Higgs searches from CDF

(+ combination with D0)

New results : Low mass Higgs
New excitement : High mass Higgs
Some SUSY Higgs perspective

Ben Kilminster
Fermilab

CERN joint EP/PP seminar
Sept. 8, 2008

Basic theory of interactions does not provide for massive particles

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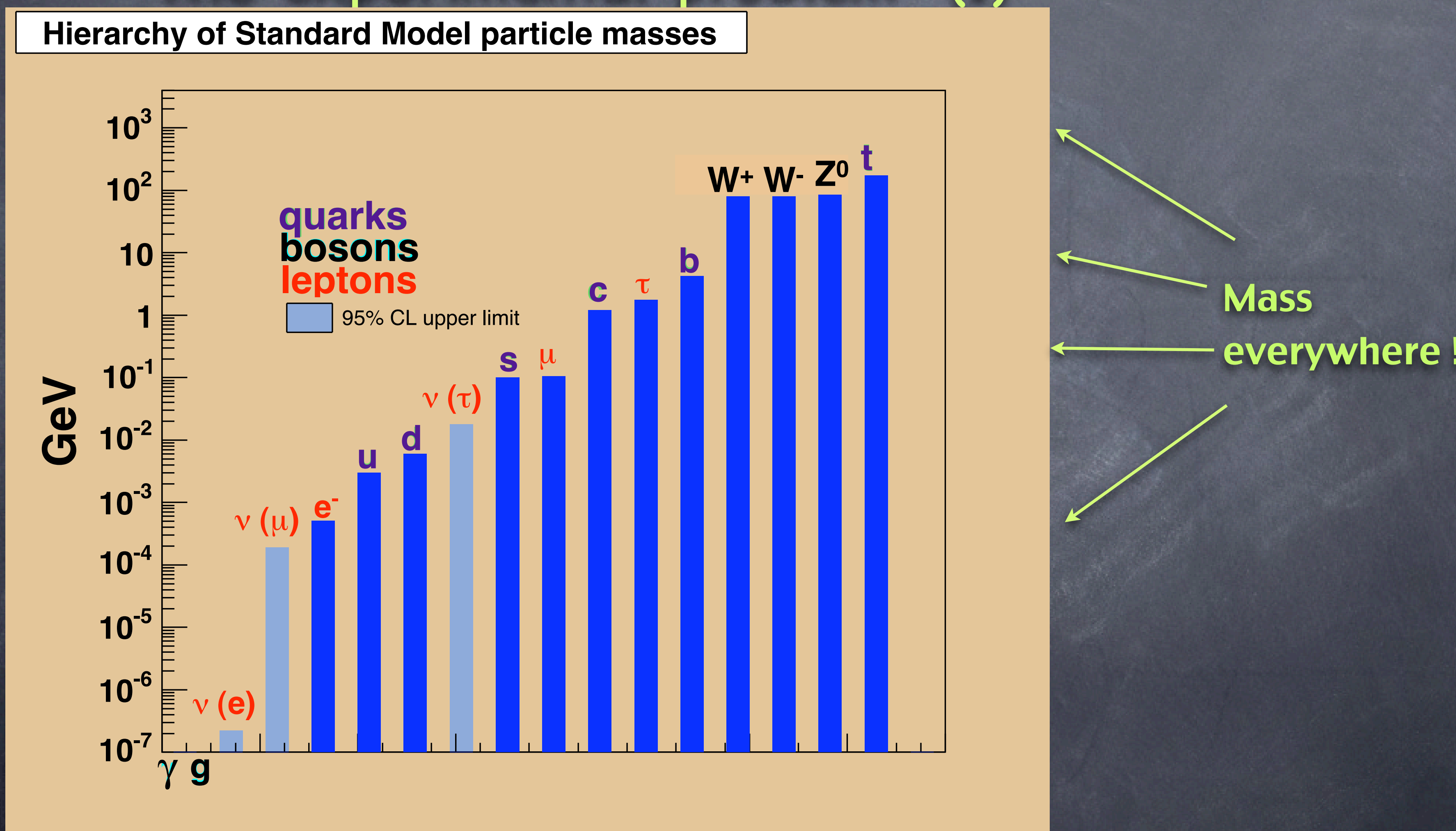
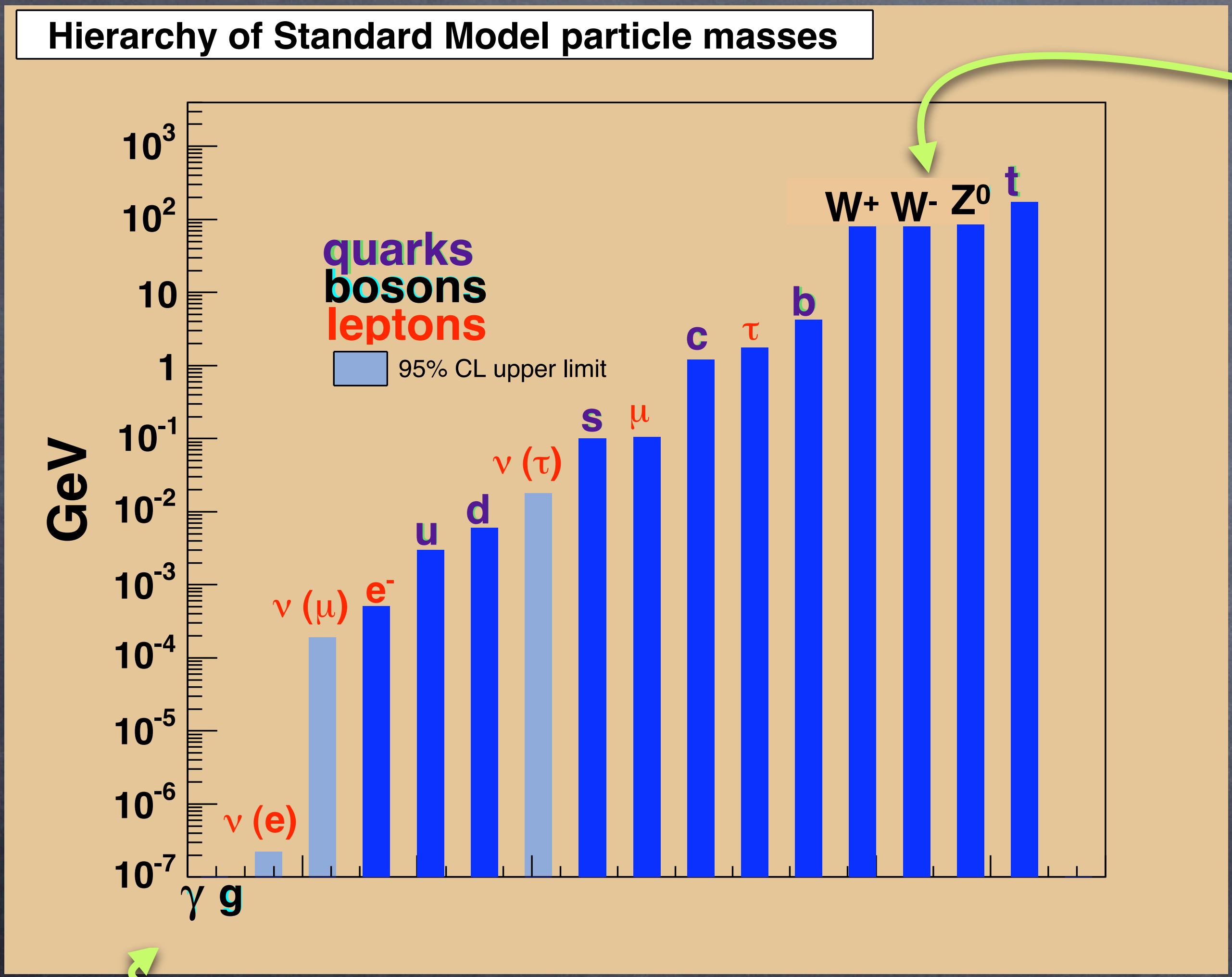
The experimental problem (1)



Explicit mass terms cause Standard Model calculations to fail

The experimental problem (2)



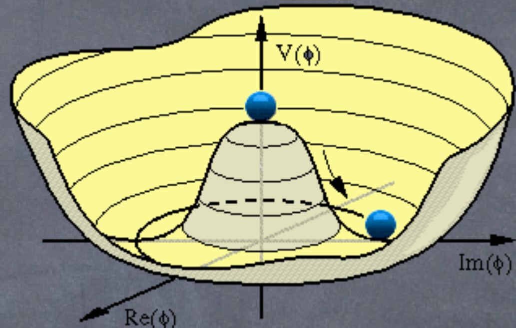
Weak force carriers

EM force carrier

Fundamental asymmetry between EM and weak force carrier mass

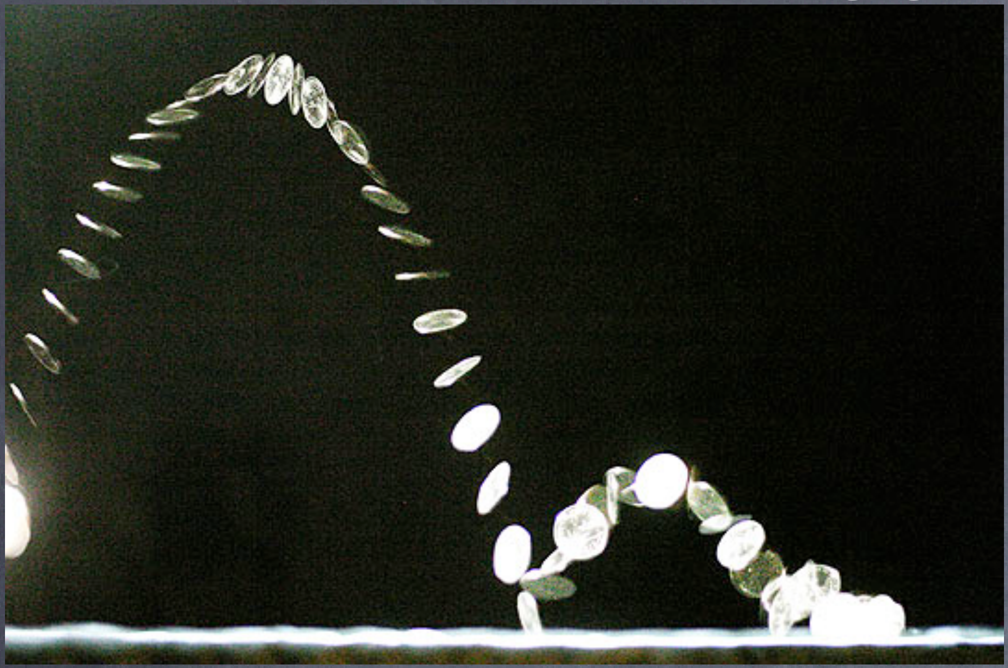
Solution: Higgs mechanism

- Add field throughout the universe
  - Potential is symmetric
  - Ground state breaks symmetry



- Cleverly
  - W and Z bosons gain masses through degrees of freedom of Higgs field
  - Masses are generated for the fermions due to their interaction with this non-zero field
  - Theory preserves symmetry (gauge invariance)
  - Standard Model calculations no longer fail
  - A new particle is predicted: the Higgs boson
- Finding the Higgs boson
  - Means Higgs field exists
    - Means we confirm our theory for the origin of mass

What is the Higgs boson mass ?



- CDF and D0 may flip coins to decide talk order

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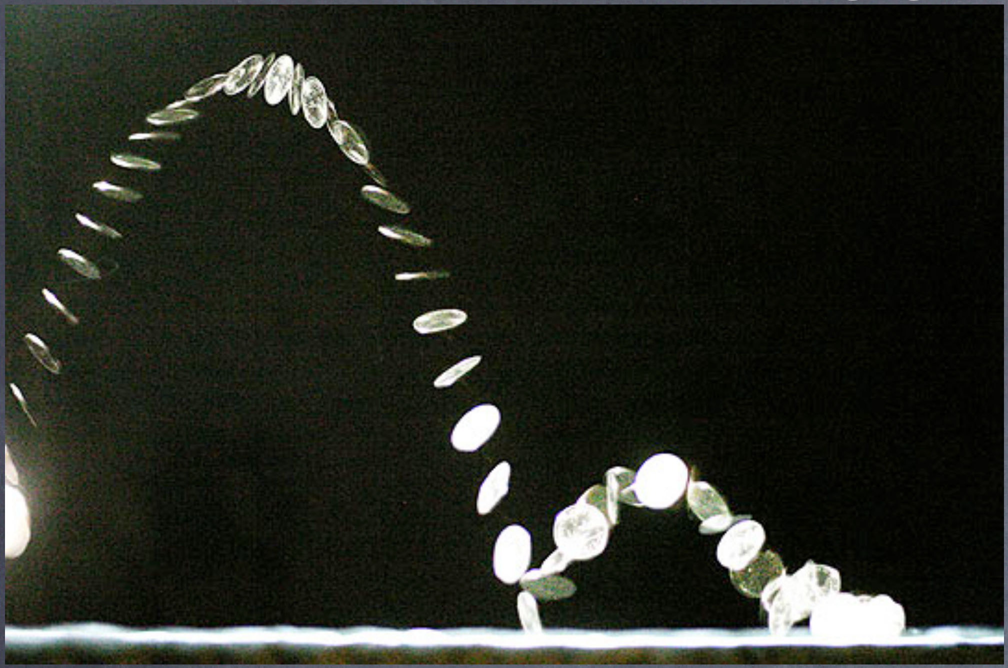

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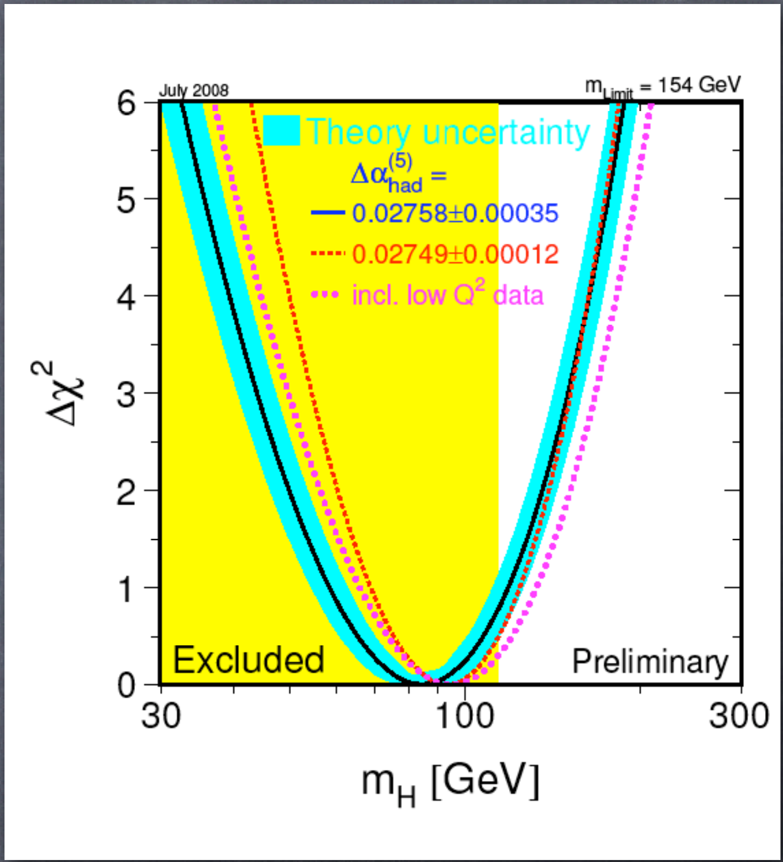
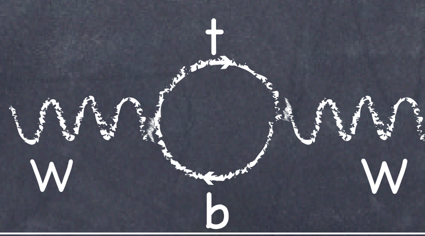
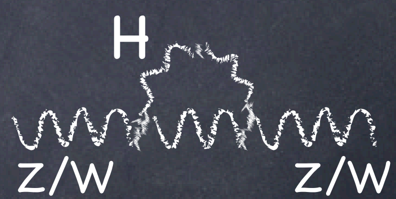


- CDF and D0 may flip coins to decide talk order

  ... but we do use a likelihood to decide where to find the Higgs boson

- Electroweak observables constrain Higgs boson mass within SM





Where is the Higgs ?

Direct searches at LEP:

$Z^* \rightarrow ZH$

Indirect searches :

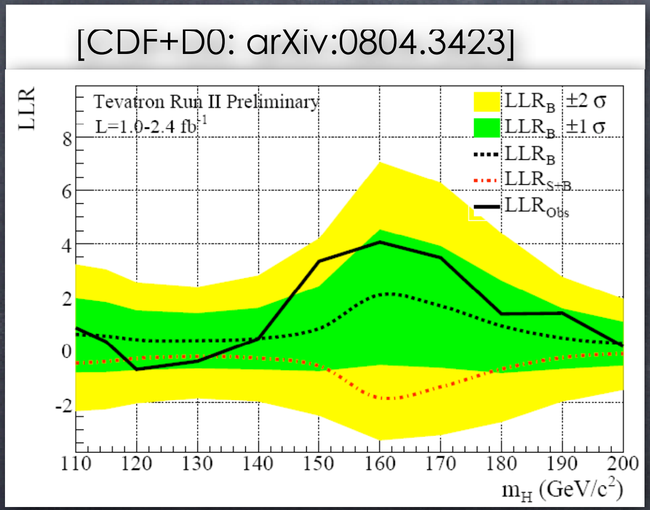
~20 measurements from Tevatron, LEP, SLD

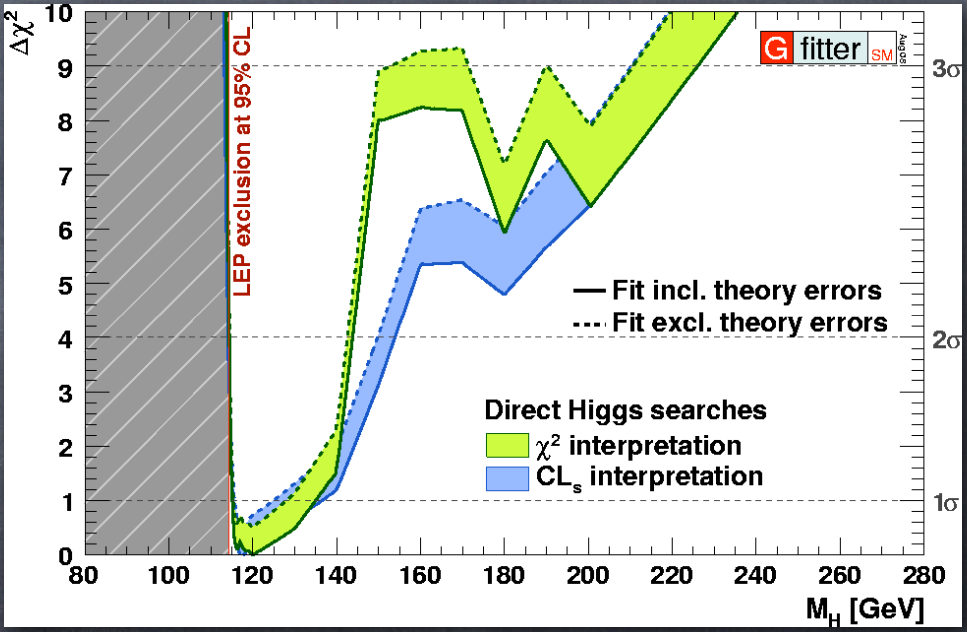
Date	Direct	Indirect		
	H mass LEP II 95% lower [GeV/c²]	Top mass [GeV/c²]	δm_W LEP, Tevatron [MeV/c²]	H mass central value, 95% upper [GeV/c²]
'98	> 89	173.5 ± 5.2	± 90, 90	74 , < 250
'00	> 108	174.3 ± 5.1	± 49, 62	76 , < 188
'04	> 114.4	178.2 ± 4.3	± 42, 59	114 , < 260
'06	> 114.4	171.4 ± 2.4	± 33, 59	85 , < 166
08	> 114.4	172.4 ± 1.2	± 33, 39	84 , < 154

source: LEPEWWG as presented at Moriond 98 & 00, ICHEP 04, 06, 08

Revisiting global electroweak fit

- Gfitter group includes
  - Indirect electroweak constraints
  - LEP direct Higgs searches
  - Tevatron Higgs searches (only up to previous combo 2.4 fb^{-1})





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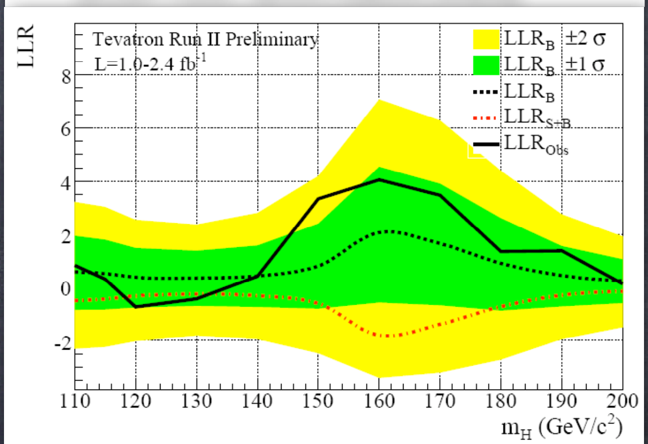
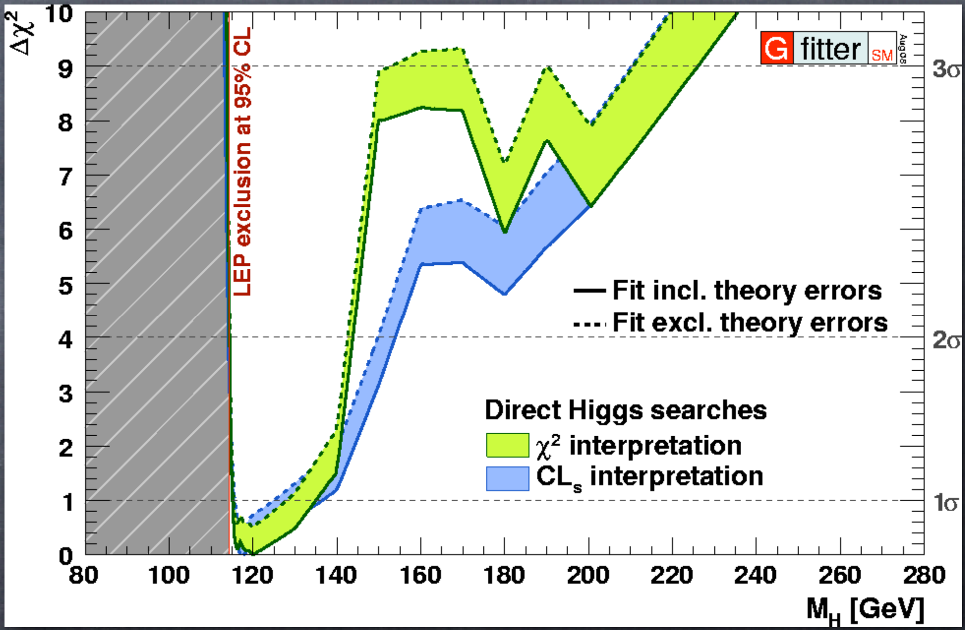
[CDF+D0: arXiv:0804.3423]

