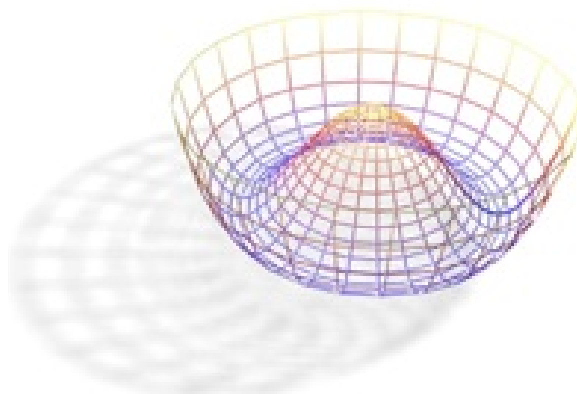
Higgs Search Results at the Tevatron



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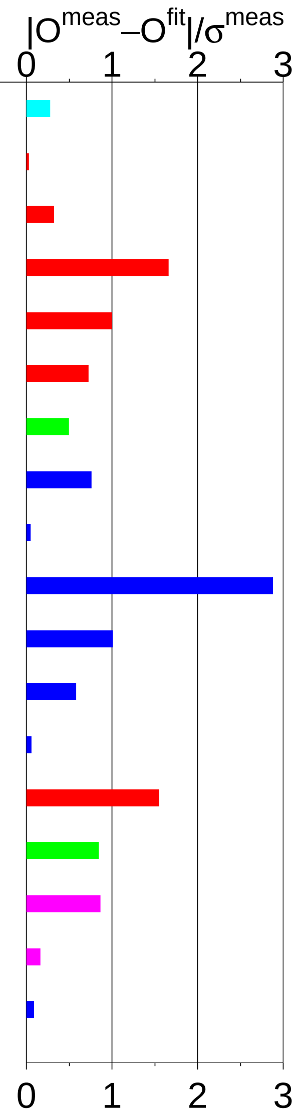
May 4, 2011

The Success of the Standard Model

- As a predictive tool, the SM has been extraordinarily successful.
- Predicted and discovered:
  - ▷ charm quark (1974)
  - ▷ gluon *g* (1979)
  - ▷ *W* and *Z* bosons (1983)
  - ▷ top quark (1995)
- SM parameters are interrelated in a predictable way:
  - ▷ electroweak measurements
  - ▷ survived all experimental tests
- But without Higgs, SM is a theory of massless particles.

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

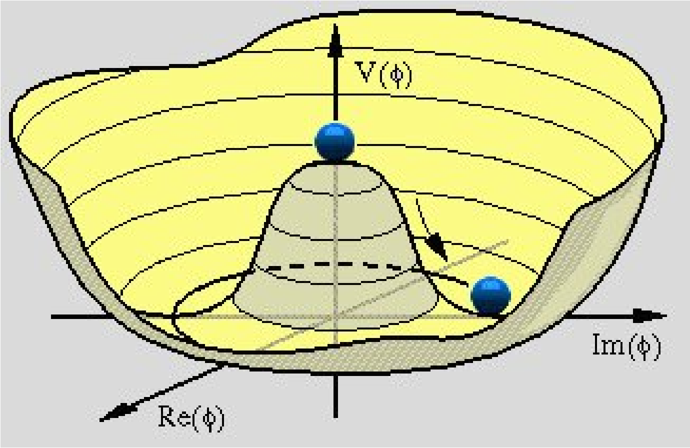


July 2010

Source: LEP Electroweak Working Group

The Origin of Mass

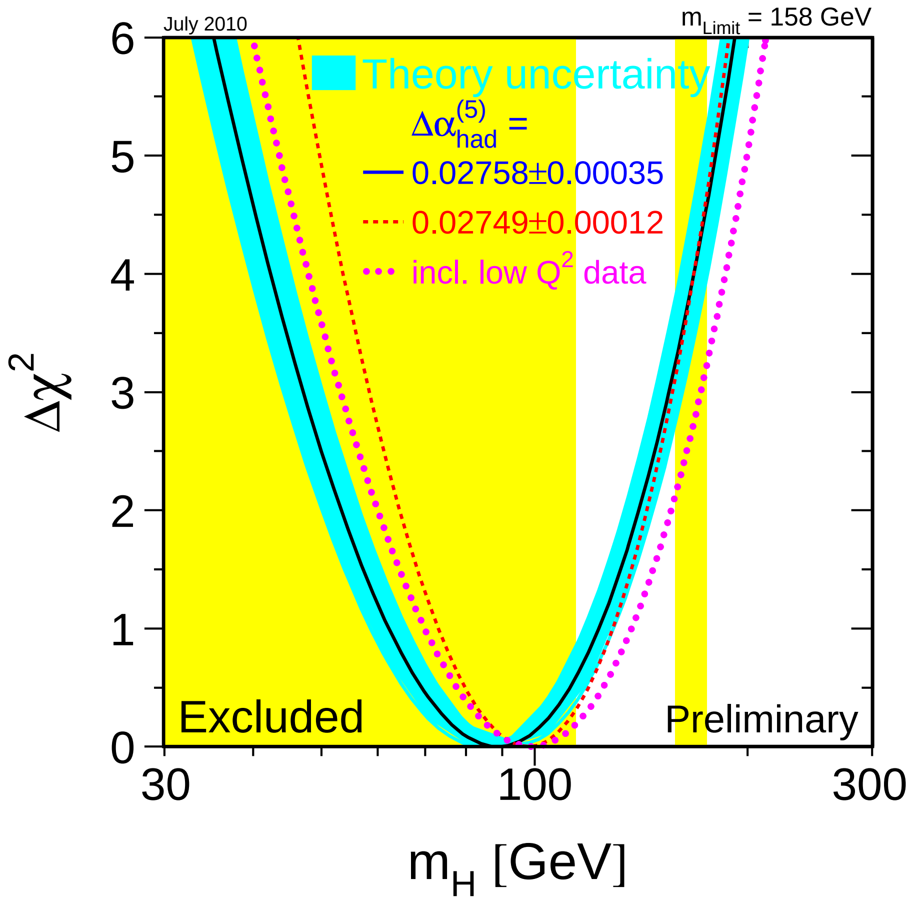
- SM unifies Electromagnetic and weak forces (predicted Z!):
  - ▷ Electroweak symmetry is broken: W and Z are massive, γ is massless.
- The Higgs mechanism provides an explanation:
  - ▷ The Higgs field permeates all of space: non-zero vacuum expectation value.
  - ▷ The symmetric Higgs potential has a degenerate ground state.

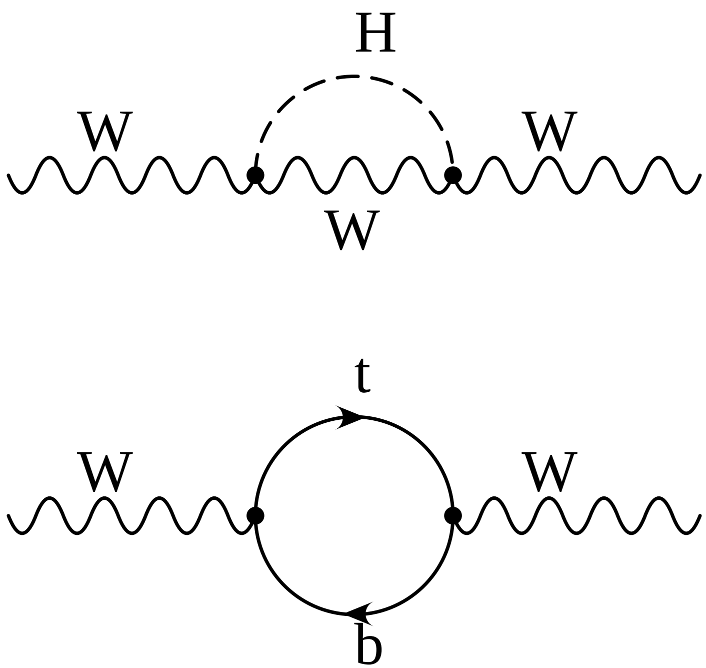


  - ▷ Symmetry is spontaneously broken to reach ground state.
- Fermions (leptons and quarks) acquire mass by coupling to the Higgs.
  - ▷ But masses are not predicted.
- Mass of the Higgs is not predicted.

Constraints on the Higgs' Mass

Global electroweak fit of m_H:



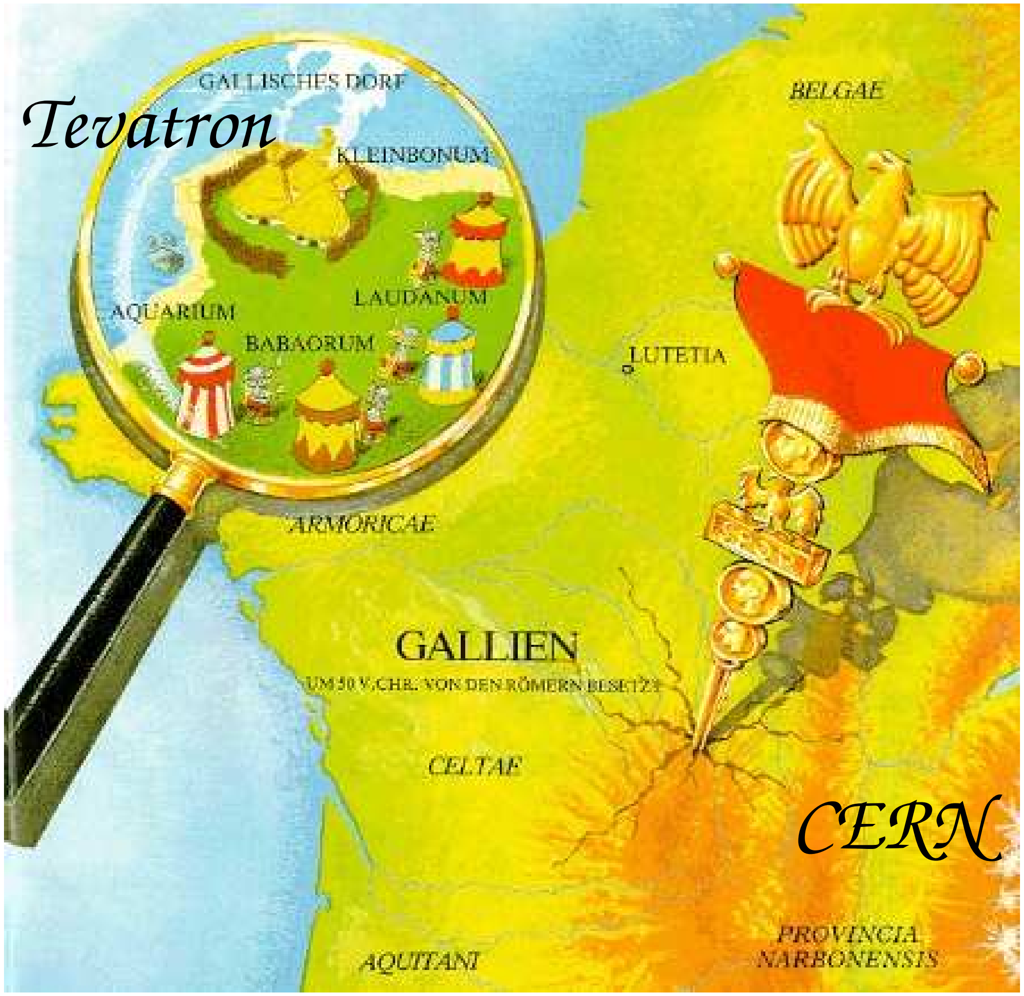


- Global electroweak fit favors a light Higgs: $m_H = 89\,^{+35}_{-26}$ GeV.
- LEP experiments at CERN excluded Higgs with $m_H < 114$ GeV at 95% CL.

