Measurements of the top quark and W boson mass and SM Higgs searches at the Tevatron

Gaston Gutierrez - Fermilab

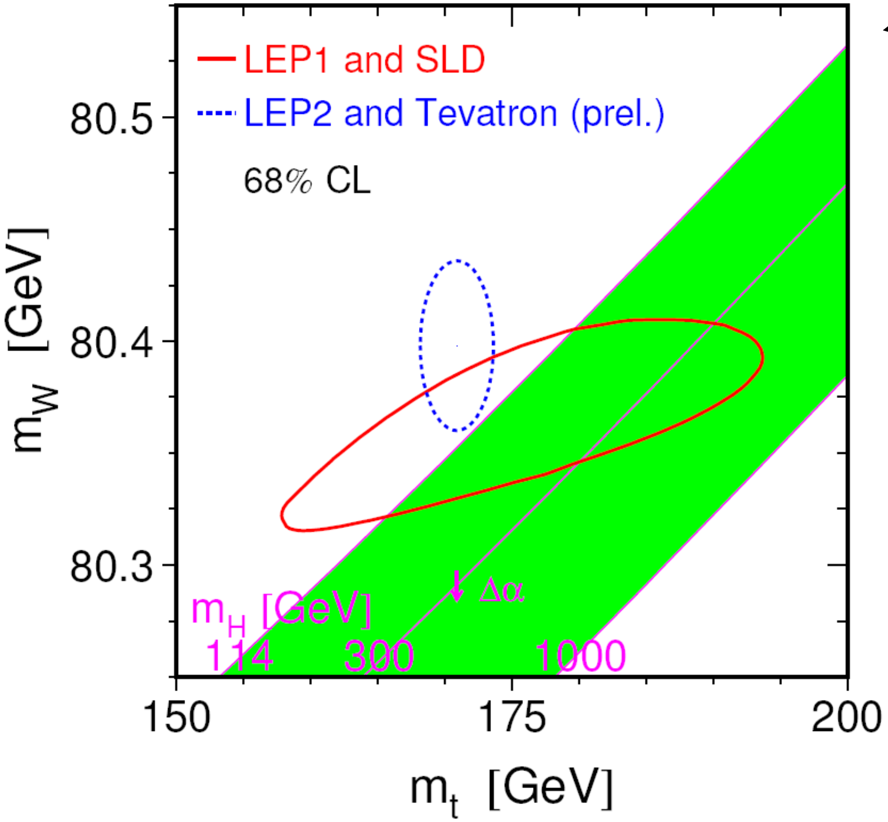
For the CDF and D0 Collaborations

- **The EW fit**

  (or why do we measure the top and W masses?)
- **Top quark mass at the Tevatron.**
- **W mass at the Tevatron.**
- **Higgs searches at the Tevatron.**

Many thanks to the CDF and D0 Top, Electroweak and Higgs group conveners

LEP EWWG as of March 2007

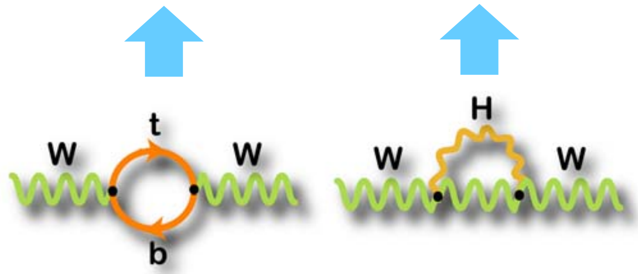


These (almost) lines are EW predictions given by:

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

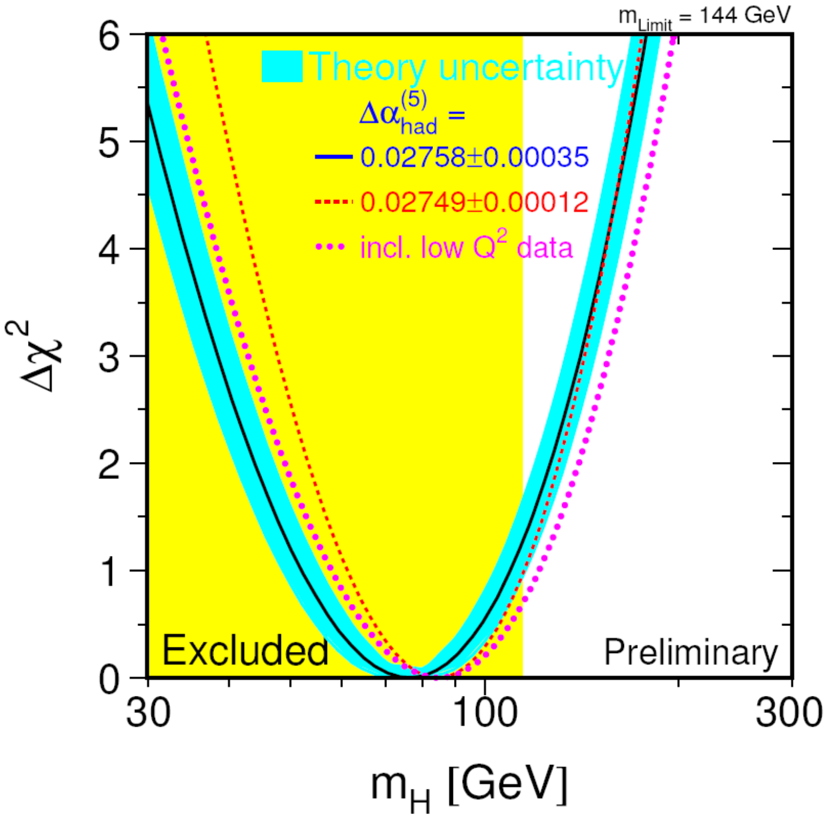
$$A = 37.2802\, GeV \quad \text{and}$$

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



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.

Higgs limits



The SM Higgs mass limit from the EW fit is: m_H<144 GeV/c^2 at 95% CL.

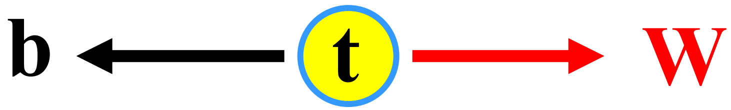
Footnote: There is a 3 σ discrepancy between the hadronic and leptonic F-B asymmetries. If any of this two are removed there are big changes in the Higgs mass limits (see M. Chanowitz, PRD 66:073002, 2002 and Fermilab W&C 2/23/2007)

Top quark mass

Top at the Tevatron

$$qq(gg) \rightarrow t\bar{t} \quad \Rightarrow$$

$$p\bar{p} \rightarrow t\bar{t} \rightarrow (\bar{b}W^{+})\,(bW^{-})$$
$$W \rightarrow (\text{lepton}\,\nu)\ \text{or}\ (q\bar{q}')$$



p = 66 GeV/c

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

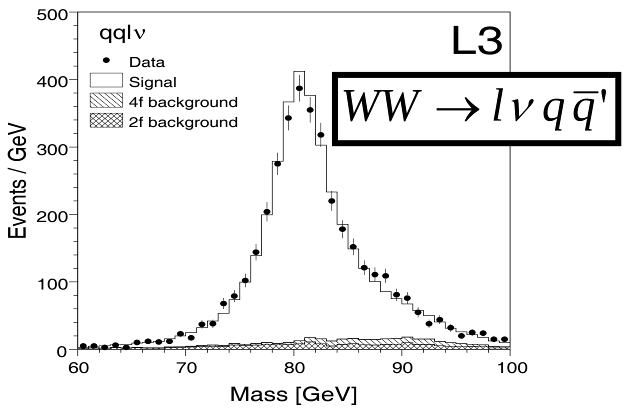
p = 40 GeV/c

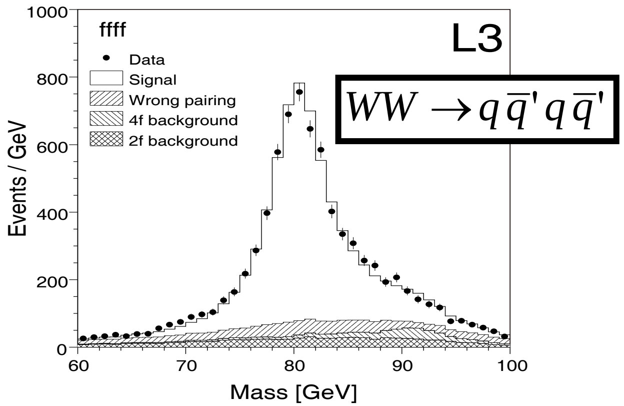
The decay to jets is 3 times more likely than to e and μ

Leptons are well understood. To first order (there is also radiation) we need to understand a 40 GeV light jet and a 66 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.

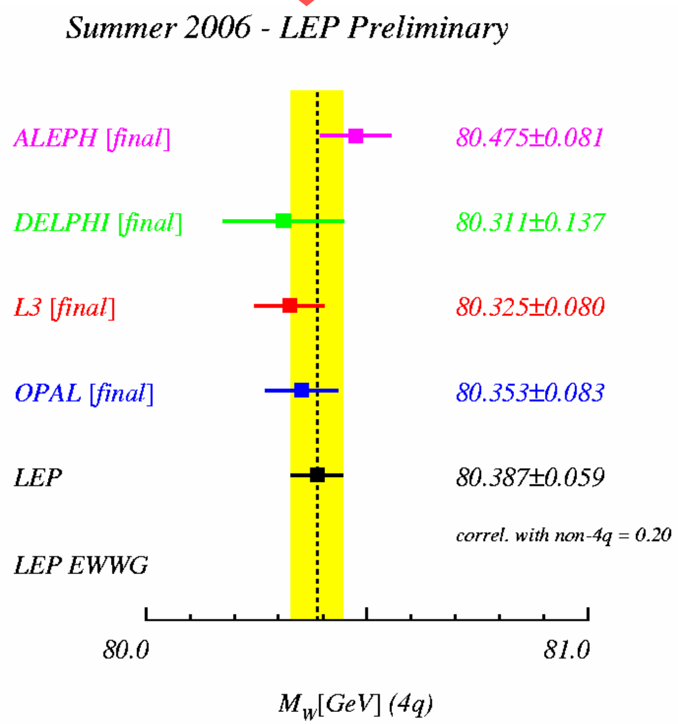
W mass at LEP

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

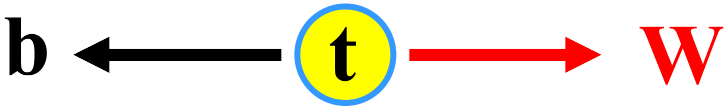




LEP all jets W mass



What about the 66 GeV b-jet?



p = 66 GeV/c

We don’t understand this 66 GeV b-jet as well as the light jets.

1. 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.

2. So the idea of a “pole mass” is an approximation (but good for now though).

3. 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)

4. This lack of experimental understanding of the b-jet and the radiation are the main systematics in the top quark mass measurement.