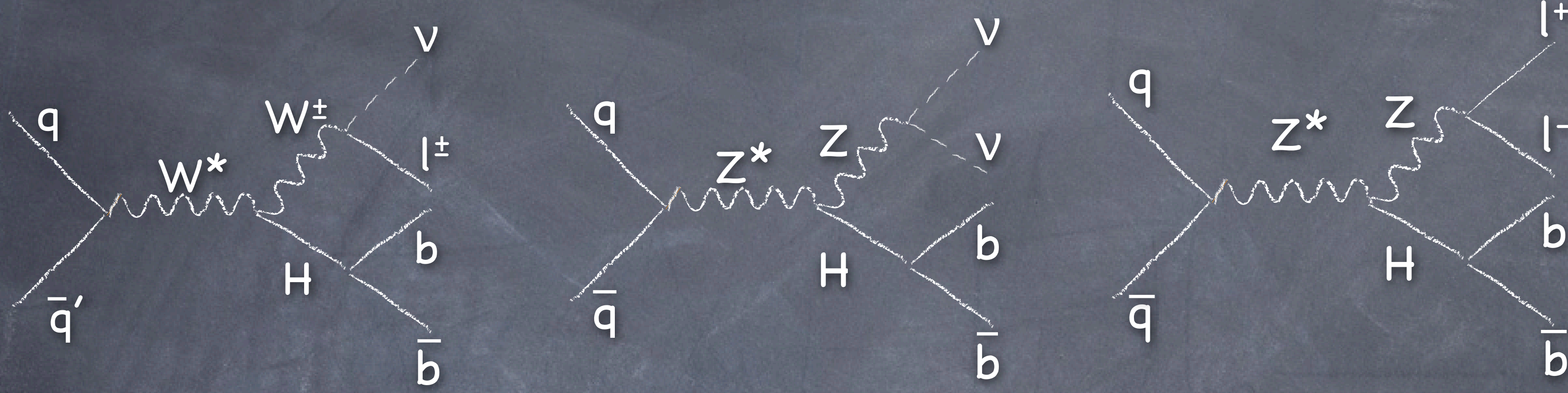




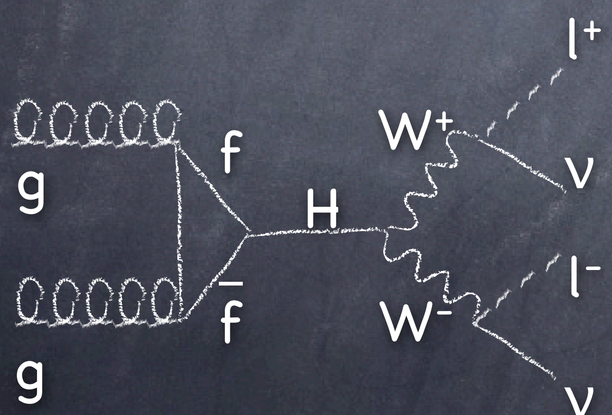
Fit finds $m_H = 120\ ^{+15}_{-5}$ GeV

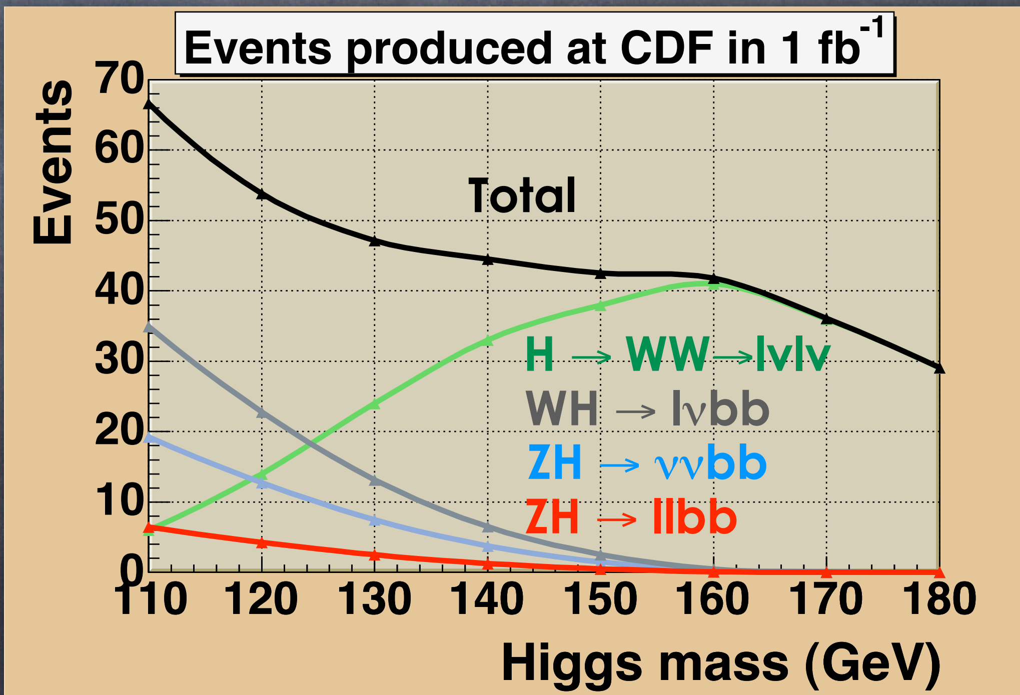
2 σ Interval : [114.4, 144] GeV

SM Higgs at the Tevatron



Main decay modes





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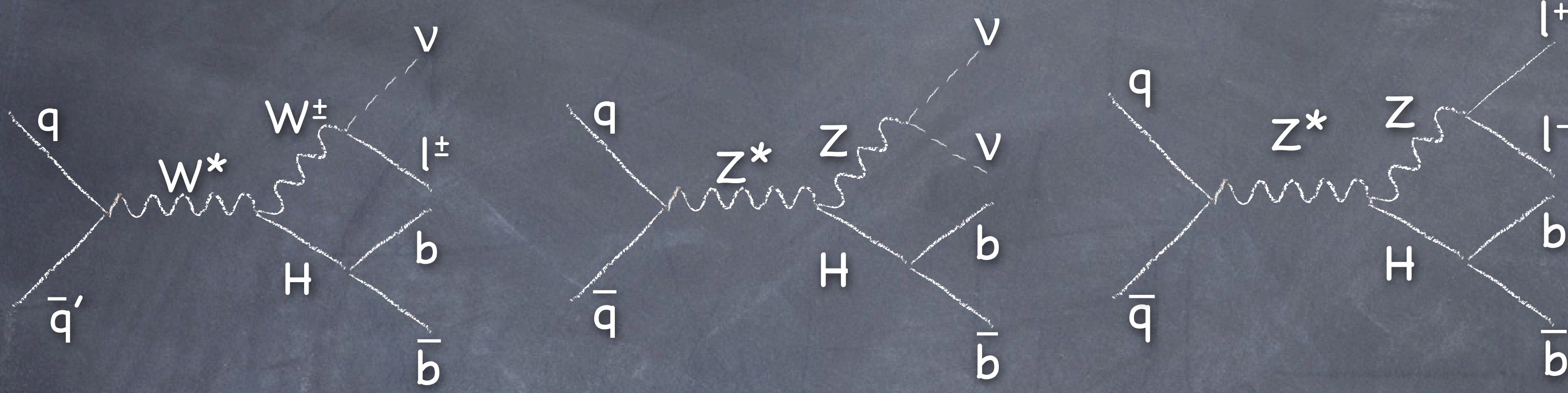

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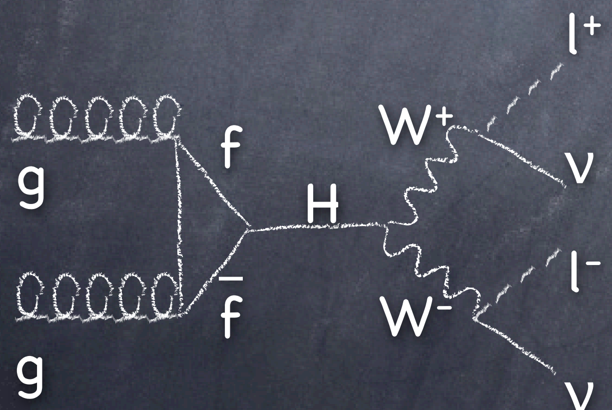

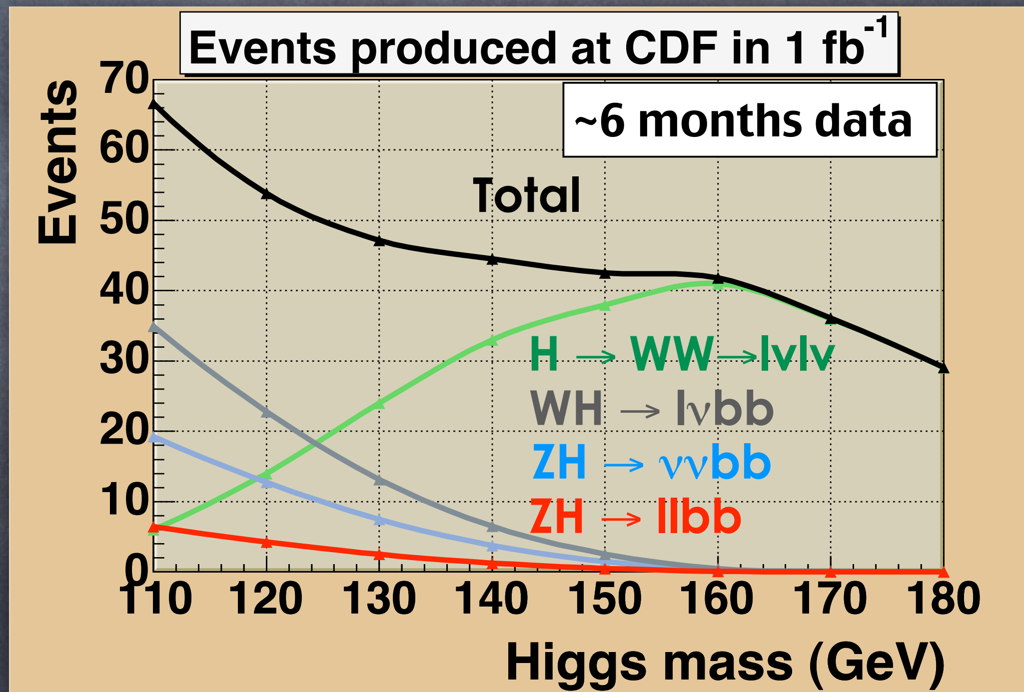

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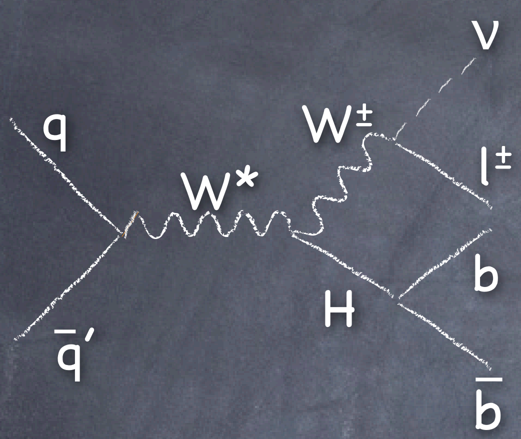

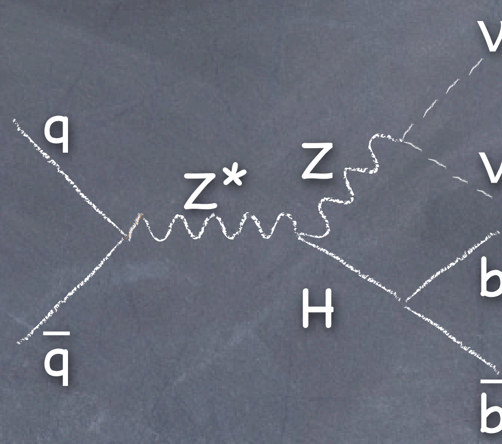

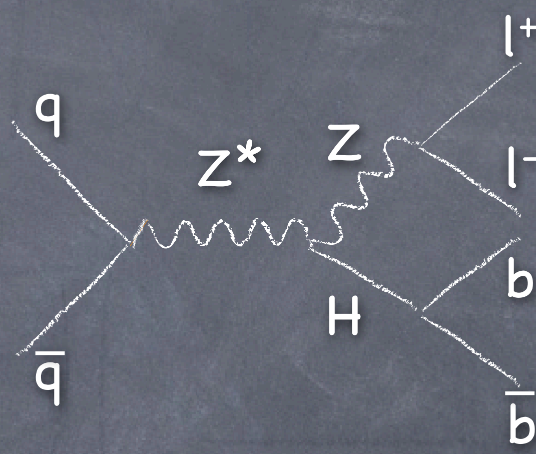

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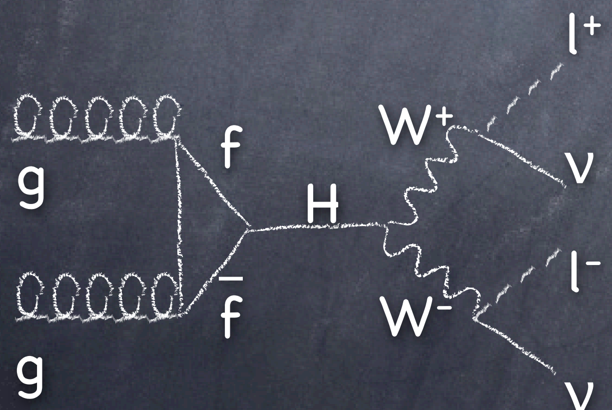
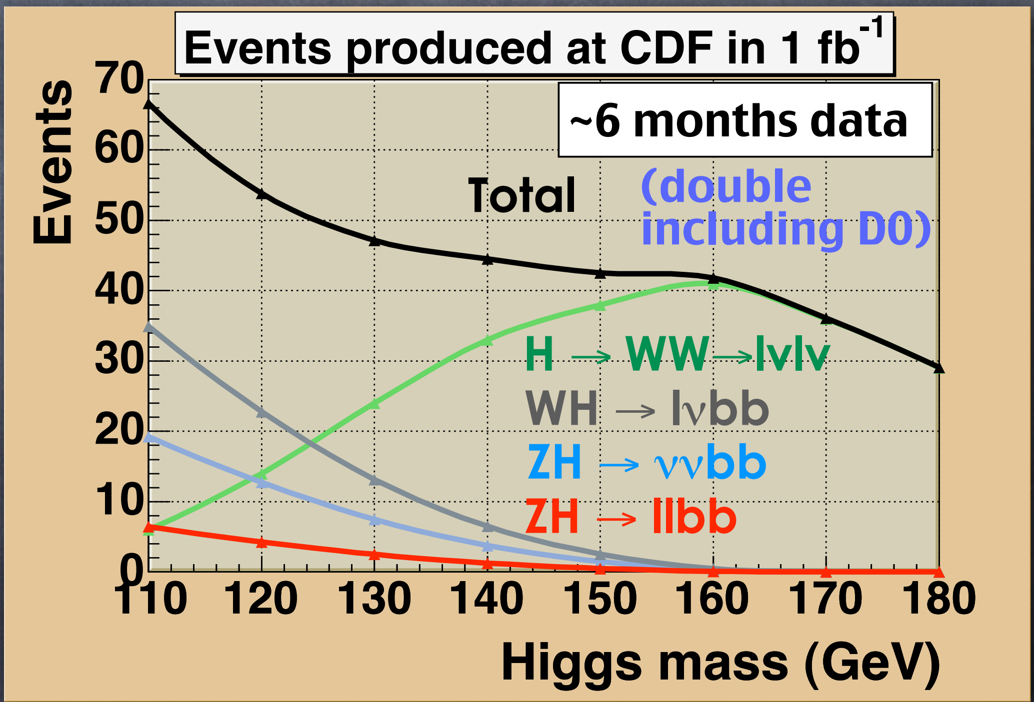
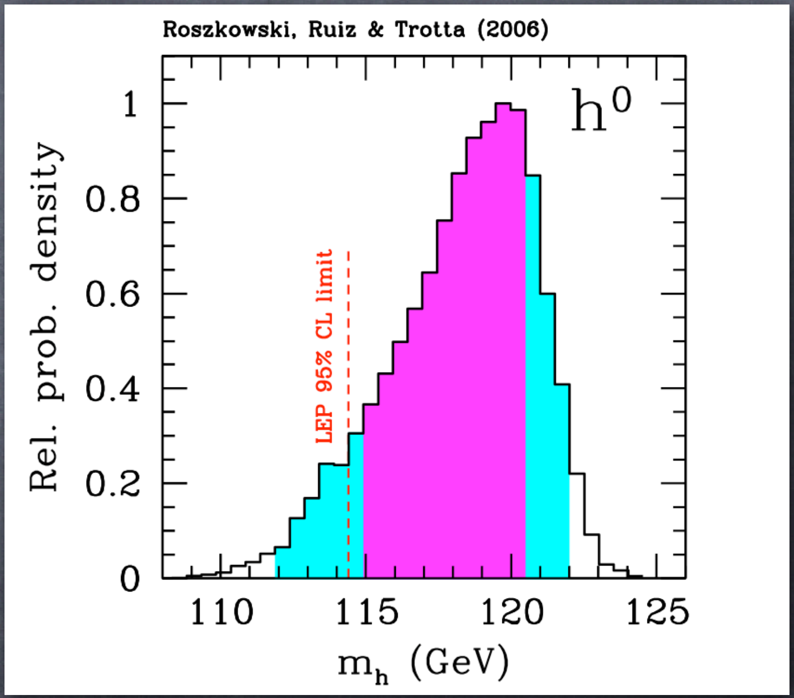




What if there is SUSY?

- One → Five Higgs bosons
- Are Tevatron **SM** Higgs searches still useful ?
  - Consider CMSSM fits
    - Electroweak constraints
    - Anomalous magnetic moment (g - 2)
    - Cosmology - relic neutralino abundance
    - Rare B decays
  - MSSM predicts a SM-like Higgs
    - $113 < m_H < 122$ GeV @ 95% region
  - $H^{\pm}$, H^0, A^0
    - 0.2 TeV < m < 3.6 TeV @ 95% region
    - Likely out of reach for Tevatron



JHEP 0704:084,2007

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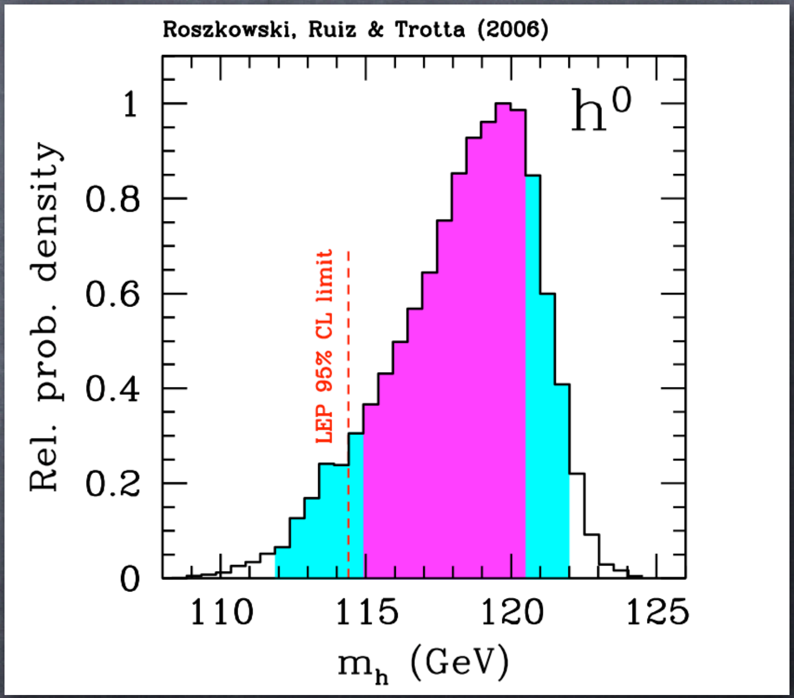
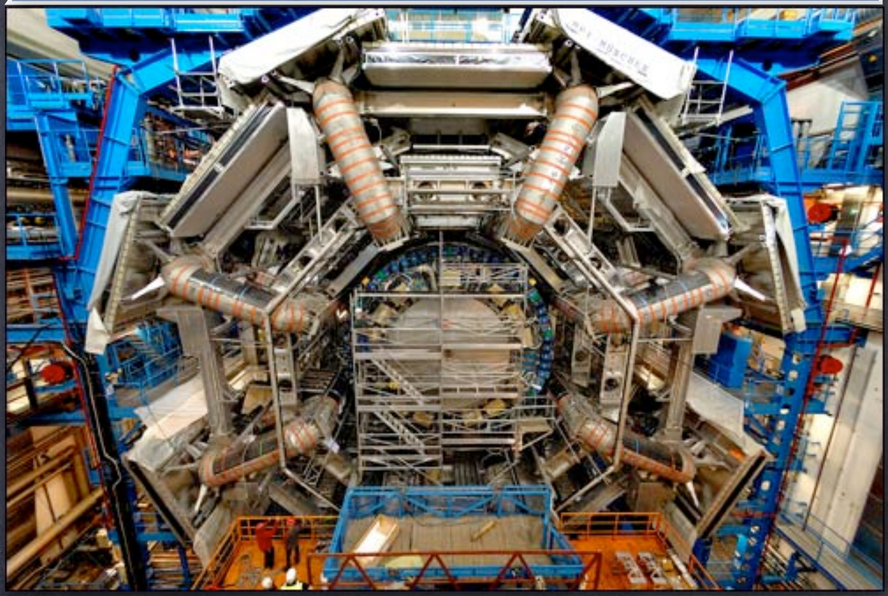


JHEP 0704:084,2007

- Low mass SM Higgs searches may be first indication of MSSM
  - Though we wouldn't know it from SM until LHC finds the others !

