Latest results from the Tevatron Collider

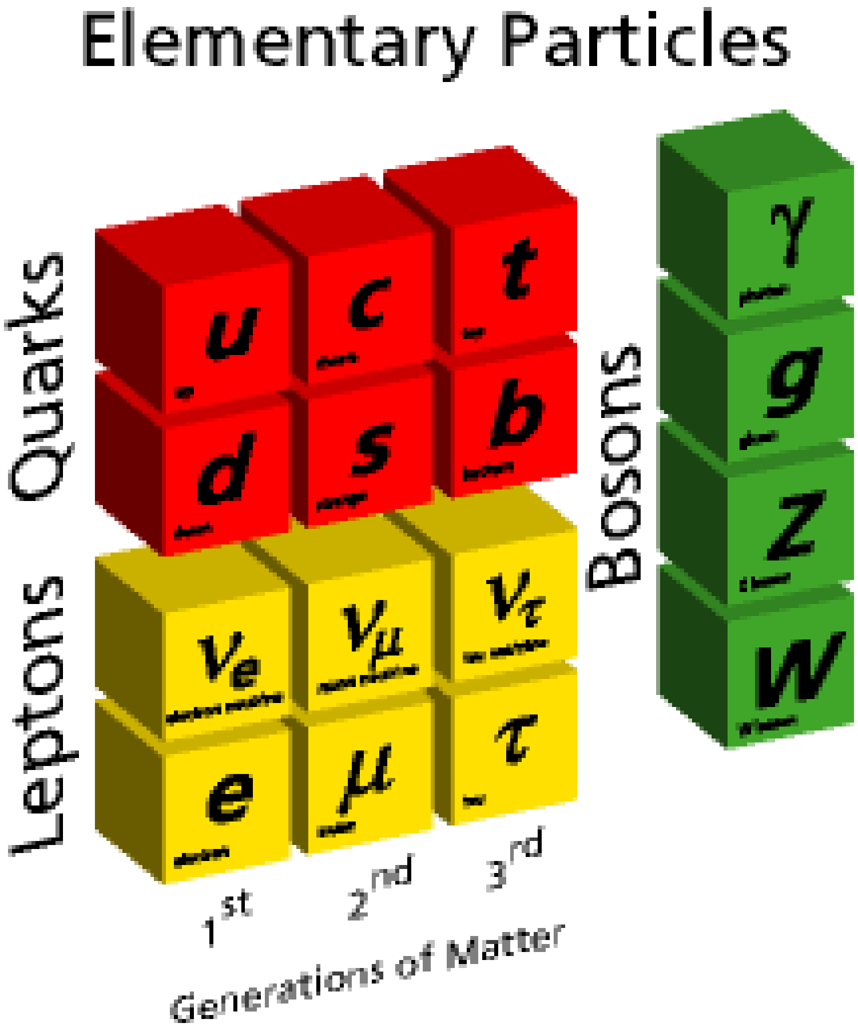
Gaston Gutierrez - Fermilab

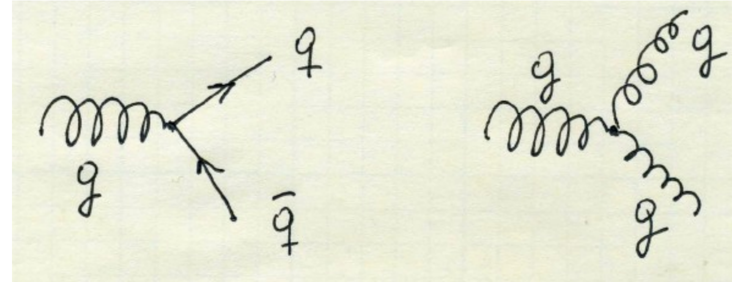
For the CDF and D0 Collaborations

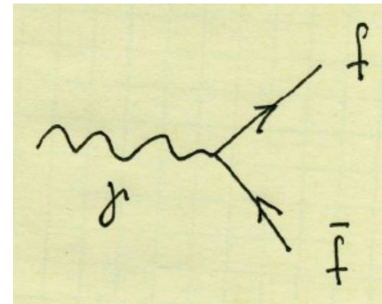
- **Top mass.**
- **W mass.**
- **Diboson production (with one boson decaying to two jets).**
- **Higgs searches.**

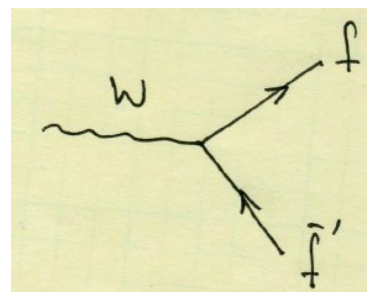
Many thanks to Pierre Petroff, Christian Schwanenberger, Krisztian Peters, Marco Verzochi, Gregorio Bernardi, Ben Kilminster, Florencia Canelli, Martina Hurwitz and Kevin Pitts.

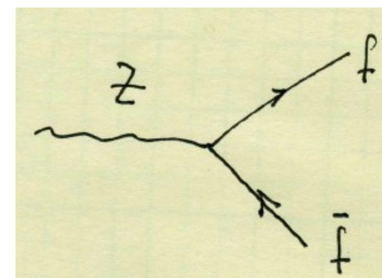
SM particles











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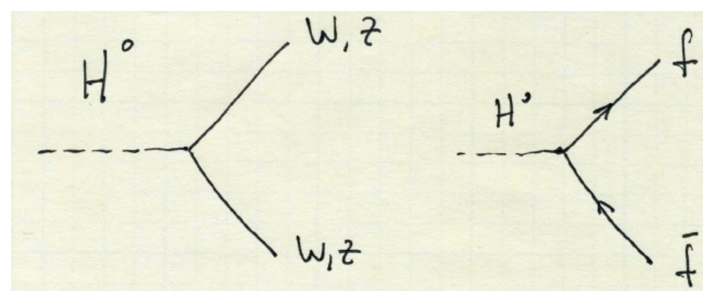

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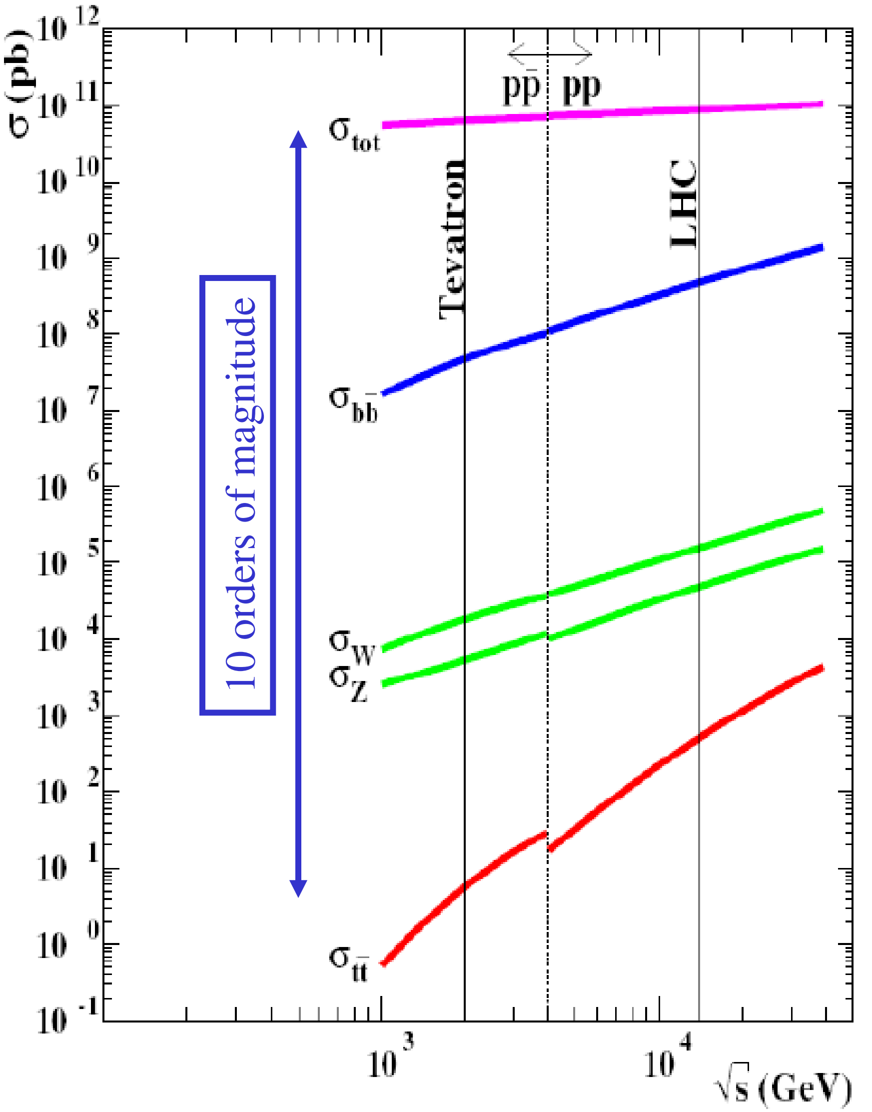
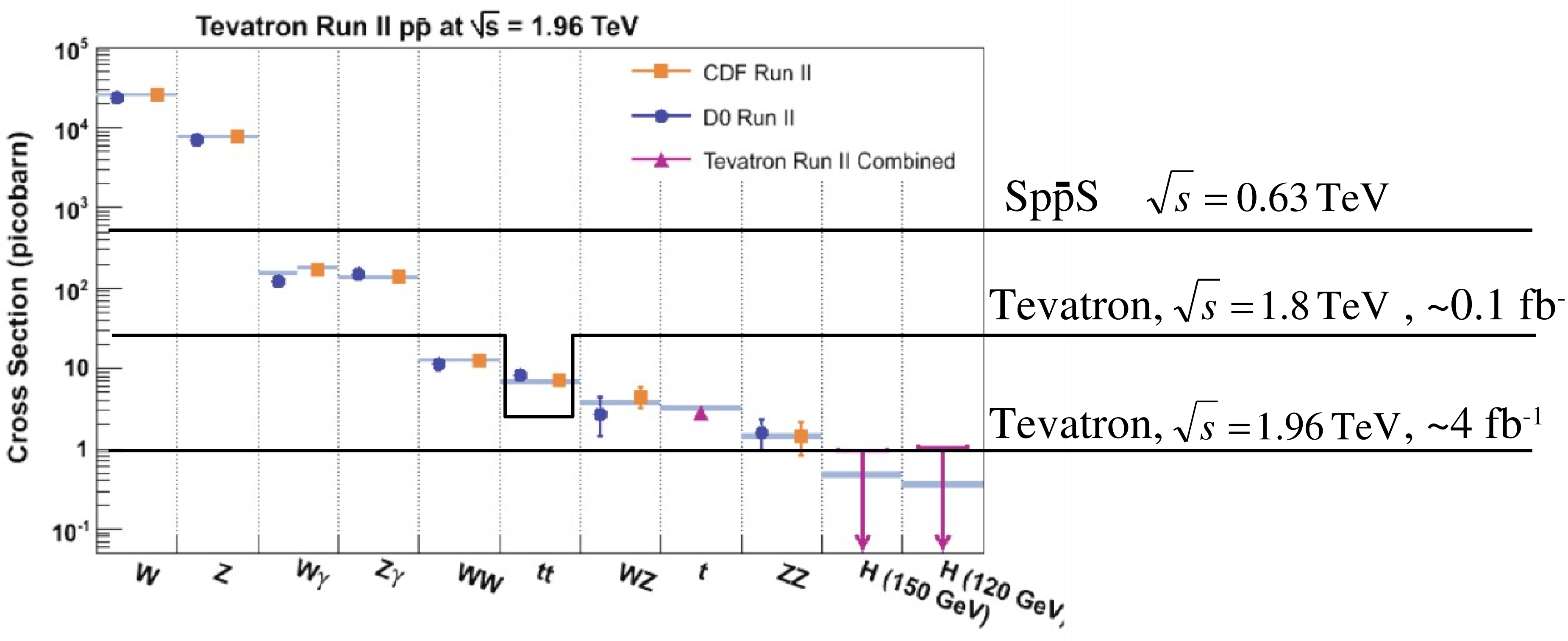
Cross section in hadron machines

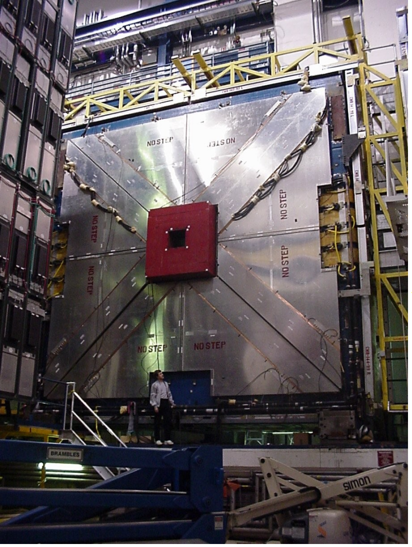


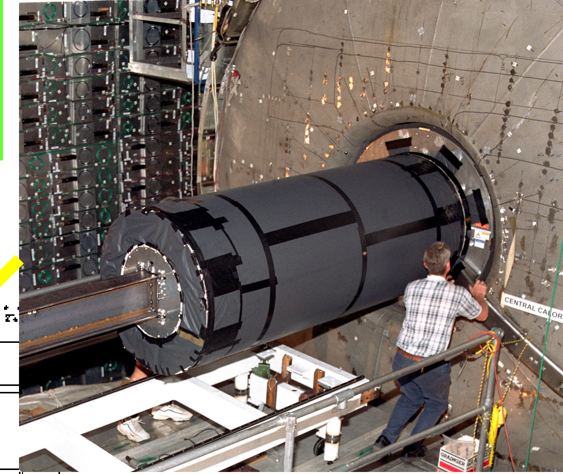
Cross section in hadron machines



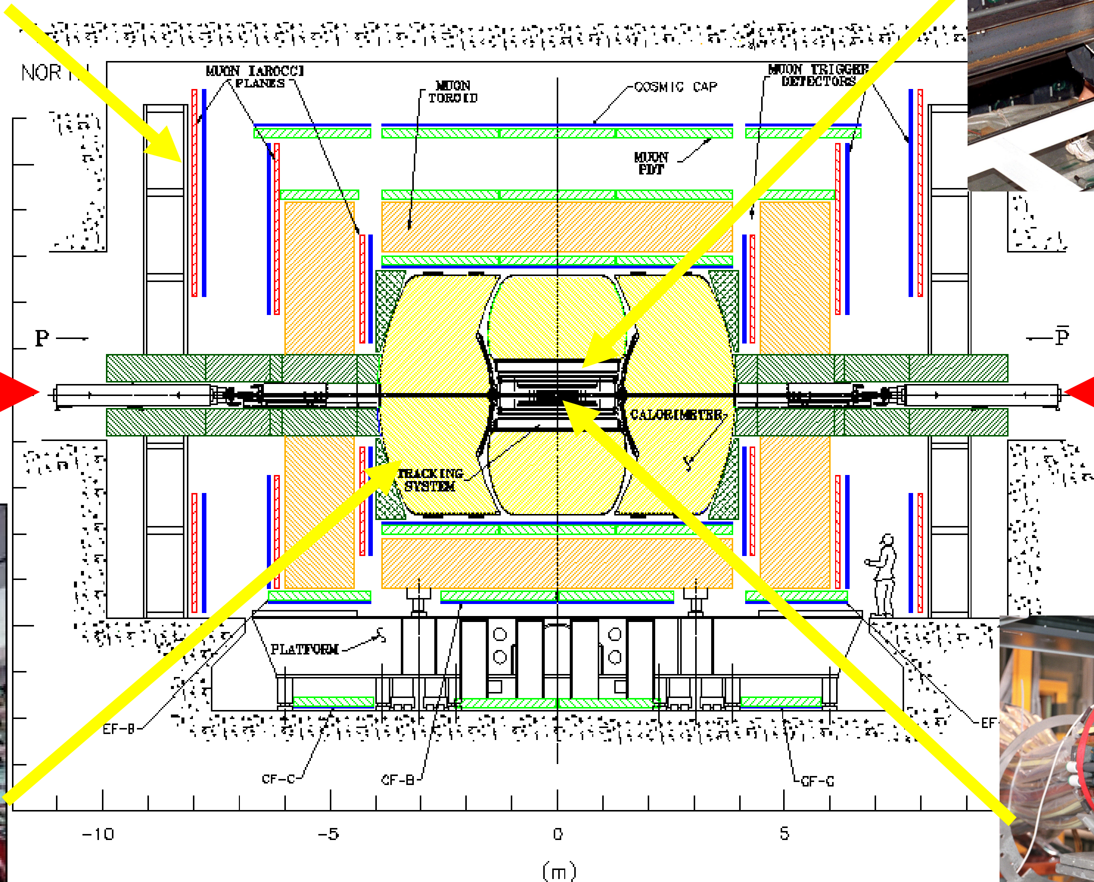
Top quark mass

The D0 detector

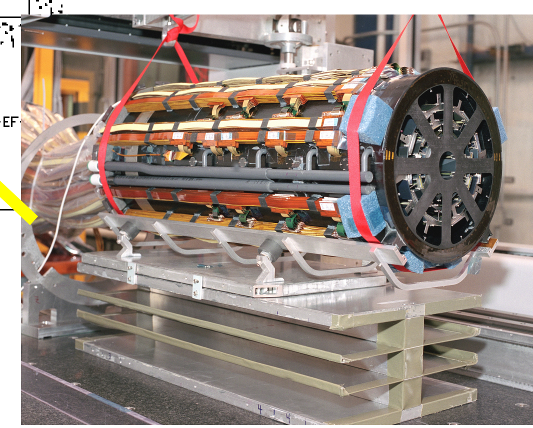




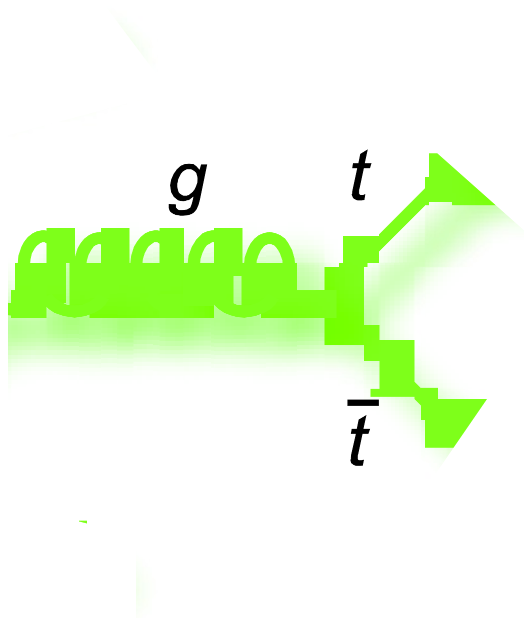
p



p-bar

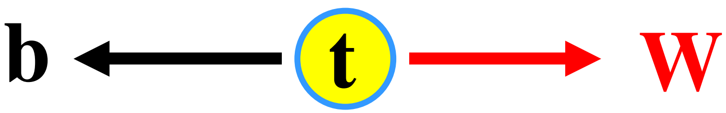


Top pair production



Top and W decay

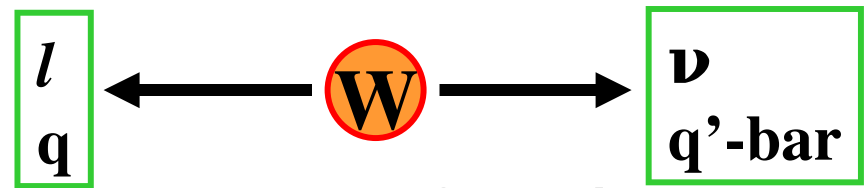
$M_t = 174\ GeV/c^2$



p ~ 70 GeV/c

Top decays to W+b essentially 100 % of the time

$M_W = 80\ GeV/c^2$

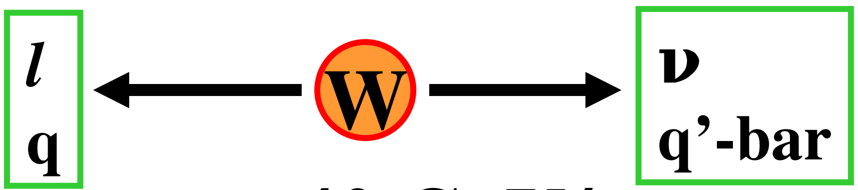


p = 40 GeV/c

The decay to jets is 3 times more likely than to e and μ

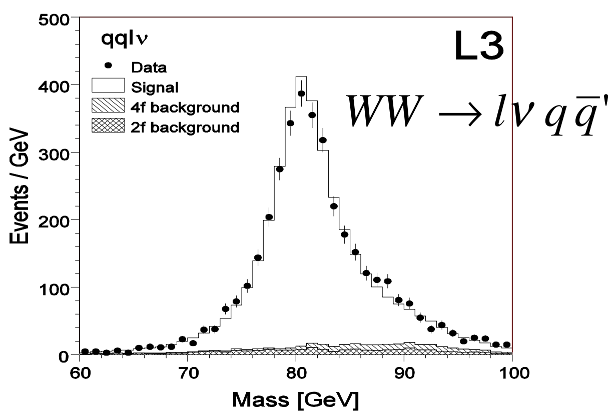
Leptons are well understood. To first order (there is also radiation) we need to understand a 40 GeV light jet and a 70 GeV b-jet, the rest are Lorentz boosts. The light 40 GeV jets were well understood at LEP. At the Tevatron W to jets is used now to set the overall JES.

