Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

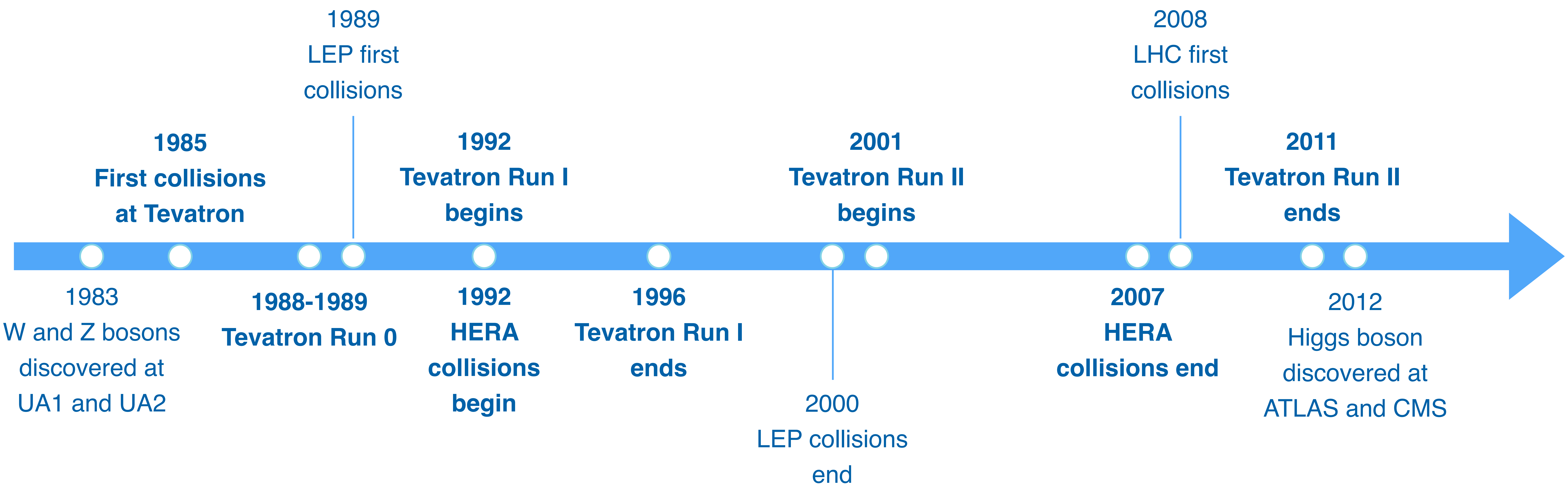
Electroweak results from the Tevatron and HERA

Bo Jayatilaka

Electroweak Milestones Symposium - CERN

31 October 2023

Introduction and timeline

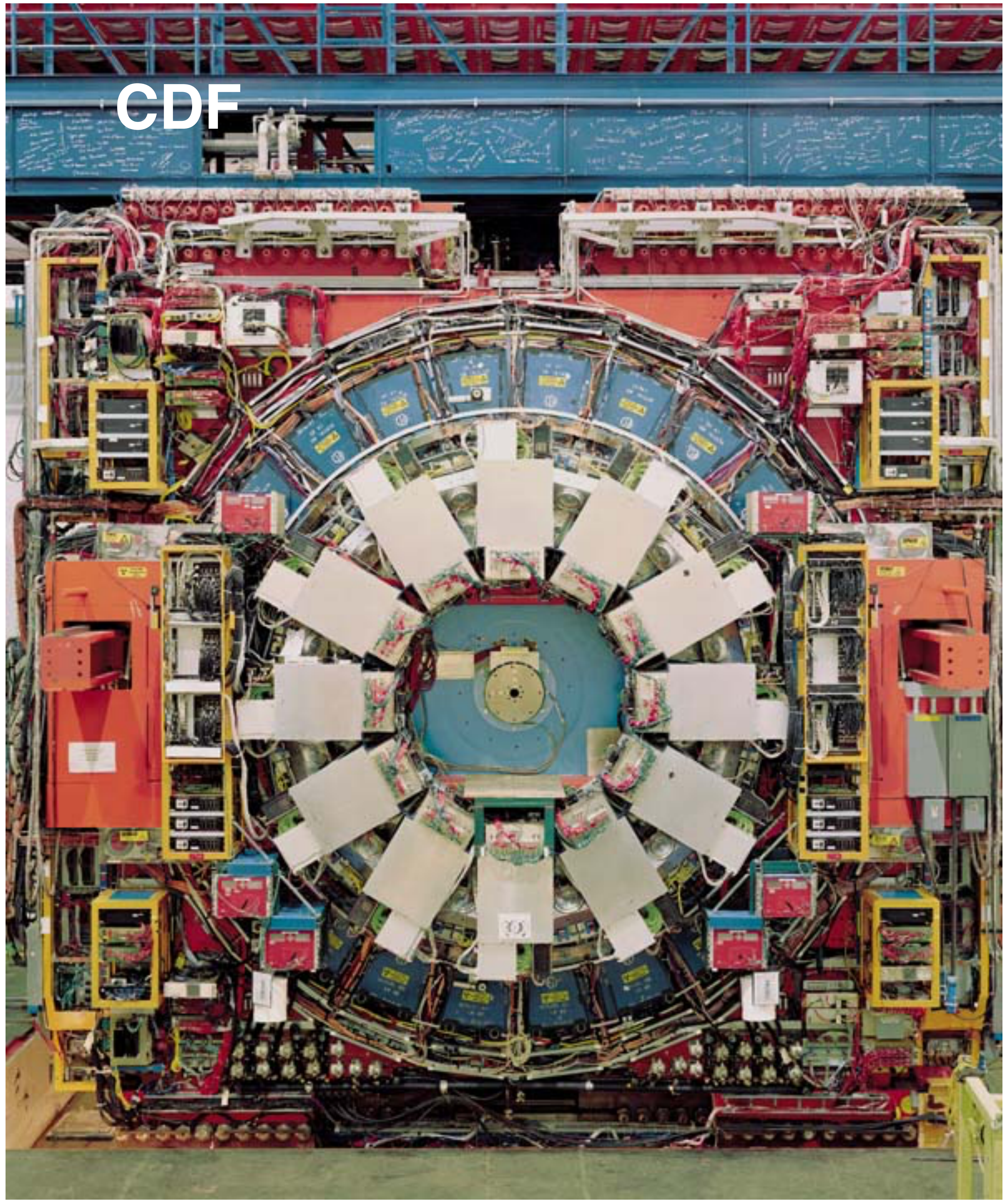


Fermilab and accelerators

- **National Accelerator Laboratory** founded 1967
  - Named after **Enrico Fermi** and dedicated ("Fermilab") in 1974
- Central facility: proton synchrotron "Main Ring"
  - 2π km circumference and initial energy of 200 GeV (1972)
  - Used for fixed target experiments
- Higher energy with **superconducting magnets**
  - **First** superconducting synchrotron
  - Initial name "Energy Doubler" or "Energy Saver". **512 GeV** (1983)
- **Antiproton source** added in 1985
  - Stochastic cooling **built on success of SppS at CERN**
  - First **collisions** at 1.6 TeV in 1985, 1.8 TeV in 1986: **TeVatron**


Helen Edwards (Tevatron lead scientist) at installation of last superconducting magnet 18-Mar-1983

Tevatron experiments: CDF and DØ



Early Tevatron results

- Tevatron first run 1988-1989
  - Retroactively named “Run 0”
  - 4 pb^{-1} lumi delivered to CDF
    - DØ still under construction at this time

- Ability to measure W and Z bosons?
  - Precision measurements *seemed* well out of reach
    - Limiting factor: calorimeter energy resolution
    - Breakthrough: **calibrating with E/p** (including tracker)

- SLC starting up around the same time
  - Who would be first to see Z bosons in the Western Hemisphere?

New York Times 19-Jul-1988

Search Quickens for Ultimate Particles

Two new American colliders start up, with a European one soon to follow.

By MALCOLM W. BROWNE

FOR the first time in five years, high-energy physicists in the United States are poised to seize a commanding lead from colleagues in Europe as they bring powerful new particle accelerators to bear on mysteries shrouding the ultimate basis of matter.

Full-scale experiments have begun at America's two largest accelerator laboratories, in California and Illinois, both of which recently completed machines even more powerful than European counterparts.

The Stanford Linear Collider (S.L.C.) in California, the Stanford Linear Accelerator Center's new entry in the high-energy physics race, began its ambitious experimental program last month. The machine hurls clusters of negatively charged electrons into oncoming clusters of their antimatter counterparts, positrons. Scientists at Stanford hope these collisions will soon produce large numbers of Z^0, or Z-zero, particles — ephemeral particles whose properties illuminate some of the enigmas that underlie material existence.

At America's other leading high-energy accelerator, the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill., scientists are also expecting important results soon. "We have just started our first real series of experiments using the new Tevatron collider," said Dr. Leon M. Lederman, its director.

One object of their work is to make progress toward testing the theory that everything in nature is made up of some combination of 16 ingredients: four classes of vector particles, six massless leptons and six heavier quarks, one of which, called the top quark, has not yet been detected.

"We think we will soon have the top quark in the bag; that's the missing quark physicists have been looking for," he said. "But in this business you learn to keep your fingers crossed."

But the technological supremacy the S.L.C. and Tevatron offer may be short-lived. A Western European scientific consortium is nearing completion of an underground accelerator 17 miles in circumference, by far the largest such machine in the world. Last Wednesday scientists successfully tested the first two-mile segment of the European Large Electron-Positron collider, prompting acclaim from scientists at competing institutions in the United States. The LEP will not be ready for experiments until 1990, however, and until then physicists in the United States are pressing their temporary advantage.

Much farther down the road, American physicists hope to build an accelerator about 52 miles in circumference, the Superconducting Supercollider, which would dwarf even the European LEP ring. The cost of the S.S.C. is so daunting, however, that even some of its proponents have begun to express doubts that it will ever be paid for. Meanwhile, the leaders of American laboratories are focusing on current developments.

"This will be a very interesting summer but a very tense one," Dr. Burton Richter, director of the Stanford Linear Accelerator Center and winner of a Nobel prize in physics, said in an interview. "In the next few weeks we hope to start producing Z^0 particles, one of the types of particle the S.L.C. was designed to make, but you never can be certain of a result until you achieve it."

"While we wait," he added with a laugh, "I've asked my department directors to go to a synagogue or a church to pray for divine help."

Dr. Richter's uneasiness stems from the fact that his S.L.C. represents an accelerator design that has never been tried. A conventional particle collider spins counter-rotating clusters of particles around a ring. In the machine Dr. Richter conceived and built, however, the opposing particle beams, each one much thinner than a human hair, are initially accelerated together down a straight, two-mile-long linear accelerator. At the end of the line, the two beams diverge and are ducted around two semi-circular arms resembling crab claws. The tips of the claws point toward each other, aiming the two beams directly at each other.

The Z^0 particle that scientists hope the S.L.C. will soon produce in large numbers is a very heavy, short-lived particle that conveys the weak nuclear force from one subnuclear particle to another. (The weak force is responsible for one form of radioactive nuclear decay.)

Five years ago, physicists in Europe created and observed Z^0 particles and two other carriers of the weak force, the W+ (W-plus) and W-

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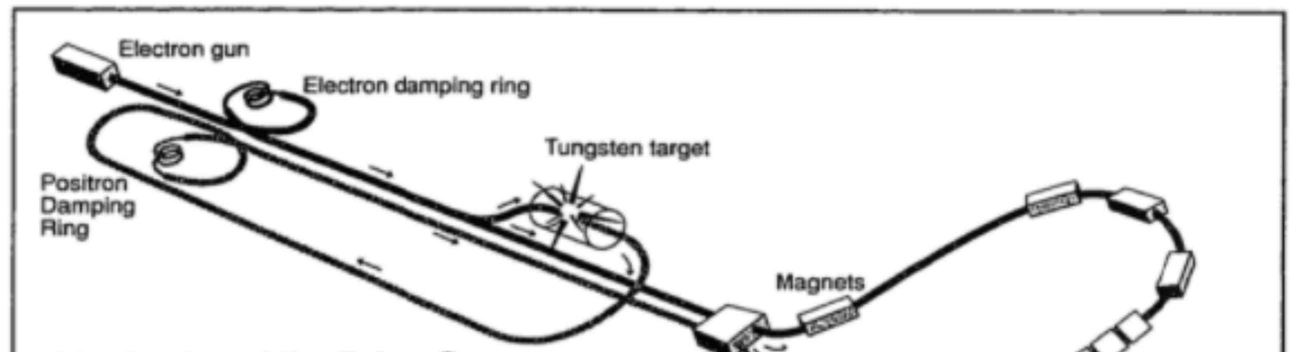
Fermi National Accelerator Laboratory

Aerial view of Fermi National Accelerator Laboratory in Batavia, Illinois, showing circular main accelerator.



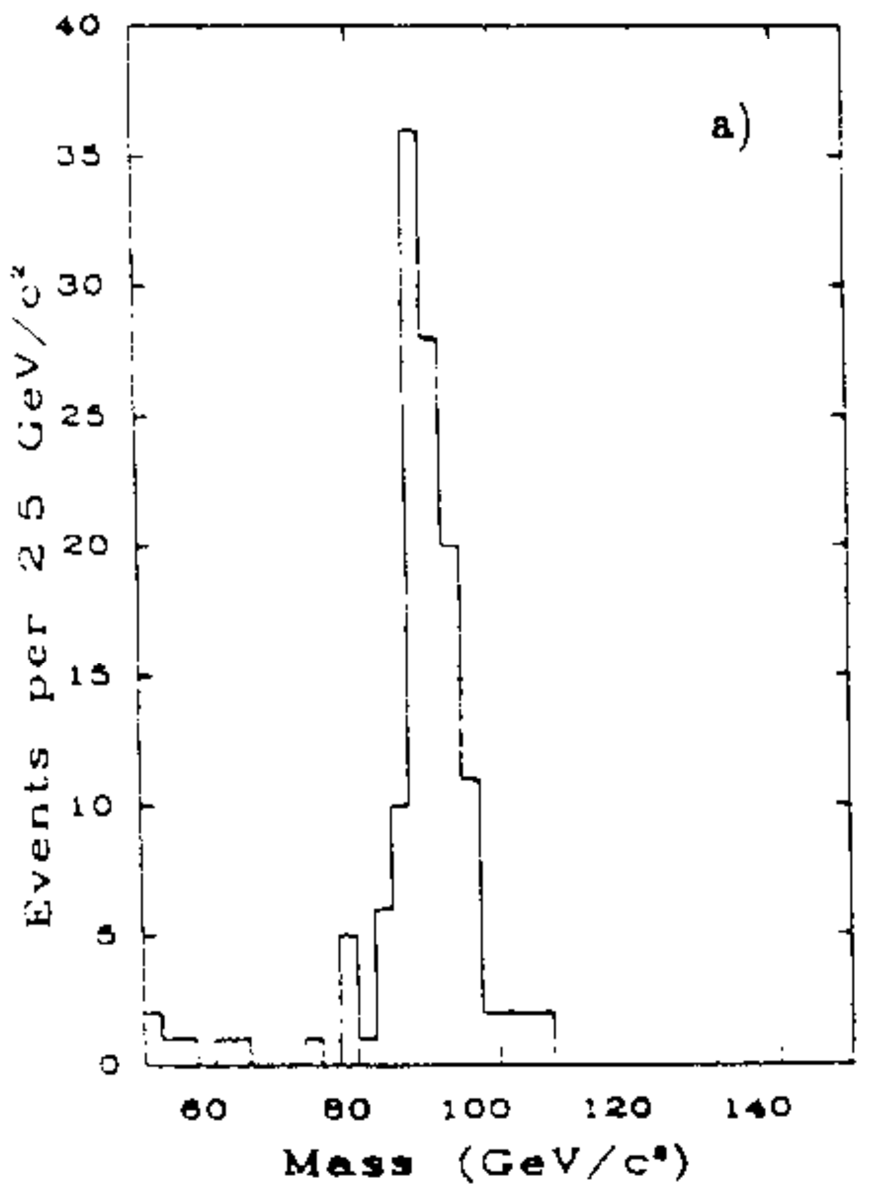
The Design of the Future?

Stanford's new linear collider uses an unusual design, avoiding some of the energy losses of the more common circular design. Electrons are fired into the system, and some are diverted to bombard a tungsten target, creating positrons, their antimatter equivalents. The beams, which are shaped in damping rings, end their two-mile journey when magnets bend them around opposing arms. The beams collide in a detector that records resulting particles.

