Searches for the Higgs Boson Decaying to W^+W^- at the Tevatron

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University of Notre Dame HEP Seminar
March 30, 2010

- Review: The Problem of Symmetry
- Theoretical status of the gg→H Production Cross Section
- CDF's Searches for H->W^+W^-
- Combining Channels: Setting Limits and
  How to Discover a New Particle
- Searches for gg→H→W^+W^- in the context of a fourth generation

Parity Violation and the Beginnings of the SM of Electroweak Interactions

- Lee and Yang, "Question of Parity Conservation in Weak Interactions" Phys. Rev. **104**, 254-258 (1956).

- C. S. Wu et al., "Experimental Test of Parity Conservation in Beta Decay" Phys. Rev. **105**, 1413-1414 (1957).

- Garwin, Lederman and Weinrich, "Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon" Phys. Rev. **105**, 1415-1417 (1957).

The Weirdness of Left-Handed Interactions

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

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

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

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

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

SU(2) x U(1) Model Consequences

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

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

- Two problems --

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

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

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

  -- conflict with observations!

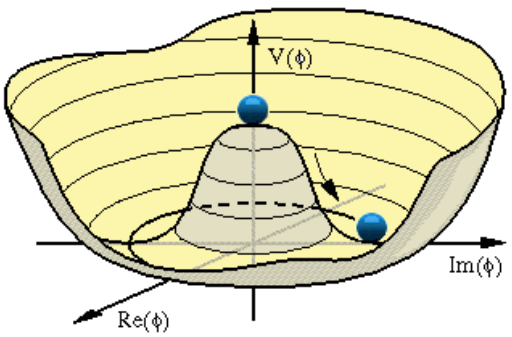
The Subterfuge -- Add a Minimal Set of New Fields and Interactions

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

Complex Doublet of fields -- four real degrees of freedom

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

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



Basic Relationships

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

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

$$m_H = \mu\sqrt{2} = v\sqrt{2\lambda} \qquad g = \frac{e}{\sin\theta_W} \qquad g' = \frac{e}{\cos\theta_W}$$

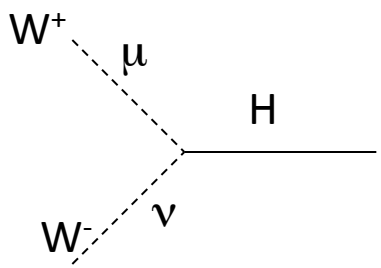
$$M_Z = \frac{v}{2}\sqrt{g^2 + g'^2} \qquad M_W = g\frac{v}{2} = M_Z \cos\theta_W$$

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

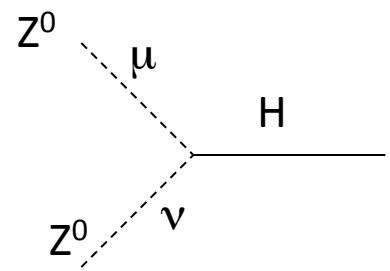
One free parameter: m_H

Conventions: Peskin and Schroeder "An Introduction to Quantum Field Theory"

Tree-Level Couplings of Higgs Bosons



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



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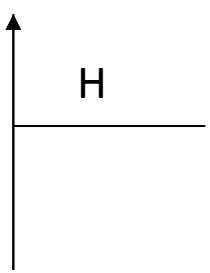
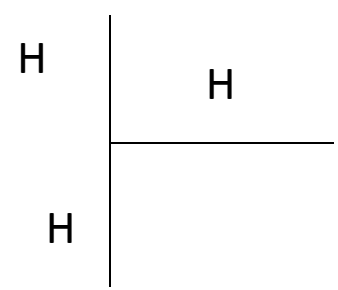


$$= -i\frac{m_f}{v}$$

Fermions



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

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

Conventions: Peskin and Schroeder "An Introduction to Quantum Field Theory"

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

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

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

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

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

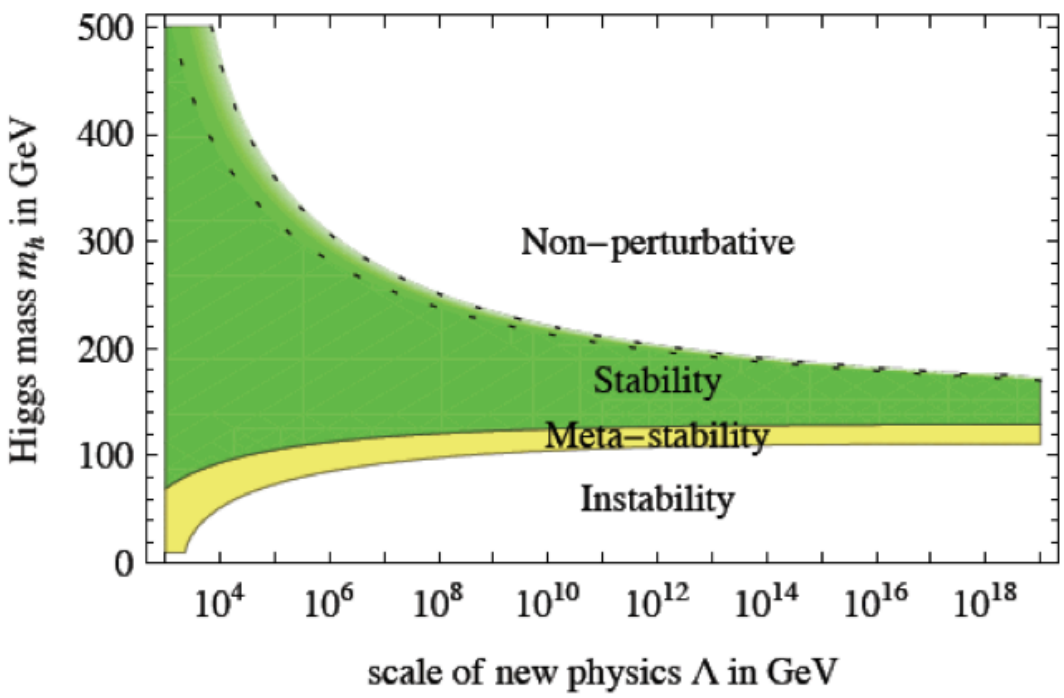
If no Higgs then something must happen!

G. Altarelli, HCPSS 2008

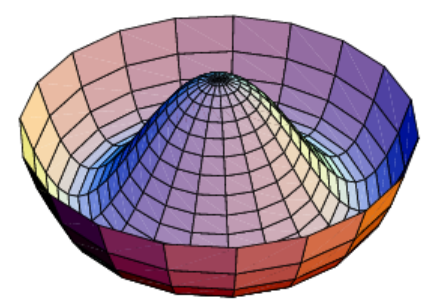
Vacuum Stability and Triviality Bounds on SM m_H

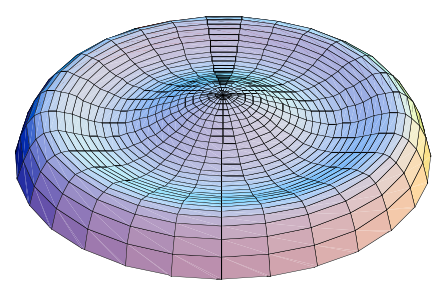
Loops with SM particles modify the effective Higgs potential.

Isidori, Rychkov, Strumia, Tetradis '08



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



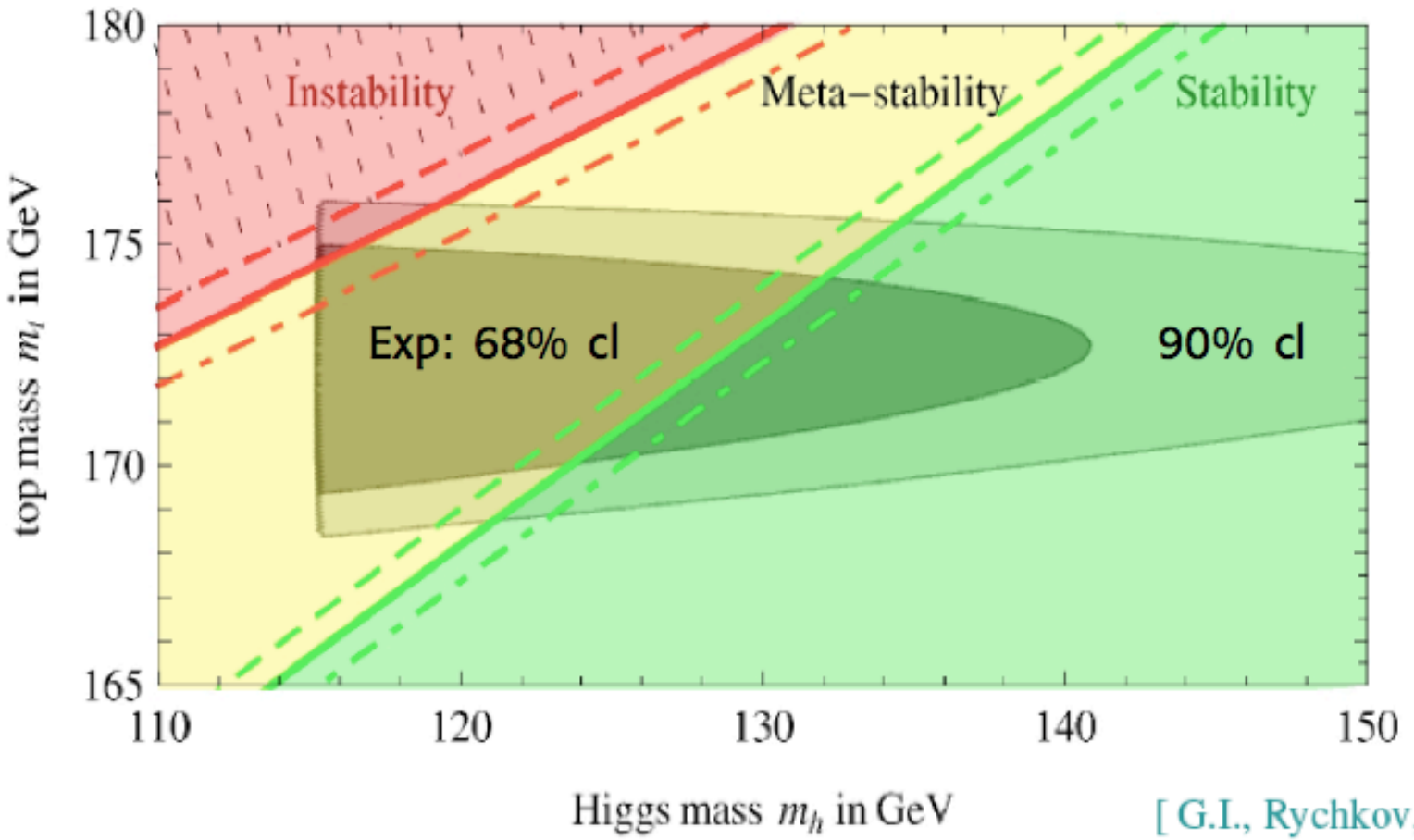


m_H too light!

See also hep-ph/9708416

Hambye and Riesselman

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

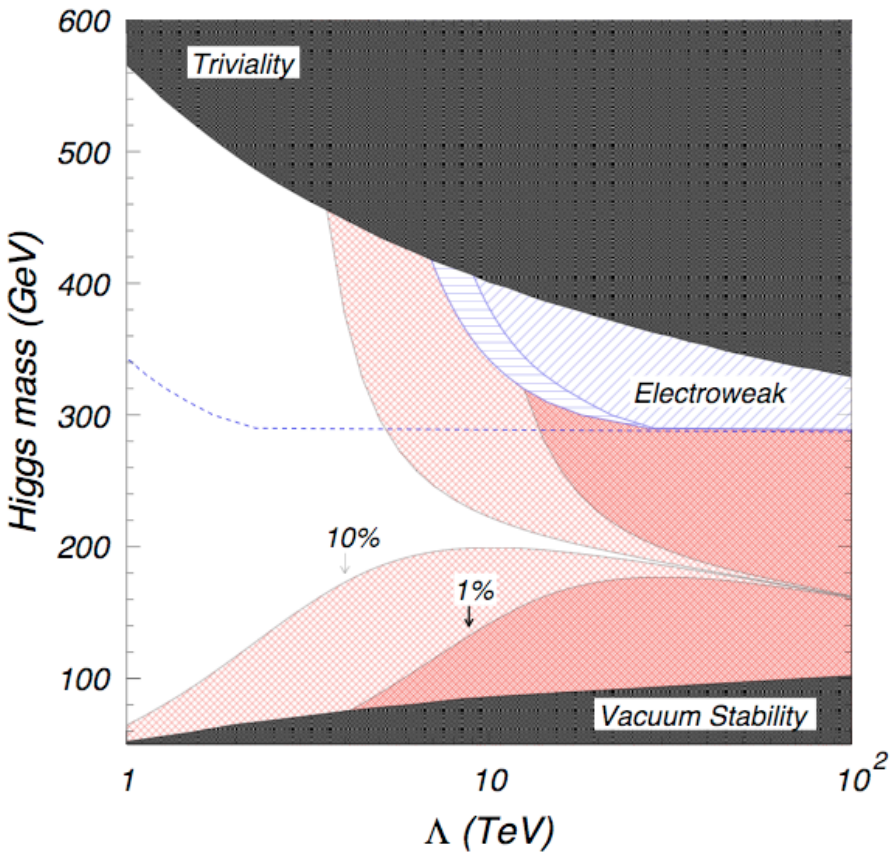


[G.I., Rychkov, Strumia, Tetradis '08]

- 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

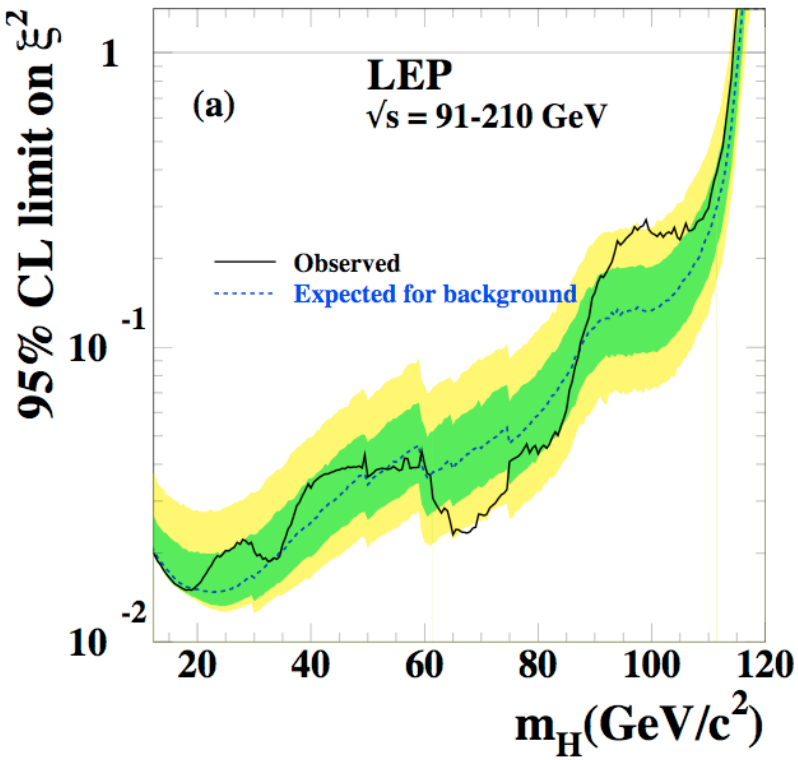
The LEP2 and Tevatron, LEP1, SLD Precision EW Legacy

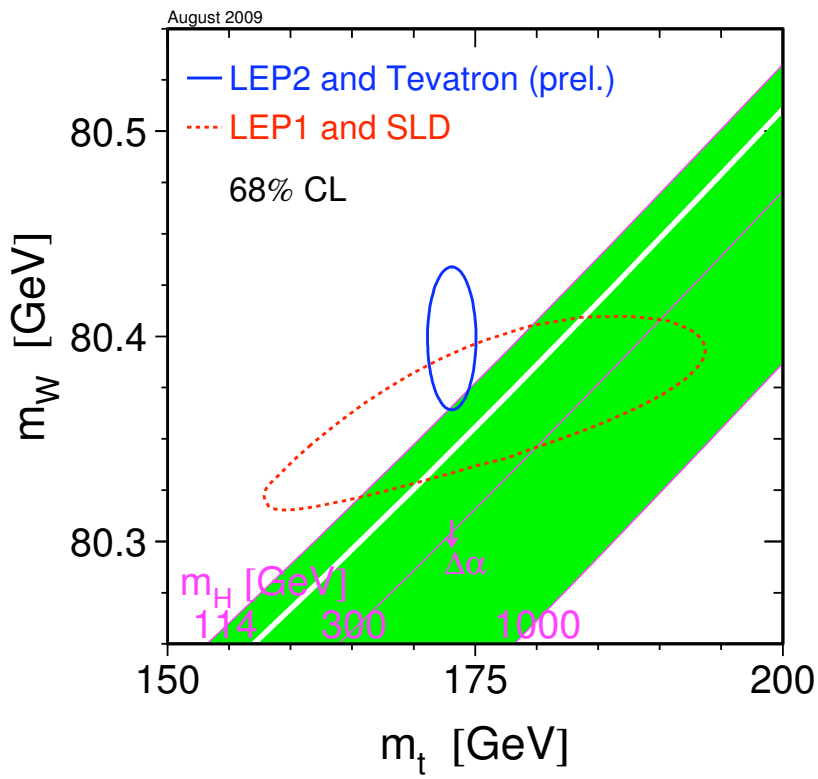
Direct searches for
$e^+e^- \rightarrow ZH$:
No evidence below

$$m_H^{SM} > 114.4 \text{ GeV}/c^2$$

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

$$m_H^{SM} = 87^{+35}_{-26} \text{ GeV}/c^2$$

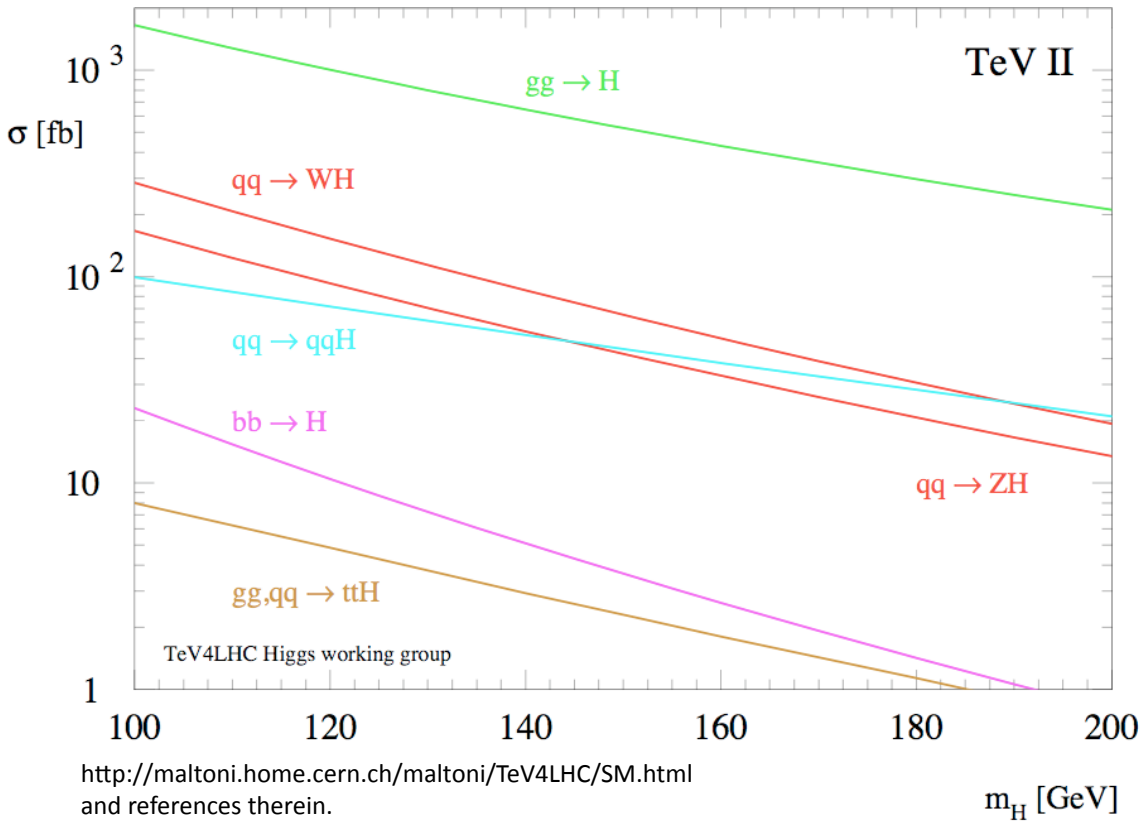




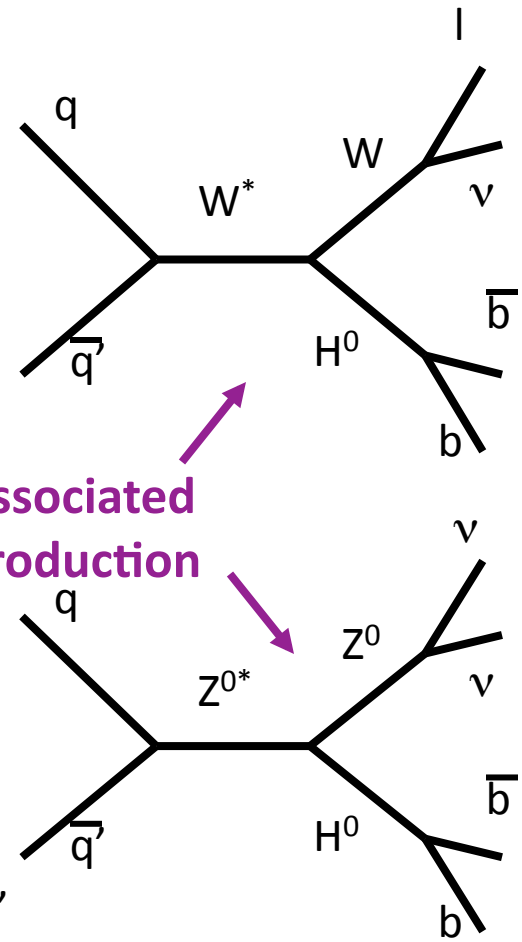
http://lepewwg.web.cern.ch/LEPEWWG
http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html

@95% CL, m_H<157 GeV/c^2
(186 including LEP2 direct limit)

SM Higgs Boson Production Mechanisms

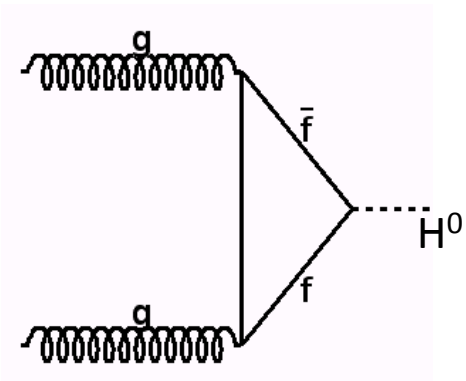


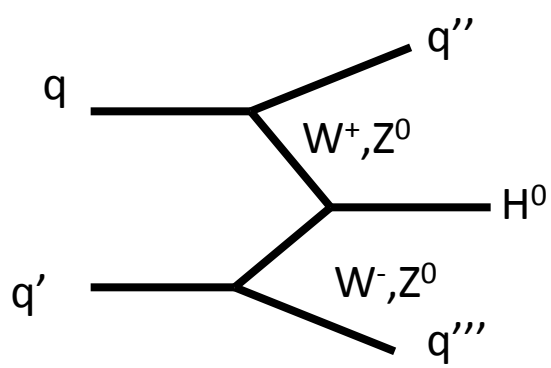
http://maltoni.home.cern.ch/maltoni/TeV4LHC/SM.html
and references therein.



Associated Production

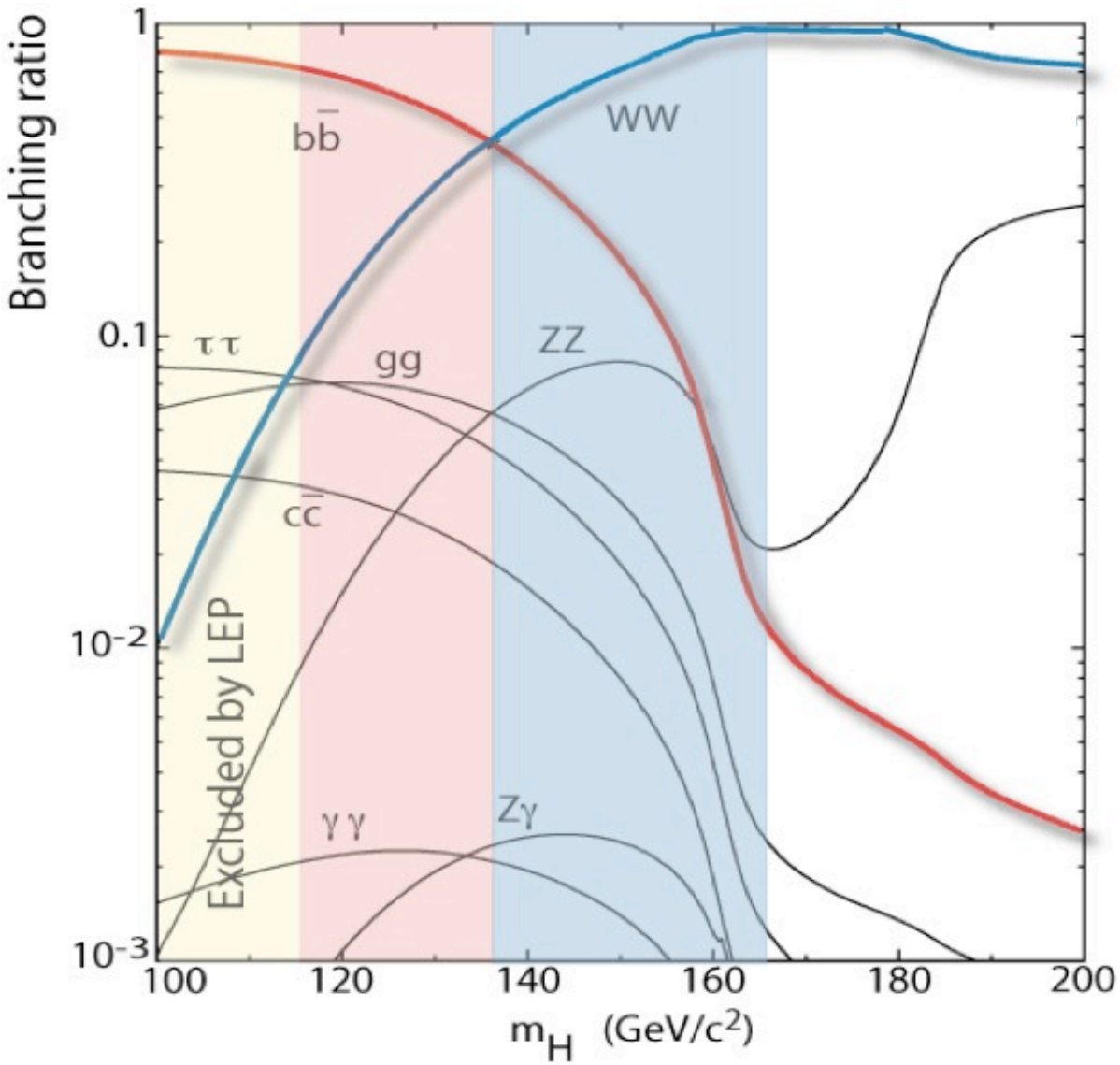
gluon fusion





Vector-Boson Fusion (VBF)

Standard Model Higgs Boson Decay Branching Fractions



HDECAY by
M. Spira

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

gg→H→bb drowned by gg→bb. Use WH, ZH.

