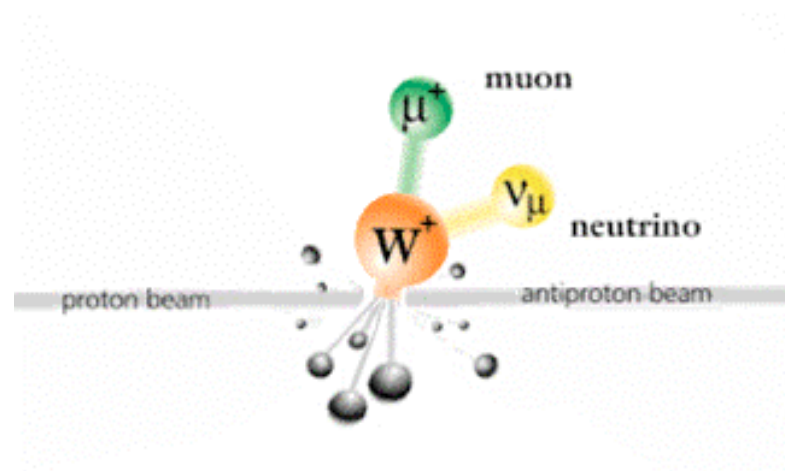# W mass measurement at the Tevatron

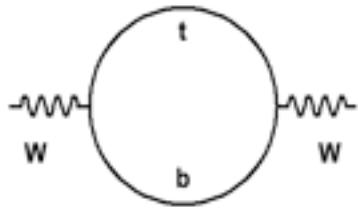Ilija Bizjak, University College London
for the CDF collaboration

Outline

1) Motivation for a W mass measurement

2) Measurement of the W mass at a p-p̄ collider

3) The first measurement of the W mass
   with Tevatron RunII data

4) Implications for the EW constraints on Higgs mass

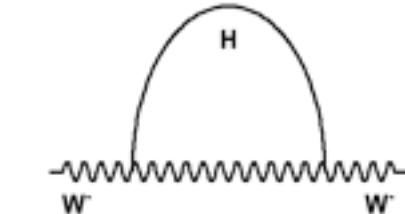5) First look at the ≈2.4fb^{-1} data

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

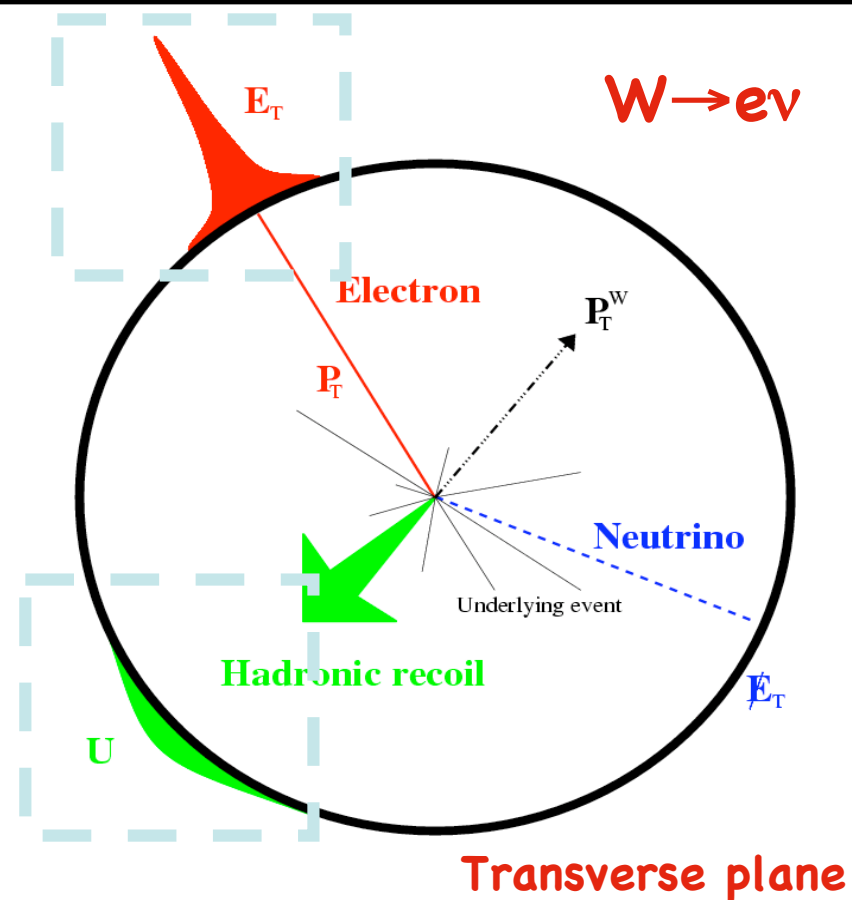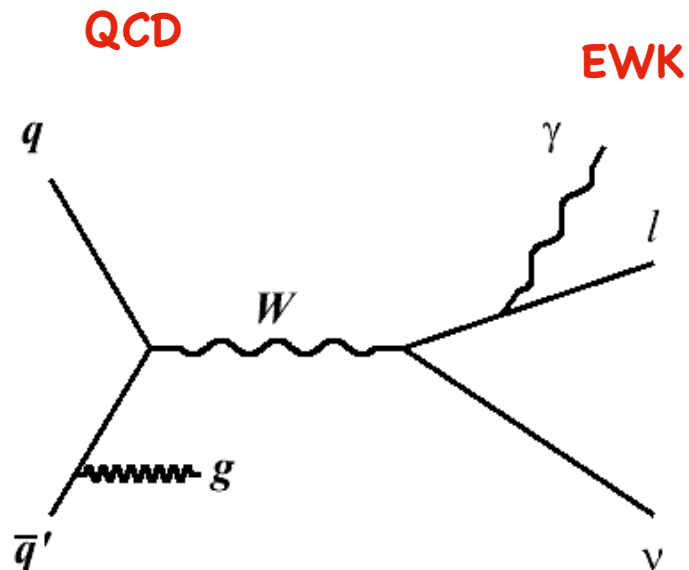$$\Delta m_W \propto m_t^2 \qquad \Delta m_W \propto \ln(m_H/m_Z)$$

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 = 1.4GeV corresponds to ΔM_W = 8MeV

The m_H constraint is limited by the uncertainty on m_W

W production and decay

PDFs

W^+

$x_p E_p$ $x_{\bar{p}} E_{\bar{p}}$

u $\bar{d}$

u Q^2 $\bar{u}$

d $\bar{u}$

QCD

EWK

q γ

l

W

g

$\bar{q}'$ ν

E_T

$W{\to}e\nu$

Electron

P_T^W

P_T

Neutrino

Underlying event

Hadronic recoil $\not{E}_T$

U

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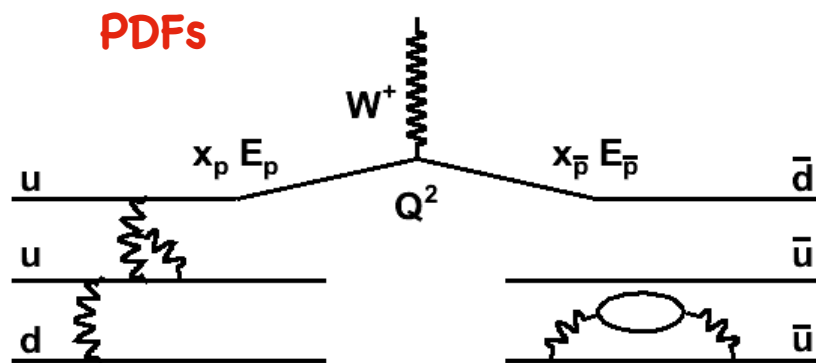
$$m_T = \sqrt{2 p_T{}^l p_T{}^\nu (1 - \cos\phi_{l\nu})}$$

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 $\not{E}_T$

For template fits we need:

m_T template

$m_W = 81$ GeV

$m_W = 80$ GeV

(y-axis: events/0.5 GeV; x-axis: Transverse Mass (GeV))

**A Fast simulator of
W/Z production/decays** - - - → PDFs, boson p_T , EWK corrections

+

**With calibrated
detector simulation** - - - → **Calibrate l± track momentum** with mass measurements of J/ψ and $\Upsilon(1S)$

Calibrate calorimeter energy using track momentum of e from W decays

+

contribution of **backgrounds**
added to the templates

Calibrate **recoil** simulation with Z decays

Momentum scale using $\Upsilon(1S)$ and J/ψ decays

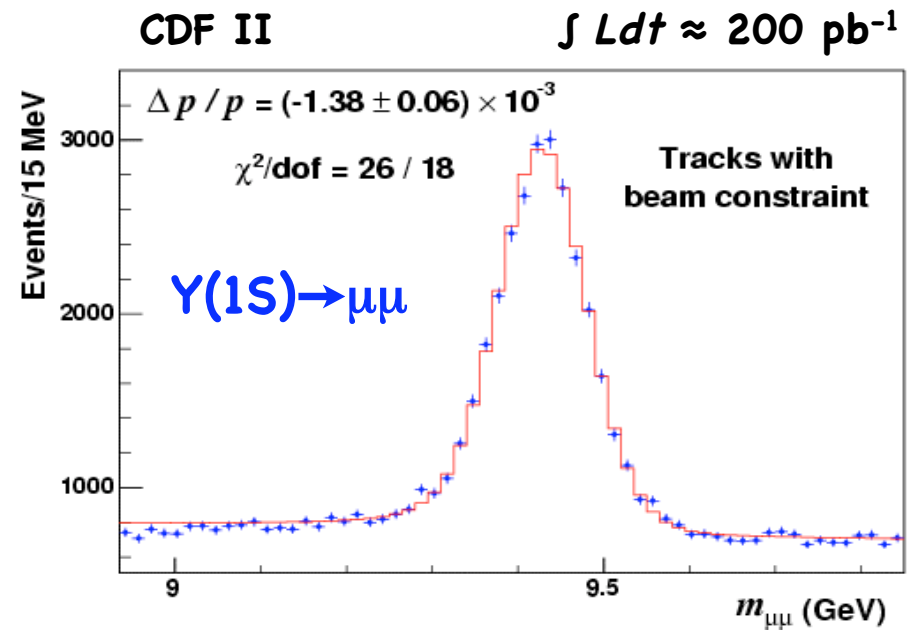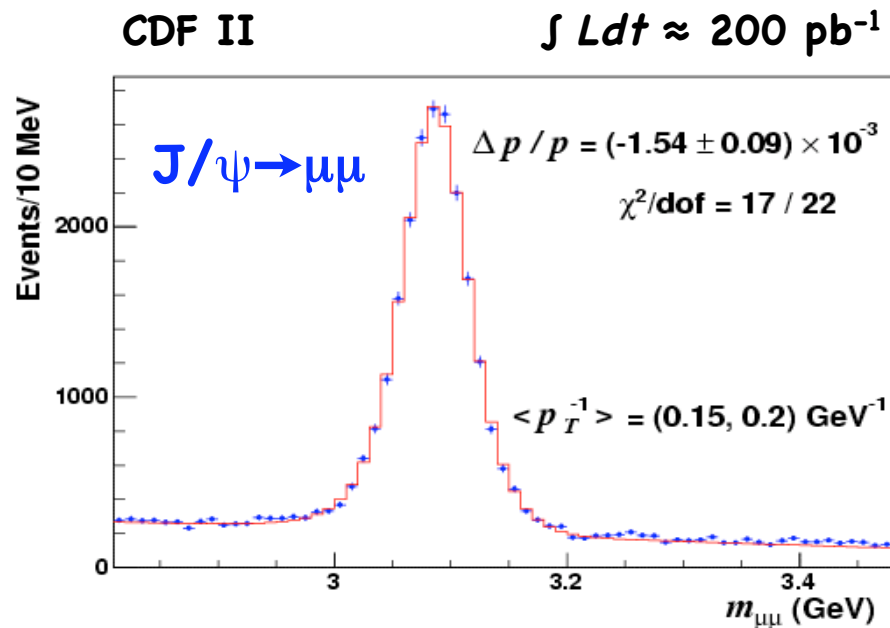Use precisely determined $\Upsilon(1S)$ and J/ψ masses to tune momentum scale in the $\mu\mu$ decay channel