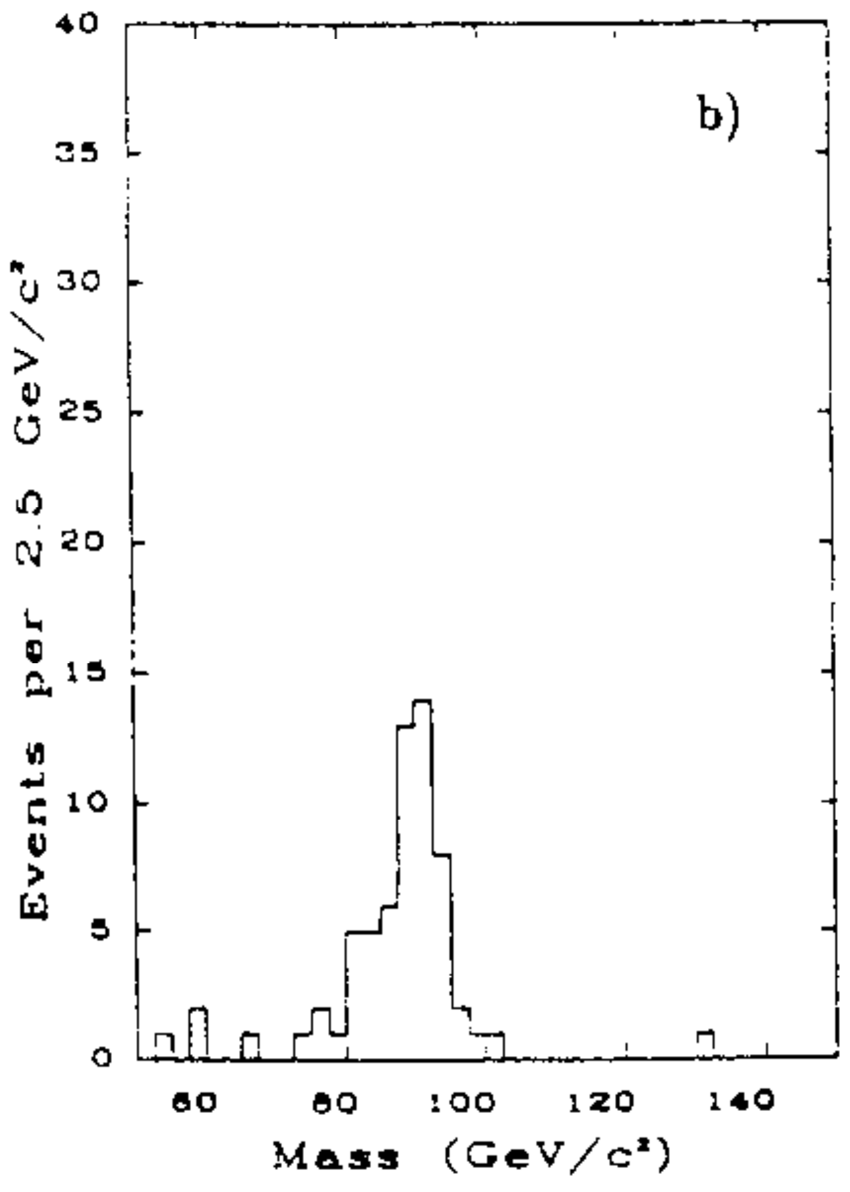
Steve Hart/The New York Times

First W and Z results: 1989

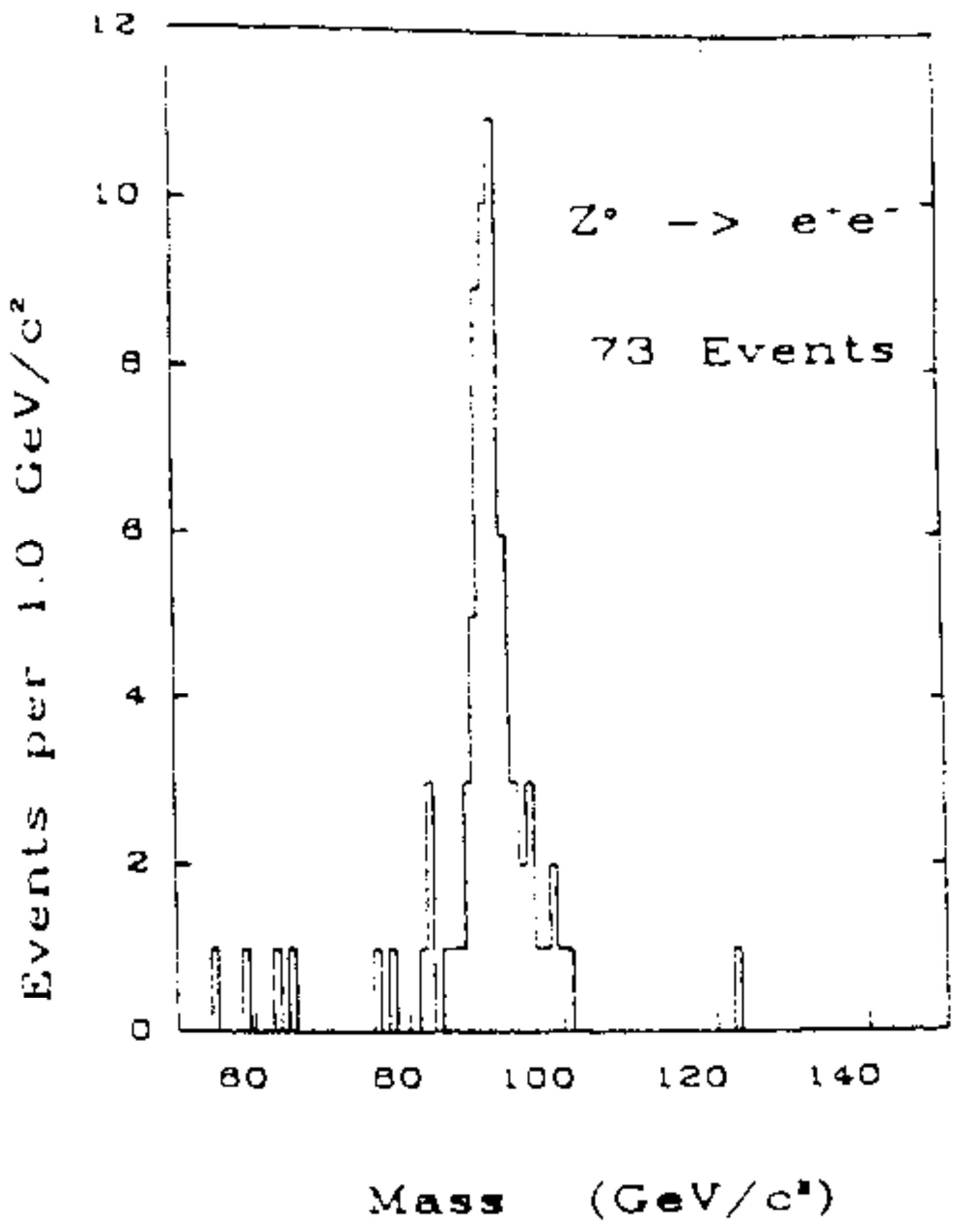
Muon Z decays



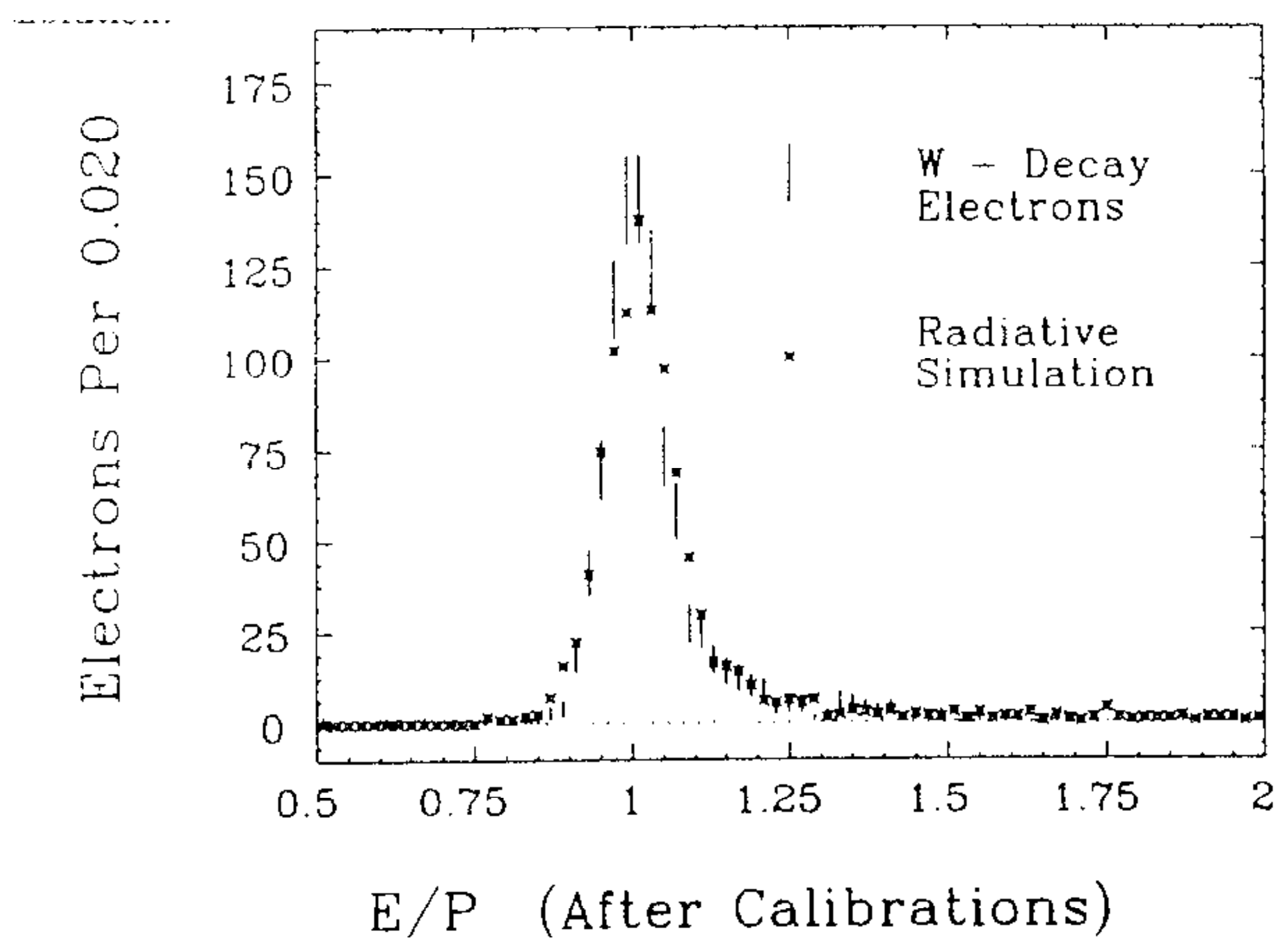
Electron Z decays (track only)

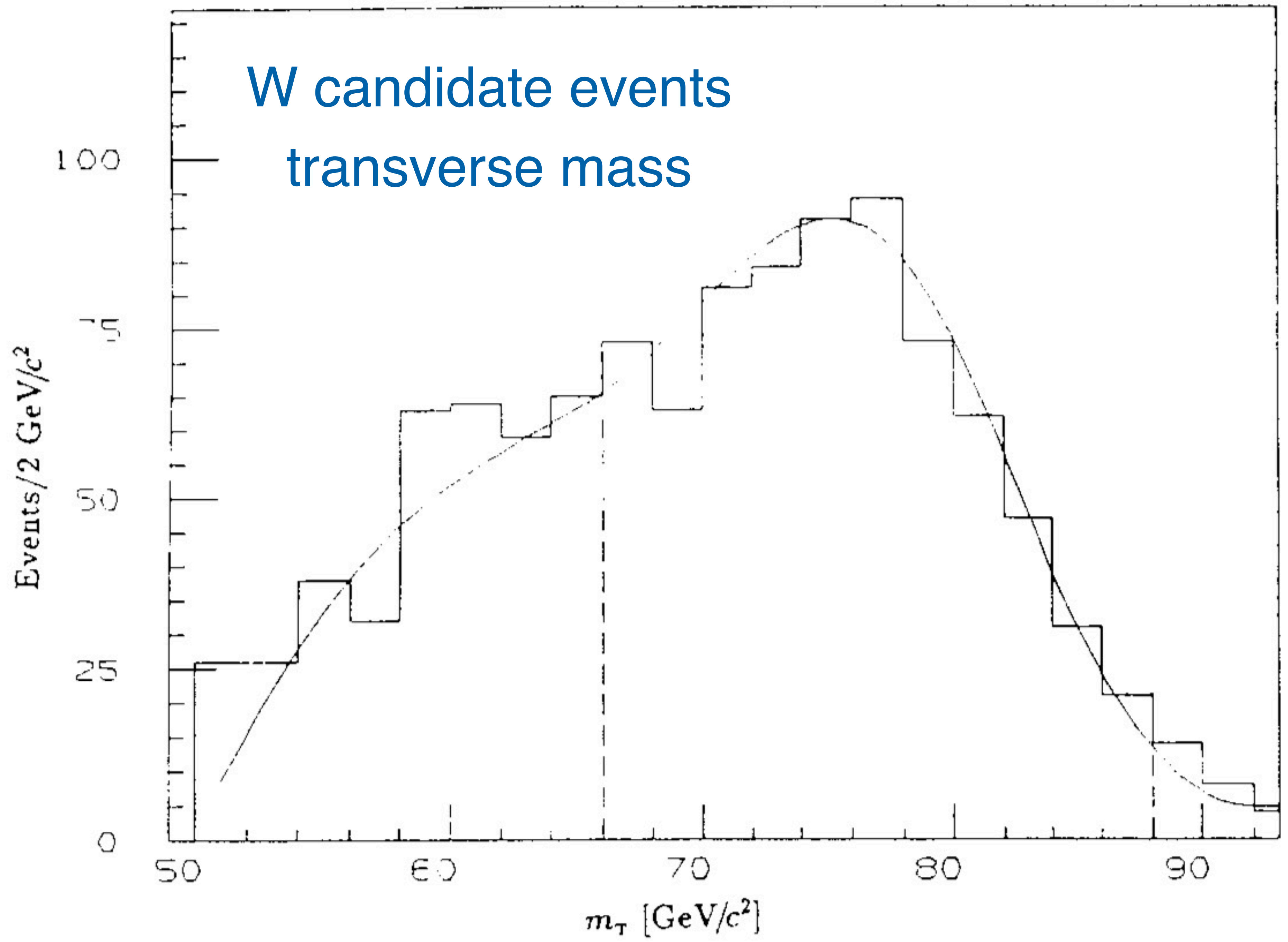


Electron Z decays (calorimeter)



Validation of E/p calibration





W candidate events transverse mass

$M_W = 80.0 \pm 0.6 \pm 0.3$ GeV

$M_Z = 90.9 \pm 0.3 \pm 0.2$ GeV

precision from a hadron collider rivaling lepton colliders!

Ken Ragan at SLAC Summer Institute 1989 [SLAC-R-361]

Run I of the Tevatron (1992-1996)

- 140 pb^{-1} of 1.8 TeV collisions delivered to both experiments
  - DØ fully online in 1992
- The top quark
  - Evidence in 1994
  - **Discovery** by both experiments in 1995


Fermilab director John Peoples with CDF and DØ spokespersons

Elusive Atomic Particle Found by Physicists

By MALCOLM W. BROWNE

Special to The New York Times

BATAVIA, Ill., March 2 — Culminating nearly a decade of intense effort, two rival groups of physicists announced today that they had found the elusive top quark — an ephemeral building block of matter that probably holds clues to some of the ultimate riddles of existence.

The announcements brought sustained applause and a barrage of questions from an overflow audience of physicists at the Fermi National Accelerator Laboratory, where the work was done. Fermilab has the

One of the teams, the CDF Collaboration (standing for Collider Detector at Fermilab) reported last April that it had found evidence of the quark's existence. But at the time, the group lacked enough statistical evidence to claim discovery, and the competing group, the D0 (for D-Zero) Collaboration, which had even less evidence of its own, branded the CDF announcement as premature.

The achievement claimed today by both teams leaves virtually no room for doubt, however, and the discovery was hailed as a landmark in science. Hazel O'Leary, who as Secretary of Energy heads the Federal agency providing most of the money for research at Fermilab, called the discovery a "major contribution to human understanding of the fundamentals of the universe."

The finding confirms a prediction based on a theory known as the Standard Model that nature has provided the universe with six types of quarks; the other five, the up, down, strange, charm and bottom quarks had all been known or discovered by

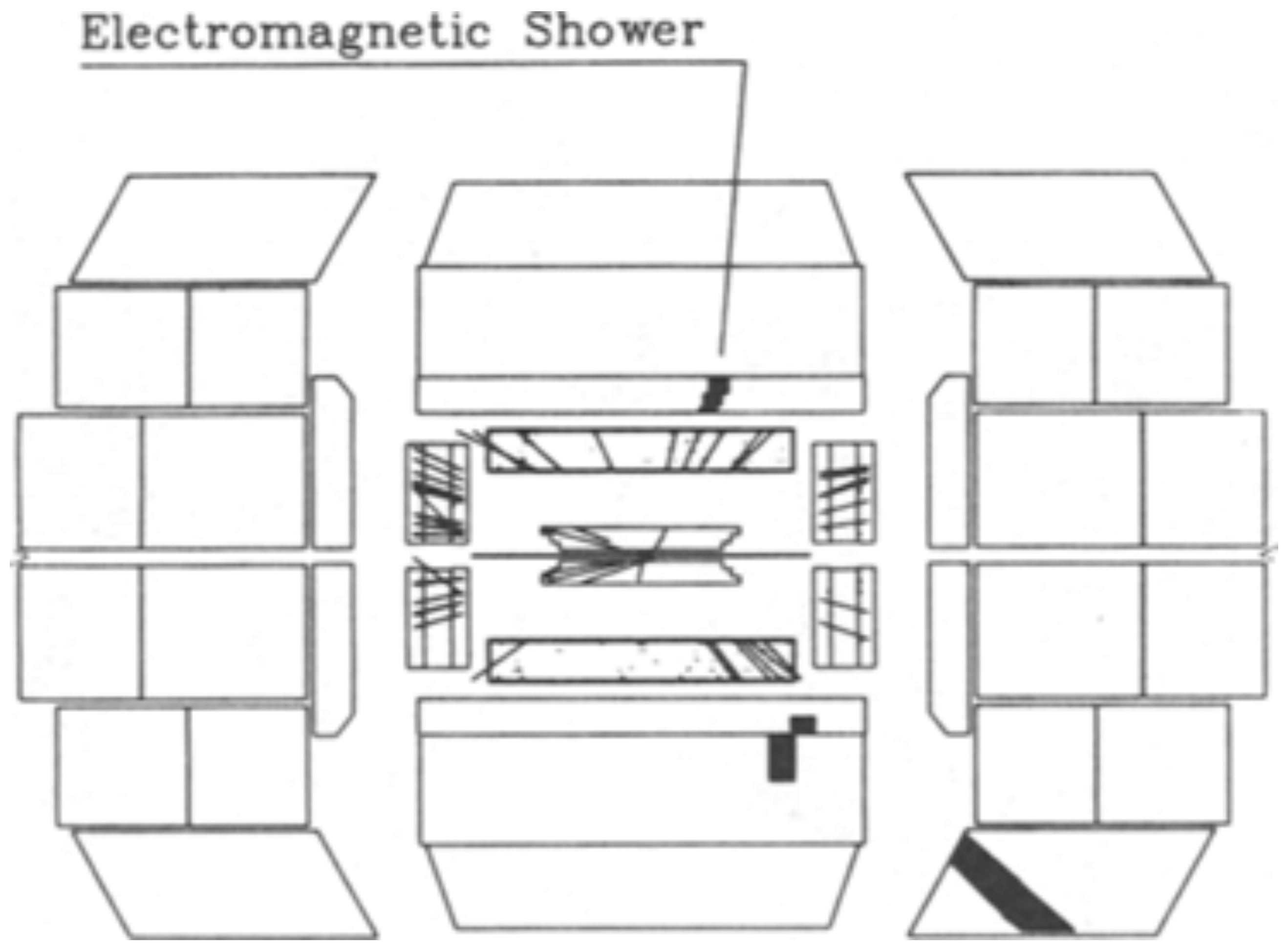
Continued on Page B7, Column 1

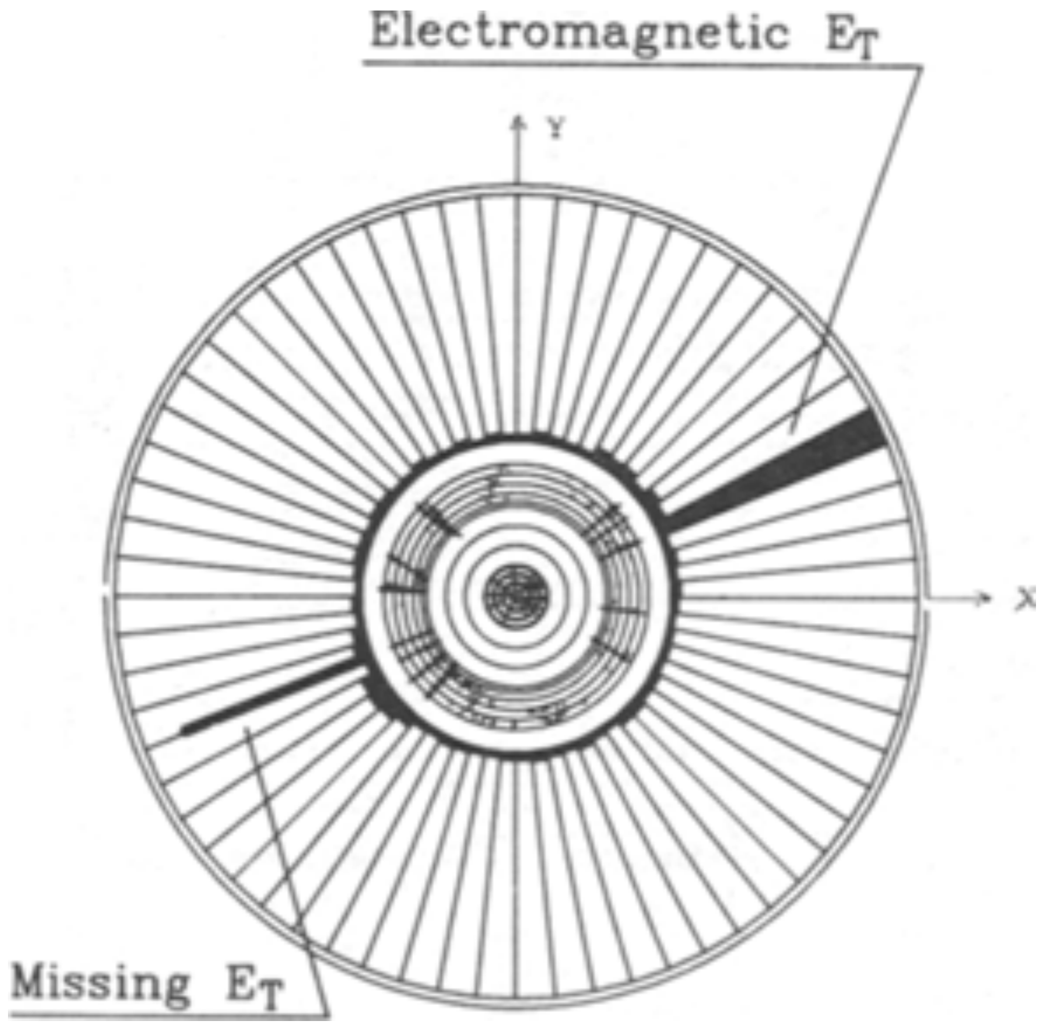
DØ gets in the game

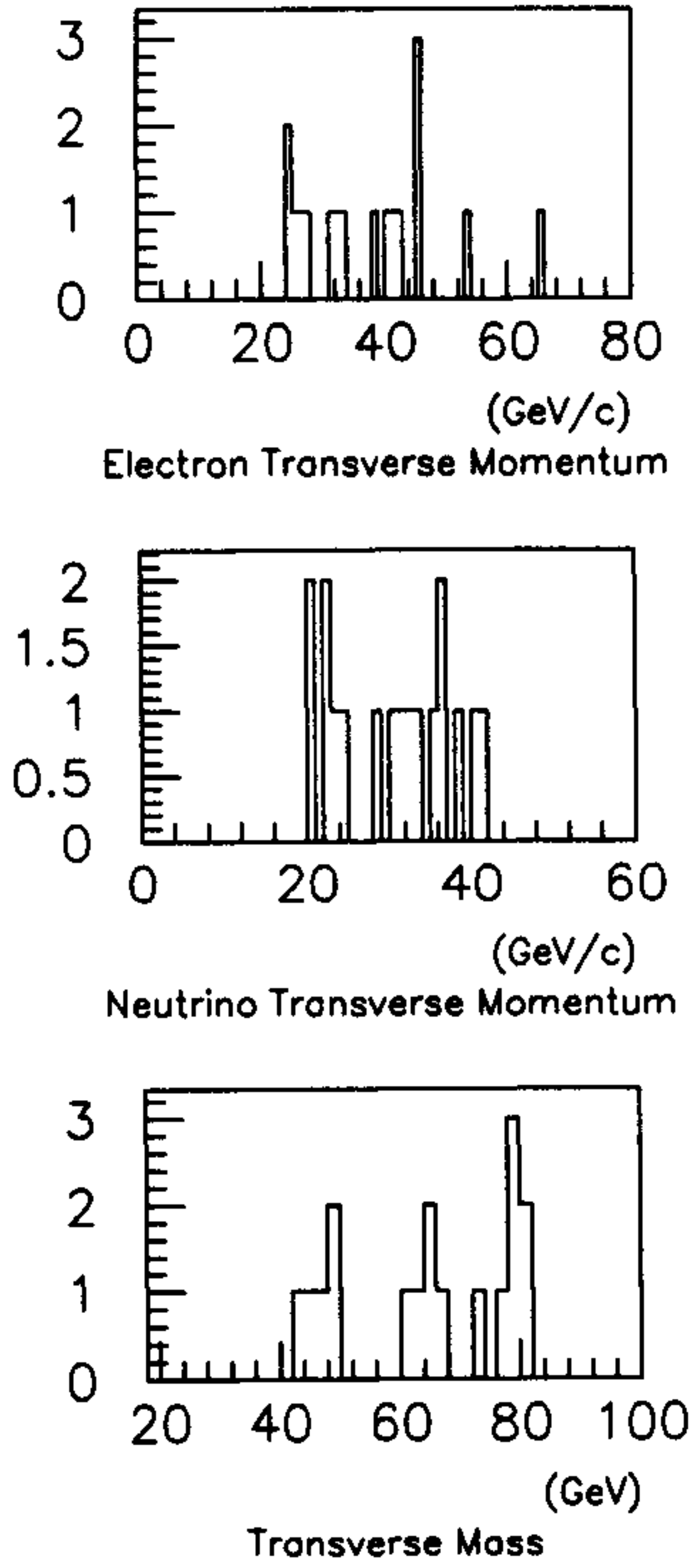
- Bruno Gobbi at ICHEP 1992 (Dallas, TX USA)
  - Shortly after the start of Run I

In the 1992 Tevatron running period, prior to this conference, about 100 nb^{-1} have been delivered. Half of this luminosity has been used to debug and calibrate the detector. A fraction of the remaining luminosity has been dedicated to the study of Ws decays.

