Tevatron Results 3: Higgs Boson Searches

Tom Junk

Fermilab

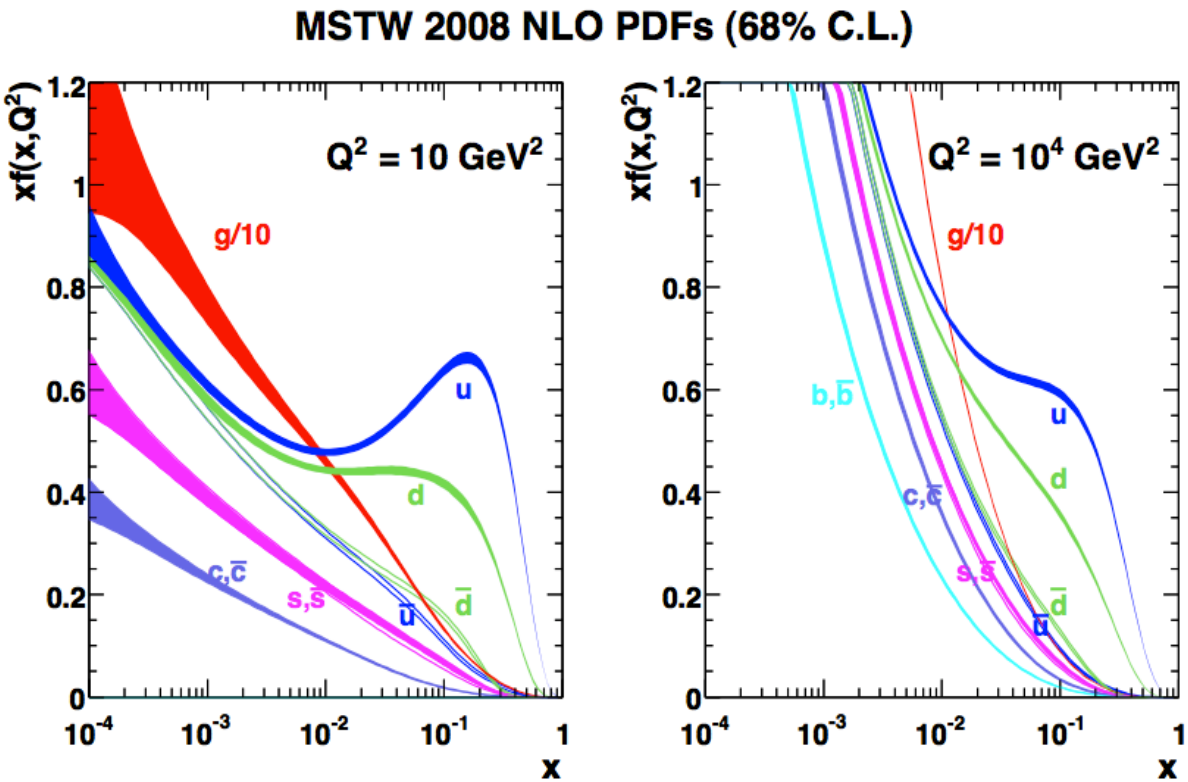
LHC PhenoNet Winter School 2012
22-29 January
Ascona, Switzerland

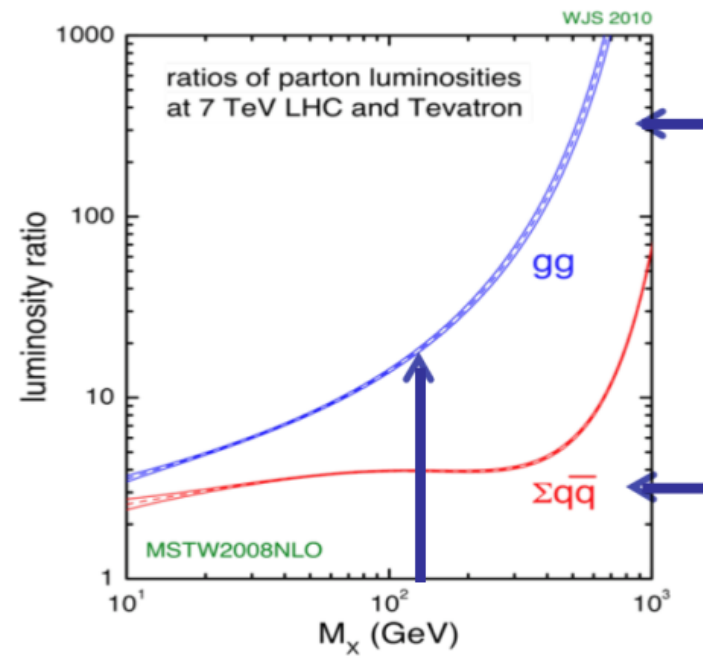
- Production and Decay modes
- High-Mass Searches: WW and ZZ
- Low-Mass Searches: WH→Wbb and ZH→Zbb
- H→$\gamma\gamma$
- Limits and p-values

http://www-cdf.fnal.gov/physics/new/hdg/hdg.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
http://tevnphwg.fnal.gov/

Parton Distribution Functions

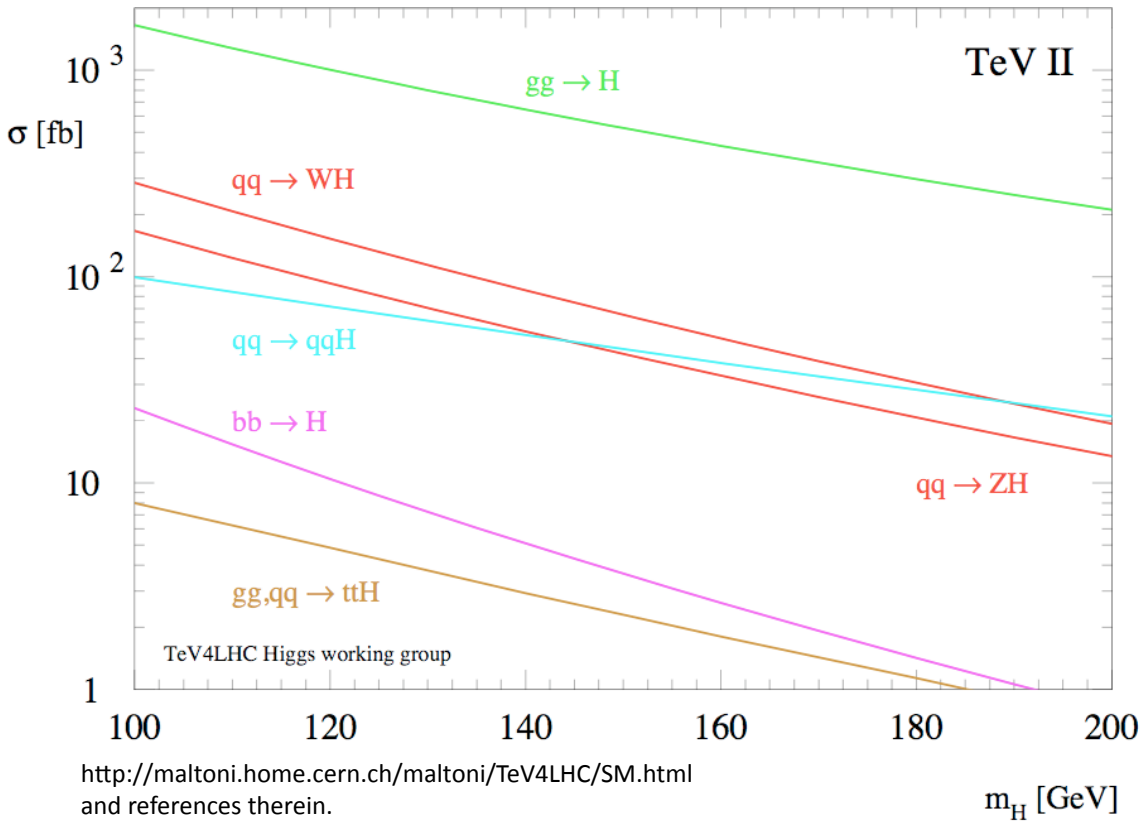
Two effects: LHC has larger beam energy, and larger Q^2



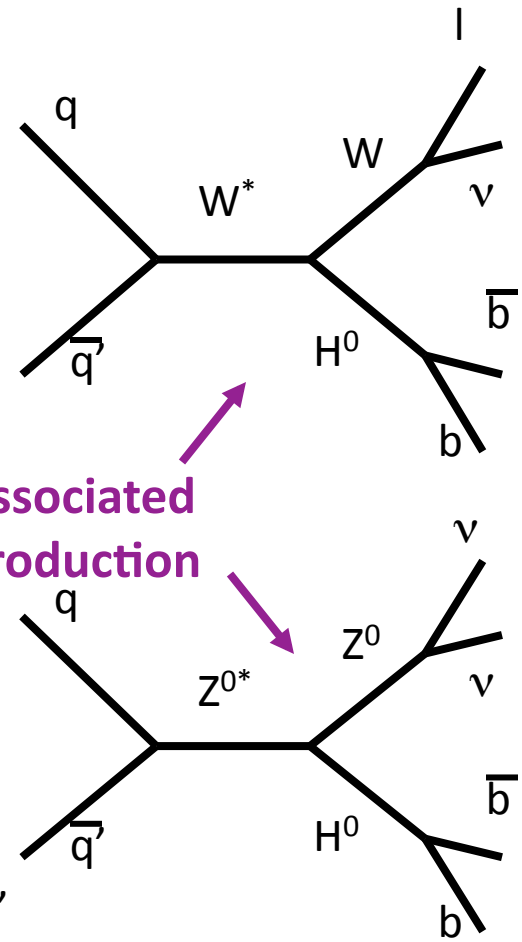


R. Thorne

SM Higgs Boson Production Mechanisms

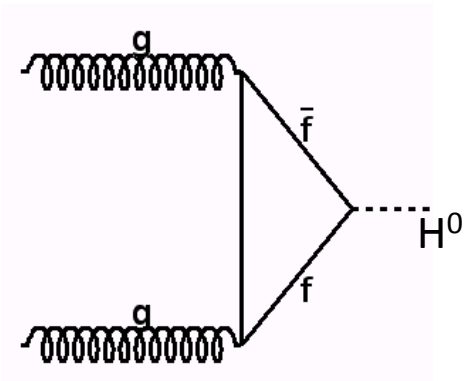


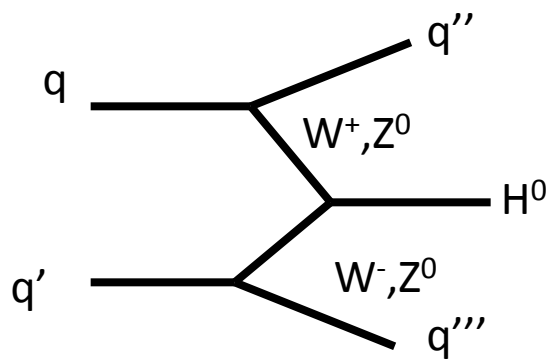
http://maltoni.home.cern.ch/maltoni/TeV4LHC/SM.html
and references therein.



Associated Production

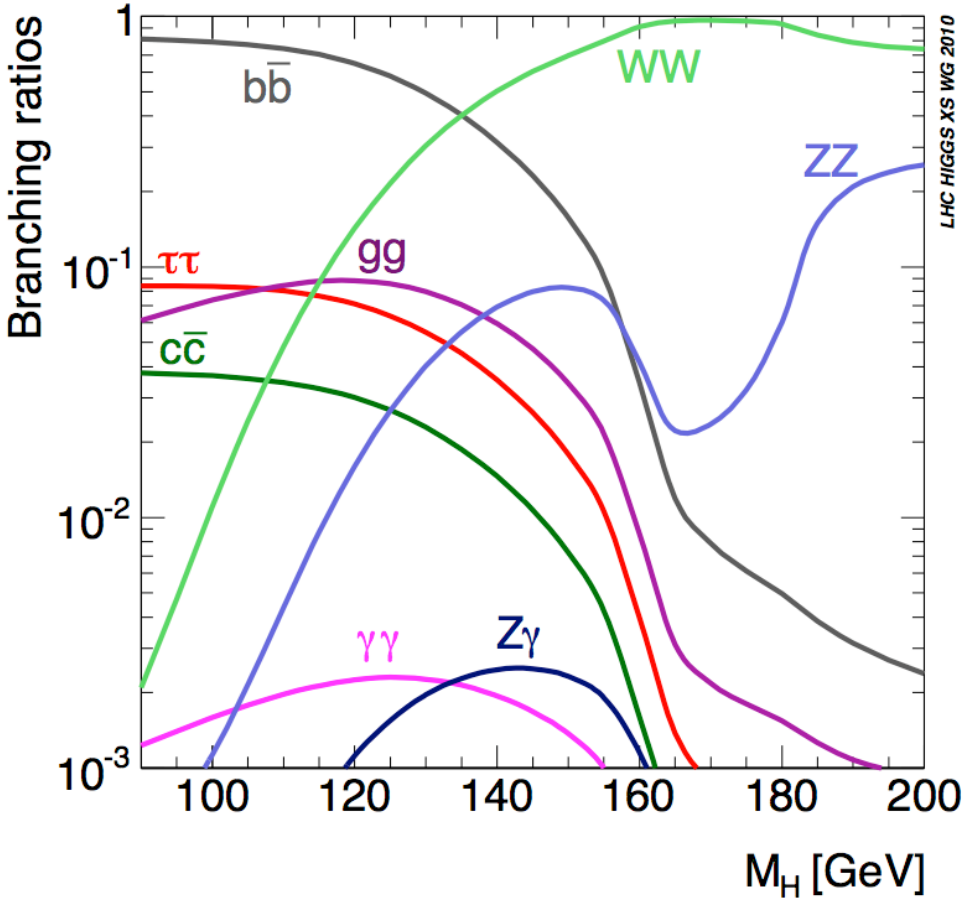
gluon fusion

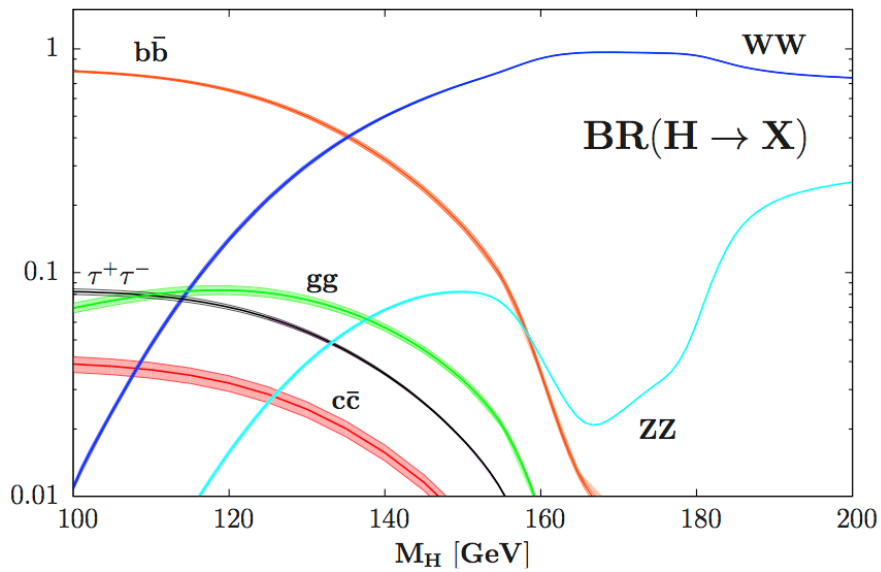




Vector-Boson Fusion (VBF)

Higgs Boson Decay Branching Ratios





HDECAY with uncertainties due to m_b, m_c, and α_s.
Baglio and Djouadi, arXiv:1012.0530

LHC Cross Section WG: HDECAY + Prophecy4f
arXiv:1101.0593v2

We use these central values

and these uncertainties

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)	$\sigma_{t\bar{t}H}$ (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to\tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to\gamma\gamma)$ (%)
100	1821.8	291.90	169.8	97.2	8.000	79.1	3.68	8.36	1.11	0.113	0.159
105	1584.7	248.40	145.9	89.7	7.062	77.3	3.59	8.25	2.43	0.215	0.178
110	1385.0	212.00	125.7	82.7	6.233	74.5	3.46	8.03	4.82	0.439	0.197
115	1215.9	174.50	103.9	76.4	5.502	70.5	3.27	7.65	8.67	0.873	0.213
120	1072.3	150.10	90.2	70.7	4.857	64.9	3.01	7.11	14.3	1.60	0.225
125	949.3	129.50	78.5	65.3	4.279	57.8	2.68	6.37	21.6	2.67	0.230
130	842.9	112.00	68.5	60.4	3.769	49.4	2.29	5.49	30.5	4.02	0.226
135	750.8	97.20	60.0	55.9	3.320	40.4	1.87	4.52	40.3	5.51	0.214
140	670.6	84.60	52.7	51.8	2.925	31.4	1.46	3.54	50.4	6.92	0.194
145	600.6	73.70	46.3	48.1	2.593	23.1	1.07	2.62	60.3	7.96	0.168
150	539.1	64.40	40.8	44.6	2.298	15.7	0.725	1.79	69.9	8.28	0.137
155	484.0	56.20	35.9	41.2	2.037	9.18	0.425	1.06	79.6	7.36	0.100
160	432.3	48.50	31.4	38.2	1.806	3.44	0.159	0.397	90.9	4.16	0.0533
165	383.7	43.60	28.4	36.0	1.607	1.19	0.0549	0.138	96.0	2.22	0.0230
170	344.0	38.50	25.3	33.4	1.430	0.787	0.0364	0.0920	96.5	2.36	0.0158
175	309.7	34.00	22.5	31.0	1.272	0.612	0.0283	0.0719	95.8	3.23	0.0123
180	279.2	30.10	20.0	28.8	1.132	0.497	0.0230	0.0587	93.2	6.02	0.0102
185	252.1	26.90	17.9	26.9	1.004	0.385	0.0178	0.0457	84.4	15.0	0.00809
190	228.0	24.00	16.1	25.0	0.890	0.315	0.0146	0.0376	78.6	20.9	0.00674
195	207.2	21.40	14.4	23.3	0.789	0.270	0.0125	0.0324	75.7	23.9	0.00589
200	189.1	19.10	13.0	21.6	0.700	0.238	0.0110	0.0287	74.1	25.6	0.00526

ggH: Grazzini, de Florian, Anastasiou, Boughezal, Petriello, Catani, Harlander, Ravindran, Van Neerven, Nason, Melnikov, Actis, Passarino, Sturm, Uccirati, Aglietti, Bonciani, Degrassi, Vicini, Maltoni

WH, ZH: Baglio, Djouadi, Spira, Brein, Harlander, Ciccolini, Dittmaier, Krämer, Ferrera, Grazzini, Tramontano

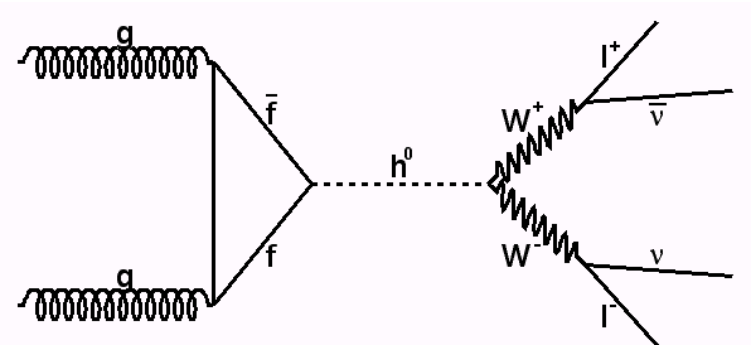
VBF: Bolzoni, Maltoni, Moch, Zaro, Ciccolini, Denner, Dittmaier

ttH: Beenaker, Dittmaier, Krämer, Plümper, Spira, Zerwas, Reina, Dawson

Branching Fractions: LHC Higgs Cross Section WG: HDECAY: Spira,Djouadi,Kalinowski,Muhlleitner +Prophecy4f:Bredenstein, Denner, Dittmaier, Weber, Mück

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

gg→H Signal Process:



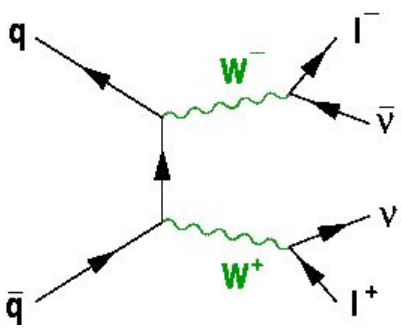
Both CDF and D0 Select events with

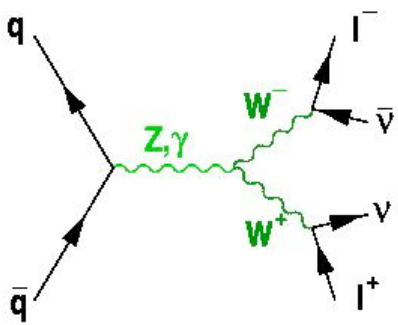
- Two isolated, opposite-signed high-p_T leptons (e,μ)
- Missing transverse energy (rejects DY background)
- m_{ll} > ~ 15 GeV (rejects DY Background)

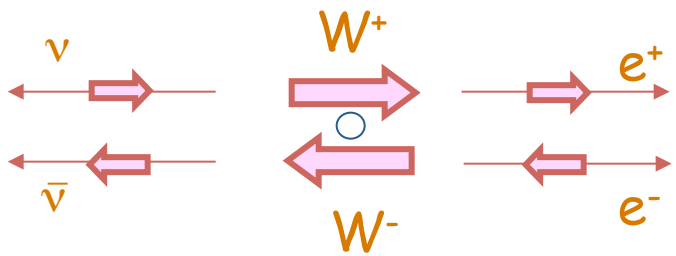
Dominant difficult background:

$qq \Rightarrow W^+W^-$

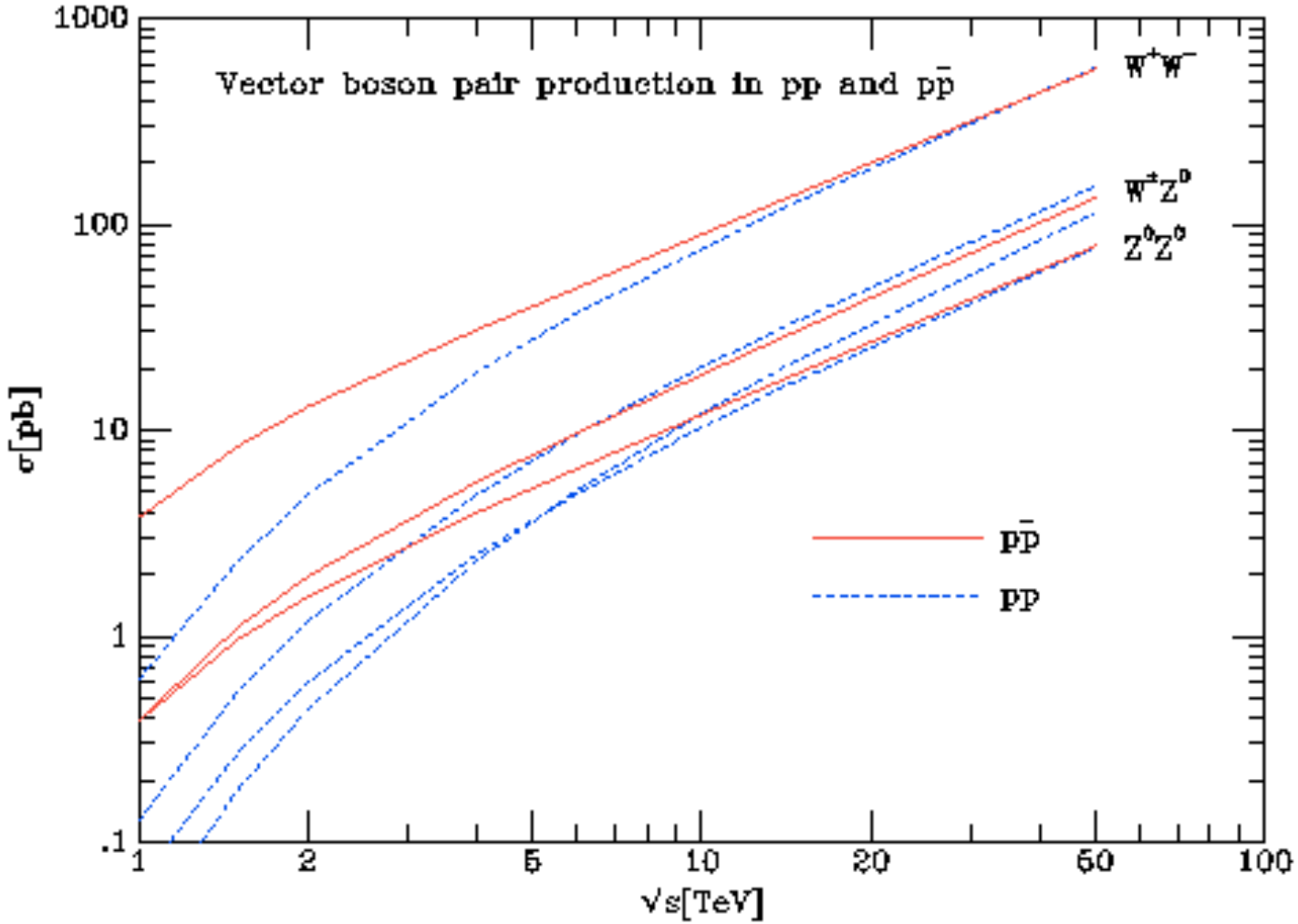
- Higgs is a Scalar! Angular correlations are different from SM W^+W^- bg
- Signal leptons come out collinear





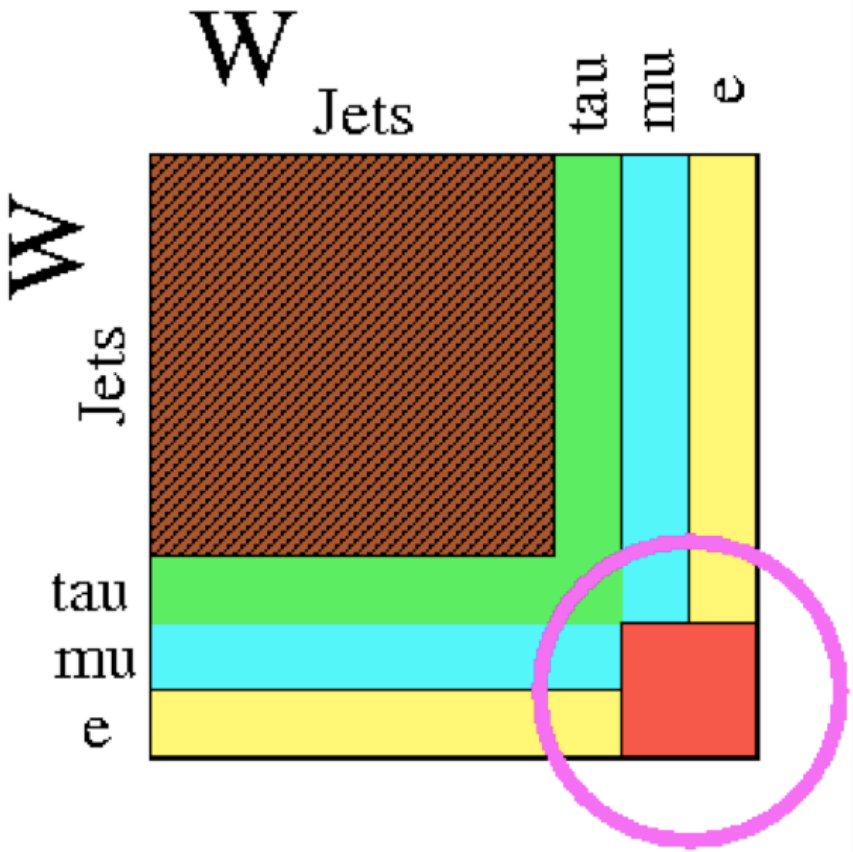


WW and WZ and ZZ Production at Hadron Colliders



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

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

Expected and Observed Yields in CDF's 0-jet H→WW Search Channels

CDF Run II Preliminary $\int \mathcal{L} = 8.2\ \mathrm{fb}^{-1}$

$M_H = 165\ \mathrm{GeV}/c^2$

$t\bar{t}$	2.48	±	0.76
DY	198	±	54
WW	573	±	57
WZ	24.6	±	3.7
ZZ	36.0	±	5.1
W+jets	112	±	27
$W\gamma$	56.4	±	8.2
Total Background	1000	±	100
$gg \to H$	18.3	±	5.4
WH	0.452	±	0.076
ZH	0.472	±	0.067
VBF	0.164	±	0.034
Total Signal	19.3	±	5.5
Data	957		

HighSB-0J

CDF Run II Preliminary $\int \mathcal{L} = 8.2\ \mathrm{fb}^{-1}$

$M_H = 165\ \mathrm{GeV}/c^2$

$t\bar{t}$	0.84	±	0.26
DY	185	±	50
WW	250	±	25
WZ	13.3	±	2.0
ZZ	18.2	±	2.6
W+jets	377	±	57
$W\gamma$	150	±	22
Total Background	994	±	93
$gg \to H$	6.4	±	1.9
WH	0.161	±	0.027
ZH	0.128	±	0.018
VBF	0.052	±	0.011
Total Signal	6.7	±	1.9
Data	1187		

