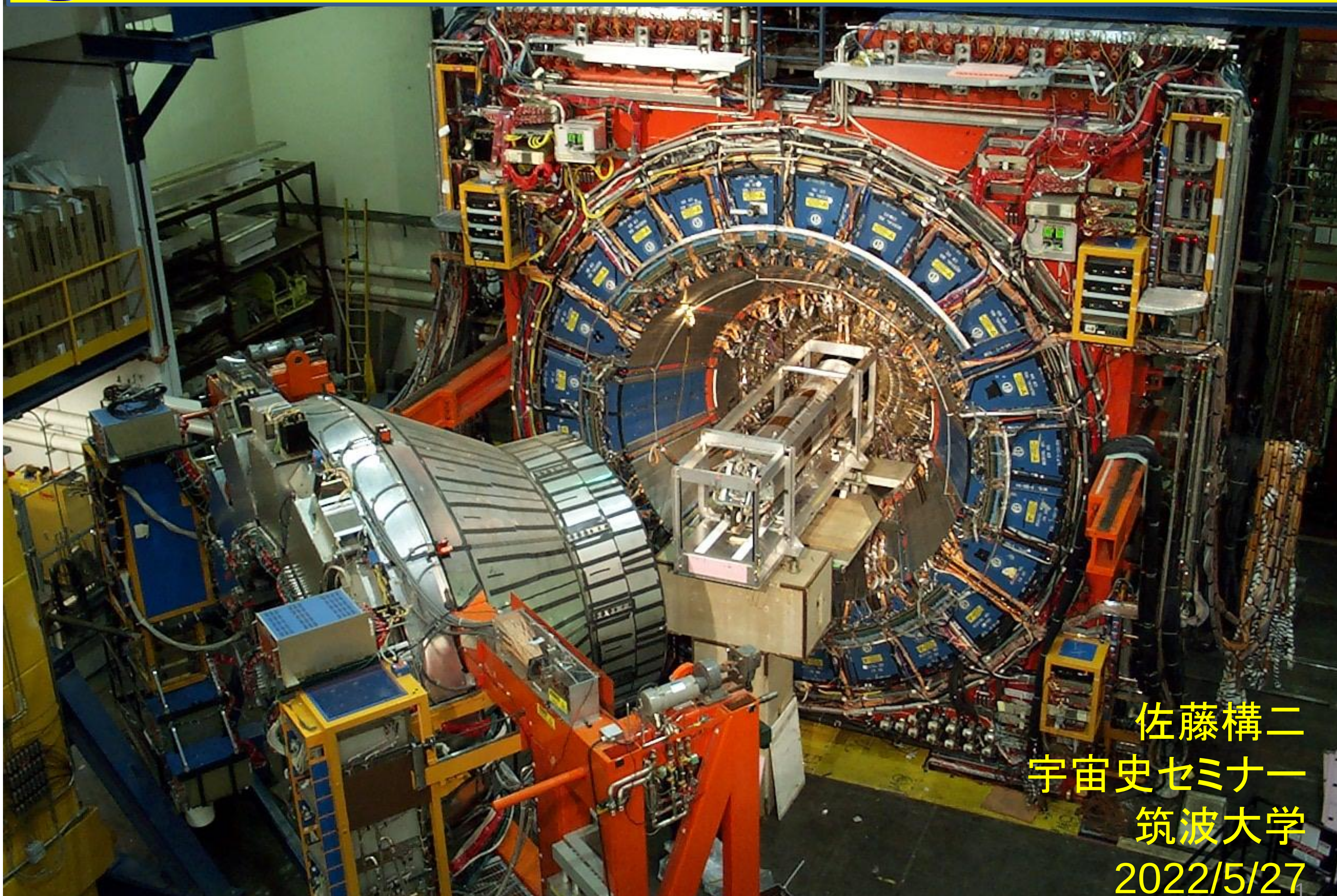
CDF実験でのWボソン質量の精密測定



佐藤構二
宇宙史セミナー
筑波大学
2022/5/27

- CDF実験が、2022年4月8日にWボソン質量の測定をアップデートした。
- T.Aaltonen *et.al* [CDF Collaboration], “High-precision measurement of the W boson mass with the CDF II detector”, *Science* 376 (2022) 6589, 170-176

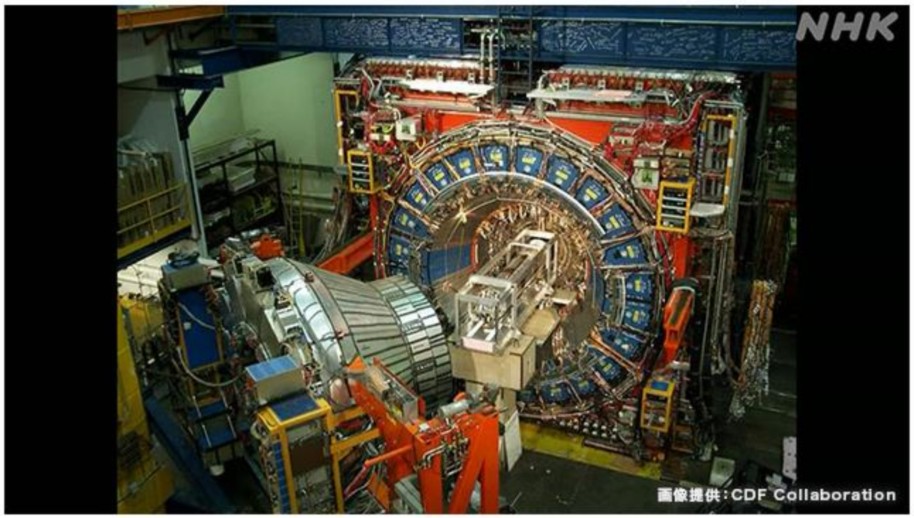
新聞やテレビでも報道された

NHK おうちで学ぼう！ for School 新型コロナ ニュース

NEWS WEB 天気 動画 News Up 特集 スペシャルコンテ

新着 | 社会 | 気象・災害 | 科学・文化 | 政治 | ビジネス | 国際 | スポーツ | 暮らし | 地域

注目ワード ウクライナ情勢 知床観光船沈没 新型コロナウイルス 新型コロナ 国内感染者数



素粒子Wボソンの質量 予測より大きく「標準理論」修正迫るか

2022年4月25日 6時13分

物質を構成する基本的な粒子である素粒子の1つについて、実験から解析された質量が予測より大きいという結果が得られたことを筑波大学などの国際的な研究グループが発表し、素粒子物理学の柱となっている「標準理論」の修正を迫る可能性があるとしてさらなる検証が必要だとしています。

「標準理論」は現在の素粒子物理学の柱となっている理論で、素粒子の種類や質量などの特性を説明できるとされています。

筑波大学の受川史彦教授などの国際的な研究グループは、力を伝えるWボソンと呼ばれる素粒子についてアメリカの研究機関で行った実験データを解析したところ、質量が標準理論の予測より0.09%ほど大きいという結果が得られたということです。

誤差は0.01%とこれまでで最も高い精度で解析しているため、「標準理論」の修正を迫る可能性があり、さらなる検証が必要だとしています。

今回の結果について、一部の研究者から新たな素粒子が存在すれば説明ができるとする論文が発表されるなど議論を巻き起こしています。

研究グループに参加する受川教授は「標準理論を超える何かがあるかもしれない可能性が出てきたことに興奮を覚えている。それが何なのかを見極めることが非常に重要だと考える」と話しています。

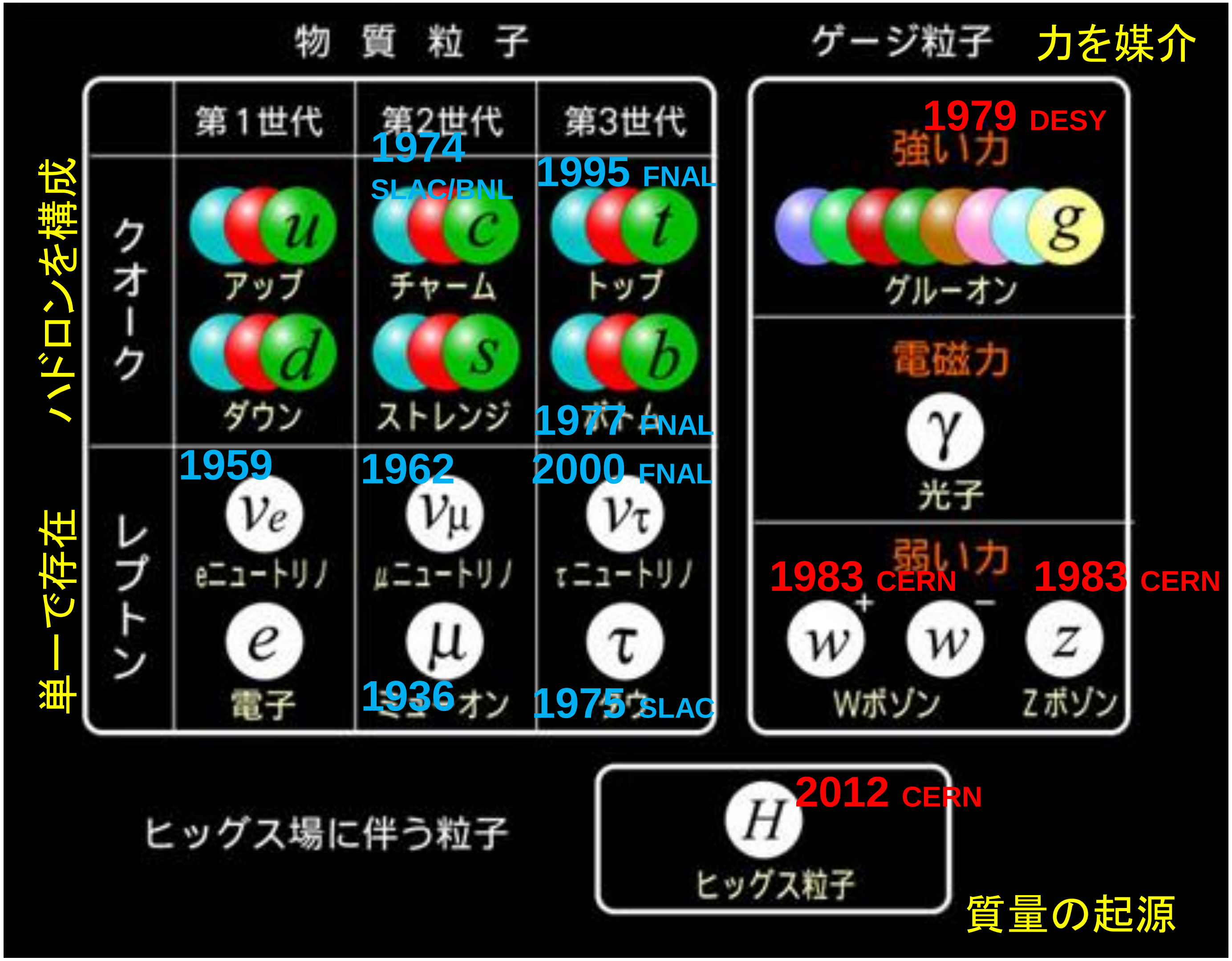
内容

– 重い標準理論粒子の質量測定の状況
– なぜWボソン質量測定は重要か
– Wボソン質量の測定の現状
– Tevatron加速器運転のエピソードをいくつか
– CDFによる最新のWボソン質量測定

– T.Aaltonen *et.al* [CDF Collaboration], “High-precision measurement of the W boson mass with the CDF II detector”, *Science* 376 (2022) 6589, 170-176

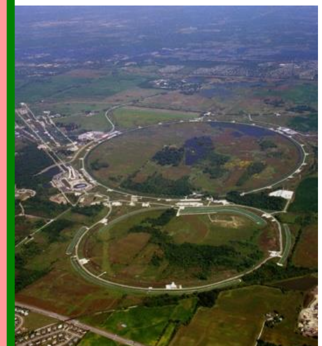
標準理論の粒子発見の歴史

- 青：アメリカで発見、 赤：ヨーロッパで発見。



1980年代以降の最高エネルギー加速器

Tevatron
$p\bar{p}$
1.8-1.96 TeV
Fermilab
USA
CDF実験
米国シカゴ郊外



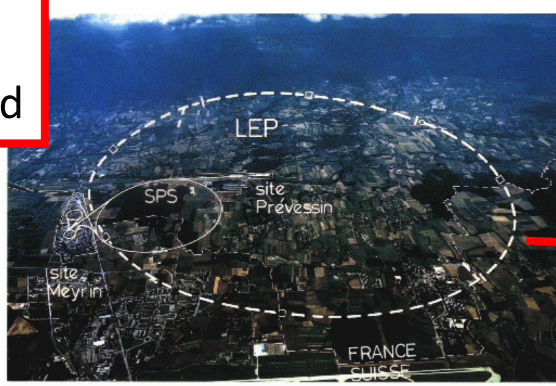
*W/Z*ボソン発見

トップクォーク発見

ヒッグス粒子発見

1985 1990 1995 2000 2005 2010 2015 2020

SppS
$p\bar{p}$
630 GeV
CERN
Switzerland



LEP
e^+e^-
91-209 GeV
CERN
Switzerland

LHC
pp
7-14 TeV
CERN
Switzerland
ATLAS実験
スイス
ジュネーブ郊外

World Averages of Heavy Particle Masses

Prog. Theor. Exp. Phys.2020, 083C01 (2020) and 2021 update

	Mass (GeV/c^2)		Precision	Contributing Experiments	discovery
W	80.387	$\pm$0.016	$\pm$0.02%	LEP, Tevatron, LHC	1983
Z	91.1876	$\pm$0.0021	$\pm$0.002%	LEP	1983
top	172.76	$\pm$0.30	$\pm$0.2%	Tevatron, LHC	1995
$Higgs$	125.25	$\pm$0.17	$\pm$0.1%	LHC	2012

- Improving top quark mass is challenging, due to top quark engagement with strong interaction.
- Higgs measurement still have room for improvement, both for systematic and statistical uncertainties.

- W boson mass measurement is at $\pm$0.02% precision.
  - Measurement technique is mature, and improvement is most challenging!

