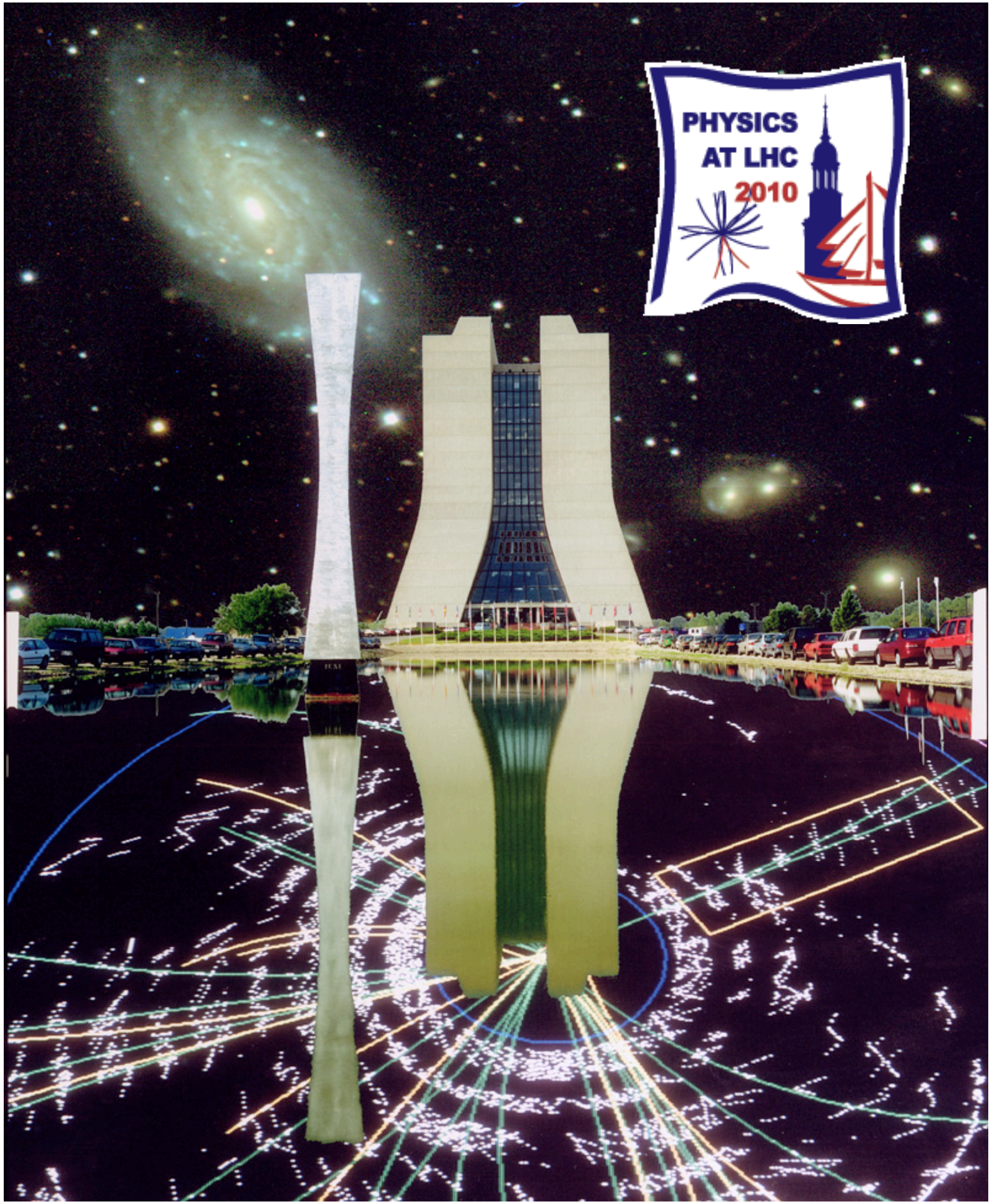


Tevatron: The Reach for the Higgs

- G. Watts (U. Washington/Seattle)
- For the CDF and D0 Collaborations

Physics at the LHC
June 8, 2010

F. Englert and R. Brout. Phys Rev. Lett. 13: 321-323(1964);
P.W. Higgs, Phys. Rev. Lett 13: 508-509 (1964);
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13: 585-587 (1964)

The Standard Model

The fundamental particles and their interactions

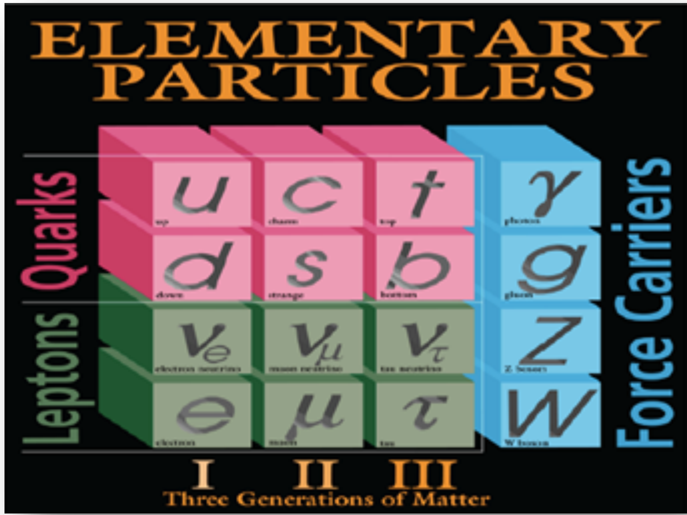
Does not predict proper masses for the bosons or fermions

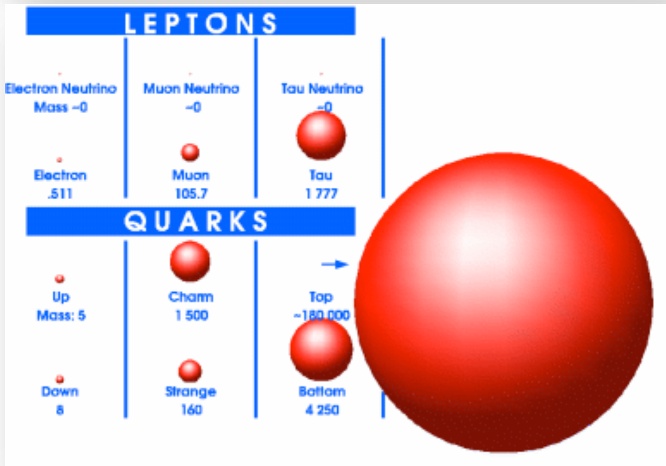
The BEGHHK mechanism is a possible solution

- Bosons $W^{\pm}$ and Z acquire mass
- The *photon* remains massless
- Fermion masses can be generated

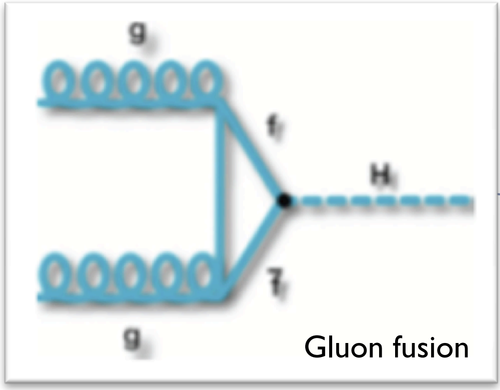
Predicts the existence of the Higgs boson → Mass is not specified

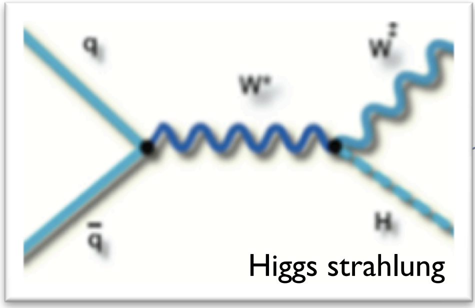
→ Not Yet Observed

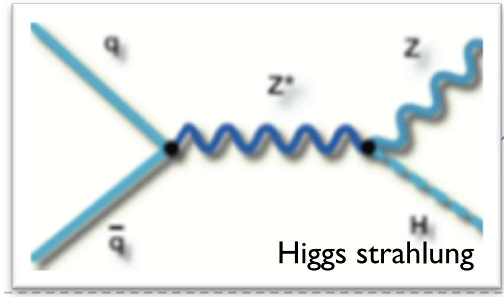


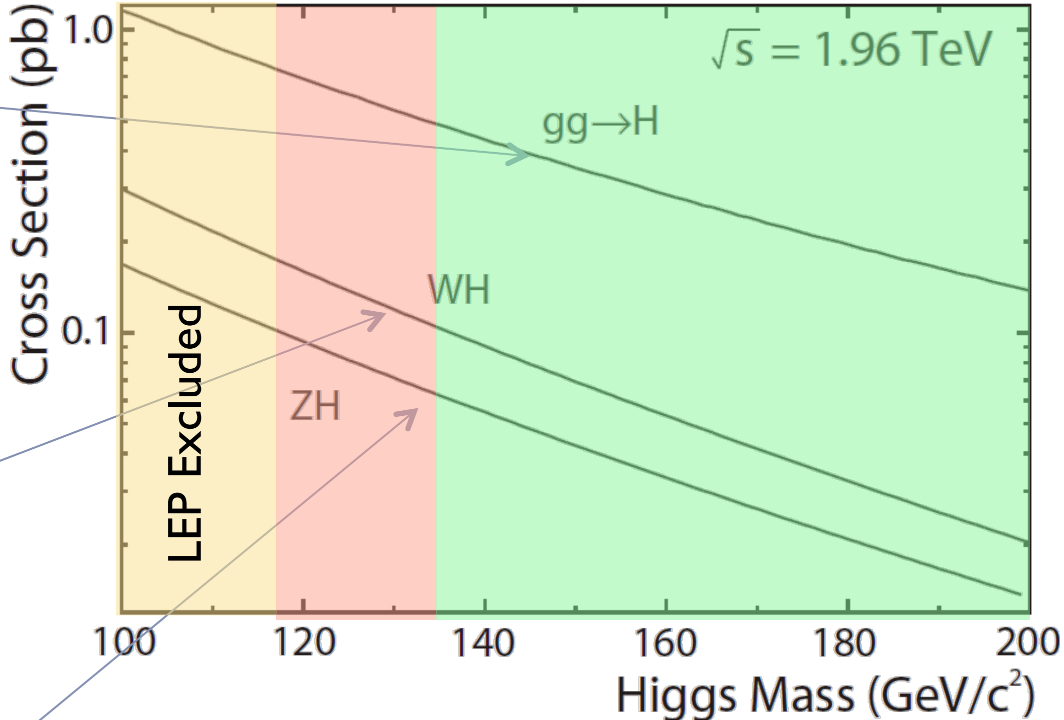


Higgs Production









For $100\ GeV < m_H < 200\ GeV$:

$$\sigma(gg \to H) \approx 2 - 0.2\ pb$$

$$\sigma(q\bar{q} \to HW) \approx 0.3 - 0.02\ pb$$

Higgs Decay

$H \rightarrow b\bar{b}$

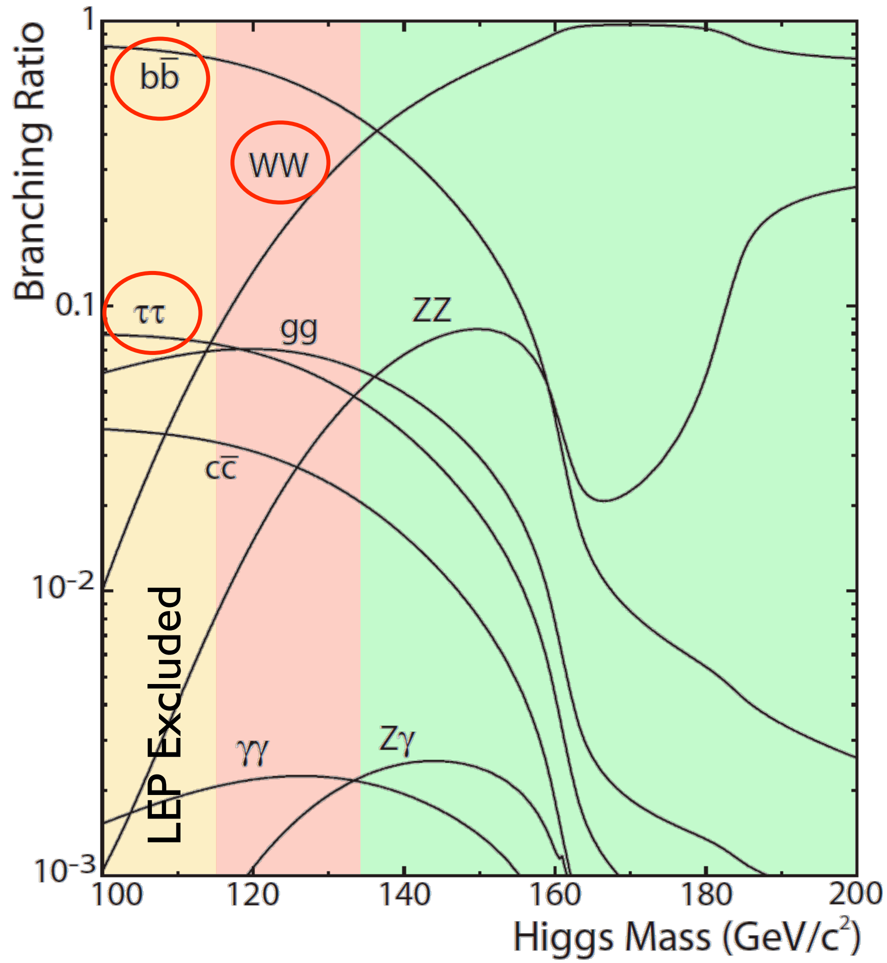
Mass Region: $m_H \lesssim 135\ GeV$
$b\bar{b}$ production overwhelms H production ($\tau\tau$ too).

Look for associated production

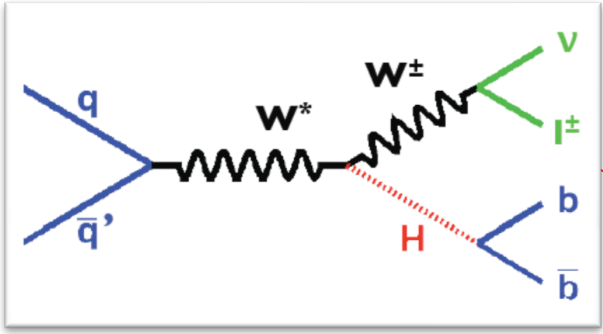
$H \rightarrow W^+W^-$

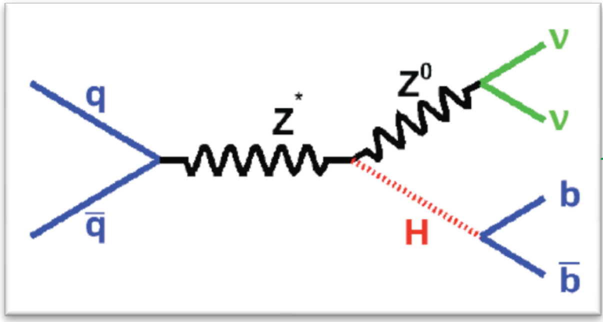
Mass Region: $m_H \gtrsim 135\ GeV$
W^+W^-, ZZ have small SM backgrounds

