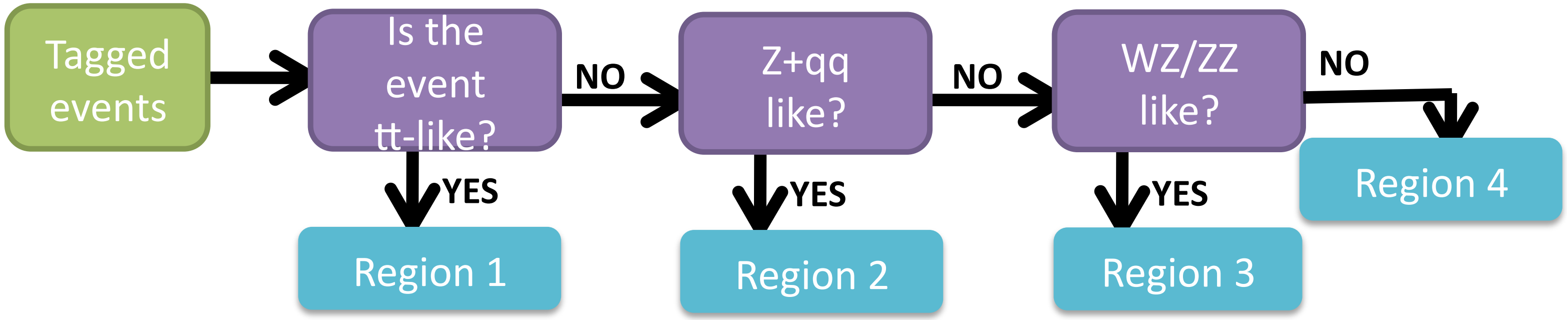
- Neural network correlates all jet-related variables and returns most probable jet energy based on bottom quark hypothesis – better signal/background separation

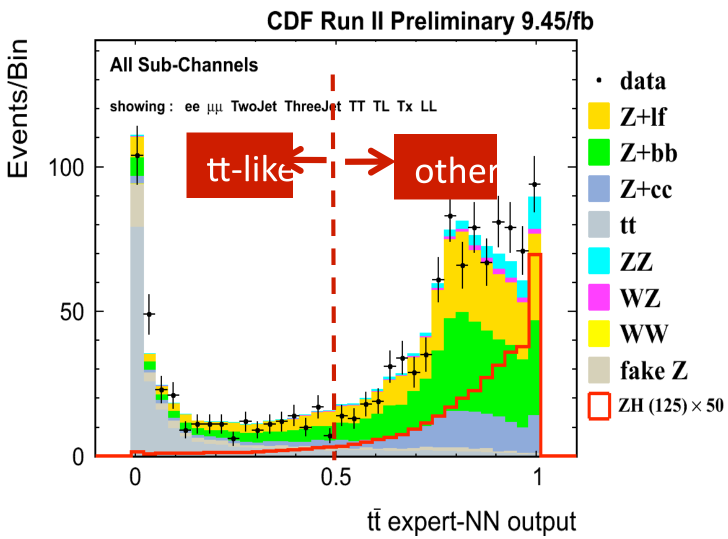


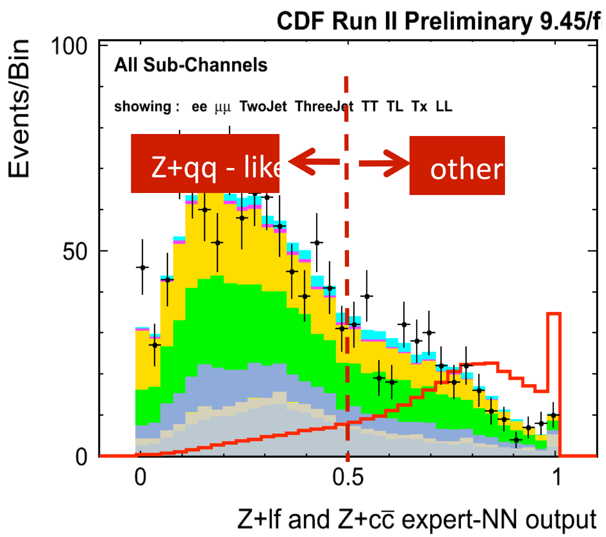
MVA improvements

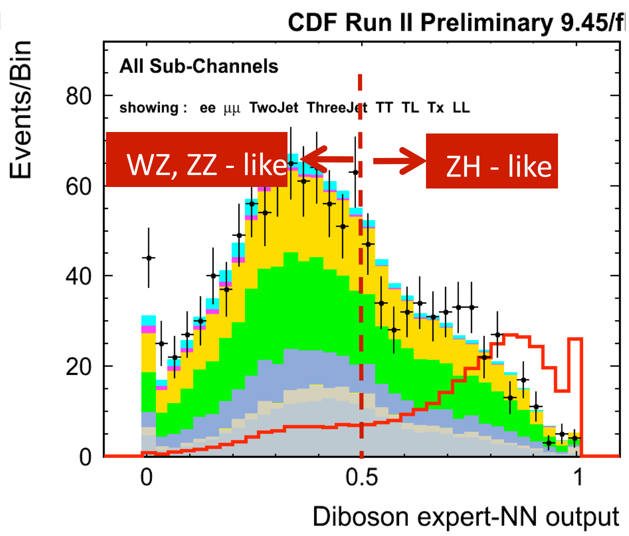


Small MVA improvements in many channels, eg ZH→llbb

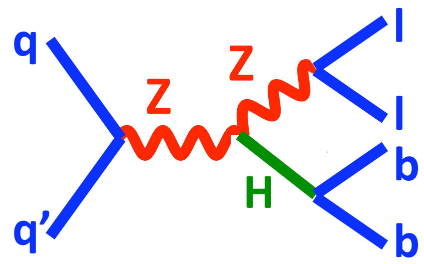


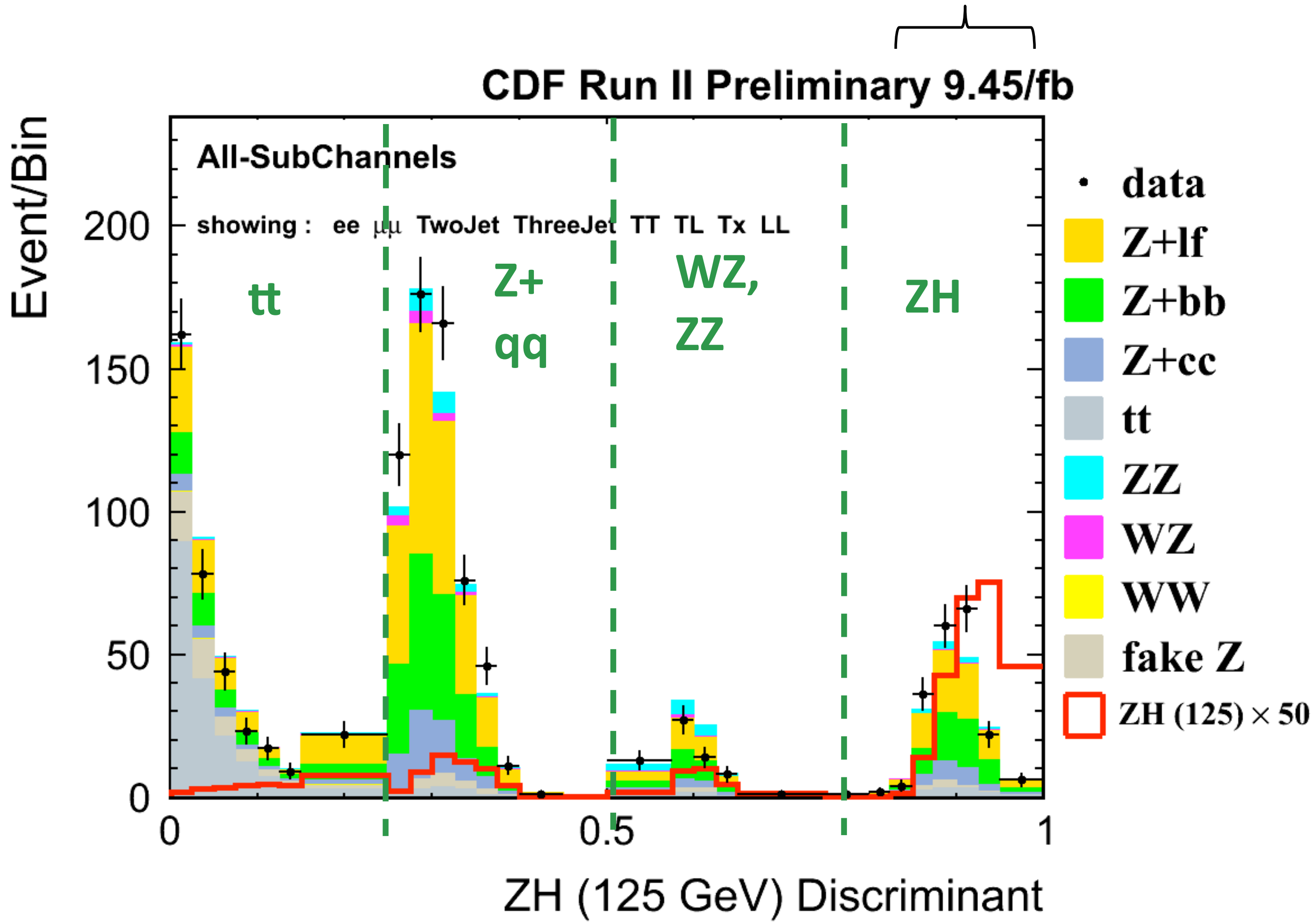




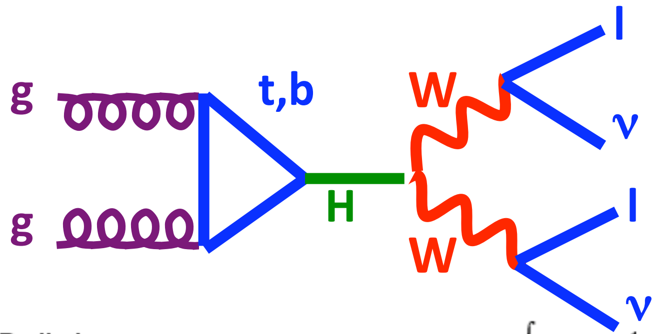


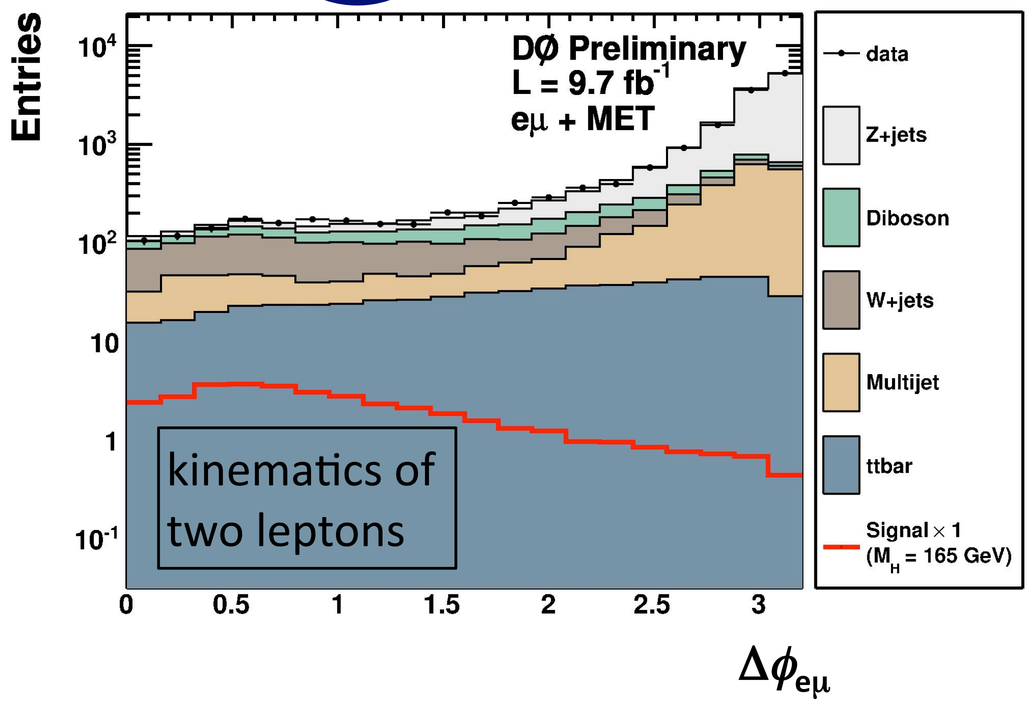
Events shuffled

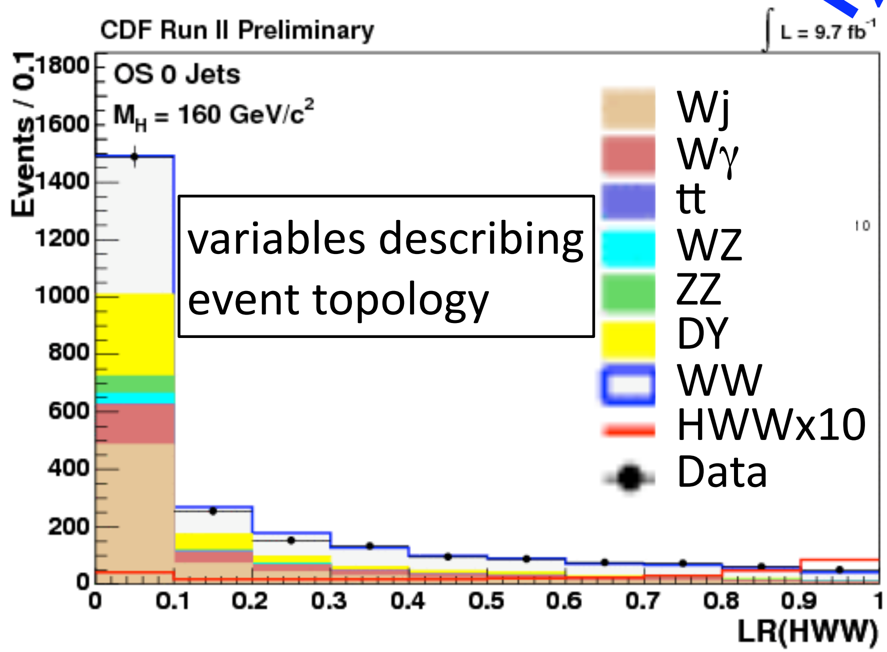


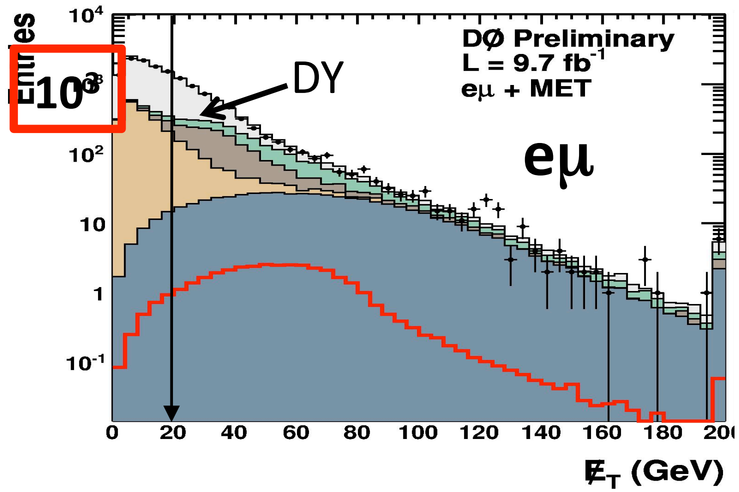


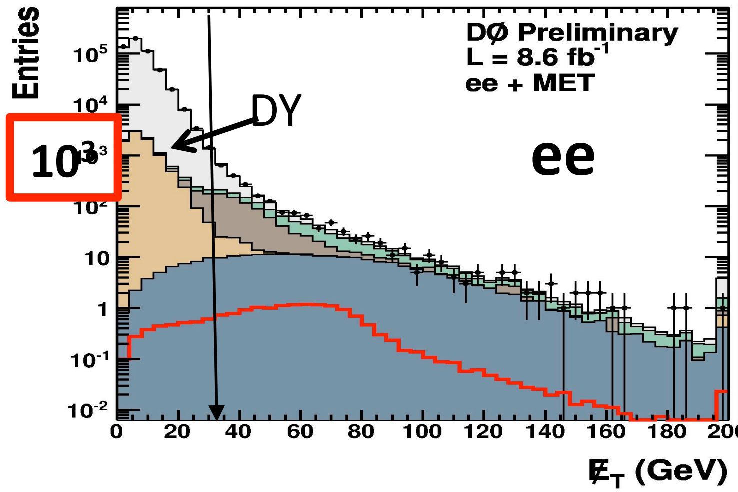
H→WW


g
g
t,b
H
W
W
l
ν
l
ν


DØ Preliminary
L = 9.7 fb^{-1}
eμ + MET
Entries
data
Z+jets
Diboson
W+jets
Multijet
ttbar
Signal × 1
(M_H = 165 GeV)
kinematics of
two leptons
$\Delta\phi_{e\mu}$

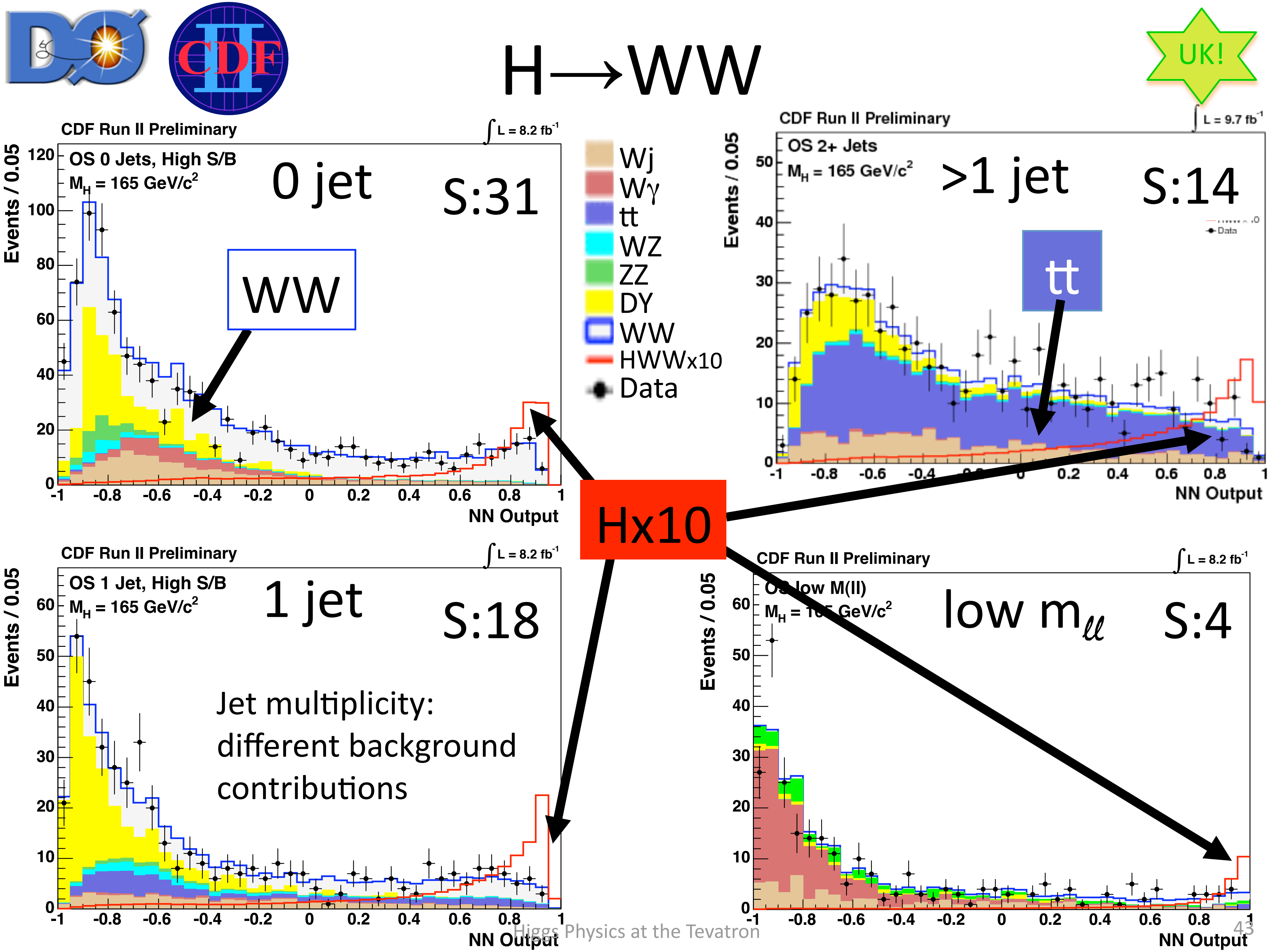

CDF Run II Preliminary
$\int$ L = 9.7 fb^{-1}
OS 0 Jets
M_H = 160 GeV/c^2
Events / 0.1
variables describing
event topology
Wj
Wγ
tt
WZ
ZZ
DY
WW
HWWx10
Data
LR(HWW)


DØ Preliminary
L = 9.7 fb^{-1}
eμ + MET
eμ
DY
10^3
$\not{E}_T$ (GeV)


DØ Preliminary
L = 8.6 fb^{-1}
ee + MET
ee
DY
Entries
10^3
$\not{E}_T$ (GeV)

UK!