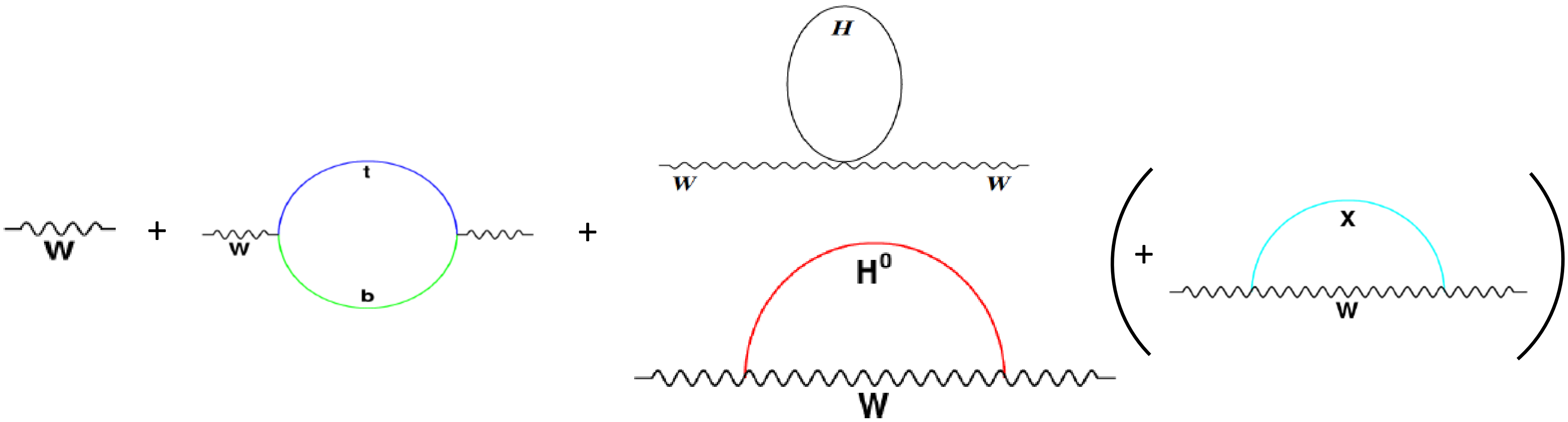
Why W mass measurement is important?

- The electroweak gauge sector of the standard model is constrained by precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\,(1) \times 10^{-5}\ \mathrm{GeV}^{-2}$
  - $M_Z = 91.1876\,(21)\ \mathrm{GeV}$
  - $m_{top} = 172.89\,(59)\ \mathrm{GeV}$
  - $M_H = 125.25\,(17)\ \mathrm{GeV}$
  - $\sin^2\theta_W = 0.2299(43)$
- M_W is related to these parameters.
  - $M_W^2 = \frac{\pi\alpha_{EM}}{\sqrt{2G_F \sin^2\theta_W}}$ (tree level)
    - θ_W : the Weinberg mixing angle, defined by

$$\cos^2\theta_W = \frac{\mathrm{M_W}}{\mathrm{M_Z}}$$

Radiative Corrections

- Radiative corrections due to heavy quark and Higgs loops (and potential undiscovered particles).

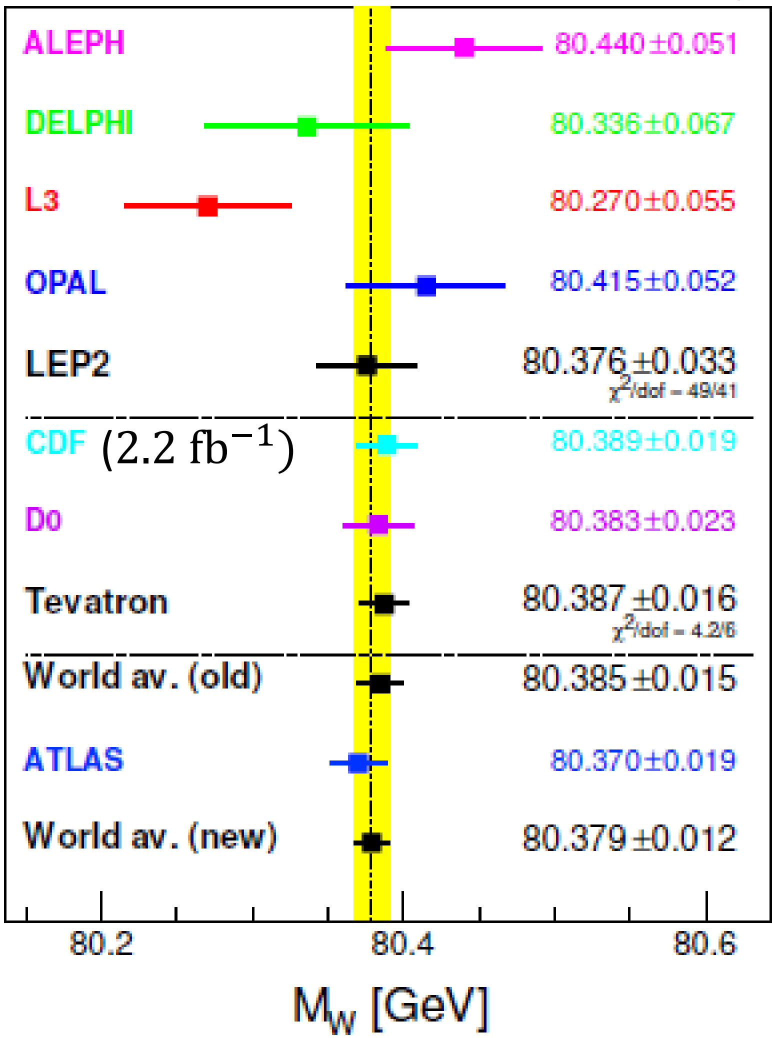


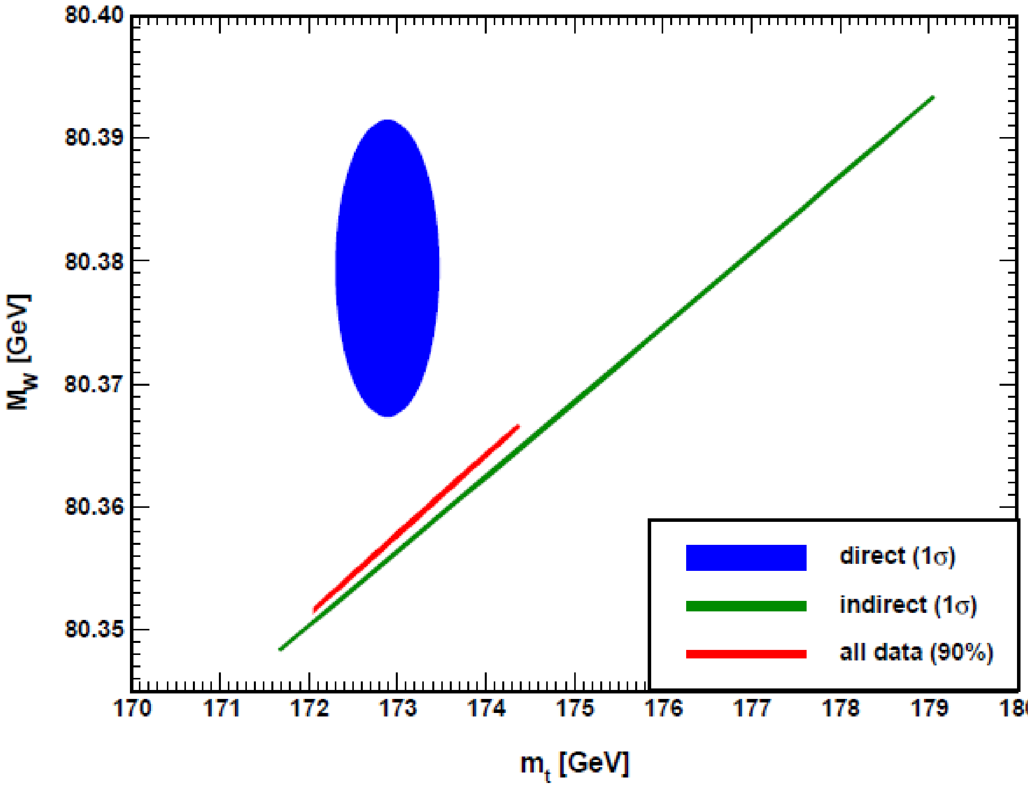
$\Delta M_W \sim M_{top}^2$ $\Delta M_W \sim \log M_{Higgs}$

- Masses of W, top and $Higgs$ are related to each other in SM.
- W boson mass is constrained by SM Global fit:
  - $M_W = 80.357 \pm 6\ \mathrm{MeV}$
    - Inputs include M_{top}, M_Z, M_H and other electroweak measured constants.

Status before 2022 CDF W Mass Update

- Prog.Theor.Exp.Phys.2020.083C01



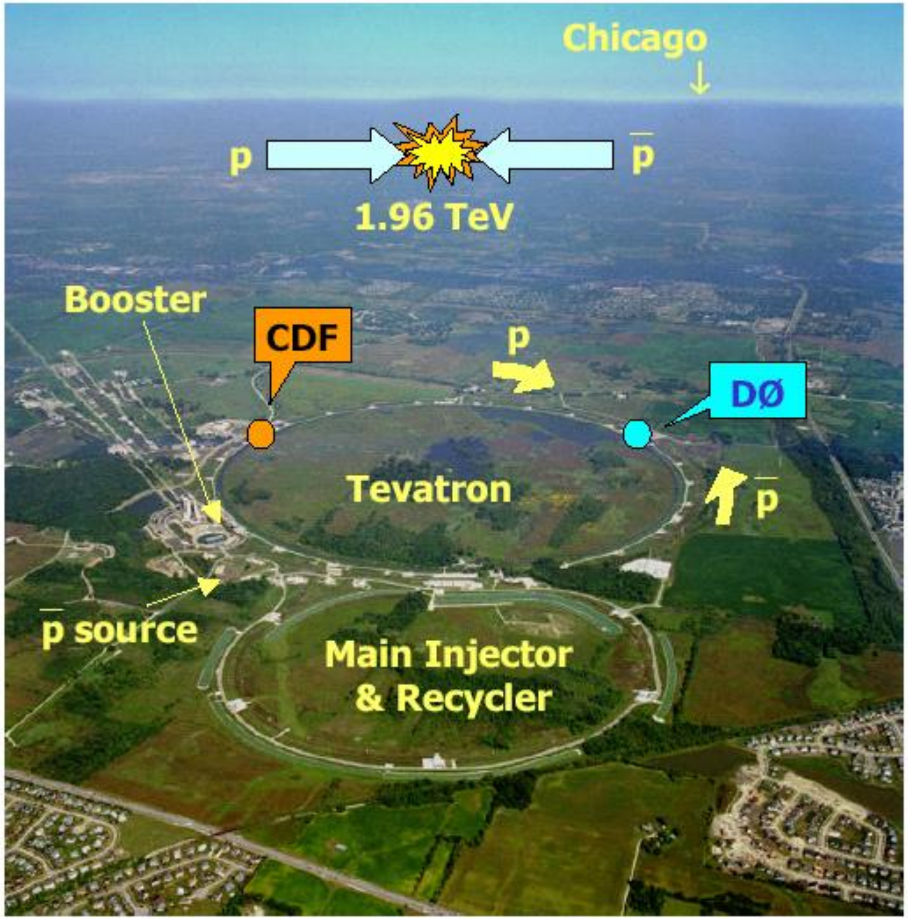


$$M_W^{Global\ fit} = 80.357 \pm 6\ \mathrm{MeV}$$

1.7σ lower than the world average

The new CDF measurement uses $8.8\ \mathrm{fb}^{-1}$ of data, $\times\ 4$ of the previous analysis.

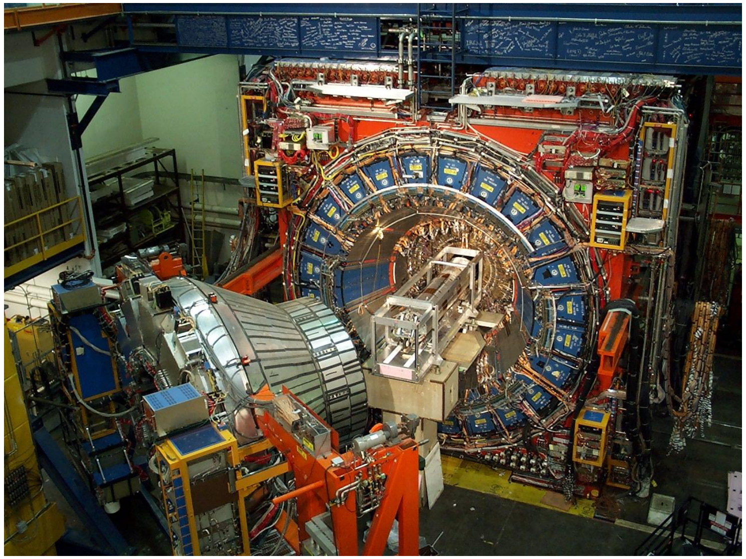
Tevatron Run II

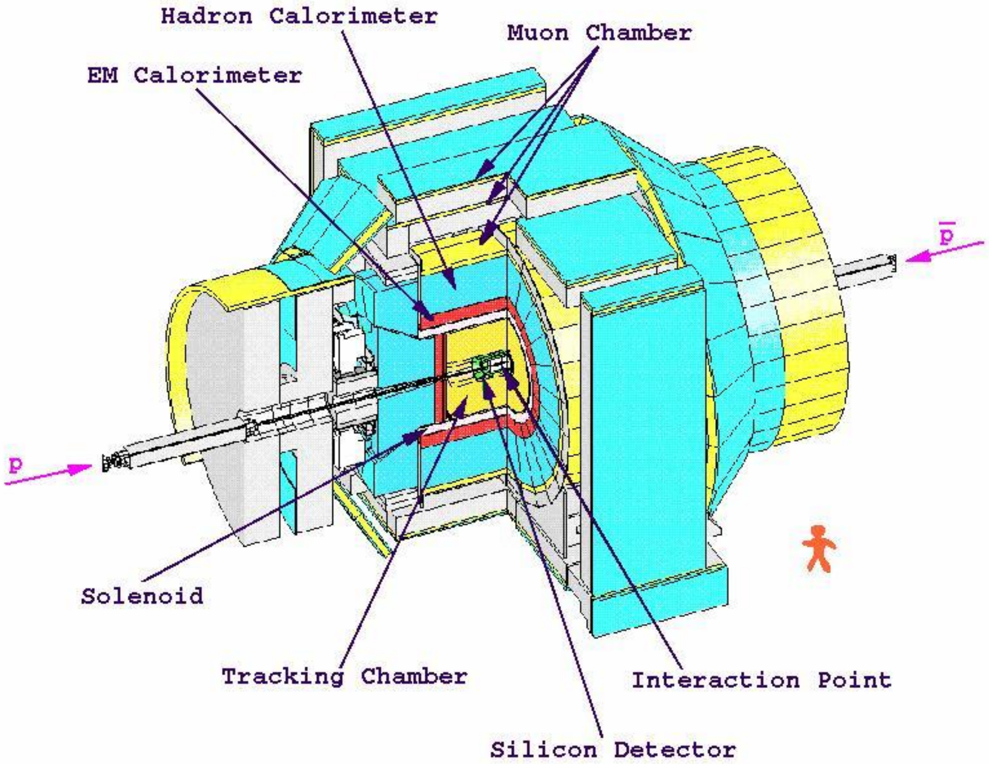


- $p\bar{p}$ collisions at √s = 1.96 TeV (1.8 TeV in Run I).
- Run II:
  Summer 2001 - Autumn 2011.
- Collisions at world highest energy until Nov 2009.
  - Energy frontier for ∼25 years!!
- Two detectors (CDF and D0) for wide range of physics studies.
- Delivered: 12 fb^{-1}.
  – Recorded by CDF: 10 fb^{-1}.
  – Recorded by D0: 10 fb^{-1}.