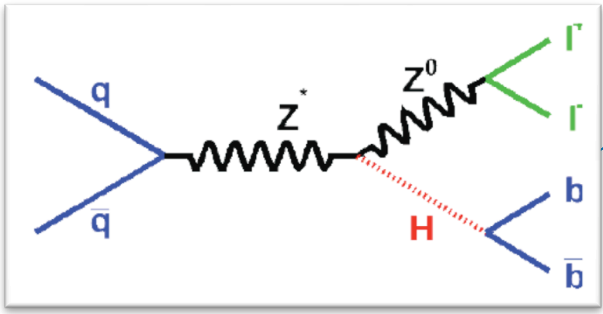
Look for gluon-gluon fusion

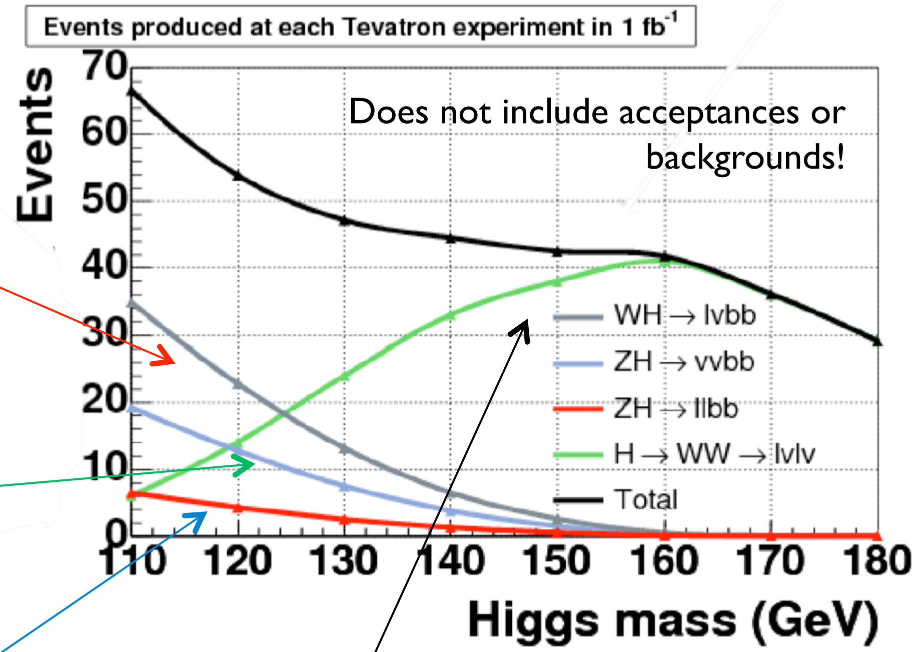


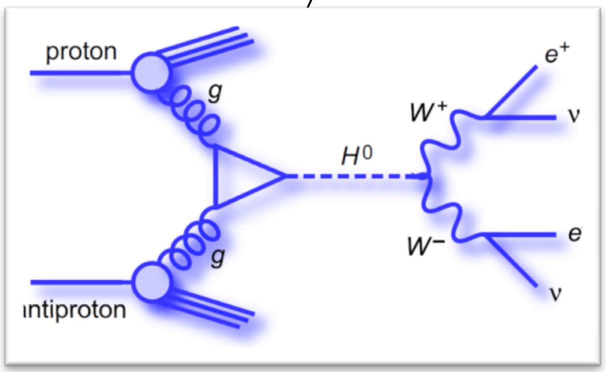
Tevatron Search Strategy





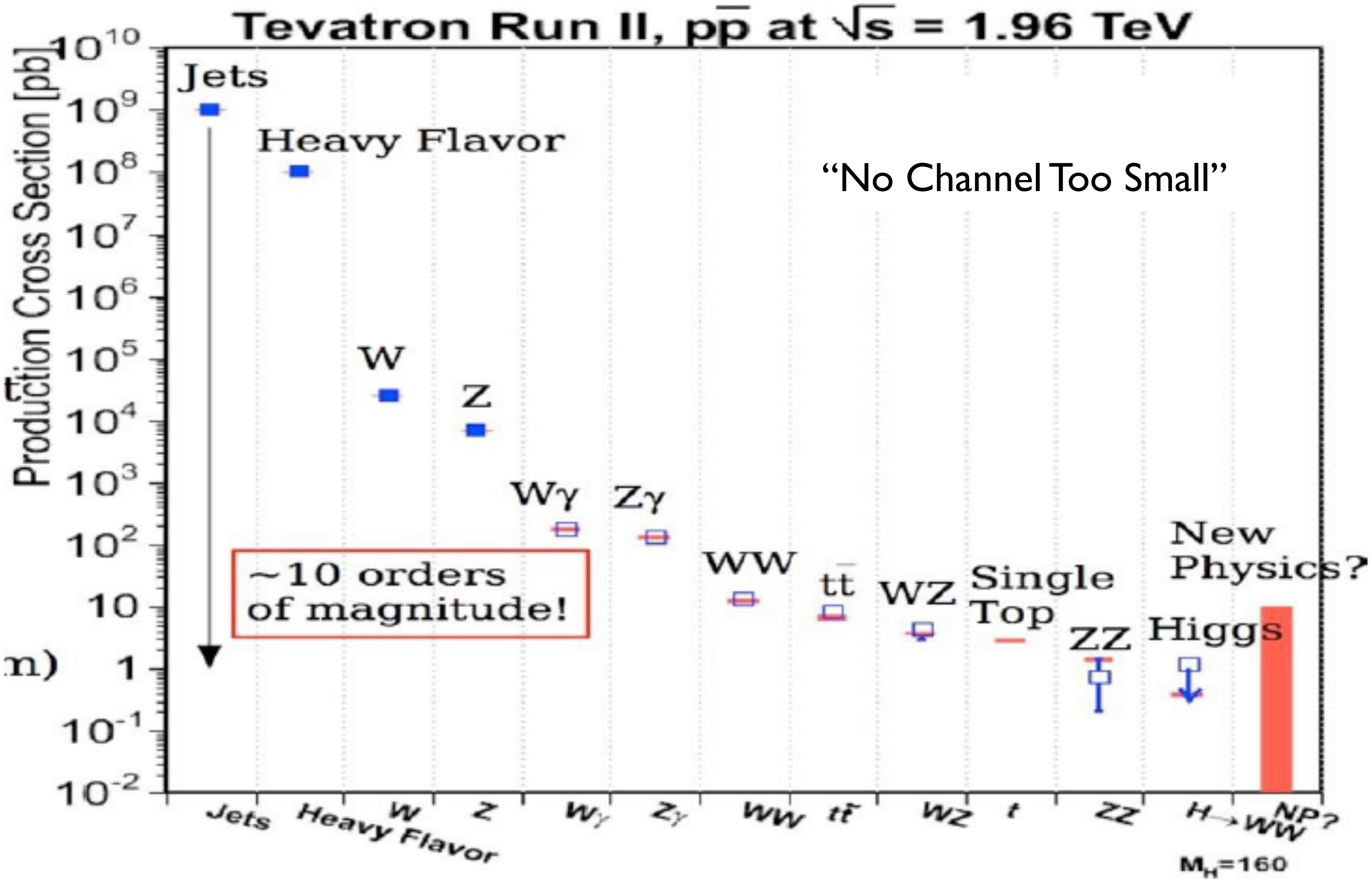






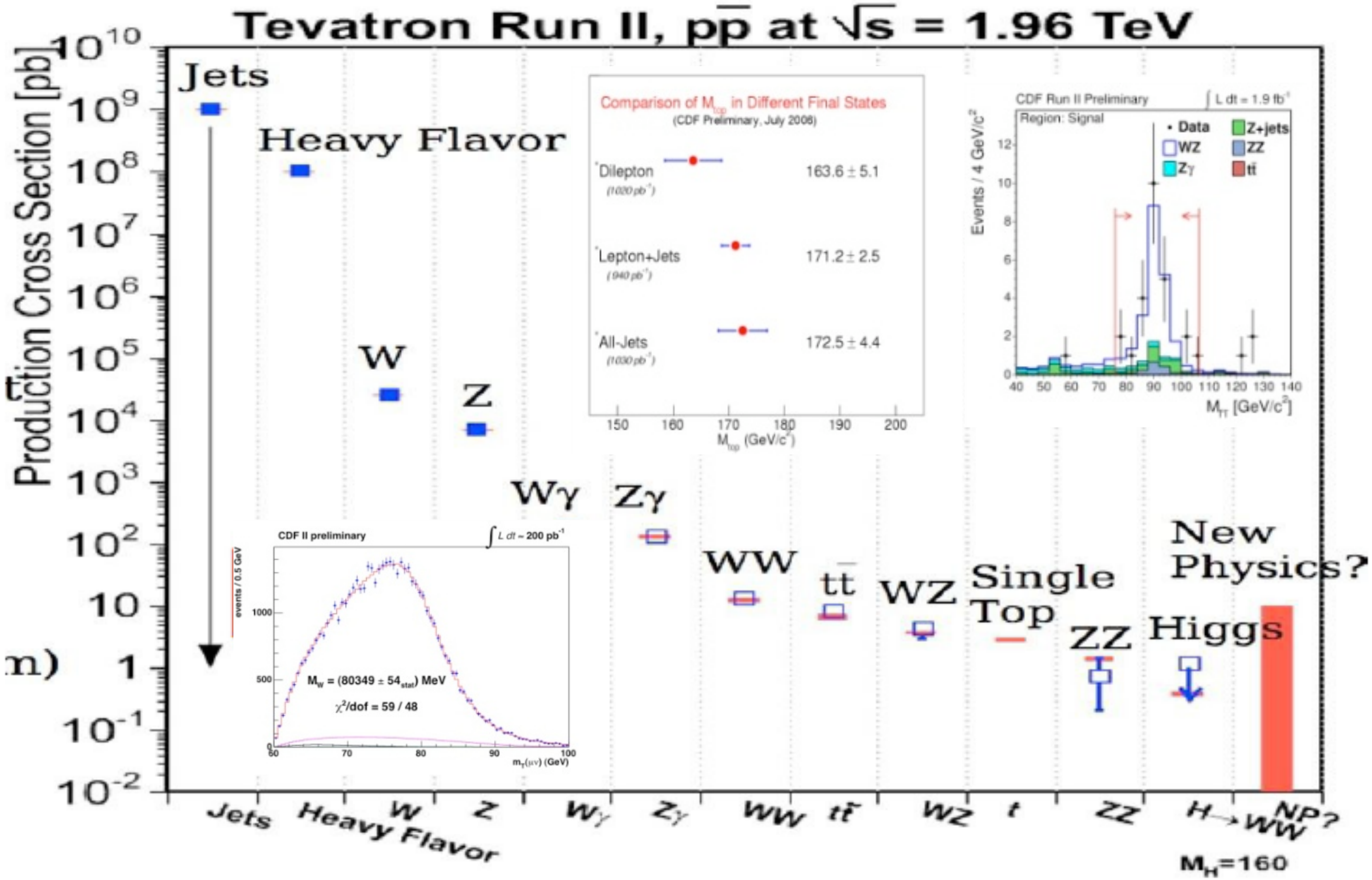
"No Channel Too Small"

Standard Model Backgrounds



“No Channel Too Small”

Standard Model Backgrounds



Past few decades

Thanks R. Heuer

"Discovery" of Standard Model

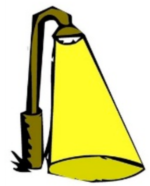
through synergy of

hadron - hadron colliders (e.g. Tevatron)

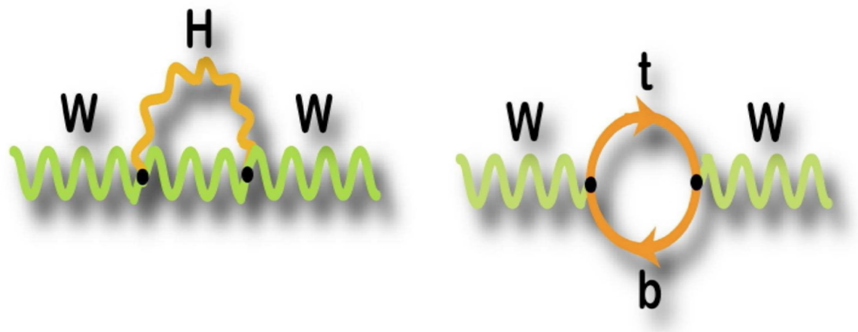
lepton - hadron colliders (HERA)

lepton - lepton colliders (e.g. LEP, SLC)

The Lamppost



Radiative Corrections point to the most likely place to search for a SM Higgs.

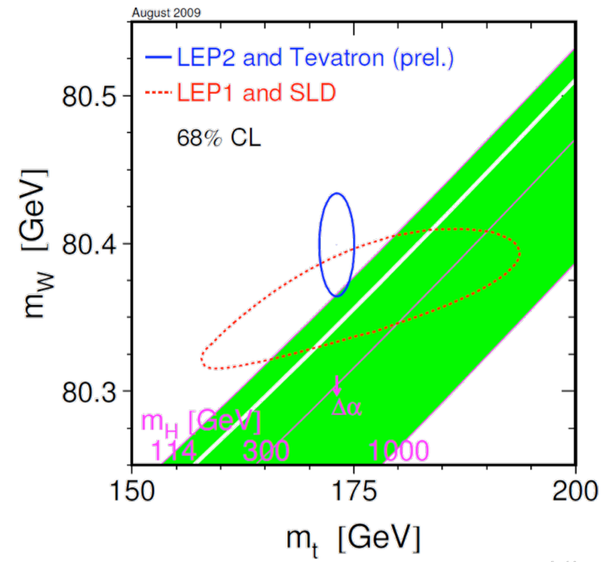


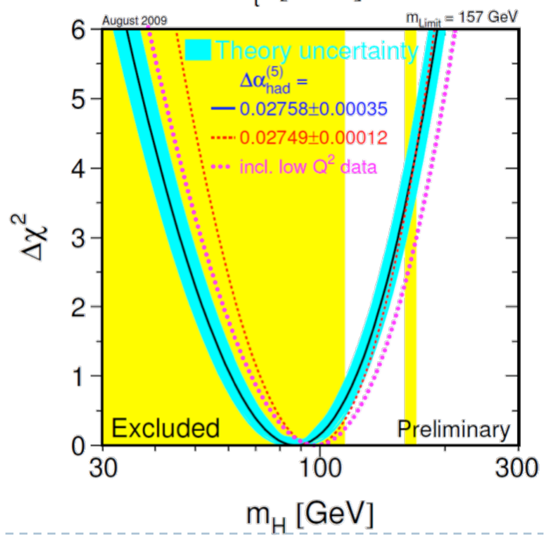
Most Likely Value $m_H = 87\ GeV$

95% C.L. $m_H < 186\ GeV$

Lower mass bound from direct searches at LEP: 114.4 GeV @ 95%CL

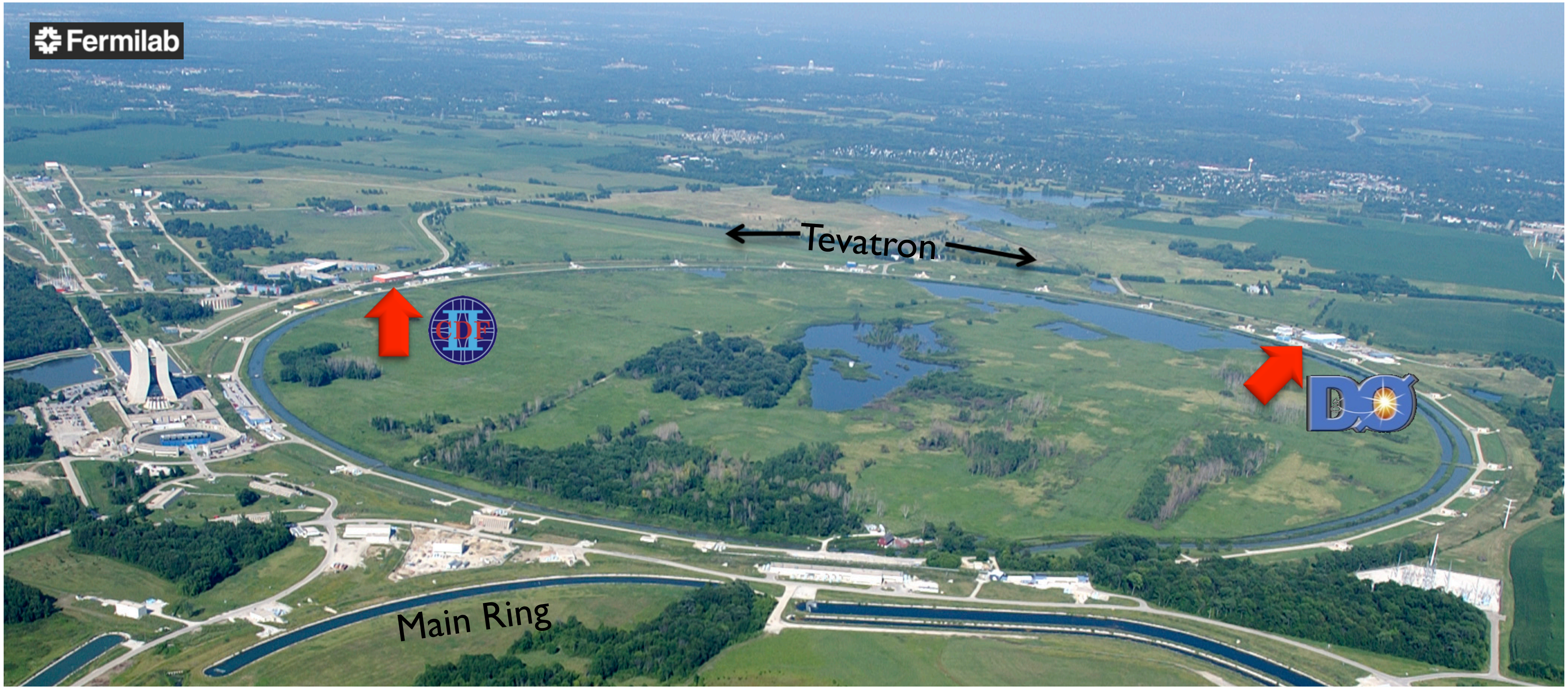
ℵ Search for neutral Higgs bosons decaying into four τ's at LEP2 (arXiv:1003.0705) (BSM Search)





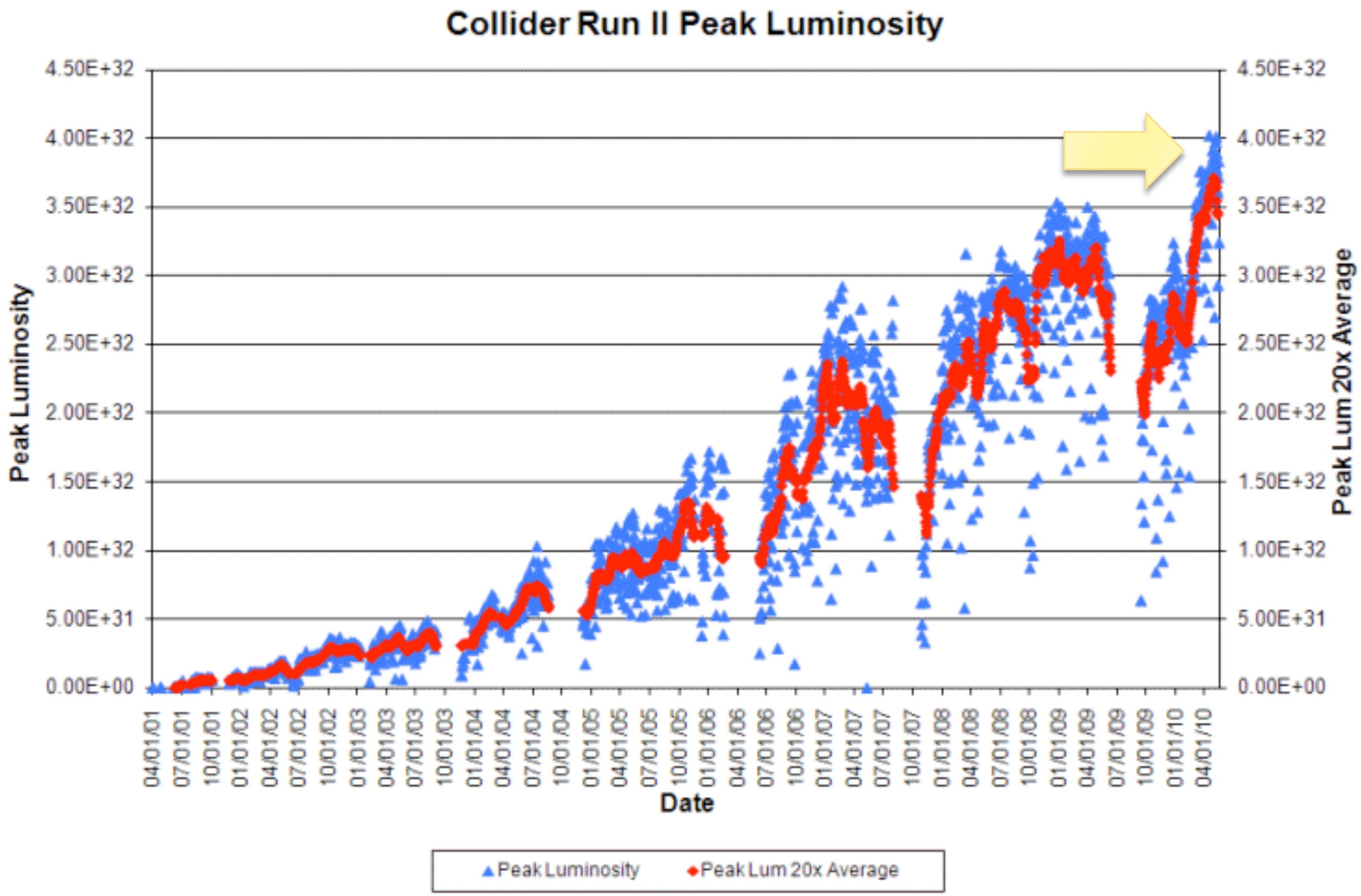
The Tevatron

The Tevatron

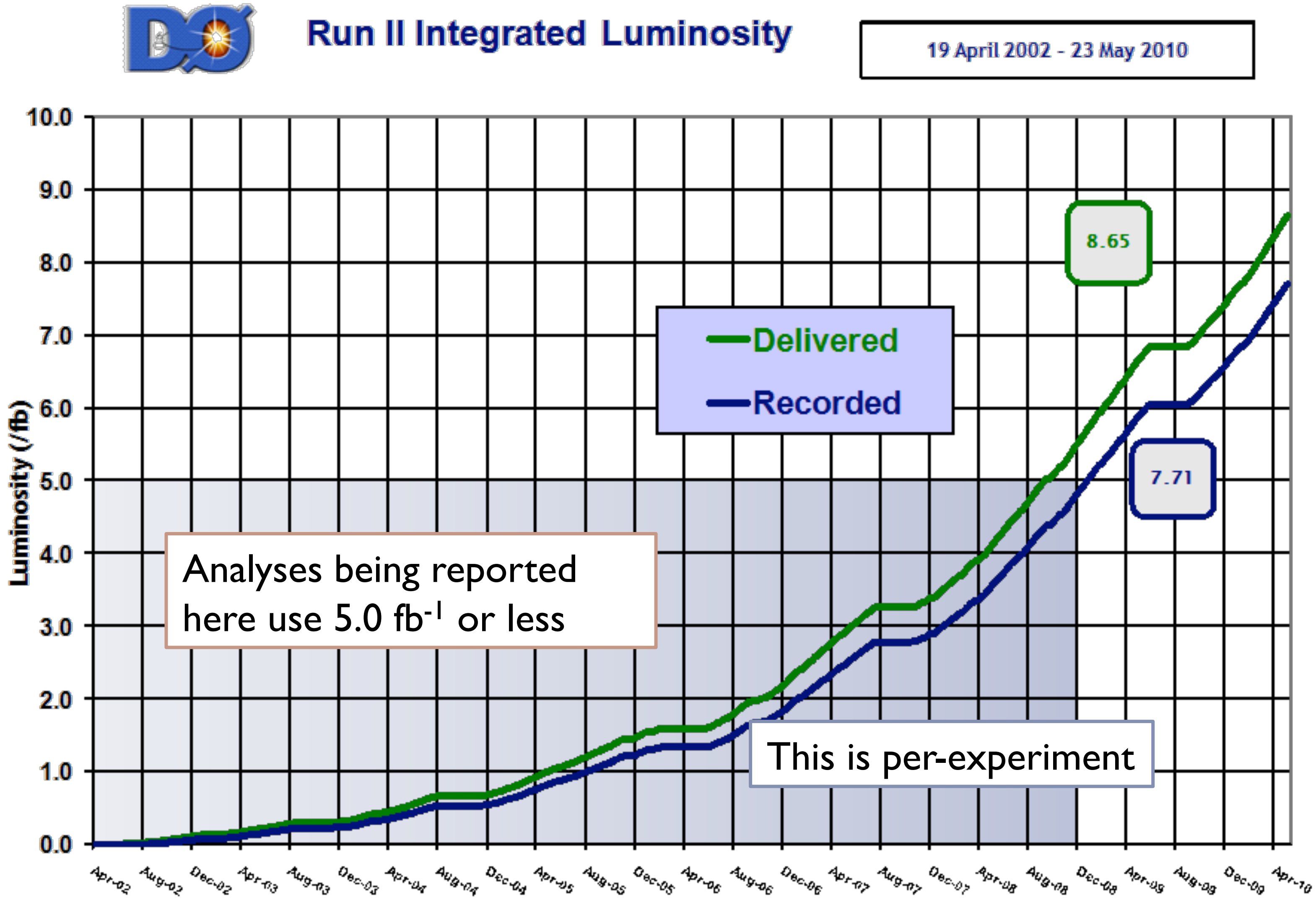


$p\bar{p}$ collider
Radius (~1 km)
$\sqrt{s}$ = 1.96 TeV
Run II Started March 2002