LowSB-0J

CDF Run II Preliminary $\int \mathcal{L} = 8.2\ \mathrm{fb}^{-1}$

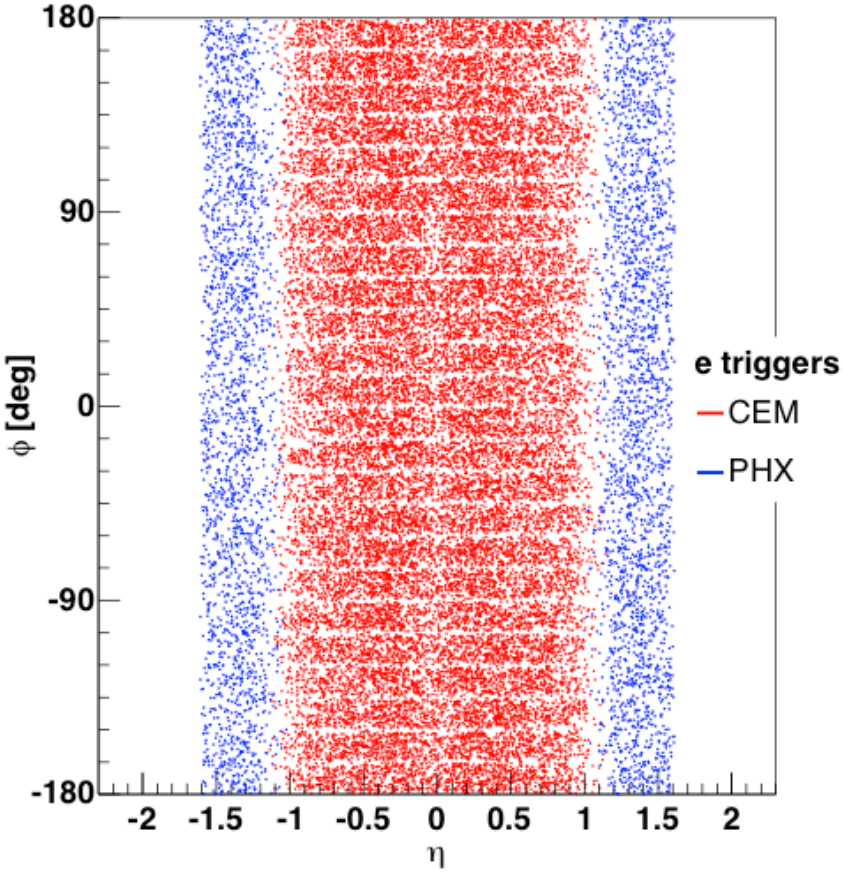
$M_H = 165\ \mathrm{GeV}/c^2$

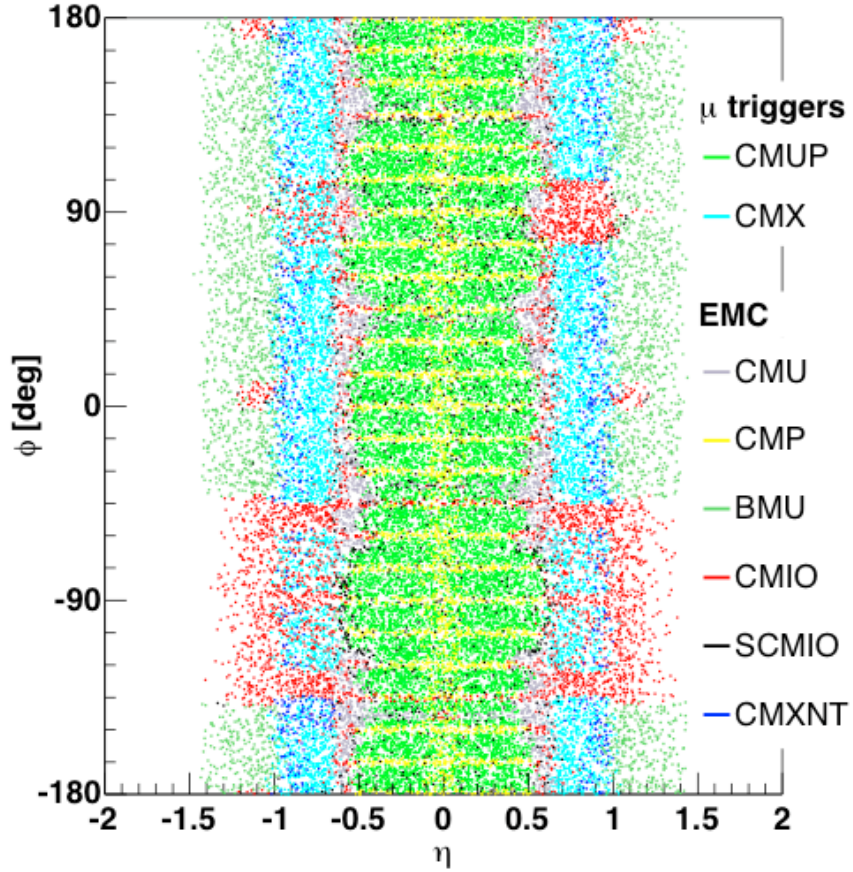
$t\bar{t}$	3.3	±	1.0
DY	380	±	100
WW	823	±	82
WZ	37.9	±	5.7
ZZ	54.2	±	7.7
W+jets	489	±	83
$W\gamma$	206	±	30
Total Background	2000	±	190
$gg \to H$	24.6	±	7.3
WH	0.61	±	0.10
ZH	0.599	±	0.085
VBF	0.215	±	0.044
Total Signal	26.1	±	7.4
Data	2144		

All

Leptons categorized as "low s/b" vs "high s/b" based on where they are found in the detector. Forward leptons, stubless tracks, all have lower s/b than "tight central leptons"

Some of CDF's Lepton Categories





CDF Opposite-sign H→WW Expected Yield Tables

CDF Run II Preliminary	$\int \mathcal{L} = 8.2\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	3.3	$\pm$	1.0
DY	380	$\pm$	100
WW	823	$\pm$	82
WZ	37.9	$\pm$	5.7
ZZ	54.2	$\pm$	7.7
W+jets	489	$\pm$	83
$W\gamma$	206	$\pm$	30
Total Background	2000	$\pm$	190
$gg \to H$	24.6	$\pm$	7.3
WH	0.61	$\pm$	0.10
ZH	0.599	$\pm$	0.085
VBF	0.215	$\pm$	0.044
Total Signal	26.1	$\pm$	7.4
Data	2144		

All

CDF Run II Preliminary	$\int \mathcal{L} = 8.2\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	85	$\pm$	16
DY	336	$\pm$	78
WW	222	$\pm$	27
WZ	36.1	$\pm$	5.0
ZZ	14.6	$\pm$	2.1
W+jets	177	$\pm$	33
$W\gamma$	34.0	$\pm$	5.8
Total Background	900	$\pm$	110
$gg \to H$	12.2	$\pm$	5.2
WH	1.64	$\pm$	0.26
ZH	0.629	$\pm$	0.097
VBF	1.14	$\pm$	0.20
Total Signal	15.6	$\pm$	5.3
Data	875		

All

CDF Run II Preliminary	$\int \mathcal{L} = 8.2\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	244	$\pm$	36
DY	132	$\pm$	53
WW	49.7	$\pm$	9.7
WZ	9.9	$\pm$	1.9
ZZ	4.47	$\pm$	0.86
W+jets	62	$\pm$	12
$W\gamma$	6.2	$\pm$	1.6
Total Background	509	$\pm$	79
$gg \to H$	4.3	$\pm$	2.1
WH	3.69	$\pm$	0.51
ZH	1.84	$\pm$	0.25
VBF	2.13	$\pm$	0.35
Total Signal	11.9	$\pm$	2.5
Data	494		

AllSB-2JOS

0J **1J** **2 or more Jets**

Different signal and background compositions!
More jets → more ttbar, less Diboson. More WH, ZH, VBF, less ggH

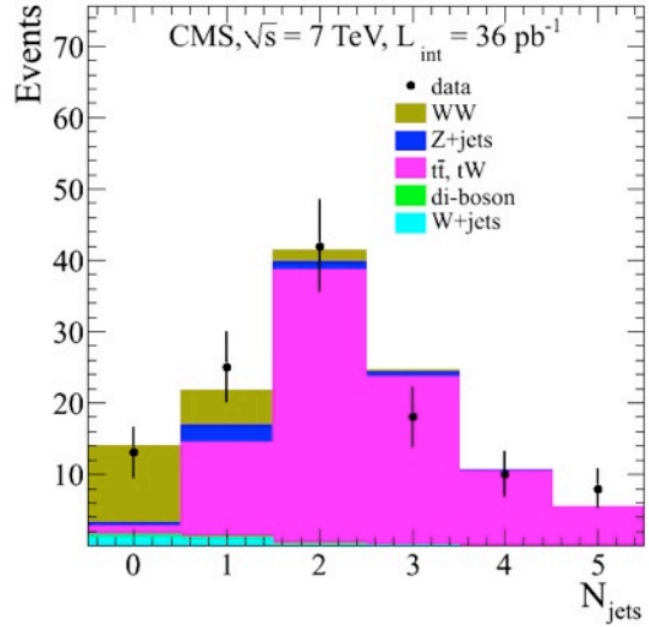
Sub-optimal to train MVA's on a rapidly varying mixture of signals and backgrounds
-- Divide and conquer.

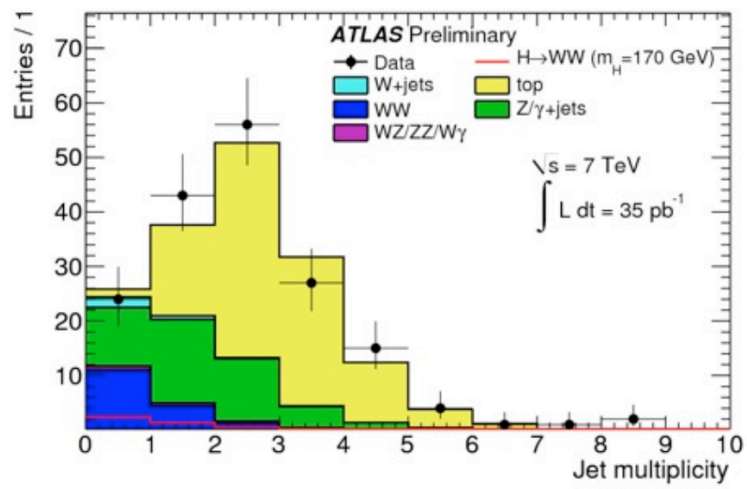
The Problem is Much More Acute at the LHC

Even accepting all the Higgs signal and binning it in each jet bin brings sensitivity to n_{jet} spectrum in the gg→H signal because of different s/b in each jet bin.

At the Tevatron, the s/b increases with the jet bin.

H+2jets theoretical prediction is highly uncertain (±50%), but the total uncertainty is much smaller.



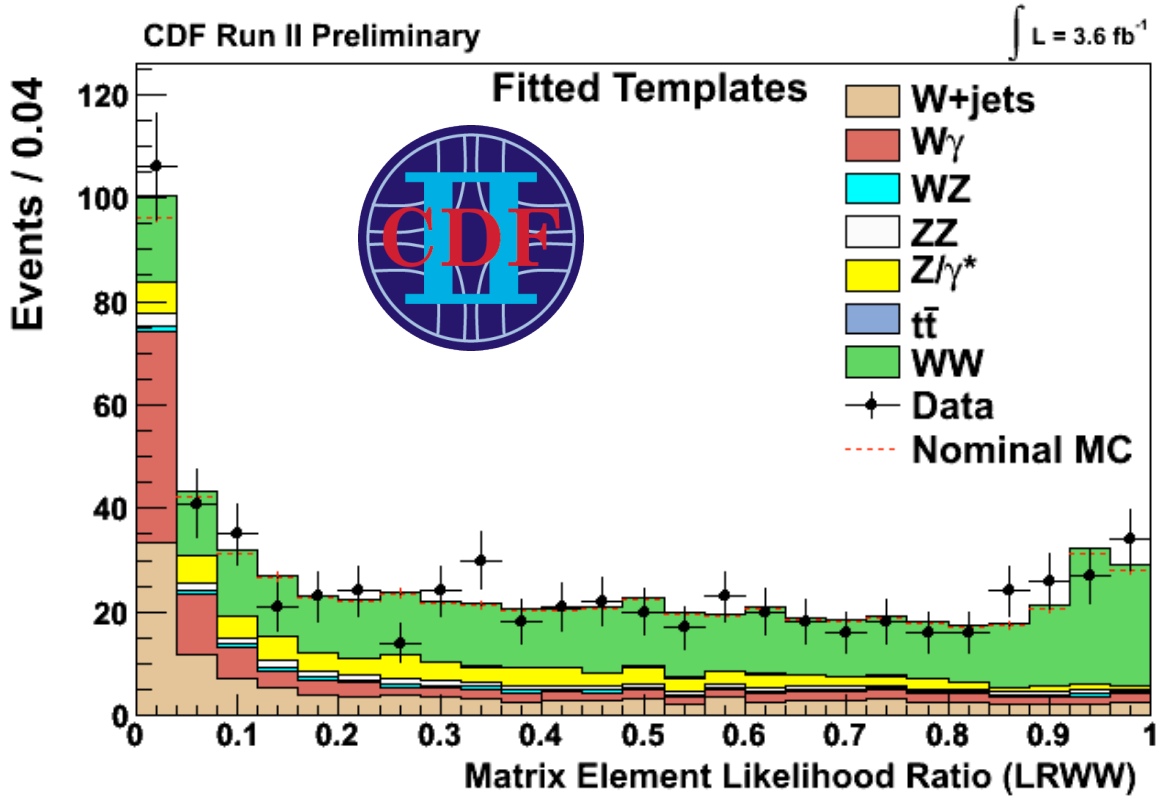


WW Cross Section Measurement

Signal model: MC@NLO

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

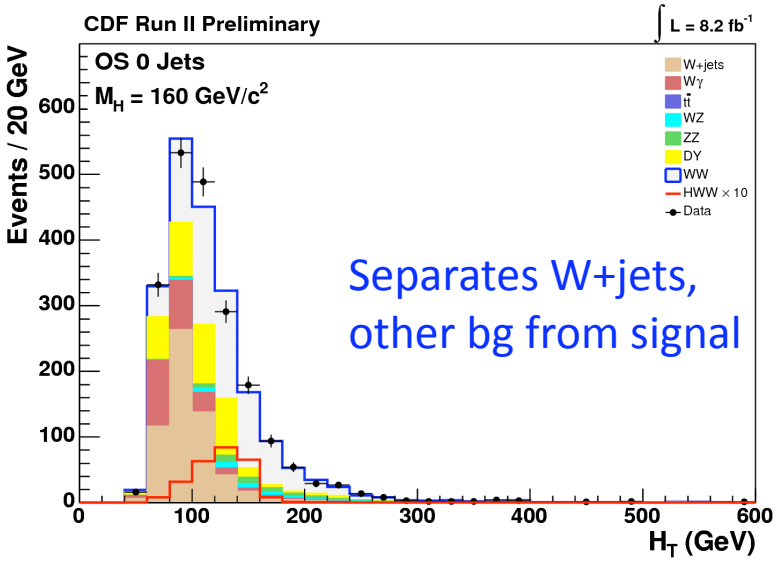
Same as Higgs search but reverse roles of signal and background

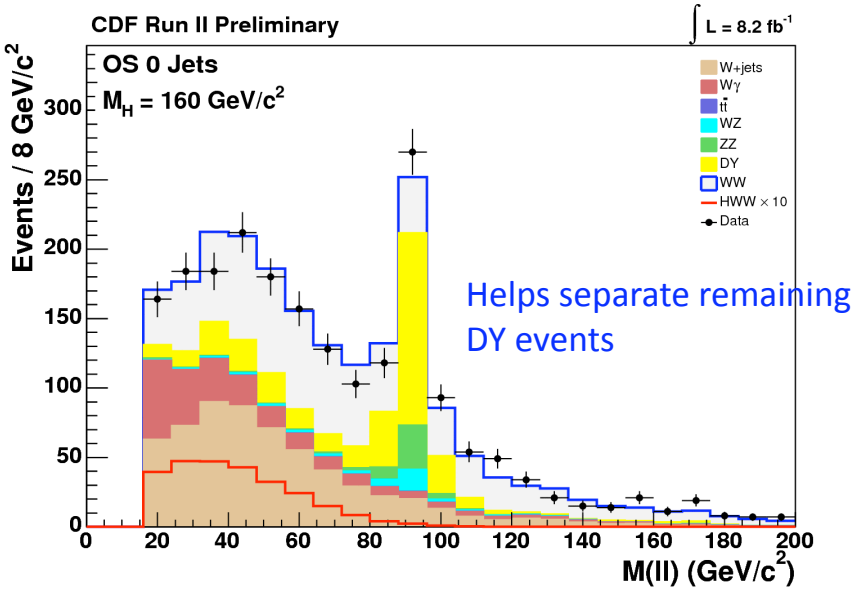


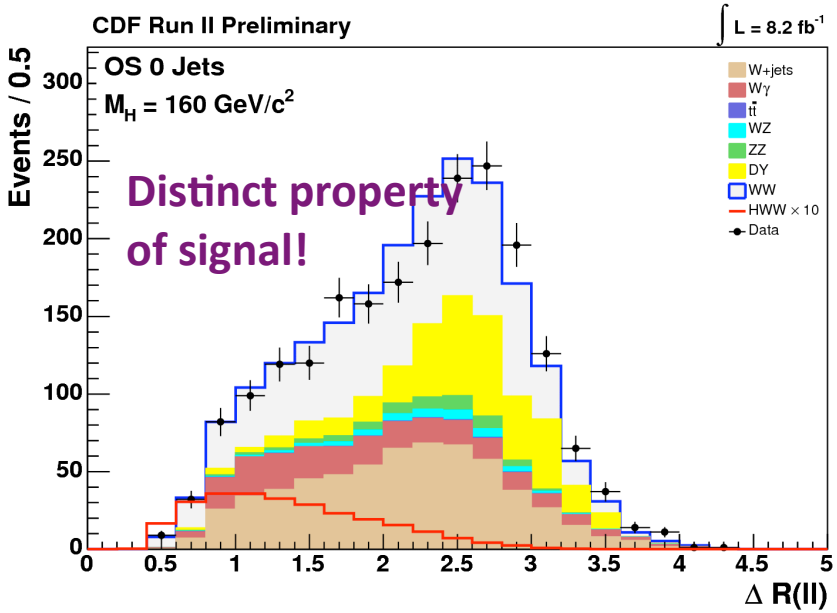
$$\sigma(p\bar{p} \rightarrow W^+W^-) = 12.1 \pm 0.9 \text{ (stat) } {}^{+1.6}_{-1.4} \text{ (syst) [pb]}$$

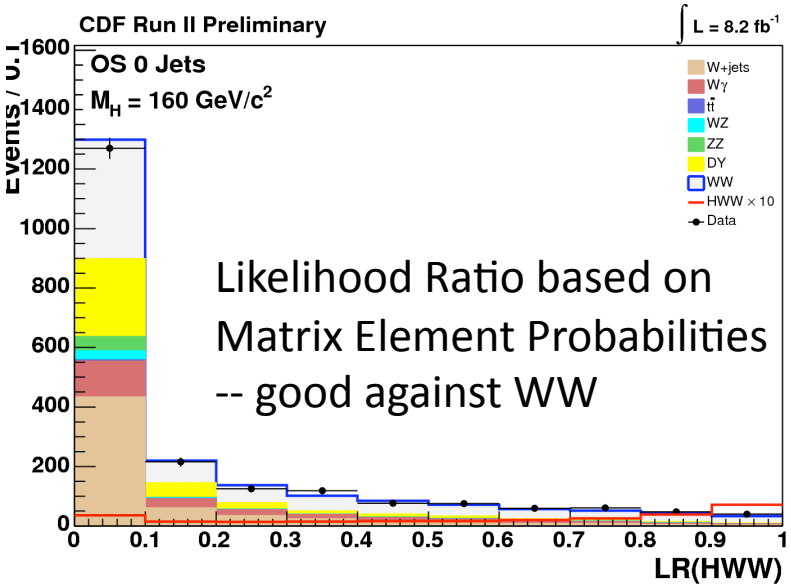
SM: 12.4 ± 0.7 pb (MCFM)

