Searches for the Standard Model Higgs Boson at the Tevatron

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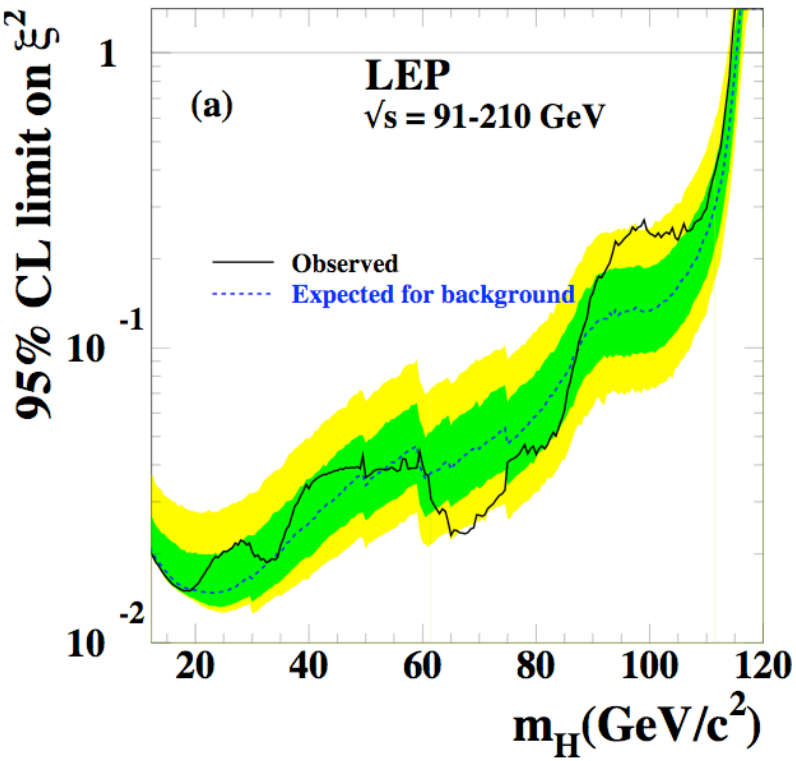
on behalf of the CDF and D0 Collaborations

CERN Joint PP/EP Seminar / 23 June, 2009

- Context and Phenomenology
- The Experiments
- High Mass (130-200 GeV): Searches for $H \rightarrow WW$
- Low Mass (114-150 GeV): Searches for $H \rightarrow bb, \tau\tau$
- Combined Results
- Plans for the Future

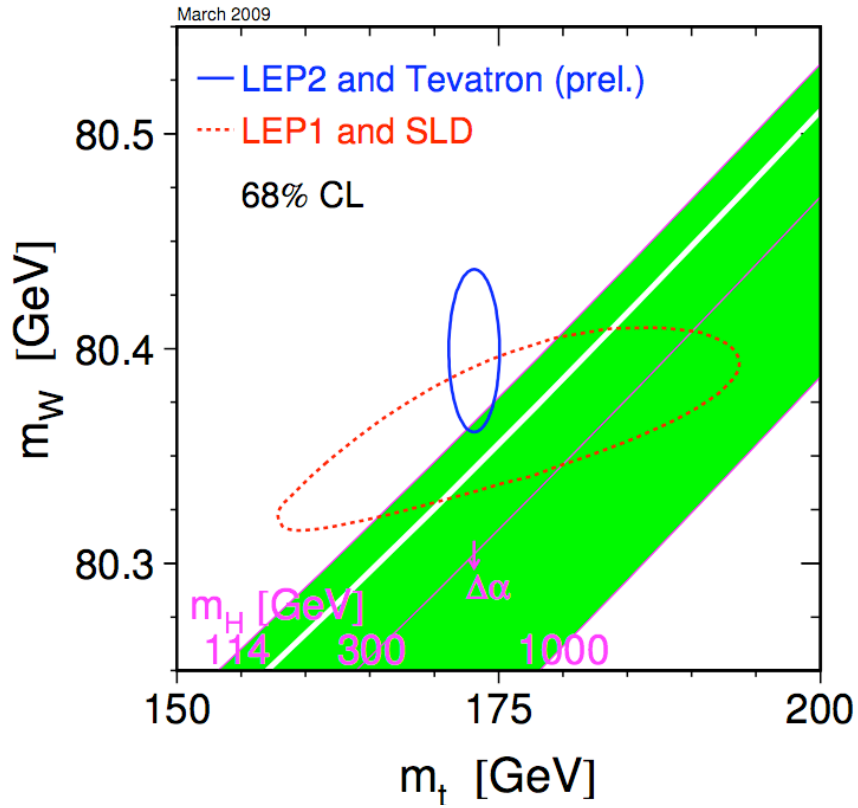
The LEP2 and Tevatron, LEP1, SLD Precision EW Legacy

Direct searches for
$e^+e^- \rightarrow ZH$: $m_H^{SM} > 114.4\ \mathrm{GeV}/c^2$
No evidence below



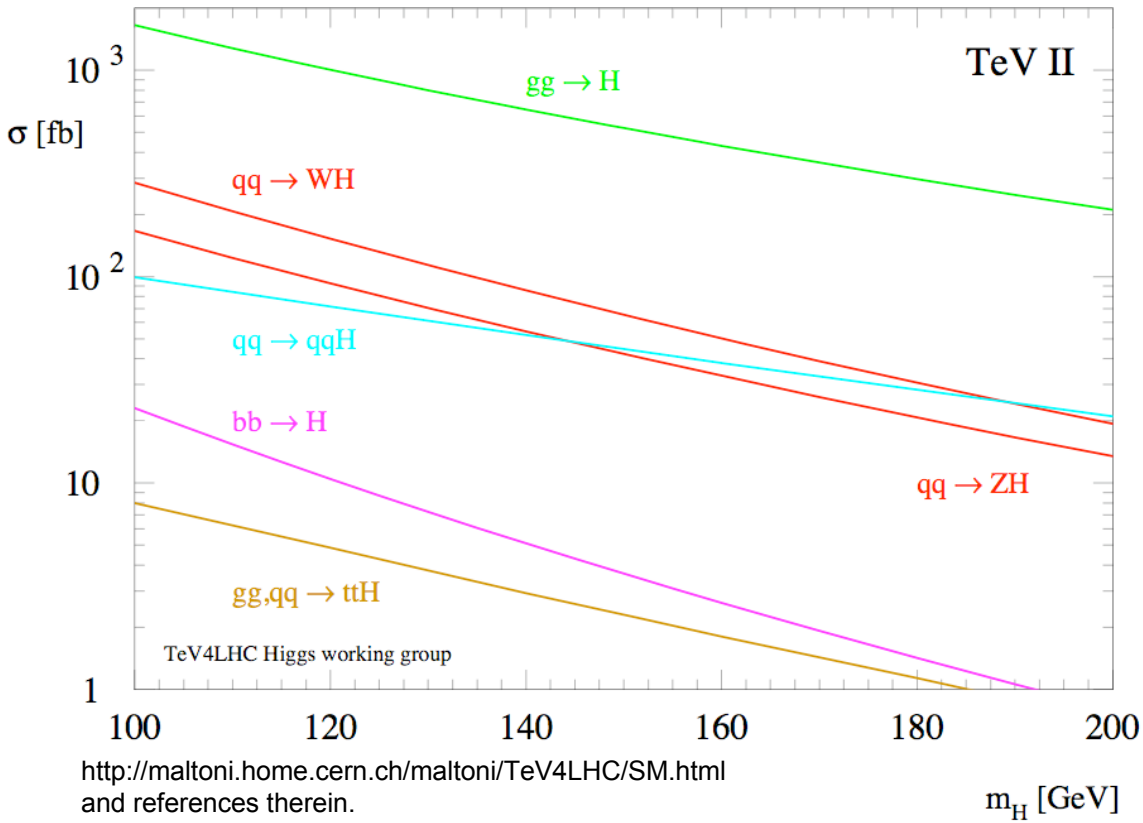
Precision m_z, m_W, m_t, Z-pole asymmetries, etc.

$$m_H^{SM} = 90^{+36}_{-27}\ \mathrm{GeV}/c^2$$

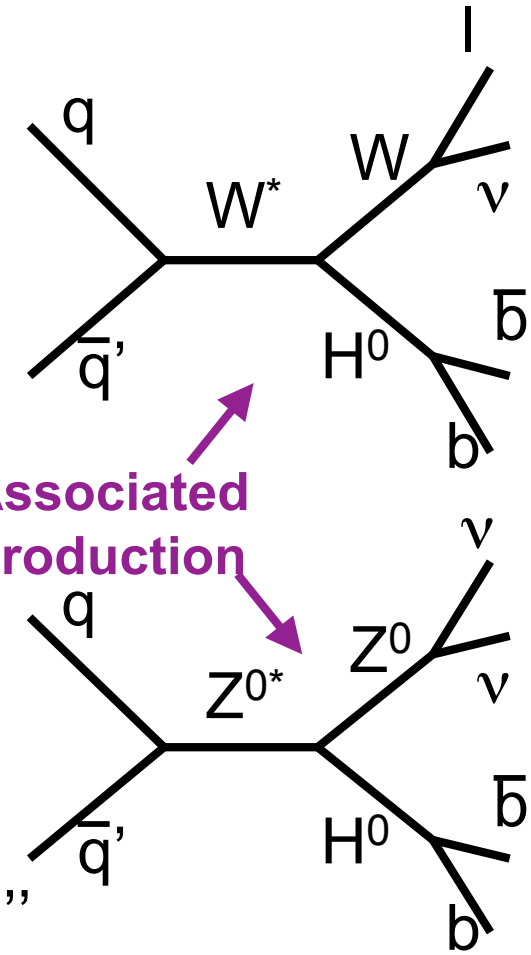


@95% CL, m_H<163 GeV/c^2
(191 including LEP2 direct limit)

SM Higgs Boson Production Mechanisms

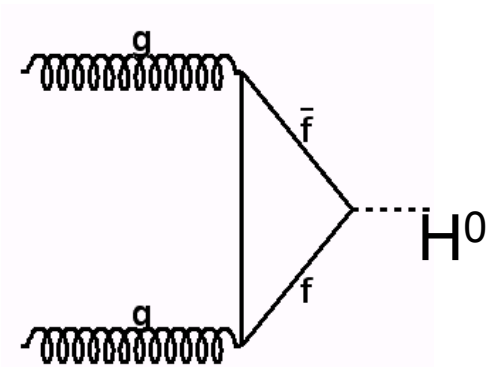


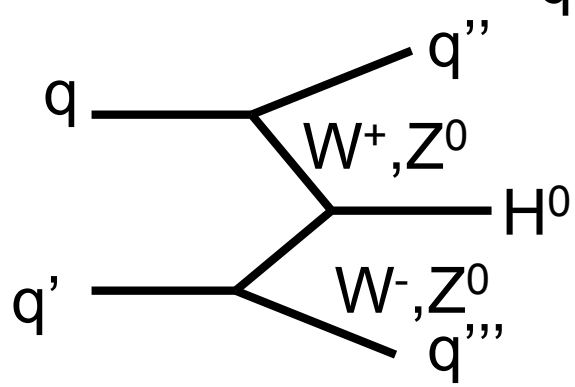
http://maltoni.home.cern.ch/maltoni/TeV4LHC/SM.html
and references therein.



Associated Production

gluon fusion





Vector-Boson Fusion (VBF)

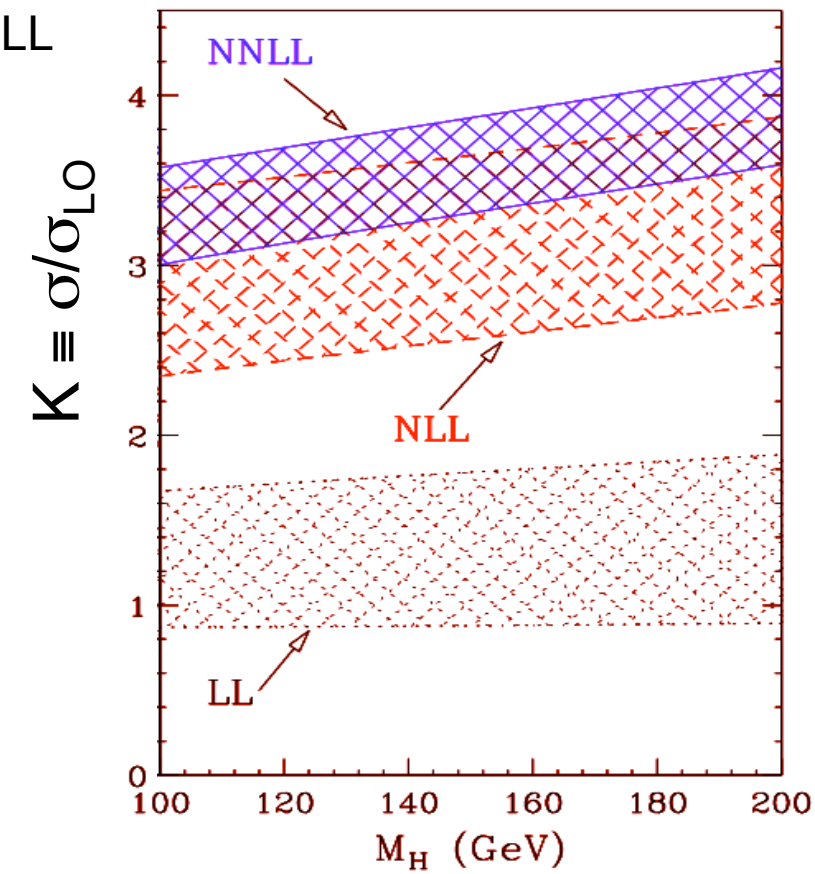
Recent gg→H Production Cross Section Progress

- 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

Also resummed QCD corrections at NNLL

NLL,NNLL bands: $0.5m_H<\mu_F,\mu_R<2M_H$.
Bands on LO and LL unreliable.

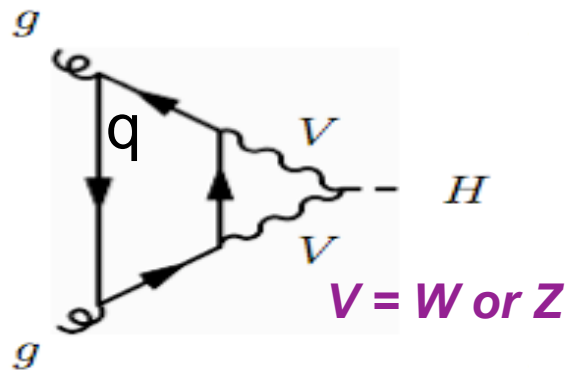
We take a ±12% uncertainty
on $\sigma_{gg\to H}$ for scale and PDF



Recent gg→H Production Cross Section Progress

- Two-loop EW corrections yield up to an 8% boost in cross section
- b-quark QCD corrections improved
- Total 14% bigger cross section at m_H=160 GeV relative to NNLO

2-Loop EW diagram: 6 quark flavors contribute



Catani, de Florian, Grazzini, JHEP **0307**, 028 (2003)
Aglietti, Bonciani, Degrassi and Vicini, Phys. Lett. B 595, 432 (2004)
} Used by the Tevatron at ICHEP08

Actis, Passarino, Sturm, Uccirati, Phys. Lett. B **670**, 12 (2008)
Anastasiou, Boughezal, Petriello, JHEP **0904**, 003 (2009)
Grazzini, De Florian, Phys. Lett. B **674**, 291 (2009)
} Used by the Tevatron at Moriond 2009

http://www.itp.uzh.ch/events/higgsboson2009 7-9 Jan.2009, Zurich

Parton Distribution Functions Are Important for gg→H

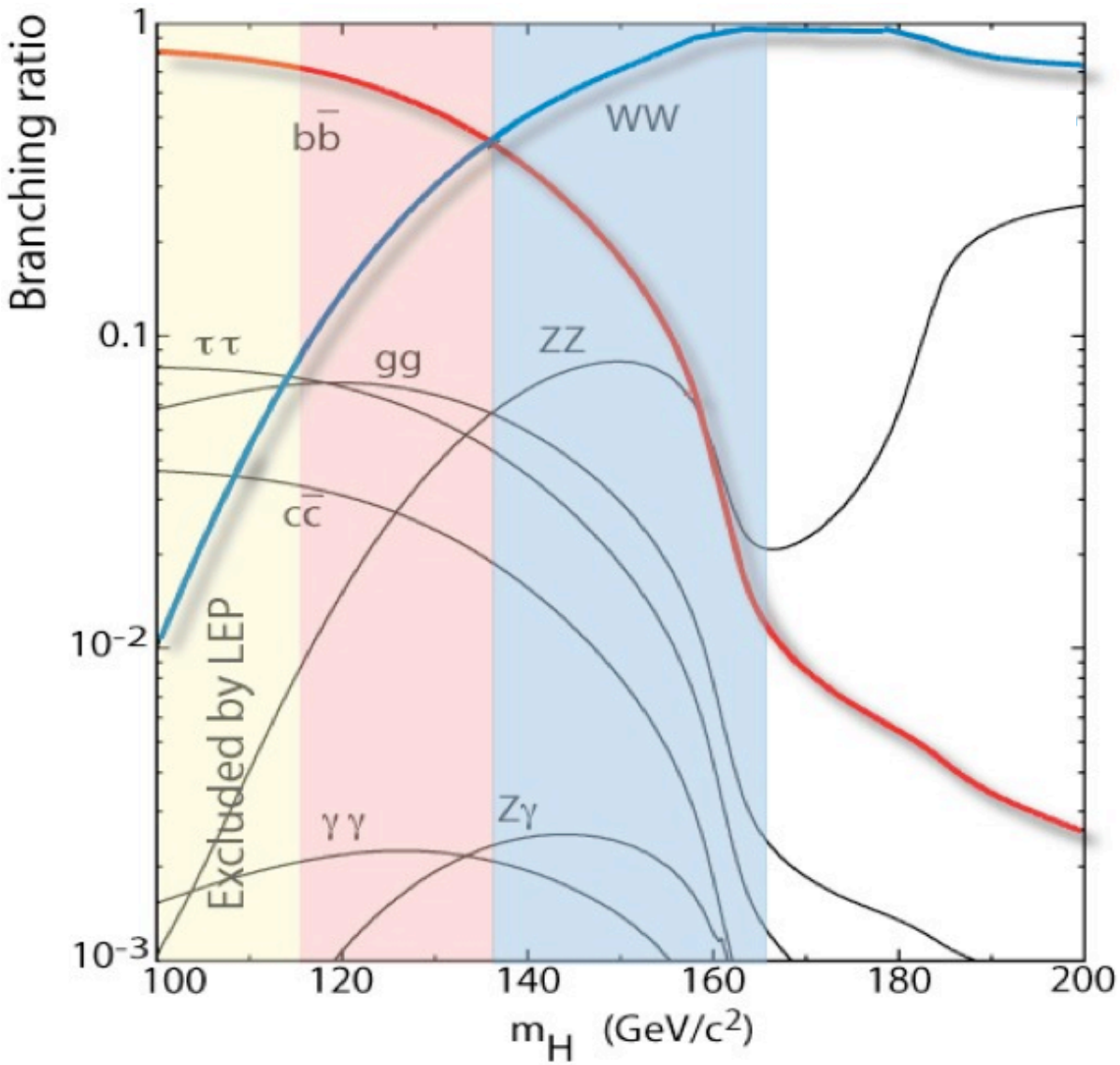
- MSTW released a new PDF set on January 5, 2009
  ("MSTW 2008")
  Includes Tevatron Run II High-E_t Jet Data
  (Less of an excess than Run I data)

- Effect: high-*x* gluon PDF x α_s is less.

Impact is ~15% **downward** shift in gg→H cross section

Included in Moriond 2009 Tevatron Higgs results

Standard Model Higgs Boson Decay Branching Fractions



HDECAY by
M. Spira

114.4 < m_H < 135 GeV:
H→bb dominates.

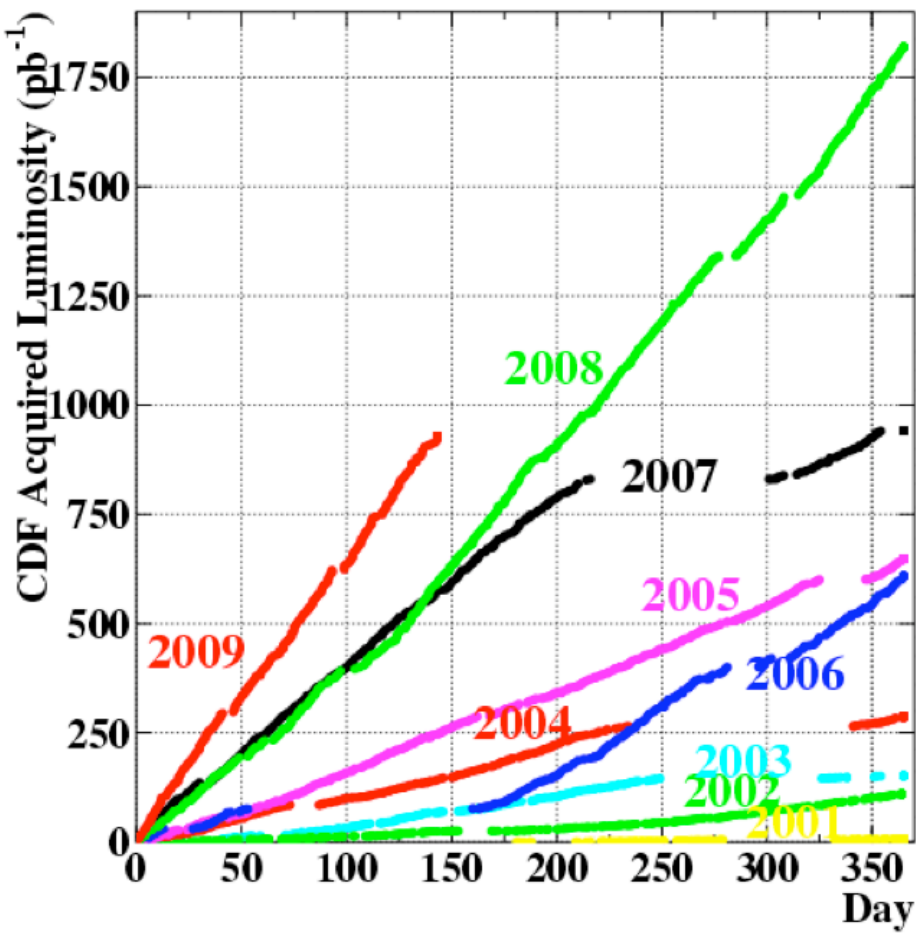
gg→H→bb drowned by gg→bb. Use WH, ZH.

135 < m_H < 200 GeV
H→W^+W^- dominates

gg→H, WH, ZH, VBF all can be used

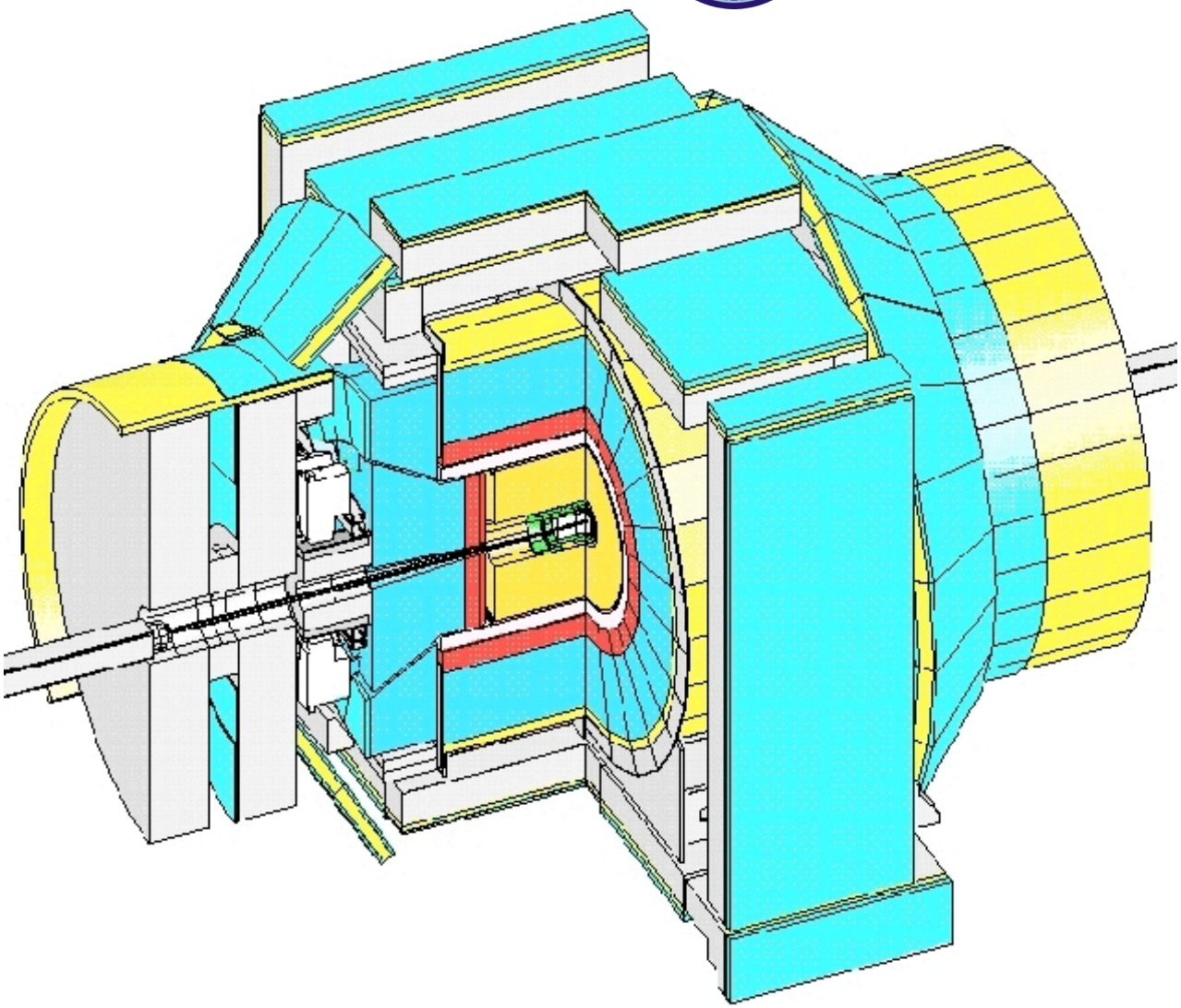
Tevatron Performance Constantly Improves

A partial list of improvements:



- Store antiprotons in recycler
- Faster transfers from pbar accumulator to recycler
- Electron cooling of pbars in recycler
- Efficiency and reliability of injection
- Faster shot setup
- Separation of orbits at parasitic crossings
- Replacement of 1200 He relief valves
- Faster beam aborts during quenches
- “cogging” pbars to prevent quenches during acceleration

The CDF II Detector



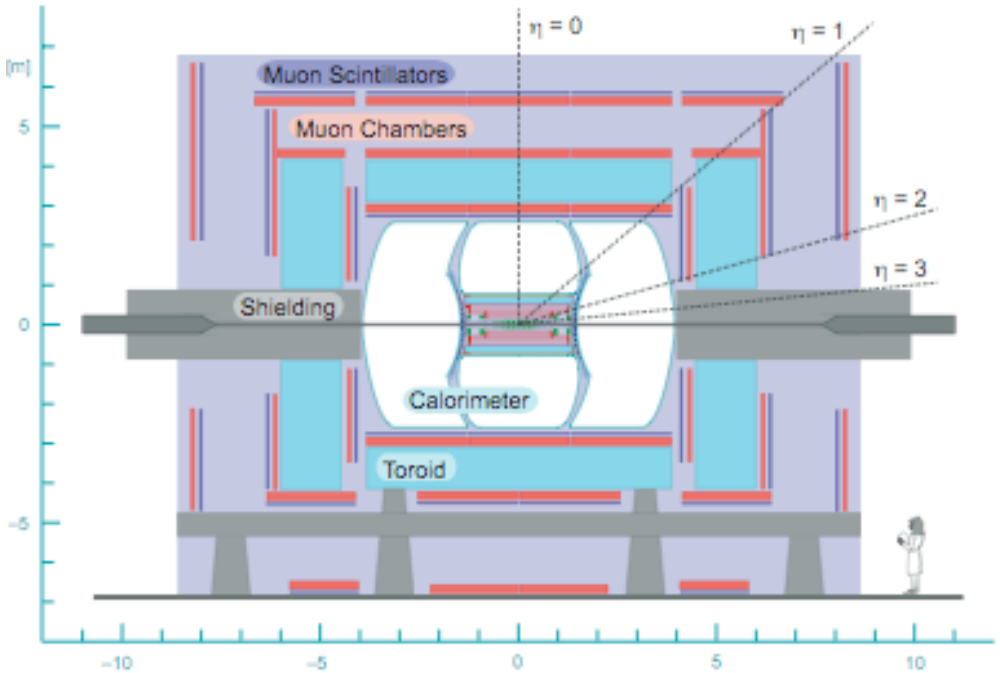
Lepton coverage:
$|\eta| < 1.5$ (muons)
$|\eta| < 2.0$ (electrons)

b-tagging with
$|\eta| < \sim 1.4$

Jets to
$|\eta| < 2.8$
Higgs analyses restrict to
$|\eta| < 2.0$

Dijet mass resolution: ~16%

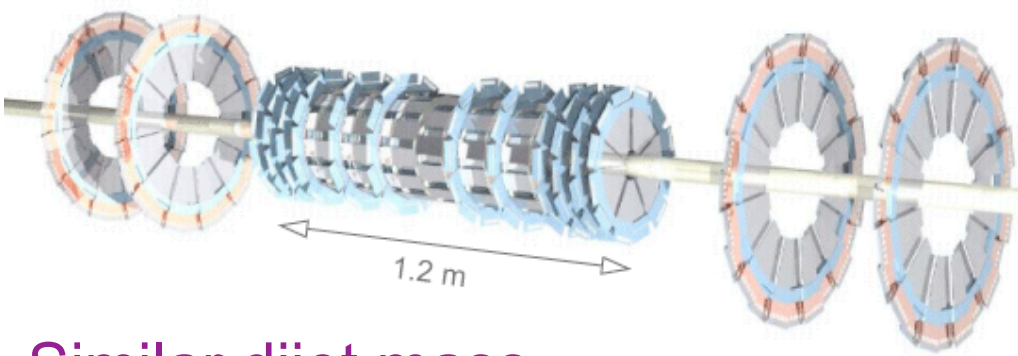
The DØ Detector



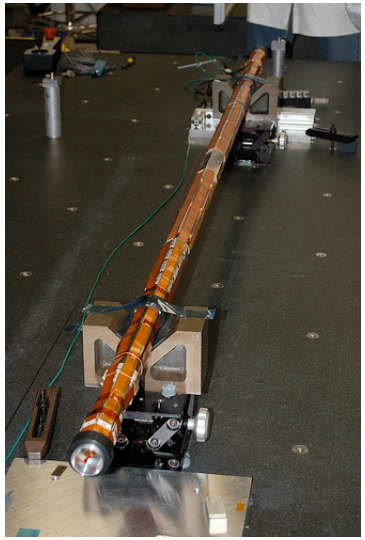
Lepton coverage:
|η| < 2 (muons)
|η| < 2.6 (electrons)

b-tagging with
|η| < ~2

Jets to
|η| < 3



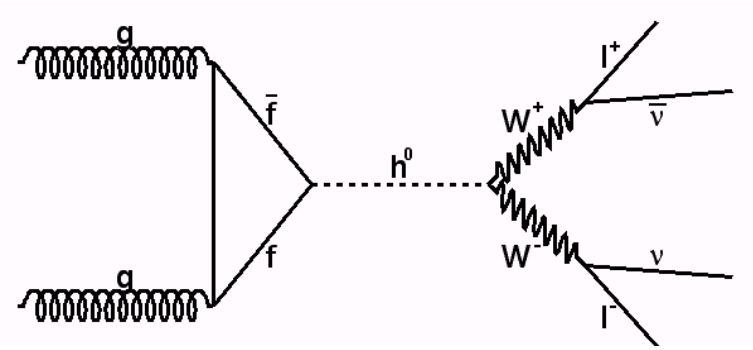
Similar dijet mass resolution to CDF



New Innermost Silicon Layer added between Run IIa and Run IIb

$H \rightarrow W^+W^-$ Signal and Background

gg→H Signal Process:



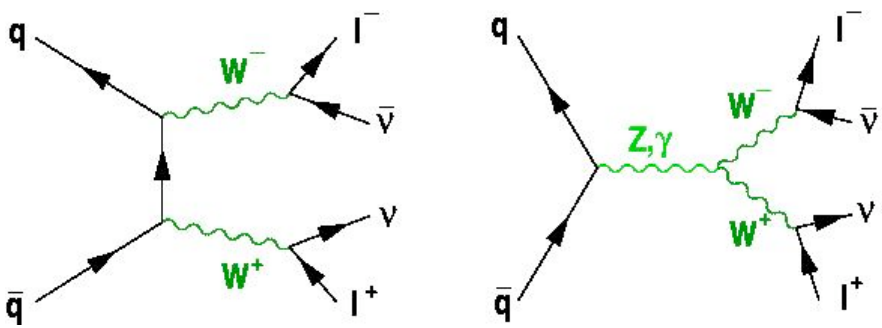
Both CDF and D0 Select events with

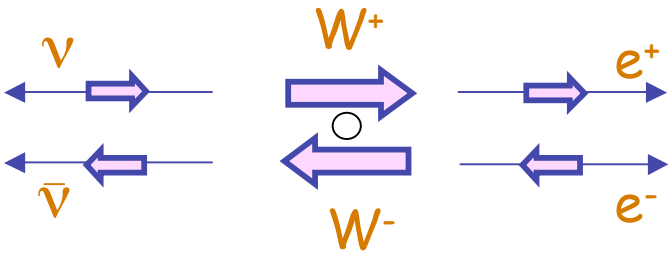
- Two isolated, opposite-signed high-p_T leptons (e,μ)
- Missing transverse energy
- m_{ll} > ~ 15 GeV

Dominant difficult background:

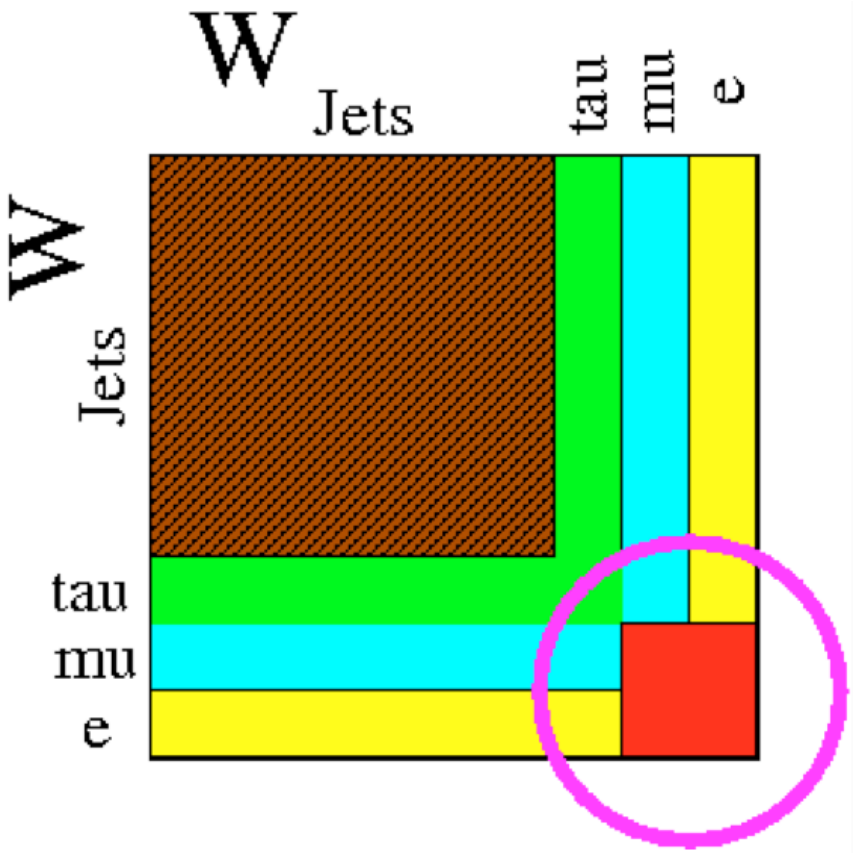
$q\bar{q} \rightarrow W^+W^-$

- Higgs is a Scalar! Angular correlations are different from SM W^+W^- bg
- Signal leptons come out collinear





WW Leptonic Decay Branching Ratios



Br(W→hadrons) ≈ 68%

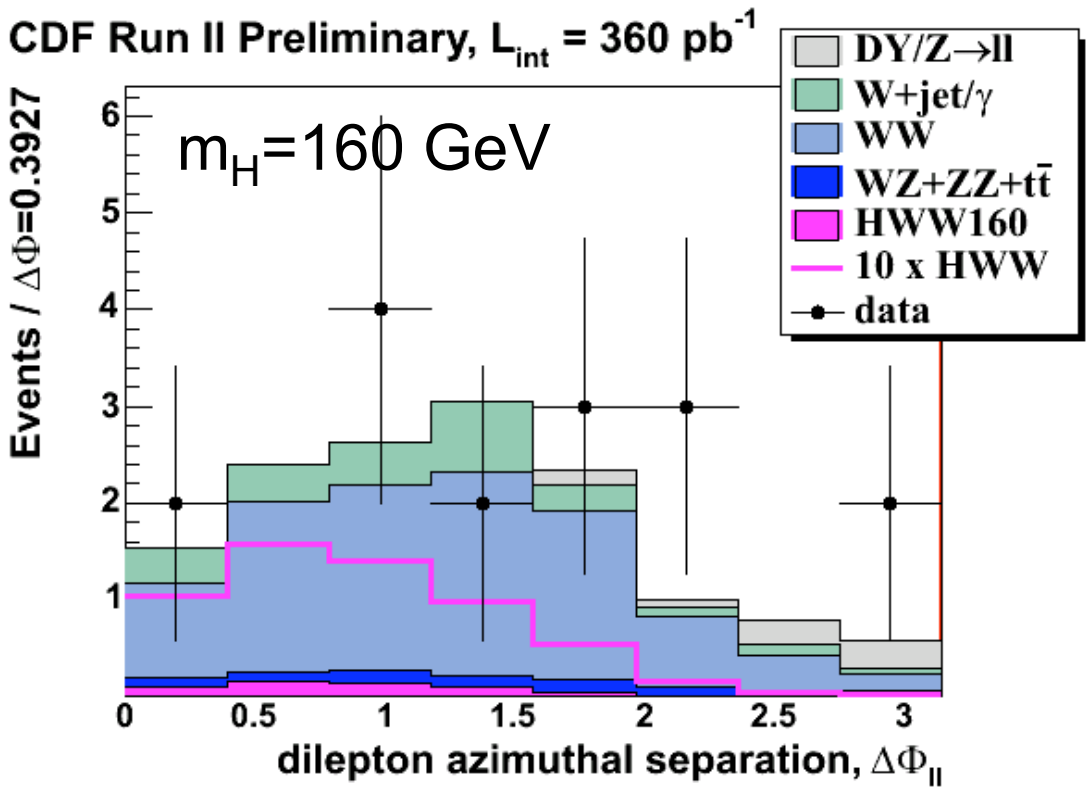
W+jets and multijet backgrounds prohibit using W→hadron decays

Br(WW→ee, eμ, μμ) ≈ 6%

- Manageable background
- Lepton triggers are easier
- Missing E_T (neutrinos) is an important signature too
- Includes some W→τ decays

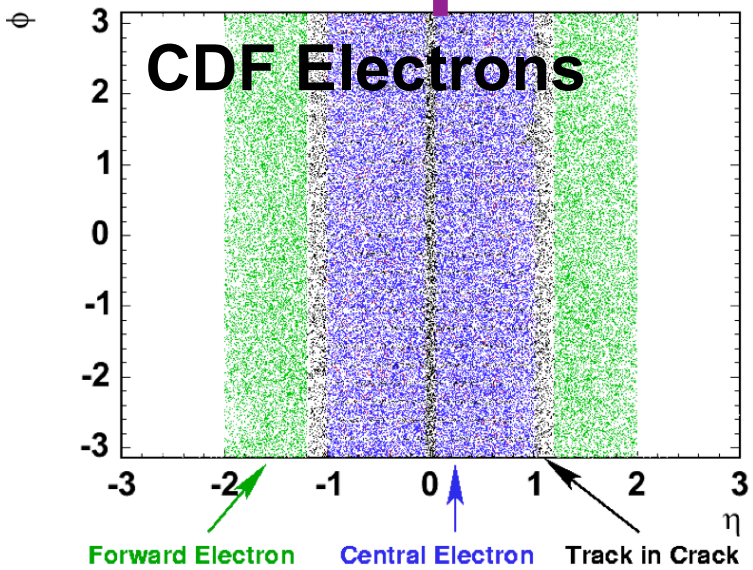
Four Years ago: 2005 H→WW Analysis

- Just used gg→H signal
  acceptance: 0.7% of ggH, or about 0.55% of all H at m_H=160 GeV
- Final discriminant: $\Delta\phi_{ll}$
- Jet vetoes to suppress ttbar

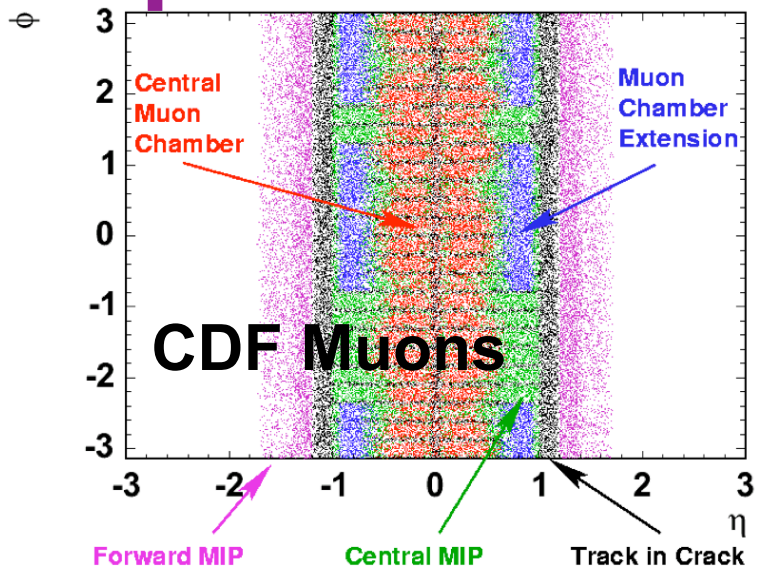


Expected limit: ~15 x SM at m_H=160 GeV

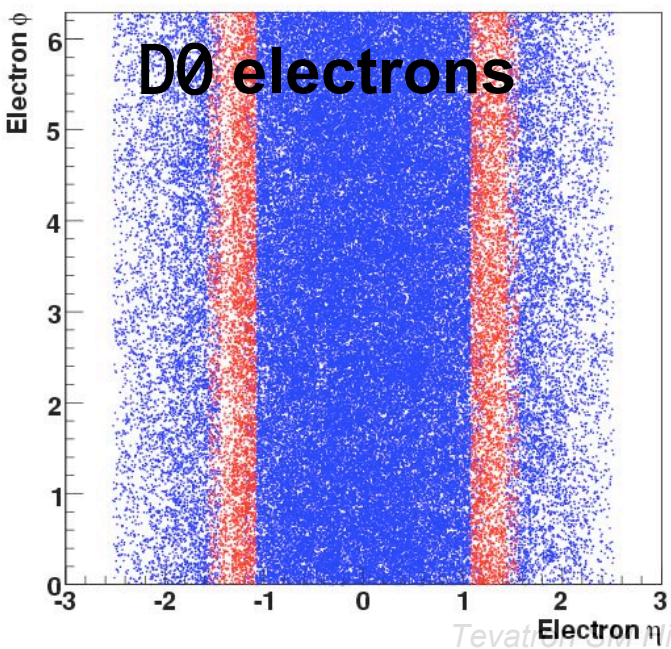
Lepton Acceptance Gains



10% gain in CDF electron acceptance



30% gain in CDF single-muon acceptance



Inter-calorimeter electrons
-- 10% gain in D0 electron acceptance

These Leptons don't all trigger!
Use another lepton, or MET+Jets triggers.

Splitting up the H→WW Sample

- Three final states, each gets a separate channel

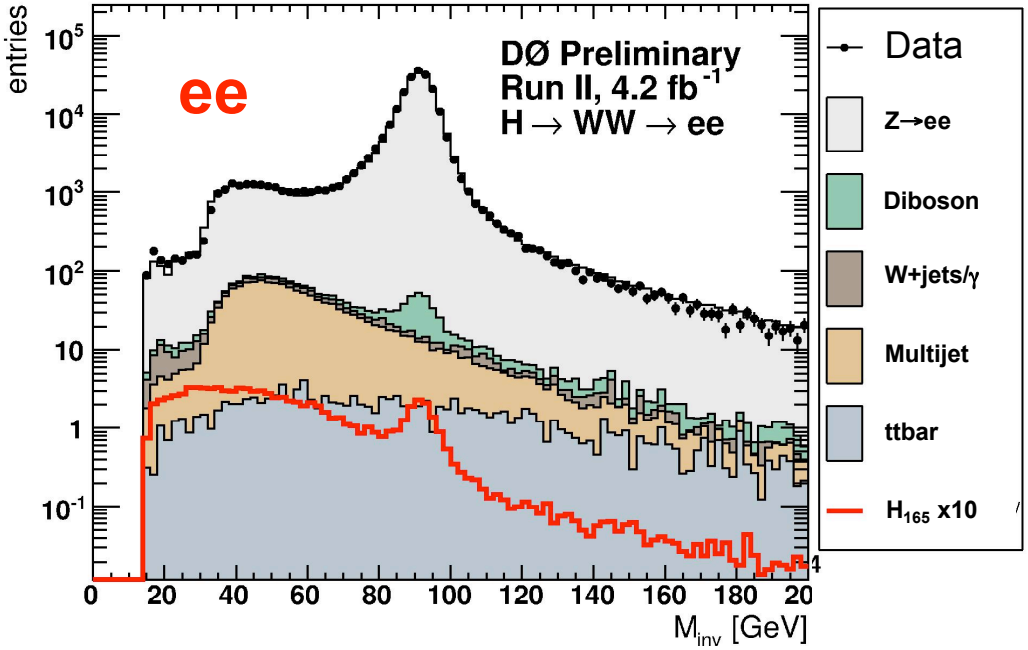
ee, eμ, μμ

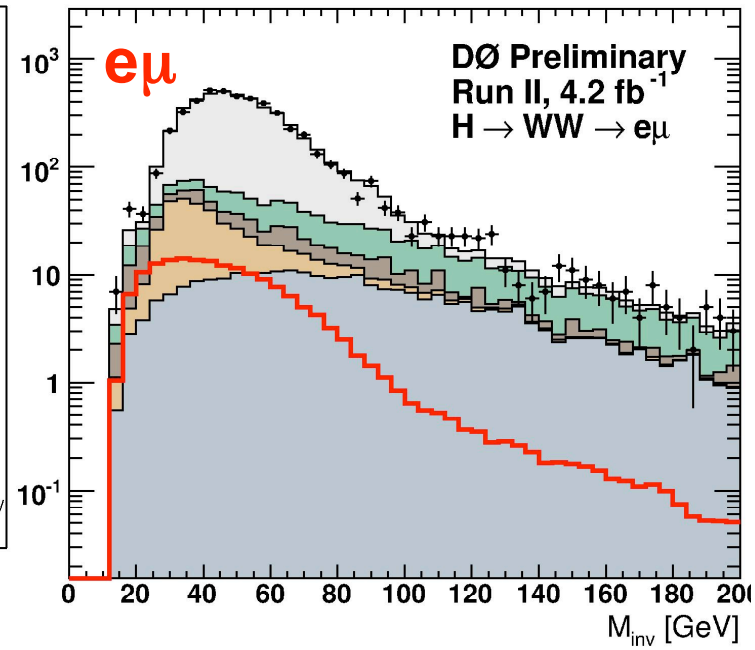
Different signal and background rates and systematics. Split and combine at the end. Preselection:

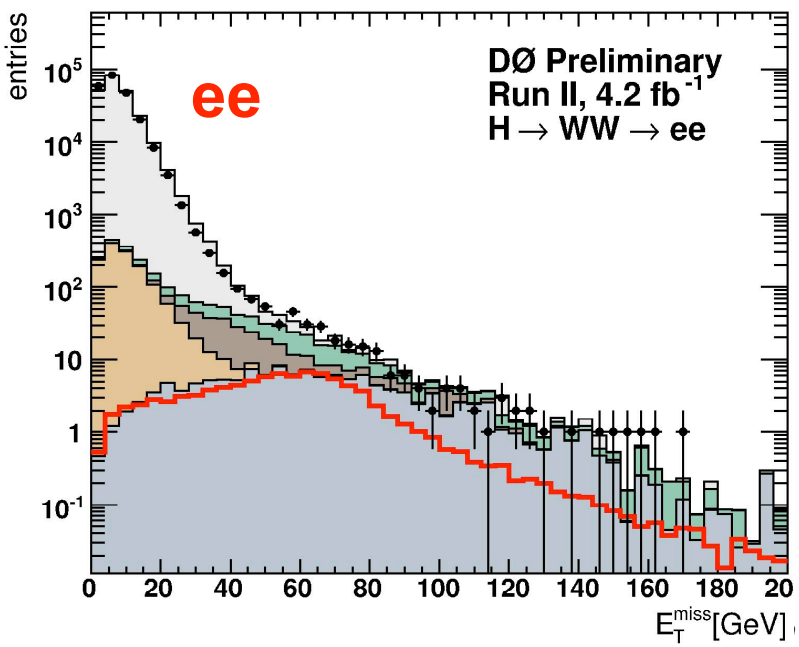
Two oppositely-signed leptons:

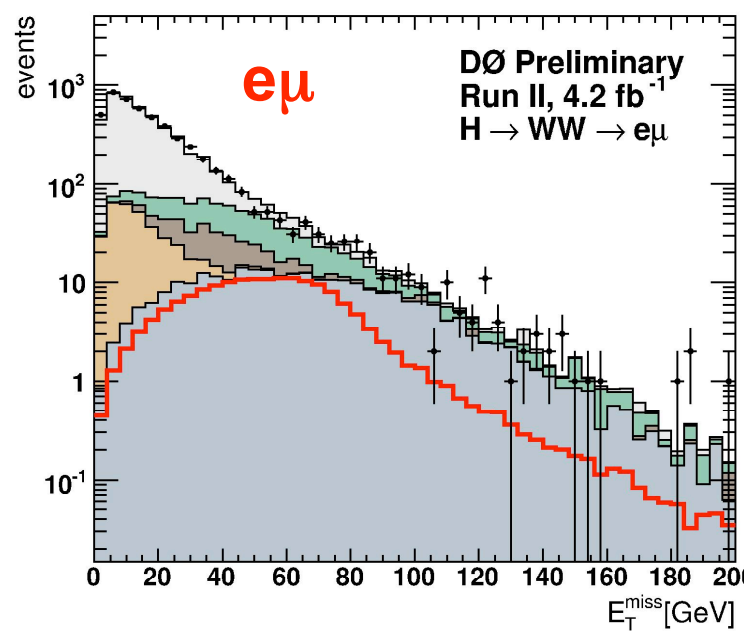
- $p_{T,e}$>15 GeV, $p_{T\mu}$>10 GeV (15 GeV for leading muon)
- m_{ll} > 15 GeV
- n_{jet} < 2 in the μμ channel

ee, eμ Samples : Preselection Level



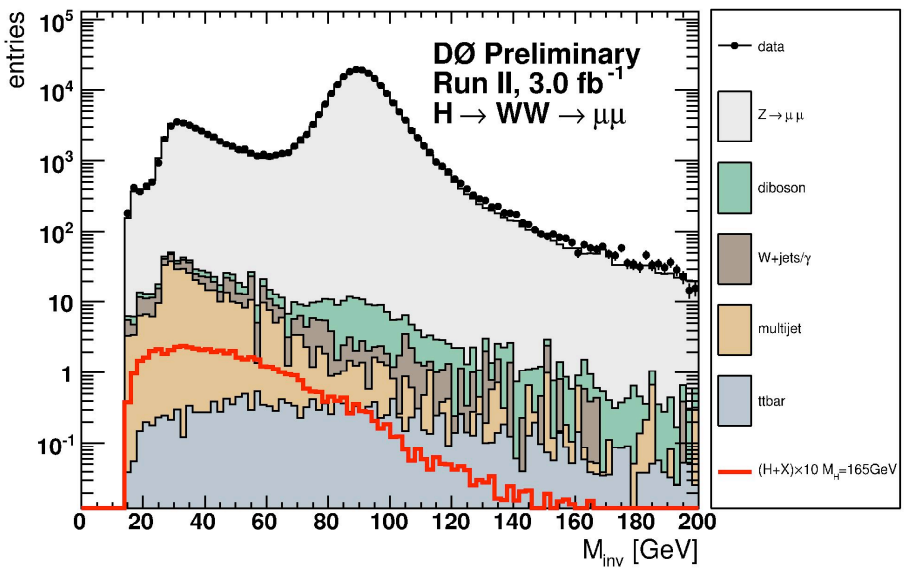


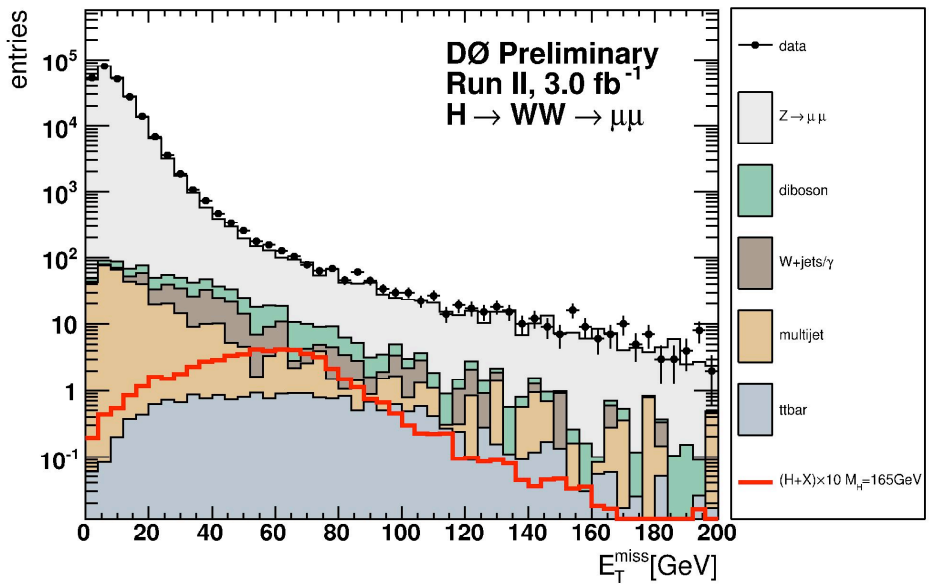




μμ Sample at Preselection Level

Missing-E_T resolution not as good. Cut MET on it only in 1-jet case for selection.





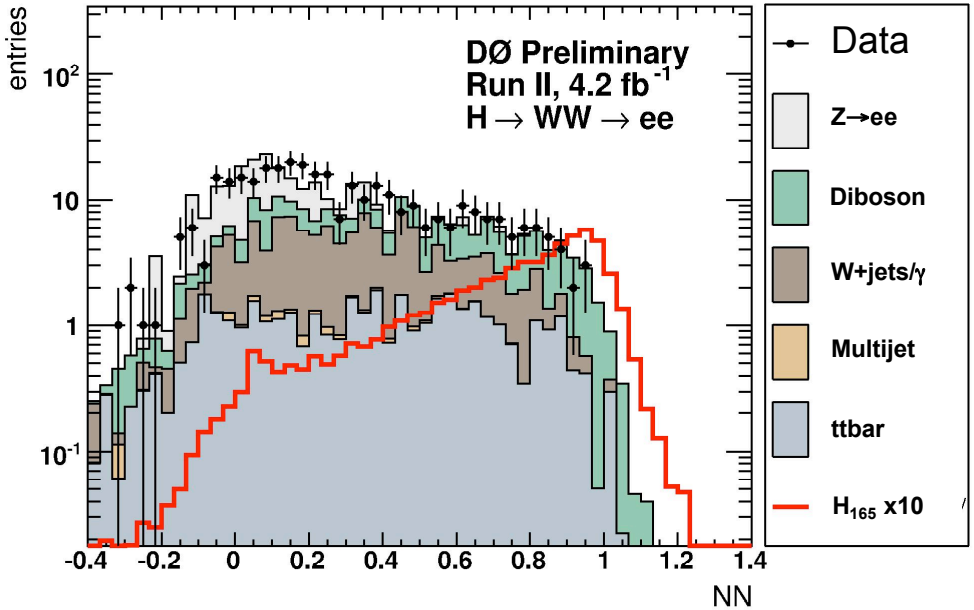
ee and eμ Selection requirements

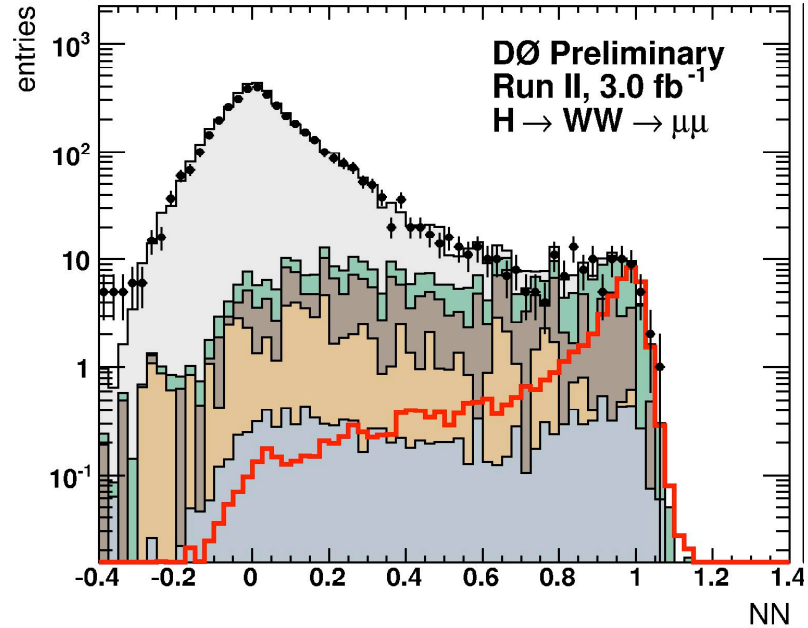
MET>20 GeV, MET_{scaled}>6

$M_{T,min}$(l,MET)>20 GeV

$\Delta\phi_{ll}$<2.0.

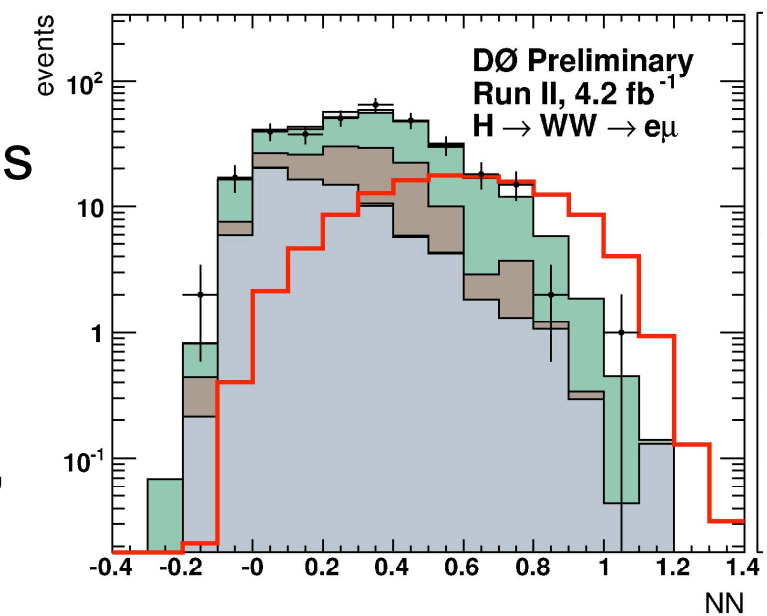
NN Discriminants m_H=165 GeV





- Different amounts of DY background in different channels due to different MET cuts

- Neural networks derived from p_t of leptons, MET, $\Delta\phi(l,l)$, $R\phi(l,l)$, $\Delta\phi(MET,l)$, $M(l,l)$, H_T



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
  - Total CDF acceptance: 1.1%: **DOUBLE the 2005 acceptance**.

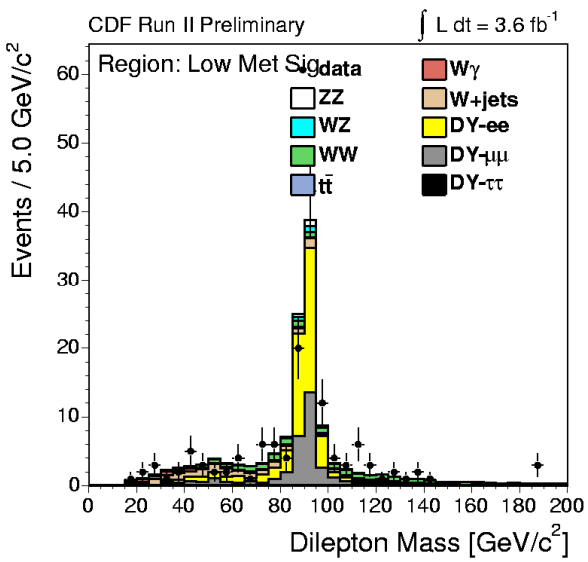
Better MET resolution -- lepton categories treated more symmetrically

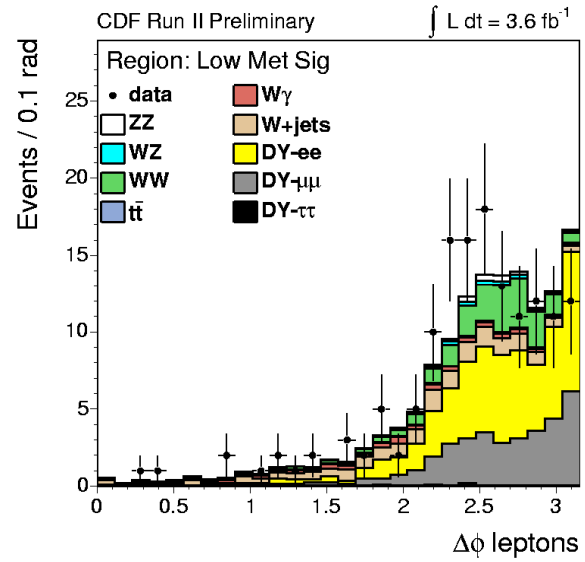
  - Same-sign dileptons + one or more jets: Mostly sensitive to WH and ZH, with leptonic W, Z decay.