The goal of DØ towards the study of the IVBs for the 1992 Tevatron running period is to measure the mass of the W with a precision of 160 MeV. This will be achievable with the expected luminosity of 25 pb^{-1}. This measurement together with the prediction of the Standard Model will set new limits on the mass of the top quark.







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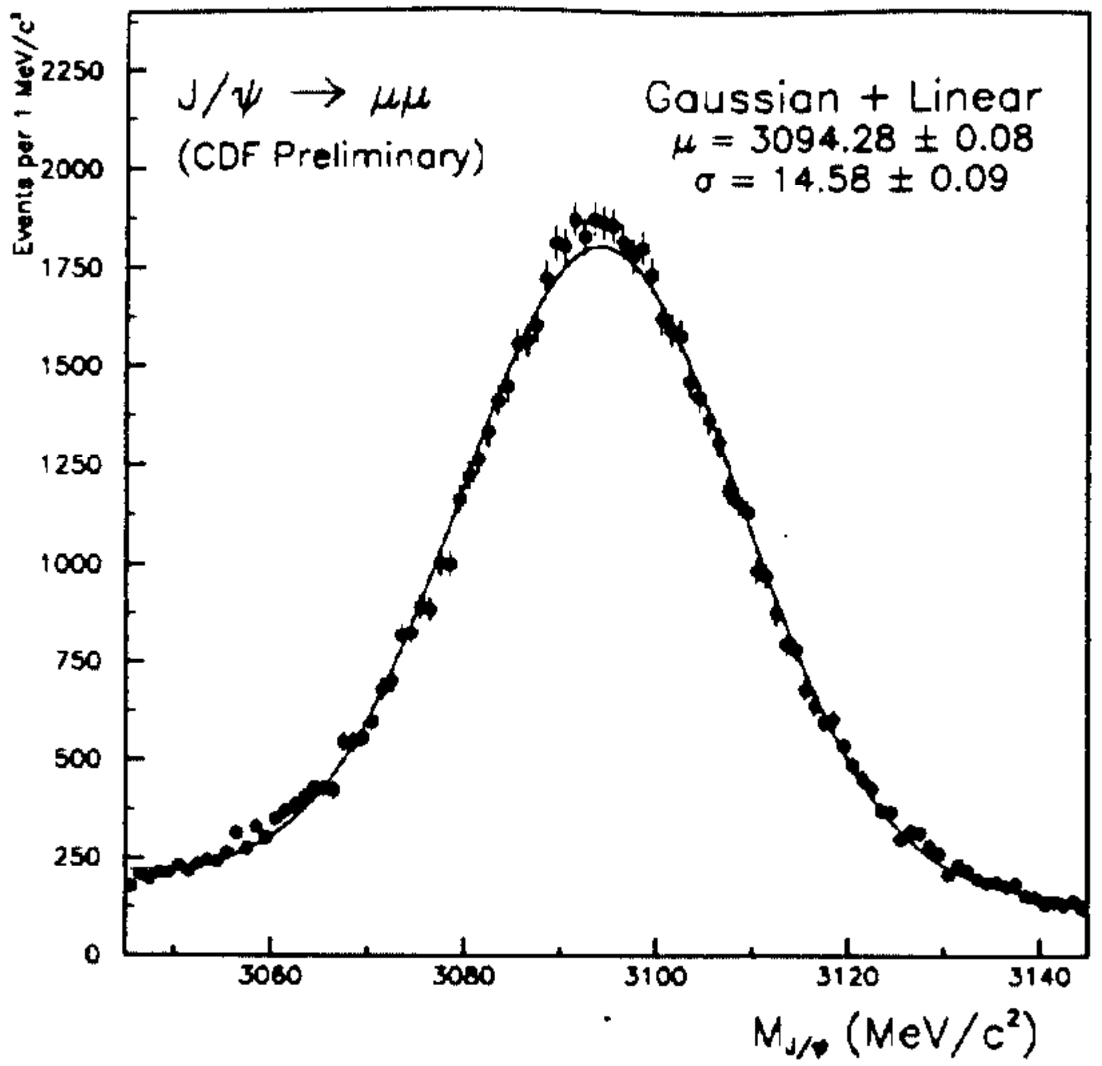
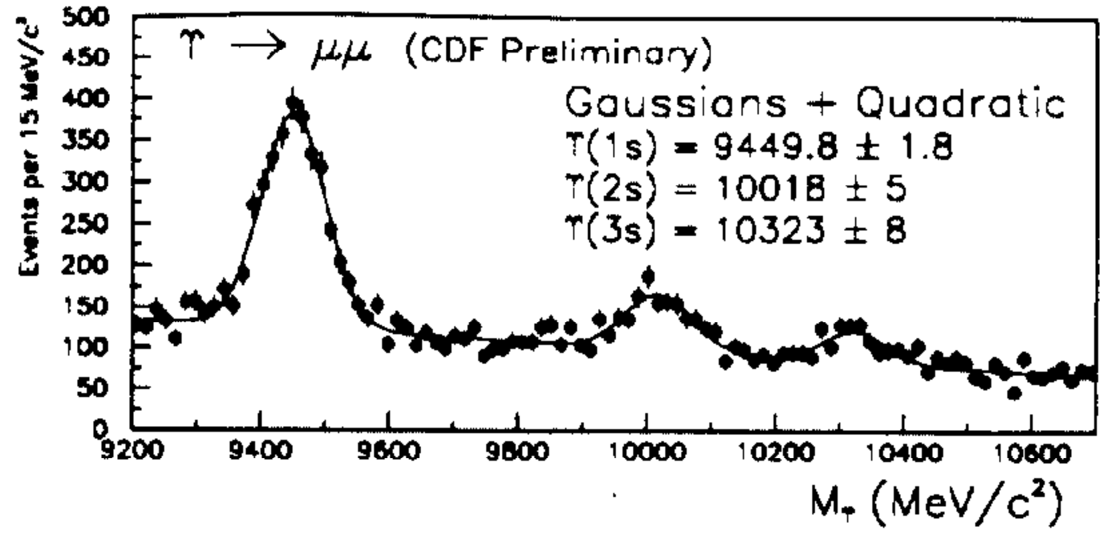
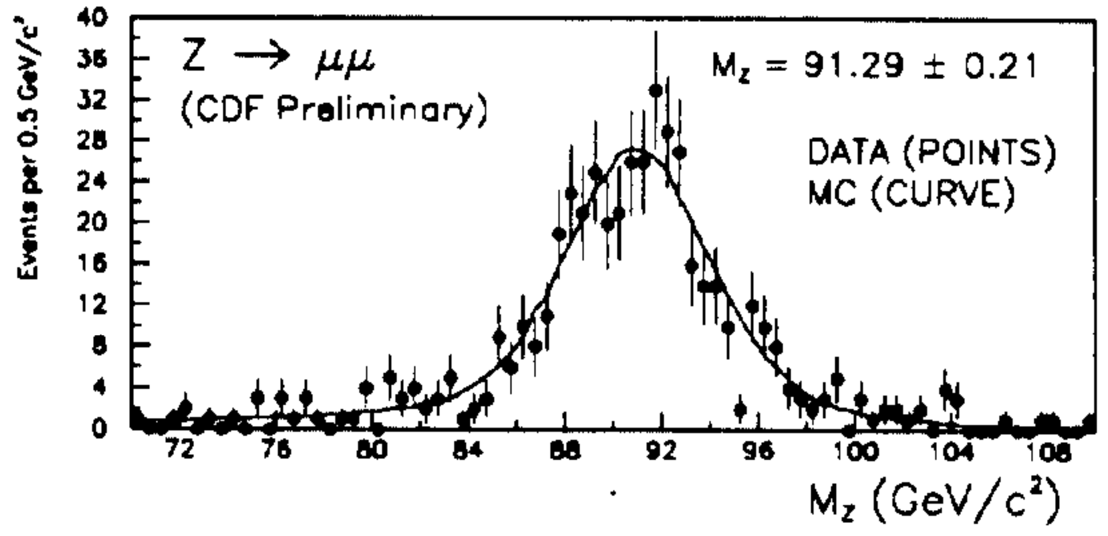
How to measure the W boson mass precisely

- Young-Kee Kim at ICHEP 1994 (Glasgow, UK)

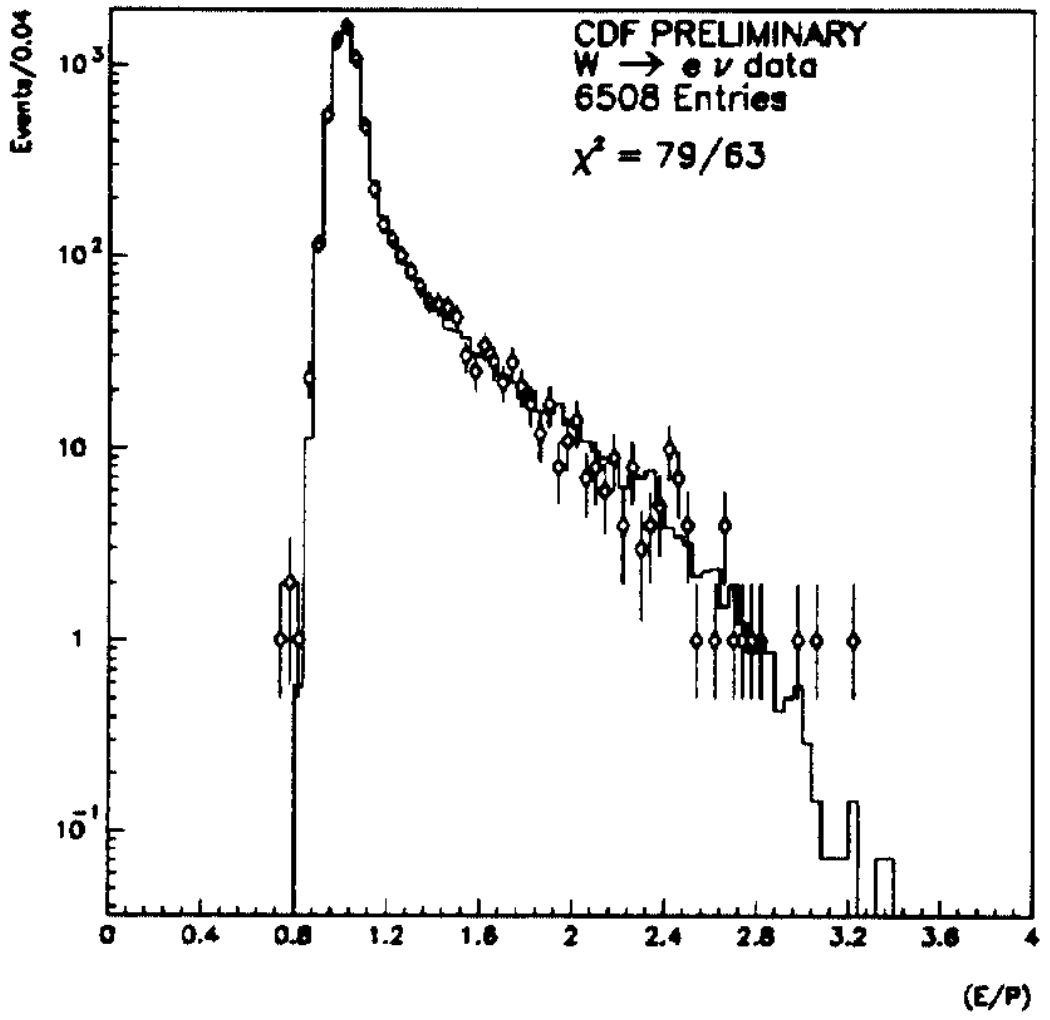
1) Calibrate track scale with dimuon resonances





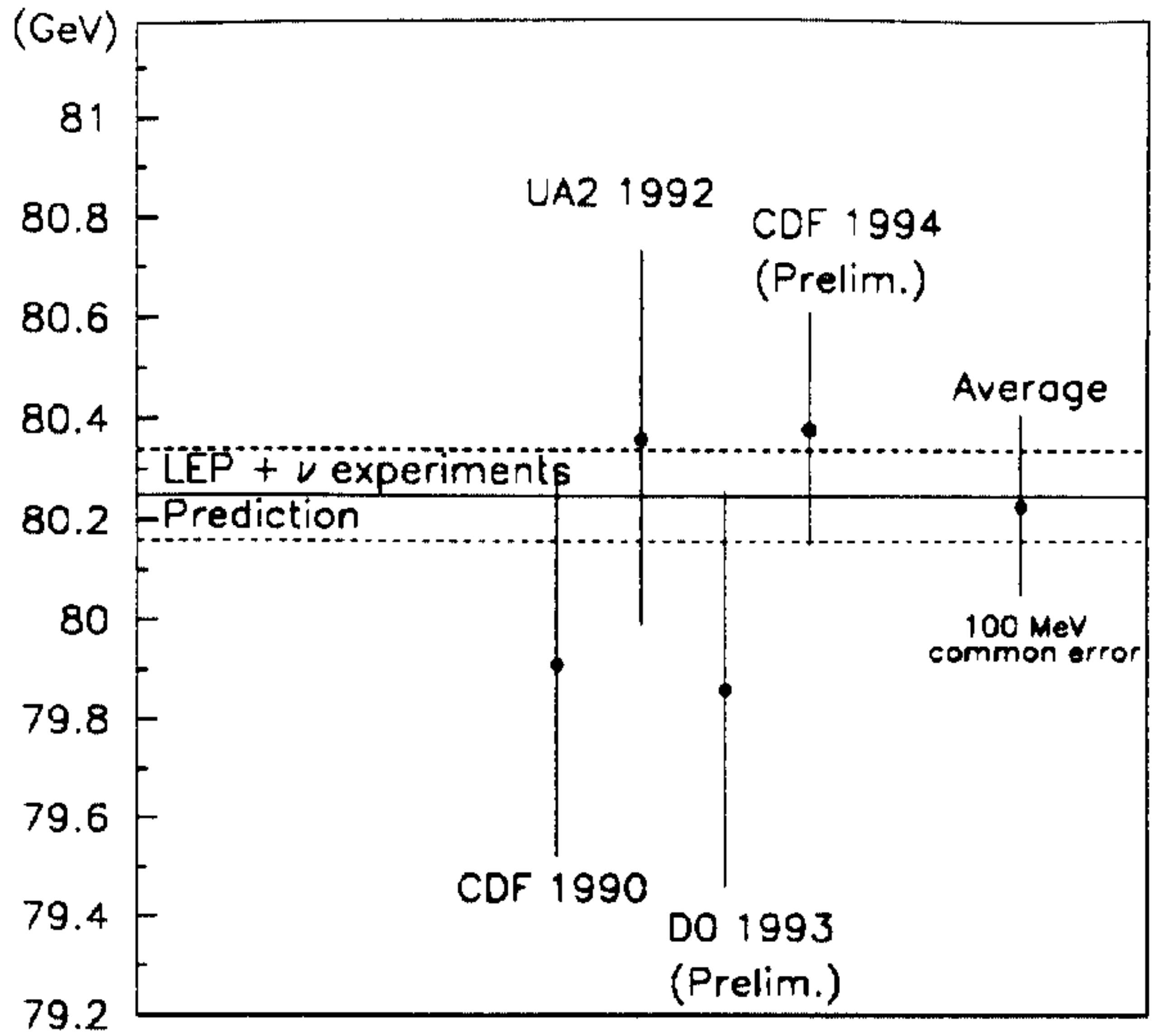


2) Calibrate EM scale with electron E/p



n) Measure m_W!

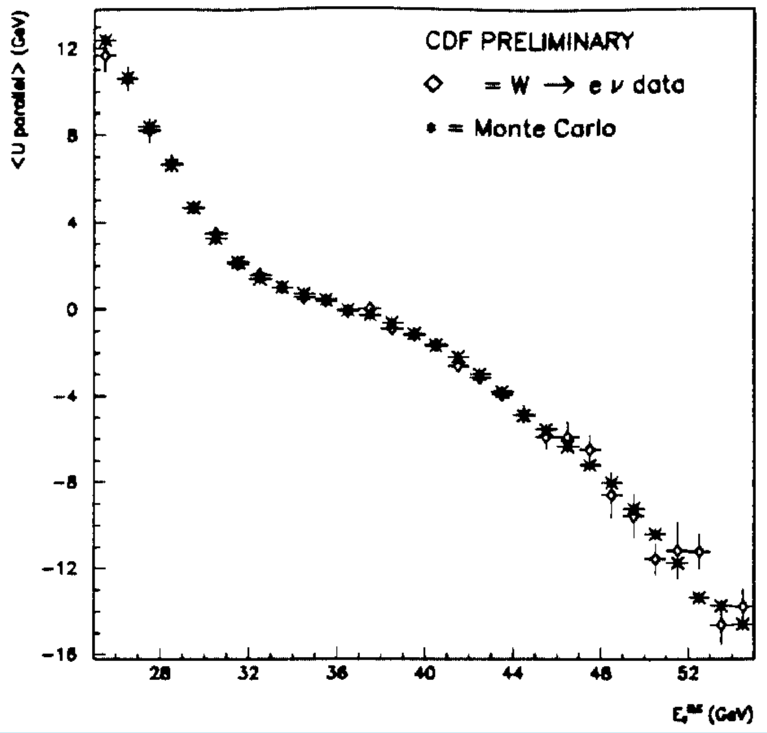
80.38±0.23 GeV

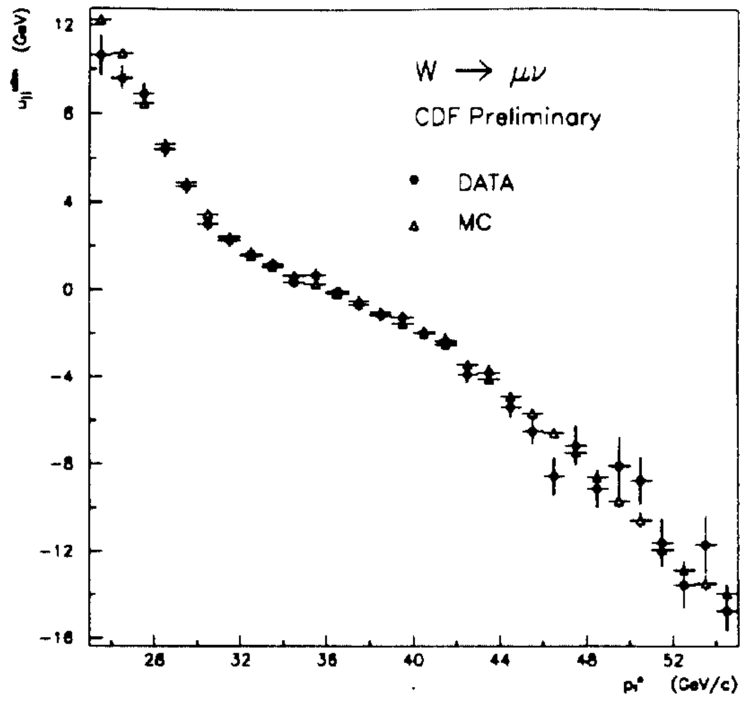


3) Calibrate hadronic recoil with Z events

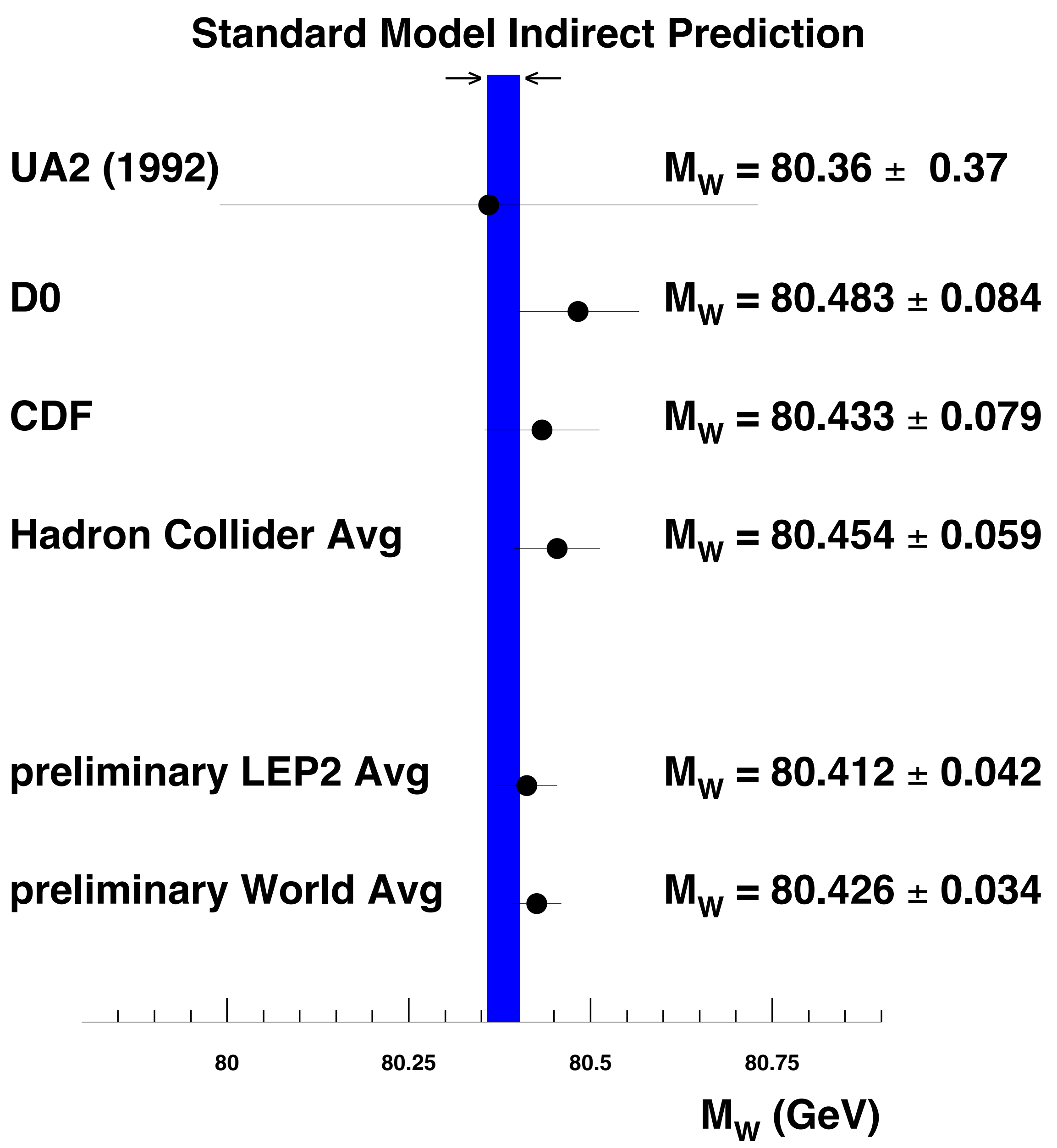
…

many other steps (bkgd, etc)

