Instituto de Fìsica Corpuscular, Valencia
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Status and Prospects of Higgs Searches at the Tevatron

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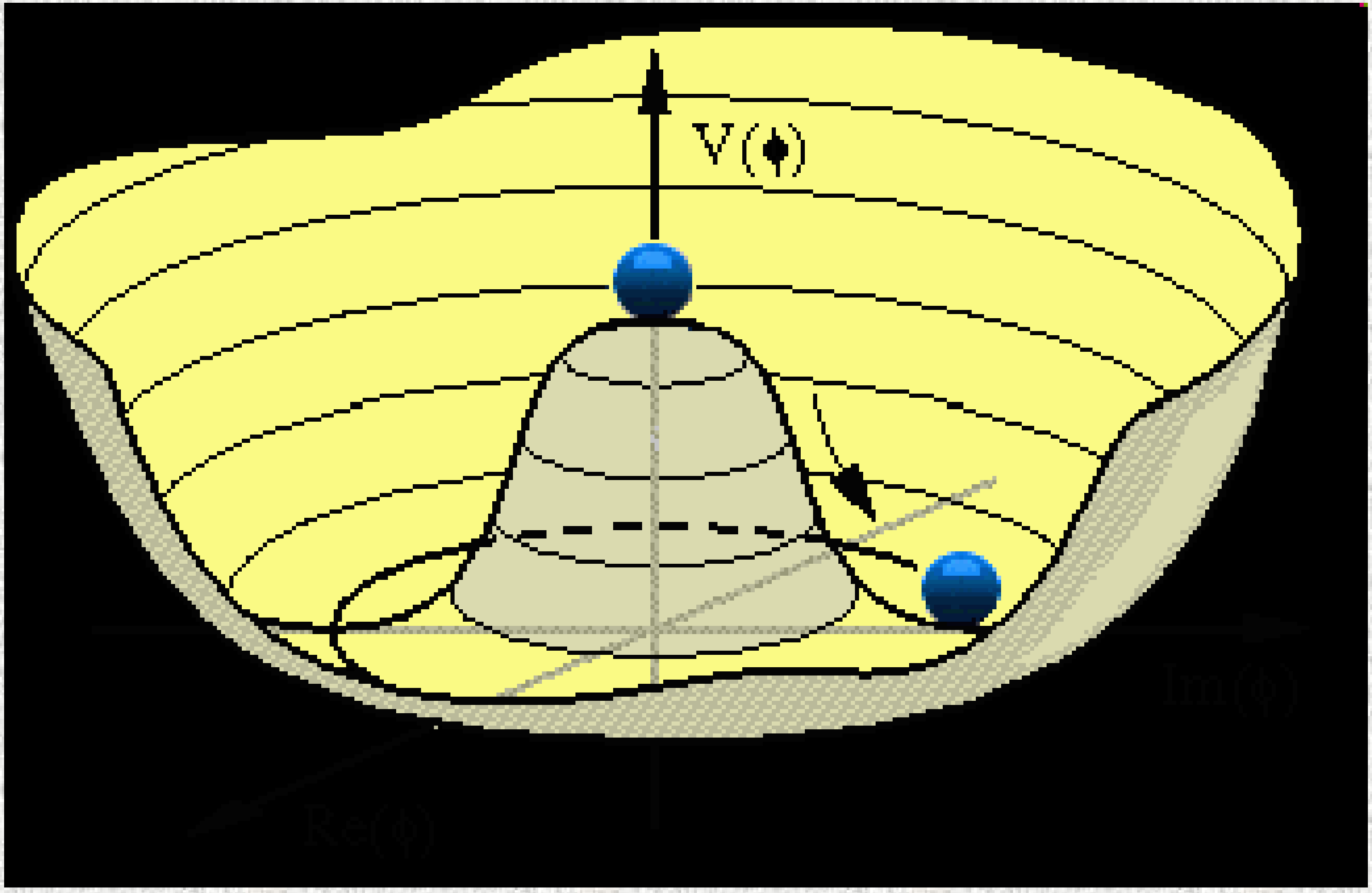
Contents

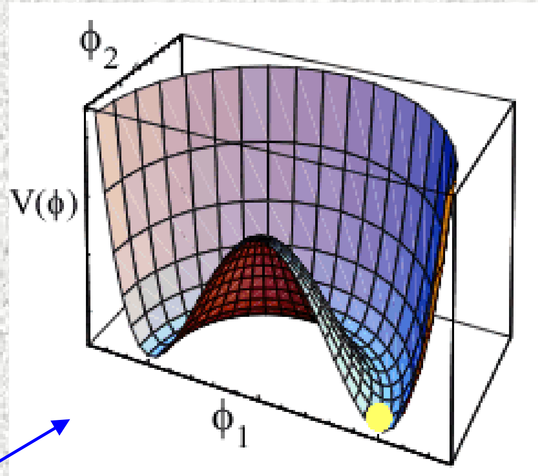
NB: when possible, direct hyperlinks to the relevant documentation are embedded

Higgs Boson Physics



The need for H in the standard model

- In the standard model, mass terms for vector bosons break local gauge invariance
- A theory with massless vectors produces divergent terms
- With spontaneous symmetry breaking, the Lagrangian stays invariant, and mass terms are provided easily



- Start with simple Lagrangian density of massless fermions:

$$L = \overline{\psi_L}\gamma^\mu[i\partial_\mu - gI\cdot W_\mu - \frac{g'}{2}YB_\mu]\psi_L + \overline{\psi_R}\gamma^\mu[i\partial_\mu - \frac{g'}{2}YB_\mu]\psi_R + \ldots$$

- Introducing a complex scalar doublet yields the terms

$$(D_\mu\phi)^\dagger(D^\mu\phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

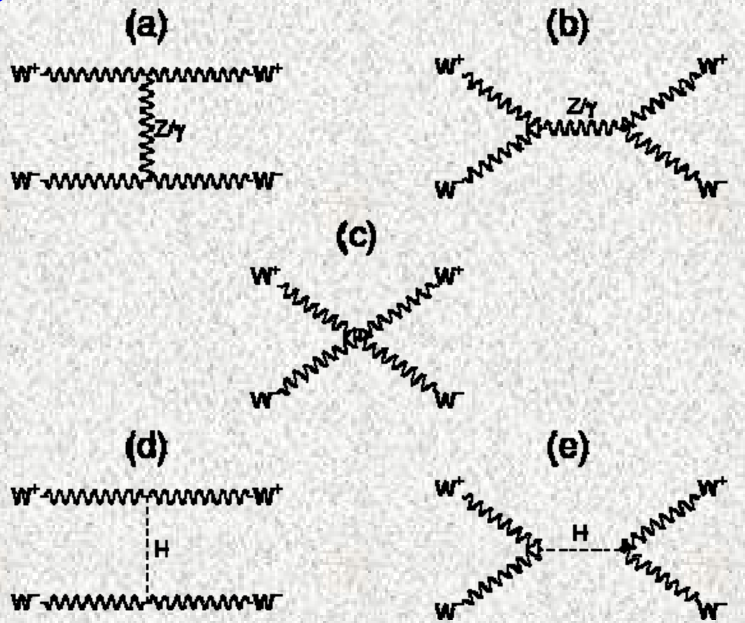
with the covariant derivative

$$D_\mu = [i\partial_\mu - gI\cdot W_\mu - (g'/2)YB_\mu]$$

By choosing $\mu^2<0$, $\lambda>0$ yields a particular form of the scalar field, with a circle of minima in field coordinates
→ a choice of the vacuum

$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

hides the symmetry.

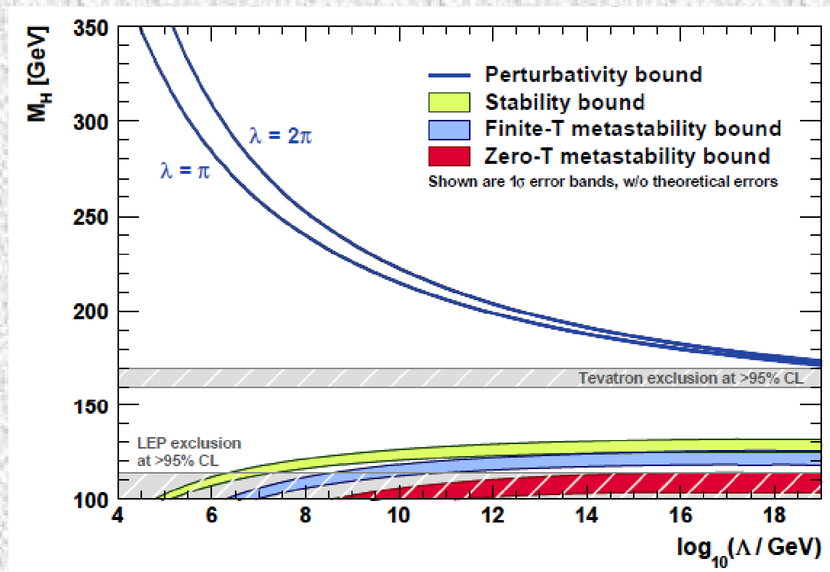


- Three of the four degrees of freedom get absorbed by mass terms for the W triplet, the fourth remains as a massive scalar H

- H also heals remaining divergences (e.g. WW scattering)

What We Know About H

- H protects the divergence of boson-scattering processes without breaking gauge-invariance – it is the saviour of the whole construct
- It is neutral, and its couplings to fermions and bosons are proportional to their masses → *production and decay modes are written on the stone* - but its own **mass is a free parameter**, driven by λ
- λ is running with the scale Λ, and receives corrections which may make it negative at high energy: potential becomes unbounded from below → implications for new physics if the Higgs mass is found to be lower than 135 GeV
- For M_H>1.8 TeV WW scattering violates unitarity at high energy → not a strong constraint to the theory, but a preference
- Very large Higgs masses however make the higgs “strongly coupled” and the resulting theory further loses some of its appeal (quartic H coupling not perturbatively calculable)
- Recently the matter has been studied in detail by some colleagues in Padova (G.F.Giudice, A.Riotto *et al.*, *The probable fate of the Standard Model*, hep-ph/0906.0954)



$$
\begin{aligned}
L = & \frac{1}{2}(\partial_\mu H)^2 - \lambda v^2 H^2 + \\
& -\frac{1}{4}(\partial_\mu W_\nu^{\,1} - \partial_\nu W_\mu^{\,1})(\partial^\mu W^{1\nu} - \partial^\nu W^{1\mu}) + \frac{g^2 v^2}{8}(W_\mu^{\,1})^2 + \\
& -\frac{1}{4}(\partial_\mu W_\nu^{\,2} - \partial_\nu W_\mu^{\,2})(\partial^\mu W^{2\nu} - \partial^\nu W^{2\mu}) + \frac{g^2 v^2}{8}(W_\mu^{\,2})^2 + \\
& -\frac{1}{4}(\partial_\mu Z_\nu - \partial_\nu Z_\mu)(\partial^\mu Z^\nu - \partial^\nu Z^\mu) + \frac{v^2}{8}(g^2 + g'^2) Z_\mu Z^\mu + \\
& -\frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)(\partial^\mu A^\nu - \partial^\nu A^\mu) + \ldots
\end{aligned}
$$

H: still-born, and already a problem child

- The Higgs potential is the source of most of our troubles in the standard model!

$$V_H = V_0 - \mu^2 \phi^+ \phi + \lambda(\phi^+ \phi)^2 + [\overline{\psi}_L Y \psi_R \phi + h.c.]$$

(1) (2) (3) (4)

1 - The constant term is vacuum energy: off by orders of magnitude from what one would need

2 - The second term is the source of the fine-tuning problem: huge loop corrections canceling out like magic

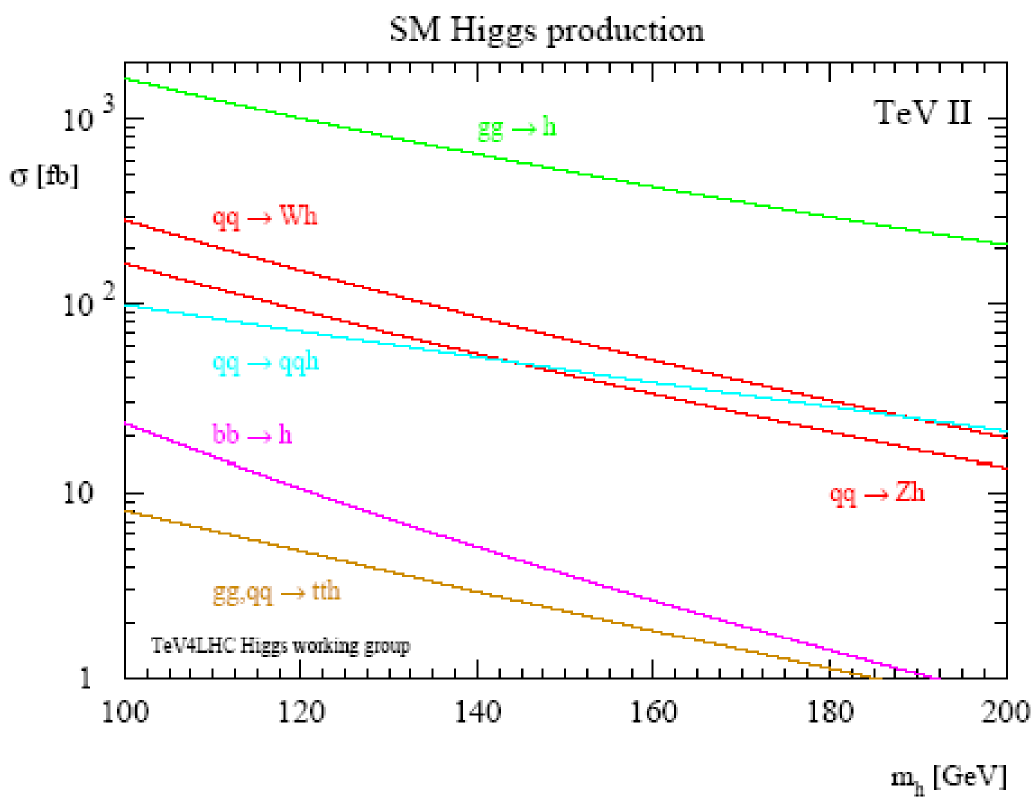
3 - The third term may produce instability in the potential, depending on the value of λ and the energy scale for which the formula holds as is

4 - Yukawa couplings to fermions are widely different; top-quark Yukawa is 1.0

The Higgs boson at the Tevatron

In proton-antiproton collisions, Higgs bosons are produced primarily by gluon-gluon fusion (green), H-strahlung from a boson (red) or quark line (brown), and vector-boson fusion (cyan)

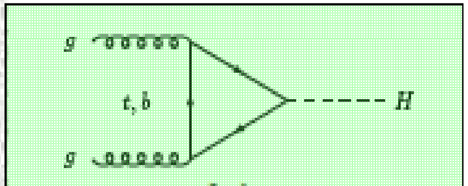
The cross-section depends on the mass due to parton distribution functions in the proton; between 100 and 200 GeV it decreases by one order of magnitude.



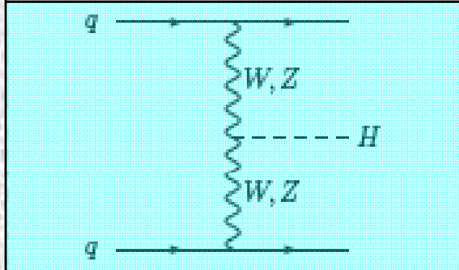
The total cross-section is of the order of 1 pb at low mass

10 events / (day exp)

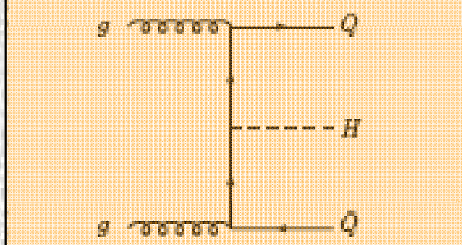
Is that enough for detection ?
We will see below.



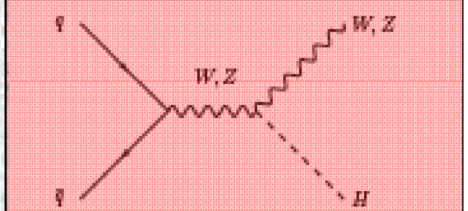
gg fusion



vector boson fusion



associated production with $Q\bar{Q}$



associated production with W, Z

Decay modes and final states

- Useful to ideally separate low-mass and high-mass ranges – boundary: when B(WW)=B(bb) ~ 135 GeV

- Direct production can hardly be exploited at low mass despite the higher cross section – bb, ττ decay signatures are not distinctive enough by themselves

- The most sensitive signatures are:

$q\bar{q}' \rightarrow WH \rightarrow l\nu_l b\bar{b}$ (low mass)

$q\bar{q} \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}, l^+l^-b\bar{b}$ (low mass)

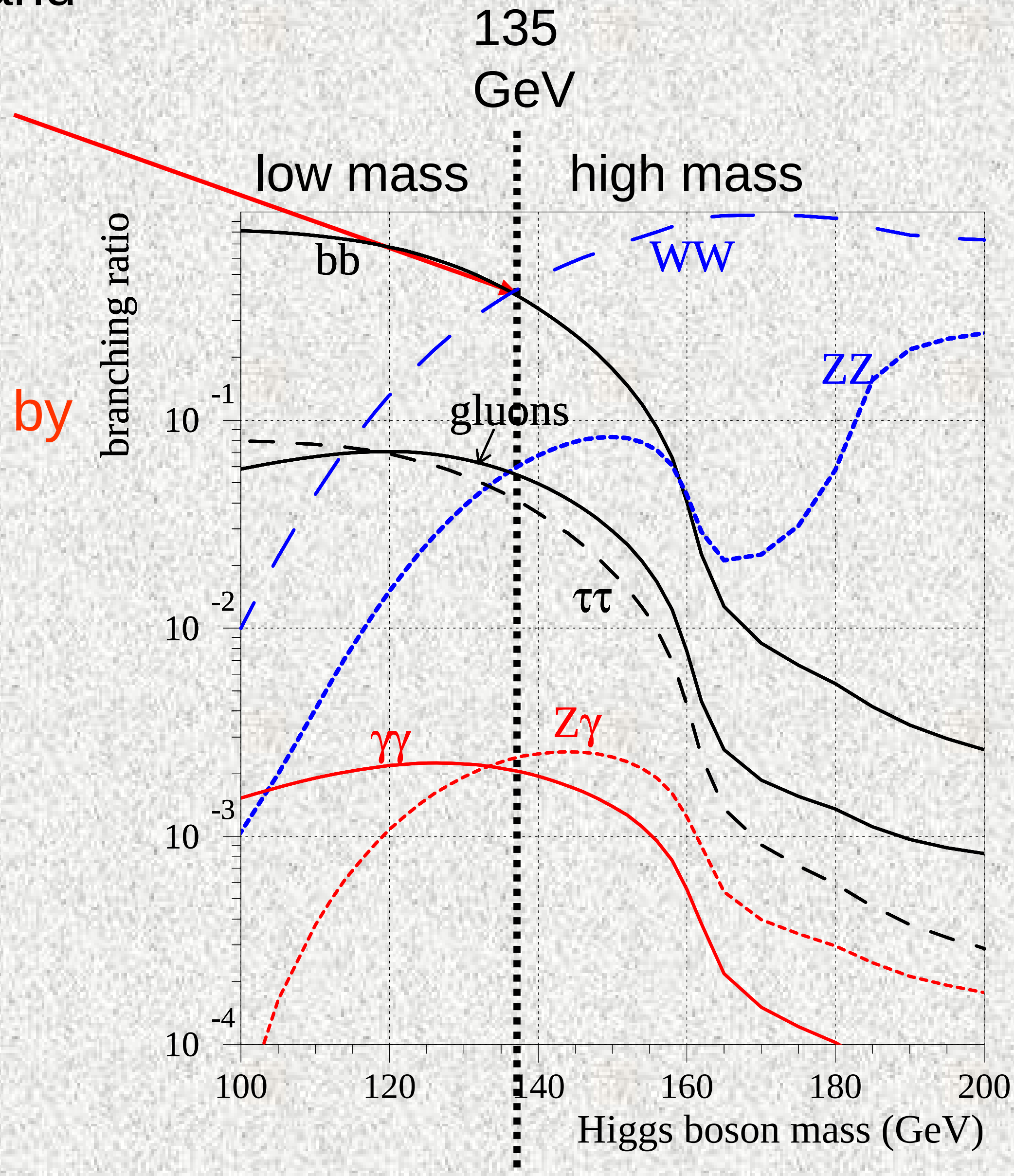
$gg \rightarrow H \rightarrow W^+W^-$ (high mass)

- Other channes can contribute only marginally to a combined result:

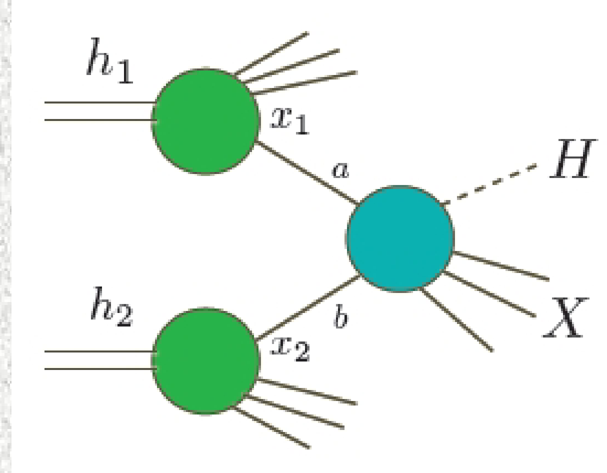
$q\bar{q}' \rightarrow WH \rightarrow WWW$

$q\bar{q} \rightarrow t\bar{t}H$

$q\bar{q} \rightarrow (q\bar{q}WW) \rightarrow q\bar{q}H$

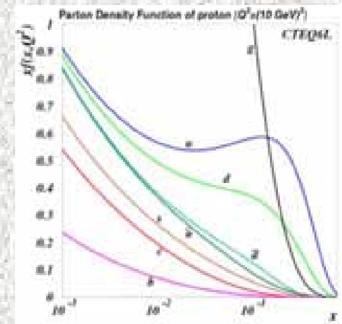


Theoretical calculation of the cross section



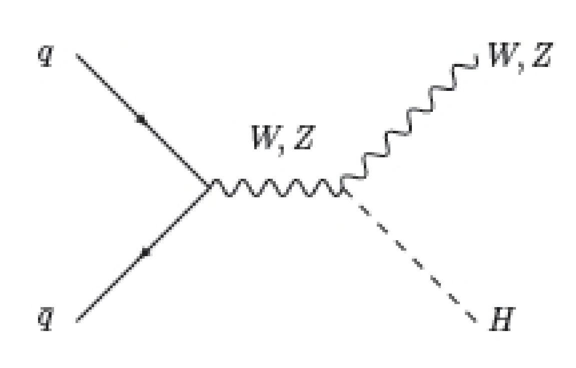
- The technology is “simple”: the basis is the QCD factorization integral,

$$\sigma(p_1, p_2; M_H) = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1, \mu_F^2)\, f_{h_2,b}(x_2, \mu_F^2)\, \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \alpha_s(\mu_R^2); \mu_F^2; M_H)$$



- Sound predictions for the cross section depend both on the knowledge of the partonic hard subprocess AND the **PDF** in their relevant range.

  Direct **gg→H production**: lots of progress in the last 20 years
  - NLO QCD increased xs by 80-100% (A. Djouadi, M. Spira, and P. Zerwas, Phys. Lett. B264 (440) 1991)
  - NNLO computed in large-M_{top} limit in the last decade (several authors) → further increase of 15-20% for M_H<200 GeV
  - soft-gluon resummation at NNLL yield additional 6% (S. Catani et al., hep-ph/0306211)
  - NLO EW effects also known (up to 5% increase) (U. Aglietti et al., hep-ph/0404071; G. Degrassi and F. Maltoni, hep-ph/0407249



WH,ZH production: most promising search channel at low M_H (leptons provide triggering; high-BR H→bb decay can be used). QCD corrections evaluated from DY

→ 30% effects at NLO (T. Han and S. Willenbrock, Phys. Lett. B273, 167 (1990); W. Van Neerven *et al*., Nucl. Phys. B359, 343 (1991))

→ At NNLO for ZH additional diagrams from a gg initial state must be considered (more important for the LHC)

Full EW corrections decrease xs by 5-10% (M.L. Ciccolini *et al.*, *hep-ph/0306234*)

ttH production: calculated as far back as in 1984 (Z. Kunszt)

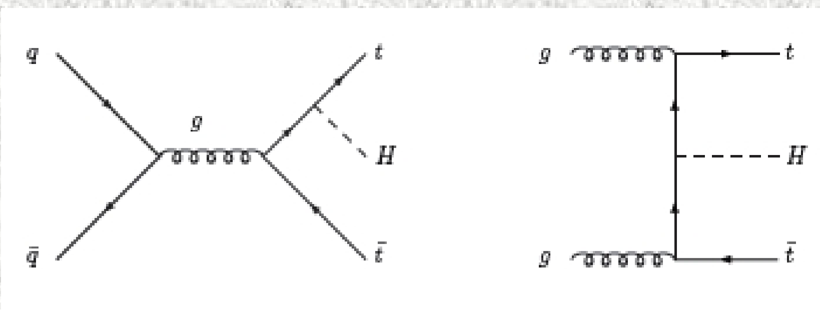
→ NLO increase xs by 20% (W. Beenakker *et al.*, *hep-ph/0211352)*

→ Relevant for measuring Yukawa coupling, considered promising, BUT:

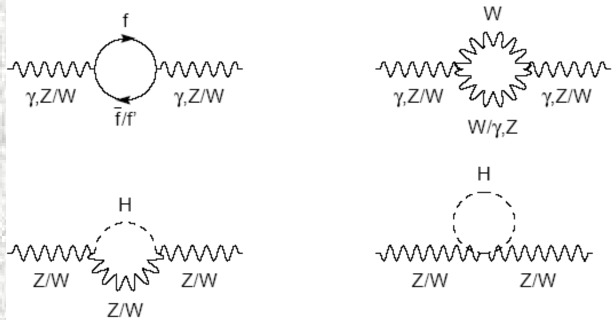
not possible at the Tevatron (too low xs); considered feasible at LHC, but recently abandoned.

Problem is QCD ttbb background,

large AND not well known.



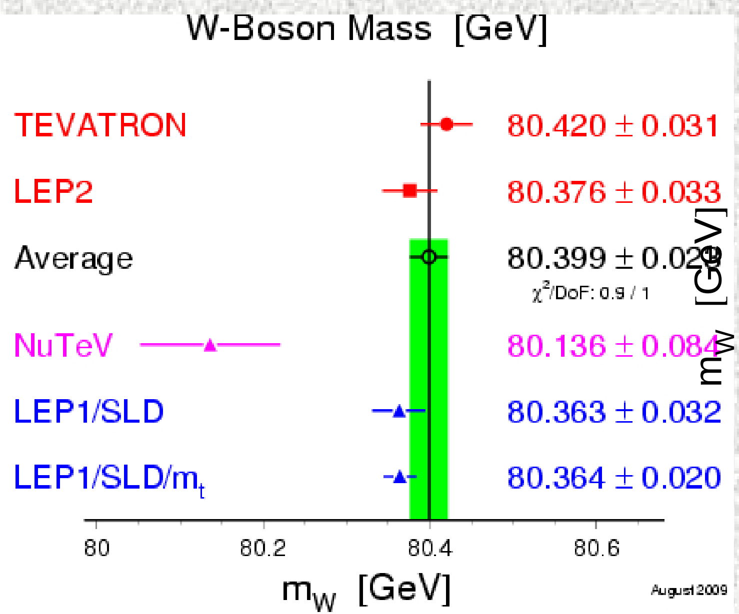
EW information on M_H

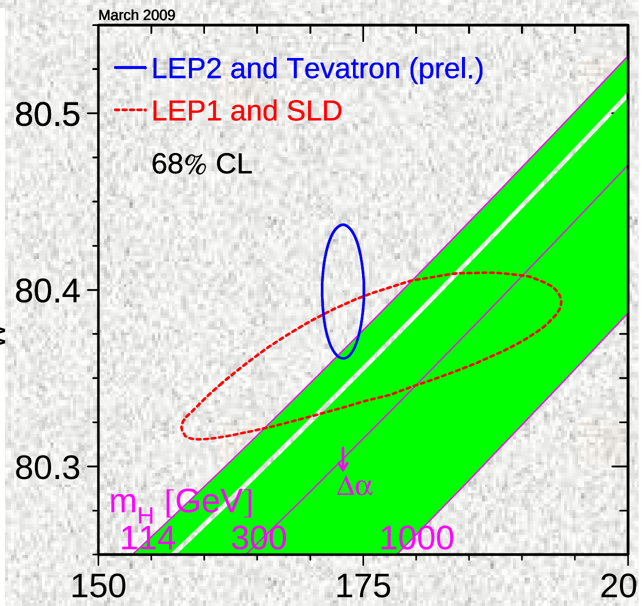


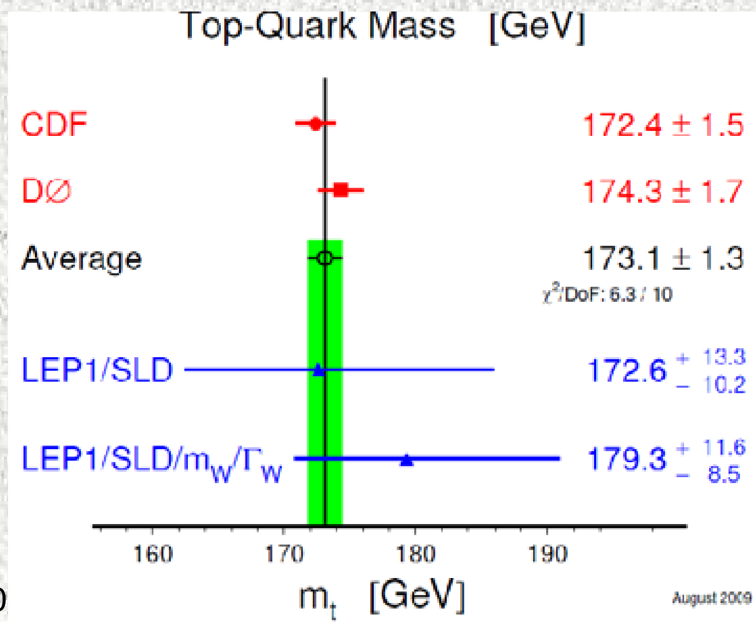
We obtain information on the Higgs boson mass by studying radiative corrections to electroweak processes, comparing results with theory, whose predictions weakly depend on M_H: for instance,

$$\Delta\rho_{se} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots\right]$$

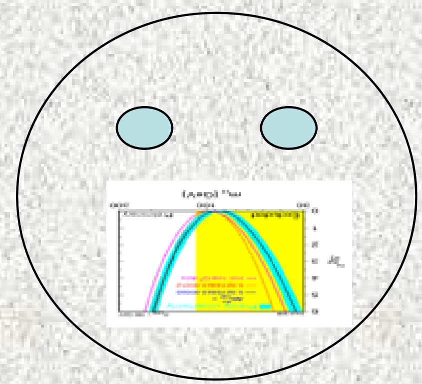
- LEP and SLC provide much of the input on electroweak parameters;
- LEP II and the Tevatron yield the critical information on the W boson mass;
- the Tevatron gives crucial input on the top quark mass;
- *NuTeV not considered in the fits*







Global Electroweak Fits



- Zfitter has been used by the LEP EWWG for a while
- now challenged by a parallel effort, GFitter
  - more aggressive (include likelihood information from direct Higgs searches, provides p-values...)
  - “standard fit” results agree with ZFitter ones
  - I like their style → screw the Zfitter iconic blue-band plot this time.

