Status and Prospects of Standard Electroweak Physics

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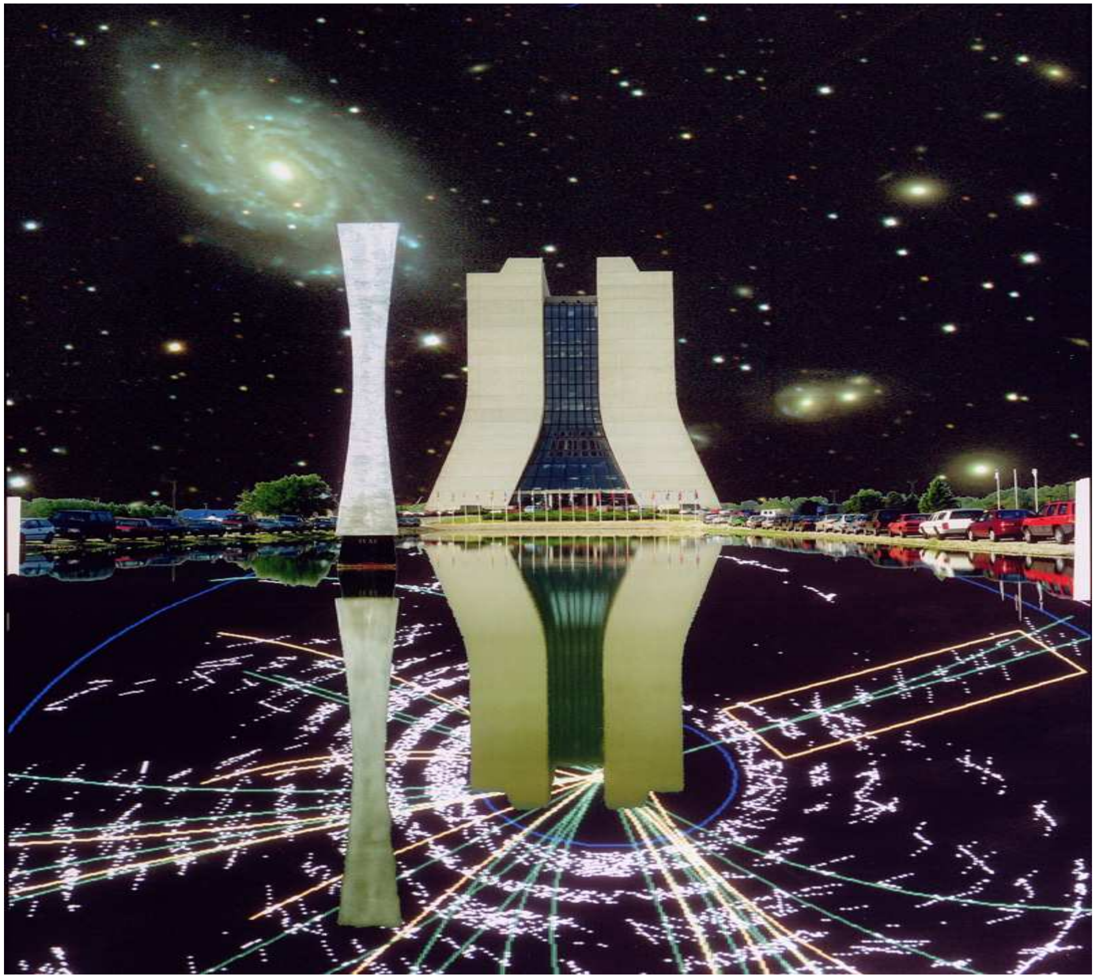
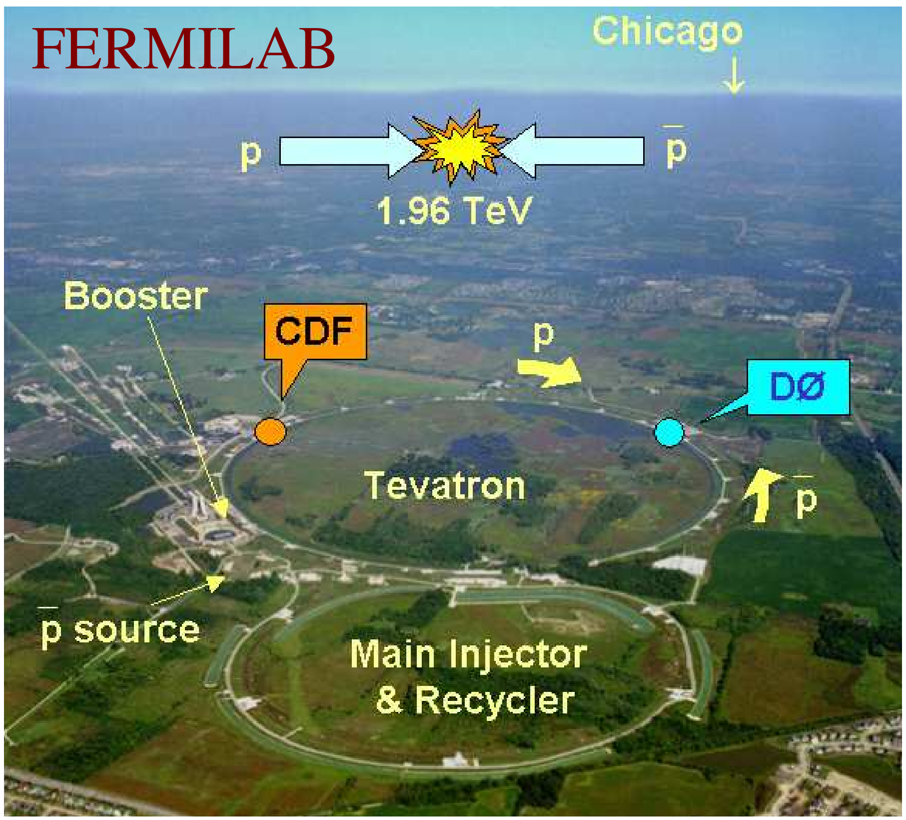


DAE Symposium on High Energy Physics
Varanasi, 18 December 2008

Electroweak Symmetry Breaking

Searches for standard model Higgs at the Tevatron

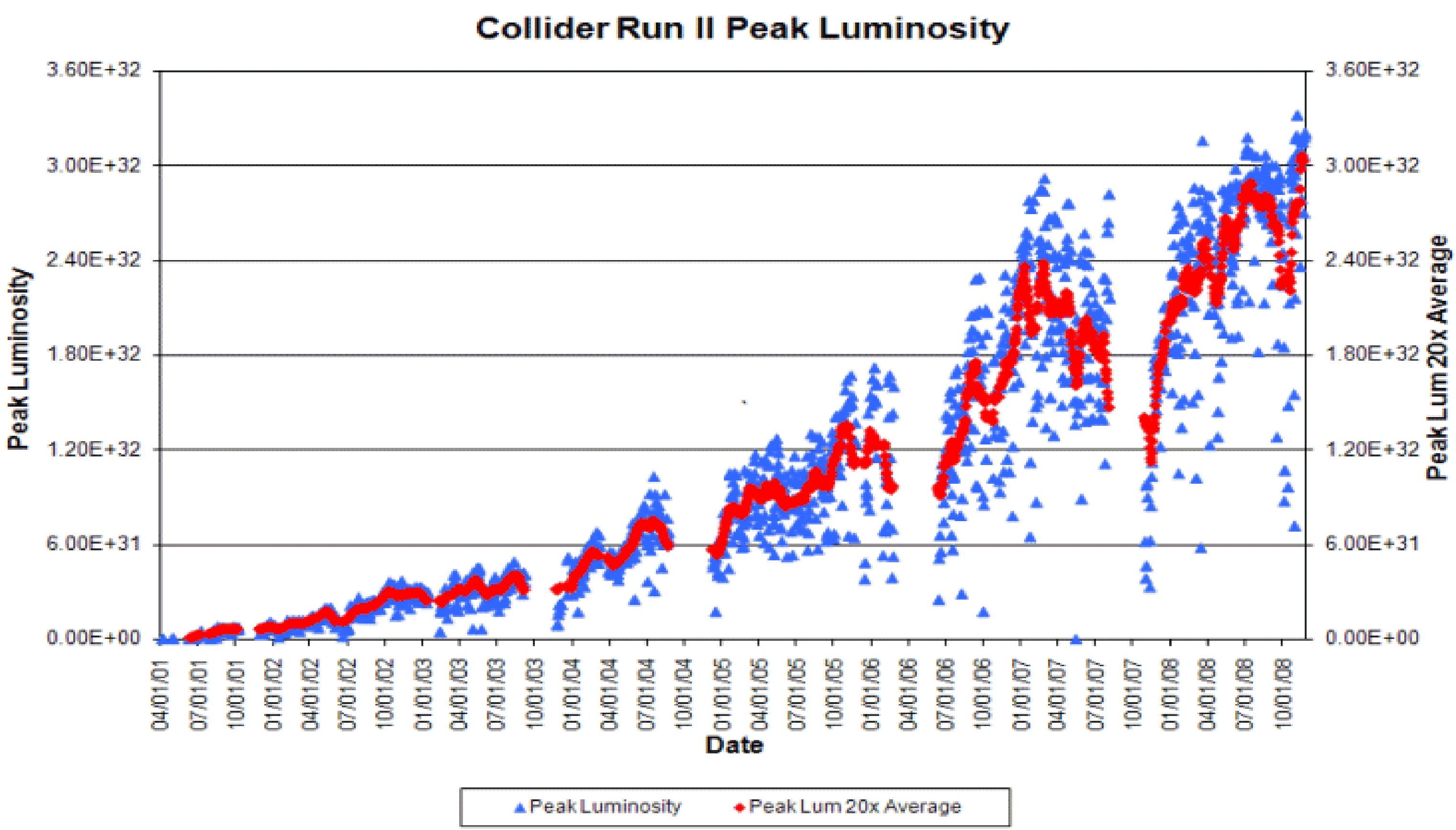
Precision measurements and Electroweak Fits



Tevatron at Fermilab

Tevatron is routinely exceeding nominal Run II instantaneous luminosity target of $2x10^{32}$ /cm^2/s

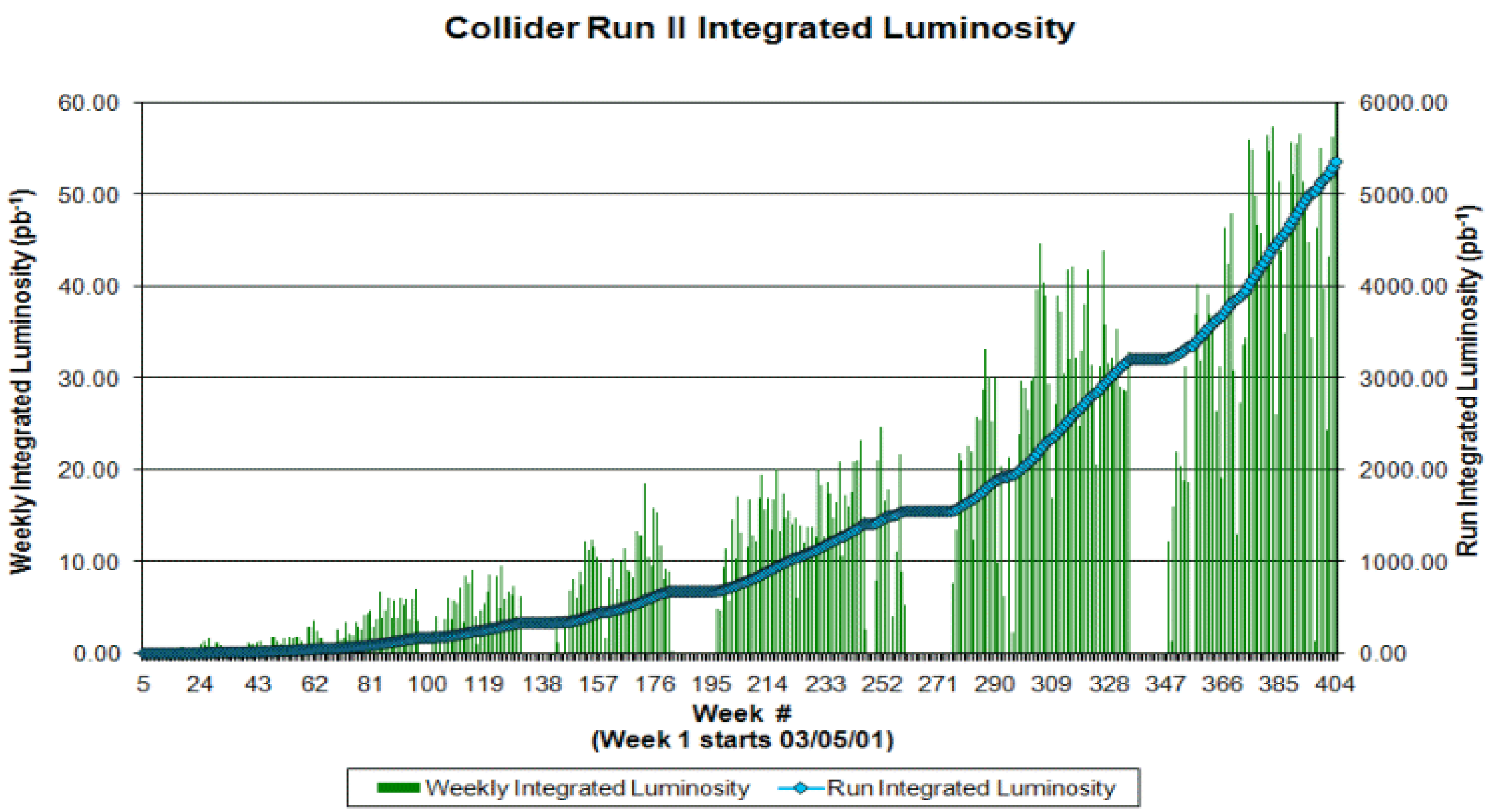
Recently achieved $3.4x10^{32}$ /cm^2/s



Tevatron at Fermilab

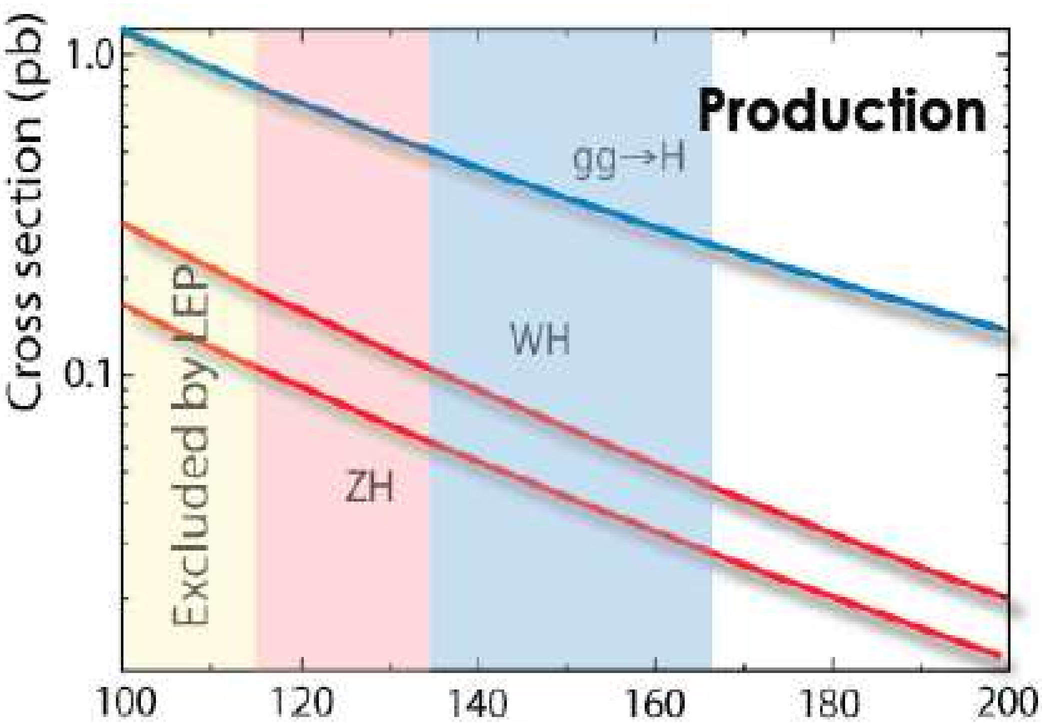
Tevatron has delivered 5 fb^{-1} of integrated luminosity

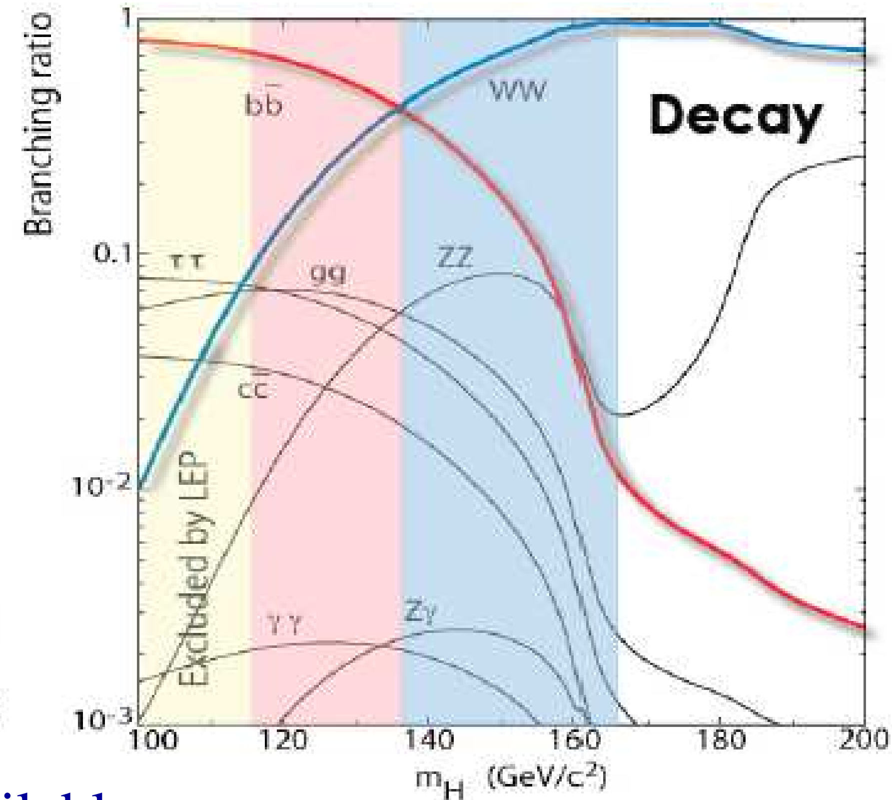
On track to deliver 8-9 fb^{-1} by 2010



Standard Model Higgs Boson Production and Decay

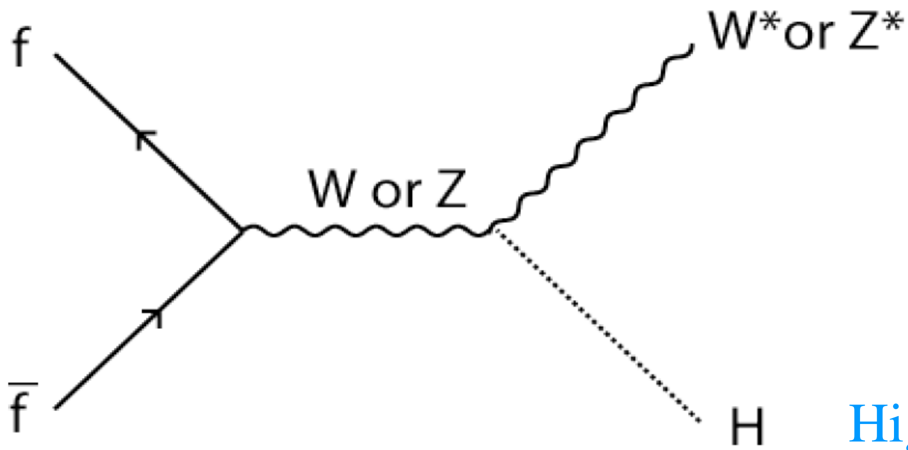
Higgs Boson Production and Decay





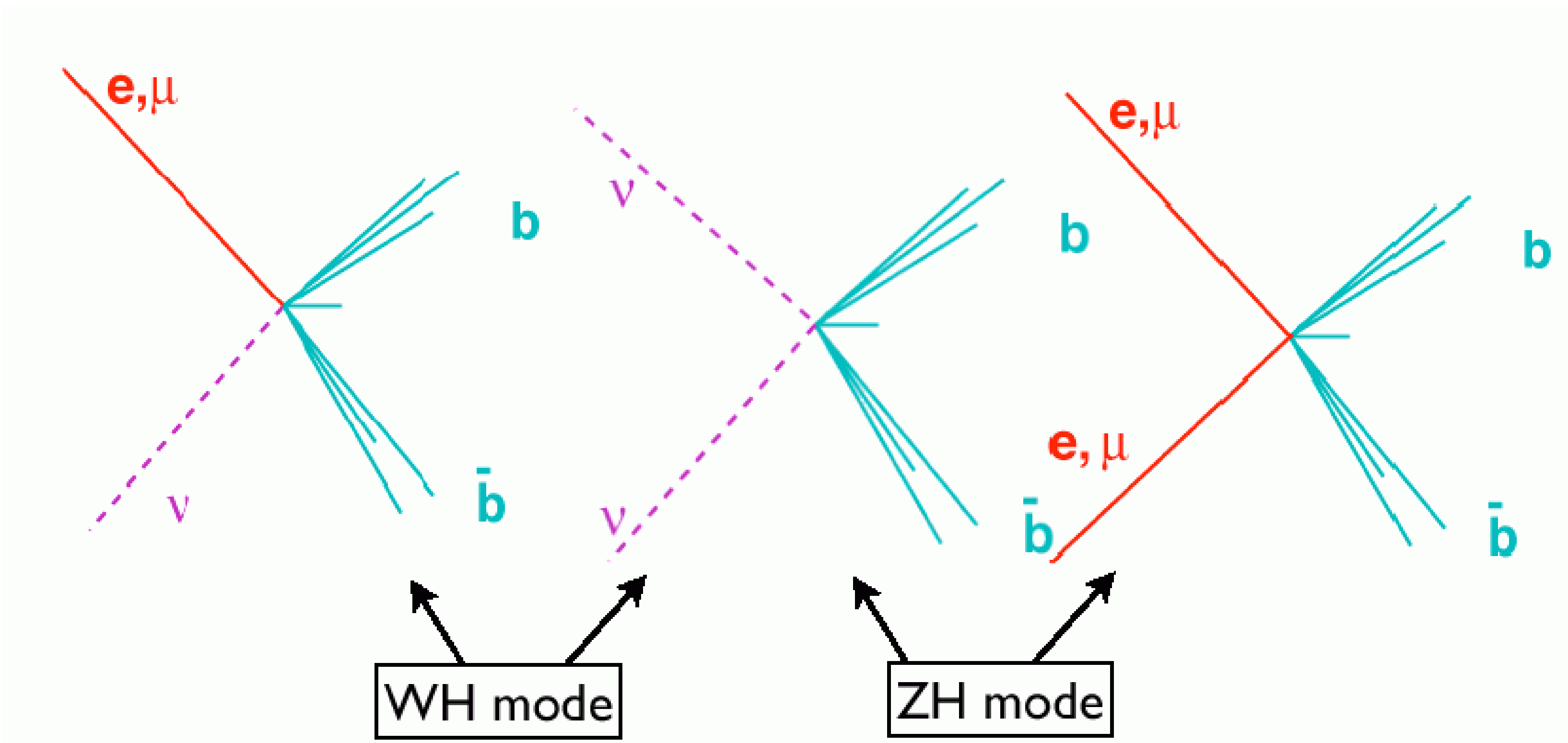
- High mass: H→WW→lνlν decay available
  - Take advantage of large gg→H production cross section
- Low Mass: H→bb, QCD bb background overwhelming
  - Use associated production with W or Z for background discrimination
  - WH→lνbb, ZH→ννbb (MET+bb), ZH→llbb
- Also: Vector Boson Fusion Production,VH→qqbb, H→ττ (with 2 jets), H→γγ, WH->WWW, ttH