H→WW



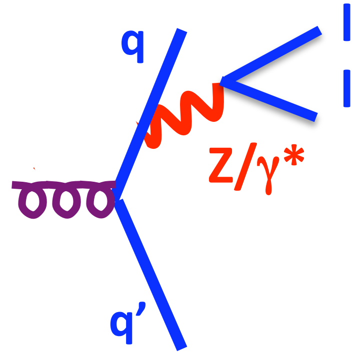
UK!
CDF Run II Preliminary
∫L = 8.2 fb⁻¹
OS 0 Jets, High S/B
M_H = 165 GeV/c²
0 jet
S:31
WW
Events / 0.05
NN Output
Wj
Wγ
tt
WZ
ZZ
DY
WW
HWWx10
Data
CDF Run II Preliminary
∫L = 9.7 fb⁻¹
OS 2+ Jets
M_H = 165 GeV/c²
>1 jet
S:14
tt
Hx10
CDF Run II Preliminary
∫L = 8.2 fb⁻¹
OS 1 Jet, High S/B
M_H = 165 GeV/c²
1 jet
S:18
Jet multiplicity:
different background
contributions
CDF Run II Preliminary
∫L = 8.2 fb⁻¹
OS low M(ll)
M_H = 165 GeV/c²
low m_ℓℓ
S:4

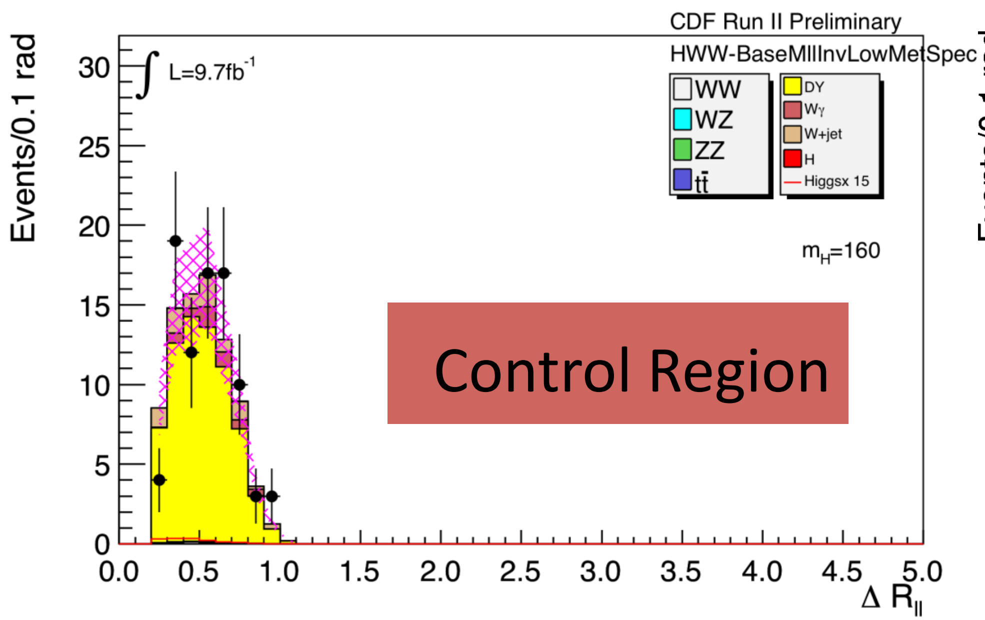
Improving ΔR_{ll} acceptance

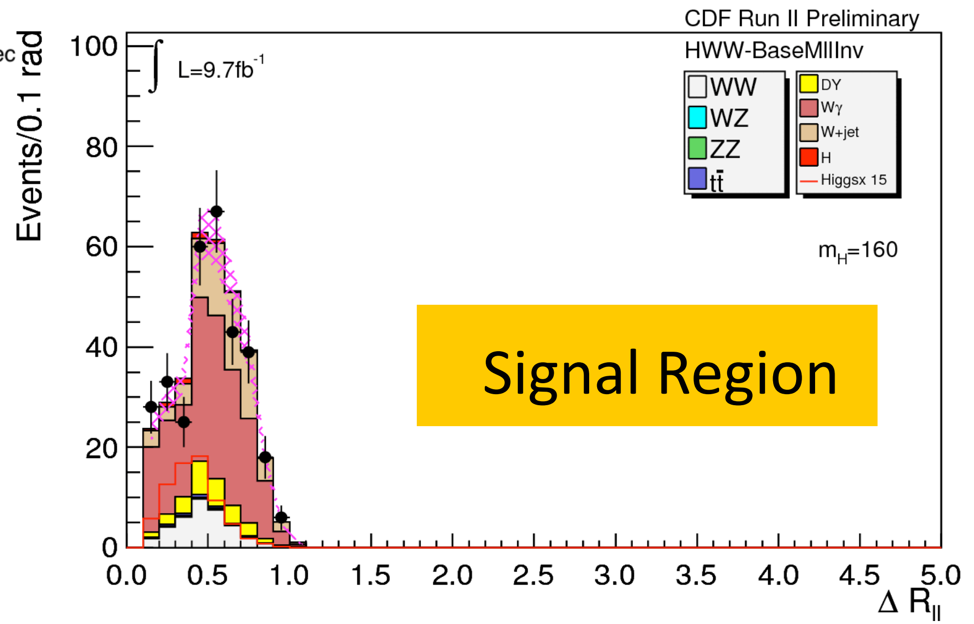
UK!

Include region $0.1 < \Delta R_{ll} < 0.2$ and $m_{ll}<16$ GeV

- special Drell-Yan modeling (MADGRAPH)
- new $W\gamma$ modeling (MADGRAPH)
- cuts to remove J/ψ and Υ resonances







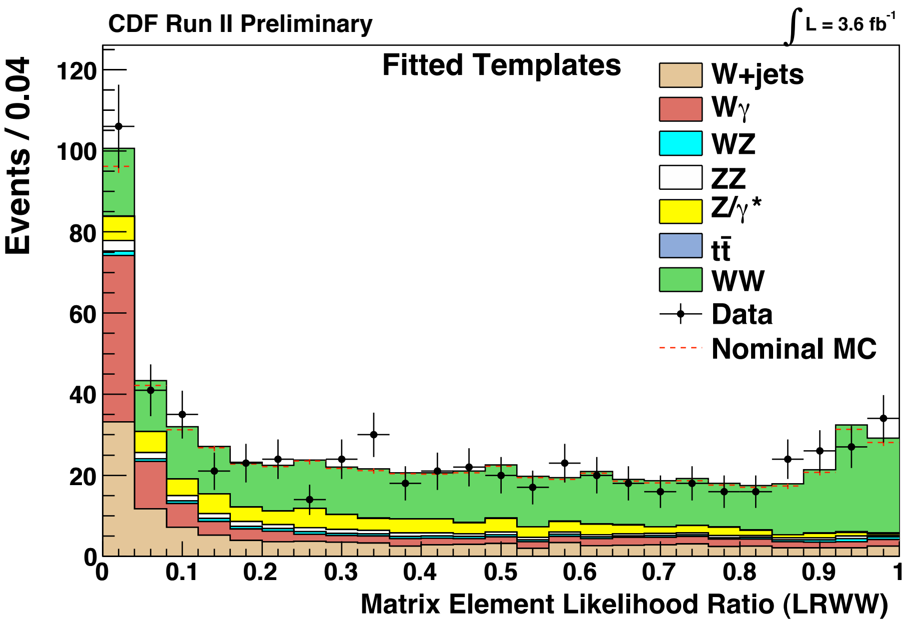
Complementarity

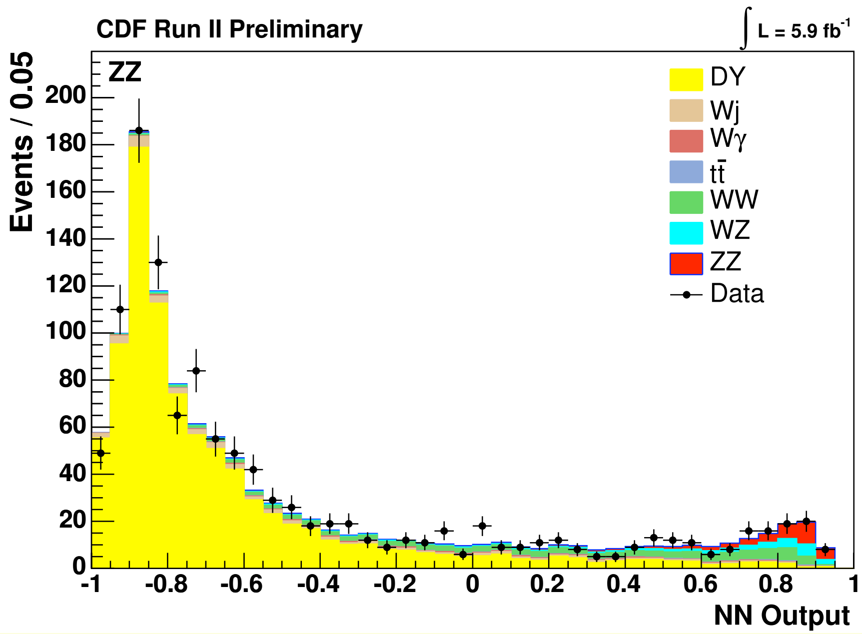
UK!

- exploit different sensitivities of matrix element / neural net
  - – ME is leading order
  - - remove variables that use jet information from neural net for comparison

- verify matrix element method: cycle signal

Redefine discriminant for WW hypothesis: $R' = \frac{P_{WW}}{P_{WW} + \sum_i k_b^i P_b^i}$





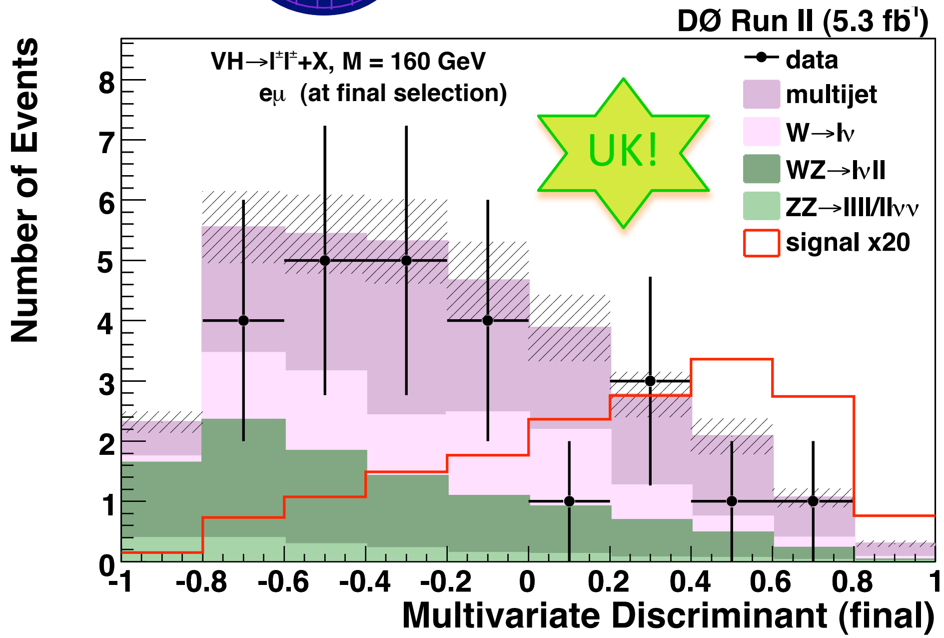
$\sigma(p\bar{p} \to WW) = 12.1 \pm 0.9(\text{stat})\ ^{+1.6}_{-1.4}\ (\text{sys})$ pb

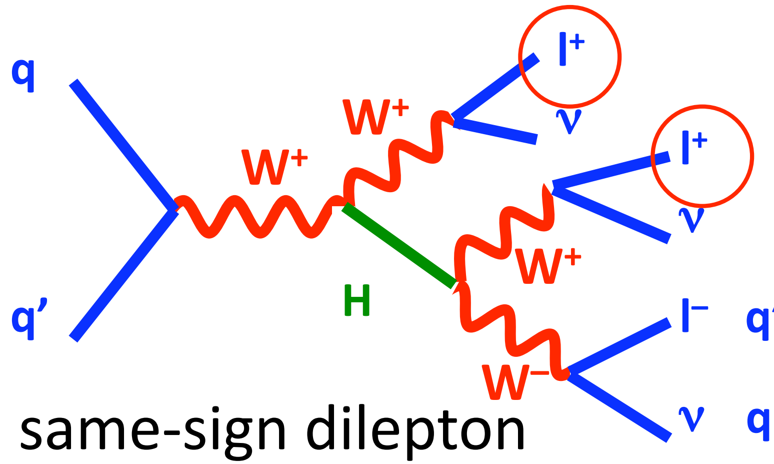
SM, NLO: (12.4± 0.8) pb

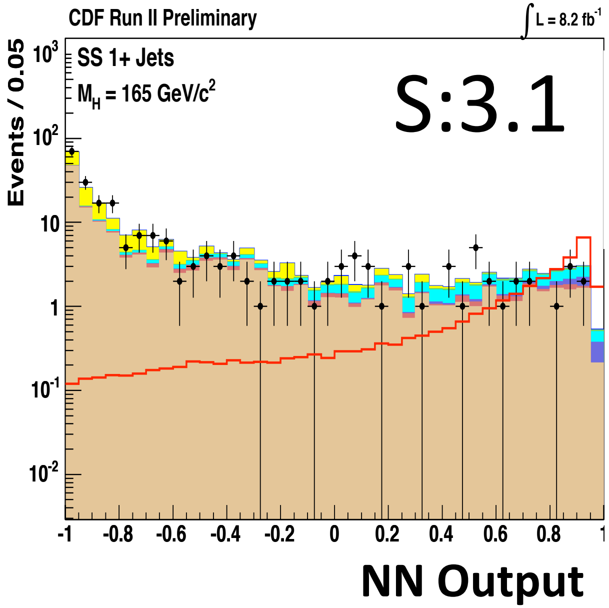
$\sigma(p\bar{p} \to ZZ) = 1.45\ ^{+0.45}_{-0.42}\ (\text{stat})\ ^{+0.41}_{-0.30}(\text{sys})$ pb

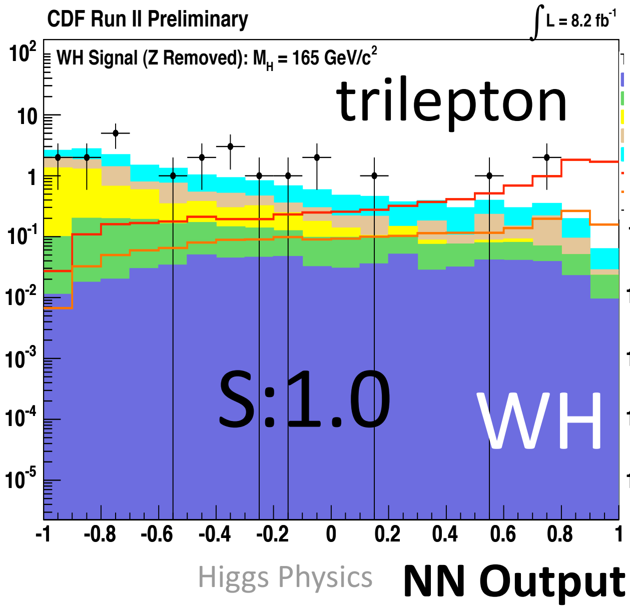
SM, NLO: (1.4± 0.1) pb

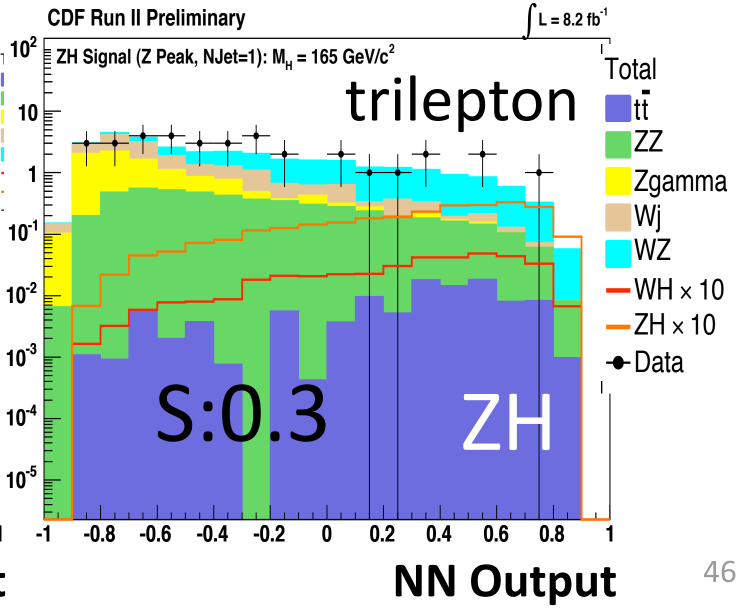
No channel too small!





