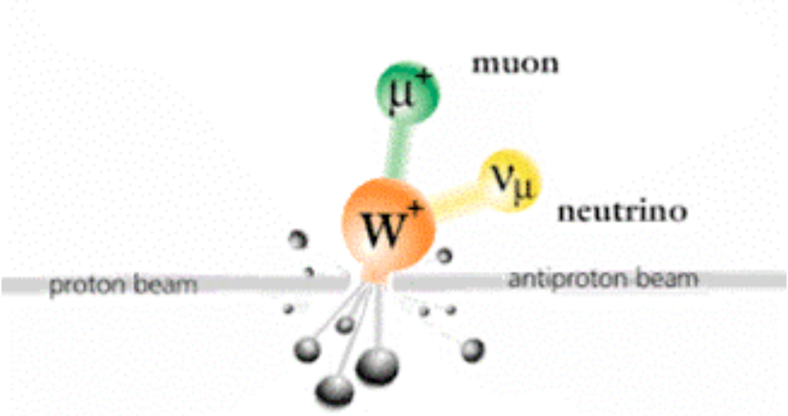
2010 - 05 - 10

The W-mass Measurement at CDF



Ilija Bizjak, University College London

Outline

1) Motivation for a W mass measurement
   Implications for the EW constraints on Higgs mass

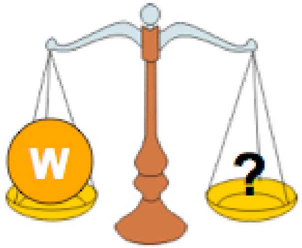
2) Measurement of the W mass at CDF

3) A look at the $\approx 2.4 \text{fb}^{-1}$ data

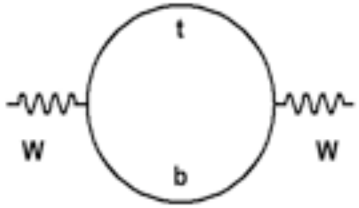
4) Current status

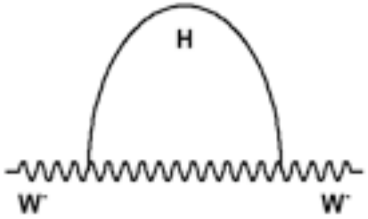
5) Conclusion

Motivation for W mass measurements



$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\left(\frac{1}{1-\Delta r}\right)$$

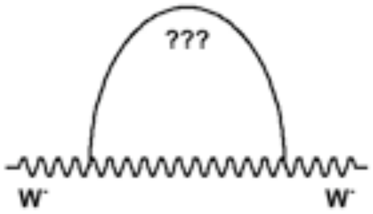




Radiative corrections (Δr) dominated by top quark and Higgs loop allows constraint on Higgs mass

$\Delta m_W \propto m_t^2$ $\Delta m_W \propto \ln(m_H/m_Z)$

With improved precision also sensitive to possible exotic radiative corrections



To achieve a similar constraint on m_H : $\Delta M_W \approx 0.006\ \Delta M_t$
Current ΔM_t = 1.3GeV corresponds to ΔM_W = 8MeV

The m_H constraint is limited by the uncertainty on M_W

Measurement History

1967 -- SU(2)xU(1) theory: weak force mediated by W and Z bosons

1983 -- W discovery UA1,UA2 @ SppS ($\sqrt{s}$ = 546GeV)

-- W mass = 81 ± 5 GeV

1990 -- First W mass with precision < 1GeV (UA2, $\sqrt{s}$ = 630GeV)

1992-1995 -- Tevatron Run I measurements (CDF & D0, $\sqrt{s}$ = 1.8TeV)

combined W mass precision 59MeV

1996-2000 -- LEP ran at $\sqrt{s} > 2M_W$: combined precision 33MeV

(4 experiments, 80375±33MeV)

2001-2011? -- Tevatron Run II: Current combined precision 31 MeV,

CDF plan for this analysis: δM_W<25MeV

2010-? -- ATLAS & CMS : δM_W < 15MeV each ?

Motivation (Current status)

Tevatron Run II results:

CDF(2007) using 200pb^{-1} :

80413 ± 48 MeV

D0(2009) using 1fb^{-1} :

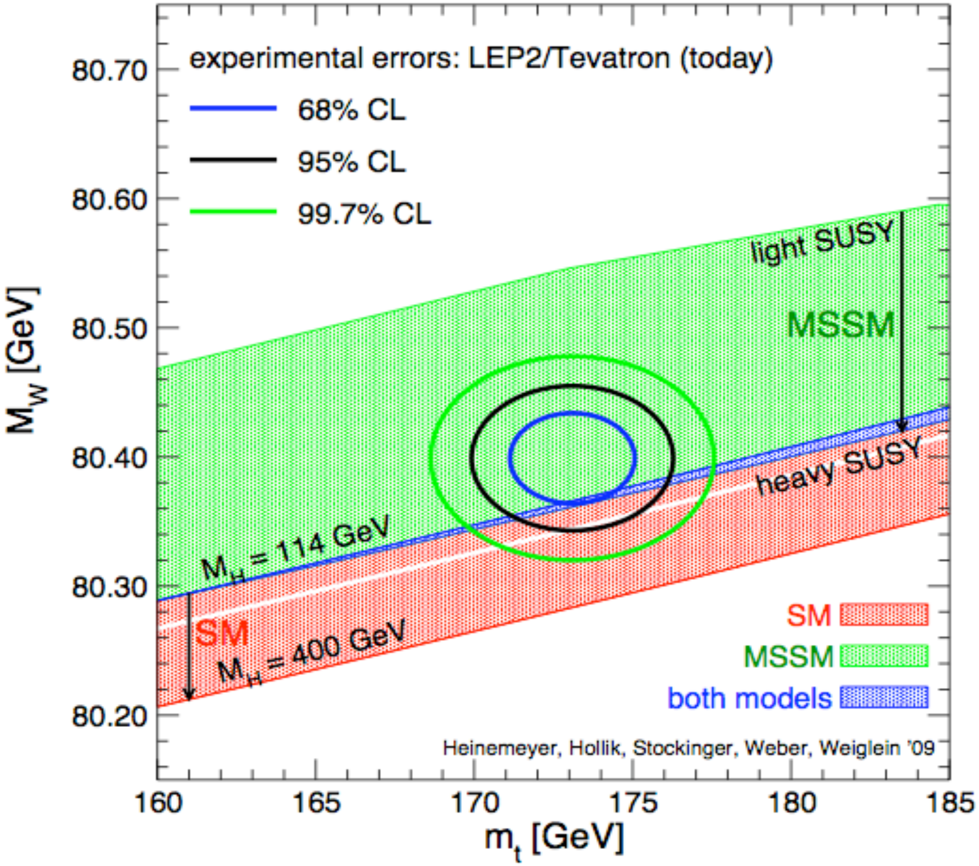
80401 ± 43 MeV

preliminary world average

80399 ± 23 MeV

+

m_t=(173.1±1.3) GeV
[arXiv:0903.2503]



Predicted Higgs mass:

83^{+30}_{-23} GeV

42 < M_H < 158 GeV @ 95% CL

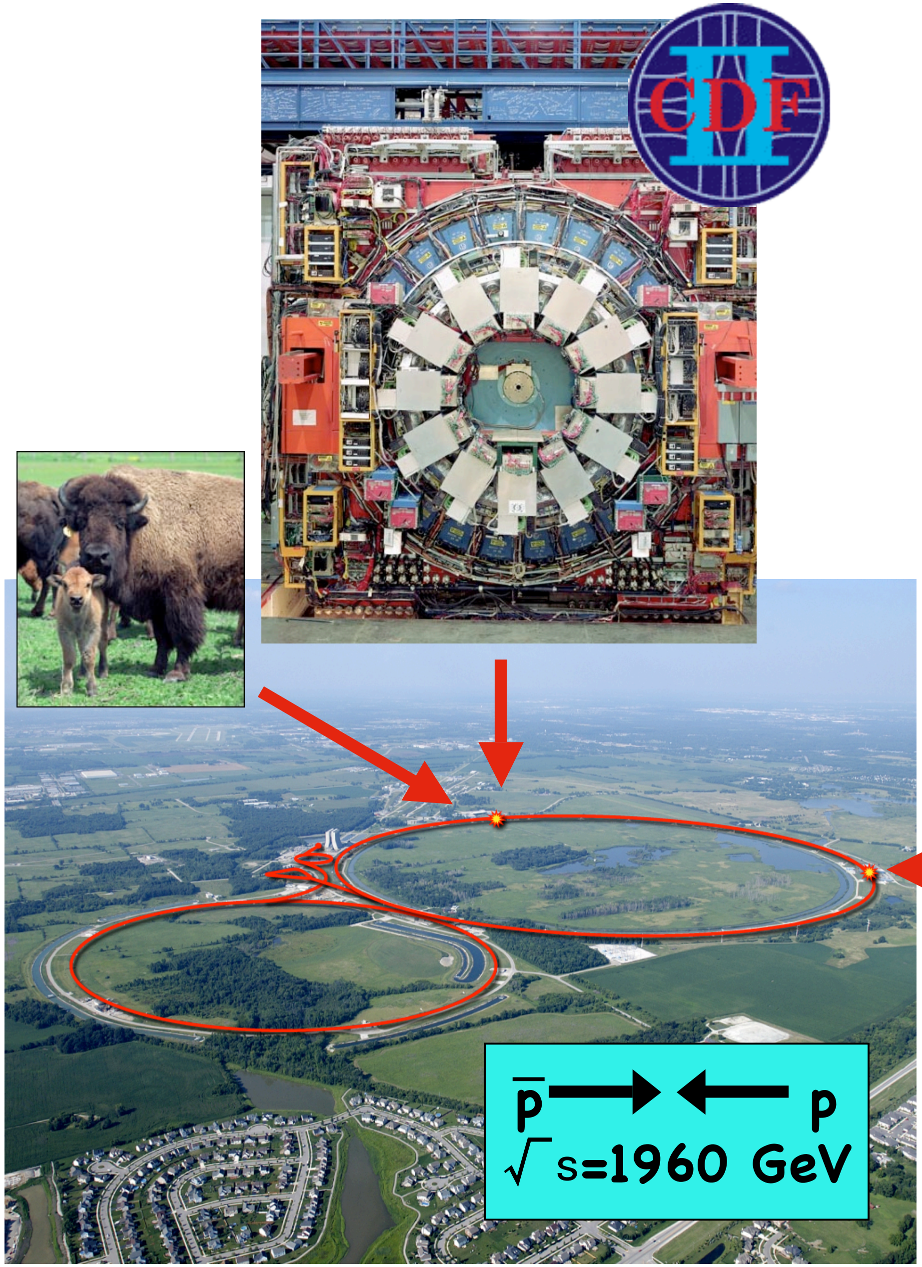
(fits and averages from
http://gfitter.desy.de/GSM/)

If … :

- M_W moves up by 0.5σ
- M_t moves down by 0.5σ
- ΔM_W=15 MeV , ΔM_t = 1 GeV

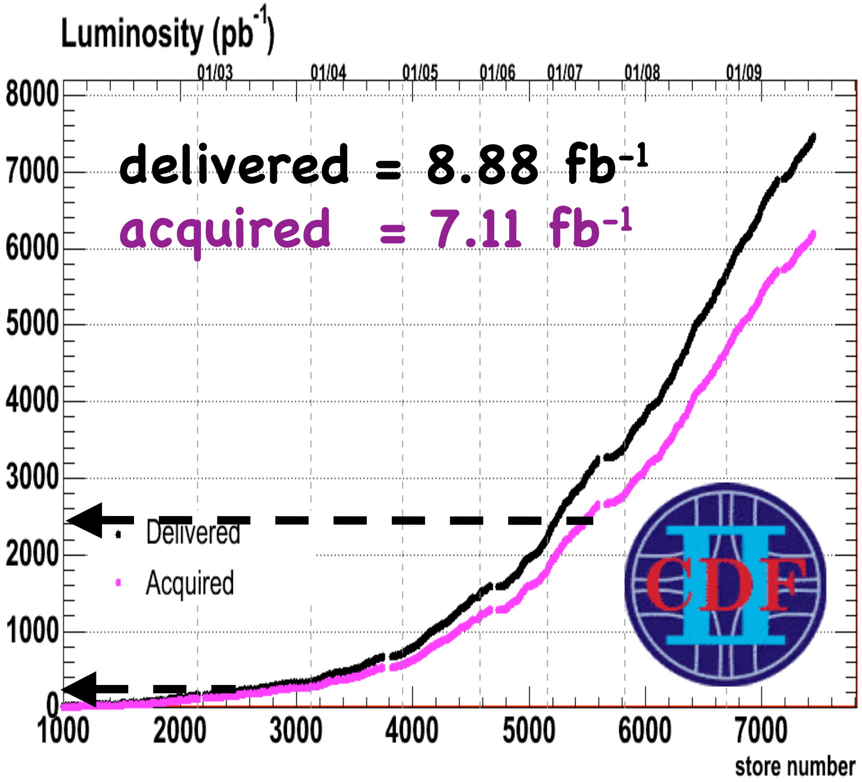
$M_H \approx$ 63±20 GeV,
upper limit of 114 GeV

