CDF's Higgs Boson Searches and Combinations

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Fermilab

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Outline:

- A Bit of Theory
- LEP (+SLD, Tevatron)'s Legacy -- SM and MSSM Higgs Boson Constraints -- and tools to use
- Low-Mass Searches: 105 GeV < m_H< 150 GeV
- High-Mass Searches: m_H > 150 GeV
- Setting Limits and How to Make a Discovery

The Weirdness of Left-Handed Interactions

- Charged Weak currents violate parity maximally -- the $W^{\pm}$ boson couples only to left-handed fermions (and right-handed anti-fermions). The Z^0 also preferentially couples to left-handed fermions.

- Left-handed fermions have different quantum numbers than their right-handed counterparts! Specifically, left-handed fermions are in SU(2) doublets while the right-handed versions are in singlets.

- Weak eigenstates are not mass eigenstates. CKM matrix expresses the linear combinations.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \qquad \begin{matrix} \nu_{e,R}\,? & \nu_{\mu,R}\,? & \nu_{\tau,R}\,? \\ e_R & \mu_R & \tau_R \end{matrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \end{matrix}$$

SU(2) x U(1) Model Consequences

- Analog to $U(1)_{EM}$ QED model -- Gauge symmetry naturally implies existence of a massless photon with observed gauge interactions. One free parameter -- α_{EM}. Spectacularly predictive!

- SU(2)xU(1) Gauge model predicts chiral structure of Weak interactions, and existence of $W^{\pm}$. Z^0 and γ

$$\mathscr{L}_{mass} = -m\overline{\psi}\psi = -m\left(\overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L\right)$$

- Two problems --
  - Dirac Fermion mass terms in the Lagrangian violate gauge invariance -- mix Left and Right components together

  - Gauge boson mass terms also violate gauge invariance, just like the photon in QED.

  -- conflict with observations!

The Subterfuge -- Add a Minimal Set of New Fields and Interactions

Higgs, Guralnik, Kibble, Englert, Brout, Anderson, Glashow, Weinberg, Salam -- 1963-1968.

Complex Doublet of fields -- four real degrees of freedom

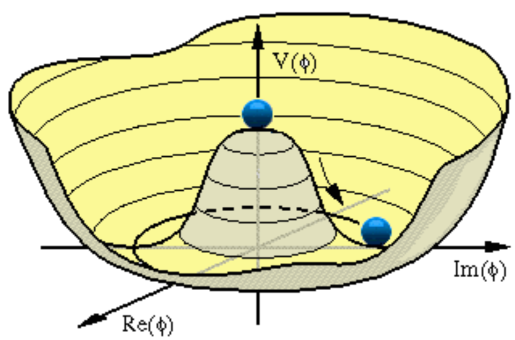
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

with a self-interaction

$$V(\Phi) = -\mu^2 \left| \Phi^* \Phi \right| + \lambda \left| \Phi^* \Phi \right|^2$$

Φ acquires a VEV (of order m_t), and three massless would-be Goldstone Boson degrees of freedom are absorbed by the $W^{\pm}$ and Z^0, while the fourth remains as a physical Higgs boson. $SU(2)_L x U(1)_Y$ is broken to $U(1)_{EM}$.

Yukawa terms allow for Fermion masses.



Basic Relationships

$$v = \left(\frac{\mu^2}{\lambda}\right)^{1/2}$$

Vacuum Expectation Value of the Higgs field -- Minimizes V(ϕ)

$$m_H = \mu\sqrt{2} = v\sqrt{2\lambda}$$

$$g = \frac{e}{\sin\theta_W} \qquad g' = \frac{e}{\cos\theta_W}$$

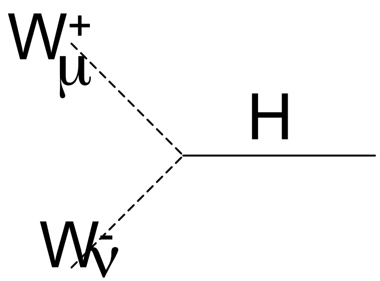
$$M_Z = \frac{v}{2}\sqrt{g^2 + g'^2} \qquad M_W = g\frac{v}{2} = M_Z\cos\theta_W$$

Fermion masses are the product of the VEV v and an arbitrary Yukawa coupling.

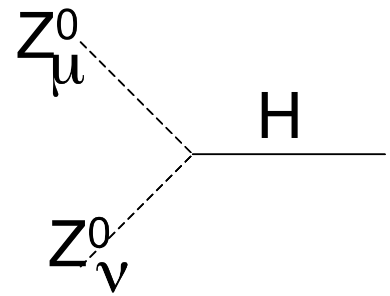
One free parameter: m_H

Conventions: Peskin and Schroeder “An Introduction to Quantum Field Theory”

Couplings of Higgs Bosons



$$= 2i \frac{M_W^2}{v} g^{\mu\nu}$$



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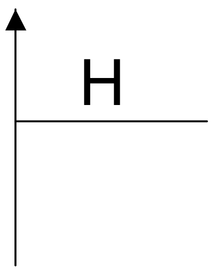
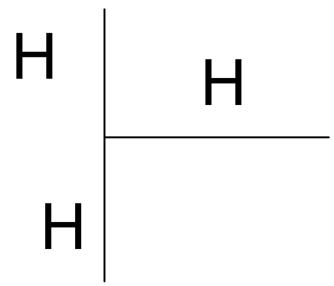


$$= -i \frac{m_f}{v}$$

Fermions



$$= -3i \frac{m_H^2}{v}$$

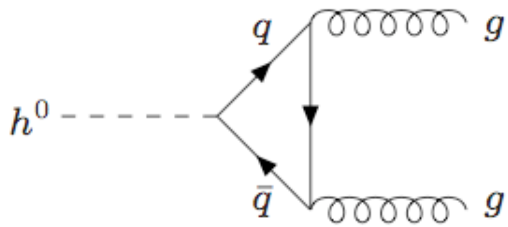
Also: Quartic W^+W^-HH
Z^0Z^0HH
HHHH diagrams.

Conventions: Peskin and Schroeder “An Introduction to Quantum Field Theory”

Higgs Boson Couplings to Gluons

H. Haber, HCPSS 2008

At one-loop, the Higgs boson couples to gluons via a loop of quarks:



m_g=0 by $SU(3)_{color}$ symmetry

This diagram leads to an effective Lagrangian

Mostly top contributes

$$\mathcal{L}^{\rm eff}_{hgg} = \frac{g\alpha_s N_g}{24\pi m_W} h^0 G^a_{\mu\nu} G^{\mu\nu a} \,,$$

where N_g is roughly the number of quarks heavier than h^0. More precisely,

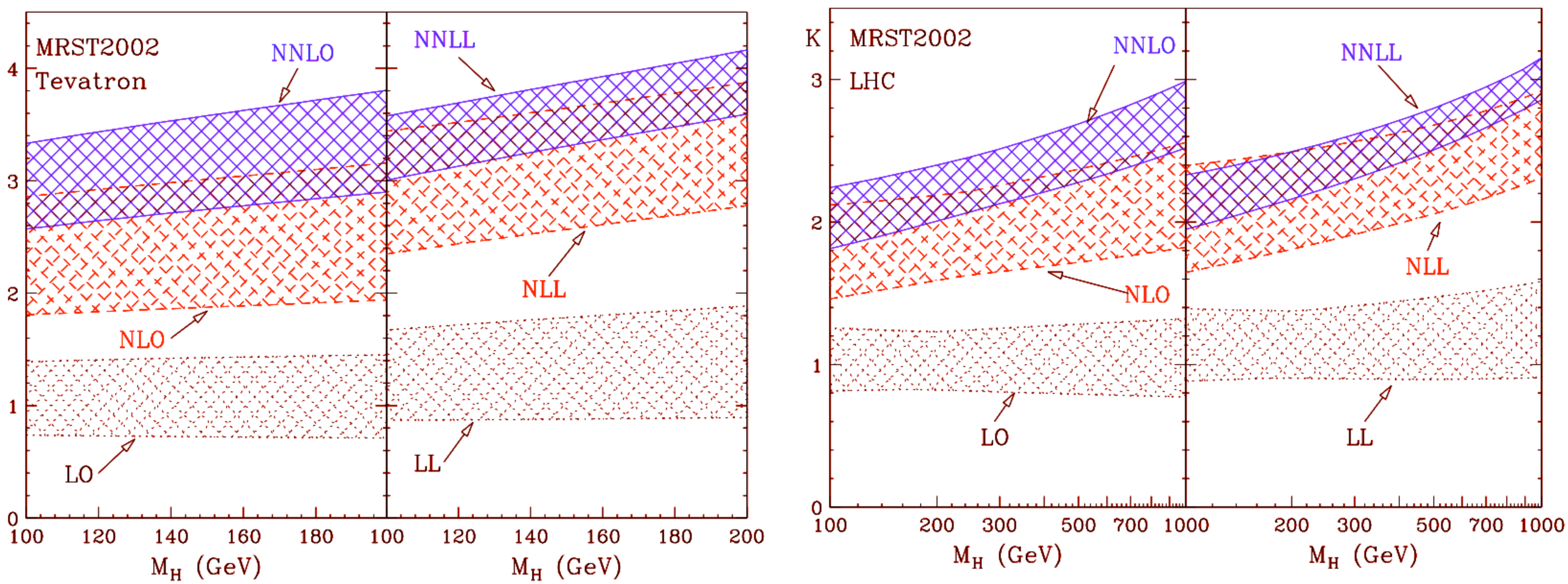
$$N_g = \sum_i F_{1/2}(x_i) \,, \qquad x_i \equiv \frac{m^2_{q_i}}{m^2_h} \,,$$

where the loop function $F_{1/2}(x) \to 1$ for $x \gg 1$.

A heavy fourth generation of quarks would scale
the $gg \to H$ production rate at colliders by a factor of ~9.
But watch out for $H \to \nu_4 \bar{\nu}_4$ decays.
E. Arik et al., Acta Phys. Polon. B **37**, 2839 (hep-ph/0502050)

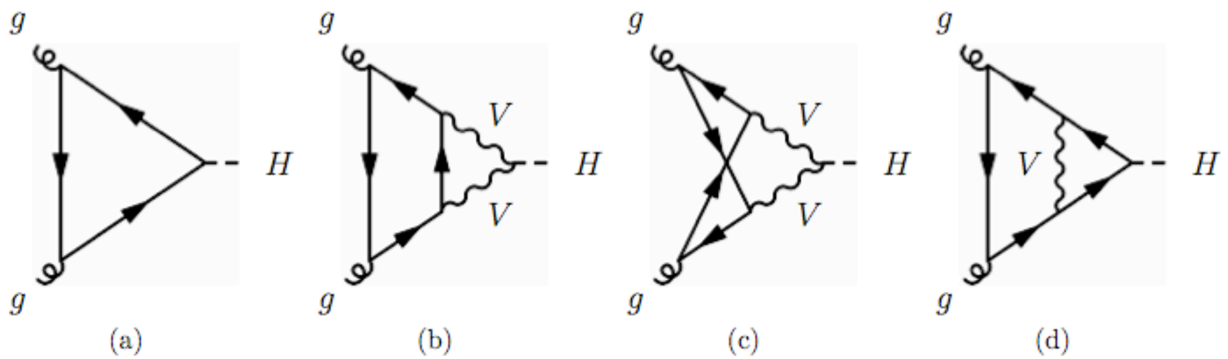
Recent gg→H Production Cross Section Progress

- Leading order is one-loop, so NLO involves more pieces -- gluon radiation from gluons, and more loops.
- NLO corrections -- ~80% (almost double the cross section)!
- NNLO QCD corrections -- An additional 40% on top of that!
  Residual uncertainty ~10%. Catani, de Florian, Grazzini, Nason
  JHEP **0307**, 028 (2003) hep-ph/0306211



NLO,NNLO bands: $0.5m_H<\mu_F,\mu_R<2M_H$. Bands on LO unreliable.

Recent gg→H Production Cross Section Progress



V=W,Z

An active area of research. See
http://www.itp.uzh.ch/events/higgsboson2009 7-9 January 2009, Zurich

- Two-loop EW corrections yield up to an 8% boost in cross section near m_H=160 GeV. Aglietti, Bonciani, Degrassi and Vicini, arXiv:hep-ph/0610033 (used by the Tevatron at ICHEP 2008)
- Newer calculations: Anastasiou, Boughezal, Petriello, arXiv:0811.3458 [hep-ph]
  Grazzini, De Florian, arXiv:0901.2427 [hep-ph]

  More modern PDF set -- MRST 2006 NNLO

  Bottom quark loops interfere destructively with top quark loops
  - Bottom quark loop contributions get smaller QCD corrections than top loops.
  - Running b mass is smaller than pole mass.

  Less contribution from b loops means more cross section

  Total 14% bigger cross section relative to NNLO QCD (Catani et. al) at m_H=160 GeV -- 0.49 pb at the Tevatron.

But: Parton Distribution Functions Can be Very Important for $gg \rightarrow H$ Predictions

Grazzini, Higgs Boson 2009:

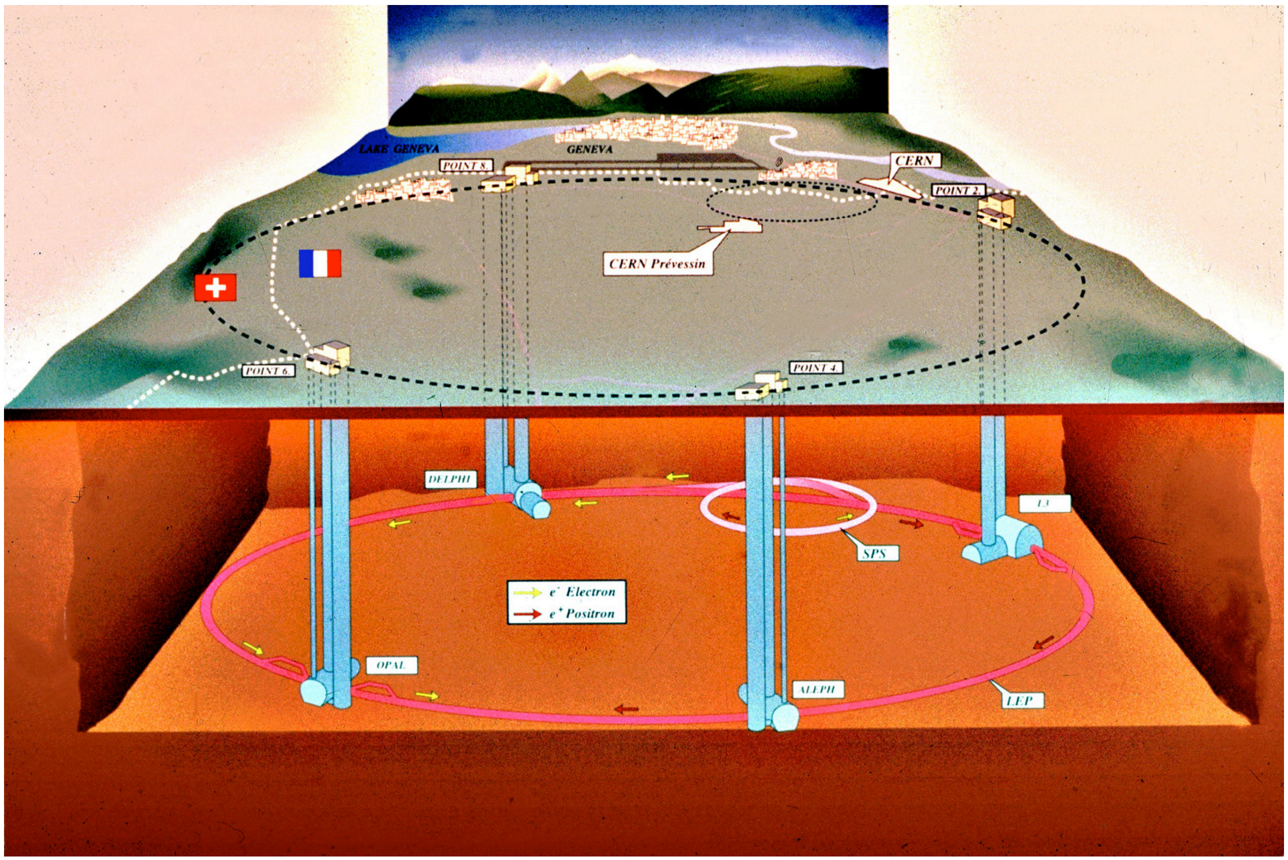
MSTW released a new PDF set on January 5, 2009

Preliminary impact on LHC $gg \rightarrow H$ cross section: ~2%
but on the Tevatron result, big differences -- 6-15% less
for $100 < m_H < 200$ GeV

Important concern: Measuring $Br(H \rightarrow WW)$ for $m_H \sim 160$ GeV relies on theoretical understanding of $\sigma(gg \rightarrow H)$, or non-observation of other modes.

The LEP Accelerator at CERN (1989-2000)

- Four experimental collaborations -- ALEPH, DELPHI, L3, OPAL
- e^+e^- Collisions at CM energies up to 209 GeV



The LEP Legacy -- SM Searches

- More than 150 people directly involved in Higgs boson searches
  (not all at the same time or in the same place)

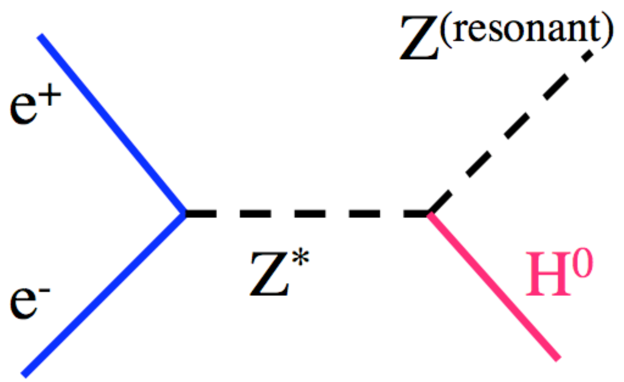
- Four search modes, qqbb, llbb, $\nu\nu$bb, qq$\tau\tau$/$\tau\tau$bb

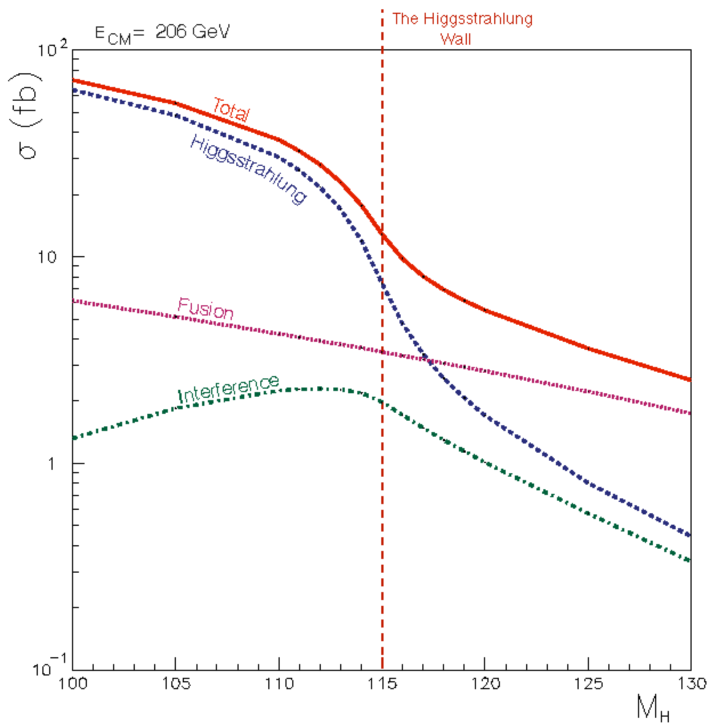
- Strategies involved m_{jj}, likelihood functions, neural networks. Some used 2D discriminants (b-tagging vs. kinematic nets) -- Evolved over time.

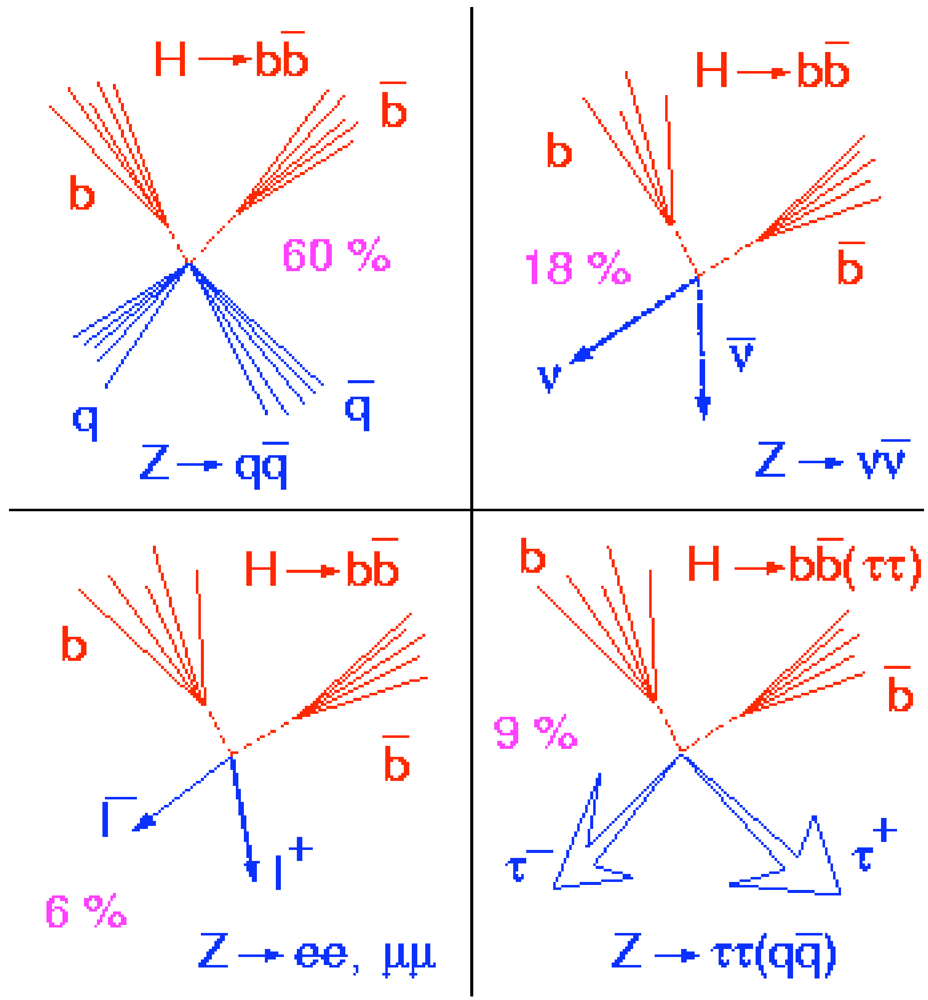
- m_{jj} much sharper at LEP than at the Tevatron -- 3 GeV mass resolution due to beam constraints.