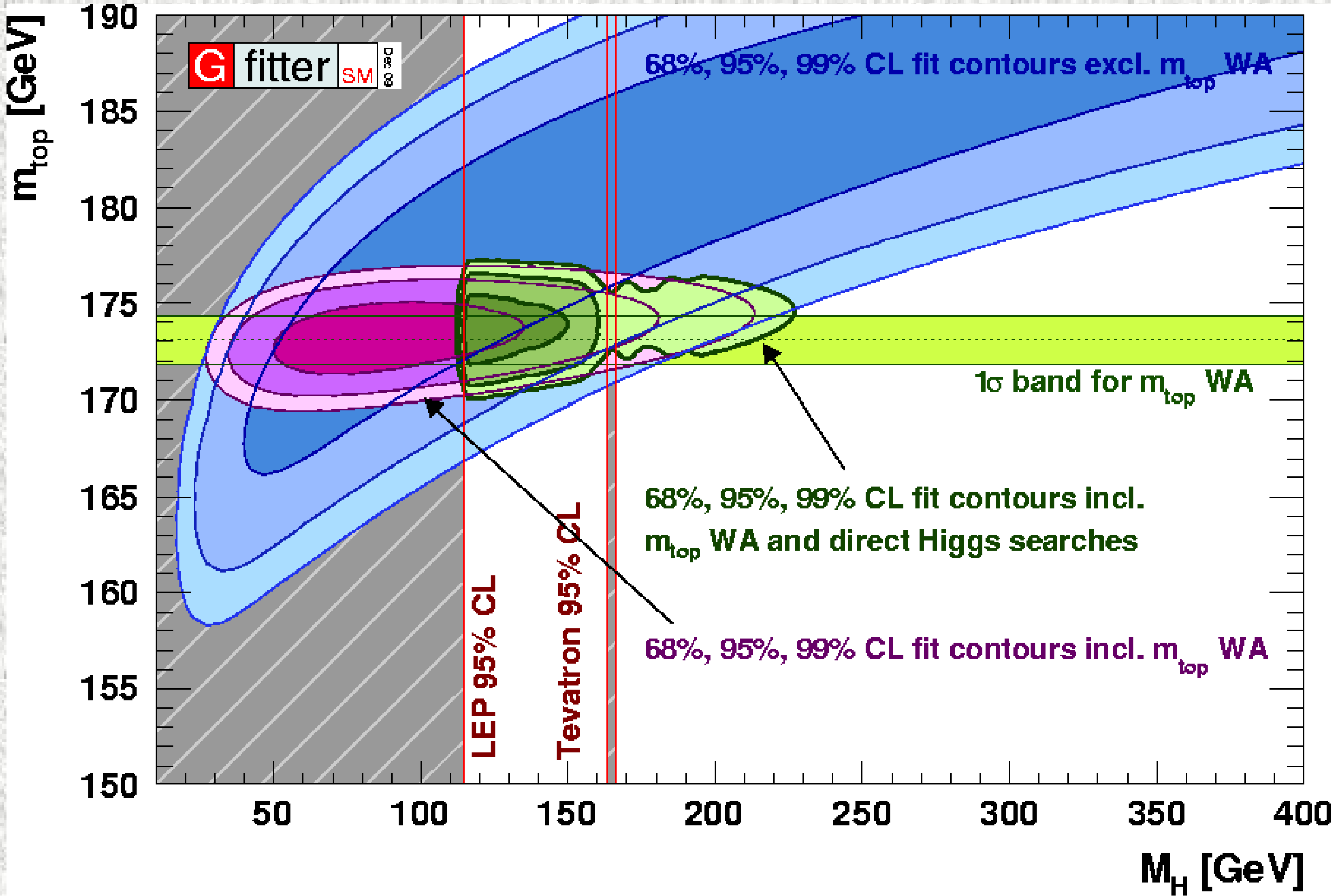
- GFitter free parameters:
  - M_z
  - M_H
  - $\Delta\alpha_{had}(M_Z)$
  - $\alpha_s(M_Z)$
  - M_t (included in some fits)
  - M_c && M_b (running MSbar values)
- Experimental inputs:
  - all EW observables measured at LEP
  - W mass and width measured at Tevatron and LEP II
  - Higgs boson log-likelihood ratio from searches at LEP and Tevatron
- Let us see what results they get with experimental inputs up to December 2009 results

Gfitter results - I

- Results appear to narrow down the allowed M_H range to very low masses –close to the LEP II limit

Note: *top mass too well known by now!*

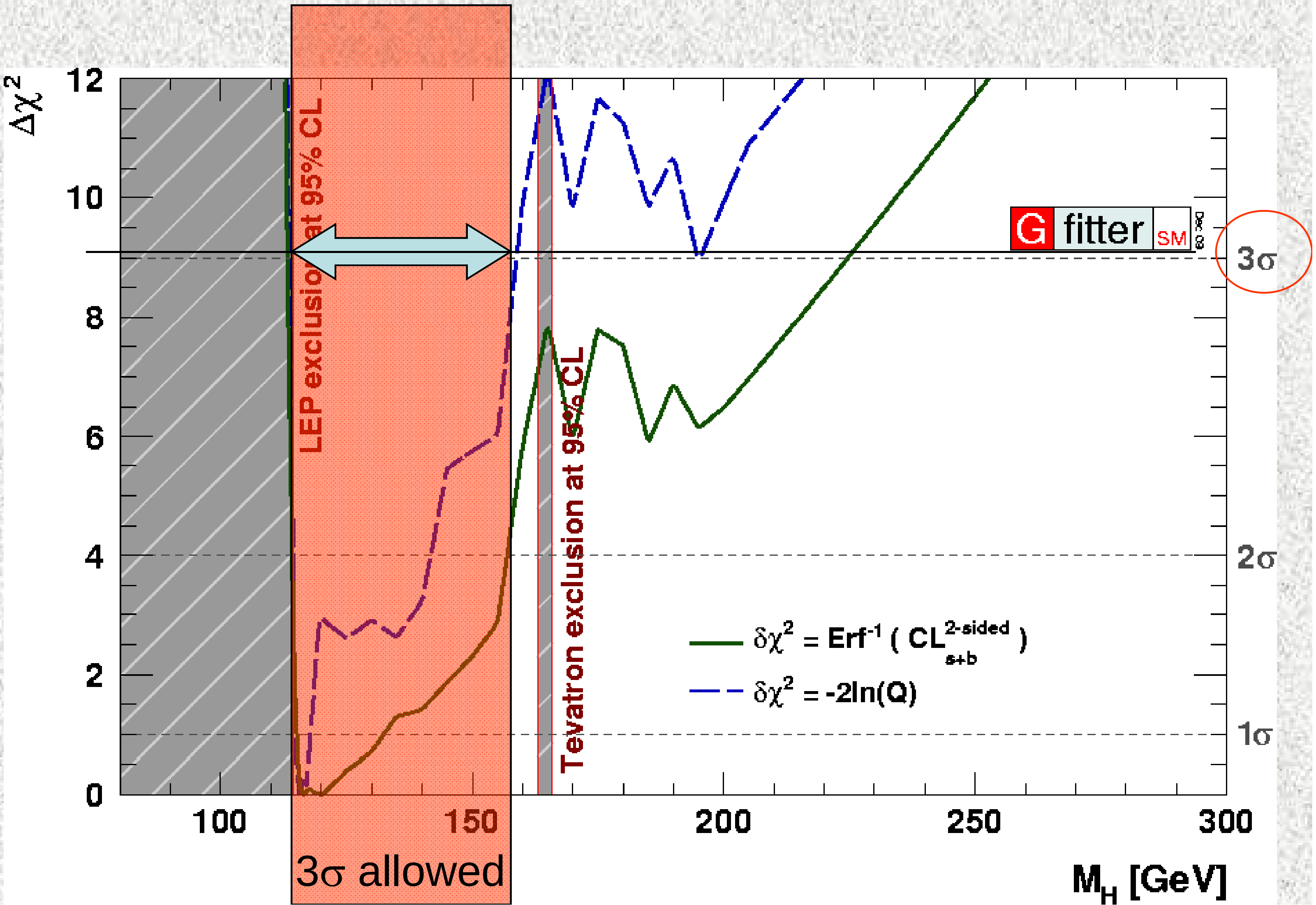
Measured value cuts away nicely the high-mass range, but future advances are not going to provide much improvement in global fits



Gfitter results - II

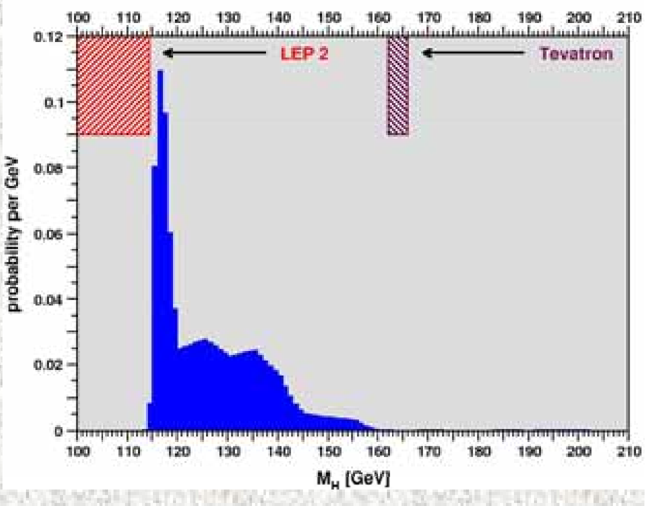
- Maybe a simpler view is given by the $\Delta\chi^2$ vs M_H plots

Once the full log-likelihood information is inserted in the fits (LEP II + March 09 TeV average) the allowed range of Higgs mass values shrinks considerably

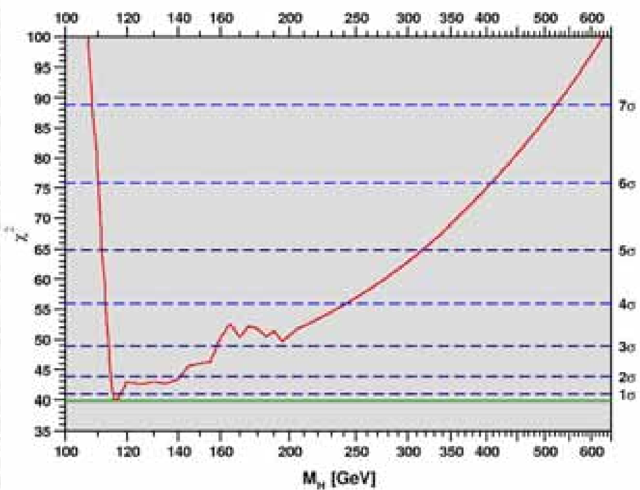


Other fits

- LEPEWWG gives **M_H=87$^{+35}_{-26}$ GeV,** GFitter **M_H=83$^{+30}_{-23}$ GeV**
- Beyond GFitter and the standard LEPEWWG fits, there are other efforts on the market
- One very recent study (M. Passera et al., hep-ph/1001.4528) tries to use the information of muon g-2 (currently sitting at about 3-sigma discrepancy with SM calculations) to evaluate the impact on M_H
  - The two ways to compute hadronic corrections (pion pair production in e+e-, or hadronic tau decay analysis) alternatively considered
  - Recent analysis of isospin-breaking effects (M.Davier, hep-ph/0906.5443) allegedly soften the long-standing disagreement between the two calculations; however, useful to hypothesize that Δa_μ is due to a underestimate of the total hadronic cross section
  - Increasing the hadronic xs has an impact in the EW fits (in particular on $\Delta\alpha$) and leads to sharper upper bounds on M_H:
    - M_H<138 GeV if tau data are used;
    - M_H<135 GeV if ee scattering data are taken as the basis.



- Another recent, independent effort is described in J.Erler, hep-ph/1002.1320
  - add low-energy data, atomic parity violation measurements, deep inelastic neutrino and polarized-electron scattering to the soup
  - The picture does not change that much: the 95% CL bounds are 115.1-148 GeV in this case

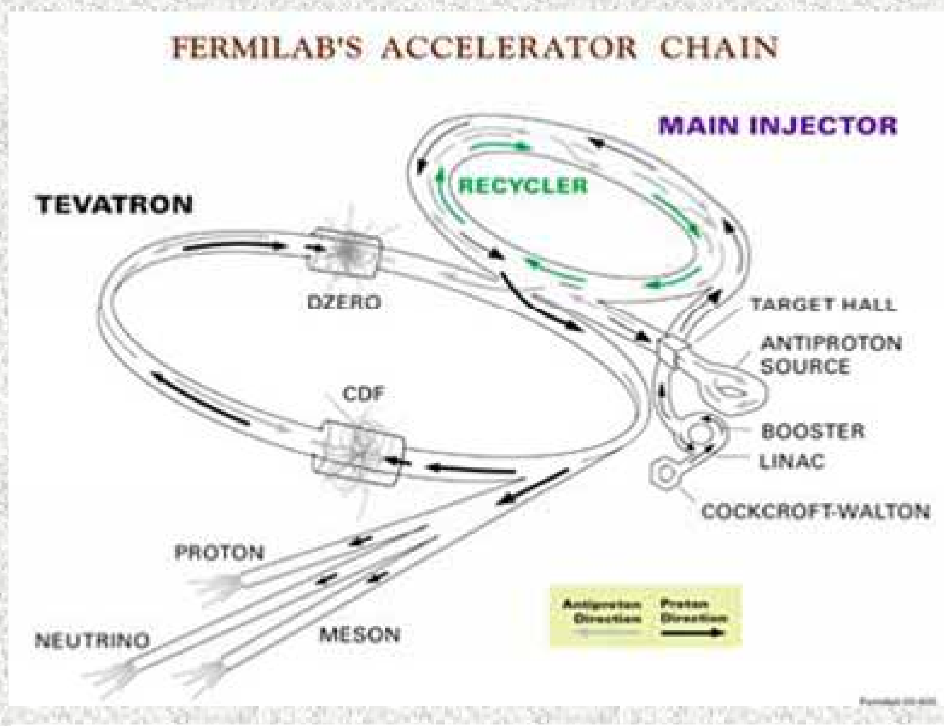


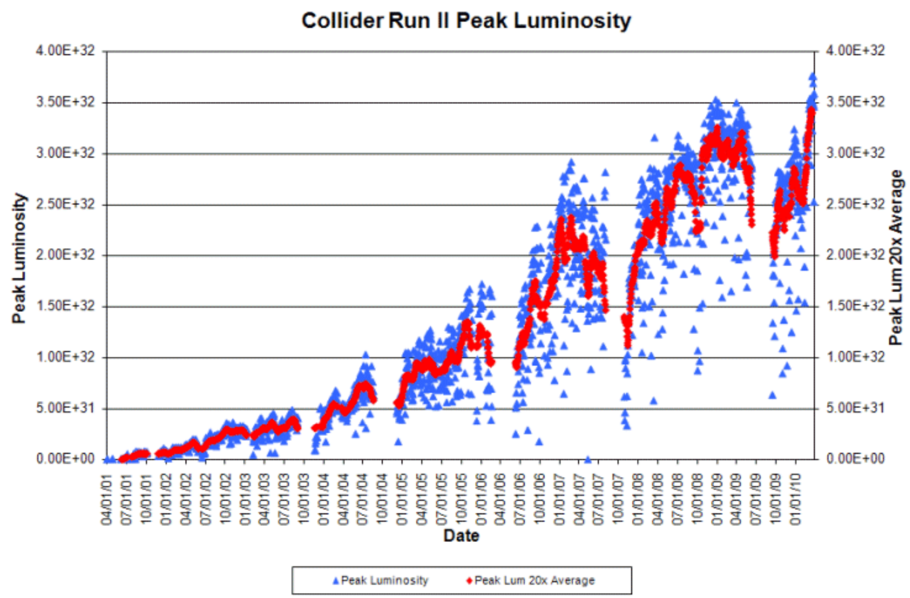
- **All points to a light higgs boson!**

The experimental landscape

The Tevatron collider

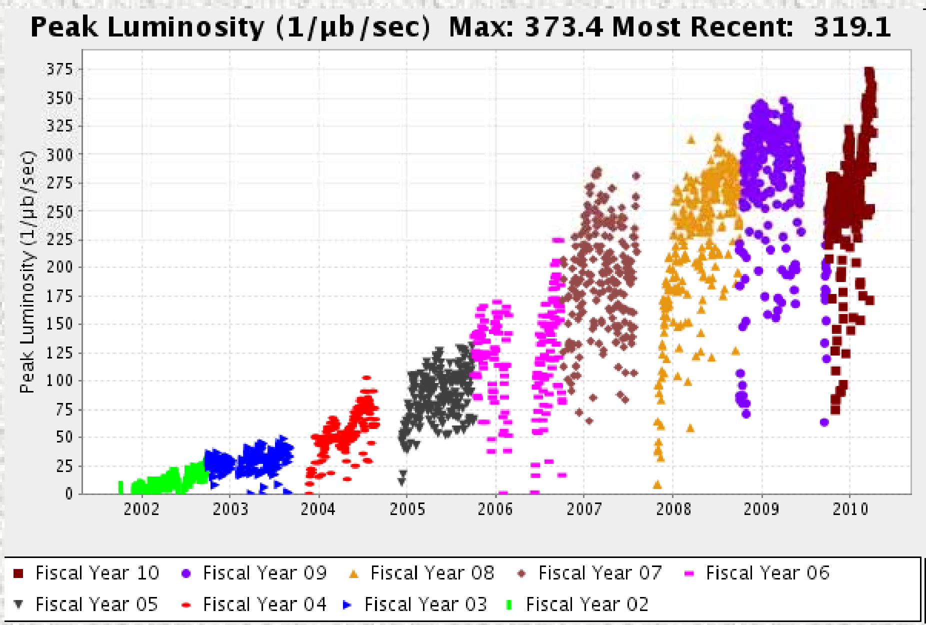
- The Tevatron collides 36 proton and 36 antiproton bunches at a 2.5MHz rate
- CM energy is 1.96 TeV
- Run 1→ Run 2 upgrades boosted capability of the machine to stack, transfer, and recycle antiprotons
- Luminosity in CDF and D0 at start of store peaks at 3E32; fast initial decrease, then slower decay
- Runs typically last 10-15 hours, collect 6/pb, then particles are dumped to set up a new run.

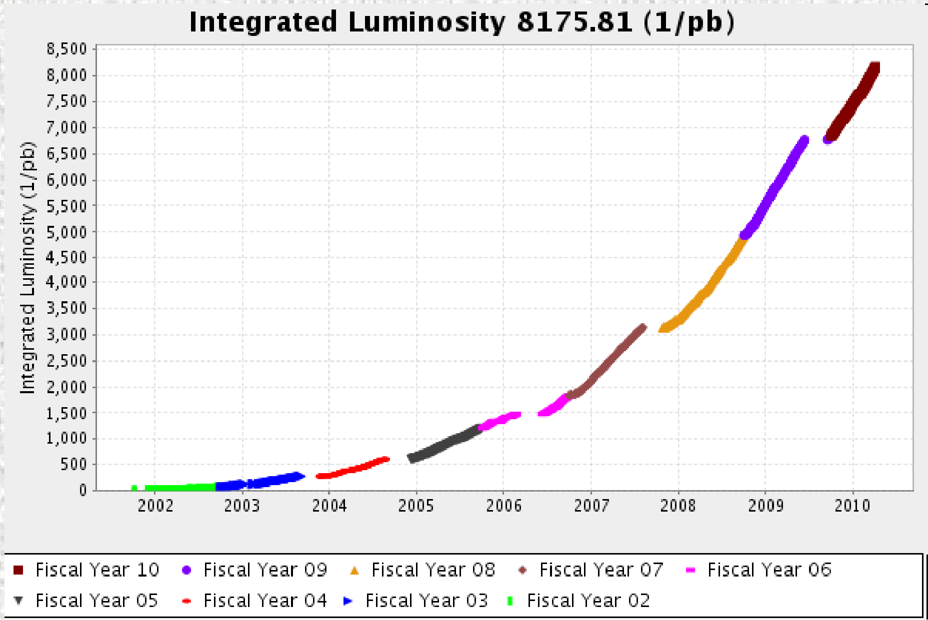




Performances of the Tevatron

- Run II started slow, but took steam after upgrades (pbar stacking, electron cooling)
- Despite upgrades, main hardware is old →after shutdowns, recovery of best tunes is complicated
- In best conditions, Tevatron delivers 70 (/pb*w), 2 /(fb*y) to CDF and DZERO (2.5 possible if no shutdowns)
- Current records:
  - L^{inst}_{max}=3.76E32
  - L_{week}= 73.1/pb
  - L_{tot} (run 2) = 8.2/fb
- **LHC delays have been the most important factor in determining the recent decisions to keep running the machine**
- Now expected to run through 2011
  → 10/fb turned from wild fantasy to very conservative bet!

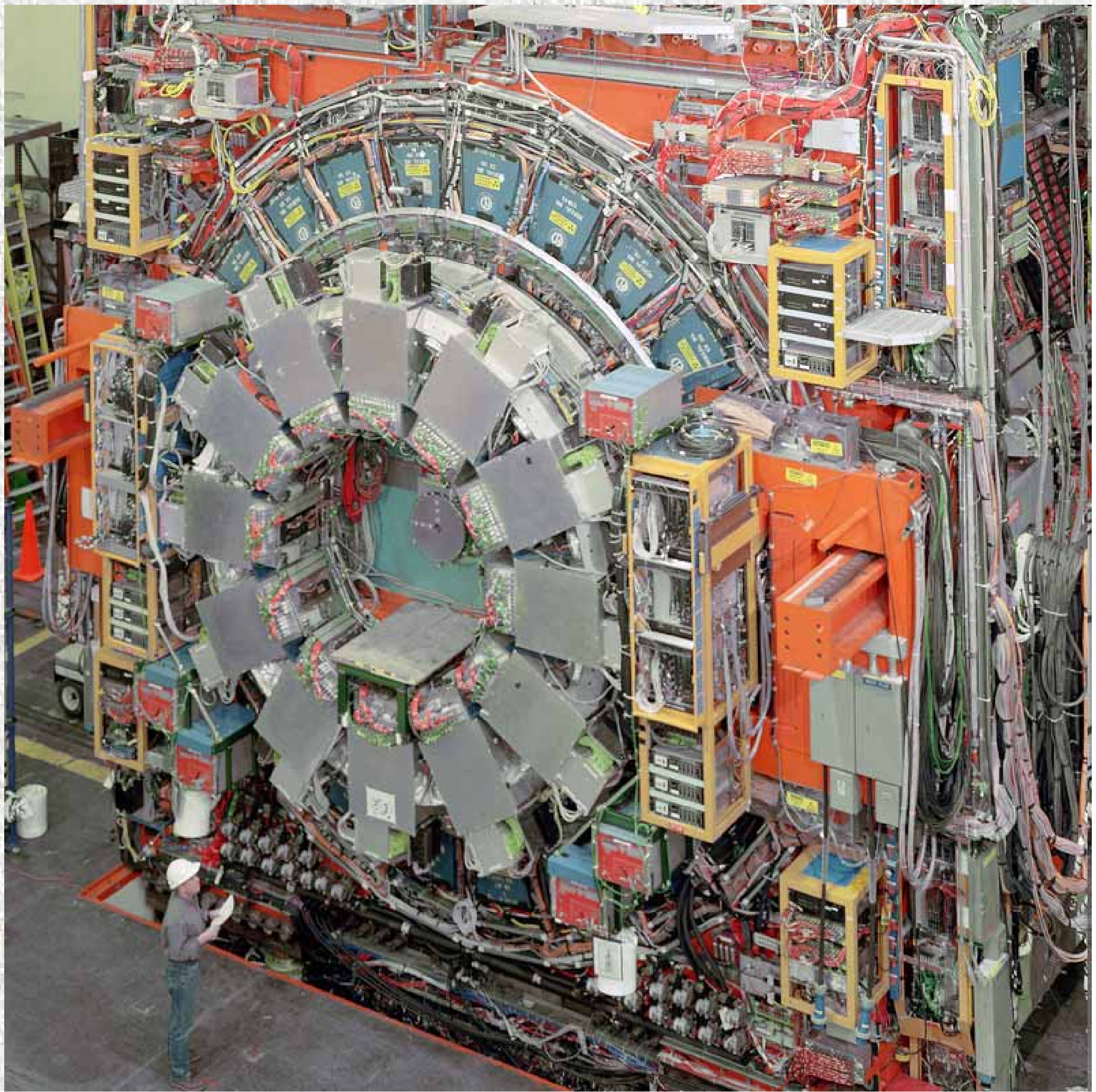




The CDF experiment

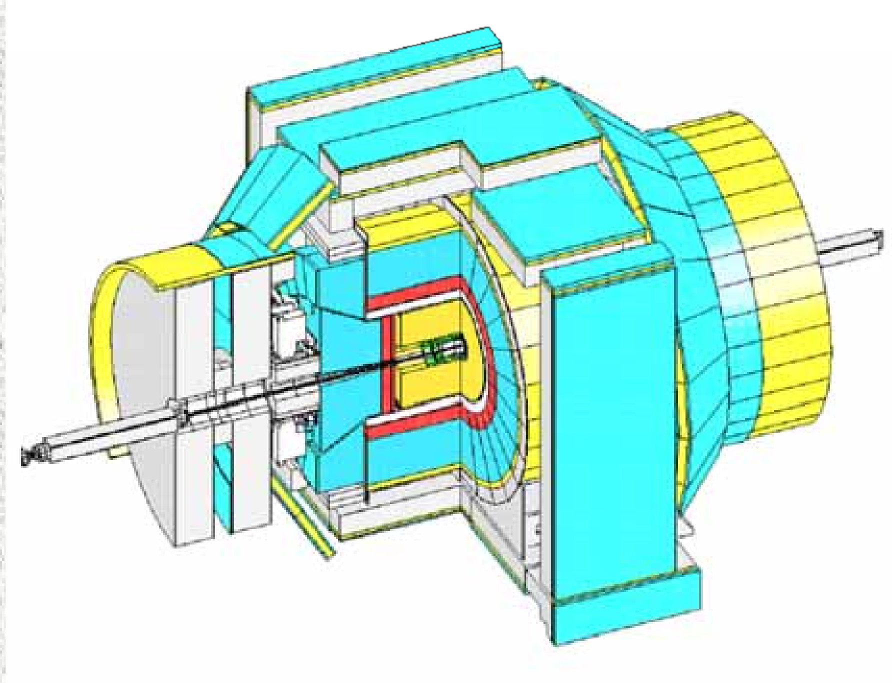
- CDF was designed in 1979, built in 1983-4, saw first light in 1985; Run 0 - 1987/88, Run I - 1992/96, Run II - 2001/10...
  → 25 years of operation: it is the longest-lasting physics experiment EVER

- Exceptional longevity due to a mix of causes:
  – Huge Tevatron potential and performances
  – A void in HEP left to fill
  – Amazing breadth of information extractable from ppbar collisions, and continued high-quality scientific output
  – The dedicated effort of quite a few brilliant minds



The CDF detector

- Inner barrel: axial-magnetic (1.4T) spectrometer with
  - 7-layer silicon detector (L00, SVX, ISL), $\sigma(d_0)$~10 μm for high-P_t tracks
  - Large 96-layer cylindrical drift chamber with stereo capabilities
  - tracks up to $|\eta|<1.5$, $\sigma(P_t)/P_t \sim 0.0015 P_t/\mathrm{GeV}$
    - → P_t of a 1-GeV track is known to ±1.5 MeV



- Calorimeter system
  - EM lead-scint., 20 X_0 13.5%/sqrt(E)+1.5% resolution
  - HAD iron-scint., $5\lambda_0$, 50% (75%)/sqrt(E)+3%(4%) resolution

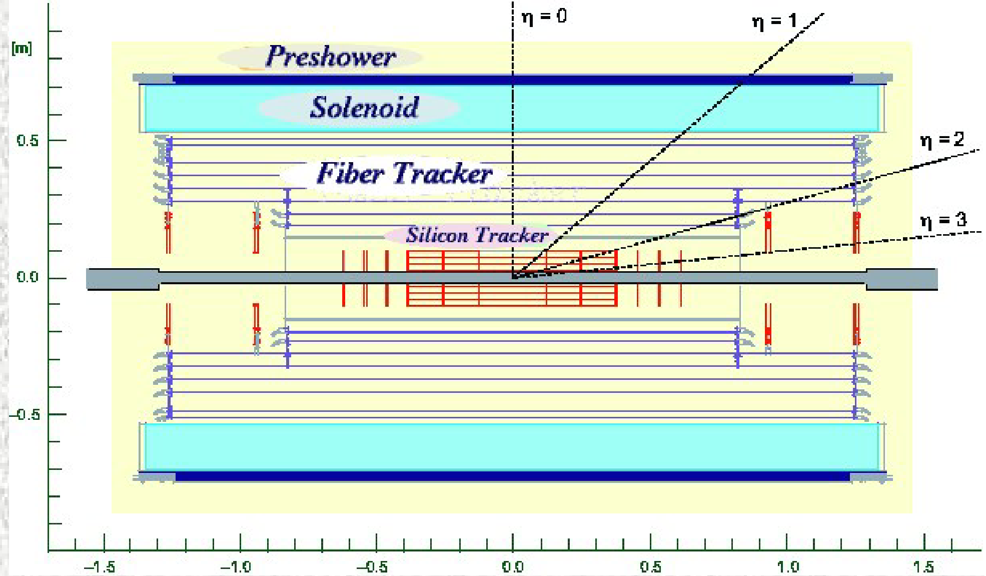
- Muon system
  - drift tubes and scintillation counters
    - CMU+CMP for $|\eta|<0.6$
    - CMX for $0.6<|\eta|<1.0$
    - IMU to $|\eta|<1.5$-2.0

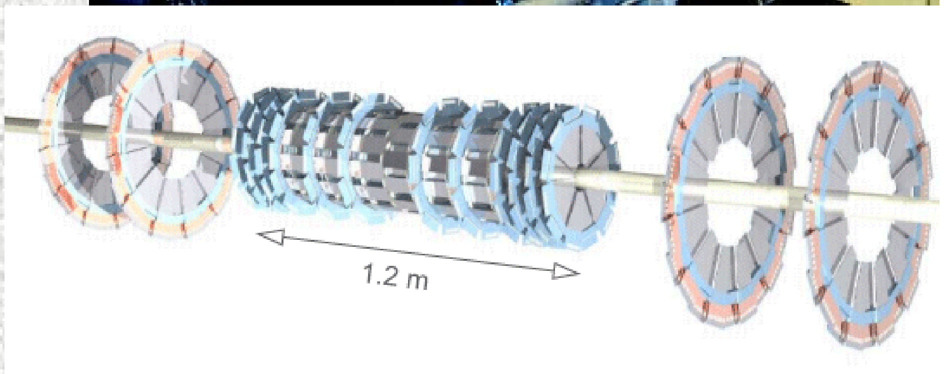
The D0 Detector

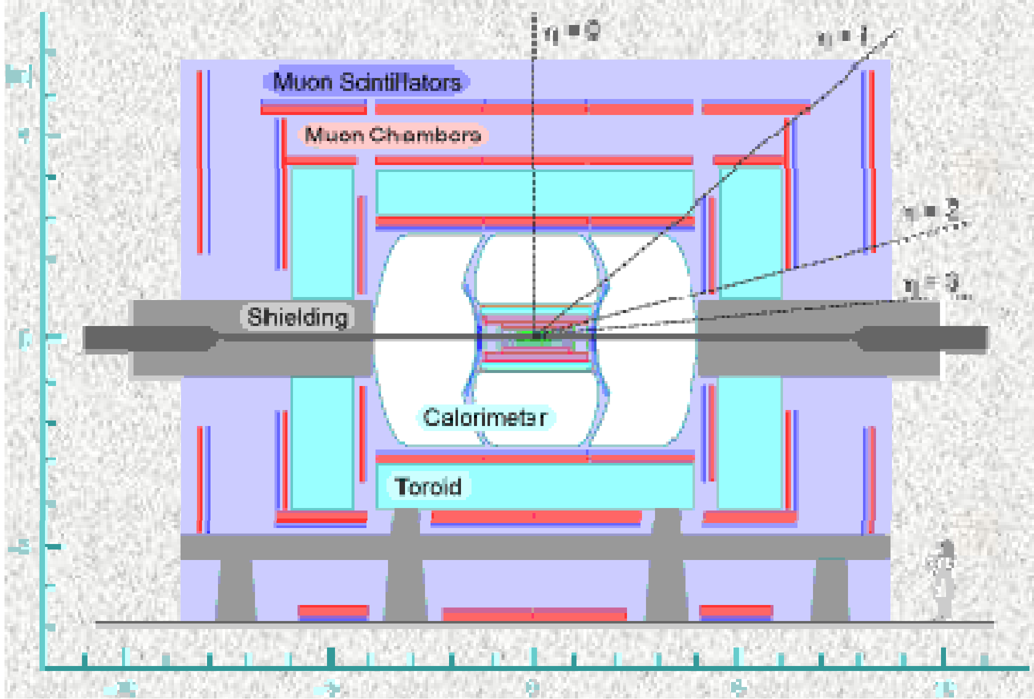
CDF's younger brother is also a complete and redundant system, endowed with

- a hermetic silicon detector
- a compact scintillating fiber tracker
- 2.0 Tesla axial B field
- a hermetic U/liquid Ar calorimeter
- Extended muon coverage

The tracker allows high performance b-jet tagging out to $|\eta|<2.0$







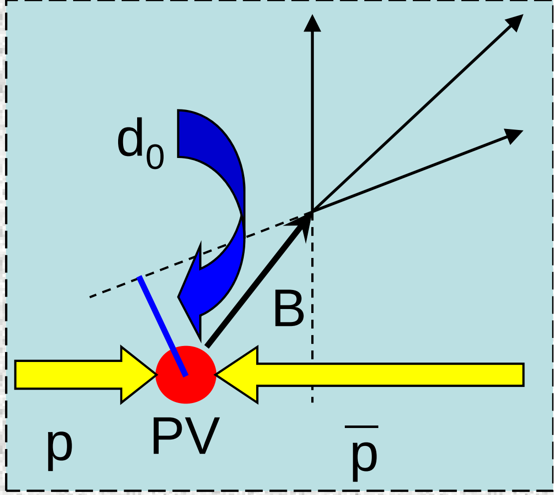
Two words on the tools

- All the searches performed by CDF and D0 would be impossible without dedicated trigger systems and carefully designed trigger paths
  - No time to discuss this fascinating issue, but if you are interested I am glad to explain

- To appreciate the analyses, we need to discuss in short the main features of the final-state objects featured in H production events
  - b-jets, as a product of H→bb decays
  - High-P_t electrons and muons, coming from W and Z
  - Missing transverse energy (ME_t), due to neutrinos in W decays
  - Going to just flash some descriptive slides –**stop me and ask** if you wish

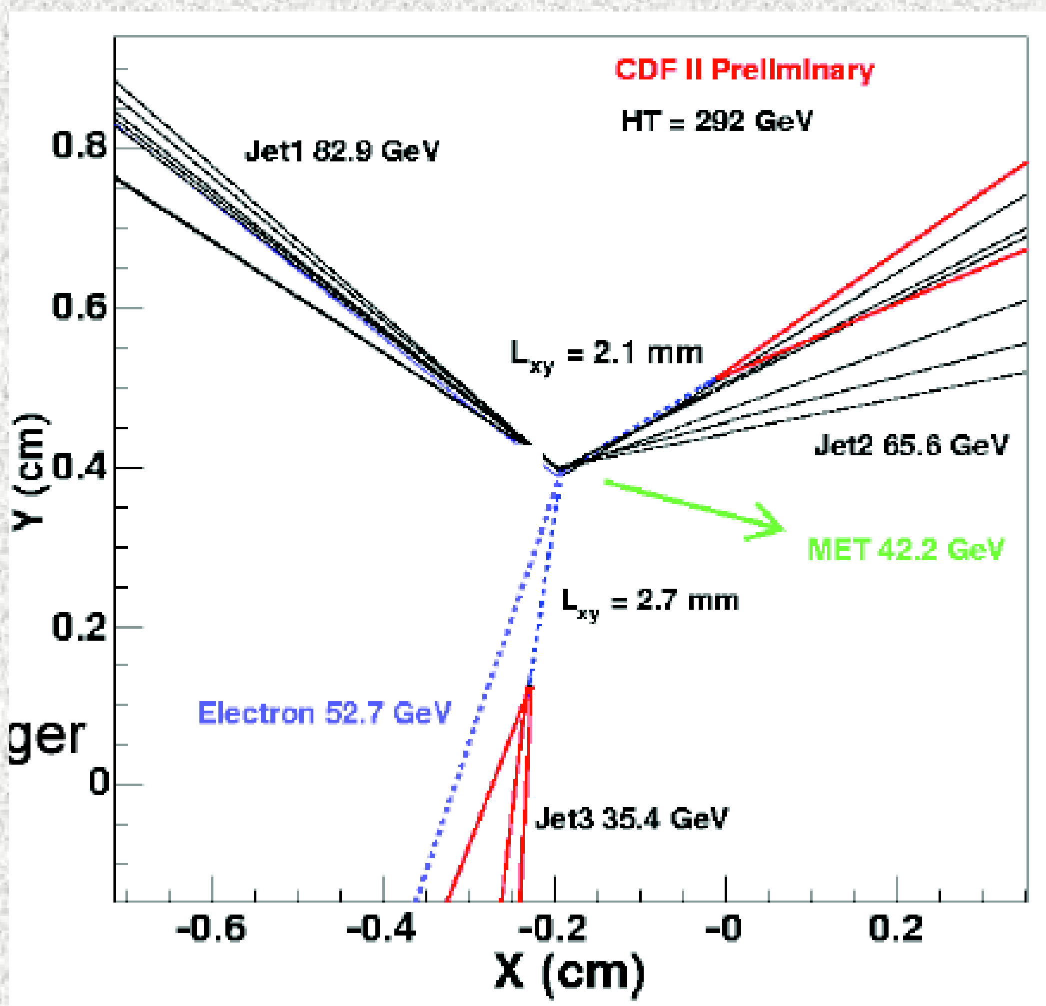
- Besides event reconstruction, quite advanced statistical tools are employed to separate signal from backgrounds, evaluate phase space probability densities, perform Bayesian likelihood fits with nuisance parameters integration
  - I will mention those later, again very briefly

B-tagging in CDF



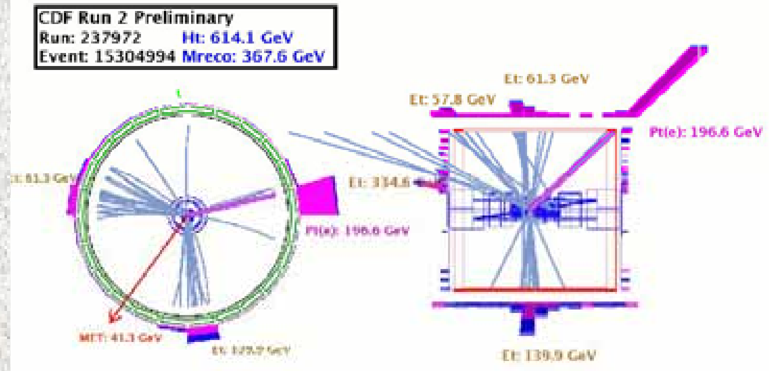
Quite advanced technology: 20-year experience at the Tevatron in b-jet-finding techinques in hadronic environment