CDF Detector

- Multipurpose detector
  - Top/EWK measurements, Searches for Higgs and New Phenomena, and B physics.
- Precision tracking with silicon in 1.5 solenoid field.
- EM/Had calorimeters for e/γ/jet measurement.
- Outer muon chambers.

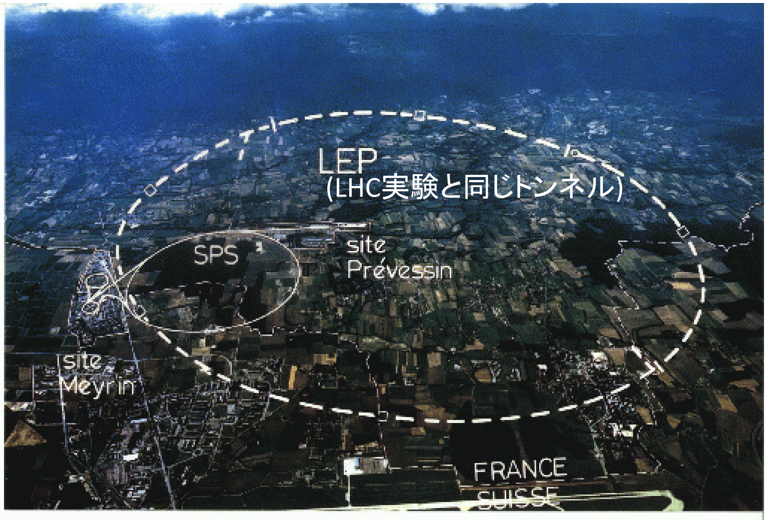


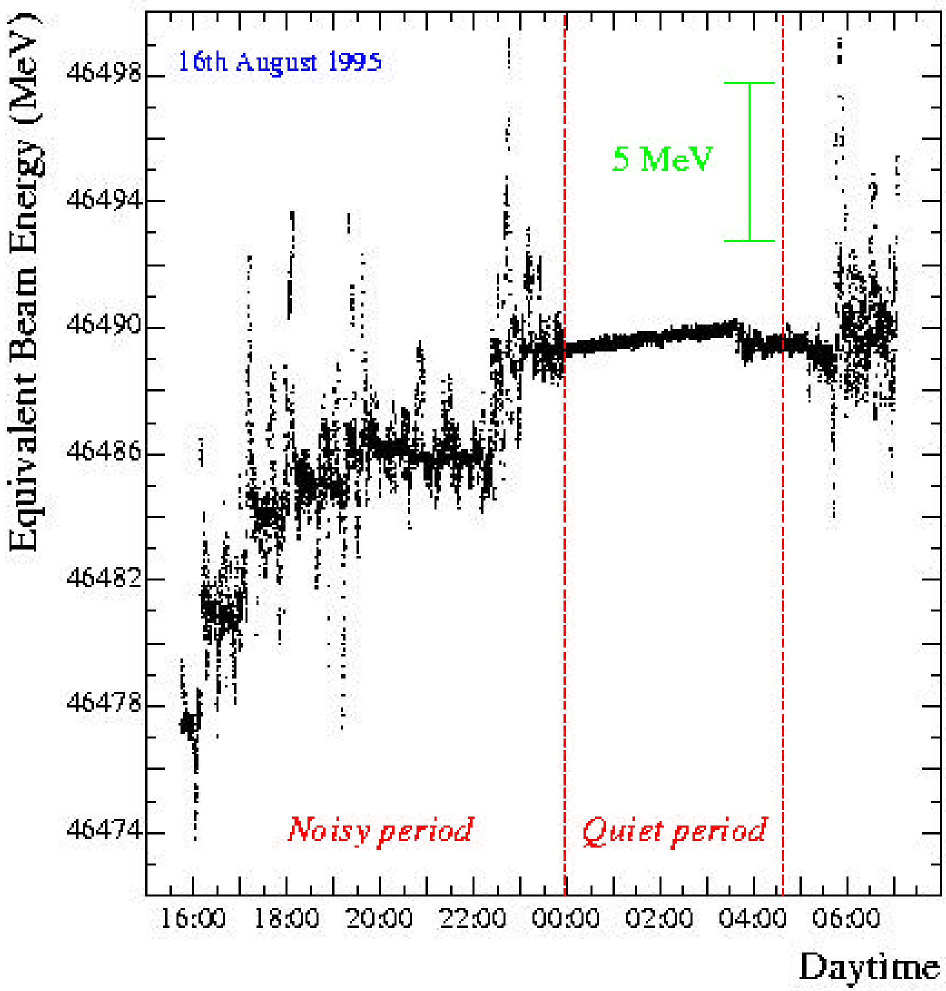


LEP実験、謎のノイズ

- LEP実験では、粒子エネルギーが安定しない問題が起きていた。

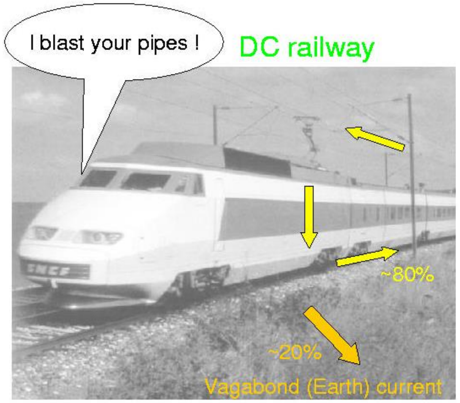
周長： 27km （c.f. 山手線周長：35km）
電子・陽電子衝突器
運転時期： 1989-2000
重心系エネルギー： 90-209 GeV
スイス、ジュネーブ郊外

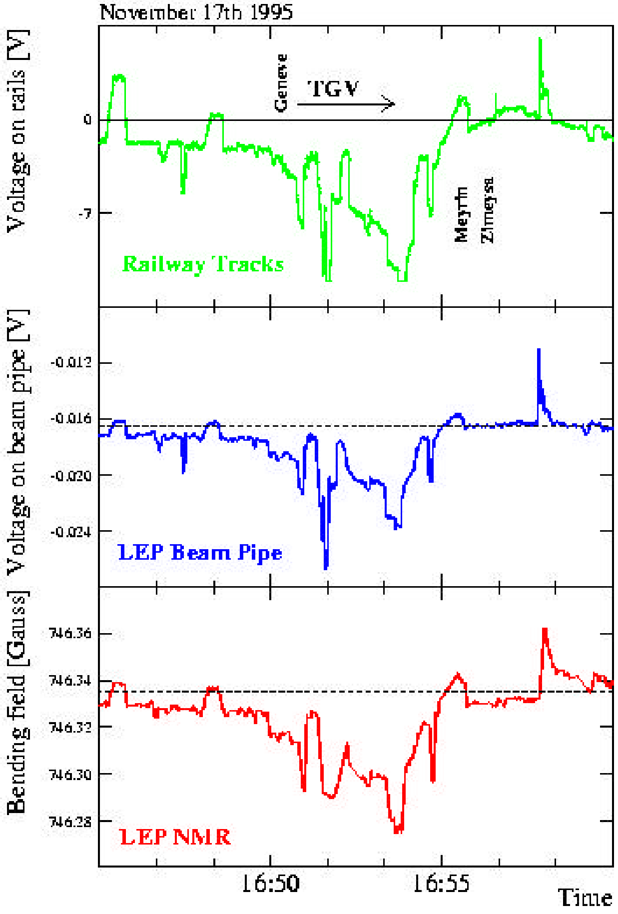


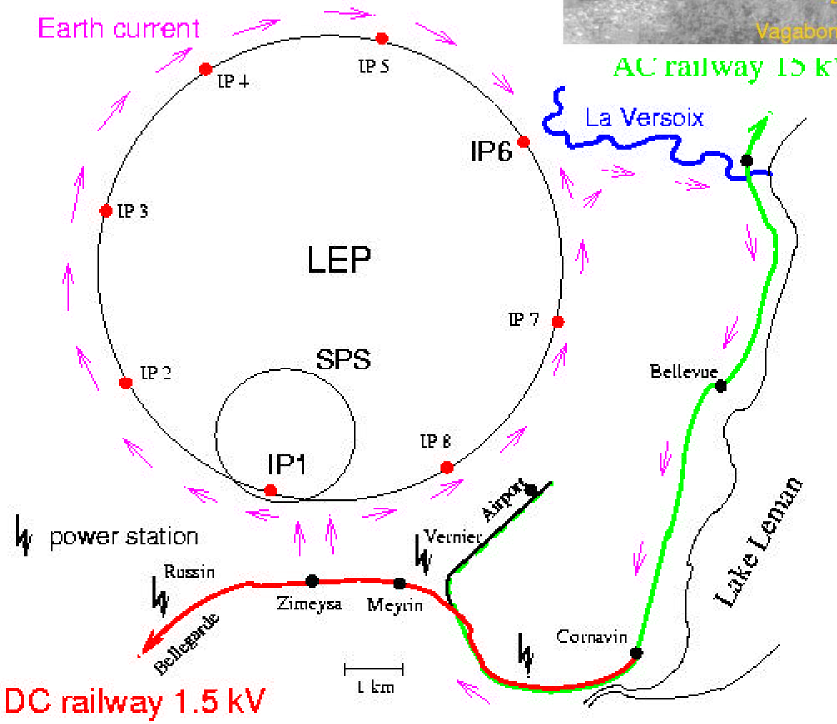


LEP実験、謎のノイズ２

- LEP実験＝ジュネーブ郊外、山手線サイズの超大型加速器
- 粒子エネルギーが安定しない問題が起きた。
- 原因は、新幹線の電流から来るノイズだった!!







テバトロン運転のあれこれ１

- サンダーストームが多いアメリカ中西部にあるTevatron。
- 落雷でビームが失われることが頻繁に起こった。

テバトロンの運転あれこれ２

Sun_Aug_5_2001_Owl.log

2001年8月5日　　加速器の運転が停止

racoon on frog farm transformer. They have disconected the power to frog farm transformer feeding NUMI. They are in the proccess of disconecting the TBM and backfeeding partial power from Pbar.

06:36:49-

2006年10月10日　　研究所全体が停電

- djinn

— *Tue Oct 10 06:39:57 comment by...djinn* — The leftmost picture shows the cause of the glitch (one crispy critter). The other 2 pictures show the aftermath. Joe Pathiyil reports that it will take at least 3 hours to repair/replace the damaged switchgear. In the meantime, they will get B0 back on for the Cryo Guys. B0 will have to go off once the repairs are complete and before they can switch D0 back into the circuit.

2016年4月　イタチがLHCを止める！

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Large Hadron Collider: Weasel causes shutdown

29 April 2016

The Large Hadron Collider is the world's most powerful particle accelerator

The Large Hadron Collider particle accelerator at Cern is offline after a short circuit - caused by a weasel.

The unfortunate creature did not survive the encounter with a high-voltage transformer at the site near Geneva in Switzerland.

The LHC was running when a "severe electrical perturbation" occurred in the early hours of Friday morning.

NATIONAL GEOGRAPHIC | PERPETUAL PLANET | PHOTO OF THE DAY | TV SCHEDULE |

ANIMALS

The day a weasel shut down CERN

...and a zoo of similar offenders that have tinkered with major science projects. | Wednesday, 16 January

By Victoria Jaggard

A common weasel peers out from the undergrowth.
PHOTO BY FLIP DE HOOYER, MINDEN PICTURES, NATIONAL GEOGRAPHIC CREATIVE

Unlocking the secrets of the universe can be a massive undertaking. Just this week, plans were announced for a new 100km particle accelerator to be built next to the Large Hadron Collider run by CERN in Geneva, Switzerland - the huge underground machine where scientists discovered the Higgs boson in 2012.

Some may be asking if there will be any advanced animal proofing included. As researchers have learned, it only takes a single furry or winged beast to throw our

CERNではしょっちゅうはこんなことはしていない様子。
イタチは、その後ロッテルダムの博物館で展示されているらしい。

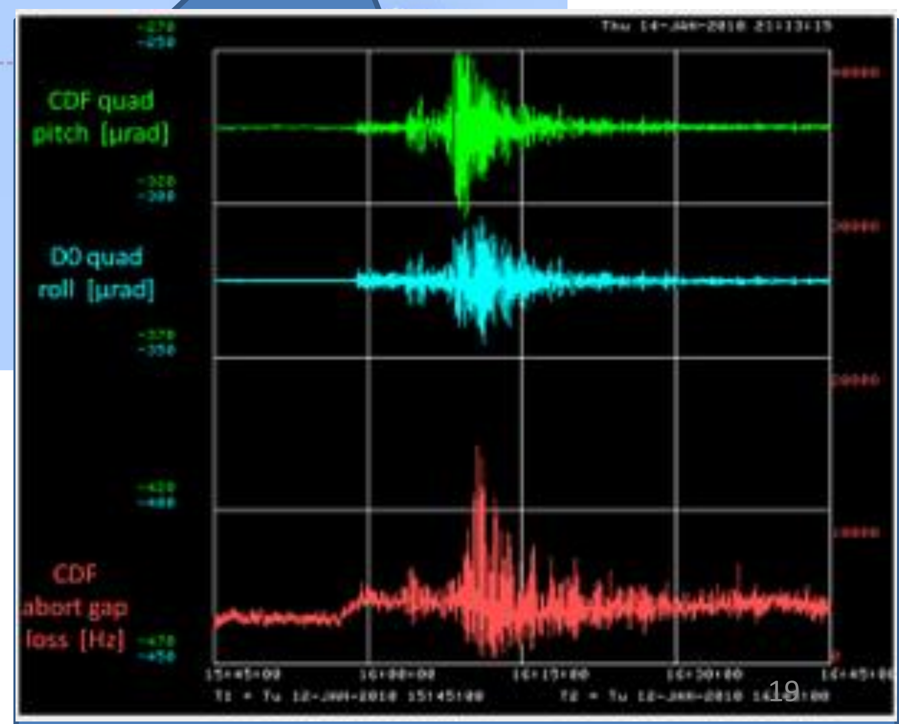
テバトロン運転のあれこれ３

- 2006年夏は暑かった。水草が大繁茂。
- 水草がパイプに詰まり、テバトロンの冷却水の流れが止まりそうになった。

加速器部門のミーティングの発表より:
“These guys are keeping our accelerator running!”