Calculating event by event probabilities

- **Most people would agree that if the probability of an event could be calculated accurately then the best estimate of a parameter will maximize a likelihood like:**

$$L(\alpha) = e^{-N\int \bar{p}(x;\alpha)dx} \prod_{i=1}^{N} \bar{P}(x_i;\alpha)$$

- **The detector and reconstruction effects are always multiplicative and independent of the parameter to be estimated:**

$$\bar{P}(x;\alpha) = Acc(x)\; P(x;\alpha)$$

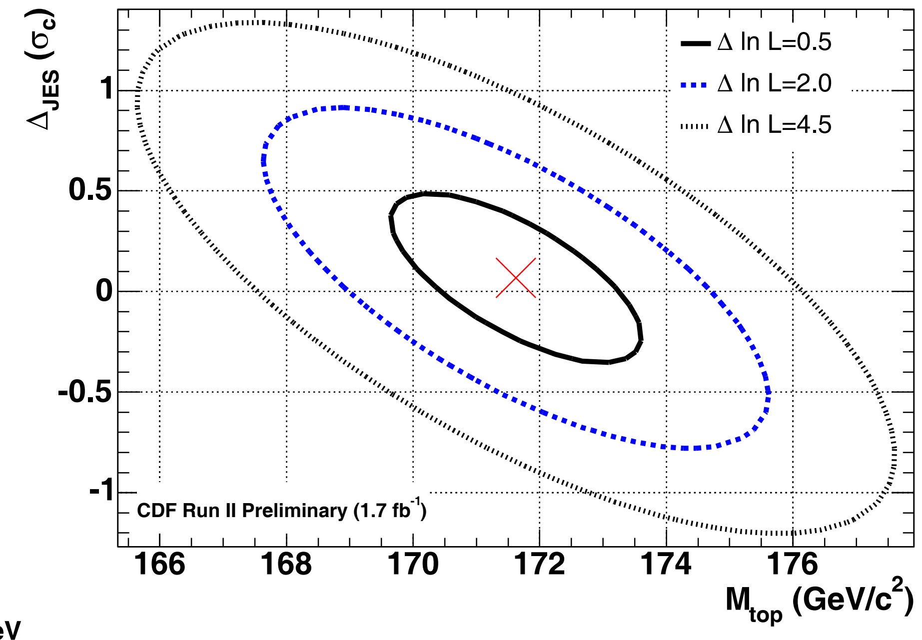
- **The probability P(x;α) can be calculated as:**

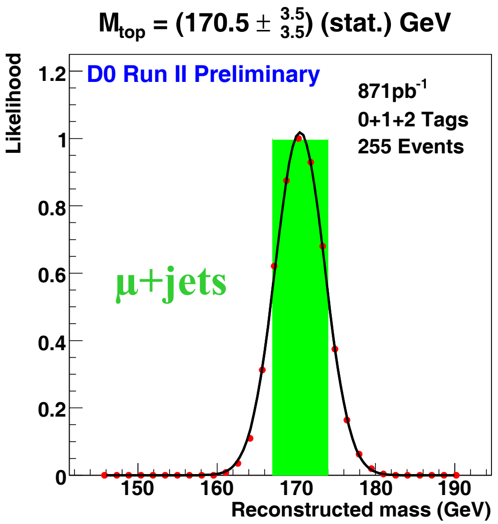
$$P(x;\alpha) = \frac{1}{\sigma_{t\bar{t}}} \int d\sigma(y;\alpha)\, dq_1\, dq_2\; f(q_1)\, f(q_2) W(x,y)$$

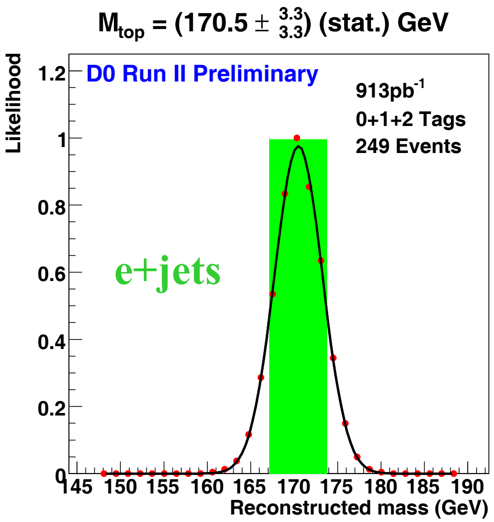
Where x is the set of variables measured in the detector, y is the set of parton level variables, dσ is the differential cross section and f(q) are the parton distribution functions. W(x,y) is the probability that a parton level set of variables y will show up in the detector as the set of variables x. The integration reflects the fact that we want to sum over all the possible parton variables y leading to the observed set of variables x.

Top mass in lepton + jets channel

CDF 1.7 fb^{-1} (templates)
171.6 ± 2.1 (stat+JES) ± 1.1 (syst) GeV/c^2





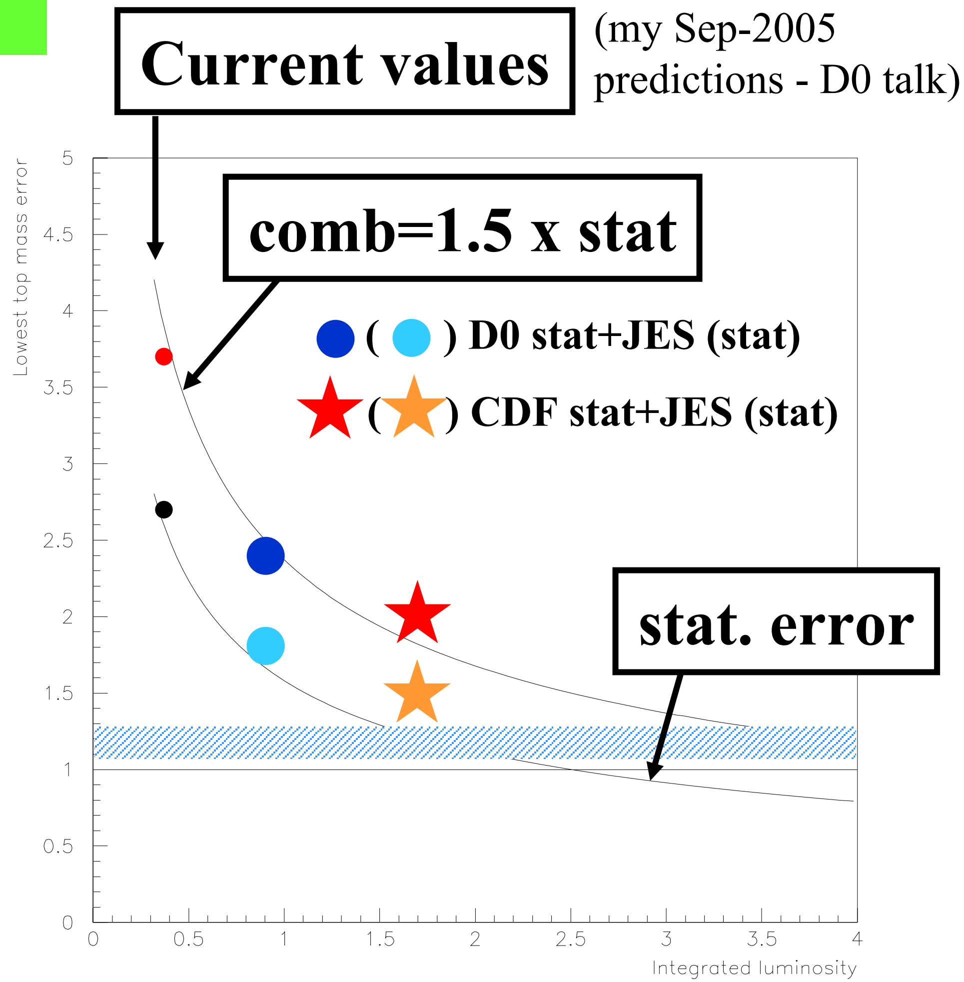


D0 0.9 fb^{-1} (ME)
170.5 ± 2.4 (stat+JES) ± 1.2 (syst) GeV/c^2

lepton + jets

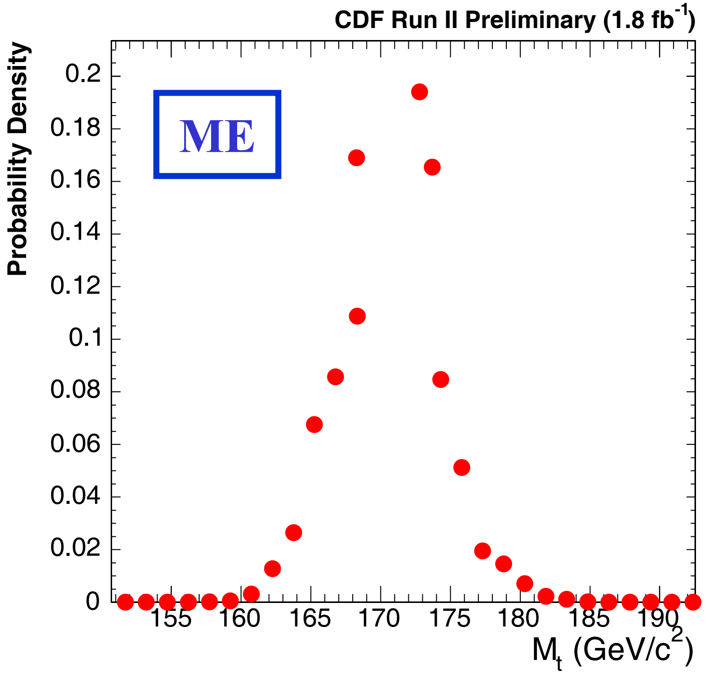
CDF systematic errors in l+jets

Effect	Systematic(GeV/c^2)
ISR	0.37
FSR	0.23
Generator	0.25
Residual JES	0.55
Background JES	0.38
PDFs	0.17
Background composition	0.24
Background shape	0.2
QCD modeling	0.11
B-JES	0.6
MC statistics	0.1
Total	1.1

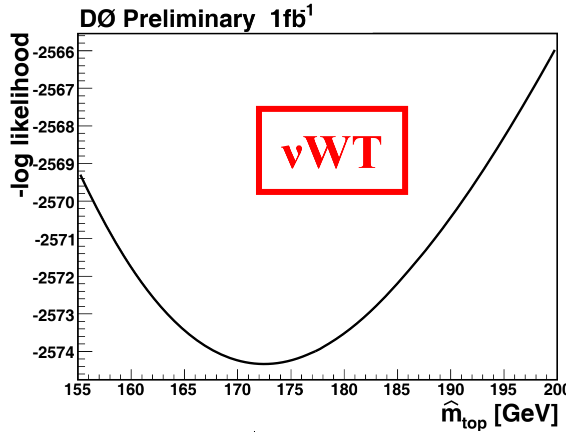


By the end of the Tevatron run (8 fb^{-1}) the D0+CDF stat+JES error will be ~0.6 GeV/c^2. The systematic error is hard to predict. We really need the other channels in case we missed something big.