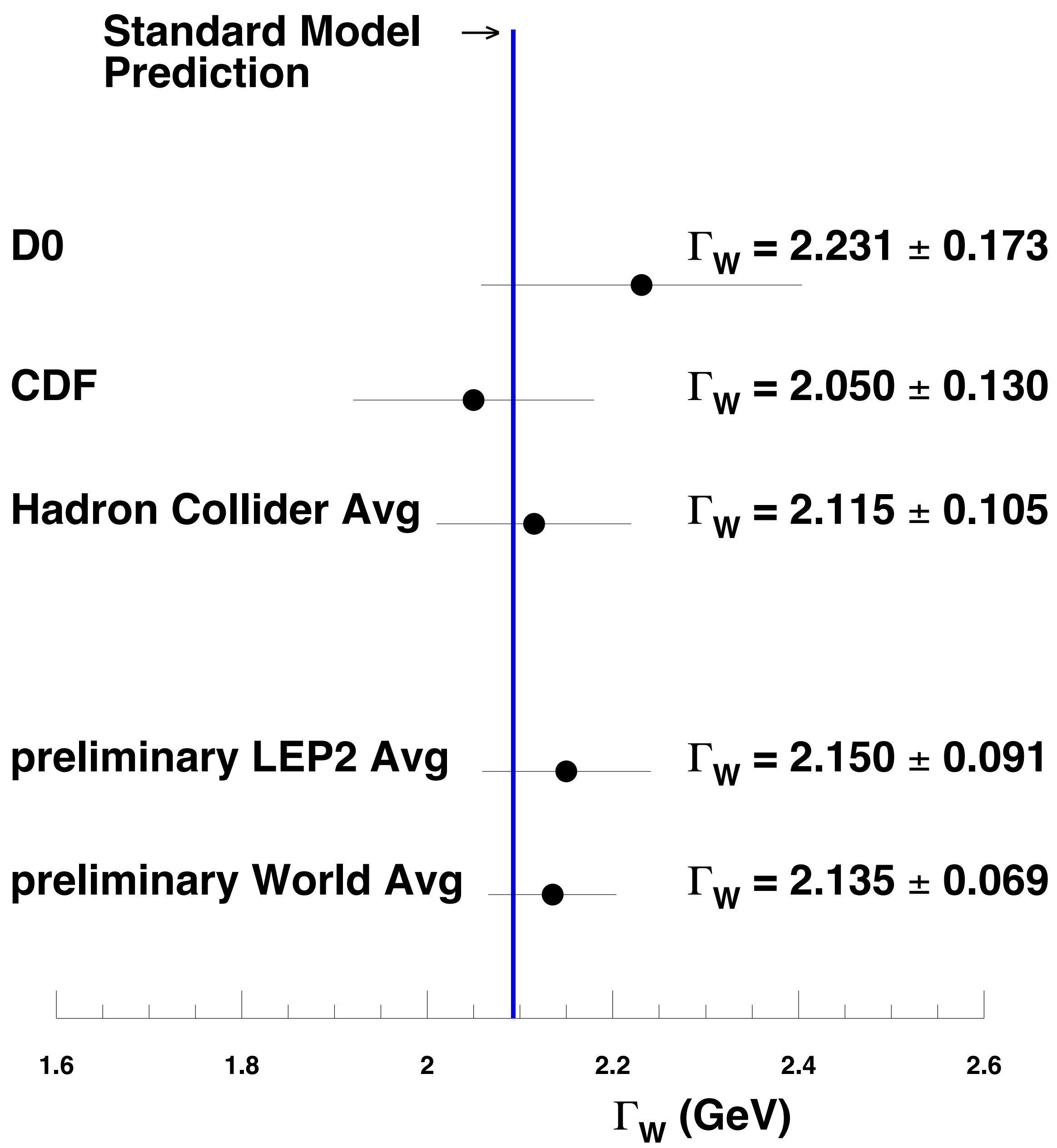


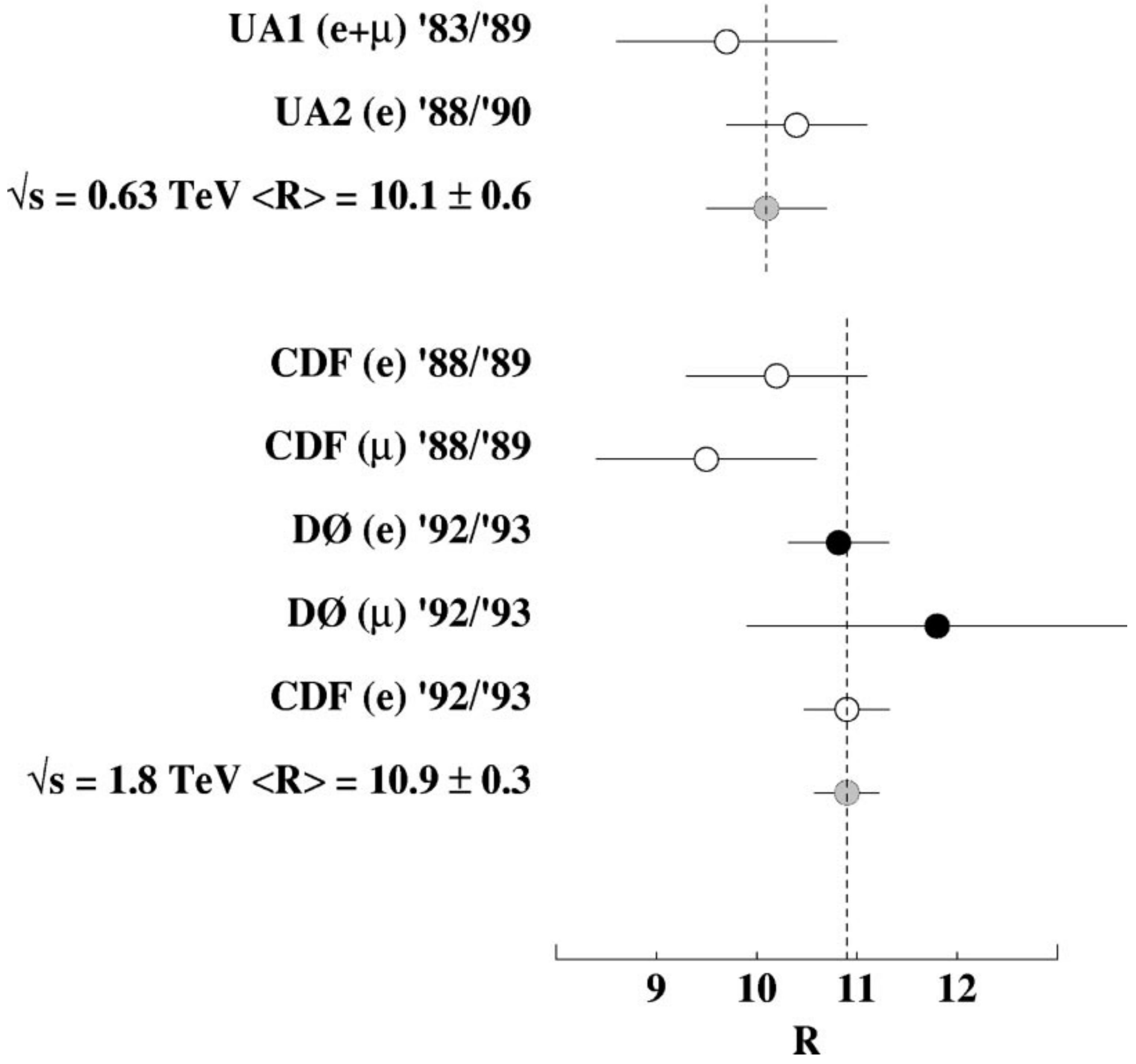


W and Z physics by the end of Run I

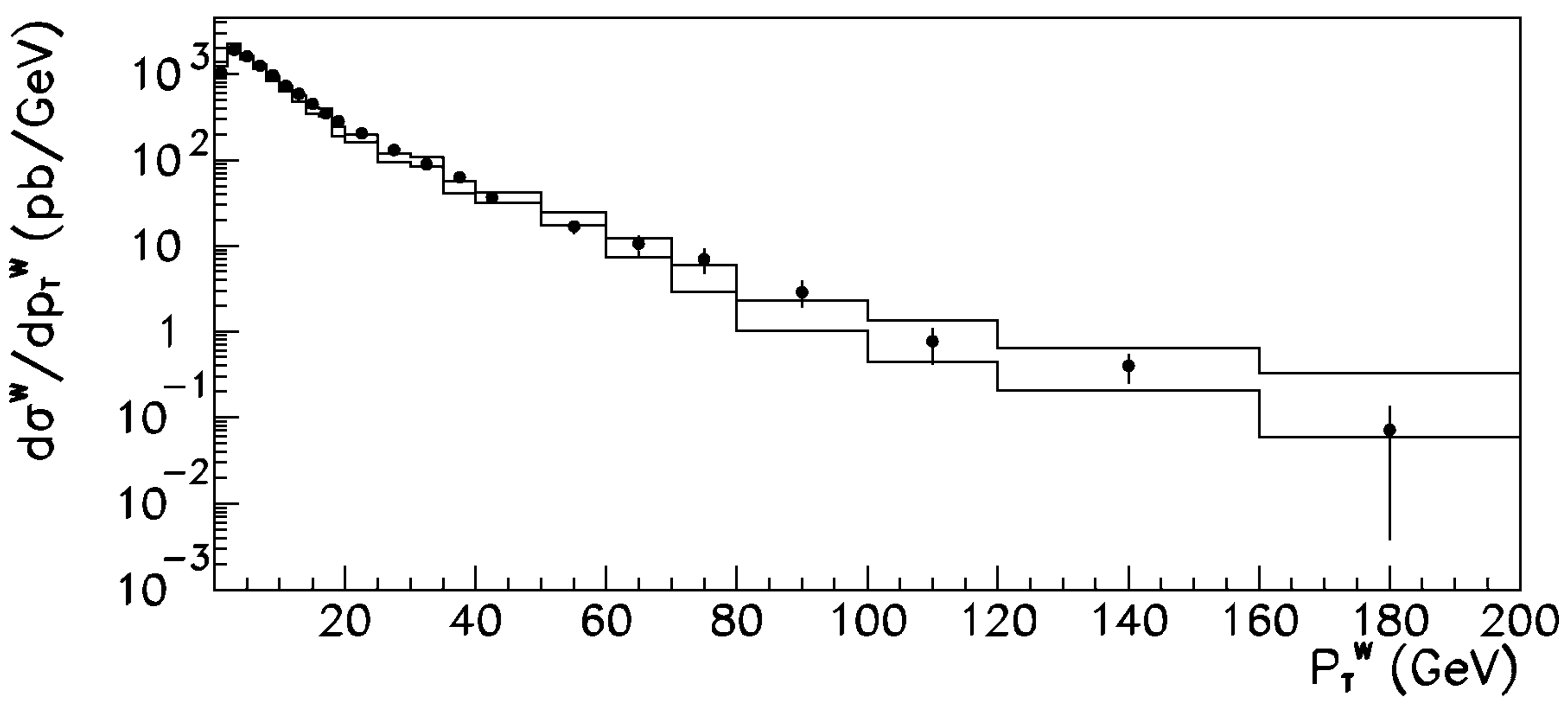


W boson mass and width
PRD **70**, 92008 (2004)





W and Z cross section Ratio R
PRD **60,** 052003 (1999)



W and Z differential cross section ratio as a function of transverse momentum
PLB **517**, 299 (2001) [DØ]

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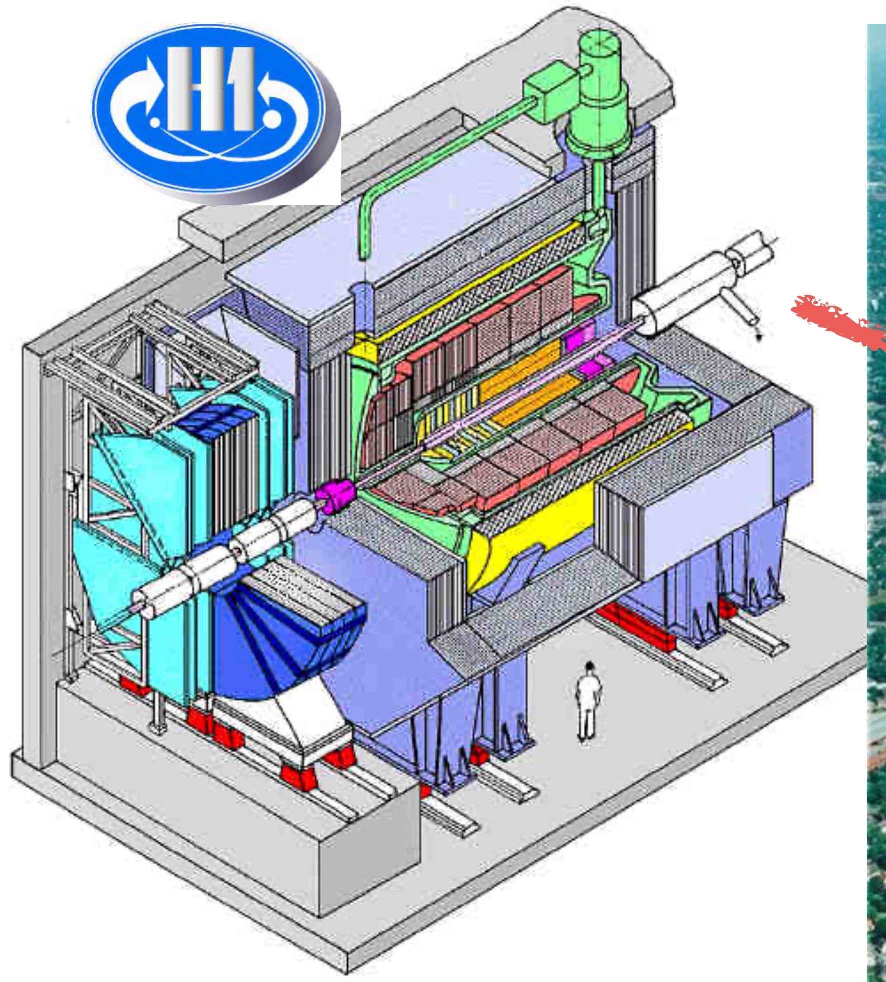
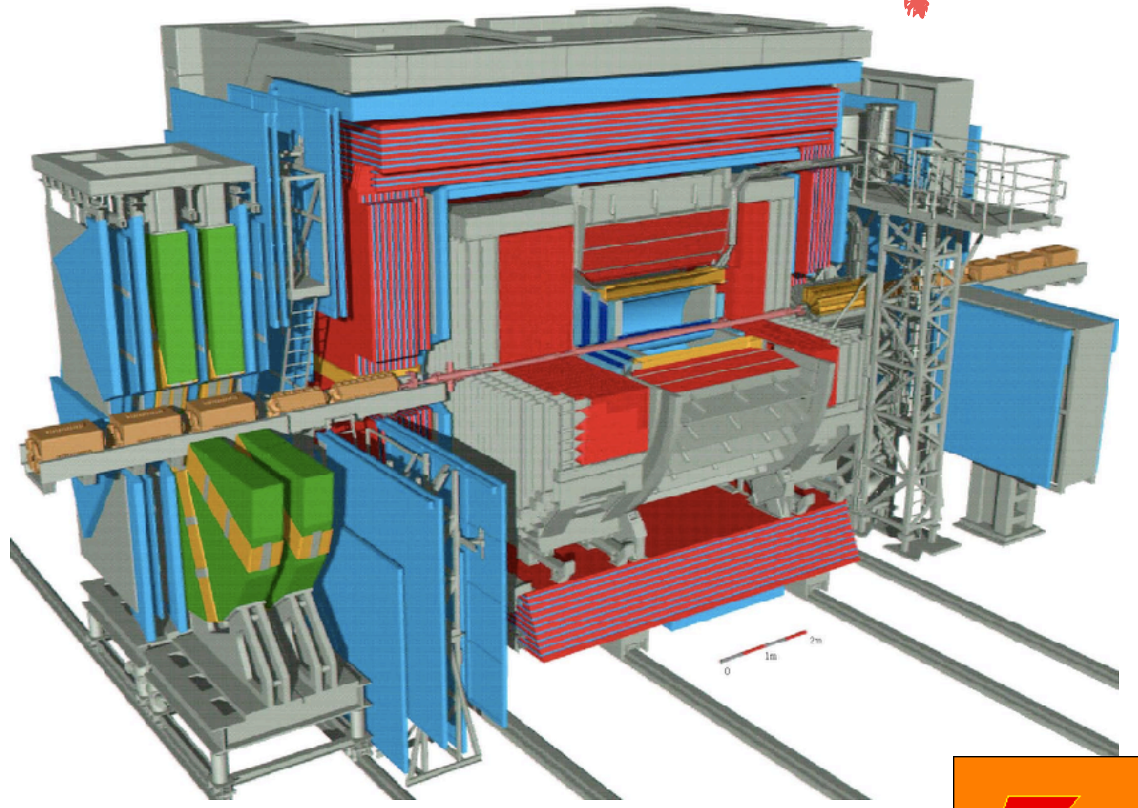
The HERA accelerator



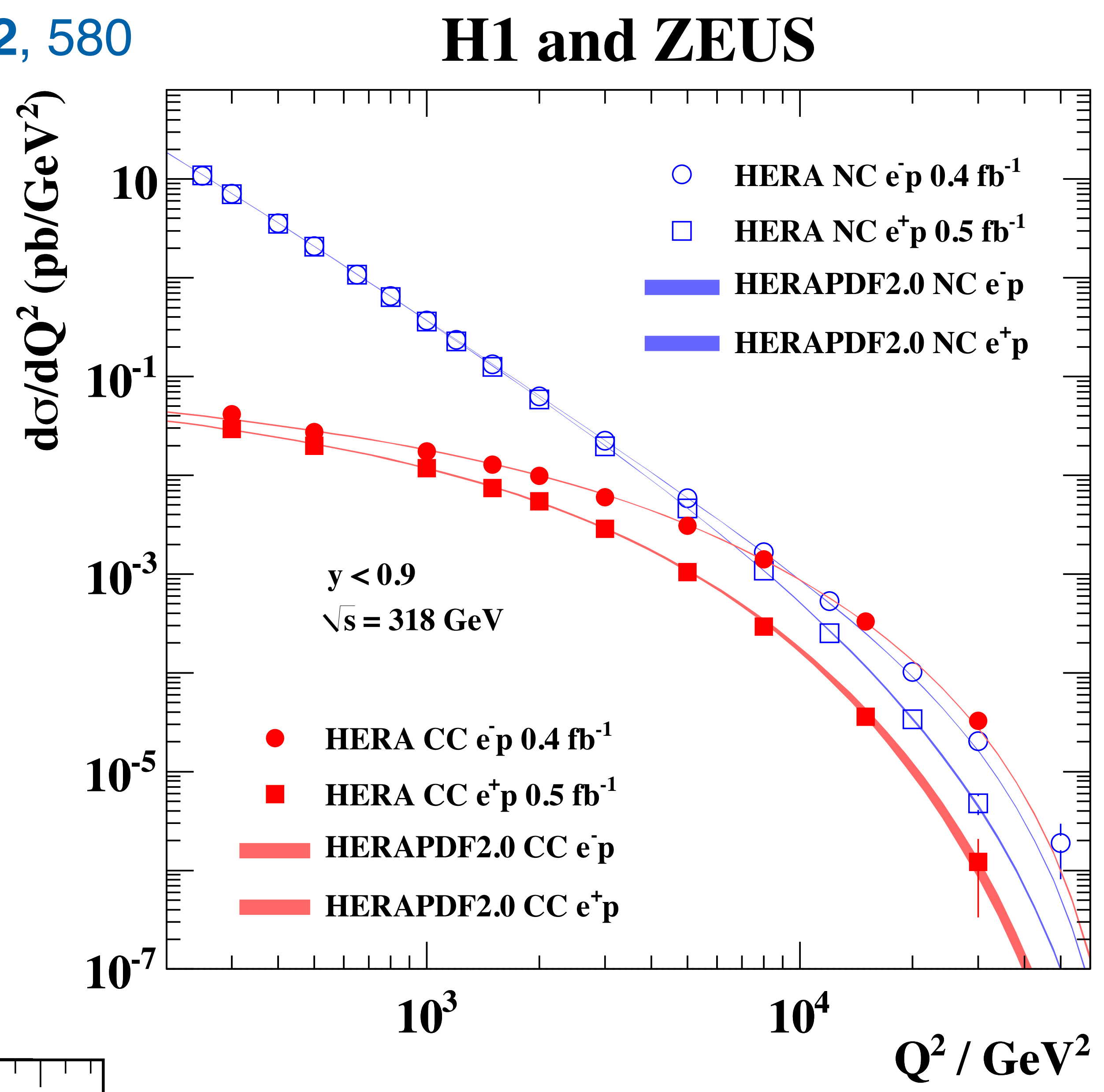
- **electron-proton** collider at DESY
  - Operated 1992-2007
  - 0.5 fb^{-1} delivered to each experiment
- Collisions of 920(p)x27.6(e) GeV
  - $\sqrt{s}$=320 GeV
- Two collider experiments **H1** and **ZEUS**
  - Specialized experiments: HERMES and HERA-B
- Precision probe of **QCD** and **parton structure**

