Electroweak Precision Measurements and Direct Higgs Searches at the Tevatron

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on behalf of the CDF & DØ Collaborations

- W Mass
- Top Physics
- Direct Higgs Searches

More details in parallel sessions :

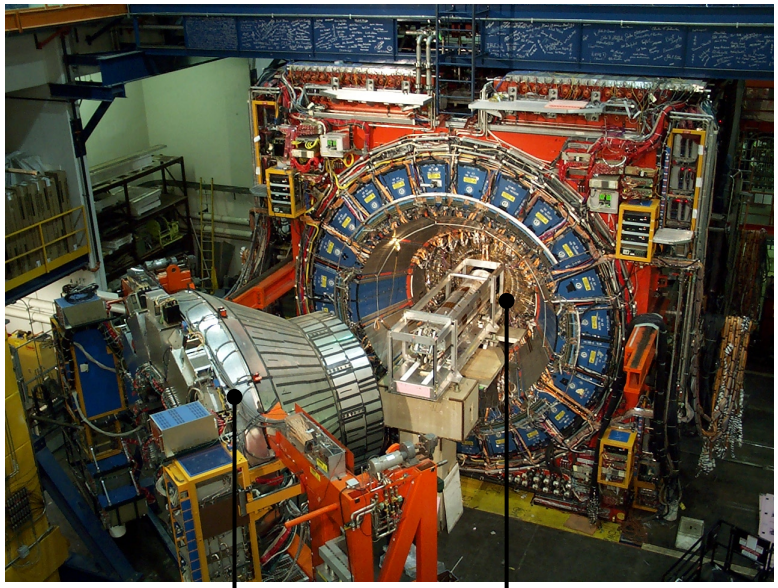
Knoepfel (27/am)	Head (27/pm)
Soustruznik (27/pm)	Riddick (28/pm)
Vellidas (27/pm)	Peters (29/am)

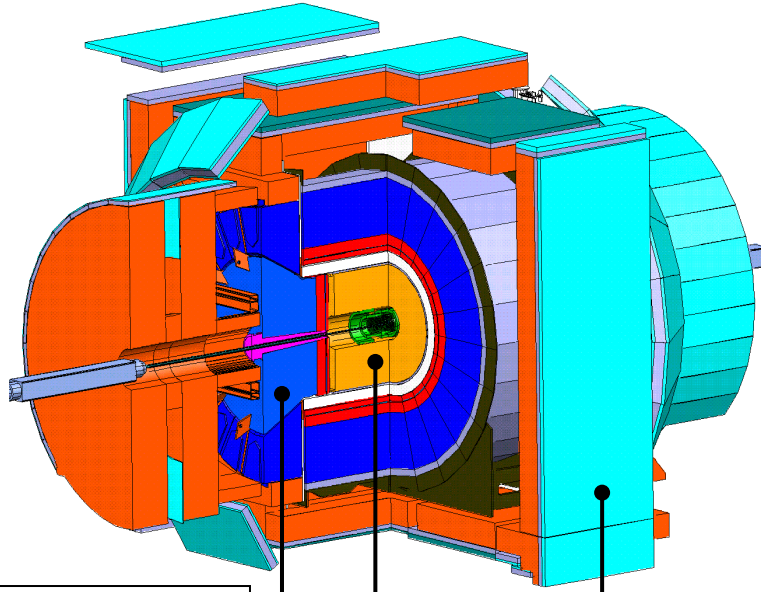
Tevatron Run II

1st March 2001 – 30th September 2011

- 12 fb^{-1} delivered to CDF and DØ ➔ ~10 fb^{-1} good data on tape.
- A enormous wealth of physics and much still to come.

CDF Detector





Drift chamber outer tracker :
$\delta p_T / p_T \approx 0.0005 \times p_T$ [GeV/c; beam constrained]; $|\eta| < 1$
Silicon vertex detector :
tracking coverage out to $|\eta| < 2.8$

Central calorimeter : $\delta E_T / E_T \approx 13.5\% / \sqrt{E_T} \oplus 1.5\%$ $|\eta| < 1.1$
Plug calorimeter : coverage out to $|\eta| < 3.0$

Muon chambers : coverage out to $|\eta| < 1.0$

DØ Detector

Central Fiber Tracker :

Tracking out to |η|<1.8 in 2 T B-field

Silicon Tracker :

Coverage out to |η|<3

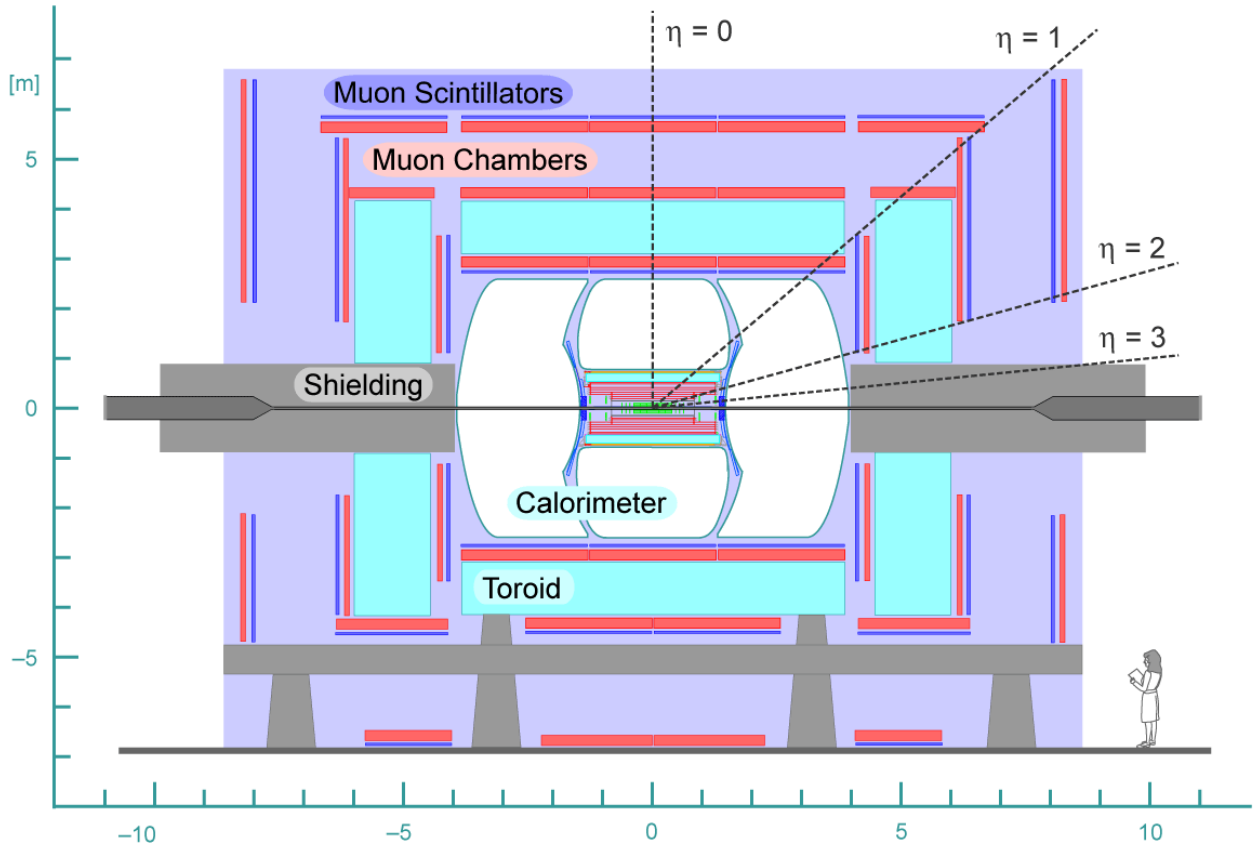
Muon System :

Near hermetic coverage out to |η|<2

Momentum measurement in 1.8 T toroidal magnet

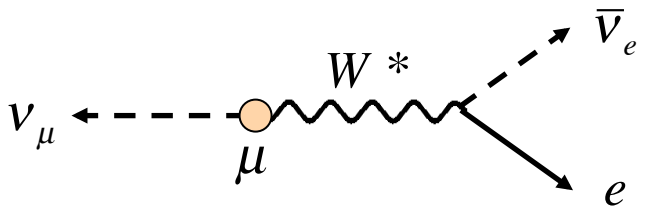
Calorimetry :

Liquid Argon/Uranium; covers |η|<4



EWK Precision Measurements : Big Picture

- Electroweak standard model relates precisely known parameters and less well known parameters through radiative corrections :



$$G_F = 1.16637(1) \times 10^{-5} \ \text{GeV}^{-2}$$

$$\alpha_{em}(0) = 1/137.03599911(46)$$

$$M_Z = 91.1876(21) \ \text{GeV}$$

$$G_F = \frac{\pi \alpha_{em}}{\sqrt{2} M_W^2 (1 - M_W^2 / M_Z^2)} \cdot \frac{1}{(1 - \Delta r)}$$

Δr **: radiative corrections (zero at tree level)**

rearranging

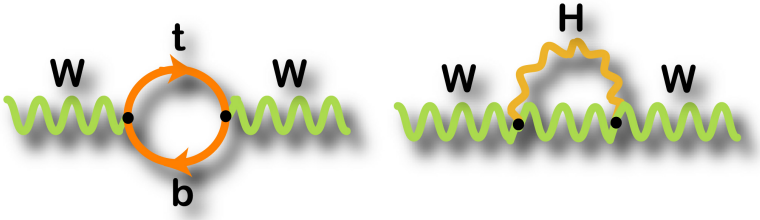
$$M_W = f(\underbrace{\alpha_{em}(0), G_F, M_Z}_{\text{exquisitely well known}}, \Delta r)$$

what goes into Δr ?

W Mass : Playing Precision Catch-Up

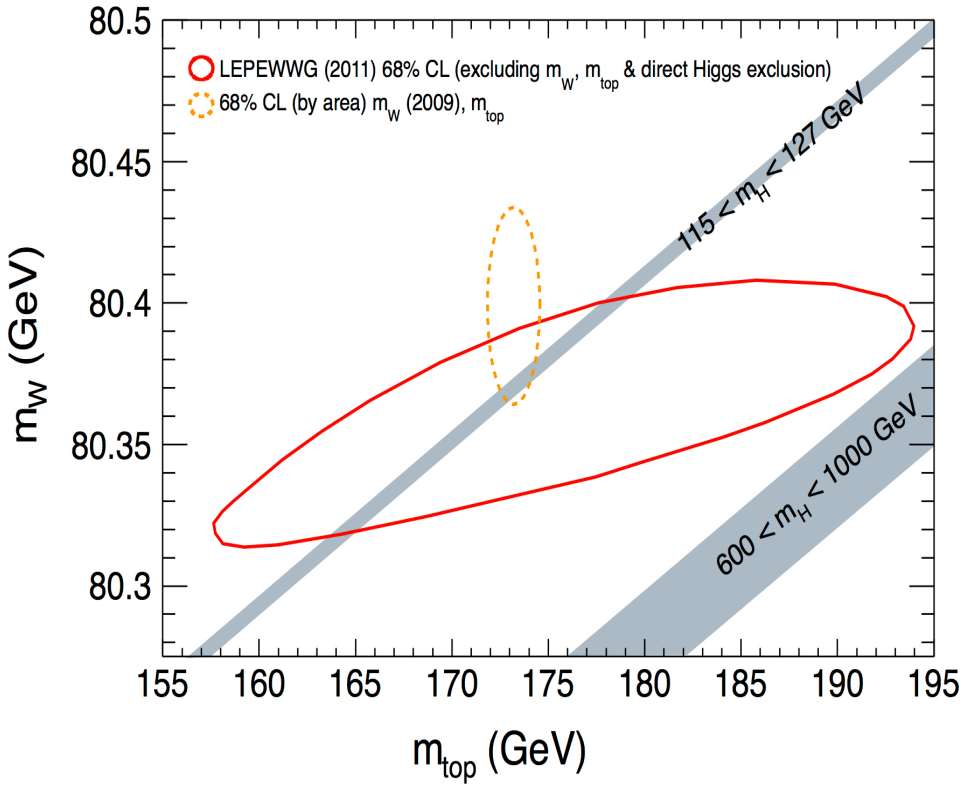
- Radiative corrections to **M_W** include those due to **top** and **Higgs** :

$$\Delta M_W \propto M_{top}^2$$



$$\Delta M_W \propto \ln M_H$$

- Equivalently, measuring **M_W** and **M_{top}** places constraints on the missing piece, **M_H**.



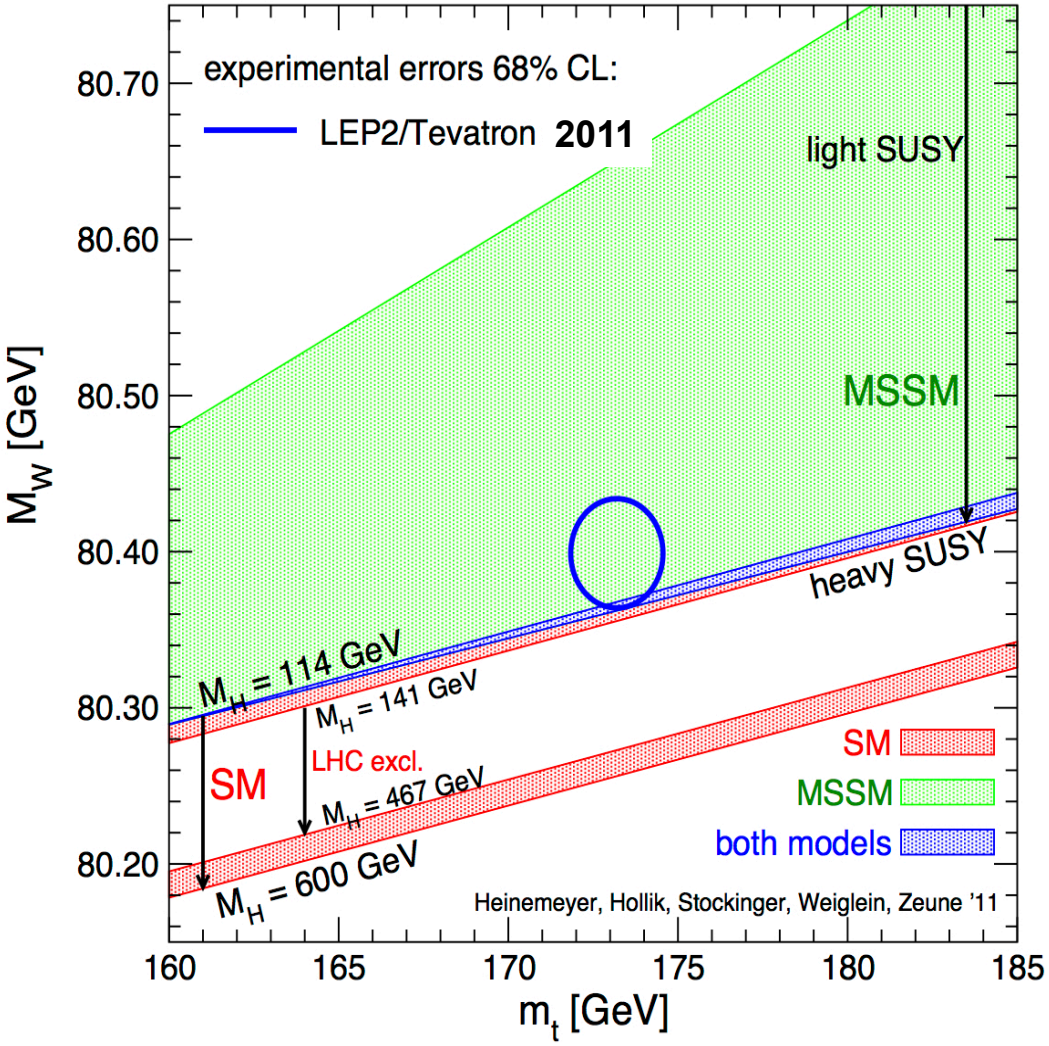
$$M_H = 92^{+34}_{-26}\ \text{GeV} \quad \text{(LEP EWWG, 2011)}$$

- How do **M_W** and **M_{top}** inputs compare ?
- Current top mass precision :

  $\Delta(M_{TOP})$ = 0.9 GeV (0.54%)
- Equivalent constraint on **M_H** would come from:

  $\Delta(M_W)$ = 6 MeV (0.001%)
- The most important measurement for us to improve now is the W mass !