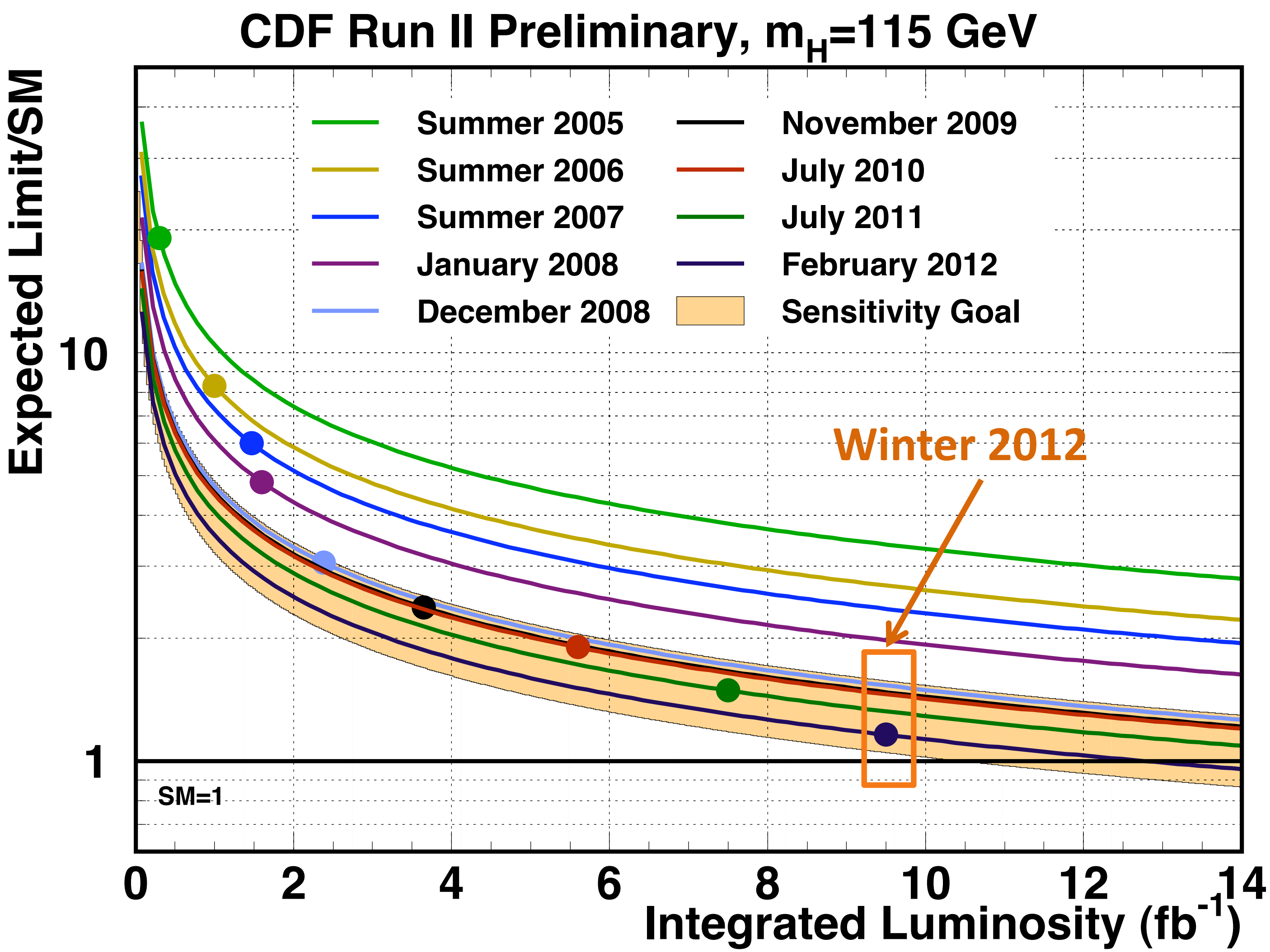




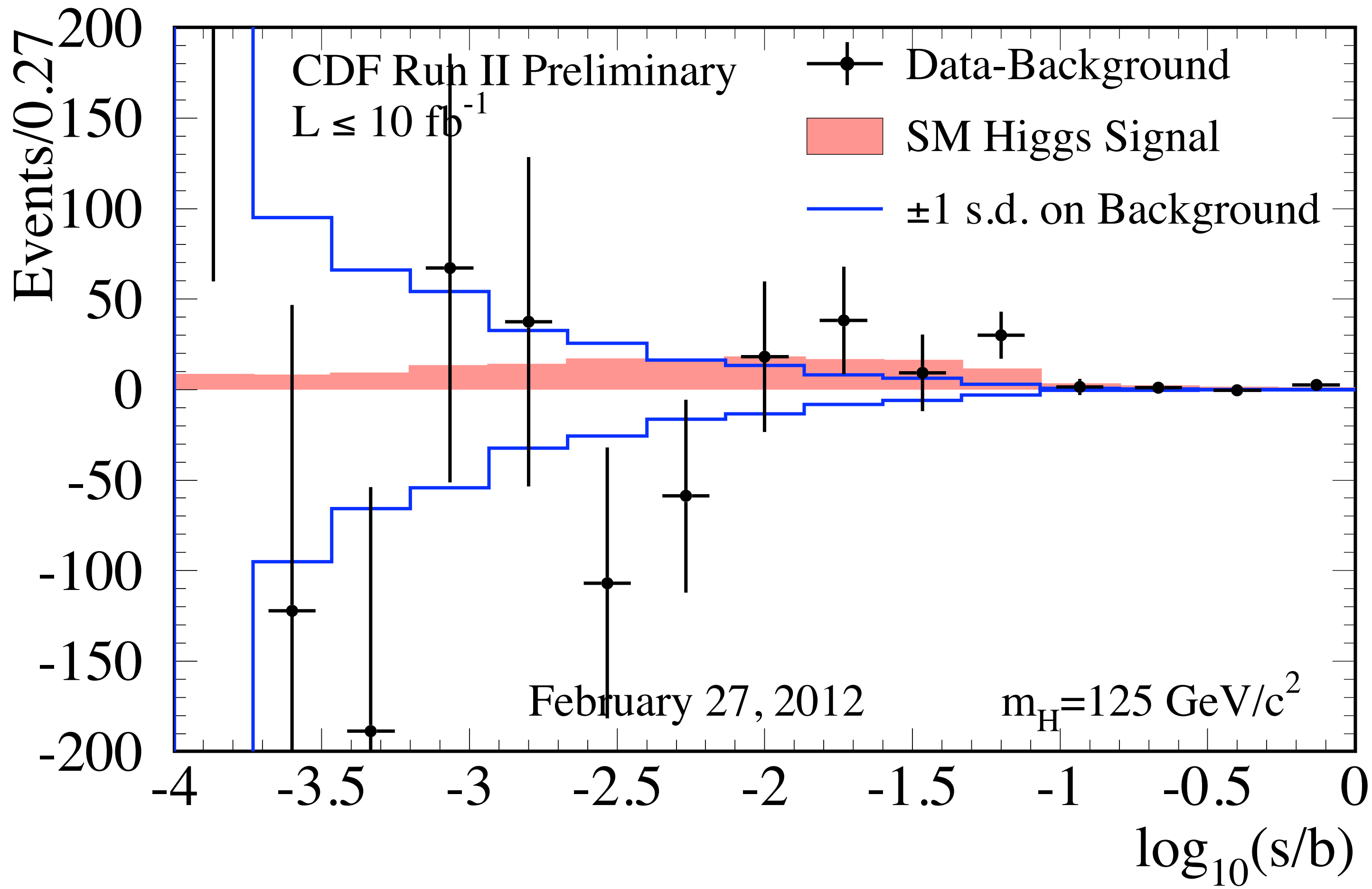


Channel	Luminosity	95% CL limit M_H=125 GeV
$H \rightarrow \gamma\gamma$	10.0 fb^{-1}	10.8 x SM
$VH \rightarrow bb$+jets	9.45 fb^{-1}	11.0 x SM
$ttH \rightarrow l\nu$+jets	9.4 fb^{-1}	12.4 x SM
$H \rightarrow \tau\tau$+jets	8.4 fb^{-1}	14.8 x SM

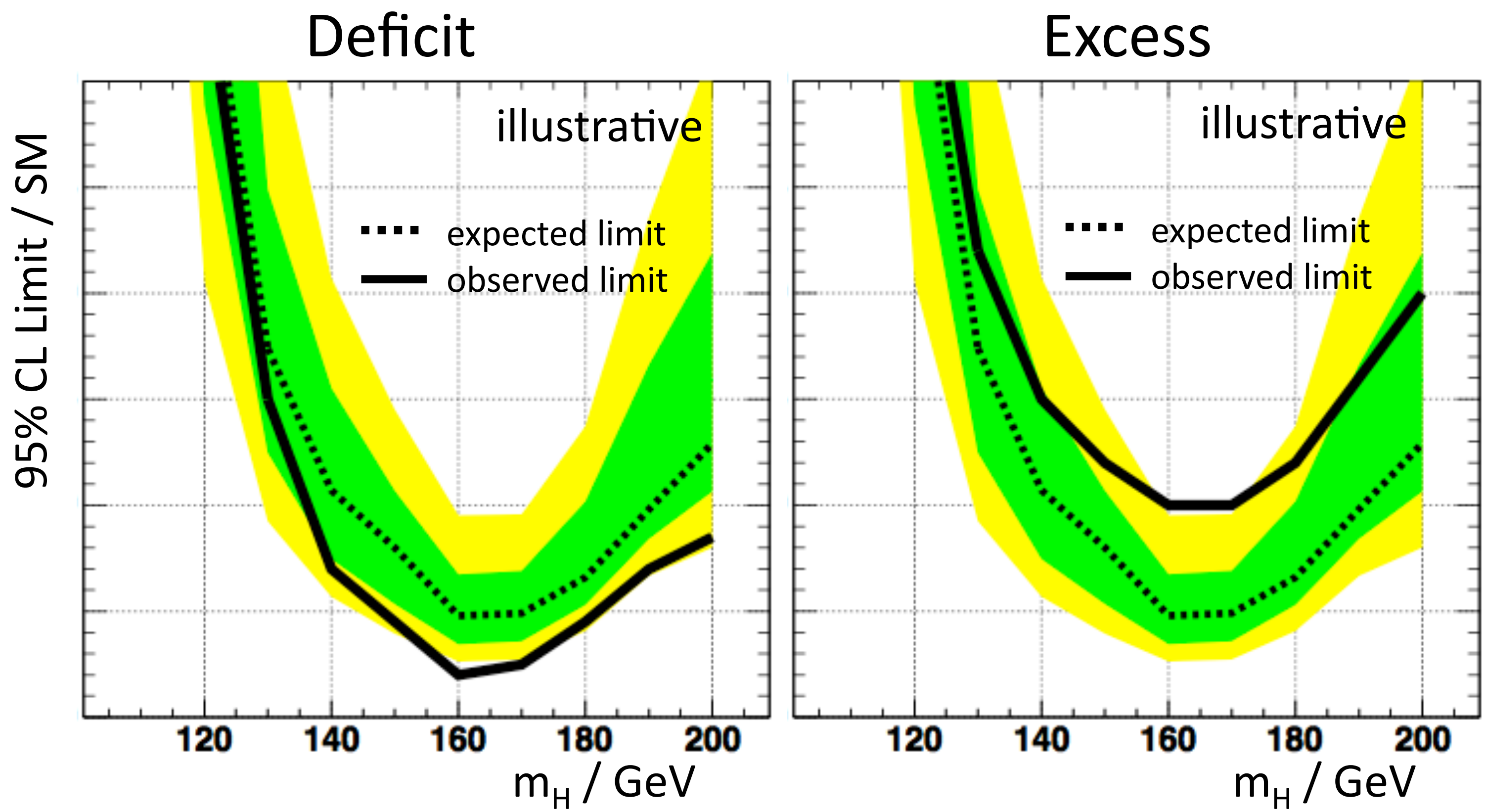
Channel	Luminosity	95% CL limit M_H=150 GeV
$H \rightarrow ZZ \rightarrow llll$	9.7 fb^{-1}	9.4 x SM


CDF Run II Preliminary, m_H=115 GeV
Expected Limit/SM
Integrated Luminosity (fb^{-1})
Summer 2005
Summer 2006
Summer 2007
January 2008
December 2008
November 2009
July 2010
July 2011
February 2012
Sensitivity Goal
Winter 2012
SM=1
10
1
0
2
4
6
8
10
12
14

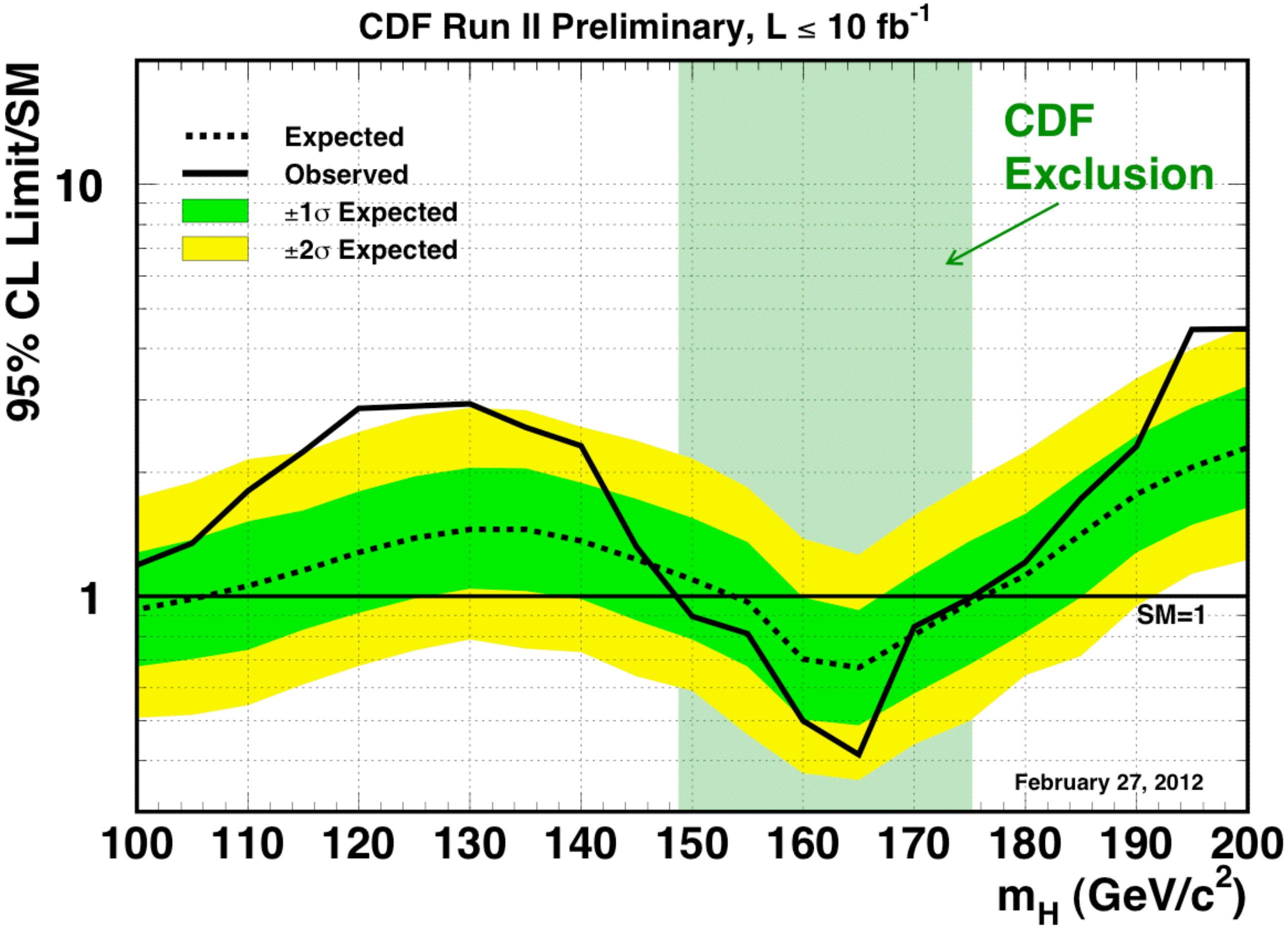
• Combine 16 analyses, 93 orthogonal channels



What have we found?