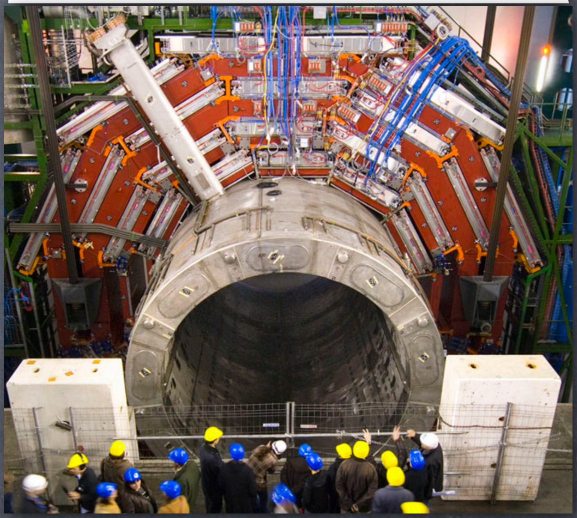
Detectors

diameter = 25 m
length = 46 m



ATLAS

d = 16 m
l = 21 m



CMS

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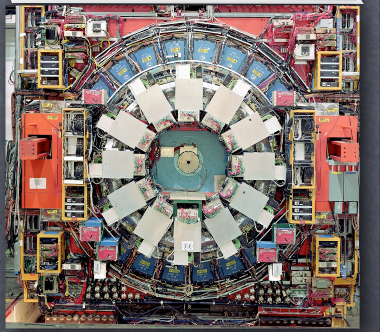

CDF

All-purpose:
Silicon vertex tracker
Drift chamber tracker
1.4 T solenoid
EM calorimeters
Had calorimeters
Muon detectors
5 fb^{-1} delivered
4 fb^{-1} acquired

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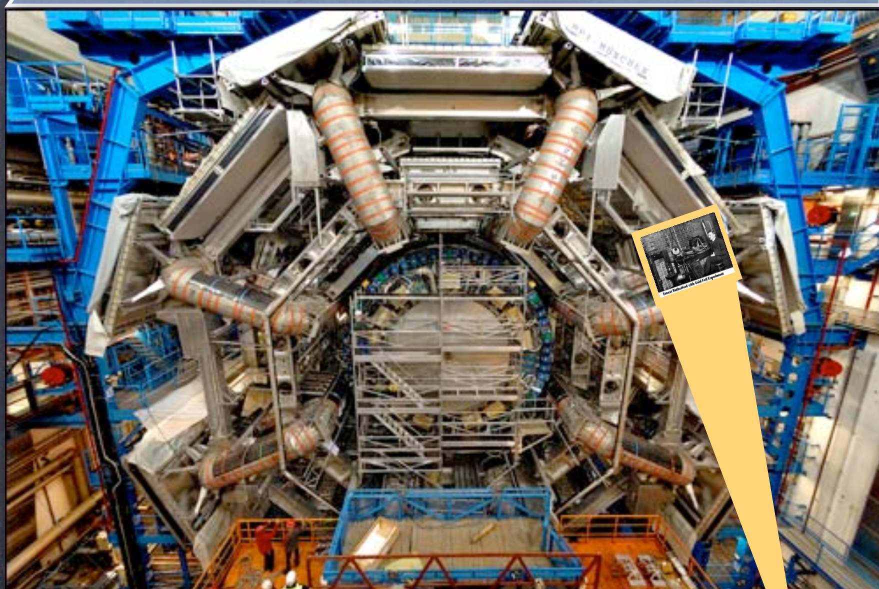

ATLAS

Rutherford
gold foil experiment 1911

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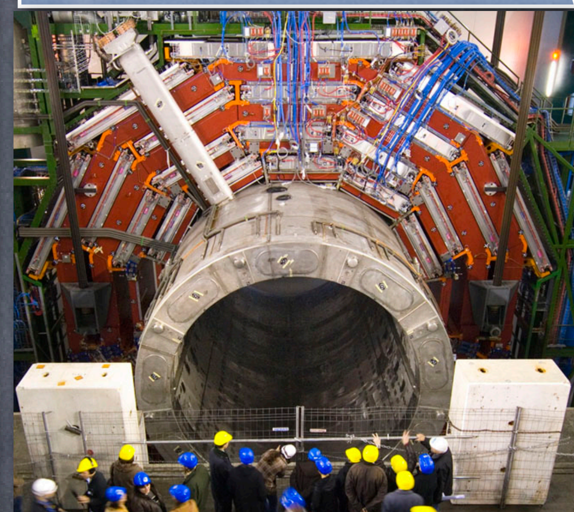

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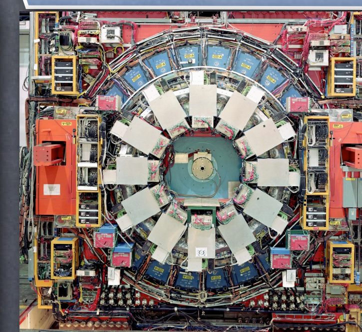

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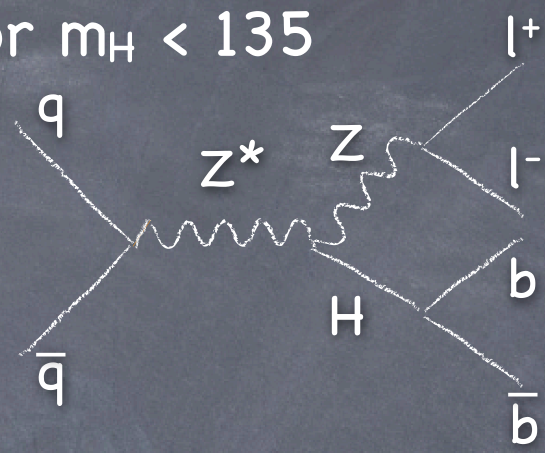
CDF Higgs storyline

- How to build an advanced Higgs analysis program
  - Start with basic analysis
  - Bootstrap special techniques to gain sensitivity
    - Improve acceptance
      - Loosen lepton ID & b-tag requirements
      - Add backup triggers
      - Relax kinematic selection
    - But... backgrounds increase & become more difficult to model
      - Incorporate specialized background rejection techniques
      - Background modeling checks ! Data must stay well modeled !
      - Separate out events into categories with better S/sqrt(B)
        - High S/sqrt(B) gives best signal sensitivity
        - Low S/sqrt(B) gives best background constraints
      - Use multivariate techniques to distinguish signal events
- Repeat for every Higgs discovery mode
- Combine taking into account uncertainties correlated between correlated backgrounds

ZH → llbb story

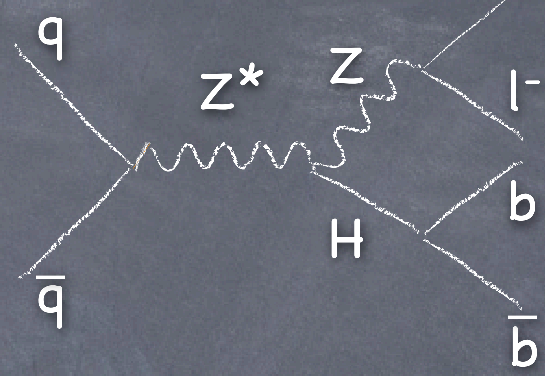
for m_H < 135



- Smallest expected signal
  - Small σ_{ZH} and BR(Z→ll)
- But, fully constrained = lower backgrounds
  - Two resonances H→bb and Z→ll
- Baseline analysis
  - Start with inclusive high P_T lepton trigger (Track + E_T > 18 GeV)
  - Select two leptons E_T > 18, 10 GeV, >= 2 jets E_T > 20, 15 GeV
  - Fit dijet mass for an excess from H → bb

ZH → llbb story

for $m_H < 135$



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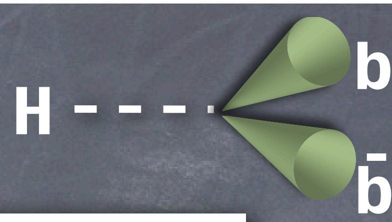
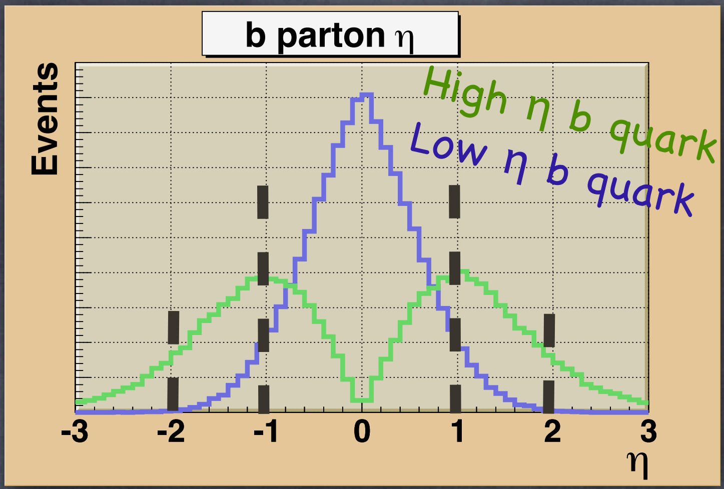
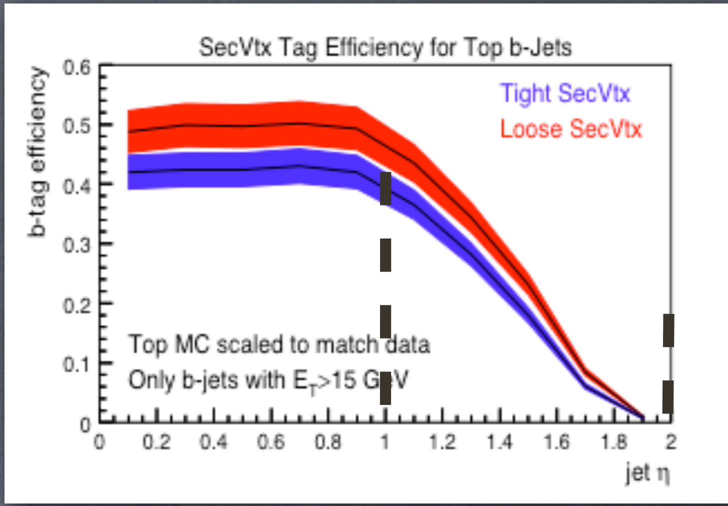
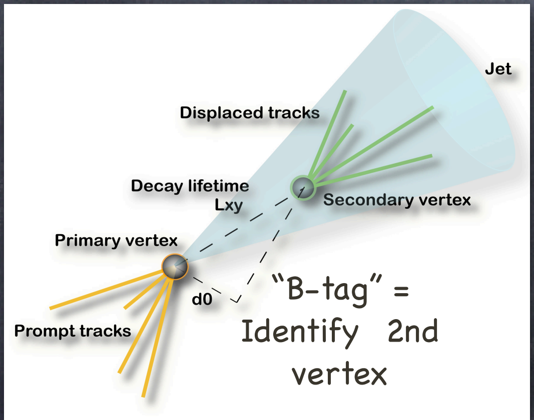
- Special techniques
  - Relax lepton requirements
    - Second muon does not require muon chamber confirmation
    - Second electron does not require track when forward in η
    - New: Dilepton categories from "no-track" trigger : two energy deposits in central or forward region
  - Use b-tagging to improve S/sqrt(B)
  - Improve dijet mass resolution
  - Employ Artificial Neural Network for improved separation

B-tagging in ZH → llbb

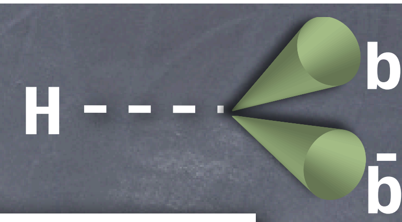


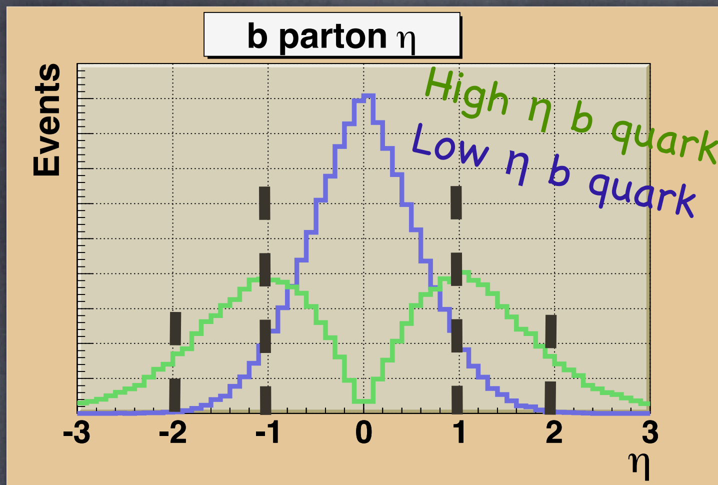


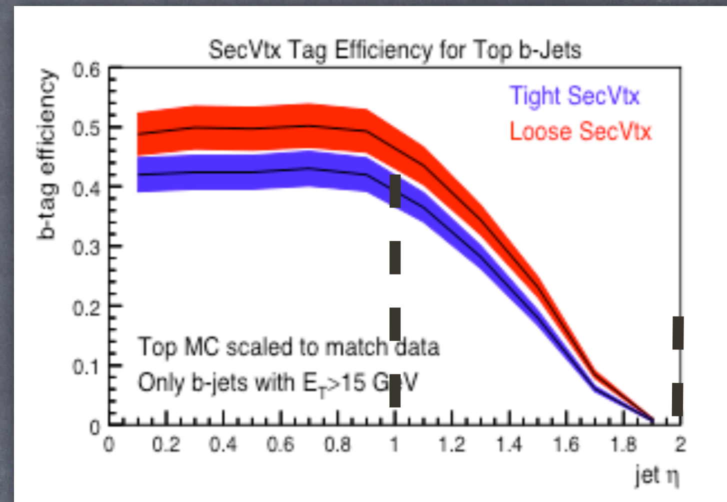


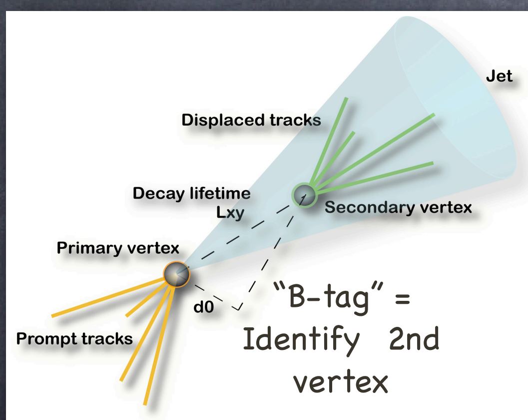


B-tagging in ZH → llbb









Divide into subsets and win

(ZH expectations shown here for 2.4 fb^{-1})

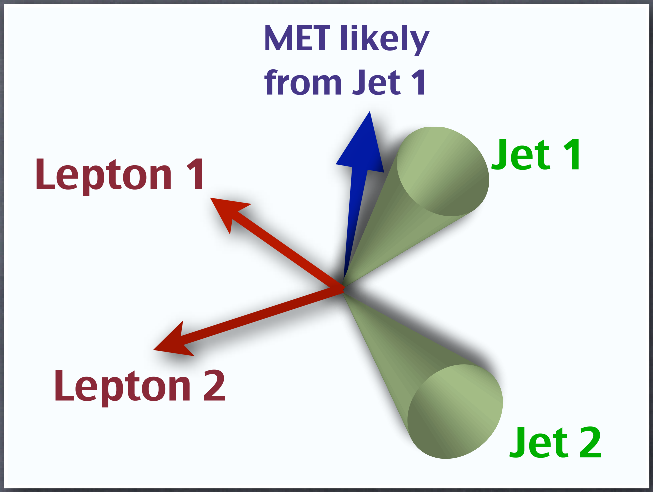
Category	S	B	S/sqrt(B)
High - 2 Loose b-tags	0.5	30	0.09
High - 1 Tight b-tag	0.9	200	0.06
Low - 2 Loose b-tags	0.1	7	0.04
Low - 1 Tight b-tag	0.1	70	0.01
Sum in quadrature of S/sqrt(B) (scales like 1 / Limit)			0.09 → 0.12

Dilepton categories

- "High" central Z purity
- "Low" central Z purity

ZH → llbb

- Can improve Mjj resolution by correcting jets according to projection onto MET direction



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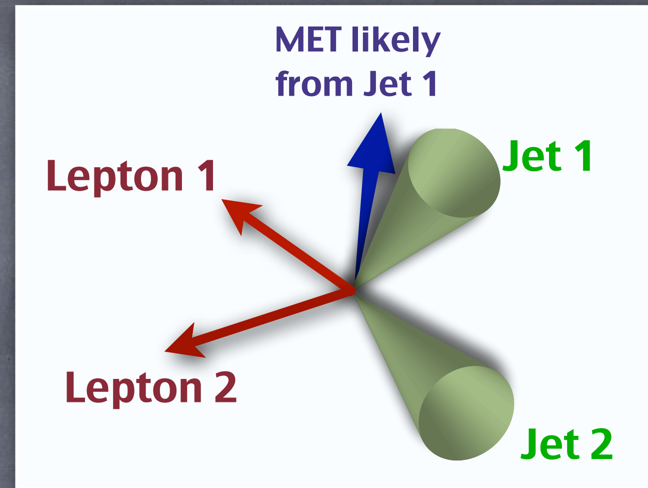

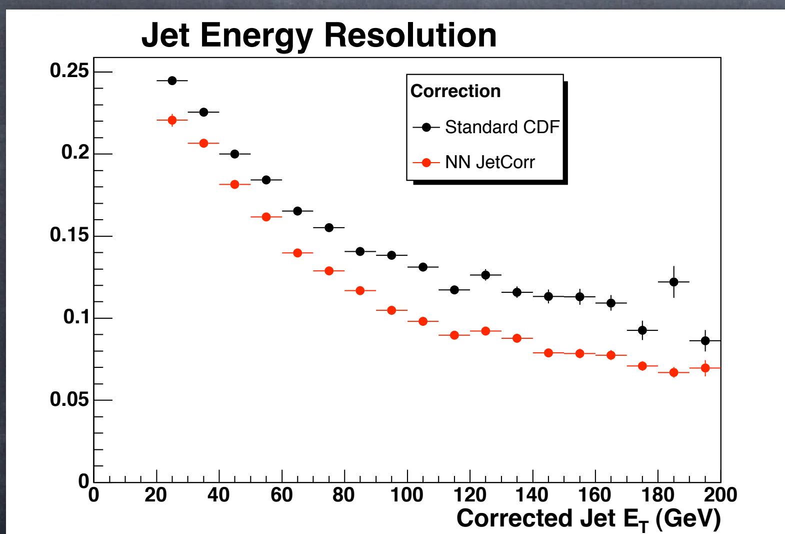

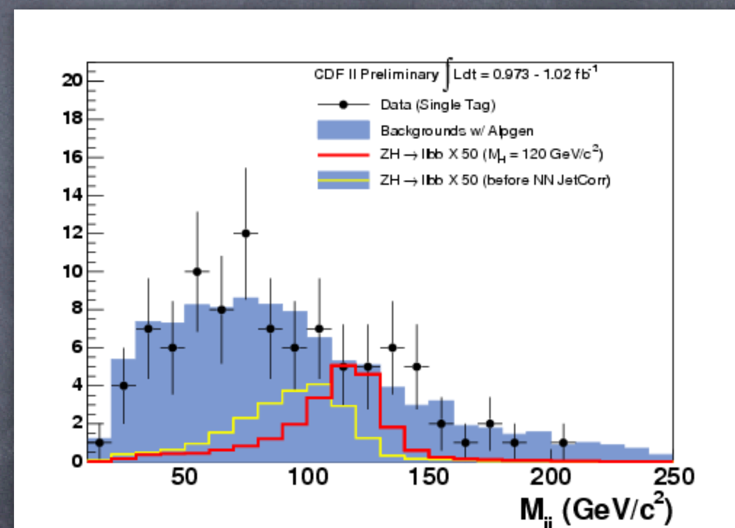

- For events w/ two b-tags, dijet mass resolution improves from 18% to 11%

Multivariate techniques

- Multivariate analysis techniques
  - Used in all CDF Higgs analyses
- Functions which transform multiple inputs into single discriminant tuned for identifying a single process
  - NN = Neural Net
  - ME = Matrix Element
  - BDT = Boosted Decision Trees
- Validation
  - Inputs must be modeled correctly
  - Correlations of inputs and output discriminant tested vigorously in independent control samples with similar kinematics and backgrounds

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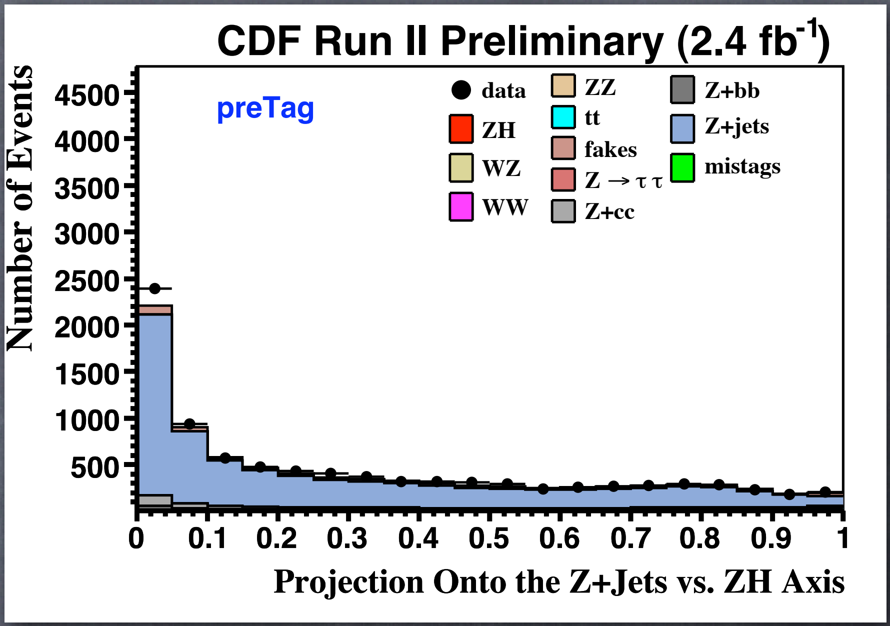
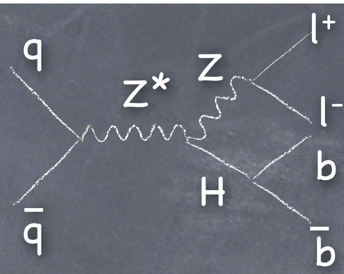


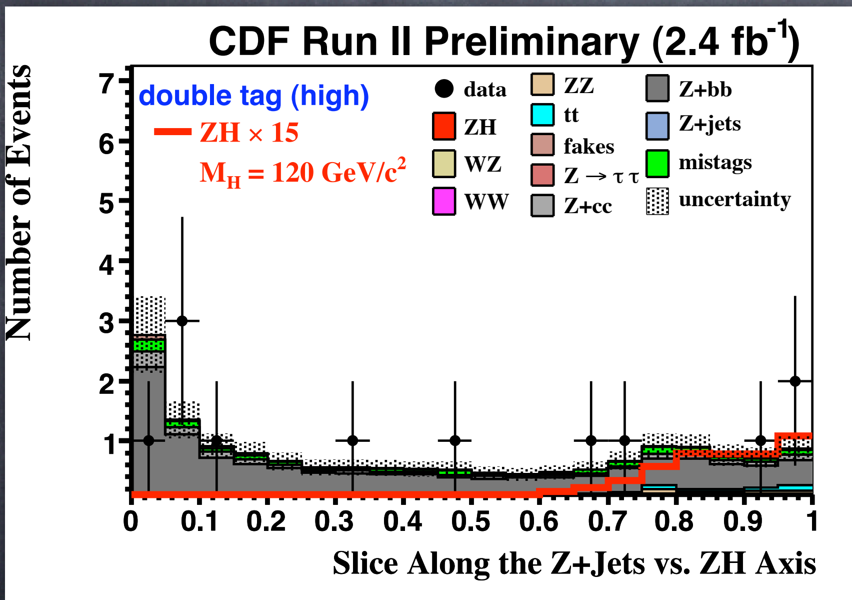
Pre b-tag NN Output for ZH

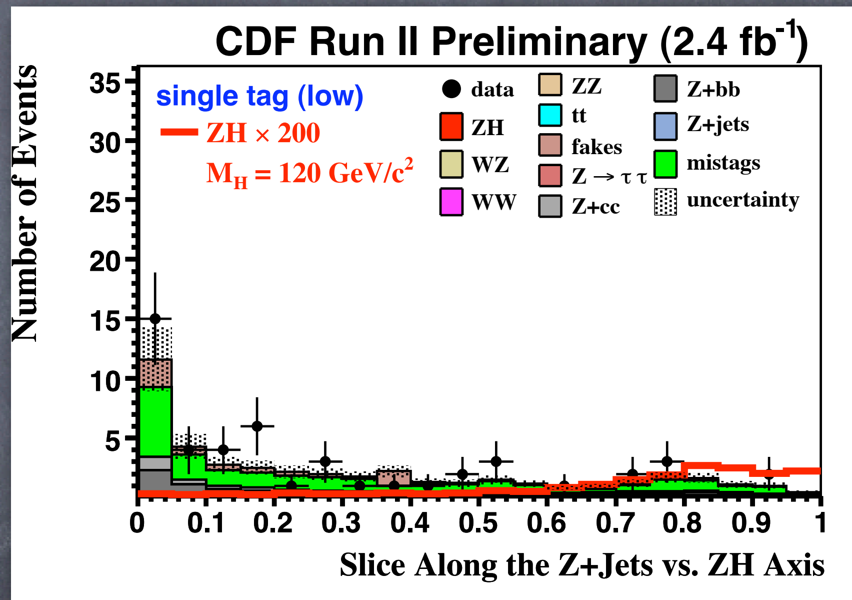
- Same object kinematics
- Statistics = 30 * tagged sample
- NN trained on :
  - Masses of combinations (j1, j2, e/μ)
  - P_T of combinations
  - Angular separations

ZH → llbb



- We use a 2D NN to distinguish ZH from tt and Z+jets
- New "low" purity lepton types from no-track trigger improve limit by 10%





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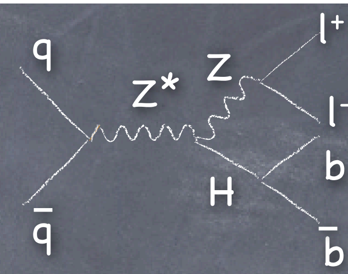