Source: LEP Electroweak Working Group

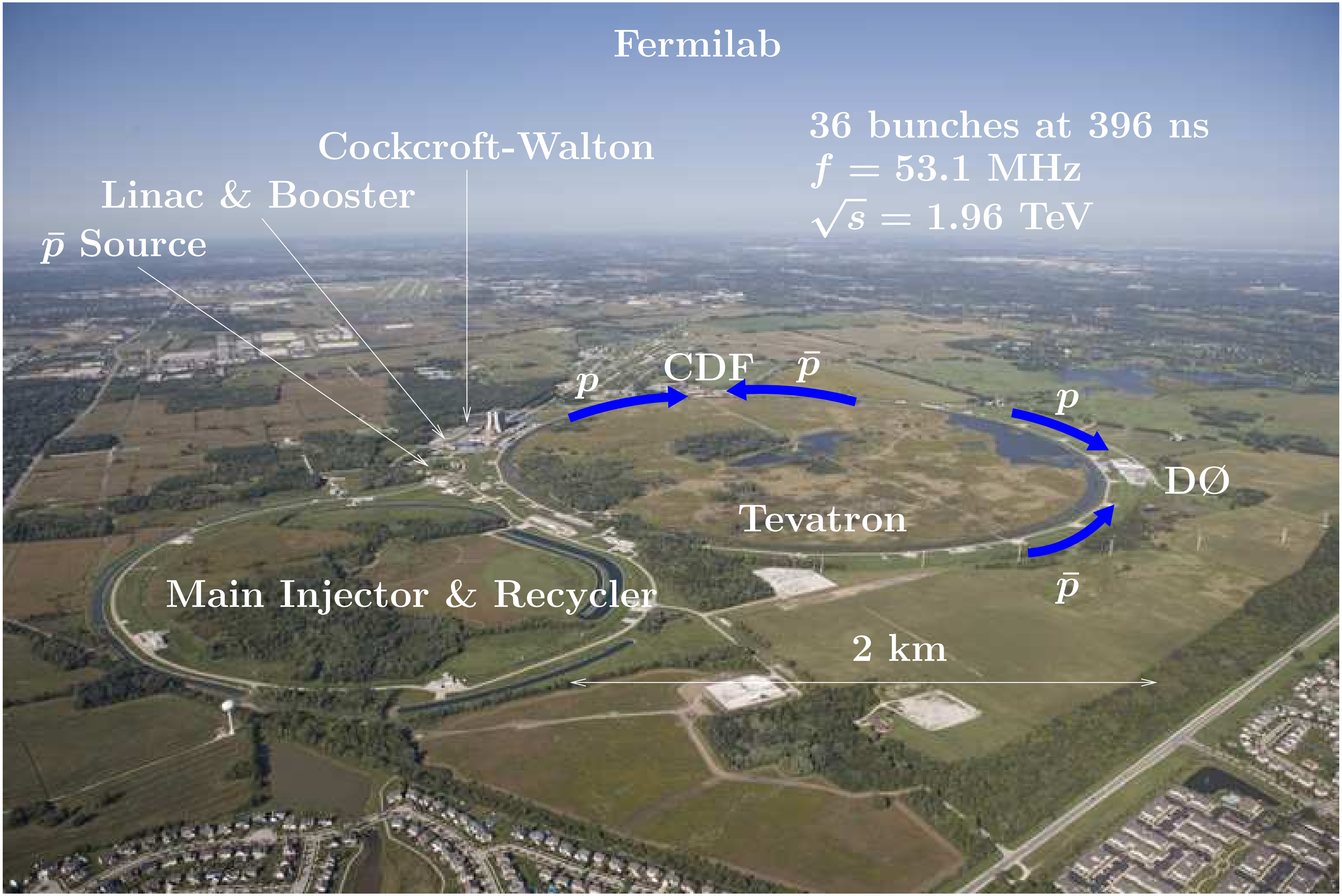
A Story about the Higgs Boson

Once upon a time, there was a small experiment in Batavia,

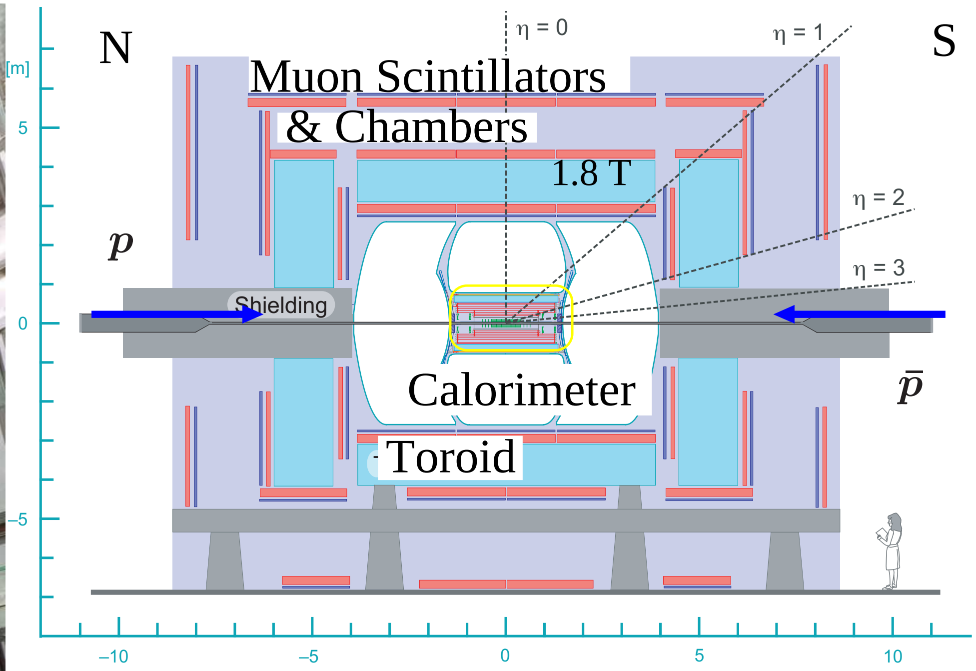


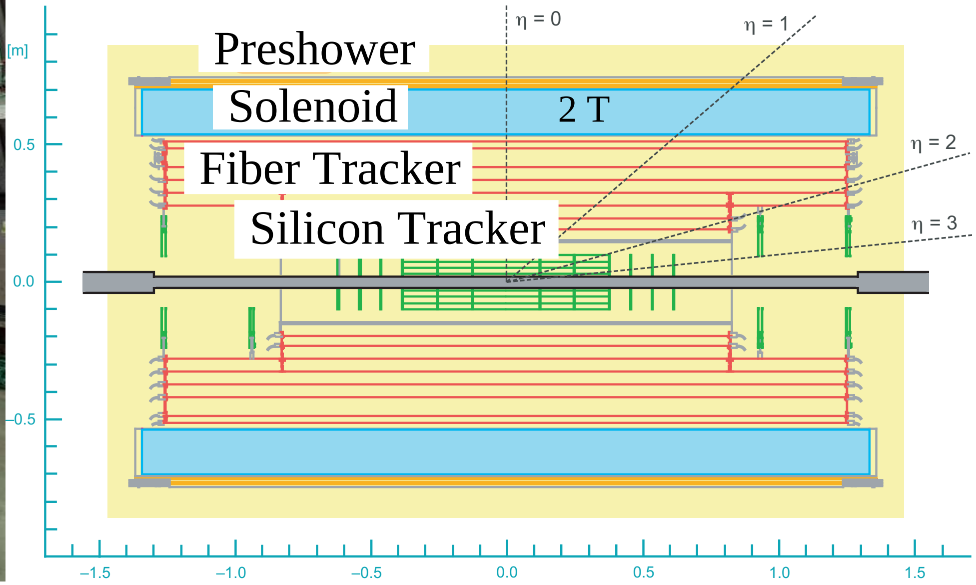
which stood alone against a horde of LHC scientists.

The Tevatron

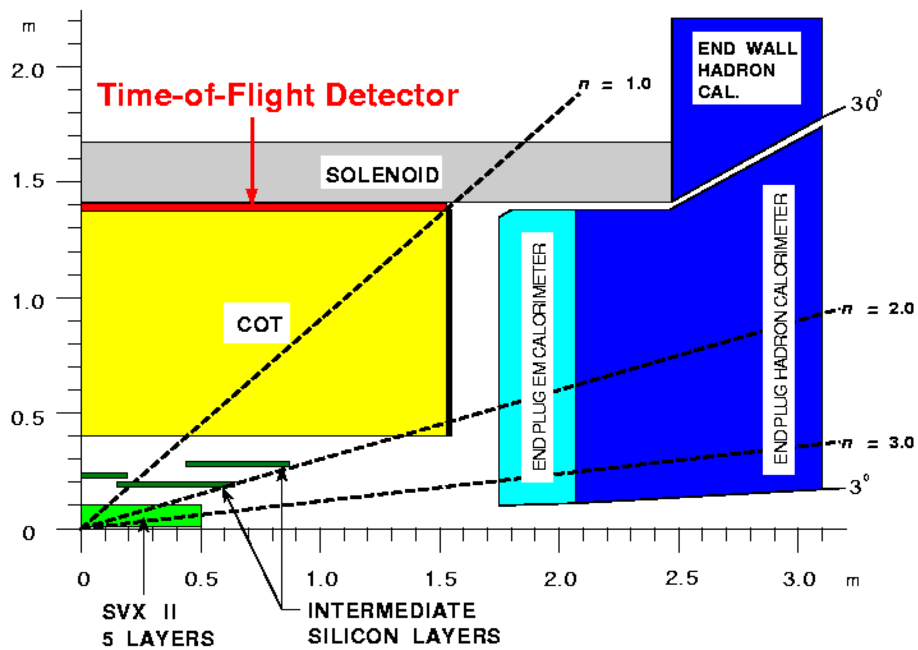


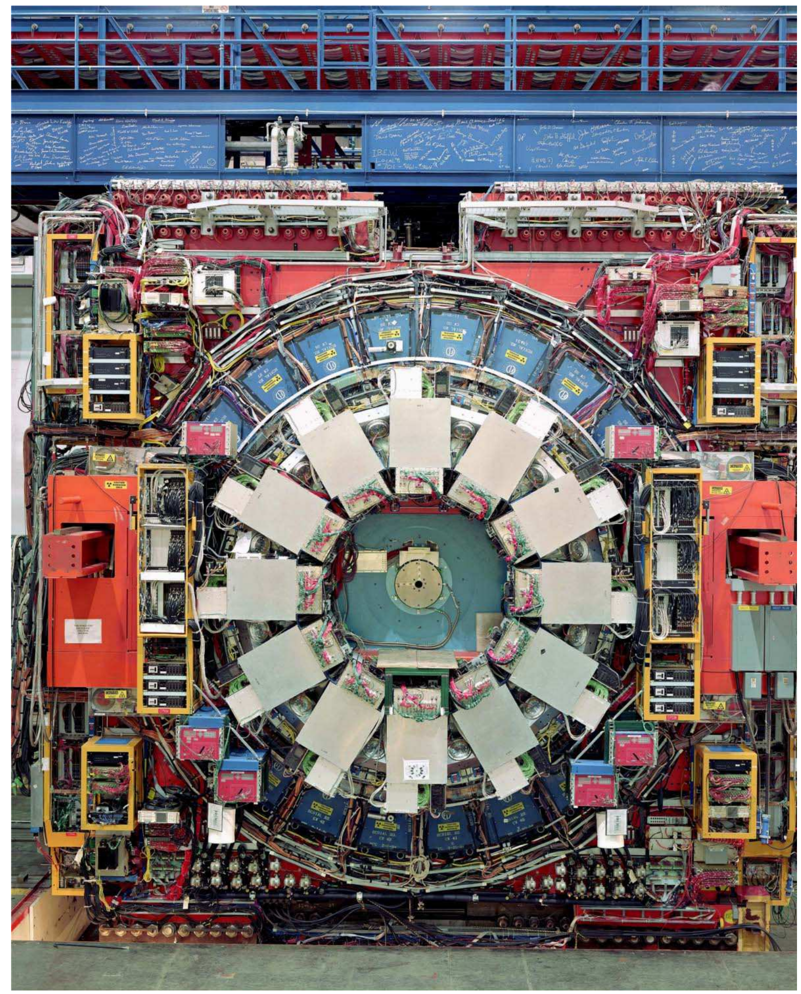
The DØ Detector



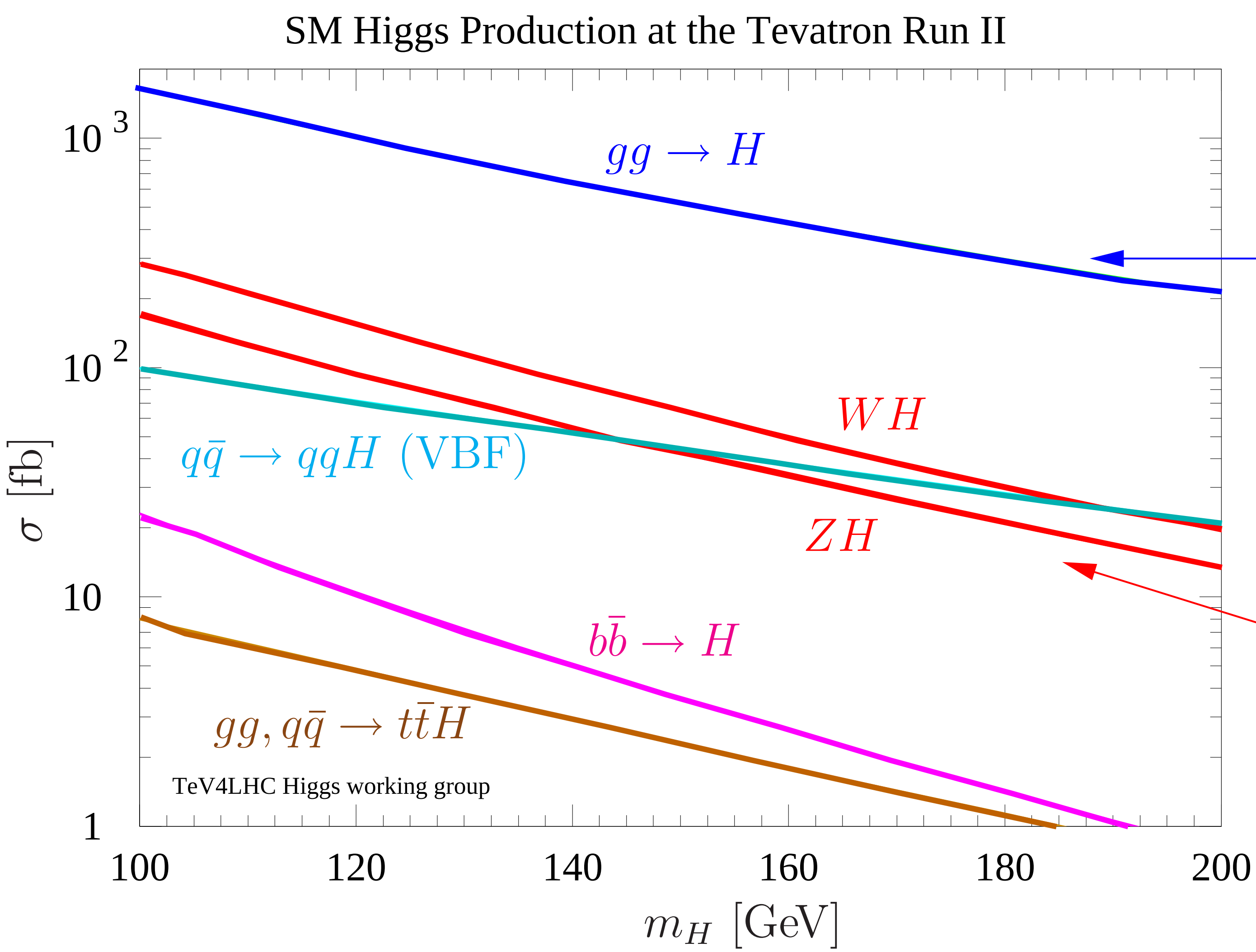


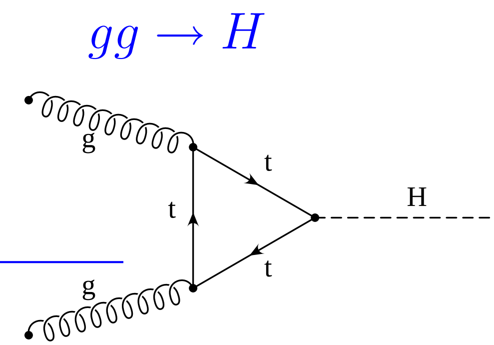
The CDF Detector

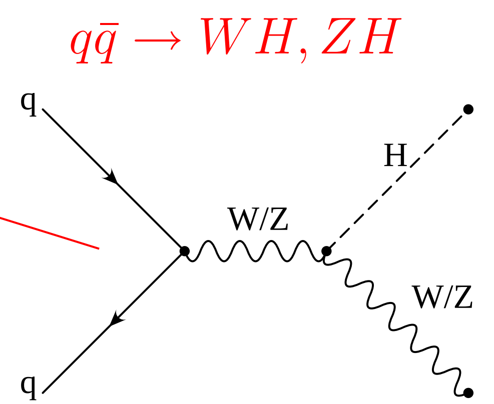




Higgs Boson Production







- ZH for $m_H = 115$ GeV produces $N = (10\ \mathrm{fb}^{-1}) \times (100\ \mathrm{fb}) = 1000$ events.