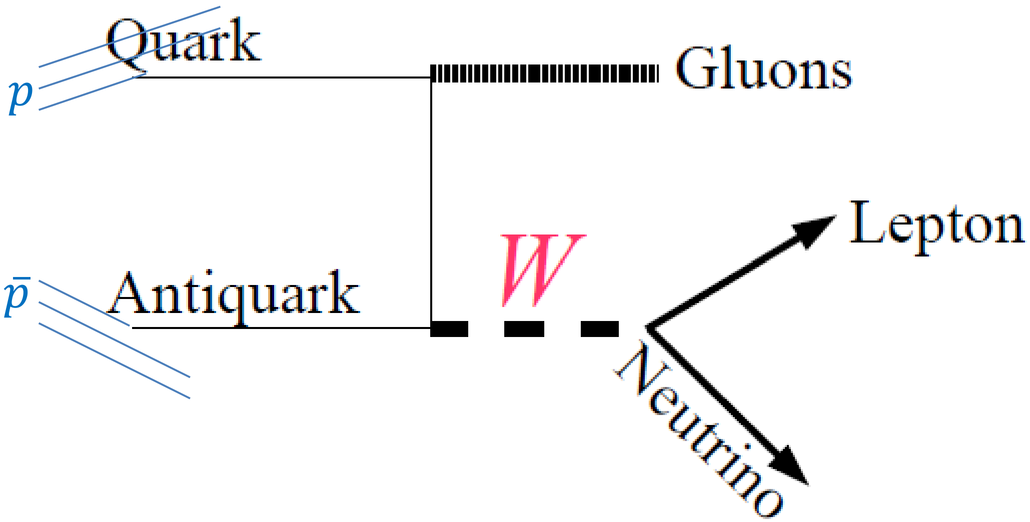
テバトロンのあれこれ４

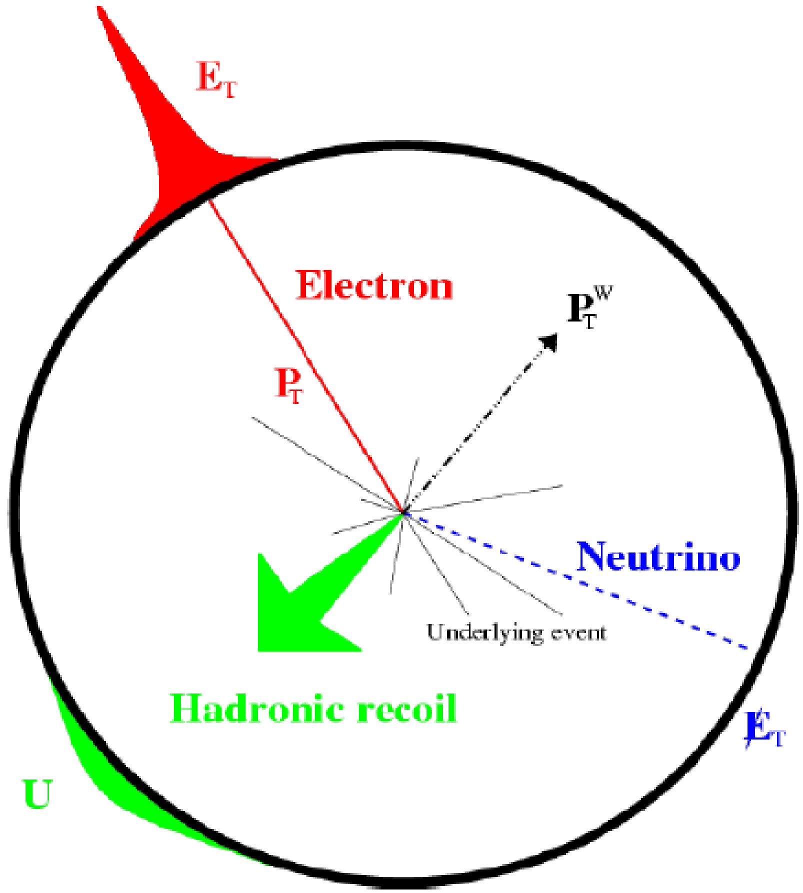
スマトラ島沖地震(2004年）
2004年12月26日
マグニチュード9.3



- 加速器はマイクロメータの精度でビームを運転している。
- 地球の裏側の地震からくる、微弱な振動を感知。

W Boson Production at the Tevatron





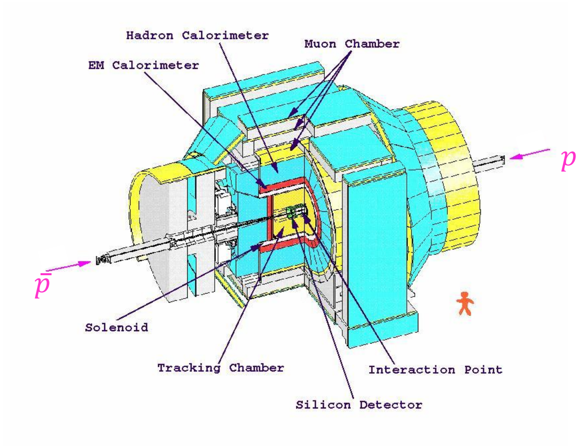
Quark-antiquark annihilation dominates (80%).

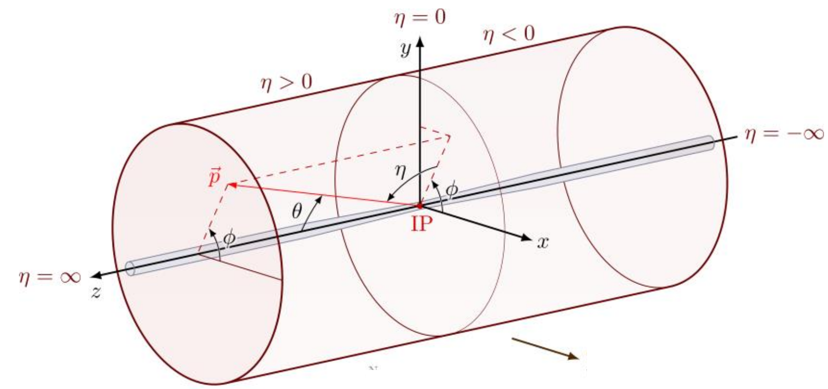
Parton distribution of valence quark in protons are well understood.

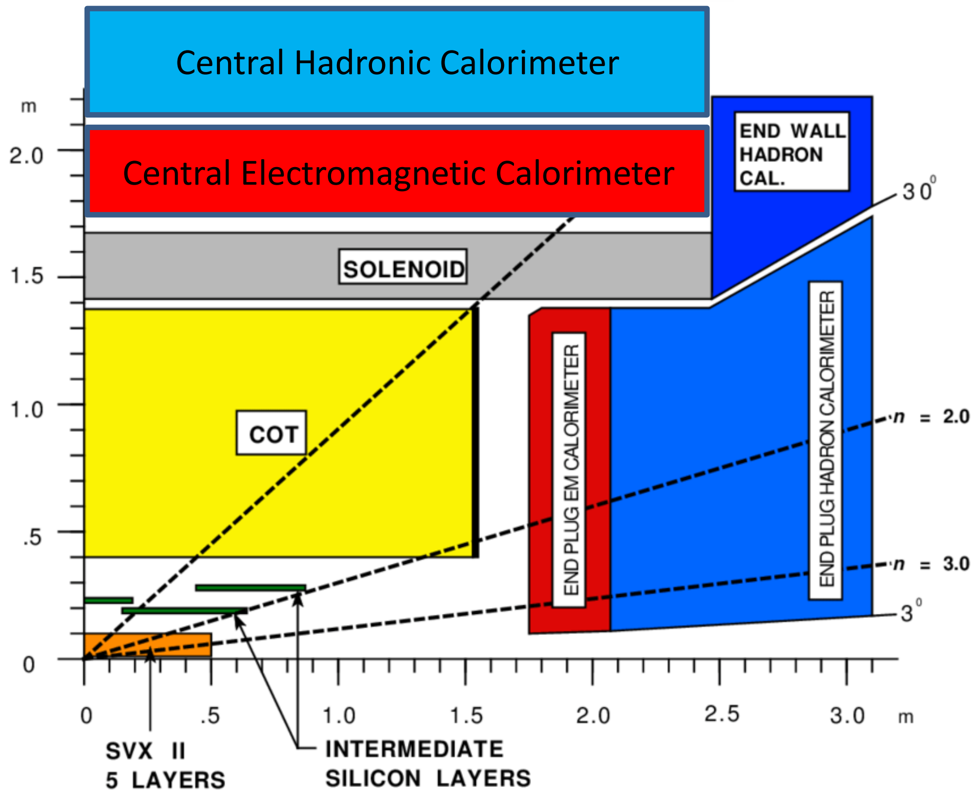
P_Z of initial partons are unknown at hadron colliders.

- P_T^{ℓ} and P_T^{ν} carry information of M_W.
- Initial state QCD radiation is soft $\sim O(10\ \mathrm{GeV})$, detected as hadronic recoil in the calorimeter.

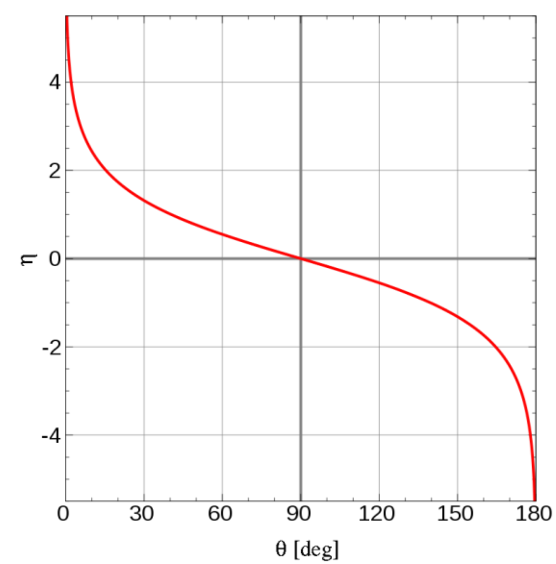
Detector Coordinates



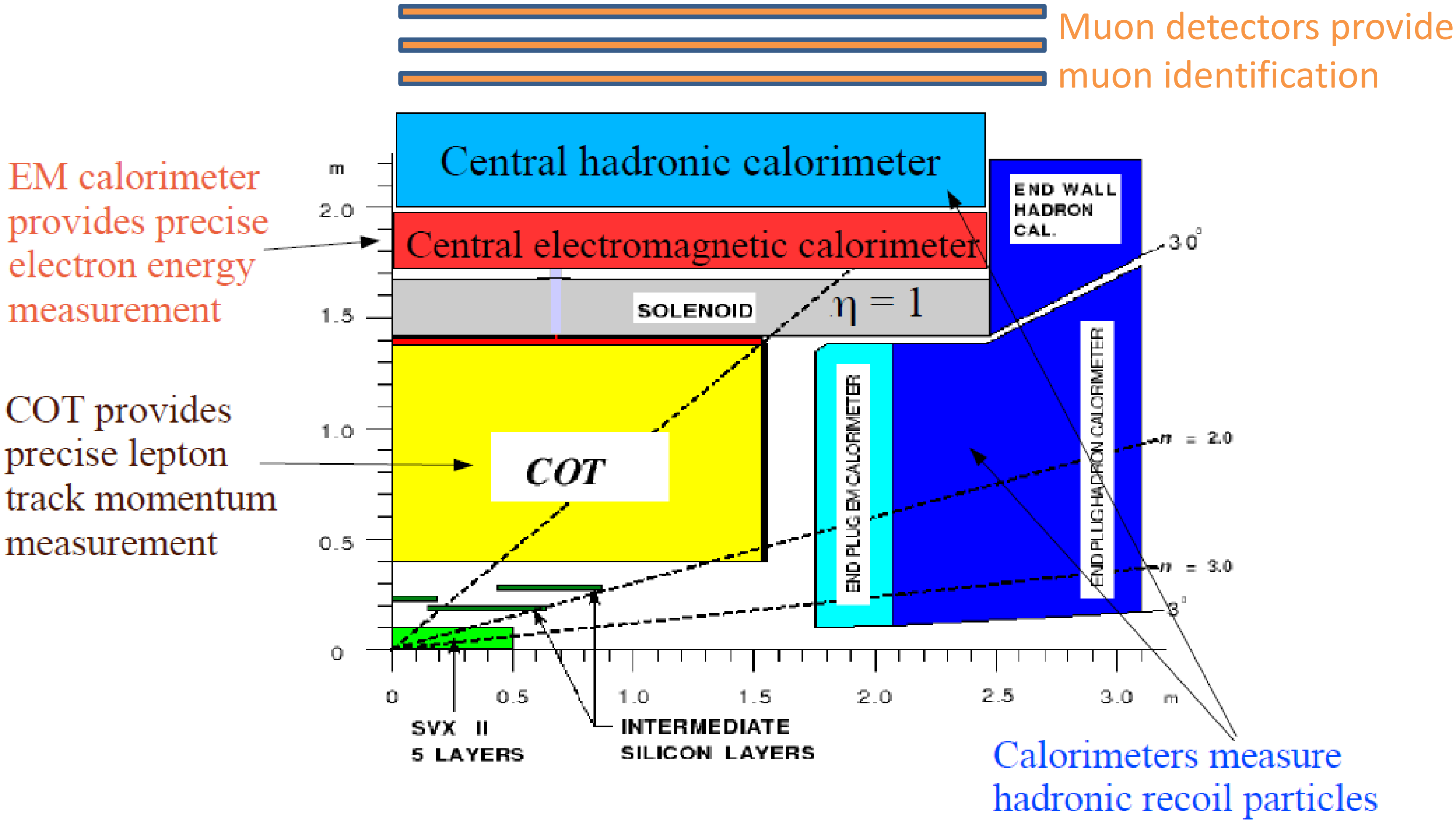




Pseudo-rapidity $\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$



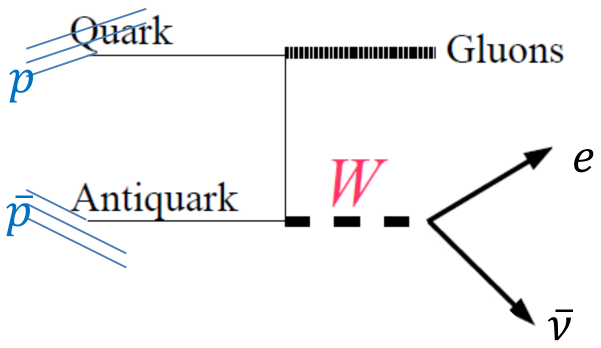
Particle measurement at CDF

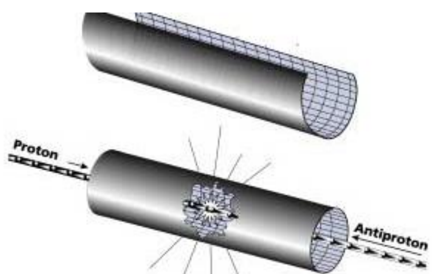


Analysis uses events with central electron or muon ($|\eta| < 1$).