Tevatron Performance



DØ Data Taking

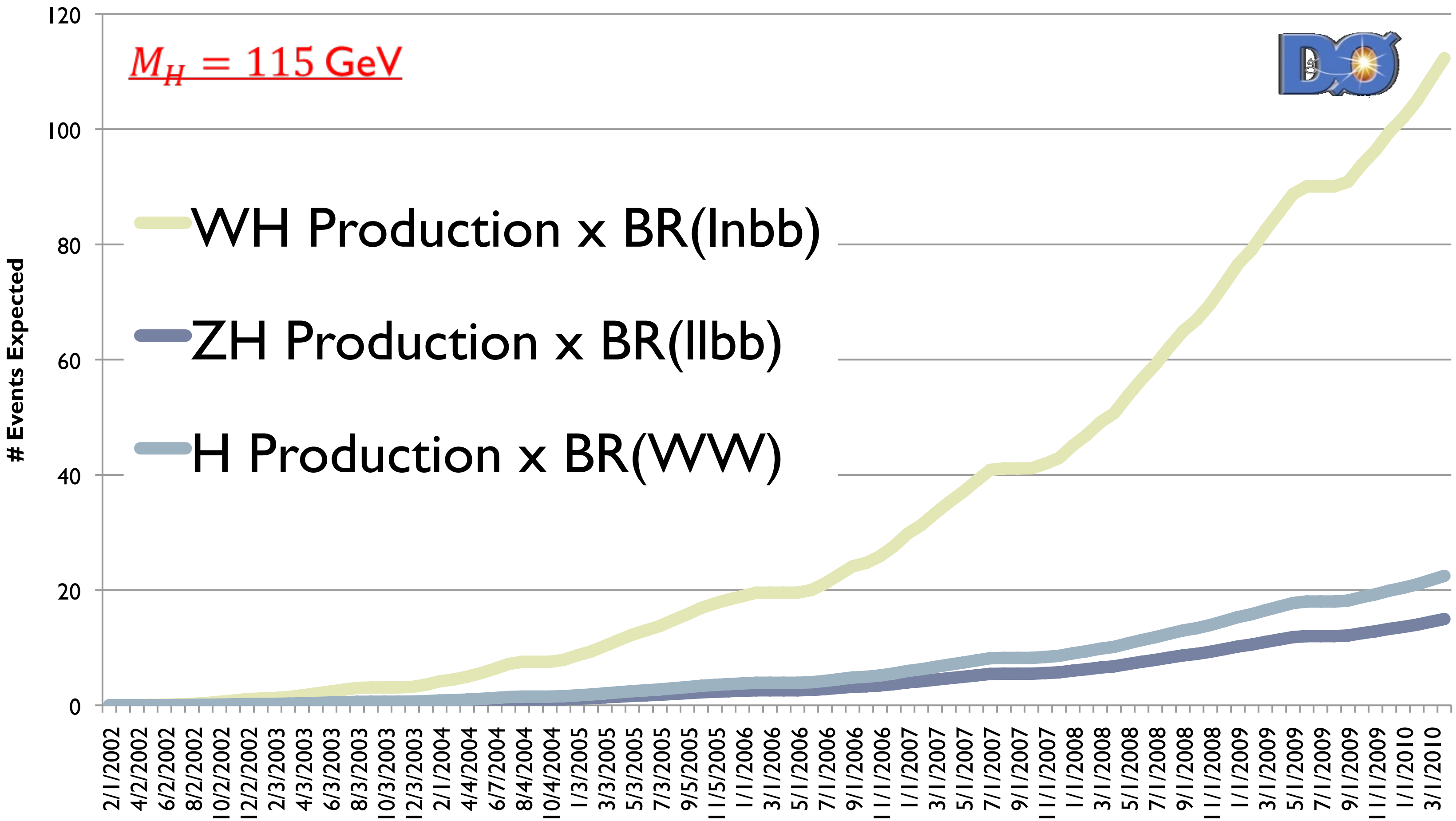


Analyses being reported here use 5.0 fb^{-1} or less

This is per-experiment

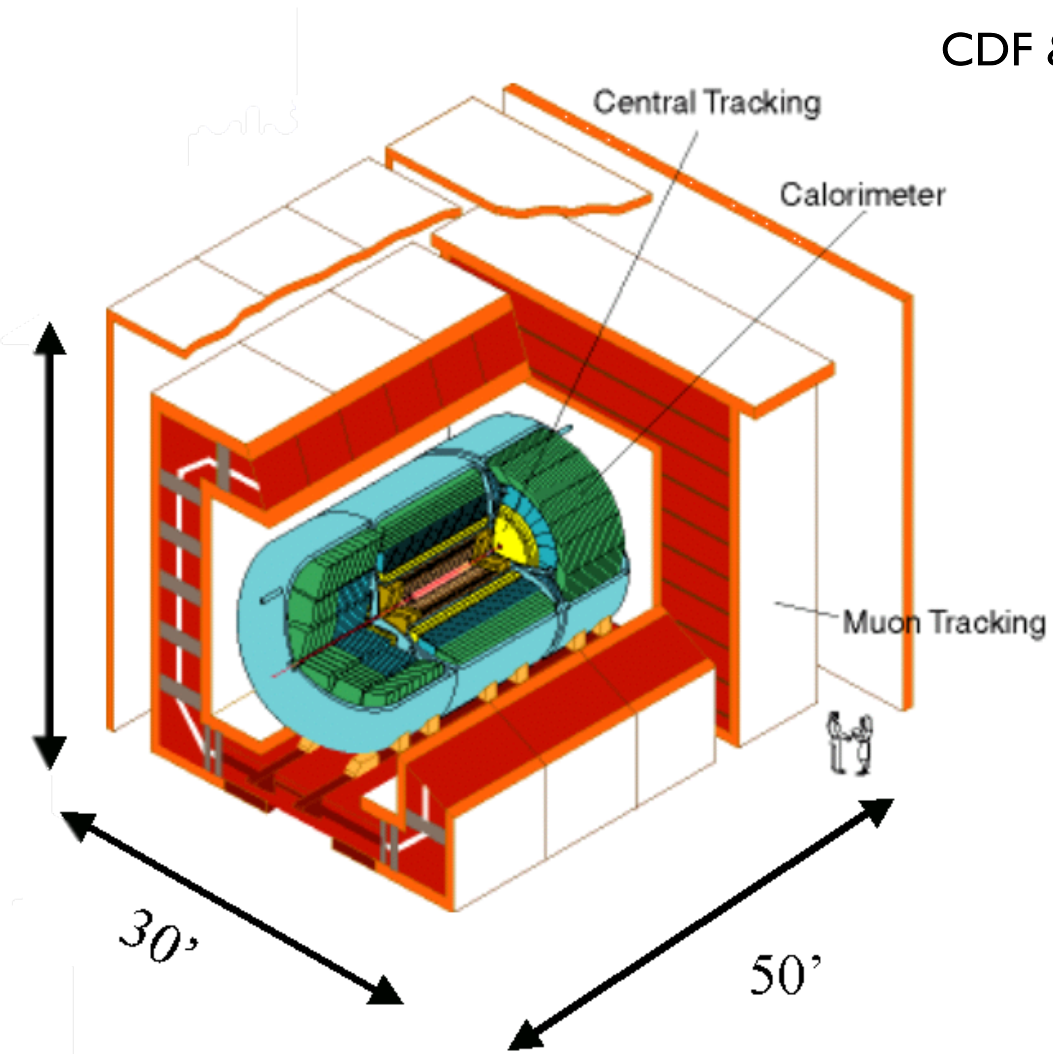
Is almost identical

Number of Higgs Recorded



Recorded Luminosity, for just DØ…

The Experiments

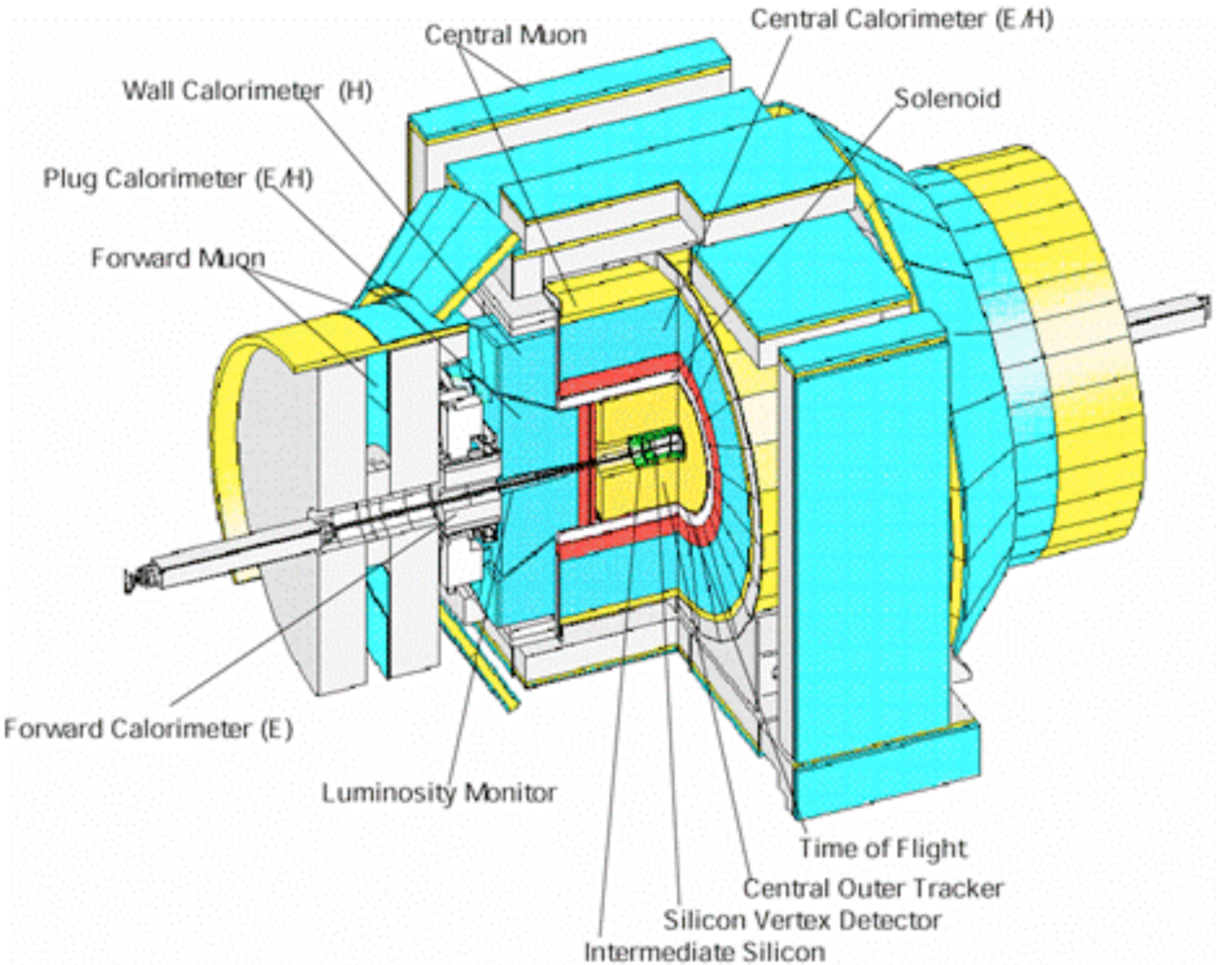


CDF & DØ are Multi-Purpose Detectors

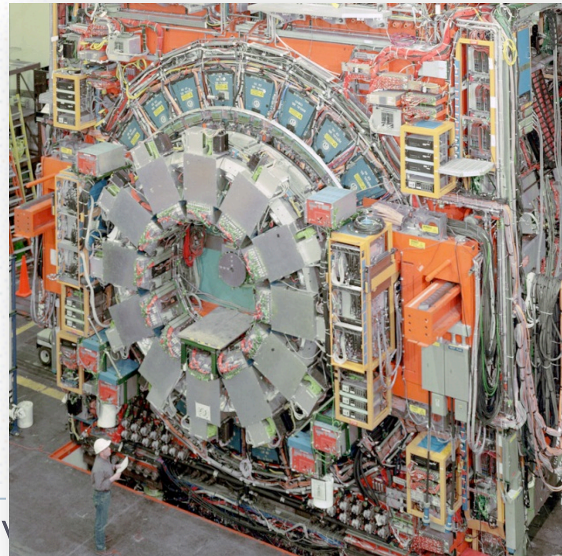
- Precision Tracking necessary for b-quark jet identification (Silicon Strips)
- Larger Volume Tracking
  - Drift Chamber in CDF
  - Fiber Straw Tracker in DØ
- Nearly 4π coverage for muon and calorimeter detectors

The Experiments

Sophisticated Trigger And Reconstruction Software



- Trigger on Significant Missing Energy, high E_T jets, and isolated high p_T particles ($e^{\pm}$,$\mu^{\pm}$).
- Excellent τ reconstruction, precision jet resolution, etc.
- DAQ Efficiency > 90%

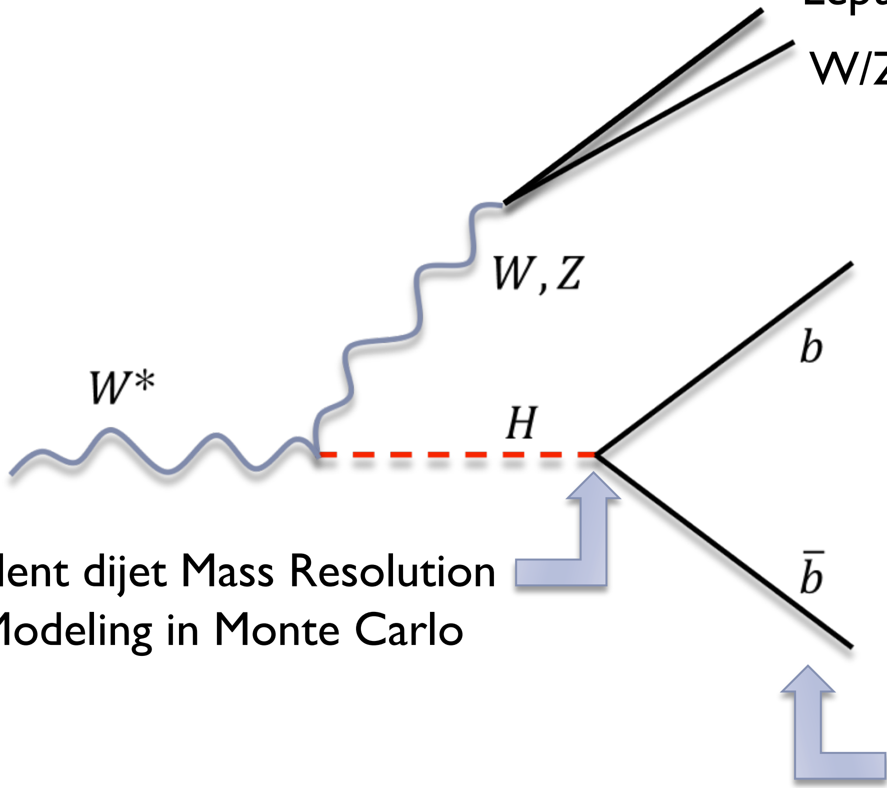


Stable: No Further Upgrades Planned!

The Low Mass Higgs Search

Low Mass Higgs Searches

Trigger: High p_T isolated leptons, or larger missing E_T.



Excellent dijet Mass Resolution and Modeling in Monte Carlo

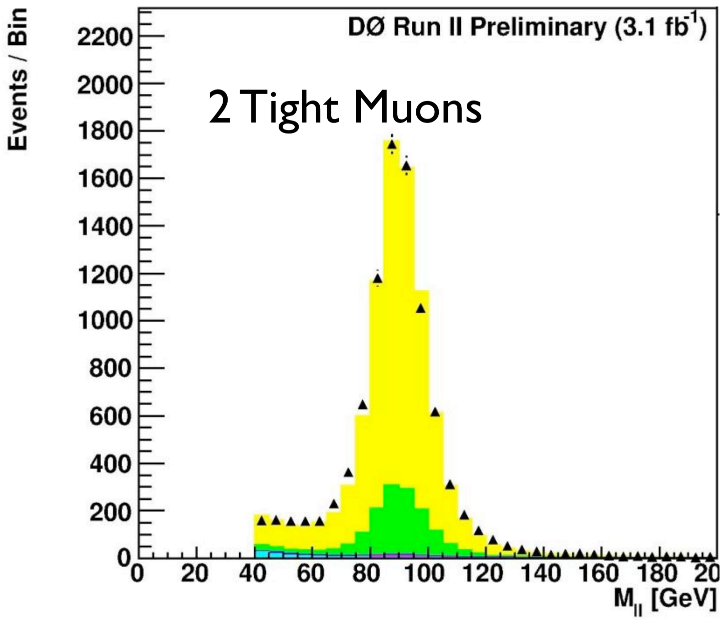
b-quark Jet Identification

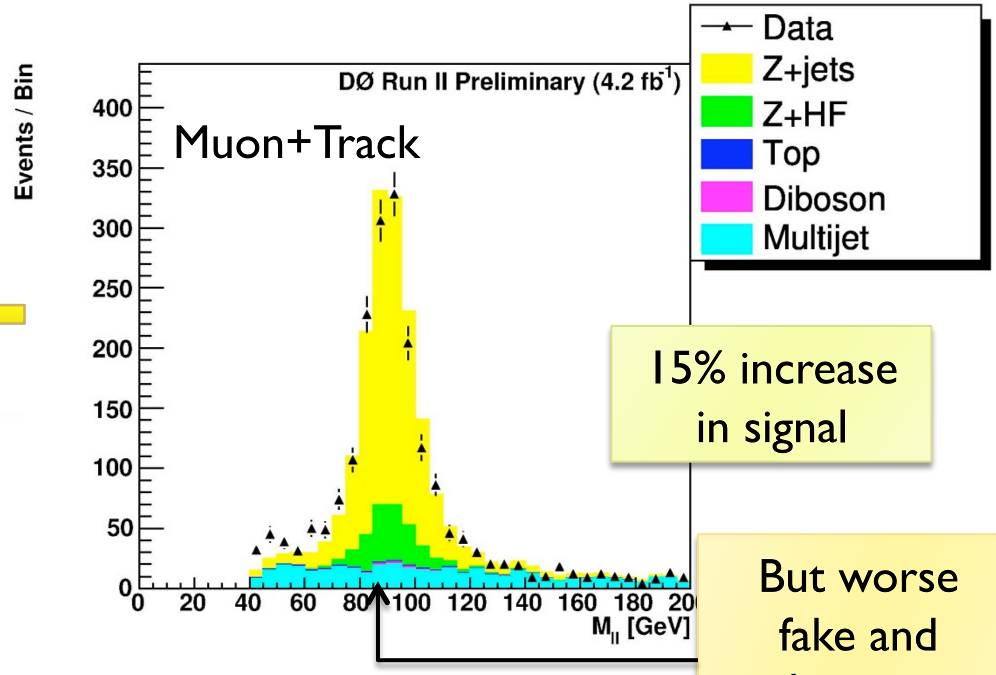
Multivariate techniques to combine everything (Neural Networks, Decision Trees, and Matrix Elements)

Acceptance Increases

$WH \to \ell \upsilon b\bar{b}, ZH \to \upsilon\upsilon b\bar{b}, ZH \to \ell\ell b\bar{b}$ are all mature analyses

- Open the Lepton ID





15% increase in signal

But worse fake and detector background

Don't pollute your good S:N *bins* with poor S:N areas of phase space: let final limit calculation combine appropriately.