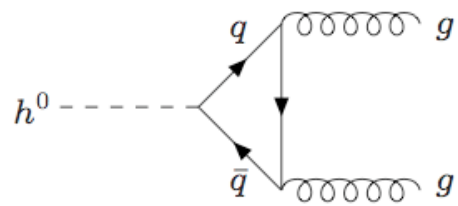
135 < m_H < 200 GeV
H→W^+W^- dominates

gg→H, WH, ZH, VBF all can be used

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,

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

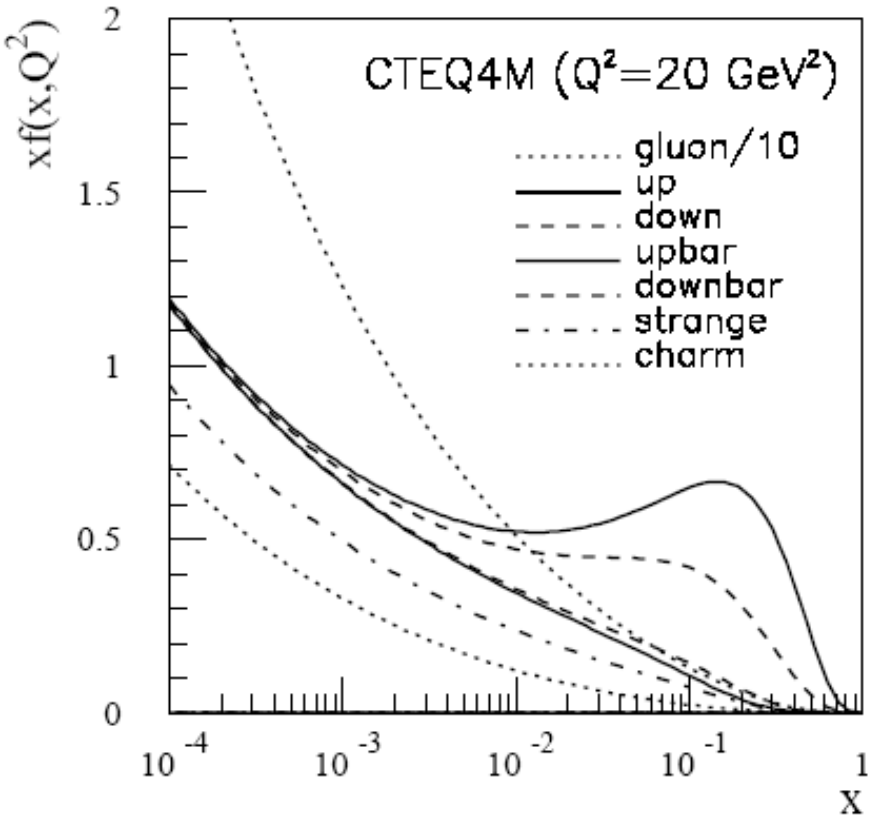
where the loop function $F_{1/2}(x) \to 1$ for $x \gg 1$.

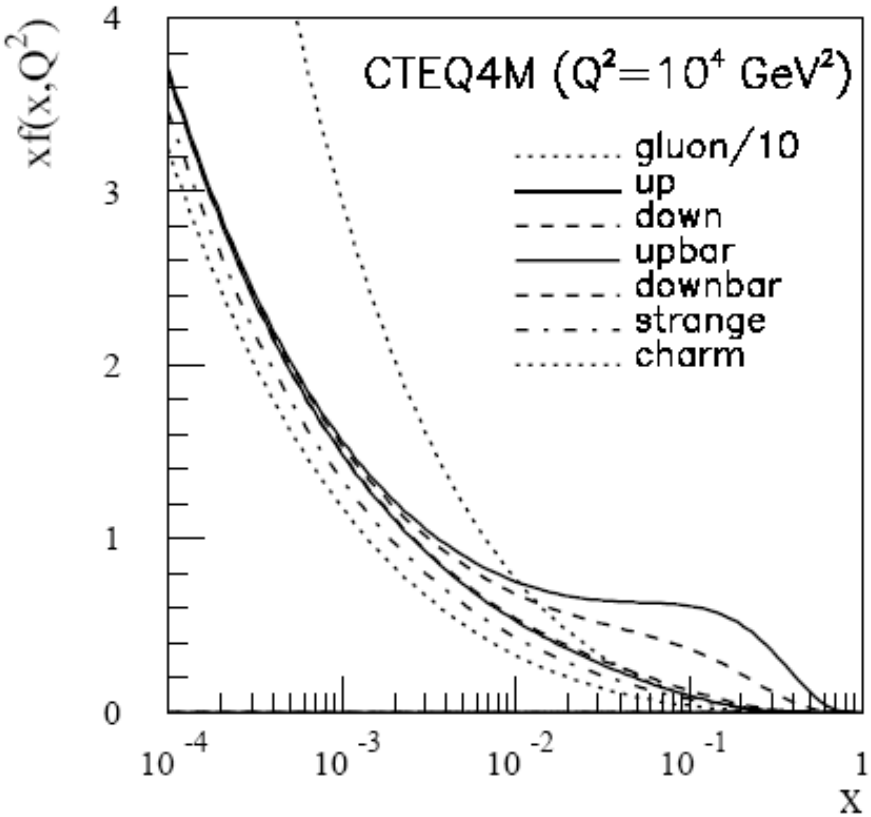
A heavy fourth generation of quarks would scale
the gg→H production rate at colliders by a factor of ~9.
But watch out for $H \to \nu_4 \bar{\nu}_4$ decays.

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])

Parton Distribution Functions of the Proton

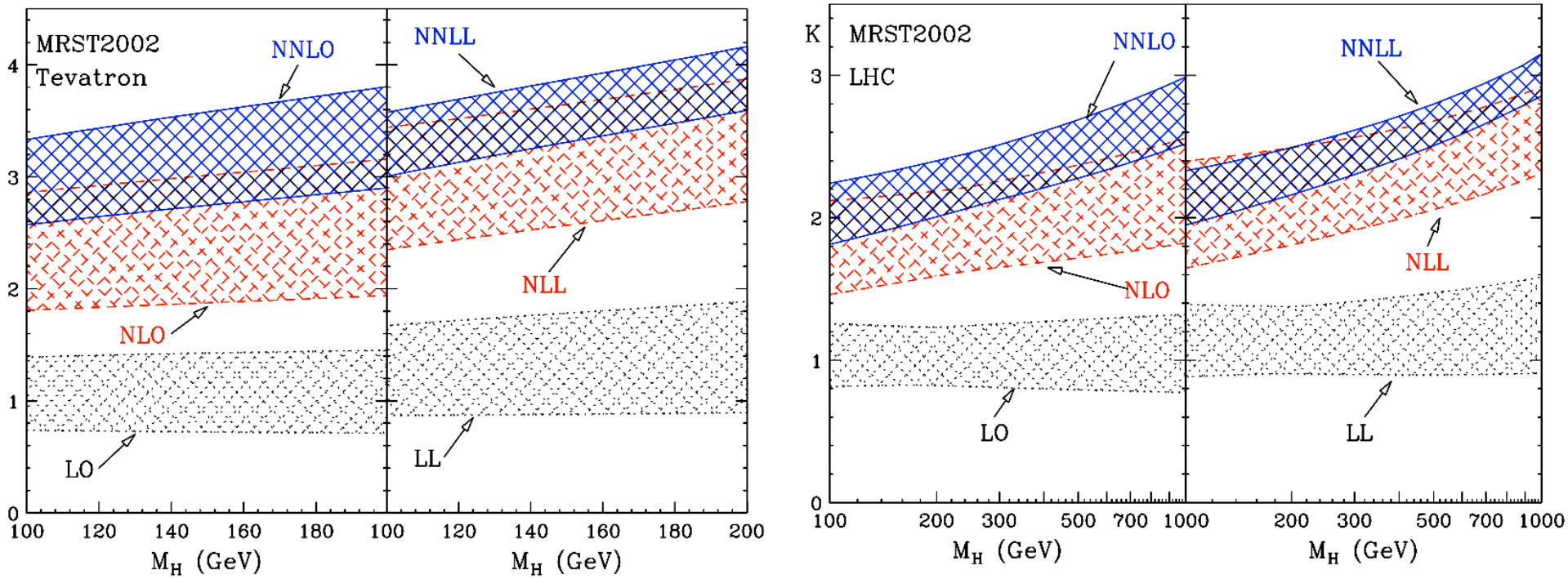




"The LHC is a gluon-gluon collider" (approximately).

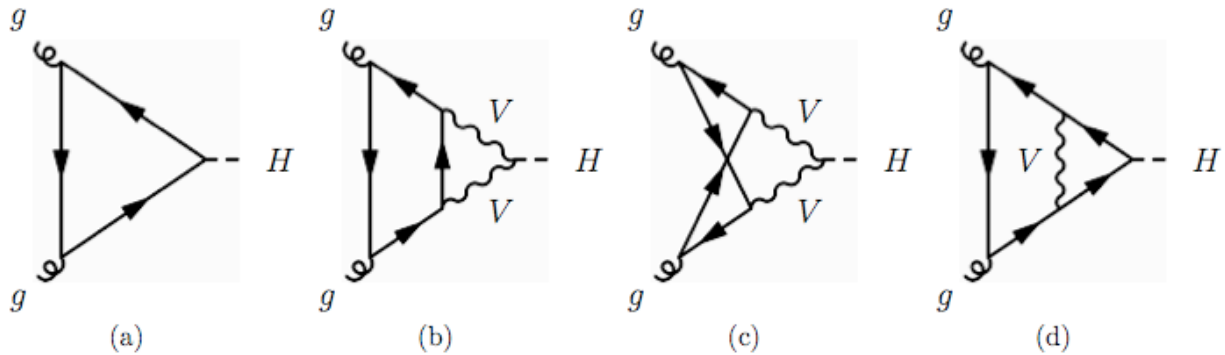
Recent gg→H Production Cross Section Progress

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



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

Recent gg→H Production Cross Section Progress



V=W,Z

An active area of research over the last years

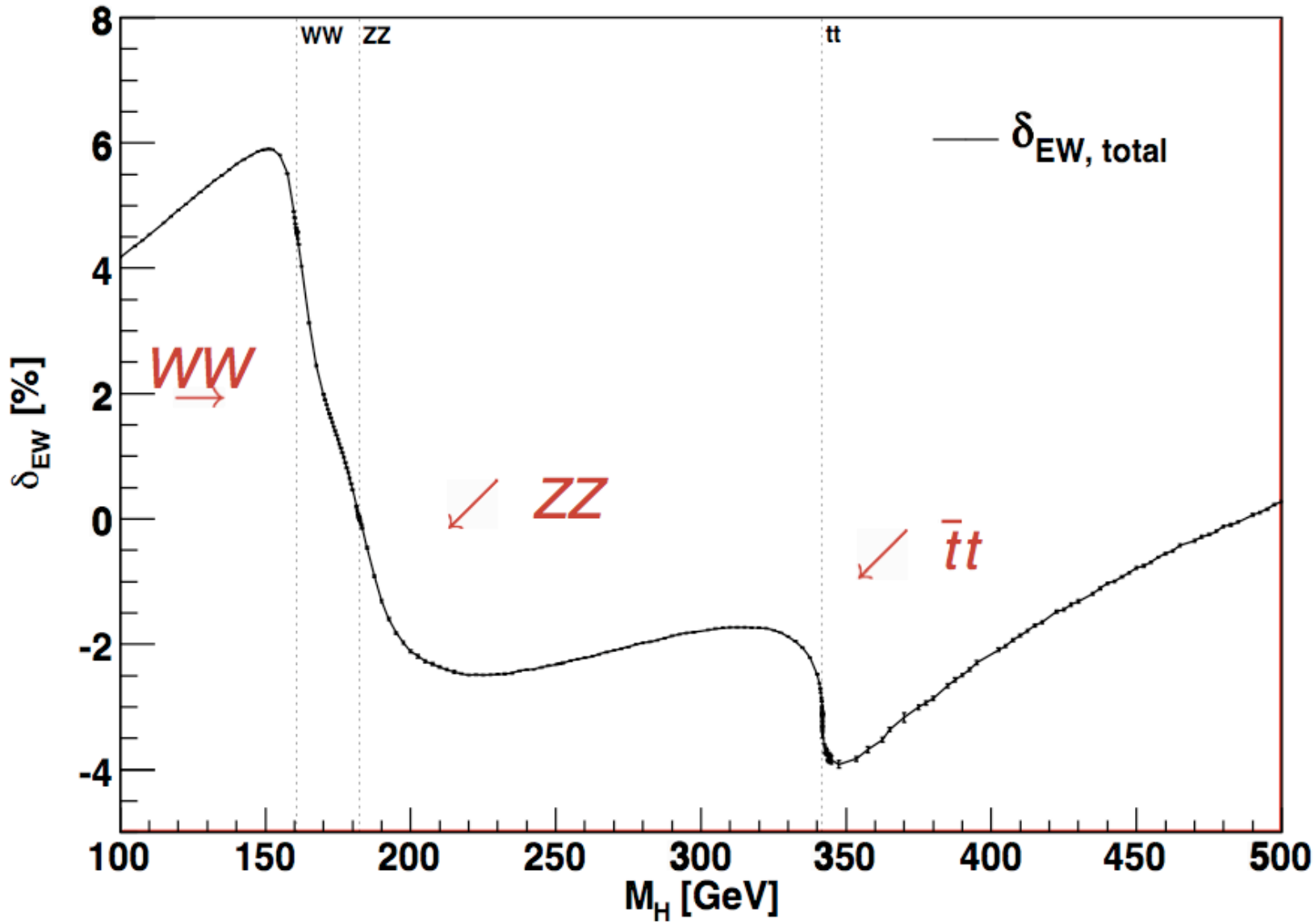
http://www.itp.uzh.ch/events/higgsboson2009 7-9 January 2009, Zurich

- 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

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.

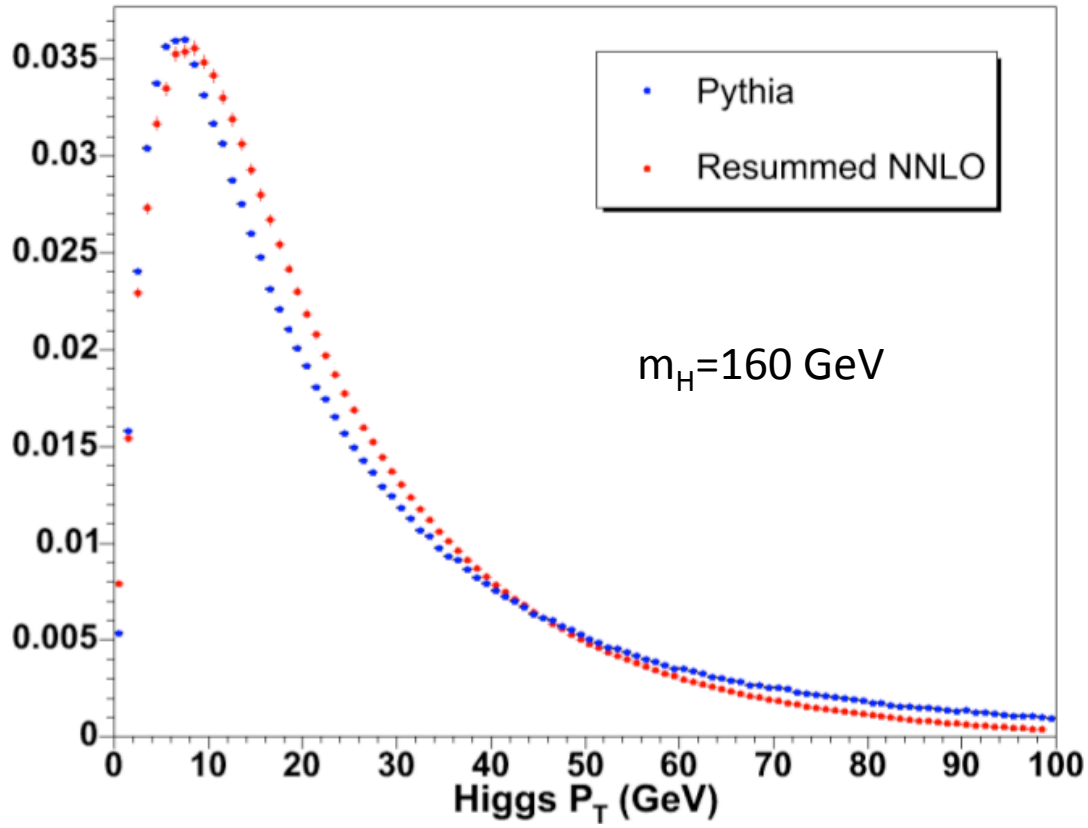
$$\frac{\Delta N_{\text{signal}}(\text{scale})}{N_{\text{signal}}} = 60\% \cdot \binom{+5\%}{-9\%} + 29\% \cdot \binom{+24\%}{-23\%} + 11\% \cdot \binom{+91\%}{-44\%} = \binom{+20.0\%}{-16.9\%}$$

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.

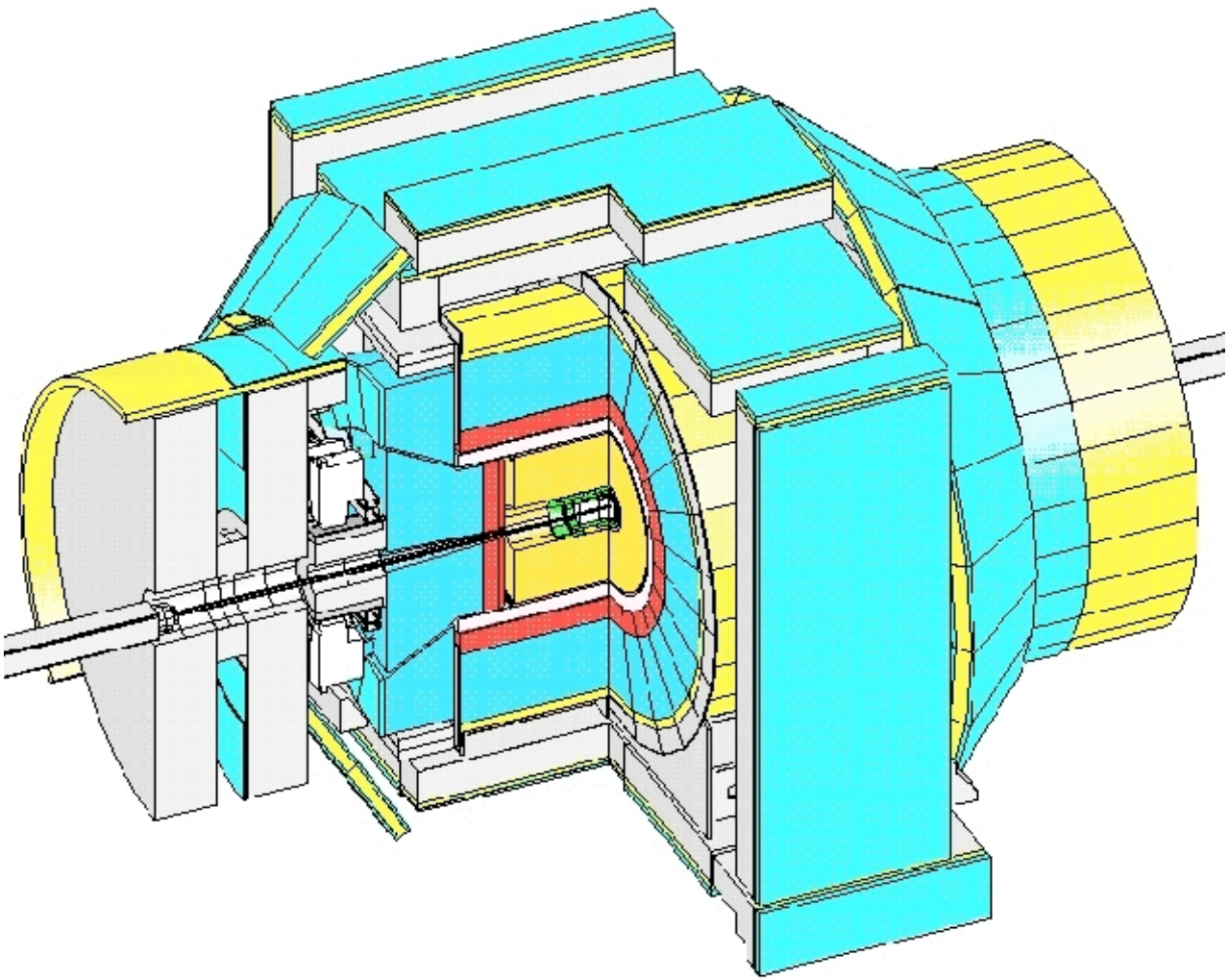
Reweighting Pythia Differential Distributions to NNLO Predictions



HNNLO 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.

The CDF II Detector



Lepton coverage:

$|\eta| < 1.5$ (muons)

$|\eta| < 2.0$ (electrons)

b-tagging with

$|\eta| < \sim 1.4$

Jets to

$|\eta| < 2.8$

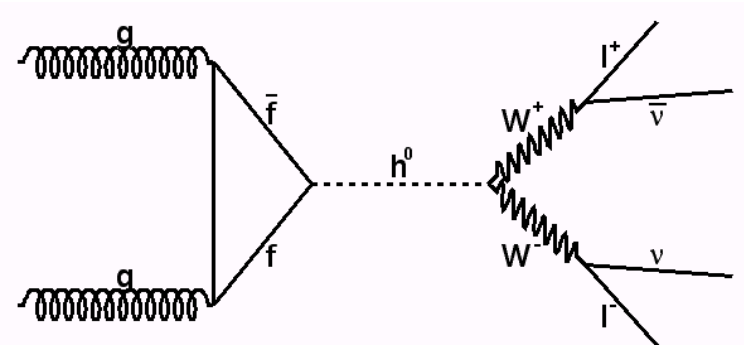
Higgs analyses restrict to

$|\eta| < 2.0$

Dijet mass resolution: ~16%

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

gg→H Signal Process:

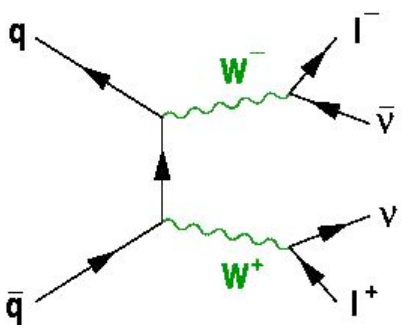


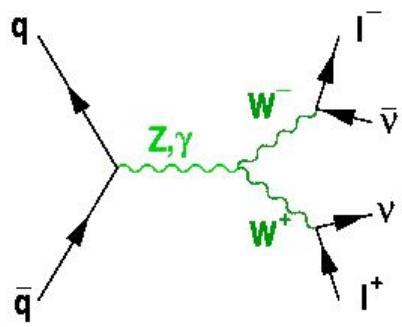
Both CDF and D0 Select events with

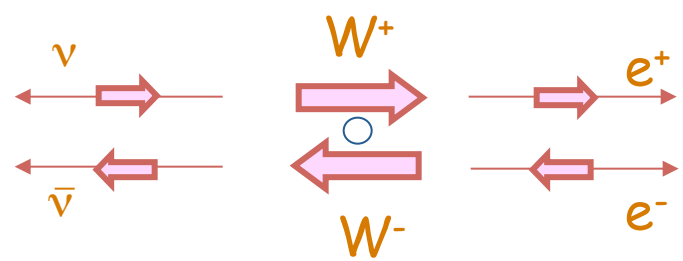
- Two isolated, opposite-signed high-p_T leptons (e,μ)
- Missing transverse energy
- $m_{ll} > 16$ GeV

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

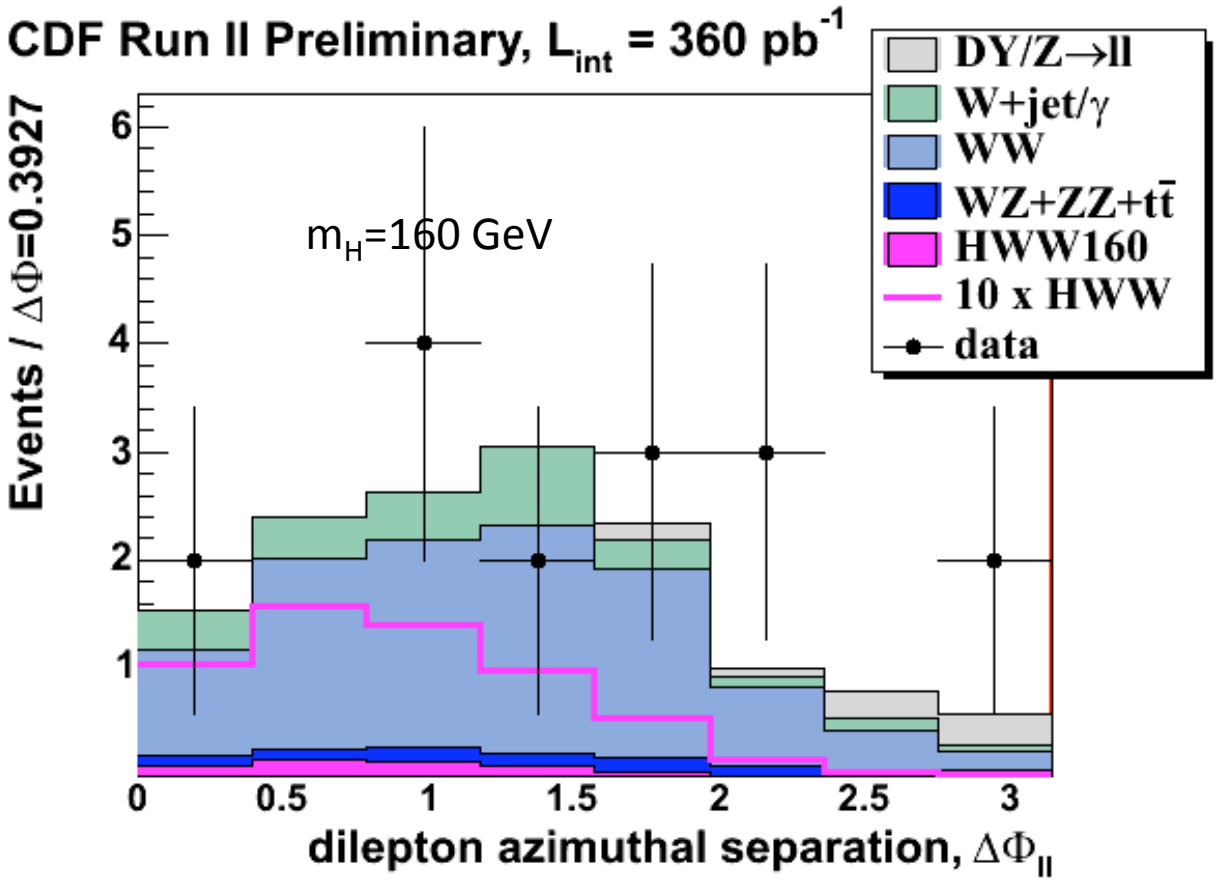






Five Years ago: 2005 CDF H→WW Analysis

- 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

Matrix Element Basics

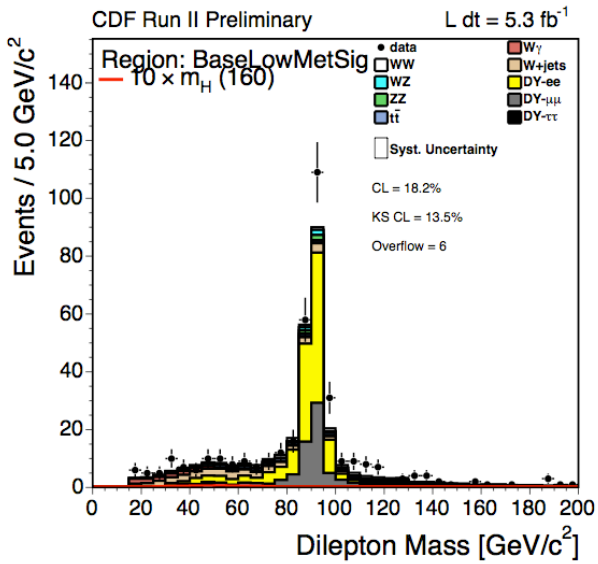
Predictions given by QM matrix element and phase space.

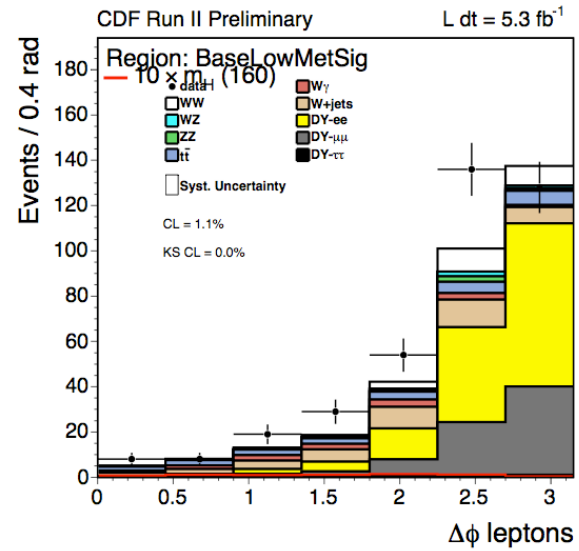
Many processes (signal and background) give the same observable quantities in the detector -- cannot assign an event to be signal or background (if we could, we would!)