CDF II $\int Ldt \approx 200$ pb^{-1}

$\Delta p / p = (-1.38 \pm 0.06) \times 10^{-3}$

$\chi^2/\text{dof} = 26 / 18$

Tracks with beam constraint

Events/15 MeV

$\Upsilon(1S) \rightarrow \mu\mu$

$m_{\mu\mu}$ (GeV)

CDF II $\int Ldt \approx 200$ pb^{-1}

Events/10 MeV

$J/\psi \rightarrow \mu\mu$

$\Delta p / p = (-1.54 \pm 0.09) \times 10^{-3}$

$\chi^2/\text{dof} = 17 / 22$

$<p_T^{-1}> = (0.15, 0.2)$ GeV^{-1}

$m_{\mu\mu}$ (GeV)

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

Momentum scale determination

CDF II $\int Ldt \approx 200\ pb^{-1}$

$\Delta p/p$

- ● J/Ψ→μμ data
- ▼ Y→μμ data
- ★ Z→μμ data

$<1/p_T^\mu>$ (GeV^{-1})
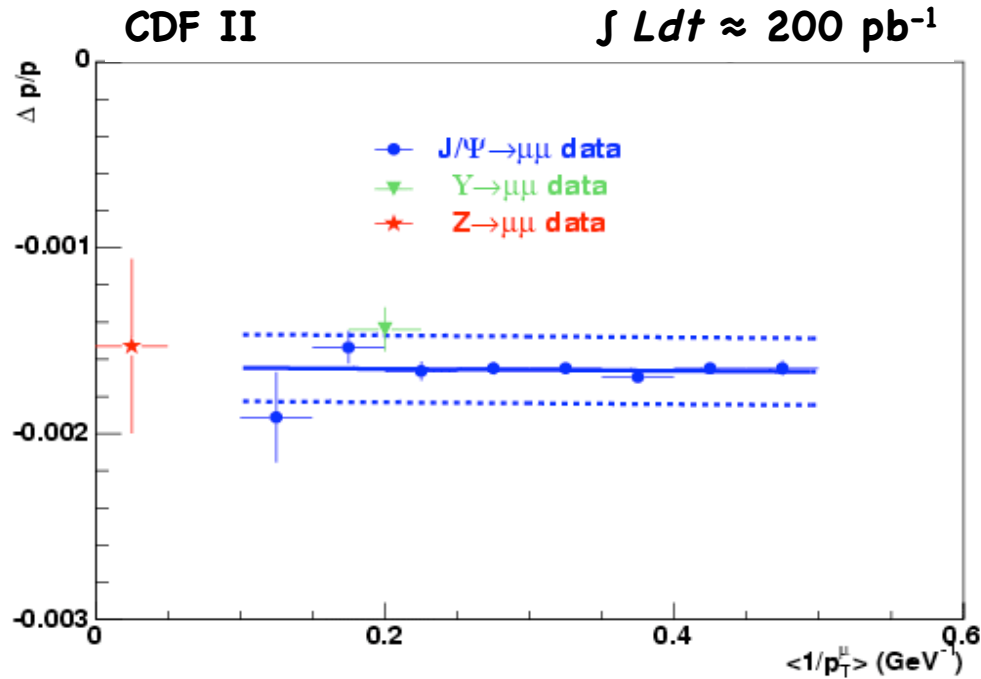
A combined **J/ψ** and **Y(1S)** momentum scale,
with the cross-check in **Z->μμ**

ΔM_W^μ (momentum scale) = 17MeV

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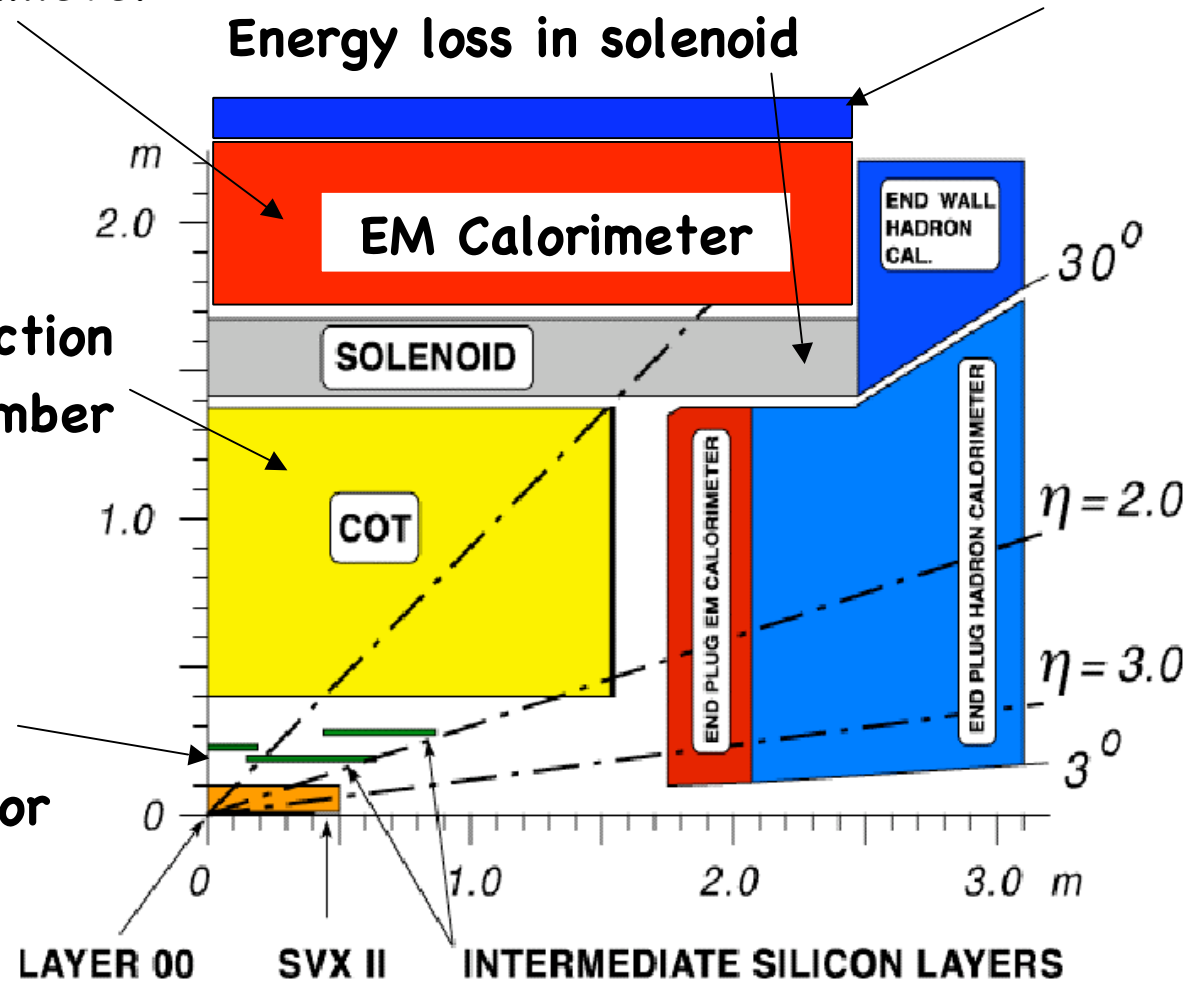compare to the world
average (91188 MeV)

CDF II $\int Ldt \approx 200\ pb^{-1}$

events / 0.5 GeV

$M_Z = (91184 \pm 43)$ MeV

$\chi^2/dof = 32\ /\ 30$

Z→μμ

$m_{\mu\mu}$ (GeV)
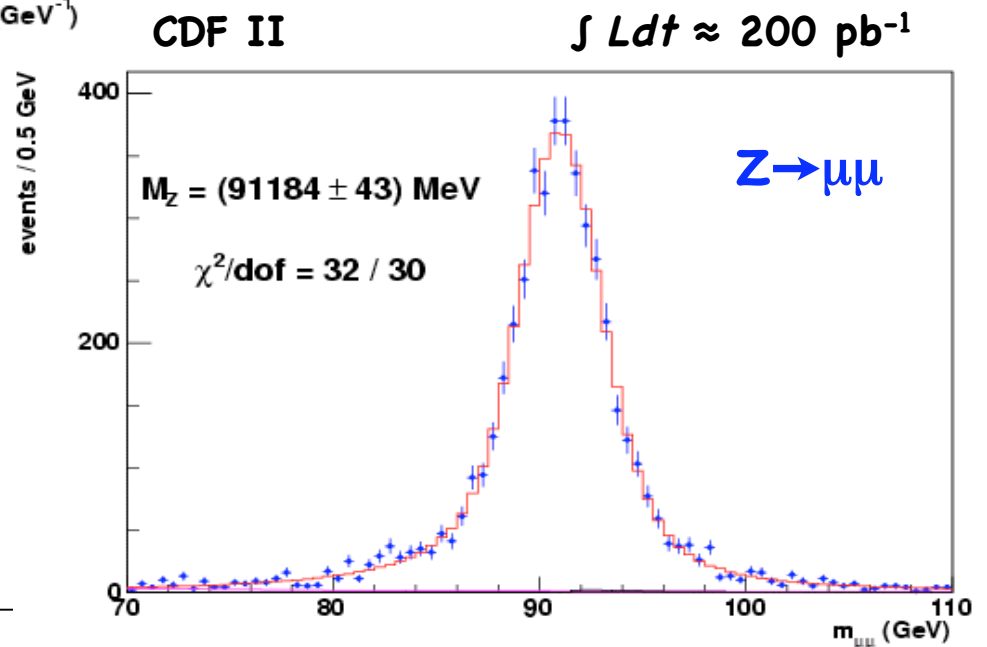
Response and resolution
of the EM calorimeter

Energy leakage into
hadronic calorimeter

Energy loss in solenoid

EM Calorimeter

END WALL HADRON CAL.

