Searches for the Standard Model Higgs Boson at the Tevatron

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Joint Theory/Experiment HEP Seminar

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

Slide from G. Altarelli, HCPSS'08

The main problems for the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ \text{eV})^4$

Origin of quadratic divergences.
Hierarchy problem

Possible instability depending on m_H

The flavour problem: large unexplained ratios of Y_{ij} Yukawa constants

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

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

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

Zwirner

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

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

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

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

If no Higgs then something must happen!

G. Altarelli, HCPSS 2008

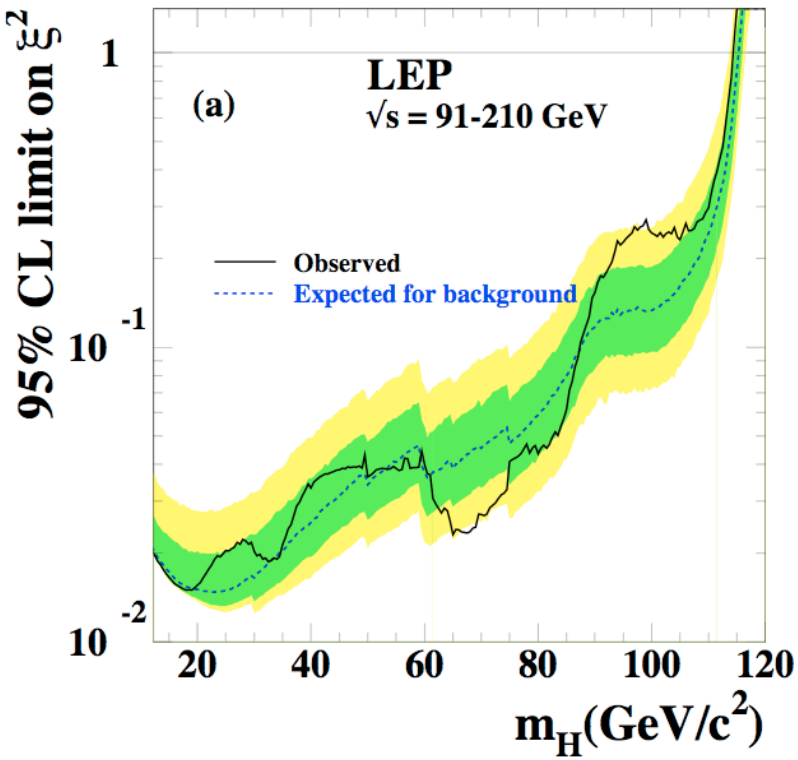
The LEP2 and Tevatron, LEP1, SLD Precision EW Legacy

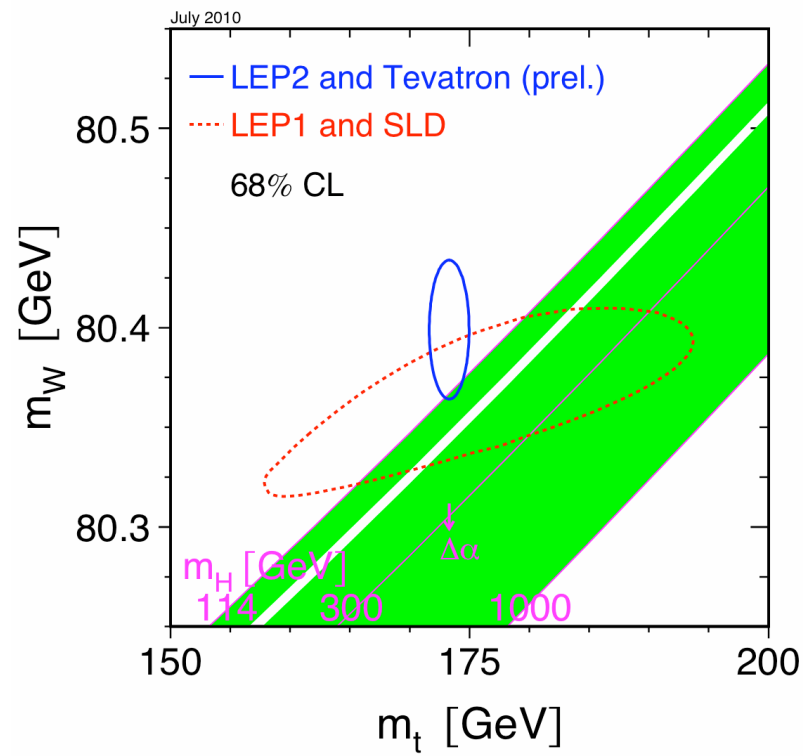
Direct searches for $e^+e^- \rightarrow ZH$: $m_H^{SM} > 114.4\ \mathrm{GeV}/c^2$

No evidence below

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

$$m_H^{SM} = 89^{+35}_{-26}\ \mathrm{GeV}/c^2$$





http://lepewwg.web.cern.ch/LEPEWWG

http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html

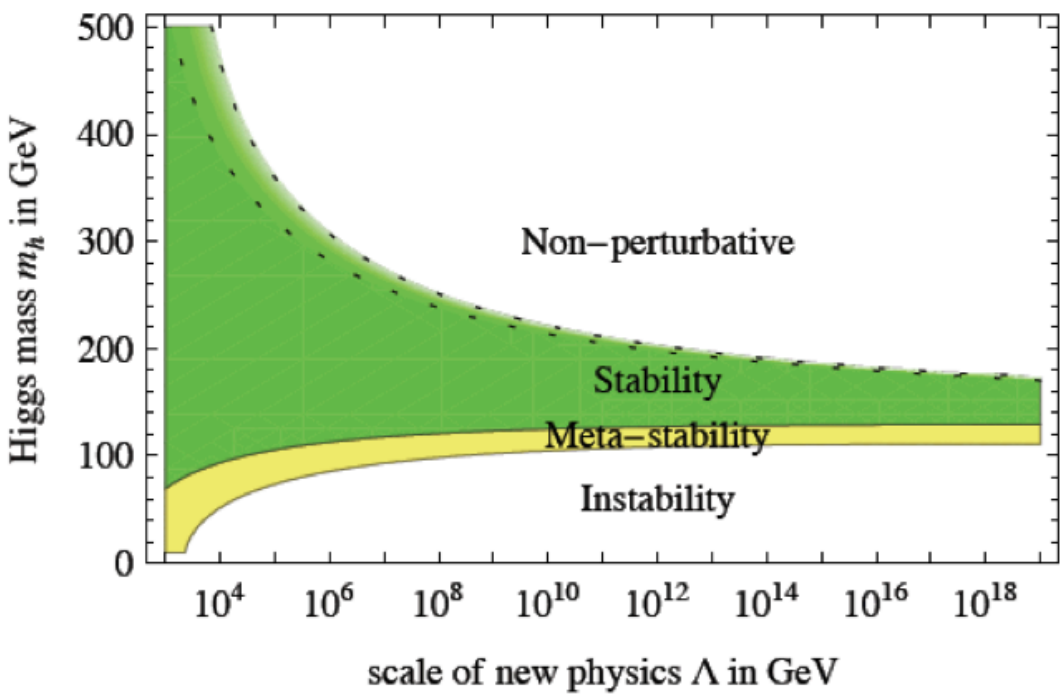
@95% CL, m_H<158 GeV/c^2

(185 including LEP2 direct limit)

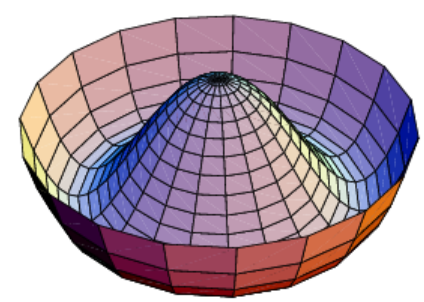
Vacuum Stability and Triviality Bounds on SM m_H

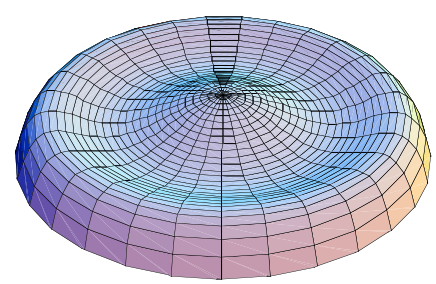
Loops with SM particles modify the effective Higgs potential.

Isidori, Rychkov, Strumia, Tetradis '08



Finding a Higgs boson with m_H "too low" or "too high" is suggestive of new physics.



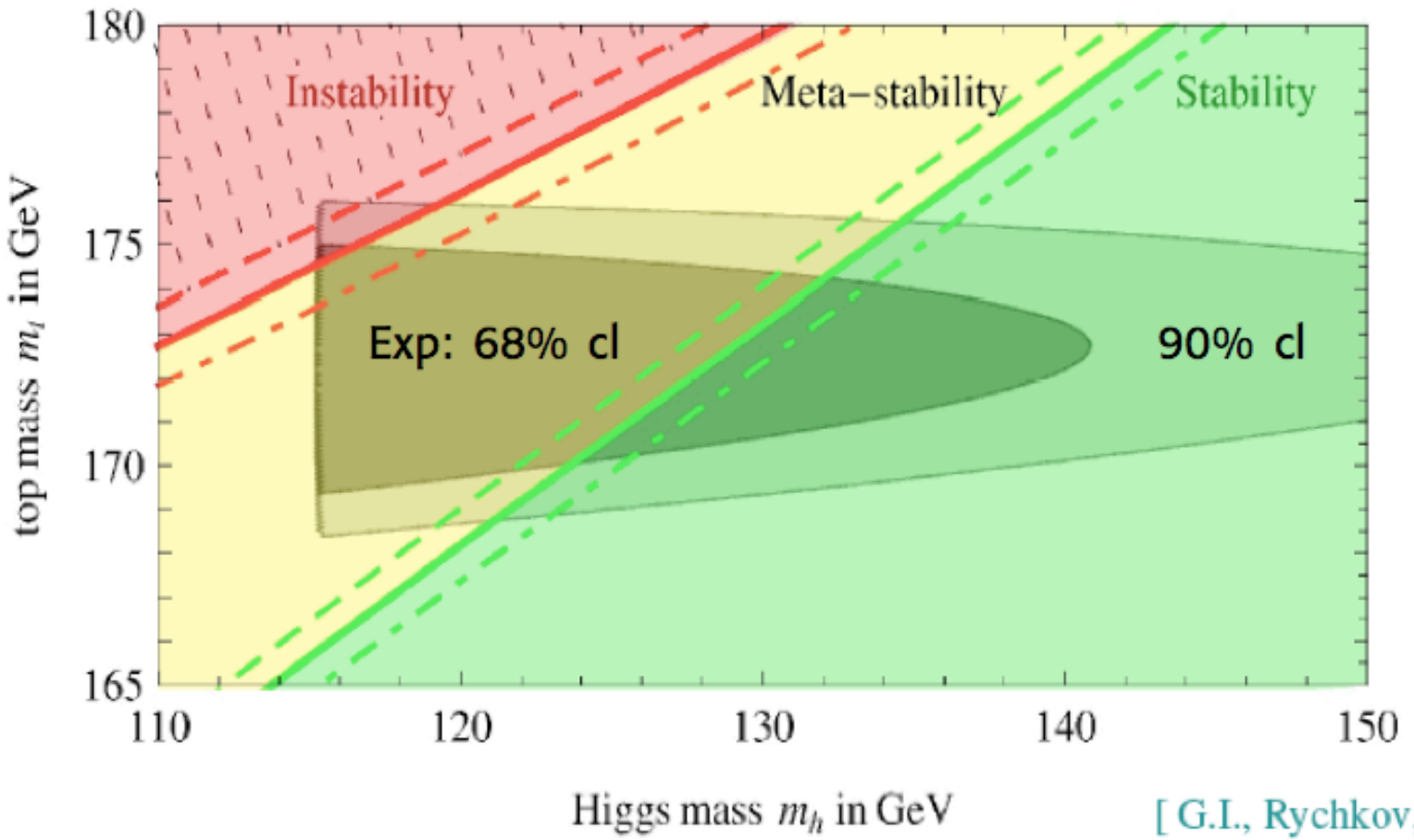


m_H too light!

See also hep-ph/9708416

Hambye and Riesselman

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

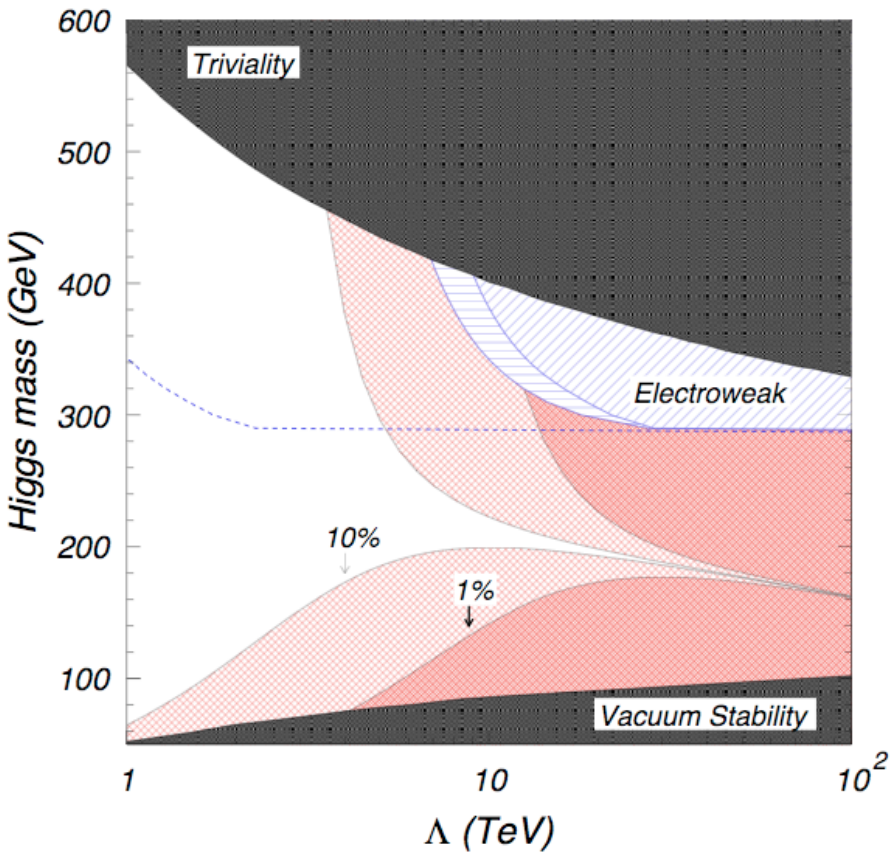


[G.I., Rychkov, Strumia, Tetradis '08]

- The unstable region is almost ruled out

a slide from G. Altarelli's HCPSS 2008 talk

How Much Fine-Tuning Can We Tolerate?



$$m_h^2 = 2\mu^2 = 4\lambda v^2$$

At one loop,

$$\mu^2 \to \mu^2 + \frac{\Lambda^2}{32\pi^2 v^2}\left(2M_W^2 + M_Z^2 + m_h^2 - 4m_t^2\right)$$

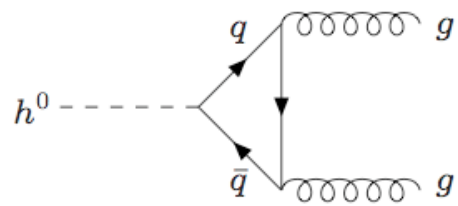
If the radiative corrections to m_h are not >> m_h, we get much stronger constraints. "Veltman Condition": term in parentheses vanishes.

C. Kolda and H. Murayama, JHEP **0007**, 035 (2000)
m_t=175 GeV

Higgs Boson Couplings to Gluons

H. Haber, HCPSS 2008

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



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

This diagram leads to an effective Lagrangian

Mostly top contributes

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

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

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

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

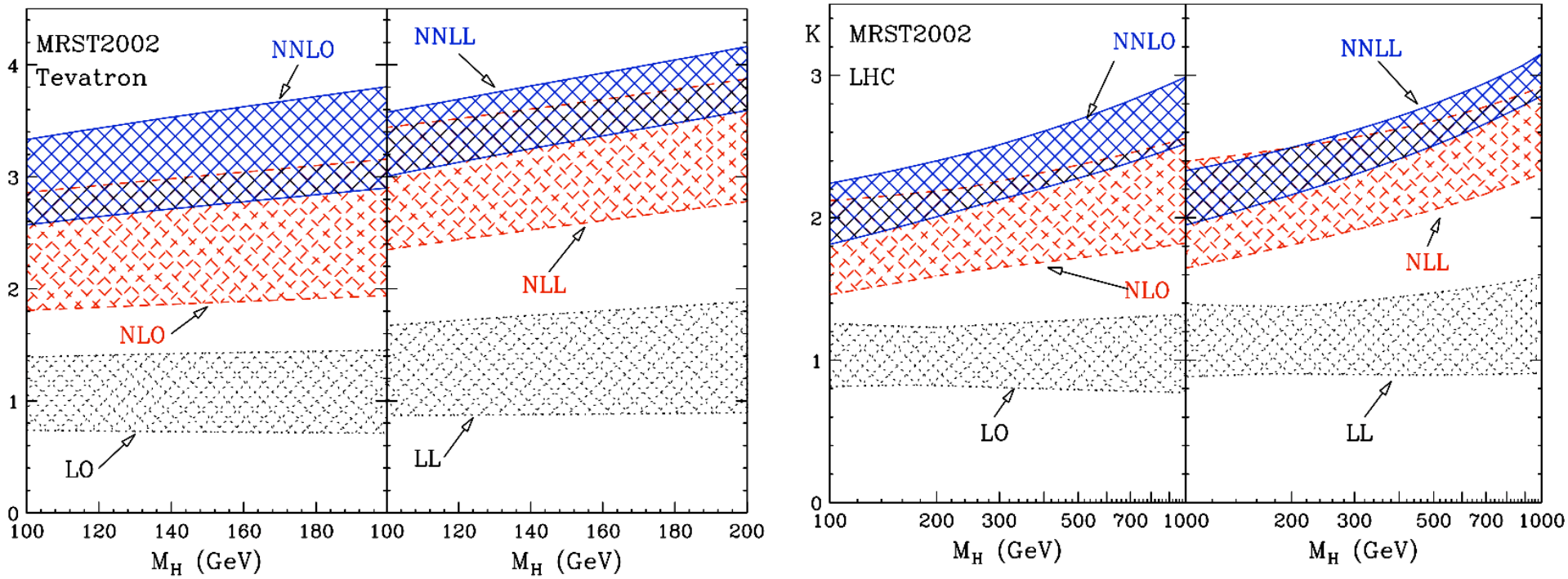
A heavy fourth generation of quarks would scale
the gg→H production rate at colliders by a factor of ~9.
But watch out for $H \to \nu_4 \bar{\nu}_4$ decays.

E. Arik et al., Acta Phys. Polon. B **37**, 2839 (2005) (hep-ph/0502050)

G. Kribs, T. Plehn, M. Spannowsky, T. Plehn, Phys. Rev. D **76** 075016 (2007). (**arXiv:0706.3718** [hep-ph])

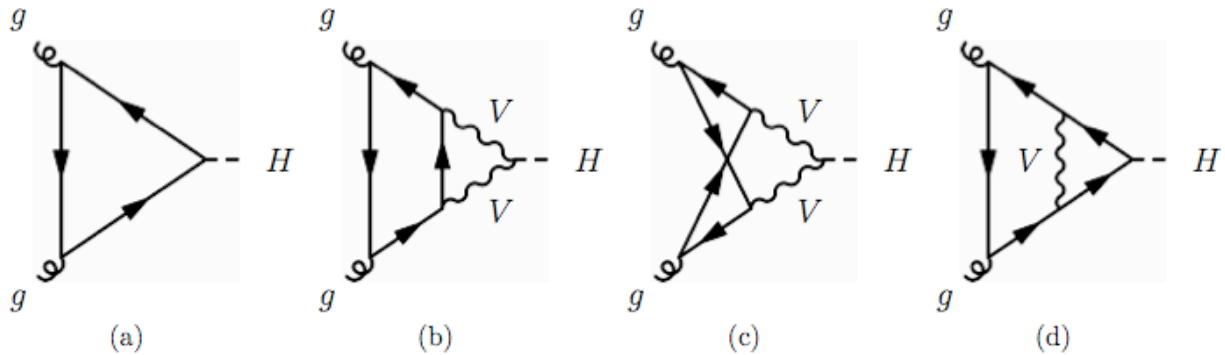
gg→H Production at NNLO

- NLO corrections -- ~80% (almost double the LO cross section)!
- NNLO QCD corrections -- An additional 40% on top of that!
  Catani, de Florian, Grazzini, Nason JHEP **0307**, 028 (2003) hep-ph/0306211
- Soft gluon resummation included at NNLL in plots below



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

Recent gg→H Production Cross Section Progress



"V"=W,Z

An active area of research over the last years

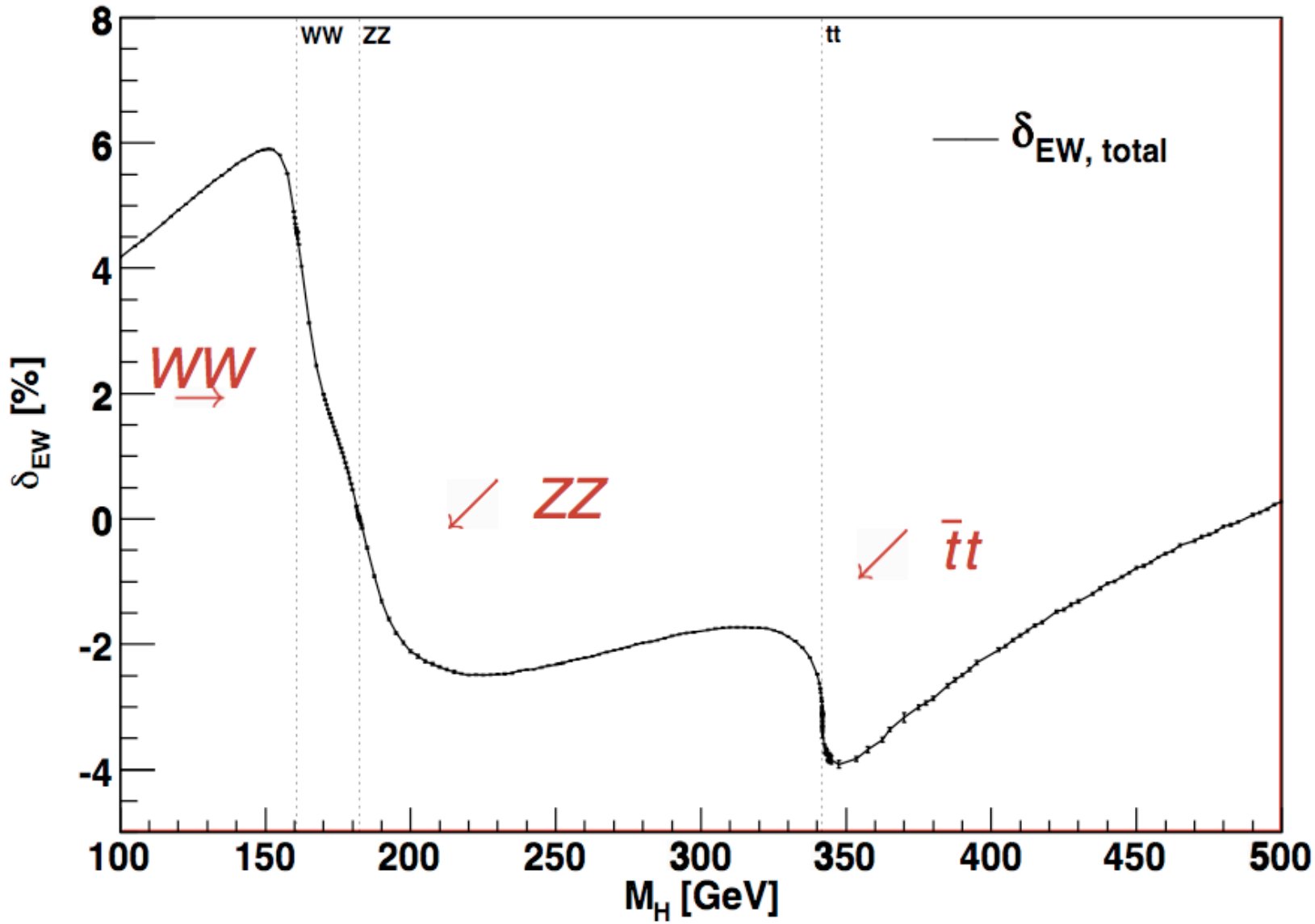
http://www.itp.uzh.ch/events/higgsboson2009 7-9 January 2009, Zurich

- Two-loop EW corrections yield up to an 6% boost in cross section near m_H=160 GeV. Aglietti, Bonciani, Degrassi and Vicini, arXiv:hep-ph/0610033 (used by the Tevatron at ICHEP 2008)
- Newer calculations: **Anastasiou, Boughezal, Petriello, JHEP 0904:003 (2009)**
  de Florian and Grazzini: Phys. Lett. B 674:291-294 (2009)
  More modern PDF set -- MSTW 2008 NNLO (lost 14% of cross section rel. to MRST 2006 NNLO)
  Bottom quark loops interfere destructively with top quark loops
    - Bottom quark loop contributions get smaller QCD corrections than top loops.
    - Running b mass is smaller than pole mass.

  Less contribution from b loops means more cross section

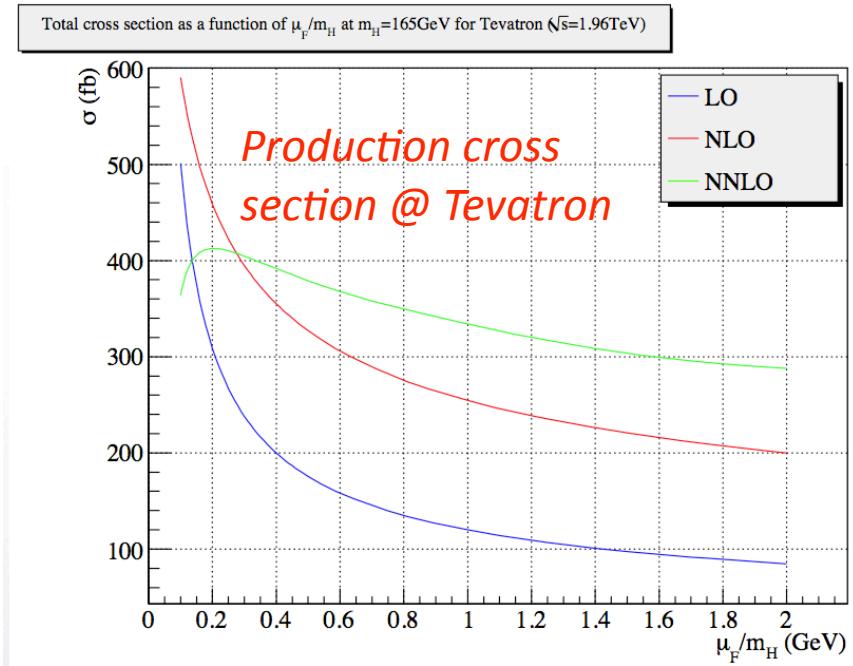
  Coincidentally almost the same cross section relative to NNLO QCD (Catani et. al) at m_H=160 GeV -- 0.44 pb at the Tevatron.

EW corrections to σ(gg→H)

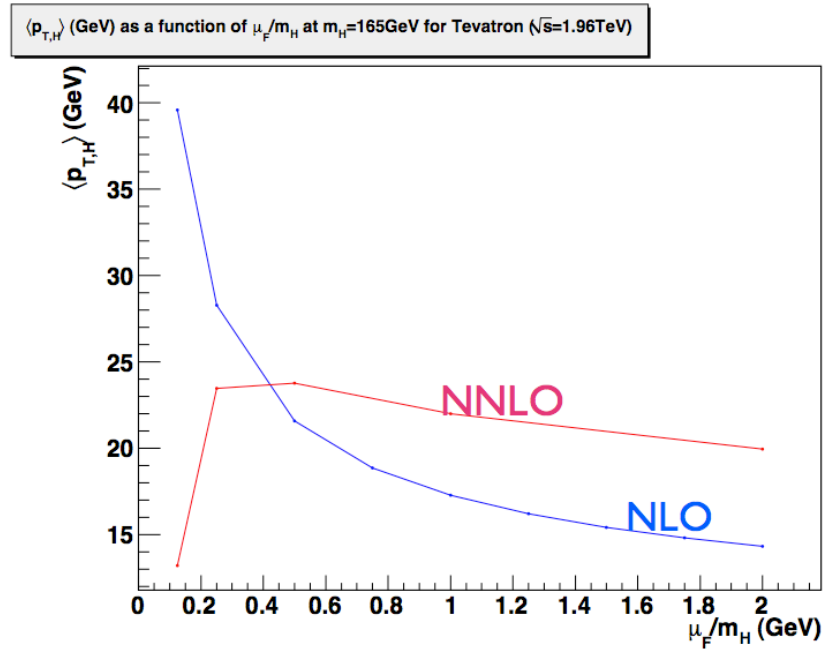


Passarino, Higgs Boson 2009, Zurich

Choosing the Right Factorization and Renormalization Scale and Uncertainty



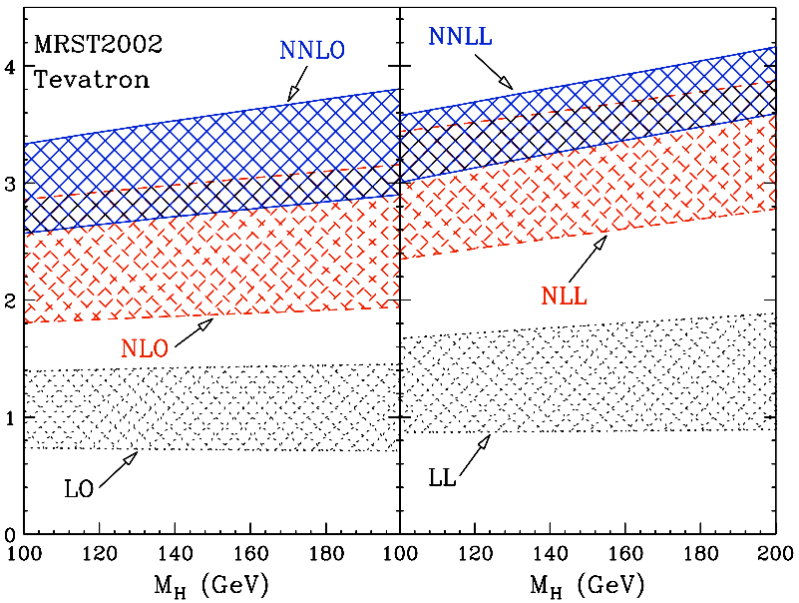
C. Anastasiou, Orsay 2010 (www.higgshunting.fr).

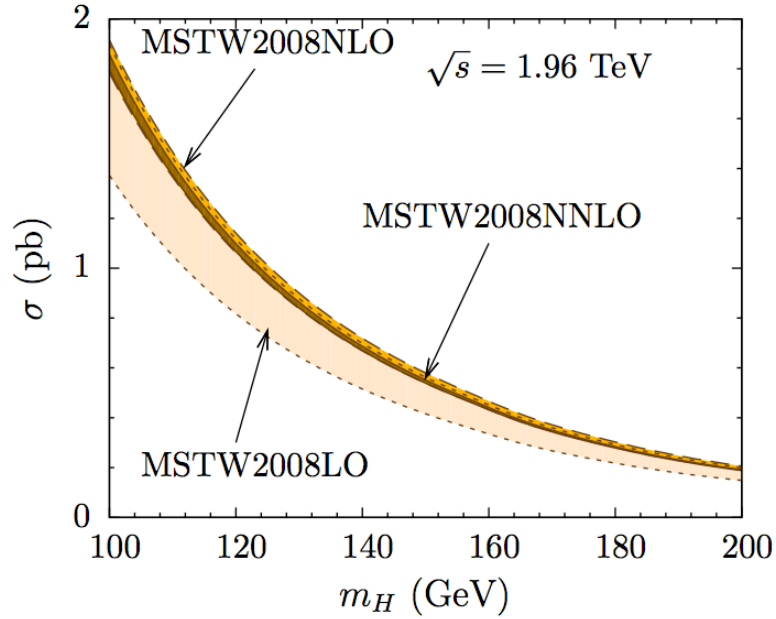


Average pt @ Tevatron

- Several points cleared up with Baglio and Djouadi – concerns raised in arXiv:1003.4266
  - Best scales are low – $m_H/2$ provides much more stability for fixed-order calcs
  - Setting $\mu_r = \mu_f$ gives the largest variation in cross section and makes more sense than exploring the (μ_r, μ_f) plane

Scale Variation – A factor of Two or Three?





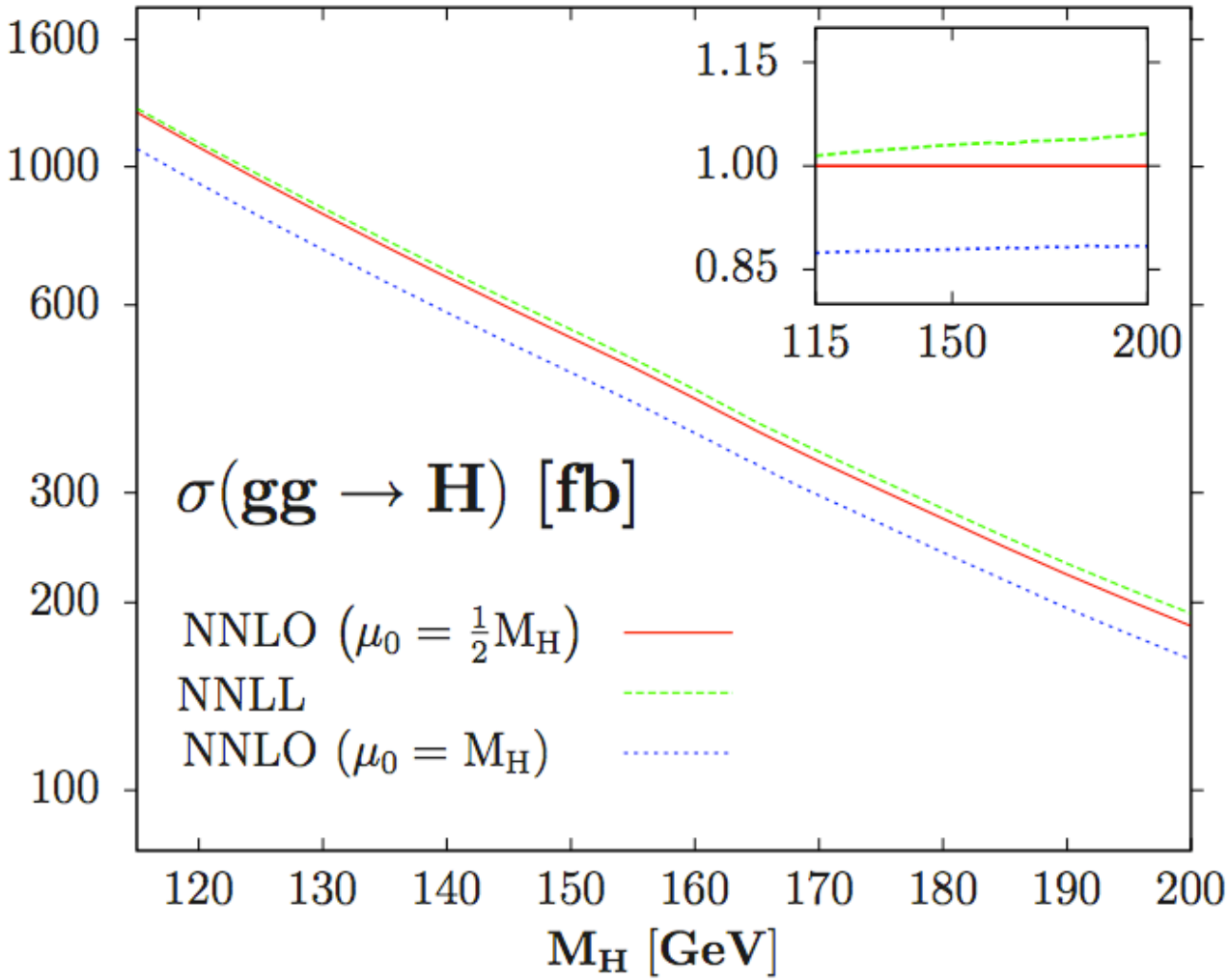
Ahrens, Becher, Neubert, Yang 2010

Perturbative series converges faster when a more detailed calculation is performed:

- RG improvement
- soft-gluon resummation
- using the PDF set which corresponds to each order

- LO calculation with no gluon emission isn't sufficiently sensitive to the scale to trust it to gauge scale uncertainty

Is it Fair to use the NNLL Cross section?