Light Higgs Boson Production and Decay

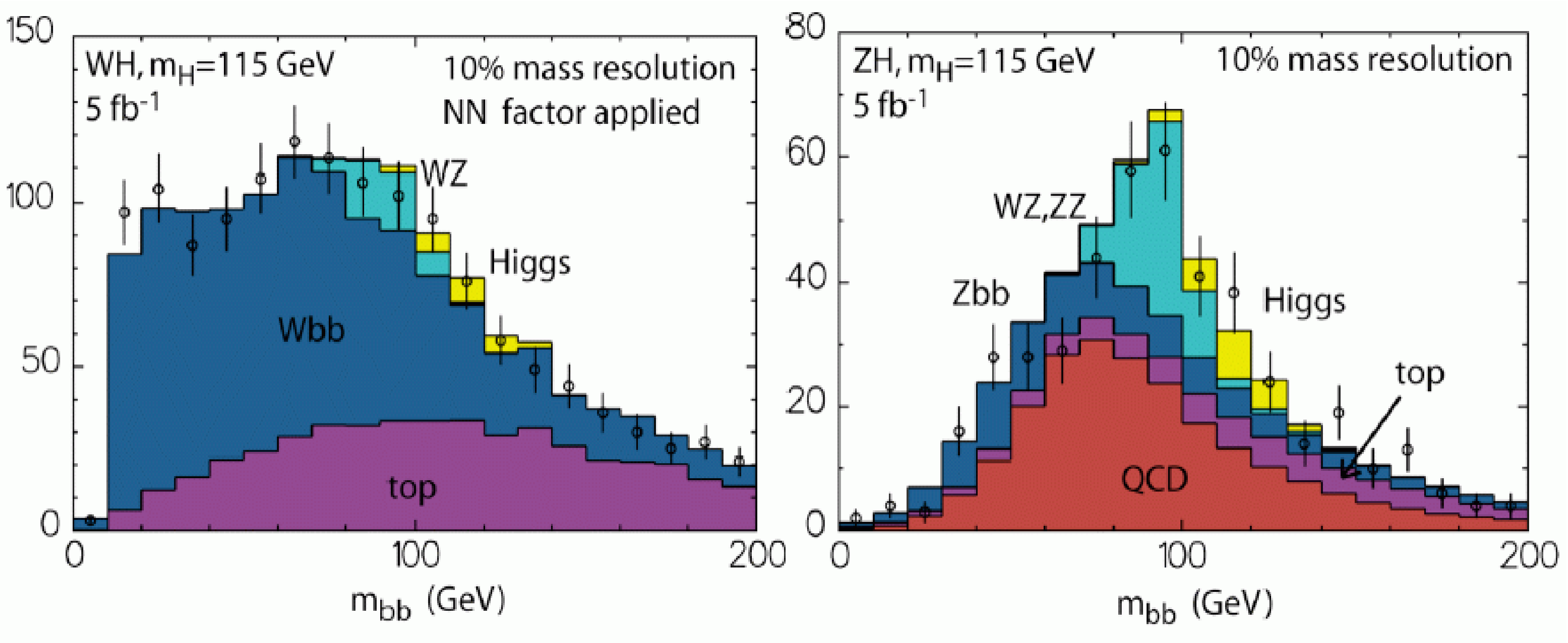


W, Z decay to electrons, muons, τ, and/or neutrinos

Higgs boson decays to bottom quarks



Simulated Higgs Signal on Expected Backgrounds



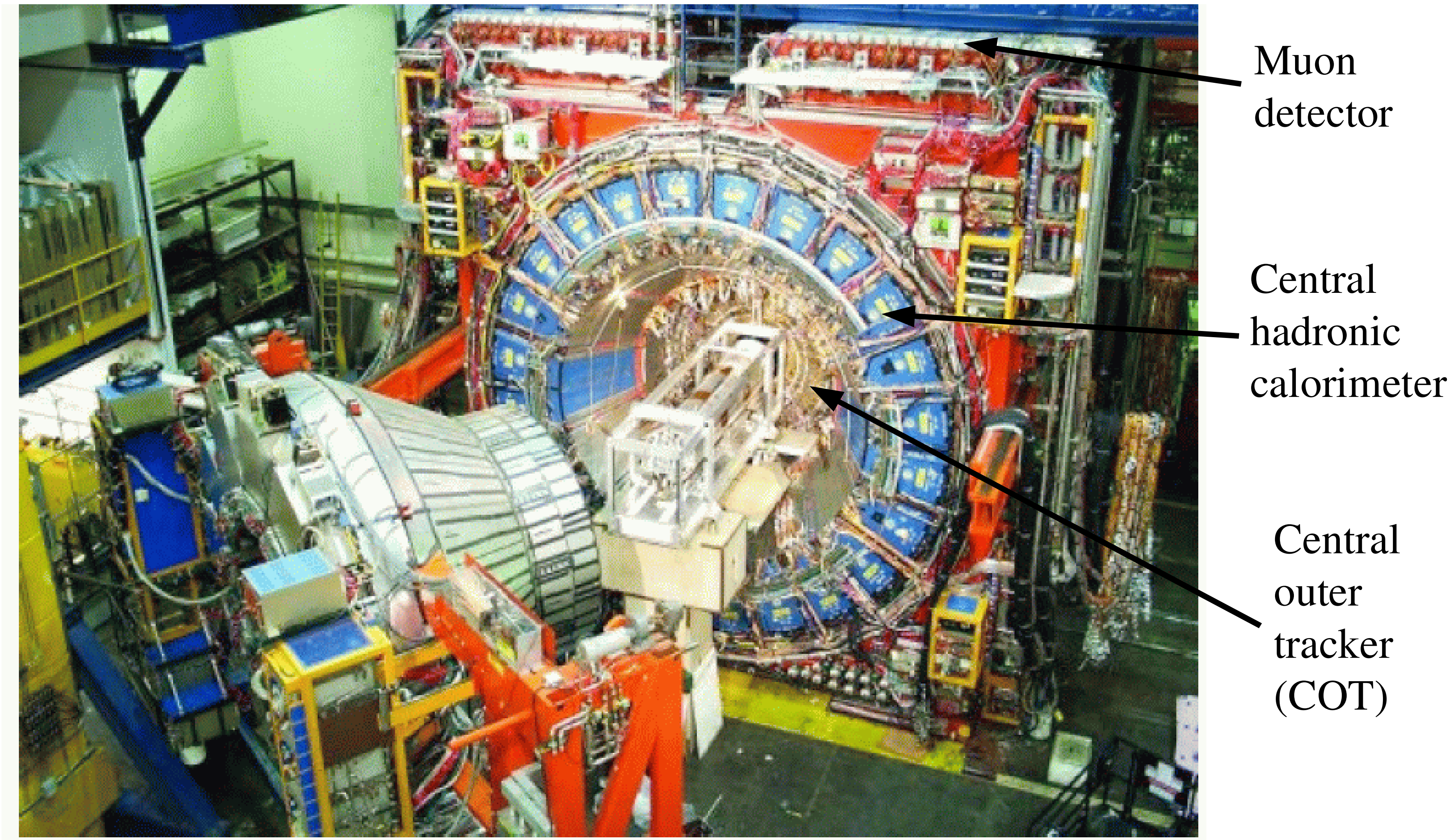
Key requirements for observing signal:

Excellent lepton identification, good calorimeters for jet and Missing E_T reconstruction, excellent silicon detectors for b jet identification

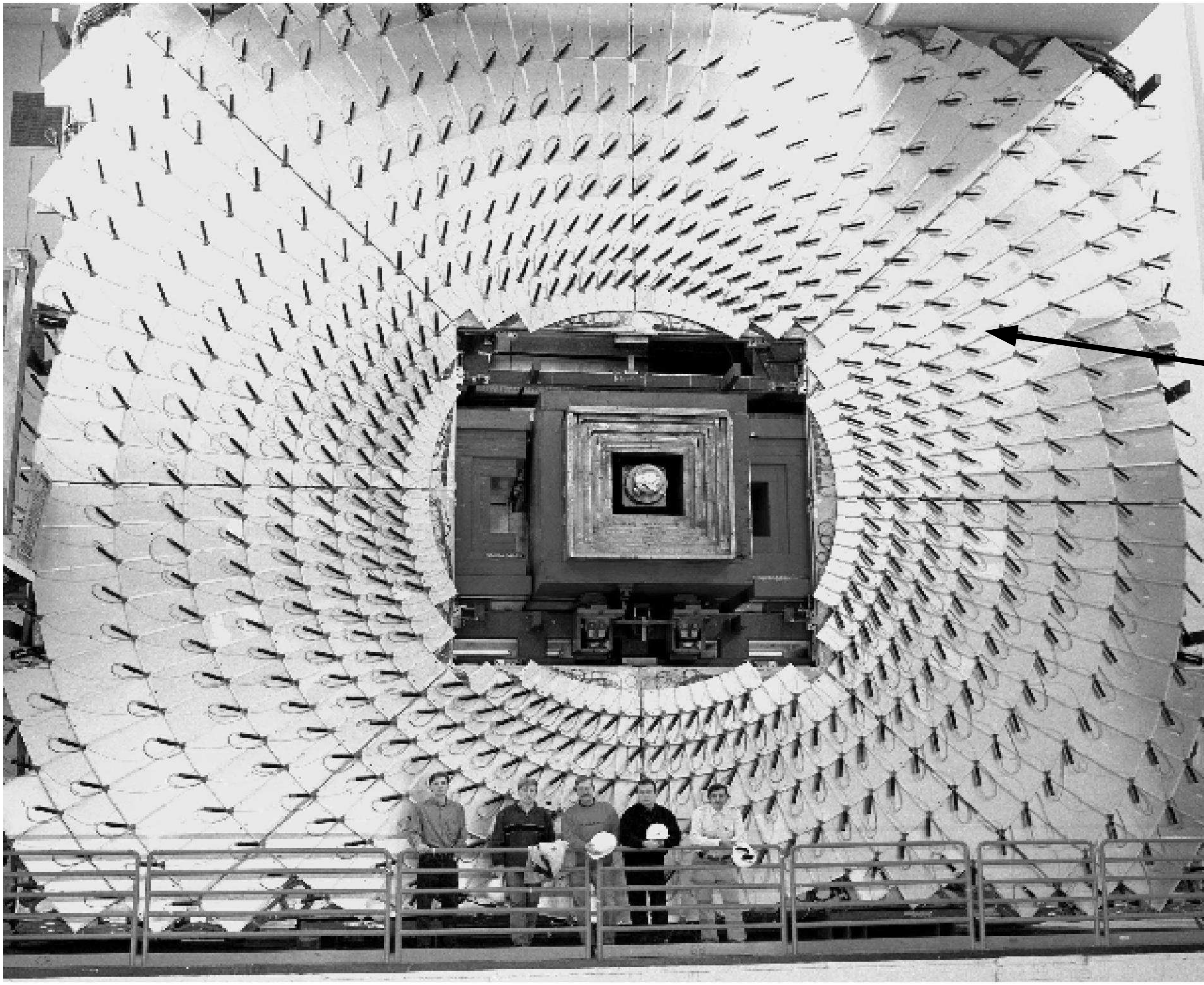
Good reconstruction of decay particle momentum vectors

Good simulation of signal and background events

Collider Detector at Fermilab (CDF)



D0 Detector



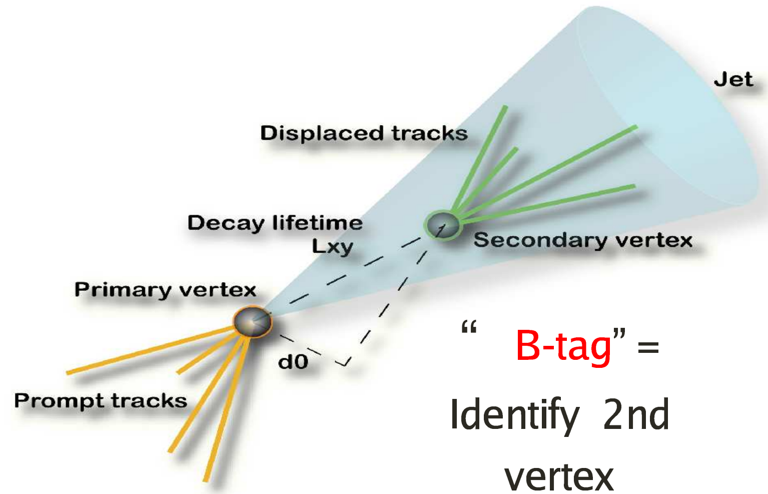
Forward
muon
detectors

Tagging of b-quark jets

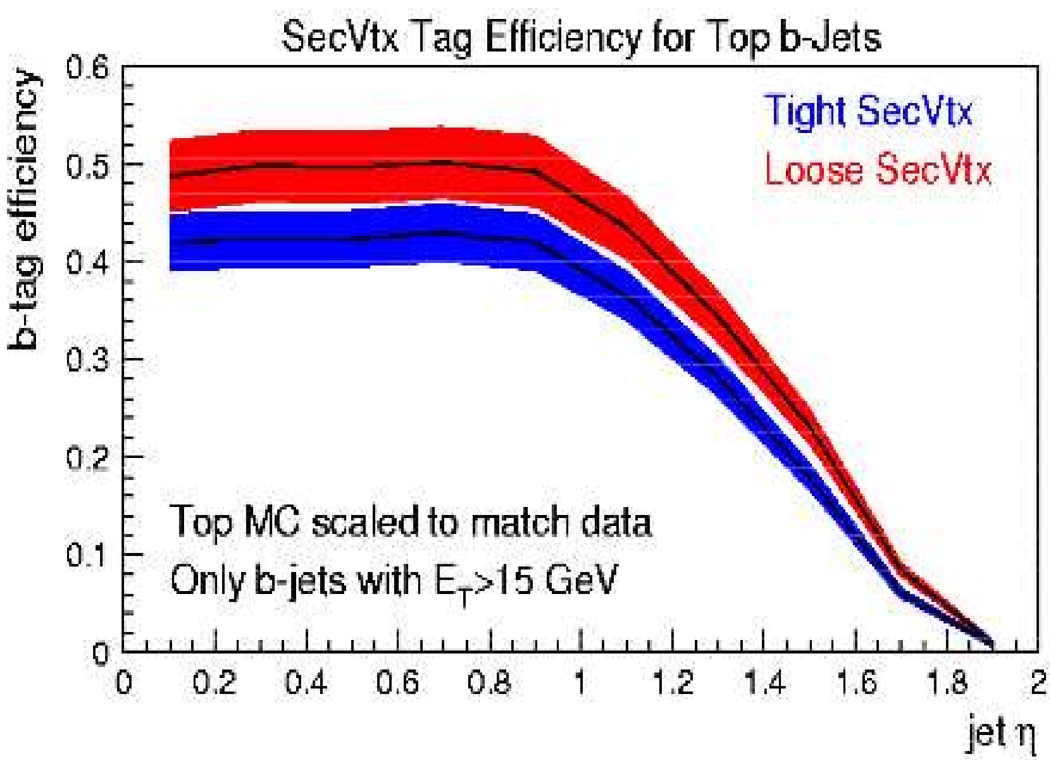
DØ: Neural Network tagger with multiple operating points

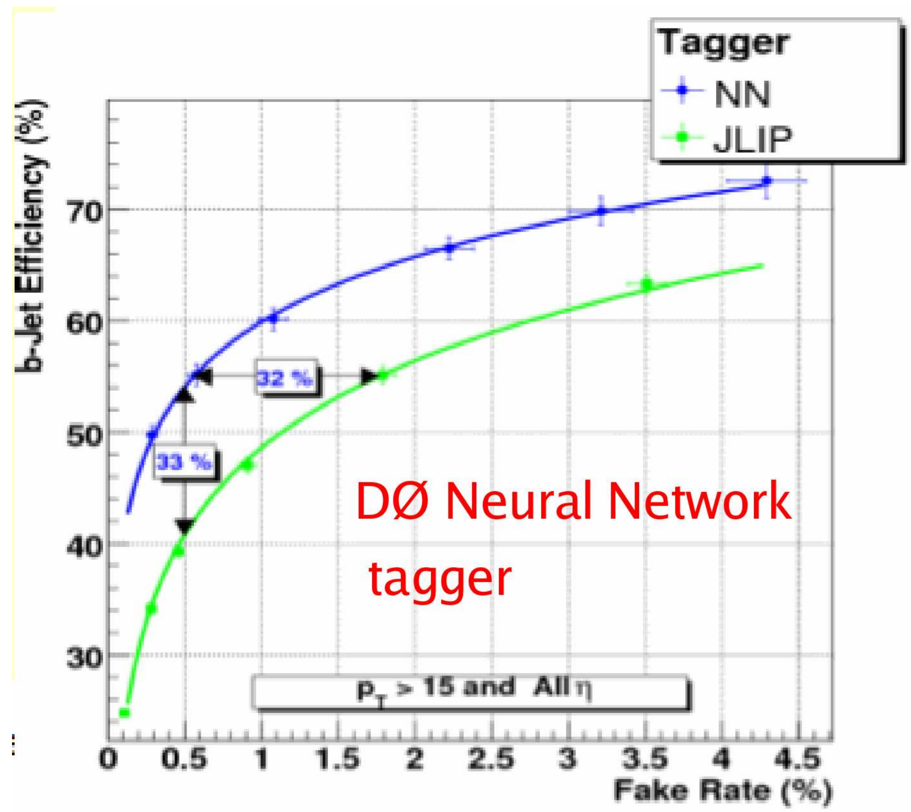
CDF: Secondary Vertex tagger, jet probability tagger, and Neural Network flavor separators

50-70% Efficient with 0.3-5% mistag rate



"B-tag" = Identify 2nd vertex

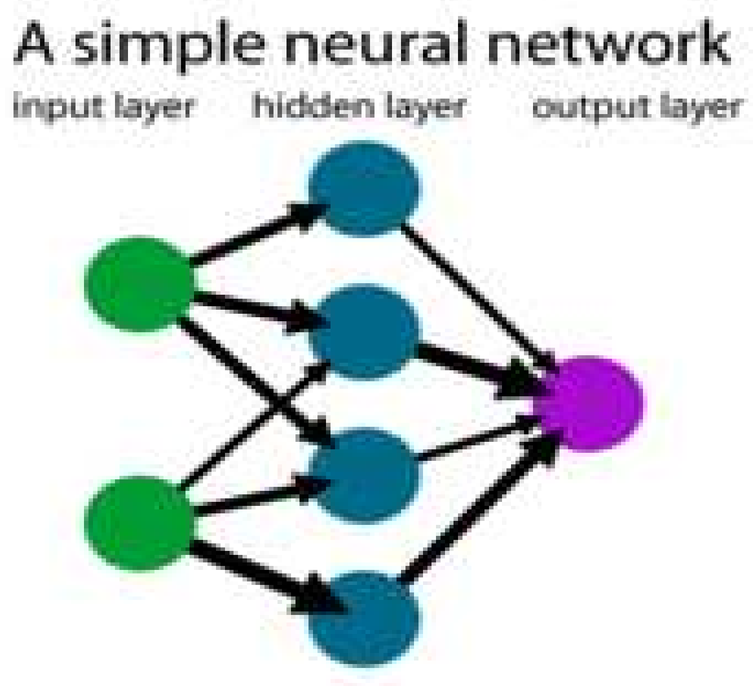




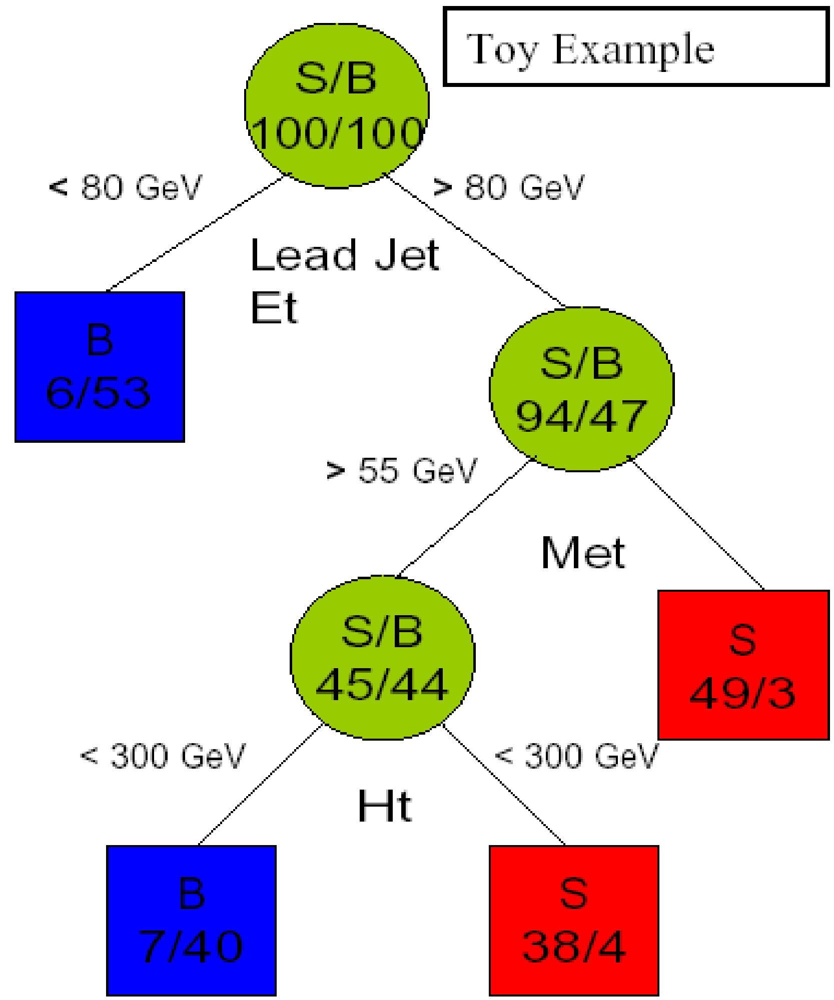
DØ Neural Network tagger

Multivariate Techniques for Signal/Background Discrimination

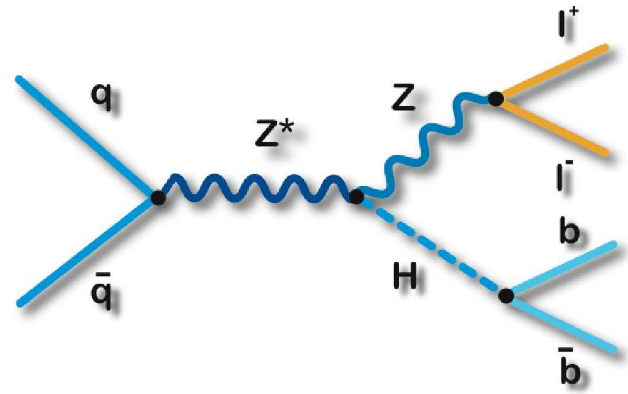
- Likelihood discriminants: Often using Standard Model Matrix Elements to compute differential probability distributions for kinematics
- Artificial Neural Networks: construct no
linear function of kinematics
- Decision trees: event classification using sequential cuts