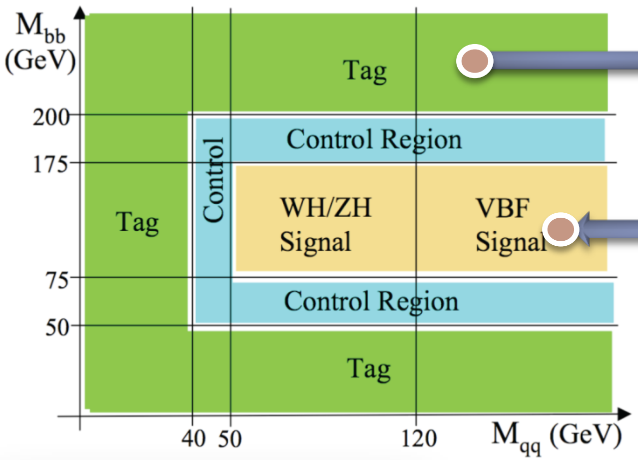
Also exploit new regions of detector and add additional triggers

Acceptance Increases

No Channel Left Behind

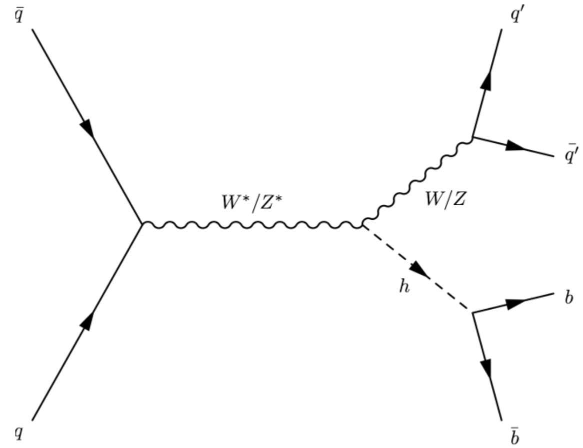
All-Hadronic Channel – VH and VBF production modes

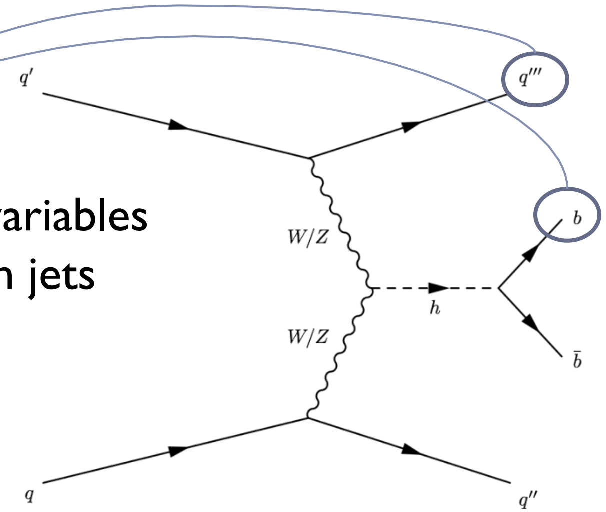
Main Background: QCD (98%)



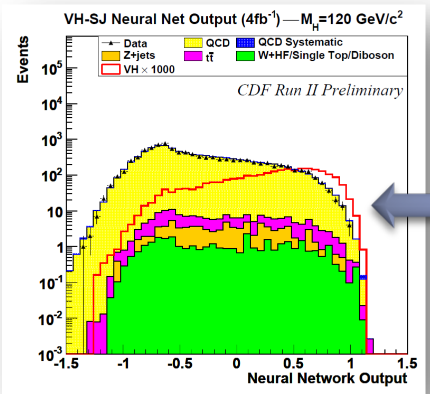
Tag Rate Function Derived on Data

Predicts QCD background in Signal Region





Further use of Jet Shape variables to separate quark/gluon jets

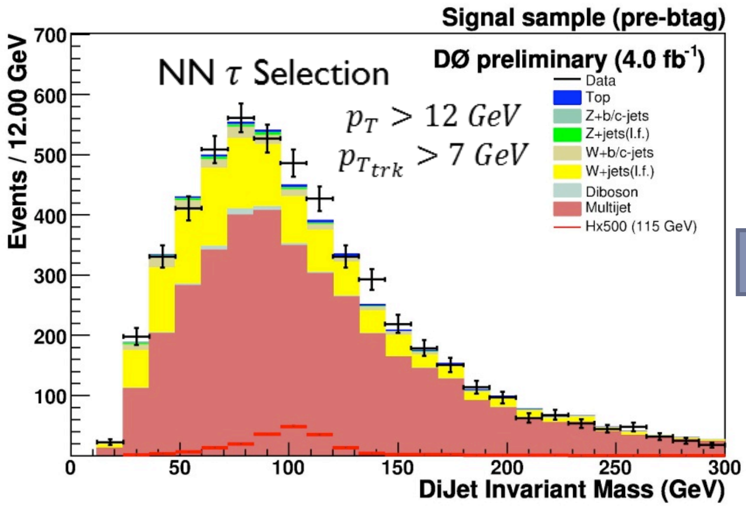


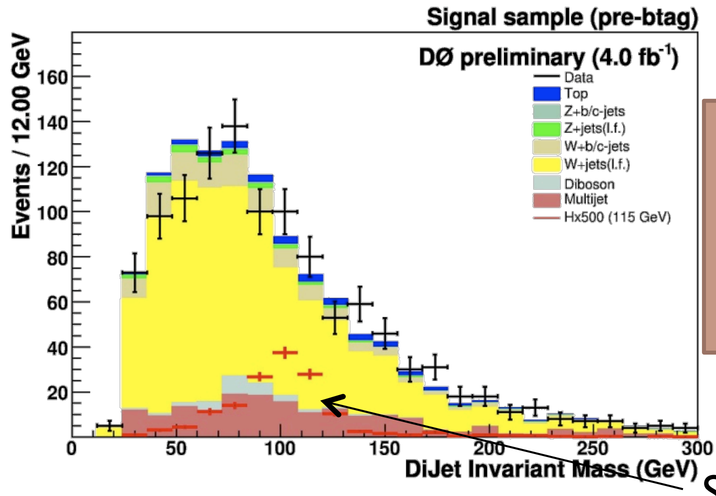
NN (m_{bb}, m_{qq}, jet shapes, etc.)

Acceptance Increases

τ Final States

$\underline{WH \to \tau \nu b\bar{b}}$ Use a neural network to select hadronic tau decays



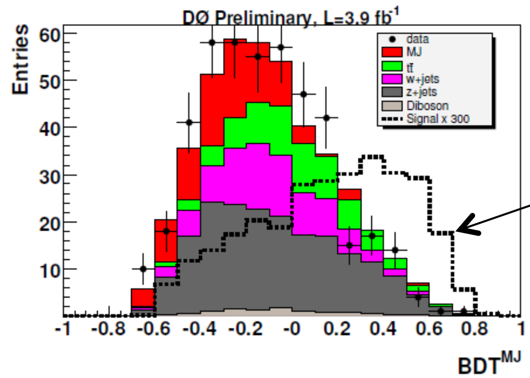


After tagging, dijet mass spectra and other variables are fed to a final NN

Signalx500

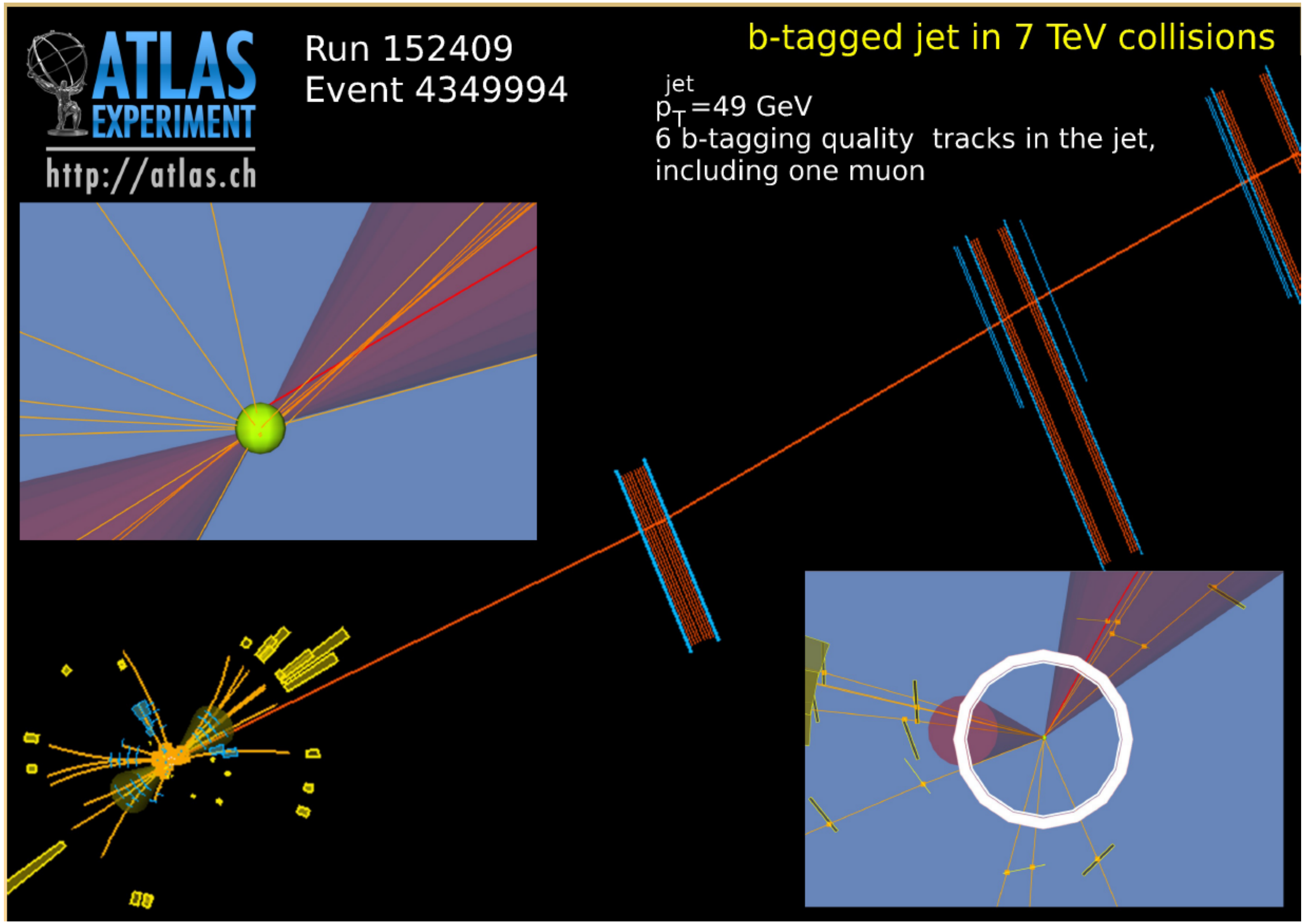
$\underline{ZH \to \tau^+\tau^-\bar{q}q, \mathrm{WH} \to \tau^+\tau^-q\bar{q}'}$ (includes VBF $q\bar{q} \to Hq\bar{q}$)

- Boosted Decision Trees are trained against $t\bar{t}$, W+jets, and multi jet background
- Master BDT to combine them



Signalx300

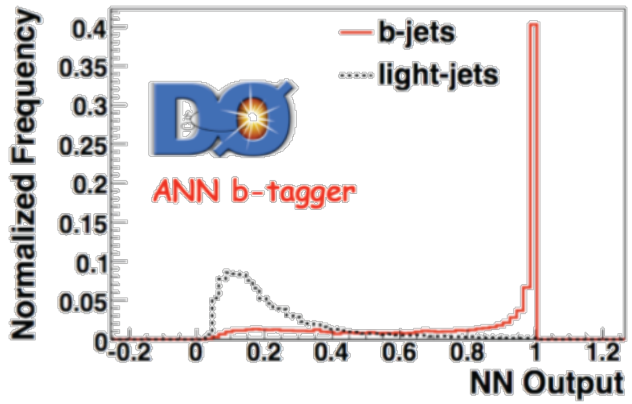
b-Jet Tagging



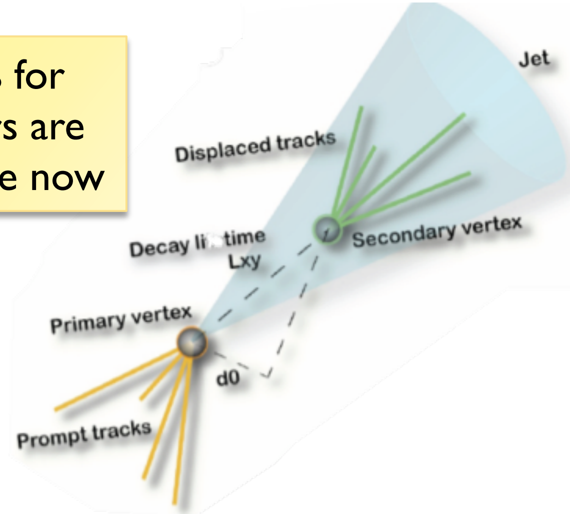
b-Jet Tagging

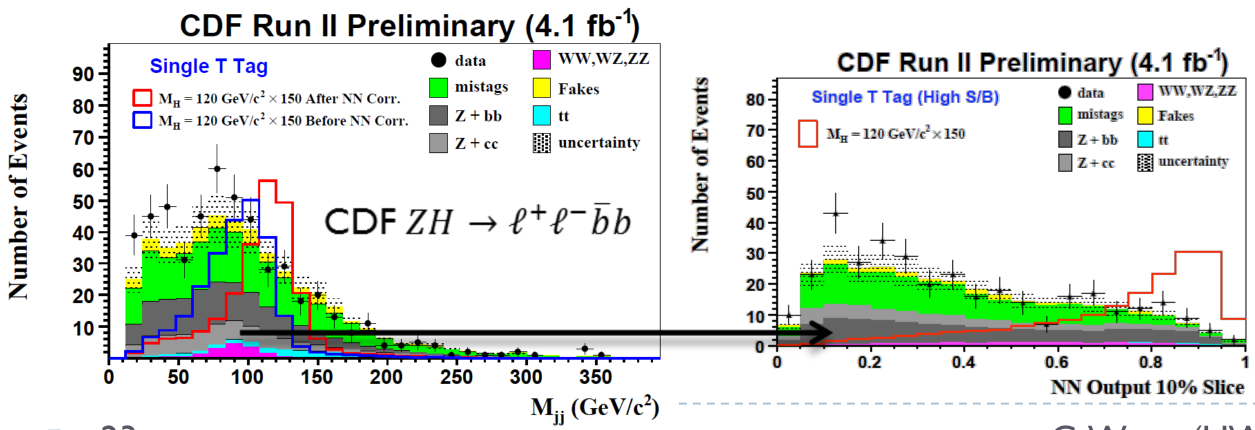
Precision Silicon Detectors can measure the weak lifetime of a B meson decay from the $H \to b\bar{b}$ decays

Efficiency is 50-60% for 1% fake rate, taggers are typically multivariate now



Due to calibration issues most analyses use a hard cut on a discriminating variable (NN output, $L_{xy}/\sigma_{L_{xy}}$, etc)



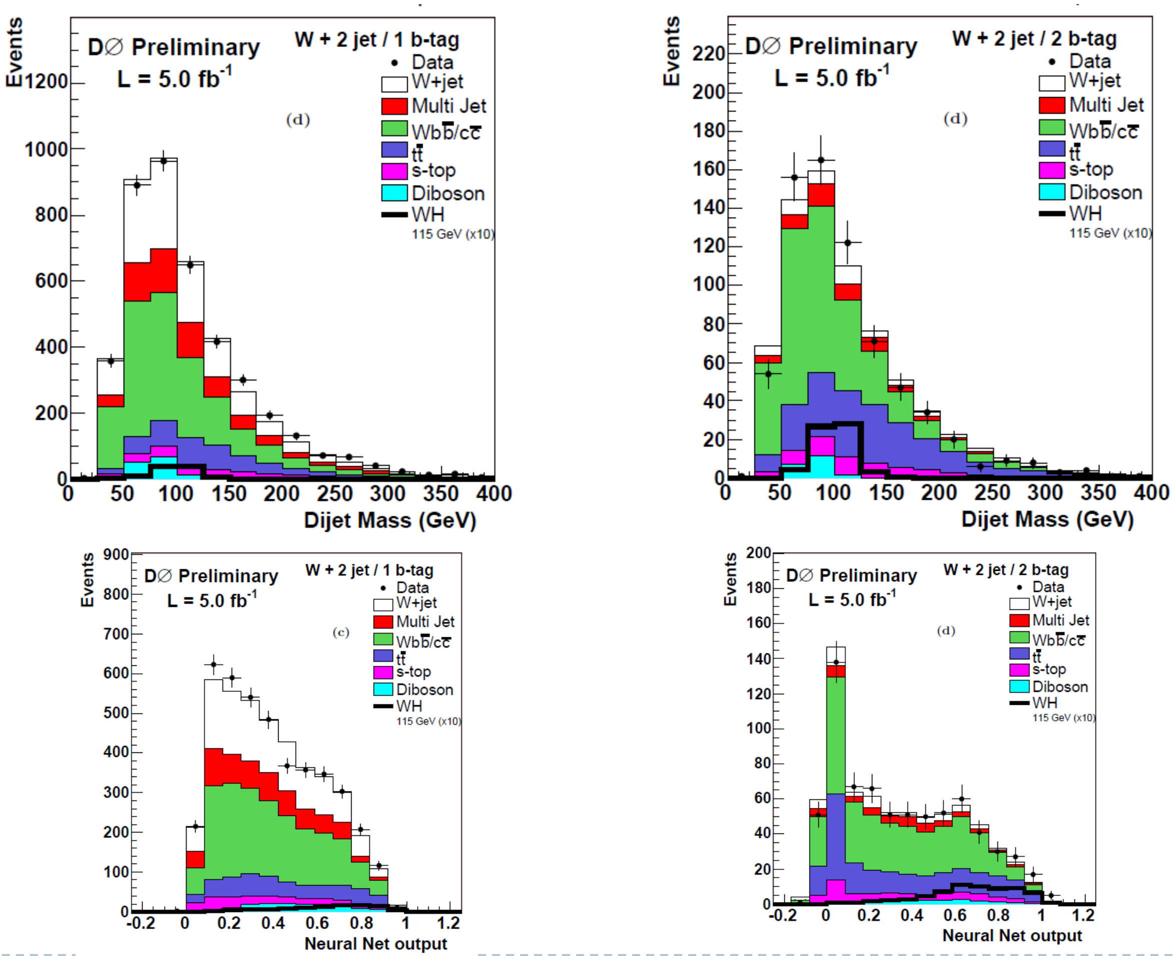


A substantial fraction of mistags are charm (40% of the real tags)