- Large s:b in highest-score bins, of order 2:1 or more

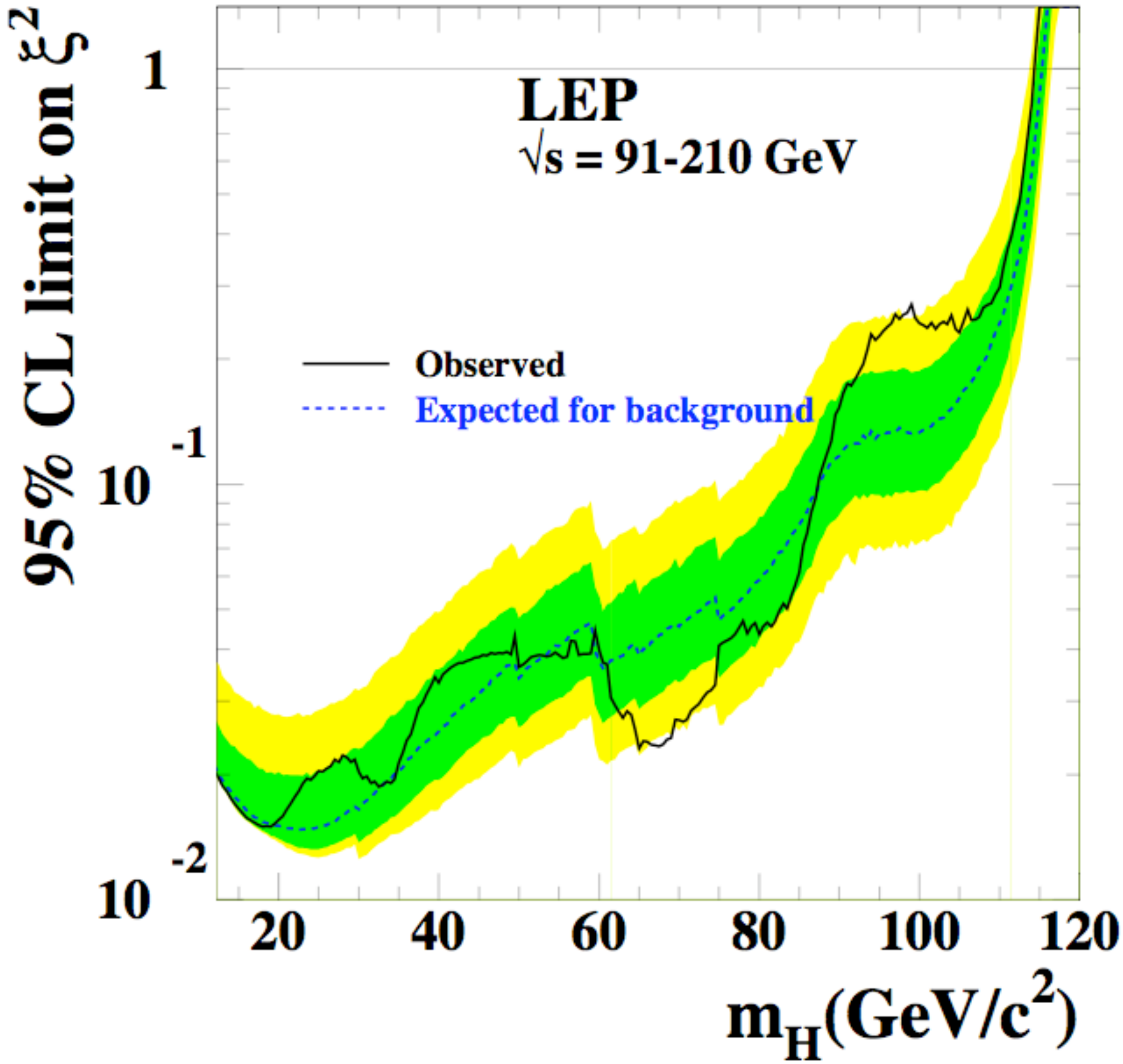
The LEP Legacy -- SM Searches



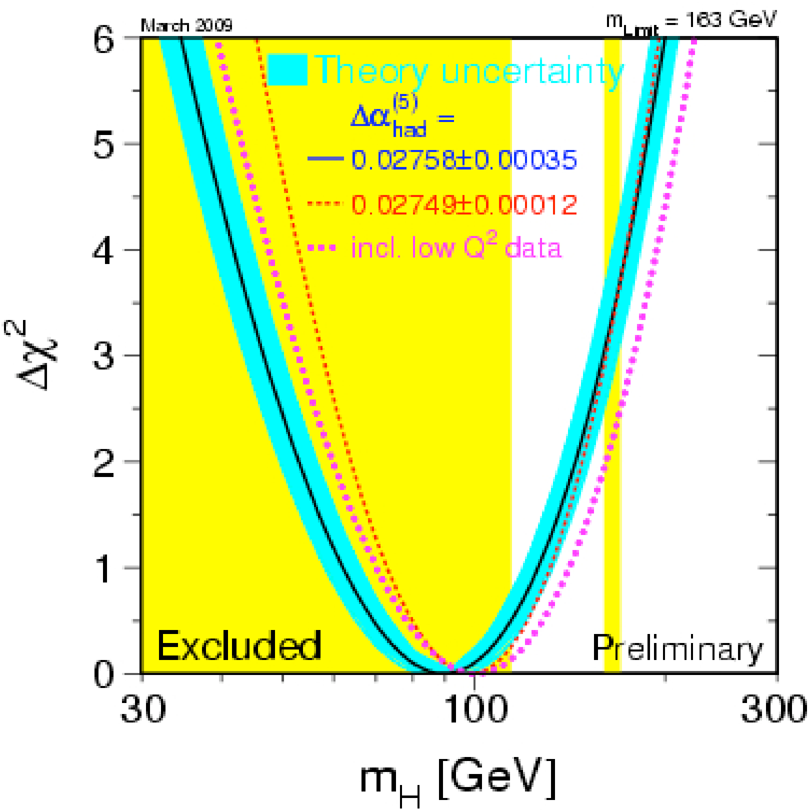


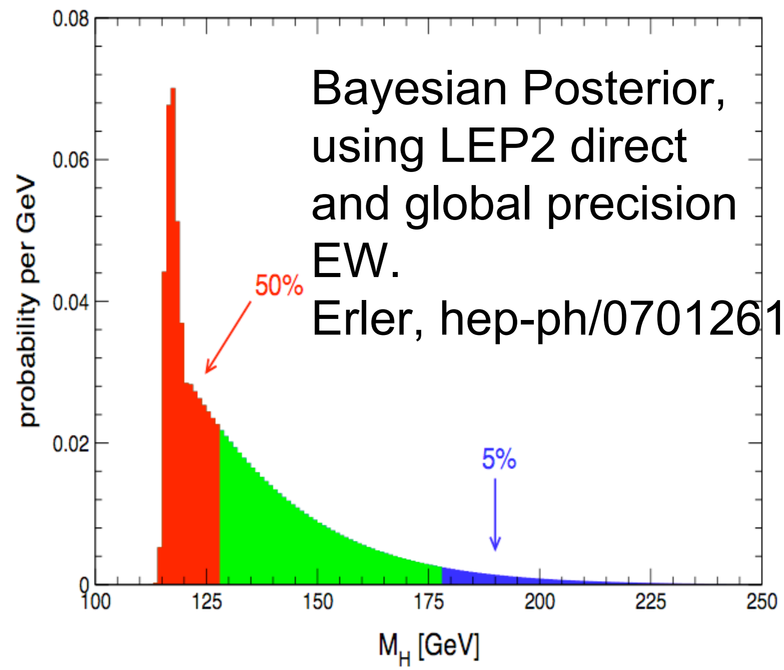


The LEP Legacy -- SM Searches



LEP, SLC and the Tevatron: Precision EW Measurements





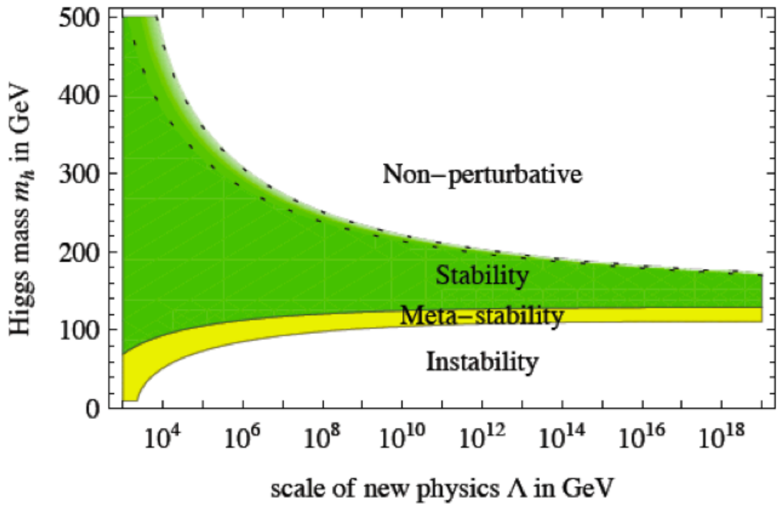
(one iteration
behind..)

Best fit $m_H = 90^{+36}_{-27}$ GeV

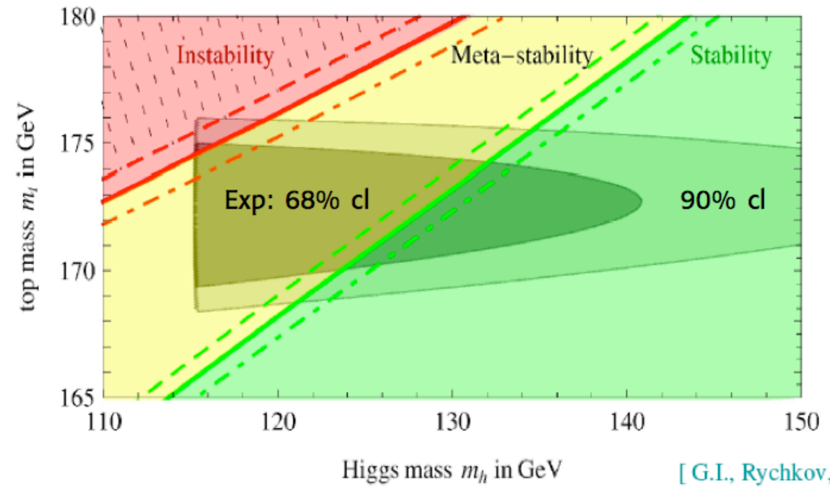
95% CL upper limit: 163 (191) GeV
Lower limit: 114.4 GeV (LEP2) @95% CL,
but CL gets much stronger just below that

More Theoretical Prejudice -- Where we Expect m_H to be

Isidori, Rychkov, Strumia, Tetradis '08

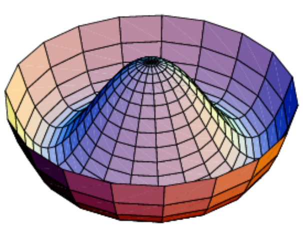


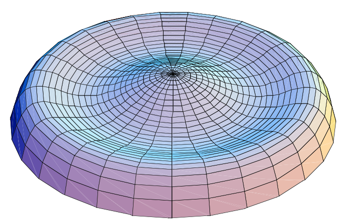
Adding the metastable possibility: Isidori, Ridolfi, Strumia '01



[G.I., Rychkov, Strumia, Tetradis '08]

- The unstable region is almost ruled out





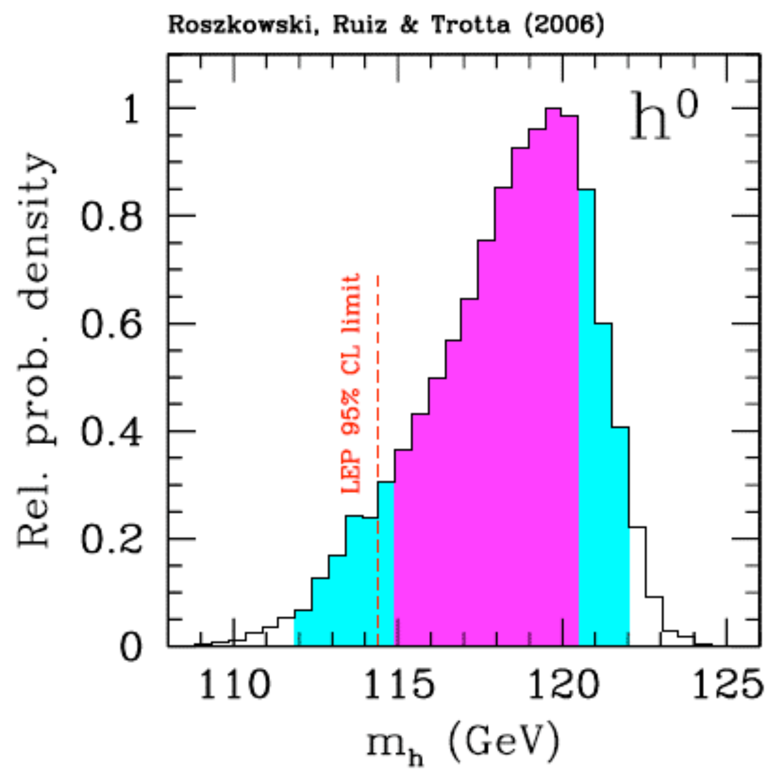
m_H too light!

CMSSM Favors m_H <120 GeV

- Bayesian scan over CMSSM parameter space.
- Inputs
  - Direct LEP2 Higgs searches
  - Precision EW
  - Muon g-2
  - WMAP assuming CDM=neutralinos: $\Omega_\chi h^2$
  - B_s Mixing Rate: ΔM_{B_s}
  - $Br(B \rightarrow s\gamma)$
  - $Br(B_s \rightarrow \mu^+\mu^-)$
- Sophisticated MCMC guided search for high-posterior-probability parameter values
- CMSSM parameters (flat prior)
  50 GeV < m_0 < 4 TeV
  50 GeV < $m_{1/2}$ < 4 TEV
  $|A_0|$ < 7 TeV   2 < $\tan\beta$ < 62

MSSM h is SM-like for these models (production, decay)

hep-ph/0611173
JHEP 0704:084 (2007)

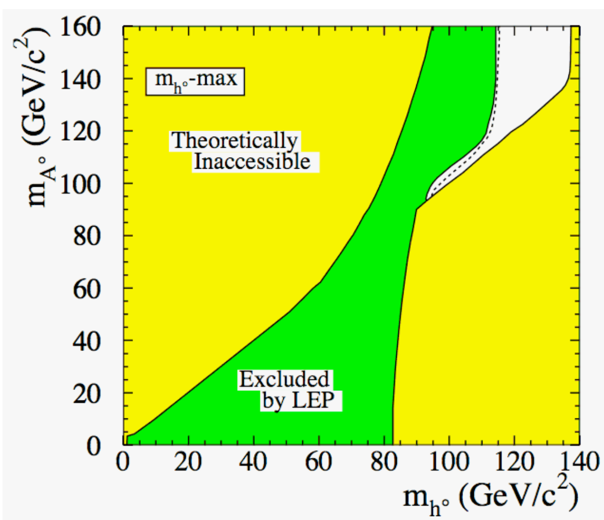


Update: R. Trotta et al., arXiv:0809.3792 [hep-ph] -- similar constraints

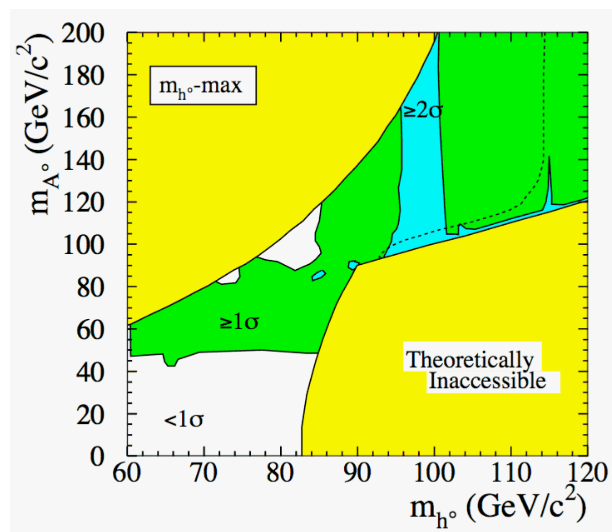
The LEP Legacy: MSSM Higgs Searches

- Additional searches for $e^+e^- \to h^0A^0$ in the four-jet and tau channels added in.
- A large parameter space covered (m_A,tanβ) even for the simplest, most constrained scenarios.
- Similar exquisite m_{jj} resolution as in the SM case
- Many chances for false bumps at the 2-3σ level
- If CL_{s+b} were used, many chances for false exclusion of signals that could not be tested at all.

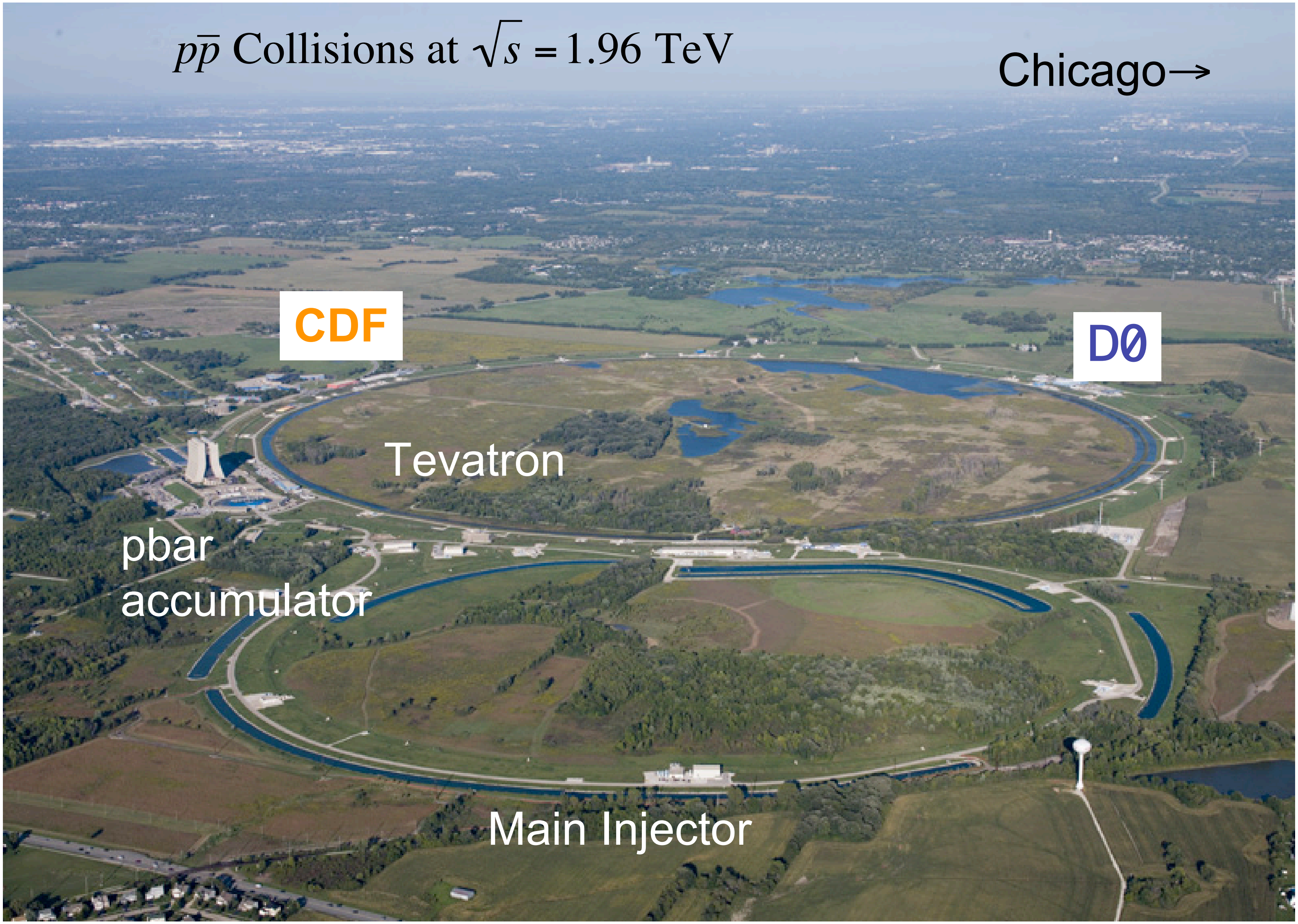
Limits:



p-values:

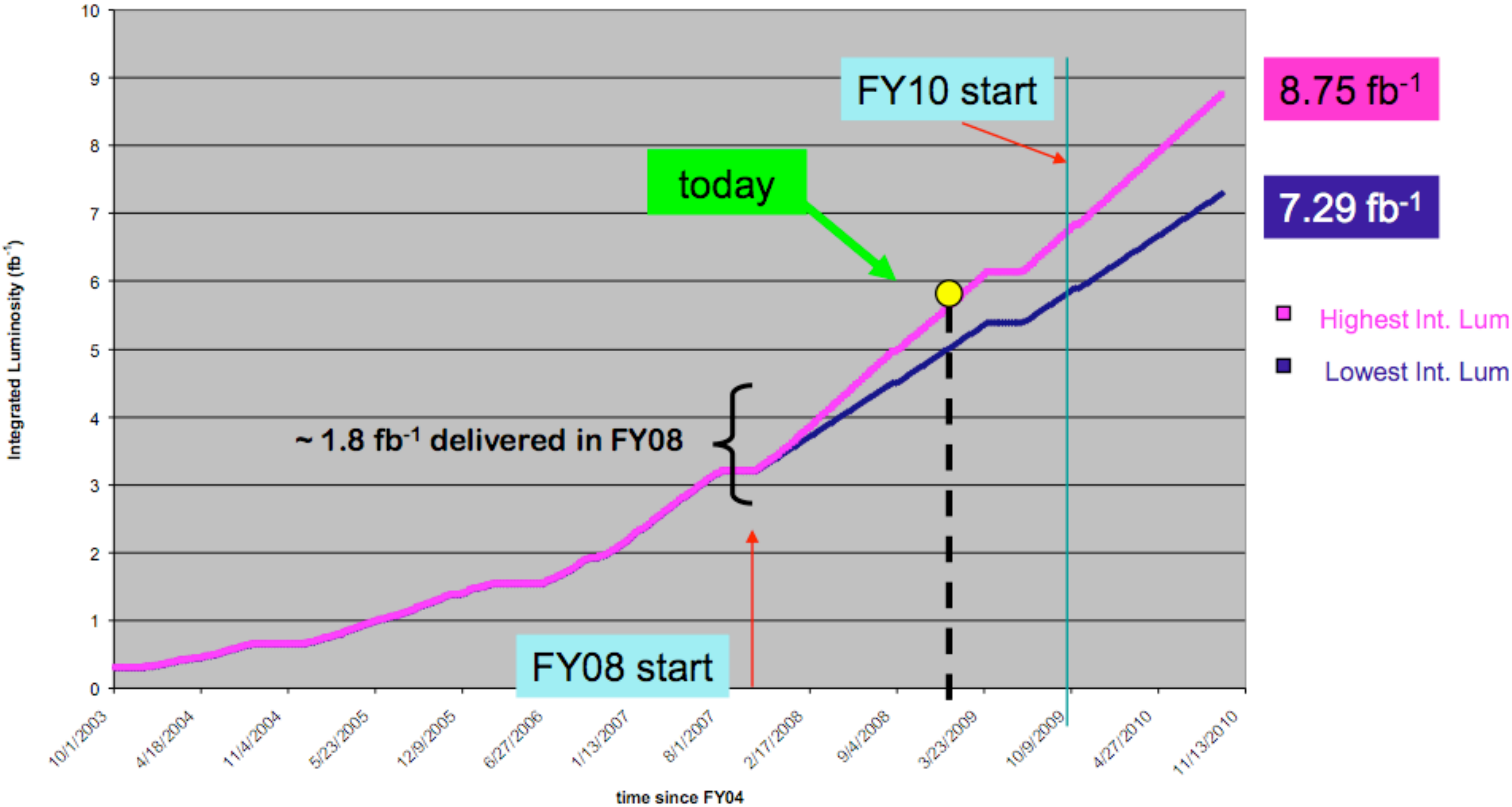


The Baton is Handed to the Tevatron

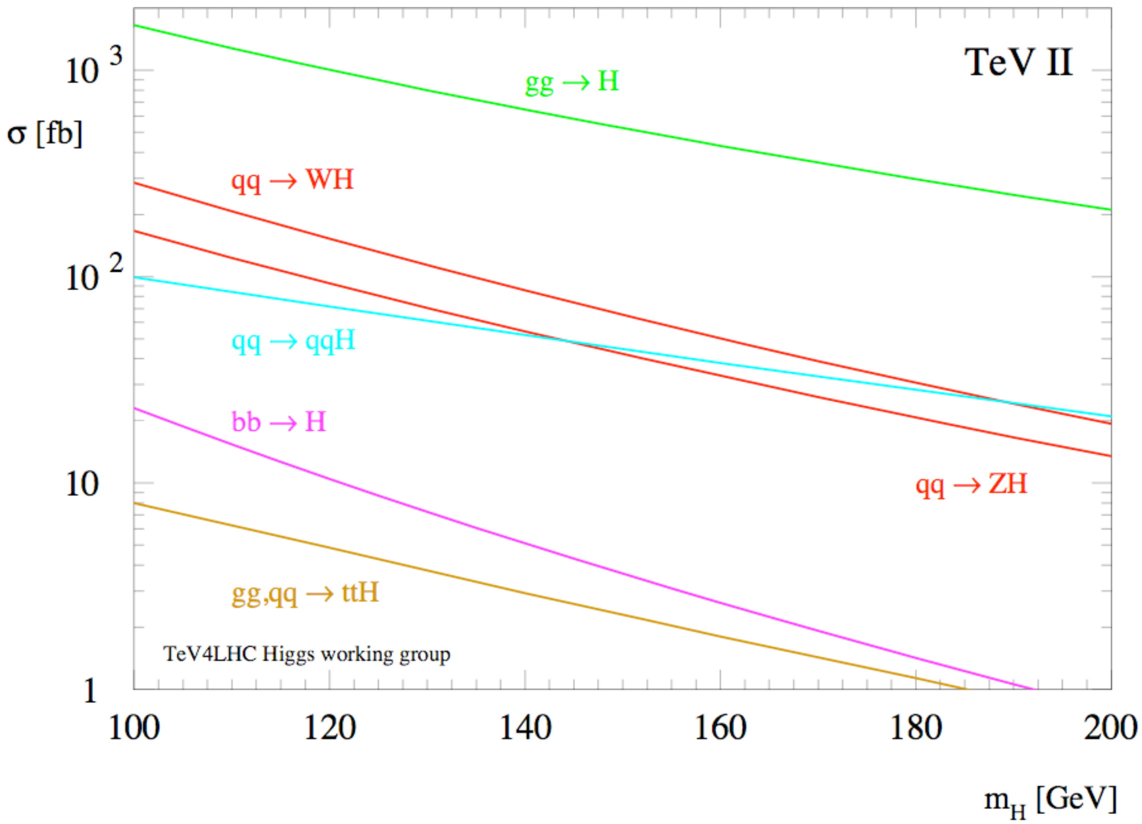


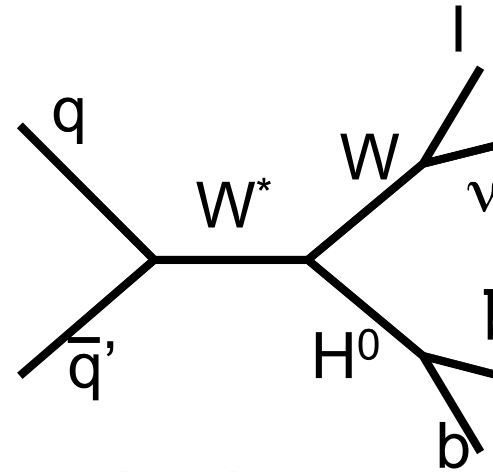
Accelerator Performance Constantly Improves

plot from January 2009

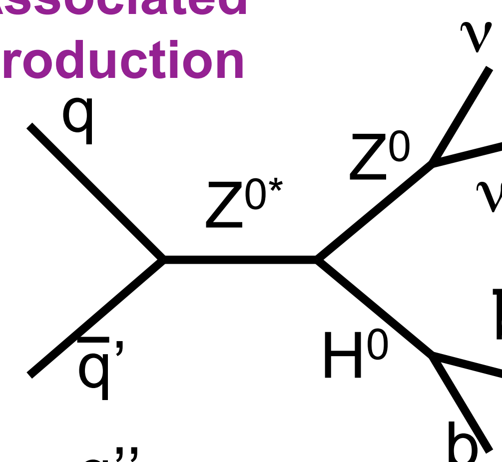


SM Higgs Boson Production Mechanisms

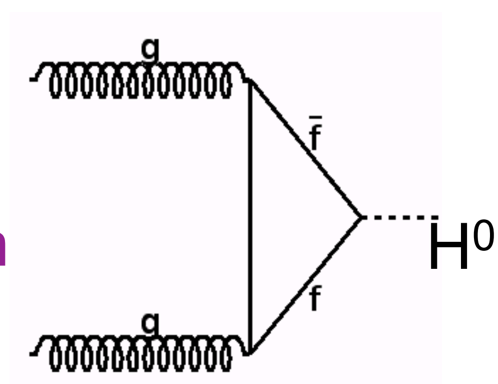


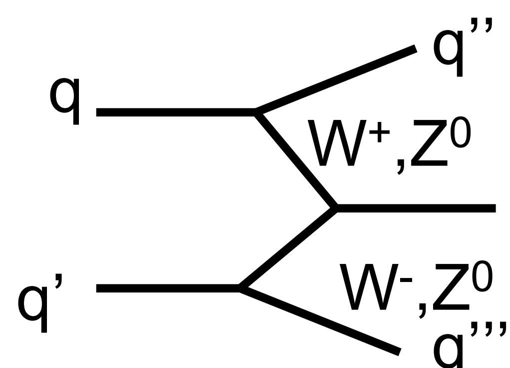


Associated Production



gluon fusion

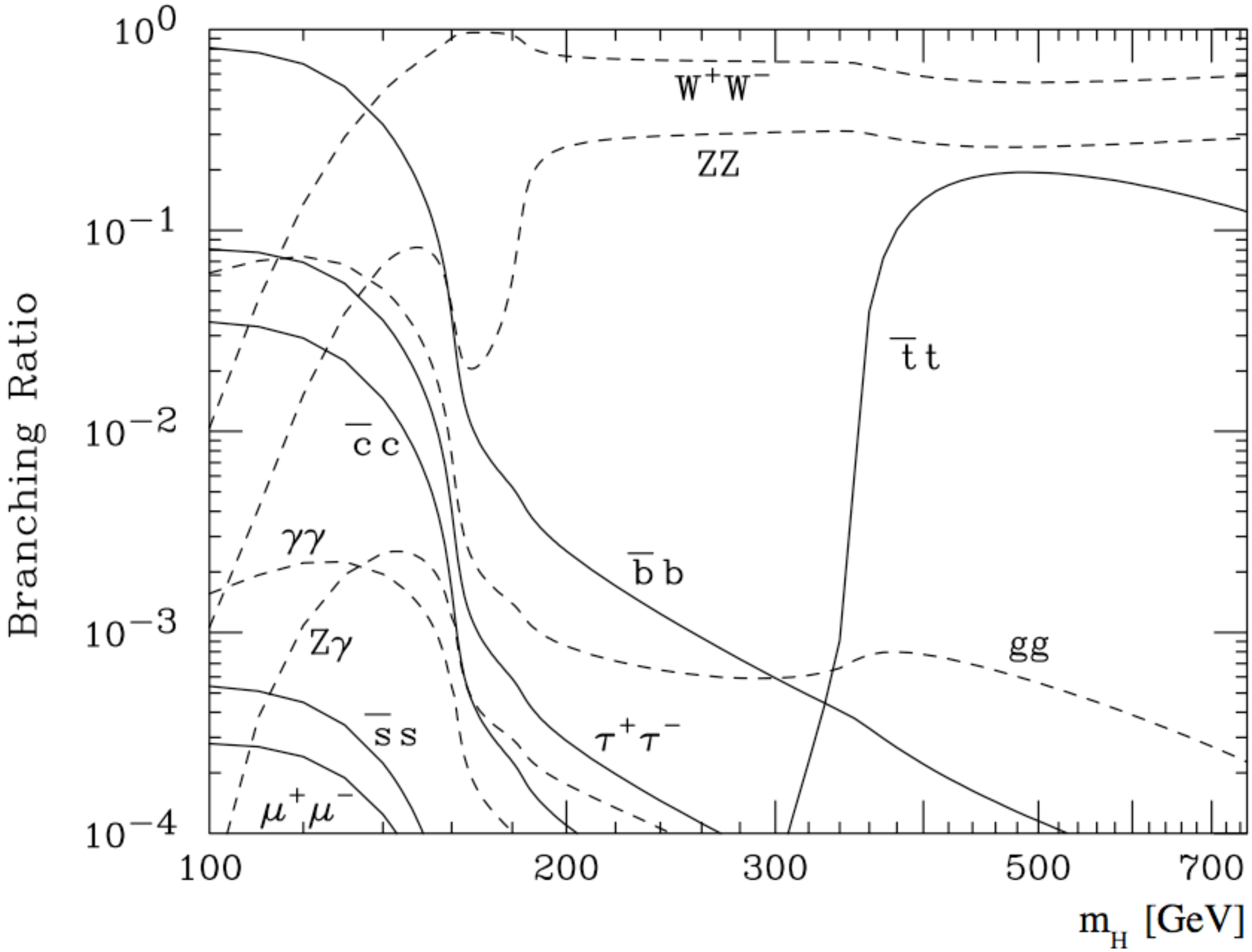




Vector-Boson Fusion (VBF)