Decays of the Higgs Boson

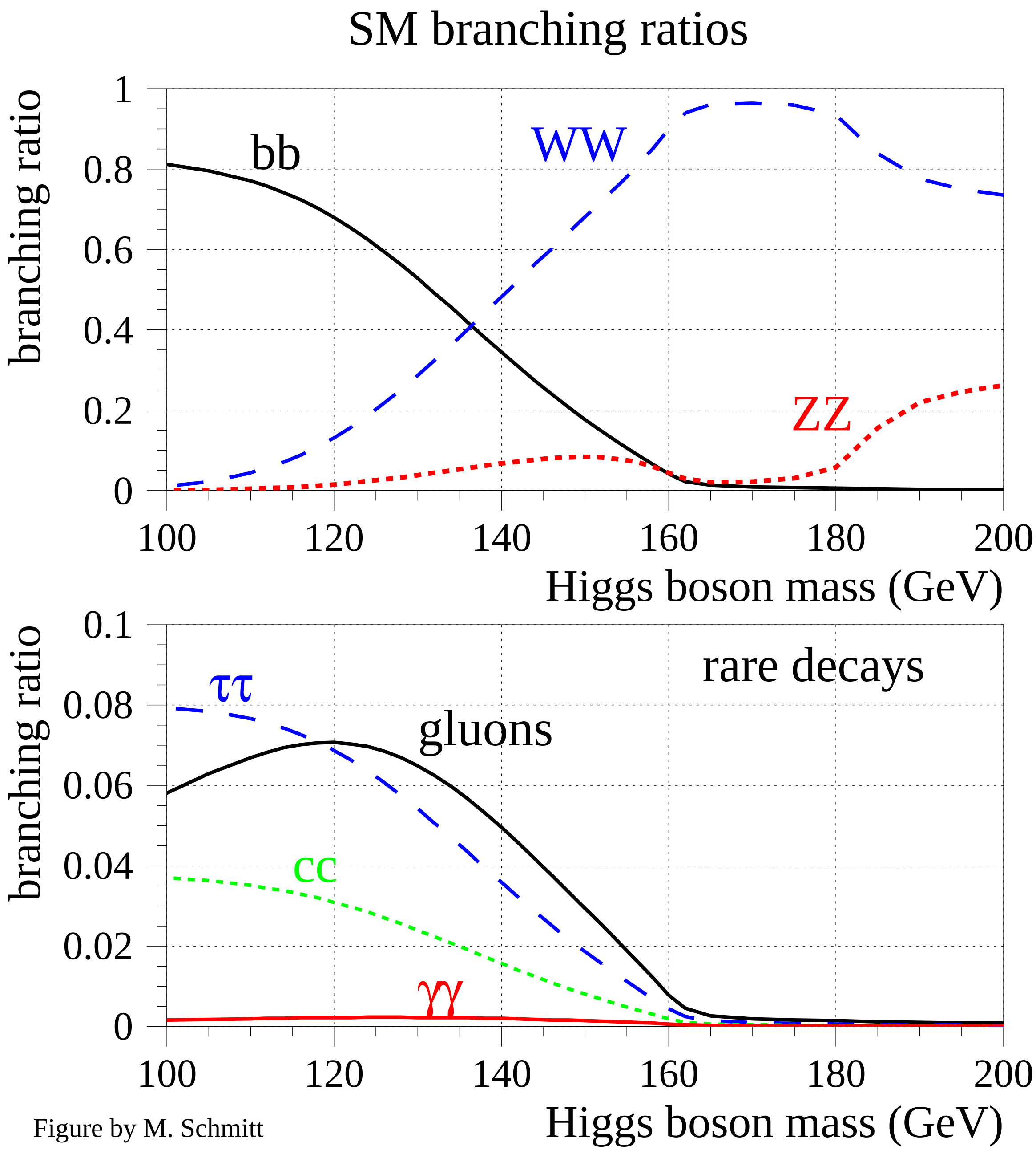


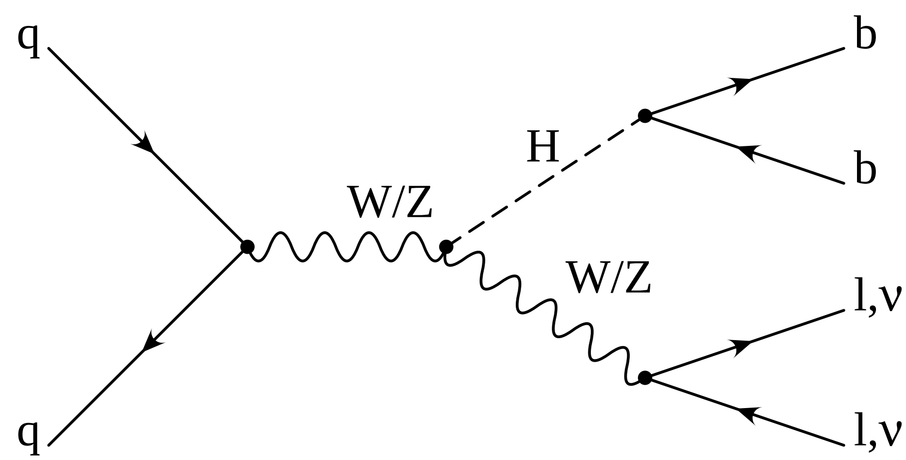
Figure by M. Schmitt

- In this talk:
  - ▷ $H \longrightarrow b\bar{b}$
  - ▷ $H \longrightarrow WW$
  - ▷ $H \longrightarrow ZZ$
  - ▷ $H \longrightarrow \tau\tau$
  - ▷ $H \longrightarrow \gamma\gamma$
  - ▷ $(H \longrightarrow c\bar{c})$

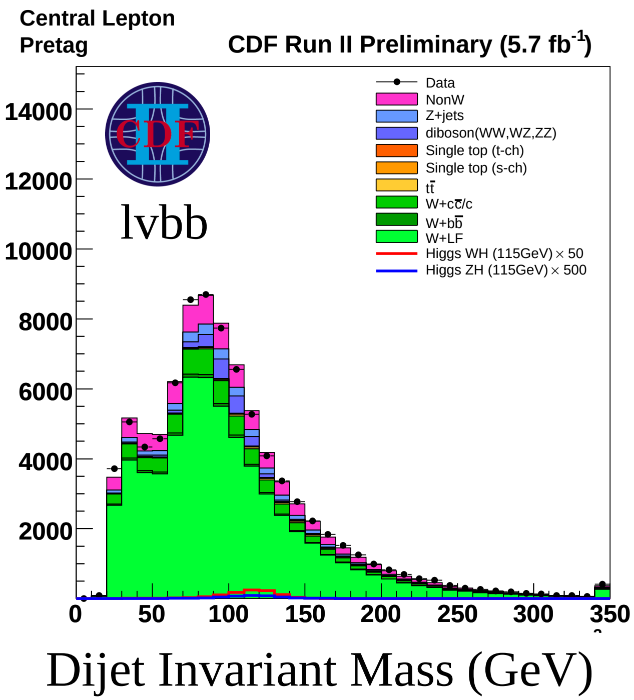
Tevatron Light Higgs Strategy

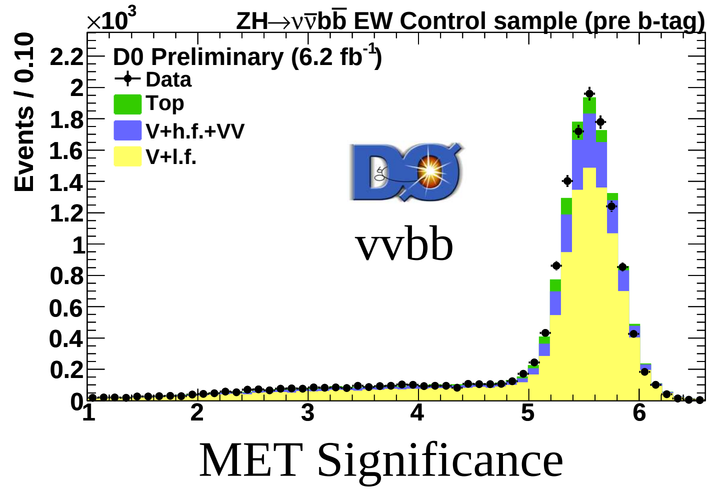
- For $m_H < 135$ GeV the primary decay is $H \to b\bar{b}$
- Primary production $gg \to H \to b\bar{b}$ $\quad (\sigma \sim 1 \text{ pb})$.
  - ▹ too much background from $q\bar{q} \to b\bar{b}$ $\quad (\sigma \sim 10^6 \text{ pb})$
- Rely on channels which produce leptons:
  - ▹ Reconstruct muons and electrons with high efficiency and purity.
  - ▹ Neutrinos undetected, but energy does not balance: $\not{E}_{\mathrm{T}}$.

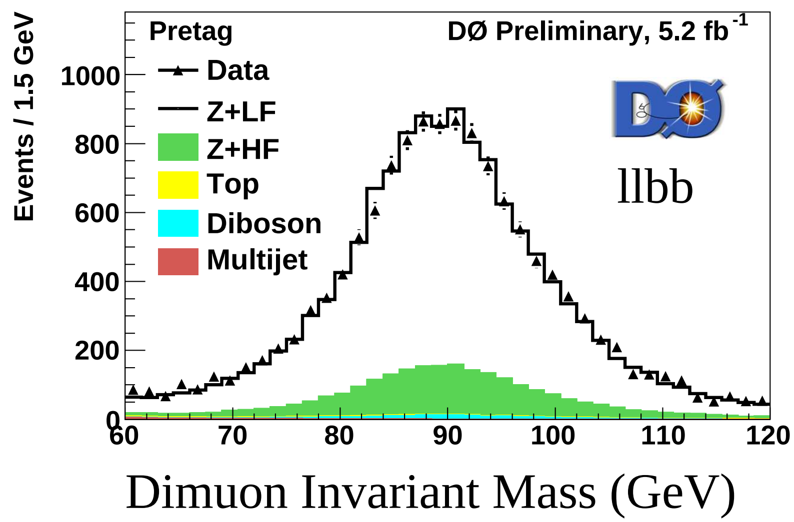
- $q\bar{q} \to WH \to \nu l b\bar{b}$
- $q\bar{q} \to ZH \to \nu\nu b\bar{b}$
- $q\bar{q} \to ZH \to llb\bar{b}$



Pretag Control Samples for $H \to b\bar{b}$



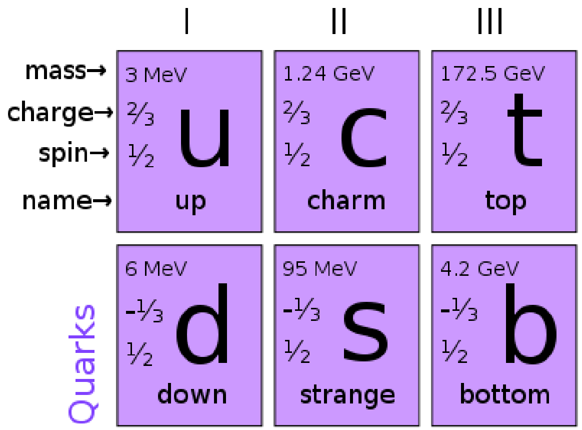


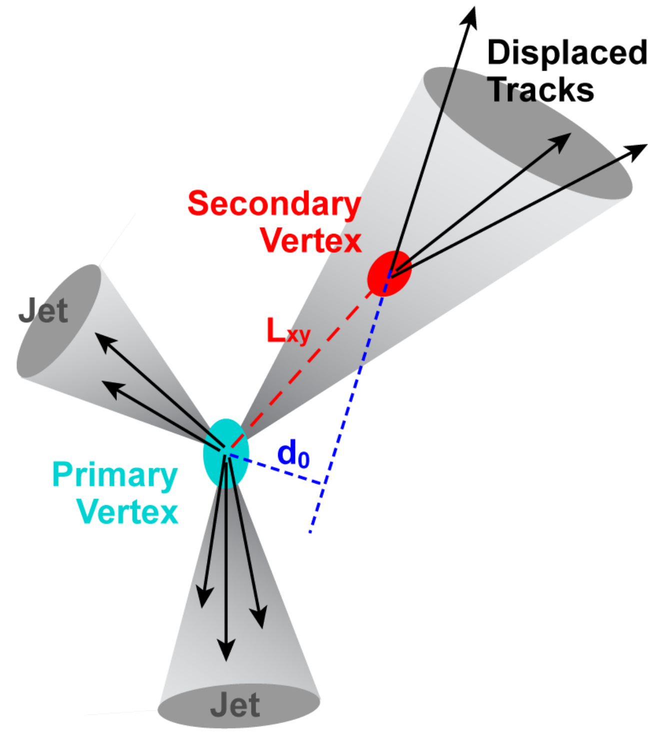


- Lepton plus jet selection is dominated by *W*+jets and *Z*+jets:
  - Use to validate background model.
- For signal selection, select jets likely originating from *b*-jets.