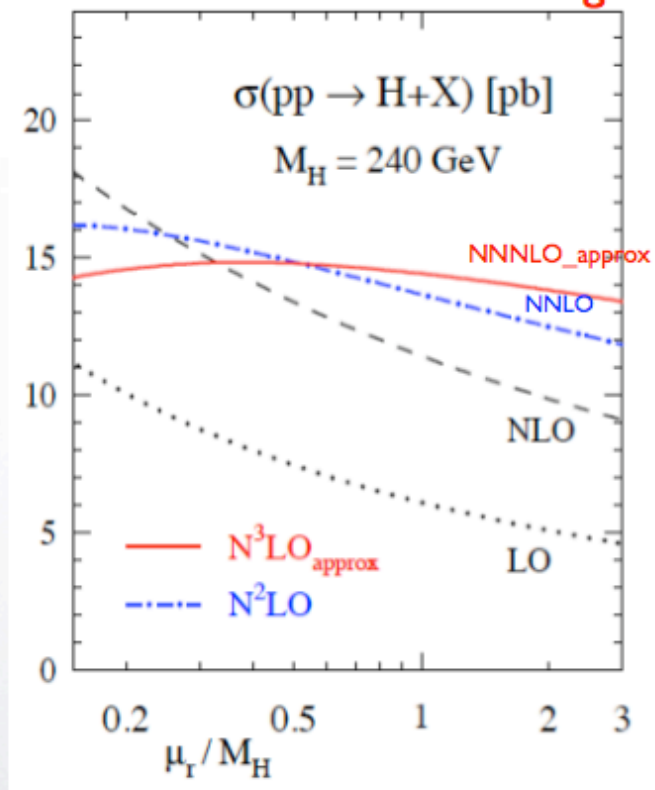
Baglio and Djouadi, arXiv:1009.1363

At $\mu_r = \mu_f = m_H/2$, the NNLL addition to the NNLO cros section is negligible

Missing higher orders?

- A small scale leads to a faster convergence from NLO to NNLO.
- Are we missing even higher order effects
- A lot is known from threshold resummation methods.
- Small mu scales are safe!

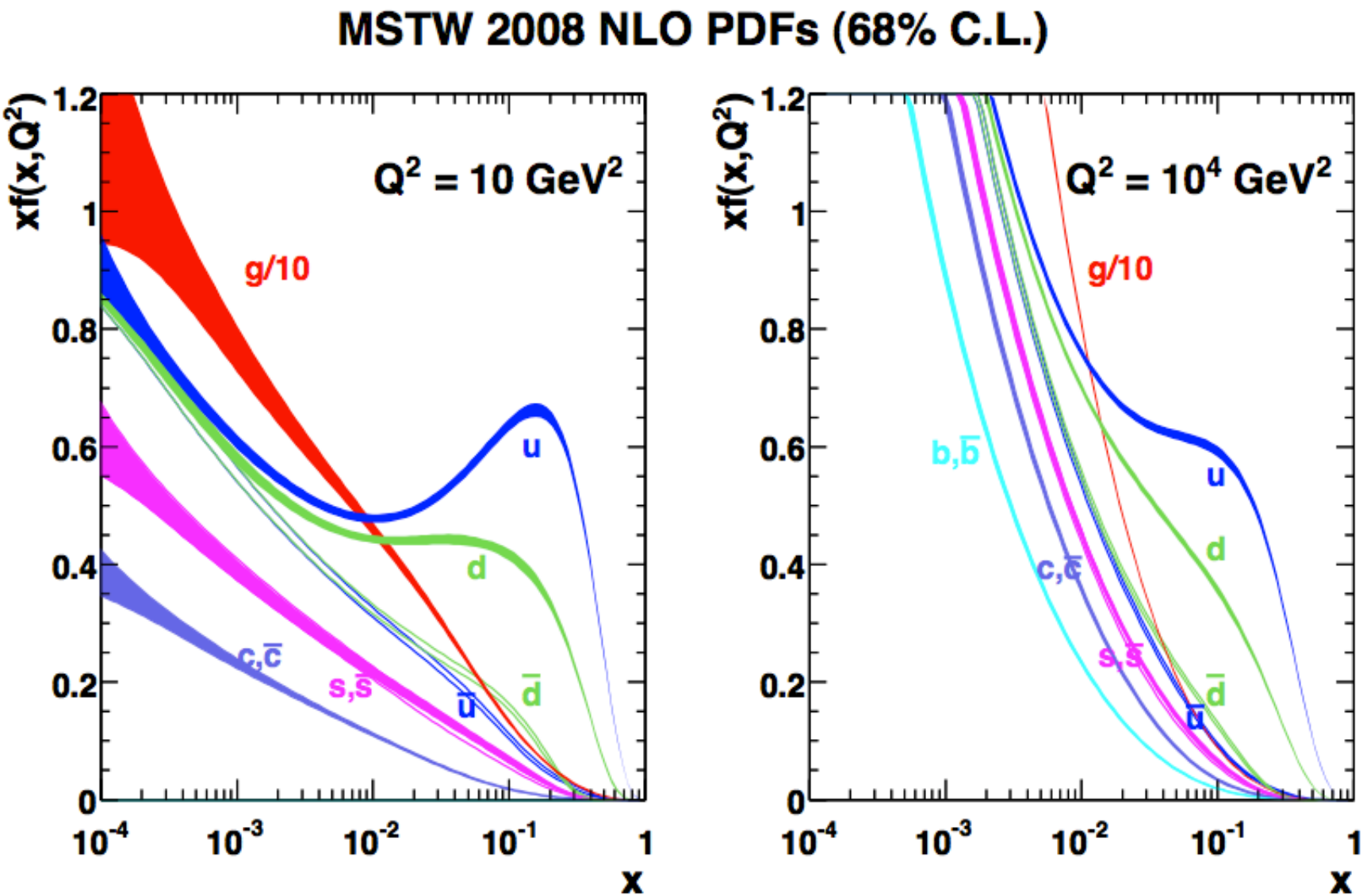
Moch and Vogt



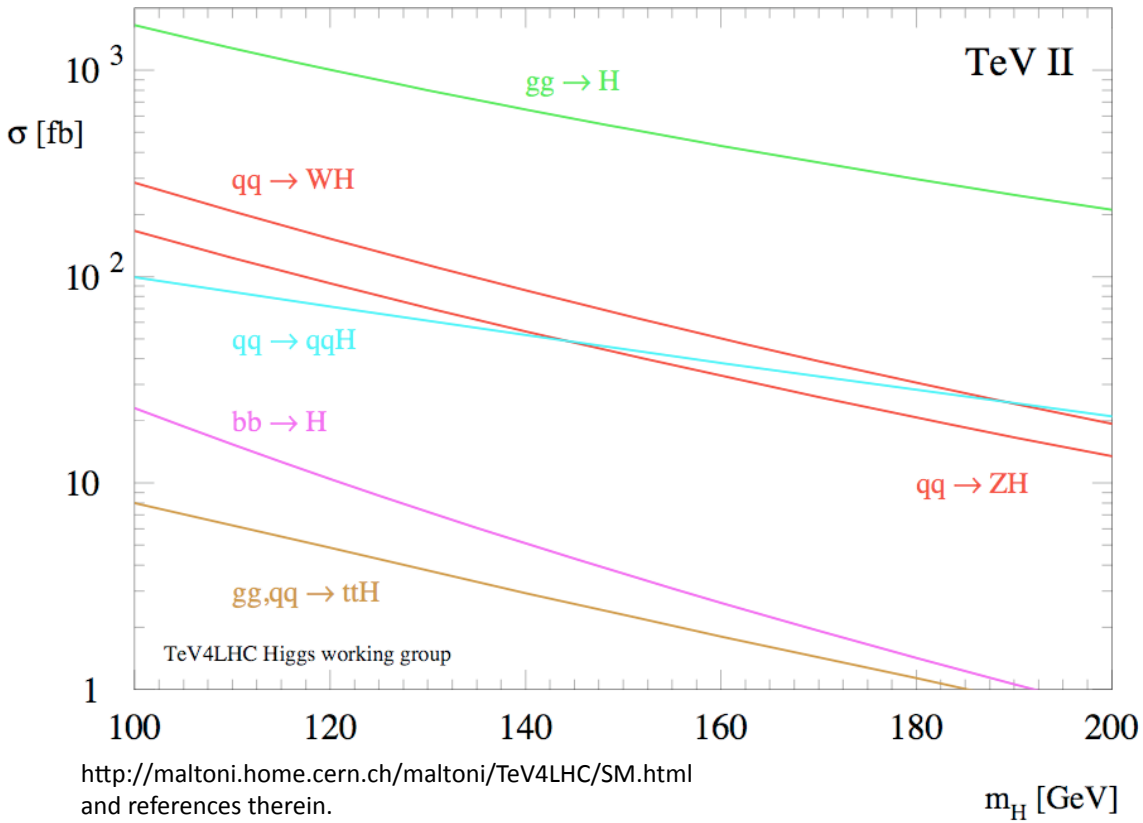
Slide from C. Anastasiou, higgshunting.fr

It does not look as if there are large negative contributions at much higher order, and a scale of $m_H/2$ seems stable.

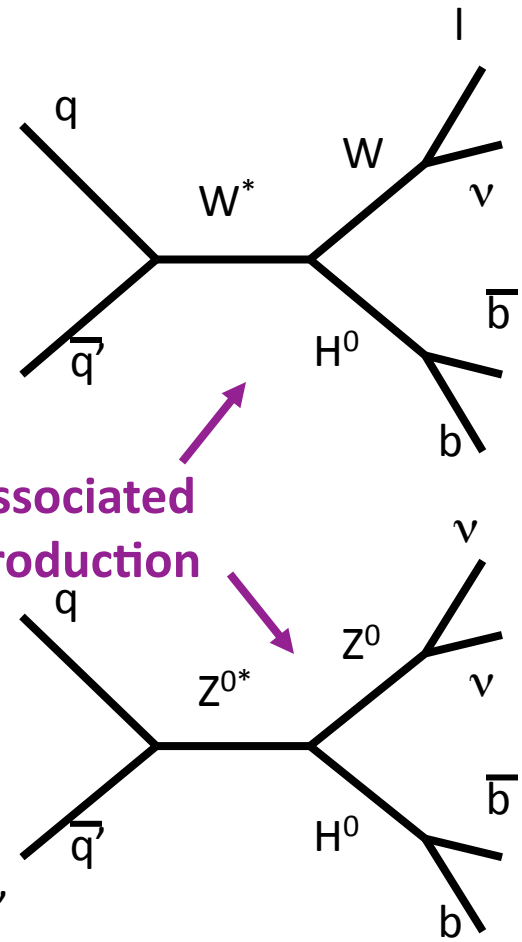
Parton Distribution Functions of the Proton



SM Higgs Boson Production Mechanisms

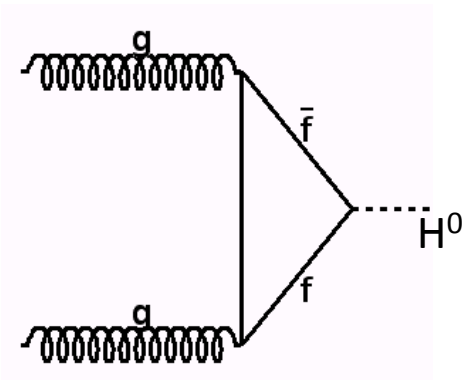


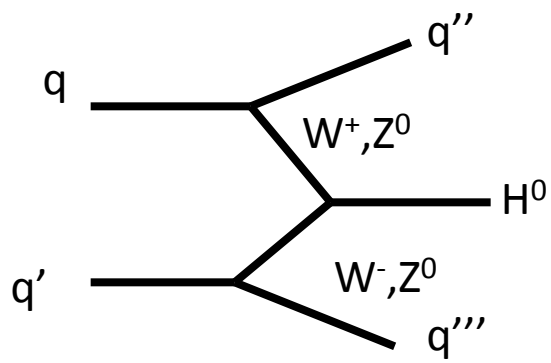
http://maltoni.home.cern.ch/maltoni/TeV4LHC/SM.html
and references therein.



Associated Production

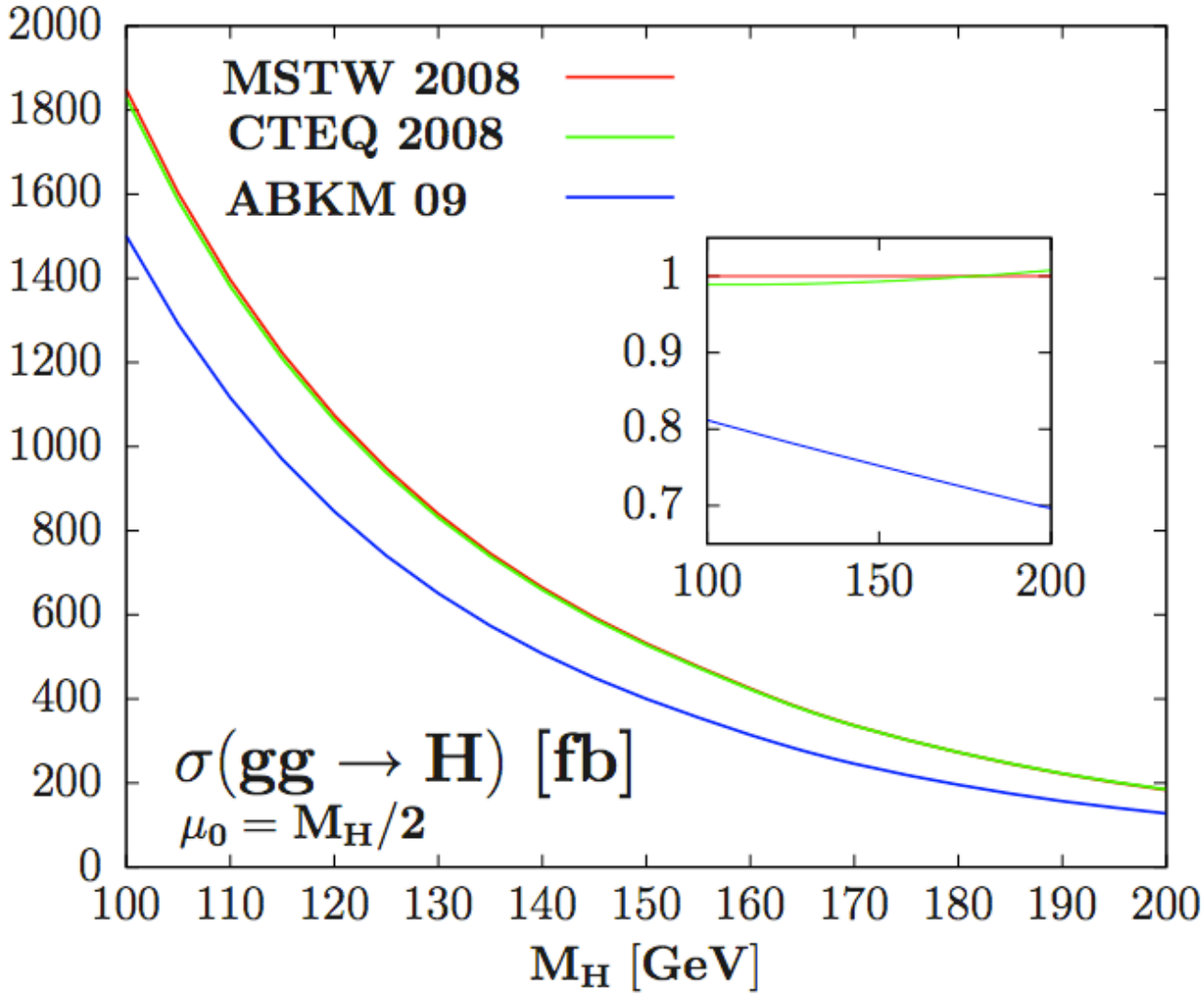
gluon fusion





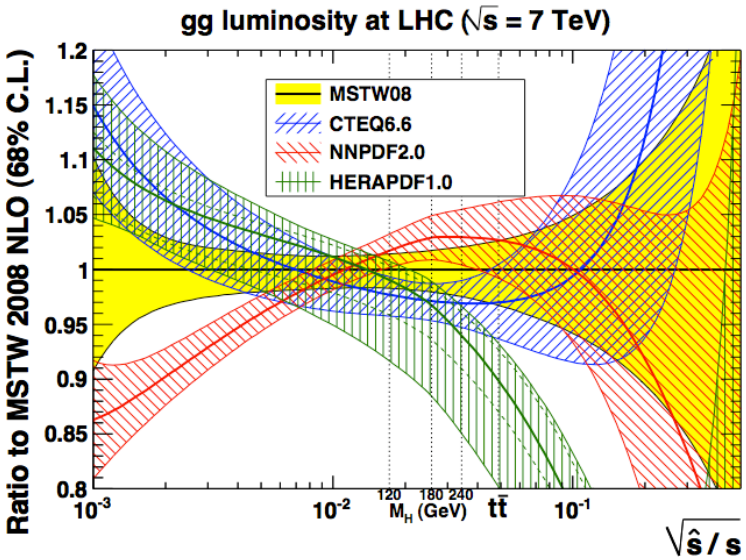
Vector-Boson Fusion (VBF)

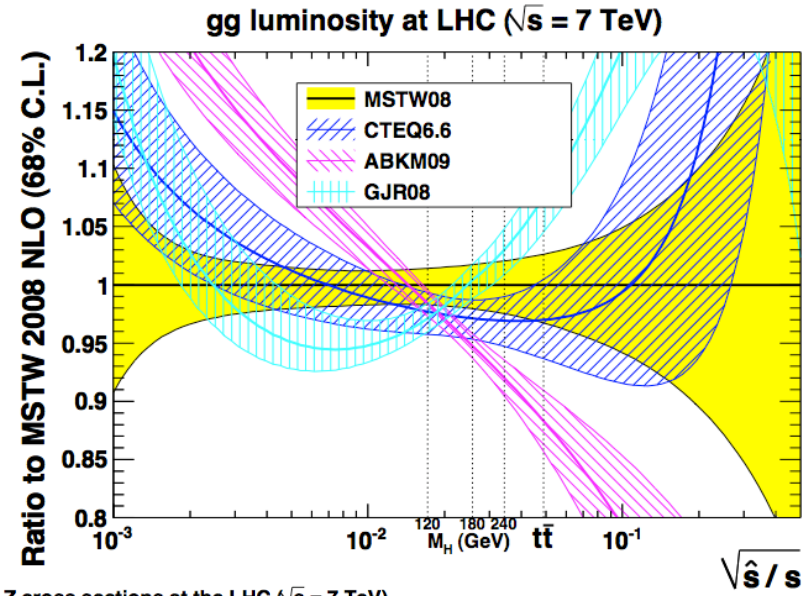
Which PDF Sets to Use?

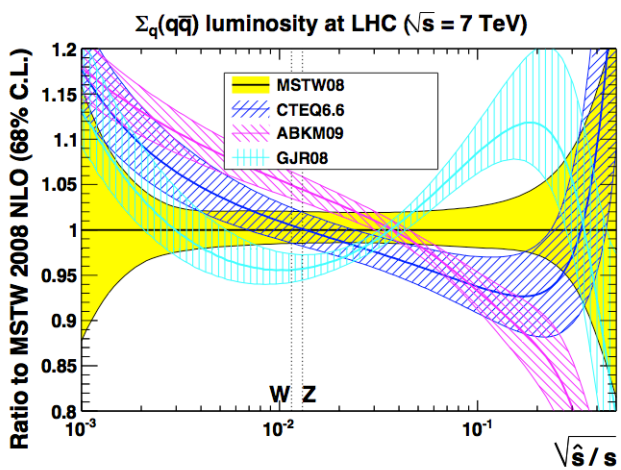


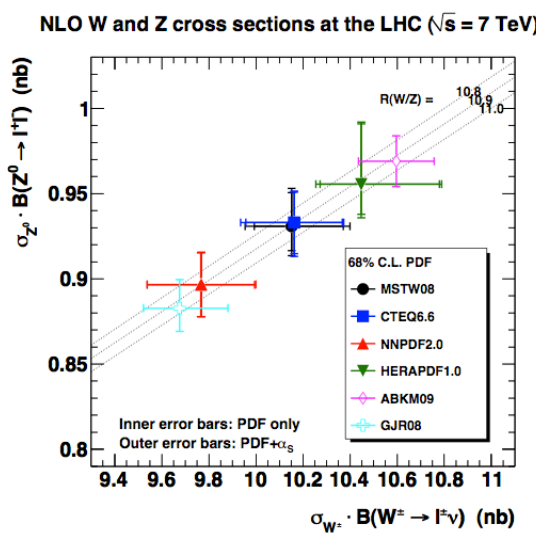
Baglio and Djouadi suggest taking the difference in the predictions of gg→H using ABKM09 and MSTW2008, CTEQ2008 PDF's as a systematic uncertainty

Variations in Predictions for Different PDF Sets









Very Measurable! (but need luminosity!)

R. Thorne, Higgs Hunting Orsay Workshop, 2010

ABKM and HERAPDF do not include Tevatron high-E_T jet data in their fits. High-x gluons are poorly constrained without those

PDF4LHC recommendation: Use CTEQ, MSTW, NNPDF as an envelope.

gg→H Cross Section Theoretical Uncertainties

- Recent Work: Anastasiou, Dissertori, Grazzini, Stockli, and Webber JHEP 0908 099 (2009).

Factorization and Renormalization scale variations are larger when requiring 2+ jets than for requiring fewer. Errors correlated, not anticorrelated. Get worse when applying other experimental cuts

σ [fb]	LO (pdfs, α_s)	NLO (pdfs, α_s)	NNLO (pdfs, α_s)
0-jets	$3.452^{+7\%}_{-10\%}$	$2.883^{+4\%}_{-9\%}$	$2.707^{+5\%}_{-9\%}$
1-jet	$1.752^{+30\%}_{-26\%}$	$1.280^{+24\%}_{-23\%}$	$1.165^{+24\%}_{-22\%}$
$\geq$ 2-jets	$0.336^{+91\%}_{-44\%}$	$0.221^{+81\%}_{-42\%}$	$0.196^{+78\%}_{-41\%}$

Table 2: Inclusive cross sections in the different jet bins.

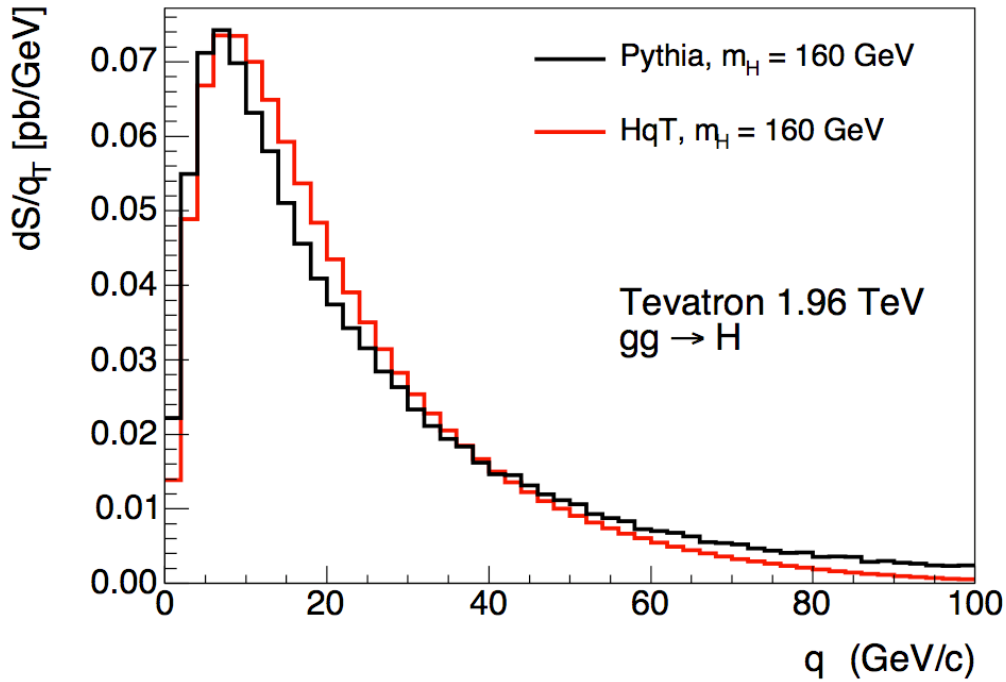
$$\frac{\Delta N_{\text{signal}}(\text{scale})}{N_{\text{signal}}} = 60\% \cdot \binom{+5\%}{-9\%} + 29\% \cdot \binom{+24\%}{-23\%} + 11\% \cdot \binom{+91\%}{-44\%} = \binom{+20.0\%}{-16.9\%}$$

Scale variation is up and down by a factor of two. Djouadi (Moriond EW 2010, arXiv:1003.4266) advocates a larger variation – currently under discussion.

Experimental issue – how to incorporate?

- Traditional: Set limits on σ x Br. Draw theory curve on same plot with error bands. Take -1σ variation on theory as the excludable prediction (why?)
- We have a problem. Combine gg→H with WH, ZH, and VBF signal searches. What's the error on the theory band now? What cross section do we exclude?
  Solution: Treat theory uncertainties like acceptance uncertainties (when it comes to the kinematics, they are hard to separate anyhow). PDF in particular should be treated as a nuisance parameter like all others.

Reweighting Pythia Differential Distributions to NLO+NNLL Predictions

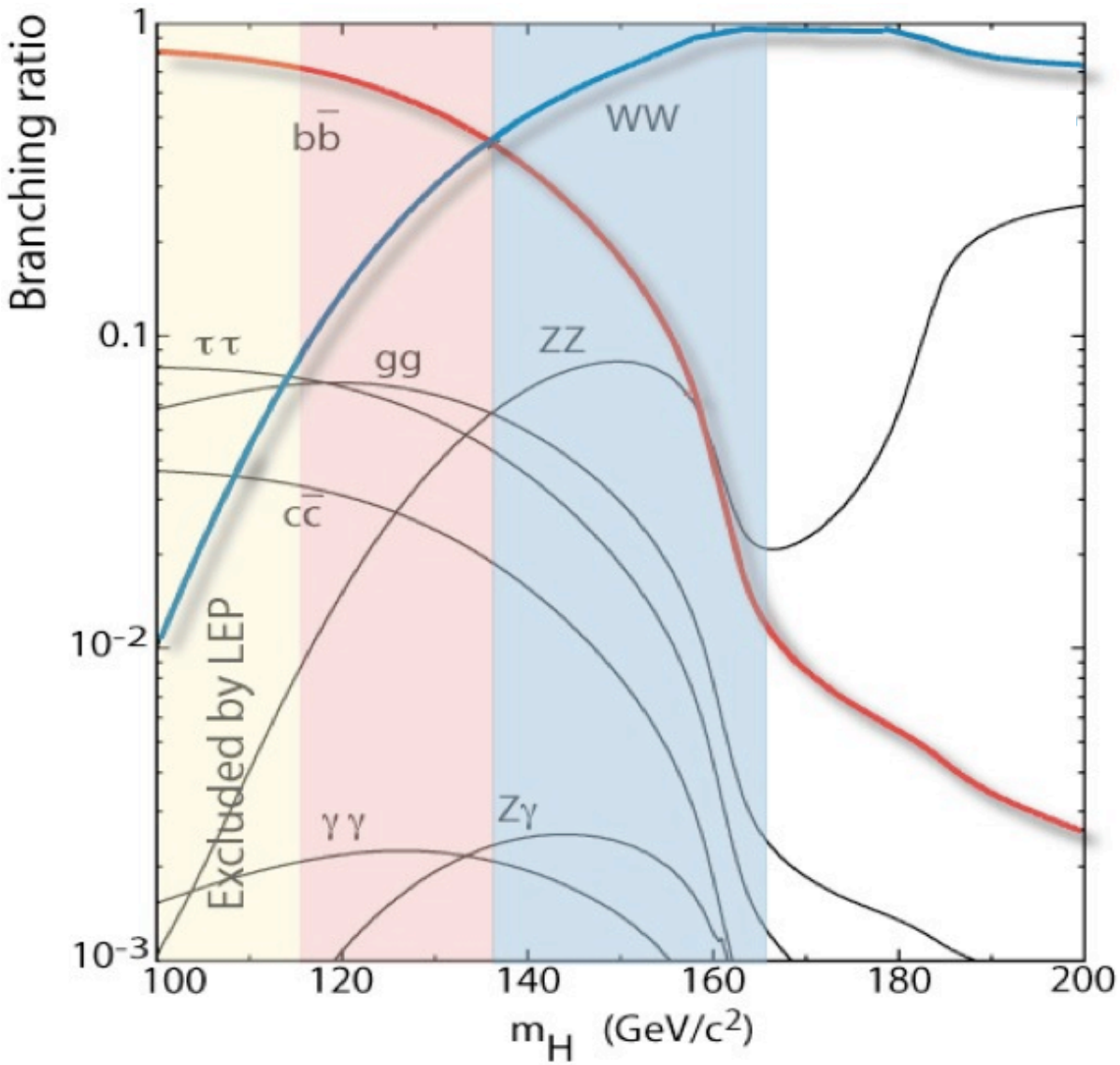


HqT program Catani and Grazzini, http://theory.fi.infn.it/grazzini/codes.html used to compute higher-order differential spectra

Formerly taken as a systematic uncertainty, now is a central value.

Scale and PDF dependence of Higgs p_T and η used as rate and shape systematics

Standard Model Higgs Boson Decay Branching Fractions



HDECAY by
M. Spira

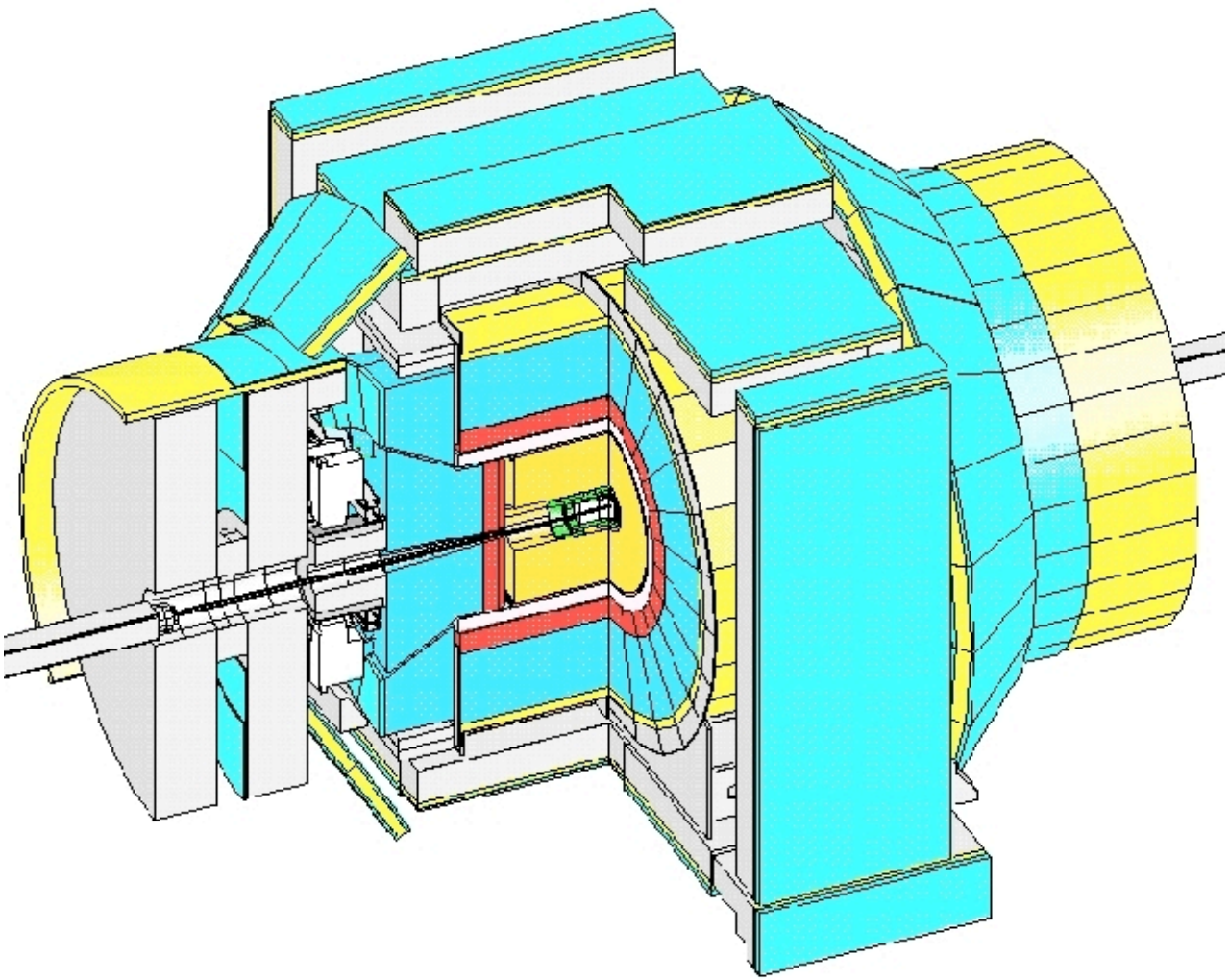
$114.4 < m_H < 135$ GeV:
$H \rightarrow bb$ dominates.

$gg \rightarrow H \rightarrow bb$ drowned by $gg \rightarrow bb$. Use WH, ZH.