CDF has developed an NN to separate charm and bottom

b-Jet Tagging

Use the number of b-tags to separate data into high and low S:B regions



DØ $WH \rightarrow \ell\nu b\bar{b}$

Separate regions are recombined in final limit setting step with appropriate weight

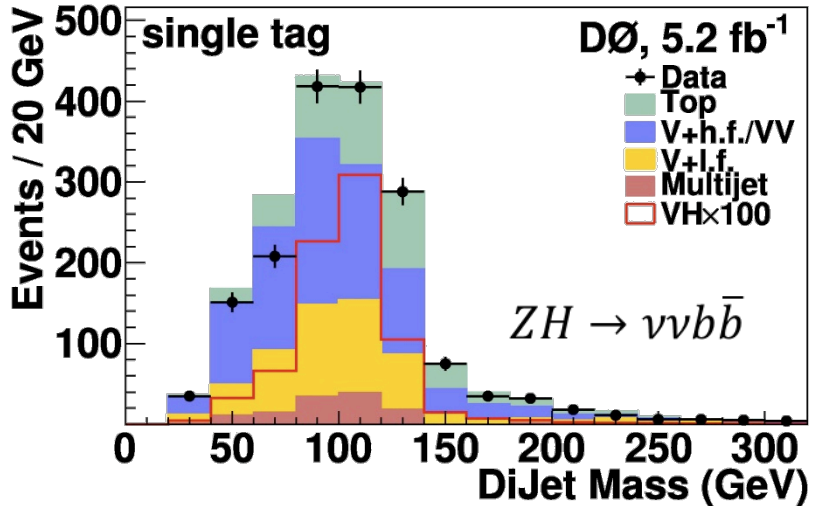
All separate regions must be completely orthogonal

Technique is common and mature

Jet Resolution

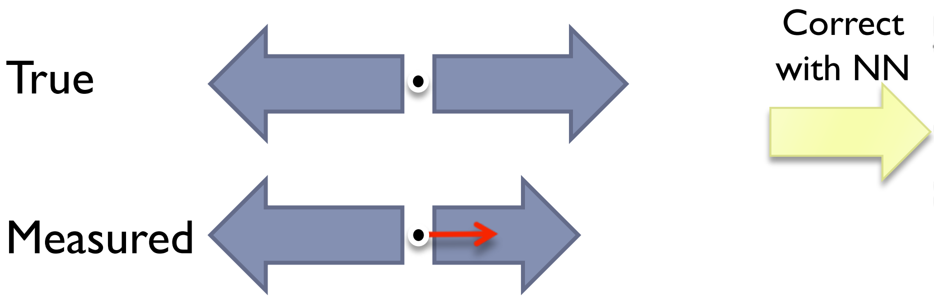
The most important discriminating variable after b-tagging.

- Use standard JES techniques
- More advanced techniques on tap

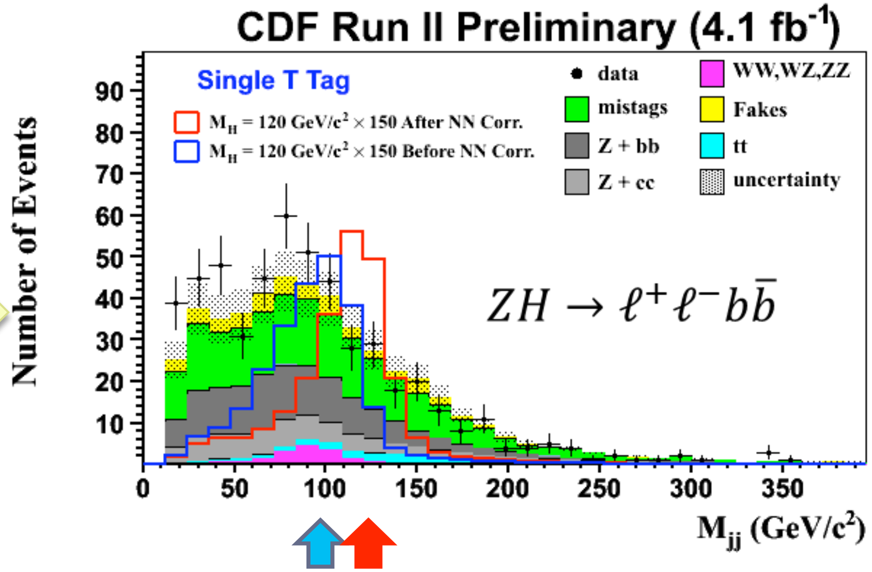


Jet Energy Mismeasurement

Often presents as missing E_T when none is expected



Missing E_T, in line with mismeasured jet

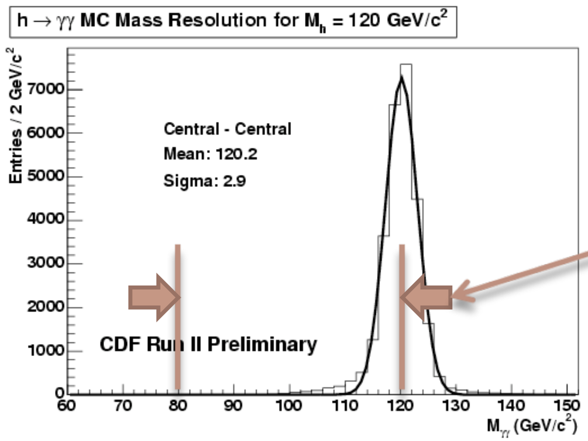


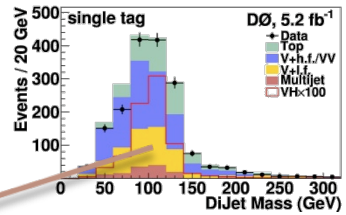
Jet Resolution

Or use a part of the calorimeter with better energy resolution

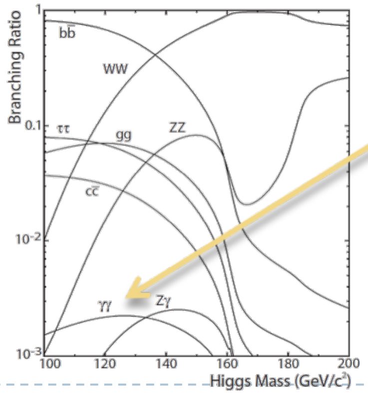
Jets mostly measured in hadronic calorimeter

Photons mostly measured in EM calorimeter



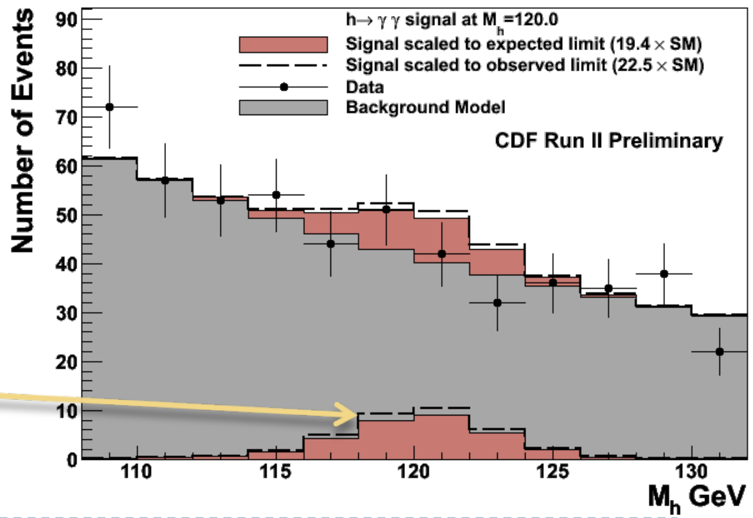


DØ has a similar analysis



BR of $H \rightarrow \gamma\gamma$ is tiny!

So expected Yield is small



Multivariate Discriminants

<u>Decision Trees</u>

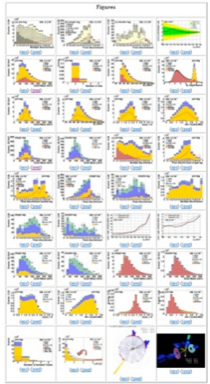
Come in many flavors.

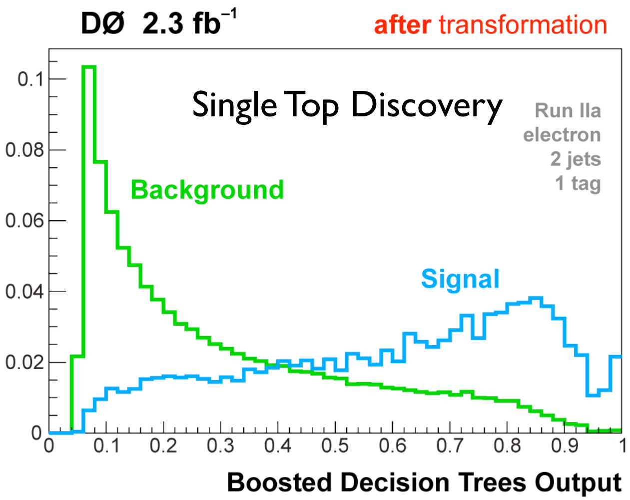
Varying robustness against over-training, amounts noise, and discrimination power

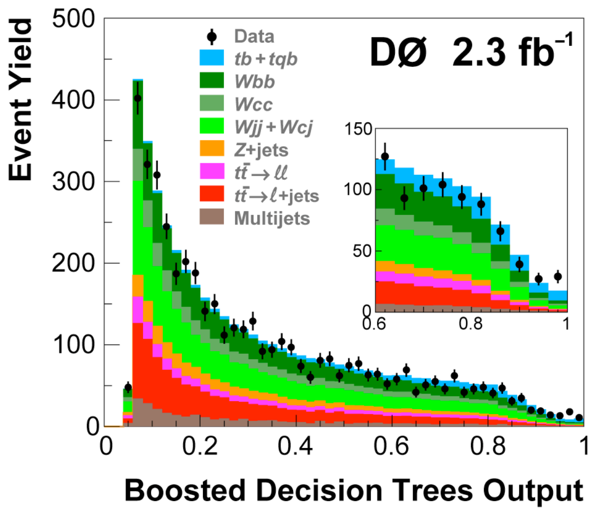
<u>Neural Networks</u>

Come in many flavors also (including boosted!).

Train on Monte Carlo. All techniques require careful cross check of all inputs and good modeling of backgrounds and of correlations between input variables







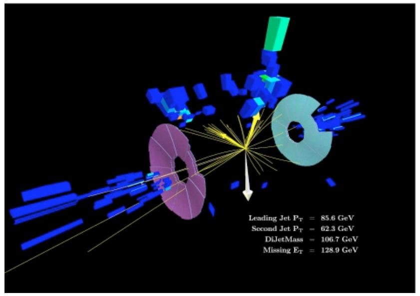
Do not cut on output of discriminant in most cases

Bin in discriminant output (bins of increasing S:N)

Depending on channel S:N can be 1:10 or 1:50 (x10 over dijet mass alone)

Matrix Element Discriminator

Reverse Monte Carlo Generator and Detector Simulation



Deconvolute Detector resolutions

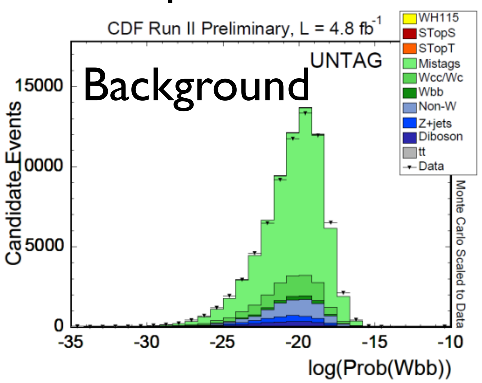
Region of MC Phase space for signal and background (P(S), P(B))

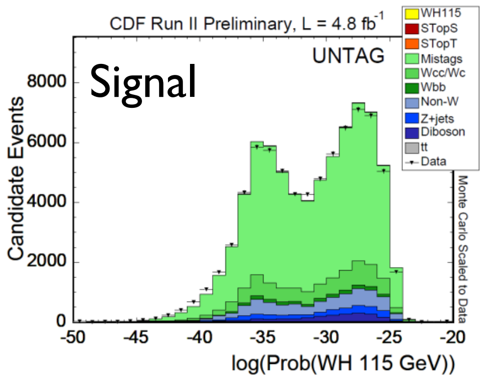
Discriminate is typically P(S)/(P(S)+P(B))

Techniques used for single-top discovery, WW, WZ observations

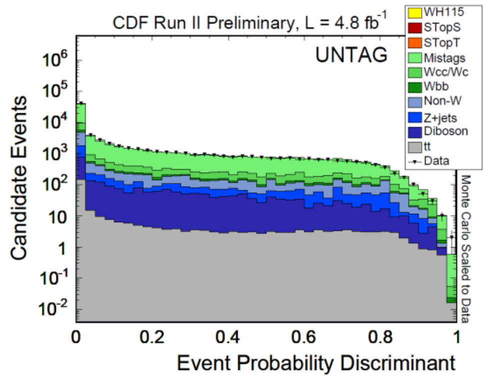
Inputs tend to be Lepton 4-vector, Jet 4-vectors, etc.

ME Outputs CDF $WH \rightarrow \ell \nu b\bar{b}$





Combine with NN

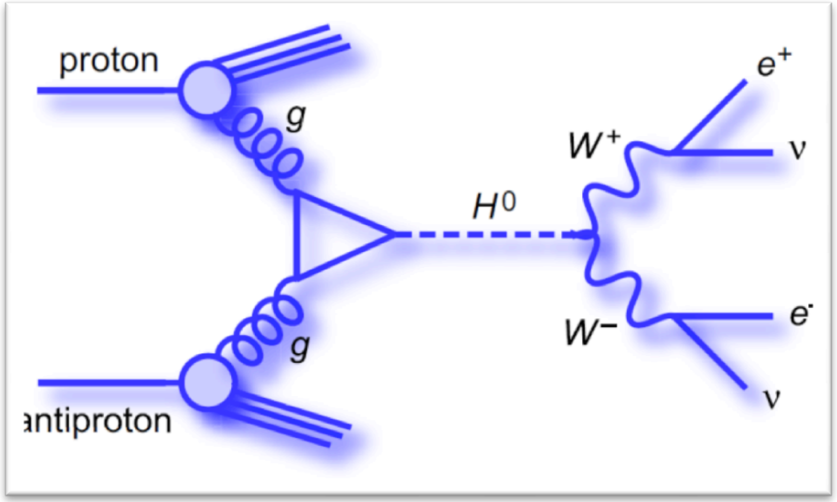


The High Mass Higgs Search

High Mass Searches

Gluon Fusion production rate is x10 higher than associated production rate

Highest BR modes are inaccessible due to overwhelming SM background



Di-boson modes are most commonly used for the search

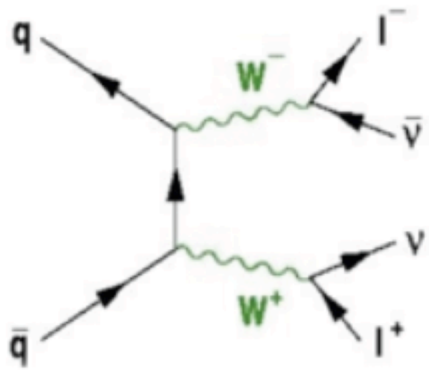
$gg \to H \to WW \to \ell\ell\nu\nu$

$\sigma \times BR = 0.04$ pb at $m_H = 160$ GeV.

About 6% of H decays…

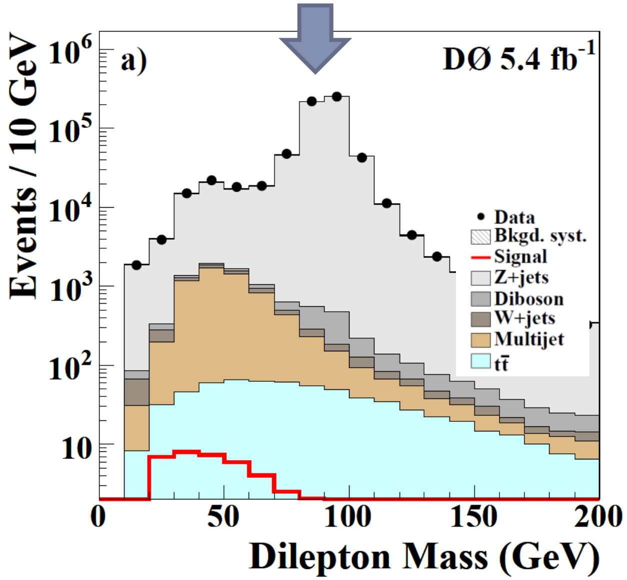
Main Backgrounds

- WW: $\sigma \times BR = 13$ pb
- W+Jets/Z+Jets
- WZ: $\sigma \times BR = 4.0$ pb
- ZZ: $\sigma \times BR = 1.5$ pb
- $t\bar{t}$: $\sigma \times BR = 7$ pb
- Single Top: $\sigma \times BR = 3$ pb

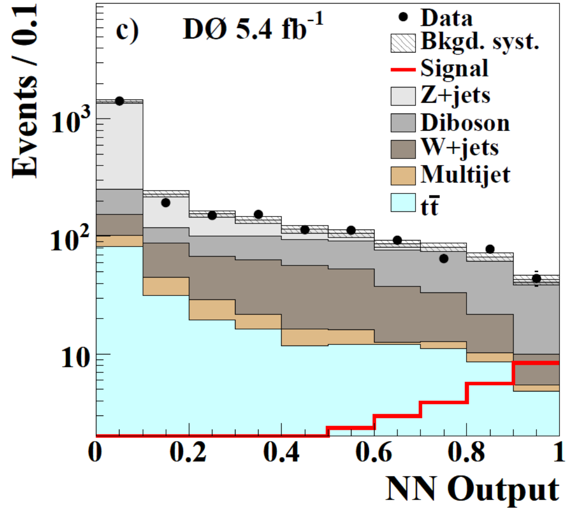


Event Selection and Background Rejection

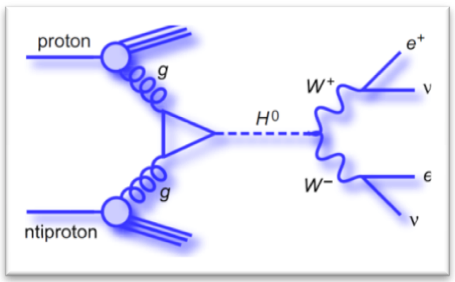
High p_t isolated muons and electrons required



Further apply missing E_T cut and a NN that uses various angles between the leptons (Higgs is spin 0) along with masses and quality information