Standard Model Higgs Boson Decay Branching Fractions

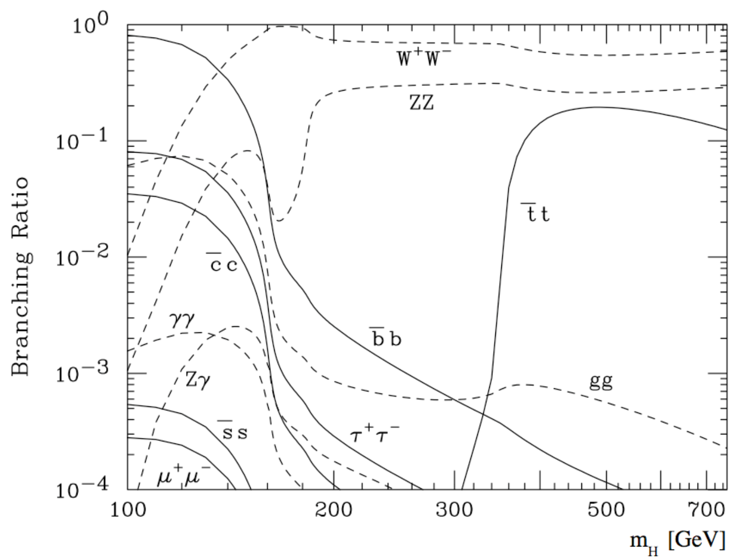
Latest
calculation:
HDECAY
by
M. Spira



CDF's Low-Mass Searches

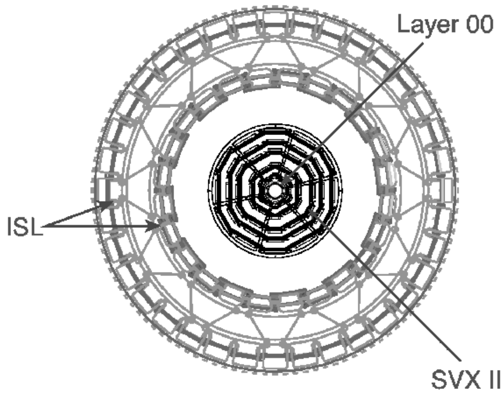
- CDF (and D0) are now mature collaborations with very sophisticated Higgs boson searches
- Five channels: $WH \rightarrow l\nu bb$, $ZH \rightarrow \nu\nu bb$, $ZH \rightarrow llbb$, $WH+ZH \rightarrow qqbb$, $H \rightarrow \tau\tau$(+jets). ($H \rightarrow \gamma\gamma$ in the works)
- Also $H \rightarrow WW$ channels contribute (less at low mass due to falling b.r.).

$H \rightarrow bb$ searches have best sensitivity for $m_H < 130$ GeV



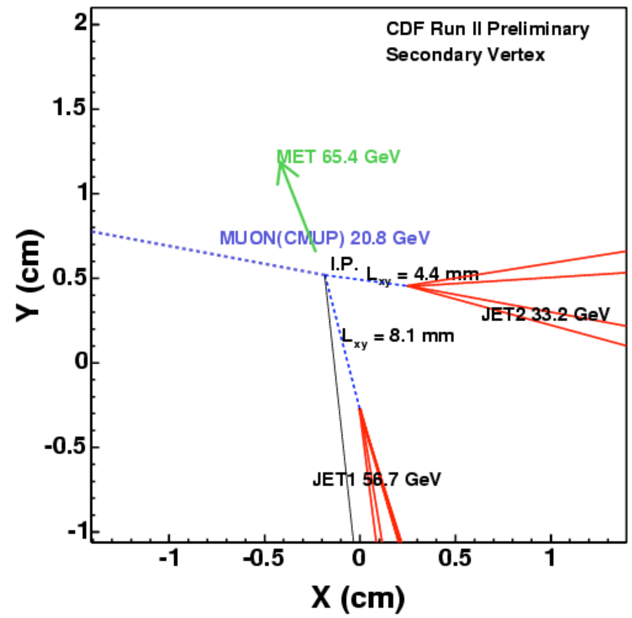
B-Tagging at CDF

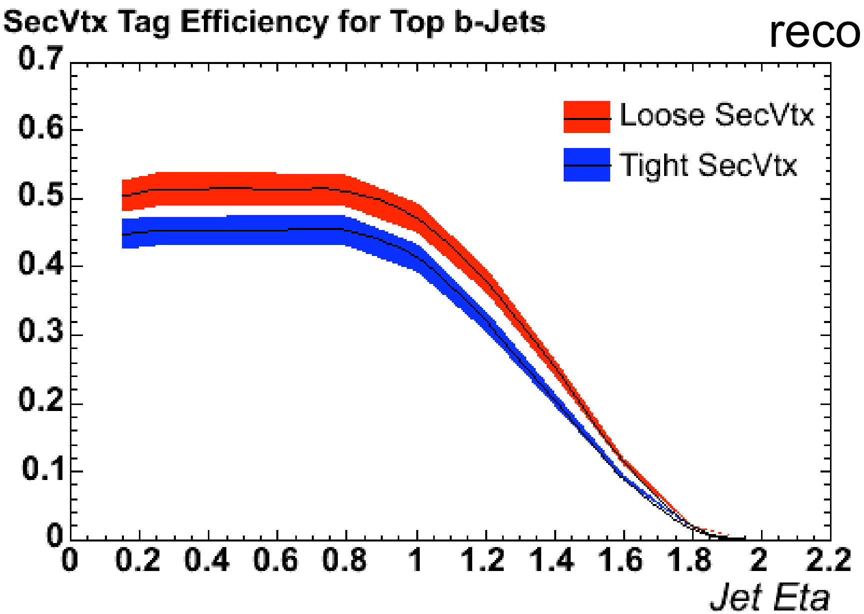
L00 single-sided silicon +
5-layer double-sided silicon+
2-layer ISL



Impact parameter resolution for high-p_T tracks ~18μm

B-tagging relies on displaced vertex reconstruction





Mistag rates typically ~1% for light-flavor jets

Example candidate event (lvbb)

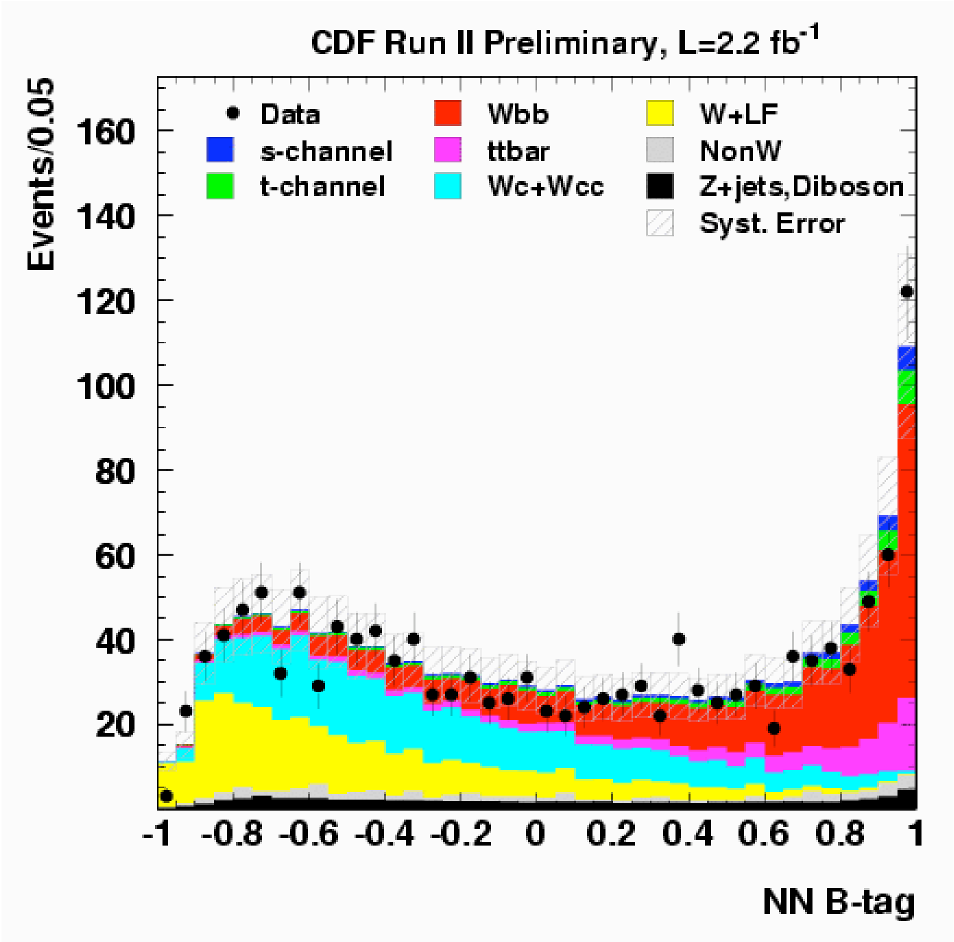
A Neural-Net B-tagging Tool

Identified secondary-vertex tags have a significant charm and mistag contamination.

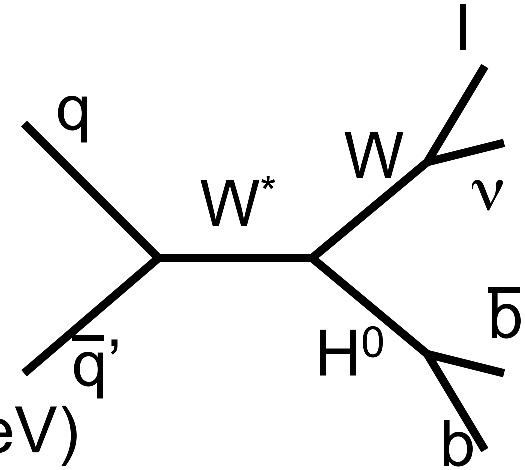
➔Train a NN to separate b, c, LF in the vertex-tagged samples.

Some of the Inputs:

Displaced vertex mass
tracks in displaced vertex
Decay flight distance and significance
Identified leptons in and near jets
Secondary vertex fit χ^2
Jet E_T



Low-Mass Search Channel 1 $WH \rightarrow l\nu bb$: Matrix Element + Boosted Decision Tree



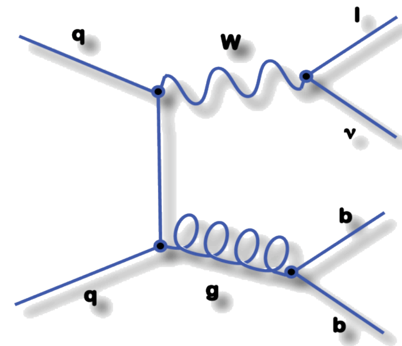
- Select events with:
  - A high-P_T lepton ($\geq$20 GeV), e or μ
    isolated track category --
    gave an extra PhD thesis
  - Missing $E_T \geq 20$ GeV
  - Two jets (cone=0.4, $|\eta|<2.0$, $E_T>20$ GeV)
  - One or two b-tags (different s/b so split these categories)
  - Veto Z's, cosmics, conversions

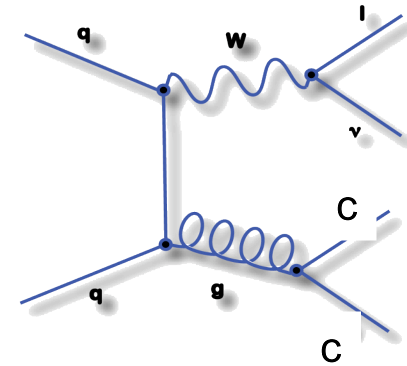
- Two analysis subteams -- a ME and a BDT team worked together (first on single top)

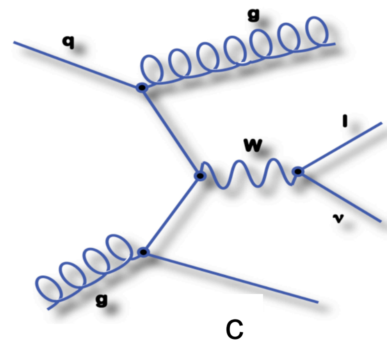
- Two larger teams -- ME+BDT and NN then collaborated with a superdiscriminant combination

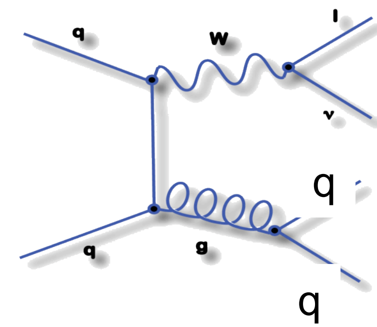
Backgrounds are Ferocious

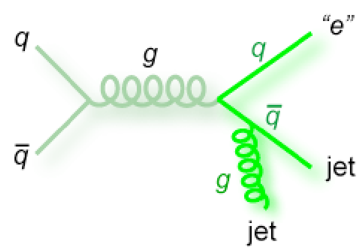
Process	1 Tag	2 Tags
WW	56.2 ± 6.2	0.4 ± 0.1
WZ	23.0 ± 1.7	4.8 ± 0.5
ZZ	0.8 ± 0.1	0.2 ± 0.0
TopLJ	121.3 ± 17.1	23.8 ± 3.9
TopDil	48.8 ± 6.8	14.1 ± 2.3
Stop T	64.0 ± 9.3	1.8 ± 0.3
Stop S	40.6 ± 5.7	12.8 ± 2.1
Z+jets	37.4 ± 5.5	2.1 ± 0.3
Wbb	538.7 ± 162.5	70.3 ± 22.5
Wcc/Wc	489.1 ± 150.9	6.8 ± 2.3
W+LF	458.0 ± 57.9	2.2 ± 0.6
QCD	135.5 ± 54.2	9.0 ± 3.6
Total Bg	2013.3 ± 324.1	148.2 ± 26.1
WH115	6.3 ± 0.5	2.0 ± 0.2
Data	1998	156

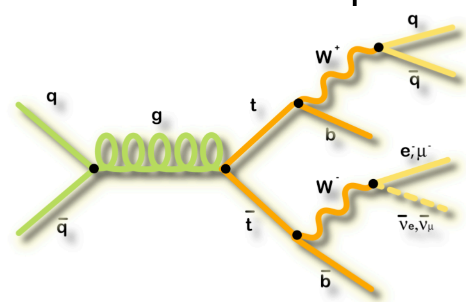


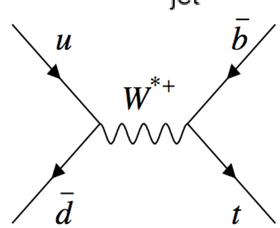


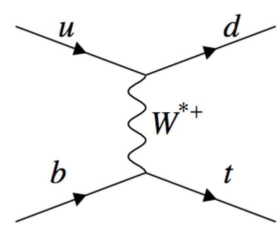












Matrix Element Basics

Predictions given by QM matrix element and phase space.

Many processes (signal and background) give the same observable quantities in the detector -- cannot assign an event to be signal or background (if we could, we would!)

Instead, ask what the ratio of chances of getting an event from signal or background processes. Need to incorporate experimental resolution effects.

Reconstruction Ambiguities

- Missing neutrino! Missing E_T resolution is about 8 GeV
- Can use M_W=80.4 GeV constraint to solve for missing $p_z(\nu)$, but with two ambiguities.
- Jet energies not perfectly measured. Directions are pretty good, and leptons are measured well.
- Need to answer question of how many true physical processes could have given us the event we observe: integrate over all possibilites weighted by their Matrix Element and a transfer function

ME PDFs transfer function

$$P(x) = \frac{1}{\sigma} \int 2\pi^4 |M|^2 \frac{f(y_1)}{|E_{q_1}|} \frac{f(y_2)}{|E_{q_2}|} W(y,x) d\Phi_4 dE_{q_1} dE_{q_2}$$

Separate P's for each matrix element for each process

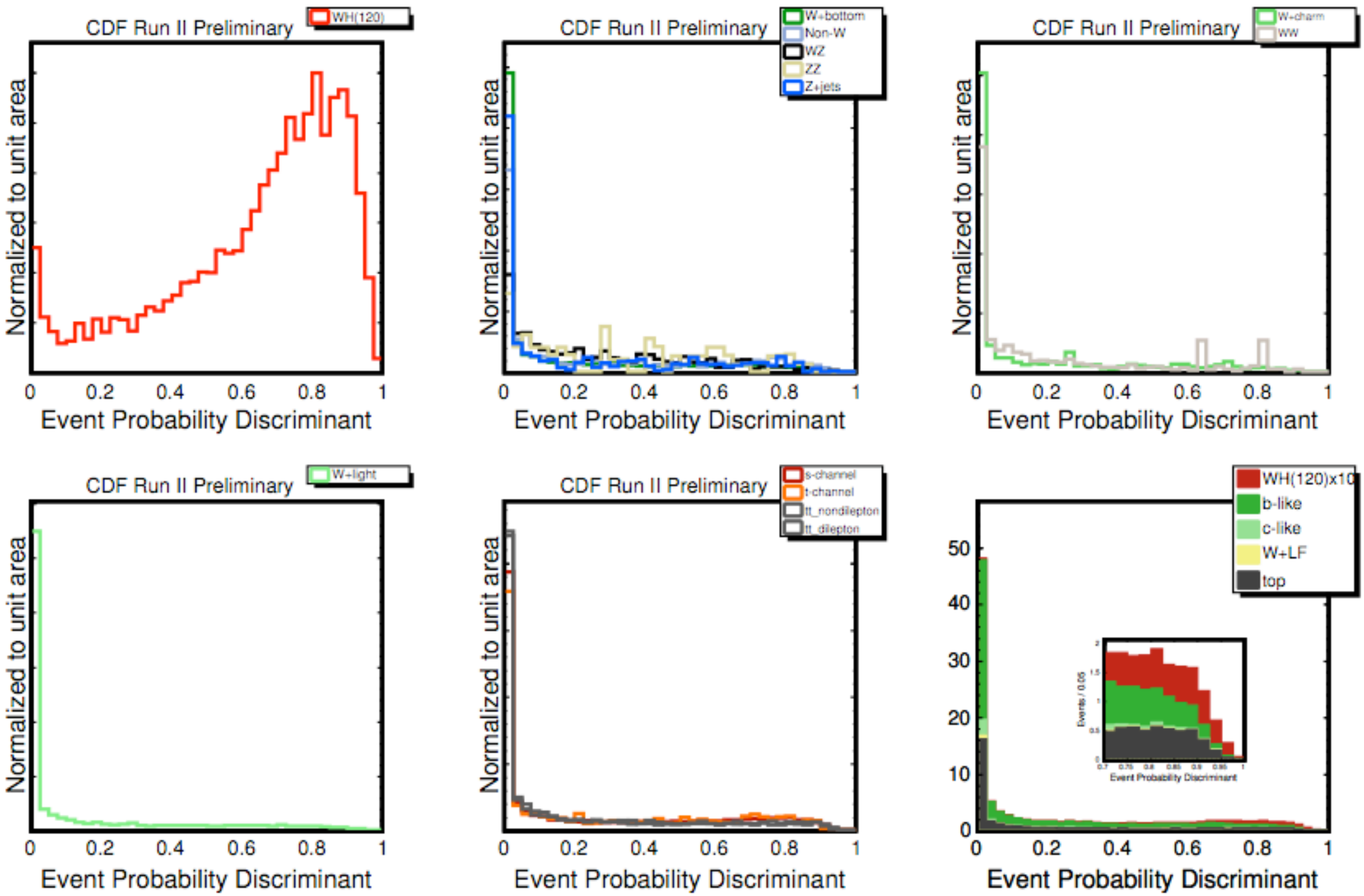
Boiling it Down into a Single Discriminant

- Not every process has a matrix element
  -- e.g. fake leptons
  -- need to have a discriminant for separating signal from background that we can test the distribution of using data-based models

- Not all information we know about goes into the matrix element
  -- e.g., the neural network flavor separator

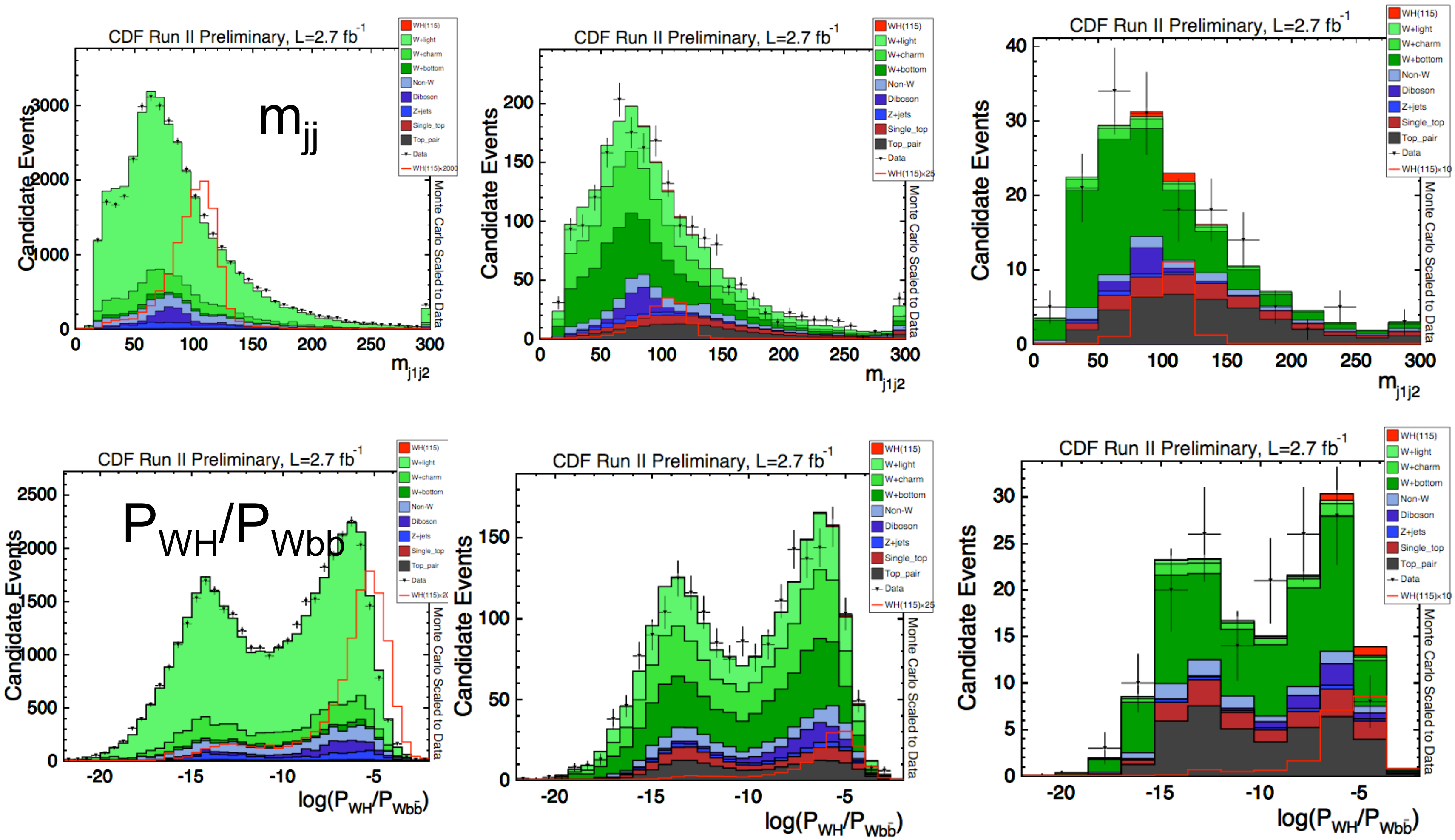
$$EPD = \frac{b \cdot P_{WH}}{b\left(P_{WH} + P_{singletop} + P_{Wb\bar{b}} + P_{t\bar{t}}\right) + (1-b)\left(P_{Wc\bar{c}} + P_{Wcj} + P_{Mistag} + P_{diboson}\right)}$$