Each major background has a dedicated control sample

Checking Control Regions

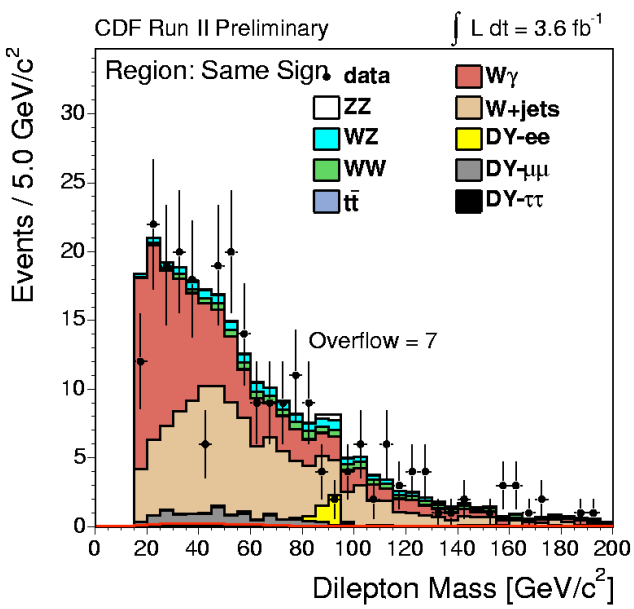
Low MET significance control region -- events with fake MET

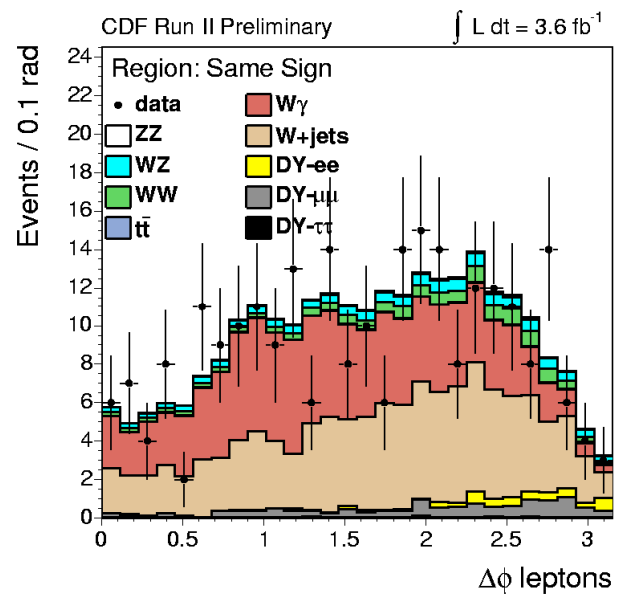




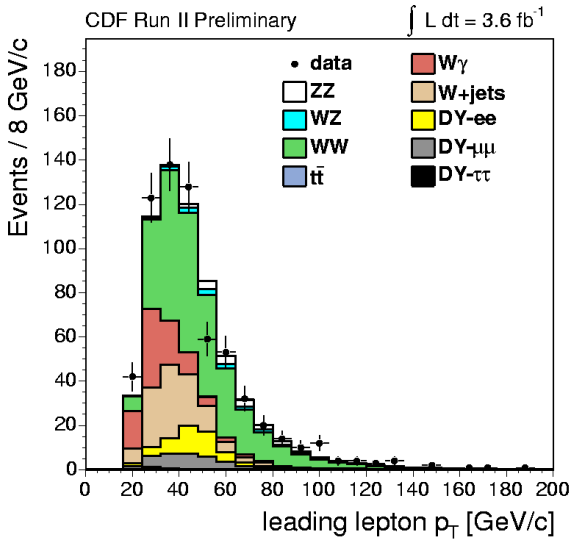
Same Sign Dileptons

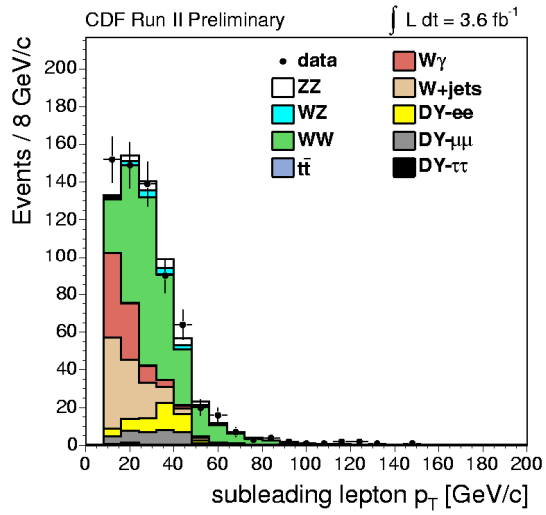
Wγ, W+jets backgrounds

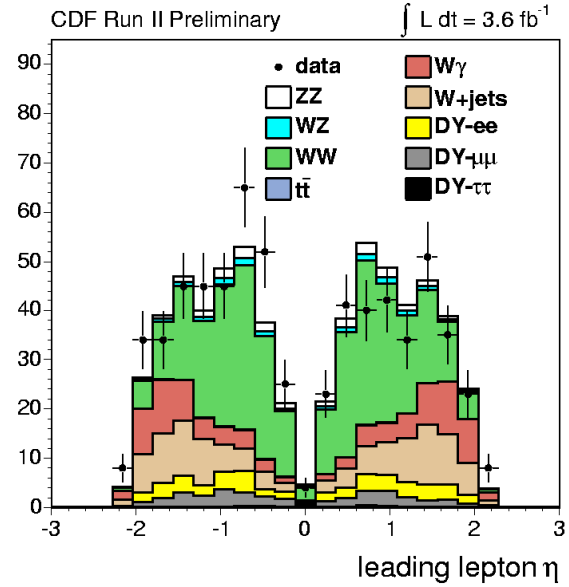


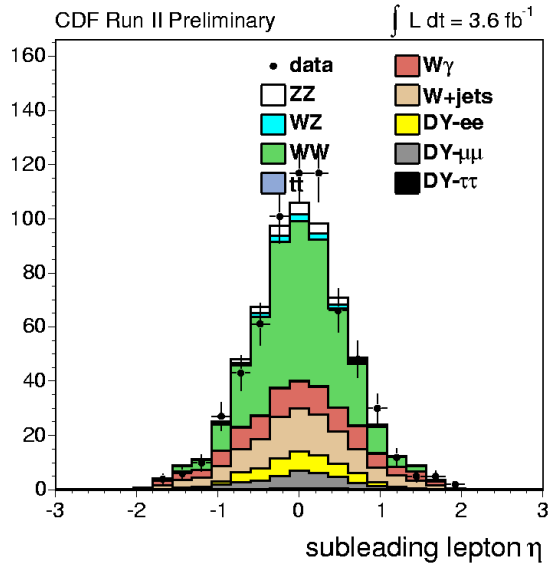


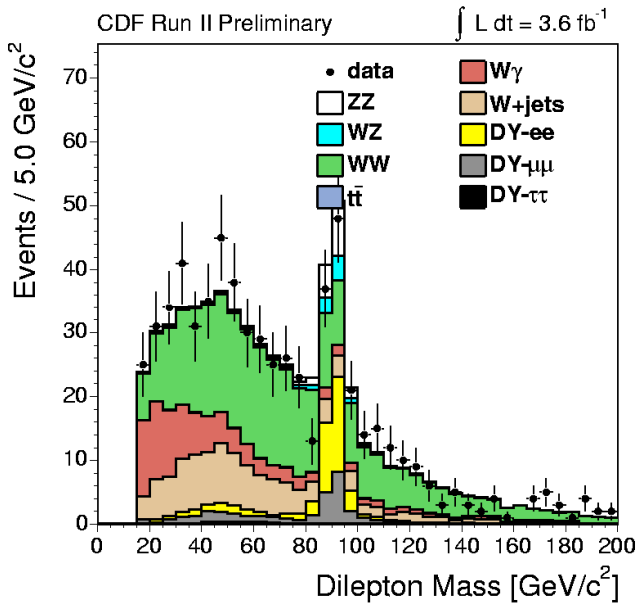
Checking The Signal Region

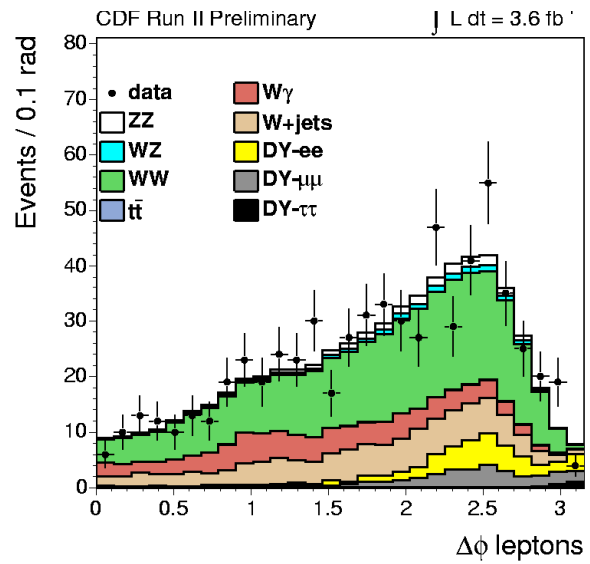












Matrix Element Basics

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.

Imperfect Reconstruction

- Missing neutrinos! Missing E_T resolution not perfect.
- Jet energies not perfectly measured. Directions are pretty good, and leptons are measured well.
- What parton 4-vectors could have given us the measured events?

ME PDFs transfer function

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

y=parton (or neutrino momenta), *x*=measured jet quantities.

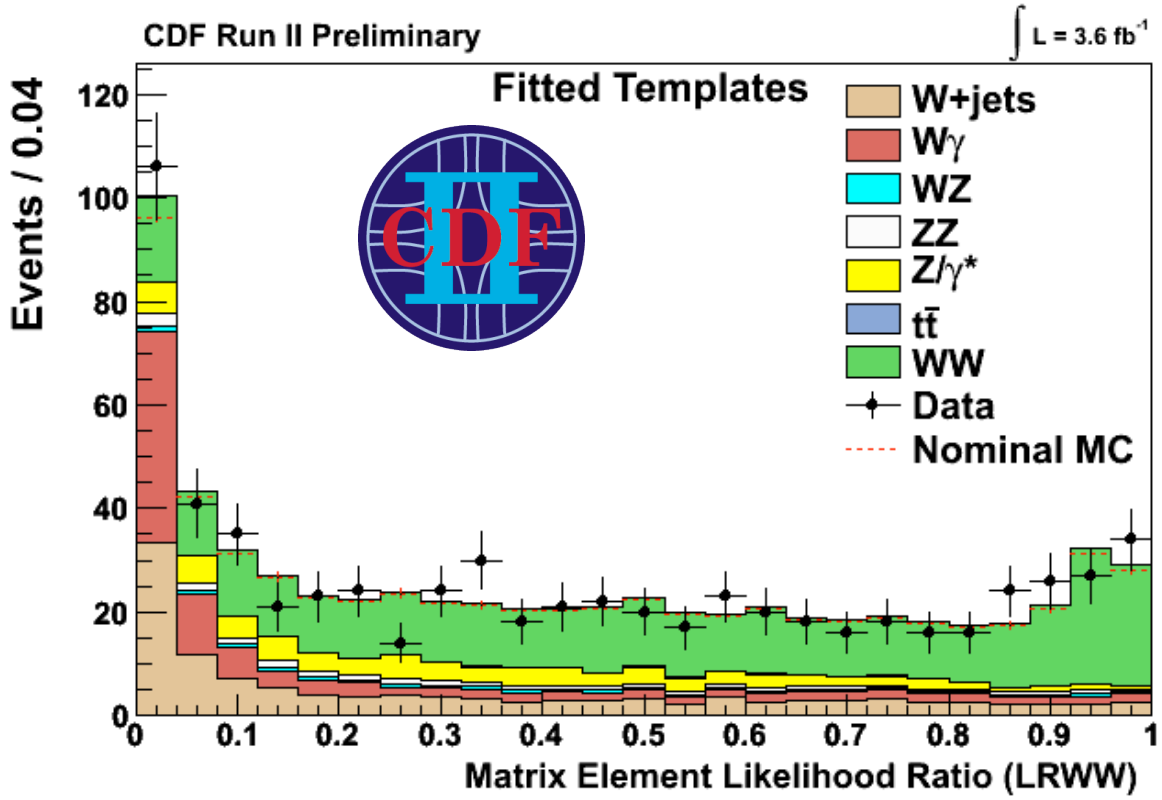
Do this for each physics process -- form a likelihood ratio from them

WW Cross Section Measurement

Signal model: MC@NLO

Checks Matrix Element discriminant shape of dominant background in the signal sample

Same as Higgs search but reverse roles of signal and background

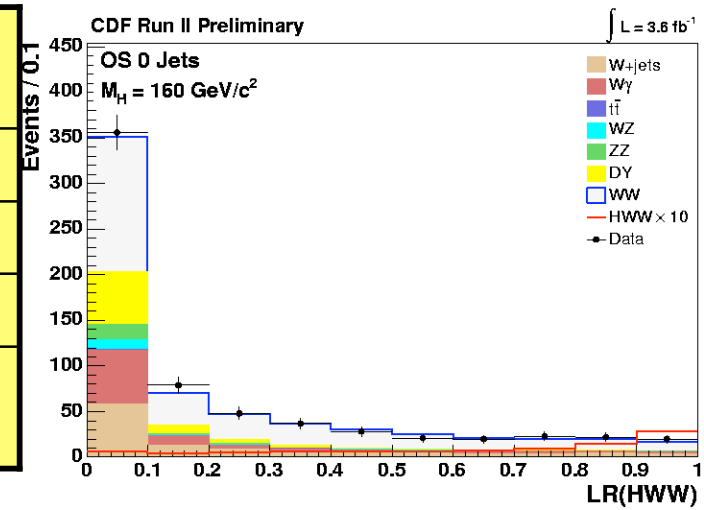


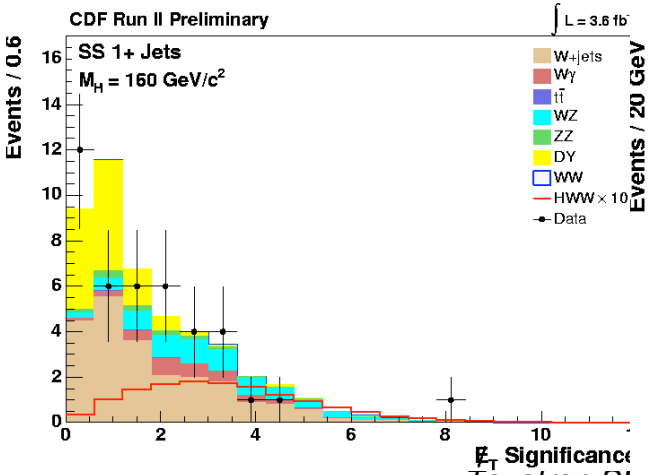
$$\sigma(p\bar{p} \rightarrow W^+W^-) = 12.1 \pm 0.9 \text{ (stat) } {}^{+1.6}_{-1.4} \text{ (syst) [pb]}$$

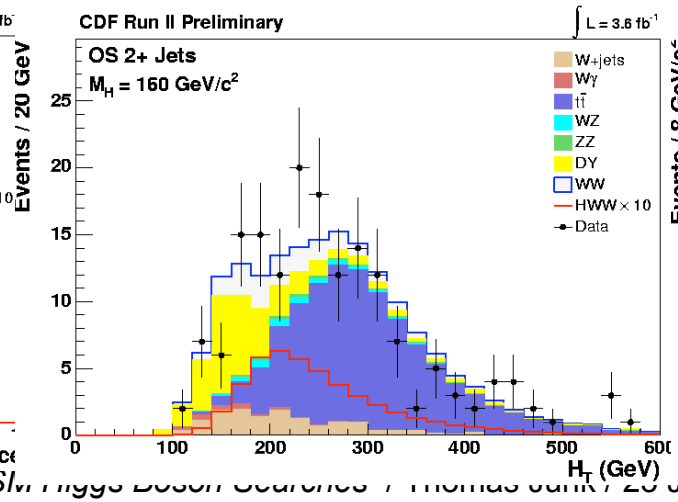
SM: 12.4 ± 0.7 pb (MCFM)

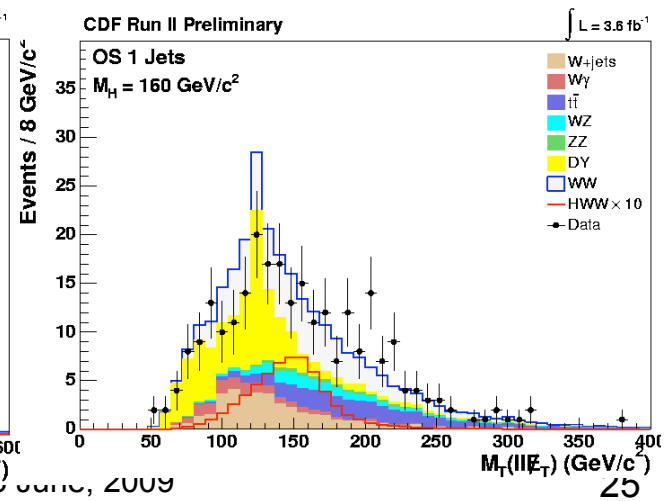
H→WW -- Event Kinematics Separating Signal from Background

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

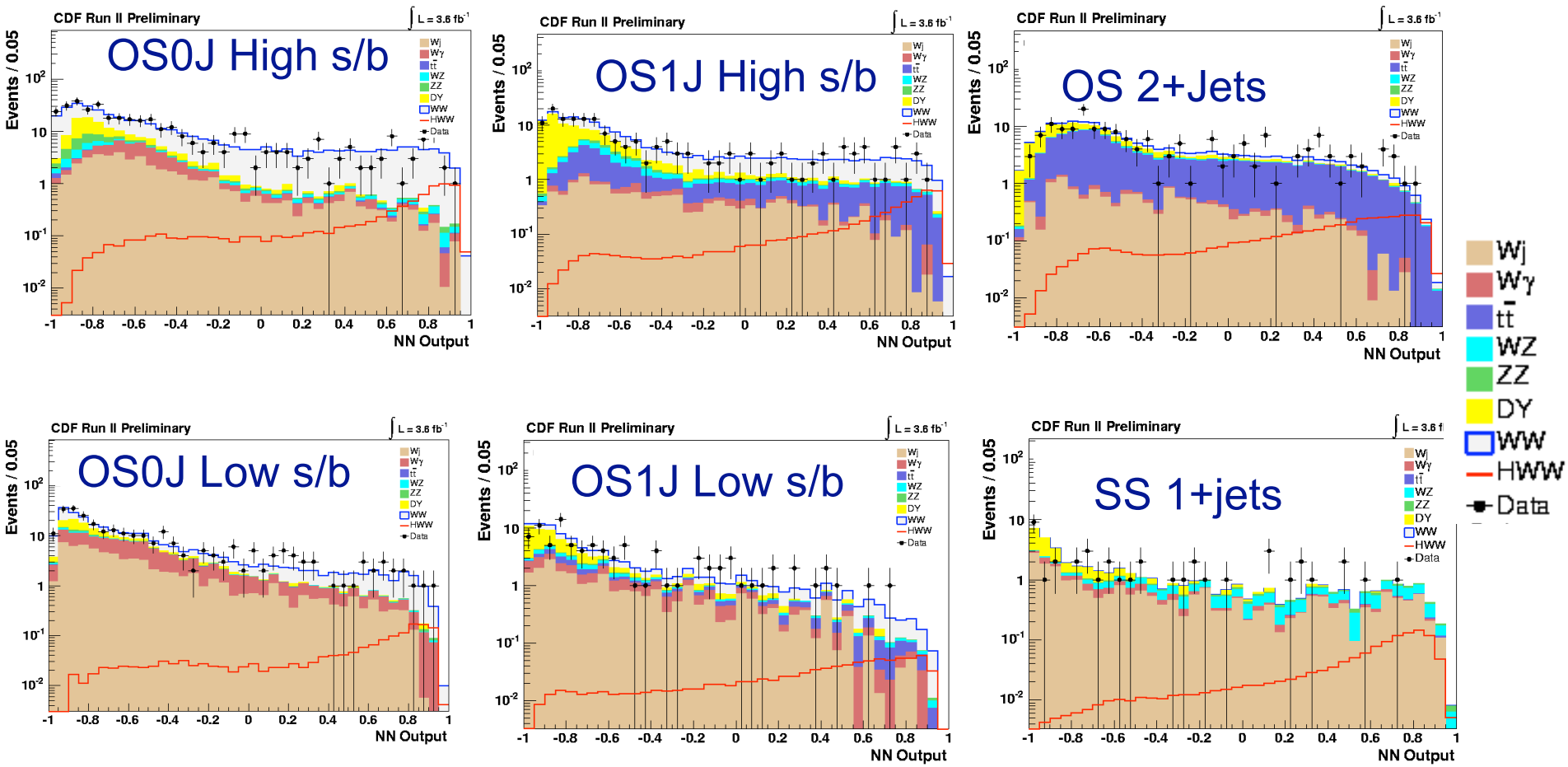






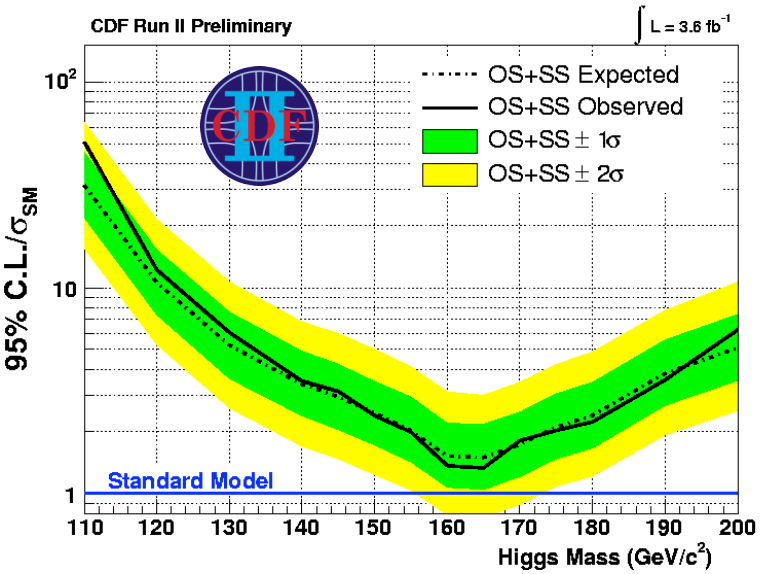


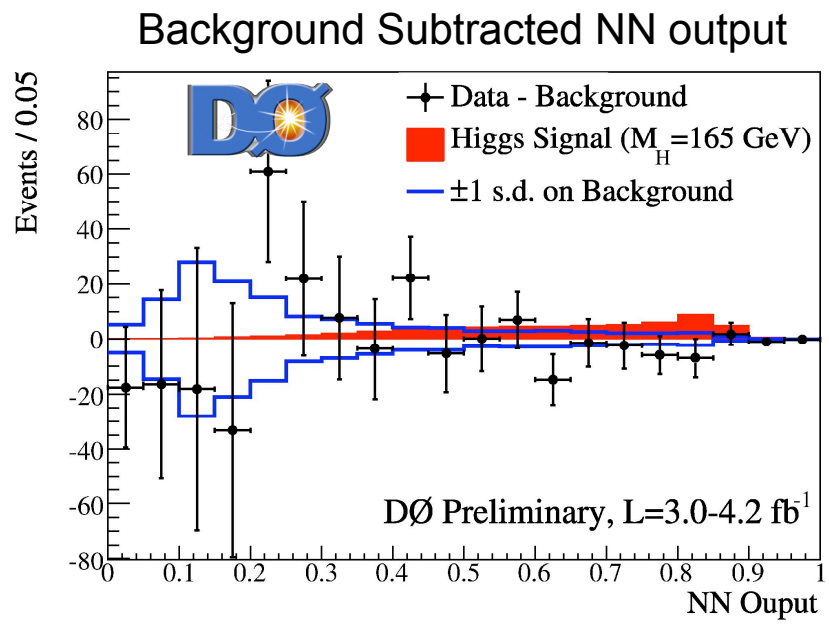
Discriminant Outputs: m_H=165 GeV



Signal x 1.0

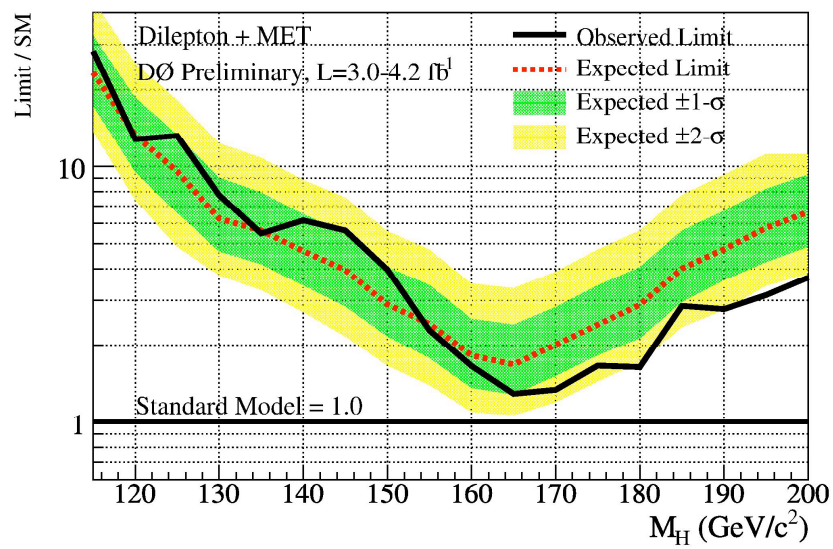
CDF and D0 limits for H→WW Channels





At m_H=165 GeV, at 95% CL

```
CDF:  obs   1.3 x SM
      exp   1.5 x SM
D0:   obs   1.3 x SM
      exp   1.7 x SM
```



CMSSM Favors m_H <120 GeV

- Bayesian scan over CMSSM parameter space.

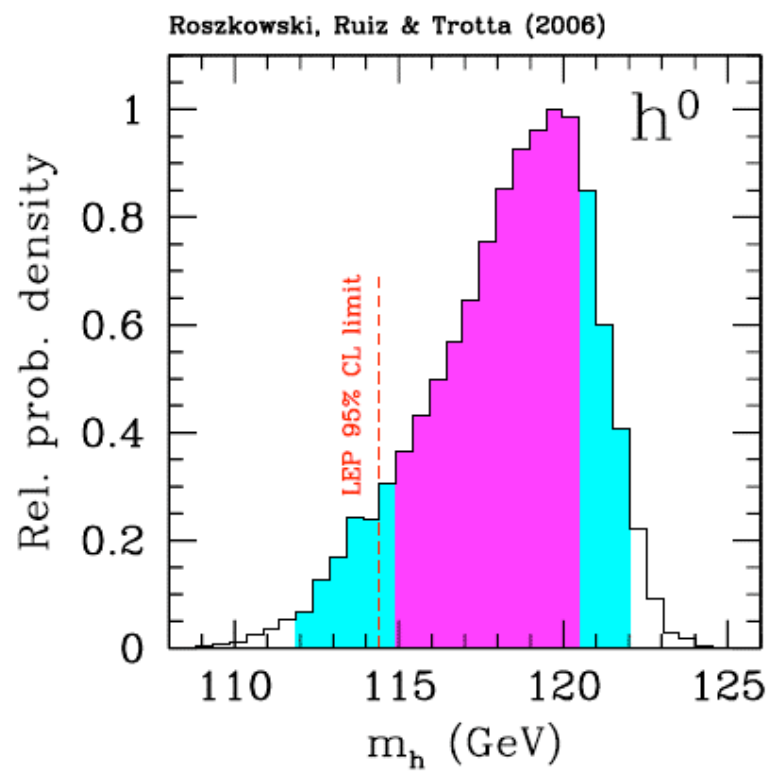
- Inputs
  - Direct LEP2 Higgs searches
  - Precision EW
  - Muon g-2
  - WMAP assuming CDM=neutralinos: $\Omega_\chi h^2$
  - B_s Mixing Rate: ΔM_{B_s}
  - $Br(B \to s\gamma)$
  - $Br(B_s \to \mu^+\mu^-)$

- Markov Chain Monte Carlo search through high-dimensional parameter space

- 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)

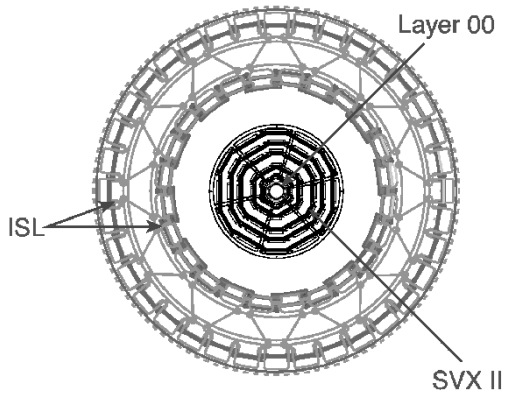
hep-ph/0611173
JHEP 0704:084 (2007)



Update: R. Trotta et al., arXiv:0809.3792 [hep-ph] -- similar constraints
See also: C. Berger, J. Gainer, J. Hewett, T. Rizzo, arXiv:0812.0980 [hep-ph]

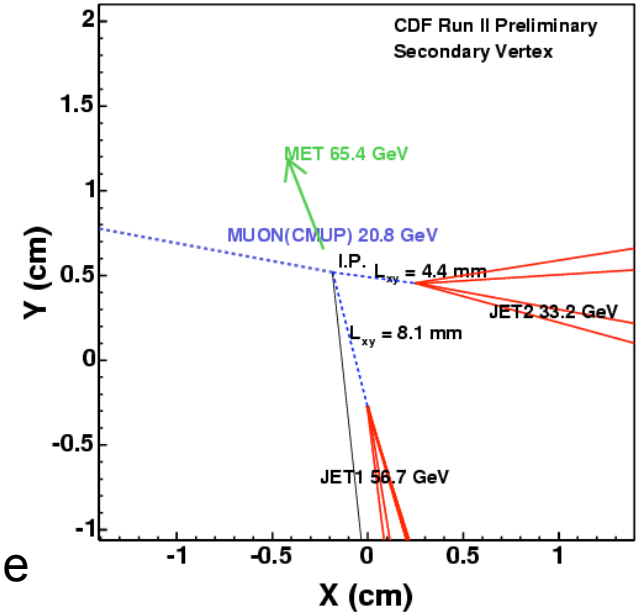
B-Tagging

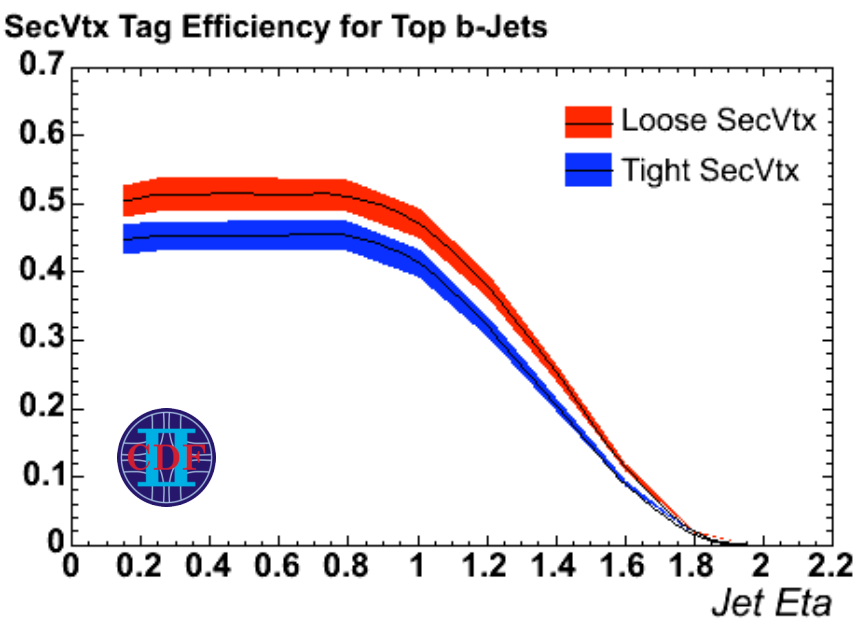
L00 single-sided silicon +
5-layer double-sided silicon+
2-layer ISL



Impact parameter resolution for high-p_T tracks ~18μm

B-tagging relies on displaced vertex reconstruction:
high mass, long lifetime





Mistag rates typically ~1% for light-flavor jets

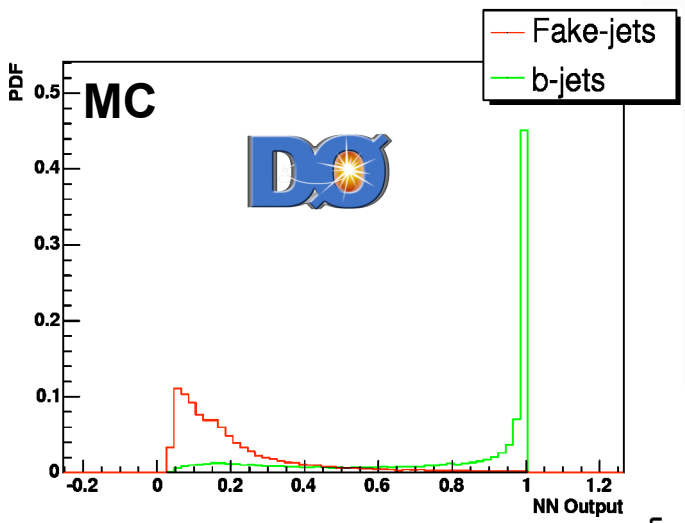
Example candidate event (lvbb)

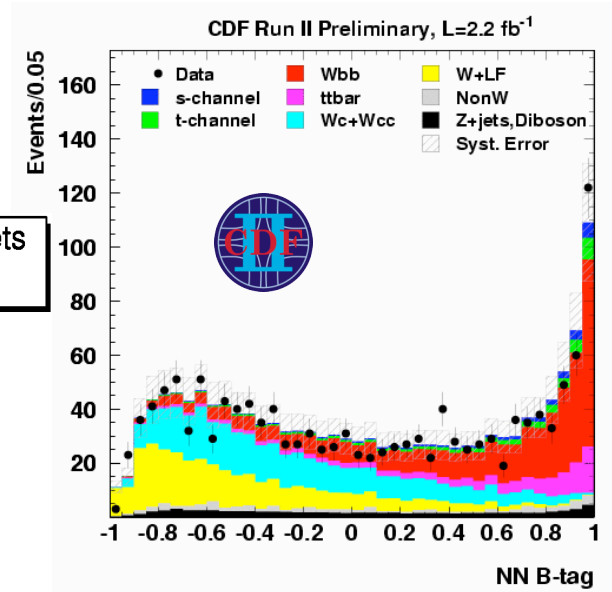
D0 B-tagging per-jet efficiency = 50-70% (of taggable jets) for 1-5% Mistag rate

Neural Networks for Better B-tagging

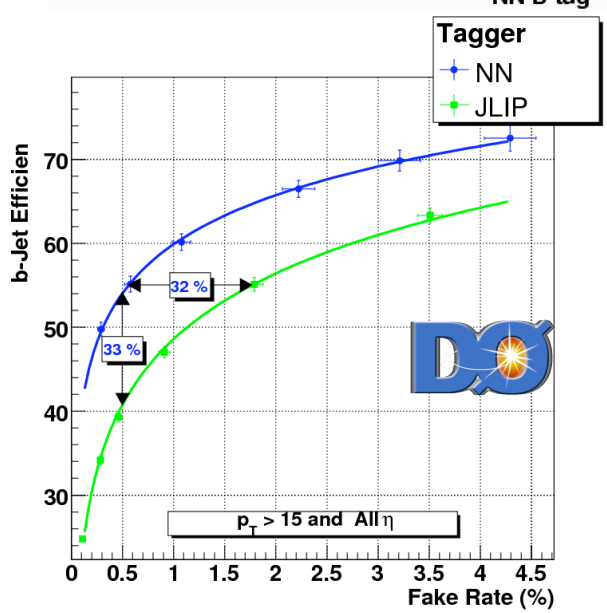
CDF: Train a NN to separate b's from charm and light flavor jets in vertex-tagged jets

D0: Use the NN as the b-tagging tool from the start. Choice of operating points.