Triangulating New Physics

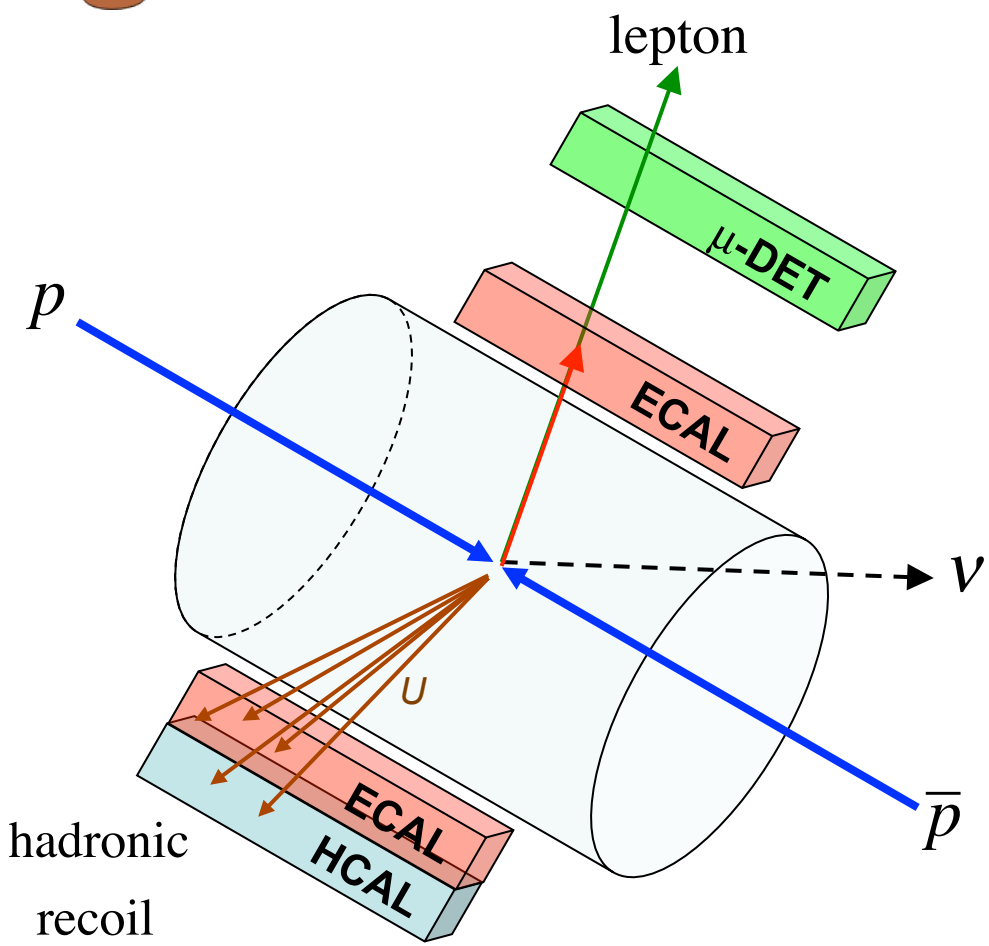


- Even after a Higgs discovery at the Tevatron or LHC, precision EWK measurements will enable powerful Standard Model consistency fits.
- May be possible to distinguish SM from MSSM and in general constrain the properties of new physics at higher mass scales.

W Mass : Observables

New !

arXiv:1203.0742 (CDF)
arXiv:1203.0293 (DØ)



$$p\bar{p} \rightarrow W(\rightarrow l\nu) + X$$

Lepton :
Measure 4-vector as precisely as possible.

Hadronic Recoil :
Measure in transverse plane only

$$\vec{u}_T = \{u_x, u_y\}$$

Neutrino :
Infer transverse momentum :

$$\vec{p}_T^{\,\nu} = -(\vec{p}_T^{\,l} + \vec{u}_T)$$

Transverse Mass :

$$M_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\Delta\phi^{l\nu}))}$$

W Mass : Yields

Channel (Exp.)	Luminosity	#Events
$W \to e\nu$	2.2 fb^{-1}	470, 126
$W \to \mu\nu$	2.2 fb^{-1}	624, 708
$Z \to ee$	2.2 fb^{-1}	16,134
$Z \to \mu\mu$	2.2 fb^{-1}	59,738
$W \to e\nu$	4.3 fb^{-1}	1,677,394
$Z \to ee$	4.3 fb^{-1}	54,512

$W \to \ell\nu$ Kinematic Cuts

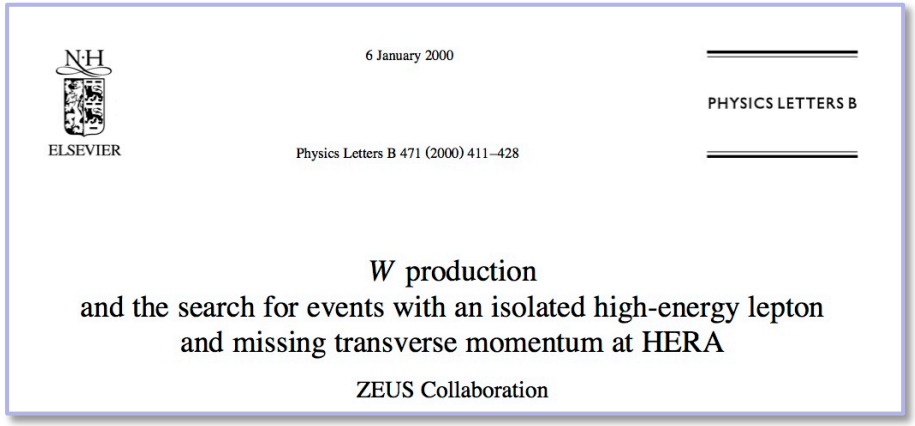
$30 < p_T^{\ell}, p_T^{\nu} < 55$ GeV

$|\vec{u}| < 15$ GeV

$p_T^{\ell}, p_T^{\nu} > 25$ GeV

$|\vec{u}| < 15$ GeV

- Selection efficiencies are *small* compared to cross-section analyses : 3% (Z) - 12% (W).
- We are trading statistics for systematics - tight fiducial and ID cuts.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6 January 2000

PHYSICS LETTERS B

Physics Letters B 471 (2000) 411–428

W production
and the search for events with an isolated high-energy lepton
and missing transverse momentum at HERA

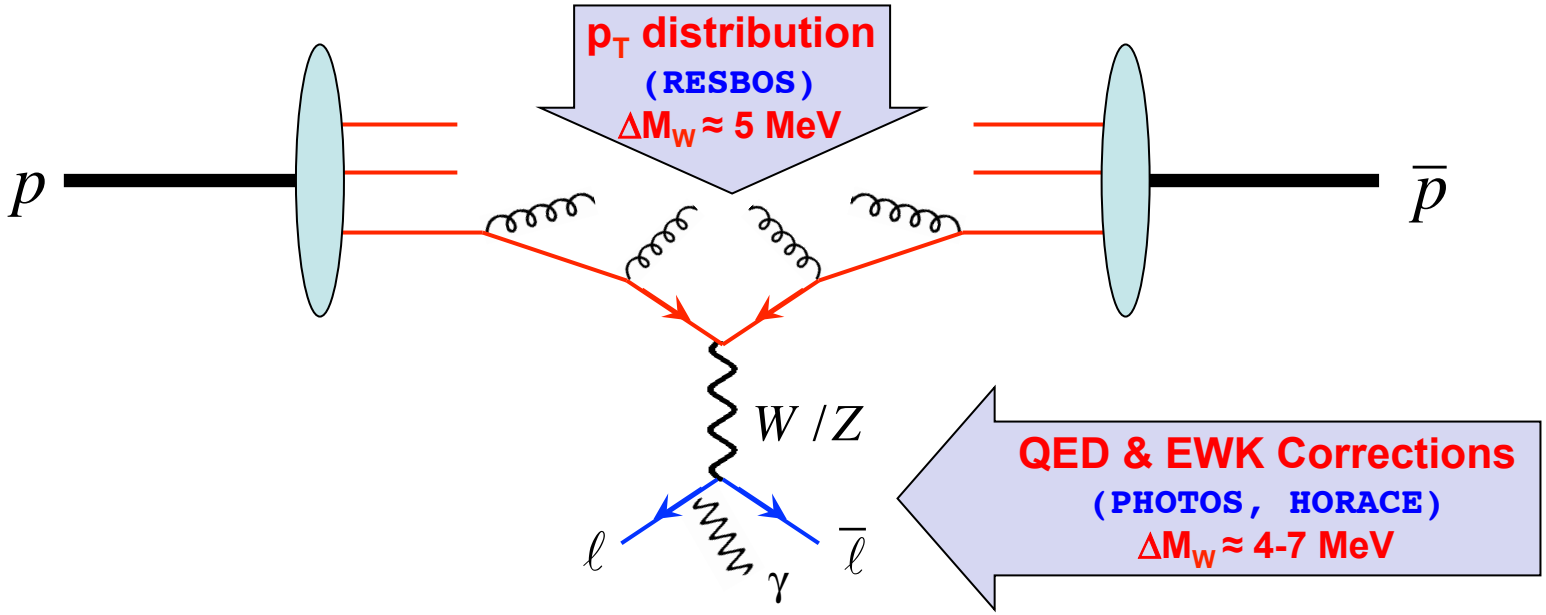
ZEUS Collaboration

My Ph.D. Thesis

3 $W \to e\nu$ events in 48 pb^{-1}

$$\sigma\left(e^+p \to e^+W^{\pm}X\right) = 0.9^{+1.0}_{-0.7} \pm 0.2 \text{ pb}$$

W Mass : Production Modelling



$$d\sigma_{p\bar{p}\to W/Z\to\ell\bar{\ell}} = \int \sum_{i,j=u,d,s,(c,b)} [f_i^q(x_p) f_j^{\bar{q}}(x_{\bar{p}}) + f_i^{\bar{q}}(x_p) f_j^q(x_{\bar{p}})] \times d\sigma_{q\bar{q}\to W/Z\to\ell\bar{\ell}} \; dx_p dx_{\bar{p}}$$

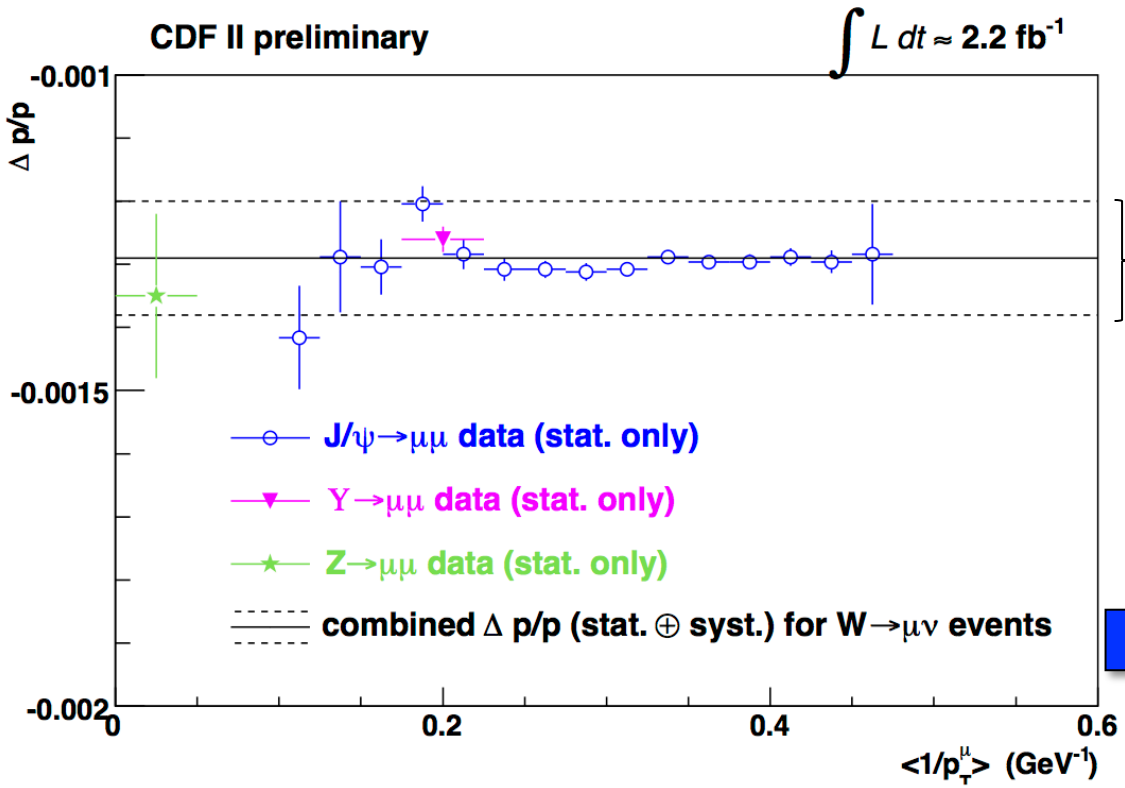
y-distribution
(MSTW2008, CTEQ6.6)
$\Delta M_W \approx 10$ MeV

angular & mass distributions (RESBOS)

$$d\sigma_{q\bar{q}\to W/Z\to l\bar{l}}(\hat{s},\theta_l,\phi_l) \propto \text{couplings} \times \left[\frac{1}{(\hat{s} - M_{W/Z}^2)^2 + (\Gamma_{W/Z}\hat{s}/M_{W/Z})^2}\right]$$

Momentum Scale

- The heart of the CDF analysis is the extremely good p_T measurement from the tracker.
- Start with a detailed cosmic ray internal alignment of the COT to **~5μm**
- Use precisely known resonances spanning a large range of curvature.