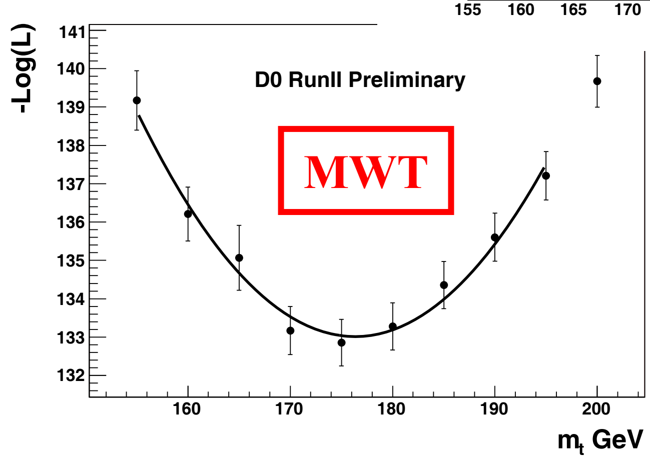
Top mass in the di-lepton channel



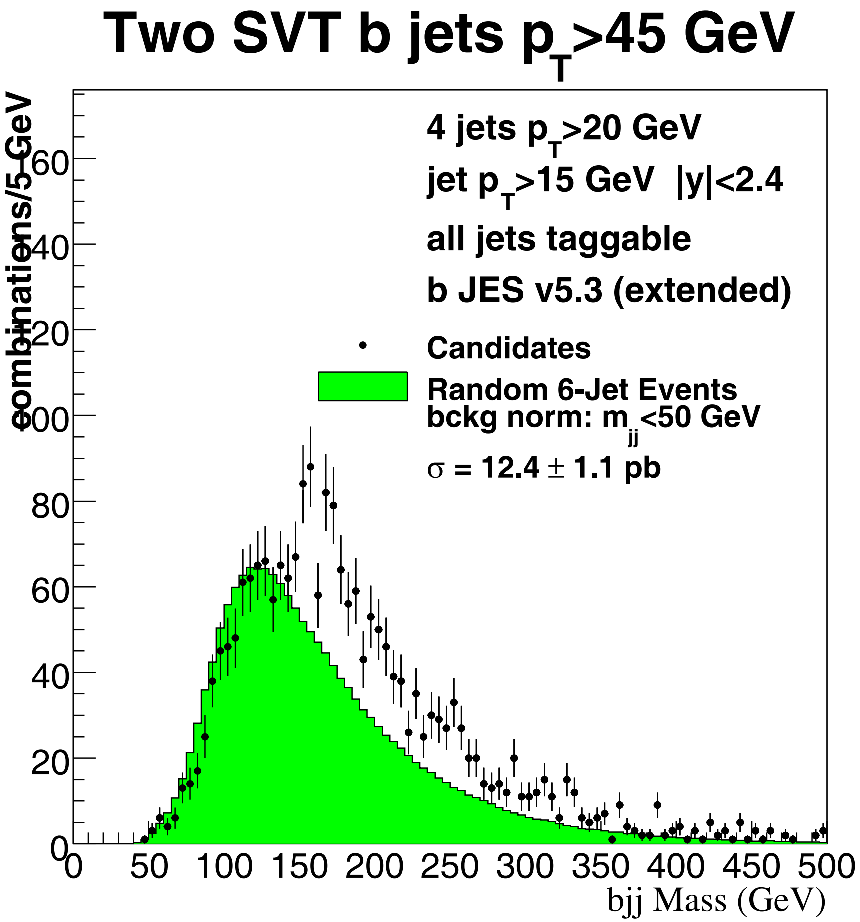
CDF 1.8 fb^{-1}
170.4 ± 3.1 (stat) ± 3.0 (syst) GeV/c^2
170.4 ± 4.3 GeV/c^2