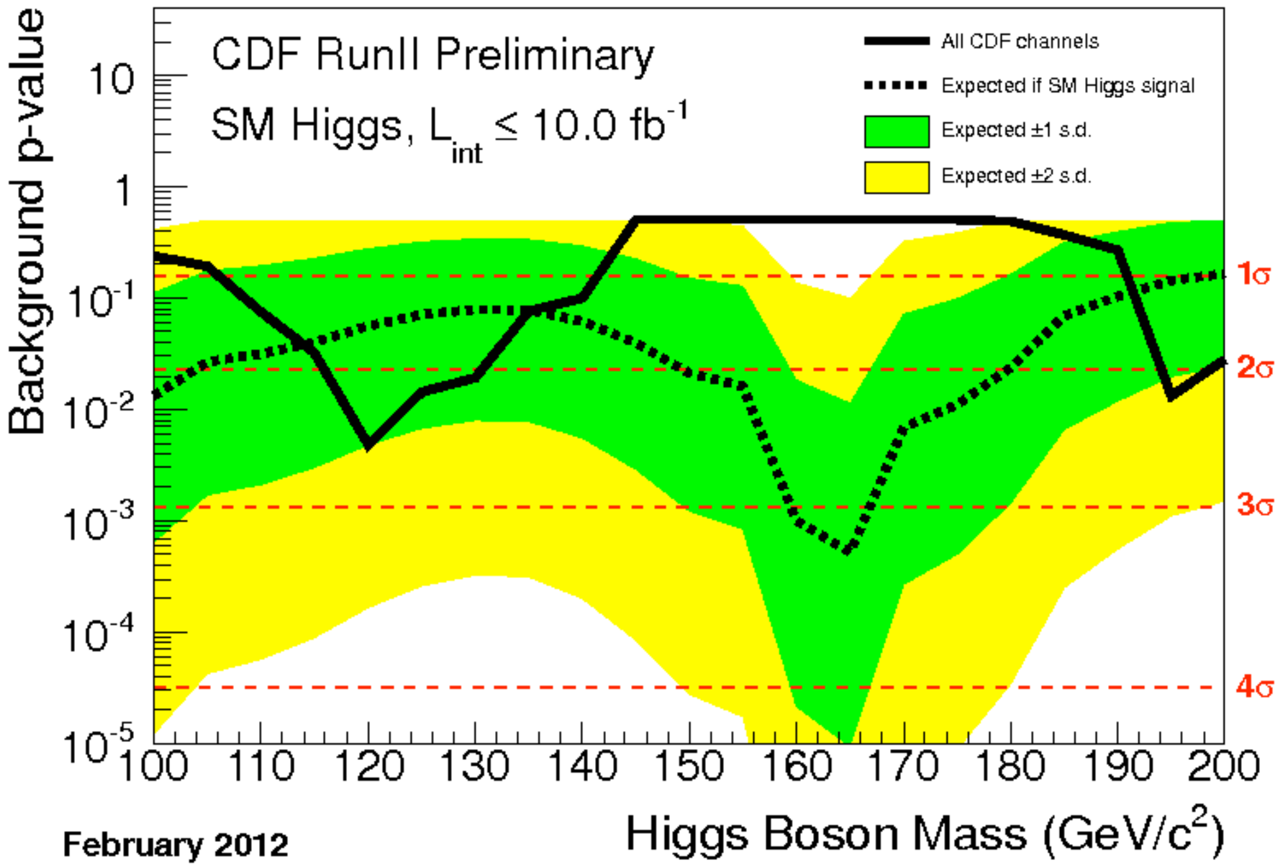


CDF combination



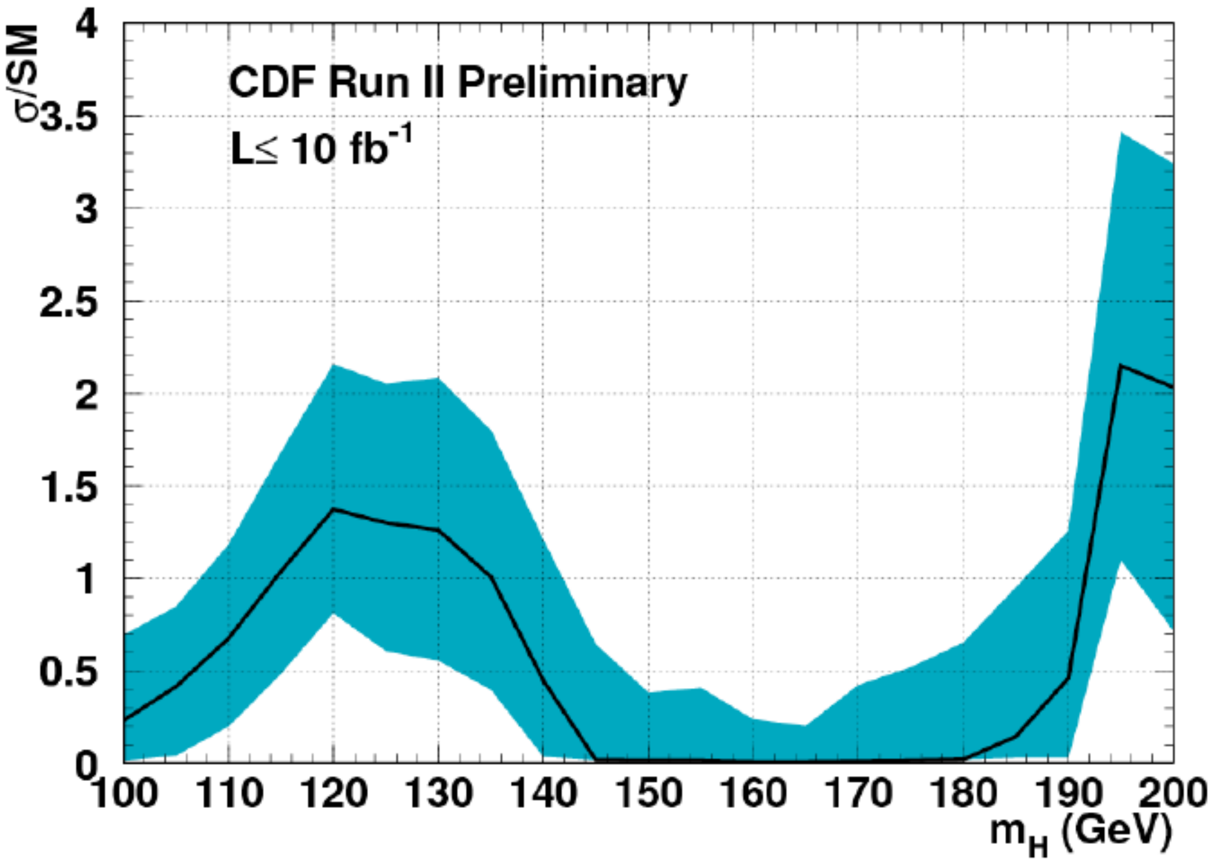
- Exclude SM Higgs at 95% C.L. : $147 < m_H < 175$ GeV/c^2
- Expect to exclude: $100 < m_H < 106$ GeV/c^2 & $154 < m_H < 176$ GeV/c^2

Compatible with bck only?



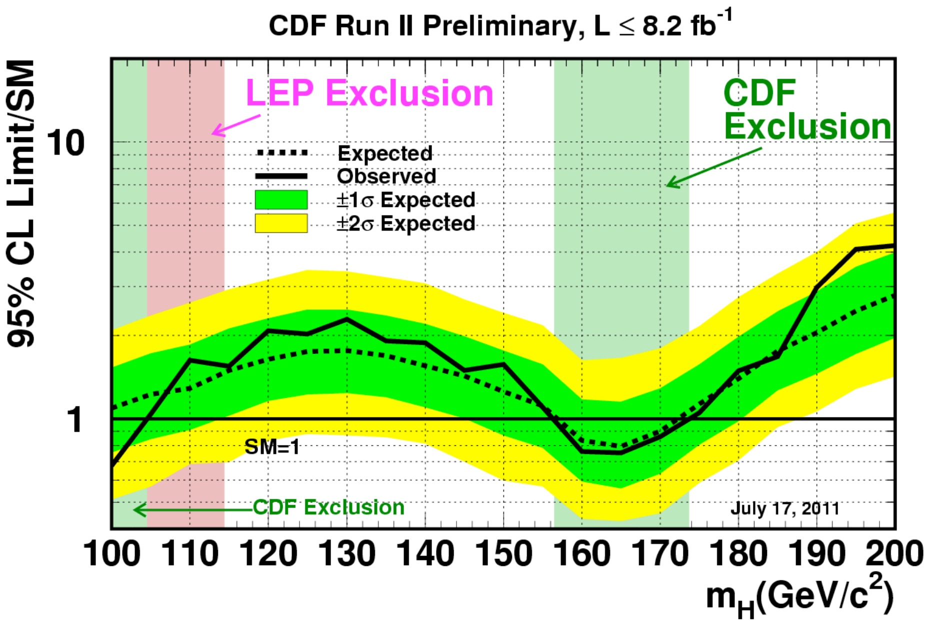
Highest local p-value, 2.6σ, is found at m_H = 120 GeV/c^2

Compatible with SM Higgs?

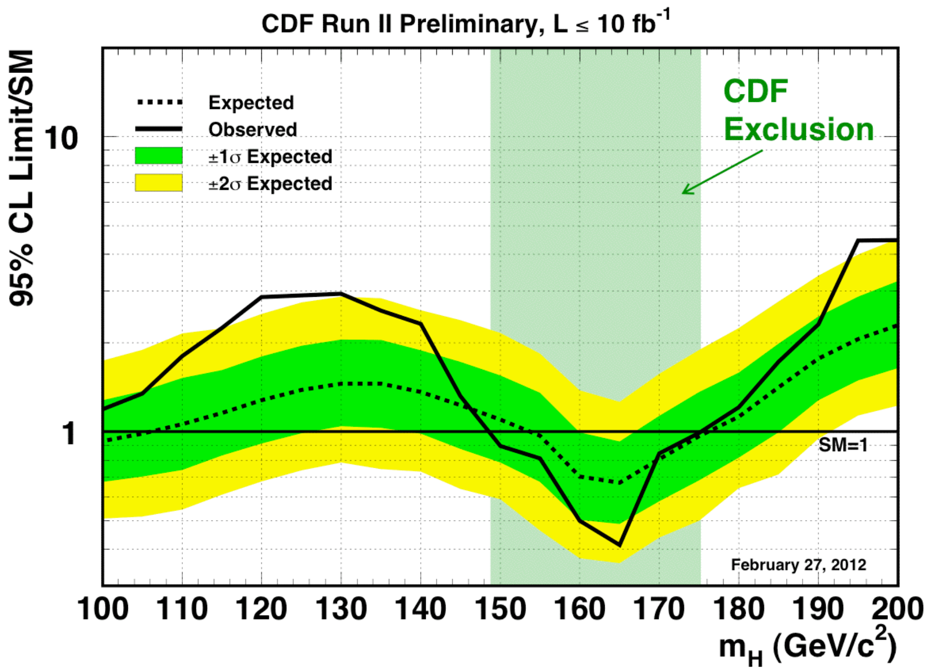


Consistent with SM Higgs at 1σ level for mass range between 107 and 142 GeV/c^2

How much did things change?



Summer 2011

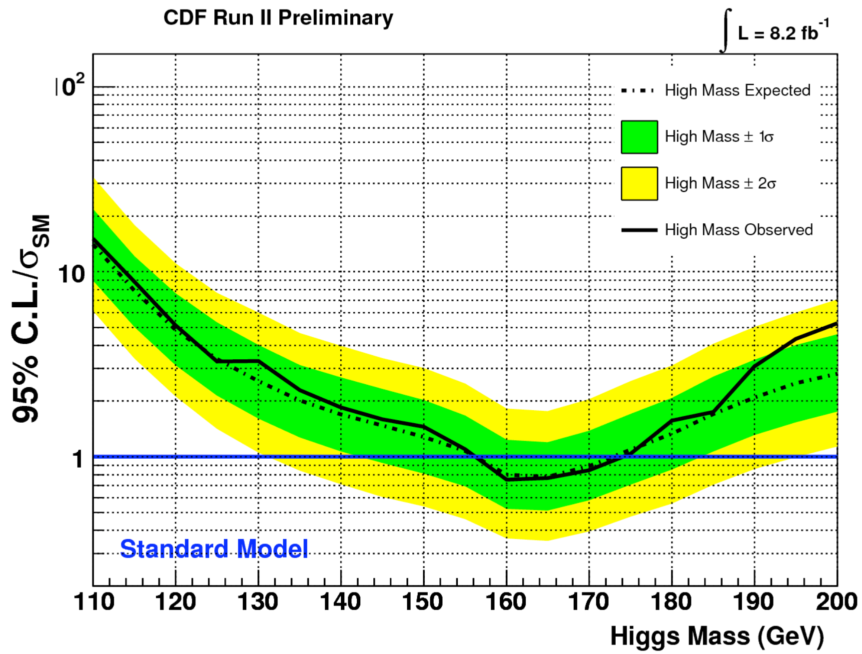


Winter 2012

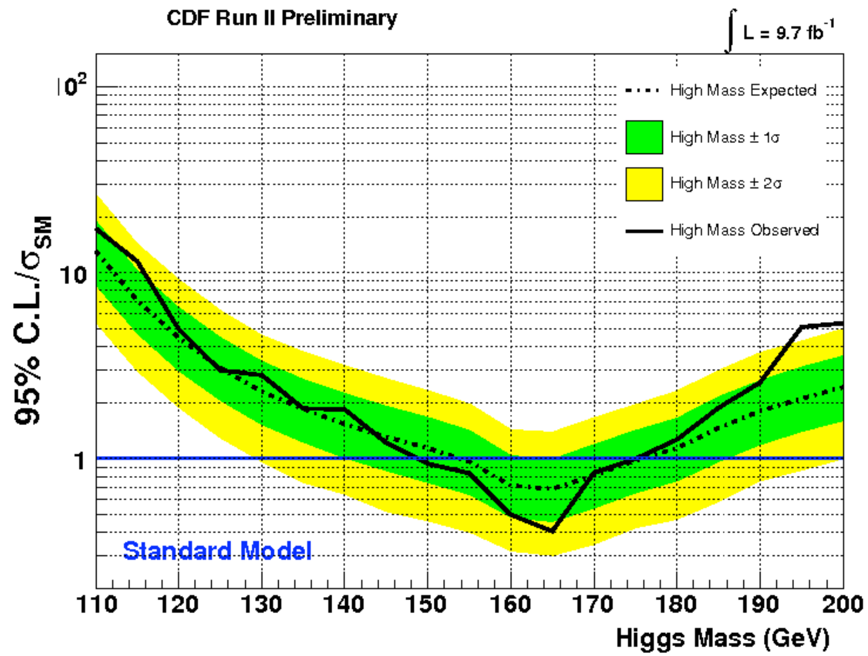
A ~0.5σ excess in mass range from 115 to 135 GeV/c^2 has become a ~2σ excess. How can this happen?

H⟶WW

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



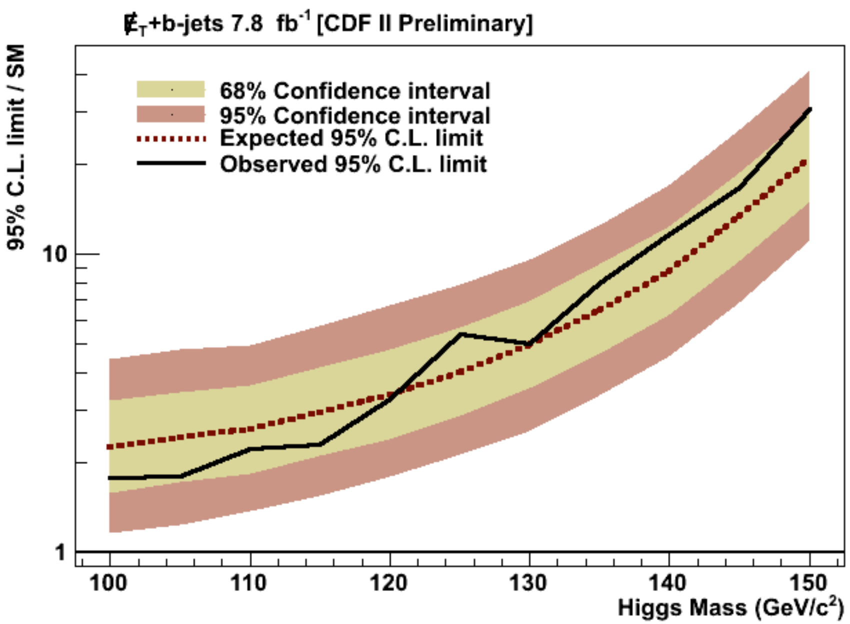
Summer 2011



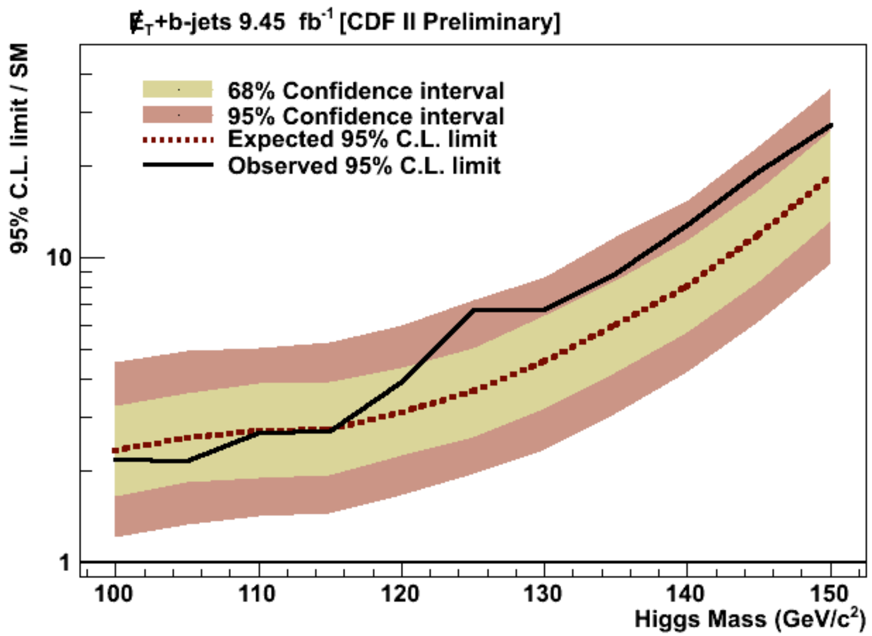
Winter 2012

ZH → ννbb

- 21% additional luminosity
- Small improvements in background rejection
- Limits show same basic behaviour with 0.5 to 1.0σ increases in significance of excess



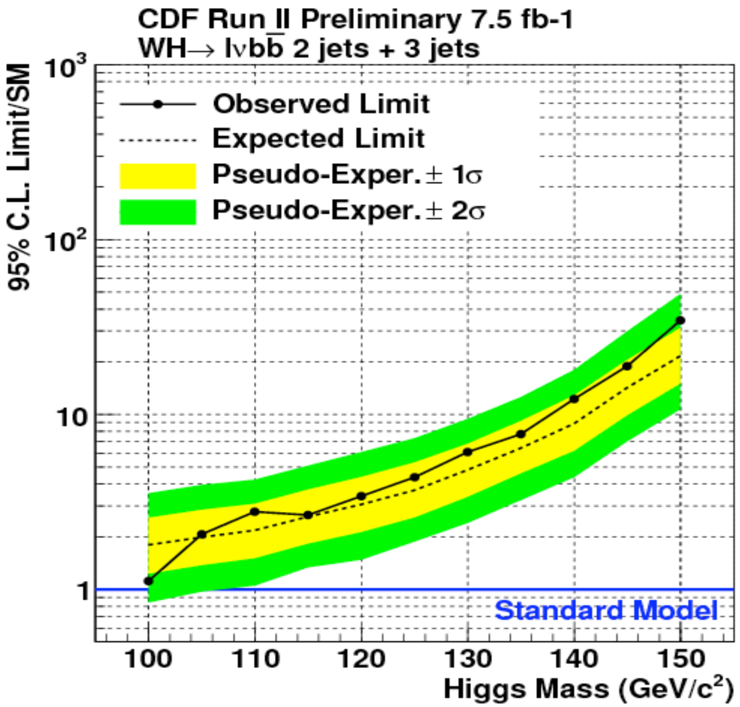
Summer 2011



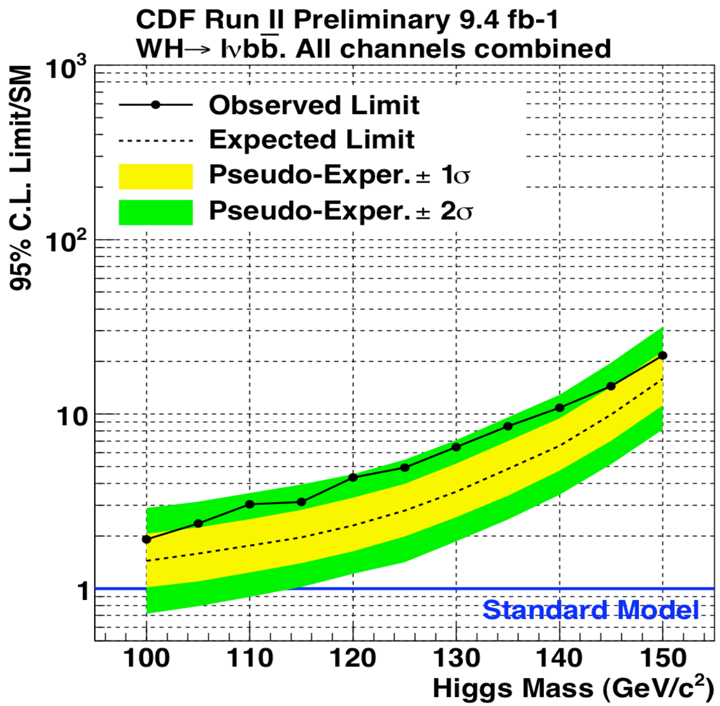
Winter 2012

$WH \rightarrow l\nu bb$

- 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 behaviour with 1.0 to 1.5σ increases in significance of excess