b-Tagging

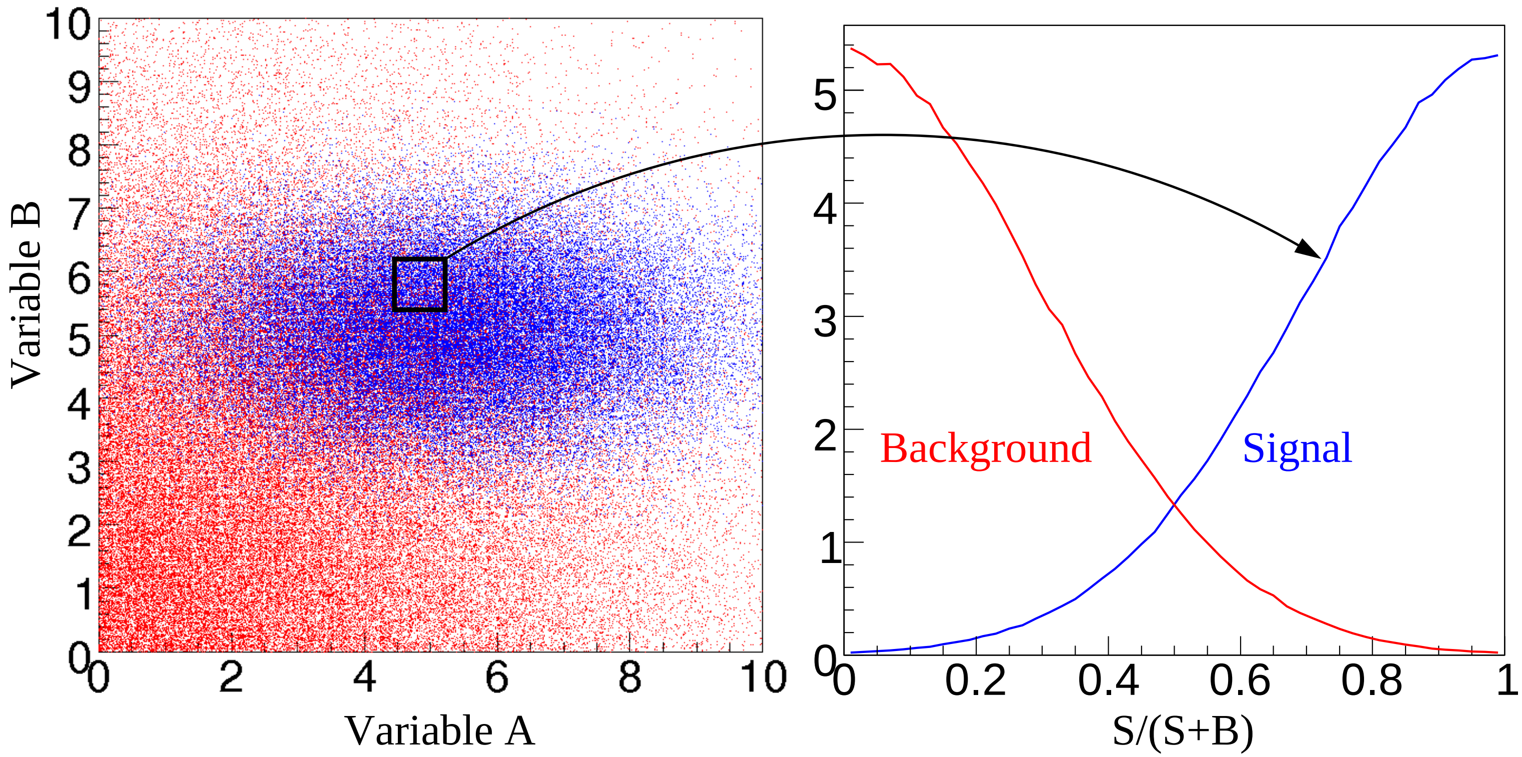
- Distinguish jets which originate from b versus lighter quarks.





- b mesons ($b\bar{q}$) are slow to decay:
  - ▷ $m_b \ll m_t$
  - ▷ Weak mixing between generations is small.
  - ▷ b-jets have displaced secondary vertices.
- b-quark is much heavier than other quarks:
  - ▷ b-jets have higher invariant mass (wider) and higher track multiplicity.
- Combine information to estimate probability each jet is from b quark.

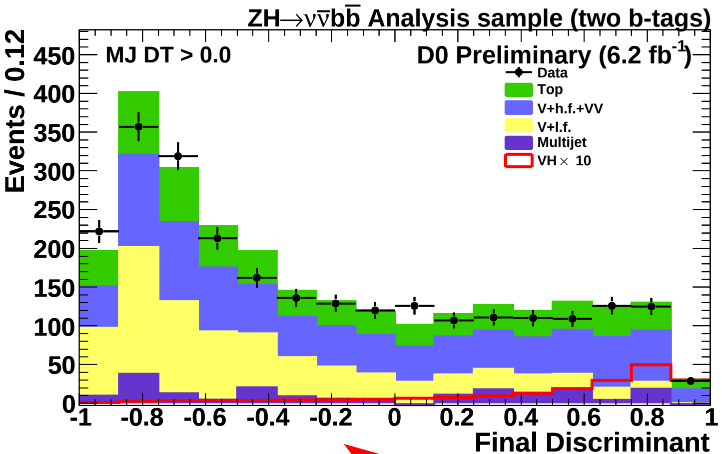
A Brute Force Approach

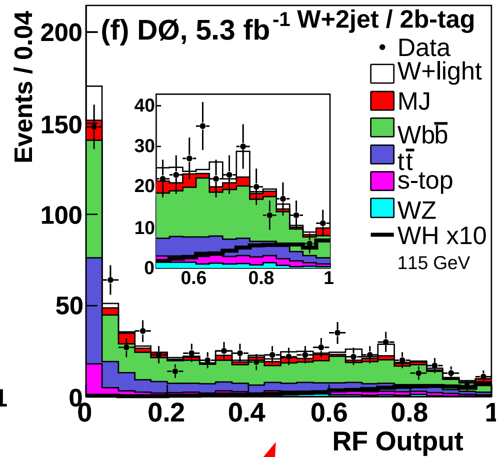


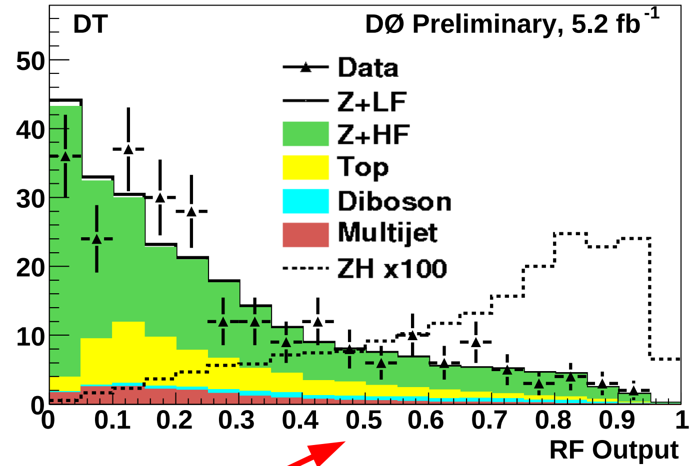
- One way to combine additional kinematic variables:
  - ▷ generate a ton of MC and classify events by local density $S/(S+B)$.
- To populate 16-D space, with four bins per D, and ten events per bin
  - ▷ Need 42,949,672,960 events!
- Left with approximations: known as Multivariate Analyses (MVAs).

$VH \to (\nu\nu, \ell\nu, \ell\ell)bb$ Results from DØ

MVA output (double b−tag sample)





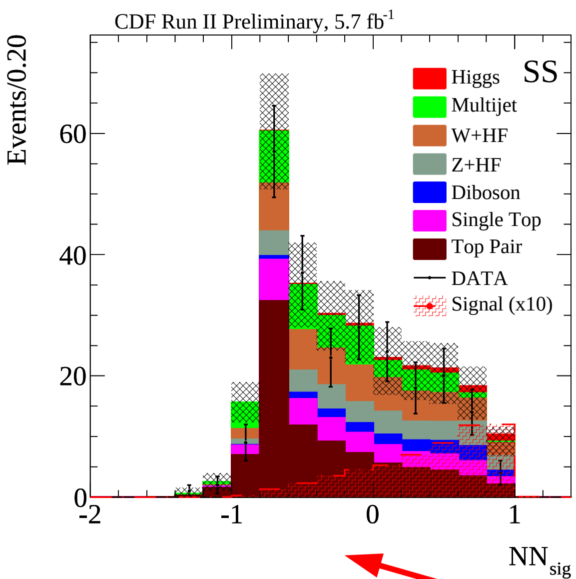


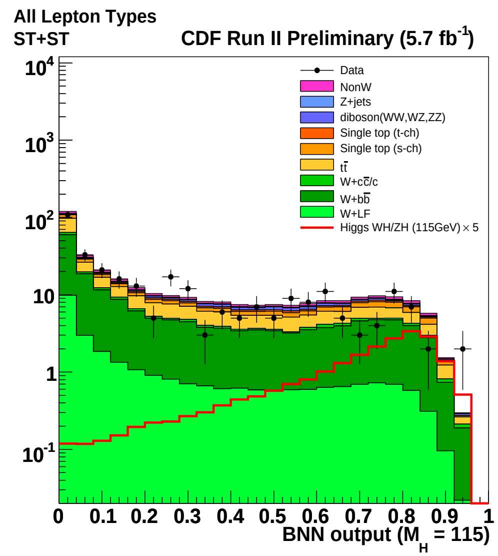
Channel:	$ZH \to \nu\nu bb$	$WH \to \ell\nu bb$	$ZH \to \ell\ell bb$
Luminosity:	$6.2\ \text{fb}^{-1}$	$5.3\ \text{fb}^{-1}$	$6.2\ \text{fb}^{-1}$
Observed:	3.4	4.5	8.0
Expected:	(4.0)	(4.8)	(5.7)

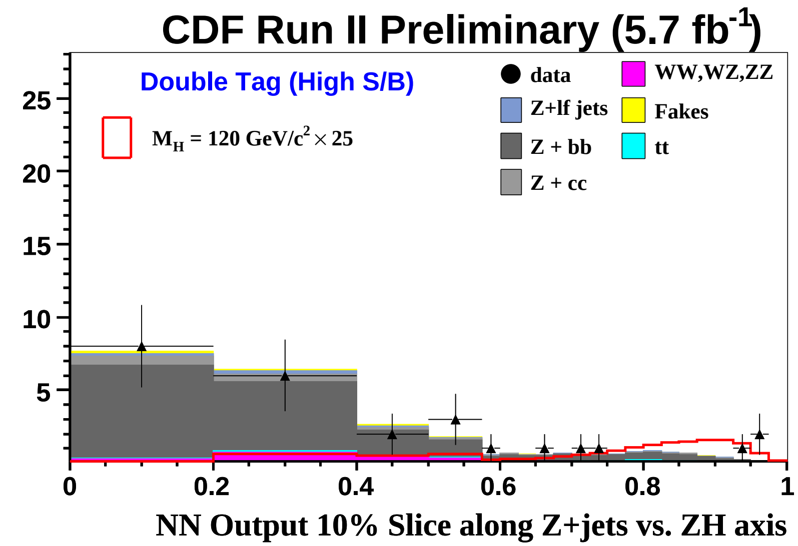
- Limits at 95% CL for $M_H = 115$ GeV in units of SM cross-section.

