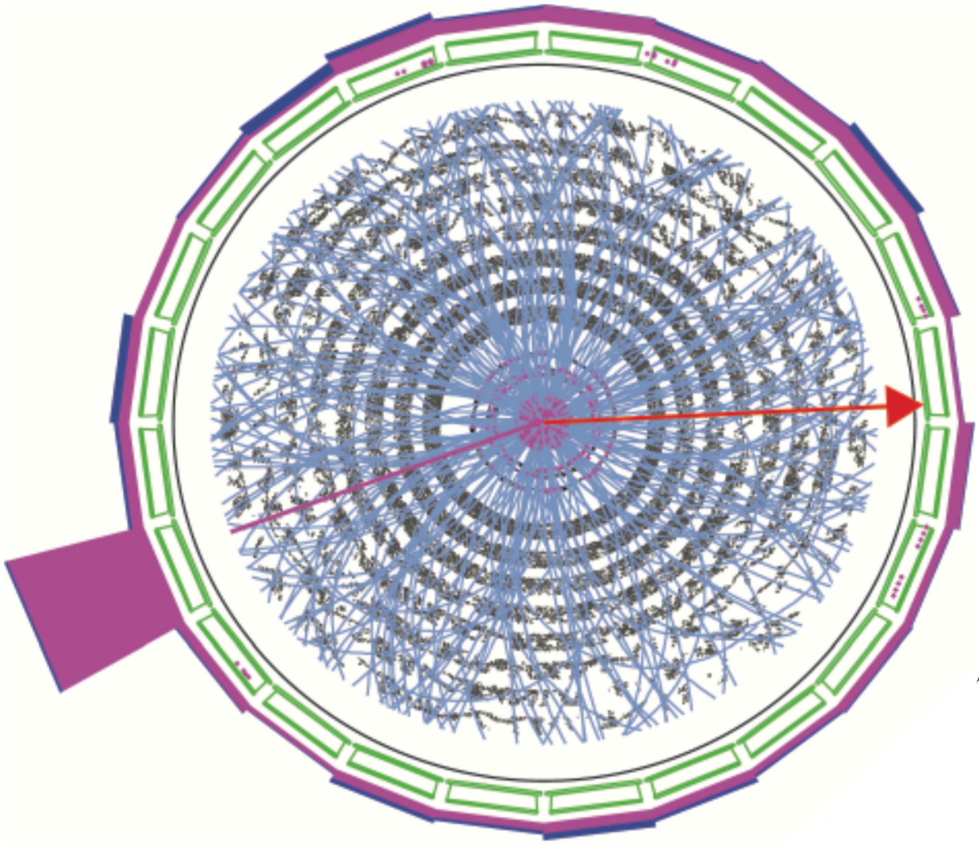
The Heavyweight W boson –
Upset to the Standard Model of Particle Physics

Ashutosh V. Kotwal
Duke University



Department of Physics & Astronomy
Texas A&M University
April 27, 2023

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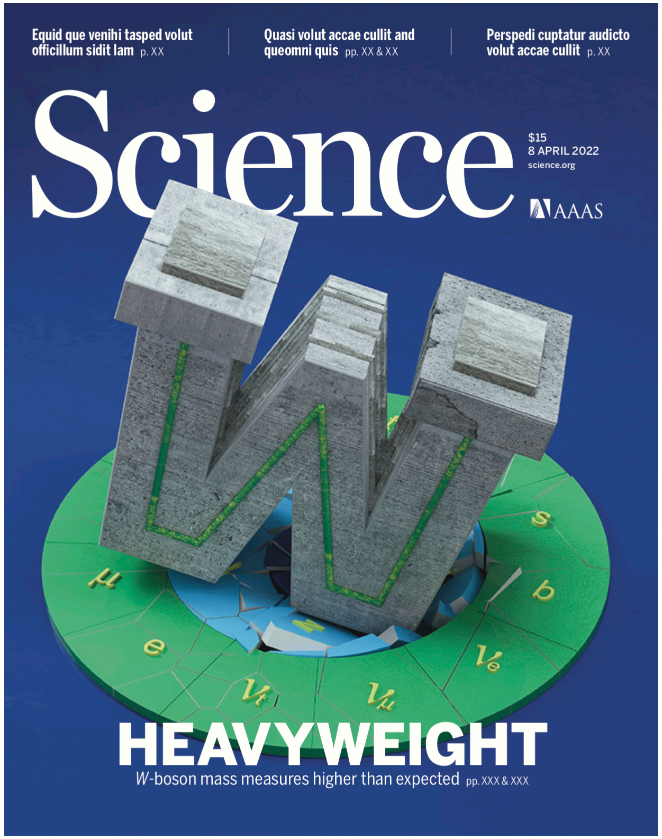