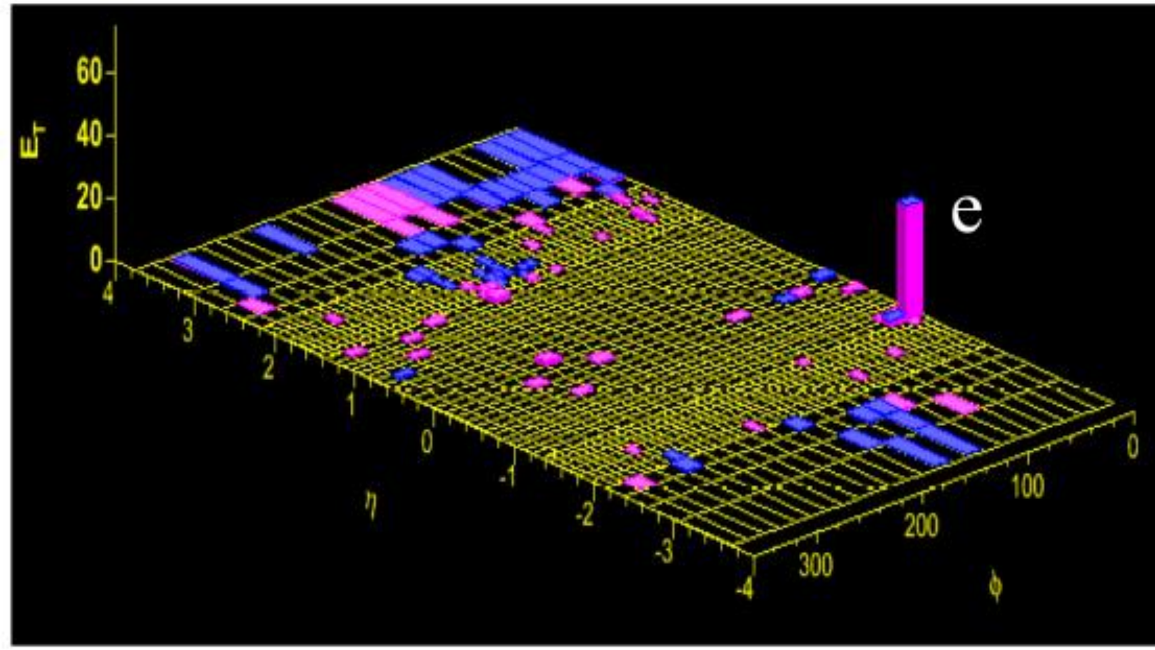
Collider Detector at Fermilab (CDF)

Calorimeter Response to $W \rightarrow e\nu$ Event



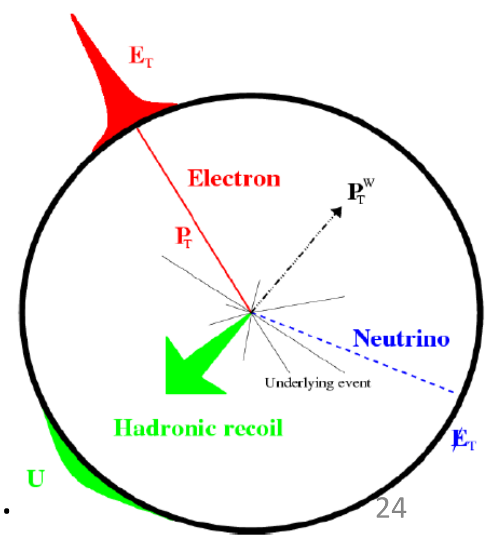


Collision in Calorimeter



- P_Z of initial partons are unknown.
- Momentum in transverse plane is conserved.

- ν does not leave hits in detector.
- $\overrightarrow{P_T^{\nu}}$ is inferred from transverse momenta.
  - $\overrightarrow{P_T^{\nu}} = -\overrightarrow{P_T^{\ell}} - \vec{u}$,   Recoil $\vec{u} = \Sigma_i E_i \sin\theta_i \,\widehat{n_i} = \Sigma_i \vec{E}_{Ti}$
    - i: all calorimeter towers except those containing leptons.



Event Selection

- Lepton selection
  - Online trigger: e/μ with $P_T > 18\ \mathrm{GeV}$.
  - Offline selection:
    - e with $E_T > 30\ \mathrm{GeV}$, track $\mathrm{P_T} > 18\ \mathrm{GeV}$
    - μ with $\mathrm{track}\ P_T > 30\ \mathrm{GeV}$
    - Identification requirements (e:shower shape, μ: hits in muon detector)
- W boson event seletion

  =1 lepton, $|\vec{u}| < 15\ \mathrm{GeV}, P_T(\nu) > 30\ \mathrm{GeV}$
- Z boson event selection (for calibration and validation)

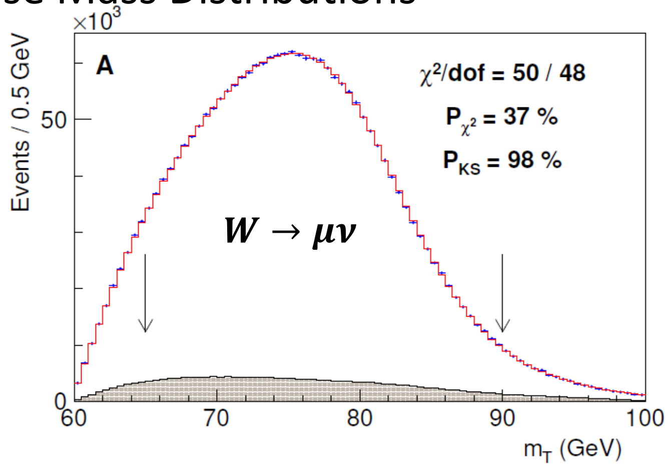
  =2 leptons with same flavor

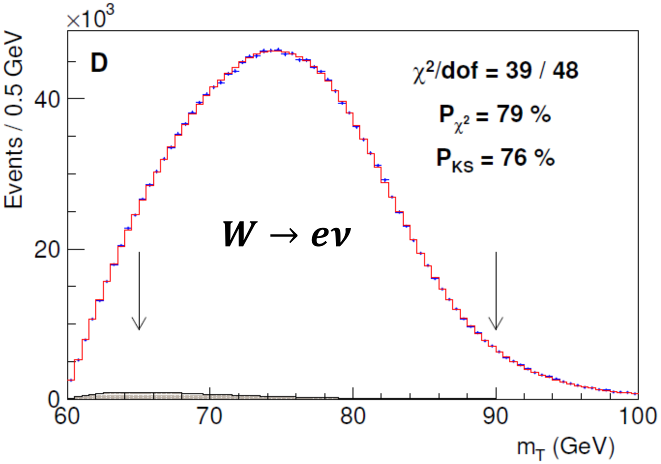
W and Z Data Samples

of candidate events passing event selection

channel	$W \to \ell\nu$	$Z \to \ell\ell$
electron	1,811,700	66,180
muon	2,424,486	238,534

Transverse Mass Distributions





Estimated background in $W \to \ell\nu$ samples

Source	Fraction (%)
$Z/\gamma^* \to \mu\mu$	7.37 ± 0.10
$W \to \tau\nu$	0.880 ± 0.004
Hadronic jets	0.01 ± 0.04
Decays in flight	0.20 ± 0.14
Cosmic rays	0.01 ± 0.01
Total	8.47 ± 0.18

Source	Fraction (%)
$Z/\gamma^* \to ee$	0.134 ± 0.003
$W \to \tau\nu$	0.94 ± 0.01
Hadronic jets	0.34 ± 0.08
Total	1.41 ± 0.08

Transverse Mass Definition

Neglecting m_ℓ, m_ν,

$$m(\ell,\nu) \sim \sqrt{(|\vec{p}^{\ell}|+|\vec{p}^{\nu}|)^2 - (\vec{p}^{\ell} + \vec{p}^{\nu})^2}$$

$$= \sqrt{2(|\vec{p}^{\ell}||\vec{p}^{\nu}| - \vec{p}^{\ell} \cdot \vec{p}^{\nu})}$$

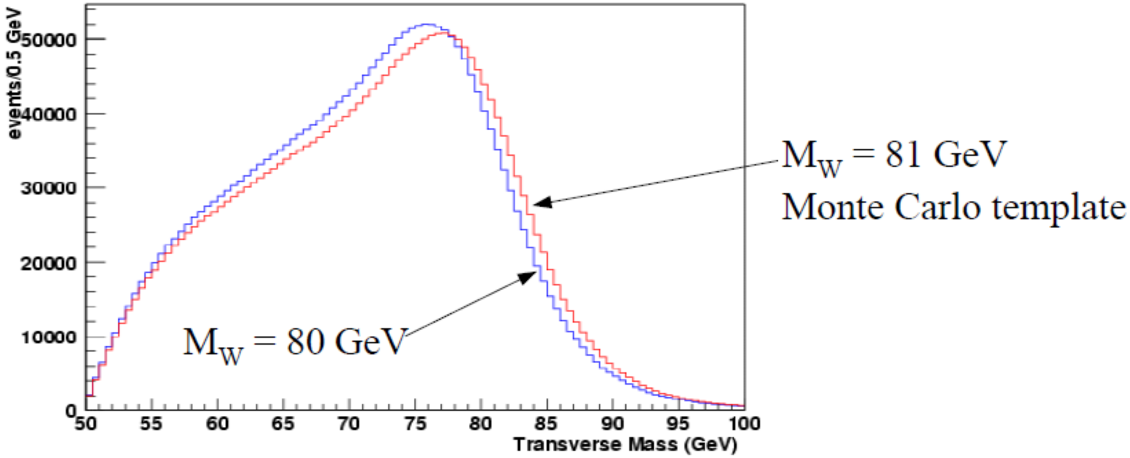
P_Z^{ν} is unknown at hadron colliders.

Transverse mass is defined as follows:

$$m_T = \sqrt{2\left(|\vec{p}_T^{\ell}||\vec{p}_T^{\nu}| - \vec{p}_T^{\ell} \cdot \vec{p}_T^{\nu}\right)}$$

M_W extraction by Template Fitting

- Signal samples are simulated using Monte Carlo
    - W (Z) boson production is simulated by RESBOS+PHOTOS MC generator.
  - generated with finely-spaced different M_W settings.



- Transverse distribution shape as a function of M_W = "template".
- M_W is extracted by maximum likelihood fit to data distribution, using "templates".

Reproduction of detector response in simulation is essential to reduce systematic uncertainties!

m_T Fit Uncertainties (MeV) from Previous CDF W mass measurement (2.2 fb^{-1})

(CDF, PRL 108 (2012) 151803; Phys. Rev. D 89 (2014) 7, 072003)

$$M_W = 80\ 387 \pm 12_{\mathrm{stat}} \pm 15_{\mathrm{syst}} = 80\ 387 \pm 19\ \mathrm{MeV}/c^2$$

	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total	23	26	15

Data increases by $\times$ 4
$\Rightarrow$ $\times$ 2 reduction of stat unc.
$\Rightarrow$ 8.9 fb^{-1} is syst. dominant!

Fine tune the alignment, materials, and response of the detector simulation.

- e/μ momentum calibrationの例

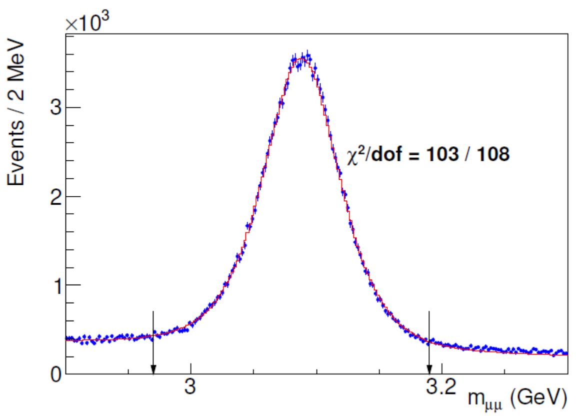
CTEQ6.6 $\Rightarrow$ NNPDF3.1

- W mass measurements always dedicated lots of efforts to reduce systematic uncertainties.
  - Other analyses don't need this level of resolution.

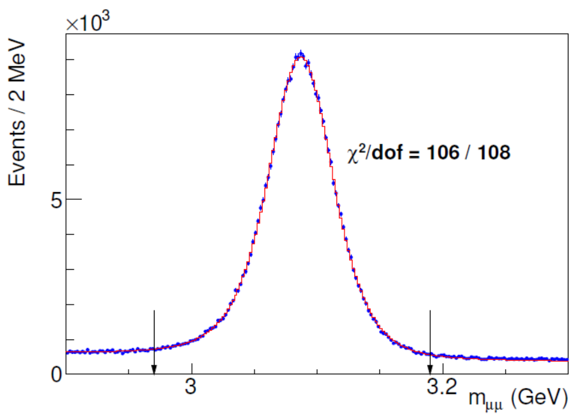
Muon Momentum Measurement

- Tracking chamber alignment using cosmic ray events.
- $J/\psi \rightarrow \mu\mu$ are used to improve geometrical modeling of the detector (distortion, magnetic field variations, materials).
- $J/\psi \rightarrow \mu\mu$ events are further used to obtain momentum correction, using $M_{J/\psi}^{World\ Ave.} = 3096.916 \pm 0.011\ \mathrm{MeV}$.

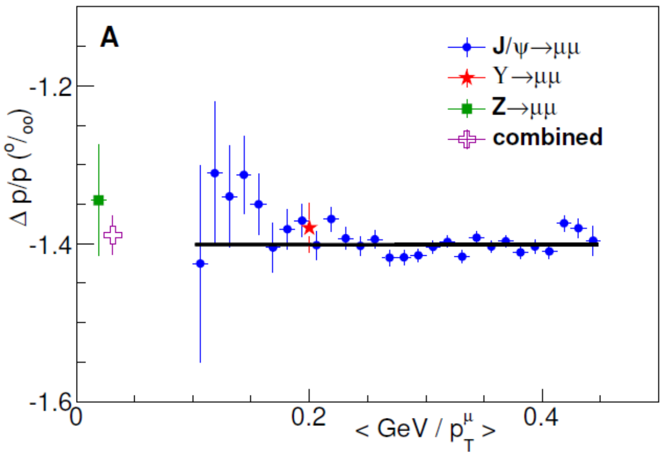
$\langle 1/p_T^{\mu} \rangle = (0.15, 0.1625)\ \mathrm{GeV}^{-1}$



$\langle 1/p_T^{\mu} \rangle = (0.1875, 0.2)\ \mathrm{GeV}^{-1}$



Fractional Deviation of momentum (per mille)