Distributions in the l^+l^-+0j Bin

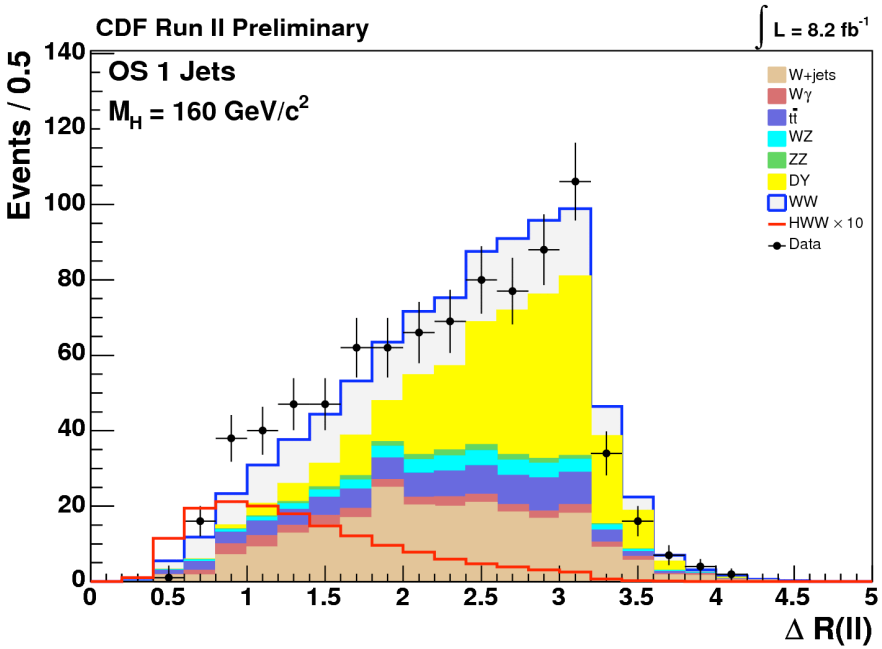


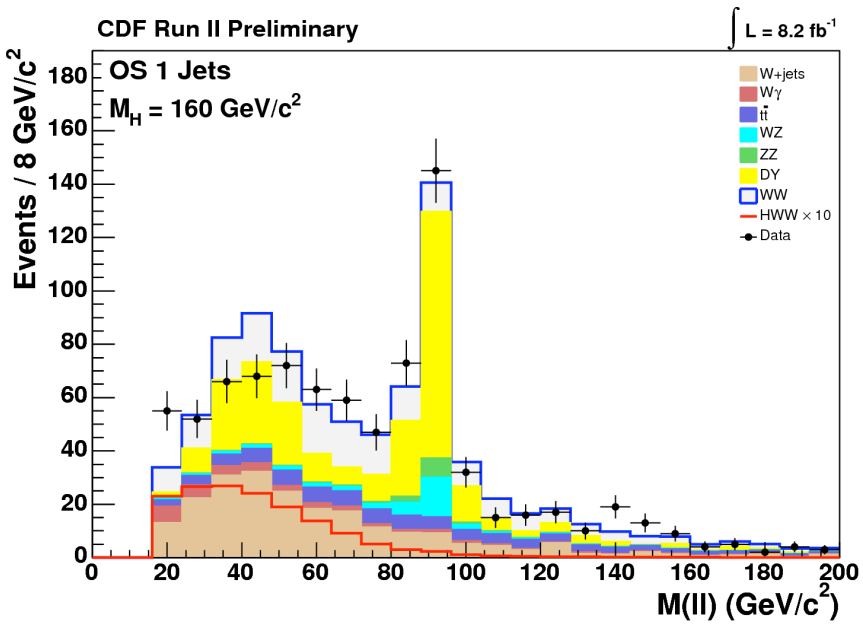


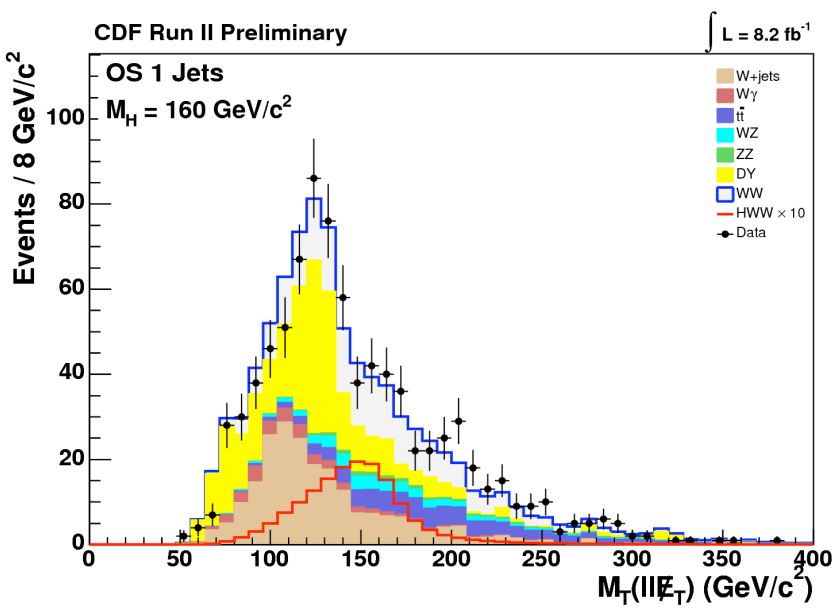


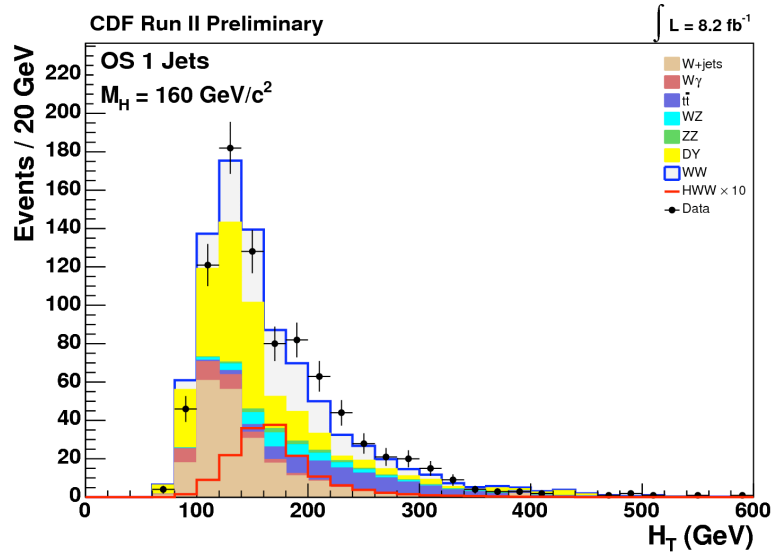


Distributions in the l^+l^-+1j Bin

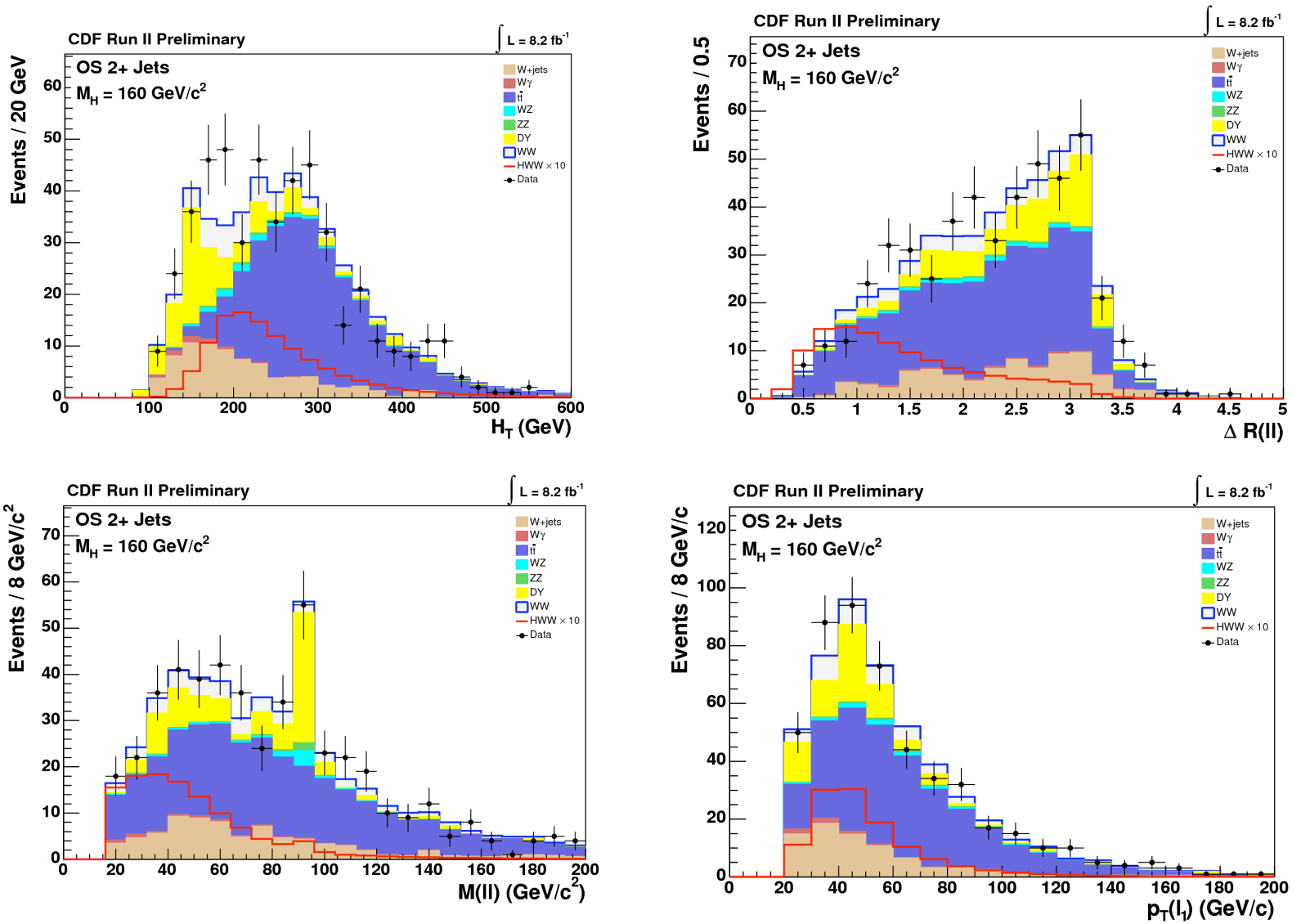




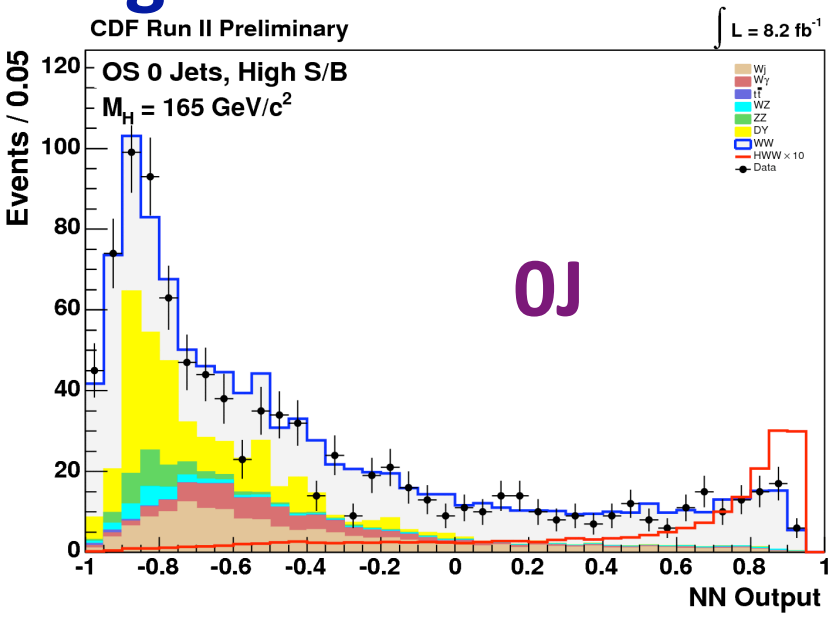


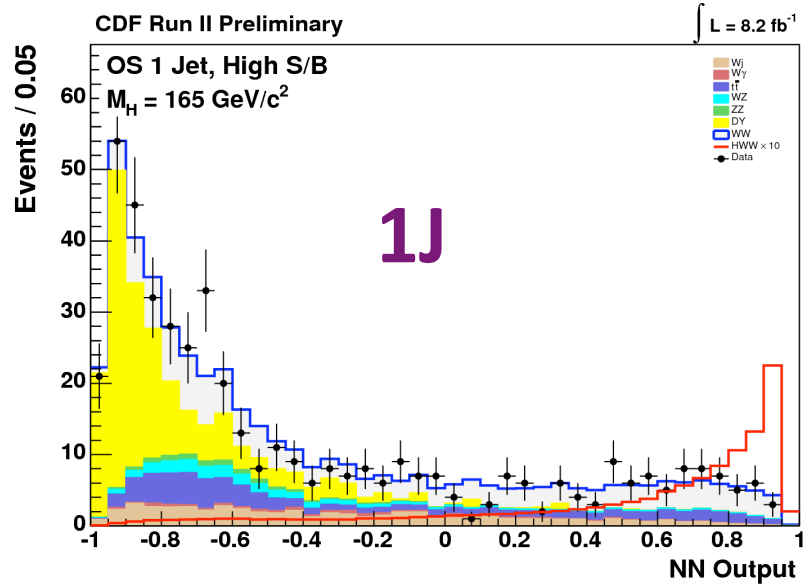


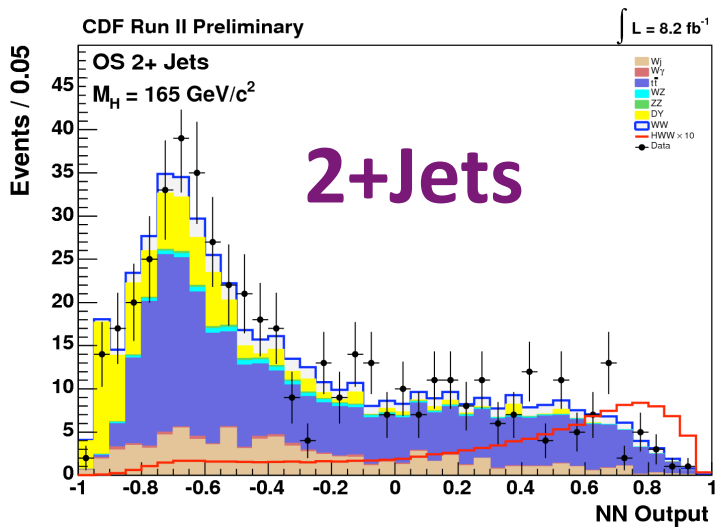
Distributions in the l^+l^-+2j Bin



Output Discriminant Distributions, CDF opposite-sign H→WW Search



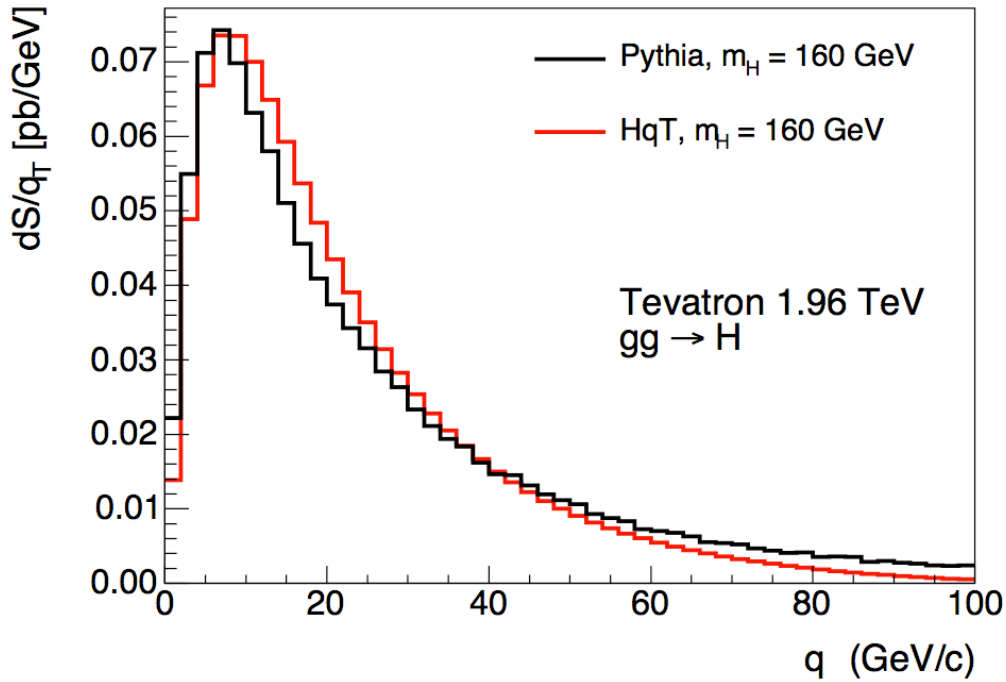




A separate set of NN's is trained for each final state, for each m_H under test.

Similar s/b in the highest-score bins in each of the categories

Reweighting Pythia Differential Distributions to NLO+NNLL Predictions



HqT program Catani and Grazzini, http://theory.fi.infn.it/grazzini/codes.html used to compute higher-order differential spectra

I'd like to compare this also with the new POWHEG Predictions – see Emmanuele Bagnaschi's talk yesterday

A Stand-In for a Jet Veto that can be Calculated at NNLO+NNLL

$$\tau = \frac{\mathcal{T}_{\rm cm}}{m_H}\,, \qquad \mathcal{T}_{\rm cm} = \sum_k |\vec{p}_{kT}|\, e^{-|\eta_k|} = \sum_k \left(E_k - |p_k^z|\right).$$

Low Beam thrust means no jets. (converse?)

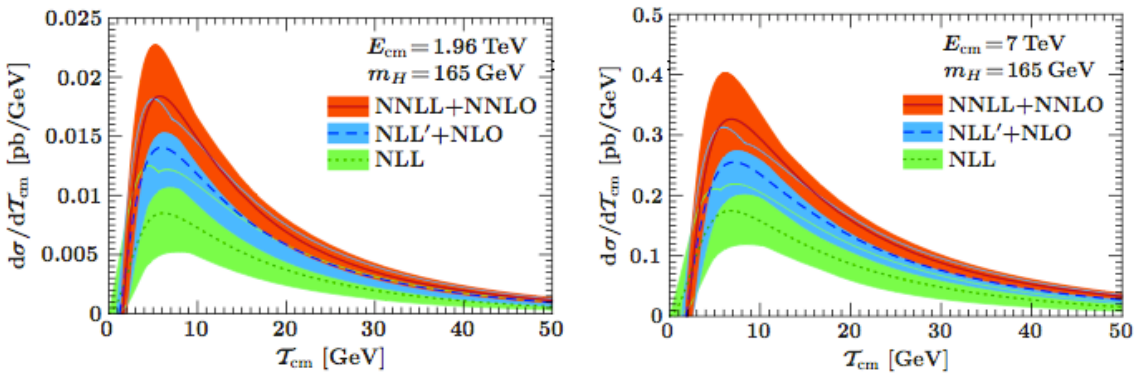


Figure 9. The beam thrust spectrum for Higgs production for $m_H = 165$ GeV at the Tevatron (left) and the LHC for $E_{\rm cm} = 7$ TeV (right). The bands show the perturbative scale uncertainties as explained in section 2.6.

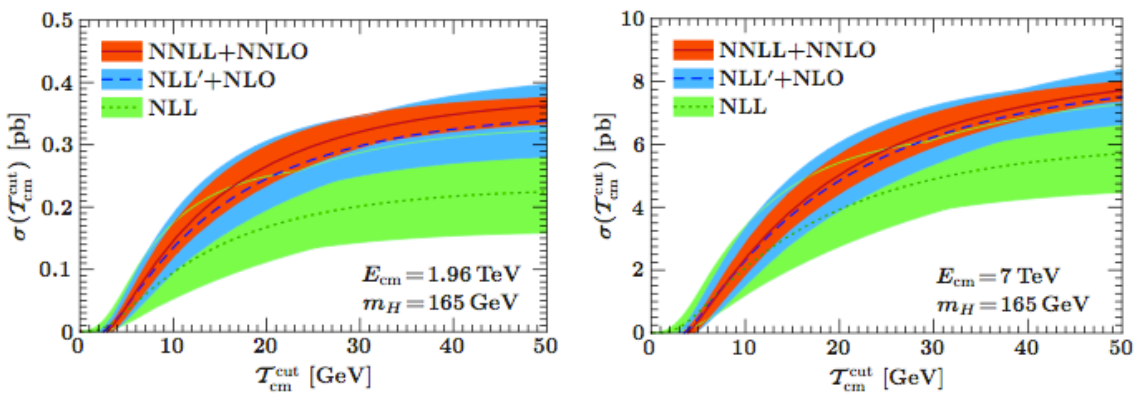
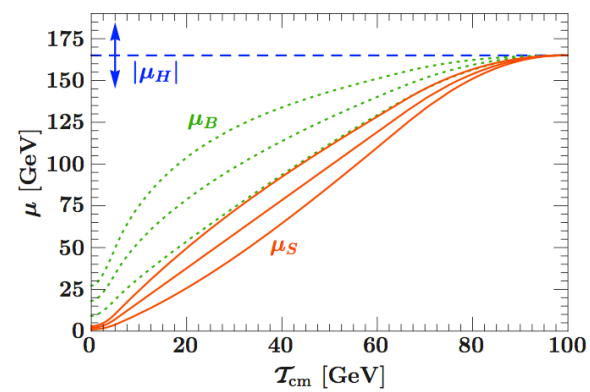


Figure 10. Higgs production cross section as a function of $\mathcal{T}_{\rm cm}^{\rm cut}$ for $m_H = 165$ GeV at the Tevatron (left) and the LHC with $E_{\rm cm} = 7$ TeV (right). The bands show the perturbative scale uncertainties as explained in section 2.6.

Three scales!



Berger, Marcantonini, Stewart, Tackmann, and Waalwijn, arXiv:1012.4480

The "BNL Accord" -- A Matrix of Uncertainties

Perturbative Uncertainties in Jet Bins

There is general agreement among theorists that one should hence treat the fixed-order perturbative series for σ_{total}, $\sigma_{\geq 1}$, $\sigma_{\geq 2}$ as independent with uncorrelated perturbative uncertainties, i.e.

- The *inclusive* jet cross sections are considered uncorrelated

$$\sigma_{\text{total}},\ \sigma_{\geq 1},\ \sigma_{\geq 2} \quad \Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\text{total}} & 0 & 0 \\ 0 & \Delta^2_{\geq 1} & 0 \\ 0 & 0 & \Delta^2_{\geq 2} \end{pmatrix}$$

- The covariance matrix for the *exclusive* jet cross sections follows from

$$\sigma_0 = \sigma_{\text{total}} - \sigma_{\geq 1}\,, \qquad \sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}\,, \qquad \sigma_{\geq 2}$$

$$\Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\text{total}} + \Delta^2_{\geq 1} & -\Delta^2_{\geq 1} & 0 \\ -\Delta^2_{\geq 1} & \Delta^2_{\geq 1} + \Delta^2_{\geq 2} & -\Delta^2_{\geq 2} \\ 0 & -\Delta^2_{\geq 2} & \Delta^2_{\geq 2} \end{pmatrix}$$

Frank Tackmann (MIT) | Perturbative Uncertainties in Jet Bins | 2011-05-10 | 3 / 12

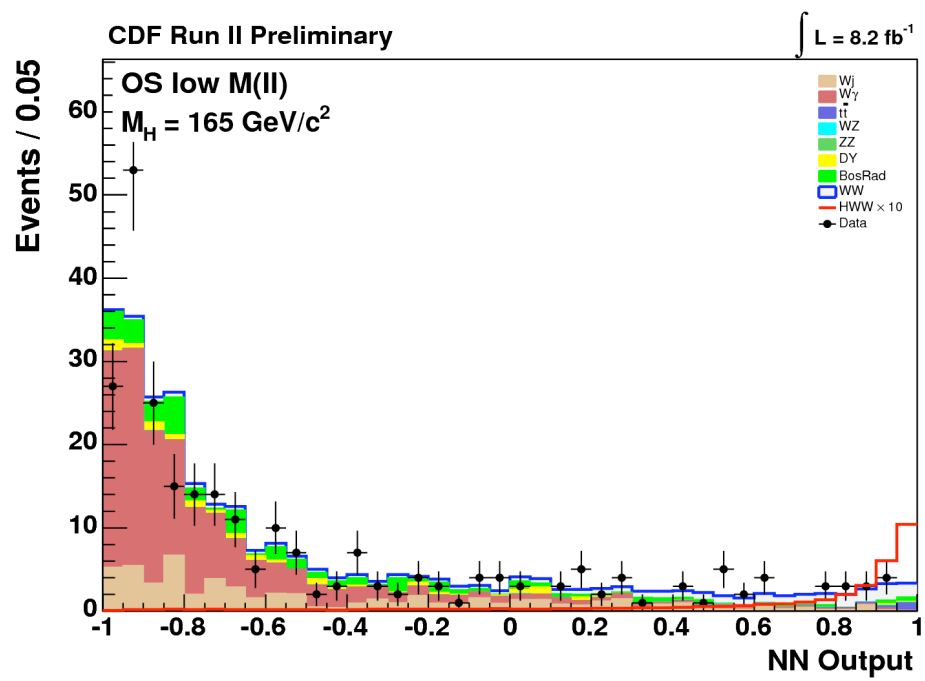
Still to do – reweight beam-thrust distributions in the MC to NNLO predictions with three scale uncertainties.

CDF's Low M_{ll} Search

- Require m_{ll}<16 GeV (non-overlapping with other channels)
- Higgs boson signal is concentrated at low m_{ll}, and low ΔR.
- Lepton Isolation requirement is a killer! Recent improvements recover events in which the two leptons spoil each other's isolation.
- Low-m_{ll} same-sign lepton control sample constrains Wγ background
- Wγ MC: U. Baur. But see new developments in Lorenzo Tancredi's talk yesterday

CDF Run II Preliminary	$\int \mathcal{L} = 8.2$ fb^{-1}		
$M_H = 165$ GeV/c^2			
$t\bar{t}$	1.47	±	0.28
DY	10.5	±	1.6
WW	29.9	±	2.9
WZ	0.79	±	0.11
ZZ	0.244	±	0.034
W+jets	48.5	±	6.5
$W\gamma$	132	±	13
$BosRad$	39	±	9.5
Total Background	262	±	21
$gg \to H$	3.12	±	0.51
WH	0.105	±	0.017
ZH	0.079	±	0.012
VBF	0.113	±	0.020
Total Signal	3.42	±	0.52
Data	260		

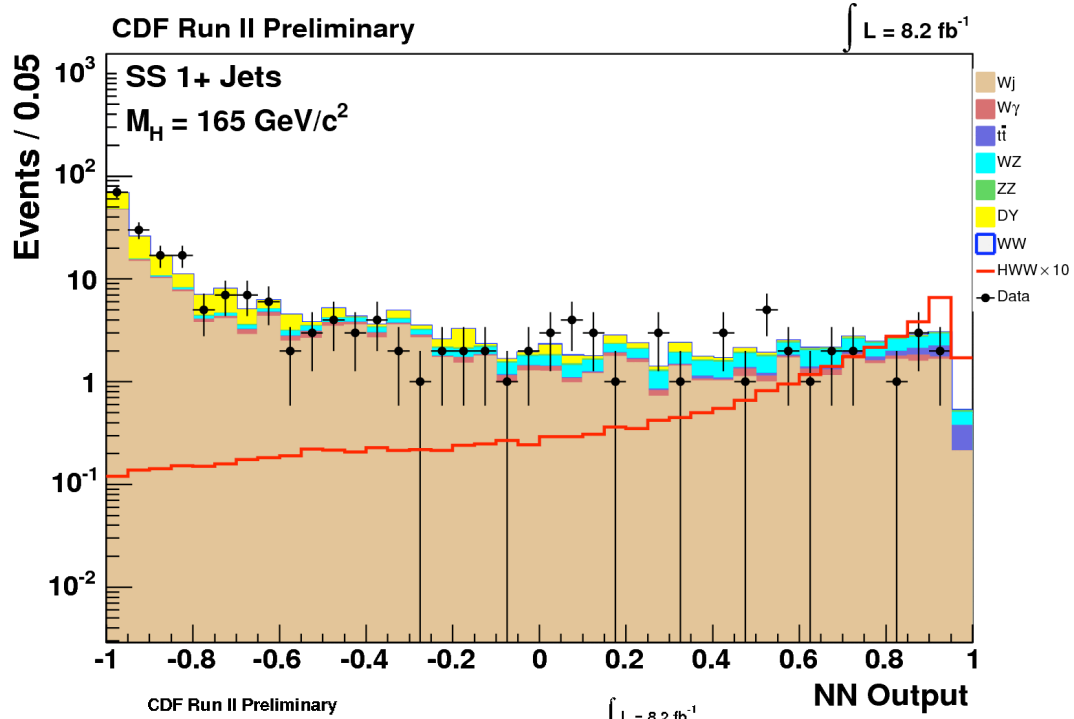
AllSB-lowMll

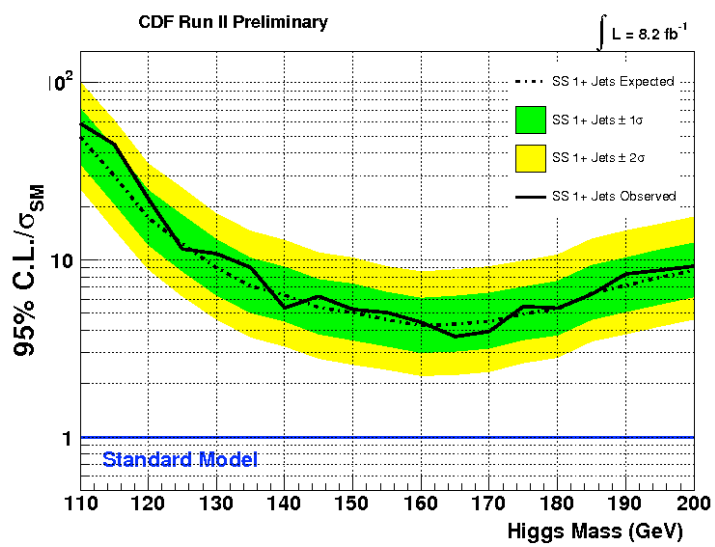


CDF's Like-sign Dileptons+1 jet Search

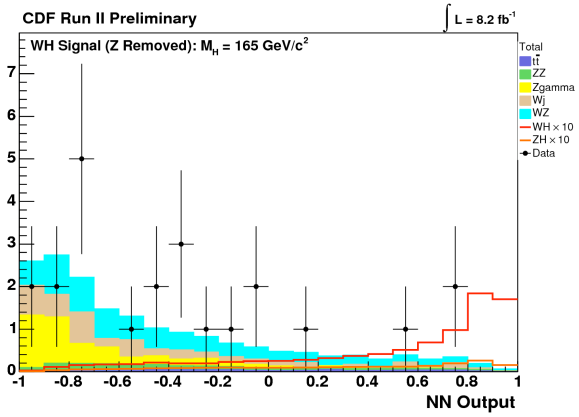
CDF Run II Preliminary	$\int \mathcal{L} = 8.2$ fb^{-1}		
$M_H = 165$ GeV/c^2			
$t\bar{t}$	2.08	$\pm$	0.30
DY	79	$\pm$	34
WW	0.169	$\pm$	0.075
WZ	14.8	$\pm$	2.0
ZZ	2.80	$\pm$	0.39
W+jets	92	$\pm$	35
$W\gamma$	6.7	$\pm$	1.1
Total Background	198	$\pm$	49
WH	2.73	$\pm$	0.36
ZH	0.404	$\pm$	0.054
Total Signal	3.13	$\pm$	0.42
Data	224		

AllSB-SS

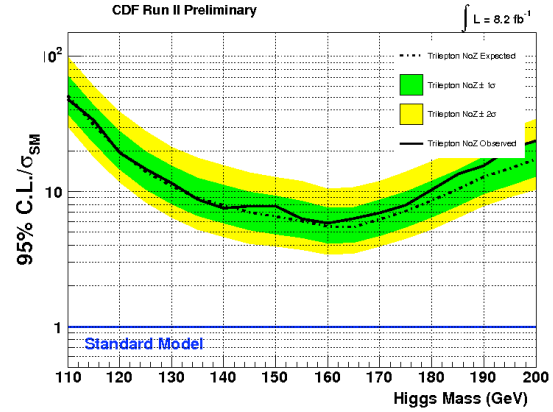


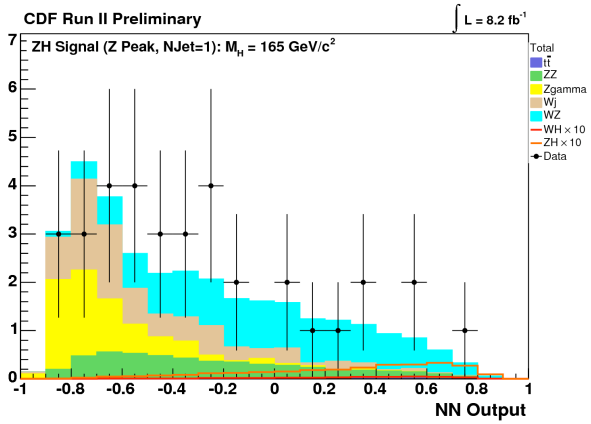


CDF's Trilepton Searches

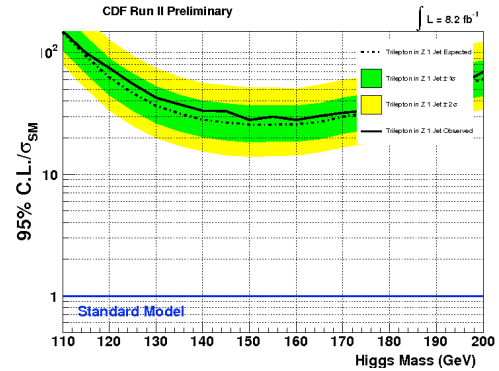


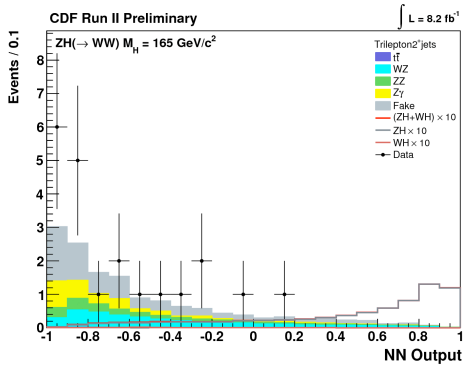
Trileptons – cut to remove m_{ll} near m_Z – enhanced in WH



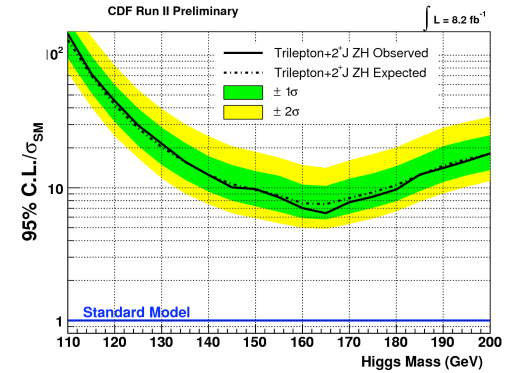


Trileptons – select m_{ll} ~ m_Z for opposite-sign, opposite flavor leptons. Require one additoinal jet Enhanced in ZH

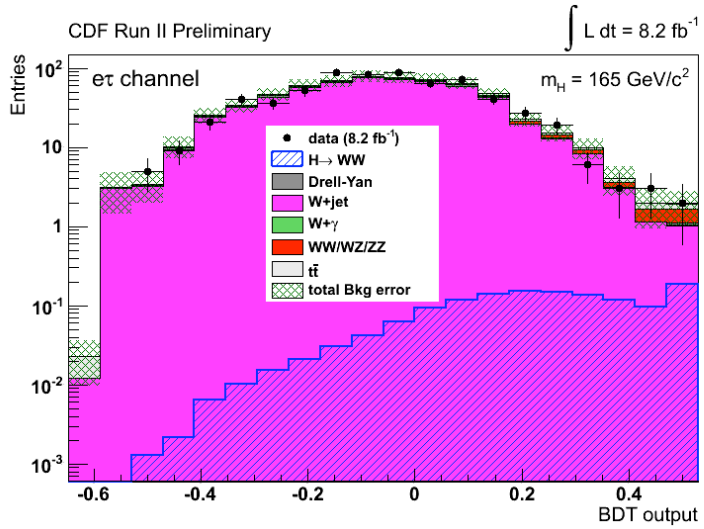




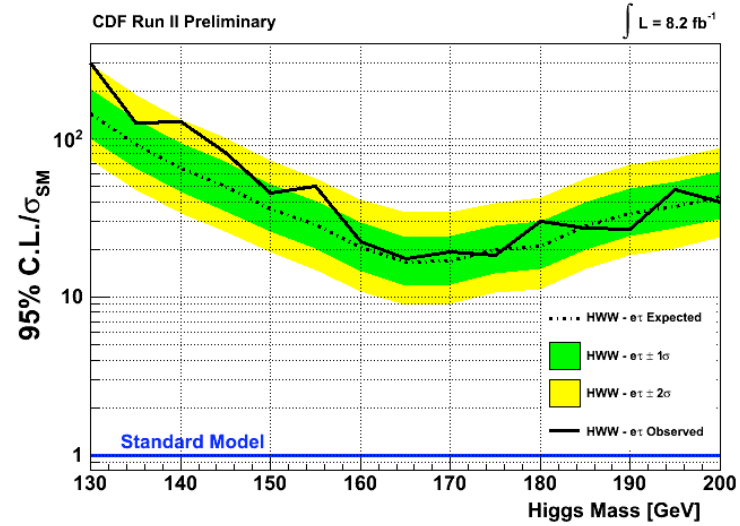
Trileptons – select m_{ll} ~ m_Z for opposite-sign, opposite flavor leptons. Require two or more additoinal jets.

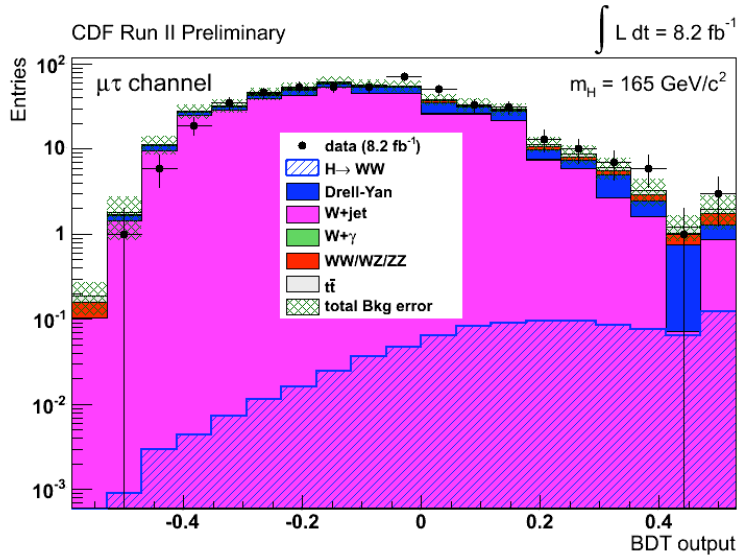


CDF's Searches for gg→H→WW with one Hadronically Decaying Tau Lepton

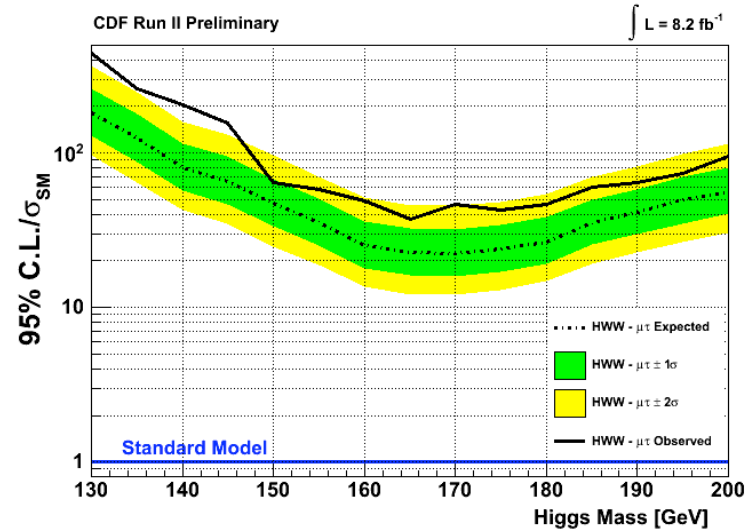


eτ





μτ



D0's H→WW Search

D0's detector differs from CDF's:

- D0 has better muon chamber coverage
- D0 has good calorimeter coverage and spatial resolution
- D0 has worse tracking efficiency and resolution

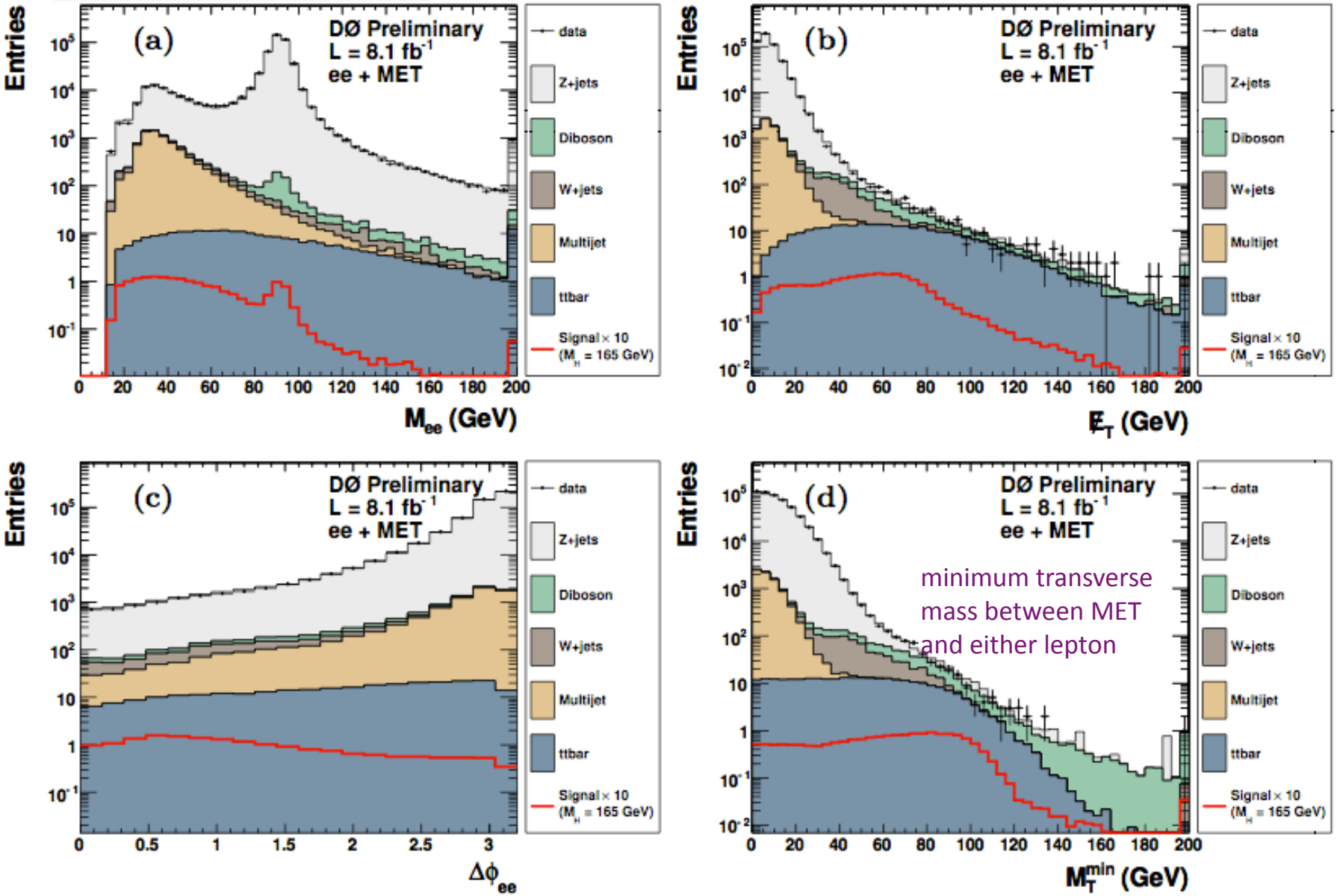
D0 therefore splits its channels up by lepton category.
Different event selection requirements, and different s/b in
final discriminants for ee, eμ and μμ
lepton combinations.