Templates For Matrix Element WH Search

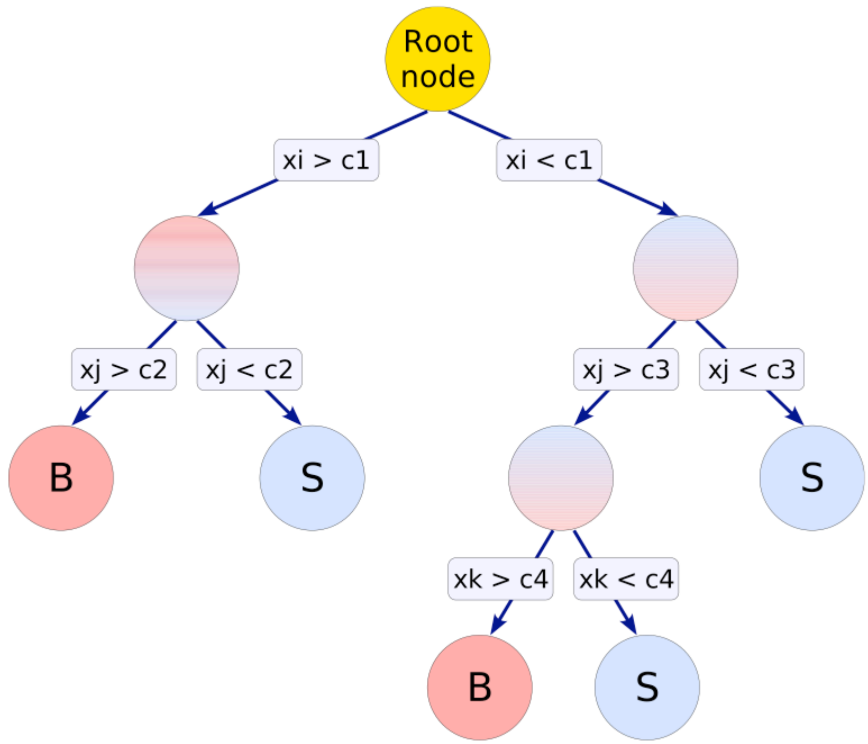


Some of the Important Distributions

No b-tags | One b-tag | Two b-tags



Step 2 -- A Boosted Decision Tree

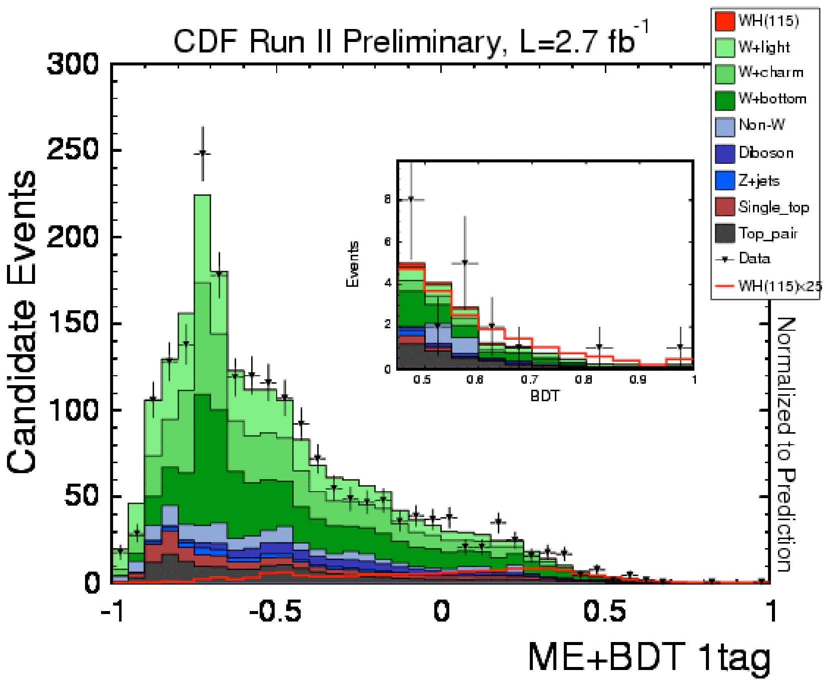


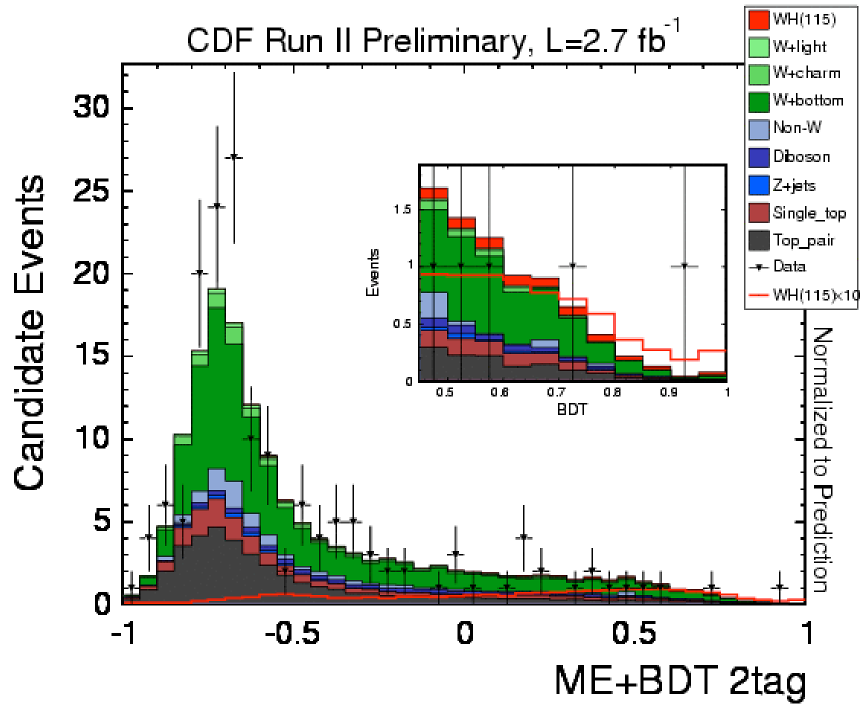
21 inputs. Important ones:

- matrix element EPD
- m_{jj}
- jet energies
- event H_T (scalar sum of object energies)
- NN flavor separator (b-tag improvement)

A standard machine-learning technique
Find the variable to cut on that gives the best improvement in Gini = p(1-p).
Next step: boosting. Reweight misclassified events and retrain a DT.

One- and Two-Tag ME+BDT Outputs





Signal systematic uncertainties

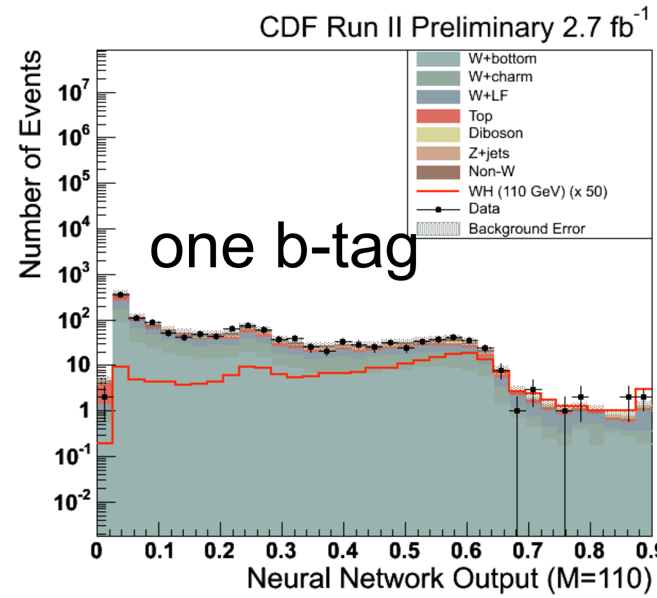
Systematic uncertainty	Single Tag	Double Tag
Jet energy scale	2.0 %	2.0 %
ISR/FSR + PDF	3.1 %	5.6 %
Lepton ID	~2.0 %	~2.0 %
Luminosity	6.0 %	6.0 %
b-tagging SF	3.5 %	8.4 %

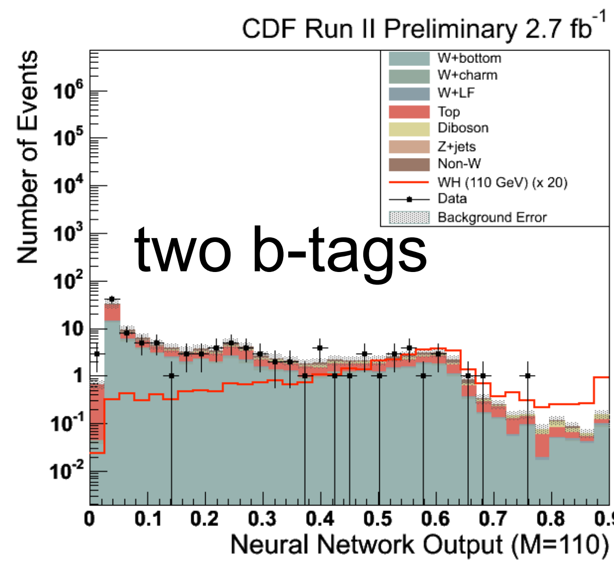
Background Systematic uncertainties

W+HF yield: ±30%
W+LF yield: ±13%
non-W yield: ±40%
ttbar yield: ±14%
(other backgrounds smaller)

Add in a Neural Network

- Separate Analysis Team,
  Same selected data events!
  Same Monte Carlo samples!
  Same Systematic Uncertainties!
  Not 100% correlated however
- Six NN input variables:
  m_{jj}
  Total system p_T
  P_T imbalance (scalar sum of lepton+jet p_T - Missing E_T)
  ΣE_T(loose jets)
  M_{min}(lepton+ν+jet)
  ΔR(lepton,ν)





Combining the Work of Two Teams Analyzing the Same Set of Events

- How do we get the most out of our work?
- Typical NN error function is not something we care about:

$$E = \sum_{events} (meas - desired)^2$$

- But it is easy to back-propagate for efficient training
- Instead we want
  - Discovery
  - failing that, exclusion
- This figure of merit works better:

$$F = \sum_{bins} s^2 / b$$

- But how do you train to optimize that?

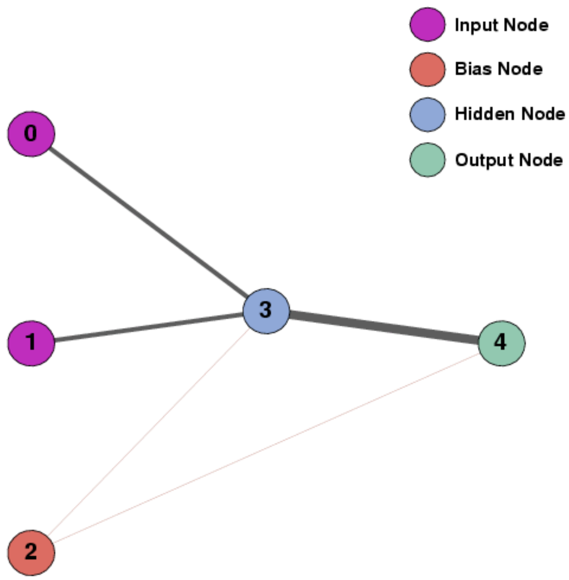
Neuro-Evolution to the Rescue!

Kenneth O. Stanley and Risto Miikkulainen (2002).
"Evolving Neural Networks Through Augmenting Topologies".
Evolutionary Computation 10 (2): 99–127;
http://en.wikipedia.org/wiki/NeuroEvolution_of_Augmented_Topologies

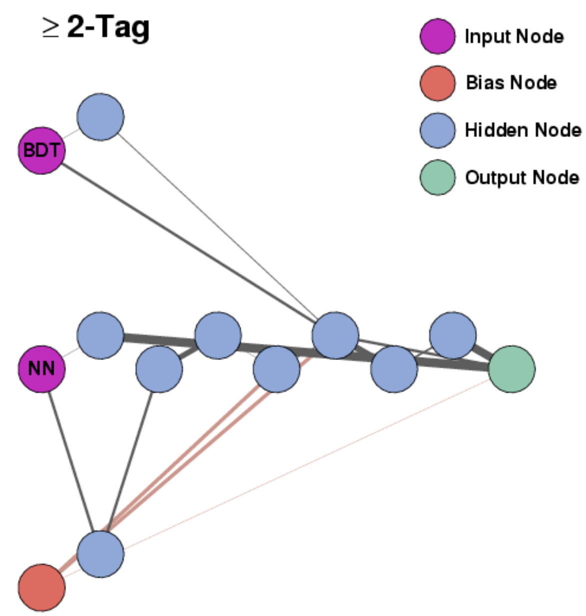
- Figure of merit difficult to calculate -- must form stacked predictions of each neural network configuration.
- Test one configuration, set of weights against others, pick features from the best performers
- Handles to optimize:
  Network topology
  Network weights
  Output binning
- Inputs MEBDT, NN outputs for each event.

- First demonstrated as a superdiscriminant with single top

Evolutionarily Trained Neural Networks



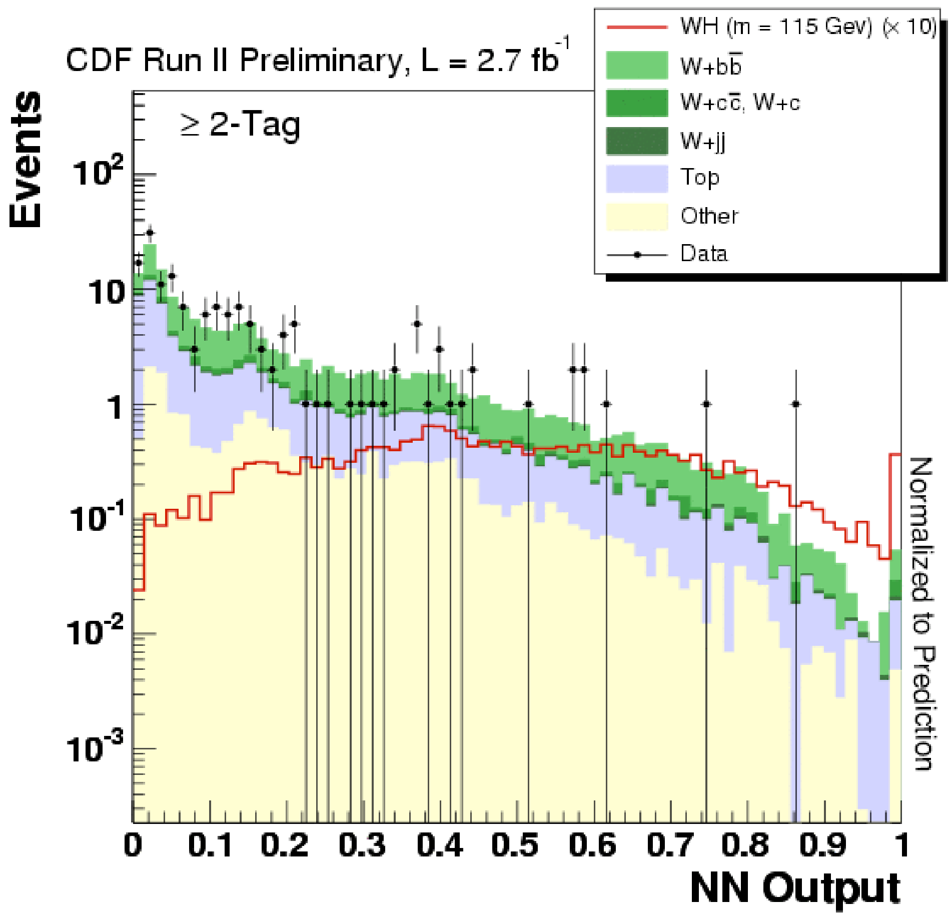
Starting Configuration...

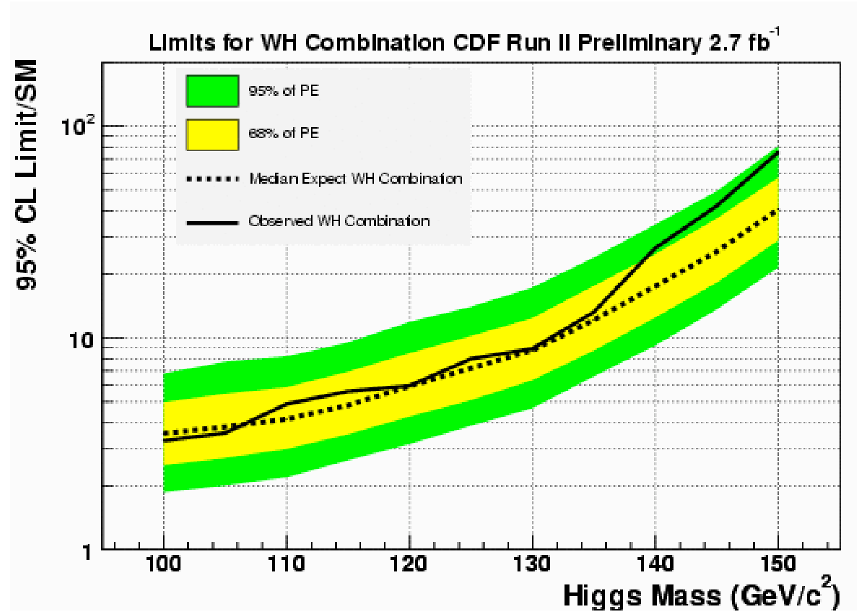


Evolved into this!

Approximately a 9% improvement in expected limit over the best input

WH→lνbb Limits in Combination





m_H (GeV)	Expected (σ/SM)	Observed (σ/SM)
100	3.5	3.3
105	3.8	3.6
110	4.1	4.9
115	4.8	5.6
120	5.9	5.9
125	7.2	8.0
130	8.7	8.9
135	12.2	13.2
140	17.5	26.5
145	25.6	42.1
150	40.5	75.5

Low-Mass Search Channel 2: WH,ZH→$\not{E}_T$bb

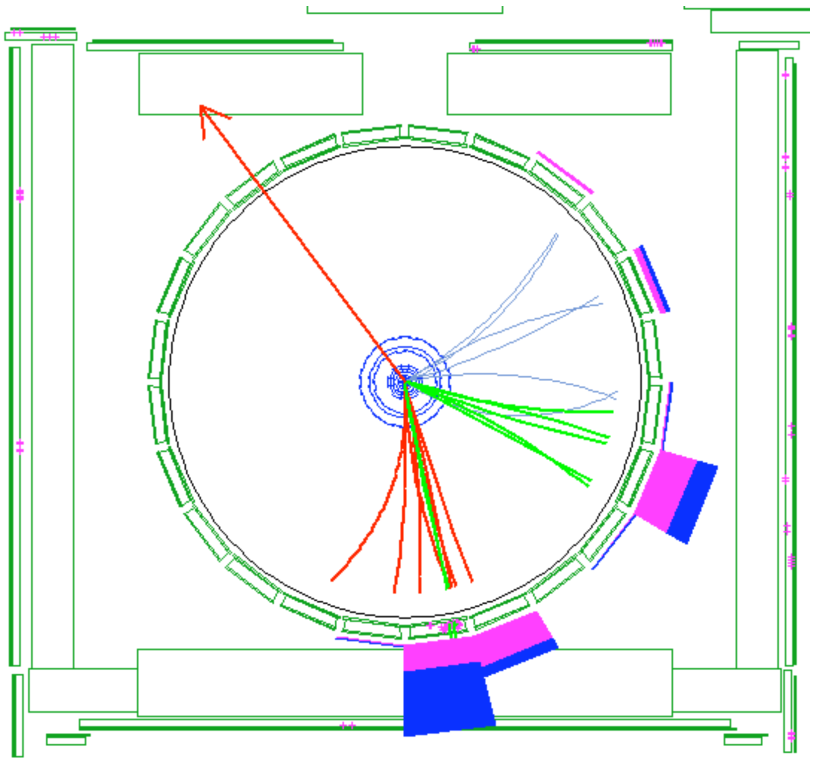
$\not{E}_T$>50 GeV
Two or three jets, E_{T1}>35 GeV, E_{T2}>25 GeV
$\Delta R_{j1,j2}$>1
Veto leptons, Jets must be separated from $\not{E}_T$
Three tag categories:

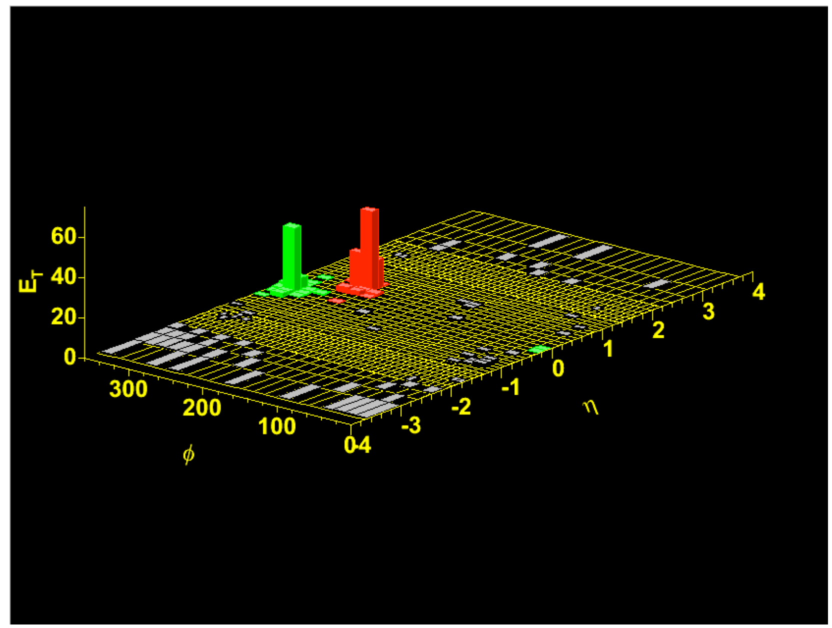
- Two tight secondary-vertex tags
- One tight and one jet-probability tag
- One tight tag

Process	Exclusive 1Tag	ST+ST	ST+JP
QCD + Mistags	941 ± 44	42.1 ± 8.7	78 ± 11
Single Top	43.2 ± 7.9	8.5 ± 1.7	7.2 ± 1.5
Top Pair	124 ± 17	27.4 ± 4.3	27.1 ± 4.6
Di-boson	35.6 ± 6.8	4.9 ± 1.2	4.3 ± 1.1
W + h.f.	297 ± 130	11.0 ± 6.5	21 ± 11
Z + h.f.	107 ± 46	10.8 ± 5.0	11.3 ± 5.2
Total Exp	1548 ± 146	105 ± 13	149 ± 17
Observed	1443	105	148
$ZH \rightarrow \nu\nu bb$ (MH115GeV)	2.1	1.0	0.8
$WH \rightarrow (l)\nu bb$ (MH115GeV)	1.8	0.9	0.7
$ZH \rightarrow (ll)bb$ (MH115GeV)	0.09	0.04	0.03

Picks up WH→lνbb signal with missing lepton.