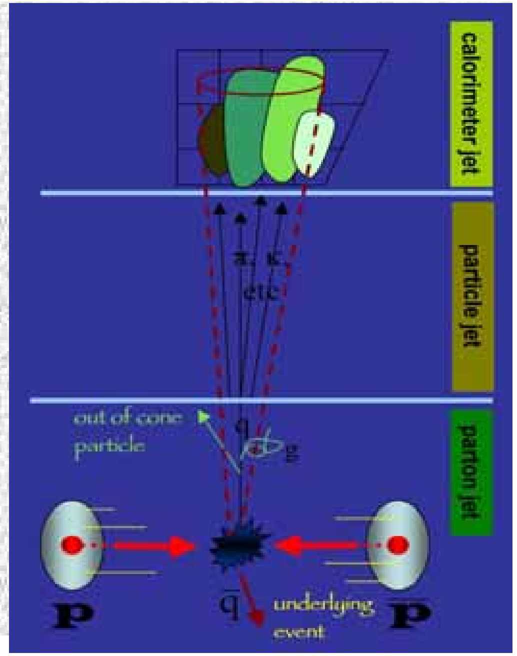
- Several algorithms available, mention those used in presented material
- **SecVtX**: secondary-vertex-finding technique, long-used in top measurements by CDF since Run I, reoptimized for Run II
  - Loop on tracks in jet with large impact parameter d_0, search for common 3-track vertex iteratively discarding high-χ^2 ones; If no vertex, tighten cuts on P_t, d_0 and search for 2-track vertex
- **JetProb**: extract probability that tracks in jet come from primary vertex
  - assign resolution on impact parameter to tracks depending on quality, determine P of PV hypothesis; construct global probability from all tracks; low-P values → b-tag

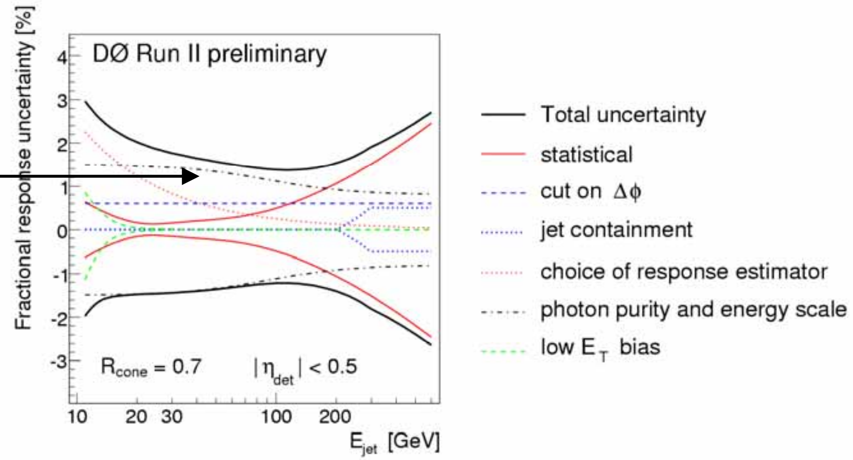


Jets and jet energy corrections

- Jet energy is measured in calorimeters
  - rich phenomenology of interaction of radiation with matter
    - EM compartments to measure π^0 signal and well-contained em showers, discriminate electrons
    - HAD sectors suffer from non-containment, non-radiative deexcitations, non-linearities
    - U-compensation (D0) partly recovers these
- Jet reconstruction: iterative cone algorithms (R=0.4 in $\eta-\phi$ space typical)... Need volumes to describe in detail the issues
- Usually detected energy requires calibration to produce best estimate of originating parton
  - Typically use dijet balancing techniques to infer biases
    - several steps: first angle-dependent correction, then absolute calibration, out-of-cone losses, UE contributions
    - Checked in Z-jet samples, gamma-jet samples
    - **Typical uncertainty on jet-energy scale 2% for high-Et jets**
  - Jet energy resolution is critical for H→bb mass reconstruction
    - studied extensively for top mass measurements, b-specific checked with Z→bb signal (CDF)
    - NN techniques improve resolution (see below)







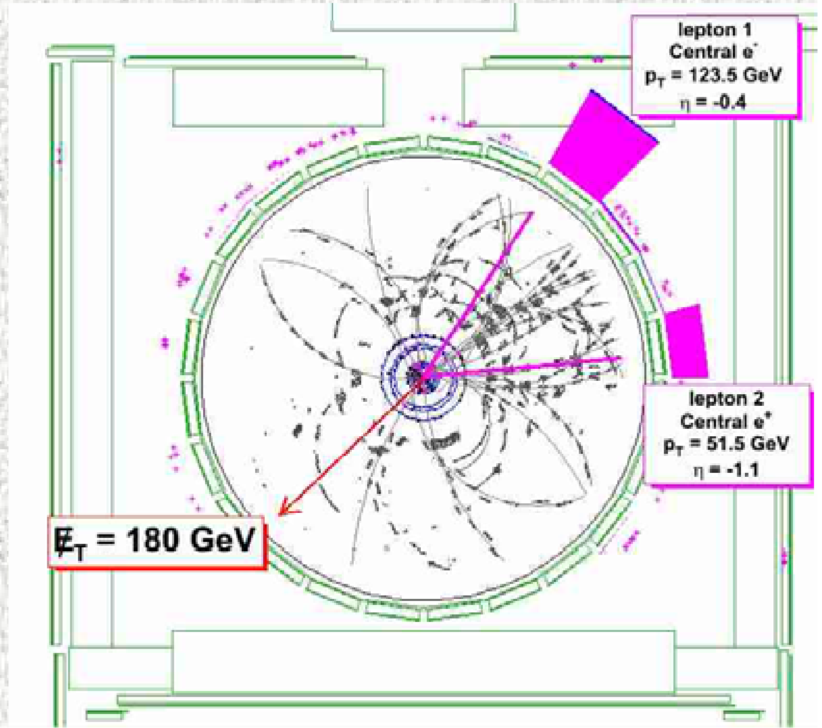
Missing Transverse Energy

- Neutrinos cannot be observed directly, but high-P_t ones are measurable via momentum conservation in the plane transverse to the beams
  - Resolution depends on precision of jet-energy calibration
  - fake signals occur most frequently when jet is pointing at azimuth of missing E_t
  - Charged tracks help discriminating true ME_t
  - Mature technology 21 years after first $W \rightarrow l\nu$ measurements!

$$ME_t = [(\Sigma E_x)^2 + (\Sigma E_y)^2]^{0.5}$$

$$\Phi = \text{atan2}(-\Sigma E_y , -\Sigma E_x)$$

Right: *a* $ZZ \rightarrow ee\nu\nu$ *candidate from CDF.*
The two (to be picky, N>0) neutrinos are inferred from the huge imbalance in transverse energy (shown by the red arrow)



Oh, and – Simulations!

Without simulations of backgrounds and signals, we would be left in the dark.

Please note: simulations combine two basic functionalities of computers: random number generation, and calculation of nasty integrals by Monte Carlo method

Despite the innocuous nature of the above claim, consider:

The word "simulation" comes from the Latin "simulacrum"…

For "simulation", my Webster's dictionary offers the following:

1) The act of simulating; pretense; feigning.
2) A simulated resemblance
3) An imitation or counterfeit
4) The use of a computer to calculate, by means of extrapolation, the effect of a given physical process

- Seems like my Webster's knows more on HEP than it wants to admit !

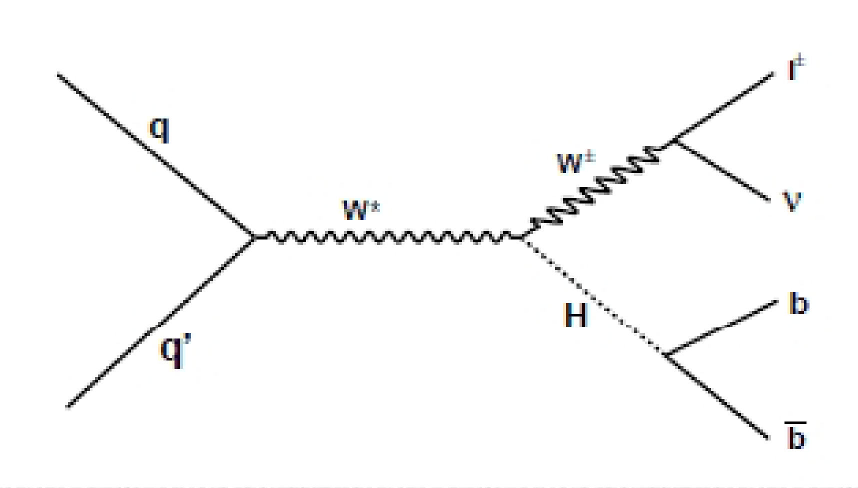
Higgs Boson Searches

Low-mass Higgs searches

- Several analyses target the low-mass range
- Three of them are distinctly more powerful than the others
  - $WH \rightarrow l\nu bb$
    - CDF: results out with 4.8/fb, Mar 2010
    - DZERO: results out with 5.0/fb, Aug 2009
  - $ZH \rightarrow llbb$
  - $ZH \rightarrow \nu\nu bb$
- Other analyses are interesting but way less sensitive
- *Will only cover in some detail the first one here*
  - *currently best single result*

WH→lνbb search by CDF

- This search was approved on February 12th, 2010
- It uses 4.8/fb collected by four different triggers:
  - Lepton-triggered
    - high-P_t electrons
    - high-P_t muons
  - Non-lepton-triggered
    - Missing transverse energy (ME_t) + 2 jets
    - High MEt
- Leptons are "central", "forward electron", or "non-triggered" (isolated tracks)
- Events must contain a lepton, large missing energy, and two or three jets, one of them b-tagged by SecVtx; b-tag on other jet defines three classes:
    - SecVtX b-tag
    - Jet Probability b-tag
    - No b-tag
  - The three classes have different background contaminations and their separate study improves the search



Details of event selection

- Veto Z→ll events, QCD multijets, identified conversions, dileptons (the latter because they enter a different search for ZH→llbb)
- Two- and three-jet events have different background contaminations, keep them separated → defines six disjunct classes
- Backgrounds and data agree in the six classes. These are the starting point of the search

Background Estimation: 4.8 fb^{-1}, 2 jets

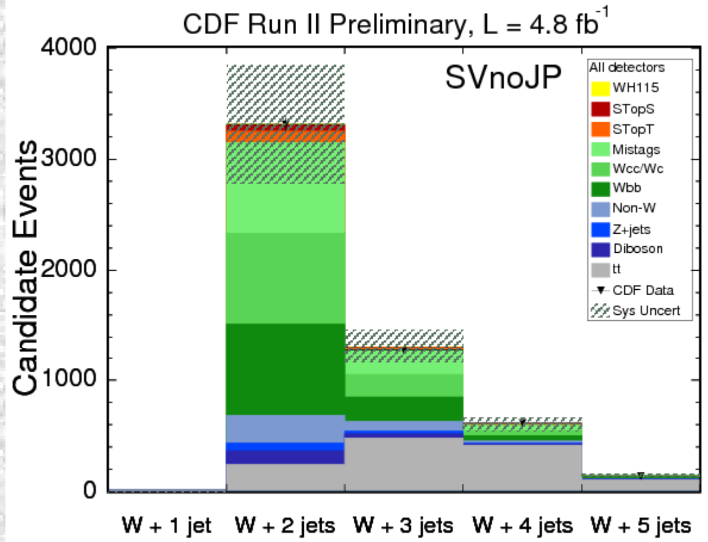
Process	SVSV	SVJP	SVnoJP
All Pretag. Cands.	103564	103564	91545
WW	0.76 ± 0.17	2.8 ± 1.1	90.5 ± 11.3
WZ	7.1 ± 1.0	5.3 ± 0.9	30.0 ± 3.3
ZZ	0.26 ± 0.04	0.22 ± 0.04	1.18 ± 0.18
$t\bar{t}$ (lepton+jets)	40.2 ± 6.6	32.2 ± 5.9	176 ± 24
$t\bar{t}$ (dilepton)	24.1 ± 4.0	17.1 ± 2.9	68.0 ± 9.4
Single top (t-channel)	5.4 ± 0.9	5.4 ± 1.1	99.0 ± 14.3
Single top (s-channel)	22.5 ± 3.7	15.7 ± 2.6	56.5 ± 7.8
Z+jets	3.6 ± 0.6	4.40 ± 1.12	68.3 ± 10.4
Total MC	**104 ± 13**	**83.0 ± 12.7**	**589 ± 51**
Wbb	122 ± 39	103 ± 34	835 ± 252
Wcc/Wc	11.9 ± 4.1	39.1 ± 14.5	818 ± 252
Total HF	**134 ± 43**	**142 ± 47**	**1653 ± 502**
Wjj	4.1 ± 1.3	16.1 ± 9.2	819 ± 119
Non$-W$	14.8 ± 5.9	25.9 ± 10.4	250 ± 100
Total Prediction	**257 ± 45**	**268 ± 51**	**3311 ± 528**
WH115	**3.5 ± 0.4**	**2.4 ± 0.3**	**8.8 ± 0.7**
Observed	**245**	**263**	**3313**

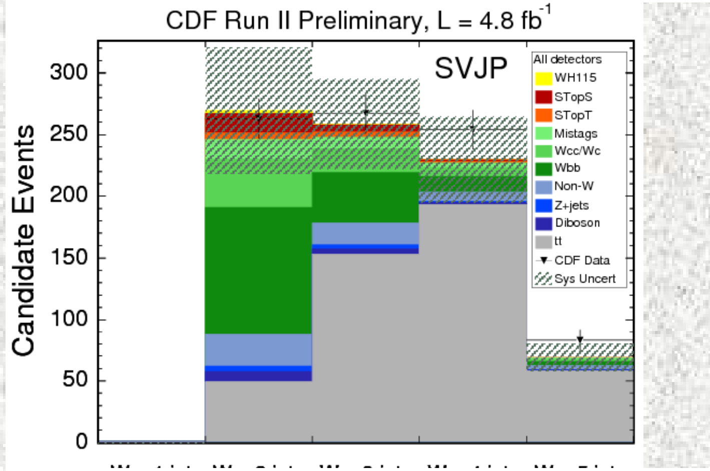
Background Estimation: 4.8 fb^{-1}, 3 jets

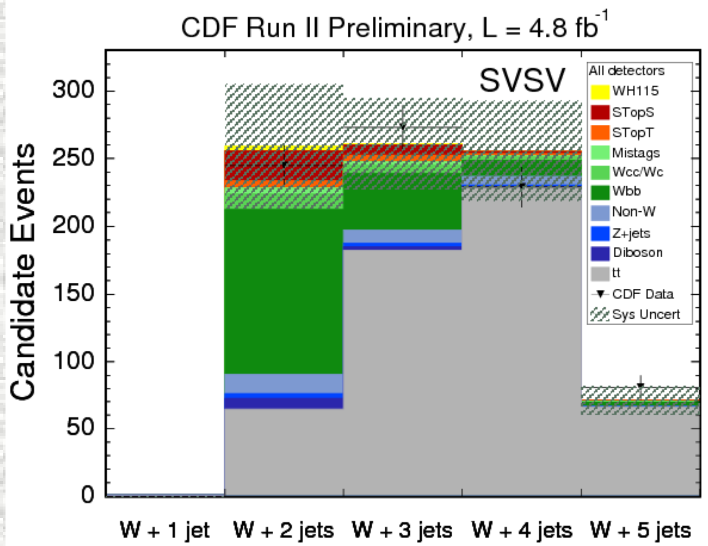
Process	SVSV	SVJP	SVnoJP
All Pretag. Cands.	18858	18858	16406
WW	0.85 ± 0.17	2.2 ± 0.8	28.1 ± 3.4
WZ	1.9 ± 0.3	1.7 ± 0.3	8.0 ± 0.9
ZZ	0.16 ± 0.03	0.13 ± 0.03	0.50 ± 0.08
$t\bar{t}$ (lepton+jets)	161 ± 26	134 ± 25	431 ± 60
$t\bar{t}$ (dilepton)	21.7 ± 3.5	15.6 ± 2.6	49.2 ± 6.8
Single top (t-channel)	4.8 ± 0.8	4.2 ± 0.8	22.4 ± 3.2
Single top (s-channel)	7.6 ± 1.2	5.8 ± 1.0	16.7 ± 2.3
Z+jets	2.5 ± 0.4	3.4 ± 0.9	25.4 ± 3.7
Total MC	**200 ± 30**	**171 ± 29**	**581 ± 65**
Wbb	41.7 ± 13.6	40.7 ± 13.5	221 ± 67
Wcc/Wc	6.1 ± 2.1	19.6 ± 7.4	202 ± 62
Total HF	**47.8 ± 15.6**	**60.3 ± 20.3**	**423 ± 128**
Wjj	2.8 ± 0.9	9.5 ± 5.1	221 ± 33
Non-W	9.8 ± 3.9	17.8 ± 7.1	86.5 ± 34.6
Total Prediction	**260 ± 34**	**258 ± 36**	**1312 ± 152**
WH115	**0.99 ± 0.12**	**0.73 ± 0.10**	**2.20 ± 0.18**
Observed	**273**	**267**	**1271**

Background estimates

- Several background processes affect the search; the most significant are
  - W+bb, W+light flavors
  - ttbar
  - single top
  - dibosons
  - non-W (a.k.a. QCD)
- Backgrounds are estimated in a variety of ways
  - Wbb: from W+jets (MEt fits provide fraction) using b-tag matrix for fake b-tags and ALPGEN+PYTHIA for real HF content
  - non-W: using ME_t shape
  - Other backgrounds: from MC
- Good agreement in different control samples, mature technology
  - much of it is >15 years old, used for precise top cross section measurements
- **N(jets) distributions** show quality of understanding of the data



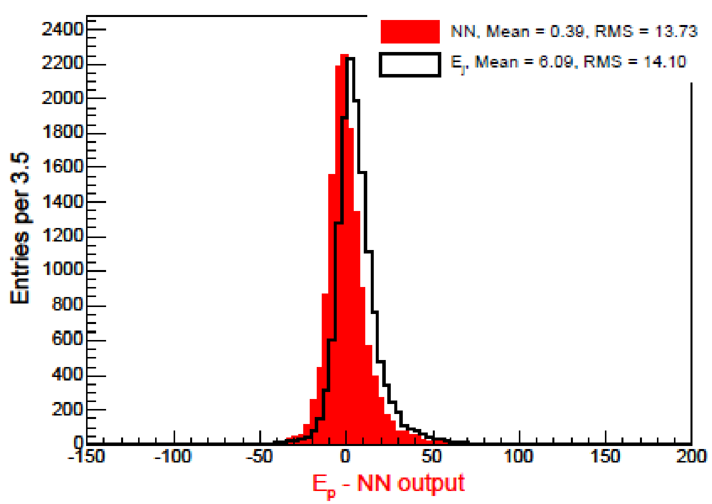




Matrix-Element discriminant

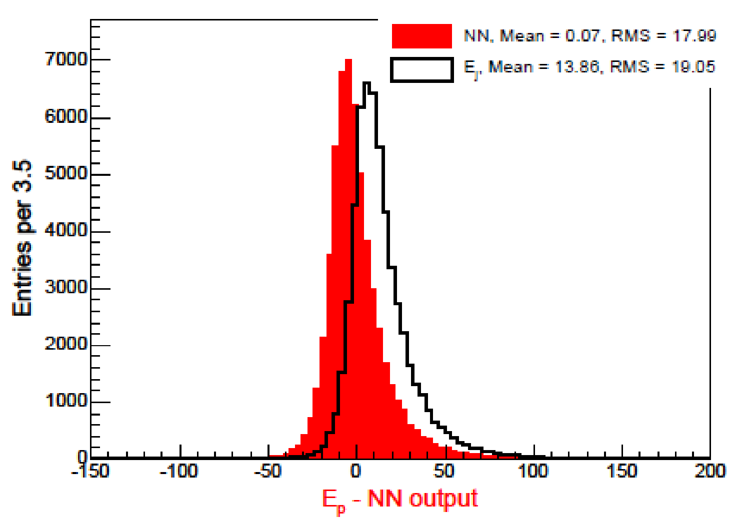
- If final-state objects were measured perfectly, a precise knowledge of the matrix element density would allow to assign a distinct probability to each element of phase space, but (1) initial state needs to be modeled, and (2) detector resolution, FSR, unmeasured quantities make things harder
  - (1) is addressed by folding in parton distribution functions
  - (2) Transfer functions enshrining detector resolution and other effects are determined

  A LO Monte Carlo (HELAS with MadGraph routines) is used to compute ME for signal and background processes
  - For well-measured objects (leptons) transfer function =1
  - For jets, model them with Gaussian functions
- To determine jet TFs, CDF uses a set of 23 Neural Networks trained on b jets, c jets, light-quark jets on the different signal and bgr processes
  - Inputs are 7 observable quantities of jets (Et, charged fraction, direction, energy in larger cone)



Left: TF for lq-jets in diboson events

Right: TF for b-jets in WH events

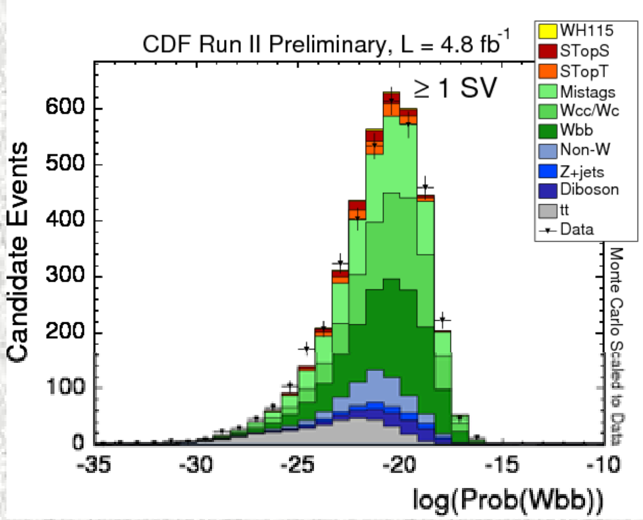


Signal extraction

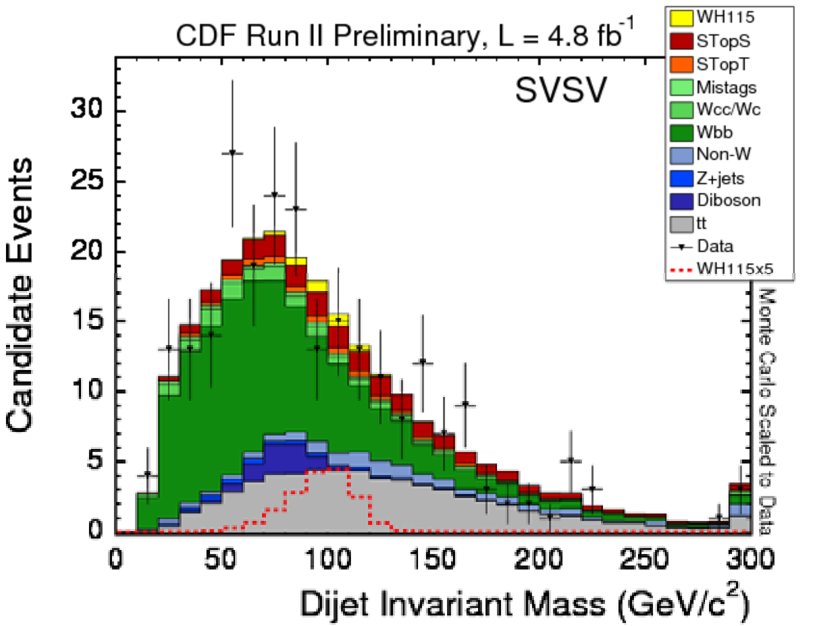
- A global "Event probability discriminant" is constructed with the output of the ME calculation, and with all the kinematical input from the jets
- Additional information is available by using another NN b-tagger assigning a probability that jets come from b-quarks

$$EPD = \frac{b \cdot P_{WH}}{b\,(P_{WH} + P_{singletop} + P_{Wbb} + P_{t\bar{t}}) + (1-b)\,(P_{Wcc} + P_{Wcj} + P_{Wjj} + P_{diboson})}$$

- The discriminant is finally combined with the dijet mass to form a "final discriminant", used to fit for a signal component .



Above: Log(P) of matrix element for the Wbb production hypothesis, for the various backgrounds



Dijet mass for double-tag events (left) is well modeled by backgrounds

Dijet mass differentiates well signal from most backgrounds
→ incorporate it in final discriminant

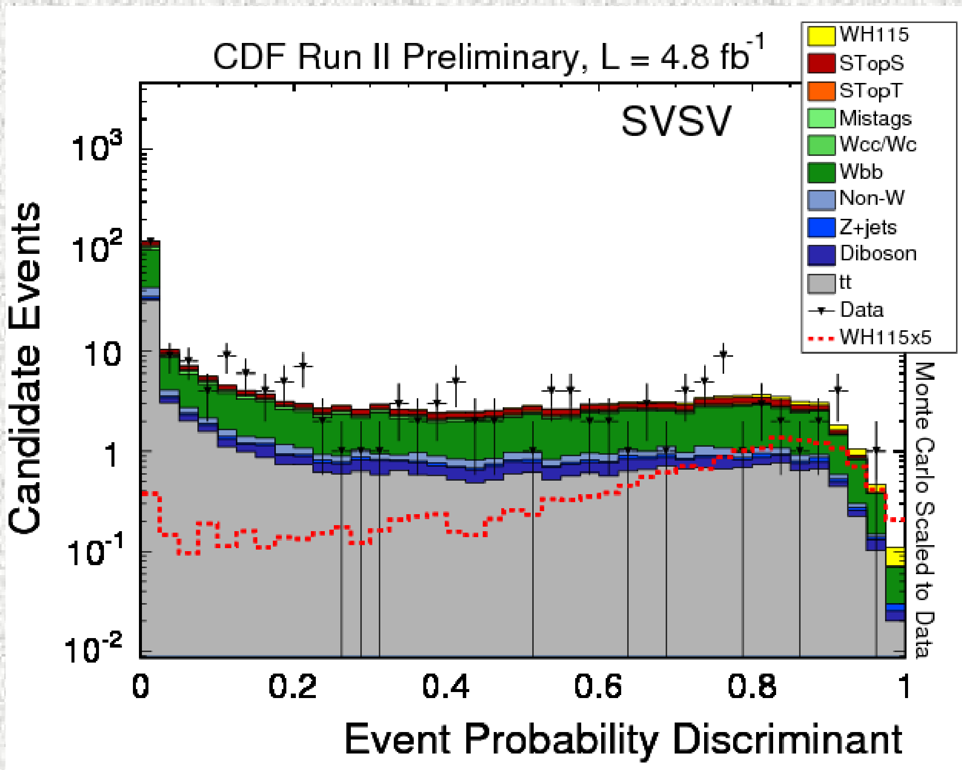
Final signal fit

- The final discriminant is fit with a binned likelihood function,

$$\mathcal{L} = \prod_{j=2}^{6} G_j(\beta_j;\sigma_j) \prod_{k=1}^{B} \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!}$$

- Systematics on signal extraction come from
  - Lepton reconstruction (2%)
  - Trigger (1-2%)
  - ISR/FSR, PDF (3-20%)
  - JES (2-16%)
  - b-tagging scale factor (3-8%)
  - Integrated luminosity (6%)
  - These are evaluated separately for the six different tagging and Njet classes

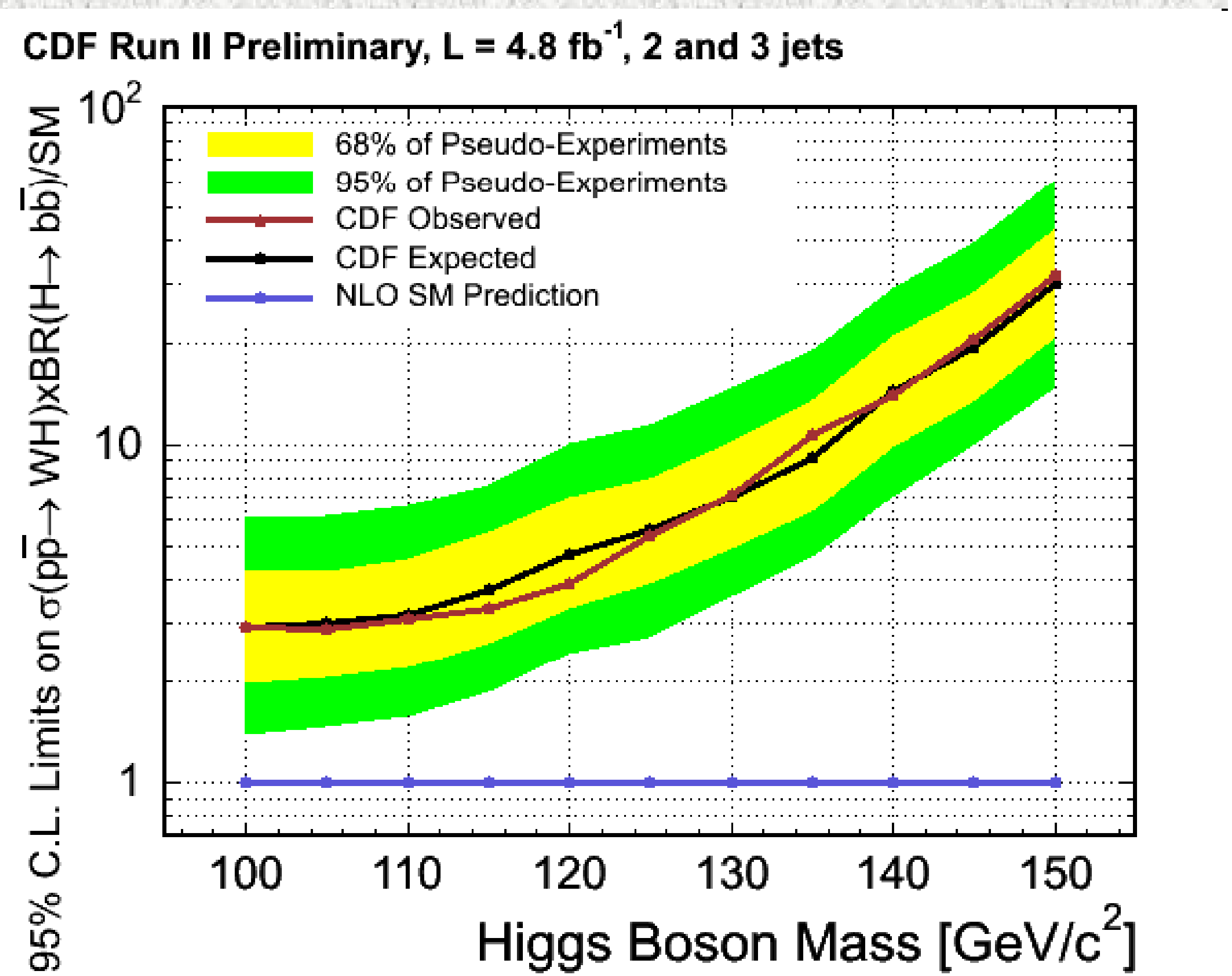
- Systematics are modeled by Gaussian functions and are incorporated in a likelihood function as nuisance parameters in a Bayesian treatment.



Above: final discriminant for one of the six classes (SVSV, 2j)

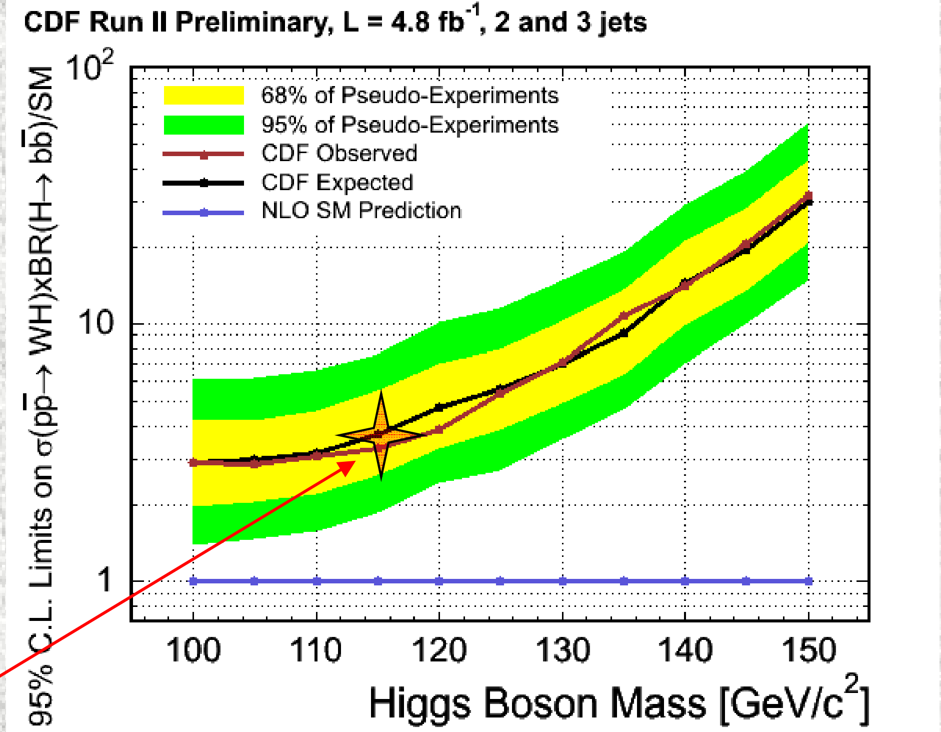
Results of WH search, CDF

- The six independent fits are combined and limits on the ratio between limit on cross section and SM expectation are obtained at 95% confidence level for each hypothesis of M_H.
- The limit reaches down to R<3 x SM rates
- Pseudo-experiments allow to verify that the observed limit is in line with predictions



Comparison with D0

- Just for fun (to add a pinch of salt), we may compare CDF and D0 in their low-mass flagship search, WH→lνbb, for a 115 GeV Higgs boson
  - D0 (5.0/fb): R<6.9 (obs), R<5.1(exp)
  - CDF (4.8/fb): R<3.8 (obs), R<3.3 (exp)



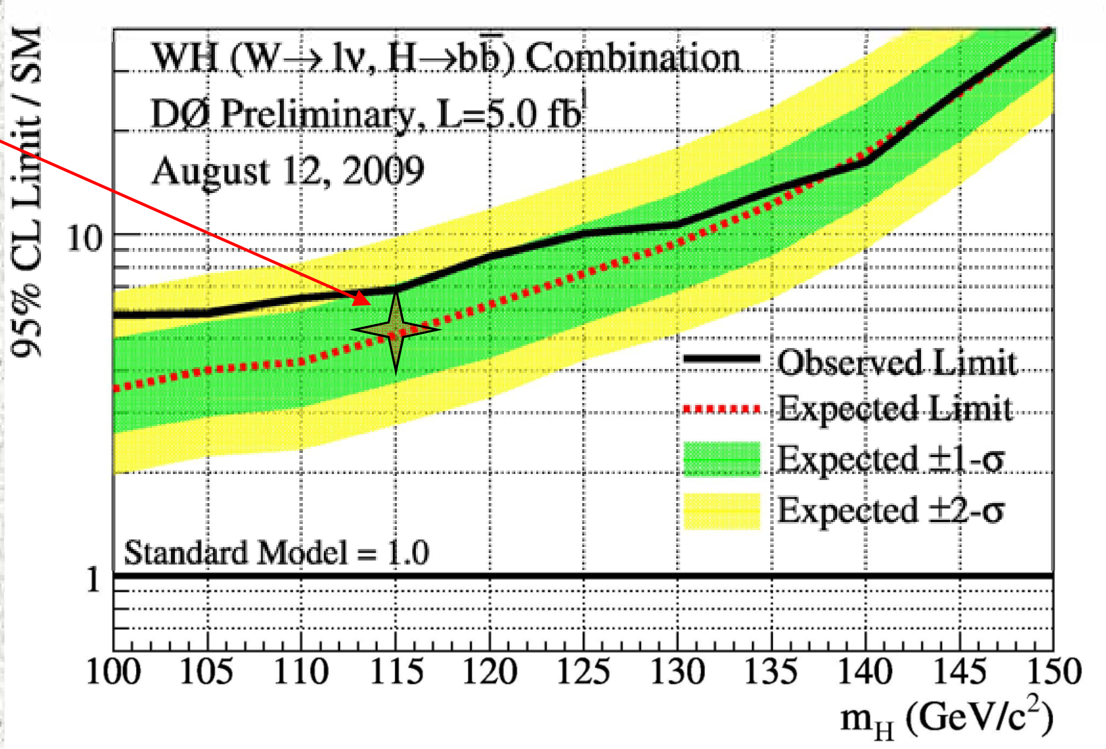
How much better is CDF doing ?

