Cracow–Warsaw Workshop on LHC
Faculty of Physics, University of Warsaw – 26 March 2010

Measurement of the W boson mass at Tevatron

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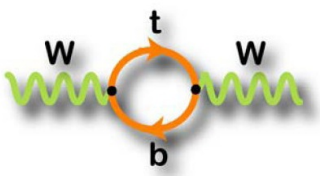
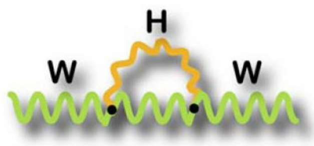
Motivation for precise W mass

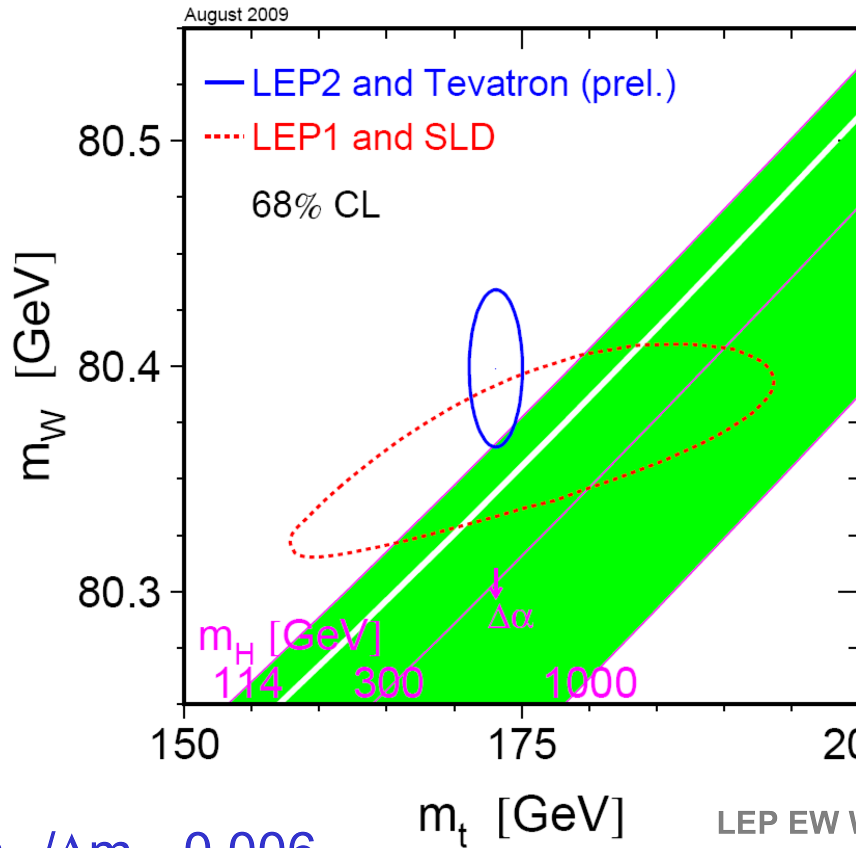
- **Precise measurements of m_W and m_t can constrain SM Higgs mass**

$$m_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \cdot \frac{1}{\sin\theta_W\sqrt{1-\mathbf{\Delta r}}}$$





$\Delta r \propto m_t^2$ $\Delta r \propto \log m_H$



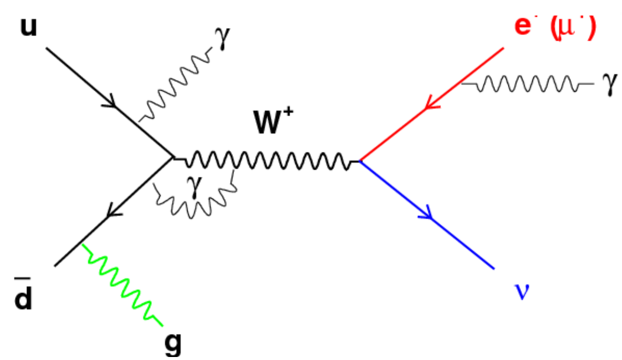
LEP EW WG
Aug 2009

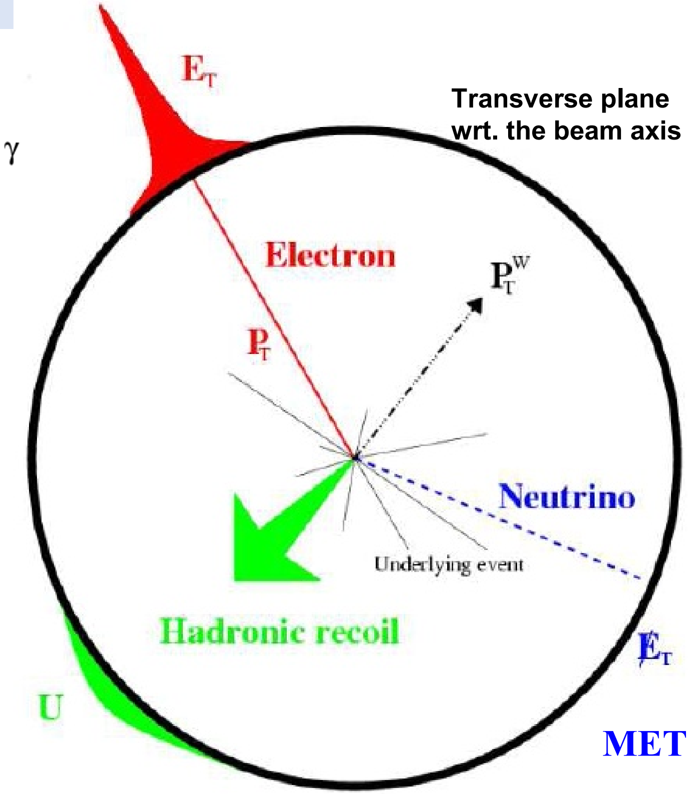
- Δm_W has same impact on Δm_H for $\Delta m_W/\Delta m_t \approx 0.006$
  - for recent Δm_t = 1.3 GeV would need: Δm_W = 8 MeV (0.01%)
  - current world average: Δm_W = 23 MeV (0.03%)

- Additional contributions to **Δr** arise in SM extensions...

Signatures & observables

- **Signature of W:**
  - isolated, high p_T lepton (e or μ)
  - missing E_T





- **Use 3 kinematic variables:** (Jacobian edge)

$$m_T = \sqrt{2\, E_T^{\ell}\, \not{E}_T\, (1 - \cos\Delta\phi_{\ell\nu})}$$

→ **affected by detector resolution (MET)**

$$p_T^{\ell}$$

→ **affected by motion of W boson (p_T^W)**

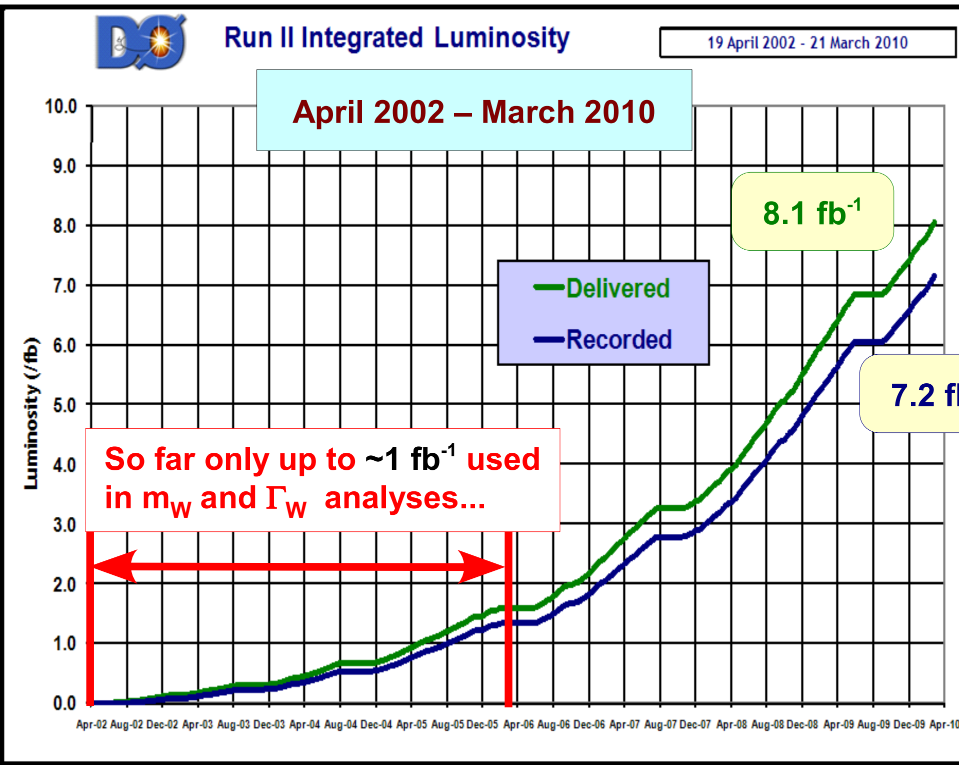
$$p_T^{\nu} = \not{E}_T$$

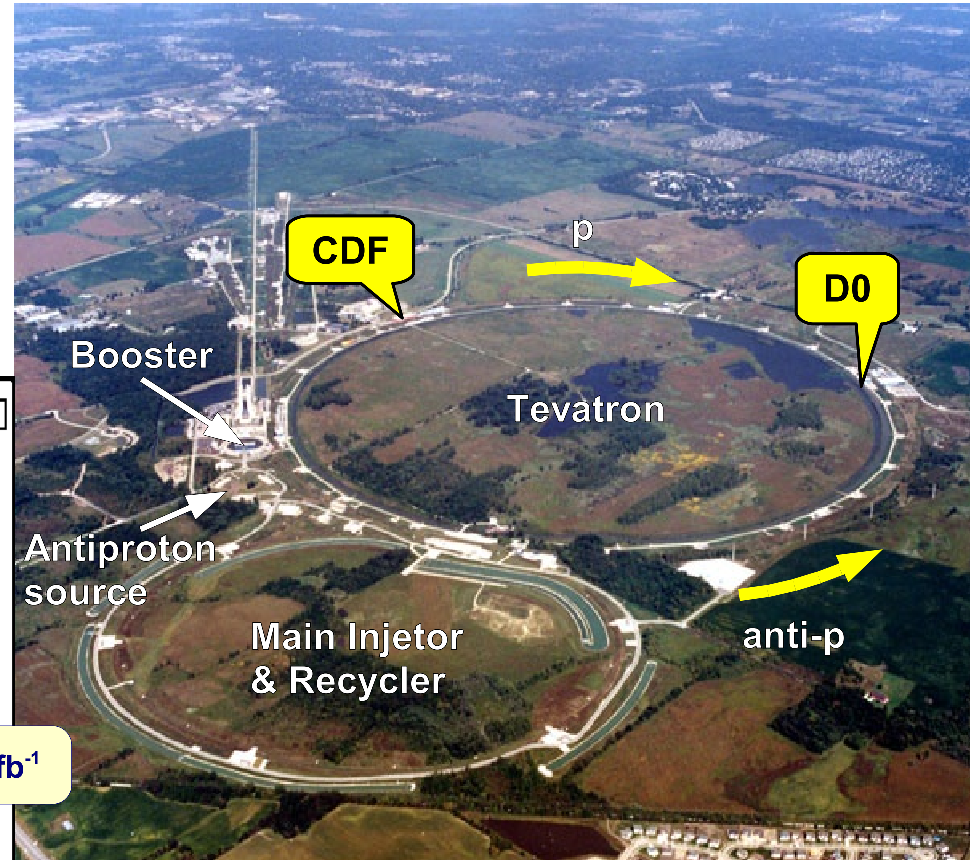
→ **sensitive to both effects, but is not 100% correlated with other 2 measurements**