CDF at the Tevatron



$\bar{p} \longrightarrow \longleftarrow p$

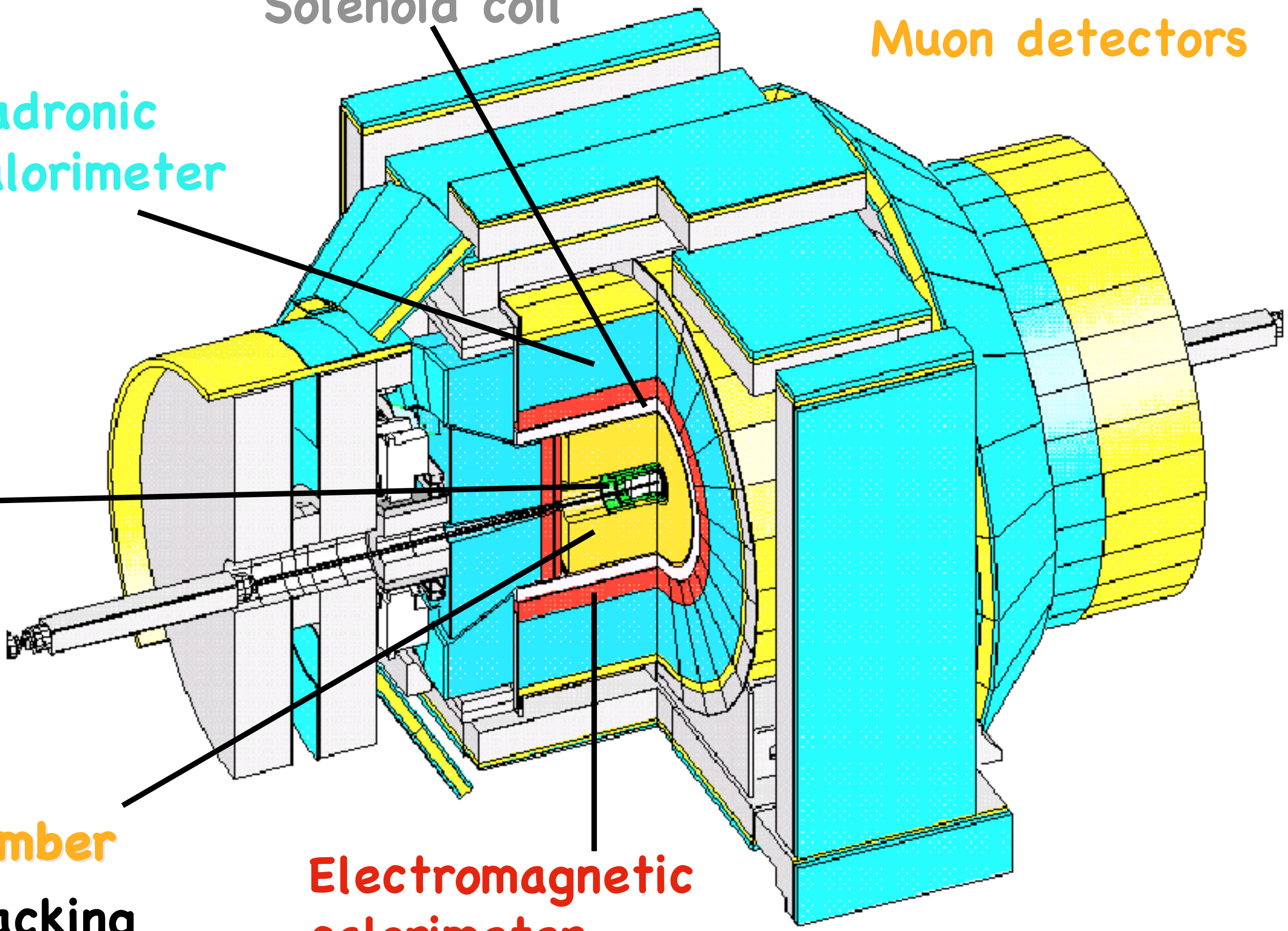
$\sqrt{s}$=1960 GeV



delivered = 8.88 fb^{-1}

acquired = 7.11 fb^{-1}

CDF detector



Solenoid coil

Muon detectors

Hadronic calorimeter

Silicon tracking detector

Central drift chamber

High-precision tracking

$dp_T/p_T = 0.05\% \times p_T$

2% for 40 GeV muon

Electromagnetic calorimeter

$dE_T/E_T = 13.5\%/\sqrt{E} \oplus 1.7\%$

3% for 40 GeV electron

W production and decay I

W produced in $q\bar{q}'$ annihilation

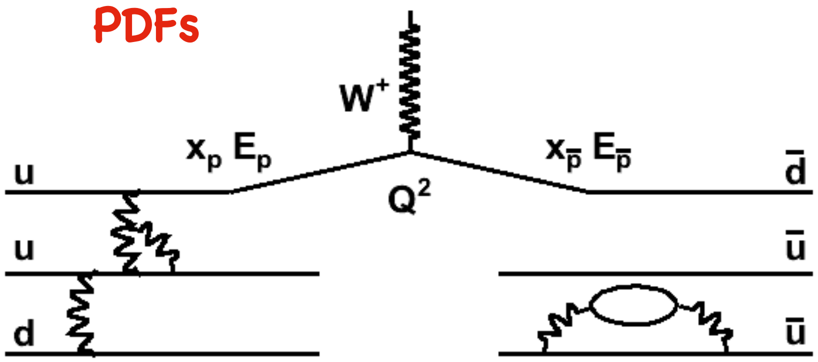
Colliding compound particles

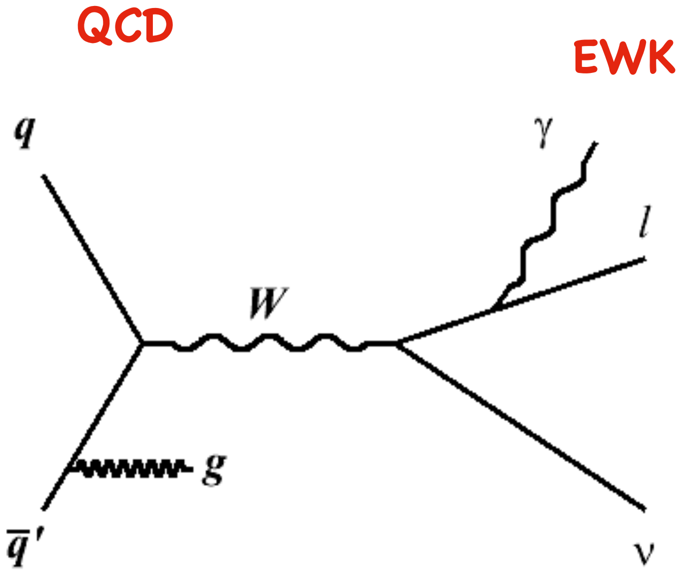
parton energies not known

Interested in W leptonic decays

W boson recoils from initial state gluon radiation

Photons emitted





W production and decay II

Neutrino reconstruction -> transverse plane

$U + p_T^{l} + \not{E}_T = 0$

p_T^{ν} from $\not{E}_T$

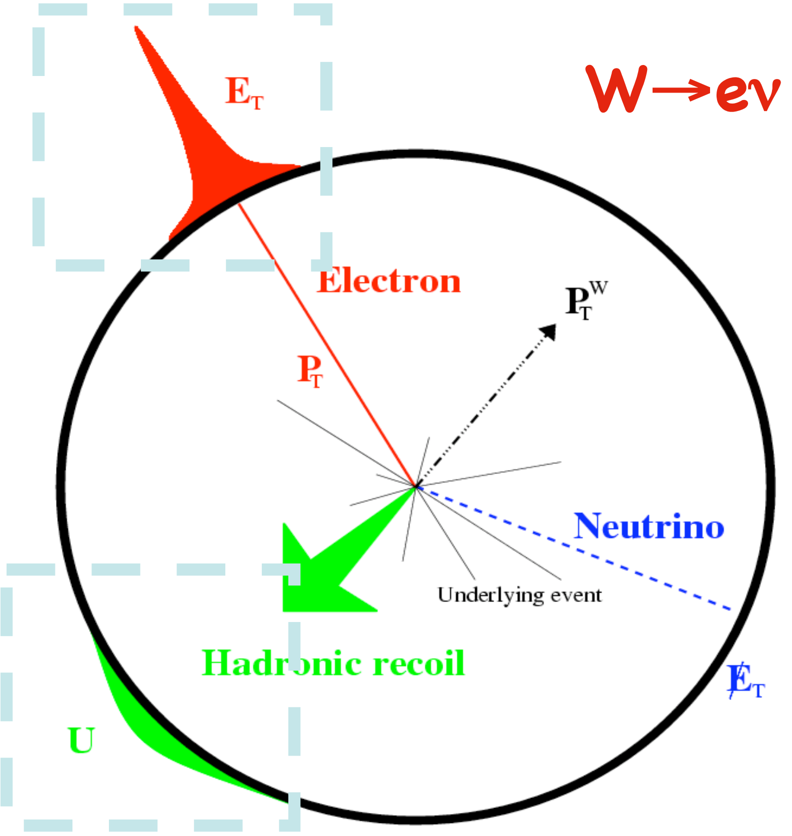
U, p_T^{l} are the measured quantities

p_T^{l} … for muons from tracking, for electrons from calorimetry

U due to the ISR gluon radiation & the underlying event

(all calorimeter deposits - lepton)

Lepton p_T carries most of W mass information



Transverse plane

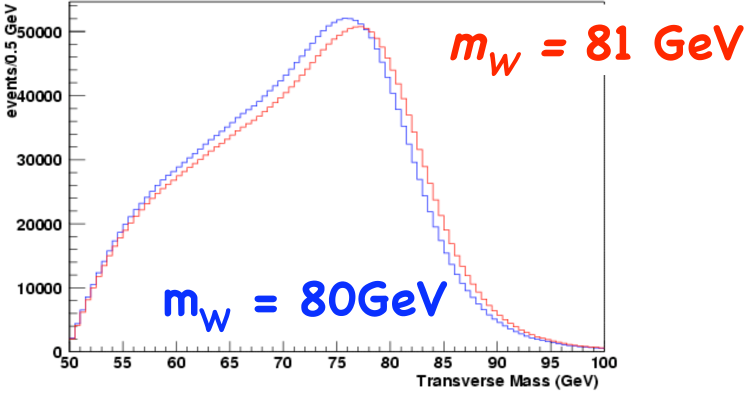
$$m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$$

Find M_W for which the simulated m_T corresponds best to the data

Measurement strategy

W mass template fits
to m_T, transverse lepton
momentum/energy and $\not{E}_T$

m_T template



For template fits we need:

A Fast simulator of
W/Z production/decays

PDFs, boson p_T, EWK corrections

+

With calibrated
detector simulation

Calibrate $l^\pm$ track momentum with mass measurements of J/ψ and Υ(1S)

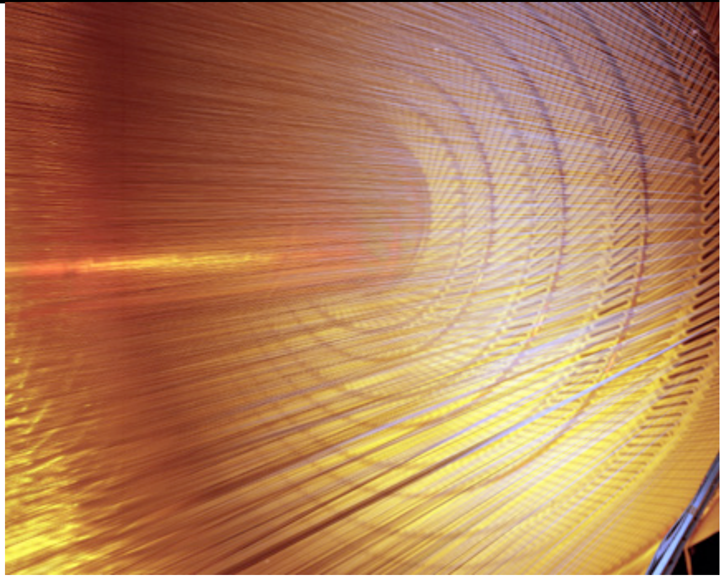
Calibrate calorimeter energy using track momentum of e from W decays

Calibrate recoil simulation with Z decays

+

contribution of backgrounds
added to the templates

Momentum measurement



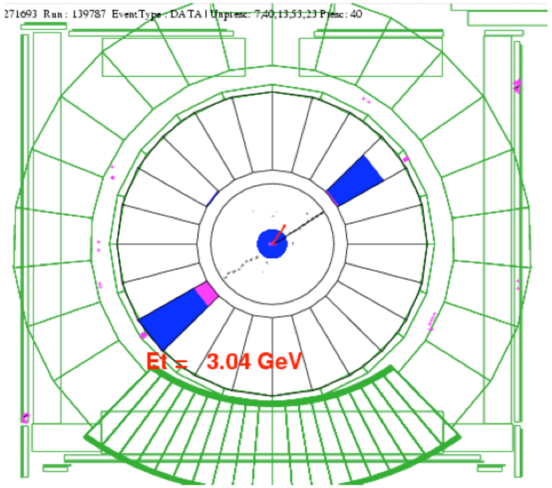
COT (central outer tracker)

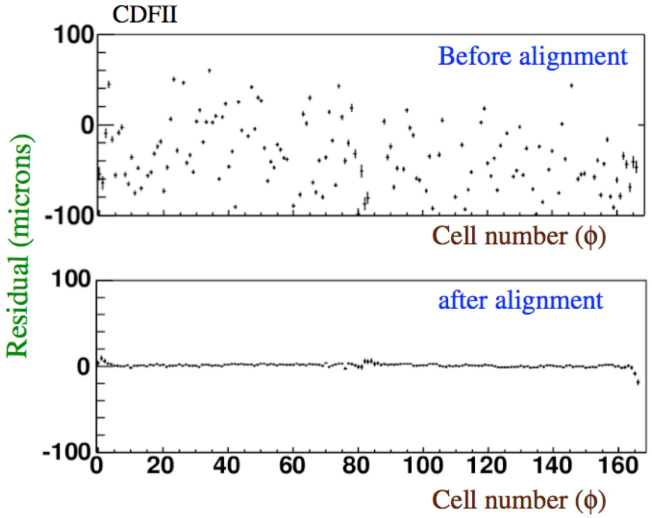
Open cell wire drift chamber

$dp_T/p_T = 0.05\% \times p_T$

2% for 40 GeV muon

Callibration using "cosmics"



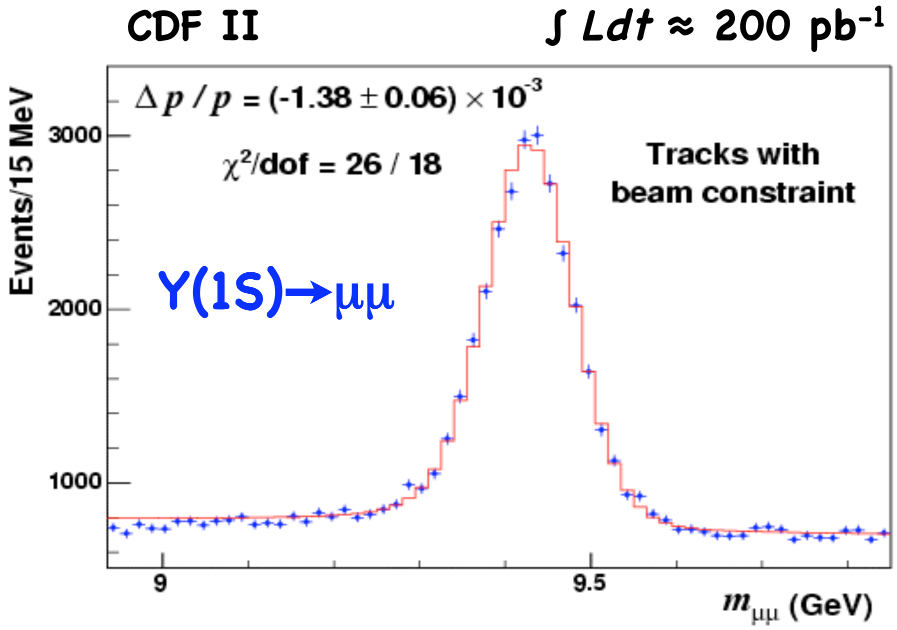


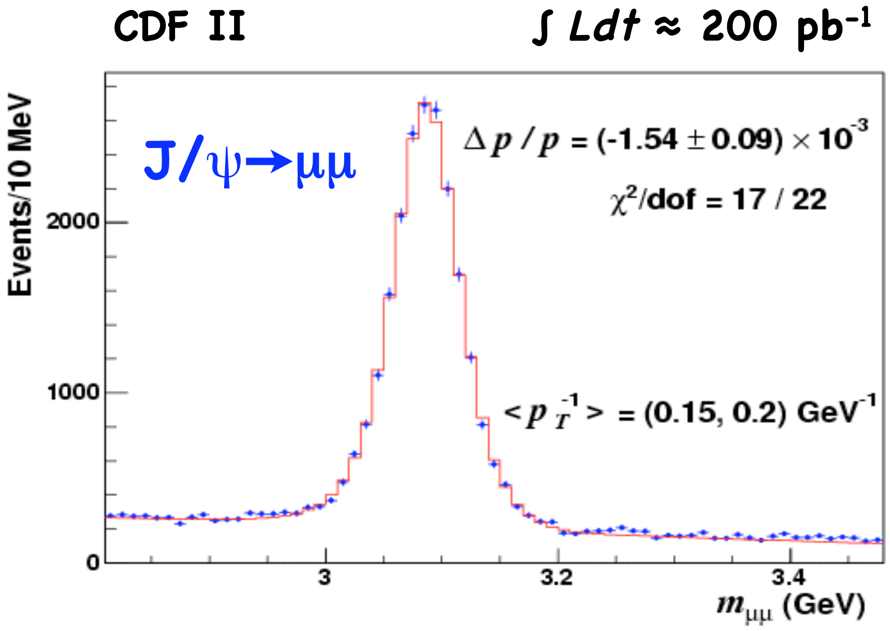
Final cell alignment ≈5μm
(initial alignment ≈50μm)