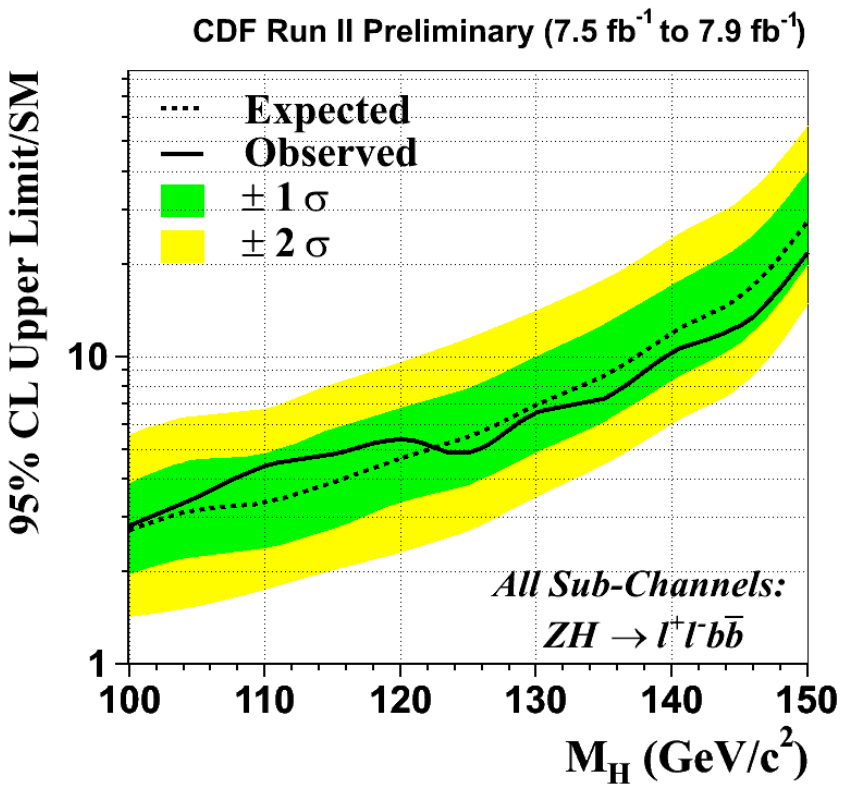
Summer 2011



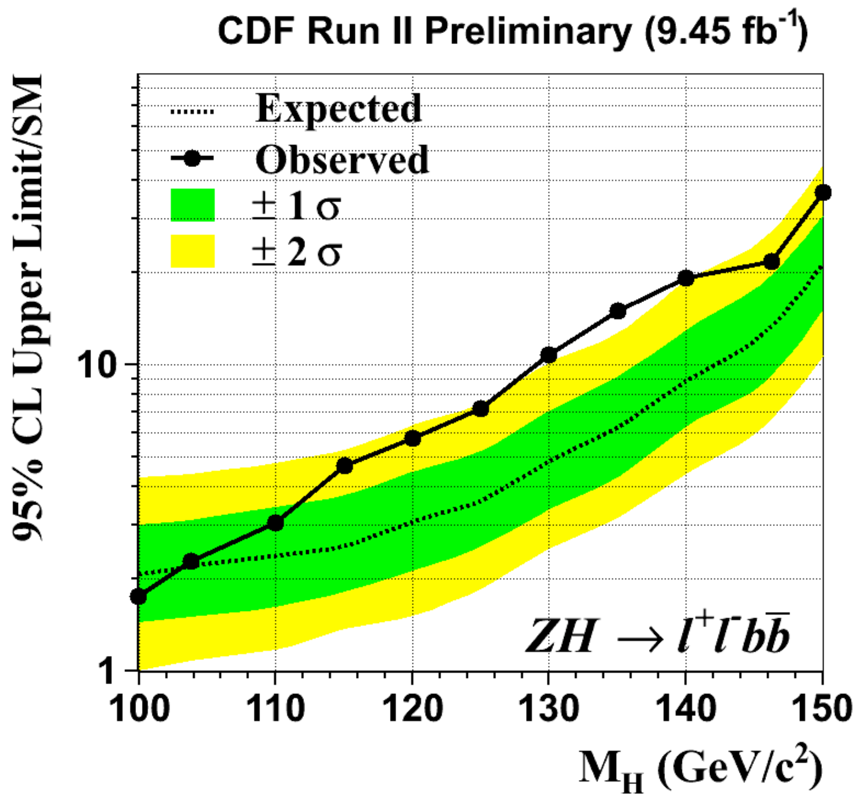
Winter 2012

ZH → ℓℓbb

- 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)



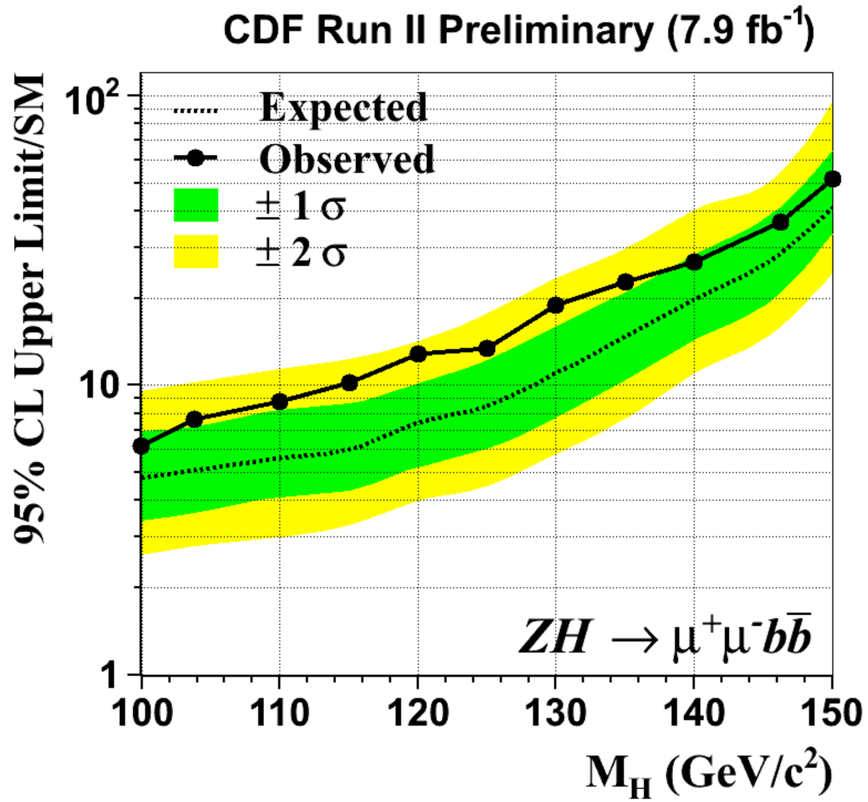
Summer 2011

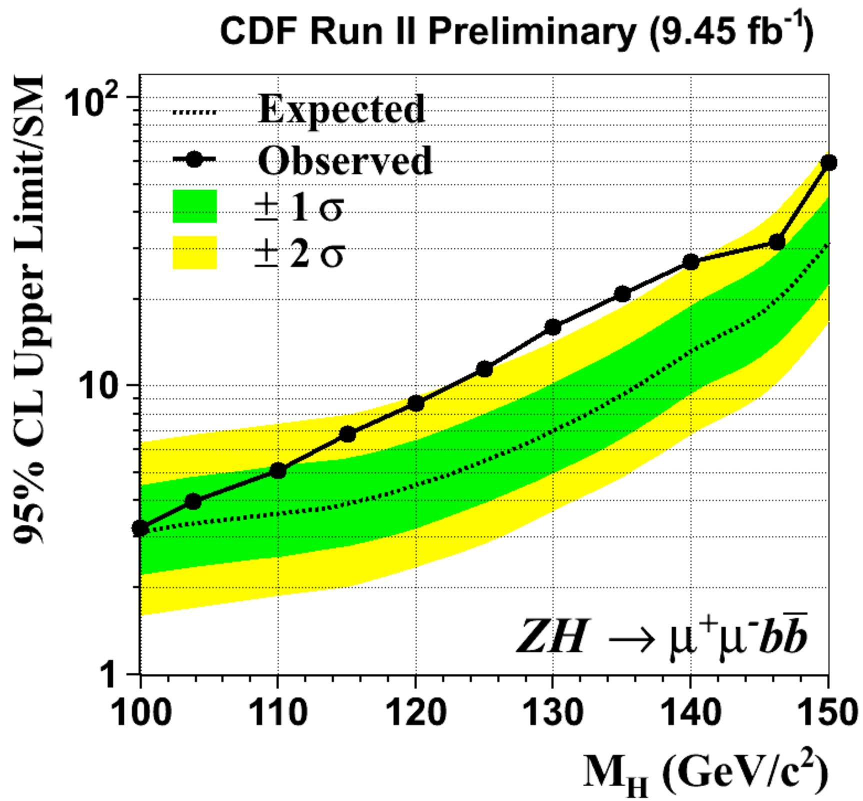


Winter 2012

ZH → ℓℓbb

- Muon channels
- See only a slight change in behaviour of limits (~0.5σ)



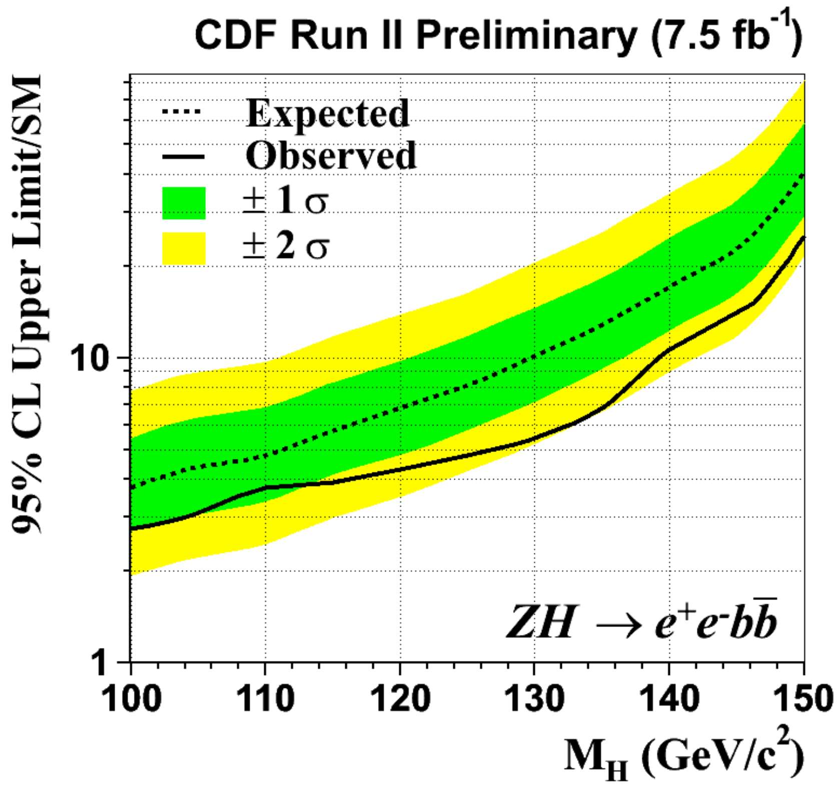


Summer 2011

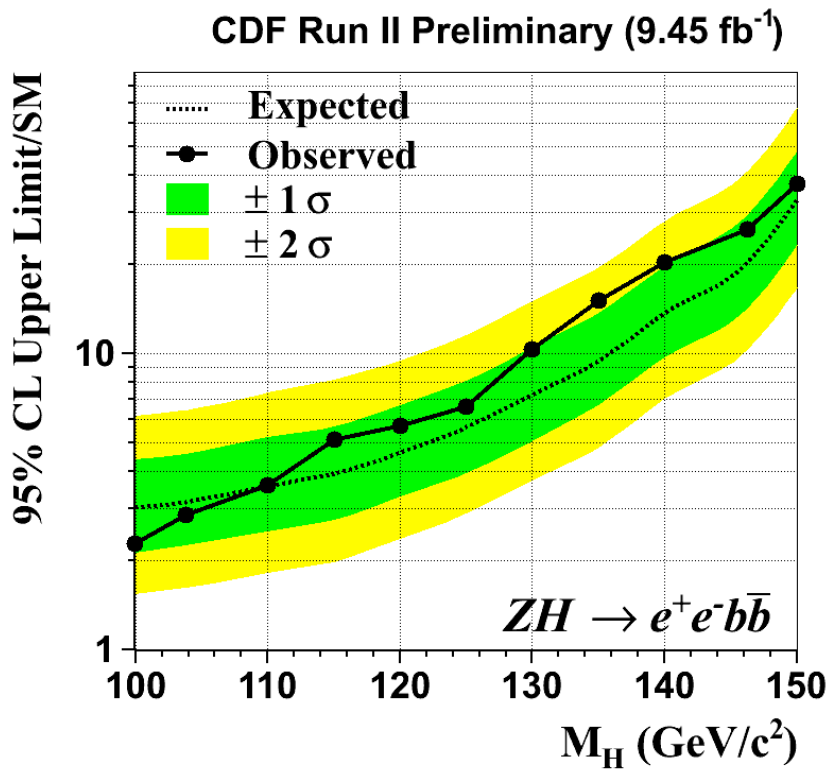
Winter 2012

ZH → ℓℓbb

- Electron channels
- Here we observe a significant change



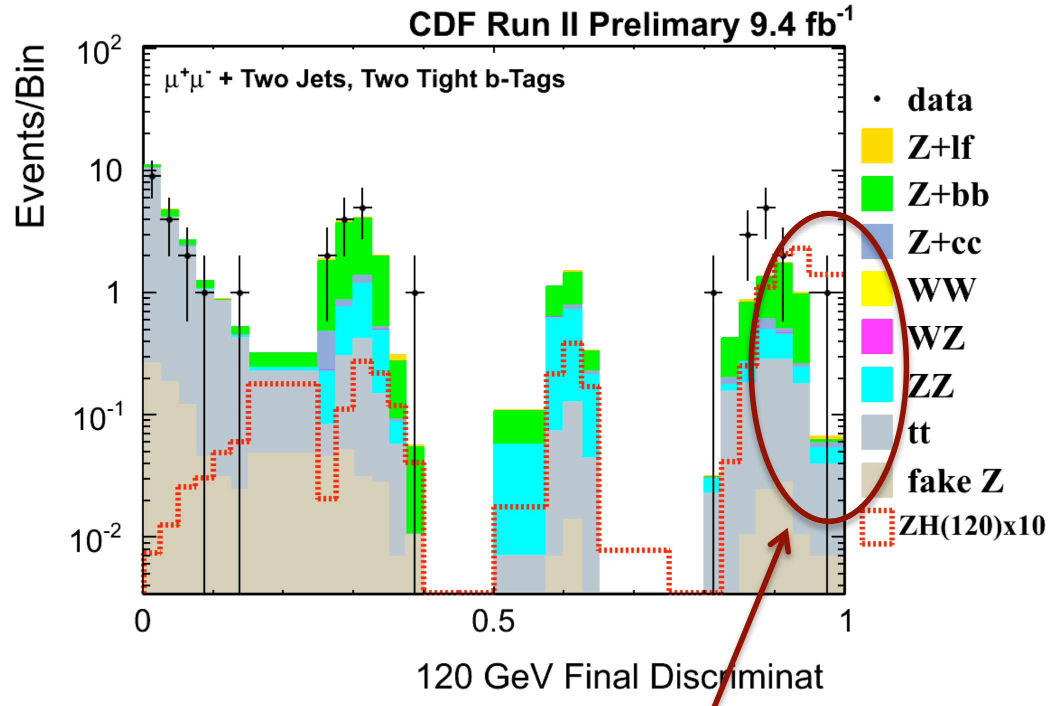
Summer 2011



Winter 2012

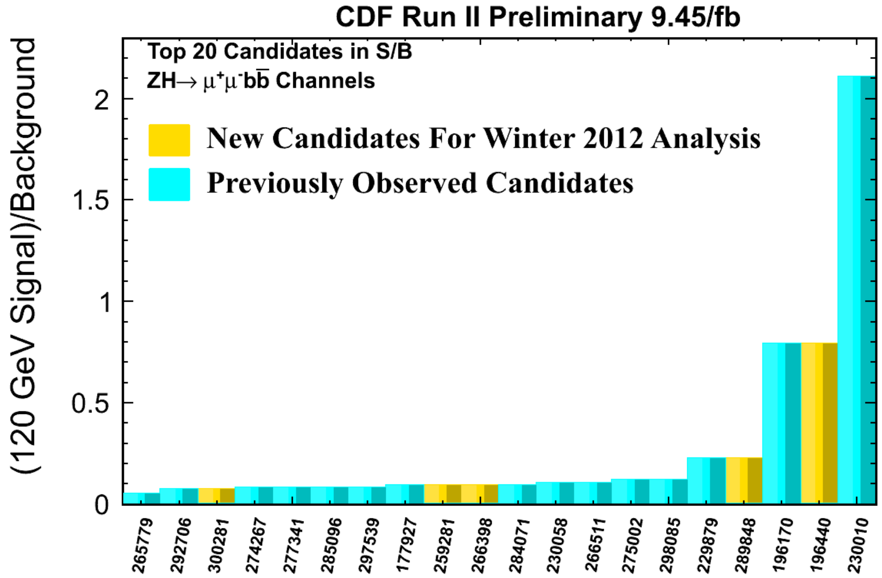
ZH → ℓℓbb

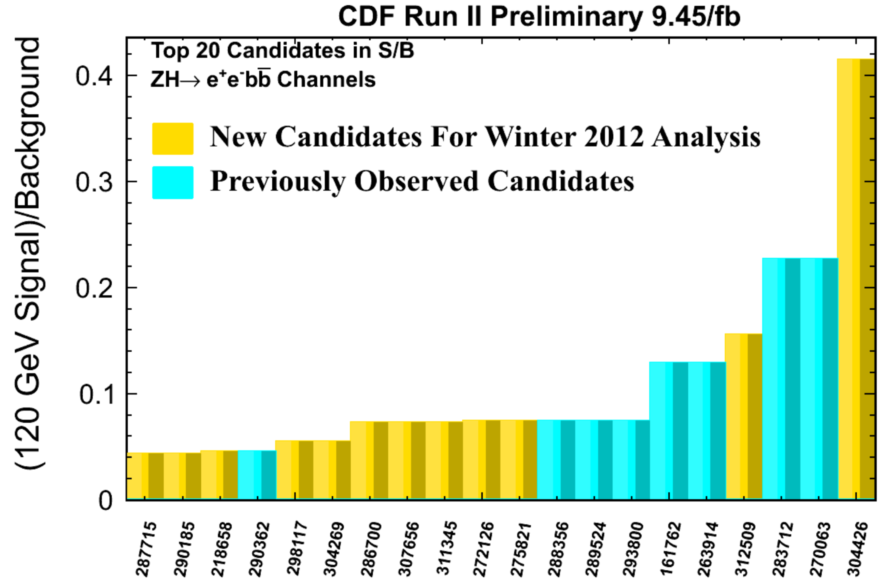
- ZH→llbb channel has . . .
  - lowest backgrounds
  - smallest expected signal yields (9 events for m_H=120 GeV/c^2)
- Some discriminant bins with large S/B
  - Low probability for observing events in these bins
  - A few such events can have substantial effects on observed limits