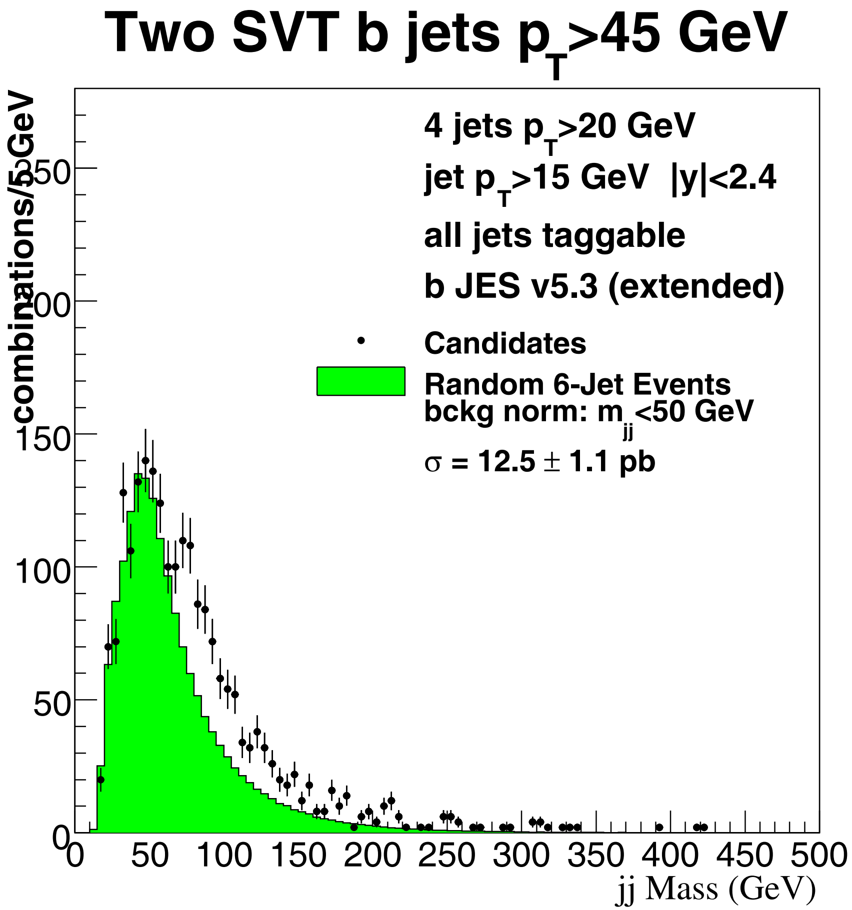


D0 1.0 fb^{-1} (combined)
173.7 ± 5.4 (stat) ± 3.4 (syst) GeV/c^2

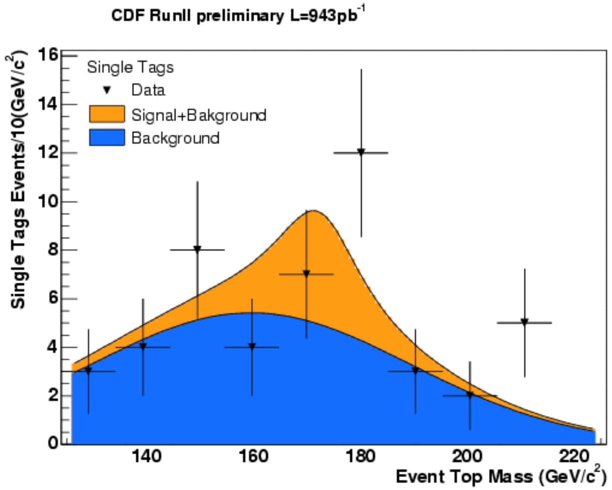


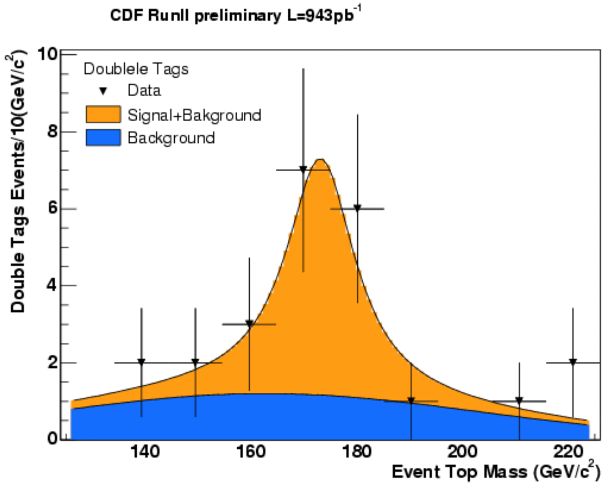
D0 top and W mass in all jets

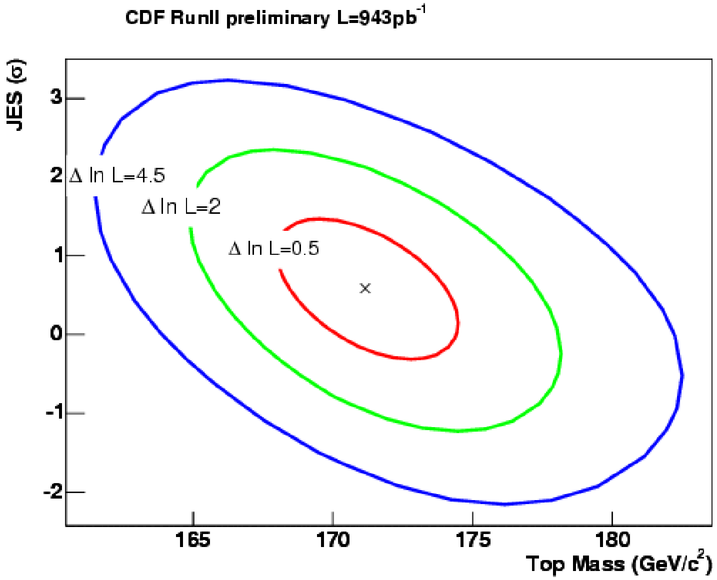




CDF top mass in all jets







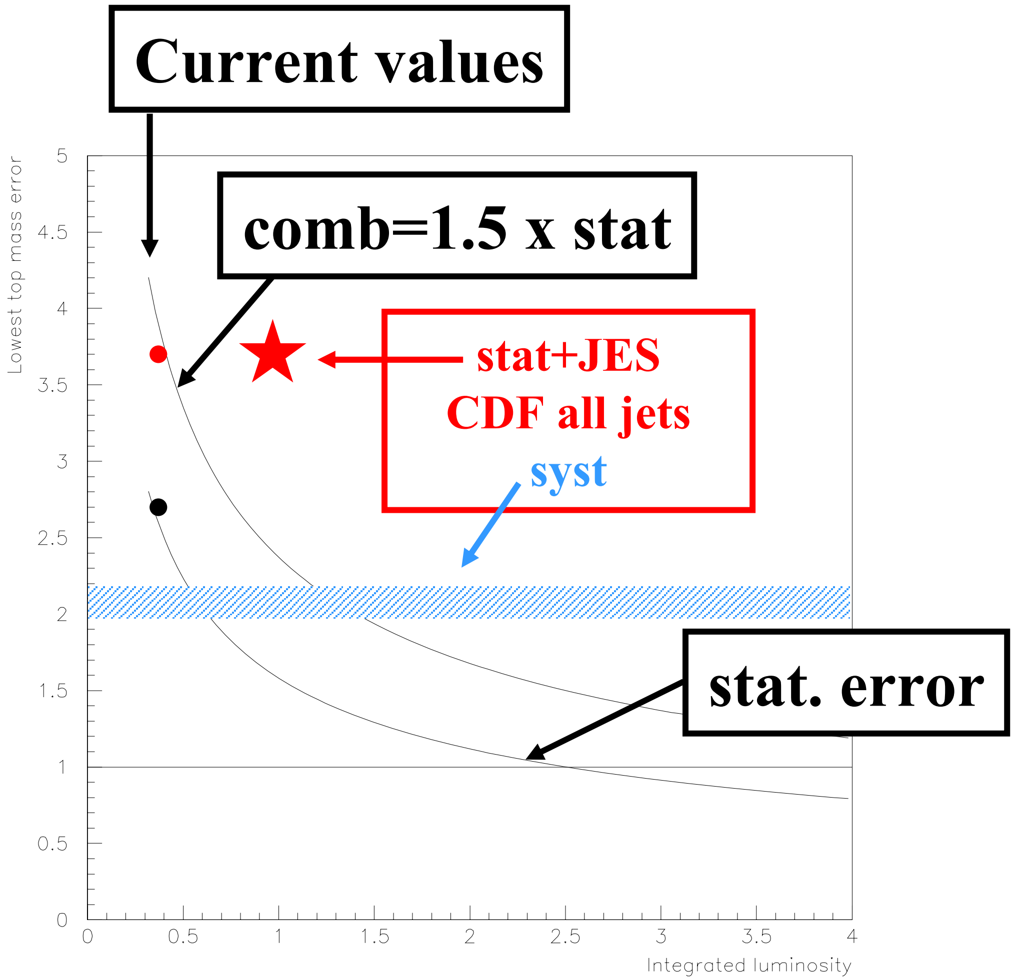
CDF 940 pb^{-1}

171.1 ± 3.7 (stat+JES) ± 2.1 (syst) GeV/c^2

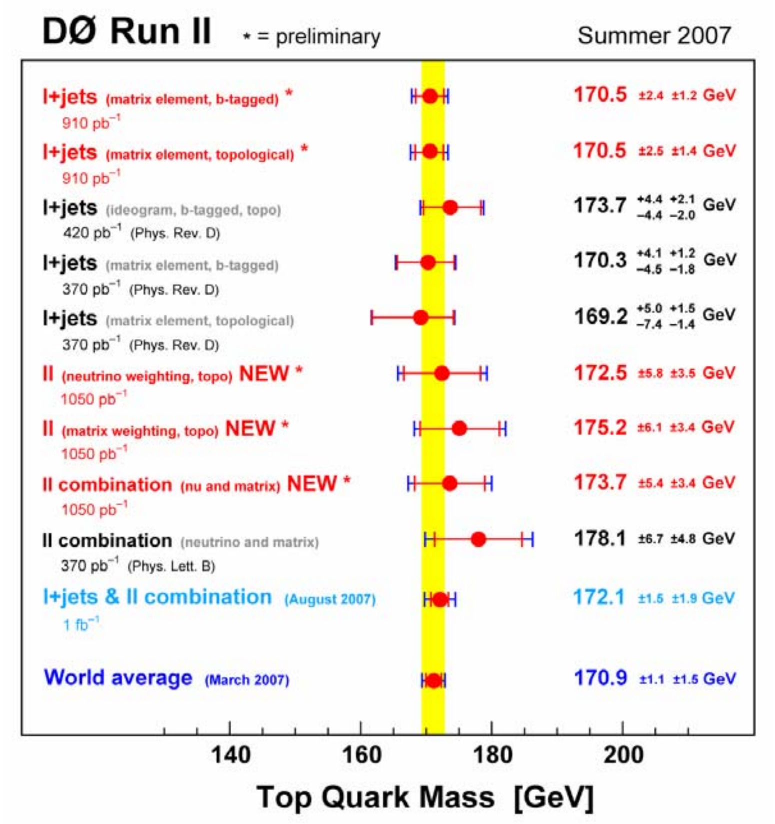
Top mass in all jets

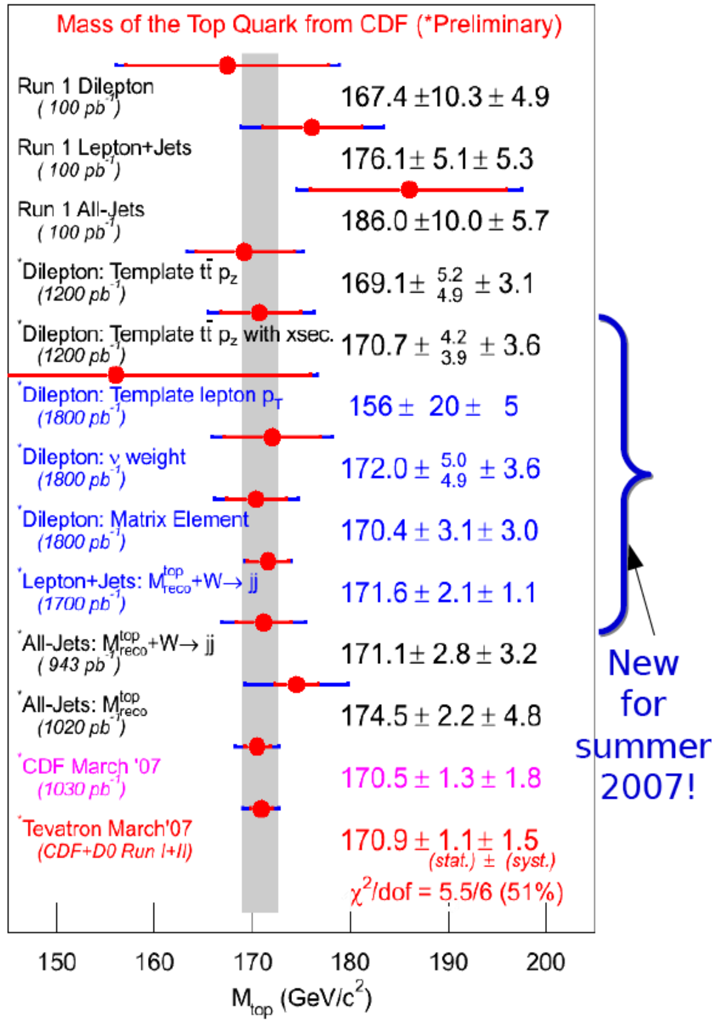
By the end of the Tevatron run (8 fb^{-1}) the D0+CDF stat+JES error in all jets will be ~ 1 GeV/c^2. The systematic error is hard to predict.

So it is very possible that by the end of the Tevatron run there will top mass measurements in 3 different channels approaching errors of 1 to 2 GeVs.



Summary of D0 and CDF results



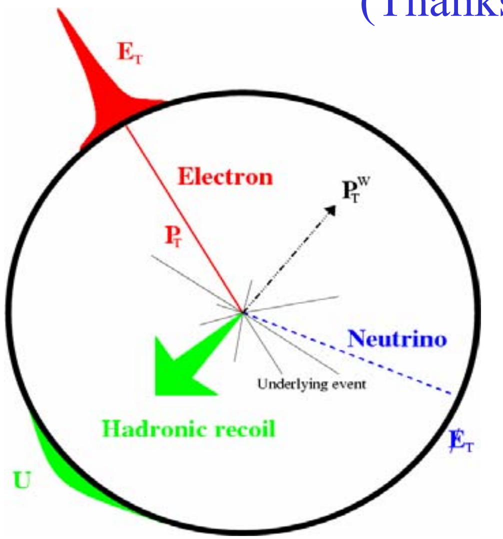


World average as of March 2007:
170.9 ± 1.1 (stat) ± 1.5 (syst) GeV/c²

W boson mass

W mass measurement at CDF

(Thanks to Pierre Petroff for providing many of the illustrations shown here)

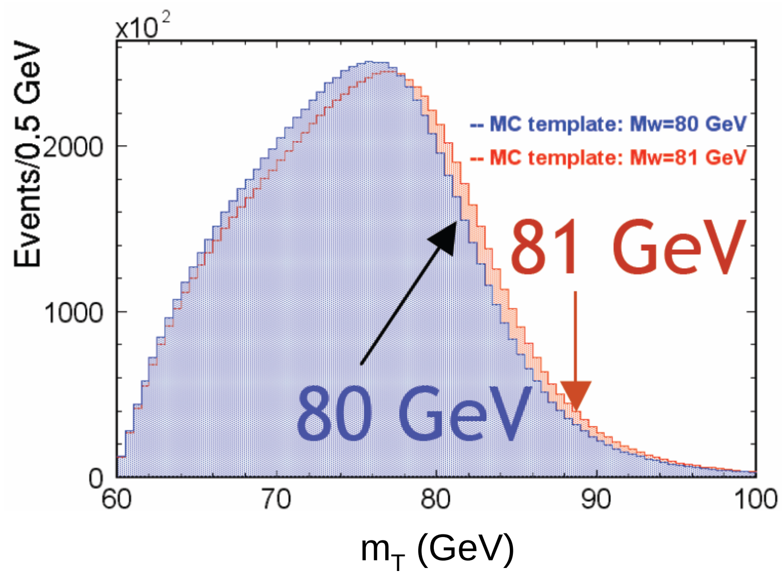


At the Tevatron the W mass is measured in the decays W→**eν** and W→**μν**. So three distributions can be used to measure the mass: 1) charge lepton p_T, 2) neutrino p_T, or 3) transverse mass. The expected shapes of the distributions (templates) are obtained from Monte Carlo.

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:

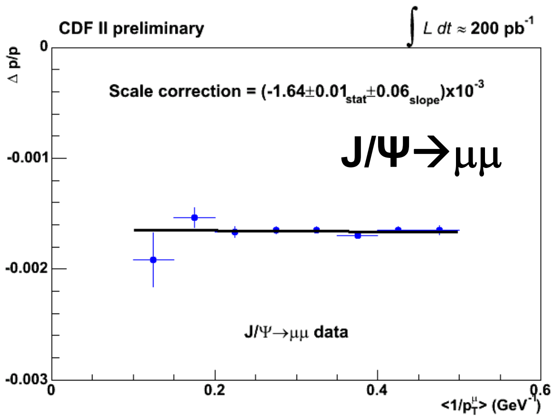
$$\frac{\sigma}{\sqrt{N}} \approx \frac{10\,\text{GeV}}{\sqrt{115{,}000}} = 30\,\text{MeV}$$

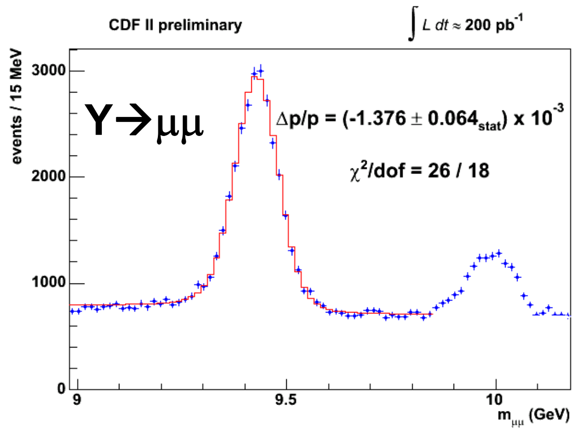
Which shows that the main problem is the systematic errors.