- **25 MeV precision on m_W requires :**
  - accuracy of lepton (e or μ) energy scale: **~0.02%**
  - accuracy of hadronic recoil scale: **~1%**

Tevatron at Fermilab

- Proton-anitproton @ √s=1.96 TeV
  every 396 ns, 36x36 bunches
- Peak luminosity: **3.5 10^{32} $cm^{-2}s^{-1}$**
- Recorded: **~7 fb^{-1} / experiment**





- By end of 2010: 9 fb^{-1} / experiment
- Running in 2011 is considered

Tevatron m_W analyses

	CDF	DØ
Luminosity	0.2 fb^{-1}	1.0 fb^{-1}
W decay channels	electron, muon	electron
Lepton Energy Scale	tracker information	$Z \rightarrow ee$ calorimeter data
Interpretation	absolute m_W	m_W/m_Z ratio
MC closure test	–	full analysis performed first on Monte Carlo
Beyond m_W	M(**W^+**) and M(**W^-**) comparison	–
	PRL **99**, 151801 (2007)	PRL **103**, 141801 (2009)

+ their combination: arXiv:0908.1374v1 [hep-ex]

Analysis overview (DØ)

- The D0 analysis exploits **W→eν channel** only
  electron energy resolution ~4%, muon momentum scale ~10% @ p_T=50 GeV
- Compare $m_T, p_T^e, \not{E}_T$ **data spectra** with **template spectra** from **MC**
- Fast **Monte Carlo** for templates generation:
  ResBos – W and Z/γ* boson production, decay kinematics
  perturbative NLO at high boson p_T, gluon resummation at low boson p_T
  PHOTOS – FSR radiation of ≤ 2 photons
  effect of full QED corrections assessed from WGRAD and ZGRAD
  Parametric MC Simulation (PMCS) – detector efficiencies, energy response & resolution for electrons and hadronic recoil
  parametric functions and binned look-up tables based on detailed GEANT simulation and fine-tuned from control data samples: Z→ee, Zero Bias, Minimum Bias
- **Blind analysis – m_W returned by fits was deliberately shifted by some unknown offset before the final fitting**
  results were unblinded after completing all consistency checks for W and Z events

Event selection (DØ)

- 1 fb^{-1} of data (Run IIa, 2002-2006)
- **W→eν** sample – **499,830** evts:
  - Electron: $|\eta| < 1.05$, spatial track match, $p_T^e > 25$ GeV
  - Missing $E_T > 25$ GeV
  - Recoil $u_T < 15$ GeV
  - $50 < m_T < 200$ GeV

  cuts preserve the Jacobian edge

  96% purity, main backgrounds: Z→ee, QCD multijet, W→τν→eννν
- **Z→ee** sample for calibration – **18,725** evts:
  - calibrate EM energy scale from Z pole
  - tune fast PMCS

Electron efficiency (DØ)

Fast MC models various **electron selection efficiencies**:

- **Electron-only:** trigger, CAL-based ID, tracking

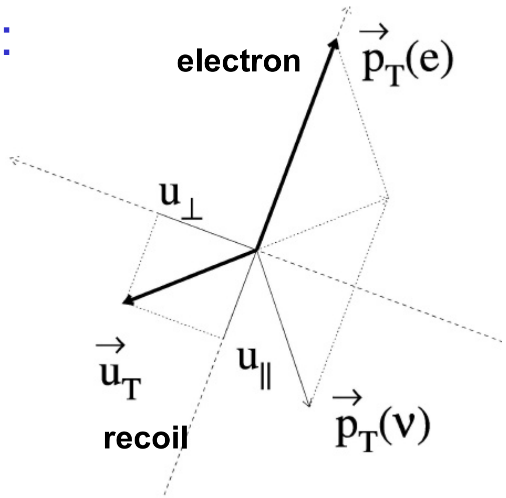
  from Z data; tag & probe; parameterized using: η^e, p_T^e, z_{vtx}

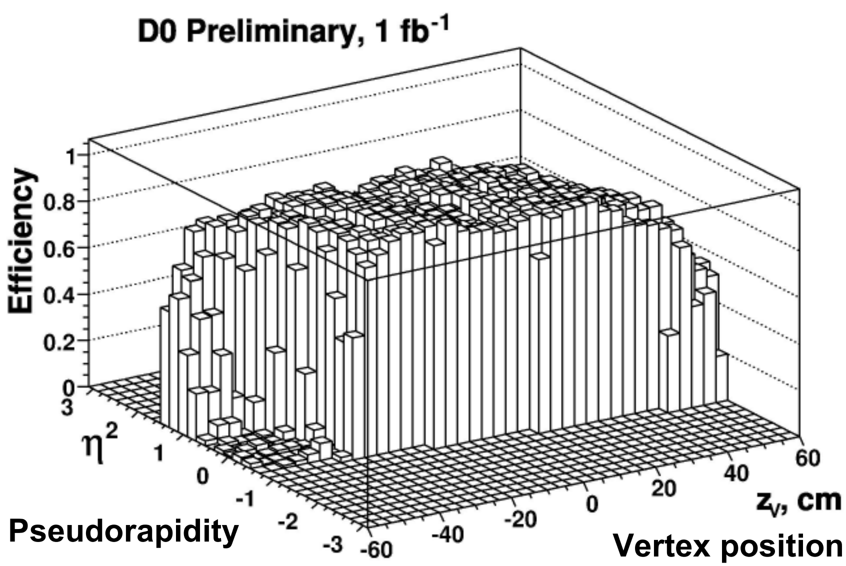
- **W event topology:** spatial proximity recoil ↔ electron

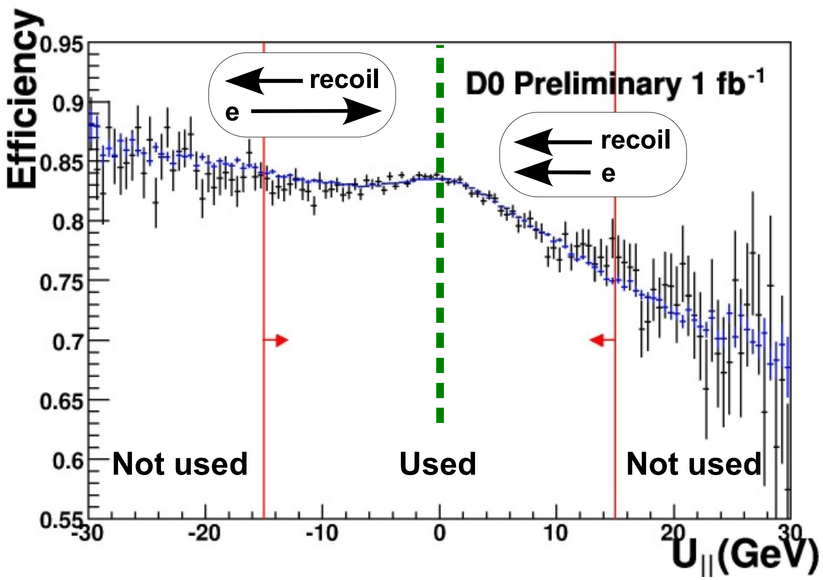
  from Z data; parameterized using: p_T^e, $u_{||}$

- **Additional hadronic energy** in CAL at high luminosity

  from full MC + ZB data; parameterized using: Scalar E_T, $u_{||}$



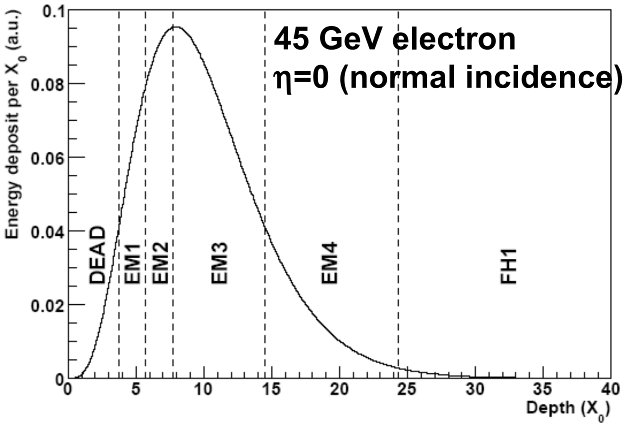




Electron model (DØ)

- Fit amount of **uninstrumented** material in front of the calorimeter with $0.01X_0$ precision
- Use precise Z mass from LEP to calibrate absolute EM energy scale
- **Simulate measured electron energy as:**

$$E\,(smear) = R_{EM}(E) \otimes \sigma_{EM}(E) + \Delta E(\mathcal{L}, u_{\parallel})$$