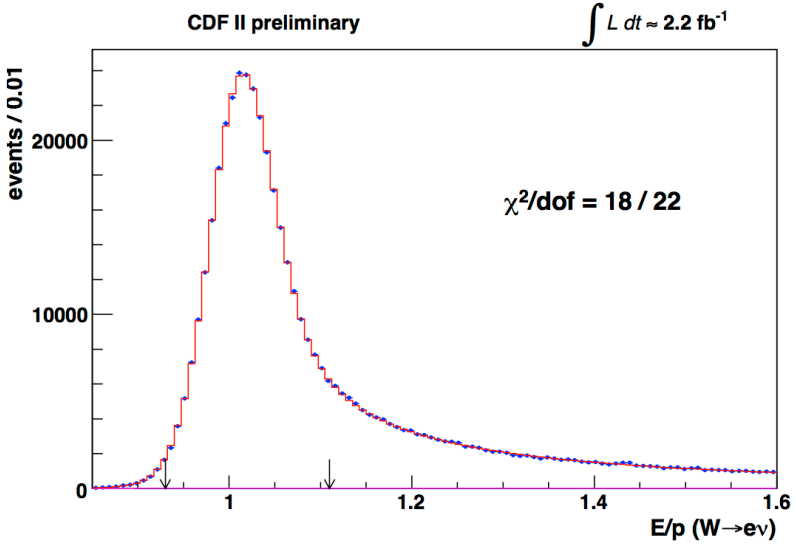
$$\Rightarrow \quad \frac{\delta p}{p} = 0.00009$$

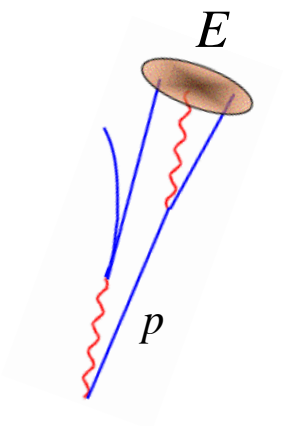
$\Delta M_W(\mu)$ = 7 MeV

Flatness over a large p_T range is also a test of dE/dx modelling

Electron Energy Scale

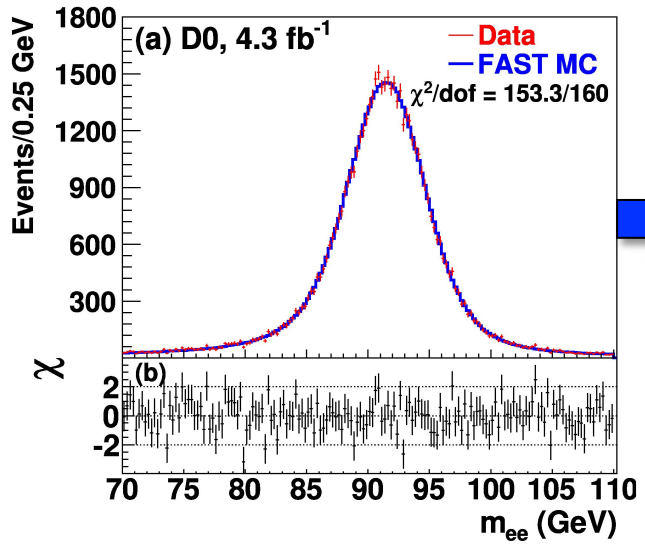
- Transfer p-scale to E-scale using E/p :





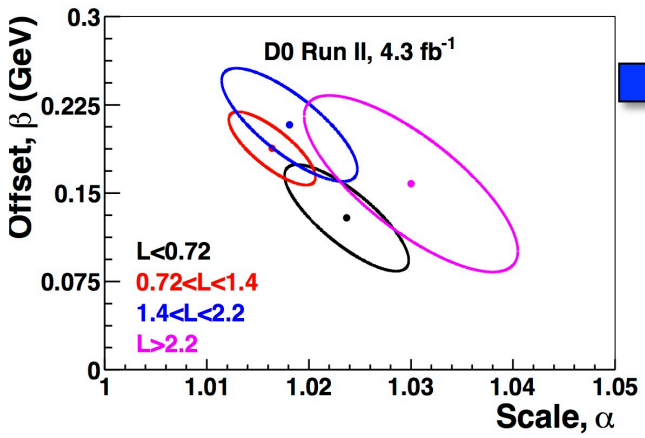
- Take advantage of large statistics in the W sample.
- Fit the peak region for the energy scale.
- E/p tail due to Bremsstrahlung in detector material ➔ constrain radiative material.

- Use $Z \to ee$ events and precisely known M_Z :



Effectively measuring M_W/M_Z

- Use dynamic range of E within the Z data to constrain parameters : $E^{\mathrm{meas}} = \alpha E^{\mathrm{true}} + \beta$



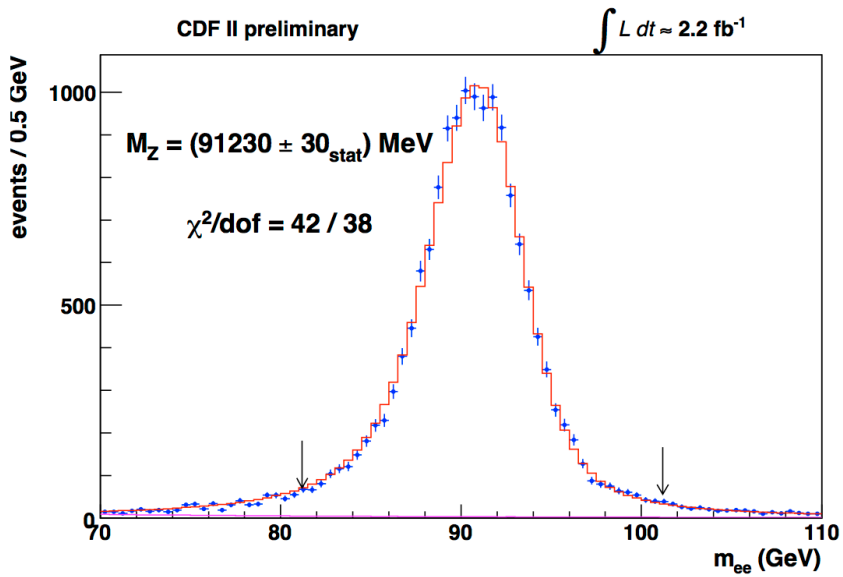
Luminosity dependence

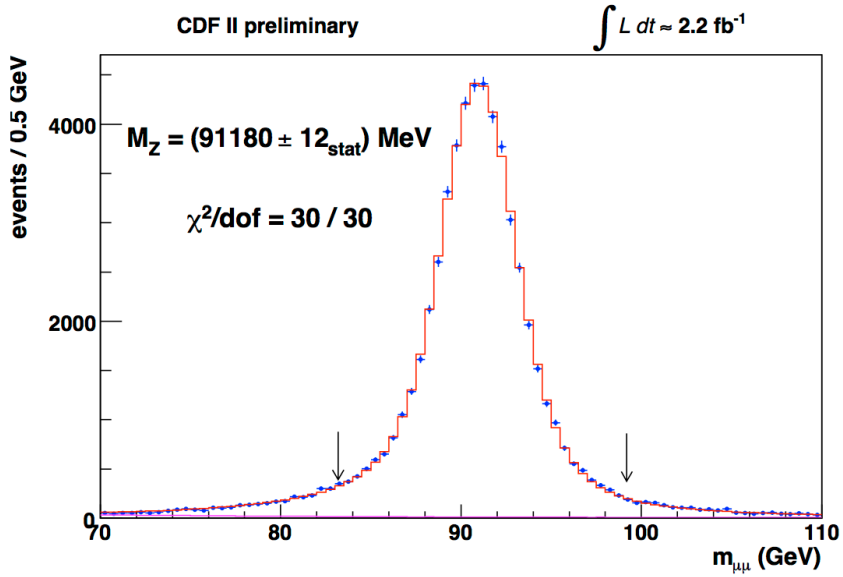
<u>Overall:</u>

ΔM_W (e) = 16 MeV

M_Z Cross-Checks

- Z mass fits blinded until the p-scale (from J/ψ and ϒ) and E-scale (from E/p) were finalised.
- Comparison of unblinded Z mass fits with PDG is a very powerful cross-check.
- Subsequently Z constraints are included in p/E-scale determinations.





combined with E/p to give :

ΔM_W (e) = 10 MeV

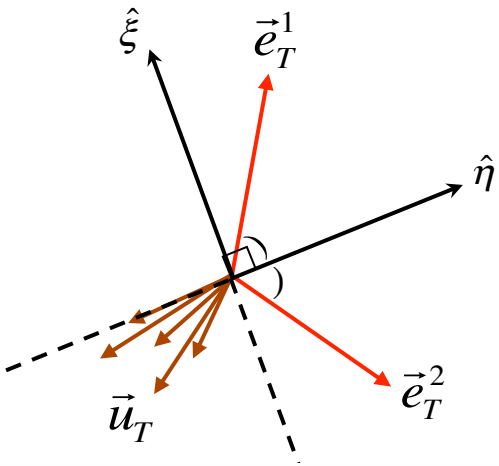
combined with J/ψ and ϒ to give :

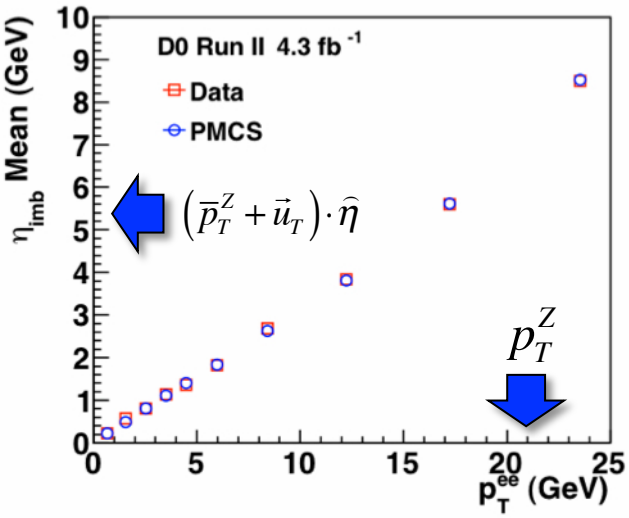
ΔM_W (μ) = 7 MeV

Recoil Modelling

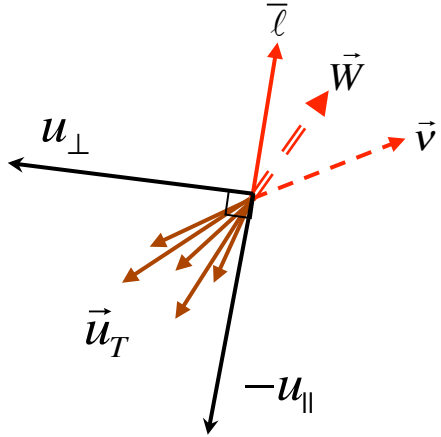
- "Recoil" from W/Z p_T, UE, overlapping MB events and any lepton energy leakage/FSR.
- Tune using Z data and minimum-bias data.

$Z \to ee$



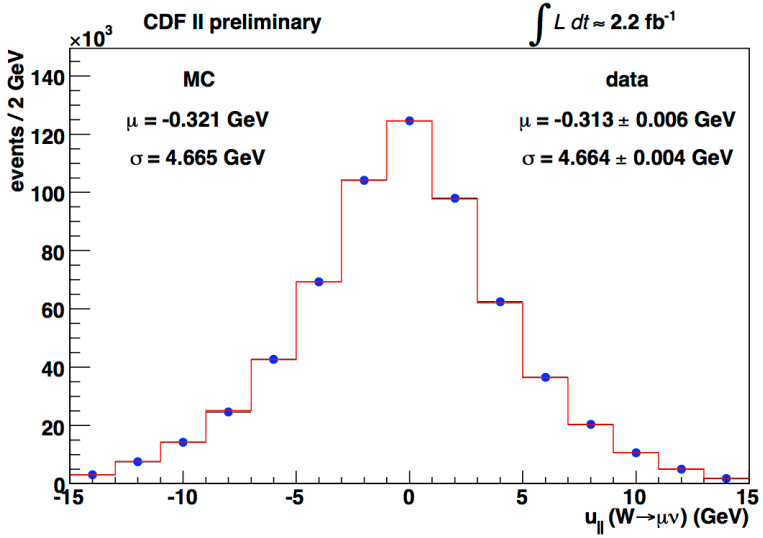


$W \to e\nu$



$$M_T \sim 2p_T^{\ell} + u_{\parallel}$$

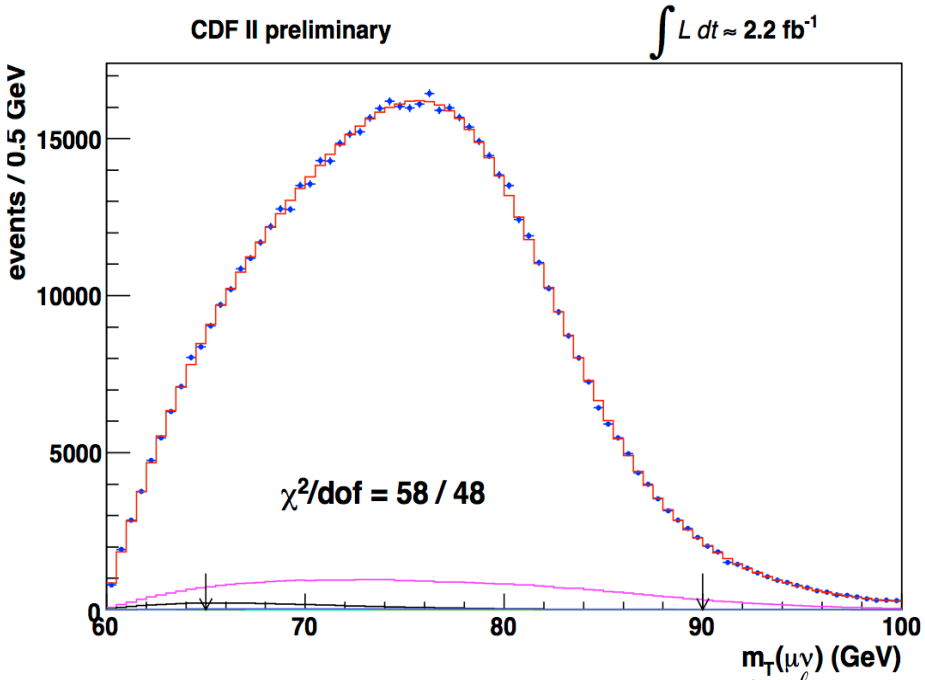
direct bias on M_W if mis-modelled



$\Delta M_W \approx 6$ MeV

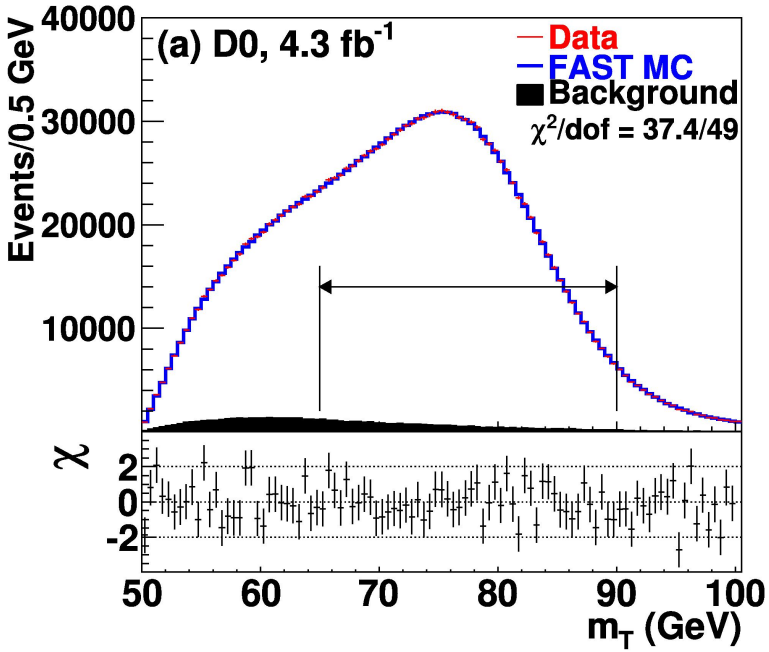
M_W Fits

- Fit the transverse mass in the range **65 < m_T < 90 GeV** :