ZH → ℓℓbb

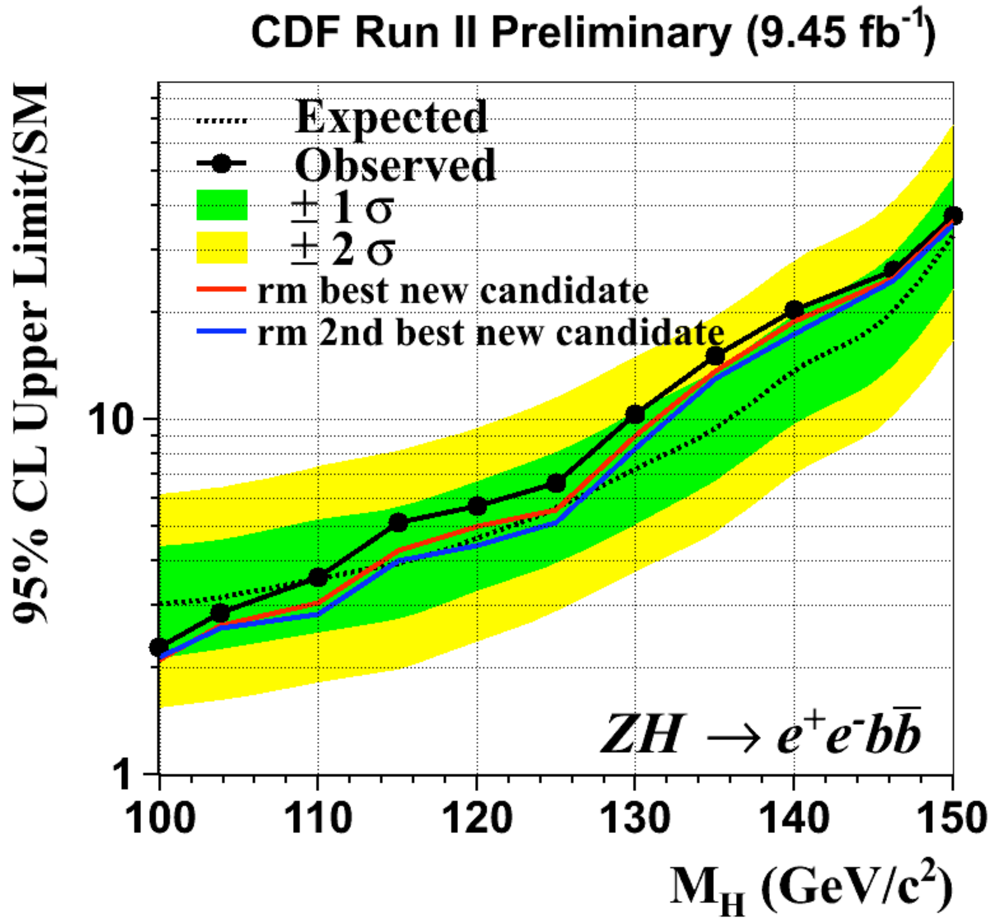
- Examine top 20 events in both channels based on S/B of the discriminant bin in which it is located
- The electron channel contains 12 new candidates within this high score region, while muon channel has 5





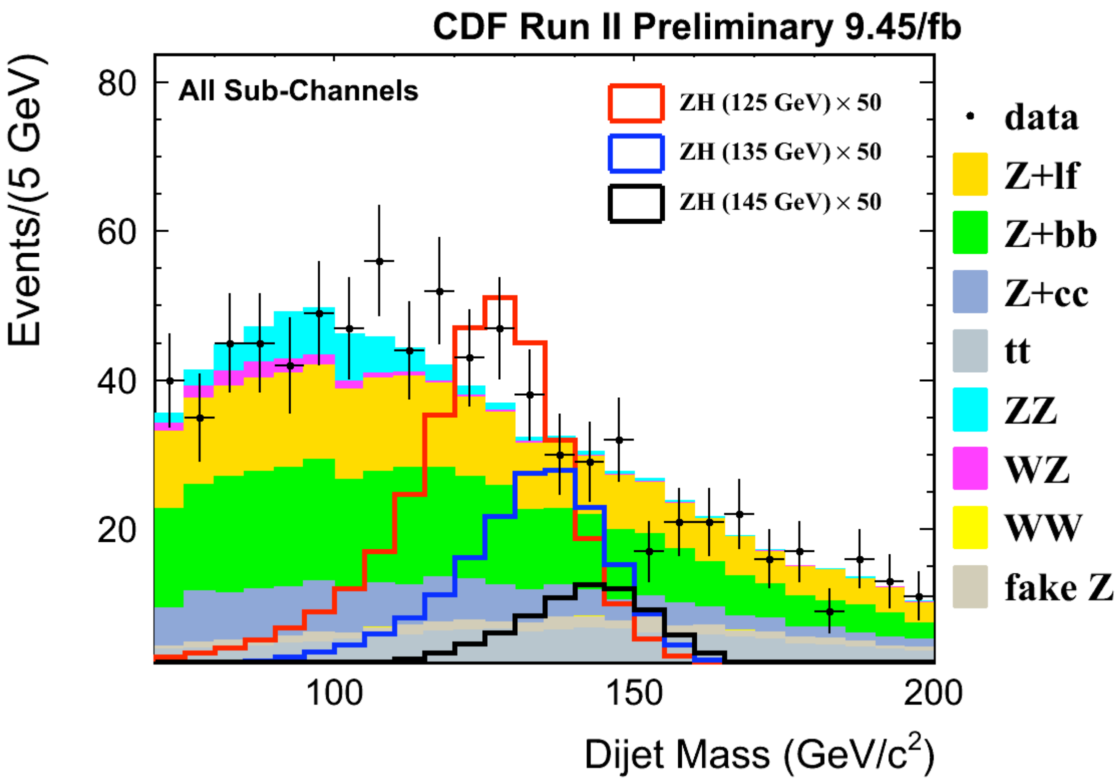
ZH → ℓℓbb

- To study the effect of high S/B events on our observed limits, we remove our best new and best two new events from the e^+e^- channel and re-run the limits
- Gives one sigma level changes in the limits at 120 GeV/c^2



Global significance of excess

- Highest local p-value at m_H = 120 GeV/c^2
- mass resolution of searches, dominated by bb at low mass and WW at high mass, is broad
- Estimate LEE of 4 for our entire SM search range from 100 to 200 GeV/c^2



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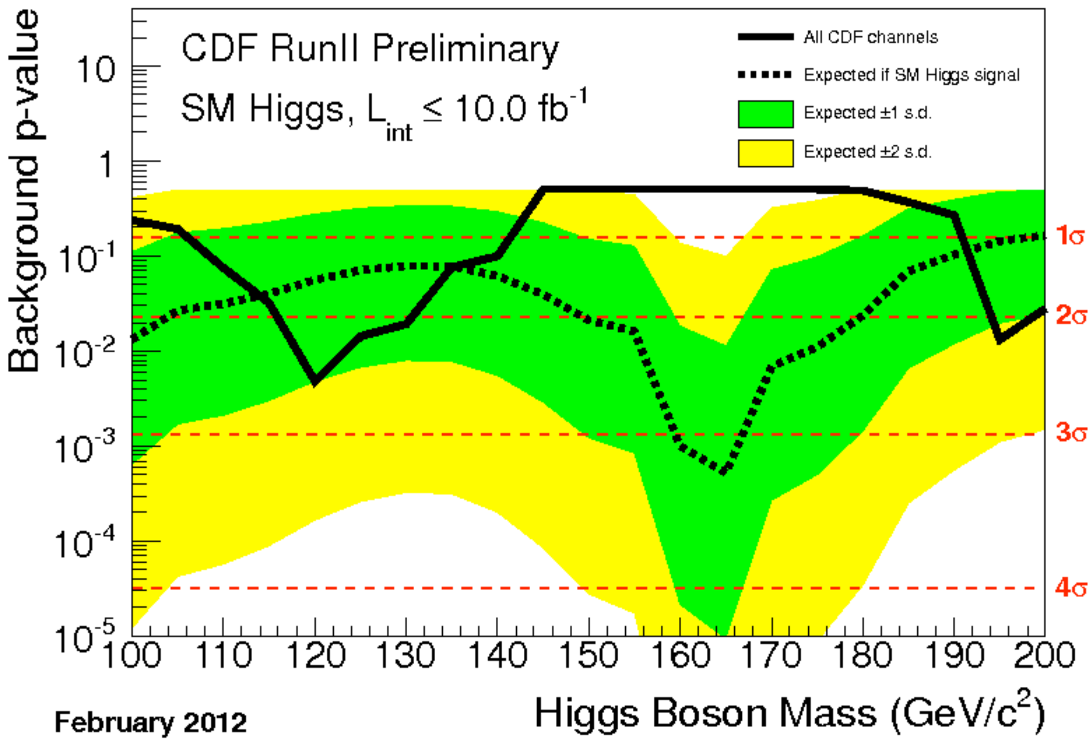
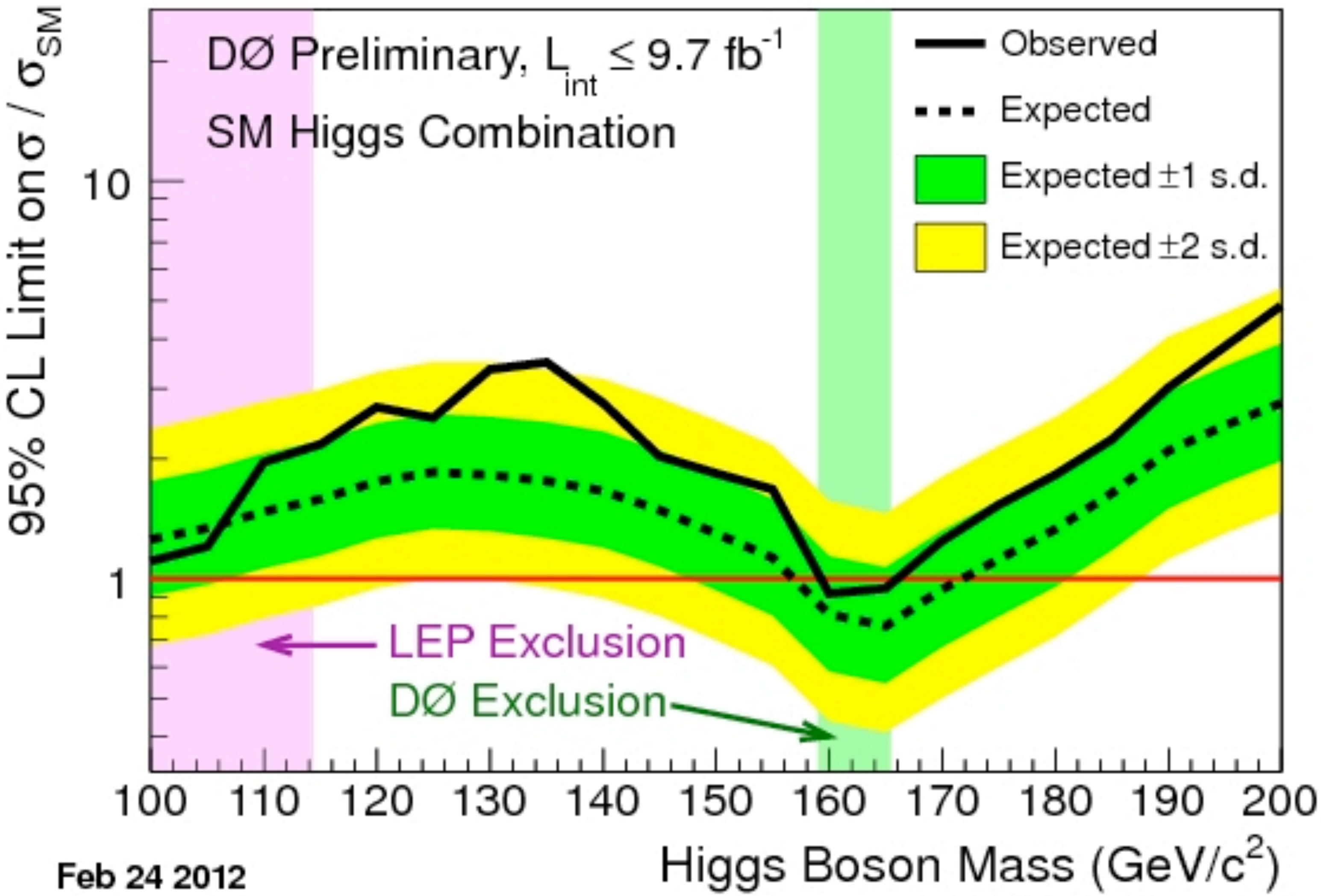


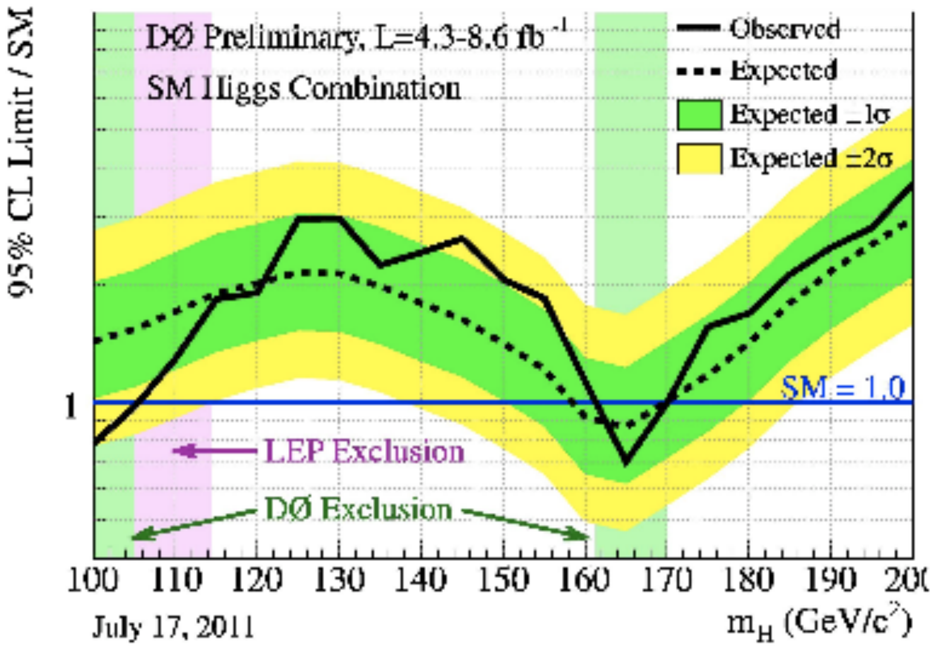
SM Higgs Searches		
Experiment	Local P-value	Global P-value
CDF	2.6σ	2.1σ
ATLAS	3.5σ	2.2σ
CMS	3.1σ	2.1σ

D0 combination

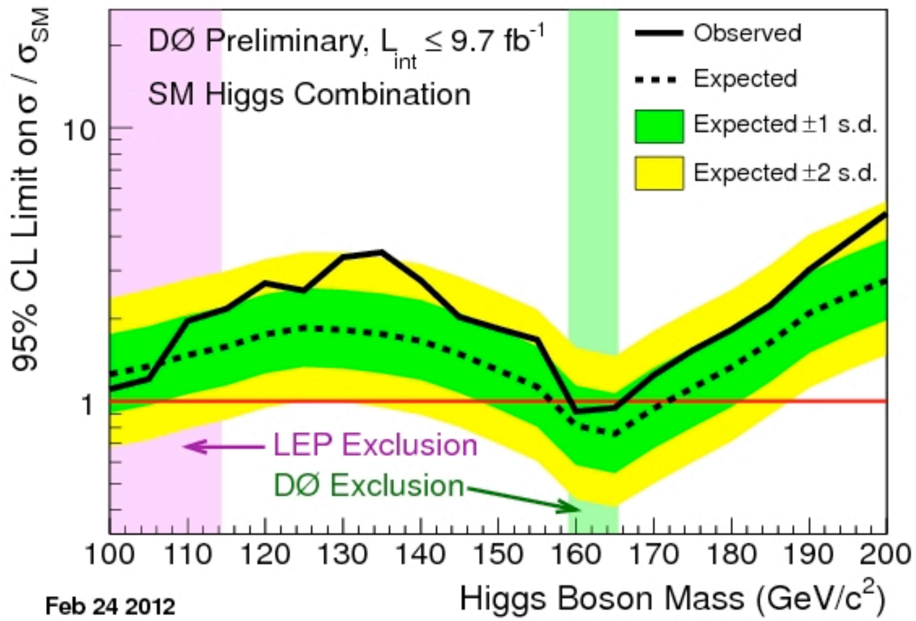


- Exclude SM Higgs at 95% C.L. : $159 < m_H < 166$ GeV/c^2
- Expect to exclude: $157 < m_H < 172$ GeV/c^2