30^0

SOLENOID

Track reconstruction
in the drift chamber

COT

END PLUG EM CALORIMETER

END PLUG HADRON CALORIMETER

$\eta = 2.0$

$\eta = 3.0$

3^0

Bremsstrahlung
and conversions
in silicon detector

m

2.0

1.0

0

0   1.0   2.0   3.0 m

LAYER 00   SVX II   INTERMEDIATE SILICON LAYERS

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
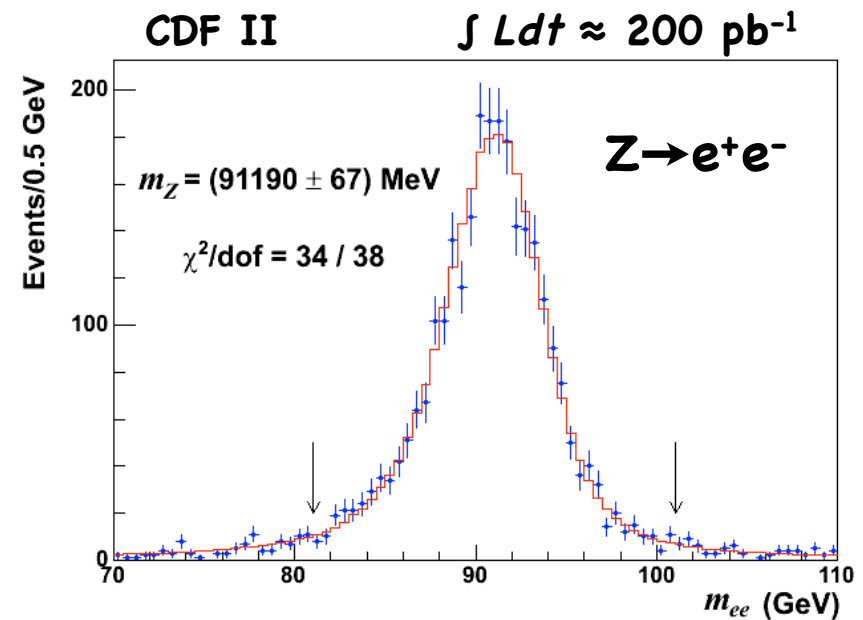
CDF II   ∫ Ldt ≈ 200 pb⁻¹

W→eν

(for the scale:)
$\chi^2/dof = 17 / 16$

Fine-tune the amount of material using the tail

$E/p \ (W \rightarrow e\nu)$
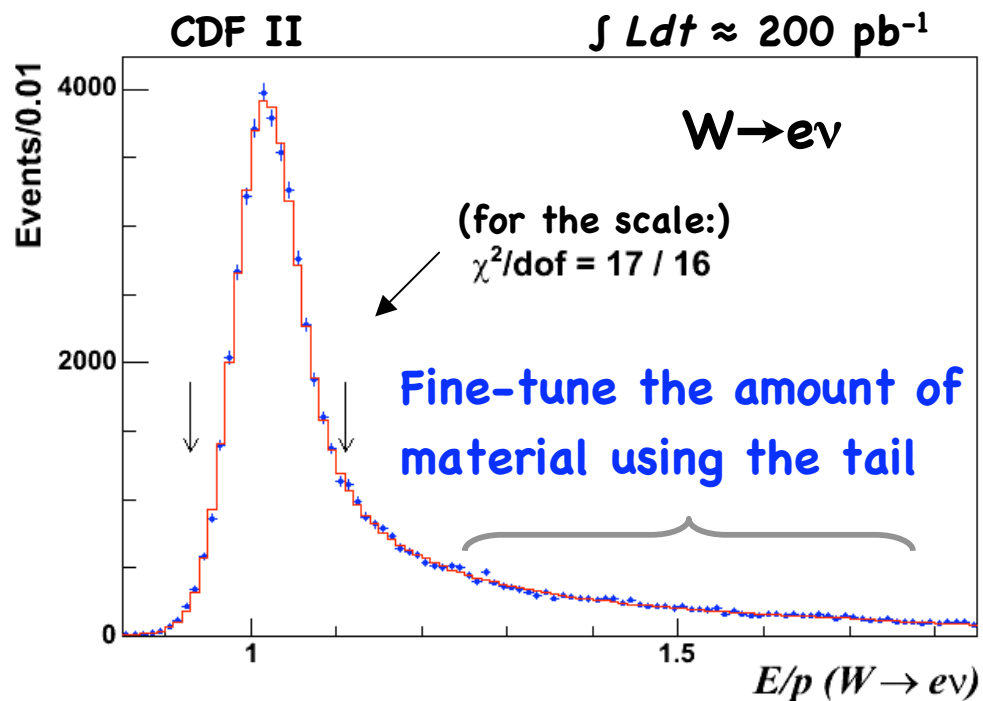
Non-linear calorimeter response
also simulated (measured on E/p)

Test the scale in a Z mass fit:

PDG m_Z=91188±2 MeV

CDF II   ∫ Ldt ≈ 200 pb⁻¹
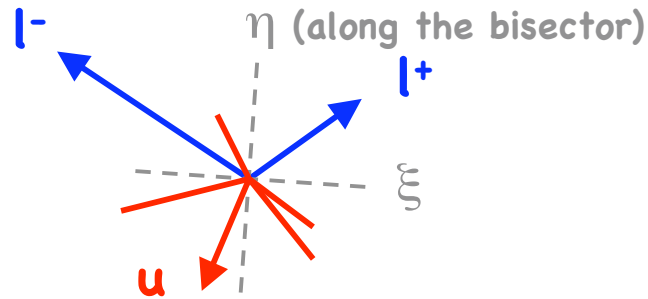
$m_Z = (91190 \pm 67)$ MeV

$\chi^2/dof = 34 / 38$

Z→e⁺e⁻

m_{ee} (GeV)

Final E/p and Z mass fit scales and resolutions combined $\begin{cases} \Delta m_{W(scale)} = 30 \text{ MeV} \\ \Delta m_{W(resol)} = \ \ 9 \text{ MeV} \end{cases}$

Hadronic Recoil

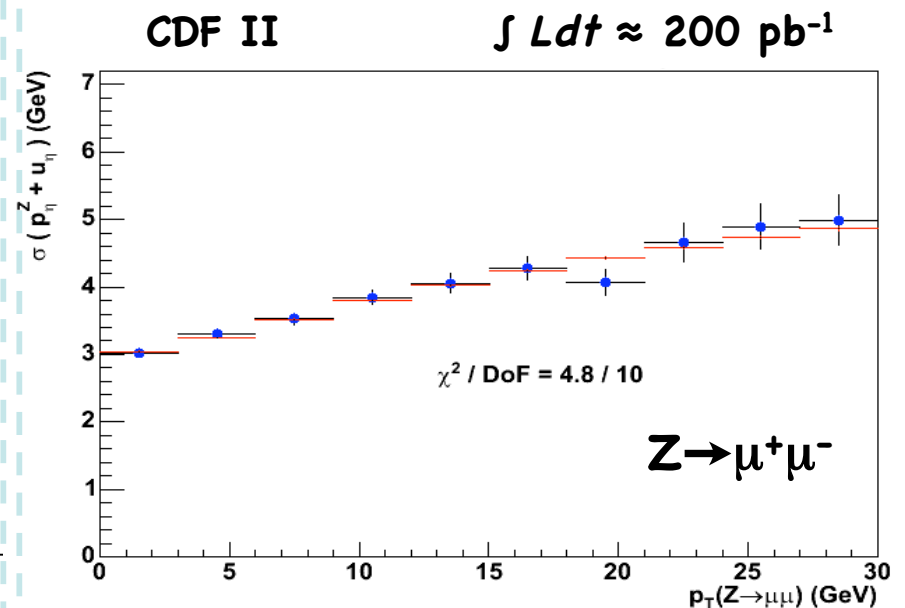**Calorimeter deposits from initial state QCD and the underlying event**

l⁻ η (along the bisector) l⁺ ξ u

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

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

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

Δm_W=9MeV

Δm_W=7MeV

CDF II $\int Ldt \approx 200$ pb⁻¹

$Z \rightarrow \mu\mu$

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

R / 2 GeV

$p_T^{\mu\mu}$ (GeV)

CDF II $\int Ldt \approx 200$ pb⁻¹

χ^2 / DoF = 4.8 / 10

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

$\sigma(p_\eta^z + u_\eta)$ (GeV)

$p_T(Z \rightarrow \mu\mu)$ (GeV)

Hadronic Recoil : W decays

Validating the recoil model:
description of the W
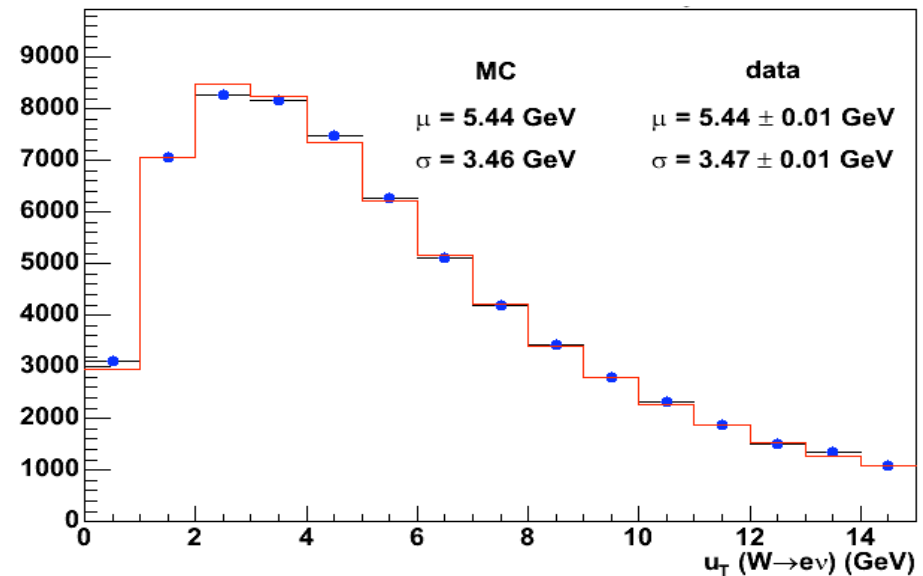recoil distributions

(W boson p_T,
measured in the recoil)

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

directly affecting m_T

CDF II $\int L dt \approx 200$ pb^{-1}

MC   data

$\mu = 5.44$ GeV $\mu = 5.44 \pm 0.01$ GeV

$\sigma = 3.46$ GeV $\sigma = 3.47 \pm 0.01$ GeV

u_T ($W \to e\nu$) (GeV)

CDF II $\int L dt \approx 200$ pb^{-1}

MC   data

$\mu = -0.46$ GeV $\mu = -0.44 \pm 0.02$ GeV

$\sigma = 4.42$ GeV $\sigma = 4.42 \pm 0.01$ GeV

$u_{||}$ ($W \to \mu\nu$) (GeV)
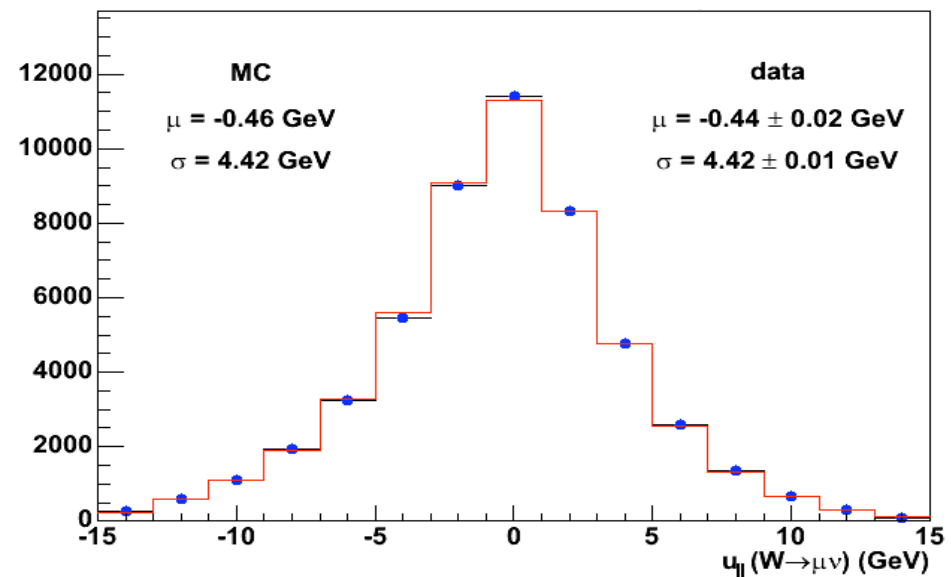
Theoretical uncertainties

Momentum fraction taken by the partons
[JHEP 0207,012 (2002)]

Use CTEQ6M Parton distribution

functions (PDFs), observe shifts

using PDFs that span the parameter uncertainty

$\Delta m_W = 11 MeV$

Final state QED radiation [PRD59,013002 (1998)]

Use a WGRAD that calculates the

exact one photon contribution,

take 10% of the 1photon effect

to estimate missing higher orders

based on Horace [PRD69,037301 (2004)]

$\Delta m_W^e = 11 MeV$
$\Delta m_W^\mu = 12 MeV$

Boson p_T simulation [PRD67,073016 (2003)]