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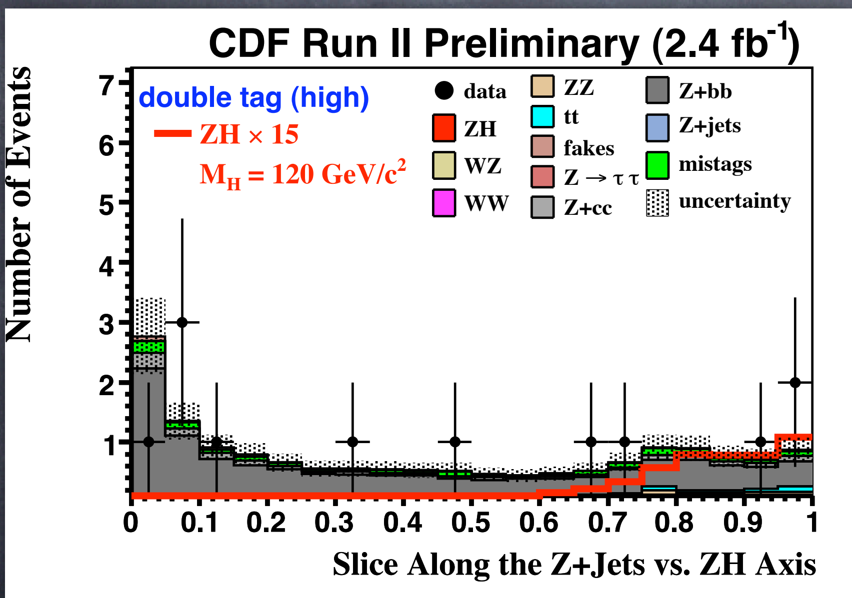
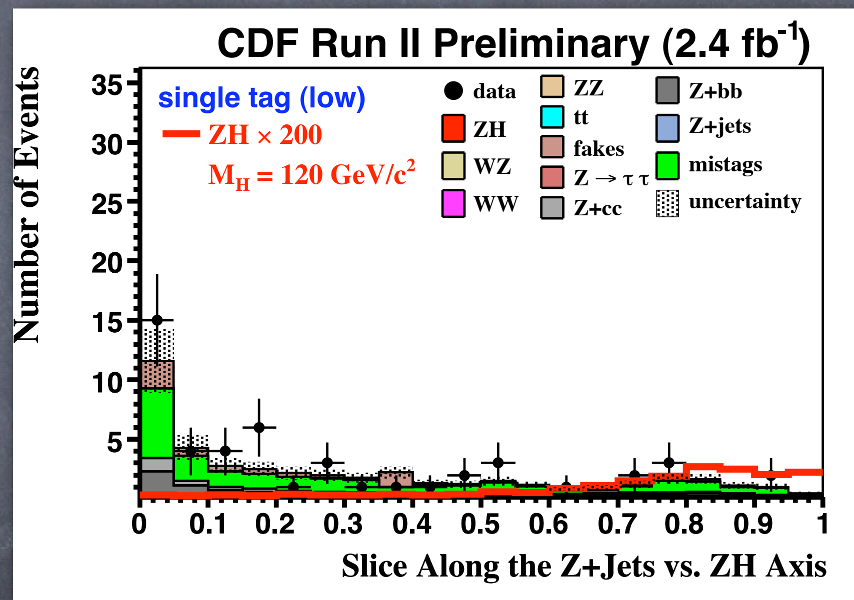
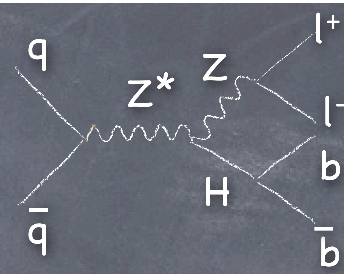




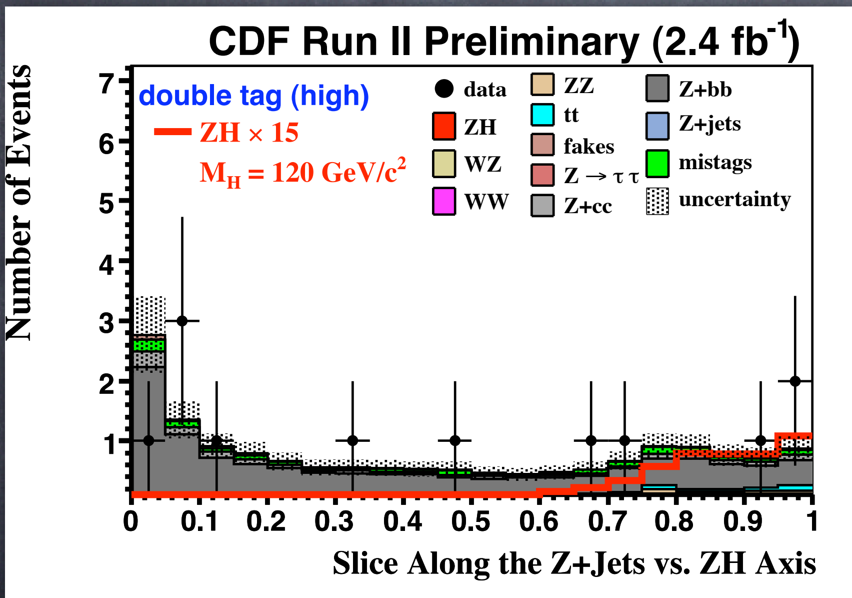
Have also done ME analysis with 2.1 fb^{-1}

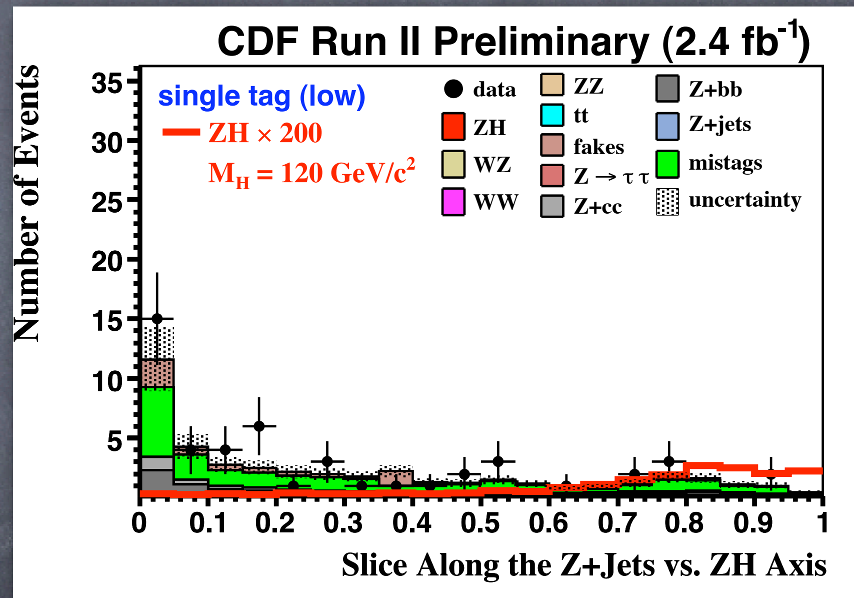
In the process of merging the two ...

ZH → llbb



- We use a 2D NN to distinguish ZH from tt and Z+jets
- New "low" purity lepton types from no-track trigger improve limit by 10%

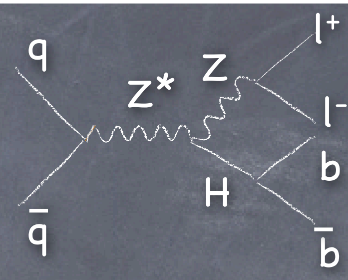




$\mathcal{L}$ = 2.4 fb^{-1}, m_H = 115 GeV
Upper limit: 11.8*SM
(expected 11.6*SM)

Have also done ME analysis with 2.1 fb^{-1}
In the process of merging the two ...

ZH → llbb



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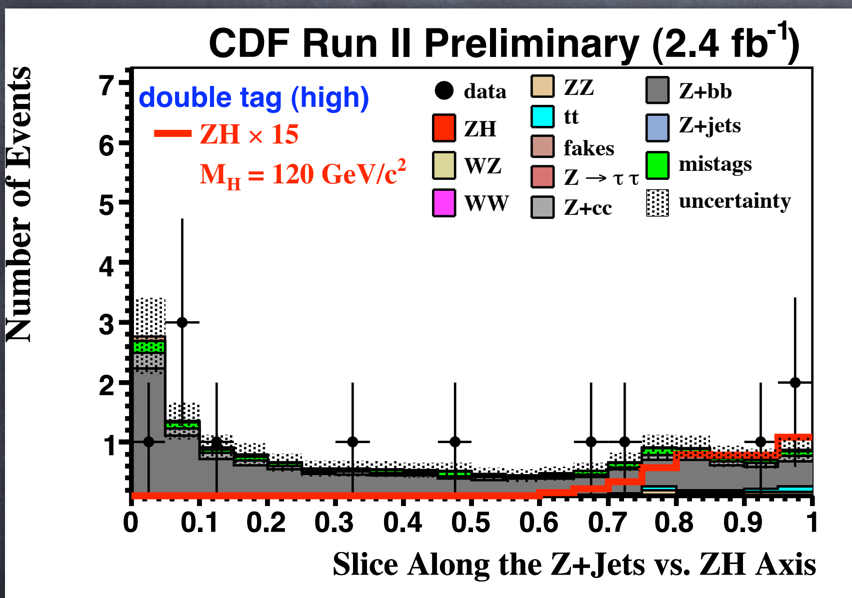

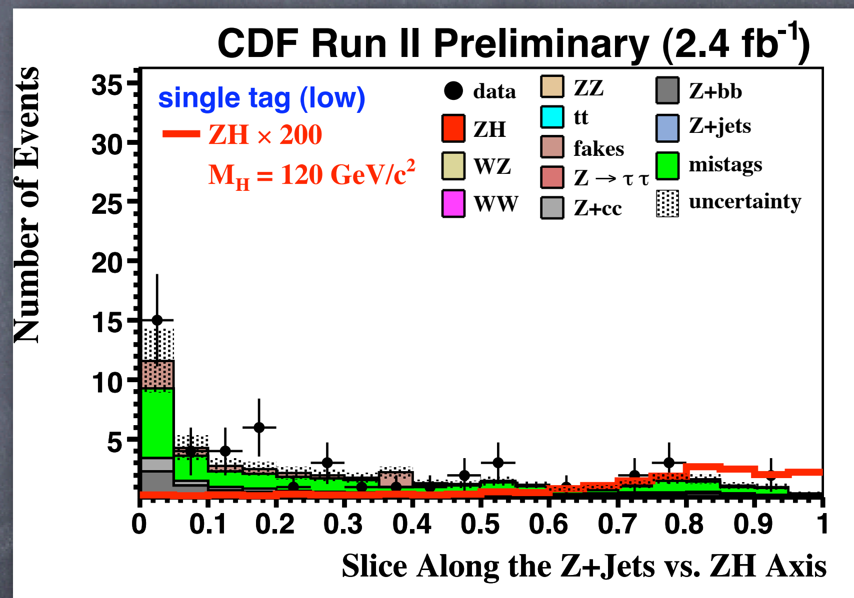

$\mathcal{L}$ = 2.4 fb^{-1}, m_H = 115 GeV
Upper limit: 11.8*SM
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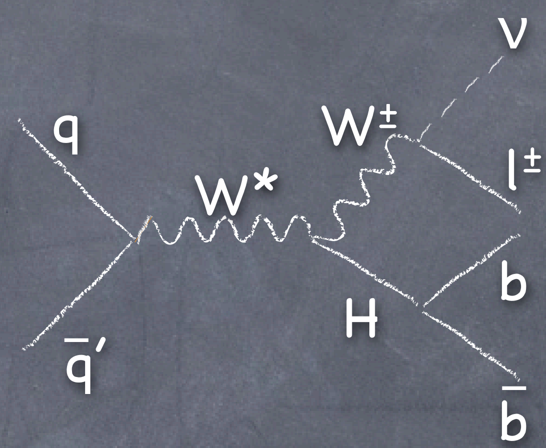
World's best exp. limit in this channel !

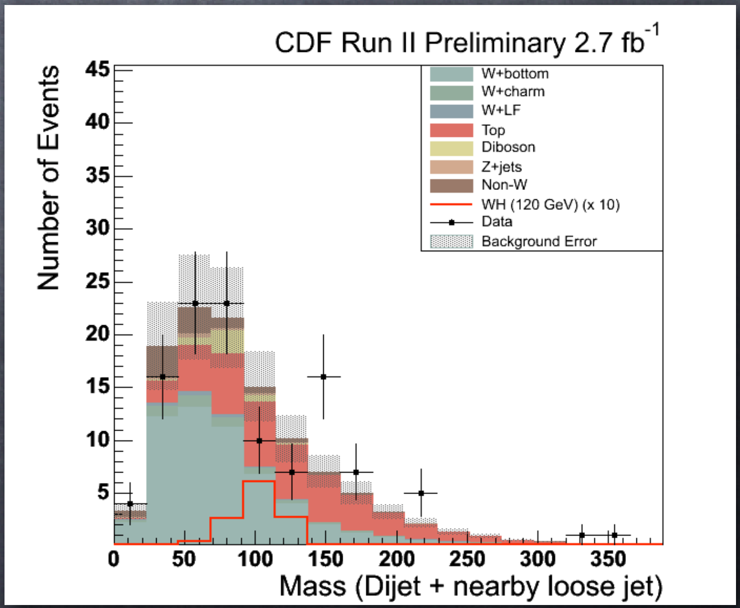
Have also done ME analysis with 2.1 fb^{-1}
In the process of merging the two ...

WH → lνbb: the golden channel

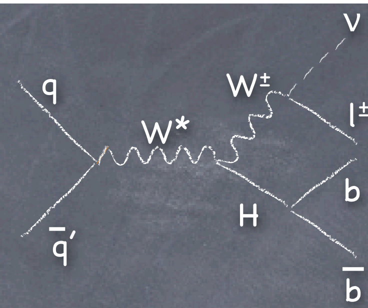
for $m_H < 135$

- Selection (l+MET +>=2jets + >= 1 b-tag)
  - one lepton, e or μ, P_T > 20 GeV
  - MET = Missing transverse energy > 20 GeV
  - >= 2 jets from bs, E_T > 15 GeV
  - Require jet to be b-tagged
- Lots of Tevatron experience
  - Same as single top - CDF had 2006 evidence
  - Similar to golden analysis for studying top quark pairs
    - l + MET + >= 4 jets + b-tag
- Basic analysis
  - Use central high Pt lepton trigger
  - Search for resonance in dijet mass



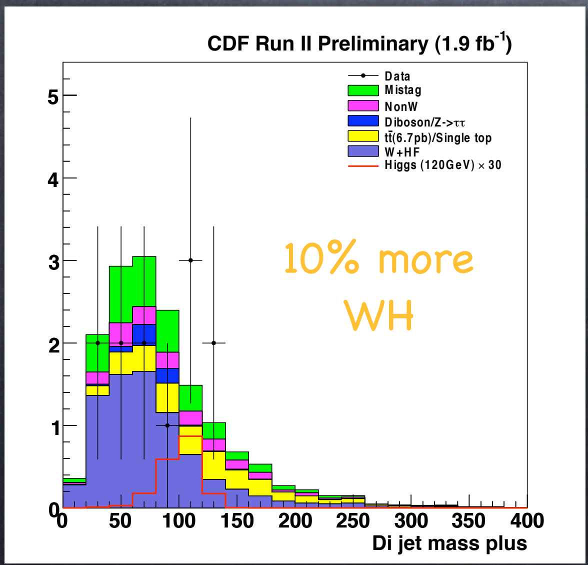


WH → lνbb



- Improving lepton acceptance

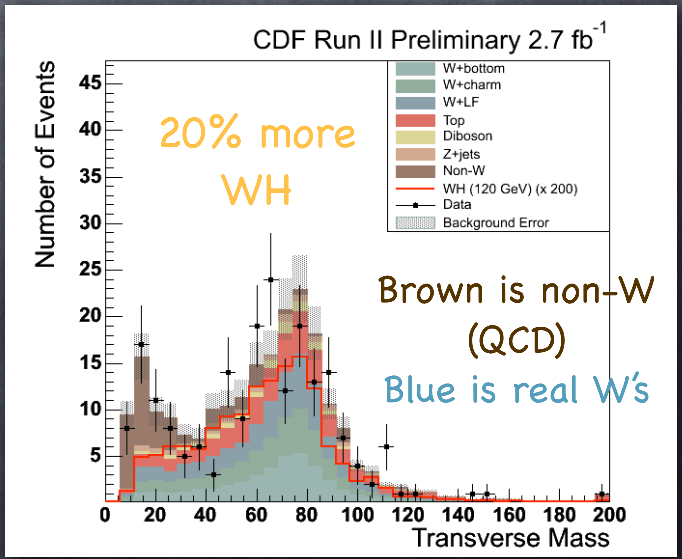
- Forward (plug) electrons
  - Plug electron trigger rate is too high since we have little tracking to reject jets
  - Use plug electron + MET trigger



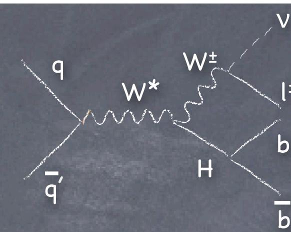
Dijet mass in plug WH candidates

- New: Incomplete muons
  - Central muon trigger requirements are stringent because trigger rate is high
  - Use jets + MET trigger
    - Select muons offline with looser criteria

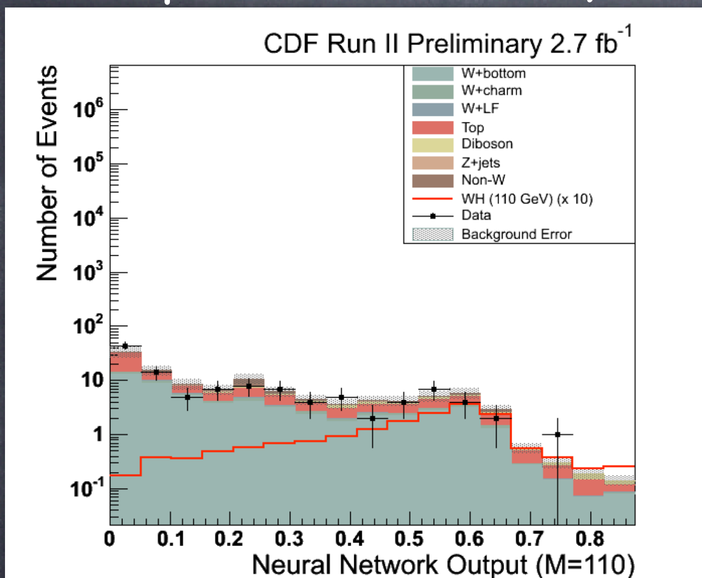
New events passing "isolated track" lepton requirements



WH → lvbb results

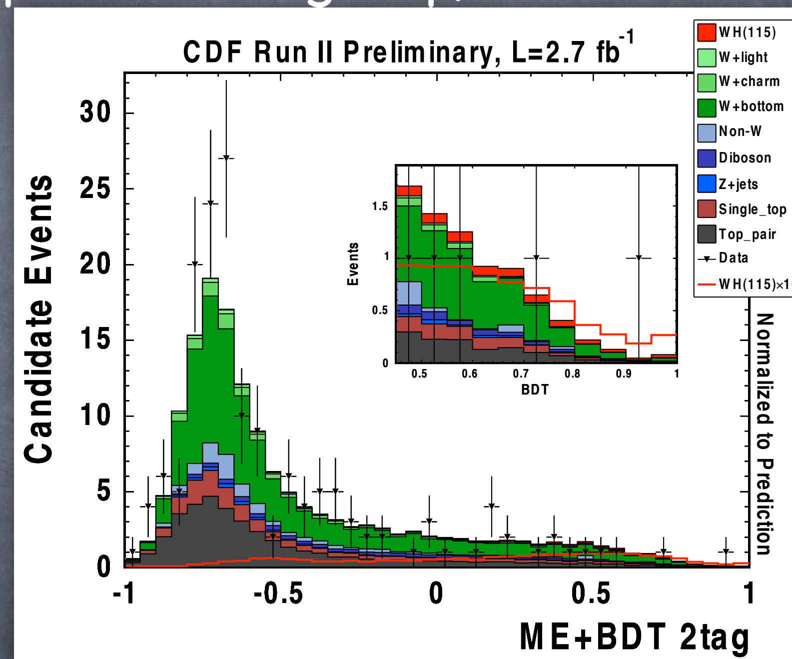


- Several iterations to optimize NN analysis



Uses 2 b-tagging categories for final result (this is one)

- Newer parallel effort with matrix elements (from single-top evidence group)



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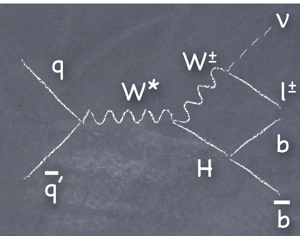

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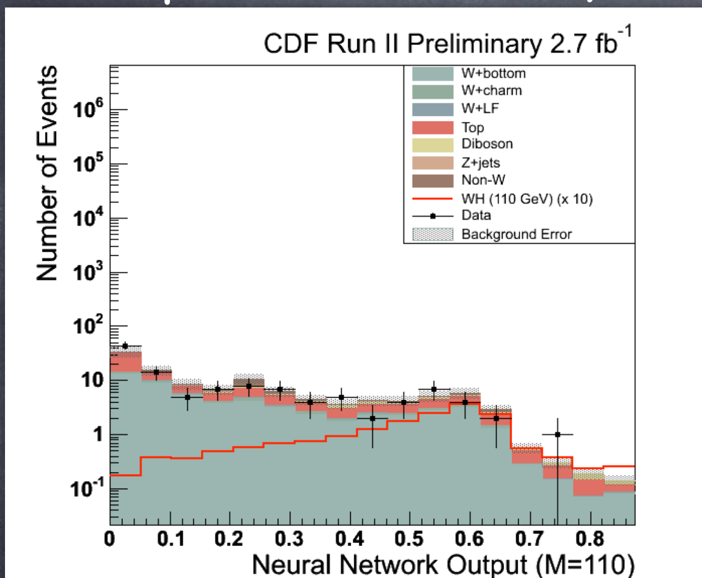

$\mathcal{L}$ = 2.7 fb^{-1}, m_H = 115 GeV
Upper limit: 5.0*SM
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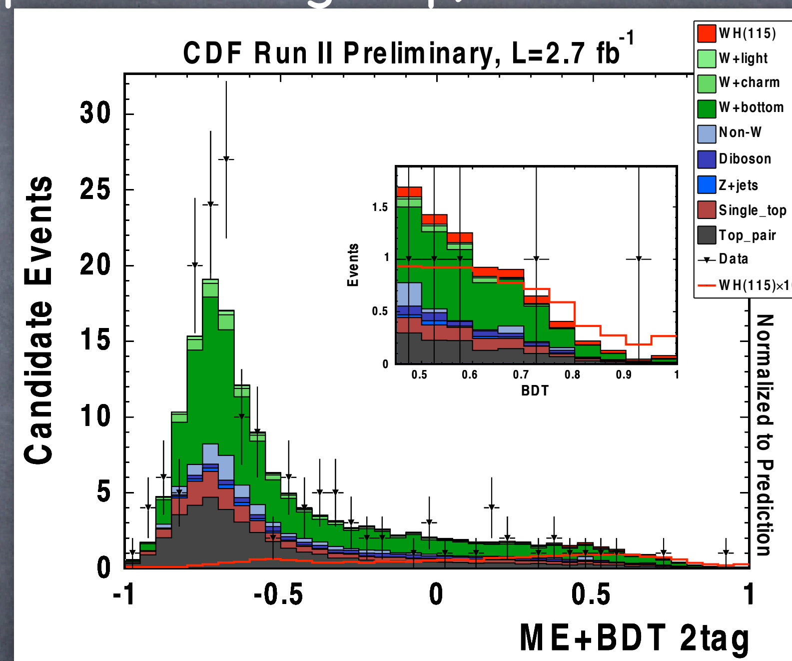

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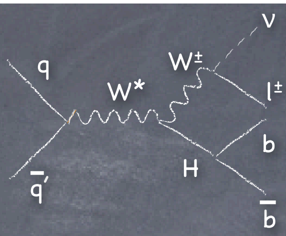

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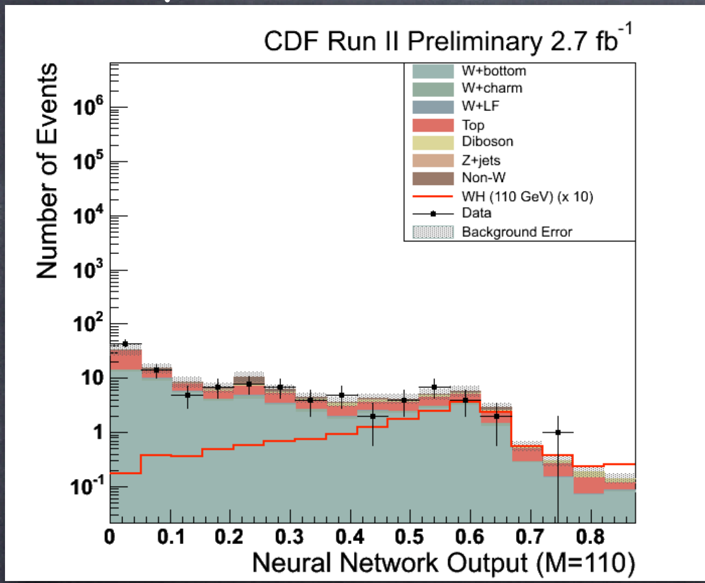

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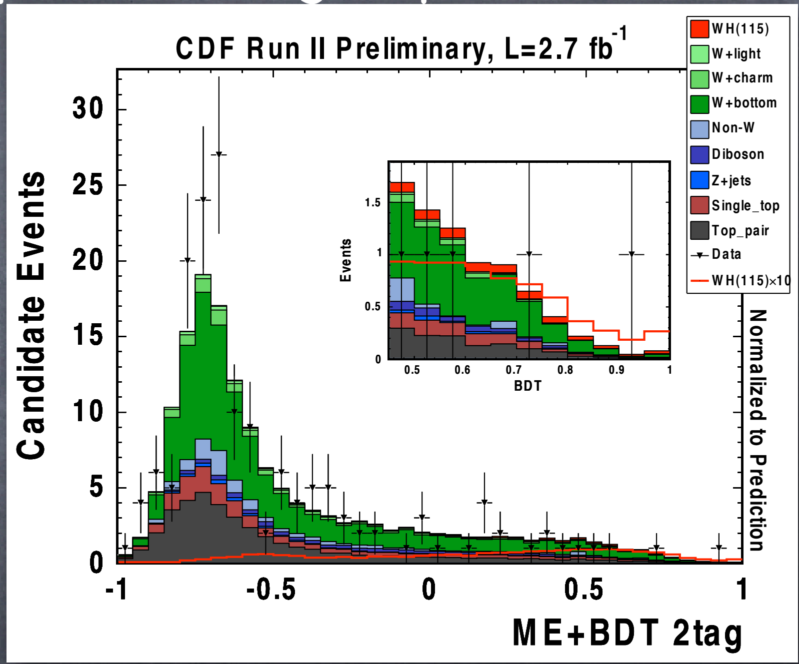

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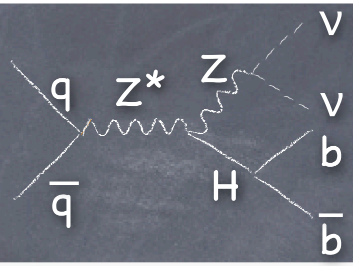
Upper limit: 5.8*SM
(expected 5.6*SM)

World's best low mass Higgs limits !