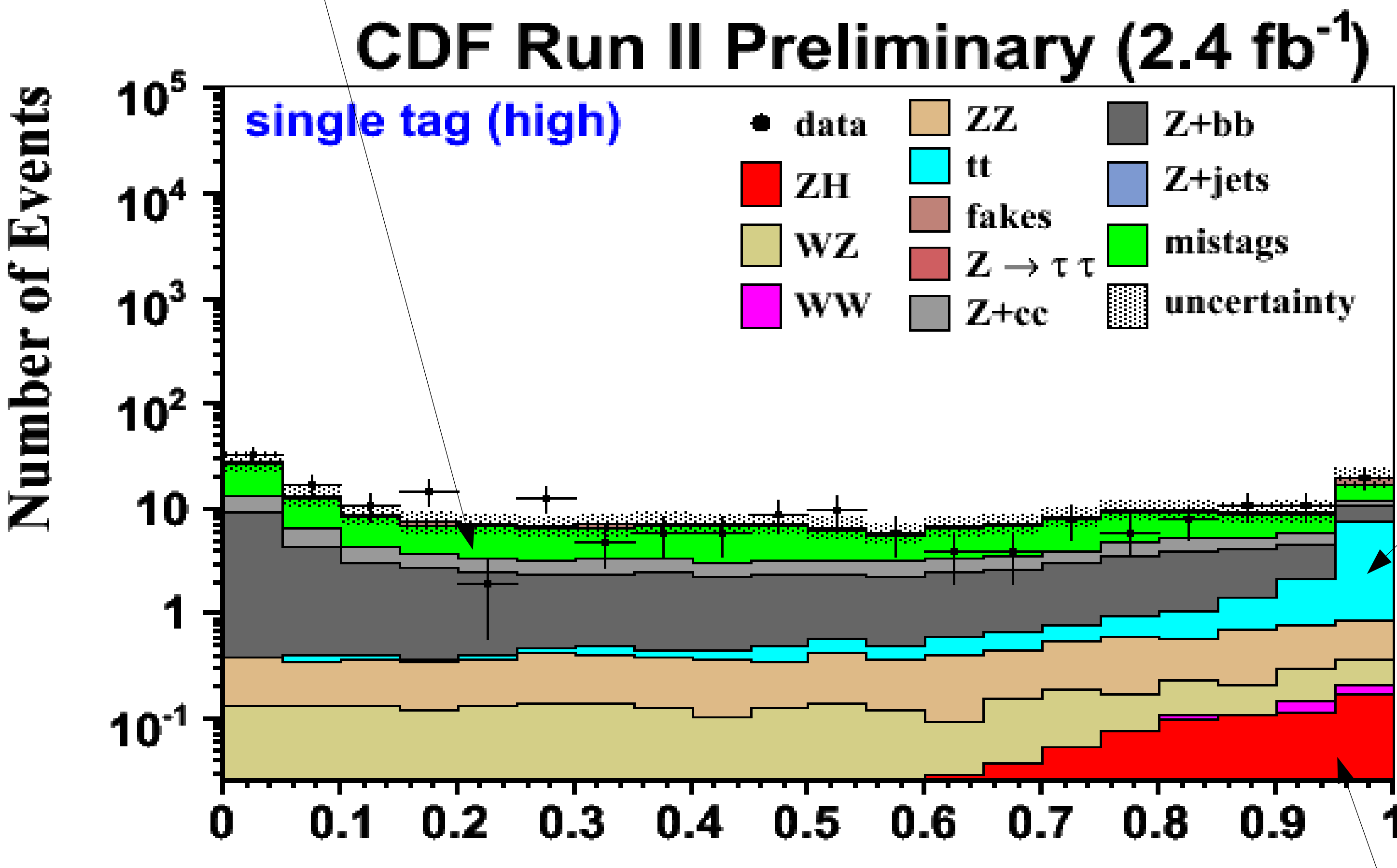
Decision Tree



SM Higgs: ZH→llbb



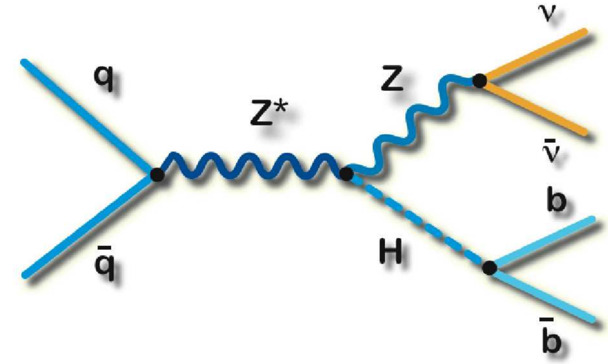
Z + 2 jets background dominant



Top quark background suppressed by another neural network

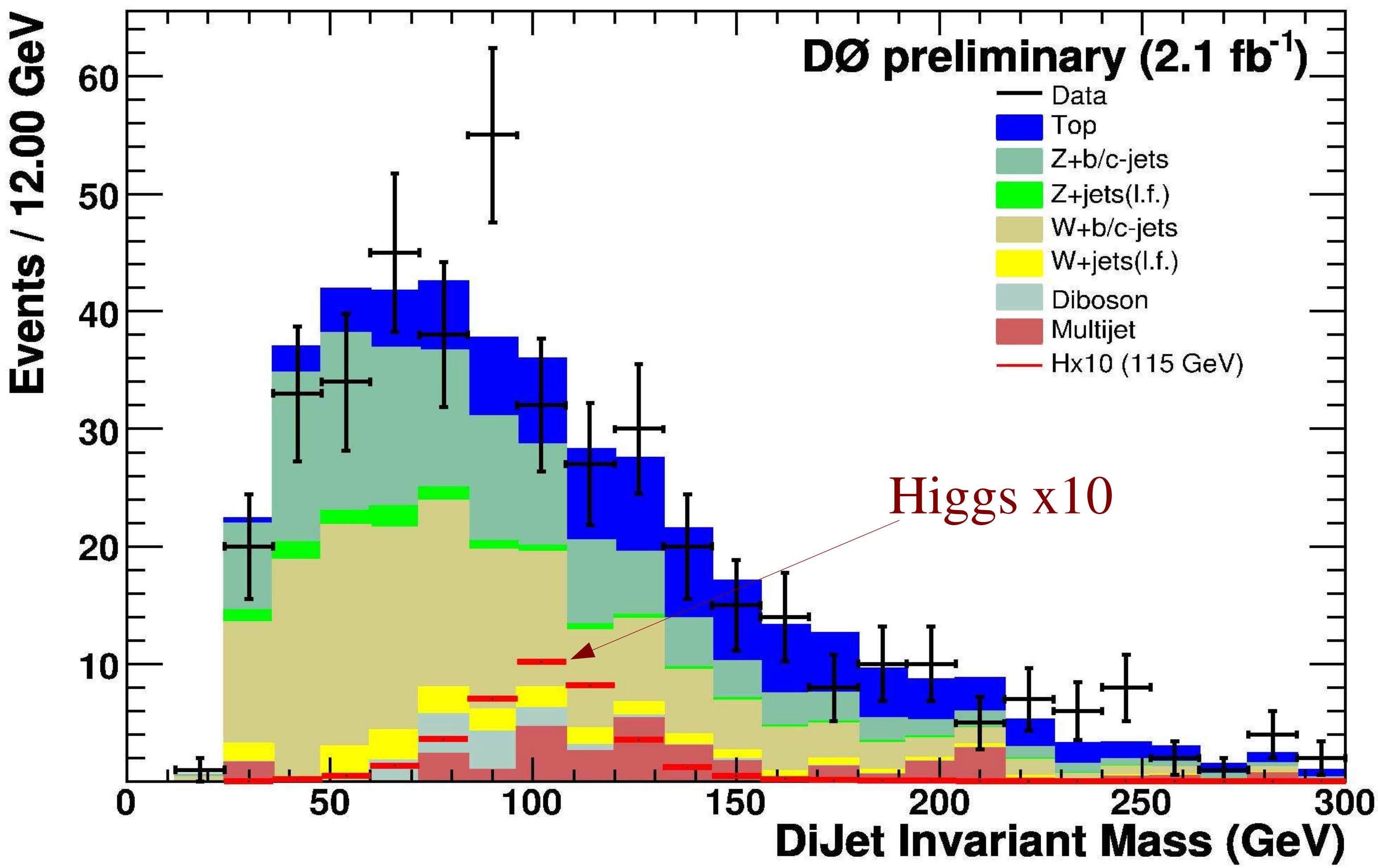
Z+2jets ← Neural Network Output → ZH

SM Higgs: VH→ννbb

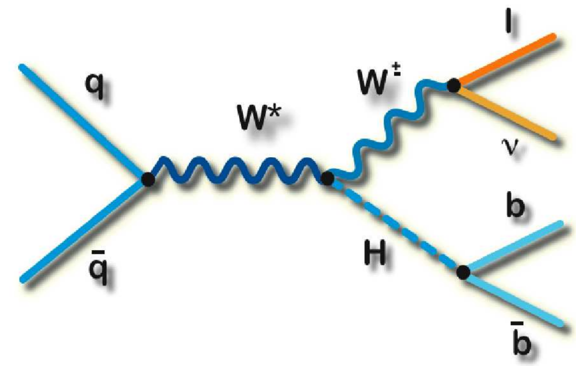


W (-> lν) + Higgs with lepton undetected also included in signal

Key issue: modelling the shape of QCD background



SM Higgs: WH→lνbb



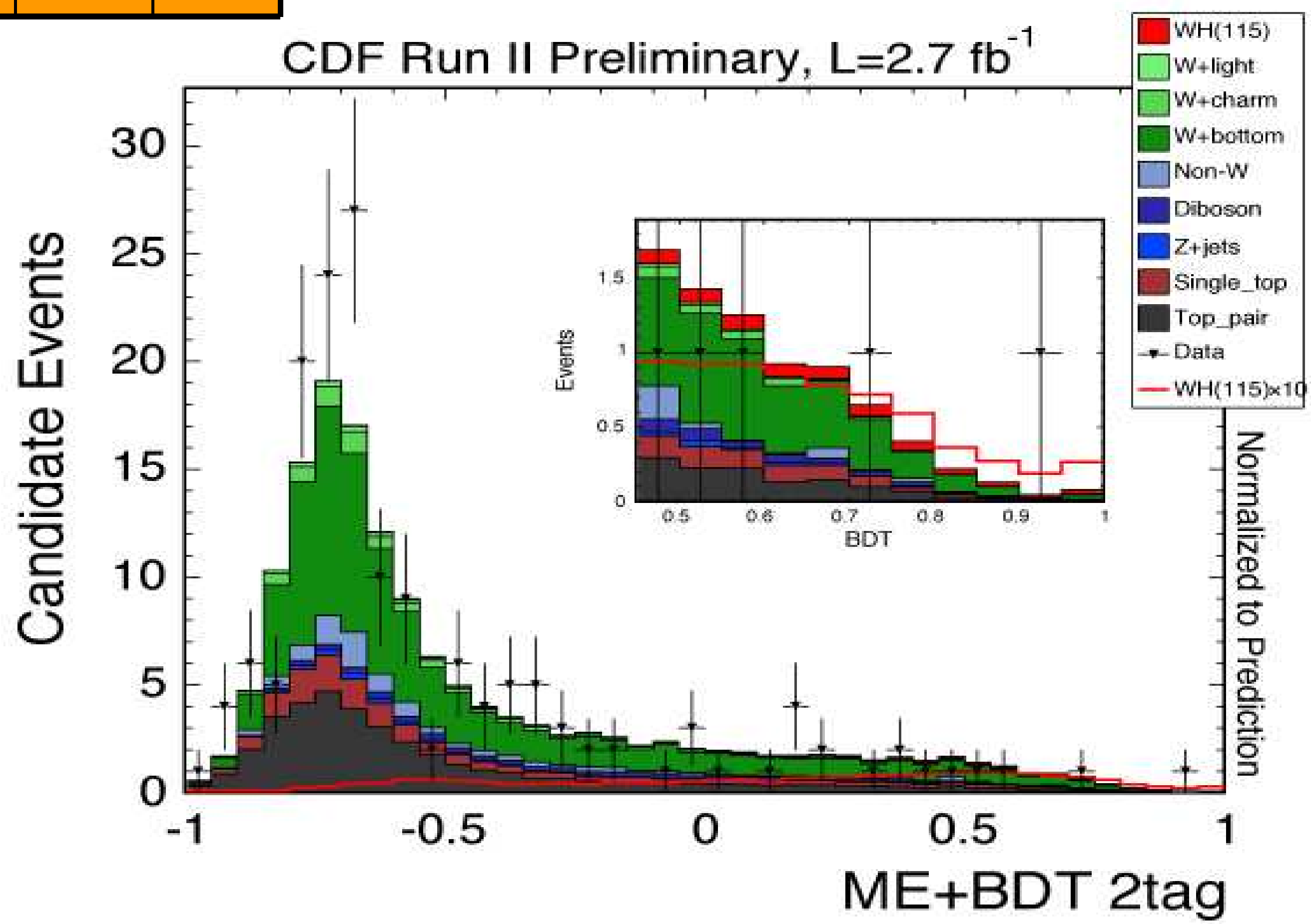
Results at mH = 115GeV: 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF NN	2.7	8.3	5.8	5.0
CDF ME+BDT	2.7	7.8	5.6	5.7
DØ NN	1.7	7.5	8.5	9.3

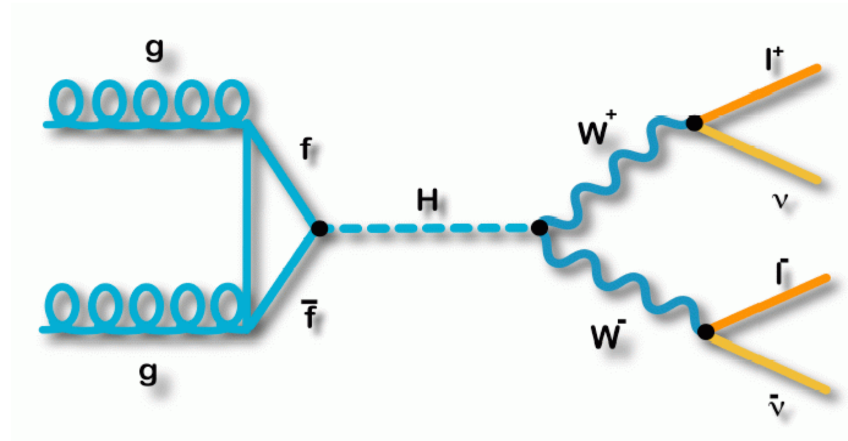
Key issue: shape of W+bb background

obtained from simulation, with normalization from data control regions

most sensitive channel for low-mass Higgs at Tevatron

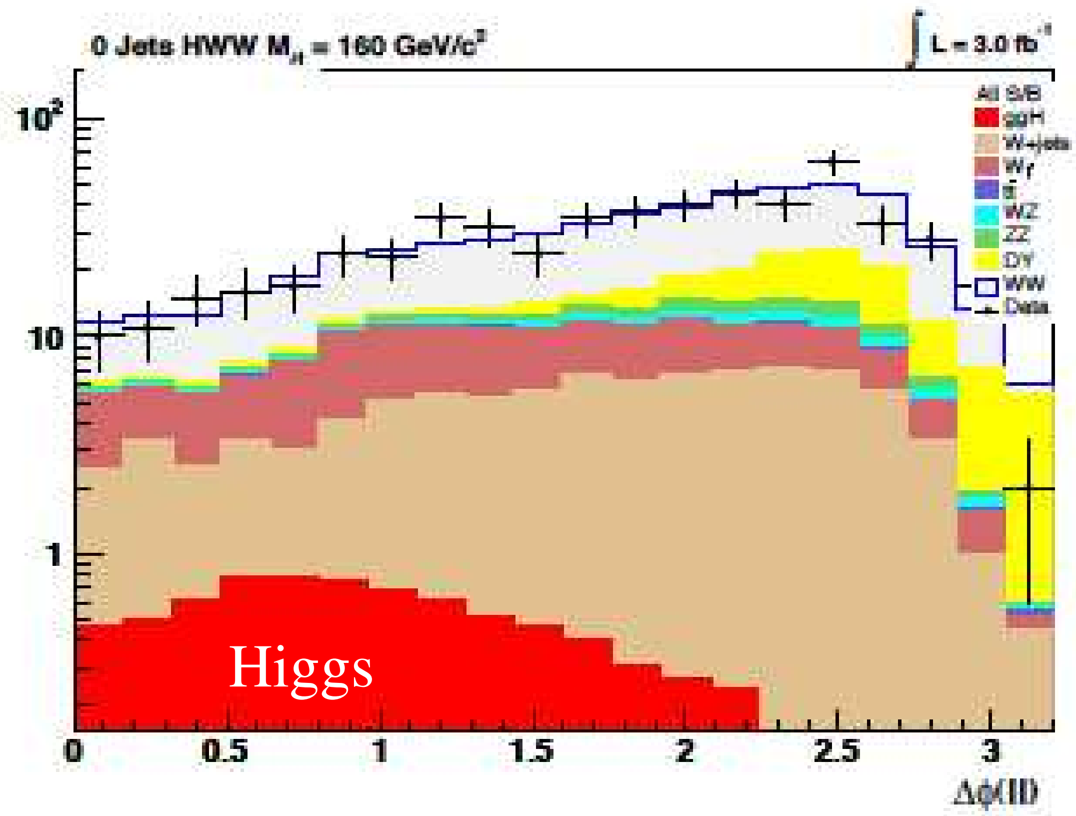


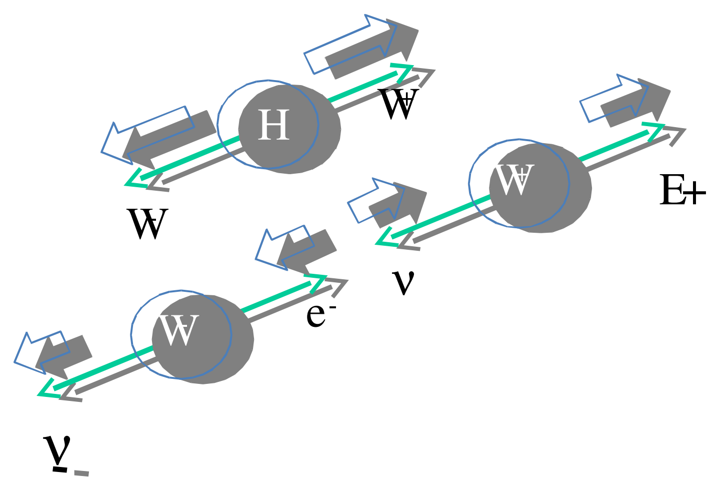
Heavy Higgs Boson Production and Decay



Most sensitive channel at the Tevatron

Key issue: maximizing lepton acceptance





Spin correlation: Charged leptons go in the same direction

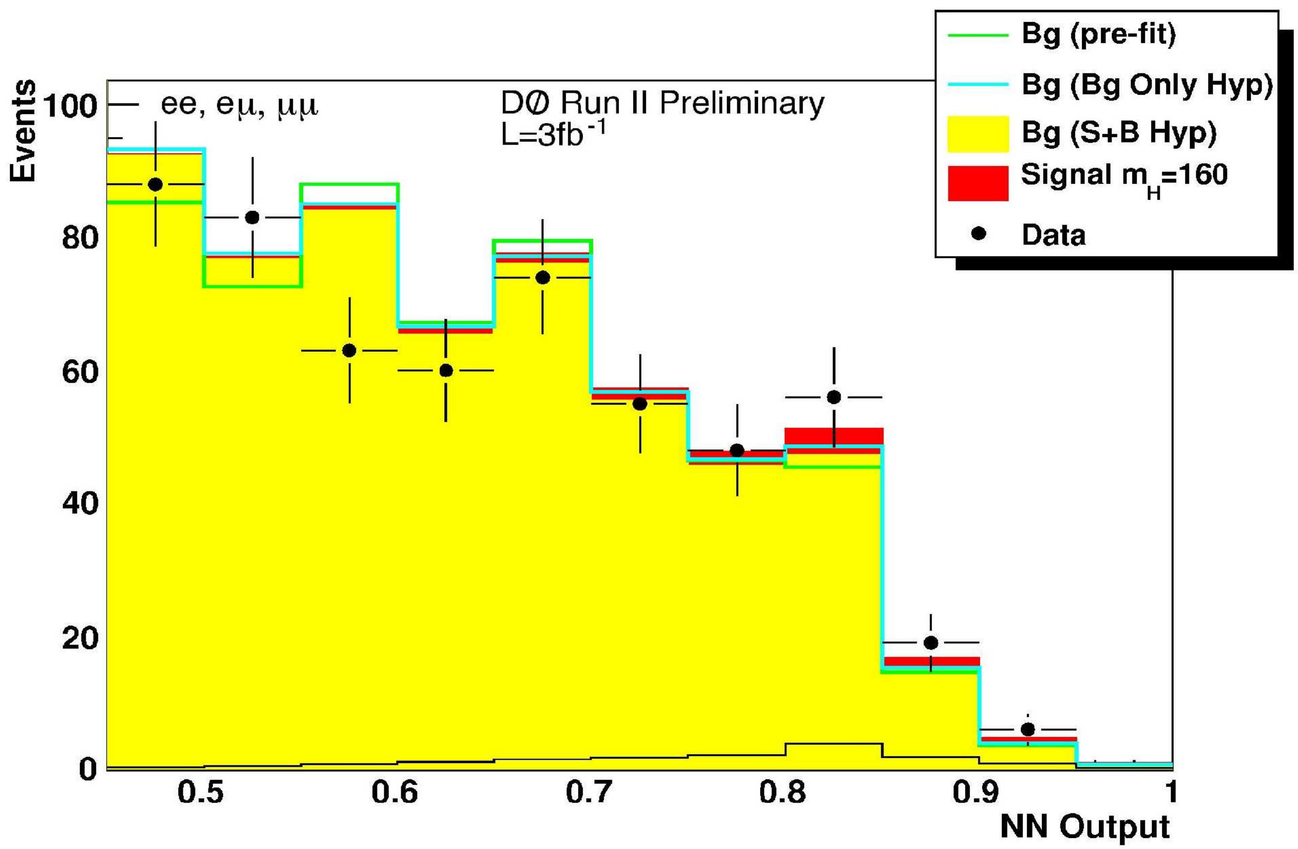
Heavy Higgs Boson Production and Decay

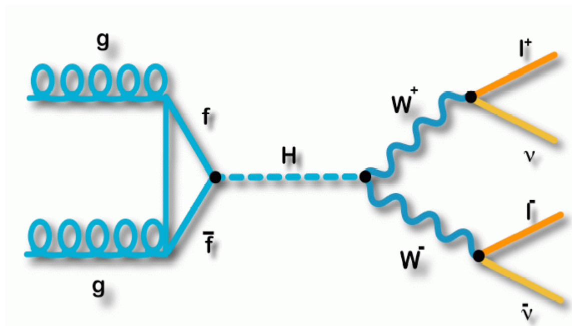
Results at mH = 165GeV : 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Higgs Events	Exp. Limit	Obs. Limit
CDF ME+NN	3.0	17.2	1.6	1.6
DØ NN	3.0	15.6	1.9	2.0