All channels are further split into 0-jet, 1-jet, and 2+jet categories in order
to take advantage of different signal composition (ggH, WH, ZH, VBF)
and backgrounds (DY, WW, WZ, ZZ, ttbar, W+jets, Wγ, Z+jets)

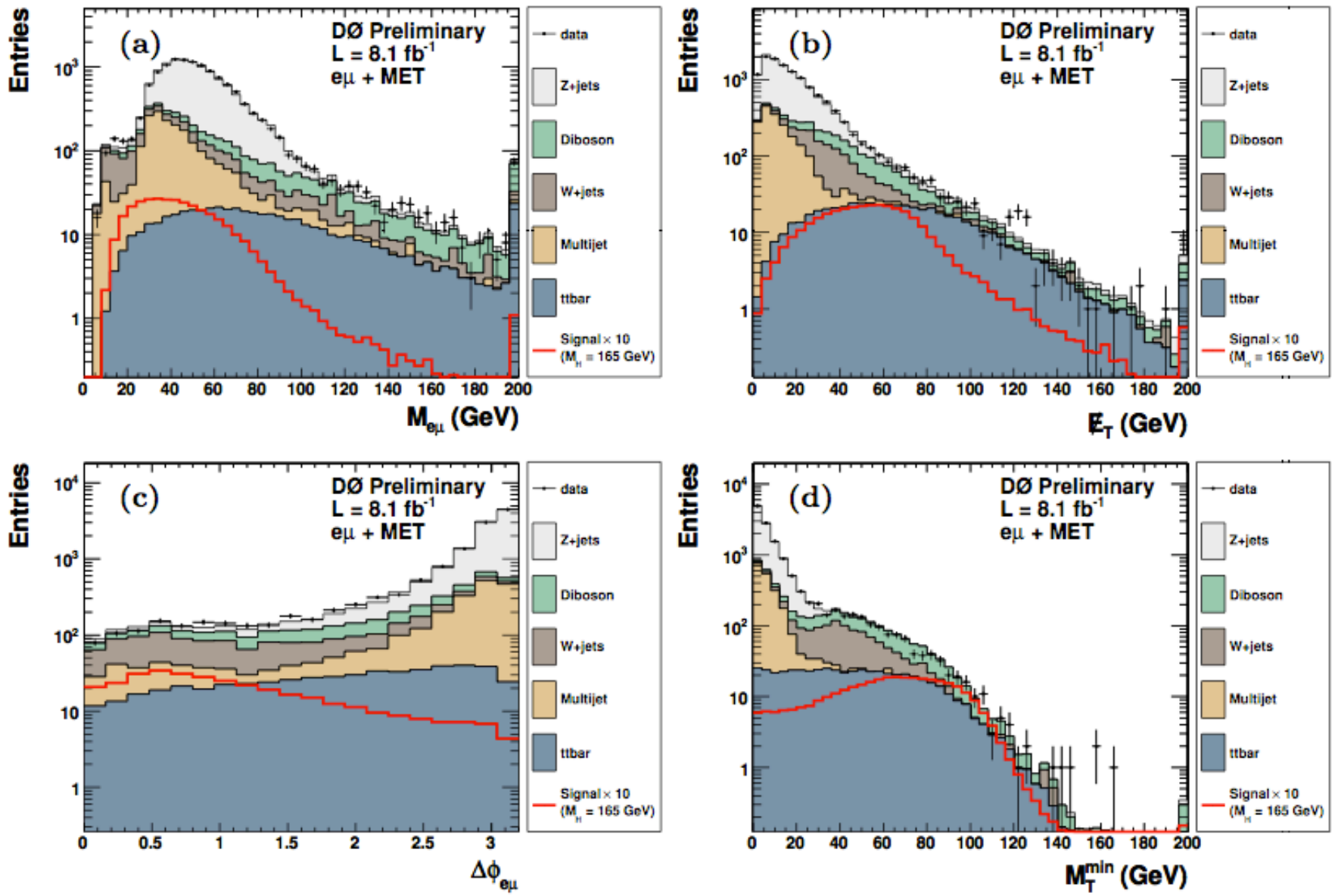
Preselection level – Just identify leptons – e and μ. Backgrounds dominated
by DY production (eμ channel dominated by Z→ττ)

D0's ee Preselection

Incudes H→ZZ→llνν
signal, and even H→ττ→lννlνν

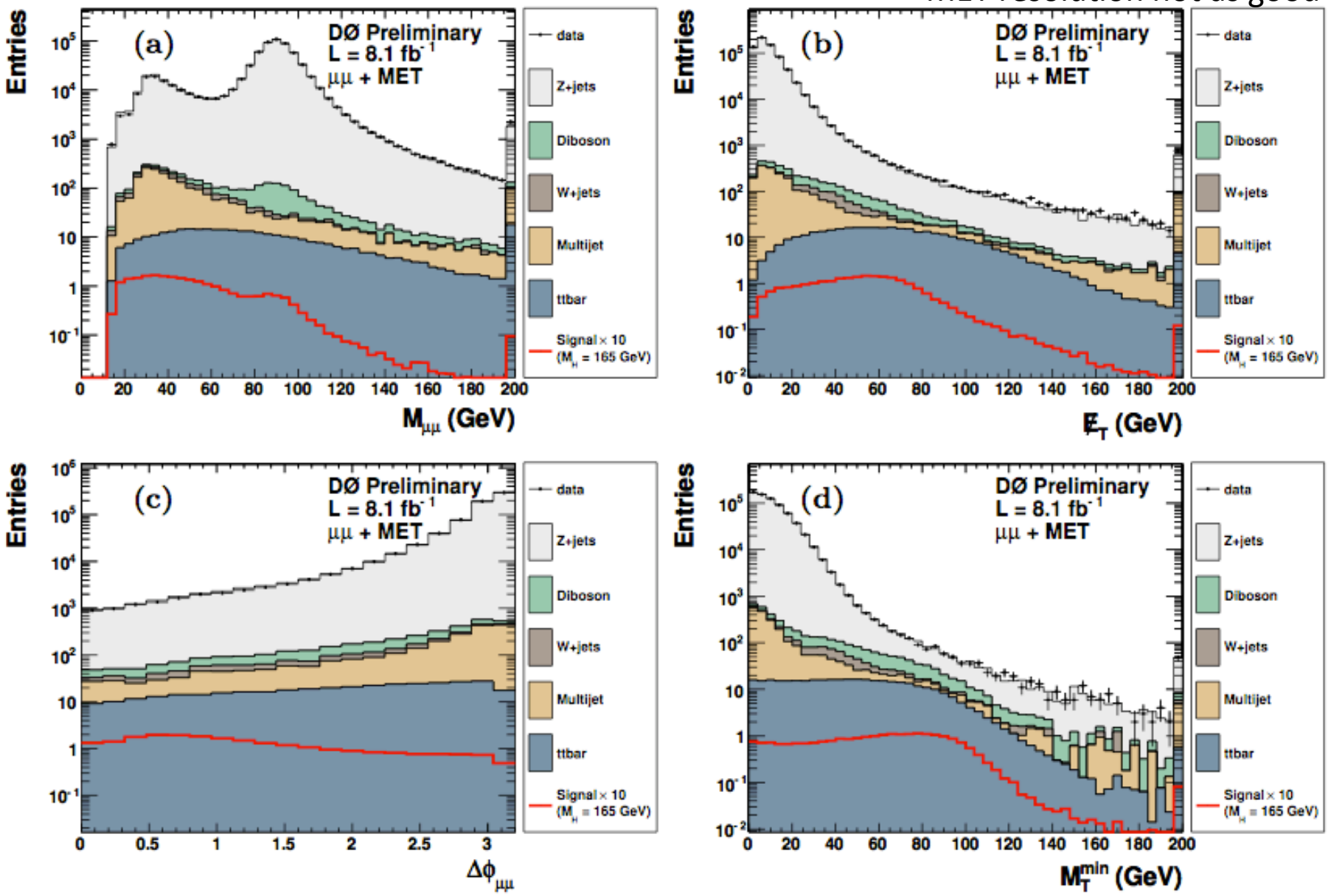


D0's eμ Preselection



D0's μμ Preselection

MET resolution not as good



Anti-Drell-Yan Boosted Decision Trees

BDT's trained to separate the Higgs boson signal against the DY background

Ingredient variables:

m_{ll}

Missing Transverse Energy (MET)