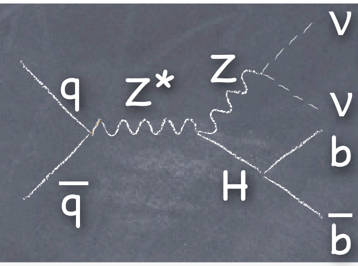
VH → MET+jets



Process	Evts 2.1 fb^{-1} 2 tight b-tags
QCD	80 ± 15
Total Bkg	149 ± 20
ZH Signal	0.8
WH Signal	0.7

- Signature
  - MET > 50 GeV, >= 2 jets, >= 1 b-tag
- Large total signal
  - 7.3 Higgs events in 2.1 fb^{-1}
- Baseline analysis
  - Uses MET + multi-jet trigger
  - Fit of M_{jj} in 2-jet data, >= 1 b-tag
- Challenge
  - Large QCD background from mismeasured jets
  - Peak in M_{jj} where signal

VH → MET+jets



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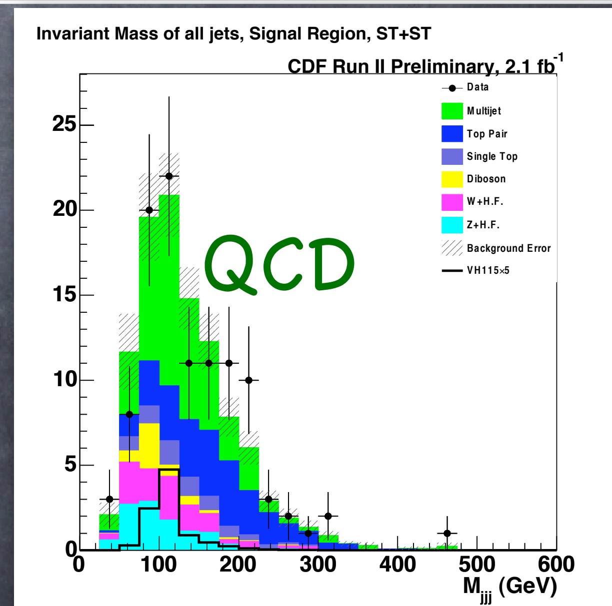
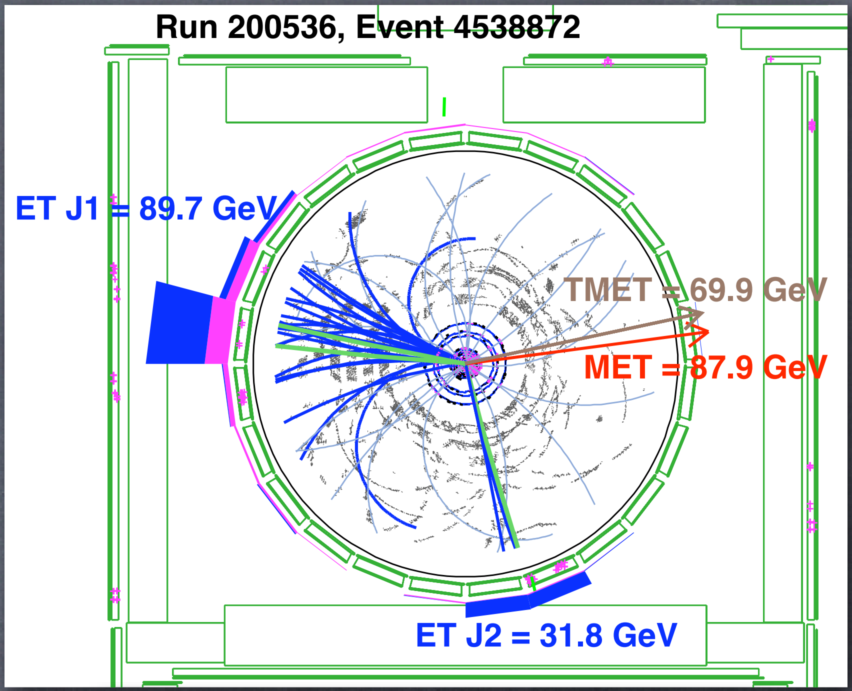
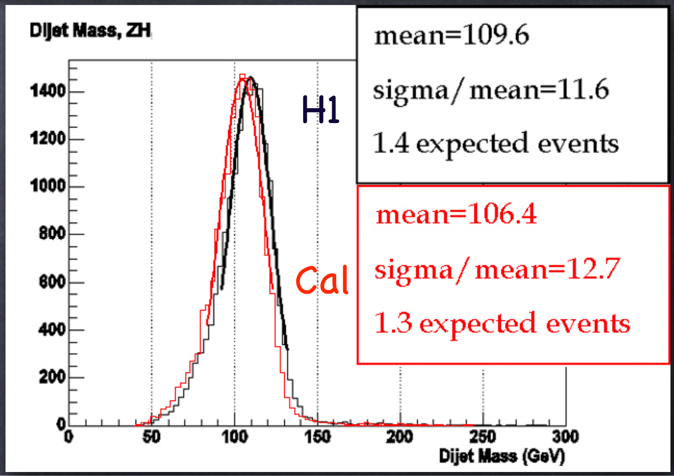


VH → MET+jets

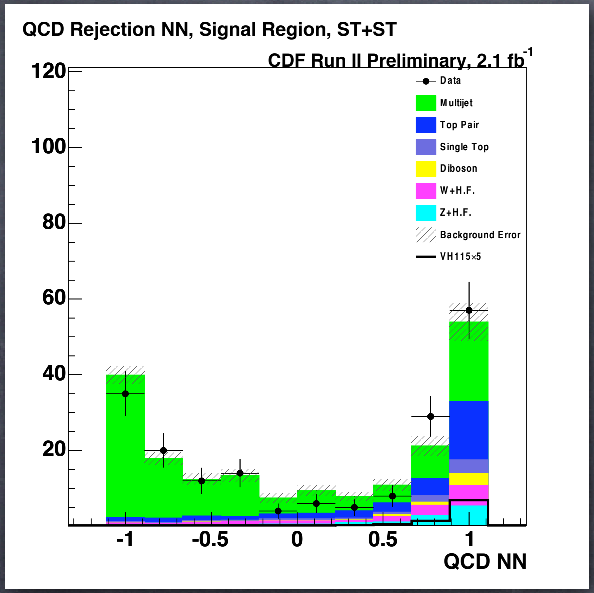
- Using tracking in 2 ways
  - Tracks have excellent momentum resolution
  - 2/3 of particles in jets are charged
- Missing P_T of tracks = TMET
  - Provides confirmation of high MET measured in calorimeter
  - Helpful for reducing QCD
- Improving jet resolution
  - H1 algorithm
    - New : 1st time in CDF analysis
  - Correct calorimeter towers with matched higher P_T tracks





VH → MET+jets result

- First stage NN
  - Trained to remove QCD



- Cut here
  - Removes 65% of Multijet
  - Removes only 5% of signal

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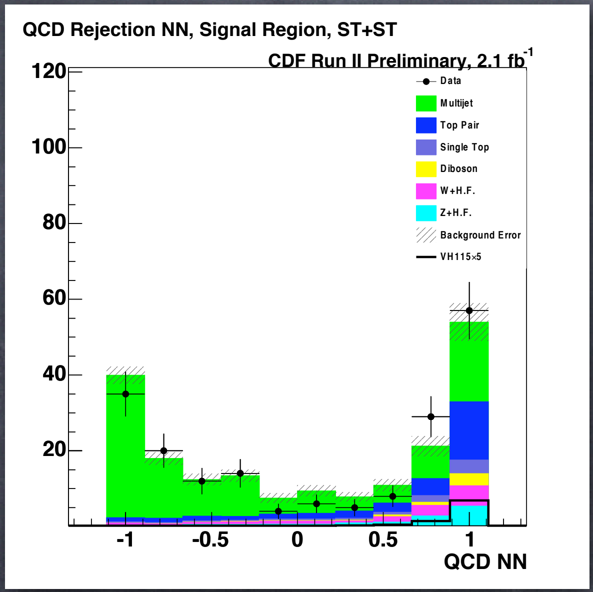
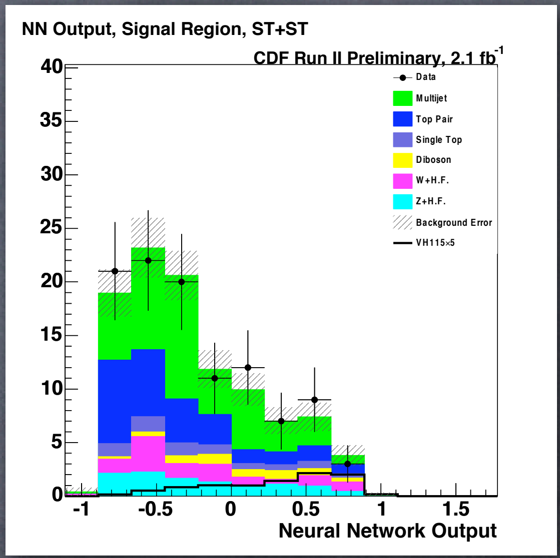


- Second stage NN
  - Removes W/Z+jets and top



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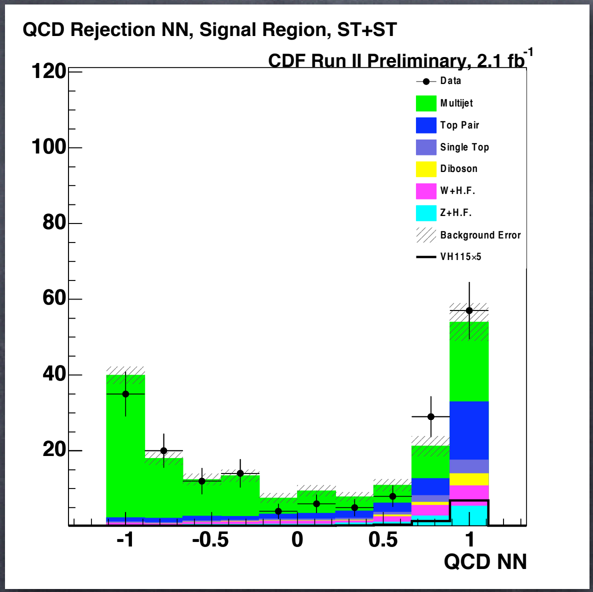

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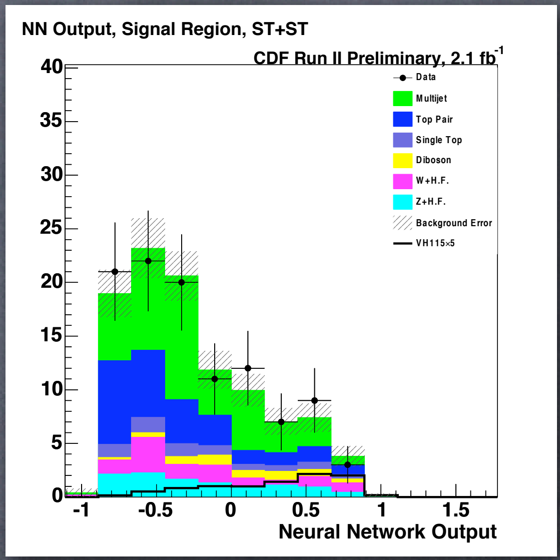

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World's best in this channel

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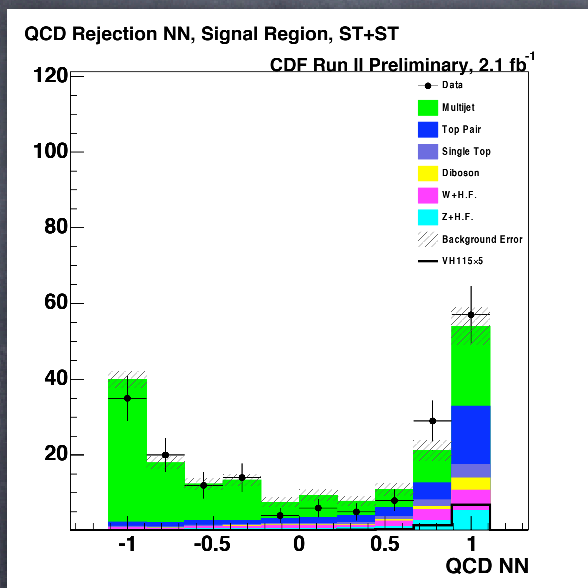

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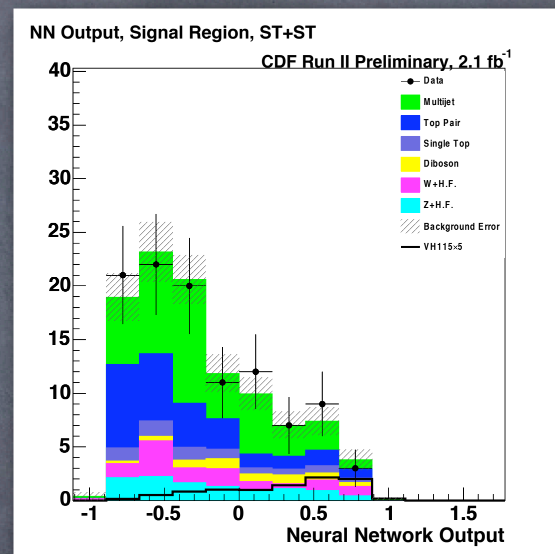

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With more $\mathcal{L}$ as good as WH "golden channel"
"Diamond in the Rough" Channel

Getting every last Higgs event at low mass

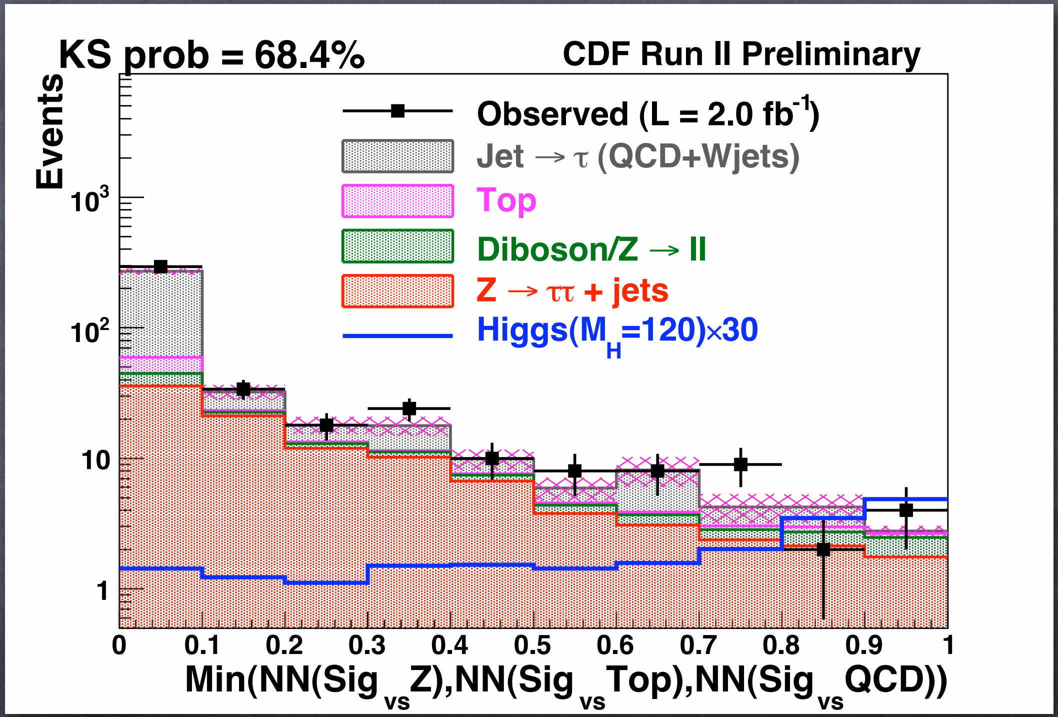
Analyses become more challenging

- $H \rightarrow \tau\tau$ decay modes
  - BR ($H \rightarrow \tau\tau$) ten times smaller than $H \rightarrow bb$
- $Z/W + H \rightarrow qq + bb$
  - More signal than lepton modes but enormous QCD backgrounds

$H \rightarrow \tau\tau$

Selection: $H \rightarrow \tau\tau$ + 2 jets

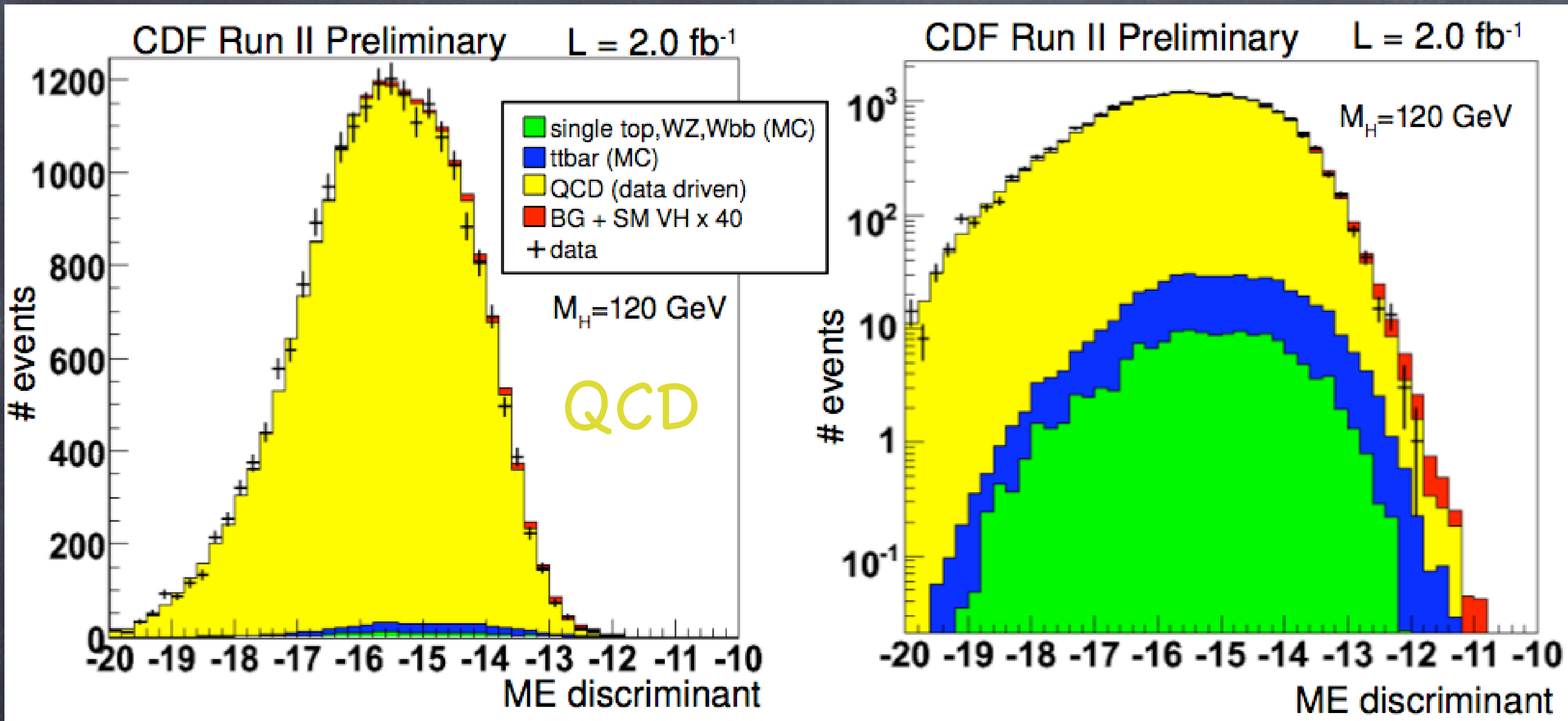
Signal : $gg \rightarrow H \rightarrow \tau\tau$, $VH \rightarrow qq\tau\tau$, V.B.F. $H \rightarrow \tau\tau qq$



- NN's trained for each of main backgrounds
  - $Z \rightarrow \tau\tau$, Top, QCD
  - Final discriminant is minimum of all

$\mathcal{L}$ = 2.0 fb^{-1} , m_H = 115 GeV
Upper limit: 26*SM
(expected 30*SM)

VH → qqbb



- QCD backgrounds enormous
  - Challenge to pull out signal
  - Matrix element analysis used

$\mathcal{L}$ = 2.0 fb^{-1} , m_H = 115 GeV
Upper limit: 37*SM
(expected 35*SM)

High Mass Higgs search

m_H ~ 160 GeV

H → WW most important channel

High mass H→WW

m_H = 160 GeV

New: dedicated analyses in different 0, 1, 2 jet bins

Process	H → WW + >=2j Evts, $\mathcal{L}$ = 3fb^{-1}
gg → H → WW	1.52 ± 0.26
WH → WWW	1.18 ± 0.16
ZH → WWW	0.59 ± 0.08
V.B.F. H → WW	0.61 ± 0.1