Need to obtain the momentum scale - using known mass of resonances

Momentum scale using Υ(1S) and J/ψ decays

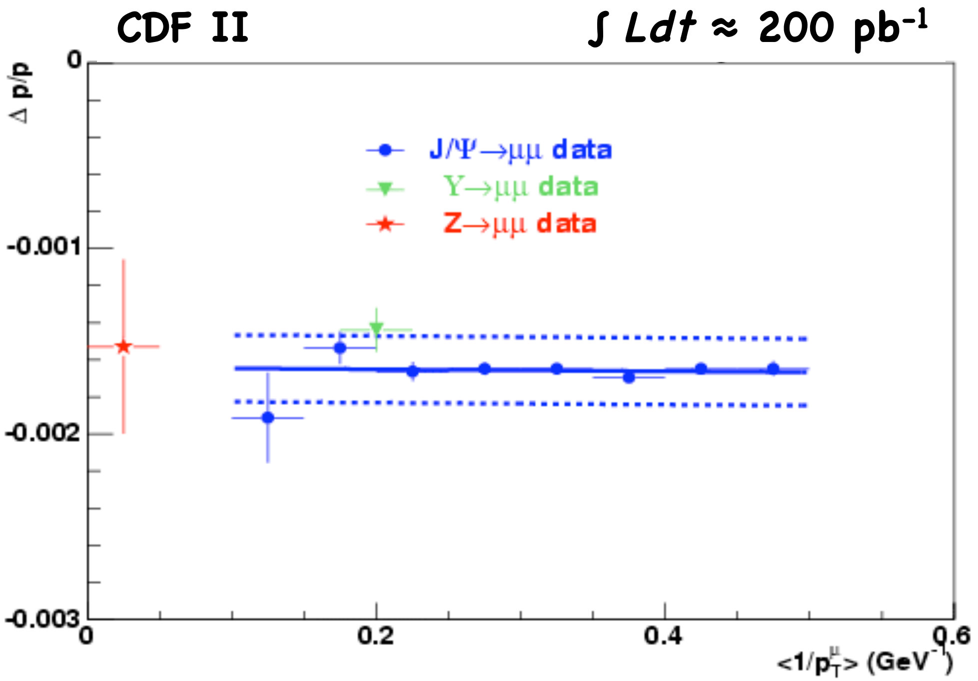
Use precisely determined Υ(1S) and J/ψ masses to tune momentum scale in the μμ decay channel





J/ψ muon momenta much lower than in W/Z decays : fit the scale in bins of $\langle 1/p_T \rangle$ and extrapolate to high momenta

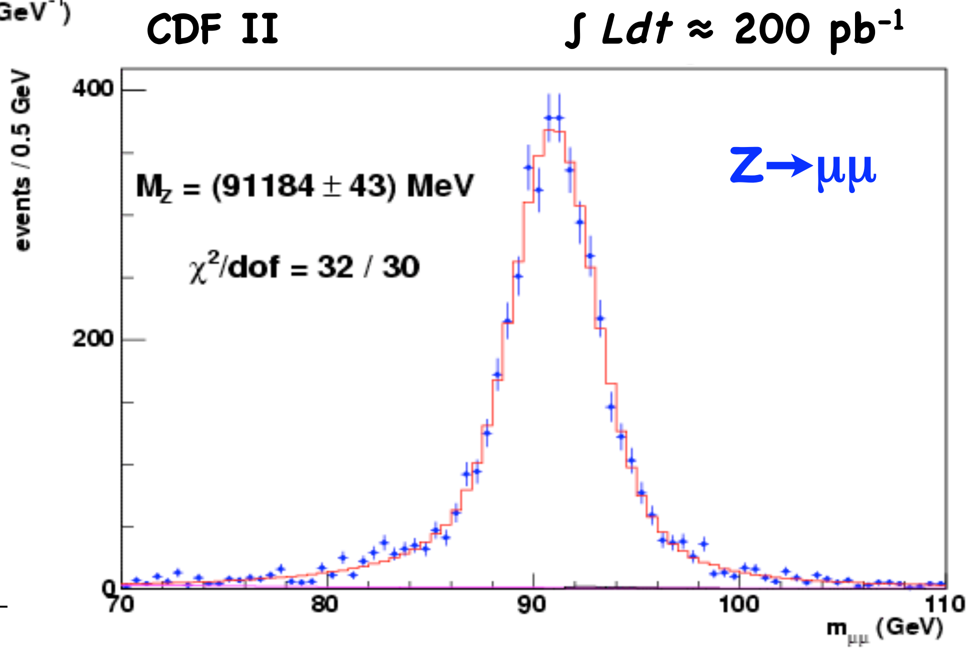
Momentum scale determination



A combined J/ψ and $\Upsilon(1S)$ momentum scale,
with the cross-check in $Z \to \mu\mu$

ΔM_W^μ (momentum scale) = 17MeV

Test the calibrated momentum scale: measure Z mass and compare to the world average (91188 MeV)



Electron simulation

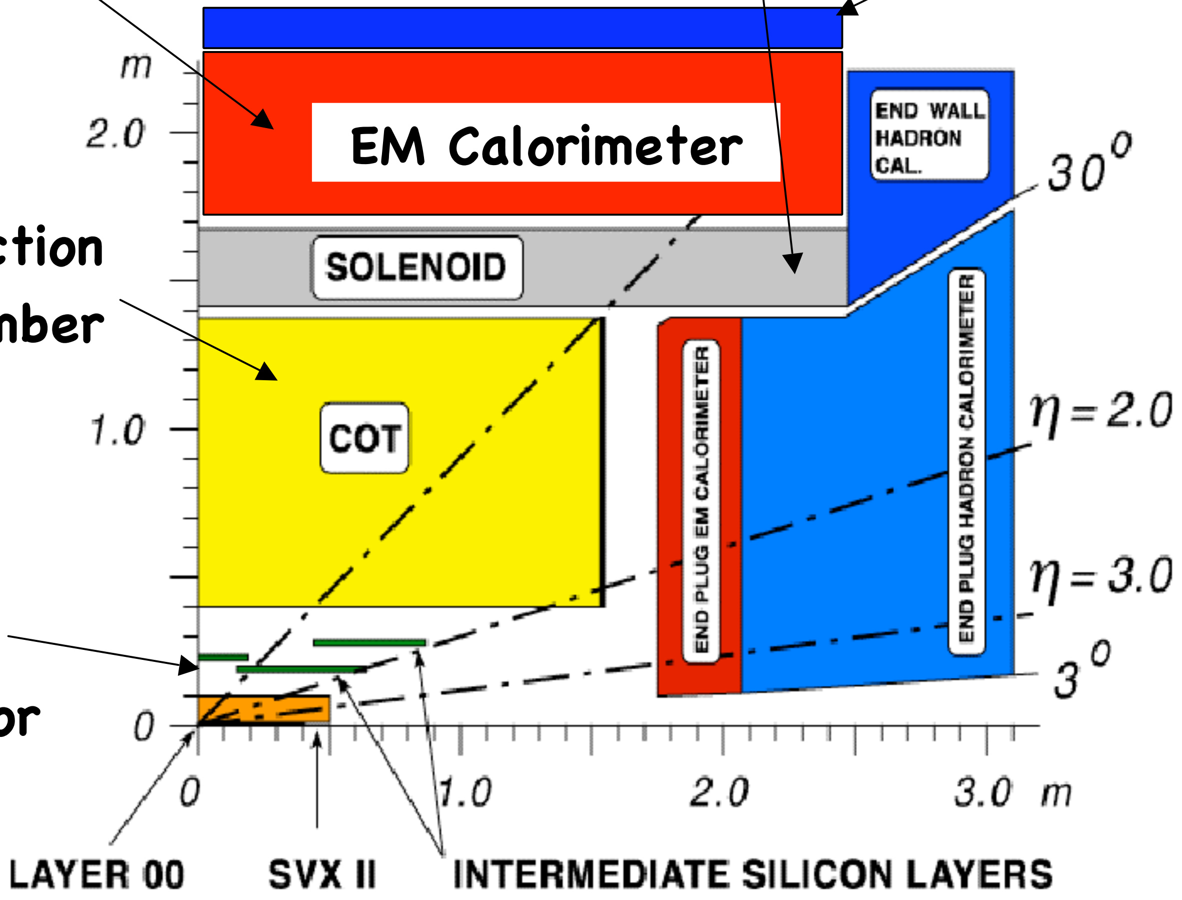
Response and resolution of the EM calorimeter

Energy leakage into hadronic calorimeter

Energy loss in solenoid

Track reconstruction in the drift chamber

Bremsstrahlung and conversions in silicon detector



Simulation of the passage through the detector

Ionization energy loss according to Landau distribution

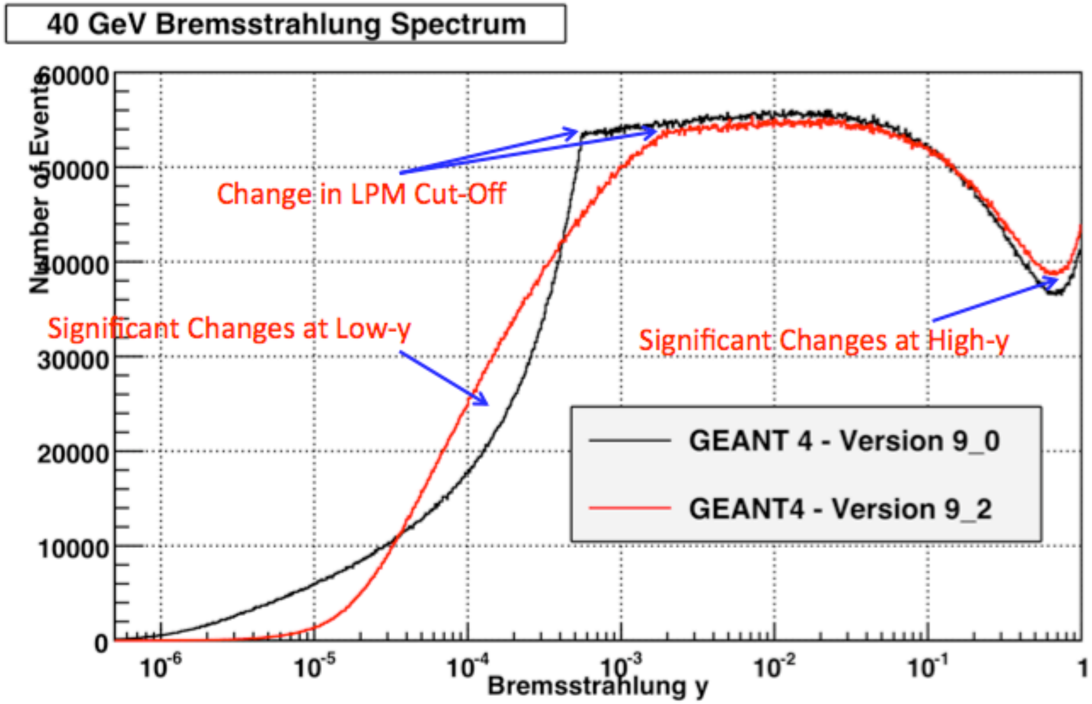
Simulate photon conversion and compton scattering

Propagate bremsstrahlung photons and conversion electrons

Simulate multiple Coulomb scattering

Bremsstrahlung photons using detailed cross section and spectrum calculations

Implementing the latest GEANT routines…



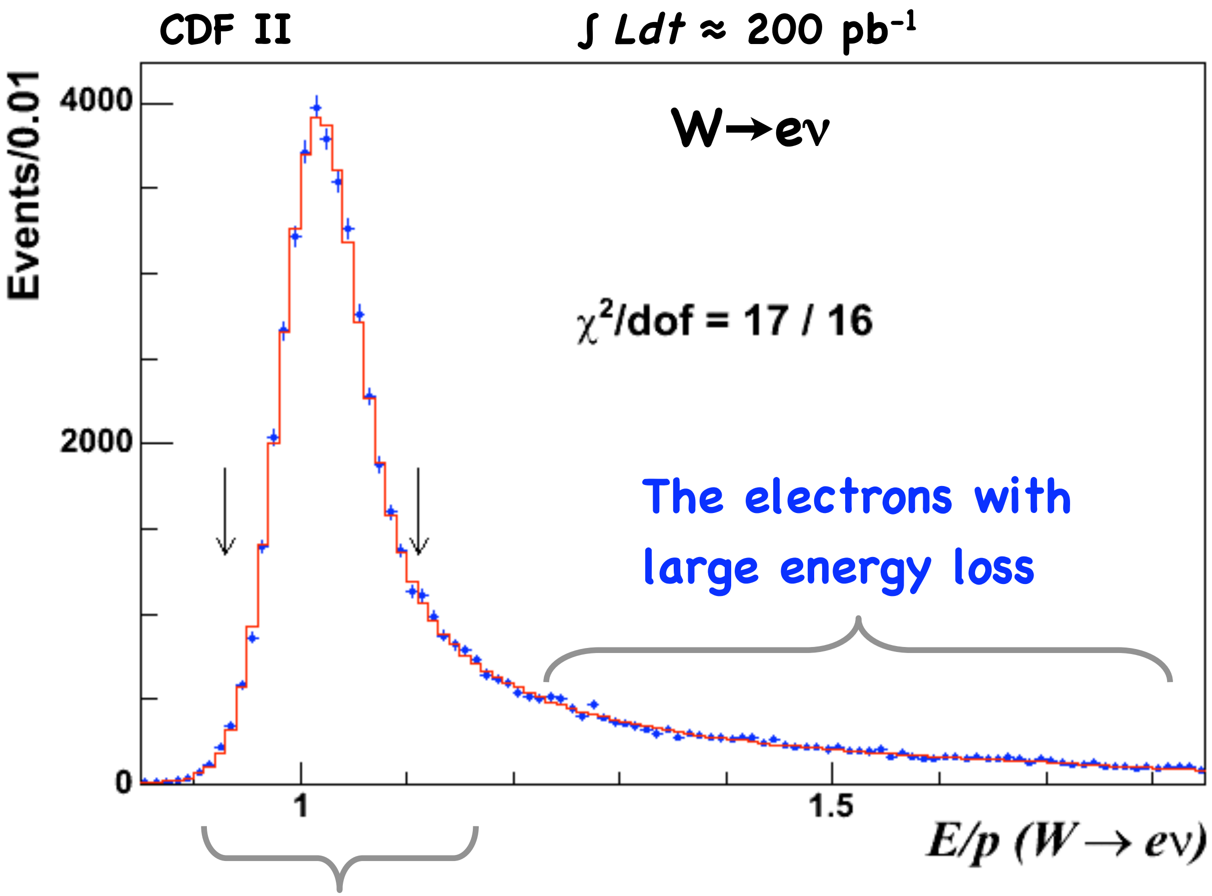
The E/p distribution of electrons

photons emitted in small angles fall into the same calorimeter tower as the electron -> measured E > p