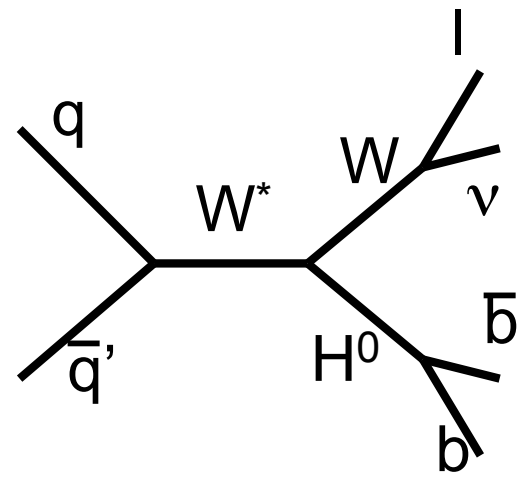


Some of the inputs:
- Displaced vertex mass
- # tracks in displaced vertex
- Decay flight distance and significance
- Identified leptons in and near jets
- Secondary vertex fit χ^2
- Jet E_T



CDF and D0: Efficiency and Mistags and NN's Calibrated with Data

Low-Mass Search Channel 1: WH→lνbb: Matrix Element + Boosted Decision Tree



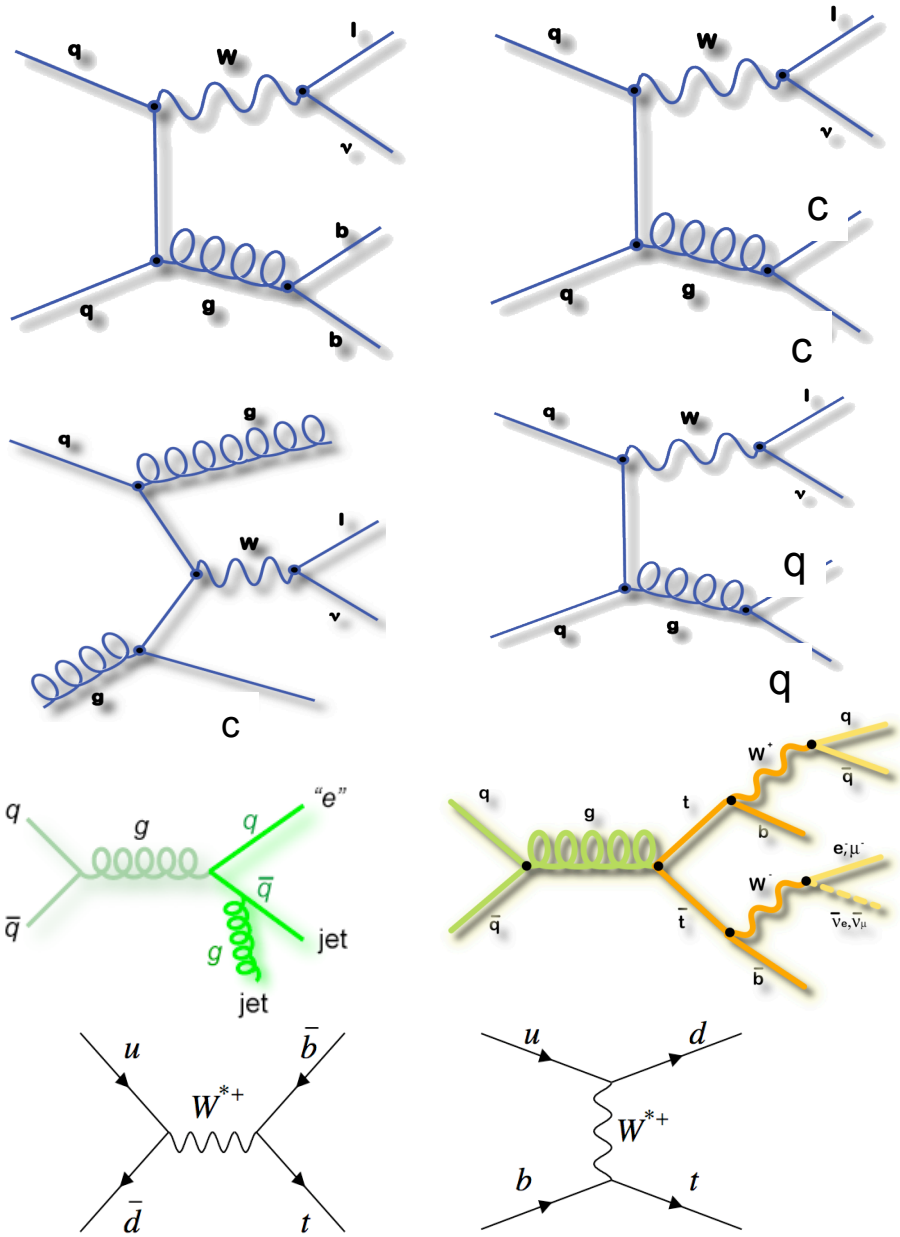
- Select events with:
  - A high-P_T lepton (≥20 GeV), e or μ
    isolated track category --
    gave an extra PhD thesis
  - Missing E_T ≥ 20 GeV
  - Two jets (cone=0.4, $|\eta|<2.0$, $E_T>20$ GeV)
  - One or two b-tags (different s/b so split these categories)
  - Veto Z's, cosmics, conversions

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

Backgrounds are Ferocious

Preliminary, 2.7 fb^{-1}

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 Analysis Optimization

- 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 *P(b-quark)* ≡ *b*

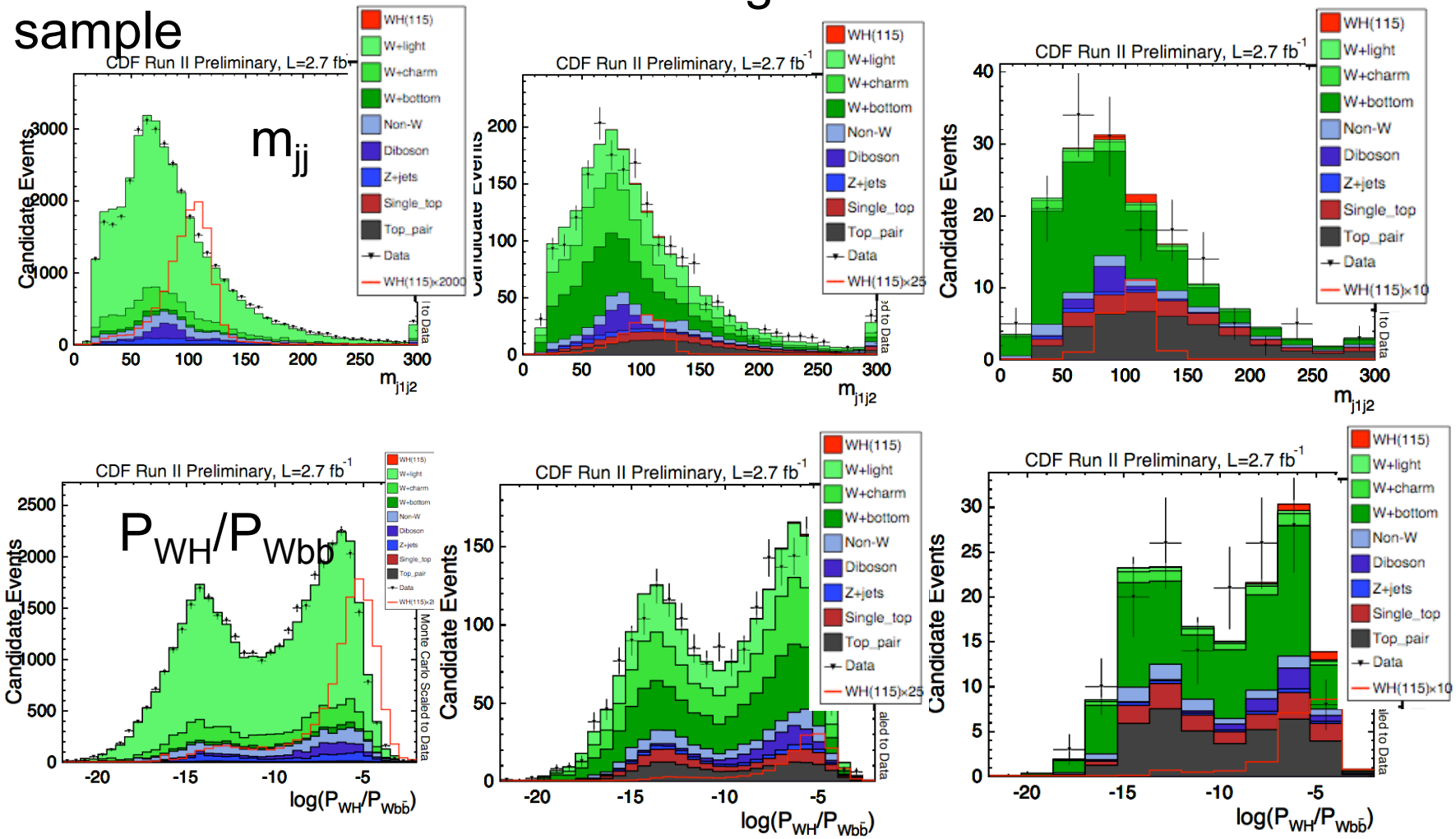
$$\mathrm{EPD} = \frac{b \times P_{WH}}{b \times \left(P_{WH} + P_{\mathrm{singletop}} + P_{Wb\bar{b}} + P_{t\bar{t}}\right) + \left(1-b\right) \times \left(P_{Wc\bar{c}} + P_{Wcj} + P_{\mathrm{Mistag}} + P_{\mathrm{Diboson}}\right)}$$

Some of the Important Distributions

No b-tags control sample

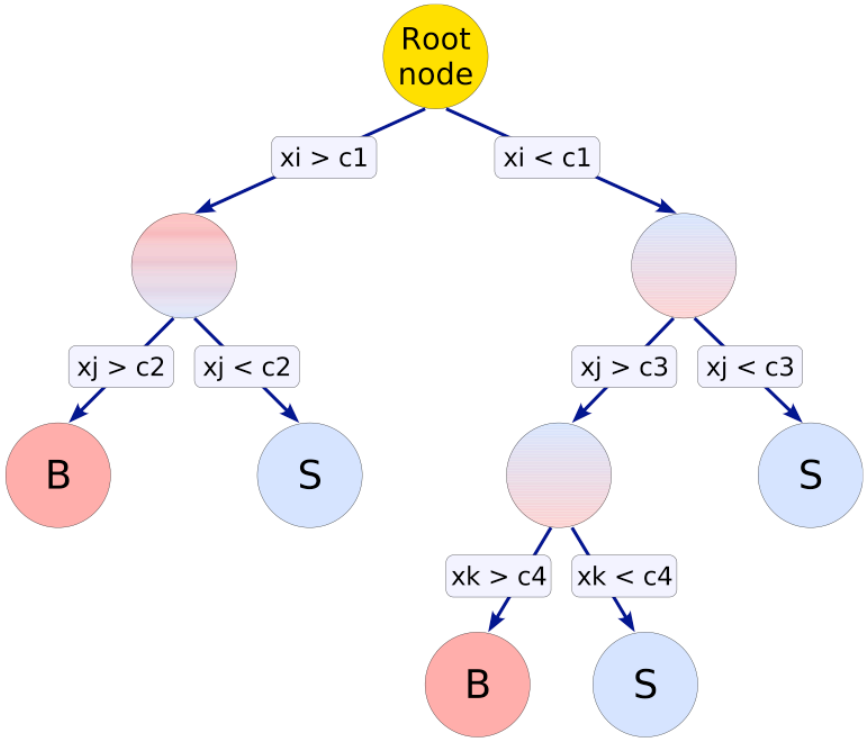
One b-tag

Two b-tags



MC scaled to data for all plots

A Boosted Decision Tree with ME Inputs

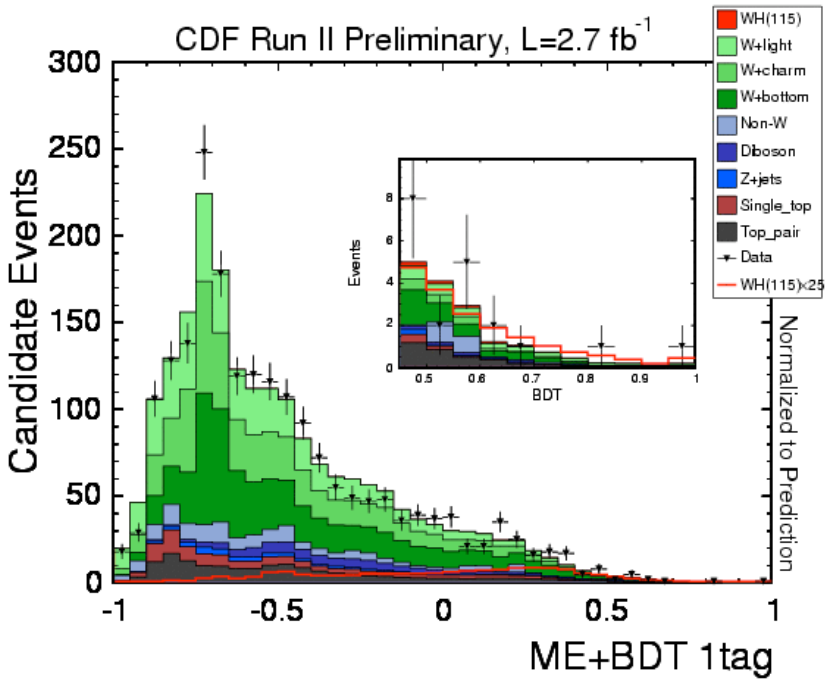


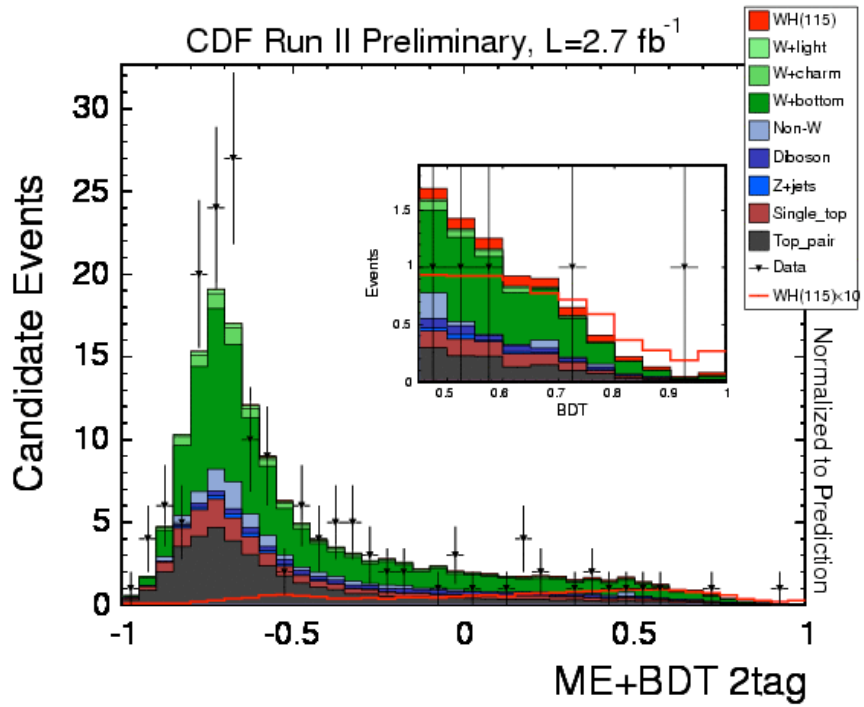
21 inputs. Important ones:

- 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).
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

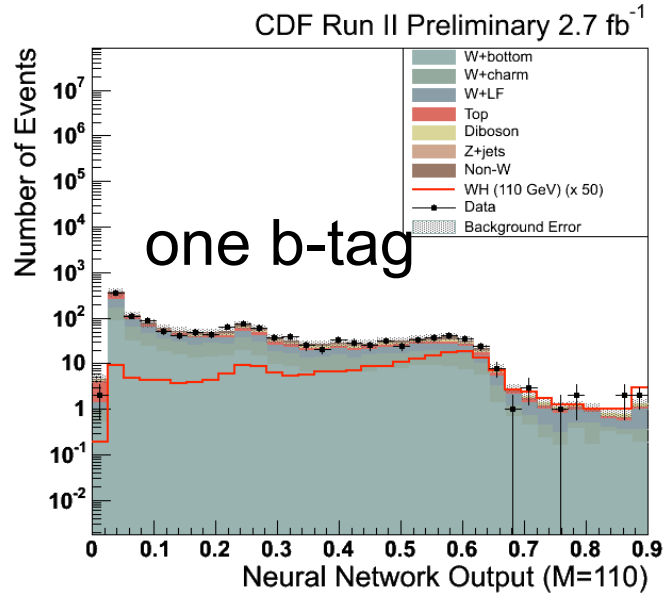
W+HF yield: ±30%
W+LF yield: ±13%
non-W yield: ±40%
ttbar yield: ±14%
(other backgrounds smaller)

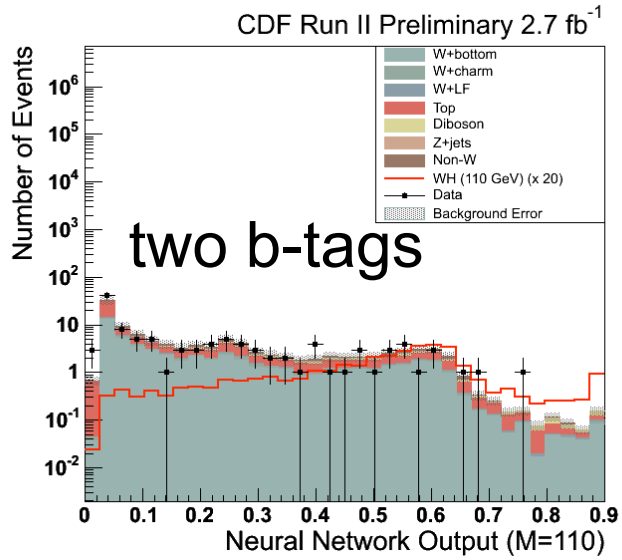
Add in a Neural Network

- 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)

Different choice of variables -- orthogonal information





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?

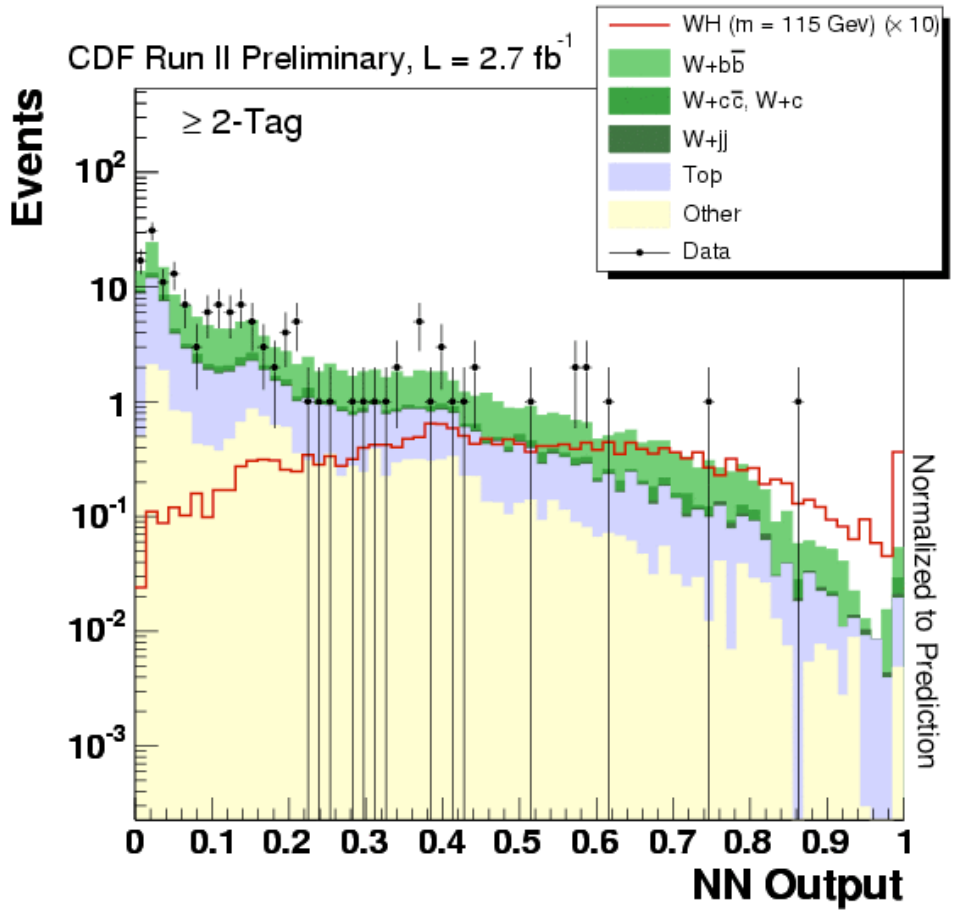
Neuro-Evolution to the Rescue!

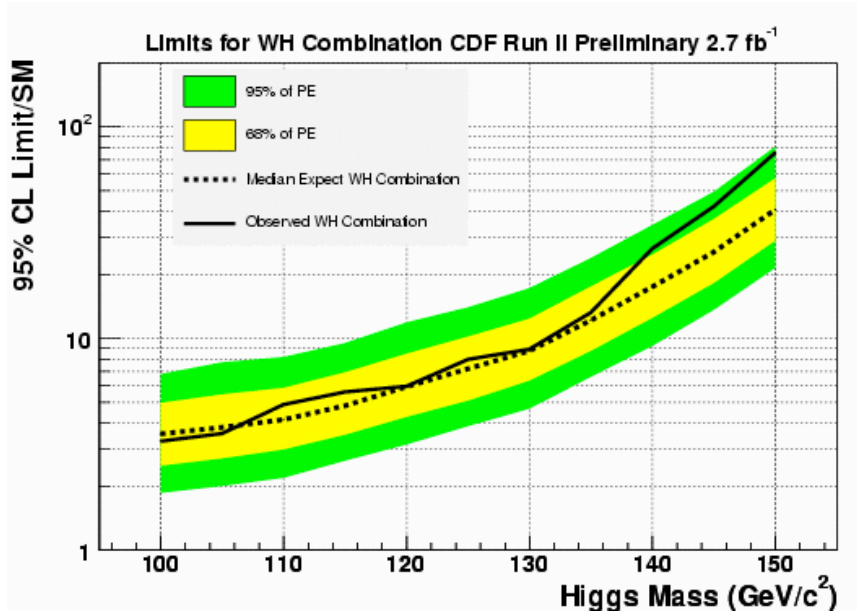
Kenneth O. Stanley and Risto Miikkulainen (2002).
"Evolving Neural Networks Through Augmenting Topologies".
Evolutionary Computation 10 (2): 99–127;
http://en.wikipedia.org/wiki/NeuroEvolution_of_Augmented_Topologies

- Figure of merit difficult to calculate
- 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.

- Sensitivity improvement -- 9% in expected limit

WH→lνbb Limits in Combination





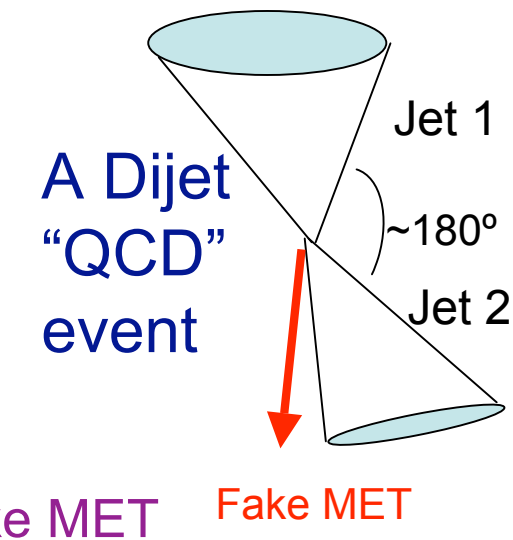
m_H (GeV)	Expected (σ/SM)	Observed (σ/SM)
100	3.5	3.3
105	3.8	3.6
110	4.1	4.9
115	4.8	5.6
120	5.9	5.9
125	7.2	8.0
130	8.7	8.9
135	12.2	13.2
140	17.5	26.5
145	25.6	42.1
150	40.5	75.5

D0 @ m_H=115: 6.4 expected, 6.7 observed

also with 2.7 fb^{-1} NN with ME

Low Mass II: WH+ZH→MET+Jets

- Large Br($Z\to\nu\nu$); Picks up signal with $W\to\nu l_{missing}$
- Multijet background with instrumental (fake) MET an issue -- Fake MET usually points along a jet!
- Require, for signal region:
  - MET>50 GeV
  - MET > 80 - 40 x min $\Delta\phi$(MET, any jet)
  - 2 or 3 jets with $|\eta|<2.5$ and $E_T>20$ GeV
  - $\Delta\phi(j_1,j_2)<165^o$
  - $-0.1 < (\text{MET-Missing } H_t)/(\text{MET+Missing } H_t)<0.2$
  - $\Delta\phi$(MET,Track-MET)<$\pi/2$ rejects events with fake MET
  - Reject isolated e, μ

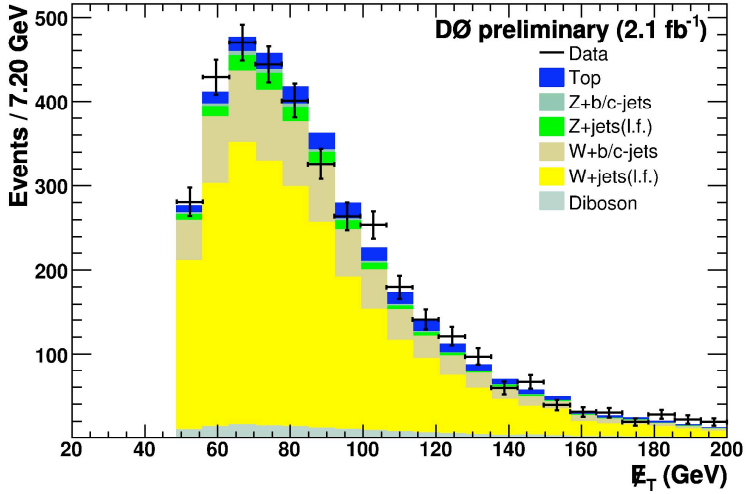


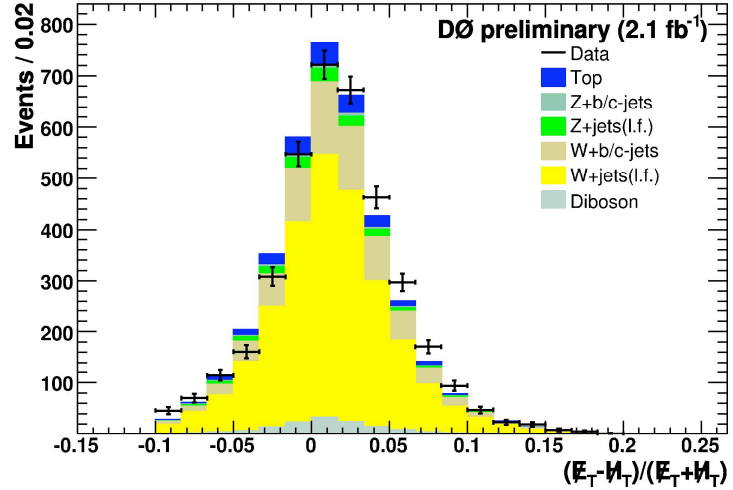
Event Yields, before and after b-tagging

Sample	HZ	HW	W+jets	Z+jets	top	VV	multijet	Total	Observed
before	6.15 ± 0.03	5.20 ± 0.04	24 357	8 199	532	814	6 438	40 340	40 340
after	2.12 ± 0.01	1.58 ± 0.01	174.0	127.3	95.2	12.5	33.8	442.8 ± 1.1	439