High mass H→WW

New: dedicated analyses in different 0, 1, 2 jet bins

- Divide and conquer

m_H = 160 GeV

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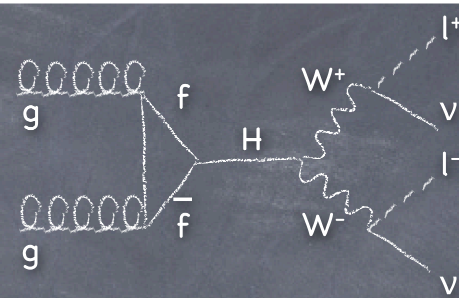
- Divide and conquer

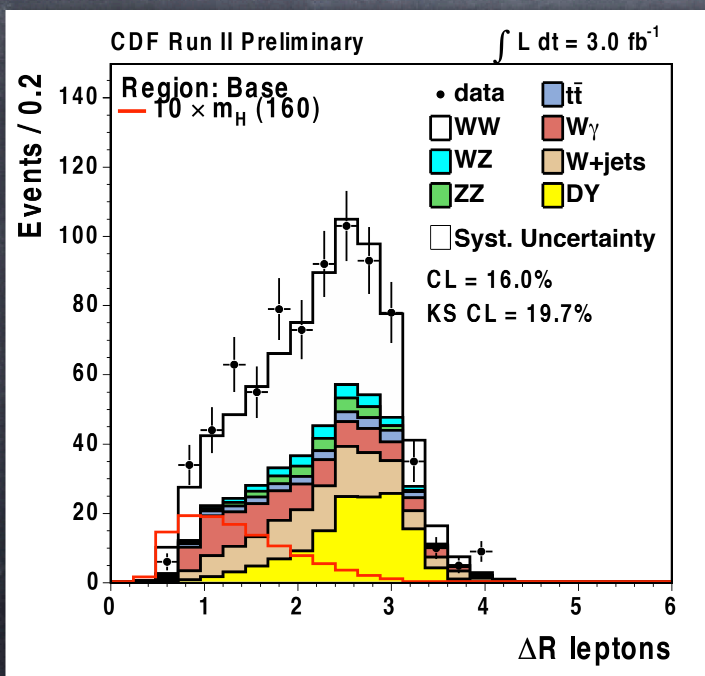
# jets	H→WW events	Total Bkg events	% WW	% Drell-Yan	% tt	% fakes & conversions
0	8	540	52	12	0.2	30
1	5	230	32	31	11	16
2	4	130	12	22	54	8

- Different background compositions
  - Analyses optimized for each jet bin

$H \rightarrow WW$: 0 jets

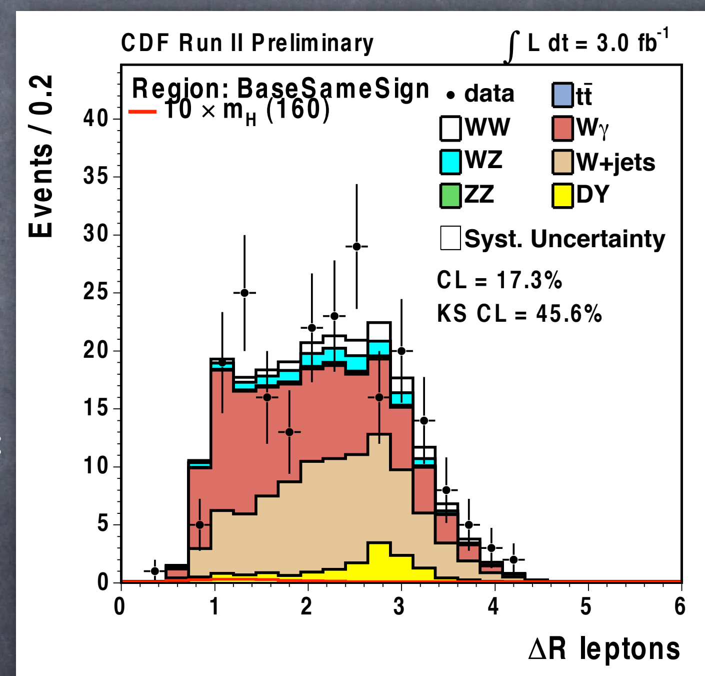


- WW background
  - Primarily distinguished by spin correlation of leptons
- Fakes and conversions
  - Difficult to model, require data validation

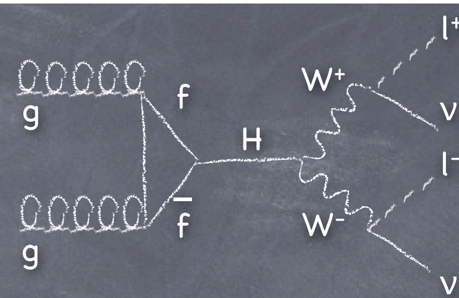


ΔR (lep 1, lep 2)
Spin 0 $H \rightarrow WW$
Spin 1 $Z \rightarrow WW$
signal region

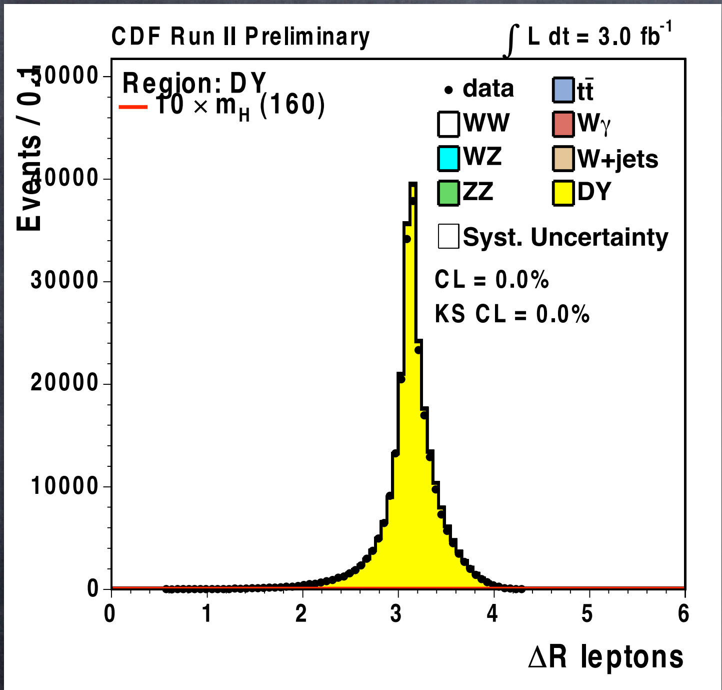
Fakes & conversions:
Control region using
Same-sign



H → WW : 1 jet

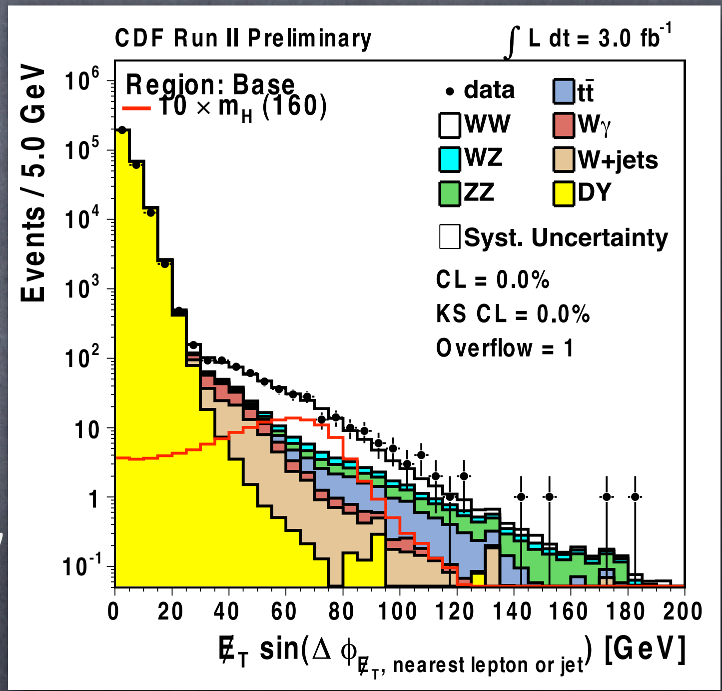


- Drell-Yan & WW bkgs contribute equally
  - Check Drell-Yan has proper dilepton & MET correlations
    - DY can be cleaned up with special MET calculations

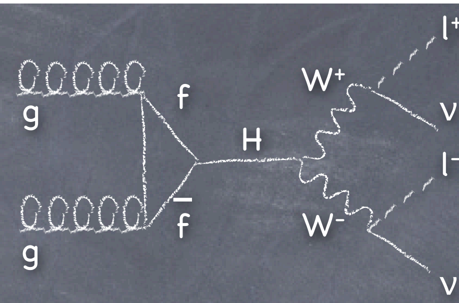


ΔR (lep 1, lep 2) in low MET region dominated by DY

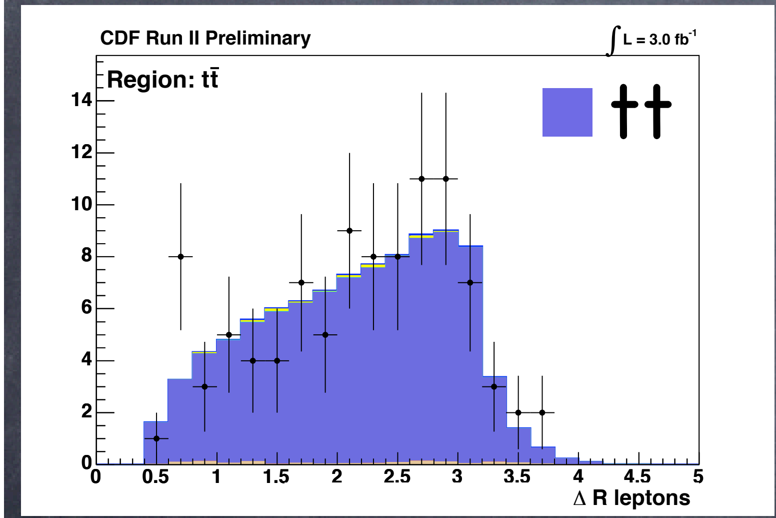
MET crossed with nearest lep or jet modeled well both in DY and WW regions



H → WW : 2 jet

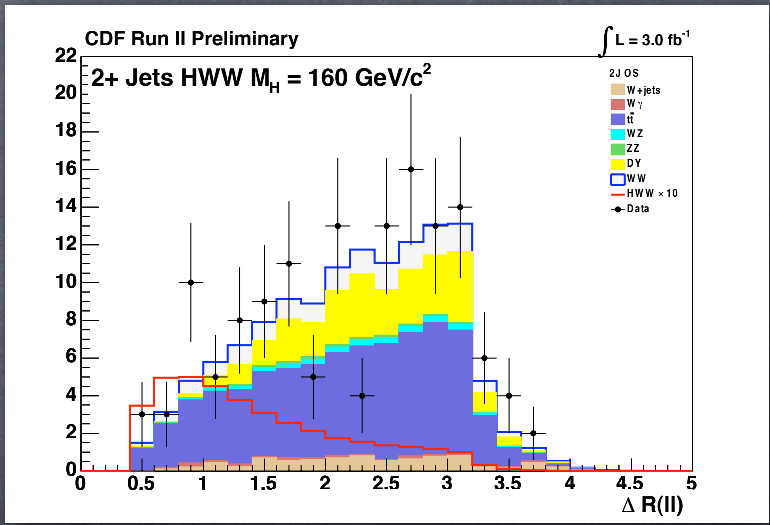


- Top pairs biggest bkg (tt → WbWb → lνlνbb)
  - Analysis requires anti-b tag to get rid of top
  - Can also examine b-tagged control region to test model



ΔR (lep 1, lep 2) in b-tagged control region

ΔR (lep 1, lep 2) in anti b-tagged signal region



observed	tt	other
98	91 ± 17	2.3 ± 0.3

H → WW analyses results

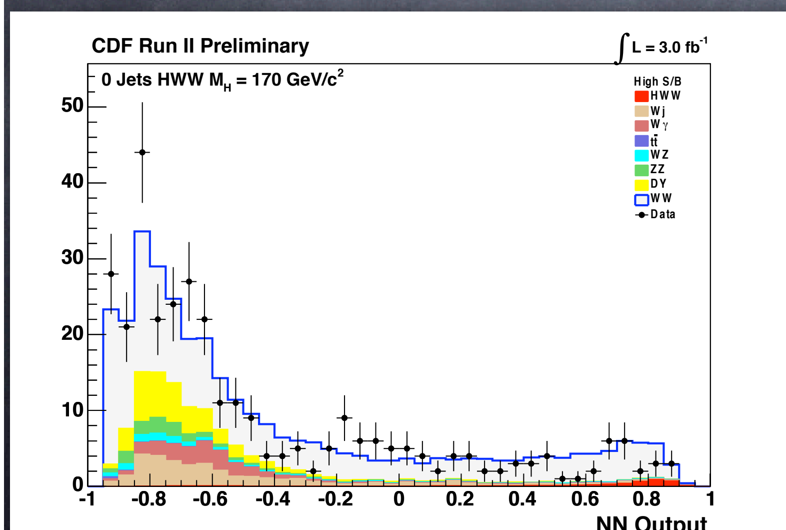
	0 J	1 J	2 J
observed	552	227	139
expected	540 ± 65	226 ± 28	129 ± 20

H → WW analyses results

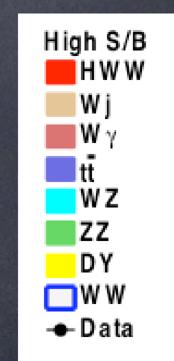
	0 J	1 J	2 J
observed	552	227	139
expected	540 ± 65	226 ± 28	129 ± 20

0 J

NN using LO matrix elements probabilities, sum transverse energies, dΦ(l1,l2), dR(l1,l2)



m_H = 170 GeV



$H \to WW$ analyses results

	0 J	1 J	2 J
observed	552	227	139
expected	540 ± 65	226 ± 28	129 ± 20

1 J

NN similar to 0J NN: adds in special MET cut, lepton P_Ts, removes LO matrix elements because of extra jets

0 J

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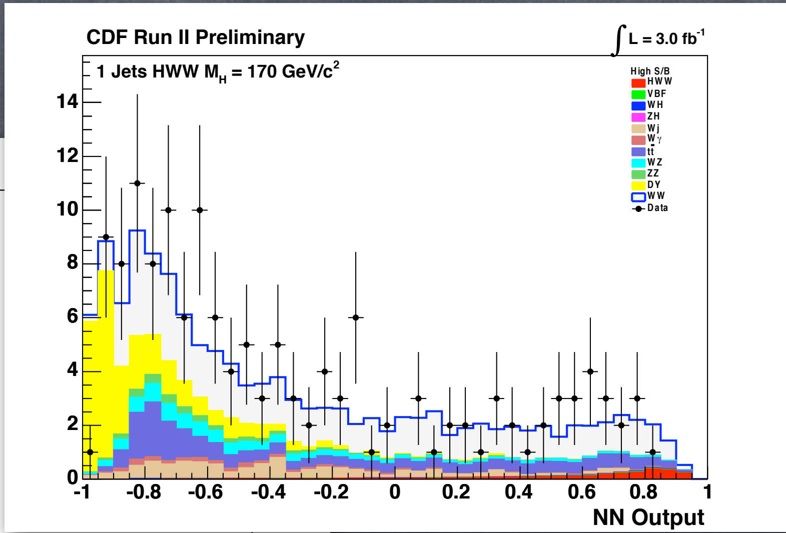
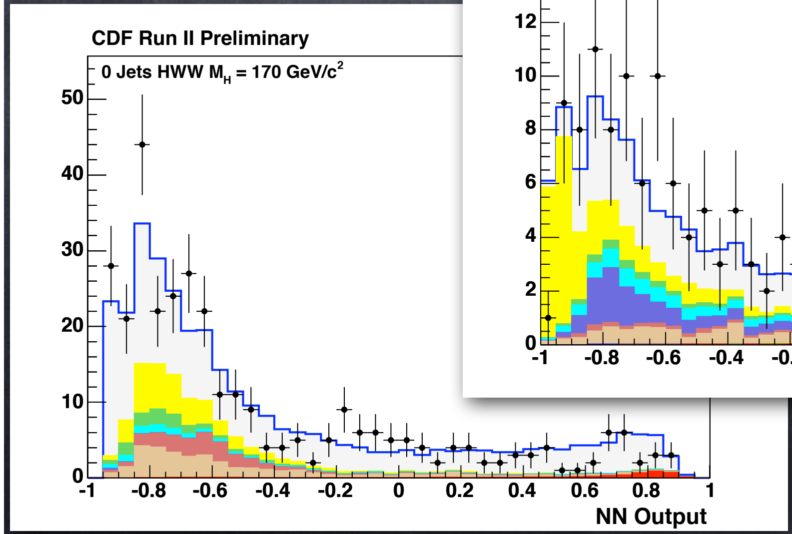




m_H = 170 GeV

H → WW analyses results

	0 J	1 J	2 J
observed	552	227	139
expected	540 ± 65	226 ± 28	129 ± 20

2 J

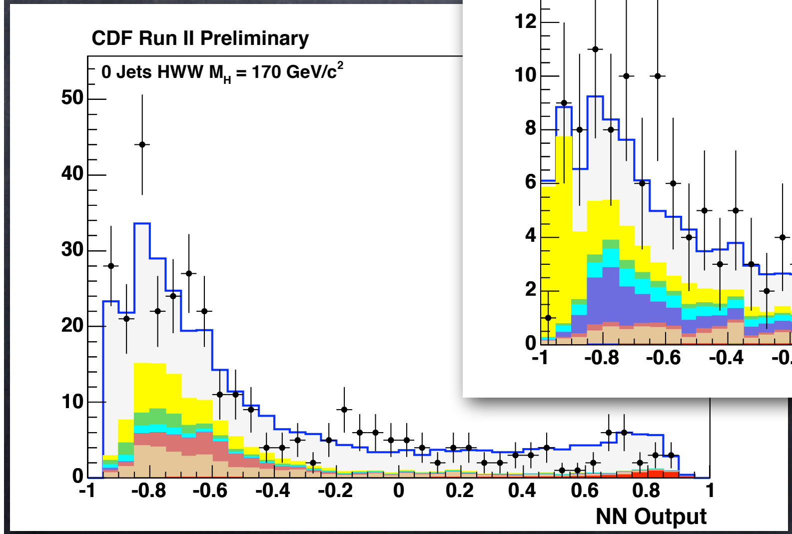
NN similar to 1J NN: adds in P_T of dijet system

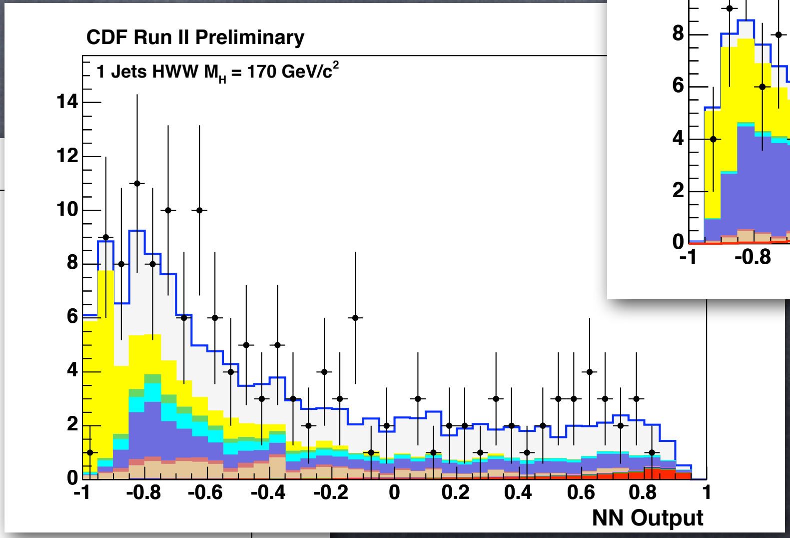
1 J

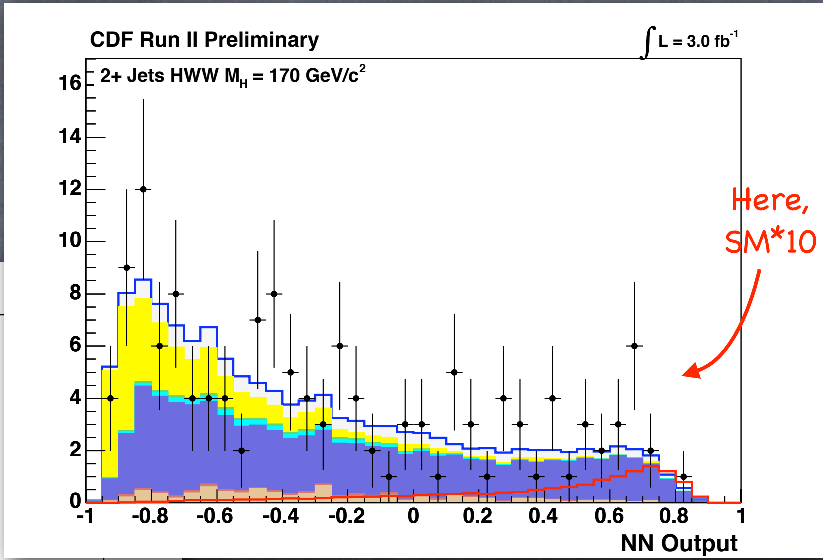
NN similar to 0J NN: adds in special MET cut, lepton P_Ts, removes LO matrix elements because of extra jets

0 J

NN using LO matrix elements probabilities, sum transverse energies, dΦ(l1,l2), dR(l1,l2)







m_H = 170 GeV

H → WW Combination at CDF

Lots of systematics uncertainties :
Correlated between backgrounds, signal processes, and between 0J, 1J, 2J channels

- Leading systematics :
  - WW, tt, H → WW
    - 10-15% cross-section
  - W+jets, W+γ
    - 20-30% jet fakes and conversions
  - Drell-Yan
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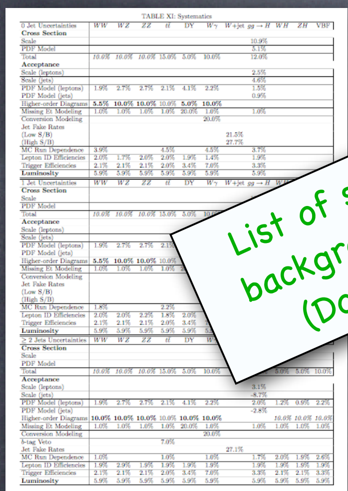
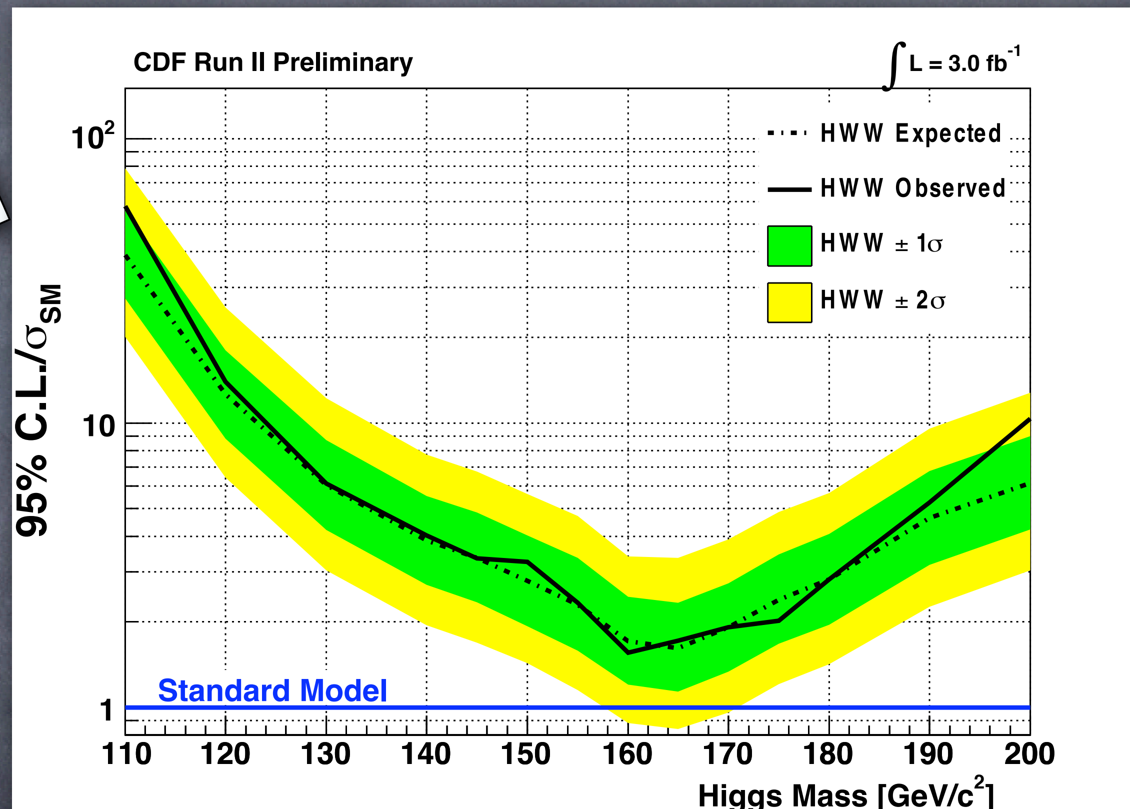