Angles between leptons and MET

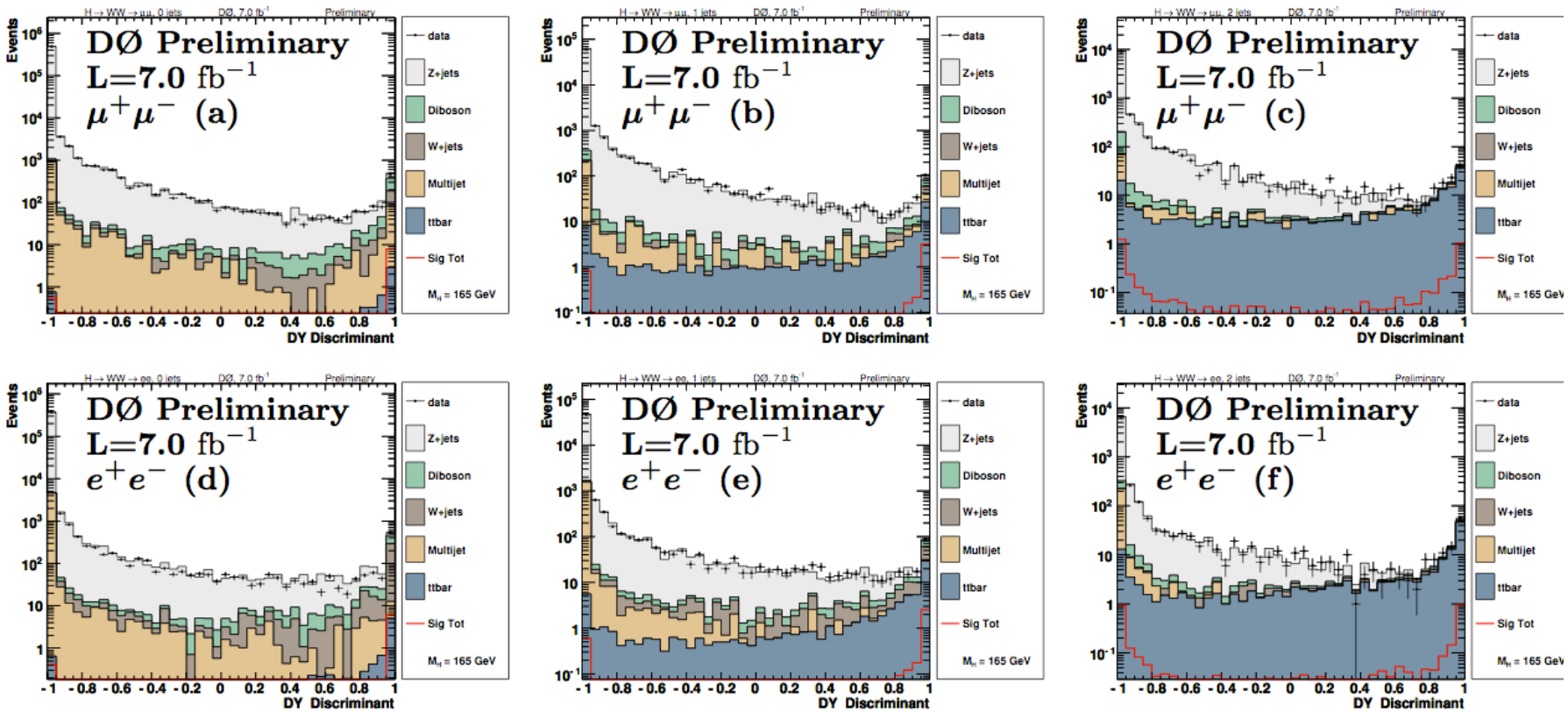
Lepton Energies

$\Delta\phi_{ll}$

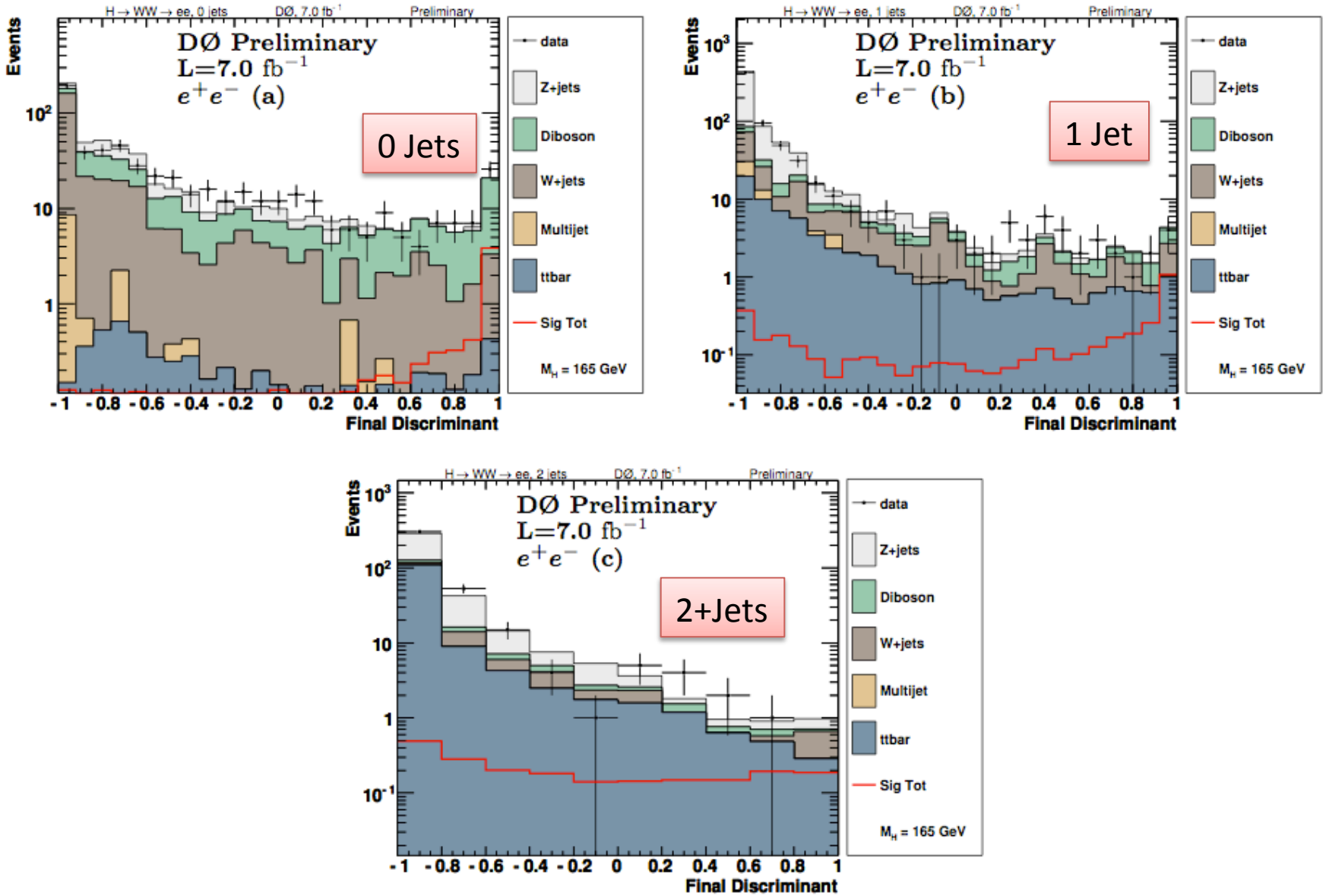
Transverse mass of llMET

Jet P_T's

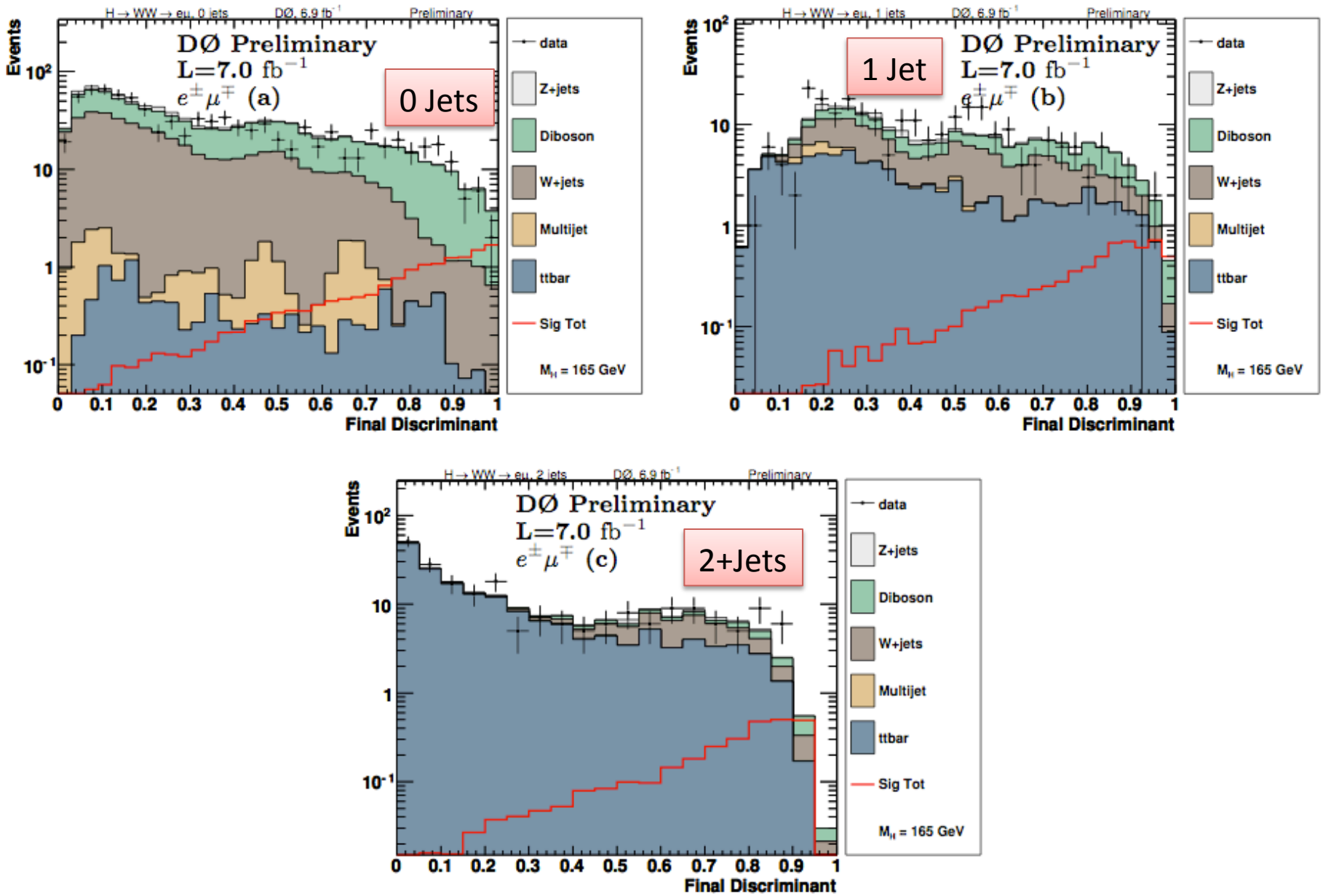
And others



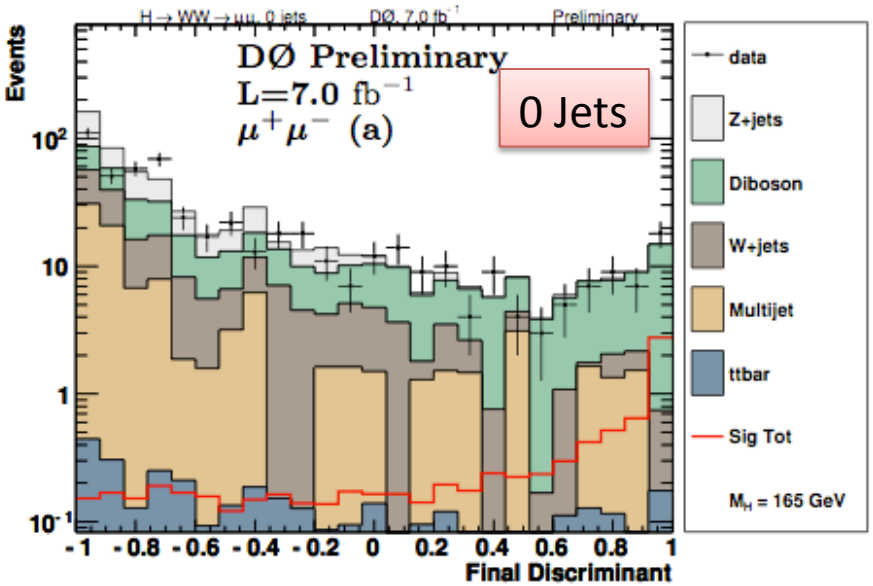
D0 Final Discriminants: ee Channels

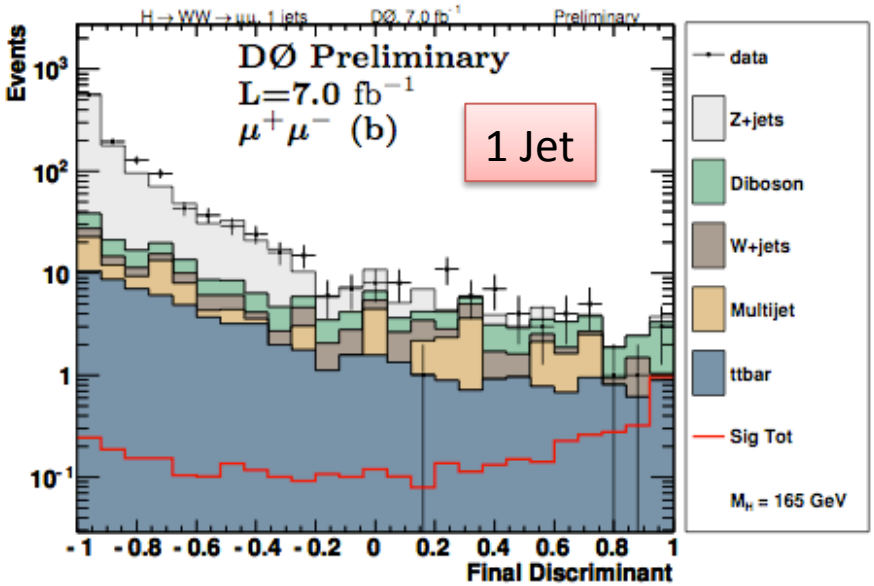


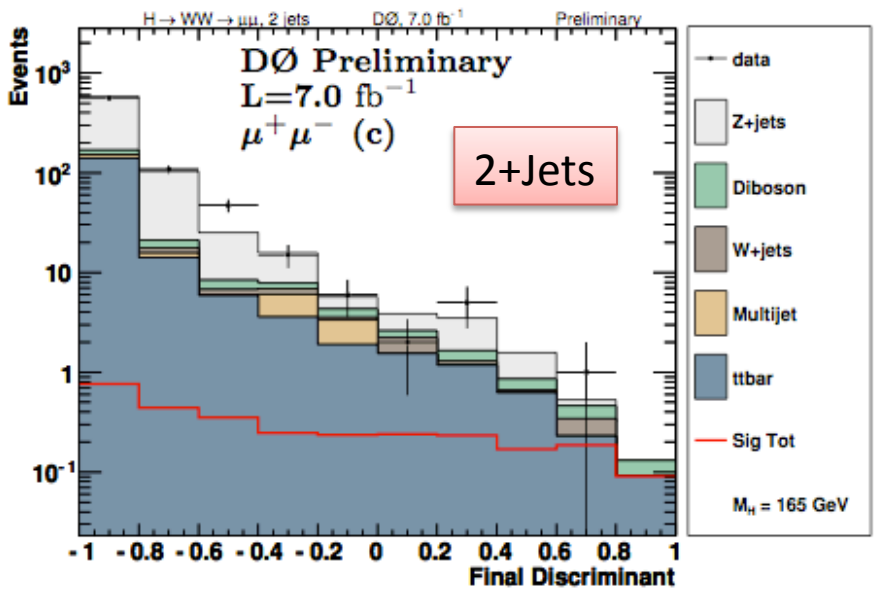
D0 Final Discriminants: eμ Channels



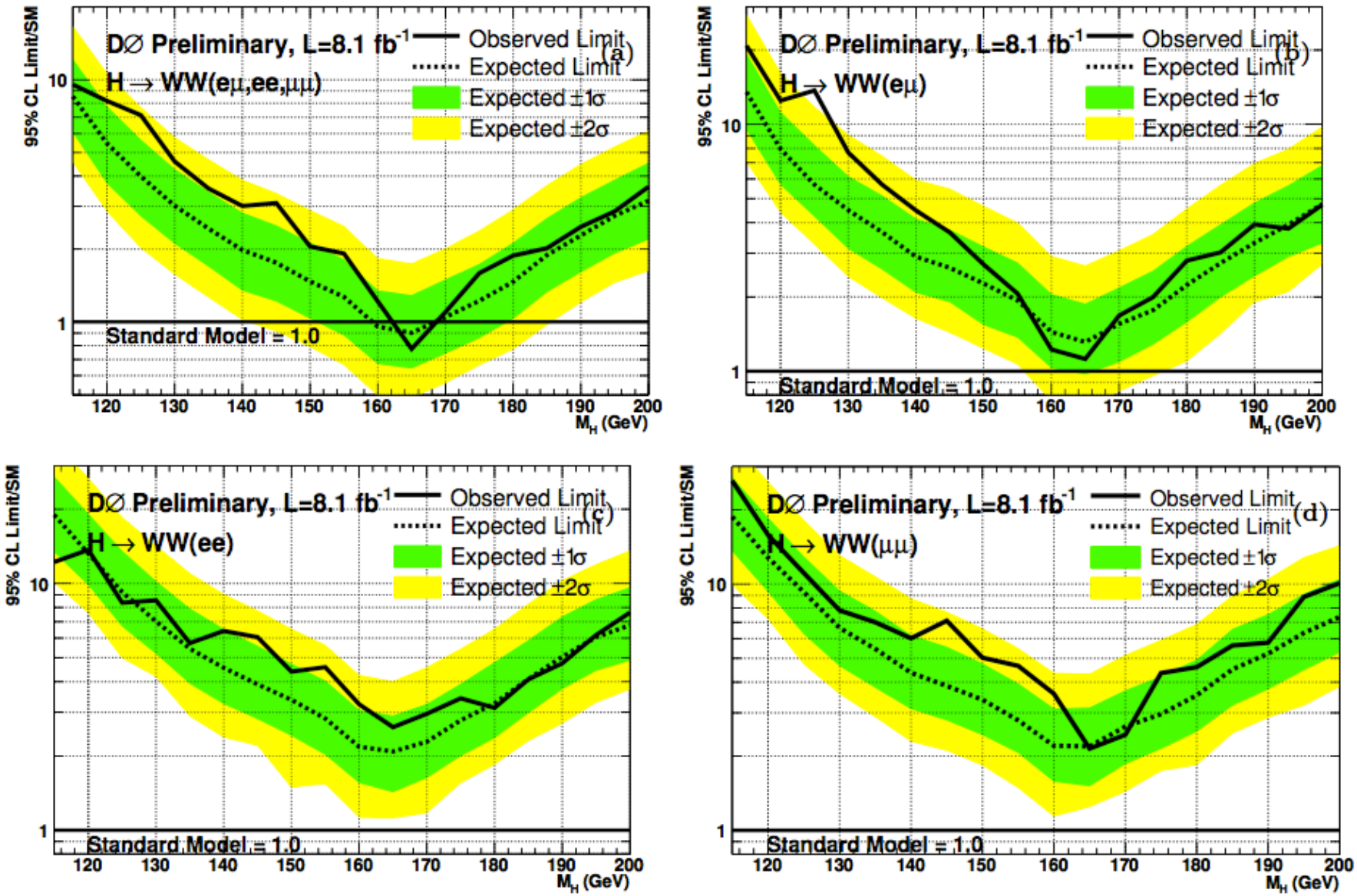
D0 Final Discriminants: μμ Channels



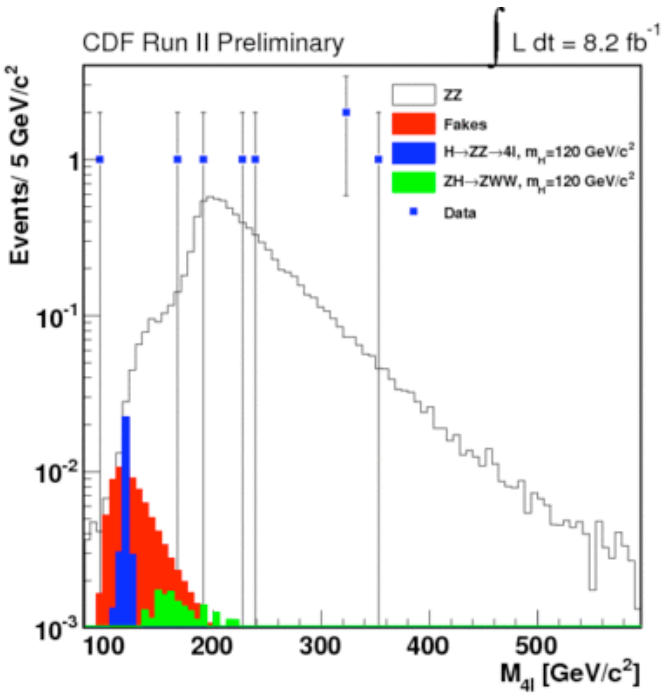


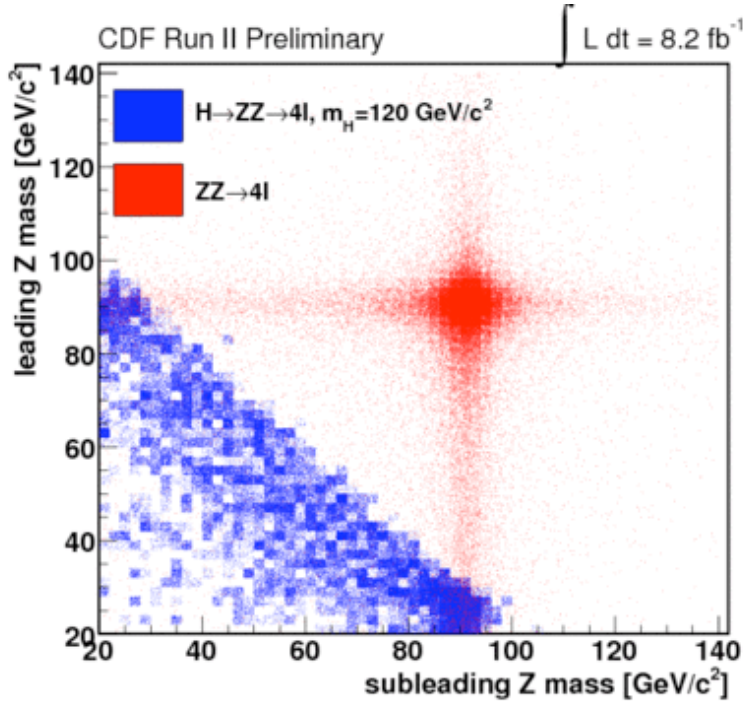


D0's H→WW Limits Channel By Channel and Combined

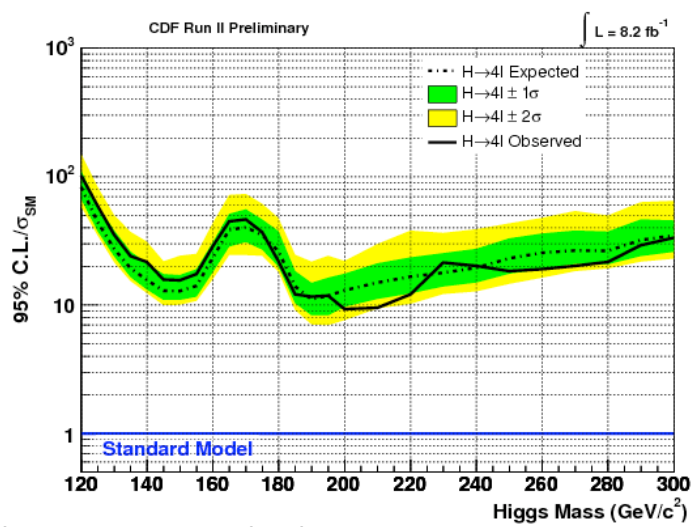


CDF's Search for H→ZZ→llll



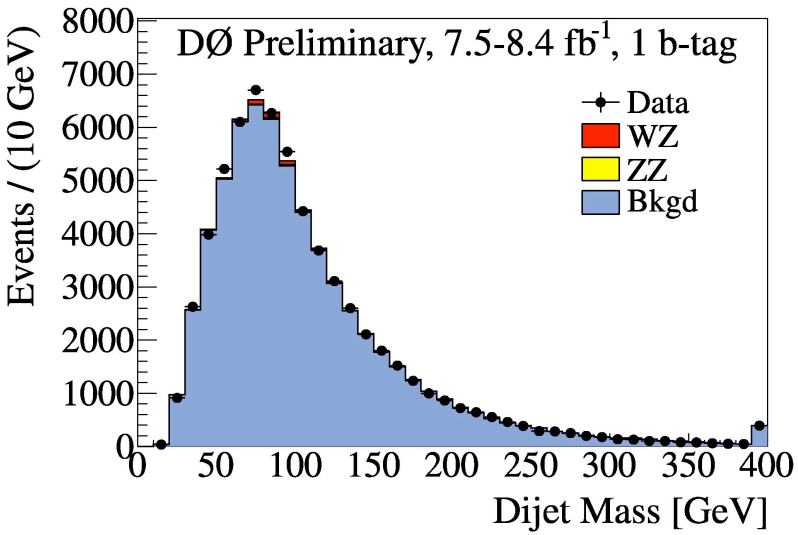


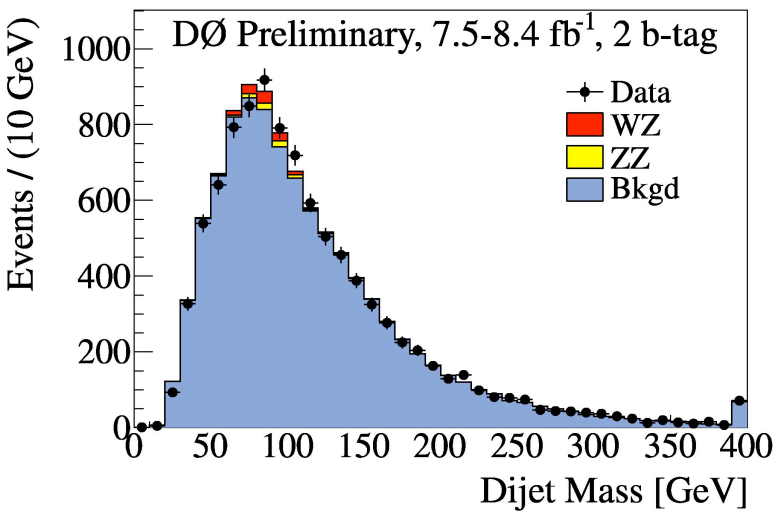
CDF Run II Preliminary	$\int \mathcal{L} = 8.2$ fb^{-1}		
$M_H = 190$ GeV/c^2			
ZZ	8.83	$\pm$	1.12
$Z(\gamma)$+jets	0.30	$\pm$	0.10
Total Background	9.13	$\pm$	1.12
$gg \to H \to ZZ$	0.329	$\pm$	0.042
$VH \to V + ZZ$	0.053	$\pm$	0.007
$ZH \to Z + WW$	0.054	$\pm$	0.007
$VBF \to H \to ZZ$	0.038	$\pm$	0.005
Total Signal	0.474	$\pm$	0.043
Data		8	
			$H \to 4\ell$

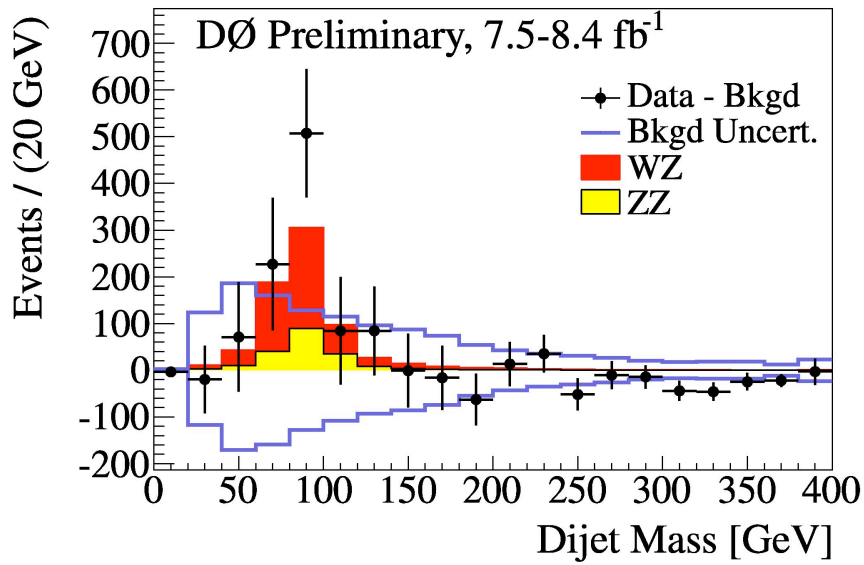


D0's B-tagged Diboson – WZ+ZZ Search

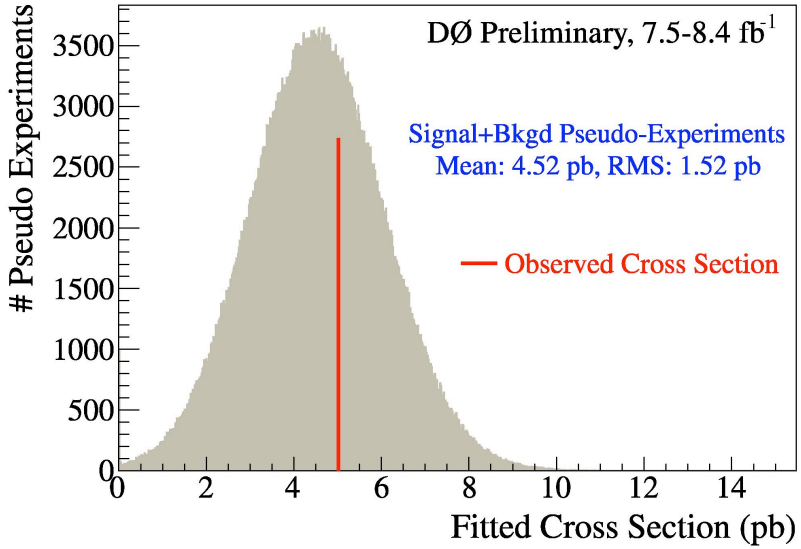
Same selection as the b-tagged WH search -- one high-P_T lepton, MET, two or three jets, one or two b-tags. Seek to find the bumps we know are there.

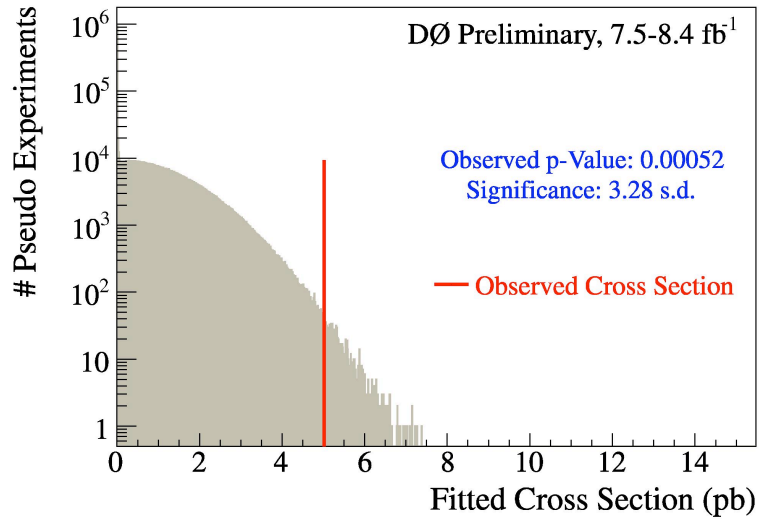


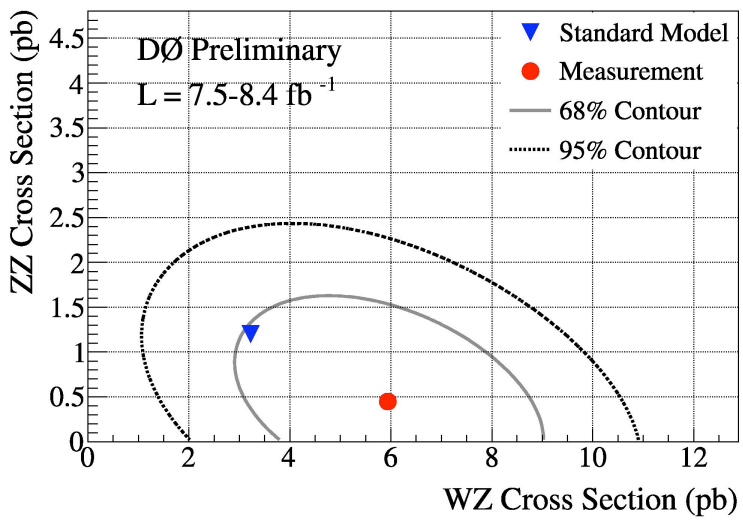


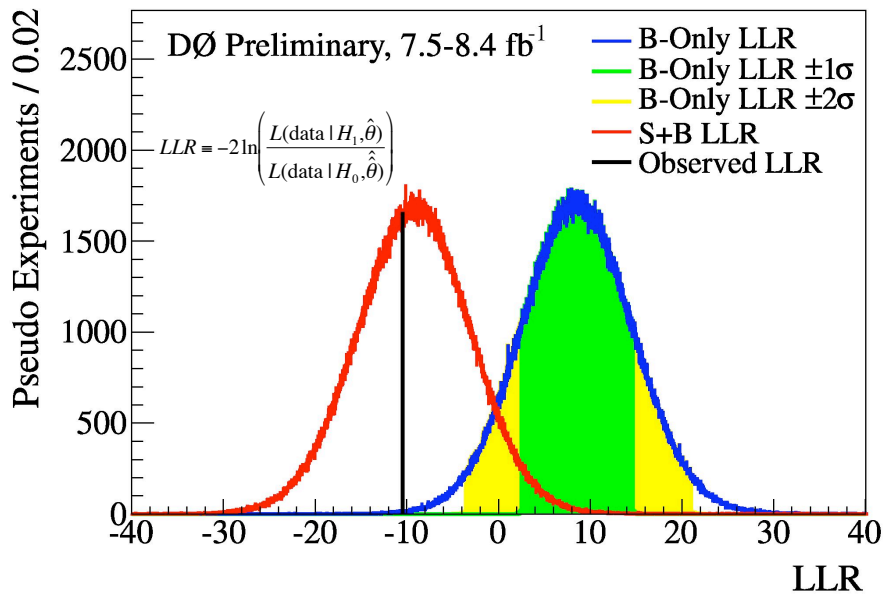


D0's B-tagged Diboson – WZ+ZZ Search

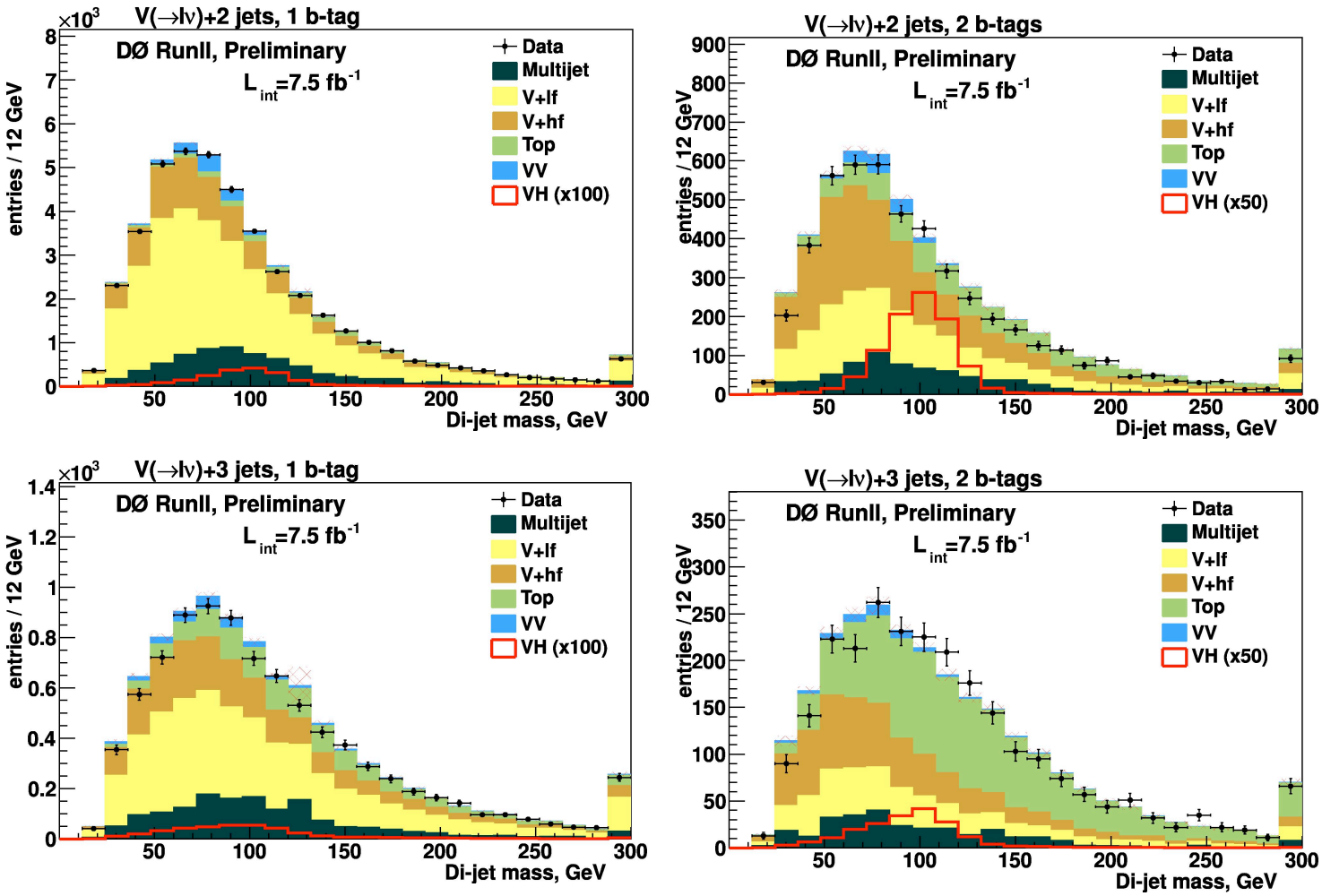








D0's WH→lνbb Search

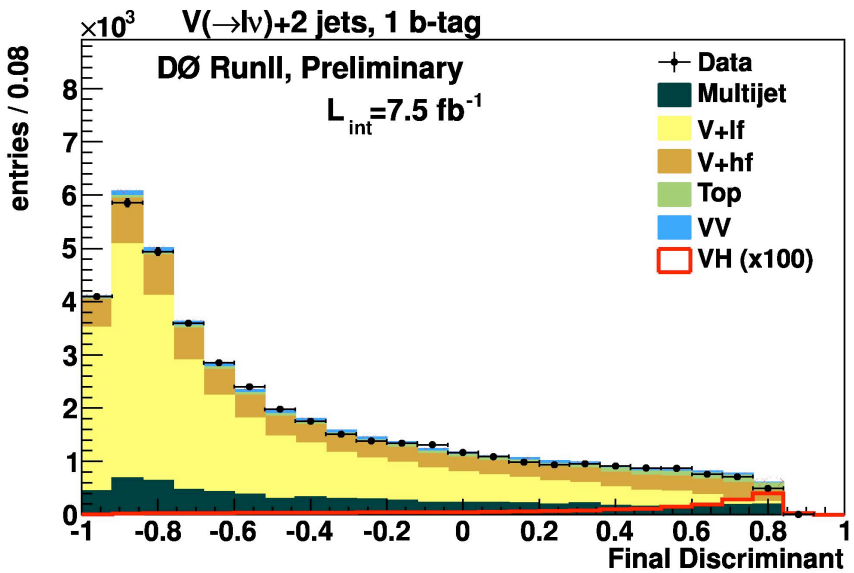


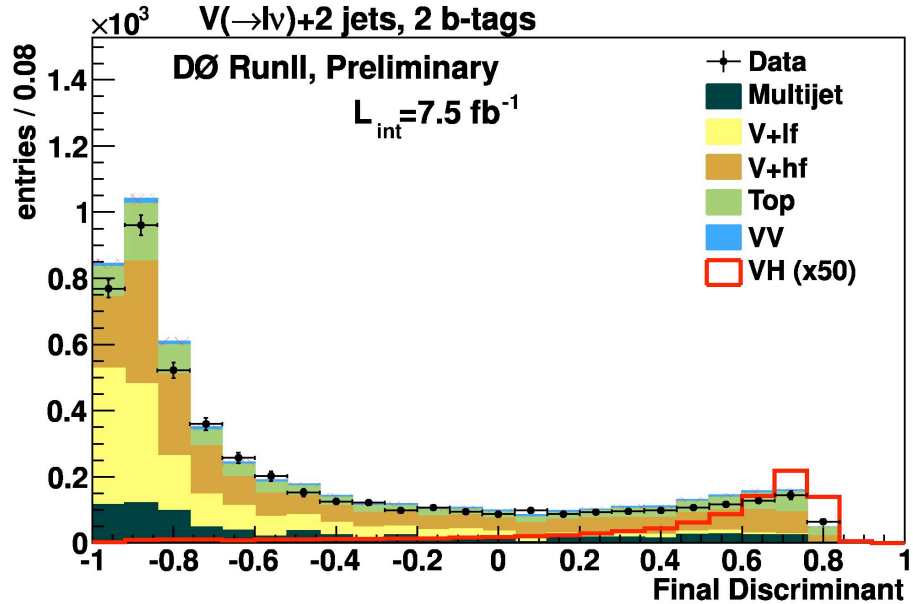
Total of 8.5 fb^{-1} of data used, but first 1 fb^{-1} was before the silicon upgrade; analyzed separately

Signal shown for m_H=115 GeV

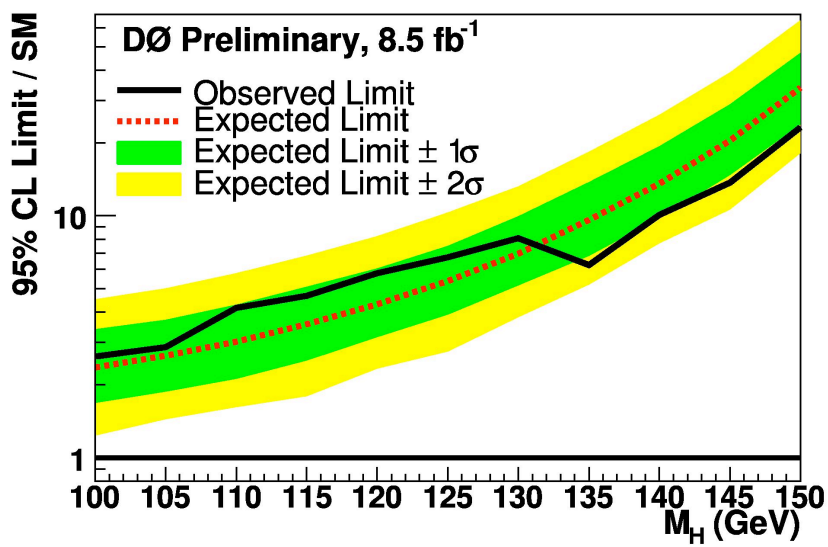
Mass resolutions best for 2 Jets 2 b-tags – know you have the right jets assigned to the Higgs boson decay. One b-tag: Get ISR jets misassigned. 3-jet events, more ambiguity

D0's WH→lvbb MVA's

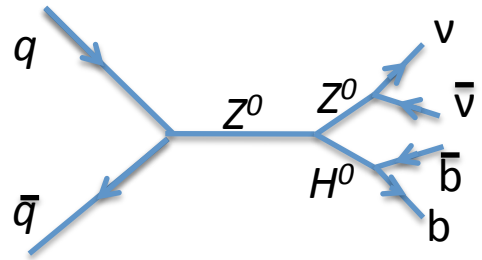




m_{jj} carries the most s/b separation, but other variables, such as helicity angle, and dijet p_T helps separate signal from background



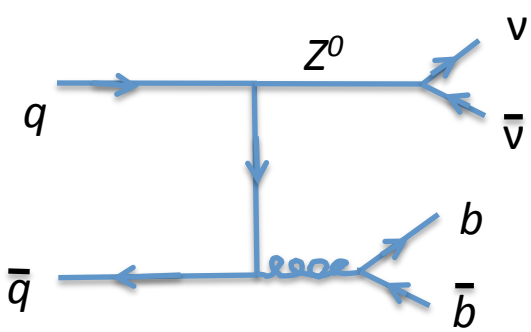
D0's WH,ZH→METbb in 8.4 fb^{-1}



Signal: ZH→ννbb

Also: WH→lνbb where the lepton is not identified

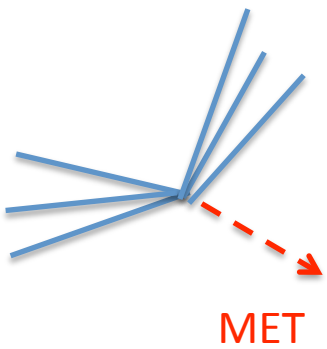
Mixture of two signals means even for this one channel we make an SM assumption of the ratio σ_{WH}/σ_{ZH}. Setting a cross section x branching ratio limit will be on a linear combination of WH and ZH



Backgrounds:

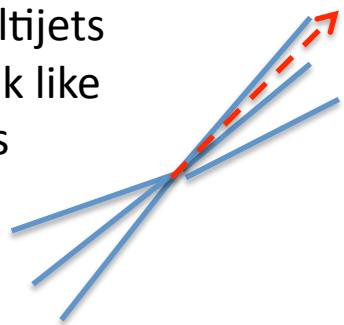
- Z+jets With Z→ννbb
  or mistagged charm, light-flavor jets
- W+jets with a missing lepton,
  +b's or mistagged charm or light-flavor jets
- Diboson: ZZ→ννbb, WZ, WW (plus mistagged jets)
- ttbar and single top with a missing lepton
- Multijets with fake MET

D0's WH,ZH→METbb in 8.4 fb^{-1}



Signal Looks Like This

Multijets Look like This



- Exactly two taggable jets (has tracks, points within coverage of silicon tracker)
- Jets must have p_T>20 GeV and $|\eta|$<2.5
- $\Delta\phi_{J1,J2}$<165°
- Missing E_T > 40 GeV
- MET significance > 5
- Scalar sum of jet P_T's > 80 GeV
- Reject events with an identified, isolated lepton (rejects W+jets, ttbar, diboson) (P_T > 15 GeV)

Require jets and MET not to point along each other

$$\mathcal{D} = (\Delta\phi(\not{p}_T, \mathrm{Jet_L}) + \Delta\phi(\not{p}_T, \mathrm{Jet_N L}))/2 \ > \pi/2$$

Control Samples:

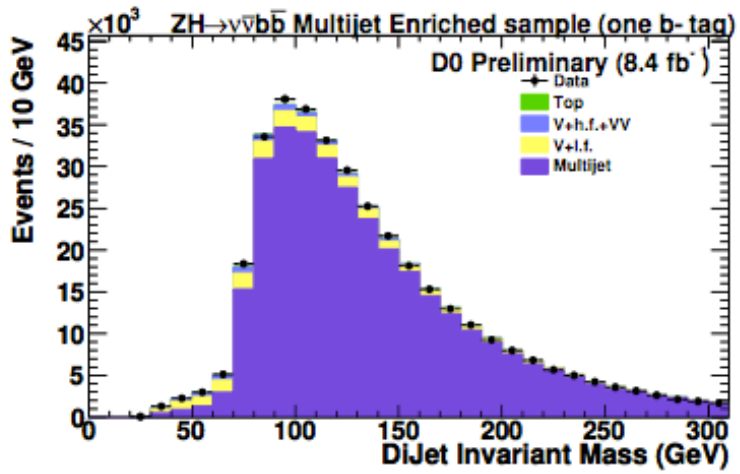
1) Multijet: Invert the cut on D. D < π/2

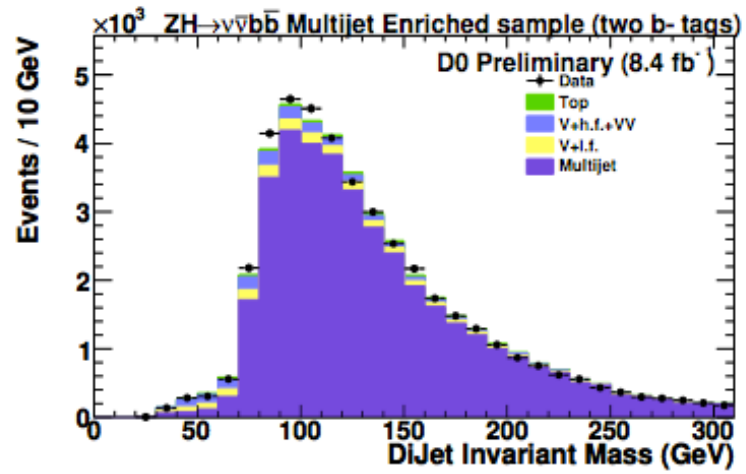
Jets now point along MET – much more likely to be fake MET