Take expected limits

$R_{exp}(D0)/R_{exp}(CDF)*(L(D0)/L(CDF))^{0.5}$

$= 5.1/3.3*(5.0/4.8)^{0.5} = 1.58$

which is equivalent to 149% more "effective luminosity" at same L!



This does not mean that D0 has a worse detector! It means they are still refining their searches → important point for future projections

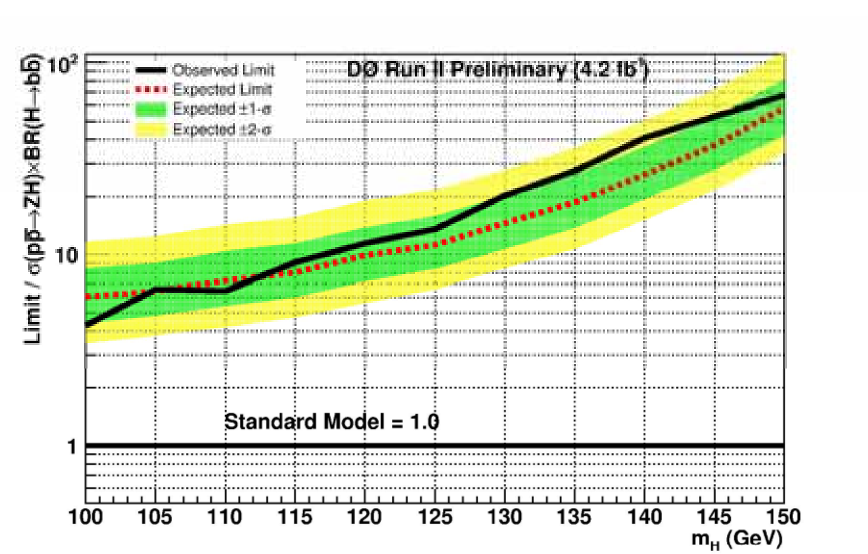
Other low-mass search results

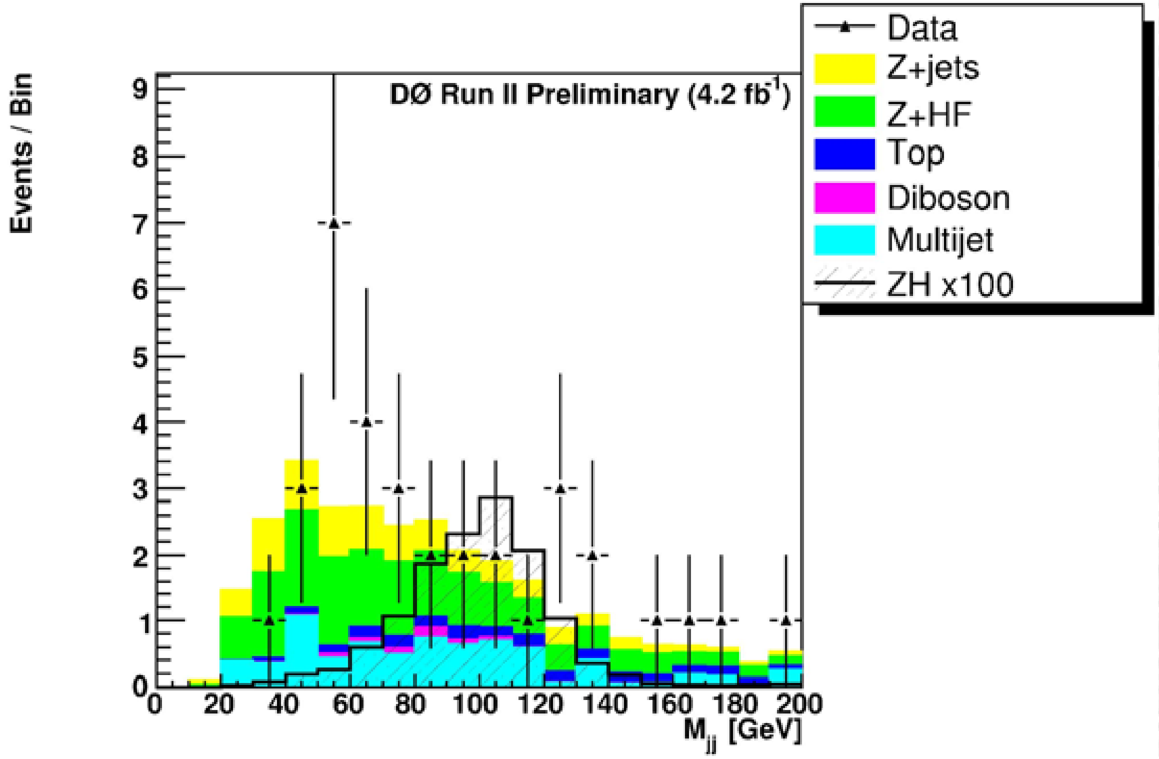
- A number of other analyses deserve to be mentioned
  - ZH→llbb
  - ZH→$\nu\nu$bb
  - VH→qqbb, VBF H→qqbb
  - WH→$\tau\nu$bb
  - ttH→(lνbjjb)(bb)
  - VH→jj$\tau\tau$
  - H→$\gamma\gamma$
- The first two are competitive with the main WH search, others are an order of magnitude less sensitive. Yet all provide useful additional information when combining results
- *Only flashing some highlights for each*

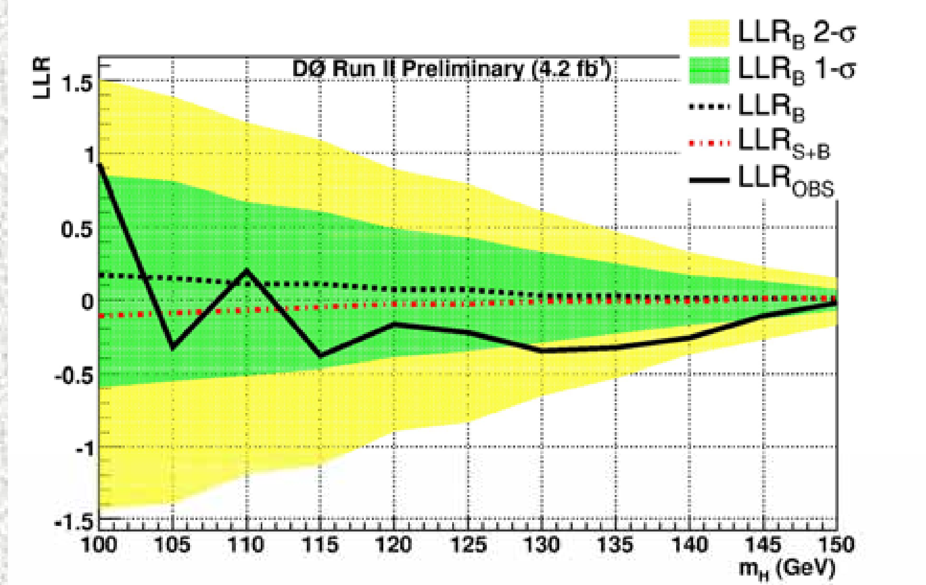
ZH→llbb, DZERO, 4.2/fb (Nov 2009)

- DZERO searches for eebb and μμbb final states by selecting Z→ee (Z→μμ) events with 2 jets, one (two) of them containing a tight (loose) NN-b-tag
- They use a multivariate discriminant (boosted decision trees) to separate signal from backgrounds (mostly Z+heavy flavor production)

- Output is used to extract R limit with relative likelihood method

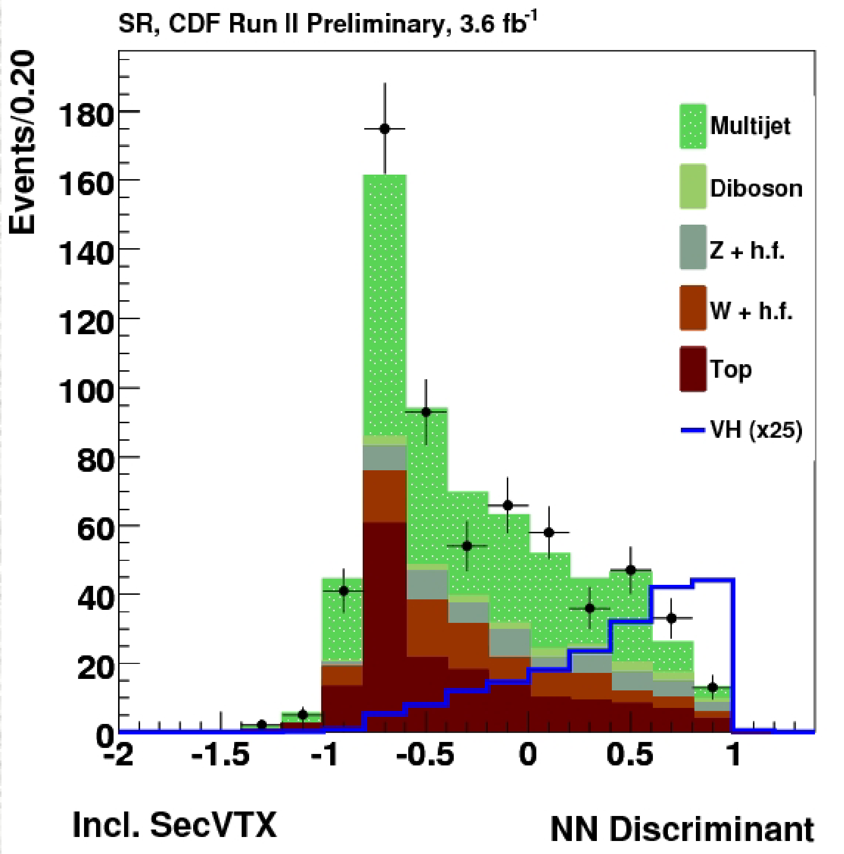


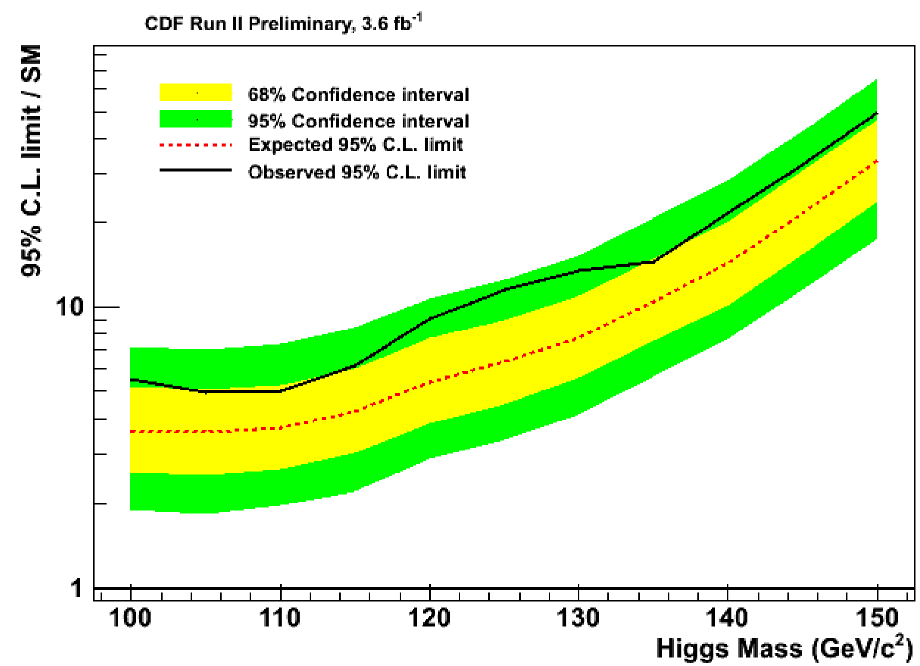




ZH→ννbb: CDF, 3.6/fb (Mar 2009)

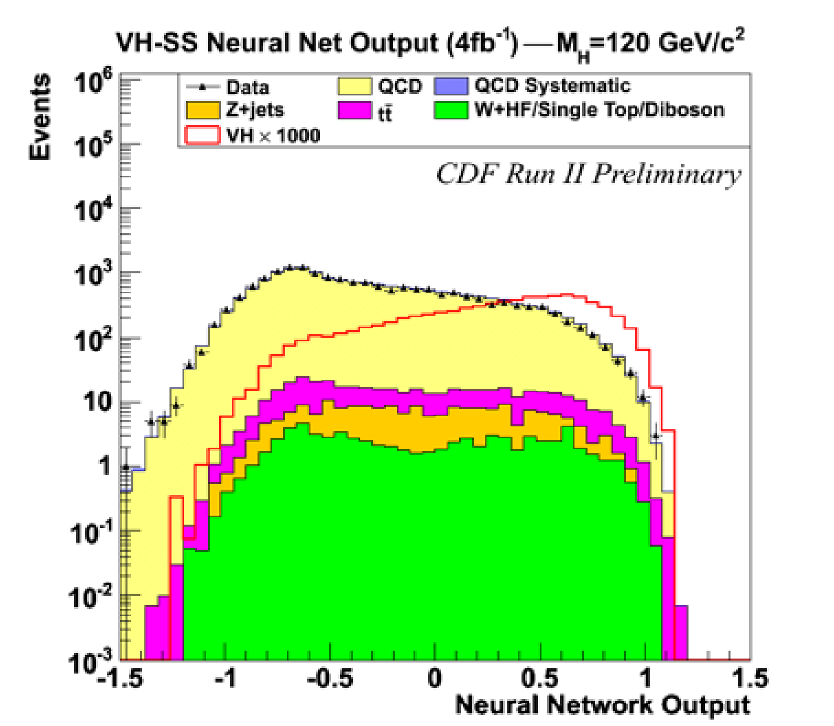
- CDF searched for missing energy and jets in a MEt+2 jet triggered sample
  - orthogonal to WH (lepton events are vetoed)
- Study "track-MEt" as a way to discern whether calorimetric MEt is instrumental
- NN trained to discriminate against backgrounds (QCD, ttbar, W/Z+h.f.) with 9 kinematical variables
- Use SecVtX and JetProb b-tagging, divide in classes (1/2 tags of different kinds)
- Observed limit over 1-sigma above expectation

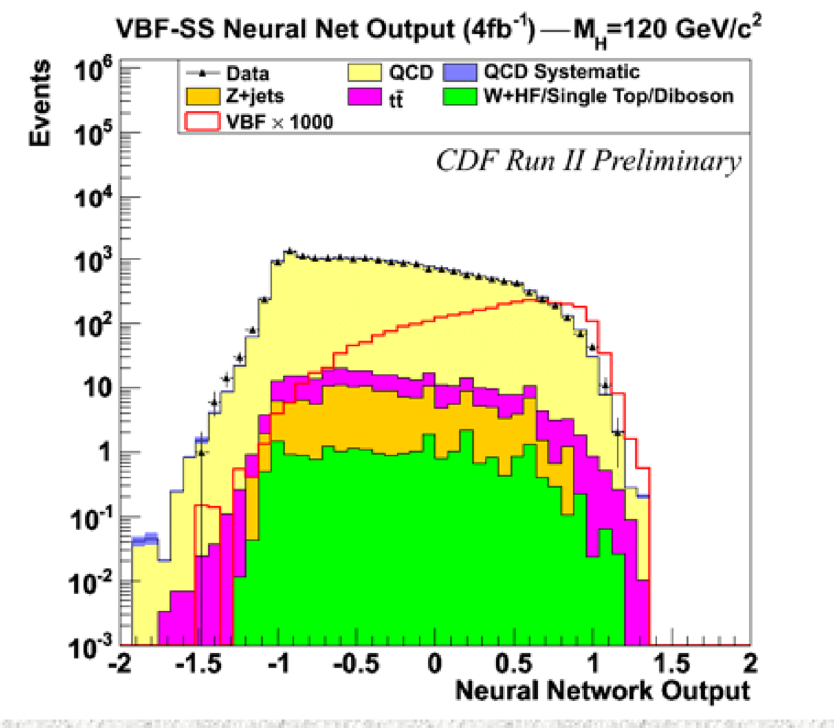


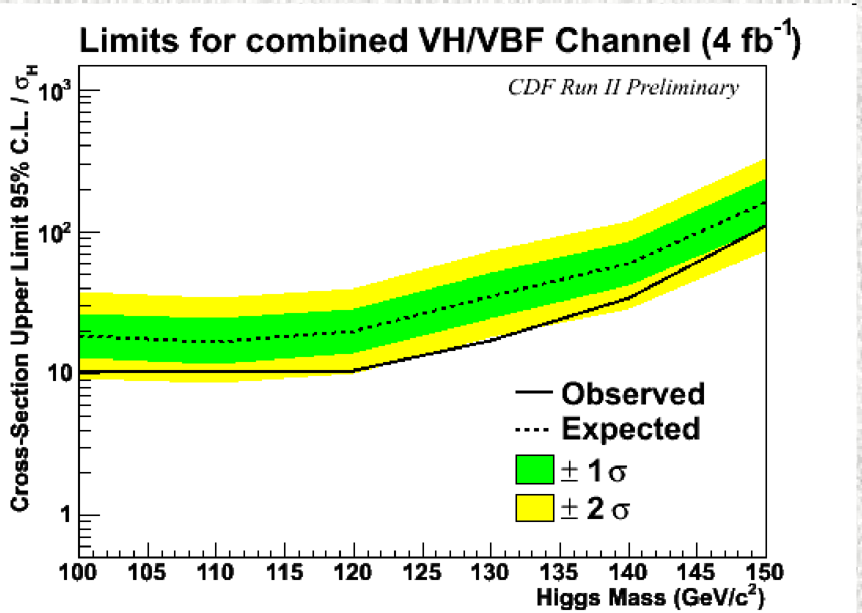


VH/qqH→qqbb, CDF 4/fb 2009

- Beating the QCD multi-jet background in search for a sub-picobarn signal is an **arduous task**
- A search by CDF tried to do precisely that, using a multi-jet trigger (high-SumEt)
- double b-tagging (SecVtx*SecVtx and SecVtx*JetProb) used to enrich in signal
- Use η and ϕ jet energy moments to reduce QCD gluon jet background
- Search for both VH and VBF H production with two separate NN
- Remarkably, **the achieved R limit is useful !**



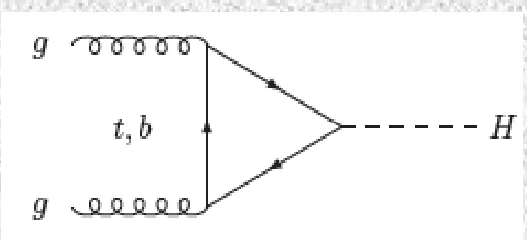




High-mass Higgs searches

For M_H>135 GeV, the sensitivity of searches involving the decay H→bb drops very quickly

For higher masses, **H→WW** is the dominant decay mode



Signal is distinctive - need not rely any more on Higgsstrahlung production (to fight backgrounds): gg→H→WW becomes the source of signal

WH→WWW can still be tried but rate is low.

H→ZZ is smaller by at least a factor $4M_W^2/M_Z^2$~3, and further depressed by small Z→ll decay BR

Will discuss in detail H→WW search only

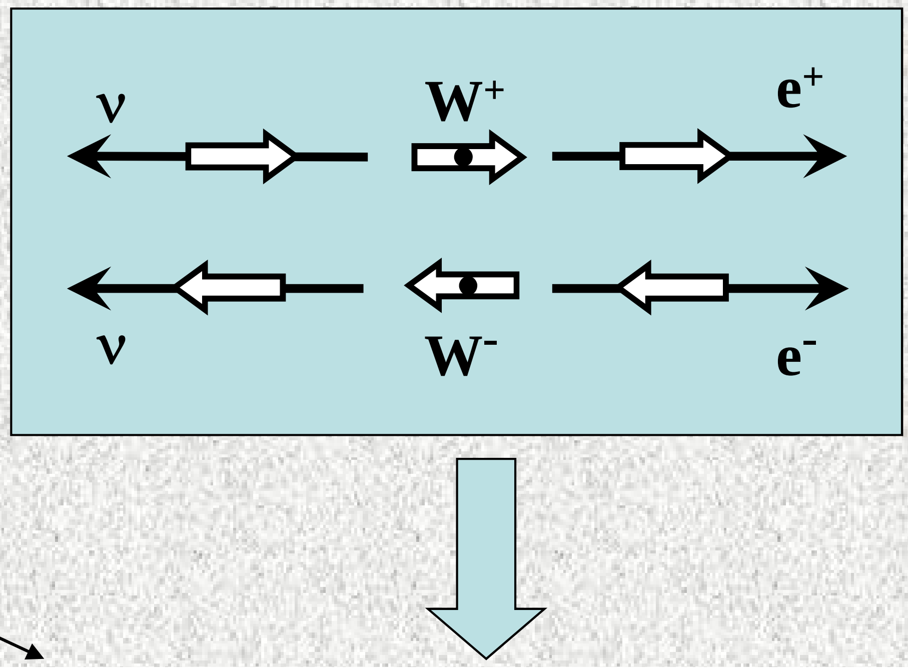
H→WW search, DZERO 5.3/fb (Nov 2009)

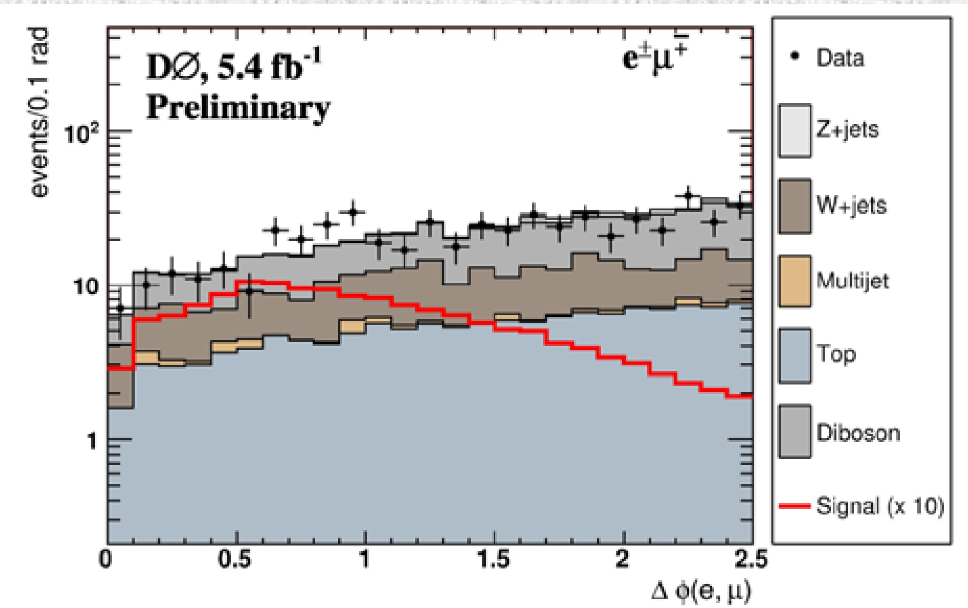
- The most powerful search strategy for a high-mass Higgs boson is to look for dilepton events (ee,eμ,μμ) with missing E_T, and discriminate backgrounds (mostly SM dibosons and W+jet events) with kinematical requirements

- Most interesting discriminating feature: spin zero of H and helicity structure of W decay forces leptons from W decay to be emitted at close angle

- DZERO select dileptons from single high-P_t lepton triggers, and imposes isolation requirements to purify the sample
- Some further cleanup is applied using the magnitude of the missing E_T and the lepton energies and direction

- A neural network is then trained to discriminate the signal using several kinematic variables

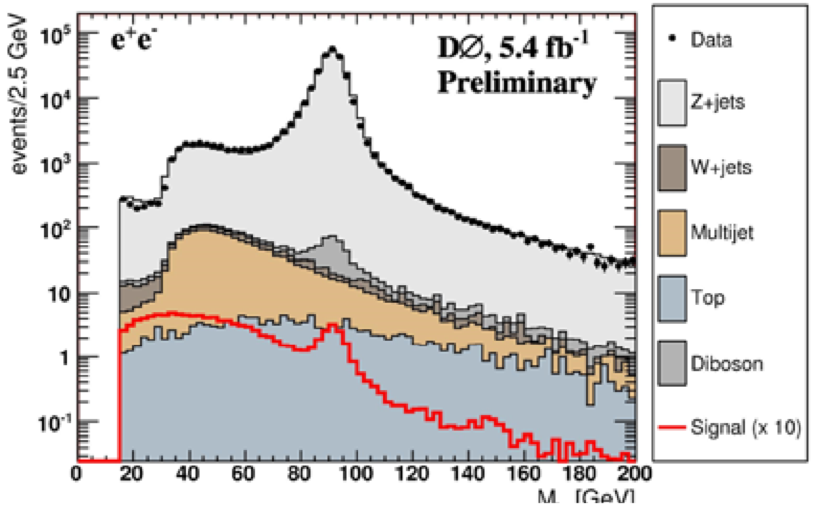


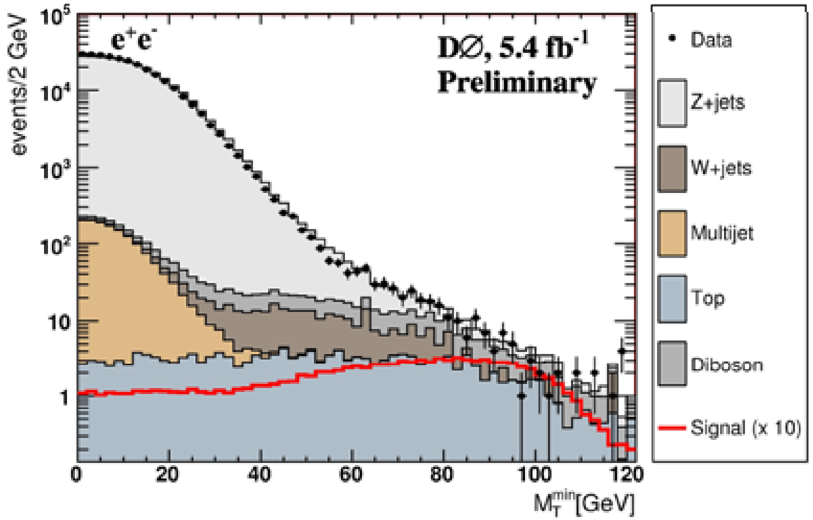


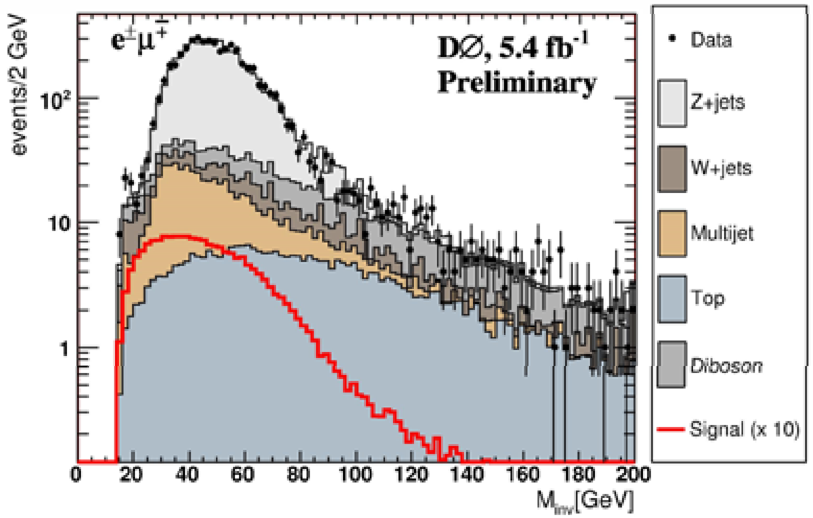
NN input variables

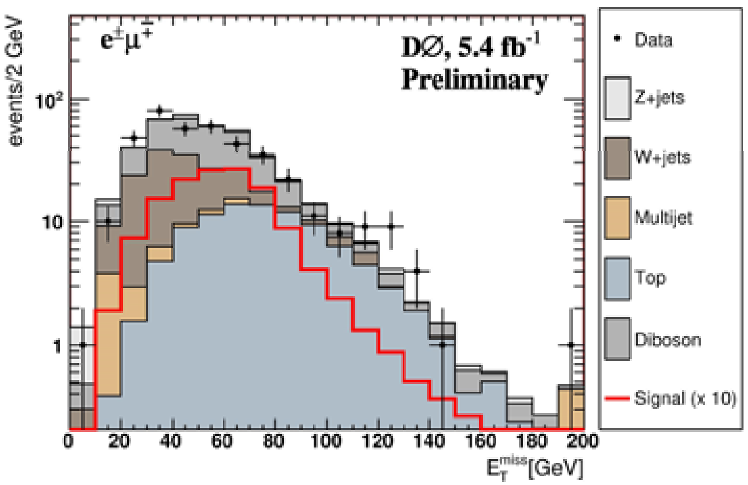
- Due to selection differences, each of the three dilepton categories gets its own NN discriminant
- The kinematics are quite distinctive

NN Analysis Variables	
p_T of leading lepton	$p_T(\ell_1)$
p_T of trailing lepton	$p_T(\ell_2)$
Lepton quality ranking	$\min(q_{\ell 1}, q_{\ell 2})$
Vector sum of the transverse momenta of the leptons:	$\vec{p}_T^{\,1} + \vec{p}_T^{\,2}$
Scalar sum of the transverse momenta of the jets:	$H_T = \sum_i p_T(\text{jet}_i)$
Invariant mass of both leptons	$M_{\text{inv}}(\ell_1, \ell_2)$
Minimal transverse mass of one lepton and $\not\!\!E_T$	M_T^{min}
Missing transverse energy	$\not\!\!E_T$
Azimuthal angle between selected leptons	$\Delta\phi(\ell_1, \ell_2)$
Azimuthal angle between leading lepton and $\not\!\!E_T$	$\Delta\phi(\not\!\!E_T, \ell_1)$
Azimuthal angle between trailing lepton and $\not\!\!E_T$	$\Delta\phi(\not\!\!E_T, \ell_2)$
Jet multiplicity	n_{jet}





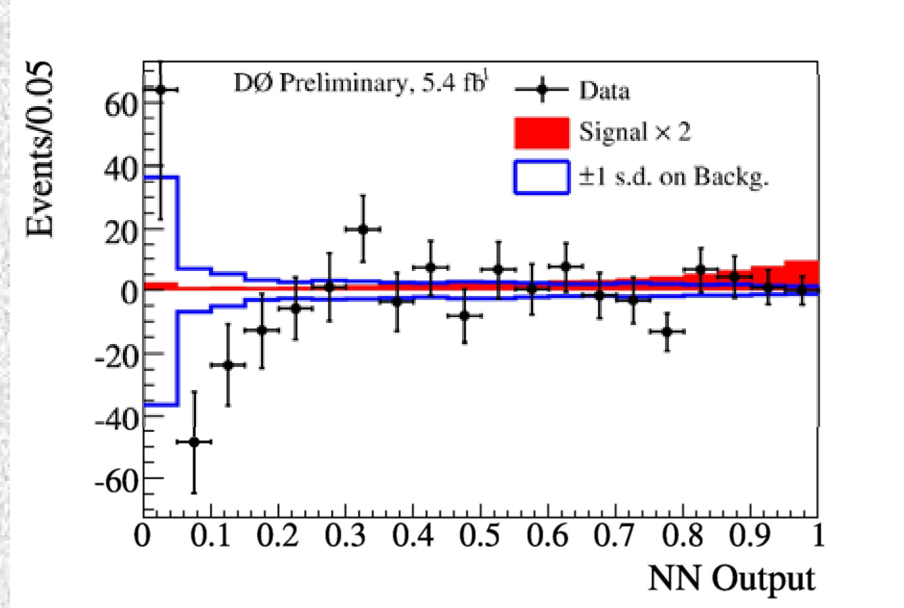


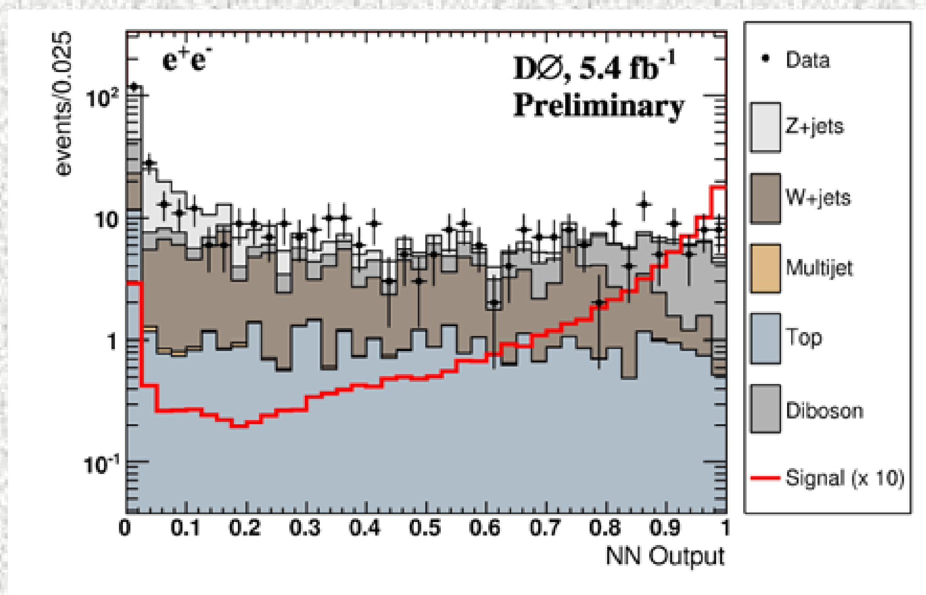


NN outputs and systematics

- Systematics affecting signal efficiency:
  - lepton reconstruction (2.5-4%)
  - lepton momentum calibration (2-8%)
  - Theoretical cross section uncertainty (6-10%)
  - PDF (8%)
  - QCD background model (2-20%)
- Systematics affecting also the shapes:
  - reconstruction eff. (6-18%)
  - JES calibration (3-17%)
  - modeling of P_t (1-5%)
- Total uncertainties: background level 10%, signal efficiency 13%
- DZERO combines the output of the three channels using the LLR as test statistics
- Suspicious trend at low NN output seen, but not very bad agreement overall