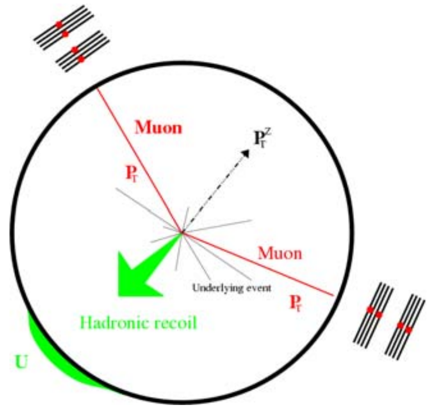


1^{st} : calibrate tracker

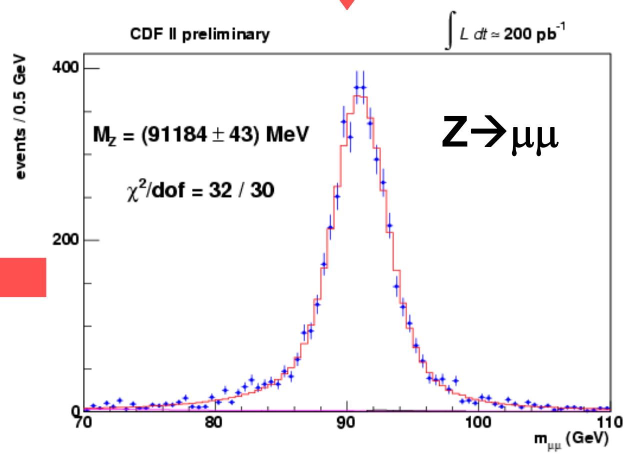
First align tracker, and get momentum scale from J/Psi and Upsilon



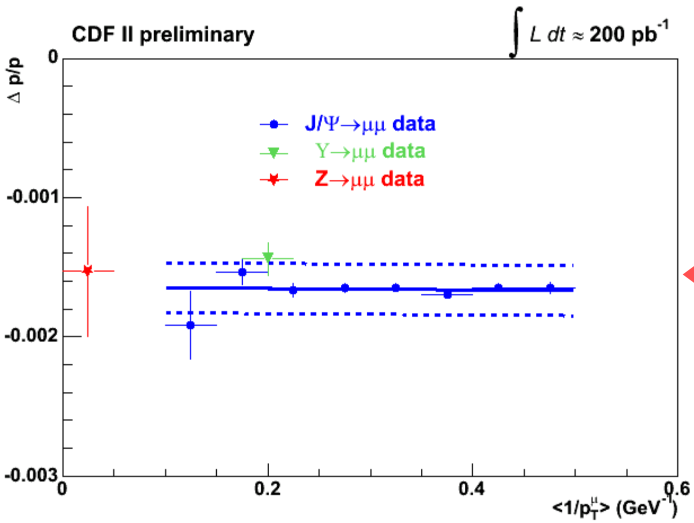




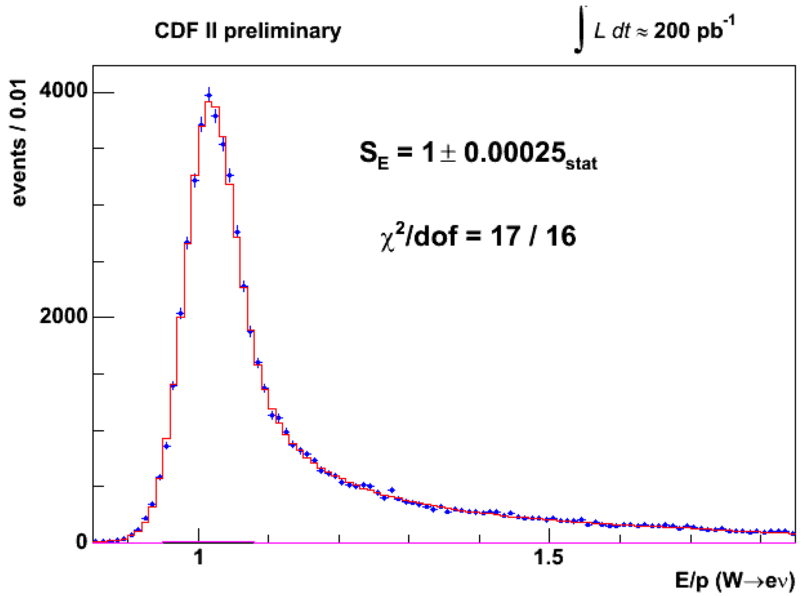
Check Z



Combine all measurements into single calibration

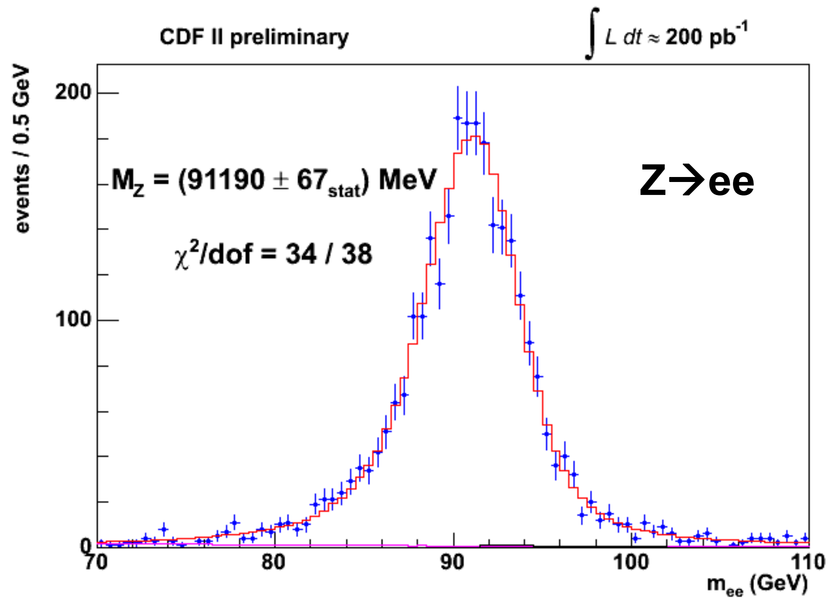


2^{nd} : with tracker calibrate EM calorimeter



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

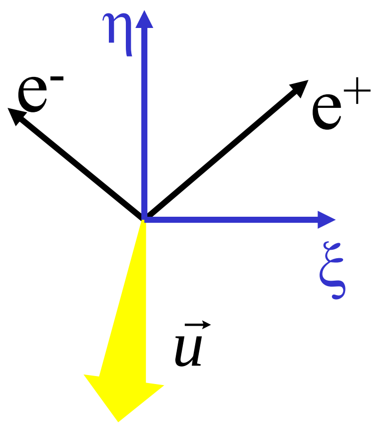


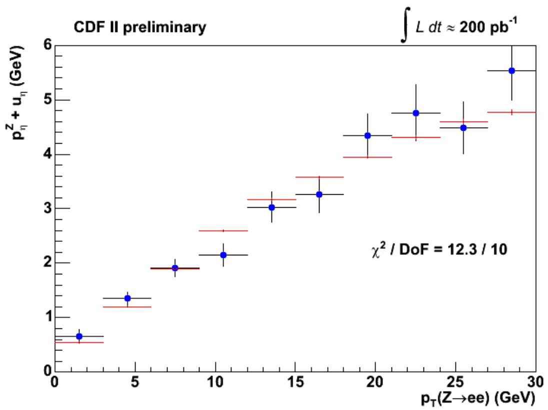
Combine results to obtain best energy calibration and resolution