E/p =
energy / momentum

momentum measurement absolutely calibrated

Transfer calibration to the energy measurement

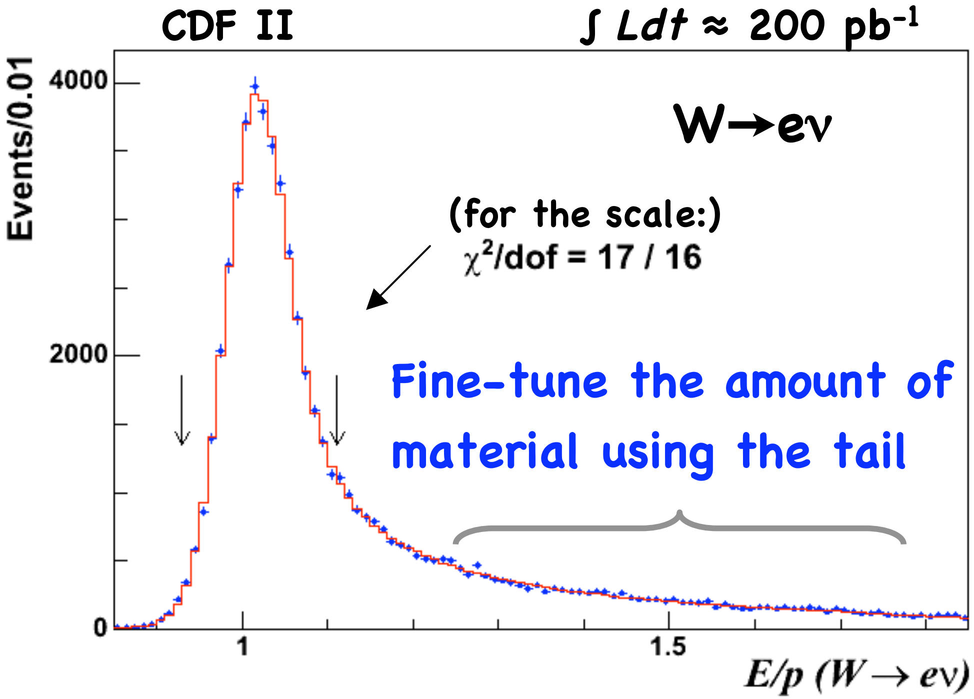


The electrons with large energy loss

non-radiative electrons

Energy scale and resolution calibration

Use calibrated momentum + electron simulation to calibrate the energy scale: peak of the E/p distribution in the W→eν decays

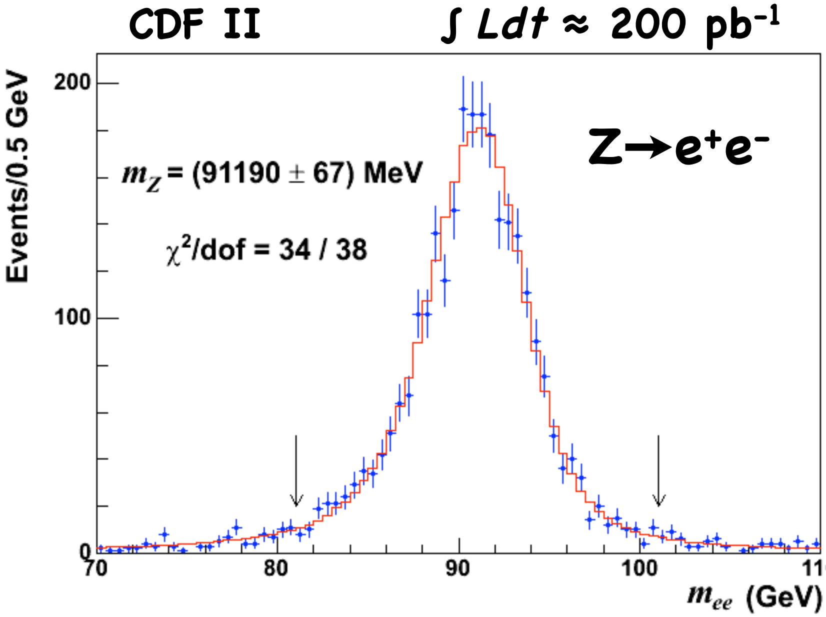


Fine-tune the amount of material using the tail

Non-linear calorimeter response also simulated (measured on E/p)

Test the scale in a Z mass fit:

PDG m_Z=91188±2 MeV



Final E/p and Z mass fit scales and resolutions combined

$$\left\{ \begin{array}{l} \Delta m_{W(scale)} = 30 \text{ MeV} \\ \Delta m_{W(resol)} = 9 \text{ MeV} \end{array} \right.$$

Recoil simulation

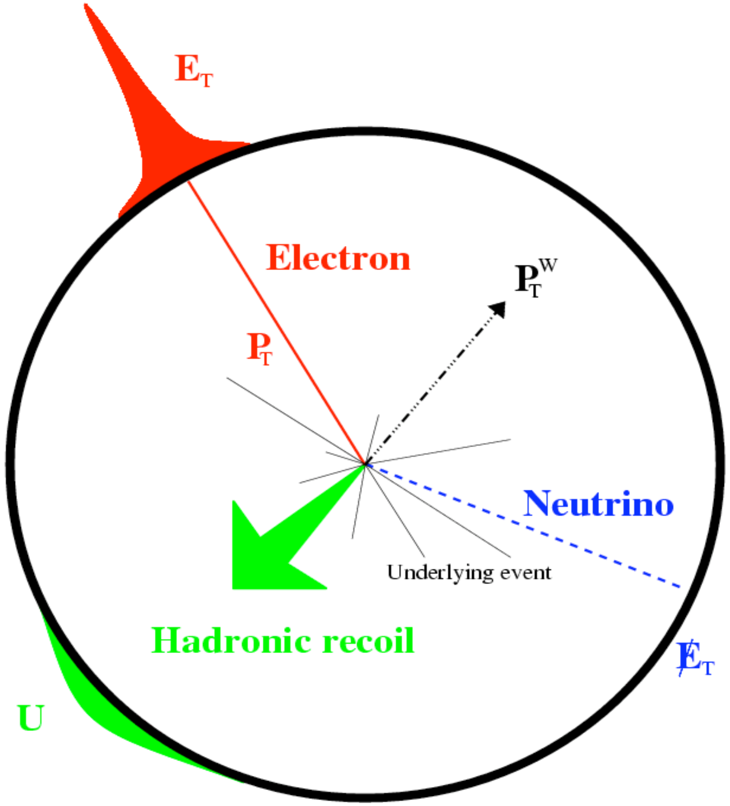
Calorimeter deposits from initial state QCD and the underlying event

Transverse momentum of hadronic recoil (U)
calculated as (2-)vector sum over calorimeter towers

The simulation of the hadronic recoil to 1×10^{-4}

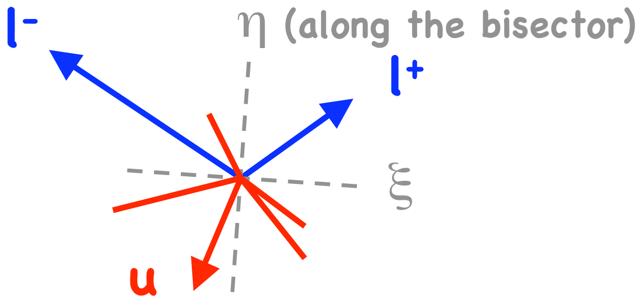
Exploit similarity in production and decay of W and Z bosons

Detector response model for hadronic recoil tuned using p_T-balance in Z->ll events



underlying event part depends on instantaneous luminosity

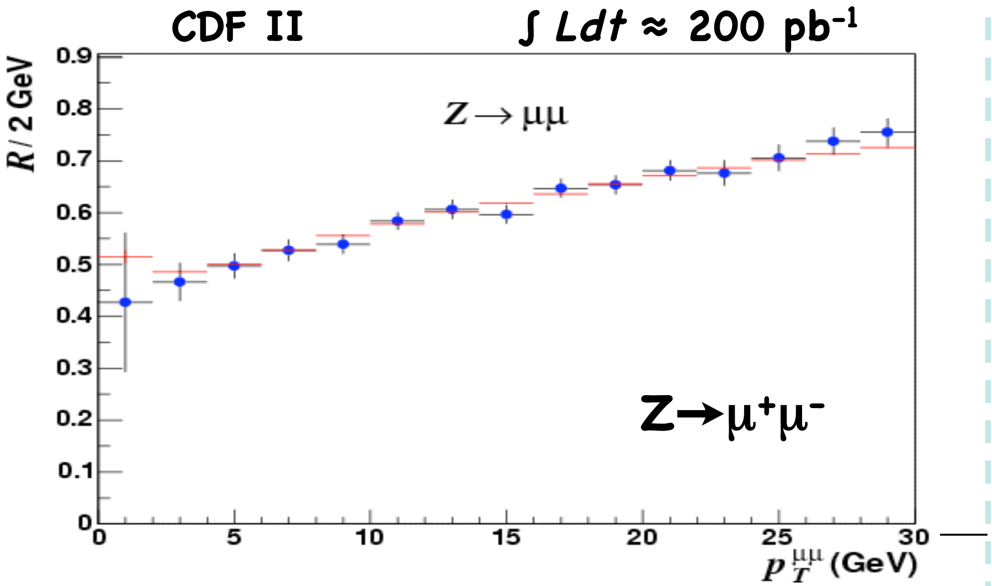
Hadronic recoil tuning



Hard and **soft** components
to the **recoil resolution**

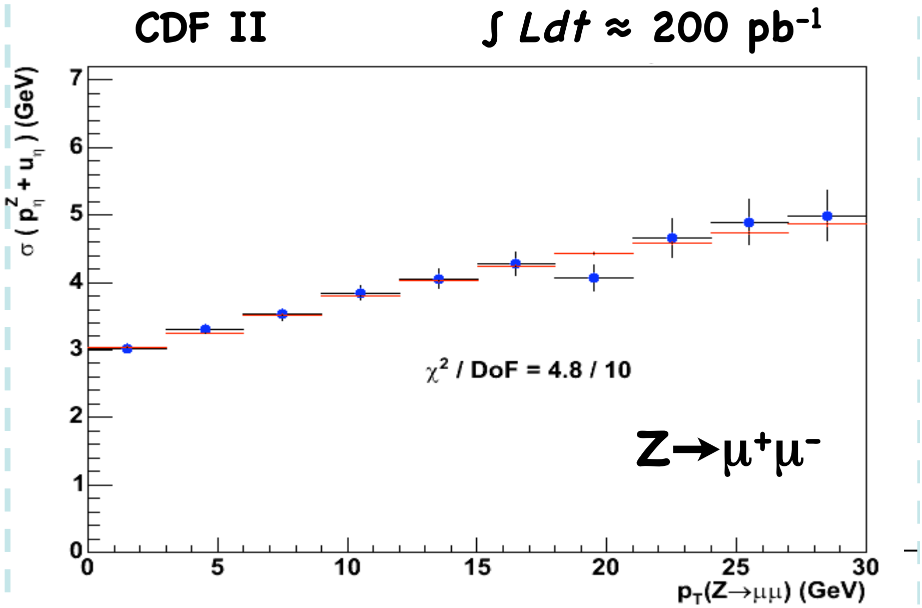
Use the Z decays to calibrate
recoil scale $R=u_{meas}/u_{true}$
as a function of Z p_T

Δm_W=9MeV



Calibrate hard and **soft**
resolution components in η and ξ

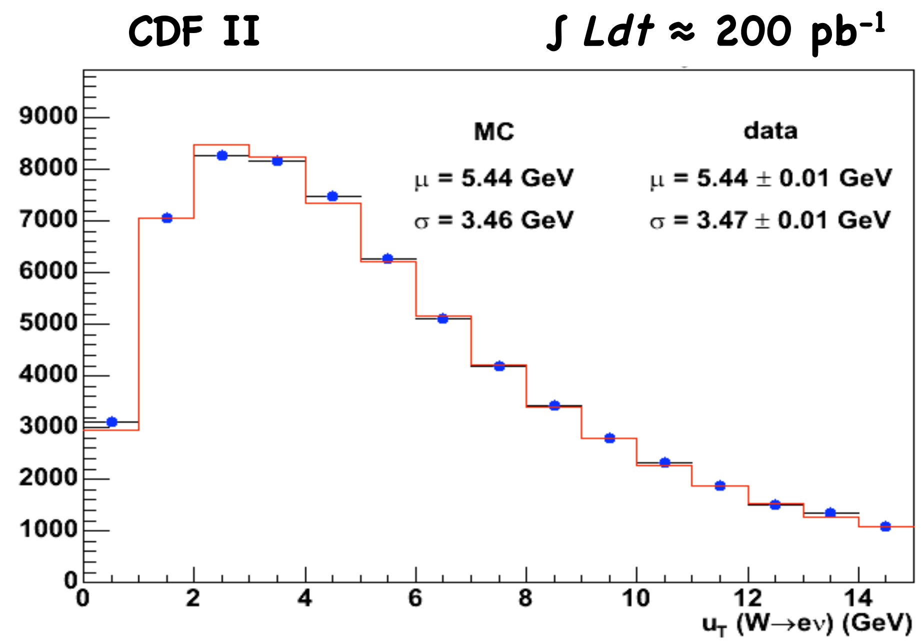
Δm_W=7MeV



Hadronic Recoil : W decays

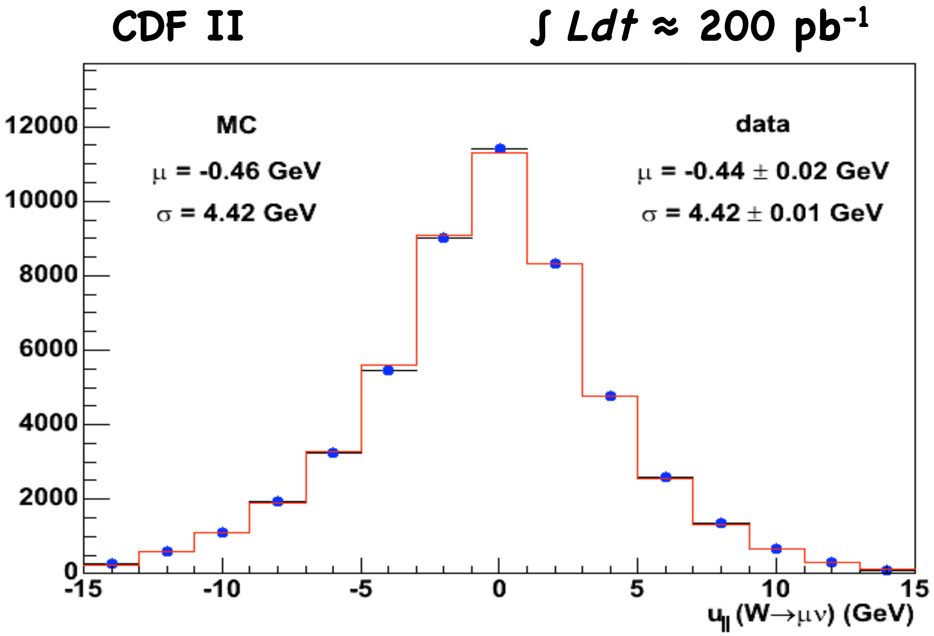
Validating the recoil model:
description of the W
recoil distributions