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

Checking Control Regions

Low MET significance control region -- events with fake MET

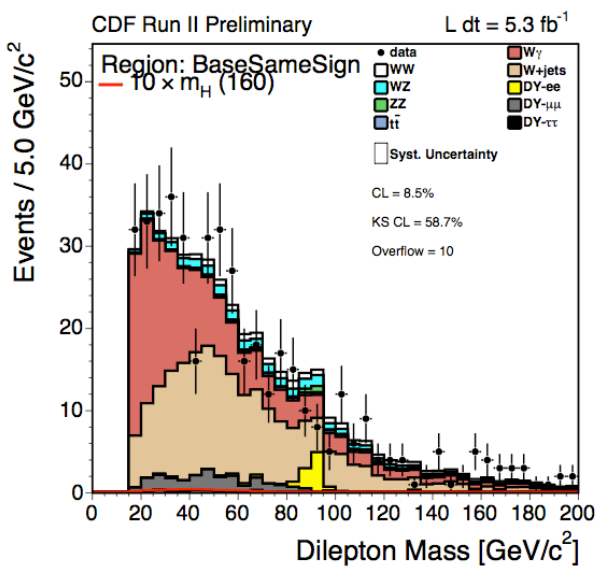


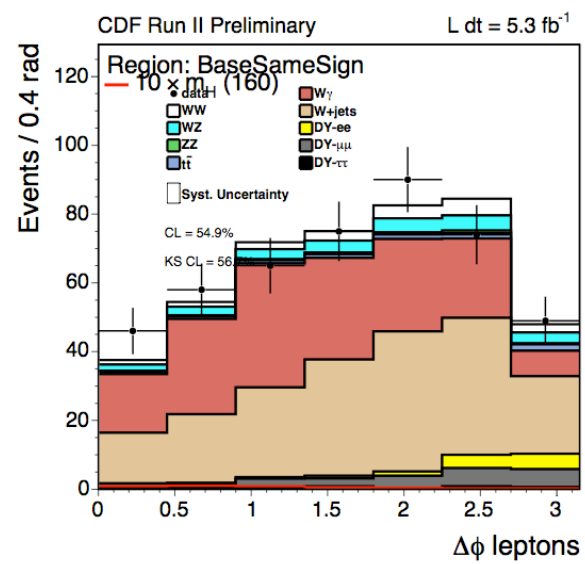


Same Sign Dileptons

Wγ, W+jets backgrounds

Low-m$_{ll}$ Same Sign is used to constrain the Wγ background





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

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. New for 5.3 fb^{-1}: add in WH, ZH, VBF here (6% more signal expectation than just gg→H)
  - 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. Main background is t-tbar
  - 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.

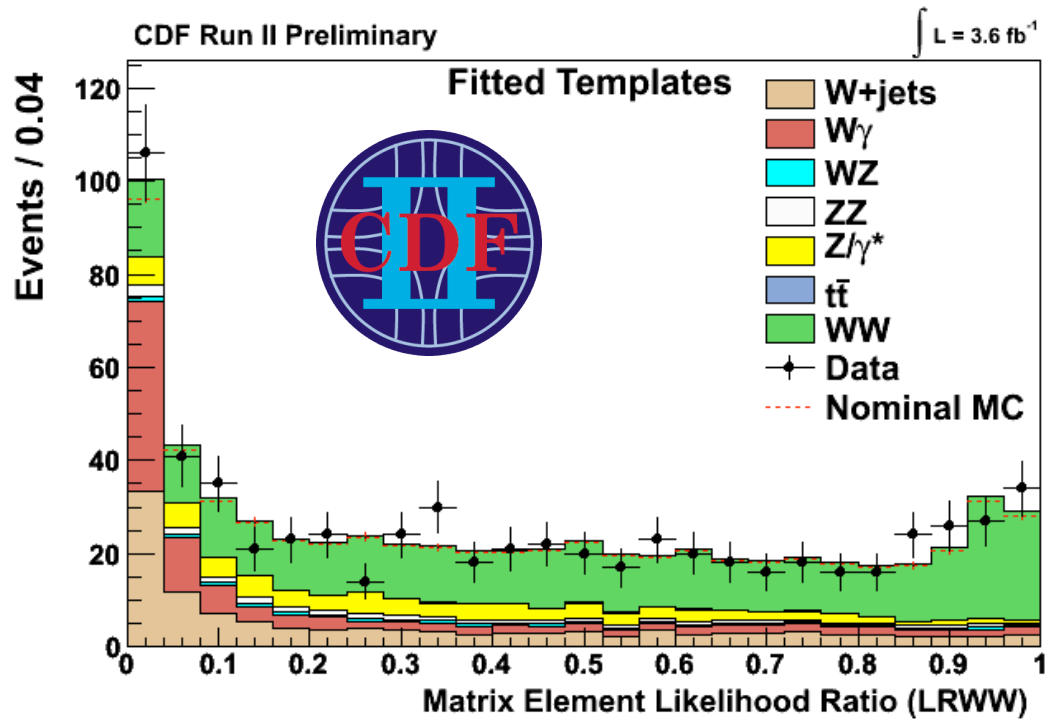
Each major background has a dedicated control sample

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



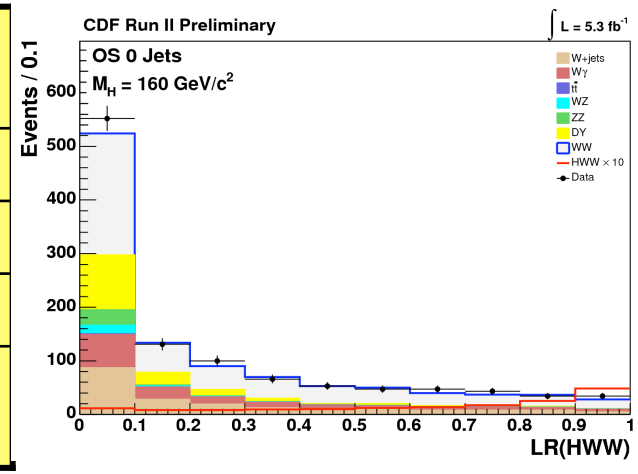
$$\sigma(p\bar{p} \rightarrow W^+W^-) = 12.1 \pm 0.9\ (\text{stat})\ ^{+1.6}_{-1.4}\ (\text{syst})\ [\text{pb}]$$

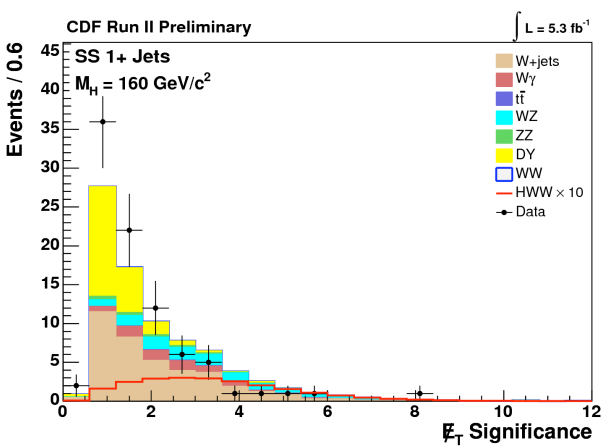
SM: 12.4 ± 0.7 pb (MCFM)

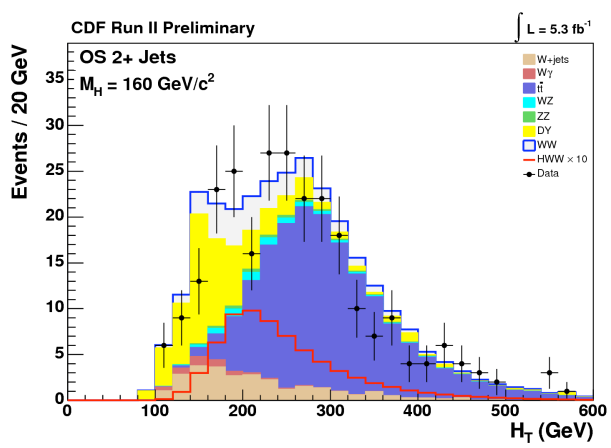
Accepted by PRL

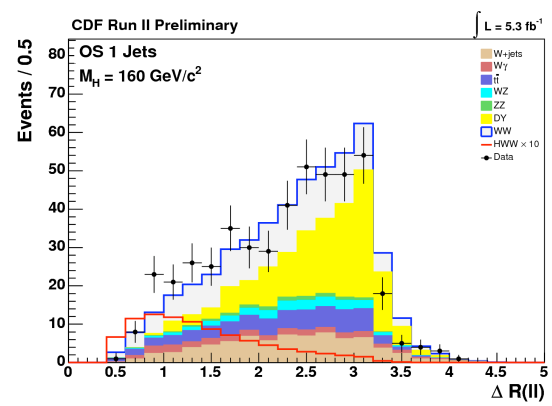
H→WW -- Event Kinematics Separating Signal from Background

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

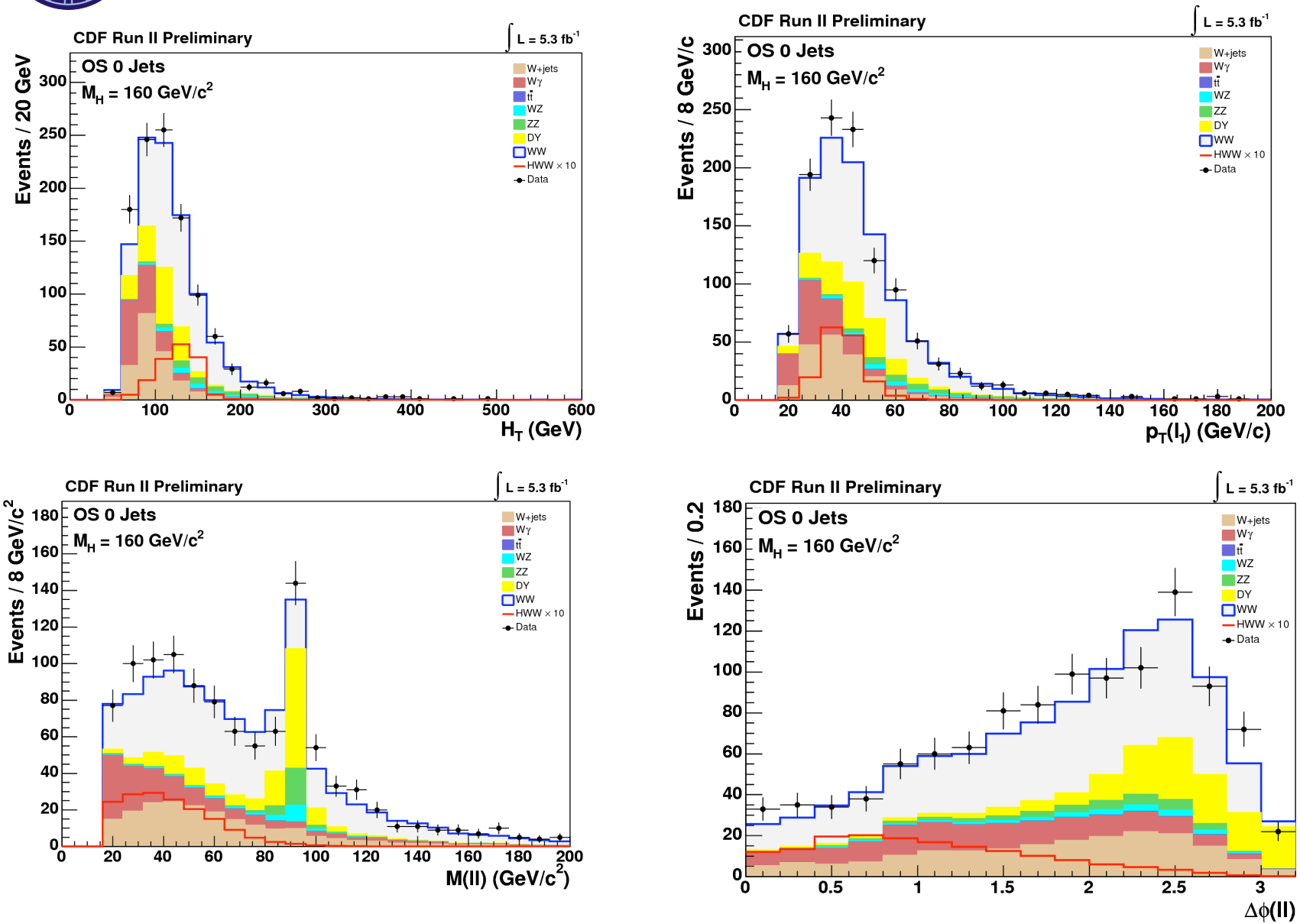






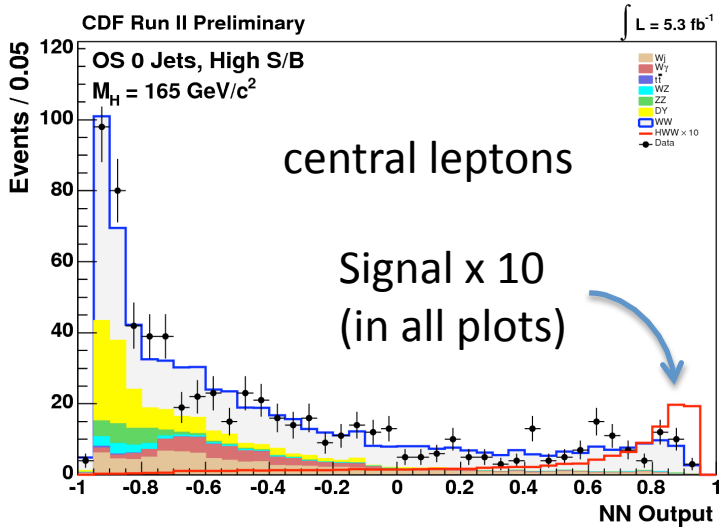


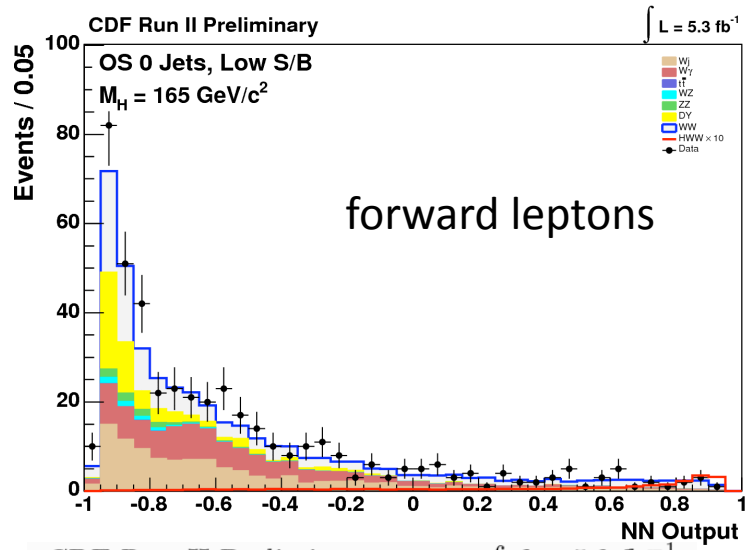
NN Input Variables in The Signal Region



Opposite-Sign, 0-jets Channel

m_H=165 GeV





CDF Run II Preliminary	$\int \mathcal{L} = 5.3$ fb^{-1}		
$M_H = 165$ GeV/c^2			
$t\bar{t}$	1.95	$\pm$	0.78
DY	101	$\pm$	34
WW	381	$\pm$	43
WZ	16.4	$\pm$	2.6
ZZ	25.5	$\pm$	3.7
W+jets	85	$\pm$	21
$W\gamma$	46.6	$\pm$	7.5
Total Background	658	$\pm$	74
$gg \to H$	12.4	$\pm$	1.9
WH	0.297	$\pm$	0.059
ZH	0.317	$\pm$	0.047
VBF	0.105	$\pm$	0.024
Total Signal	13.1	$\pm$	2.0
Data	664		
			OS 0 Jets, HighSB

CDF Run II Preliminary	$\int \mathcal{L} = 5.3$ fb^{-1}		
$M_H = 165$ GeV/c^2			
$t\bar{t}$	0.37	$\pm$	0.15
DY	55	$\pm$	18
WW	127	$\pm$	14
WZ	6.4	$\pm$	1.0
ZZ	8.7	$\pm$	1.3
W+jets	111	$\pm$	24
$W\gamma$	95	$\pm$	15
Total Background	403	$\pm$	43
$gg \to H$	2.69	$\pm$	0.41
WH	0.067	$\pm$	0.013
ZH	0.0554	$\pm$	0.0082
VBF	0.0208	$\pm$	0.0047
Total Signal	2.83	$\pm$	0.43
Data	443		
			OS 0 Jets, LowSB

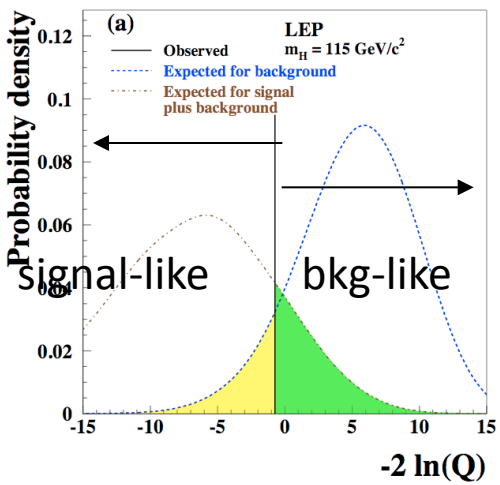
Opposite-Sign, 0-jets Channel Systematic Uncertainties

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet	$gg \to H$	WH	ZH	VBF
Cross Section											
Scale								7.0%			
PDF Model								7.7%			
Total	*6.0%*	*6.0%*	*6.0%*	10.0%	5.0%				**5.0%**	**5.0%**	10.0%
Acceptance											
Scale (leptons)								2.5%			
Scale (jets)								4.6%			
PDF Model (leptons)	*1.9%*	*2.7%*	*2.7%*	*2.1%*	*4.1%*			*1.5%*	*1.2%*	*0.9%*	*2.2%*
PDF Model (jets)								0.9%			
Higher-order Diagrams	*5.0%*	*10.0%*	*10.0%*	10.0%		11.0%			**10.0%**	**10.0%**	**10.0%**
$\not{E}_T$ Modeling					20.0%						
Conversion Modeling						11.0%					
Jet Fake Rates											
(Low S/B)							22.0%				
(High S/B)							24.0%				
Jet Energy Scale	*2.6%*	*6.1%*	*3.4%*	*26.0%*	*17.5%*	*3.1%*		*5.0%*	*10.5%*	*5.0%*	*11.5%*
MC Run Dependence	2.6%										
Lepton ID Efficiencies	*2.0%*	*1.7%*	*2.0%*	*2.0%*	*1.9%*			*1.9%*	*1.9%*	*1.9%*	*1.9%*
Trigger Efficiencies	*2.1%*	*2.1%*	*2.1%*	*2.0%*	*3.4%*			*3.3%*	*2.1%*	*2.1%*	*3.3%*
Luminosity	*5.9%*	*5.9%*	*5.9%*	*5.9%*	*5.9%*			*5.9%*	*5.9%*	*5.9%*	*5.9%*

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}

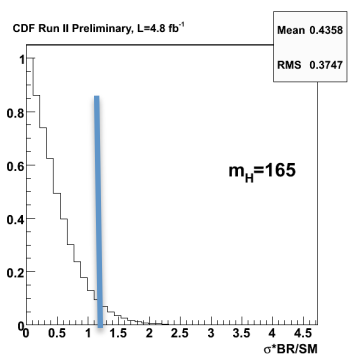
Expected limits can be computed from the distributions of -2lnQ

Bayesian (used by CDF)

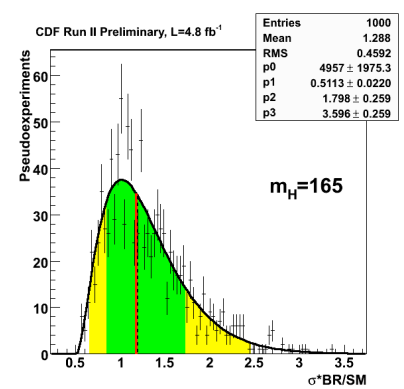
$$L'(data\,|\,R) = \int L(data\,|\,R,\theta)\pi(\theta)d\theta$$

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

Jusing Joel and Luc's "correlated" prior – flat in the accepted signal yield

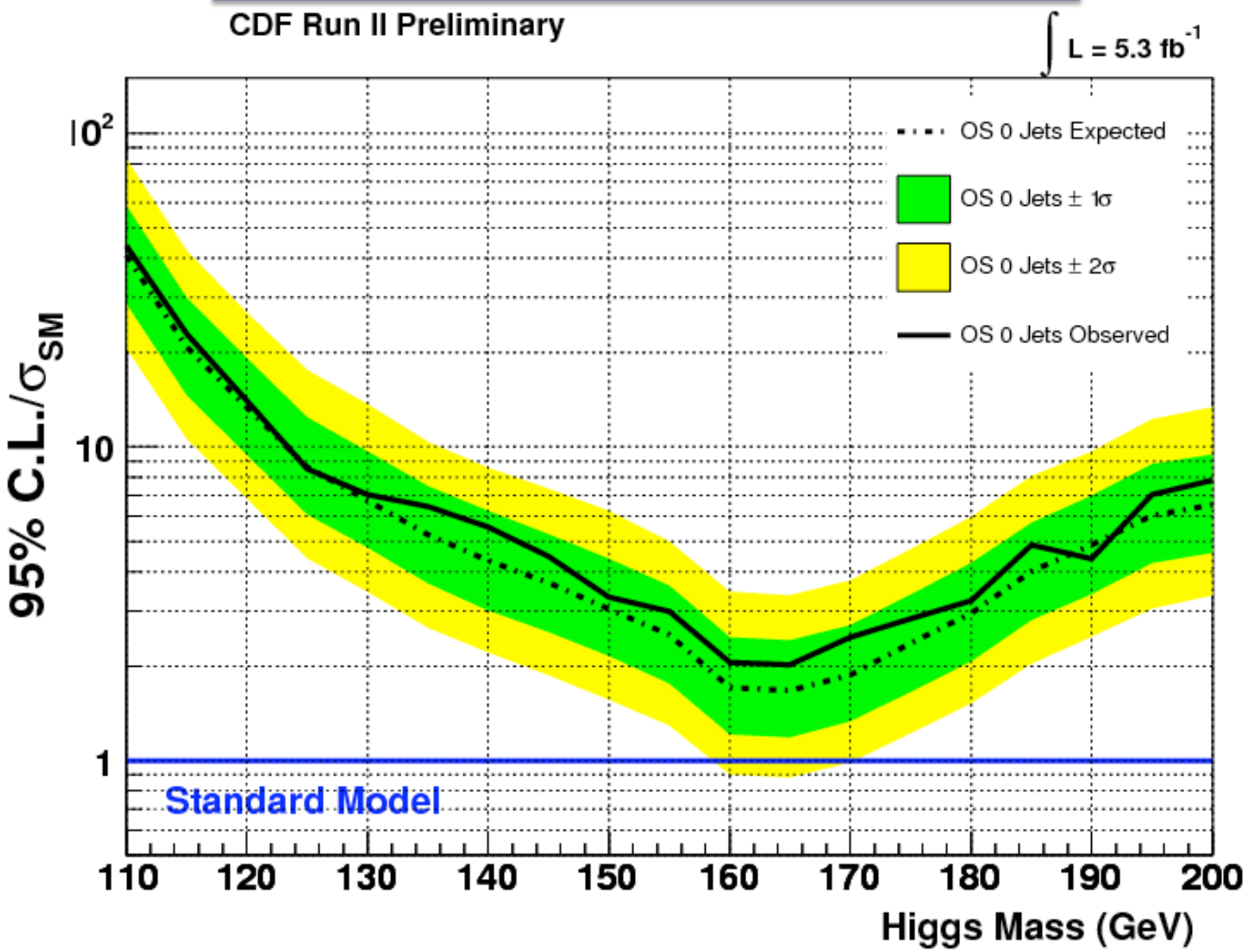


Example: CDF at 165 GeV

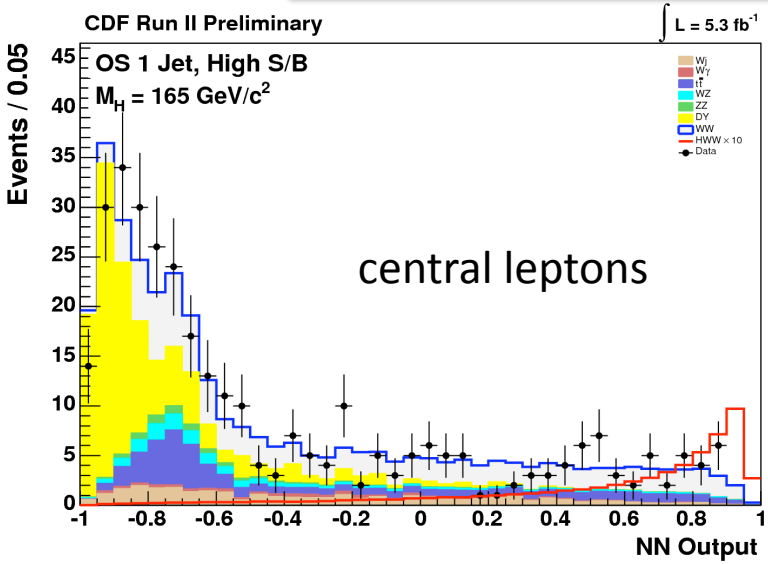


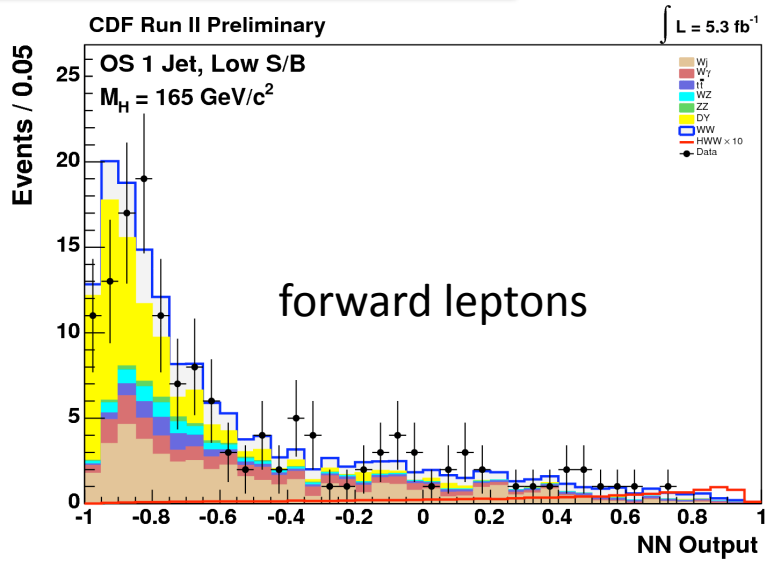
Expected limits are computed with pseudoexperiments

