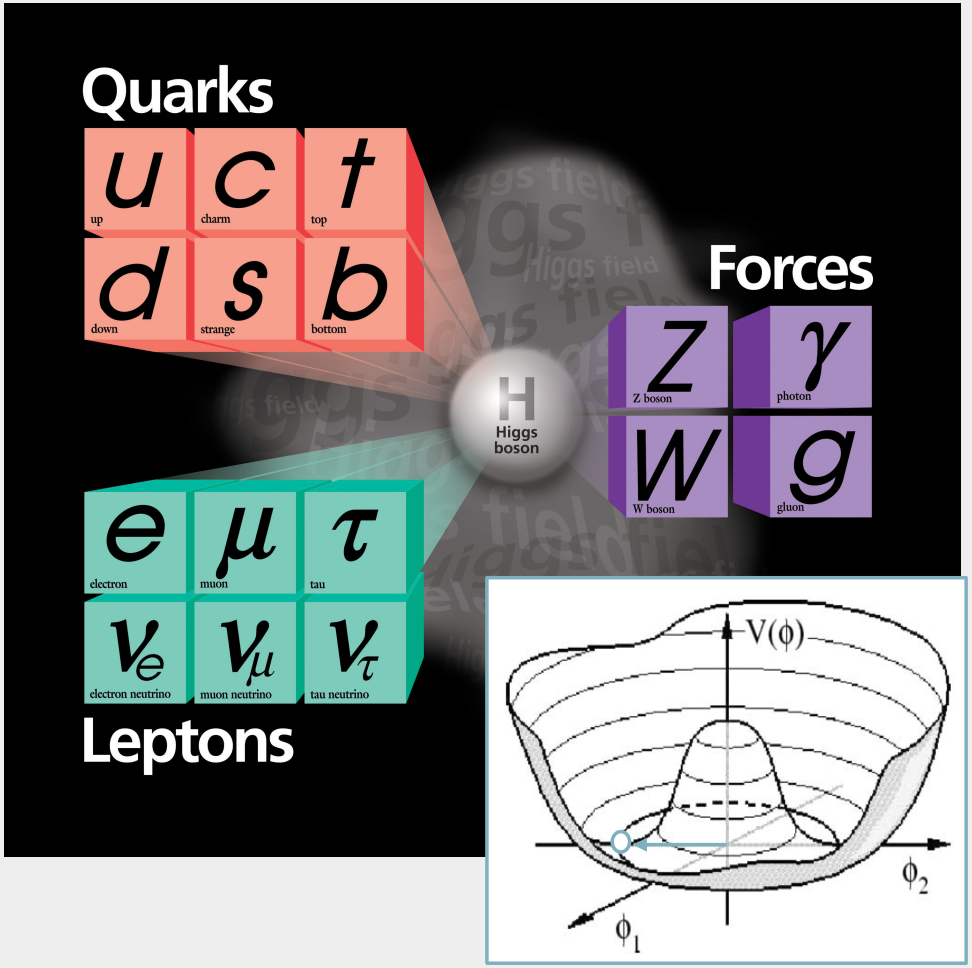
Higgs boson searches at the Tevatron

Yuri Oksuzian on behalf of CDF&D0 collaborations

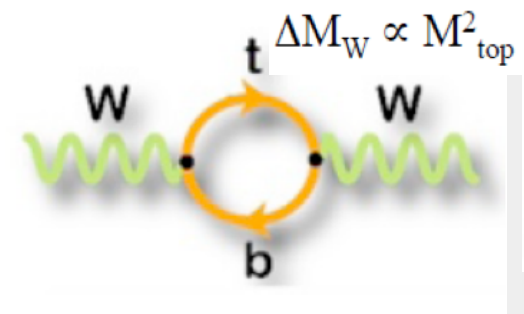
Higgs boson

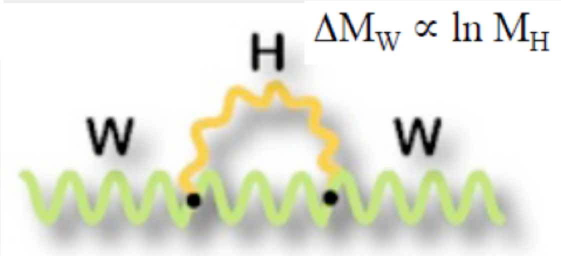
- SM describes interaction between elementary particles
- It is incomplete without the EWK symmetry breaking via Higgs mechanism
- Higgs mechanism predicts:
  - Massive vector bosons and massive terms for fermions
  - Effective mass term for Higgs fields
  - Does not predict the Higgs mass

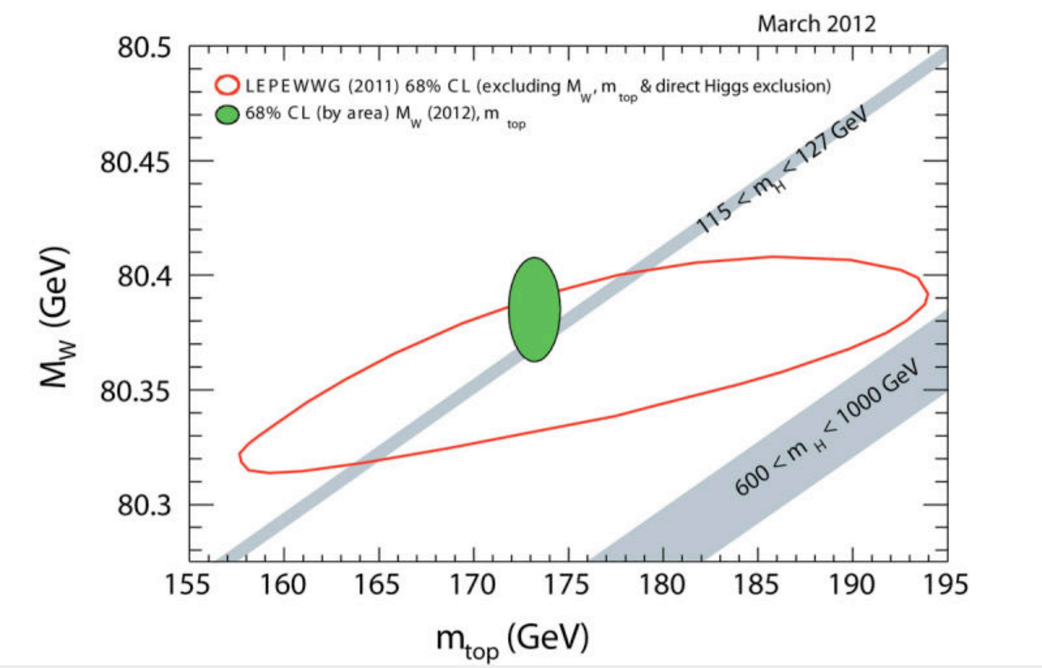


Indirect Higgs mass constraints from Tevatron

- Higgs mass is the free parameter in SM, but constrained from indirect EW measurements
- (M_W, M_{top}) prefer a SM Higgs Boson with M_H below 152 GeV
- New CDF&DØ 2012 W mass
  - 80387 +- 17 MeV/c^2
- Less than 1% uncertainty on top mass
  - M_{top} = 173.2 ± 0.9 GeV/c^2
- Some of the biggest achievements from Tevatron
- Still only direct discovery can prove EWK symmetry breaking due to Higgs mechanism

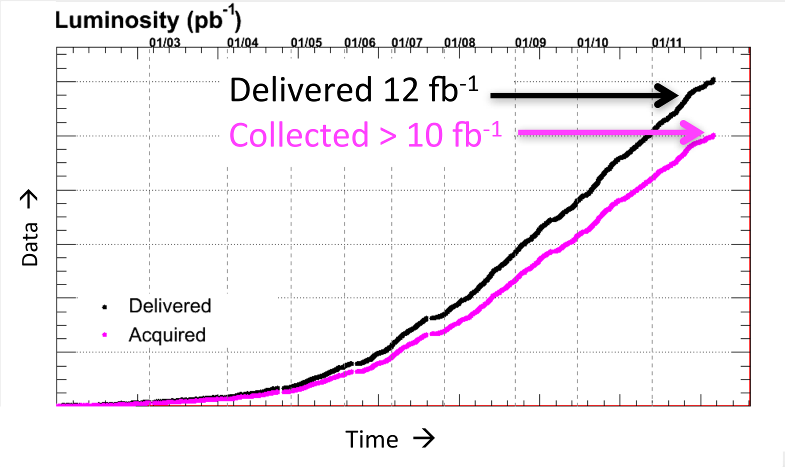






Tevatron

- p-pbar collider at Ecm = 1.96 TeV
- Two detectors: CDF & D0
- Records
  - Peak luminosity: 430×10^{30} cm^{-2} s^{-1}
  - Best week: 85/pb
- Run II: 2001-2011
  - 12 fb-1 delivered
  - 10 fb-1 collected



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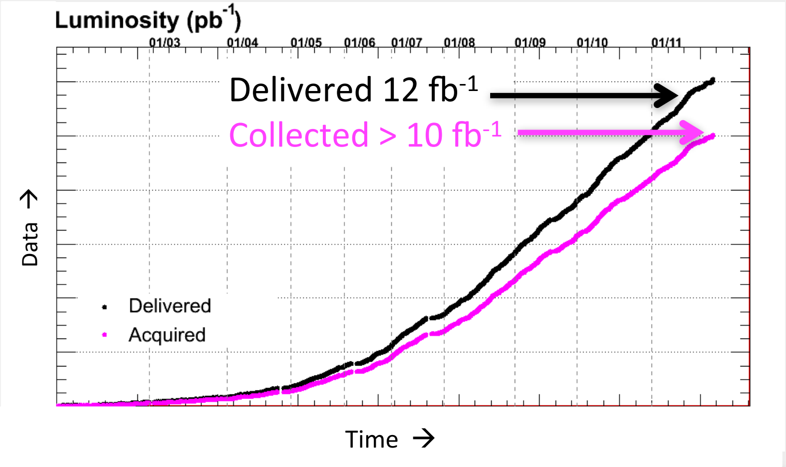
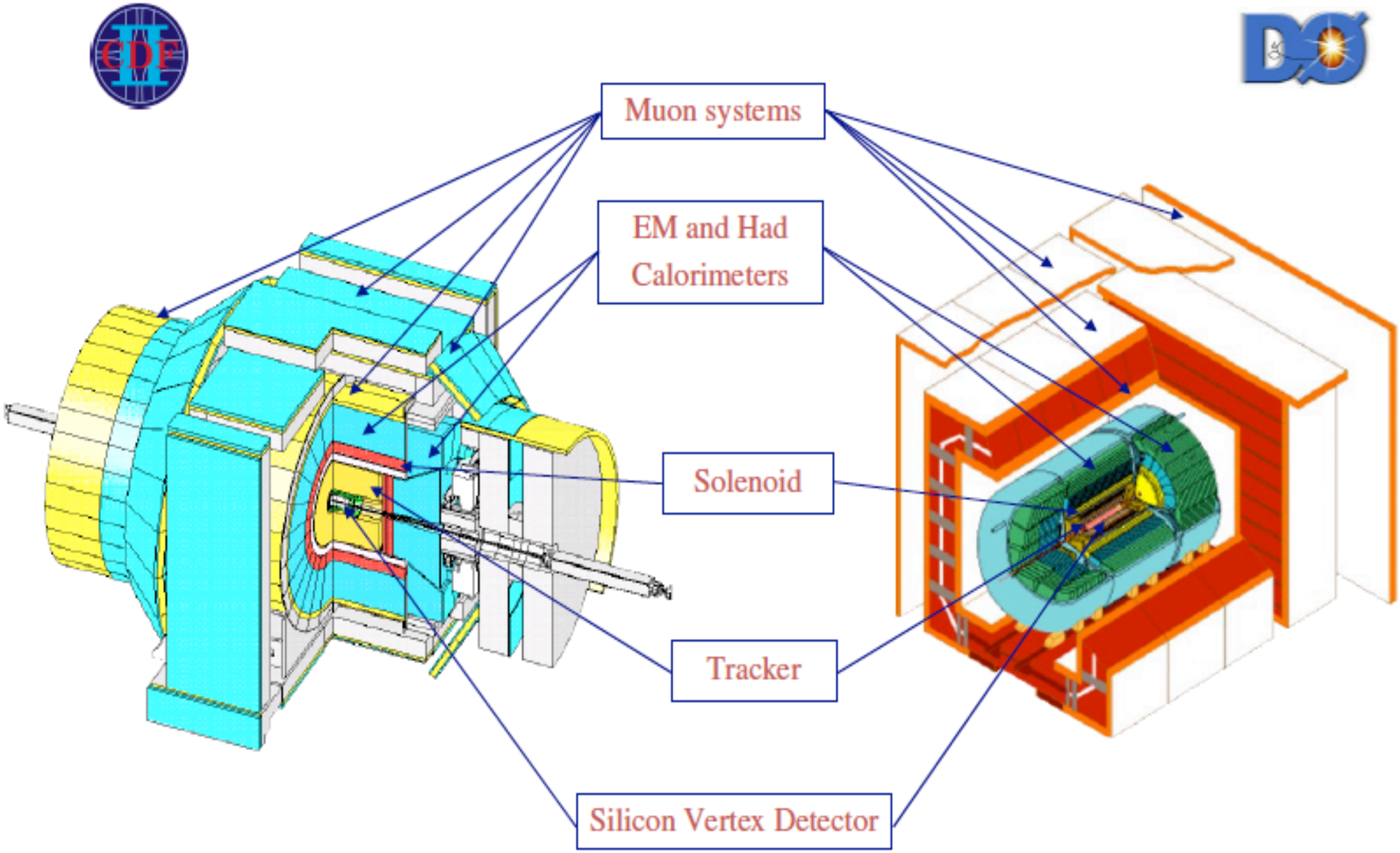
- Last collision on Sep 30th 2011
- 25 years of data-taking and exciting physics results



CDF & D0



CDF
Muon systems
EM and Had
Calorimeters
Solenoid
Tracker
Silicon Vertex Detector

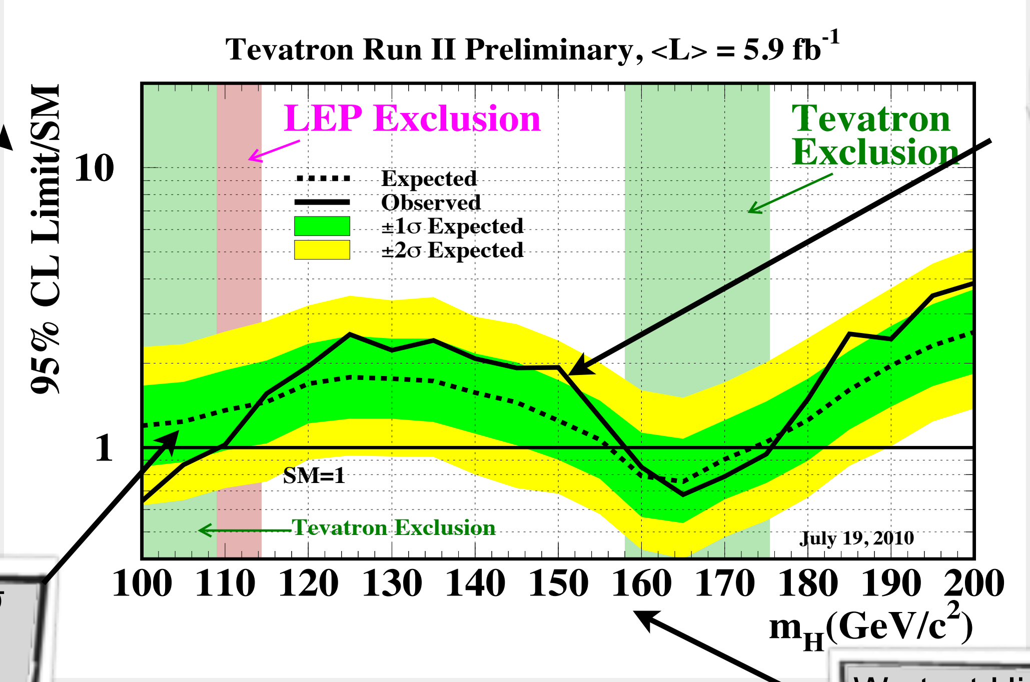
Higgs timeline at Tevatron

- Couple of results in Run I at 1.8TeV in 1998
- First results at 1.96TeV in 2004
- First Tevatron combination in 2007
- First Higgs exclusion at hadron collider in 2008
  - First time since the LEP era
- First single experiment exclusion in 2011

Previous results. Goals.

- Summer 2010, Tevatron sensitivity was <2xSM
- ~30% gain in sensitivity by using full dataset
- Crucial to improve the analysis technique
  - Luminosity only improvements were not sufficient

Upper limits on cross section for Higgs production relative to SM prediction

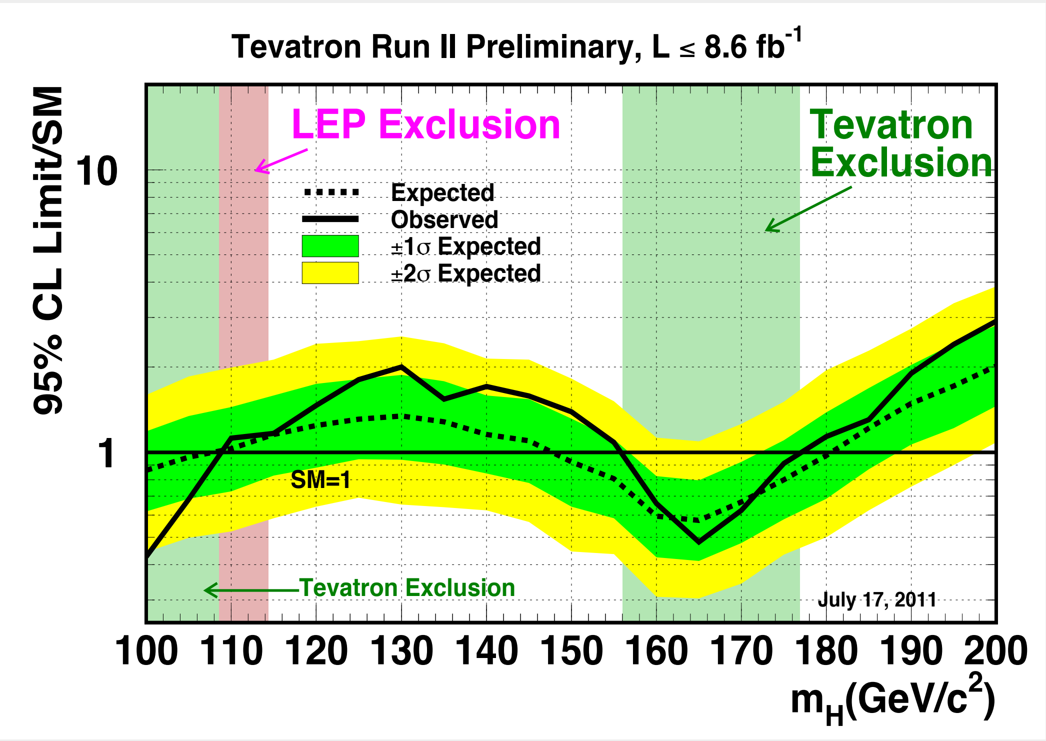


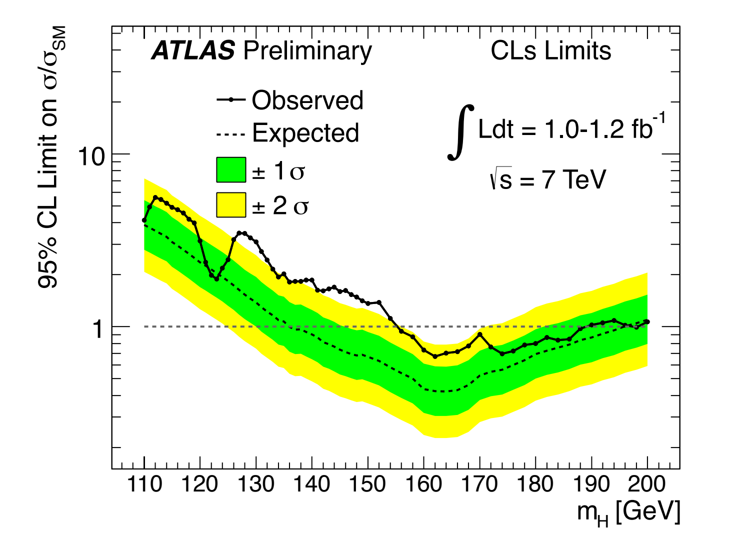
Observed limit from data

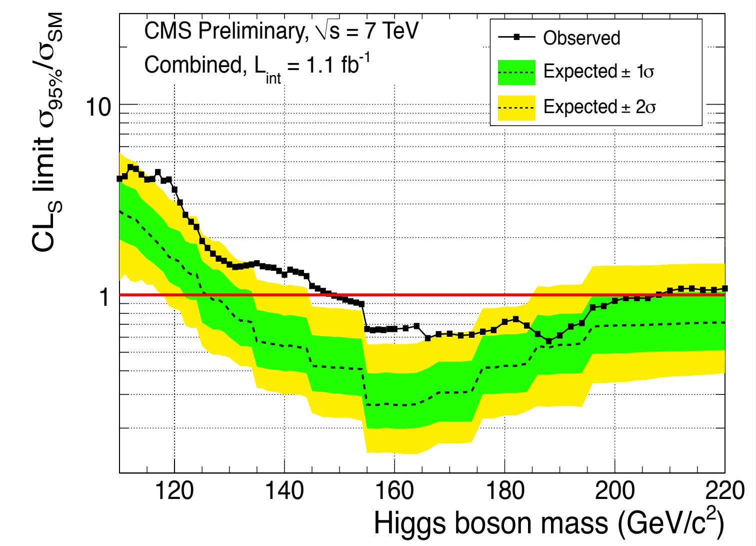
Expected limit and 1σ/2σ from background only pseudo-experiments