$135 < m_H < 200$ GeV
$H \rightarrow W^+W^-$ dominates

$gg \rightarrow H$, WH, ZH, VBF all can be used

The CDF II Detector



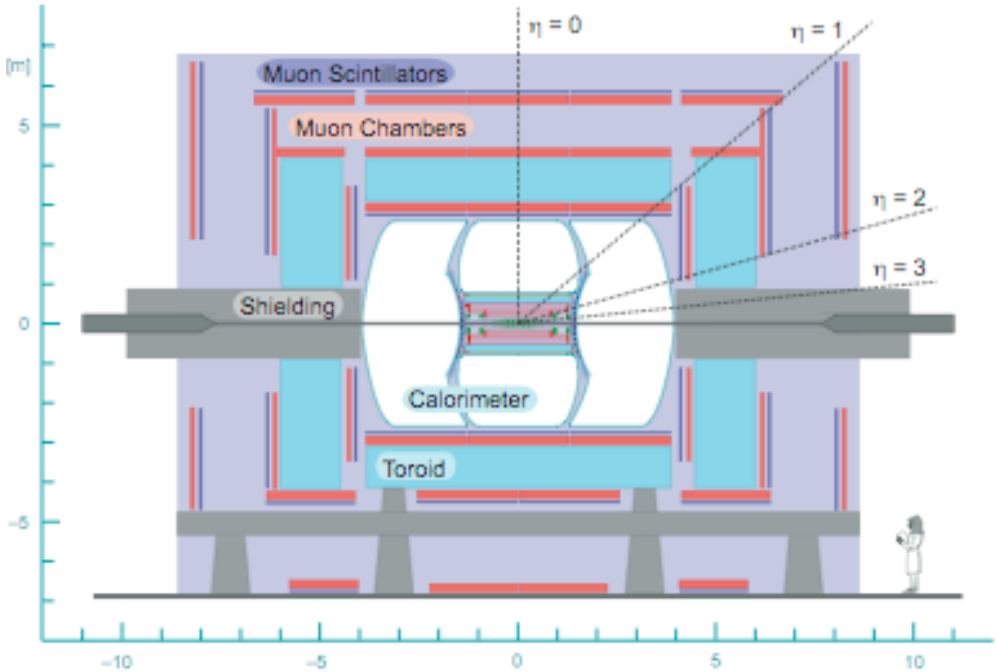
Lepton coverage:
$|\eta| < 1.5$ (muons)
$|\eta| < 2.0$ (electrons)

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)

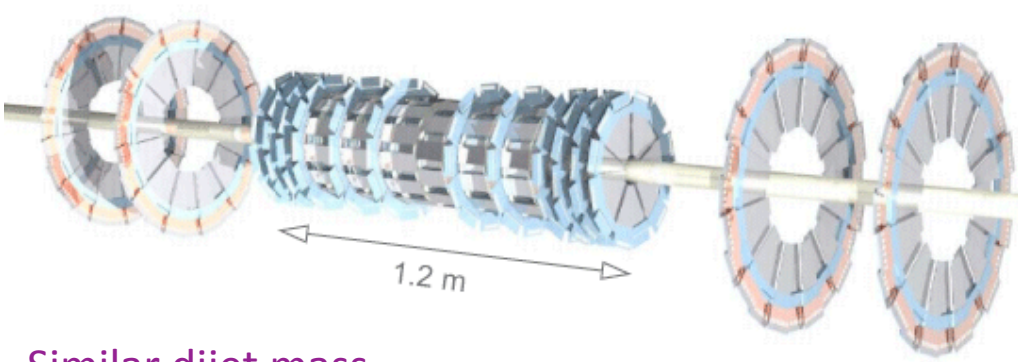
|η| < 2.6 (electrons)

b-tagging with

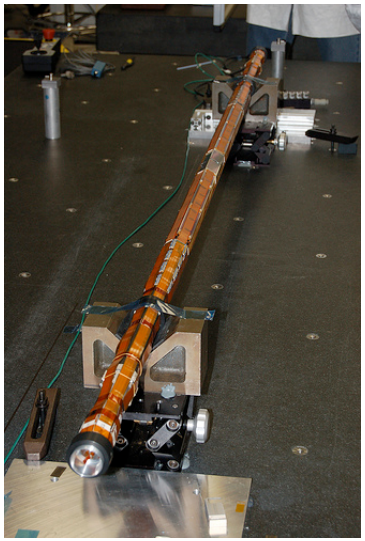
|η| < ~2

Jets to

|η| < 3



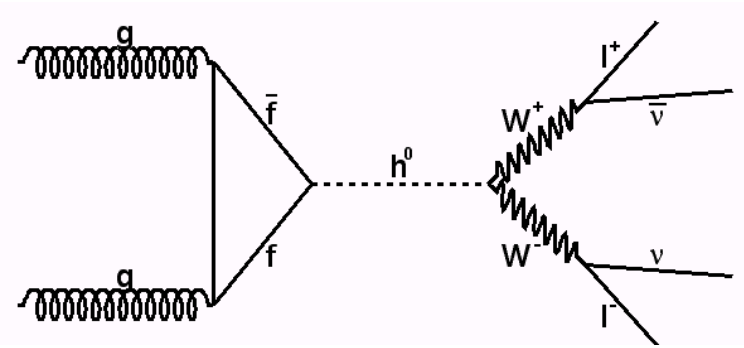
Similar dijet mass resolution to CDF



New Innermost Silicon Layer added between Run IIa and Run IIb

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

gg→H Signal Process:



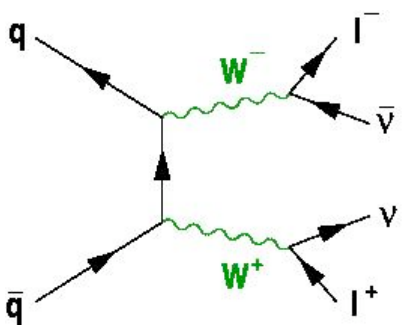
Both CDF and D0 Select events with

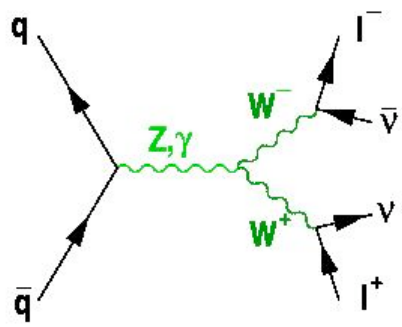
- Two isolated, opposite-signed high-p_T leptons (e,μ)
- Missing transverse energy
- m_{ll} > 16 GeV (except now with a new low m_{ll} analysis from CDF)

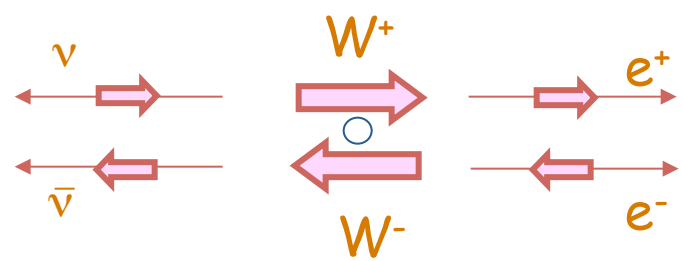
Dominant difficult background:

$qq \Rightarrow W^+W^-$

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

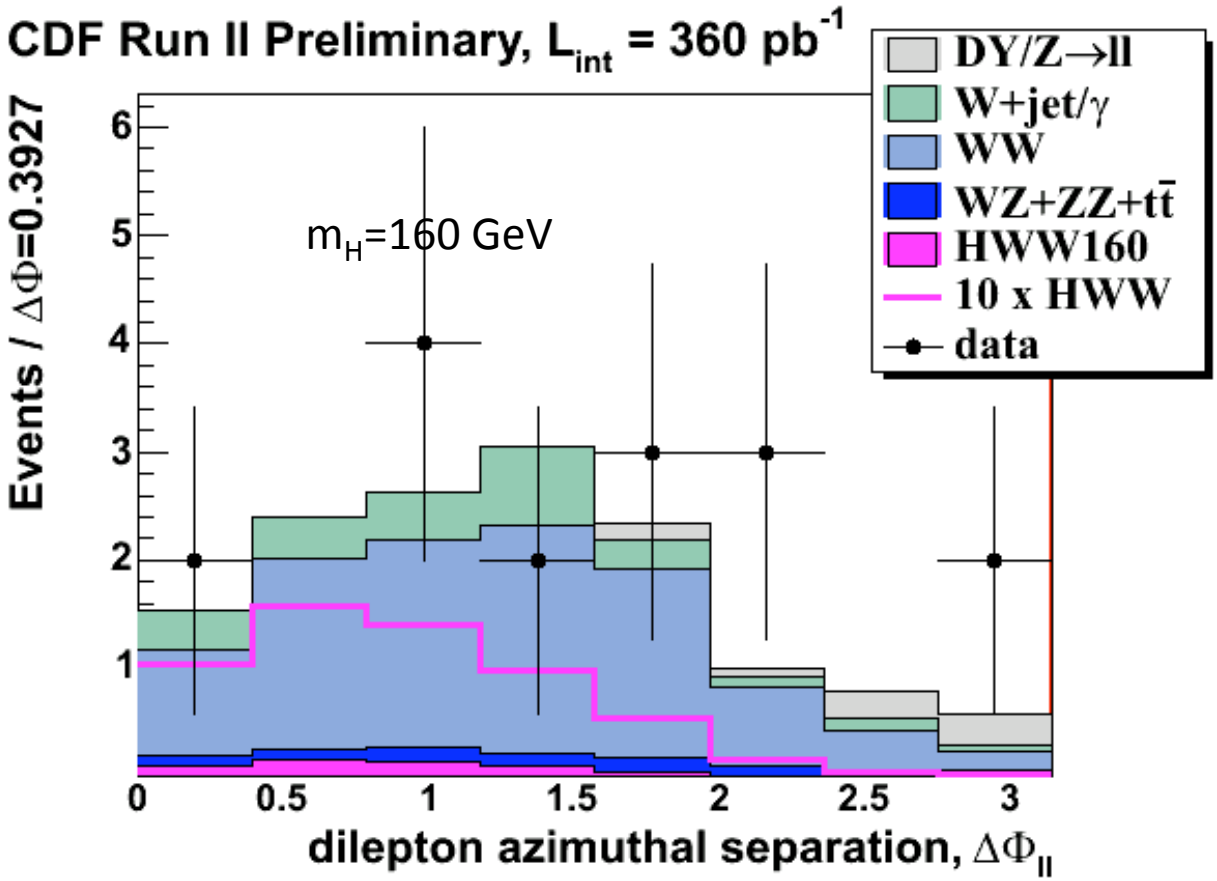






Five Years ago: 2005 CDF H→WW Analysis

- 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

Splitting up H→WW Into Subsamples

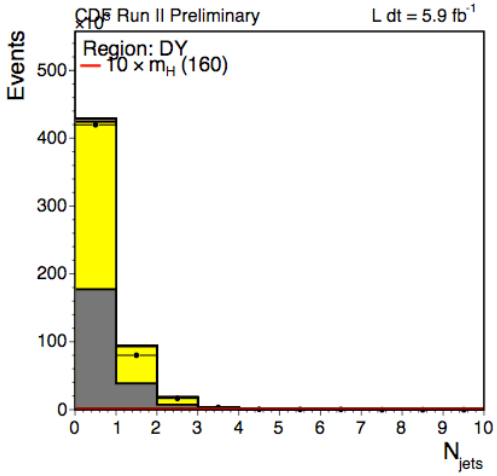
- Original analysis vetoed on extra jets
- But We can analyze these events one category at a time
  - WW+0 jets : gg→H. Mostly gg→H, but add in WH, ZH, VBF here (6% more signal expectation)
  - WW+1 jet : gg→H, WH, ZH, VBF signals (20% more signal than just gg→H)
  - WW+2 jets (or more) 60% more signal from WH, ZH and VBF. – most of the signal! Main background is t-tbar. Veto events with b-tags and use them as a control region
  - Total CDF acceptance summer 2009: 1.1%: **DOUBLE the 2005 acceptance**. Further improvements since then!

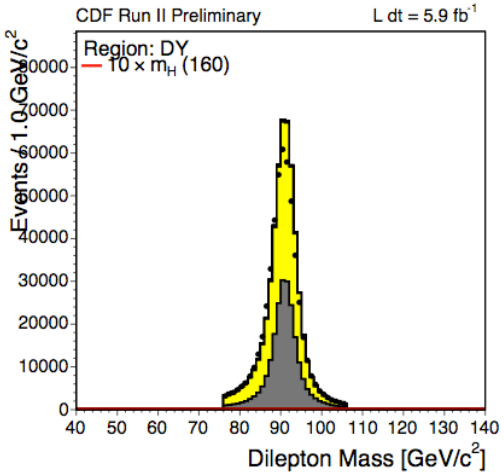
    Comparable MET resolution for different lepton categories – ee, eμ, μμ handled together. Forward leptons treated differently from central leptons since the fake rates are different. Called High s/b (central leptons) and Low s/b (forward)

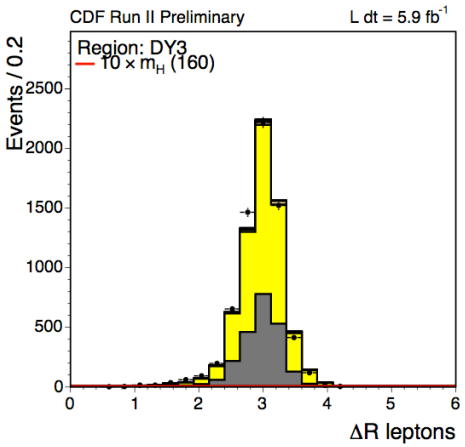
  - Same-sign dileptons + one or more jets: Mostly sensitive to WH and ZH, with leptonic W, Z decay.
  - New for Summer 2010: Channels with one lepton and a hadronic tau candidate, and also two new trilepton channels

Each major background has a dedicated control sample

Drell-Yan Control Region

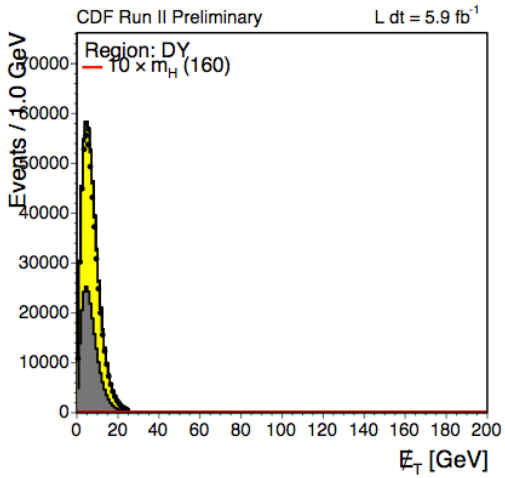


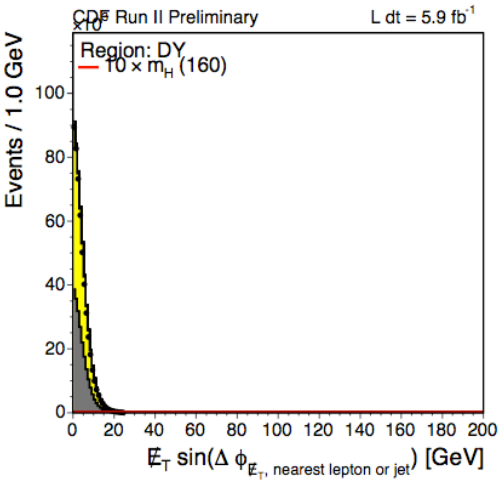




Opposite-sign, same-flavor leptons

MET<25 GeV
76<M_{ll}<106 GeV



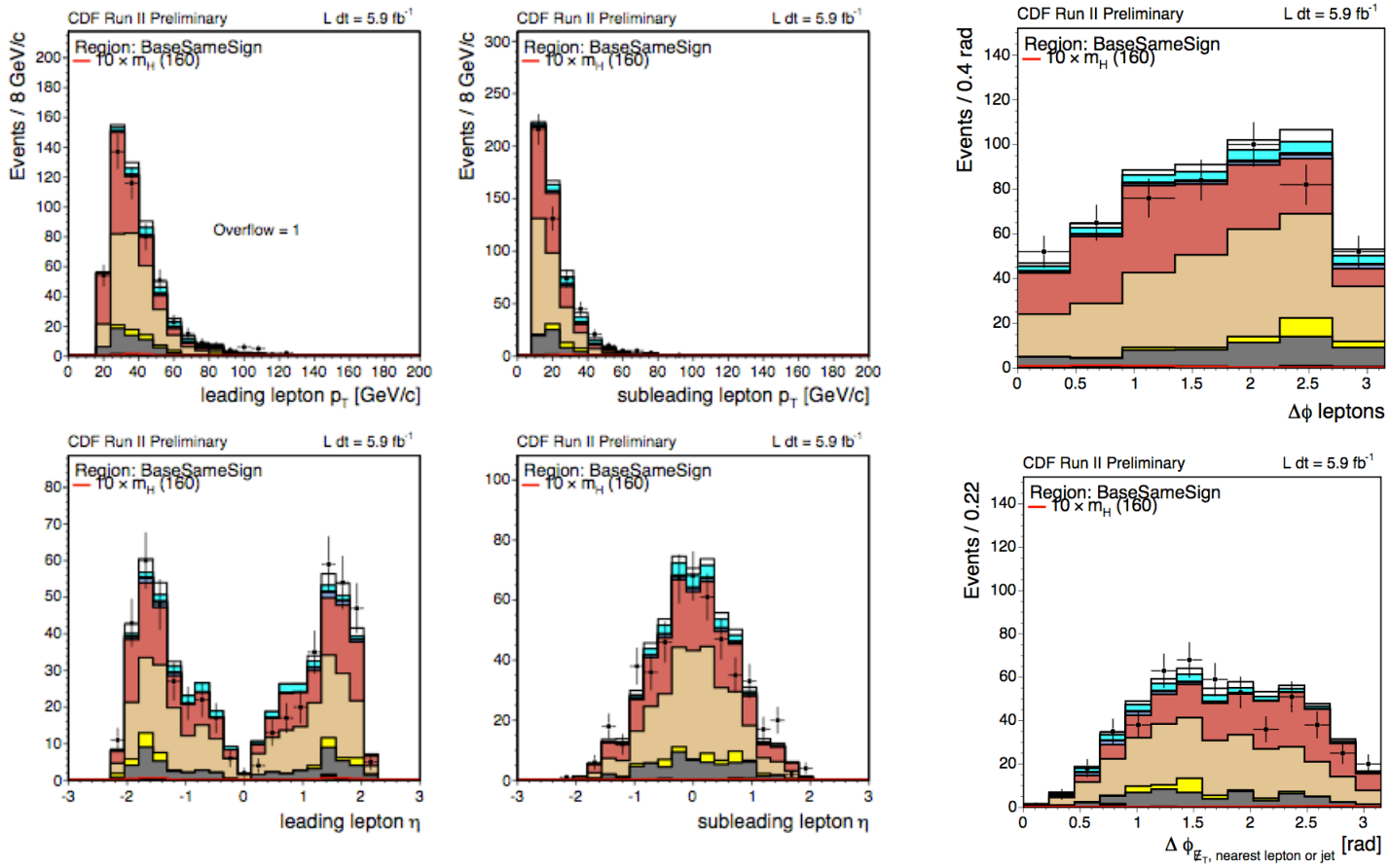


Same Sign Dilepton Control Region

Wγ, W+jets backgrounds

Low-m_{ll} Same Sign is used to constrain the Wγ background

W+jets data times a fake rate function gives W+jets background



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.

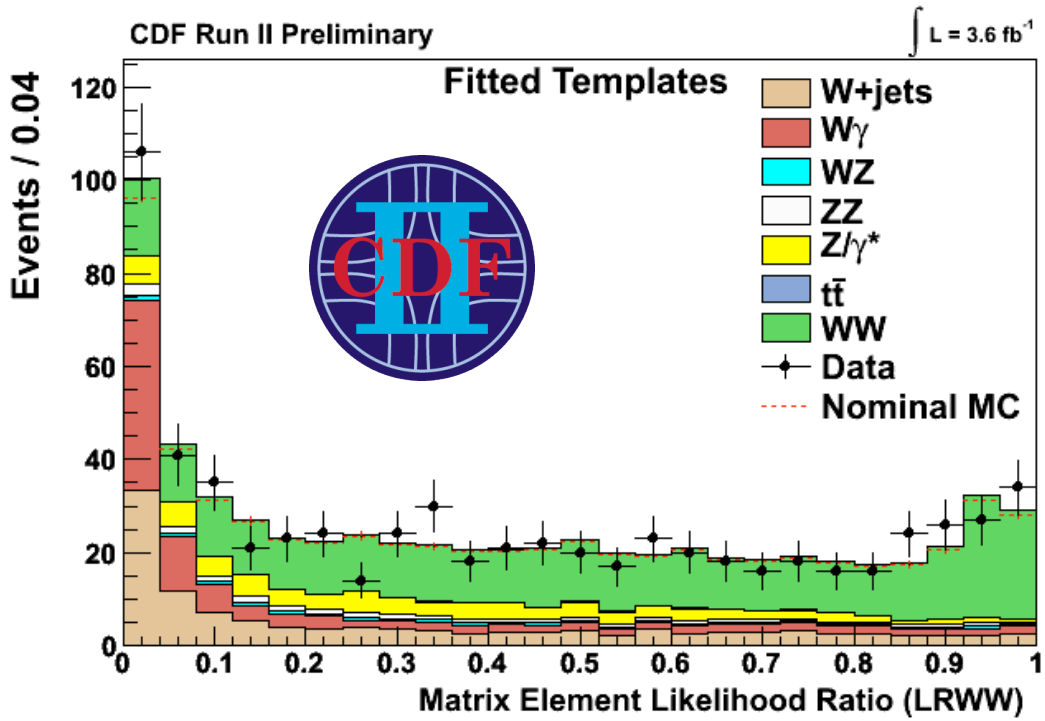
Do this for each physics process -- form a likelihood ratio from them

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



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

SM: 12.4 ± 0.7 pb (MCFM)

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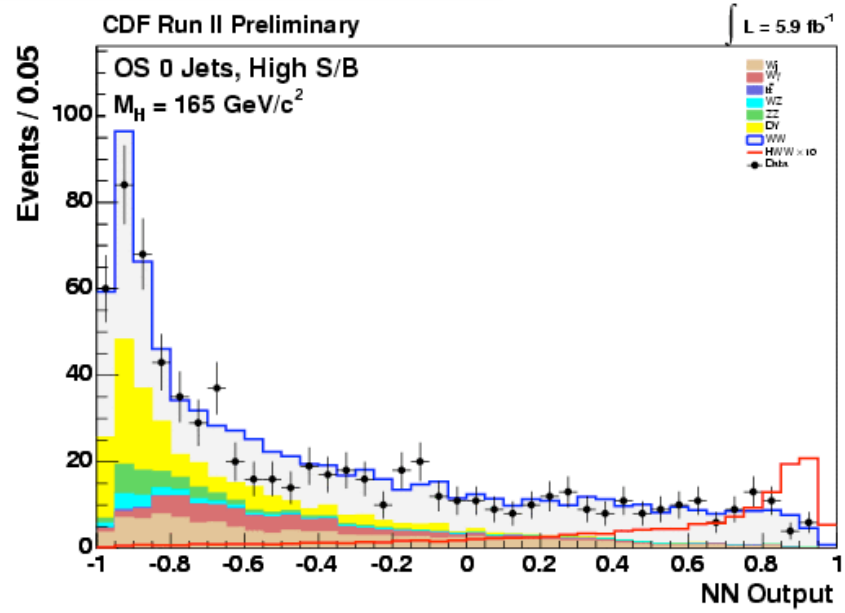
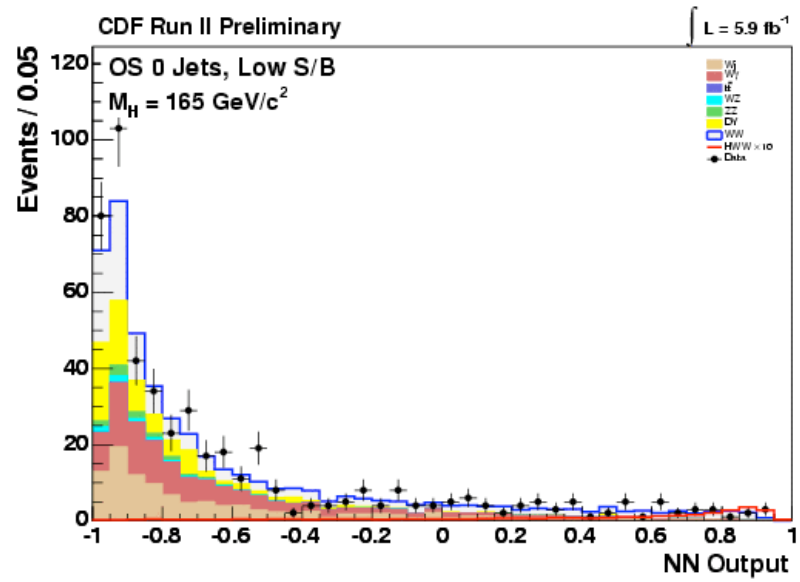
CDF H→WW Opposite sign leptons, 0 Additional Jets

Final Discriminant: NN (NeuroBayes(TM)) with Matrix element, and other, inputs

CDF Run II Preliminary	$\int \mathcal{L} = 5.9$ fb^{-1}		
$M_H = 165$ GeV/c^2			
$t\bar{t}$	2.23	$\pm$	0.66
DY	227	$\pm$	62
WW	563	$\pm$	56
WZ	25.5	$\pm$	3.8
ZZ	38.3	$\pm$	5.4
W+jets	215	$\pm$	51
$W\gamma$	155	$\pm$	22
Total Background	1226	$\pm$	120
$gg \to H$	16.9	$\pm$	3.0
WH	0.410	$\pm$	0.070
ZH	0.416	$\pm$	0.059
VBF	0.140	$\pm$	0.028
Total Signal	17.8	$\pm$	3.1
Data	1230		

OS 0 Jets

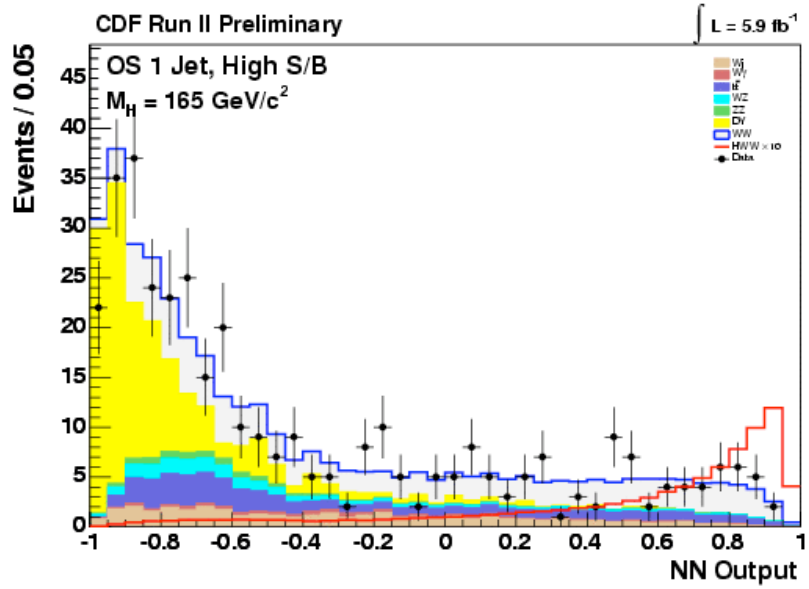


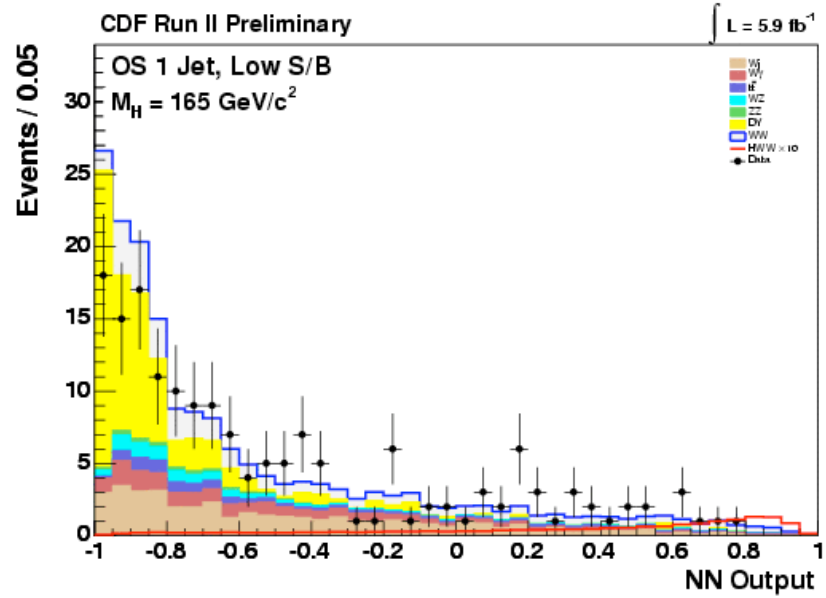


CDF H→WW Opposite sign leptons, 1 Additional Jet

CDF Run II Preliminary	$\int \mathcal{L} = 5.9$ fb^{-1}		
$M_H = 165$ GeV/c^2			
$t\bar{t}$	56	$\pm$	11
DY	218	$\pm$	49
WW	151	$\pm$	18
WZ	25.4	$\pm$	3.5
ZZ	10.3	$\pm$	1.5
W+jets	77	$\pm$	20
$W\gamma$	25.1	$\pm$	4.3
Total Background	563	$\pm$	69
$gg \to H$	8.0	$\pm$	2.4
WH	1.13	$\pm$	0.18
ZH	0.439	$\pm$	0.066
VBF	0.74	$\pm$	0.13
Total Signal	10.3	$\pm$	2.5
Data		533	

OS 1 Jet

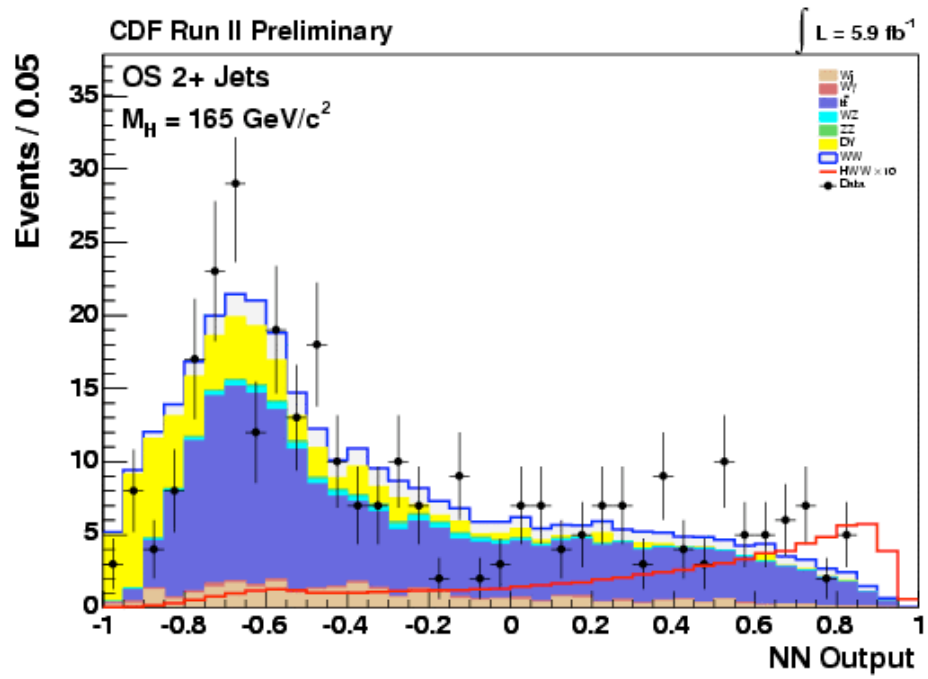




CDF H→WW Opposite sign leptons, Two or More Additional Jets

CDF Run II Preliminary $\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$			
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	169	$\pm$	24
DY	80	$\pm$	31
WW	33.6	$\pm$	6.1
WZ	6.8	$\pm$	1.3
ZZ	3.10	$\pm$	0.57
W+jets	26.7	$\pm$	7.5
$W\gamma$	4.4	$\pm$	1.2
Total Background	324	$\pm$	50
$gg \to H$	2.6	$\pm$	1.8
WH	2.50	$\pm$	0.35
ZH	1.28	$\pm$	0.17
VBF	1.37	$\pm$	0.23
Total Signal	7.8	$\pm$	2.0
Data	307		

A11SB-2JOS



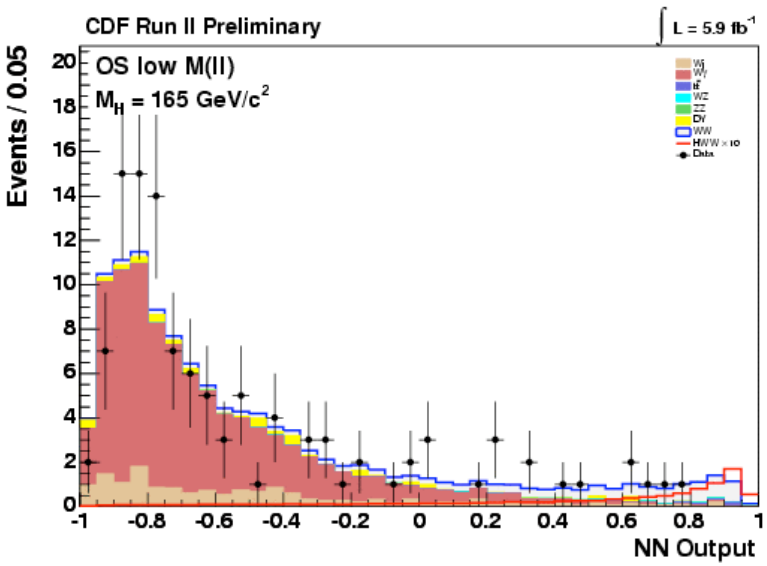
CDF H→WW Opposite sign leptons, Low M_{ll} and Same-Sign Channels

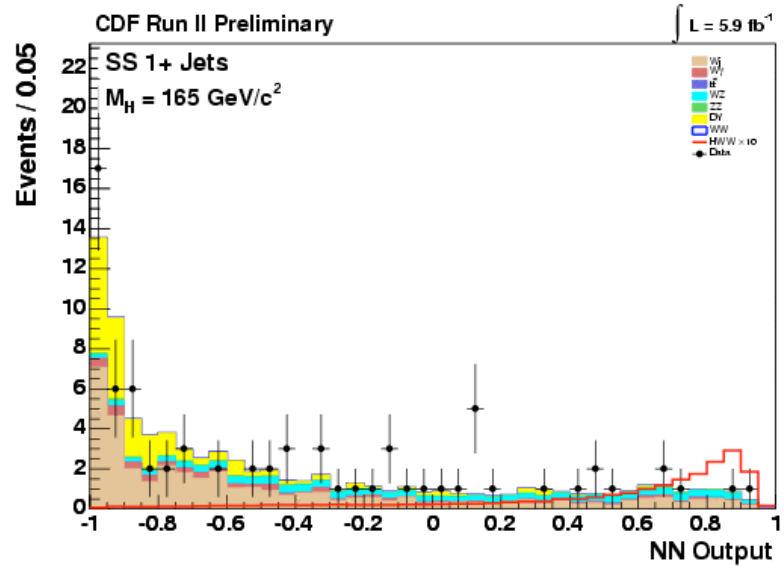
CDF Run II Preliminary	$\int \mathcal{L} = 5.9$ fb^{-1}		
$M_H = 165$ GeV/c^2			
$t\bar{t}$	0.55	$\pm$	0.10
DY	4.35	$\pm$	0.78
WW	13.8	$\pm$	1.3
WZ	0.371	$\pm$	0.052
ZZ	0.139	$\pm$	0.019
W+jets	16.2	$\pm$	3.0
$W\gamma$	76.8	$\pm$	7.7
Total Background	112.2	$\pm$	8.6
$gg \to H$	1.00	$\pm$	0.20
Total Signal	1.00	$\pm$	0.20
Data	112		

