THE UNIVERSITY of WISCONSIN MADISON

CDF II

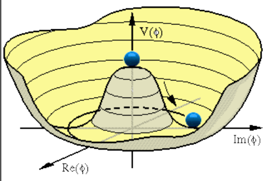
Argonne NATIONAL LABORATORY

ILLINOIS INSTITUTE OF TECHNOLOGY

Searches for the Standard Model Higgs Boson

Matthew Herndon, University of Wisconsin Madison

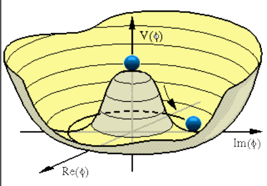
Collider Physics 2009, ANL & IIT



Electroweak Symmetry Breaking

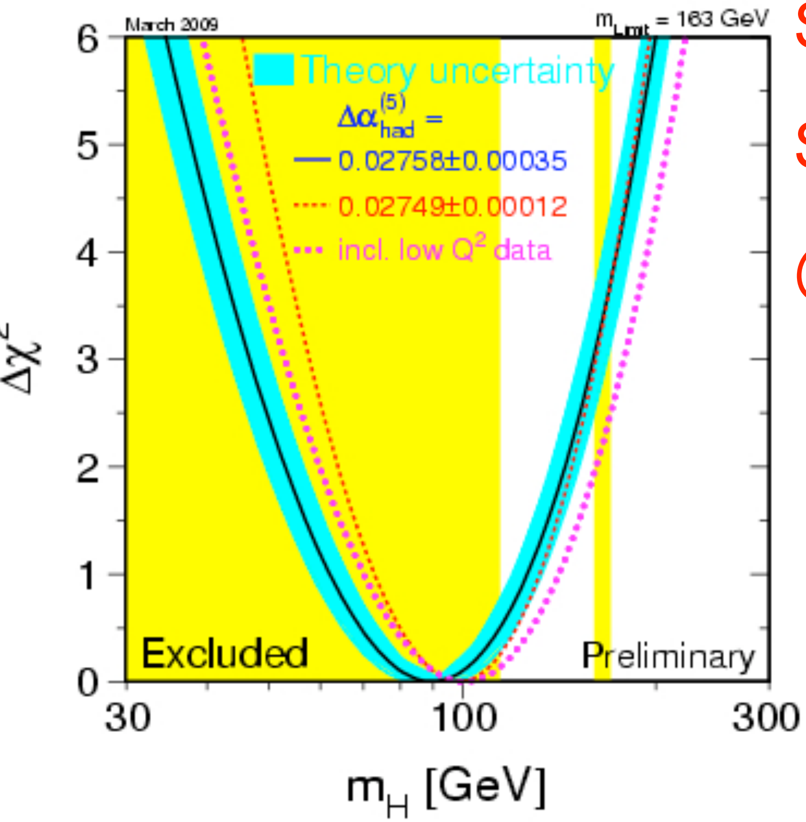
- An experimentalists conception
- Consider the Electromagnetic and the Weak Forces
- Coupling at low energy: EM: $\sim\alpha$, Weak: $\sim\alpha/(M_{W,Z})^2$
  - Fundamental difference in the coupling strengths at low energy, but apparently governed by the same dimensionless constant
  - Difference due to the massive nature of the W and Z bosons
- SM postulates a mechanism of electroweak symmetry breaking via the Higgs mechanism
  - Results in massive vector bosons and mass terms for the fermions
  - Directly testable by searching for the Higgs boson

A primary goal of the Tevatron and LHC



Electroweak Constraints

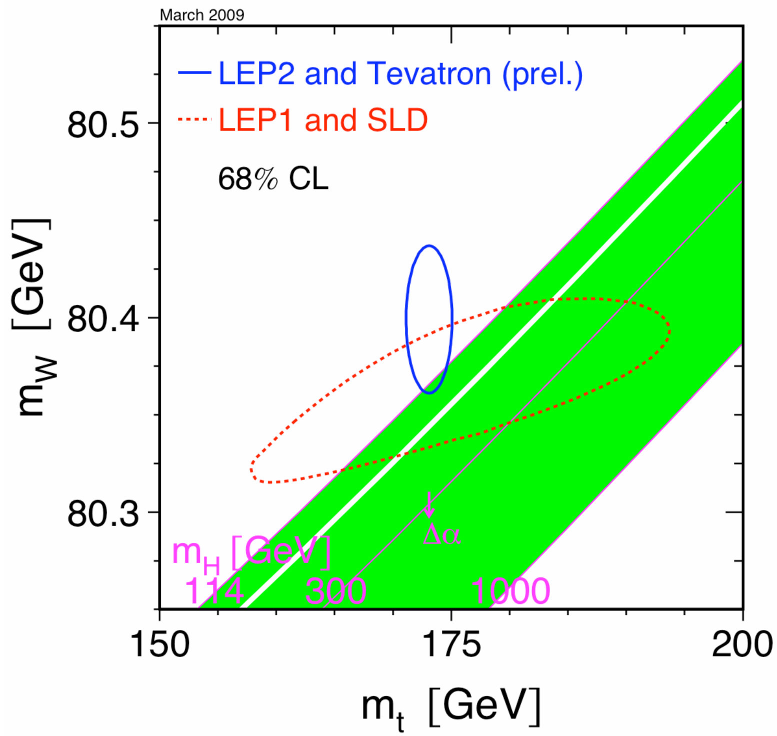
- Higgs couples strongly to massive particles
  - Introduces corrections to W and top masses - sensitivity to Higgs mass

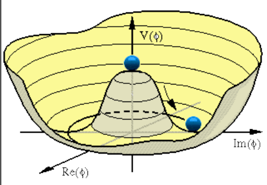


SM LEP Direct search: m_H > 114GeV

SM indirect constraint: m_H < 163GeV

@ 95% CL





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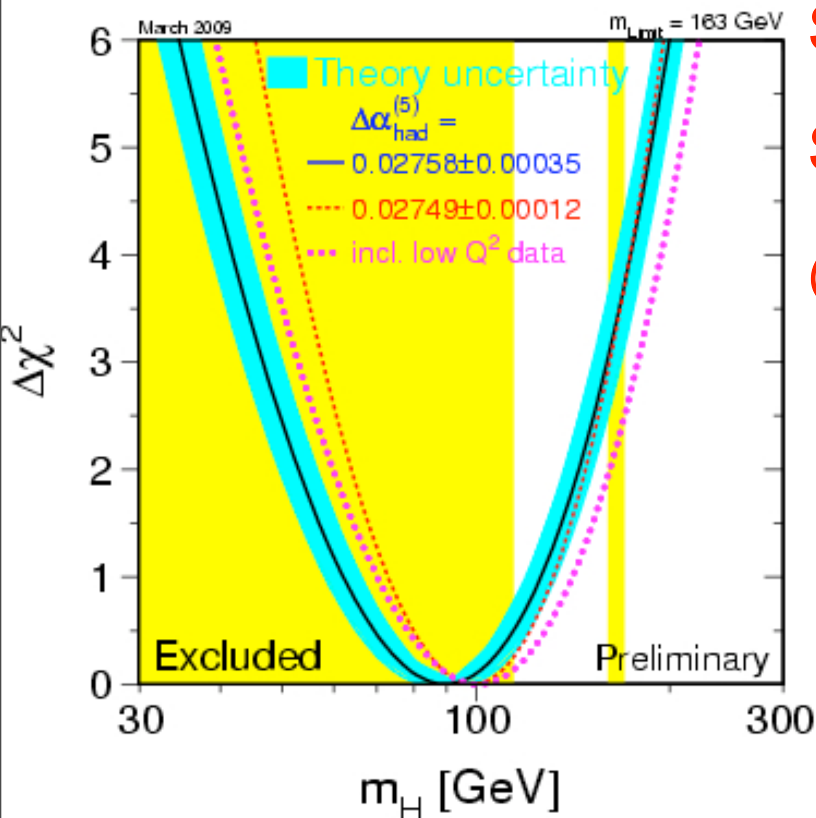

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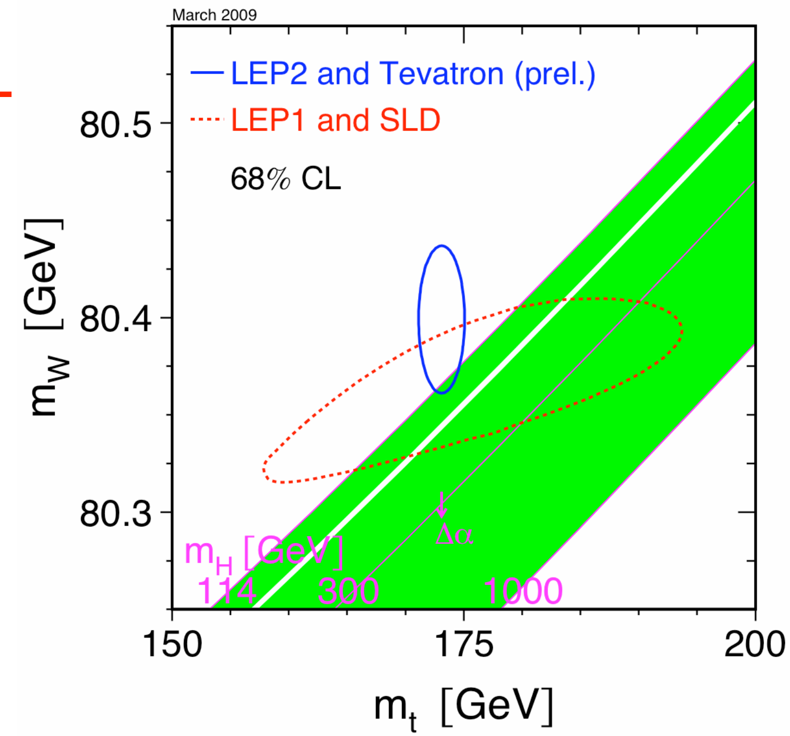
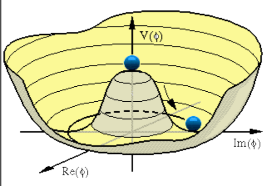
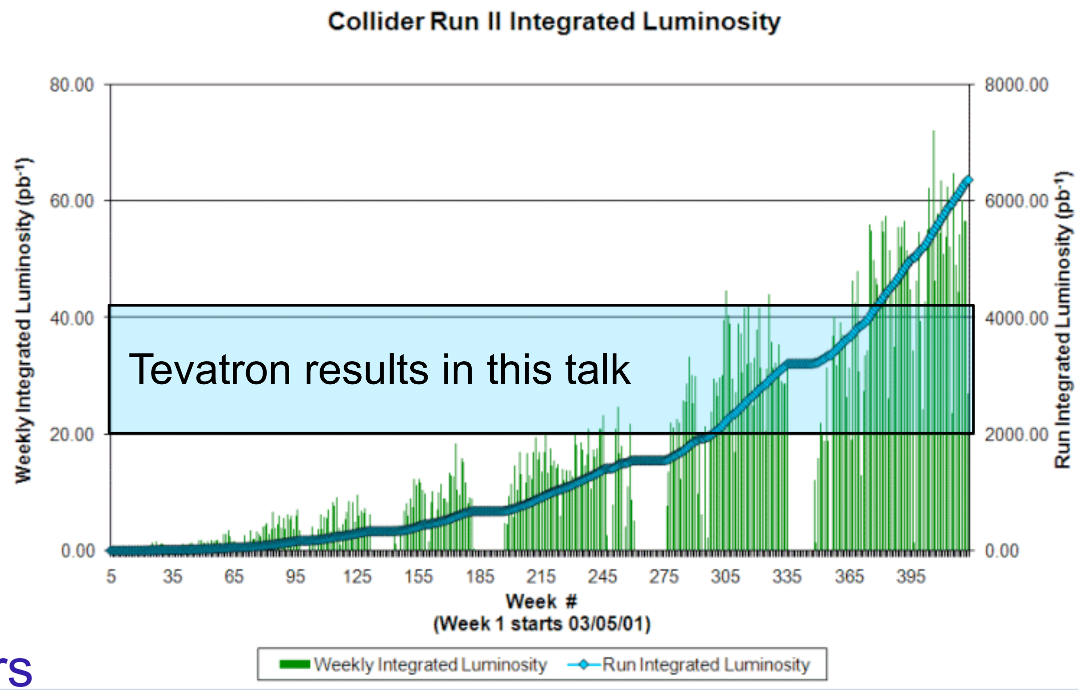


SM: We know where to look



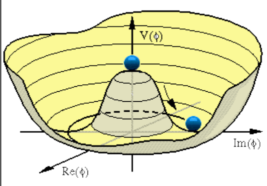
Colliders and Experiments

- Tevatron: 2TeV $p\bar{p}$ collider with two general purpose detectors: CDF, DØ
  - Excellent lepton Id
  - Good to excellent calorimeters for jet and MET reconstruction
  - Excellent silicon detectors for b jet identification
  - Higgs analysis uses full capabilities of the detectors



Given a SM Higgs

Tevatron: Higgs mass exclusions or evidence



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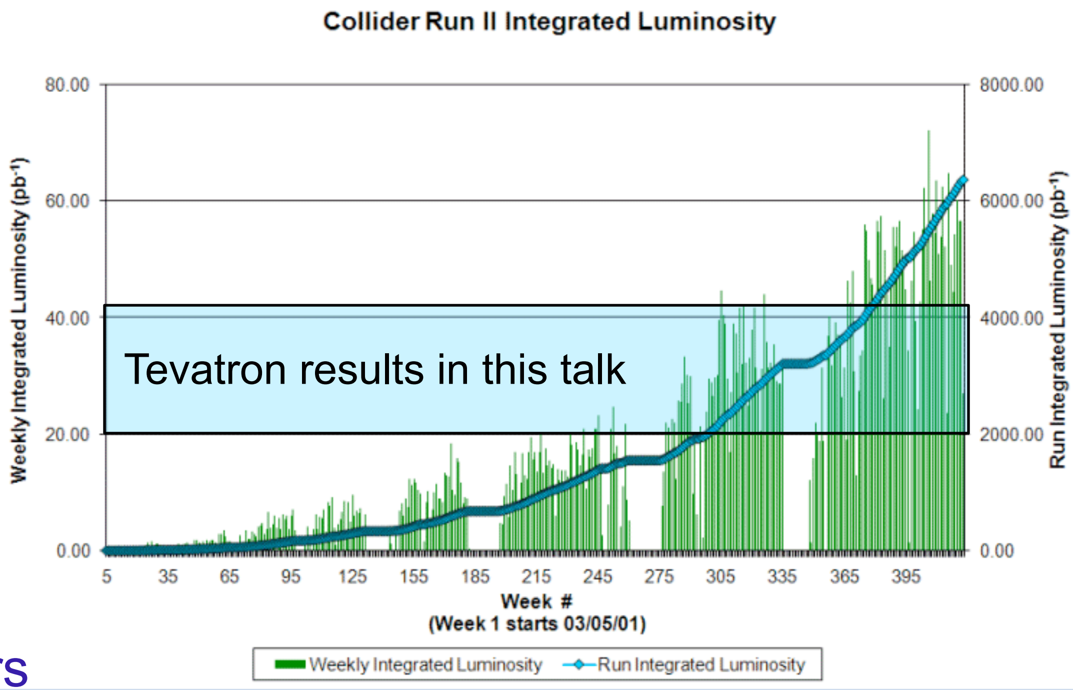
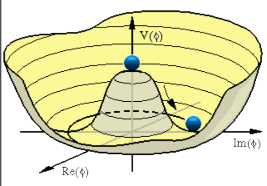