$m_T\ /\ p_T^{\ell}$

$$M_W(\mu;\mathrm{CDF}) = 80379 \pm 16(\mathrm{stat.})\ \mathrm{MeV}$$



$$M_W(e;\mathrm{D}\varnothing) = 80371 \pm 13(\mathrm{stat.})\ \mathrm{MeV}$$

- Fits are also performed to p_T^{ℓ} and p_T^{ν} distributions : all fits are consistent with χ^2 probabilities of ~5% (DØ) and ~25% (CDF).
- $m_T\ /\ p_T^{\ell}$ (DØ) and $m_T\ /\ p_T^{\ell}\ /\ p_T^{\nu}$ (CDF) fit results are combined taking into account (large) correlations.

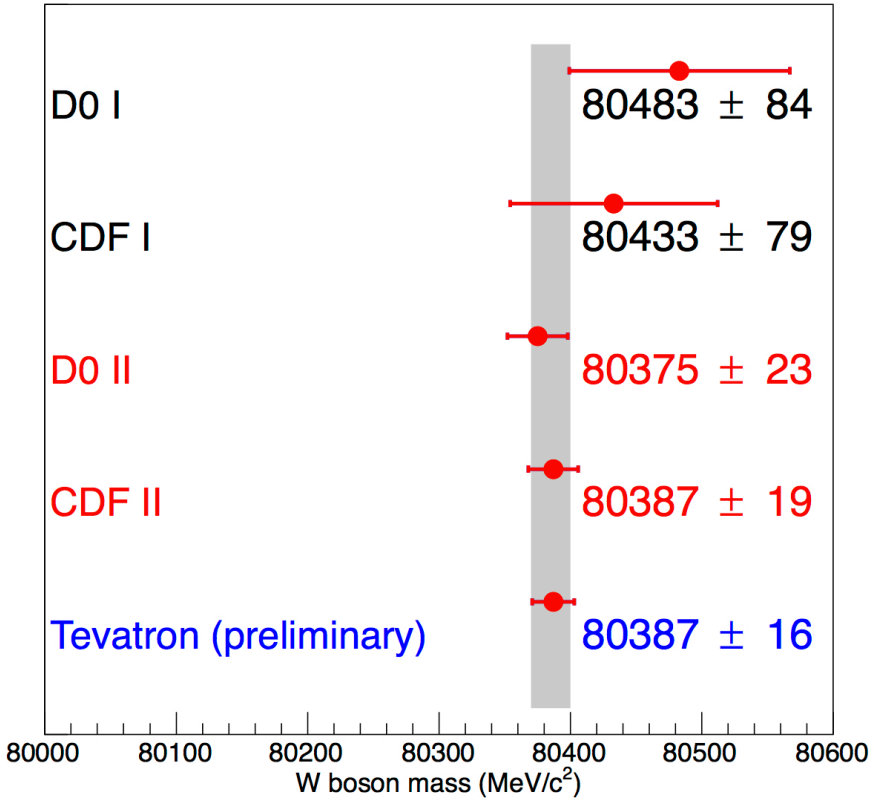
M_W : Comparison of Uncertainties

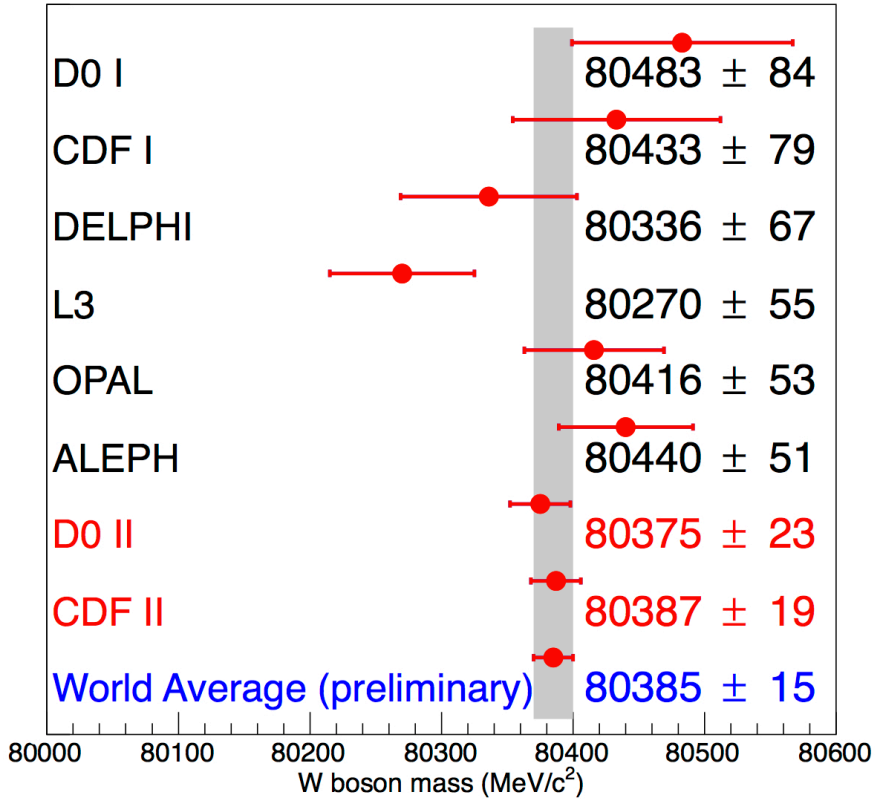
Uncertainties on Transverse Mass Fits for M_W (MeV)

Source	Electron (DØ)	Electron (CDF)	Muon (CDF)
Lepton Energy Scale + Nonlinearity	17	10	7
Lepton Energy Resolution	2	4	1
Recoil Model	5	9	9
Lepton Efficiency	1	-	-
Backgrounds	2	4	3
PDF	11	10	10
QED	7	4	4
Boson p_T	2	3	3
Total Systematic	**22**	**18**	**16**
Statistical	13	19	16
Total Uncertainty	**26**	**26**	**23**

- Modelling uncertainties (especially PDF's) are starting to dominate.

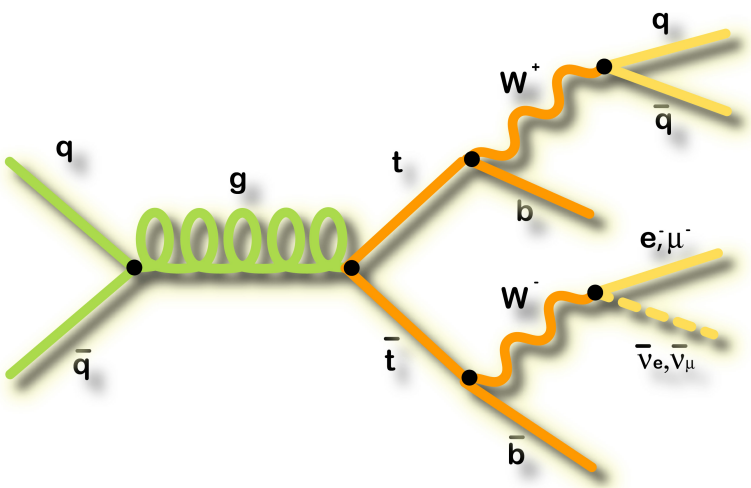
New M_W Average

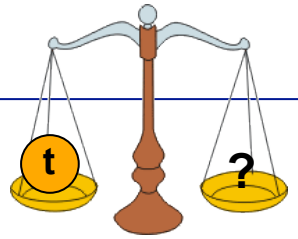




Previous World Average (2009) : **M_W = 80399 ± 23 MeV**

Top Mass : Overview





- Most important channel is lepton + jets
- The final **J**et **E**nergy **S**cale is determined in-situ from M_W constraint.
- Latest measurements beginning to be limited by non-JES systematics (production model uncertainties).

Template Method :

- fit reconstructed mass distributions between simulation and data
- mass determined using a kinematic fit taking into account combinations & smearing

$$P_{sig}\left(x;m_{top};JES\right) = \frac{1}{\sigma_{obs}\left(m_{top}\right)} \times \int dq_1\, dq_2 f\left(q_1\right) f\left(q_2\right) \cdot \frac{\left(2\pi\right)^4 \left|M\left(y,m_{top}\right)\right|^2}{4\sqrt{q_1 \cdot q_2 - m_1 m_2}} d\phi \cdot W\left(y,x,JES\right)$$

probability density | **parton densities** | **LO matrix element** | **Transfer Function**

Matrix-Element Method

$$\text{parton-level } (y) \otimes \text{ detector-resolutions } \Rightarrow \text{ measured } (x)$$

M_{top} in Lepton+Jets using 8.7 fb^{-1}

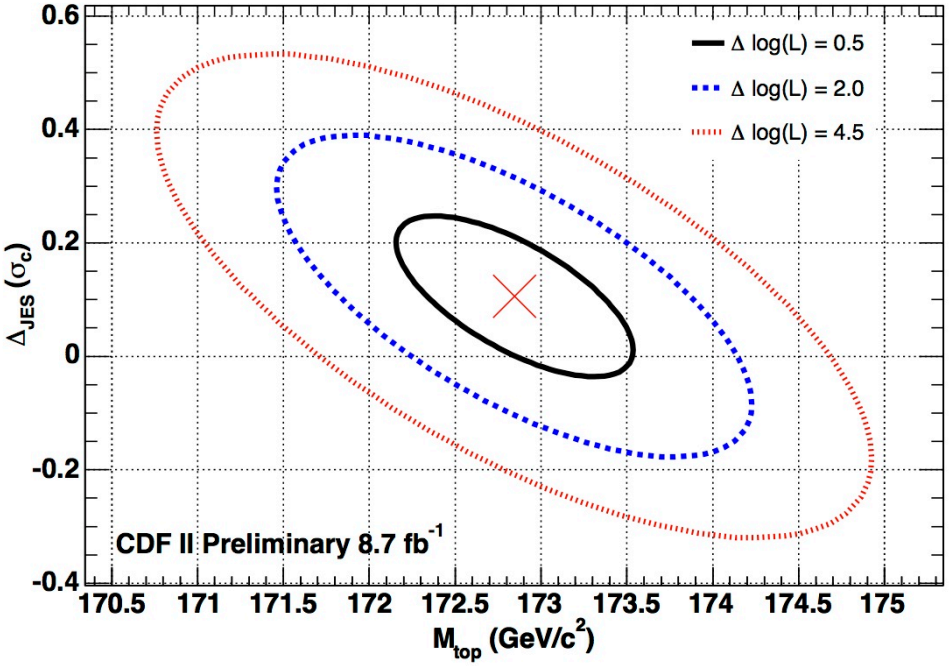
New !

- Reconstruct the mass for each event using over-constrained kinematics :

$$\chi^2 = \sum_{i=\ell,4-jets} \frac{\left(p_T^{i,fit} - p_T^{i,meas}\right)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{\left(U_j^{fit} - U_j^{meas}\right)^2}{\sigma_j^2} + \frac{\left(M_{jj} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{\ell\nu} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{bjj} - M_{top}^{reco}\right)^2}{\Gamma_{top}^2} + \frac{\left(M_{b\ell\nu} - M_{top}^{reco}\right)^2}{\Gamma_{top}^2}$$

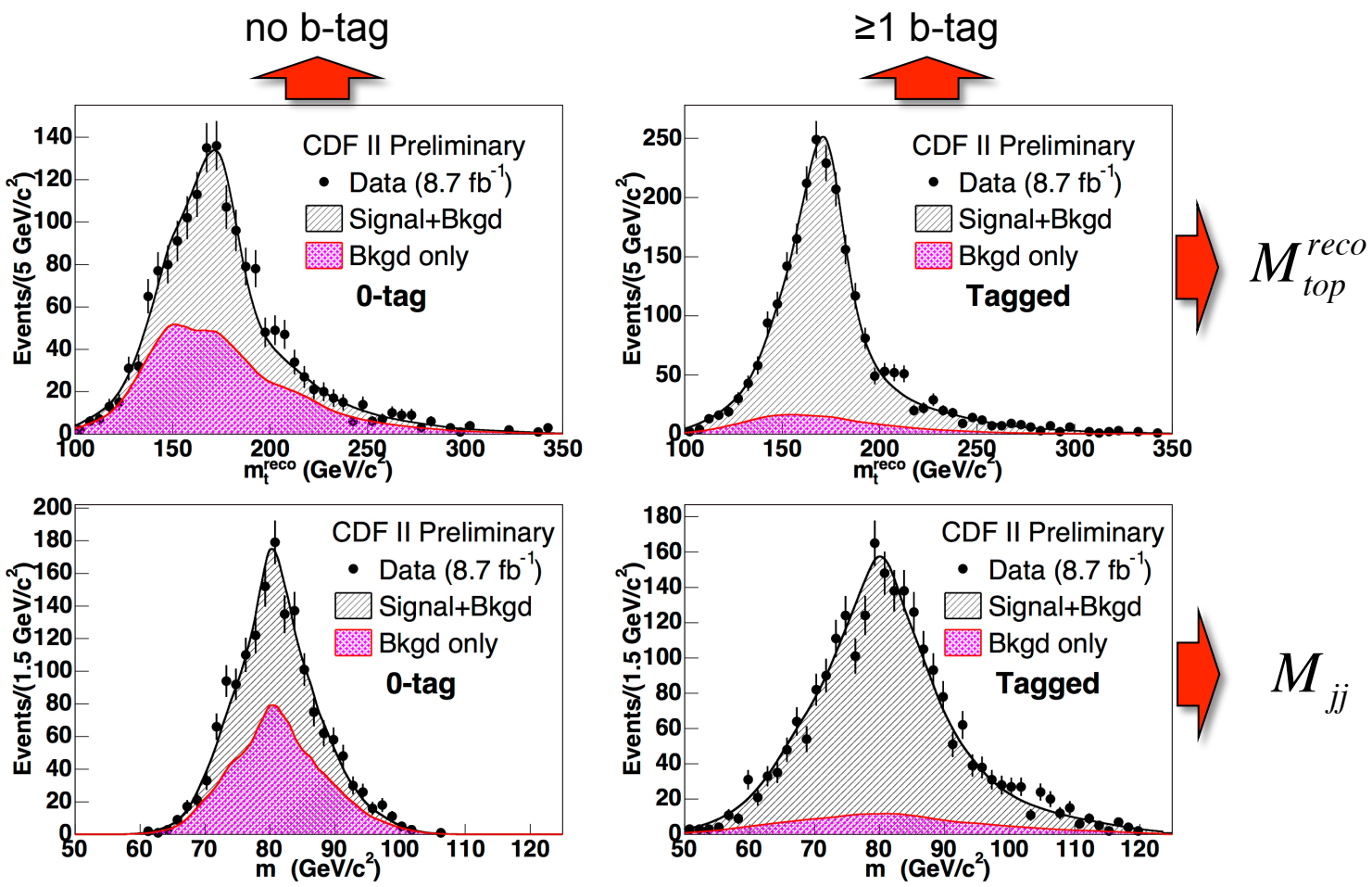
variables entering mass fit:

$$M_{jj},\ M_{top}^{reco},\ M_{top}^{reco,2}$$



- 2-D fit for M_{top} and ΔJES
- Result shows a best fit jet-energy scale shifted by about $0.11\sigma_C$ with respect to nominal.
- The size of the ellipse shows that the JES is considerably more constrained in-situ : $\delta(\Delta JES) \approx 0.15\sigma_C$