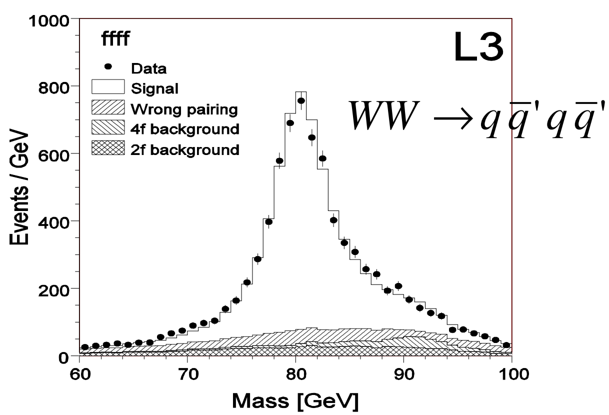
W mass at LEP



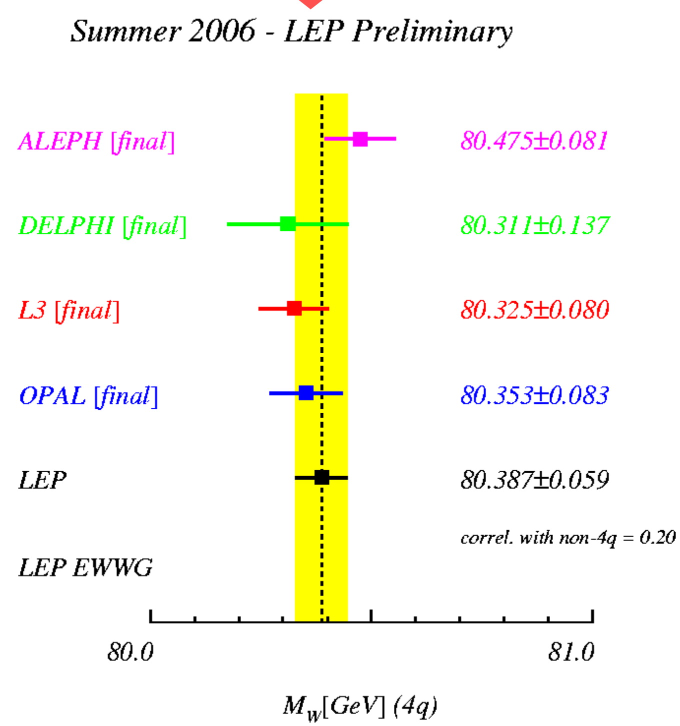
p = 40 GeV/c

I think it is fair to assume that this 40 GeV jet is understood.

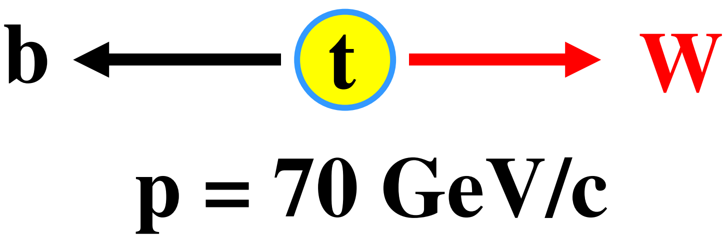




LEP all jets W mass



What about the 70 GeV b-jet?

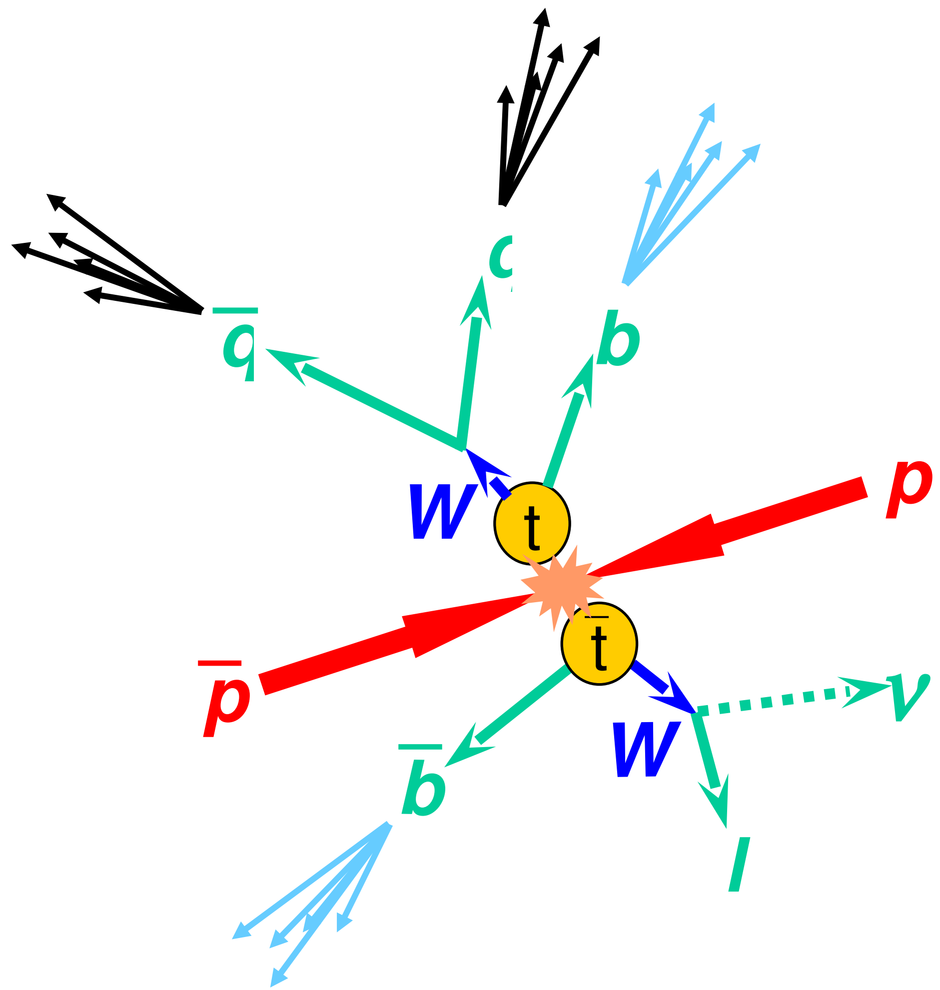


We don’t understand this 70 GeV b-jet as well as the light jets.

- To neutralize color the b-quark talks to the beam partons → the “top decay products” used to calculate an invariant mass are not well defined.
- So the idea of a “pole mass” is an approximation which is as good as the MC approximations to the t-tbar production and hadronization.
- There is also radiation from the b quark and the initial partons (I would argue that the radiation from the 40 GeV light jets is understood from LEP)
- The lack of experimental understanding of the b-jet (as opposed to MC modeling) is one of the main systematics in the top quark mass measurement.

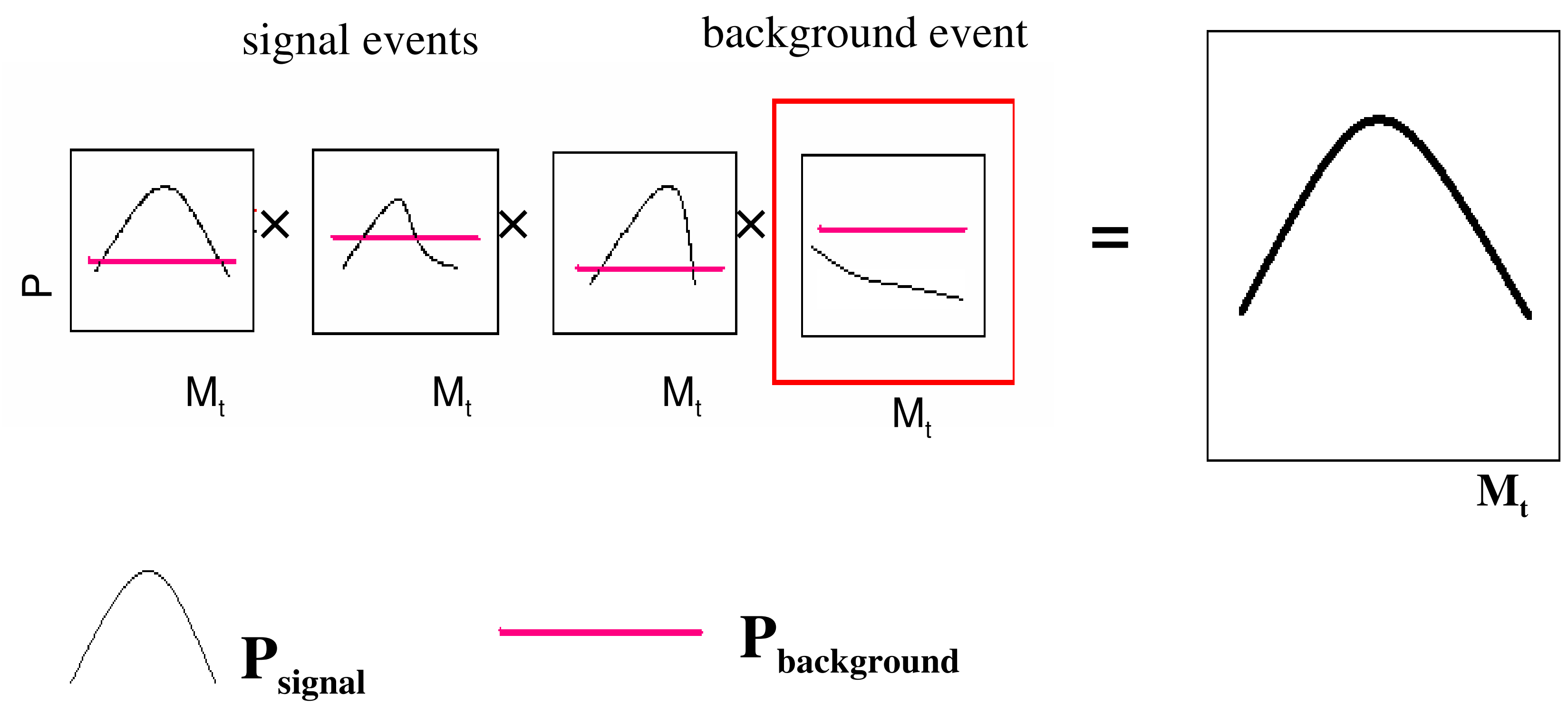
lepton+jets top event

- **pt cut: all particles ≥ 15-20 GeVs**
- **η cuts depend on detector acceptance**
- **Cuts in the number of jets**
- **at least one b-tag**
- **selection of a permutation or in some cases the use of all of them**



24 jet permutations per event

Using probabilities to measure the top mass



Analysis strategies

(Note: I am only mentioning the most accurate result from each experiment.)

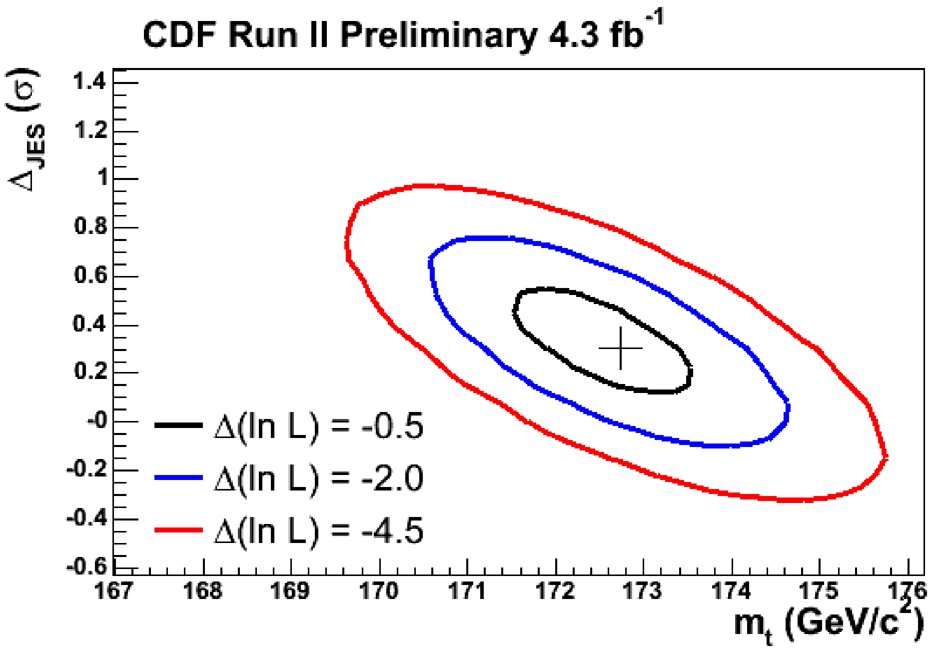
CDF (4.3 fb^{-1}):

- **Use a signal probability with two variables: a) the top mass, b) the Jet Energy Scale.**
- **Use a NN discriminant to separate signal from background.**
- **Project on the top axis to extract the mass**

D0 (3.6 fb-1):

- **Use signal plus background probabilities with three variables: a) the top mass, b) the Jet Energy Scale, c) the signal fraction.**
- **Project on the top axis to extract the mass**

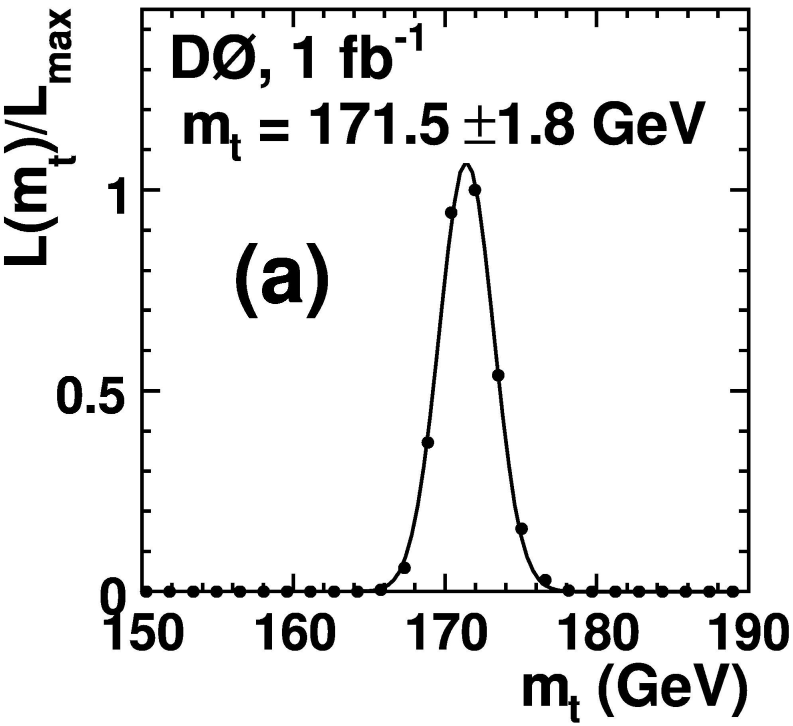
Top mass (CDF)

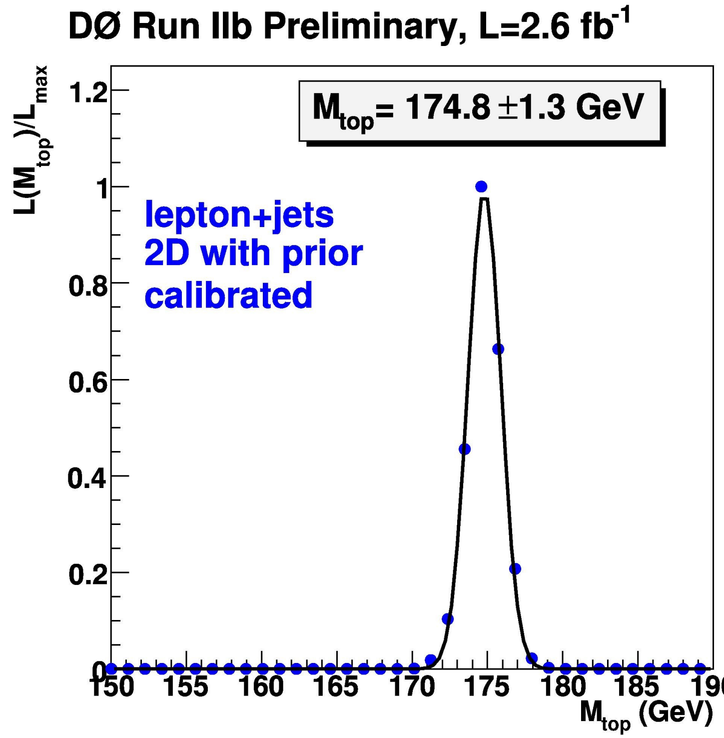


M_{top}= 172.6 ± 1.1 (stat+JES) ± 1.1 (sys) GeV/c

= 172.6 ± 1.6 GeV/c

Top mass (D0)