Given a SM Higgs

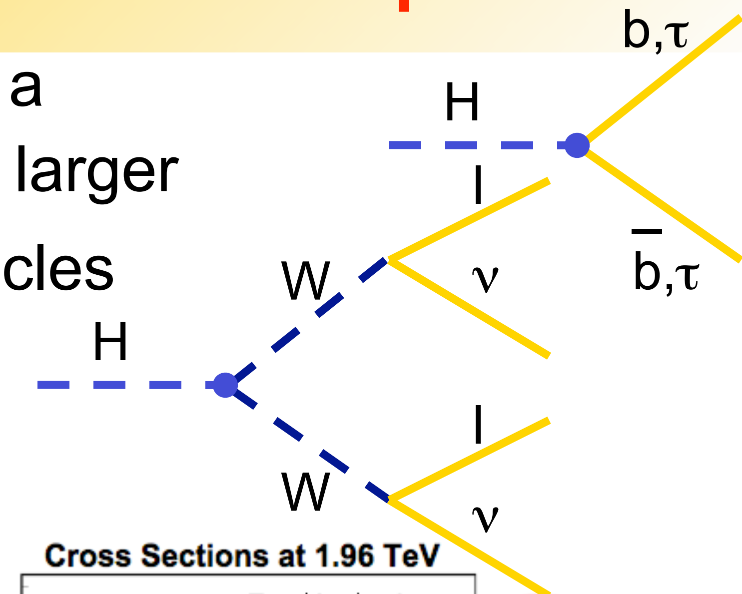
Tevatron: Higgs mass exclusions or evidence

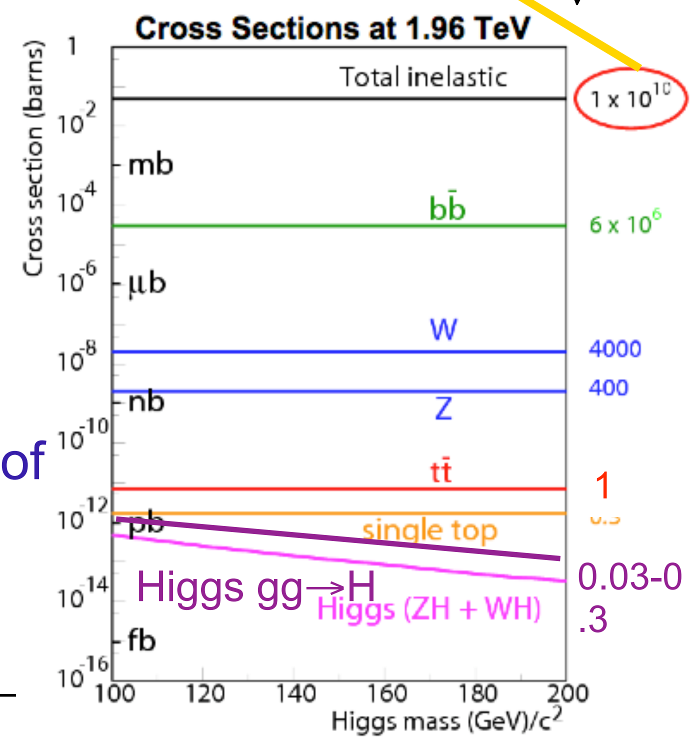
LHC: Observation over full mass range. Study Higgs properties



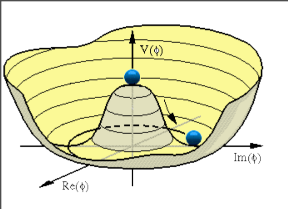
Tools: Triggers and Leptons

- Extract handful of Higgs events from a background 11 orders of magnitudes larger
- Higgs couples, decays to heavy particles
- Primary triggers: High p_T e and μ
  - Jet+MET triggers: modes with no charged leptons, supplement lepton triggers for gaps in coverage
  - Dedicated τ triggers: track+MET+Cal Energy
- Lepton Id
  - Optimize lepton Id on large samples of W, Z bosons

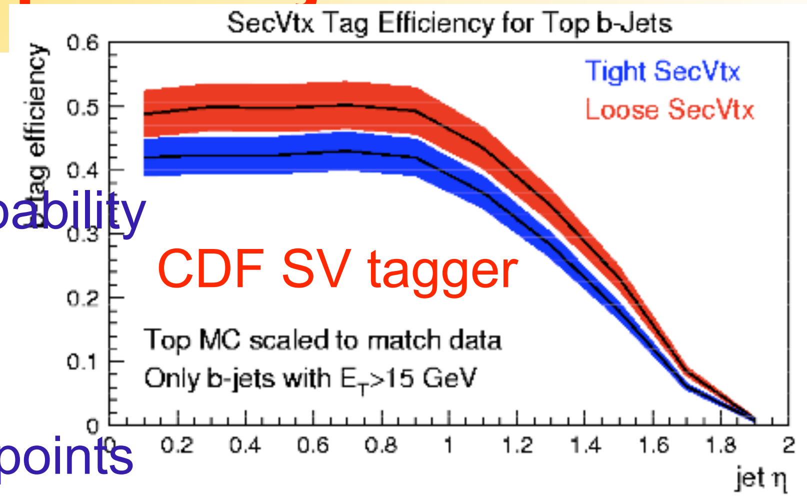




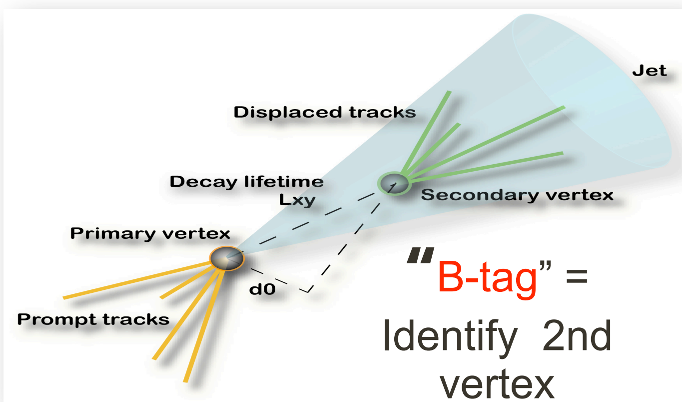
Maximizing Higgs acceptance

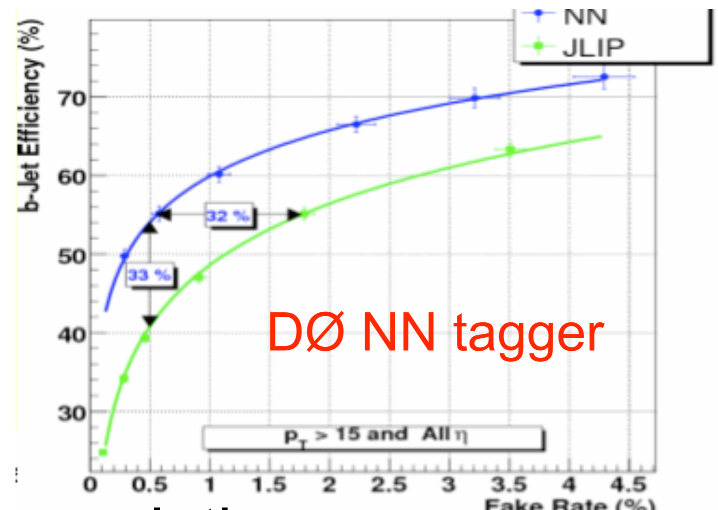


Tools: b quark jets

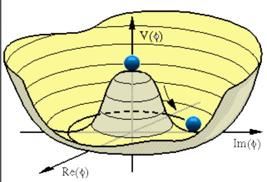


- b jet tagging
  - CDF: Secondary Vertex tagger, jet probability tagger, NN flavor separators
    - NN tagger soon +10% efficiency
  - DØ: NN tagger with multiple operating points
    - 40-70% Efficient with 0.3-5% mistag rate



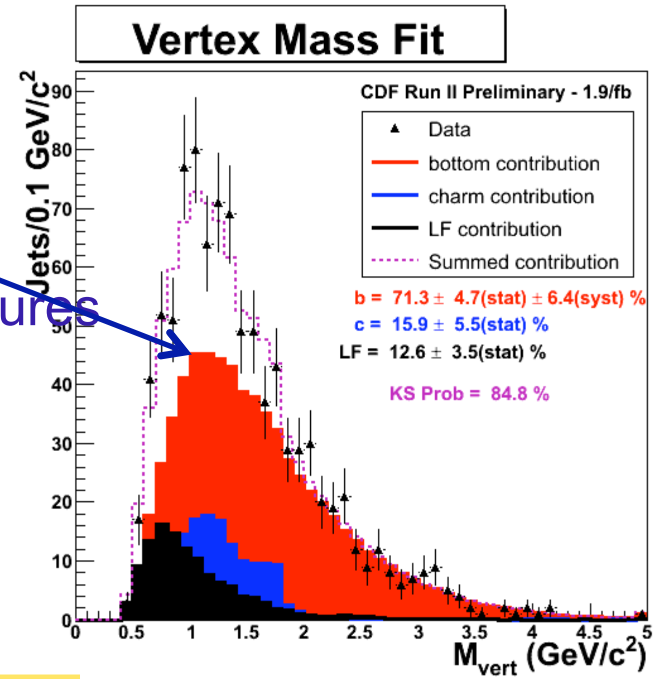


- Improvements in jet energy(dijet mass) resolution
  - Jet energy measurement combining calorimeter and tracking information
  - NN based jet energy corrections, constrained kinematic fits

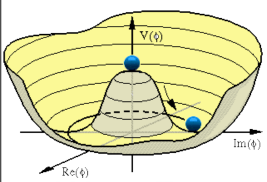


Tools: Backgrounds

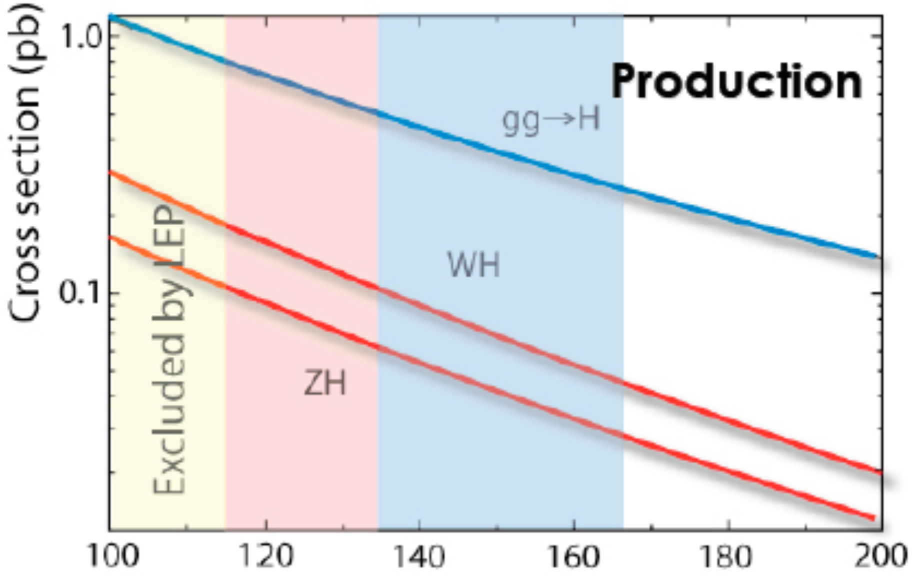
- SM processes create a variety backgrounds to Higgs detection
- Discovery analyses: WW, WZ, ZZ, single top, and from run 1 - top pairs
- Total and differential cross section measurements
  - QCD dijets, W+c, W+b, Z+b
- Critical to Higgs
  - Some backgrounds cannot be predicted using MC. QCD with fake lepton signatures
  - Constrain background predictions
  - Testing ground for tools and techniques
  - Control regions

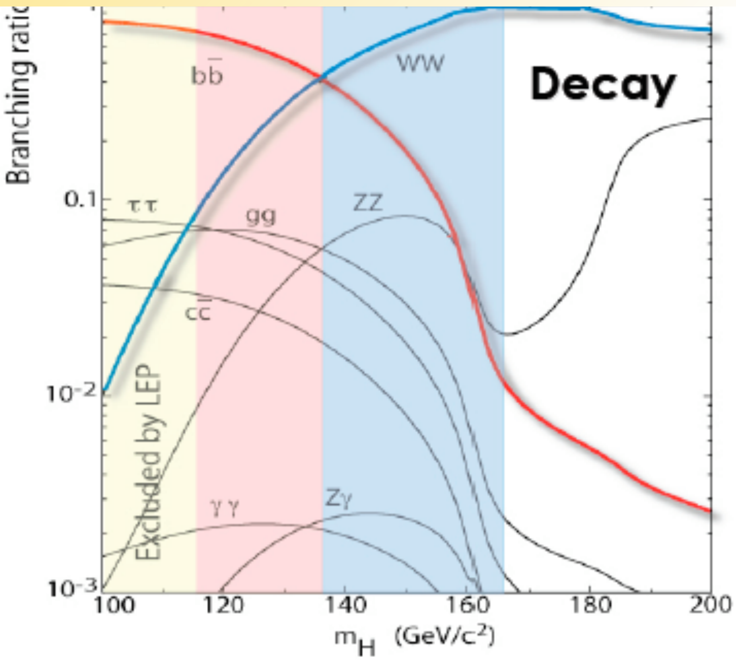


Higgs search built on a foundation of the entire collider physics program

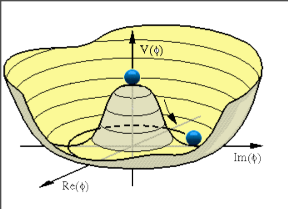


SM Higgs Production and Decay

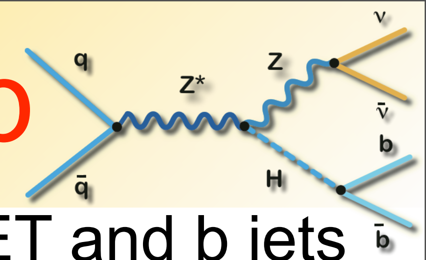




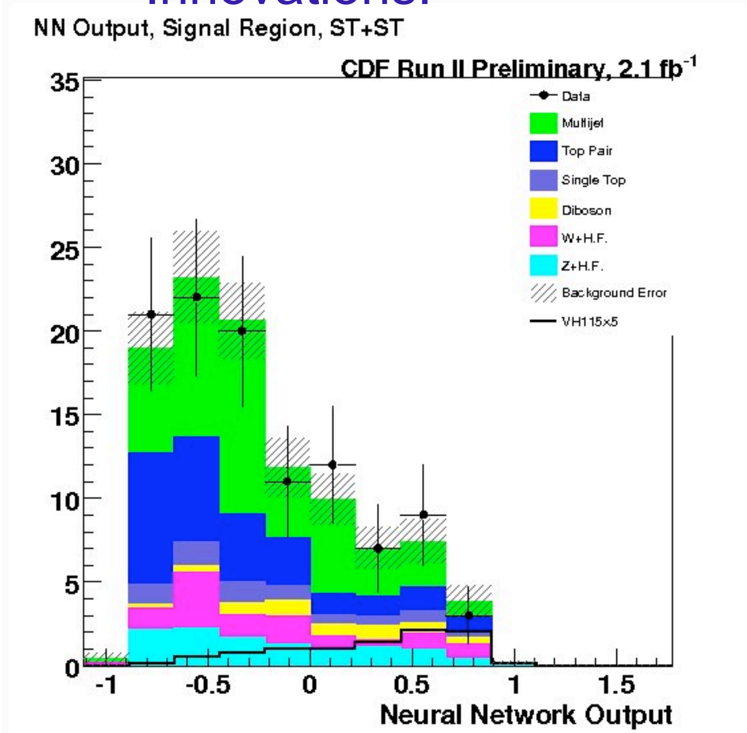
- High mass: H→WW→lνlν decay available
  - Take advantage of large gg→H production cross section, ZZ in progress
- Low Mass: H→bb, QCD bb background overwhelming
  - Use associated production with W or Z for background discrimination
  - WH→lνbb, ZH→ννbb (MET+bb), ZH→llbb
  - Also: VBF Production, VH→qqbb, H→ττ(with 2jets), H→γγ, VH->VWW, ttH



SM Higgs: VH→METbb



- ZH→ννbb, WH→lνbb(l not detected) - signature: MET and b jets
  - Primary Bkg: QCD b jets and mistagged light quark jets with false MET
  - Key issue: Building a model of the QCD background
    - Shape from 0 and 1 b tagged data samples with tag and mistag rates applied
  - Innovations:



Use of track missing p_T to define control regions and suppress backgrounds

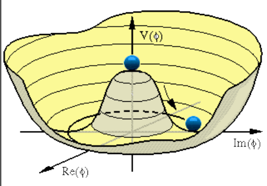
Uses of H1 Jet Algorithm combining tracking and calorimeter information(CDF)

3 jet events including W→τμ acceptance(CDF)

DØ also performs a dedicated W→τμ

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

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN	2.1	7.6	5.6	6.9
DØ BDT	2.1	3.7	8.4	7.5



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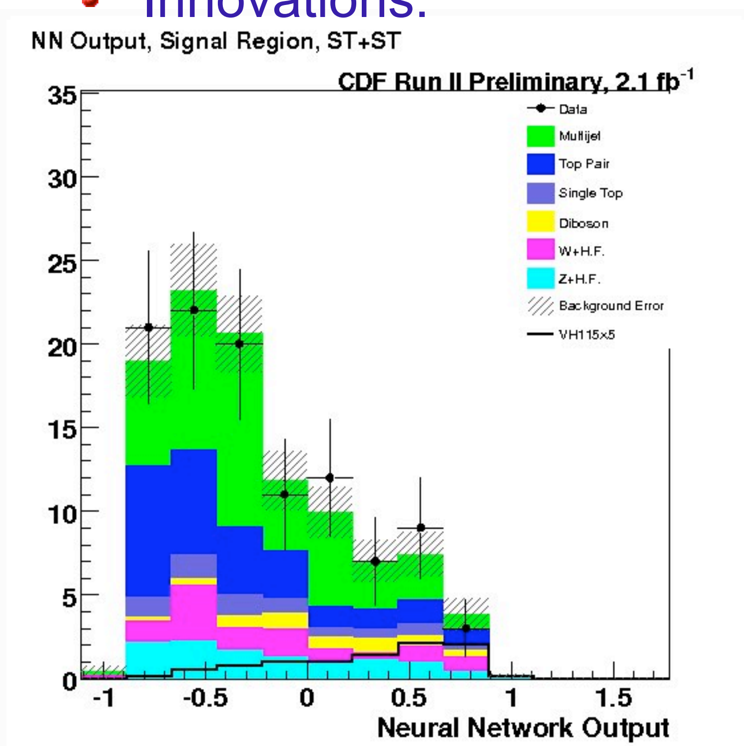

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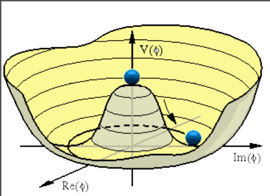

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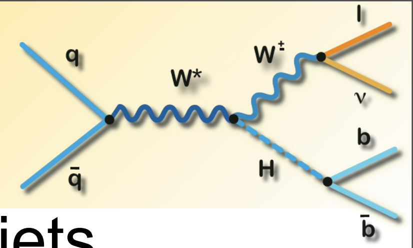
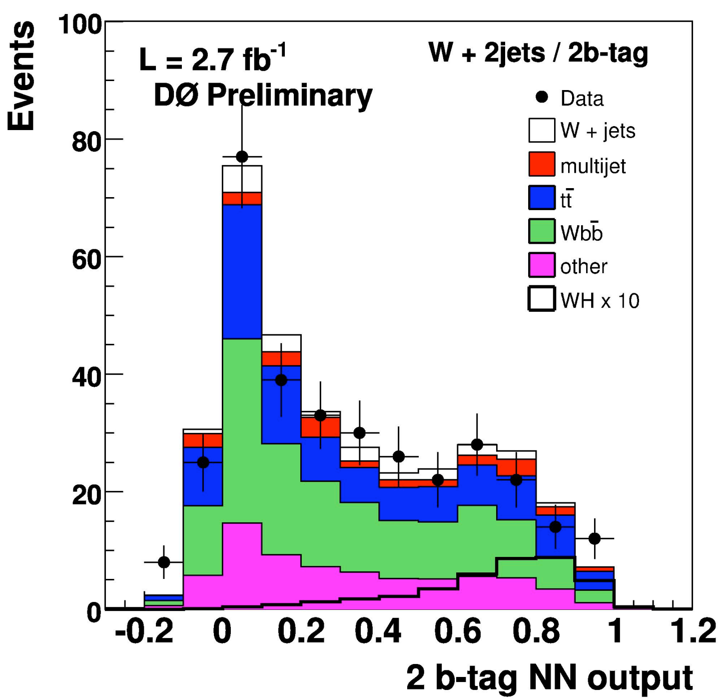


- WH→lνbb - signature: high pT lepton, MET and b jets
  - Backgrounds: W+bb, W+qq(mistagged), single top, Non W(QCD)
  - Single top: yesterday's discovery is today's background
  - Key issue: estimating W+bb background
    - Shape from MC with normalization from data control regions - compare MCs for sys
  - Innovations: 20% acceptance from isolated tracks(CDF)

Combination of NN and ME+BDT(CDF), ME+NN(DØ)



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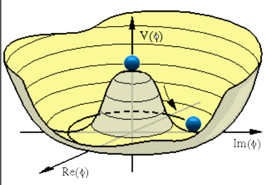
CDF NN+ME+BDT	2.7	8.4	4.8	5.8
DØ ME+NN new	2.7	13.3	6.7	6.4



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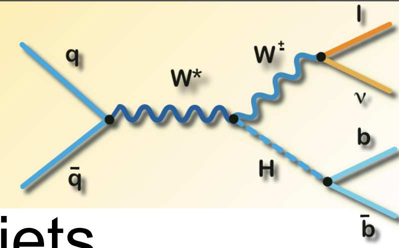

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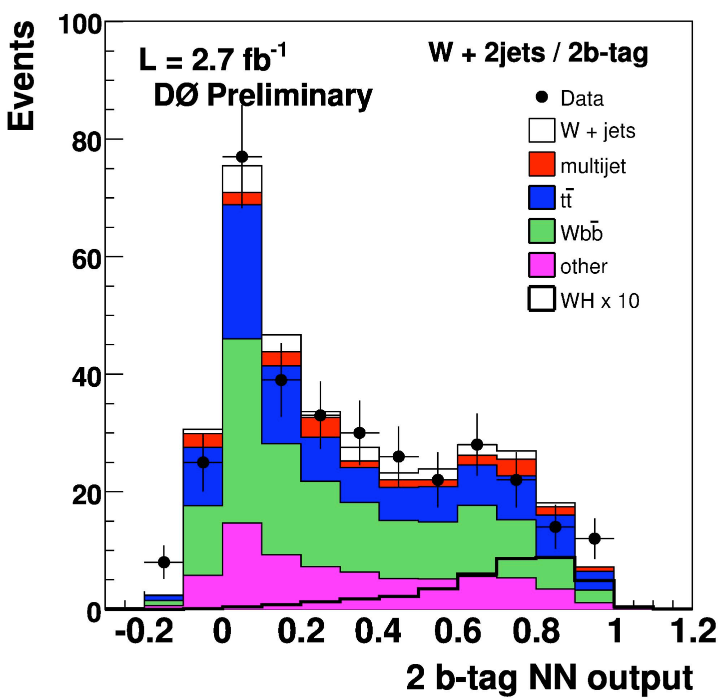

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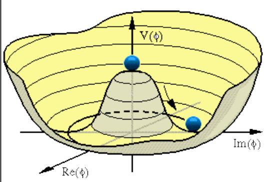
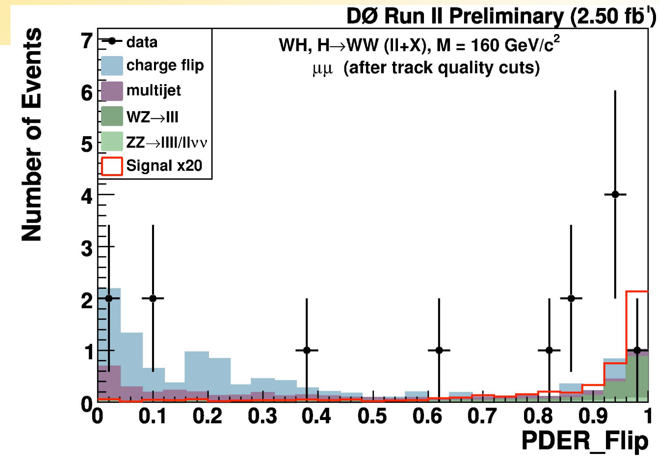
Worlds most sensitive low mass Higgs search - Still a long way to go!



Low Mass Higgs Searches

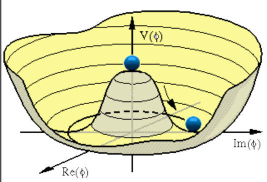
- We gain our full sensitivity by searching for the Higgs in every viable production and decay mode



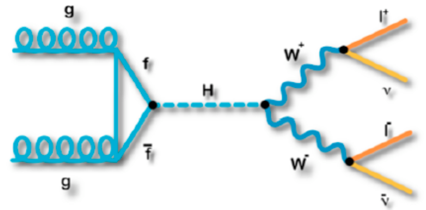
Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN: ZH→llbb new	2.7	2.2	9.9	7.1
DØ BDT new	4.2	3.1	8.0	9.1
CDF NN: VH→METbb	2.1	7.6	5.6	6.9
DØ BDT	2.1	3.7	8.4	7.5
CDFComb: WH→lνbb	2.7	8.4	4.8	5.8
DØ ME+NN new	2.7	13.3	6.7	6.4

Analysis: Limits @ 160/115 GeV	Exp. Limit	obs. Limit
DØ WH→WWW	10	18
CDF WH→WWW	19	24
DØ H→γγ	18	16
CDF H→ττ	25	31
DØ inclusive τ	28	29
CDF VH→qqbb	37	37
DØ ttH	45	64

- Sensitivity to 38 Higgs events
- A new round of analysis, 2x data and 1.5x improvements will bring us to SM sensitivity.

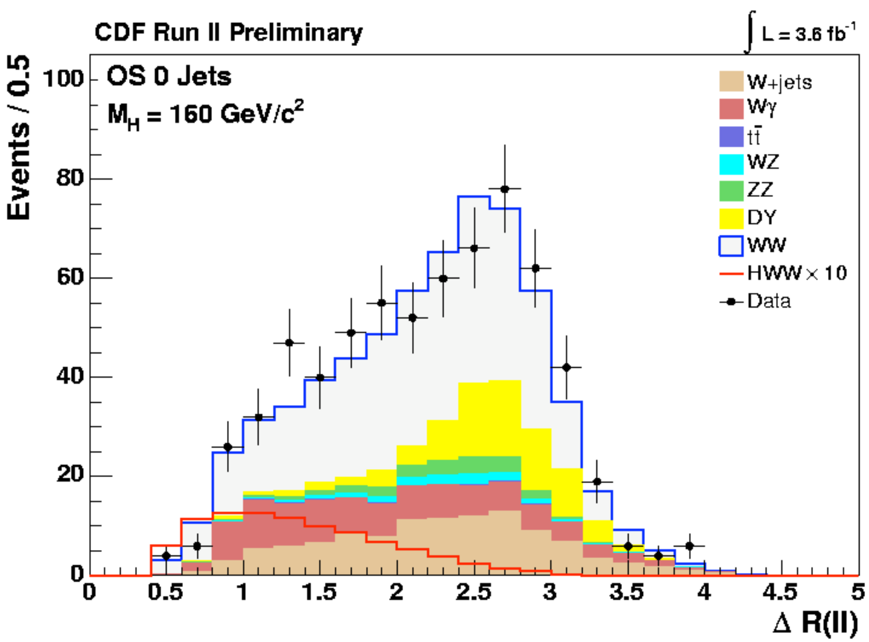


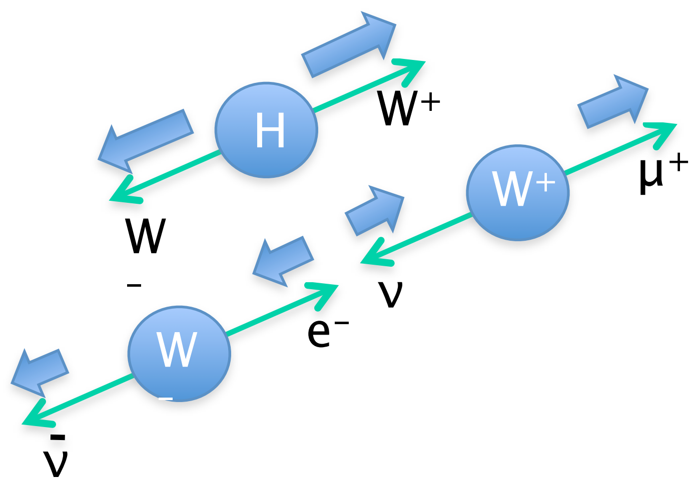
SM Higgs: H→WW



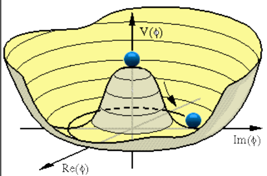
- H→WW→lνlν - signature: Two high p_T leptons and MET
  - Primary backgrounds: WW and top in di-lepton decay channel
  - Key issue: Maximizing lepton acceptance
  - Innovations: Inclusion of acceptance from VH and VBF

Combination of ME and NN approaches(CDF), same sign leptons





Spin correlation: Charged leptons go in the same direction



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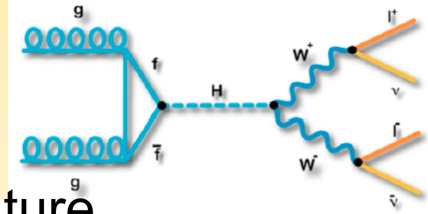
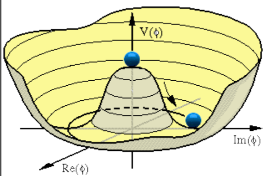


- Example: CDF: Inclusive H→WW analysis: lνlνMET - signature
- Optimize in jet bins & lepton charge configuration(CDF), Lepton type(DØ)

Channel	Signal	Primary background	Primary discriminants
0 Jets	gg→H	WW, DY	$\Delta\phi$/R,MET,ME
1 Jet	gg→H, VH, VBF	WW, DY	$\Delta\phi$/R,MET,m_{TH}
2+ Jets	gg→H, VH, VBF	Top dilepton	MET,HT,m_{TH}
1+ Jets SS lepton	VH	W+Jets	Good lepton ID, MET

- Control regions
  - Low MET: Understand DY, lepton Id efficiencies
  - Large MET aligned along jet of lepton: Understand false MET
  - SS: Understand false leptons
  - High WW ME likelihood: measure WW cross section
  - B tagged jets, understand top dilepton



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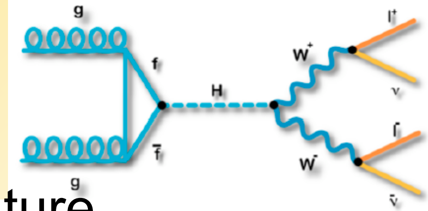

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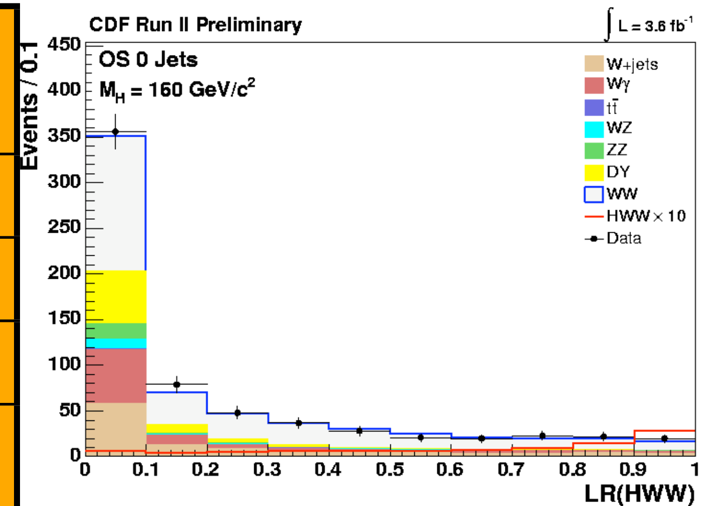