List of systematics and background correlations (Don't try to read)



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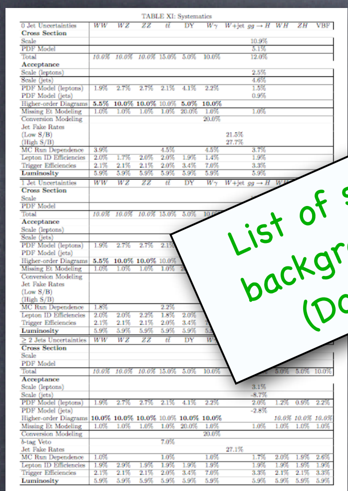

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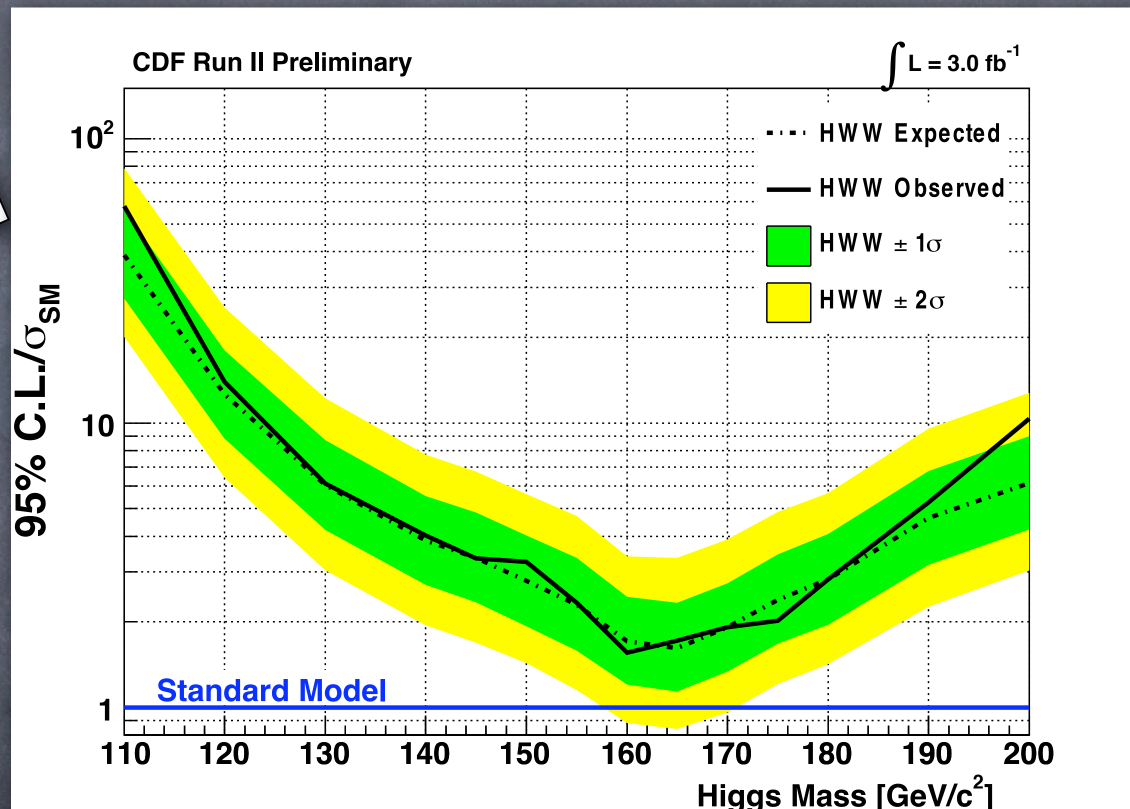

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mH	120	130	160	165
expected	13	6	1.7	1.6
observed	14	6	1.6	1.7

* σ_{SM}

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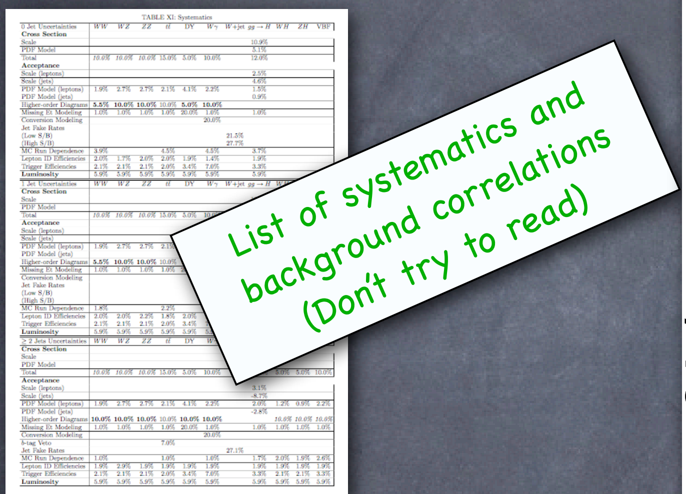

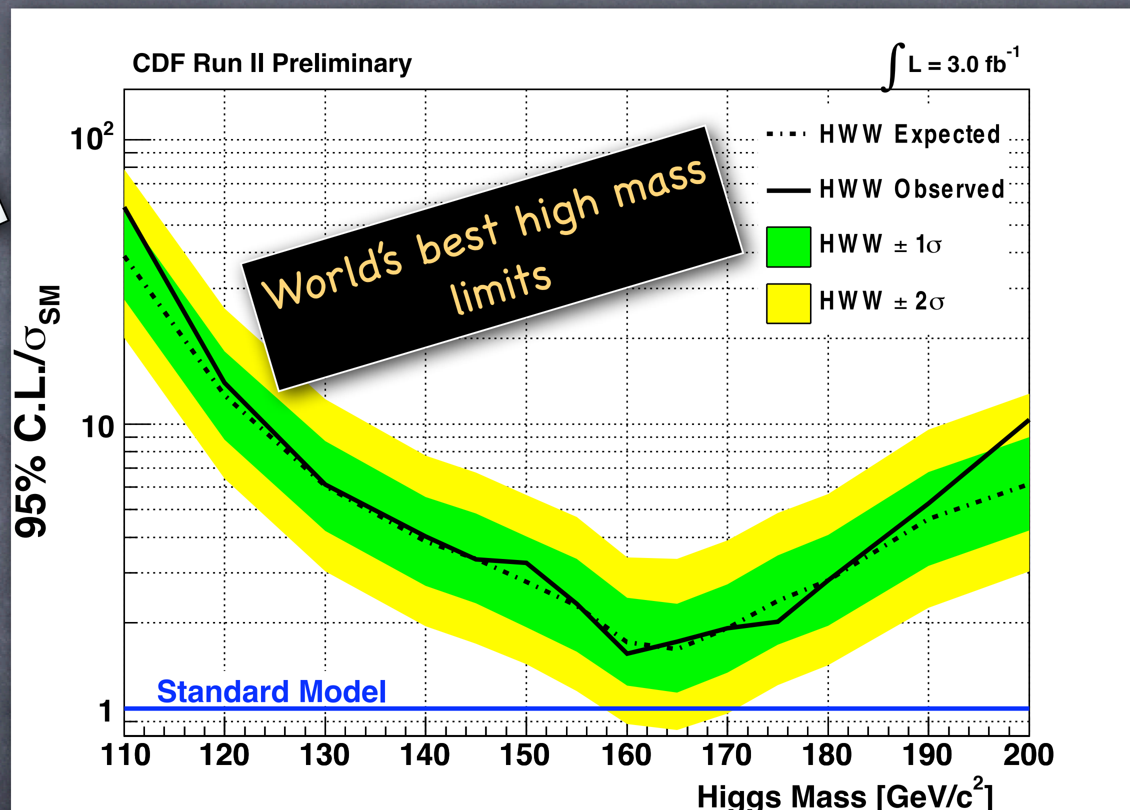

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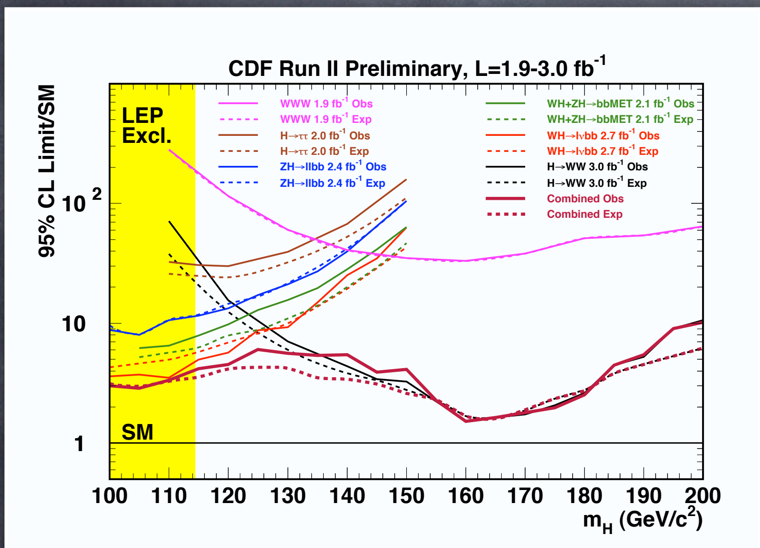
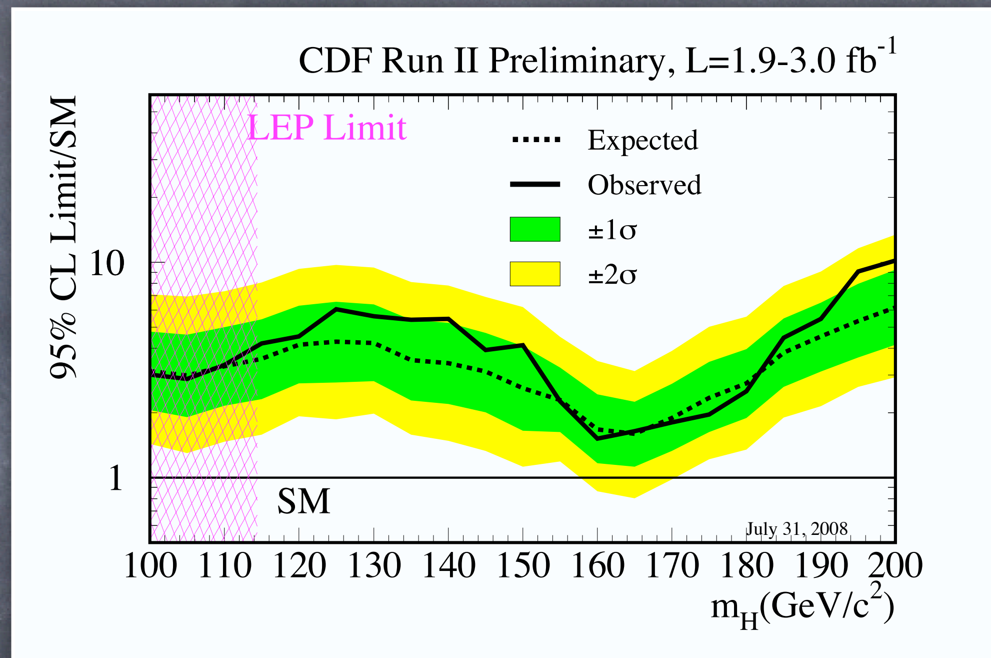
- Low and high mass Higgs channels combined for CDF





Channel	Limit @ 115 GeV
WH	5 (6)
VH → MET+bb	8 (6)
ZH → llbb	12 (12)
H → ττ + jets	26 (30)

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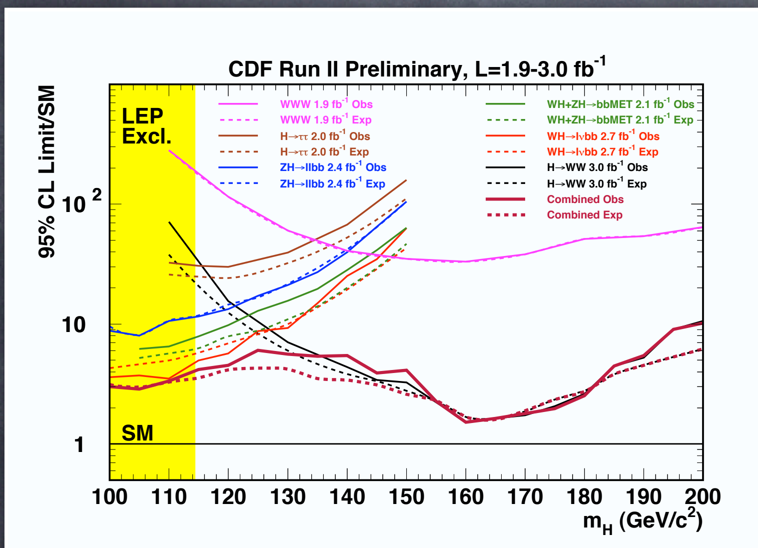

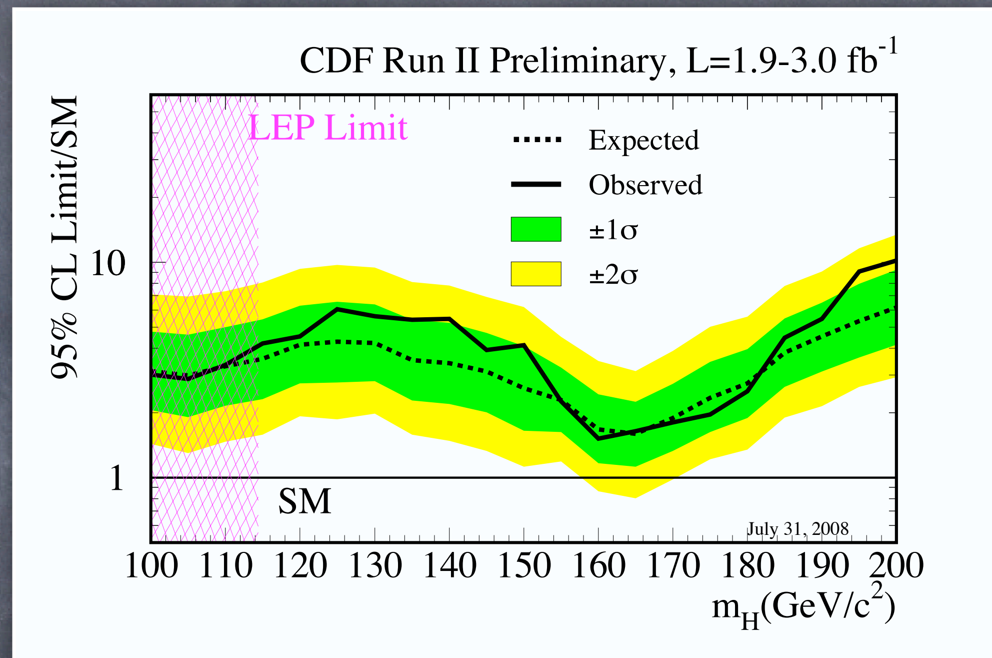

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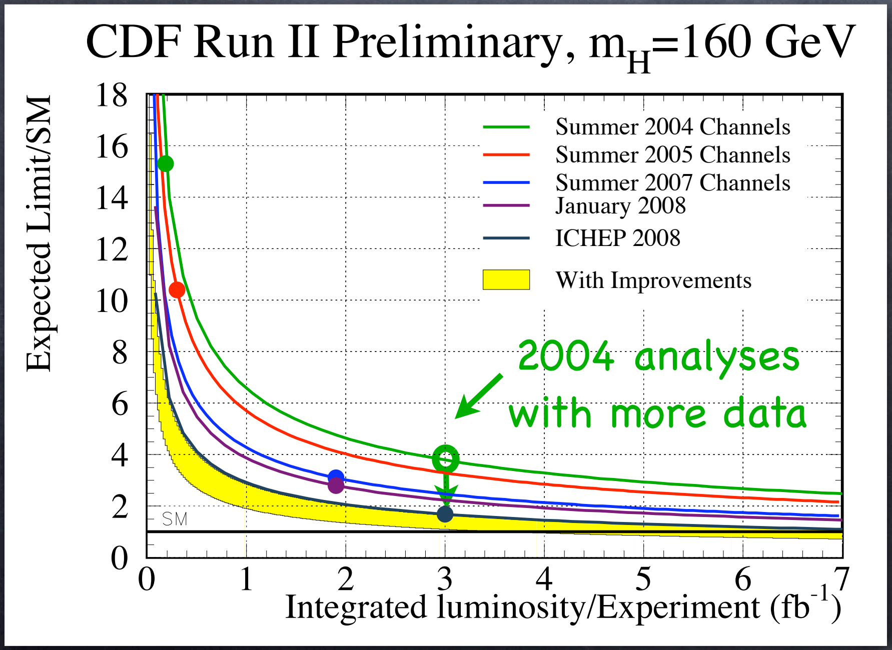
CDF combined upper limits:
m_H = 115 GeV 3.6*SM expected
m_H = 165 GeV 1.6*SM expected

CDF results - Past and Future

- For m_H = 160 GeV
  - Baseline analysis (2004) would require 36 fb^{-1} for 2σ sensitivity
  - Advanced analysis now sensitive with < 5 fb^{-1}
  - CDF only limit is 1.6*SM
  - Goal is bottom of yellow band
  - Expect to exclude significant region around m_H = 160 GeV with more data



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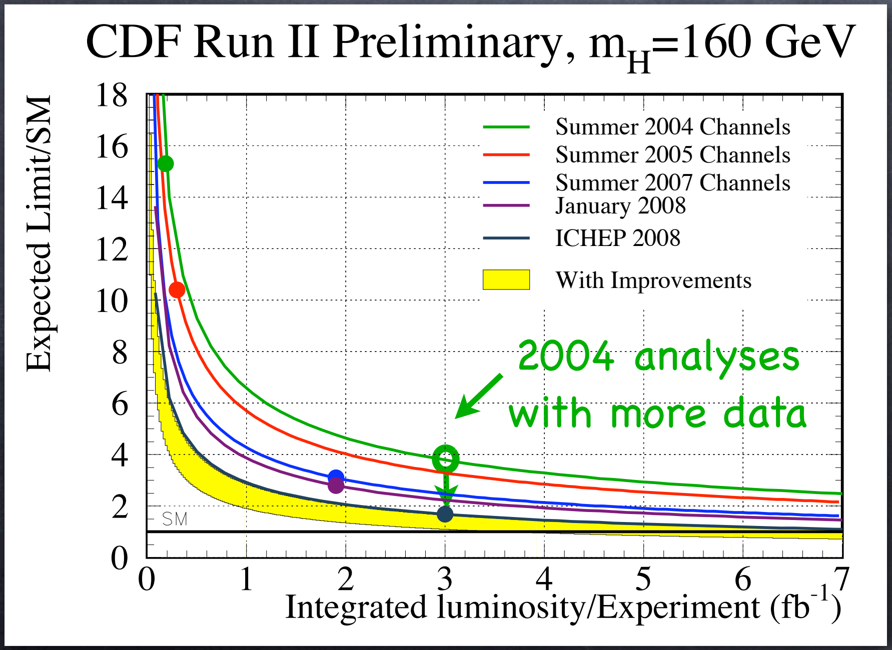

- For m_H = 115 GeV
  - Ongoing improvements
    - B-tagging
    - Lepton acceptance
    - Jet / Met resolution
    - Complementary triggers
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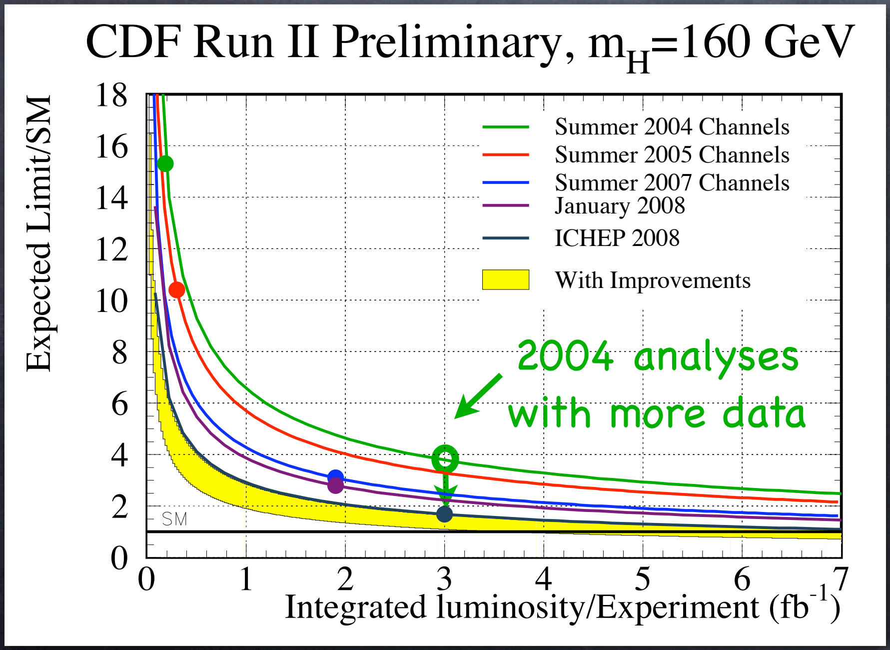
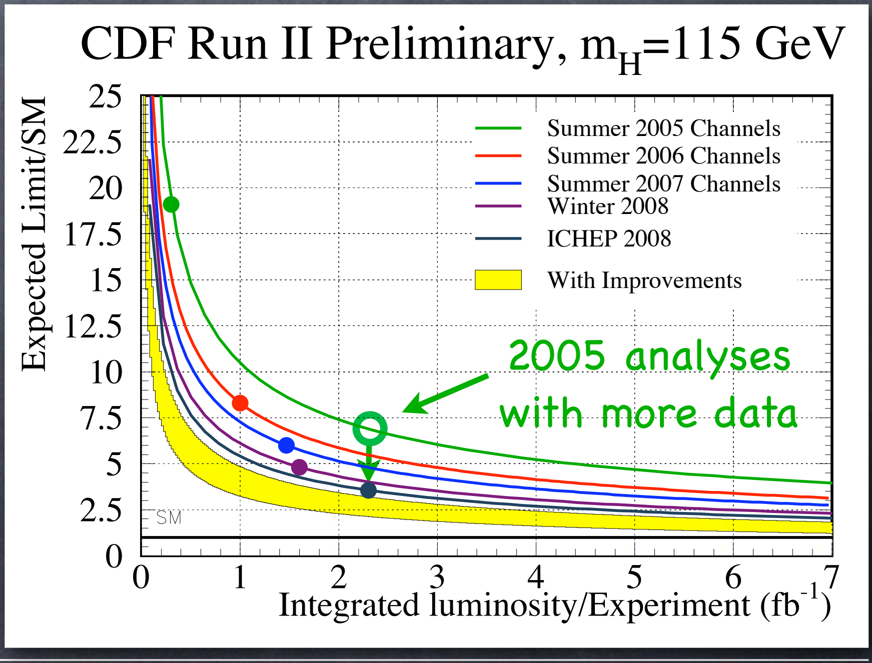
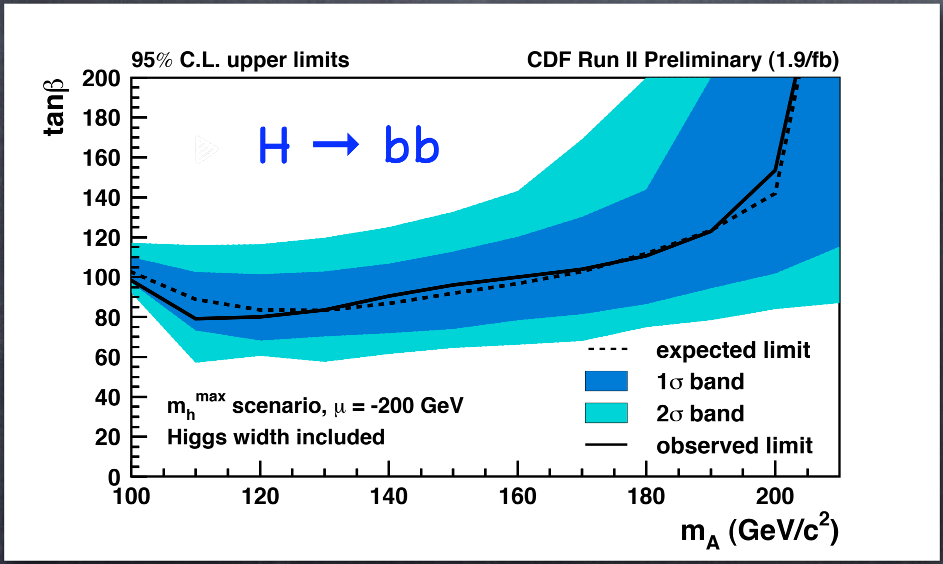
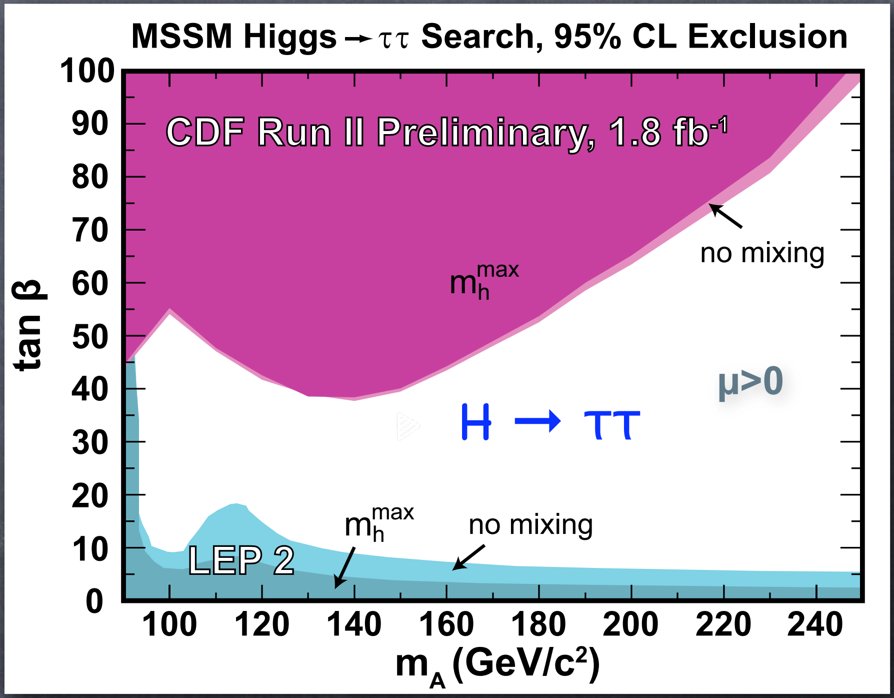