(W boson p_T ,
measured in the recoil)



$u_{||}$ -the component parallel to the charged lepton direction

directly affecting m_T



Theoretical uncertainties

Momentum fraction taken by the partons

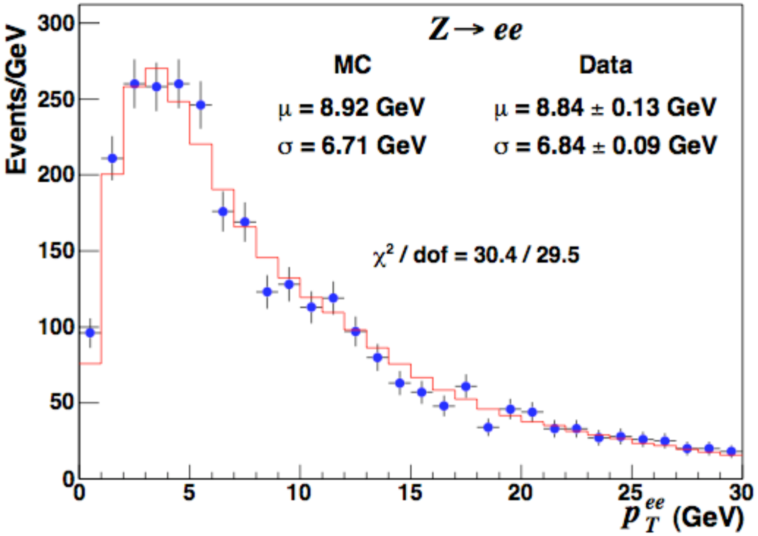
Use CTEQ6M/MRST Parton distribution functions (PDFs), observe shifts using PDFs that span the parameter uncertainty

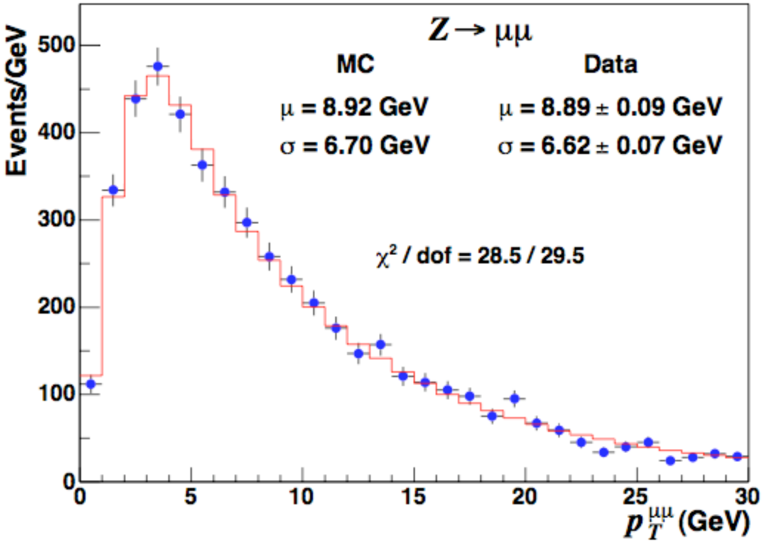
Δm_W= 11MeV

Boson p_T simulation [PRD67,073016 (2003)]

Predicted by the RESBOS generator, where the non-perturbative region of low p_T is parameterized and obtained from a fit to Z boson p_T

Δm_W= 3MeV





Electroweak modeling uncertainties

Final state QED radiation affects the m_W at the level of 150 MeV

Using the currently most advanced generator (HORACE)

LL approximation for each photon is scaled to match the exact $O(\alpha)$ matrix element calculation

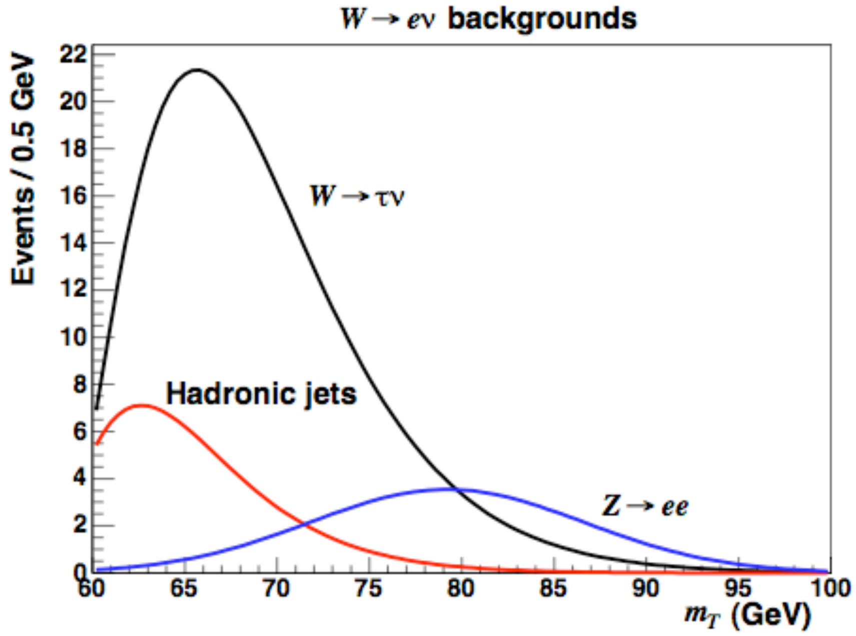
Total EWK uncertainty is now 7 MeV (was 11 MeV in 0.2 fb^{-1})

some effects never studied before or in this detail for a M_W measurement:

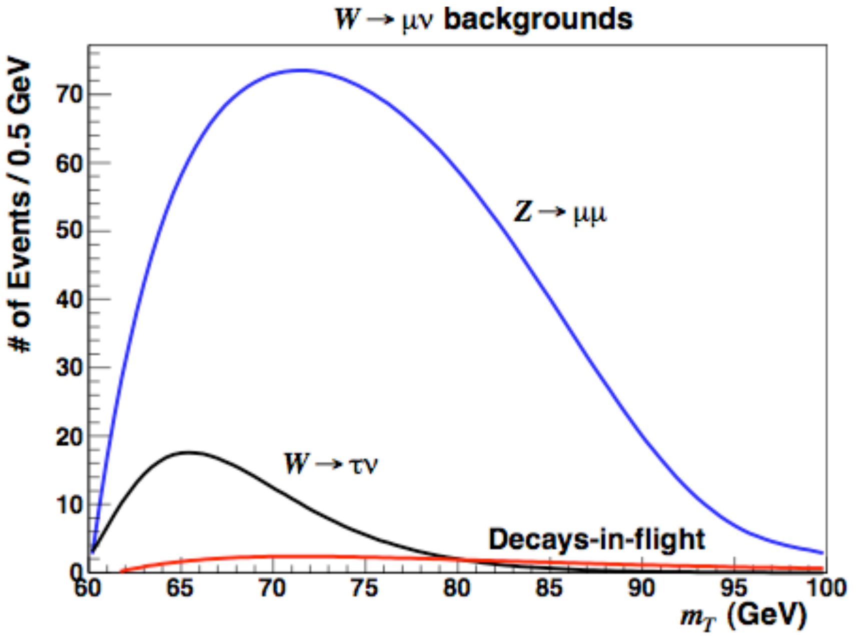
CDF Note 9987

- n-photon emission
- accuracy of the matching of leading-log to exact ME
- EWK scheme dependence
- pair creation
- QED ISR with QCD ISR
- Correlation of EWK corrections between Z and E/p CEM scales (needed to understand how to combine results with D0)

Backgrounds



	% of	δm_W (MeV)		
Background	$W \to e\nu$ data	m_T fit	p_T fit	$\not{p}_T$ fit
$W \to \tau\nu$	0.93 ± 0.03	2	2	2
Hadronic jets	0.25 ± 0.15	8	9	7
$Z/\gamma^* \to ee$	0.24 ± 0.01	1	1	0
Total	1.42 ± 0.15	8	9	7



	% of	δm_W (MeV)		
Background	$W \to \mu\nu$ data	m_T fit	p_T fit	$\not{p}_T$ fit
$Z/\gamma^* \to \mu\mu$	6.6 ± 0.3	6	11	5
$W \to \tau\nu$	0.89 ± 0.02	1	7	8
Decays in flight	0.3 ± 0.2	5	13	3
Hadronic jets	0.1 ± 0.1	2	3	4
Cosmic rays	0.05 ± 0.05	2	2	1
Total	7.9 ± 0.4	9	19	11

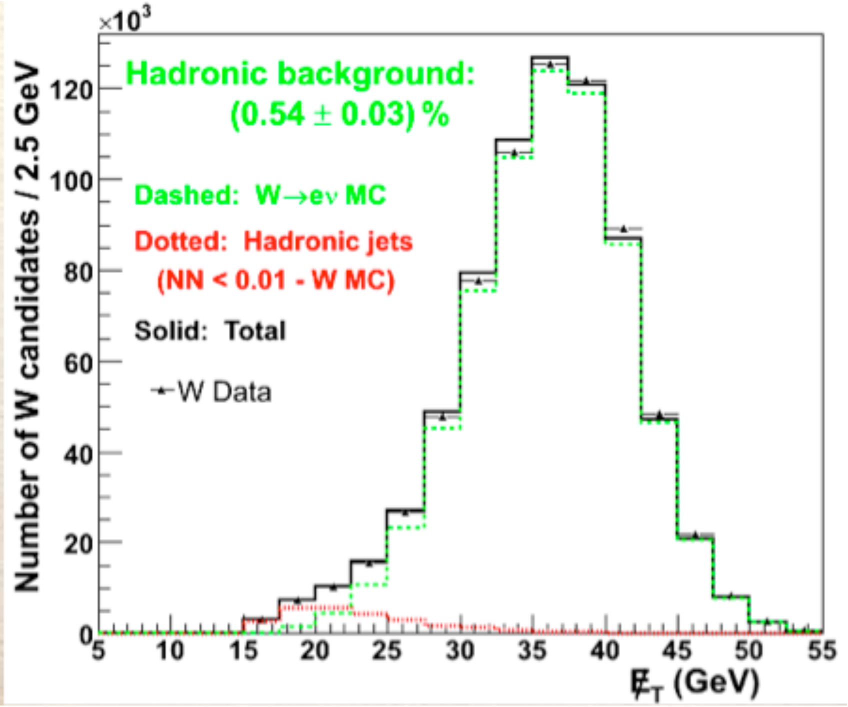
QCD background in W→eν decays

1) Find the shape from a QCD dominated region

2) fit for the normalization in the signal region

QCD dominated regions:

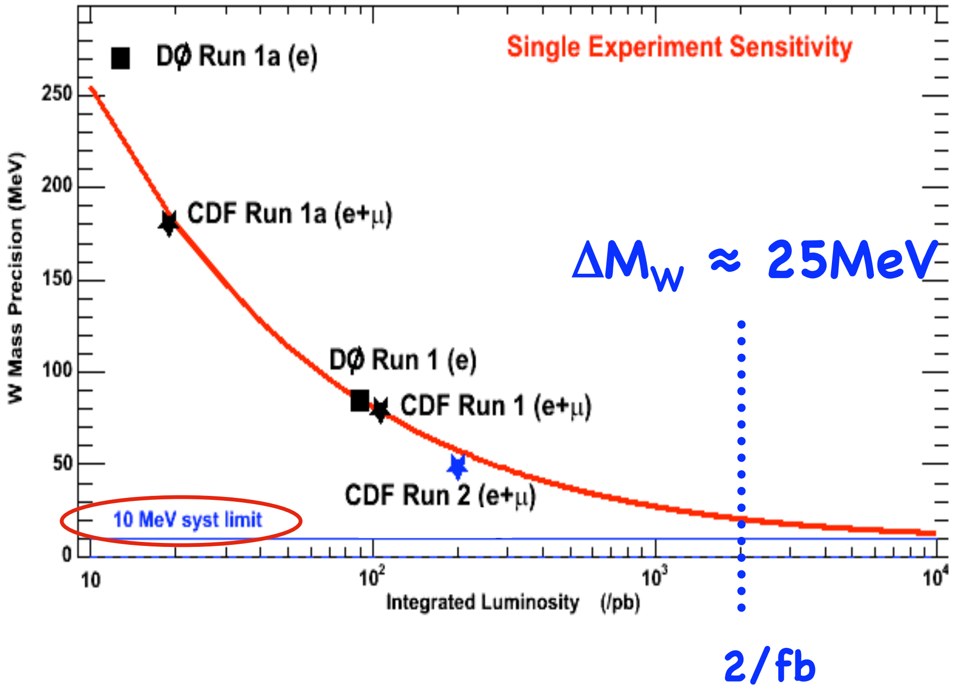
- **W** … Low $\not{E}_T$, high isolation, low neural-network (NN) value
- **Z** … Same-charge electrons, high isolation



Method	QCD bcgr
Track isolation fit	0.49 ± 0.08%
NN fit	0.32 ± 0.04%
ET fit (W-corrected NN)	0.54 ± 0.03%

QCD b. fraction:
0.43 ± 0.1%

What can we do with > $2fb^{-1}$?