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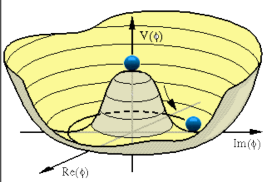

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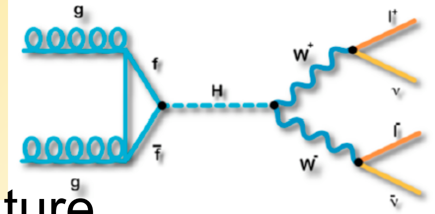

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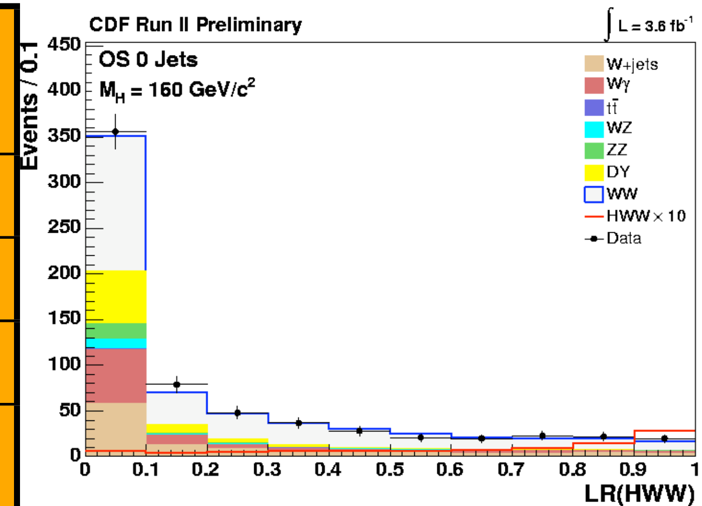
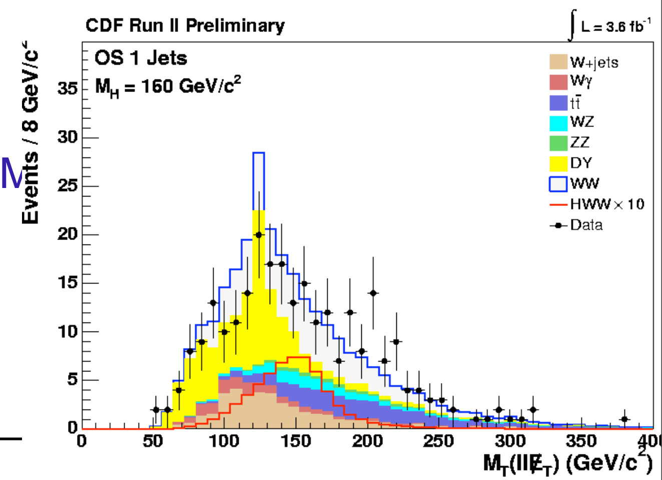
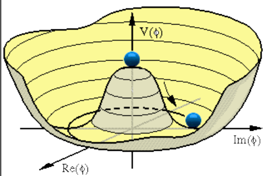
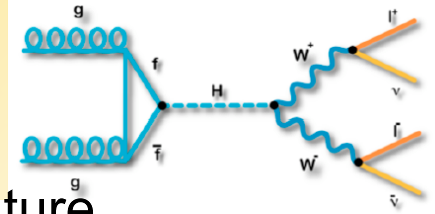


- Control regions
  - Low MET: Understand DY, lepton Id efficiencies
  - Large MET aligned along jet of lepton: Understand false M
  - SS: Understand false leptons
  - High WW ME likelihood: measure WW cross section
  - B tagged jets, understand top dilepton



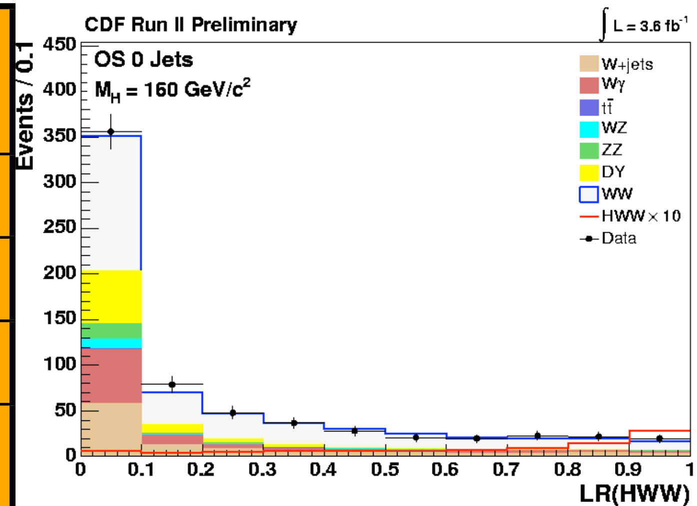


SM Higgs: H→WW



- Example: CDF: Inclusive H→WW analysis: lνlνMET - signature
- Optimize in jet bins & lepton charge configuration(CDF), Lepton type(DØ)

Channel	Signal	Primary background	Primary discriminants
0 Jets	gg→H	WW, DY	Δϕ/R,MET,ME
1 Jet	gg→H, VH, VBF	WW, DY	Δϕ/R,MET,m_{TH}
2+ Jets	gg→H, VH, VBF	Top dilepton	MET,HT,m_{TH}
1+ Jets SS lepton	VH	W+Jets	Good lepton ID, MET



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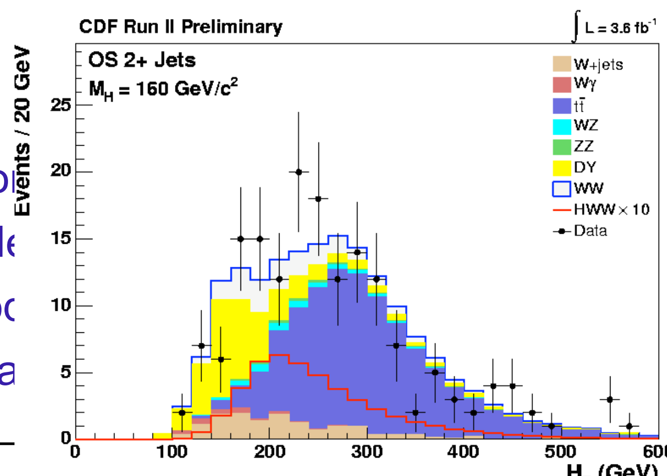

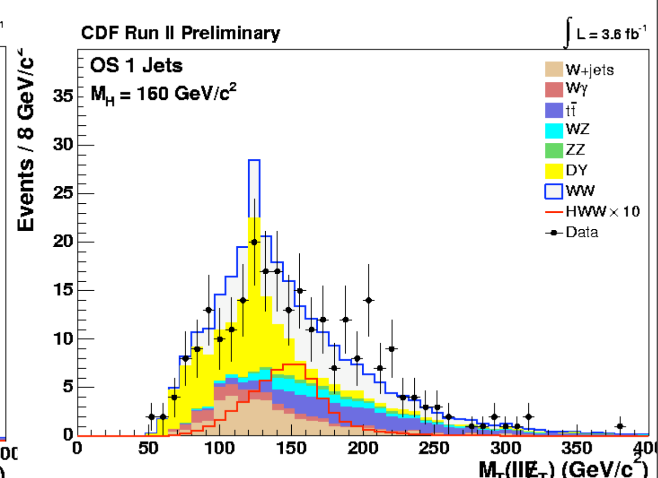

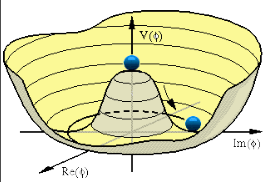

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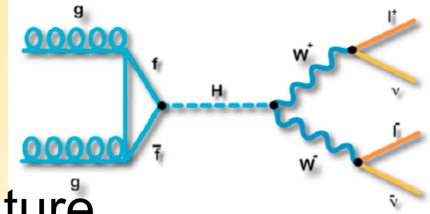

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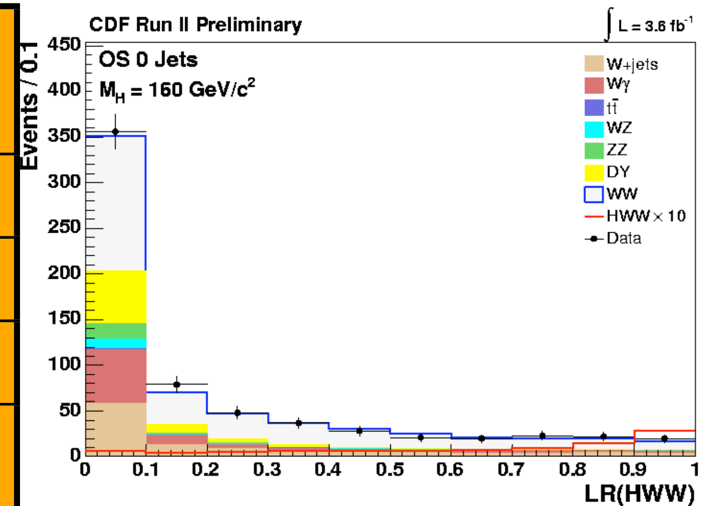

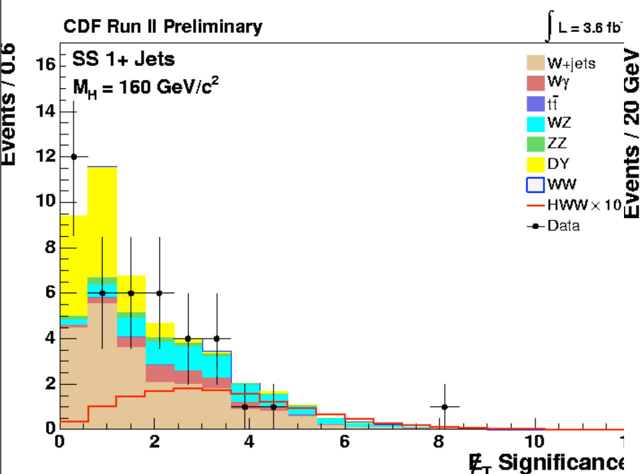

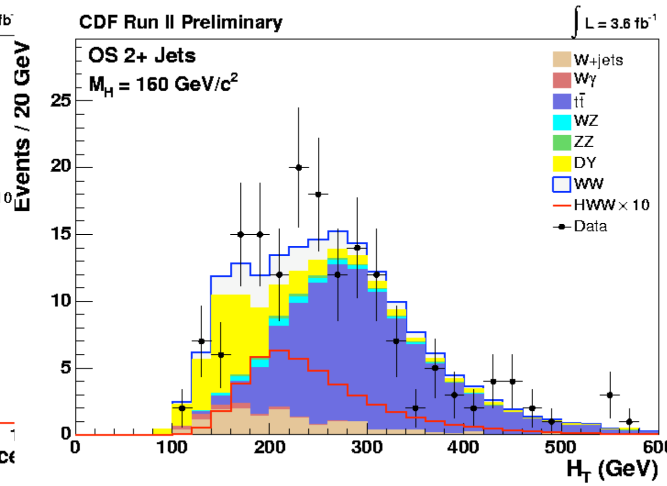

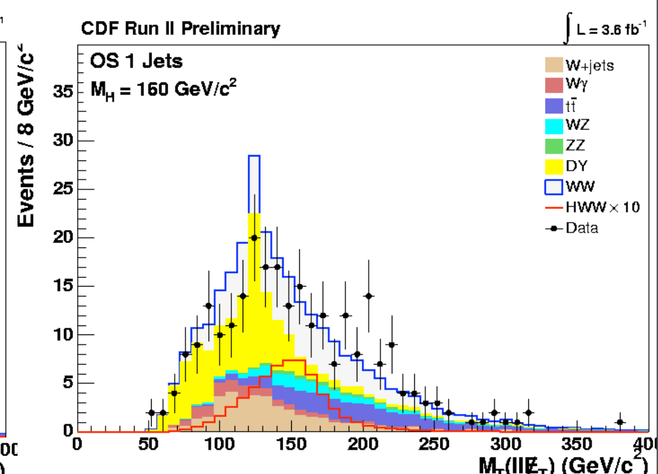

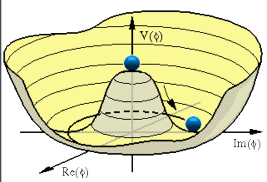

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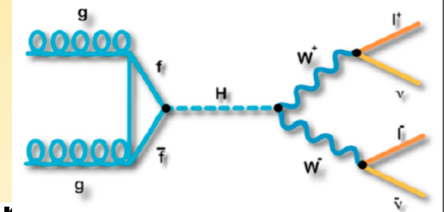
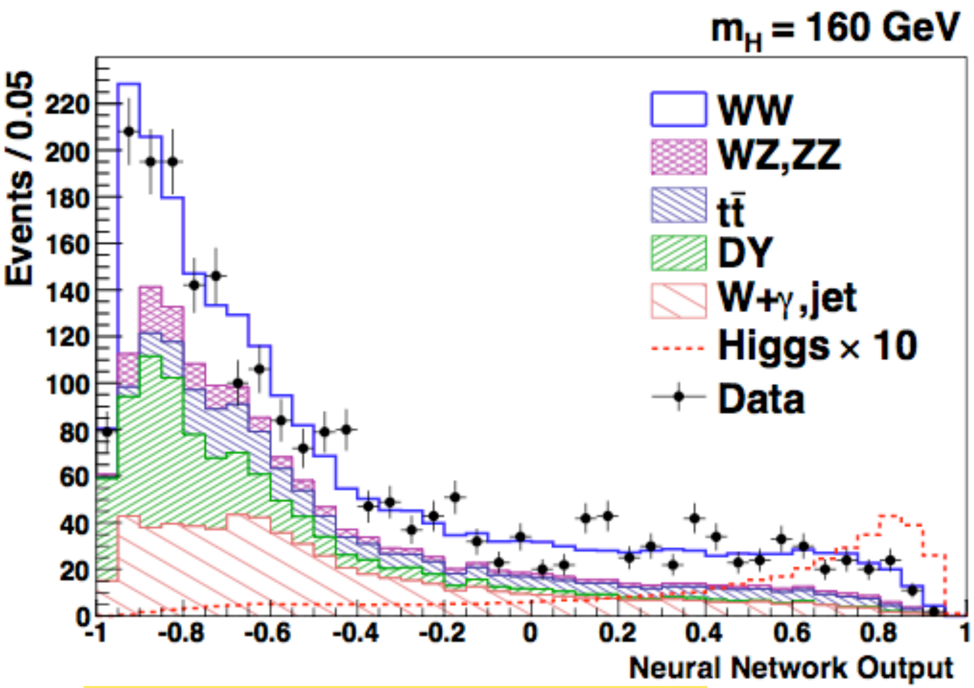
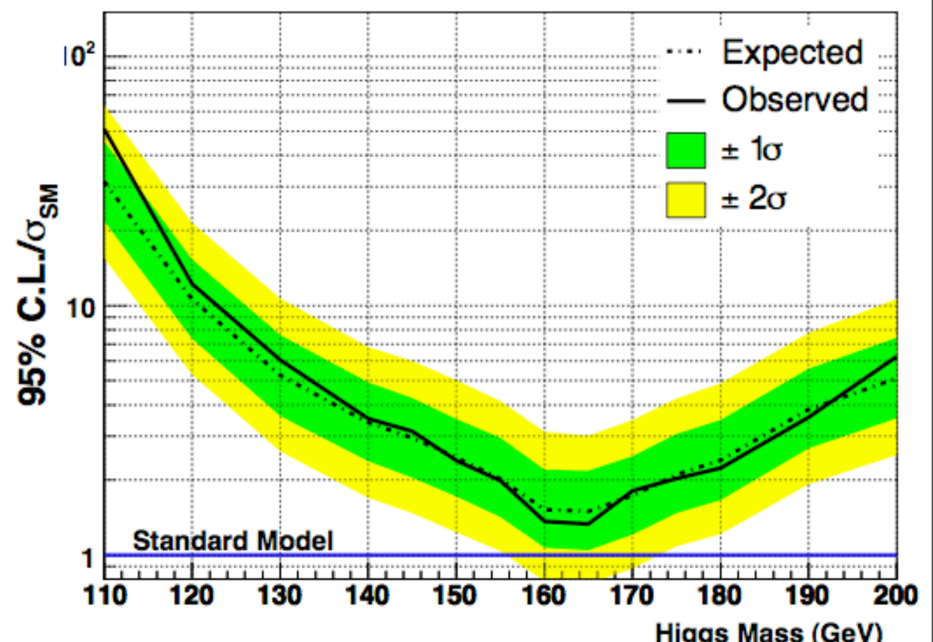


- Most sensitive Higgs search channel at the Tevatron

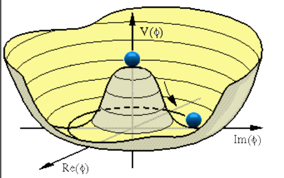




Both experiments
Approaching
SM sensitivity!
43.5 Higgs Events!