Predicted by the resbos generator,

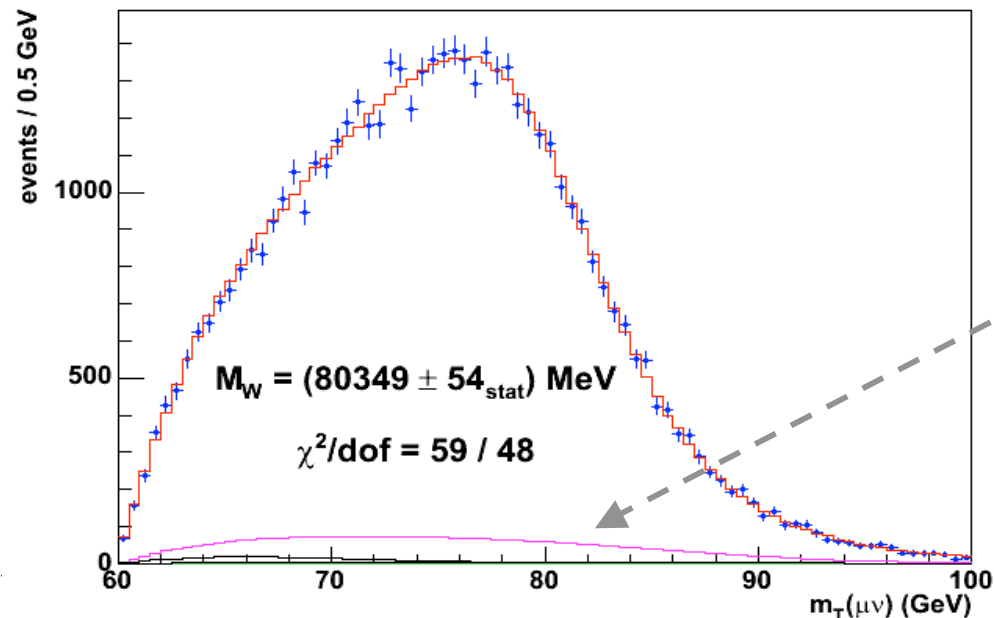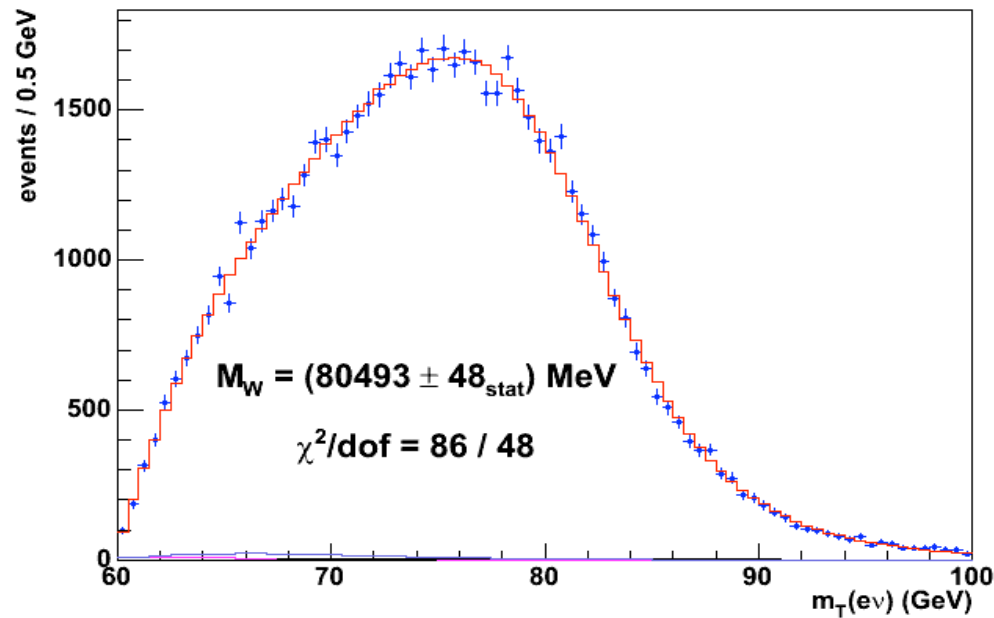where the non-perturbative region

of low p_T is parameterized and

obtained from a fit to Z boson p_T

$\Delta m_W = 3 MeV$

Fits for the W mass – m_T

$M_W = (80493 \pm 48_{stat})$ MeV

$\chi^2/\mathrm{dof} = 86 / 48$

$m_T(e\nu)$ (GeV)

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
$u_{\parallel}$ 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

$M_W = (80349 \pm 54_{stat})$ MeV

$\chi^2/\mathrm{dof} = 59 / 48$

$m_T(\mu\nu)$ (GeV)

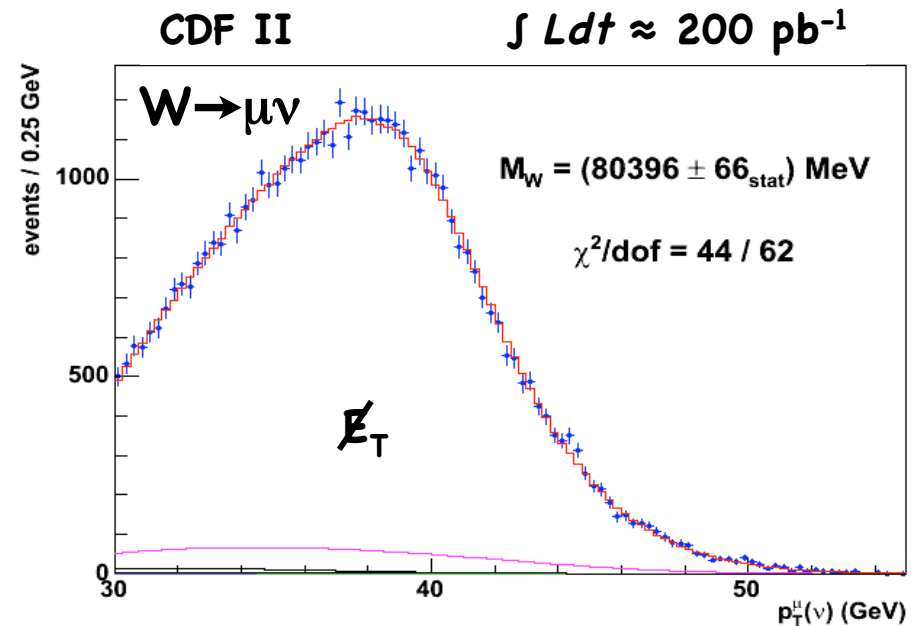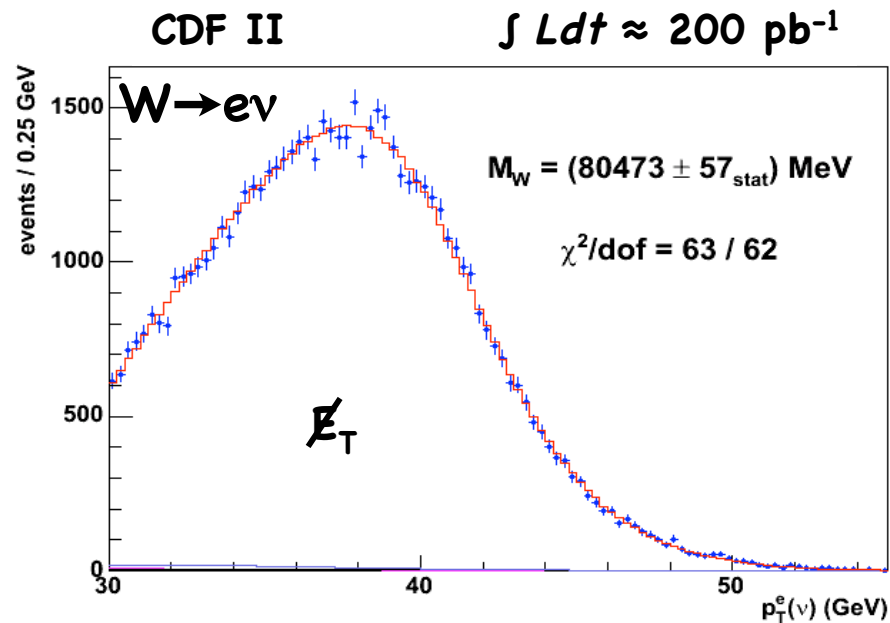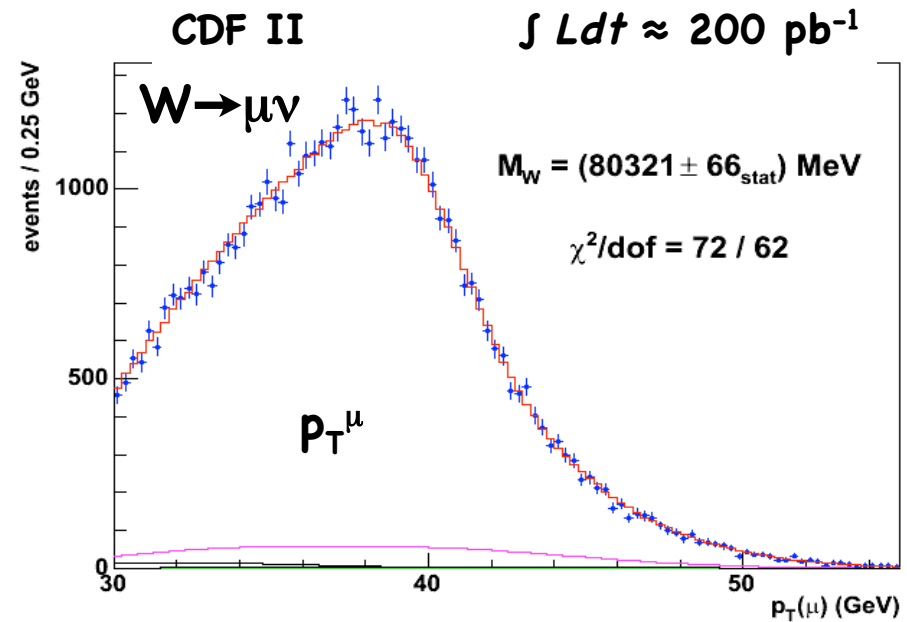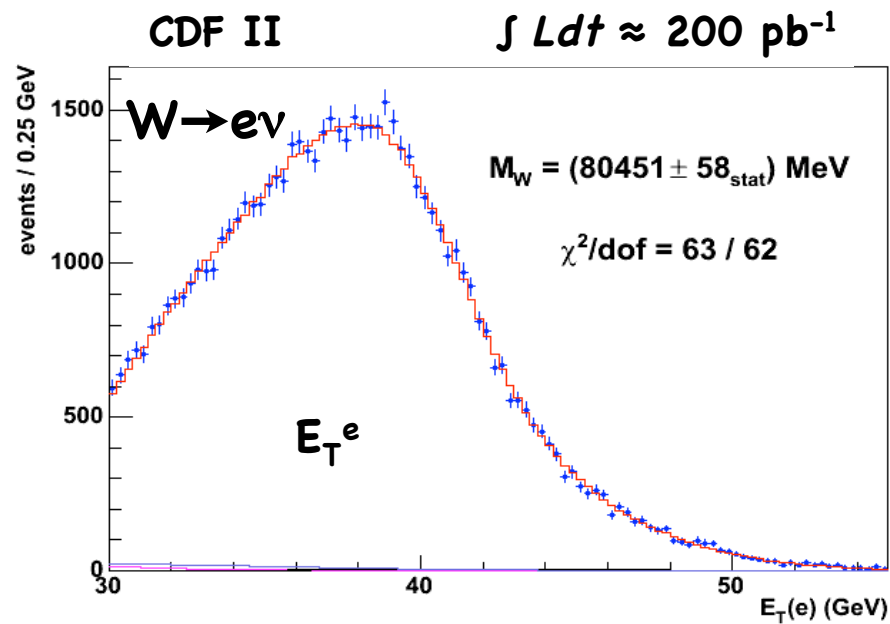**Background contributions:**

simulate using MC:

W EWK backgrounds (Z , τ decays)

Obtain from sidebands in data:

Electrons: Multi-jet backgrounds

Muons: decays in COT of π and kaons

Fits for the W mass II

CDF II $\int Ldt \approx 200\ pb^{-1}$

$W \to e\nu$

$M_W = (80451 \pm 58_{stat})$ MeV

$\chi^2/dof = 63 / 62$

E_T^e

$E_T(e)$ (GeV)

CDF II $\int Ldt \approx 200\ pb^{-1}$

$W \to \mu\nu$

$M_W = (80321 \pm 66_{stat})$ MeV

$\chi^2/dof = 72 / 62$

p_T^μ

$p_T(\mu)$ (GeV)

CDF II $\int Ldt \approx 200\ pb^{-1}$

$W \to e\nu$

$M_W = (80473 \pm 57_{stat})$ MeV

$\chi^2/dof = 63 / 62$

$\not{E}_T$

$p_T^e(\nu)$ (GeV)

CDF II $\int Ldt \approx 200\ pb^{-1}$

$W \to \mu\nu$

$M_W = (80396 \pm 66_{stat})$ MeV

$\chi^2/dof = 44 / 62$

$\not{E}_T$

$p_T^\mu(\nu)$ (GeV)

The result and constraints

m_W = 80413 ± 34 MeV (stat) ± 34 MeV (sys)
    = 80413 ± 48 MeV (stat + sys)   [PRL 99,151801 (2007)]

200pb⁻¹

Central value: 80392 -> 80398 MeV
Uncertainty: -15% (29 to 25 MeV)

March 2008

— LEP2 and Tevatron (prel.)
···· LEP1 and SLD

68% CL

m_W [GeV]

80.5

80.4

80.3

m_H [GeV]
114   300   1000

$\Delta\alpha$

150   175   200

m_t [GeV]
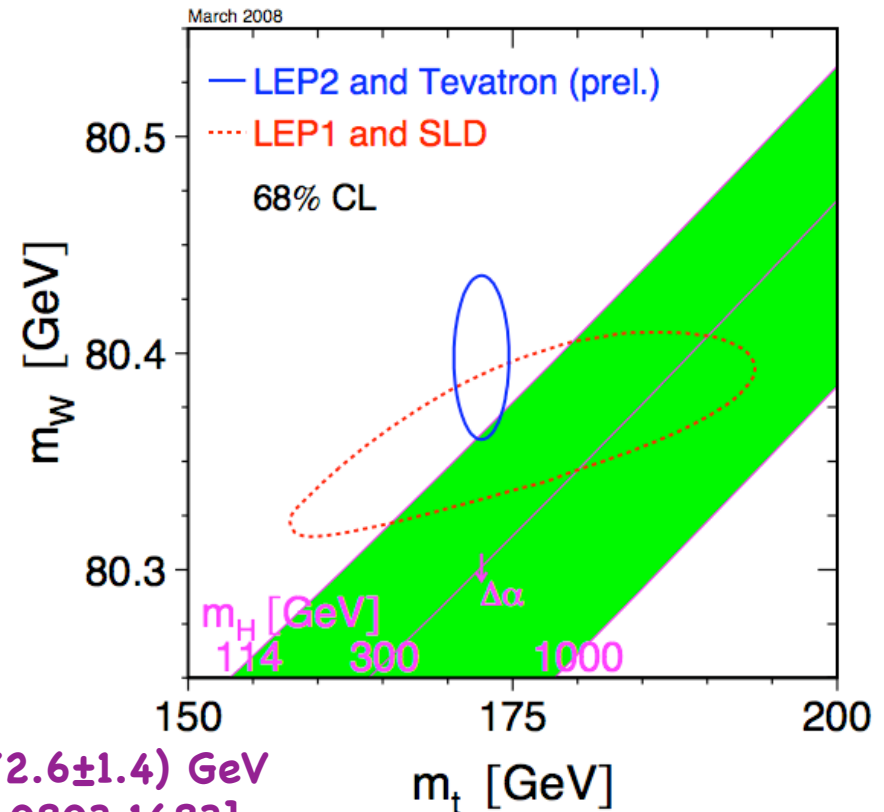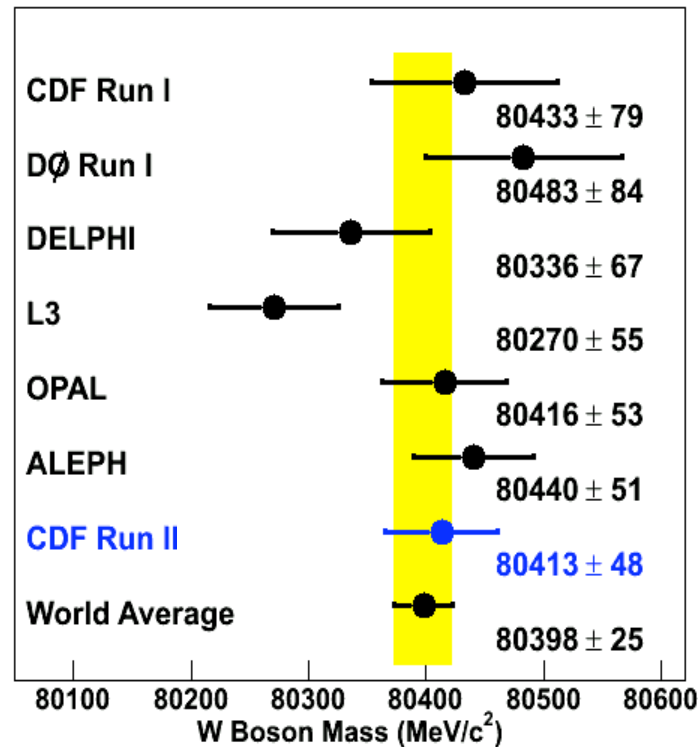
m_t=(172.6±1.4) GeV
[arXiv:0803.1683]

predicted Higgs mass: 86^{+36}_{-27} GeV
M_H < 160 GeV @ 95% CL

CDF Run I   80433 ± 79

DØ Run I   80483 ± 84

DELPHI   80336 ± 67

L3   80270 ± 55

OPAL   80416 ± 53

ALEPH   80440 ± 51

CDF Run II   80413 ± 48

World Average   80398 ± 25

80100   80200   80300   80400   80500   80600
W Boson Mass (MeV/c²)

What can we do with > 2fb⁻¹ ?

$\Delta M_W \approx 25\,\text{MeV}$

2/fb

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
$u_{\parallel}$ 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

(Plot: Single Experiment Sensitivity — W Mass Precision (MeV) vs Integrated Luminosity (/pb); data points: D∅ Run 1a (e), CDF Run 1a (e+μ), D∅ Run 1 (e), CDF Run 1 (e+μ), CDF Run 2 (e+μ); 10 MeV syst limit)

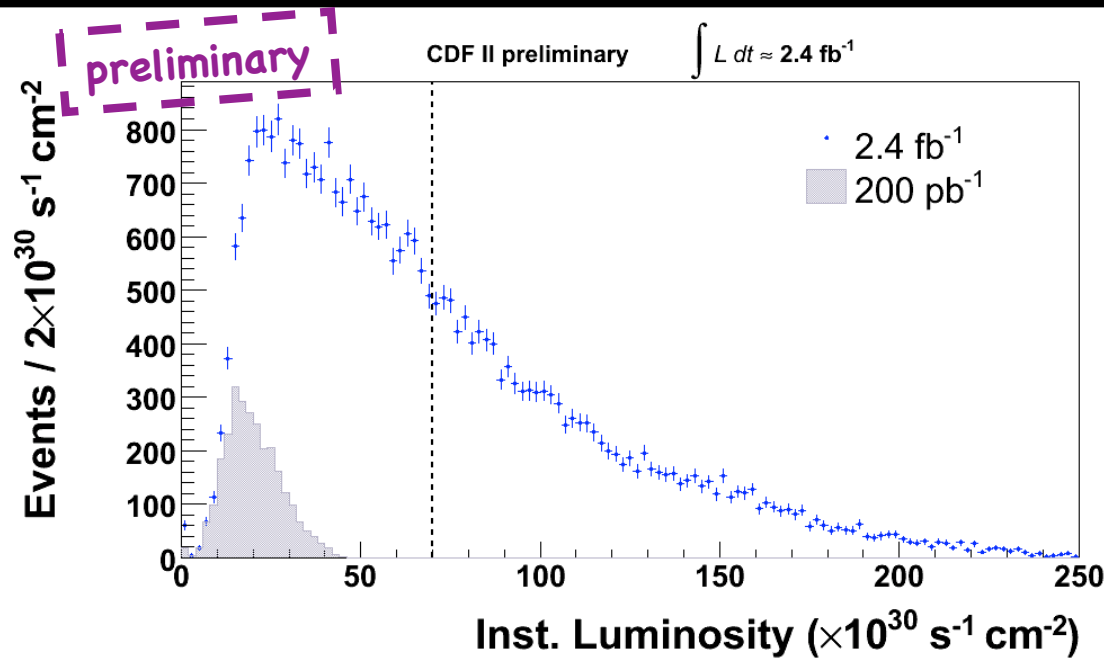Can surpass the current world average with a single measurement:
$\Delta M_W^{CDF} < 25\,\text{MeV}$

Provided:

- detector **aging**

- averaging over **longer** data-taking **period**

- larger spread and higher average **luminosity**

do not deteriorate data quality
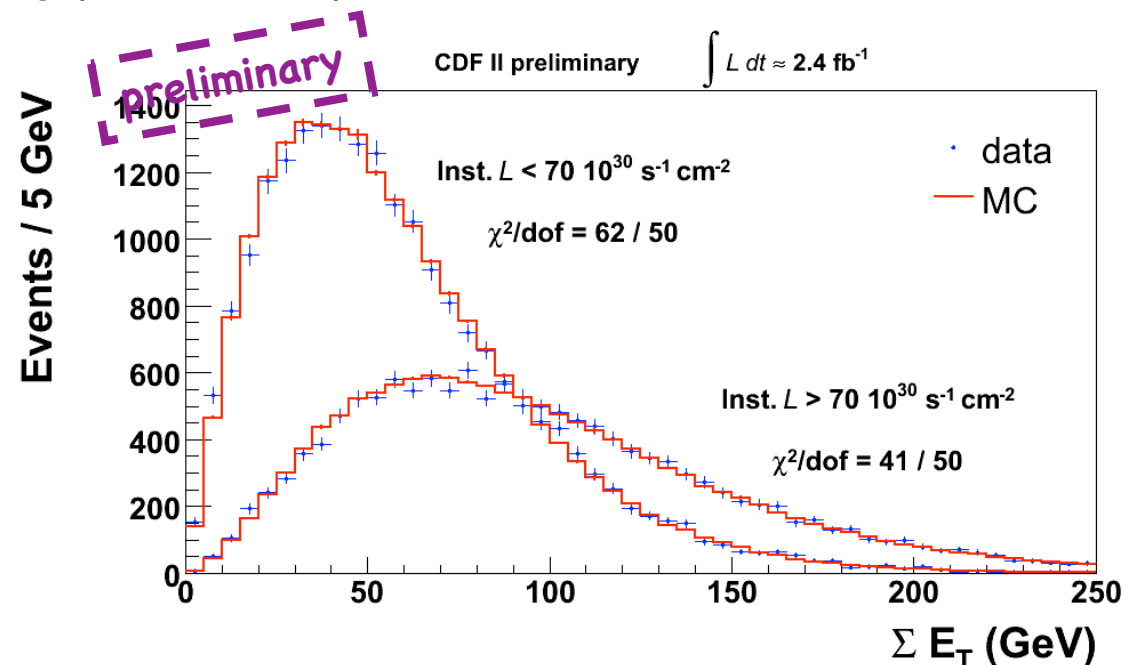
Instantaneous luminosity
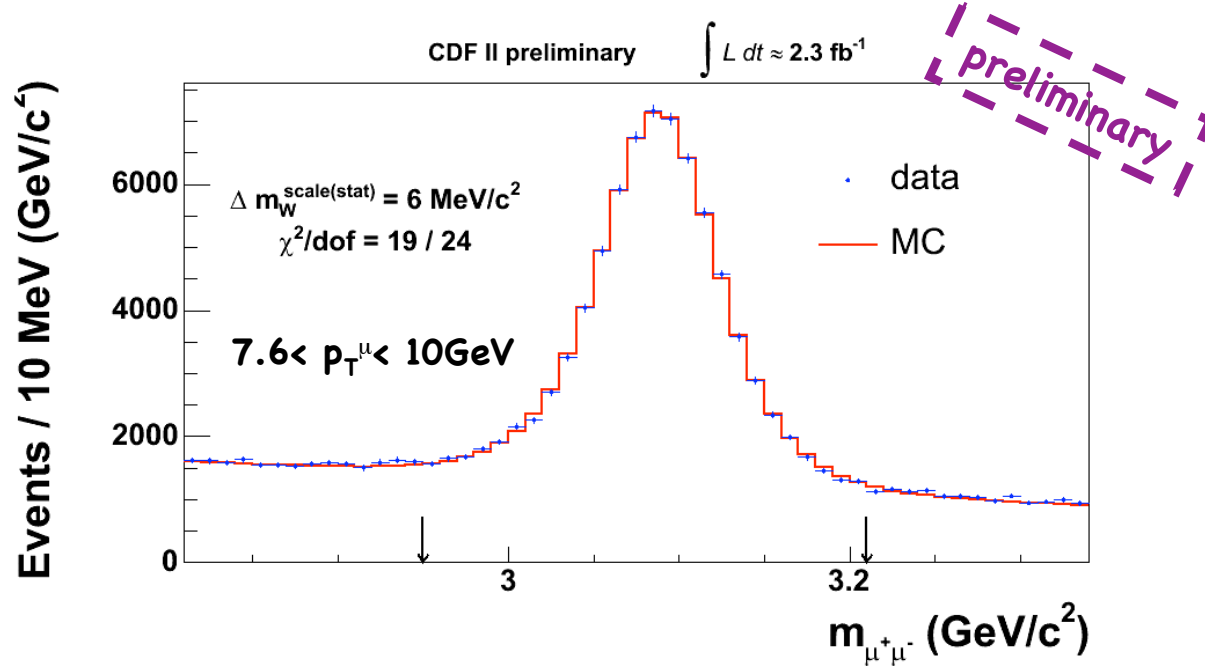

Higher instantaneous luminosities L and much **larger spread**

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

We are able to capture luminosity dependence of the sum of all deposits in the calorimeter (ΣE_T)
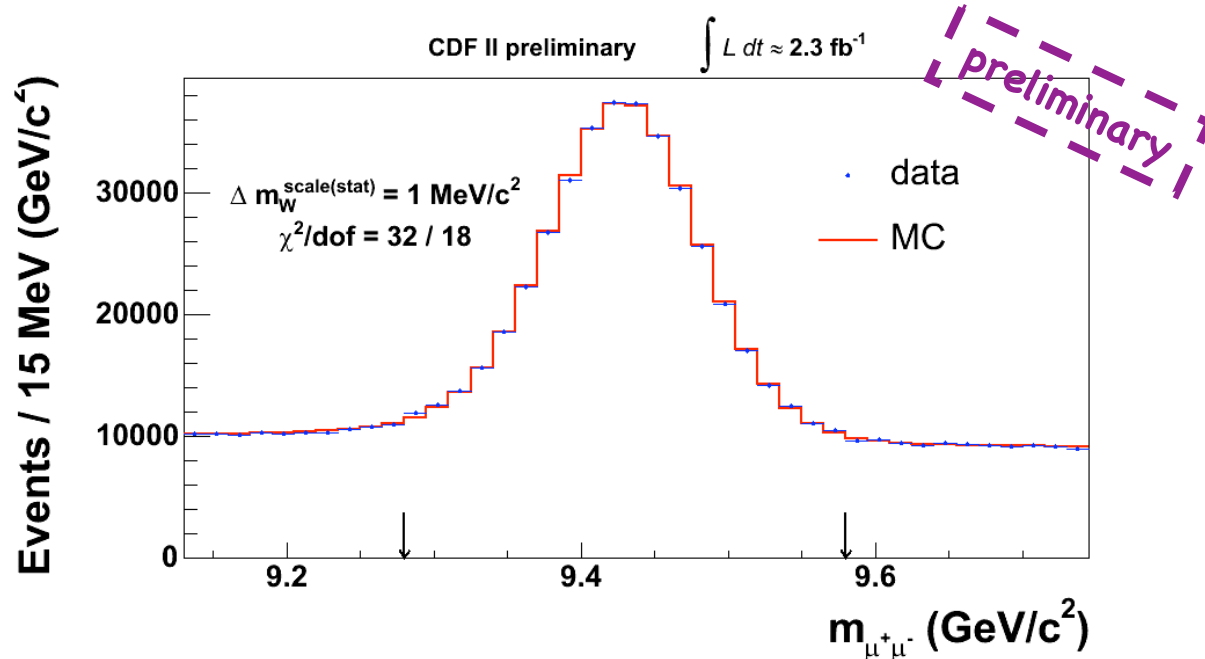
ΣE_T is the basis for recoil resolution description

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

CDF II preliminary $\int L\, dt \approx 2.3\ \text{fb}^{-1}$

Preliminary

$\Delta m_W^{\text{scale(stat)}} = 6\ \text{MeV}/c^2$

$\chi^2/\text{dof} = 19/24$

$7.6 < p_T^\mu < 10\ \text{GeV}$

· data

— MC

Events / 10 MeV (GeV/c^2)

$m_{\mu^+\mu^-}\ (\text{GeV}/c^2)$

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

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

(Expected from scaling the integrated luminosity)

CDF II preliminary $\int L\, dt \approx 2.3\ \text{fb}^{-1}$

Preliminary

$\Delta m_W^{\text{scale(stat)}} = 1\ \text{MeV}/c^2$

$\chi^2/\text{dof} = 32/18$

· data

— MC

Events / 15 MeV (GeV/c^2)

$m_{\mu^+\mu^-}\ (\text{GeV}/c^2)$

Y(1S)→μ⁺μ⁻ (beam constrained fit)

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

Z mass fits
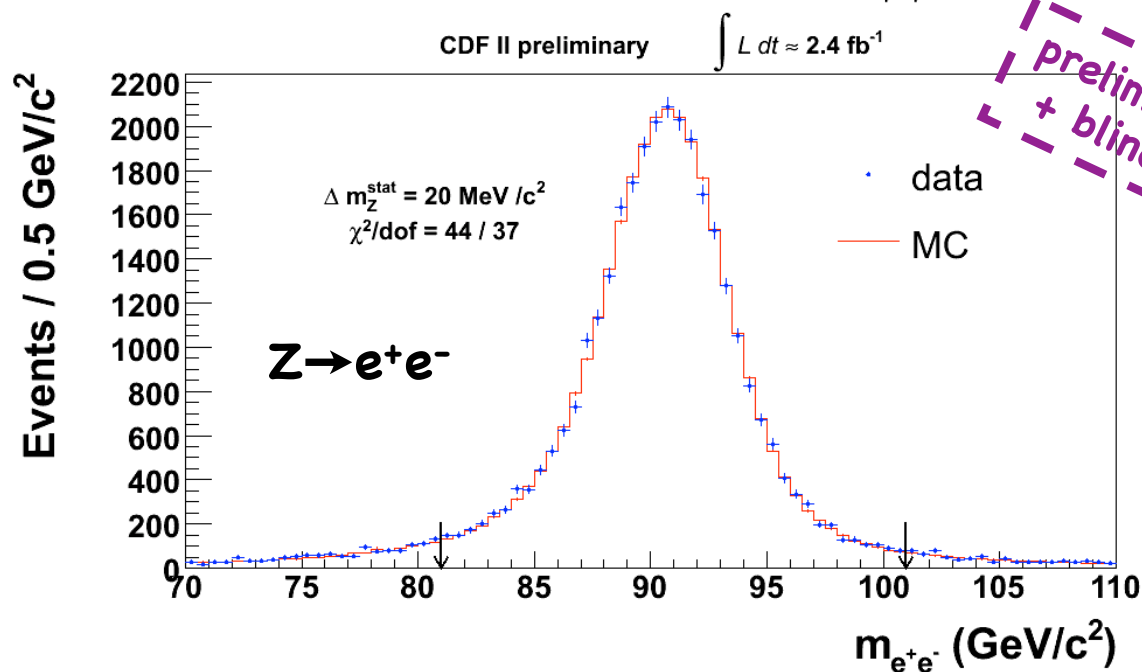
Z mass fit using tracking info only

Z→e⁺e⁻ (track only)

	Δm_Z^{stat}
published (200pb⁻¹)	143MeV
expected (2.4fb⁻¹)	42MeV
fit (2.4fb⁻¹)	42MeV
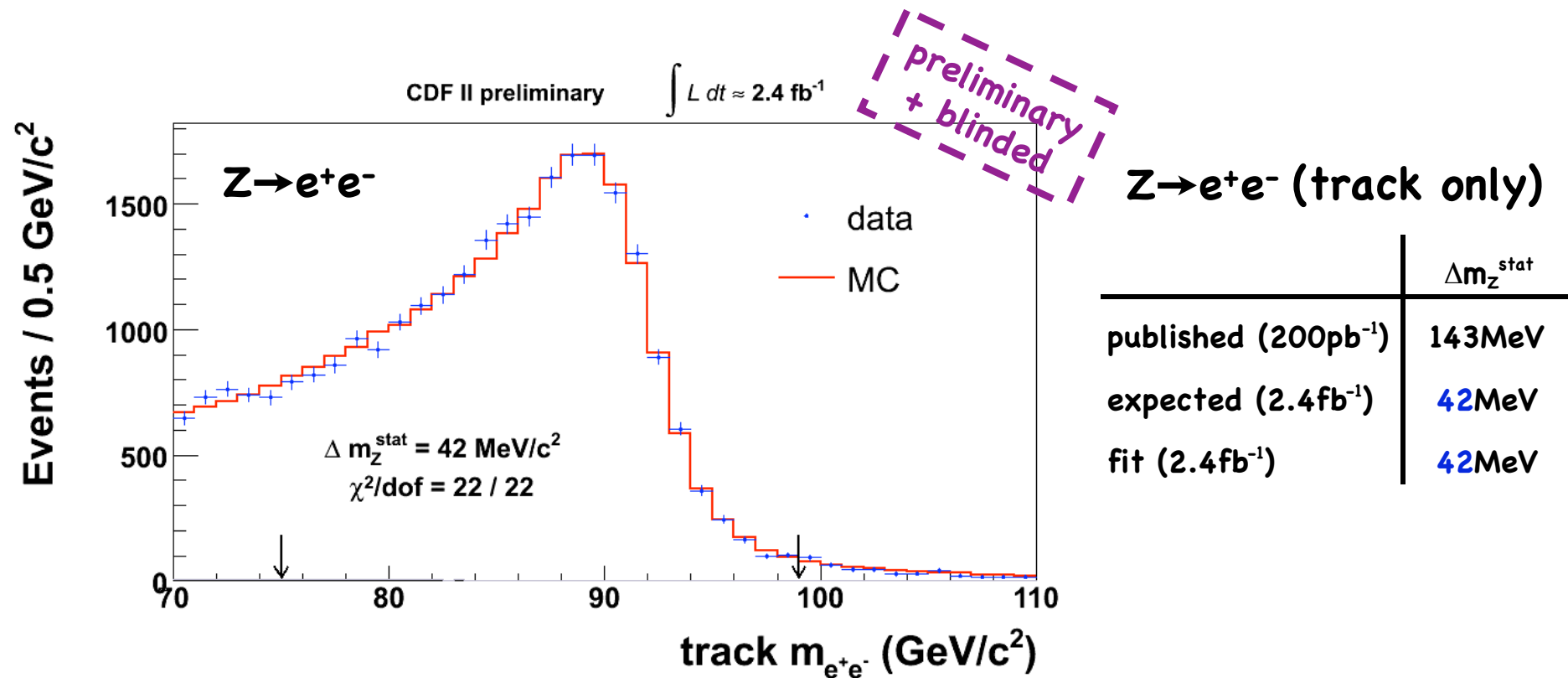
Sensitive to photon emission modelling (bremsstrahlung).