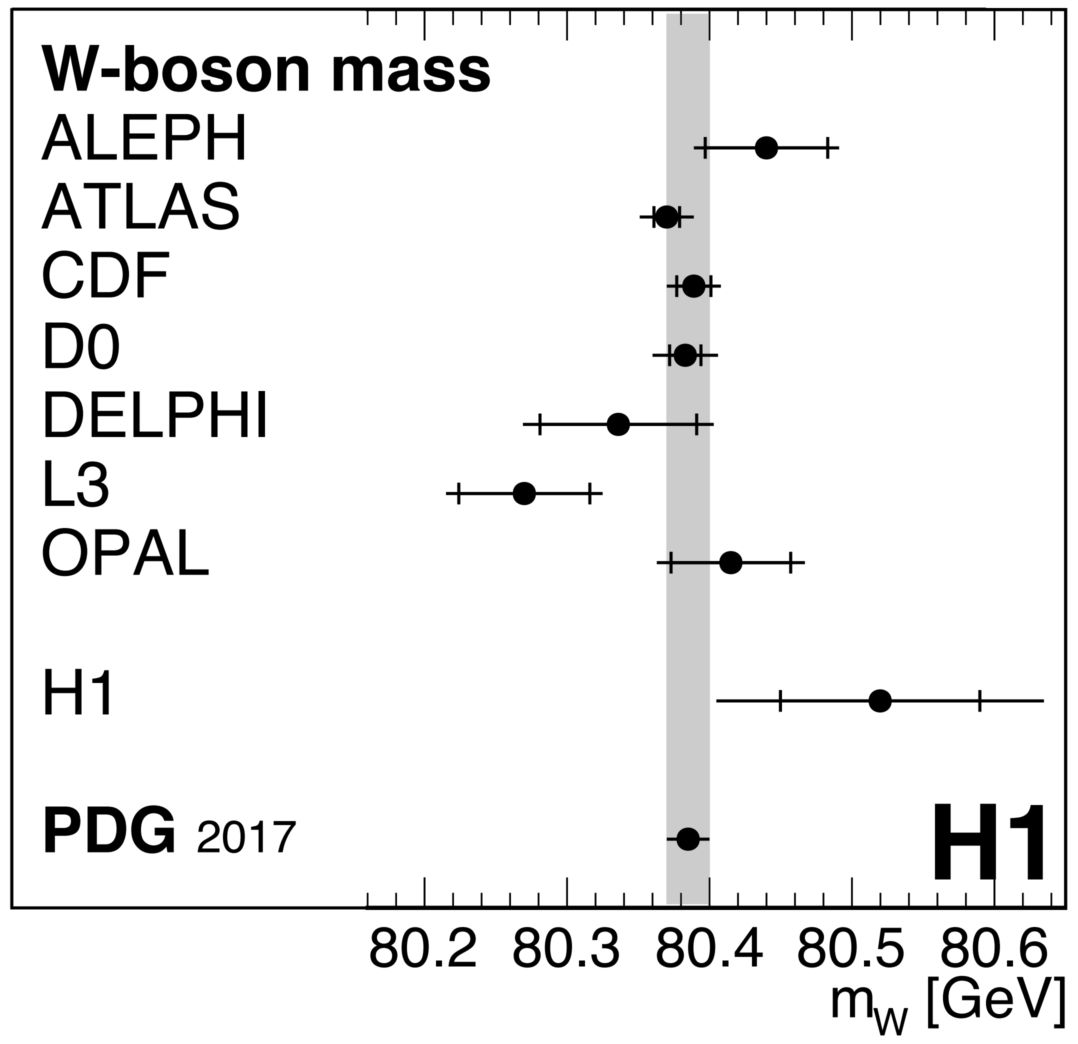


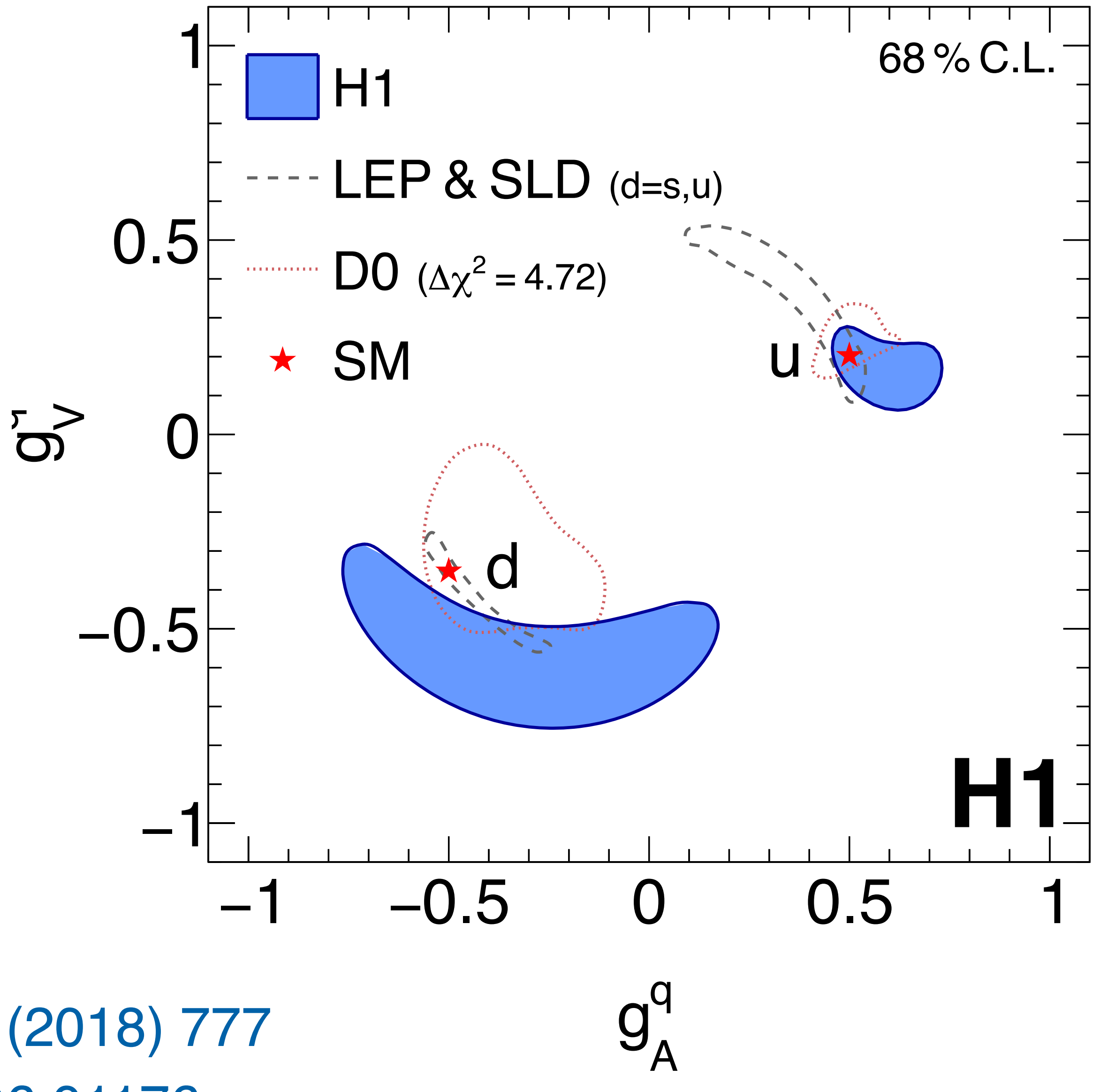
Electroweak probes at HERA

- Differential cross sections for ep scattering
  - Charged current (W boson) and Neutral current (Zγ interference) probes
- Simultaneous electroweak+PDF fits
  - Indirect measure of W/Z masses and other SM parameters
  - $M_W = 80.520 \pm 0.115$ GeV, $M_Z = 91.08 \pm 0.11$ GeV
- Can also probe couplings
  - e.g. axial and vector couplings of Z boson

EPJ C75 (2015) **12**, 580
arXiv:1506.06042





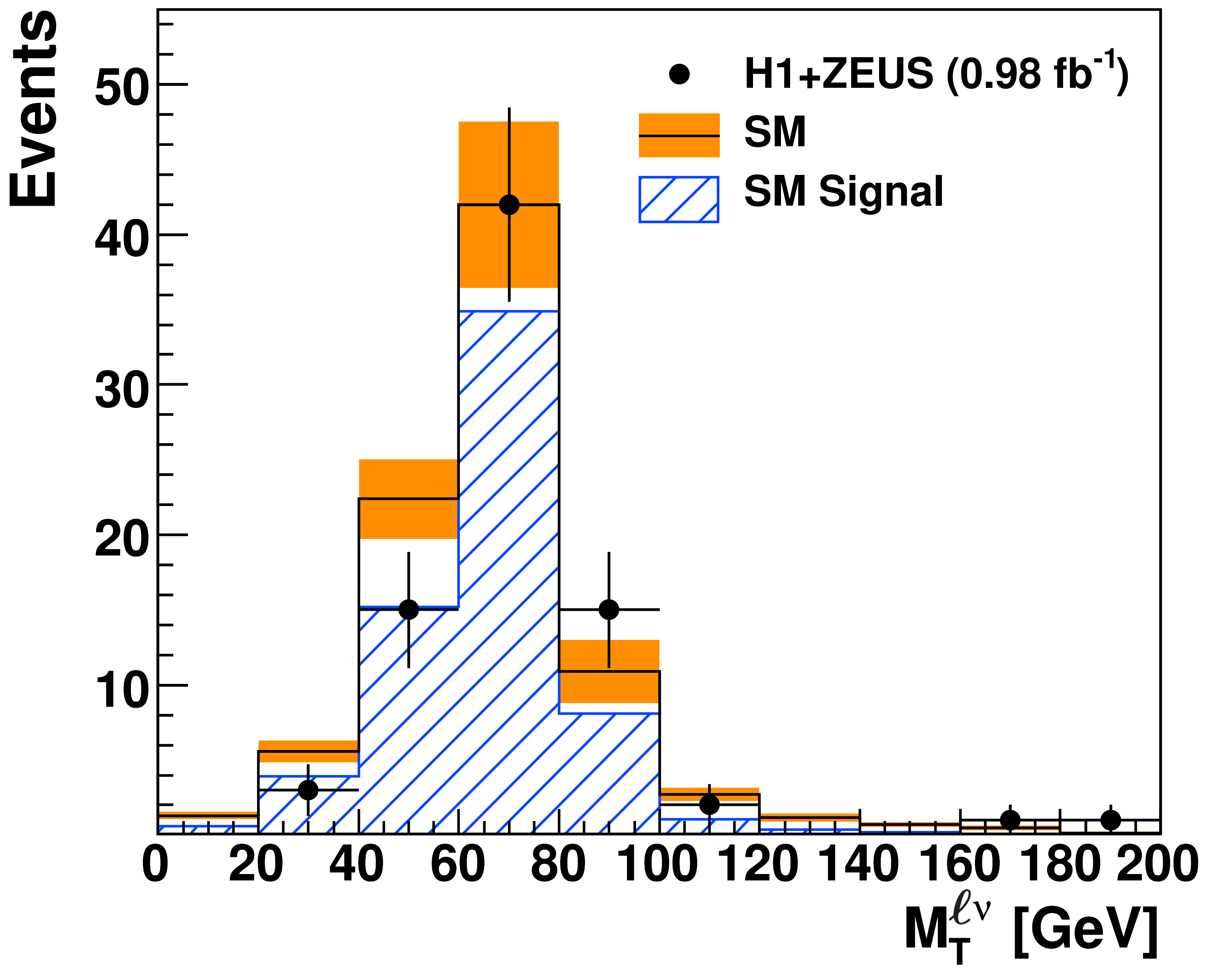


EPJ C78 (2018) 777
arXiv:1806.01176

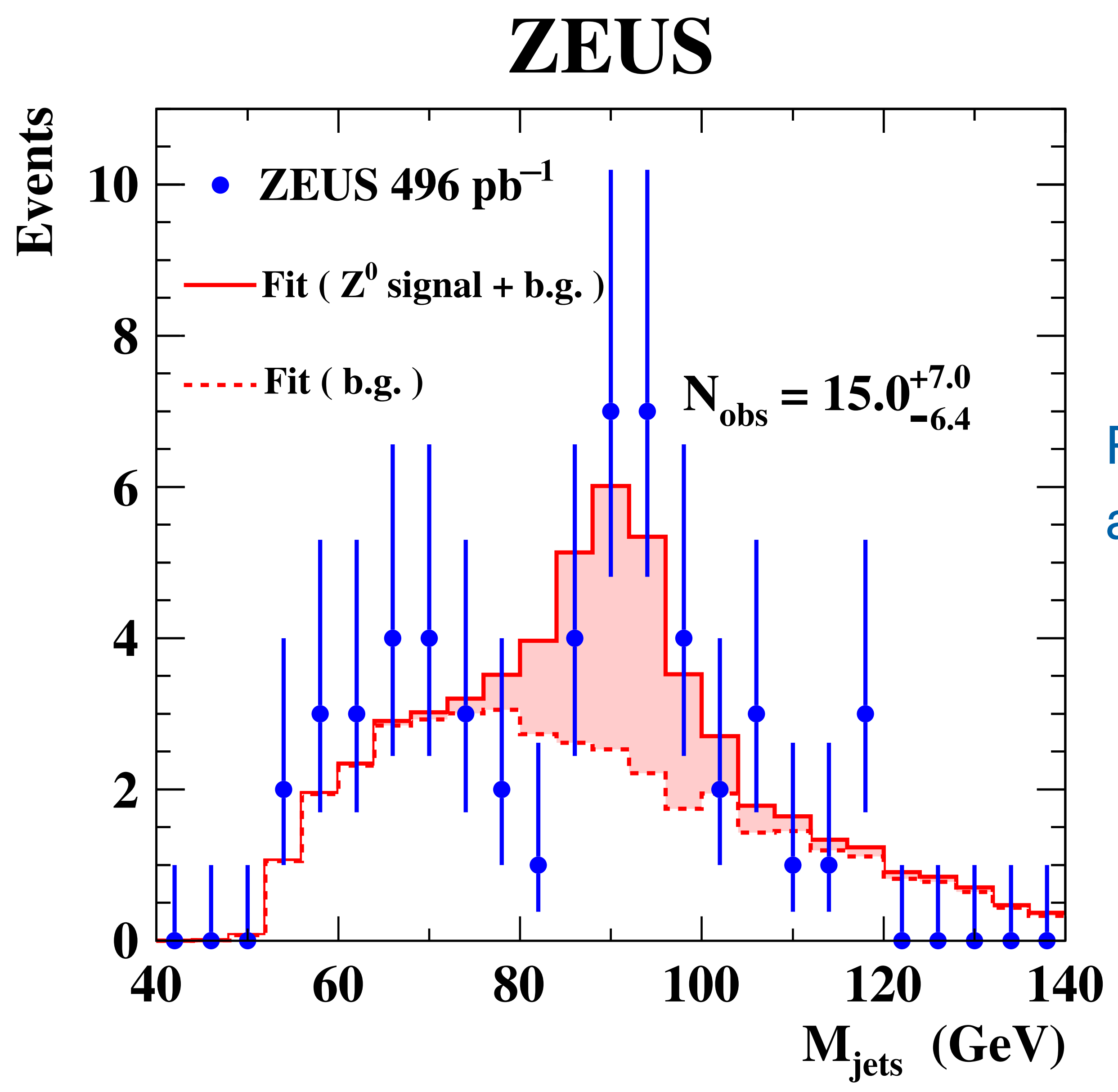
Observing W and Z bosons at HERA?

- Real W production incredibly rare at HERA
  - Combined H1+ZEUS measurement: 23 events
  - Measured σ = 1.06±0.17 pb
    - SM prediction of σ = 1.26±0.19 pb

JHEP 0910:013,2009
arXiv:0907.3627



- Z bosons: even rarer
  - ZEUS sees Z production in hadronic decays
  - Measured σ = 0.13±0.06 pb
    - SM prediction of σ = 0.16 pb
  - Leptonic decays of Zs not observed in searches at both H1 and ZEUS

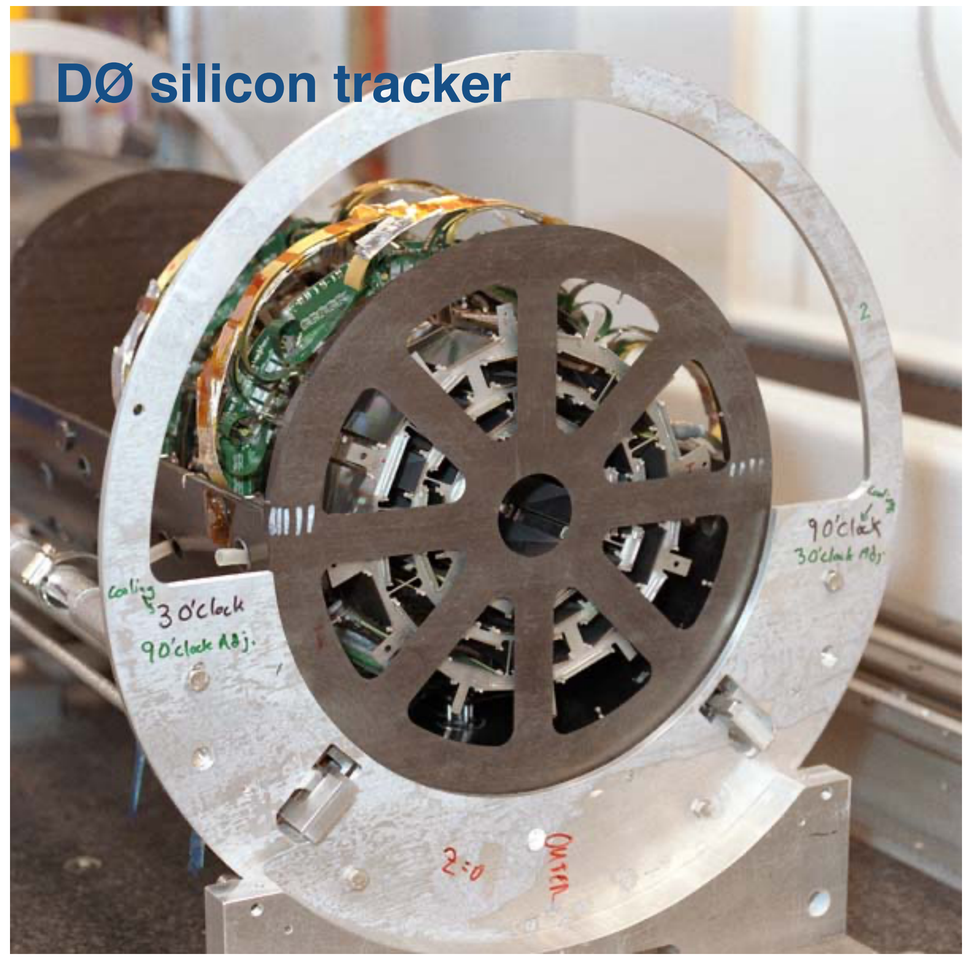


PLB **718**, 915 (2013)
arXiv:1210.5511

Tevatron Run II

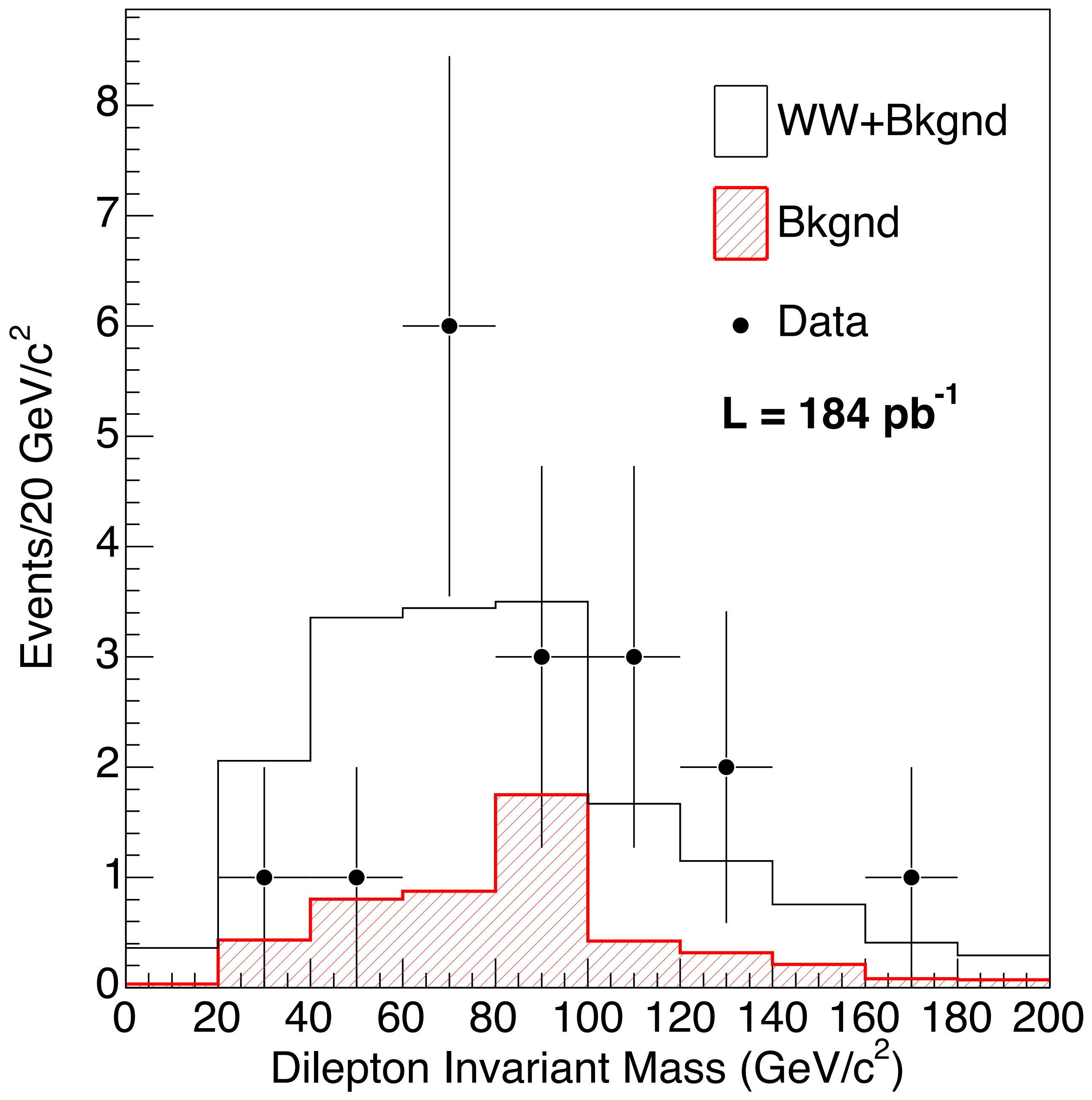
- Major upgrade after Run I ended (1996)
  - Increase in peak luminosity from 10^{30} cm^{-2} s^{-1} to over **4×10^{32} cm^{-2} s^{-1}**
  - Increase of beam energy from 900 GeV to **980 GeV**
- Construction of **Main Injector**
  - New 150 GeV accelerator stage
  - Essential in increase in luminosity
  - Still used at Fermilab for neutrino experiments
- Significant upgrades to both CDF and DØ
  - e.g. upgraded trackers and triggers
  - Solenoid magnet in DØ
- Run II delivered data from **2001-2011**
  - **12 fb^{-1}** to each experiment