Results at mH = 165GeV : 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF ME+NN	3.6	20.3	1.5	1.3
DØ NN	4.2	23.2	1.7	1.3



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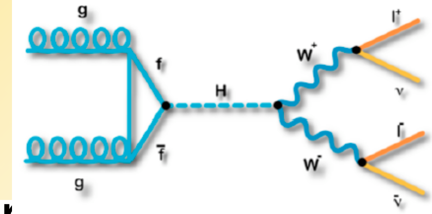

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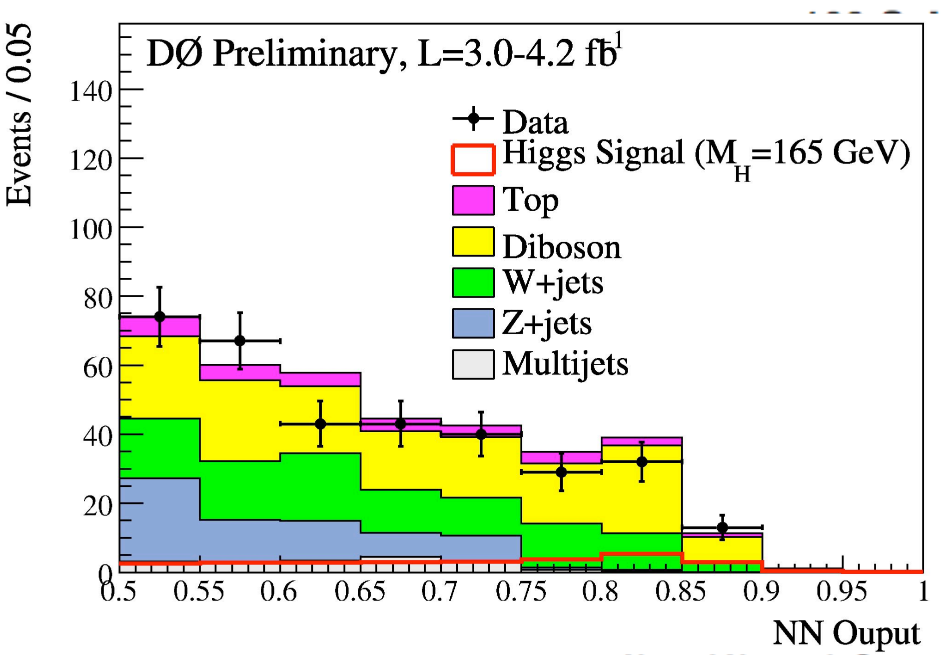
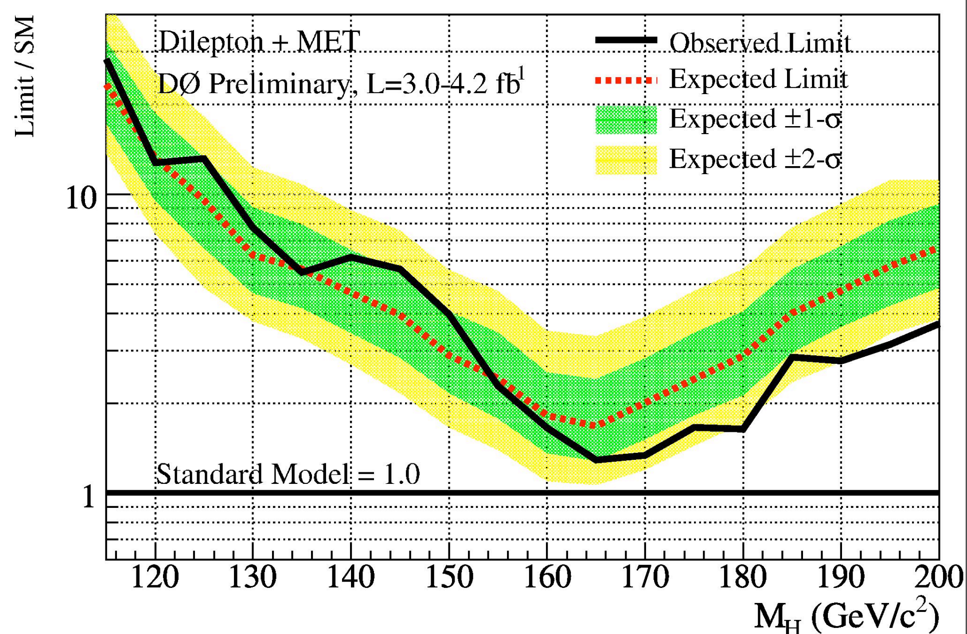


Neural Network Output



Higgs Mass (GeV)

Both experiments Approaching SM sensitivity!
43.5 Higgs Events!

Results at mH = 165GeV : 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
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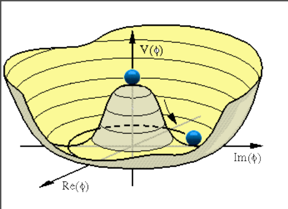
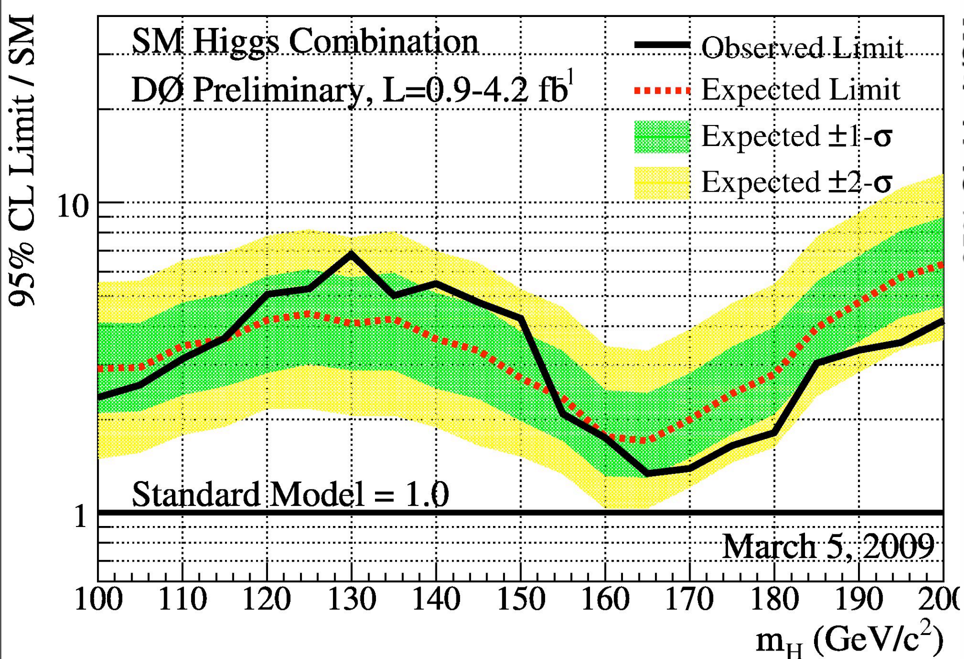
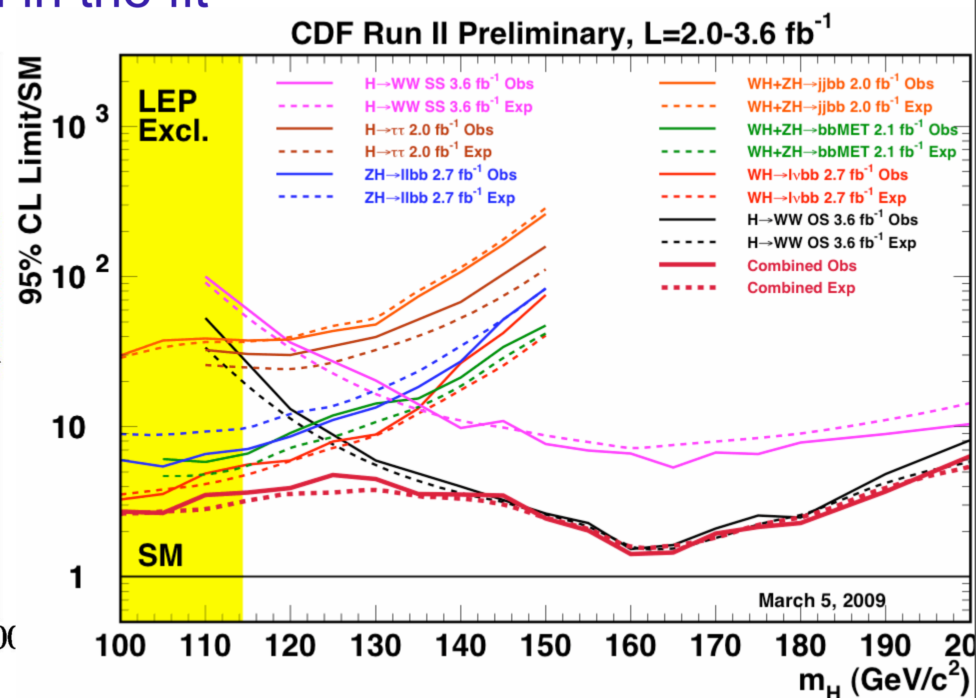
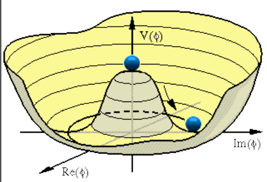


SM Higgs Combined Limits

- Limits calculation and combination
  - Using Bayesian and CLs(DØ) methodologies.
  - Incorporate systematic uncertainties using pseudo-experiments (shape and rate included) (correlations taken into account between experiments)
  - Backgrounds can be constrained in the fit







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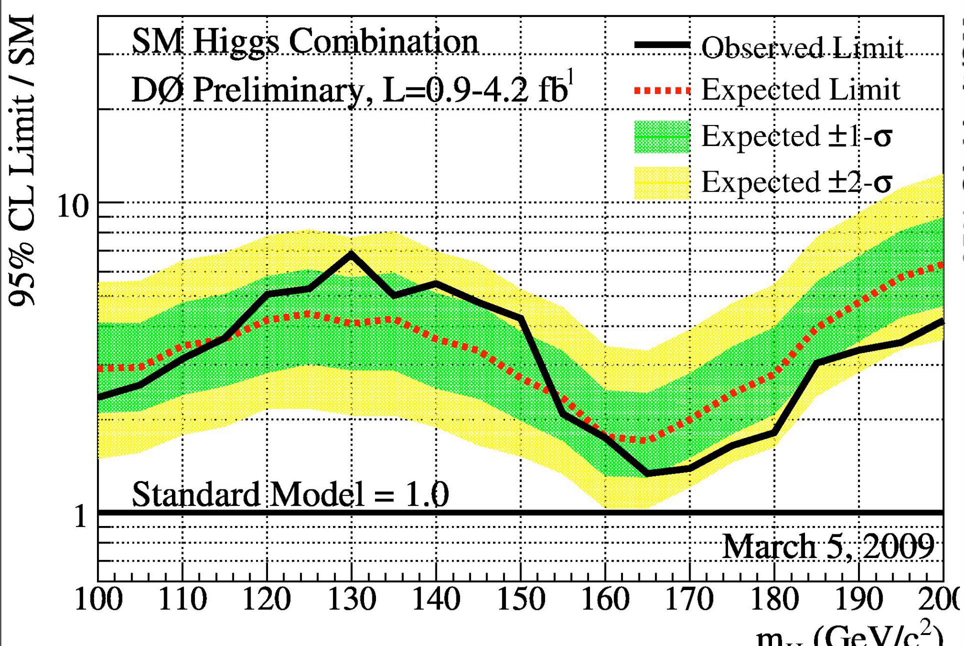
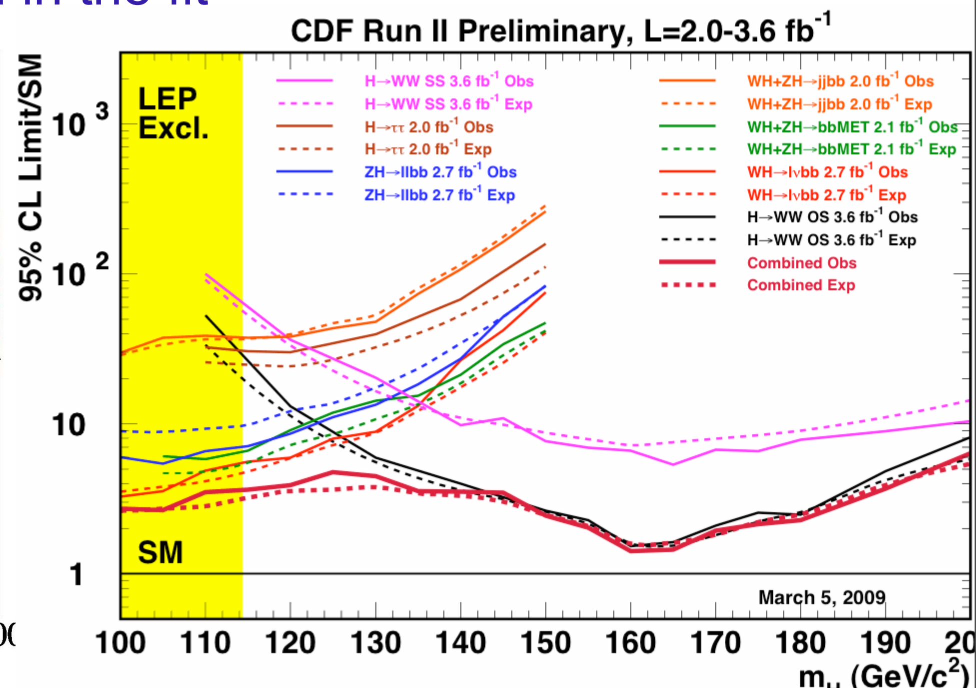
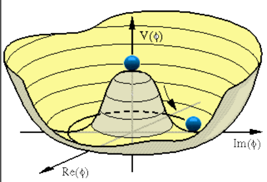




DØ Exp. 3.6, Obs 3.7, CDF Exp. 3.2, Obs 3.6 @ 115 GeV



H→WW Some Details

- Previous NNLL cross section: S. Catani, D. de Florian, M. Grazzini, and P. Nason, JHEP 07, 028 (2003), hep-ph/0306211 CTEQ5L
  - Include two loop EW diagrams: U. Aglietta, B. Bonciani, G. Degrassi, and A. Vivini (2006), hep-ph/0610033.
  - 2009 MSTW PDFs
    Martin Sterling Thorne Watt hep-ph/0901.0002
- Integrated together into the latest state of the art predictions
  - Latest gluon PDF, full treatment of EW contribution, better treatment of b quark masses