$VH \to (\nu\nu, \ell\nu, \ell\ell)bb$ Results from CDF

MVA output (double b−tag sample)



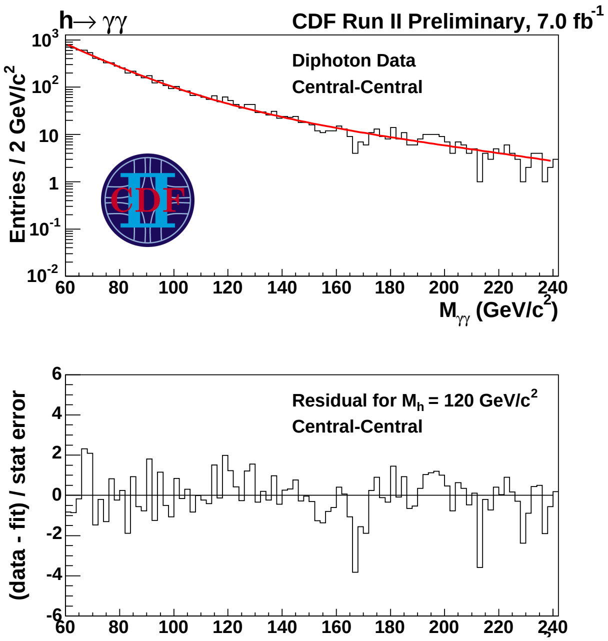




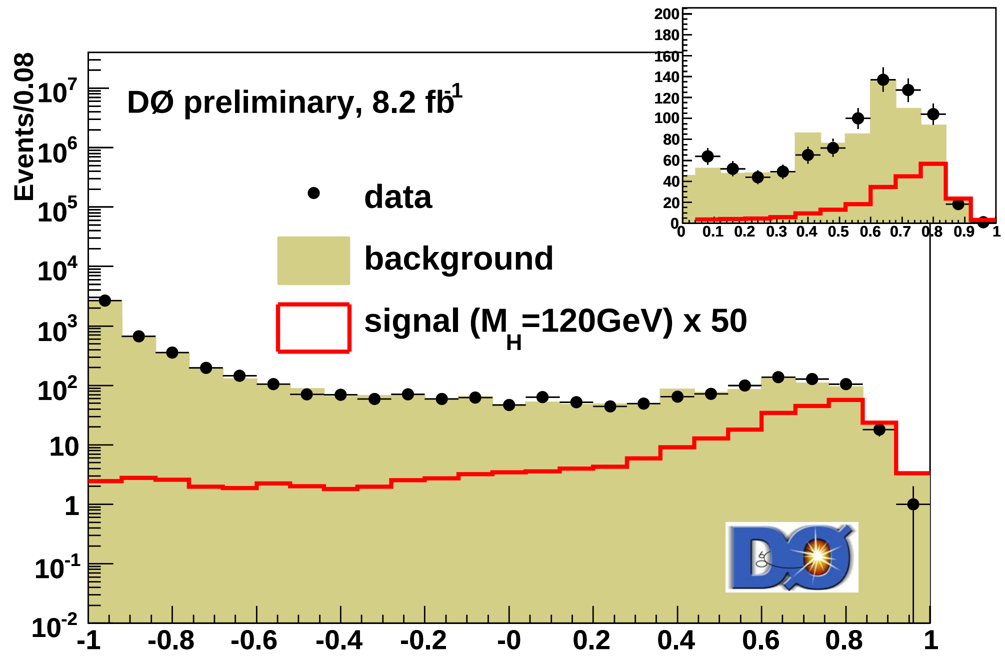
Channel:	$ZH \to \nu\nu bb$	$WH \to \ell\nu bb$	$ZH \to \ell\ell bb$
Luminosity:	5.7 fb^{-1}	5.7 fb^{-1}	5.7 fb^{-1}
Observed:	2.3	4.5	6.0
Expected:	(4.0)	(3.5)	(5.5)

- Limits at 95% CL for $M_H = 115$ GeV in units of SM cross-section.

$H \to \gamma\gamma$



Diphoton Mass

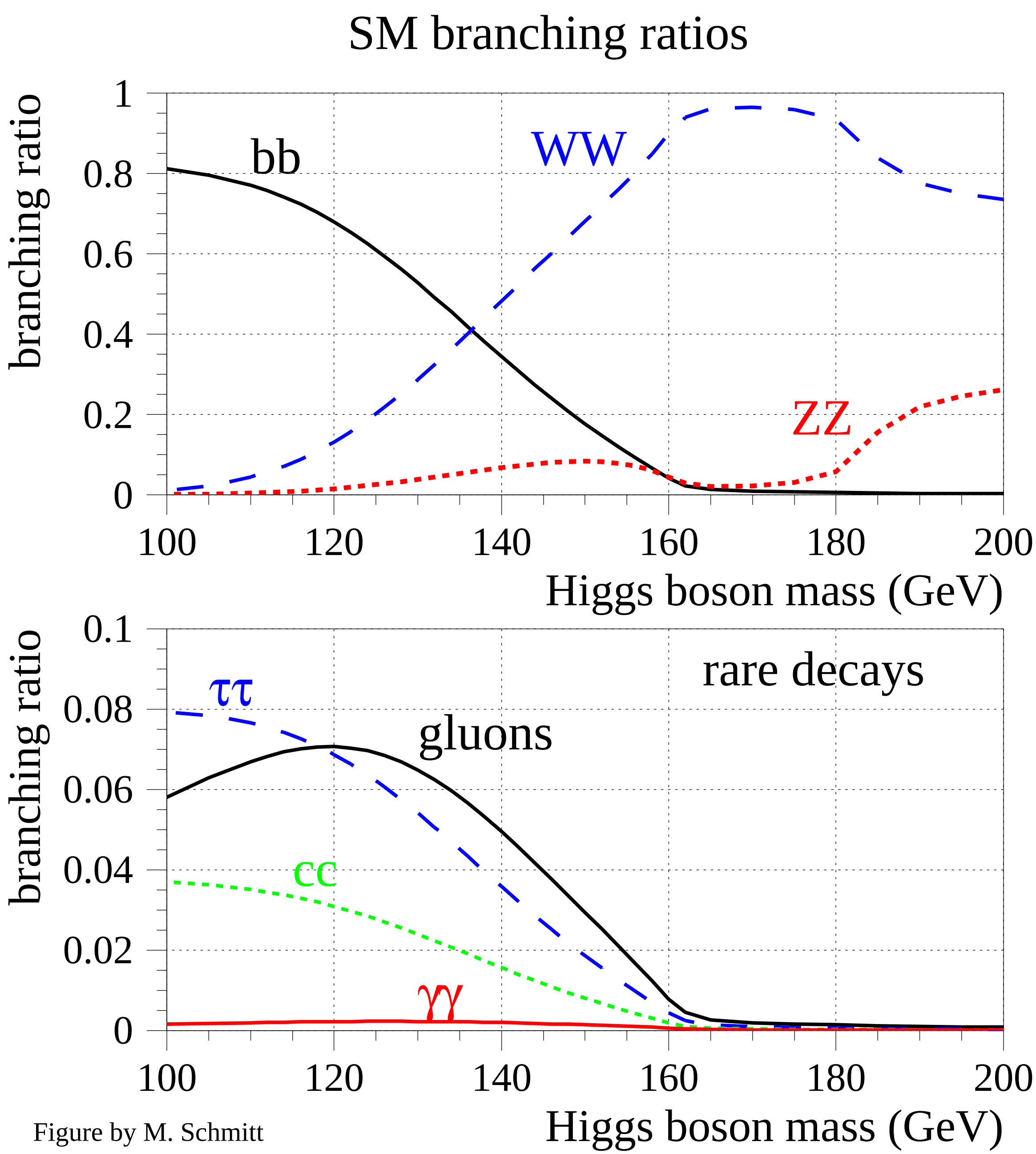


MVA Ouput

- Small branching ratio compensated by clean final state.
- CDF uses MVA based photon ID, and includes plug photons and conversions.
- DØ improves sensitivity with MVA final discriminant.

CDF	7.0 fb^{-1}	Obs:	14.1	Exp:	13.5 at $M_H = 115$ GeV
DØ	8.2 fb^{-1}	Obs:	19.9	Exp:	11.0 at $M_H = 115$ GeV

Recall: Decays of the Higgs Boson



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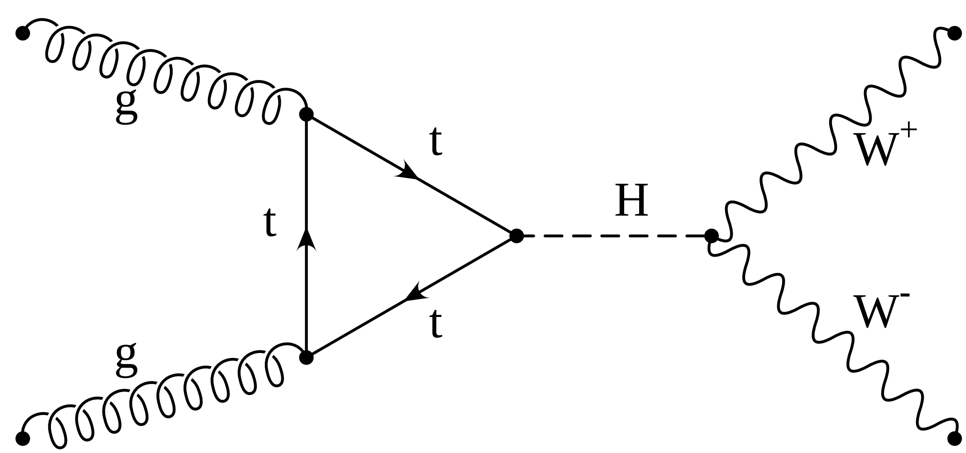
  - ▷ $H \longrightarrow \gamma\gamma$
  - ▷ $(H \longrightarrow c\bar{c})$

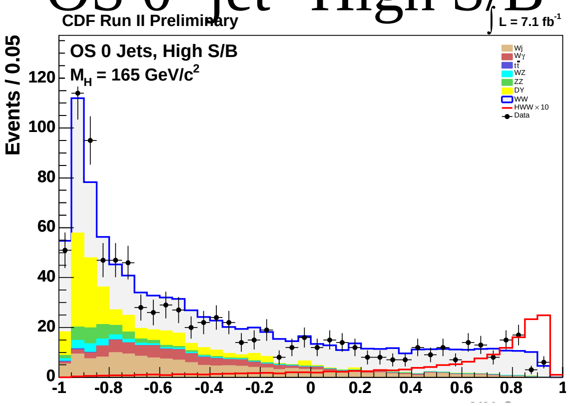
Tevatron Heavy Higgs Strategy

- For $m_H > 135$ GeV the primary decay is $H \rightarrow WW$.
- Primary senstivity from $gg \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell\nu$.
  - ▹ Opposite sign ee, $\mu\mu$, $e\mu$ and $\not{E}_{\mathrm{T}}$.
- Additional contributions from $(W/Z)H \rightarrow (W/Z)WW$.
  - ▹ Same-sign dileptons or trileptons and $\not{E}_{\mathrm{T}}$.
- New channel: $H \rightarrow WW \rightarrow \ell\nu qq$.
- Leptonic τ decays included above, hadronic decays:
  - ▹ $H \rightarrow WW \rightarrow \ell\nu\tau_{\mathrm{had}}\nu$
  - ▹ $X + H \rightarrow \tau\tau jj$



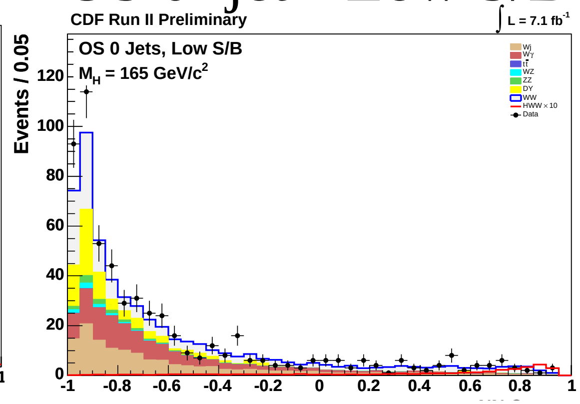
Different approaches to $H \rightarrow WW$

OS 0−jet High S/B



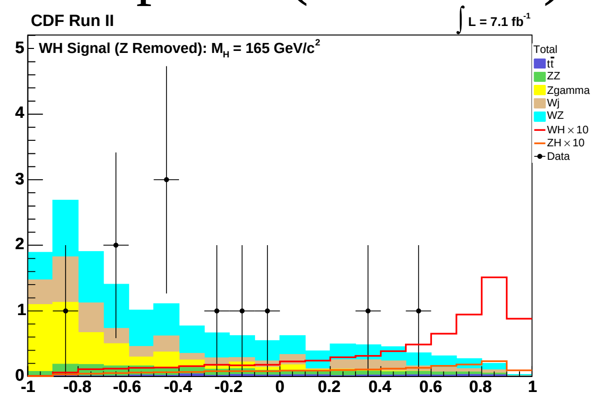
MVA output

OS 0−jet Low S/B



MVA output

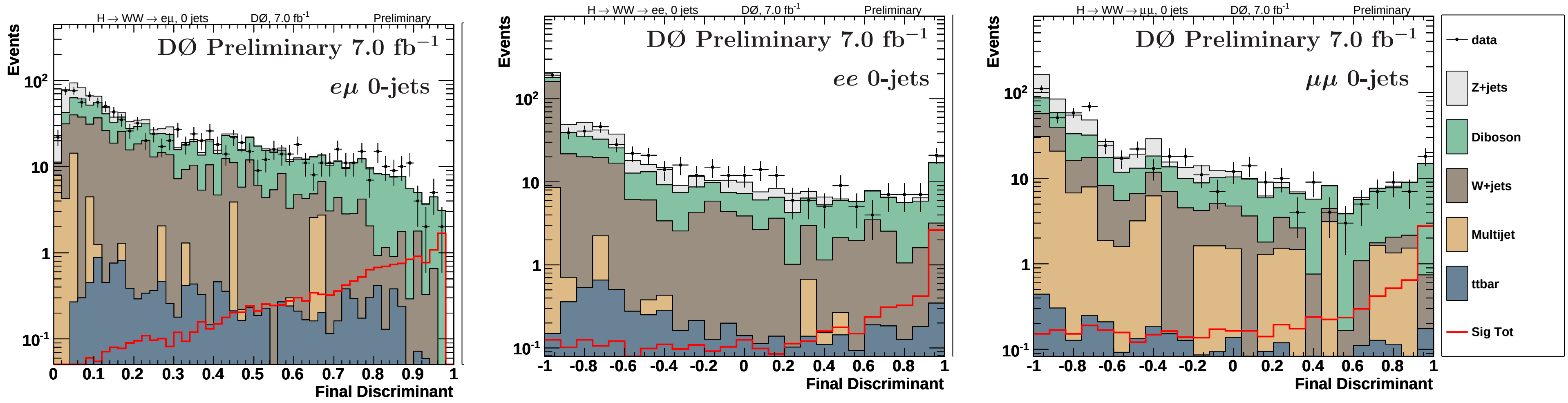
Trileptons (outside Z)