Improved CDF Run II measurement
analyzing 12x more data: $2.4fb^{-1}$

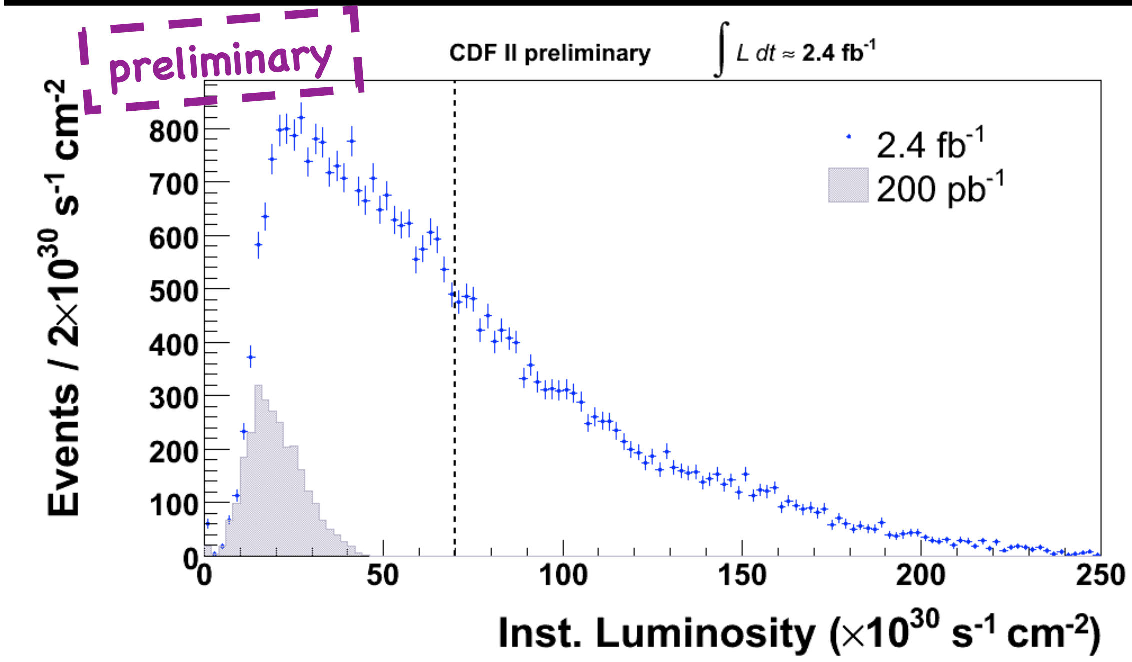
Can match the current
world average
with a single measurement:
$\Delta M_W^{CDF} < 25$ MeV

Provided:

- detector aging
- averaging over longer data-taking period
- larger spread and higher average luminosity

do not deteriorate
data quality

Instantaneous luminosity

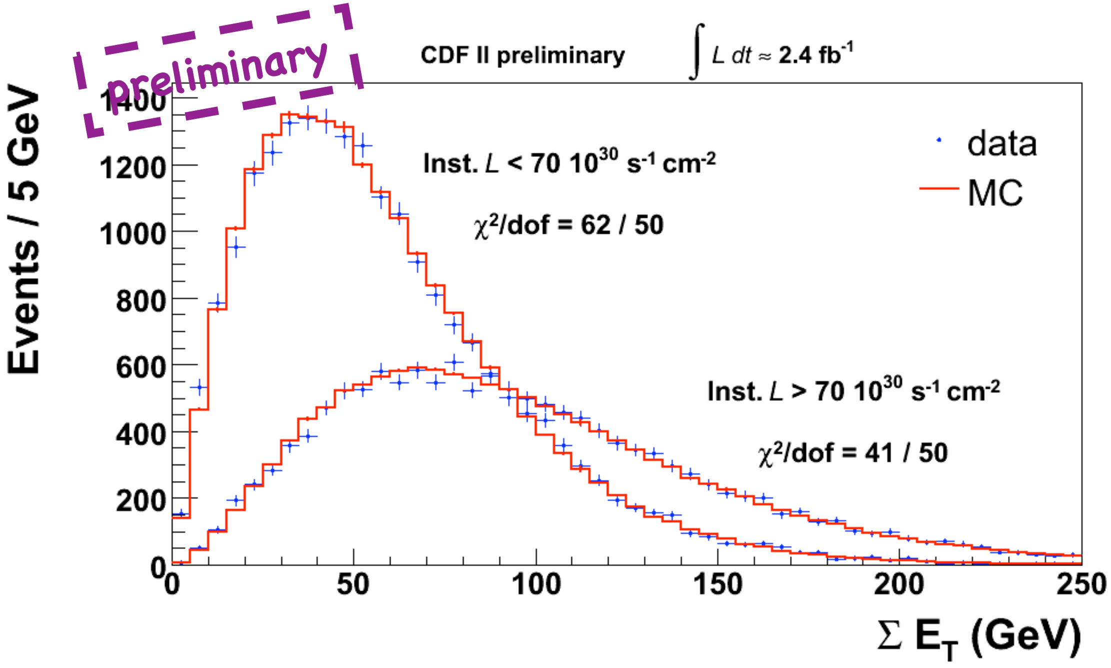


Higher instantaneous luminosities L and much larger spread

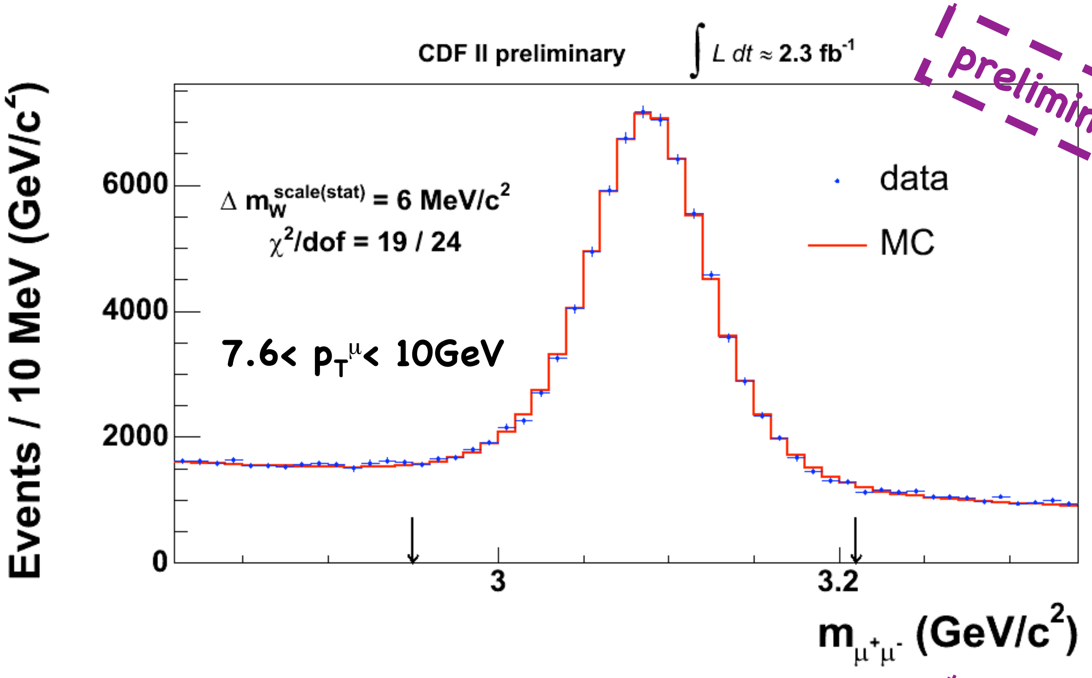
$\langle L \rangle = 70 \times 10^{30}\ s^{-1} cm^{-2}$ (dotted line)

We are able to capture luminosity dependence of the sum of all deposits in the calorimeter (ΣE_T)

ΣE_T is the basis for recoil resolution description



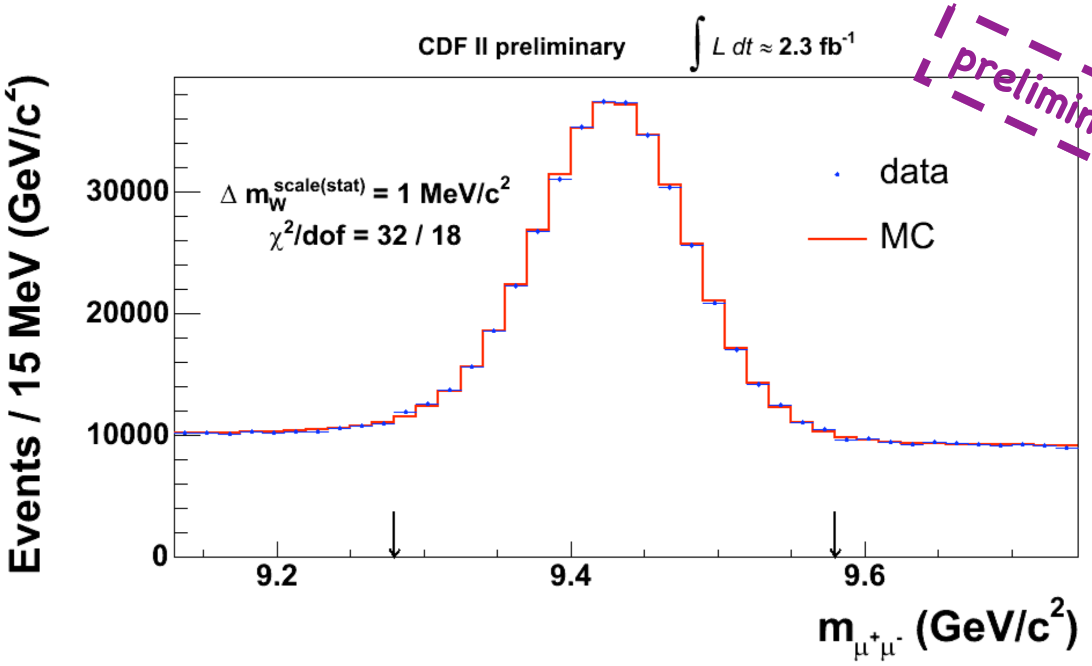
J/ψ and Υ(1S) fits for the momentum scale



Example J/ψ plot for the high momentum bin $7.6 < p_T^{\mu} < 10\mathrm{GeV}$

	$\Delta m_W^{\mathrm{scale\ (stat)}}$
published (200pb^{-1})	20MeV
expected (2.3fb^{-1})	6MeV
fit (2.3fb^{-1})	6MeV

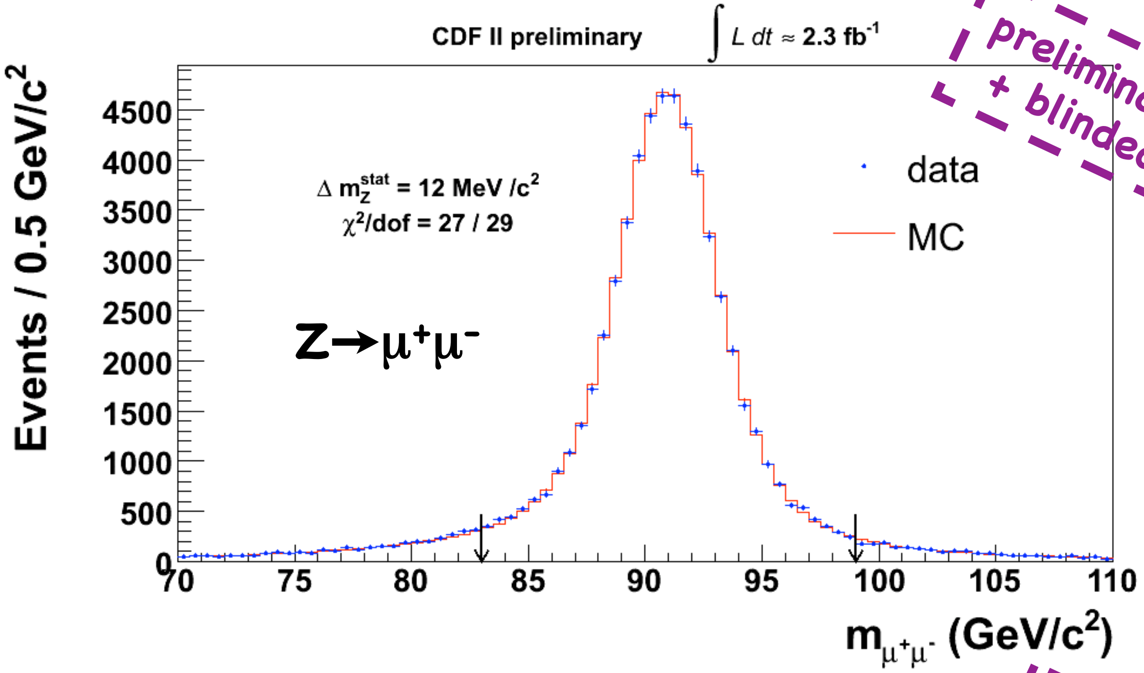
(Expected from scaling the integrated luminosity)



$\Upsilon(1S) \rightarrow \mu^+\mu^-$
(beam constrained fit)

	$\Delta m_W^{\mathrm{scale\ (stat)}}$
published (200pb^{-1})	5MeV
expected (2.3fb^{-1})	1MeV
fit (2.3fb^{-1})	1MeV

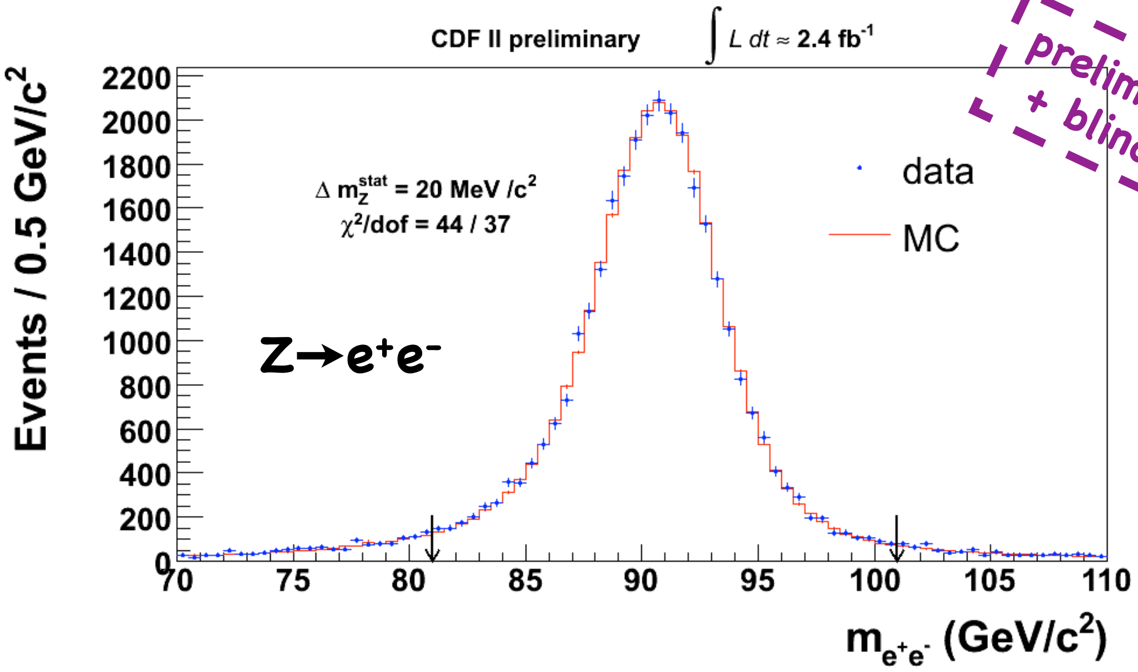
Z mass fits



preliminary + blinded

$Z \rightarrow \mu^+\mu^-$

	Δm_Z^{stat}
published (200pb^{-1})	43MeV
expected (2.3fb^{-1})	13MeV
fit (2.3fb^{-1})	12MeV