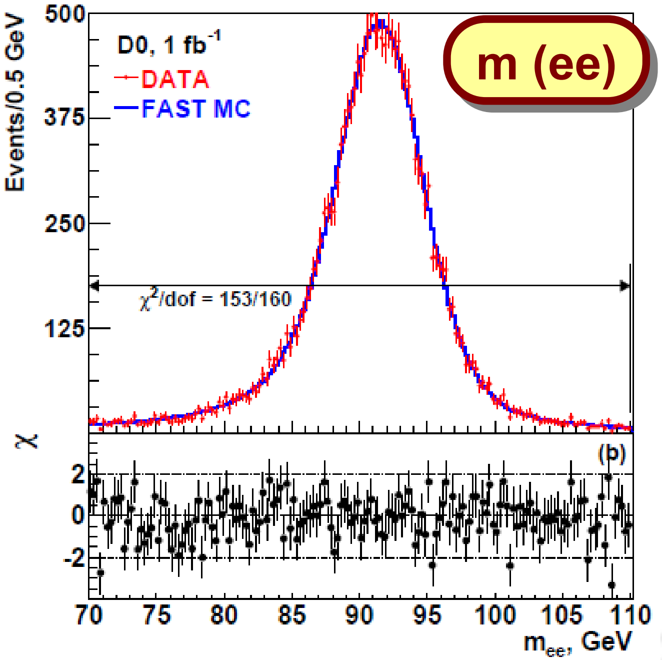


Energy response: $R_{EM}(E) = \alpha \cdot E + \beta$

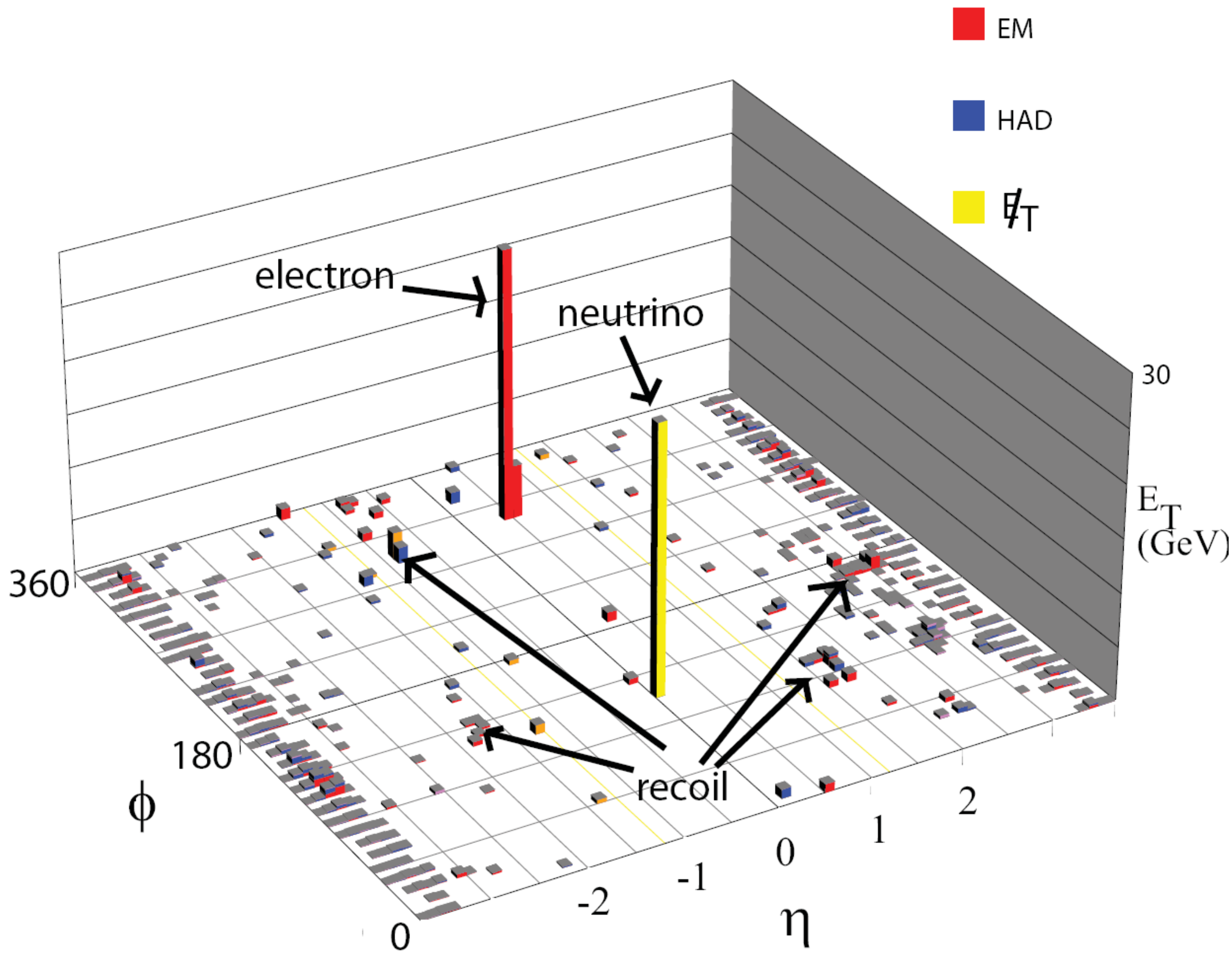
- **dominant source in m_W systematics: 34 MeV**
- fitted from electron energy spread in Z→ee data

Energy resolution: $\frac{\sigma_{EM}(E)}{E} = \sqrt{C_{EM}^2 + \frac{S_{EM}(E,\theta)^2}{E}}$

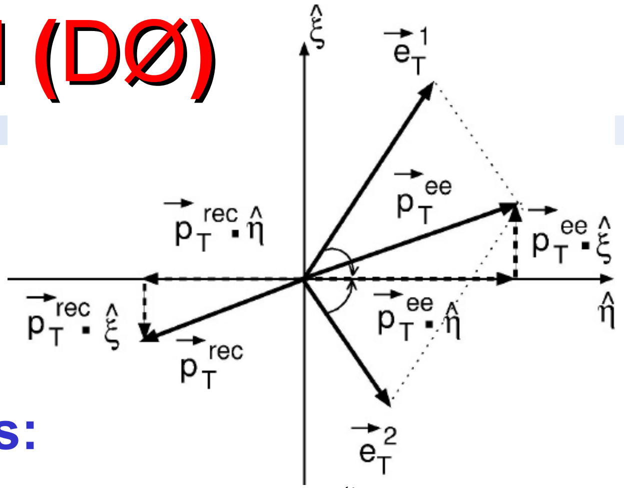
- **S_{EM} depends on energy and incidence angle**, from improved full GEANT simulation featuring: lower energy cut offs, updated interaction x-sections
- **C_{EM} = 2.05% ± 0.10%**; from fit to the m_{ee} distribution from Z→ee data



W→eν candidate event (DØ)



Hadronic recoil model (DØ)



η and ξ coordinates in Z→ee events (UA2 convention)

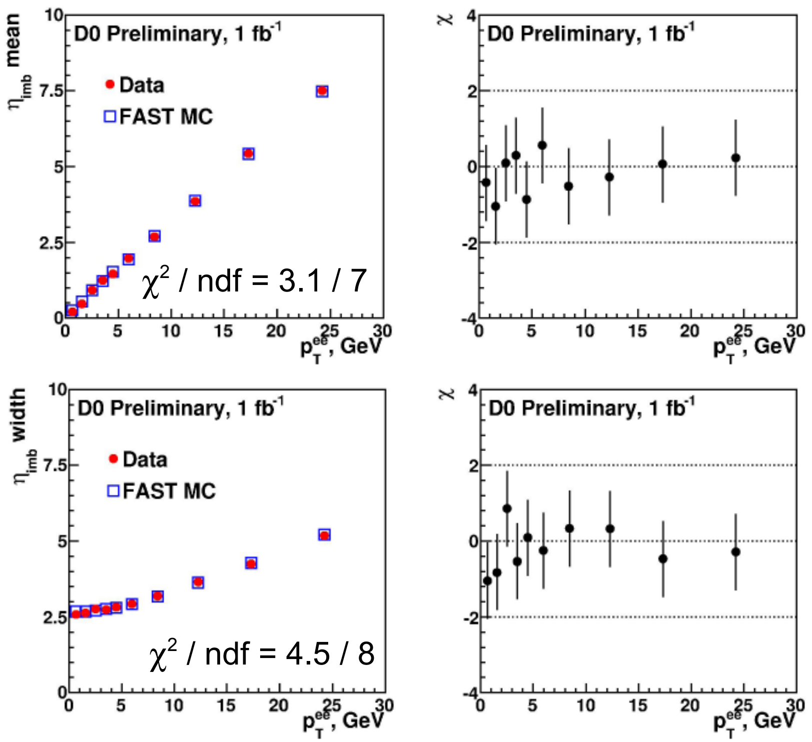
- **Neutrino p_T is simulated as:**

$$\vec{\not{E}}_T = -\vec{p}_T^{\,e} - \vec{u}_T$$

- **Recoil model has HARD and SOFT components:**

$$\vec{u}_T\,(smear) = \vec{u}_T^{\,\mathrm{HARD}} + \vec{u}_T^{\,\mathrm{SOFT}} + \vec{u}_T^{\,\mathrm{ELEC}} + \vec{u}_T^{\,\mathrm{FSR}}$$

- **Model is derived from detailed GEANT simulation** (Z→νν) **and control data samples** (Z→ee, Zero Bias, Minimum Bias)
- **Recoil response and resolution are fine-tuned from Z→ee data:**
  – require balancing of u_T and $p_T(ee)$
  – mean and width of η_{imb} distribution depend on hadronic recoil response and resolution
- **Scalar E_T is also modeled for electron selection efficiencies**



Hadronic recoil - details (DØ)

HARD COMPONENT:

- hard component balancing q_T of the vector boson
- from Z->nn full MC
- fine-tuned from Z→ee data

SOFT COMPONENT:

- energy not correlated with the vector boson (additional interactions in same BX, spectator partons, detector noise)
- uses ZB & MB event libraries
- fine-tuned from Z→ee data

$$\vec{u}_T^{\,\mathrm{HARD}} = \vec{f}(\vec{q}_T)$$

$$\vec{u}_T^{\,\mathrm{SOFT}} = -\sqrt{\alpha_{MB}} \cdot \vec{\not{E}}_T^{\,\mathrm{MB}} - \vec{\not{E}}_T^{\,\mathrm{ZB}}$$

$$\vec{u}_T^{\,\mathrm{ELEC}} = -\sum_e \Delta u_{\|} \cdot \hat{p}_T^{\,e}$$

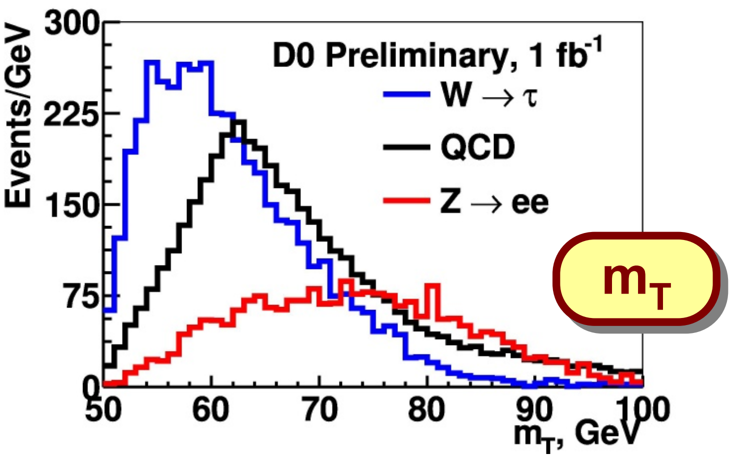
- correction for energy leakage outside electron cones
- from W data (azimuthally separated window)