MVA output

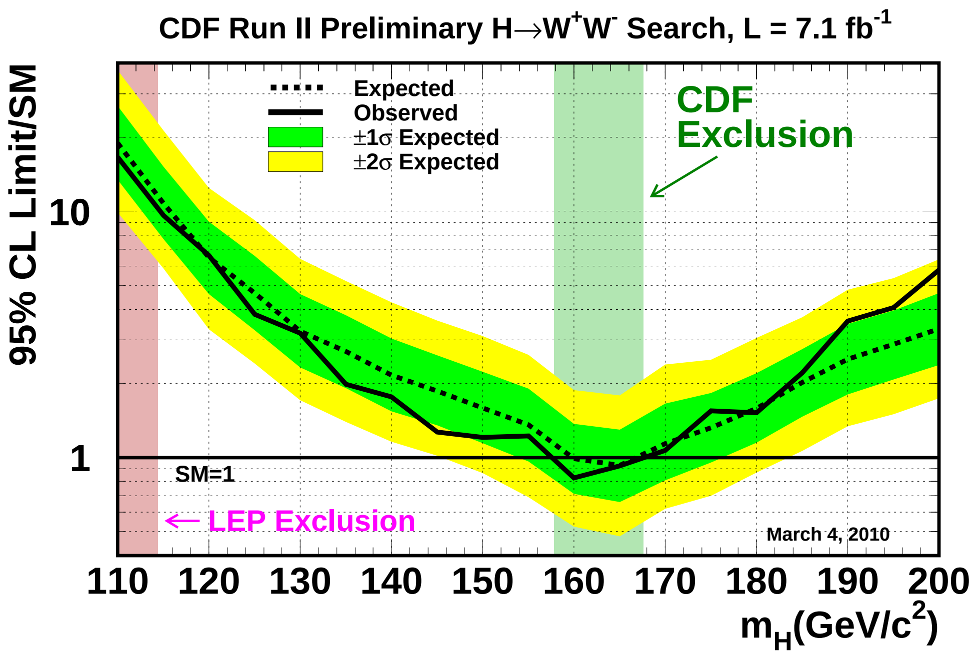
- The CDF approach:
  - Separate high S/B and low S/B leptonic selections combine lepton types.
  - Separate jet bins: 0-jet, 1-jet, and 2 or more jets.
  - Separate trileptons by in or out of Z peak.
  - Separate opposite sign and same sign dileptons.

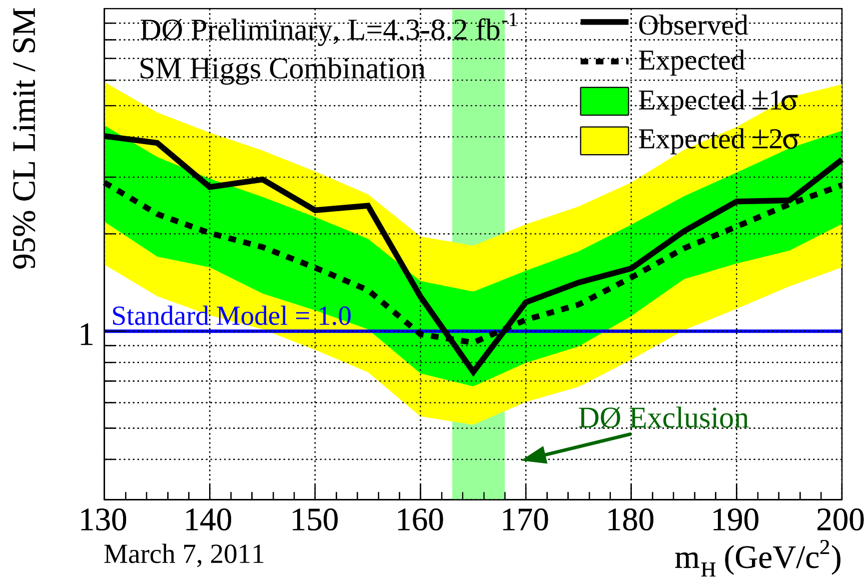
Different approaches to $H \rightarrow WW$



- The DØ approach:
  - ▷ Oposite sign ee,$\mu\mu$, $e\mu$ leptonic channels.
  - ▷ Separate jet bins: 0-jet, 1-jet, and 2 or more jets.
  - ▷ Same sign ee,$\mu\mu$, $e\mu$ leptonic channels.
  - ▷ New trilepton analysis effort underway for summer.

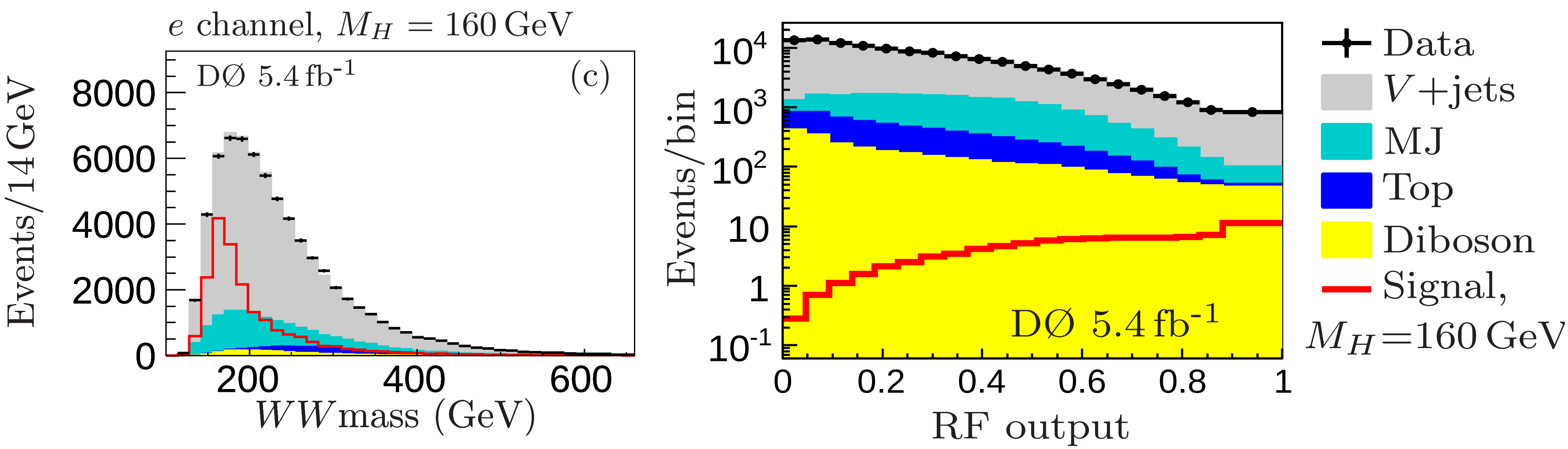
High Mass Results





- Both CDF and DØ independently exclude a SM Higgs near $M_H = 165$ GeV.

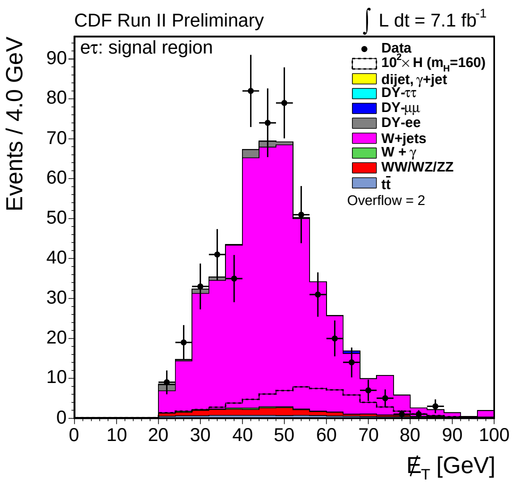
$H \to WW \to \ell\nu qq$

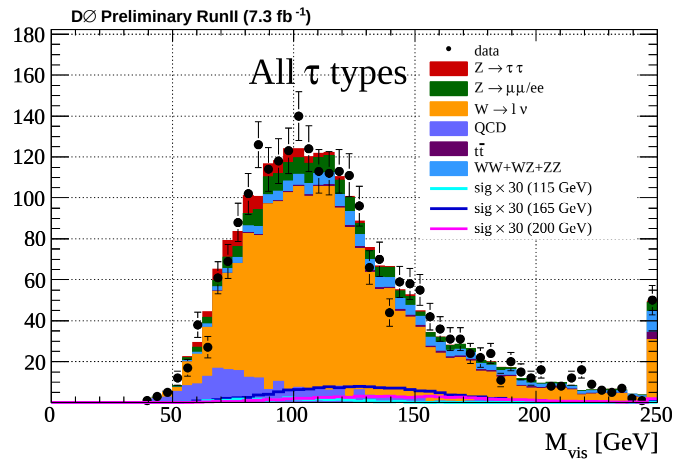


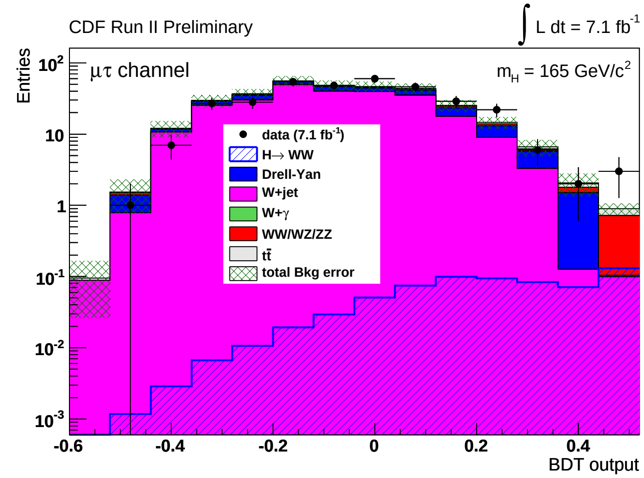
- New channel at D0 allows hadronic decay of one W.
- Larger signal contribution at the price of larger background.
- Key to this analysis is accurate modeling of the W+jets and $Z + jets$ background.

DØ 5.4 fb^{-1} Obs: 3.9 Exp: 5.0 at $M_H = 160$ GeV

$H \to WW \to \ell\nu\tau_{\text{had}}\nu$





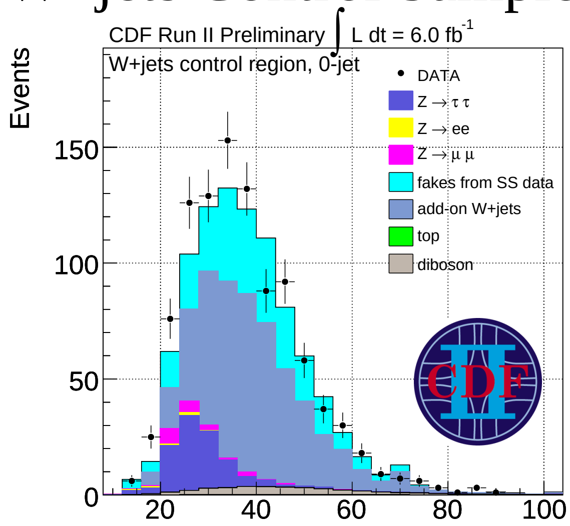


- Leptonic τ decays included in dilepton channels: add hadronic decays.
- Use control regions for W+jets, multijet, and $Z \to \tau\tau$ to validate model.
- After kinematic cuts, train MVA's to further separate signal and background.