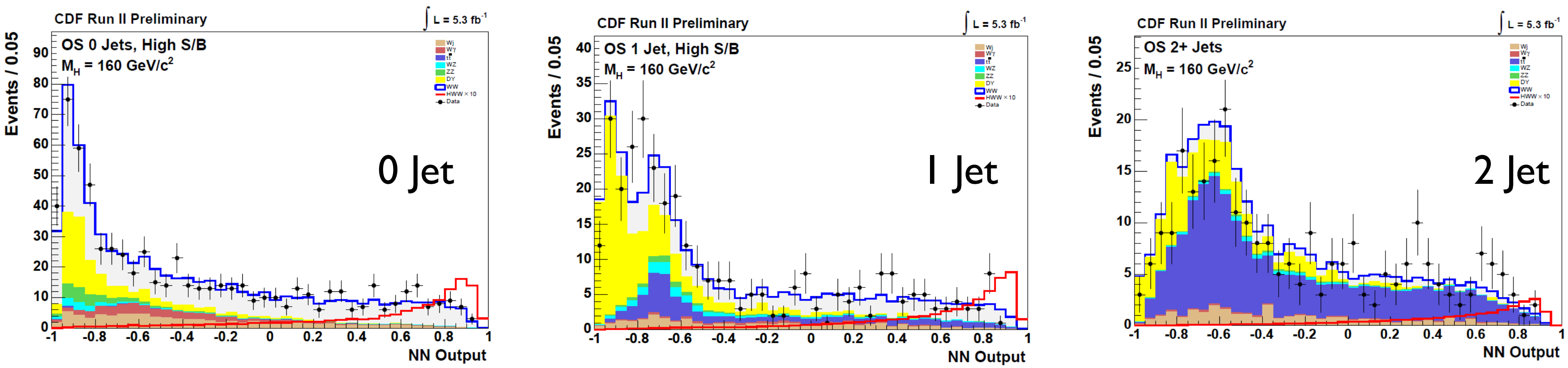


There should be no b-quark jets in these events



CDF Rejects events with a good b-quark tag

Further S:N Enhancements



Increasing significance

Instead of jet bins, DØ uses N_{Jets} as input to its NN

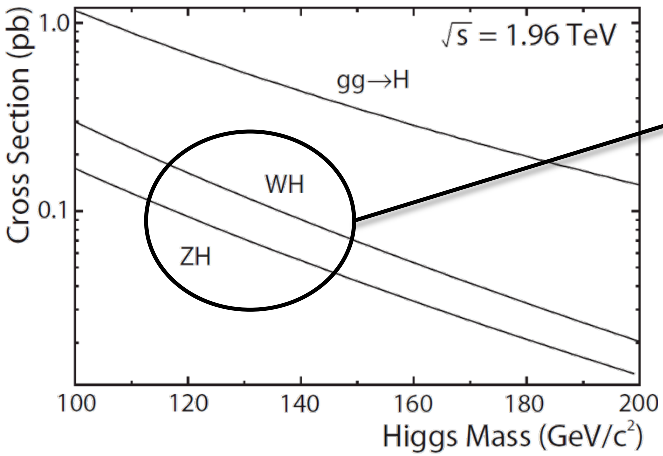
Both experiments also split leptons into high/low S:N regions

Different fractions of back ground and S:N mean better handling by a profile fitter as well

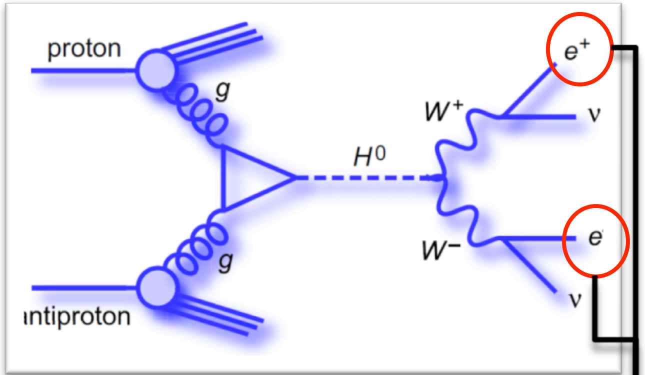
CDF uses a Matrix Element technique in its 0 Jet bin, and a NN in the other bins

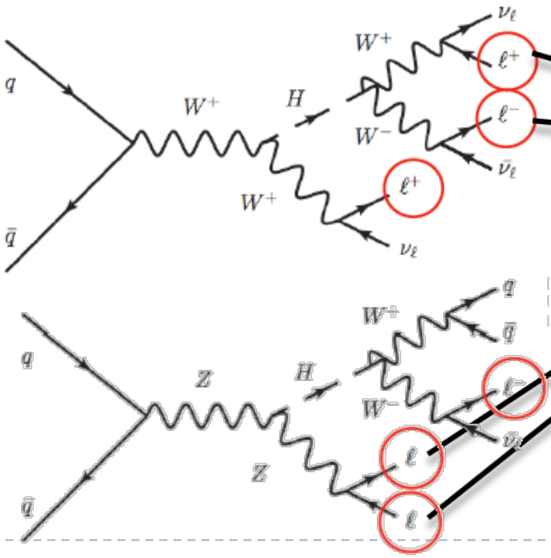
DØ uses a NN in all jet bins

Increasing the Significance



High Mass Higgs will still be produced in association with a W or a Z

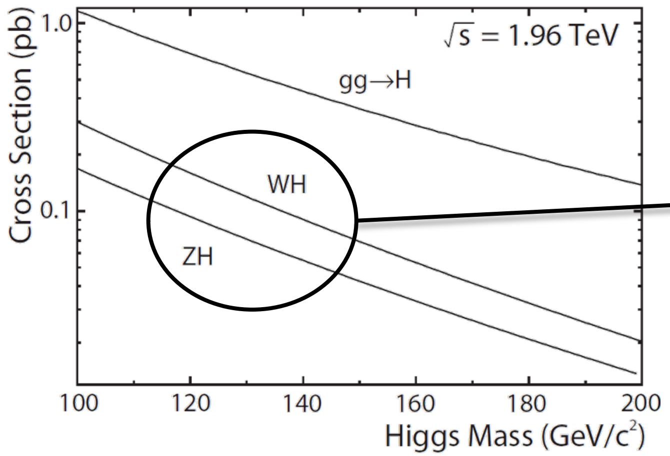




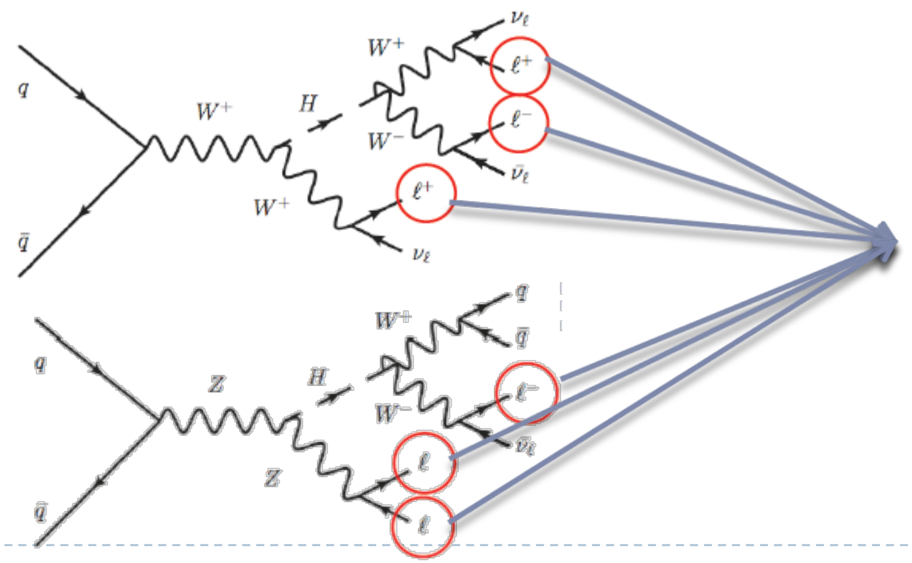
Traditional Opposite Sign Search
(includes missed leptons!)
Trilepton Search

Same Sign Search

Increasing the Significance



High Mass Higgs will still be produced in association with a W or a Z

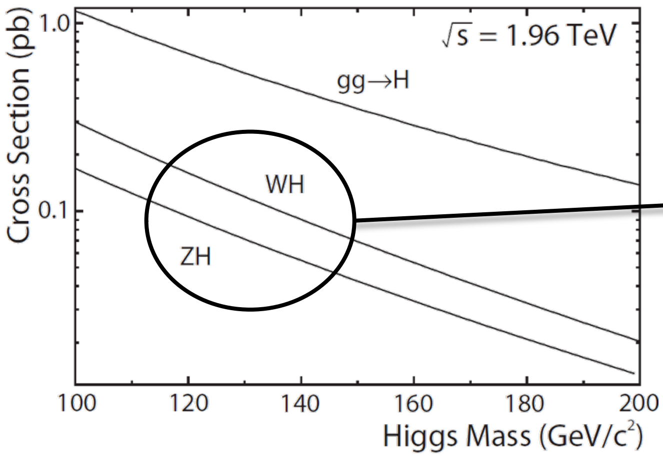


Traditional Opposite Sign Search

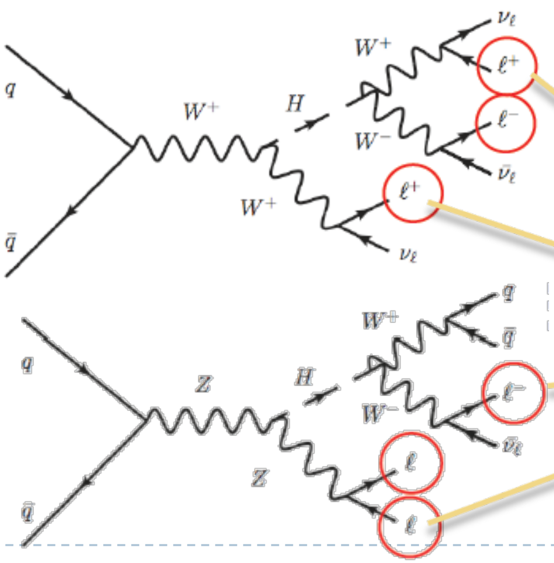
Trilepton Search

Same Sign Search

Increasing the Significance



High Mass Higgs will still be produced in association with a W or a Z

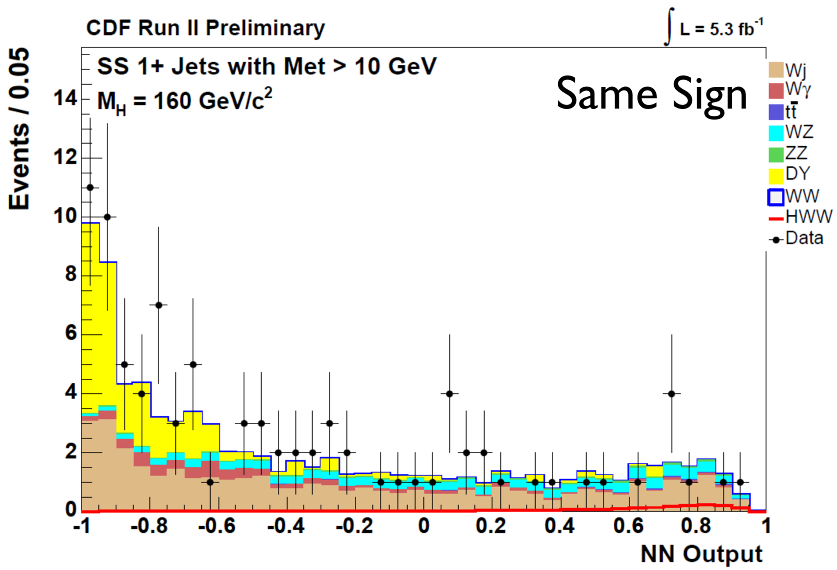


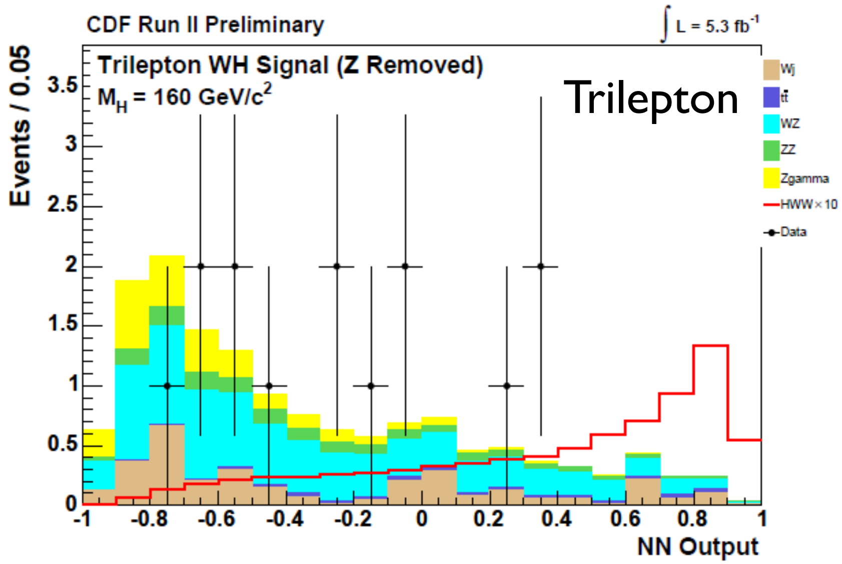
Traditional Opposite Sign Search

Trilepton Search

Same Sign Search

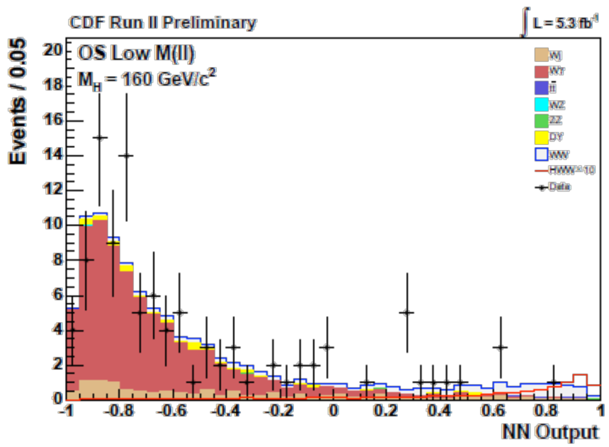
Increasing the Significance





Low Mass Dilepton

$M_{ll} < 16\ GeV$ region dominated by W-gamma
Consider only 0 and 1-jet events
W-gamma background modeled with data



Combining Standard Model Higgs Results

Combined Limits

Tevatron working group combines results from both CDF and DØ.

Experiments have agreed on treatment of

- Luminosity
- Systematic Errors
- Theory Cross Sections

CLs and Modified Baysean Methods are used; results agree to 5%

CDF

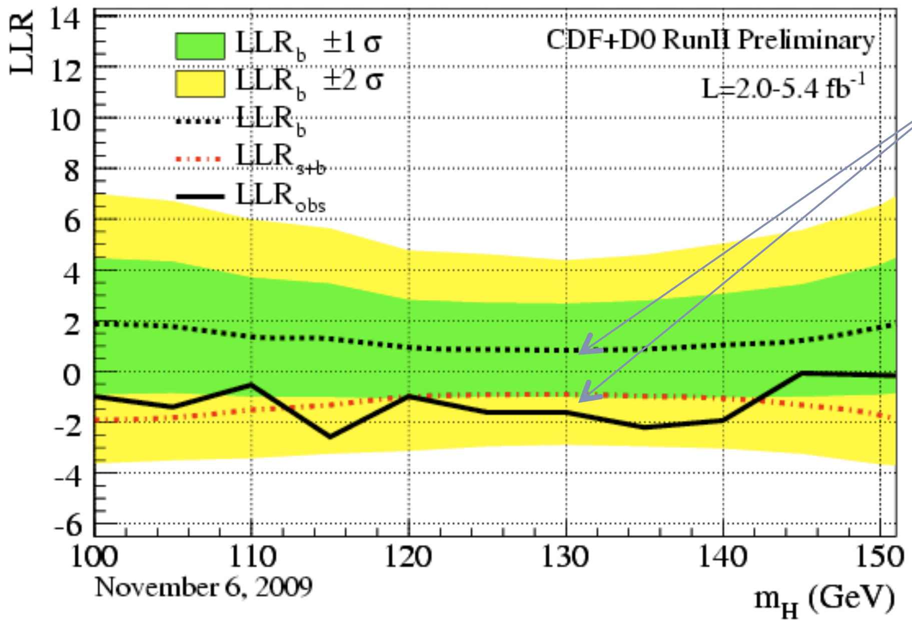
Channel	
$WH \to \ell\nu bb$ 2-jet channels	$3\times$(TDT,LDT,ST,LDTX)
$WH \to \ell\nu b\bar{b}$ 3-jet channels	$2\times$(TDT,LDT,ST)
$ZH \to \nu\bar{\nu}b\bar{b}$	(TDT,LDT,ST)
$ZH \to \ell^+\ell^- b\bar{b}$	(low,high s/b)$\times$(TDT,LDT,ST)
$H \to W^+W^-$	(low,high s/b)$\times$(0,1 jets)+(2+ jets)+Low-$m_{\ell\ell}$
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	
$H + X \to \tau^+\tau^- + 2$ jets	
$WH + ZH \to jjb\bar{b}$	

DØ

Channel	
$WH \to \ell\nu b\bar{b}$	$2\times$(ST,DT)
$VH \to \tau\tau b\bar{b}/q\bar{q}\tau\tau$	
$ZH \to \nu\bar{\nu}b\bar{b}$	(ST,TLDT)
$ZH \to \ell^+\ell^- b\bar{b}$	$2\times$(ST,DT)
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$	
$H \to \gamma\gamma$	
$t\bar{t}H \to t\bar{t}b\bar{b}$	$2\times$(ST,DT,TT)