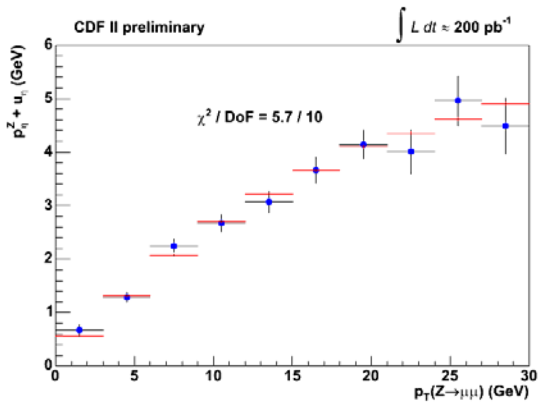
3^{rd} : calibrate hadronic recoil

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

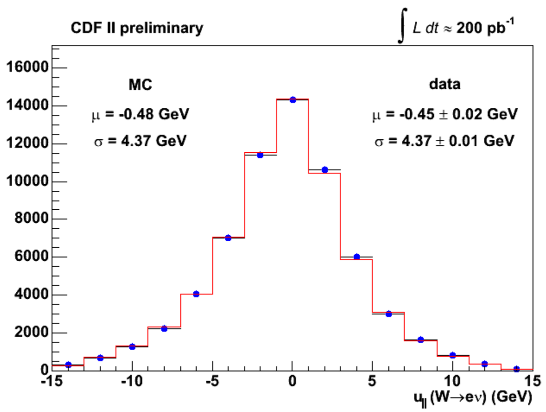
Calibrate with Z→ee or Z→μμ

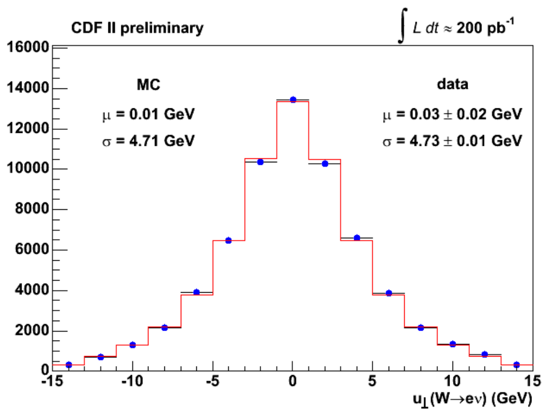


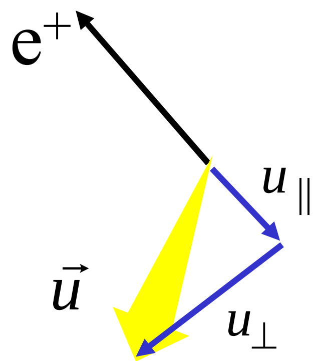




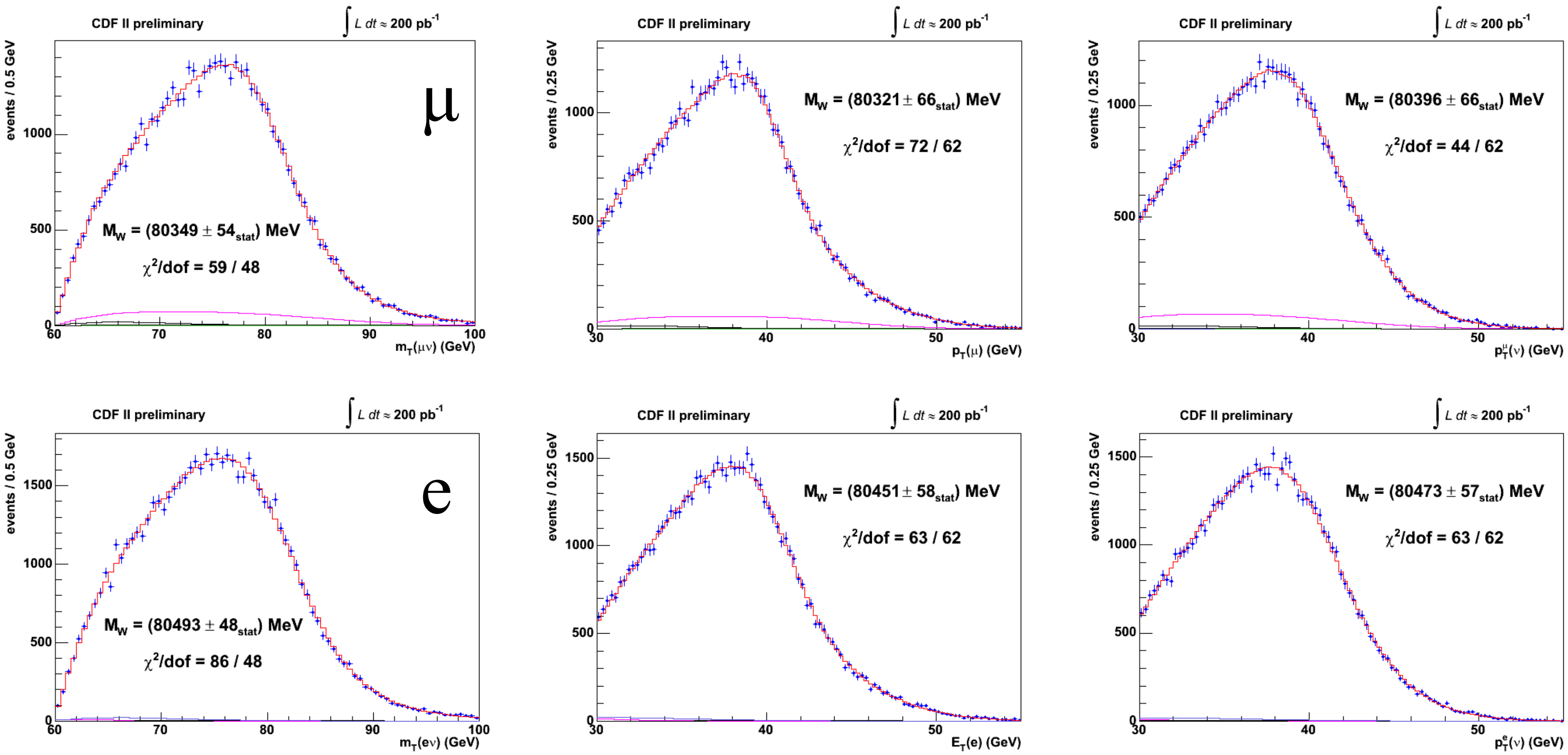
Validate with W→eν or W→μν







4^{th} : measure W mass



$$m_W = 80413 \pm 34\ (\text{stat}) \pm 34\ (\text{syst})\ \ \text{MeV}/c^2$$
$$= 80413 \pm 48\ \text{MeV}/c^2$$

Systematics errors and world average

CDF II preliminary — $L = 200\ pb^{-1}$

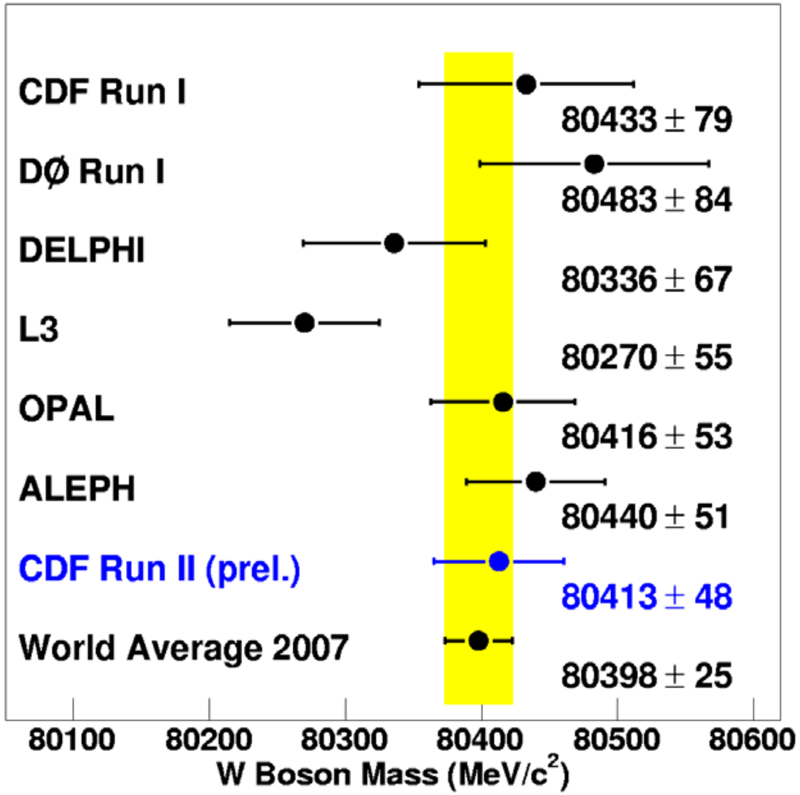
MET Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	5	0
Recoil Scale	15	15	15
Recoil Resolution	30	30	30
$u_{\|\|}$ Efficiency	16	13	0
Lepton Removal	16	10	10
Backgrounds	7	11	0
$p_T(W)$	5	5	5
PDF	13	13	13
QED	9	10	9
Total Systematic	54	46	42
Statistical	57	66	0
Total	79	80	42

CDF II preliminary — $L = 200\ pb^{-1}$

p_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	17	17	17
Recoil Resolution	3	3	3
$u_{\|\|}$ Efficiency	5	6	0
Lepton Removal	0	0	0
Backgrounds	9	19	0
$p_T(W)$	9	9	9
PDF	20	20	20
QED	13	13	13
Total Systematic	45	40	35
Statistical	58	66	0
Total	73	77	35

CDF II preliminary — $L = 200\ pb^{-1}$

m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\|\|}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26



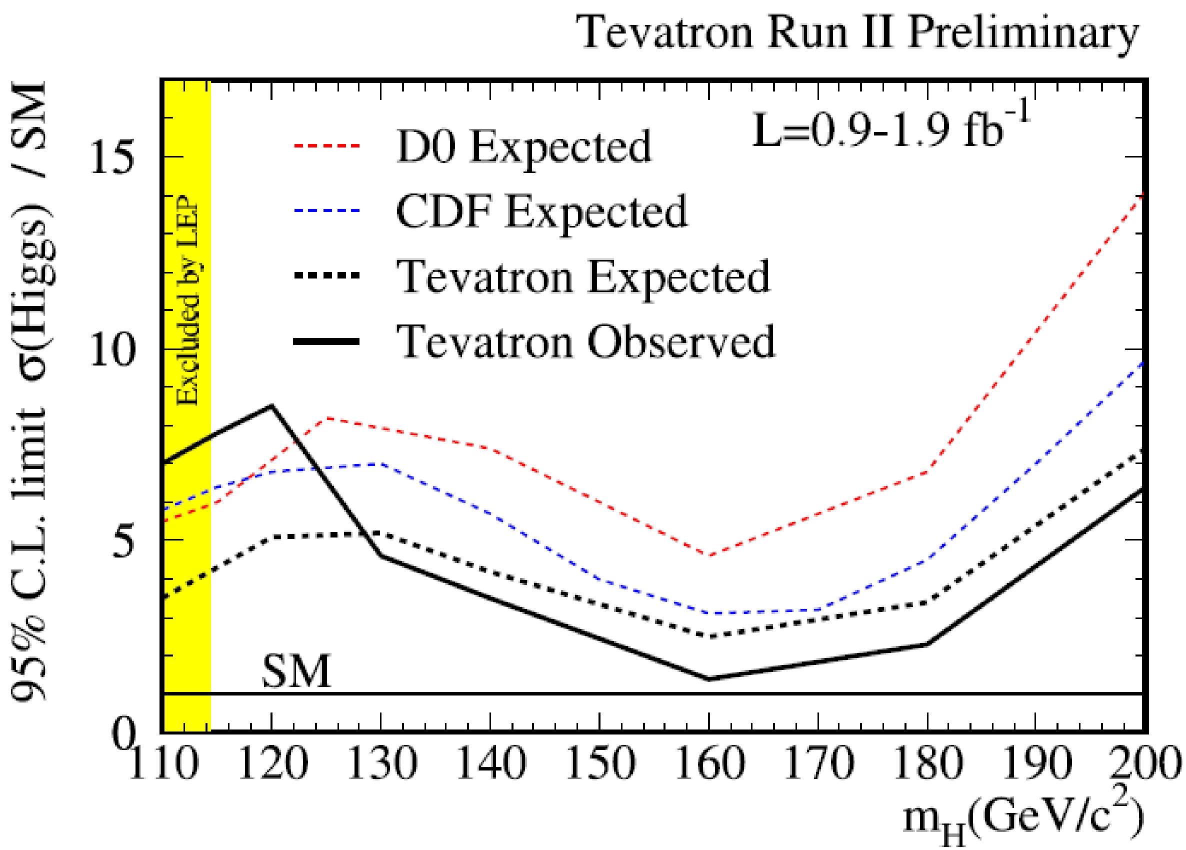
- World's most precise single measurement
- World average increases from 80392 to 80398 MeV
- Uncertainty reduced by 15%: 29 MeV to 25 MeV
- Expected CDF error with $2fb^{-1}$ is ~20 MeV

Higgs searches

Summer 2007 Higgs limits

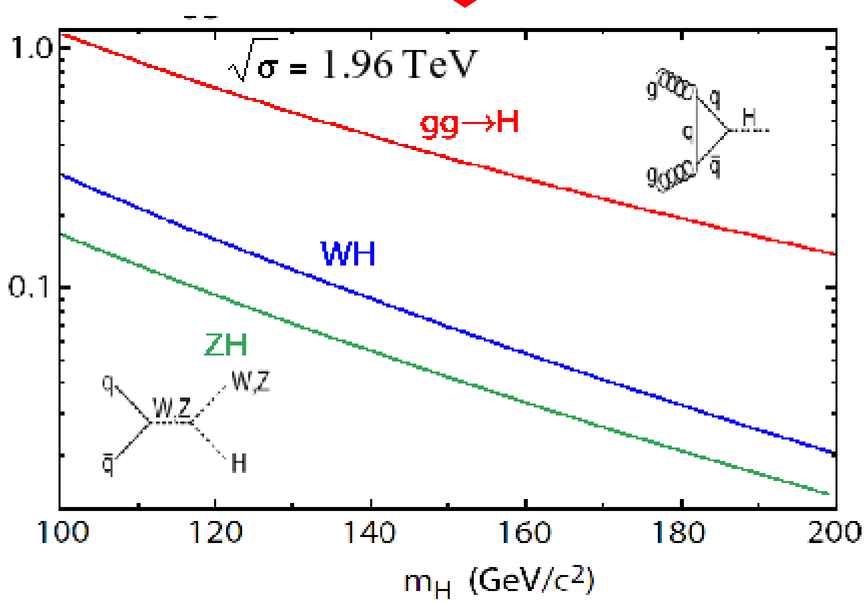
(Thank you to Stefan Soldner-Rembold for providing many of the plots presented here)