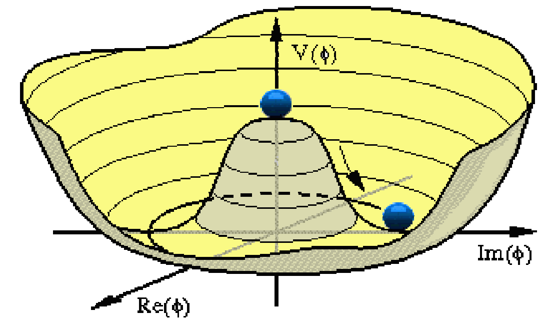
Most sensitive channel at the Tevatron

Key issue: maximizing lepton acceptance





SM Higgs Boson Production Limits

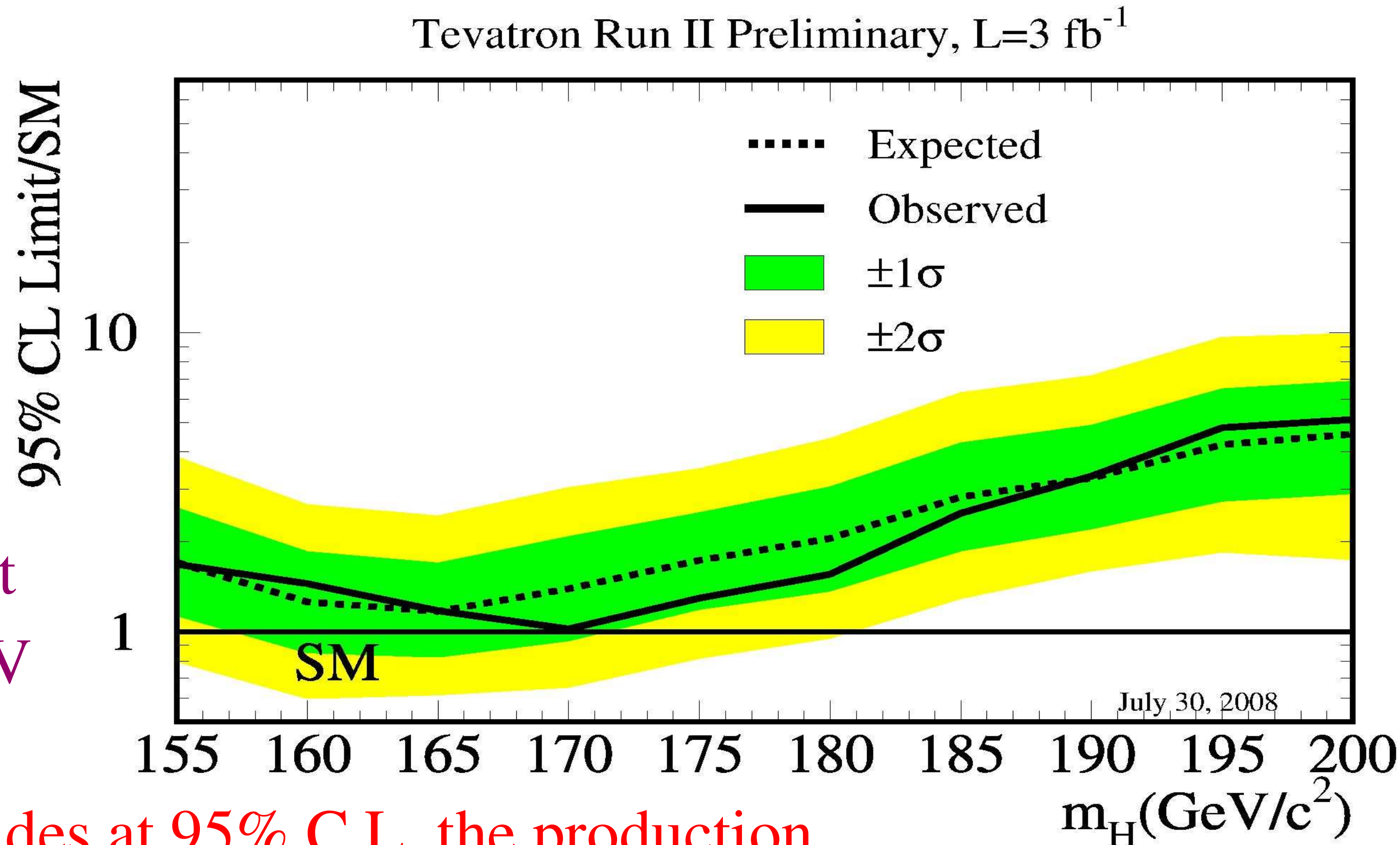


Comparison of Higgs boson production cross section upper limit to the theoretical expectation

Expected Limits on ratio: 1.2 @ 165, 1.4 @ 170 GeV

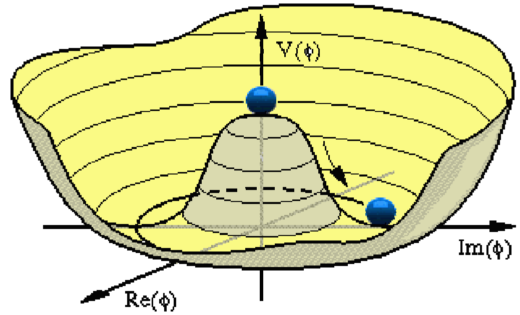
Observed Limit

1.0 @ 170 GeV

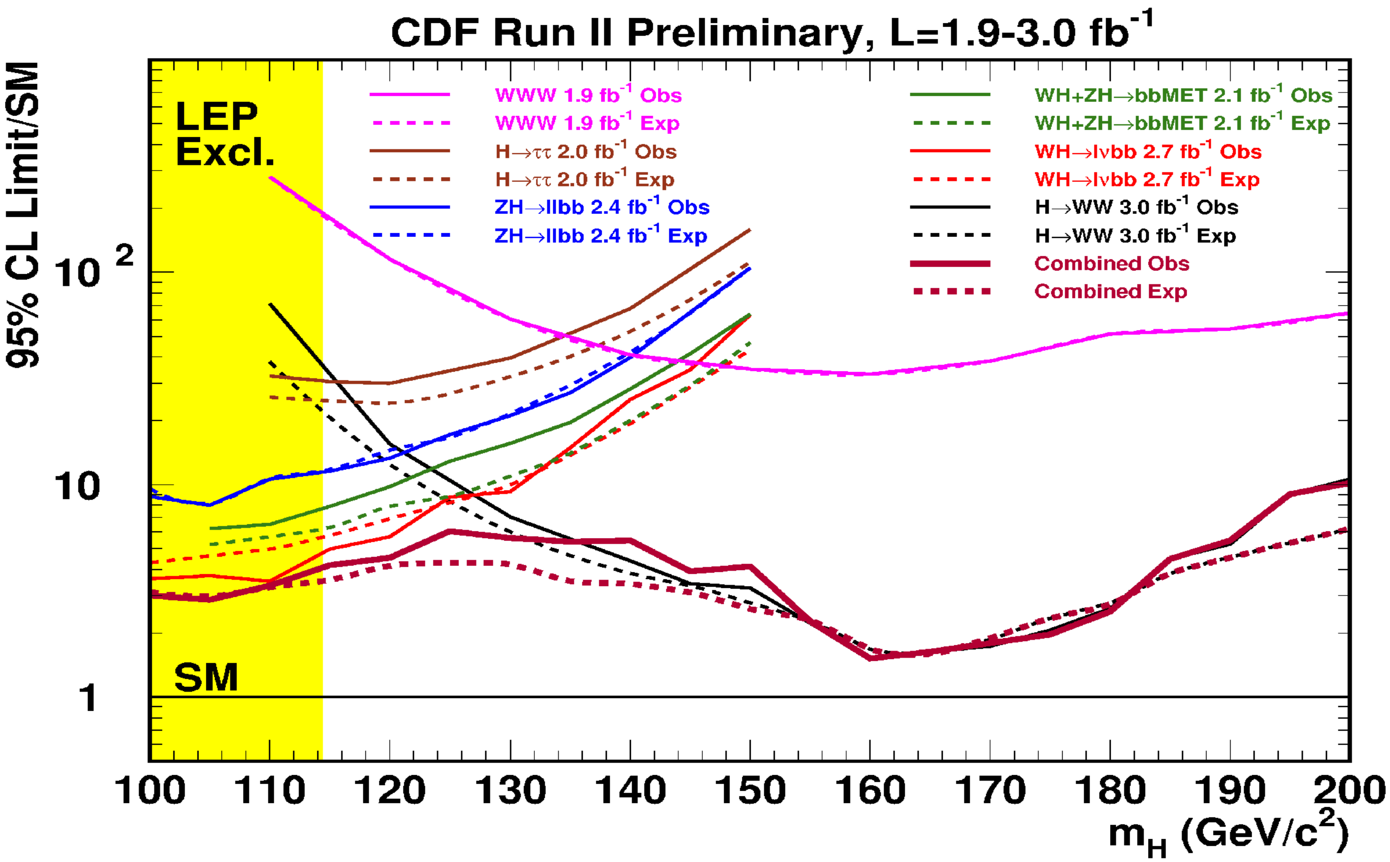


Tevatron excludes at 95% C.L. the production of a SM Higgs boson of 170 GeV

SM Higgs Boson Production Limits

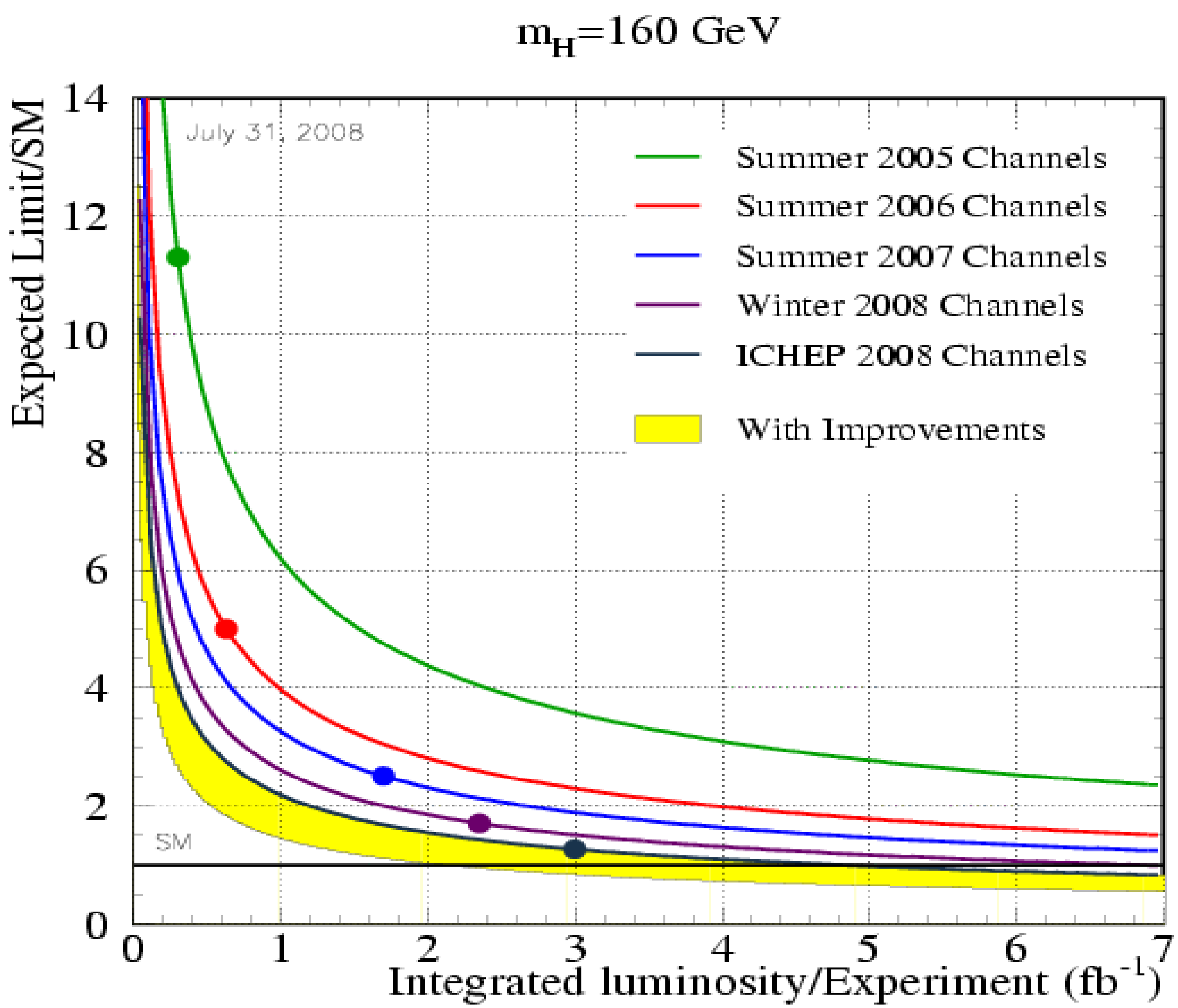


Comparison of Higgs boson production cross section upper limit to the theoretical expectation



- Low mass combination difficult due to ~70 channels
- Expected sensitivity of CDF/DØ combined: <3.0xSM @ 115GeV

Tevatron Higgs Search Projections



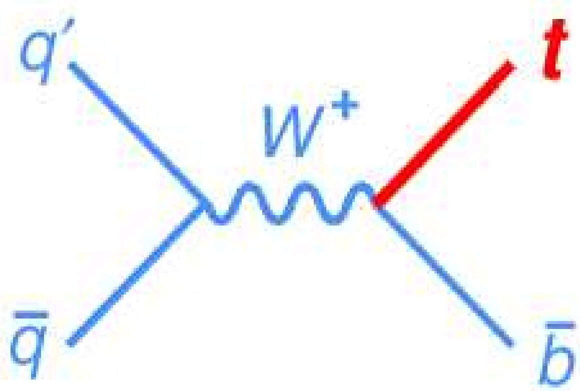
- Improvements for low-mass Higgs also in progress
  - Dijet mass resolution, increased lepton acceptance and b-tagging efficiency

Milestones in Standard Model Observations towards the Higgs

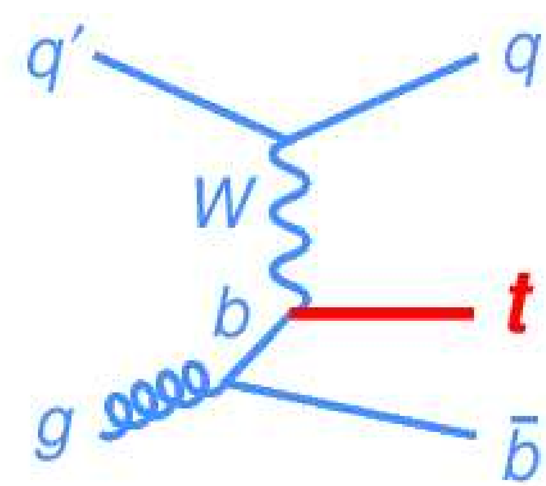
Single Top Production

- Top quark discovered in 1995 at the Tevatron using the pair production mode
- Important measurement of the *t*-*b* coupling
- Similar final state as WH -> *lv* + *bb* search
  - Therefore also a key milestone in the Higgs search

(a)

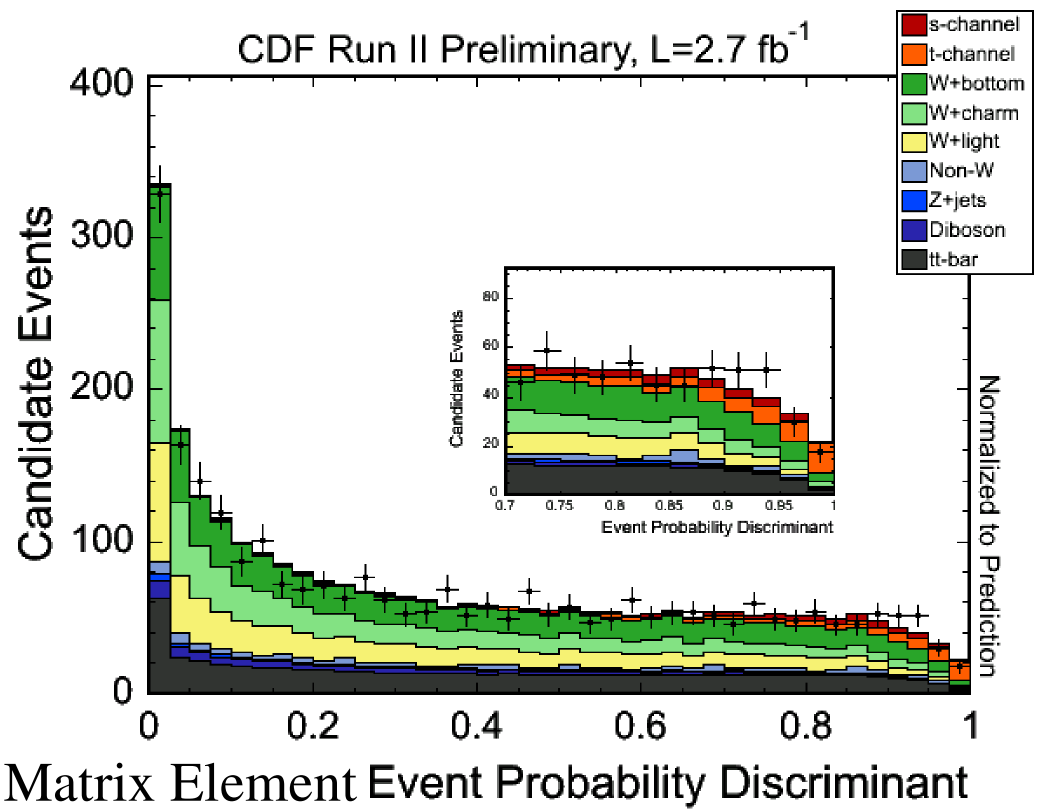


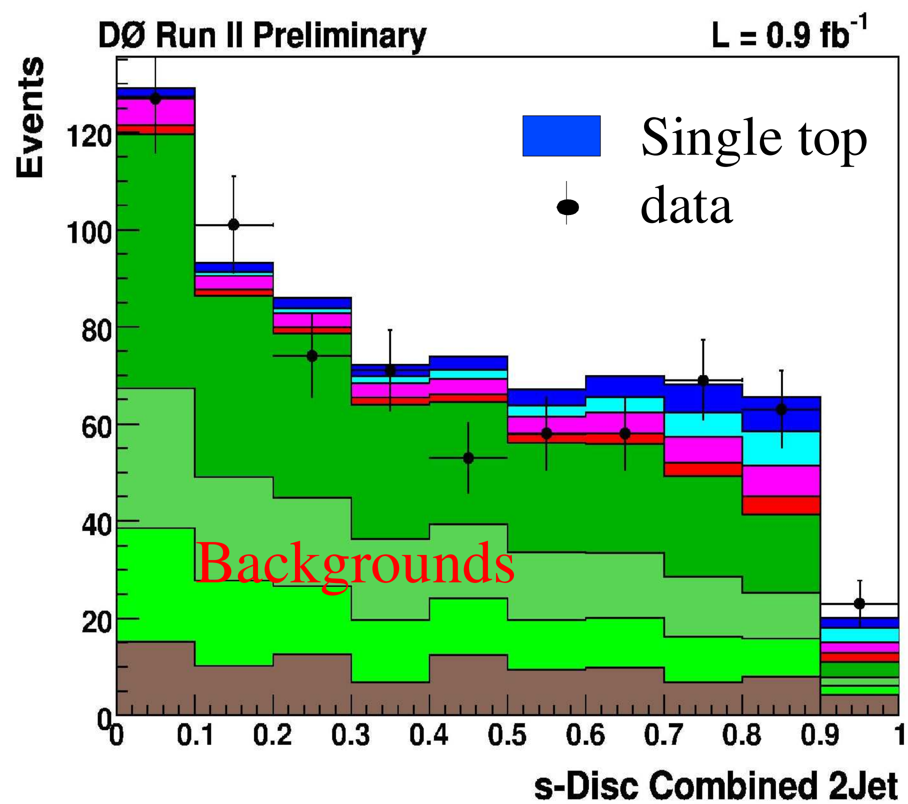
(b)