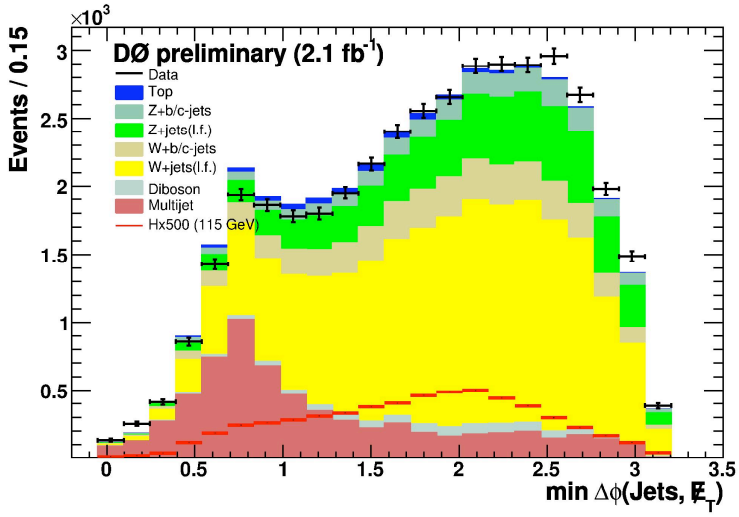
MET+Jets: Control Samples

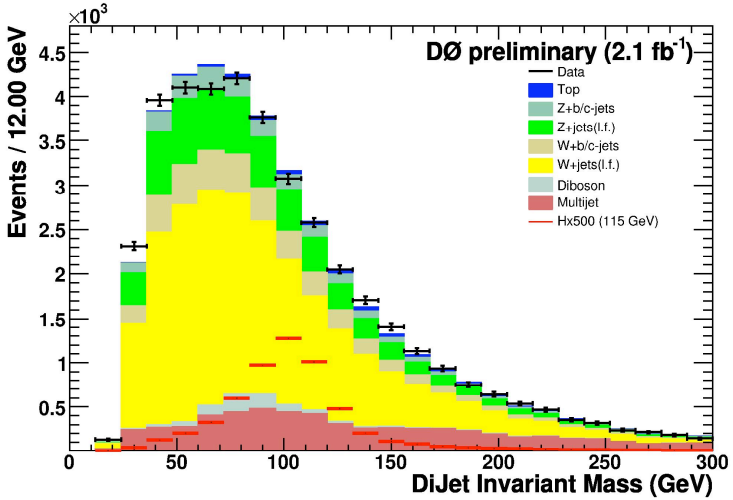
Require a lepton: check W+jets modeling



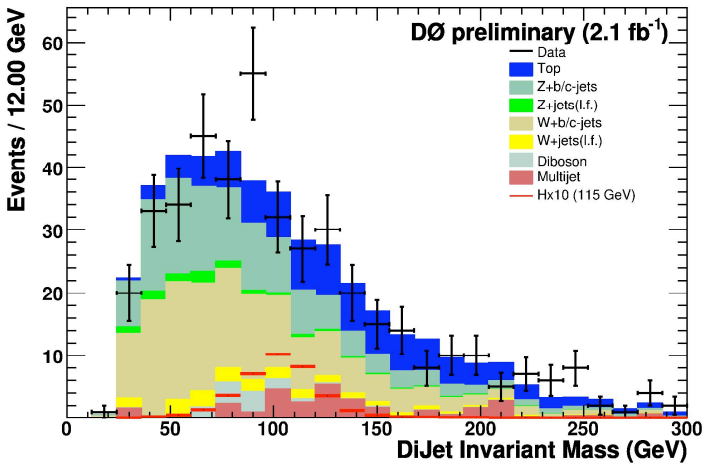


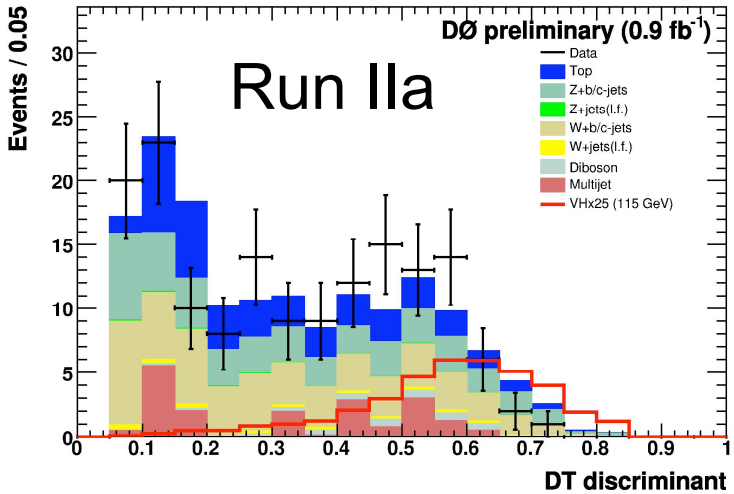
Analysis sample before b-tagging

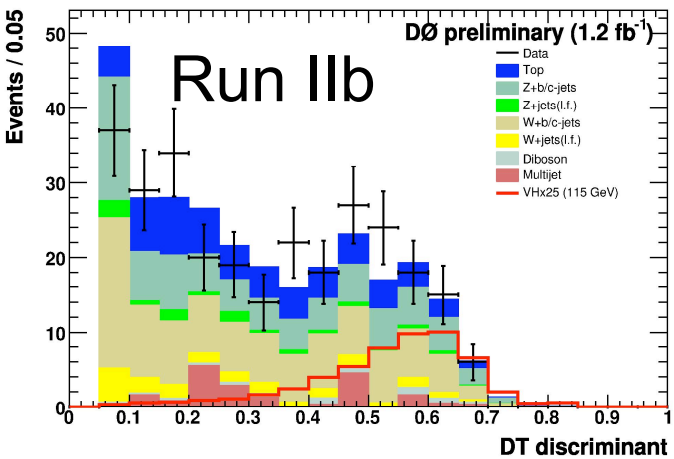




B-tagged MET+bb Signal Region

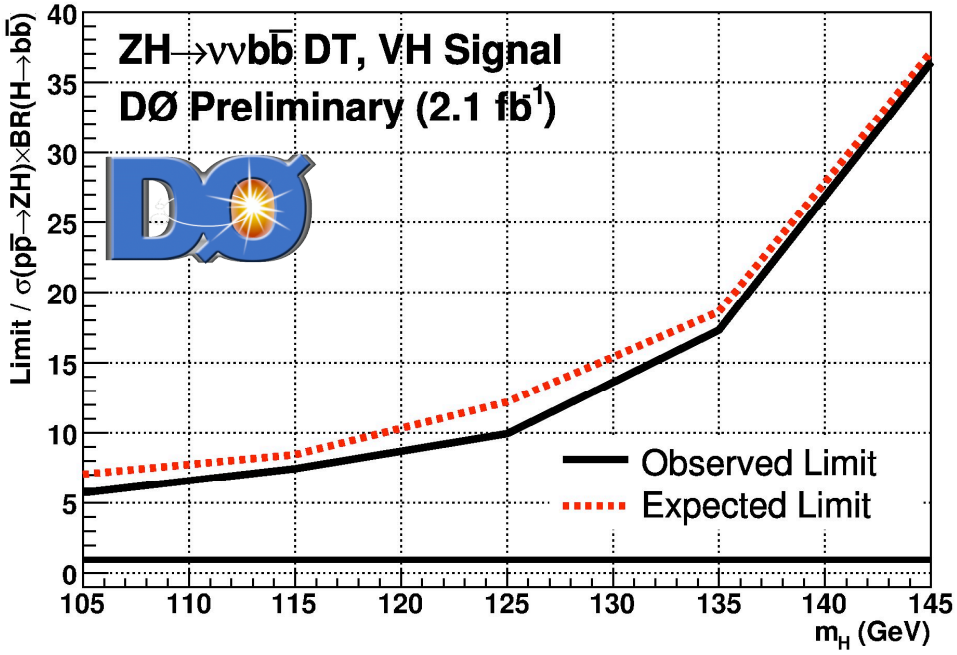






Some variables;
MET, ΣE_T, Missing H_T,
H_T, Missing H_T/H_T,
(MET-Missing H_t)/(MET+Missing H_t)
ΔR_{JJ}, min $\Delta\phi$(MET, any jet)
Track-MET (missing-P_T)

Observed and Expected Limits: METbb



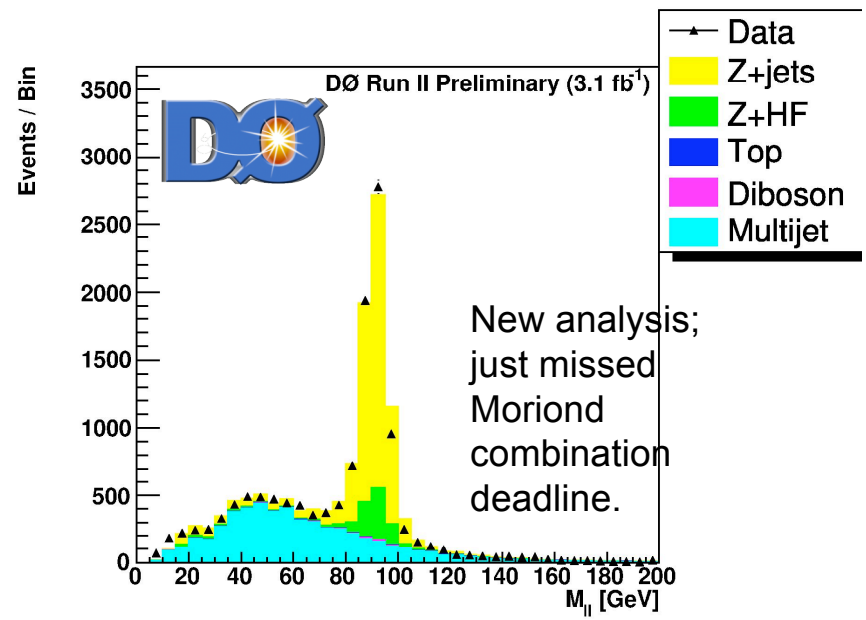
m_H (GeV)	Observed Limit/SM	Expected Limit/SM
105	5.7	7.0
115	7.5	8.4
125	9.9	12.2
135	17.3	18.6
145	36.4	37.1

CDF @m_H=115 GeV
Expects 5.6*SM, Observes 6.9*SM
also with 2.1 fb^{-1}

Low-Mass Searches III: ZH→eebb and ZH→μμbb

- Clean events -- Z→ll has almost no multijet or W background
- No real MET! Can use Σp_T constraint to sharpen m_{jj} resolution with a kinematic fit (DØ) or NN (CDF)
- Low B(Z→ll) (3% per lepton): low signal acceptance
- DØ: electrons with $|\eta|<2.5$, muons with $|\eta|<2.0$

Select events with two isolated, high-p_T leptons and two or more jets



New analysis; just missed Moriond combination deadline.

Multijet background estimated from data: electron candidates which fail shower-shape requirements (e) or isolation (μ)

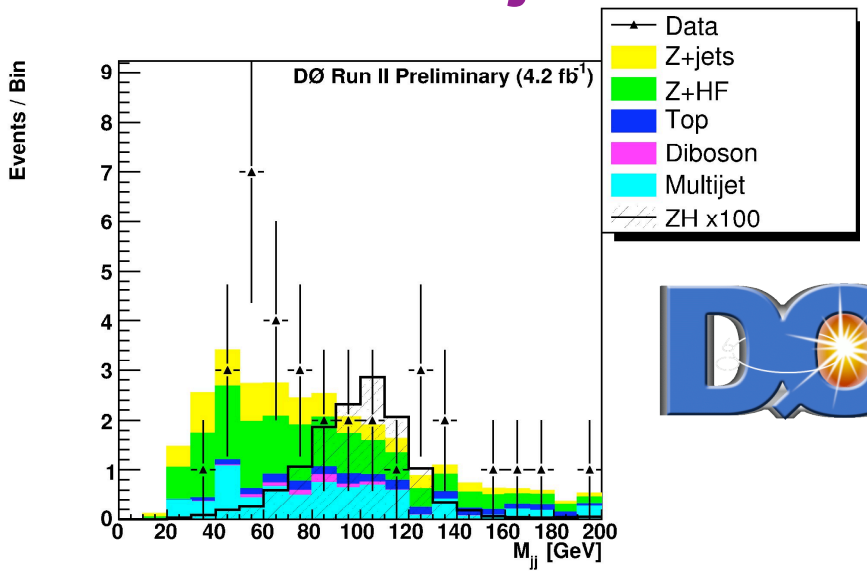
Low-Mass Searches III: ZH→eebb and ZH→μμbb

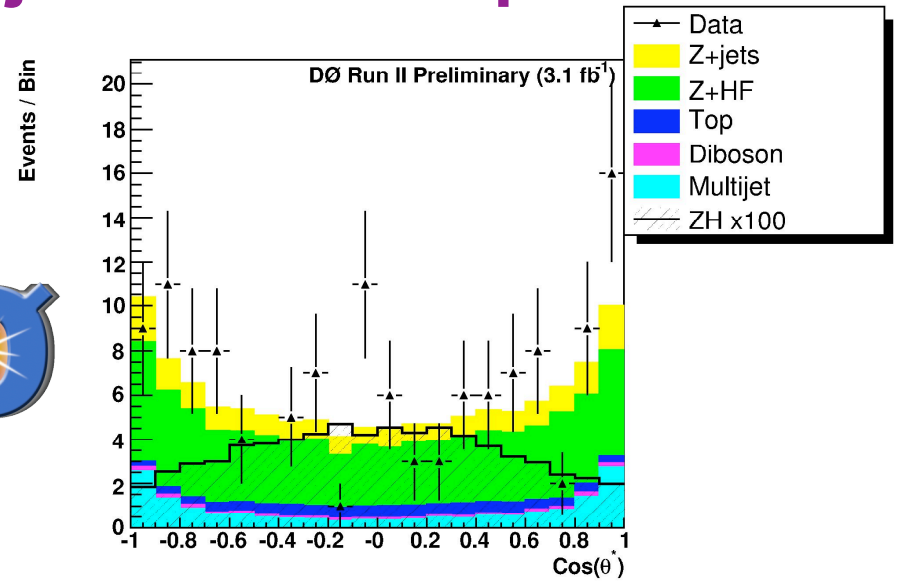
Split sample into 1, 2 b-tags (looser tags for double-tagged events) and by lepton category

	pre-selection	$70 < M_{ee} < 110$ GeV	1 tight b-tag	2 loose b-tags
Data	12747	7610	201	131
Bkg	12926 ± 73	7900 ± 44	198.3 ± 1.3	119.0 ± 0.9
$ZH(115)$	2.09 ± 0.02	1.98 ± 0.02	0.52 ± 0.005	0.69 ± 0.007
Multijet	5303 ± 62	1368 ± 25	32.1 ± 0.6	16.6 ± 0.3
Zjj	6301 ± 37	5458 ± 35	29.6 ± 0.2	21.8 ± 0.1
$Zb\bar{b}$	352.6 ± 3.5	308.3 ± 3.3	80.4 ± 1.0	45.7 ± 0.8
$Zc\bar{c}$	798.0 ± 7.3	663.7 ± 6.6	45.5 ± 0.5	22.5 ± 0.3
ZZ	36.4 ± 0.6	32.6 ± 0.5	2.46 ± 0.08	2.47 ± 0.10
WZ	43.8 ± 0.9	40.7 ± 0.9	1.53 ± 0.05	0.61 ± 0.02
WW	9.42 ± 0.74	2.97 ± 0.40	0.096 ± 0.035	0.028 ± 0.007
$t\bar{t}$	81.9 ± 0.5	25.5 ± 0.3	6.58 ± 0.08	9.21 ± 0.12

Also: Muons and Inter-cryostat electrons similar tables

More than just the Dijet Mass is Important!





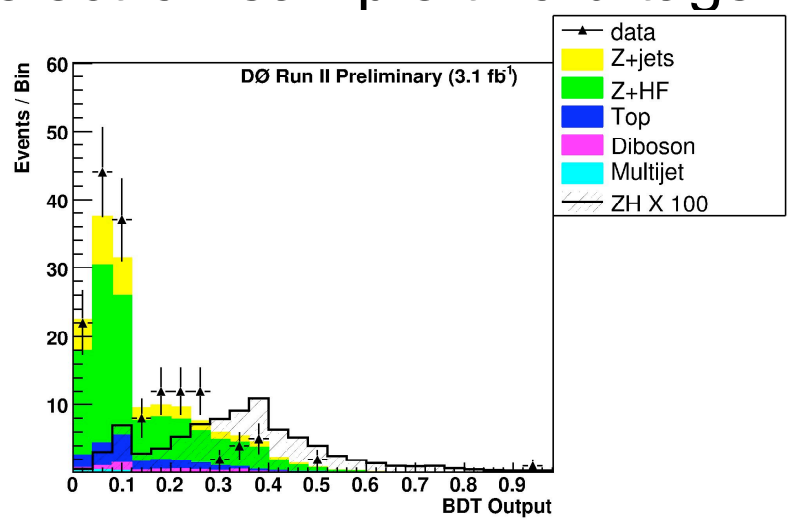
m_{jj}, muons, two b-tags

Helicity angle of dijets, electron sample two b-tags

BDT Input variables:

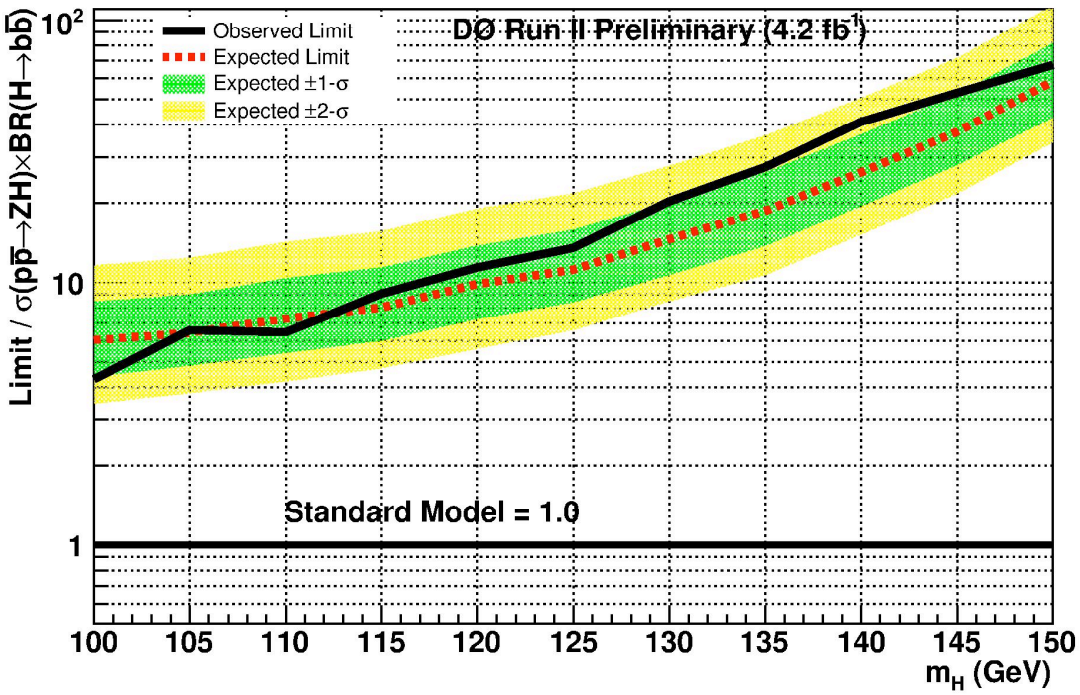
m_{ll}, m_{bb}, transverse versions, $\Delta\phi$(Z,dijet), $\Delta\eta$(ll), η(Z), η(bb)

BDT, electron sample, two b-tags



ZH→llbb Limits

L=4.2 fb^{-1}



m_H (GeV)	Observed Limit/SM	Expected Limit/SM
100	4.3	6.0
105	6.6	6.4
110	6.5	7.3
115	9.1	8.0
120	11.4	9.9
125	13.5	11.2
130	20.3	14.5
135	27.5	18.7
140	40.8	26.2
145	52.7	37.5
150	67.6	58.3

CDF @m_H=115 GeV
Expects 9.9*SM, Observes 7.1*SM
with 2.7 fb^{-1}

Data Used for the Moriond 2009 Combinations

Channel	CDF Lumi [fb^{-1}]	D0 Lumi [fb^{-1}]
$WH \rightarrow l\nu bb$	2.7	2.7
$ZH \rightarrow llbb$	2.7	2.3
METbb	2.1	2.1
jjbb	2.0	
$H \rightarrow WW$ Opposite-Sign dileptons	3.6	3.0 - 4.2
$WH \rightarrow WWW$ Same-Sign dileptons	3.6	1.1
$H \rightarrow \tau\tau$	2.0	1.0
$H \rightarrow \gamma\gamma$		4.2
$ttH \rightarrow ttbb$		2.1

Steps Required for Combination

- Histograms and named rate ***and shape*** errors exchanged
- Check stacked histograms and systematic tables with analysis documentation total counts:
  data, signal, background
  - look for bins with b=0 and have data events (bad!)
- Repeat individual channel limits -- compare against approved results.
- Assess correlations on systematics

CDF and D0 teams each do three combinations, using Bayesian and CL_s techniques.

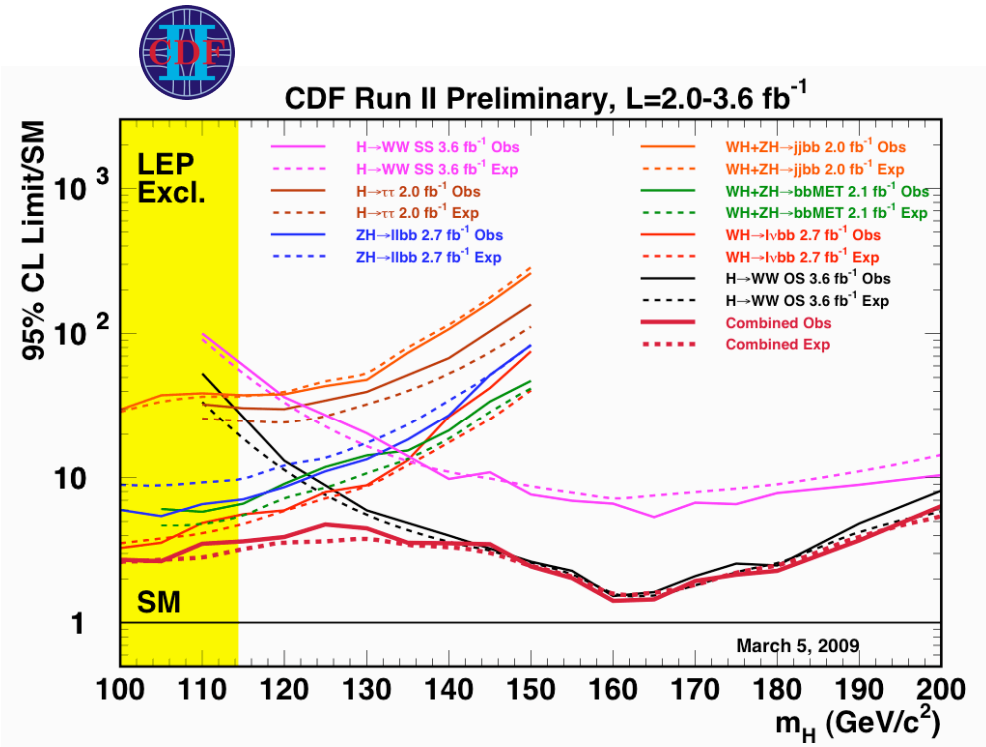
CDF

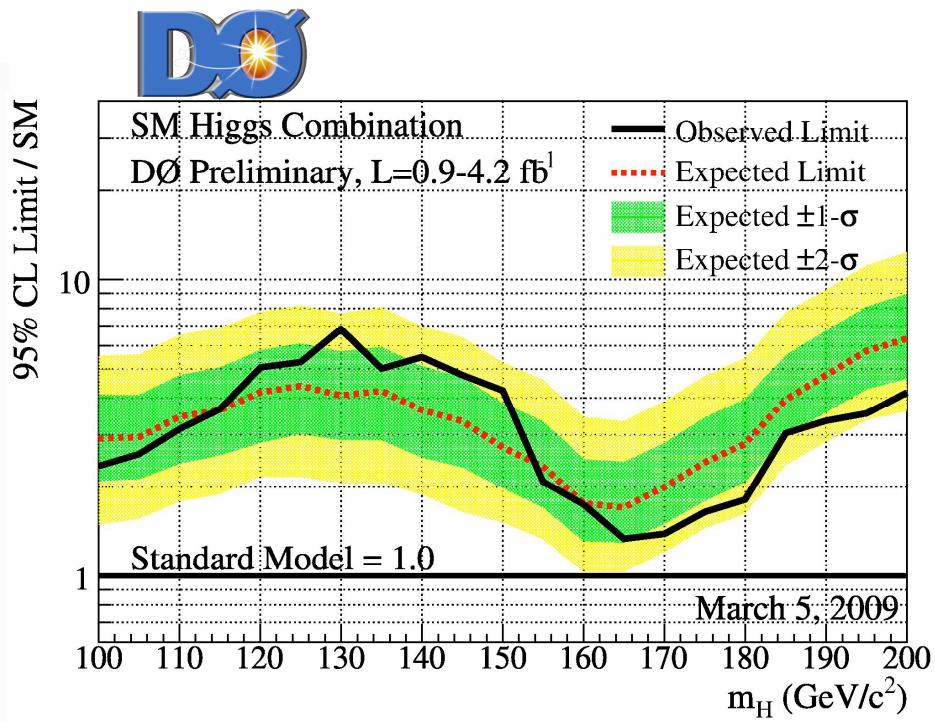
D0

Tevatron

Consistency at the better than 10% level required for all combinations at all test masses. **Take the weaker limits.**

Combinations as done by CDF and D0





m_H=115 GeV: CDF/D0 3.6/3.7 (3.2/3.6) observed (expected)

m_H=165 GeV: CDF/D0 1.5/1.3 (1.6/1.7) observed (expected)

Tevatron Correlated Systematic Errors I

Total Systematic error count: 109 (not counting bin-by-bin errors)

Note: correlation in errors on backgrounds between experiments helps sensitivity! One experiment is another experiment's control sample.

Luminosity: 3.8% Correlated CDF and D0 σ_{inel}(ppbar)
4.4% detector-specific

Diboson Cross Sections: WW, WZ and ZZ
Cross sections used (6% relative uncertainty)
σ_{WW} = 12.4 ± 0.7 pb
σ_{WZ} = 3.7 ± 0.2 pb
σ_{ZZ} = 3.8 ± 0.2 pb

ttbar Cross Section: Moch and Uwer, evaulated at
m_t=172.4±1.2 GeV is σ_{tt}=7.794 with a 10% syst. assigned

Tevatron Correlated Systematic Errors II

Signal Cross Section uncertainties:

WH, ZH: ± 5%
gg→H: ± 12%
VBF: ± 10%

Applied to SM interpretations, but taken off for cross-section times branching ratio limits.

CDF-D0 Uncorrelated errors:

K-factors (data driven)
trigger efficiency
b-tag efficiency and mistags
jet energy scale
lepton ID, fakes and conversions
MET modeling

Correlated *within* CDF and D0 where appropriate

Any Hint of a Higgs Boson?

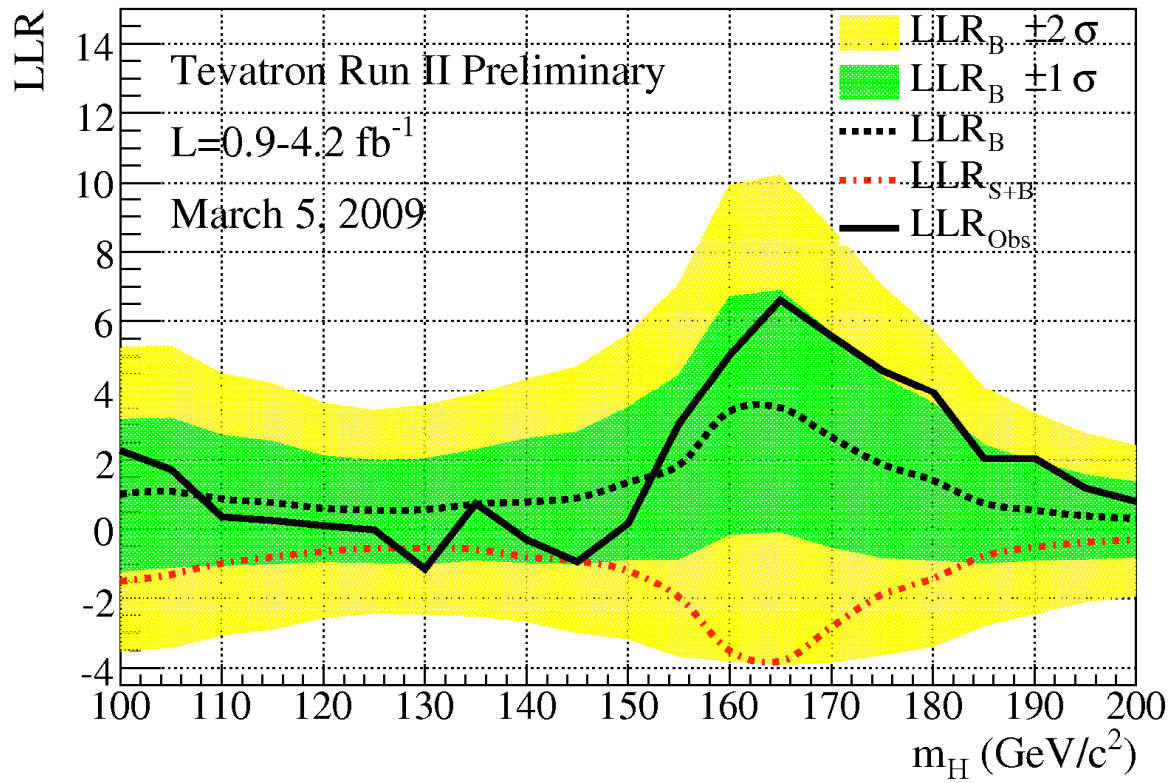
Neyman-Pearson Lemma says the Likelihood Ratio is uniformly most powerful test statistic

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

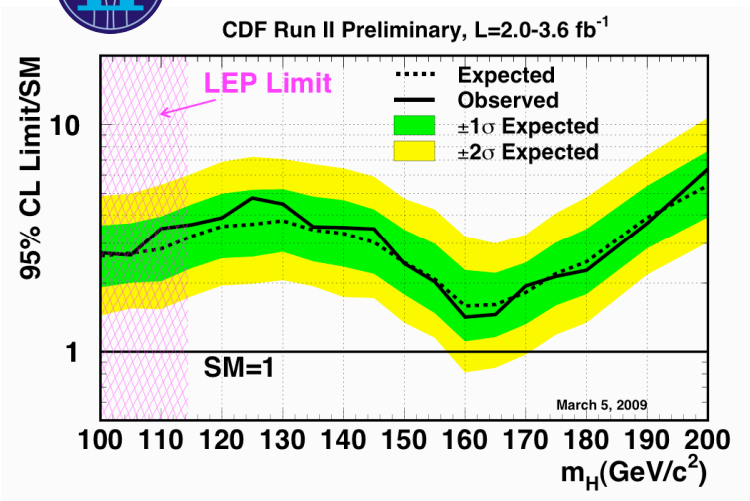
Negative values: signal-like outcomes, Positive values: background-like outcomes.

No obvious hint of a signal.

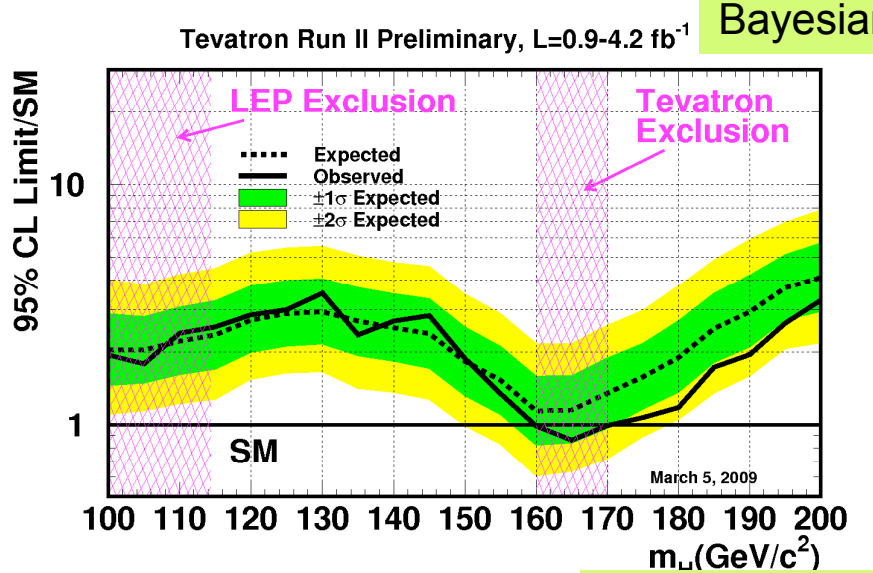
Getting sensitive, though!