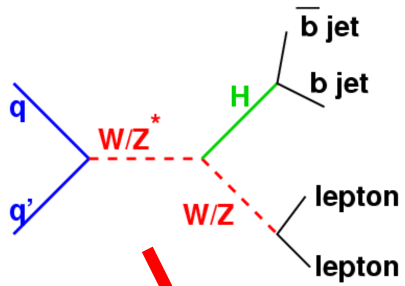
D0 and CDF combination (released last week)

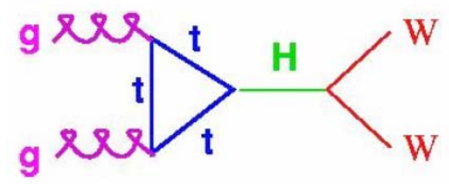


Cross section and branching ratios

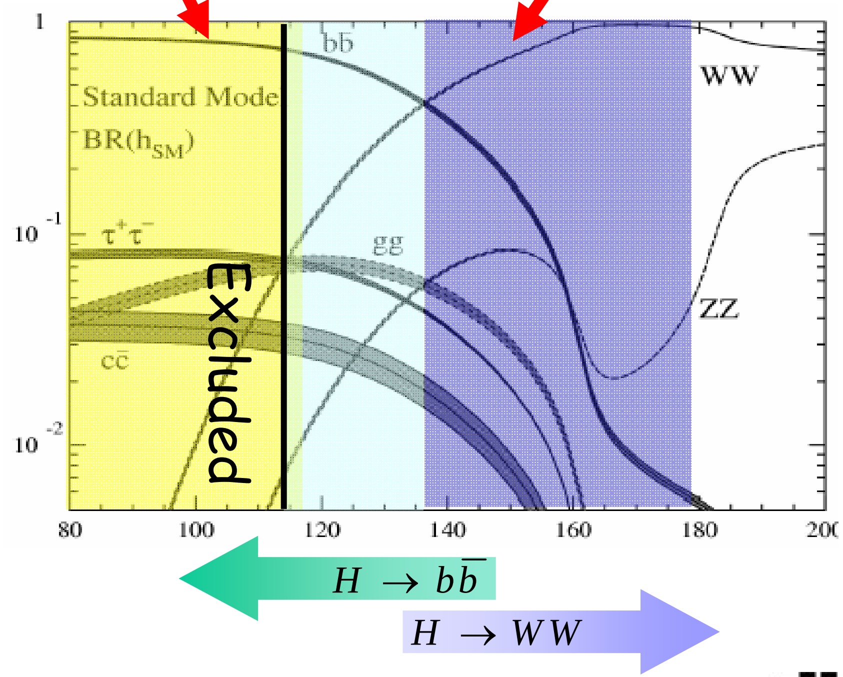
Production







Decay



Channels that enter in the combination

CDF

TABLE I: The luminosity, mass range explored and reference for the CDF analyses. ℓ stands for e or μ.

	$WH \to \ell\nu b\bar{b}$ TDT(LDT)	$ZH \to \nu\bar{\nu}b\bar{b}$ DT(ST)	$ZH \to \ell^+\ell^- b\bar{b}$ DT(ST)	$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$
Luminosity (fb^{-1})	1.7	1.0	1.0	1.9
m_H range (GeV/c^2)	110-150	110-150	110-150	120-200
Reference	[12]	[13]	[14]	[15]

D0

TABLE II: The luminosity, mass range explored and reference for the DØ $H \to b\bar{b}$ analyses. ℓ stands for e or μ.

	$WH \to e\nu b\bar{b}$ DT(ST)	$WH \to \mu\nu b\bar{b}$ DT(ST)	$WH \to \ell\nu b\bar{b}$ DT(ST)	$ZH \to \nu\bar{\nu}b\bar{b}$ DT(ST)	$ZH \to \ell^+\ell^- b\bar{b}$
Luminosity (fb^{-1})	1.7	1.7	0.9	0.9	1.1
m_H range (GeV/c^2)	105-145	105-145	105-135	105-135	105-145
Reference	[16]	[16]	[17]	[17]	[18]

TABLE III: The luminosity, mass range explored, and reference for the DØ $WH \to WW^+W^-$ and $H \to W^+W^-$ analyses.

	$WW^+W^- \to e^\pm\nu e^\pm\nu$ $WW^+W^- \to e^\pm\nu\mu^\pm\nu$ $WW^+W^- \to \mu^\pm\nu\mu^\pm\nu$	$H \to W^+W^- \to e^+\nu e^-\nu$ $H \to W^+W^- \to e^\pm\nu\mu^\mp\nu$ $H \to W^+W^- \to \mu^+\nu\mu^-\nu$	$H \to W^+W^- \to e^\pm\nu\mu^\mp\nu$
Luminosity (fb^{-1})	1.1	1.0	0.6
m_H range (GeV/c^2)	120-200	120-200	120-200
Reference	[19]	[20, 21]	[22]

Due to lack of time I will only cover the highlighted channels (main channels)

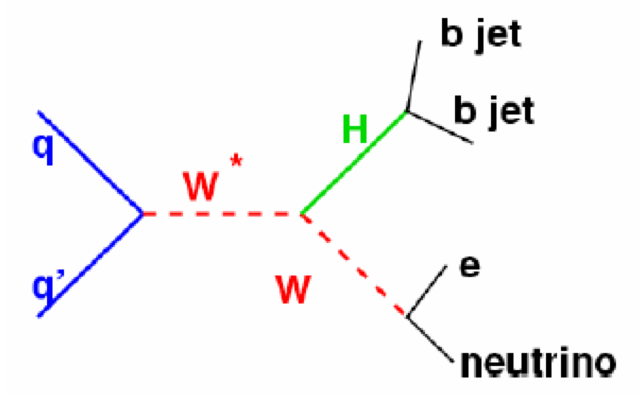
$q\bar{q}' \rightarrow WH \rightarrow l\nu b\bar{b}$

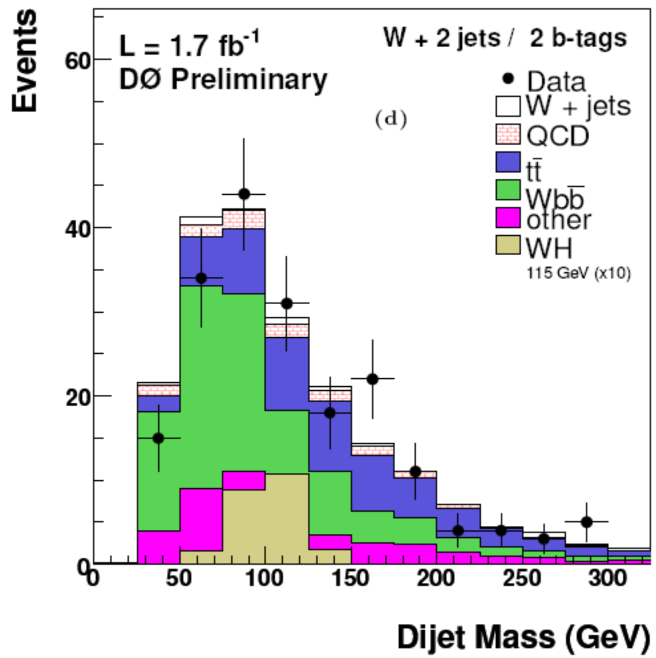
Basic selection:

- exactly one isolated leptons
- missing transverse momentum
- 2 or 3 jets, at least one b-tagged

Main backgrounds:

- W b b-bar (irreducible)
- t t-bar



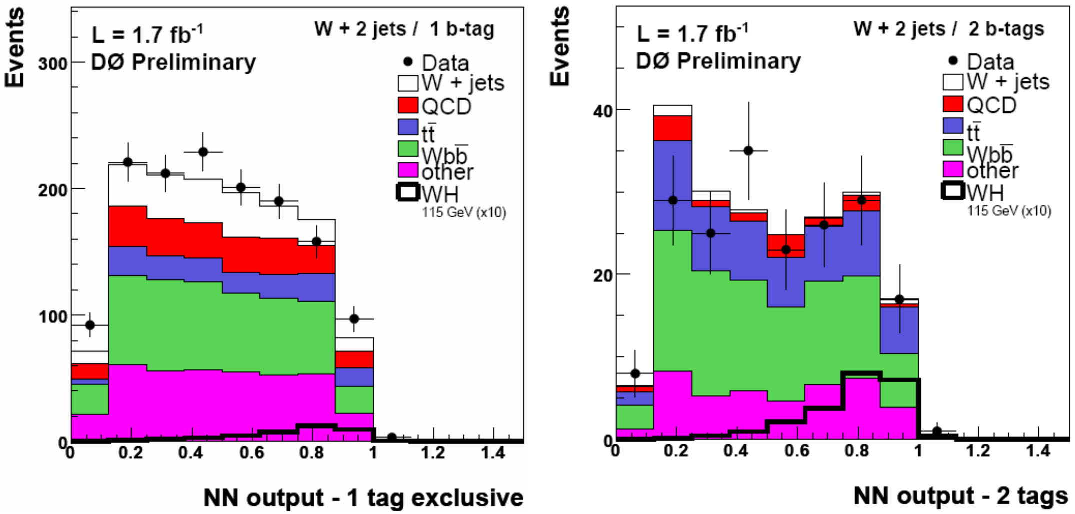


Dijet mass is the largest discriminat. But other variable can be used in a NN

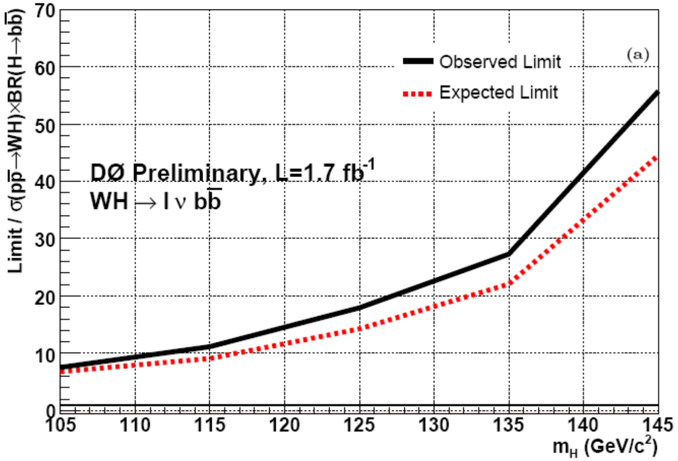
D0 uses NN in Higgs search

$H \to b\bar{b}$ in D0 (1.7 fb^{-1})