Main Injector



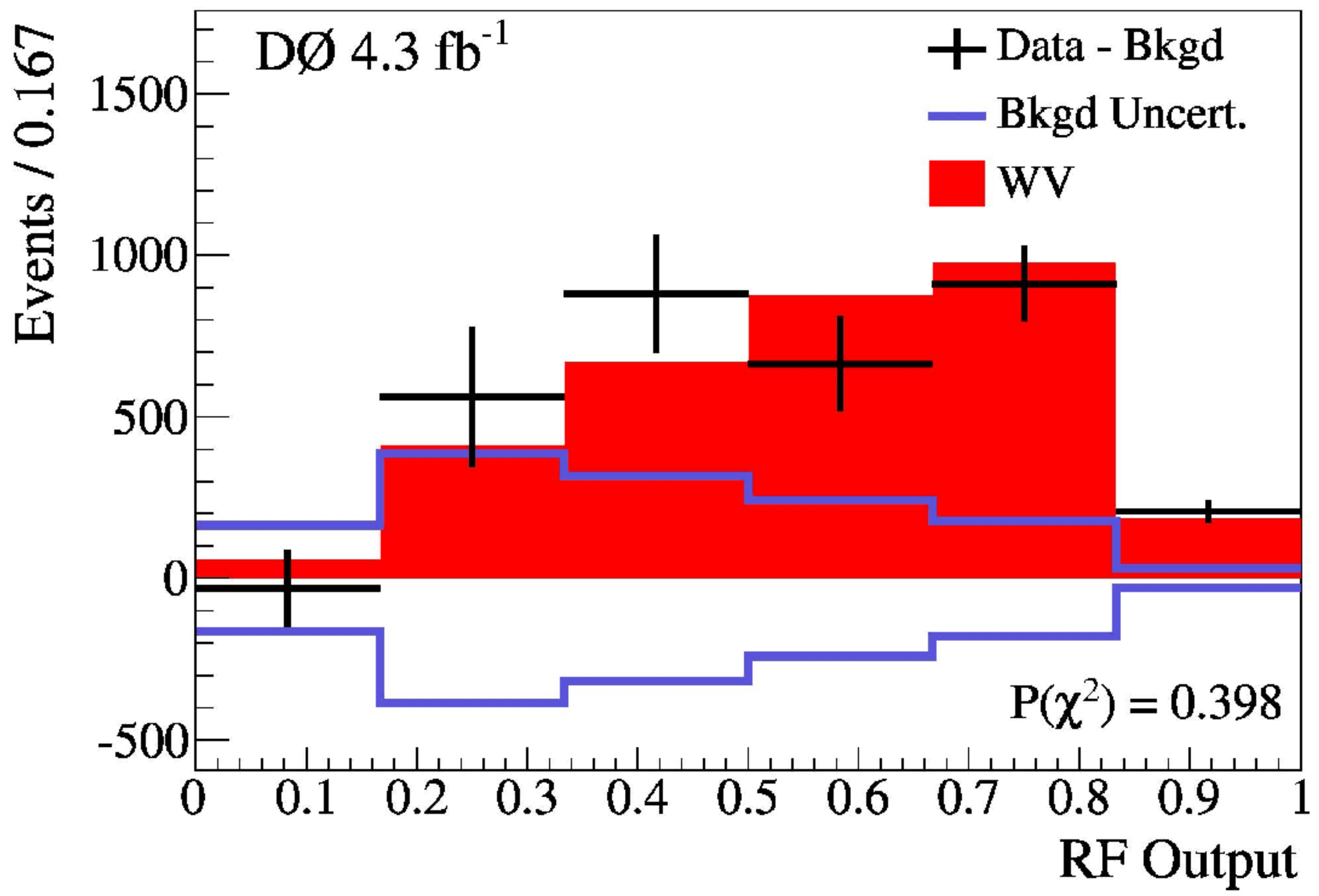
Vector boson pairs

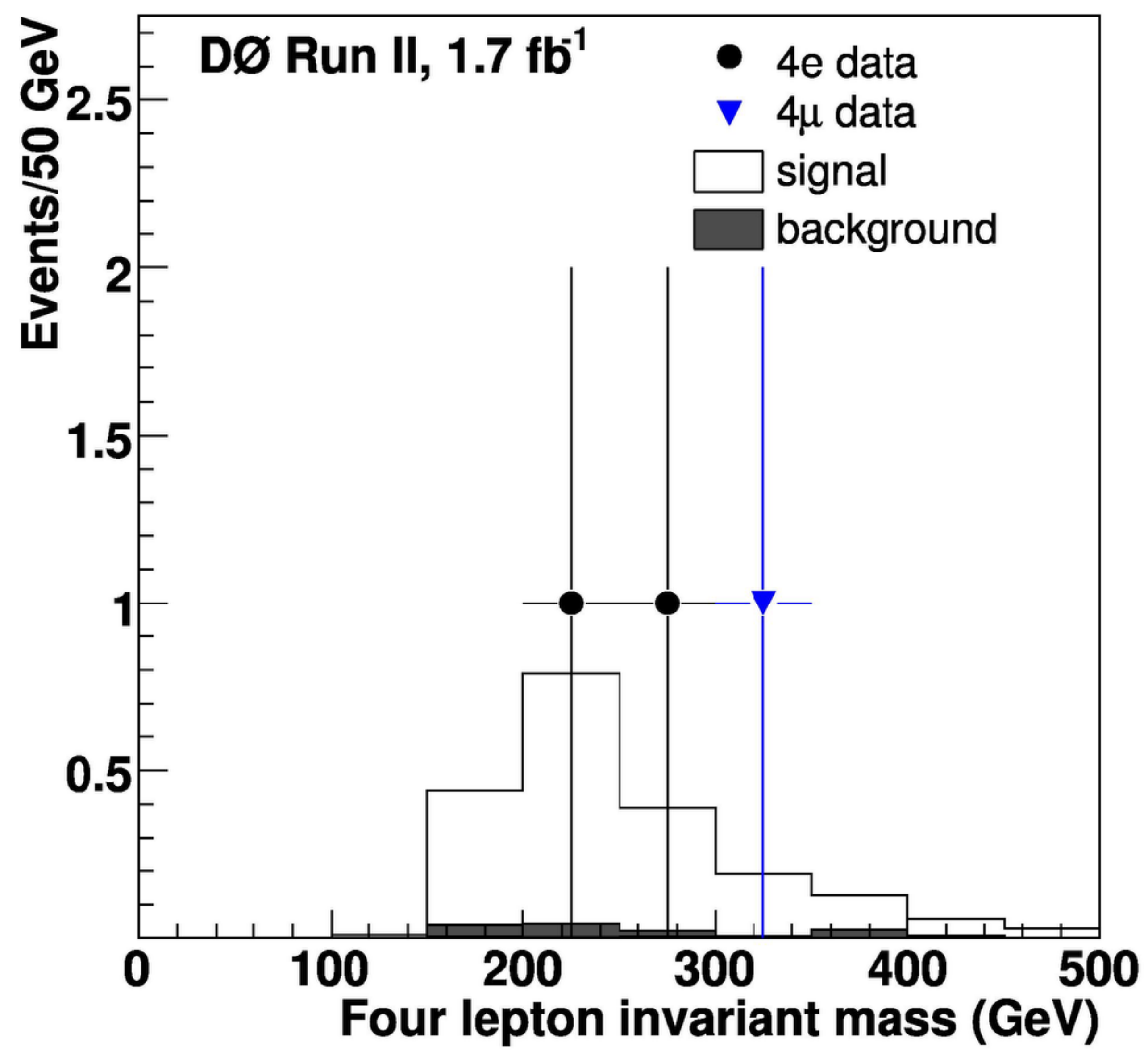
- Vector boson pairs: WW, WZ, ZZ
  - Critical test of standard model and probe for potential new physics
  - Run II dataset enabled measurement
    - Only evidence seen for WW in Run I
  - Crucial backgrounds for Higgs boson searches
  - Provides validation of theoretical calculations



CDF WW observation (leptonic)
PRL **94** 211801 (2005)
hep-ex/0501050

DØ WW+WZ observation (W+jets final state)
PRL **108,** 181803 (2012)
arXiv:1112.0536





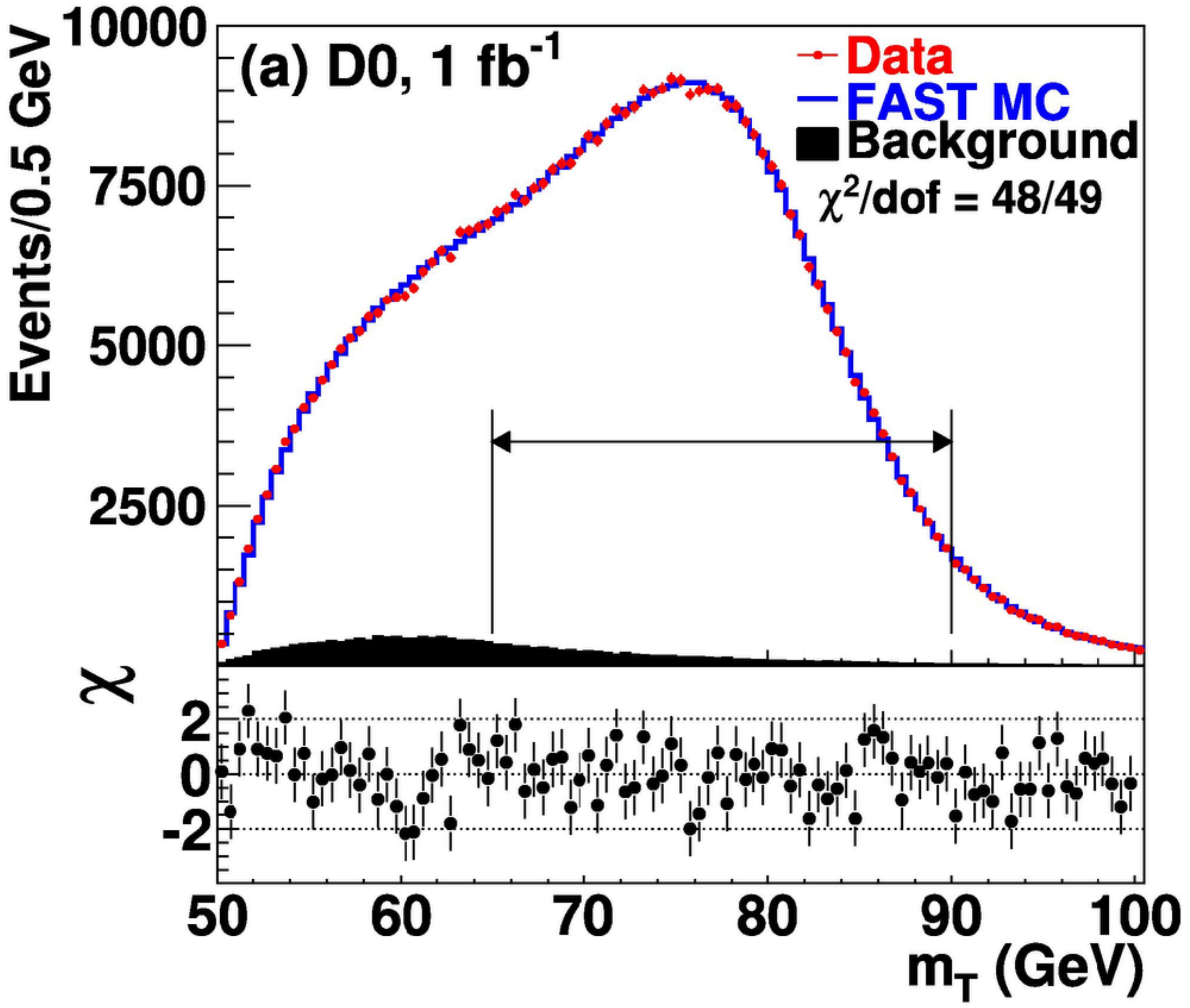
DØ ZZ observation (leptonic)
PRL **101,** 171803 (2008)
arXiv:0808.0703

Fermilab

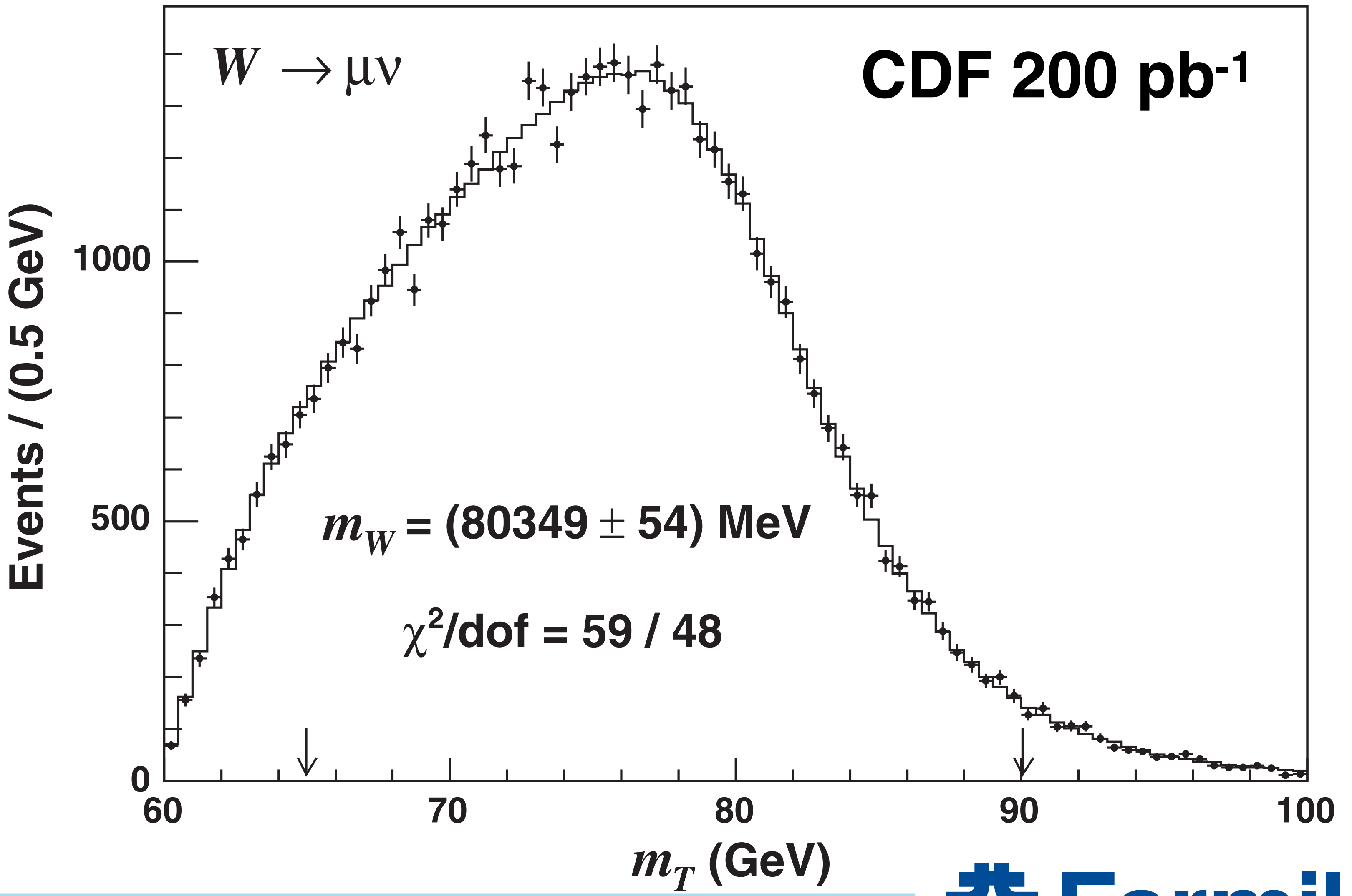
W boson mass: towards unprecedented precision

- LEP set the standard by 2004
  - Uncertainty: 33 MeV combined (51 MeV single best)
- CDF/DØ goals
  - Exceed single best LEP measurement
    - ~0.2 fb^{-1} CDF, ~1 fb^{-1} DØ
  - Exceed world average with single measurement
    - ~2 fb^{-1} CDF, ~5 fb^{-1} DØ

PRL **103** 141801 (2009)



PRL **99** 151801 (2007)



First Run II measurements

80413 ± 48 MeV (CDF, 2006)

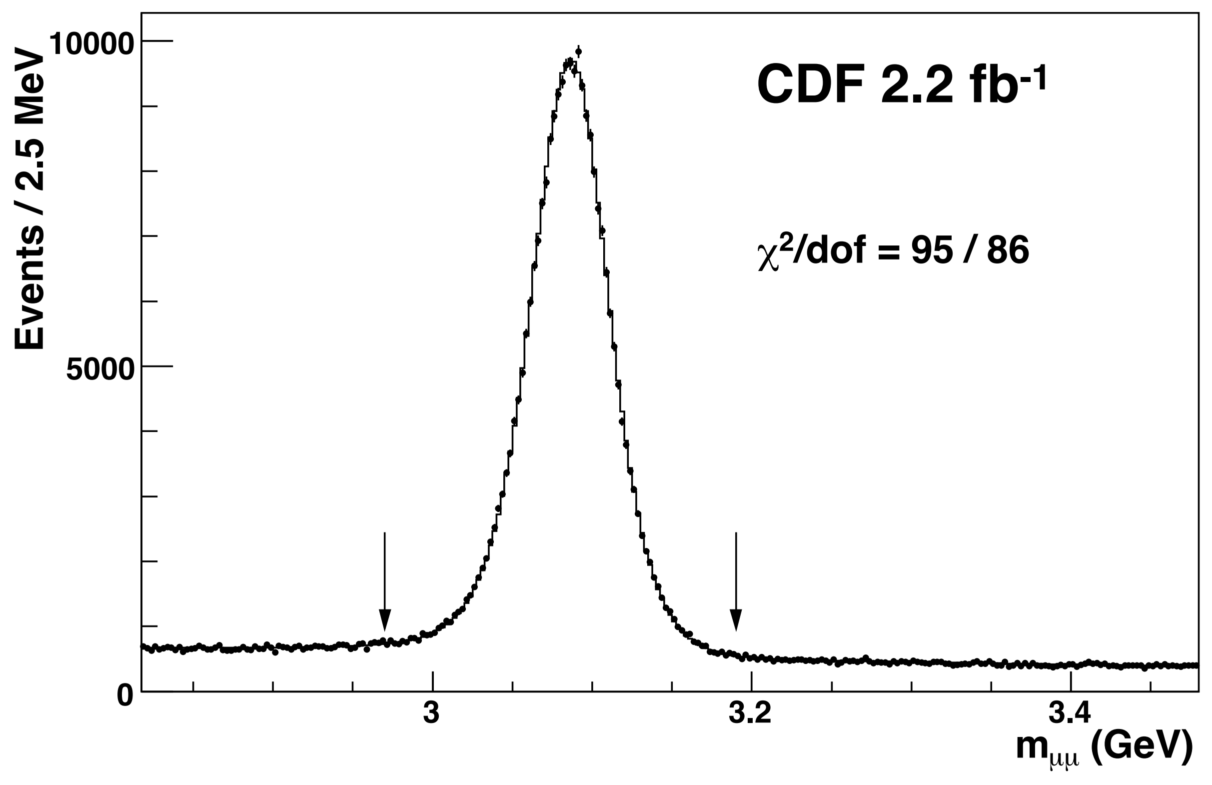
80401 ± 43 MeV (DØ, 2009)