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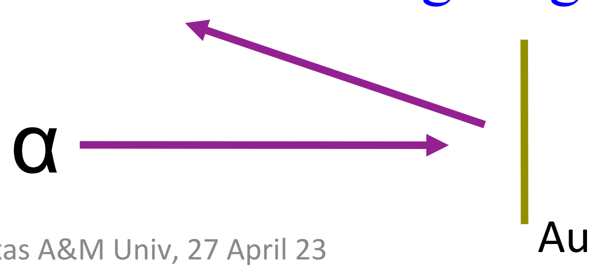
Origin of Particle Physics

- Search for the constituents of matter has been one of the central themes of physics
- Aristotle's “elements” → earth, air, fire & water
- Chemists understood that molecules were the units carrying chemical properties of materials

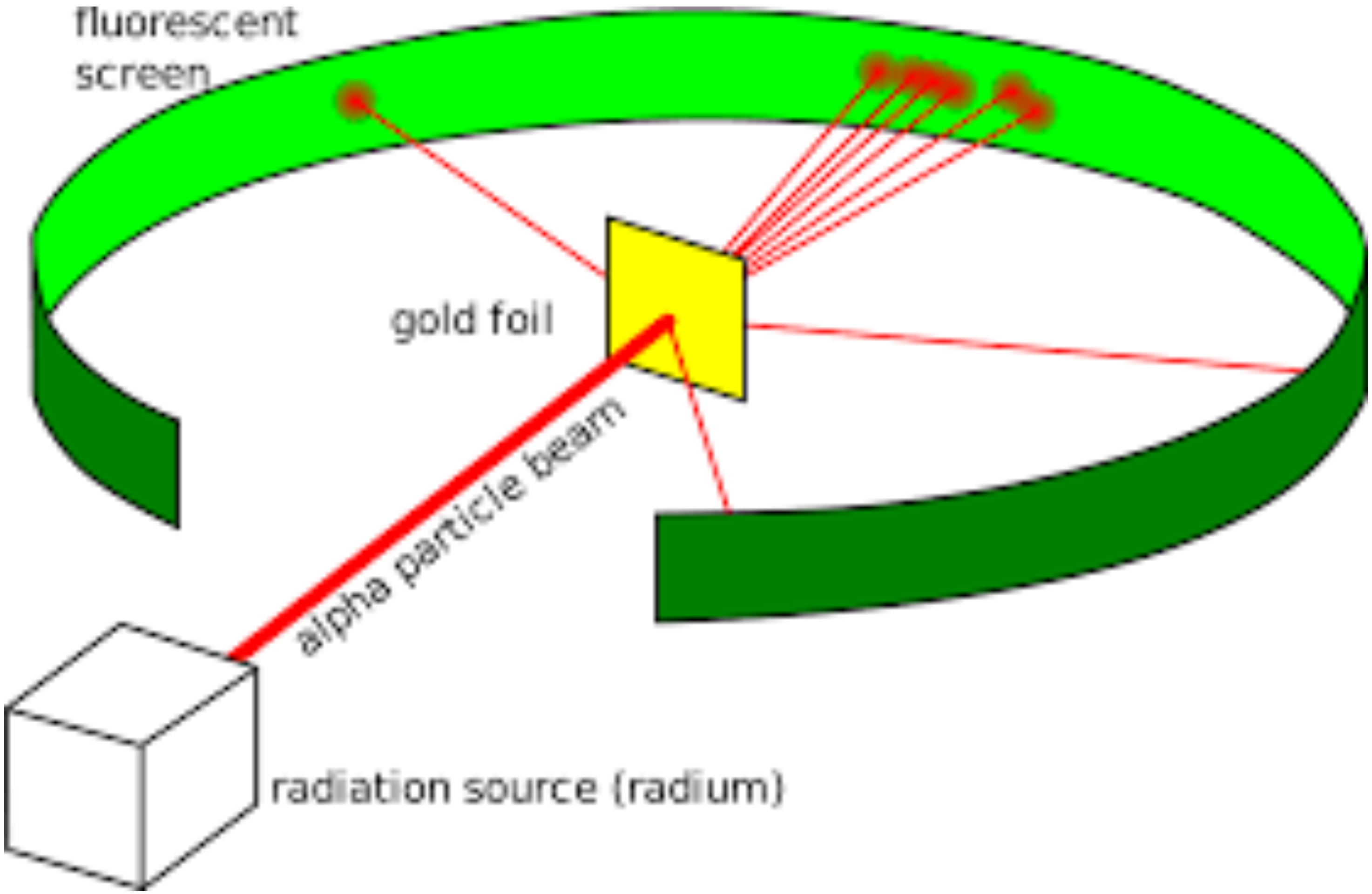
Molecules
↓
Atoms
↓
Positive and negative charges