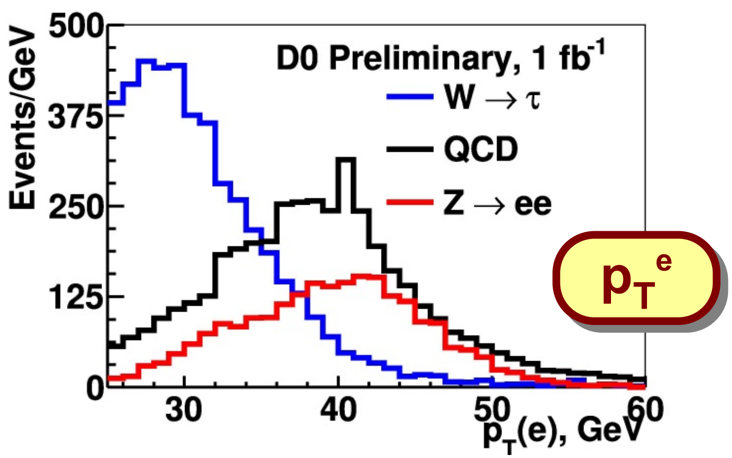
$$\vec{u}_T^{\,\mathrm{FSR}} = \sum_\gamma \vec{p}_T^{\,\gamma}$$

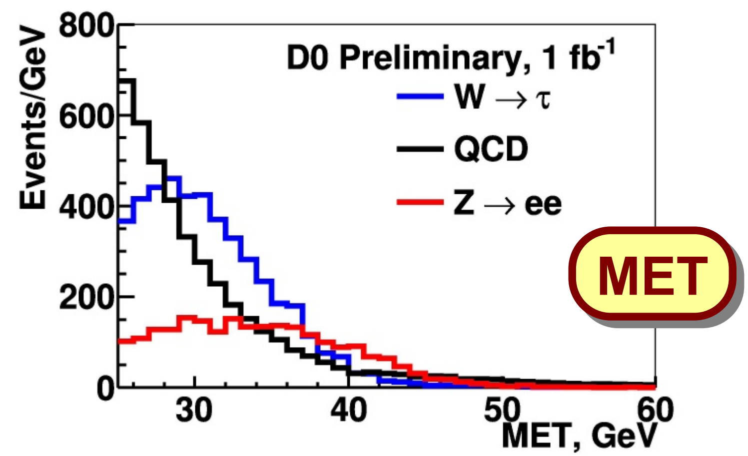
- FSR photons far away from electron(s) are reconstructed as recoil energy

Backgrounds (DØ)

- **Purity of W sample : 96%**
- Backgrounds:
  - **$Z \rightarrow ee$:** 0.80% (Data)
  - **QCD multijet :** 1.49% (Data)
  - **$W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$:** 1.60% (GEANT)
- For 3 observables: estimated backgrounds are added to the simulated signal from W (PMCS)



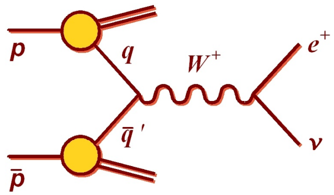


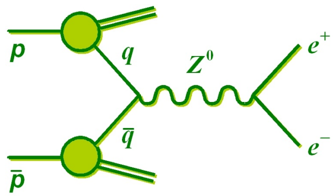


W production & decay models (DØ)

- Generators for W and Z processes at hadron colliders:

Tool	Process	QCD	EW
RESBOS	W,Z	NLO	-
WGRAD	W	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
ZGRAD	Z	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
PHOTOS			QED FSR, ≤ 2 photons





- **ResBos+Photos** as main generator
  - reasonable $\mathbf{p_T}^{W,Z}$ spectra
  - leading EWK effects (1st and 2nd FSR photon)

Balazs, Yuan; Phys Rev D56, 5558
Barbiero, Was; Comp Phys Com 79, 291

- WGRAD & ZGRAD to estimate effects of full EWK corrections

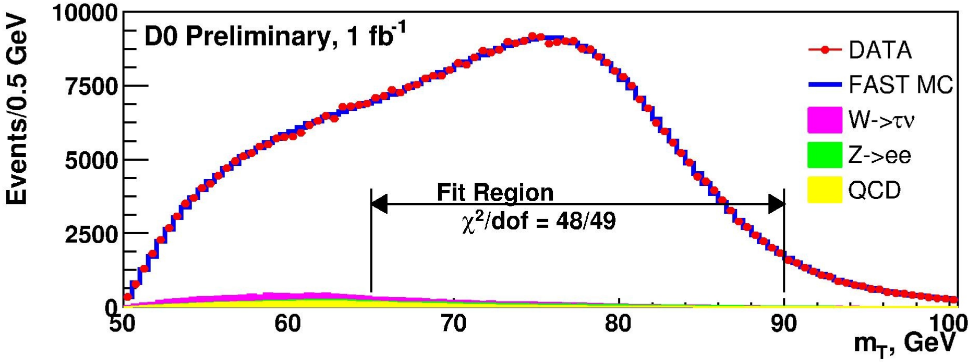
Baur, Wackeroth; Phys. Rev D70, 073015

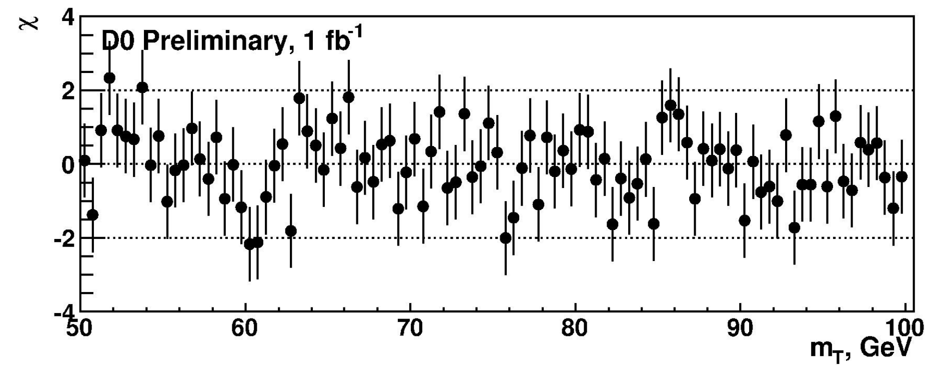
- Final QED m_W uncertainties are 7,7,9 GeV for $m_T, p_T^e, \not{E}_T$
  - comparison of "FSR only" and "full EWK" from W/ZGRAD
  - comparison of "FSR only" W/ZGRAD and Photos

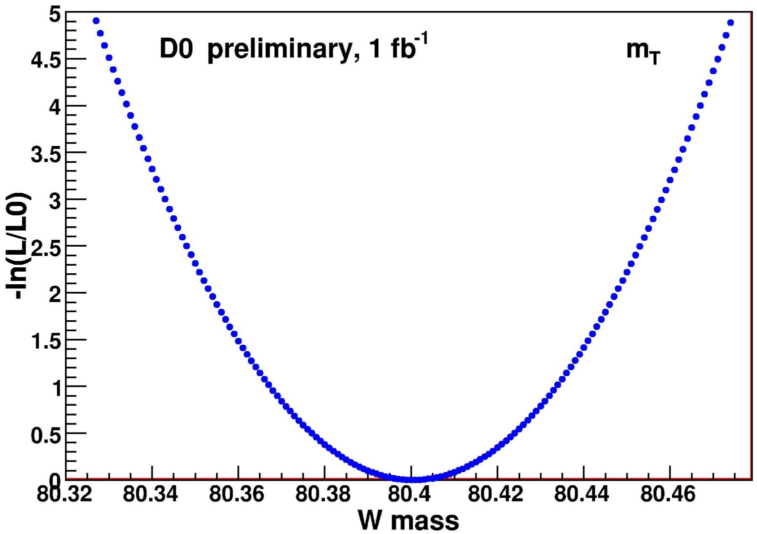
W mass fits (DØ)

m_T method

- Templates for different m_W hypotheses at 10 MeV intervals: W signal (PMCS) + background
- Compute binned likelihood between data and template
- Fit m_W for each of 3 observables







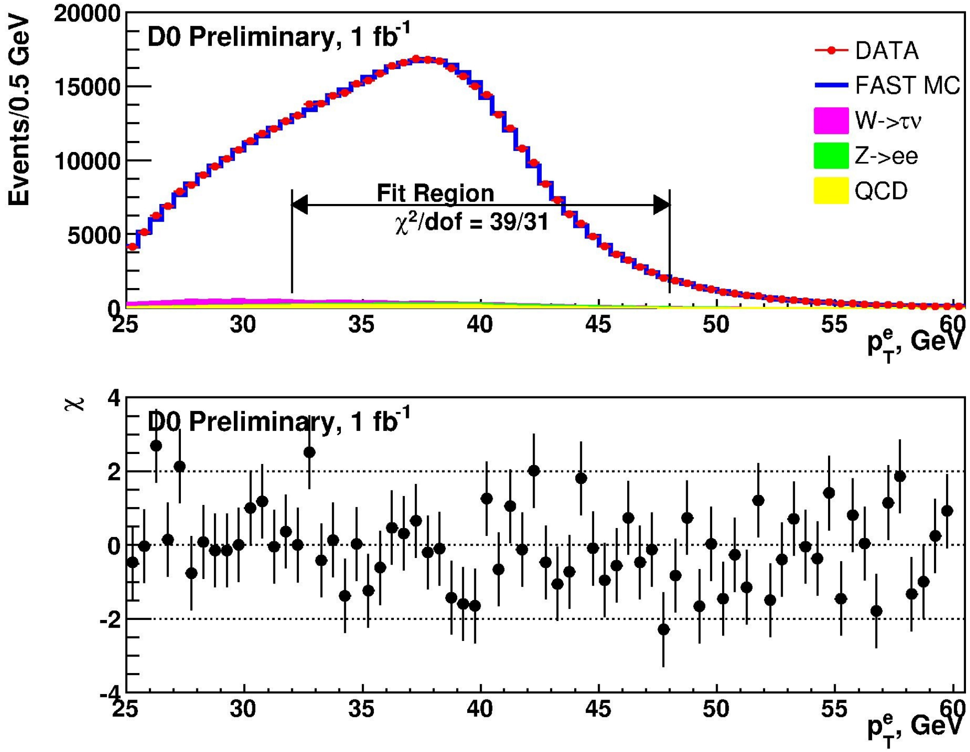
m_W = 80.401 ± 0.023 GeV (stat)