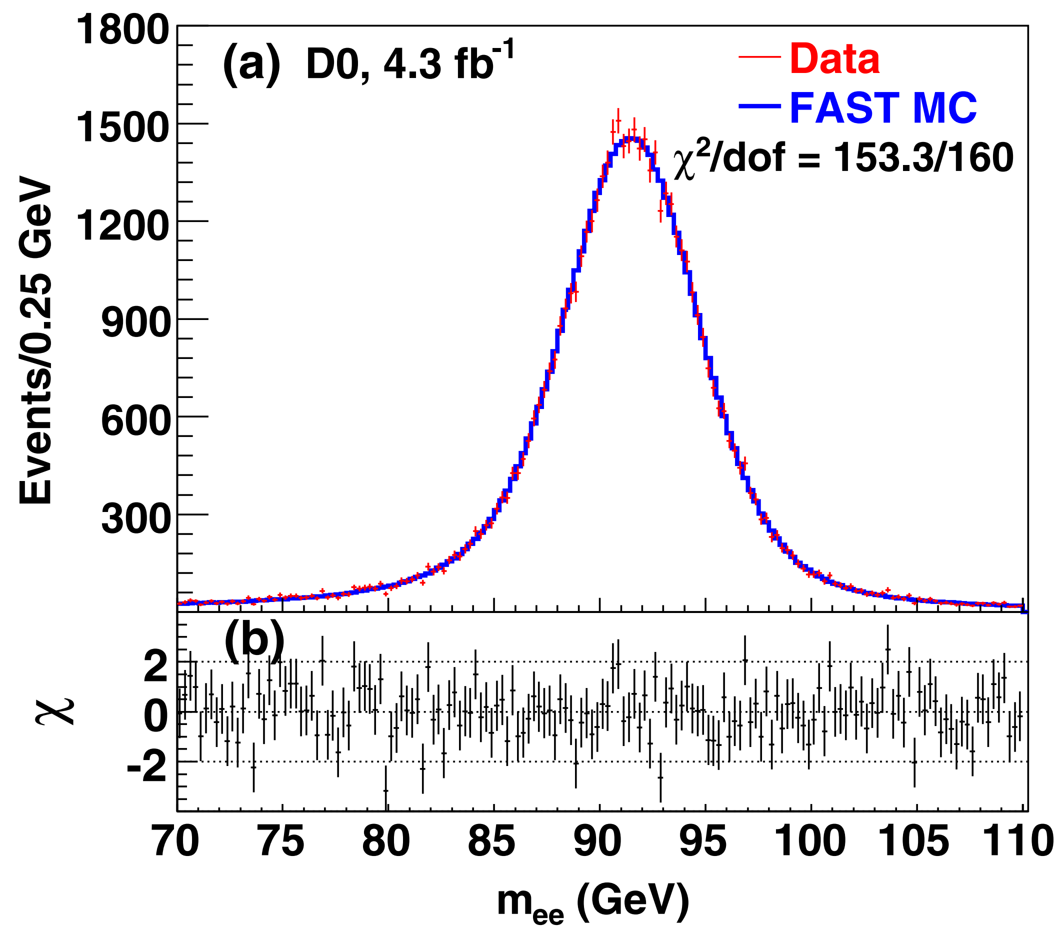
nb. CDF e+μ, DØ e only

W boson mass: achieving unprecedented precision

Calibrating with well-known resonances:

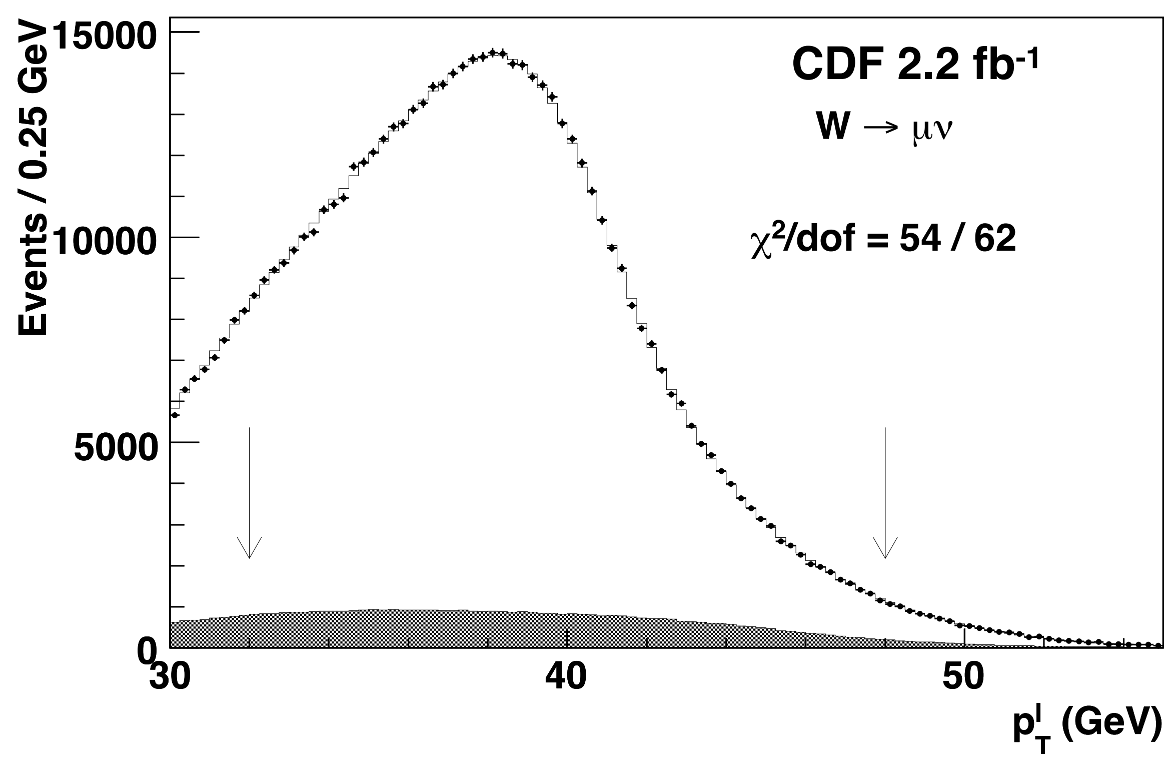
J/ψ,Υ, Z at CDF; Z at DØ

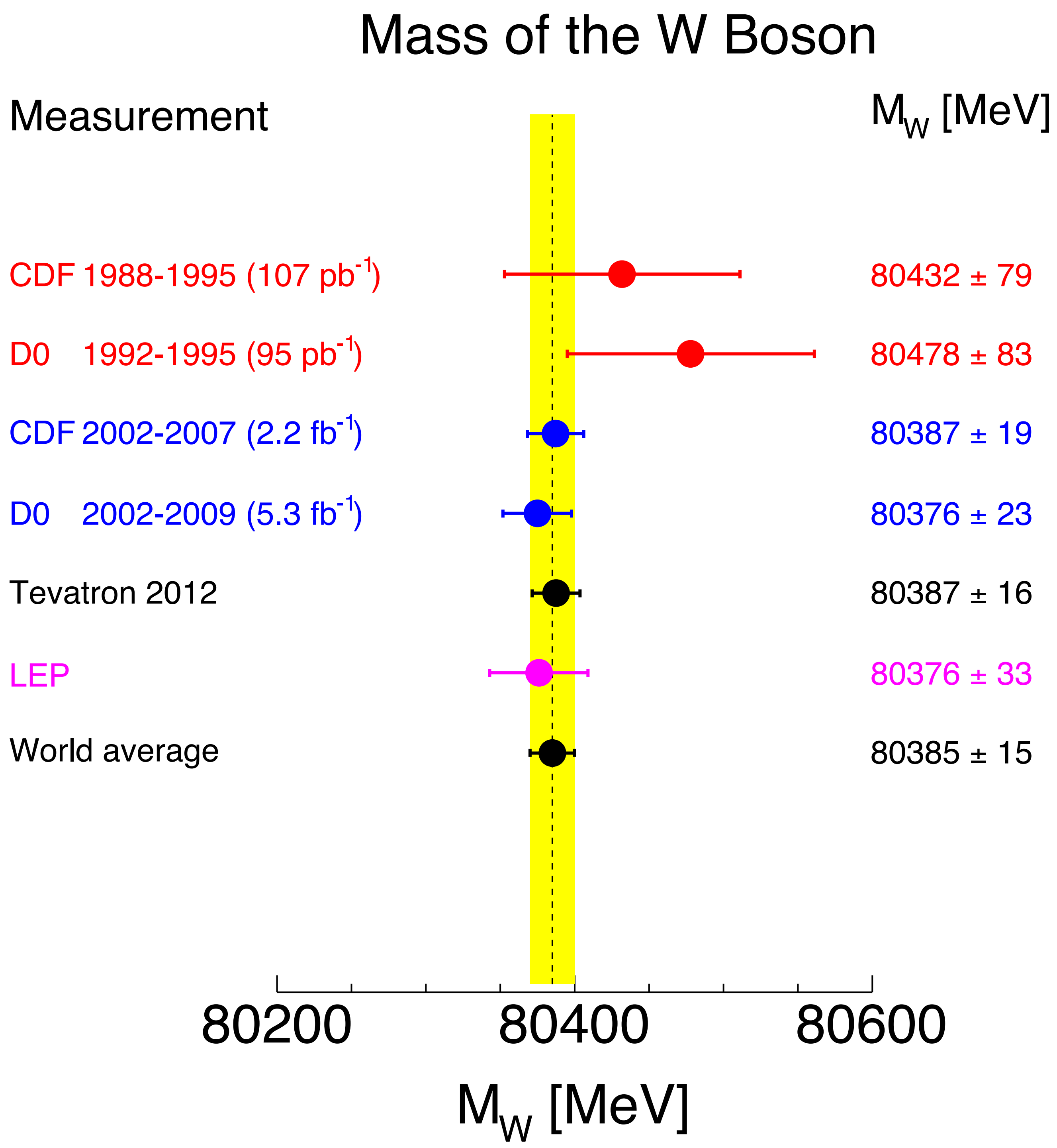


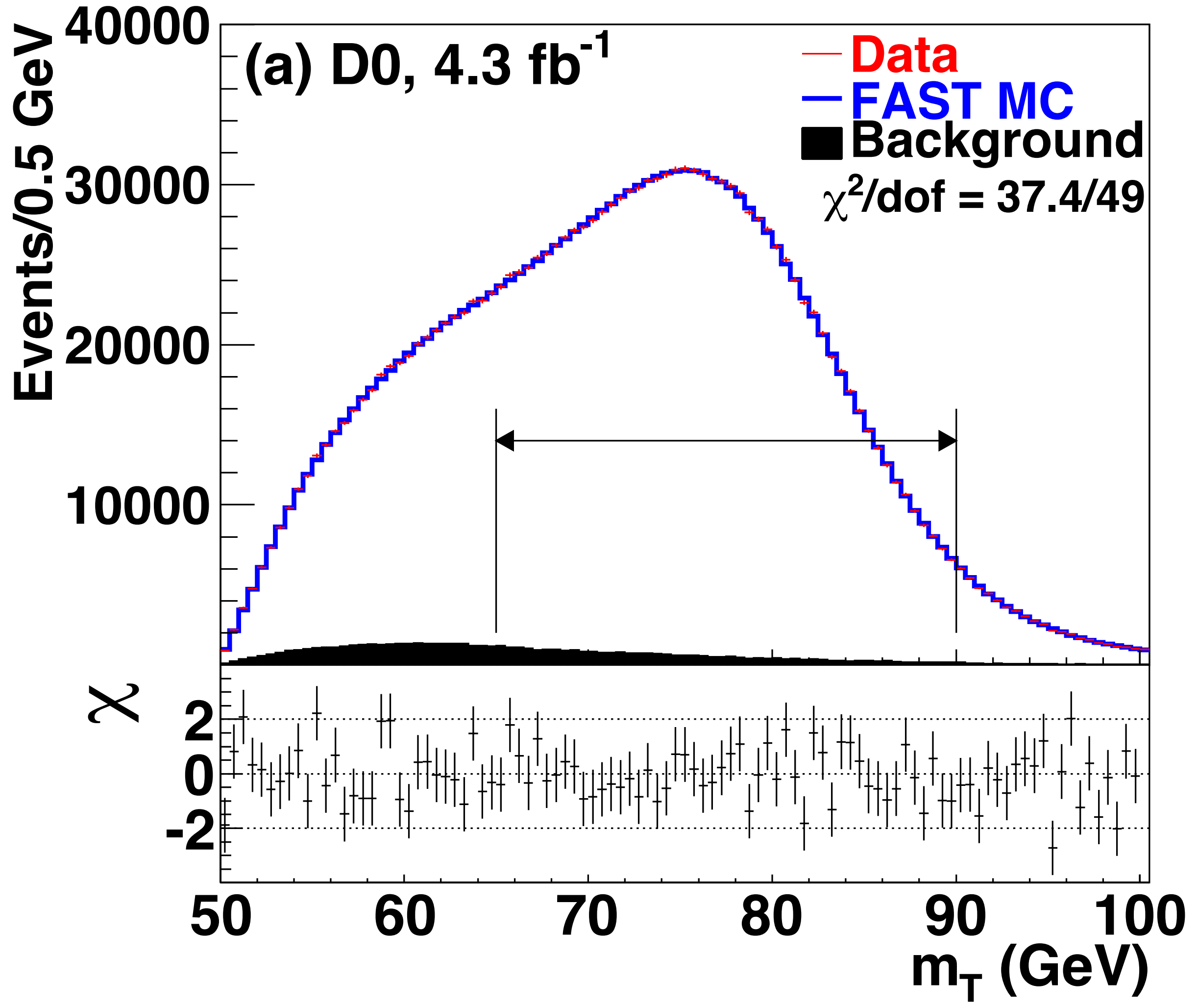


Fits to m_T, lepton p_T, missing p_T,

Combined for final result

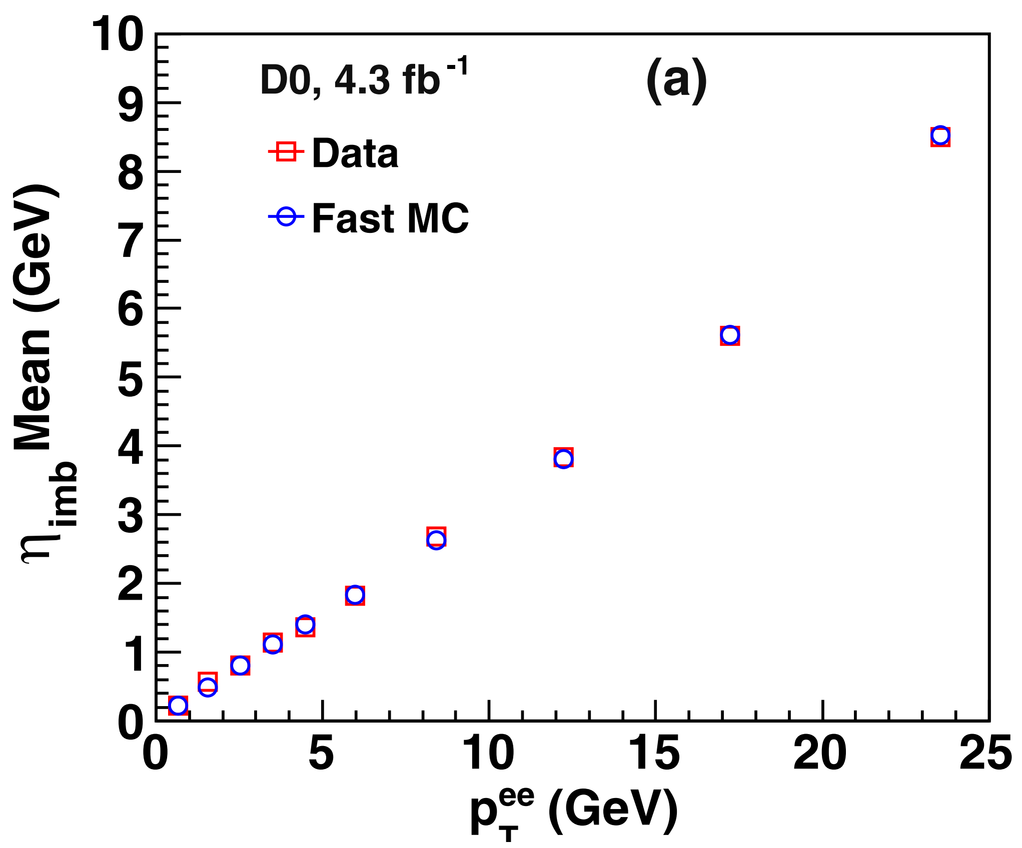


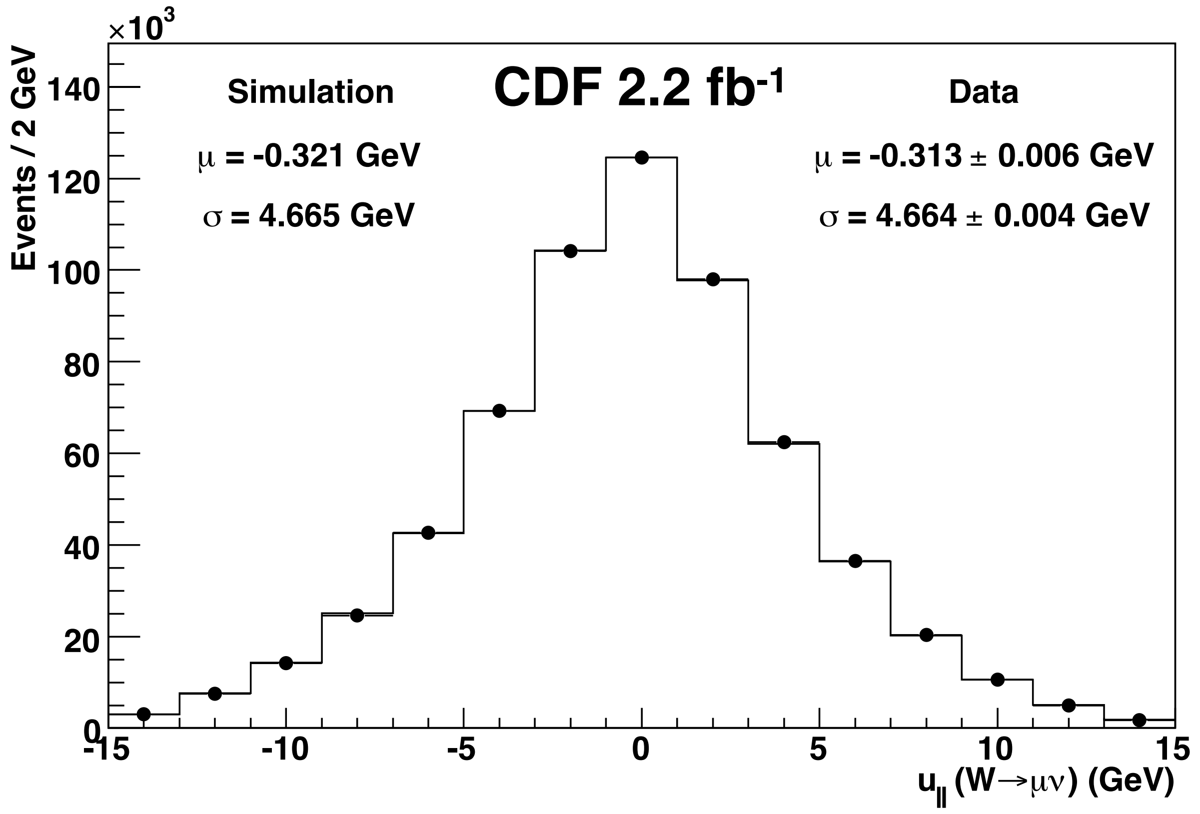




CDF: PRD **89**, 072003 (2014)
DØ: PRD **89**, 012005 (2014)
CDF+DØ: PRD **88**, 052018 (2013)