AllSB-lowMll

CDF Run II Preliminary	$\int \mathcal{L} = 5.9$ fb^{-1}		
$M_H = 165$ GeV/c^2			
$t\bar{t}$	0.159	$\pm$	0.037
DY	21.0	$\pm$	5.6
WW	0.047	$\pm$	0.013
WZ	10.4	$\pm$	1.4
ZZ	2.07	$\pm$	0.28
W+jets	36	$\pm$	14
$W\gamma$	4.89	$\pm$	0.78
Total Background	75	$\pm$	15
WH	1.81	$\pm$	0.24
ZH	0.283	$\pm$	0.038
Total Signal	2.09	$\pm$	0.28
Data	74		

AllSB-SS





CDF H→WW Trilepton Channels

CDF Run II Preliminary	$\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	0.37	$\pm$	0.11
WZ	5.35	$\pm$	0.76
ZZ	1.30	$\pm$	0.18
W+jets	2.92	$\pm$	0.72
$Z\gamma$	3.13	$\pm$	0.62
Total Background	13.1	$\pm$	1.5
WH	0.611	$\pm$	0.084
ZH	0.159	$\pm$	0.022
Total Signal	0.77	$\pm$	0.11
Data	11		

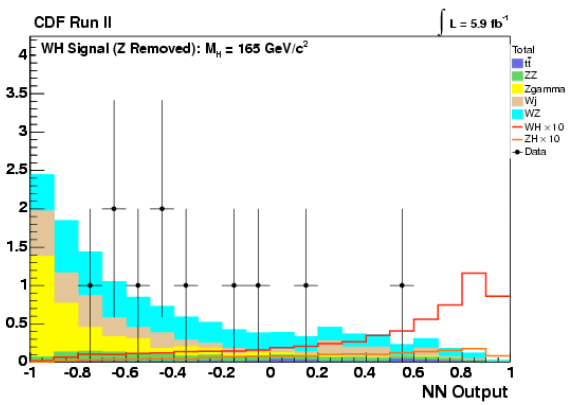
AllSB-trilepNoZ

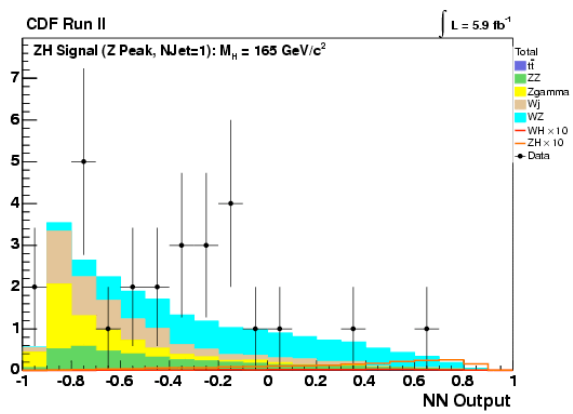
CDF Run II Preliminary	$\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	0.067	$\pm$	0.030
WZ	8.5	$\pm$	1.4
ZZ	3.97	$\pm$	0.57
W+jets	5.1	$\pm$	1.3
$Z\gamma$	4.14	$\pm$	0.85
Total Background	21.8	$\pm$	2.7
WH	0.0280	$\pm$	0.0046
ZH	0.203	$\pm$	0.032
Total Signal	0.231	$\pm$	0.035
Data	26		

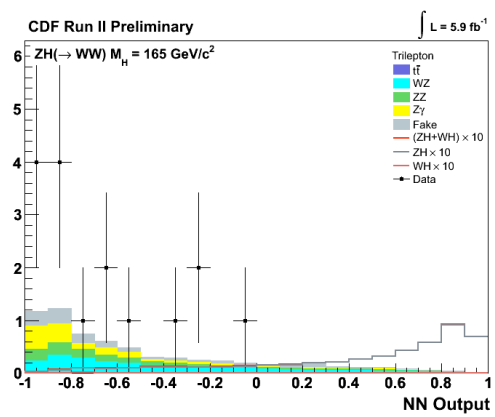
AllSB-trilepZ1j

CDF Run II Preliminary	$\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	0.084	$\pm$	0.022
WZ	2.30	$\pm$	0.52
ZZ	1.34	$\pm$	0.26
W+jets	1.41	$\pm$	0.36
$Z\gamma$	1.42	$\pm$	0.38
Total Background	6.5	$\pm$	1.1
WH	0.0085	$\pm$	0.0017
ZH	0.491	$\pm$	0.072
Total Signal	0.500	$\pm$	0.073
Data	16		

AllSB-trilepZ2j







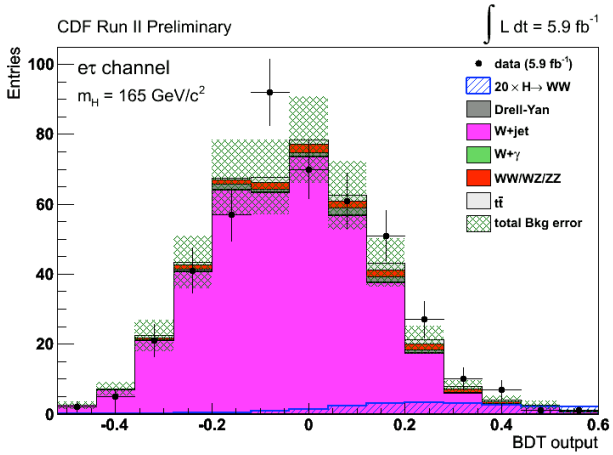
CDF H→WW Lepton + τ_{had} Channels (e and μ Channels)

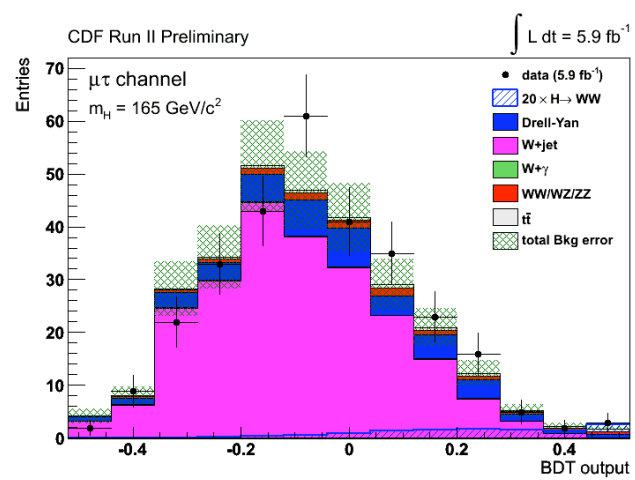
CDF Run II Preliminary	$\int \mathcal{L} = 5.9$ fb^{-1}		
$m_H = 160$ GeV/c^2			
dijet, γ+ jet	4	$\pm$	22
$Z \to \tau\tau$	0.3	$\pm$	0.2
$Z \to \ell\ell$	7.7	$\pm$	1.6
W+jets	395	$\pm$	66
Wγ	2.1	$\pm$	0.3
Diboson (WW, WZ, ZZ)	15.2	$\pm$	2.3
$t\bar{t}$	10.7	$\pm$	2.6
Total Background	435	$\pm$	70
$gg \to H$	0.677	$\pm$	0.085
WH	0.160	$\pm$	0.022
ZH	0.104	$\pm$	0.014
VBF	0.059	$\pm$	0.009
Total Signal	1.000	$\pm$	0.089
Data	446		

$e\tau$ channel

CDF Run II Preliminary	$\int \mathcal{L} = 5.9$ fb^{-1}		
$m_H = 160$ GeV/c^2			
dijet, γ+ jet	5	$\pm$	16
$Z \to \tau\tau$	0.5	$\pm$	0.3
$Z \to \ell\ell$	41.1	$\pm$	6.2
W+jets	229	$\pm$	39
Wγ	1.2	$\pm$	0.2
Diboson (WW, WZ, ZZ)	10.1	$\pm$	1.5
$t\bar{t}$	4.8	$\pm$	0.9
Total Background	291	$\pm$	43
$gg \to H$	0.408	$\pm$	0.052
WH	0.099	$\pm$	0.014
ZH	0.063	$\pm$	0.009
VBF	0.036	$\pm$	0.006
Total Signal	0.606	$\pm$	0.055
Data	295		

$\mu\tau$ channel

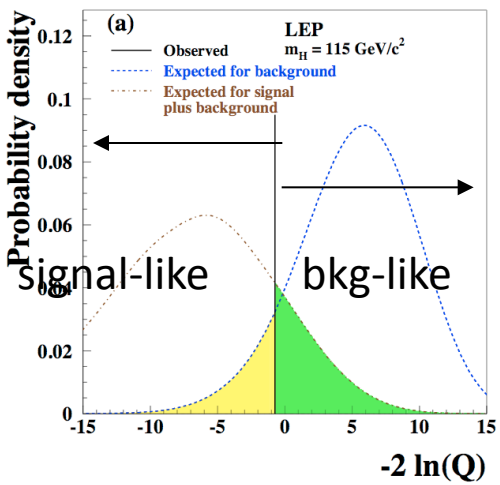




Two Techniques for Computing Limits

CL_s (used by D0)

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



p-values:

$CL_b = P(-2\ln Q \geq -2\ln Q_{obs}\,|\,\text{b only})$

Green area = $CL_{s+b} = P(-2\ln Q \geq -2\ln Q_{obs}\,|\,\text{s+b})$

Yellow area = "1-CL_b" = $P(-2\ln Q \leq -2\ln Q_{obs}\,|\,\text{b only})$

$CL_s \equiv CL_{s+b}/CL_b \geq CL_{s+b}$

Exclude at 95% CL if $CL_s<0.05$

Vary r until $CL_s=0.05$ to get R_{lim}

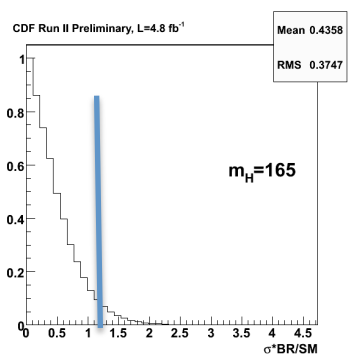
Expected limits can be computed from the distributions of -2lnQ

Bayesian (used by CDF)

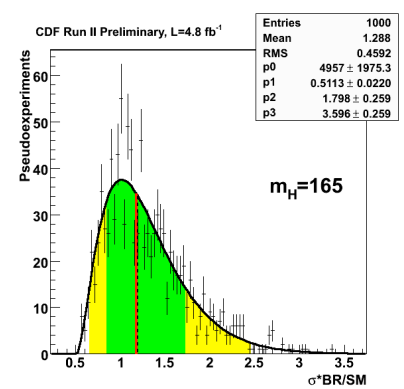
$$L'(data\,|\,R) = \int L(data\,|\,R,\theta)\pi(\theta)d\theta$$

$$0.95 = \frac{\int_0^{R_{lim}} L'(data\,|\,R)\pi(R)dR}{\int_0^{\infty} L'(data\,|\,R)\pi(R)dR}$$

Using Joel Heinrich's and Luc Demortier's "correlated" prior – flat in the accepted signal yield

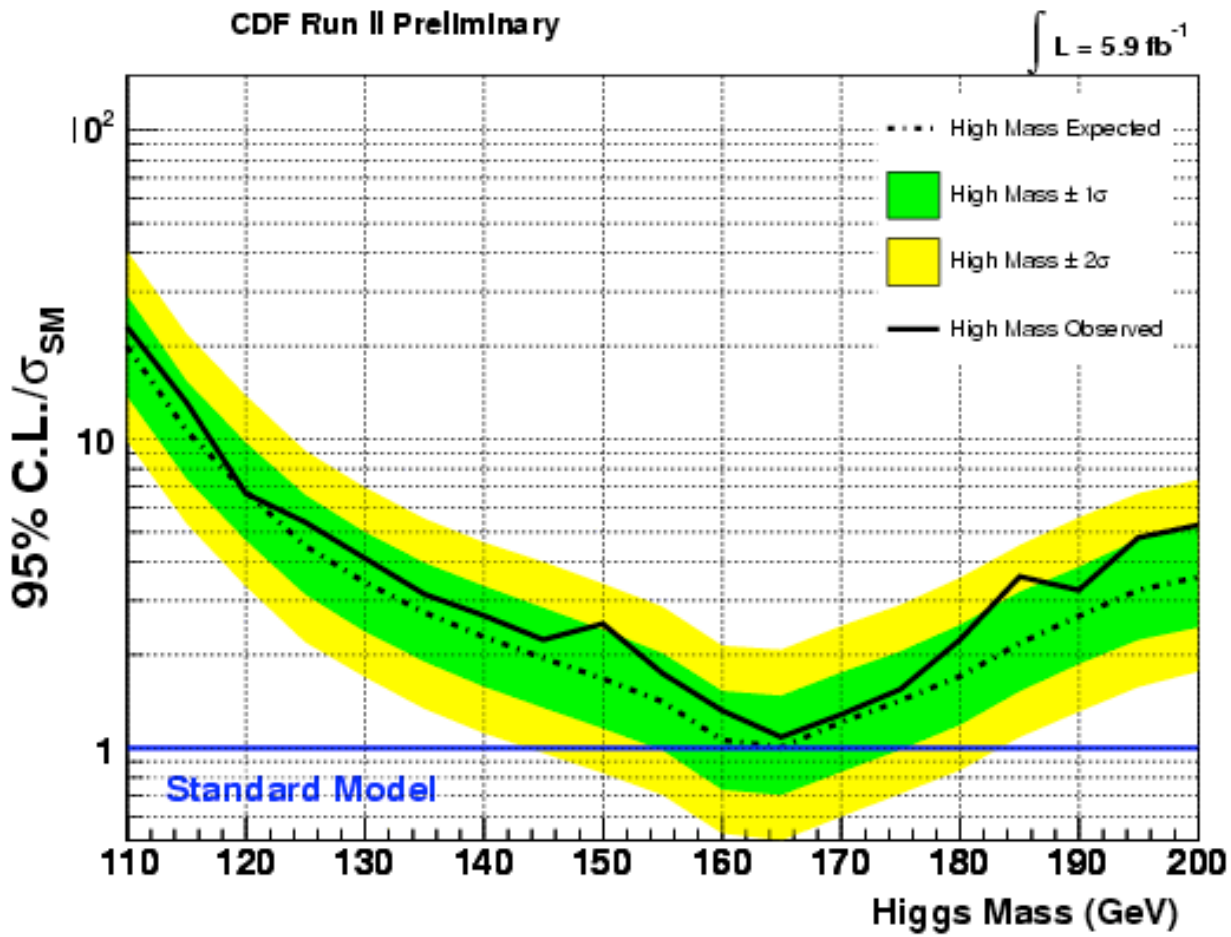


Example: CDF at 165 GeV



Expected limits are computed with pseudoexperiments

CDF Combined H→WW Limits, ICHEP 2010

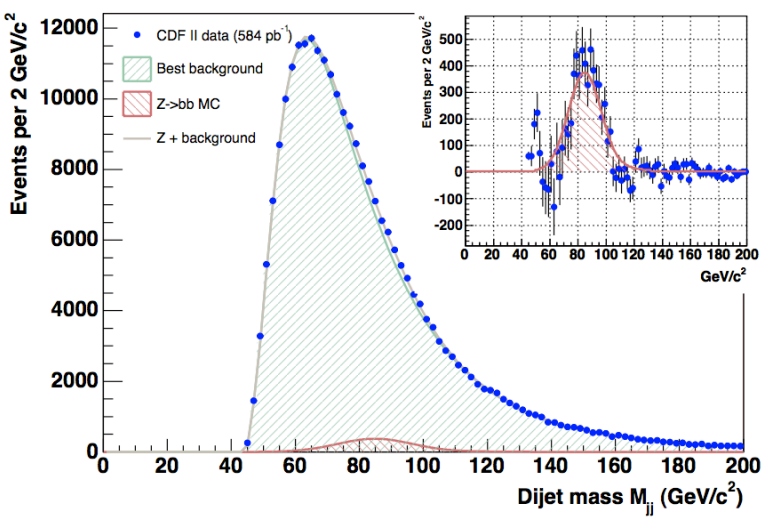


High Mass	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
$-2\sigma/\sigma_{SM}$	9.85	5.31	3.34	2.19	1.69	1.34	1.12	0.96	0.83	0.70	0.53	0.50	0.60	0.71	0.85	1.08	1.30	1.57	1.76
$-1\sigma/\sigma_{SM}$	13.78	7.41	4.69	3.13	2.38	1.90	1.58	1.35	1.15	0.98	0.73	0.70	0.83	0.99	1.18	1.53	1.86	2.23	2.45
Median/σ_{SM}	**19.90**	**10.59**	**6.74**	**4.50**	**3.42**	**2.74**	**2.28**	**1.95**	**1.67**	**1.40**	**1.05**	**1.00**	**1.20**	**1.42**	**1.70**	**2.17**	**2.67**	**3.23**	**3.57**
$+1\sigma/\sigma_{SM}$	29.02	15.36	9.73	6.57	4.98	3.95	3.33	2.83	2.41	2.02	1.53	1.47	1.75	2.05	2.49	3.20	3.83	4.72	5.16
$+2\sigma/\sigma_{SM}$	40.58	21.79	13.83	9.11	6.95	5.50	4.62	3.99	3.40	2.86	2.14	2.07	2.48	2.90	3.55	4.51	5.55	6.67	7.35
Observed/σ_{SM}	**22.98**	**13.12**	**6.65**	**5.37**	**4.10**	**3.13**	**2.68**	**2.23**	**2.51**	**1.74**	**1.32**	**1.08**	**1.28**	**1.54**	**2.24**	**3.57**	**3.23**	**4.79**	**5.24**

CDF's Low-Mass Searches

Lepton + MET + bb -- Primarily WH→lνbb signal
MET + bb (veto leptons) -- Z→νν, but also WH→lνbb
llbb Primarily ZH→llbb
H→ττ+2 jets WH, ZH, ggH and VBF all included

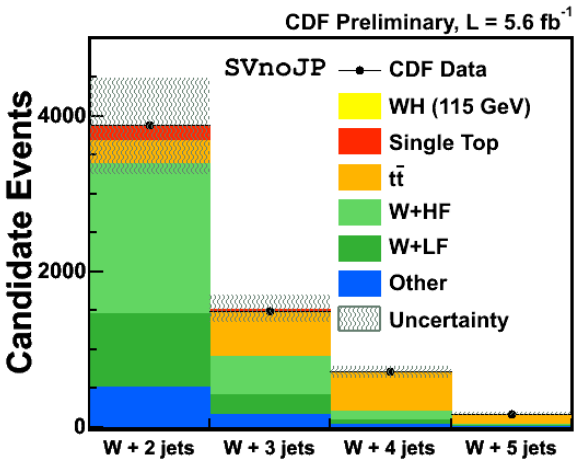
What's not included: gg→H→bb: dominant production and decay, but gg→bb is millions of times bigger.



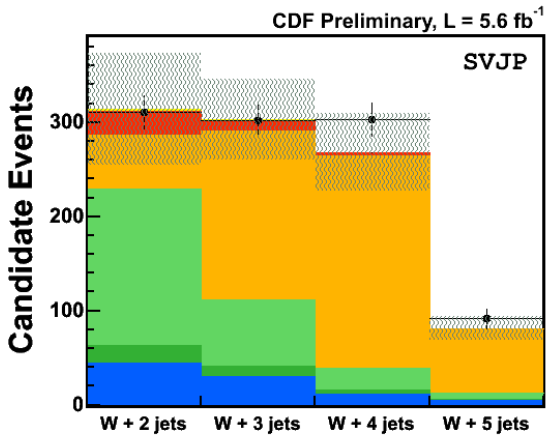
We can see Z→bb in this last channel but the s/b is small and the Z production cross section is about 8000 pb instead of 1 pb

CDF's Searches for WH→lvbb

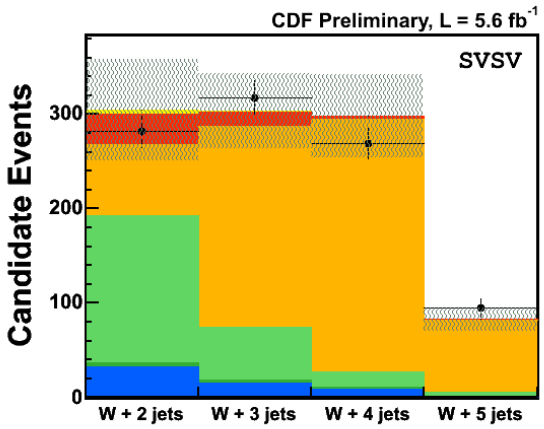
- Select events with an identified lepton (e, mu, or isolated track), MET, two or three jets, and one or more b-tags
- Divide search channels by b-tag category (one or two tags, loose and tight b-taggers), lepton, and jet categories.
  - Different signal and background contributions,
  - Different s/b (better dijet mass resolution in double-tag events!)
  - Different systematics
- Train separate neural networks/matrix element discriminants in each category



Single b-tag

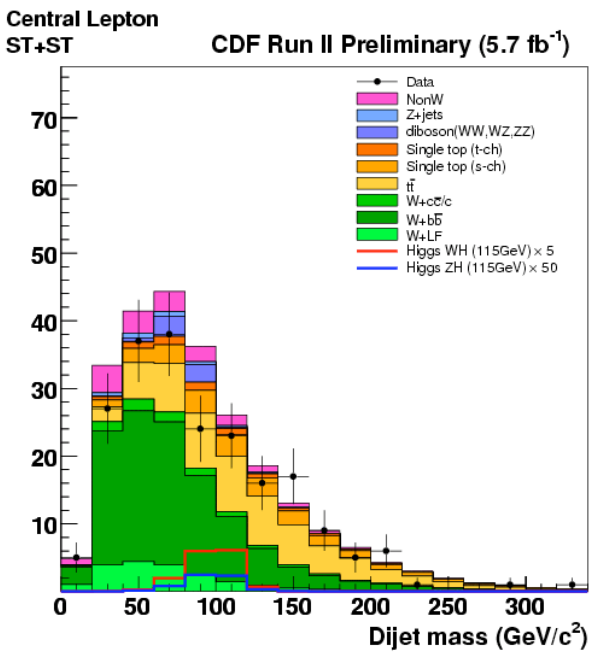


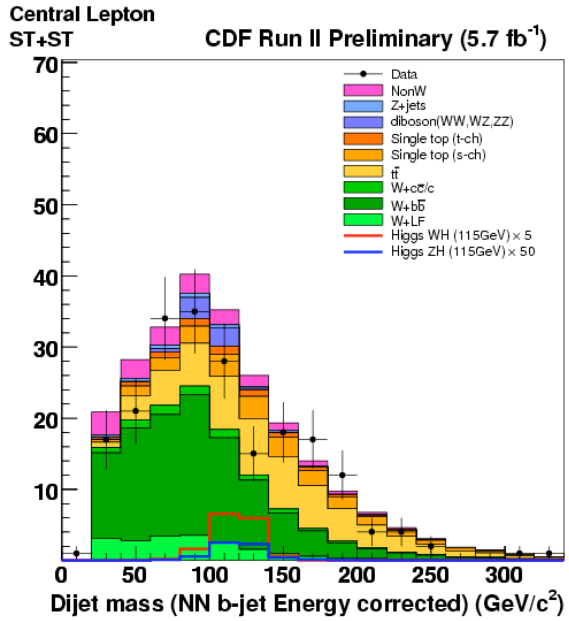
Tight+Loose b-tag



Two tight b-tags

CDF's Searches for WH→lvbb



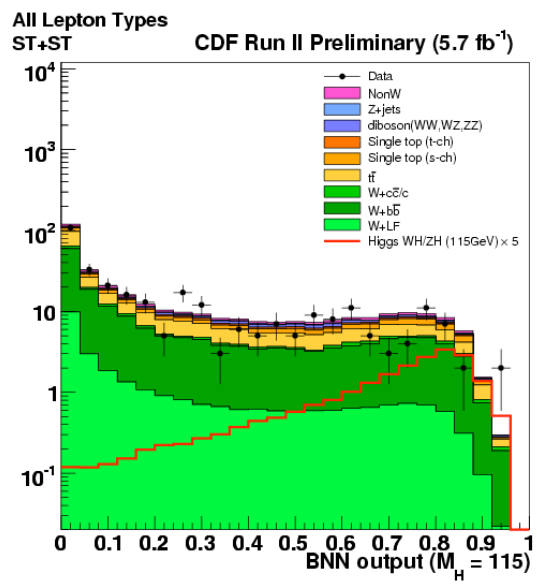


NN b-jet energy corrections – similar width of m_{jj} for signal, but higher average, so better relative resolution.

Does not sculpt background

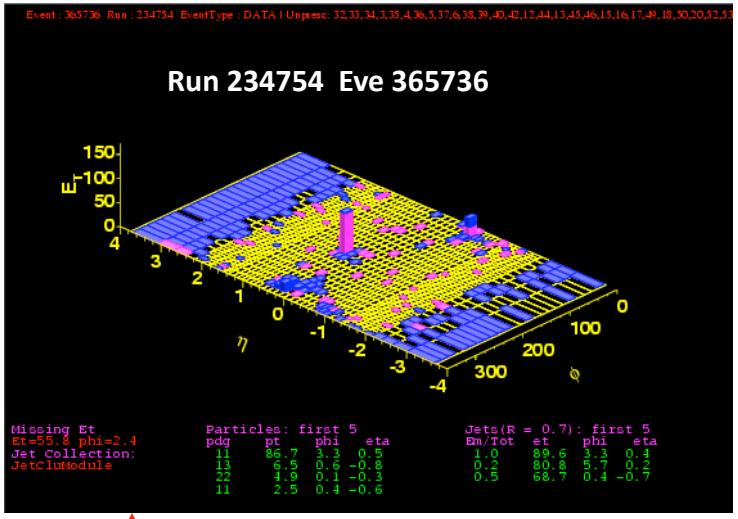
NN Built out of (example, double-tight tag, two-jet events):

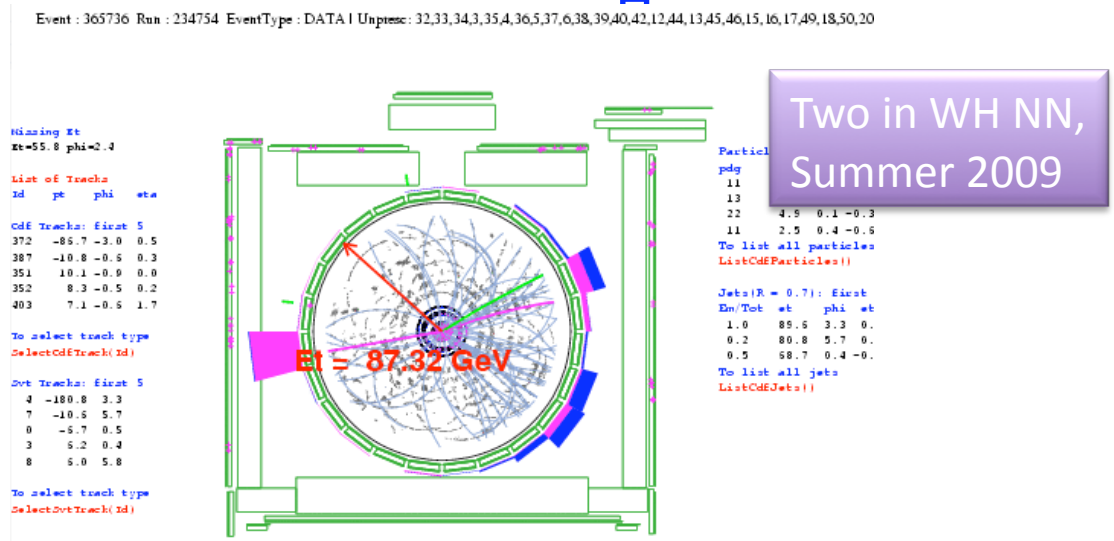
m_{jj}
P_T Imbalance
M_{max}(l+v+jet)
Qxη_{lepton}
Sum E_T(loose jets)
P_T(W)
H_T



3-jet events use matrix-element (+ flavor-separator) discriminants

The Top Two WH Events at m_H=115 GeV

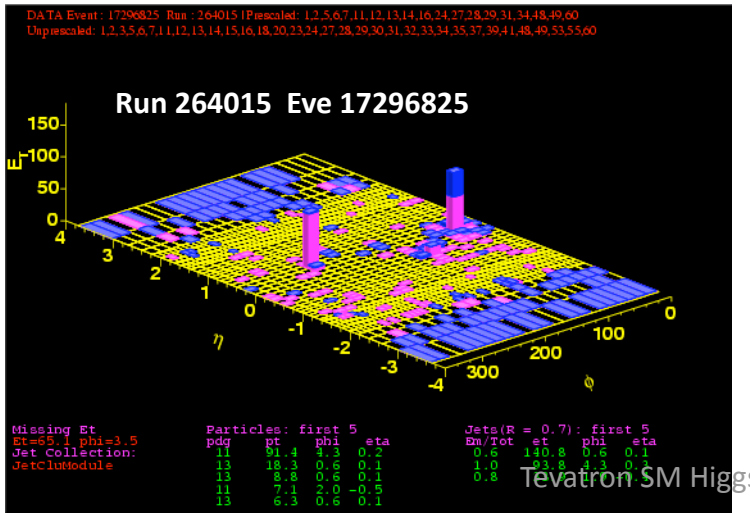


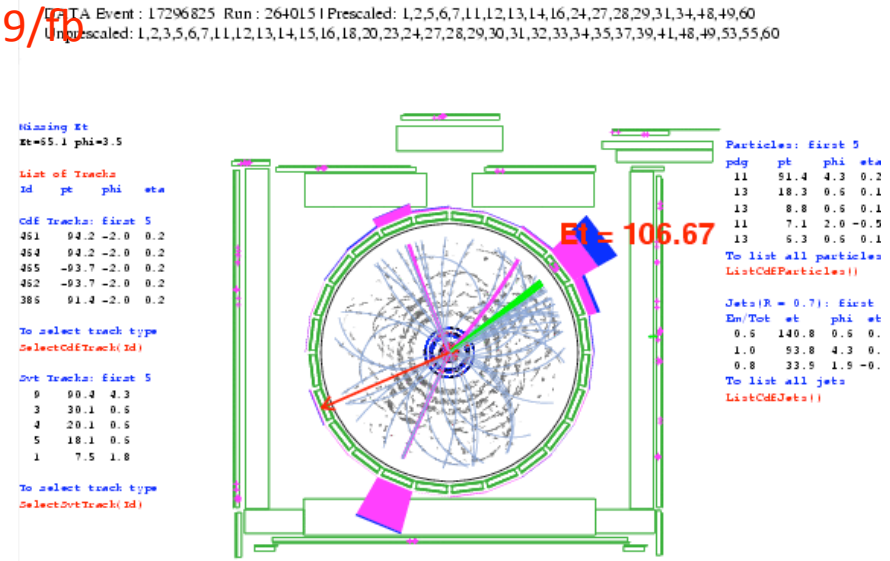


Two in WH NN, Summer 2009

This was found as the most Higgs like event at 1.9/fb analysis (event display was blessed).