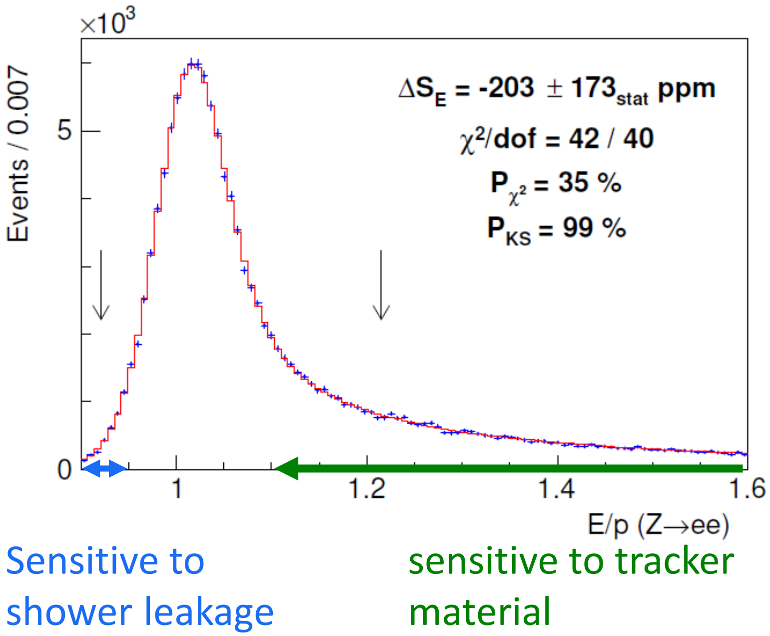


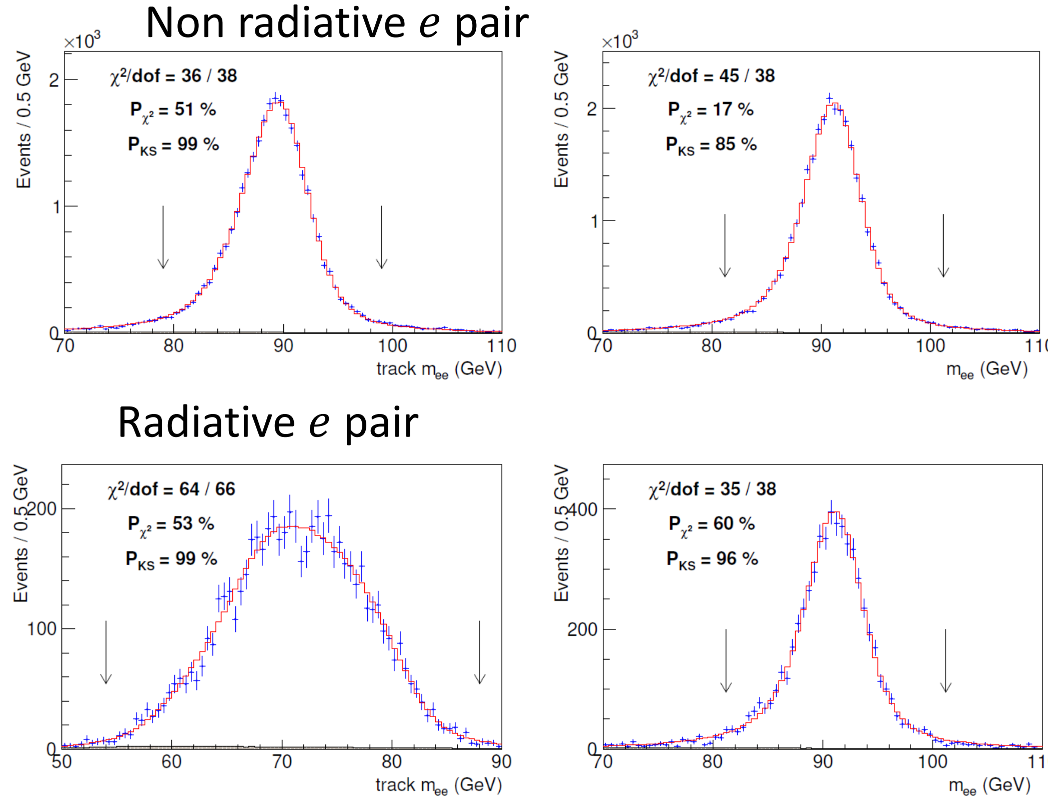
Electron Momentum Measurement

- Electron radiates bremsstrahlung photons in materials of tracking system

  ⇒ we measure electron energy with calorimeter.

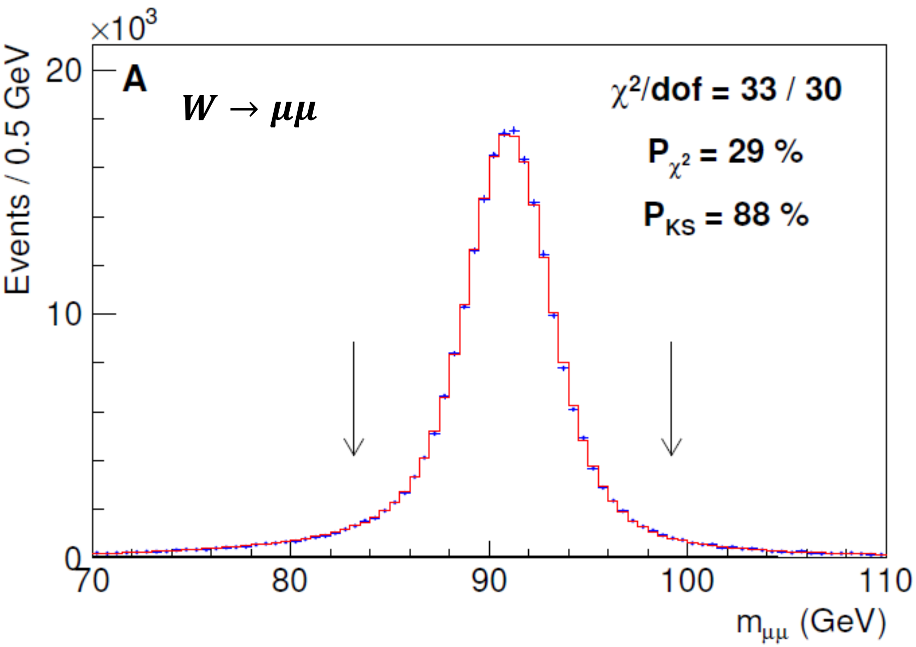
- $\frac{E}{p}$ distribution in $Z \rightarrow ee$ are used to obtain special uniformity calibration, material in tracking volume, shower leakage modelling.

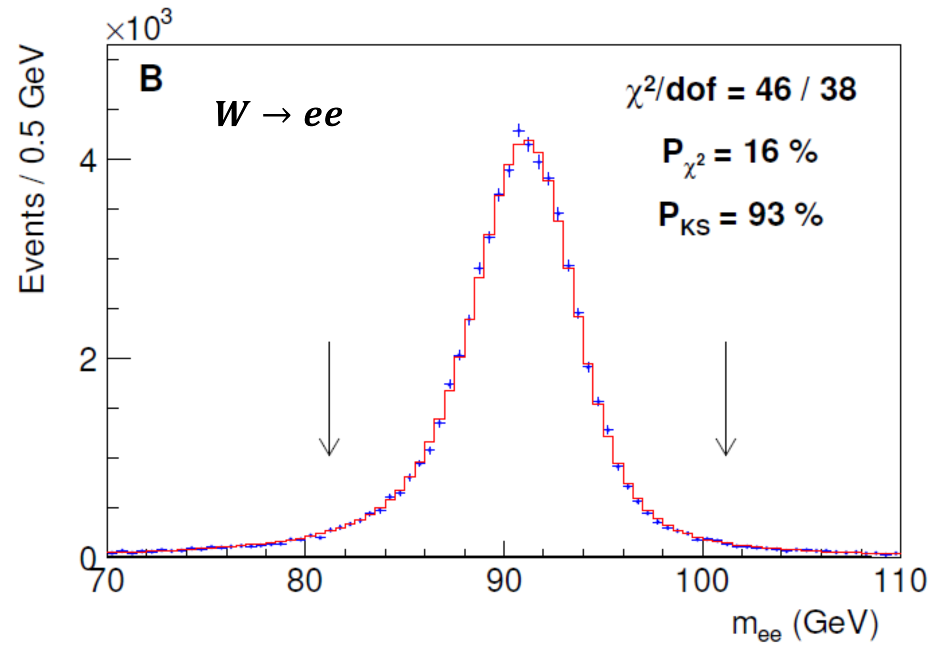




Z Boson Mass Measurement

- Z boson mass is measured, to check that everything works. to cross check with world average.
- Checked to check everything works correctly.





$M_Z = 91\,192.0 \pm 6.4_{stat} \pm 4.0_{syst}$ MeV

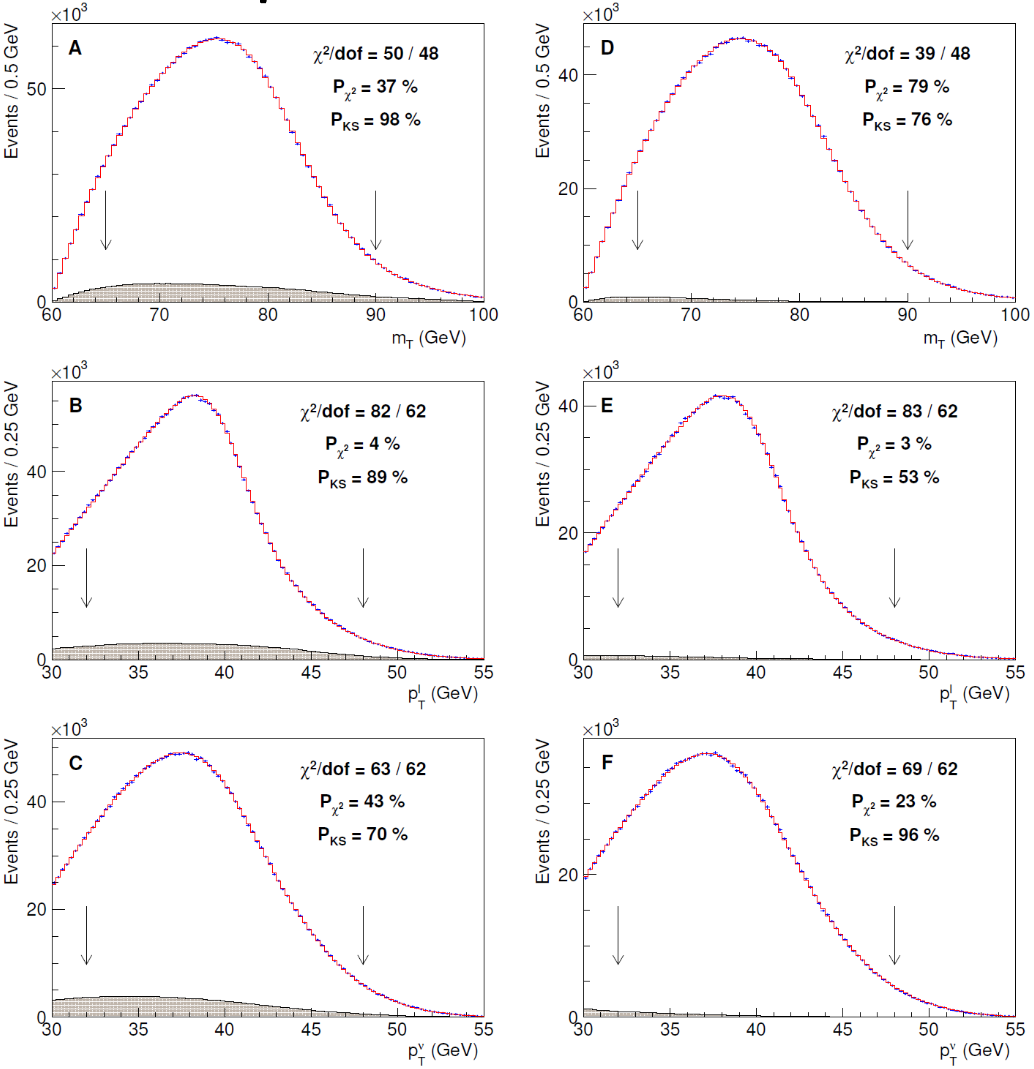
$M_Z = 91\,194.3 \pm 13.8_{stat} \pm 7.6_{syst}$ MeV

Good agreement with World Average $M_Z = 91\,187.6 \pm 2.1$ MeV

W mass fits

M_W measurement by fitting $m_T, P_T^{\ell}, P_T^{\nu}$.

$W \rightarrow \mu\nu$ **$W \rightarrow e\nu$**



Mass Fit Results

Distribution	W-boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80\ 429.1 \pm 10.3_{\text{stat}} \pm 8.5_{\text{syst}}$	39/48
$p_T^{\ell}(e)$	$80\ 411.4 \pm 10.7_{\text{stat}} \pm 11.8_{\text{syst}}$	83/62
$p_T^{\nu}(e)$	$80\ 426.3 \pm 14.5_{\text{stat}} \pm 11.7_{\text{syst}}$	69/62
$m_T(\mu,\nu)$	$80\ 446.1 \pm 9.2_{\text{stat}} \pm 7.3_{\text{syst}}$	50/48
$p_T^{\ell}(\mu)$	$80\ 428.2 \pm 9.6_{\text{stat}} \pm 10.3_{\text{syst}}$	82/62
$p_T^{\nu}(\mu)$	$80\ 428.9 \pm 13.1_{\text{stat}} \pm 10.9_{\text{syst}}$	63/62
combination	$80\ 433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}}$	7.4/5

Summary of Systematics

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Comparison of Systematics with 2.2 fb^{-1} analysis

2.2 fb^{-1}

$$M_W = 80\ 387 \pm 12_{\text{stat}} \pm 15_{\text{syst}} = 80\ 387 \pm 19\ \text{MeV}/c^2.$$