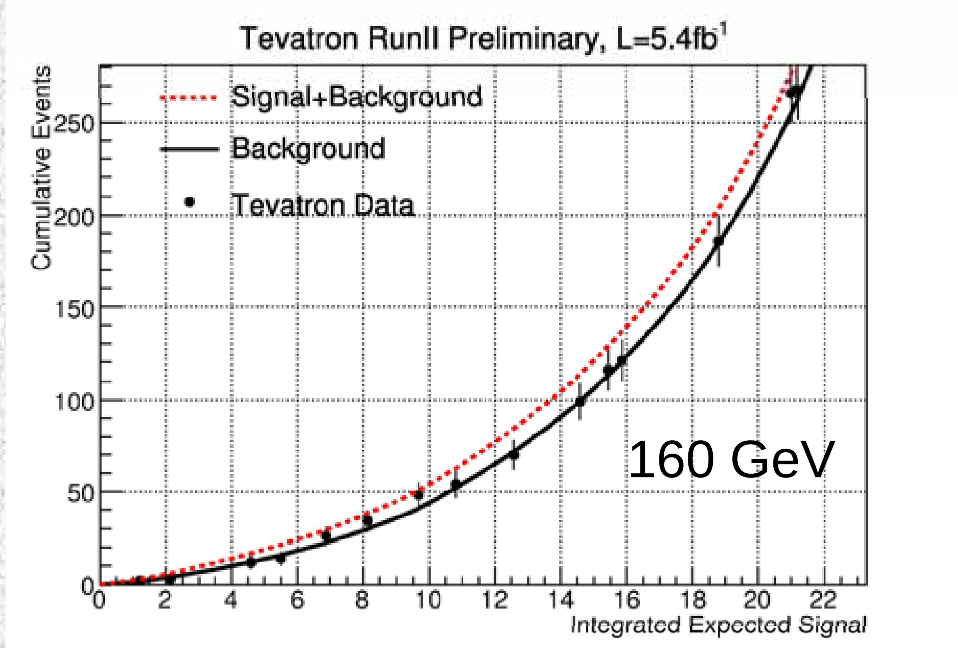
  Several control samples confirm soundness of NN

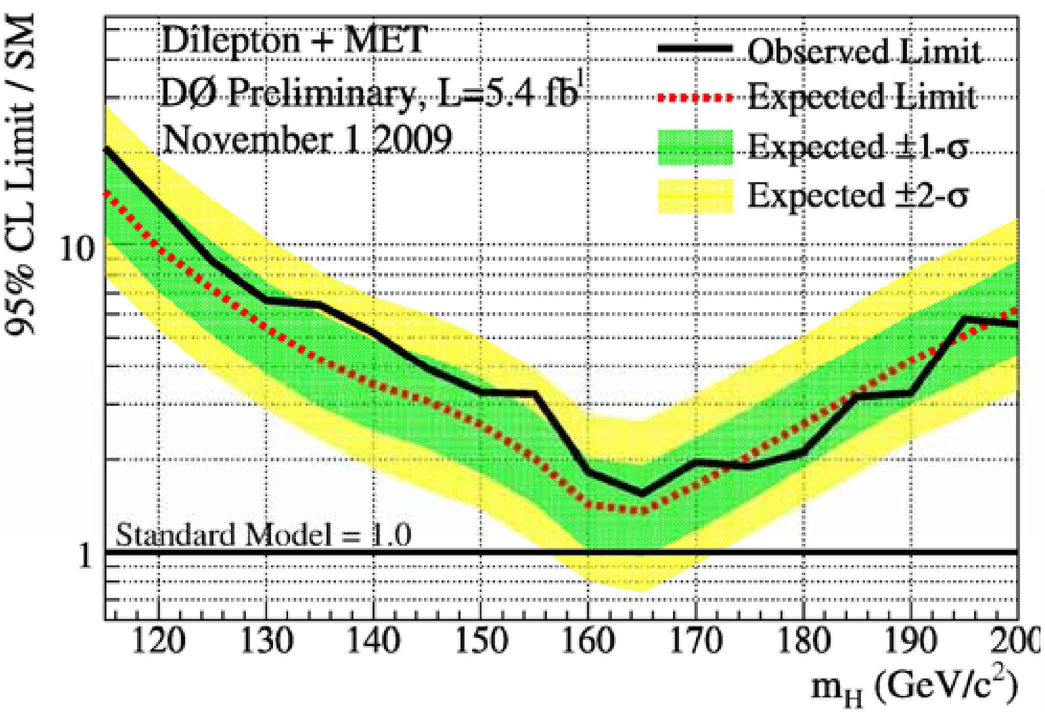


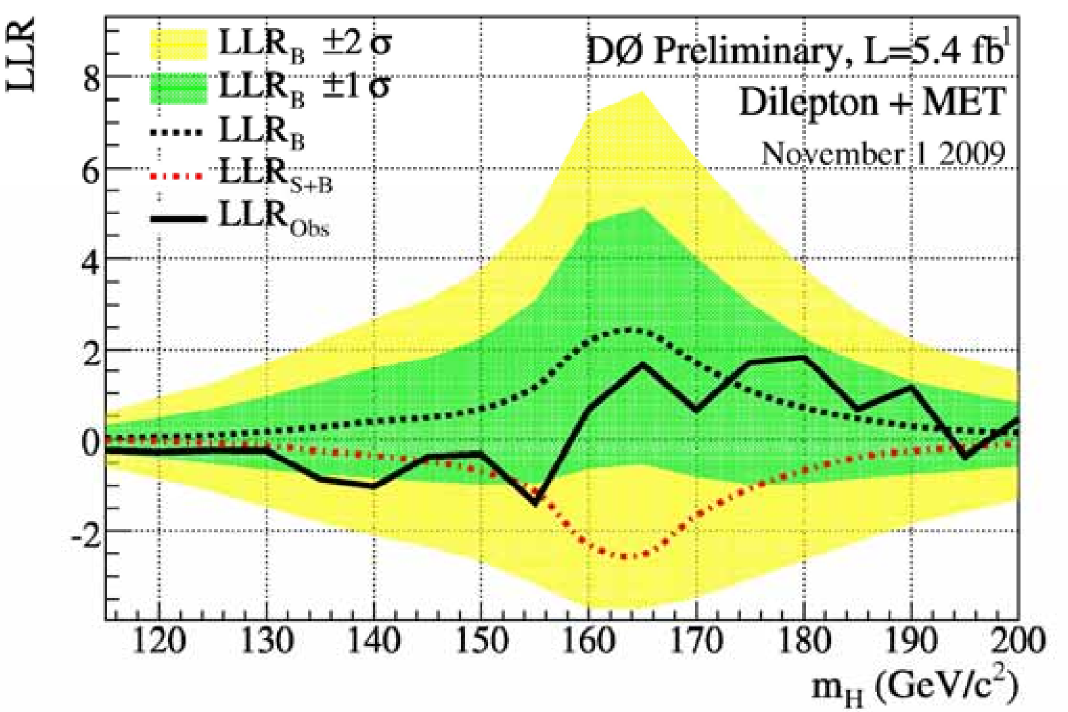


Results

- This is one of the single most performant searches – almost getting to exclude Higgs masses by itself
- Data is signal-like (background-like) for M_H below (above) 160 GeV

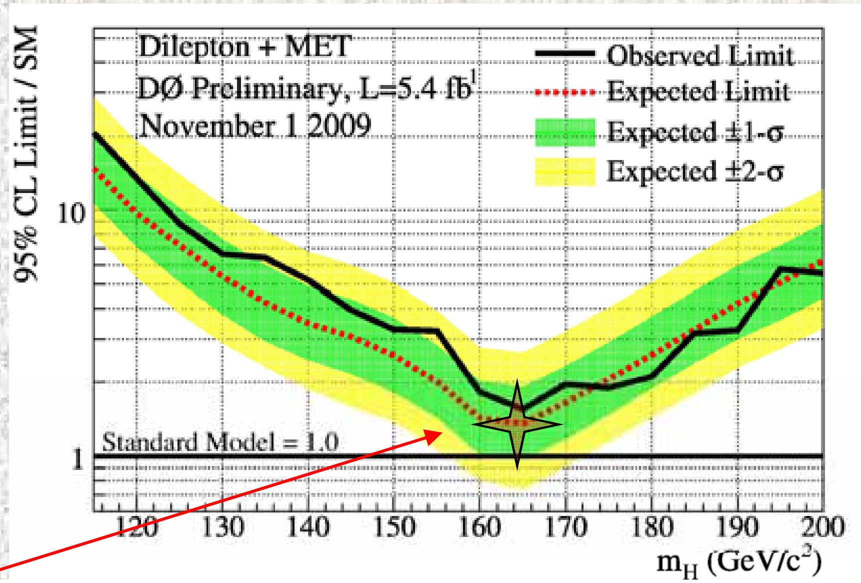






Comparison with CDF result

- As for the WH search, let us be nasty and compare CDF and D0 on the flagship H→WW search
- CDF uses 4.8/fb (12% less data)
- at 165 GeV:
  - R<1.39 (exp. 1.25) (CDF),
  - R<1.36 (exp. 1.55) (D0)



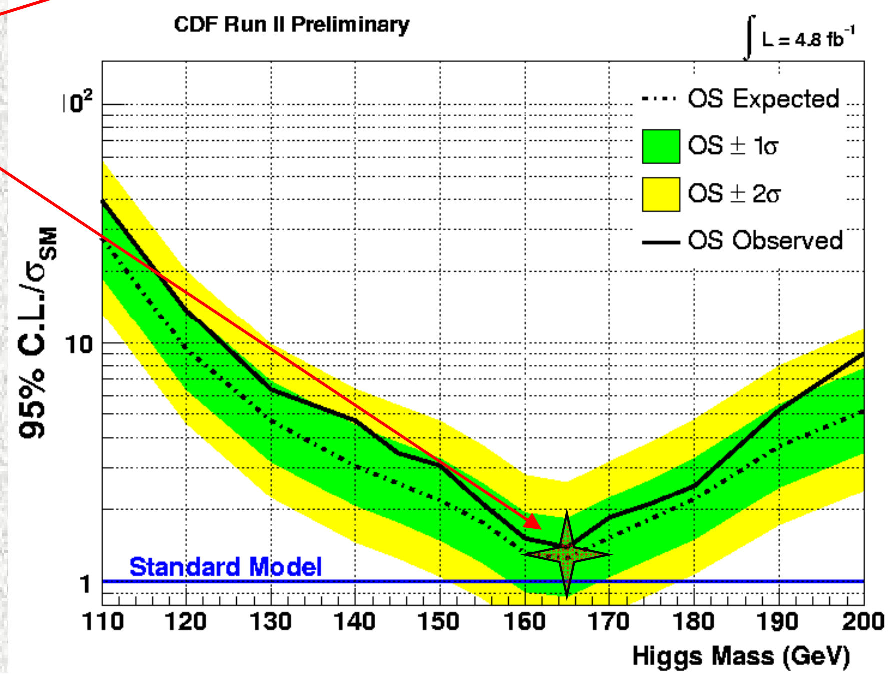
How much better is CDF doing ?

Take expected limits

$R_{exp}(D0)/R_{exp}(CDF)*[L(D0)/L(CDF)]^{0.5}$

$= 1.55/1.25 * (5.4/4.8)^{0.5} = 1.32$

which is like having 73% more luminosity!



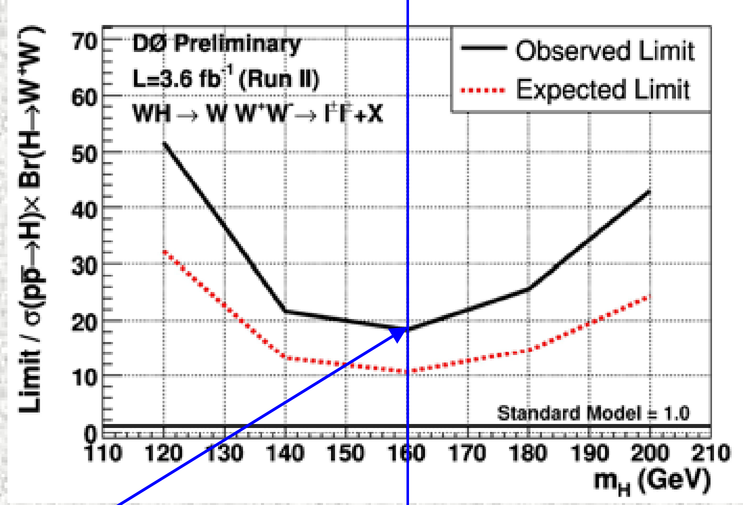
Again, remember the point made before: D0 has more possible improvements ahead.

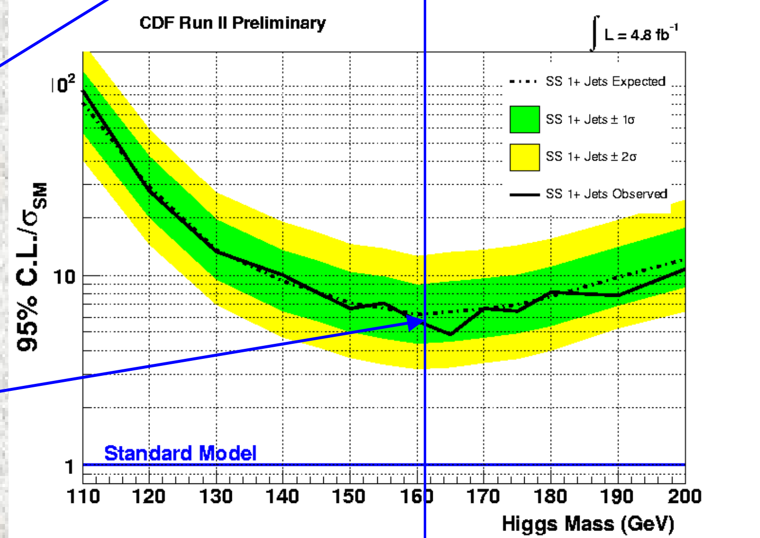
Other High-mass Searches

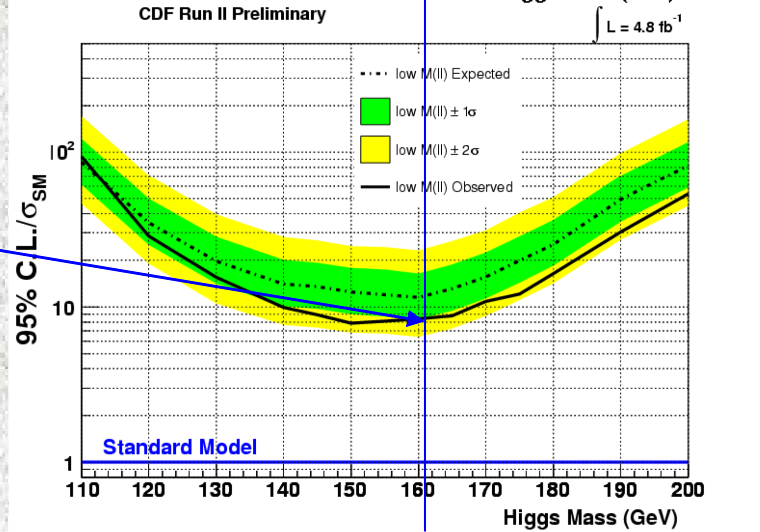
- Other decays of H besides WW are insensitive at the Tevatron

- A few other analysis techniques targeting the M_H>135 GeV region deserve a quick mention

  - WH→WWW$^{(*)}$ producing like-sign dileptons: for 160 GeV limits at:
    - R<18 (D0, 3.5/fb),
    - R<6 (CDF, 4.8/fb)
  - H→WW$^{(*)}$ at low-M_{ll}: for 160 GeV limits at
    - R<8 (CDF, 4.8/fb)







Combination of Limits

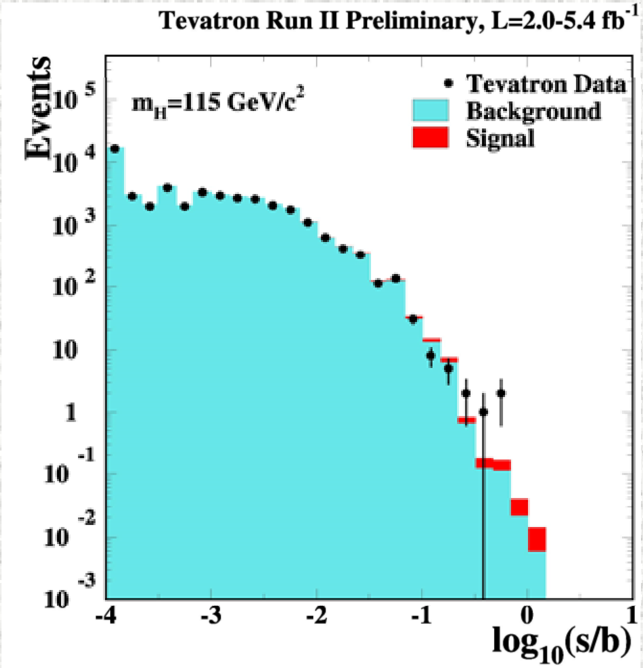
- CDF and DZERO have been in this business for a while now –they have converged to a well-agreed-upon technology
- Limits are computed with two different methods to keep things under control
- The combination is a tough business! Some simplifications and short-cuts which appear to detract nothing from the results are applied
- Base of data for Nov 2009 combination:
  - CDF: analyses based on 2.0/fb – 4.8/fb datasets
  - D0: analyses based on 2.1/fb – 5.4/fb datasets
- Considered production processes: basically ALL OF THEM
  - gg→H; qq→WH; qq→ZH; VBF qqH; qq(gg)→ttH
- Considered decay modes: H→bb; H→$\gamma\gamma$; H→$\tau\tau$; H→WW
- 90 mutually-exclusive final states:
  - 36 for CDF
  - 54 for D0
  - these correspond to sub-sets in the analyses: i.e., different dilepton categories, different b-tag subcategories, different jet multiplicities within one signature.

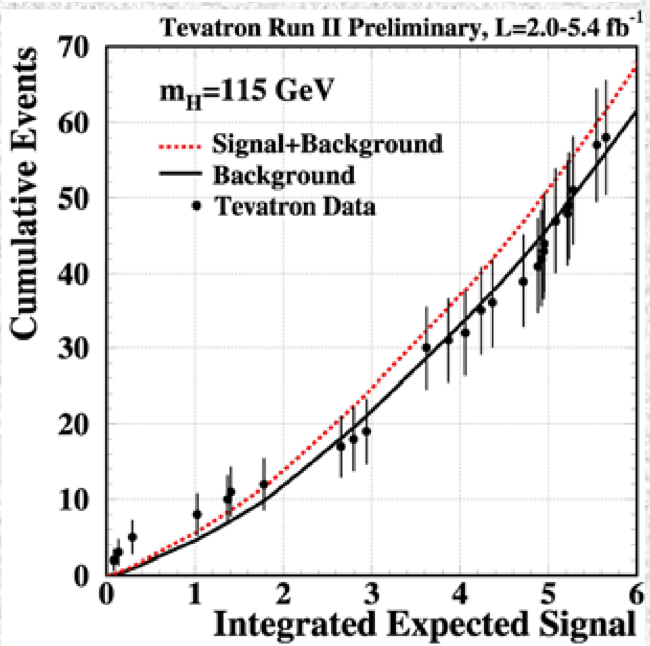
Theoretical inputs

- Lots of advances in the theoretical inputs!
  - reevaluated theoretical uncertainties in gg→H production due to scale and PDF variations, which affect differently each N_{jet} subsample →treat new uncertainties 100% correlated between jet bins & between CDF and D0.
  - Calculation now at NNLL QCD with two-loop EW effects included, and treatment of high-order radiative corrections, especially those involving b-quark loops → xs increased quite a bit from NLO
  - Pythia used for signal generation; state-of-the-art MC used for backgrounds (Pythia, Alpgen, MC&NLO, Herwig, CompHEP); MCFM also used for some W+HF processes
  - Main references:
    - C. Anastasiou et al., JHEP 0908, 099 (2009) Arxiv:0905.3529
    - C. Anastasiou et al., ArXiv:0811.3458
    - D. de Florian, M. Grazzini, ArXiv:0901.2427v2

Technology of the combination

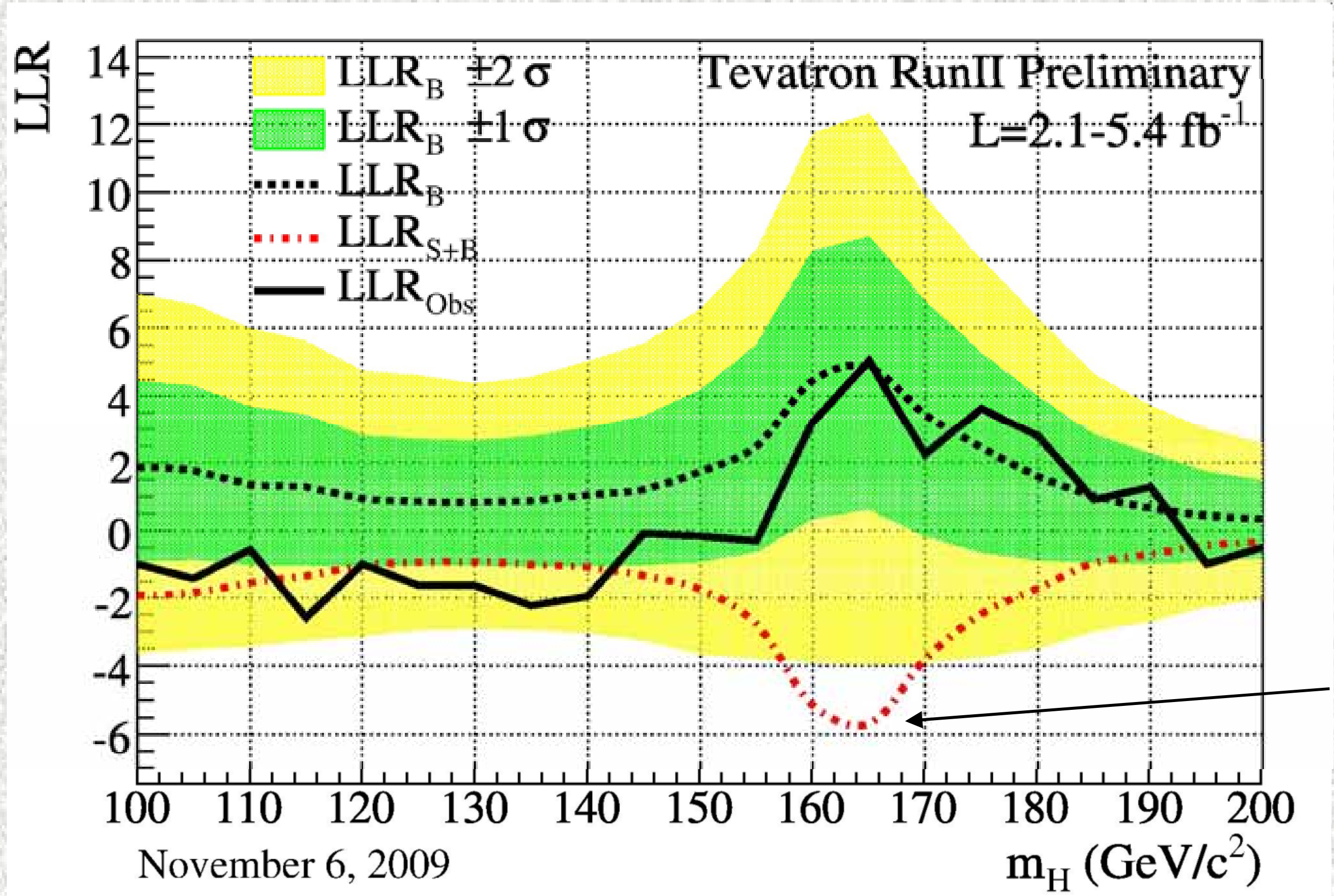
- All analyses provide binned histograms of the final discriminant variables for signal and background predictions, from all sources, and data.
- Histograms may be assembled in ordered-view of equal S/N bins → shown to produce no loss in sensitivity, while simplifying task considerably
- reverse integrals of distributions interesting to examine –provide quick “view” of behaviour and most significant candidates
- Low S/N bins provide feeling of good agreement of background predictions with data





Combined results

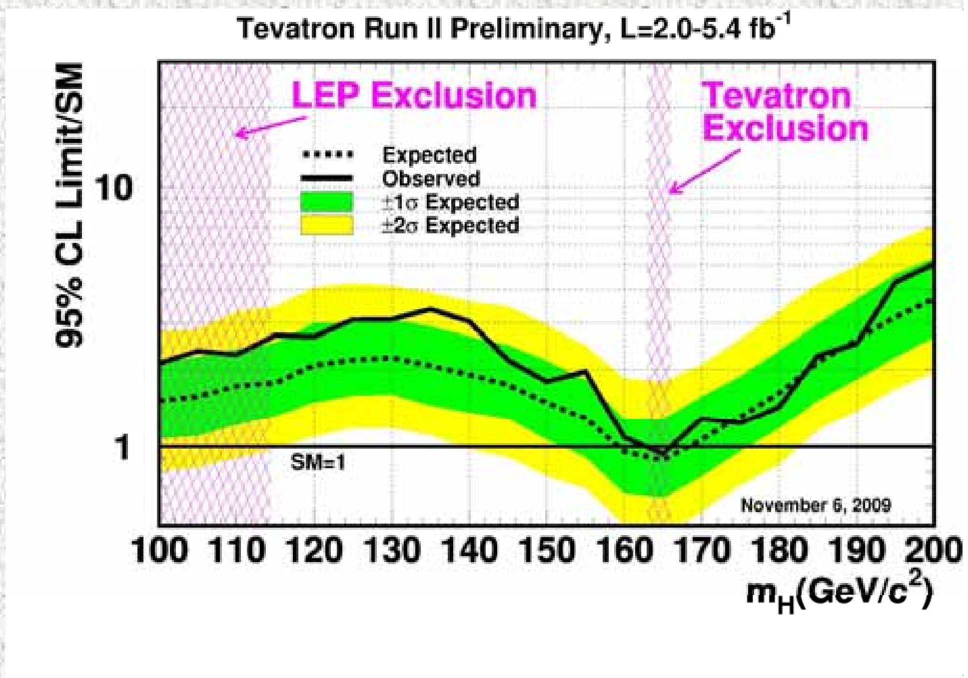
- Let us first of all look at LLR function
- This provides a nice view of sensitivity across the board
- It also shows where the data favors one or the other hypothesis
- LLR is then converted into 95% CL limit as discussed above

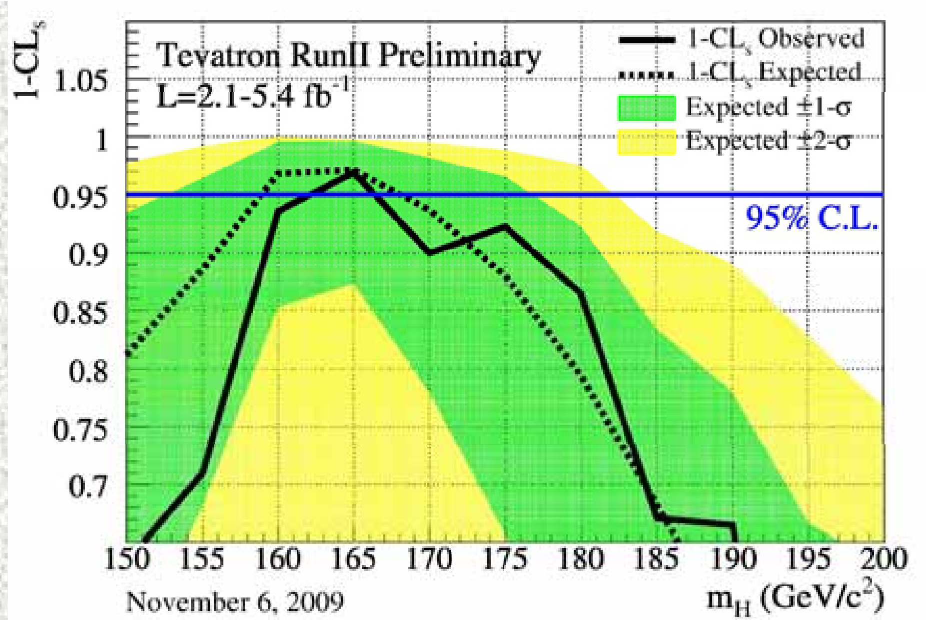


Interesting to note:
a 165 GeV Higgs boson
could already produce
a LLR fluke at ~2.5 sigma

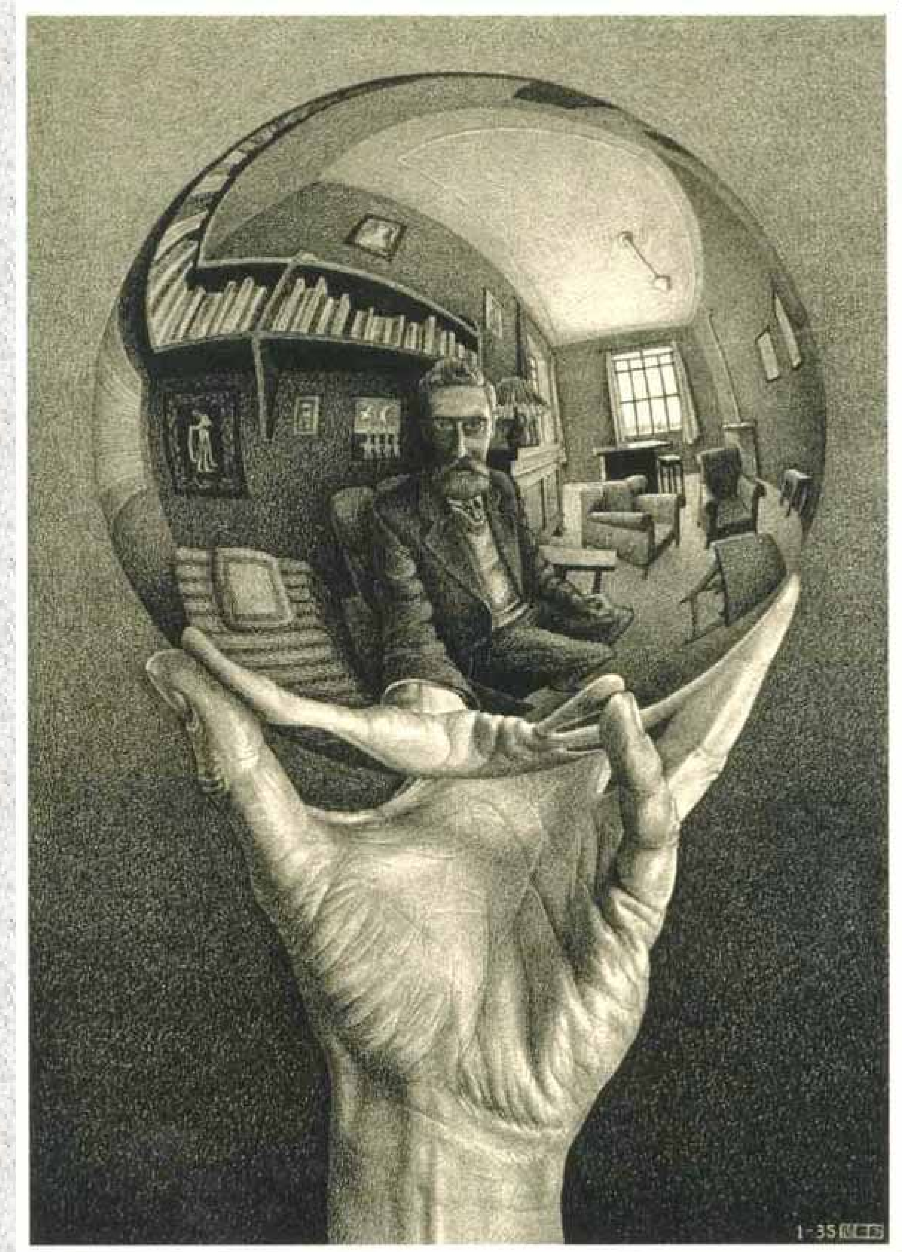
R limits

- Single-experiment combinations:
  - CDF 115 GeV: R<3.10 (exp.2.38)
  - D0 115 GeV: R<4.05 (exp.2.80)
  - CDF 165 GeV: R<1.18 (exp. 1.19)
  - D0 165 GeV: R<1.53 (exp 1.35)
- Tevatron combination: use Bayesian method (*a priori* choice)
  - 115 GeV: R<2.70 (1.78), 165 GeV: R<0.94 (0.89)
  - Turns out to be slightly worse than CL_s - that's life (it sucks)
- Tevatron excludes 163-166 GeV range (expected to exclude 159-168 GeV range)
- 1-CLs shows actual strength of exclusion





The Future

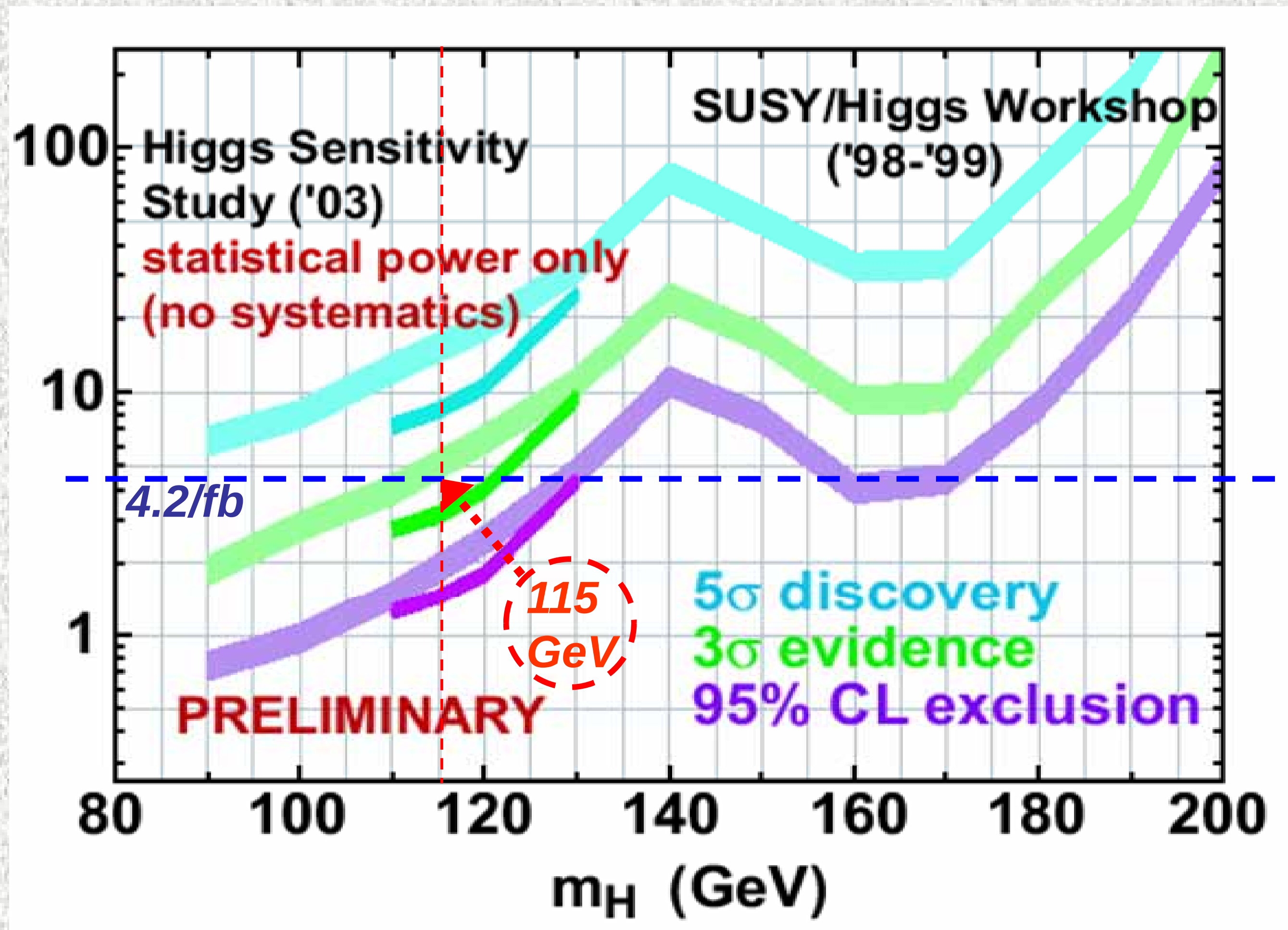


The Future

"To guess the future, you have to know the past" ...