M_{top}= 173.7 ± 0.8 (stat) ± 1.6 (sys) GeV/c

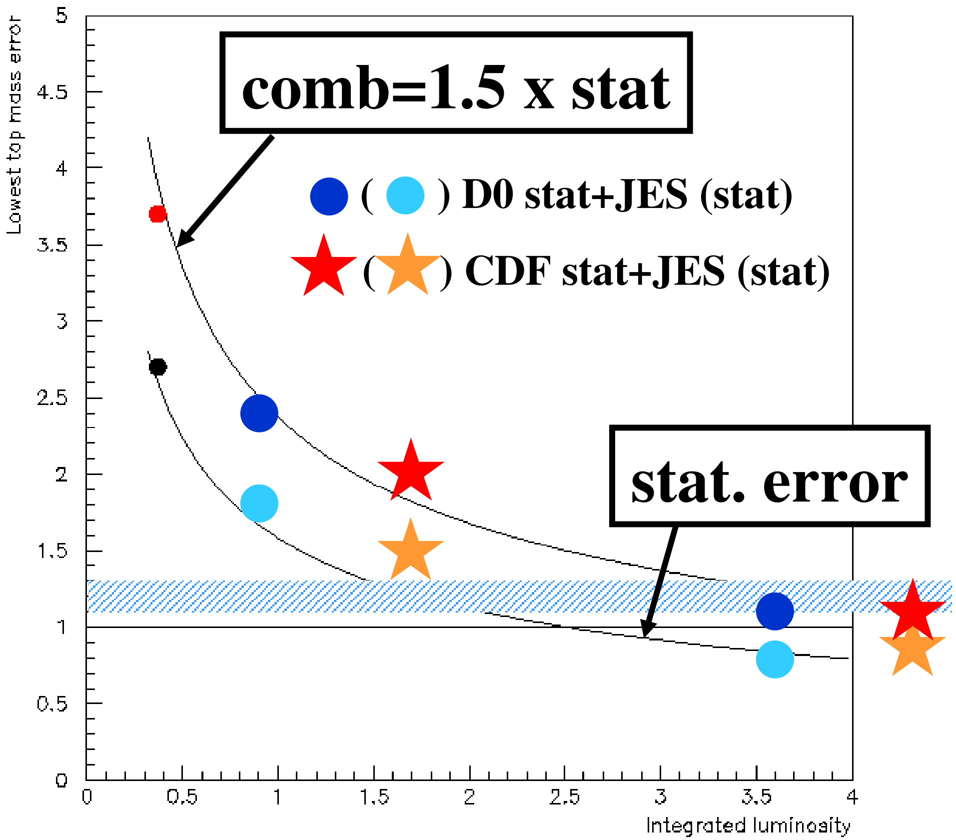
= 173.7 ± 1.8 GeV/c

lepton + jets

CDF systematic errors in l+jets

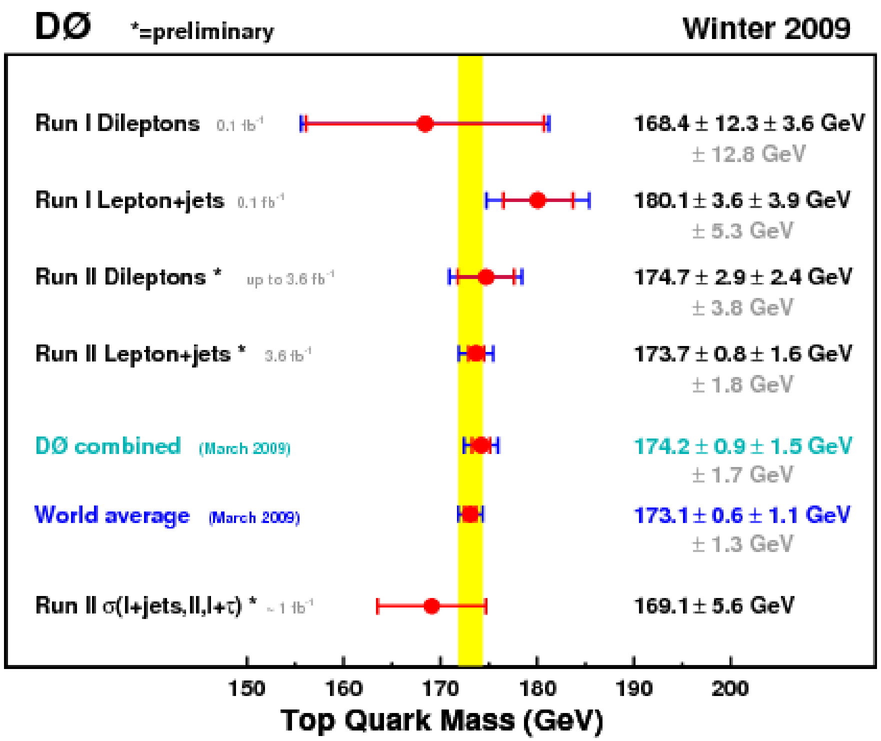
Systematic Source	m_{top} (GeV)
Calibration	0.1
MC generator	0.5
Radiation	0.4
Residual jet energy scale	0.5
b-jet energy scale	0.4
Lepton p_T	0.2
Multiple hadron interactions	0.1
PDFs	0.2
Background	0.5
Color reconnection	0.3
Total	**1.1**

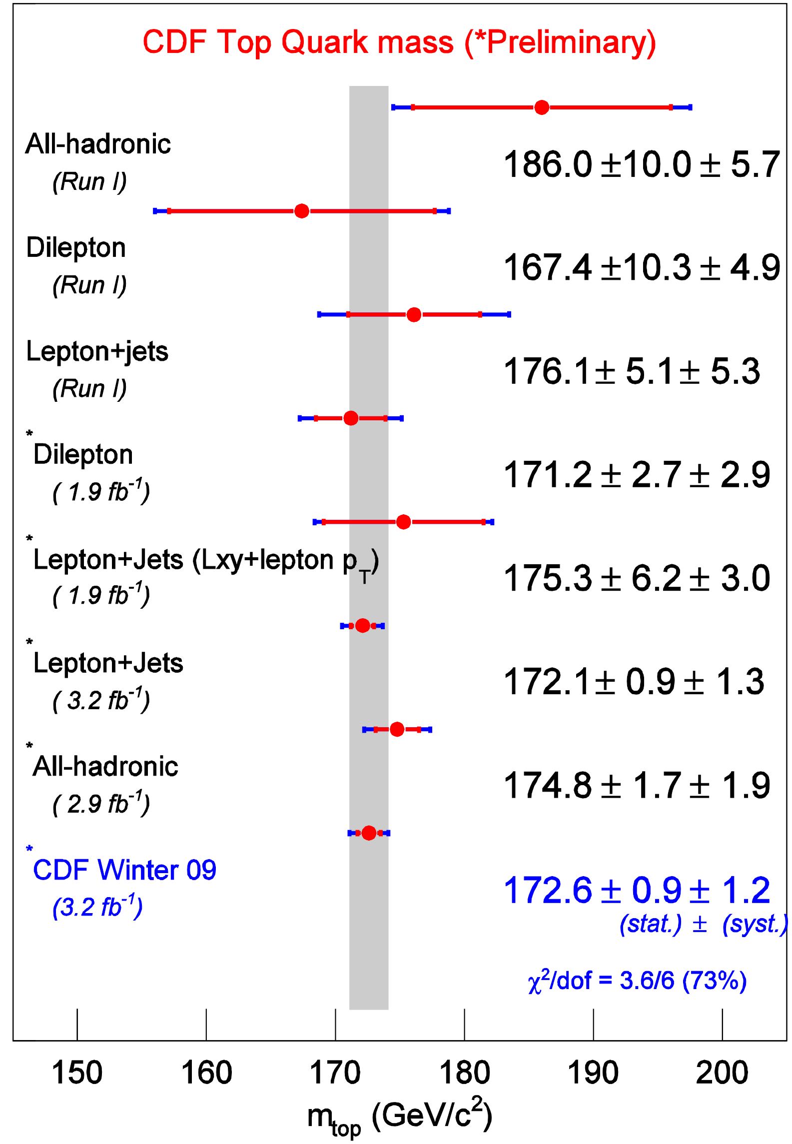
(my Sep-2005 predictions - D0 talk)



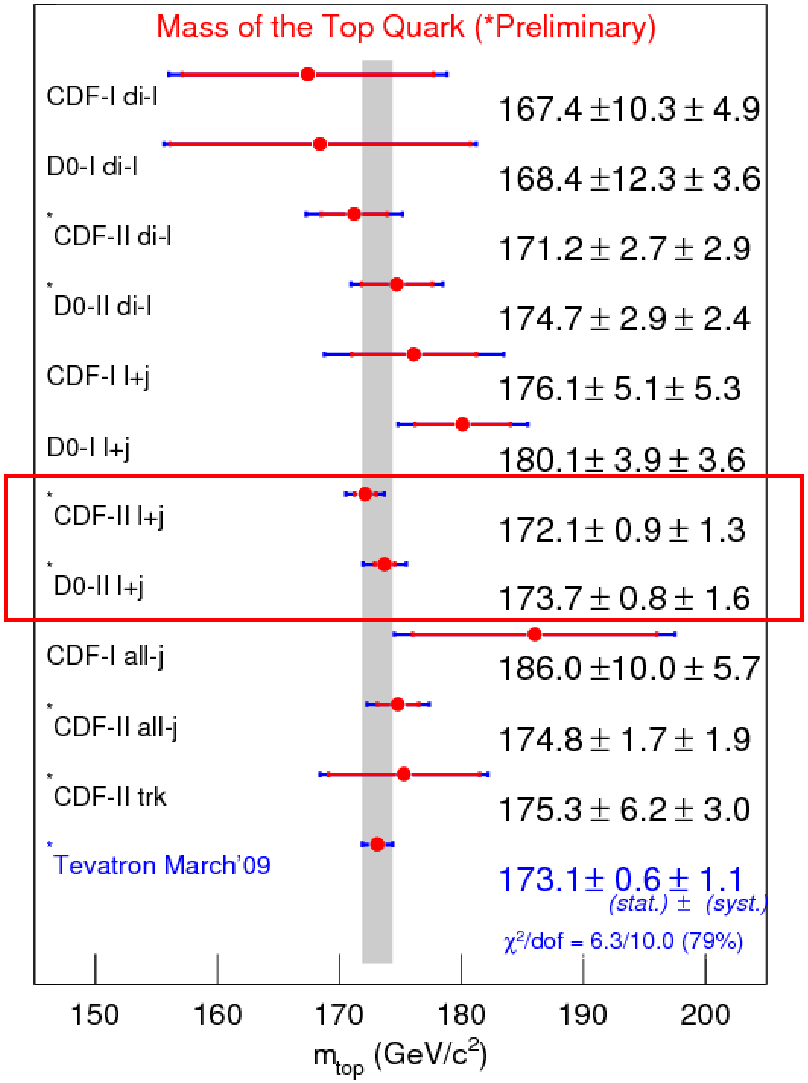
By the end of the Tevatron run the stat+JES error per single measurement will be ~0.6 GeV/c². So the top mass measurement will be dominated by systematic errors. We really need the other channels in case we missed something big.

Summary of D0 and CDF results





World average top mass



World average:

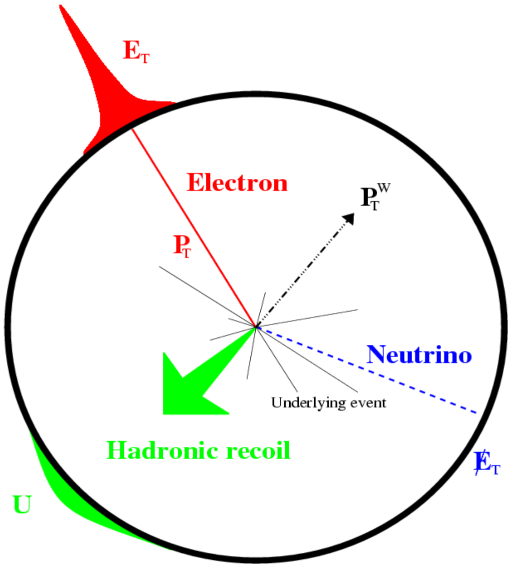
M_{top} = 173.1 ± 0.6 (stat) ± 1.1 (sys) GeV/c

= 173.1 ± 1.3 (stat+sys) GeV/c

- All channels are consistent with each other
- The top mass measurement is dominated by systematic errors

W boson mass

W mass and what can be measured?



$$W \to \mu \nu \text{ , or } W \to e \nu$$

Quantities that can be measured:

- The electron/muon momentum
- The hadronic recoil

Quantities that can be calculated:

- The neutrino transverse momentum

  (remember that the longitudinal momentum of the event can not be measured)
- m_T or the mass calculated with transverse quantities

W mass measurement at CDF

CDF strategy:

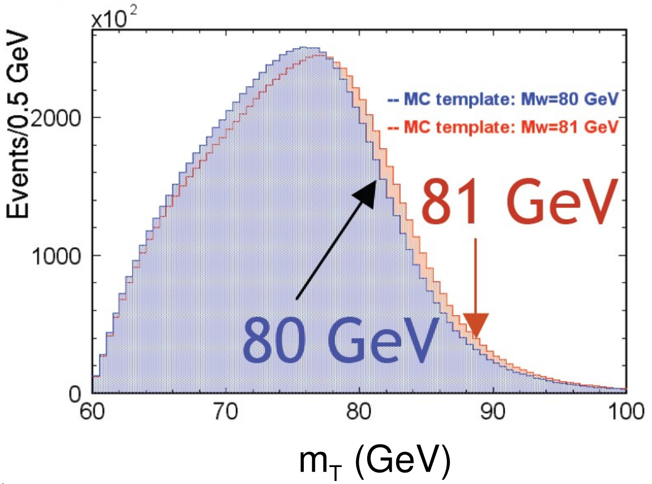
- **Calibrate the tracker with muons from J/ψ, upsilons and Z decays.**
- **Extend the calibration to the calorimeter for electrons.**
- **Measure the hadronic recoil u_T using Z decays and p_T conservation.**
- **Measure the W mass with a data to MC comparison of the transverse mass, and the electron/muon and neutrino's transverse momentum.**

A comment on the statistical error:

With 200 pb^{-1} of data CDF has 115,092 events that pass all the cuts. If σ is the rms of distribution used to extract the W mass, then the statistical error in its mean is:

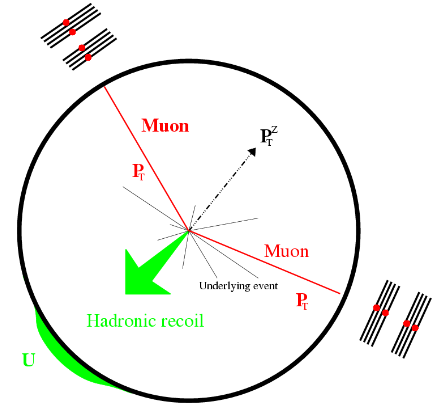
$$\frac{\sigma}{\sqrt{N}} \approx \frac{10\,\text{GeV}}{\sqrt{115{,}000}} = 30\,\text{MeV}$$

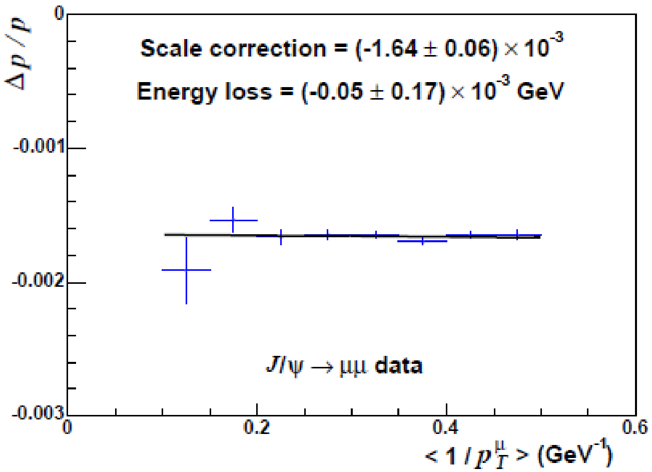
Which shows that the main problem is the systematic errors.

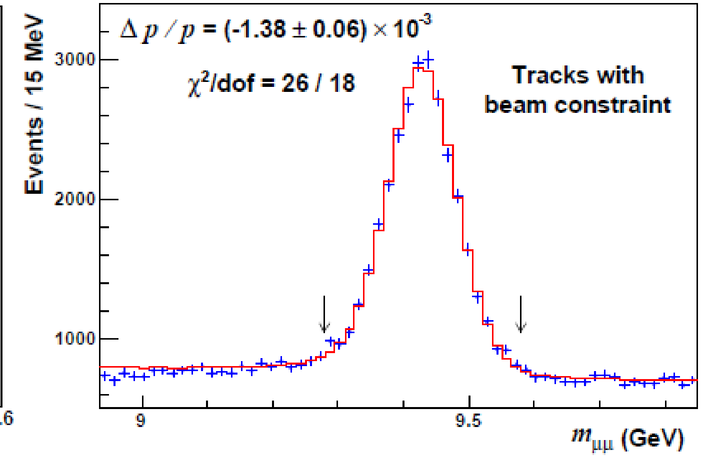


1^{st} : calibrate tracker

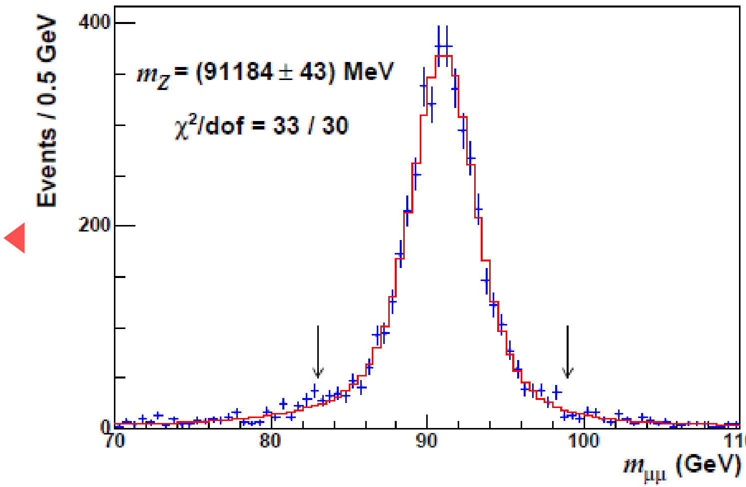
First align tracker, and get momentum scale from J/Psi and Upsilon