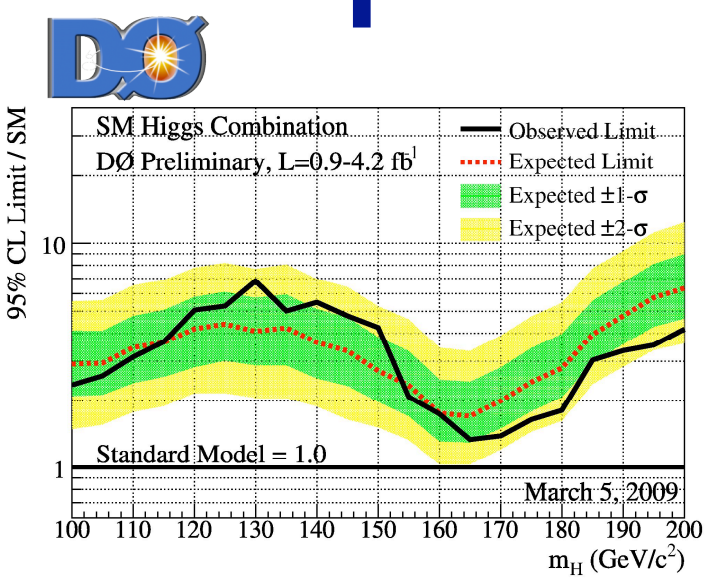
Tevatron Higgs Limits



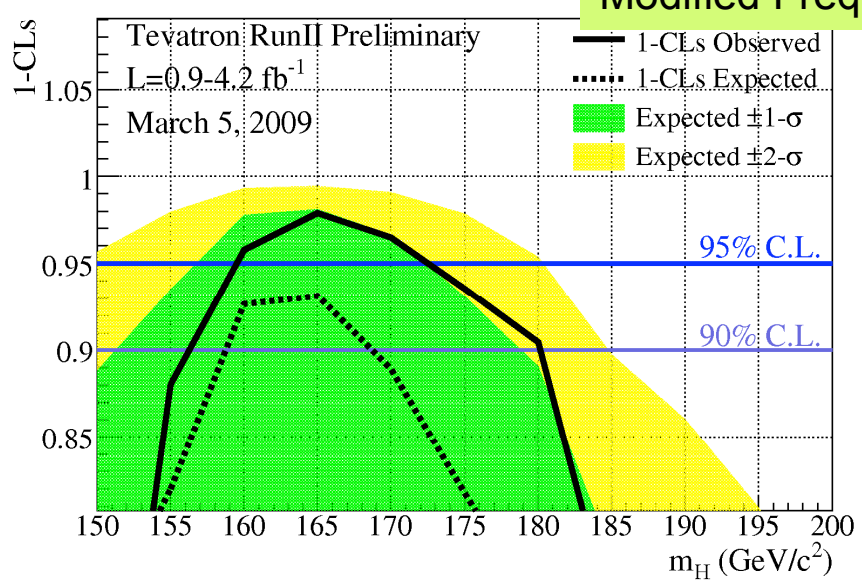
Bayesian



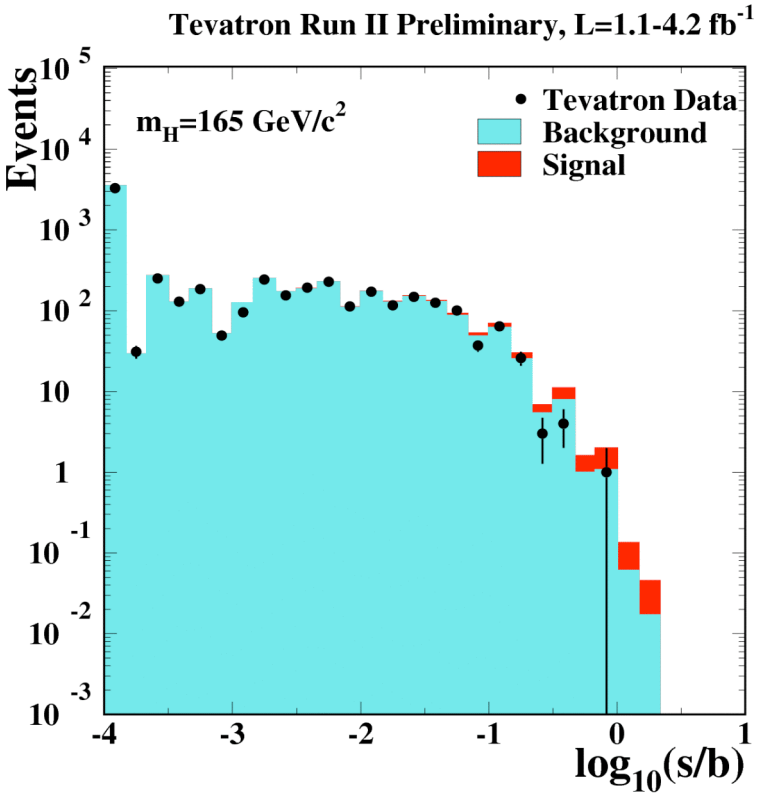
+

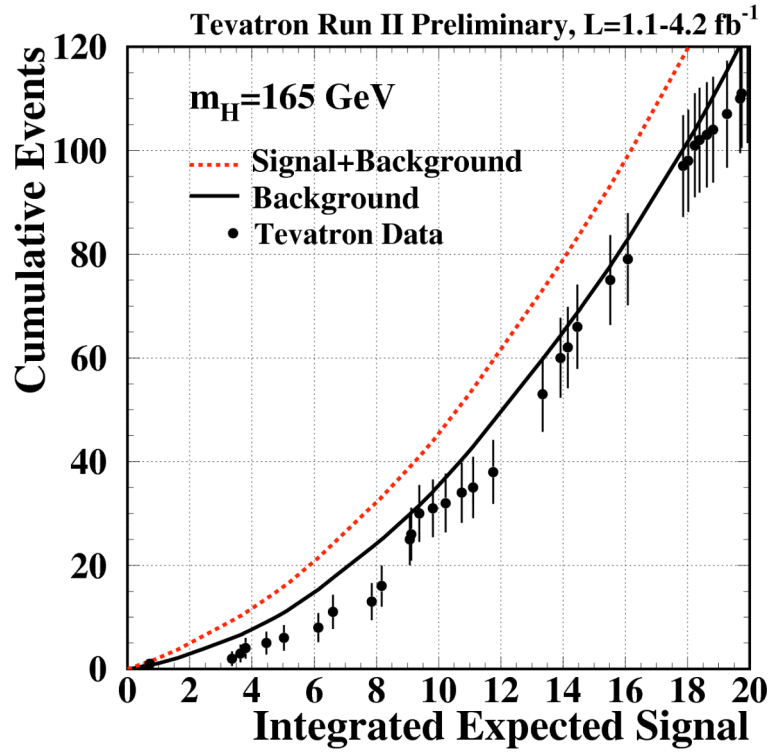


Modified Frequentist



Tevatron Combination at m_H=165 GeV



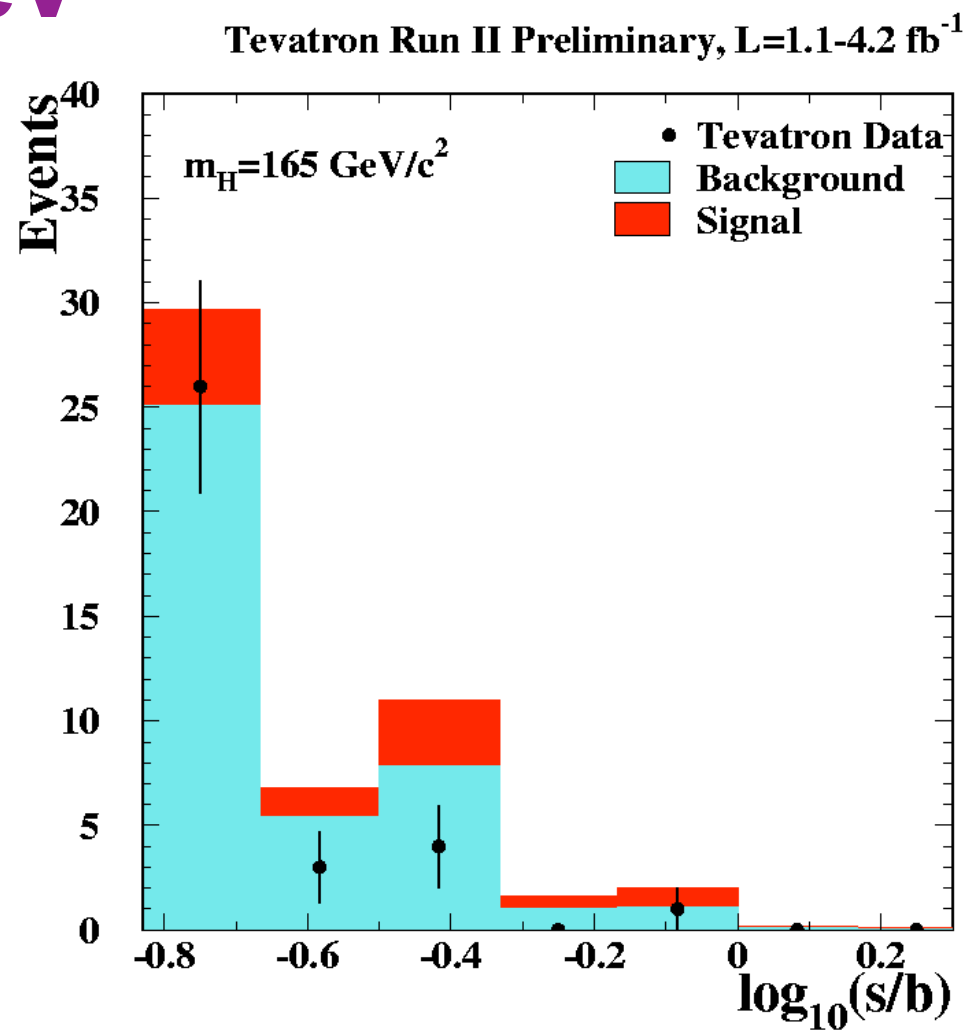


	observed	expected
CDF	1.33	1.50
D0	1.74	1.87
Tevatron	0.86	1.15

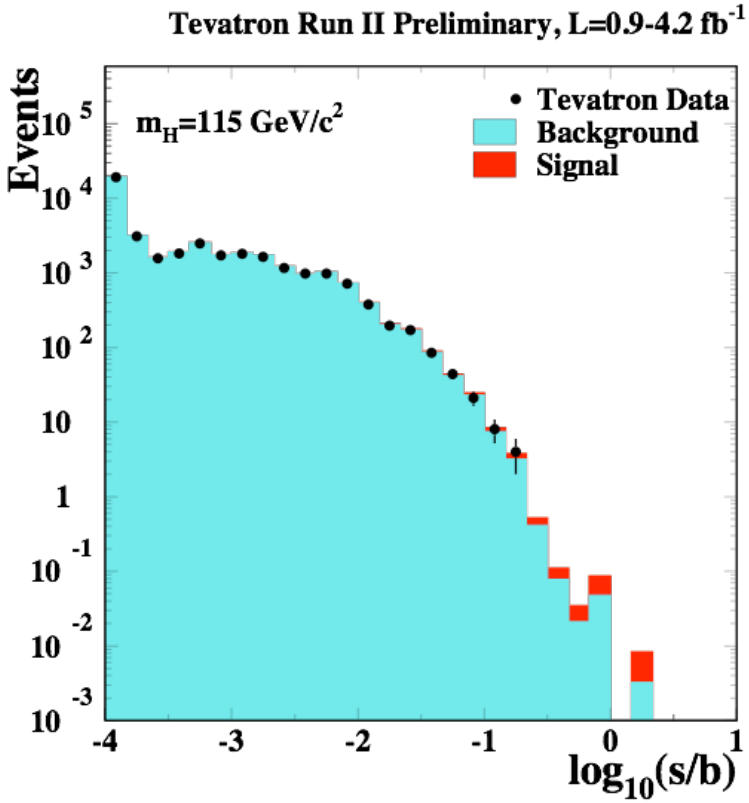
A Close-Up in the Highest *s*/*b* bins at m_H=165 GeV

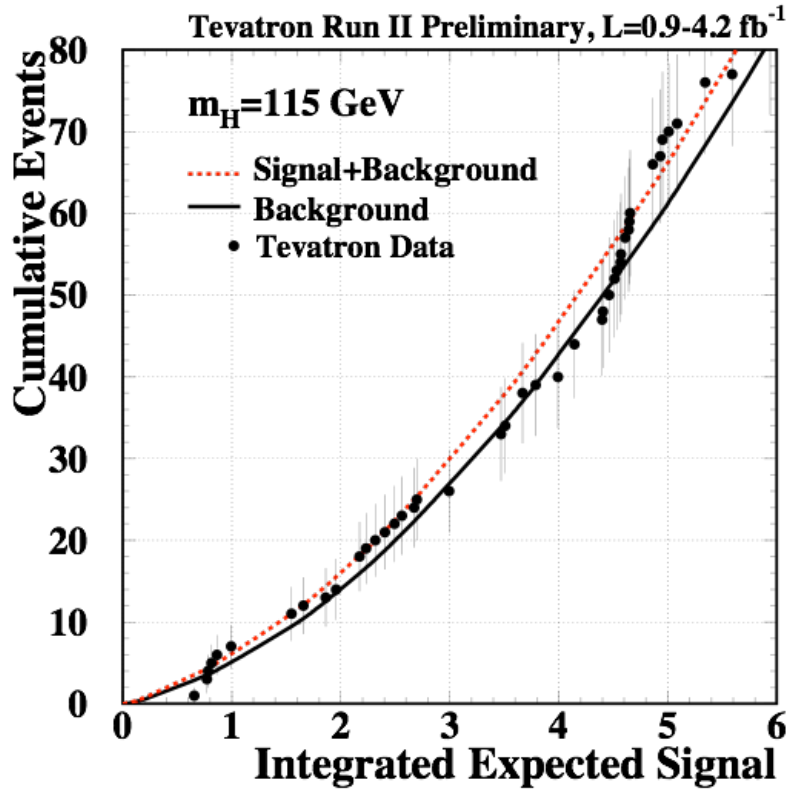
The Last Few Bins' Contents:

Signal yield (events)	Background yield (events)	Data
0.028	0.017	0
0.073	0.060	0
0.918	1.065	1
0.598	0.987	0
3.14	7.84	4
1.38	5.38	3
4.61	25.0	26



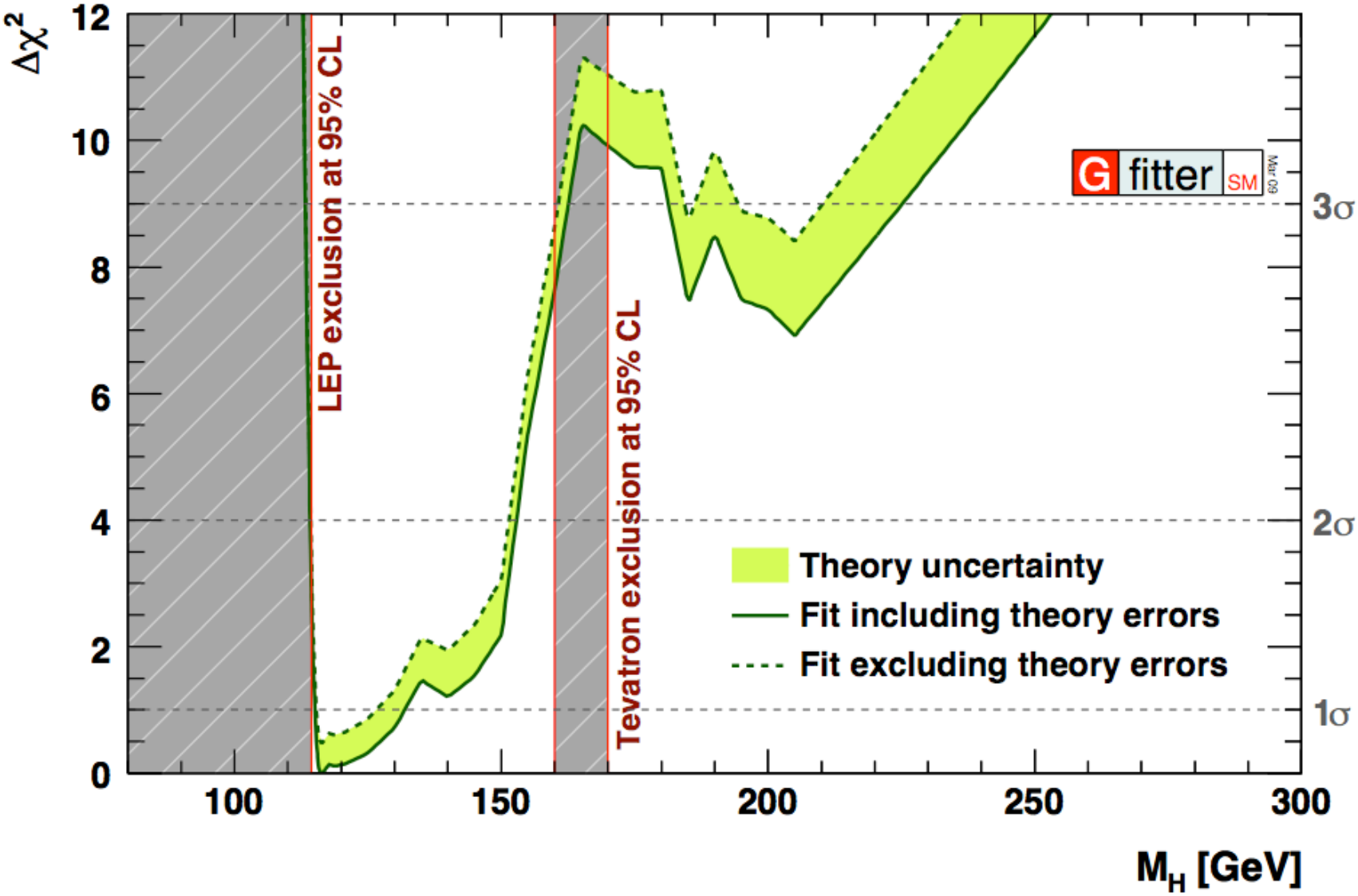
Tevatron Combination at m_H=115 GeV





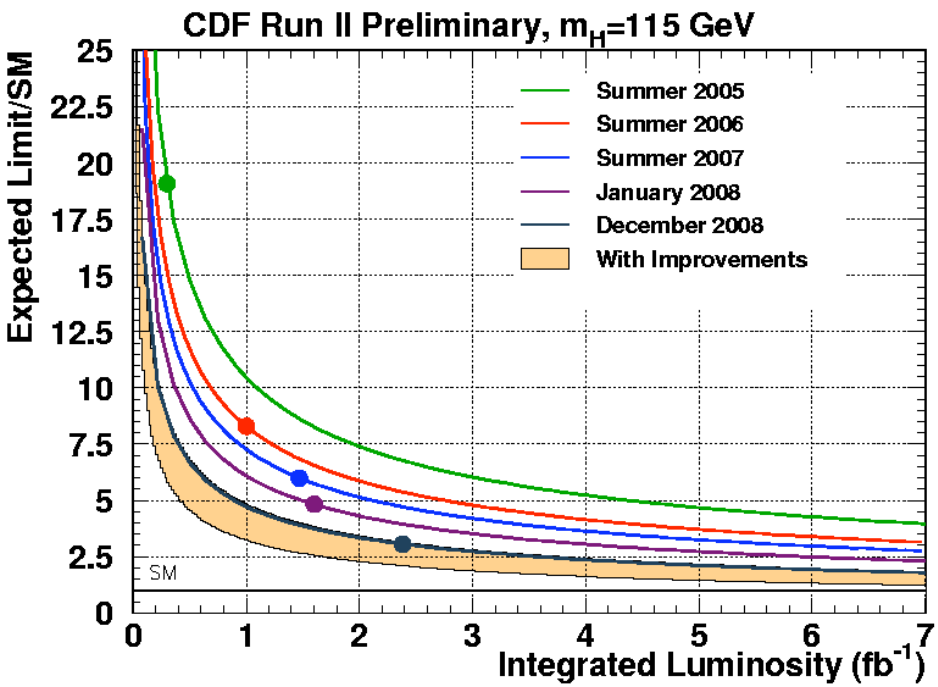
	observed	expected
CDF	3.64	3.22
D0	3.70	3.89
Tevatron	2.54	2.36

SM Fit From Gfitter

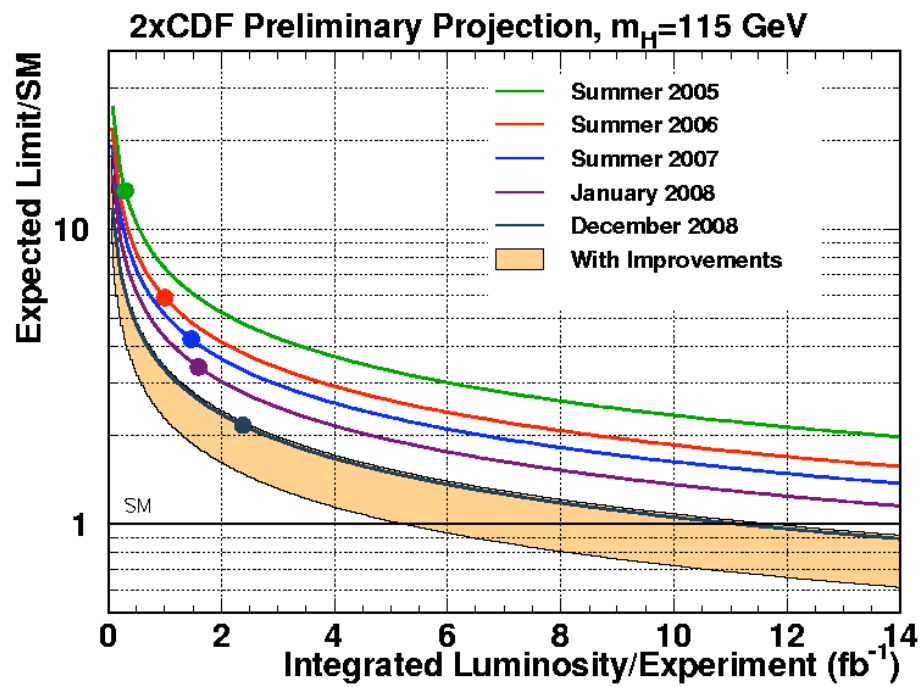


M. Baak et al., http://gfitter.desy.de/GSM/

Sensitivity and Projections -- m_H=115 GeV

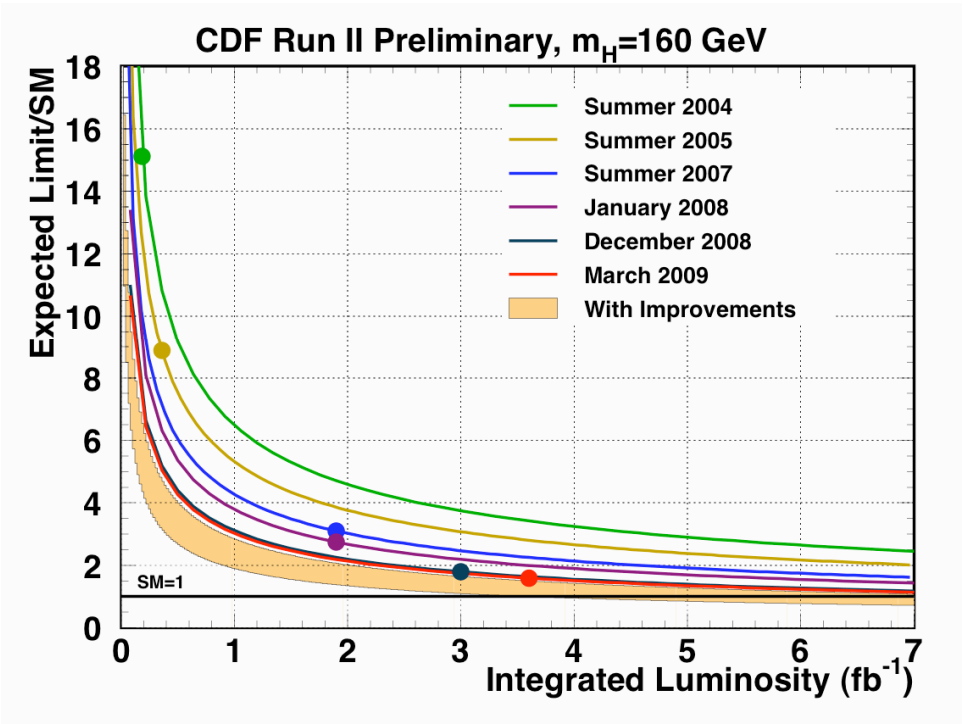


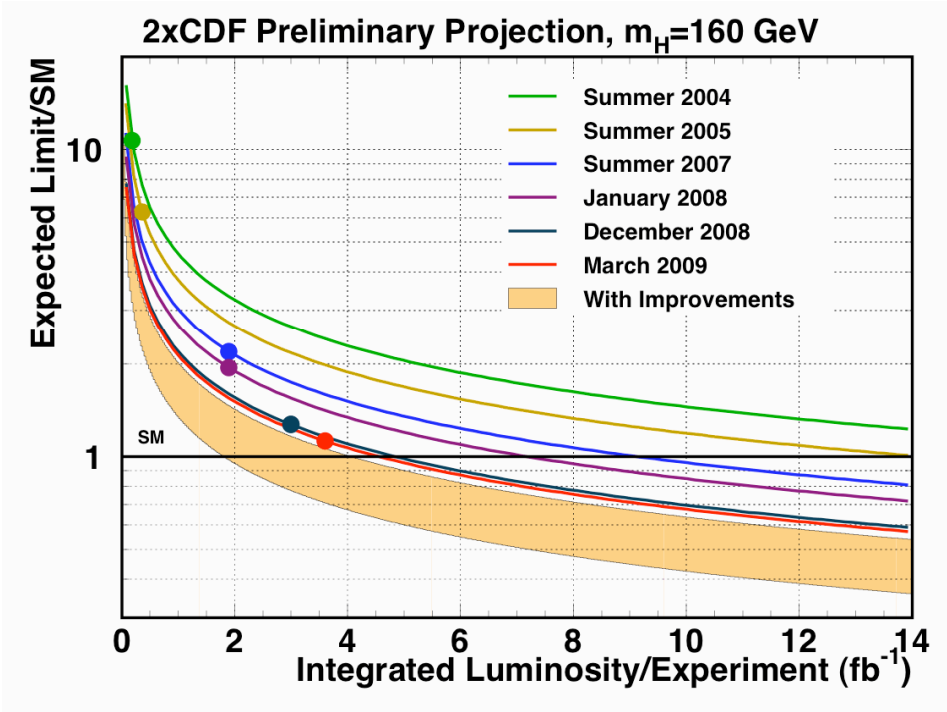
Tevatron sensitivity approximated by 2xCDF



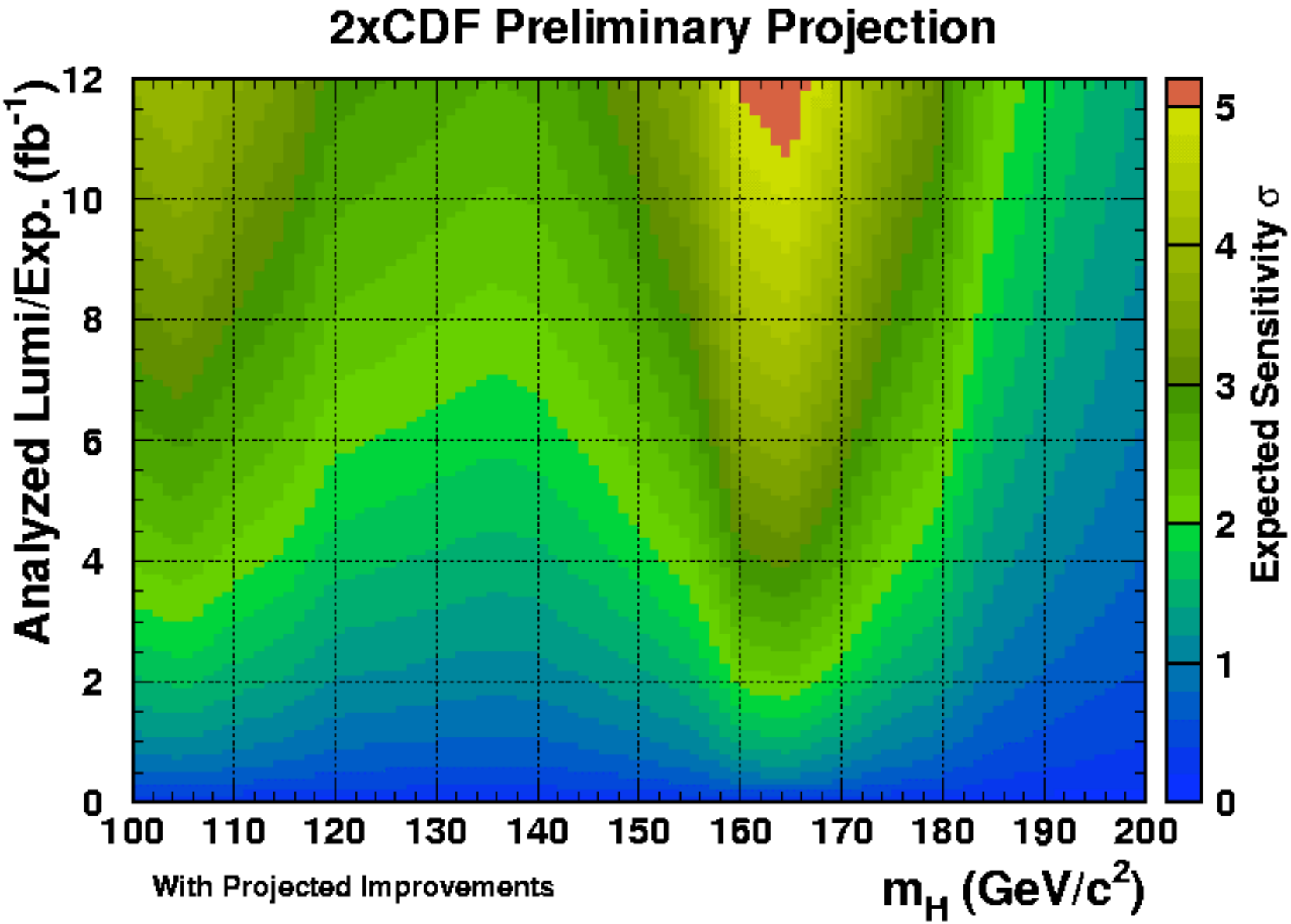
Steady improvement in analysis technique and better understanding of systematic uncertainties

Sensitivity and Projections -- m_H=160 GeV





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



Median sensitivity: 50% more lucky, 50% less lucky

Summary

- The Tevatron is running very well
- We will run in 2010; planning for 2011
- Higgs boson search efforts on CDF and D0 are vigorous
- We are finding more acceptance and improving our analysis techiques as we collect more data
- Our hard work is bearing fruit! The combined sensitivity is now at 2.36*SM (m_H=115 GeV), and 1.15*SM at m_H=165 GeV. A 1σ deficit of candidates provides exclusion of 160<m_H<170 GeV.
- Another factor of two to four in data sample size is coming.