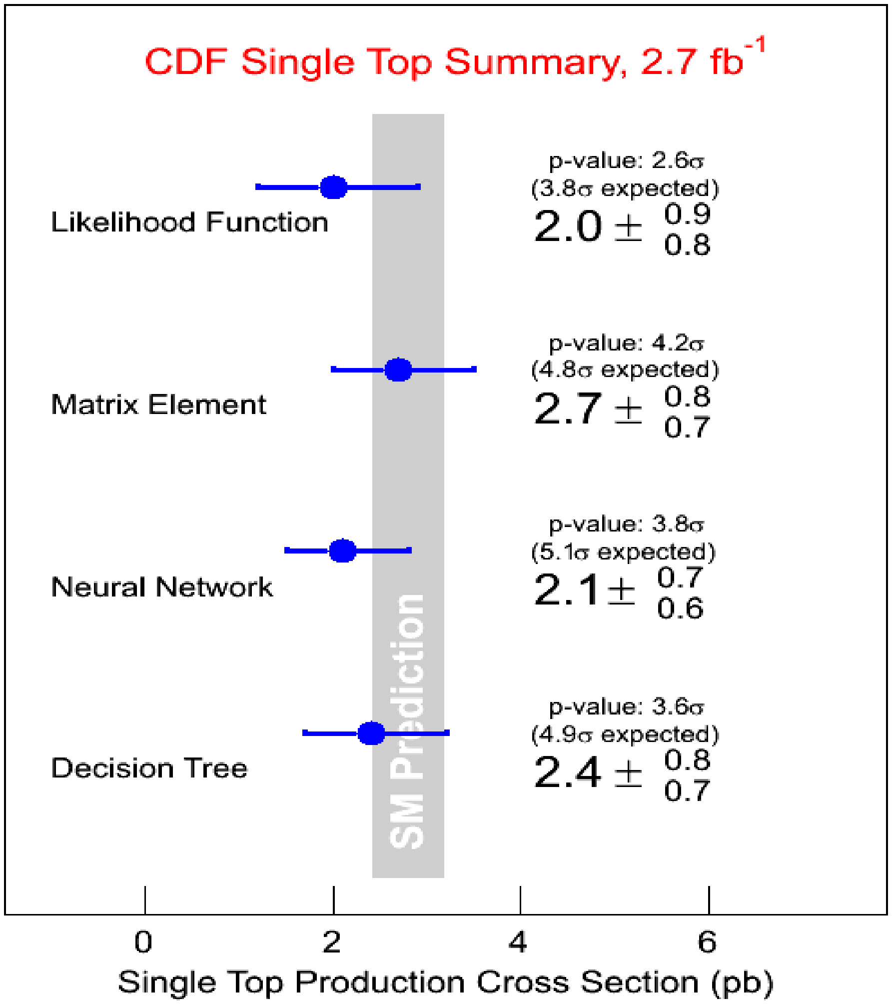
Single Top Production – Multivariate Techniques

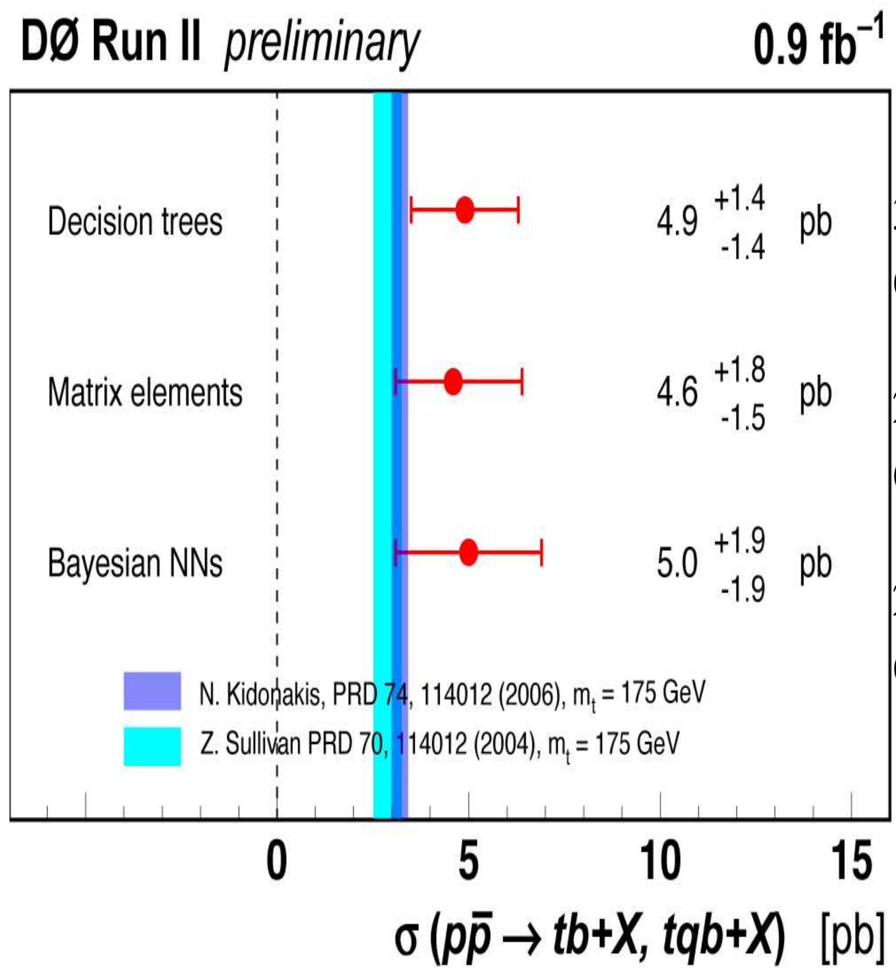
- Small Signal/Background: ½ of top pair production cross section
- Fewer particles in the final state that top pair production
- Full power of diverse techniques employed:
  - Likelihoods based on SM matrix element probabilities
  - Neural networks
  - Decision trees





Single Top Production – Cross Sections





Obs
(exp)

3.4σ
(2.1σ)

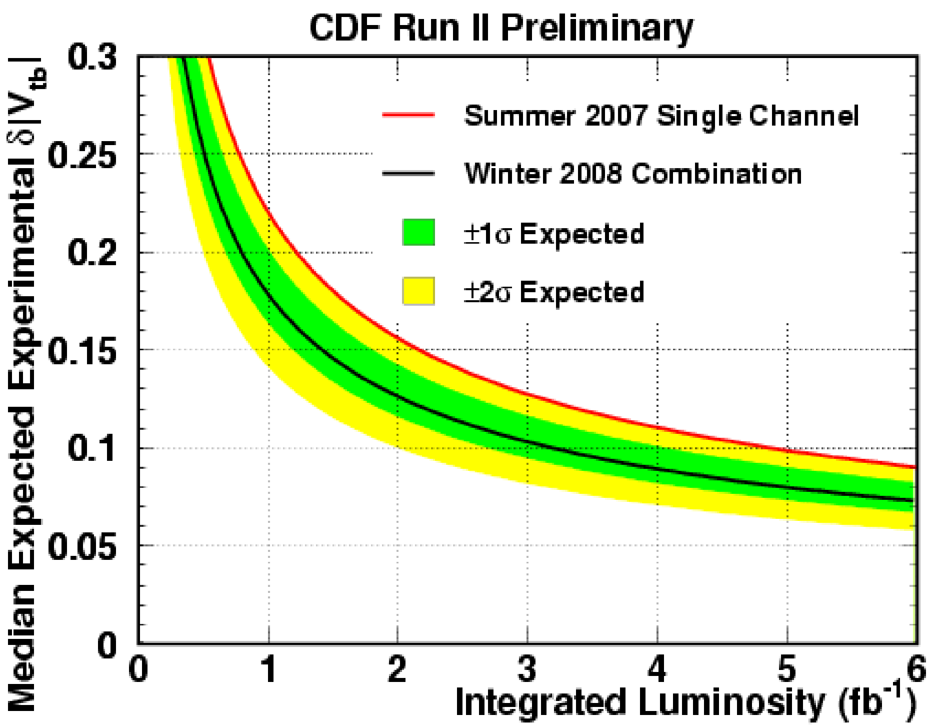
2.9σ
(1.8σ)

2.4σ
(1.3σ)

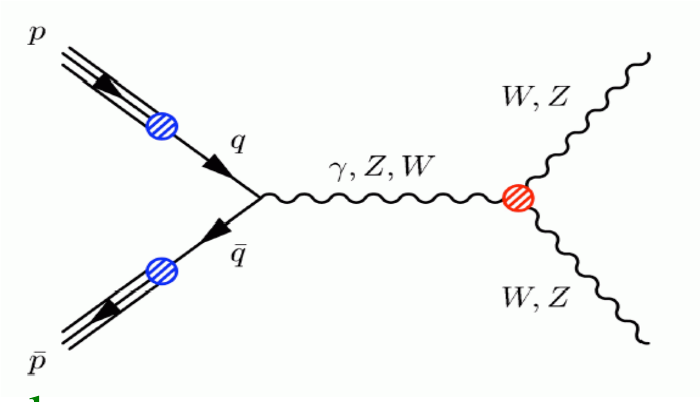
CDF results from 2.2 fb^{-1} accepted for publication in PRL (arXiv:0809.2581v2)

Single Top Production & $|V_{tb}|$

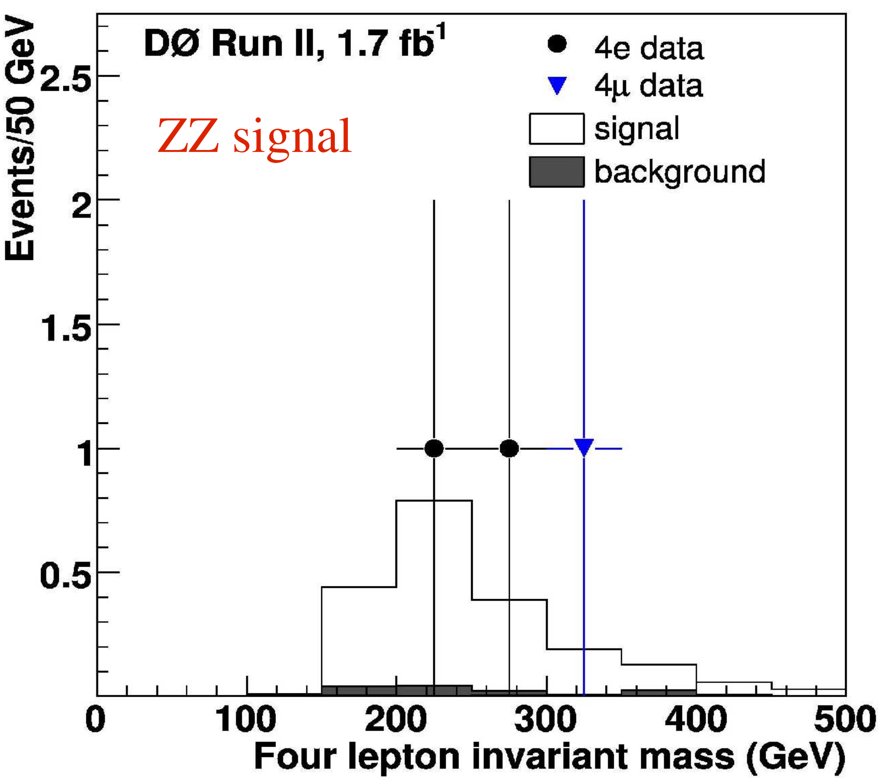
- CKM matrix element V_{tb}
  - CDF: $V_{tb} = 0.88 \pm 0.14$ (stat+syst) ± 0.07 (theory)
    - $1 > V_{tb} > 0.66$ (95% CL)
  - D0: $V_{tb} = 1.3 \pm 0.2$
    - $1 > V_{tb} > 0.68$ (95% CL)
- No assumption on CKM unitarity or number of quark families

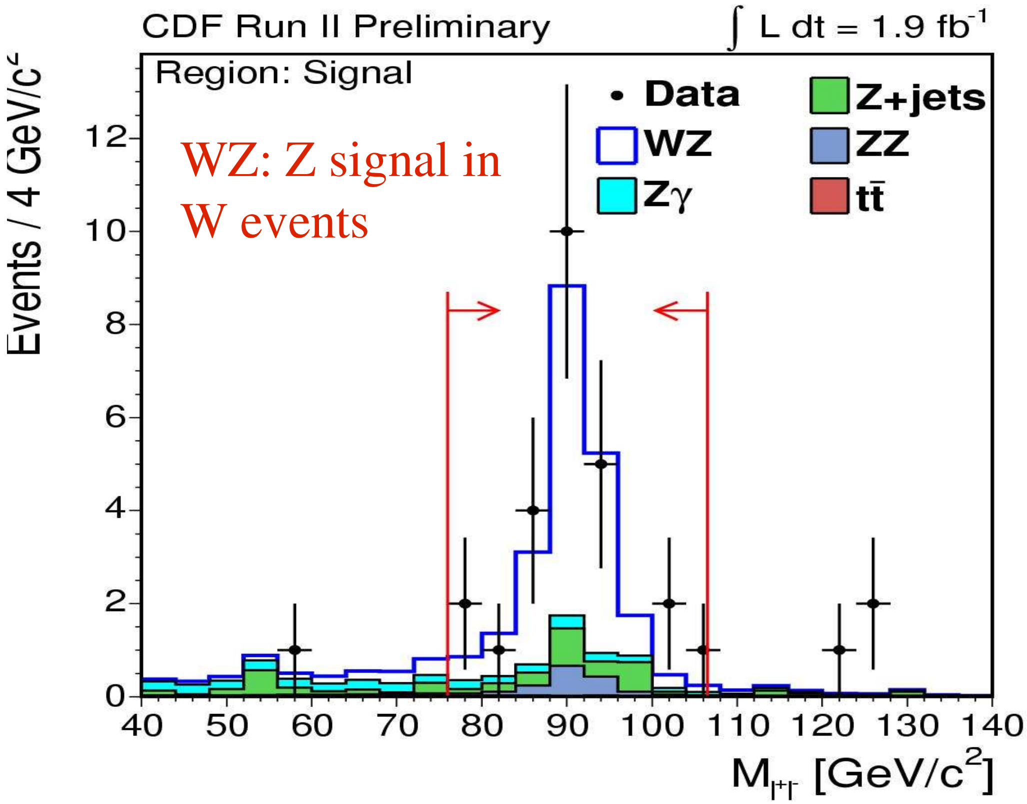


Observation of W+Z Associated Production



- Recent confirmation of this fundamental prediction of the standard model provided by 1-2 fb^{-1} of D0 and CDF data
- Published results from both experiments: another key milestone in the Higgs boson search

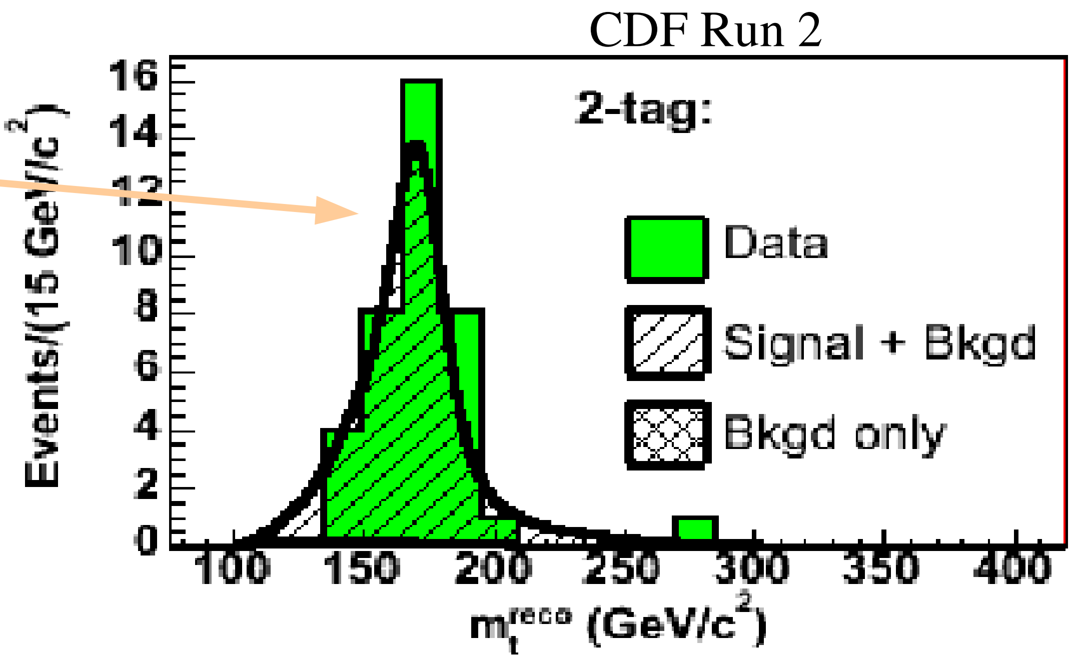


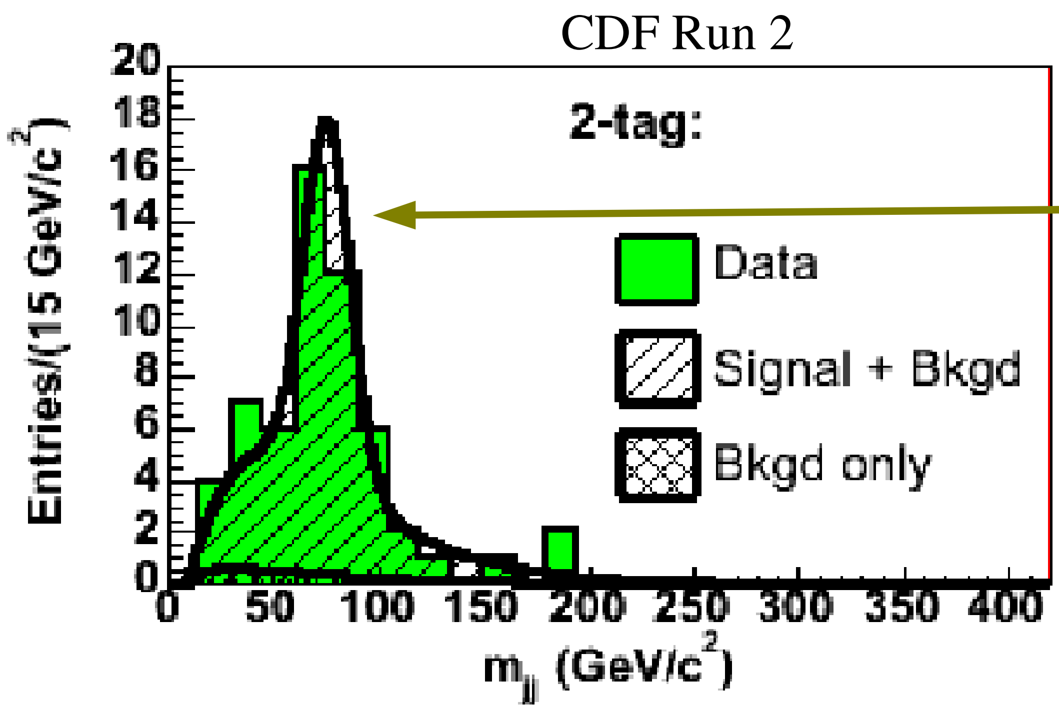


Precision Standard Model Measurements Constraining the Higgs and New Physics

Progress on M_{top} at the Tevatron

Reconstructed top mass in 680 pb^{-1}of CDF data, fit with simulated lineshape





Improved top mass precision due to in-situ calibration of jet energy using W->jj decays in the same events

Progress on M_{top} at the Tevatron

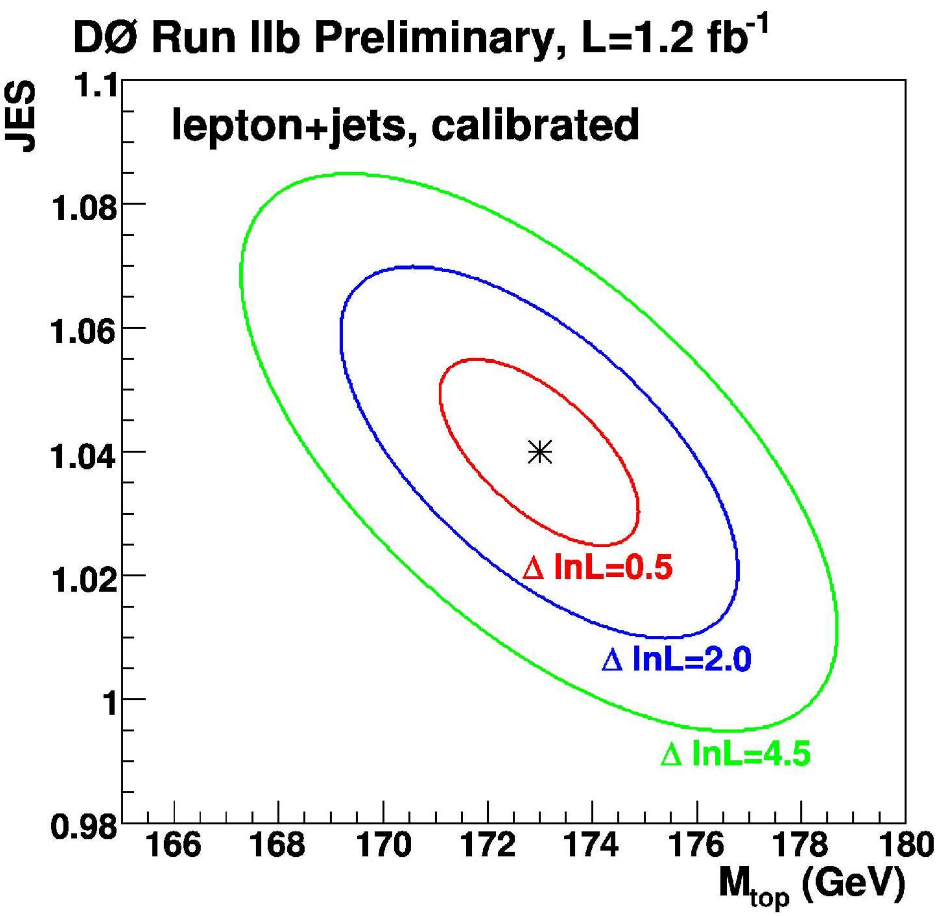
- Exploiting all top quark decay channels
  - Lepton + jets + missing E_T (one W decays hadronically, one leptonically, most sensitive channel)
  - Dilepton + 2 b-quark jets (largest signal/background ratio)
  - All-jets (both W's decay hadronically, largest signal)
- ...and different techniques
  - Fitting reconstructed top mass with simulated templates
  - Maximizing dynamical likelihood computed using SM matrix elements
  - Neutrino-weighting
  - Ideogram method