An Interesting Candidate Event





Two b-tagged jets

m_{jj}= 82 GeV

Missing E_T=145 GeV

Jet$_1$ E_T= 100.3 GeV
Jet$_2$ E_T= 54.7 GeV

Could be ZZ

Control Regions and QCD Rejection

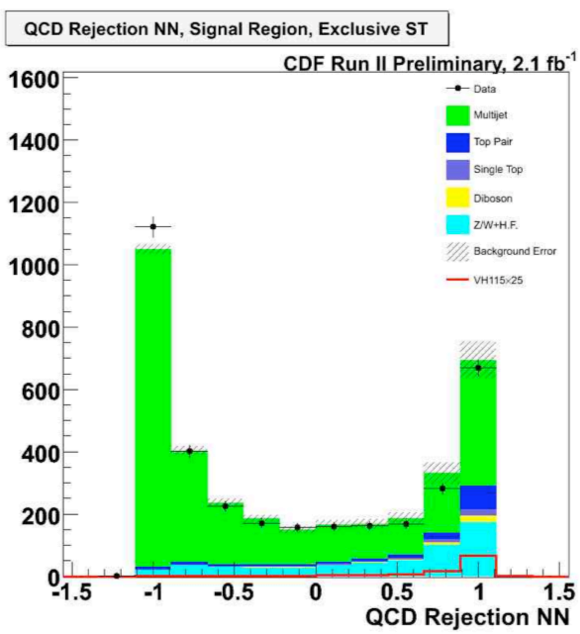
Difficult to predict background from multijet events

Control regions:

Region 1: $\Delta\phi(\not\!\!E_T, J2) < 0.4$, otherwise like signal

Region 2: Require a lepton, otherwise like signal

Region 3: Other side of Anti-QCD NN cut



1-tag, similar for double-tag samples

Anti-QCD NN inputs:

- $\max(\Delta\phi_{jj})$
- $\max(\Delta R_{jj})$
- $\min(\Delta\phi_{j,MET})$
- $\min(\Delta\phi_{j,Ptmis})$
- $\not\!\!E_T$
- Missing P_T
- H_T
- $\not\!\!H_T / \not\!\!E_T$
- $\Delta\phi(\not\!\!E_T, \not\!p_T)$

QCD normalized on background-side of the cut, tag rates parameterized with a tag-rate function

Signal Region Neural Network

Mostly m_{jj} is powerful, but also

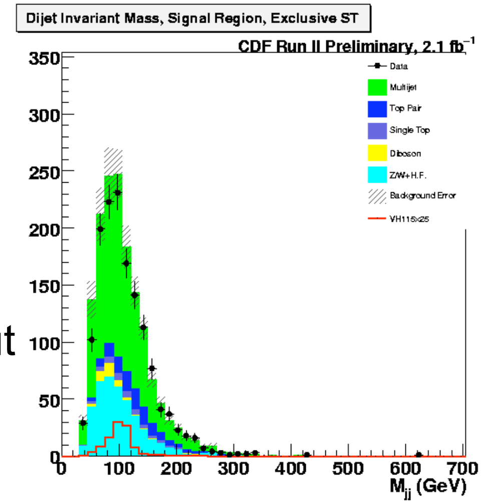
$m_{jets,MET}$

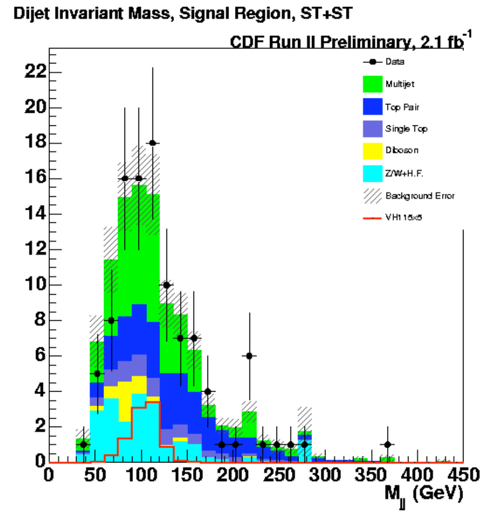
H_T-$\not{E}_T$

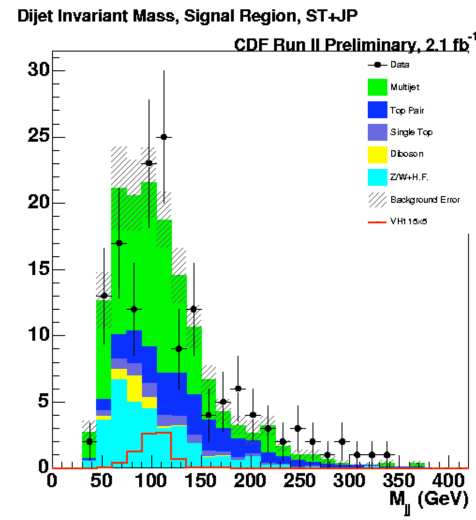
$\not{H}_T$-$\not{E}_T$

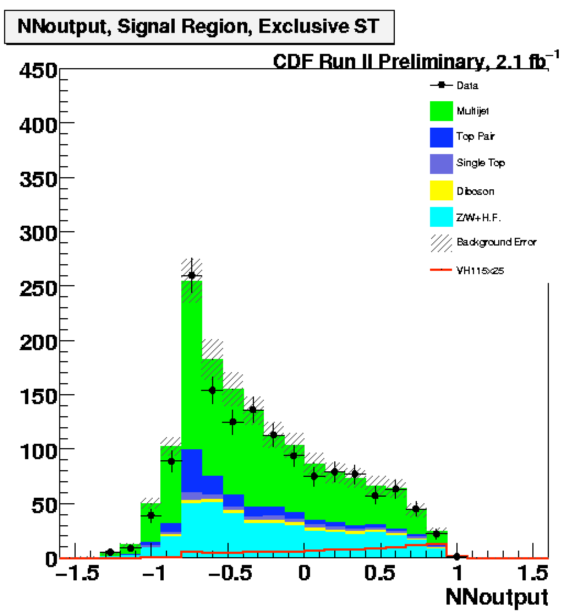
Track-$\not{E}_T$ NN output

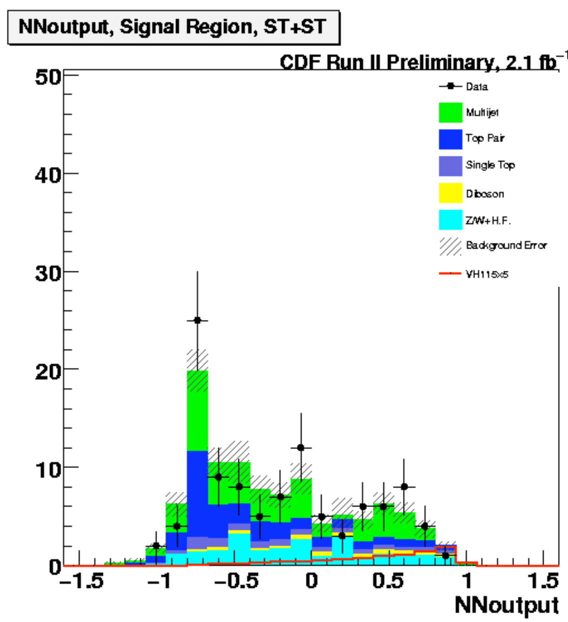
$\max(\Delta R_{jj})$

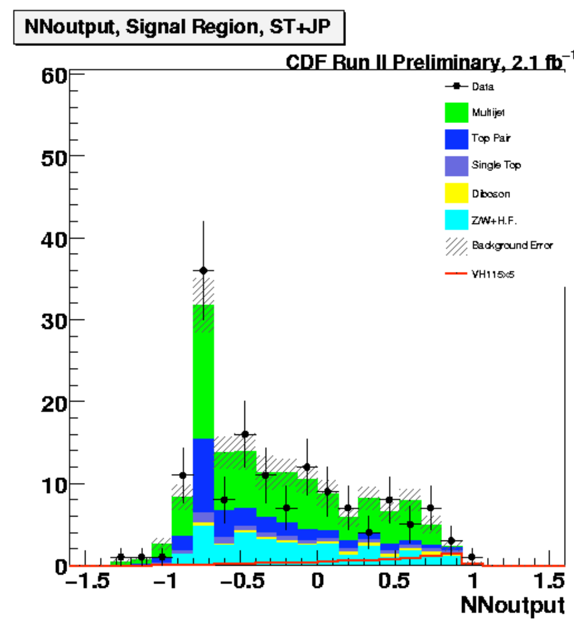






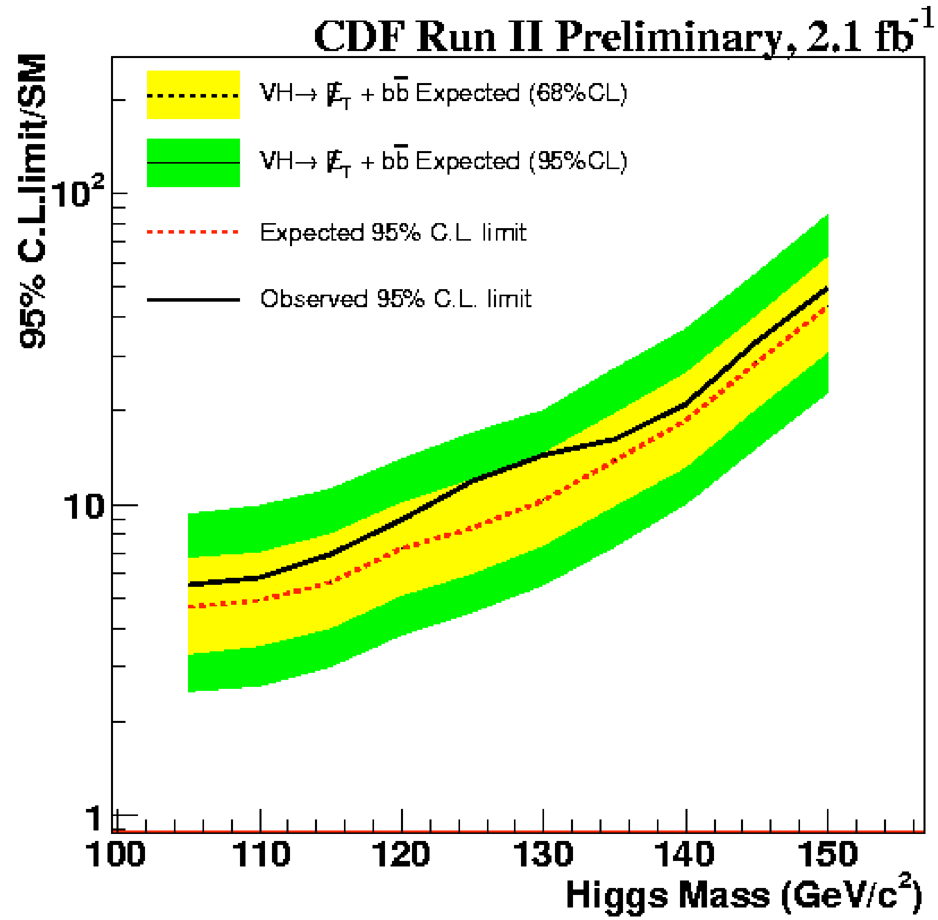






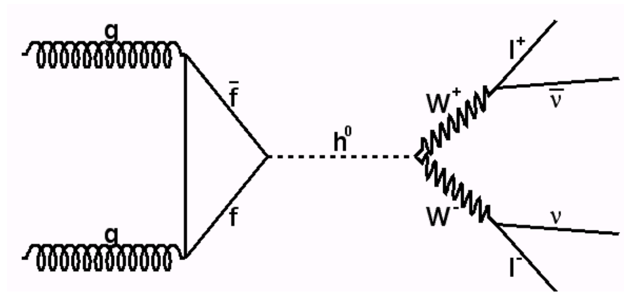
$\not{E}_T$+bb Exclusions

Higgs mass (GeV)	VH limit, Combined	
	Predicted	Observed
105	$4.7^{+2.0}_{-1.4}$	5.5
110	$4.9^{+2.1}_{-1.4}$	5.8
115	$5.6^{+2.4}_{-1.6}$	6.9
120	$7.2^{+2.9}_{-2.1}$	8.9
125	$8.4^{+3.6}_{-2.4}$	11.9
130	$10.3^{+4.3}_{-2.9}$	14.4
135	$13.8^{+5.8}_{-3.9}$	16.2
140	$18.6^{+7.8}_{-5.4}$	21.0
145	$28.6^{+11.8}_{-8.2}$	33.4
150	$43.3^{+19.0}_{-12.4}$	49.8



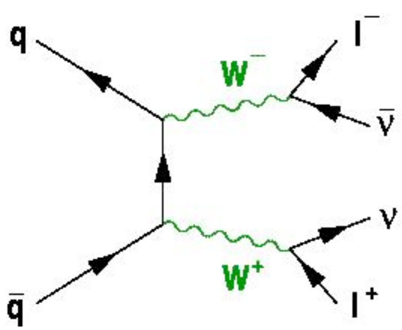
The H → W^+W^- Channels

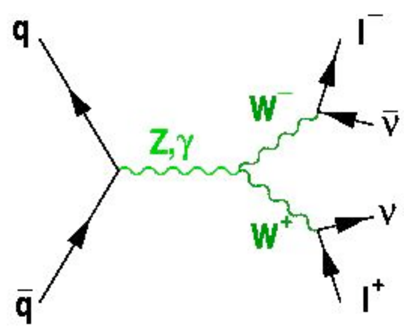
$gg \to H$
Signal Process:



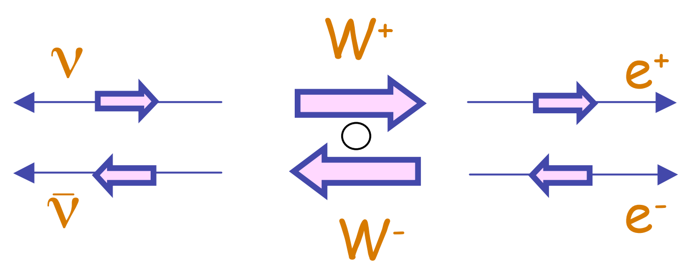
- Interesting Angular Correlation due to Scalar nature of Higgs Boson

Dominant background:
$q\bar{q} \to W^+W^-$

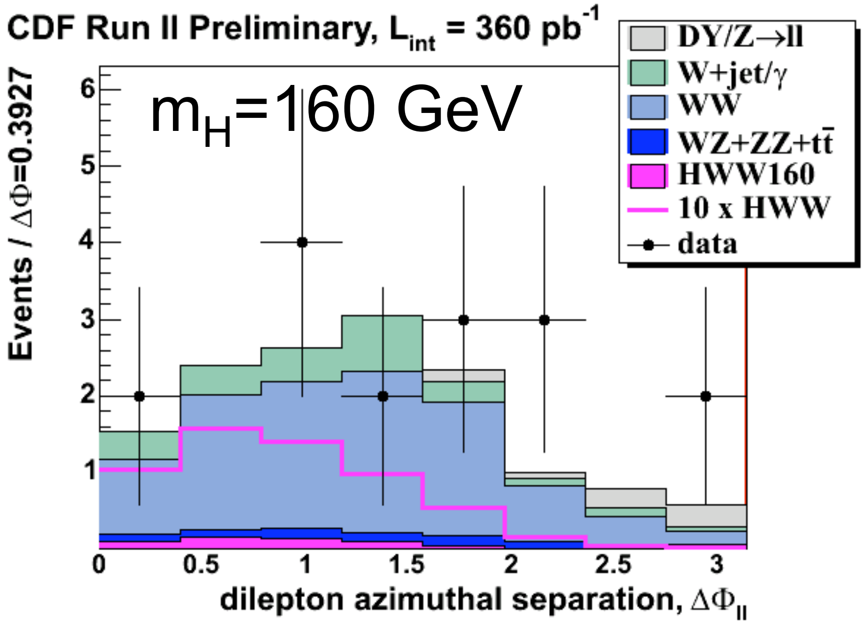


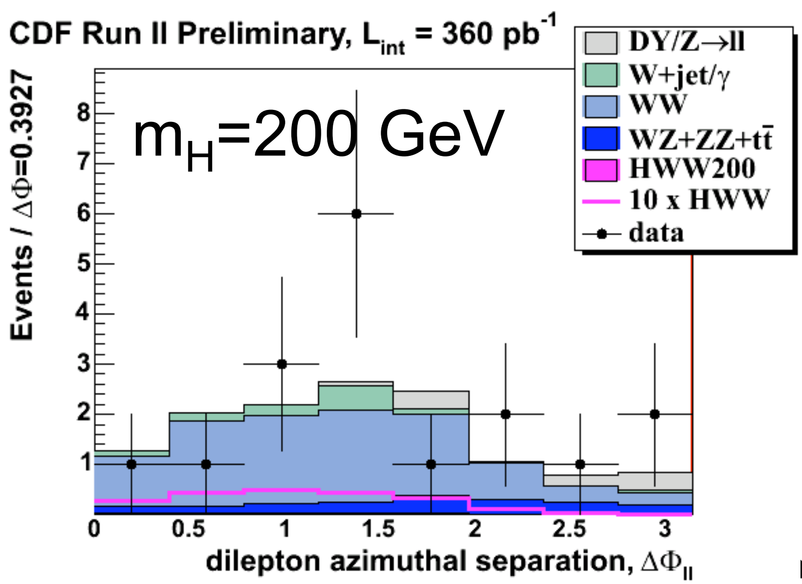


- Different from SM W^+W^- bg decay angular correlation!

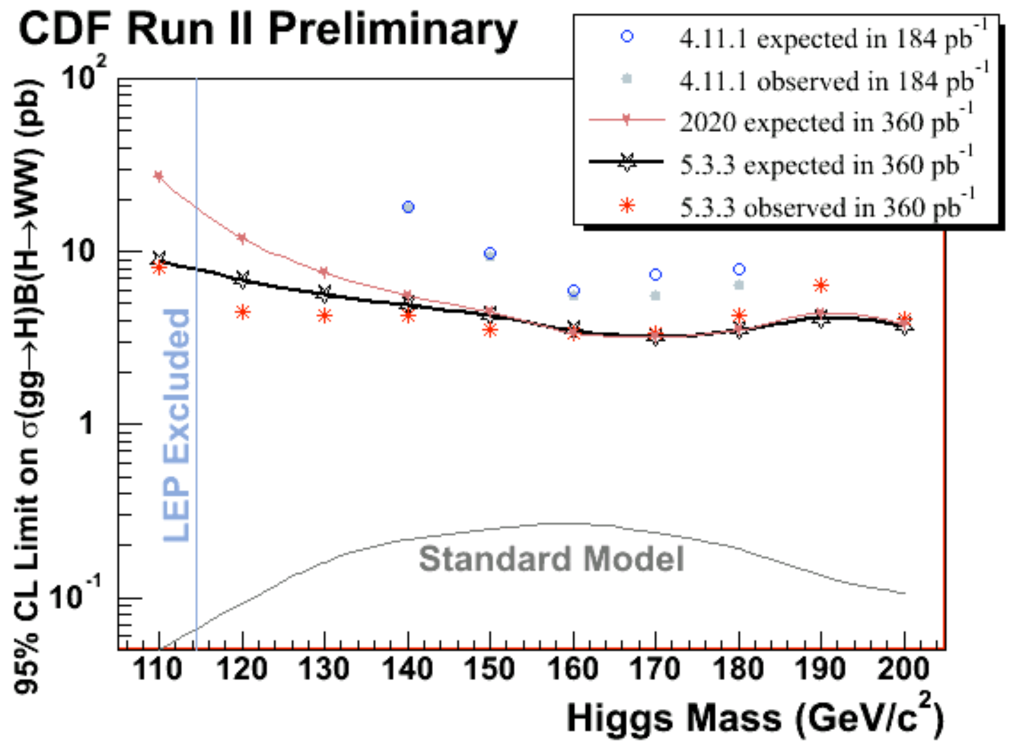


Four Years ago: 2005 H→WW Analysis





- Just used gg→H signal
- Final discriminant was $\Delta\phi_{ll}$
- Jet vetos to suppress ttbar

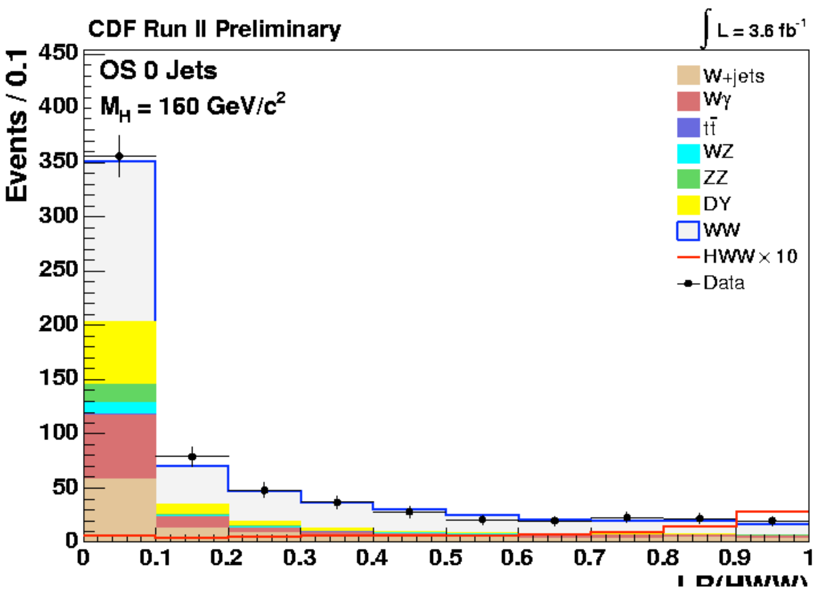


Splitting up H→WW Into Subsamples

- Original analysis vetoed on extra jets
- But We can analyze these events one category at a time
  - WW+0 jets : gg→H signal
  - WW+1 jet : add in WH, ZH, VBF signals (20% more signal)
  - WW+2 jets (or more) 60% more signal from WH, ZH and VBF. Main background is t-tbar
  - Same-sign dileptons+any number of jets: Mostly sensitive to WH and ZH, with leptonic W, Z decay.

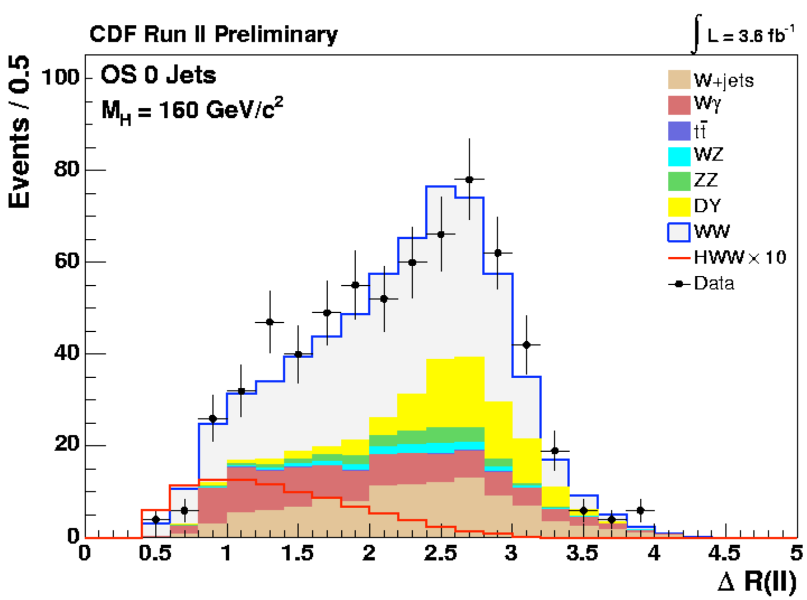
- Adding data in subsamples with different s/b is less optimal than splitting and doing a joint fit.

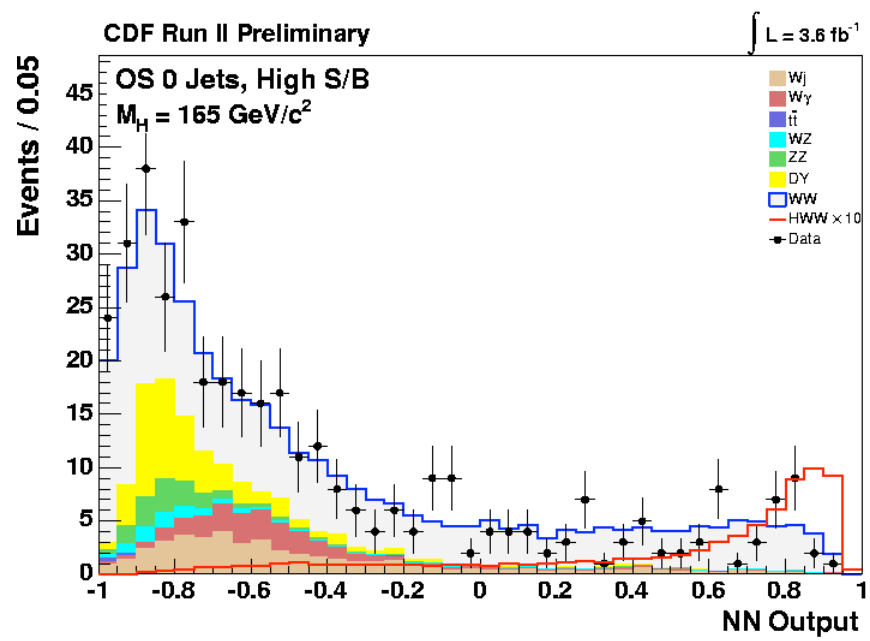
Opposite-Sign Leptons + Zero Jets H→WW Search



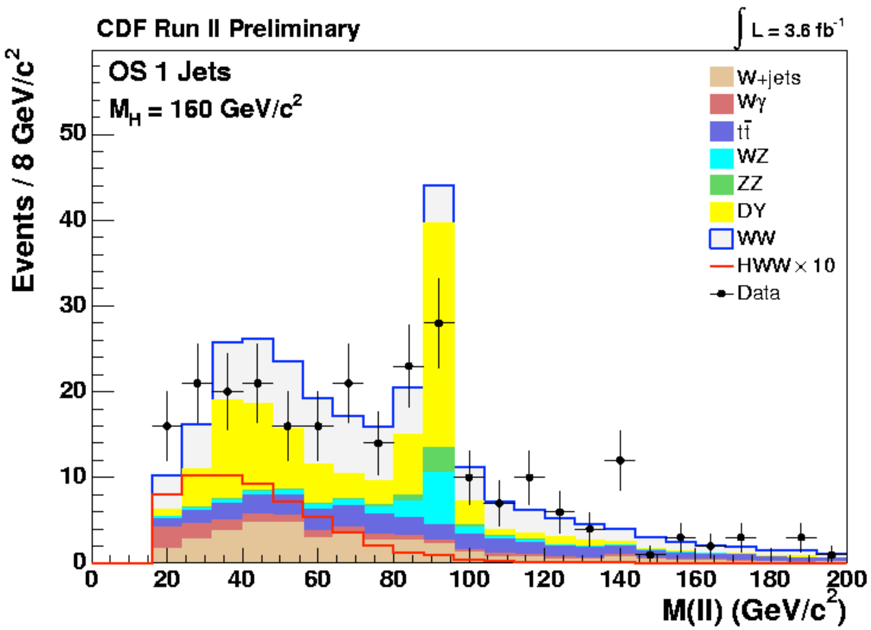
CDF Run II Preliminary	$\int \mathcal{L} = 3.6$ fb^{-1}		
	$M_H = 160$ GeV$/c^2$		
$t\bar{t}$	1.35	±	0.21
DY	80	±	18
WW	318	±	35
WZ	14	±	1.9
ZZ	20.7	±	2.8
W+jets	113	±	27
$W\gamma$	92	±	25
Total Background	637	±	67
$gg \to H$	9.5	±	1.4
Total Signal	9.5	±	1.4
Data		654	

OS 0 Jets





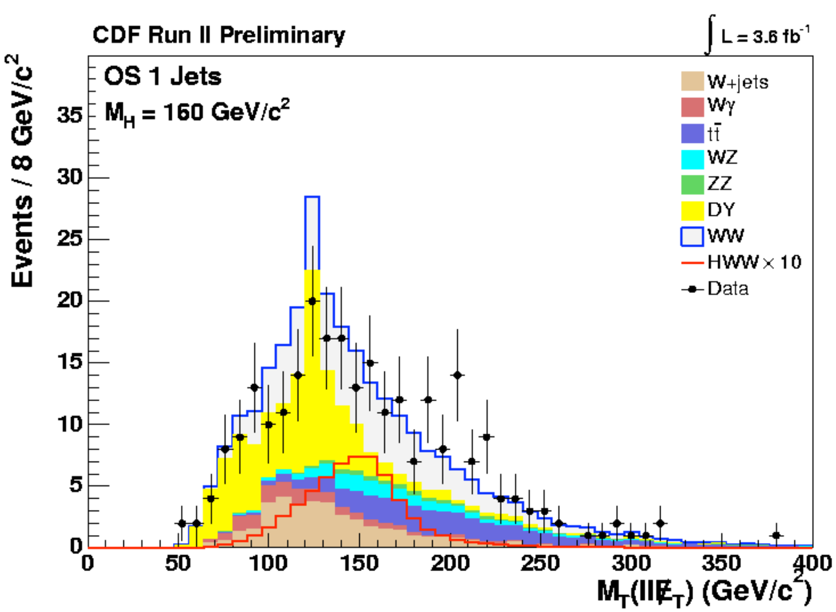
Opposite-Sign Leptons + One Jet H→WW Search