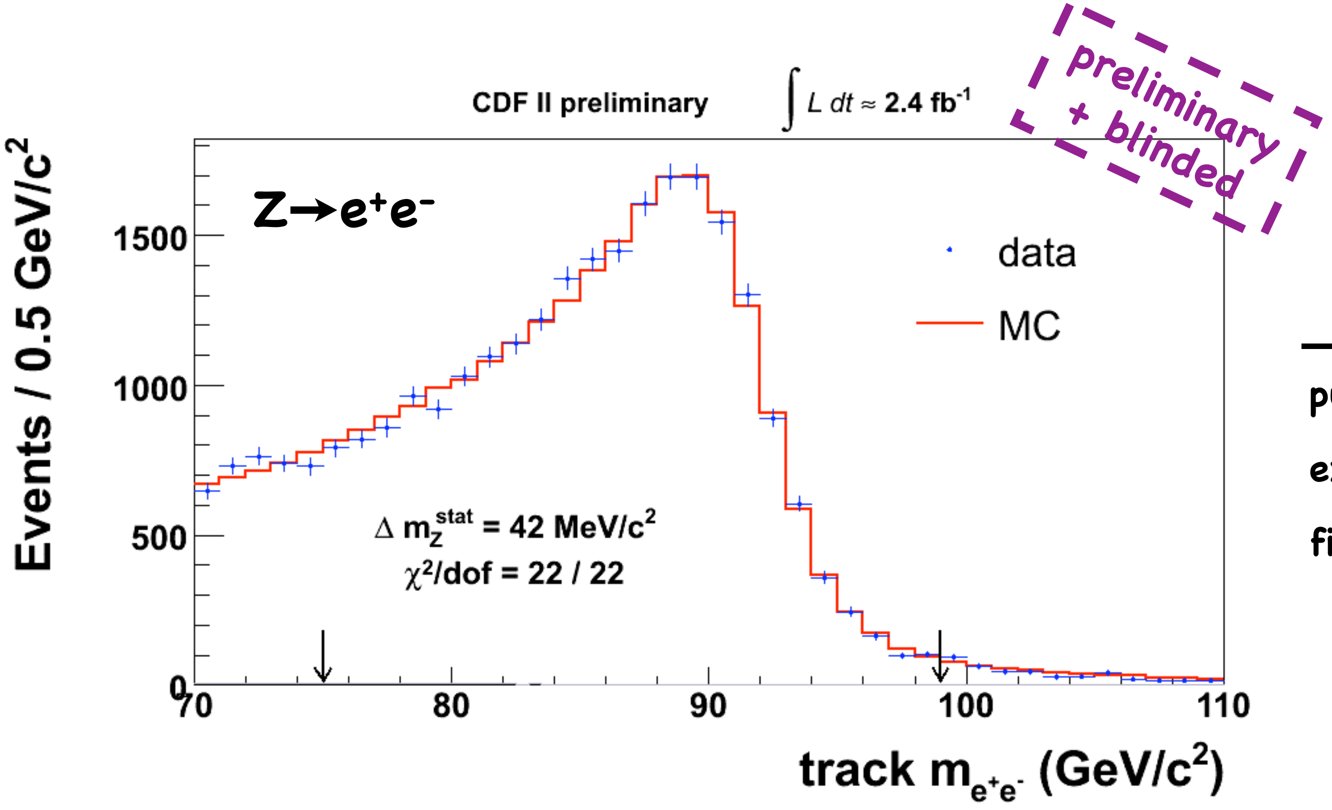


preliminary + blinded

$Z \rightarrow e^+e^-$

	Δm_Z^{stat}
published (200pb^{-1})	67MeV
expected (2.4fb^{-1})	20MeV
fit (2.4fb^{-1})	20MeV

Z mass fit using tracking info only

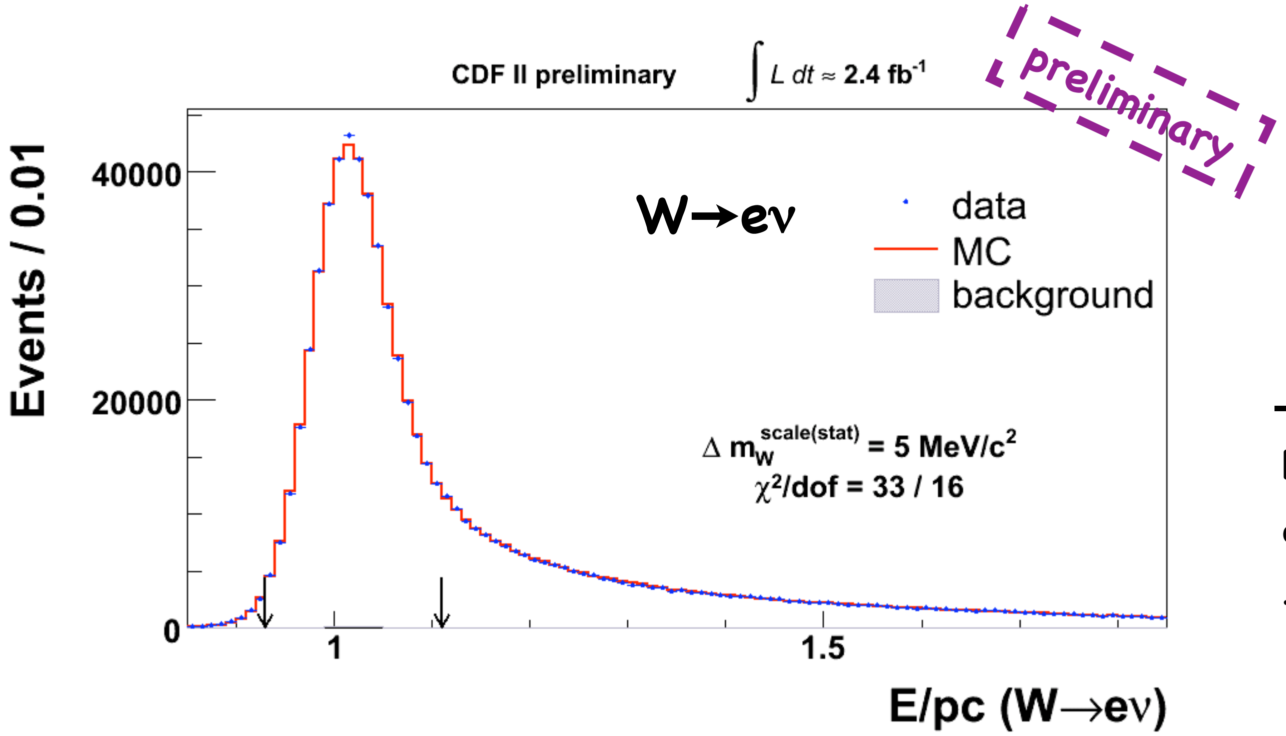


$Z \to e^+e^-$ (track only)

	Δm_Z^{stat}
published (200pb^{-1})	143MeV
expected (2.4fb^{-1})	42MeV
fit (2.4fb^{-1})	42MeV

Sensitive to energy loss modelling (bremsstrahlung).

E/p

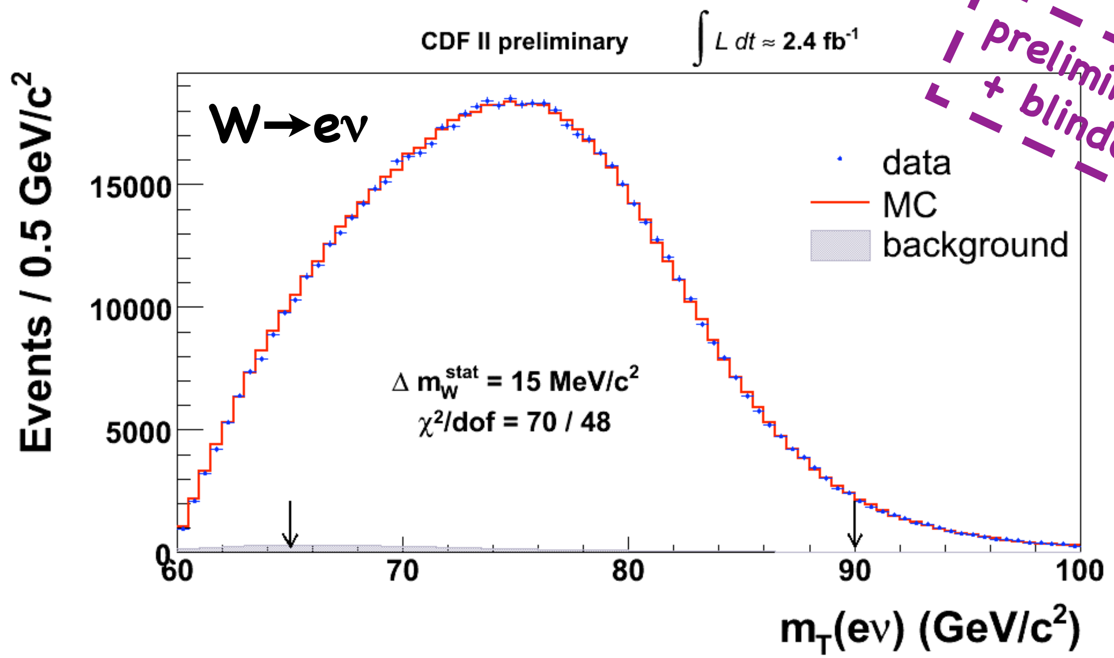


W→eν

	$\Delta m_W^{\text{scale (stat)}}$
published (200pb^{-1})	20MeV
expected (2.4fb^{-1})	6MeV
fit (2.4fb^{-1})	5MeV

Sensitive to material, momentum and energy calibrations.

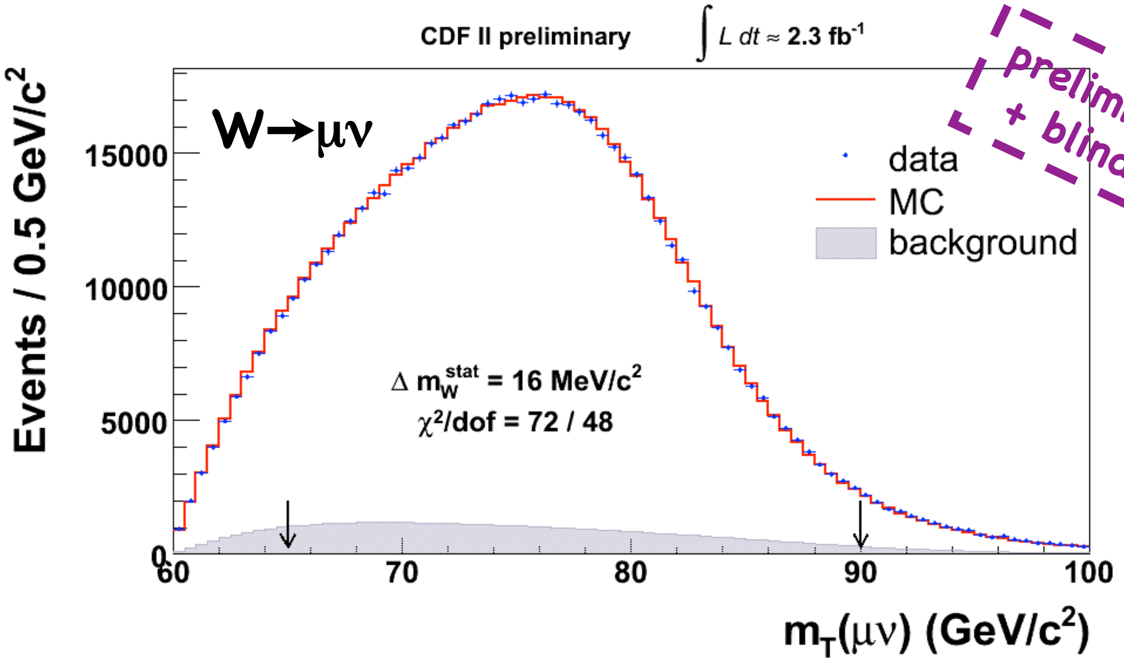
m_T fits



preliminary + blinded

W→eν

	Δm_W^{stat}
published (200pb^{-1})	48MeV
expected (2.4fb^{-1})	14MeV
fit (2.4fb^{-1})	15MeV



preliminary + blinded

W→μν

	Δm_W^{stat}
published (200pb^{-1})	54MeV
expected (2.3fb^{-1})	16MeV
fit (2.3fb^{-1})	16MeV

Where are we now

$200 pb^{-1}$

m_W = 80413 ± 34 MeV (stat) ± 34 MeV (sys)

= 80413 ± 48 MeV (stat + sys) [PRL 99,151801 (2007)]

- significant improvement of ionisation loss simulation
- recoil simulation using instant luminosity dependence
- improved description of the E/p distribution
- inclusion of higher order EWK corrections

highlights of the $2.4\ fb^{-1}$ analysis

	$200\ pb^{-1}$	$2.3\ fb^{-1}$	$200\ pb^{-1}$	$2.3\ fb^{-1}$
	Electrons		**Muons**	
Momentum Scale	17	**10**	17	10
Energy Scale	25	**8**	▨	▨
Lepton resolution	9	9	3	3
Lepton Efficiency	3	3	1	1
Lepton Removal	8	8	5	5
Recoil Scale	9	9	9	9
Recoil Resolution	7	7	7	7
Backgrounds	8	**6**	9	**5**
PDFs	11	**12**	11	**12**
$p_T(W)$	3	**3**	3	**3**
EWK	11	**7**	12	**7**
Statistical	48	**15**	54	**16**
TOTAL	62	30	61	27

If the rest stays the same as in $200\ pb^{-1}$:

e + μ average:

25 MeV (was 48 MeV)

Conclusions

The first CDF and D0 Run II W mass measurements are the two single most precise W mass measurements,
combined uncertainty better than LEP combination: 31MeV

CDF one is better than expected by statistical scaling of the Run I measurements :
using quarkonia for momentum scale determination,...