CDF	7.1 fb^{-1}	Obs:	23.1	Exp:	15.1	at $M_H = 160$ GeV
DØ	7.3 fb^{-1}	Obs:	8.5	Exp:	7.2	at $M_H = 160$ GeV ($\mu\tau$ only)

$X + H \to \tau\tau jj$

W+jets Control Sample



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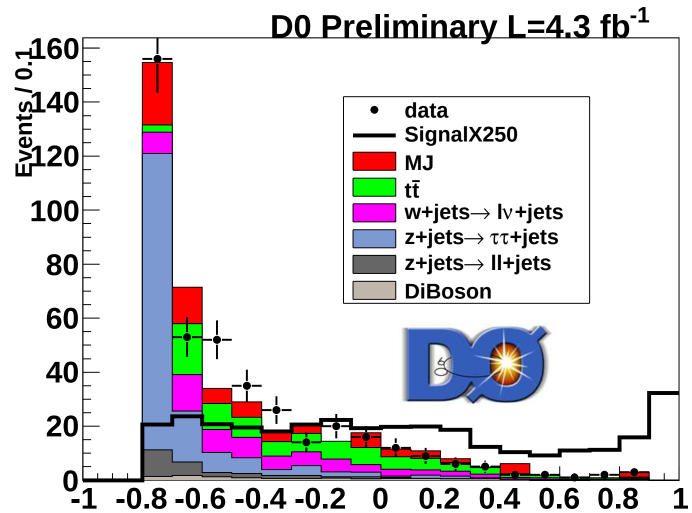


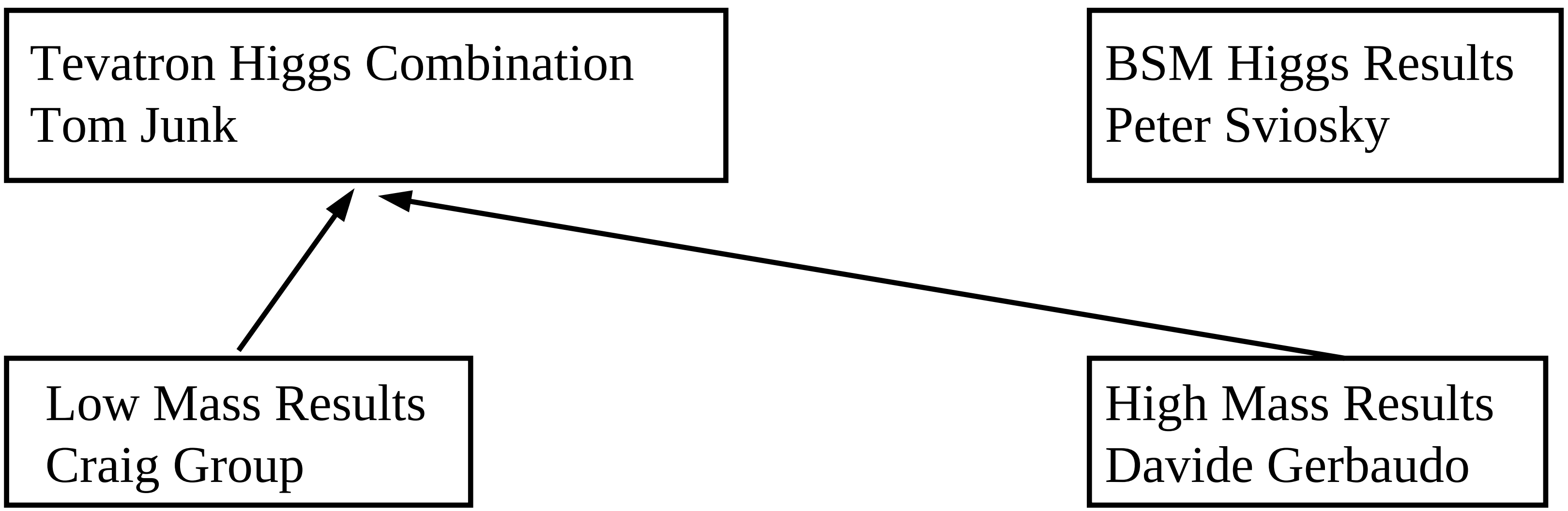
MVA output

- Two taus, one hadronic decay, one e or μ, plus two jets.
- Contributions from $H \to \tau\tau$ and $H \to WW$ decays.
- Contributions from gluon-gluon fusion, vector boson fusion, and associated production.

CDF	8.0 fb^{-1}	Obs:	14.7	Exp:	15.2	at $M_H = 115$ GeV
DØ	4.3 fb^{-1}	Obs:	12.2	Exp:	11.3	at $M_H = 160$ GeV

Additional Talks

- For further details on the Tevatron Higgs program, see these talks:



Outlook

- The decision not to run the Tevatron beyond 2011 has not stopped us.
- We are aggressively pursuing analysis improvements:
  - ▷ Will have more than 10 fb^{-1} (Summer results with 6 fb^{-}1).
  - ▷ Adding new channels like $H \to WW \to \ell\nu jj$ and $\mu\nu\tau\nu$.
  - ▷ Improved modeling, looser selections, smaller systematics.
- *In our search for the Higgs, we are leaving no stone unturned!*

Backup . . .

Setting Limits

- DØ uses a frequentist approach to setting limits:

  If this experiment were repeated many times, how often would we obtain a result which is as signal-like as what we have observed?

Background−Like

Signal−Like

- A 95% CL observed exclusion means:

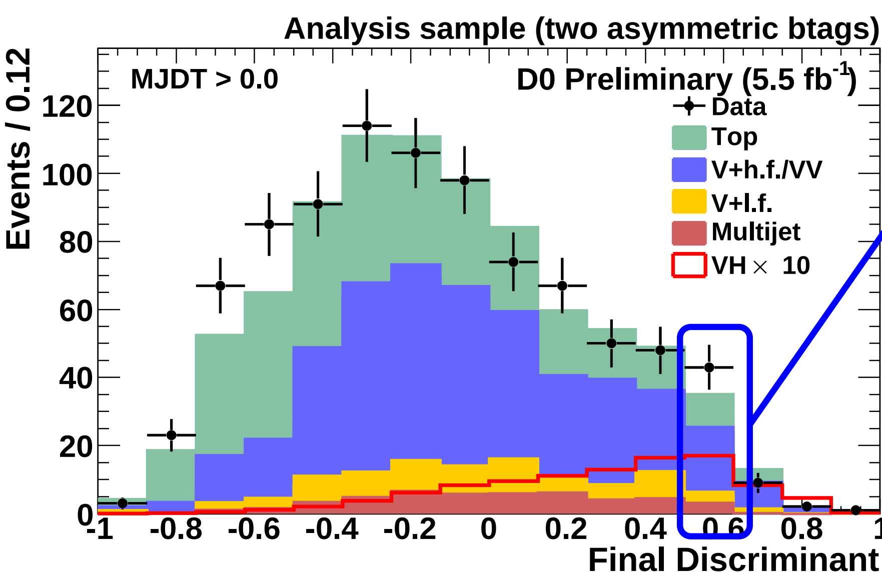
  If the excluded signal exists in nature, then only 5% of the time would we obtain a result as background-like as observed in this case.

Test Statistic

- Compare Poisson likelihood of B hypothesis to S+B hypothesis, and calculate their negative log likelihood ratio (LLR):

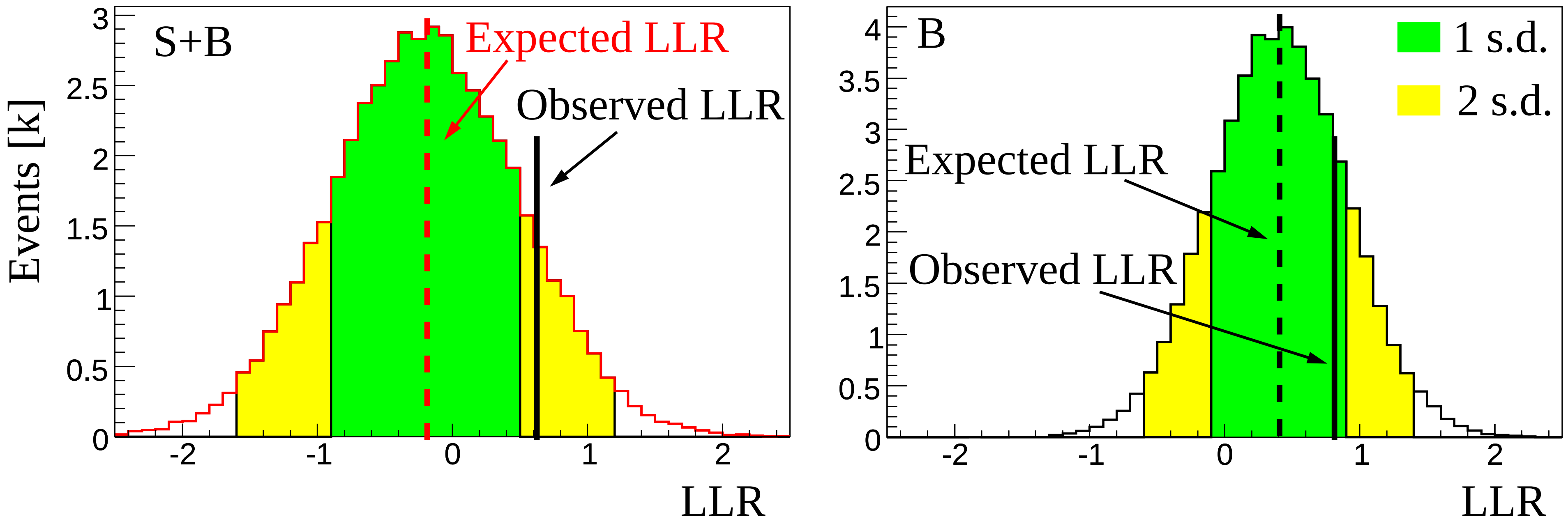
$L(B)$	$L(S+B)$	LLR
$\prod_i \frac{b_i^{d_i}\exp(b_i)}{d_i!}$	$\prod_i \frac{(s_i+b_i)^{d_i}\exp(s_i+b_i)}{d_i!}$	$2\cdot\sum_i s_i - d_i\cdot\log(1+s_i/b_i)$

where d_i events observed in bin i with S and B expectations s_i and b_i.



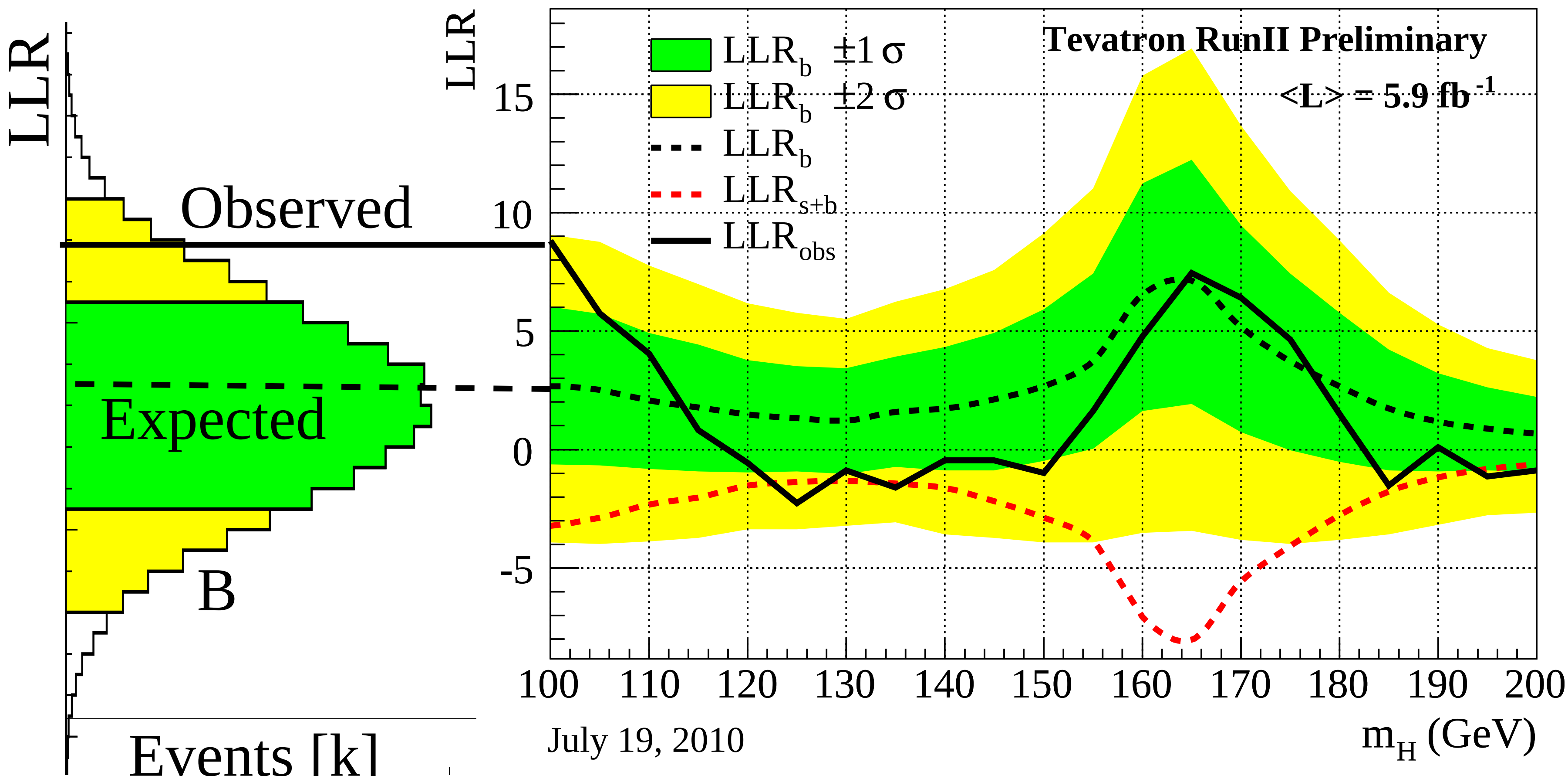
- $d_i = 42$, $b_i = 35$, $s_i = 1.5$.
- LLR = -0.52
- Sum overall all bins to compute Observed LLR.
- Add additional channels as new bins.