2) EW: Require an isolated muon with P_T>15 GeV

METbb Control Samples

Multijet Sample

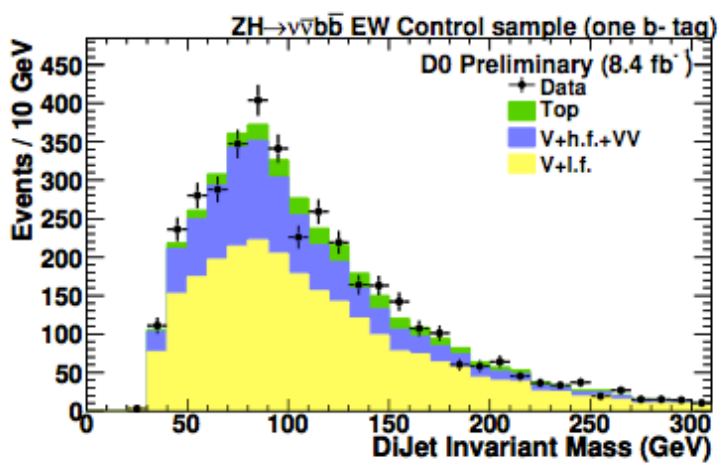


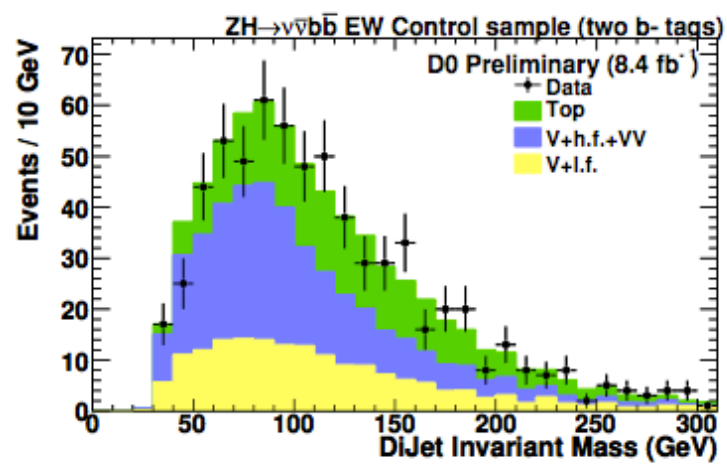


One b-tag

Two b-tags

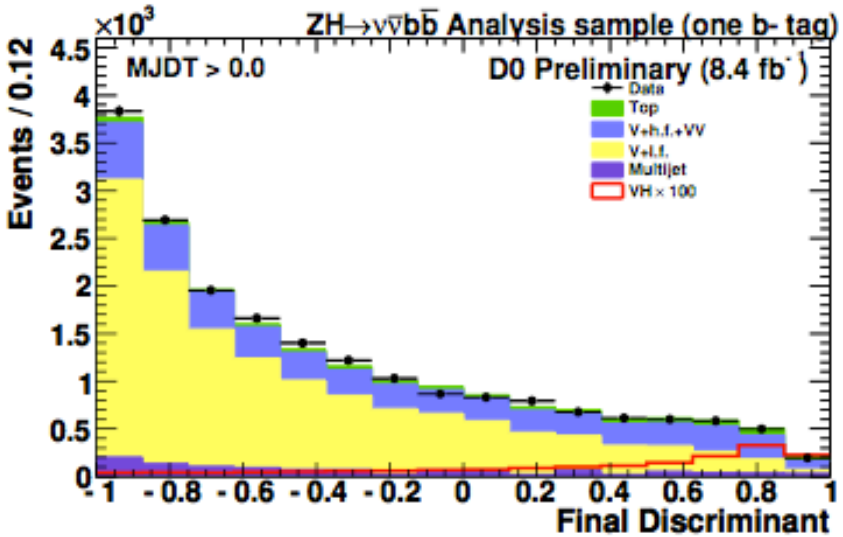
EW Sample

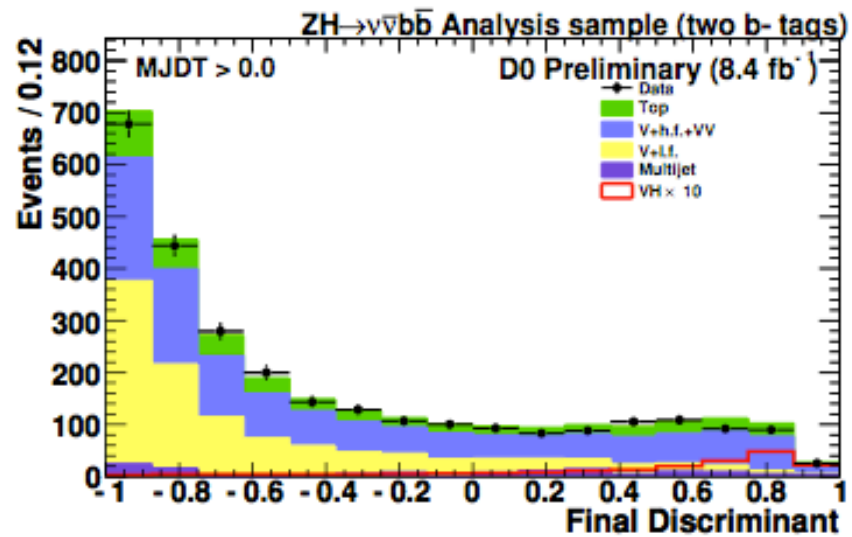




METbb Signal Sample Composition and Final Discriminants

Sample	ZH	WH	W+jets	Z+jets	Top	VV	Multijet	Total Background	Observed
Pre-tag	21.78 ± 0.09	18.49 ± 0.13	46070	19119	1342	2329	5291	74151 ± 230	72190
Single tag	8.99 ± 0.06	7.81 ± 0.09	12027	4695	681	711	1095	19209 ± 99	19426
Double tag	10.60 ± 0.06	8.80 ± 0.09	1479	673	440	121	125	2838 ± 36	2763

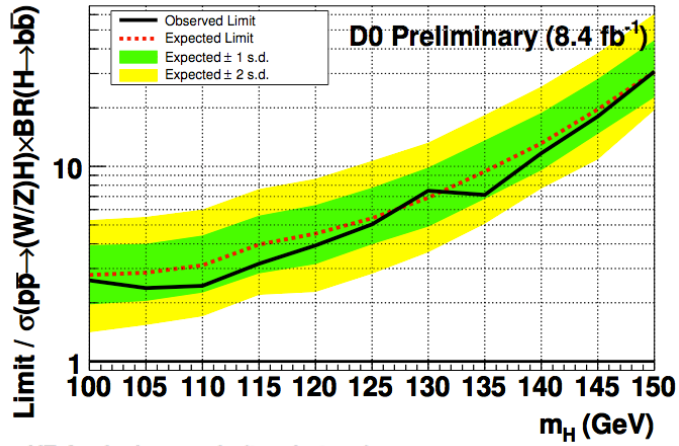


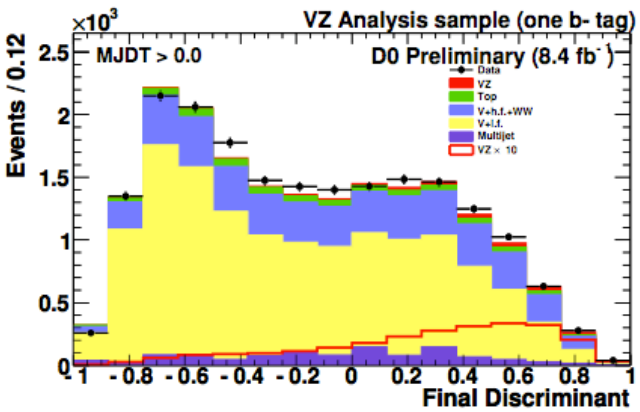


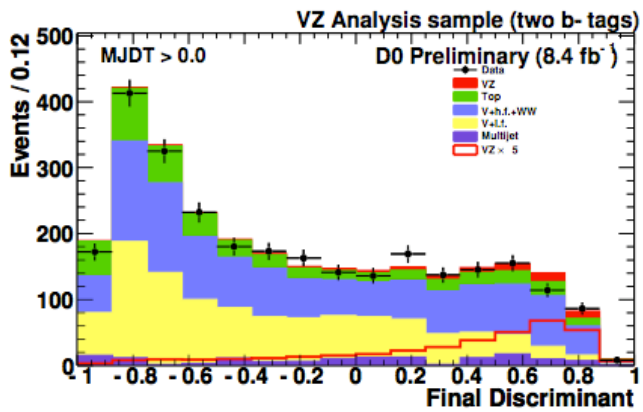
Boosted Decision tree output built on kinematic variables. m_{jj} is one of the strongest ones (12%-15% m_{jj} resolution)

Interpretation in the Signal Region

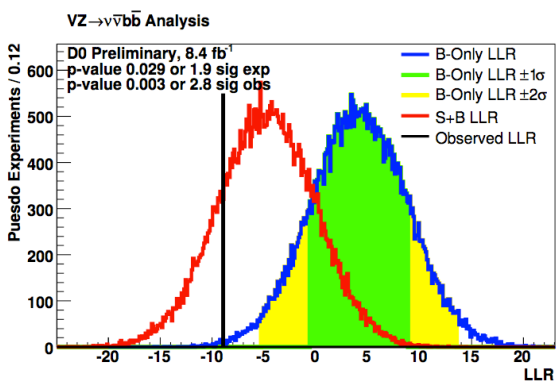
Observed and Expected limits on Higgs production





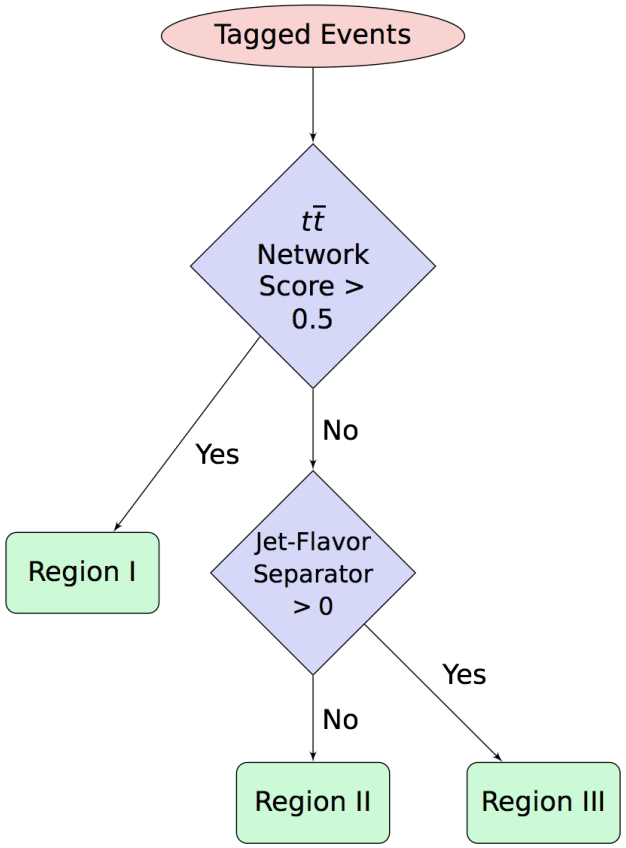


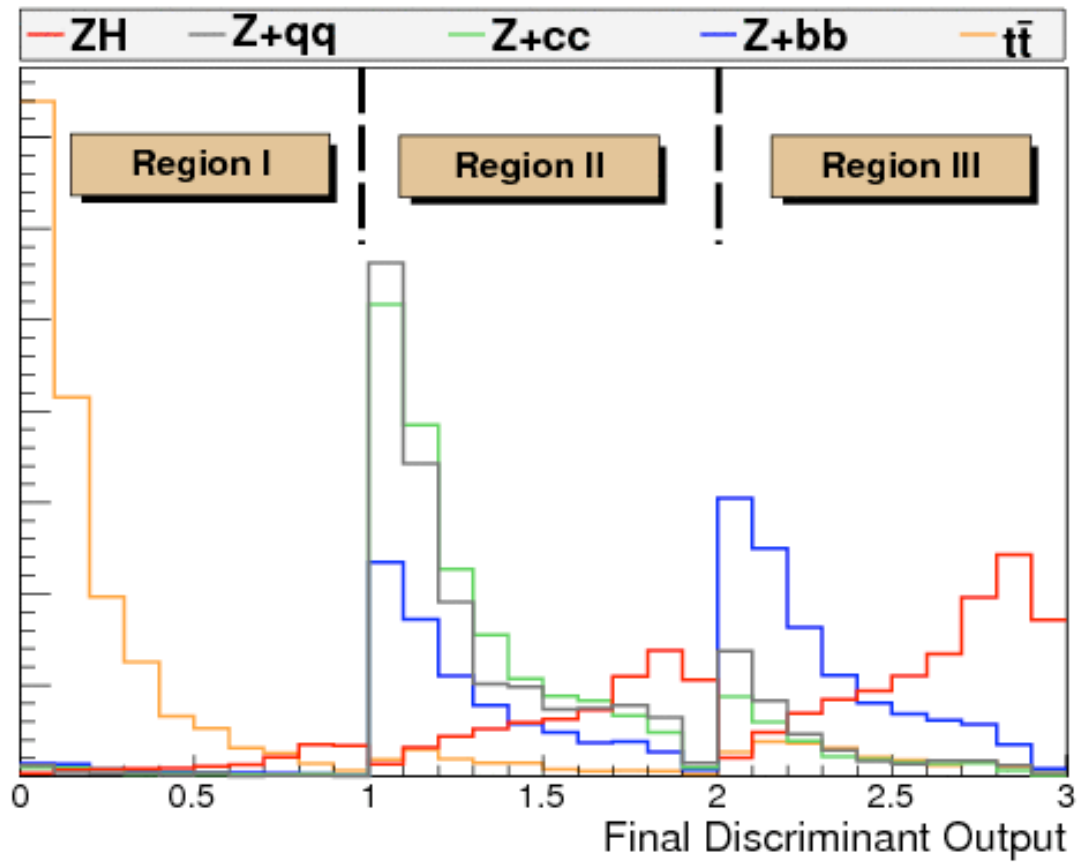
Diboson Search:
Same event selection as the Higgs search, but treat WZ+ZZ as a signal (WW) is a background.



Likelihood Ratio test: LLR = -2ln(P(data|s+b)/p(data|b)
Fitting systematic uncertainties separately in the numerator and denominator.
Observed significance: 2.8σ, Expected: 1.9σ

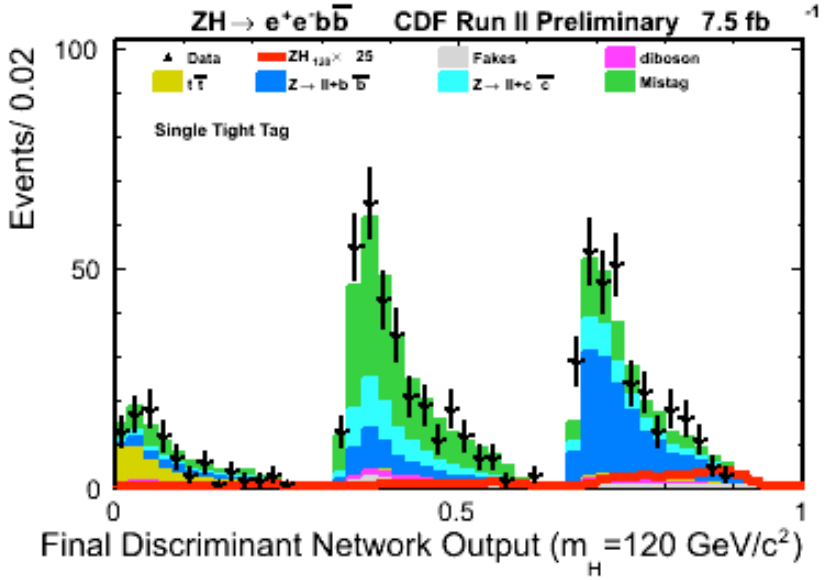
CDF's ZH→llbb Analysis Strategy

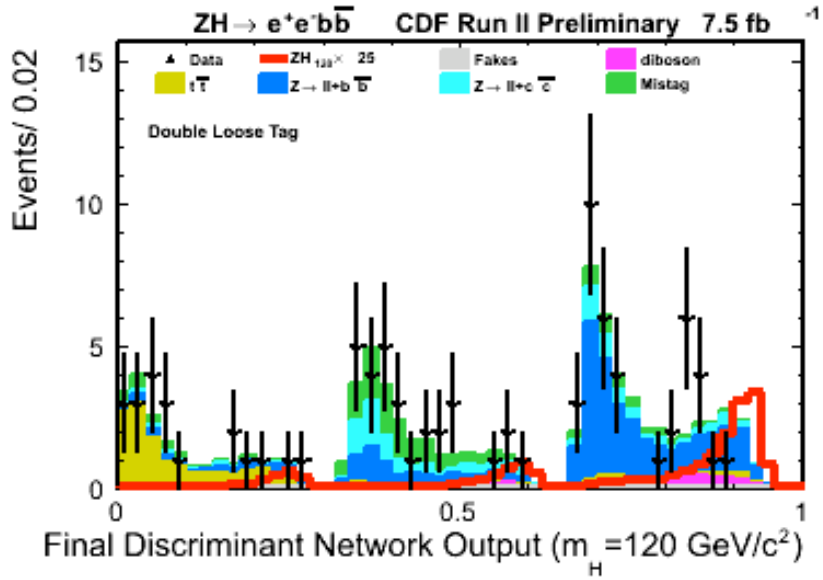


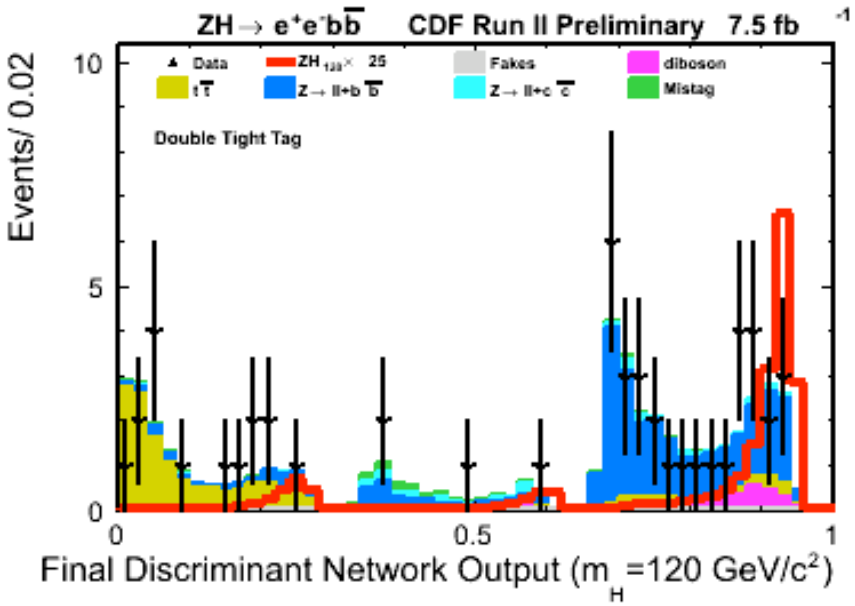


- Select events with Z→ll + jets with as loose a lepton selection as possible – still quite pure in Z decays.
- Train NN's first against ttbar, then to separate out the different flavor Z+jet samples (Zcc, Zbb, Z+LF (mistag)).

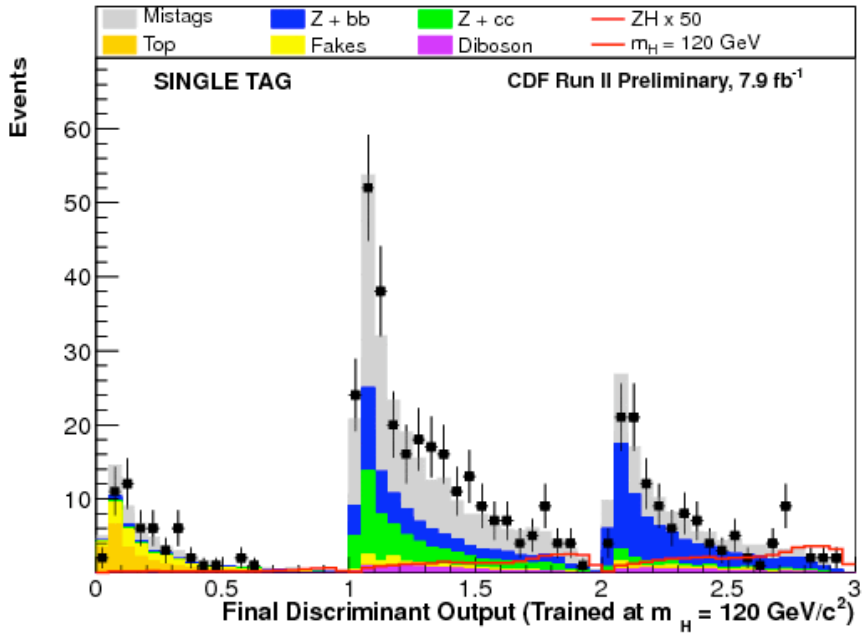
CDF's ZH→llbb Output Disriminants – Electron Channels

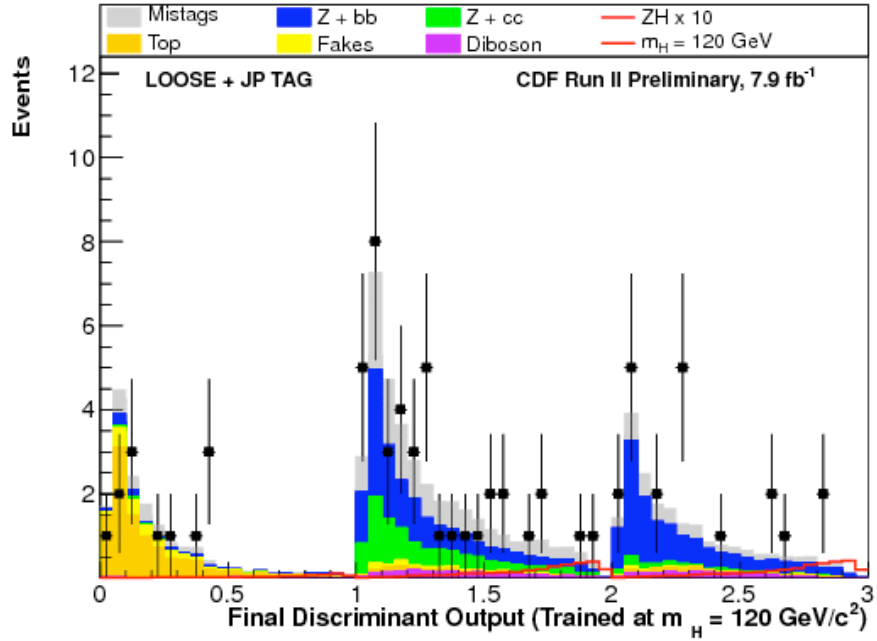


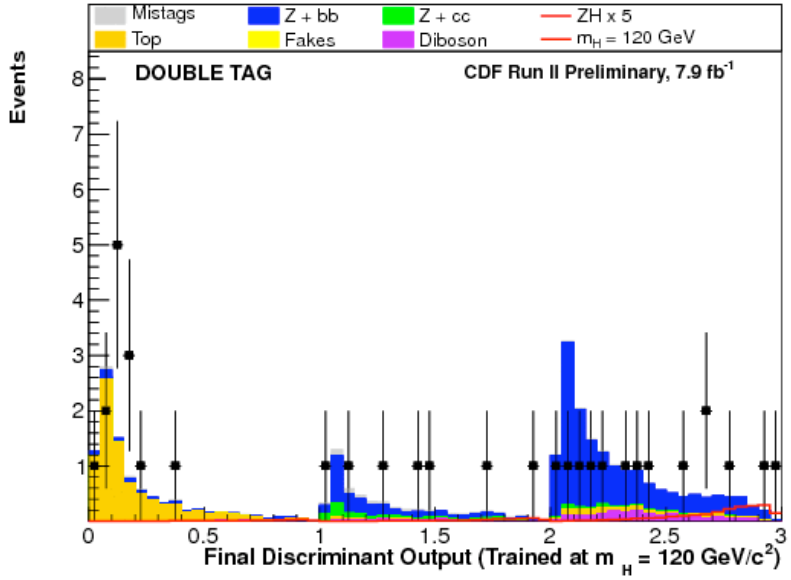




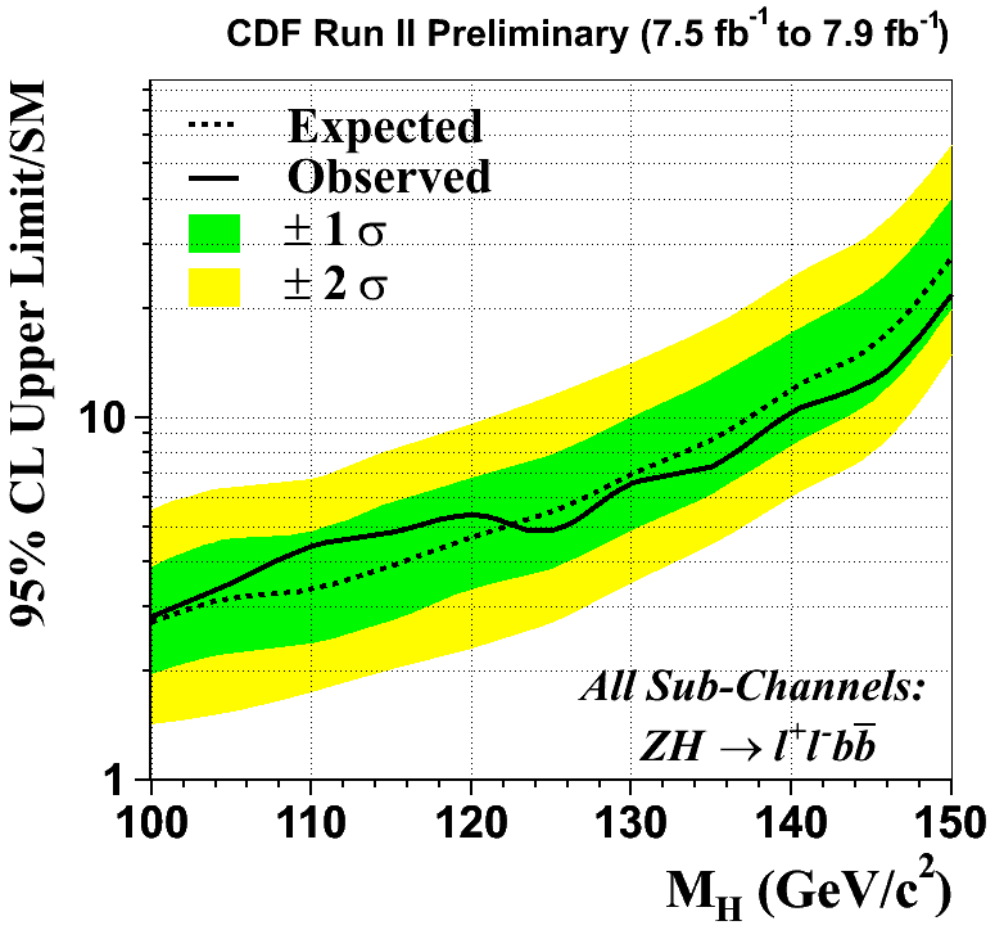
CDF's ZH→llbb Output Disriminants – Muon Channels

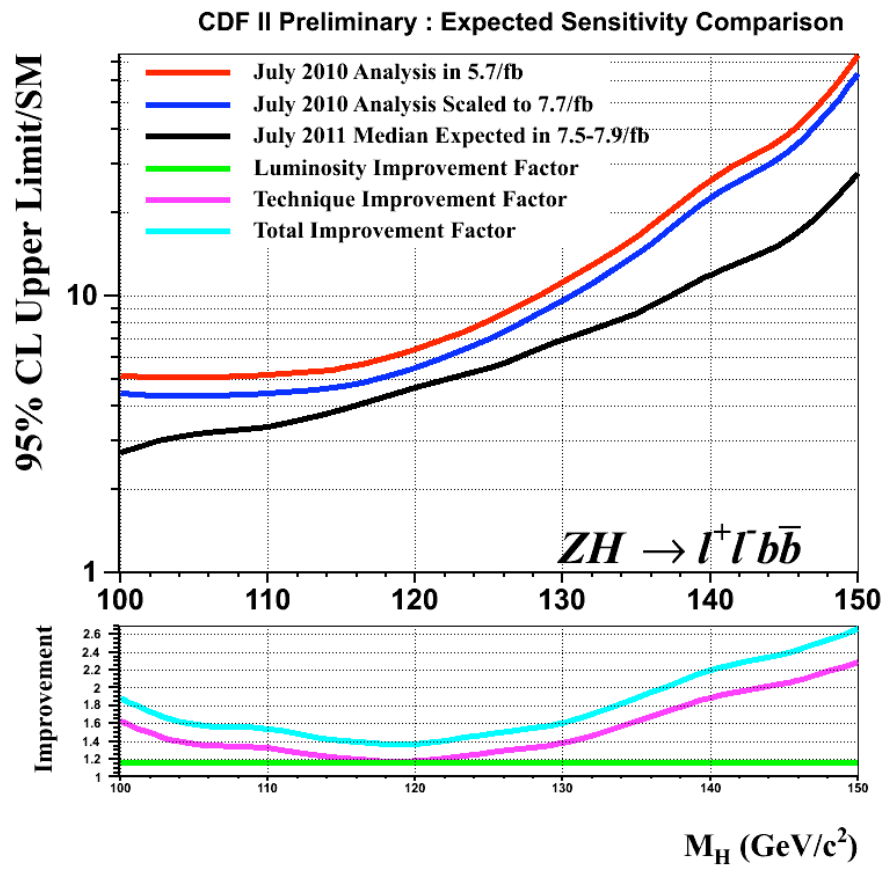






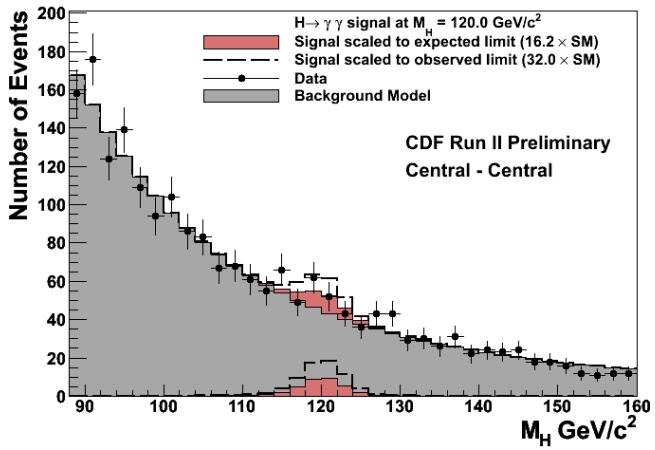
CDF's ZH→llbb Limits and Improvement Factors

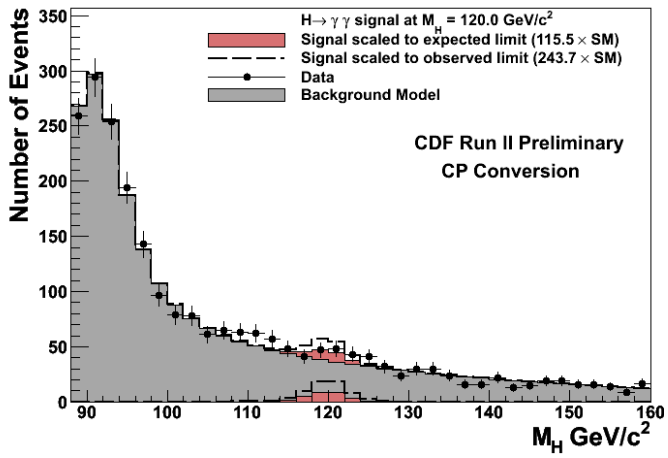




Previous iterations of the analysis had trained the MVA on m_H=120 GeV signal MC. Not wrong, but not optimal for other m_H.