    C Anastasiou, R Boughezal, F Petriello, hep-ph/0811.3458

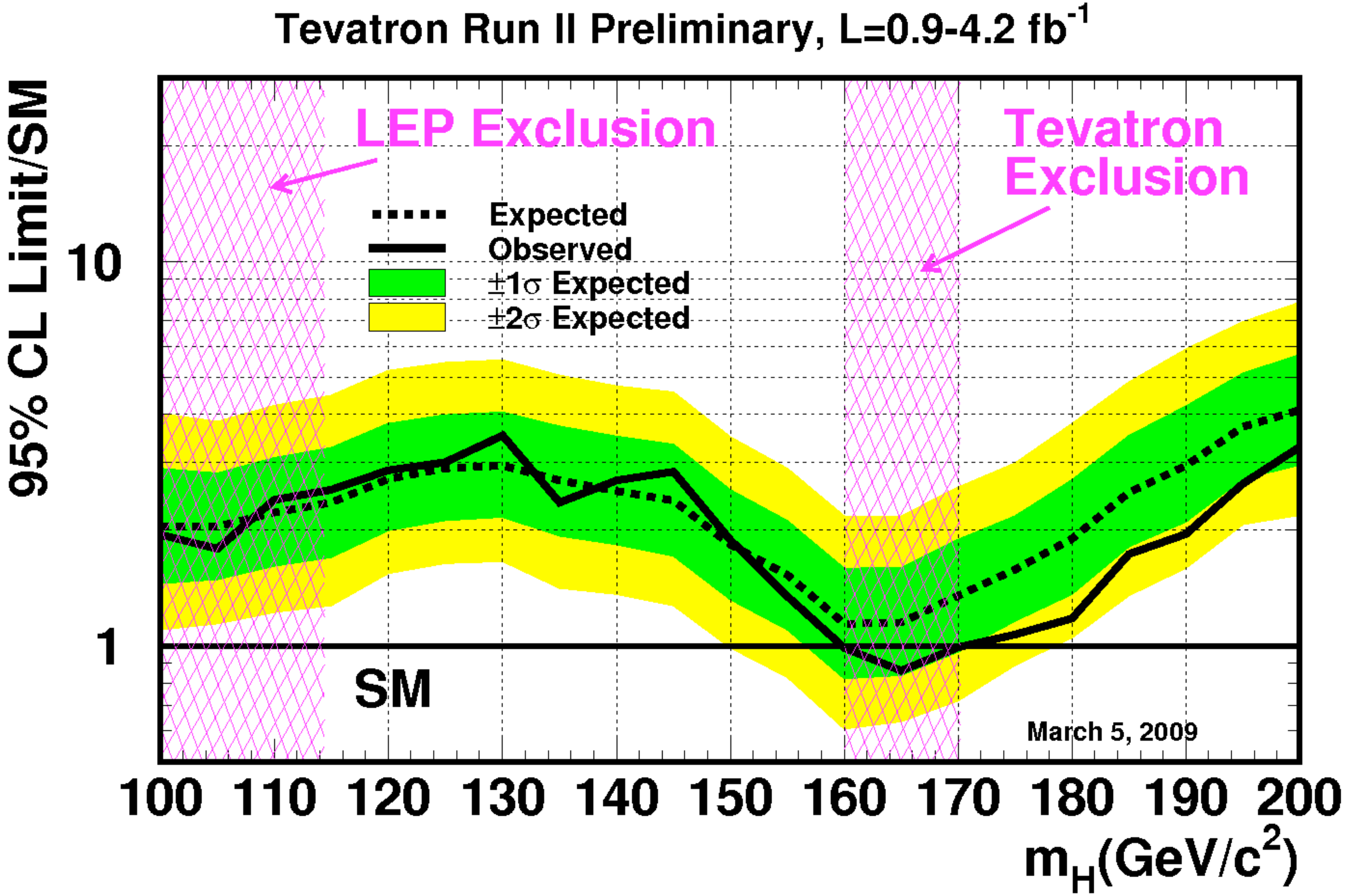
    D. de Florian, M. Grazzini, hep-ph/0901.2427
- Example systematic table
  - Rates and shapes considered
  - Shape: Scale variations, ISR, gluon pdf, Pythia vs. NNL0 kinematics, DY pt distribution, jet energy scale, lepton fake rate shapes: for signal and backgrounds. Included in limit setting if significant.

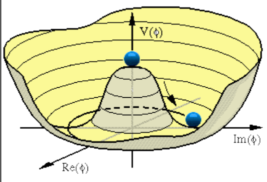
CDF: $H \to WW \to \ell^{\pm}\ell'^{\mp} + 0$ Jets Analysis

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet	$gg \to H$	WH	ZH	VBF
Cross Section											
Scale								10.9%			
PDF Model								5.1%			
Total	*10.0%*	*10.0%*	*10.0%*	15.0%	5.0%	10.0%		12.0%			
Acceptance											
Scale (leptons)								2.5%			
Scale (jets)								4.6%			
PDF Model (leptons)	1.9%	2.7%	2.7%	2.1%	4.1%	2.2%		1.5%			
PDF Model (jets)								0.9%			
Higher-order Diagrams	**5.5%**	**10.0%**	**10.0%**	10.0%	**5.0%**	**10.0%**					
Missing Et Modeling	1.0%	1.0%	1.0%	1.0%	20.0%	1.0%		1.0%			
Conversion Modeling						20.0%					
Jet Fake Rates											
(Low S/B)							21.5%				
(High S/B)							27.7%				
MC Run Dependence	3.9%			4.5%		4.5%		3.7%			
Lepton ID Efficiencies	2.0%	1.7%	2.0%	2.0%	1.9%	1.4%		1.9%			
Trigger Efficiencies	2.1%	2.1%	2.1%	2.0%	3.4%	7.0%		3.3%			
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%	5.9%		5.9%			

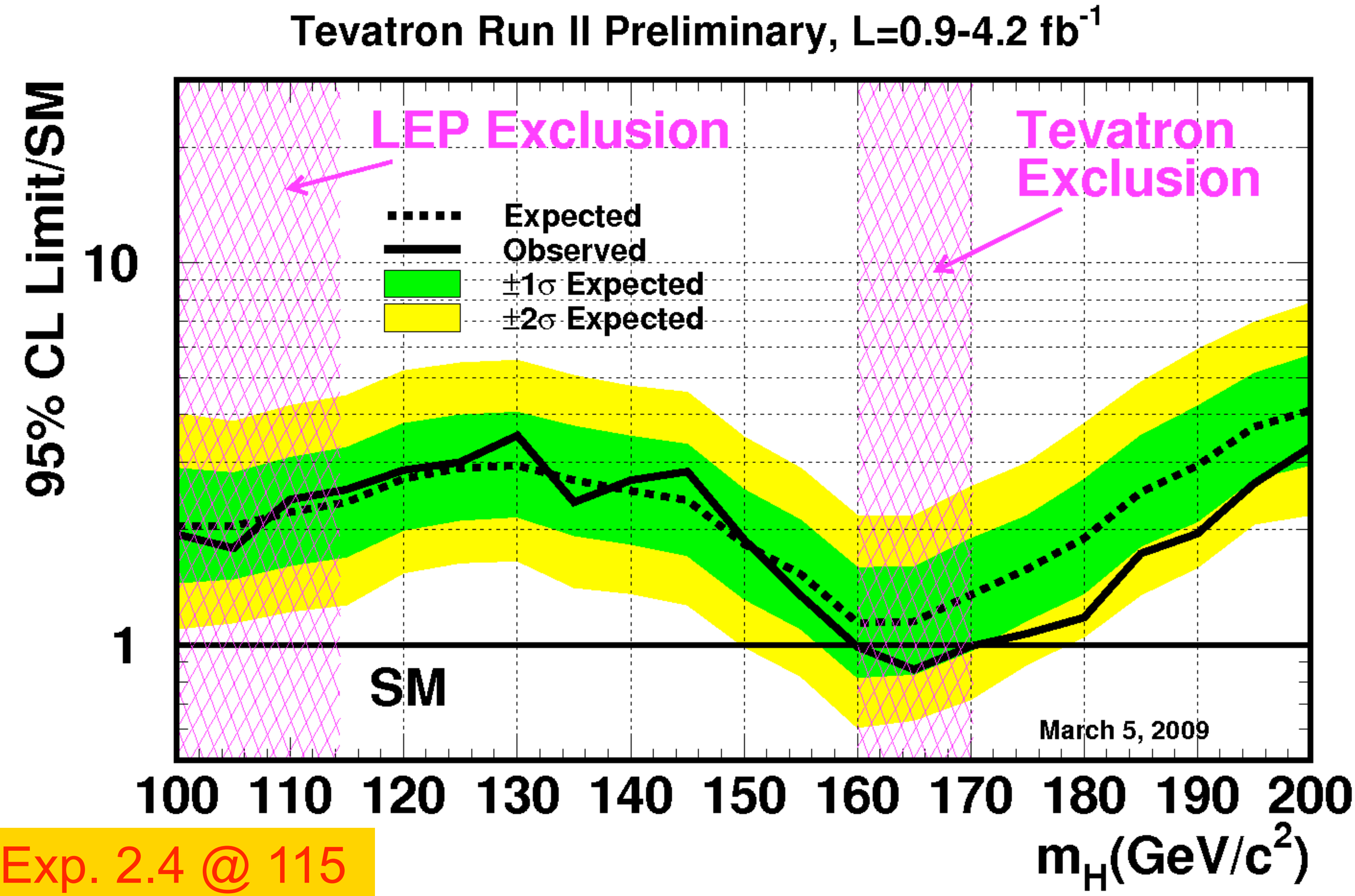
Treatment developed jointly by CDF and DØ

SM Higgs Combination

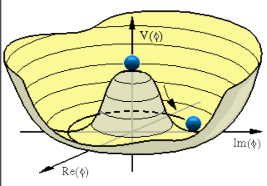




SM Higgs Combination

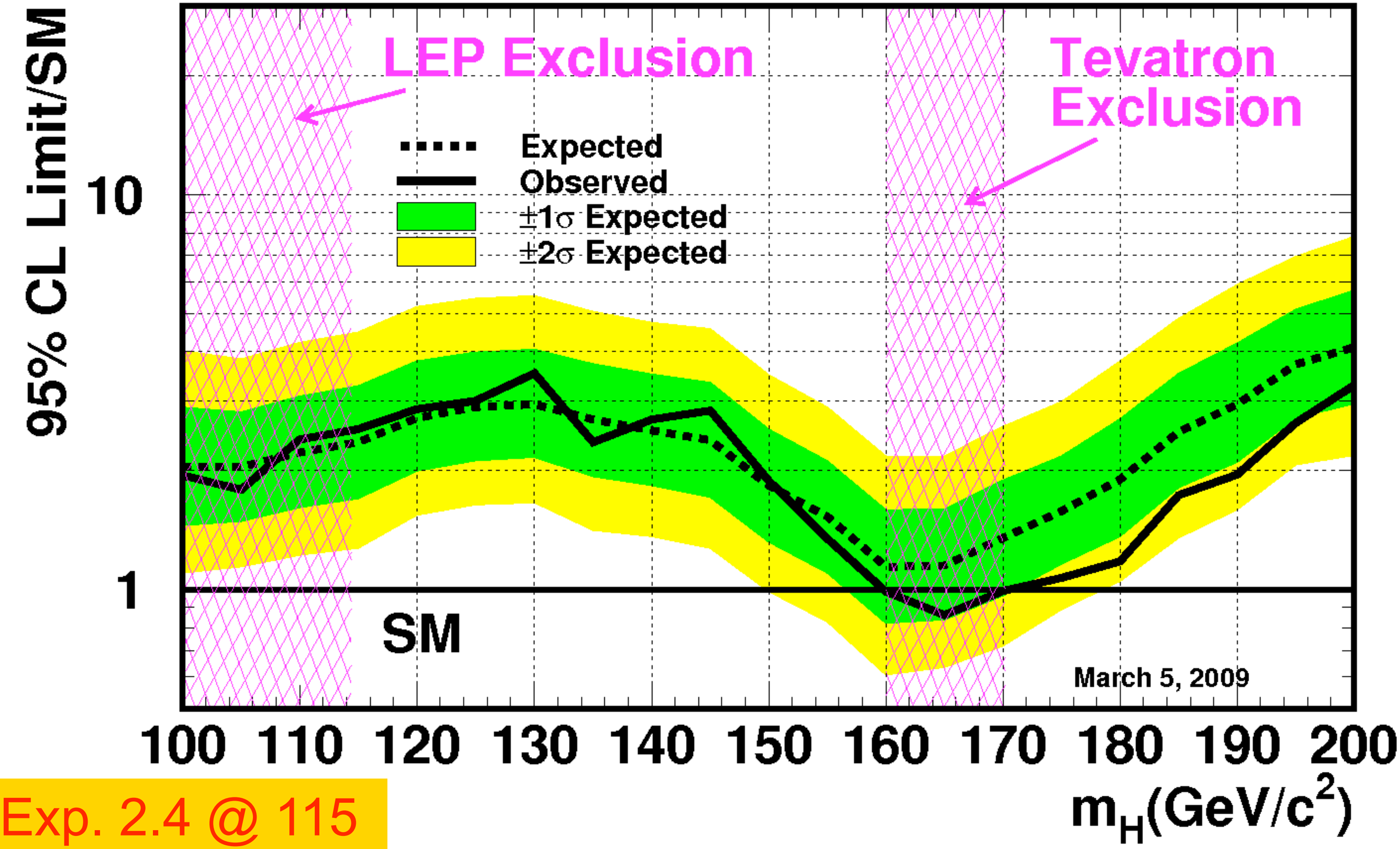


Exp. 2.4 @ 115



SM Higgs Combination

Exp. 1.1 @ 160/165, 1.4 @ 170 GeV



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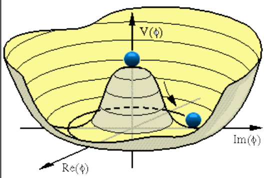

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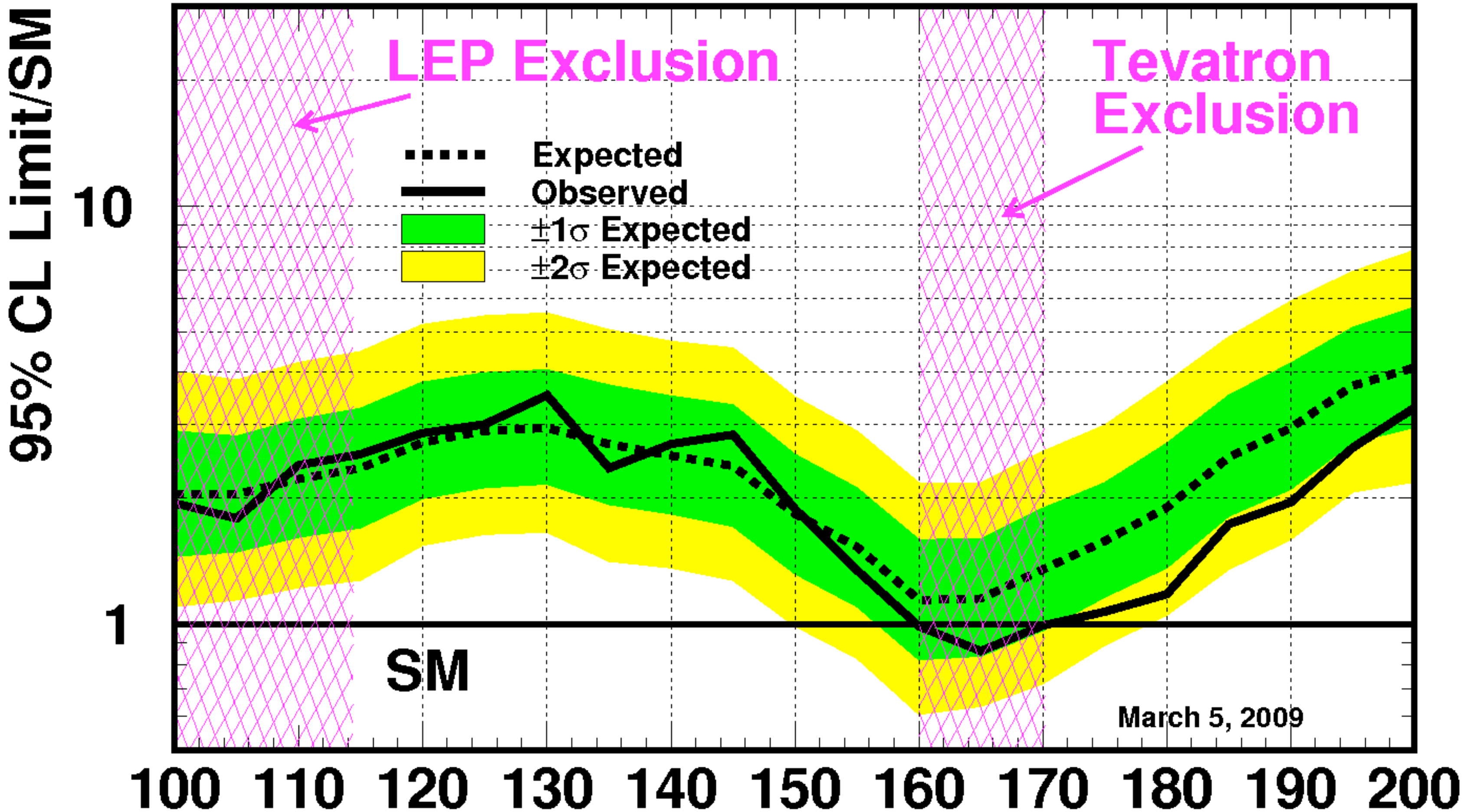
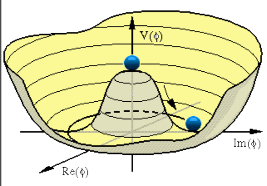