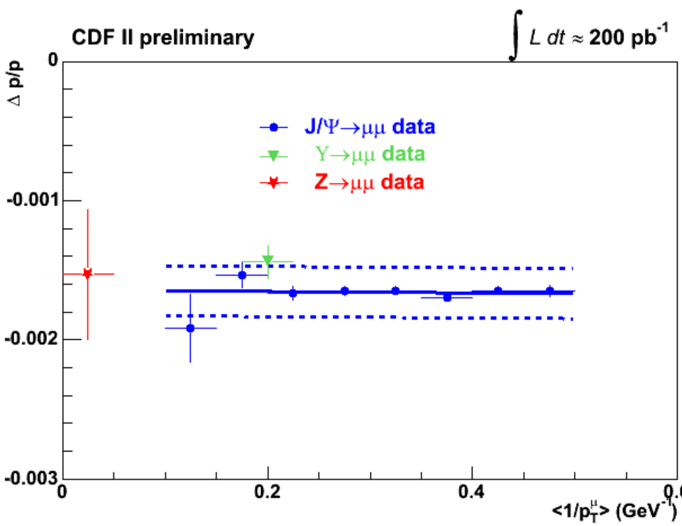




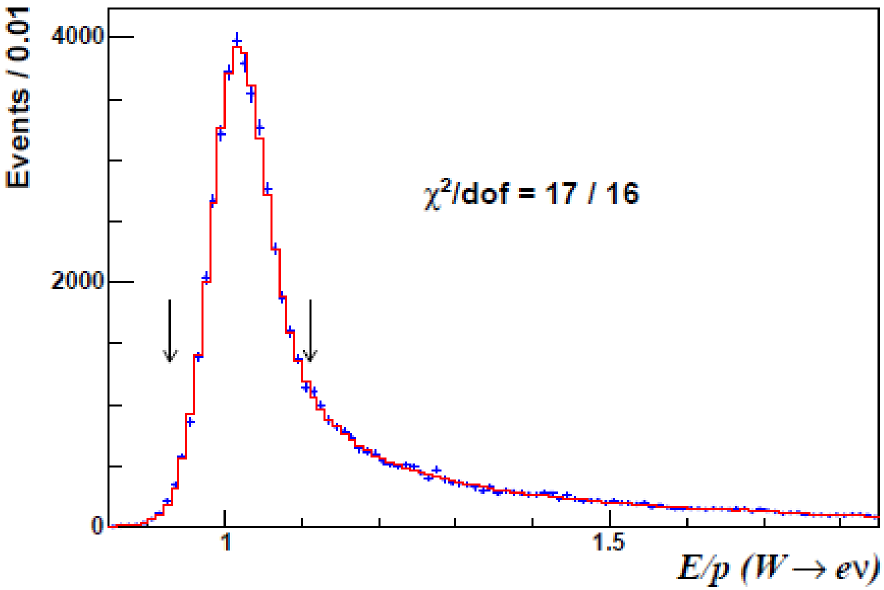
Check Z



Combine all measurements into single calibration

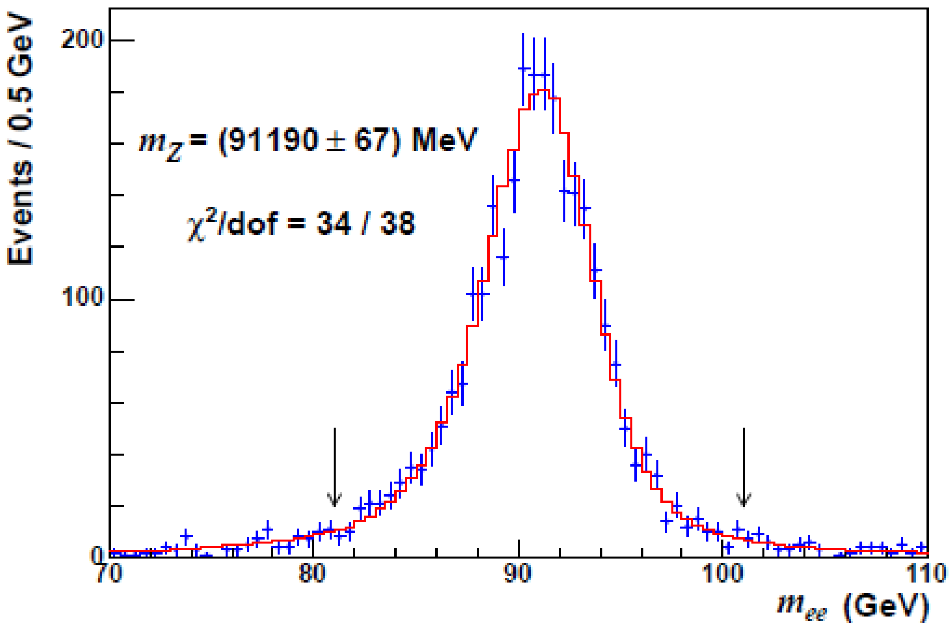


2^{nd} : with tracker calibrate EM calorimeter



Fitting E/p peak and width as a function of electron's E_T calibrate energy scale, resolution and amount of material (number of radiation lengths)

Check Z→ee

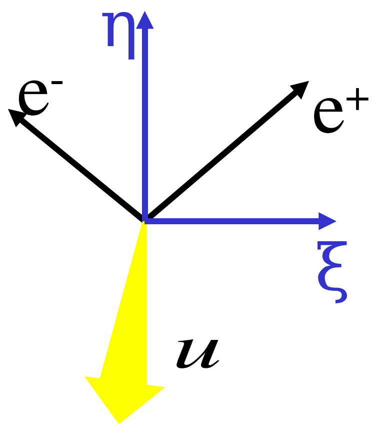


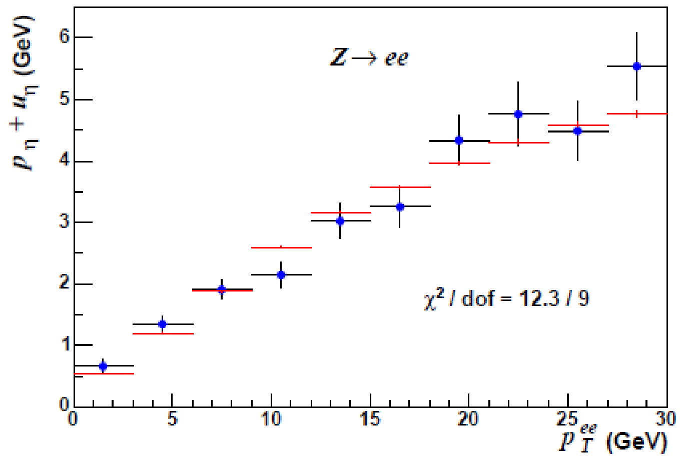
Combine results to obtain best energy calibration and resolution

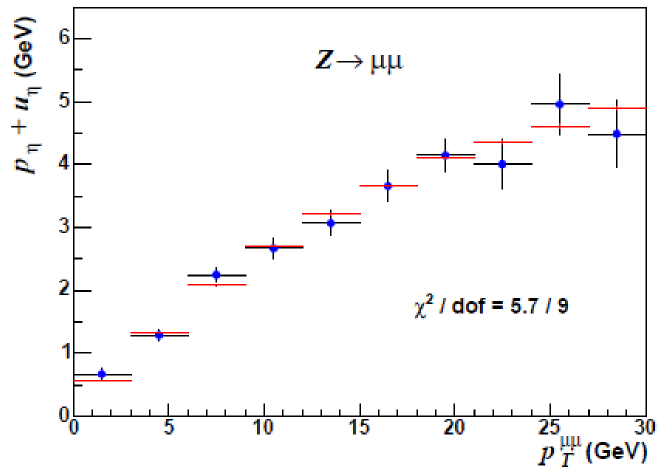
3rd : calibrate hadronic recoil

To calibrate the hadronic recoil a transverse vector sum over calorimeter towers $u = \sum_i E_i \sin\theta_i n_i / c$ is defined and compared to the lepton pT in Z→ee and Z→μμ events.

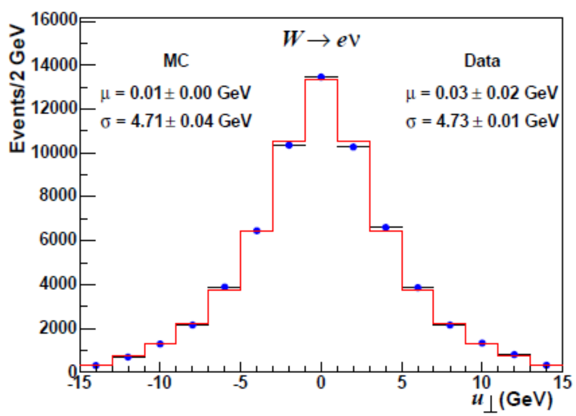
Calibrate with Z→ee or Z→μμ

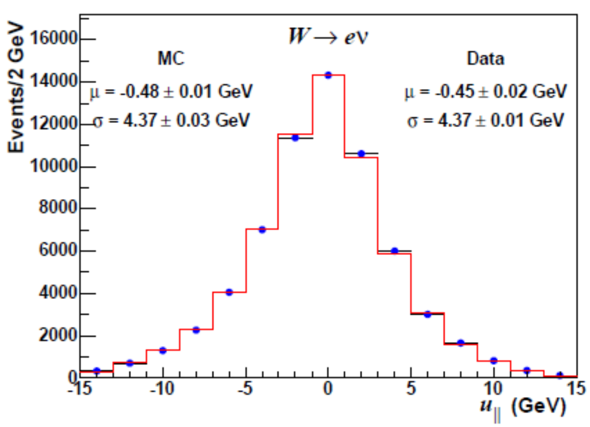


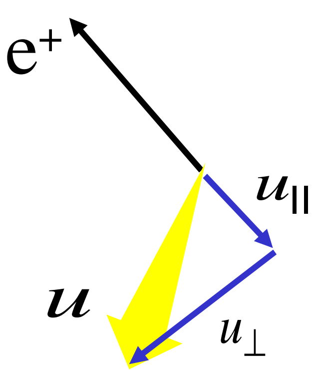




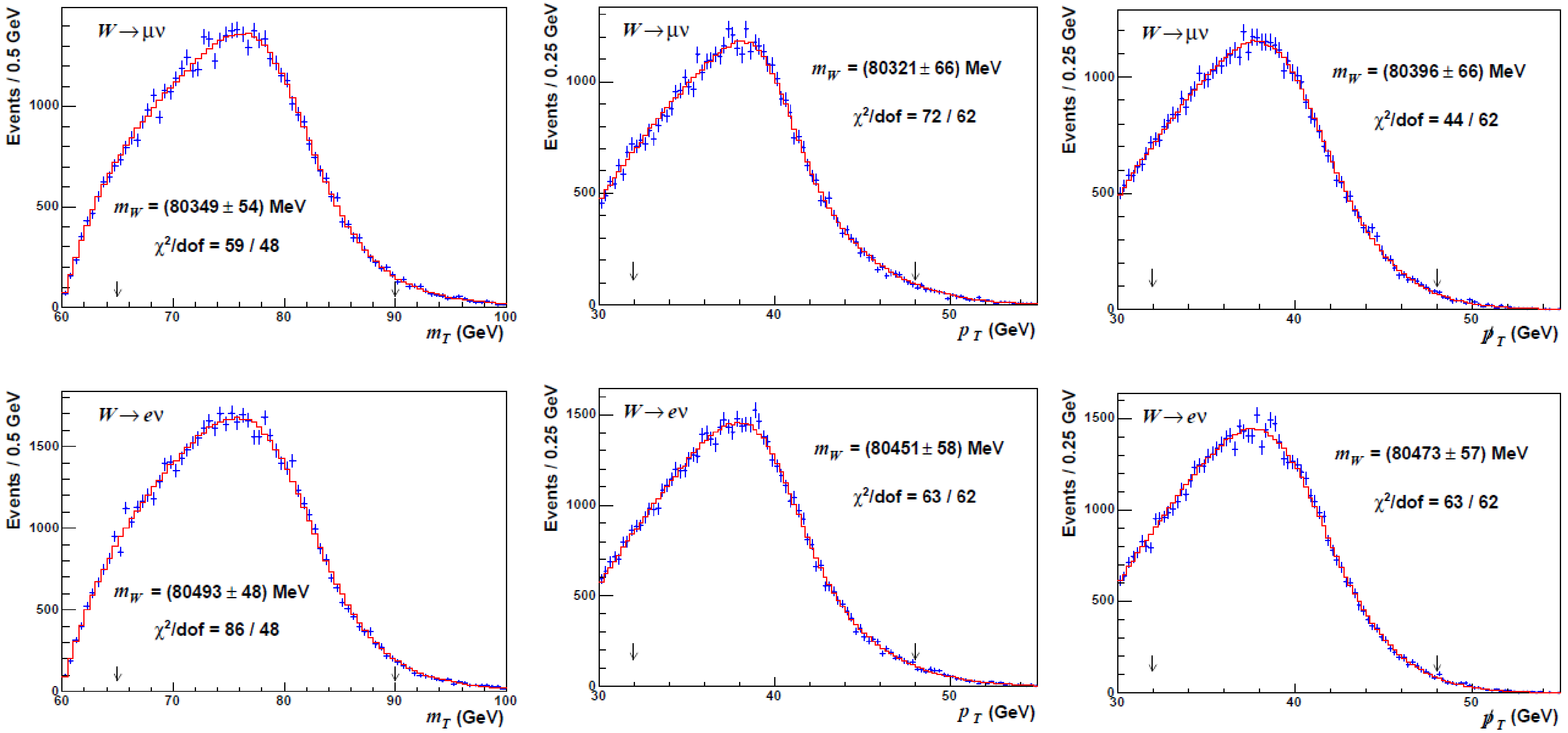
Validate with W→eν or W→μν







4^{th} : measure W mass



$$m_W = 80413 \pm 34\ (stat) \pm 34\ (syst)\ \ MeV/c^2$$

$$= 80413 \pm 48\ MeV/c^2$$

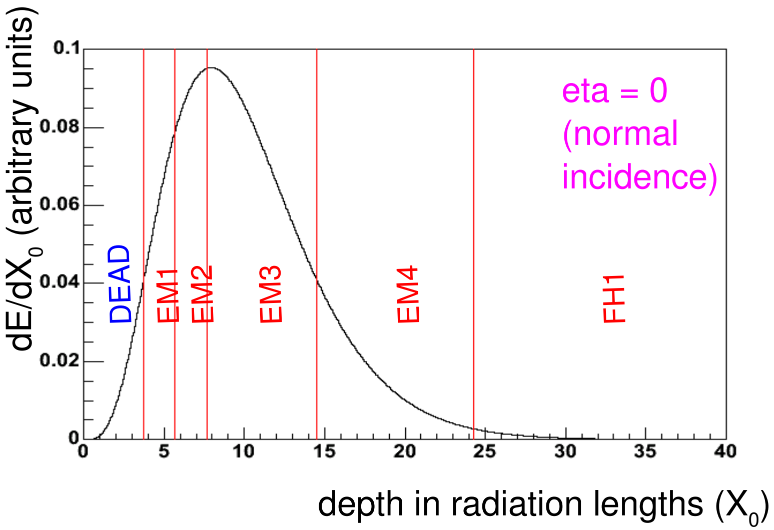
W mass measurement at D0

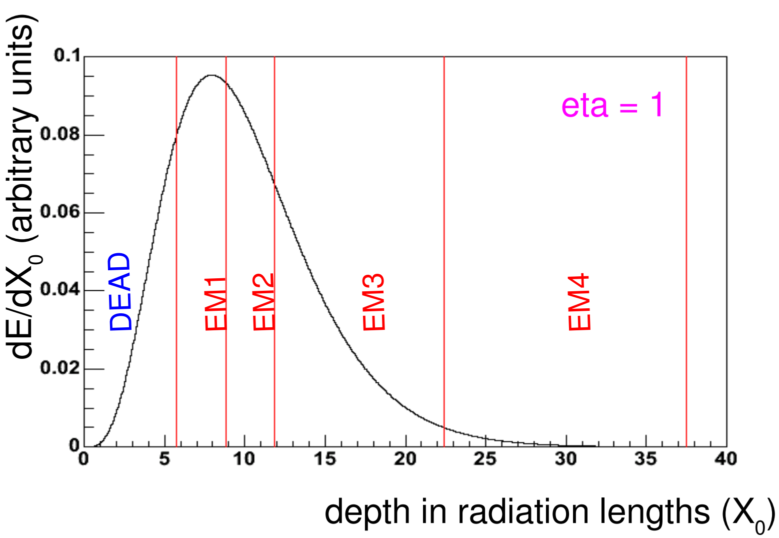
D0 strategy:

- Use only the calorimeter and therefore only $W \rightarrow e\, \nu$.
- Use data to measure the amount of material in front of the calorimeter.
- Make the calorimeter uniform in φ (using trigger with EM energy).
- Use $Z \rightarrow ee$ to make the calorimeter uniform in η and for the absolute energy scale.
- Measure the hadronic response.
- Measure the W mass with a data to MC comparison of the transverse mass, and the electron and neutrino's transverse momentum.

1^{st} : measure material in front of EM calorimeter

45 GeV electron

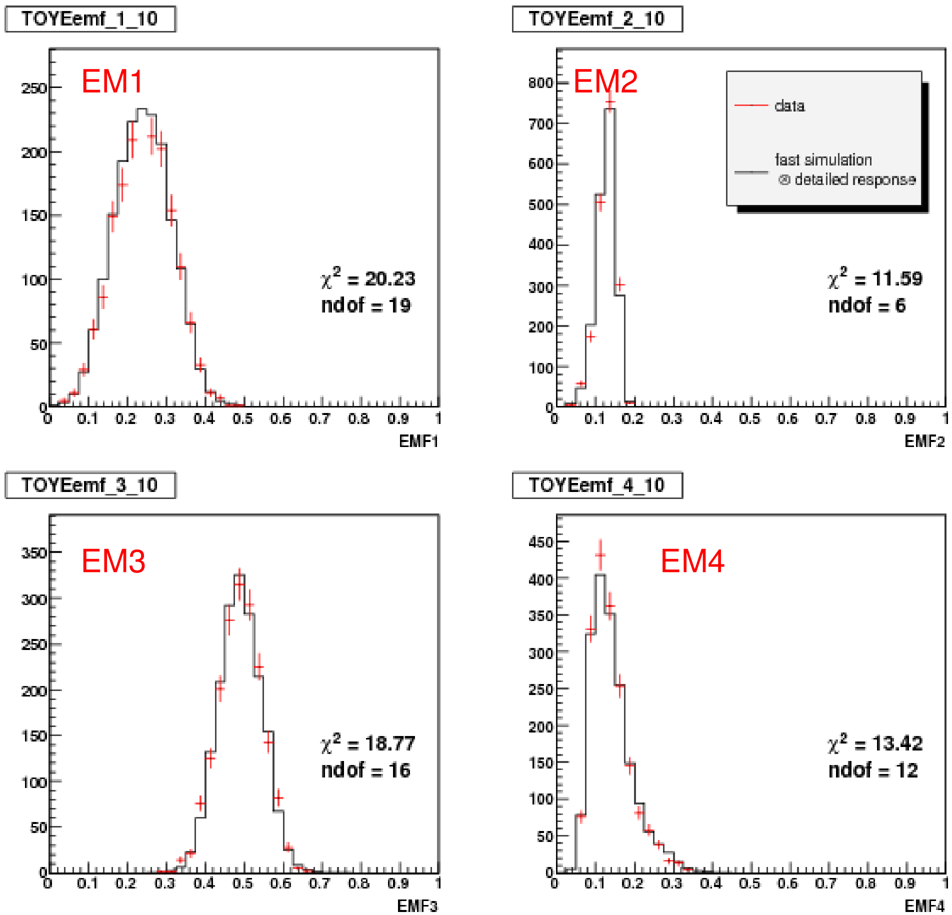


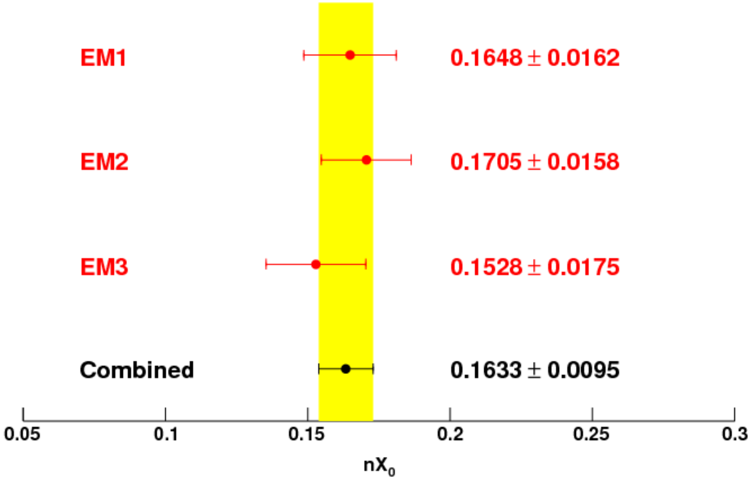


Use longitudinal shower profile in Z→ee events to measure the amount of material in front of the calorimeter.

1st : measure material in front of EM calorimeter

Example: |η|<0.2 after corrections





Measured amount of extra material 0.16 X_0. Repeat for different values of η.