So, in order to make sense of current Tevatron predictions, let us first of all have a look at how well the early predictions for Tevatron sensitivity have worked...

According to the 1999 SUSY/Higgs working group predictions –revised in 2003 after real data was studied by CDF and DZERO- we should be excluding a much wider range of masses, especially below 130 GeV. At 115 GeV FNAL should have close to 3-sigma sensitivity!



- Remember,the silicon upgrades envisioned by the 2003 studies were not financed →significant impact on low mass reach

- Things should be studied with more care... See next slide

Checking past extrapolations

It is possible (although not recommended ☺) to verify how well the Tevatron is doing in the Higgs searches with respect to earlier predictions, by rescaling the expected exclusion limit of the present combination, accounting for the luminosity used in the various channels.

The procedure involves a bit of black magic, some handwaving, and a lot of trust in the magician *–peruse at your own risk!*

The inputs include the luminosity predicted in 1999 to be required by CDF and DZERO to exclude at 95% a given Higgs mass; the luminosity of each of the CDF searches in the past iteration (November 2009), weighted by the square of their expected limits; and the combined 95% CL limit expected by CDF with the data and analyses used.

NB: I do not use the actual result, which is subject to random stat flukes, but the expected limit, which gives a better picture of the experimental sensitivity.

higgs_comparison_pred_exp_cdf

Visualizza Inserisci Formato Strumenti Dati Finestra ?

C	D	E	F	G	H	I	J	K	L	M	N
					Misure a CDF						
		Tev 2000			WH llbb	Lum (fb-1)		VH vvbb	Lum (fb-1)		ZH llbb
Higgs mass		L(95) (fb-1)			exp R lim			exp R lim			exp R lim
		min	max								
100		0,8	1,1		2,7	4,3		3,7	3,6		6,
110		1,3	1,6		3,4	4,3		3,7	3,6		6,
120		2,2	2,8		4,5	4,3		5,5	3,6		8,
130		4,0	5,5		7,5	4,3		8,0	3,6		1
140		9,5	13,0		16,0	4,3		16,0	3,6		
150		6,8	9,0								
160		3,5	4,5								
170		4,0	5,0								
180		8,0	12,0								
190		20,0	27,0								
200		70,0	90,0								

Recipe

- Take CDF November 2009 combination as a starting point
- Luminosity employed is different for different searches → obtain weighted average at each mass point by scaling individual analysis luminosities by square of expected limit on R at that mass

$$L_{eq}(m_H) = \frac{\sum_{i=channels} \frac{L_i}{R(m_H)^2_{i,\exp}}}{\sum_{i=channels} \frac{1}{R(m_H)^2_{i,\exp}}}$$

- Take band of Higgs 99 prediction for $L(m_H)$ @ 95%CL and extract (minimum and maximum) predicted luminosity needed for a 95% CL exclusion of SM Higgs production (i.e. at R=1), $\mathbf{L^{95}_{Higgs\ WG1999}}$
- Obtain R which should be excluded by the weighted CDF luminosity (assume DZERO==CDF →scale by $2^{1/2}$)

$$R(m_H)^{95}_{\exp.CDF\,09} = \sqrt{\frac{2L^{95}_{HiggsWG\,1999}}{L_{eq}(m_H)}}$$

- Compare with $R(m_H)$ *actually obtained* by CDF in 2009 by computing double ratio **O** (optimism factor):

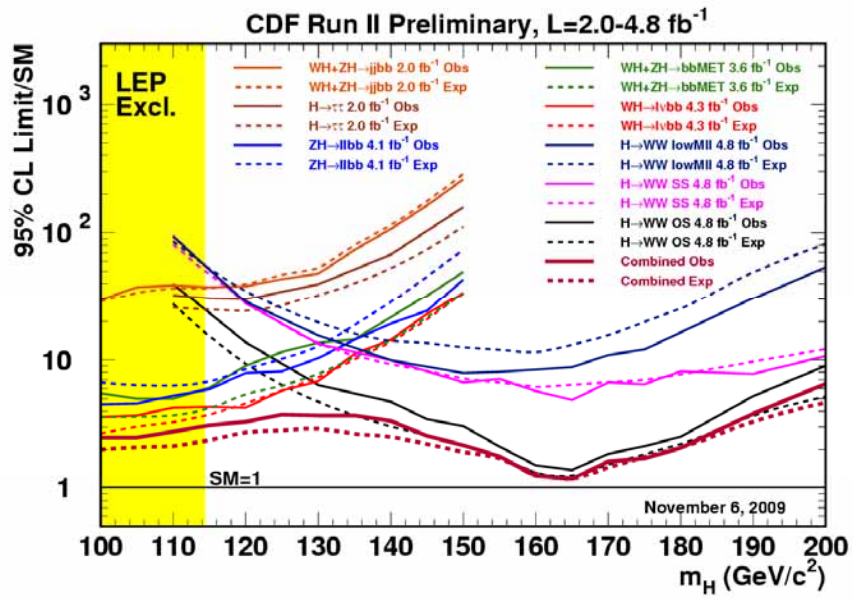
$$O = \frac{R(m_H)^{95}_{CDF\,09}}{R(m_H)^{95}_{\exp.CDF\,09}}$$

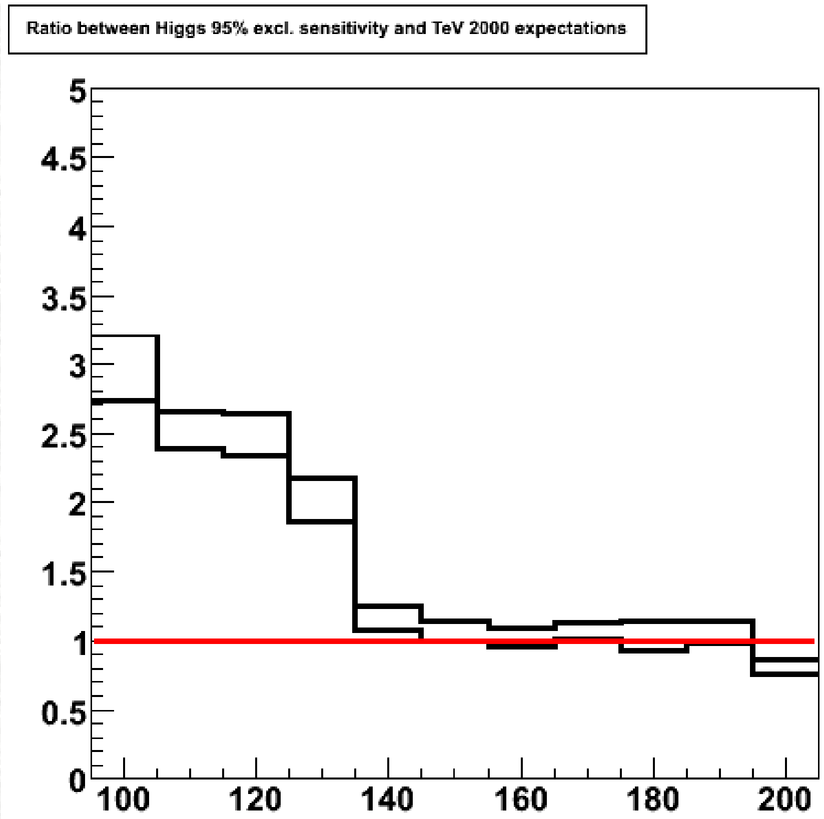
NNBB as justified above, by "actually obtained" I mean the limit expected by CDF given the analyses methods and the size of the datasets, NOT the one observed

Results

- The two black lines show lower and upper bounds (roughly at 1σ) for the ratio between the CDF combined 95% limits with up to 4.8/fb, and predictions based on the TeV 2000 study.
- Amazing agreement at high mass!
- At low mass, predictions wrong by x2.5 ← partly justified by lack of financing of silicon upgrade (forward b-tagging, higher efficiency)
- *Personal feeling:*

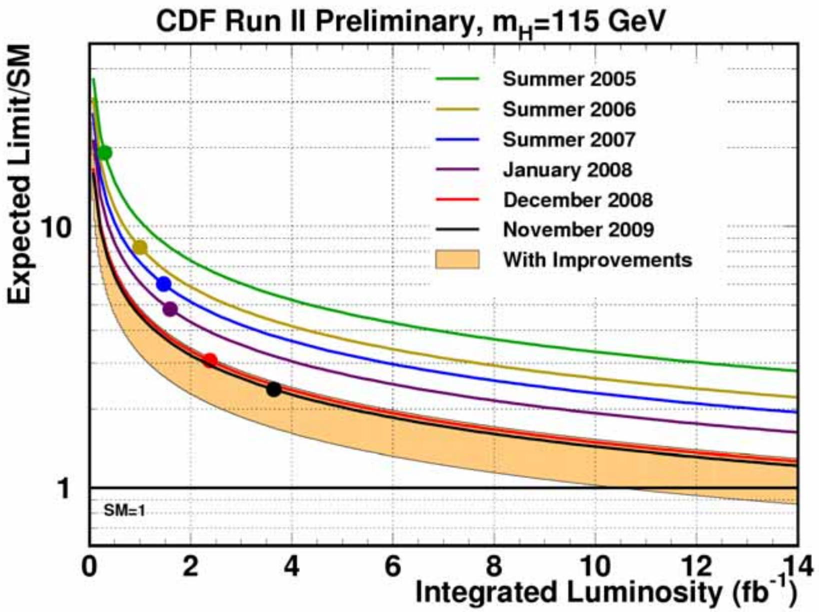
  Overall, I am way more impressed by the high-mass agreement than bothered by the low-mass optimism!

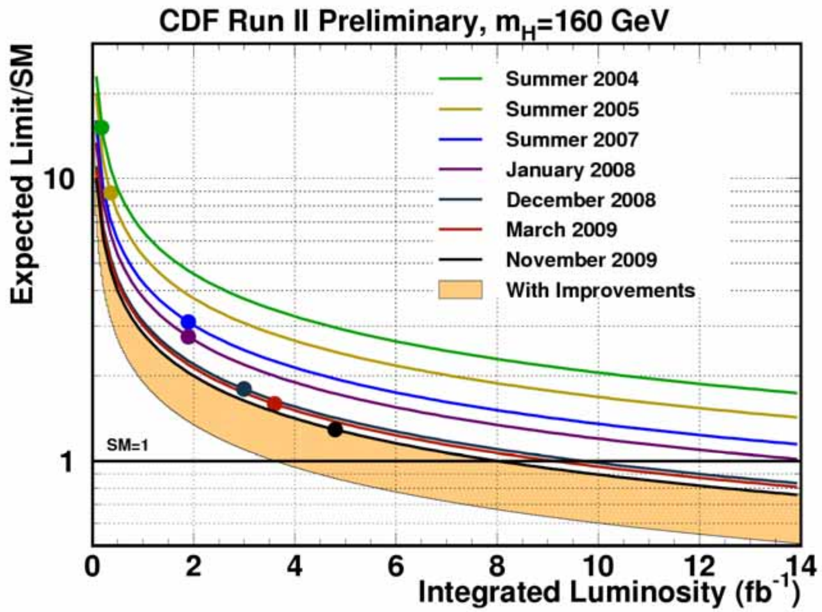




The future according to CDF

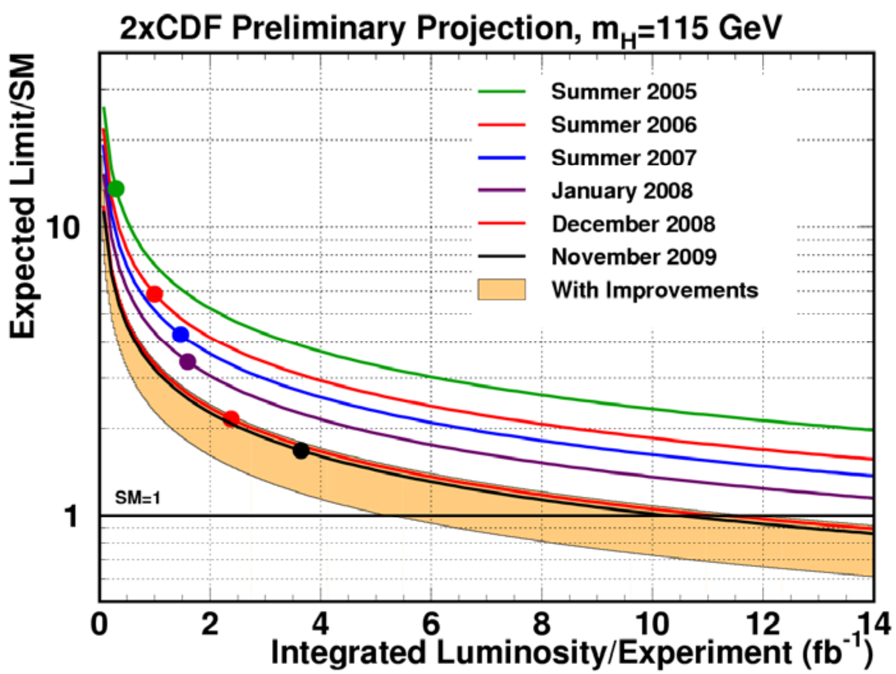
- Of course, the 2000 and 2003 predictions are the physics equivalent of the Neolithic. Better to use the present results for the expected limit as a function of luminosity, and guesstimate what else is left to **change** future performances
- Mass points at 115 and 160 GeV are taken here as a benchmark
- One observes that indeed, the progress of data analysis techniques and the formidable dedication of a hundred brilliant minds *have proven equivalent to a factor 5 in luminosity!*
- One also sees that **CDF does not foresee much additional improvement in the future** (light brown bands at the bottom) –pretty much they out-did themselves already to get here.

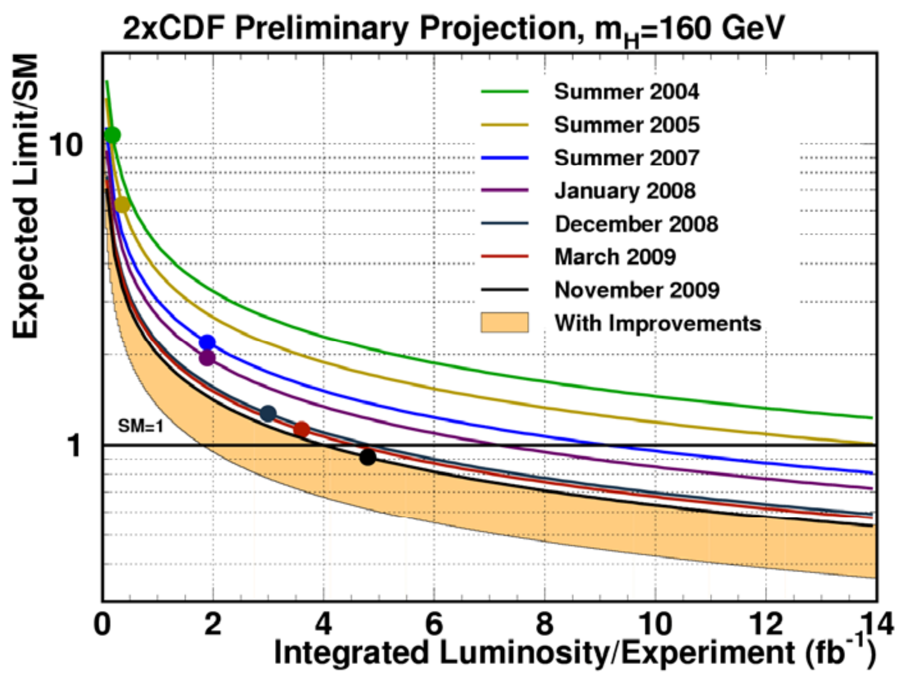




DZERO==CDF →Tevatron=2xCDF

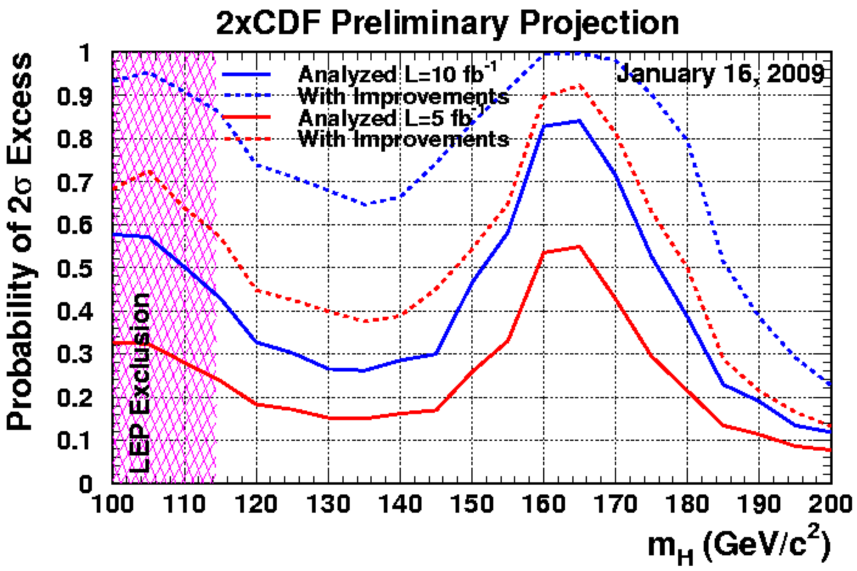
- We may rescale the plots of the previous slide to make up for the lack of similar DZERO prediction figures, to see what is to be expected by the Tevatron combinations
- Together with present R limits and previous extrapolations, these plots indicate (at least to me!) that the Tevatron can exclude the mass range $115<M_H<180$ GeV with integrated luminosities of O(10/fb)/exp.
- Given the way the Tevatron is running, that much data should be in the bag by 2012.

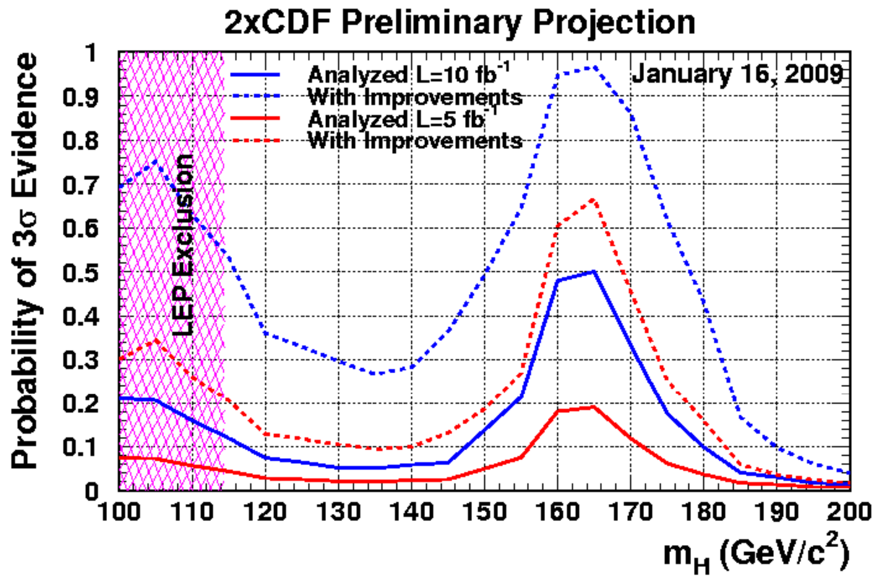




Turning it into discovery prospects

- As if the previous exclusion reach graphs were not enough, **CDF also produced some plots that sent real cold shivers down the spine of the European experiments**
- These show the probability that, by combining 5/fb or 10/fb results of CDF and DZERO, a signal can be found, at the 2-sigma or 3-sigma level
- **The odds look pretty large!**





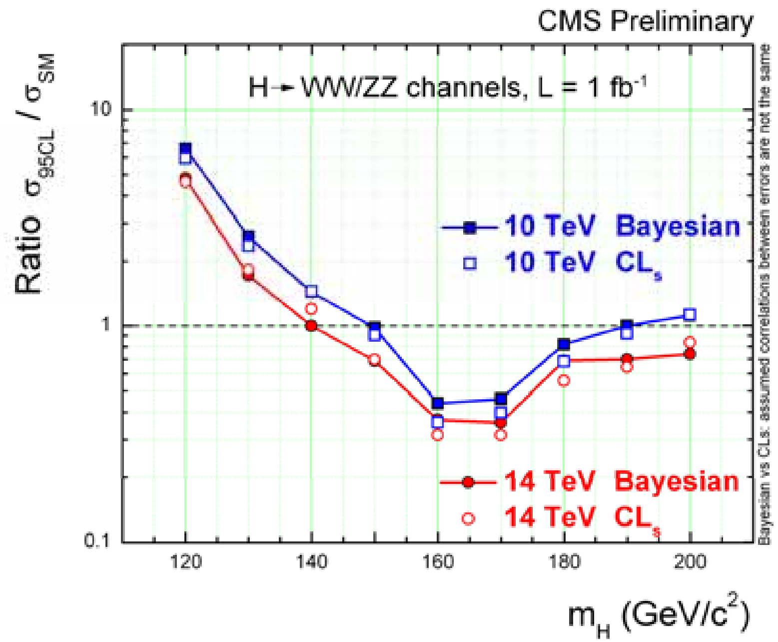
- However, please consider:
  - no provision for how likely it is that the Tevatron delivers that luminosity is accounted
  - no provision is made for shortcomings of CDF and DZERO (technical problems, worsening of silicon performance, etc.)
- All in all, these figures show a very optimistic view of the future. But it is right to be otpimistic, with such amazing success behind your back!

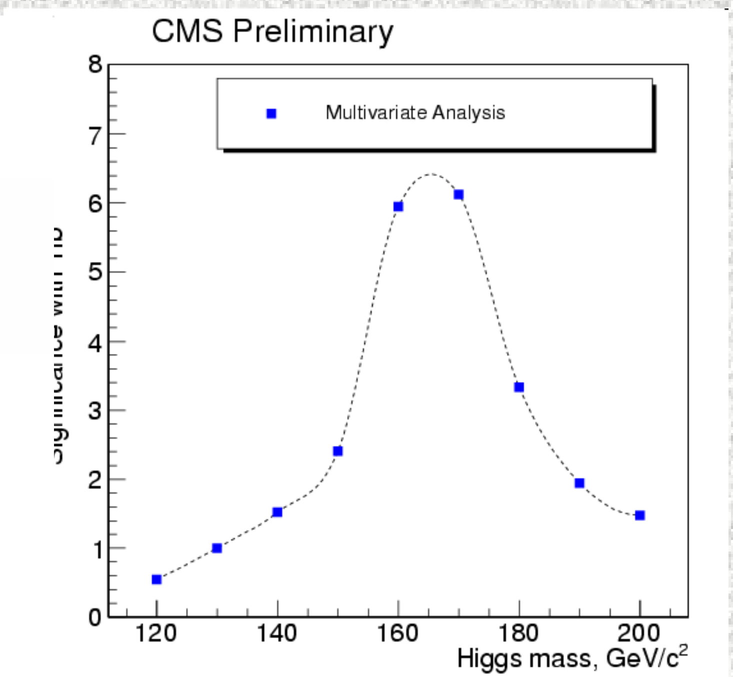
The Future at CERN

In the meantime, on this side of the Atlantic...

- The decisions taken at the Chamonix workshop two months ago implies a continuous running of the LHC until the end of 2011 or early 2012.

- **O(1/fb)** of data are expected to be collected **at 7 TeV cm energy**
- By 2012 CMS and ATLAS, combining their results and adding other channels to **WW and ZZ,** might reach an exclusion limit similar to that shown below (left) for 10 TeV 1/fb CMS only: roughly, **an exclusion of 150-200 GeV mass range**
- It appears possible to reach a 3-4 sigma evidence with 1/fb of data only if the Higgs has a mass close to 160 GeV.





The significance of the H→WW search is shown here for 1/fb at 14 TeV; at 7 TeV the gg→H cross section is two to three times smaller

A few scenarios

Of course, what you saw is just my very own "wild speculation" corner. Use at your own risk.

- The Tevatron experiments have been in the game for a long time already – **their starting advantage is huge**
  - (7/fb)/exp collected by CDF and D0 - already in the bag
  - Tevatron now delivering O(2/fb)/year
  - analysis techniques are quite refined; Higgs searches "run themselves" by now
- However, the x3.5 energy factor is a big asset for LHC
  - The increase in cross-sections is larger at higher mass, but it is big across the board
  - Backgrounds are larger, but critically, so is the S/N
- **Scenario 1**: there is **no SM Higgs** (or similar SUSY thing) to be found. Who gets the better mass limits in 2012 ?
  - The Tevatron should be able to reach down to lower masses better than the LHC; high-mass reach is 180 GeV at FNAL and 200 GeV at CERN. A strong hint that the Higgs is a fairy field might come by a combination of R limits
- **Scenario 2**: the Higgs is at **150 GeV**. Who sees it with the better significance ?
  - The LHC experiments. They might reach a 4-sigma effect by combining channels and effort, while the Tevatron would not exceed 3-sigma
  - In that case, the pressure toward a continuation of the LHC run until a definitive confirmation is achieved would be enormous → **LHC discovers the Higgs in 2013.**
- **Scenario 3**: the Higgs hides at **115 GeV**. What happens ?
  - The Tevatron may be able to find a 2-sigma evidence, more is unlikely
  - The LHC needs to take a long pit-stop, and **a signal has to wait at least until 2014 to be definitively seen**!

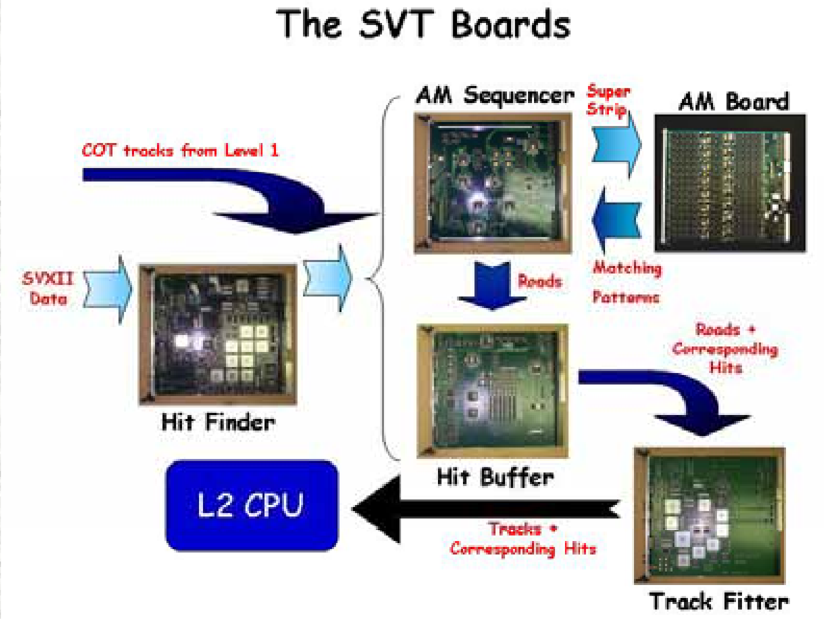
Conclusions

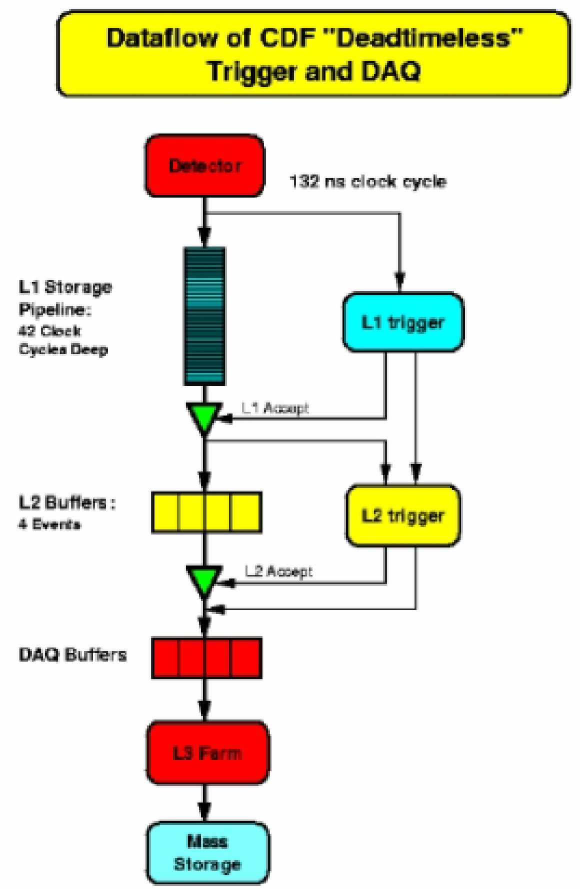
- CDF and DZERO are seriously challenging the LHC experiments in the search for the SM Higgs boson –something which just a few years ago **appeared quite unlikely**
- All the critical analyses are now using aggressive multi-variate approaches
  – This did not fail to raise a few eyebrows, despite the impressive quality of the analyses - hard to let the gazillion details transpire through space-limited public documents
  – CDF shares quite a few very fine statisticians with LHC experiments (Lyons, Demortier, Conway) plus some (Heinrich) – rather silly to assume things are done sloppily
- The experiments regularly combine their results using a well-tested recipe
  – The most recent excluded region is: **! $163<M_H<166$ GeV at 95% CL.**
- **Early predictions for the sensitivity at $M_H>130$ GeV have proven right on the money;** low-mass reach overestimated due to a combination of factors, the largest being the fact that the silicon upgrade was not funded.
- While high-mass searches are arguably going to improve their sensitivity only as sqrt(L), **at low mass there is *some* room for improvement still left**
- Fermilab will most likely **not manage to observe a signal** of SM Higgs at above 3 standard deviations; however, if the particle is not there **the experiments might come first to exclude the whole mass range allowed by EW fits** before LHC does.
- **However it goes, these are exciting times for experimental HEP!**

Back-up slides

The CDF trigger

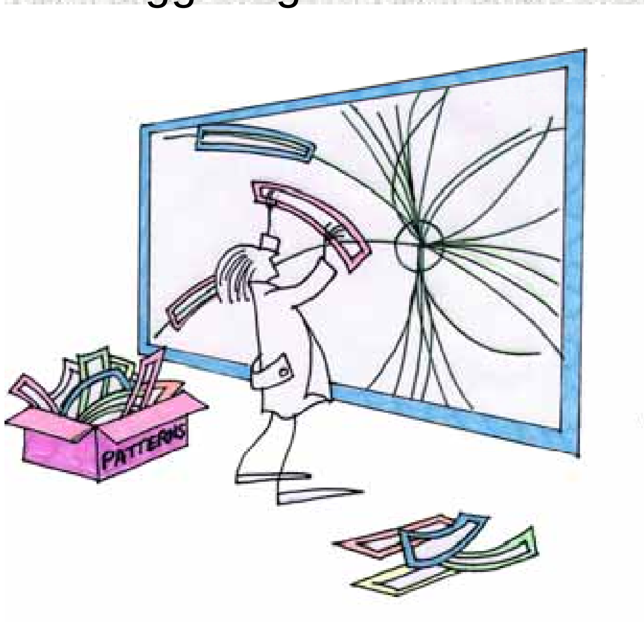
- A three-level system
  - L1 selects primitives for interesting objects:
    - muon stubs with slope compatible with high-P_t
    - tracks in COT using fast hardware, XFT
    - EM, HAD towers above thresholds
    - pipelined, decision in 5 μs
  - L2 has ~30 μs to perform a full reconstruction with dedicated hardware boards
    - SVT finds d_0 , P_t and ϕ of tracks above 2 GeV (see next slide)
    - Hardware cluster finder for jets and electrons
    - input: <35 kHz, output <600 Hz
  - L3 performs offline-quality reconstruction with CPU farm and further reduces rate to 100 Hz