- Ernest Rutherford: scattering of probe particles off matter as a means of investigating substructure



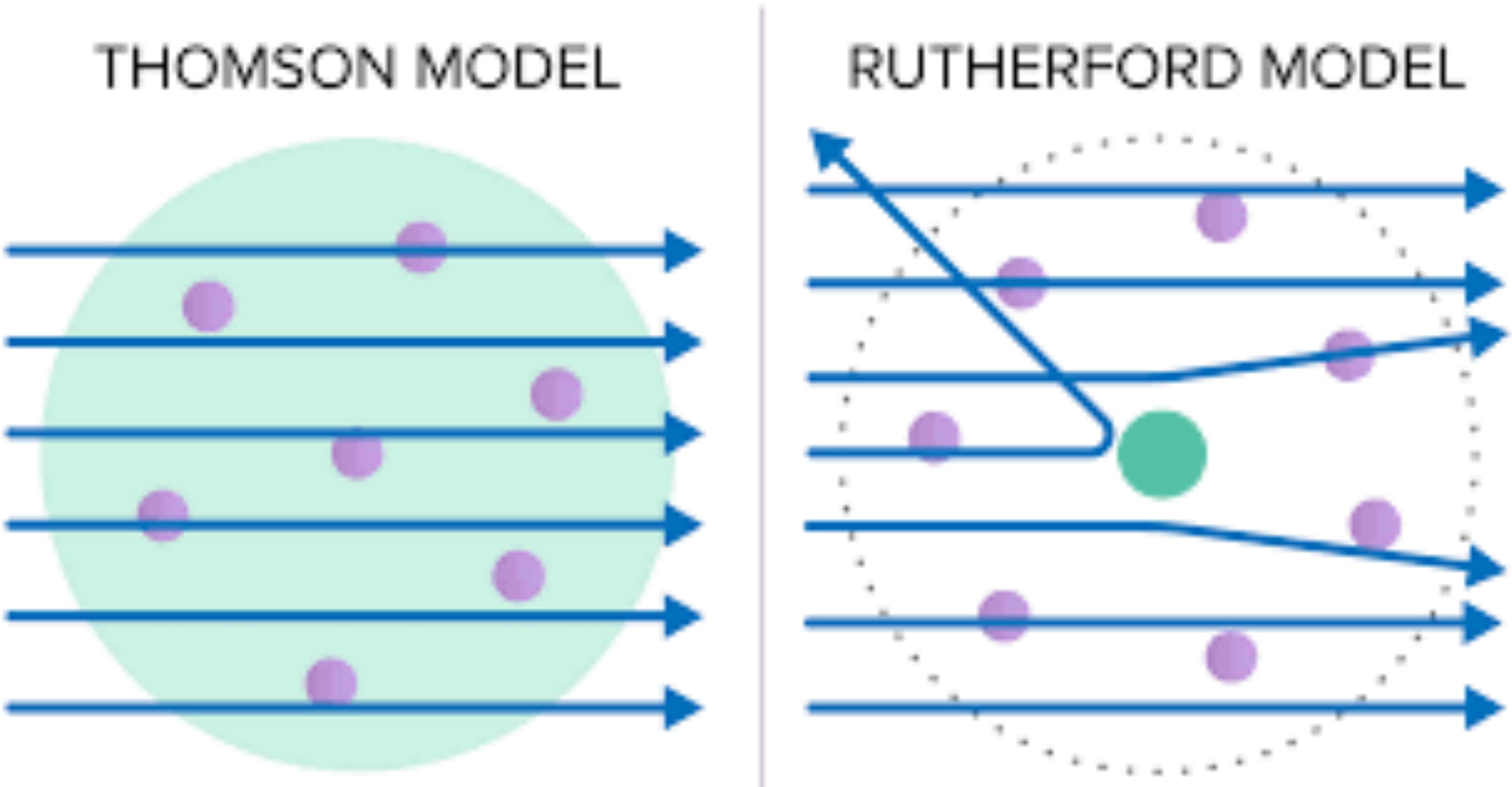
Scattering at large angle due to small, heavy charged core: atomic nucleus