More on SUSY

- If SUSY is the correct theory
  - Some Higgs production mechanisms enhanced by $(\tan\beta)^2$
  - Direct $gg \to H \to bb$ and $H \to \tau\tau$ modes become viable searches for neutral SUSY Higgs mass < ~200 GeV





- Between CDF and D0
  - $H \to bb$, $H \to \tau\tau$, $H \to \tau\tau + b$
  - Will have 6 channels with comparable sensitivity
  - Plan to combine for MSSM tan β limits

CDF Conclusions

- Searching for every available Higgs boson
- Low mass Higgs
  - World's best limits in ZH → llbb, WH → lνbb, VH → MET+bb
    - Additional all-jets and ττ modes improve total sensitivity
  - Combined limit 3.6 * SM expected with 3 fb^{-1}
  - Steady improvements since 2005
    - Near sensitivity for low mass exclusion with full dataset & D0
- High mass Higgs
  - World's best limits in H → WW
  - 1.6 * SM expected with 3 fb^{-1}
  - Goal is single-experiment exclusion for range of masses
- MSSM Higgs
  - Low mass ZH/WH Higgs searches may be best way to find CMSSM
  - SUSY searches for H → bb and H → ττ extend limits on tan β

CDF + D0 Combination

- We use two different methods (done by different people on different experiments) to verify accuracy
  - Method 1 : CLs
  - Method 2 : Bayesian - expected to be more conservative (coverage is greater than 95%)

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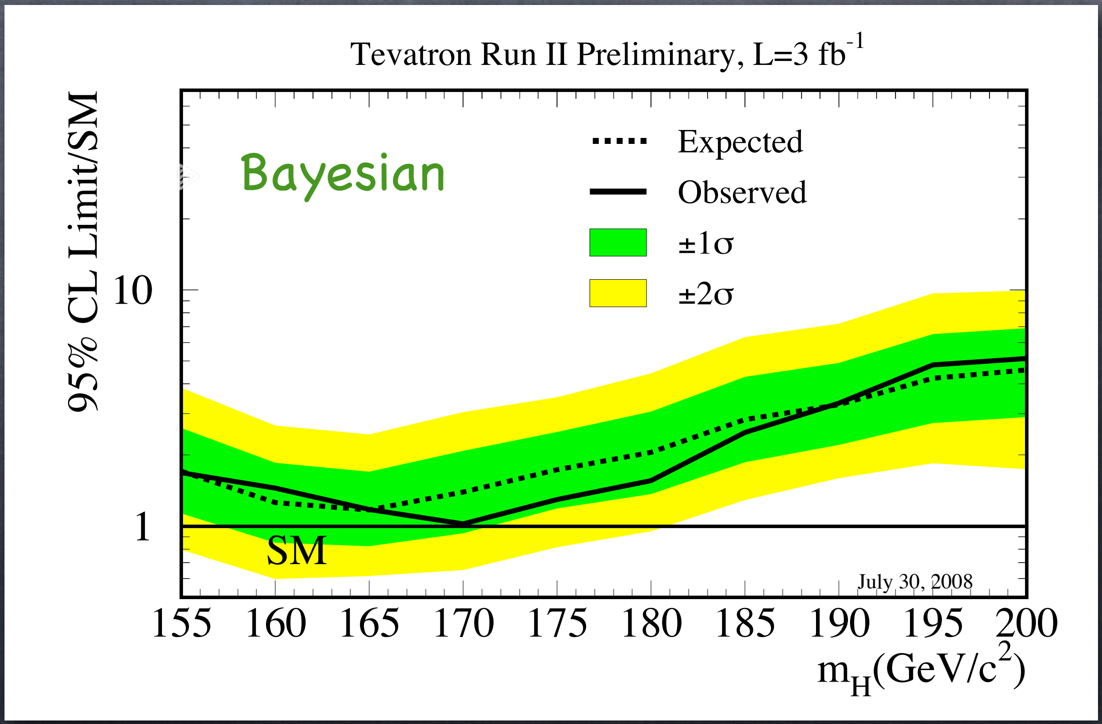
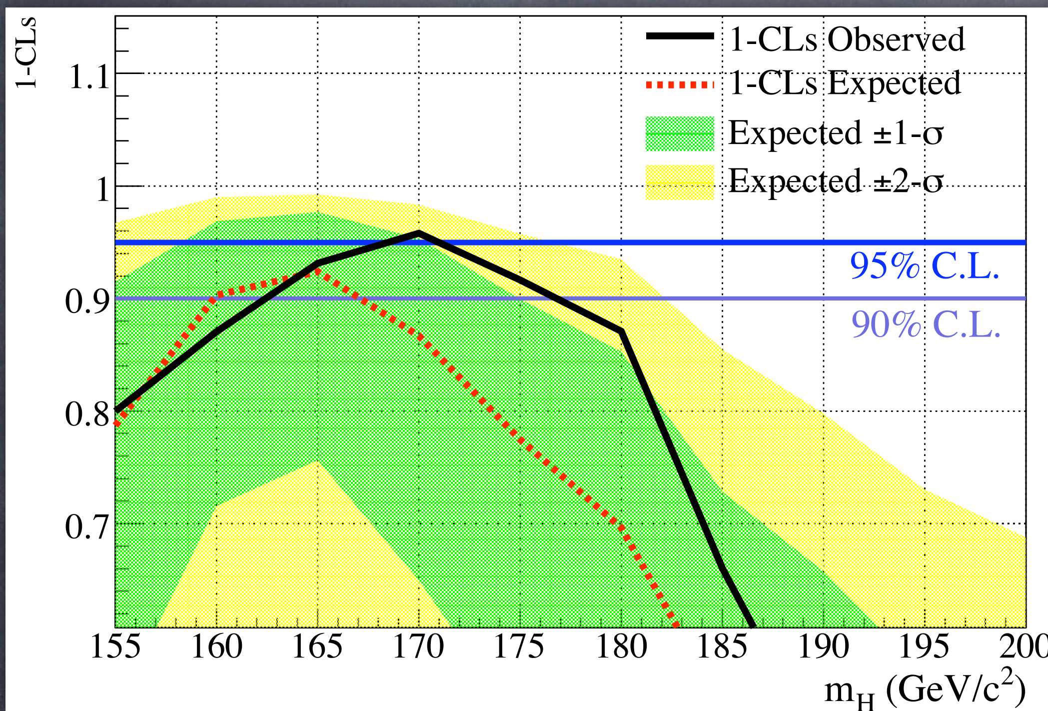


Combination with D0

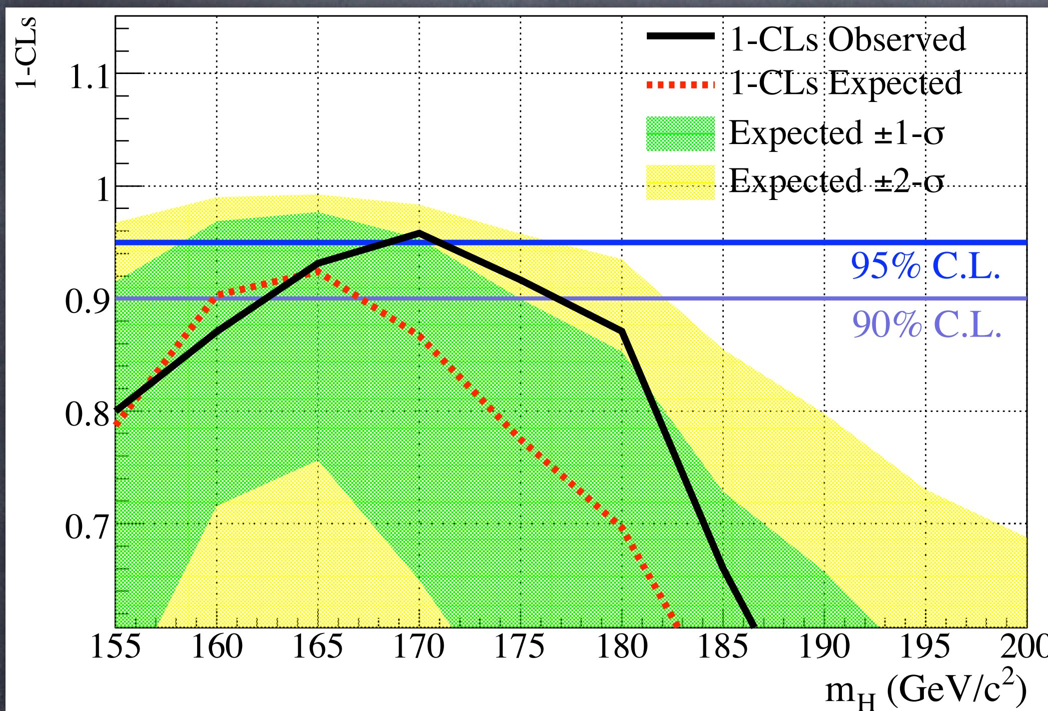
- CLs combination plot



	95%CL Limits/SM			
M Higgs(GeV)	160	165	**170**	175
Method 1: Exp	1.3	1.2	1.4	1.7
Method 1: Obs	1.4	1.2	**1.0**	1.3
Method 2: Exp	1.2	1.1	1.3	1.7
Method 2: Obs	1.3	1.1	**0.95**	1.2

Combination with D0

- CLs combination plot



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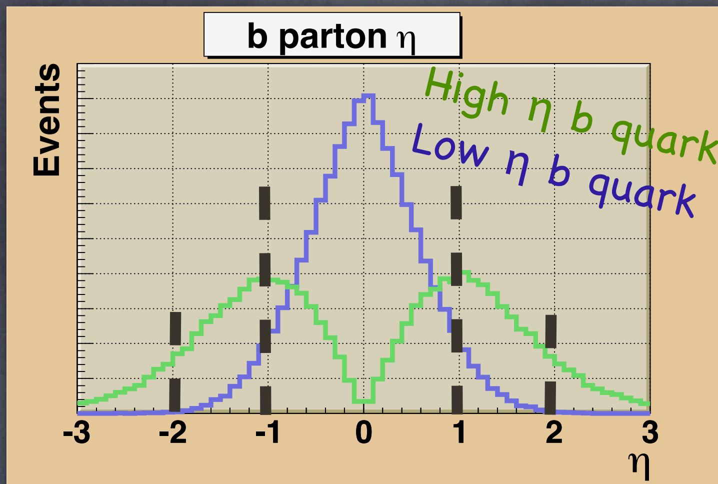
Results are consistent :
m_H at 170 GeV ruled out at 95% CL

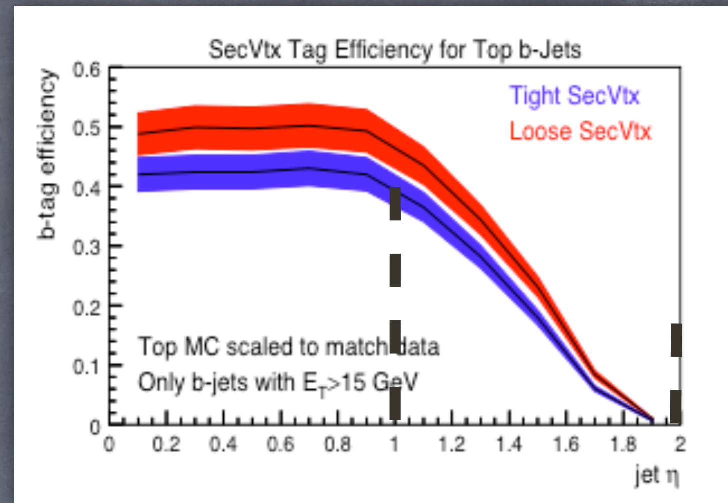
CDF + D0 Conclusions

- Searching for every available Higgs boson
  - Using up to 3 fb^{-1} of data per experiment
    - Current full dataset is ~4 fb^{-1}
    - Expect 6 - 8 fb^{-1} total per experiment
- MSSM Higgs
  - Low mass ZH/WH Higgs searches may be best way to find CMSSM
  - SUSY searches for $H \to bb$ and $H \to \tau\tau$ extend limits on $\tan\beta$
- Low mass Higgs
  - Steady improvements since 2005
    - Near sensitivity for low mass exclusion with full dataset & D0
- High mass Higgs
  - Excluded m_H at 170 GeV !!
  - Goal is combined exclusion for wide range of high mass Higgs

Backups

B-tagging jets in WH → lνbb





Algorithms :

- SVX Tag "ST"
- Loose SVX Tag
- Jet probability Tag "JP"
- NN flavor separator

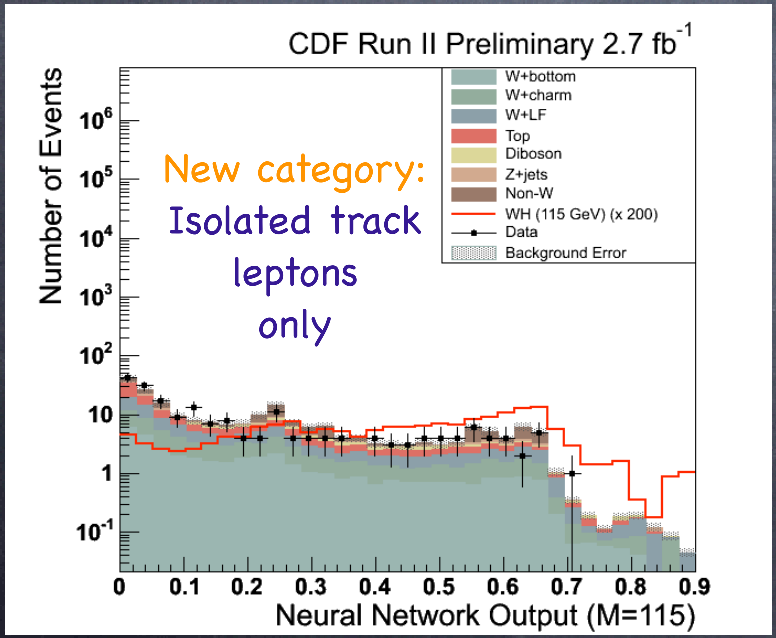
Divide into subsets and win

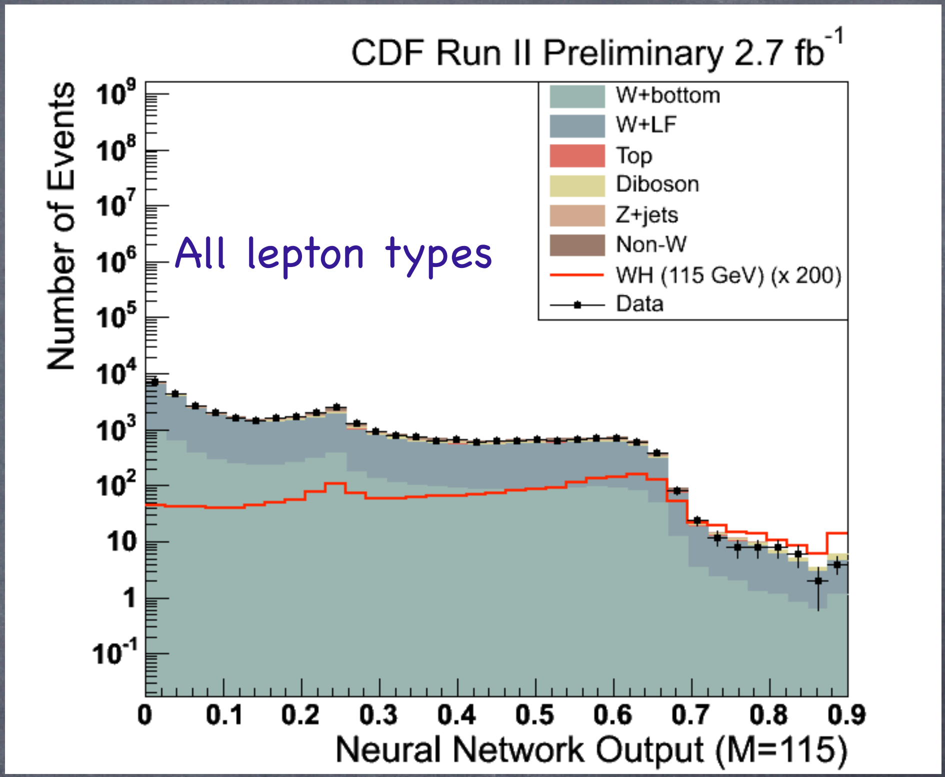
(WH expectations shown here)

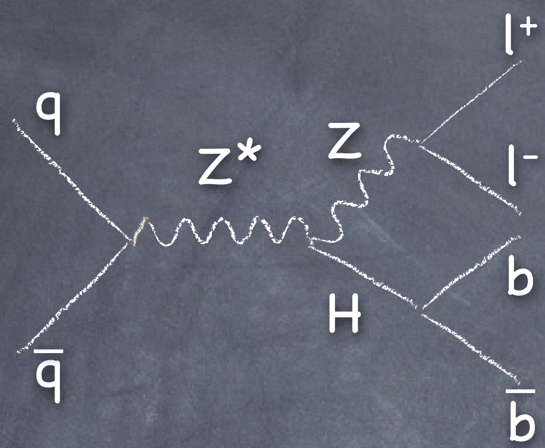
B-tags	S	B	S/sqrt(B)
2 ST	1.6	150	0.13
ST+JP	1.1	160	0.09
1 ST	3.6	1750	0.09
sum in quadrature of S/sqrt(B) good figure of merit for sensitivity			0.14 → 0.18

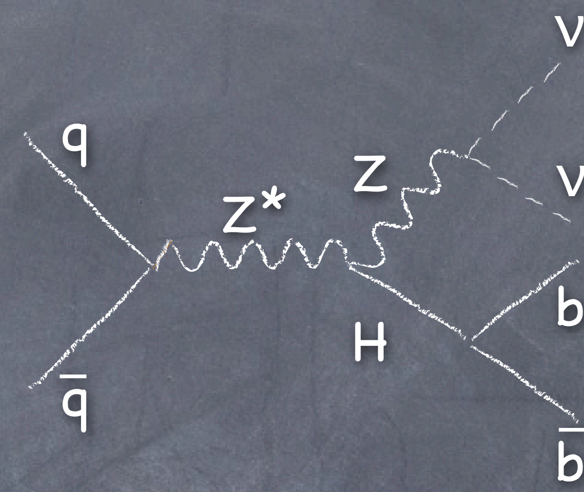
WH → lvbb backup

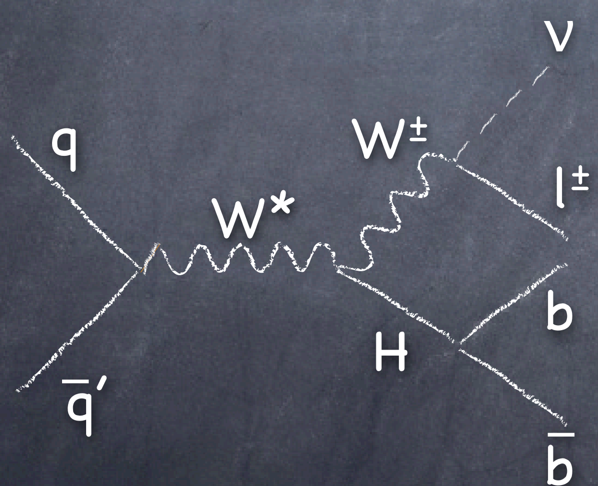
- Test of NN in WH analysis
  - Control region with same kinematic selection
  - Using high statistics pretagged events

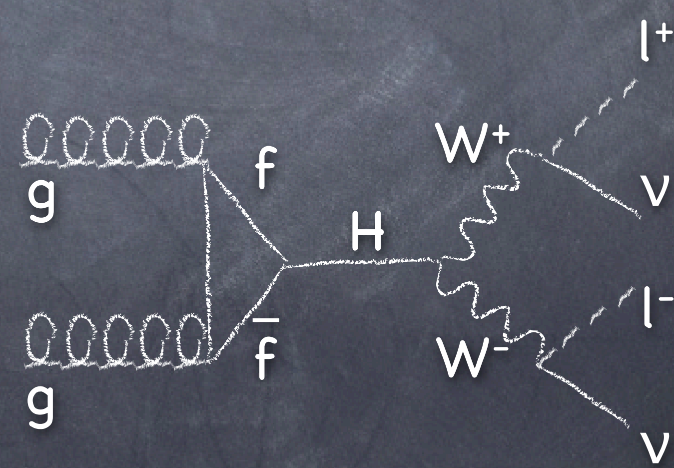





q
q̄
Z*
Z
H
l+
l-
b
b̄


q
q̄
Z*
Z
H
ν
ν
b
b̄


q
q̄'
W*
W±
H
ν
l±
b
b̄


g
g
f
f̄
H
W+
W-
l+
ν
l-
ν