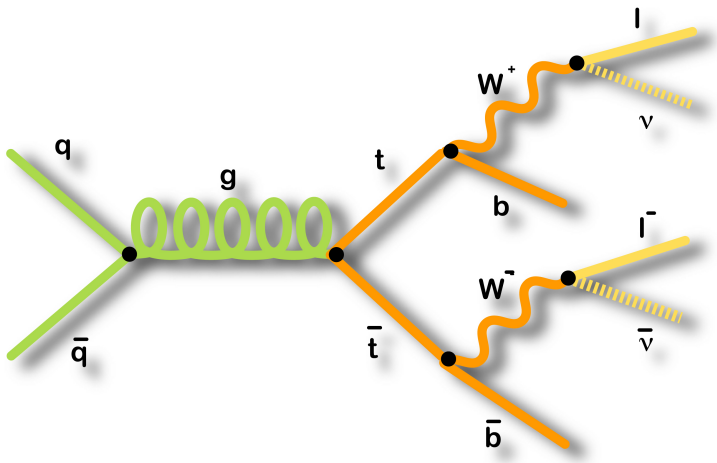
M_{top} in Lepton+Jets using 8.7 fb^{-1}



$$M_t = 172.85 \pm 0.71\ (\text{stat.}) \pm 0.84\ (\text{syst.}) = 172.85 \pm 1.10\ \text{GeV/c}^2$$

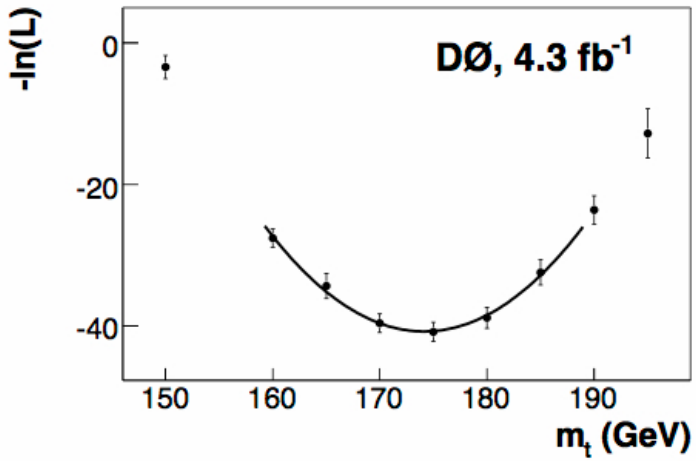
- JES and generator systematics dominate the total
- Approximately 15% smaller error than 5.8 fb^{-1} analysis

M_{top} in Dilepton Events with 4.3 fb^{-1}



- Statistically limited ✗
- 2 neutrinos in final state : under-constrained kinematics requires integration over invisible momenta to generate fitting templates ✗
- Precisely measured leptons ✓
- JES is still a critical issue for b-jets.
- A new analysis from DØ transfers the in-situ JES from lepton+jets events taking into account sample differences. [Similar to combined fits across samples from CDF]

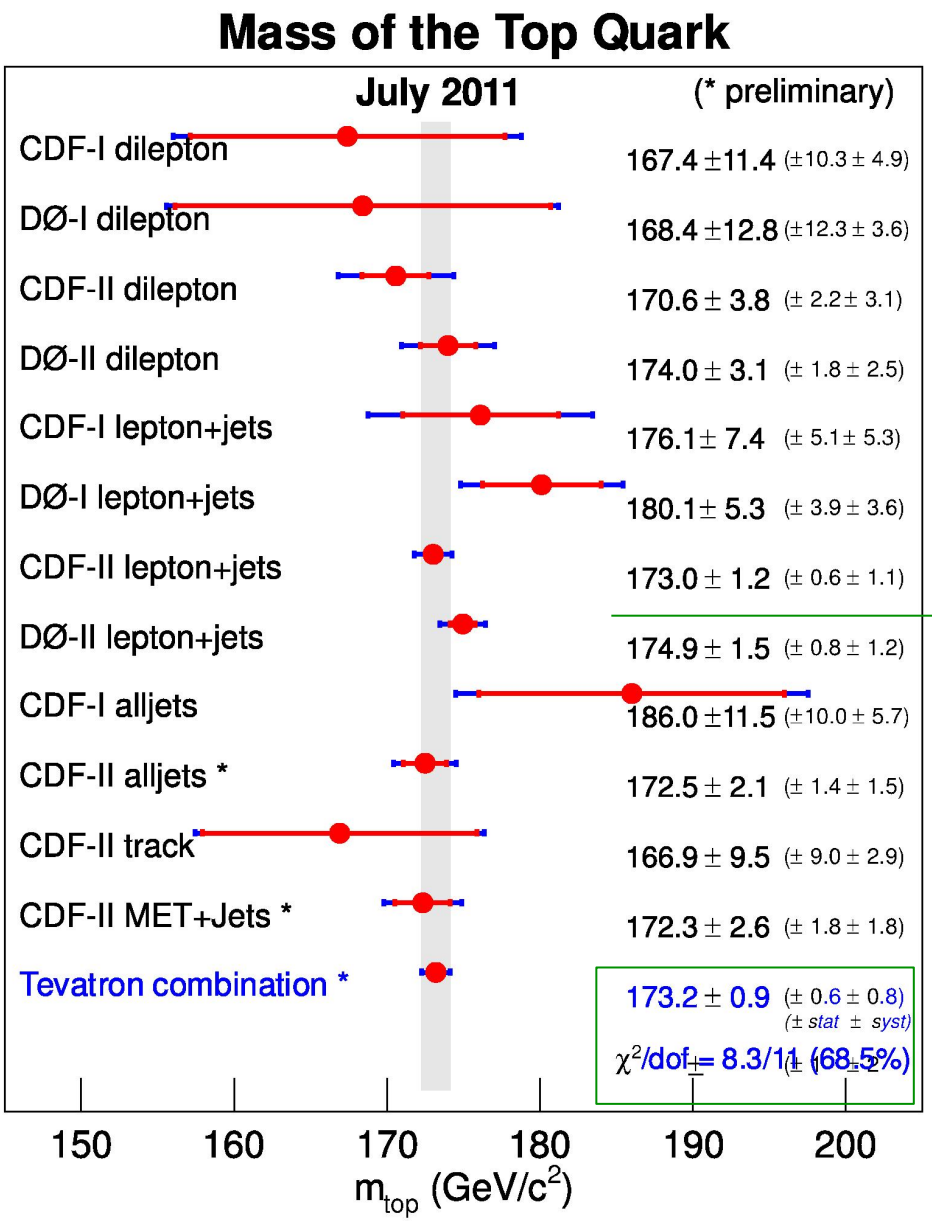
arXiv:1201.5172

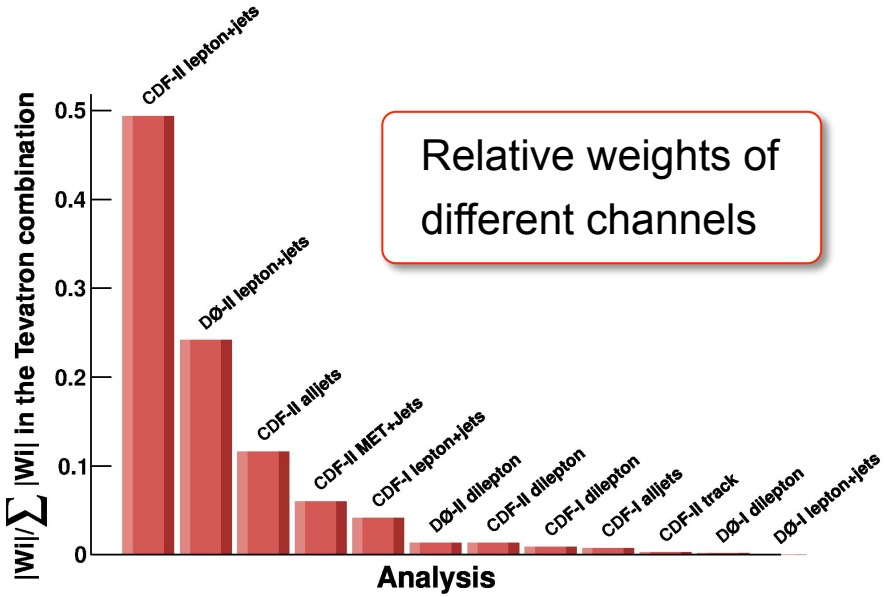


$$M_t = 174.0 \pm 2.4\ (\text{stat.}) \pm 1.4\ (\text{syst.}) = 174.0 \pm 2.8\ \text{GeV/c}^2$$

- JES and generator systematics dominate the total
- Approximately 7% smaller error than similar analysis w/o new treatment of JES.

Tevatron M_t Combination with 5.8 fb^{-1}





Relative weights of different channels

Update with 8.7 fb^{-1}:

$$M_t = 172.9 \pm 1.1 \text{ GeV/c}^2$$

- Precision better than 1.0 GeV (0.54%)
- Consistency between individual measurements and also channels [χ^2(dilepton vs. lepton+jets)=1.77/1]

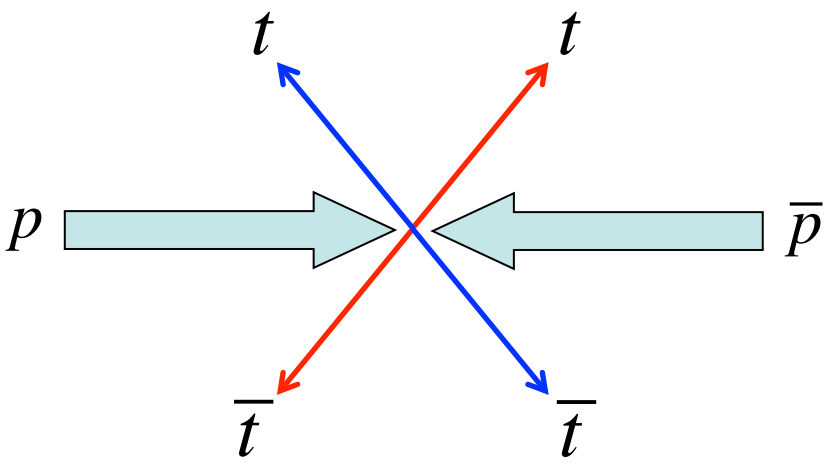
Tevatron M_t Combination with 5.8 fb^{-1}

$$M_t = 173.2 \pm 0.6(\text{stat.}) \pm 0.8(\text{syst.}) = 173.2 \pm 0.9 \text{ GeV/c}^2$$

Error Source	Tevatron Combined Value (GeV/c^2)
Signal Modeling (ISR/FSR, PDF, Generator, Colour-Reconnection)	0.51
Jet Energy Scale (JES) Related	0.49
Backgrounds	0.26
Other Experimental (Lepton Energy Scale, Detector Modeling)	0.18
Total Systematic	0.76
Statistical	0.56
Total	**0.94**

- Some systematics (JES) have statistical components : hence an improvement with the final dataset can still be expected.