Pseudo-Experiments and Expected LLRs



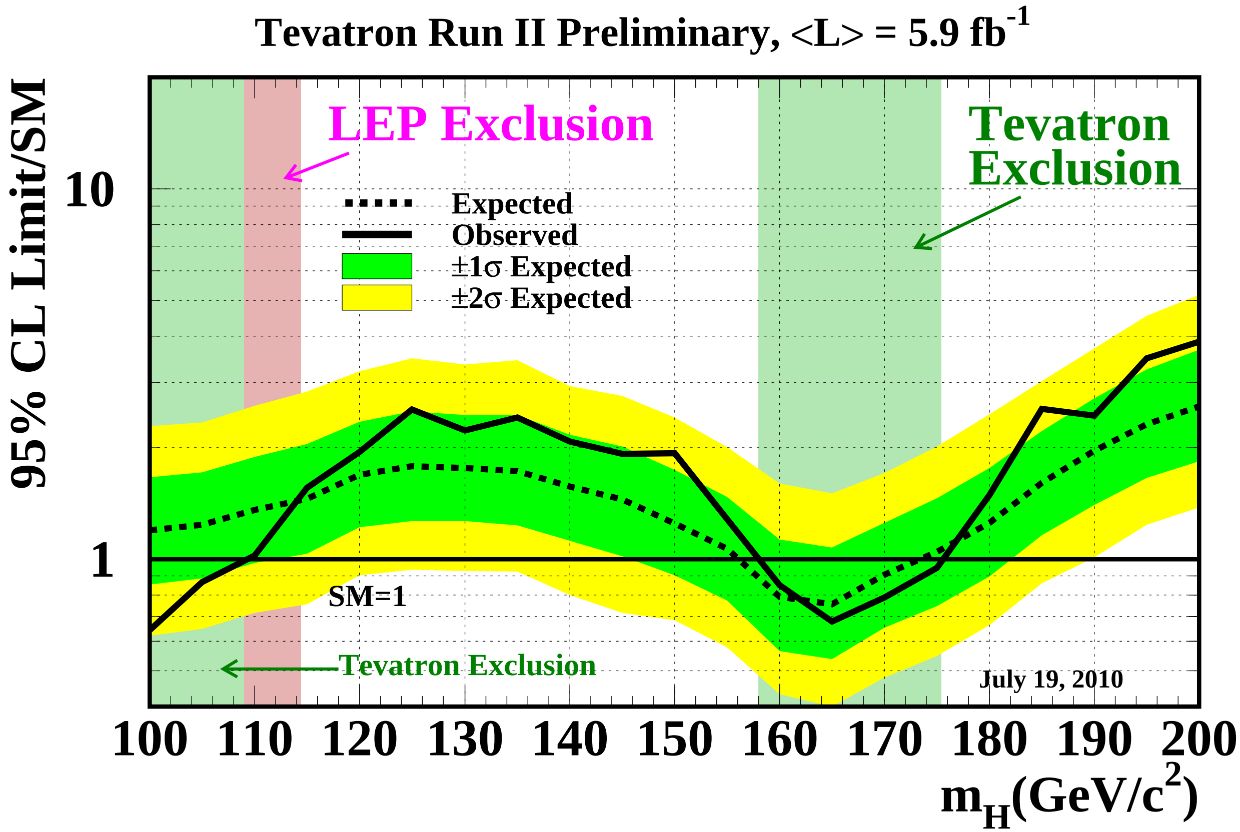
- Repeat calculation but with pseudo-data obtained by a Poisson fluctuation of b_i in each bin (B) or $s_i + b_i$ in each bin (S+B).
- Repeat many times to obtain LLR distribution: median is Expected LLR
- Nuisance parameters (systematics) alter prediction: $b_i \to b_i + \theta_i$.
- Smear pseudo-experiments by Gaussian priors for nuisance parameters.
- Fit systematics: $L(S+B)/L(B) \to L(S+B,\theta_{S+B}^{\mathrm{FIT}})/L(B,\theta_B^{\mathrm{FIT}})$

Tevatron Combination LLR



- At each mass point, calculate observed LLR.
- And generate pseudo-experiments to calculate expected LLR.
- Scale all signals, red and black lines diverge, until CL is reached.

Tevatron Cross-Section Limits



- Report cross-section limit as ratio to SM (different processes!)
- Limit at $M_H = 115$ GeV observed 1.64, expected 1.50.
- Limit at $M_H = 165$ GeV observed 0.69, expected 0.73.

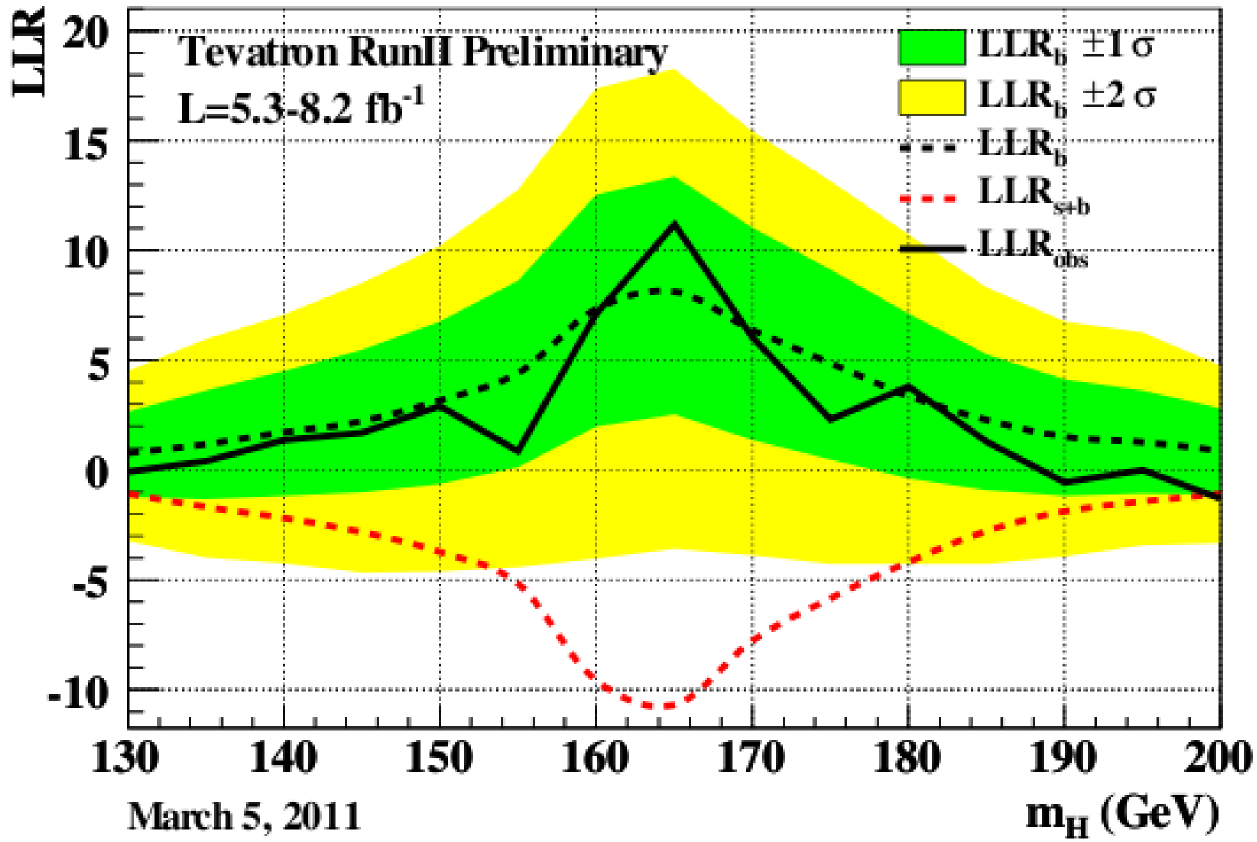
Tevatron Update for Winter 2011

- Tevatron Winter 2011 combination inputs (high-mass only):

Channel	CDF Lumi [fb^{-1}]	DØ Lumi [fb^{-1}]
$H \to W^+W^- \to \ell\nu\ell\nu$	7.1	8.1
$H \to W^+W^- \to \ell\nu\tau_{\mathrm{h}}\nu$	7.1	7.3
$(W/Z)H \to (W/Z)W^+W^-$	7.1	5.3
$H \to \gamma\gamma$	-	8.2
$H \to W^+W^- \to \ell\nu jj$	5.4	-

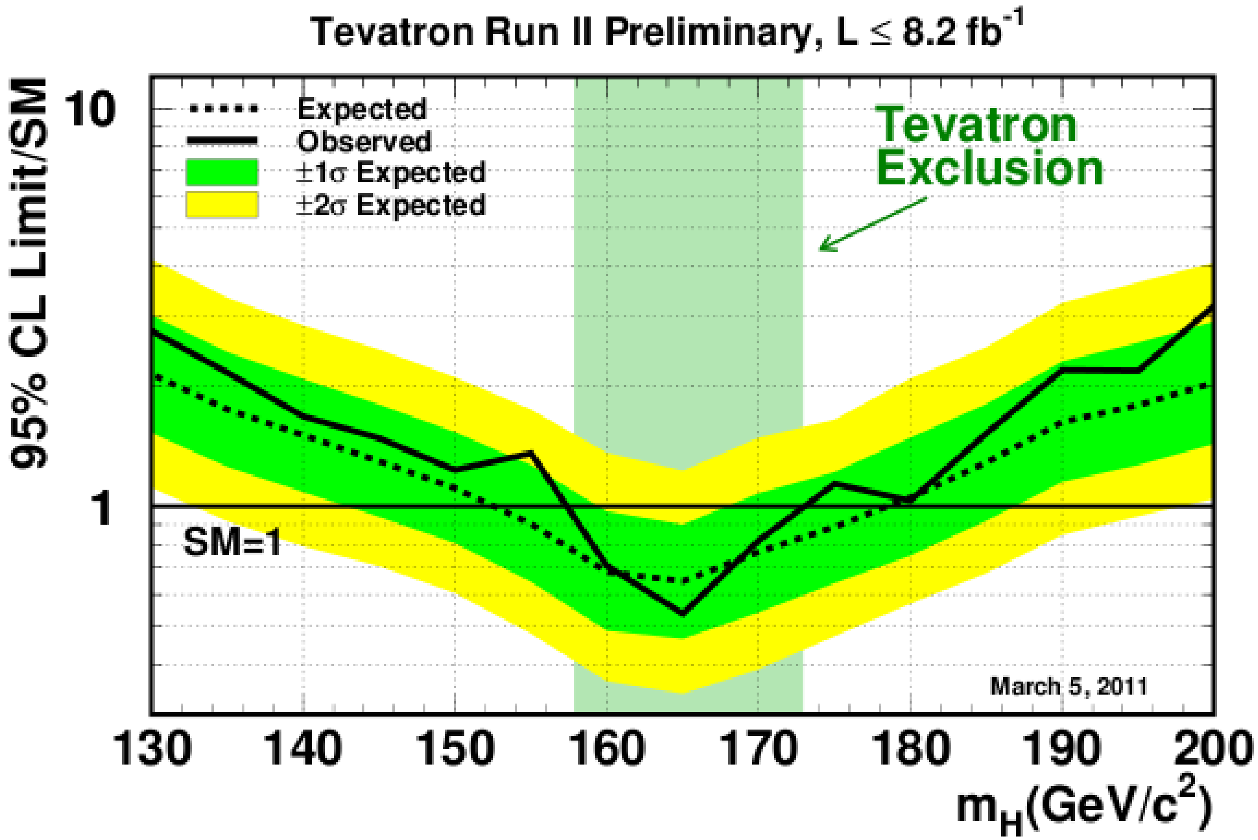
- DØ high-mass objectives for Winter 2011 which were met are in blue.
- Objectives not met are in red.

Tevatron LLR Winter 2011



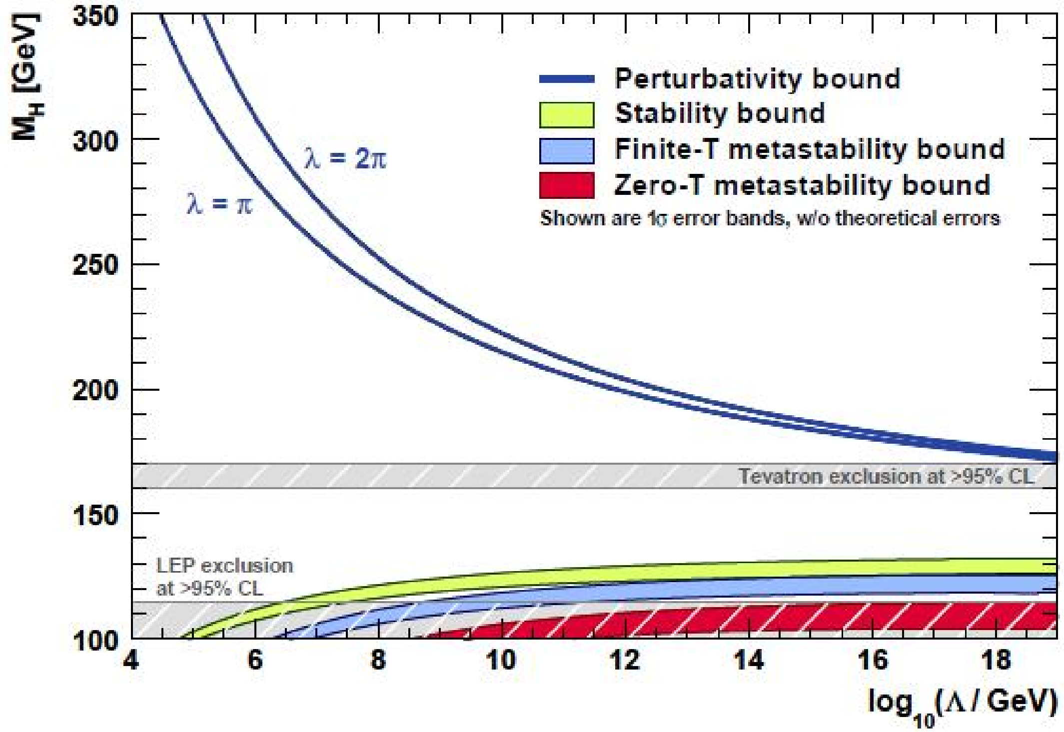
- Just presented at Moriond Electroweak, in La Thuile, Italy.

Tevatron Limits Winter 2011



- Just presented at Moriond Electroweak, in La Thuile, Italy.
- 95% CL Exclusion: $158 < m_H < 173$ GeV ($153 < m_H < 178$ GeV exp)
- Summer 2010 expected: $156 < m_H < 173$ GeV.

The Fate of the SM Might Still be in Our Hands



- Require the Higgs self-coupling to remain finite and positive.
- Adding Tevatron exclusion rules out blow-up at 99% CL.
- Additional Tevatron exclusion would further limit SM survival region.
- Hint of low-mass Higgs would be hint of new physics as “low” as 10^8 GeV.
- From: J. Ellis *et al.*, “The Probable Fate of the SM” [arXiv:0906.0954].