CDF II preliminary $\int L\,dt \approx 2.4\ \text{fb}^{-1}$

preliminary

W→eν

- · data
- — MC
- ▦ background

$\Delta m_W^{\text{scale(stat)}} = 5\ \text{MeV/c}^2$
$\chi^2/\text{dof} = 33 / 16$

E/pc (W→eν)

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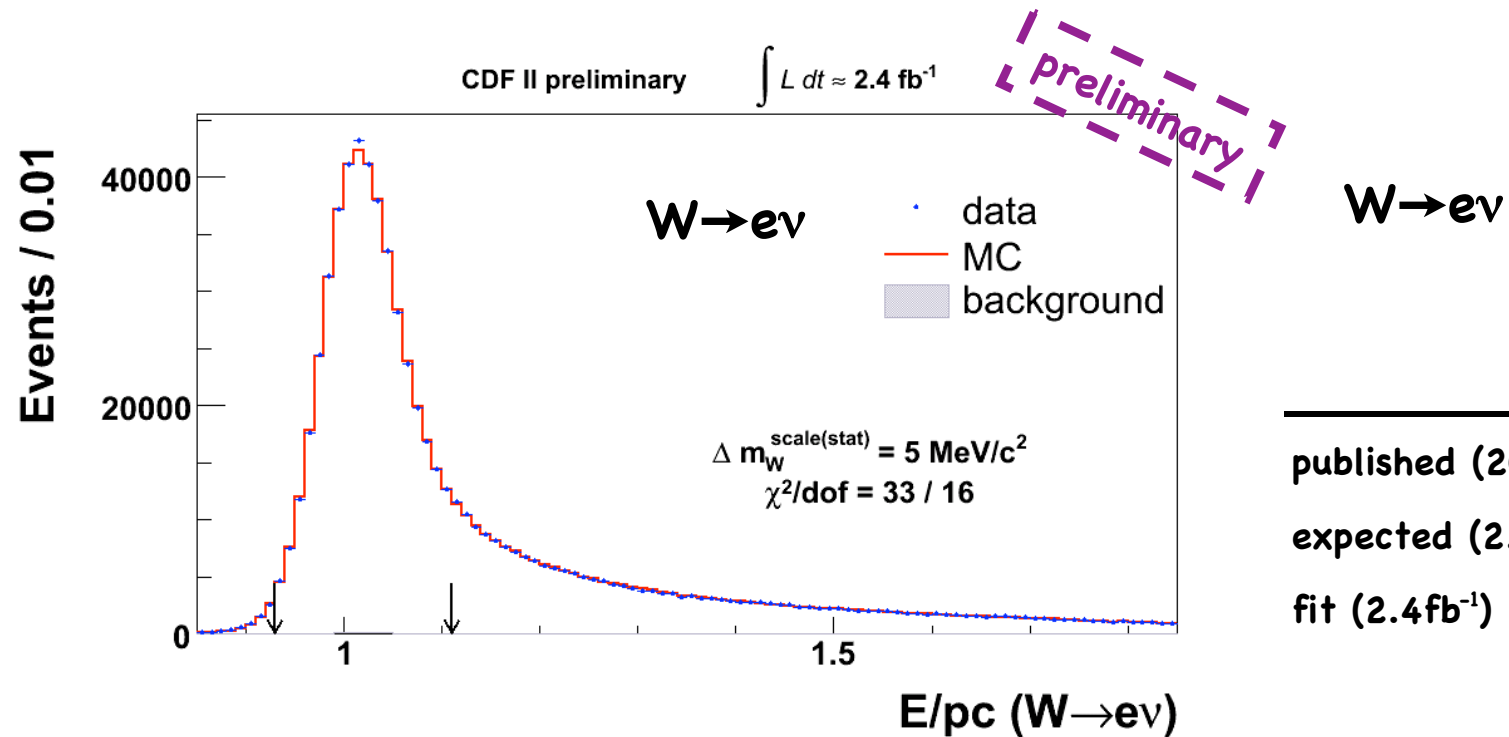
	$\Delta m_W^{\text{scale (stat)}}$
published (200pb^{-1})	20MeV
expected (2.4fb^{-1})	6MeV
fit (2.4fb^{-1})	5MeV

Sensitive to material, momentum and energy calibrations.

m$_T$ fits

CDF II preliminary $\int L\, dt \approx 2.4\ \text{fb}^{-1}$

W→eν

- data
- MC
- background

Preliminary + blinded

$\Delta m_W^{stat} = 15\ \text{MeV/c}^2$

$\chi^2/\text{dof} = 70 / 48$

m$_T$(eν) (GeV/c^2)

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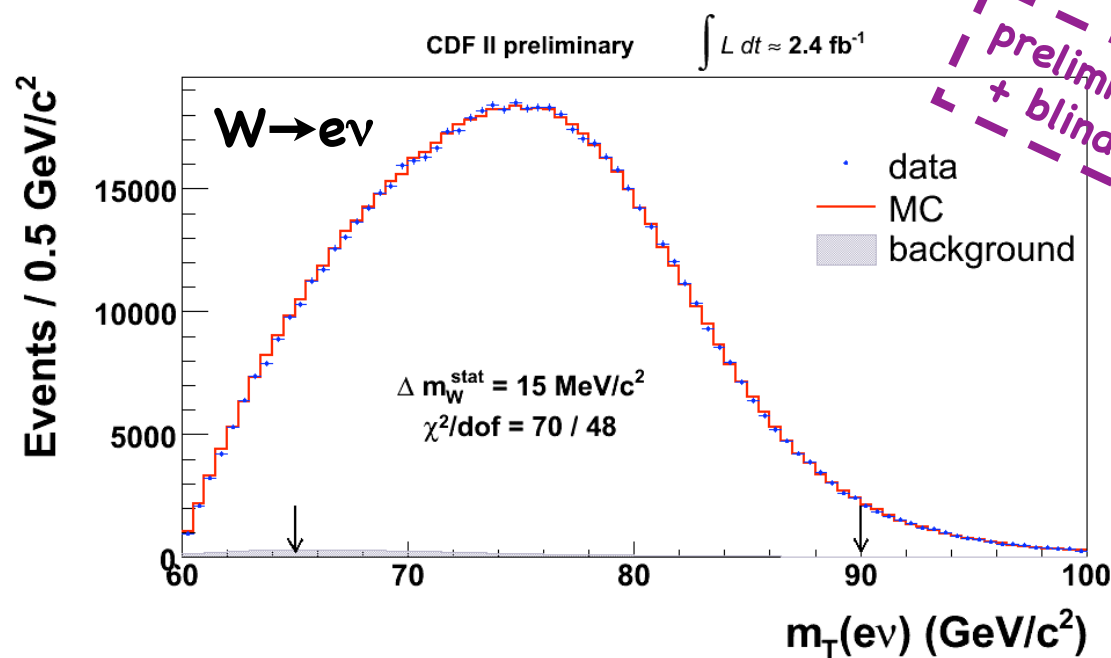
	Δm_W^{stat}
published (200pb^{-1})	48MeV
expected (2.4fb^{-1})	14MeV
fit (2.4fb^{-1})	15MeV

CDF II preliminary $\int L\, dt \approx 2.3\ \text{fb}^{-1}$

W→μν

- data
- MC
- background

Preliminary + blinded

$\Delta m_W^{stat} = 16\ \text{MeV/c}^2$

$\chi^2/\text{dof} = 72 / 48$

m$_T$(μν) (GeV/c^2)

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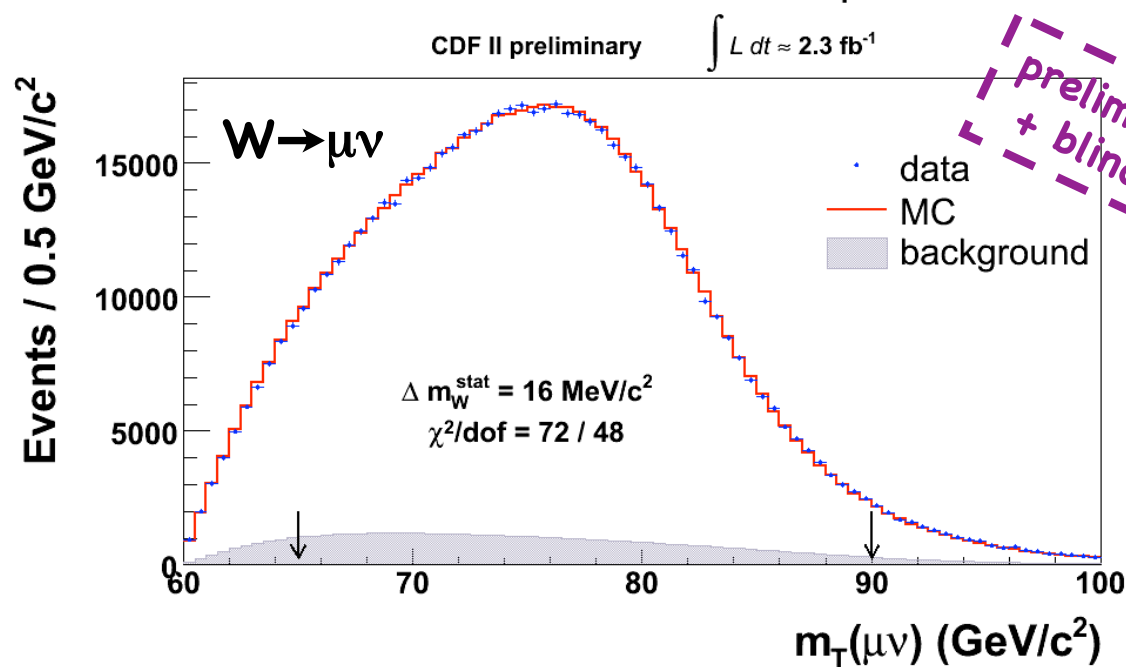
	Δm_W^{stat}
published (200pb^{-1})	54MeV
expected (2.3fb^{-1})	16MeV
fit (2.3fb^{-1})	16MeV

Conclusions

The first RunII CDF W mass measurement is the single best W mass measurement, the total uncertainty is 48MeV