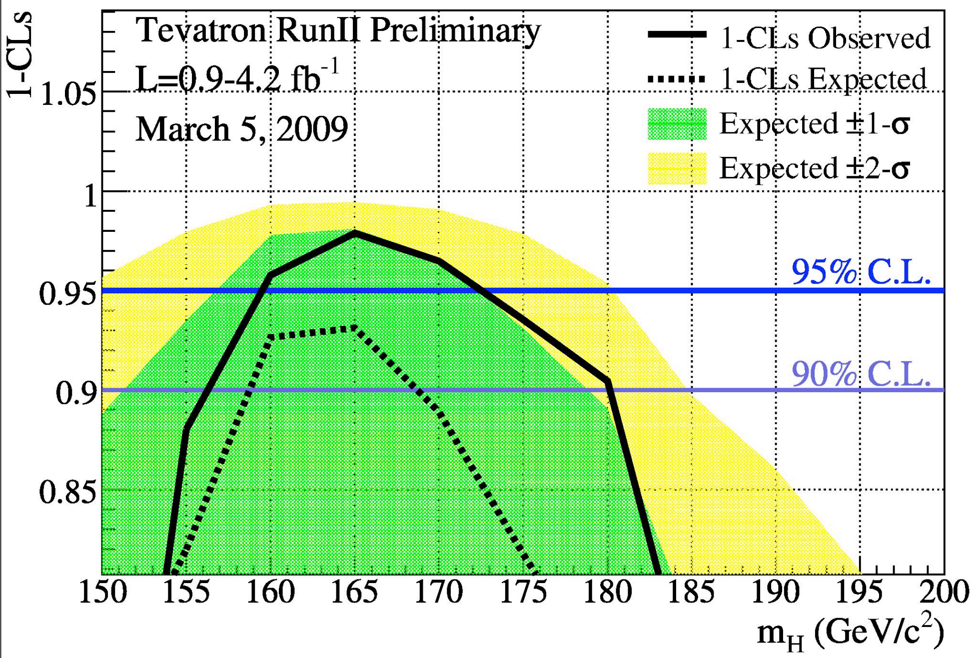
Exp. 2.4 @ 115

Obs. 0.99 @ 160/170, 0.86 @ 165 GeV



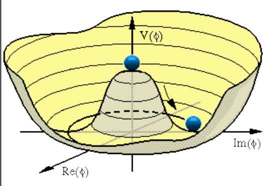
SM Higgs Combination

- Result verified using two independent methods(Bayesian/CLs)



95%CL Limits/SM

M Higgs(GeV)	155	**160**	**165**	**170**	175
Method 1: Exp	1.5	**1.1**	**1.1**	1.4	1.6
Method 1: Obs	1.4	**0.99**	**0.86**	**0.99**	1.1
Method 2: Exp	1.5	**1.1**	**1.1**	1.3	1.6
Method 2: Obs	1.3	**0.95**	**0.81**	**0.92**	1.1



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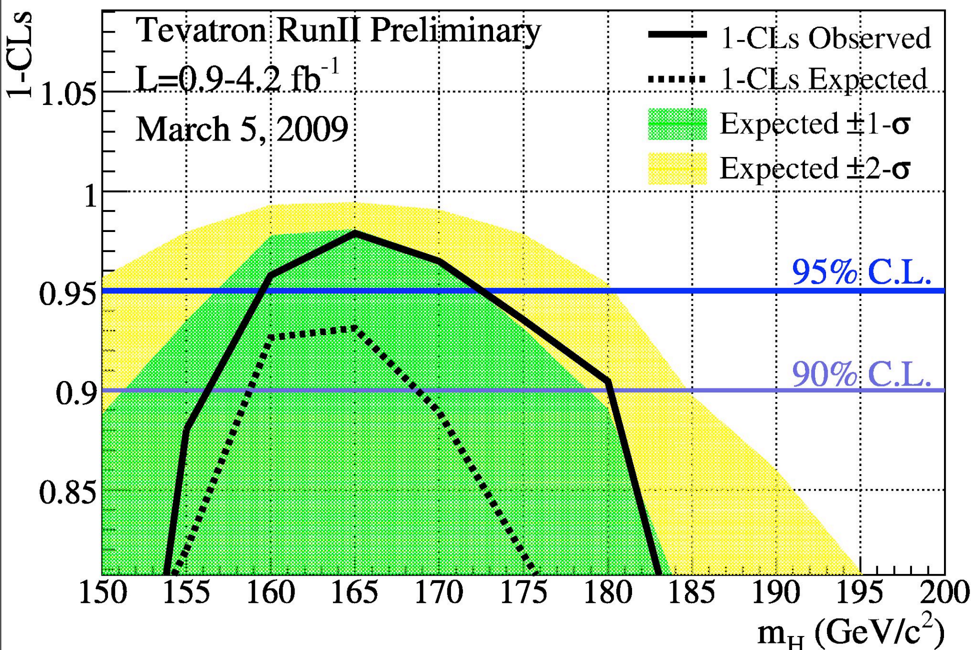

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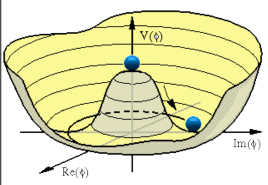
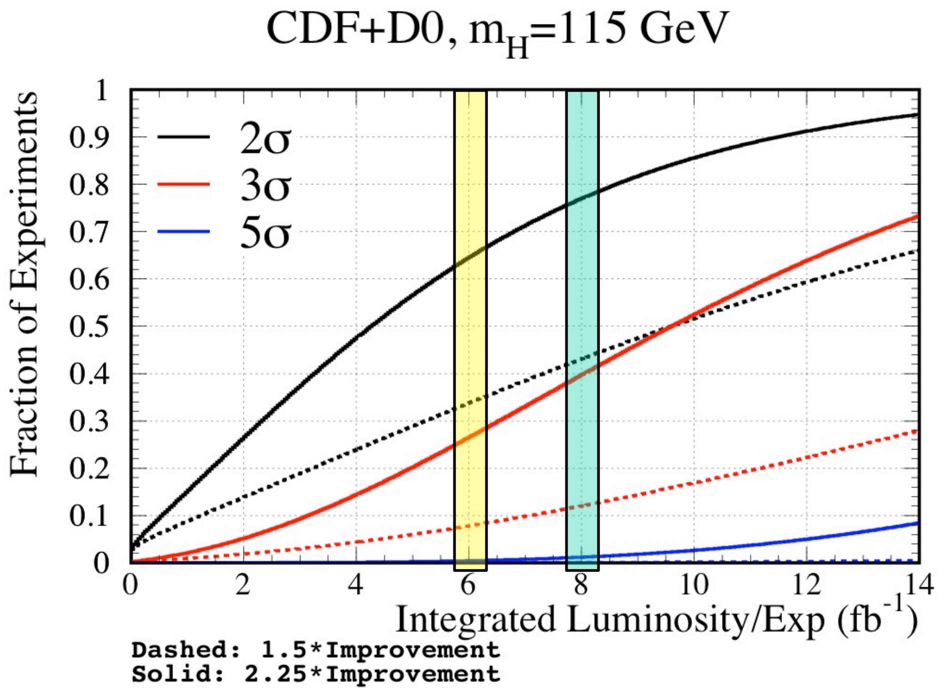
SM Higgs Excluded: m_H = 160-170 GeV

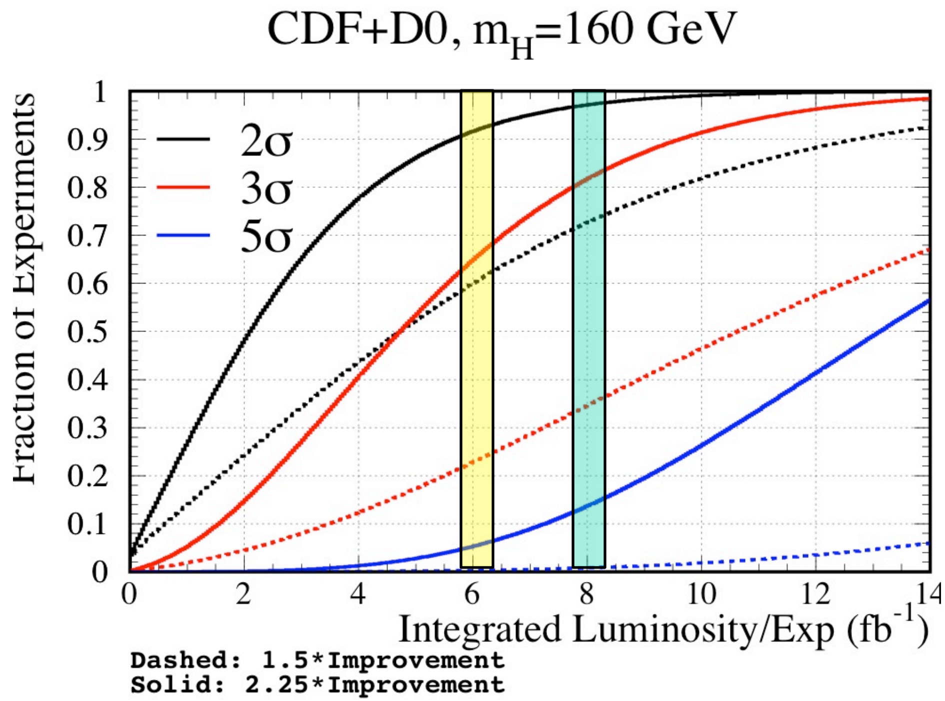
- We exclude at 95% C.L. the production of a SM Higgs boson of 160-170 GeV

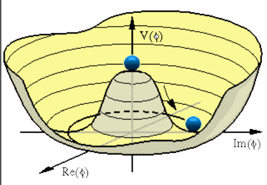


Discovery

- Discovery projections: chance of 3σ or 5σ discovery
  - Two factors of 1.5 improvements examined relative to summer Lepton Photon 2007 analyses, low and high mass
  - First 1.5 factor achieved for summer ICHEP 2008 analysis
  - Result: exclusion at m_H = 170 GeV. Already extended to 160-170 GeV
  - Expect large exclusion(or evidence): Full Tevatron dataset/improvements



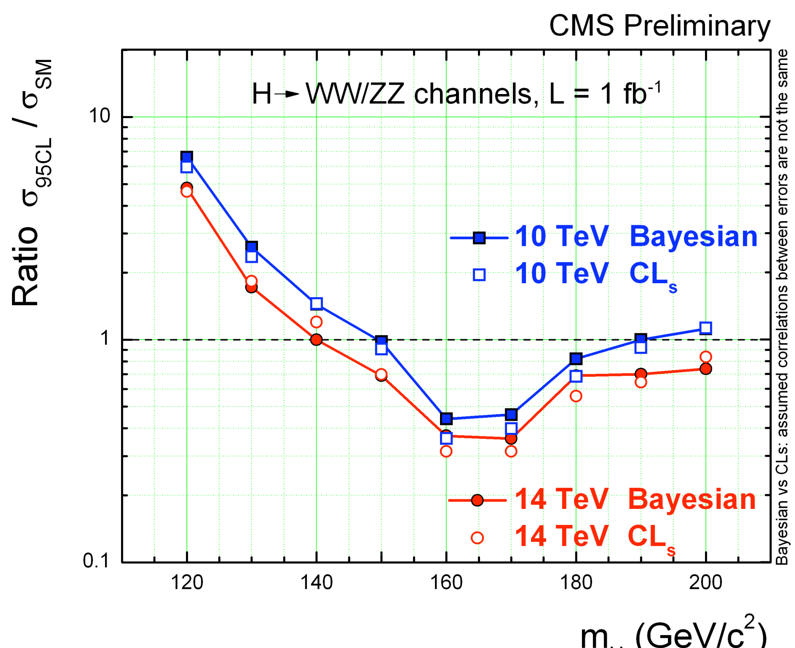


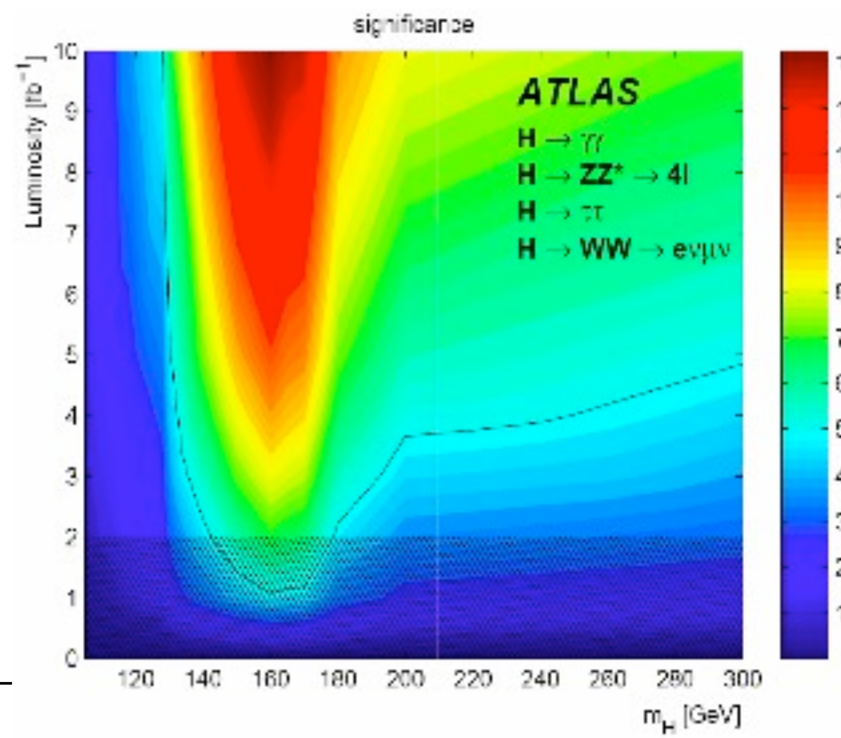


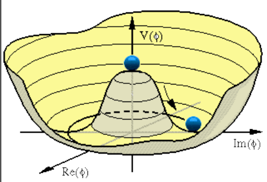
LHC Prospects: SM Higgs

- LHC experiments: Potential to observe a SM Higgs at 5σ over a large mass region, 95% CL with 200pb^{-1} @10TeV at high mass
  - Observation: gg→H→γγ, VBF H→ττ, H→WW→lνlν, and H→ZZ→4l
  - Possibility of measurement in multiple channels
  - Properties W, Z coupling in associated production
  - Yukawa top coupling in ttH
  - Spin in diffractive production