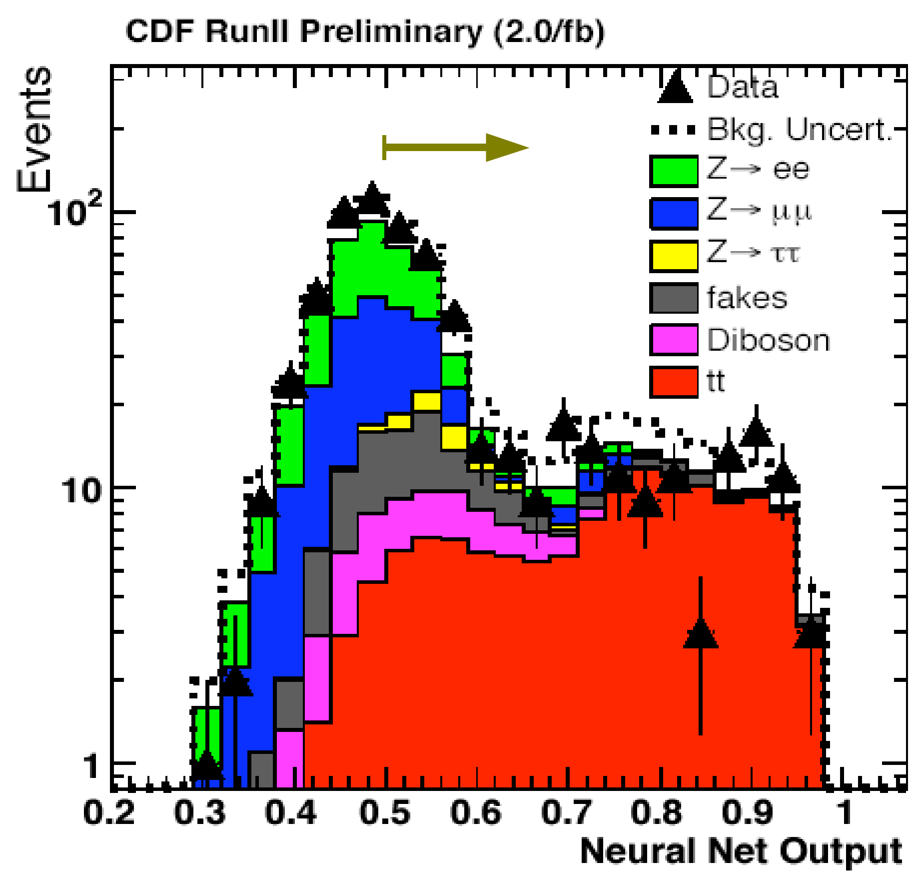
Progress on M_{top} at the Tevatron

2D fit for W->jj mass (to obtain jet energy scale JES) and top quark mass

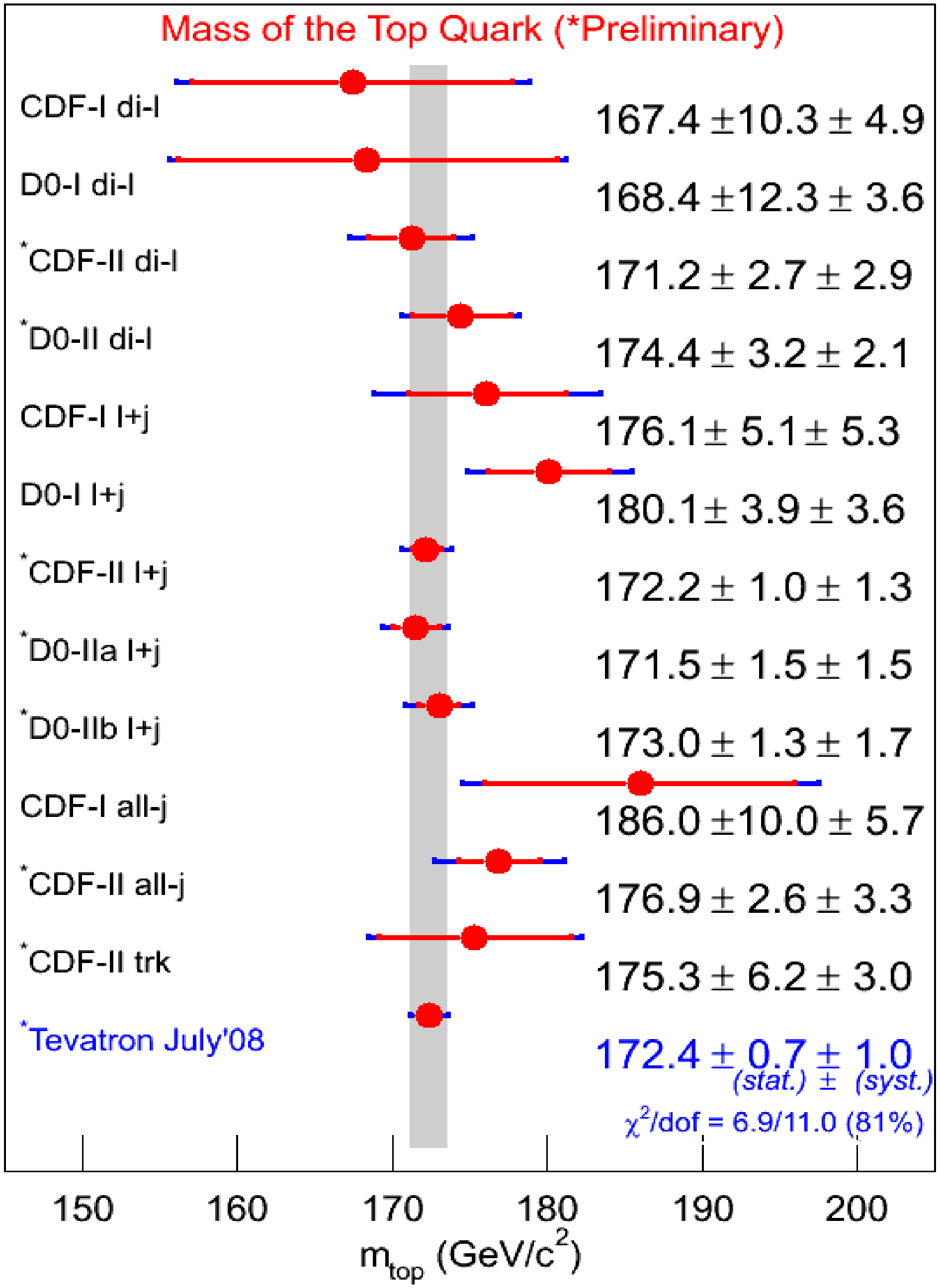
Neural Network for optimized event selection

Matrix-element-based likelihood fitting in dilepton channel





Progress on M_{top} at the Tevatron



CDF lepton+jets systematics (preliminary)

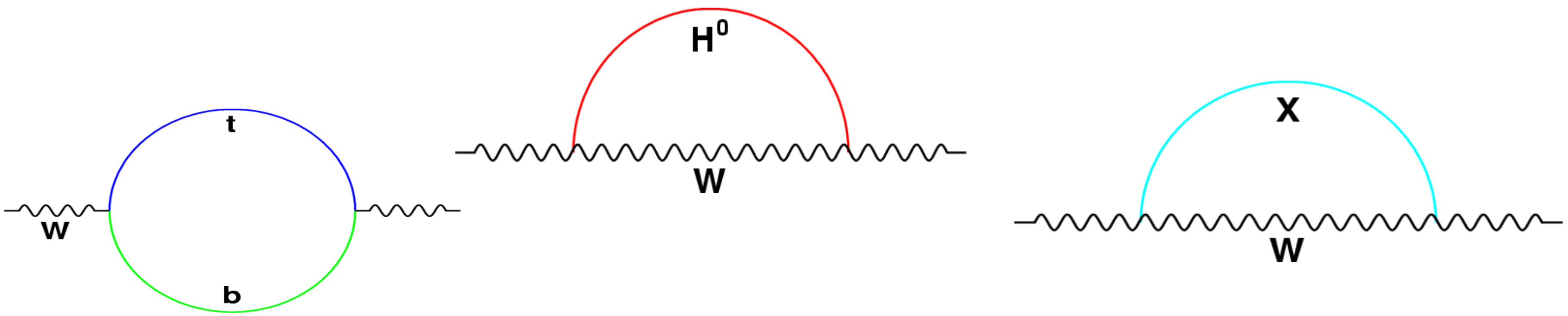
Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.1
MC generator	0.5 ←
ISR and FSR	0.3
Residual JES	0.5 ←
b-JES	0.4 ←
Lepton P_T	0.2
Pileup	0.1
PDFs	0.2
Background	0.4 ←
Total	1.0

Dominant systematic uncertainties can be reduced with improved understanding of the data and generator models

$\delta M_{top} < 1$ GeV may be possible

Motivation for W Boson Mass Measurement

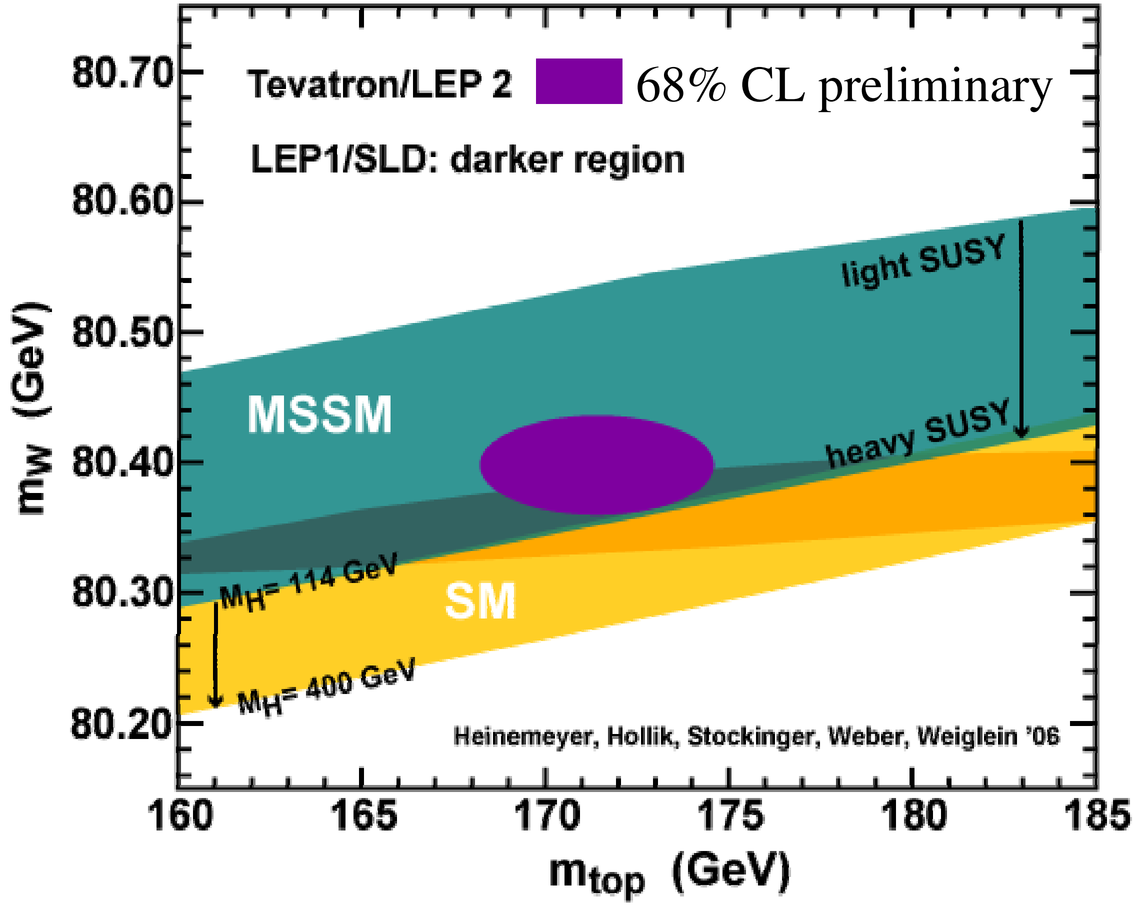
- Radiative corrections due to heavy quark and Higgs loops and exotica



Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $(\rho-1) \sim M_{top}^2$ and $(\rho-1) \sim \ln M_H$

- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

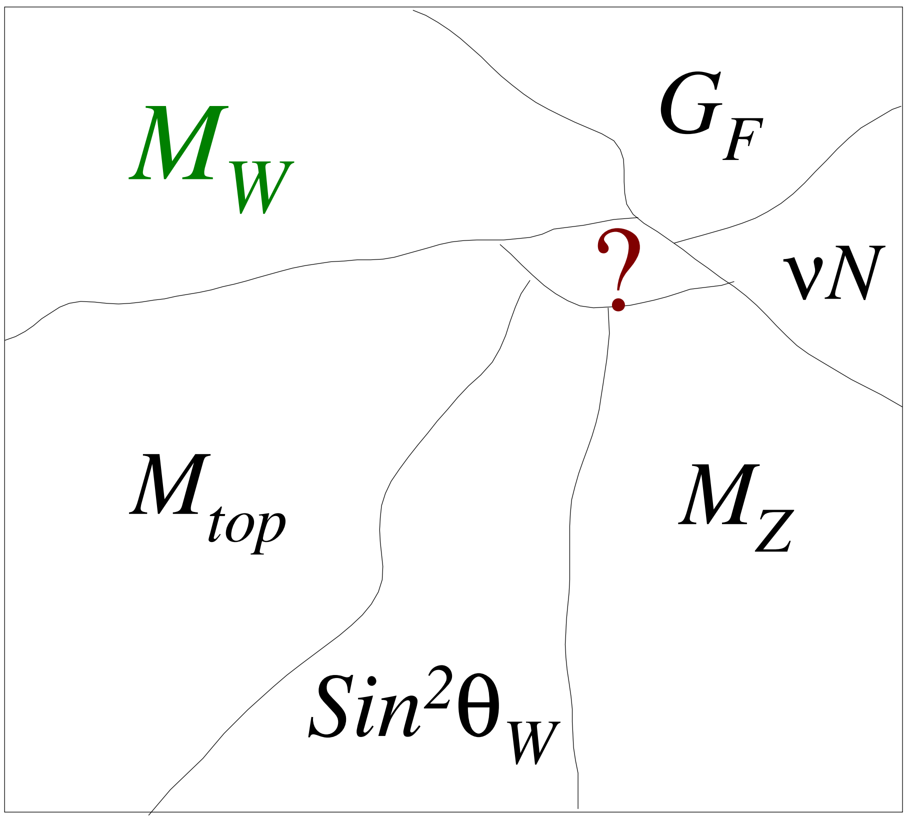
Progress on M_{top} at the Tevatron



- From the Tevatron, δM_{top} = 1.2 GeV => $\delta M_H / M_H$ = 10%
- equivalent δM_W = 7 MeV for the same Higgs mass constraint
- Current world average δM_W = 25 MeV
  - progress on δM_W now has the biggest impact on Higgs constraint!

Motivation for M_W measurement

- SM Higgs fit: $M_H = 84^{+34}_{-26}$ GeV (LEPEWWG & TeVEWWG)
- LEPII direct searches: $M_H > 114.4$ GeV @ 95% CL (PLB 565, 61)



In addition to the Higgs, is there another missing piece in this puzzle?

(A_{FB}^b *vs* A_{LR}: 3.2σ)

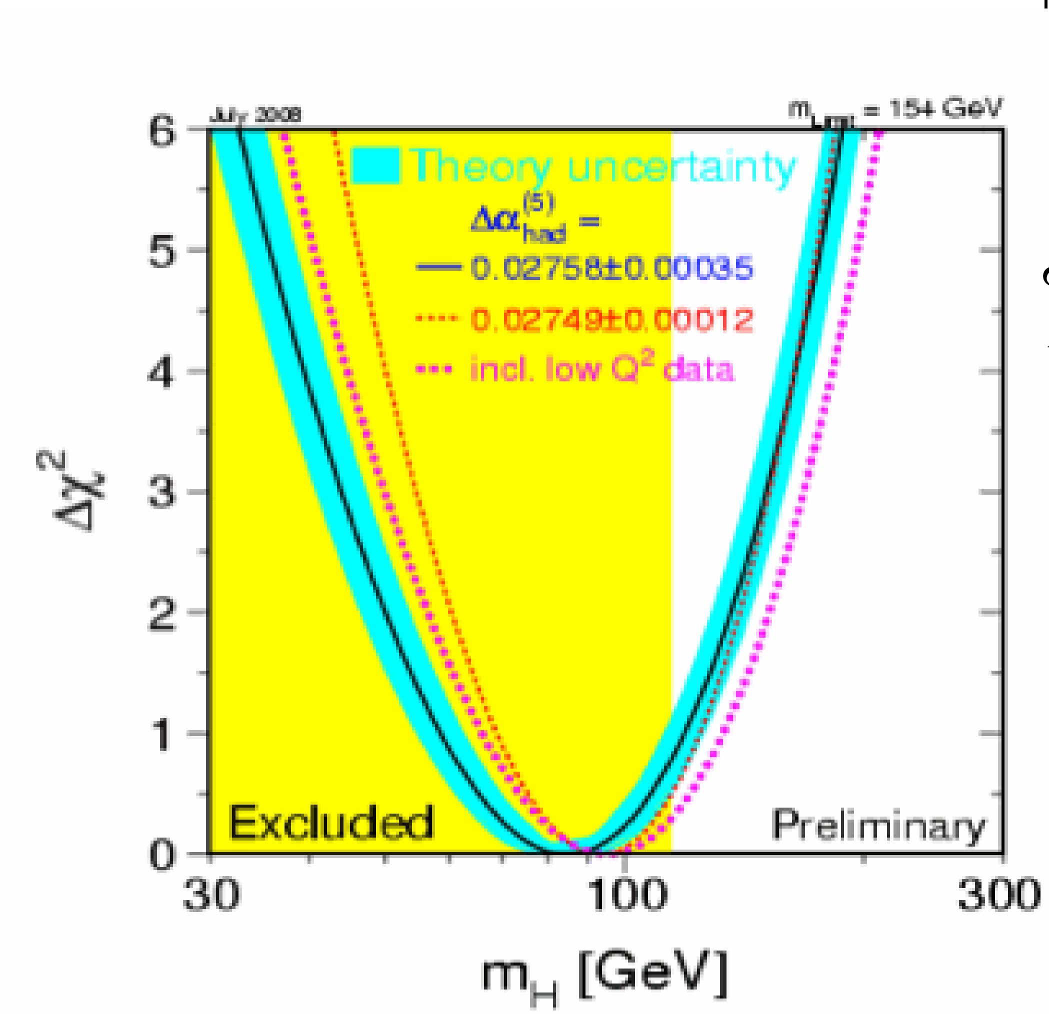
Must continue improving precision of M_W, M_{top} ...