We are analyzing 12x more data:

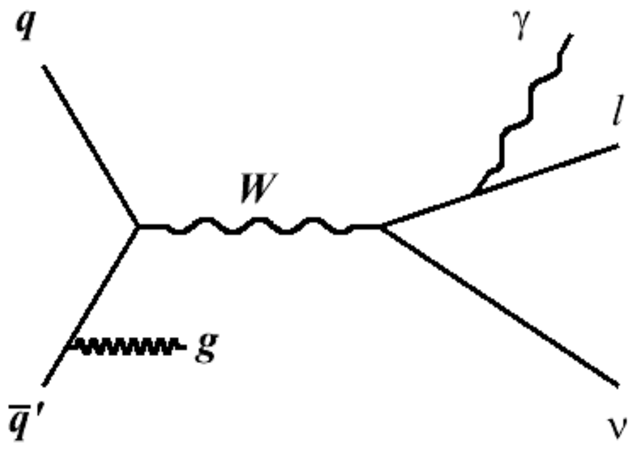
Data quality good

- Statistical uncertainty as expected
- Instantaneous luminosity distribution seems to not be an issue

CDF and D0 are both finalizing measurements
with $\delta M_W \approx$ 25 MeV using 2fb^{-1} (CDF) and 4fb^{-1} (D0)

Backup slides

Event selection for the published analysis ($200pb^{-1}$)



$s(W \to l\nu) = 2775$ pb

After event selection

p_T^l / E_T^l > 30 GeV

$\not{E}_T > 30$ GeV

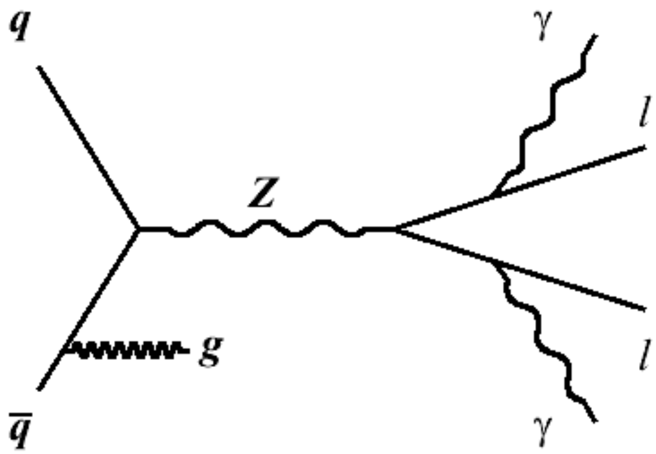
$u < 15$ GeV

$60 < m_T < 100$ GeV

...

51,128 $W \to \mu\nu$ candidates

63,964 $W \to e\nu$ candidates



$s(Z \to ll) = 254.9$ pb

After event selection

p_T^l / E_T^l > 30 GeV

$u < 15$ GeV

$66 < m_{ll} < 116$ GeV

...

4,960 $Z \to \mu\mu$ candidates

2,919 $Z \to ee$ candidates

Prospects at the LHC

Conventional templates method:

detailed detector response needs to be understood

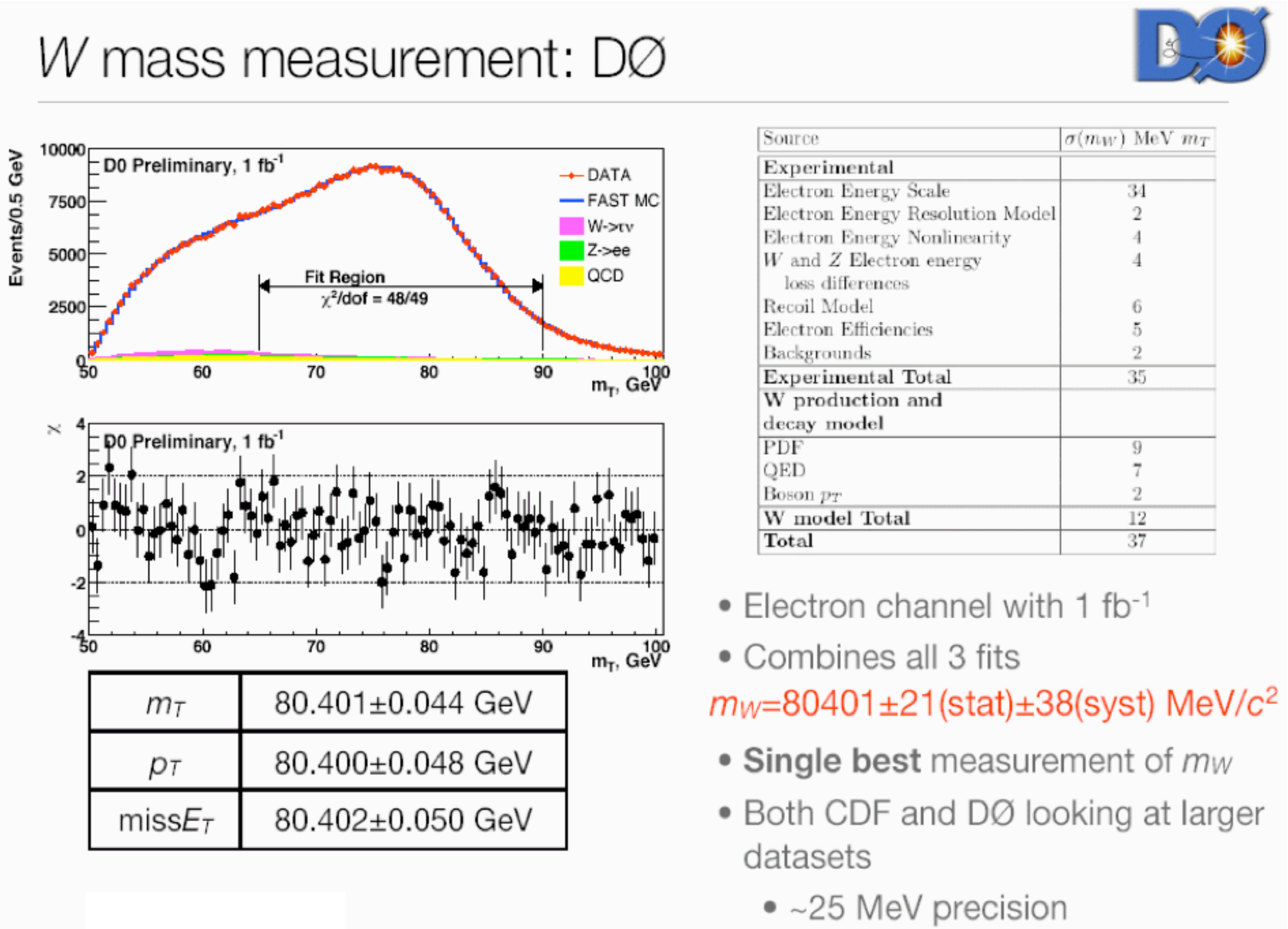
Much (7x) larger cross-section for W and Z production at 14TeV
10 fb^{-1} : 45,000,000 $W\rightarrow\mu\nu$ and 4,500,000 $Z\rightarrow\mu^{+}\mu^{-}$

Z data driven methods possible:

Z/W “ratio method”
Using Z data decays to mimic W decays (“transformation method”)

Estimates of 7MeV to 15 MeV precision at LHC using 10fb^{-1}

D0 measurement



W mass measurement: DØ

Source	$\sigma(m_W)$ MeV m_T
Experimental	
Electron Energy Scale	34
Electron Energy Resolution Model	2
Electron Energy Nonlinearity	4
W and Z Electron energy loss differences	4
Recoil Model	6
Electron Efficiencies	5
Backgrounds	2
Experimental Total	35
W production and decay model	
PDF	9
QED	7
Boson p_T	2
W model Total	12
Total	37

m_T	80.401±0.044 GeV
p_T	80.400±0.048 GeV
missE_T	80.402±0.050 GeV

- Electron channel with 1 fb^{-1}
- Combines all 3 fits

m_W=80401±21(stat)±38(syst) MeV/c^2

- **Single best** measurement of m_W
- Both CDF and DØ looking at larger datasets
  - ~25 MeV precision

LEP measurement

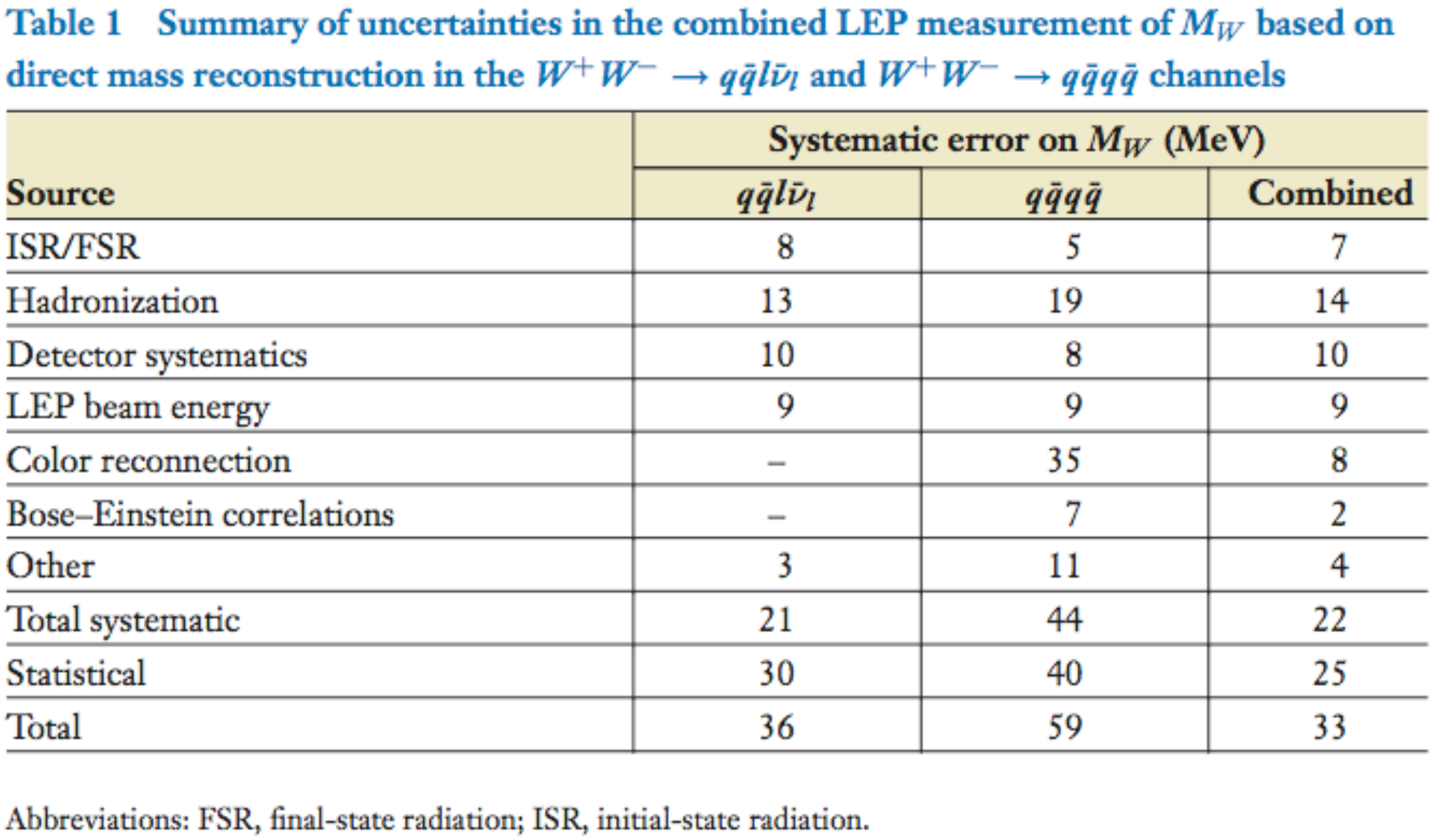


Table 1 Summary of uncertainties in the combined LEP measurement of M_W based on direct mass reconstruction in the $W^+W^- \rightarrow q\bar{q}l\bar{\nu}_l$ and $W^+W^- \rightarrow q\bar{q}q\bar{q}$ channels

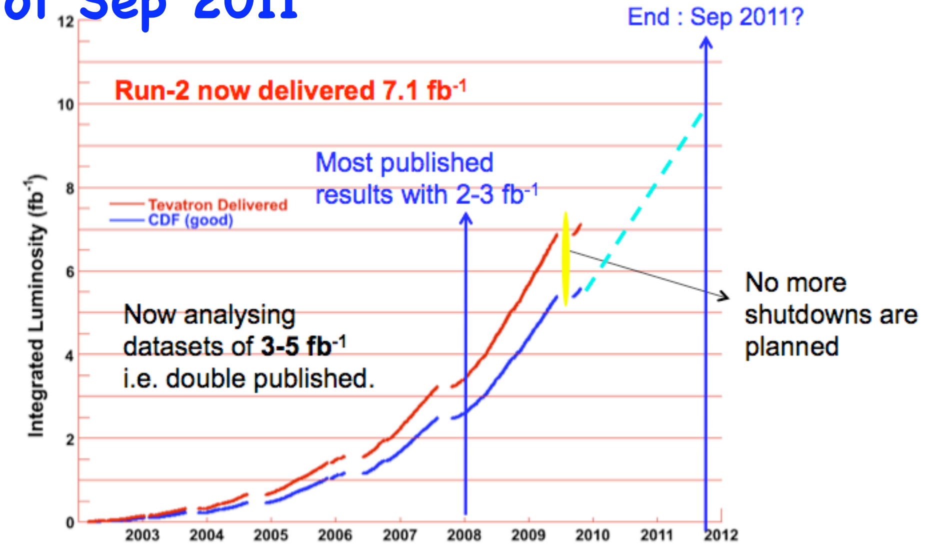
	Systematic error on M_W (MeV)		
Source	$q\bar{q}l\bar{\nu}_l$	$q\bar{q}q\bar{q}$	**Combined**
ISR/FSR	8	5	7
Hadronization	13	19	14
Detector systematics	10	8	10
LEP beam energy	9	9	9
Color reconnection	–	35	8
Bose–Einstein correlations	–	7	2
Other	3	11	4
Total systematic	21	44	22
Statistical	30	40	25
Total	36	59	33

Abbreviations: FSR, final-state radiation; ISR, initial-state radiation.

Status of the Tevatron

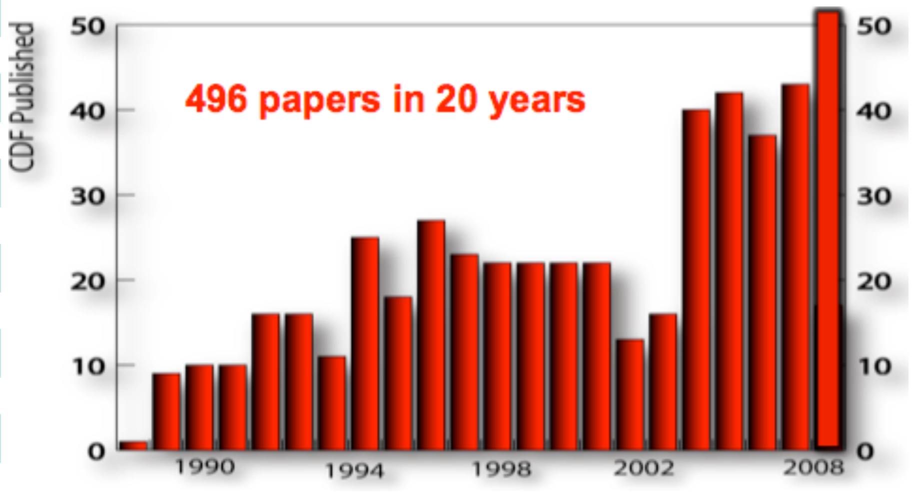
For now agreement to run until the end of 2010

Proposal to extend running until end of Sep 2011



Now accumulated 6.2 fb^{-1}

Expected (Sep 2011) = 10 fb^{-1}



CDF published 59 papers in 2009

500th paper submitted