Calibrating hadronic recoil with Z, validate with W

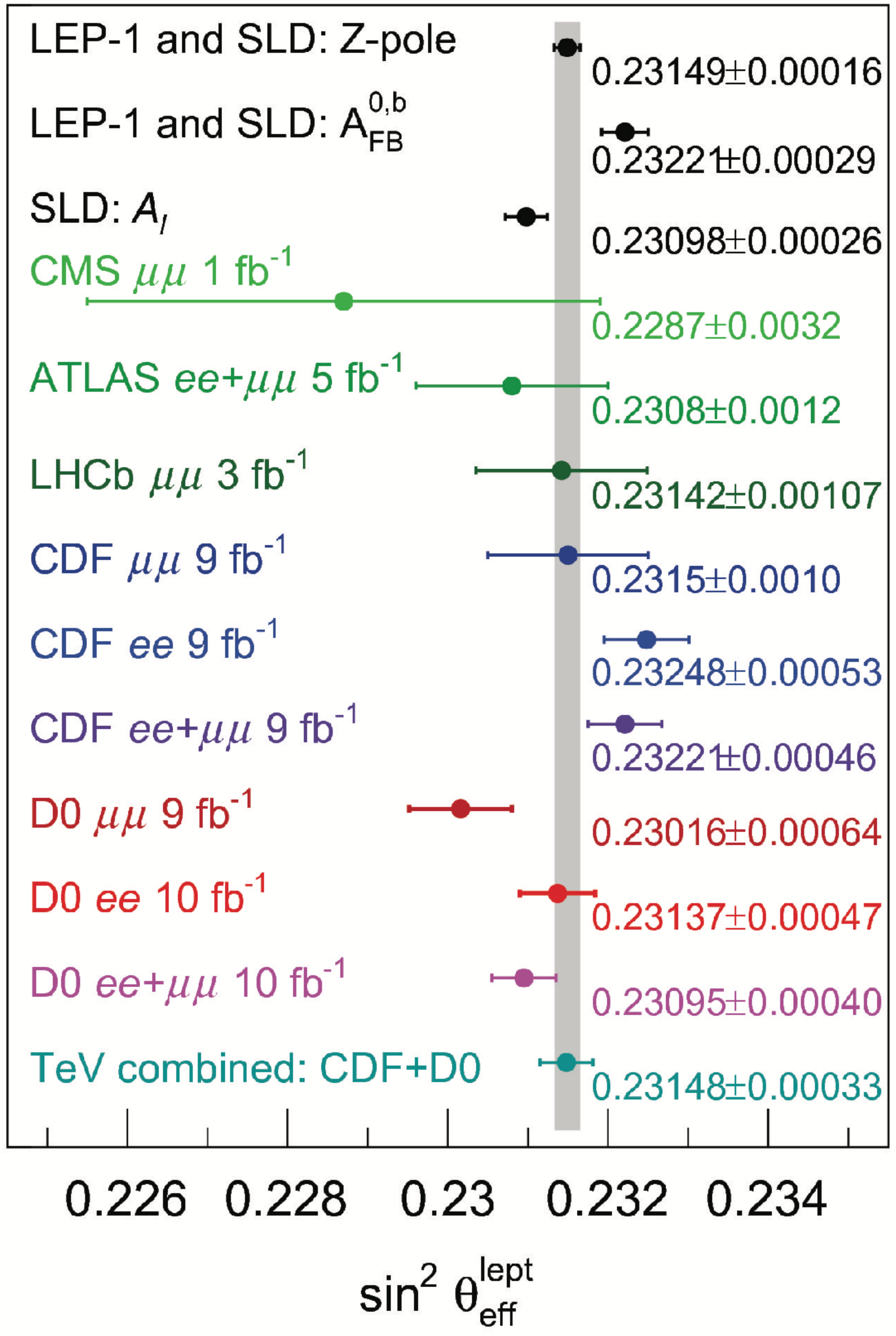




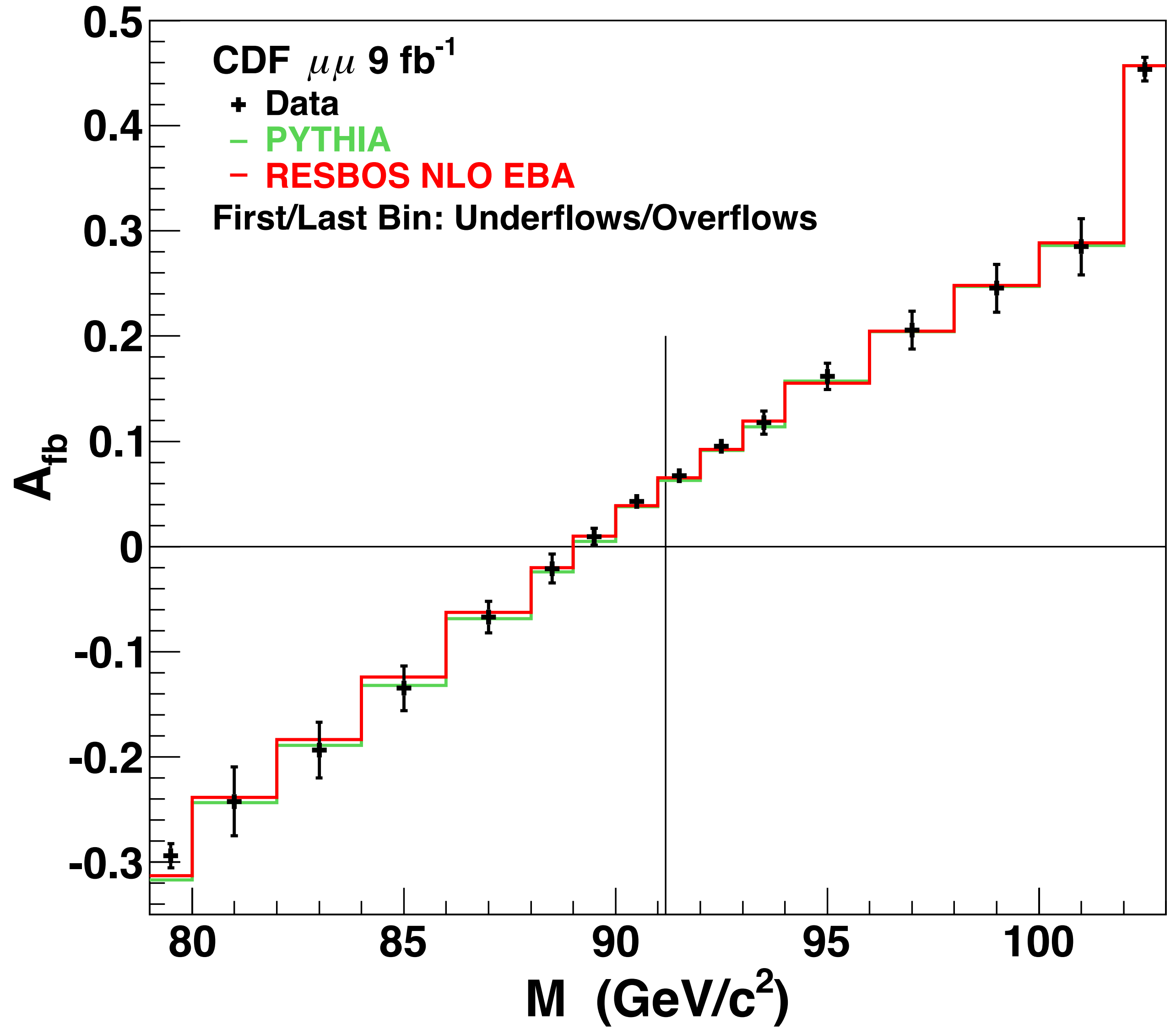
Forward-backward asymmetry: measuring $\sin^2\theta_W$

- Indirect measurement of weak mixing angle
  - Obtain from angular distribution of leptons in Z decays
  - Extract **forward-backward asymmetry** (A_{FB})
  - Measure $A_{FB} \rightarrow \sin^2\theta_{eff}^{lep} \rightarrow \sin^2\theta_W$
    - Can also obtain indirect measurement of M_W
- CDF+DØ: most precise determination at hadron colliders!

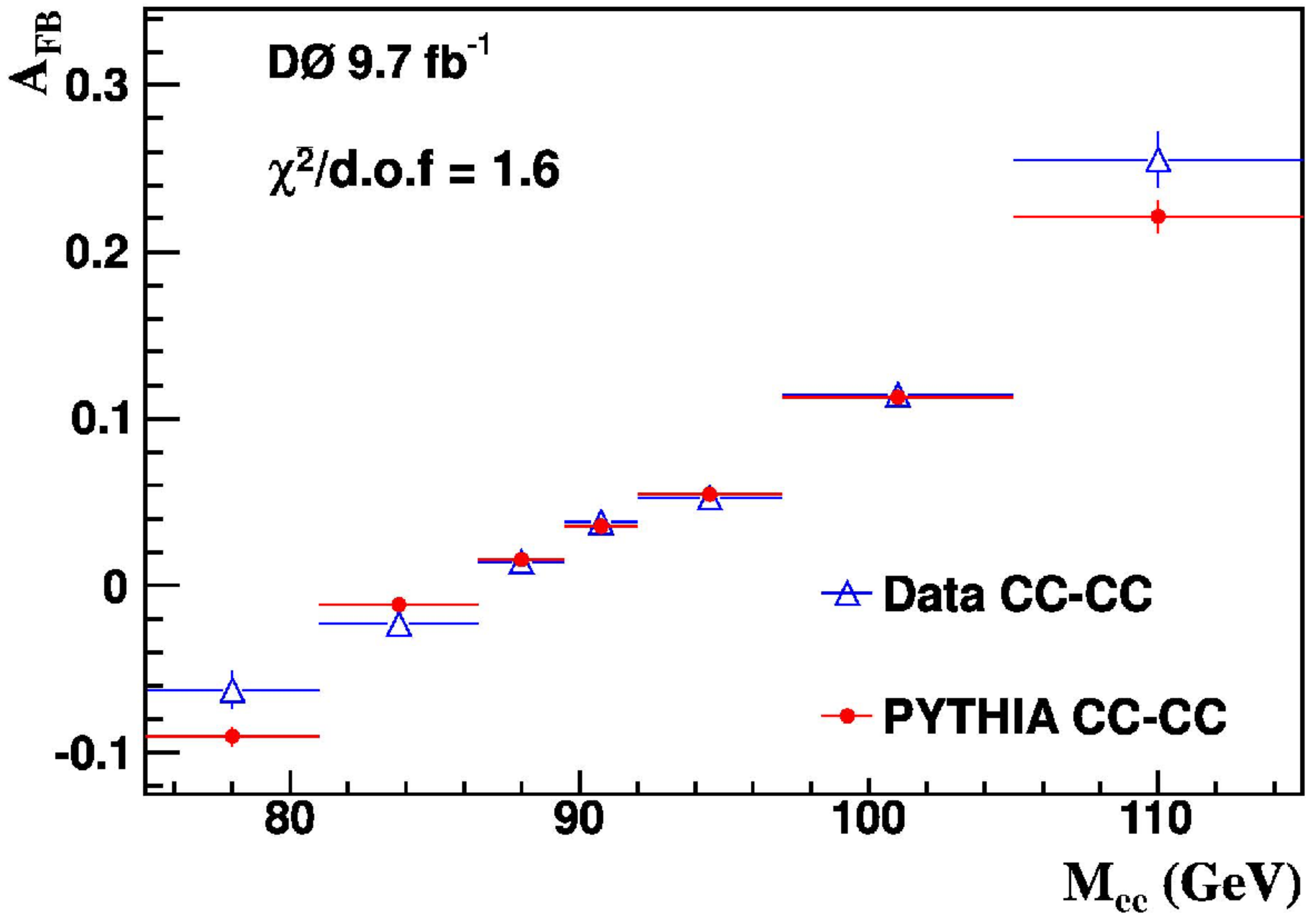
PRD **97**, 112007 (2018)



PRD **89**, 072005 (2014)



PRL **115**, 041801 (2015)



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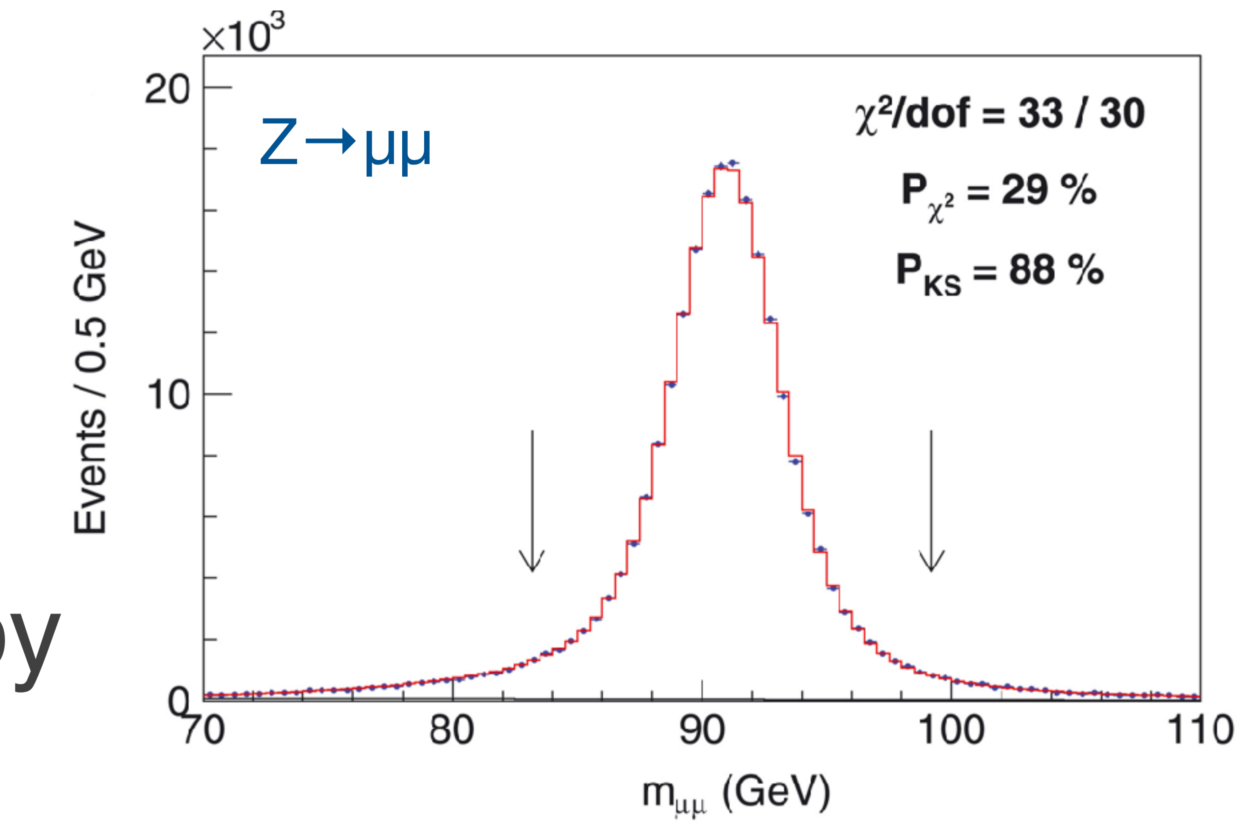
W boson mass: one final surprise?

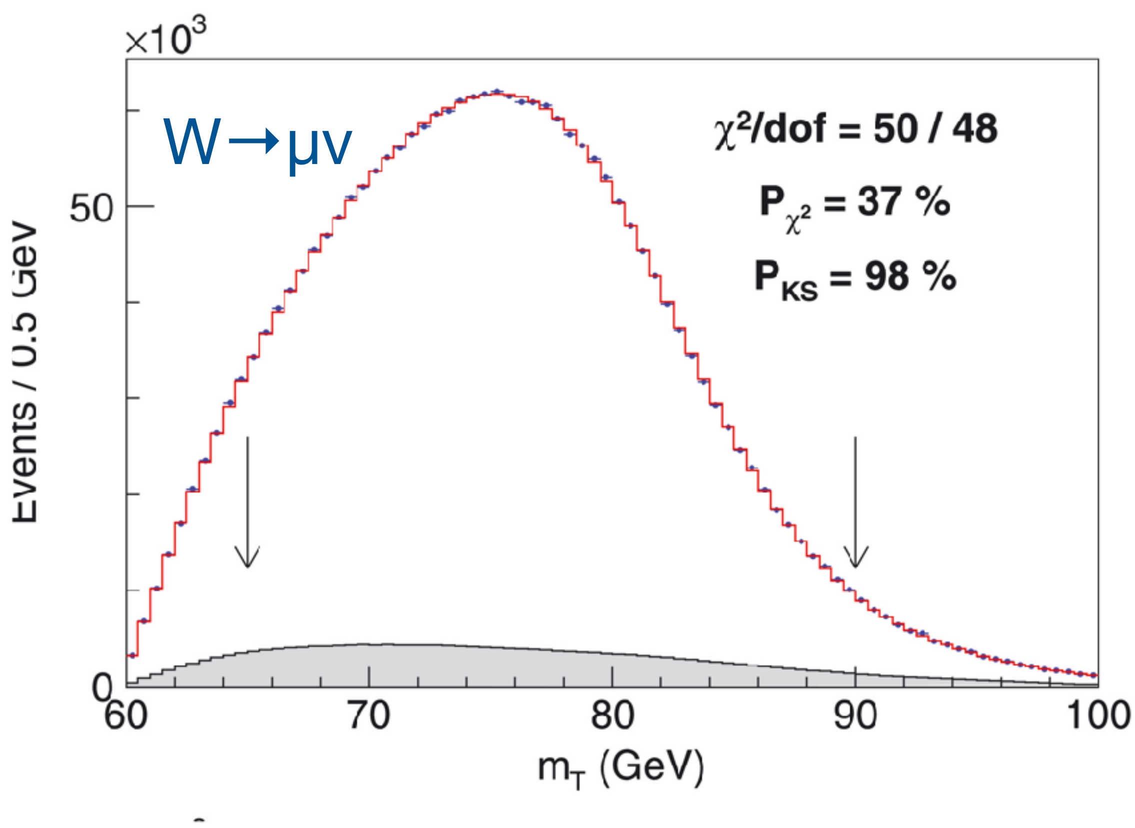
- CDF goal with the **full** Tevatron dataset
  - Once again exceed world average precision
  - < 10 MeV total uncertainty
    - Nearly every systematic uncertainty constrained by data

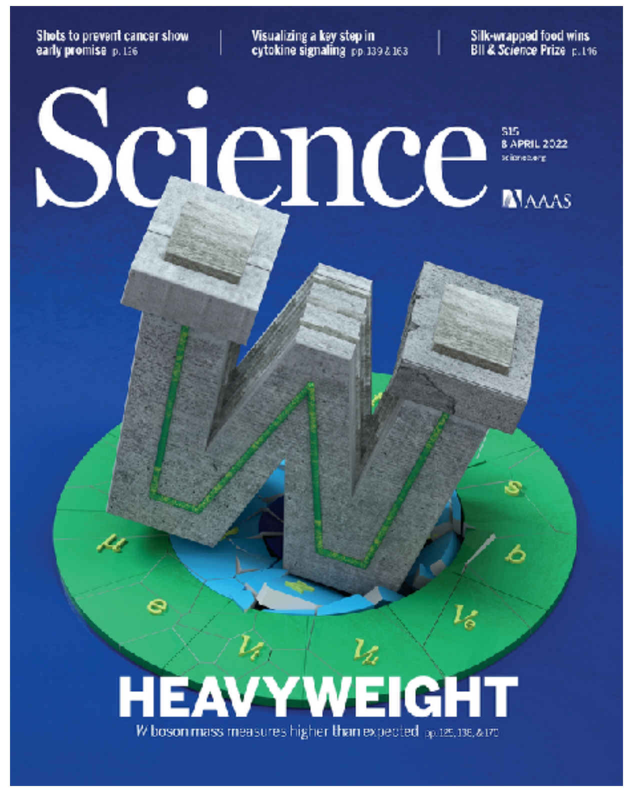
- Powerful validation: independent Z mass
  - $M_Z = 91192.0 \pm 7.5$ MeV (muons)
    - Single most precise hadron collider measurement!

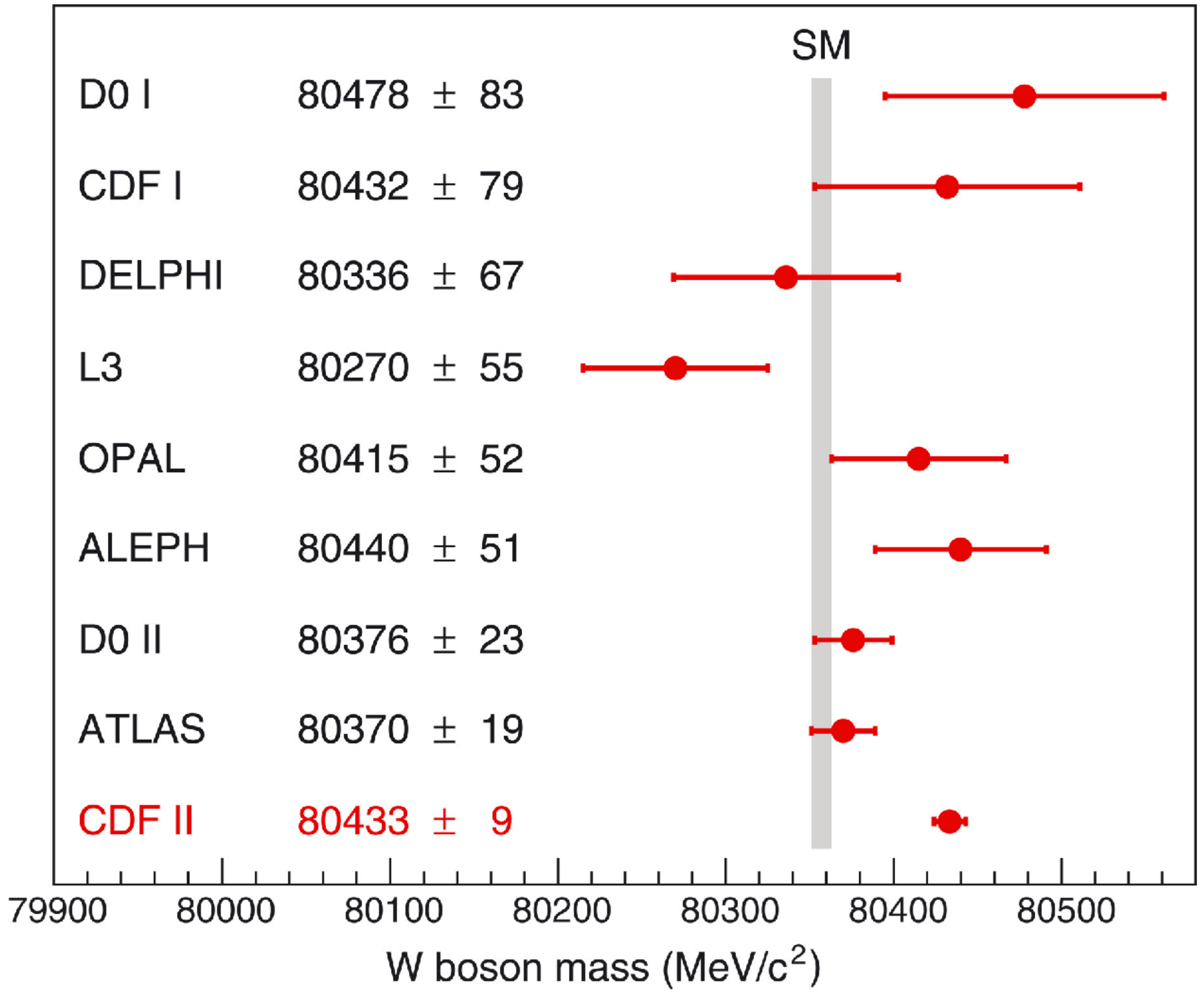
- **$M_W = 80433.5 \pm 9.4$ MeV**
  - Significant tension with SM prediction!

Science **376**, 170 (2022)









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Conclusions

- The Tevatron
  - Hadron collider discovery frontier after SppS
    - Highest energy collider in the world from 1985 to 2009
  - Pushed the boundaries of precision physics at a hadron collider

- HERA
  - First ever electron-proton collider
  - Precision probe of parton structure: unique test of electroweak physics

- Foundation for the next generation
  - Expertise from both sets of experiments crucial for LHC physics program
  - See next talks!

Many thanks

- To CERN and the organizers of this symposium
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