Over 90 channels

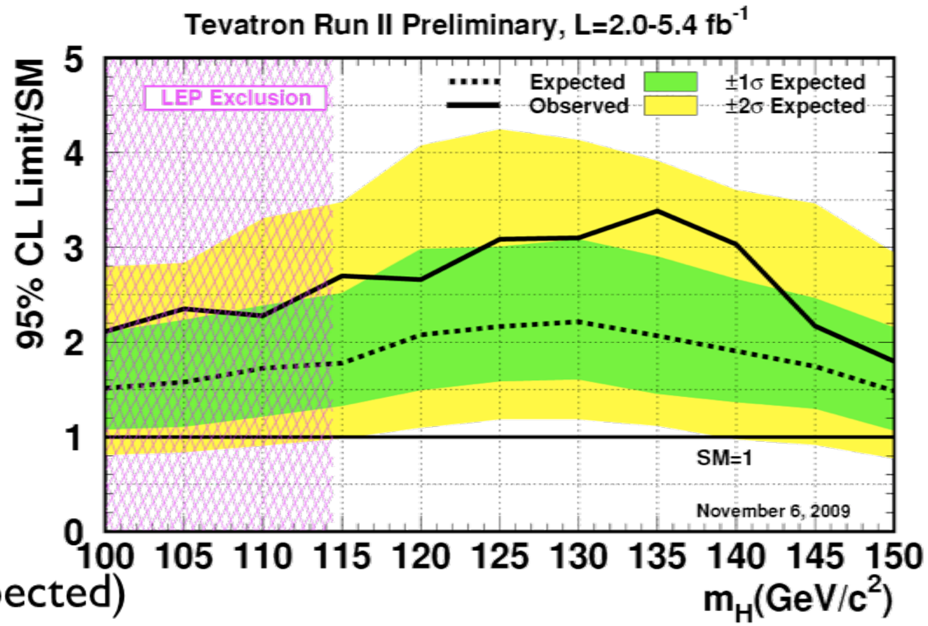
Combining The Low Mass Results



Sensitivity is the differences between LLR_b and LLR_{s+b}

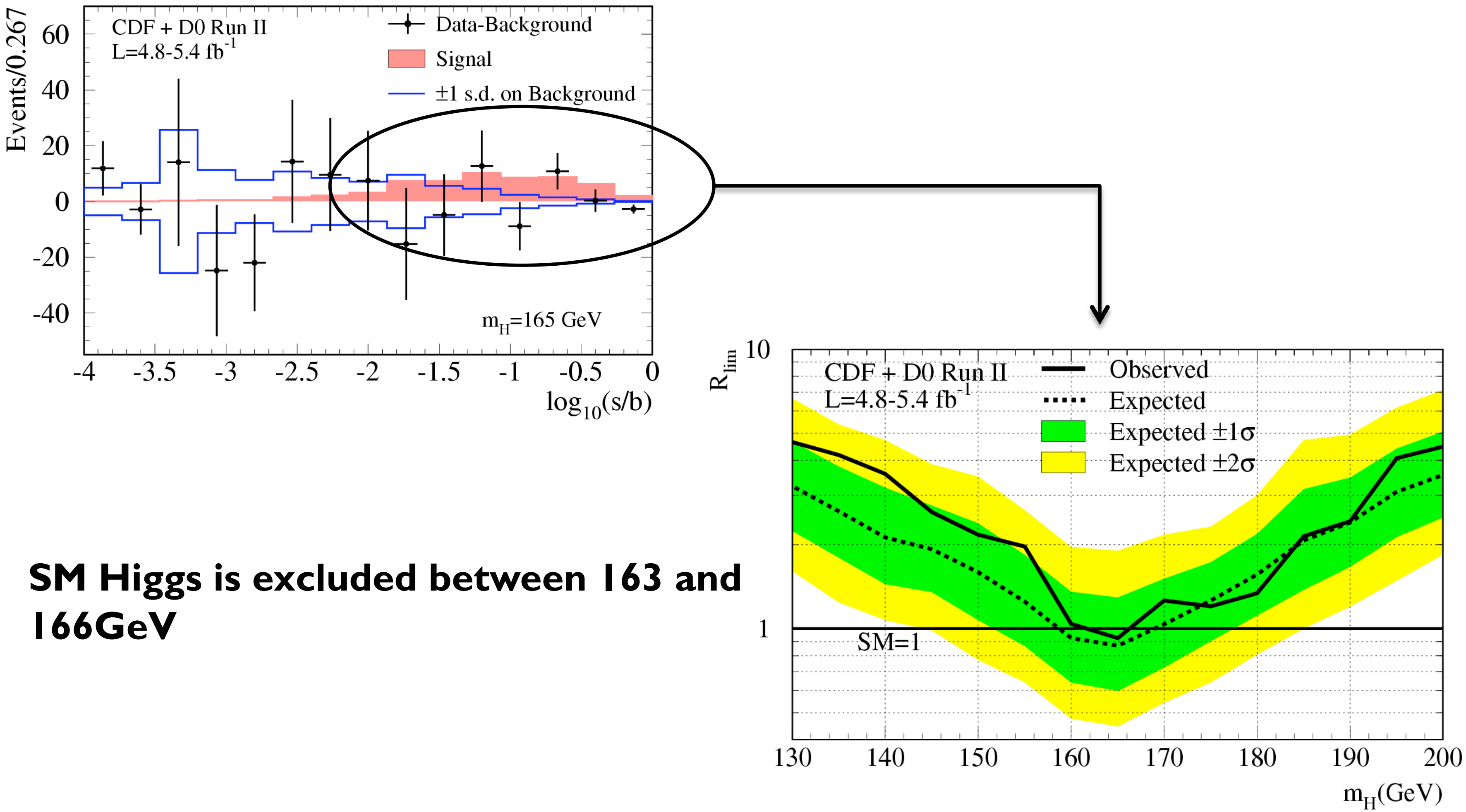
How far are we from reaching the SM?

Many production and decay channels are included in this plot!



$M_H = 115\ GeV$: 2.70 (1.78) observed(expected)

Combining The High Mass Results



SM Higgs is excluded between 163 and 166GeV

Only published results included…

Beyond The Standard Model

Beyond The Standard Model

Higgs Sector Enriched → Huge Parameter Space To Explore

➡ Search for specific, predictive, models…

Fermiophobic Higgs

Enhanced coupling to 2-photon final state

Doubly charged Higgs

See public results pages for CDF and DØ.

MSSM

Two additional doublets couple to the up and down fermions

Symmetry breaking gives 5 Higgs left over:

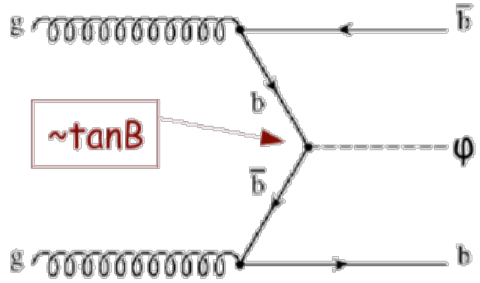
Neutral: A (CP Odd), H, h (CP Even)

Charged: $H^{\pm}$

m_A

$tan\beta$ – Ratio of doublet vev

MSSM – high *tanβ* regime



A/h or A/H are degenerate (Φ)
Enhanced coupling to $\tau^+\tau^-$ (10%) and $b\bar{b}$ (90%)

$\Phi \rightarrow b\bar{b}$ - Multi-Jet Background

$(b\bar{b})\Phi \rightarrow b\bar{b}(b\bar{b})$ – Associated Production

$\Phi \rightarrow \tau^+\tau^-$ - Also associated production with a b-quark

Same philosophy: Tevatron Combination

General Performance of b and τ tagging

b – 50% efficiency; 0.5% fake
τ – 60% efficiency; 1% fake

Charged Higgs Decays – not discussed here

$b\Phi \to \tau^+\tau^- + b$

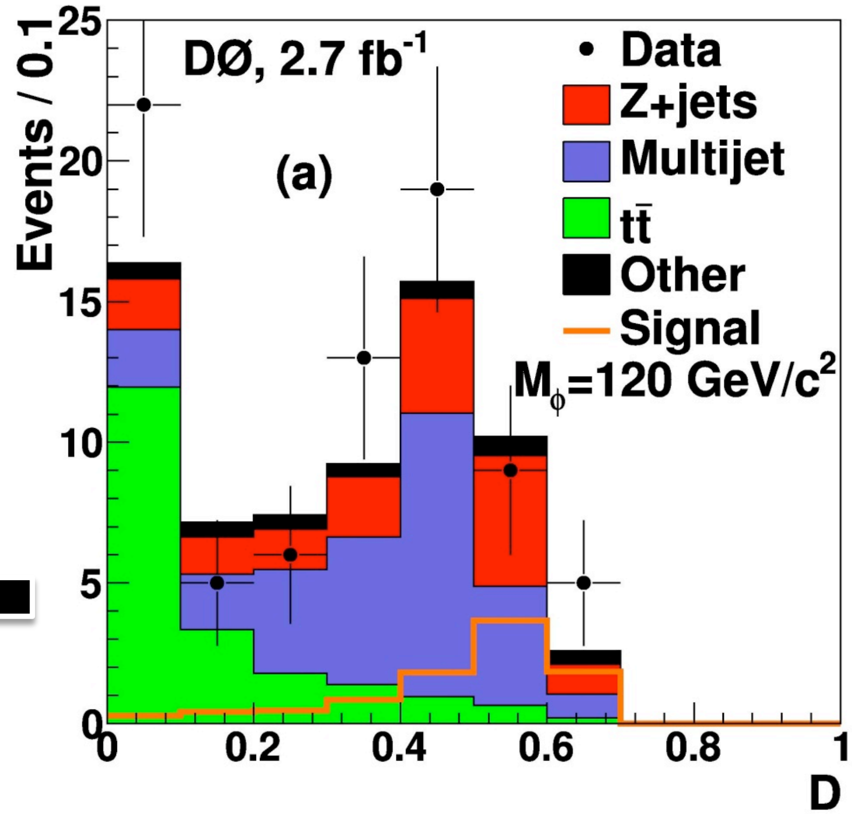
Main Backgrounds: Z+jets, multijet, and $t\bar{t}$
Orthogonal to $\Phi \to \tau^+\tau^-$

Look for:
- Isolated lepton ($\tau \to \ell\nu_\ell\bar{\nu}_\tau$)
- Hadronic tau (opposite charge)
- Tagged b-jet

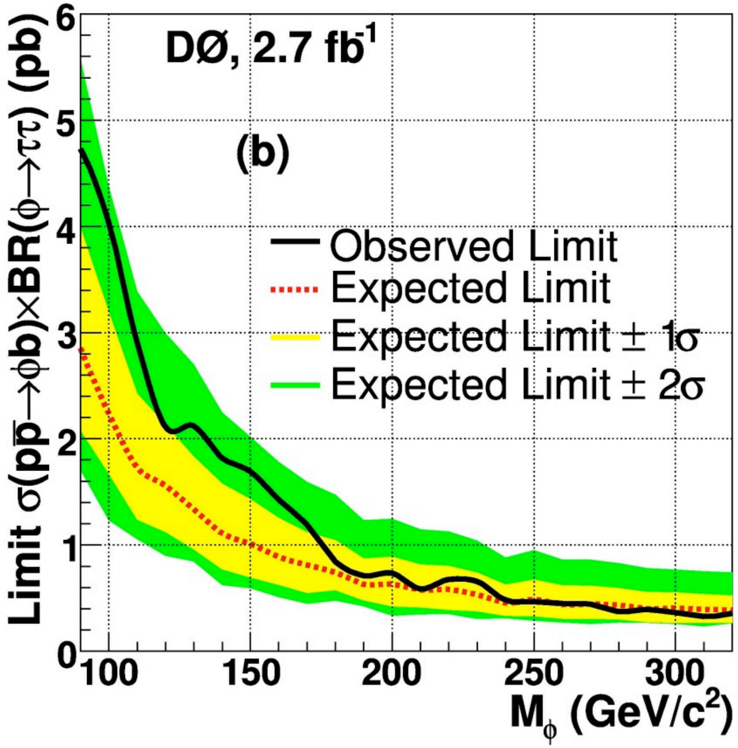
Cleaner than $\Phi \to \tau^+\tau^-$, smaller BR

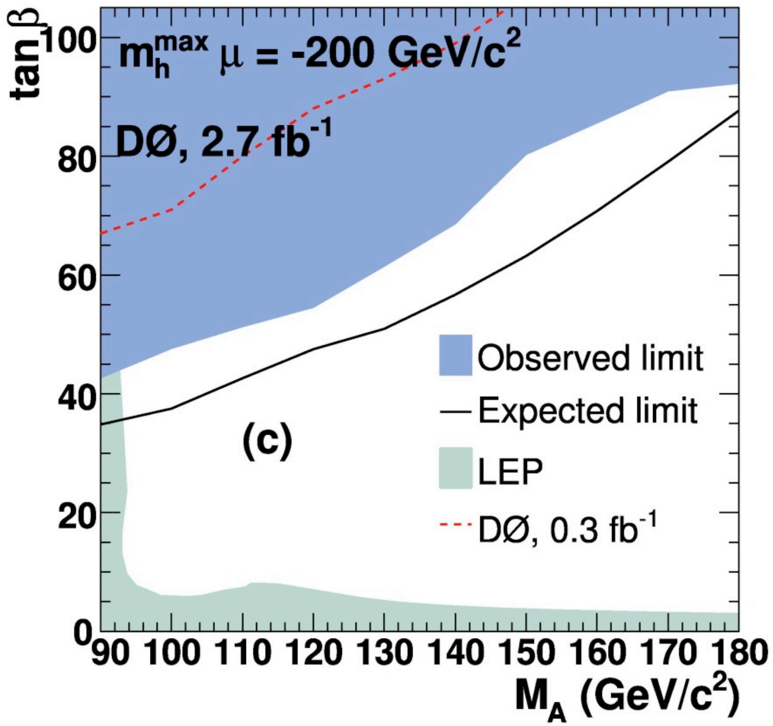
$$D = NN \times LH$$

Suppress $t\bar{t}$ Suppress MultiJet



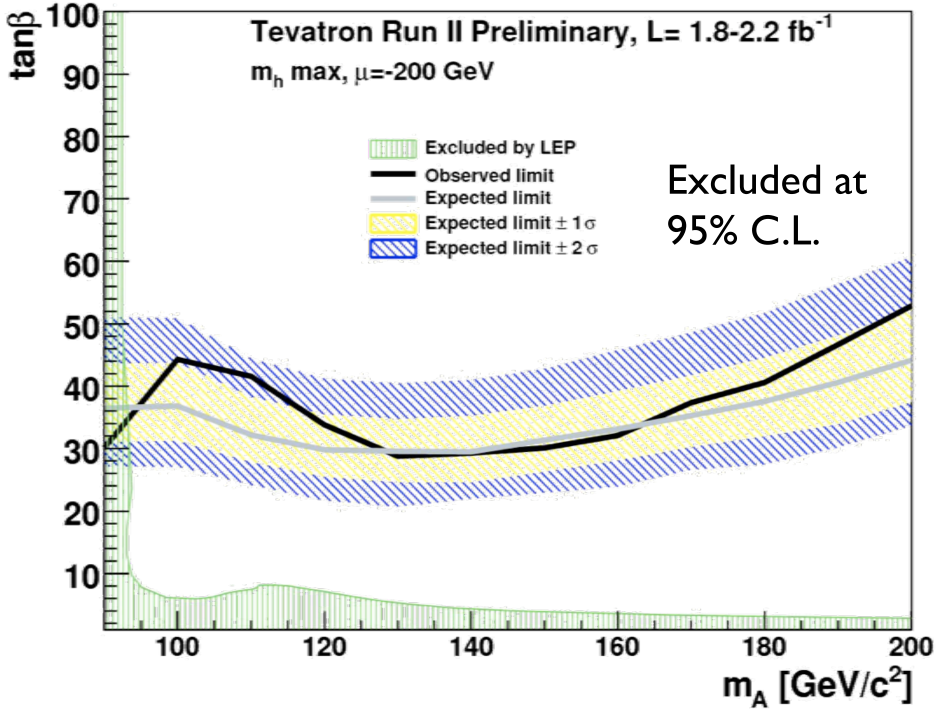
$b\Phi \rightarrow \tau^+\tau^- + b$ Results



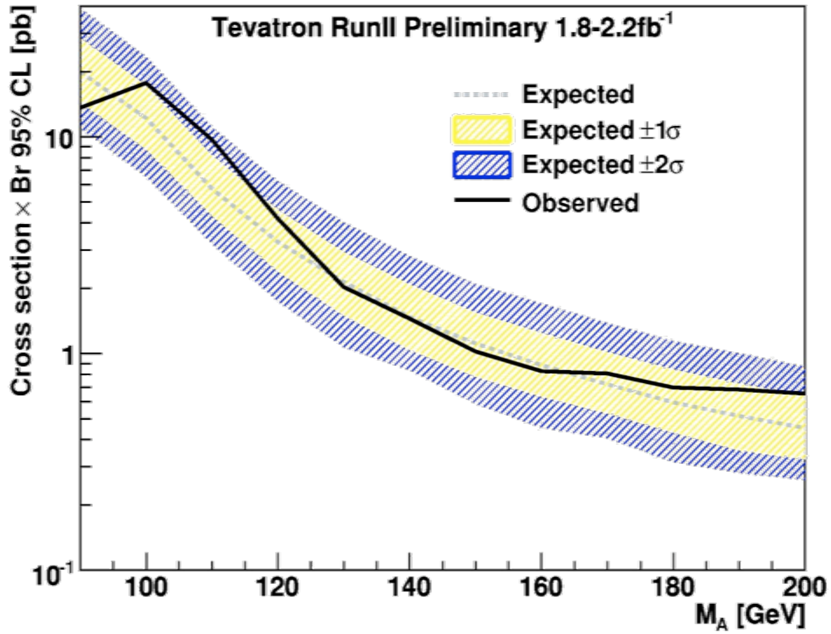


$\Phi \rightarrow \tau^+\tau^-$ Combination

Same techniques and toolbox is used to combined $\tau\tau$ results from both experiments



Excluded at 95% C.L.

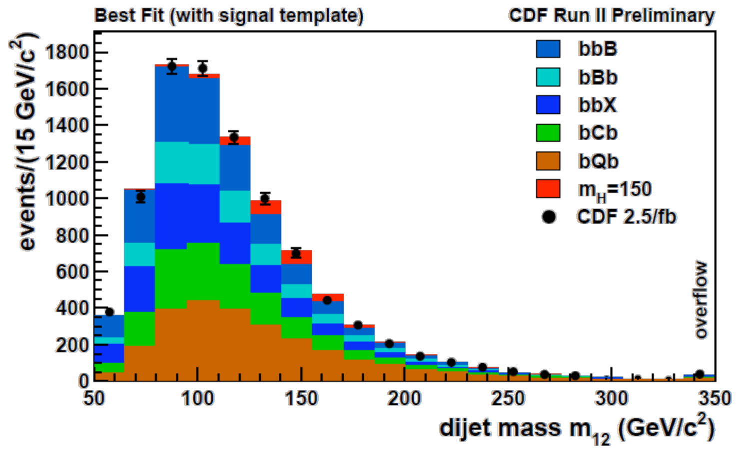


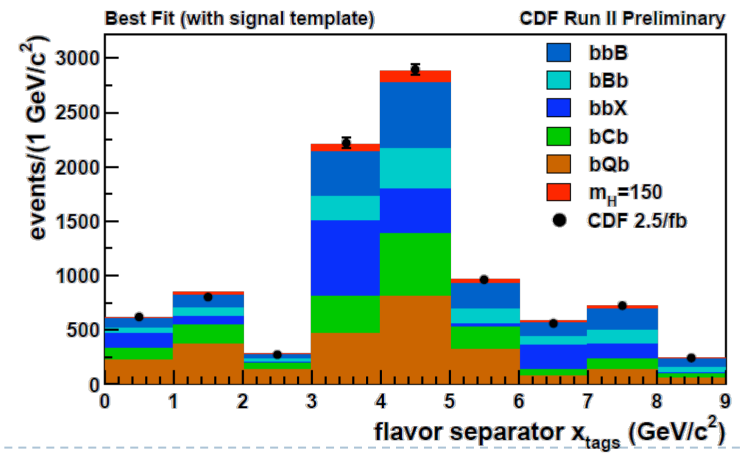
But currently this is using data from late 2009 – aiming for an update in summer 2010

$b\Phi \rightarrow 3b$

Very challenging measurement: multi-jet $b\bar{b}$ production is overwhelming

Background multi-jet determination is data driven.