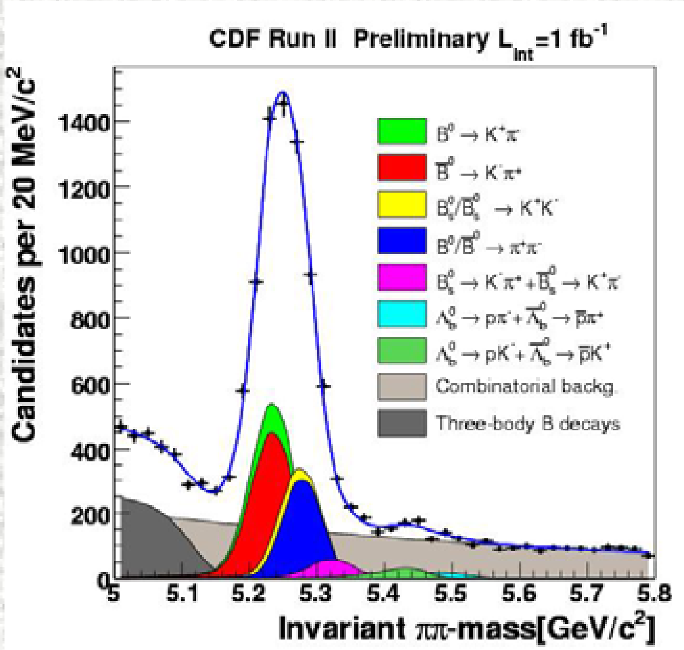




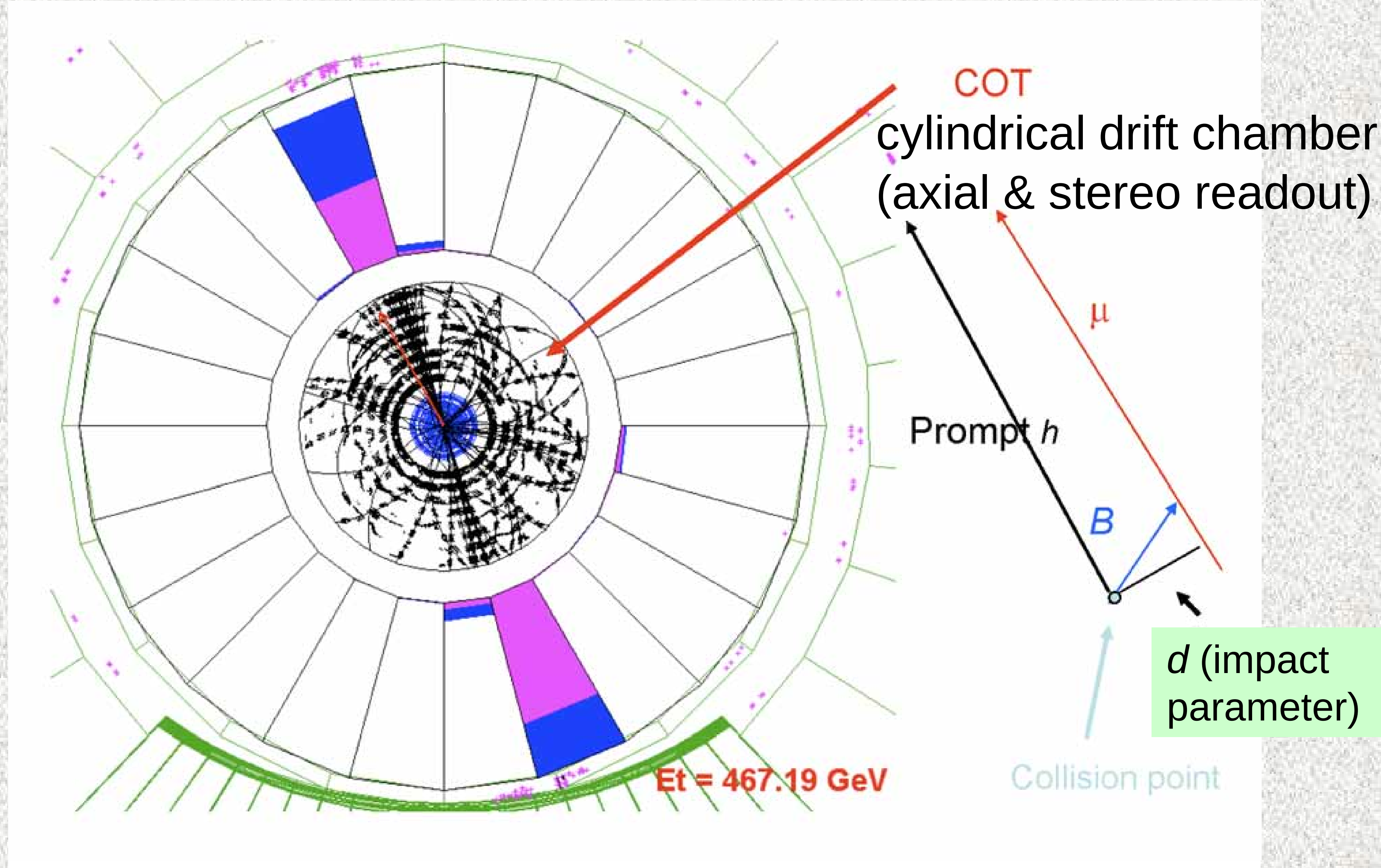
SVT – the Silicon Vertex Tracker

- SVT is a highly-parallelized hardware system which reads out silicon strip outputs, finds hits, merges them into roads, and compares those to patterns stored in associative memory banks
- P_t, ϕ, and d_0 are determined for each track with P_t>2 GeV, d_0<1mm from linearized fits in 20 μs
- The resolution achieved in the measured quantities is comparable to the best one achievable by offline re-fitting
- SVT has opened to CDF the road of studying huge hadronic B decay signals, enabling scores of world-class measurements in the B_s sector (B_s oscillations, lifetimes,...), and discoveries (fully-reconstructed new baryons)
- It also greatly boosts CDF's discovery potential for low-mass Higgs bosons through b-jet triggering





Transverse view of an event in CDF II



The large-M_t limit

For light Higgs, one may take an effective Lagrangian approach and compute things in the limit $M_t \rightarrow$ inf

Taking the limit means collapsing the top-quark loop to a point → the effective vertex replaces the loop, and one gets to compute diagrams with one less loop

Recently sub-leading terms in the large-M_t limit have been evaluated at NNLO

→ The approximation works to better than 0.5% if M_H<300 GeV

(R.Harlander *et al.*,2009)

Two methods for limit extraction

- Two methods are used to gauge the impact of different statistical treatments of the problem
  - Bayesian method:
    - a flat prior is assigned to the total number of selected Higgs events
    - Likelihood is product on bins and channels:

$$\mathcal{L}(R, \vec{s}, \vec{b} | \vec{n}, \vec{\theta}) \times \pi(\vec{\theta}) = \prod_{i=1}^{N_C} \prod_{j=1}^{Nbins} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}} / n_{ij}! \times \prod_{k=1}^{n_{np}} e^{-\theta_k^2/2}$$

    - $\mu_{ij}=Rs_{ij}(\theta)+b_{ij}(\theta)$, where θ is the vector of nuisance parameters (for which truncated G functions are used – truncation prevents negative predictions)
    - Integration of posterior density over all parameters except R provides distribution, R(95) extracted from it

Modified frequentist method

- LEP-style, modified to allow for shape information
- CLs using LLR as test statistics:

$$LLR = -2\ln\frac{p(data\,|\,H_1)}{p(data\,|\,H_0)}$$

- probabilities p are computed using best-fit value of nuisance parameters for each pseudoexperiment, and their variation within G priors.
- Defining

  CL_b = 1- p(LLR<$LLR_{obs}|H_0$) → 1-CL_b prob of observing signal-like data when H0 is true

  CL_{s+b} = p(LLR>$LLR_{obs}|H_1$) → CL_{s+b} describes downward fluke of S and B in data when H_1 is true

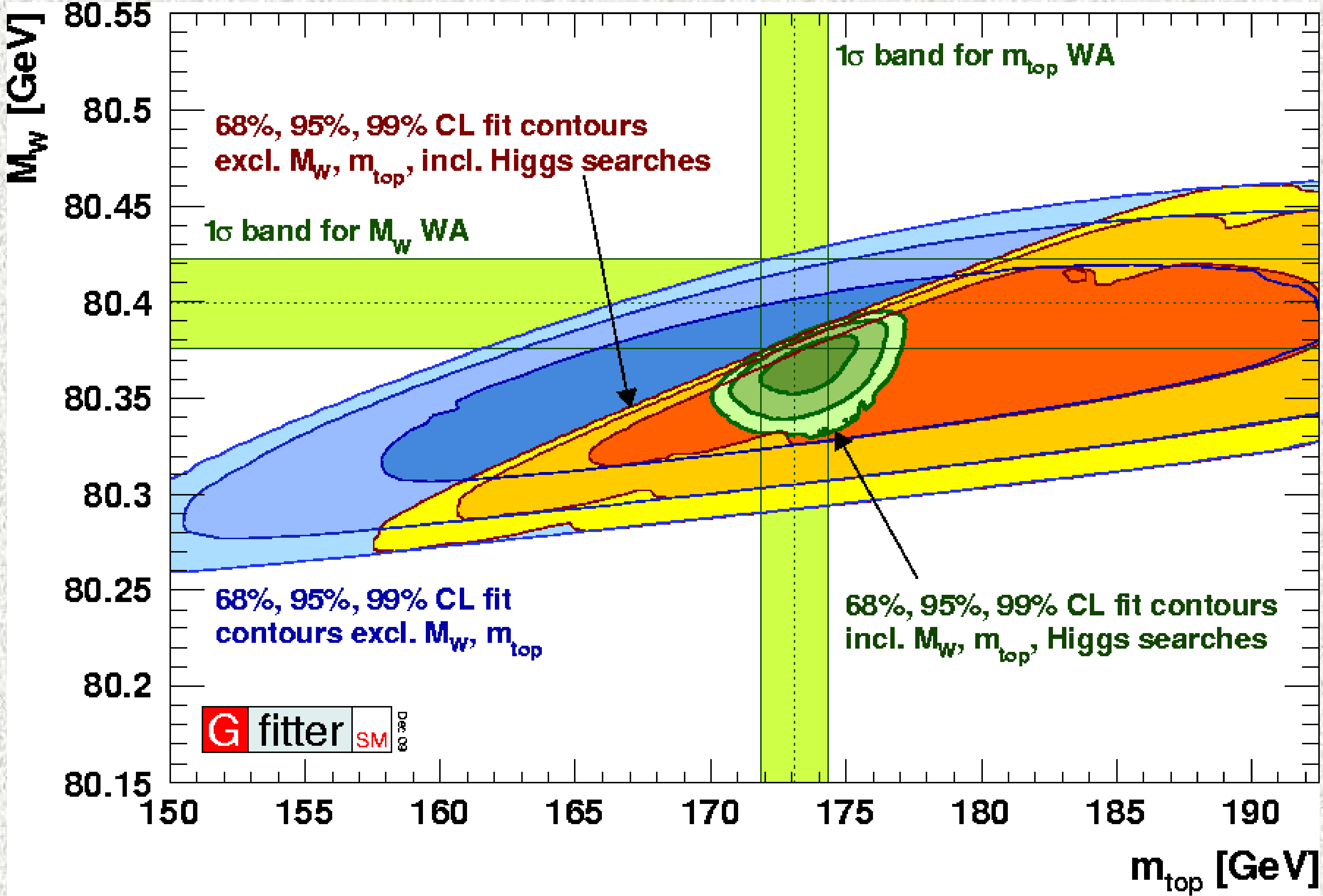
  → to avoid small values of CL_{s+b} due to downward flukes even in cases when experiment is insensitive to expected signal, divide the two:

  $CL_s=CL_{s+b}/CL_b$ is the estimator: if $CL_s<0.05$ for a particular H_1, that hypothesis is excluded at 95% CL.

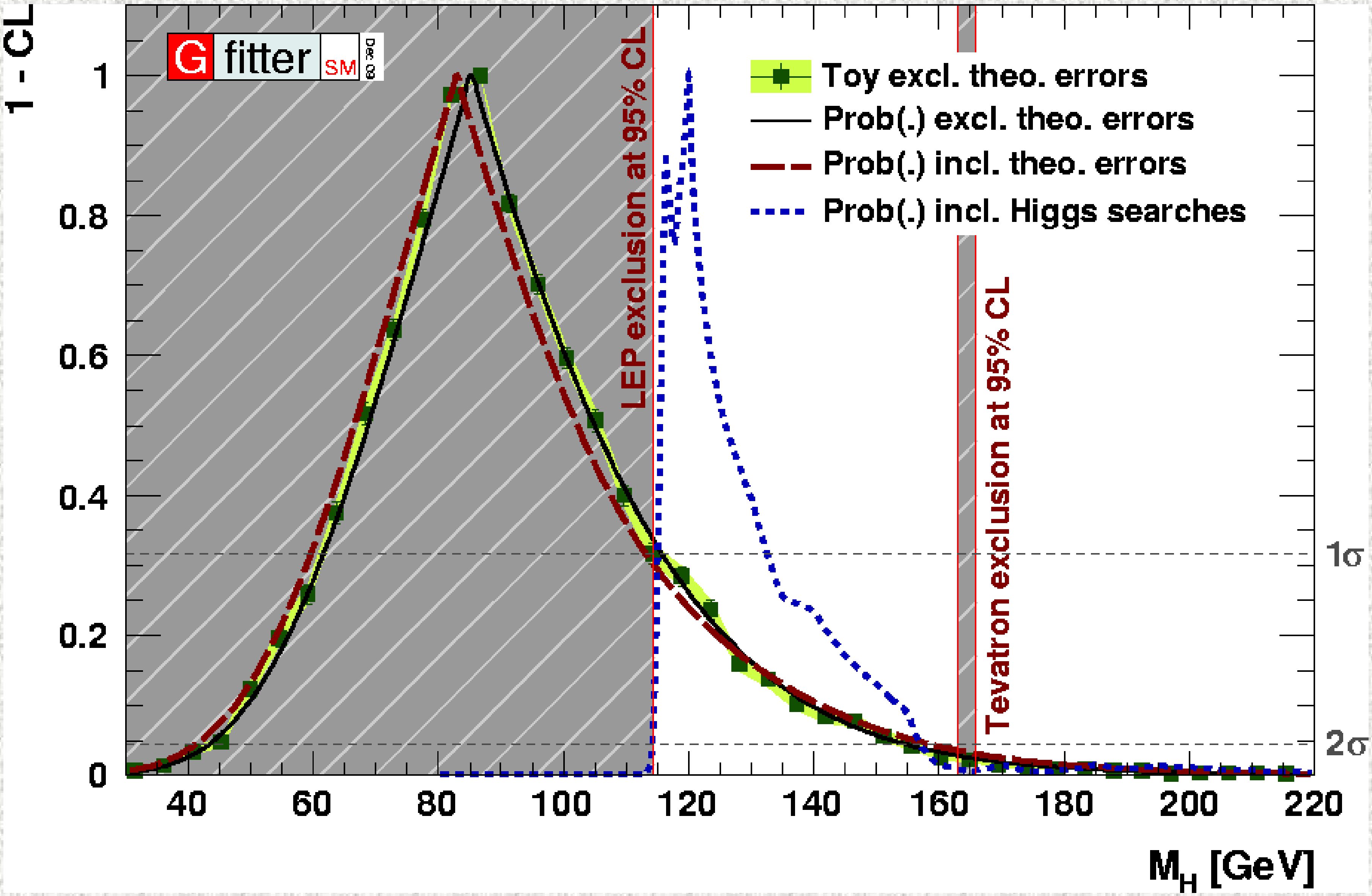
Correlated Systematics

- Huge tables
- Most notable systematics correlated across the ring:
  - Luminosity (6.0/6.1% CDF/D0) has a common part (4%) from uncertainty of inelastic xs
  - xs of several backgrounds
- Correlated systematics within CDF:
  - too many to list. Just a few mentions
    - lepton acceptance,
    - b-tagging scale factor,
    - Jet energy scale
  - etcetera
- Correlated systematics within D0:
  - too many to list
    - b-tagging rate
    - jet energy scale and resolution
    - W+hf background normalization
    - multijet backgrounds
    - cross-sections for simulated backgrounds
  - etcetera

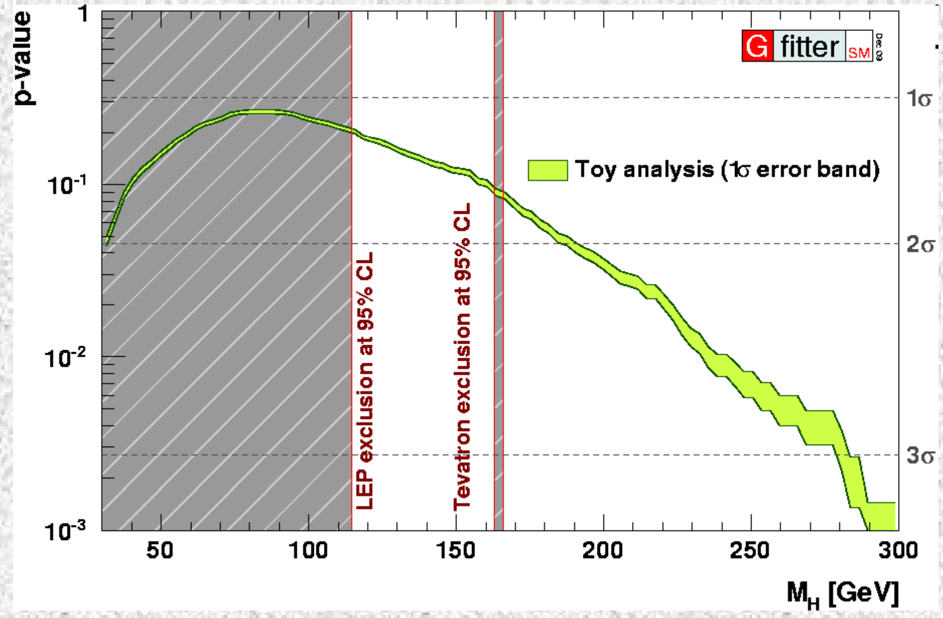
GFitter add-ons - 1

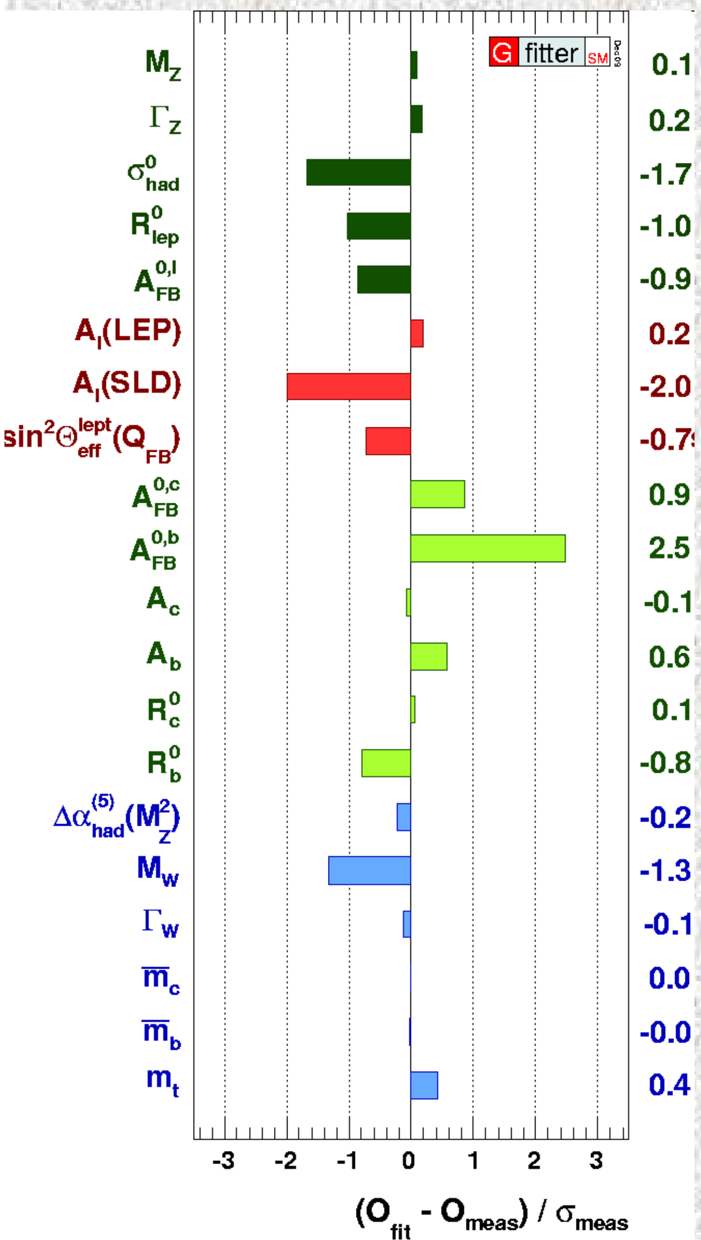


GFitter add-ons - 2



More detail

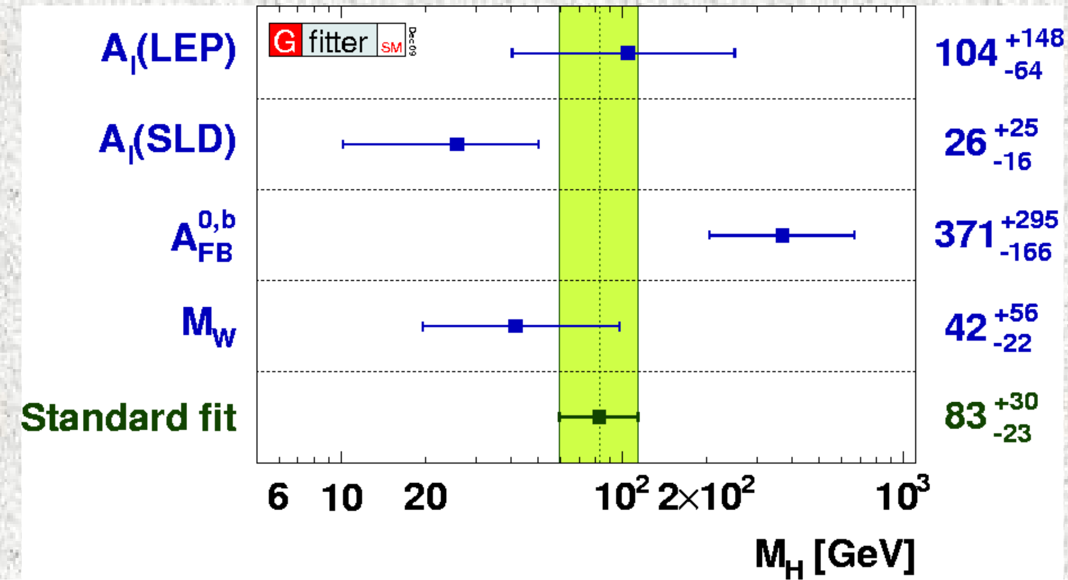




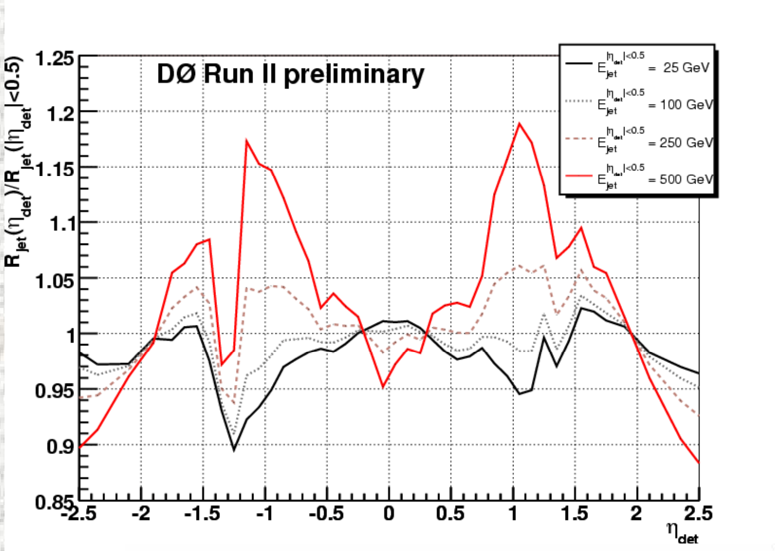
Above: p-value as a function of M_H from a toy analysis (excluding limits!)

Left: pulls of the complete fit

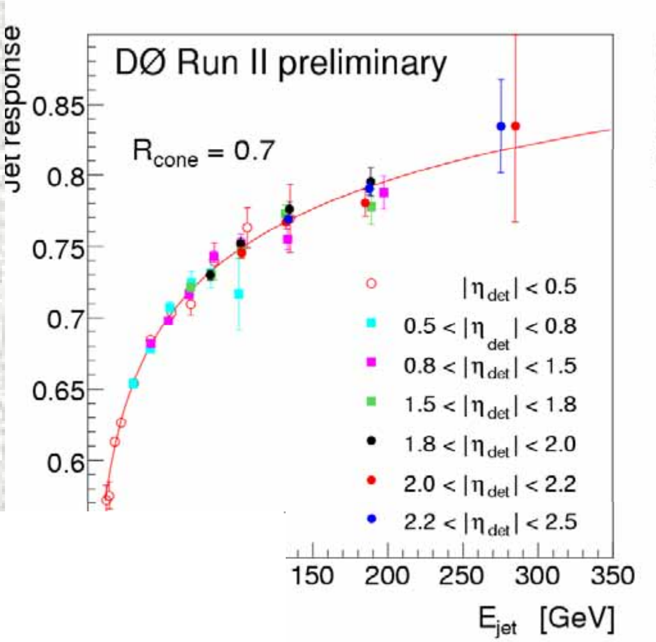
Below: using only one sensitive var at a time...

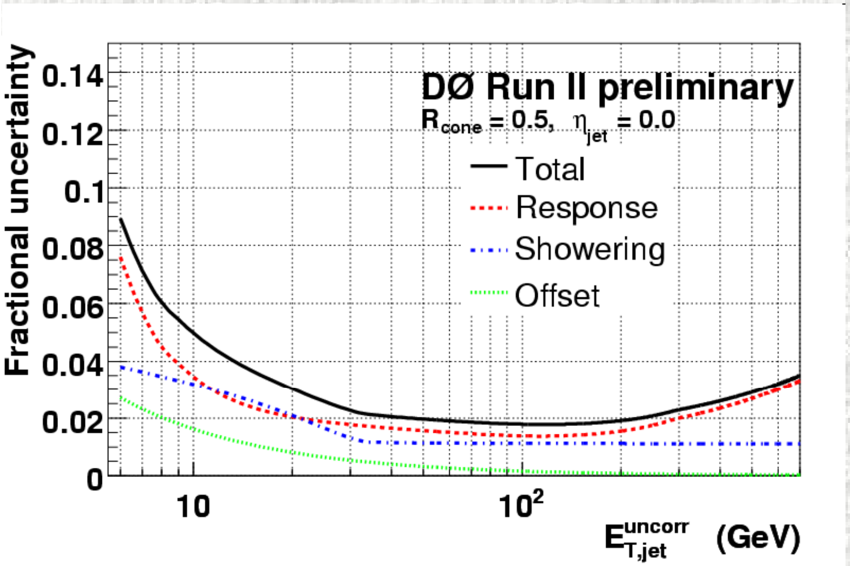


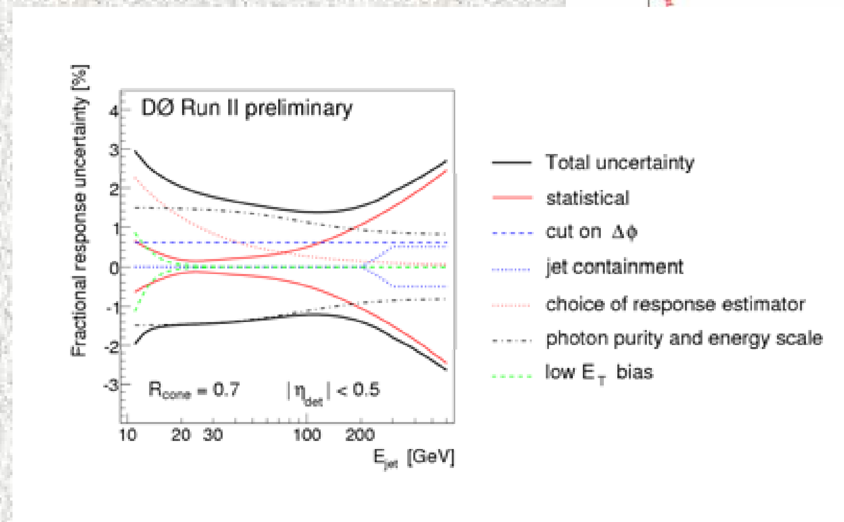
Jet energy scale



- Both CDF and D0 adjust jet energies back to generated-jet level (and parton-level when needed) with a series of corrections, the most relevant being
  - η-dependent detector equalization
  - – absolute energy scale
  - – out-of-cone losses
- The uncertainty on the scale and the resolution are verified with several methods (γ-j balancing, Z-j balancing)
- Run-II advance: use W→jj in top decays to fit top mass simultaneously with JES → reduce uncertainties







Details of selection

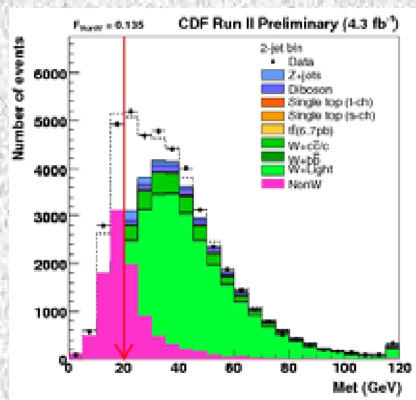
Event Selection for Lepton Triggered Events				
Category	Double SECVTX	One SECVTX + One JetProb	One SECVTX + One NN b-tag	One SECVTX
Lepton	Central isolated electron or muon and Plug isolated electron (Pt>20 GeV)			
Missing Et	> 20 GeV(Central), > 25 GeV(Plug)			
Two Jets	> 20 GeV, |η| < 2.0			
b-tagging (one jet)	tight SecVtx b-tag			
b-tagging (another jet)	tight SecVtx b-tag	JetProb b-tag	NN b-tag	No b-tag
QCD veto	Plug electron only			QCD Veto

First b-tag always SecVtX, second may belong to either of 2 categories
Missing E_t cut depends on quality of electron
Single b-tags and plug ele events get additional QCD veto to increase signal purity
Jet E_t cut tighter if jets are trigger objects

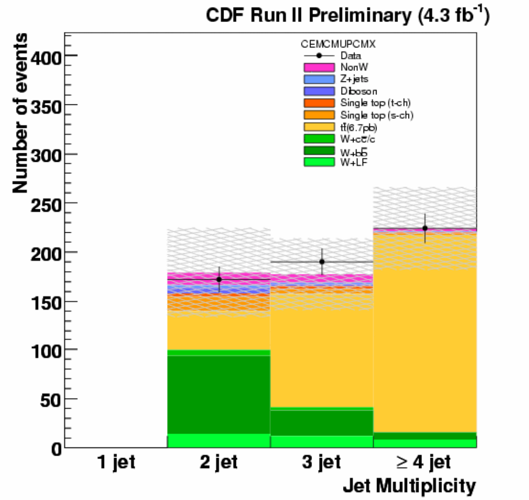
Event Selection for (MET + 2 Jets / MET) triggered Events				
Category	Double SECVTX tag	One SECVTX + One JetProb	One SECVTX + One NN b-tag	One SECVTX tag
Lepton	Isolated track (Pt > 20 GeV)			
Missing Et	> 20 GeV			
Two Jets	> 25 GeV (MET + 2 Jets), > 20 GeV (MET), |η| < 2.0			
b-tagging (one jet)	tight SecVtx b-tag			
b-tagging (another jet)	tight SecVtx b-tag	JetProb b-tag	NN b-tag	No b-tag
QCD Veto	No QCD Veto			QCD Veto

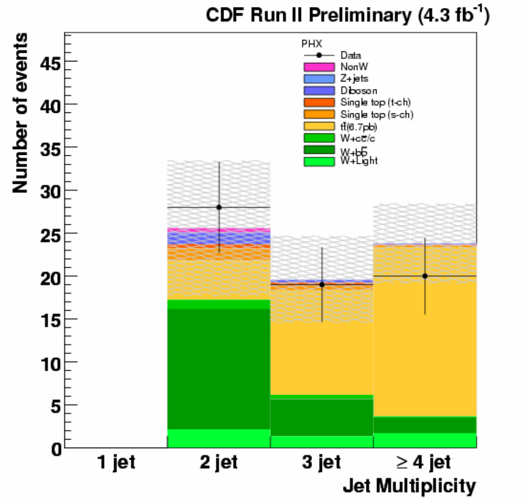
Background estimate and control regions

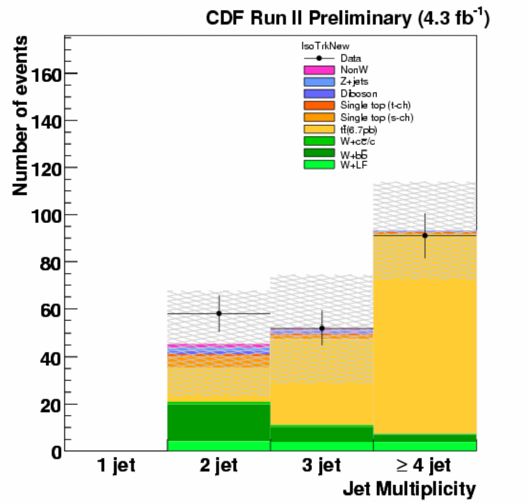
- Two-jet bin is signal-rich, other bins are used to verify background prediction
  - Several background processes affect the search; the most significant are
    - W+bb, W+light flavors
    - ttbar
    - single top
    - dibosons
    - non-W (aka QCD)



- Backgrounds are estimated in a variety of ways
  - Wbb: from W+jets (MEt fits provide fraction) using b-tag matrix for fake b-tags and ALPGEN+PYTHIA for real HF content
  - non-W: using ME_t shape
  - Other backgrounds: from MC
- Good agreement in different control samples, mature technology
  - much of it is >15 years old, used for precise top cross section measurements

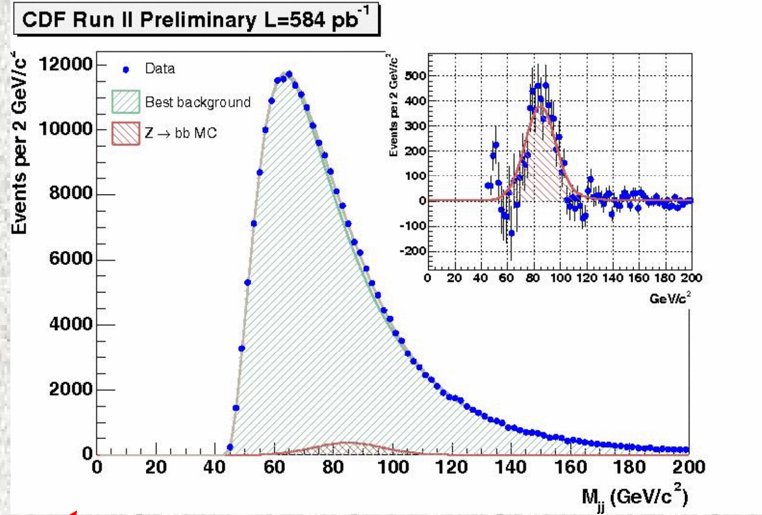




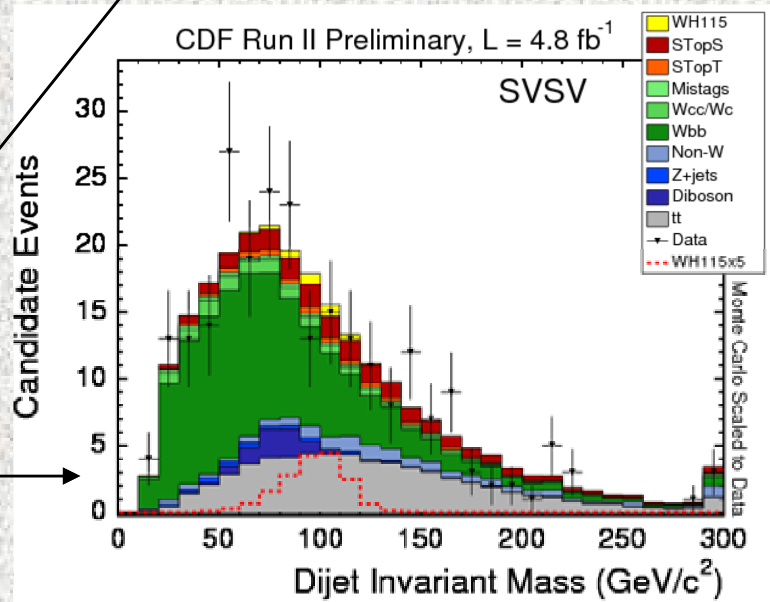


Jet energy corrections

- One of the critical tools for this search
- A variety of attempts have been deployed in the past, with good prospects and mixed success
  - H1-like
  - Particle flow
  - Neural networks
- Studies capitalize on experience gained with generic energy scale corrections, top mass measurements with in-situ W→jj calibrations, Z→bb signal
- Both the mass reconstruction and the transfer functions p→j in the WH analysis use jet energies corrected with a set of 23 Neural Networks
  - 8 inputs describing observed detail of jet fragmentation
    - Divided in b-jet, c-jet, lq-jet, and different signal and background processes
  - better-determined transfer functions improve discrimination power of matrix-element technique
  - Mass resolution not yet reaching goal of 10%, but close (10.5% for 2-btags, 12% for 1-btag)



b-jets in WH evts



- Full formulation of final likelihood for WH analysis in CDF:

$$\mathcal{L} = \prod_{j=2}^{6} G_j(\beta_j;\sigma_j) \prod_{k=1}^{B} \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!} \quad (6)$$

The Gaussian constraints to the backgrounds are given by:

$$G_j(\beta_j;\sigma_j) = \frac{1}{\sqrt{2\,\pi \cdot \sigma_j^2}} \exp\left[-\frac{1}{2} \cdot \left(\frac{\beta_j - 1.0}{\sigma_j}\right)^2\right] \quad (7)$$

$$\mu_k = \beta_{\mathrm{WH}} \cdot T_{jk} + \beta_{\mathrm{single\ top}} \cdot T_{jk} + \beta_{\mathrm{W+b\ jets}} \cdot T_{jk} + \beta_{\mathrm{W+c\ jets}} \cdot T_{jk} + \beta_{\mathrm{mistags}} \cdot T_{jk} + \beta_{\mathrm{t\bar{t}}} \cdot T_{jk} \quad (8)$$

The index k runs over the bins of the fitted histogram. The template histograms are normalized to the predicted number of events as shown in Table III and IV. This means, $\sum_{k=1}^{B} T_{jk} = N_j^{pred}$.