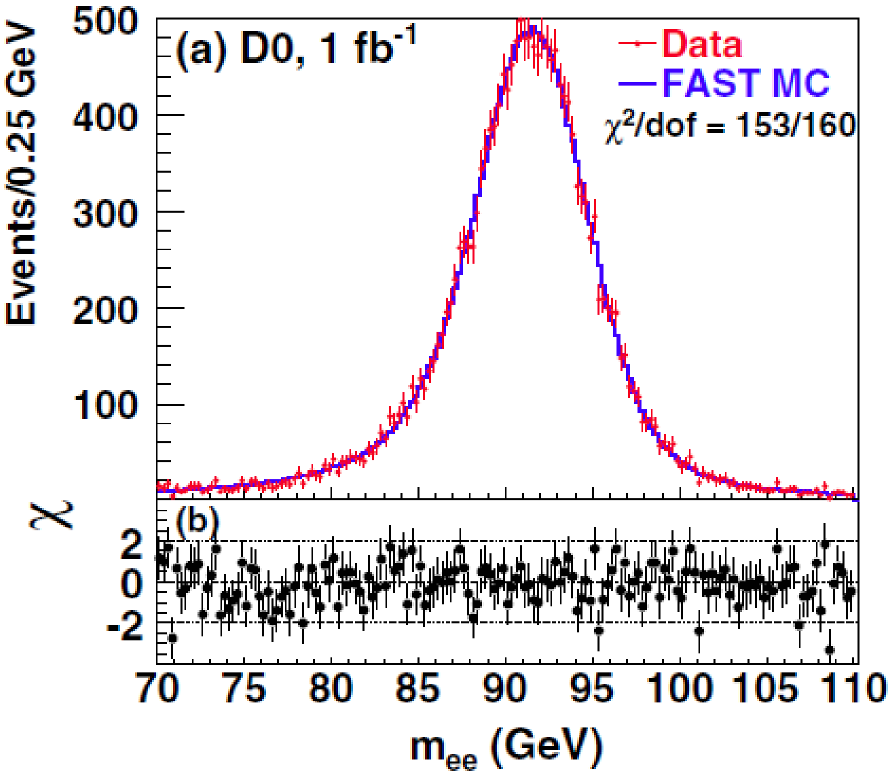
2nd : use Z→ee to calibrate calorimeter

Use spread in the electron energies in Z→ee to determine α and β in:

$E_{measured} = \alpha \times E_{true} + \beta$

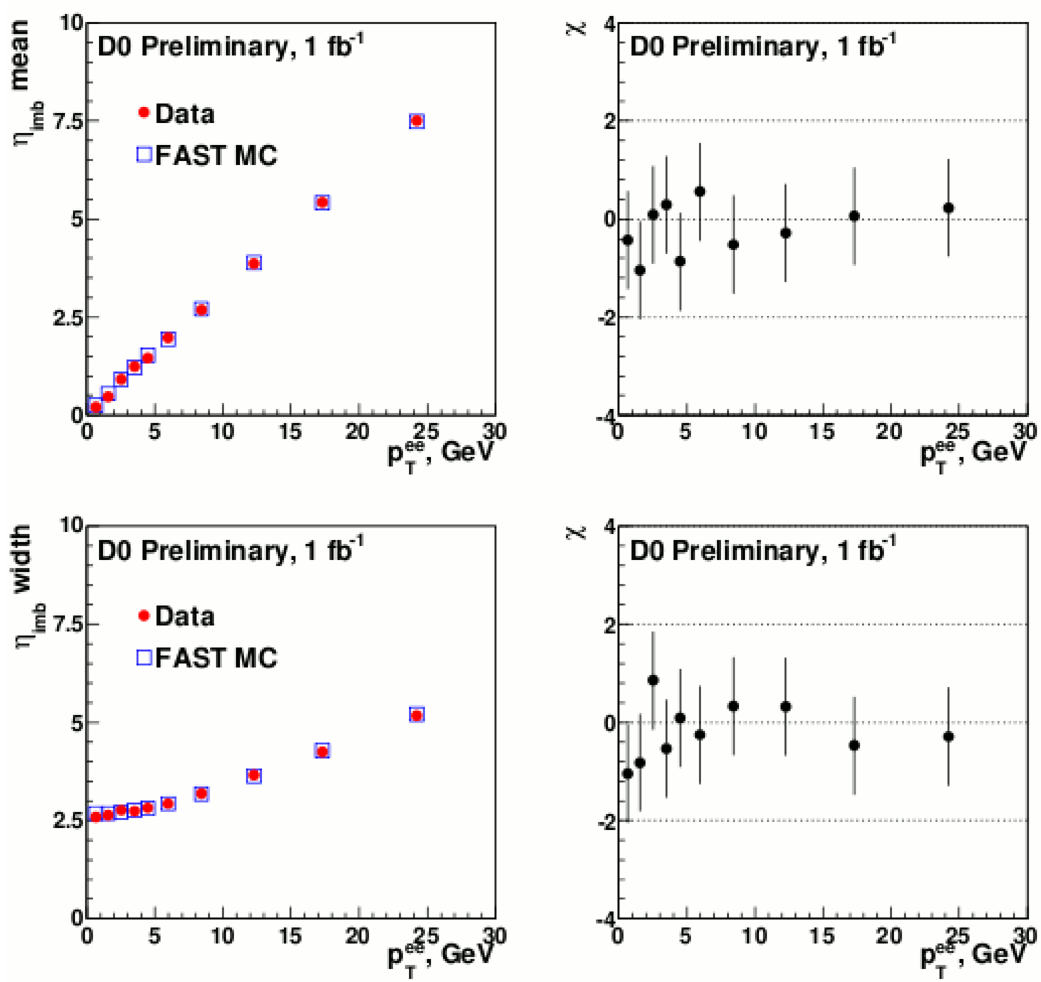
α = 1.0111 ± 0.0043
β = -0.404 ± 0.209 GeV
correlation: -0.997

Perform closure check by measuring the Z mass



3rd : use Z→ee to calibrate hadronic recoil

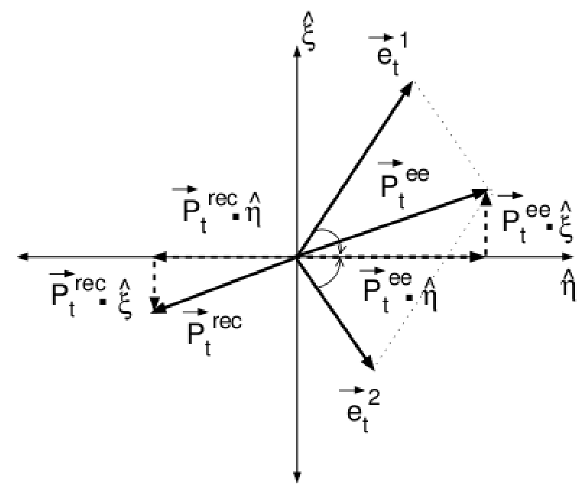
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in Z → e e events and the standard UA2 observables.



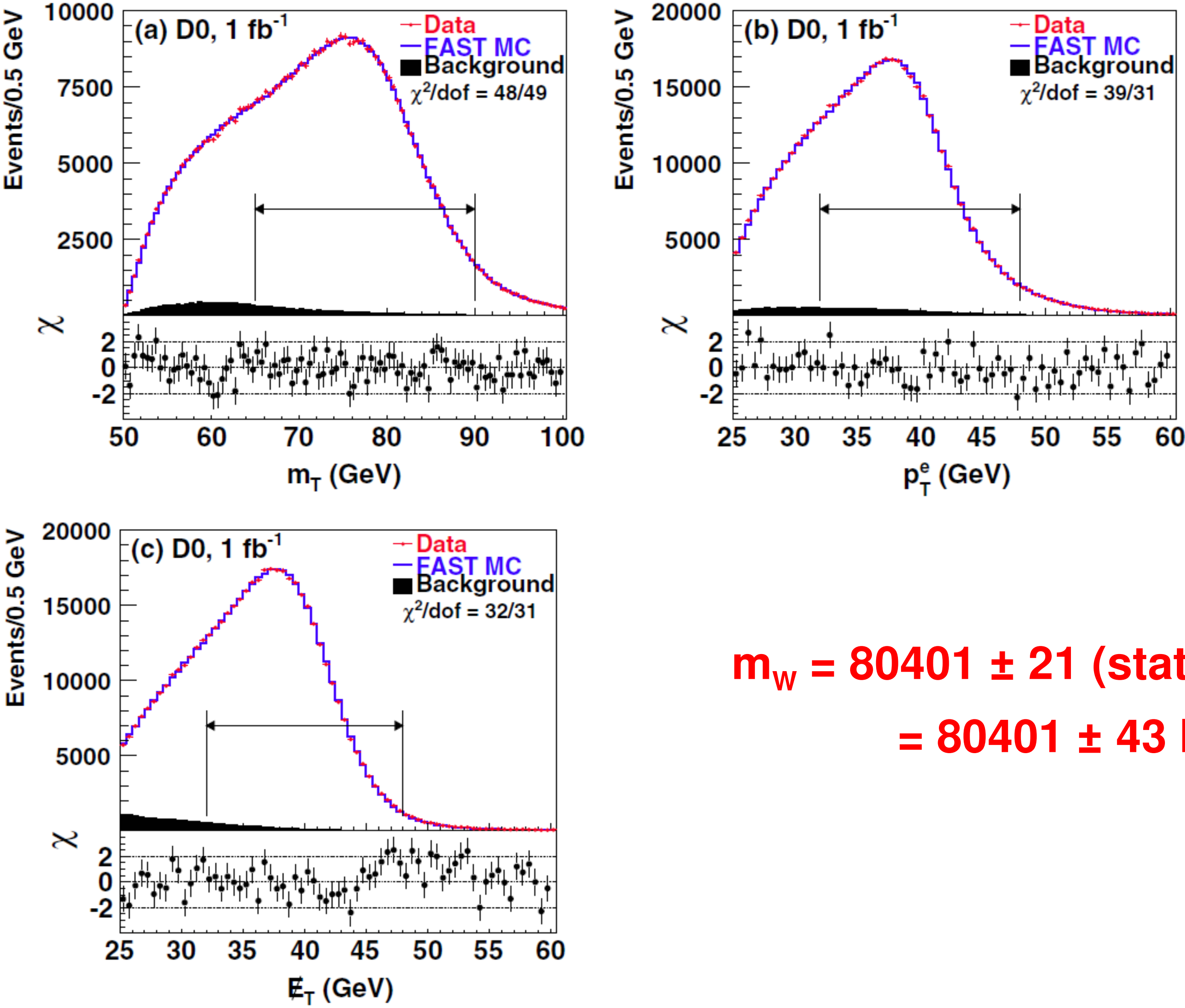
UA2 observables:
In transverse plane, use a coordinate system defined by the bisector of the two electron momenta.

η-imbalance : $(\vec{P}_t^{\,ee} + \vec{P}_t^{\,rec}) \cdot \hat{\eta}$

ξ-imbalance : $(\vec{P}_t^{\,ee} + \vec{P}_t^{\,rec}) \cdot \hat{\xi}$



4^{th} : measure W mass



m_W = 80401 ± 21 (stat) ± 38 (syst)

= 80401 ± 43 MeV/c^2

Systematics errors and world average

TABLE II. Systematic uncertainties of the M_W measurement.

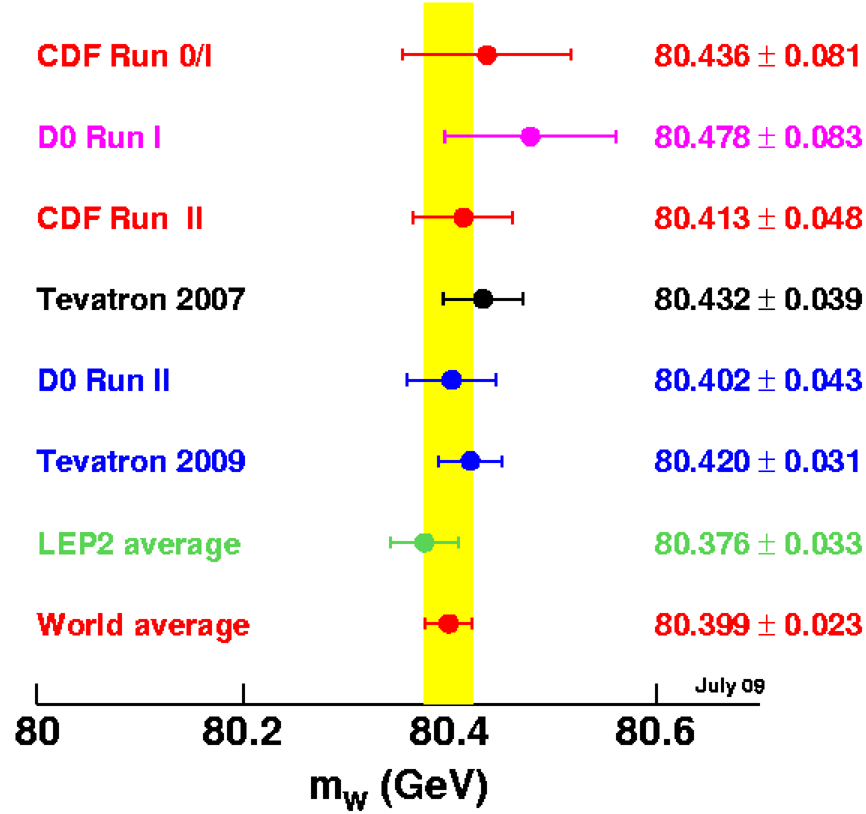
Source	ΔM_W (MeV) m_T	p_T^e	$\not{E}_T$	
Electron energy calibration	34	34	34	*
Electron resolution model	2	2	3	
Electron shower modeling	4	6	7	
Electron energy loss model	4	4	4	
Hadronic recoil model	6	12	20	*
Electron efficiencies	5	6	5	
Backgrounds	2	5	4	
Experimental subtotal	35	37	41	
PDF	10	11	11	
QED	7	7	9	
Boson p_T	2	5	2	
Production subtotal	12	14	14	
Total	37	40	43	

(*) error will scale like $N^{-1/2}$

D0

Systematic	$W \to e\nu$	$W \to \mu\nu$	Common
$p_T(W)$ model	3	3	3
QED radiation	11	12	11
Parton distributions	11	11	11
Lepton energy scale	30	17	17
Lepton energy resolution	9	3	0
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
$u_\parallel$ efficiency	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
Total systematic	39	27	26
Total uncertainty	62	60	26

CDF



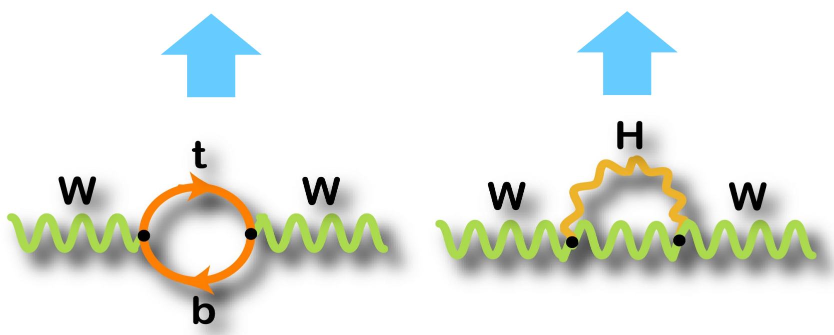
~ 10 MeV/c² is the expected error for CDF/DØ combined with 10 fb⁻¹ of data