Opposite-Sign, 0-jets Channel



Opposite-Sign, 1-jet Channel

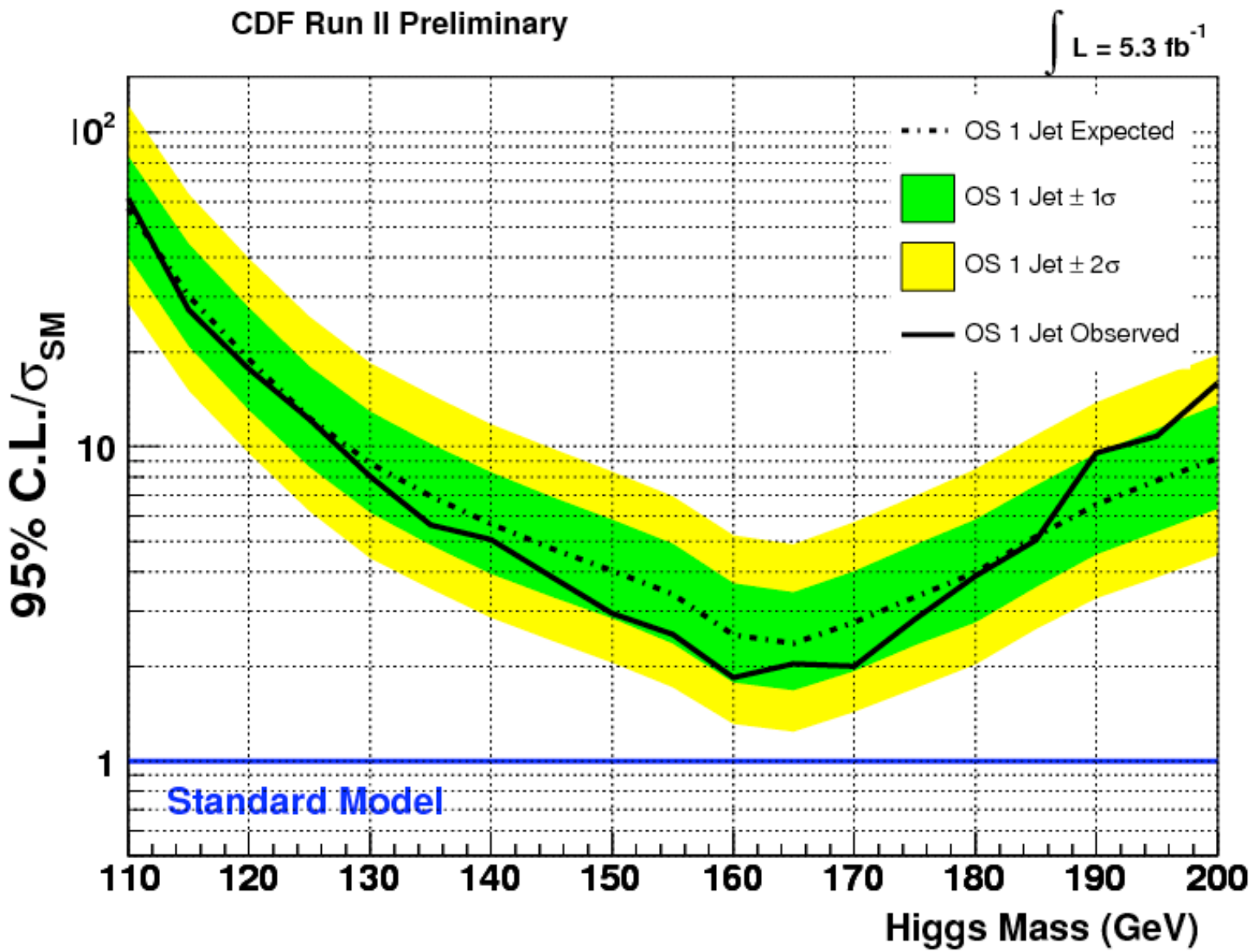




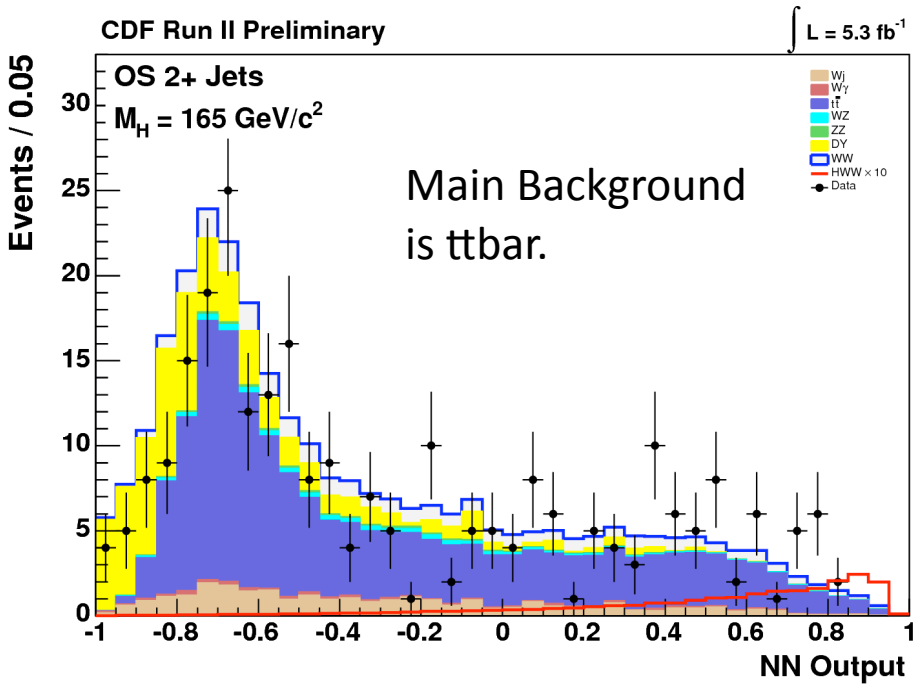
CDF Run II Preliminary	$\int \mathcal{L} = 5.3\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	47	$\pm$	11
DY	116	$\pm$	28
WW	107	$\pm$	14
WZ	15.8	$\pm$	2.2
ZZ	6.9	$\pm$	1.0
W+jets	30.9	$\pm$	8.0
$W\gamma$	6.7	$\pm$	1.4
Total Background	330	$\pm$	46
$gg \to H$	5.9	$\pm$	1.6
WH	0.84	$\pm$	0.15
ZH	0.328	$\pm$	0.054
VBF	0.56	$\pm$	0.10
Total Signal	7.6	$\pm$	1.7
Data	327		
			OS 1 Jet, HighSB

CDF Run II Preliminary	$\int \mathcal{L} = 5.3\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	9.2	$\pm$	2.2
DY	46	$\pm$	11
WW	31.7	$\pm$	4.1
WZ	6.82	$\pm$	0.94
ZZ	2.28	$\pm$	0.34
W+jets	44.8	$\pm$	9.8
$W\gamma$	16.4	$\pm$	3.4
Total Background	157	$\pm$	19
$gg \to H$	1.18	$\pm$	0.32
WH	0.172	$\pm$	0.031
ZH	0.064	$\pm$	0.011
VBF	0.102	$\pm$	0.019
Total Signal	1.52	$\pm$	0.34
Data	145		
			OS 1 Jet, LowSB

Opposite-Sign, 1-jet Channel



Opposite-Sign, 2 or more jets Channel

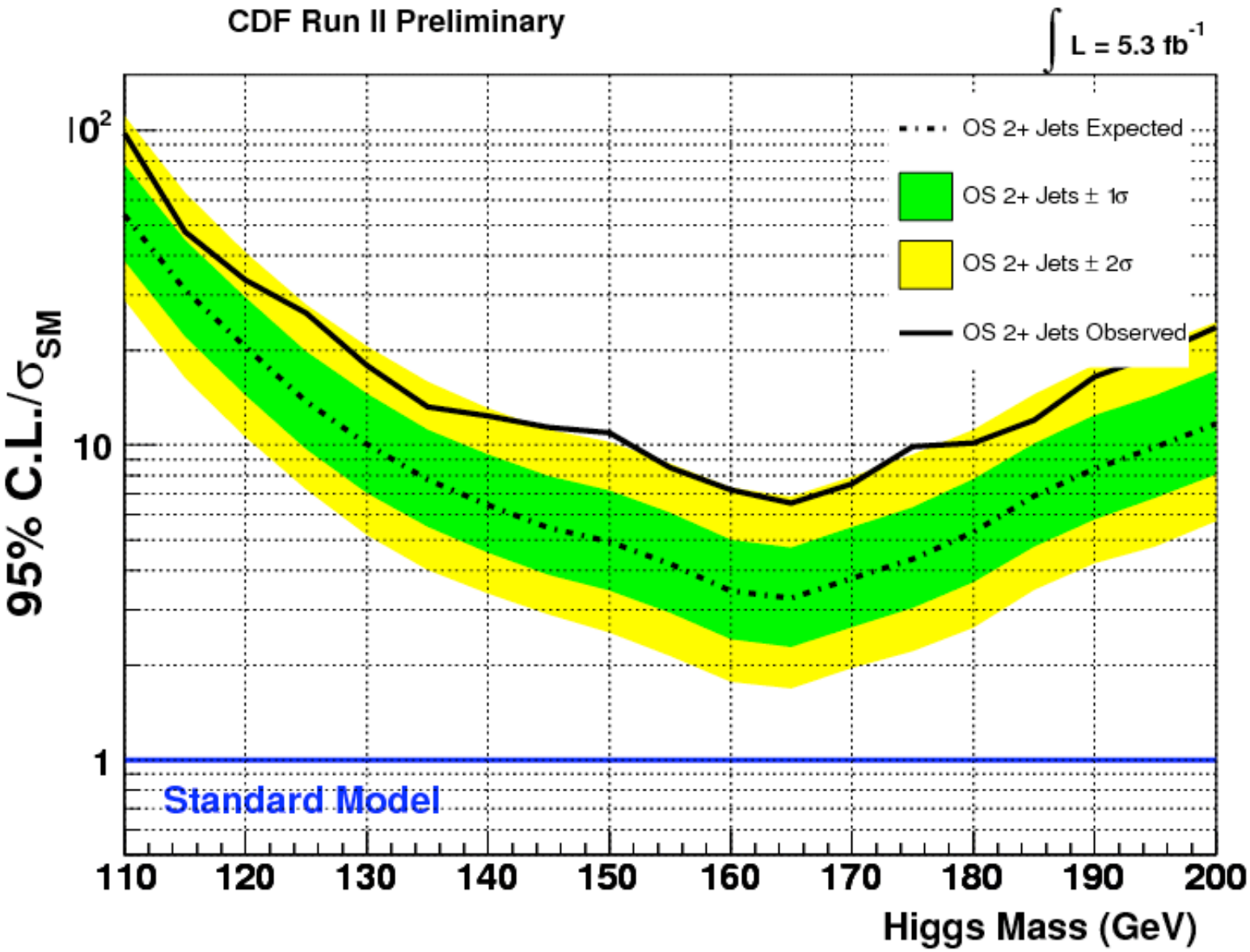


CDF Run II Preliminary $\int \mathcal{L} = 5.3\ \mathrm{fb}^{-1}$			
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	163	$\pm$	27
DY	60	$\pm$	28
WW	29.4	$\pm$	6.9
WZ	6.1	$\pm$	1.4
ZZ	2.75	$\pm$	0.60
W+jets	27.8	$\pm$	6.9
$W\gamma$	4.1	$\pm$	1.4
Total Background	293	$\pm$	50
$gg \to H$	2.3	$\pm$	1.7
WH	2.23	$\pm$	0.32
ZH	1.14	$\pm$	0.15
VBF	1.23	$\pm$	0.21
Total Signal	6.9	$\pm$	1.9
Data	264		

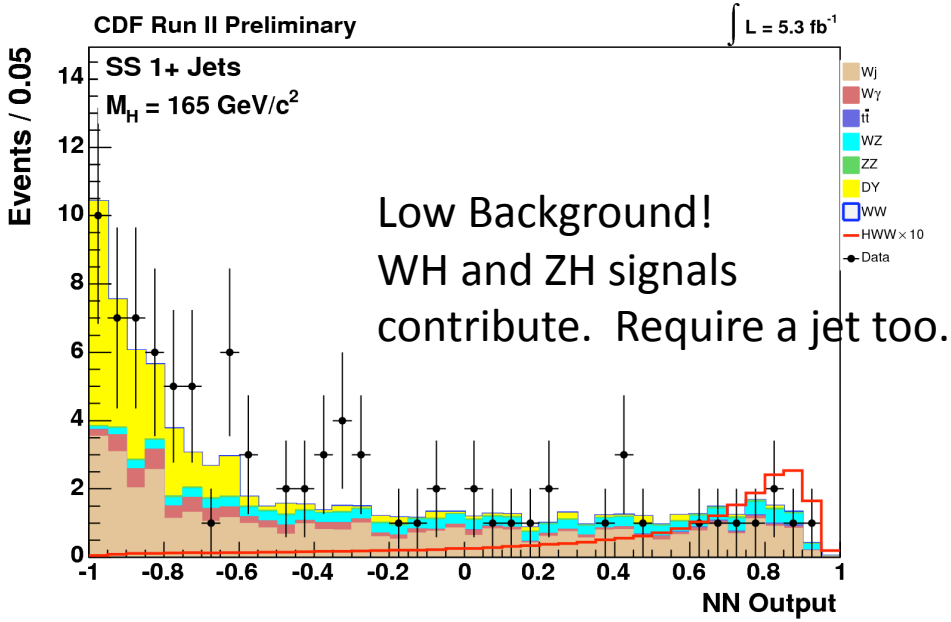
OS 2+ Jets

Even though the gg→H signal is highly uncertain, WH, ZH and VBF provide a larger contribution to the expected signal in this channel.

Opposite-Sign, 2 or more jets Channel



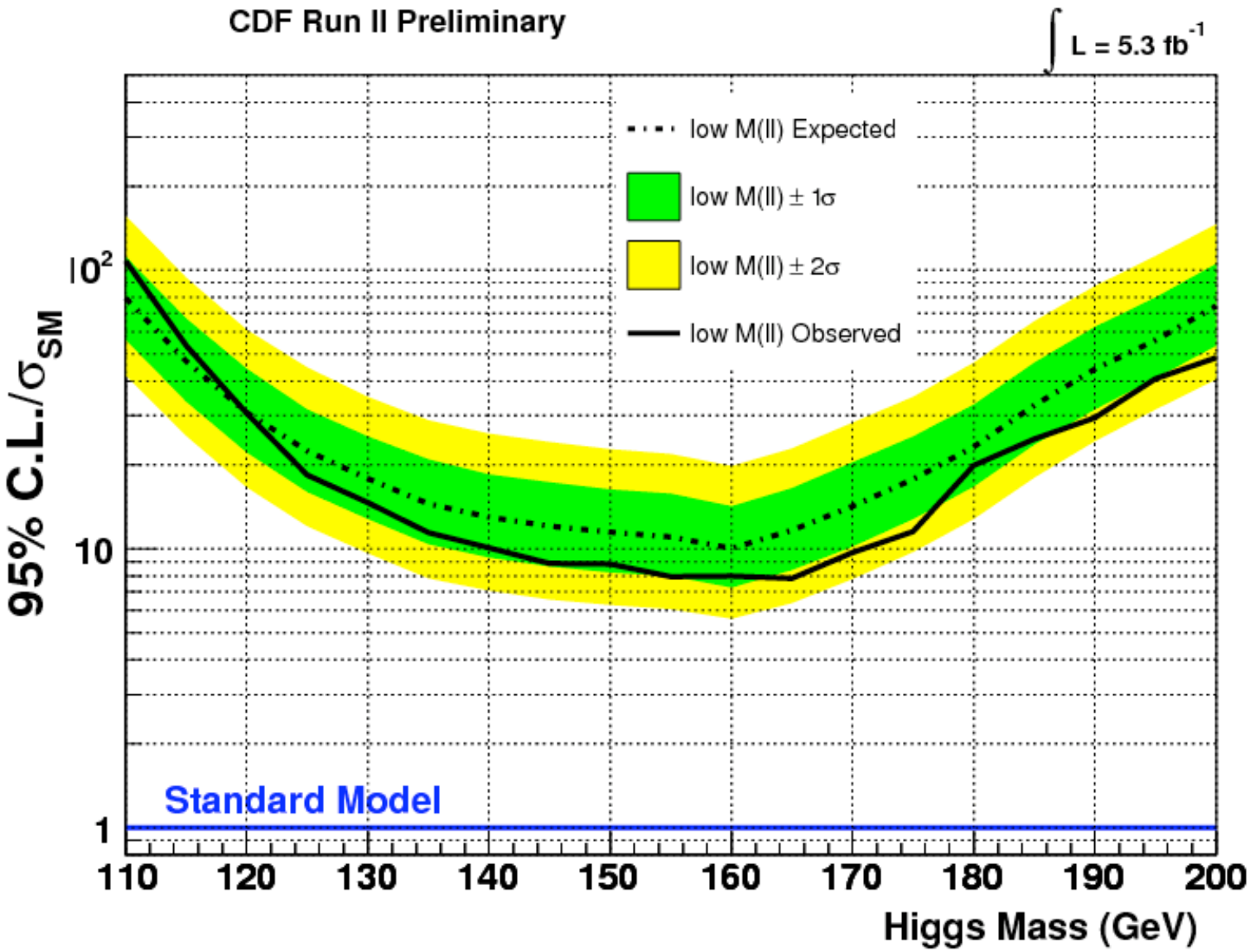
Same-Sign, 1 or more jets Channel



CDF Run II Preliminary	$\int \mathcal{L} = 5.3\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	0.41	$\pm$	0.12
DY	23.3	$\pm$	8.1
WW	0.064	$\pm$	0.021
WZ	10.4	$\pm$	1.5
ZZ	1.88	$\pm$	0.27
W+jets	39	$\pm$	13
$W\gamma$	6.5	$\pm$	1.2
Total Background	81	$\pm$	16
WH	1.83	$\pm$	0.24
ZH	0.292	$\pm$	0.038
Total Signal	2.13	$\pm$	0.28
Data		88	

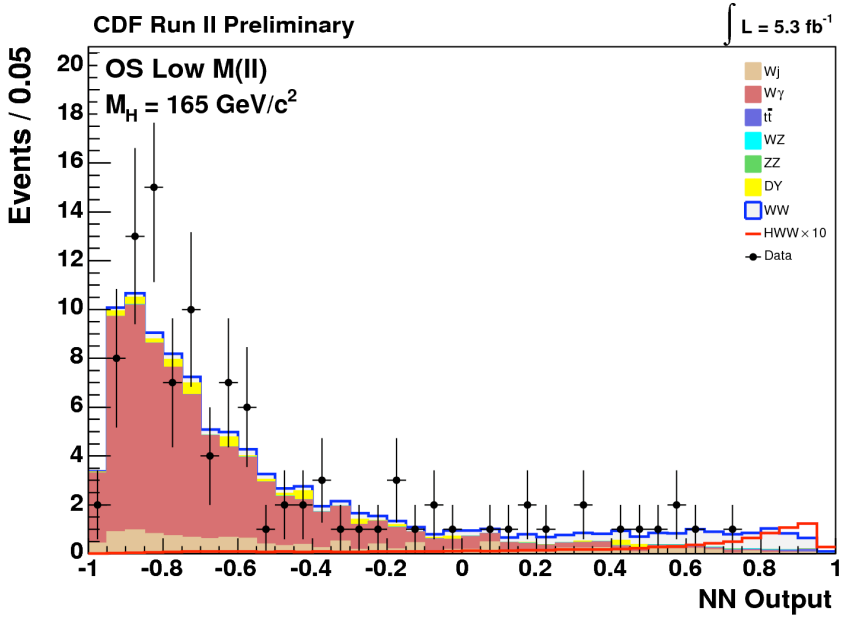
SS 1+ Jets

Same-Sign, 1 or more jets Channel



Opposite-Sign, low-m_{ll} Channel

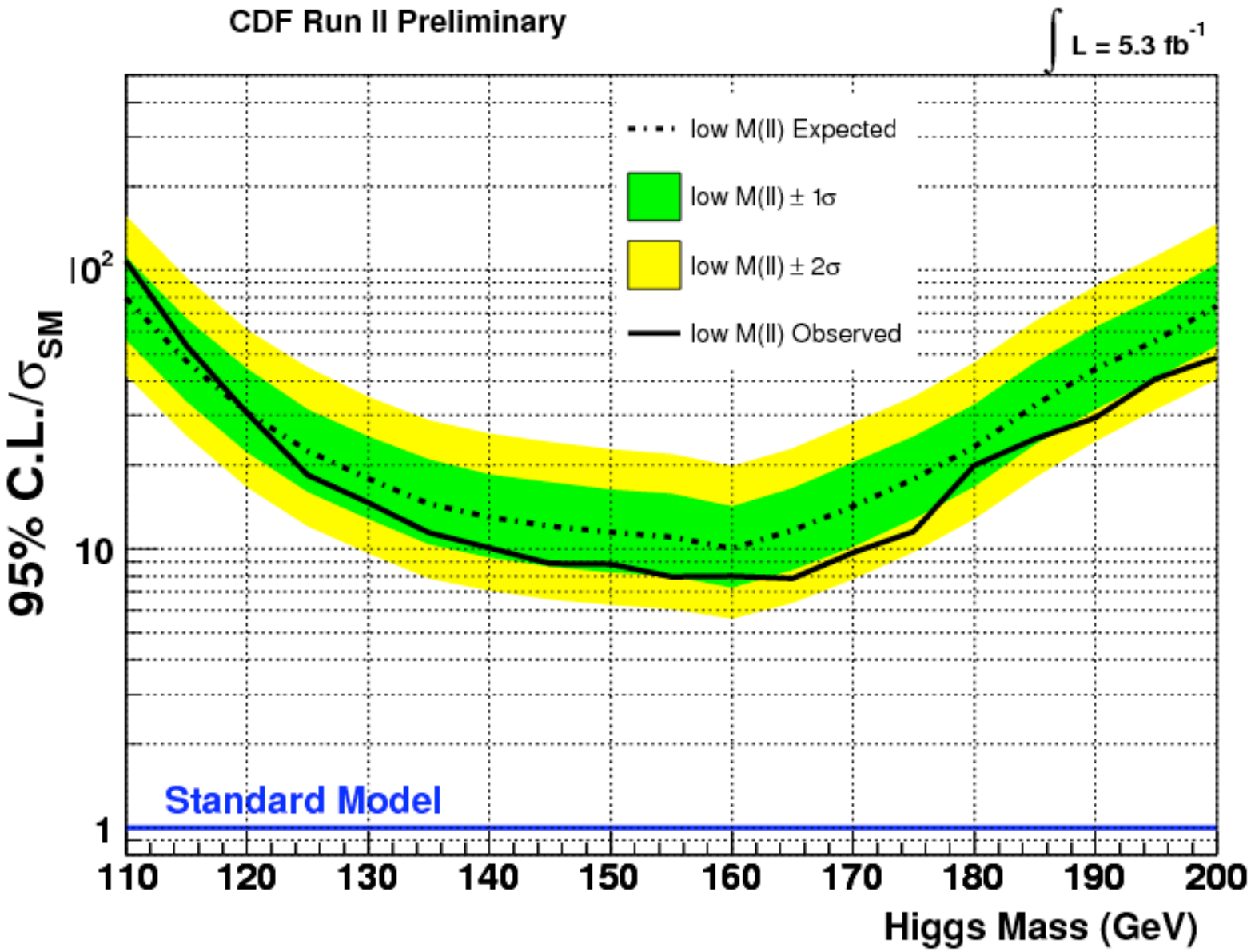
m_{ll}<16 GeV, other cuts the same



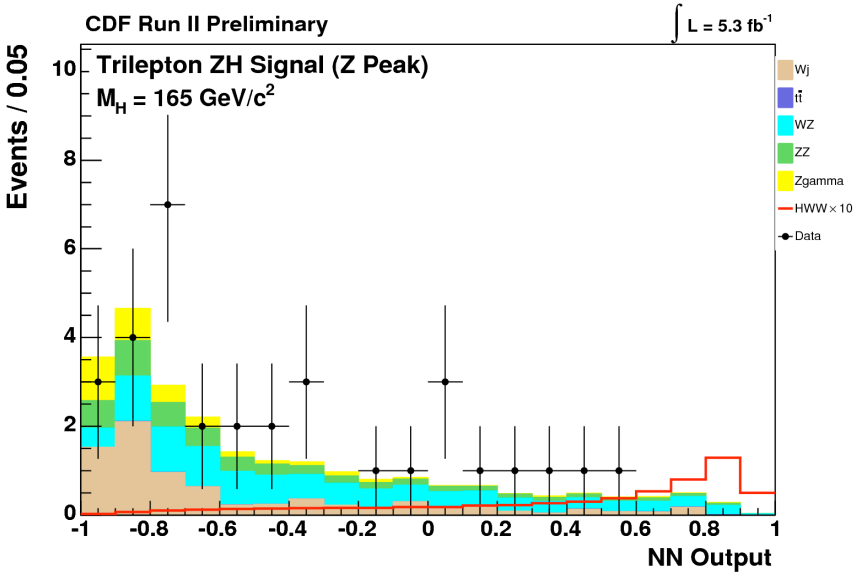
CDF Run II Preliminary	$\int \mathcal{L} = 5.3\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	0.384	$\pm$	0.092
DY	3.67	$\pm$	0.88
WW	12.6	$\pm$	1.5
WZ	0.329	$\pm$	0.049
ZZ	0.123	$\pm$	0.018
W+jets	12.6	$\pm$	2.4
$W\gamma$	69.3	$\pm$	7.7
Total Background	99.0	$\pm$	8.4
$gg \to H$	0.89	$\pm$	0.15
Total Signal	0.89	$\pm$	0.15
Data	104		

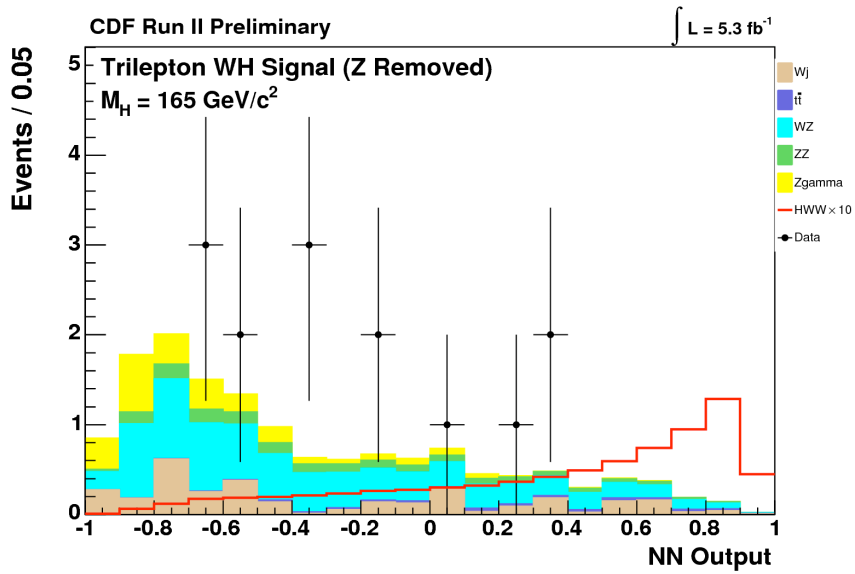
OS Low M(ll)

Opposite-Sign, low-m_{ll} Channel



Trilepton Channels





CDF Run II Preliminary $\int \mathcal{L} = 5.3\ \mathrm{fb}^{-1}$

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

$t\bar{t}$	0.070	$\pm$	0.023
WZ	9.0	$\pm$	1.7
ZZ	4.41	$\pm$	0.68
WW/Z+jets	7.7	$\pm$	1.8
$Z\gamma$	3.00	$\pm$	0.66
Total Background	24.2	$\pm$	3.3
WH	0.0222	$\pm$	0.0040
ZH	0.579	$\pm$	0.076
Total Signal	0.601	$\pm$	0.079
Data	33		

Trilepton inZ

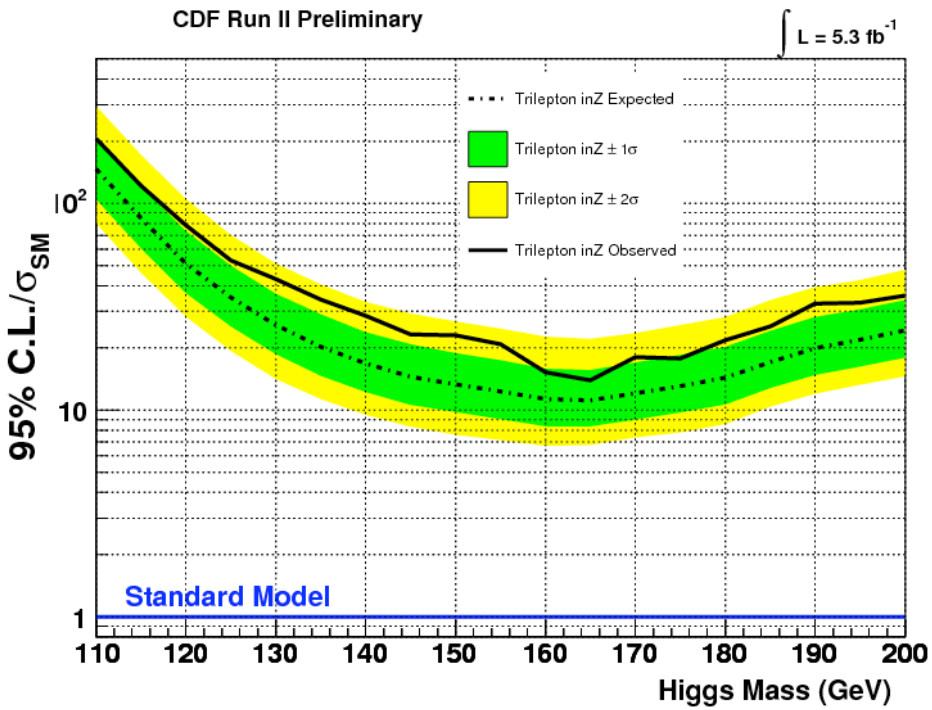
CDF Run II Preliminary $\int \mathcal{L} = 5.3\ \mathrm{fb}^{-1}$

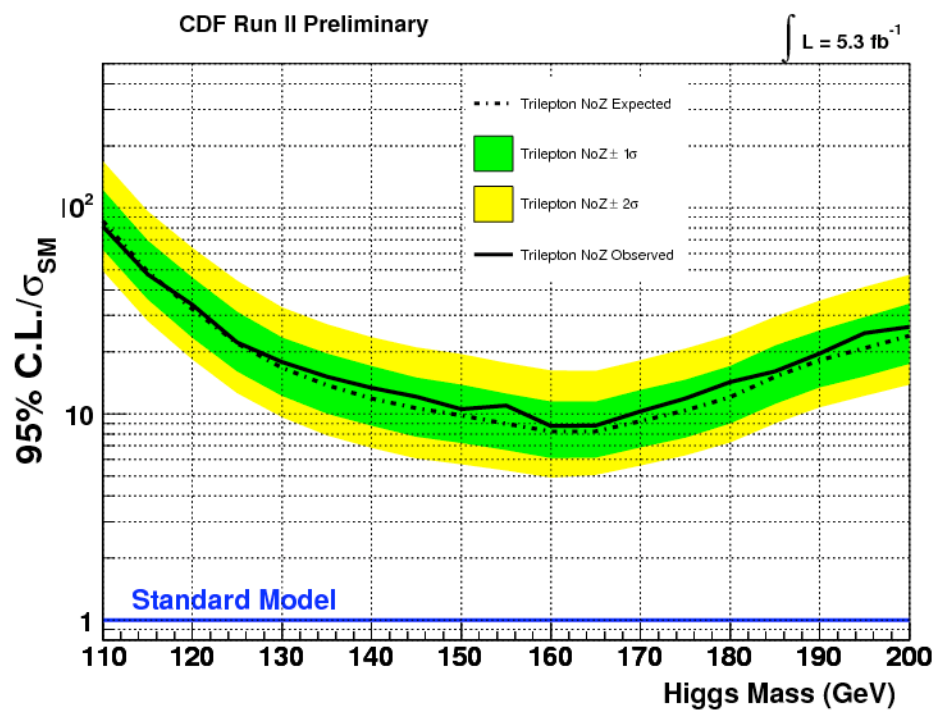
$M_H = 165\ \mathrm{GeV}/c^2$

$t\bar{t}$	0.39	$\pm$	0.12
WZ	7.01	$\pm$	0.96
ZZ	1.49	$\pm$	0.20
WW/Z+jets	3.22	$\pm$	0.72
$Z\gamma$	2.47	$\pm$	0.44
Total Background	14.6	$\pm$	1.5
WH	0.584	$\pm$	0.076
ZH	0.182	$\pm$	0.024
Total Signal	0.766	$\pm$	0.100
Data	14		