WH CDF Systematics

Central leptons

b-tagging category	Lep Reco	Trigger	ISR/FSR/PDF	JES	b-tagging	Total
One SECVTX tag	2%	< 1%	3.0%	2.3%	4.3%	6.1%
Double SECVTX tag	2%	< 1%	4.9%	2.0%	8.6%	10.3%
One SECVTX tag + one JetProb tag	2%	< 1%	4.9%	2.8%	8.1%	10.1%
One SECVTX tag + one NN b-tag	2%	< 1%	7.7%	2.2%	13.6%	15.9%

Plug electrons

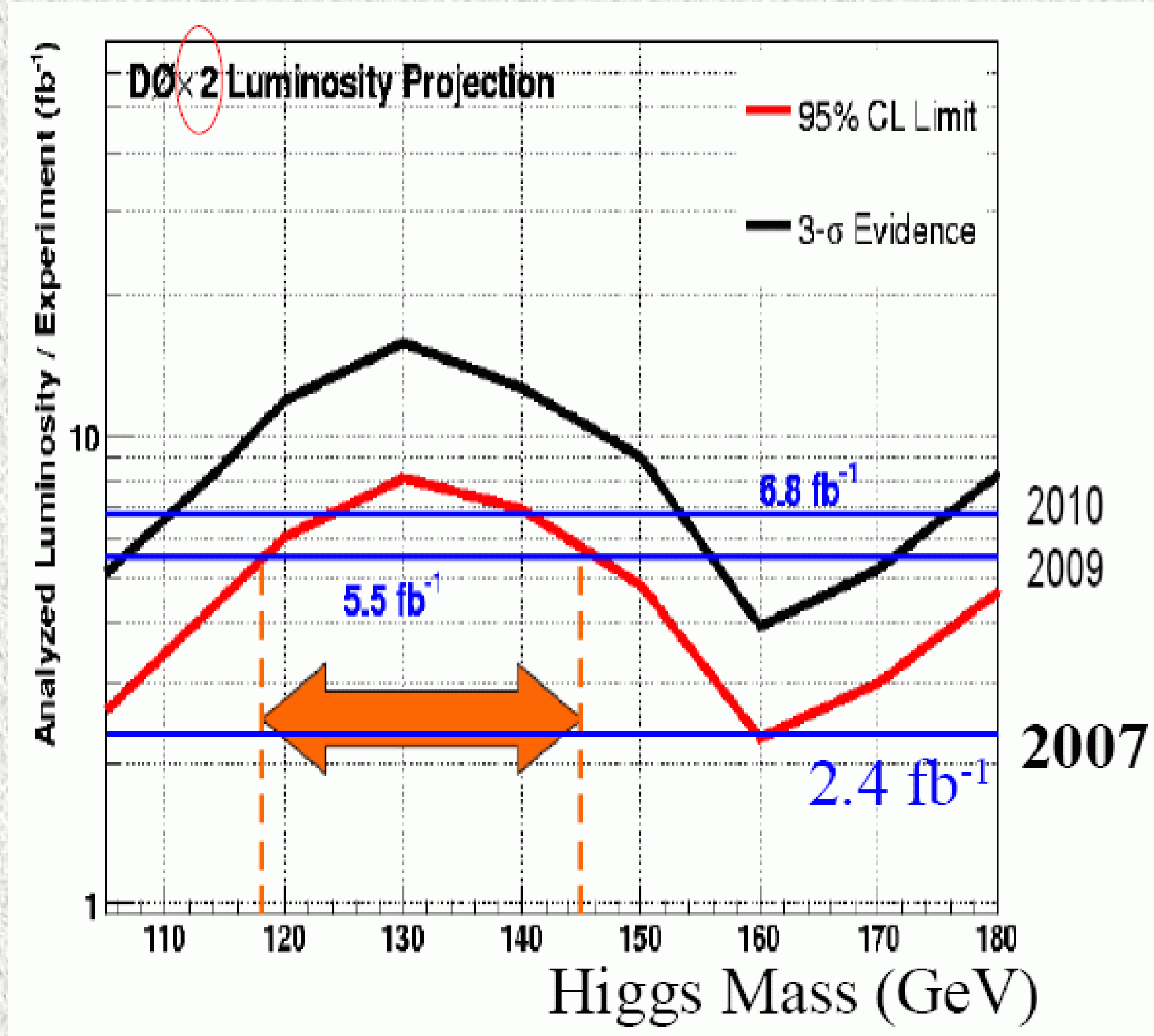
b-tagging category	Lep Reco	Trigger	ISR/FSR/PDF	JES	b-tagging	Total
One SECVTX tag	2%	< 1%	5.7%	2.9%	4.3%	8.0%
Double SECVTX tag	2%	< 1%	7.7%	2.4%	8.6%	12.0%
One SECVTX tag + one JetProb tag	2%	< 1%	4.5%	3.9%	8.1%	10.3%
One SECVTX tag + one NN b-tag	2%	< 1%	12.9%	6.7%	13.6%	20.0%

Isolated tracks

b-tagging category	Lep Reco	Trigger	ISR/FSR/PDF	JES	b-tagging	Total
One SECVTX tag	8.85%	2%	8.4%	4.7%	4.3%	13.9%
Double SECVTX tag	8.85%	2%	7.1%	1.7%	8.6%	14.5%
One SECVTX tag + one JetProb tag	8.85%	2%	6.4%	2.4%	8.1%	14.0%
One SECVTX tag + one NN b-tag	8.85%	2%	19.5%	1.9%	13.6%	25.5%

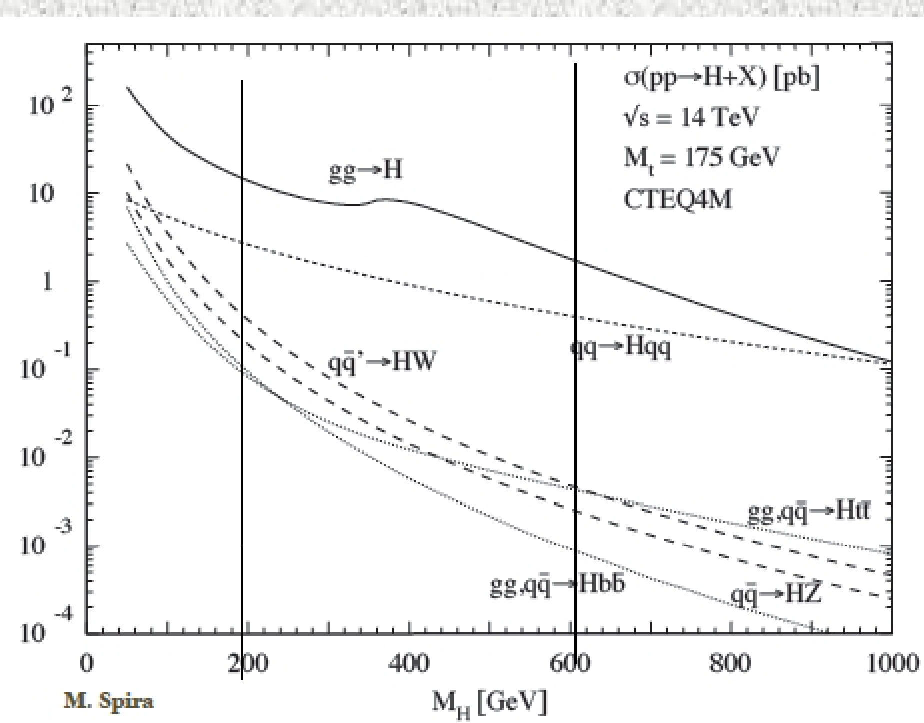
DZERO's view

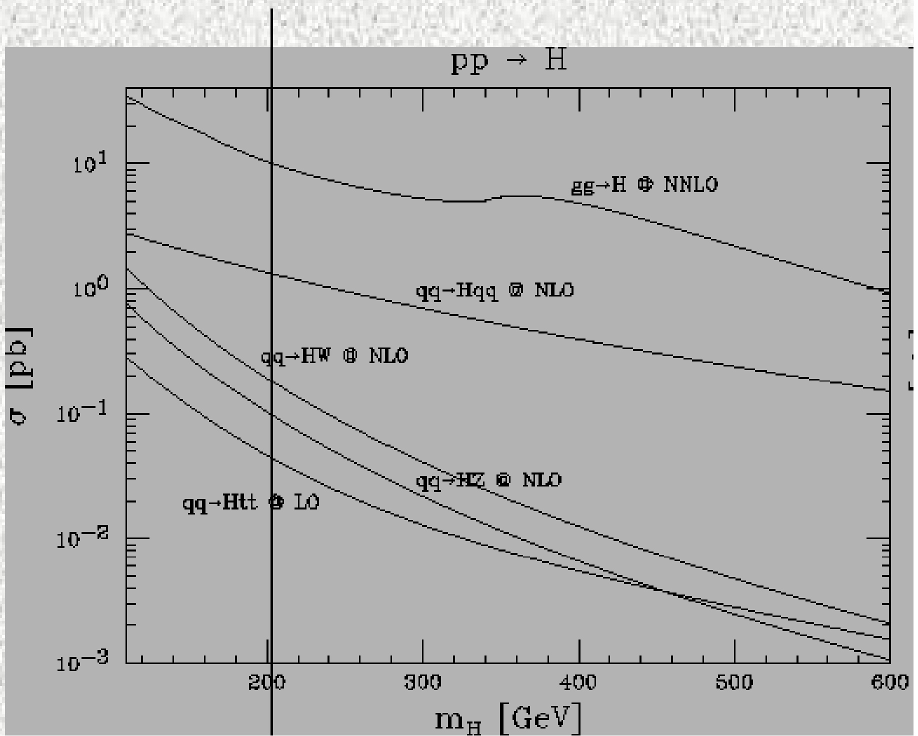
- DZERO also produced extrapolations of their discovery reach in 2007
- Unfortunately their predictions are overoptimistic



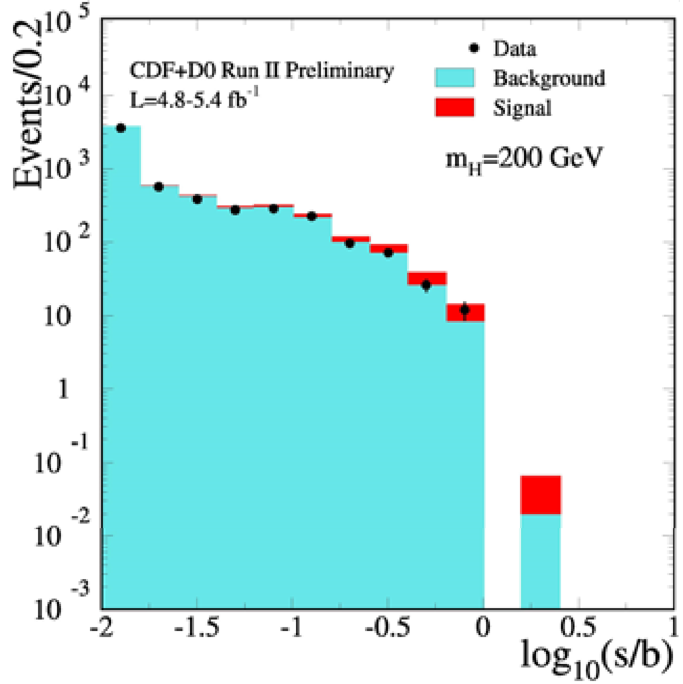
7 TeV vs 14 TeV at LHC

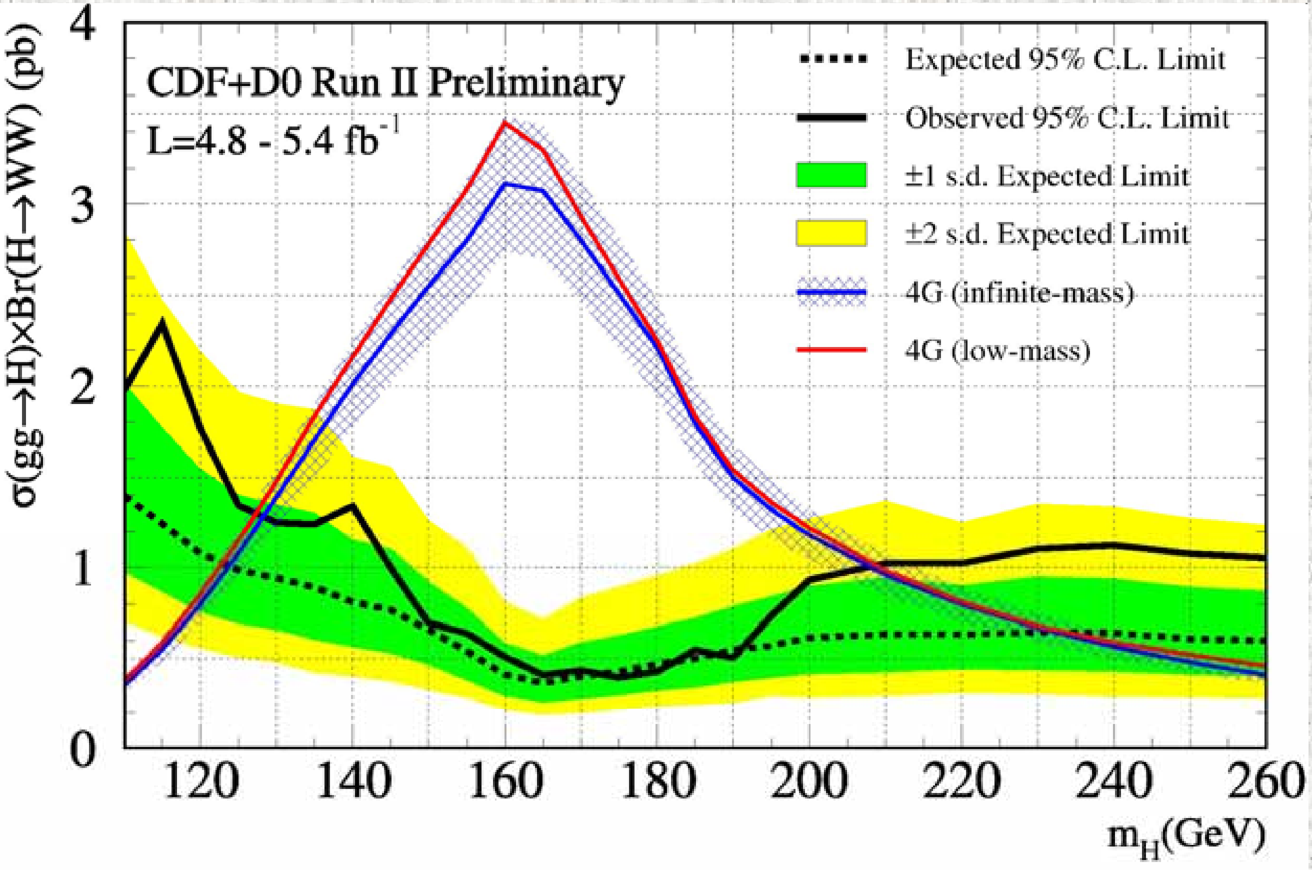
- All Higgs reach predictions of LHC have been done with 10 (or 14) TeV cm energy
- Going down to 7 means taking a hit in signal cross sections
- Recently re-evaluated (and promptly stolen) graph (right)
- Comparison with older 14 TeV evaluation shows decrease is not as large as one might think → due to increases in NNLO results





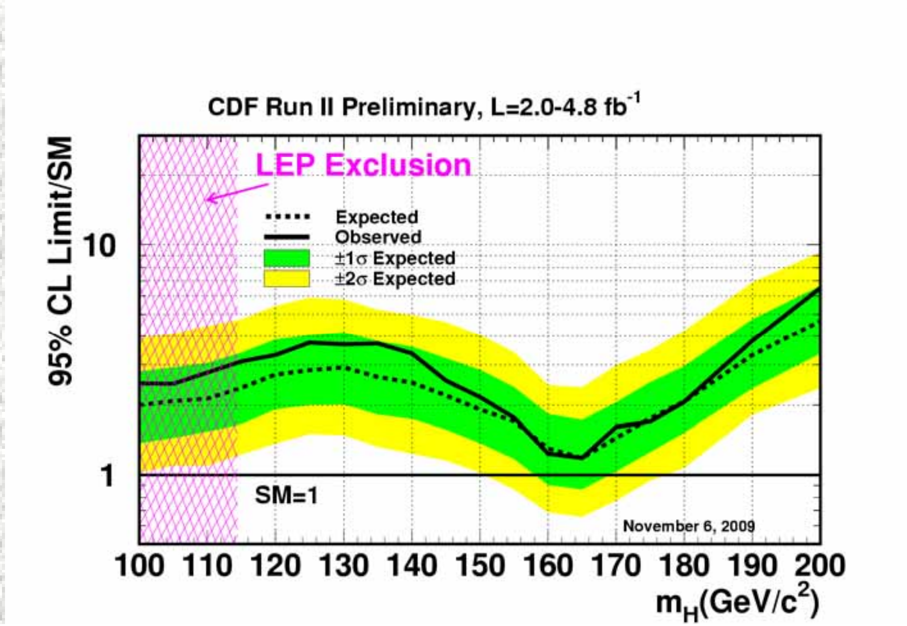
The 4-generations case

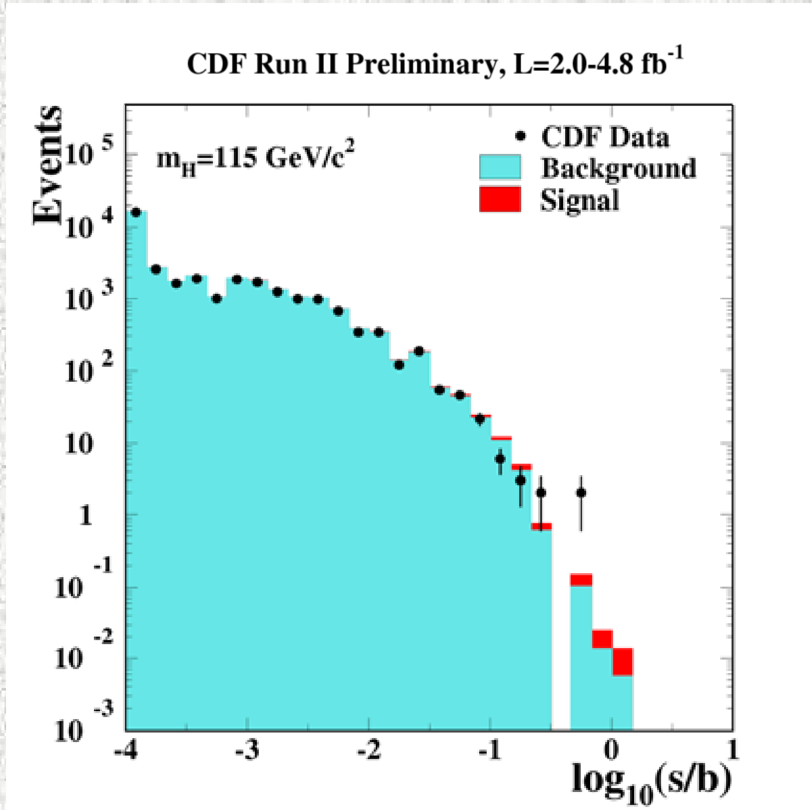


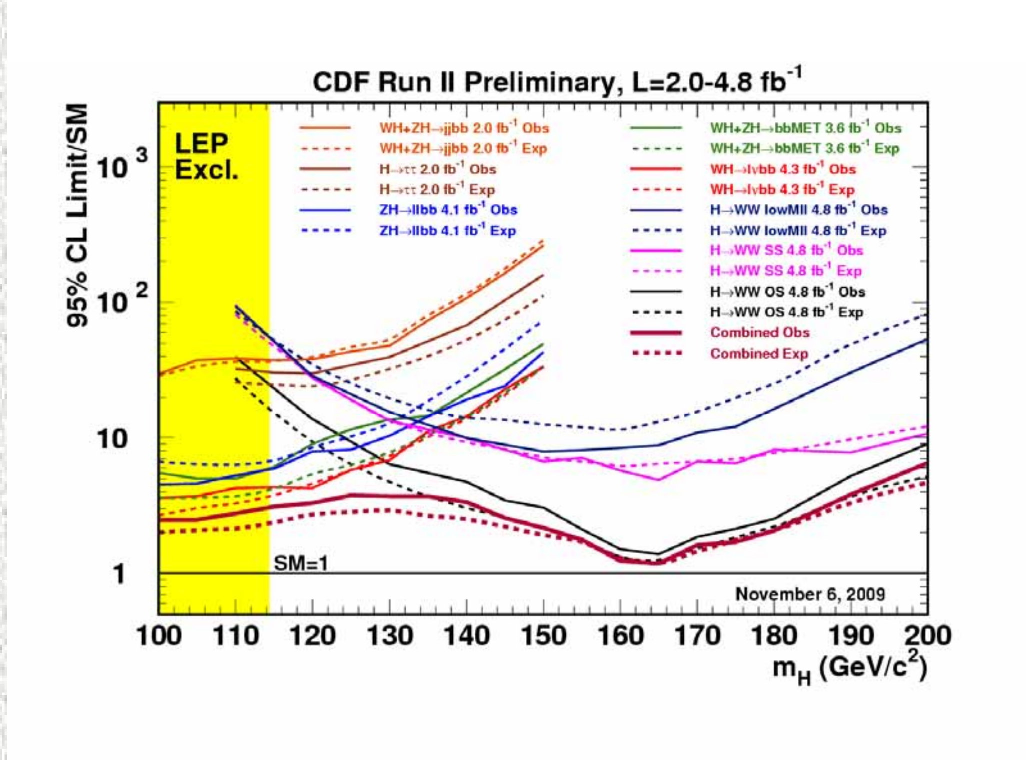


CDF Combination

- CDF combine results of all their searches, performed until november 2009 in 2.0:4.8/fb
- Limit not yet capable of excluding any MH→ this is really a Tevatron-wide business

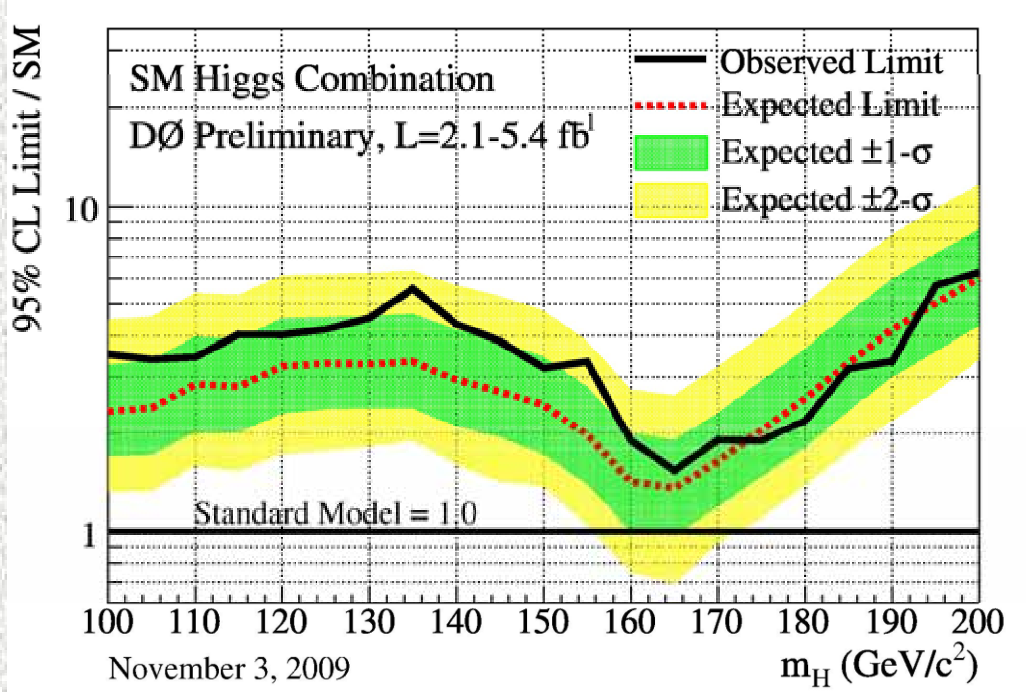


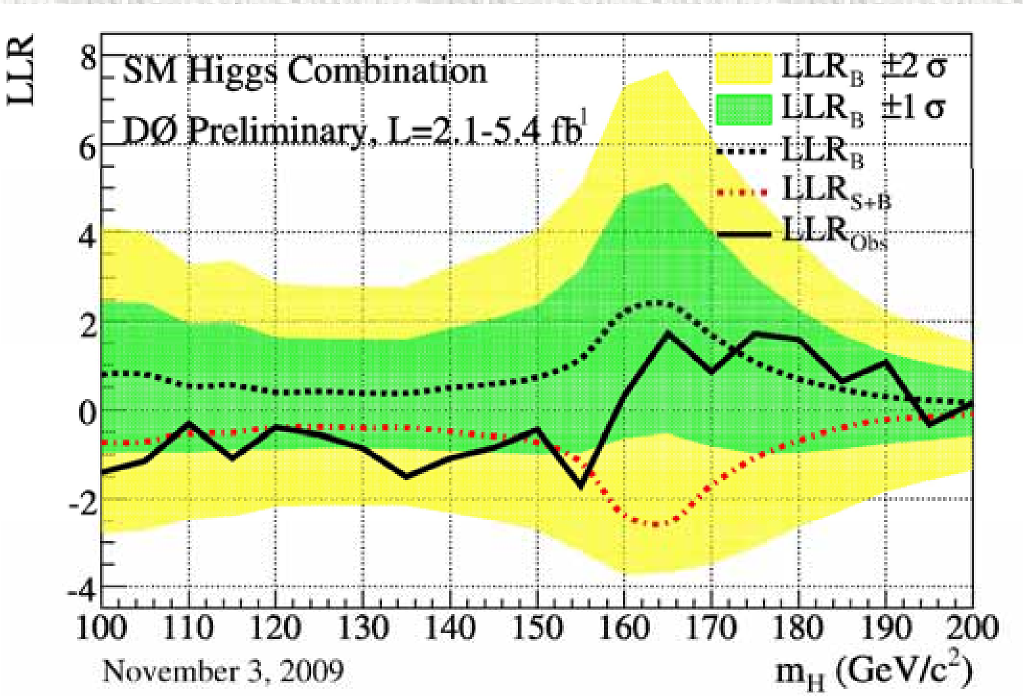




D0 combination

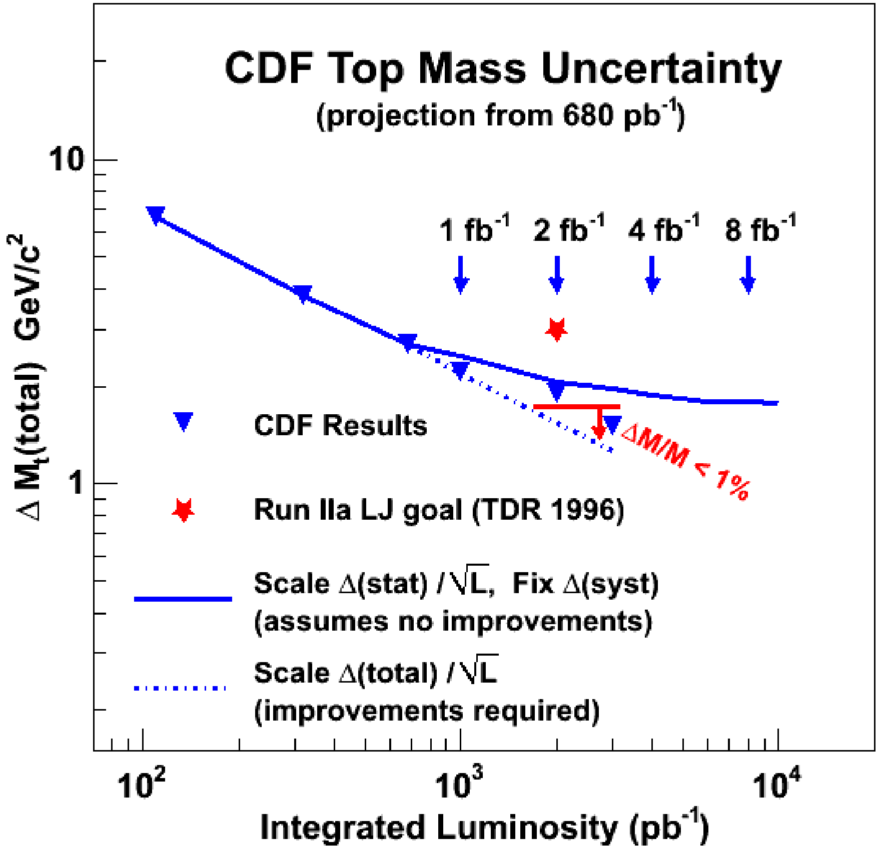
- In november 2009 D0 also combined their H searches in a single limit, using the CLs technology
- 2.1:5.4/fb of data enter the combination

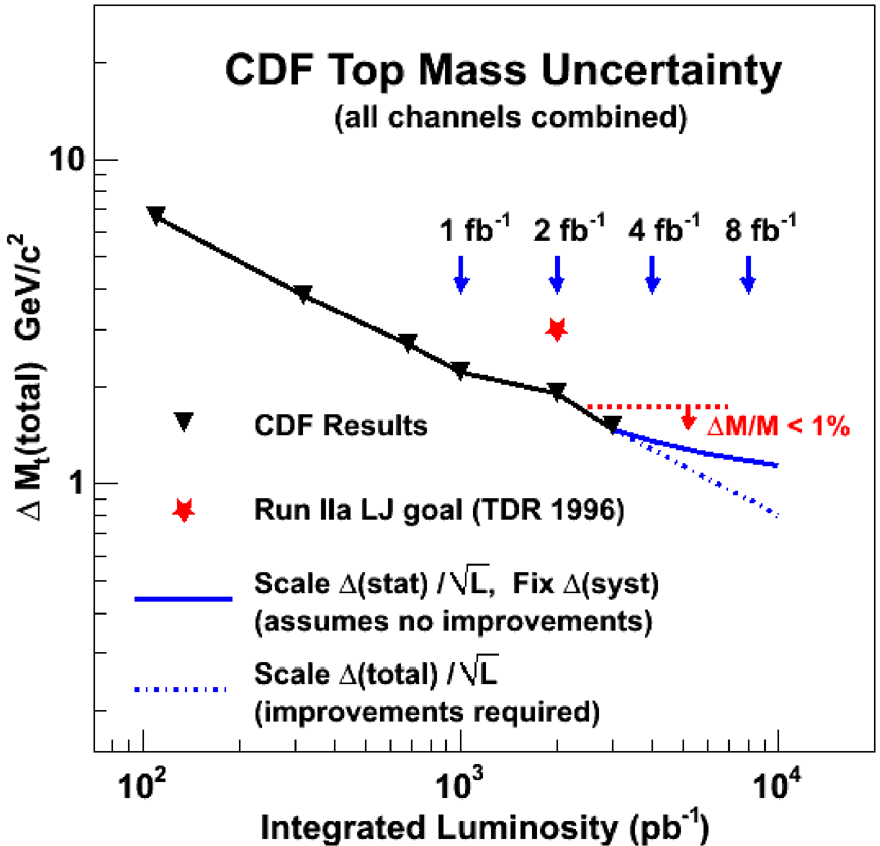




Reasons to be optimistic

- There are reasons for optimism. I will make just one example, which I consider appropriate –it is one “flagship” analysis which was considered one of the justifications of an extended Run II at the Tevatron, about a dozen years ago: the top mass measurement
- The results, in that case too, have exceeded expectations at the end, for a number of small reasons, one of them out-standing: the detector has worked like a charm.





And what if instead...

- A SM Higgs seminar would not be complete without a walk on the wild side
- The SM is a overwhelmingly successful theory, but we know it is not enough
  - does not include gravity
  - naturalness problem
  - lots of unexplained parameters
- With the precision of mass measurements and other observables (rare B decays, anomalous couplings...) increasing, the mountain of evidence could start to crumble under its own weight

- In the context of MSSM models things still look quite good for a wide chunk of the parameter space of some benchmark scenarios

Reminder: the MSSM

- The MSSM is a minimal version of SUSY
- Two doublets of complex scalars, each with its own v.e.v., are added to the Lagrangian → eight d.o.f. → 5 Higgs bosons remain after SSB
  - h,H, a pseudoscalar A, and two charged states: H^+,H^-
  - The lowest-mass neutral state (h or H) can be quite “SM”-like
- Phenomenology studied as a function of two main parameters:
  - $\tan\beta$
  - M_A
  - other three parameters have smaller impact
- CMSSM is a constrained version
- NUHM1: model with added freedom with non-universal Higgs couplings

MSSM global fits

- One may include in the picture all meaningful data (CDM relic density, B physics observables, muon g-2, direct SUSY searches) and verify range of allowed parameters within CMSSM, NUHM1...
- Many efforts going on
- Let us just pick one of them, as discussed in hep-ph/0912.1036, as an illustrative example

- A frequentist analysis samples the space of parameter values
  - Results for Mw and Mt may be compared to observed values
    - Mt = 173.1 +- 1.3 GeV
    - Mw=80.399 +- 0.023 GeV
  - Results of direct H searches included in the fits (Mh receives contributions from scalar top and bottom masses)
  - LEP II limit applicable for the CMSSM, not always for NUHM1 (hZZ coupling suppression)

The M_W-M_t view

- Studies of "constrained" versions of the MSSM indicate that there is consistency between the indications of a light Higgs boson and the combination of astrophysical, B-physics, and SM inputs, if one buys that framework

  Tendency of light SUSY pulls favored region towards higher Mw values with respect to SM fit

  NUHM1 less deterred by LEP II constraint

  "Predictions" of CMSSM and NUHM1 for Mw given all inputs are in better agreement with experimental values than SM fits:

  M_W=80.379+-0.013 GeV (CMSSM fit),
  M_W=80.370$^{+0.024}_{-0.011}$ GeV (NUHM1 fit)

  For a SUSY believer, this is good news!

Heinemeyer et al. 2009, hep-ph/0912.1036