Our BNN re-finds this event!!





s/b of each of these events is 0.3 to 0.4

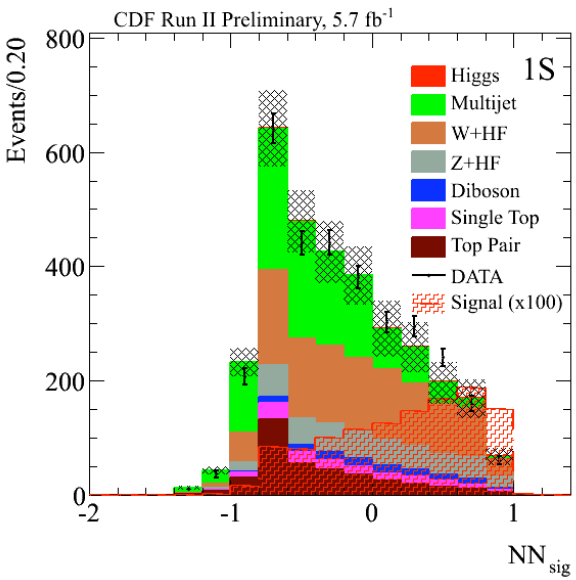
CDF's MET+bb Search

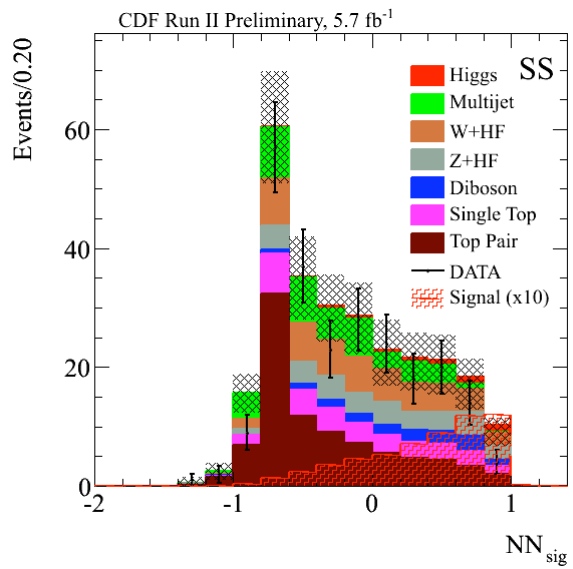
- Events collected with a MET+jets trigger
- MET>50 GeV, 2 or 3 jets, one or two b-tags, lepton veto to be orthogonal to lvbb analysis
- Anti-QCD neural network to target dominant background – dijet events with mismeasured MET (usually MET points along one of the jets, and calorimeter MET and track MET are misaligned if it's fake)

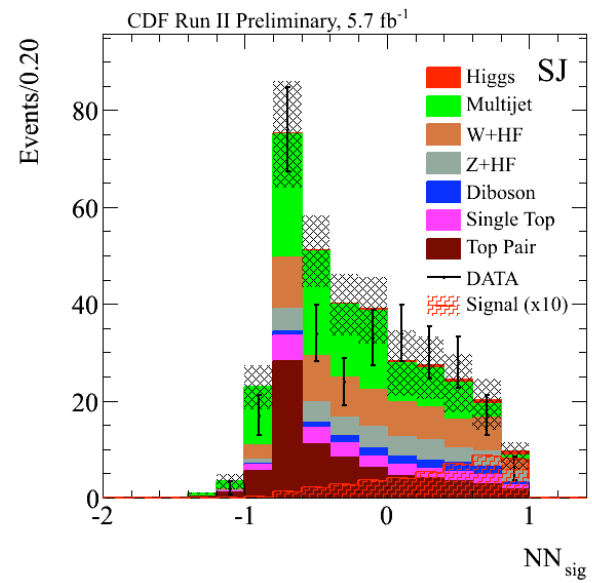
CDF Run II Preliminary, 5.7 fb^{-1}

Process	Excl. ST	ST+ST	ST+JP
Top Pair	381.1 ± 46.4	89.7 ± 13.0	76.7 ± 13.0
Single Top	136.4 ± 24.5	32.3 ± 6.3	24.6 ± 5.3
Diboson	106.5 ± 17.3	14.2 ± 2.6	12.4 ± 2.5
Z+HF	399.7 ± 129.6	32.7 ± 11.1	35.0 ± 12.3
W+HF	1065.2 ± 356.0	49.7 ± 17.4	68.5 ± 24.9
Multi-jet	1108.0 ± 113.8	43.5 ± 9.7	120.3 ± 13.3
Exp. Background	3196.9 ± 501.8	262.2 ± 33.5	337.7 ± 42.0
Observed	3220	237	301
$ZH \to ll b\bar{b}$ ($m_H = 115$ GeV)	0.3 ± 0.02	0.2 ± 0.02	0.1 ± 0.02
$WH \to l\nu b\bar{b}$ ($m_H = 115$ GeV)	5.9 ± 0.3	2.8 ± 0.2	2.1 ± 0.3
$ZH \to \nu\nu b\bar{b}$ ($m_H = 115$ GeV)	5.6 ± 0.2	2.8 ± 0.2	2.0 ± 0.2

CDF's MET+bb Search

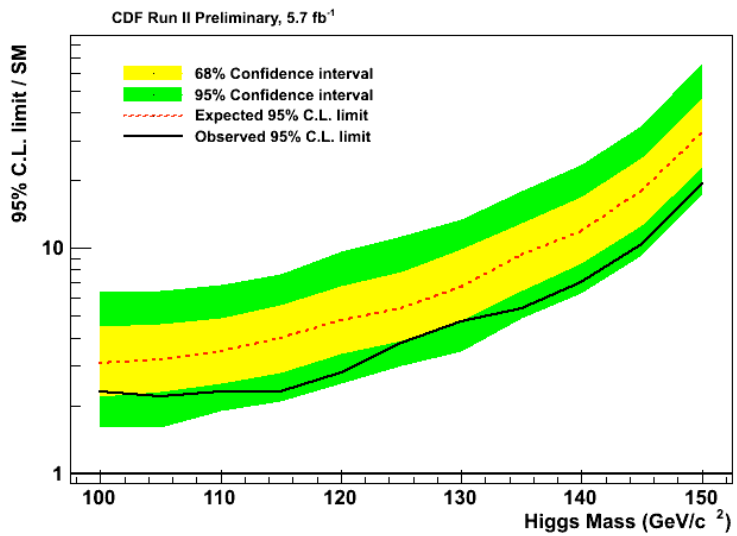






CDF Run II Preliminary, 5.7 fb^{-1}

Higgs mass (GeV)	VH limit, combined	
	Predicted	Observed
100	$3.1\ ^{+1.4}_{-0.9}$	2.3
105	$3.2\ ^{+1.4}_{-0.9}$	2.2
110	$3.5\ ^{+1.4}_{-1}$	2.3
115	$4\ ^{+1.6}_{-1.2}$	2.3
120	$4.8\ ^{+2}_{-1.4}$	2.8
125	$5.4\ ^{+2.5}_{-1.5}$	3.8
130	$6.7\ ^{+3.2}_{-1.9}$	4.7
135	$9.3\ ^{+3.6}_{-2.8}$	5.4
140	$11.9\ ^{+4.9}_{-3.4}$	7
145	$18\ ^{+7.2}_{-5.4}$	10.4
150	$32.5\ ^{+13.8}_{-9.5}$	19.4



CDF's llbb Search

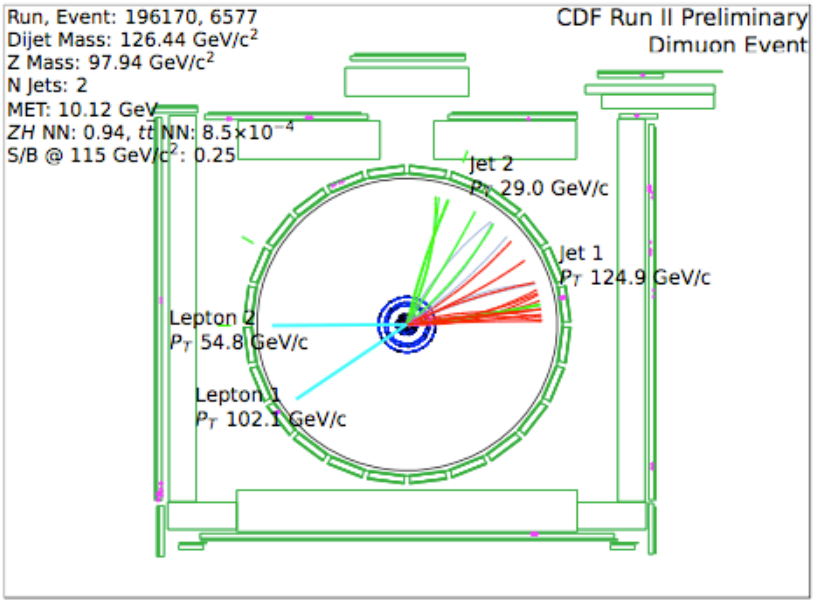
- High purity sample of Z→ee, Z→μμ + jets
- Technical challenge to loosen all the lepton ID requirements and calibrate efficiencies and fake rates for loose lepton categories
- Special feature: No real MET in signal events (and most background events). Use MET projections and a neural network to improve m_{bb} resolution
- Low expected signal yield though (Br(Z→ll) ~ 3%)

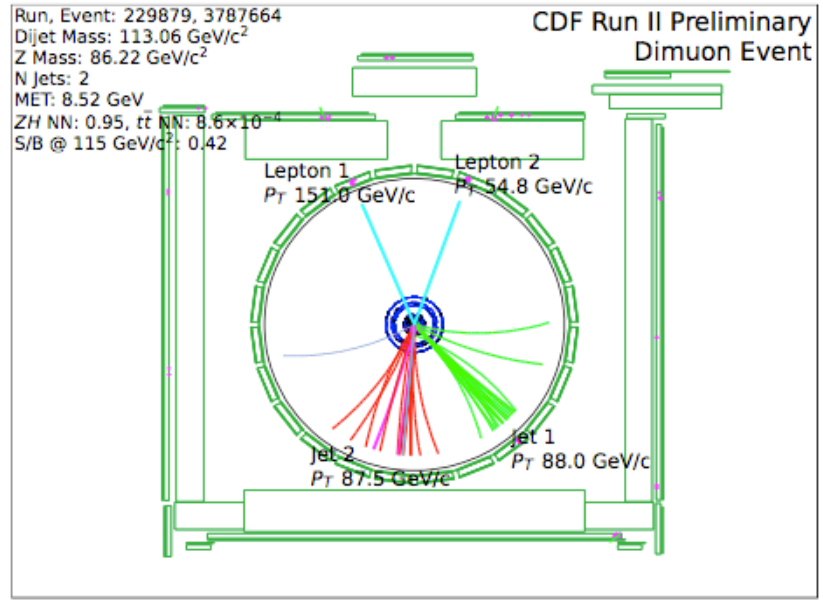
Example yield table:
Two tight b-tags

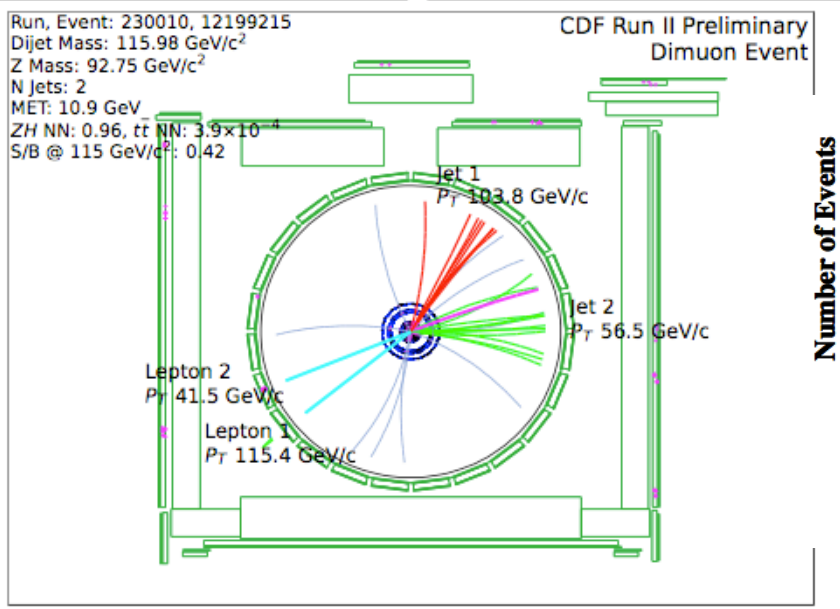
High s/b and low s/b indicate different lepton ID categories

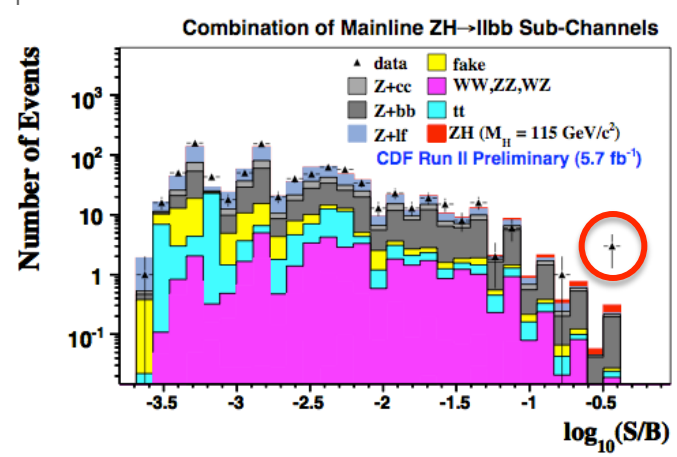
	High $S/\sqrt{B}$			Low $S/\sqrt{B}$		
ZH	0.7	±	0.1	0.1	±	0.02
$t\bar{t}$	9.9	±	1.5	4.4	±	0.7
WW	0.02	±	0.003	0	±	0.0
WZ	0.1	±	0.02	0.03	±	0.004
ZZ	3.6	±	0.5	0.7	±	0.1
$Z \to \ell\ell + b\bar{b}$	22.1	±	9.2	4.6	±	1.9
$Z \to \ell\ell + c\bar{c}$	2.4	±	1.0	0.5	±	0.2
$Z \to \ell\ell + l.f.$	1.2	±	0.2	0.5	±	0.1
fakes	0.9	±	0.5	2.1	±	1.0
Total Bkg	40.3	±	9.4	12.7	±	2.3
Total Data	37			14		

Three High s/b Candidates in the llbb Channels





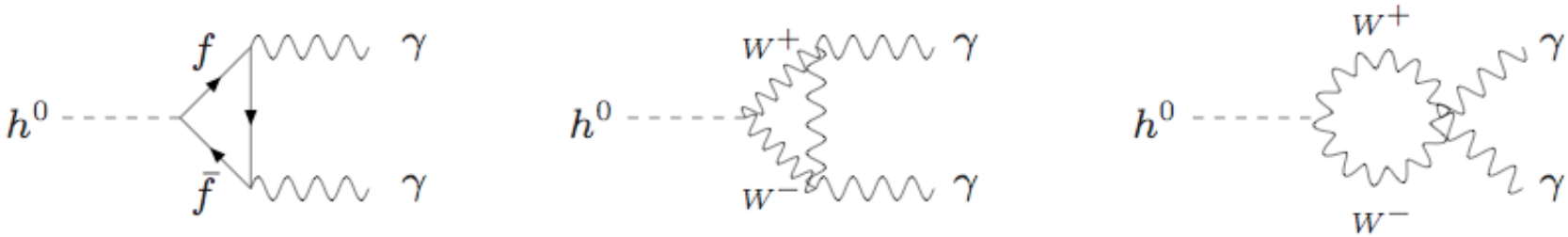




s/b of each of these events is 0.3 to 0.4

Higgs Boson Couplings to Photons

At one-loop, the Higgs boson couples to photons via a loop of charged particles:



If charged scalars exist, they would contribute as well. These diagrams lead to an effective Lagrangian

$$\mathcal{L}^{\rm eff}_{h\gamma\gamma} = \frac{g\alpha N_\gamma}{12\pi m_W} h^0 F_{\mu\nu}F^{\mu\nu} \,,$$

where

$$N_\gamma = \sum_i N_{ci} e_i^2 F_j(x_i) \,, \qquad x_i \equiv \frac{m_i^2}{m_h^2} \,.$$

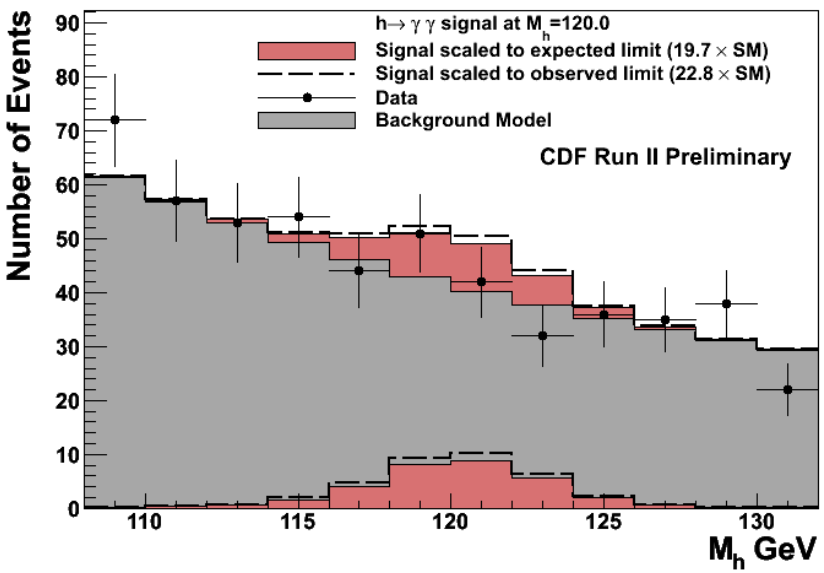
In the sum over loop particles i of mass m_i, $N_{ci} = 3$ for quarks and 1 for color singlets, e_i is the electric charge in units of e and $F_j(x_i)$ is the loop function corresponding to ith particle (with spin j). In the limit of $x \gg 1$,

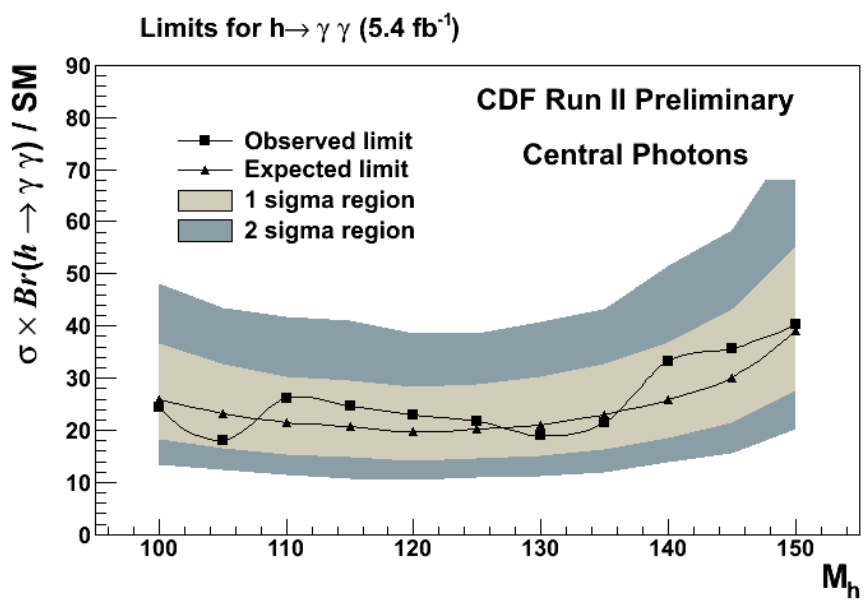
$$F_j(x) \longrightarrow \begin{cases} 1/4 \,, & j = 0 \,, \\ 1 \,, & j = 1/2 \,, \\ -21/4 \,, & j = 1 \,. \end{cases}$$

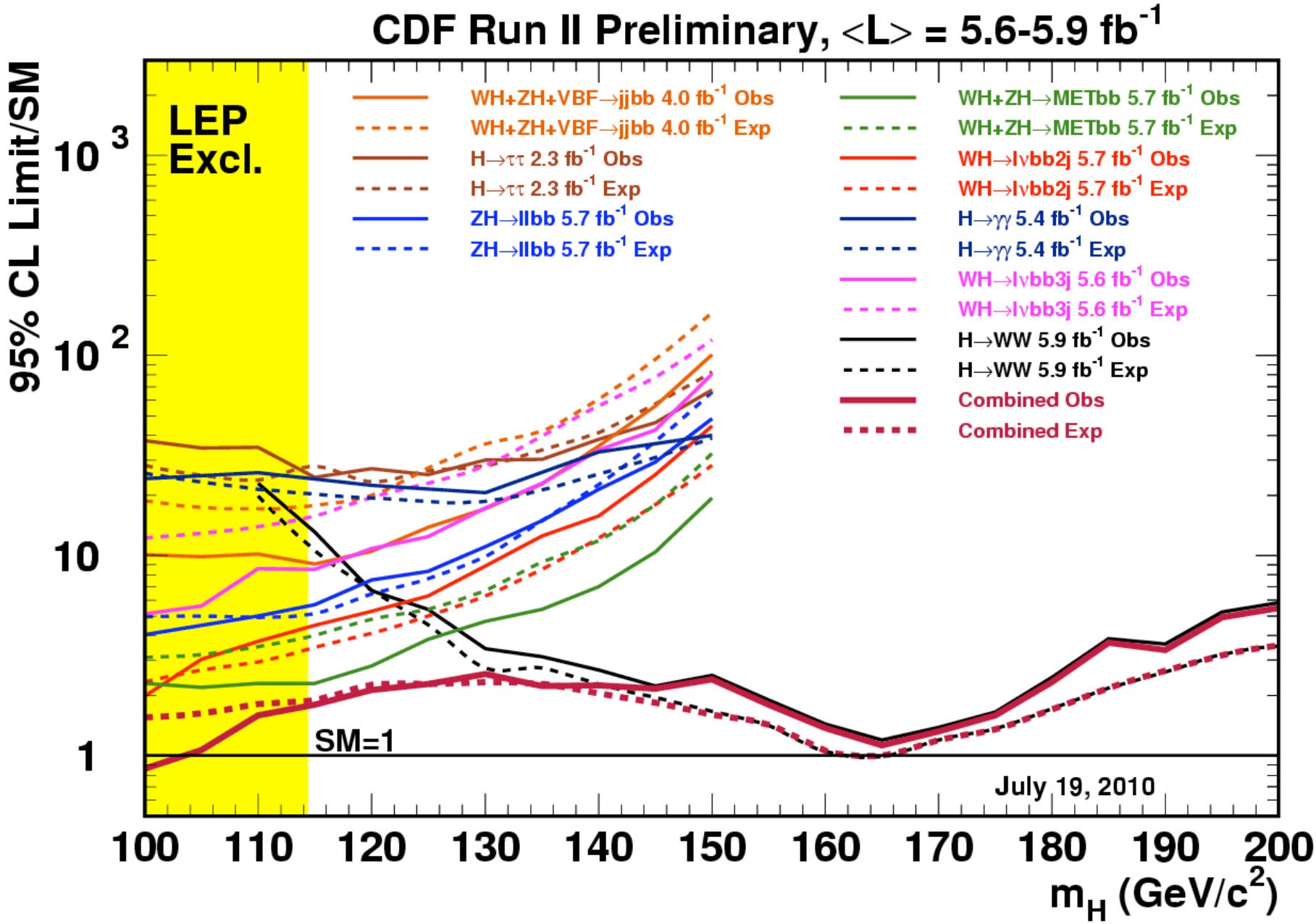
H. Haber, HCPSS 2008

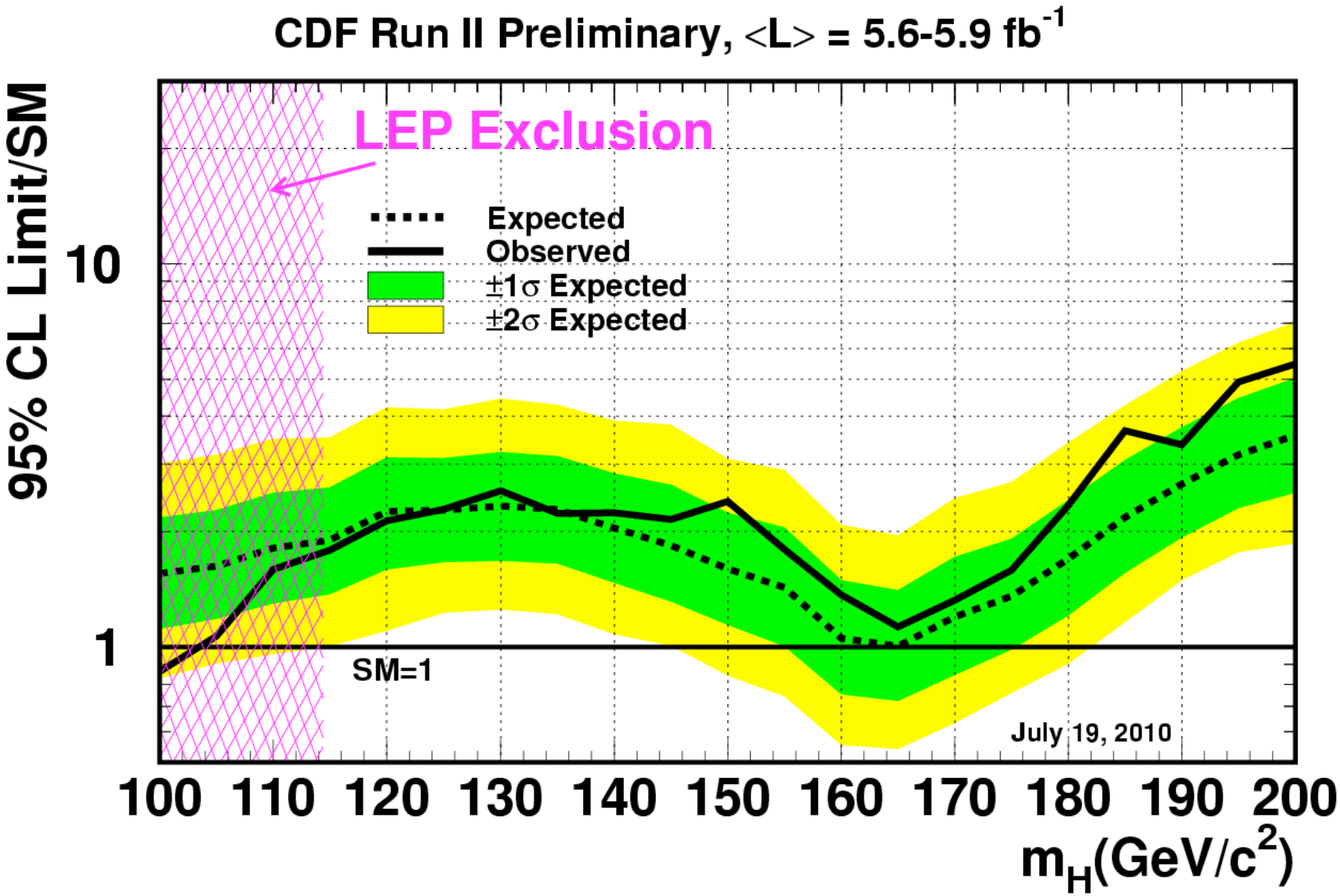
A New Diphoton Channel

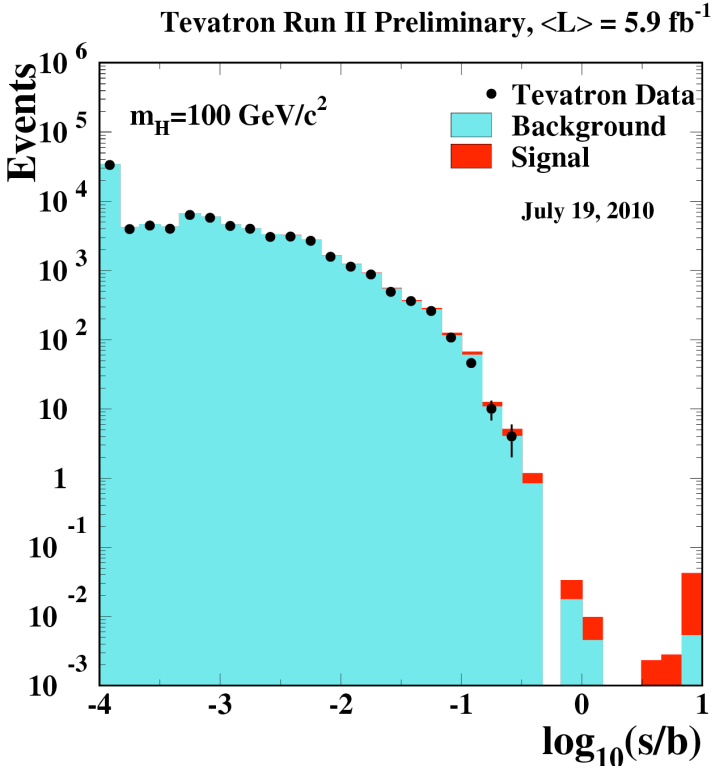
- Uses triggers based on 2 or more EM clusters. Lower-energy threshold triggers have isolation requirements, higher-energy triggers loosen this. Single-photon triggers
- Photons are required to be central -- |η|<1.04
- Isolation required – < 2 GeV of tracks pointing at a photon candidate and < 2 GeV of non-photon candidate calorimeter energy

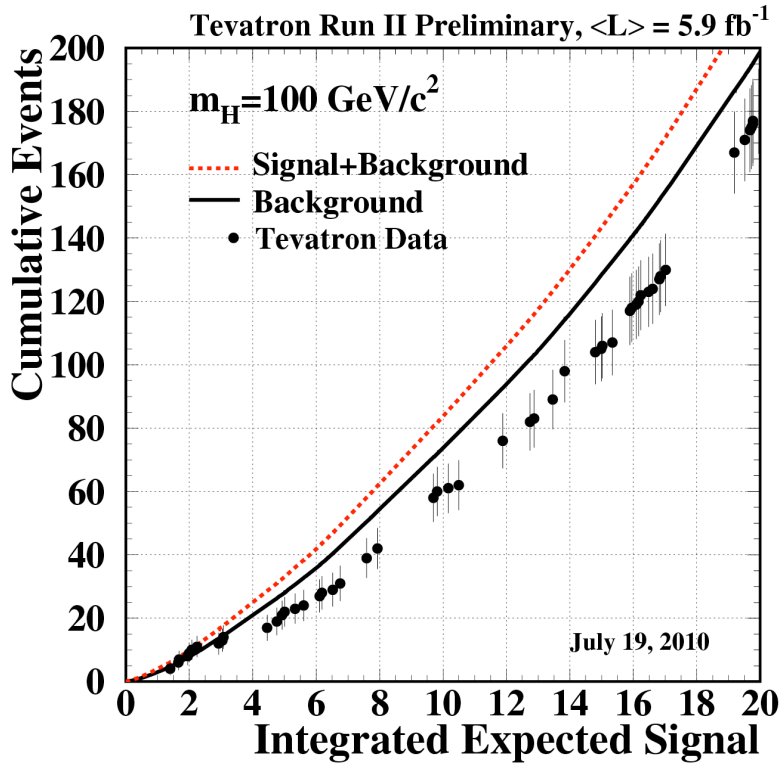


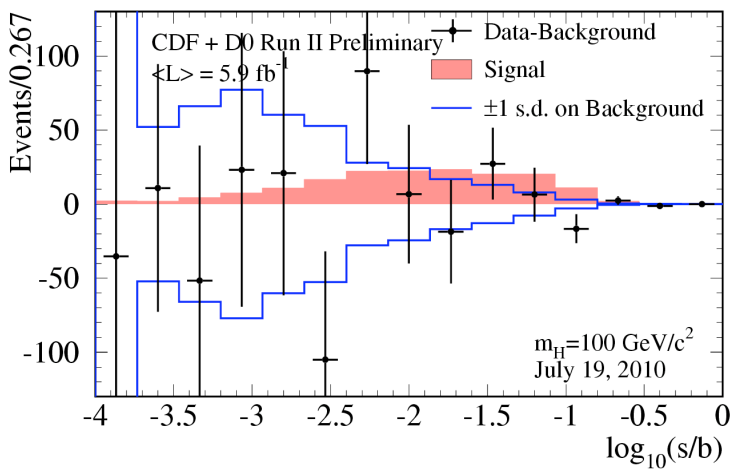


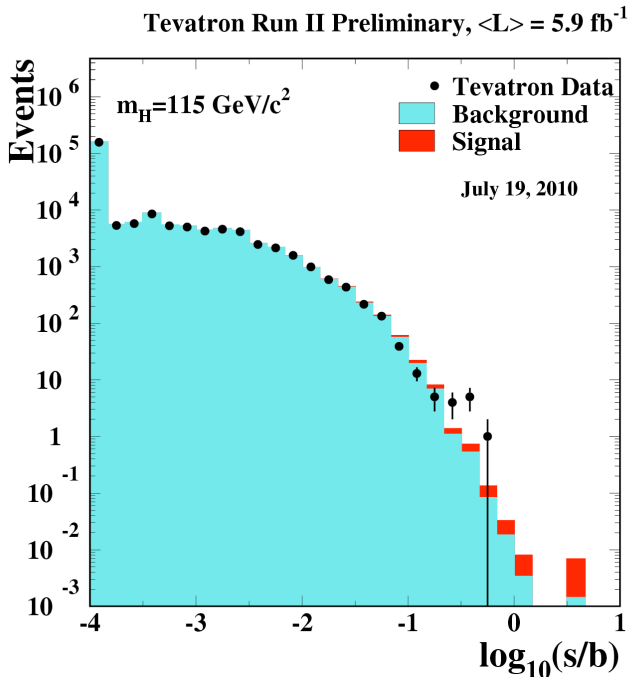

CDF Run II Preliminary, <L> = 5.6-5.9 fb-1
95% CL Limit/SM
LEP Excl.
WH+ZH+VBF→jjbb 4.0 fb-1 Obs
WH+ZH+VBF→jjbb 4.0 fb-1 Exp
H→ττ 2.3 fb-1 Obs
H→ττ 2.3 fb-1 Exp
ZH→llbb 5.7 fb-1 Obs
ZH→llbb 5.7 fb-1 Exp
WH+ZH→METbb 5.7 fb-1 Obs
WH+ZH→METbb 5.7 fb-1 Exp
WH→lνbb2j 5.7 fb-1 Obs
WH→lνbb2j 5.7 fb-1 Exp
H→γγ 5.4 fb-1 Obs
H→γγ 5.4 fb-1 Exp
WH→lνbb3j 5.6 fb-1 Obs
WH→lνbb3j 5.6 fb-1 Exp
H→WW 5.9 fb-1 Obs
H→WW 5.9 fb-1 Exp
Combined Obs
Combined Exp
SM=1
July 19, 2010
mH (GeV/c2)

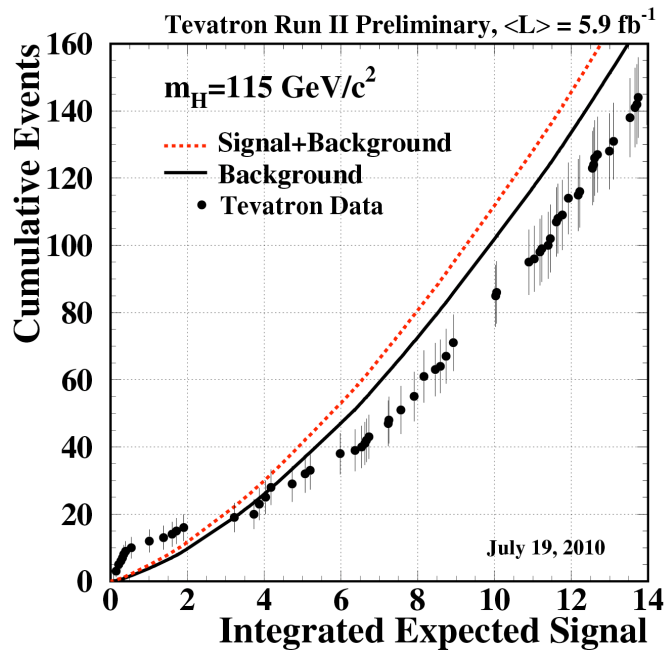

CDF Run II Preliminary, <L> = 5.6-5.9 fb^{-1}
95% CL Limit/SM
LEP Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
July 19, 2010
10
1
100 110 120 130 140 150 160 170 180 190 200
m_H(GeV/c^2)

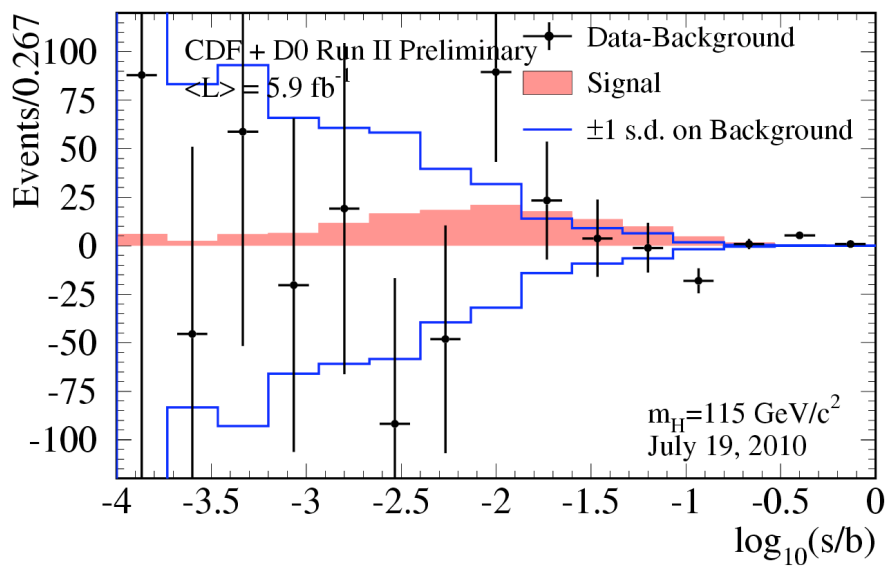

Tevatron Run II Preliminary, <L> = 5.9 fb^{-1}
Events
m_H=100 GeV/c^2
Tevatron Data
Background
Signal
July 19, 2010
$\log_{10}$(s/b)

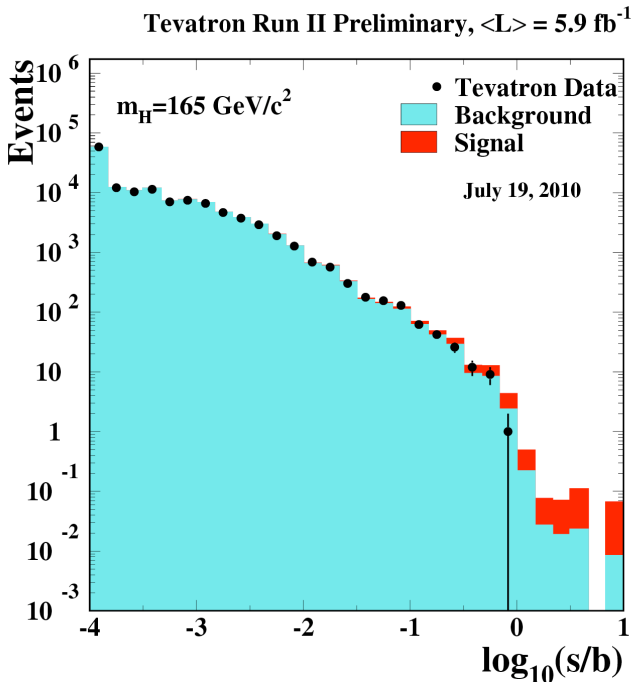

Tevatron Run II Preliminary, <L> = 5.9 fb^{-1}
Cumulative Events
m_H=100 GeV/c^2
Signal+Background
Background
Tevatron Data
July 19, 2010
Integrated Expected Signal