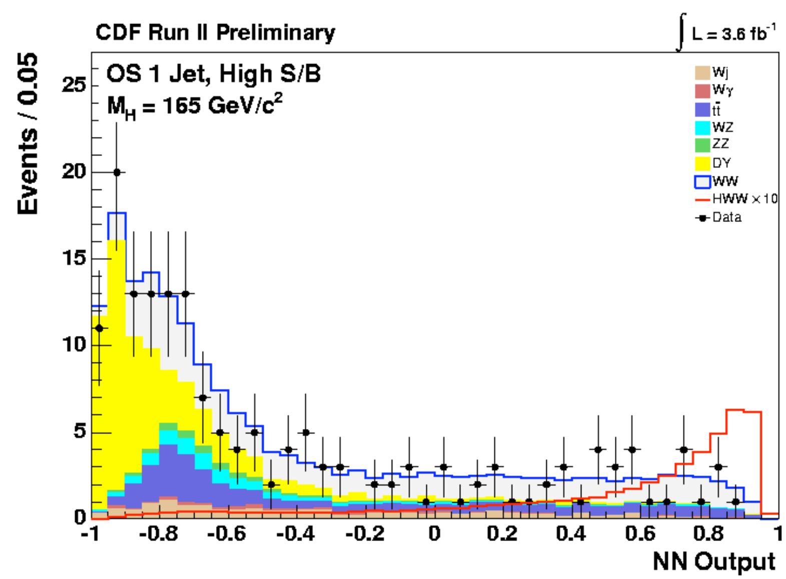


CDF Run II Preliminary $\int \mathcal{L} = 3.6$ fb^{-1}

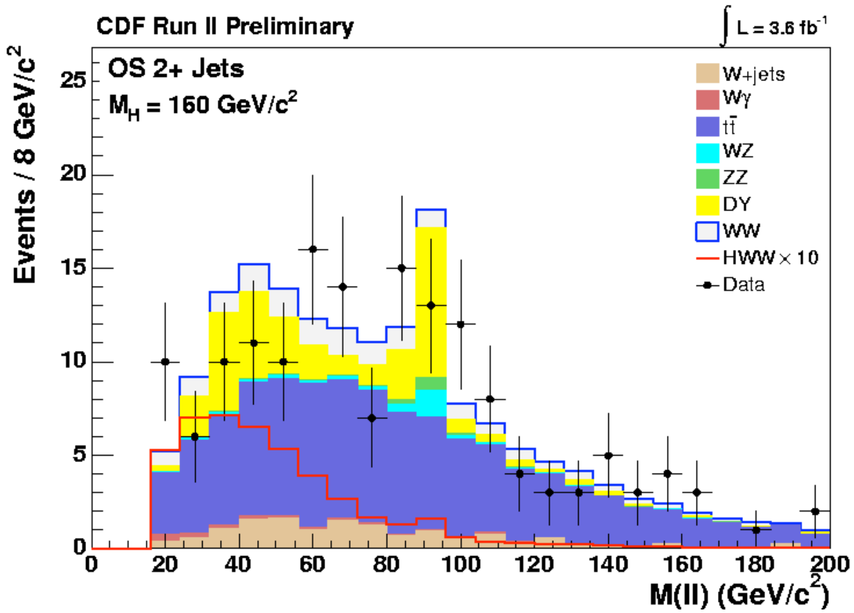
$M_H = 160$ GeV/c^2			
$t\bar{t}$	34.9	±	5.5
DY	85	±	27
WW	85.3	±	9.1
WZ	14.5	±	2.0
ZZ	5.48	±	0.75
W+jets	40	±	10
$W\gamma$	13.2	±	4.0
Total Background	278	±	35
$gg \to H$	4.70	±	0.72
WH	0.661	±	0.086
ZH	0.244	±	0.032
VBF	0.381	±	0.061
Total Signal	5.98	±	0.78
Data	262		

OS 1 Jet





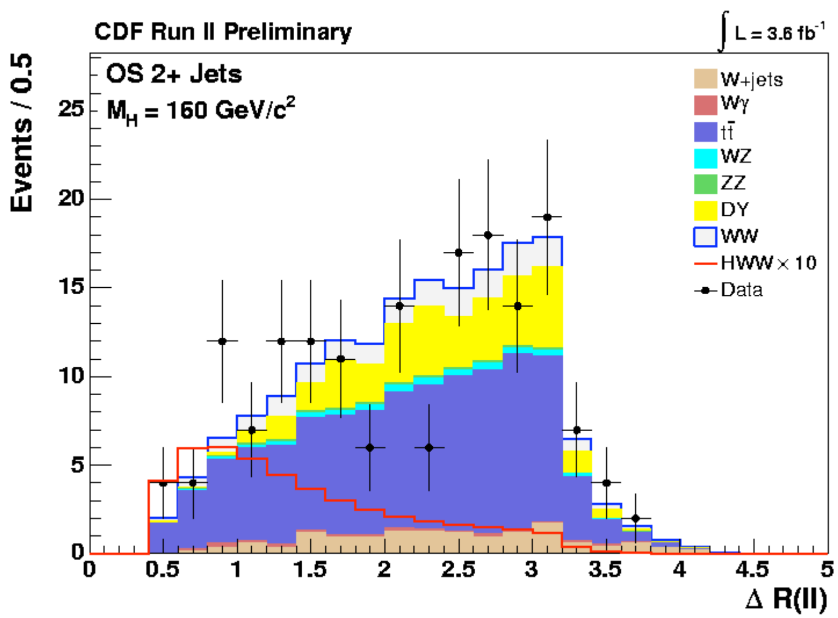
Opposite-Sign Leptons + Two or More Jets H→WW Search

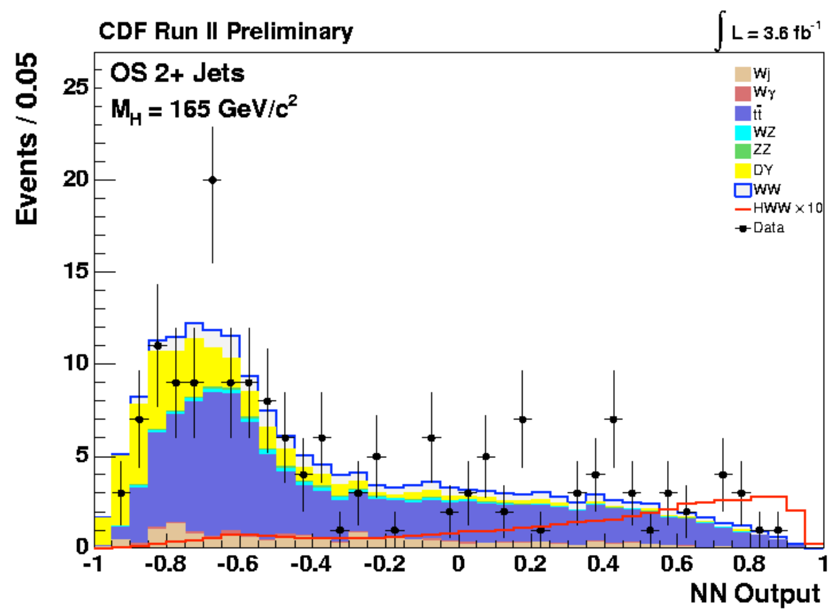


CDF Run II Preliminary $\int \mathcal{L} = 3.6\ \text{fb}^{-1}$

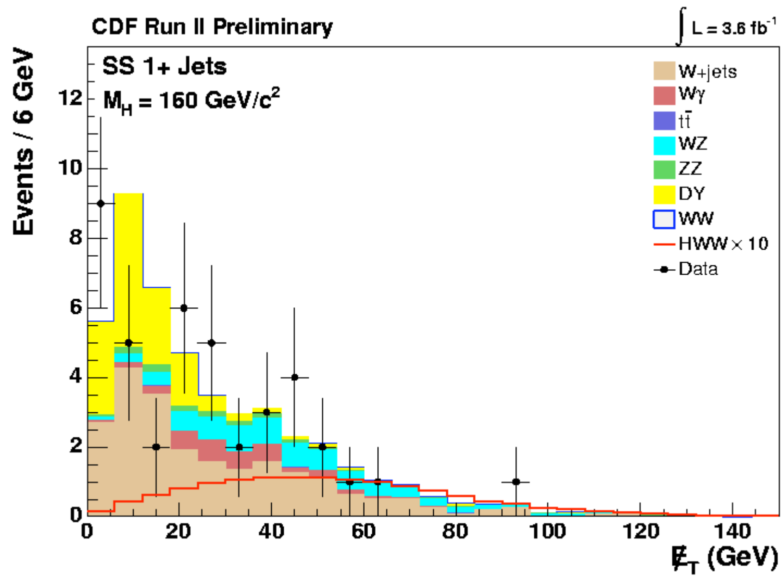
$M_H = 160\ \text{GeV}/c^2$			
$t\bar{t}$	100	±	17
DY	33	±	11
WW	17.6	±	4.0
WZ	3.76	±	0.52
ZZ	1.62	±	0.22
W+jets	14.7	±	4.0
$W\gamma$	2.12	±	0.70
Total Background	173	±	23
$gg \to H$	1.75	±	0.30
WH	1.39	±	0.18
ZH	0.693	±	0.090
VBF	0.70	±	0.11
Total Signal	4.53	±	0.52
Data	169		

OS 2+ Jets



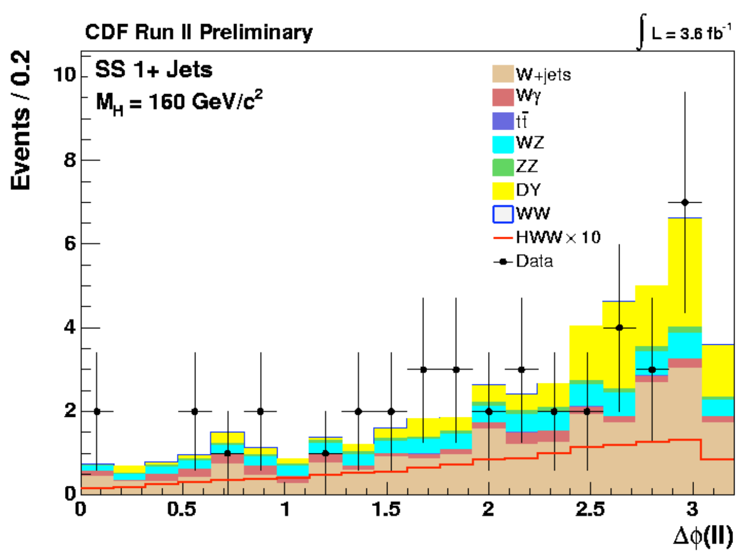


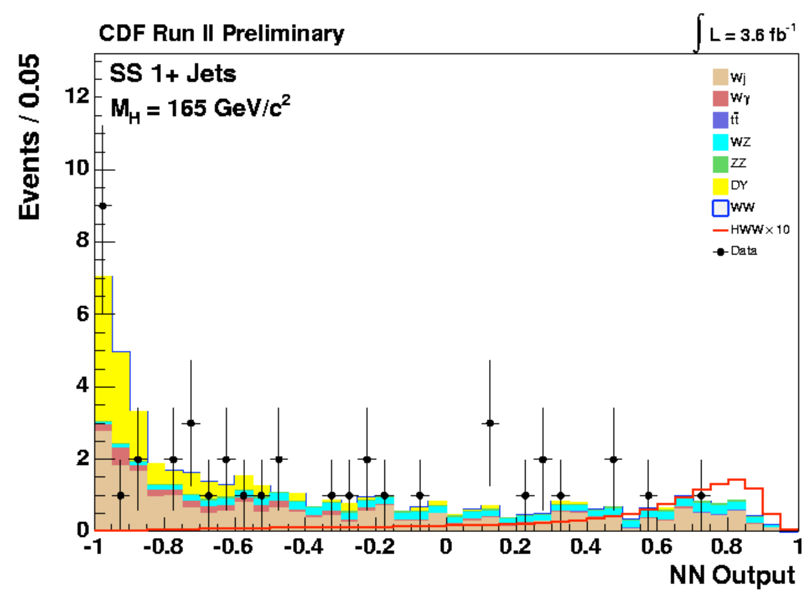
Same-Sign Plus 1 or more Jets H→WW Search



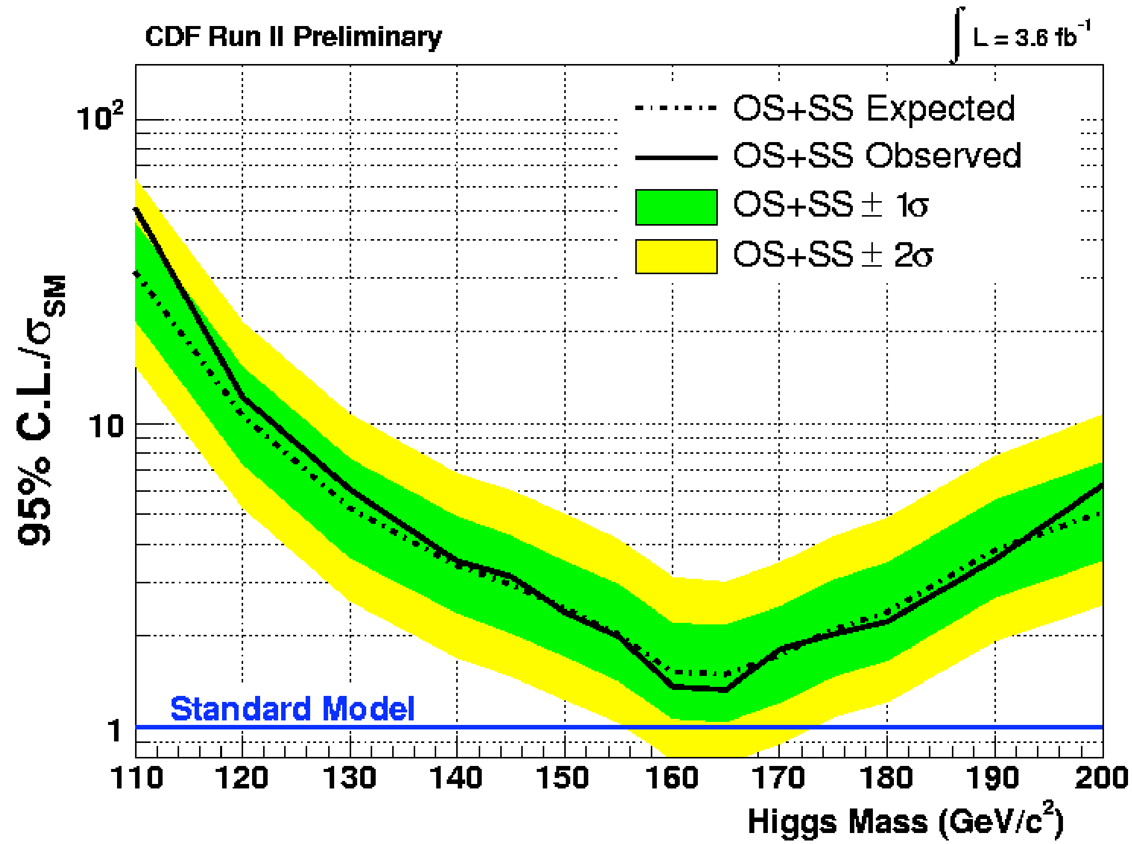
CDF Run II Preliminary	$\int \mathcal{L} = 3.6$ fb^{-1}		
	$M_H = 160$ GeV$/c^2$		
$t\bar{t}$	0.11	±	0.03
DY	11.99	±	3.65
WW	0.020	±	0.005
WZ	6.82	±	0.93
ZZ	1.44	±	0.20
W+jets	22.45	±	6.73
$W\gamma$	3.23	±	1.00
Total Background	**46.07**	±	**8.02**
WH	1.19	±	0.16
ZH	0.19	±	0.02
Total Signal	**1.38**	±	**0.18**
Data	41		

SS 1+ Jets



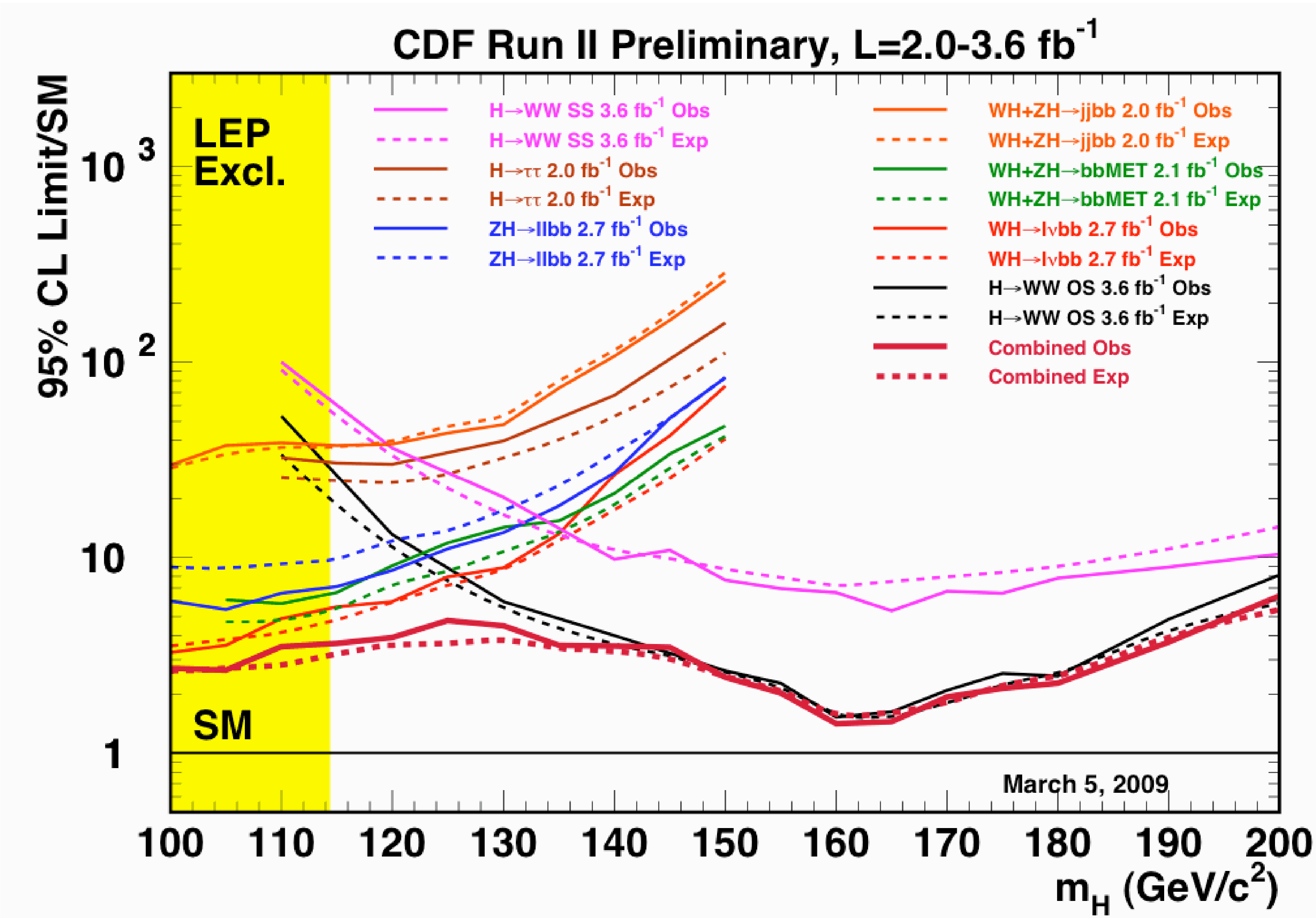


Exclusions from CDF's H→WW Searches



OS+SS	110	120	130	140	145	150	155	160	165	170	175	180	190	200
$-2\sigma/\sigma_{SM}$	15.48	5.31	2.60	1.69	1.47	1.23	1.04	0.79	0.77	0.88	1.08	1.21	1.92	2.52
$-1\sigma/\sigma_{SM}$	21.85	7.39	3.61	2.38	2.04	1.72	1.42	1.07	1.05	1.21	1.47	1.66	2.68	3.54
Median/$\sigma_{\rm SM}$	**31.48**	**10.62**	**5.26**	**3.40**	**2.94**	**2.46**	**2.02**	**1.52**	**1.50**	**1.73**	**2.10**	**2.40**	**3.84**	**5.11**
$+1\sigma/\sigma_{SM}$	45.61	15.32	7.61	4.92	4.26	3.51	2.95	2.19	2.18	2.49	3.05	3.47	5.59	7.43
$+2\sigma/\sigma_{SM}$	63.79	21.54	10.71	6.82	6.01	5.02	4.14	3.12	3.00	3.49	4.24	4.88	7.78	10.66
Observed/$\sigma_{\rm SM}$	**51.05**	**12.22**	**6.06**	**3.52**	**3.14**	**2.39**	**1.99**	**1.37**	**1.33**	**1.81**	**2.02**	**2.23**	**3.56**	**6.24**

Limits From All CDF Higgs Search Channels



Mini-Review: Bayesian Limits

$$L(r,\theta) = \prod_{channels} \prod_{bins} P_{Poiss}(data \mid r,\theta)$$

Where *r* is an overall signal scale factor, and θ represents all nuisance parameters.

$$P_{Poiss}(data \mid r,\theta) = \frac{(rs_i(\theta) + b_i(\theta))^{n_i} \, e^{-(rs_i(\theta)+b_i(\theta))}}{n_i!}$$

where n_i is observed in each bin *i*, s_i is the predicted signal for a fiducial model (SM), and b_i is the predicted background. Dependence of s_i and b_i on θ includes rate, shape, and bin-by-bin independent uncertainties.

Mini-Review: Bayesian Limits

Including uncertainties on nuisance parameters θ

$$L'(data \mid r) = \int L(data \mid r, \theta) \pi(\theta) d\theta$$

where $\pi(\theta)$ encodes our prior belief in the values of the uncertain parameters. Usually Gaussian centered on the best estimate and with a width given by the systematic. Includes rate uncertainites, shape uncertainites, MC statistics in each bin.

$$0.95 = \int_0^{r_{\lim}} L'(data \mid r) \pi(r) dr$$

Sensitivity = Median Expected Limit

- Run simulated background-only MC pseudoexperiments (fluctuate all systematics)
- Compute r_{lim} for each one; find medain and ±1,2σ variations.

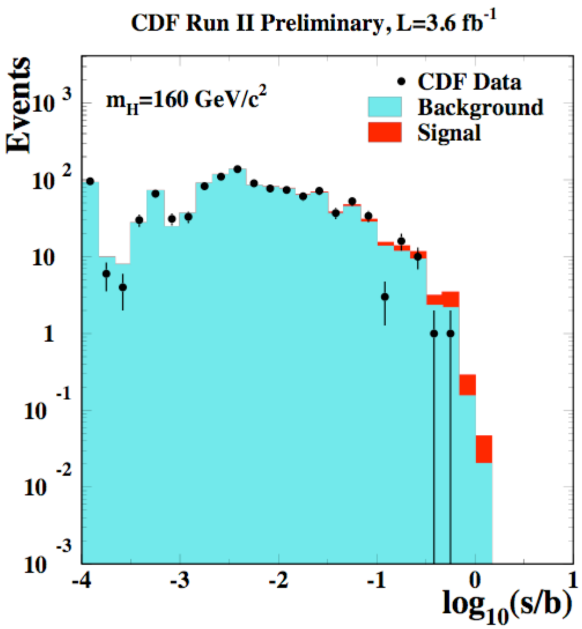
Markov Chain Monte Carlo Integration

- Monte Carlo integration method
- improvement on scattershot MC
- faster and more stable results

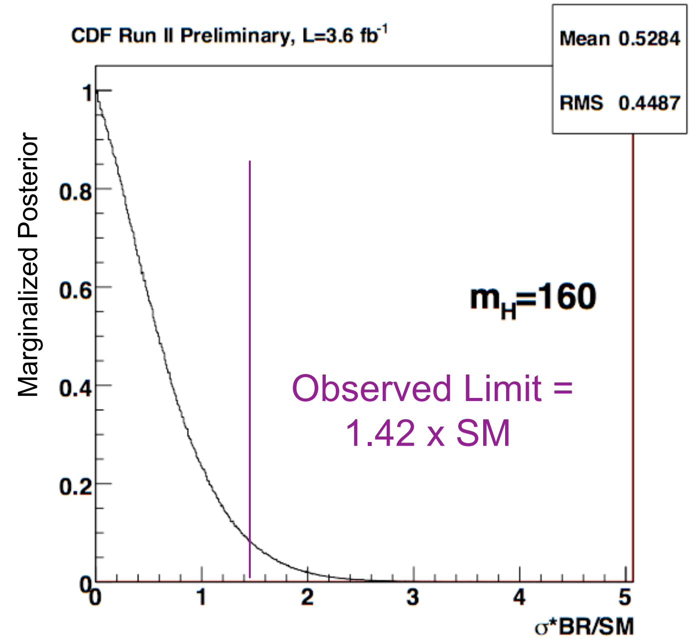
- problem: most integration points contribute little
- would like to sample only the peaks of the distribution
- problem: we throw nuisance parameters, not likelihood

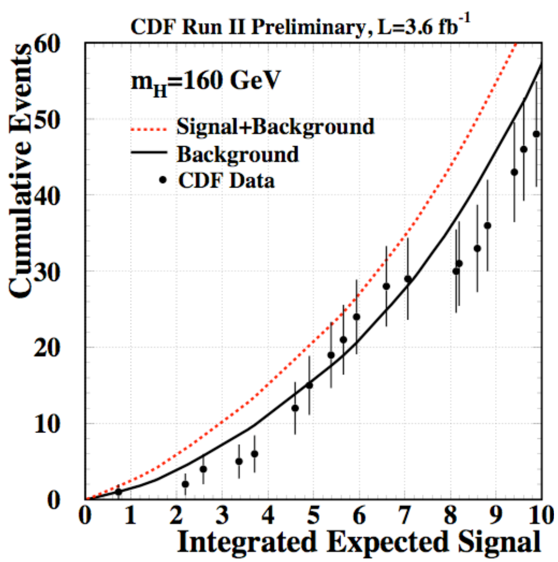
- solution: we slowly walk along the peaks taking care not to step into the valley
  - Markov Chain Monte Carlo