CDF's 2011 H→$\gamma\gamma$ Search

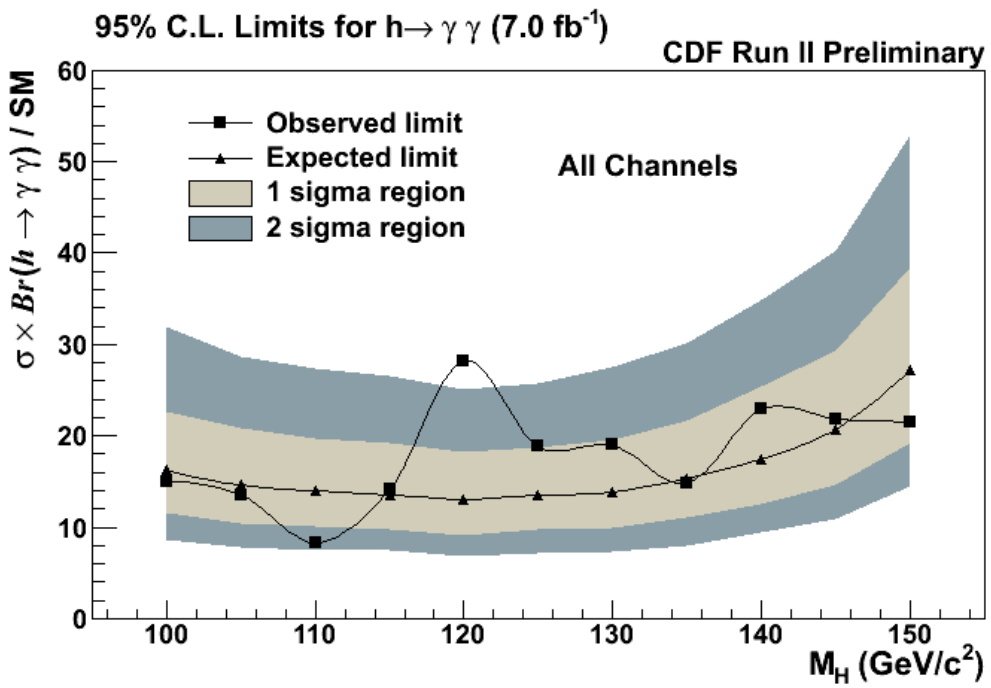




+2 other channels with smaller excesses

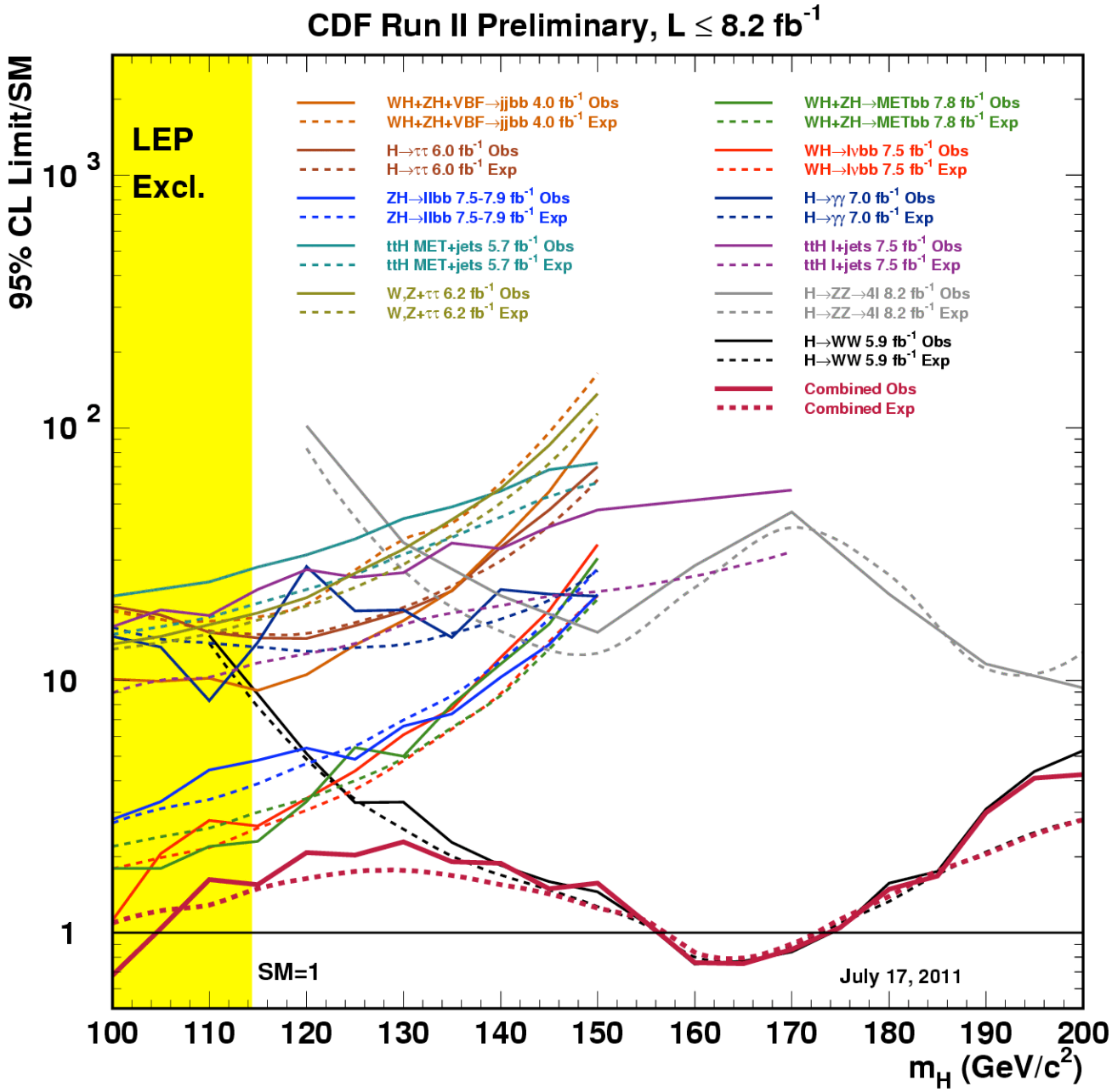
Signal Model: Pythia MC, but really it could be just a Gaussian.

Background Model: Smooth function fit outside of signal window (slides with mass being sought).

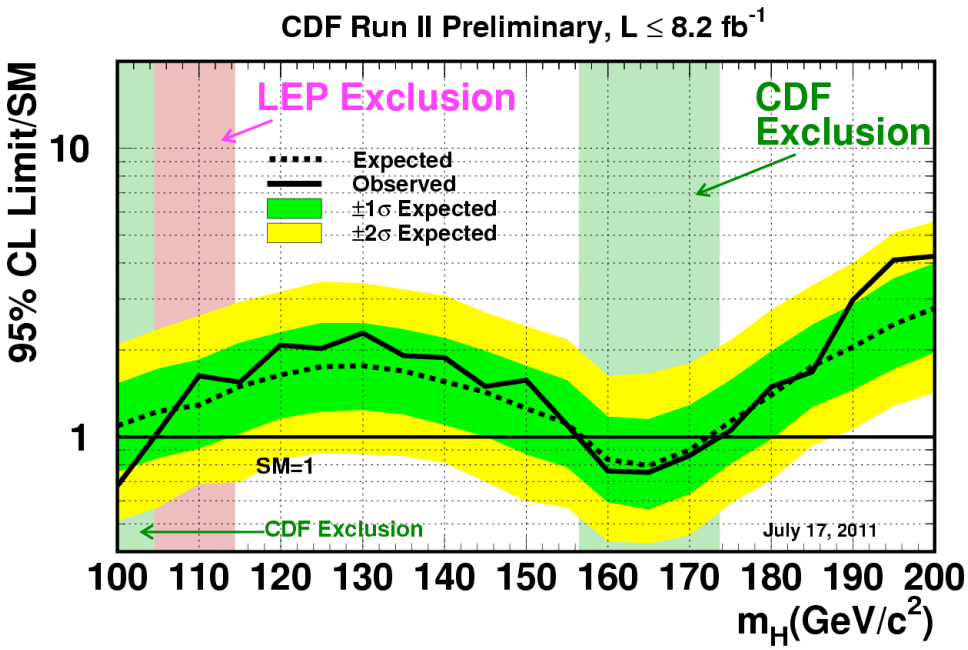


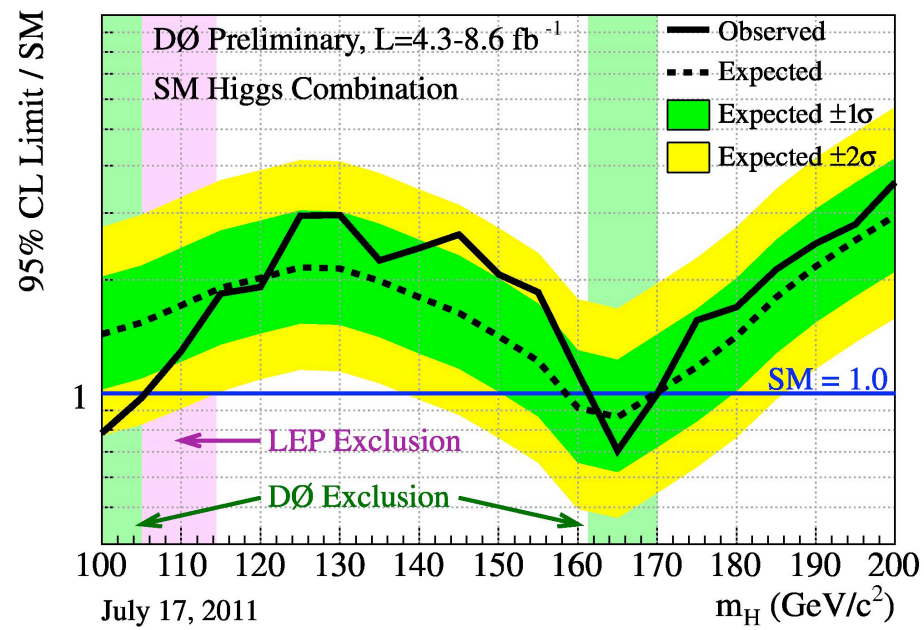
Insufficient sensitivity to a SM Higgs boson. Rate ruled out by other searches (gg→H→WW for example). So we know the bump is a stat fluctuation.

All CDF Channels Observed and Expected Limits On One Plot



CDF and D0's Combined Limits

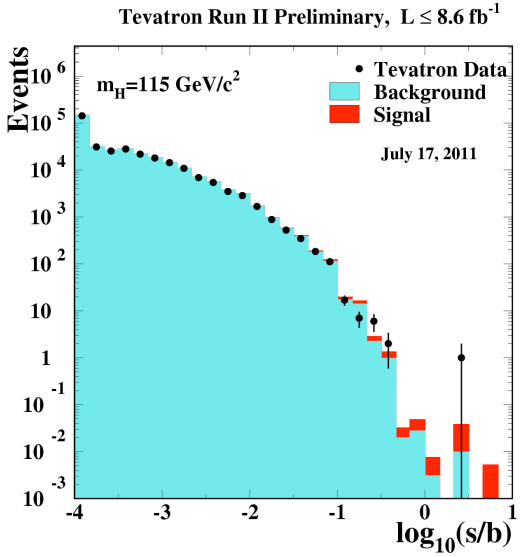


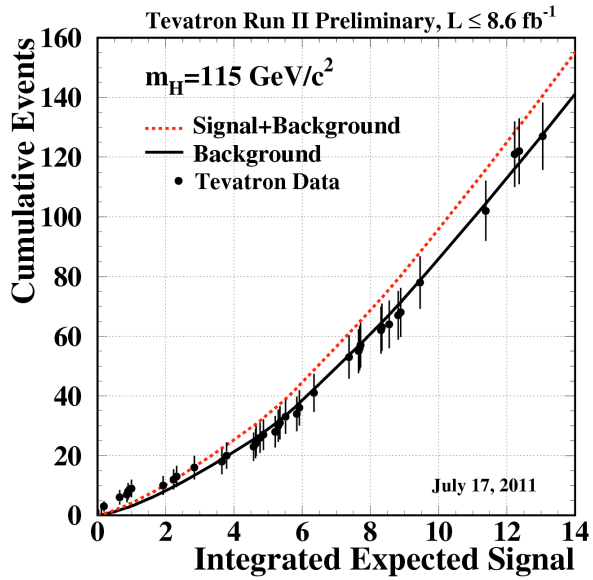


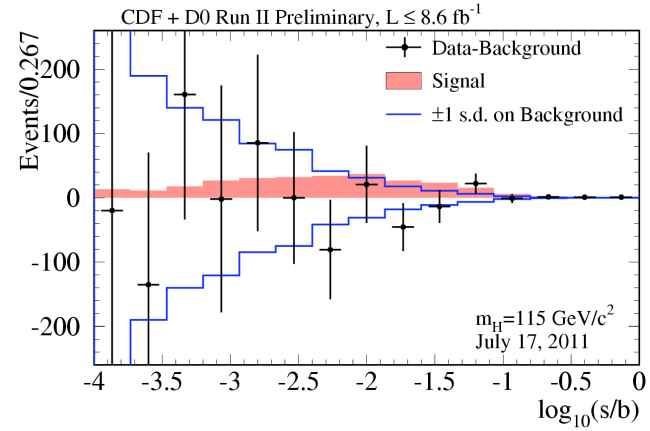
- Necessary steps in producing final results
  - CDF combines CDF's results; D0 combines CDF's results and compares
  - D0 combines D0's results; CDF combines D0's results and compares

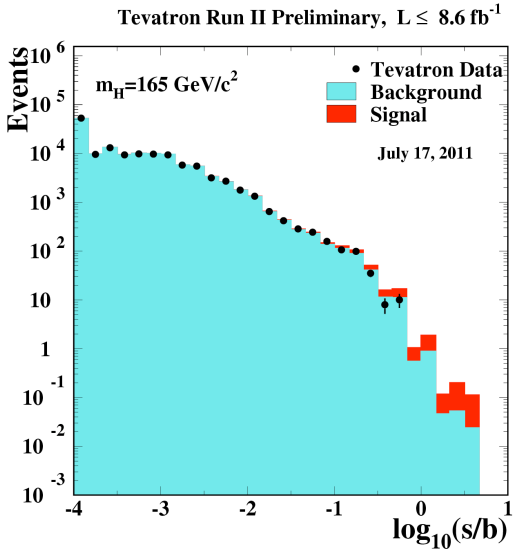
If either of these comparisons fails (~5% tolerance) we check individual channels. Can cause scheduling issues, finding problems at the last minute.

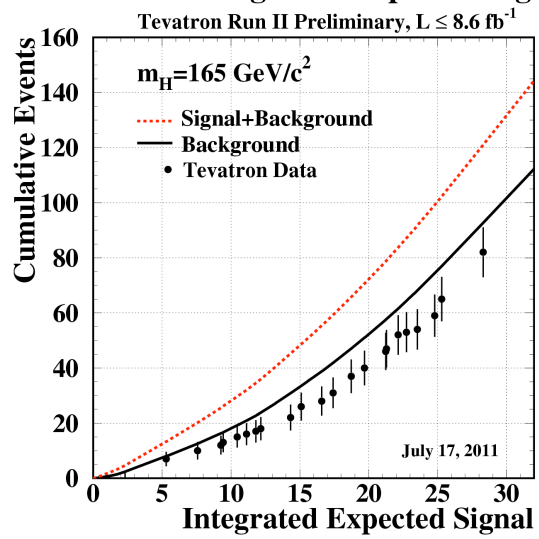
Candidate Distributions Sorted by s/b

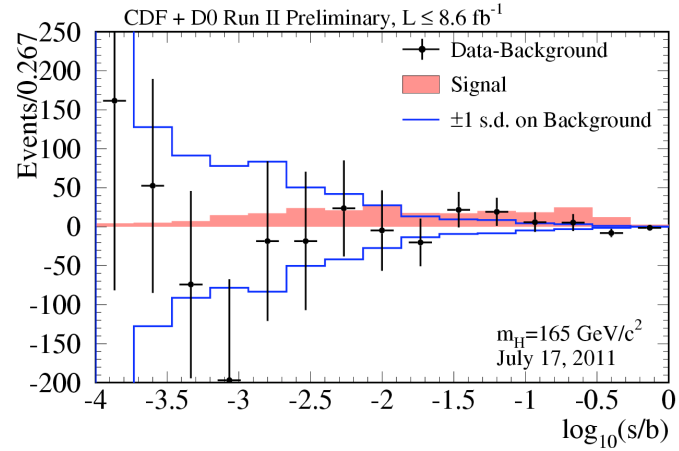






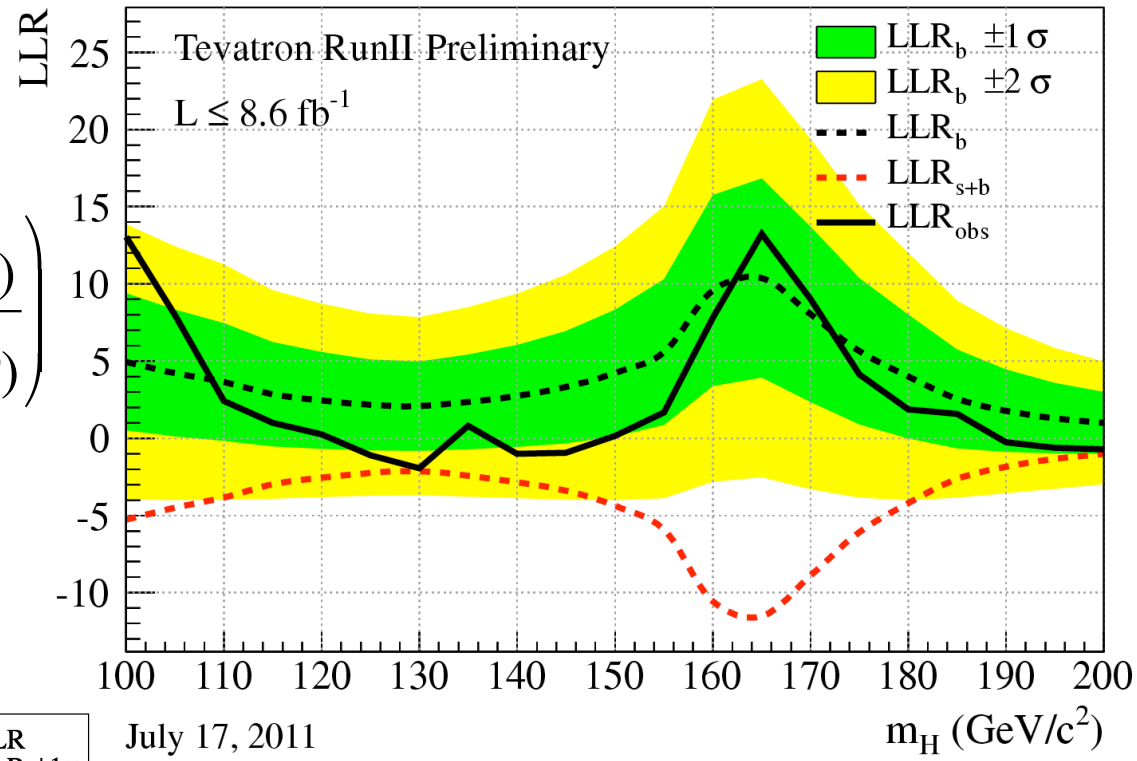


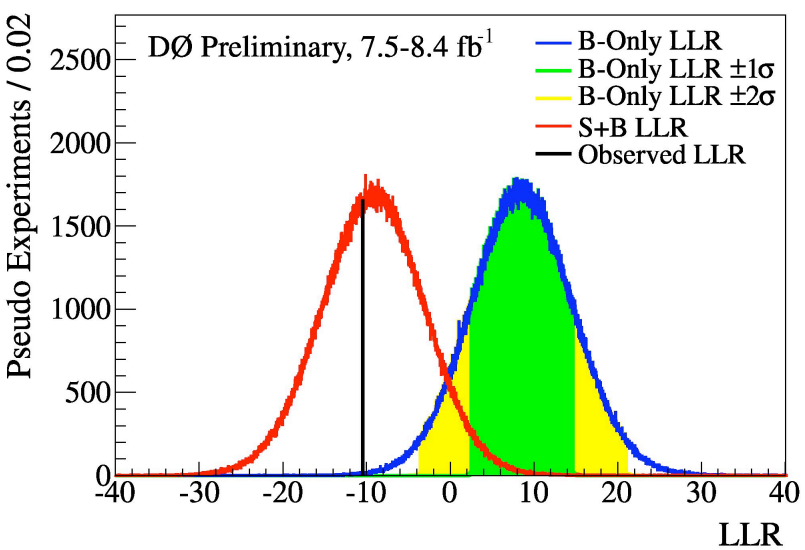




The Logarithm of the Likelihood Ratio – Optimized Discovery Test Statistic

$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\,|\,H_1,\hat{\theta})}{L(\text{data}\,|\,H_0,\hat{\hat{\theta}})}\right)$$

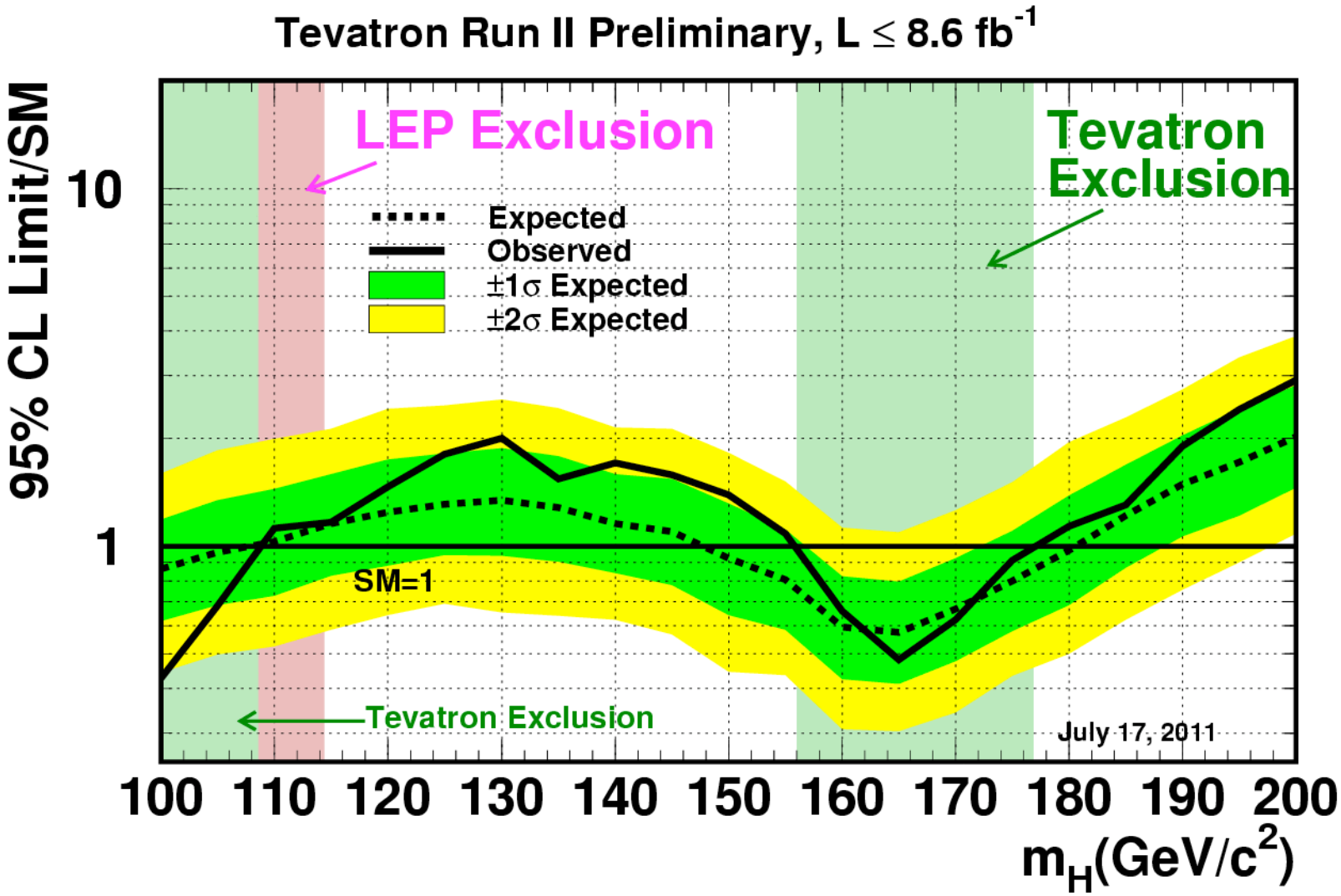




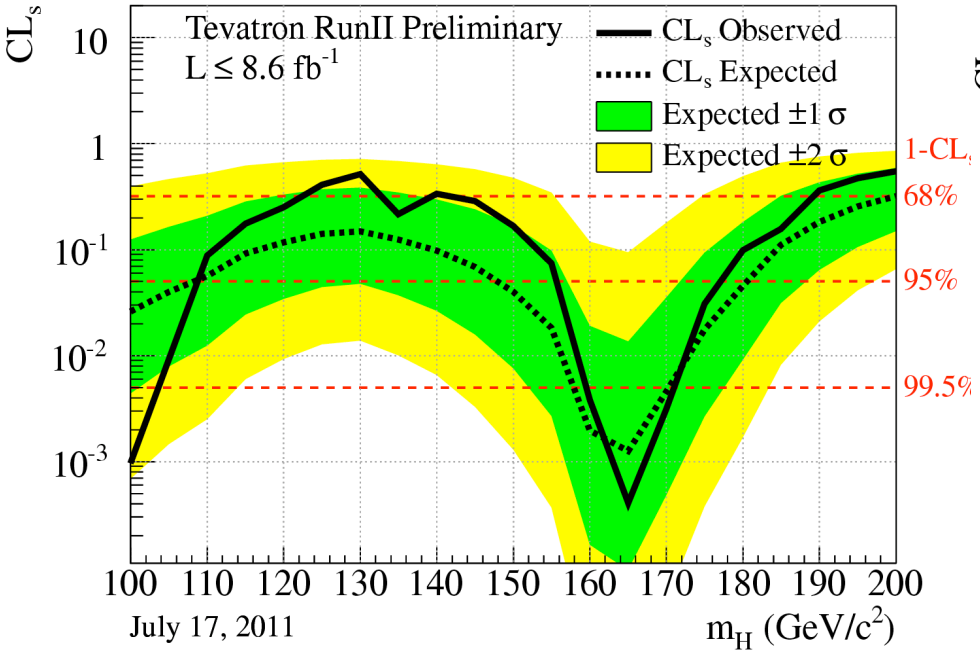
Reminder of what this looks like for a single signal hypothesis (along with an outcome that's very signal-like: D0's b-tagged WZ+ZZ search)

Rate Limits for All Channels Together

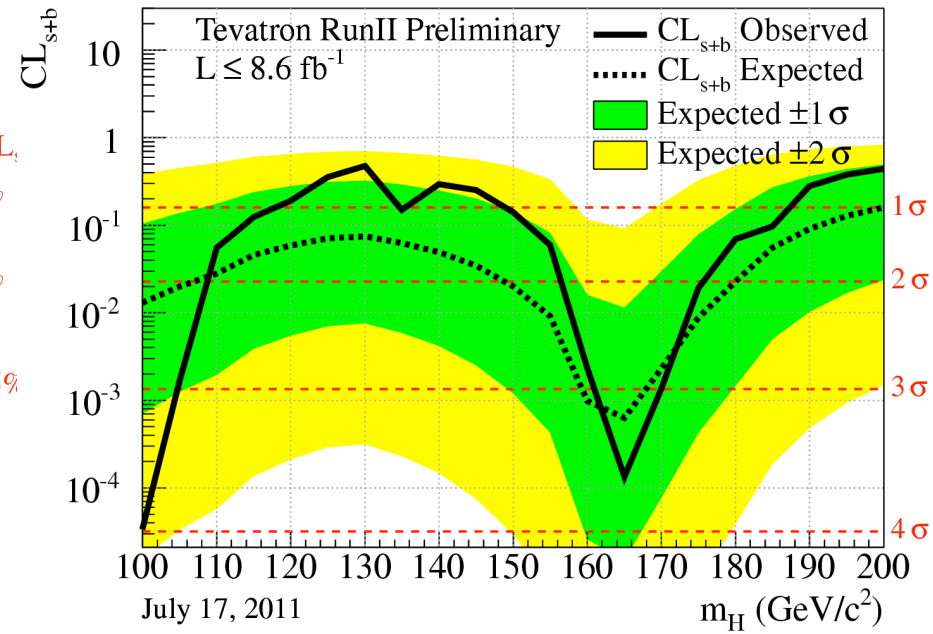
Assumes SM ratios for production and decay



Testing the SM Prediction with CL_s and CL_{s+b}



$CL_s = CL_{s+b}/CL_b$

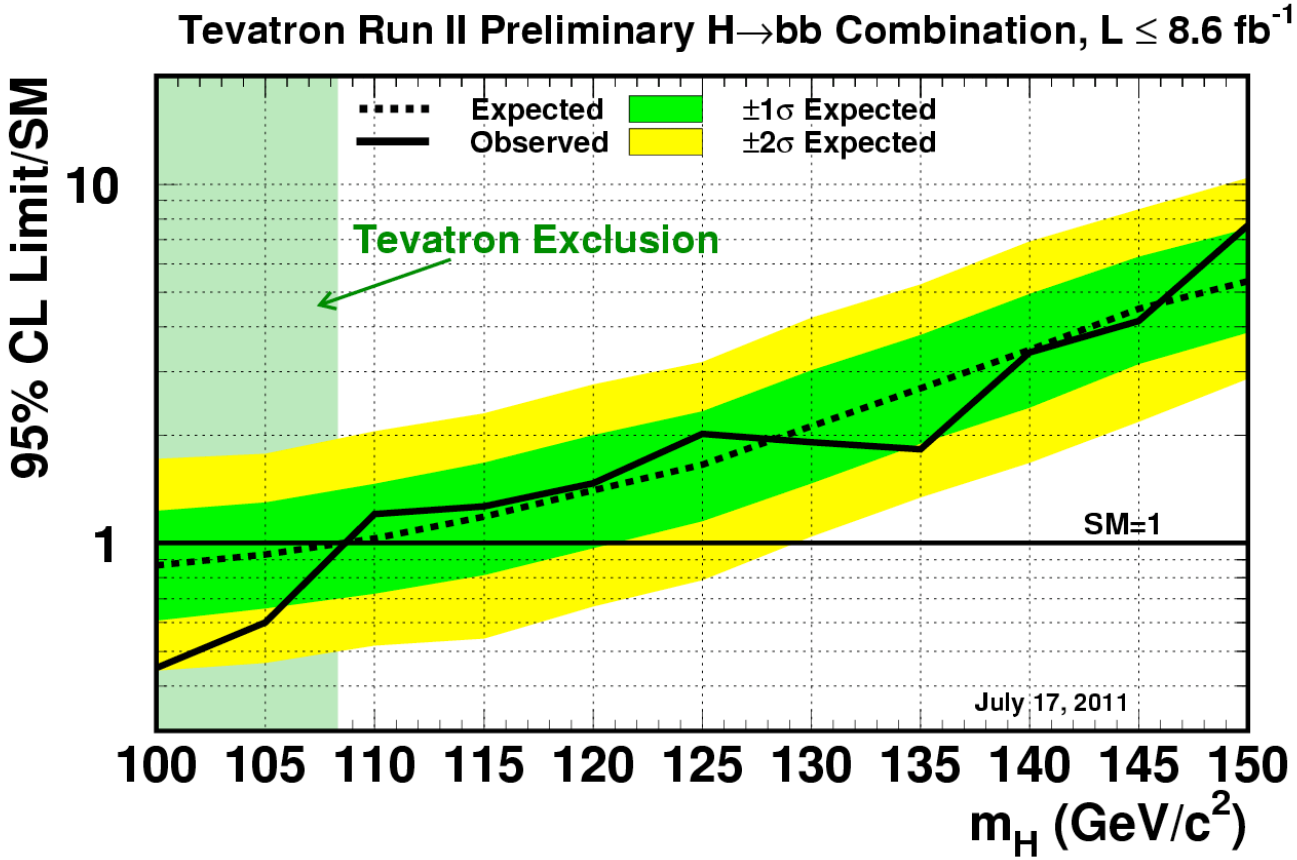


CL_{s+b} Covers, but it has a chance of excluding masses that are not tested.