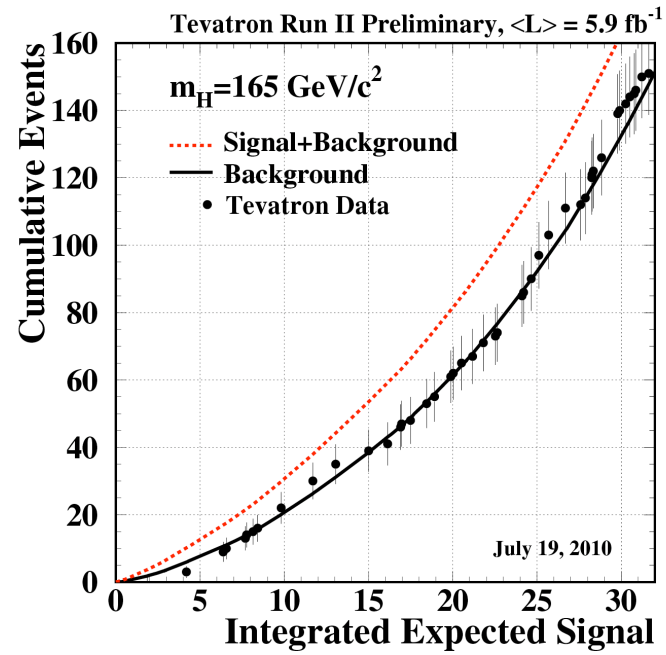

CDF + D0 Run II Preliminary
<L> = 5.9 fb^{-1}
Data-Background
Signal
±1 s.d. on Background
Events/0.267
m_H=100 GeV/c^2
July 19, 2010
$\log_{10}$(s/b)

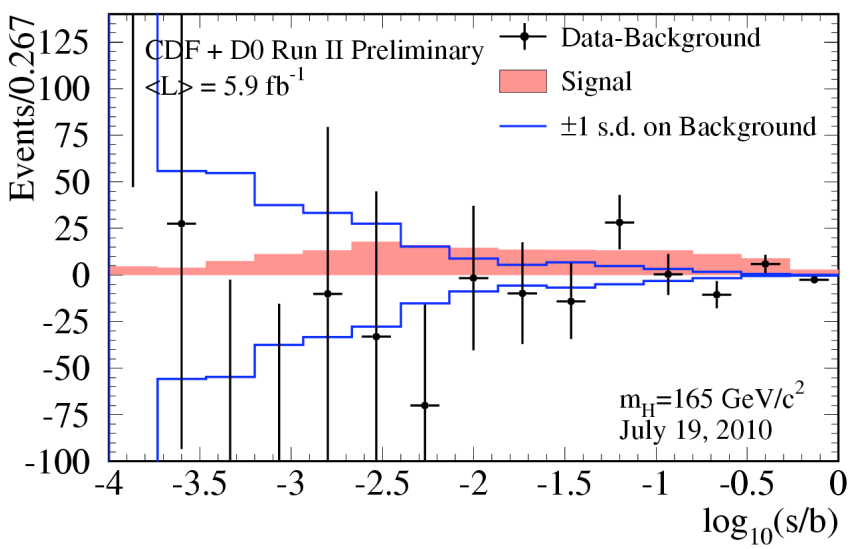

Tevatron Run II Preliminary, <L> = 5.9 fb-1
Events
mH=115 GeV/c2
Tevatron Data
Background
Signal
July 19, 2010
log10(s/b)


Tevatron Run II Preliminary, <L> = 5.9 fb-1
Cumulative Events
mH=115 GeV/c2
Signal+Background
Background
Tevatron Data
July 19, 2010
Integrated Expected Signal

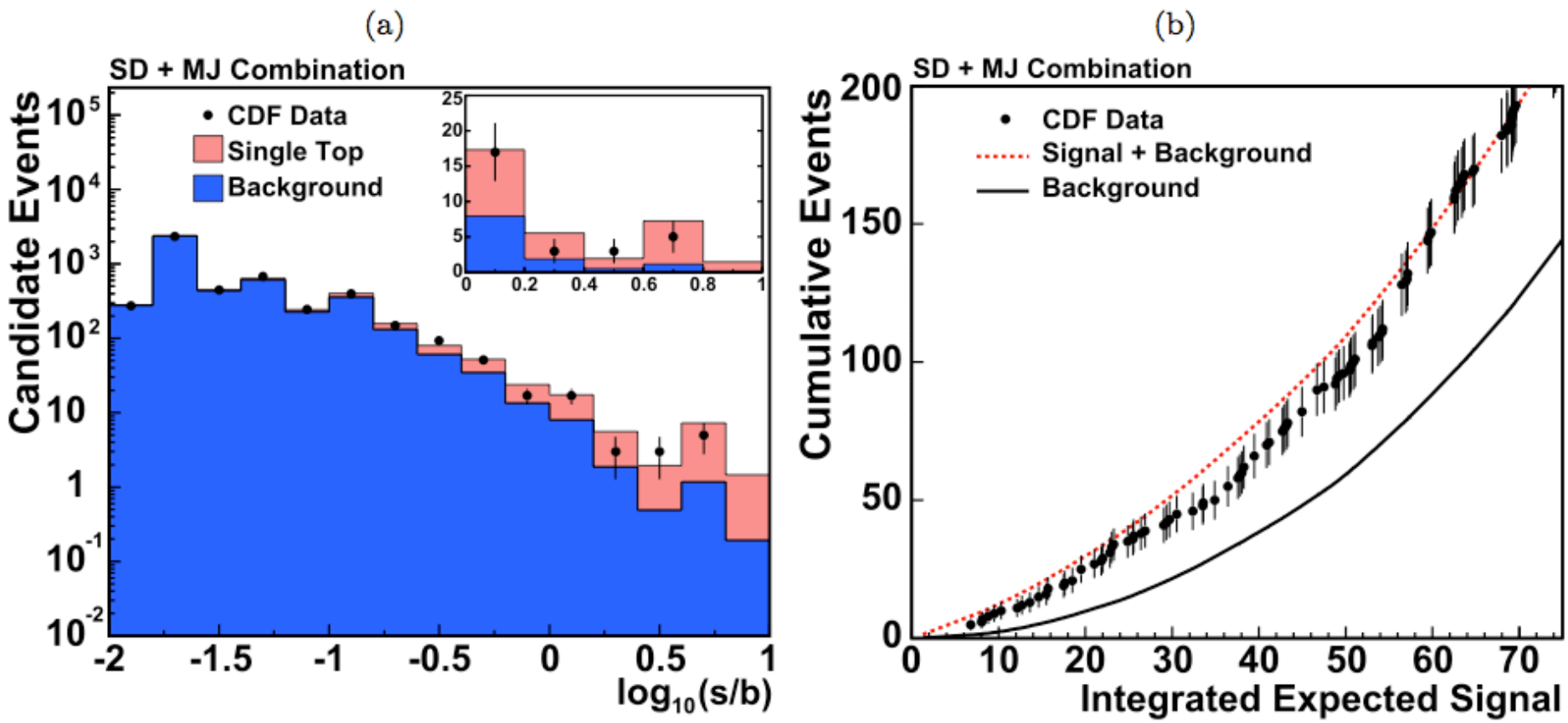

CDF + D0 Run II Preliminary
<L> = 5.9 fb-1
Data-Background
Signal
±1 s.d. on Background
Events/0.267
mH=115 GeV/c2
July 19, 2010
log10(s/b)


Tevatron Run II Preliminary, <L> = 5.9 fb-1
Events
mH=165 GeV/c2
Tevatron Data
Background
Signal
July 19, 2010
log10(s/b)


Tevatron Run II Preliminary, <L> = 5.9 fb-1
Cumulative Events
mH=165 GeV/c2
Signal+Background
Background
Tevatron Data
July 19, 2010
Integrated Expected Signal


CDF + D0 Run II Preliminary
<L> = 5.9 fb-1
Data-Background
Signal
±1 s.d. on Background
Events/0.267
mH=165 GeV/c2
July 19, 2010
log10(s/b)

What These Look Like for a 5.0σ Observation



arXiv:1004.1181 Accepted by PRD

CDF Single Top, 3.2 fb^{-1}

Tevatron Correlated Systematic Uncertainties 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 DØ 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 Uncertainties II

Signal Cross Section uncertainties:

WH, ZH: ± 5%

gg→H: ± 23% (Weighted over the jet bins with different uncertainties)

VBF: ± 10%

These uncertainties are treated like other systematic uncertainties, e.g. acceptance uncertainties.

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

CDF-D0 Uncorrelated uncertainties:

- 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

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

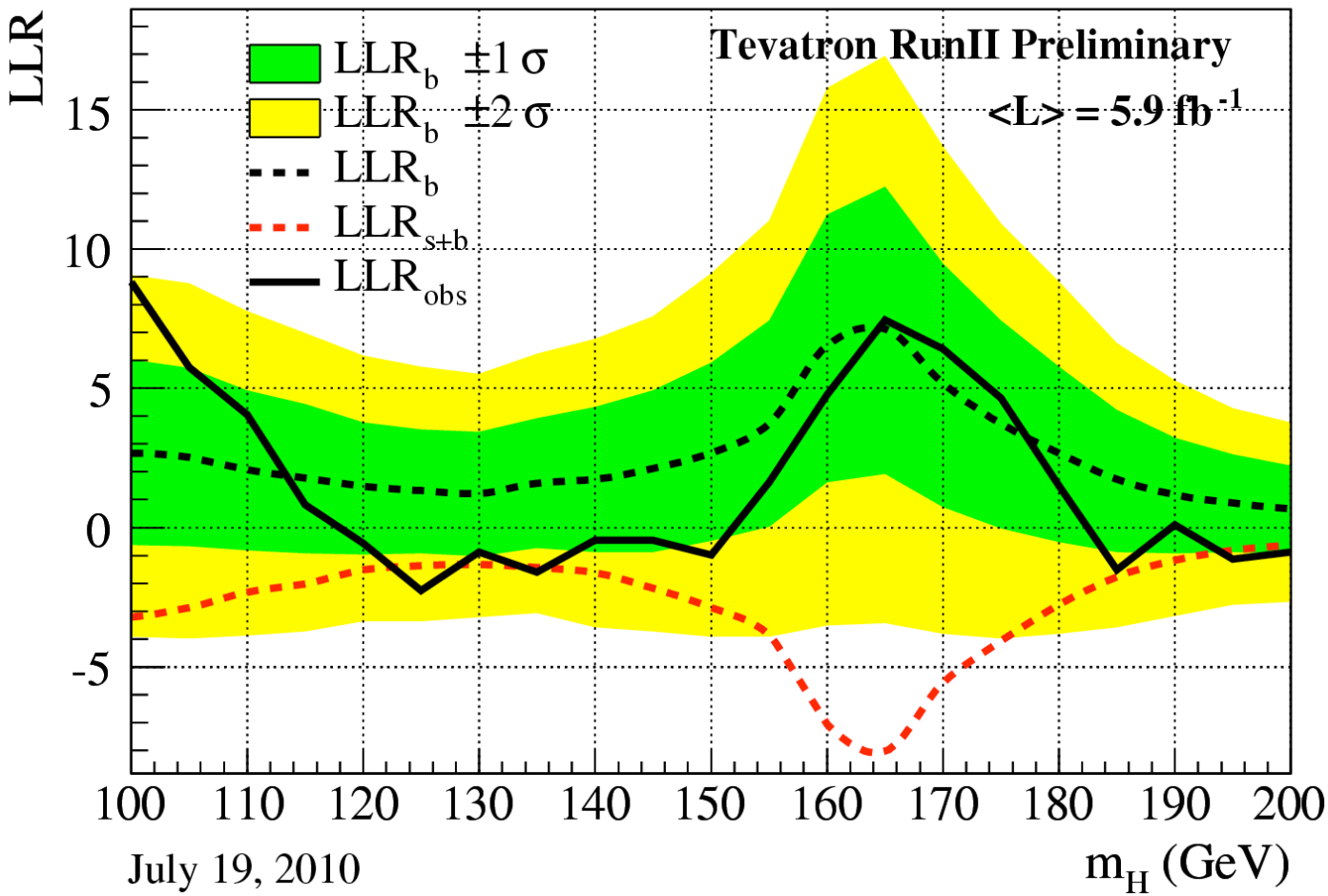
D0

Tevatron

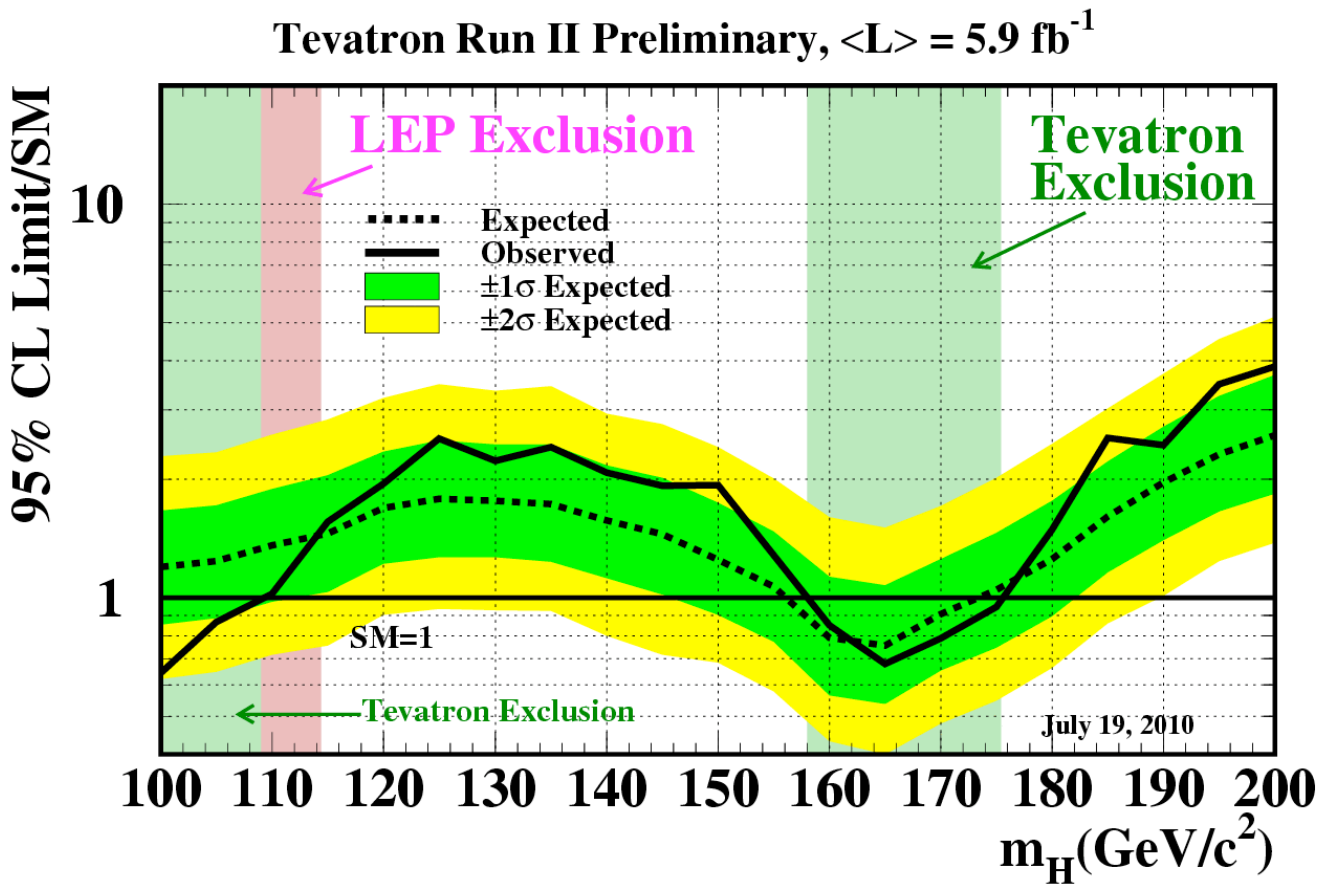
Consistency at the better than 5% level required for all combinations at all test masses. **Take the Bayesian limits (a priori, if for no reason than because we always have).**

Looking for a Hint of a Signal

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



Tevatron Observed and Expected Limits



Bayesian

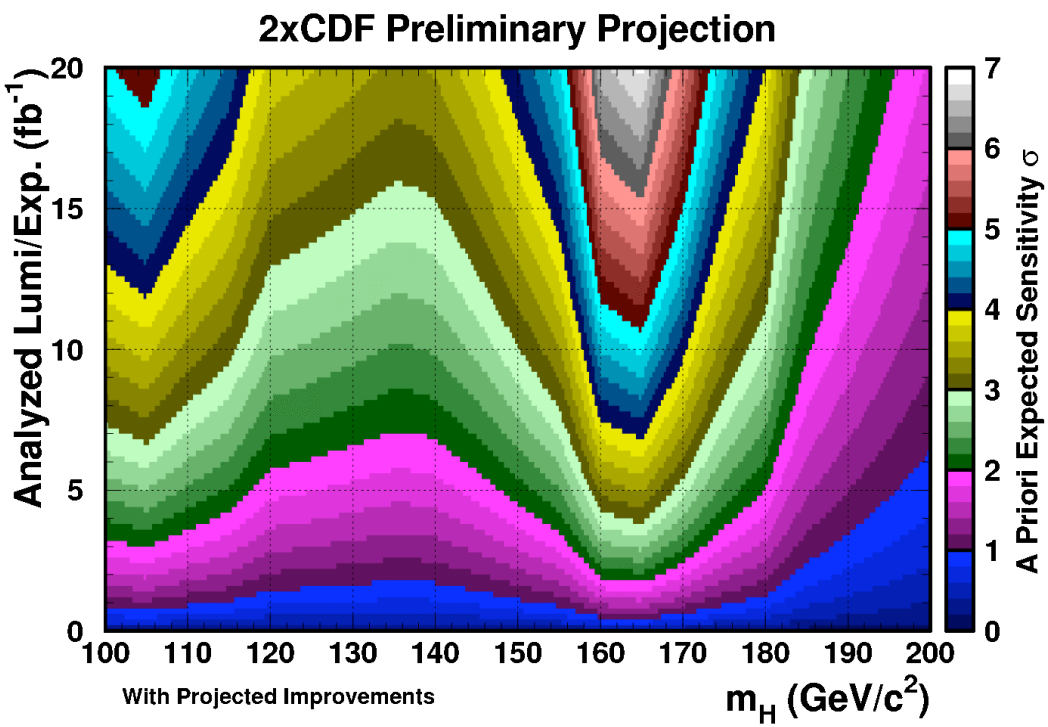
Excluded regions:

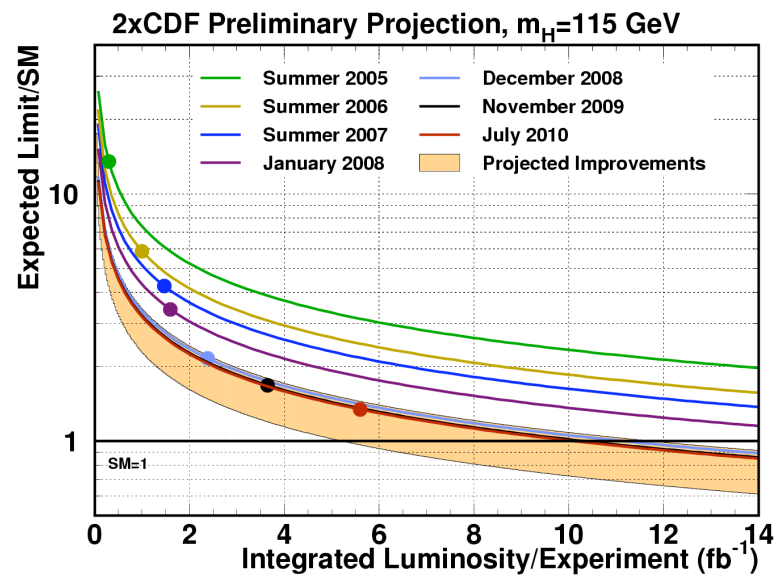
$158 < m_H < 175$ GeV
$100 < m_H < 109$ GeV

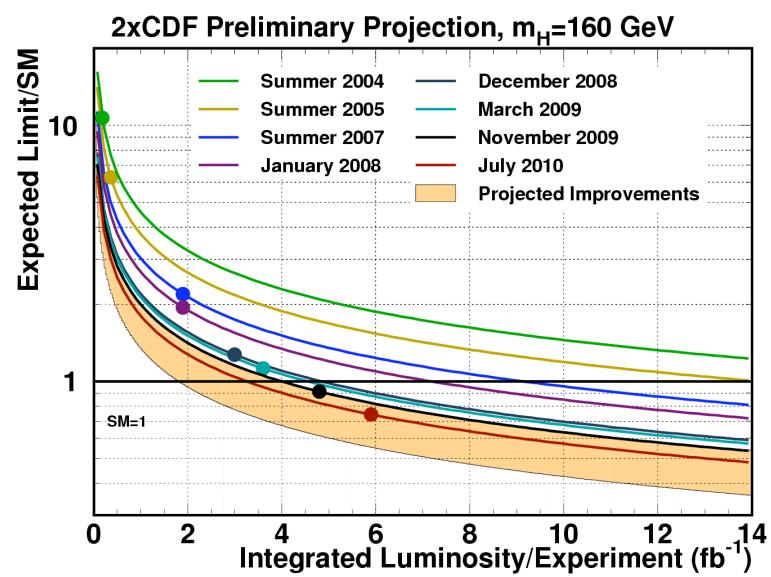
Expected Exclusion
(if no signal is present):

$156 < m_H < 173$ GeV

Tevatron Projected Performance

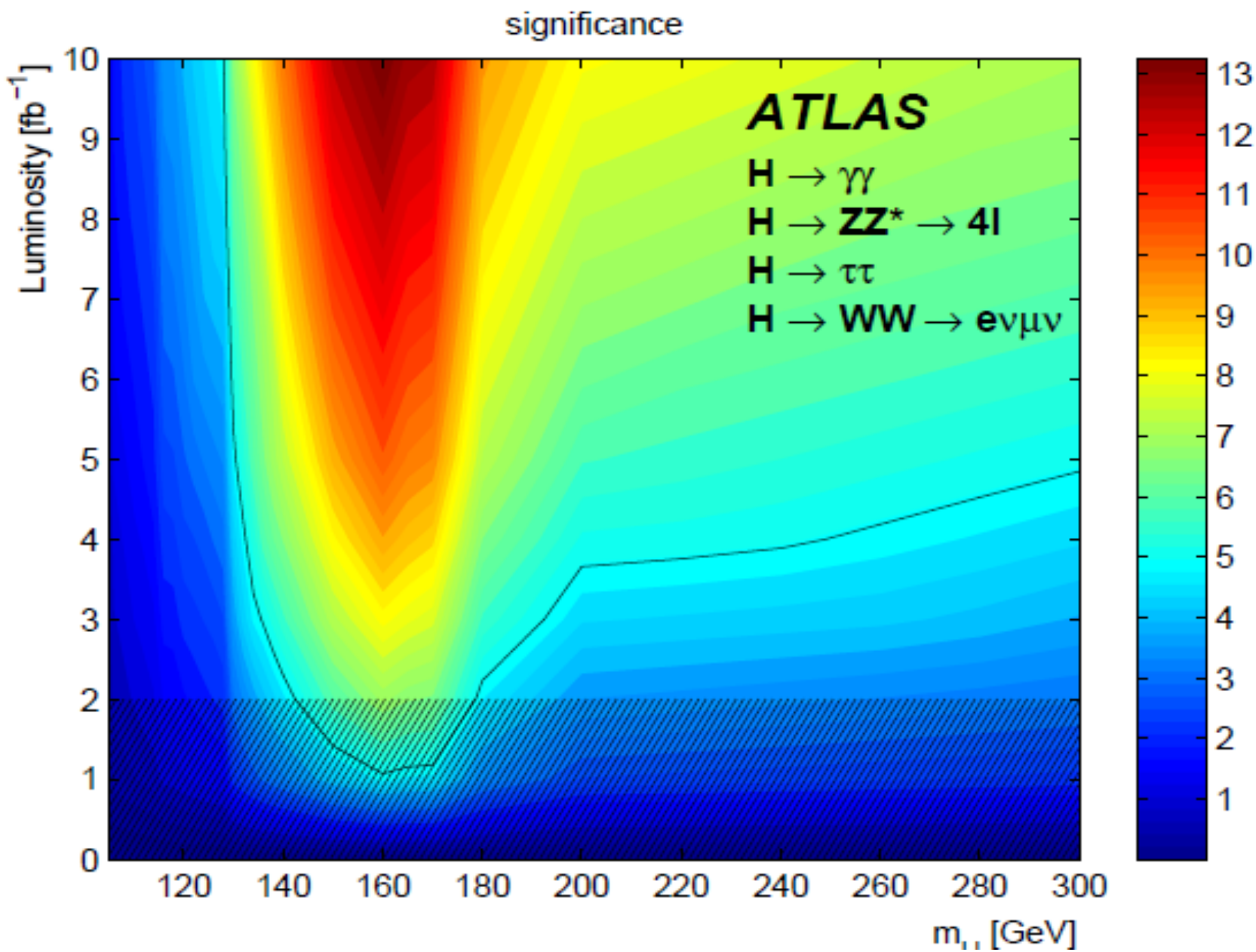






We continue to improve our analyses as well as collect more data.

Multivariate analyses are pretty much at their limit: We now seek more acceptance, looser requirements, new channels...


significance
ATLAS
H → γγ
H → ZZ* → 4l
H → ττ
H → WW → eνμν
Luminosity [fb^{-1}]
m$_{H}$ [GeV]
0
1
2
3
4
5
6
7
8
9
10
120
140
160
180
200
220
240
260
280
300
1
2
3
4
5
6
7
8
9
10
11
12
13

PRL in February 2010

- Issues: not all input channels are final and published. low-m_{ll}, taus and trileptons (new for Moriond 2010). Most low-mass channels are newer and have more data than their last publications.

- Still want to publish the test of $m_H \sim 2M_W$. So publish three PRL's, one from CDF, one from D0, and one combining them, for all the OS+SS channels.

- On agreement of CDF and D0, produce a single author list sorted alphabetically. 1042 Authors! 132 Institutions!

Version 2.5 FERMILAB-PUB-10-xxx-E

Combination of Tevatron searches for the standard model Higgs boson in the W^+W^- decay mode

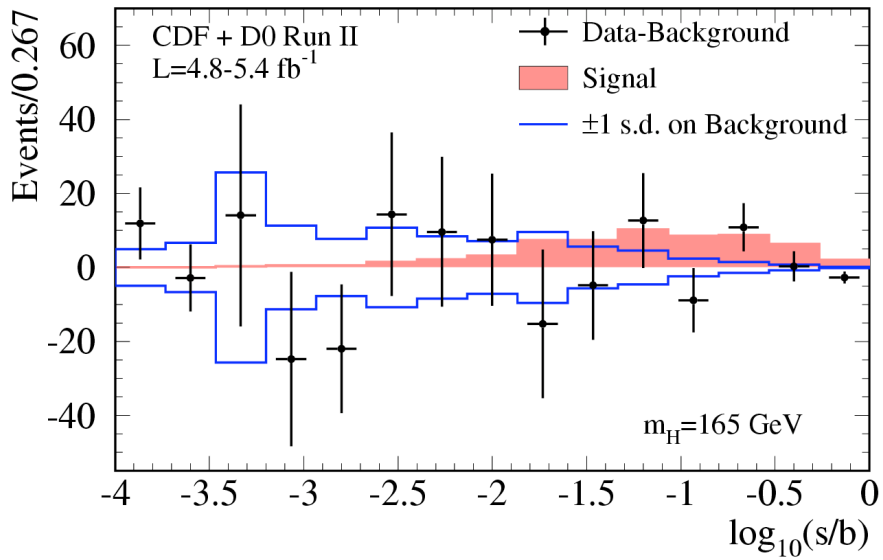
February 2010 PRLs

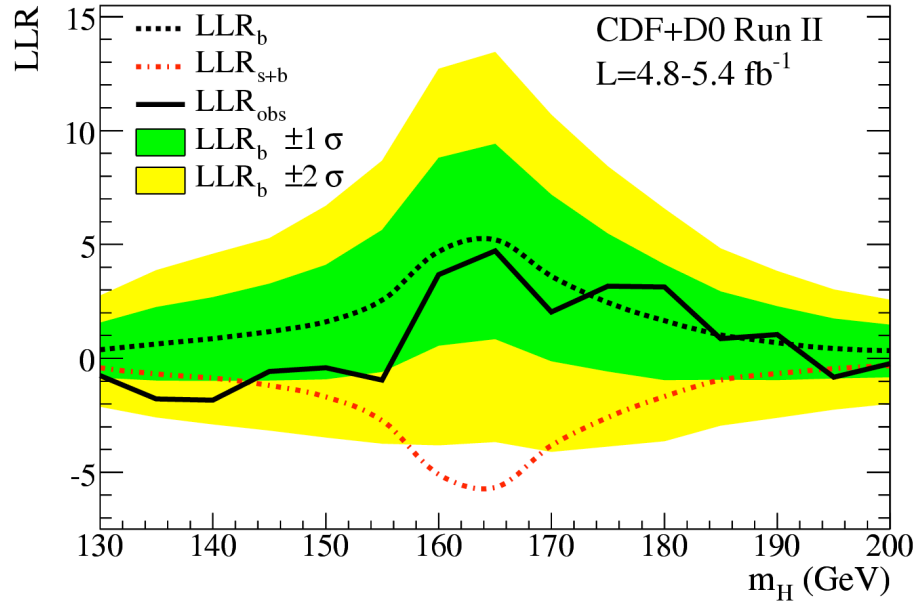
Inclusive Search for Standard Model Higgs Boson Production in the *WW* Decay Channel Using the CDF II Detector
T. Aaltonen et al. (CDF Collaboration)
Phys. Rev. Lett. **104**, 061803 (2010) – Published February 12, 2010

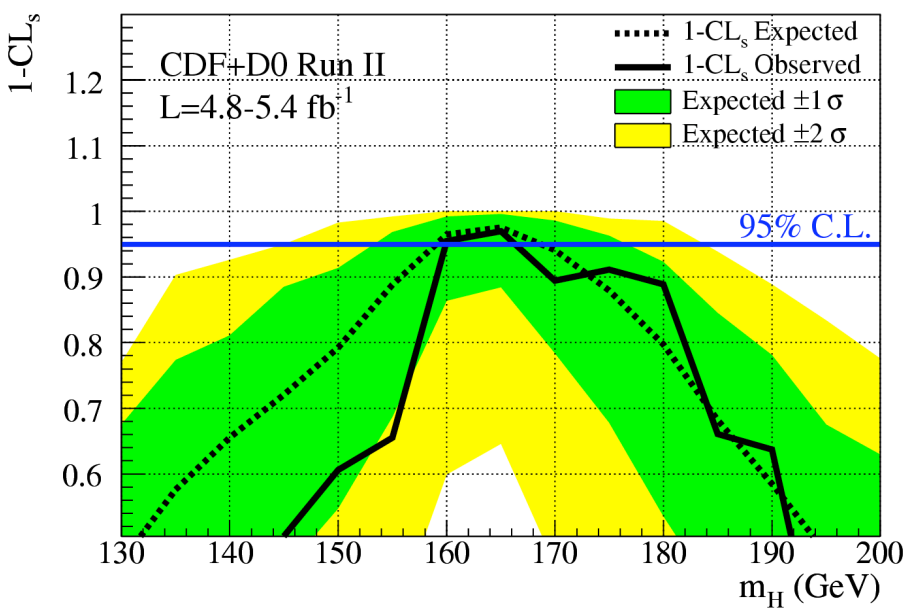
Search for Higgs Boson Production in Dilepton and Missing Energy Final States with 5.4 fb^{-1} of $p\bar{p}$ Collisions at *sqrt*[*s*] =1.96 *TeV*
V. M. Abazov et al. (D0 Collaboration)
Phys. Rev. Lett. **104**, 061804 (2010) – Published February 12, 2010

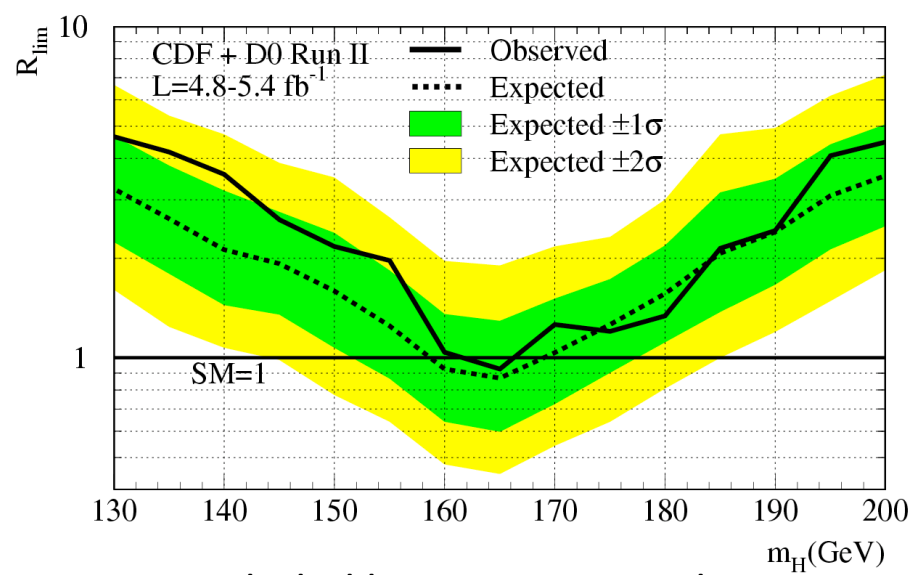
Combination of Tevatron Searches for the Standard Model Higgs Boson in the W^+W^- Decay Mode
T. Aaltonen et al. (CDF and D0 Collaborations) **1042 Authors!**
Phys. Rev. Lett. **104**, 061802 (2010) – Published February 12, 2010

The February 2010 H→WW (well, llMET really) Combination PRL









m_H excluded between 162 and 166 GeV

We made the cover!