All key channels explored

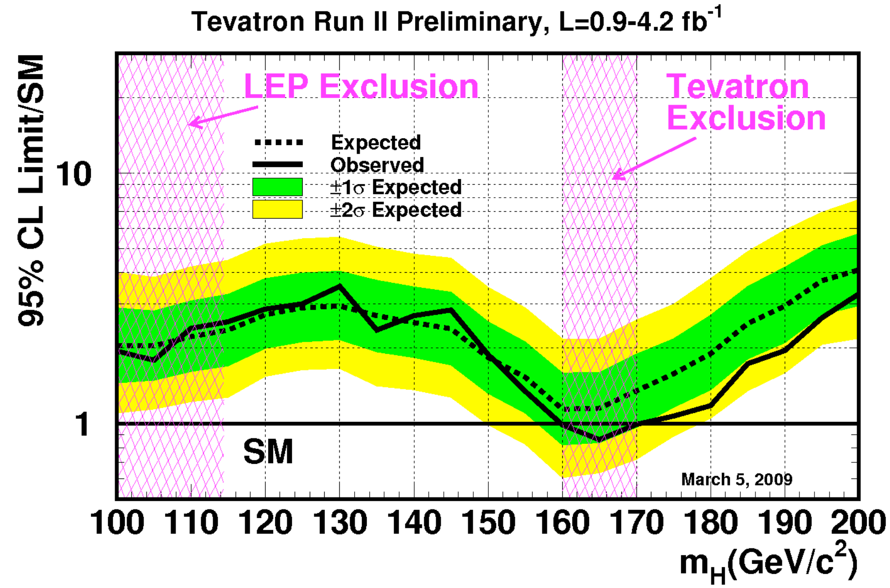




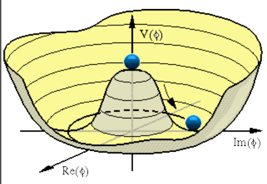


Conclusions

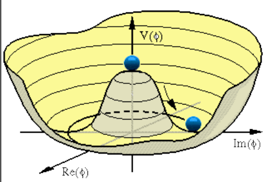
- The Higgs boson search is in its most exciting era ever
  - The Tevatron experiments have achieved sensitivity to the SM Higgs boson production cross section
  - With the advent of the LHC we will have the potential to observe the SM Higgs boson and study it's properties.
- We exclude at 95% C.L. the production of a SM Higgs boson of 160-170 GeV
  - Expect large exclusion, or evidence, with full Tevatron data set and improvements



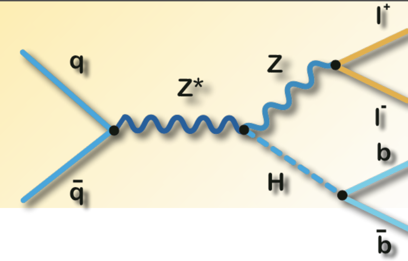
SM Higgs Excluded: m_H = 160-170 GeV



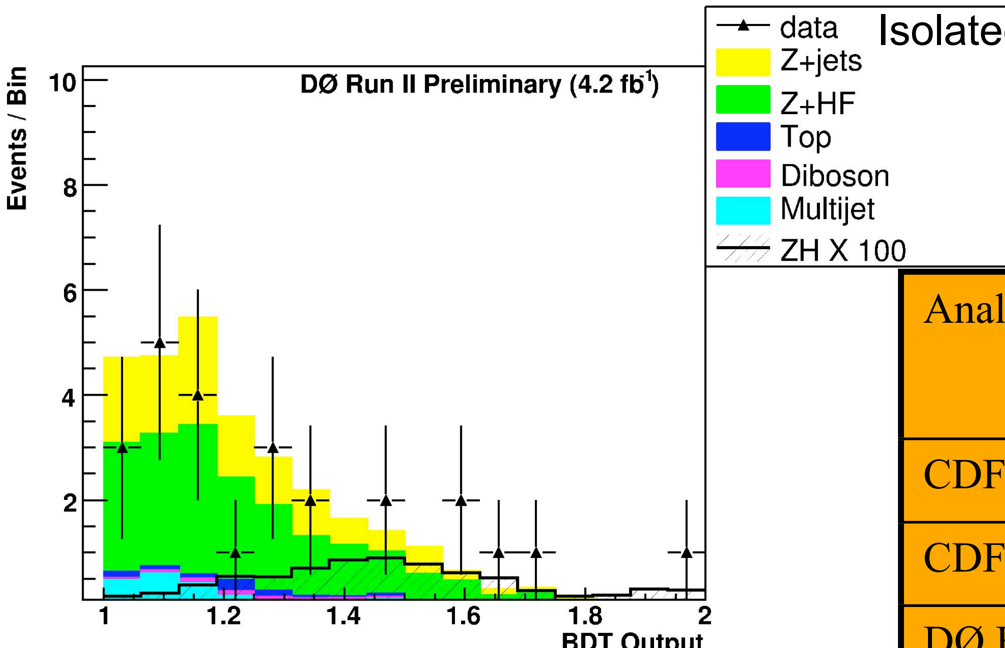
Backup



SM Higgs: ZH→llbb



- ZH→llbb - signature: two leptons and b jets
  - Primary background: Z + b jets
  - Key issue: Maximize lepton acceptance and b tagging efficiency
  - Innovations Extensive use of loose b tagging(DØ NN)



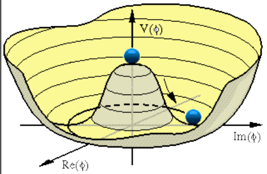
Isolated tracks(shown) and forward electrons

MET used to correct jet energies(CDF)

ME analysis(CDF), BDT analysis(DØ)

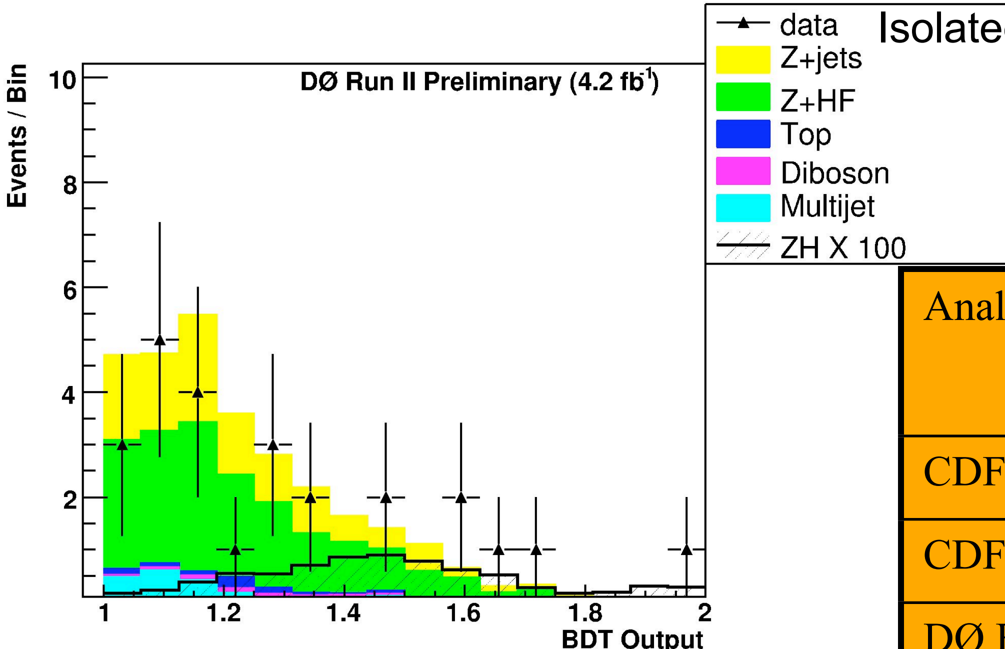
Results at mH = 115GeV: 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN	2.7	2.4	9.9	7.1
CDF ME new	2.7	2.4	12.3	7.8
DØ BDT new	4.2	3.1	8.0	9.1



SM Higgs: ZH→llbb

- ZH→llbb - signature: two leptons and b jets
  - Primary background: Z + b jets
  - Key issue: Maximize lepton acceptance and b tagging efficiency
  - Innovations Extensive use of loose b tagging(DØ NN)



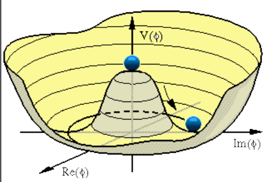
Isolated tracks(shown) and forward electrons

MET used to correct jet energies(CDF)

ME analysis(CDF), BDT analysis(DØ)

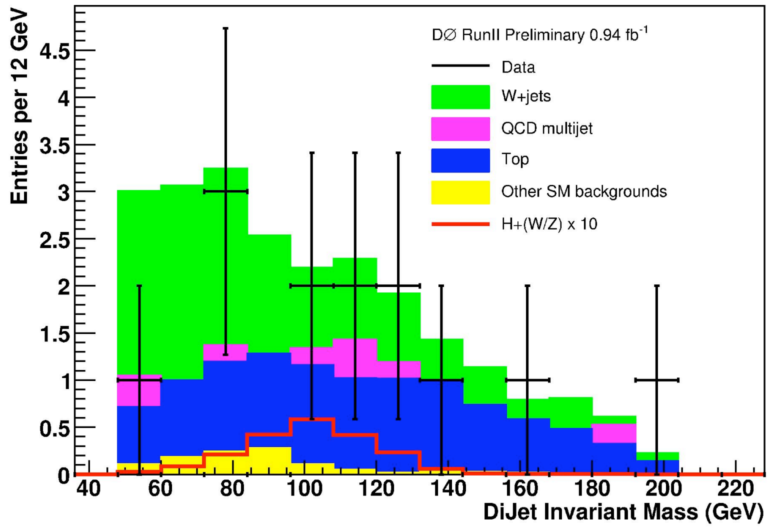
Results at mH = 115GeV: 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN	2.7	2.4	9.9	7.1
CDF ME new	2.7	2.4	12.3	7.8
DØ BDT new	4.2	3.1	8.0	9.1

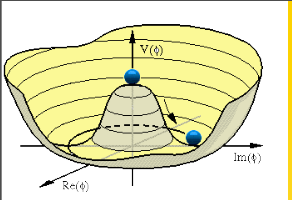


Other SM Higgs Searches

- CDF and DØ are performing searches in every viable mode
  - CDF: VH→qqbb: 4 Jet mode.
  - CDF: H→ττ with 2jets
    - Simultaneous search for Higgs in VH, VBF and gg→H production modes
    - Interesting benchmark for LHC
  - DØ: VH,VBF,gg→H→ττjj+WH→τνbb
    - Inclusive tau search
  - DØ: ttH
    - Leverages strong coupling to top

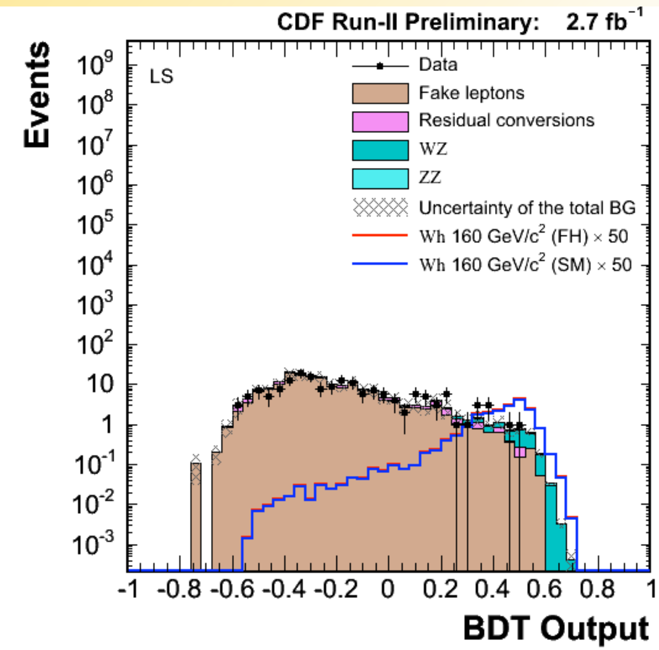


Analysis: Limits at 160 and 115GeV	Exp. Limit	obs. Limit
CDF H→ττ	25	31
DØ Inclusive τ new	28	29
CDF VH→qqbb	37	37
DØ ttH	45	64



BSM/SM Higgs Searches

- H→γγ
  - At lower mass large BR(H→γγ) ~10% for Fermiophobic Higgs
  - SM search also sensitive at low mass
  - Key issue: understanding QCD
  - CDF - has not yet calculated SM limits

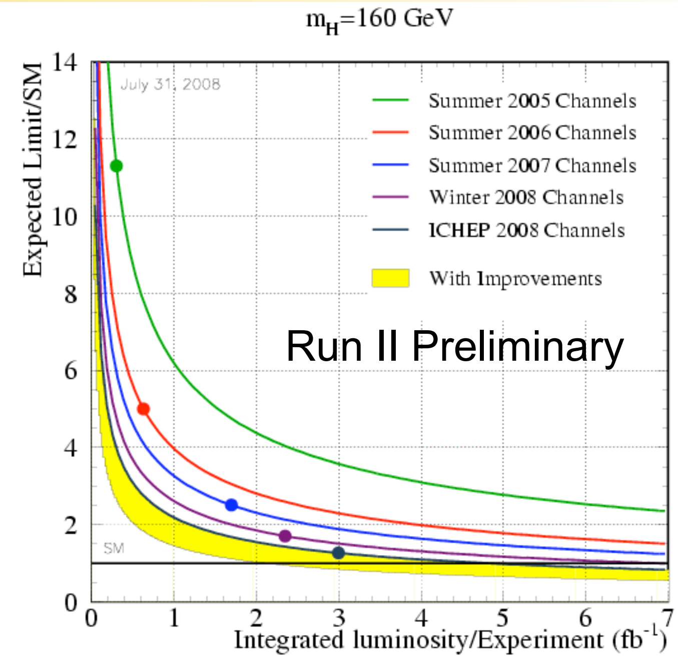


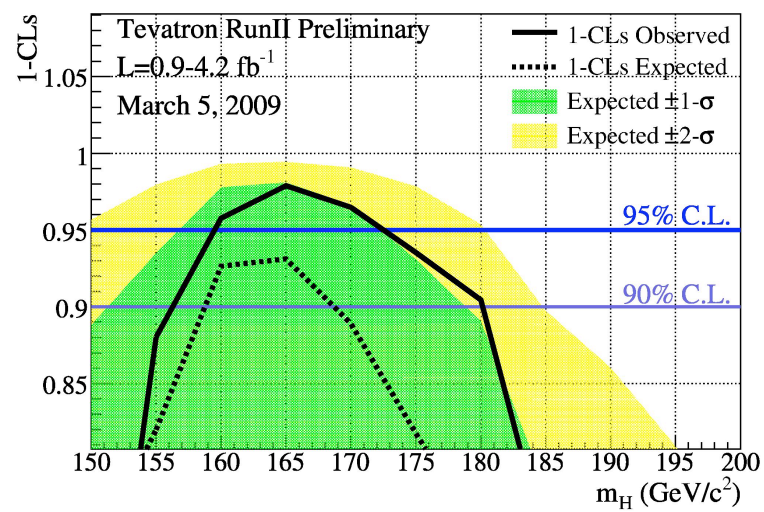
- WH→WWW
  - Strong sensitivity as both a SM and a fermiophobic Higgs search
  - Same sign dilepton signature
  - SM: sensitive at high and medium mass
  - Now included in inclusive CDF H→WW search

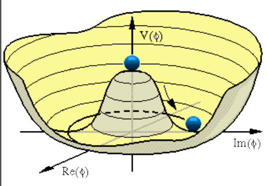
Analysis: Limits at 115/160 GeV	Exp. Limit	obs. Limit
DØ H→γγ new	18	16
CDF WH→WWW new	19	24
DØ WH→WWW new	10	18

Projections

- Goals for increased sensitivity achieved
  - Goals set after 2007 Lepton Photon conference
  - First stage target was sensitivity for possible exclusion at high mass
    A similar magnitude improvement factor target was set at low mass
  - Second stage goals in progress
    - B tag, jet energy resolution, tau modes, ZZ







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