Origin of Particle Physics



Rutherford's scattering experiment of 1911

Origin of Particle Physics



From Atoms to Quarks

- Technique of scattering exploited repeatedly with beams of higher energy to probe smaller distances

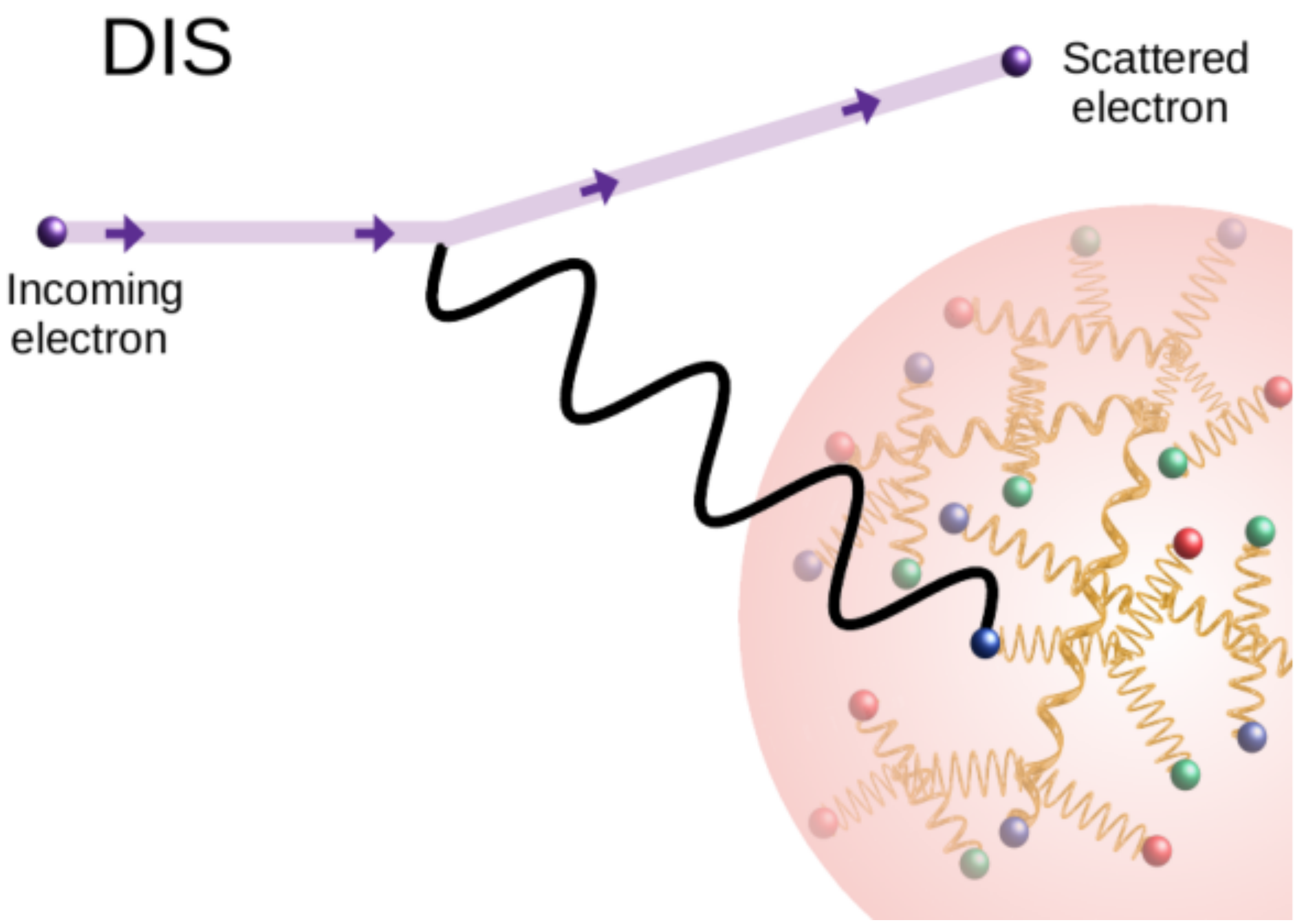
$$\Delta r \sim \hbar c / \Delta E$$

	r	Energy
Atom	10^{-10} m	10 electron-Volts (eV)
↓ Nucleus	10^{-15} m	10^{6} eV (MeV)
↓ Proton, neutron	10^{-18} m	1000 MeV (GeV)
↓ 'partons'	$<10^{-18}$ m	> GeV

- Scattering of electrons at high energy (early 1970's by the SLAC-MIT experiment) provided evidence of nucleon constituents: quarks