CDF's Combined Higgs Boson Search at m_H=160 GeV

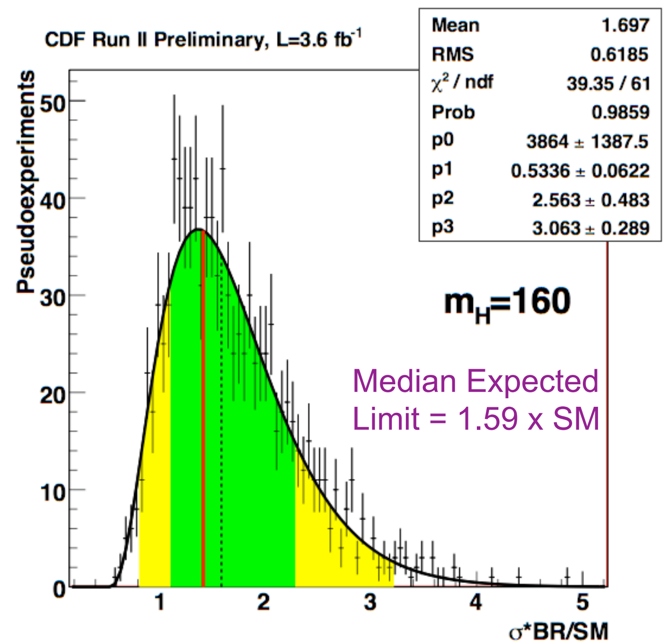


Candidates
in all channels
sorted by s/b

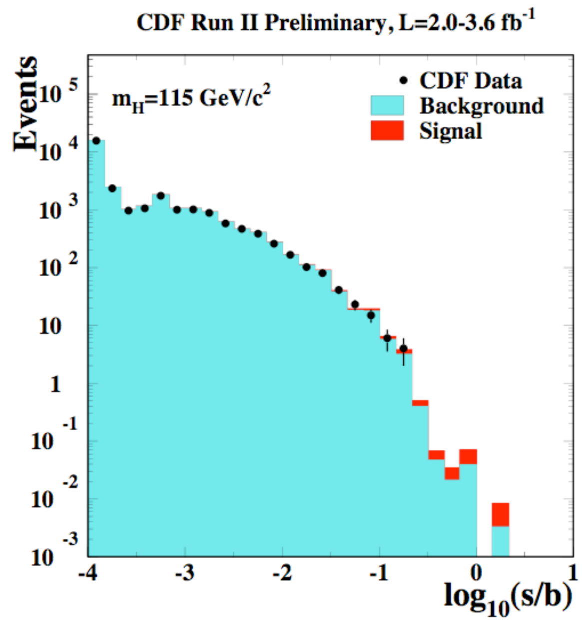


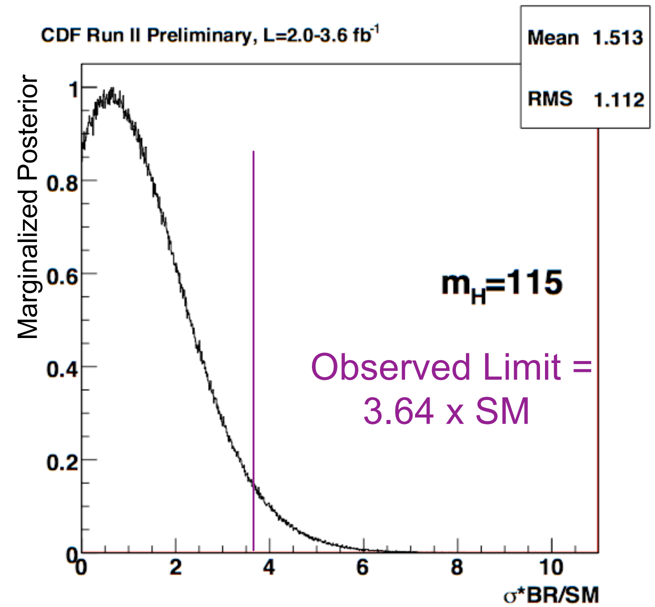


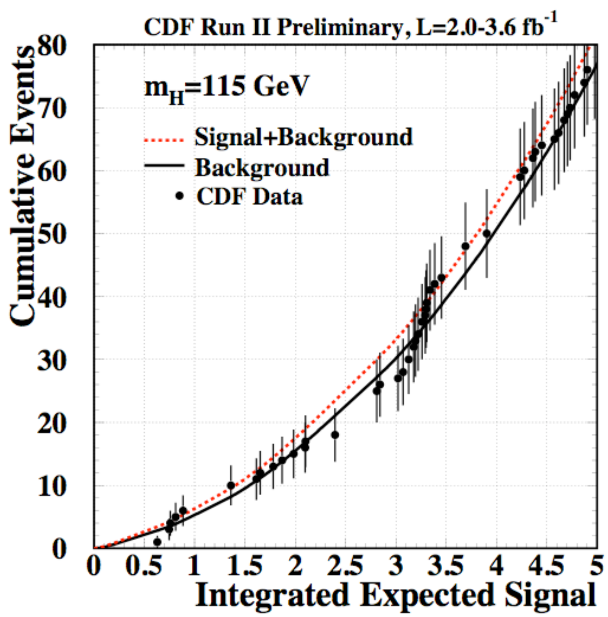
s/b histogram
integrated from
high s/b
side

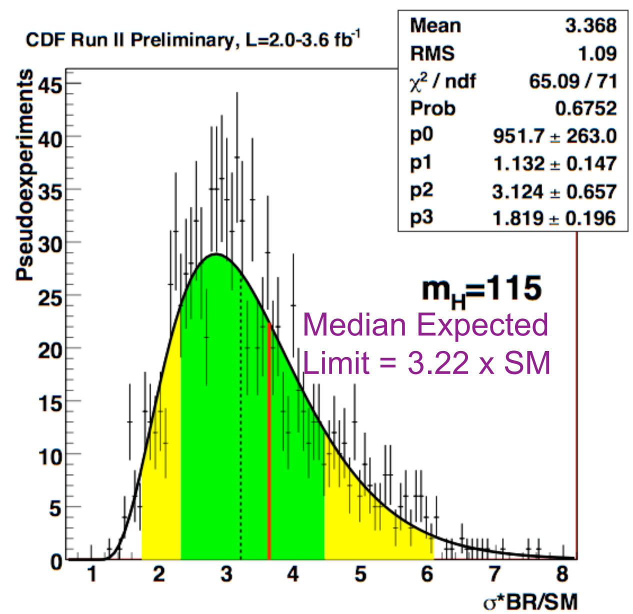


CDF's Combined Higgs Boson Search at m_H=115 GeV

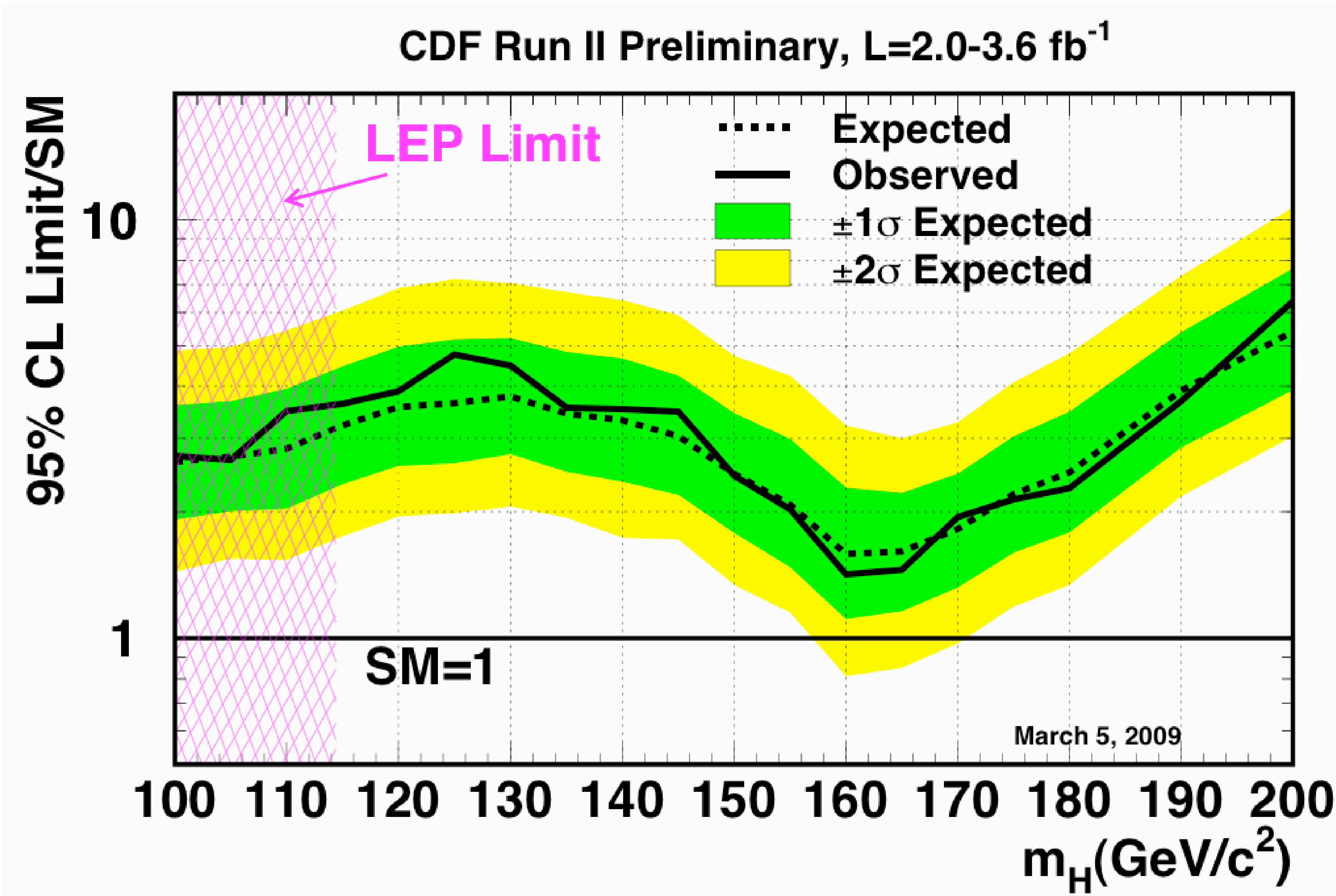




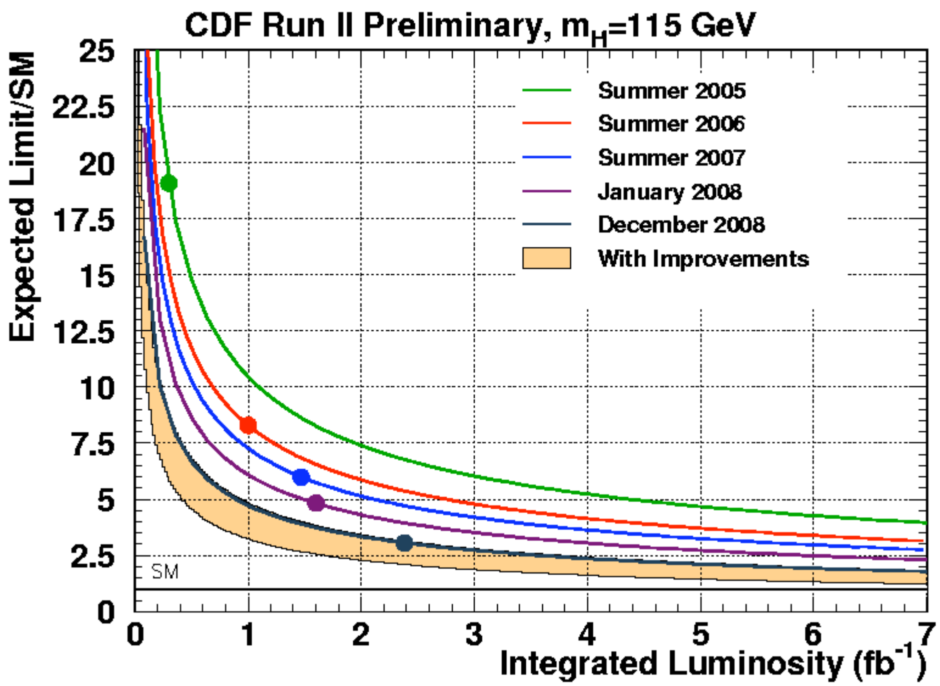




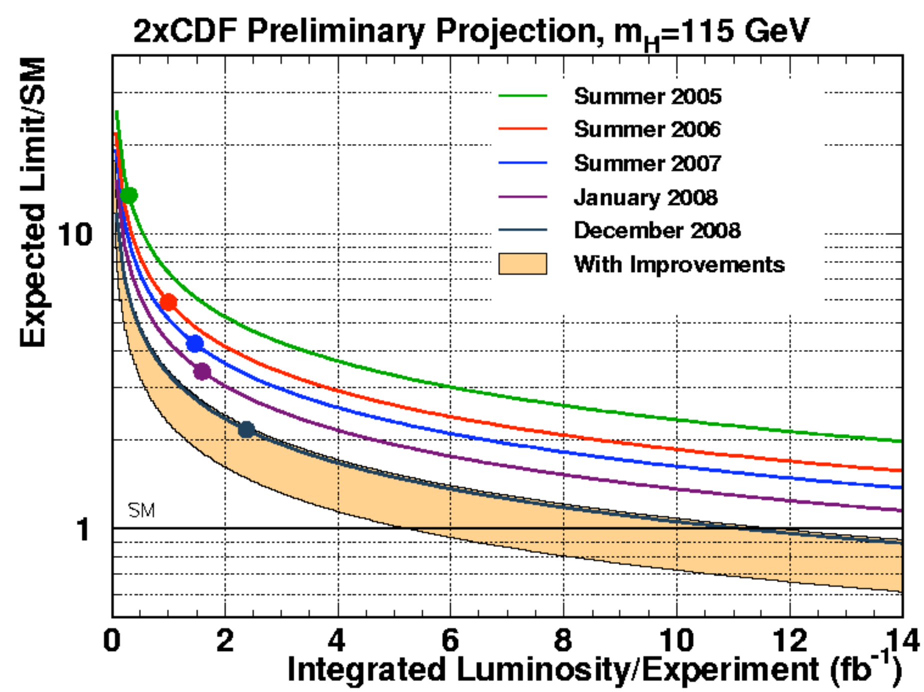
CDF's Combined Higgs Limits



Sensitivity and Projections -- m_H=115 Gev

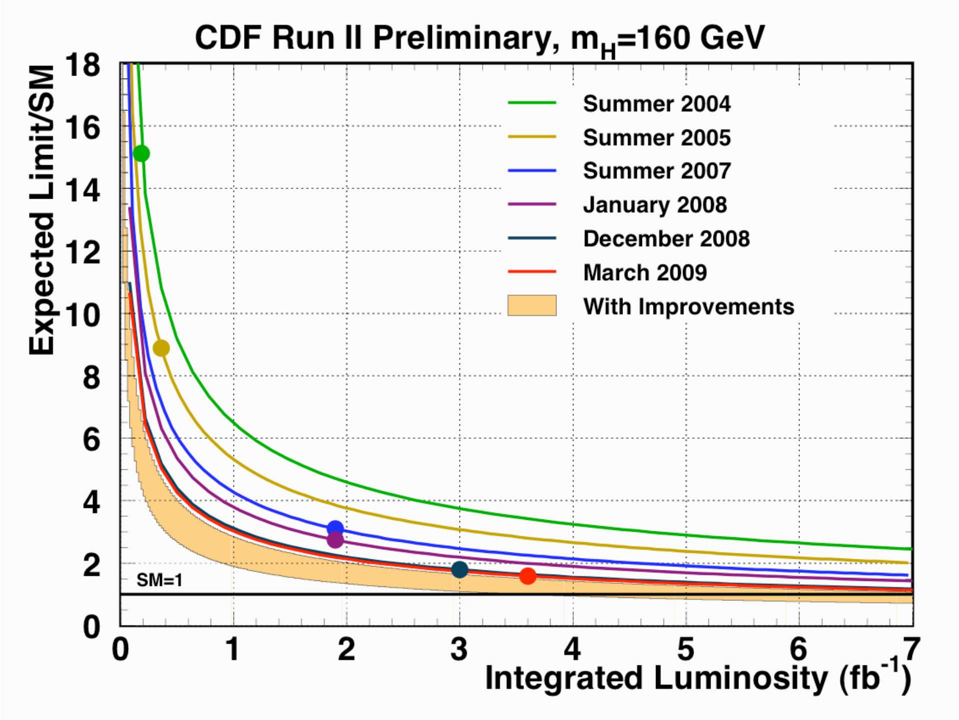


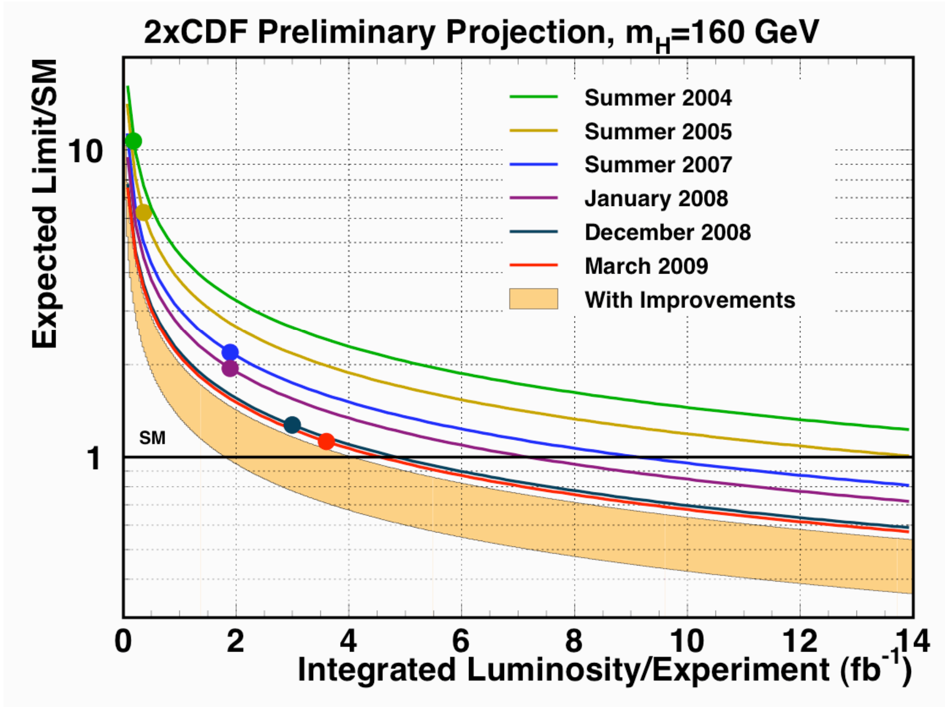
Tevatron sensitivity approximated by 2xCDF



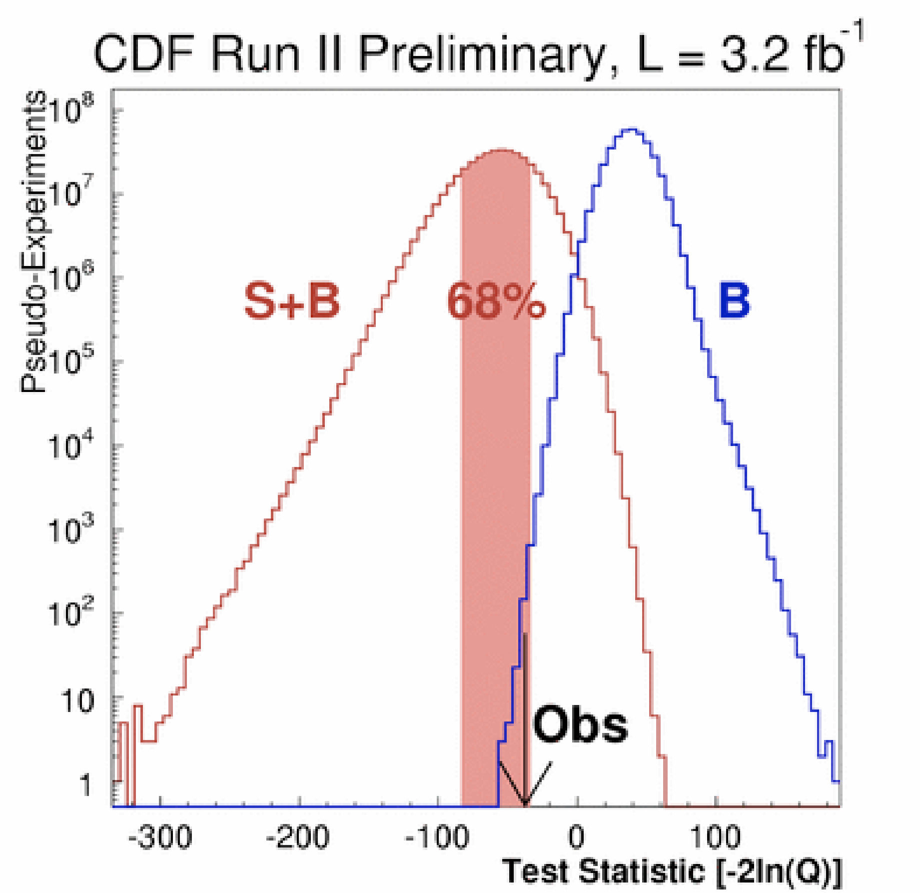
Steady improvement in analaysis technique and better understanding of systematic uncertainties

Sensitivity and Projections -- m_H=160 GeV





Discovery with p-Values



Example: CDF's single top observation

arXiv:0903.0885 [hep-x]

$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\mid s+b,\hat{\theta})}{L(\text{data}\mid b,\hat{\hat{\theta}})}\right)$$

100 M s+b and b-only pseudoexperiments, each with fluctuated nuisance parameters, and fit twice.

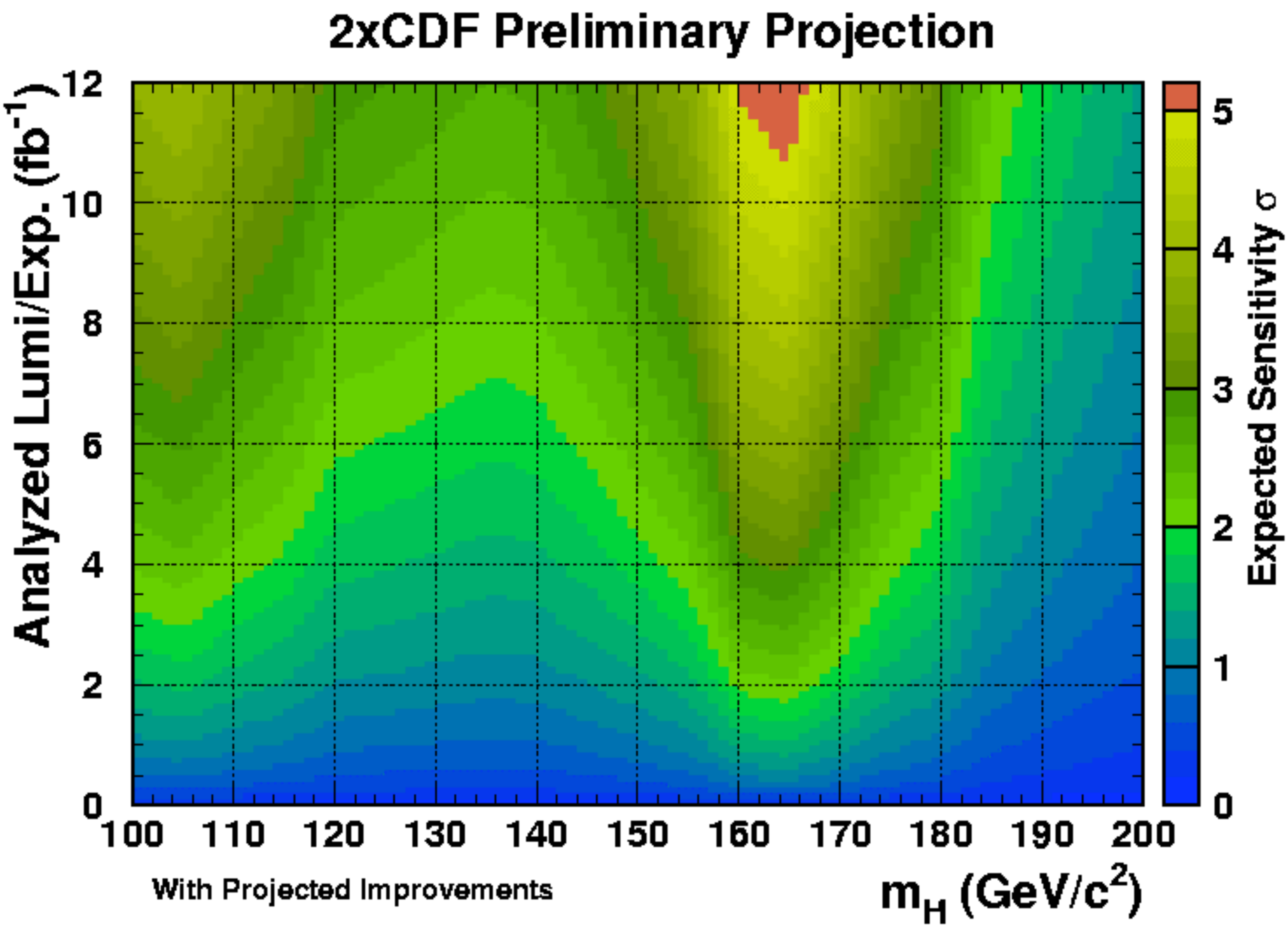
Systematics varied in each pseudoexperiment

5σ: p-value of $2.77\text{x}10^{-7}$ or less.