Top, W and Higgs masses are related

$$M_W^2(1 - M_W^2 / M_Z^2) = A^2 / (1 - \Delta r)$$

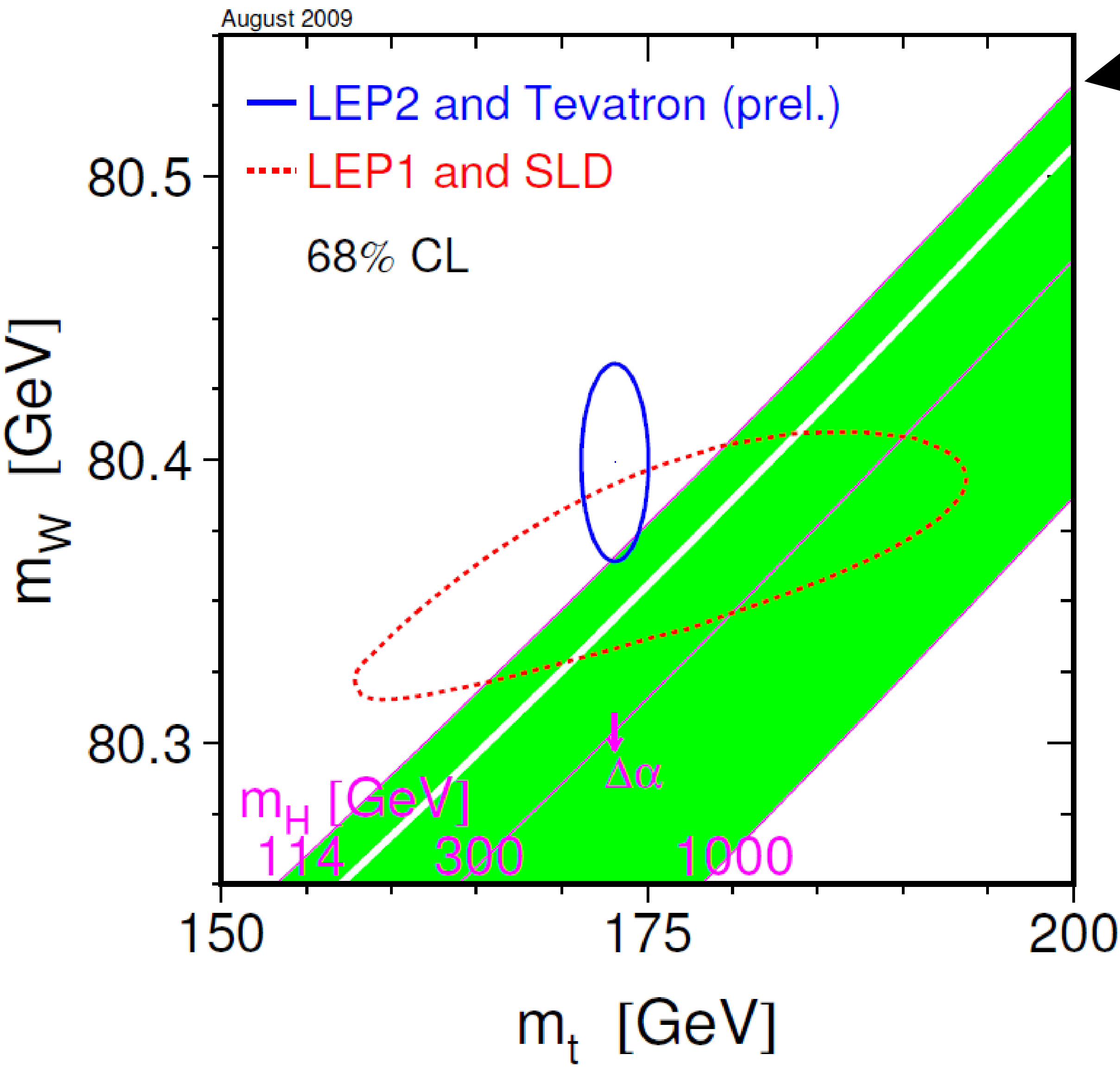
$$A = 37.2802\, GeV \quad \text{and}$$

$$\Delta r \approx a + b\ m_t^2 + c \ln(M_H^2 / M_W^2)$$



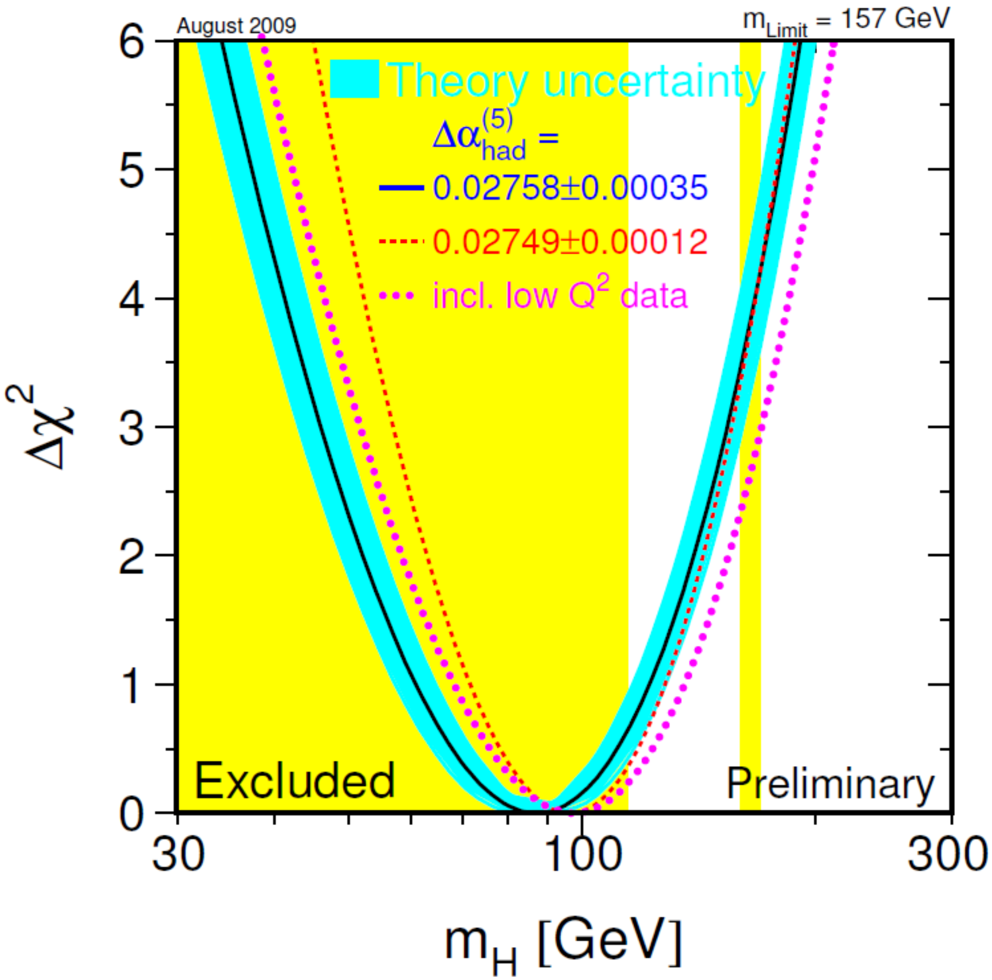
Accurate measurements of the top quark and W boson masses put constraints on the mass of the Higgs boson. Because of the log dependence to have meaningful constraints on the Higgs mass high precision measurement of the W and top quark masses are required.

LEP EWWG as of August 2009



These (almost) lines are the EW predictions.

Higgs limits



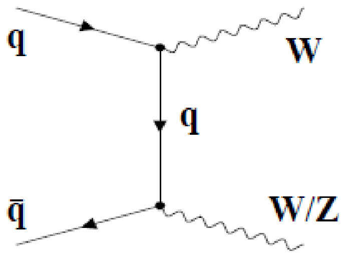
The SM Higgs mass limit from the EW fit is: m_H<157 GeV/c^2 at 95% CL.

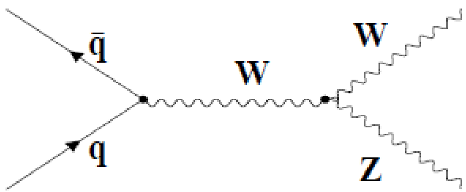
Footnote: There is a 3 σ discrepancy between the hadronic and leptonic F-B asymmetries. If any of this two are removed there are big changes in the Higgs mass limits (see M. Chanowitz, PRD 66:073002, 2002 and Fermilab W&C 2/23/2007)

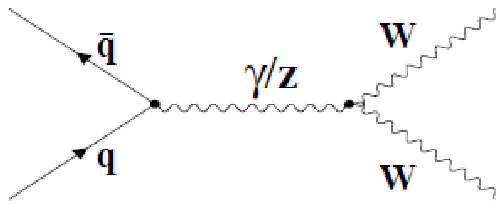
WW/WZ and jets

Dibosons and Higgs

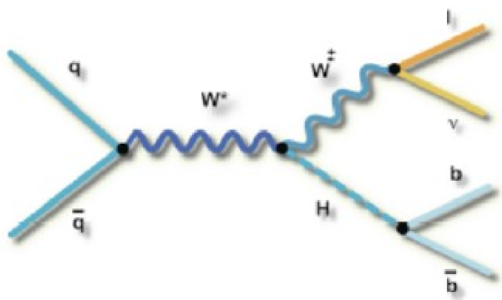
Main processes for WW+WZ production:

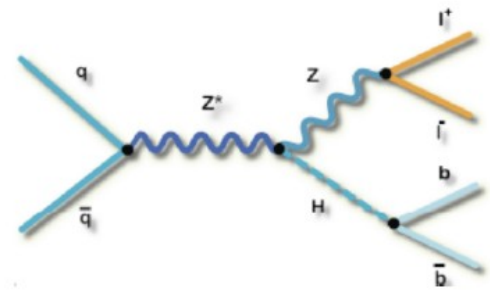






Low mass Higgs production:





The study of diboson production when a boson decays in two jets is a perfect training ground for Higg searches. So far no b-tagging has been used, this is clearly the next step.

Analysis strategies

D0 (1.1 fb-1, 4.4σ significance):

- Select lνjj final state (WW+WZ with W→lν and W/Z → jets).
- Build RF discriminant to separate signal from background.
- Extract signal from a fit to the RF output.

CDF (2.7 fb^{-1} , 5.4σ significance):

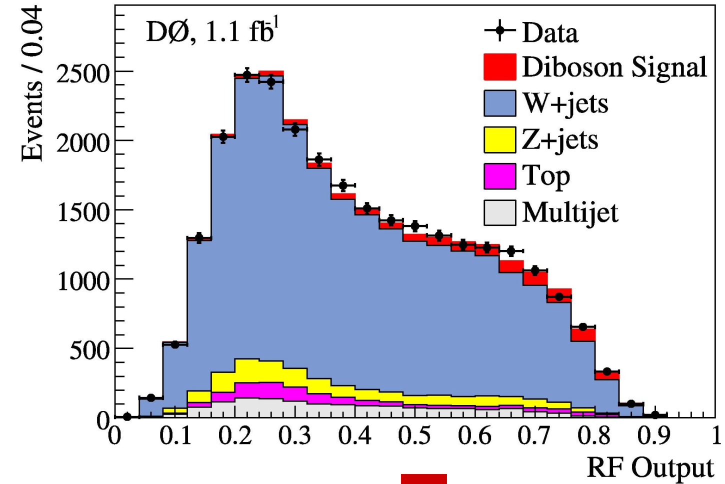
- Select lνjj final state (WW+WZ with W→lν and W/Z → jets).
- Build ME discriminant to separate signal from backgound.
- Fit di-jet invariant mass with and without discriminant cut.

CDF (3.5 fb^{-1}, 5.3σ significance):

- Select jj+missing E_T final state (WW+WZ+ZZ with W/Z→anything and W/Z → jets.
- Extract signal fitting di-jet invariant mass.

D0 lνjj analysis

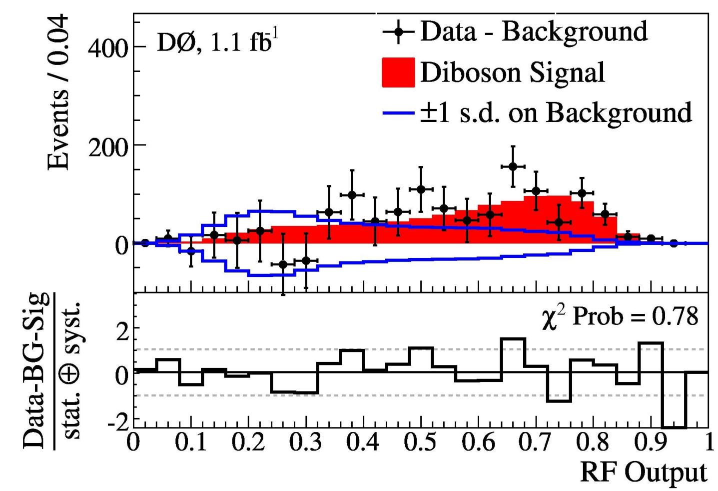
Train RF discriminant for signal and all the different backgrounds. Plot RF output.



Select events:

- **e, μ ,ν, jets P_T> ~20 GeV**
- **|η| < 1.1 - 2.0 - 2.5 for e - μ - jets**

Subtract background



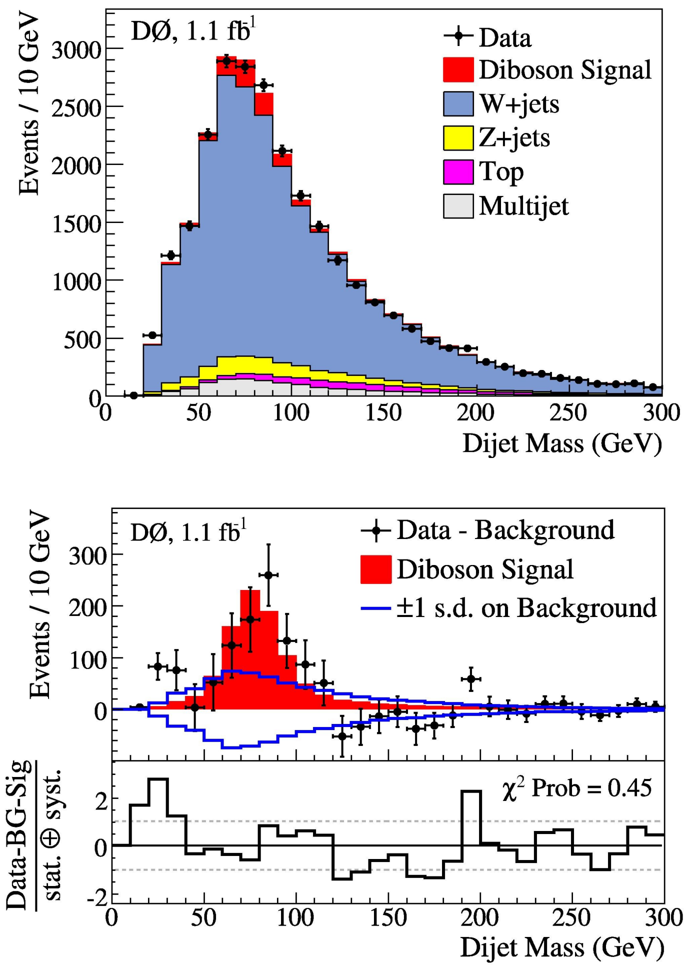
Measure WW+WZ cross section

20.2 ± 2.5 (stat) ± 3.8 (sys) pb

D0 lνjj analysis

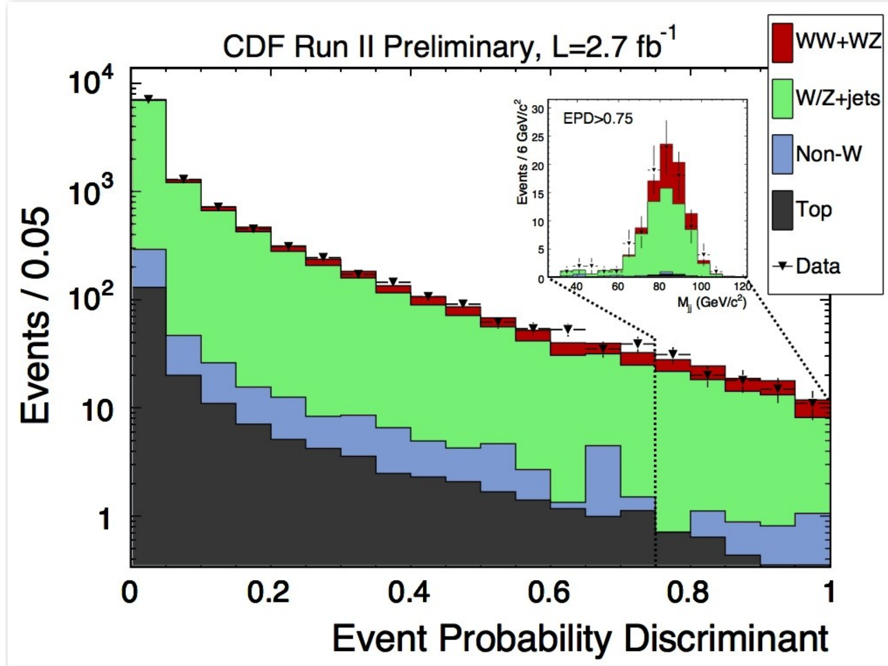
WW+WZ cross section can also be extracted from a direct fit to the di-jet invariant mass (albeit with a bigger error):

18.5 ± 2.8 (stat) ± 5.0 (sys) pb



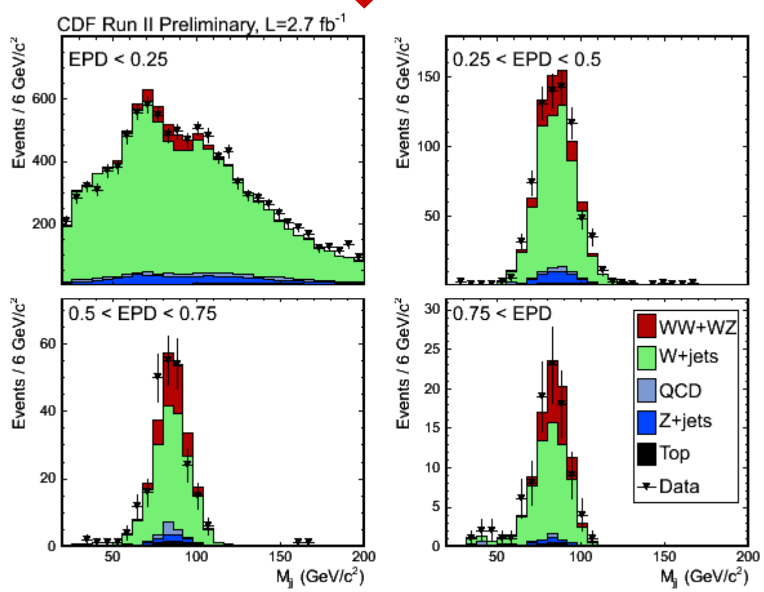
CDF lνjj analysis

Calculate an Event Probability Discriminant (EPD) using probability calculation for signals and backgrounds. Extract x-sec from fit to EPD, check di-jet invariant masses.



Select events:

- Cuts similar to D0 but tighter for electron events
- Geometric cuts adjusted for detector geometry



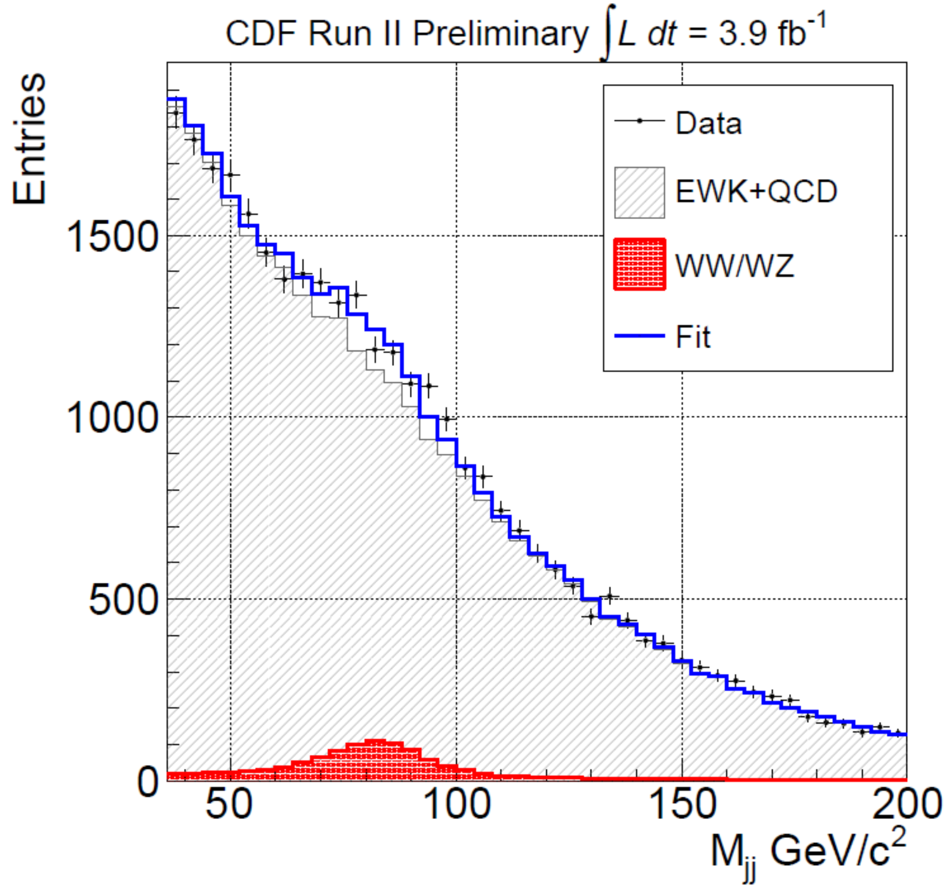
Measure WW+WZ cross section

17.7 ± 3.1 (stat) ± 2.4 (sys) pb

CDF lνjj analysis

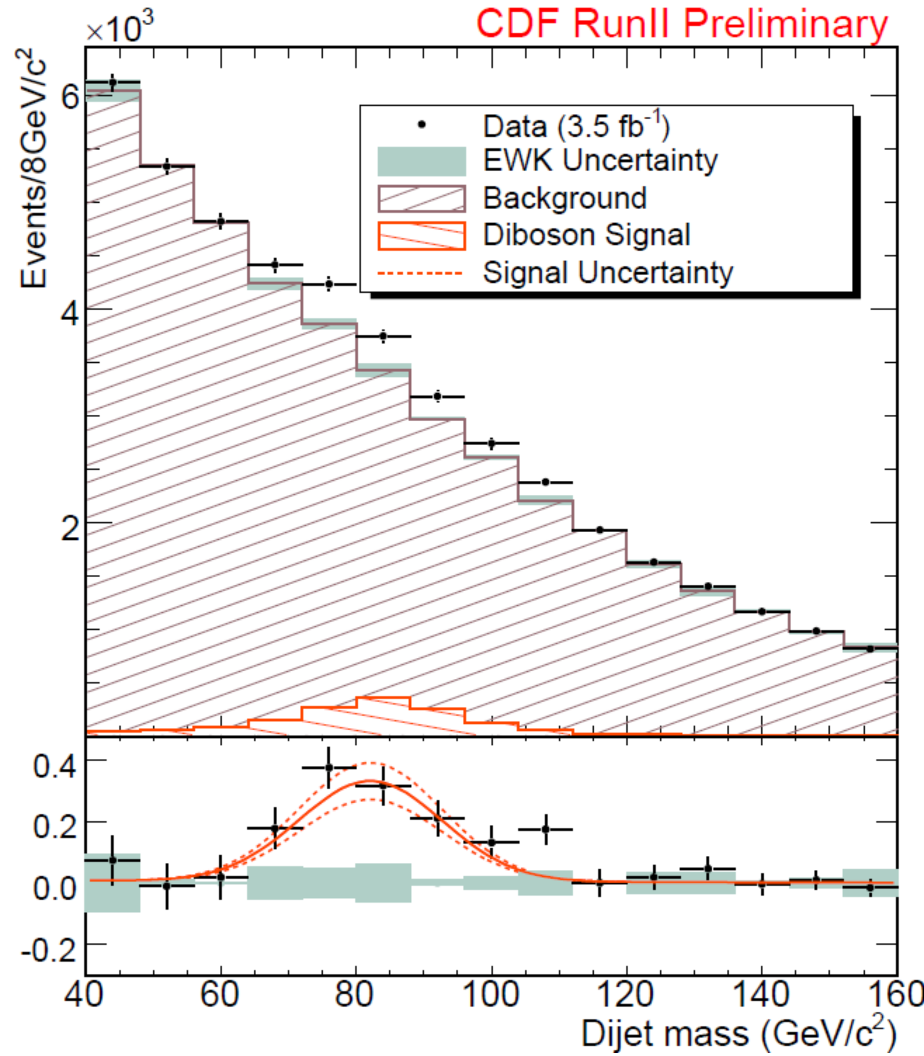
WW+WZ cross section can also be extracted from a direct fit to the di-jet invariant mass (albeit with a bigger error):