Not fully frequentist or Bayesian, but has elements of both. Cannot be fully frequentist due to systematic uncertainties anyhow. Expected to perform somewhat better than Bayesian but quite similar.

Starting to get small p-values for the signal hypothesis

Limits Just for the CDF+D0 H→bb Searches

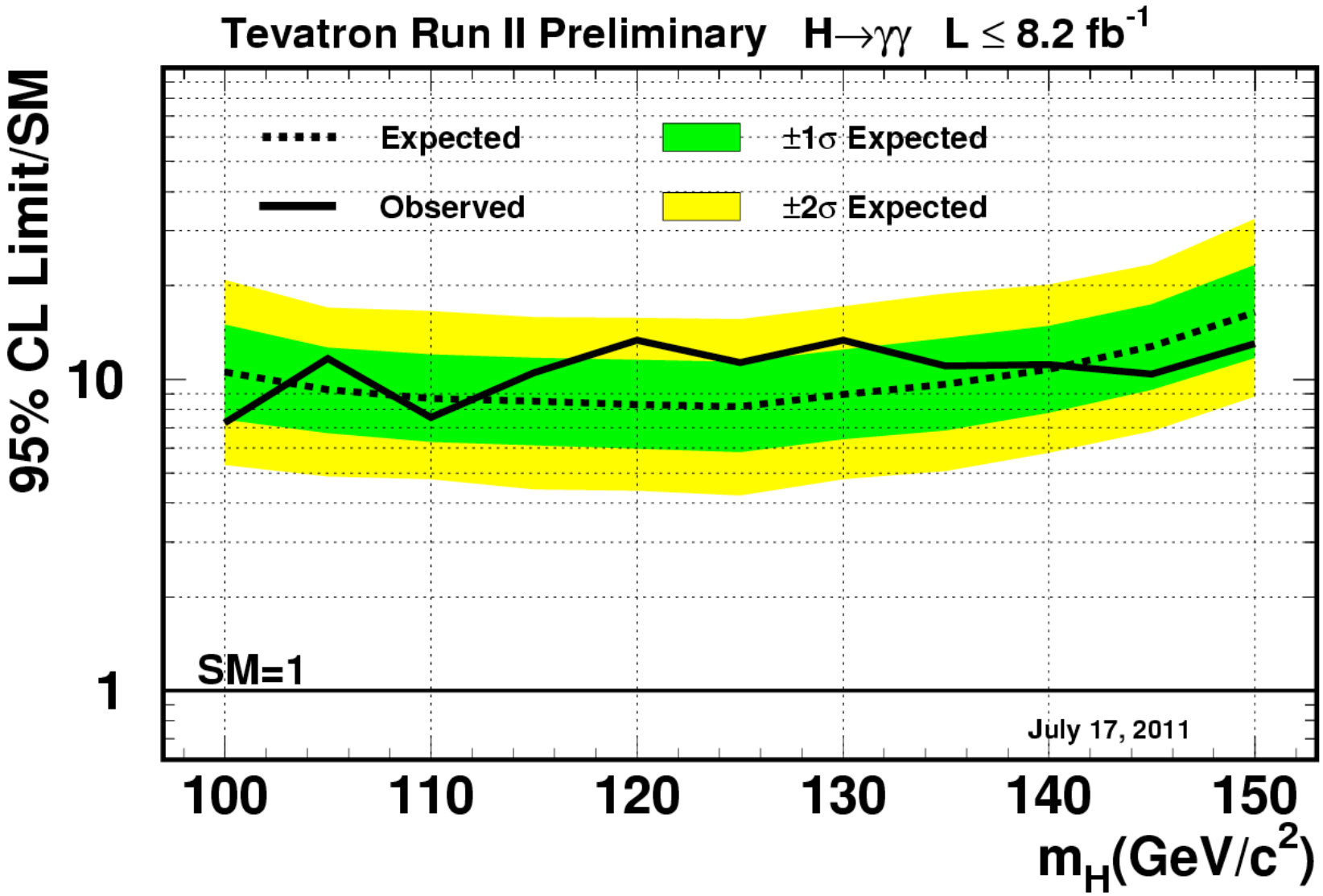


Cross Section x B.R. interpretation to be prepared.

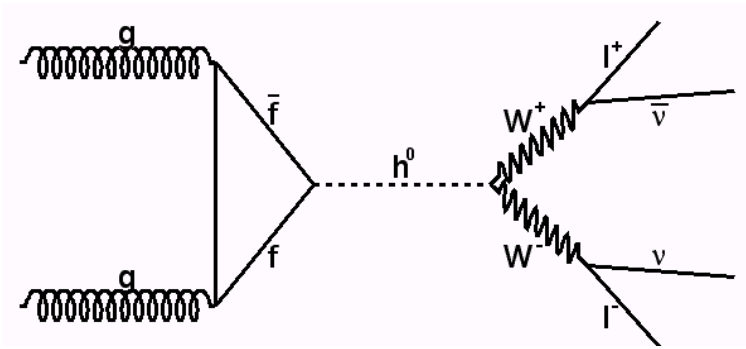
Best-fit cross section times b.r. will be zero everywhere the black line is below the dotted line though. Large uncertainties though.

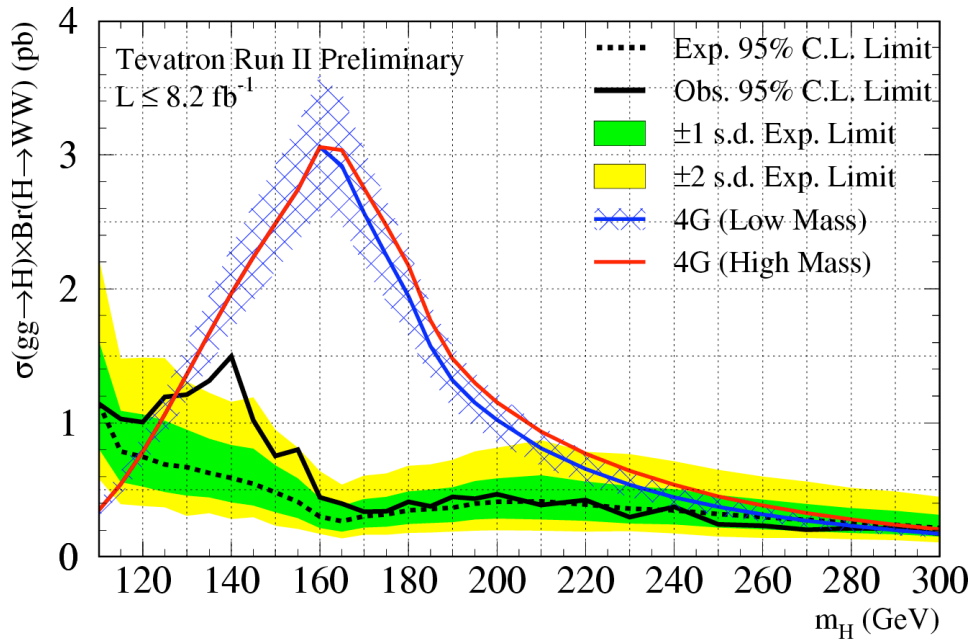
Tevatron remains competitive with H→bb for some time to come.

Limits Just for the CDF+D0 H→$\gamma\gamma$ Searches

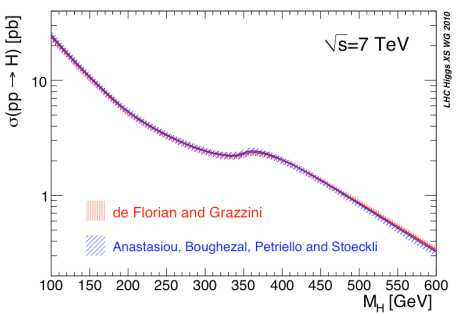


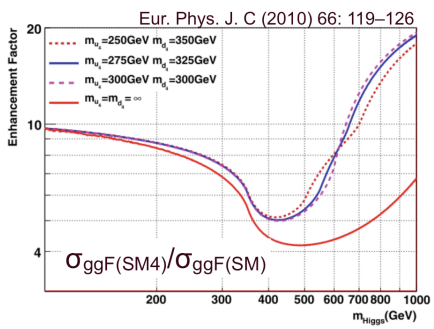
Searches for H→WW→lνlν Assuming a 4th Sequential Generation of Fermions



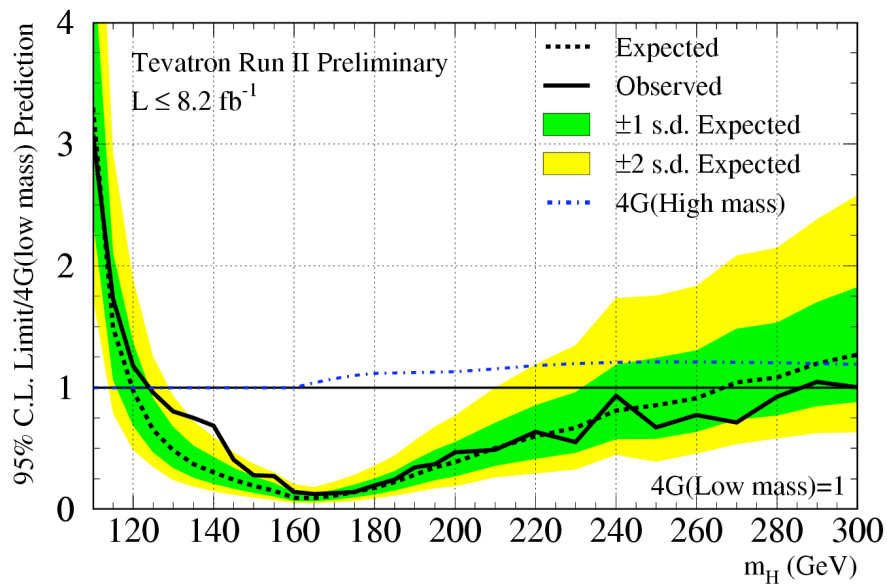


Two extra heavy quarks in the loop – Naive factor of 9. But less since tt is light enough to be sensitive to resonating propagators.





Tevatron SM4 Cross sections computed at NNLO by Anastasiou, Boughezal, and Furlan JHEP **1006**, 101 (2010).

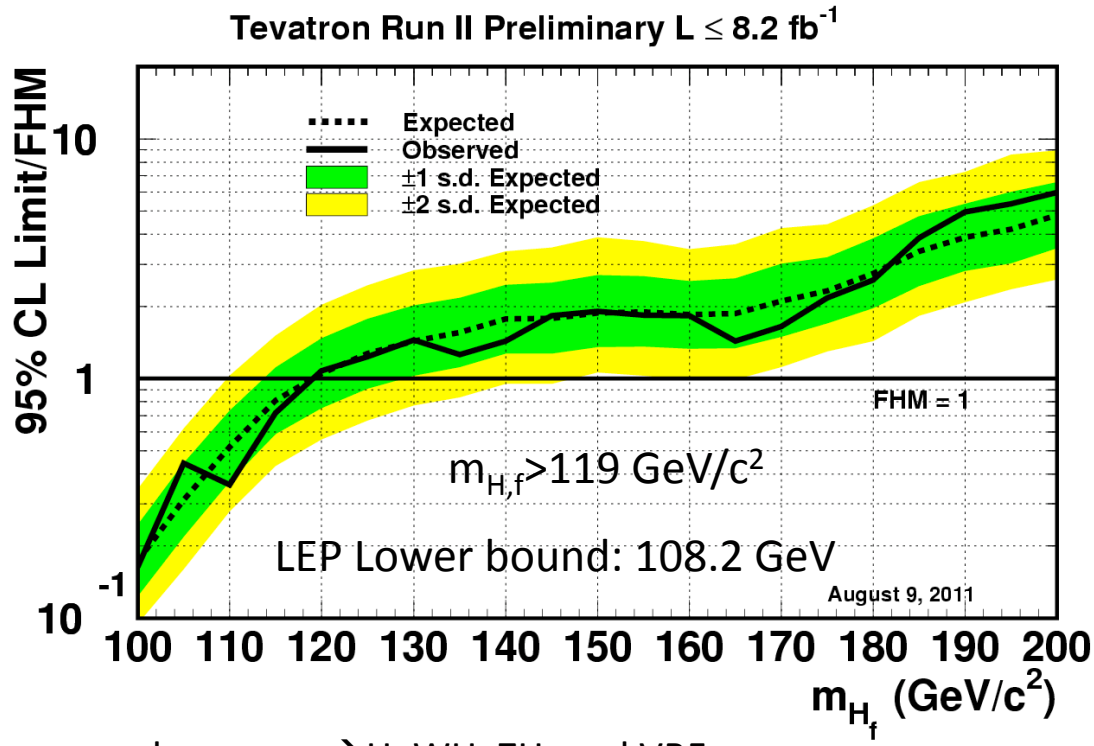


Decay branching ratios affected by the presence of massive neutrinos within the kinematic reach.

Tevatron Constraints on a Fermiophobic Higgs Model

Simple to construct using SM predictions:

- gg→H production almost vanishes (2-loop EW corrections are still present but are very small)
- WH, ZH, and VBF production are assumed to be Standard
- Decay b.r.'s: zero width to bb, cc, ττ, gg (almost).
- Remaining b.r.'s to WW, ZZ, γγ, are modified (increased). Special Fermiophobic version of HDECAY used.

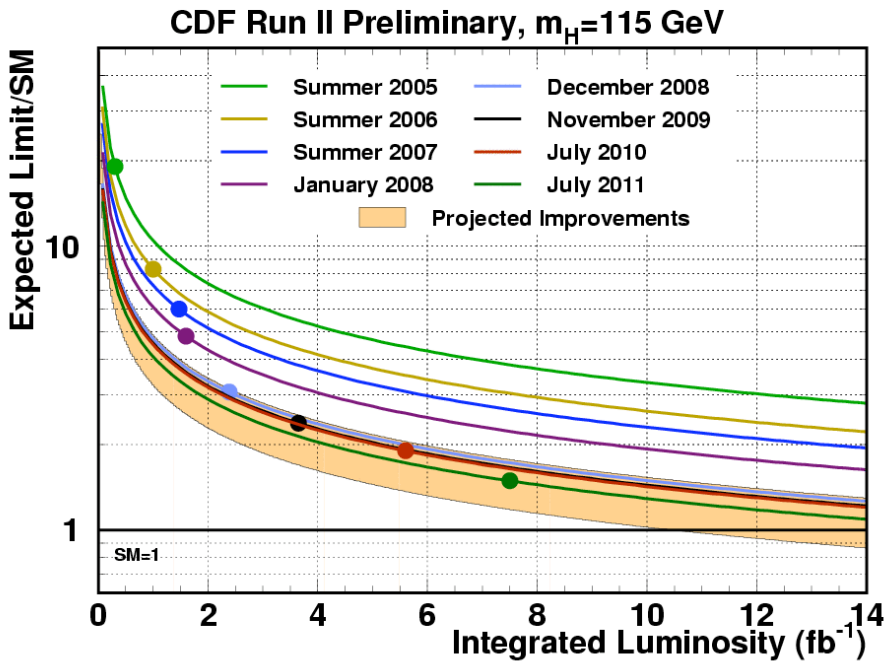


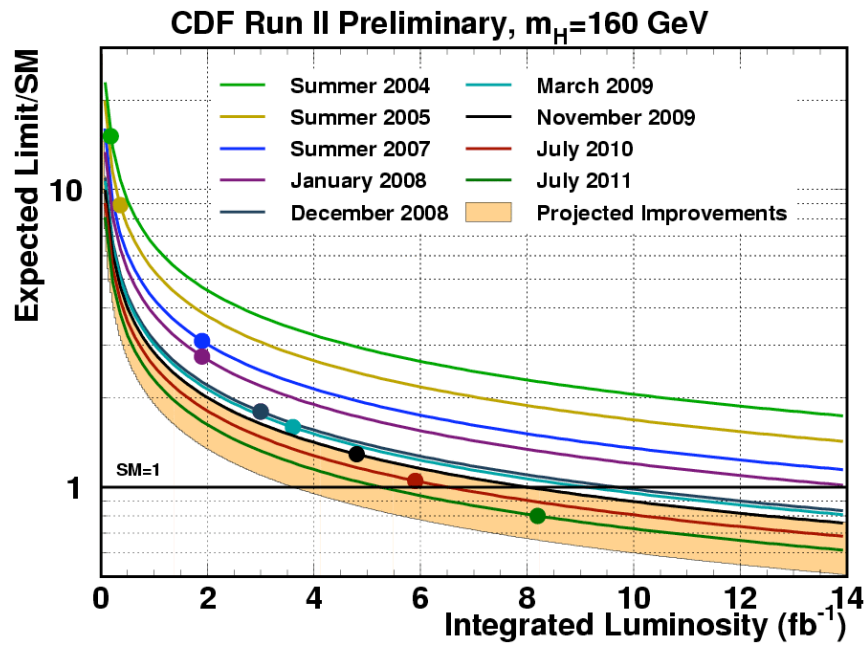
SM experimental inputs also easy to re-purpose, as long as gg→H, WH, ZH, and VBF signals are separated and clearly labeled. Already, the H→WW searches are split by jet bin and identify WH, ZH, VBF and gg→H signals separately.

H→γγ Searches re-optimized for the Fermiophobic model – P_T spectrum is harder in WH and ZH than it is in gg→H. Uses same data-based background parameterization as SM search.

WW and WH→WWW, ZH→ZWW (trileptons and like-sign dileptons) also used
D0 OS dileptons not included yet (has tau signal in it)

Sensitivity Improves Over Time



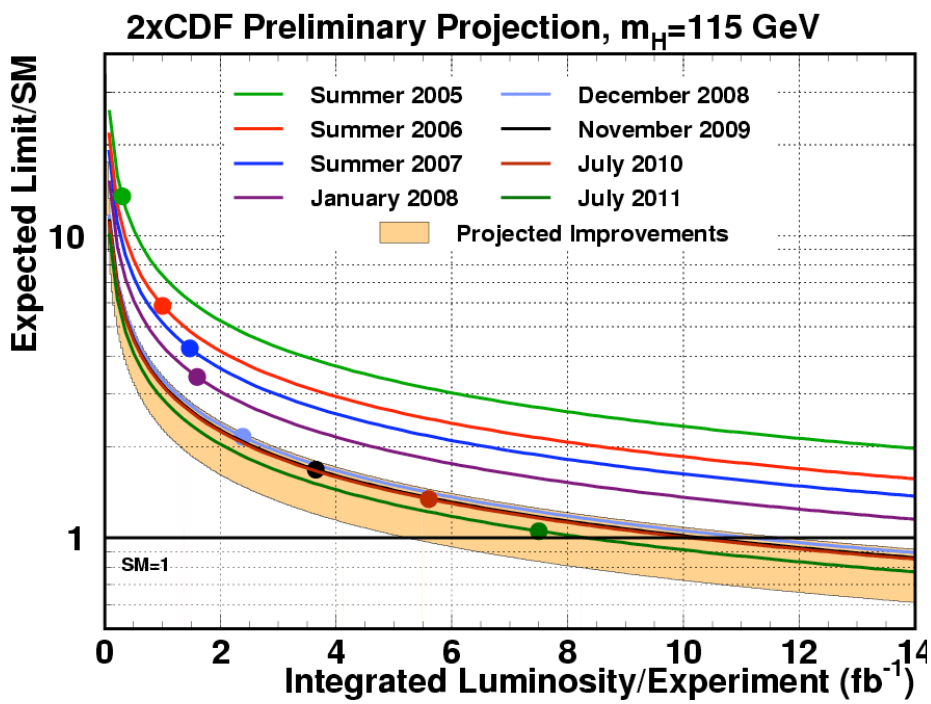


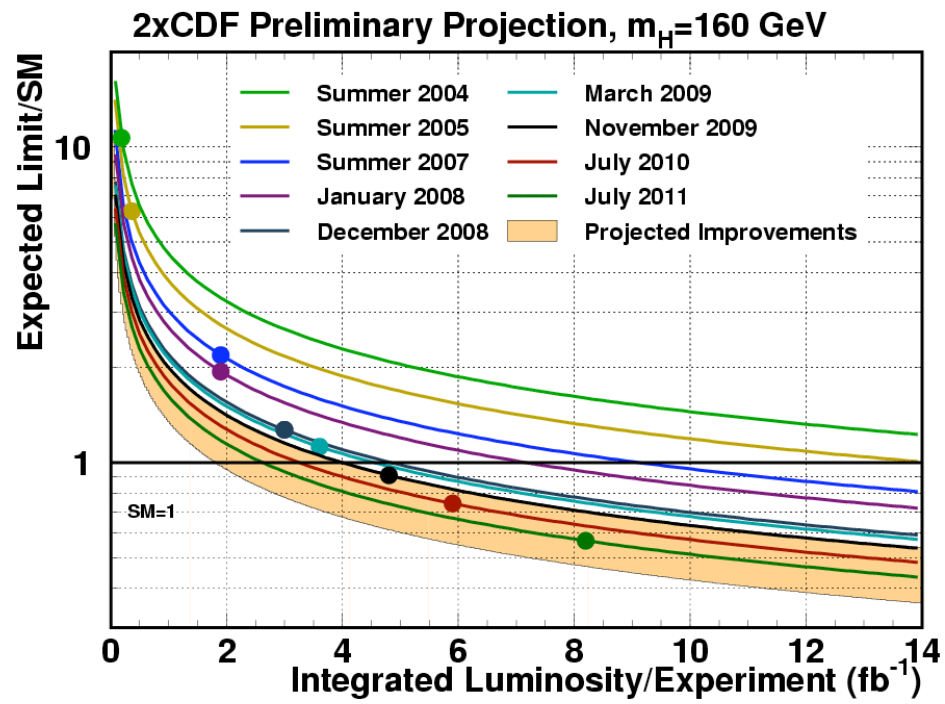
Naive Expectation: Expected rate limit scales as 1/sqrt(L_{int}). Assumes b>>1 event.

Exceptions to the rule:

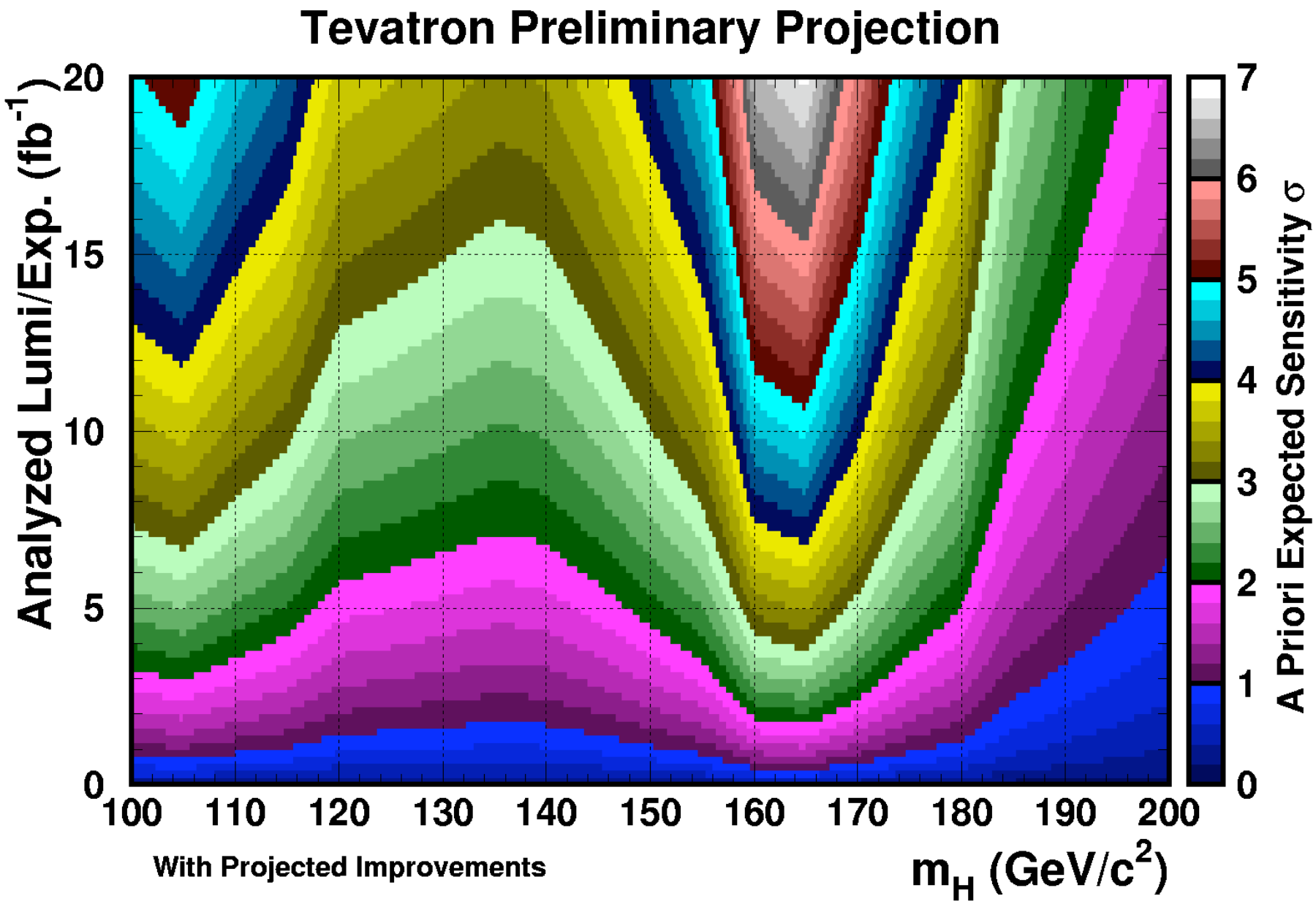
- b<1: Expected limit scales as 1/L_{int}. As L_{int} grows, b grows, and the dependence departs from 1/L_{int} anyway. Not an issue for our searches (trilepton ones have low bg though)
- Systematics could hit a "brick wall". Background and signal efficiency systematics are constrained by data, so we expect these to scale as 1/sqrt(L_{int}).
- **Analyses improve!** New taggers, more acceptance, trigger improvements, smarter MVA's.
- Theorists give us new cross sections and b.r.'s (we scale these out so it's apples to apples).

Multiplying the Luminosity by Two





Assumes CDF and D0 achieve the same sensitivity.


Tevatron Preliminary Projection
Analyzed Lumi/Exp. (fb^{-1})
20
15
10
5
0
100
110
120
130
140
150
160
170
180
190
200
m_H (GeV/c^2)
With Projected Improvements
A Priori Expected Sensitivity σ
7
6
5
4
3
2
1
0

Tevatron Shutdown – September 30, 2011

+1 month of Silicon Annealing studies (CDF) and cosmic-ray data (D0).

Still lots of work to do!

- Finish off main analyses with the full ~10 fb^{-1} data sample
- Produce combinations of channels, between CDF and D0, and with the LHC, where appropriate