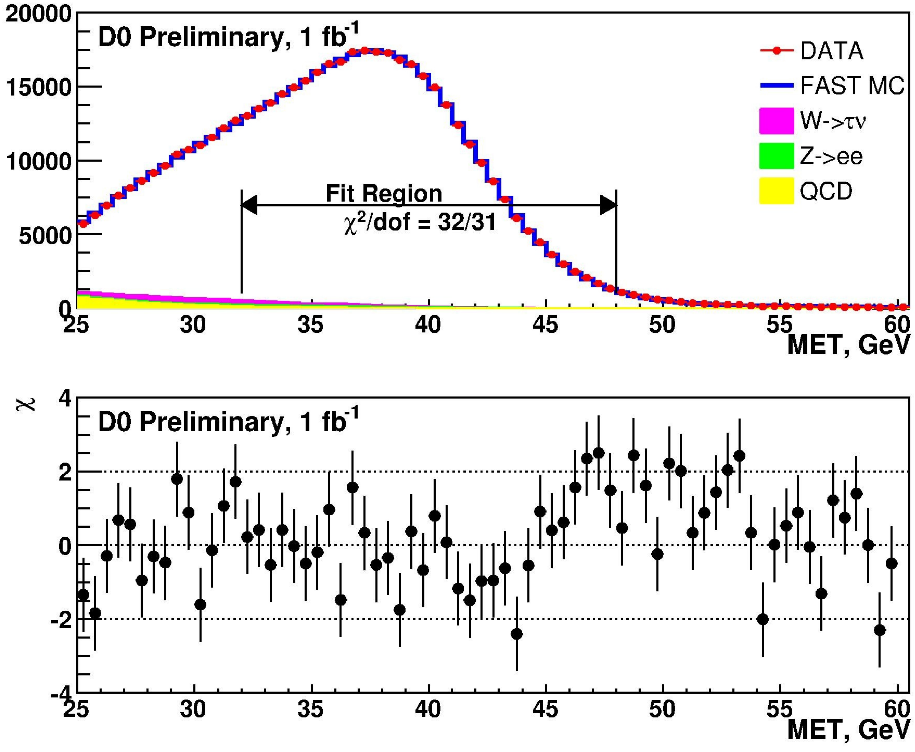
Fit range: $65 < m_T < 90$ GeV

W mass fits (DØ)

Electron p_T method

Neutrino p_T method





m_W = 80.400 ± 0.027 GeV (stat)

m_W = 80.402 ± 0.023 GeV (stat)

Fit range: $32 < p_T^e < 48$ GeV

Fit range: $32 < \not{E}_T < 48$ GeV

Uncertainties (DØ)

		m_W uncertainty [MeV]	
Source	m_T	$p_T(e)$	Missing E_T
Electron energy response	**34**	**34**	**34**
Electron energy resolution	2	2	3
Electron energy non-linearity	4	6	7
Electron energy loss differences for W and Z	4	4	4
Electron efficiencies	5	6	5
Recoil model	6	12	20
Backgrounds	2	5	4
Subtotal Experimental	**35**	**37**	**41**
PDF CTEQ6.1M	**10**	**11**	**11**
QED	7	7	9
Boson p_T	2	5	2
Subtotal Theory (W/Z production & decay)	**12**	**14**	**14**
Total Systematics	**37**	**40**	**43**
Total Statistics	**23**	**27**	**23**
TOTAL	**44**	**48**	**50**

EXPERIMENT

THEORY

Combined DØ m_W result

PRL **103**, 141801 (2009)

- **Correlation matrix of the three methods:**
  - Partially correlated:

    Statistics, Electron response,

    Recoil model, PDF
  - Other sources: 100% correlated

	m_T	$p_T(e)$	MET
m_T	1	0.83	0.82
$p_T(e)$		1	0.68
MET			1

- **DØ Run II combination:**

m_W = **80.401** ± **0.021** (stat) ± **0.038** (syst) GeV

Δm_W (total) = **0.043** GeV

Combined Tevatron m_W result

- **Combination performed with B.L.U.E. method:**

  CDF Run II (200 pb^{-1})

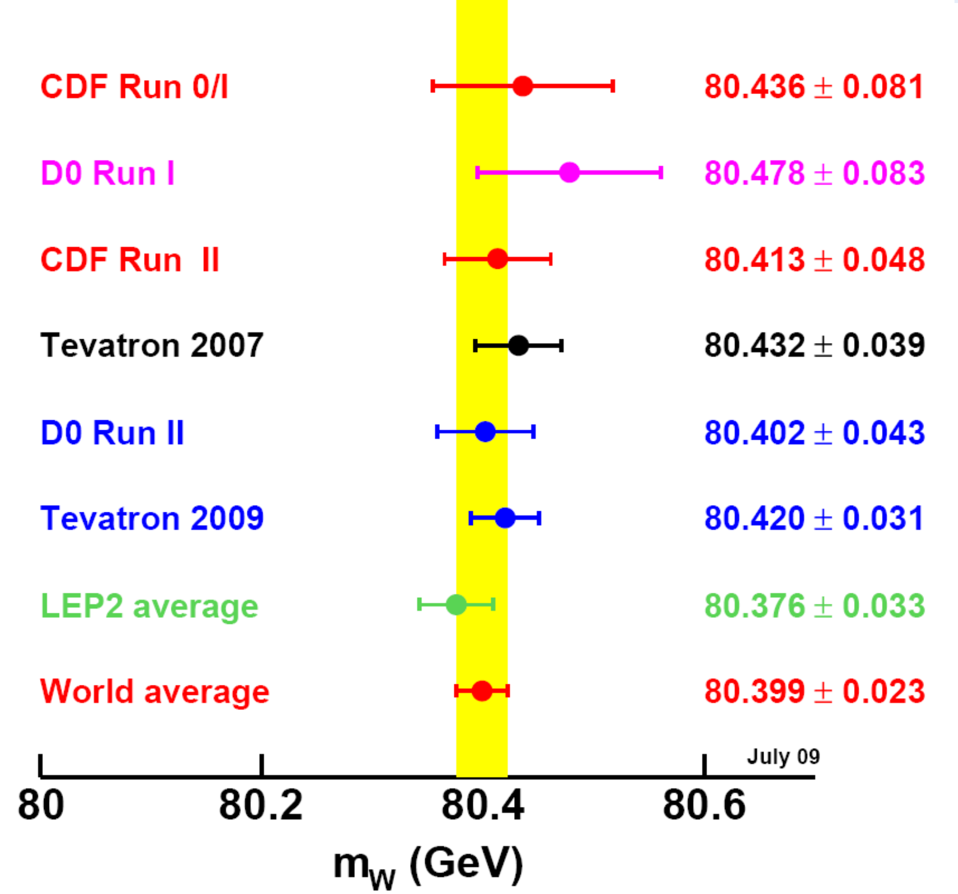
  → PRL **99**, 151801 (2007)

  DØ Run II (1 fb^{-1})

  → PRL **103**, 141801 (2009)

  CDF Run 0/I, DØ Run I, LEP2

- **For the first time Tevatron average is more precise than LEP2 direct measurement**



arXiv:0908.1374v1 [hep-ex]

Tevatron 2009: m_W = **80.420 ± 0.031** GeV

World average: m_W = **80.399 ± 0.023** GeV

Improved by:

20 %

8 %

Combined Tevatron Γ_W result

- **Combination performed with B.L.U.E. method:**

  CDF Run II (350 pb^{-1})

  → PRL **100**, 071801 (2008)

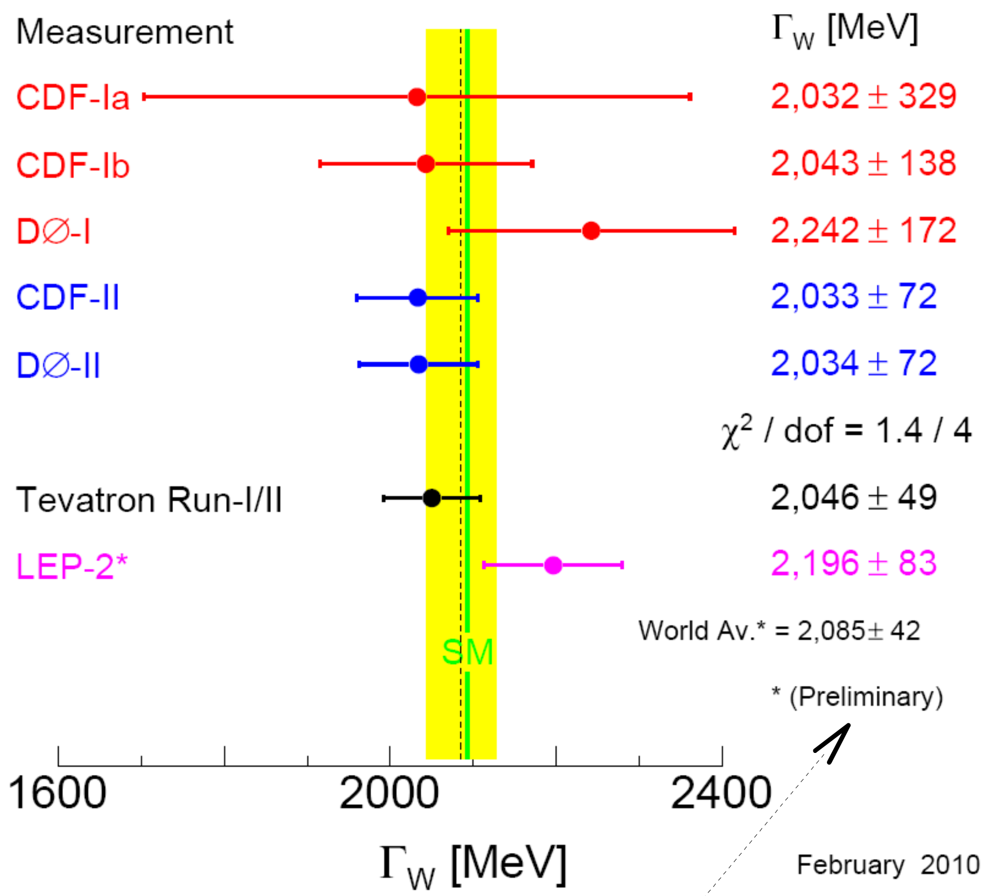
  DØ Run II (1 fb^{-1})