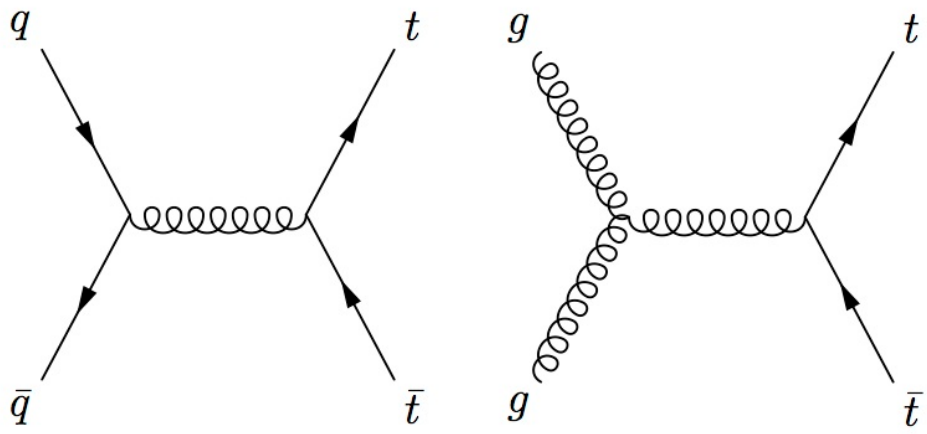
Top Forward-Backward Asymmetry



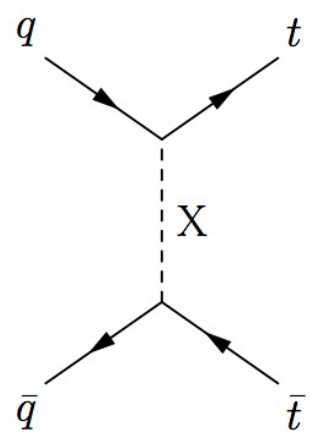
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

where : $\Delta y = y_t - y_{\bar{t}}$

LO production mechanisms are symmetric : A_{FB}=0

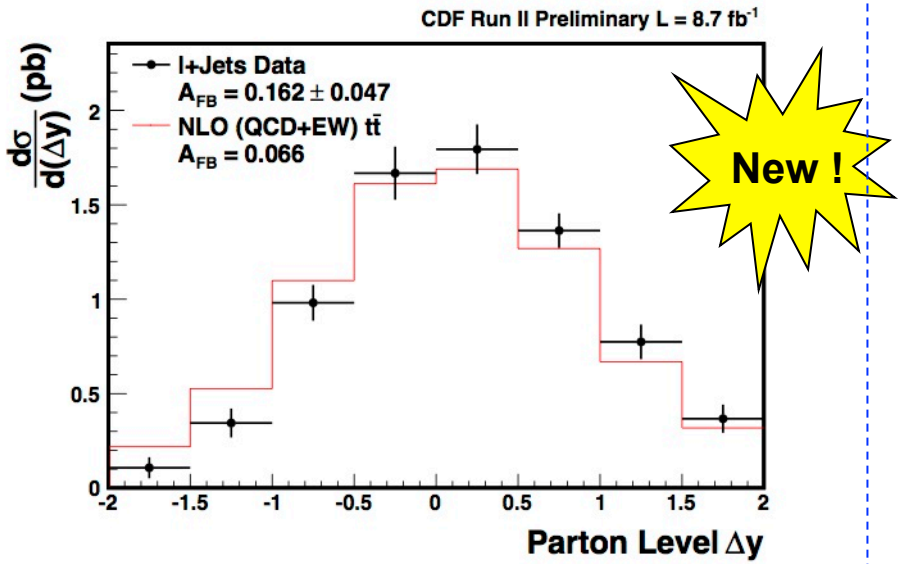


New physics can be asymmetric :

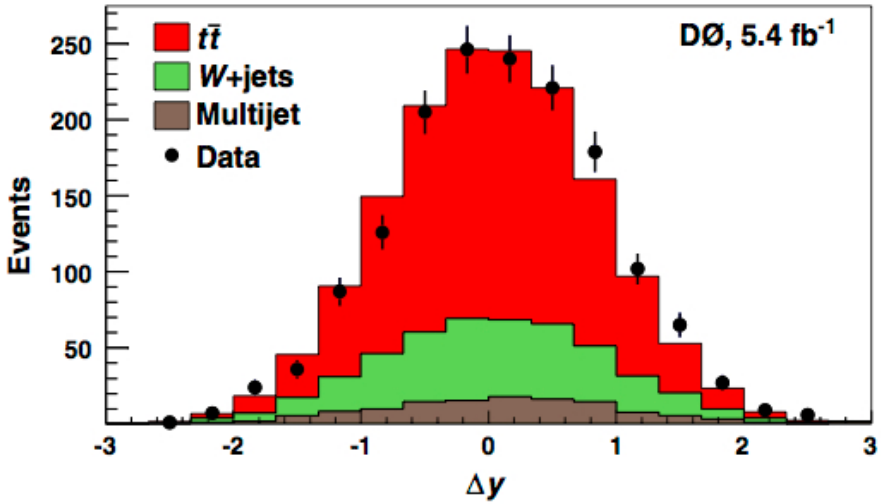


Higher order QCD effects can give a small $A_{FB} \approx$ 6-7%

Top Forward-Backward Asymmetry

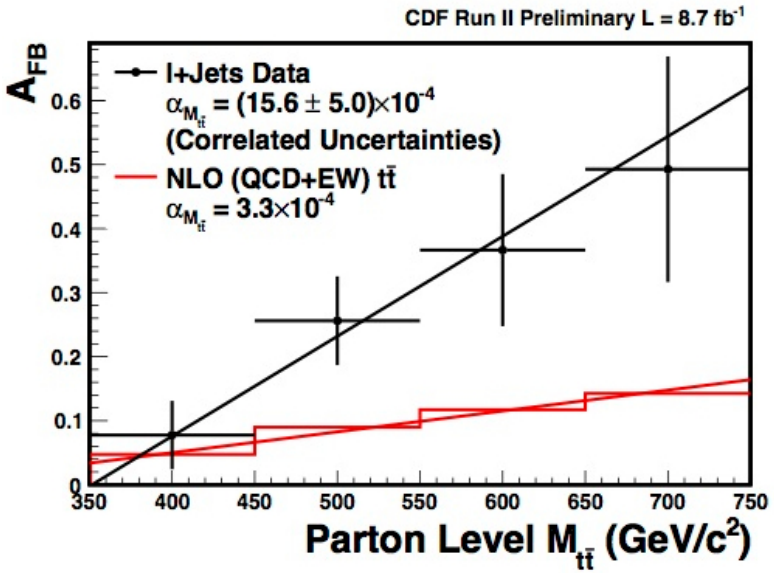


PRD 84, 112005 (2011)



- Analysis in lepton+jets mode with 5.4 fb^{-1}

$$A_{FB}(\text{inclusive}) = 0.196 \pm 0.065$$



- Analysis in lepton+jets mode with 8.7 fb^{-1}

$$A_{FB}(\text{inclusive}) = 0.162 \pm 0.047$$

- In agreement with previous results with 30% smaller uncertainty.
- Linear empirical parameterisations of A_{FB} versus $t\bar{t}$ invariant mass and Δy.

Combined Higgs Search with ≤ 10 fb^{-1}

New !

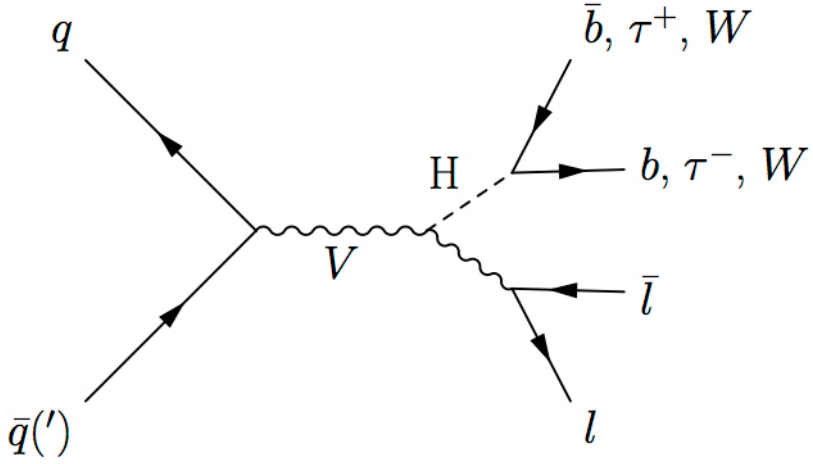
- 20 decay channels combined, the most important ones with full luminosity.
- Large number of analysis improvements :
  - Additional acceptance (e.g. loose lepton categories, cut optimisation)
  - Improved b-tagging (boosted decision tree/neural network)
  - Improved multi-variate analysis techniques for a number of different topologies.

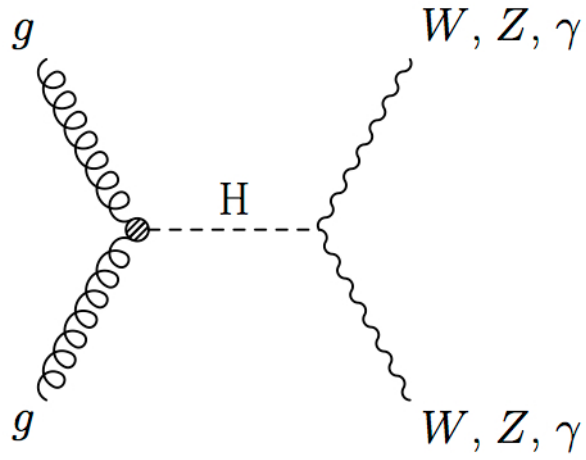
M_H < 125 GeV
Sensitivity dominated by :

$$VH \to \ell\nu b\bar{b}, \ell^+\ell^- b\bar{b}, \nu\bar{\nu} b\bar{b}$$

M_H > 125 GeV
Sensitivity dominated by :

$$H \to W^{(*)}W^{(*)}$$





+ VBF, $t\bar{t}H$

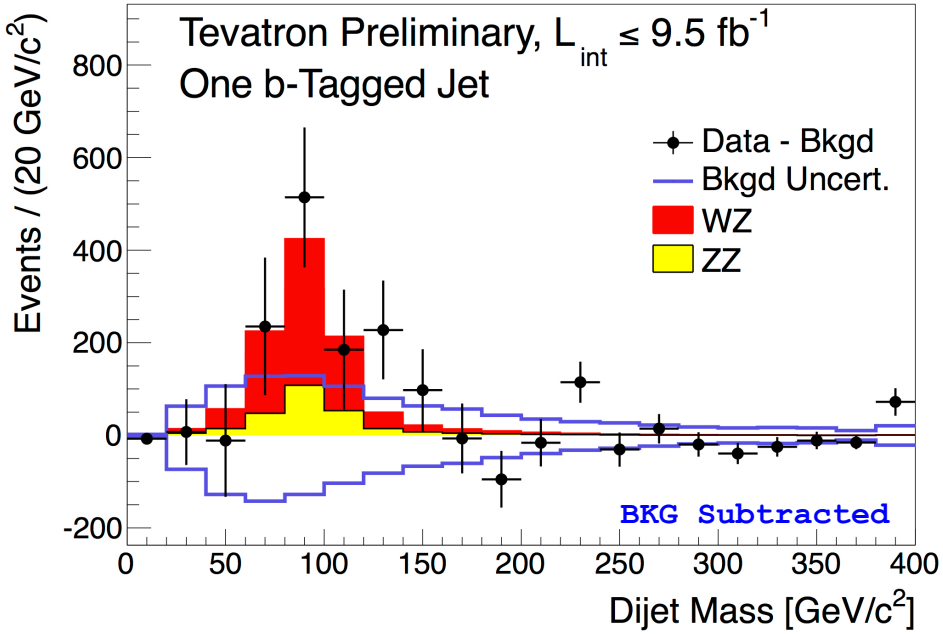
Higgs Search : Sensitivity Demonstration

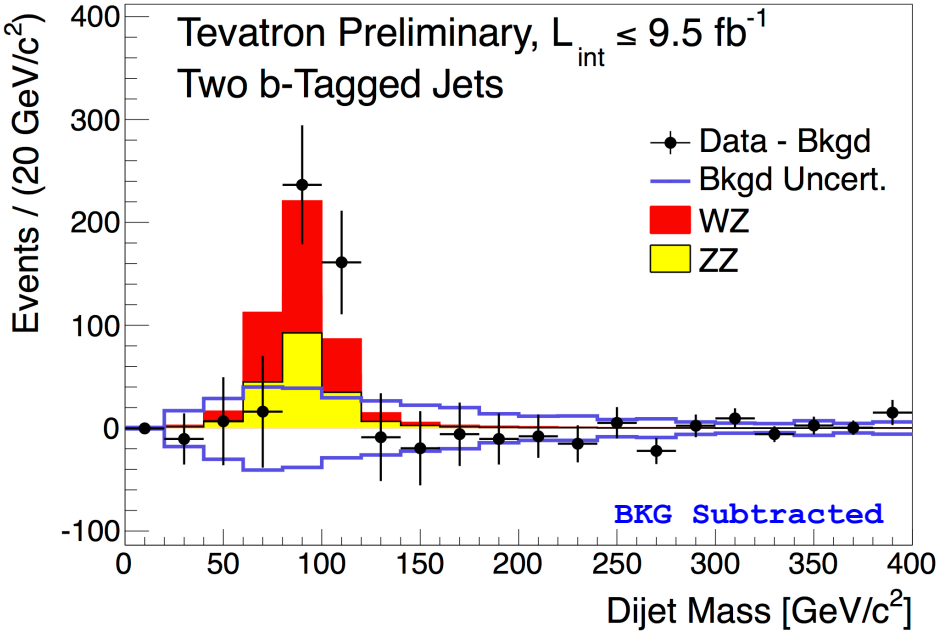
New !

- WZ/ZZ production provides an ideal *standard candle* for low-mass Higgs searches:

$$VZ \rightarrow \left.\begin{array}{l} \ell\nu b\bar{b} \\ \ell^+\ell^- b\bar{b} \\ \nu\bar{\nu} b\bar{b} \end{array}\right\}$$

- b-tagging
- di-jet mass reconstruction
- signal & background modelling

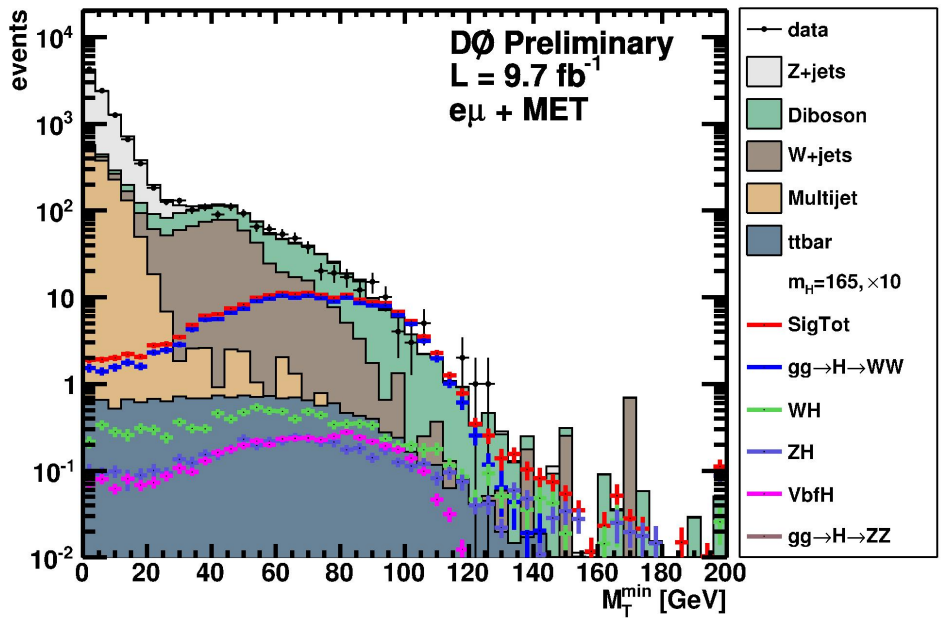




$$\sigma(WZ+ZZ) = 4.47 \pm 0.64(\text{stat})\ ^{+0.73}_{-0.72}(\text{syst})\ \text{pb}$$

$$\sigma(WZ+ZZ)_{\text{SM}} = 4.4 \pm 0.3\ \text{pb}$$

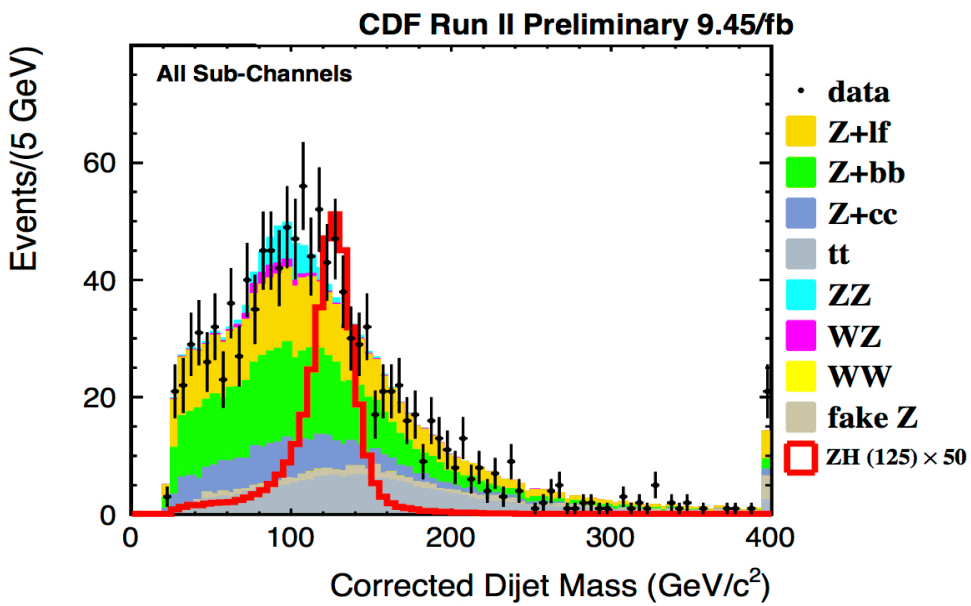
Higgs Searches : Example Channels



$$H \to WW \to \ell^+\ell^-\nu\bar{\nu}$$

- Optimise sensitivity by splitting into flavour and jet-multiplicity sub-sets.
- Boosted Decision Tree discriminants.