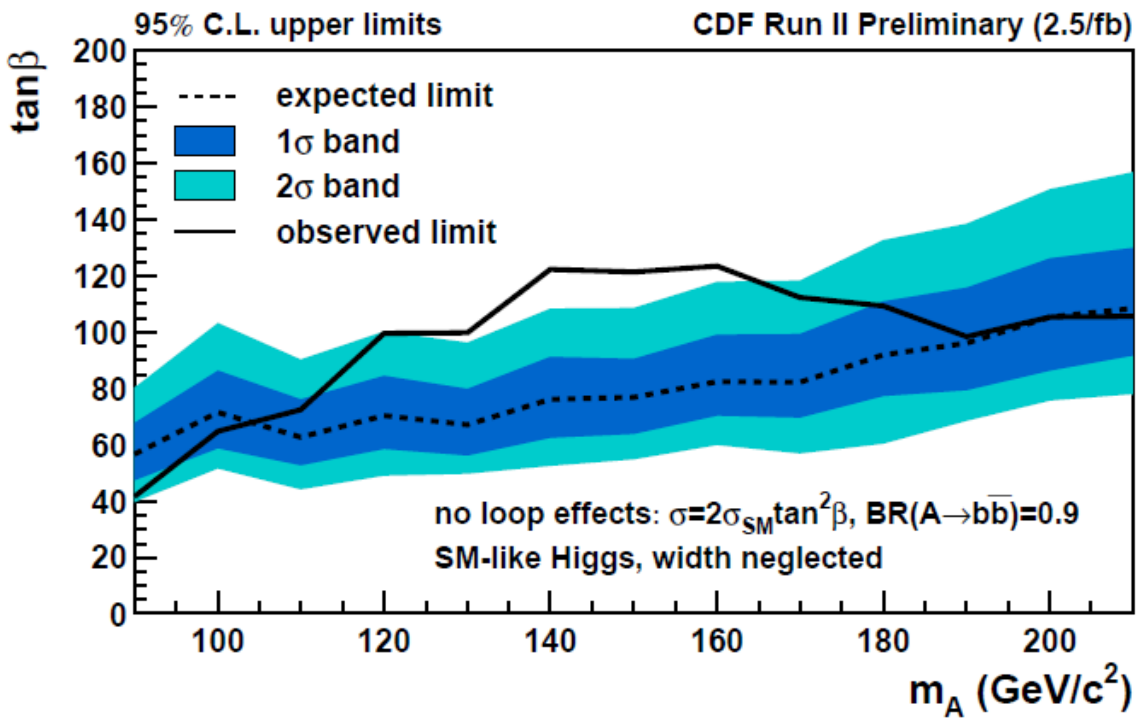


m_{12} is the mass of the leading two jets

Different possible flavor combinations for the 3 tagged jets

x_{tags} classifies the event by the b-tag vertex mass

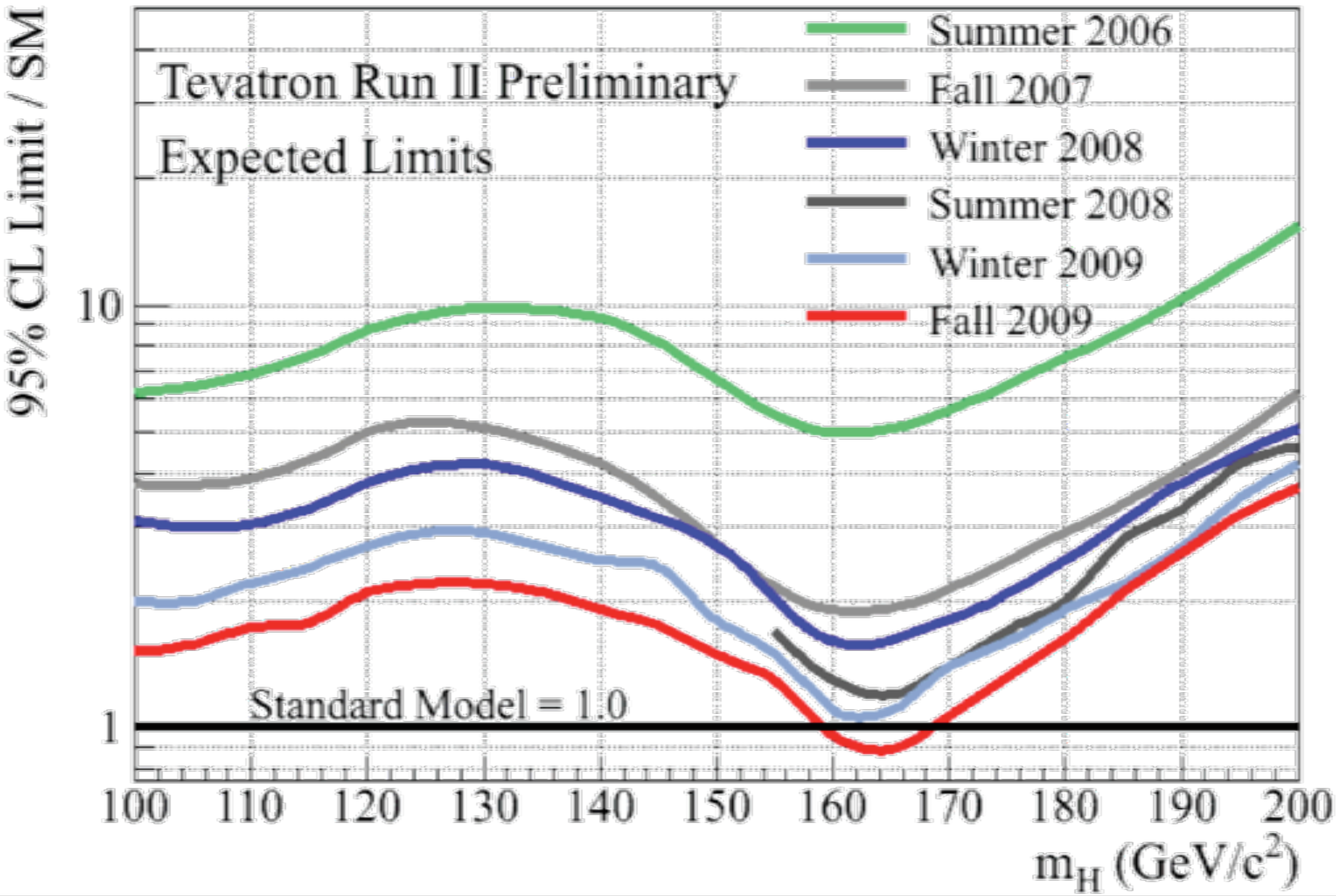
$b\Phi \rightarrow 3b$



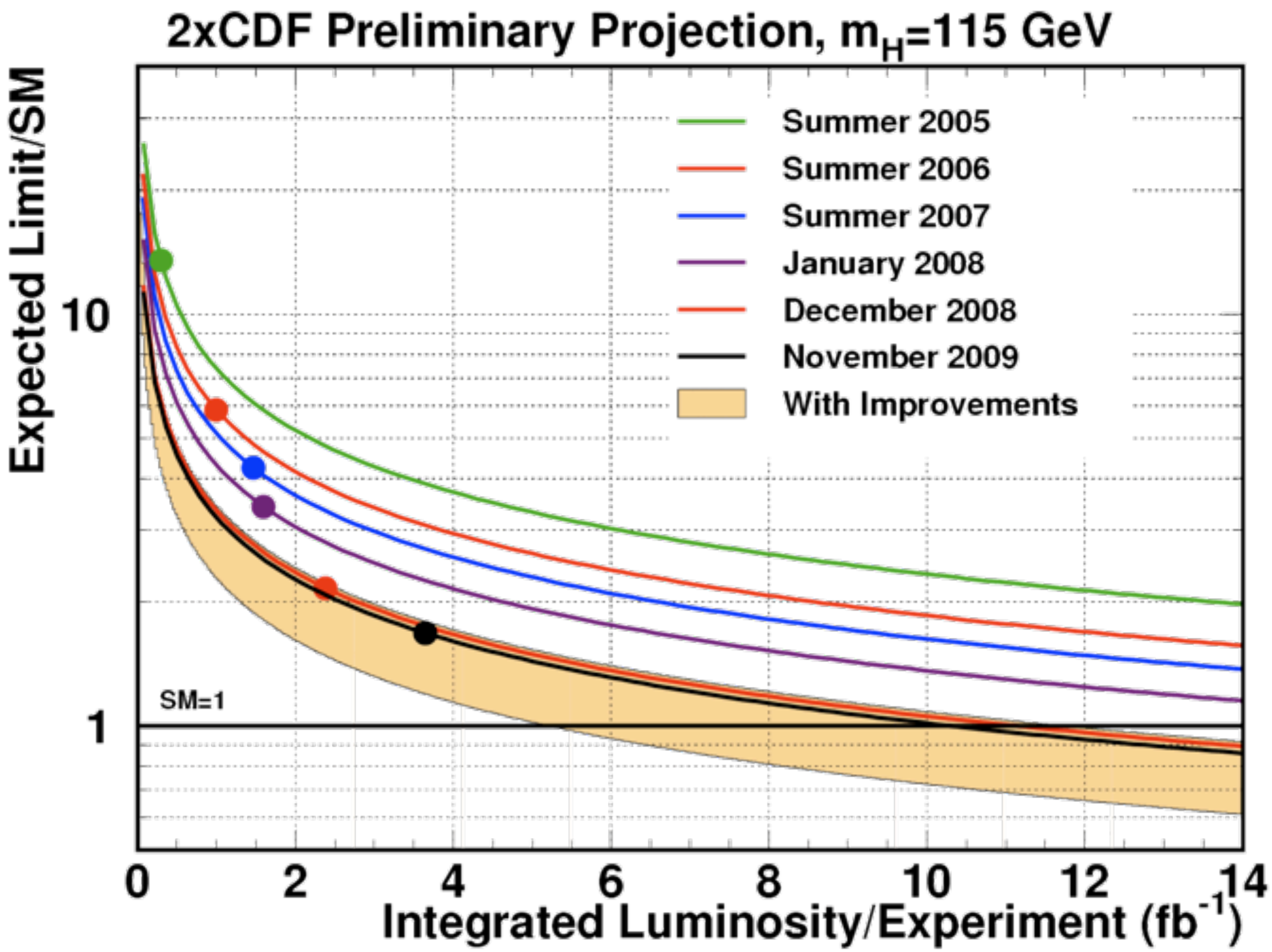
Use CL_s method and fits to these two distributions to come up with final limits

Conclusions

The Past Is The Best Predictor



The Past Is The Best Predictor

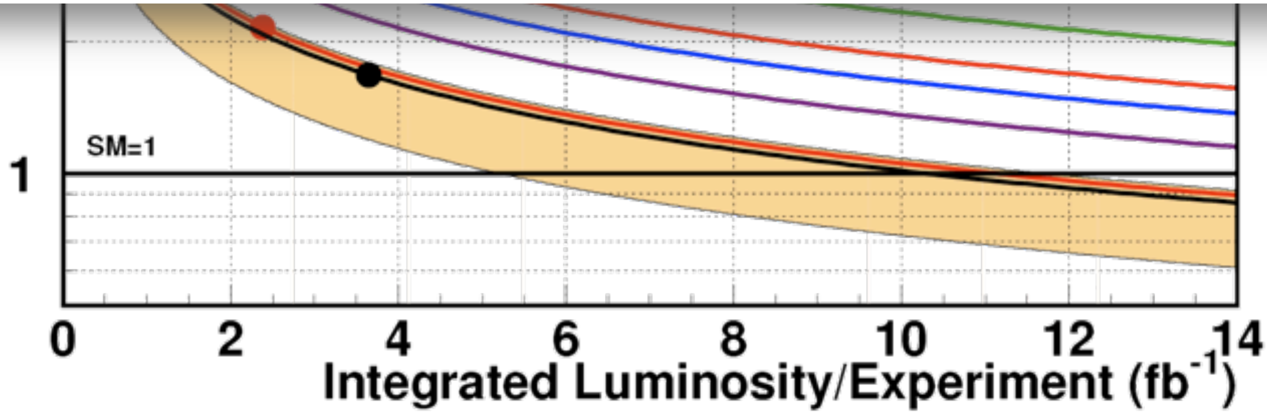


The Past Is The Best Predictor

2xCDF Preliminary Projection, m_H=115 GeV

Demonstrated charm quark discrimination ability:	~30% equiv lumi gain
Improved usage of b-Tagging information:	~20% equiv lumi gain
Reduced dijet mass resolution:	~15% equiv lumi gain
for every 1% absolute gain in σ_{Mbb} for up to ~50-60% possible	
Addition of lower yield final states (H→$\tau\tau/\gamma\gamma$/ZZ/lvjj, etc):	~5-10% equiv lumi gain
Improved lepton ID eff & reduced inst. lumi dependence:	~5-10% equiv lumi gain

These factors alone can buy us ~1.4× in the limit (~2× in effective luminosity)



Conclusions

- Mature Analyses – Rapid inclusion of new data into each analysis
  - No channel is too small to explore
  - SM Exclusion between 162 – 166 GeV
  - Average luminosity in SM channels is about 4.4 fb^{-1}. Each experiment has about 7.8 fb^{-1} recorded.
  - New combination for > 6 fb^{-1} is hoped for the summer
- BSM Higgs Searches are catching up
  - Combination Machinery is now working – update this summer
  - Many more channels to be explored
  - MSSM $tan\beta > 30 - 50$ is already ruled out.
- New Developments constantly being brought online
  - Not all results presented in this talk have been folded into the combination yet
- Stay tuned for the next year of running!

Systematic Uncertainties

- Two types of systematics on estimated signal and background:
  - Rate systematics: only affect overall normalization
  - Shape systematics: change differential distribution, i.e. due to JES, MC modeling
- Systematics correlated between CDF and D0:
  - Integrated luminosity (4% correlated out of 6%)
  - Theoretical cross sections for signal and backgrounds (5-10%)
- Other Sources correlated within experiment:
  - Lepton ID, 2-4%
  - Btag SF, JES, FSR/ISR, 5-10%
  - Jet/Missing Et modeling
  - MC simulated backgrounds (W/Z+HF)
  - instrumental backgrounds(non-W, mistag)

- Something on that paper on how the Tevatron isn't doing the PDF errors correctly?

CDF Published Limits

M_H (GeV/c^2)	110	120	130	140	145	150	155	160	165	170	175	180	190	200
Bayesian Expected	26.3	8.85	4.41	2.85	2.43	2.05	1.67	1.26	1.20	1.44	1.72	2.09	3.24	4.53
Bayesian Observed	38.9	12.0	6.38	4.21	3.23	2.62	2.04	1.34	1.29	1.69	1.94	2.24	4.06	6.74

D0 Published Limits

M_H (GeV/c^2)	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
Expected	14.9	9.74	7.20	5.40	4.23	3.48	3.07	2.58	2.02	1.43	1.36	1.65	2.06	2.59	3.28	4.20	5.08	6.23
Observed	30.8	13.6	8.81	6.63	6.41	5.21	3.94	3.29	3.25	1.82	1.55	1.96	1.89	2.11	3.17	3.27	5.77	5.53

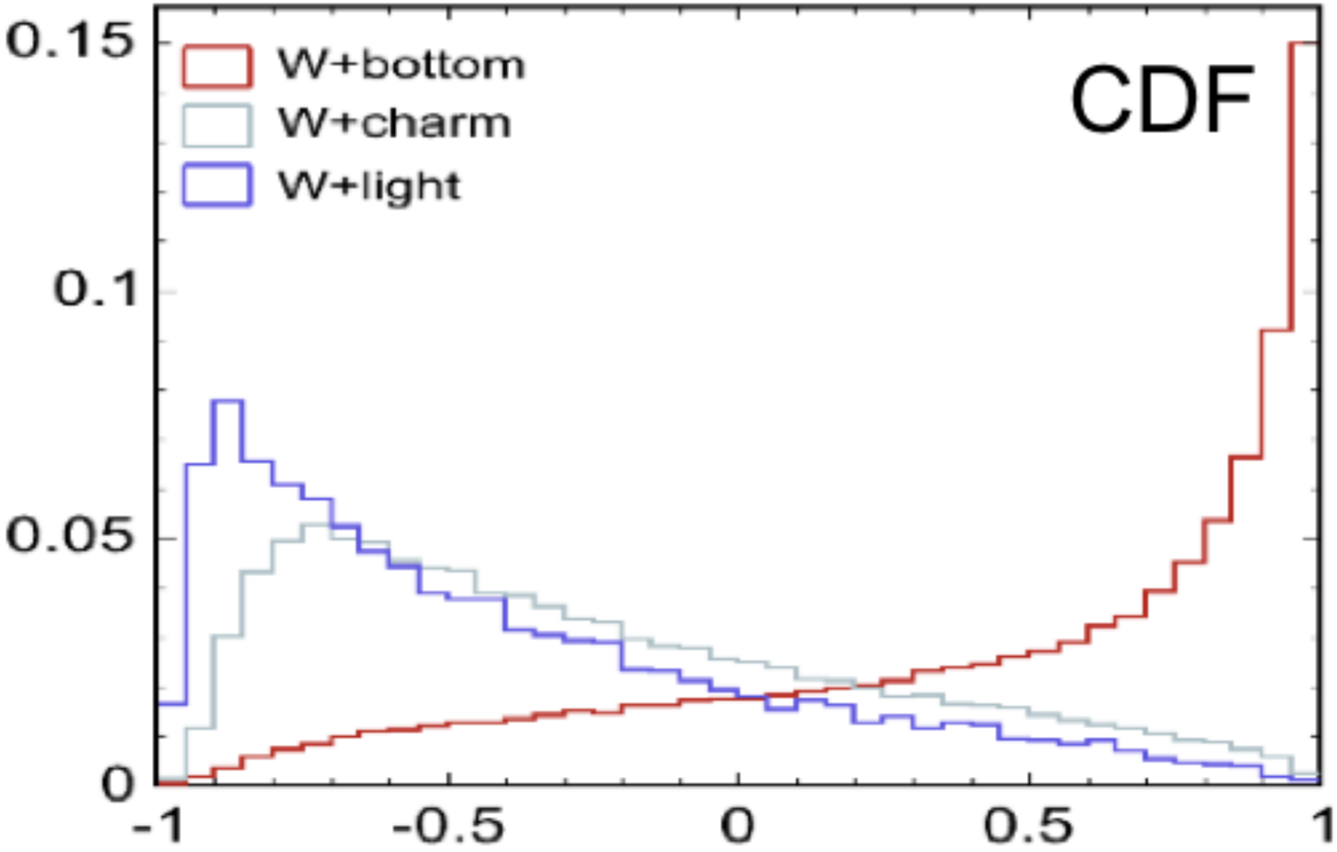
CDF+D0 Published limits

M_H (GeV/c^2)	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
Bayesian Expected	3.24	2.63	2.12	1.92	1.59	1.25	0.92	0.87	1.04	1.26	1.56	2.07	2.40	3.09	3.55
Bayesian Observed	4.65	4.18	3.58	2.61	2.17	1.96	1.04	0.93	1.26	1.20	1.34	2.14	2.42	4.07	4.47
CLs Expected	3.26	2.52	2.18	1.87	1.53	1.24	0.89	0.84	1.06	1.28	1.56	2.07	2.46	3.17	3.62
CLs Observed	4.49	4.06	3.45	2.49	2.12	1.84	0.98	0.89	1.21	1.18	1.31	2.15	2.36	4.10	4.35

CDF limits for March 2010

M_H (GeV/c²)	110	115	120	125	130	135	140	145	150	155
$-2\sigma/\sigma_{SM}$	9.97	5.40	3.48	2.31	1.72	1.37	1.13	0.95	0.81	0.69
$-1\sigma/\sigma_{SM}$	14.50	7.91	5.12	3.37	2.52	1.99	1.63	1.37	1.18	0.99
Median/σ_{SM}	21.88	11.93	7.70	5.11	3.83	3.02	2.51	2.09	1.78	1.48
$+1\sigma/\sigma_{SM}$	32.92	17.98	11.66	7.67	5.83	4.54	3.79	3.18	2.70	2.22
$+2\sigma/\sigma_{SM}$	47.49	25.75	16.80	11.00	8.30	6.57	5.57	4.59	3.89	3.22
Observed/σ_{SM}	28.72	13.03	8.47	5.33	4.25	3.69	3.45	2.30	2.01	1.60

M_H (GeV/c²)	160	165	170	175	180	185	190	195	200
$-2\sigma/\sigma_{SM}$	0.52	0.50	0.56	0.69	0.81	1.07	1.30	1.52	1.72
$-1\sigma/\sigma_{SM}$	0.74	0.70	0.80	0.97	1.18	1.54	1.88	2.24	2.51
Median/σ_{SM}	1.09	1.03	1.17	1.43	1.75	2.32	2.82	3.39	3.80
$+1\sigma/\sigma_{SM}$	1.61	1.54	1.75	2.14	2.63	3.53	4.28	5.11	5.79
$+2\sigma/\sigma_{SM}$	2.35	2.22	2.57	3.11	3.79	5.06	6.28	7.55	8.47
Observed/σ_{SM}	1.07	1.13	1.34	1.86	2.11	2.75	4.15	5.45	6.78


0.15
0.1
0.05
0
-1
-0.5
0
0.5
1
W+bottom
W+charm
W+light
CDF