  → PRL **103**, 231802 (2009)

  CDF Run I, D0 Run I, LEP2

- **New world average agrees with SM prediction of Γ_W = 2.093 ± 0.002 GeV**

arXiv:1003.2826v1 [hep-ex]



For consistency the published Γ_W values have been corrected for the world averaged m_W value from Dec 2009

Tevatron 2009: Γ_W = **2.046 ± 0.049** GeV

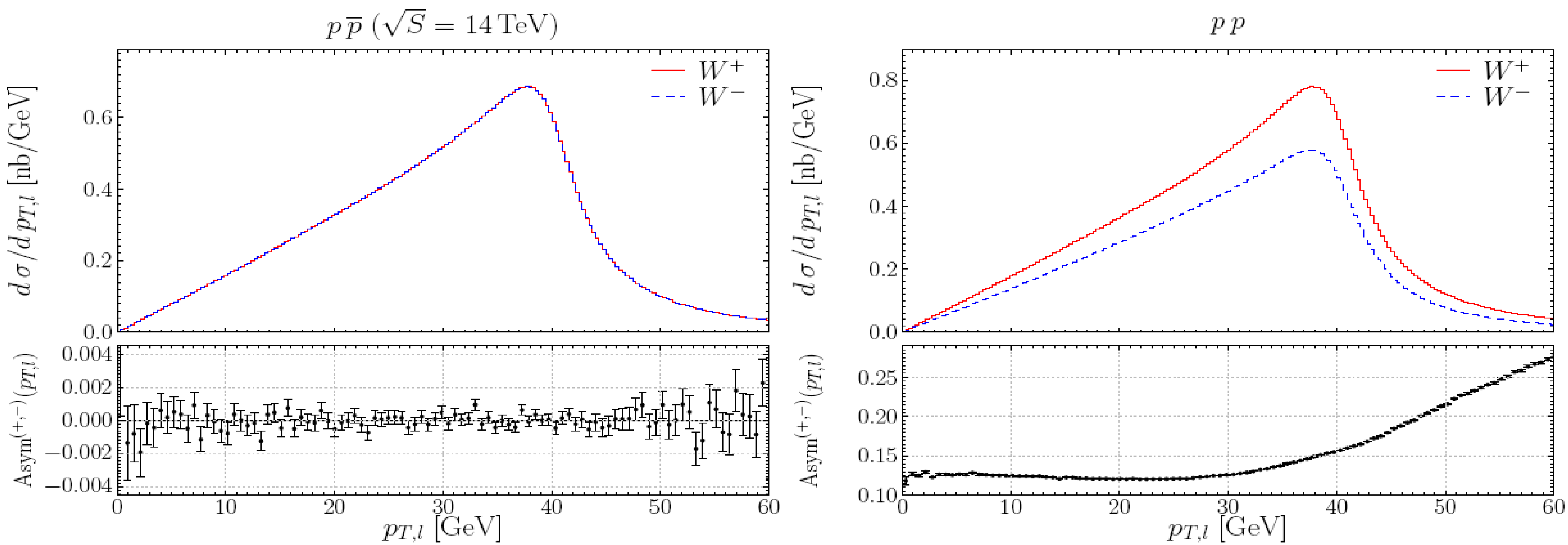
World average: Γ_W = **2.085 ± 0.042** GeV

M_W prospects for Tevatron

- **Expected total (stat) uncertainty:**
  - **CDF (2.3 fb^{-1}) : 25 (15) MeV** per channel
  - **DØ (4.4 fb^{-1}) : 25 (11) MeV**

- **Systematics:**
  - Some experimental sources will be reduced after collecting more data (DØ: larger Z sample ⇒ electron energy scale 34 → 16 MeV)
  - Different techniques used by CDF & DØ for lepton energy scale are good for combination and cross checks
  - Theory errors are 100% – correlated between CDF and DØ
  - Controlling systematics at ~10 MeV level requires:
    - including higher order QED radiation
    - better constrained PDFs

M_W prospects for LHC

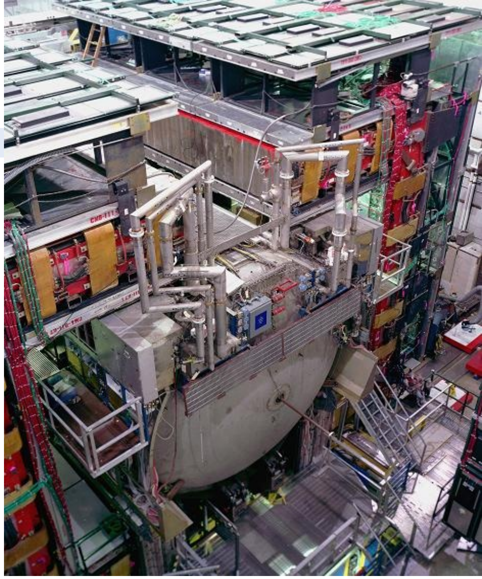


F.Fayette talk at EPS 2009

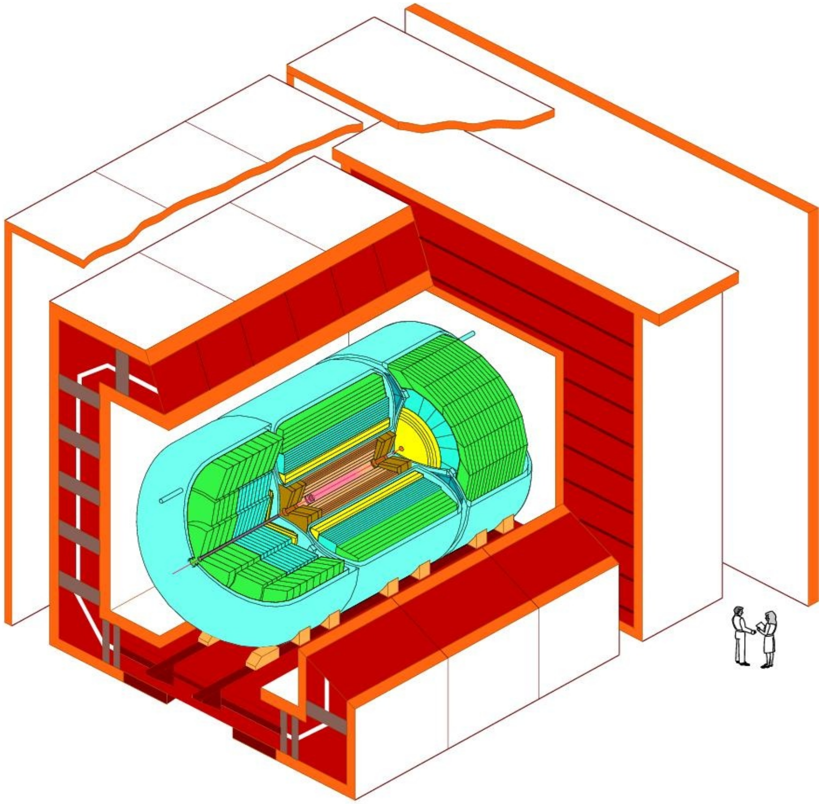
- **In p-p collisions:**
  - Loss of charge symmetry $\mathbf{W^+ \Leftrightarrow W^-}$
  - Stronger dependencies from PDFs
  - Need to measure: $\mathbf{m_{W+}}$ **&** $\mathbf{m_{W-}}$ or: $\mathbf{(m_{W+}-m_{W-})}$ **&** $\mathbf{(m_{W+}-m_{W-})}$
- **Ultimately expect <10 MeV precision from the LHC era**

BACKUP Slides

DØ detector

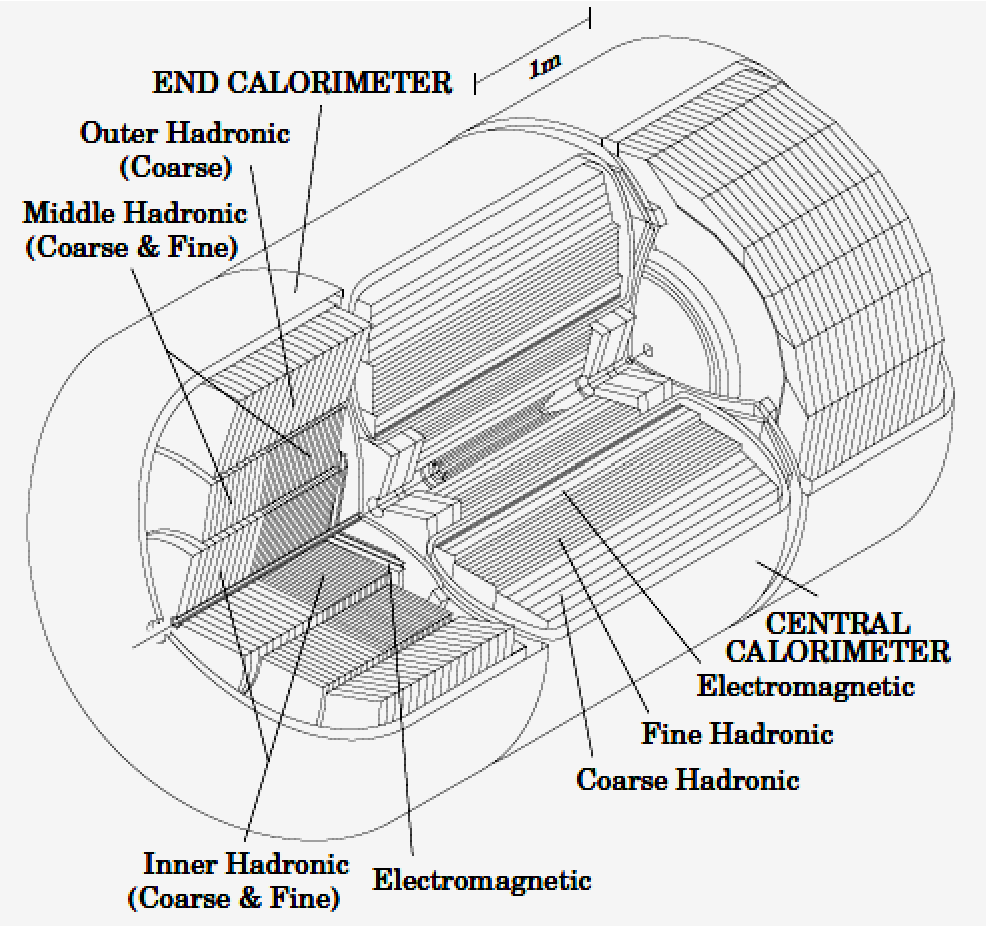


- **Tracker:**
  - silicon microstrips + scintillating fibers
  - covers |η| < 2.5 inside 2T superconducting solenoid