- Many particles explained as different combinations of few quarks

From Atoms to Quarks

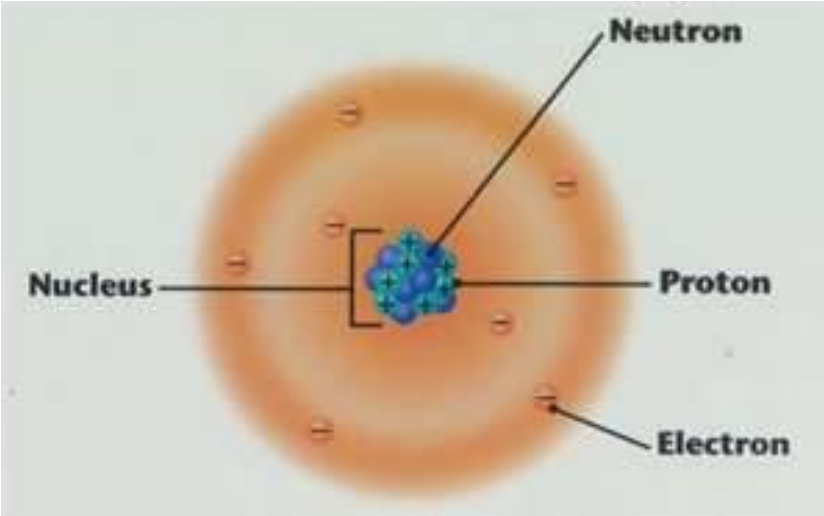


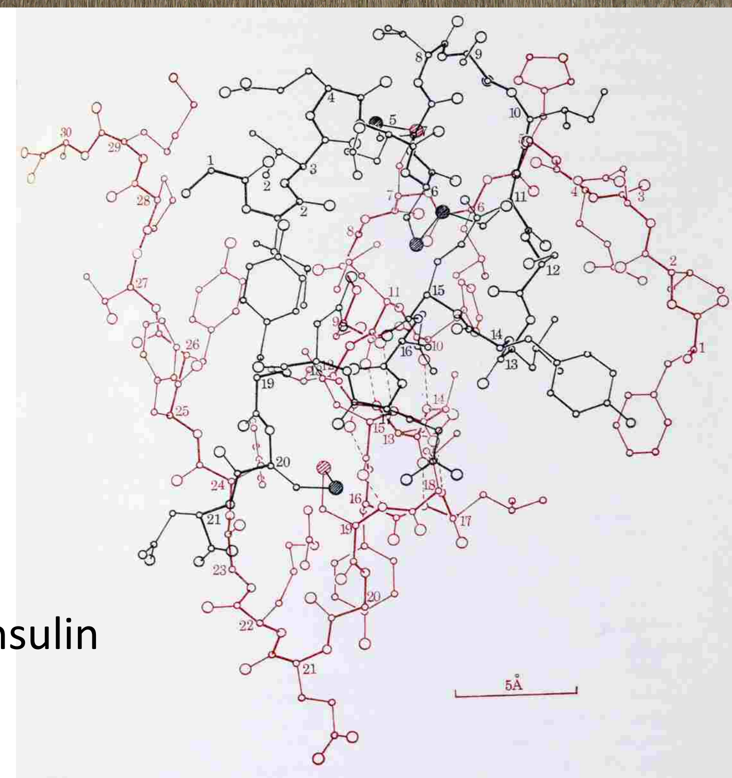
DIS = Deep Inelastic Scattering

20^{th} Century Built on Quantum Mechanics

- The scientific advances of the 20^{th} century have transformed our lifestyle

- Impact of Quantum Mechanics