Backup Material

Higgs Boson Production Cross Sections and 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

gg→H from Grazzini and de Florian, similar to those of other authors

Tevatron Combined Limits

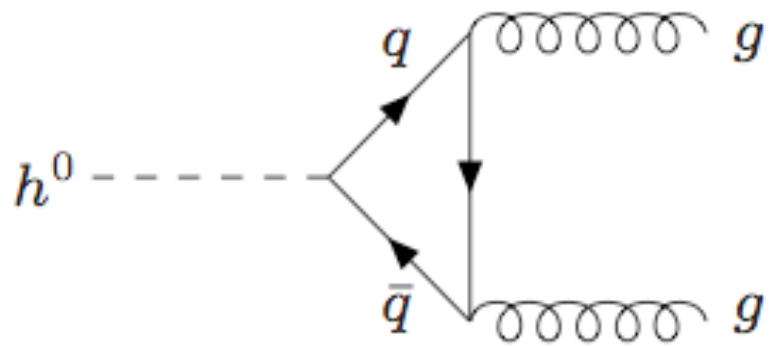
mass	obs	-2σ	-1σ	exp	+1σ	+2σ
100	1.95	1.1	1.45	2.04	2.89	4.02
105	1.79	1.14	1.49	2.04	2.82	3.84
110	2.40	1.22	1.61	2.22	3.09	4.23
115	2.54	1.27	1.70	2.36	3.28	4.48
120	2.86	1.54	1.99	2.72	3.79	5.21
125	3.00	1.64	2.12	2.89	3.99	5.45
130	3.53	1.66	2.16	2.94	4.06	5.55
135	2.36	1.41	1.93	2.69	3.73	5.06
140	2.69	1.36	1.83	2.53	3.51	4.75
145	2.84	1.27	1.71	2.39	3.35	4.57
150	1.88	0.99	1.32	1.83	2.55	3.50
155	1.35	0.83	1.10	1.53	2.12	2.90
160	0.99	0.61	0.82	1.14	1.59	2.18
165	0.86	0.64	0.84	1.15	1.60	2.18
170	0.99	0.72	0.96	1.35	1.89	2.59
175	1.07	0.89	1.16	1.58	2.18	2.99
180	1.18	1.05	1.36	1.90	2.71	3.79
185	1.73	1.35	1.81	2.51	3.52	4.85
190	1.96	1.59	2.10	2.94	4.20	5.92
195	2.64	2.07	2.72	3.72	5.12	6.96
200	3.29	2.19	2.96	4.11	5.72	7.83

CDF Higgs Combination Limits

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

Higgs Boson Couplings to Gluons

Lowest order: Fermion Loops



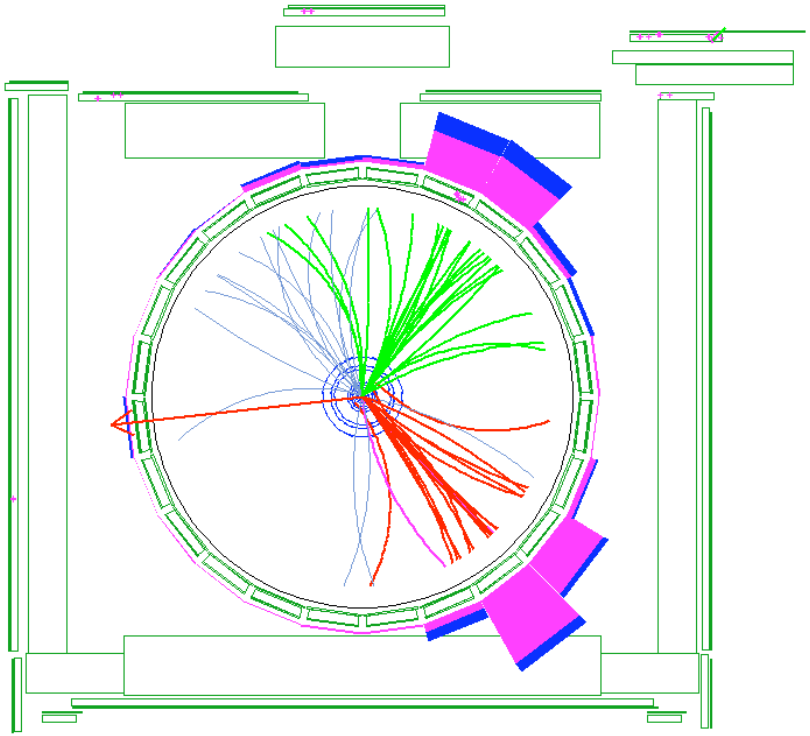
Mostly top contributes in SM

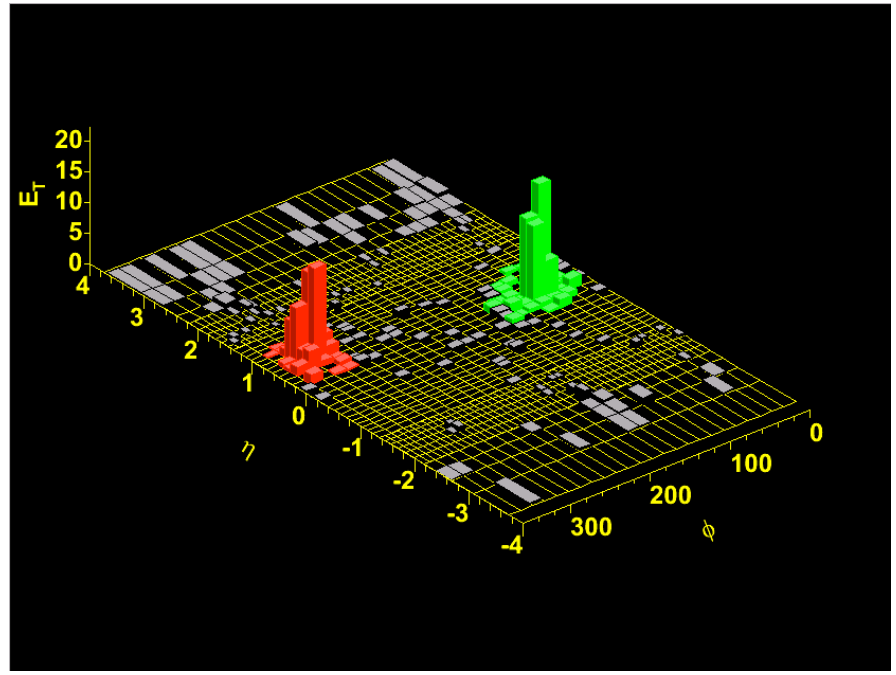
Heavier 4th generation quarks contribute as much as top quark, almost independent of m_Q.

A heavy 4th generation would scale the $gg \rightarrow H$ production rate at colliders by a factor of ~9. But watch out for $H \rightarrow \nu_4 \nu_4$ decays.

E. Arik et al., Acta Phys. Polon. B **37**, 2839 (hep-ph/0502050)

Another Interesting Candidate Event



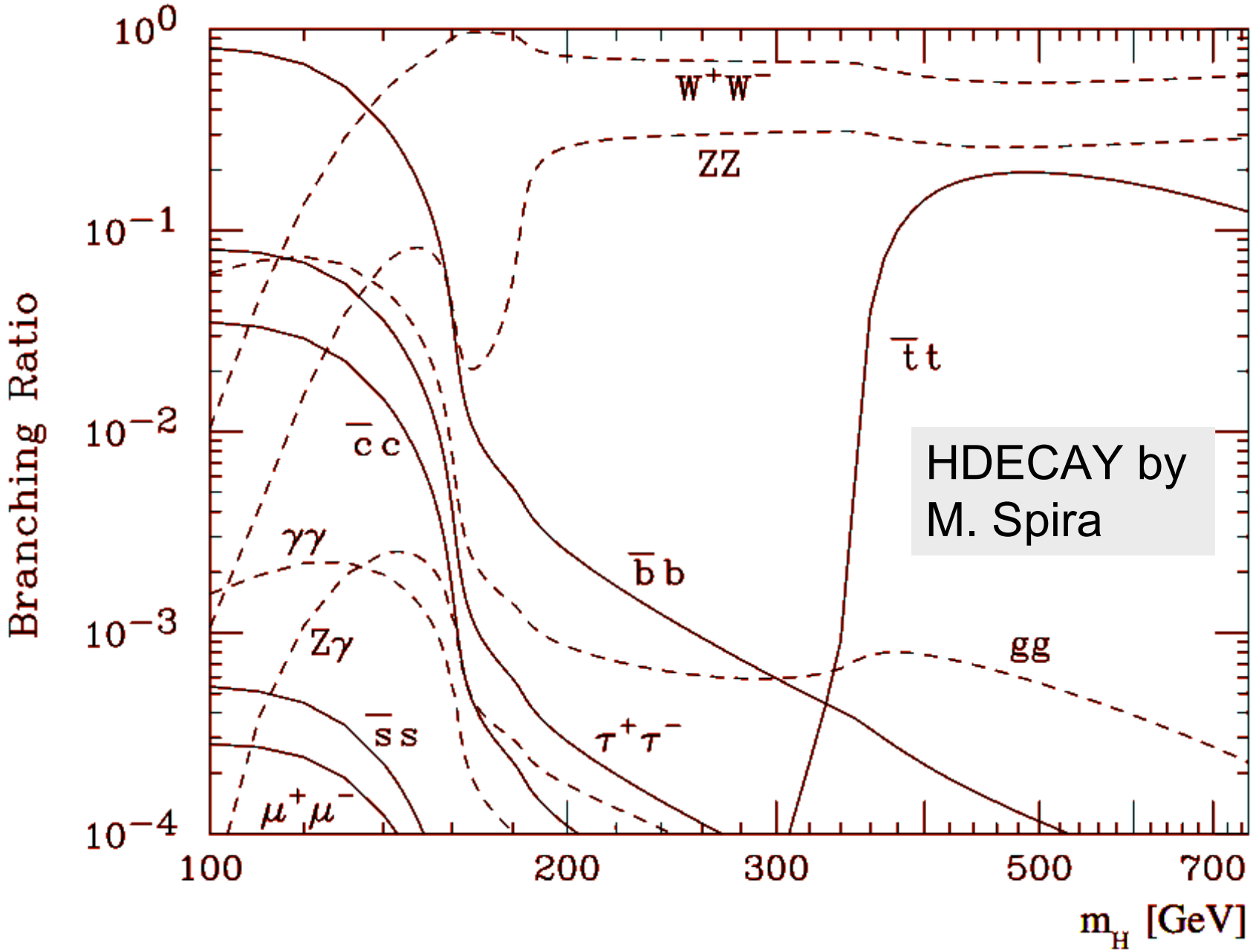


Jet_1 E_T=84.7 GeV
Jet_2 E_T=71.9 GeV -- Tagged

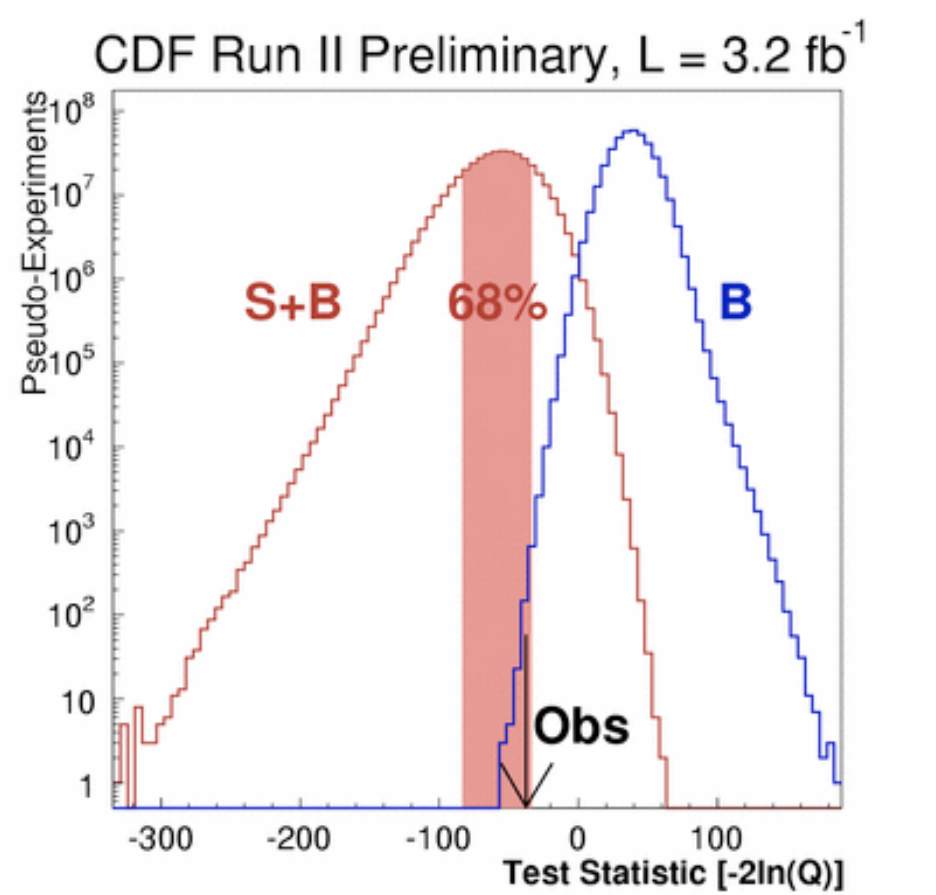
m_{jj} = 129 GeV

Missing E_T = 98 GeV

Standard Model Higgs Boson Decay Branching Fractions



Discovery with p-Values



Systematics varied in each pseudoexperiment

Example: CDF's single top observation

arXiv:0903.0885 [hep-x]

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

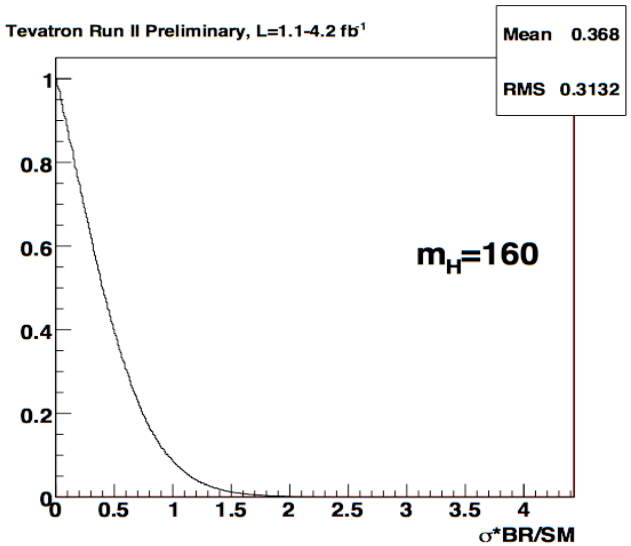
100 M s+b and b-only pseudoexperiments, each with fluctuated nuisance parameters, and fit twice.

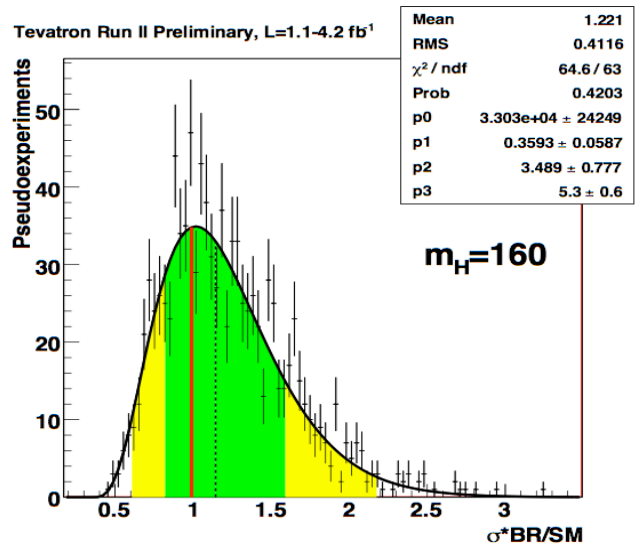
5σ: p-value of 2.77x10^{-7} or less.

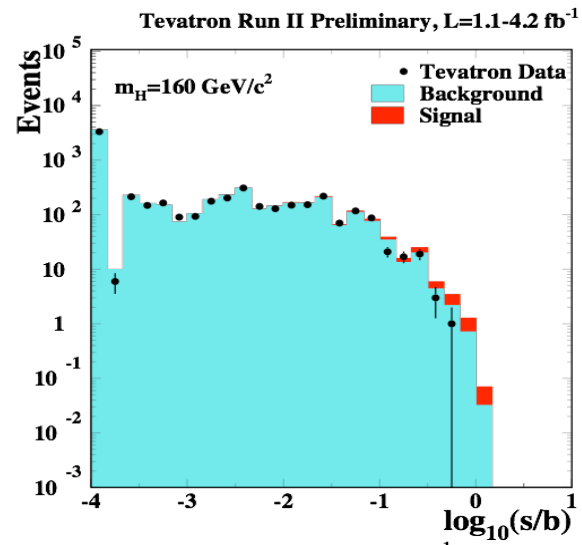
3σ: p-value of 1.35x10^{-3} or less

2σ: p-value of 2.28% or less

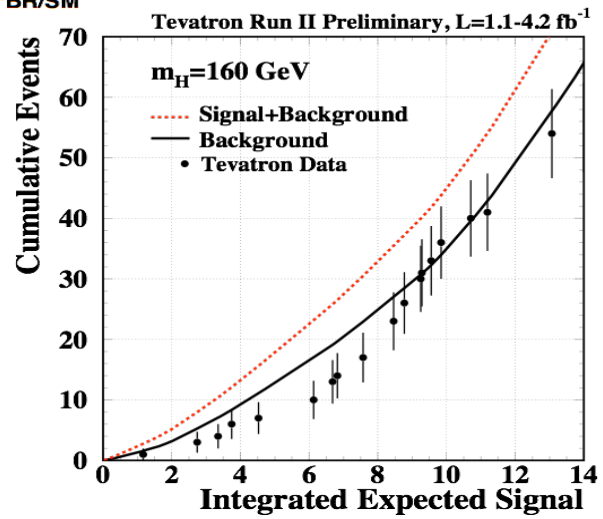
Tevatron Combination at 160 GeV



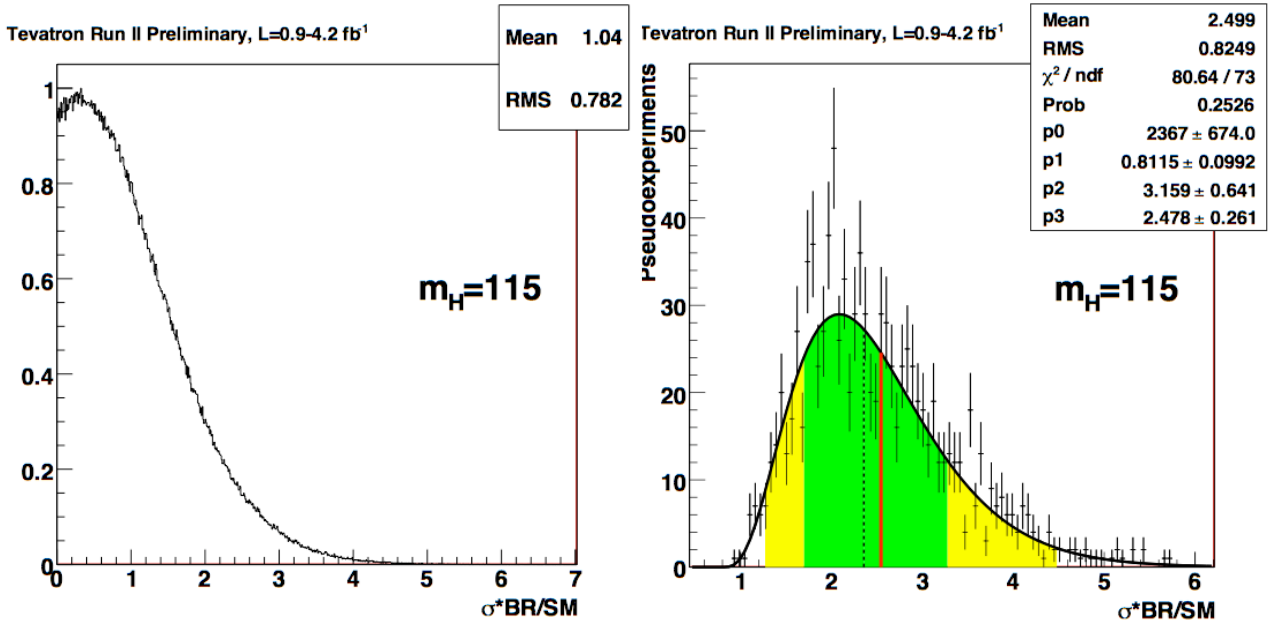




	observed	expected
CDF	1.42	1.59
D0	1.74	1.87
Tevatron	0.99	1.14

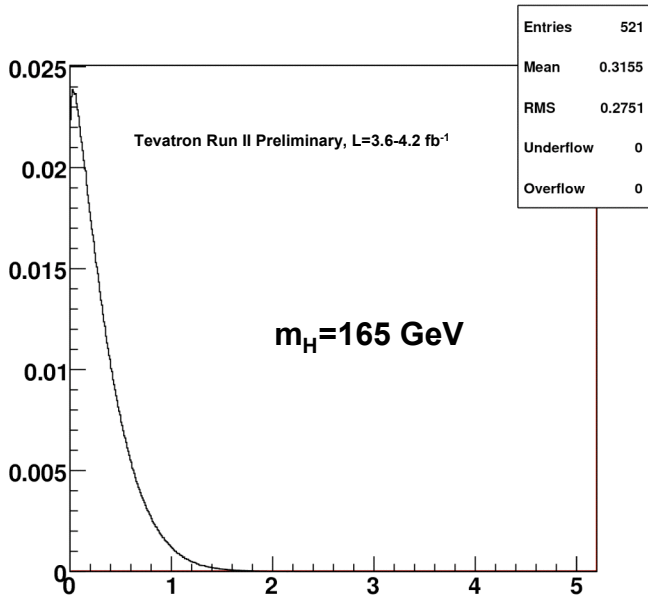


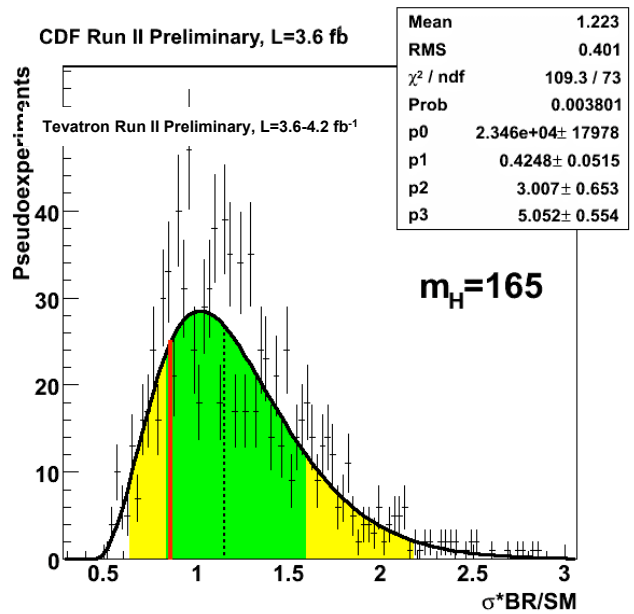
Tevatron Combination at m_H=115 GeV



	observed	expected
CDF	3.64	3.22
D0	3.70	3.89
Tevatron	2.54	2.36

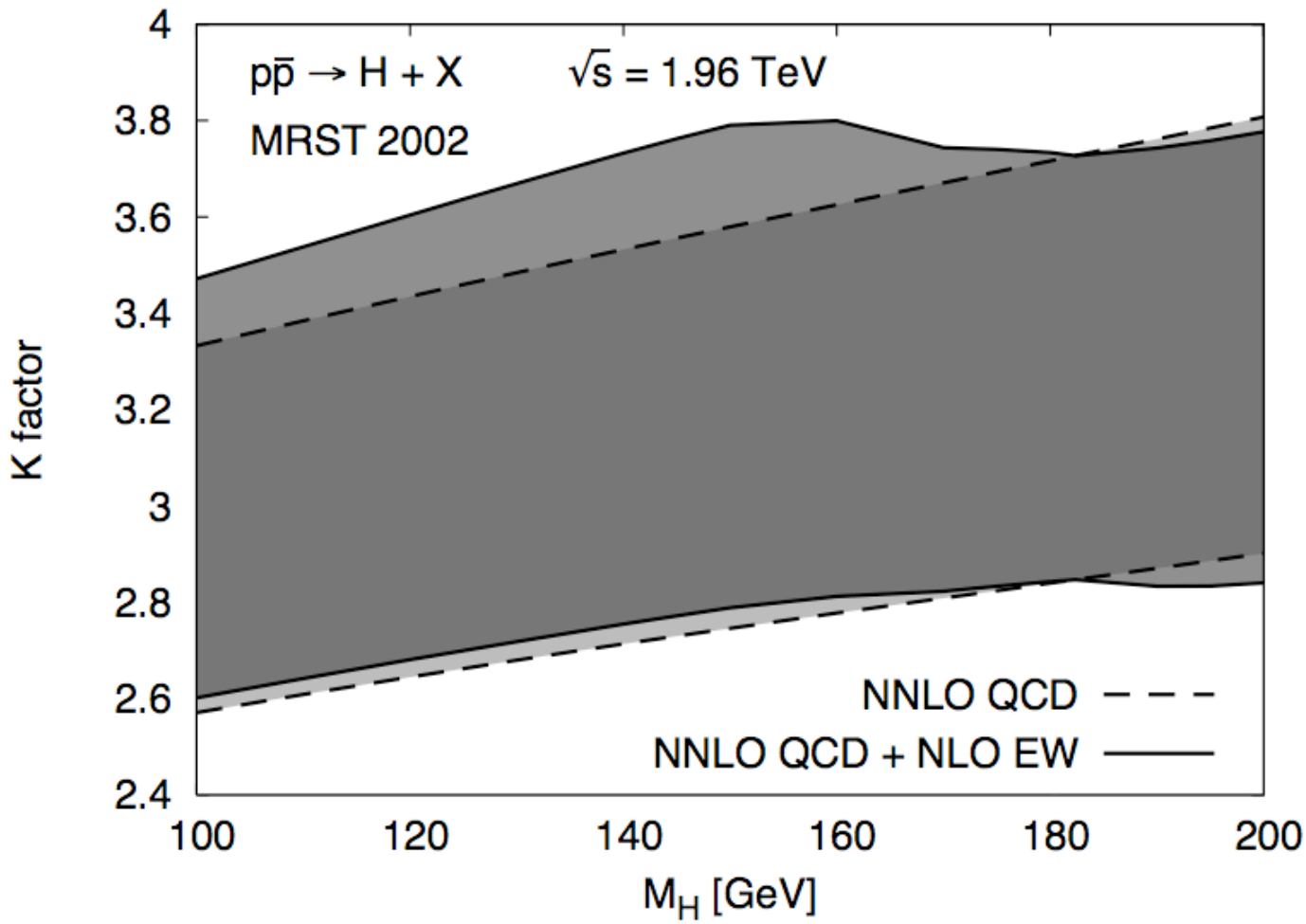
Tevatron Combination at m_H=165 GeV





	observed	expected
CDF	1.33	1.50
D0	1.74	1.87
Tevatron	0.86	1.15

NNLO+EW K-factor (vs. LO) At Tevatron Energies



We assume 12% uncertainty in the total cross section

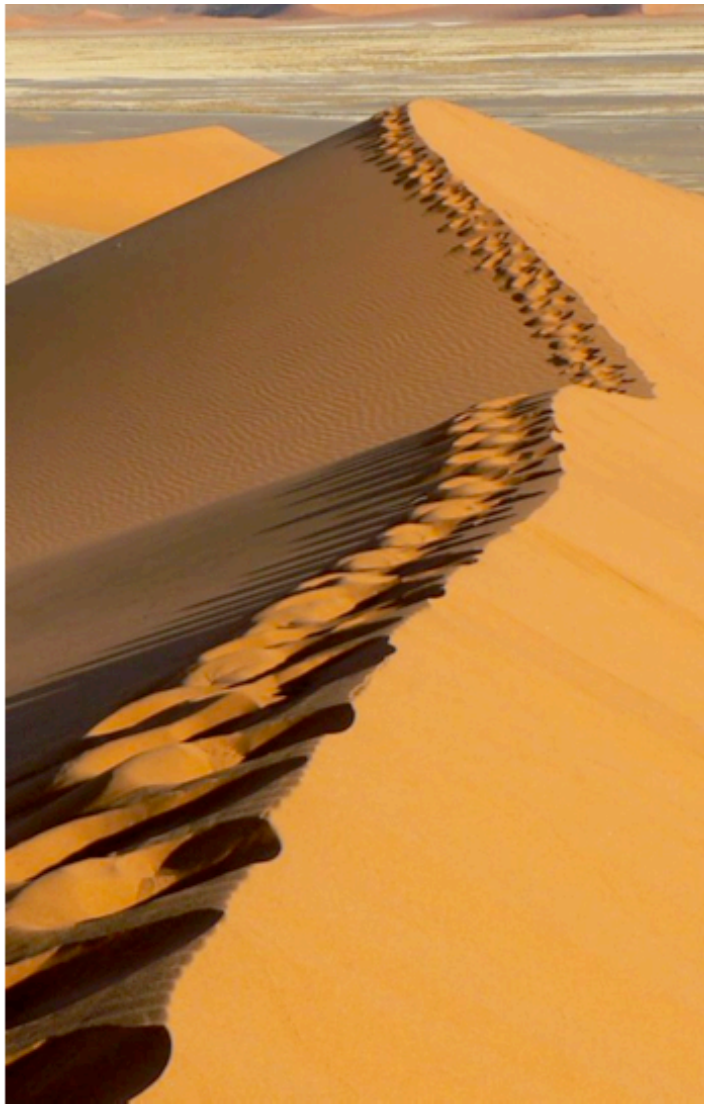
Actis, Passarino, Sturm, Uccirati Phys. Lett. B670:12 (2008)
arXiv:0809.1301 [hep-ph]

Markov Chain Monte Carlo Integration

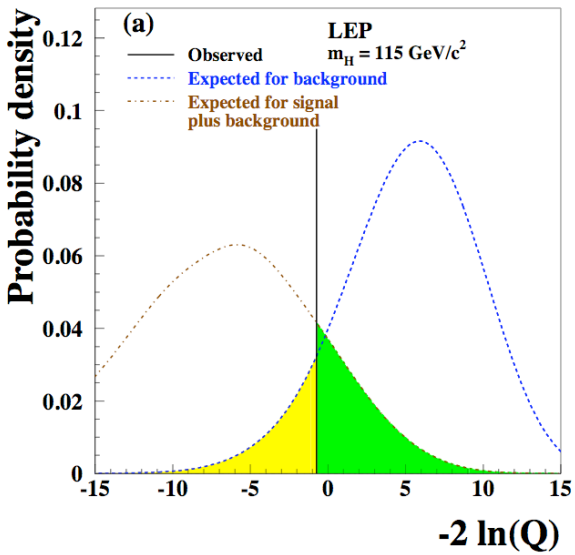
- Monte Carlo integration method
- improvement on scattershot MC
- faster and more stable results

- 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



Mini-Review: CL_s Limits



p-values:
Yellow area = $1-CL_b = 1-P(-2\ln Q>-2\ln Q_{obs}|$ b only)
Green area = $CL_{s+b} = P(-2\ln Q>-2\ln Q_{obs}$ | s+b)

$CL_s \equiv CL_{s+b}/CL_b \geq CL_{s+b}$
Exclude if $CL_s<0.05$
Vary r until $CL_s=0.05$ to get r_{lim}

- Advantages:
  - Exclusion and Discovery p-values are consistent. Example -- a 2σ upward fluctuation of the data with respect to the background prediciton appears both in the limit and the p-value as such
  - Does not exclude where there is no sensitivity (big enough search region with small enough resolution and you get a 5% dusting of random exclusions with CL_{s+b})

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.