And we are the subject
of a Viewpoint article
by Klaus Mönig

http://physics.aps.org/articles/v3/14

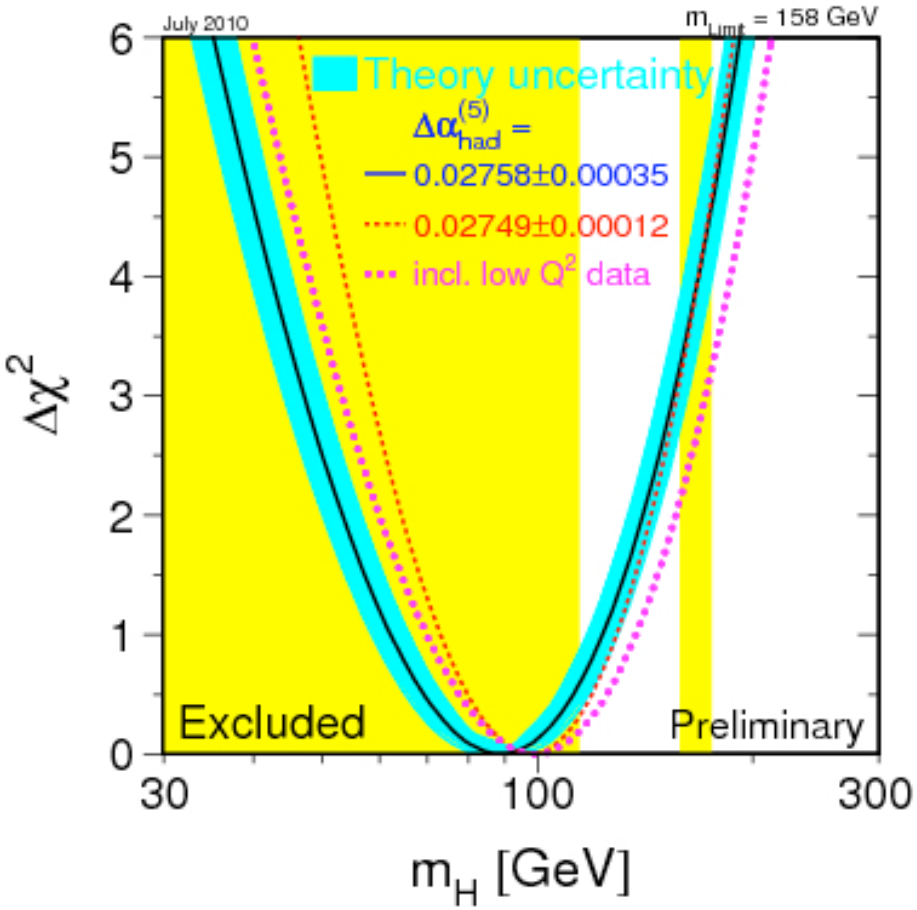
Fourth Generation Analysis Strategy

- **Not a straight-up model drawn on the same exclusion curve:**
  - $\sigma(gg \rightarrow H)$ is enhanced by a factor of 9 (m_H=100 GeV) to 7.5 (m_H=300 GeV) but WH, ZH, and VBF remain unchanged
  - SM combination assumes SM mixture of $gg \rightarrow H$, WH, ZH, and VBF

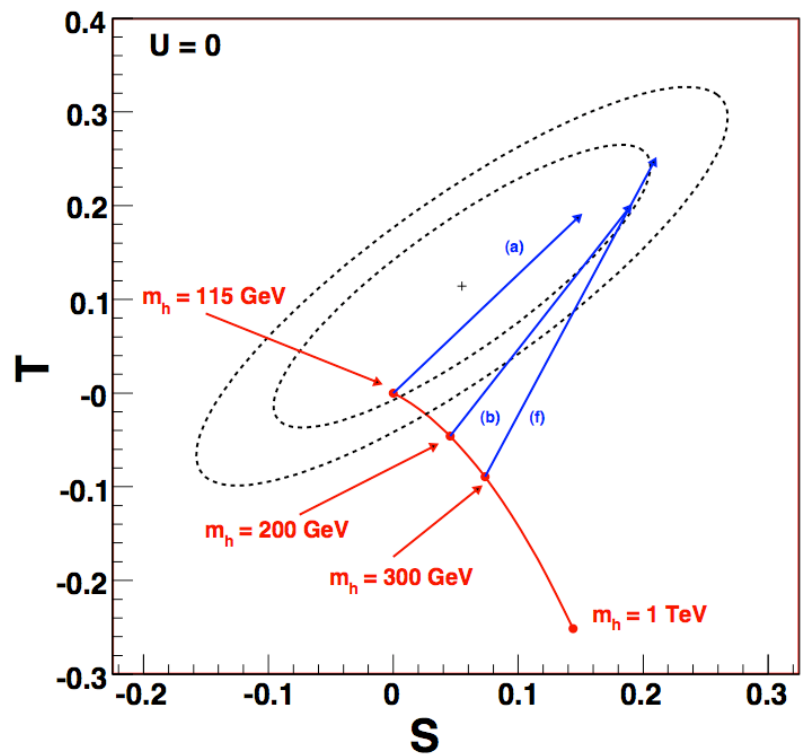
- **Strategy:**
  - Remove WH, ZH, and VBF signals, and retrain discriminants just for $gg \rightarrow H$
  - Extend mass range $110<m_H<260$ GeV (up to 300 GeV coming soon)
  - Compute $\sigma(gg \rightarrow H)$ assuming enhancement factor from Tait, Plehn, Kribs and Spannowsky's HDECAY. Note: 2-loop EW piece does not get enhanced!
    But the interference term does (but by only one power).
    Waiting for a full NNLL calculation, but private communications indicate we're very close with this prescription.
  - Set limits on $\sigma(gg \rightarrow H)$ x Br ($H \rightarrow WW$). Draw theory curves on top
  - Also produce a mass limit assuming theory and uncertainties treated the same way as for the SM.

  - Something to be careful about at high m_H: $\Delta\Phi_{ll}$ no longer peaks at low values for the signal. W's are boosted!

Fourth Generations Possible – Affects the Precision EW Constraint on m_H

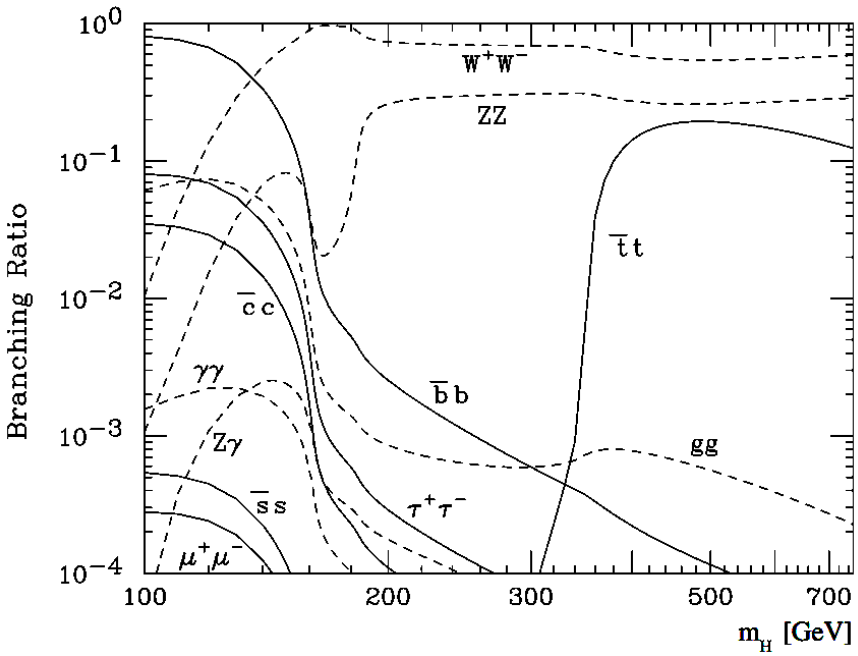


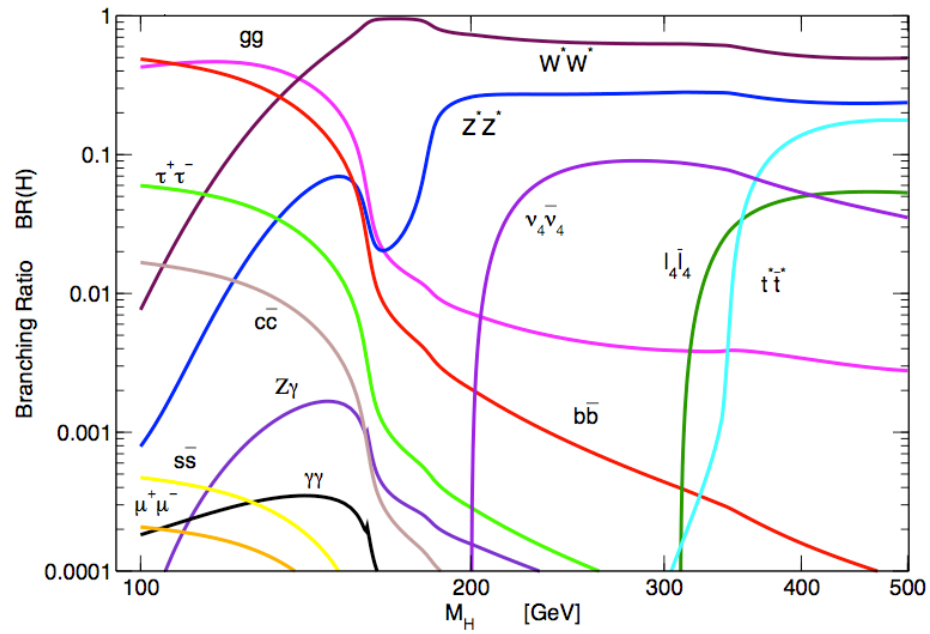
Four Generations and Higgs Physics
Kribs, Tait, Spannowsky, Plehn
Phys.Rev.D76:075016,2007.
arXiv:0706.3718 [hep-ph]



Higgs Boson Decay Branching Fractions and Scenarios

ggH coupling is enhanced, so Br(H→gg) is enhanced.





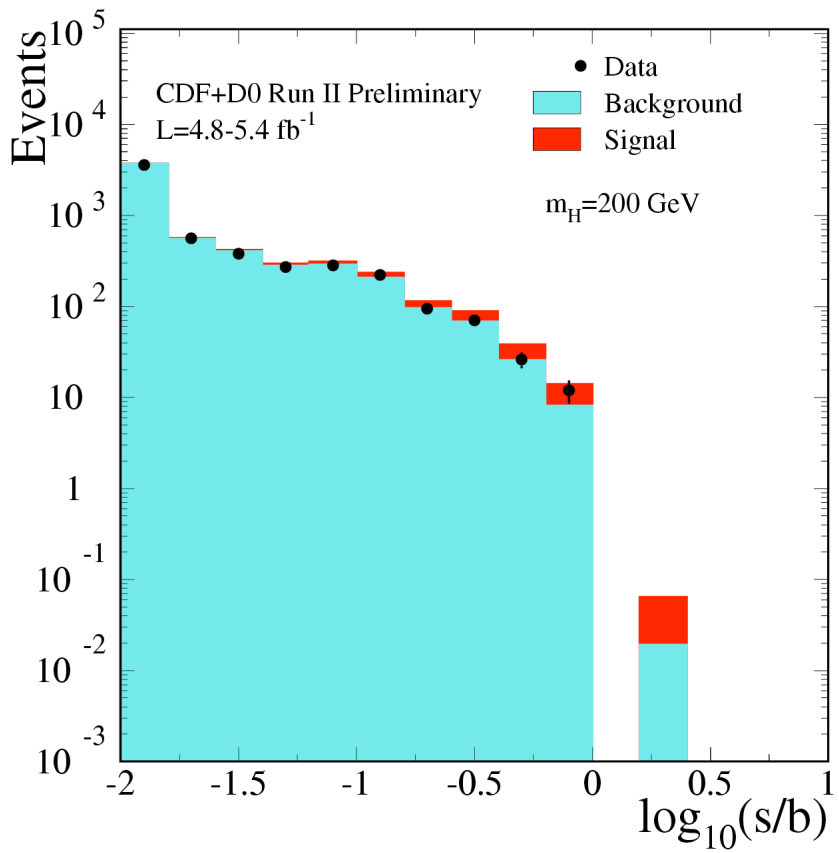
4G (Kribs, Tait, Plehn, Spannowsky)

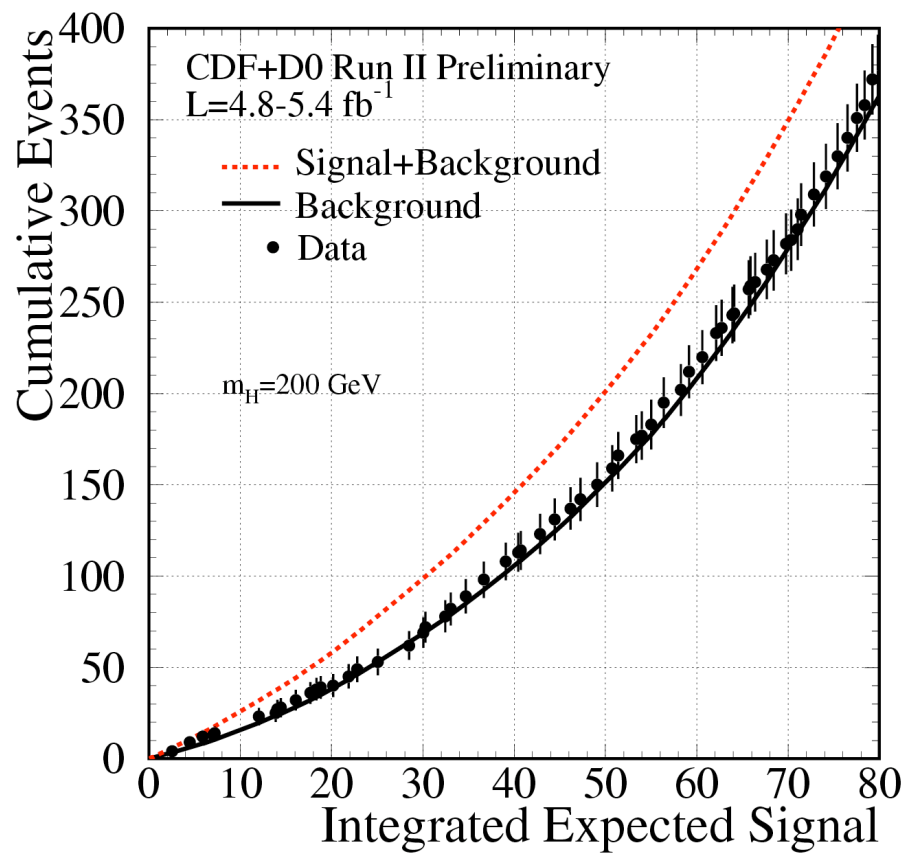
SM (Spira)

Two Scenarios: "Infinite Mass: " $M(f_4)$=1 TeV, Low-Mass: $M(b_4)$=128 GeV, $M(t_4)$=256 GeV, $M(l_4)$=100 GeV, $M(v_4)$=80 GeV

Candidate Summaries in the gg→H Searches, Summed over CDF+D0, all Channels

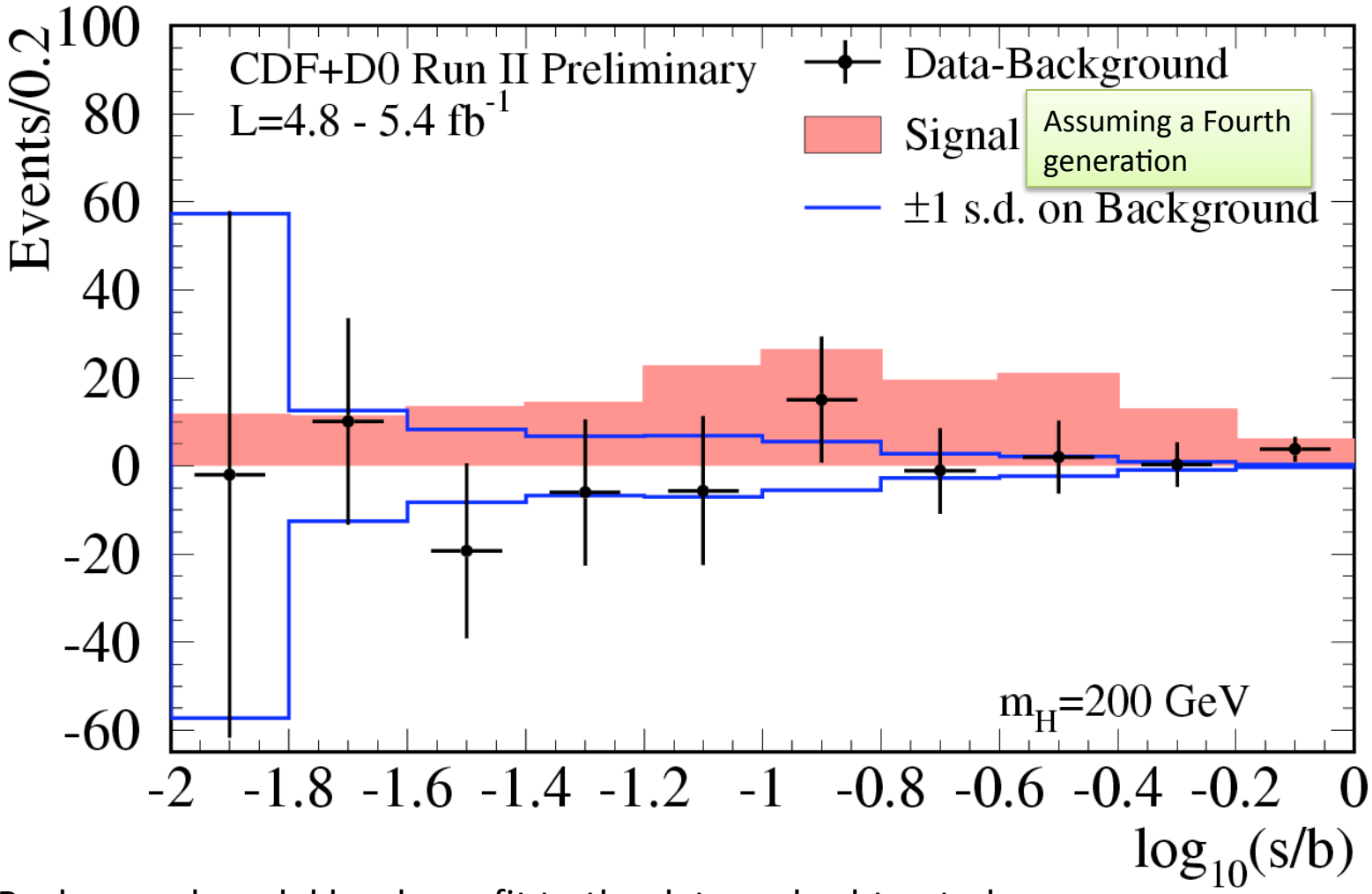
Bins sorted by s/b, and summed over all channels.
Signal normalized to the infinite-mass scenario



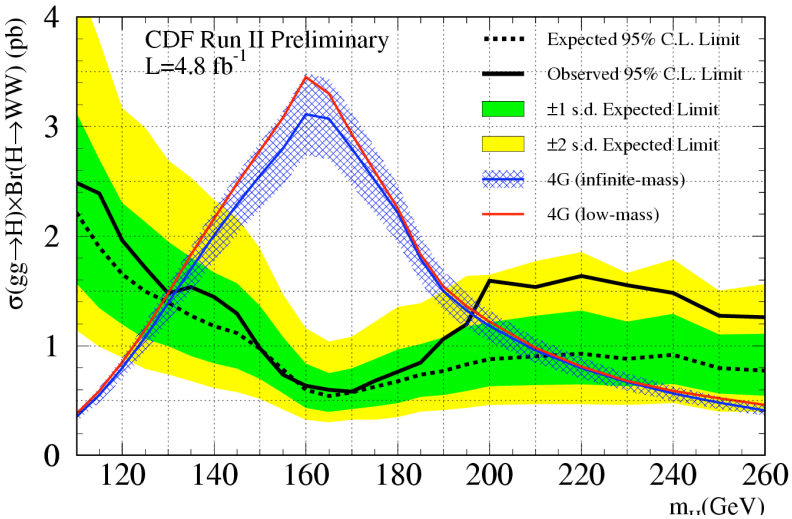


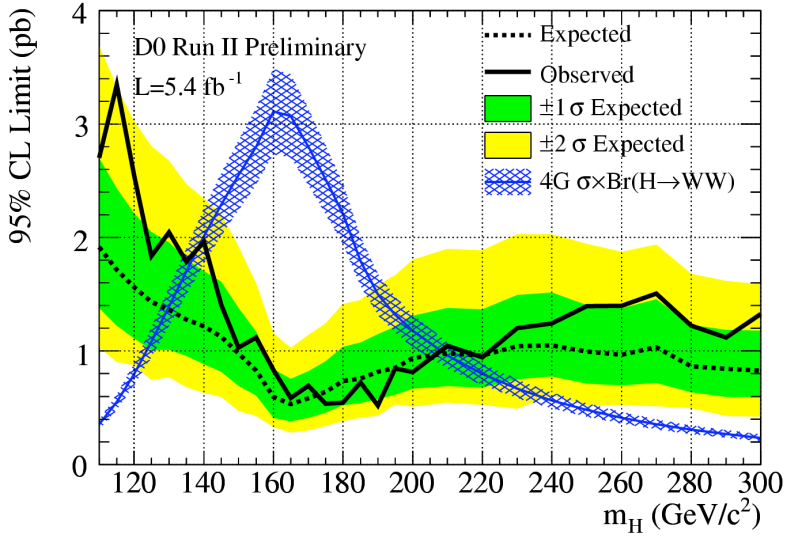
Testing the Fourth-Generation "infinite-mass" scenario at m_H=200 GeV

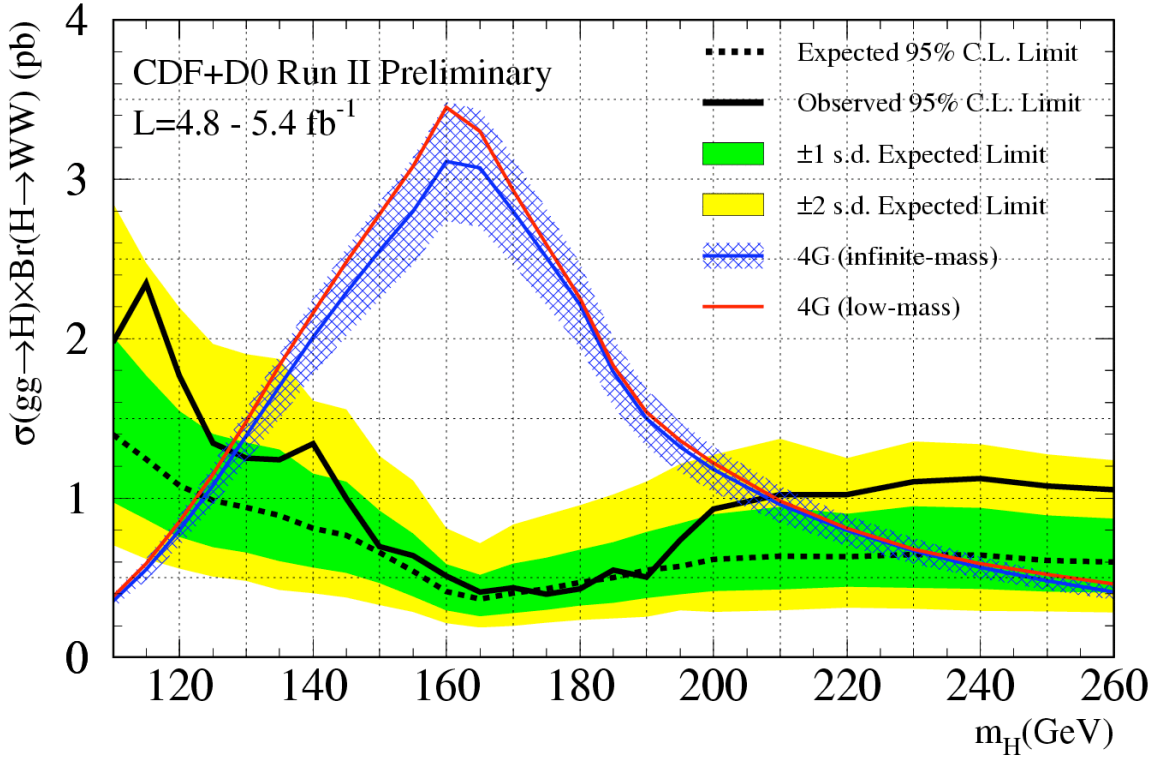
Background-Subtracted Data Distribution, with Signal



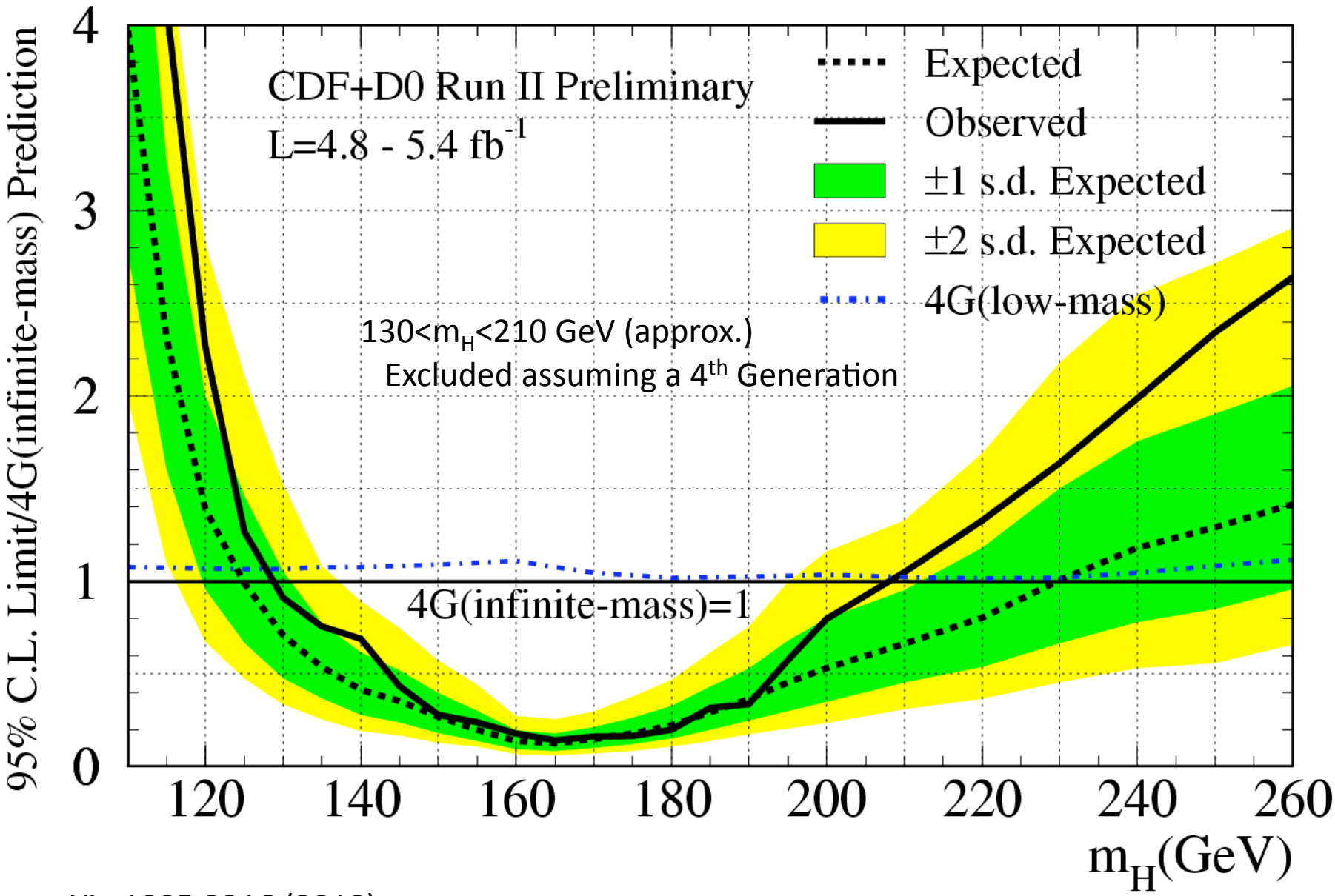
Background model has been fit to the data and subtracted
Error on data – background is sqrt(background)
Blue histogram is the post-fit uncertainty on the background.


CDF Run II Preliminary
L=4.8 fb^{-1}
Expected 95% C.L. Limit
Observed 95% C.L. Limit
±1 s.d. Expected Limit
±2 s.d. Expected Limit
4G (infinite-mass)
4G (low-mass)
σ(gg→H)×Br(H→WW) (pb)
m$_H$(GeV)


D0 Run II Preliminary
L=5.4 fb^{-1}
Expected
Observed
±1 σ Expected
±2 σ Expected
4G σ×Br(H→WW)
95% CL Limit (pb)
m$_H$ (GeV/c^2)

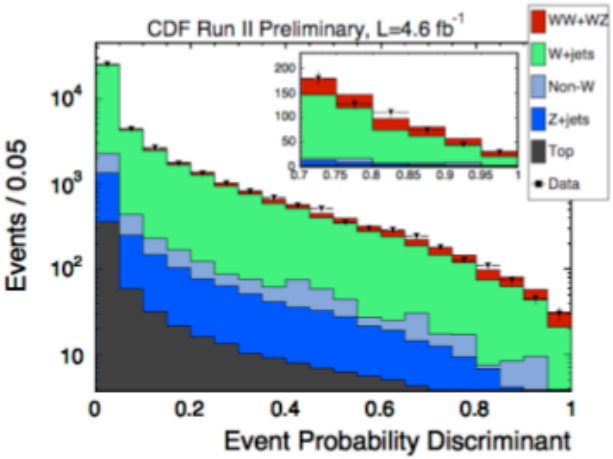

CDF+D0 Run II Preliminary
L=4.8 - 5.4 fb^{-1}
Expected 95% C.L. Limit
Observed 95% C.L. Limit
±1 s.d. Expected Limit
±2 s.d. Expected Limit
4G (infinite-mass)
4G (low-mass)
σ(gg→H)×Br(H→WW) (pb)
m$_H$(GeV)

Test of the Fourth Generation Hypothesis with m_H



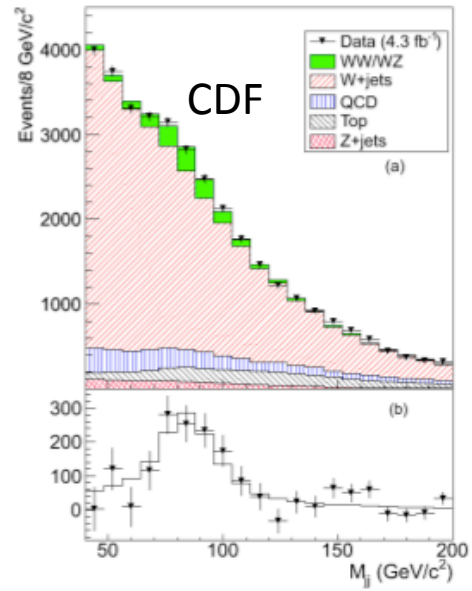
arXiv:1005.3216 (2010)

Multivariate Analyses and Mass Measurement



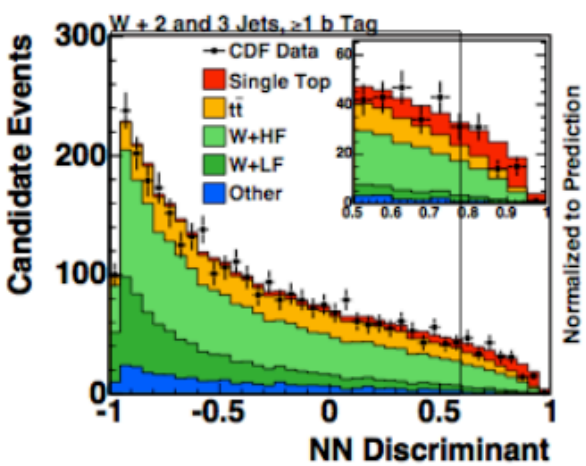
σ(WW+WZ)= 16.5 + 3.2 pb

lvjj
Diboson

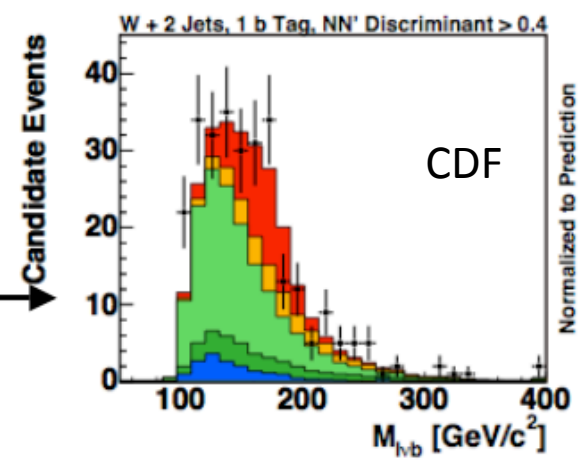


σ(WW+WZ)= 18.1 + 4.1 pb

SM prediction of 16.1 +/- 0.9 pb.



lvjj
Sinlge top

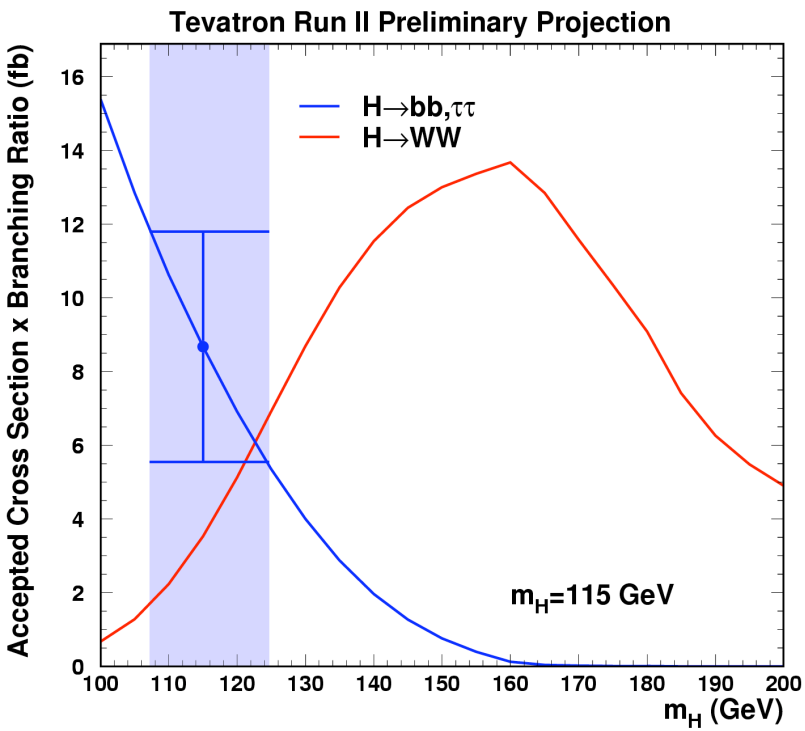


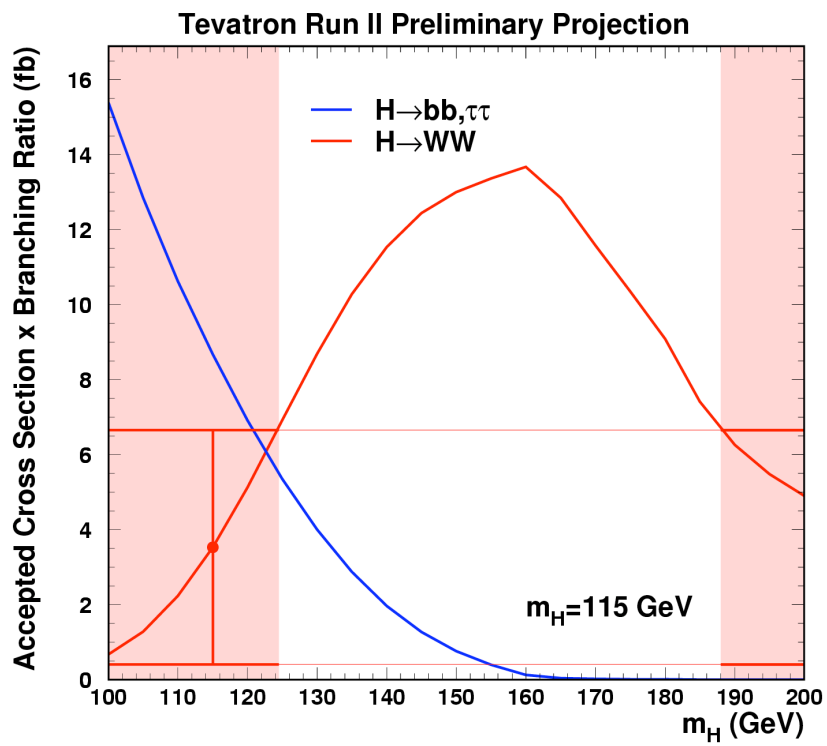
arXiv:1004.1181 Accepted by PRD

No attempt at measuring the mass, but mass peak now visible

Leveraging our Rate Measurements to Measure the Higgs Boson Mass

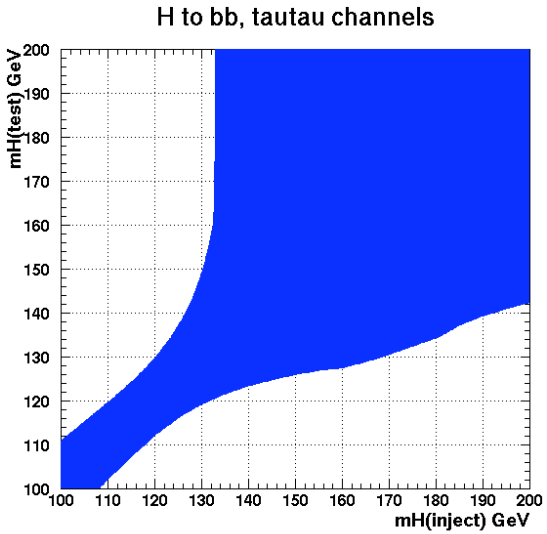
Assuming SM cross sections and branching fractions, measured rates are strong functions of m_H. Example at m_H=115 GeV, assuming +3 sigma excess, and a median outcome in both the bb,ττ channels and the WW channels:

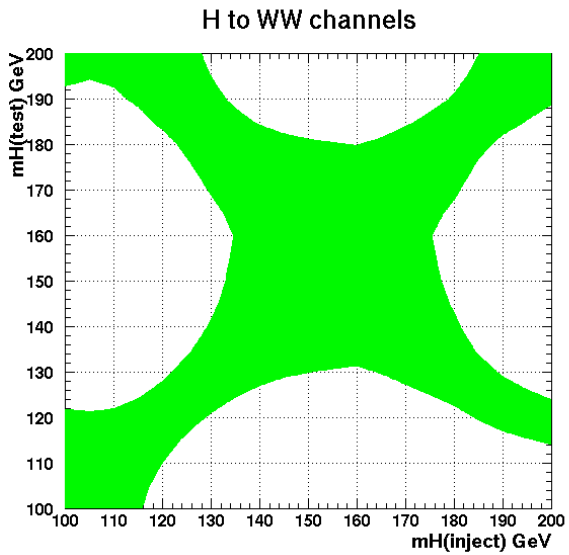


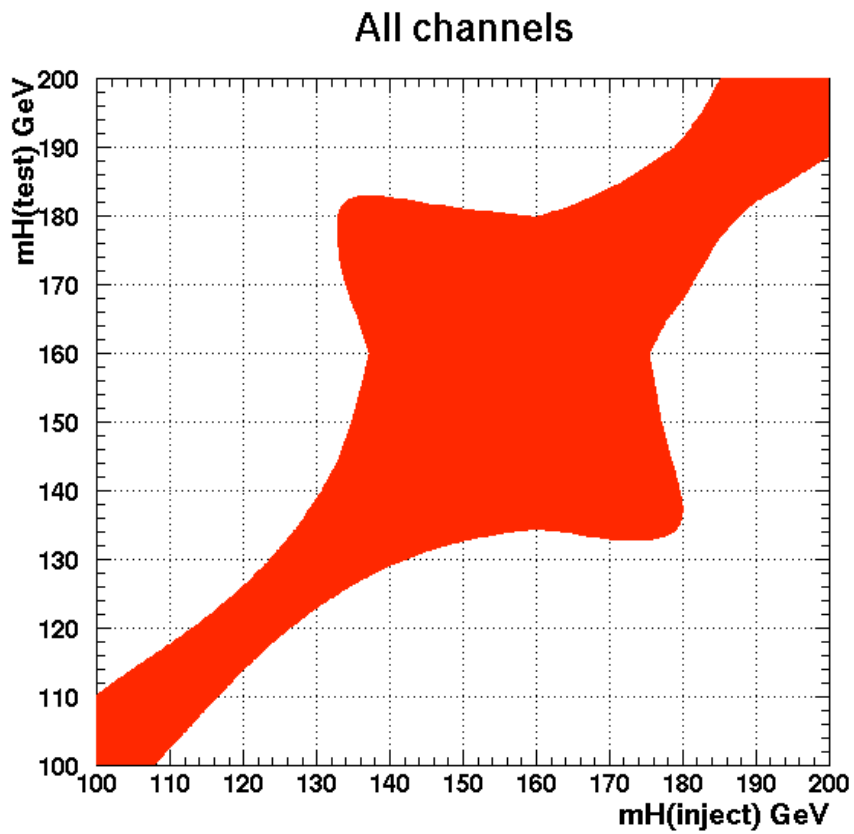


Tau channels can contribute here, even with less precise m_{rec} than the bb channels

What this looks like at all m_H, assuming getting the median SM outcome and have a +3 sigma excess

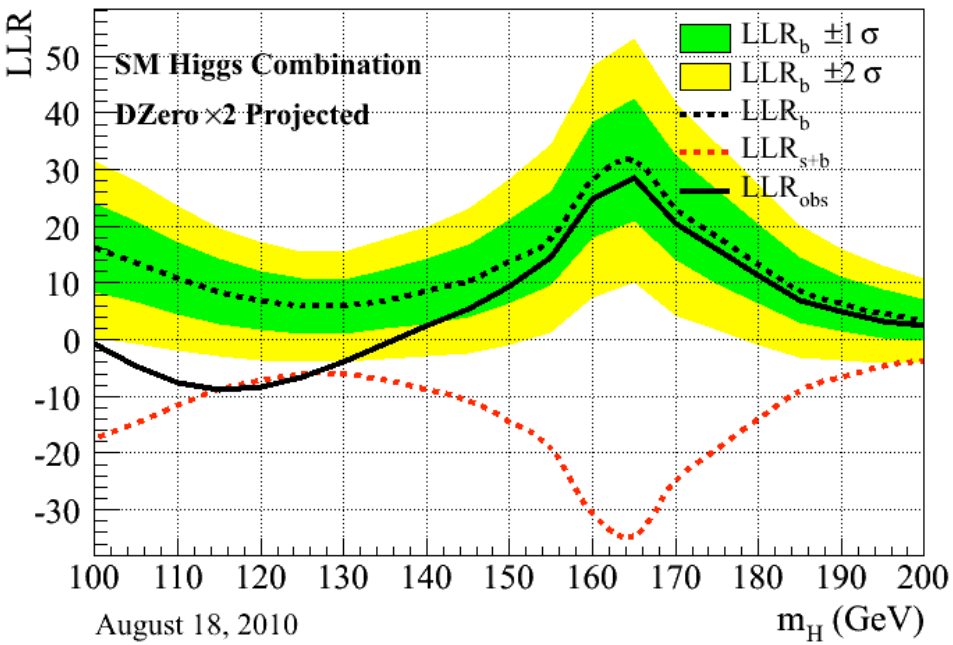


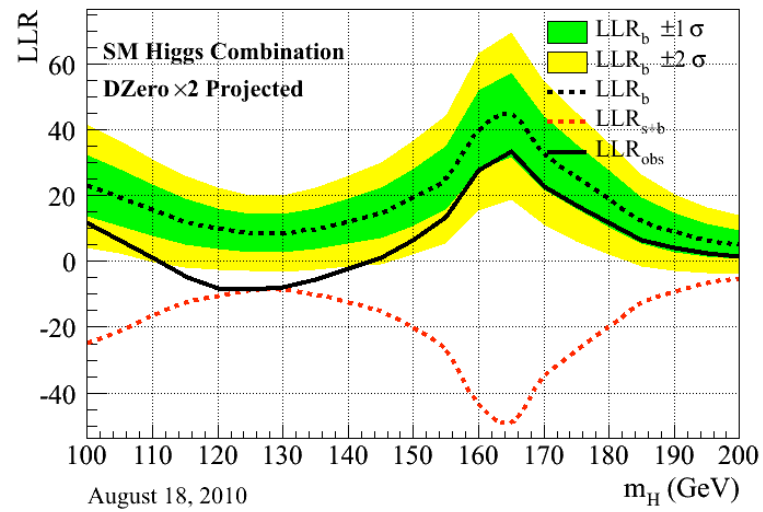


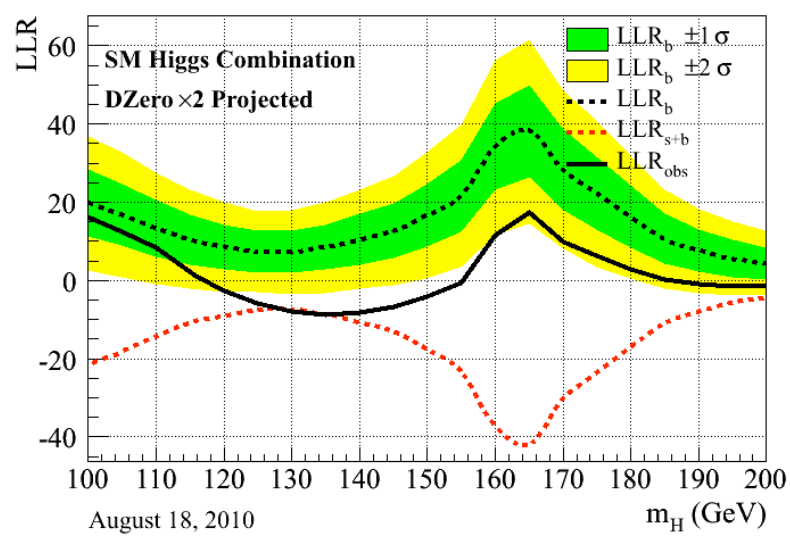


Assumes: Same uncertainty on cross section times b.r. for equal lumi and in bb+ττ and WW channels

Stirring it All Together – The LLR Test







Assuming observed and expected +3 sigma excess, and median outcome. Resolution from $-2\Delta LLR = \Delta\chi^2=1$

Resolution at 115 GeV: ±5 GeV
Resolution at 135 GeV: ~±10 GeV

Summary

- The Tevatron is working VERY WELL!
  We congratulate the Beams Division for their achievements.

- CDF and D0 have vigorous Higgs boson search efforts

- CDF and D0 together exclude m_H between 158 and 175 GeV assuming the SM
  And we *expected* to do that! (assuming a Higgs boson is truly not there).

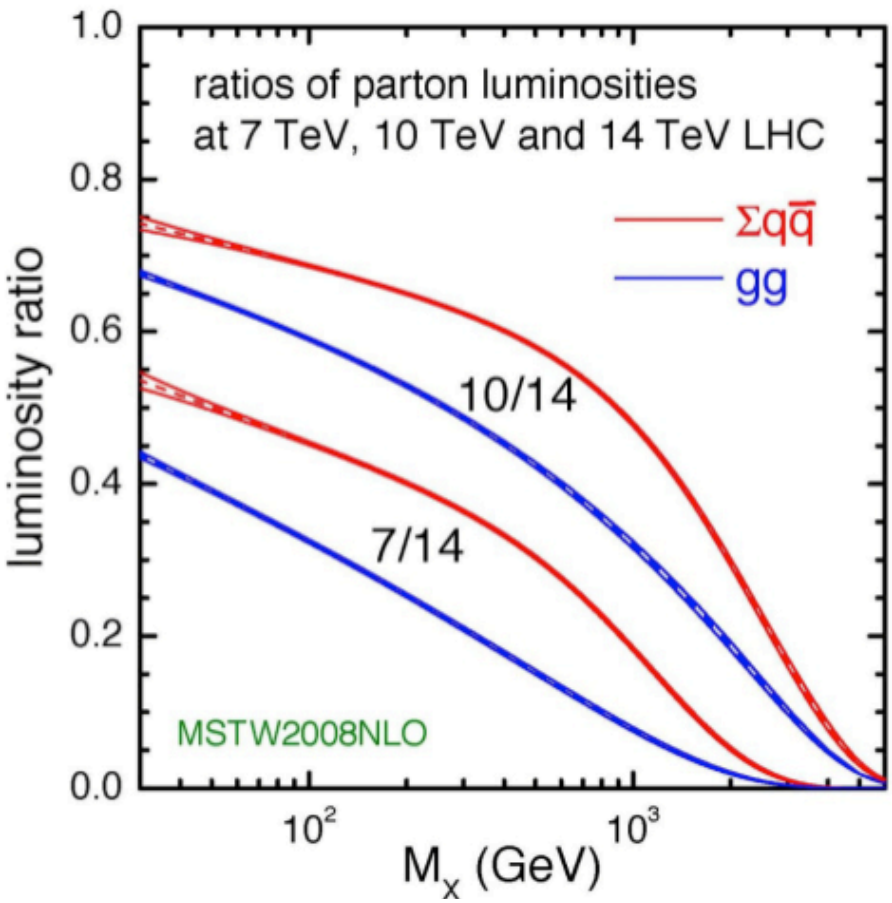
- CDF Sensitivity alone is at the SM level at m_H=165 GeV

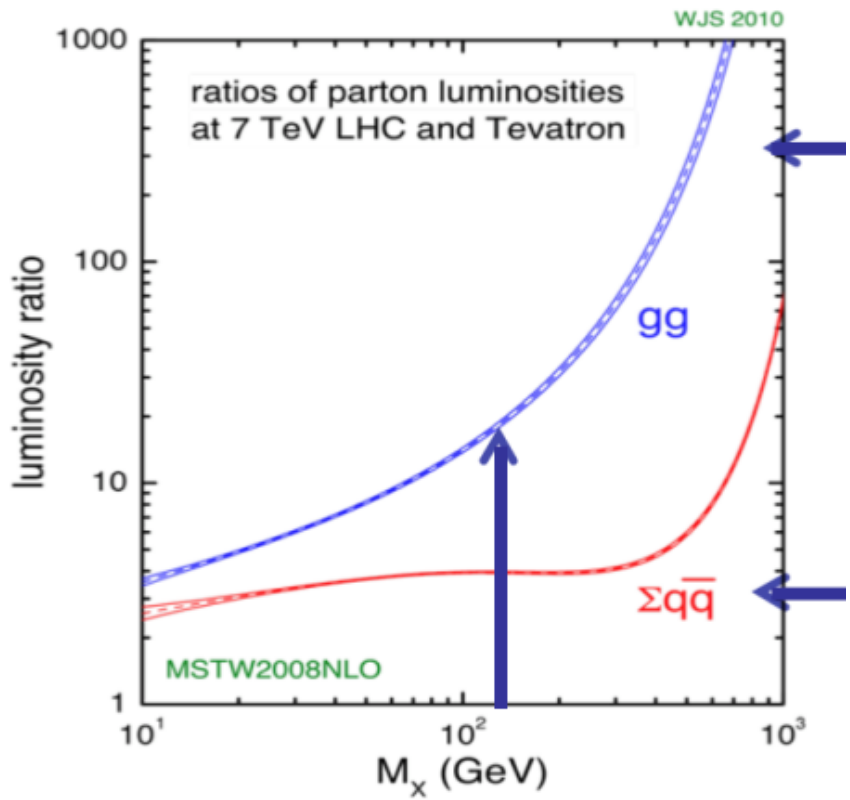
- CDF and D0 together exclude m_H between 130 and 210 GeV (approx)
  assuming a fourth generation of heavy fermions exists

- CDF and D0 hope to accumulate 10 to 12 fb^{-1} of data by the end of Run II.
  Possible run beyond 2011 would raise this number.

Backup Material

Parton Luminosities – Comparing 14 TeV LHC to 10 and 7 TeV LHC, and the Tevatron





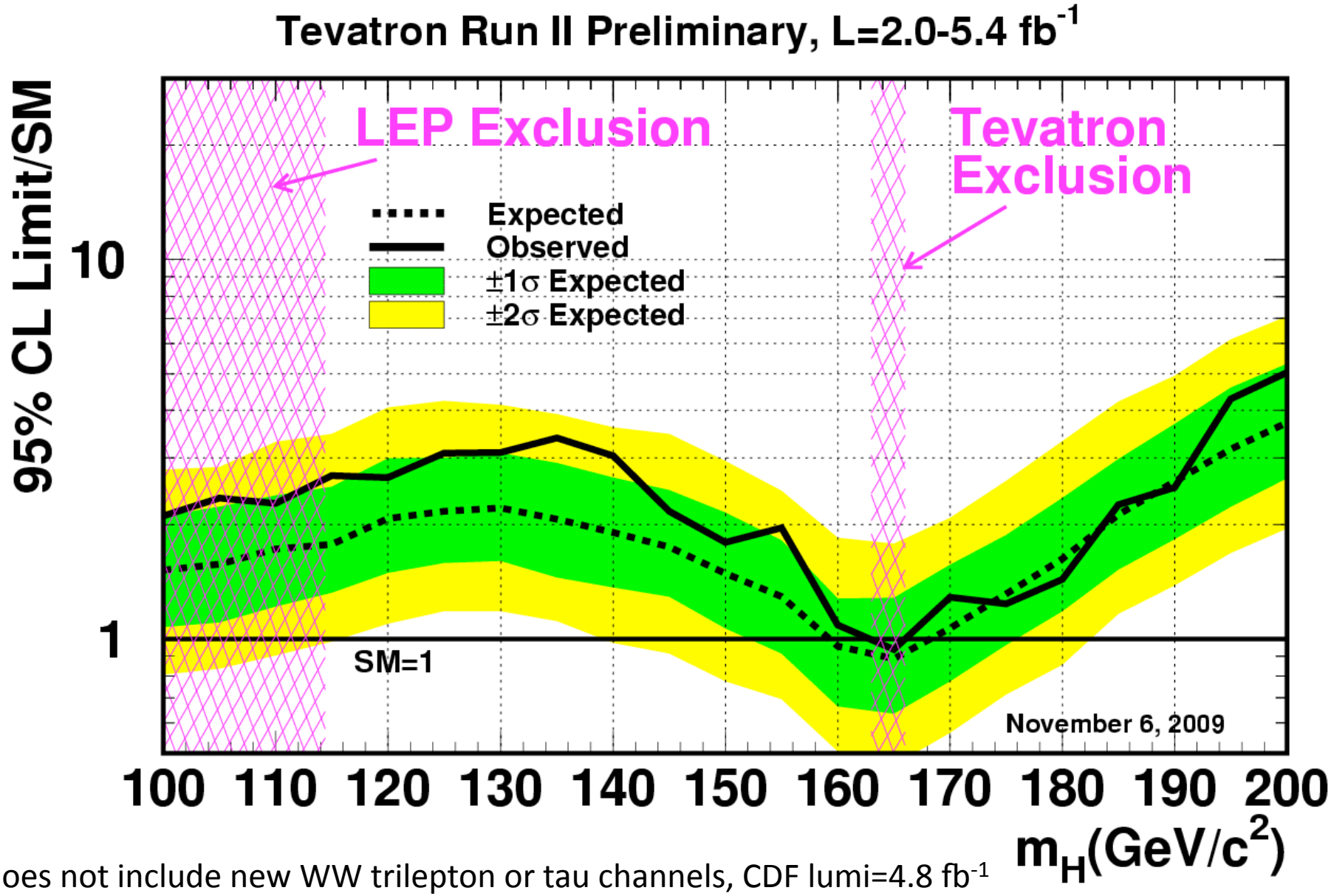
Tevatron: 10 fb^{-1} analyzable/exp at 1.96 TeV by end 2011. Asking for three more years.
LHC: 1 fb^{-1} per exp by end 2011.
Much more data and energy later

Different PDF sets

- MSTW08 – fit all previous types of data. Most up-to-date Tevatron jet data. Not most recent HERA combination of data. PDFs at LO, NLO and NNLO.
- CTEQ6.6 – very similar. Not quite as up-to-date on Tevatron data. PDFs at NLO. New – CT10 include HERA combination and more Tevatron data. Little changes.
- NNPDF2.0 – include all except HERA jet data (not strong constraint) and heavy flavour structure functions. Include HERA combined data. PDFs at NLO.
- HERAPDF1.0 – based entirely on HERA inclusive structure functions, neutral and charged current. Use combined data. PDFs at LO, NLO and now NNLO.
- ABKM09 – fit to DIS and fixed target Drell-Yan data. PDFs at NLO and NNLO.
- GJR08 – fit to DIS, fixed target Drell-Yan and Tevatron jet data. PDFs at NLO and NNLO.

Use of HERA combined data instead of original data slight increase in quarks at low x (depending on procedure).

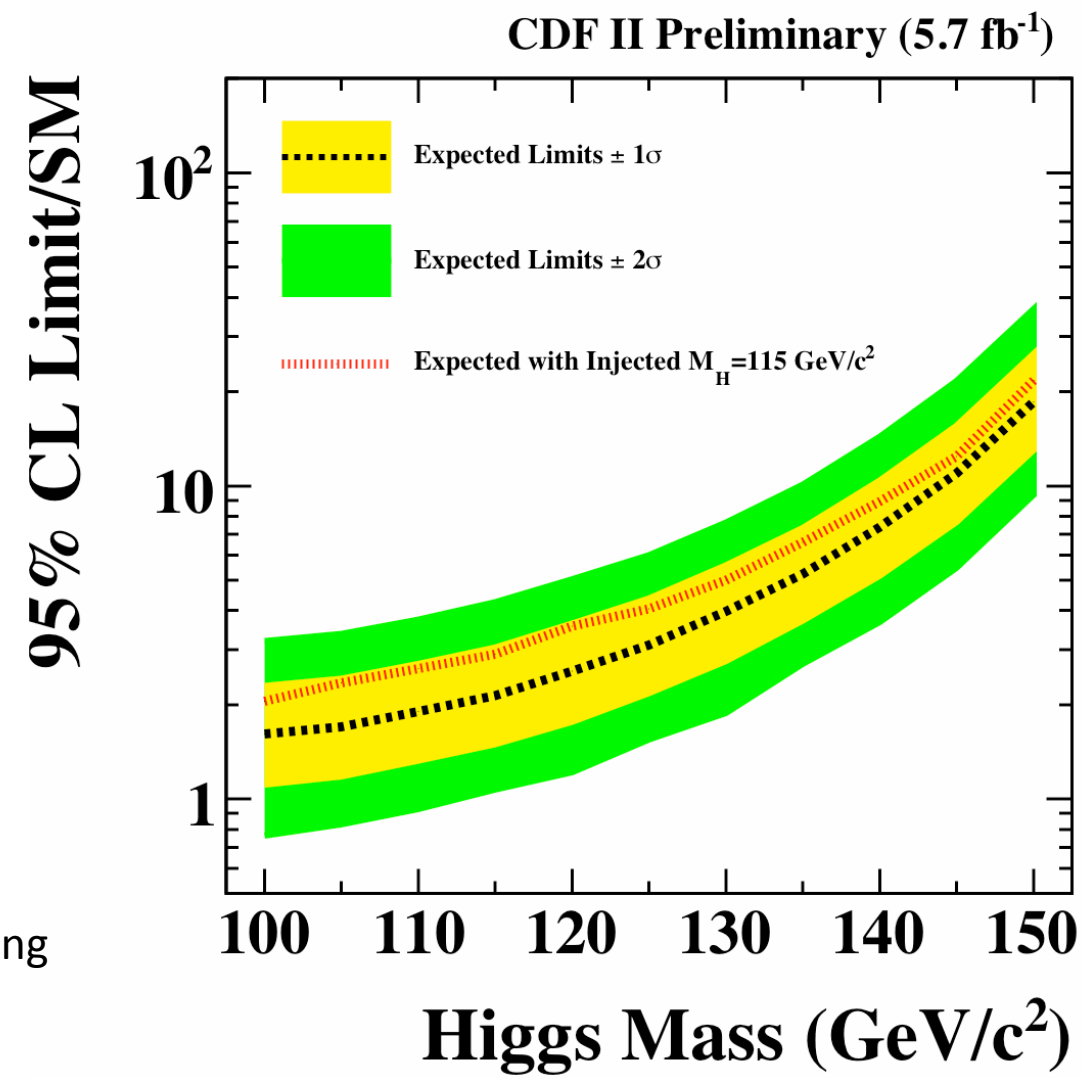
November 2009 Combination (Low and High-mass) for HCP 2009



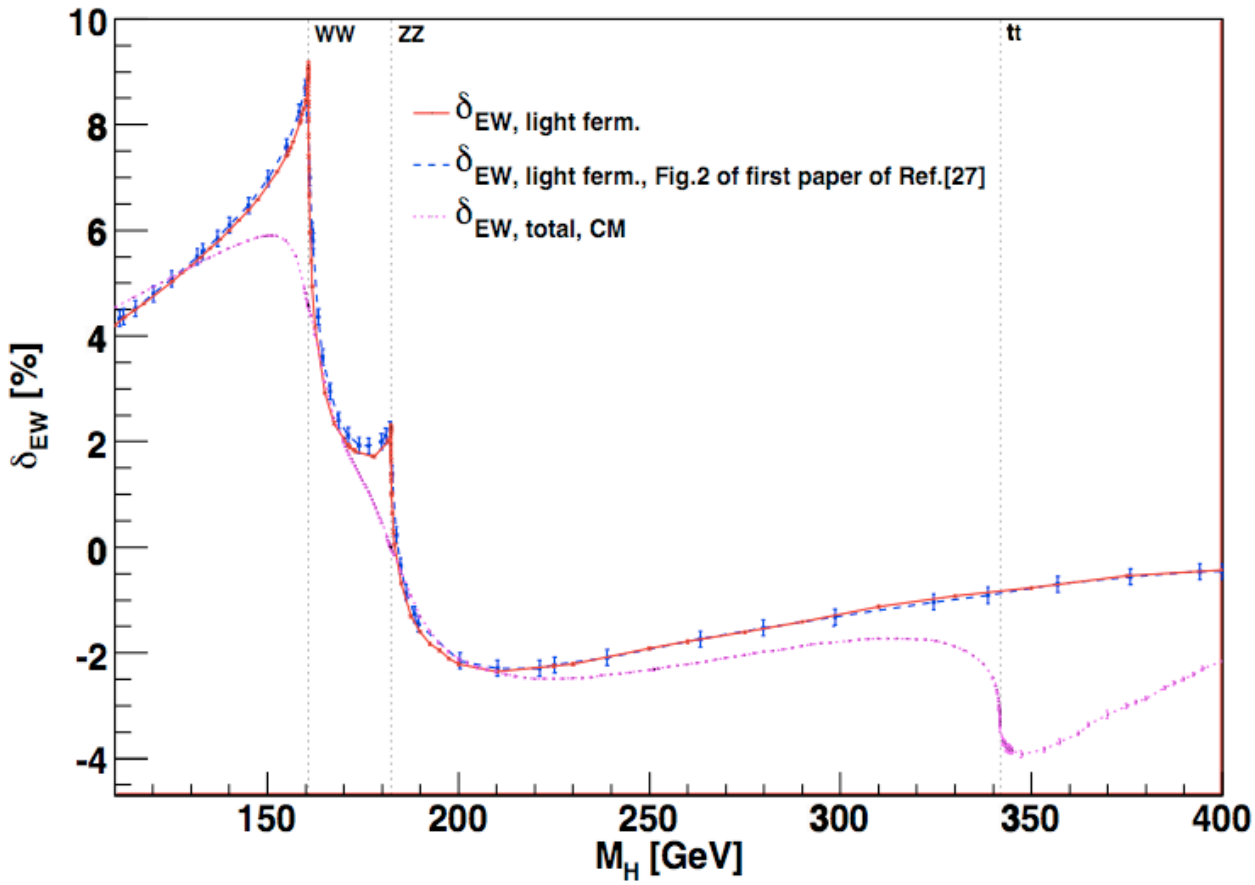
does not include new WW trilepton or tau channels, CDF lumi=4.8 fb^{-1}

Studies of Injecting a Signal at m_H=115 GeV

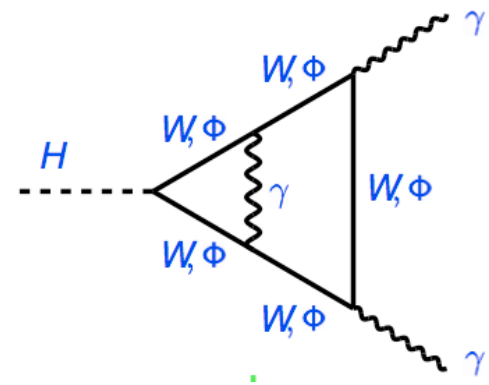
- lvbb, METbb, and llbb channels included
- Inject SM*1.0 signal at m_H=115 GeV on top of SM backgrounds, and generate pseudoexperiments with that.
- Analyze 115 signal+background pseudoexperiments at other test masses – 100 GeV to 150 GeV
- Find the median expected limit assuming signal is there (compute it just as you would without the signal) and compare with the distribution of limits assuming the signal is completely absent.



Comparing H→γγ with gg→H coupling shifts

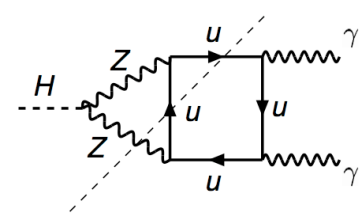


Passarino



Coulomb singularity not present in ggH coupling

Moderated by Γ_W and Γ_Z



Passarino, Zurich 2009

Comparing Pythia Differential Distributions to NLO and Resummed Predictions

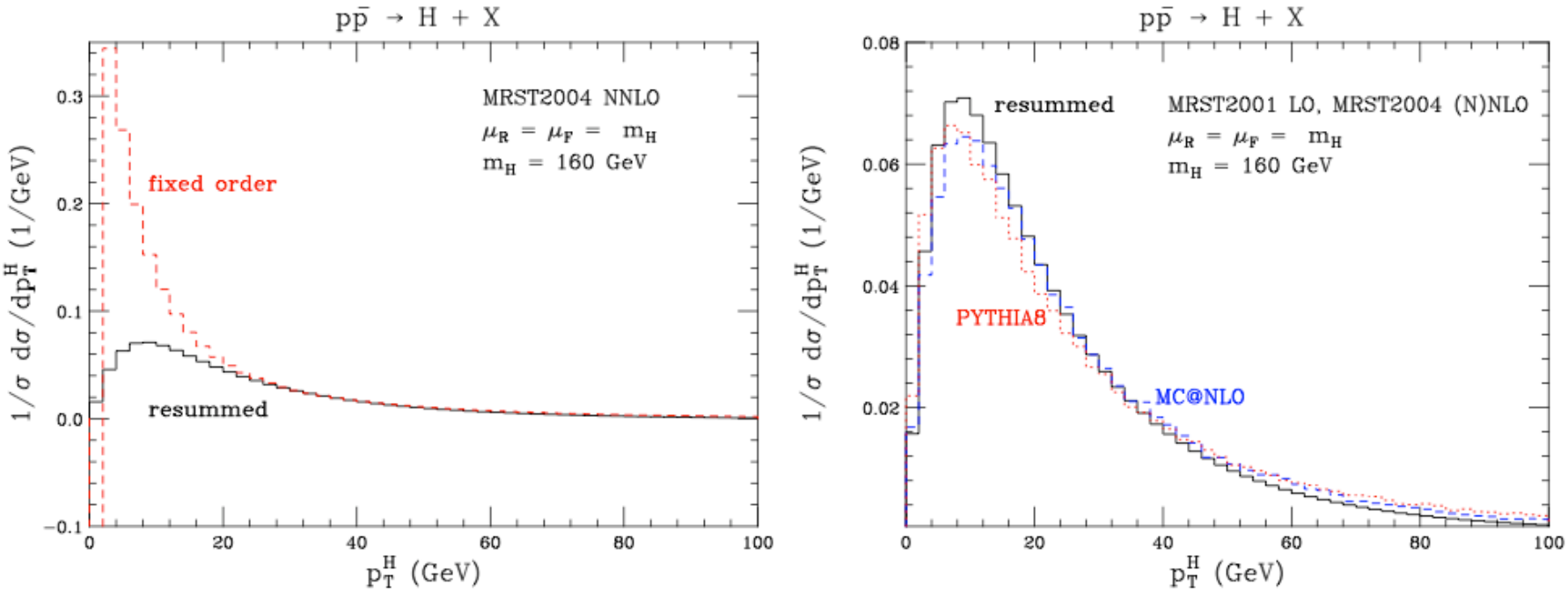


Figure 1: On the left figure, we show the normalized transverse momentum distributions for $m_H = 160\,\text{GeV}$ and $\mu = \mu_R = \mu_F = m_H$ using NNLO fixed-order perturbation theory and the resummed calculation of Ref. [56]. On the right figure, the same distribution is shown for MC@NLO, PYTHIA8, and the calculation of Ref. [56].

Anastasiou, Dissertori, Grazzini, Stockli, and Webber 2009

Cross Sections and Branching Fractions used for ICHEP 2010

m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to \tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to \gamma\gamma)$ (%)
100	1861	291.9	169.8	99.5	80.33	3.542	7.920	1.052	0.1071	0.1505
105	1618	248.4	145.9	93.3	78.57	3.463	7.821	2.307	0.2035	0.1689
110	1413	212.0	125.7	87.1	75.90	3.343	7.622	4.585	0.4160	0.1870
115	1240	181.9	108.9	79.07	71.95	3.169	7.288	8.268	0.8298	0.2029
120	1093	156.4	94.4	71.65	66.49	2.927	6.789	13.64	1.527	0.2148
125	967	135.1	82.3	67.37	59.48	2.617	6.120	20.78	2.549	0.2204
130	858	116.9	71.9	62.5	51.18	2.252	5.305	29.43	3.858	0.2182
135	764	101.5	63.0	57.65	42.15	1.854	4.400	39.10	5.319	0.2077
140	682	88.3	55.3	52.59	33.04	1.453	3.472	49.16	6.715	0.1897
145	611	77.0	48.7	49.15	24.45	1.075	2.585	59.15	7.771	0.1653
150	548	67.3	42.9	45.67	16.71	0.7345	1.778	68.91	8.143	0.1357
155	492	58.9	37.9	42.19	9.88	0.4341	1.057	78.92	7.297	0.09997
160	439	50.8	33.1	38.59	3.74	0.1646	0.403	90.48	4.185	0.05365
165	389	44.6	30.0	36.09	1.29	0.05667	0.140	95.91	2.216	0.02330
170	349	40.2	26.6	33.58	0.854	0.03753	0.093	96.39	2.351	0.01598
175	314	35.6	23.7	31.11	0.663	0.02910	0.073	95.81	3.204	0.01236
180	283	31.4	21.1	28.57	0.535	0.02349	0.059	93.25	5.937	0.01024
185	255	28.2	18.9	26.81	0.415	0.01823	0.046	84.50	14.86	0.008128
190	231	25.1	17.0	24.88	0.340	0.01490	0.038	78.70	20.77	0.006774
195	210	22.4	15.3	23	0.292	0.01281	0.033	75.88	23.66	0.005919
200	192	20.0	13.7	21.19	0.257	0.01128	0.029	74.26	25.33	0.005285

ggH: Grazzini and de Florian; Anastasiou, Boughezal, Petriello

WH, ZH: Baglio and Djouadi (June 2010, update in hep-ph Sep. 2010 came too late, even though we knew about it a few weeks before ICHEP by e-mail)

VBF: MCFM

Branching Fractions: Spira's HDECAY v.3.53 (April 2010)