$$M_T^{\min} = \min\left(M_T^{\ell_1}, M_T^{\ell_2}\right)$$

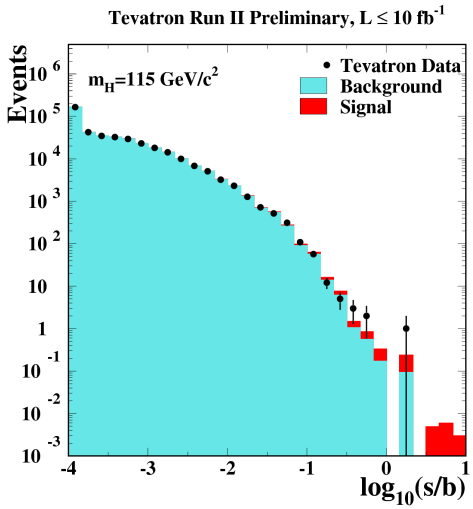


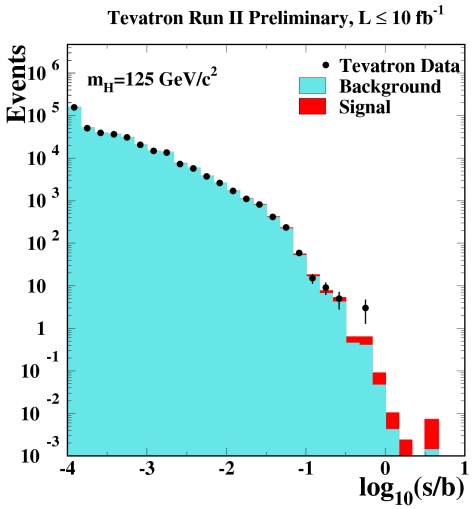
$$ZH \to \ell^+\ell^-b\bar{b}$$

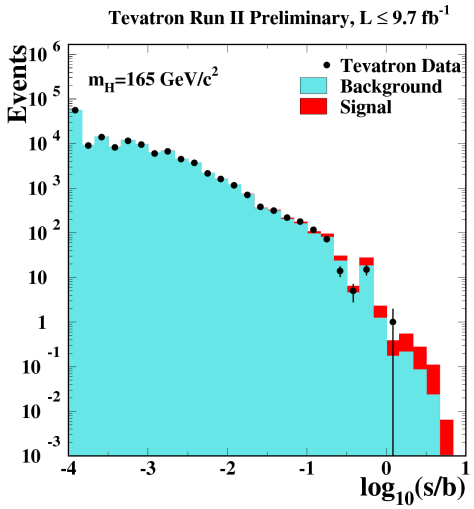
- New multi-variate b-jet identification, di-jet mass reconstruction and neural network background discrimination.
- 34% increase in signal sensitivity.

Higgs Search : Combining Channels

- Aggregate the discriminant distributions across all channels, combining bins of equal S/B:

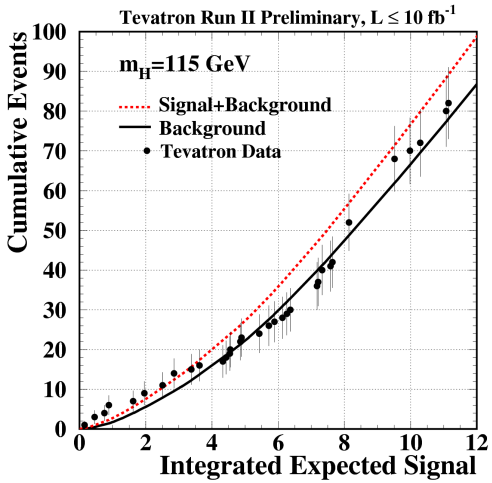


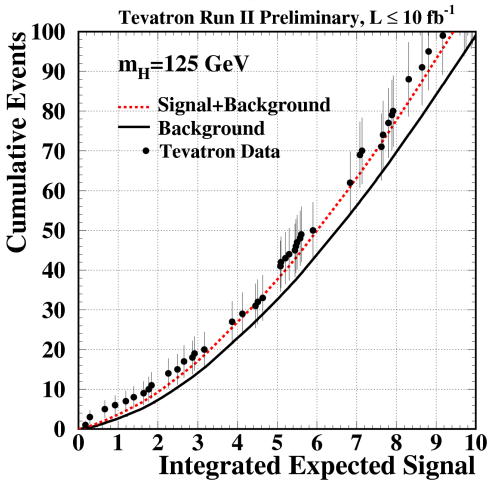


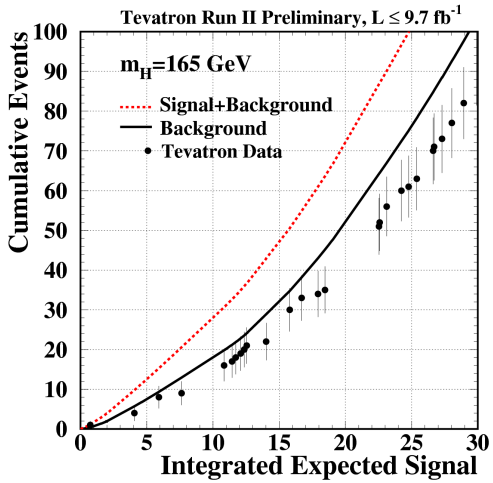


- Integrate from $(S/B)_{max}$ downwards :

Consistent with (S+B) [correlated errors !]







Higgs Search : Combining Channels

- Bayesian :

N_C analysis channels

N_b bins per channel

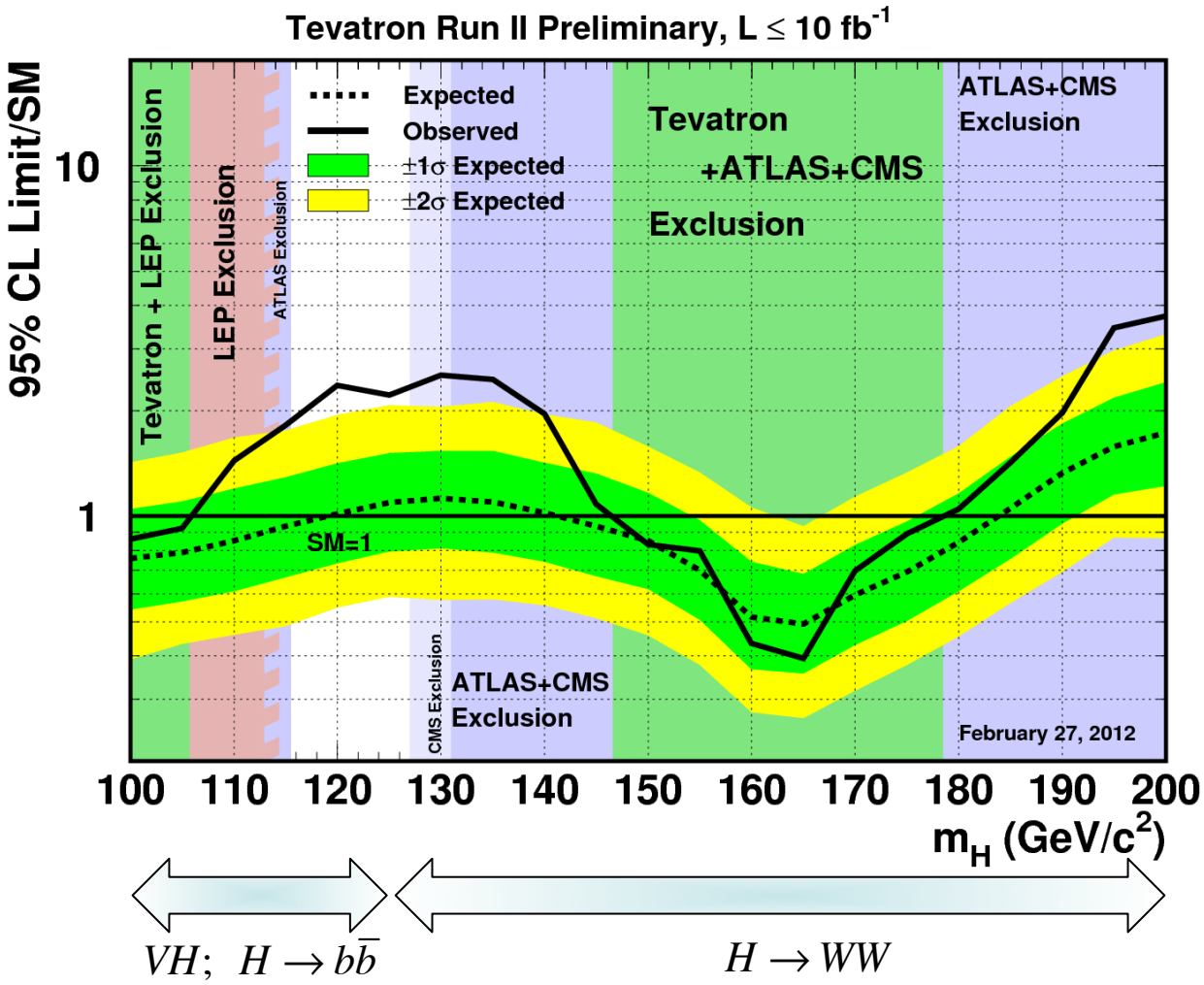
$$\mathcal{L}\left(R,\vec{s},\vec{b}\,\middle|\,\vec{n},\vec{\theta}\right) \times \pi\left(\vec{\theta}\right) = \prod_{i=1}^{N_C}\prod_{j=1}^{N_b} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}} \Big/ n_{ij}! \times \prod_{k=1}^{n_{np}} e^{-\theta_k^2/2}$$

$$\mu_{ij} = \underbrace{R \times s_{ij}\left(\vec{\theta}\right) + b_{ij}\left(\vec{\theta}\right)}_{\text{scaled signal + background expectation in each bin}}$$

Gaussian nuisance parameters

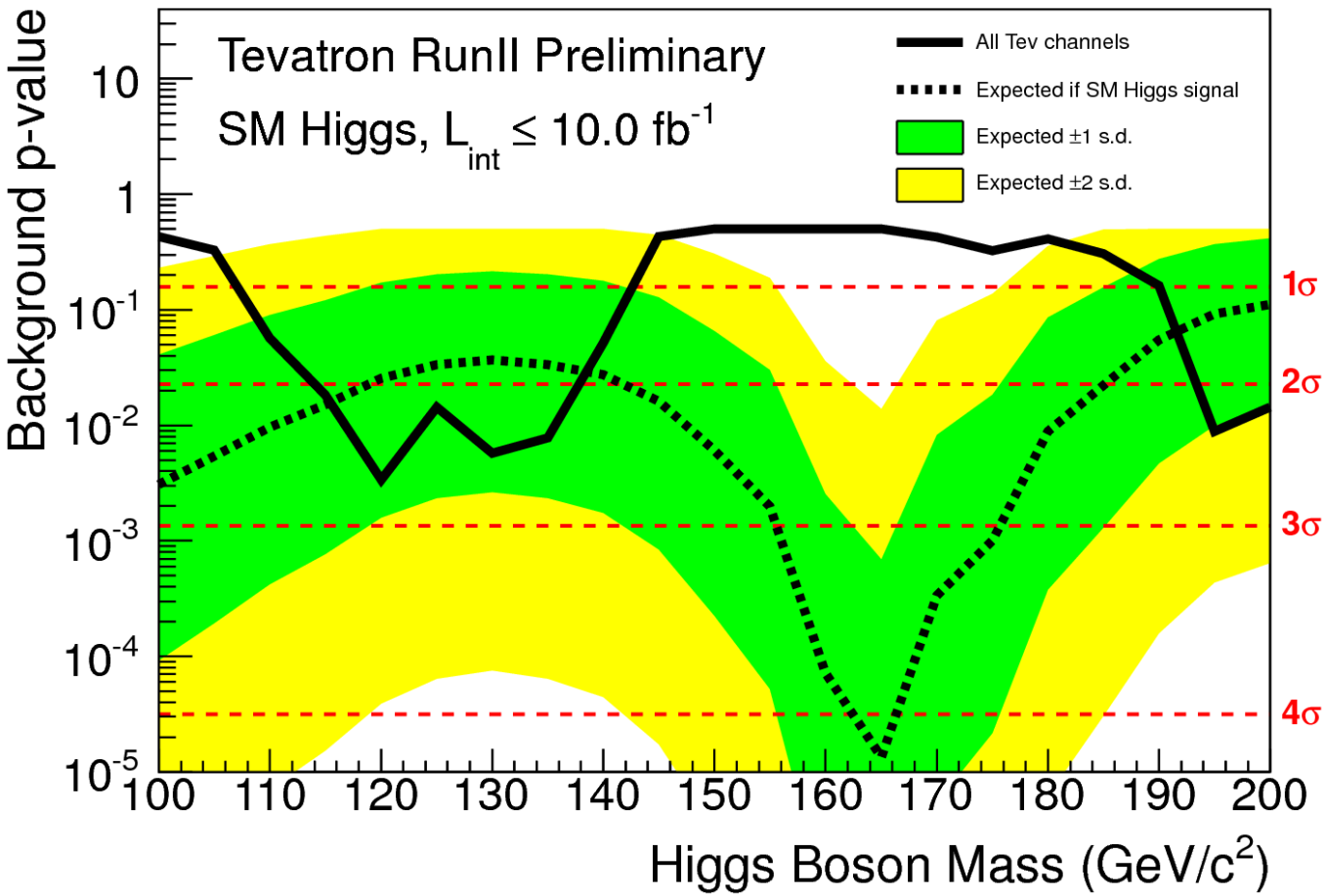
- Cross-checked with modified frequentist treatment (i.e. CL_S), used to provide p-values.