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

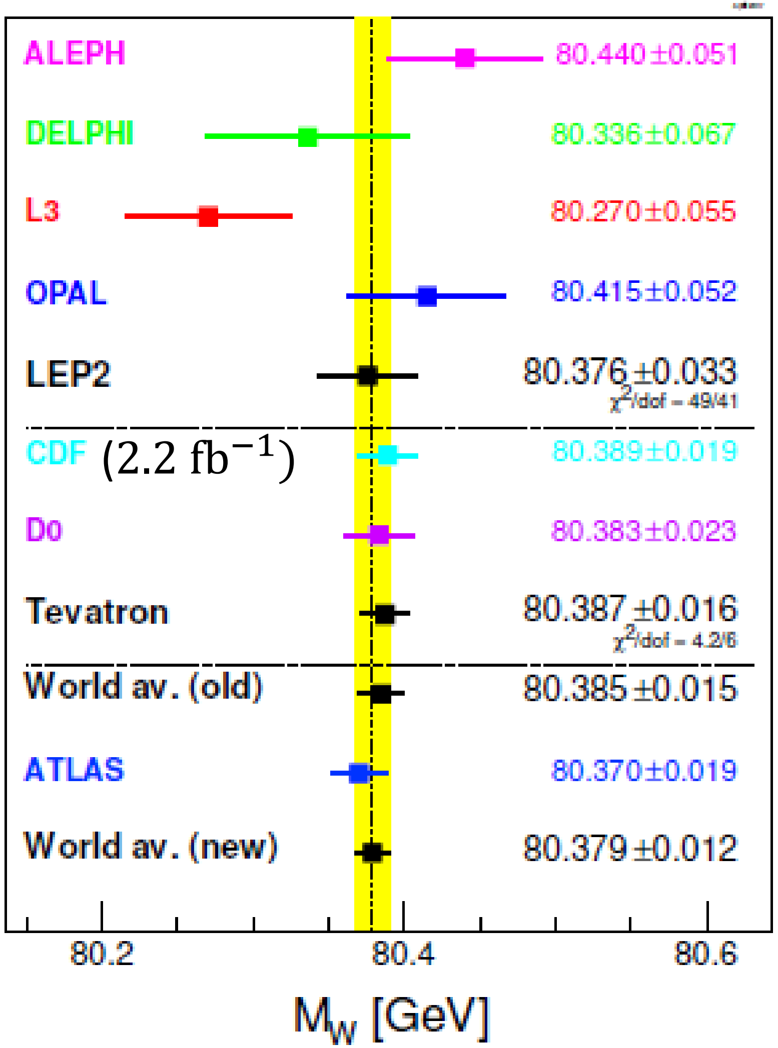
8.8 fb^{-1}

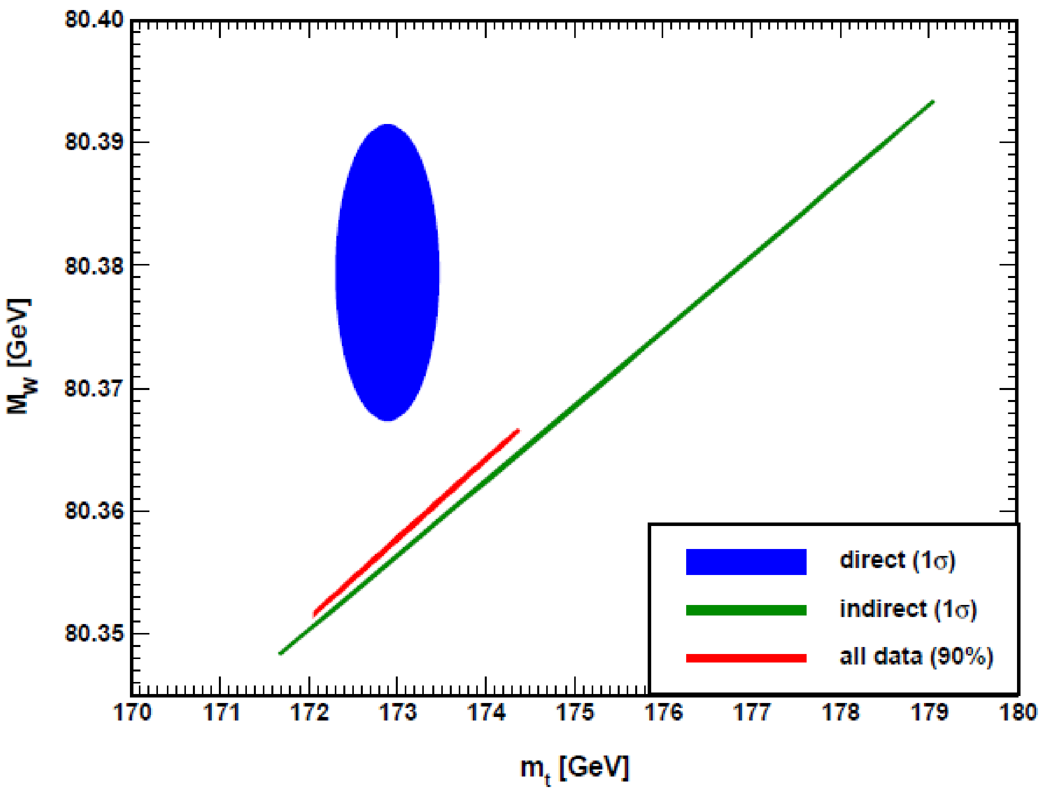
$$M_W = 80\ 433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80\ 433.5 \pm 9.4\ \text{MeV}/c^2$$

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Status before 2022 CDF W Mass Update

- Prog.Theor.Exp.Phys.2020.083C01





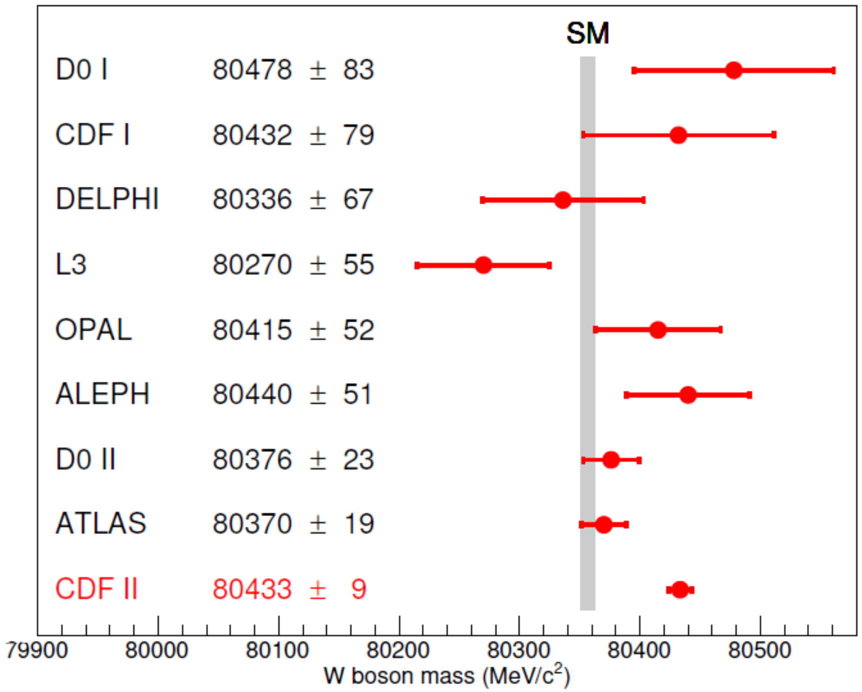
$$M_W^{Global\ fit} = 80.357 \pm 6\ \mathrm{MeV}$$

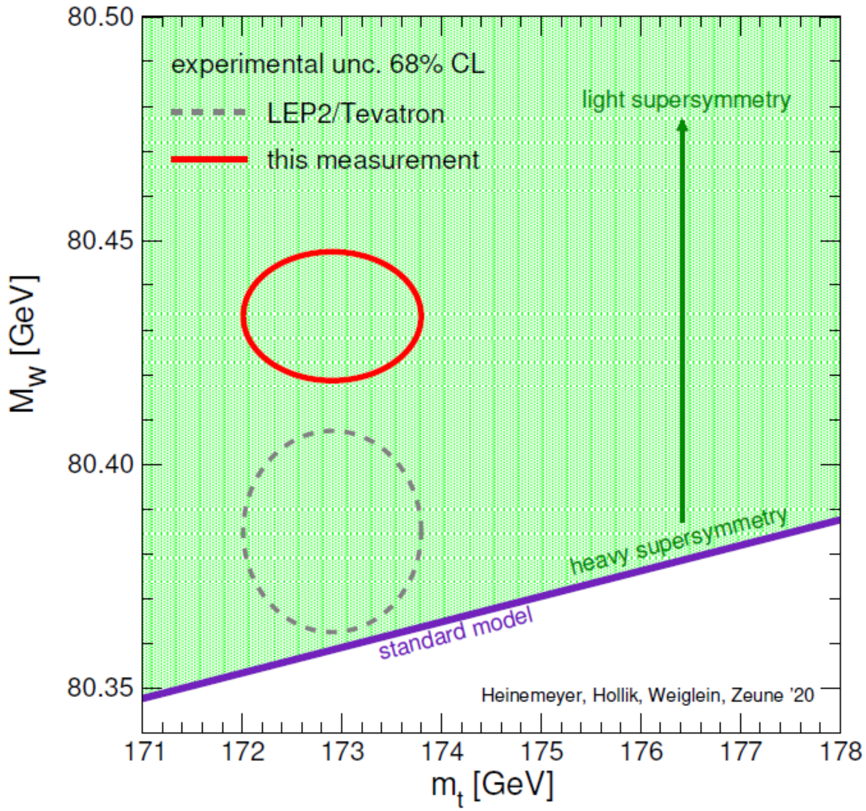
1.7σ lower than the world average

The new CDF measurement uses $8.8\ \mathrm{fb}^{-1}$ of data, $\times$ 4 of the previous analysis.

W Mass Status

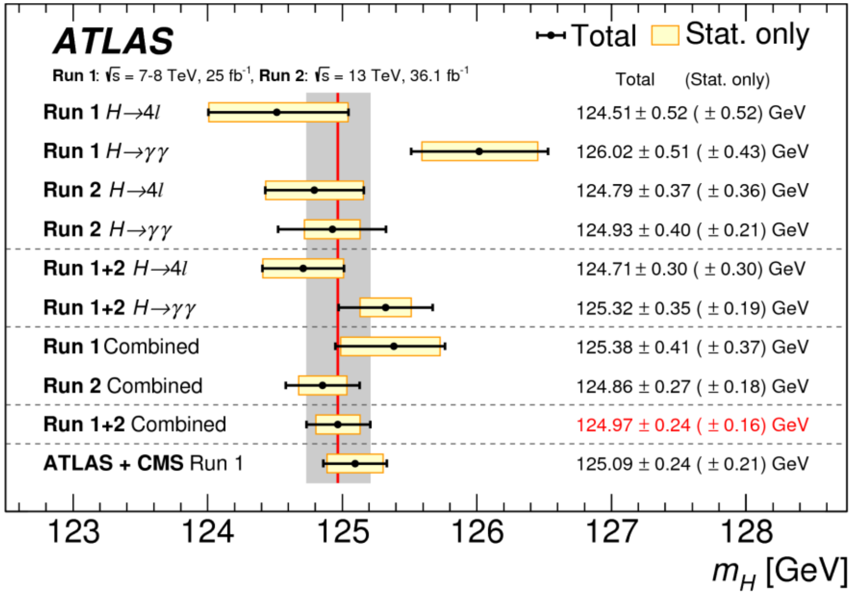
- CDF update: $M_W = 80\,433.5 \pm 9.4\ \mathrm{MeV}$
  - More precise than all previous measurement combined.
  - Tension of 7σ with SM expectation.
- SM expectation: $M_W = 80\,357 \pm 6\ \mathrm{MeV}$

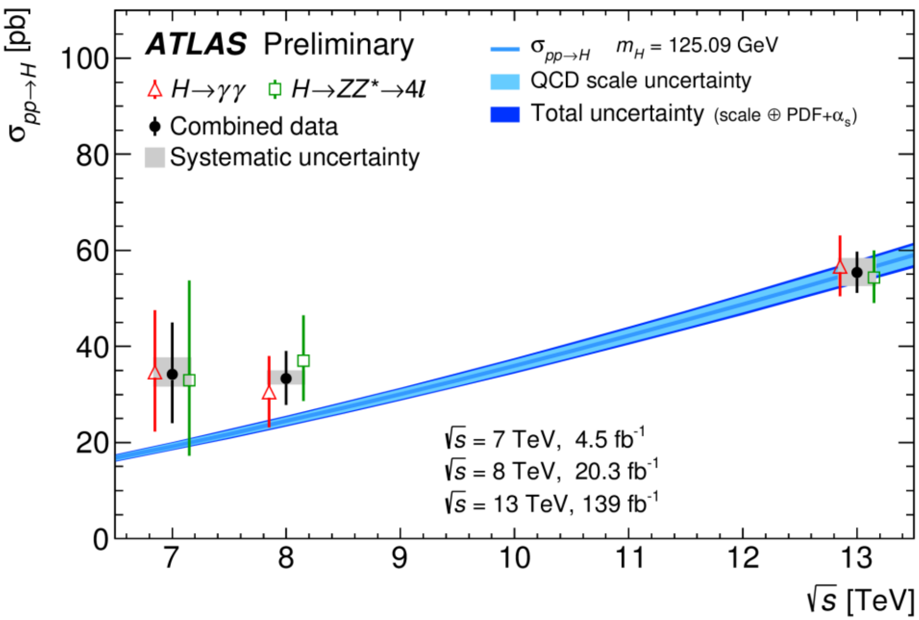




backup

Higgs mass measurements at ATLAS





Top Mass status

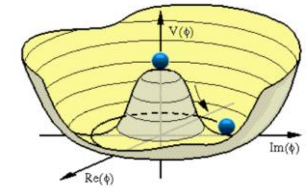
$\pm stat \pm syst$

Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
172.76 ± 0.30 OUR AVERAGE	Error includes scale factor of 1.2.			
172.6 ± 2.5	[1] SIRUNYAN	20AR	CMS	jet mass from boosted top
172.69 ± 0.25 ± 0.41	[2] AABOUD	19AC	ATLS	7, 8 TeV ATLAS combination
172.26 ± 0.07 ± 0.61	[3] SIRUNYAN	19AP	CMS	lepton+jets, all-jets channels
$172.33 \pm 0.14 {}^{+0.66}_{-0.72}$	[4] SIRUNYAN	19AR	CMS	dilepton channel ($e\mu$, $2e$, 2μ)
$172.95 \pm 0.77 {}^{+0.97}_{-0.93}$	[5] SIRUNYAN	17L	CMS	t-channel single top production
172.44 ± 0.13 ± 0.47	[6] KHACHATRY...	16AK	CMS	7, 8 TeV CMS combination
174.30 ± 0.35 ± 0.54	[7] TEVEWWG	16	TEVA	Tevatron combination

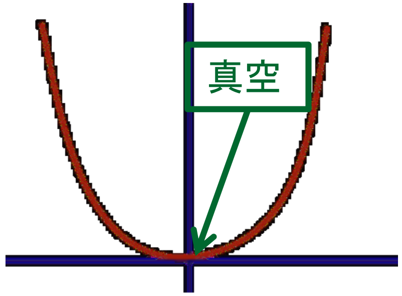
Ring Rd

ヒッグス機構



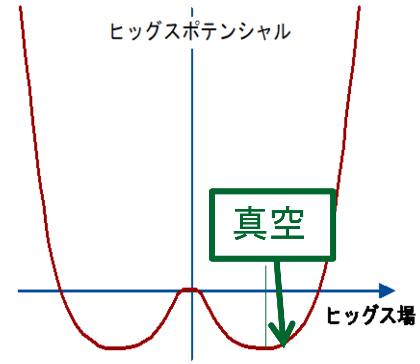
ヒッグスポテンシャル $V(\phi) = \mu^2\phi^2 + \lambda\phi^4$ $(\lambda>0)$