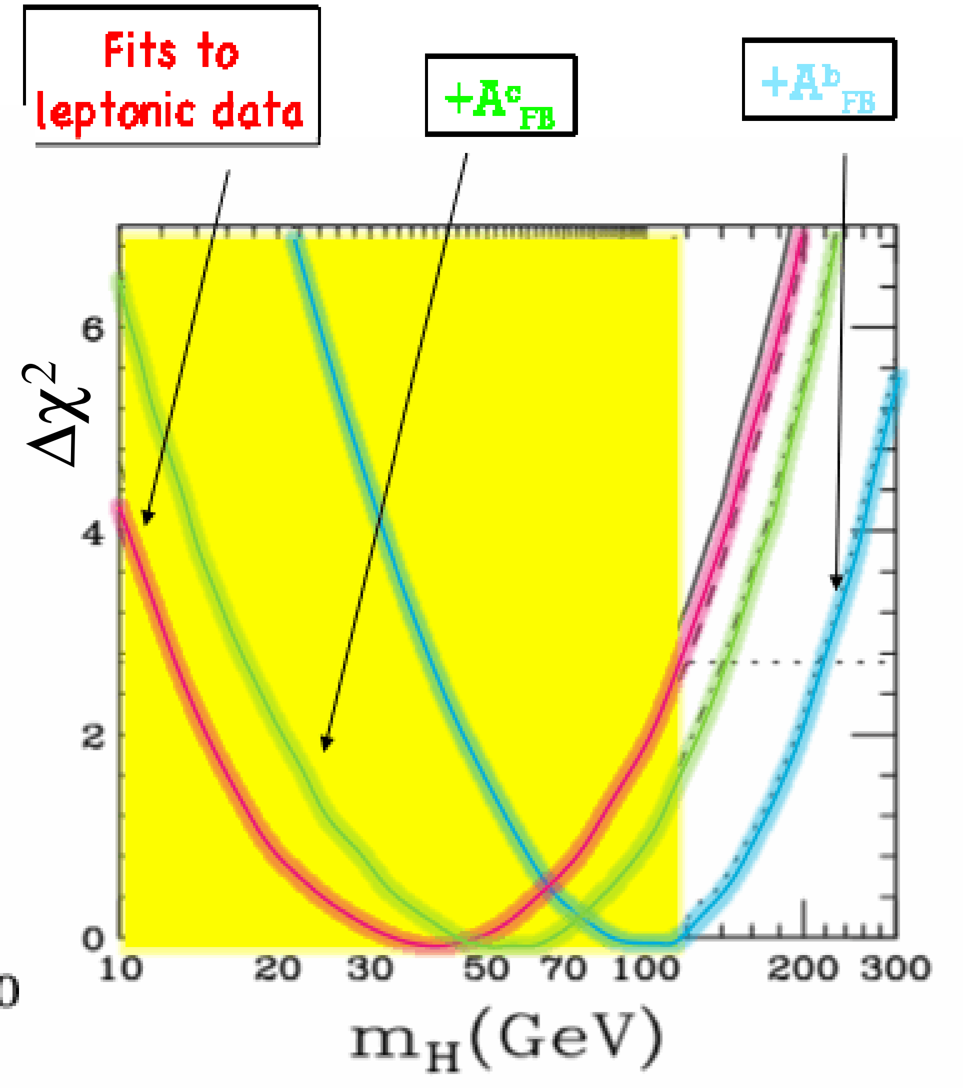
other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 20$ MeV

Motivate direct measurement of M_W at the 20 MeV level

Standard Model Higgs Constraint

M_W and leptonic measurements of $\sin^2\theta$ prefer low SM Higgs mass, hadronic (heavy flavor) measurements of $\sin^2\theta$ prefer higher SM Higgs mass (A^b_{FB} prefers ~ 500 GeV Higgs)

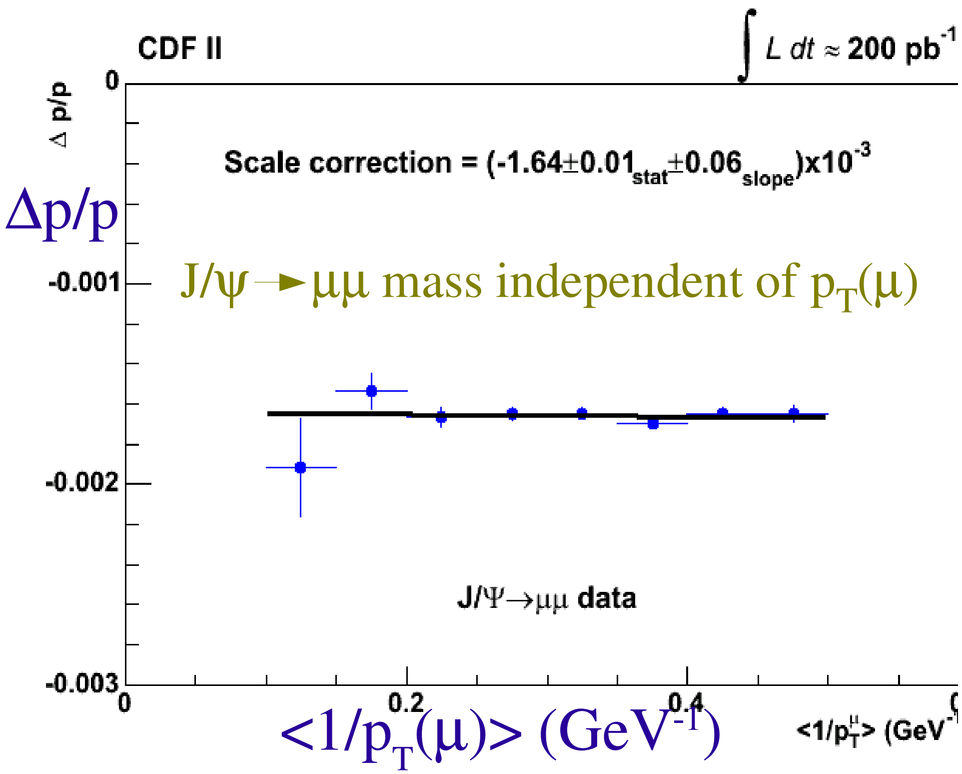


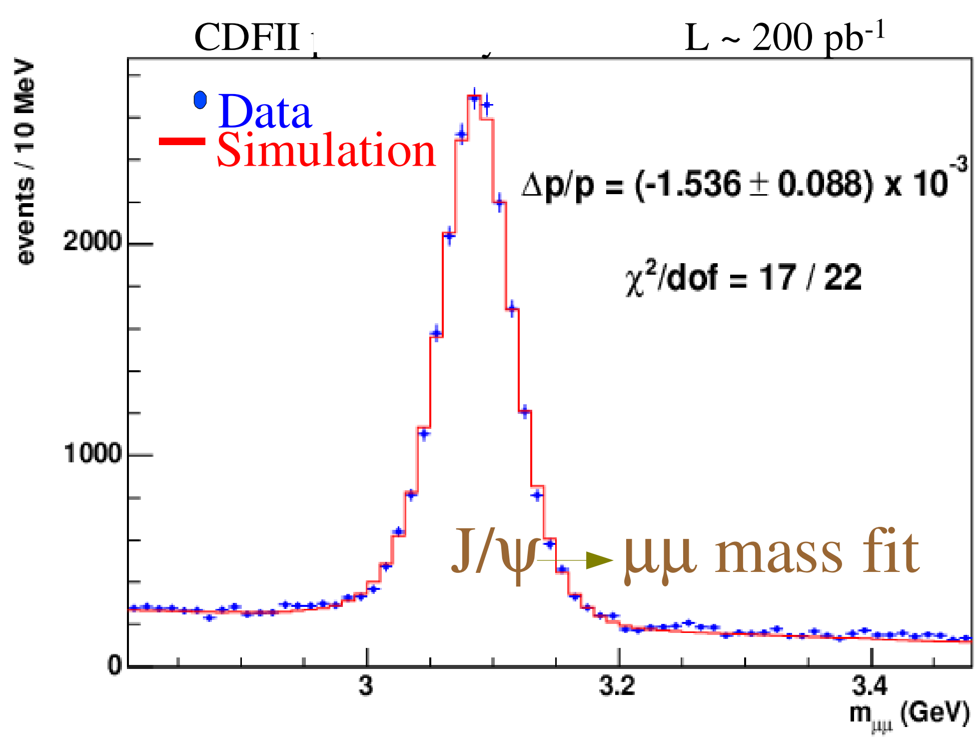


M. Chanowitz, PRL 97 (2001) 231802

Tracking Momentum Scale

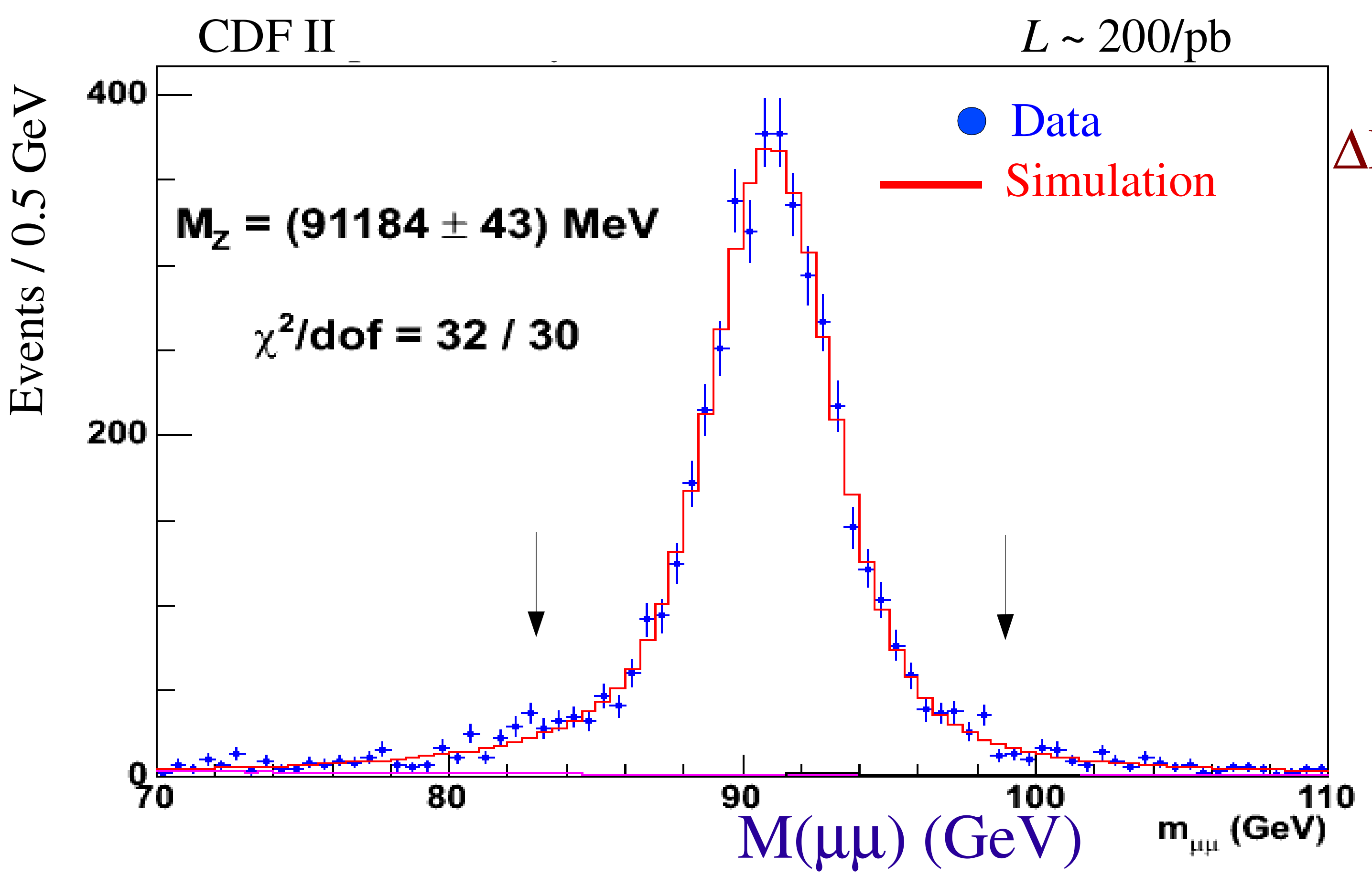
- Set using $J/\psi \rightarrow \mu\mu$ and $Y \rightarrow \mu\mu$ resonance and $Z \rightarrow \mu\mu$ masses
  - All are individually consistent with each other
- J/ψ: $\Delta p/p = (-1.64 \pm 0.06_{stat} \pm 0.24_{sys}) \times 10^{-3}$
  - Extracted by fitting J/ψ mass in bins of $<1/p_T(\mu)>$, and extrapolating momentum scale to high momentum





$Z \rightarrow \mu\mu$ Mass Cross-check & Combination

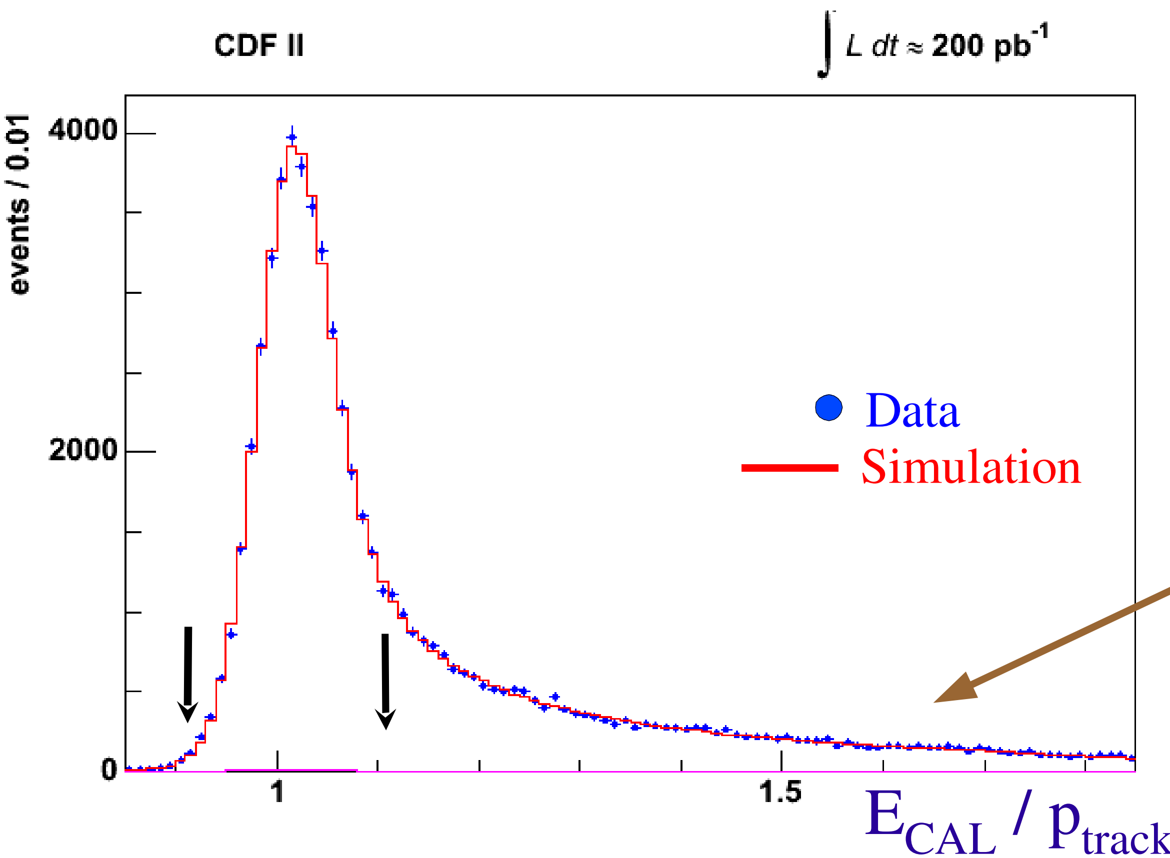
- Using the J/ψ and Υ momentum scale, measured Z mass is consistent with PDG value
- Final combined: $\Delta p/p = (-1.50 \pm 0.15_{independent} \pm 0.13_{QED} \pm 0.07_{align}) \times 10^{-3}$



ΔM_W = 17 MeV

EM Calorimeter Scale

- E/p peak from $W \rightarrow e\nu$ decays provides measurements of EM calorimeter scale and its (E_T-dependent) non-linearity
  - $S_E = 1 \pm 0.00025_{stat} \pm 0.00011_{X0} \pm 0.00021_{Tracker}$
- Setting S_E to 1 using E/p calibration

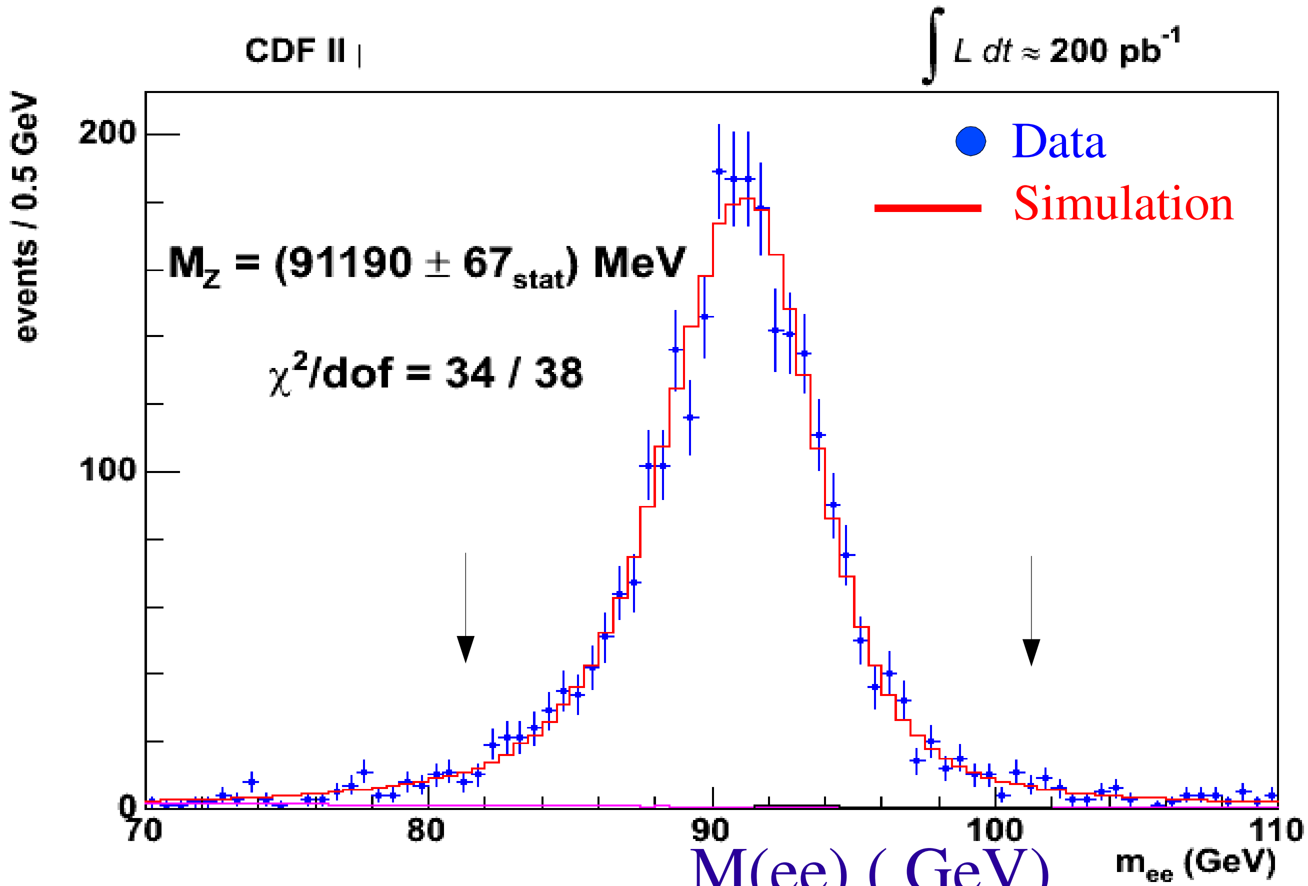


Tail region of E/p spectrum used for tuning model of radiative material

Z→ee Mass Cross-check and Combination

- Z mass consistent with E/p-based measurements
- Combining E/p-derived scale & non-linearity measurement with *Z→ee* mass yields the most precise calorimeter energy scale:
  - $S_E = 1.00001 \pm 0.00037$

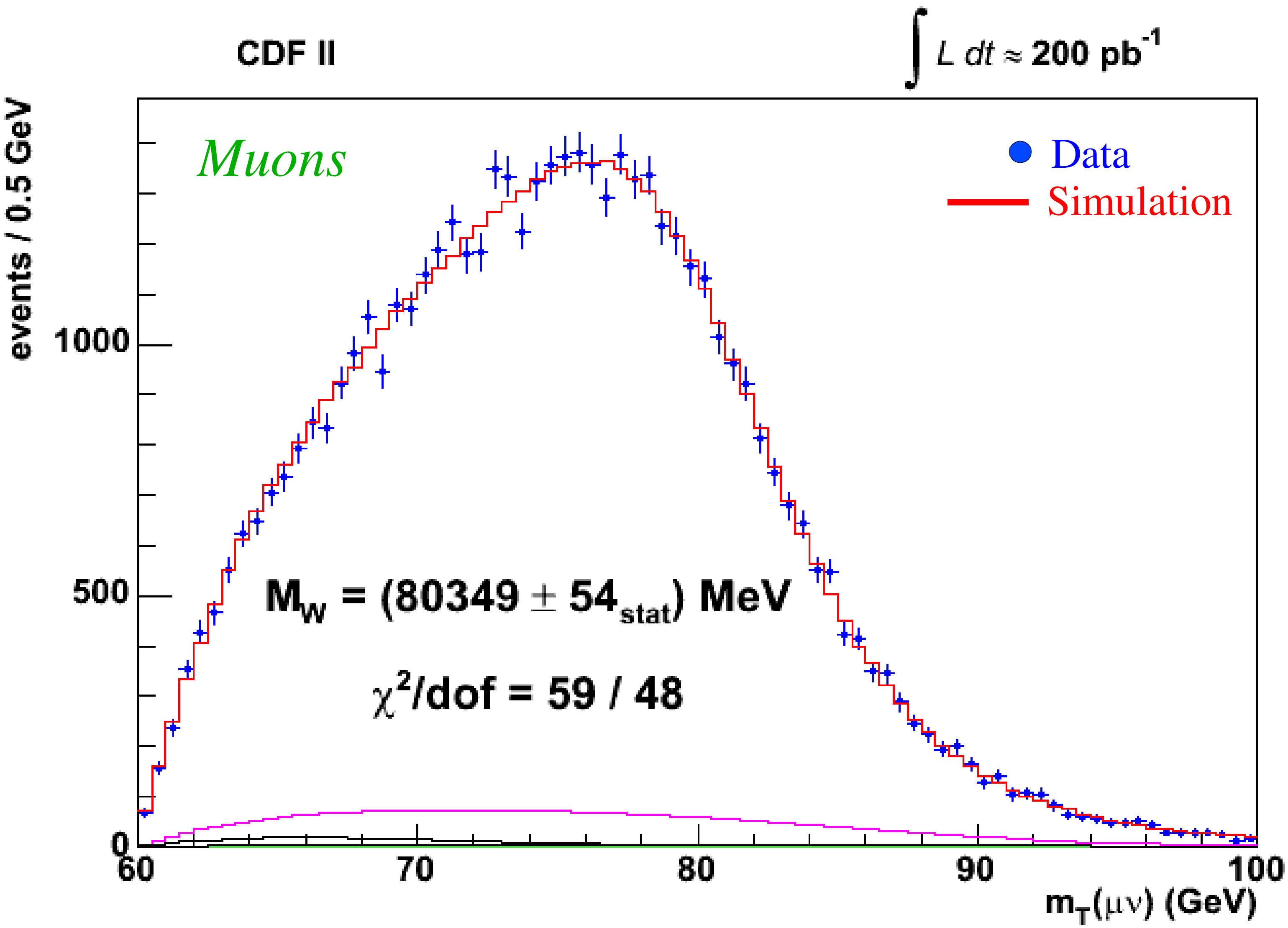
$\Delta M_W = 30$ MeV



M(ee) (GeV)