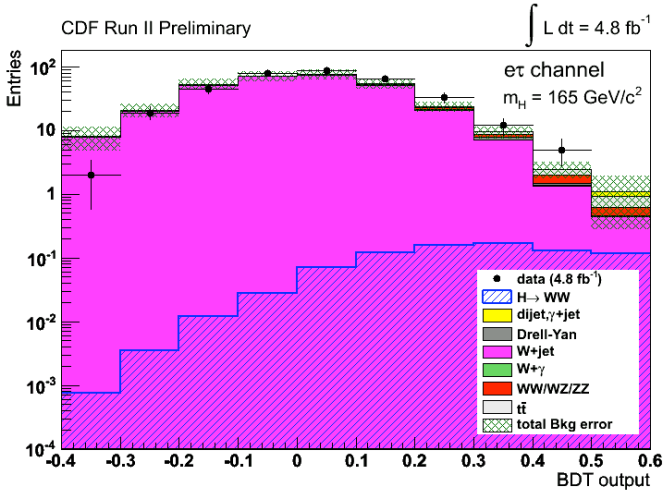
Trilepton NoZ

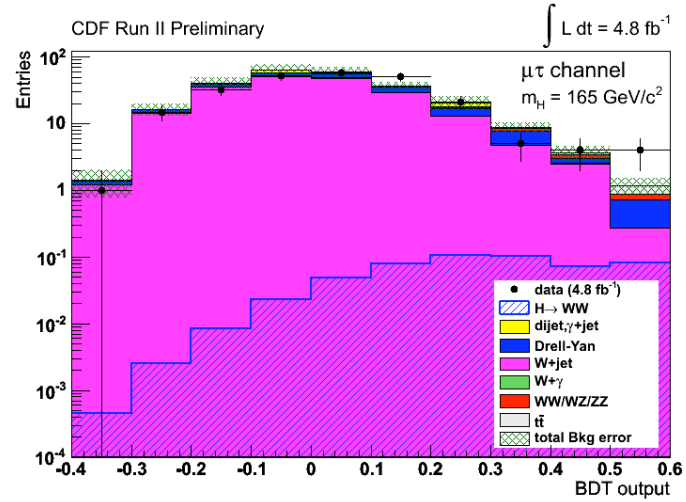
Trilepton Channels





Channels with H→WW→eτ$_{had}$, μτ$_{had}$





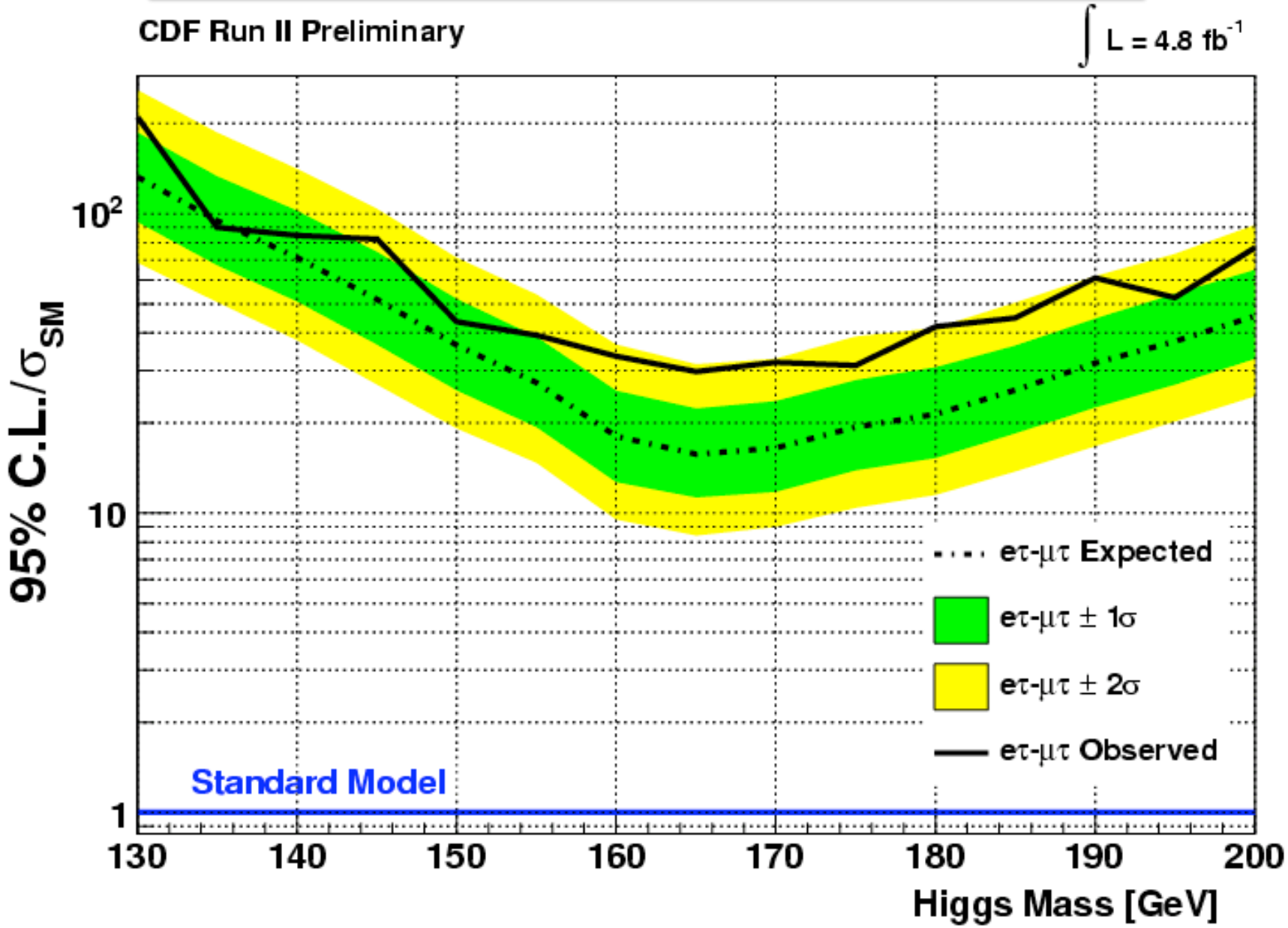
CDF Run II Preliminary	$\int \mathcal{L} = 4.8$ fb^{-1}		
$m_H = 165$ GeV/c^2			
dijet, γ+ jet	3	$\pm$	17
$Z \to \tau\tau$	0.52	$\pm$	0.21
$Z \to \ell\ell$	5.47	$\pm$	0.94
W+jets	304	$\pm$	53
Wγ	0.78	$\pm$	0.14
Diboson (WW, WZ, ZZ)	4.11	$\pm$	0.60
$t\bar{t}$	4.34	$\pm$	0.73
Total Background	322	$\pm$	55
$gg \to H$	0.557	$\pm$	0.076
WH	0.124	$\pm$	0.018
ZH	0.080	$\pm$	0.011
VBF	0.050	$\pm$	0.008
Total Signal	0.811	$\pm$	0.079
Data	348		

$e\tau$ channel

CDF Run II Preliminary	$\int \mathcal{L} = 4.8$ fb^{-1}		
$m_H = 165$ GeV/c^2			
dijet, γ+ jet	12	$\pm$	18
$Z \to \tau\tau$	0.66	$\pm$	0.28
$Z \to \ell\ell$	33.4	$\pm$	3.6
W+jets	201	$\pm$	37
Wγ	0.51	$\pm$	0.10
Diboson (WW, WZ, ZZ)	2.74	$\pm$	0.40
$t\bar{t}$	2.64	$\pm$	0.45
Total Background	253	$\pm$	41
$gg \to H$	0.366	$\pm$	0.051
WH	0.077	$\pm$	0.011
ZH	0.050	$\pm$	0.007
VBF	0.032	$\pm$	0.005
Total Signal	0.525	$\pm$	0.053
Data	243		

$\mu\tau$ channel

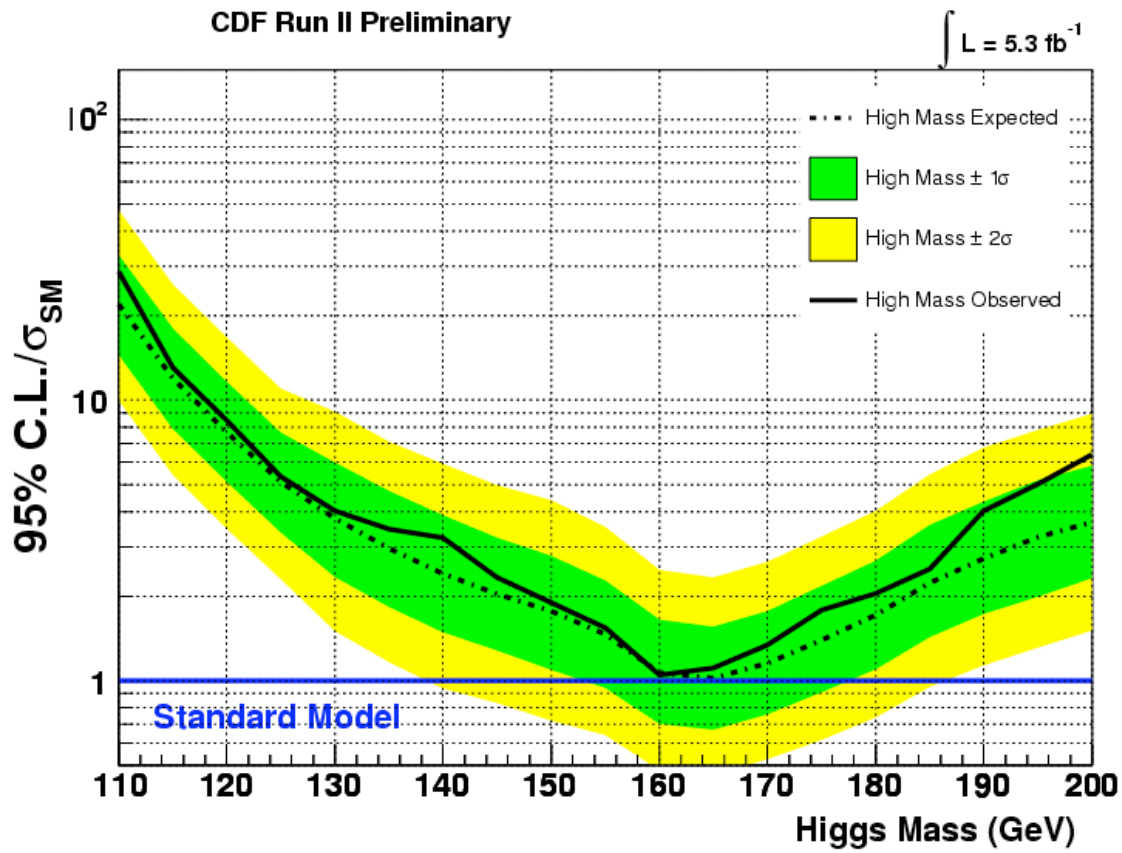
Channels with H→WW→$e\tau_{had}$, $\mu\tau_{had}$



All H→ WW Channels Together!

OS0J (2 channels)
OS1J (2 channels)
OS2+J (1 channel)
SS1+J (1 channel)
Low-M_{ll} (1 channel)
Trileptons (2 channels)
\+ Taus (2 channels)

11 Channels



High Mass	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
$-2\sigma/\sigma_{SM}$	9.97	5.40	3.48	2.31	1.50	1.16	0.94	0.83	0.72	0.64	0.48	0.46	0.52	0.62	0.74	0.95	1.13	1.31	1.51
$-1\sigma/\sigma_{SM}$	14.50	7.91	5.12	3.37	2.35	1.84	1.49	1.28	1.09	0.94	0.70	0.67	0.76	0.91	1.10	1.43	1.73	2.00	2.32
Median/σ_{SM}	**21.88**	**11.93**	**7.70**	**5.11**	**3.78**	**2.95**	**2.40**	**2.04**	**1.77**	**1.47**	**1.07**	**1.02**	**1.15**	**1.39**	**1.72**	**2.24**	**2.73**	**3.24**	**3.68**
$+1\sigma/\sigma_{SM}$	32.92	17.98	11.66	7.67	5.98	4.75	3.88	3.24	2.79	2.28	1.65	1.55	1.77	2.17	2.67	3.59	4.34	5.17	5.84
$+2\sigma/\sigma_{SM}$	47.49	25.75	16.80	11.00	9.09	7.12	5.93	4.98	4.41	3.53	2.48	2.33	2.65	3.27	4.03	5.43	6.76	7.84	8.92
Observed/σ_{SM}	**28.72**	**13.03**	**8.47**	**5.33**	**4.02**	**3.47**	**3.23**	**2.33**	**1.89**	**1.54**	**1.05**	**1.11**	**1.34**	**1.78**	**2.05**	**2.50**	**4.03**	**5.02**	**6.40**

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).**

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 D0 σ_{inel}(ppbar)
4.4% detector-specific

Diboson Cross Sections: WW, WZ and ZZ
Cross sections used (6% relative uncertainty)
$\sigma_{WW} = 12.4 \pm 0.7$ pb
$\sigma_{WZ} = 3.7 \pm 0.2$ pb
$\sigma_{ZZ} = 3.8 \pm 0.2$ 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: ± 12% (inclusive, but CDF takes Anasasiou et al's uncertainties in each jet bin)

VBF: ± 10%

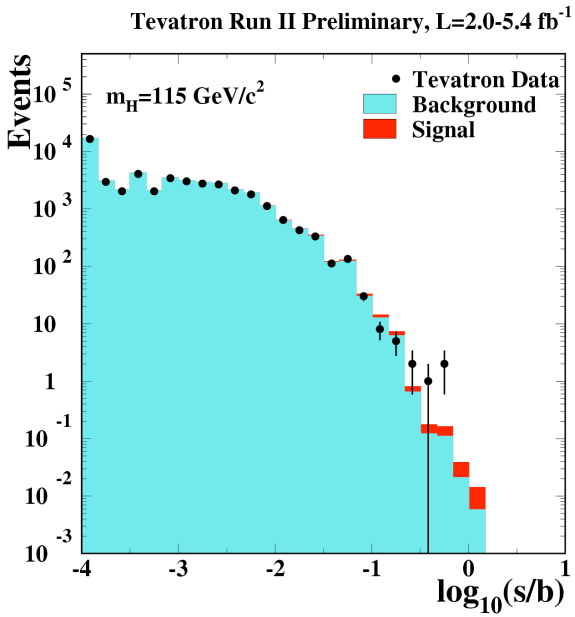
Applied to SM interpretations, but taken off for cross-section times branching ratio limits.

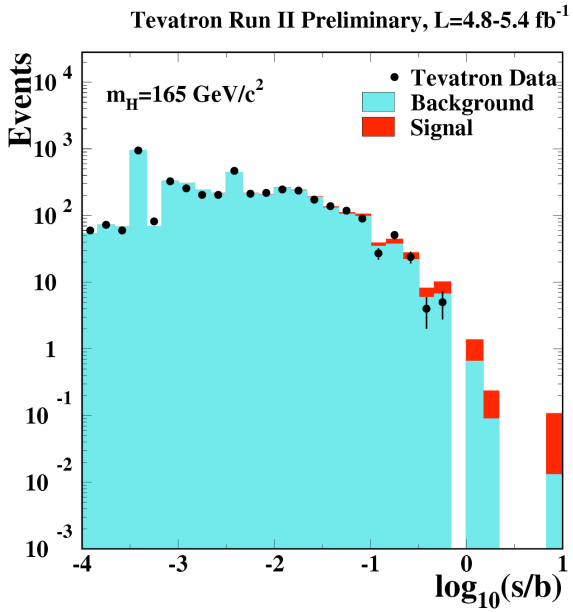
CDF-D0 Uncorrelated uncertainties:

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

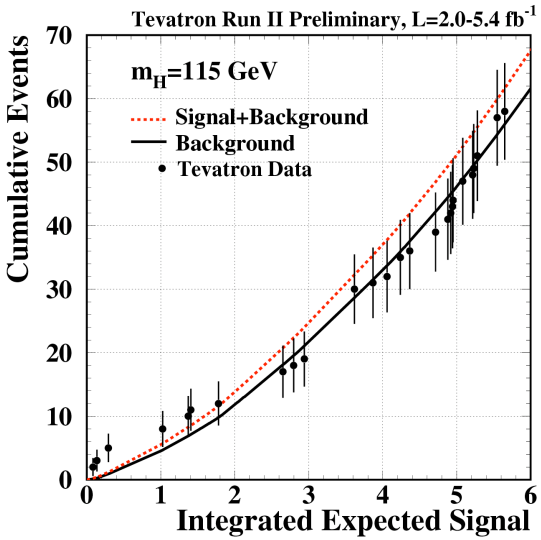
Correlated *within* CDF and D0 where appropriate

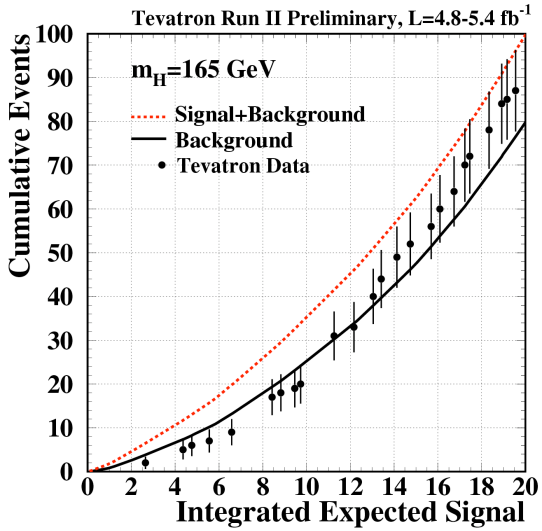
Tevatron Combination: Too Many Histograms to show in a talk – Collect Data by s/b



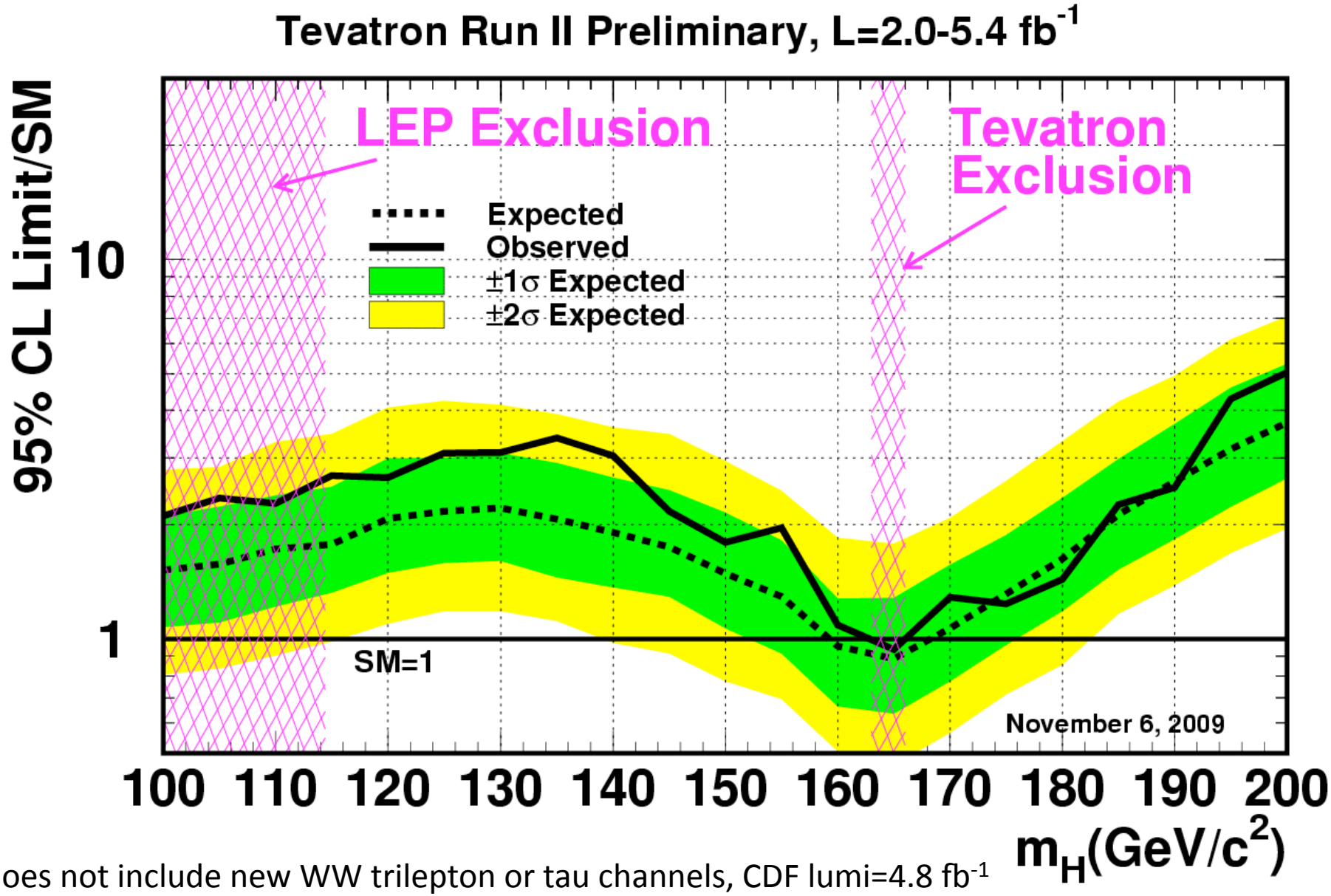


November 2009 all-mass combination





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



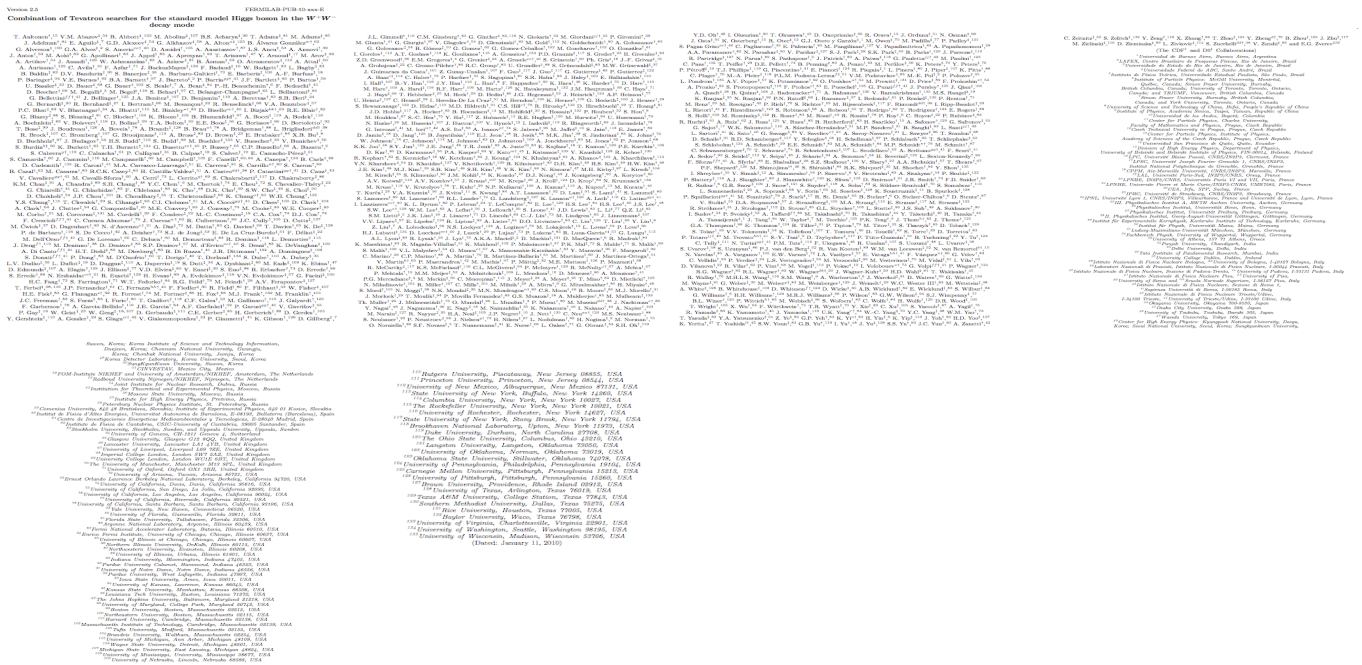
does not include new WW trilepton or tau channels, CDF lumi=4.8 fb^{-1}

Great! Now let's Publish!

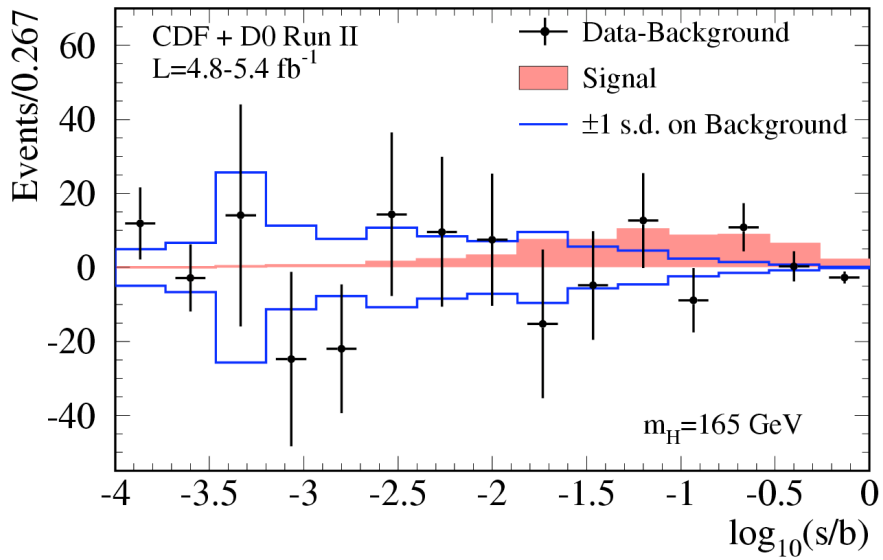
- Issues: not all input channels are final and published. low-m_{ll}, taus and trileptons (new for Moriond 2010). Most low-mass channels are newer and have more data than their last publications.

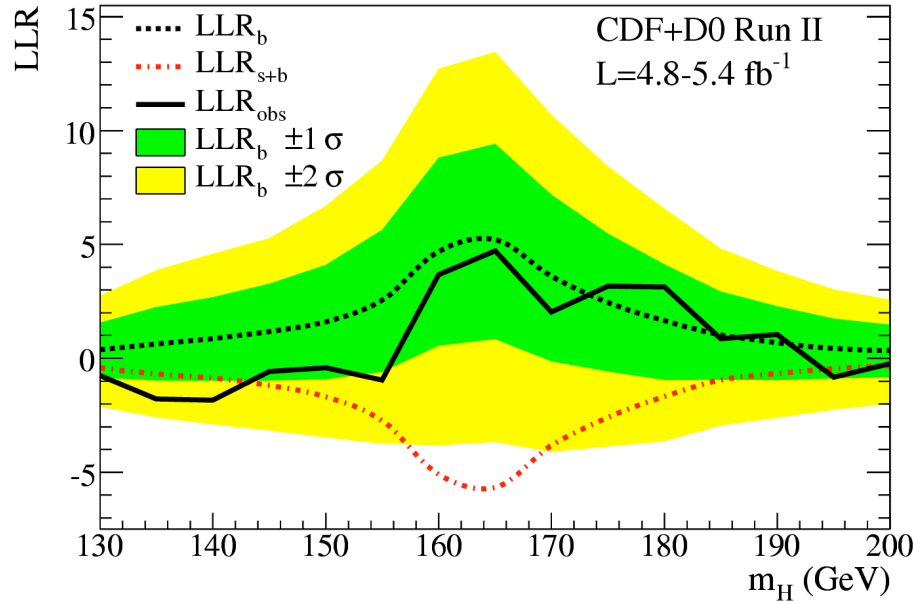
- Still want to publish the test of $m_H \sim 2M_W$. So publish three PRL's, one from CDF, one from D0, and one combining them, for all the OS+SS channels.