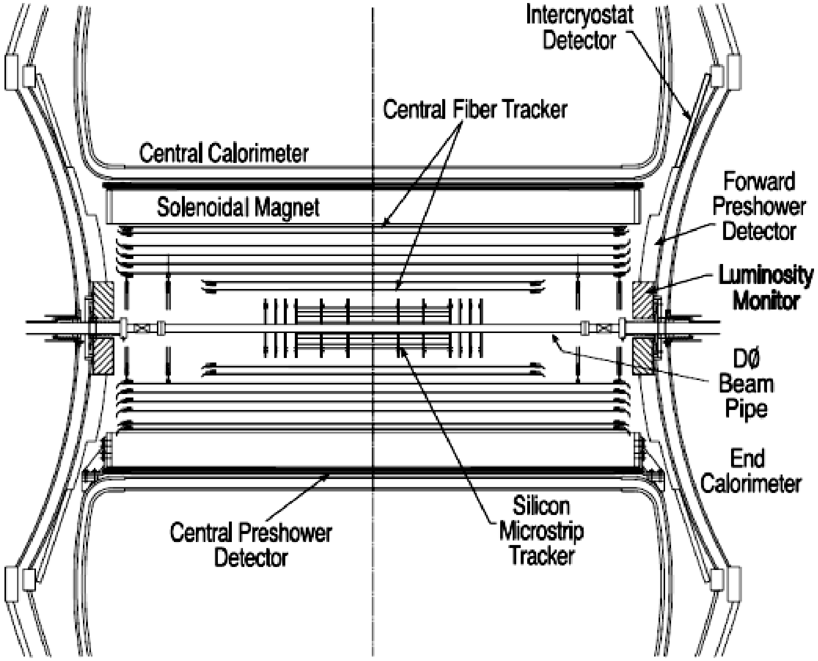


- **Calorimeter:**
  - sampling U/LAr
  - hermetic coverage: |η| < 4.2
- **Muon system:**
  - wire chambers + scintillators
  - covers |η| < 2 before and after 1.8T toroid

DØ LAr calorimter



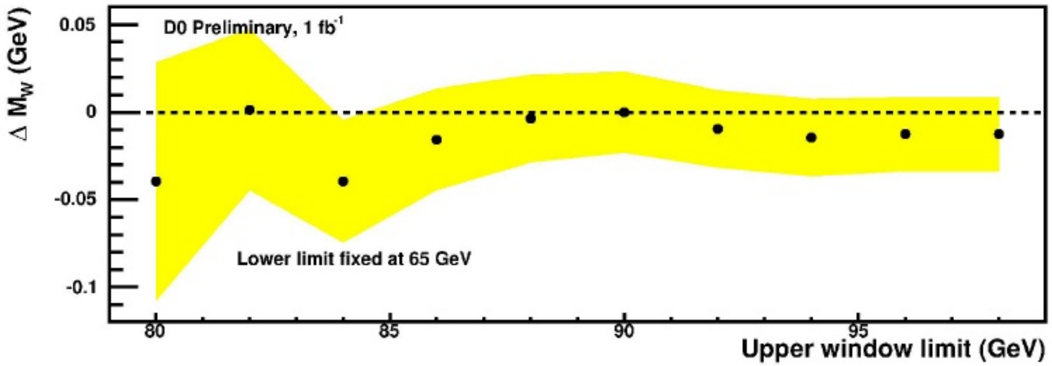
- Active medium: Liquid argon
- Absorber: Uranium (mostly)
- 3 cryostats: Central CAL (CC) and two End CALs (EC)
- Hermetic with full coverage: $|\eta| < 4.2$
- In Run II there is more uninstrumented material in front of the CAL than in Run I



- 46,000 cells
- Segmentation (towers): $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ (0.05 x 0.05 in third EM layer, near shower maximum)

Consistency checks (DØ)

- Vary **fitting ranges** for all 3 observables



e.g. upper m_T limit
(yellow = stat. uncert.)

- Split W & Z data samples into statistically independent **categories** or **vary the cuts** and compare relative change in m_Z/m_W ratio:
  - Different electron η ranges
  - Different EM calorimeter ϕ fiducial cuts
  - High and low instantaneous luminosity
  - Different data taking periods
  - High and low scalar E_T
  - Different recoil u_T cuts
  - Negative and positive $u_{||}$

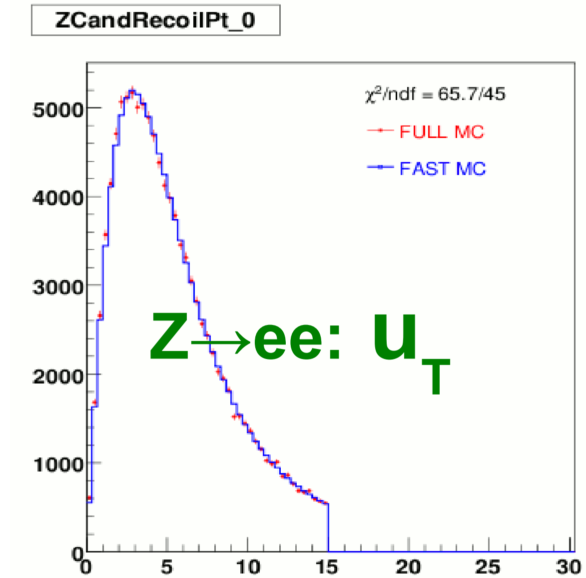
Result is stable within one standard deviation !

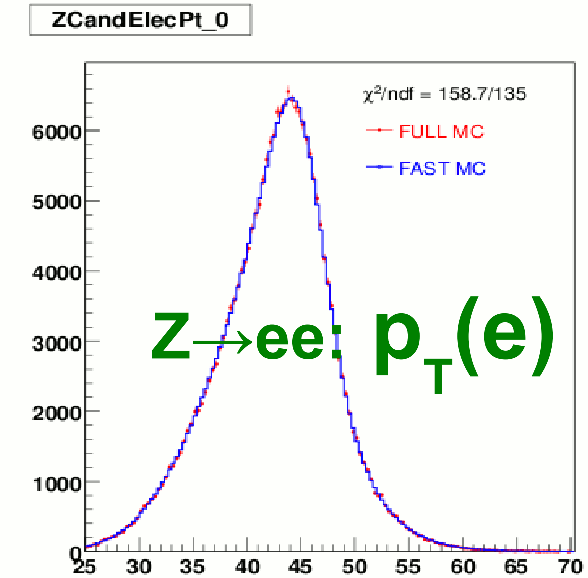
MC closure test (DØ)

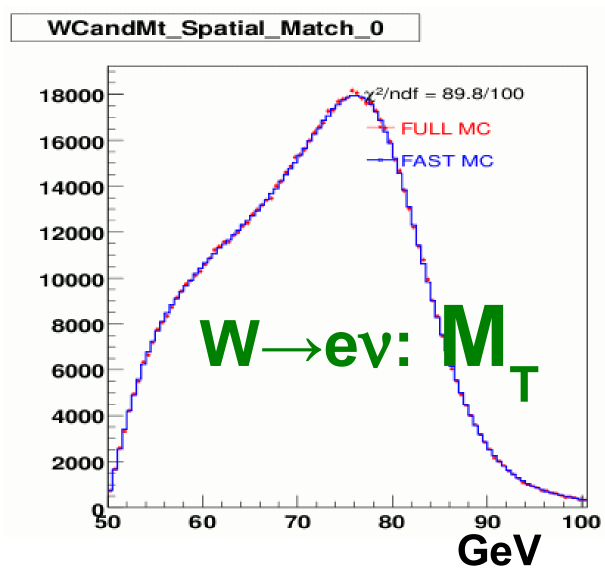
Test analysis methodology with Full GEANT MC treated as the collider data

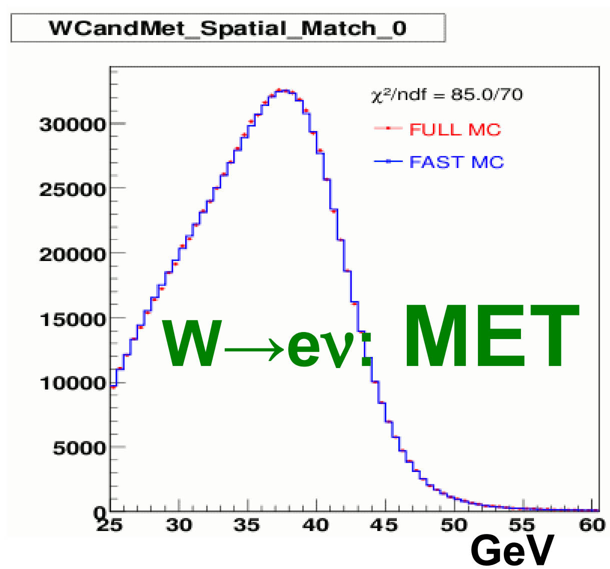
Good agreement between Full MC and Fast MC (PMCS)

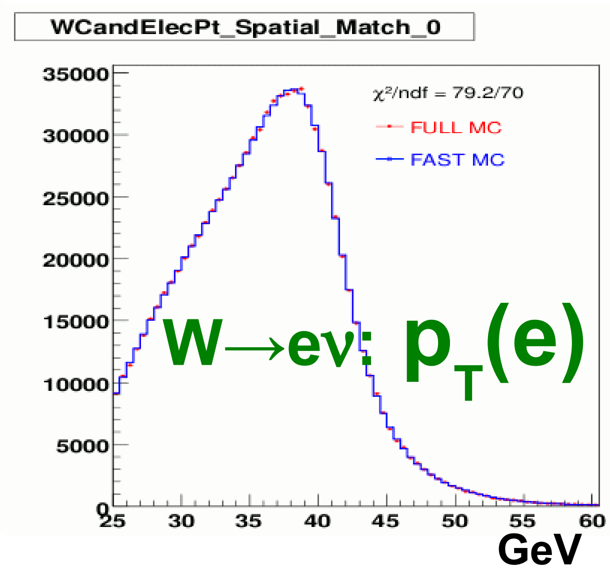
Fitted W mass and width agree with input values