We test Higgs mass ranges of 100-200 GeV in 5 GeV steps

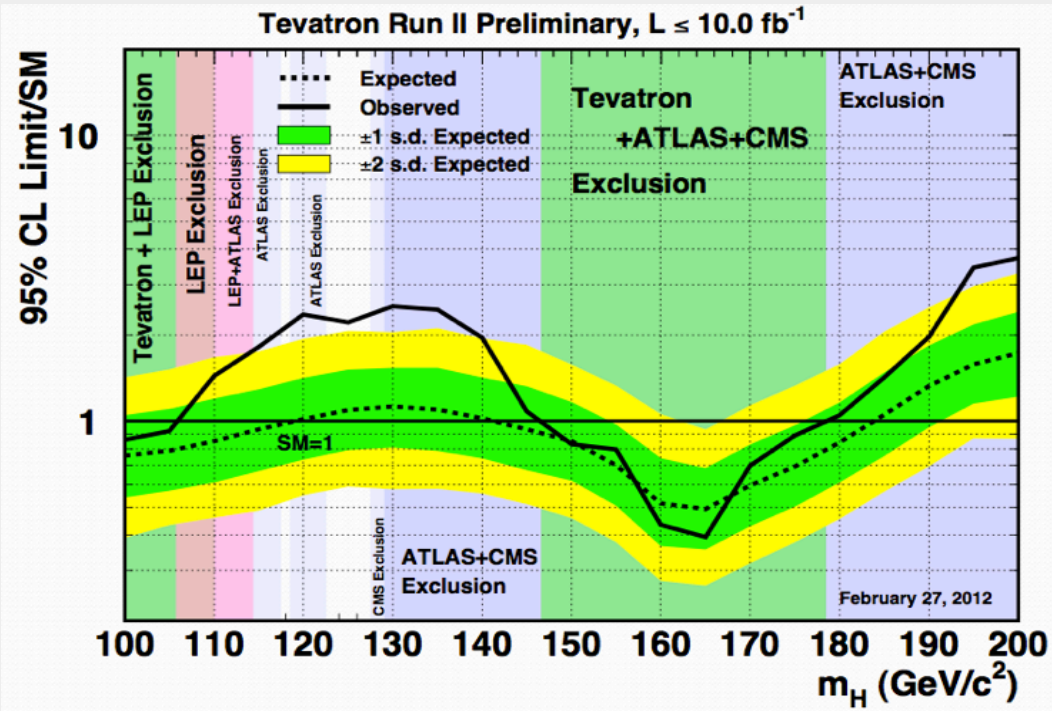
Summer 2011

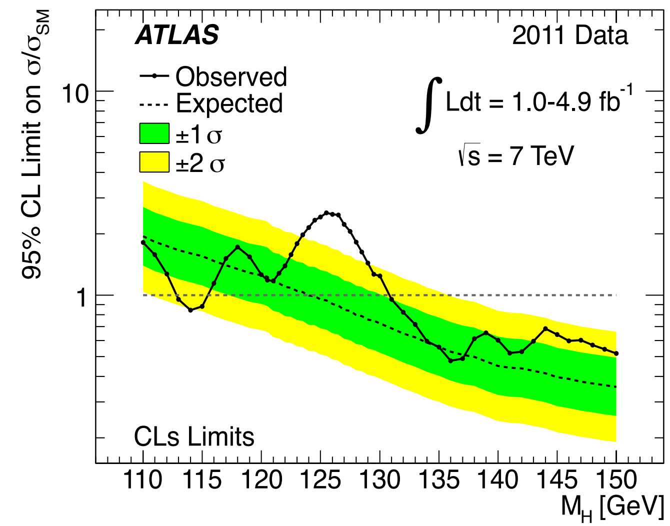

Tevatron Run II Preliminary, L ≤ 8.6 fb-1
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 17, 2011
95% CL Limit/SM
10
1
100 110 120 130 140 150 160 170 180 190 200
mH(GeV/c2)

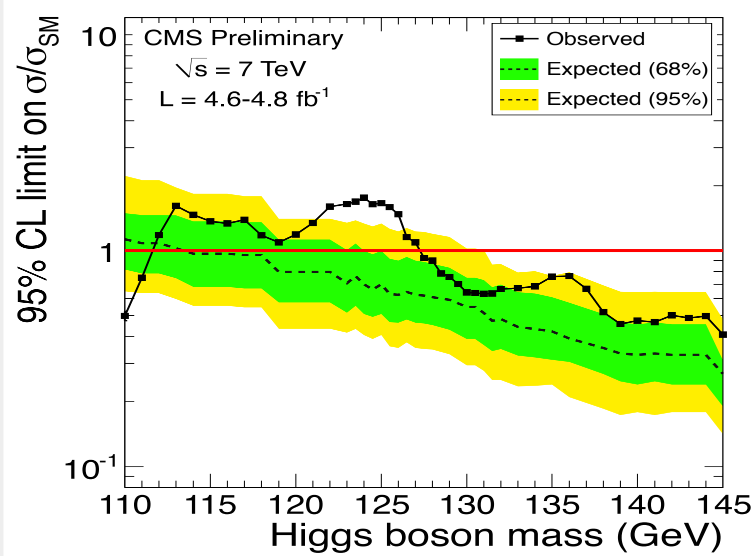

ATLAS Preliminary
CLs Limits
Observed
Expected
± 1 σ
± 2 σ
∫Ldt = 1.0-1.2 fb-1
√s = 7 TeV
95% CL Limit on σ/σSM
10
1
110 120 130 140 150 160 170 180 190 200
mH [GeV]


CMS Preliminary, √s = 7 TeV
Combined, Lint = 1.1 fb-1
Observed
Expected ± 1σ
Expected ± 2σ
CLS limit σ95%/σSM
10
1
120 140 160 180 200 220
Higgs boson mass (GeV/c2)

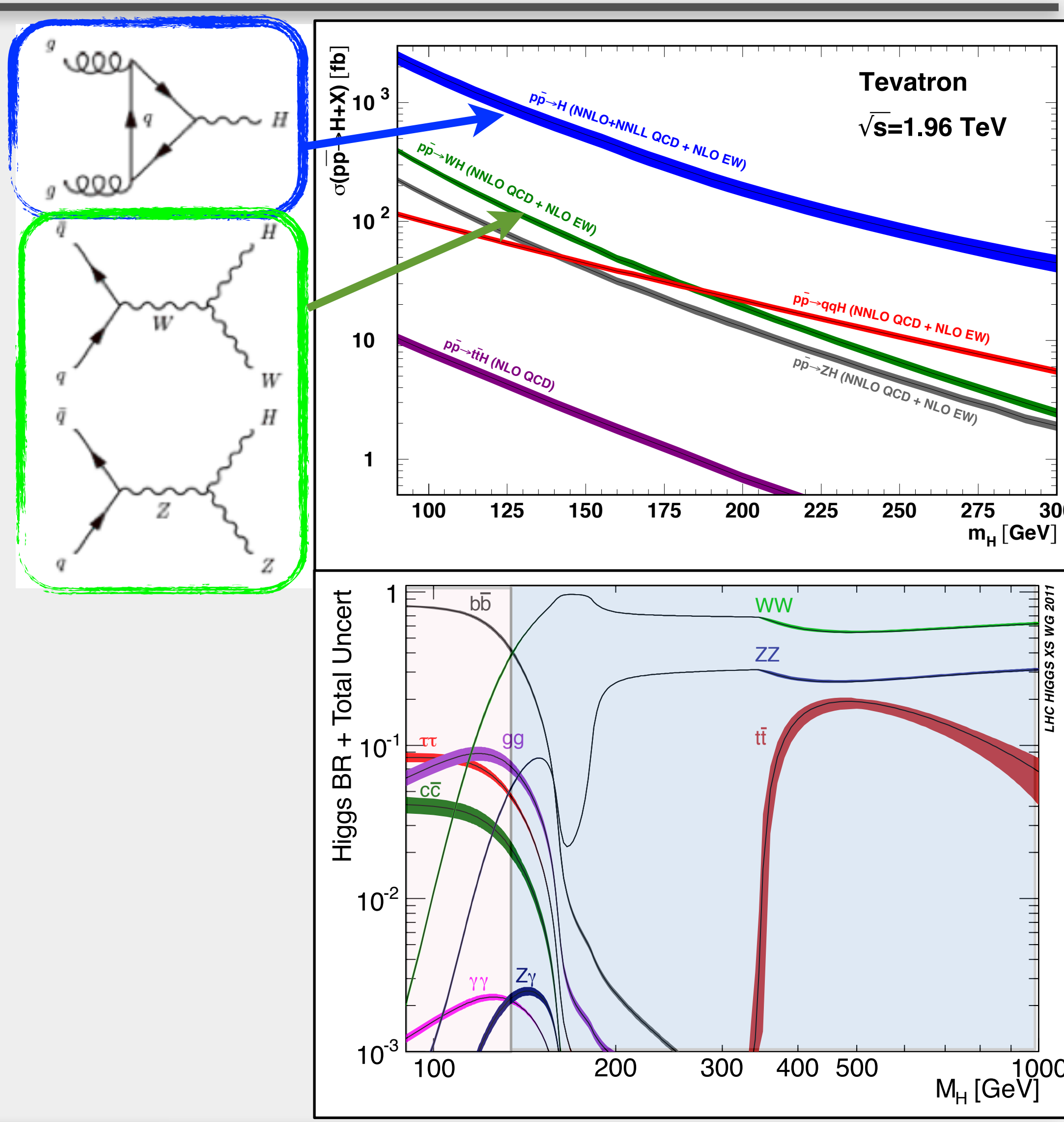
Winter 2012


Tevatron Run II Preliminary, L ≤ 10.0 fb⁻¹
95% CL Limit/SM
Expected
Observed
±1 s.d. Expected
±2 s.d. Expected
Tevatron + LEP Exclusion
LEP Exclusion
LEP+ATLAS Exclusion
ATLAS Exclusion
ATLAS Exclusion
Tevatron
+ATLAS+CMS
Exclusion
ATLAS+CMS
Exclusion
SM=1
CMS Exclusion
ATLAS+CMS
Exclusion
February 27, 2012
100 110 120 130 140 150 160 170 180 190 200
m_H (GeV/c²)


ATLAS
2011 Data
Observed
Expected
±1 σ
±2 σ
∫Ldt = 1.0-4.9 fb⁻¹
√s = 7 TeV
95% CL Limit on σ/σ_SM
CLs Limits
110 115 120 125 130 135 140 145 150
M_H [GeV]

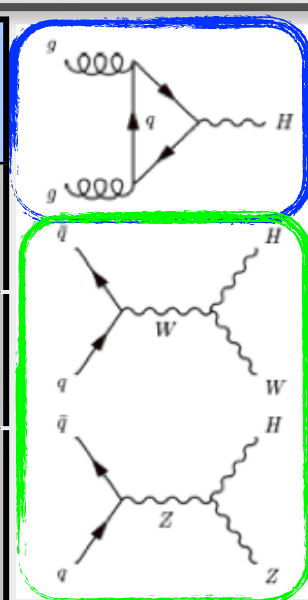

CMS Preliminary
√s = 7 TeV
L = 4.6-4.8 fb⁻¹
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σ_SM
110 115 120 125 130 135 140 145
Higgs boson mass (GeV)

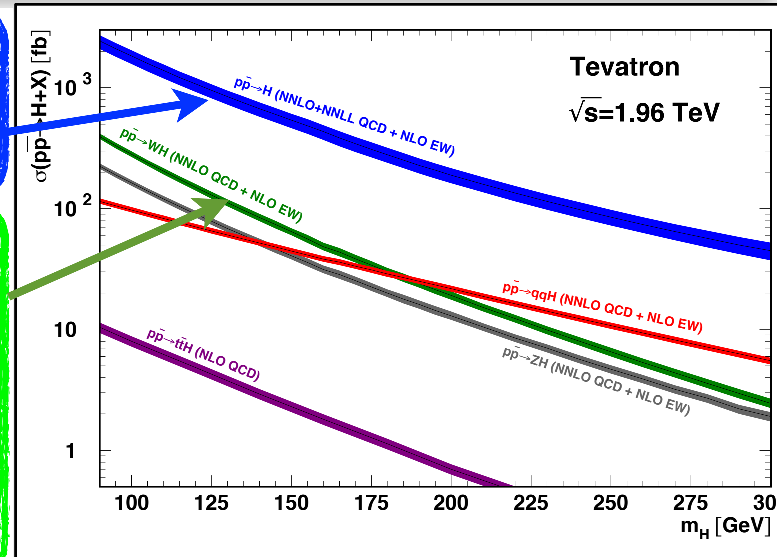
Higgs production

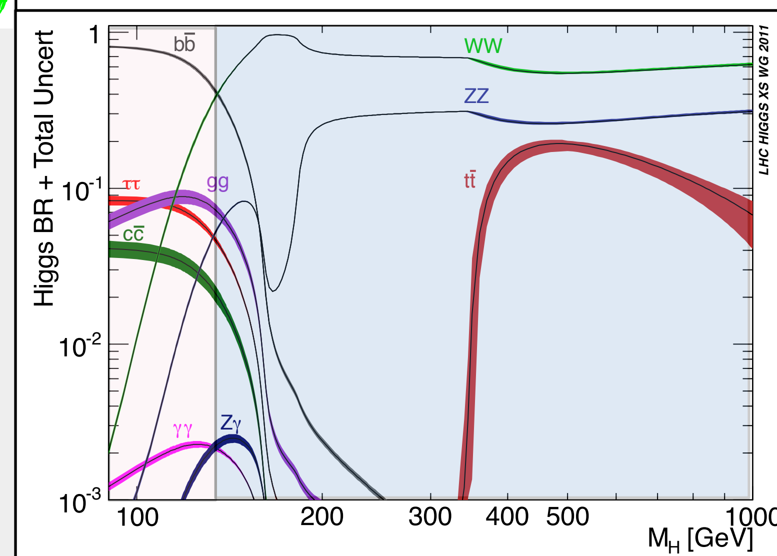


Higgs production

	Low mass	High mass
Production*	WH, ZH	gg→H
Decay	H→*bb*	H→WW
Main modes	*bb*+ℓν *bb*+ℓℓ *bb*+νν	ℓℓ+νν

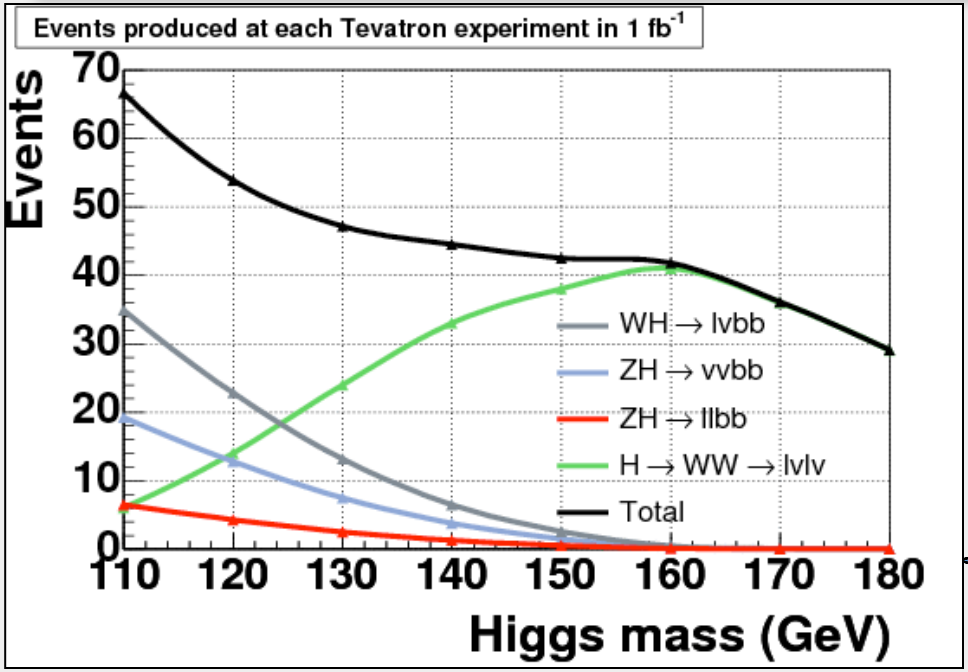


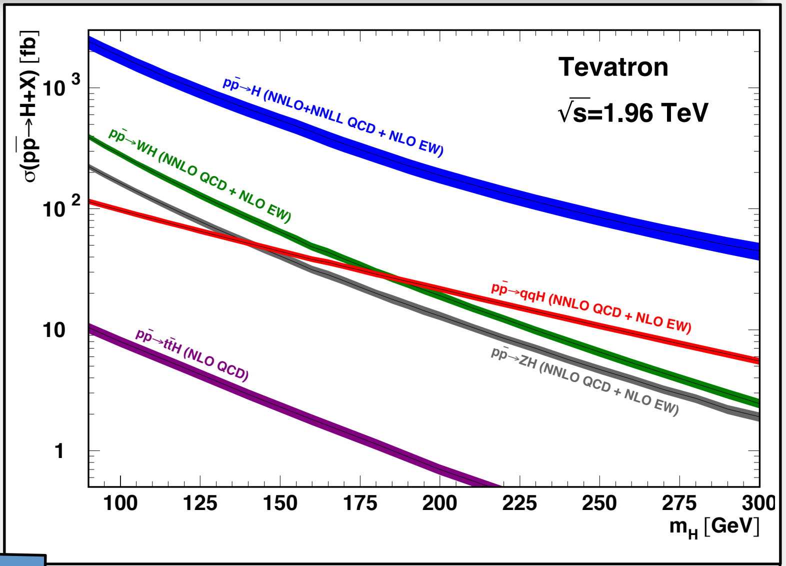


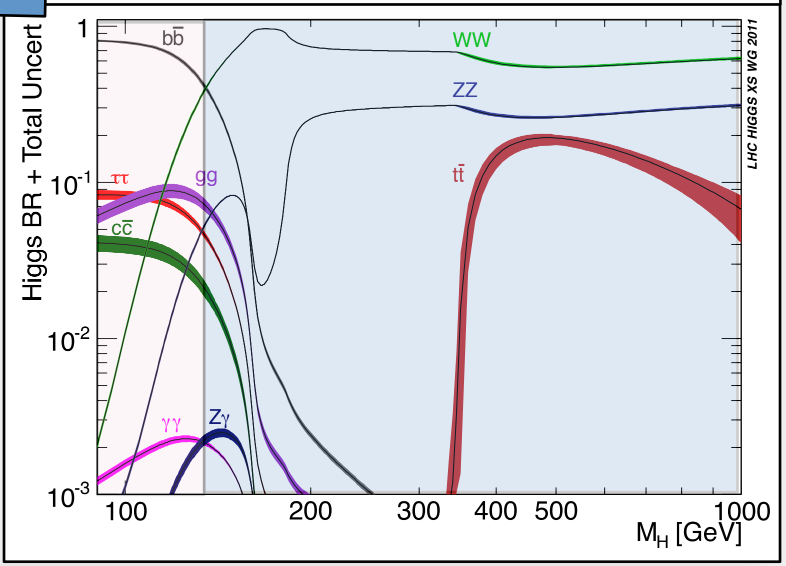


* No channel is left behind. LONG list of "secondary"channels with total weight of 10% to the final combination