D0 combination

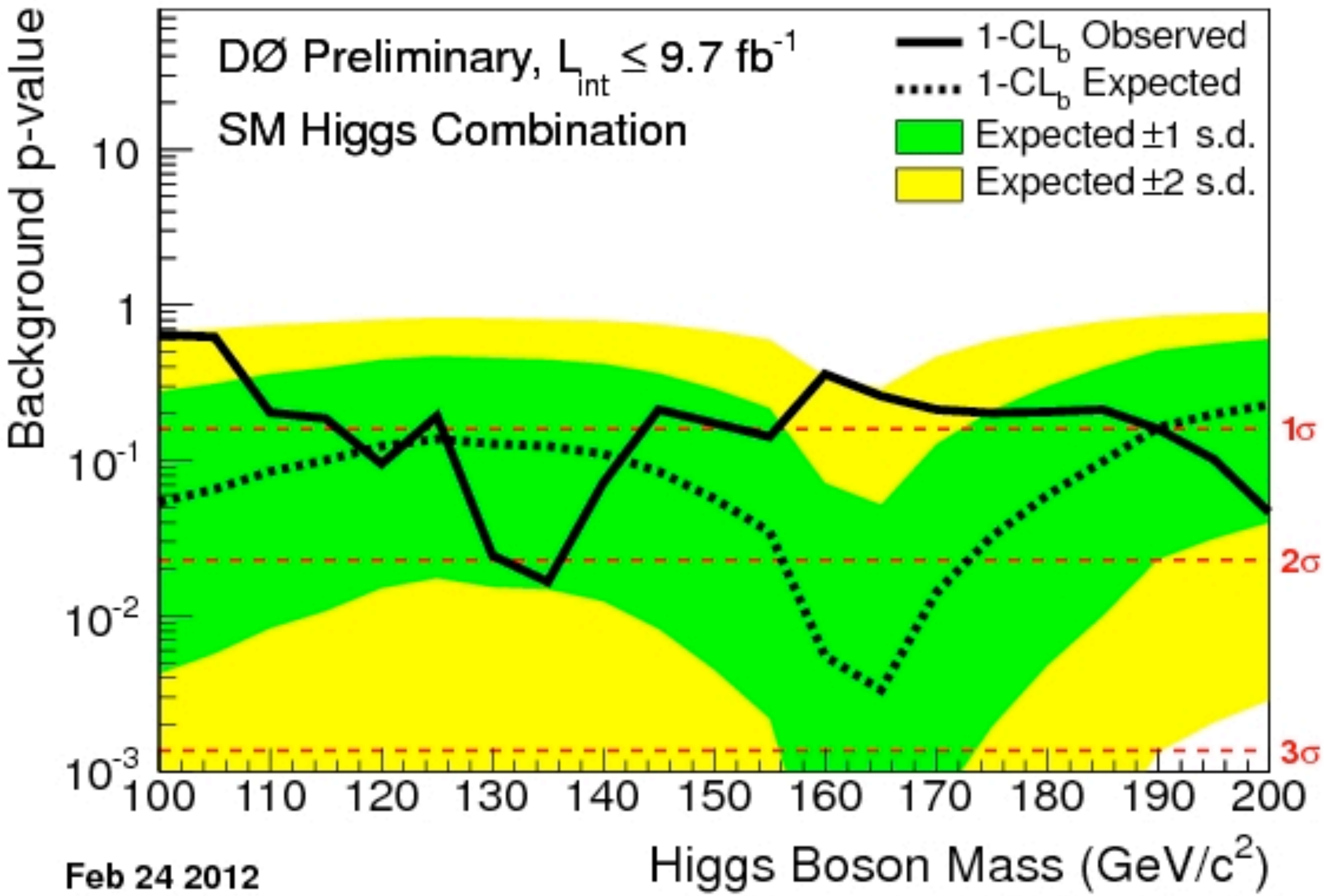


Summer 2011

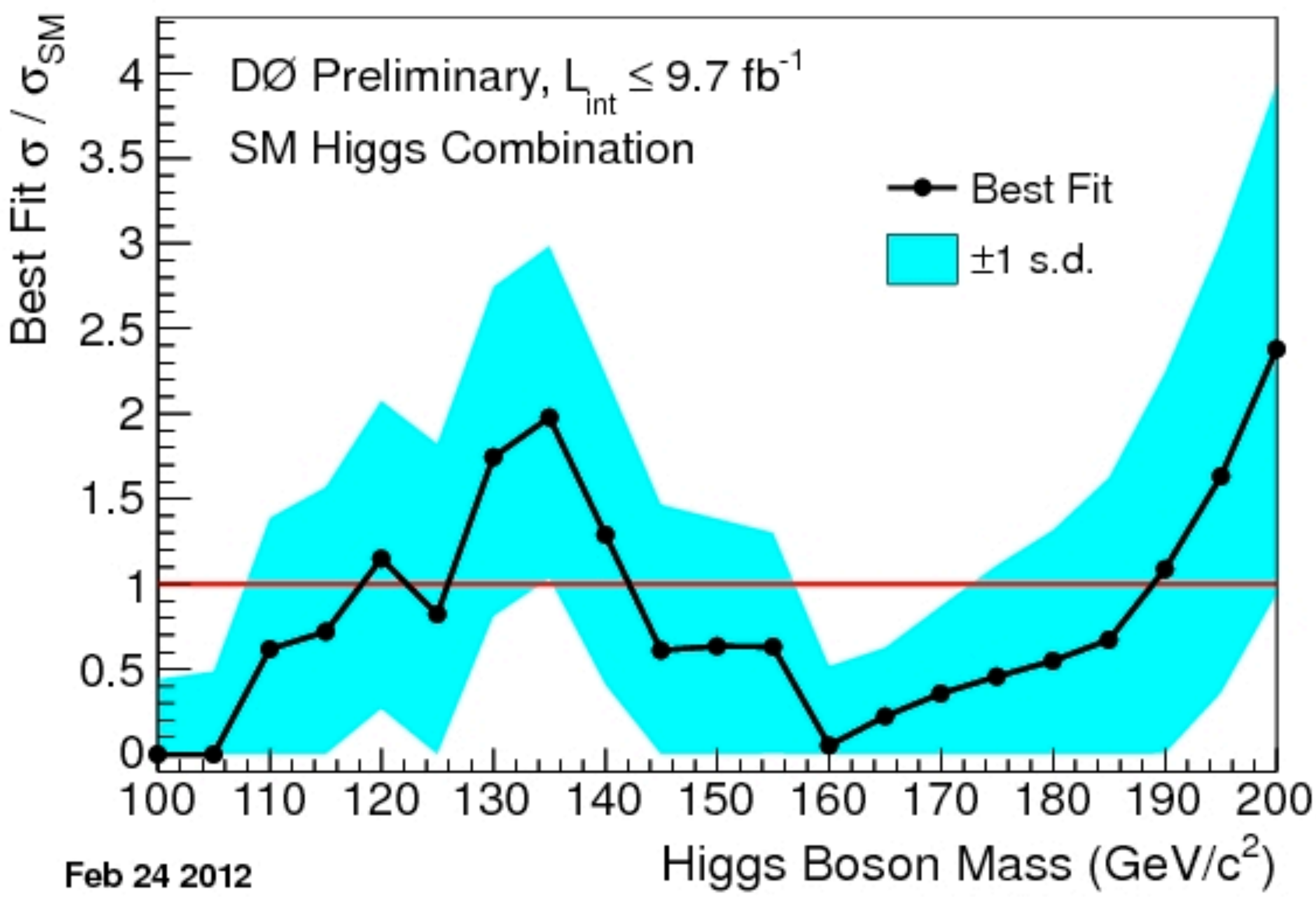


Winter 2012

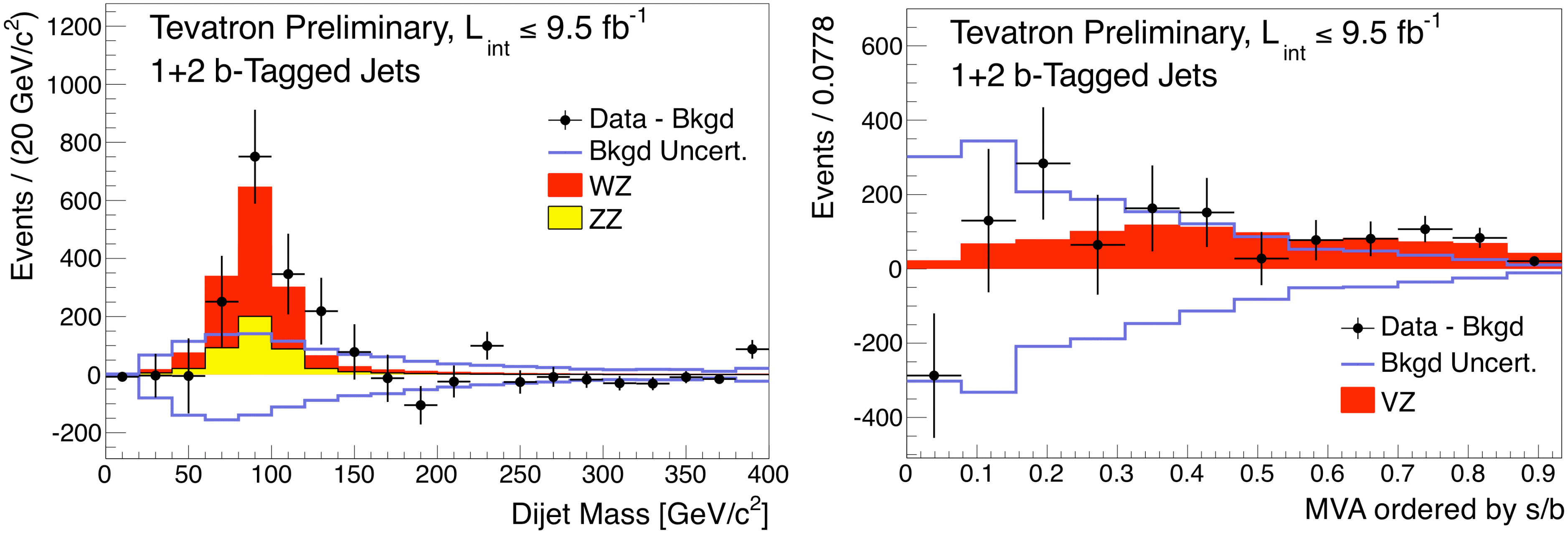
D0 combination



D0 combination



Tevatron combination: WZ/ZZ

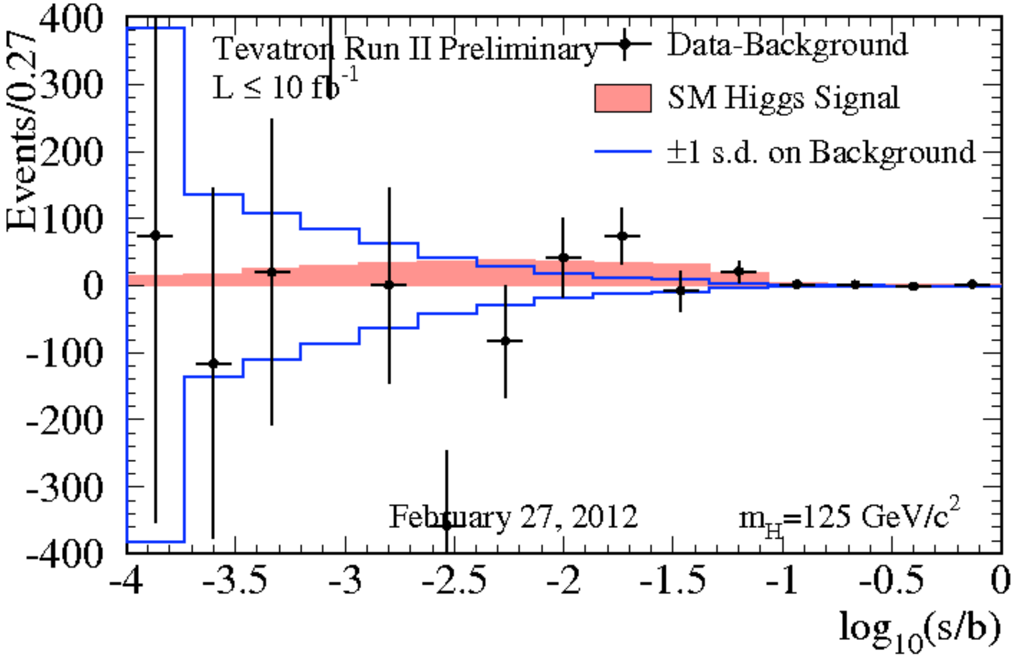


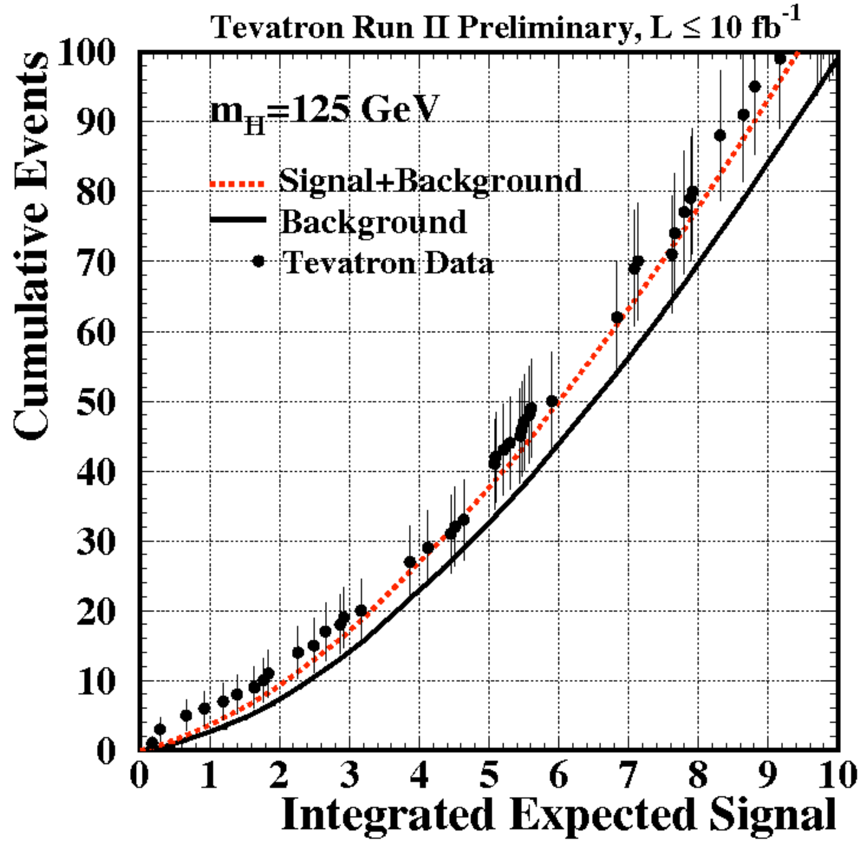
σ(WZ+ZZ)= 4.47 +/- 0.64 (stat) +/- 0.73 (syst) pb