14.4 ± 3.1 (stat) ± 2.2 (sys) pb



CDF jj+missing E_T analysis

Calculate templates for multijet backgrounds from data. All other templates are calculated using MC. Fit di-jet mass to extract x-sec



Select events:

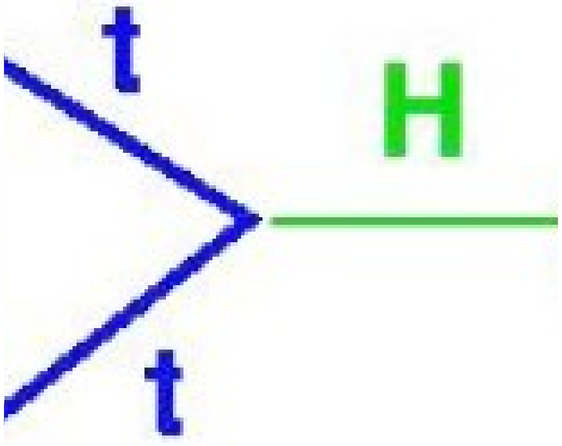
- $\not{E}_T > 60$ GeV, 2 jets with $E_T > 25$ GeV and $|\eta| < 2$
- $\not{E}_T$ significance > 4, angle between $\not{E}_T$ and jets > 0.4

Measure WW+WZ cross section

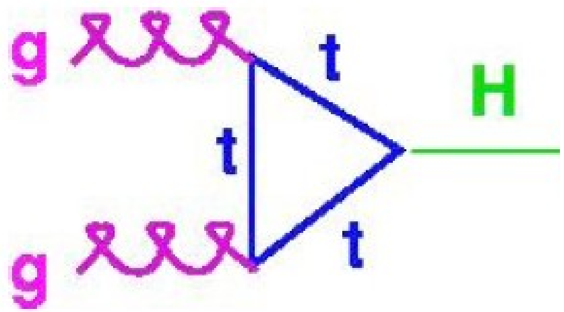
18.0 ± 2.8 (stat) ± 2.6 (sys) pb

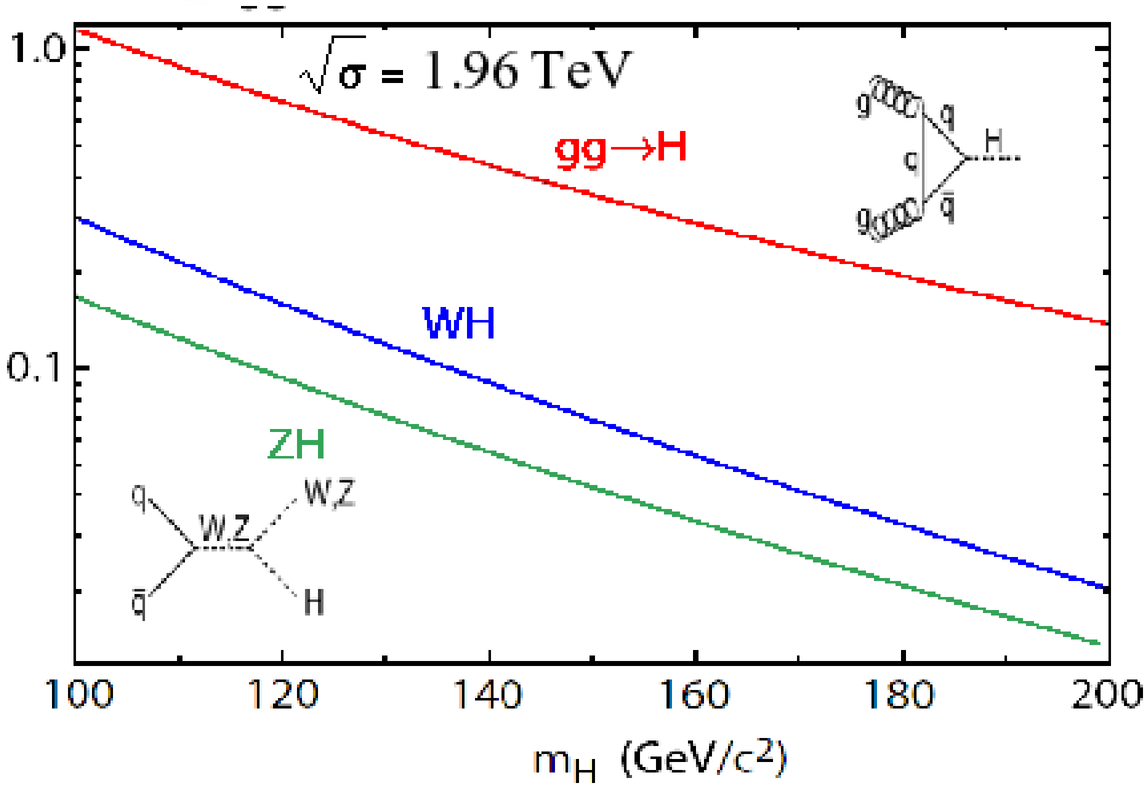
Higgs searches

Higgs production

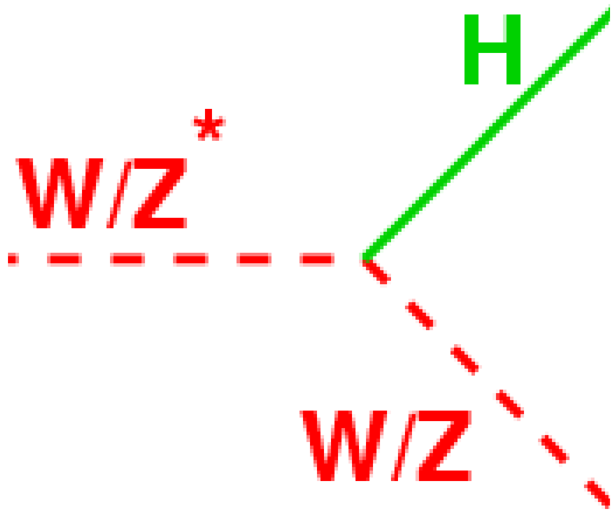


Higgs cross section



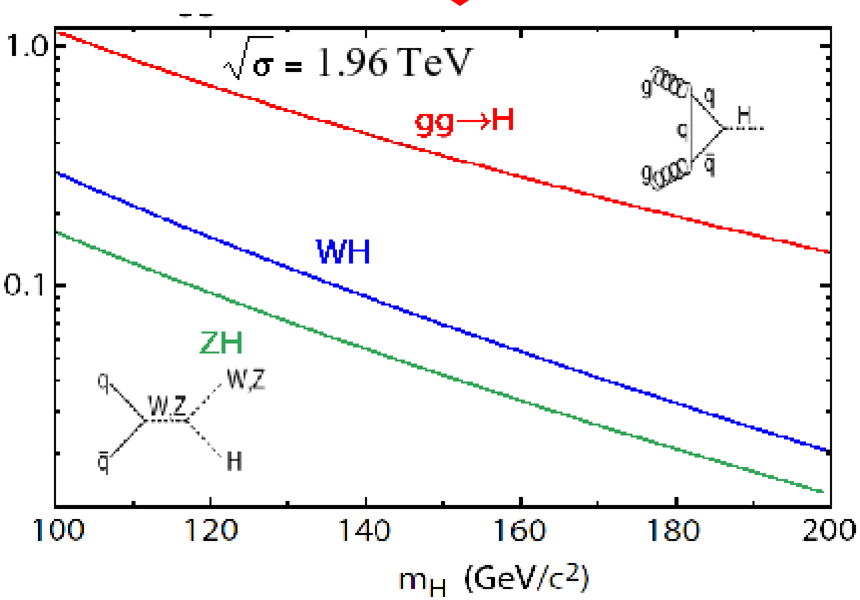


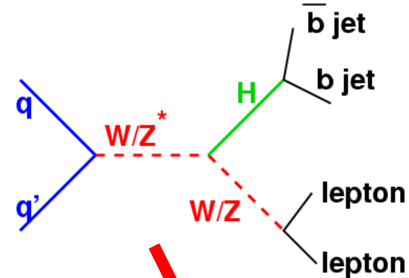
Higgs production

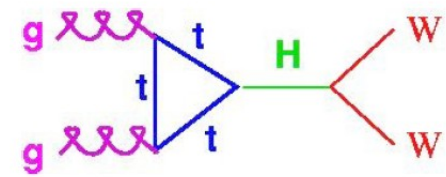


Cross section and branching ratios

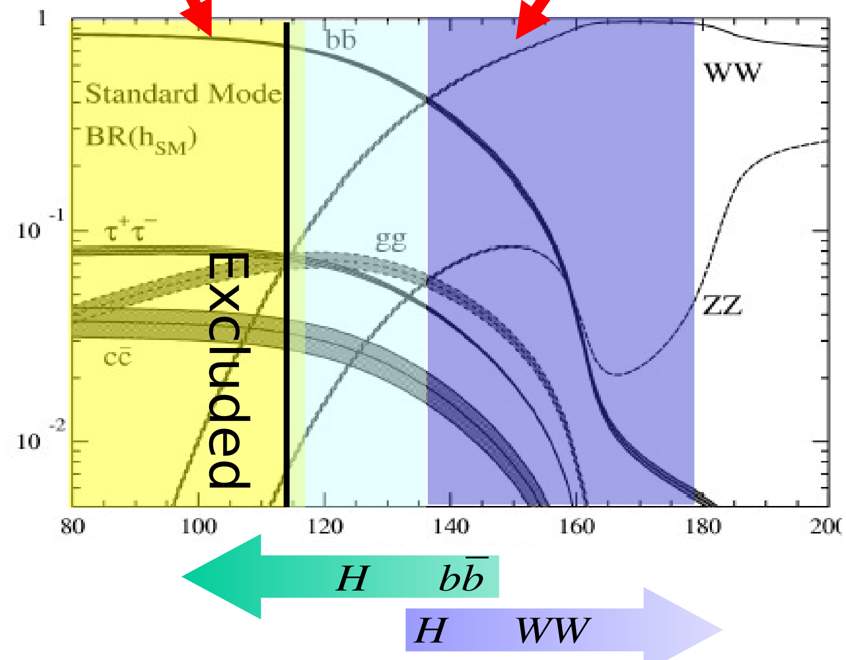
Production







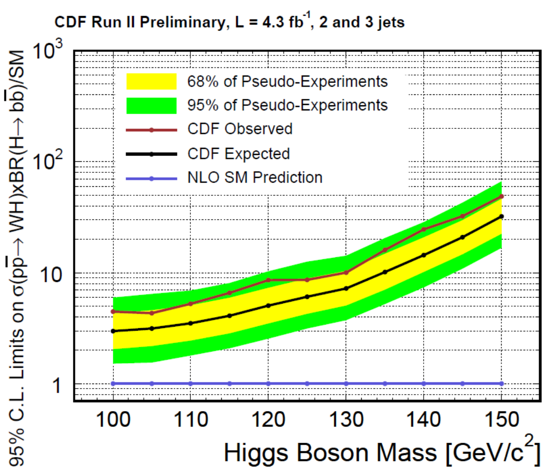
Decay



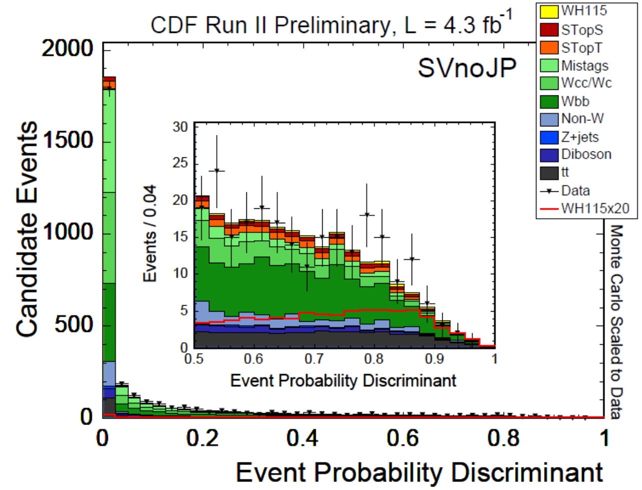
CDF light Higgs (ME)

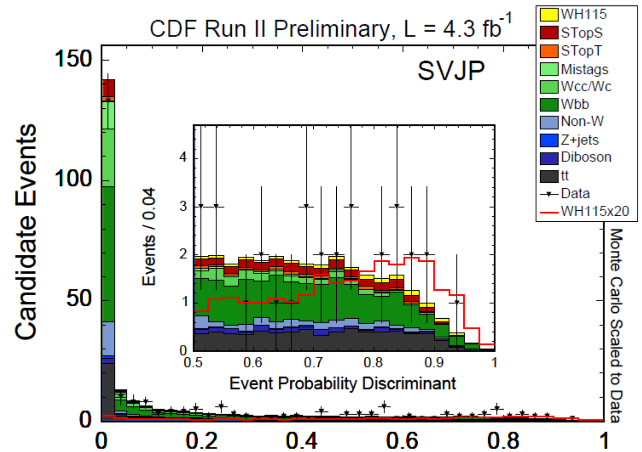
Calculate an Event Probability Discriminant (EPD) using probability calculation for signals and backgrounds. Extract limits from fit to EPD

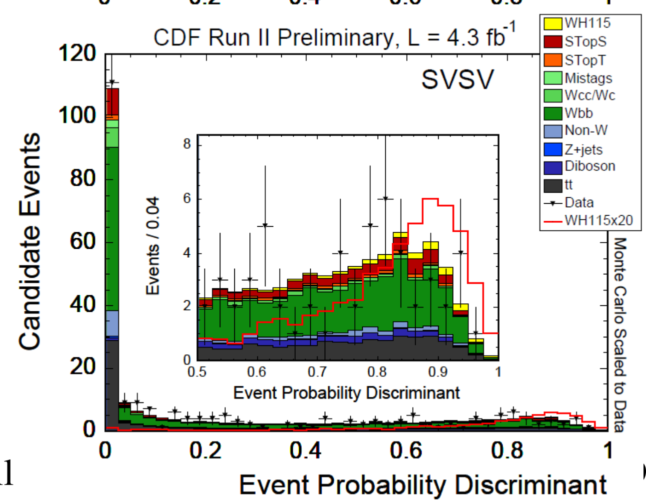
Select events:
- e, μ ,ν, jets P_T> ~20 GeV
- 2 or 3 jets with |η| < 2.0 and at least one b-tag
- b-tagging alg.: secondary vertex (SV), JetPob (JP)



Calculate limits

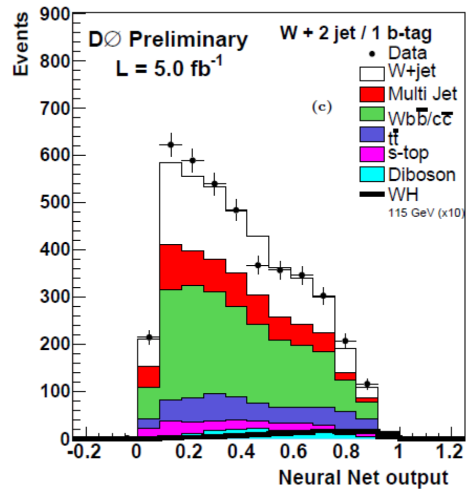


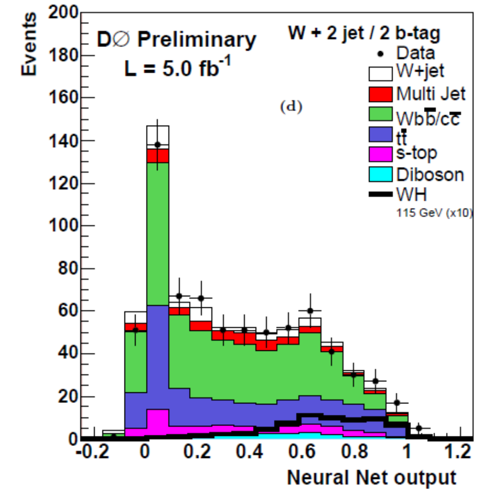




D0 light Higgs

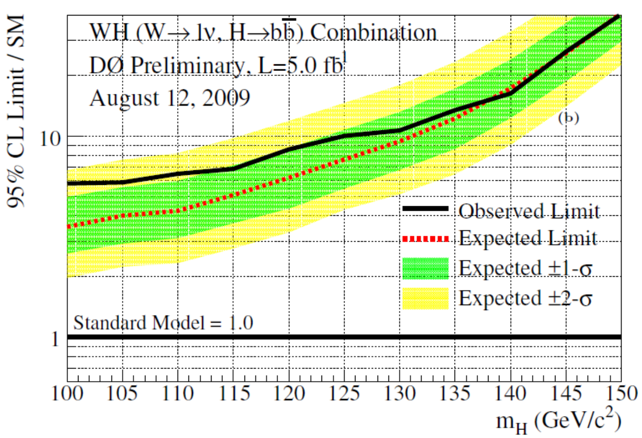
Build discriminant using a NN. Extract limits from NN output for W+2 jets and from di-jet mass in W+3 jets.