Higgs production

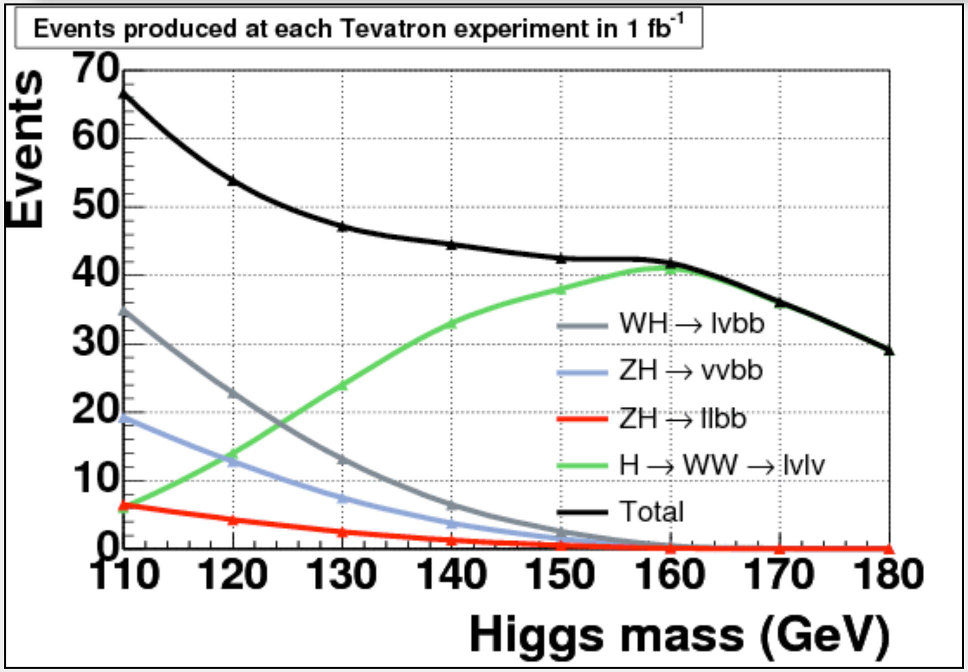




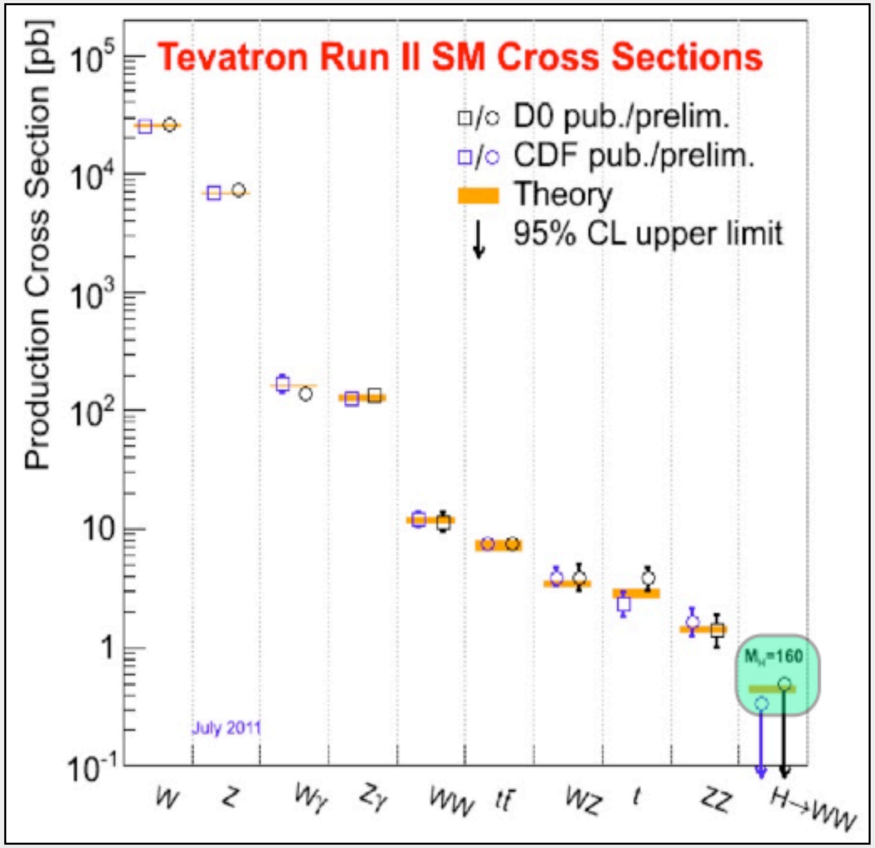


- About 1000 Higgs events expected in main channels of full Tevatron dataset (10 fb^{-1})
- 10-20% survive trigger+reconstruction +selection efficiency

Higgs production



- Higgs signal is buried under overwhelmed SM background processes
- Yesterday's signal is today's background



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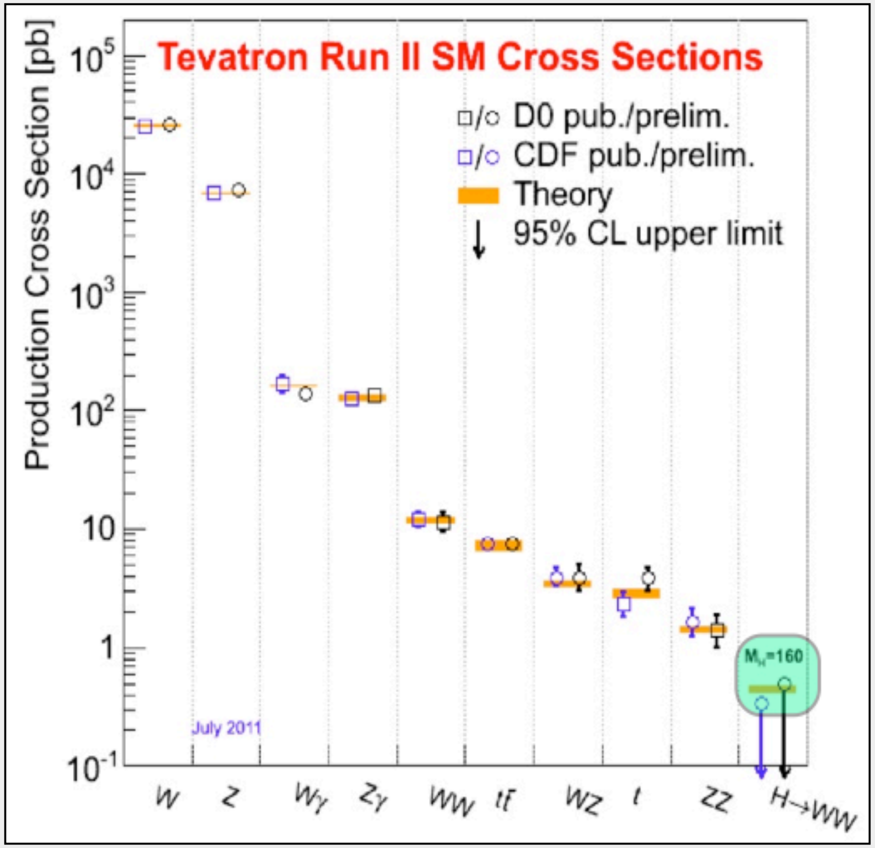
Higgs production

- Higgs signal is buried under overwhelmed SM background processes
- Yesterday's needles is today's haystack

- How to find a needle?
  - Maximize signal acceptance
    - ✓ triggers
    - ✓ leptons
    - ✓ b-jet tagging and resolution
    - ✓ explore all final states
  - Model signal and all background processes well to reduce BG
  - Counting won't work
    - ✓ Advanced MVA analysis technique



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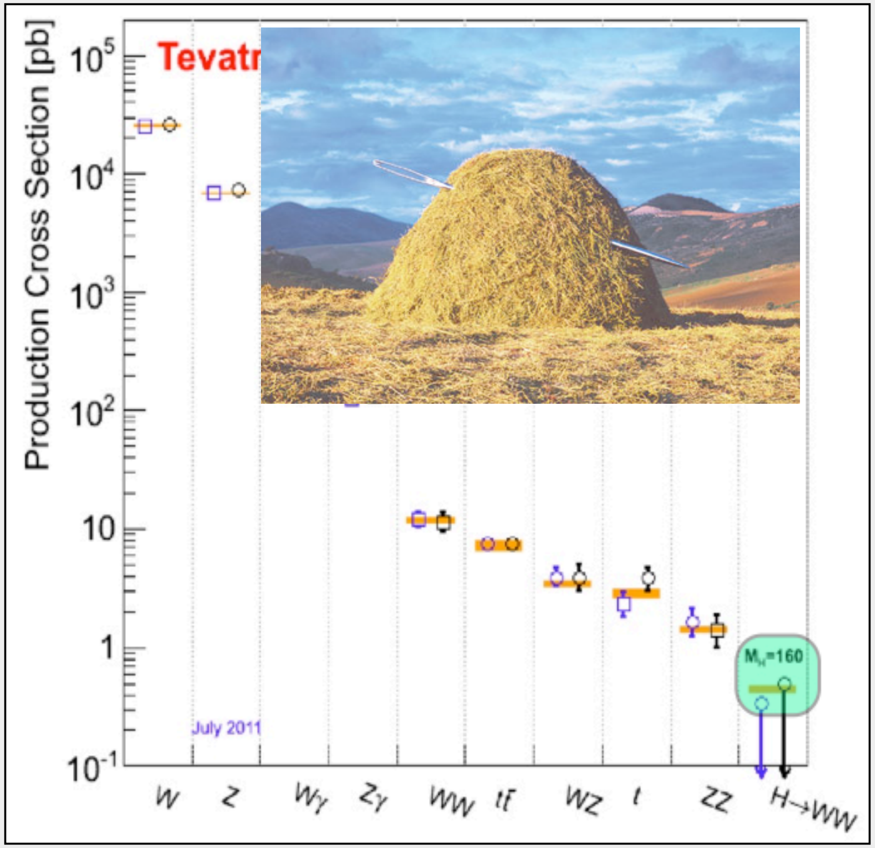
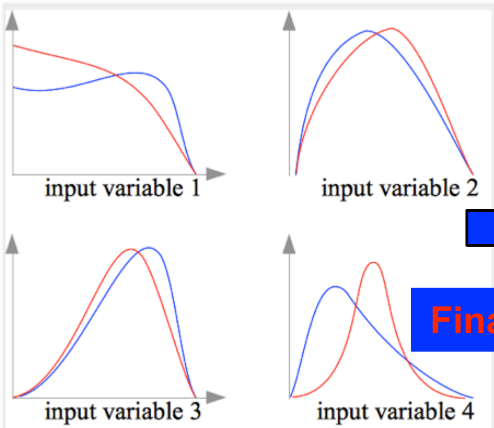


Multivariate techniques

Event kinematics

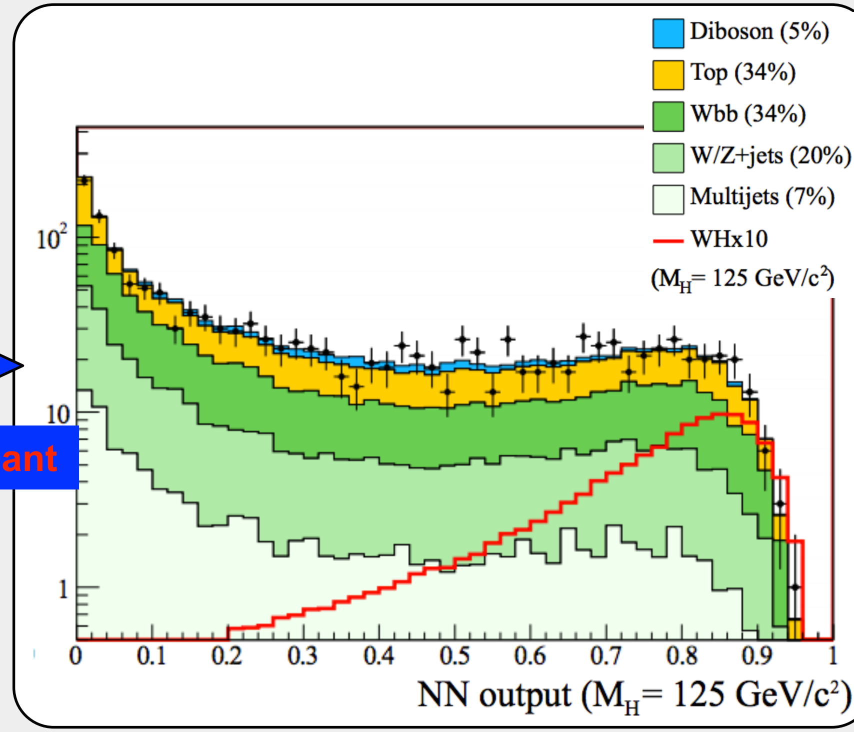
Signal

Backgrounds



Correlate multiple input variables

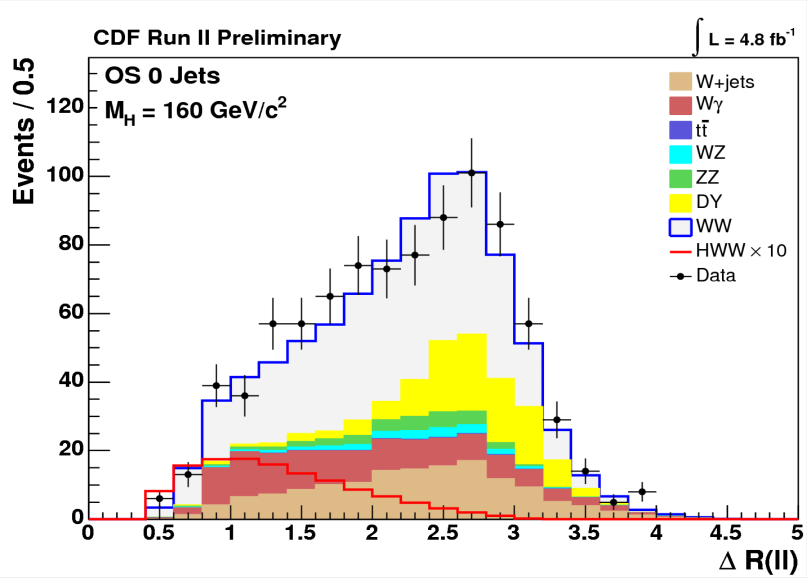
Final discriminant

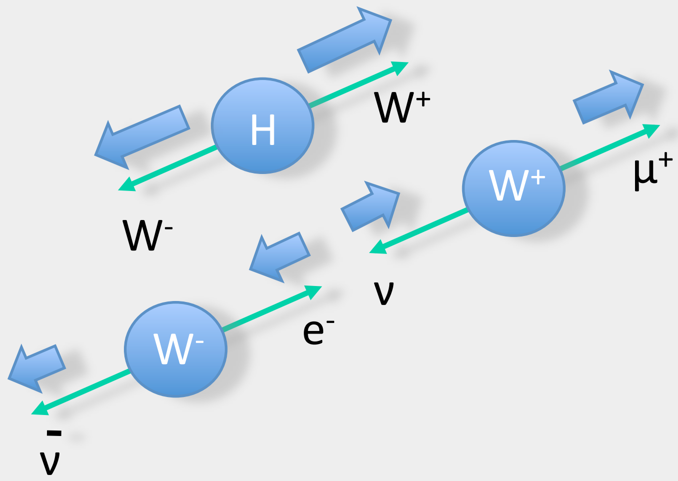


1-2 years of data taking

Improve analysis by ~20% compared to the fit of the most sensitive variable

H→WW strategy

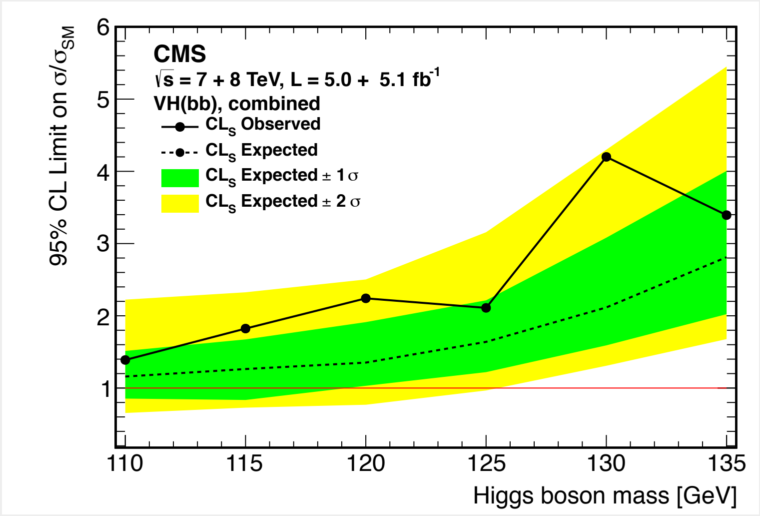


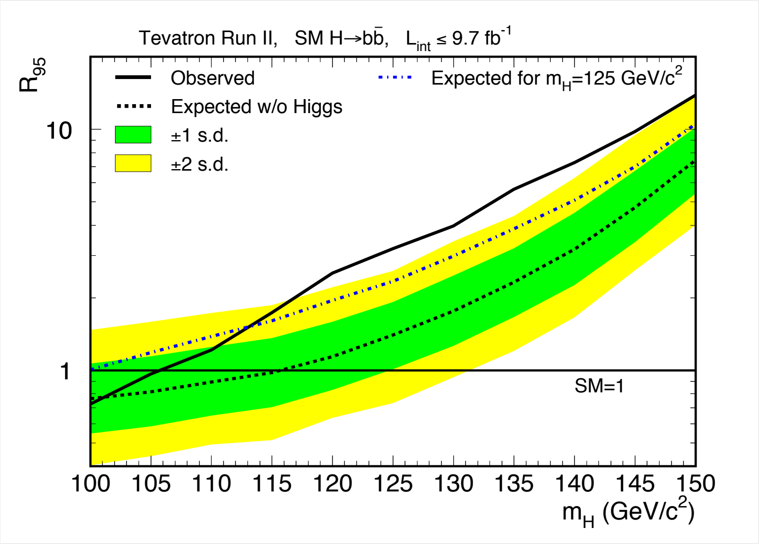


- Two opposite charge lepton, large missing Et
- No resonance - smeared by neutrino. Angular distributions are useful to distinguish
- Spin correlations: lepton go in the same direction
- Dilepton opening angle is strongest discriminant
- To take full advantage MVA is used.

Strength of Tevatron is H→bb

Sensitivity at M_H=125 GeV		
	Tevatron	Atlas, CMS
H→WW	~3.5xSM	1xSM
H→γγ	<10xSM	0.5-1xSM
H→bb	1.5xSM	1.6xSM





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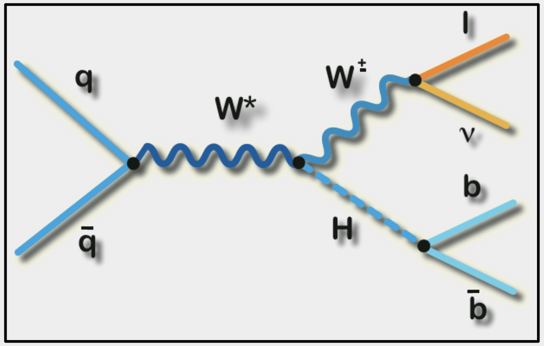
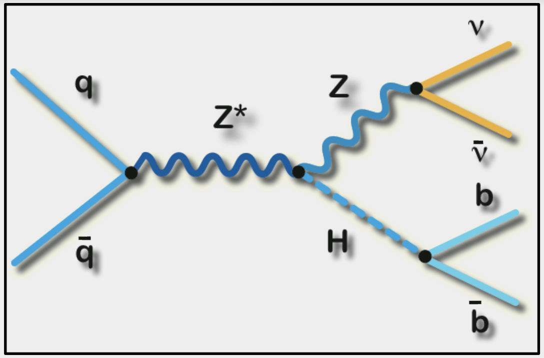
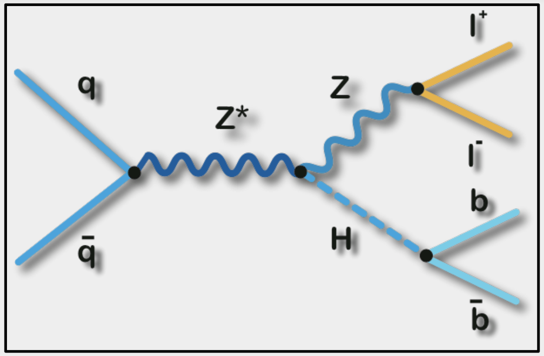
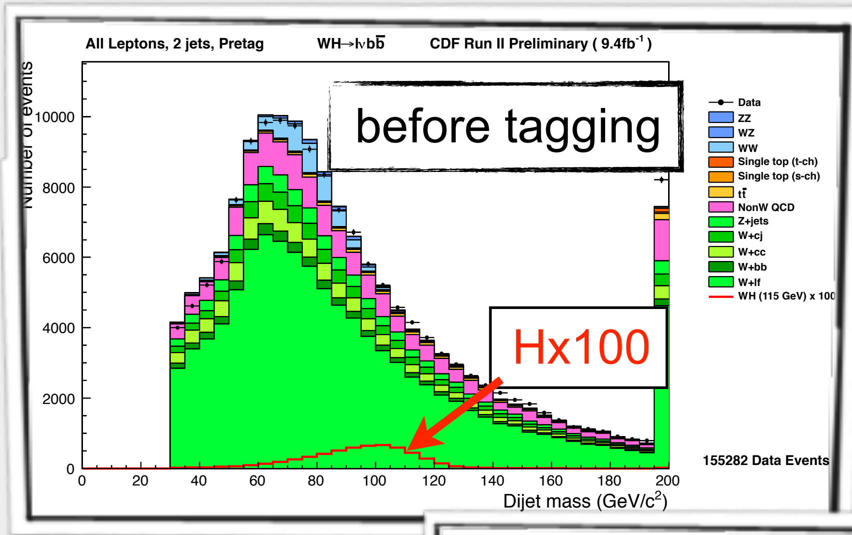