Combined Higgs Searches : Results



- Observed exclusion : **$100 < m_H < 106$ GeV/c^2** **$147 < m_H < 179$ GeV/c^2**
- Expected exclusion : **$100 < m_H < 119$ GeV/c^2** **$141 < m_H < 184$ GeV/c^2**

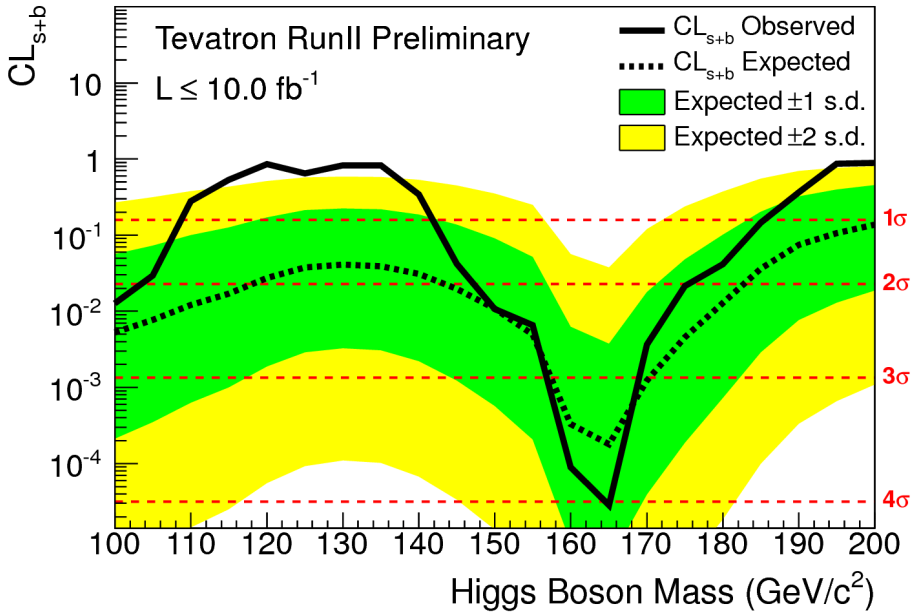
Combined Higgs Search : p-Value

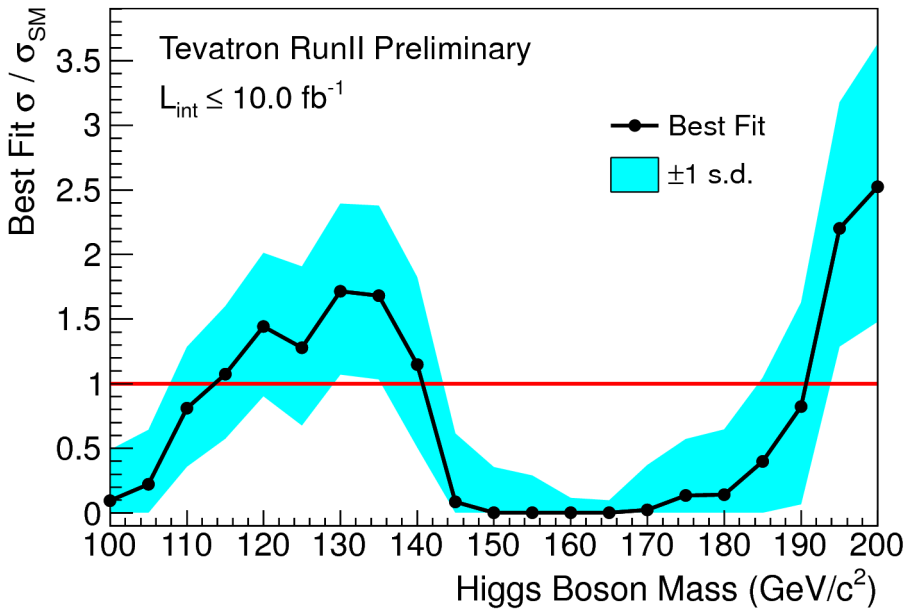


- The smallest local p-value corresponds to **2.7σ**
- An estimate of the *look-elsewhere effect* over the full range reduces this to **~2.2σ**

  [Not a large effect due to the "resolution" of each search point]

Combined Higgs Search : Signal Compatibility



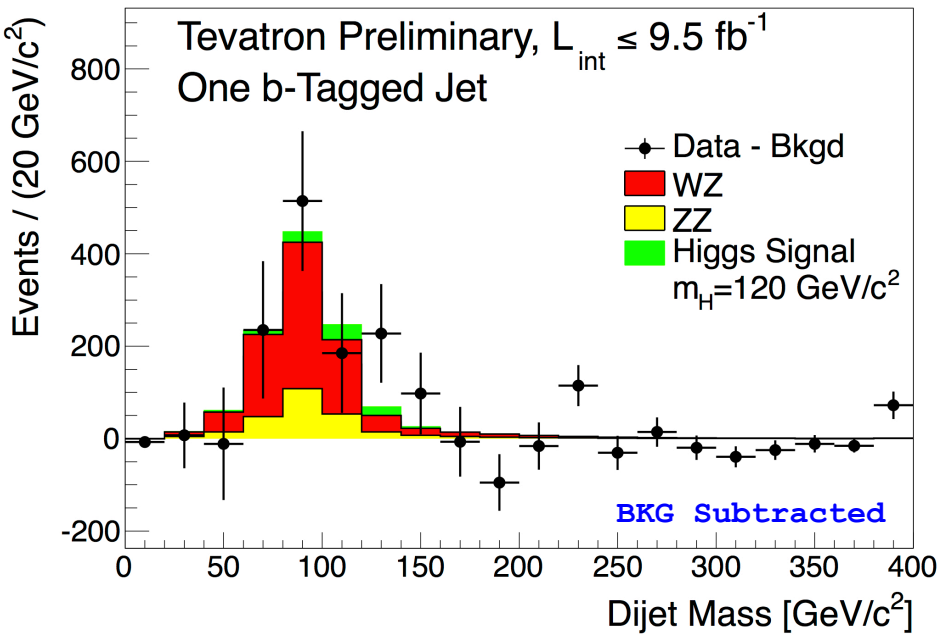


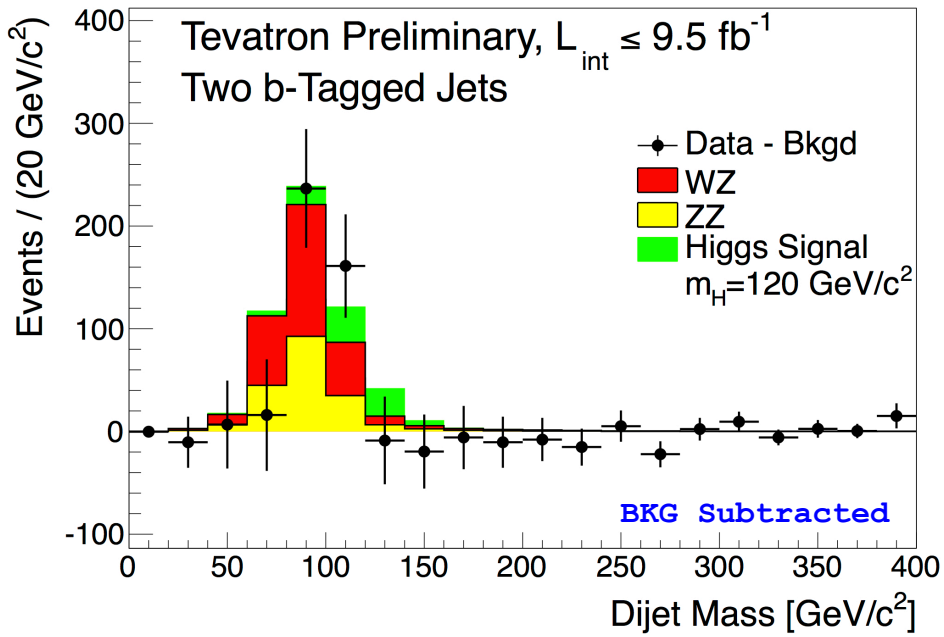
confidence level of signal hypothesis larger than expected for background-only

best-fitting signal size is larger than SM but consistent within (large) errors.

Combined Higgs Search : Signal Compatibility

- Would such a signal be consistent with the di-boson control sample discussed earlier ?
- Overlay the signal prediction for m_H = 120 GeV/c^2 :

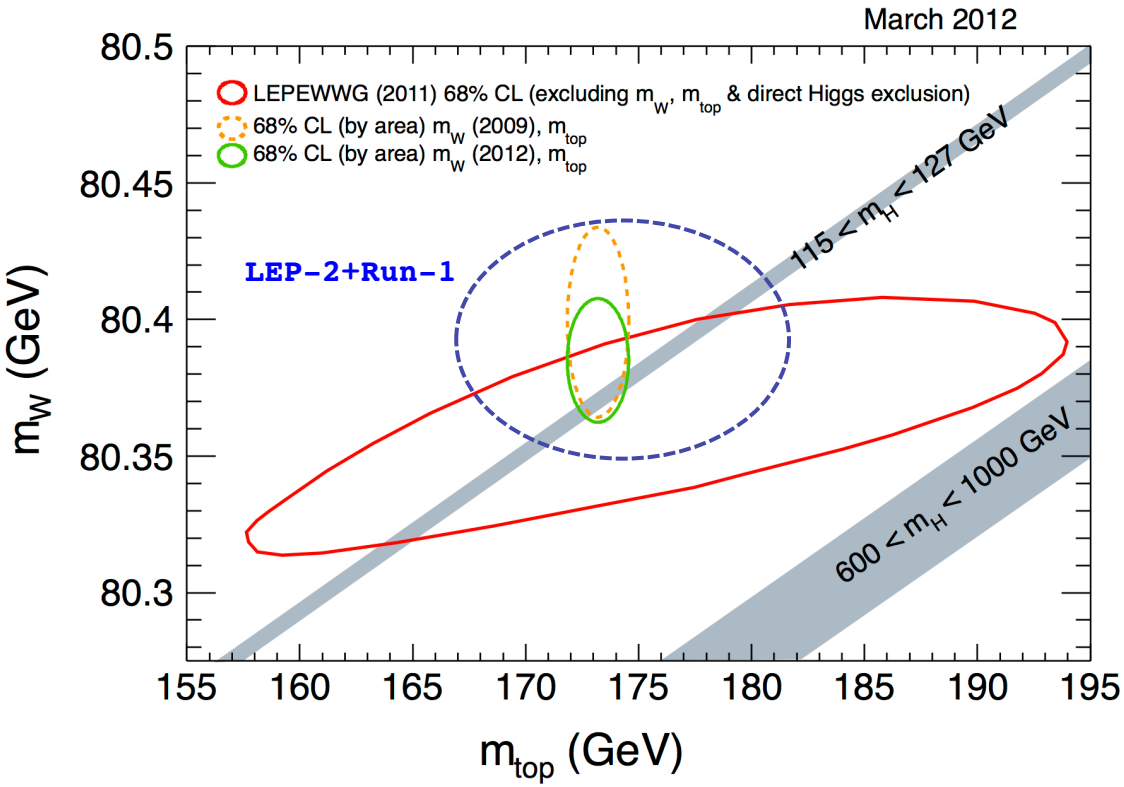




- The data are *not inconsistent* with such a signal .
- Quite compatible with a measurement of σ(WZ+ZZ) in agreement with SM (no Higgs) prediction.

Summary

- A new precision measurement of M_W from the Tevatron has reduced the World Average uncertainty by one third :



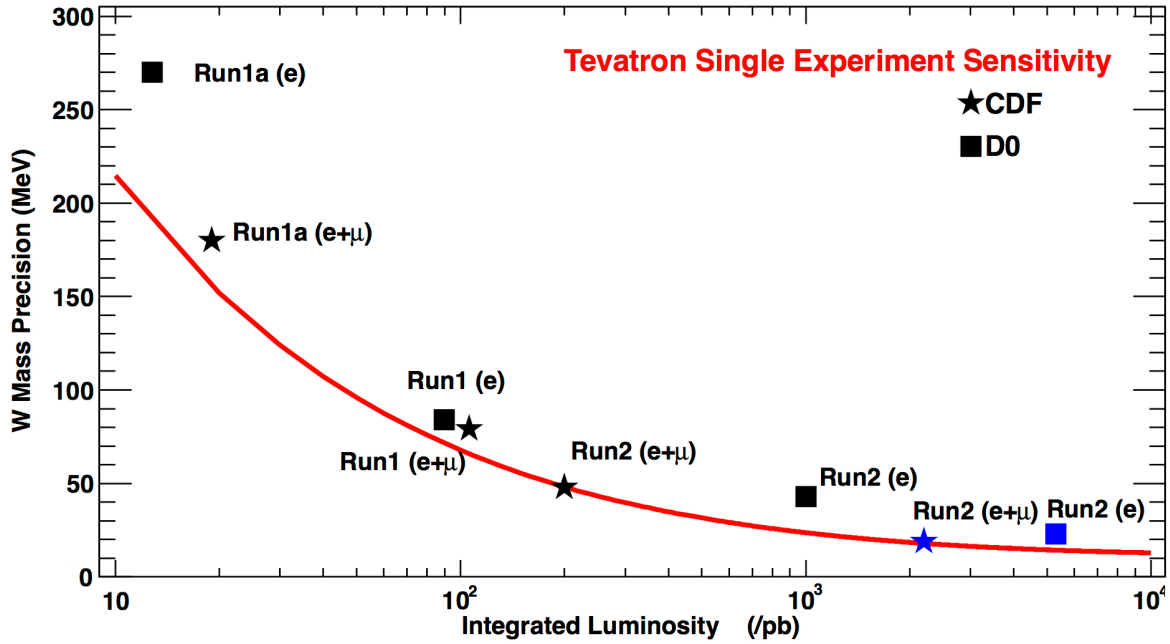
$$M_W = 80385 \pm 15 \text{ MeV}$$
$$M_{top} = 173.2 \pm 0.9 \text{ GeV}$$

$$M_H = 94^{+29}_{-24} \text{ GeV}$$
$$M_H < 152 \text{ GeV@95\% C.L.}$$
(LEPEWWG/Zfitter)

- Almost final Higgs searches using the full Tevatron data have excluded **$100 < m_H < 106$ GeV/c^2** and **$147 < m_H < 179$ GeV/c^2**.
- There is an excess in the mass range 115-135 GeV with a statistical significance of **2.2σ**

Outlook

- Improvements in M_{top} precision of between 10-15% are still possible using the full dataset and including the latest analysis improvements.
- The W mass measurement will be further improved – for CDF only ¼ of the final dataset has been analysed :



- Model systematics are becoming the limiting factor. New techniques or inputs required to reduce the PDF uncertainty on M_W.
- Precision electroweak measurements - especially M_{top} and M_W - are incredibly difficult and will be an enduring legacy of the Tevatron.