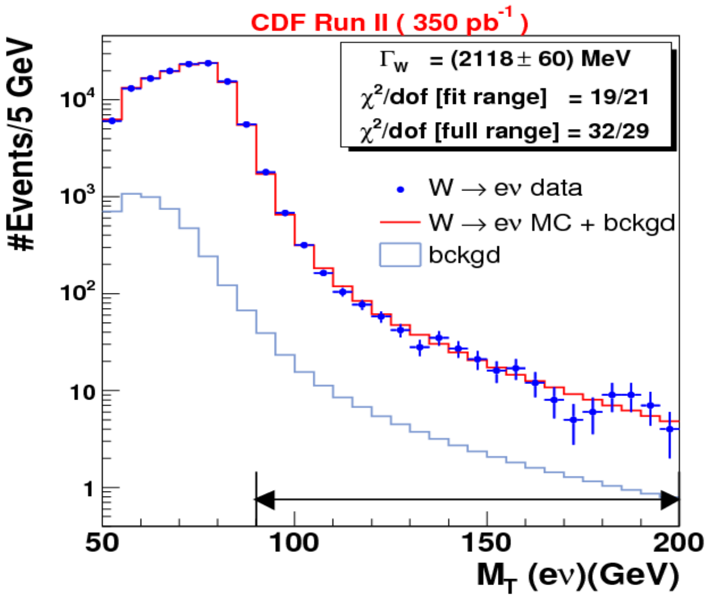


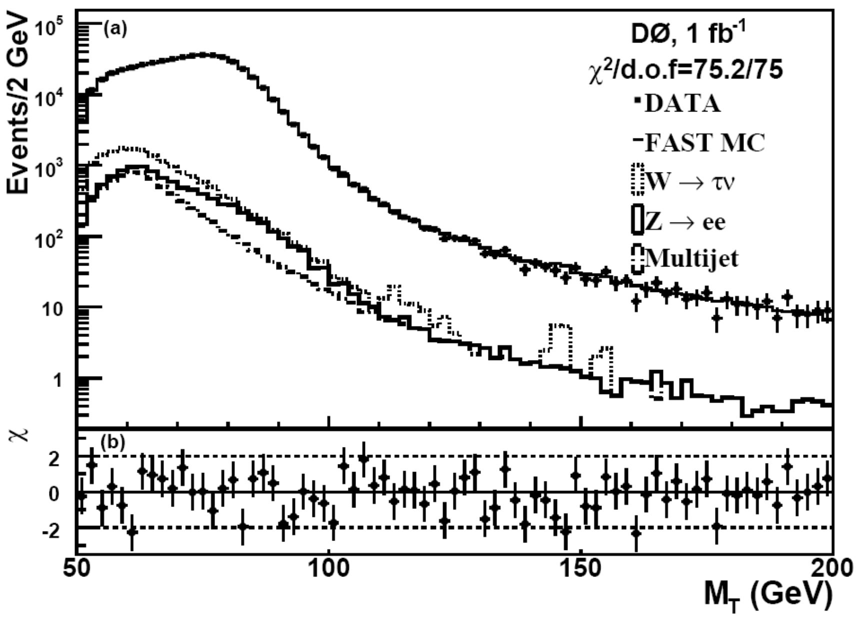






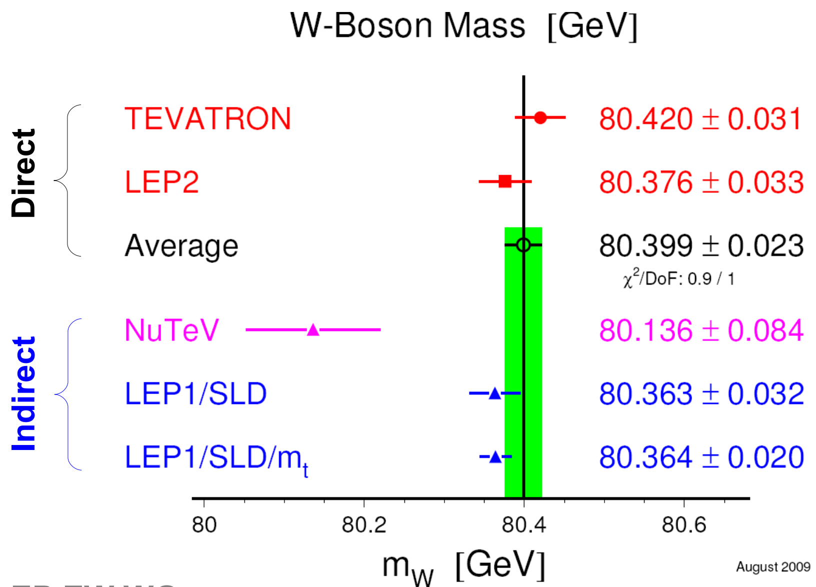
Tevatron Γ_W analyses



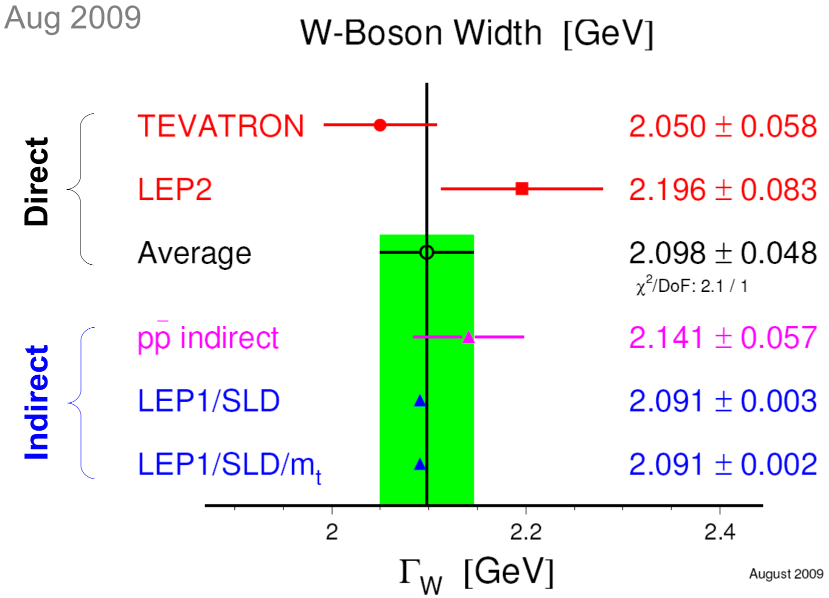


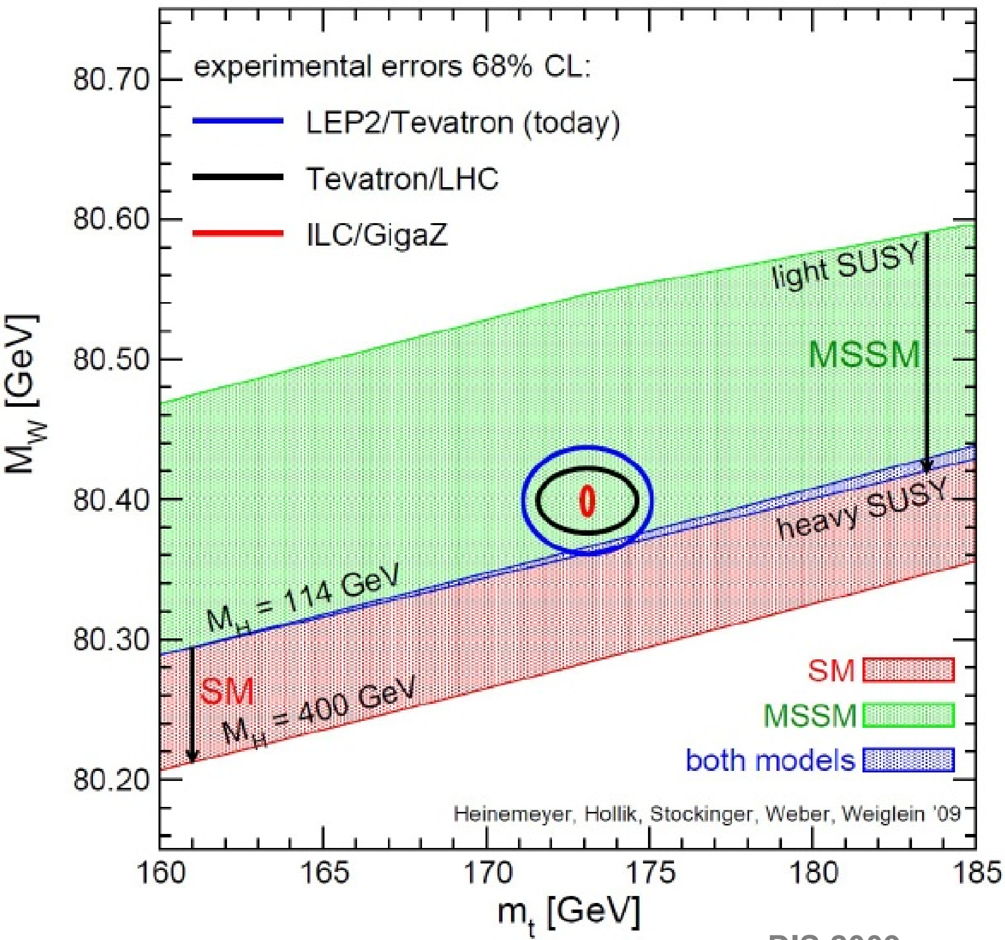
- Use high-end tail of the transverse mass peak
  - CDF Run II (350 pb^{-1}) : Γ_W = 2.033 ± 0.072 GeV
  - DØ Run II (1 fb^{-1}) : Γ_W = 2.034 ± 0.072 GeV
  - using world average of m_W = 80.399 ± 0.023 GeV from Dec 2009
- Combined Tevatron Run I/II result: Γ_W = 2.046 ± 0.049 GeV
  - surpassed average LEP2 direct measurements ($\delta\Gamma_W$=83 MeV)
  - far less precise than EWK fit using Z-pole data + m_{top} measurement ($\delta\Gamma_W$=2 MeV)

M_W & Γ_W – today and future



LEP EW WG
Aug 2009





DIS 2009
S.Heinemeyer