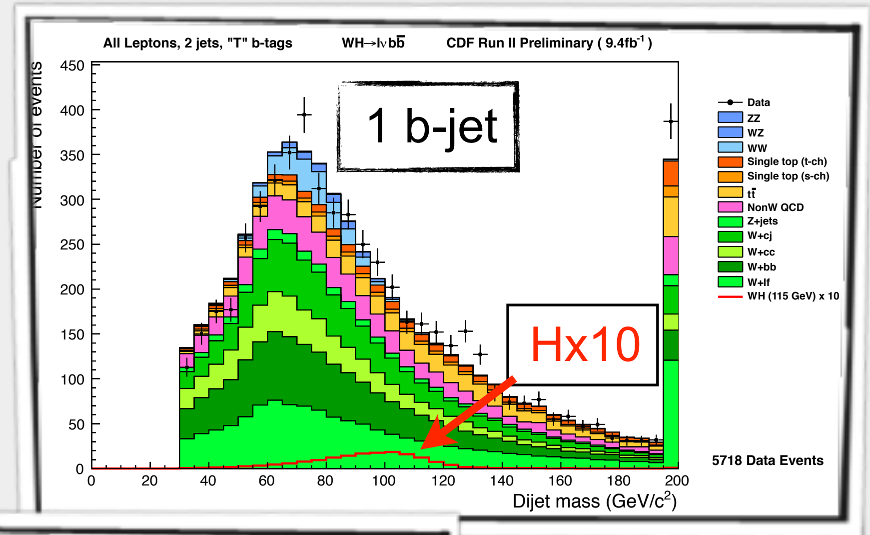


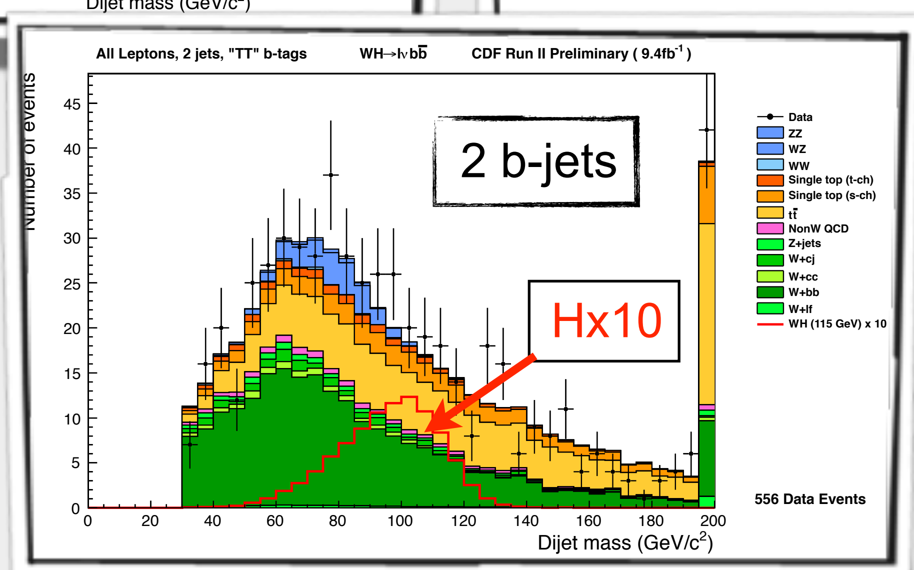


- It's all about b-jets.
  - b-tagging ID efficiency
  - di-jet mass resolution
- Higher lepton acceptance helps as well
- Use MVA analyses to discriminate between signal and background or various background components

Effect of b-tagging

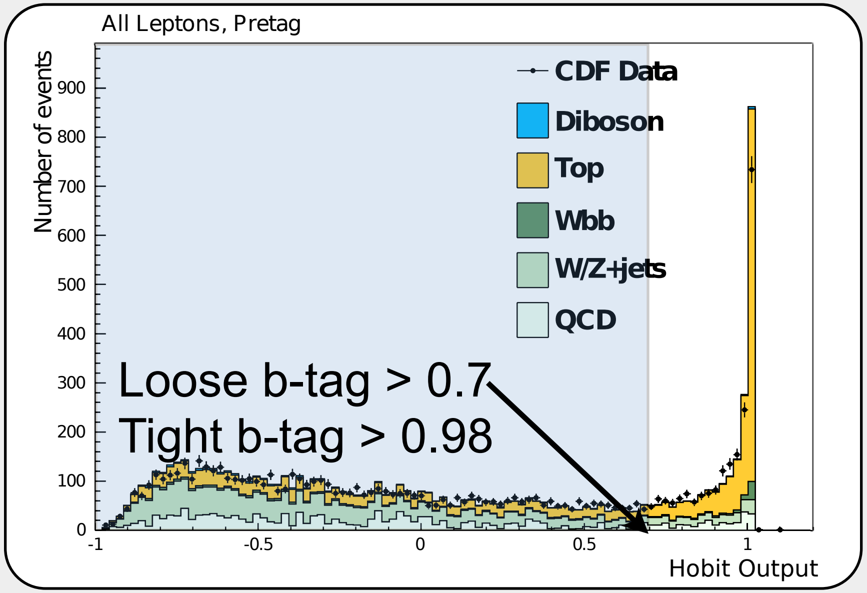






The Higgs-Optimized b-Identification Tagger(HOBIT)

- Take advantage b-meson lifetime(displaced vertex) and soft lepton from semi-leptonic decays.
- By 2010 CDF had at least 5 types of b-taggers
- We incorporate the knowledge from previous taggers into:
  - The Higgs-Optimized b-Identification Tagger (HOBIT) - multivariate b-jet tagger



mistag rate	SecVtx efficiency* (old tagger)	b-tag efficiency* (new tagger)
~1%	39%	54%
~3%	47%	59%

Operating Point	mistag rate*	b-tag efficiency*
Tight	~1%	54%
Loose	~9%	70%

Form 5 orthogonal tagging categories: TT, TL, T, LL, L

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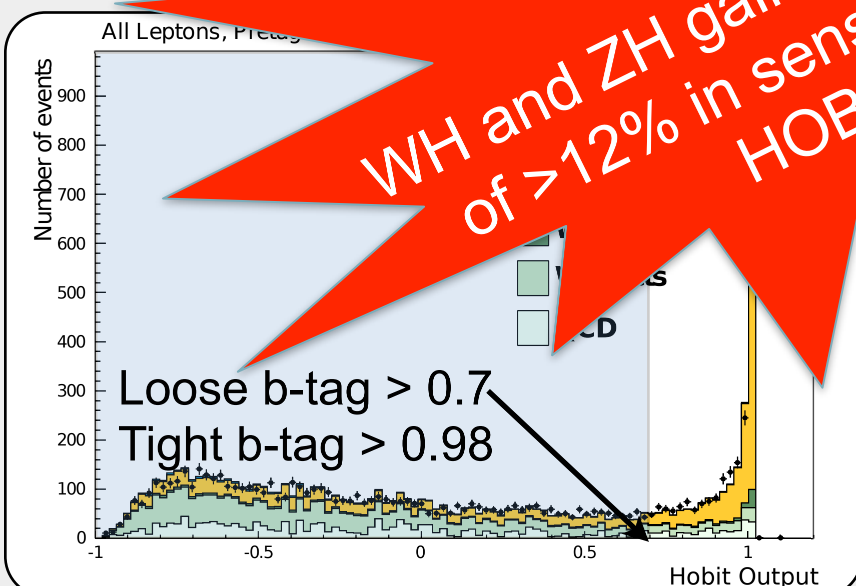
- We incorporate the knowledge from p
  - The Higgs-Optimized b-Ide

WH and ZH gained huge boost of >12% in sensitivity from HOBIT



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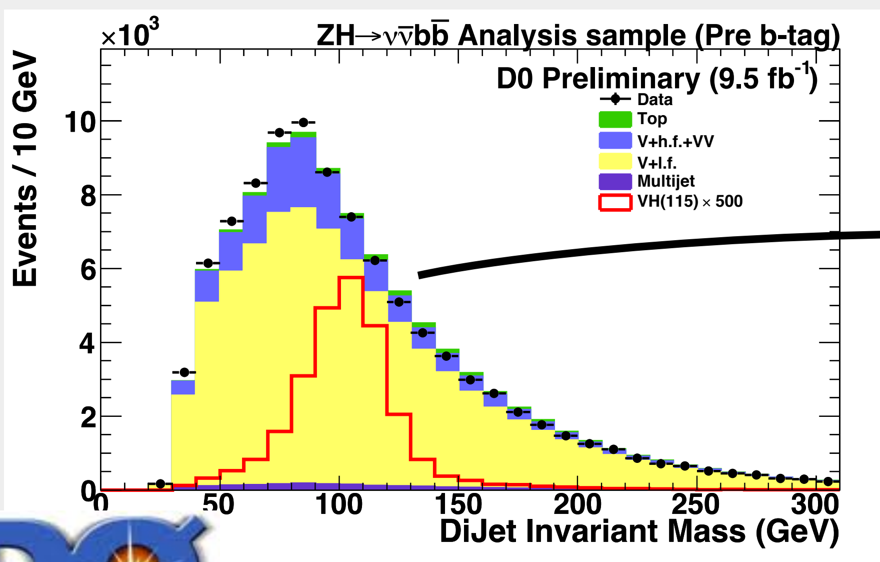
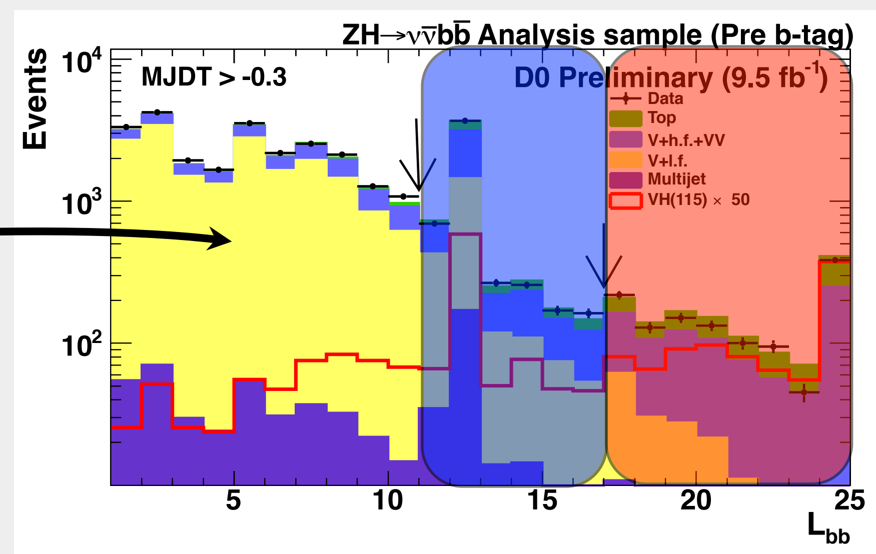
b-tagging at D0

- Several(12) operating points were implemented for D0 MVA b-tagger
  - L_b=[0, 12]; L_b=0 - untagged jet, L_b=12 - high purity b-jet
- Use all 12 operating points
  - Add L_b values for each jet to form per event likelihood
  - Cut on sum to define **medium** and **tight** b-tag sample





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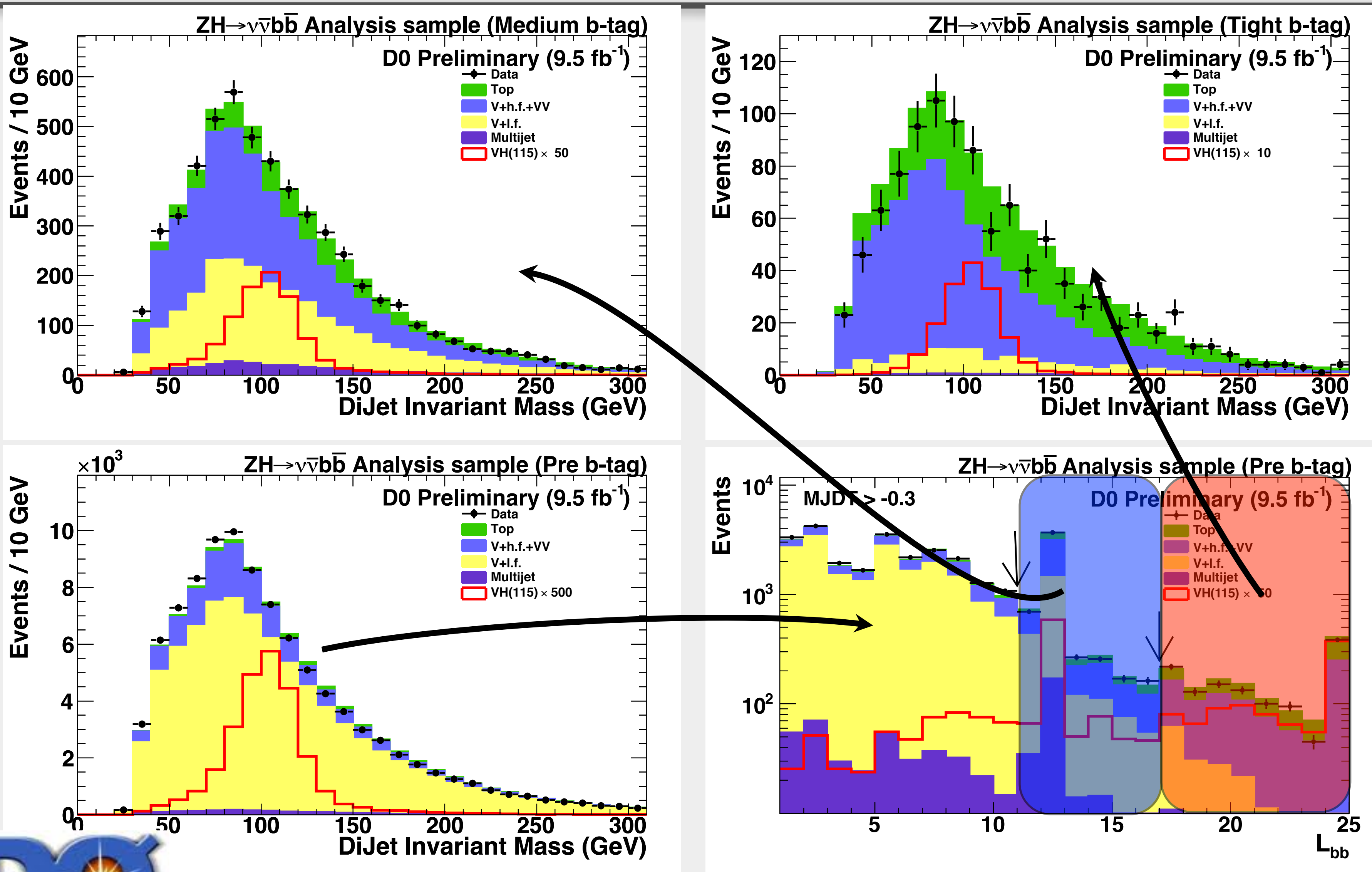
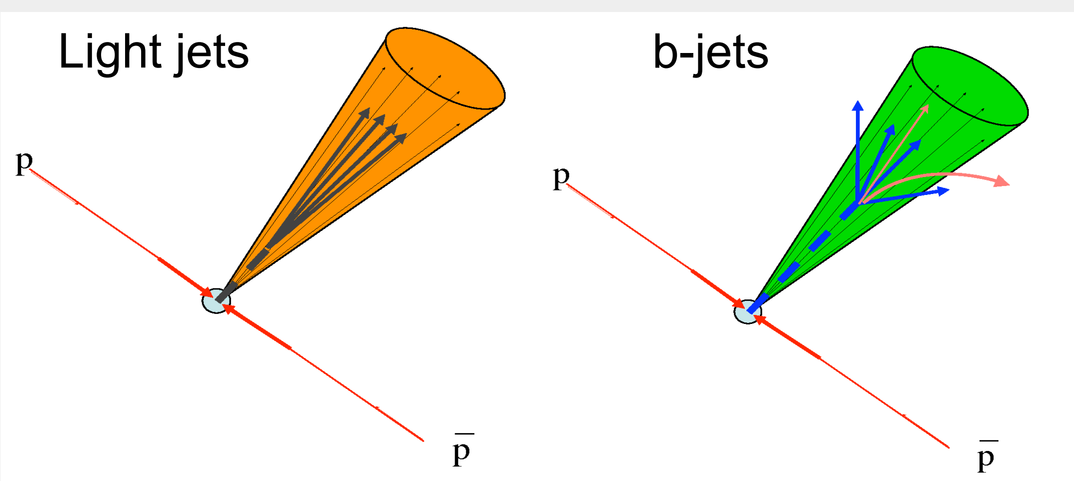
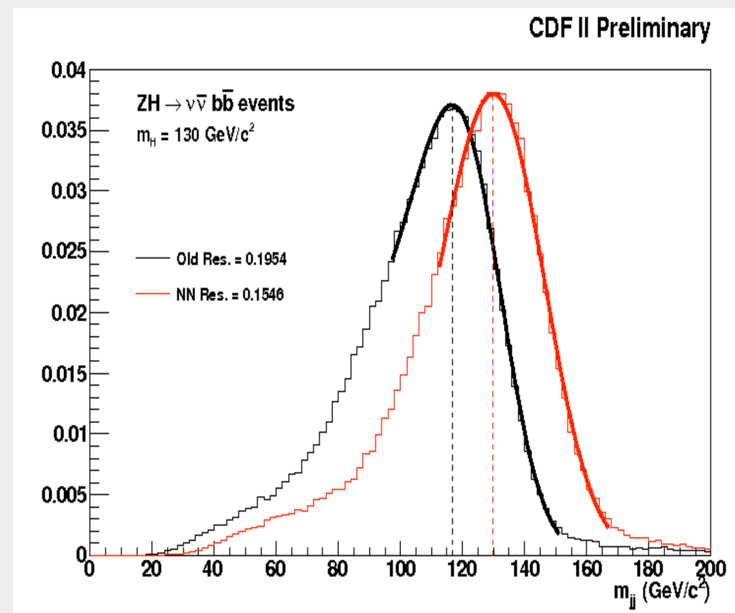


Mass Resolution

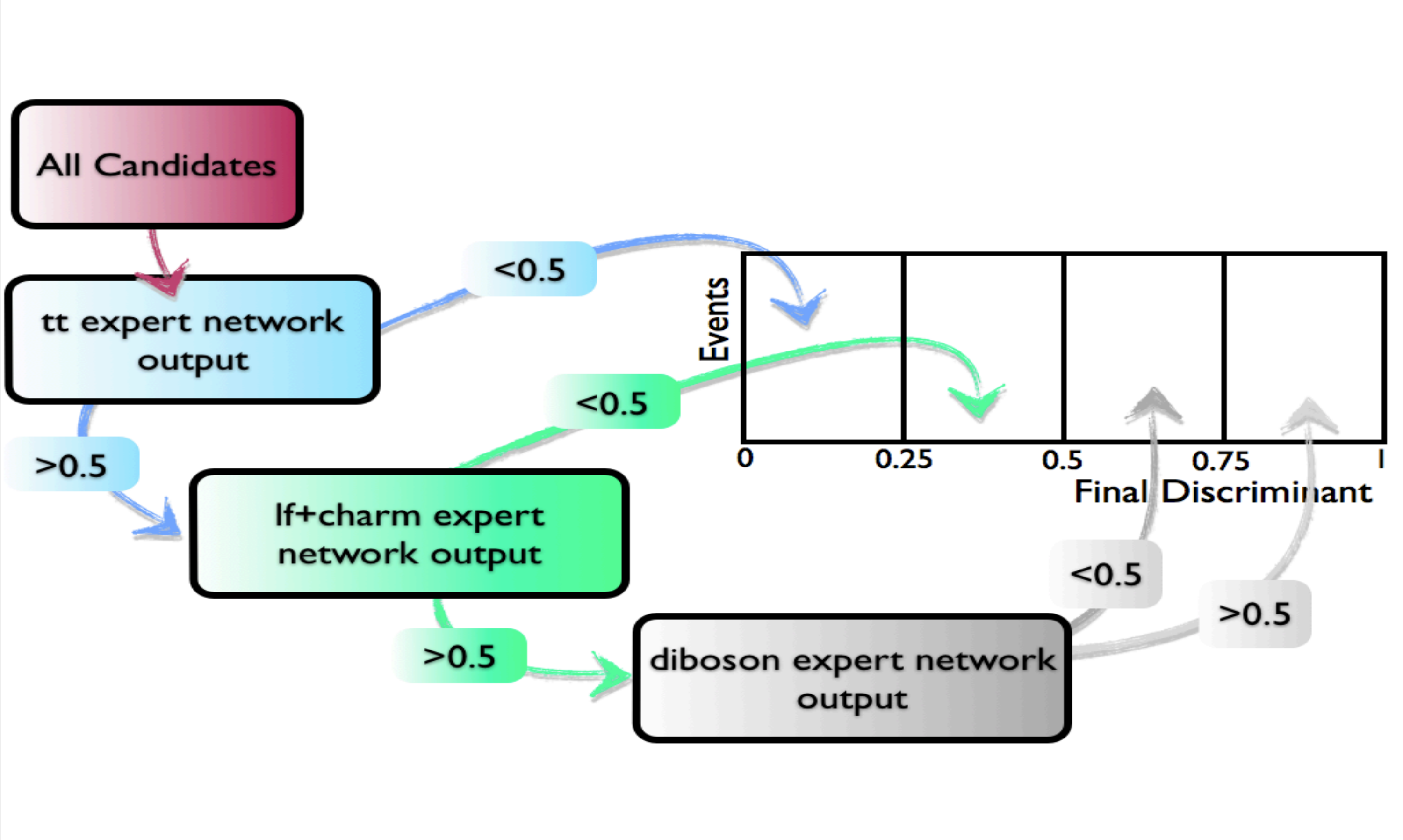
- Dijet mass is the MOST powerful variable - 75% of total sensitivity
  - Peaking for Higgs signal and falling for most of background
- Jet-energy corrections generally derived from light-quark jets
- b-jets have properties which are very different from light flavor quark jets
  - Wider, presence of muon and neutrino.
- MVA algorithms correlate jet related variable and return most probable jet energy, improving resolution by ~20%