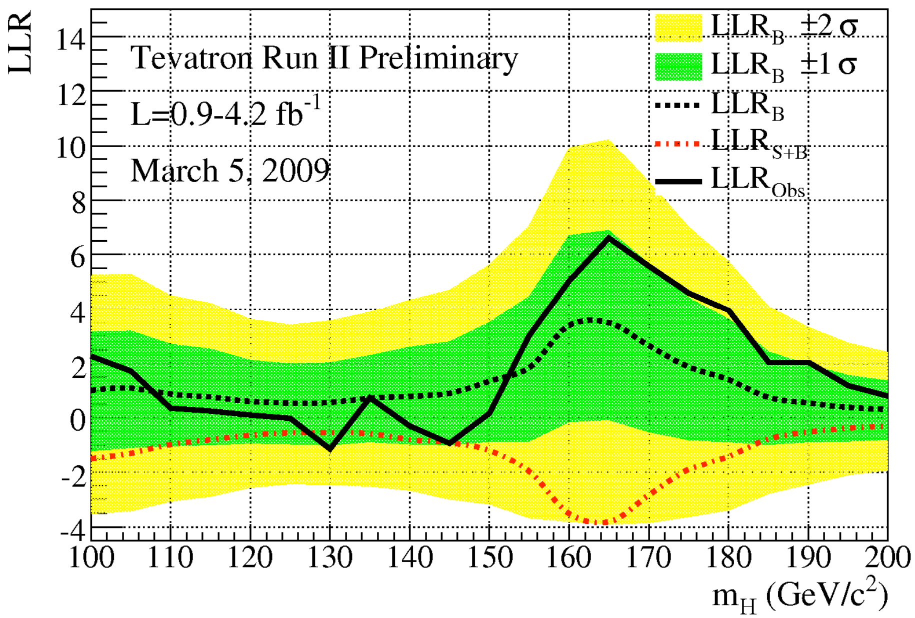
3σ: p-value of $1.35\text{x}10^{-3}$ or less

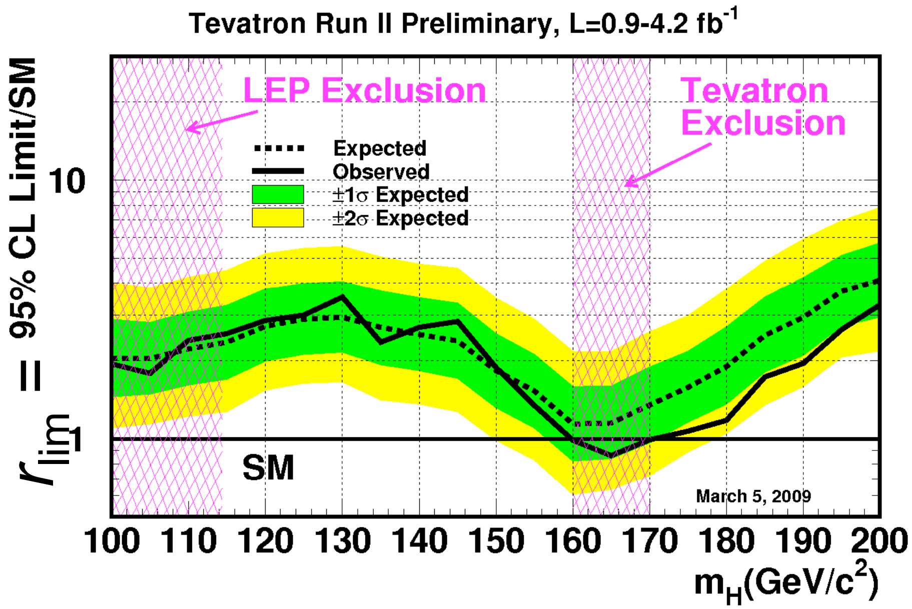
2σ: p-value of 2.28% or less

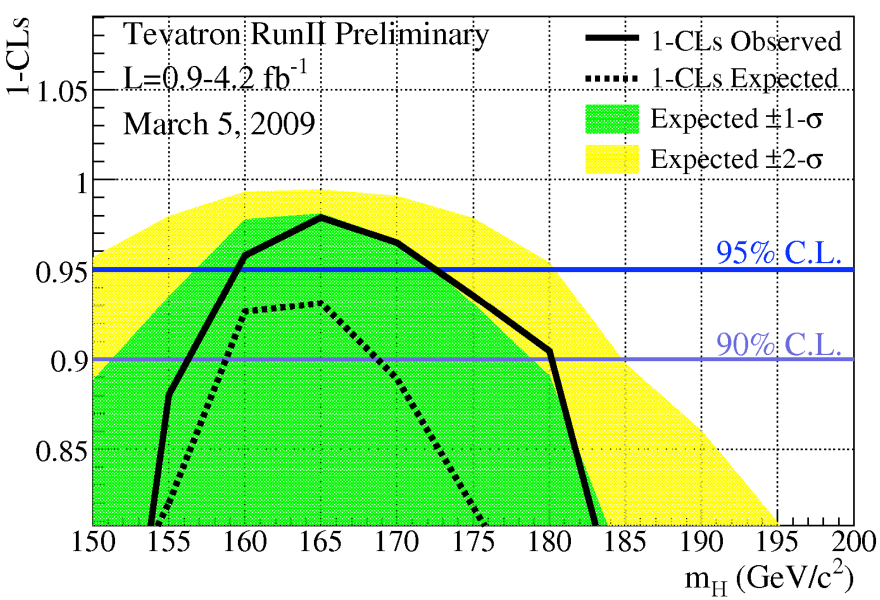
A Priori Chances of Seeing Something *If It's There*



Tevatron Higgs Combination -- A Monumental Achievement!







- Done Twice! -- Bayesian and CL_s techniques
- Exchange histograms of all background and signal predictions, and data
- Itemize systematic uncertainties by named source.
- **Exclude $160<m_H<170$ GeV**

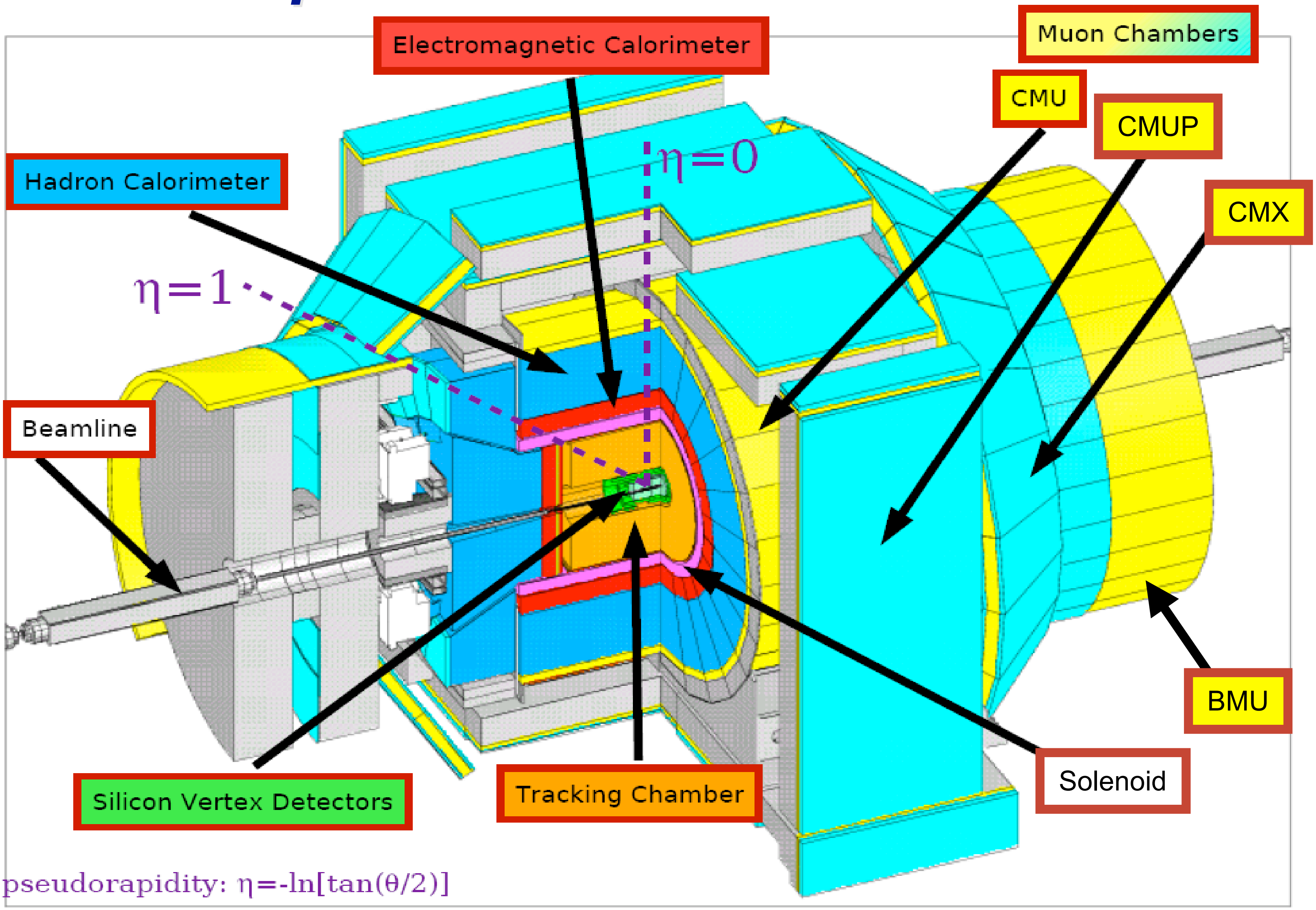
arXiv:0903.4001 [hep-ex]

Summary

- CDF's and DØ's Higgs Searches are Proceeding Well
- Data samples up to 4.2 fb^{-1} have been analyzed and shown at conferences
- Calibration, Processing, Analysis and Combination machinery is very smooth.
- Constant analysis improvements gain in sensitivity over time
- Theorists have gotten excited!
- High-mass Higgs bosons excluded for $160<m_H<170$ GeV
- Practice discovering Single Top
- Low-Mass preferred by Supersymmetry -- let's do it!

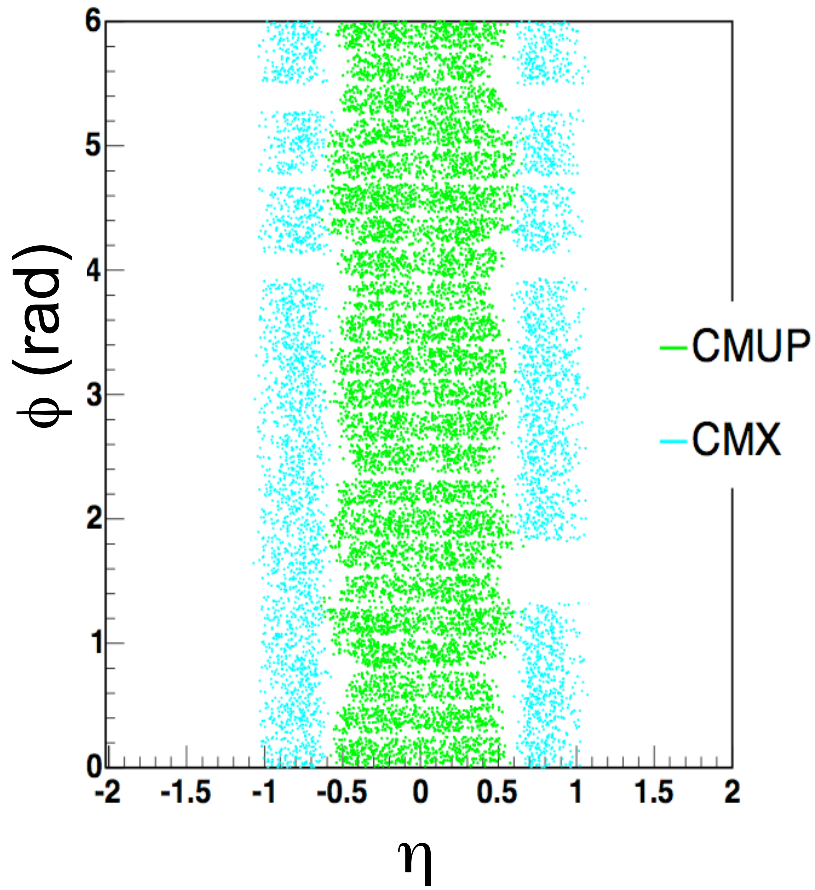
Backup Material

CDF Components

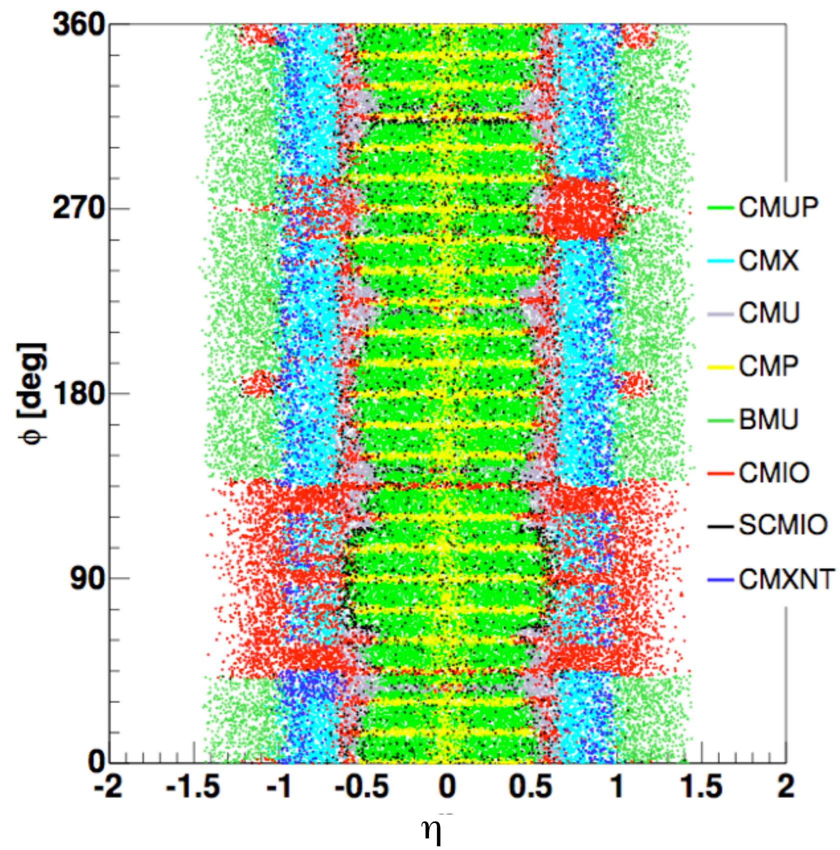


Finding More Muons in CDF

Muon coverage used for LP07



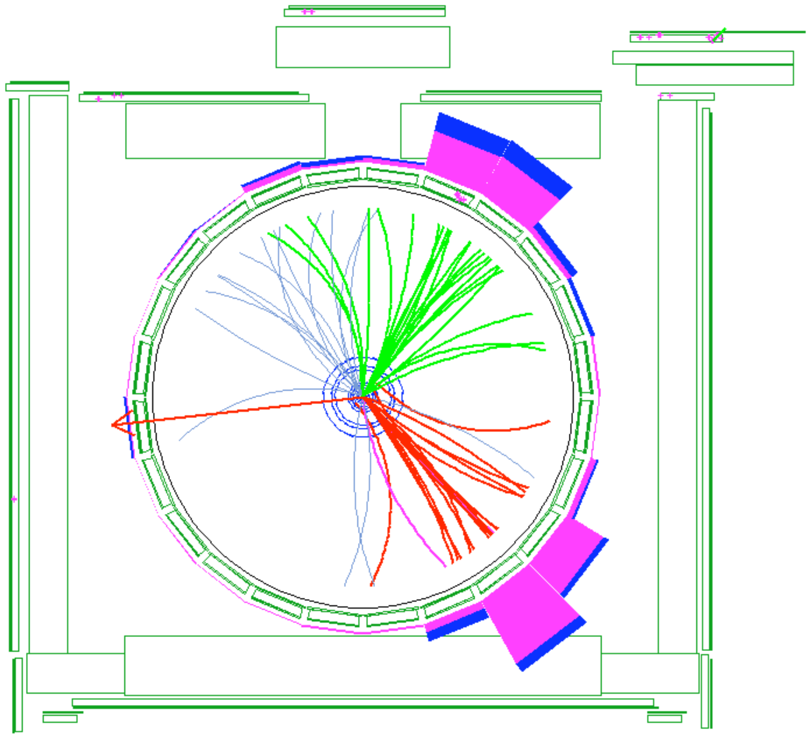
Gains from Missing-E_T+jets triggered events

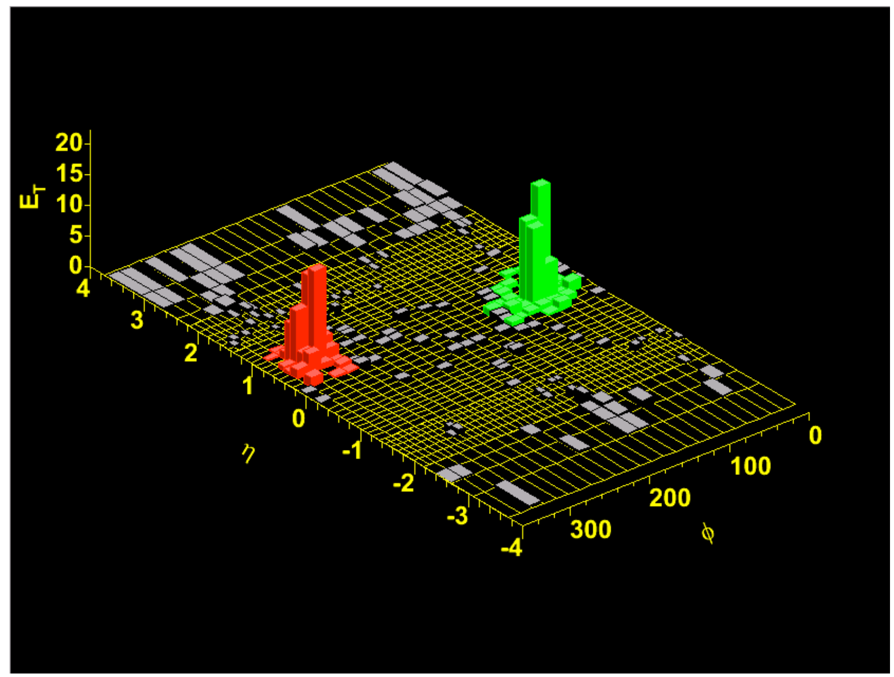


Additional requirement:
$\Delta R_{jj}>1.0$

~30% gain in muon acceptance,

Another Interesting Candidate Event





Jet$_1$ E_T=84.7 GeV
Jet$_2$ E_T=71.9 GeV -- Tagged

m_{jj} = 129 GeV

Missing E_T = 98 GeV

The LEP Legacy -- CL_s Limits

- Based on p-values. Programs easily switch between limits and discovery.

CL_{s+b} = p($-2\ln Q \geq -2\ln Q_{obs}$|s+b hypothesis)
CL_b=p($-2\ln Q \geq -2\ln Q_{obs}$|b-only hypothesis)

p-value = 1-CL_b commonly used for discovery.
p-value < 2.77×10^{-7} is a 5σ discovery

$CL_s=CL_{s+b}/CL_b$ is used for limits. Not a probability, or a confidence level, but it has good properties.
$CL_s<0.05 \rightarrow$ exclusion
Properties: $CL_s \geq CL_{s+b}$ always, and $CL_s=1$ when there is no sensitivity (s=0 or just very small).

$CL_{s+b}=CL_b$ is uniformly distributed between 0 and 1 when the signal s is very small or zero.

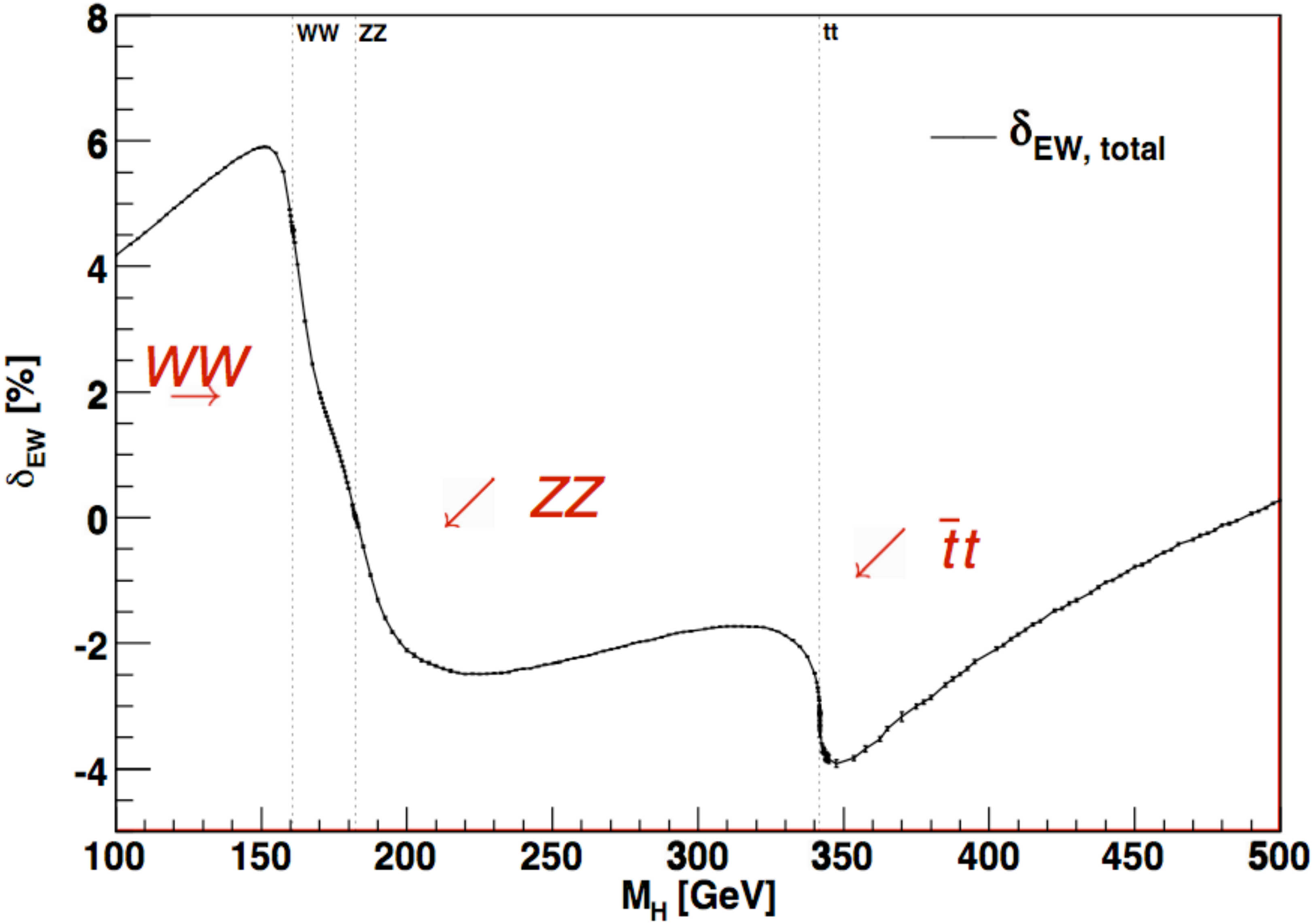
The LEP Legacy -- SM Searches

- A great variety of E_{beam} data. MC had to follow closely
- Interpolation strategies developed both for E_{beam} and m_H in order to reduce the Monte Carlo load
- Still -- each E_{CM}, each experiment, each search mode: about 200 channels total.
- Hard kinematic wall at $2E_{beam}$-M_Z=(206-91=115) GeV
- CL_s limits used for each channel, combinations
- Rate systematics included; shape systematics usually not evaluated.

Higgs Boson Production Cross Sections and Decay Branching Ratios

m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to\tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)
100	1861	286.1	166.7	99.5	81.21	7.924	1.009
105	1618	244.6	144.0	93.3	79.57	7.838	2.216
110	1413	209.2	124.3	87.1	77.02	7.656	4.411
115	1240	178.8	107.4	79.07	73.22	7.340	7.974
120	1093	152.9	92.7	71.65	67.89	6.861	13.20
125	967	132.4	81.1	67.37	60.97	6.210	20.18
130	858	114.7	70.9	62.5	52.71	5.408	28.69
135	764	99.3	62.0	57.65	43.62	4.507	38.28
140	682	86.0	54.2	52.59	34.36	3.574	48.33
145	611	75.3	48.0	49.15	25.56	2.676	58.33
150	548	66.0	42.5	45.67	17.57	1.851	68.17
155	492	57.8	37.6	42.19	10.49	1.112	78.23
160	439	50.7	33.3	38.59	4.00	0.426	90.11
165	389	44.4	29.5	36.09	1.265	0.136	96.10
170	349	38.9	26.1	33.58	0.846	0.091	96.53
175	314	34.6	23.3	31.11	0.663	0.072	95.94
180	283	30.7	20.8	28.57	0.541	0.059	93.45
185	255	27.3	18.6	26.81	0.420	0.046	83.79
190	231	24.3	16.6	24.88	0.342	0.038	77.61
195	210	21.7	15.0	23	0.295	0.033	74.95
200	192	19.3	13.5	21.19	0.260	0.029	73.47

EW corrections to $\sigma(gg \to H)$



Passarino, Higgs Boson 2009, Zurich

Parity Violation and the Beginnings of the SM of Electroweak Interactions

- Lee and Yang, "Question of Parity Conservation in Weak Interactions" Phys. Rev. 104, 254-258 (1956).
- C. S. Wu et al., "Experimental Test of Parity Conservation in Beta Decay" Phys. Rev. 105, 1413-1414 (1957).
- Garwin, Lederman and Weinrich, "Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon" Phys. Rev. 105, 1415-1417 (1957).

With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints
[Veltman, 1977; Lee-Quigg-Thacker, 1977; …]

Zwirner

An example: $\mathcal{A}(W_L^+ W_L^- \to Z_L Z_L) \quad (s \gg m_W^2)$

$$i\frac{s}{v^2}$$

$$-i\frac{s^2}{v^2(s-m_h^2)}$$

$$\to \quad -i\frac{m_h^2}{v^2}\frac{s}{s-m_h^2}$$

If no Higgs then something must happen!

G. Altarelli, HCPSS 2008

CDF's Combined Higgs Limits -- By the Numbers

m_H (GeV/c^2)	Observed limit/SM	-2σ expected	-1σ expected	median expected	$+1\sigma$ expected	$+2\sigma$ expected
100	2.72	1.44	1.92	2.63	3.61	4.87
105	2.66	1.55	2.01	2.71	3.69	4.97
110	3.49	1.54	2.04	2.83	3.95	5.44
115	3.64	1.75	2.33	3.22	4.46	6.08
120	3.90	1.95	2.58	3.57	4.98	6.86
125	4.76	1.99	2.62	3.65	5.17	7.22
130	4.48	2.06	2.75	3.78	5.21	7.08
135	3.55	1.94	2.50	3.44	4.83	6.71
140	3.53	1.74	2.36	3.32	4.67	6.44
145	3.48	1.72	2.20	3.03	4.25	5.91
150	2.44	1.34	1.78	2.47	3.45	4.74
155	2.03	1.15	1.48	2.08	2.99	4.24
160	1.42	0.81	1.11	1.59	2.29	3.22
165	1.46	0.85	1.16	1.61	2.22	3.00
170	1.94	0.97	1.32	1.82	2.47	3.29
175	2.15	1.19	1.60	2.21	3.03	4.09
180	2.28	1.34	1.79	2.49	3.48	4.80
190	3.68	2.18	2.85	3.90	5.38	7.35
200	6.39	3.03	3.92	5.41	7.64	10.70

Tevatron Combined Higgs Limits -- By the Numbers

Bayesian	100	105	110	115	120	125	130	135	140	145	150
Expected	2.0	2.0	2.2	2.4	2.7	2.9	2.9	2.7	2.5	2.4	1.8
Observed	1.9	1.8	2.4	2.5	2.8	3.0	3.5	2.4	2.7	2.8	1.9

CL_S	100	105	110	115	120	125	130	135	140	145	150
Expected	1.9	1.9	2.1	2.4	2.6	2.7	2.9	2.7	2.5	2.2	1.8
Observed	1.7	1.7	2.2	2.6	2.8	2.9	4.0	2.6	3.1	2.8	2.0

Bayesian	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.4	1.6	1.9	2.2	2.7	3.5	4.2
Observed	1.4	0.99	0.86	0.99	1.1	1.2	1.7	2.0	2.6	3.3

CL_S	155	160	165	170	175	180	185	190	195	200
Expected	1.5	1.1	1.1	1.3	1.6	1.8	2.5	3.0	3.5	3.9
Observed	1.3	0.95	0.81	0.92	1.1	1.3	1.9	2.0	2.8	3.3

For details, see arXiv:0903.4001 [hep-ex]