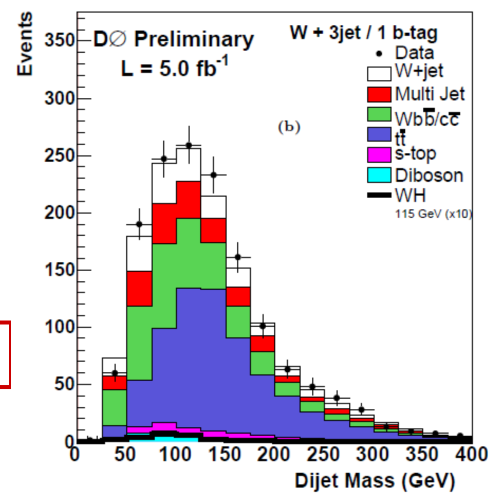


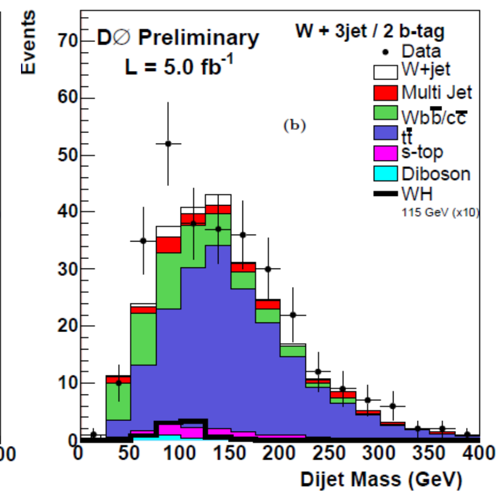


Select events:

- **e, μ P_T> 15 GeV; ν, 2 or 3 jets with P_T> 20 GeV**
- **e |η|<1.1 or 1.5< |η|<1.1; μ |η|<2.0; jets |η|<2.5**







Calculate limits

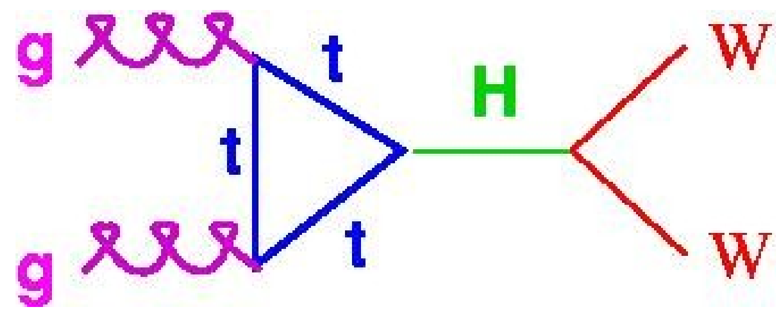
$gg \rightarrow H \rightarrow W^+W^- \rightarrow l^+\nu\ l^-\nu$

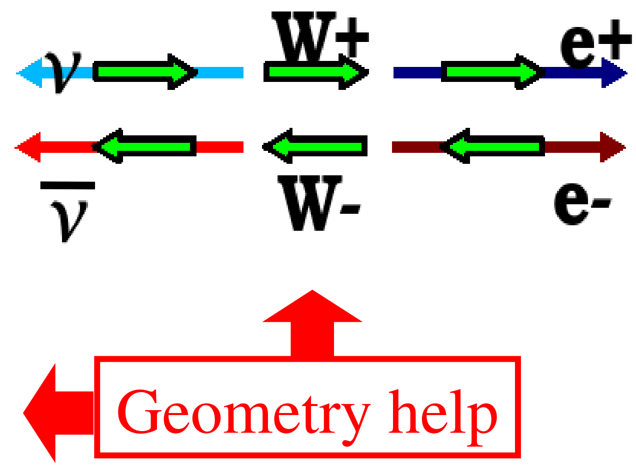
Basic selection:

- Two opposite sign isolated leptons
- missing transverse momentum

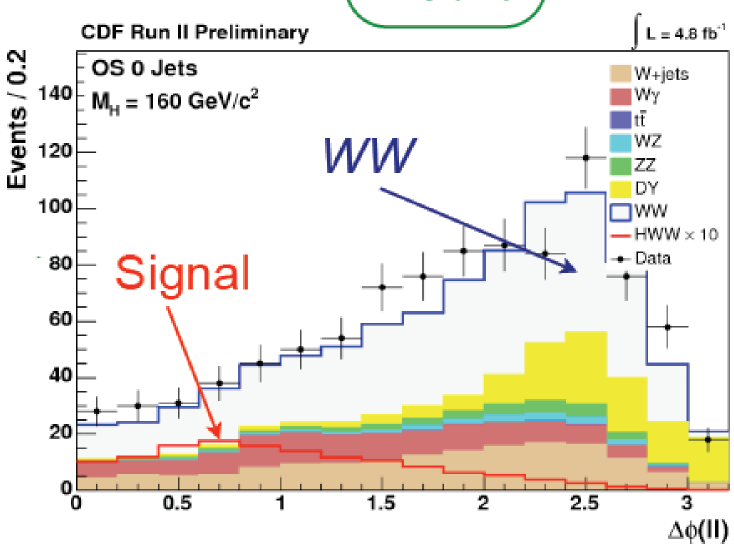
Main backgrounds:

- WW, WZ, ZZ
- W+jets and Drell-Yang

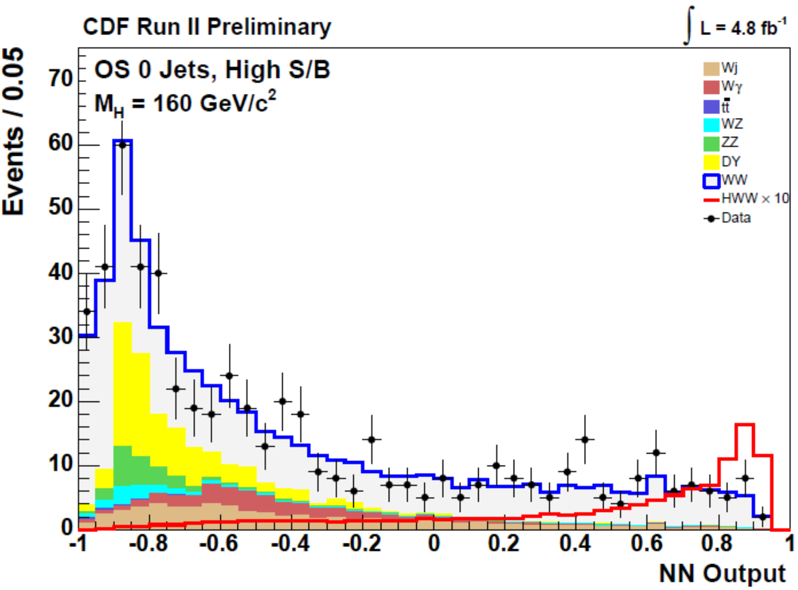


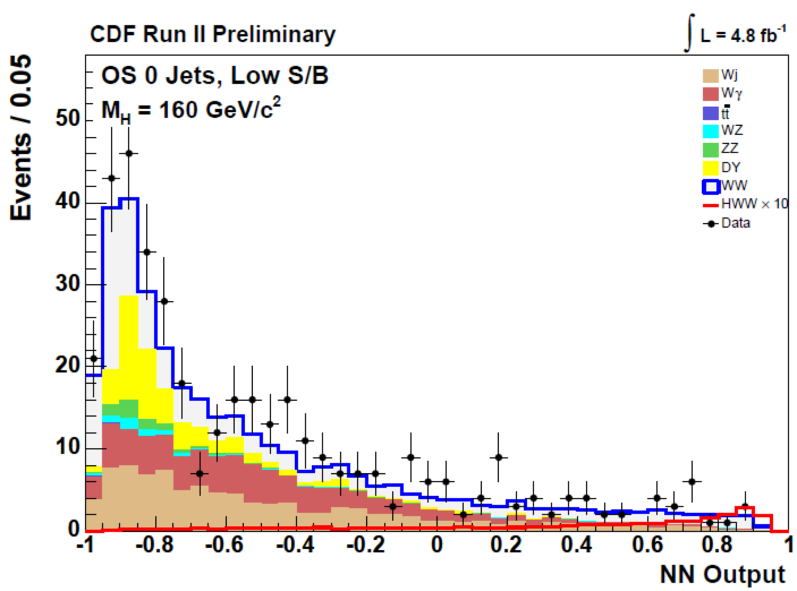


Δφ(l,l)



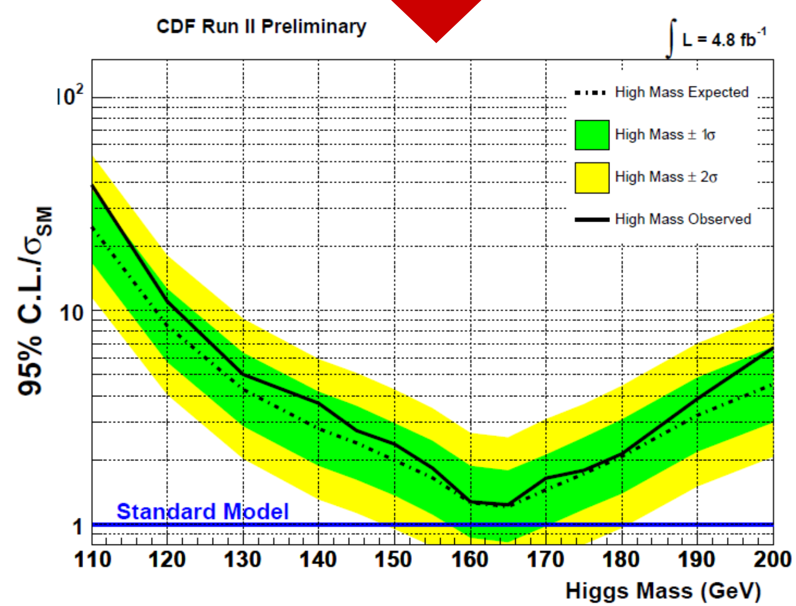
CDF: $H \rightarrow W^+W^- \rightarrow l^+\nu\ l^-\nu$





To increase sensitivity CDF splits the sample into opposite sign (OS) leptons with 0, 1 and 2 or more jets; OS with low M_{ll} and same sign leptons.

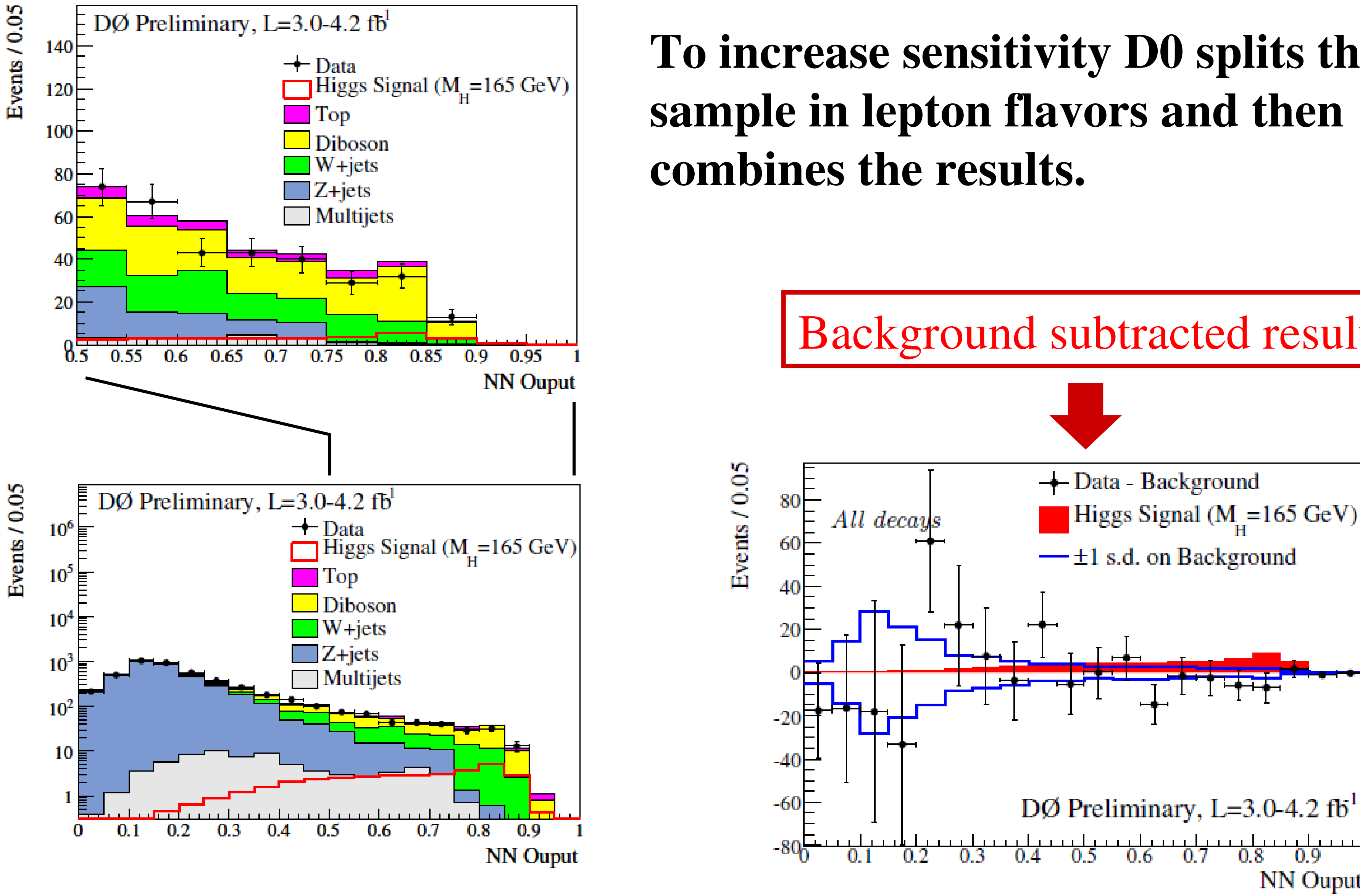
Combine all channels and set a 95% confidence limit



D0: H→W⁺W⁻→l⁺ν l⁻ν

To increase sensitivity D0 splits the sample in lepton flavors and then combines the results.

Background subtracted result



Channels that enter in the combination

CDF

TABLE I: Luminosity, explored mass range and references for the different processes and final state ($\ell = e, \mu$) for the CDF analyses

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ 2×(TDT,LDT,ST)	2.7	100-150	[7]
$ZH \to \nu\bar{\nu}b\bar{b}$ (TDT,LDT,ST)	2.1	105-150	[8]
$ZH \to \ell^+\ell^- b\bar{b}$ 2×(TDT,LDT,ST)	2.7	100-150	[9]
$H \to W^+W^-$ (low,high s/b)×(0,1 jets)+(2+ jets)	3.6	110-200	[10]
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	3.6	110-200	[10]
$H + X \to \tau^+\tau^- + 2$ jets	2.0	110-150	[11]
$WH + ZH \to jjb\bar{b}$	2.0	100-150	[12]

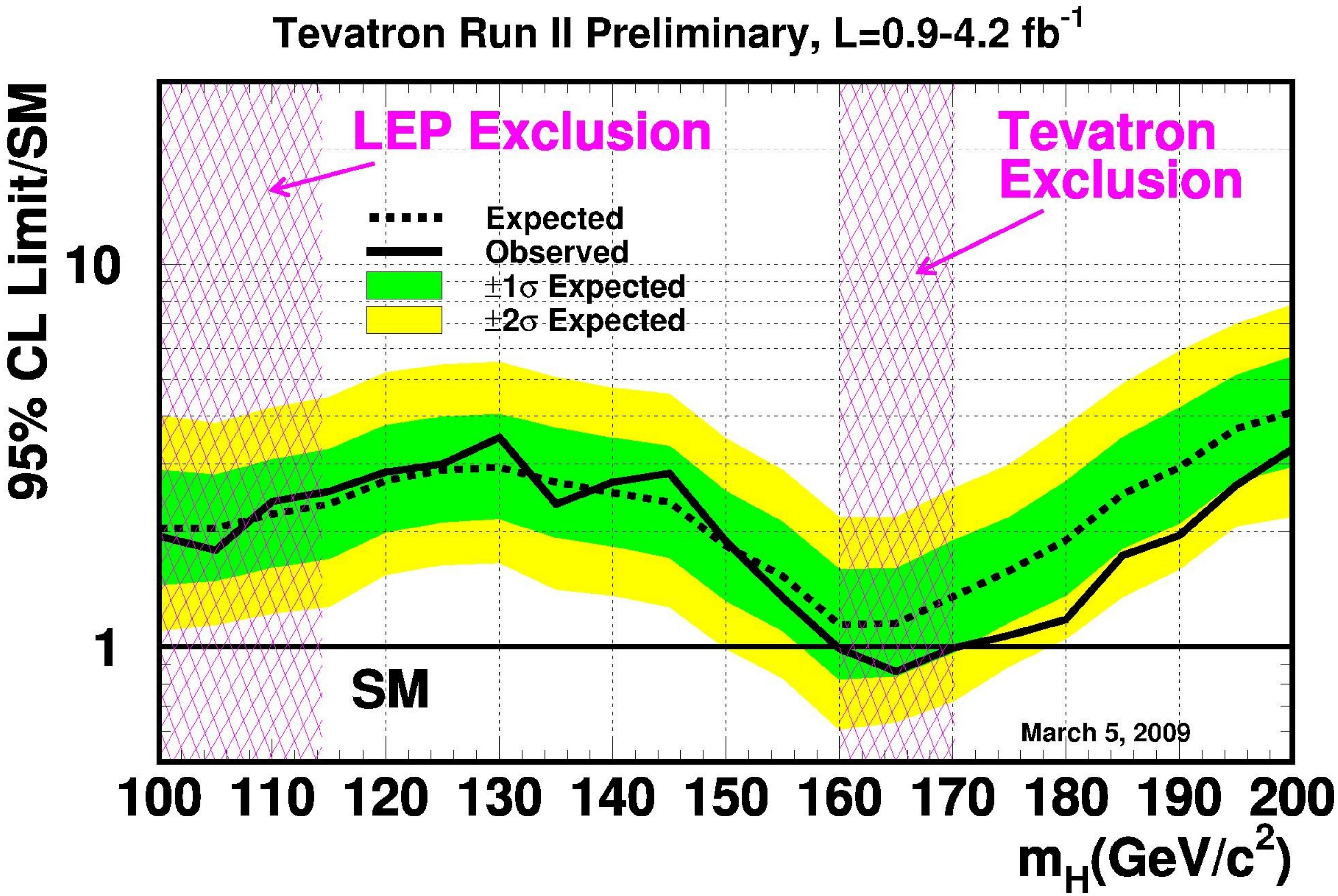
D0

TABLE II: Luminosity, explored mass range and references for the different processes and final state ($\ell = e, \mu$) for the DØ analyses

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ 2×(ST,DT)	2.7	100-150	[13]
$WH \to \tau\nu b\bar{b}$ 2×(ST,DT)	0.9	105-145	[14]
$VH \to \tau\tau b\bar{b}/q\bar{q}\tau\tau$	1.0	105-145	[14]
$ZH \to \nu\bar{\nu}b\bar{b}$ (DT)	2.1	105-145	[15]
$ZH \to \ell^+\ell^- b\bar{b}$ 2×(ST,DT)	2.3	105-145	[16]
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	1.1	120-200	[17]
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$	3.0–4.2	115-200	[18]
$H \to \gamma\gamma$	4.2	100-150	[19]
$t\bar{t}H \to t\bar{t}b\bar{b}$ 2×(ST,DT,TT)	2.1	105-145	[20]

Winter 2009 Higgs limits

D0 + CDF all channels combined



Conclusions

• The top mass is now known with an error of 1.3 GeV/c^2. It is likely to end up slightly below 1 GeV/c^2 before the end of the Tevatron run.

• The W mass now has an error of 23 MeV/c^2. An error of ~10 MeV/c^2 is expected for CDF+D0 by the end of the Tevatron run.

• In my personal opinion the next big step in the Higgs search will be to measure the Z mass in WZ+ZZ with b-tagging.

• A big region at high Higgs mass will be excluded at 95% confidence level. Time will tell about the chances of seeing a low mass Higgs at the Tevatron (> 50% chance?).