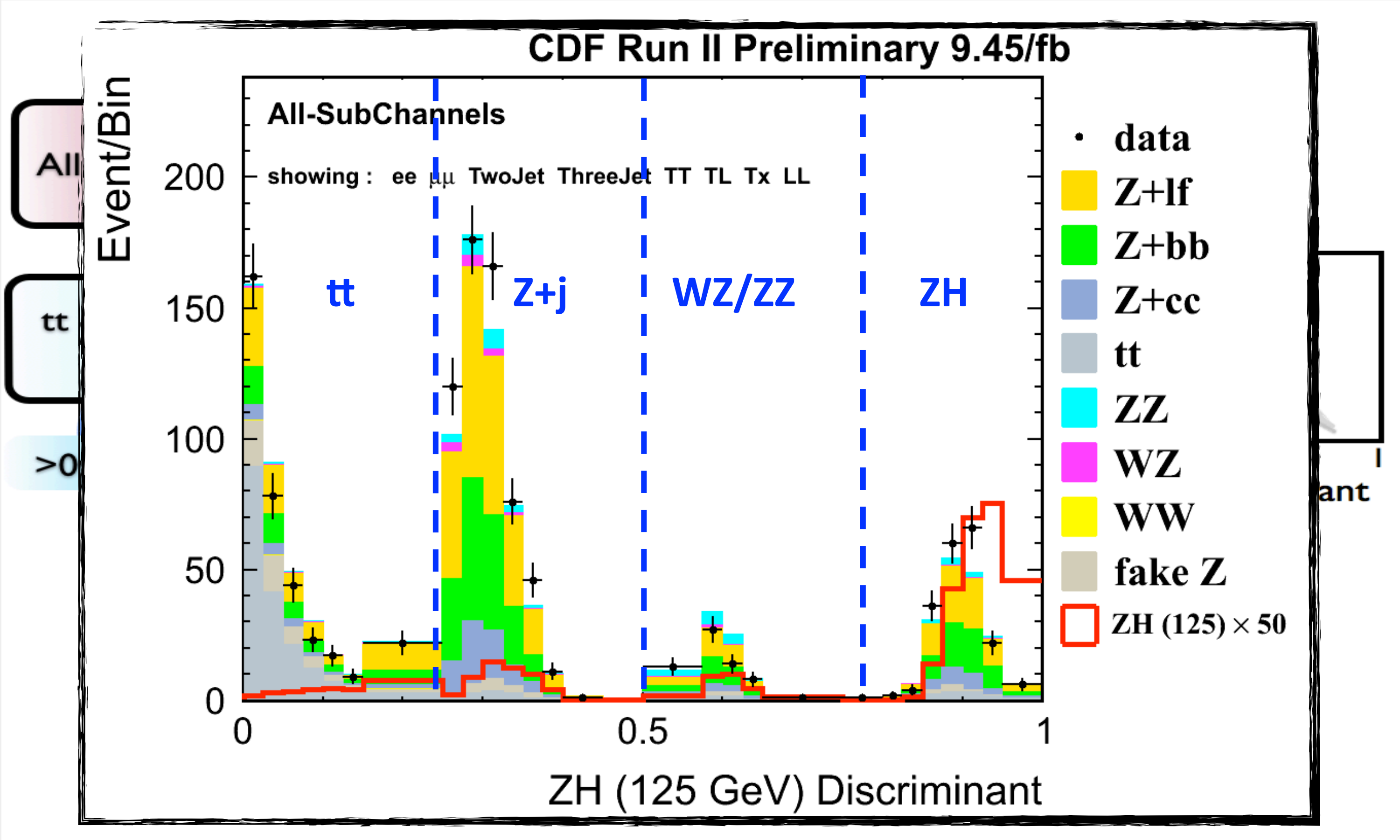
MVA improvements

- Three major backgrounds in ZH->llbb
- Train dedicated neural net for each type
- Good alternative to Matrix Element technique



MVA improvements

- No events are discarded
  - Keep signal to increase significance
  - Background to constrain uncertainties



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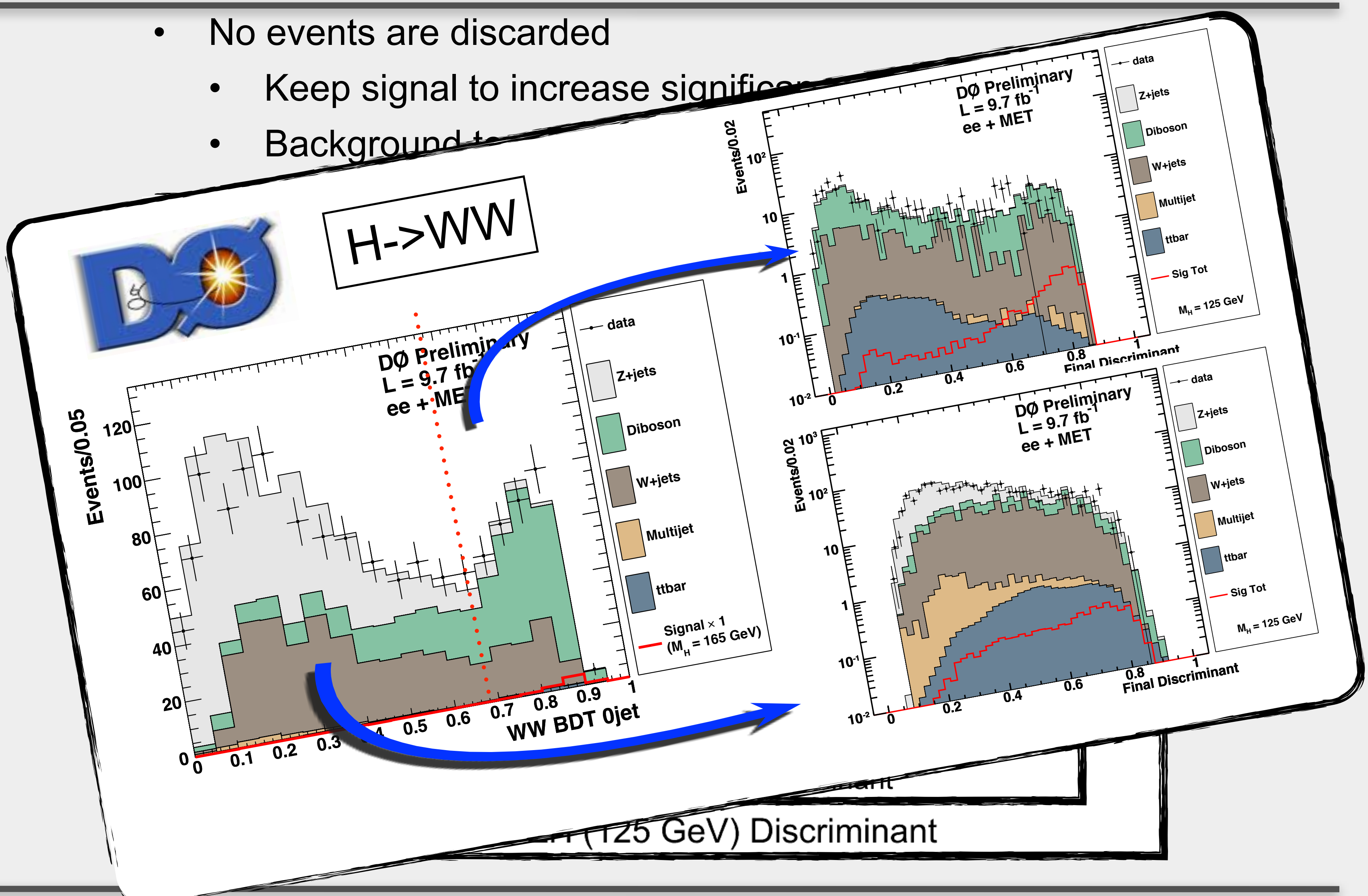

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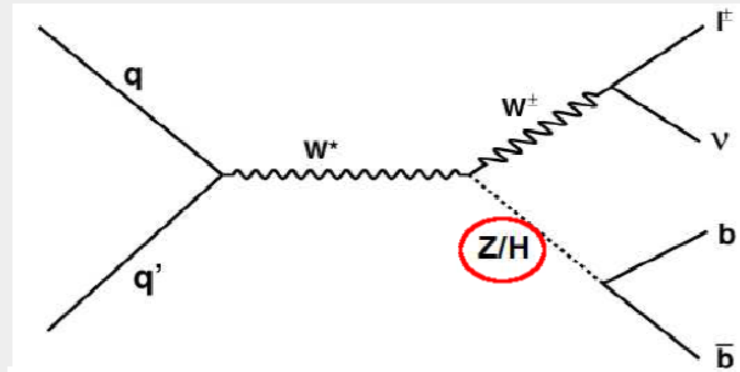
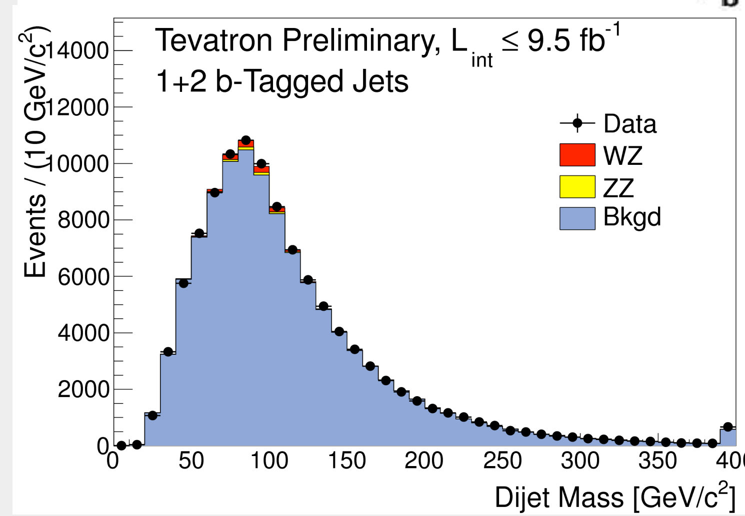
H (125 GeV) Discriminant

Diboson Fit

- We check the modeling
  - Each individual input to MVA is tested in the control regions
  - Well known SM processes: single top and diboson in particular
- σ(WZ+ZZ)*Br(Z->bb) = 0.68 ± 0.05 pb (SM), six times larger than
- σ(WH+ZH)*Br(H_{125}->bb)=0.12±0.01 pb





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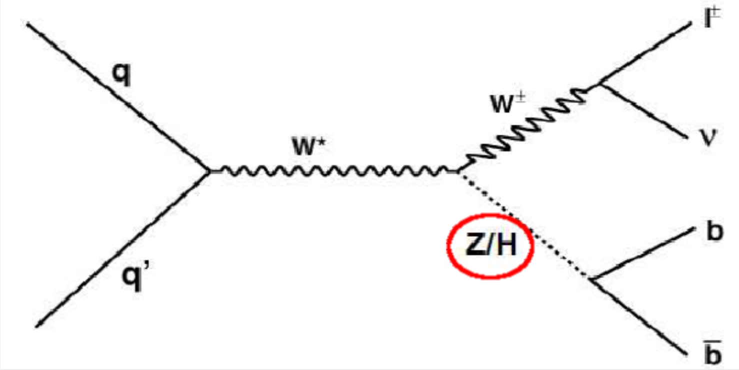
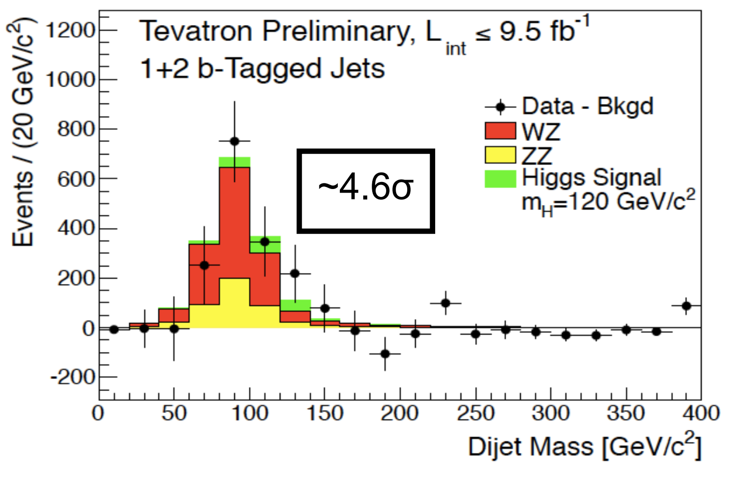
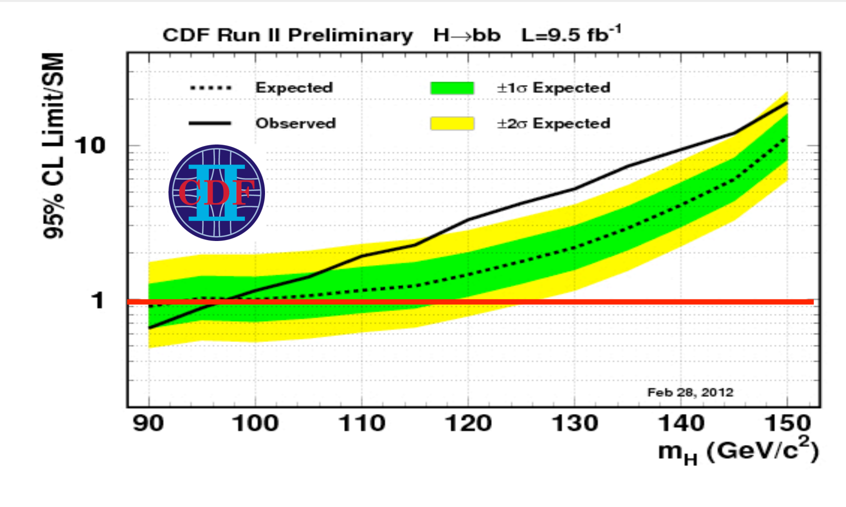
- We find perfect agreement with SM prediction

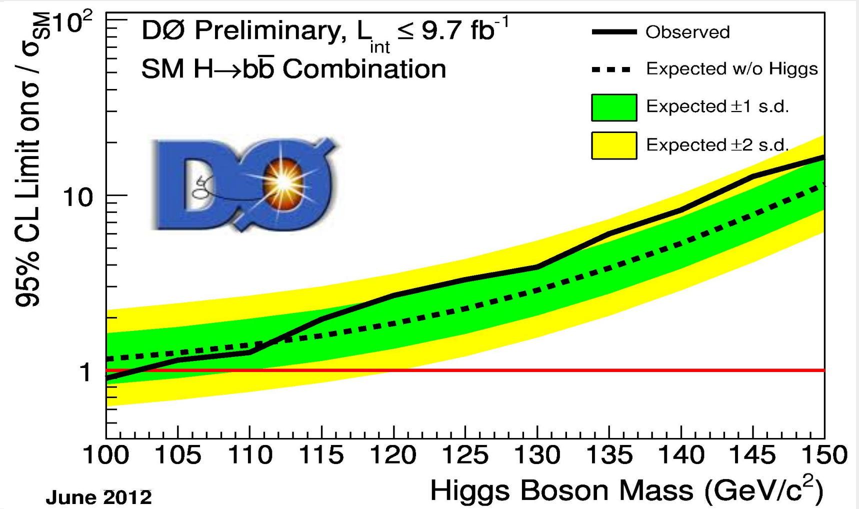




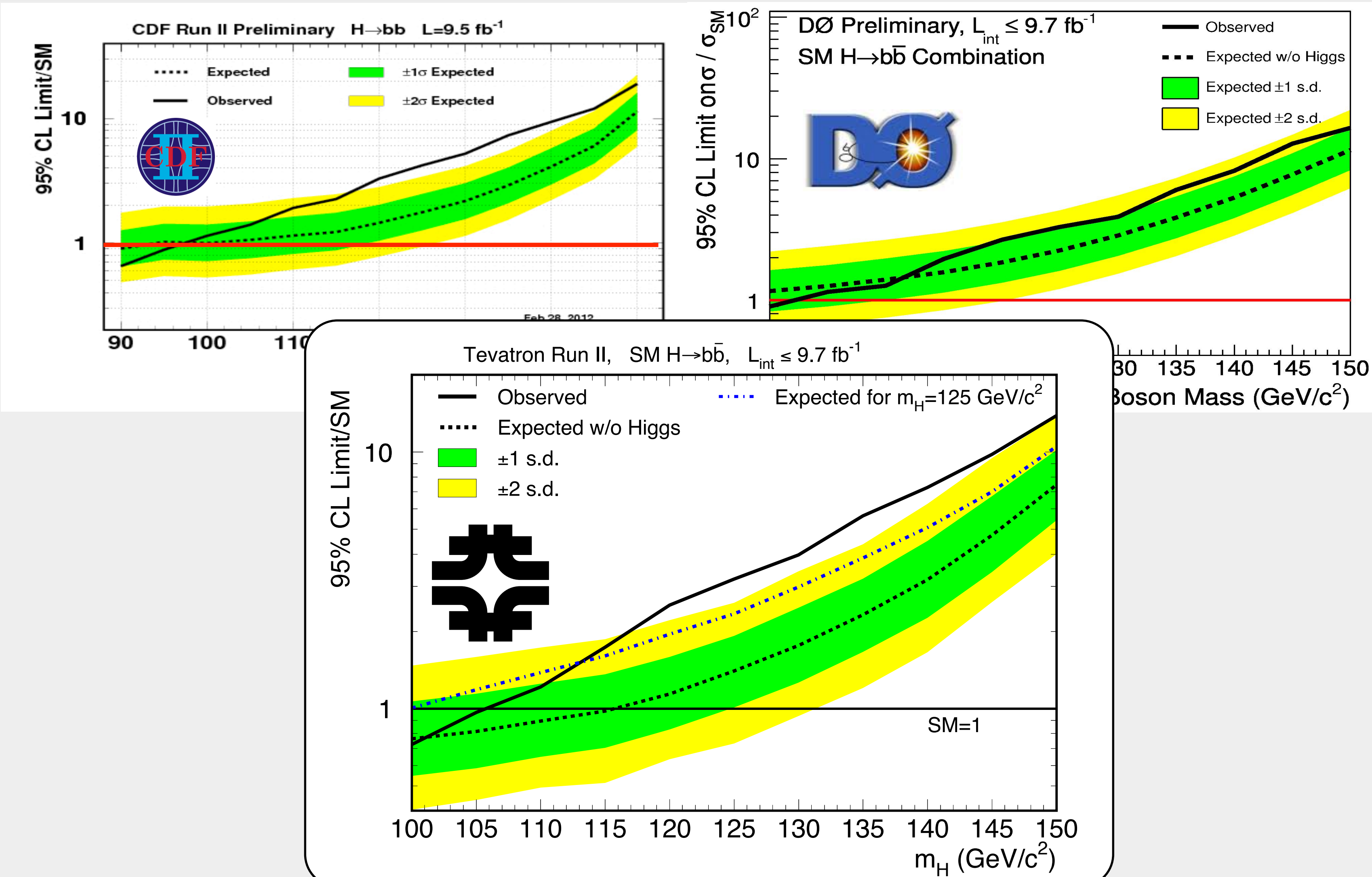
σ(WZ+ZZ)= 4.47 ± 0.64 (stat) ± 0.73 (syst) pb
(SM Prediction = 4.4 ± 0.3 pb)

H->bb limits

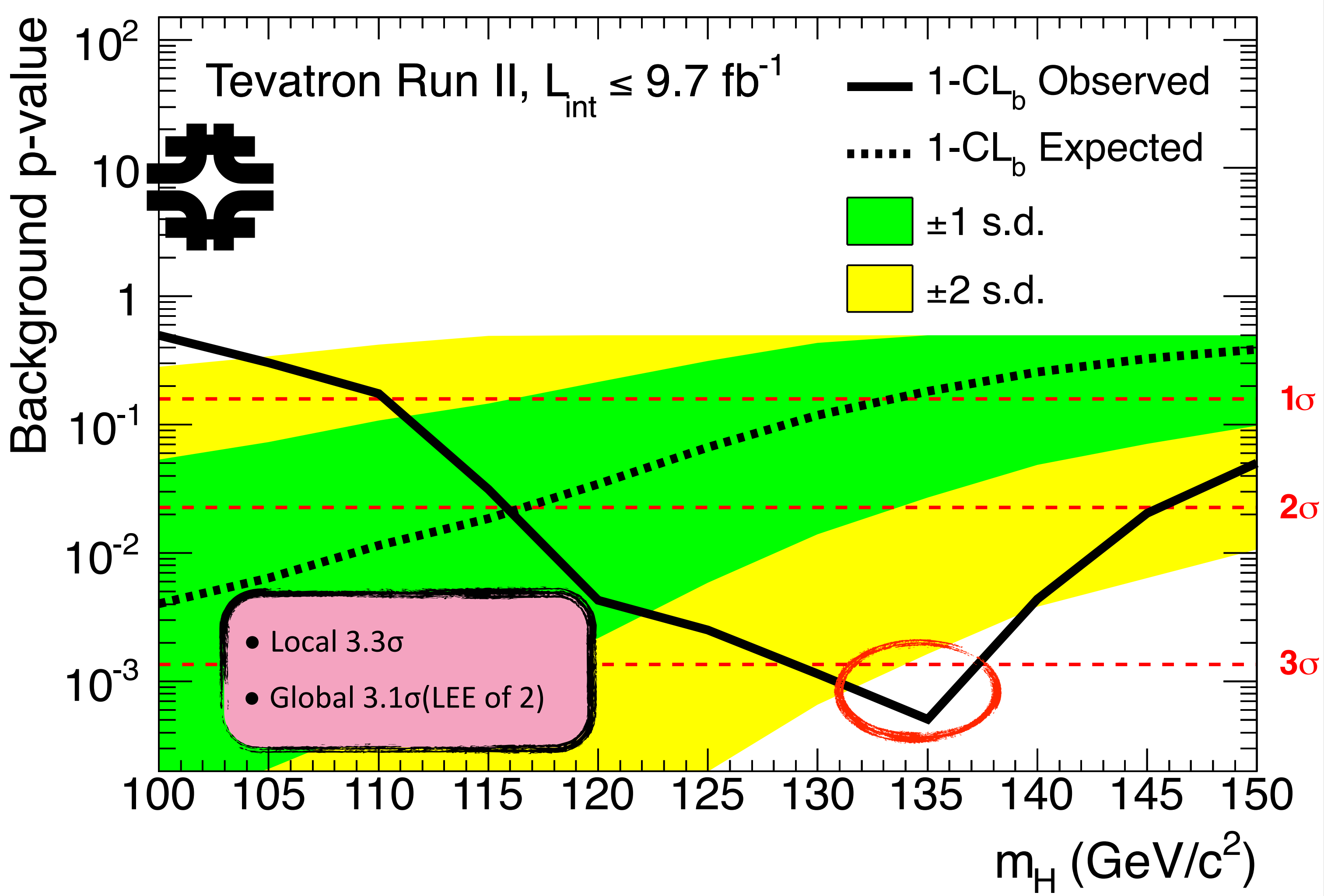

CDF Run II Preliminary H→bb L=9.5 fb-1
95% CL Limit/SM
Expected
Observed
±1σ Expected
±2σ Expected
Feb 28, 2012
90
100
110
120
130
140
150
mH (GeV/c2)
10
1