  - All electronics devices, computers and communication
  - Nuclear power
  - Atomic and molecular manipulation of materials for chemical and biological applications





Molecule of Insulin

Foundations of 20th Century Physics

- Quantum Mechanics

- Special Relativity

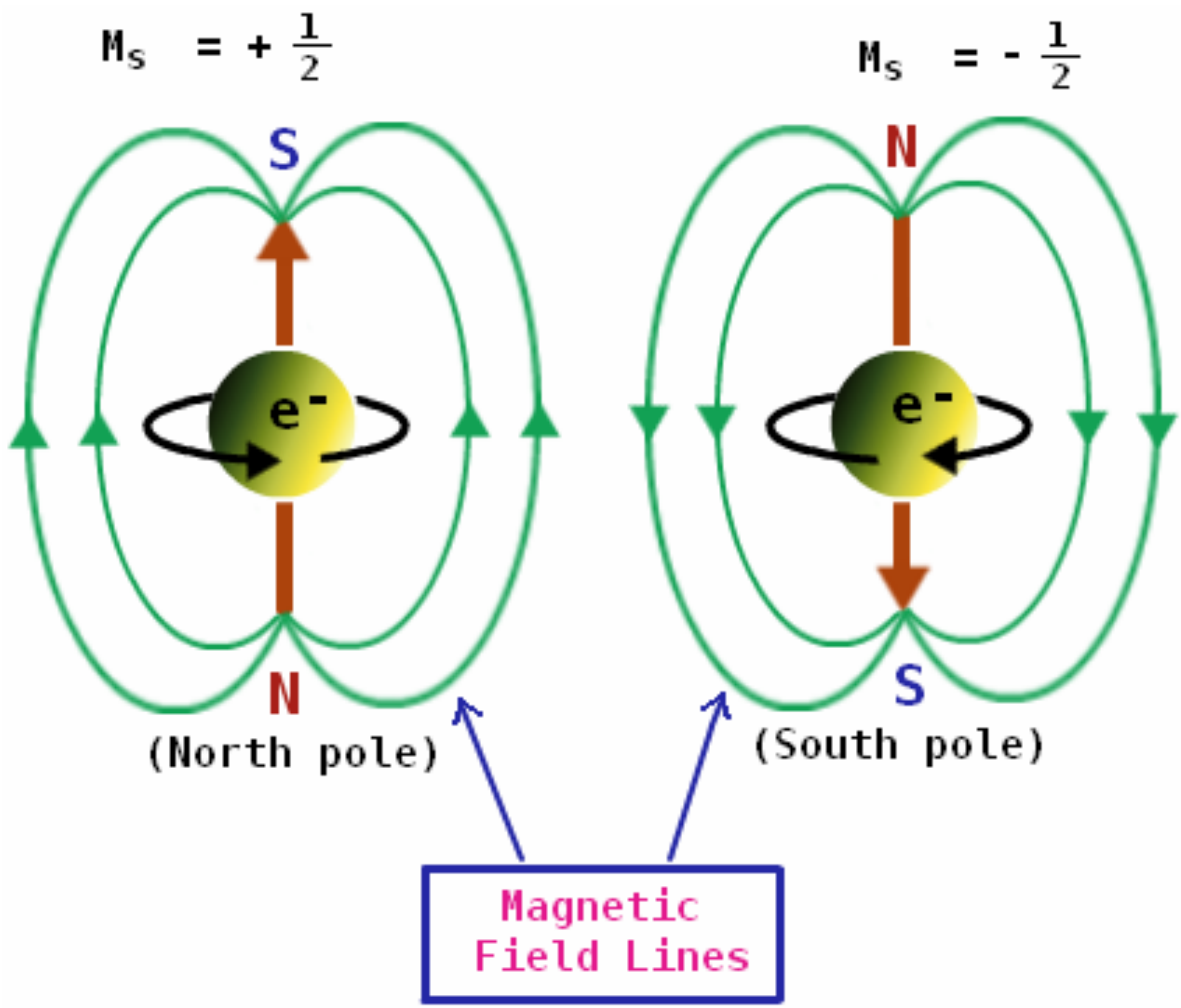
- Combination of these fundamental principles – Relativistic Quantum Theory