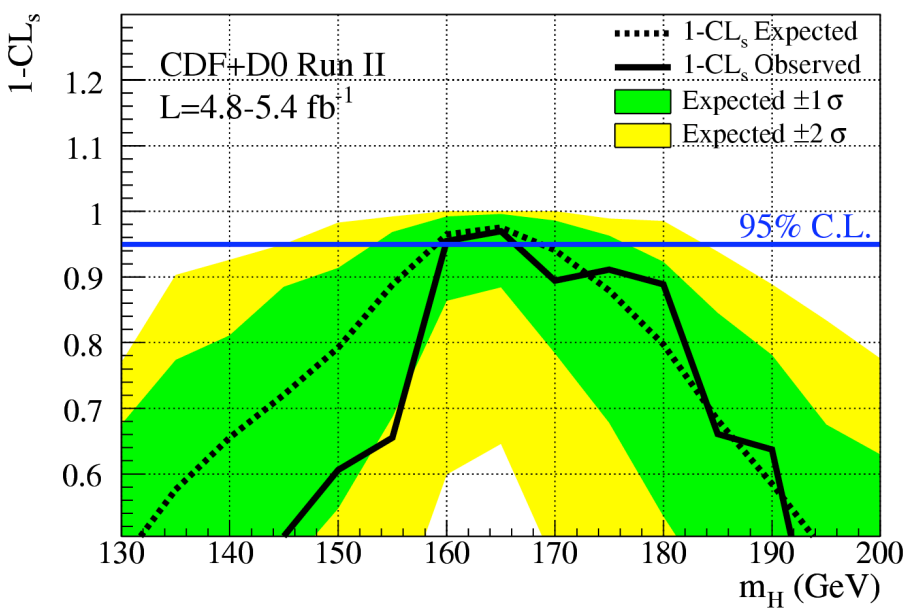
- On agreement of CDF and D0, produce a single author list sorted alphabetically. 1042 Authors! 132 Institutions!

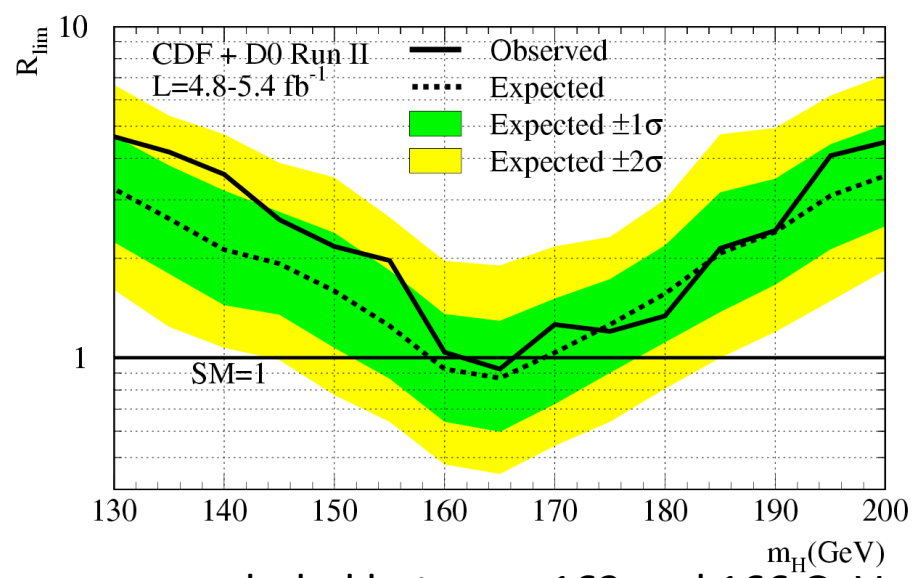

Version 2.5 FERMILAB-PUB-10-xxx-E
Combination of Tevatron searches for the standard model Higgs boson in the W^+W^- decay mode

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









m_H excluded between 162 and 166 GeV

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

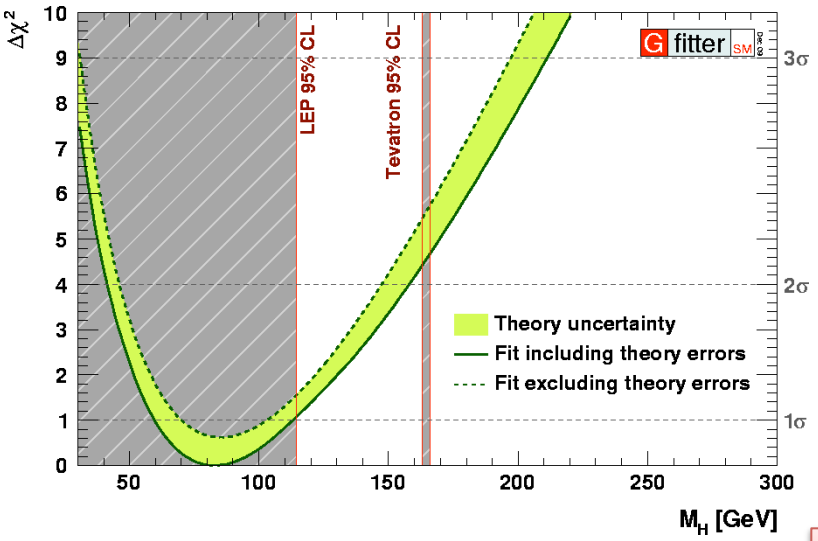
Combination of Tevatron Searches for the Standard Model Higgs Boson in the W^+W^- Decay Mode
T. Aaltonen et al. (CDF and D0 Collaborations) **1042 Authors!**
Phys. Rev. Lett. **104**, 061802 (2010) – Published February 12, 2010

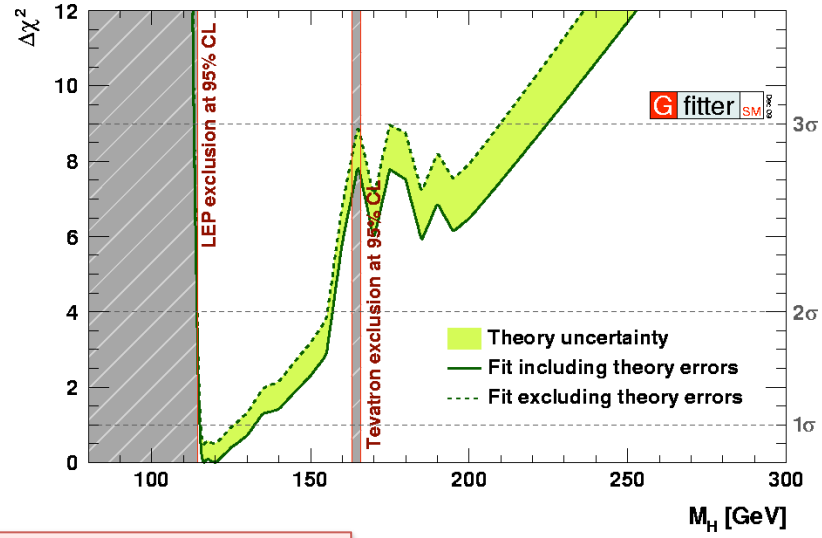
We made the cover!

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

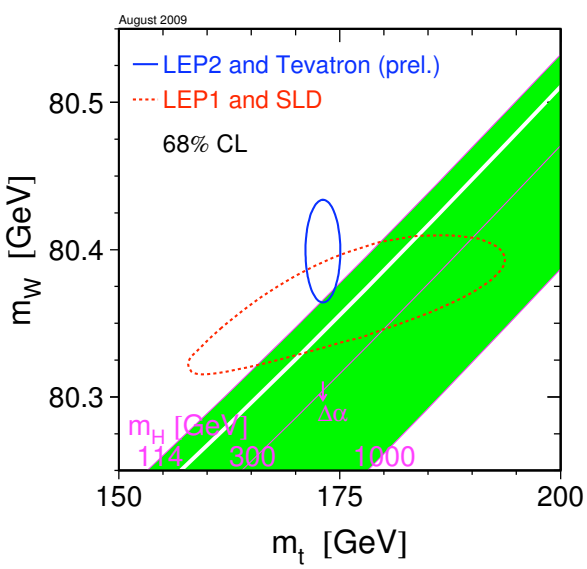
http://physics.aps.org/articles/v3/14

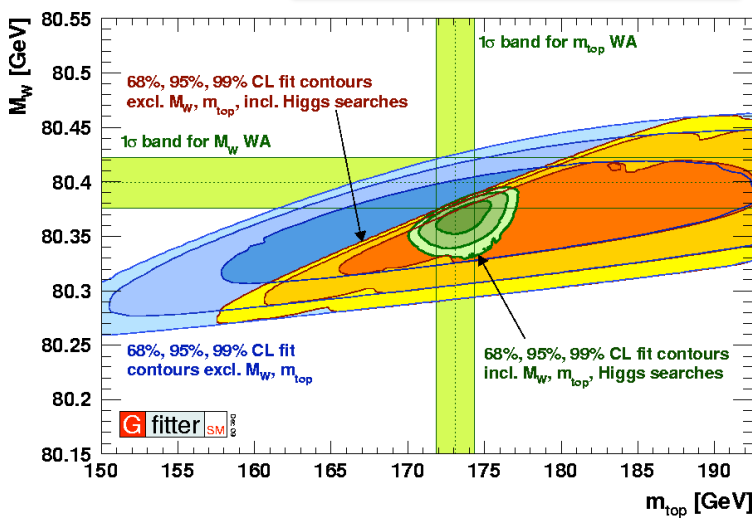
Global Electroweak Fit Including Direct Searches





http://gfitter.desy.de





Contours of 68%, 95% and 99% CL obtained from scans of fits with fixed variable pairs MW vs. mt. The largest/blue (narrower/yellow) allowed regions are the results of the standard fit excluding (including) the direct Higgs searches at LEP and Tevatron. The narrowest/green areas indicate the constraints obtained for the complete fit including all the available data. The horizontal bands indicate the 1σ regions of measurements (world averages).

Any Hint of a Higgs Boson?

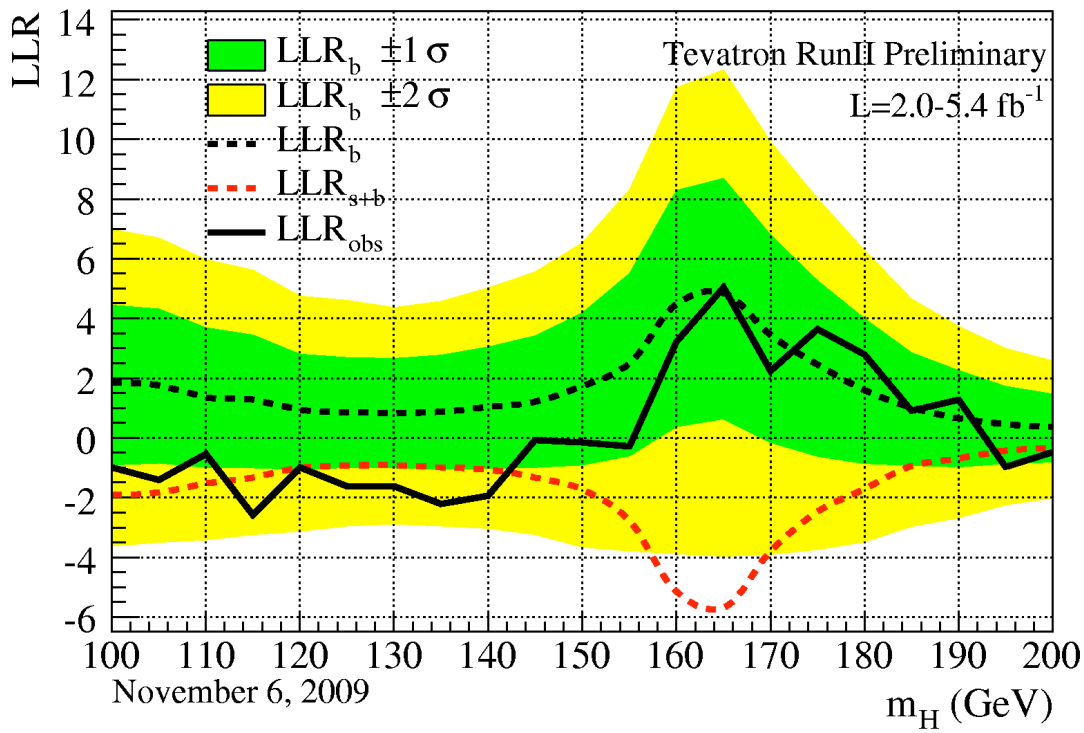
Neyman-Pearson Lemma says the Likelihood Ratio is uniformly most powerful test statistic

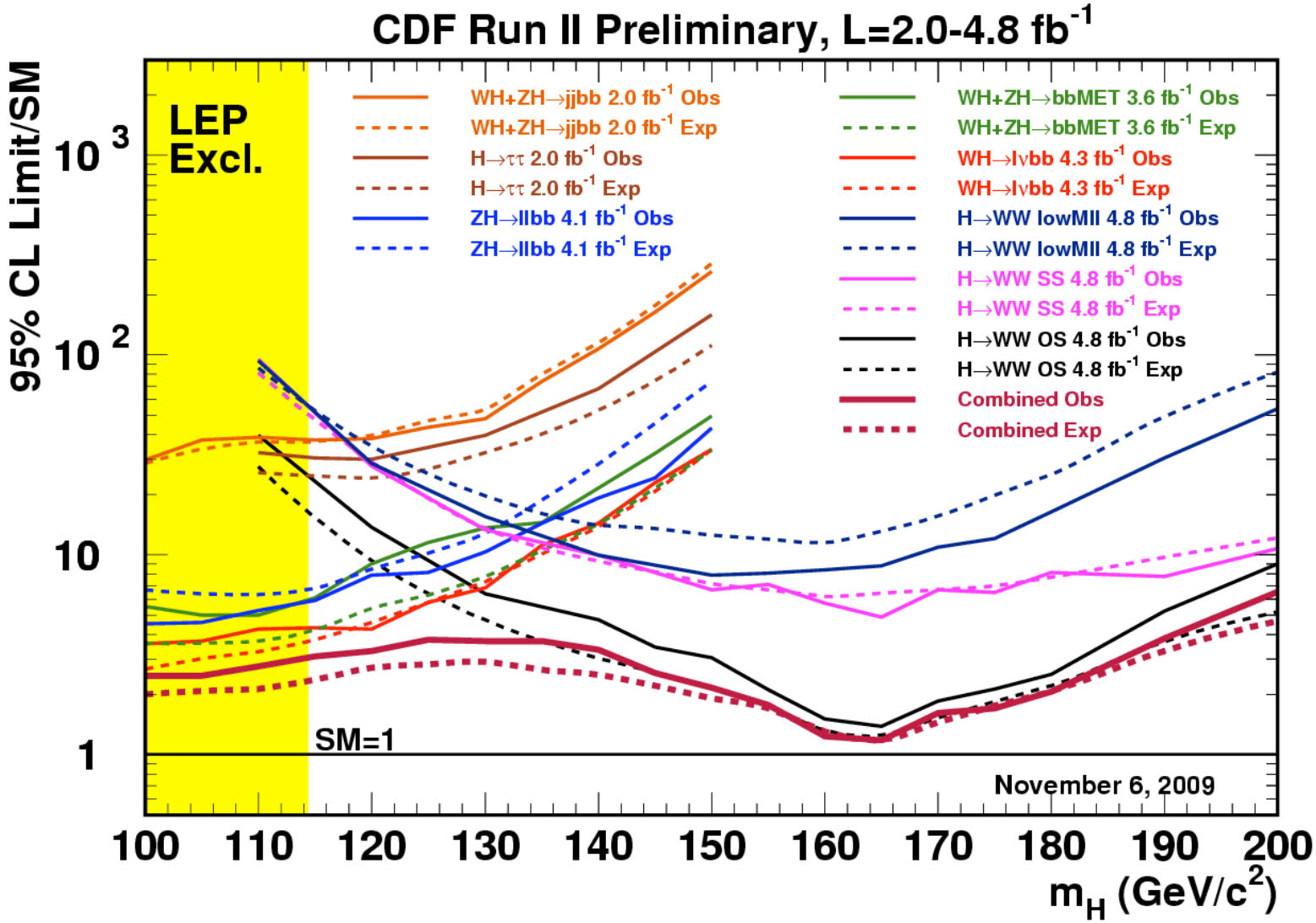
$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\,|\,s+b,\hat{\theta})}{L(\text{data}\,|\,b,\hat{\hat{\theta}})}\right)$$

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

No obvious hint of a signal.

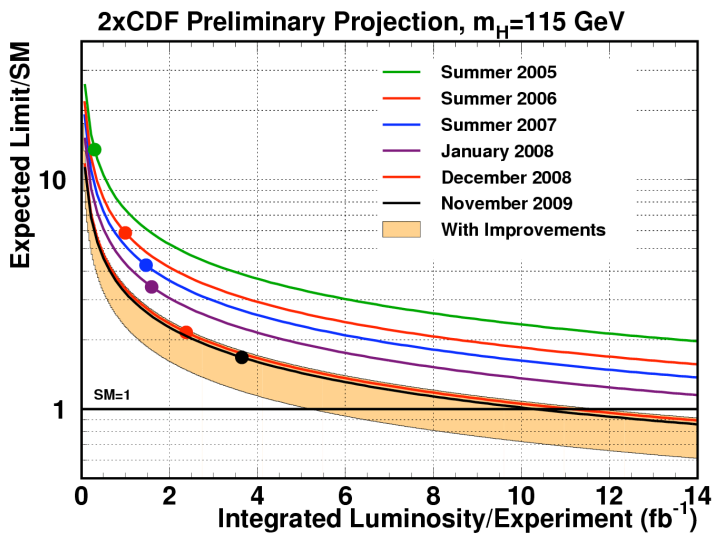
Getting sensitive, though!





Note: Last CDF all-mass combination used 4.8 fb^{-1} H→WW results and not the Moriond 2010 5.3 fb^{-1} results

As we get older, we collect more data and we also get smarter

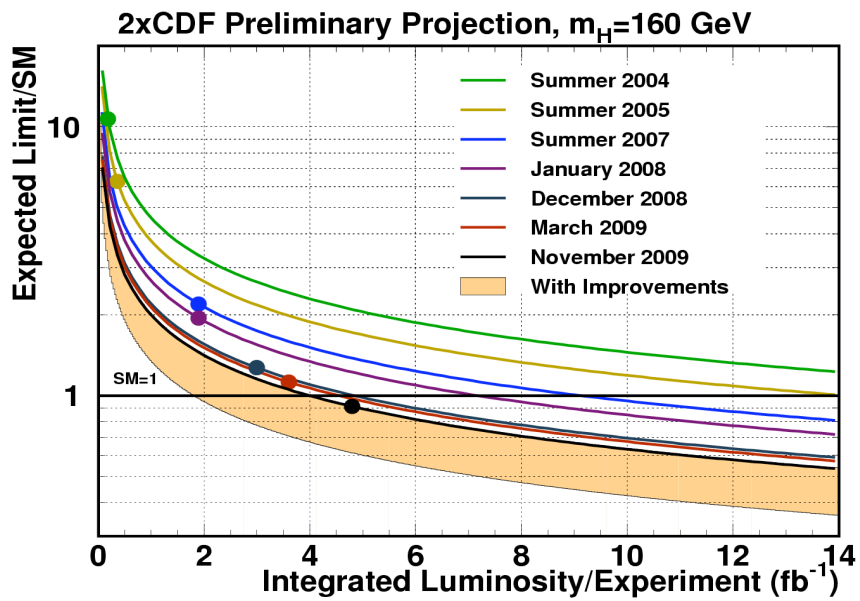


High-Mass: Improvements made to

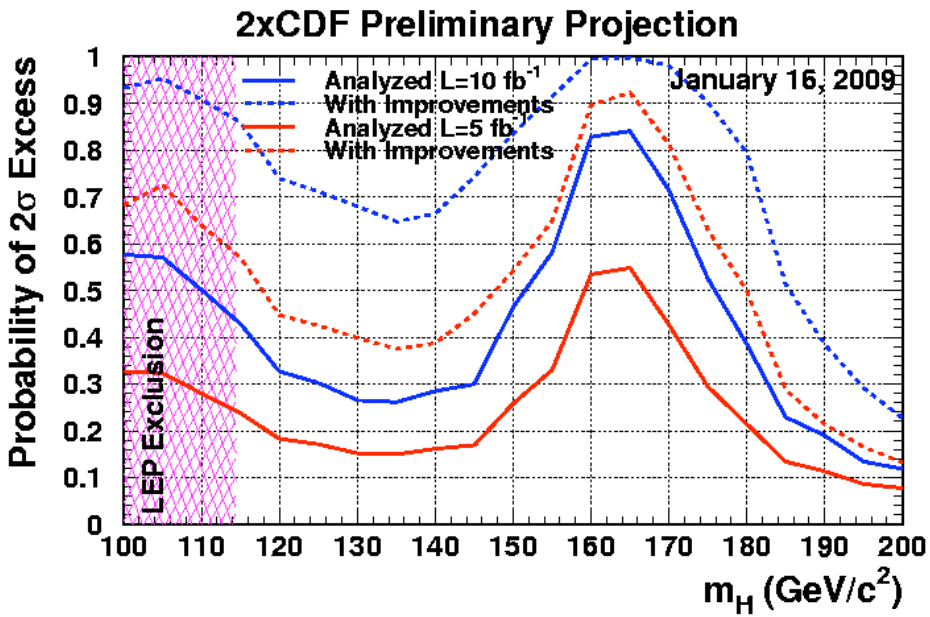
- excavating for more lepton acceptance (isolated tracks, taus, leptons in cracks)
- Split jet samples, central and forward leptons
- Tighter control over backgrounds in control regions
- Adding new channels – same sign, low-m_{ll}, and trileptons
- Matrix Elements and Neural Networks

Low-Mass: Improvements made to

- triggers (leptons, MET+Jets)
- excavating for more lepton acceptance (isolated tracks, taus, leptons in cracks)
- Split single tag and double-tagged samples
- B-tag improvements – loose double tags, increased acceptance
- Tighter control over QCD background – rejection and modeling
- Improved dijet mass resolution (esp. in llbb channel)
- Matrix Elements and Neural Networks and BDTs

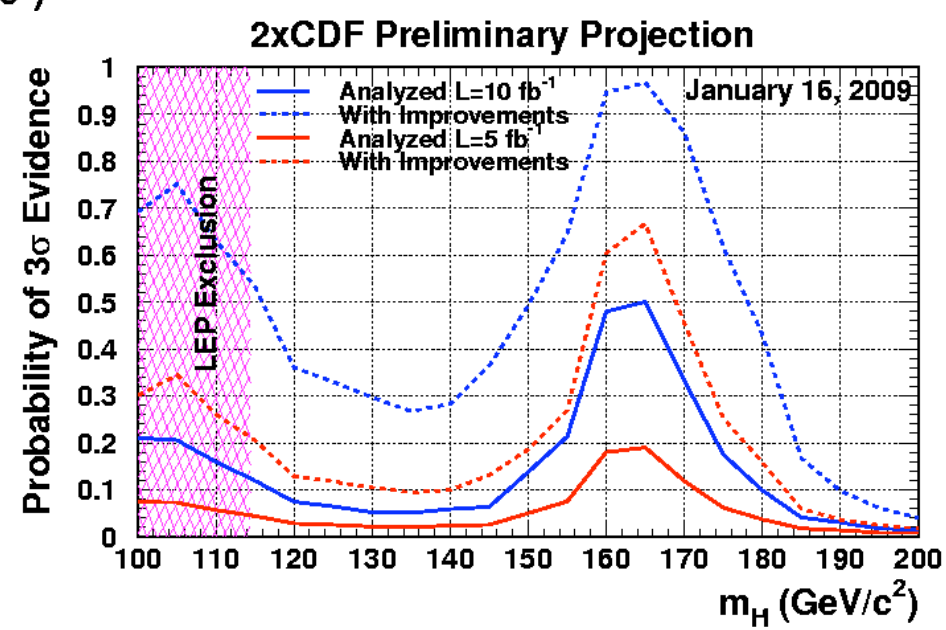


Chances of Two- and Three-sigma Excesses

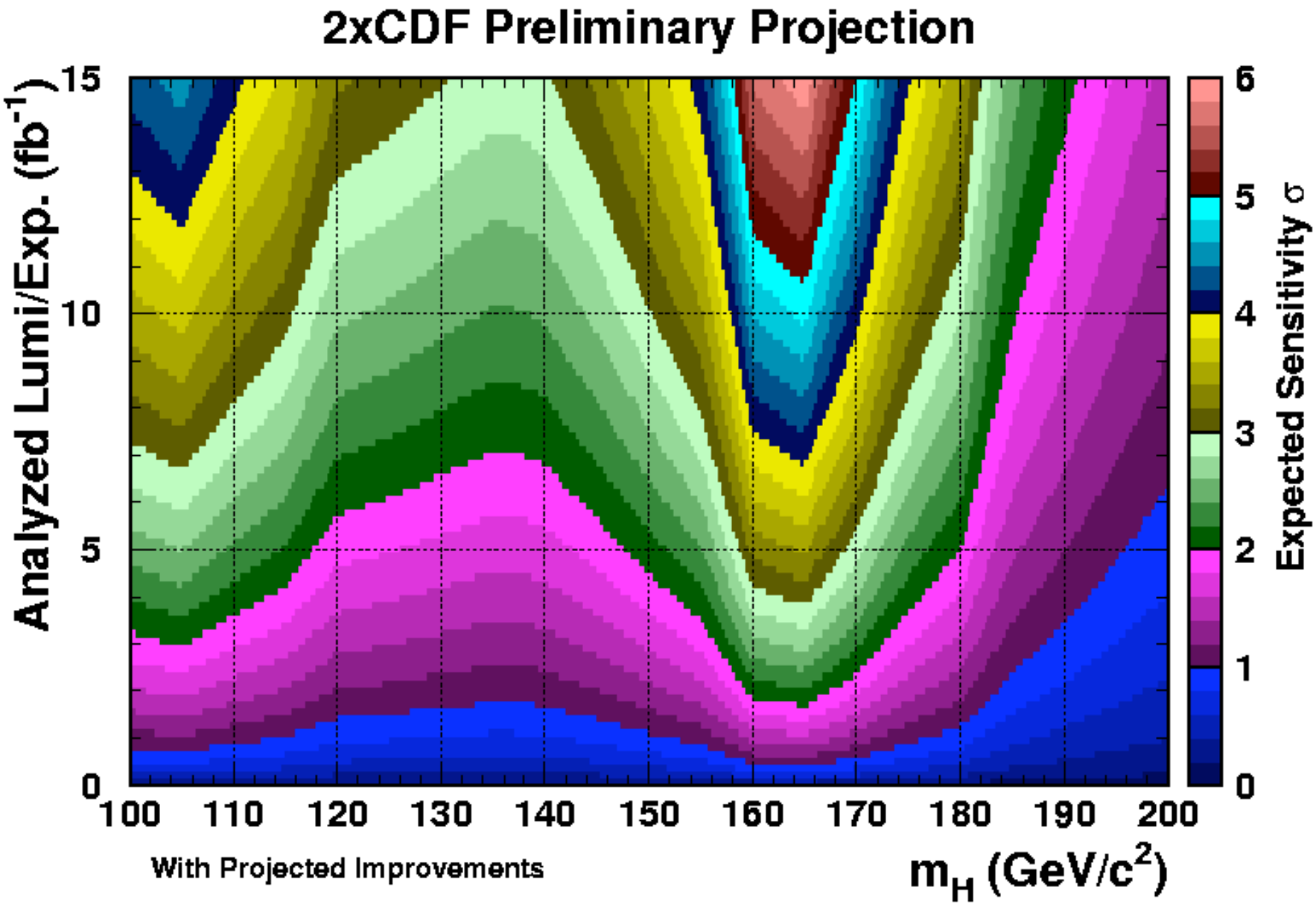


Gaussian, sqrt(L) extrapolations

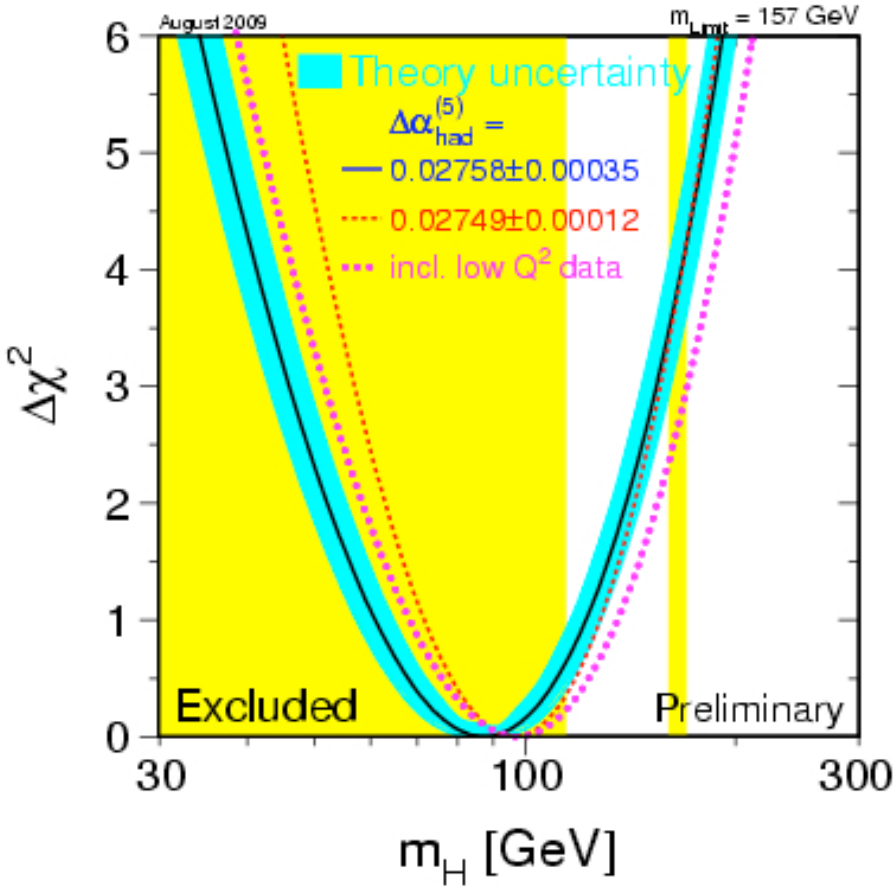
Systematic uncertainties are fit for in the data – constraints get better with larger samples