Train NN for different Higgs masses. Plot discriminant



If no signal is seeing set limits



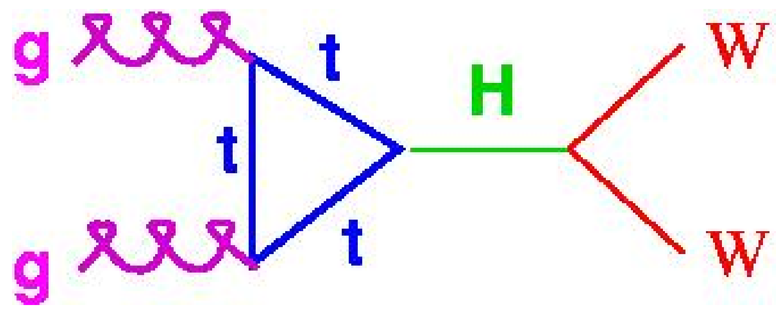
$gg \rightarrow H \rightarrow W^+W^- \rightarrow l^+\nu l^-\nu$

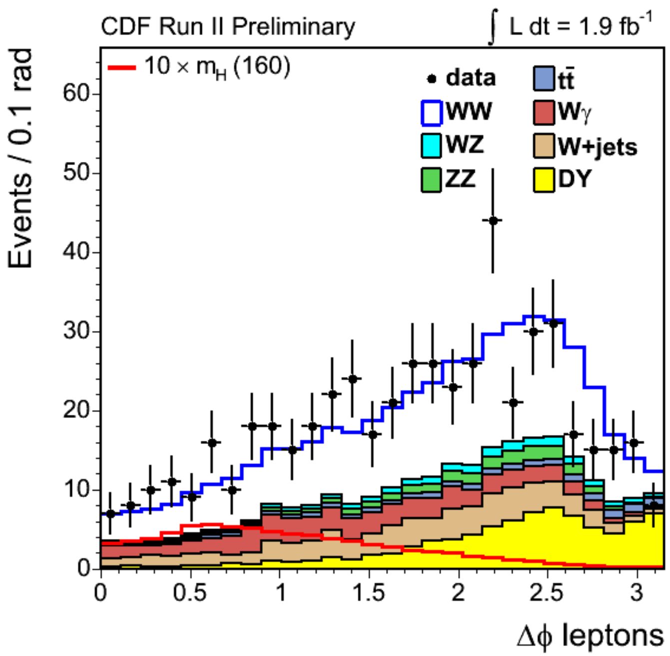
Basic selection:

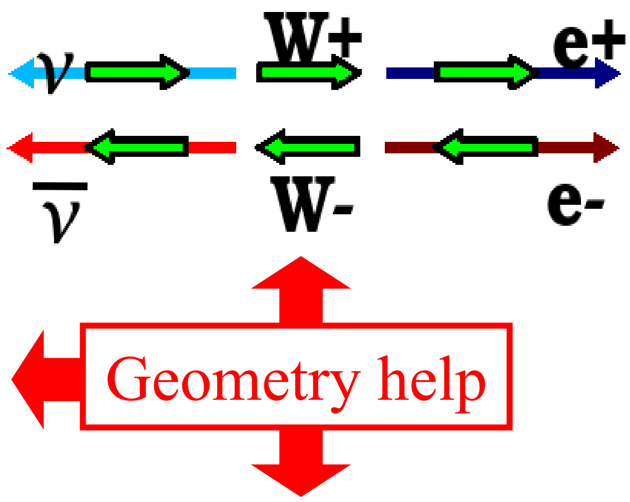
- Two opposite sign isolated leptons
- missing transverse momentum

Main backgrounds:

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







Use full power of Matrix element

$H \to W^+W^-$ in CDF (1.9 fb^{-1})

Calculate probabilities

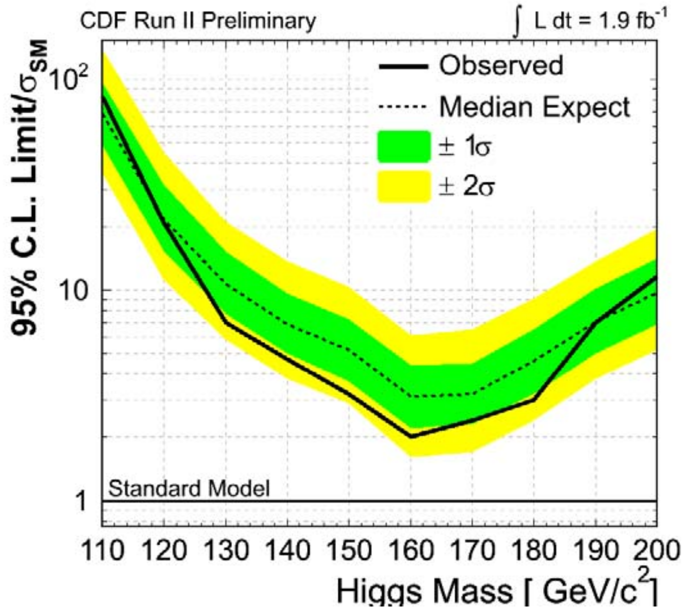
$$P_m(\vec{x}_{obs}) = \frac{1}{\langle \sigma_m \rangle} \int d^n \sigma_m^{theory}(y) \epsilon(y) G(\vec{x}_{obs}, y)$$

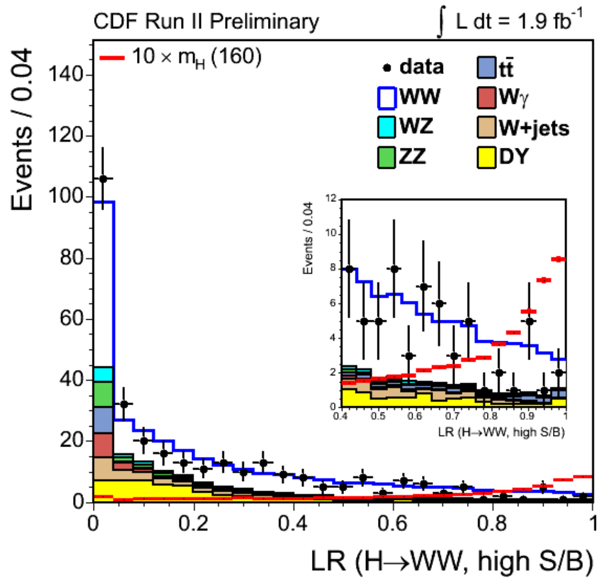
P_m : Event-by-event probability for process m
y : true lepton kinematics, incl. neutrinos
$\vec{x}_{obs}$: observed kinematics
ϵ : lepton efficiencies
G : detector resolution function

Calculate discriminant

$$LR(m_H) = \frac{P_{Higgs}(m_H)}{P_{Higgs}(m_H) + \sum_{bg=WW,WZ,tt,..} f_{bg} P_{bg}}$$

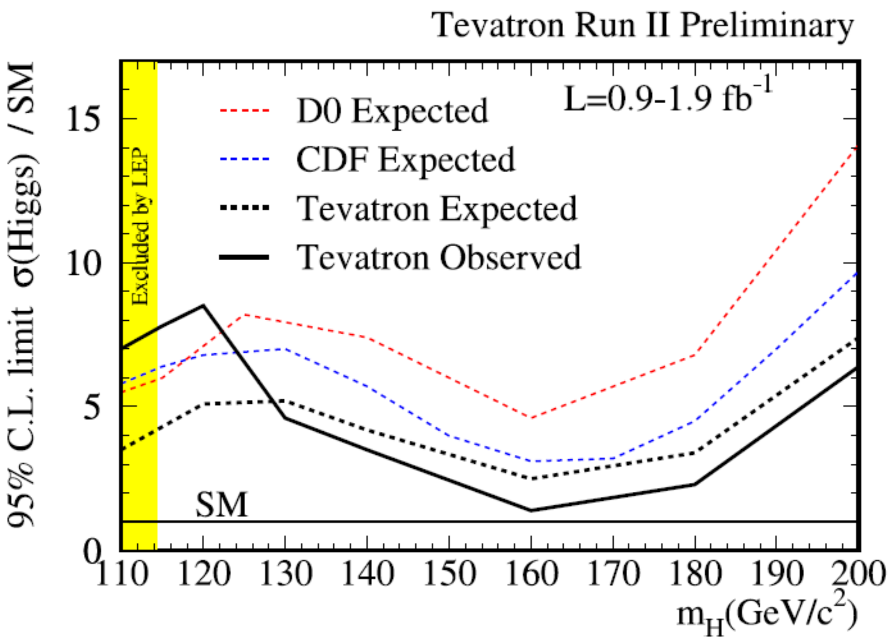
Check for observation





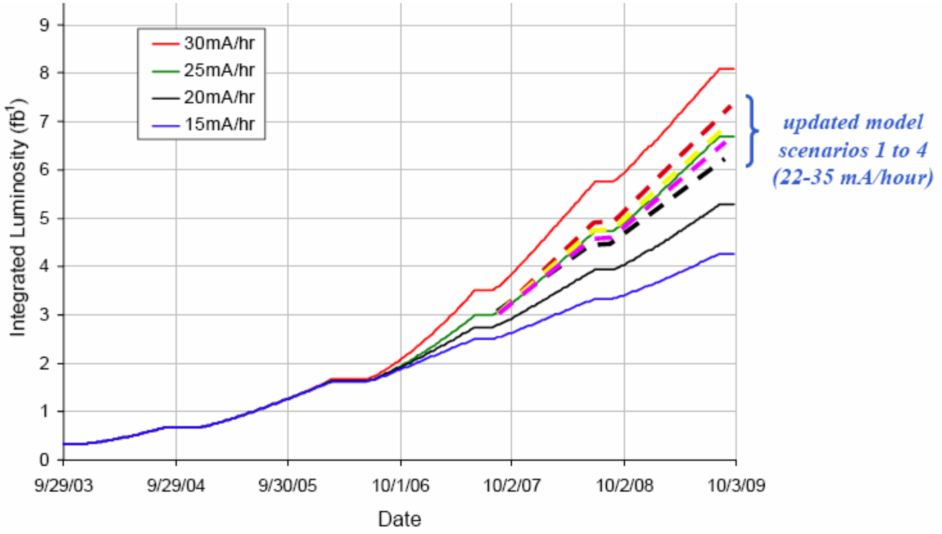
If no observation set limit

CDF+D0 combination



CDF and D0 combination for the summer 2007

Expected Tevatron luminosity



Conclusions

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

• The W mass at the Tevatron (CDF only right now) has an error of 48 MeV/c^2. An error of ~20 MeV/c^2 is expected with 2 fb^{-1} of data.

• A big region at high Higgs mass will be excluded at 95% confidence level. At lot more work is necessary to reach exclusion or evidence at low masses.