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

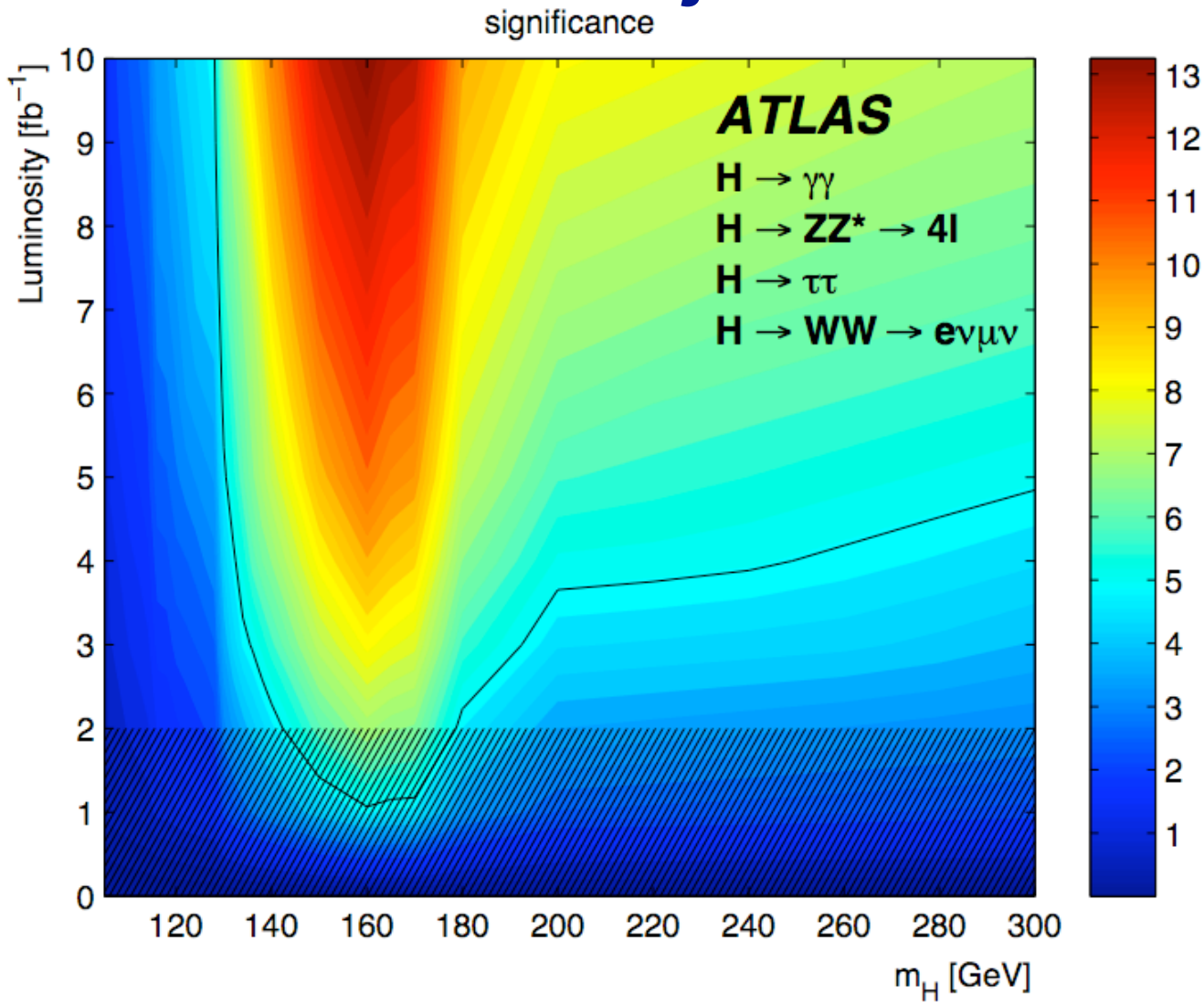
CL_S	100	105	110	115	120	125	130	135	140	145	150
Expected	1.9	1.9	2.1	2.4	2.6	2.7	2.9	2.7	2.5	2.2	1.8
Observed	1.7	1.7	2.2	2.6	2.8	2.9	4.0	2.6	3.1	2.8	2.0

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

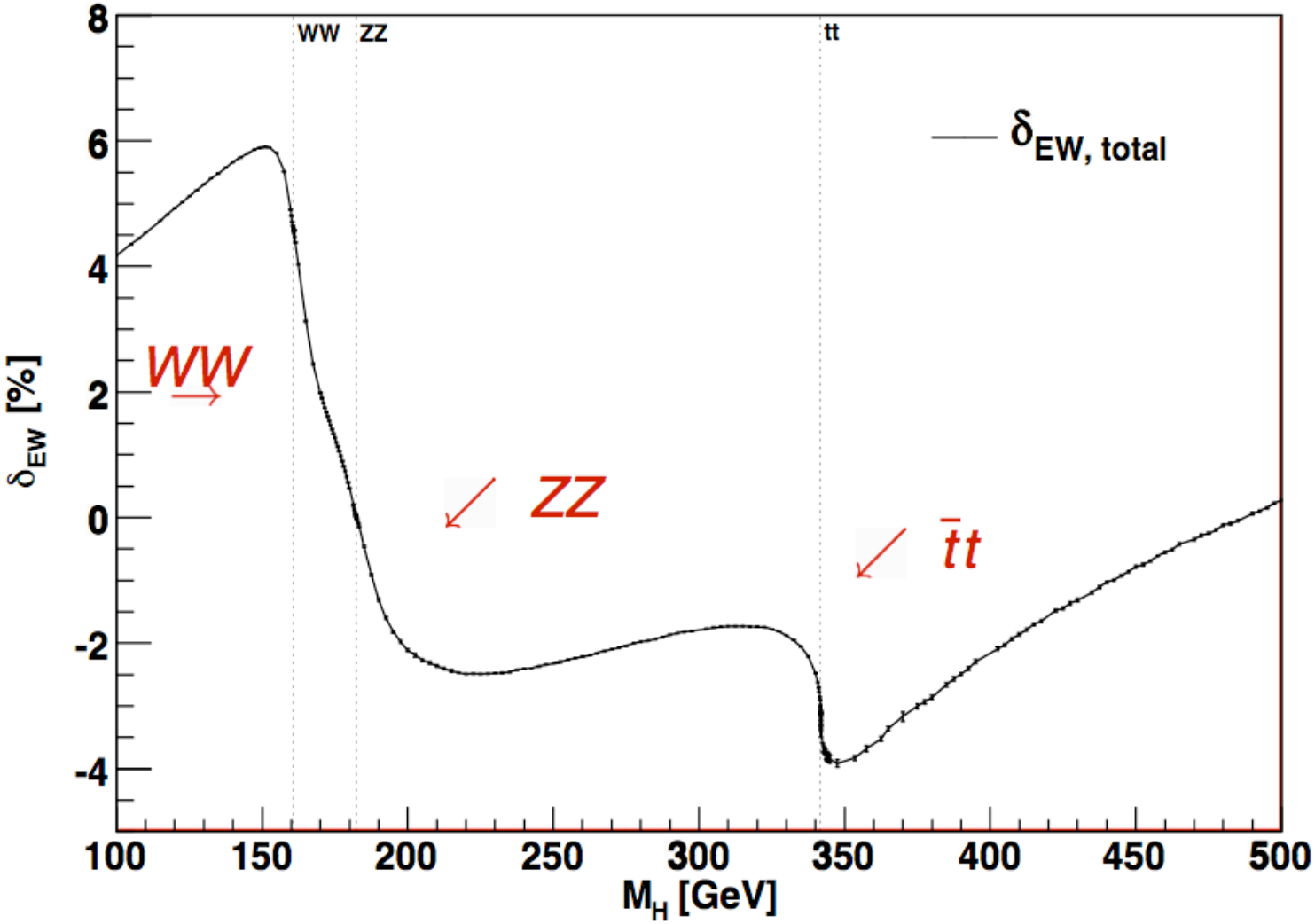
For details, see arXiv:0903.4001 [hep-ex]

ATLAS's Projections



CERN-OPEN-2008-020, "Expected Performance of the ATLAS Experiment": arXiv:0901.0512v3 [hep-ex]

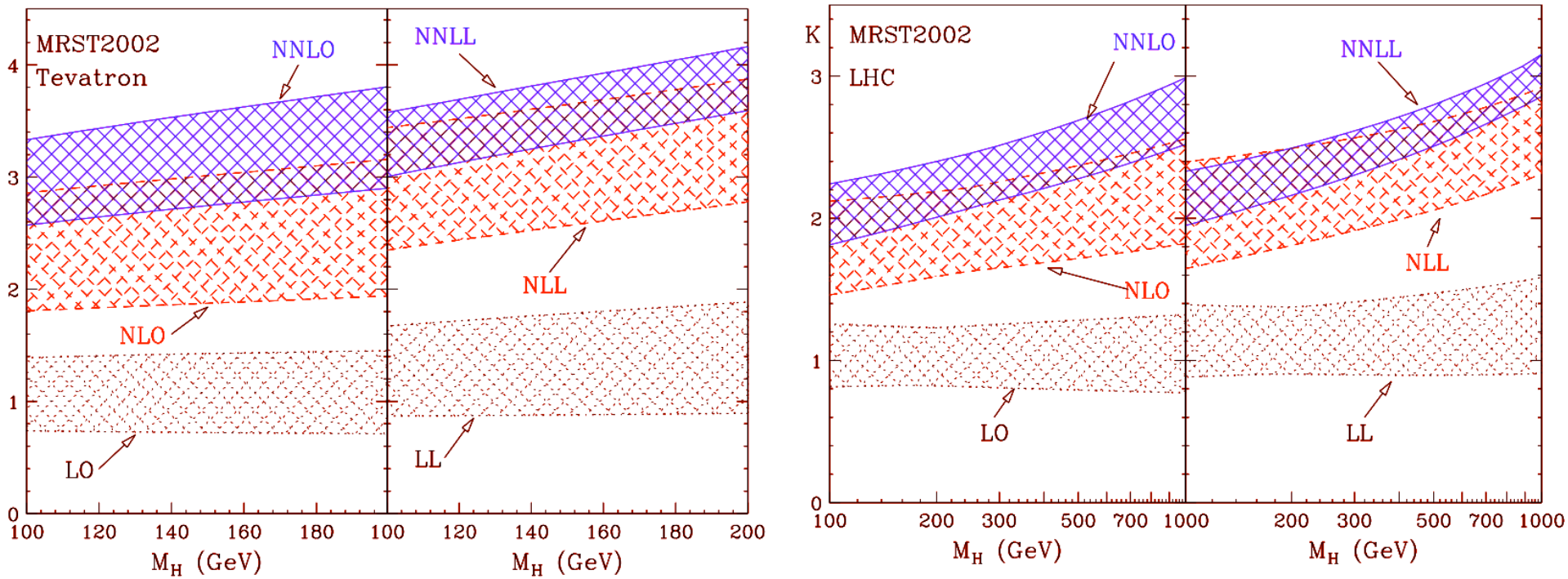
EW corrections to σ(gg→H)



Passarino, Higgs Boson 2009, Zurich;
Actis, Passarino, Sturm, Uccirati Phys. Lett. B670:12 (2008)
arXiv:0809.1301 [hep-ph]

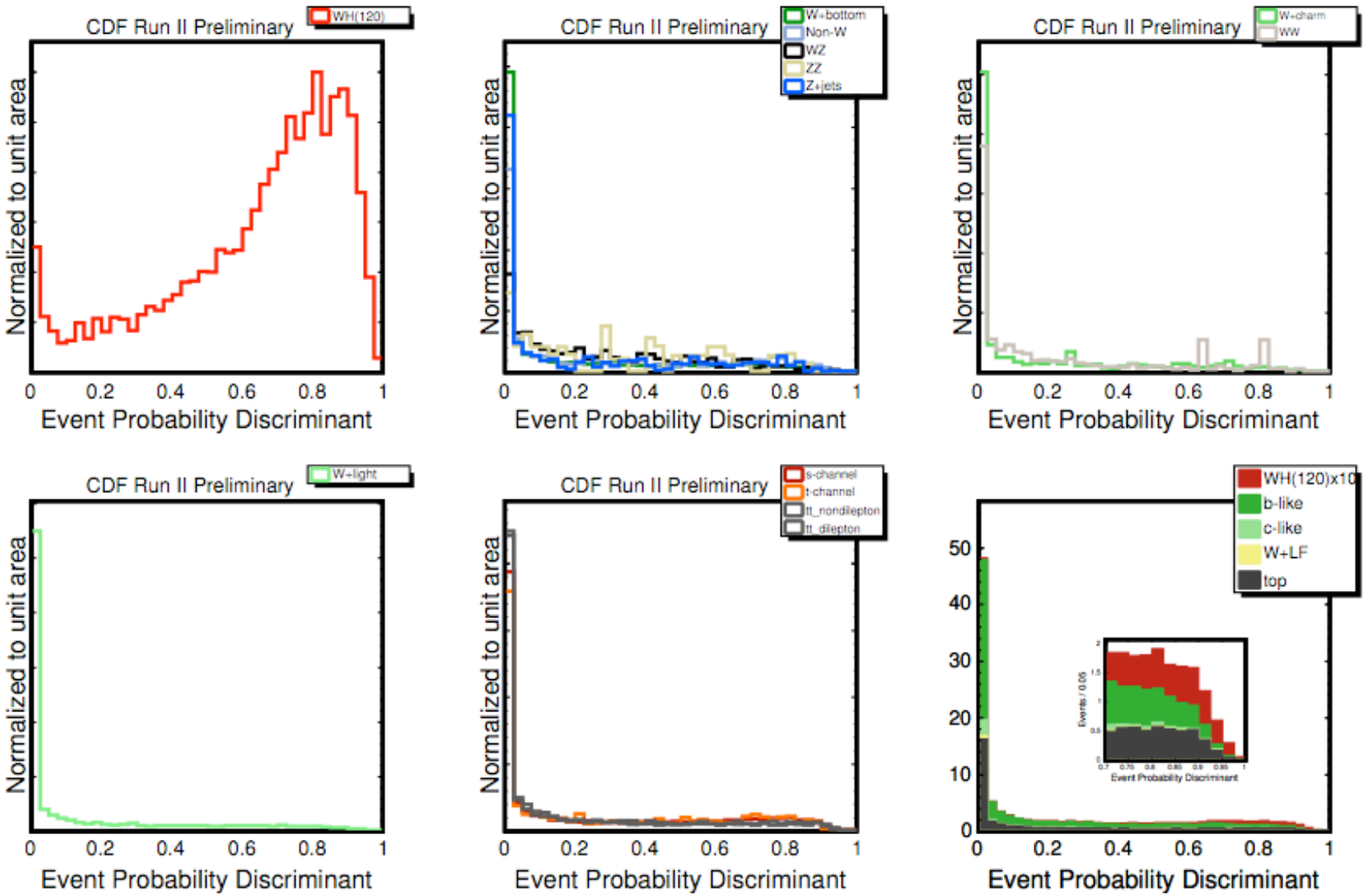
Recent gg→H Production Cross Section Progress

- 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

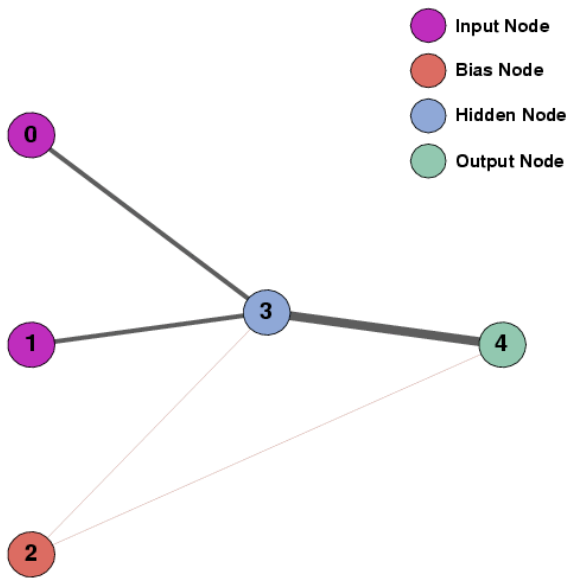


NLO,NNLO bands: $0.5m_H<\mu_F,\mu_R<2M_H$. Bands on LO unreliable.

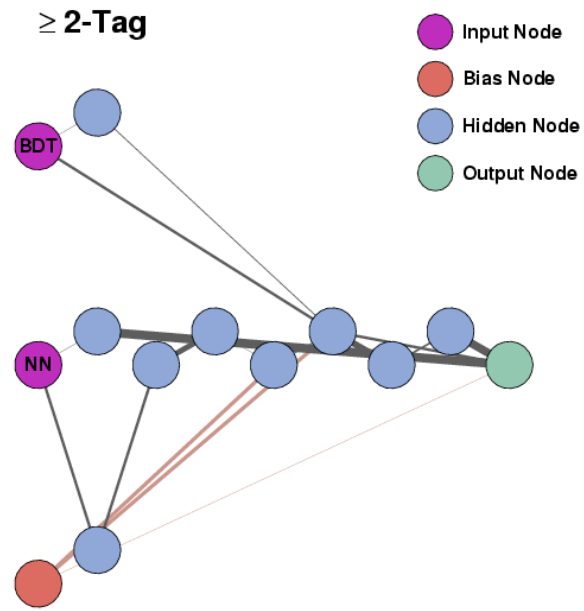
Templates For Matrix Element WH Search



Evolutionarily Trained Neural Networks



Starting Configuration...



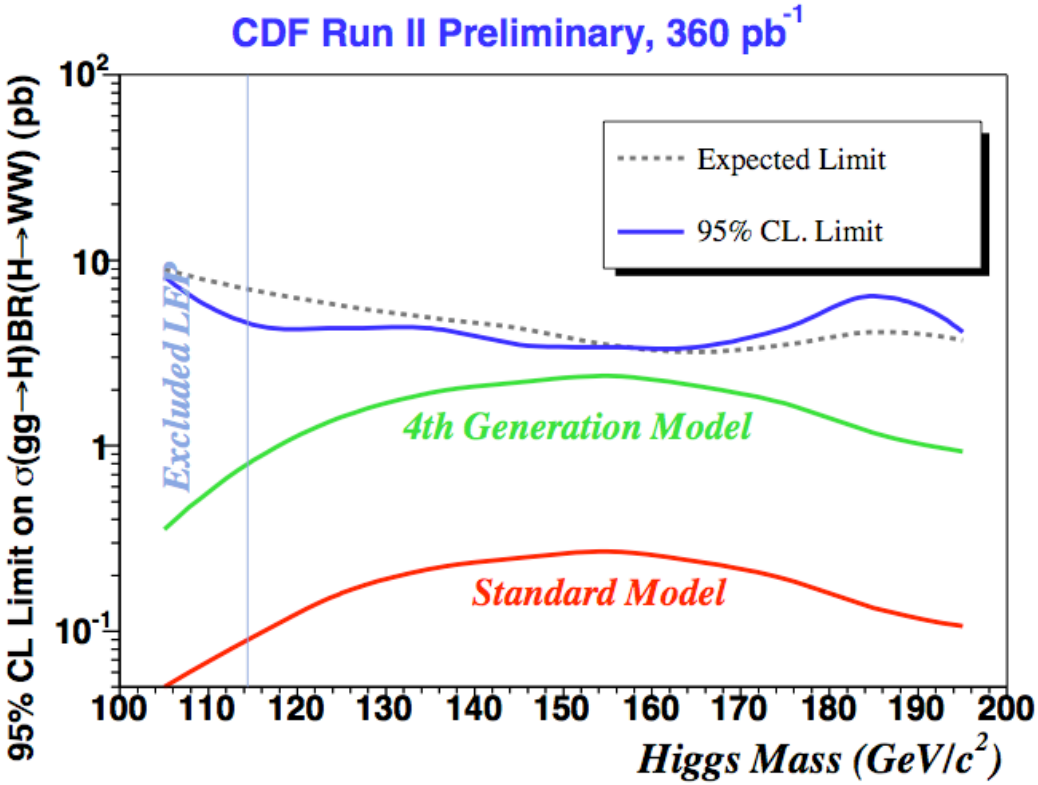
Evolved into this!

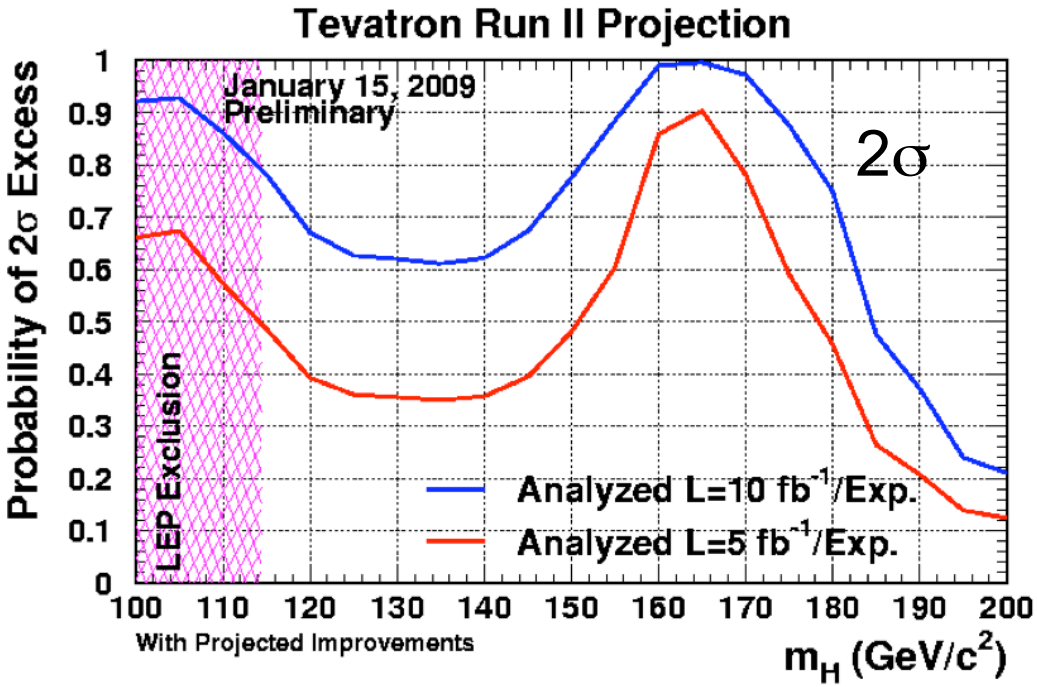
Approximately a 9% improvement in expected limit over the best input

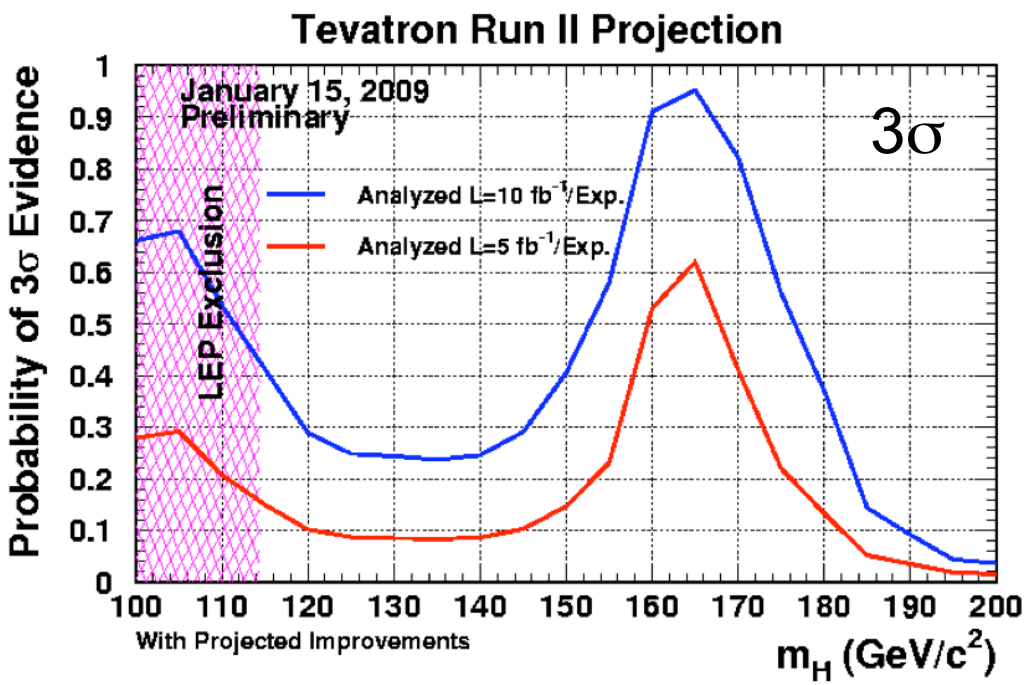
H→WW Sample Composition after Cuts

	ee pre-selection	ee final	$e\mu$ pre-selection	$e\mu$ final	$\mu\mu$ pre-selection	$\mu\mu$ final
$Z \to ee$	218695 ± 704	108 ± 14	280.6 ± 3.3	$0.0^{+0.1}_{-0.0}$	–	–
$Z \to \mu\mu$	–	–	274.6 ± 0.9	5.8 ± 0.1	235670 ± 158	3921 ± 22
$Z \to \tau\tau$	1135 ± 16	1.4 ± 0.5	3260 ± 3	7.3 ± 0.1	1735 ± 10	66 ± 2
$t\bar{t}$	131.4 ± 1.4	39.9 ± 0.8	272.0 ± 0.3	82.5 ± 0.2	19.93 ± 0.05	12.55 ± 0.04
W+jets	241 ± 5	98 ± 3	183 ± 4	78.6 ± 2.8	214 ± 7	134 ± 5
WW	172.2 ± 2.6	66.8 ± 1.6	421.2 ± 0.1	154.7 ± 0.1	159.0 ± 0.3	92.8 ± 0.3
WZ	112.5 ± 0.2	9.68 ± 0.05	20.5 ± 0.1	6.6 ± 0.1	47.3 ± 0.5	19.4 ± 0.3
ZZ	98.2 ± 0.2	7.68 ± 0.07	5.3 ± 0.1	0.60 ± 0.01	40.5 ± 0.2	15.1 ± 0.1
Multijet	1351 ± 55	$1.7^{+2.0}_{-1.7}$	279 ± 168	$1.1^{+9.6}_{-1.1}$	386 ± 20	64 ± 8
Signal ($M_H = 165$ GeV)	9.45 ± 0.01	6.13 ± 0.01	17.1 ± 0.01	12.2 ± 0.1	5.43 ± 0.01	4.85 ± 0.01
Total Background	221937 ± 707	332 ± 15	4995 ± 168	337 ± 10	238272 ± 159	4325 ± 24
Data	221530	336	4995	329	239923	4084

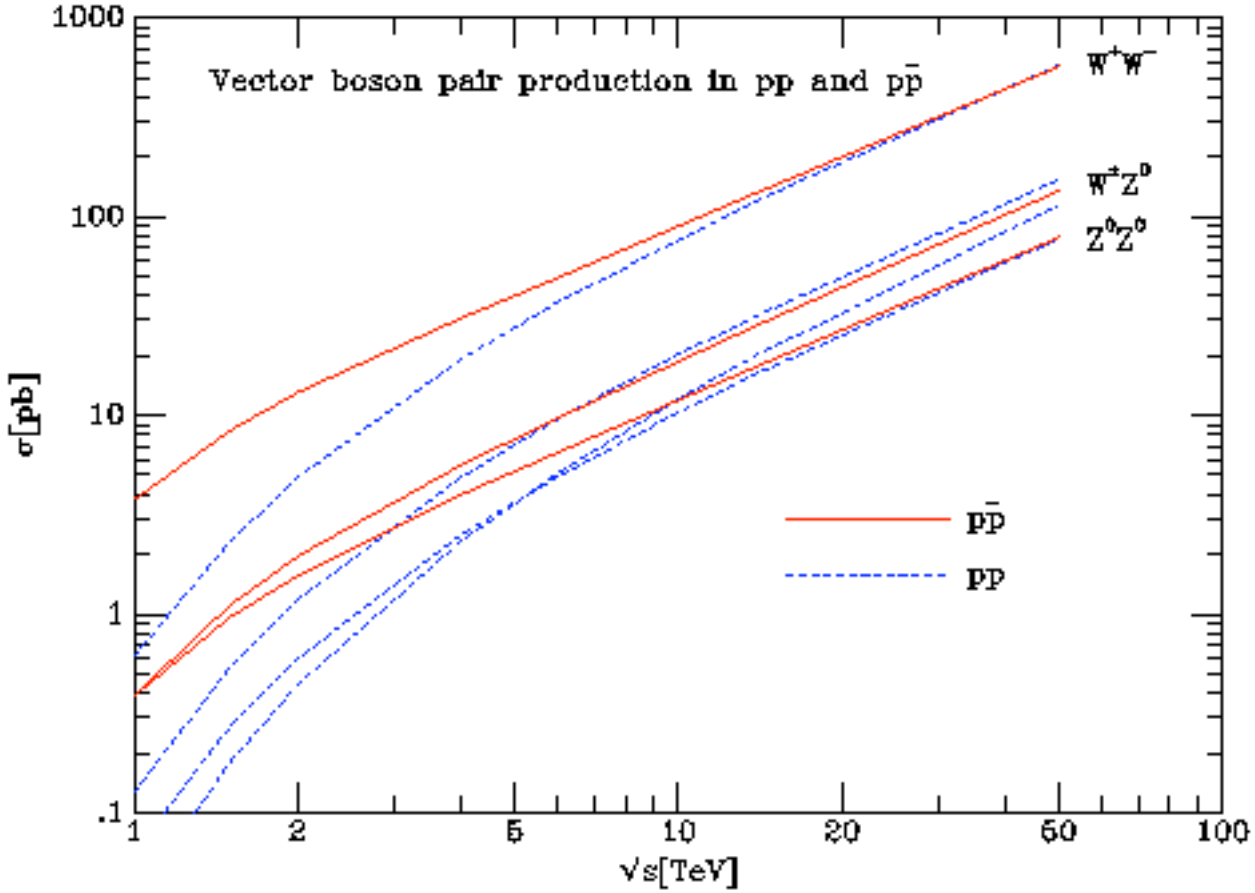
Amount of DY background left after cuts different.
WW not so different between channels


CDF Run II Preliminary, 360 pb^{-1}
95% CL Limit on σ(gg→H)BR(H→WW) (pb)
10^2
10
1
10^{-1}
Expected Limit
95% CL. Limit
Excluded LEP
4th Generation Model
Standard Model
100
110
120
130
140
150
160
170
180
190
200
Higgs Mass (GeV/c^2)


Tevatron Run II Projection
January 15, 2009
Preliminary
2σ
LEP Exclusion
Analyzed L=10 fb^{-1}/Exp.
Analyzed L=5 fb^{-1}/Exp.
Probability of 2σ Excess
With Projected Improvements
m_H (GeV/c^2)


Tevatron Run II Projection
January 15, 2009
Preliminary
3σ
LEP Exclusion
Analyzed L=10 fb^{-1}/Exp.
Analyzed L=5 fb^{-1}/Exp.
Probability of 3σ Evidence
With Projected Improvements
m_H (GeV/c^2)

WW and WZ and ZZ Production at Hadron Colliders



Campbell and Ellis
Phys.Rev.D **60** 113006,1999.
e-Print: hep-ph/9905386

H→WW Selection Requirements

	Final state	$e\mu$	ee	$\mu\mu$
Cut 0	Pre-selection	lepton ID, leptons with opposite charge and $p_T^\mu > 10$ GeV and $p_T^e > 15$ GeV invariant mass $M_{\ell\ell} > 15$ GeV $\mu\mu$: $n_{\rm jet} < 2$ for $p_{\rm T}^{\rm jet} > 15$ GeV, $\Delta\mathcal{R}(\mu, {\rm jet}) > 0.1$ and $p_T^\mu > 15$ GeV for the leading μ		
Cut 1	Missing Transverse Energy $\not{E}_T$ (GeV)	> 20	> 20	
Cut 2	$\not{E}_T^{\rm Scaled}$	> 6	> 6	
Cut 3	M_T^{min} $(\ell, \not{E}_T)$ (GeV)	> 20	> 30	
Cut 4	$p_{\rm T}^{\mu\mu}$ (GeV) for $n_{\rm jet} = 0$			> 20
	$\not{E}_T$ (GeV) for $n_{\rm jet} = 1$			> 20
Cut 5	$\Delta\phi(\ell, \ell)$	< 2.0	< 2.0	< 2.5