DØ Preliminary, Lint ≤ 9.7 fb-1
SM H→bb̄ Combination
Observed
Expected w/o Higgs
Expected ±1 s.d.
Expected ±2 s.d.
95% CL Limit on σ / σSM
102
10
1
100
105
110
115
120
125
130
135
140
145
150
Higgs Boson Mass (GeV/c2)
June 2012

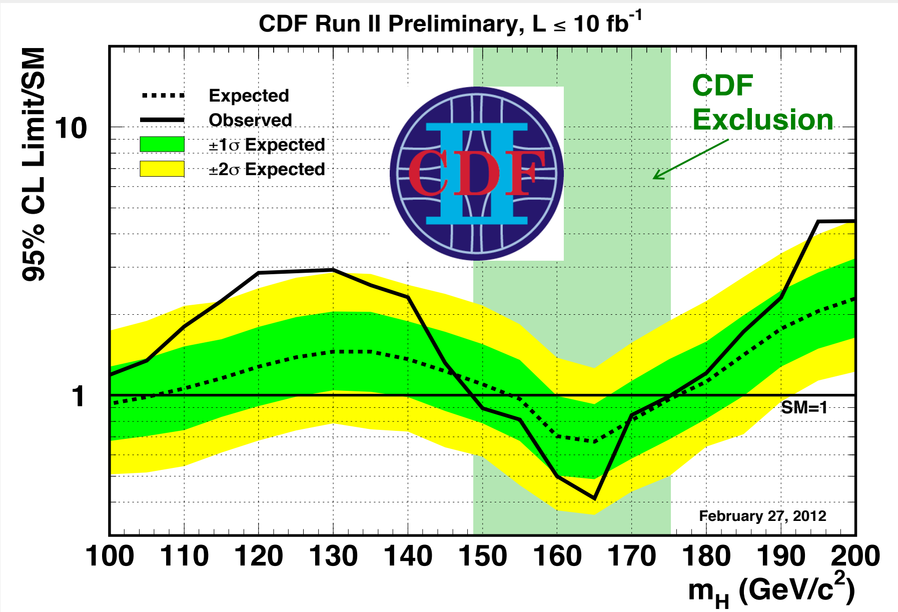
H->bb limits

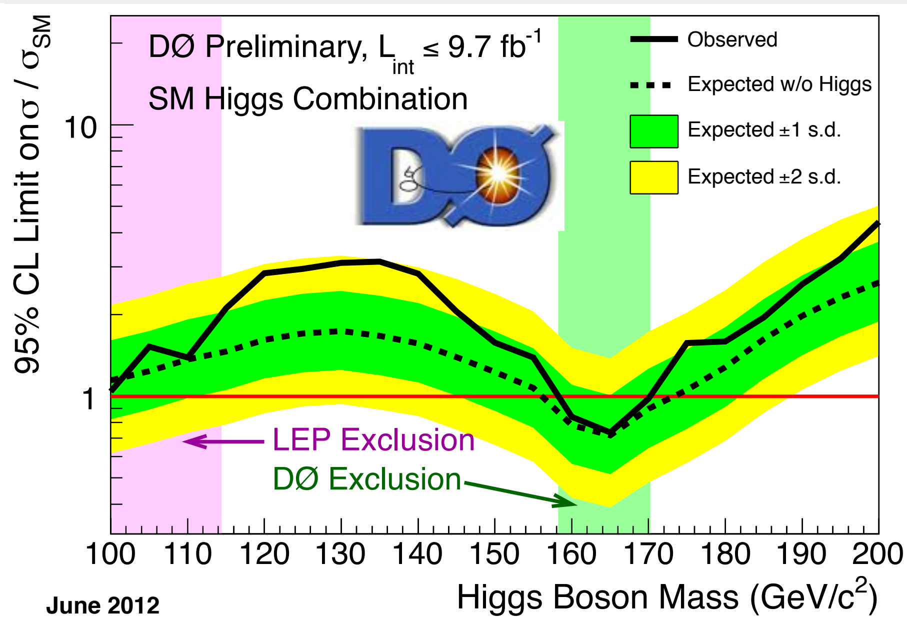

CDF Run II Preliminary H→bb L=9.5 fb-1
Expected
Observed
±1σ Expected
±2σ Expected
95% CL Limit/SM
10
1
90
100
110
Feb 28, 2012
DØ Preliminary, L_int ≤ 9.7 fb-1
SM H→bb̄ Combination
Observed
Expected w/o Higgs
Expected ±1 s.d.
Expected ±2 s.d.
95% CL Limit on σ / σ_SM
10^2
10
1
30 135 140 145 150
Boson Mass (GeV/c2)
Tevatron Run II, SM H→bb̄, L_int ≤ 9.7 fb-1
Observed
Expected w/o Higgs
±1 s.d.
±2 s.d.
Expected for m_H=125 GeV/c2
95% CL Limit/SM
10
1
SM=1
100 105 110 115 120 125 130 135 140 145 150
m_H (GeV/c2)

H->bb excess significance



Limits from CDF/D0

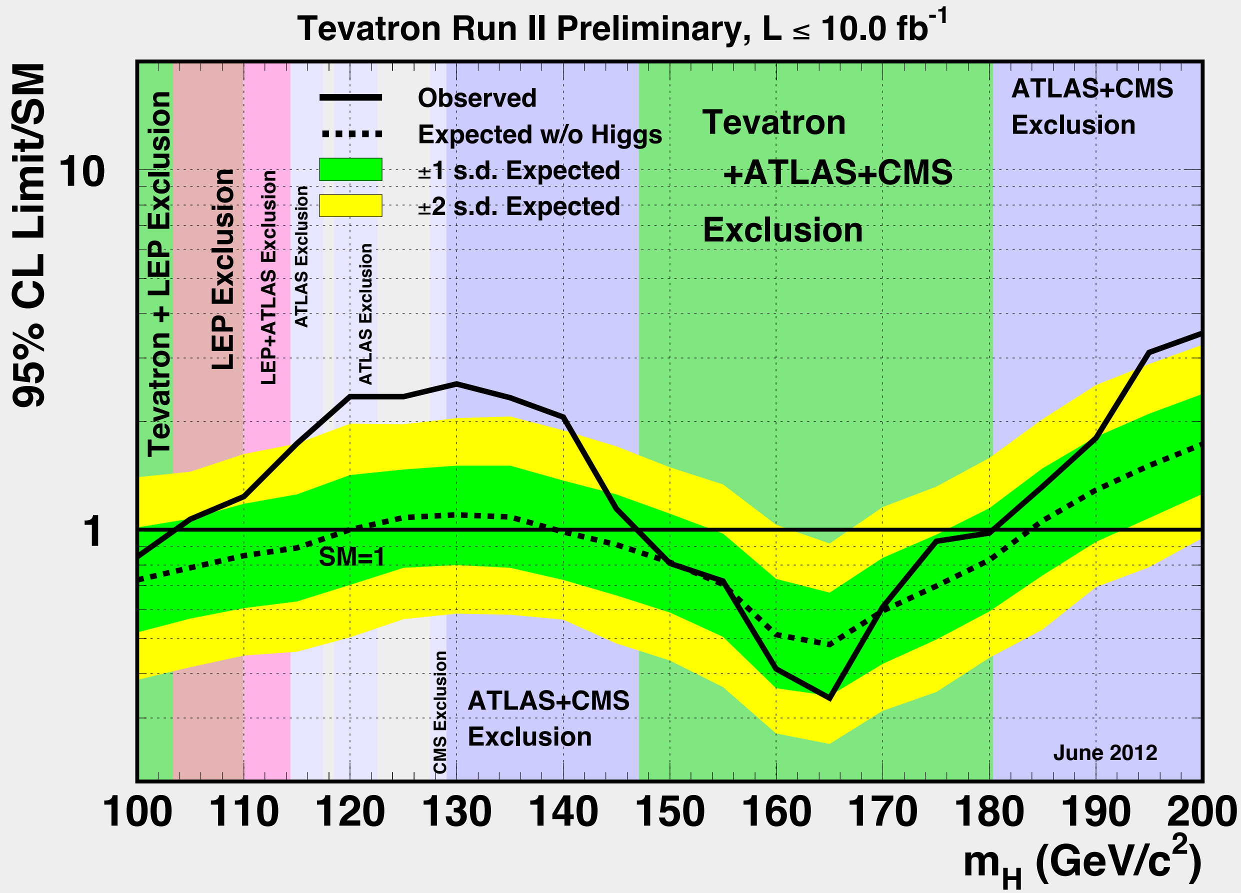




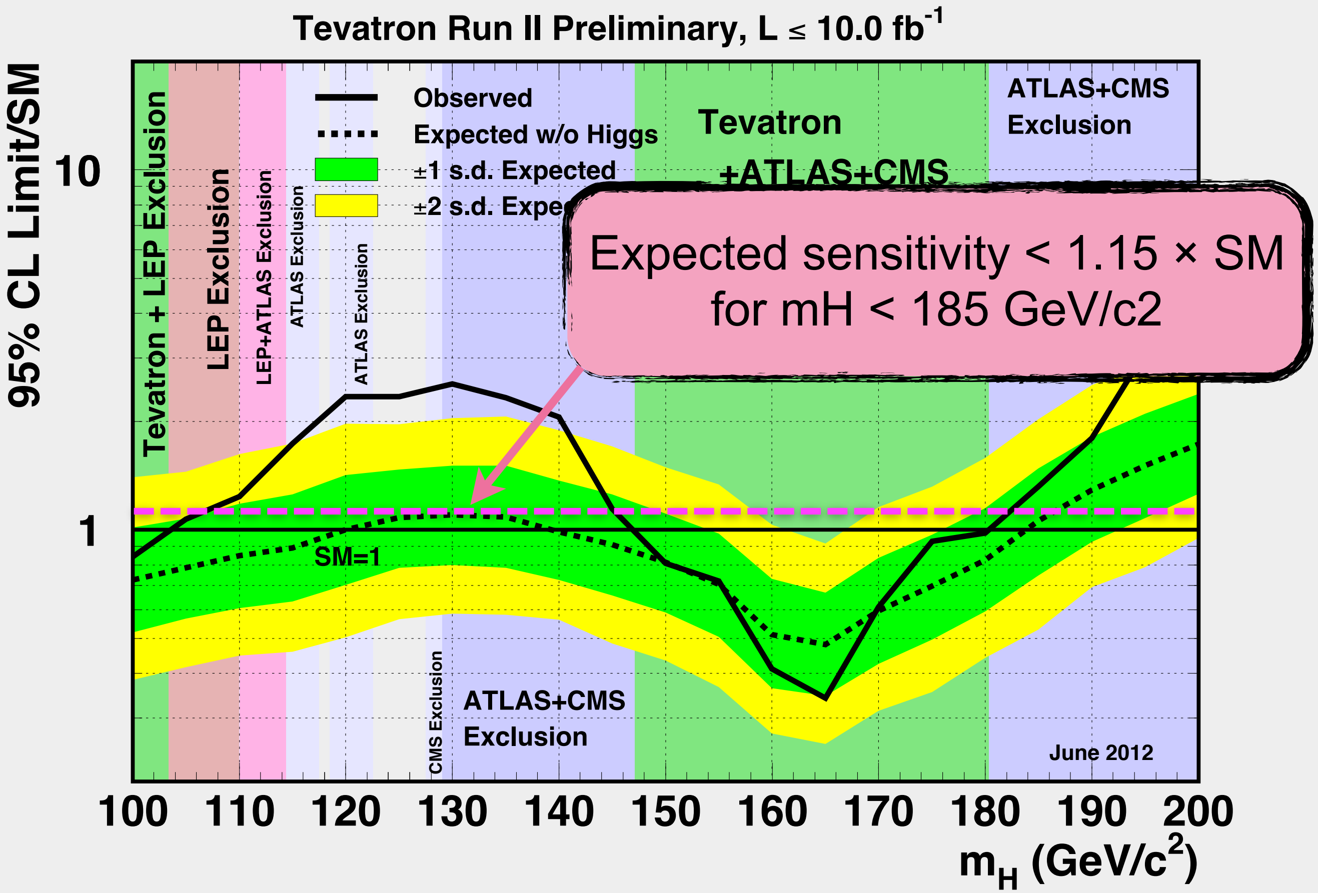
Exp. Exclusion: $154 < m_H < 176$ GeV
Obs. Exclusion: $149 < m_H < 175$ GeV

Exp. Exclusion: $156 < m_H < 173$ GeV
Obs. Exclusion: $159 < m_H < 170$ GeV

Combined limits



Combined limits

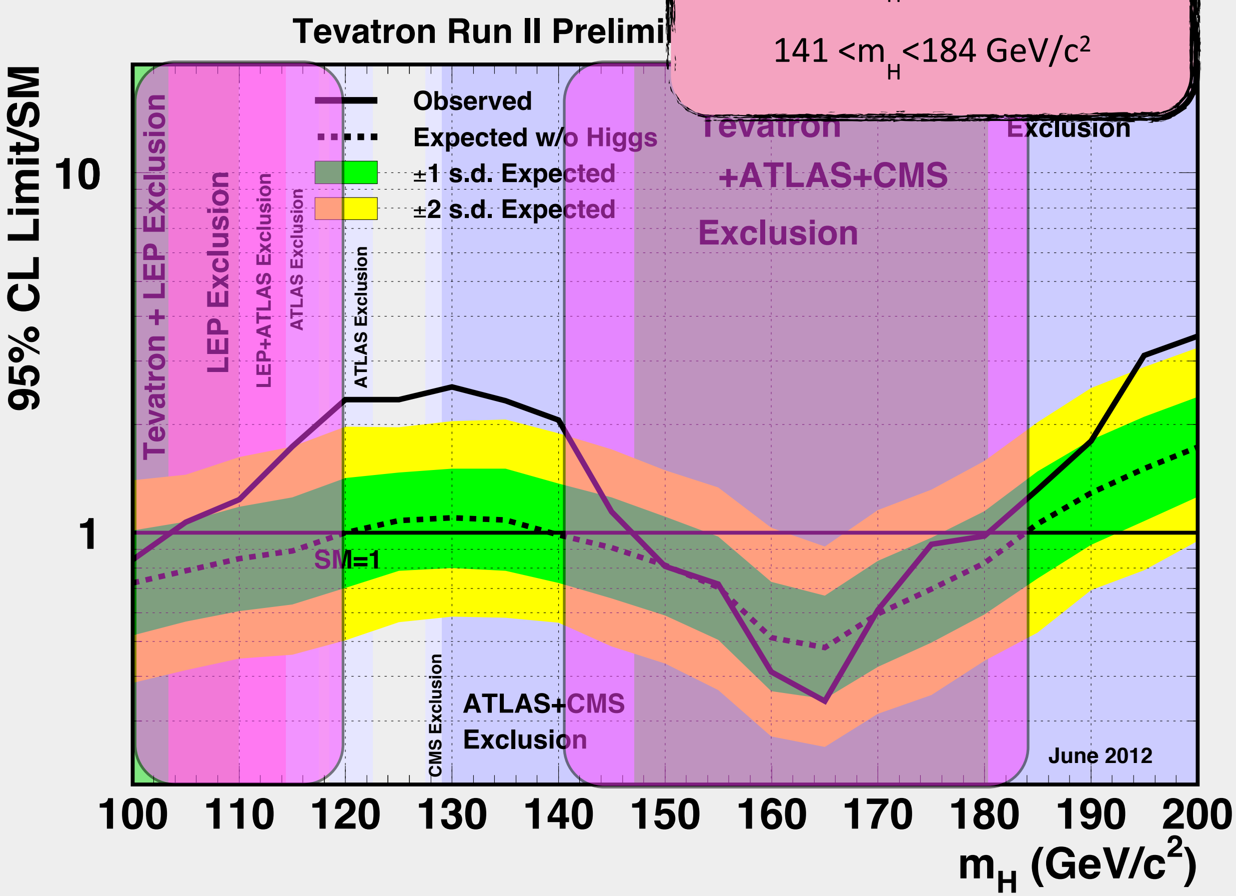


Combined limits

Expected exclusion:

100 <m_H<119 GeV/c^2

141 <m_H<184 GeV/c^2

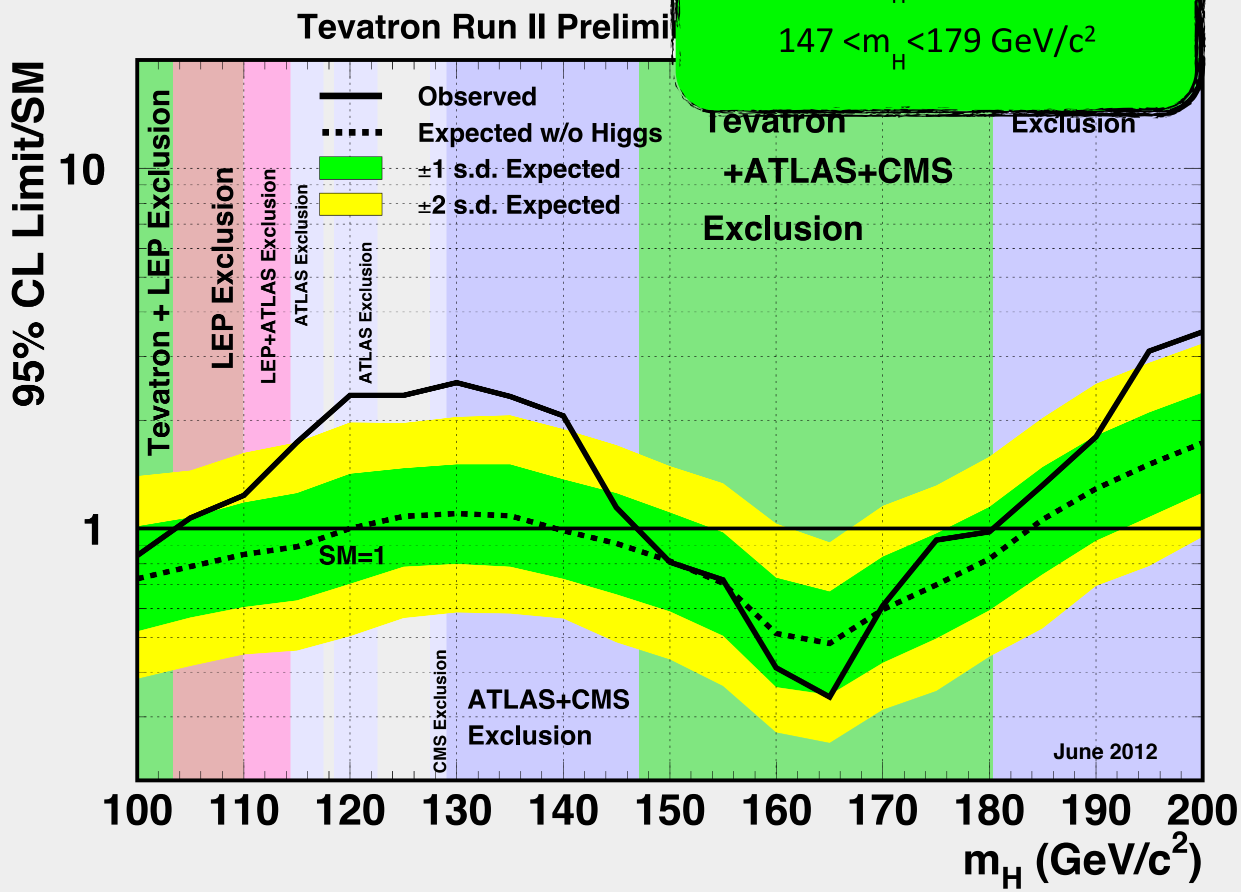


Combined limits

Observed exclusion:

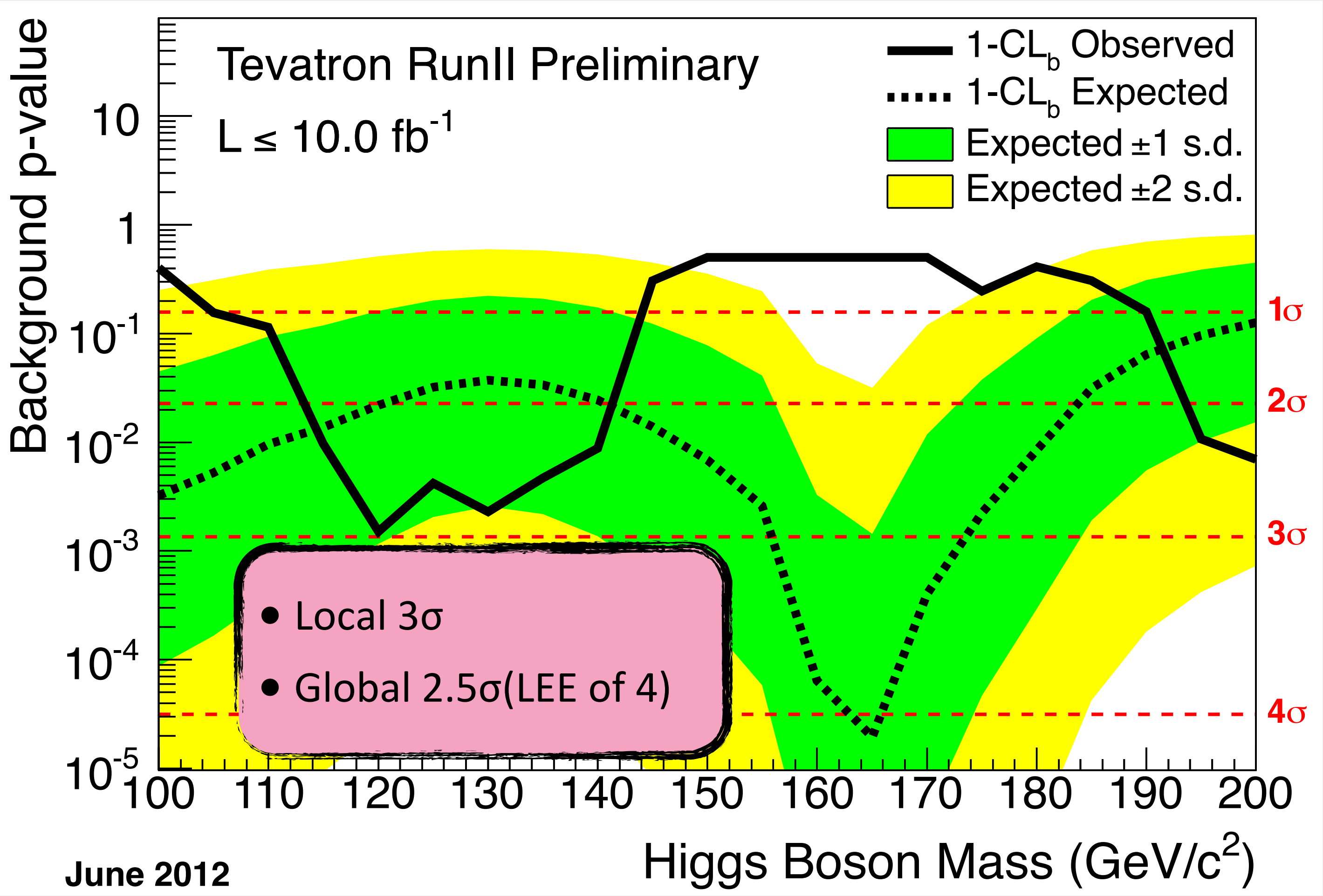
$100 < m_H < 106$ GeV/c^2

$147 < m_H < 179$ GeV/c^2

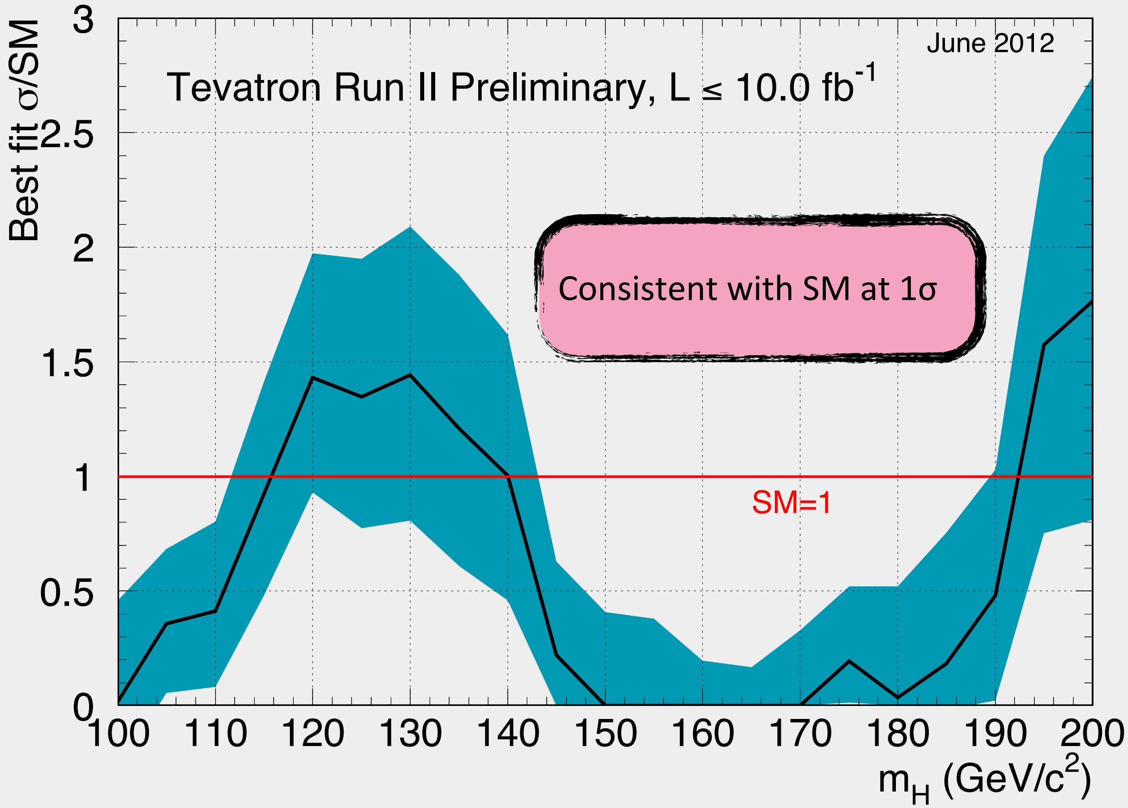


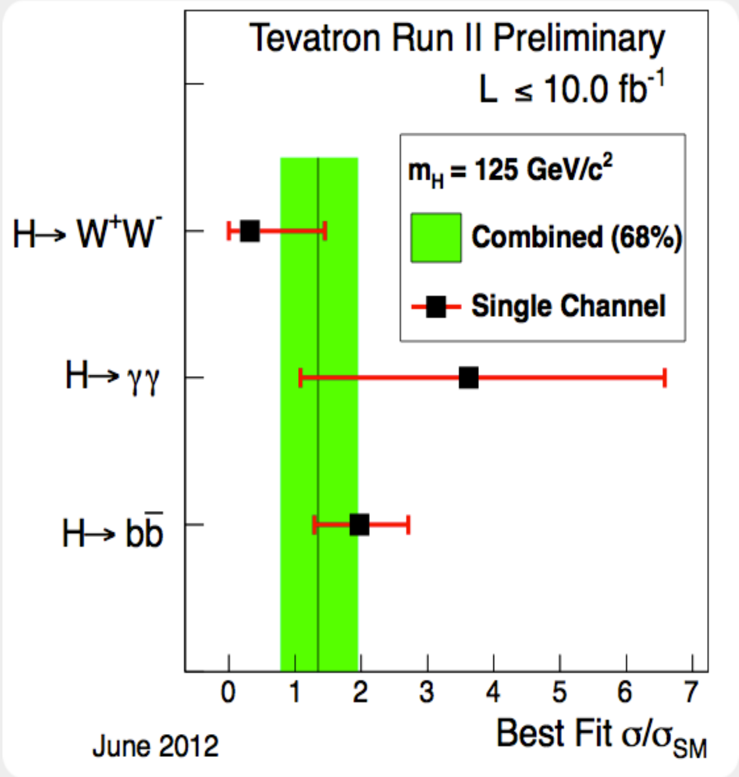
Excess significance

Is the excess consistent with background only assumption?



Best σ_H fit





Higgs Summary

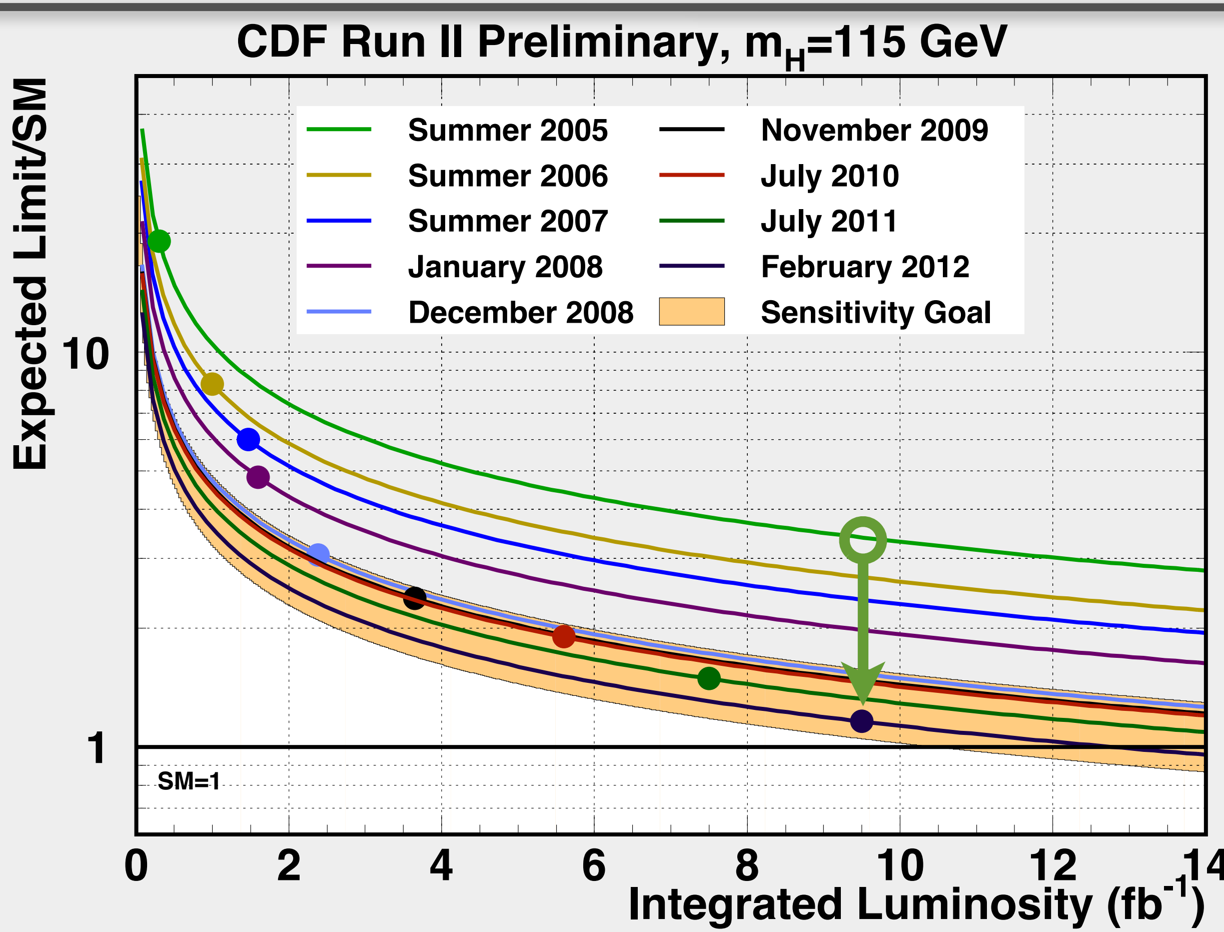
Excluded values of MH @ 95% CL

Expected	Observed
100-120 GeV	100-103 GeV
139-184 GeV	147-180 GeV

Significance of observed excess

Channels	Local	Global
All Tevatron	3 σ	2.5 σ
H→bb	3.3 σ	3.1 σ

Make the results possible



- Amazing performance from accelerator division
- More than a factor of 2 in improvement over what is expected from luminosity!

Conclusion

- Full Tevatron dataset incorporated into most of Higgs search channels
  - Overall sensitivity better than 1.15xSM
  - Broad excess(2.5σ) in the data in the low mass region(105< m_H<145 GeV)
- Tevatron results are complimentary and competitive in H->bb
- We observe a significant excess in H->bb final state
  - Local excess significance of 3.3σ
  - Global excess significance of 3.1σ
- We interpret that as an evidence of Higgs-like boson produced in association with a weak vector boson and decays to a bb pair

Conclusion

Results

- **Tevatron:**
  - http://tevnphwg.fnal.gov
- **D0:**
  - http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
- **CDF:**
  - http://www-cdf.fnal.gov/physics/new/hdg/Results.html

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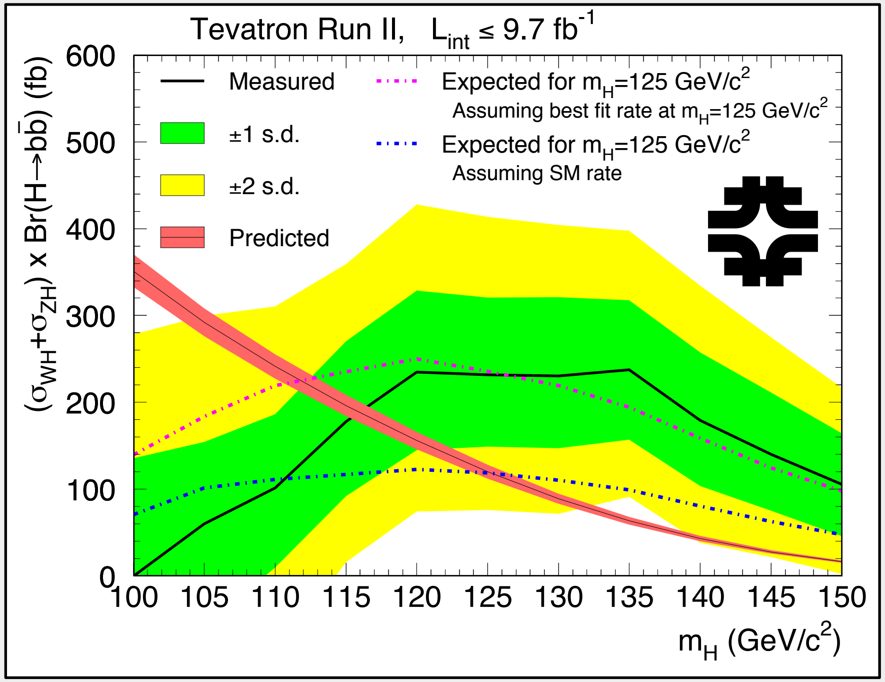
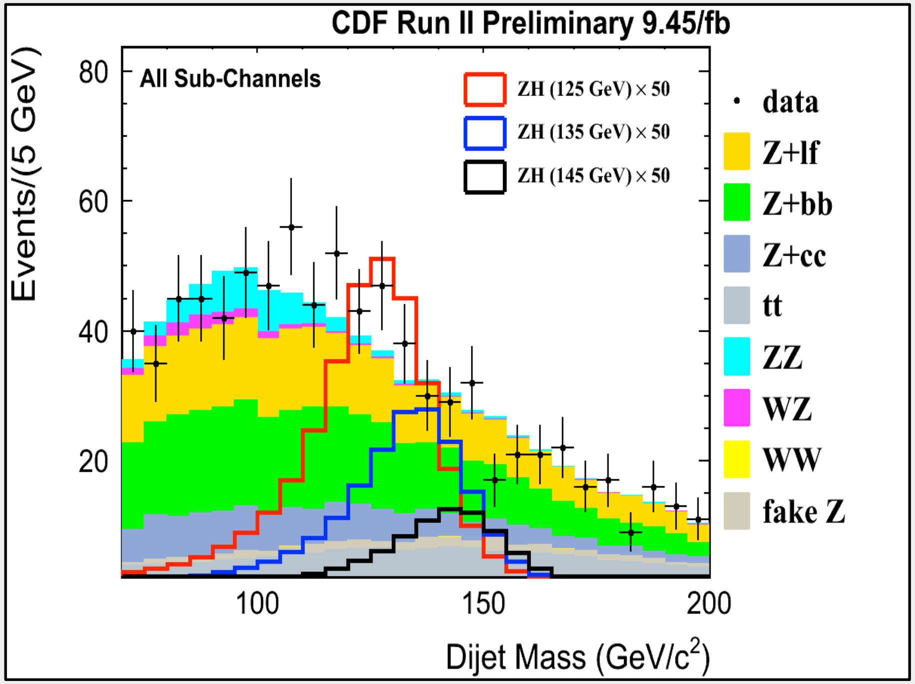
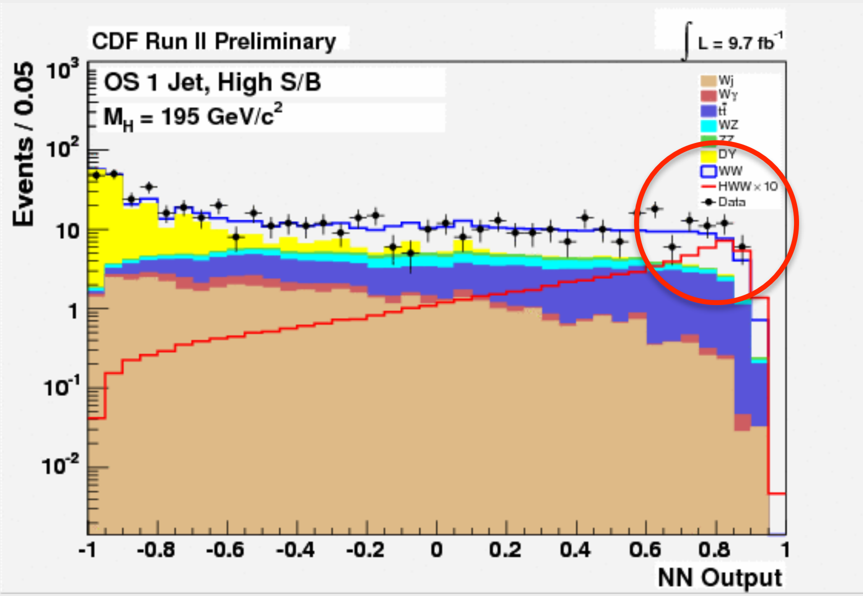
Backup

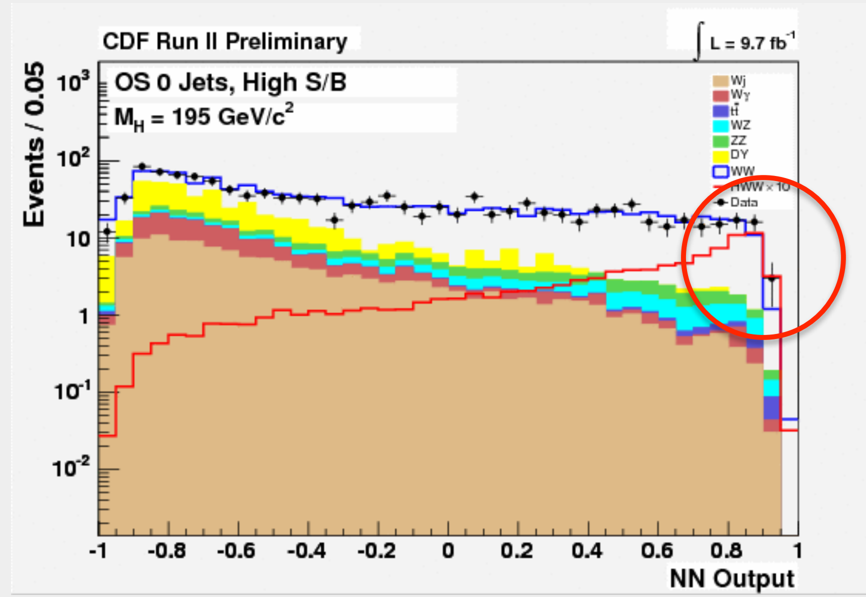
Best $\sigma_{H\to bb}$ fit





High mass excess





Behavior of observed limits driven by small event excesses in the high S/B regions of opposite-sign dilepton 0 and 1 jet channels

Nothing peculiar in the modeling of these distributions

Of course, ATLAS and CMS have ruled out a mH = 195 GeV/c2 SM Higgs based primarily on equivalent searches in H WW