This measurement is better than expected by statistical scaling the RunI measurements :
using quarkonia for momentum scale determination,...
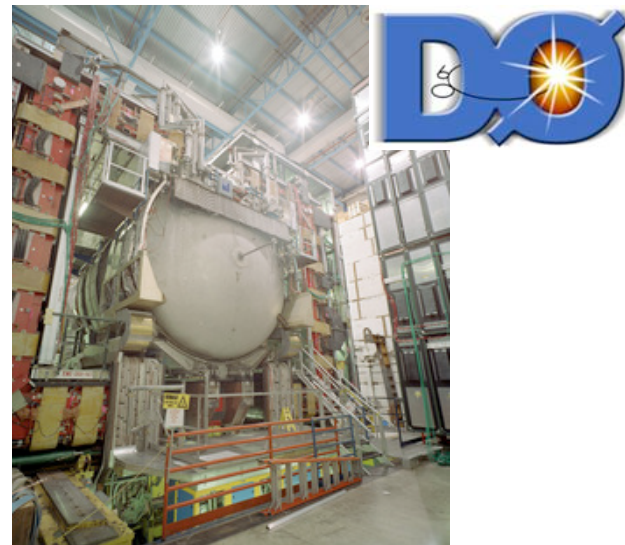
We started looking at 12x more data:
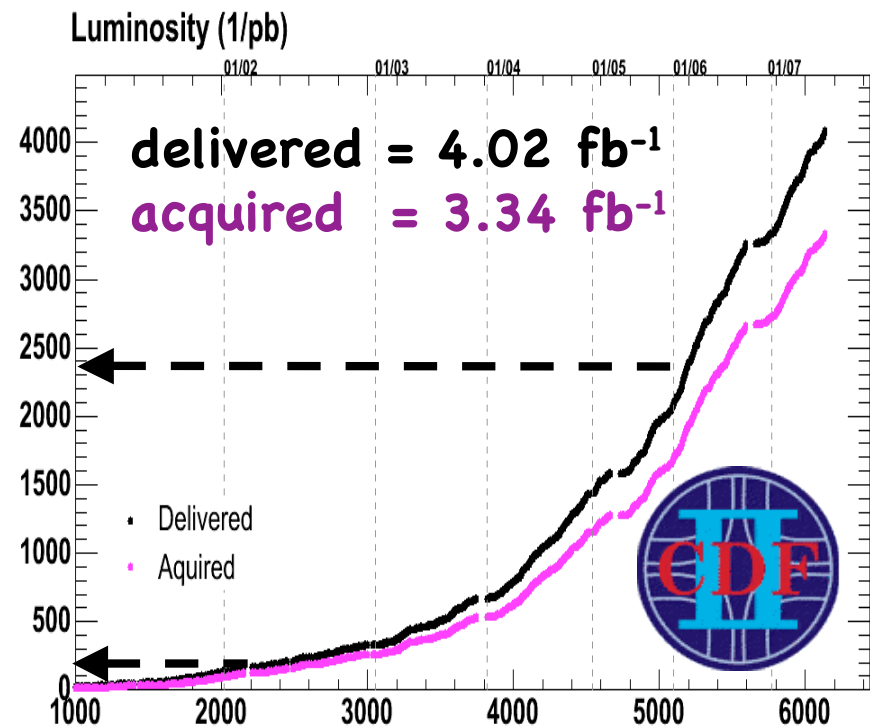
Data quality good

- Statistical uncertainty as expected

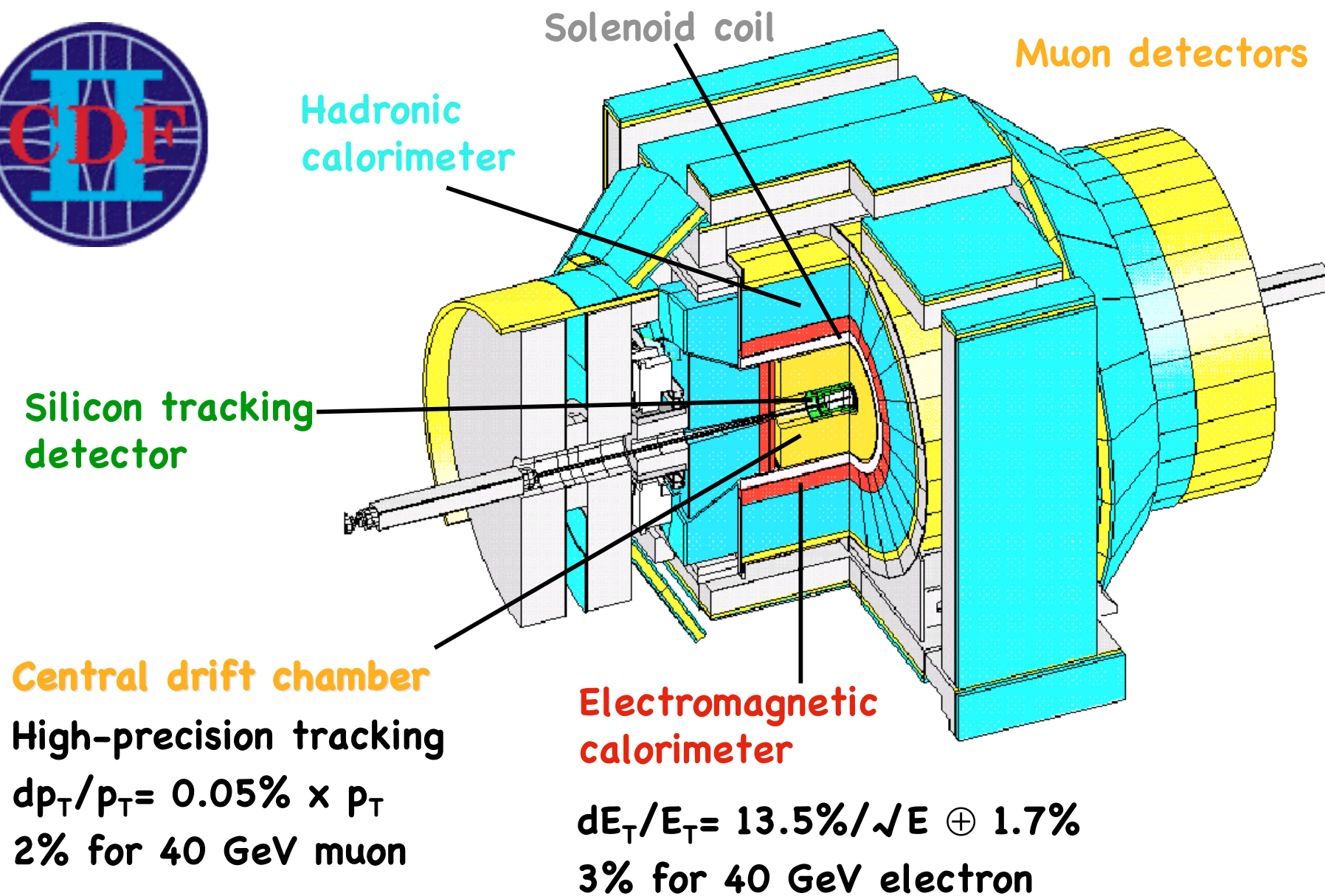- Instantaneous luminosity distribution seems to not be an issue

We aim for a W mass determination with a total uncertainty of < 25MeV!

Backup slides

Luminosity (1/pb)

delivered = 4.02 fb^{-1}
acquired = 3.34 fb^{-1}

· Delivered
· Aquired

$\bar{p} \rightarrow \leftarrow p$
$\sqrt{s}$=1960 GeV

CDF detector

Solenoid coil

Muon detectors

Hadronic calorimeter

Silicon tracking detector

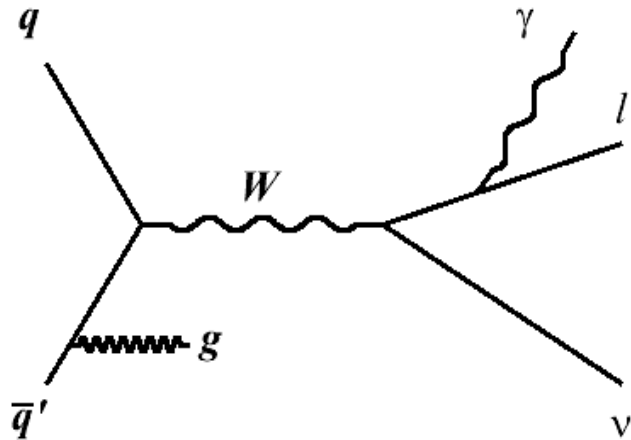**Central drift chamber**

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

$s(W \rightarrow l\nu)$ = 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→μν candidates
63,964 W→eν candidates
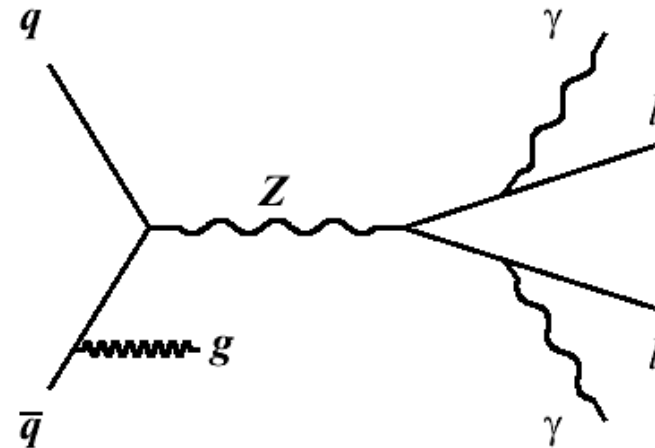
$s(Z \rightarrow ll)$ = 254.9 pb

After event selection
p_T^l / E_T^l > 30 GeV
u < 15 GeV
66 < m_{ll} < 116 GeV
...

4,960 Z→μμ candidates
2,919 Z→ee candidates

Simulating the passage through detector material

CDF II $\int Ldt \approx 200\ pb^{-1}$

$200pb^{-1}$

$S_{mat} = 1 \pm 0.009_{stat}$

$\chi^2/dof = 0.7 / 1$

events / 0.33

40000

20000

1   1.5

$E/p\ (W \rightarrow e\nu)$
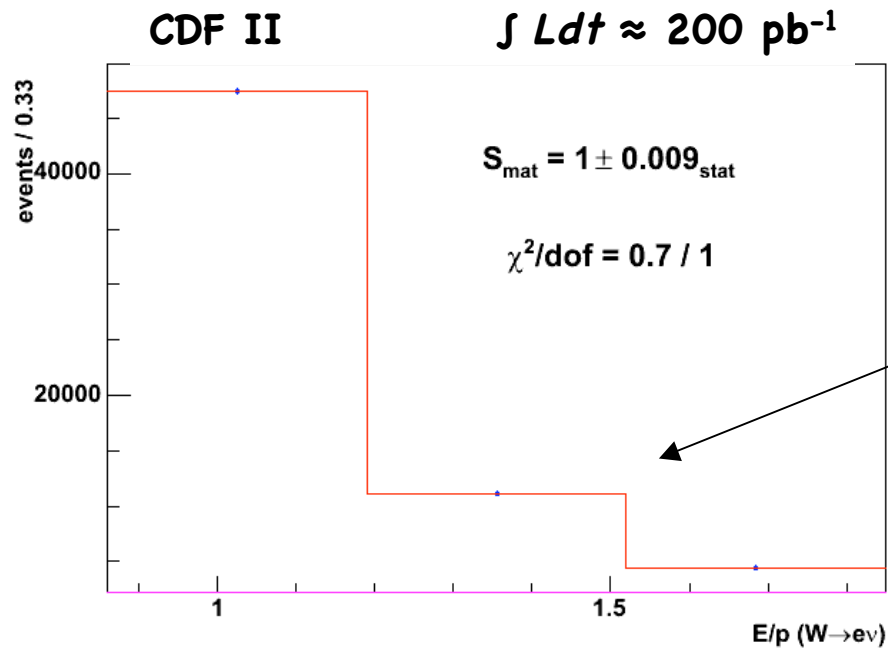
**Material scale S_{mat}:
Fine-tune the amount of
material using the tail**

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

**Fitted value consistent
with world average value
(91188 MeV)**

CDF II $\int Ldt \approx 200\ pb^{-1}$

Events/GeV

150

100

50

0

$m_Z = (91282 \pm 143)\ MeV$

$\chi^2/dof = 30 / 22$

70   80   90   100   110

Track m_{ee} (GeV)