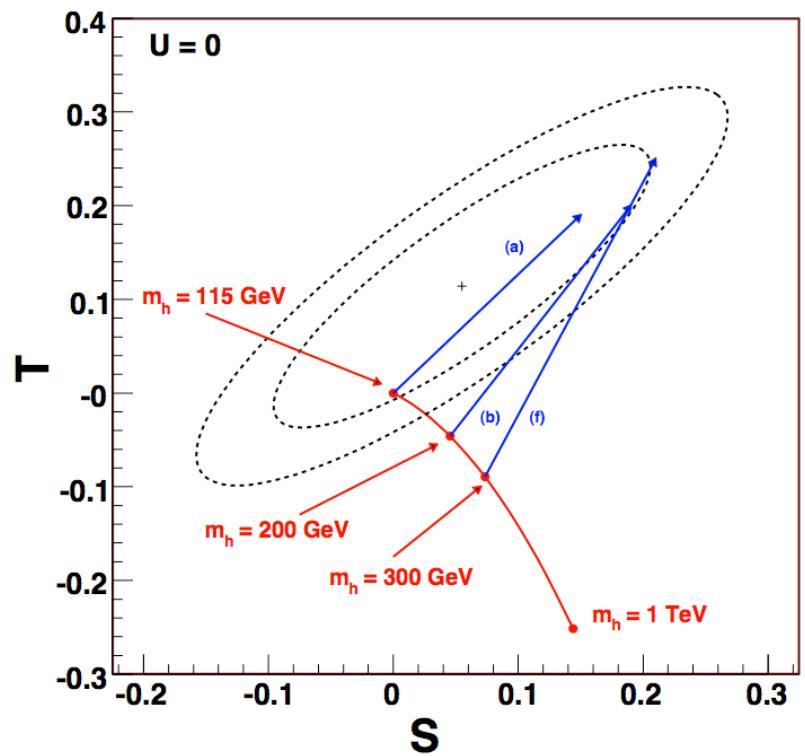
Median A Priori Expected Excess as a Function of mH and Analyzed Luminosity



Fourth Generations Possible – Affects the Precision EW Constraint on m_H

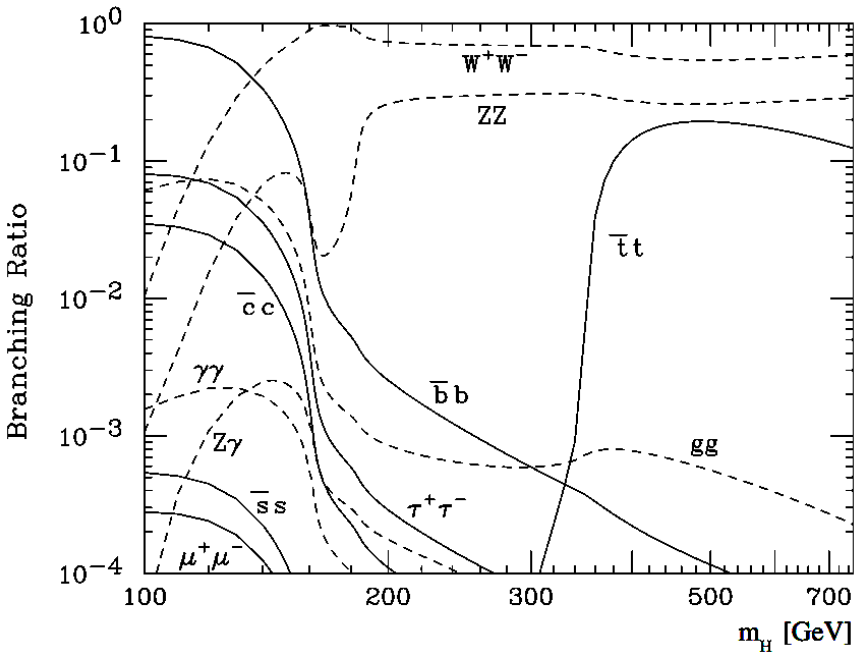


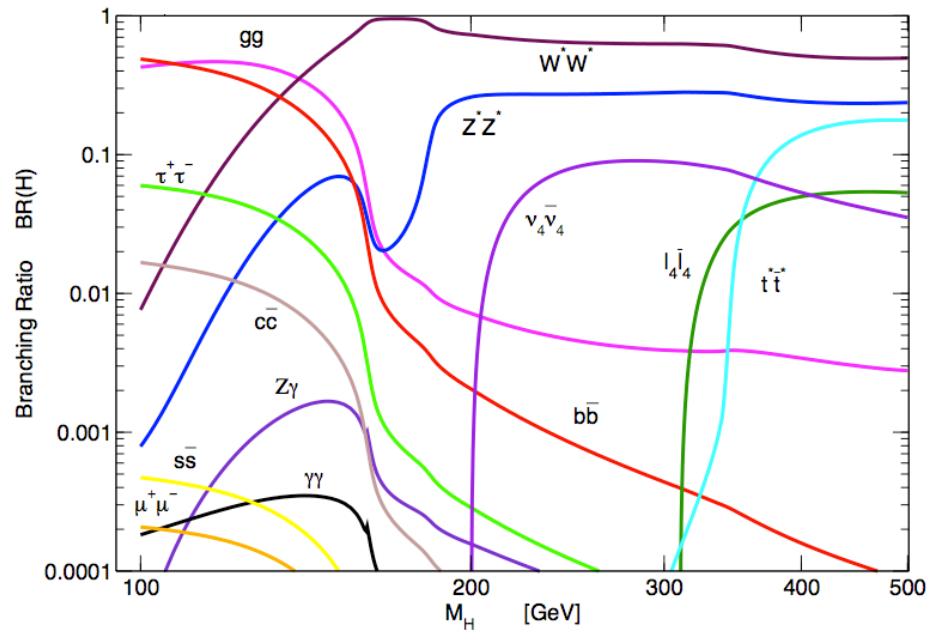
Four Generations and Higgs Physics
Kribs, Tait, Spannowsky, Plehn
Phys.Rev.D76:075016,2007.
arXiv:0706.3718 [hep-ph]



Higgs Boson Decay Branching Fractions and Scenarios

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





SM (Spira)

4G (Kribs, Tait, Plehn, Spannowsky)

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

Fourth Generation Analysis Strategy

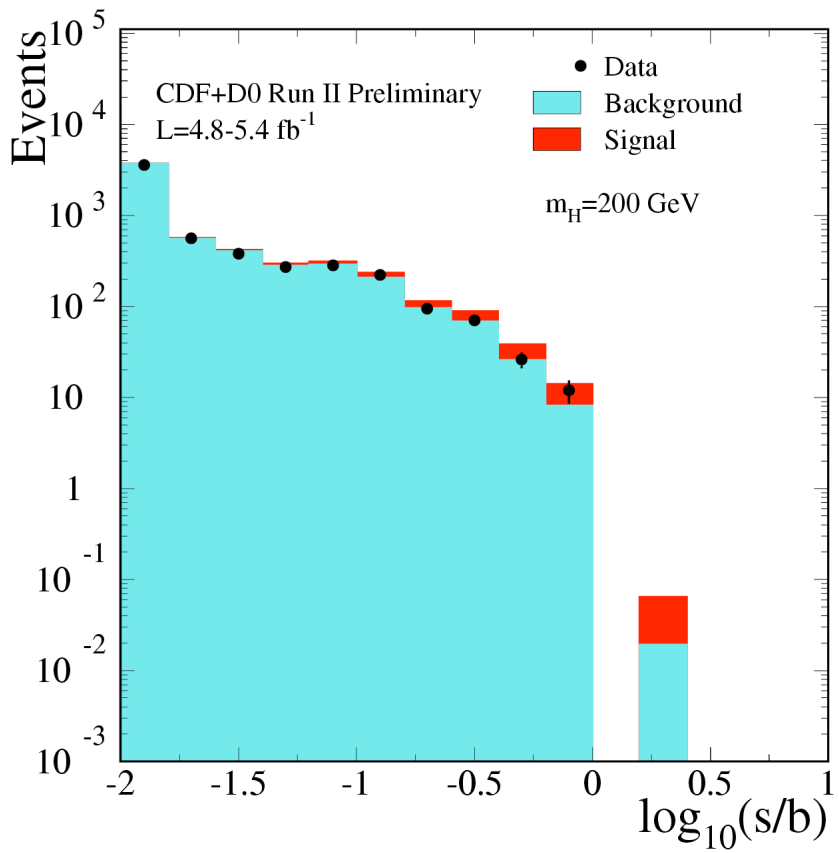
- **Not a straight-up model drawn on the same exclusion curve:**
  - $\sigma(gg \rightarrow H)$ is enhanced by a factor of 9 (m_H=100 GeV) to 7.5 (m_H=300 GeV) but WH, ZH, and VBF remain unchanged
  - SM combination assumes SM mixture of $gg \rightarrow H$, WH, ZH, and VBF

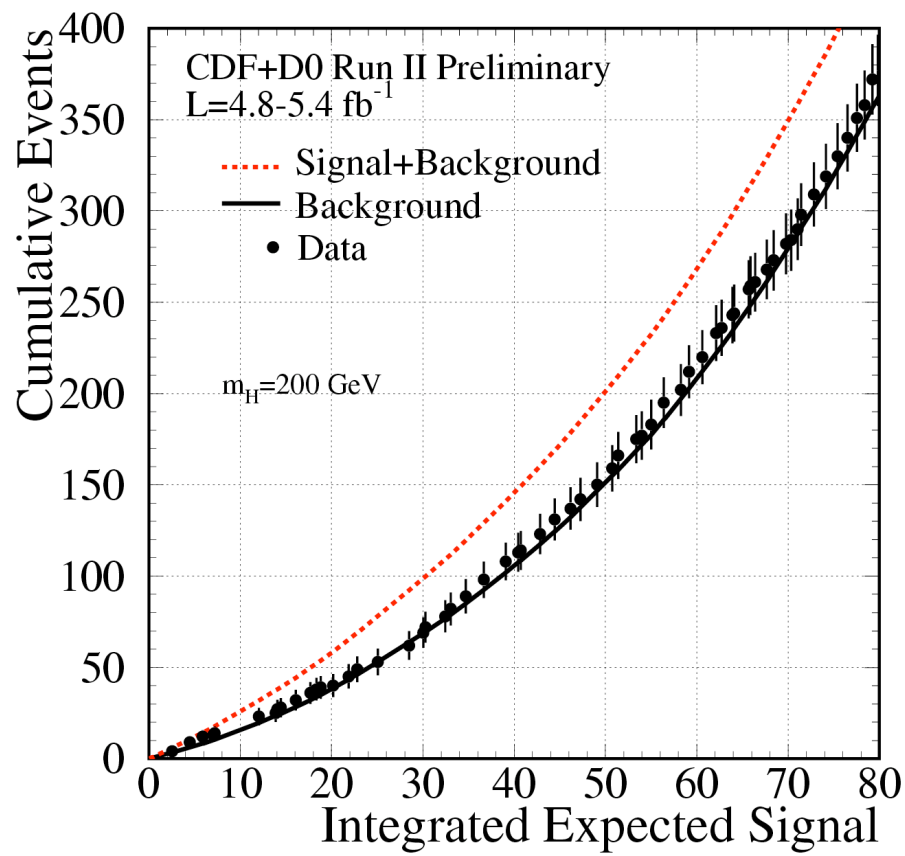
- **Strategy:**
  - Remove WH, ZH, and VBF signals, and retrain discriminants just for $gg \rightarrow H$
  - Extend mass range $110 < m_H < 260$ GeV (up to 300 GeV coming soon)
  - Compute $\sigma(gg \rightarrow H)$ assuming enhancement factor from Tait, Plehn, Kribs and Spannowsky's HDECAY. Note: 2-loop 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 $\sigma(gg \rightarrow H) \times Br(H \rightarrow WW)$. 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!

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

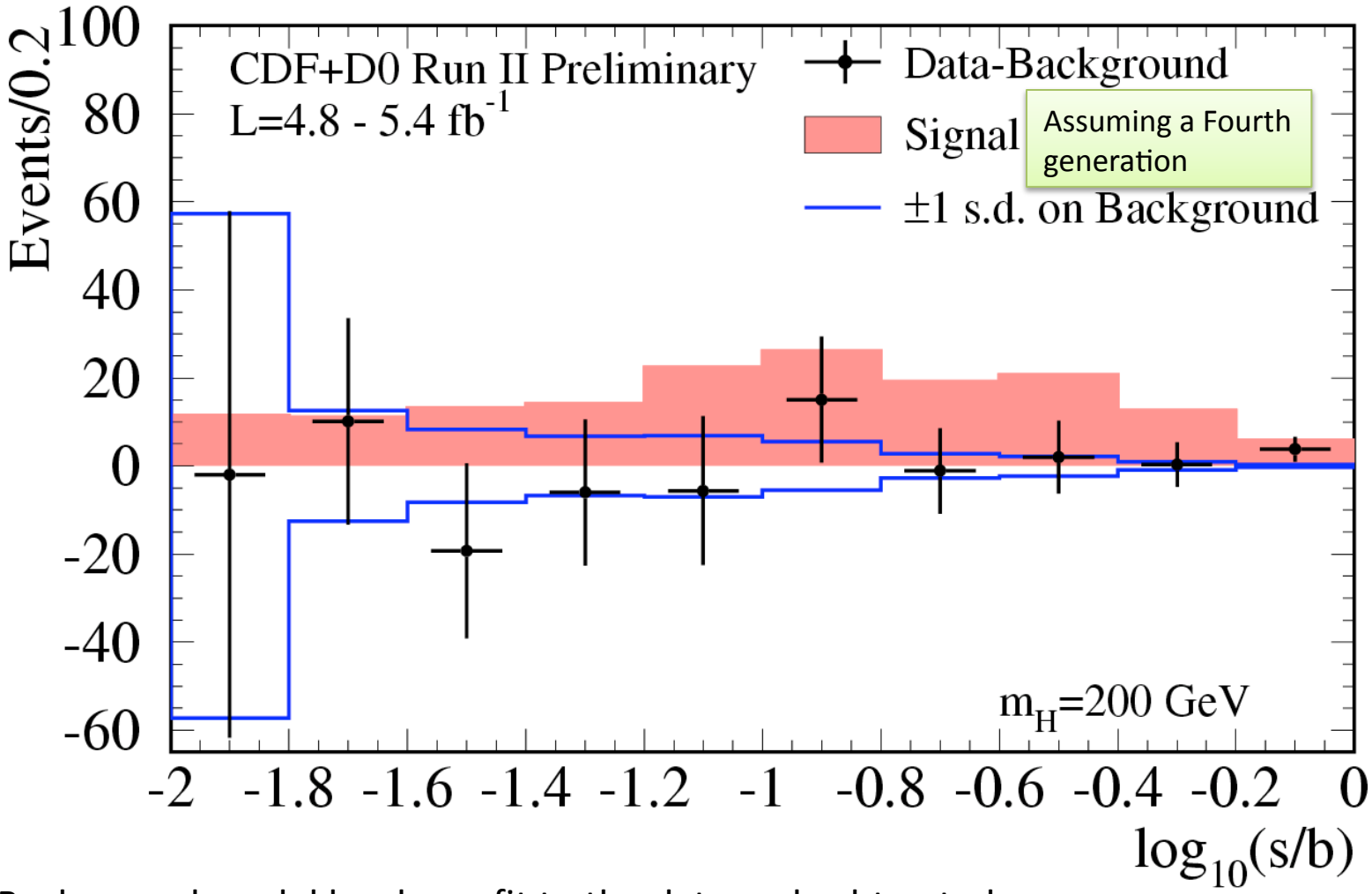
Bins sorted by s/b, and summed over all channels.
Signal normalized to the infinite-mass scenario



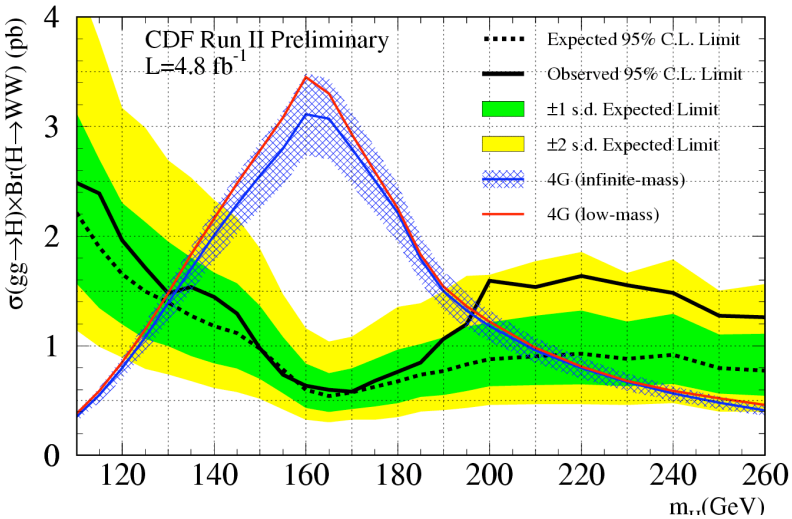


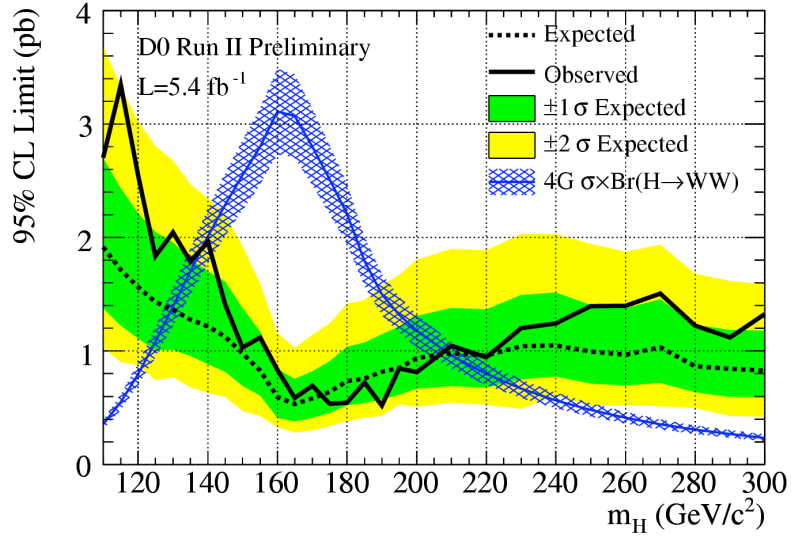
Testing the Fourth-Generation "infinite-mass" scenario at m_H=200 GeV

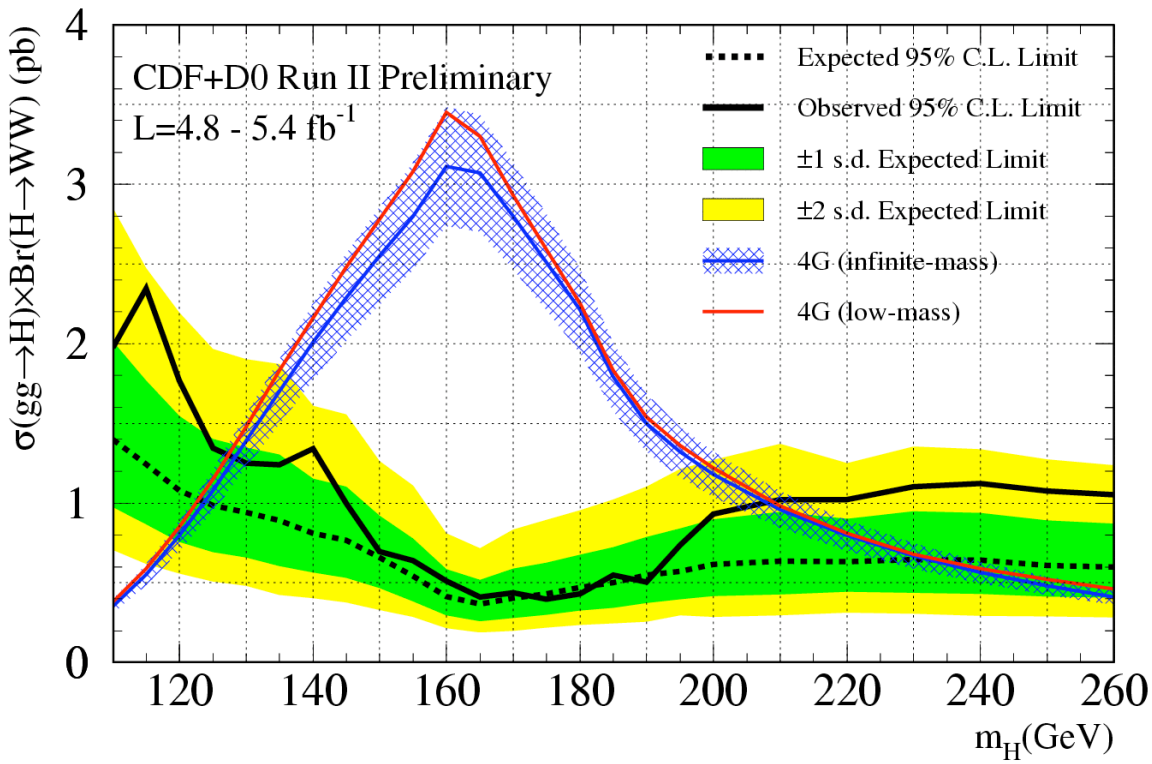
Background-Subtracted Data Distribution, with Signal



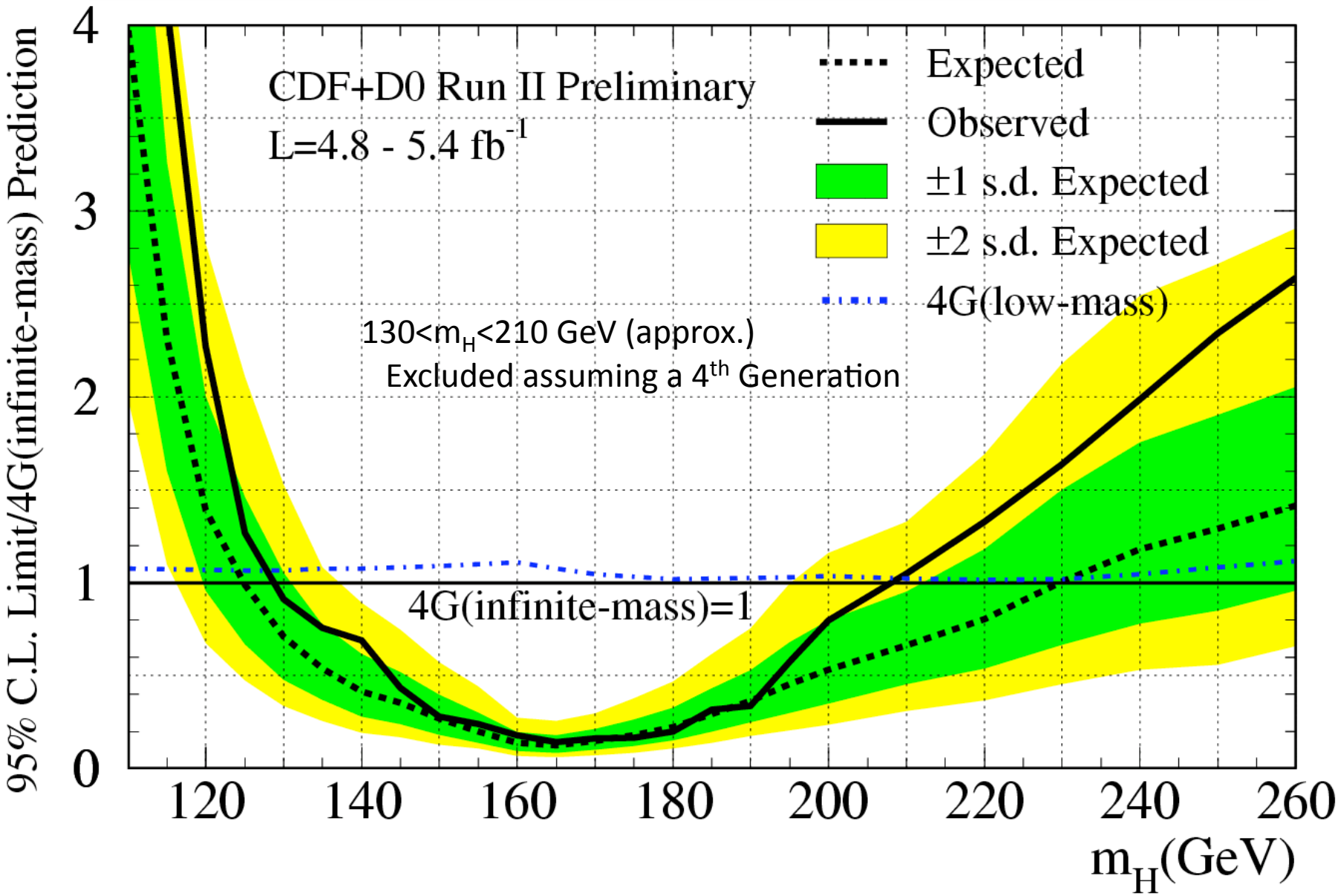
Background model has been fit to the data and subtracted
Error on data – background is sqrt(background)
Blue histogram is the post-fit uncertainty on the background.


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)

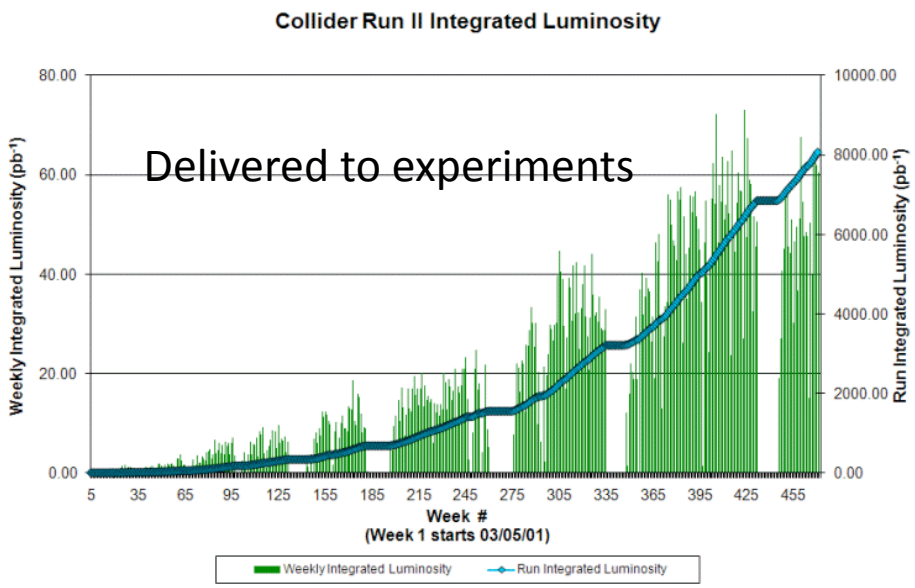

D0 Run II Preliminary
L=5.4 fb^{-1}
Expected
Observed
±1 σ Expected
±2 σ Expected
4G σ×Br(H→WW)
95% CL Limit (pb)
m$_H$ (GeV/c^2)

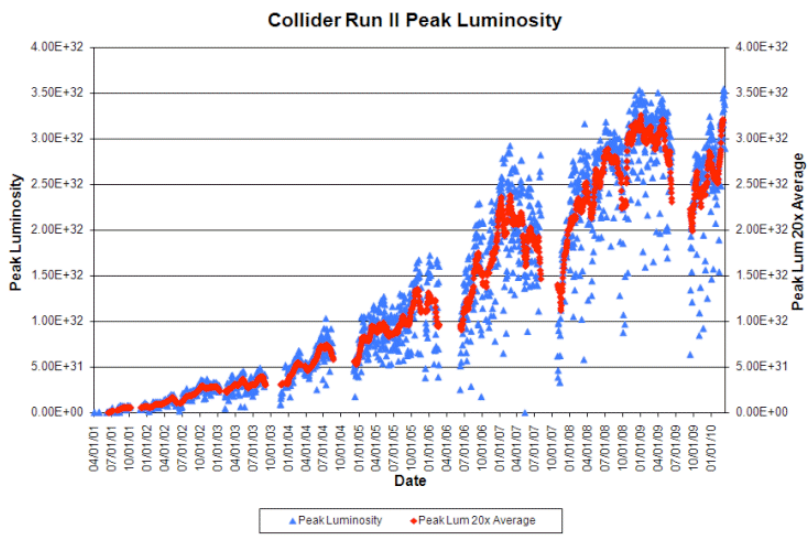

CDF+D0 Run II Preliminary
L=4.8 - 5.4 fb^{-1}
Expected 95% C.L. Limit
Observed 95% C.L. Limit
±1 s.d. Expected Limit
±2 s.d. Expected Limit
4G (infinite-mass)
4G (low-mass)
σ(gg→H)×Br(H→WW) (pb)
m$_H$(GeV)

Test of the Fourth Generation Hypothesis with m_H



Where We are Headed





- The Tevatron is running very well
- CDF and D0 will run in FY11 (ends Sep. 2011). 10 to 12 fb^{-1} of analyzable data planned.
- Further running under discussion
- The Tevatron will remain the leader in sensitivity for the SM Higgs boson for the next three years

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 162 and 166 GeV assuming the SM
  And we *expected* to do that! (assuming a Higgs boson is truly not there).