CDF W+jets bump

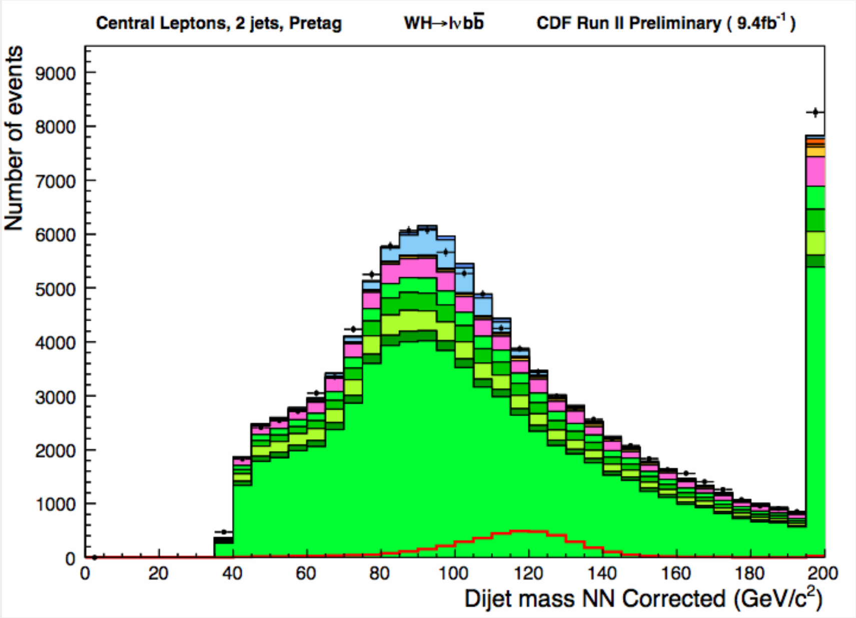
studies indicate that JES for gluon jets needs to be shifted by 2σ in MC to match with data

The JES for quark jets is good – not surprising since well constrained by top mass measurements

In CDF Higgs, -2σ JES corrections are applied to the gluon jets in the MC samples

In the end, since there are so few gluon jets in tagged samples, the effect is small

With these corrections in place modeling looks pretty good in the pre-tag region of the WH Higgs search



Likelihood

- We set limits on the Higgs boson production rate
- Use a combined binned likelihood fit:

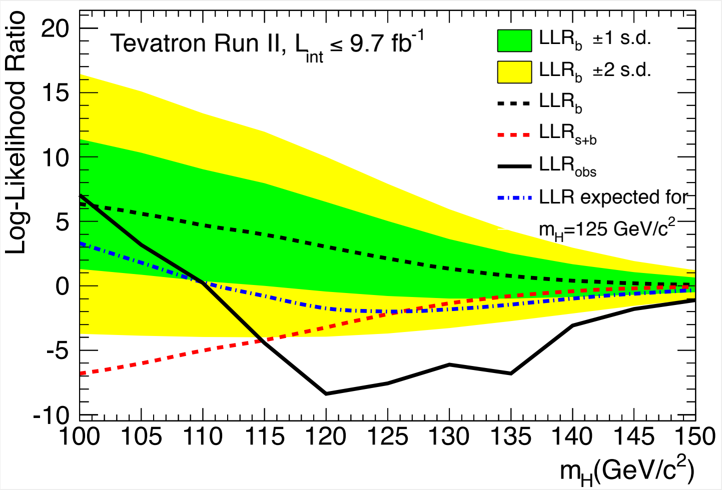
$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} \times \prod_{k=1}^{N_{\text{np}}} e^{-\theta_k^2/2}$$

- Uncertainties incorporated as nuisance parameters. Shape and normalization of background and signal
- Determine best-fit nuisance-parameters by maximizing likelihood

LLR

$$LLR = -2\ln\frac{p(\text{data} \mid s+b)}{p(\text{data} \mid b)}$$

LLR>0: Background-like experimental outcome
LLR<0: Signal-like experimental outcome



p-value

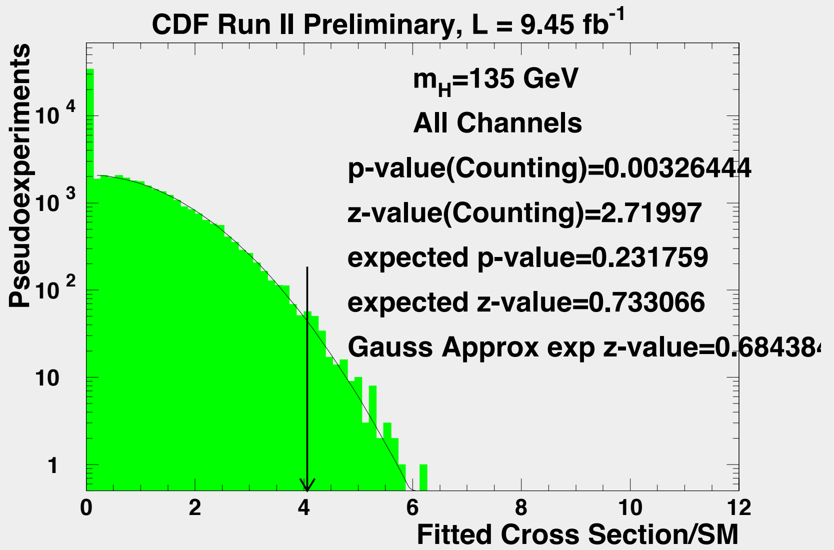
Strategy – Run the cross section fit on background-only pseudo-experiments

Count the pseudo-experiments with $R^{fit} \geq R^{fit,obs}$. The fraction is the p-value

Convert to a significance in “standard deviations”.

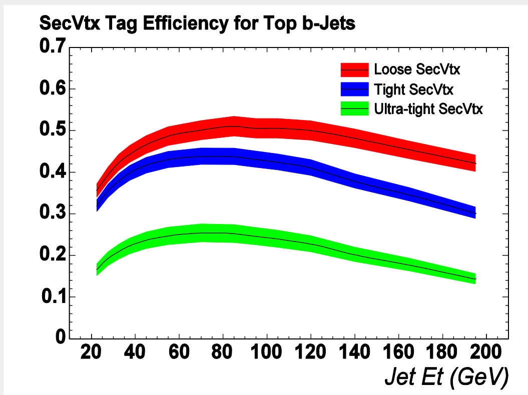
Do this at each mH value separately

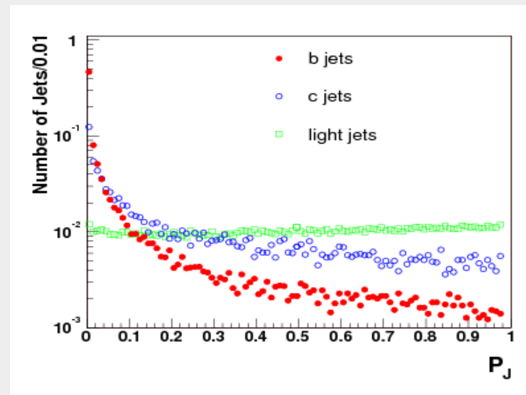
Using LLR instead of Rfit is supposed to be more optimal, cross section fits are better behaved.

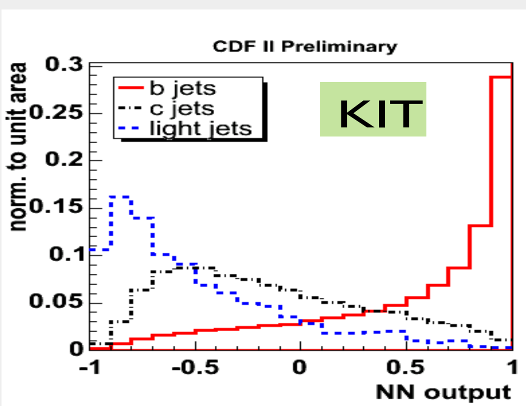


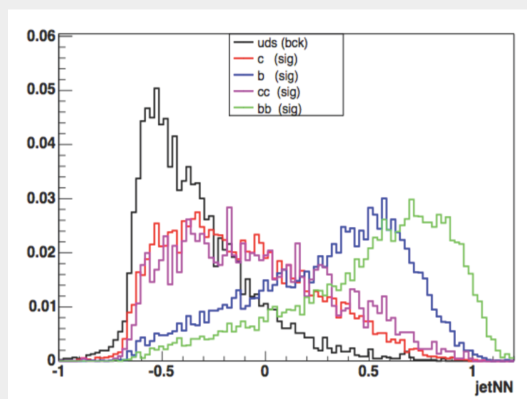
History of b-taggers at CDF

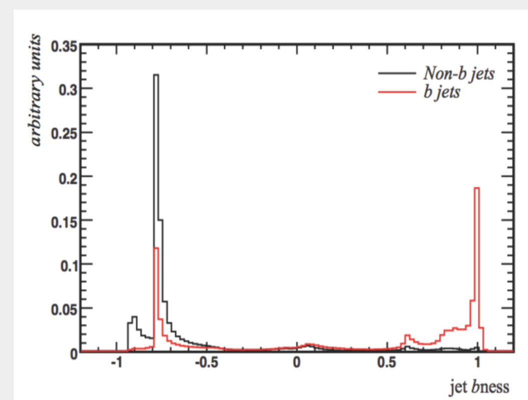
- Improvement in b-tagging efficiency are crucial to various high Pt analysis
  - By 2010 we had at least 5 types of b-taggers





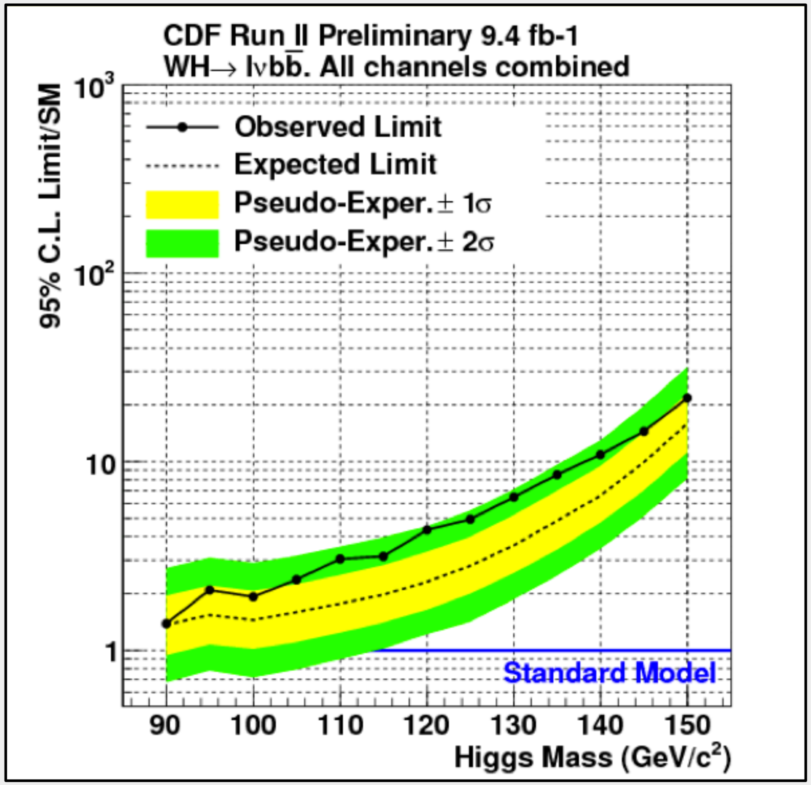




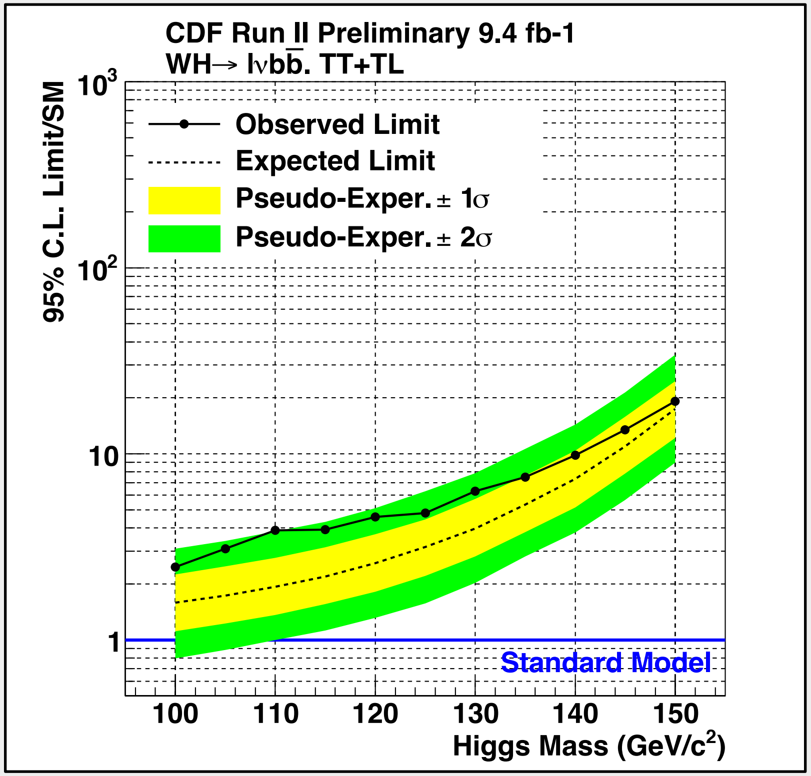


Tight b-tags only

All



TT+TL only



OLD vs NEW b-tagging strategy

- Previous version of WH analysis used 3 types of b-tagger by forming exclusive b-tagging categories:
  - SVTSVT, SVTJP05, SVTnoJPRoma, SVTnoJPnoRoma

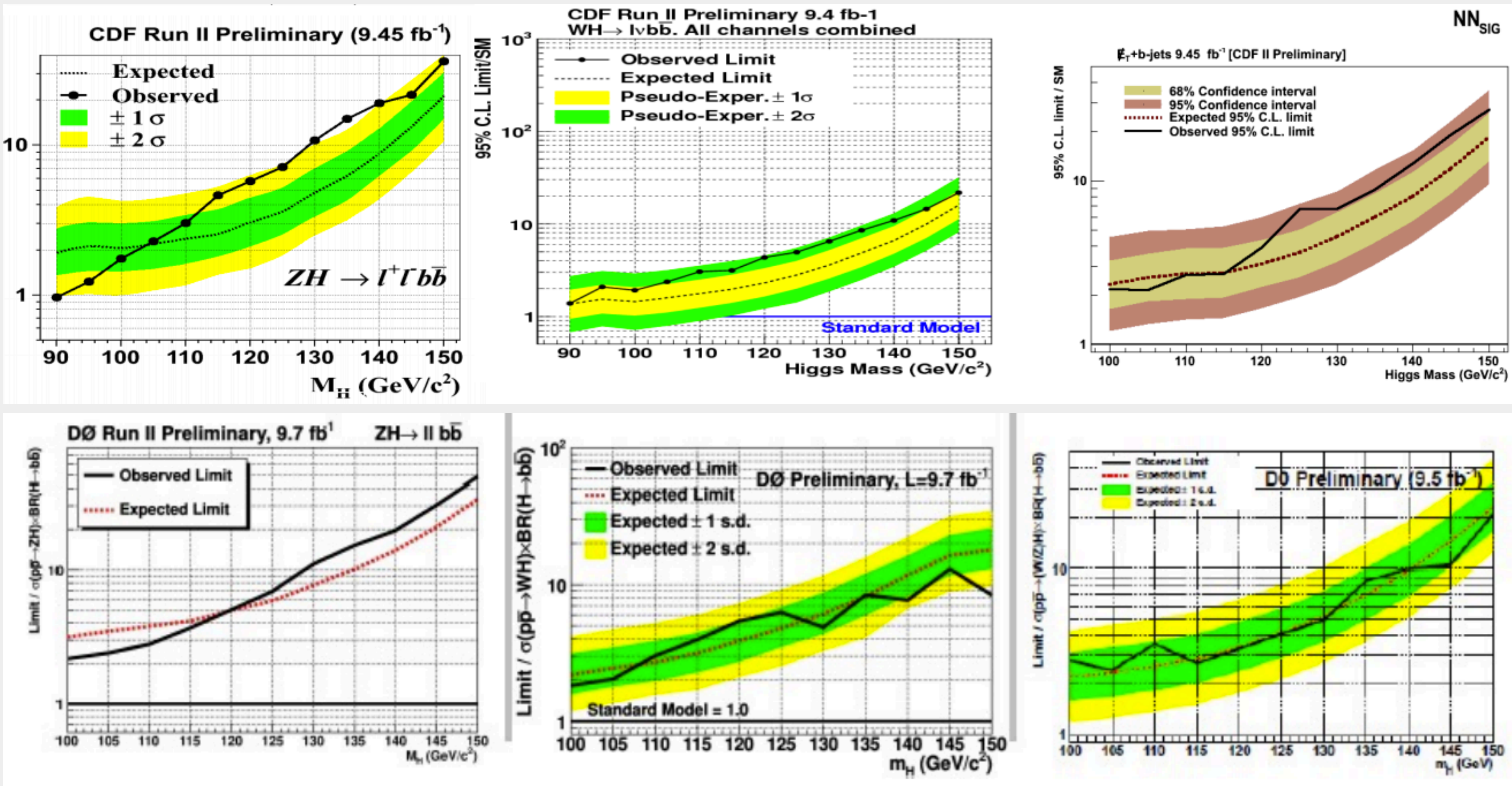
Tagging Category	S/√B
SecVtx+SecVtx	0.228
SecVtx+JetProb	0.160
SecVtx+Roma	0.103
Single SecVtx	0.146
Sum	0.331

- The improvement in sensitivity ~scales with improvements in signal significance

NEW - HOBIT

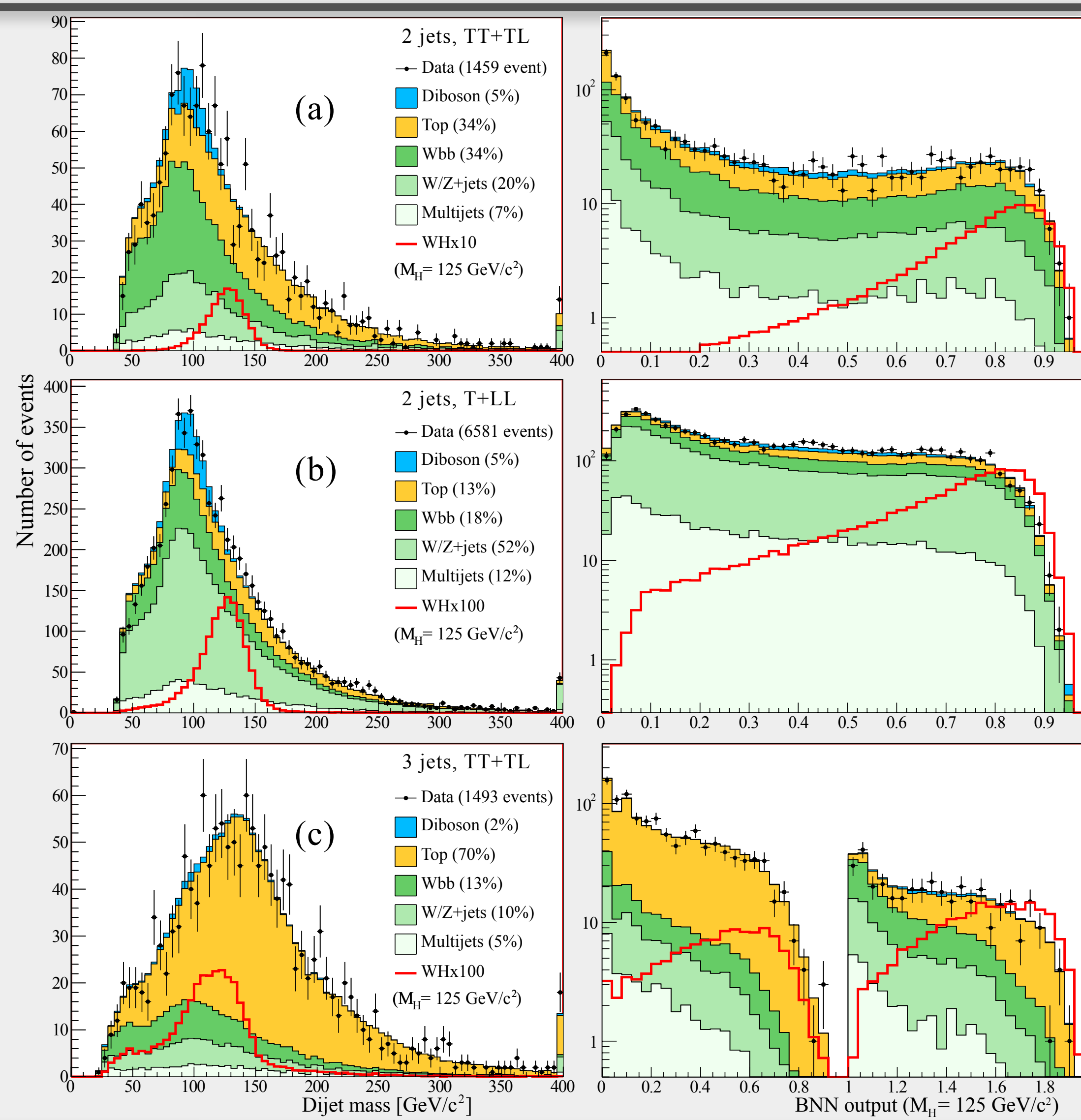
Tagging Category	S/√B
Tight-Tight	0.266
Tight-Loose	0.200
Single Tight	0.143
Loose-Loose	0.053
Single Loose	0.044
Sum	0.369

bb fitted x-section



WH@CDF results

- 2-jet
- tight b-tagging categories



- 2-jet
- loose b-tagging categories

- 3-jet
- tight b-tagging categories
- We split the data into 2 regions:
  - ttbar
  - Wbb