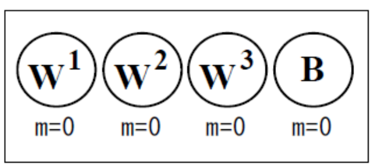
ビッグバン直後 $\mu^2>0$



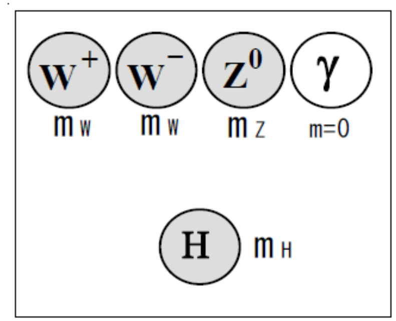
自発的対象性の破れ
（真空の相転移）

現在 $\mu^2<0$





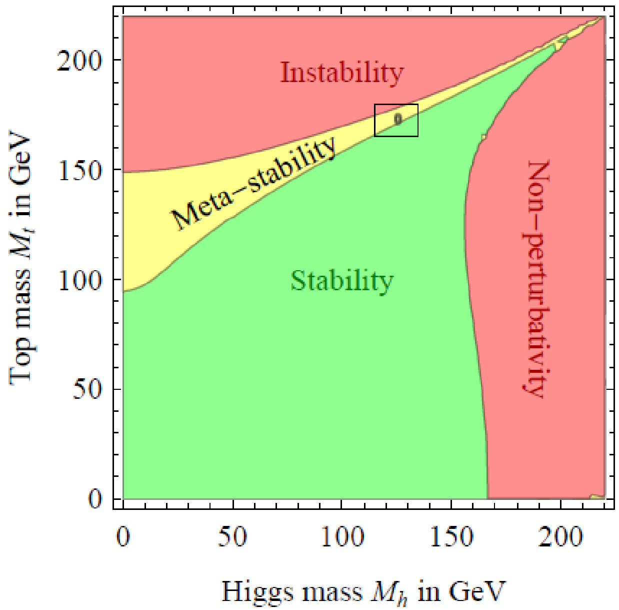
ヒッグス場 $\Phi = \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$

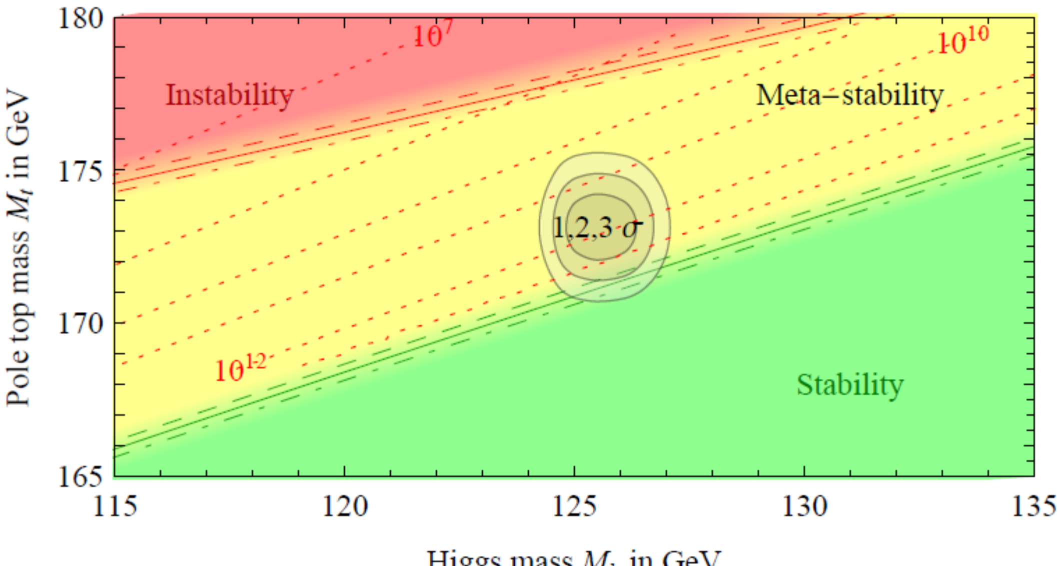


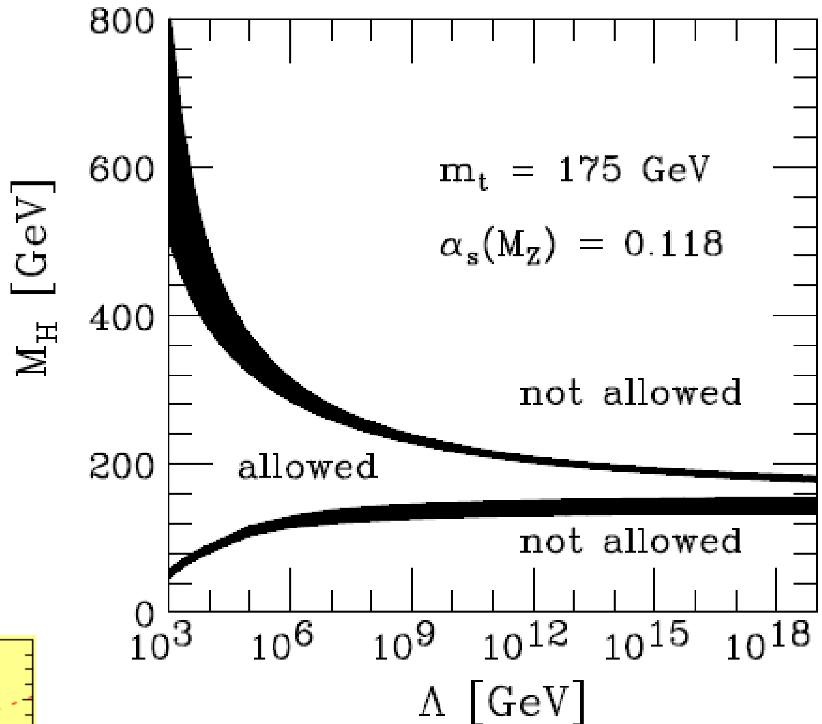
Φ_1, Φ_2は複素数（4つの自由度） → 3つの自由度は、W^+, W^-, Z^0の質量になった。残った1自由度がヒッグス粒子になった。

$$m_H = \lambda v^2 = -\mu^2,\ v = \sqrt{-\frac{\mu^2}{\lambda}}$$

Vacuum stability

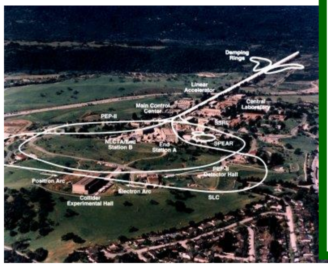






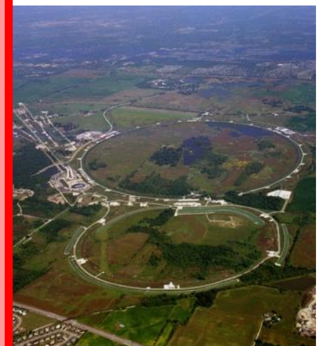
Lower bound:
    Vacuum stability
Upper bound:
    Purtabative validity of SM

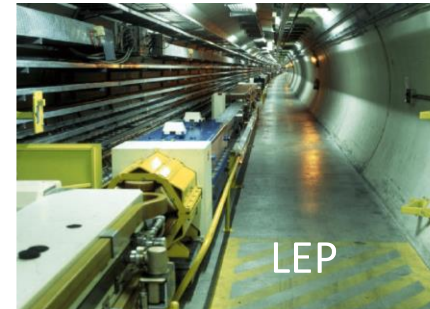
最高エネルギー加速器



SLC
e^+e^-
91 GeV
SLAC
USA

Tevatron
$p\bar{p}$
1.8-1.96 TeV
Fermilab
USA
CDF実験
米国シカゴ郊外





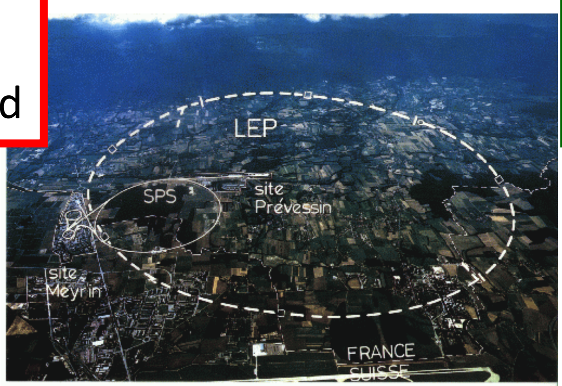
*W/Z*ボソン発見

トップクォーク発見

ヒッグス粒子発見

1985 1990 1995 2000 2005 2010 2015 2020

SppS
$p\bar{p}$
630 GeV
CERN
Switzerland



LEP
e^+e^-
91-209 GeV
CERN
Switzerland

LHC
pp
7-14 TeV
CERN
Switzerland
ATLAS実験
スイス
ジュネーブ郊外

テバトロン実験のシャットダウン

- テバトロン加速器の最後のビームは2011年9月30日に止まった。

A 'Bittersweet' Celebration of the Tevatron

Tevatron Shuts Down, September 30, 2011 at Fermi National Accelerator Laboratory, Batavia, Illinois, USA

Blind Analysis Technique

- All W and Z mass fit results were blinded with a random [-50,50] MeV offset hidden in the likelihood fitter
- Blinding offset removed after the analysis was declared frozen
- Technique allows to study all aspects of data while keeping Z boson mass and W boson mass result unknown within ±50 MeV

Comparison of fit results with 2.2 fb^{-1} analysis

Center value increased by +44 MeV

2.2 fb^{-1}

$$M_W = 80\ 387 \pm 12_{stat} \pm 15_{syst} = 80\ 387 \pm 19\ \mathrm{MeV}/c^2.$$

Distribution	W-boson mass (MeV)	χ^2/dof	Weight in Combination
$m_T(e,\nu)$	$80\ 408 \pm 19_{stat} \pm 18_{syst}$	52/48	17.5%
$p_T^\ell(e)$	$80\ 393 \pm 21_{stat} \pm 19_{syst}$	60/62	13.8%
$p_T^\nu(e)$	$80\ 431 \pm 25_{stat} \pm 22_{syst}$	71/62	7.1%
$m_T(\mu,\nu)$	$80\ 379 \pm 16_{stat} \pm 16_{syst}$	58/48	33.5%
$p_T^\ell(\mu)$	$80\ 348 \pm 18_{stat} \pm 18_{syst}$	54/62	17.3%
$p_T^\nu(\mu)$	$80\ 406 \pm 22_{stat} \pm 20_{syst}$	79/62	8.8%

8.8 fb^{-1}

$$M_W = 80\ 433.5 \pm 6.4_{stat} \pm 6.9_{syst} = 80\ 433.5 \pm 9.4\ \mathrm{MeV}/c^2$$

Distribution	W-boson mass (MeV)	χ^2/dof	Weight in Combination
$m_T(e,\nu)$	$80\ 429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48	30.0%
$p_T^\ell(e)$	$80\ 411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62	6.7%
$p_T^\nu(e)$	$80\ 426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62	0.9%
$m_T(\mu,\nu)$	$80\ 446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48	34.2%
$p_T^\ell(\mu)$	$80\ 428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62	18.7%
$p_T^\nu(\mu)$	$80\ 428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62	9.5%
combination	$80\ 433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5	

TABLE S1: Summary of analysis updates

Method or technique	impact	section of paper
Detailed treatment of parton distribution functions	+3.5 MeV	IV A
Resolved beam-constraining bias in CDF reconstruction	+10 MeV	VI C
Improved COT alignment and drift model [65]	uniformity	VI
Improved modeling of calorimeter tower resolution	uniformity	III
Temporal uniformity calibration of CEM towers	uniformity	VII A
Lepton removal procedure corrected for luminosity	uniformity	VIII A
Higher-order calculation of QED radiation in J/ψ and Υ decays	accuracy	VI A & B
Modeling kurtosis of hadronic recoil energy resolution	accuracy	VIII B 2
Improved modeling of hadronic recoil angular resolution	accuracy	VIII B 3
Modeling dijet contribution to recoil resolution	accuracy	VIII B 4
Explicit luminosity matching of pileup	accuracy	VIII B 5
Modeling kurtosis of pileup resolution	accuracy	VIII B 5
Theory model of p_T^W/p_T^Z spectrum ratio	accuracy	IV B
Constraint from p_T^W data spectrum	robustness	VIII B 6
Cross-check of p_T^Z tuning	robustness	IV B

of these updates is presented in Table S1, along with the expected impact and references to the sections of this supplement where the respective descriptions are provided. In some cases, the additive change induced by the update can be added to our previously published M_W value of $M_W = 80\ 387 \pm 19$ MeV [41, 43] since the updated procedures can be incorporated into the previous analysis without repeating the latter. In other cases, the impact is classified in terms of the expected improvement in detector uniformity, analysis accuracy, or robustness. The shifts shown in the first two rows of Table S1 result in an updated value of $M_W = 80\ 400.5$ MeV. With the correlations due to parton distribution functions, the momentum scale calibration and QED radiative corrections taken into account, the consistency between the updated previous measurement and the new measurement is at the percent level, assuming purely Gaussian fluctuations. Considering the large number of systematic improvements in analysis techniques, the best estimate of M_W quoted in this paper is a freestanding result obtained from a blind procedure, and supersedes our 2012 result [41, 43] in the same spirit as the latter superseding our 2007 result [38]. Subsequent analyses with new or modified procedures, such as independently blinded measurements in subsamples of data, are being pursued.

Combinations of Fit Results

Combination	m_T fit		p_T^ℓ fit		p_T^ν fit		Value (MeV)	χ^2/dof	Probability (%)
	Electrons	Muons	Electrons	Muons	Electrons	Muons			
m_T	✓	✓					$80\ 439.0 \pm 9.8$	1.2 / 1	28
p_T^ℓ			✓	✓			$80\ 421.2 \pm 11.9$	0.9 / 1	36
p_T^ν					✓	✓	$80\ 427.7 \pm 13.8$	0.0 / 1	91
m_T & p_T^ℓ	✓	✓	✓	✓			$80\ 435.4 \pm 9.5$	4.8 / 3	19
m_T & p_T^ν	✓	✓			✓	✓	$80\ 437.9 \pm 9.7$	2.2 / 3	53
p_T^ℓ & p_T^ν			✓	✓	✓	✓	$80\ 424.1 \pm 10.1$	1.1 / 3	78
Electrons	✓		✓		✓		$80\ 424.6 \pm 13.2$	3.3 / 2	19
Muons		✓		✓		✓	$80\ 437.9 \pm 11.0$	3.6 / 2	17
All	✓	✓	✓	✓	✓	✓	$80\ 433.5 \pm 9.4$	7.4 / 5	20

Table S9

- Combined electrons (3 fits): $M_W = 80424.6 \pm 13.2$ MeV, $P(\chi^2) = 19\%$
- Combined muons (3 fits): $M_W = 80437.9 \pm 11.0$ MeV, $P(\chi^2) = 17\%$
- All combined (6 fits): $M_W = 80433.5 \pm 9.4$ MeV, $P(\chi^2) = 20\%$

Previous CDF Result (2.2 fb^{-1}) Transverse Mass Fit Uncertainties (MeV)

	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic	18	16	15
Total	26	23	

Systematic uncertainties shown in green: statistics-limited by control data samples

New CDF Result (8.8 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

	electrons	*muons*	*common*
W statistics	10.3	9.2	0
Lepton energy scale	5.8	2.1	1.8
Lepton resolution	0.9	0.3	-0.3
Recoil energy scale	1.8	1.8	1.8
Recoil energy resolution	1.8	1.8	1.8
Selection bias	0.5	0.5	0
Lepton removal	1	1.7	0
Backgrounds	2.6	3.9	0
pT(Z) & pT(W) model	1.1	1.1	1.1
Parton dist. Functions	3.9	3.9	3.9
QED rad. Corrections	2.7	2.7	2.7
Total systematic	8.7	7.4	5.8
Total	13.5	11.8	5.8