with approximate significance of 4.6σ

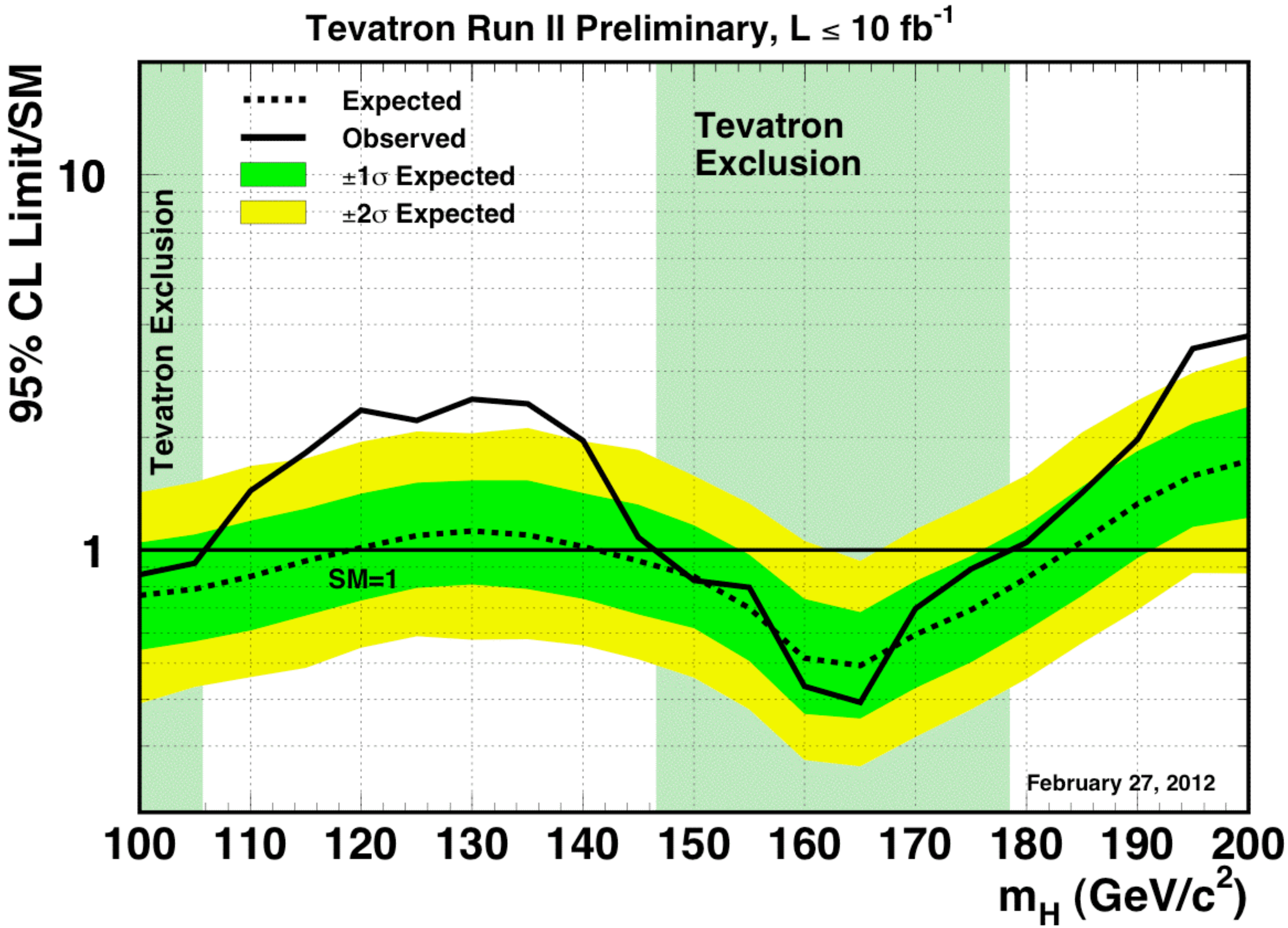
SM Prediction = 4.4 +/- 0.3 pb

Combined Higgs discriminants





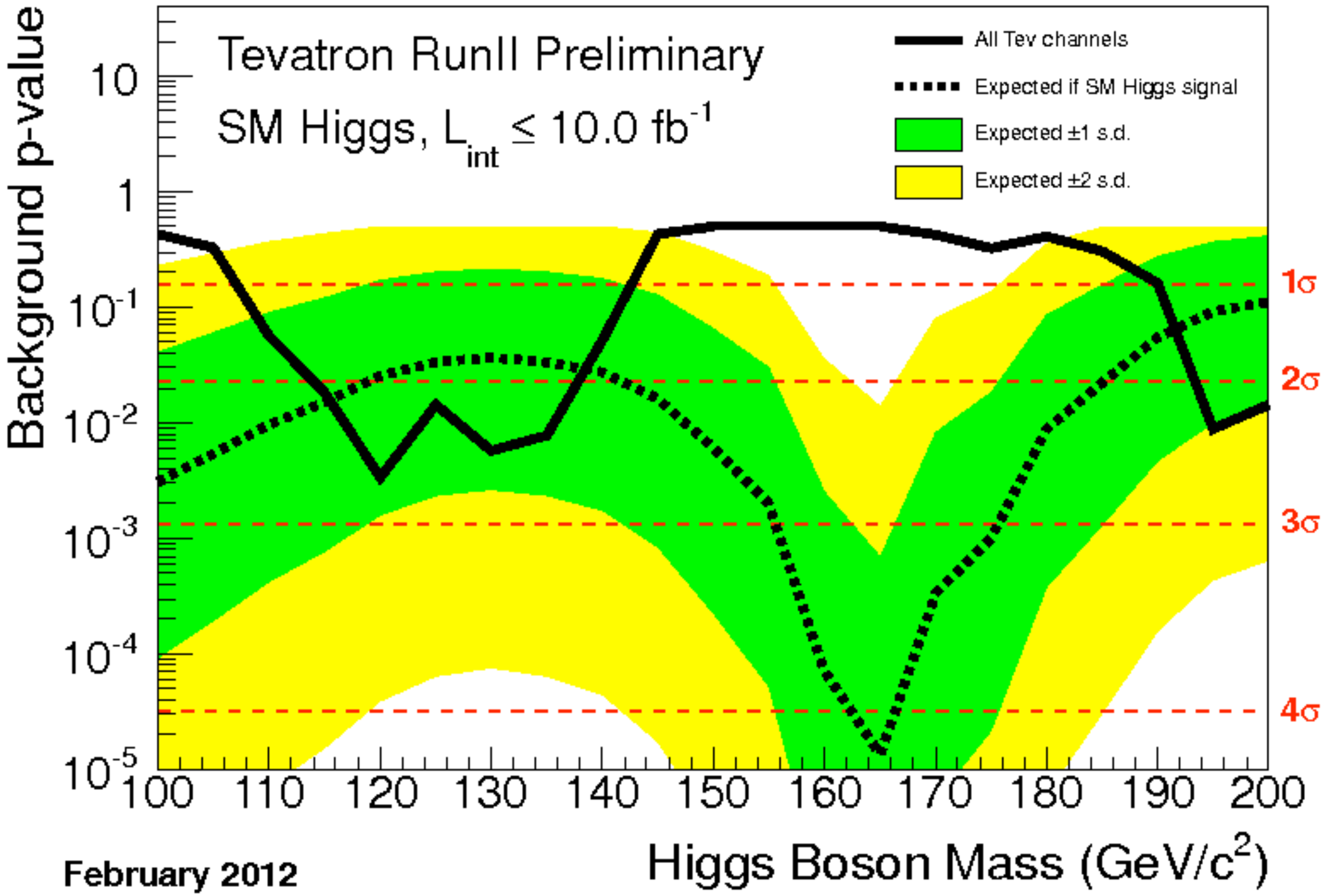
Tevatron combined limits



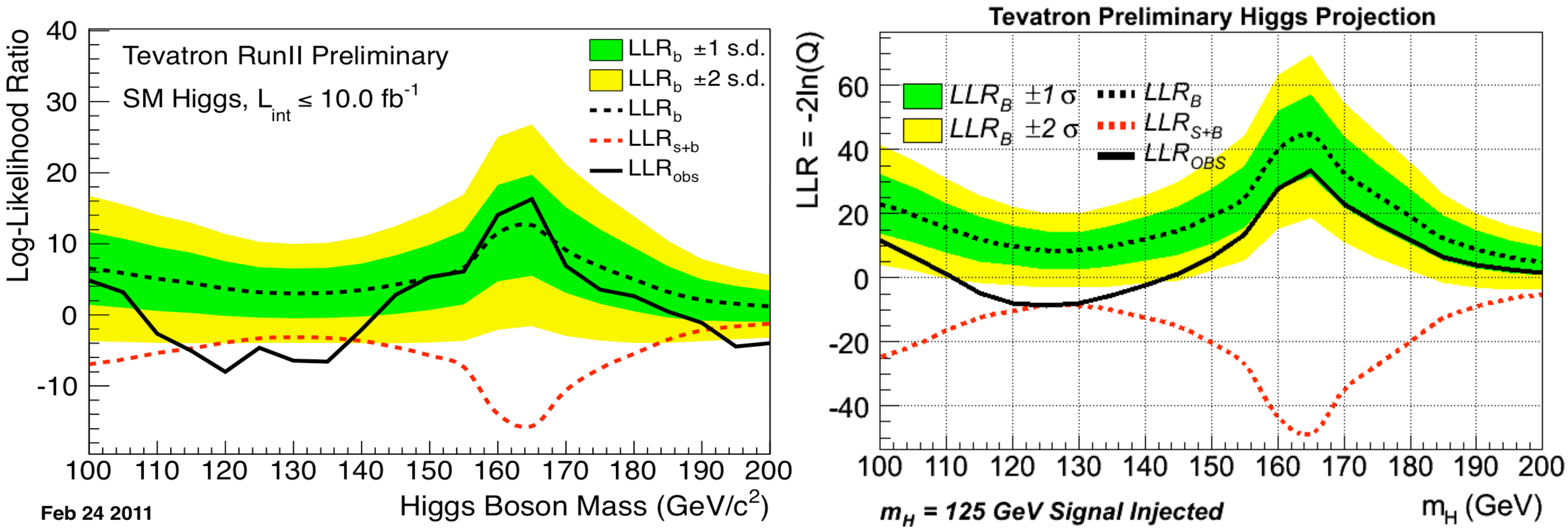
Exclude SM Higgs at 95% C.L. for $147 < m_H < 179$ GeV/c^2

Expect to exclude $100 < m_H < 120$ GeV/c^2 & $141 < m_H < 184$ GeV/c^2

Compatible with bck-only?



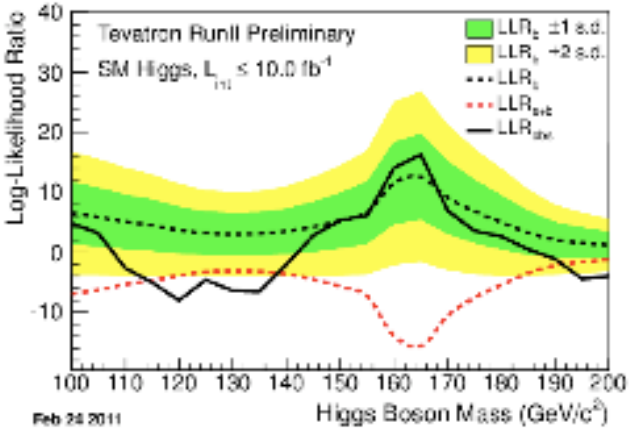
Compatible with SM Higgs?



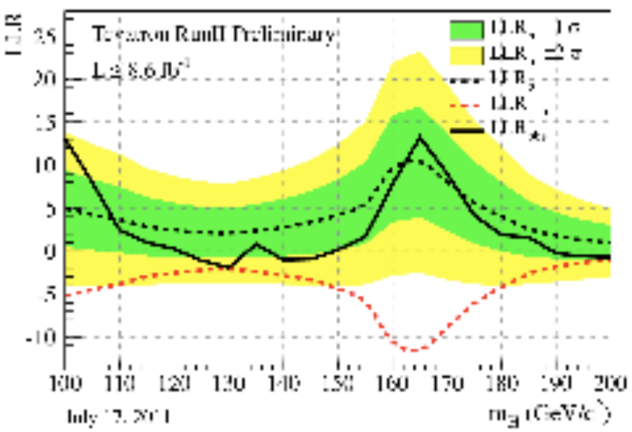
Consistent with SM signal plus background hypothesis over Higgs mass range from 110 to 140 GeV/c^2

Compatible with SM Higgs?

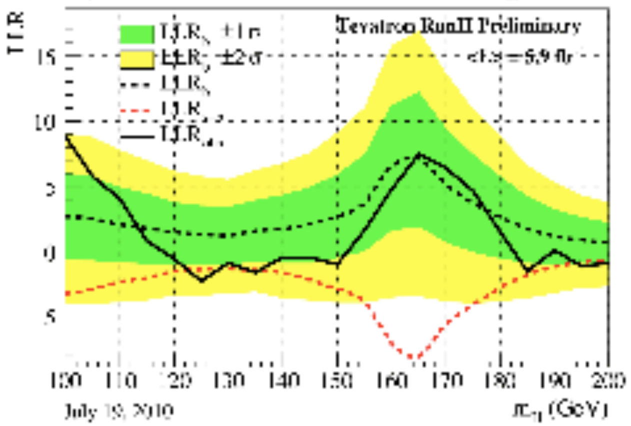
2012



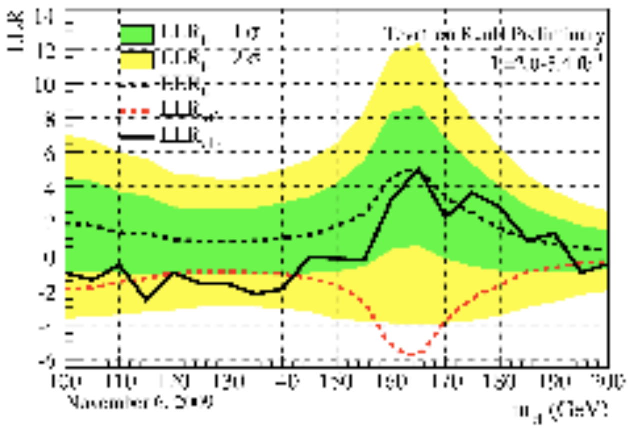
2011



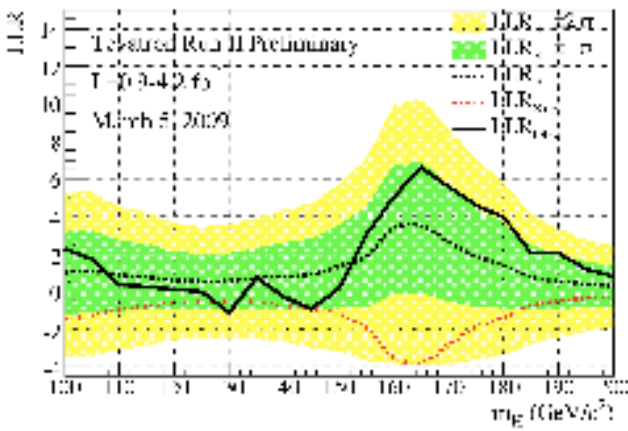
2010



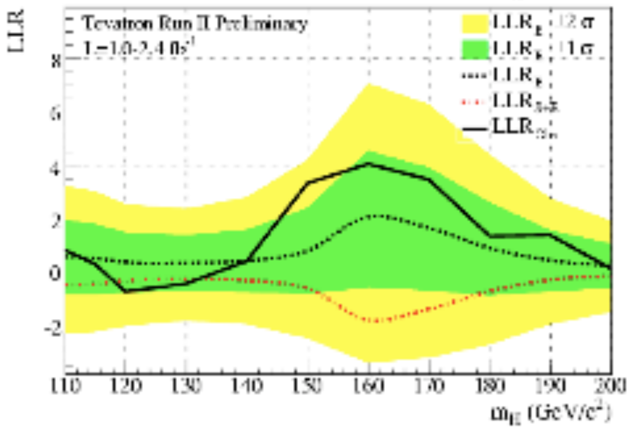
2009



2008



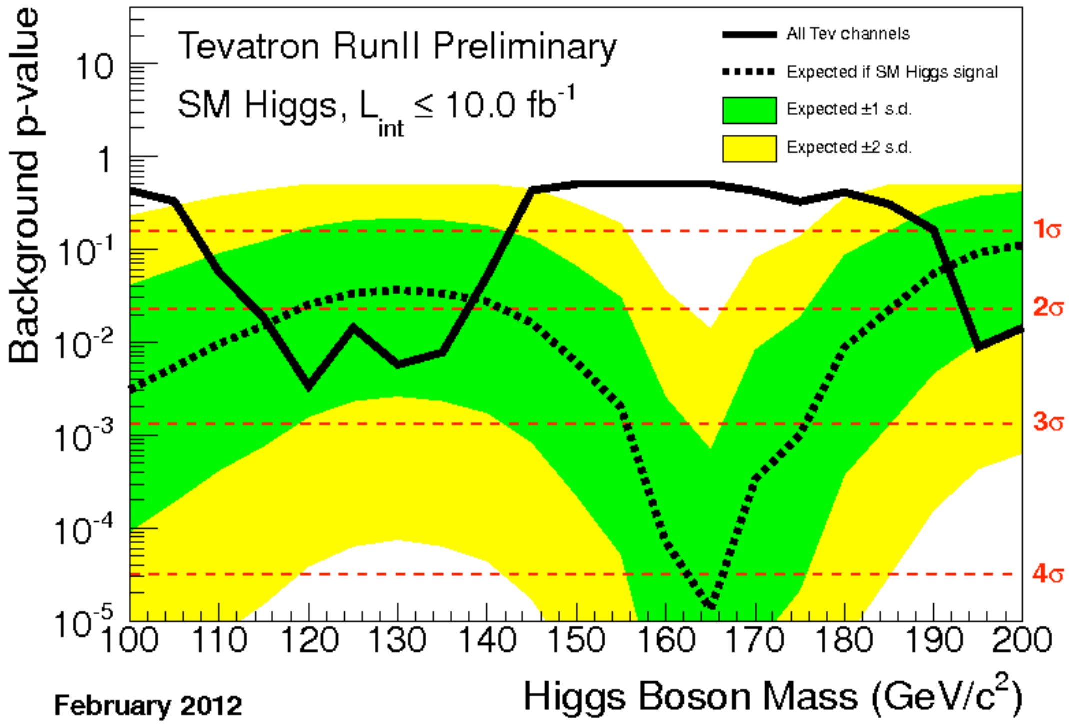
2007



Global significance

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

Same LEE of 4 for entire SM search range from 100 to 200 GeV/c^2



SM Higgs Searches		
Experiment	Local P-value	Global P-value
CDF+D0	2.8σ	2.2σ
ATLAS	3.5σ	2.2σ
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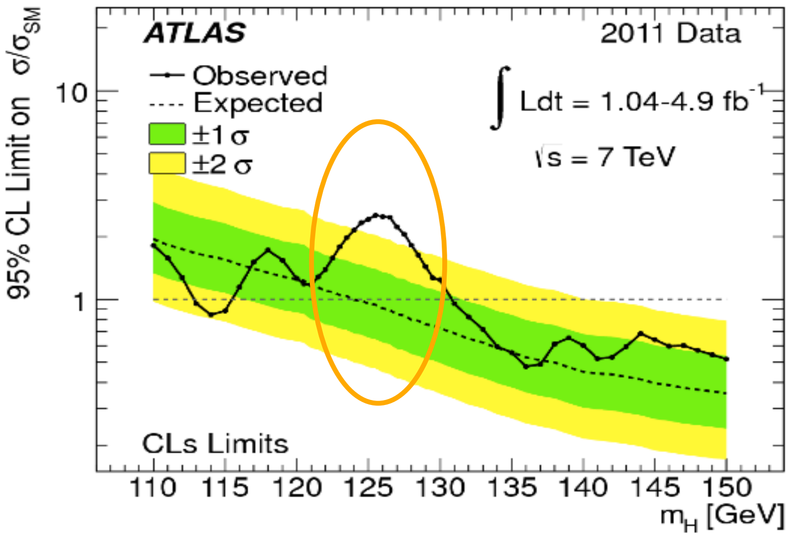
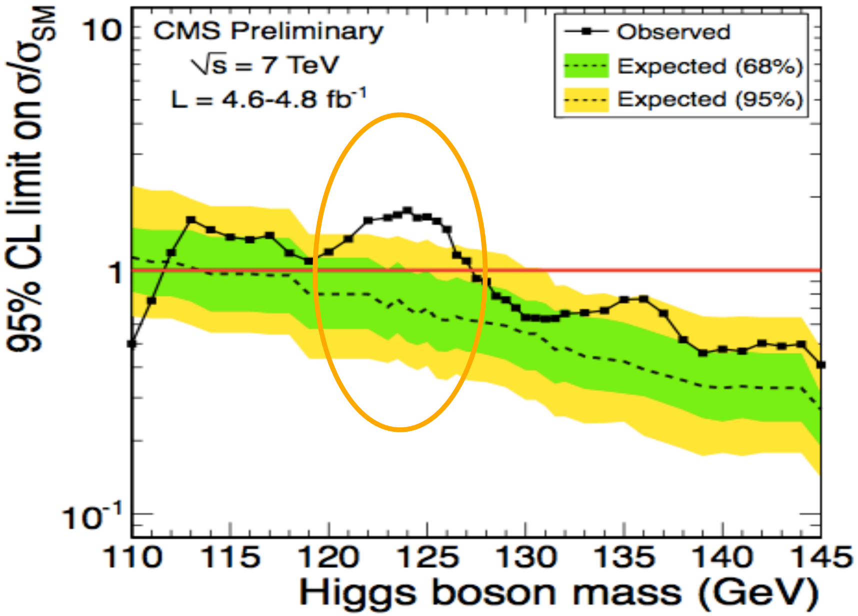
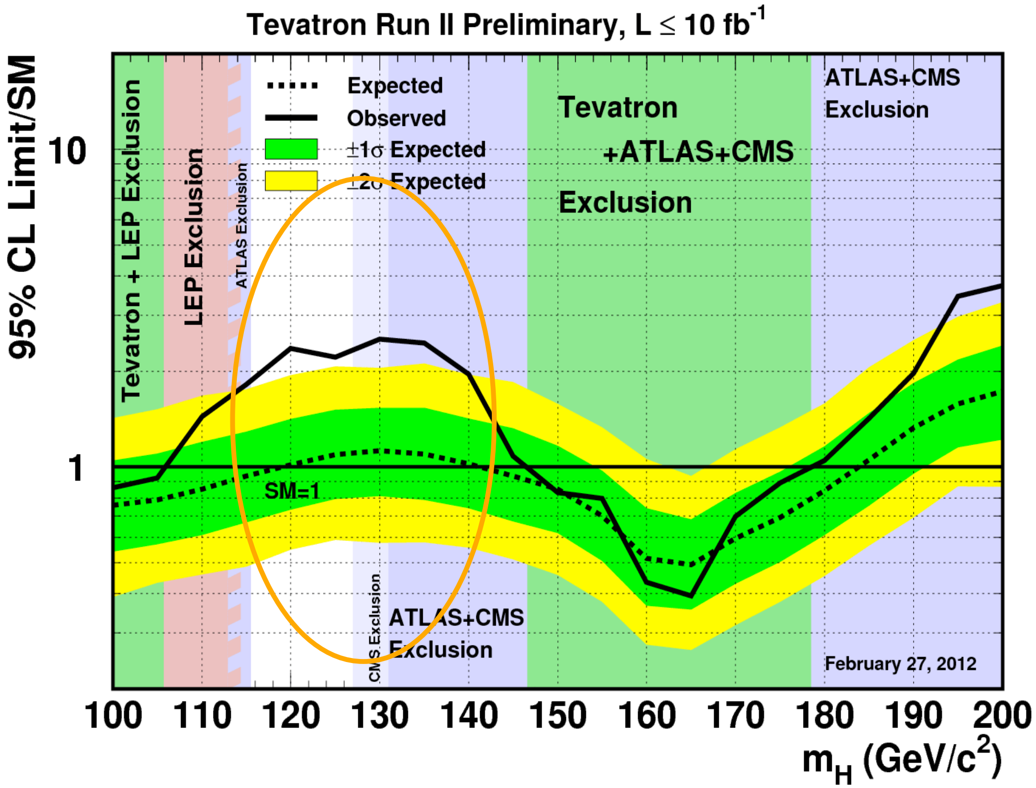
Global significance







- CDF and D0 have significantly increased the sensitivity of their Higgs searches by incorporating the full 10 fb^{-1} dataset and a wide range of analysis improvements
- We measure σ(WZ+ZZ) with a significance of 4.6σ and a value compatible with SM
- We observe an excess of Higgs-like events consistent with SM Higgs production in the mass range from 115 to 140 GeV/c^2.
- The global significance of this excess is 2.2σ