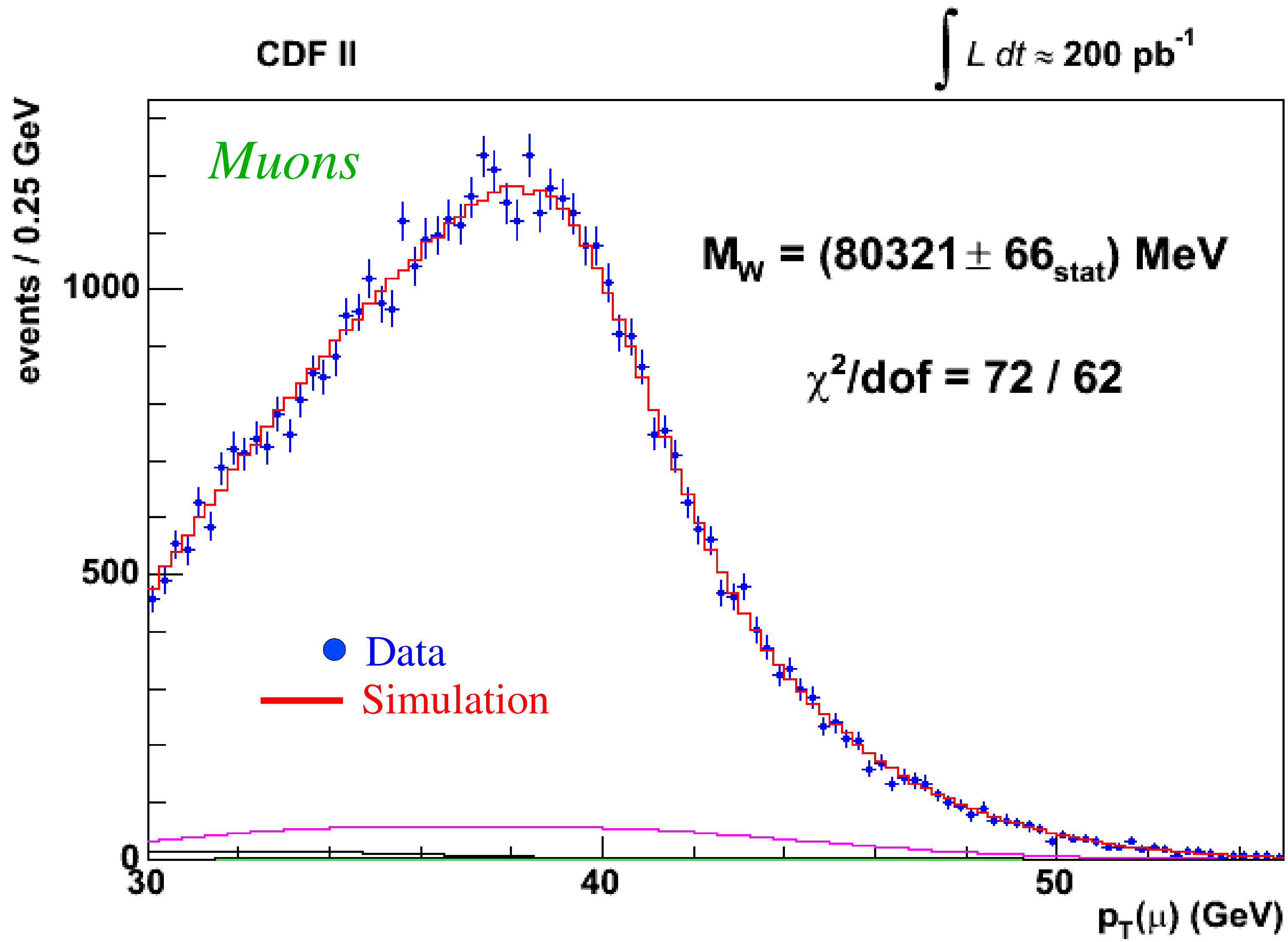
W Boson Mass Fits

(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)



W Lepton p_T Fits

(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)



Transverse Mass Fit Uncertainties (MeV)

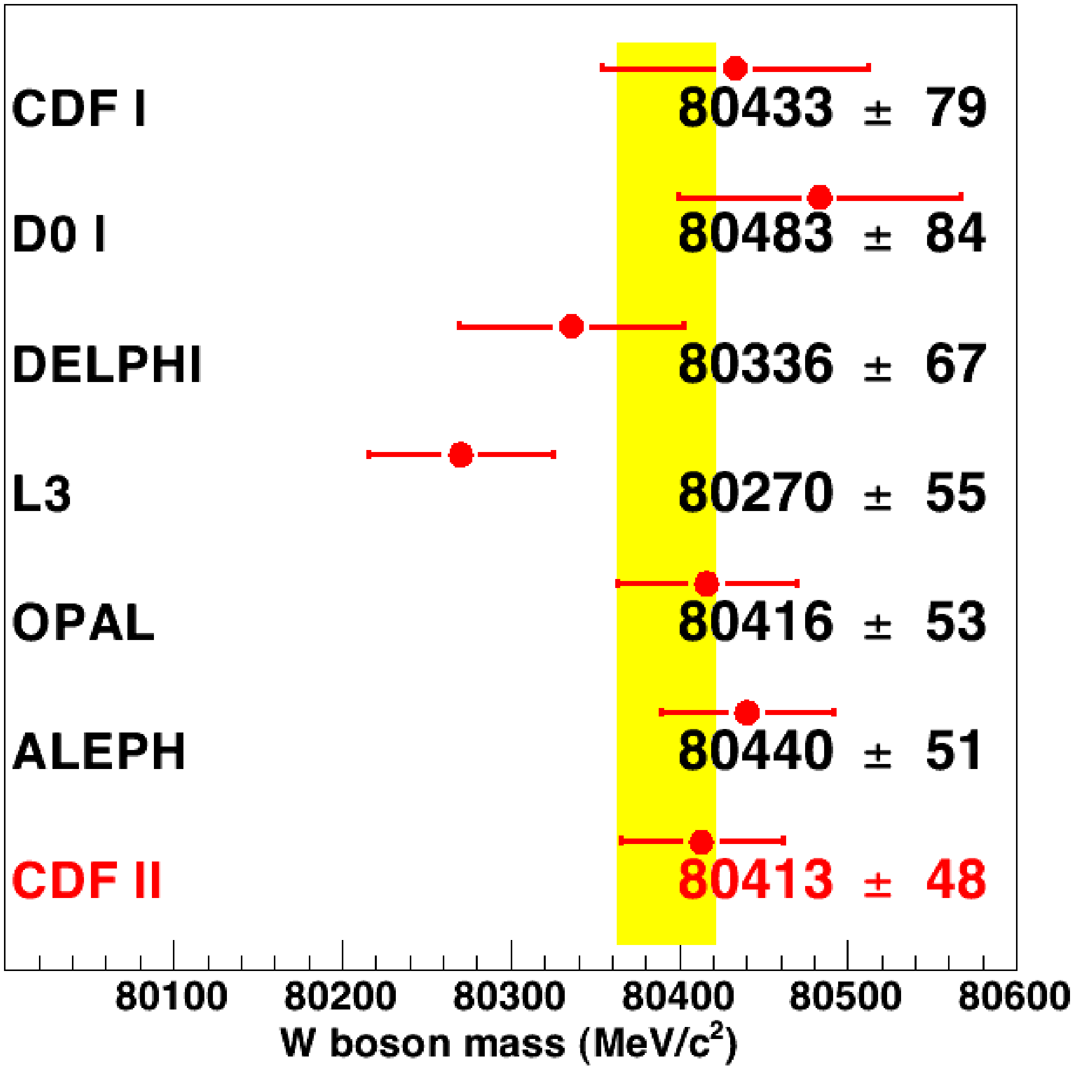
(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
pT(W) model	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	**39**	**27**	**26**
Total	**62**	**60**	

W charge asymmetry from Tevatron helps with PDFs → Parton dist. Functions

Systematic uncertainties shown in green: statistics-limited by control data samples

Comparisons

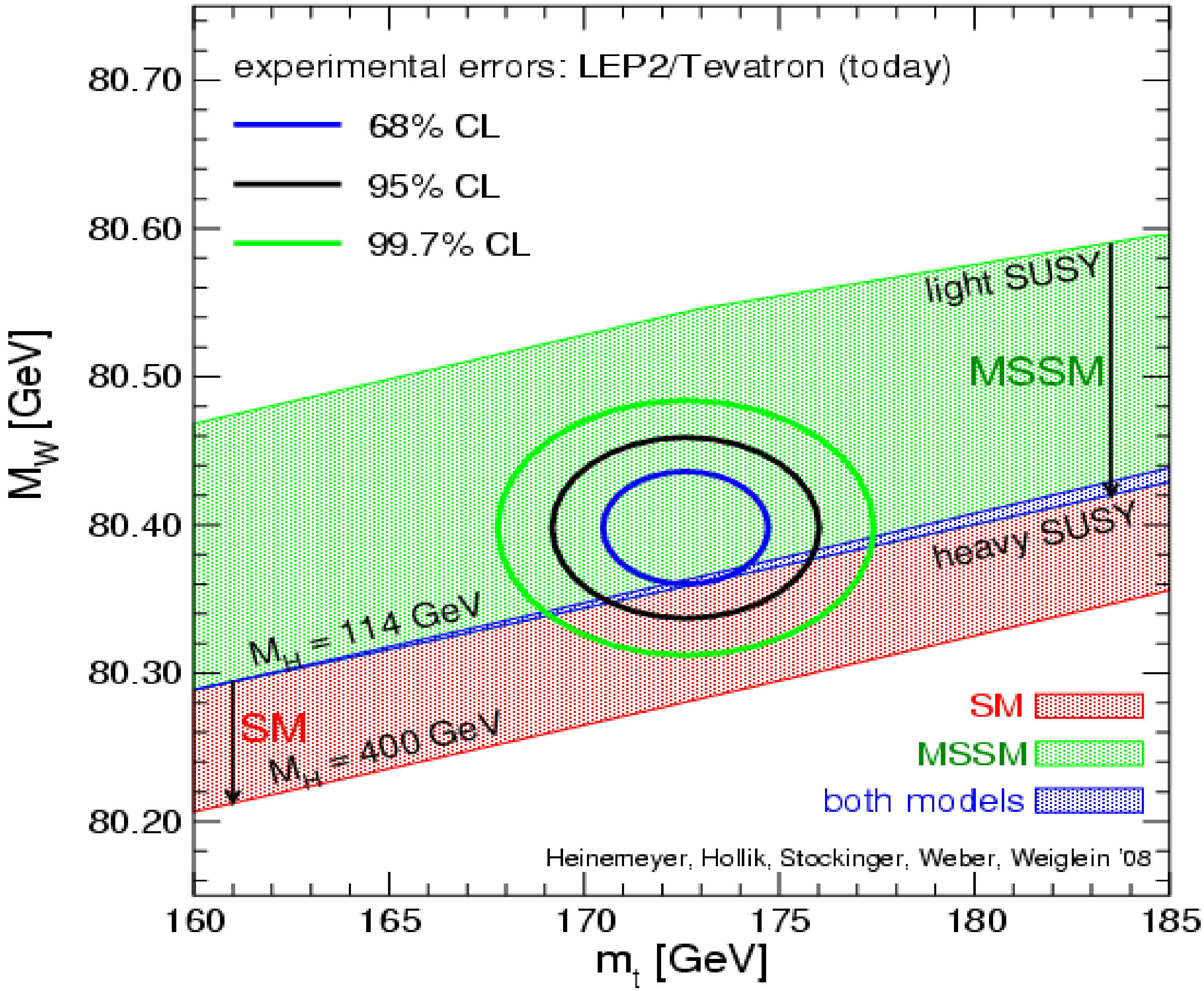


The CDF Run 2 result is the most precise single measurement of the W mass

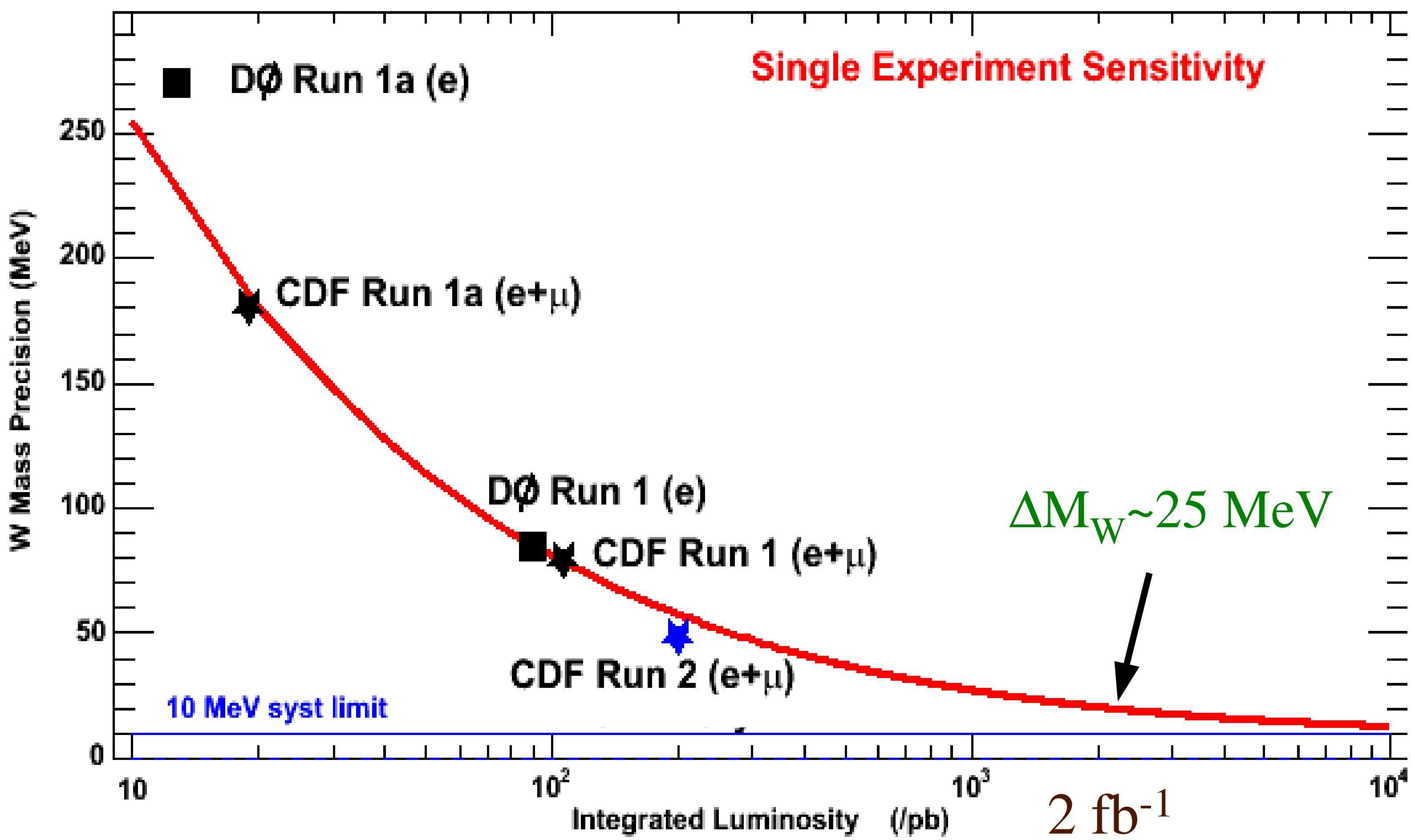
(PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

... and factor of 10 more data being analyzed now!

M_W *vs* M_{top}

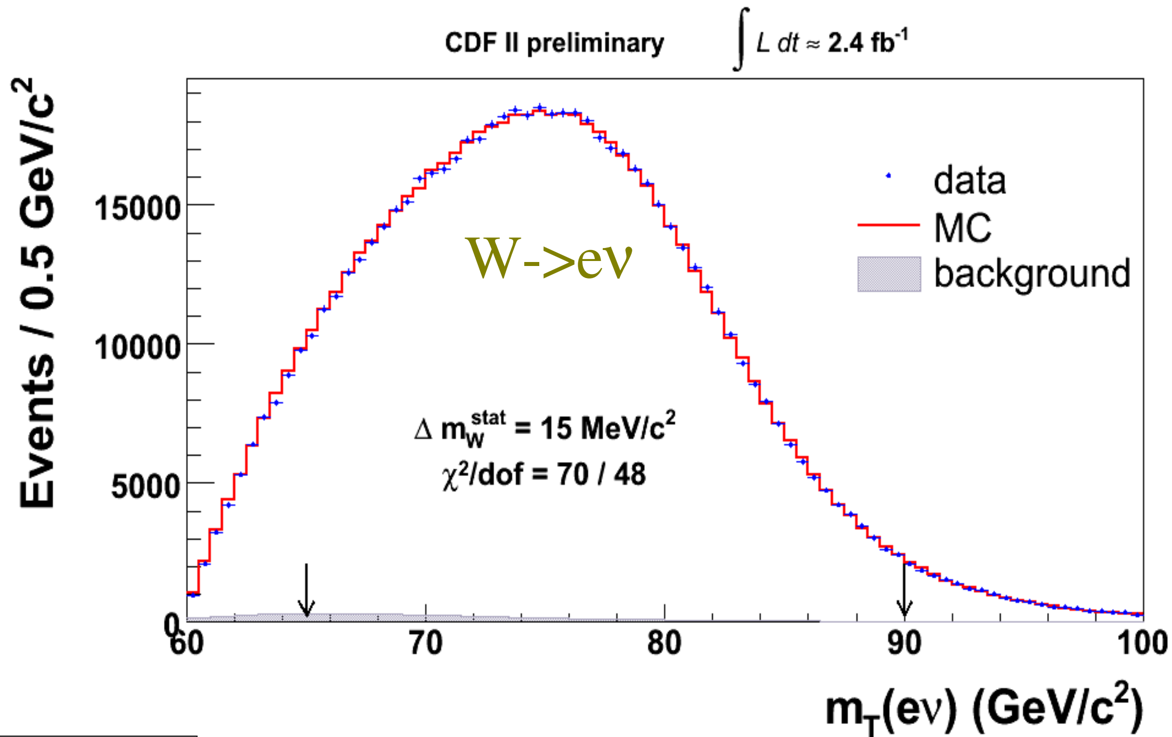

experimental errors: LEP2/Tevatron (today)
68% CL
95% CL
99.7% CL
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM
M_H = 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '08
80.70
80.60
80.50
80.40
80.30
80.20
M_W [GeV]
160
165
170
175
180
185
m_t [GeV]

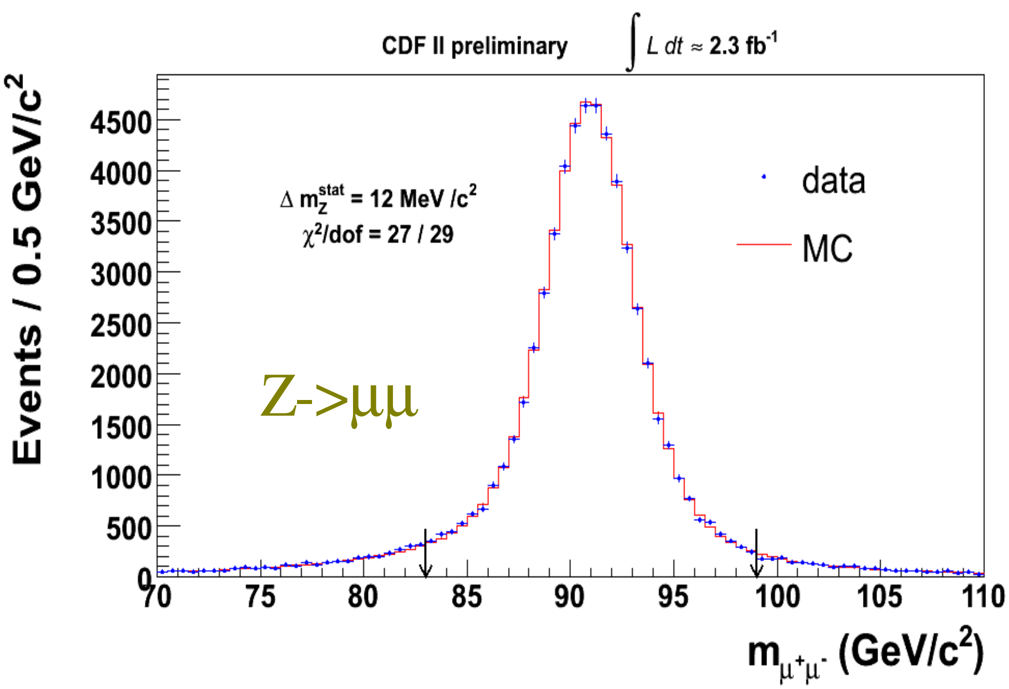
Preliminary M_W Studies of 2.4 fb^{-1} Data from Tevatron



Preliminary Studies of 2.4 fb^{-1} Data at CDF

CDF has started the analysis of 2.4 fb^{-1} of data, with the goal of measuring M_W with precision better than 25 MeV





statistical errors on W and Z boson mass fits and calibrations are scaling with statistics

Large Hadron Collider Prospects

- prospects for W boson mass measurement: 20 million W's / fb^{-1} per leptonic decay channel
  - Consider statistical and systematic uncertainties that can be calibrated with Z boson data
  - estimated W mass uncertainty of 7 MeV
  - Key issues: backgrounds, production and decay model uncertainties, cross-checks on calibrations
- prospects for top mass measurement: 800,000 tt pairs / fb^{-1} per leptonic decay channel
  - Suggested top mass precision ~ 1 GeV
- References: SN-ATLAS-2008-070; Eur. Phys. J. C 41 (2005), s19-s33; CMS-NOTE-2006-061; CMS-NOTE-2006-066; arXiv:0812.0470

Summary

- CDF and D0 experiments at Fermilab Tevatron in pursuit of direct observation of standard model Higgs in the 115-200 GeV range
  - SM Higgs excluded at 170 GeV @ 95% CL
- Production of single top quarks observed at the Tevatron
- Production of WZ and ZZ production observed at the Tevatron
- Top quark mass $M_{top} = 172.4 \pm 0.7_{stat} \pm 1.0_{syst}$ GeV = 172.4 ± 1.2 GeV
- CDF Run 2 W mass result is the most precise single measurement:
  - $M_W = 80413 \pm 34_{stat} \pm 34_{syst}$ MeV
    $= 80413 \pm 48$ MeV
- Tevatron pushing towards $\delta M_W < 25$ MeV and $\delta M_{top} < 1$ GeV

NuTeV Measurement of $\sin^2\theta_W$

Using neutrino and anti-neutrino beams at Fermilab, NuTeV measured

$$\sin^2\theta_W^{(on\text{-}shell)} = 0.2277 \pm 0.0013(\text{stat.}) \pm 0.0009(\text{syst.})$$

With a standard model prediction of 0.2227 ± 0.0003, ~3σ deviation

Paschos - Wolfenstein Relation

$$R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \rho^2\left(\tfrac{1}{2} - \sin^2\theta_W\right) = g_L^2 - g_R^2$$

$$g^2_{L,R} = u^2_{L,R} + d^2_{L,R}$$

Minimizes sensitivity to charm quark production and sea quarks

no obvious experimental problem in the measurement

Beyond SM Physics explanations are not easy to construct

QCD effects are a possibility: large isospin violation, nuclear effects,

NLO effects...QED radiative corrections also large

Large amount of literature generated, studying various hypotheses!

NuSonG: Neutrino Scattering on Glass (experiment proposed at Fermilab)

Global Electroweak fit for SM Higgs not changed much by inclusion of NuTeV and other low Q^2 measurements of $\sin^2\theta_W$