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

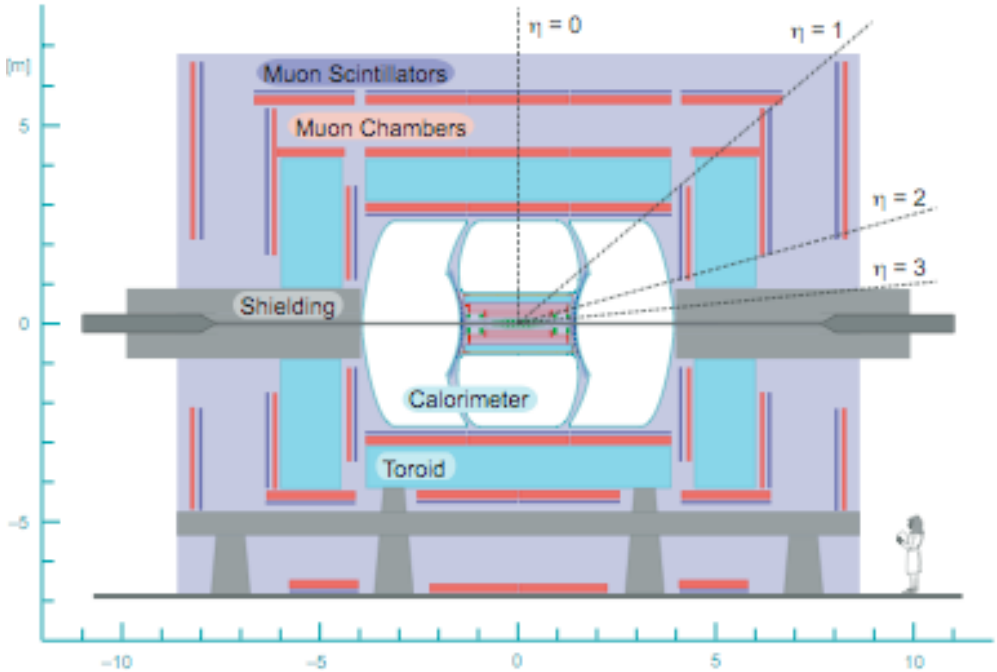
- CDF and D0 together exclude m_H between 130 and 210 GeV (approx)
  assuming a fourth generation of heavy fermions exists

- 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

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

The DØ Detector



Lepton coverage:

$|\eta| < 2$ (muons)

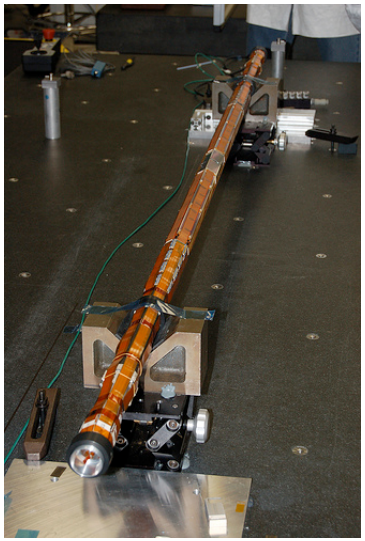
$|\eta| < 2.6$ (electrons)

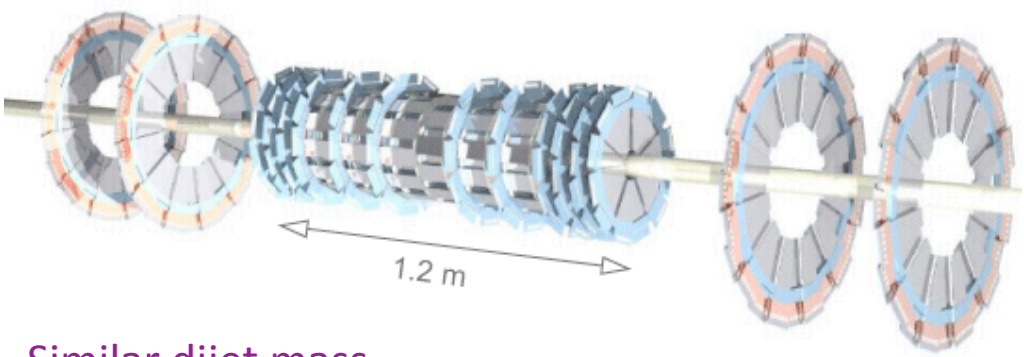
b-tagging with

$|\eta| < \sim 2$

Jets to

$|\eta| < 3$

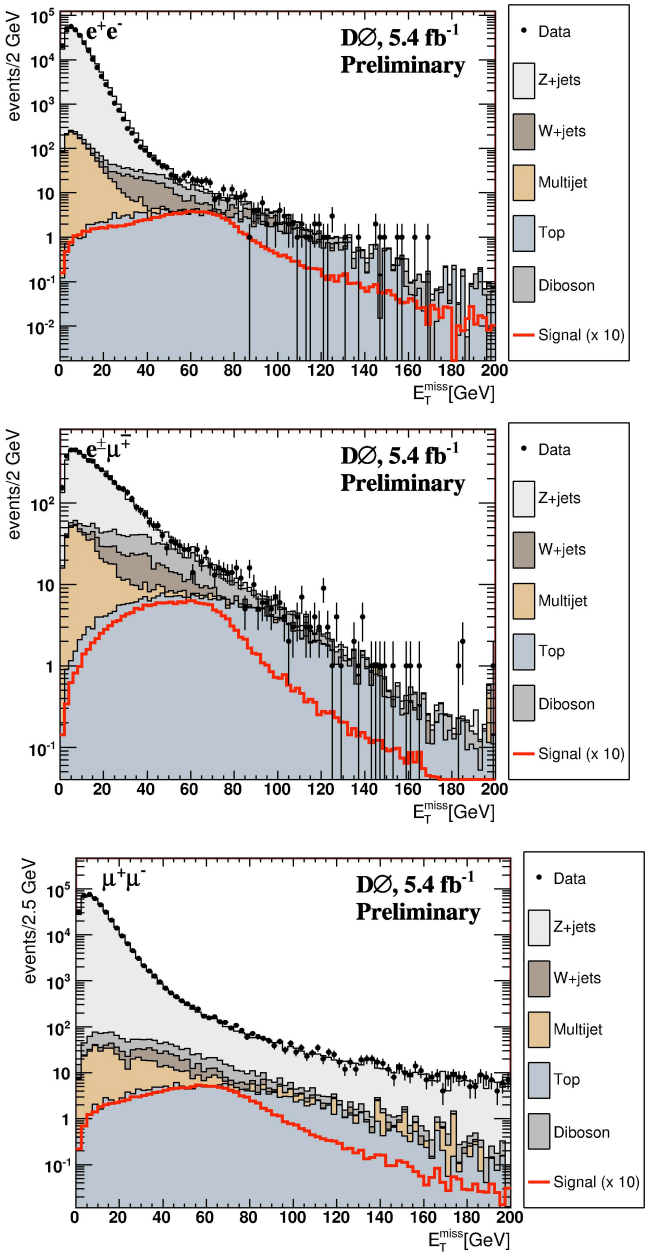


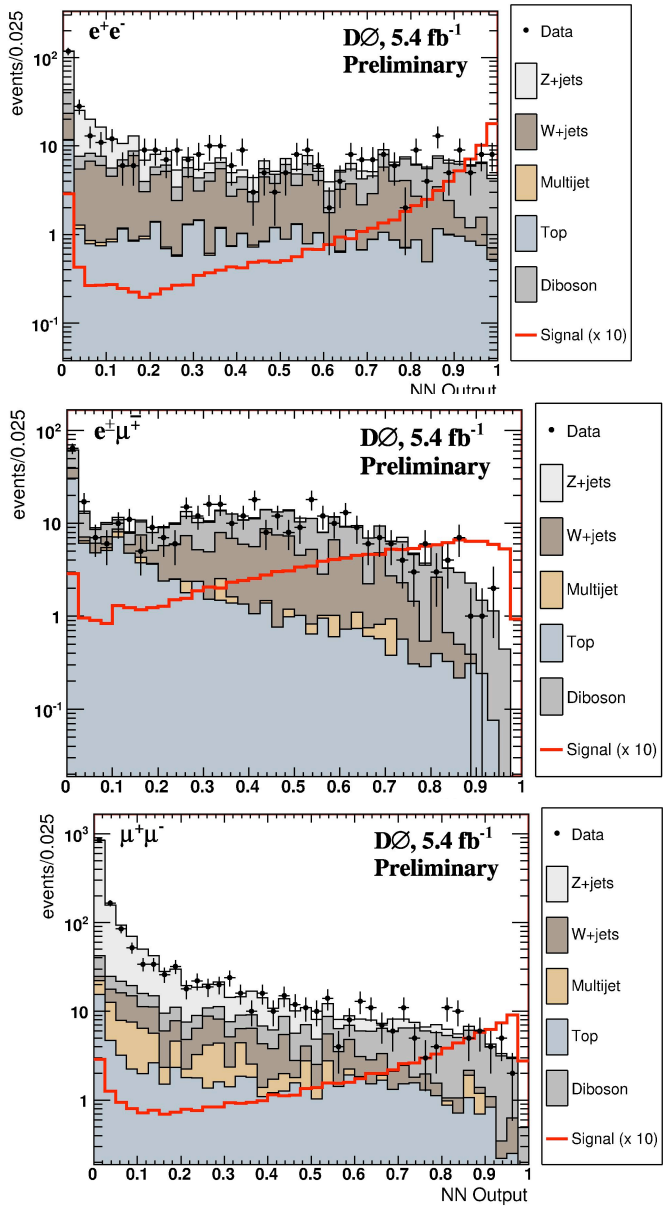


Similar dijet mass resolution to CDF

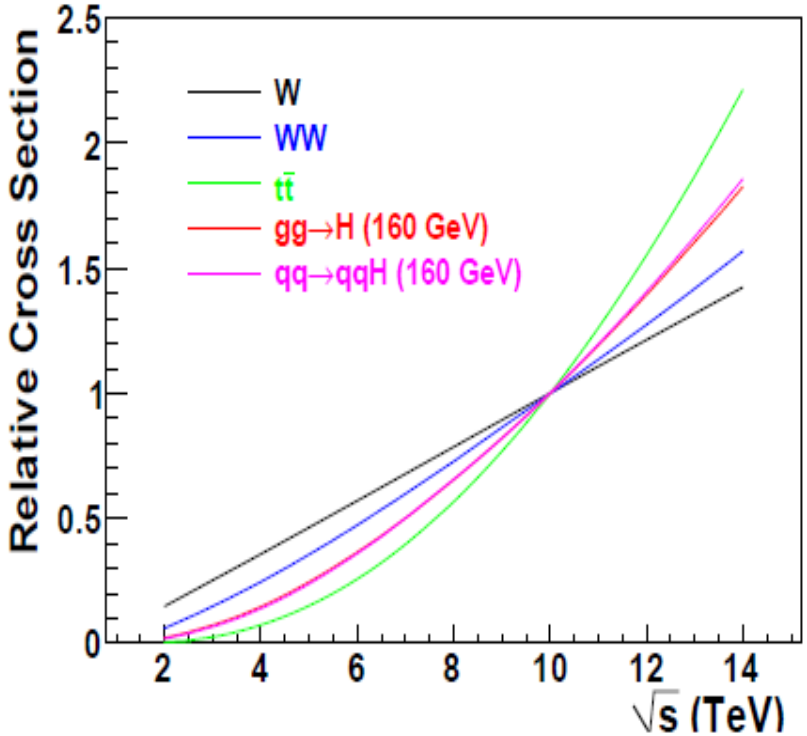
New Innermost Silicon Layer added between Run IIa and Run IIb

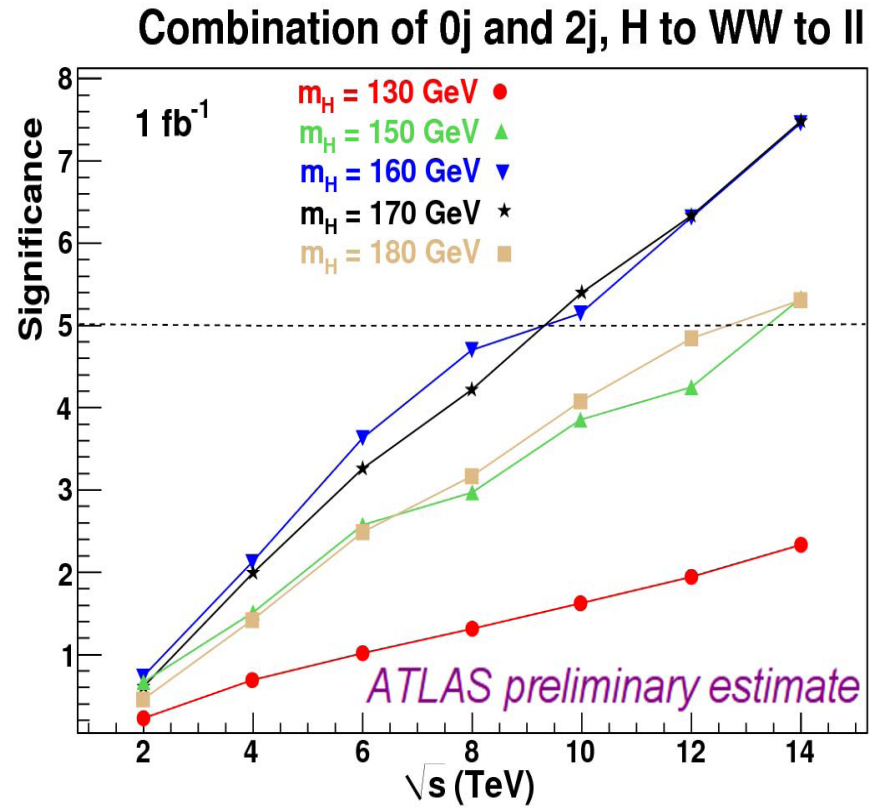
D0's Preliminary Results for HCP09 – MET and Discriminant Plots





A Slide Peter Jenni Showed at Moriond EW 7 March 2010



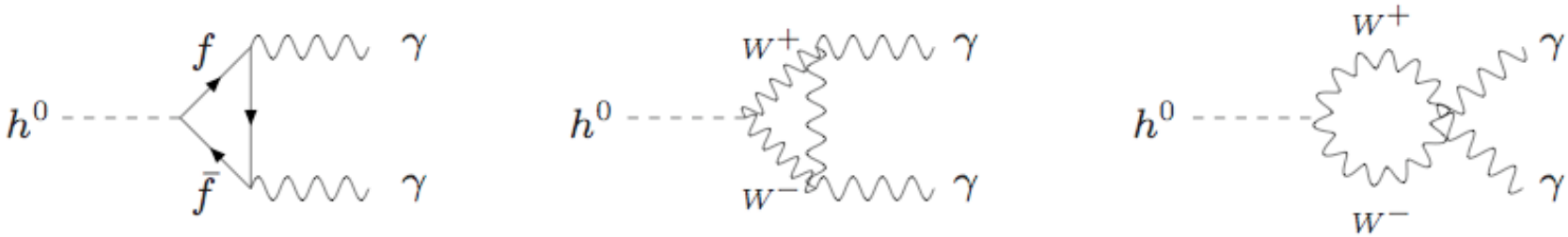


One can expect for the end of 2011 that ATLAS and CMS can exclude each the mass range 145 – 180 GeV, and that combined they could reach a 4.5 σ signal at a mass of 160 GeV

Moriond EW, 7-March-2010
Peter Jenni (CERN)

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

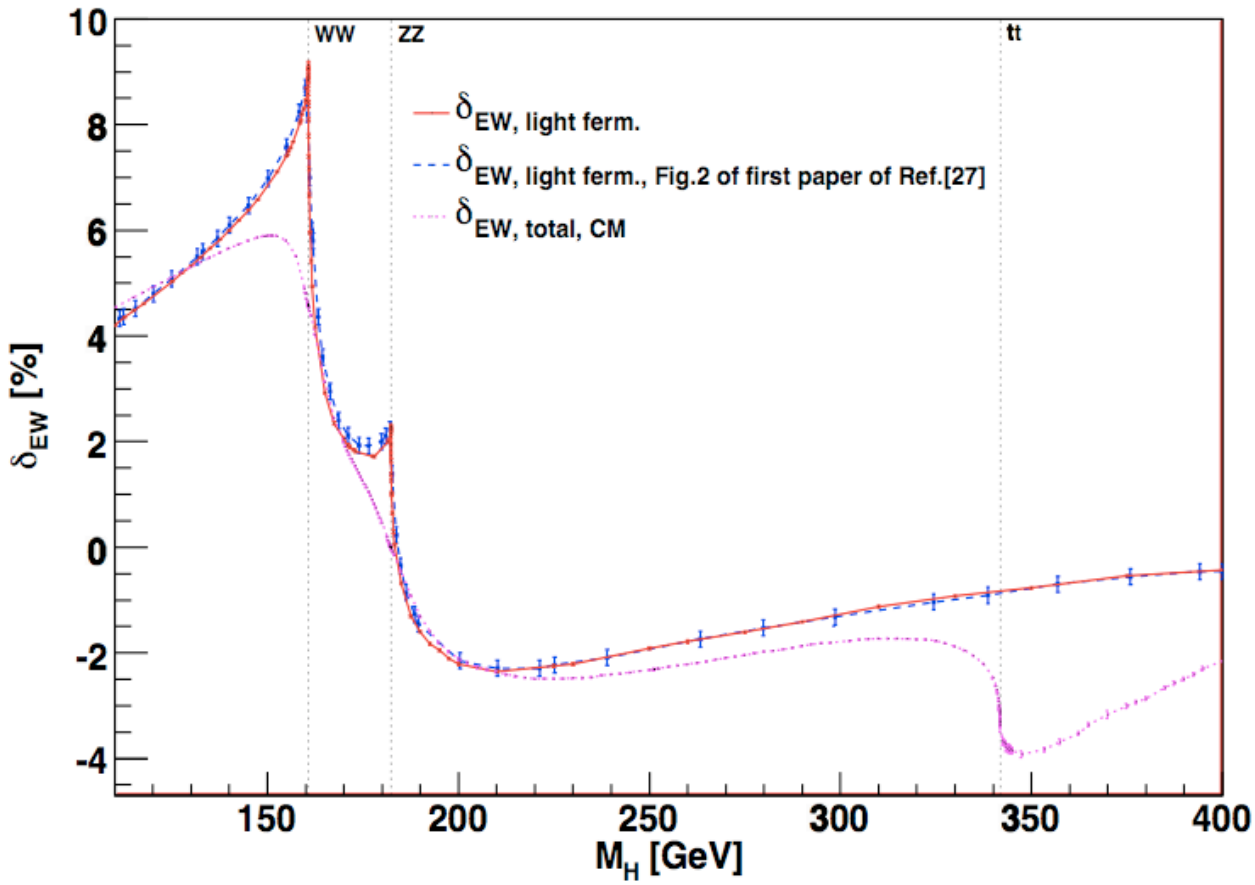
$$N_\gamma = \sum_i N_{ci} e_i^2 F_j(x_i) \,, \qquad x_i \equiv \frac{m_i^2}{m_h^2} \,.$$

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 $x \gg 1$,

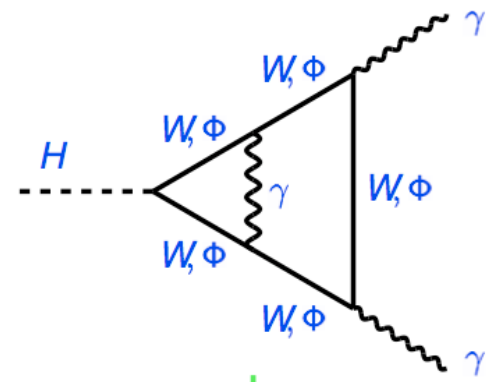
$$F_j(x) \longrightarrow \begin{cases} 1/4 \,, & j = 0 \,, \\ 1 \,, & j = 1/2 \,, \\ -21/4 \,, & j = 1 \,. \end{cases}$$

H. Haber, HCPSS 2008

Comparing H→γγ with gg→H coupling shifts

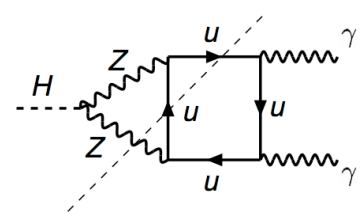


Passarino

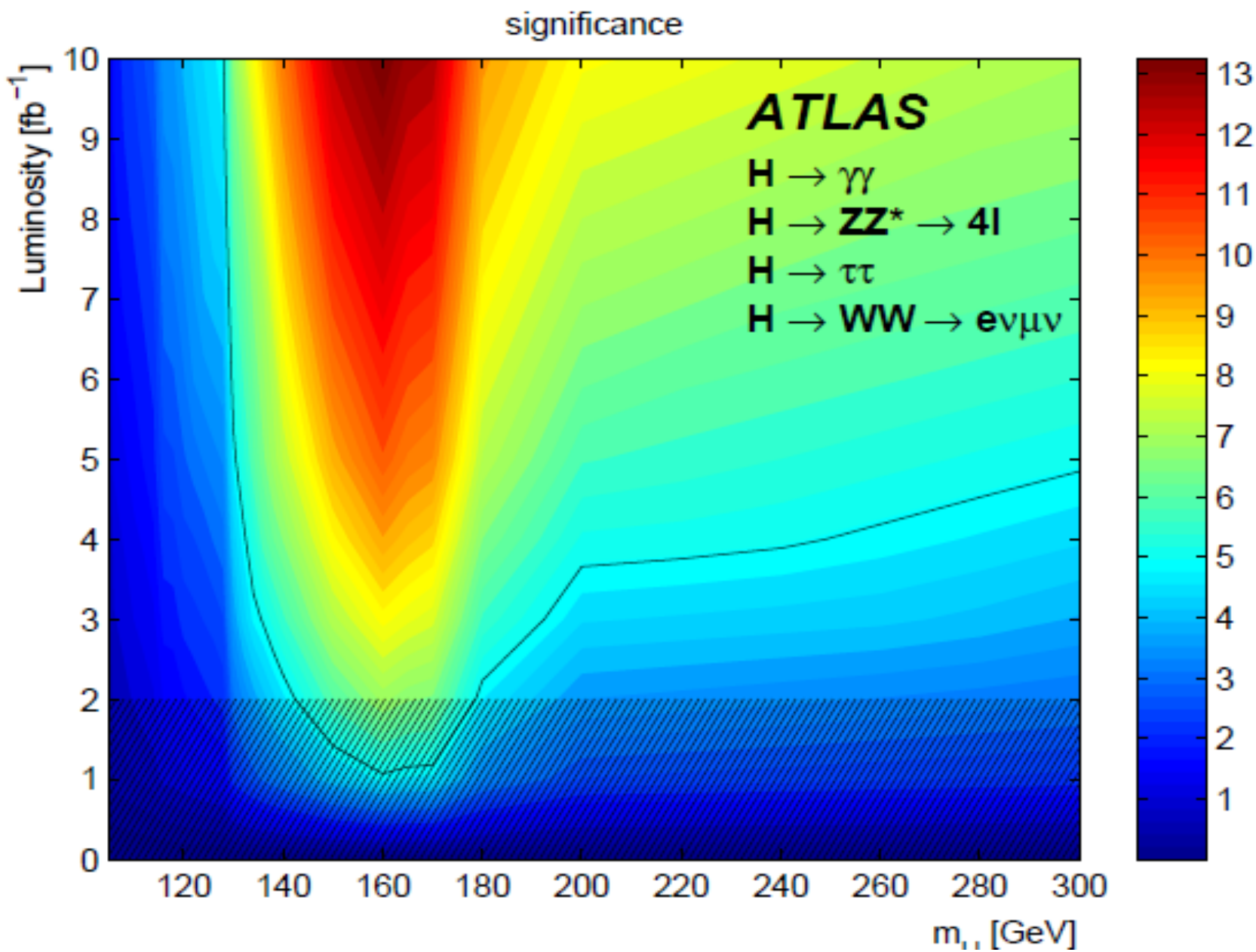


Coulomb singularity not present in ggH coupling

Moderated by Γ_W and Γ_Z



Passarino, Zurich 2009


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

Comparing Pythia Differential Distributions to NLO and Resummed Predictions

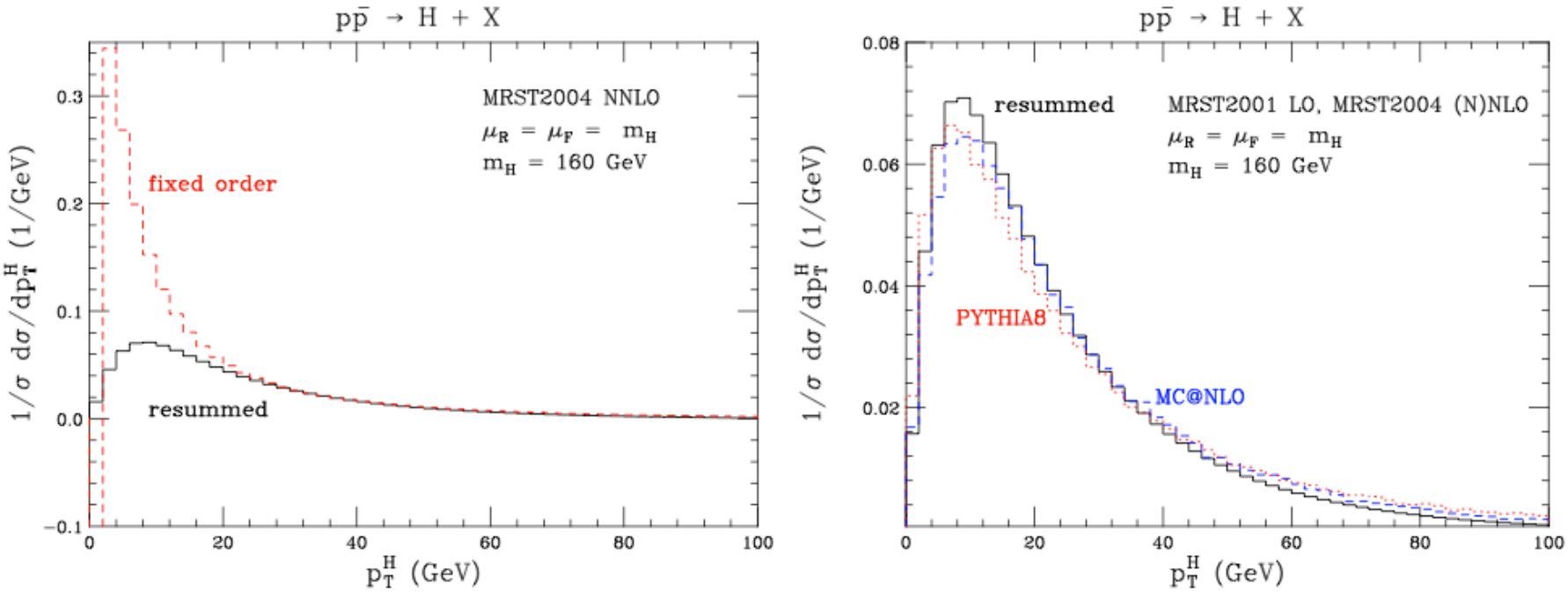


Figure 1: On the left figure, we show the normalized transverse momentum distributions for $m_H = 160\,\text{GeV}$ and $\mu = \mu_R = \mu_F = m_H$ using NNLO fixed-order perturbation theory and the resummed calculation of Ref. [56]. On the right figure, the same distribution is shown for MC@NLO, PYTHIA8,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

Anastasiou, Dissertori, Grazzini, Stockli, and Webber 2009