Founders of 20th Century Physics

Foundations of 20th Century Physics

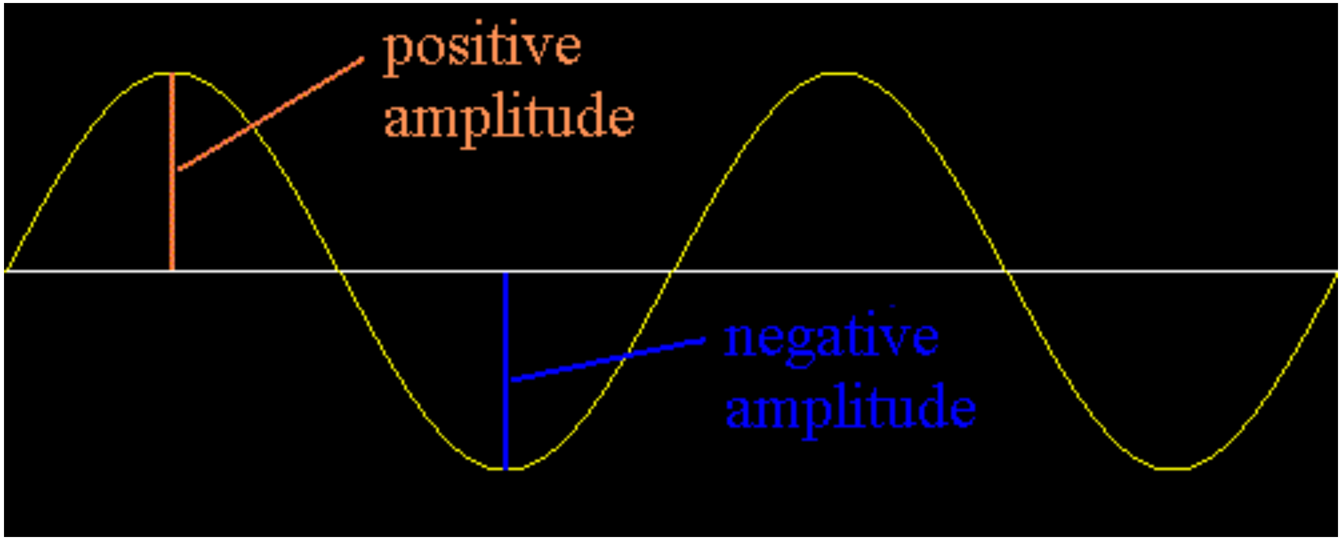
- Quantum Mechanics
- Special Relativity
- Combination of these fundamental principles – Relativistic Quantum Theory
  - Initiated by Paul Dirac

Fundamental Properties of Electrons



Effect of Complete Rotation

- Quantum Mechanics + Special Relativity =>
  Dirac and others showed mathematically that electron can be the type of particle that becomes negative of itself under a complete rotation



Identical Particles are Indistinguishable

- Bose solved a major puzzle in quantum mechanics by proving that particles of the same type are indistinguishable

Satyendra Nath Bose in 1920's

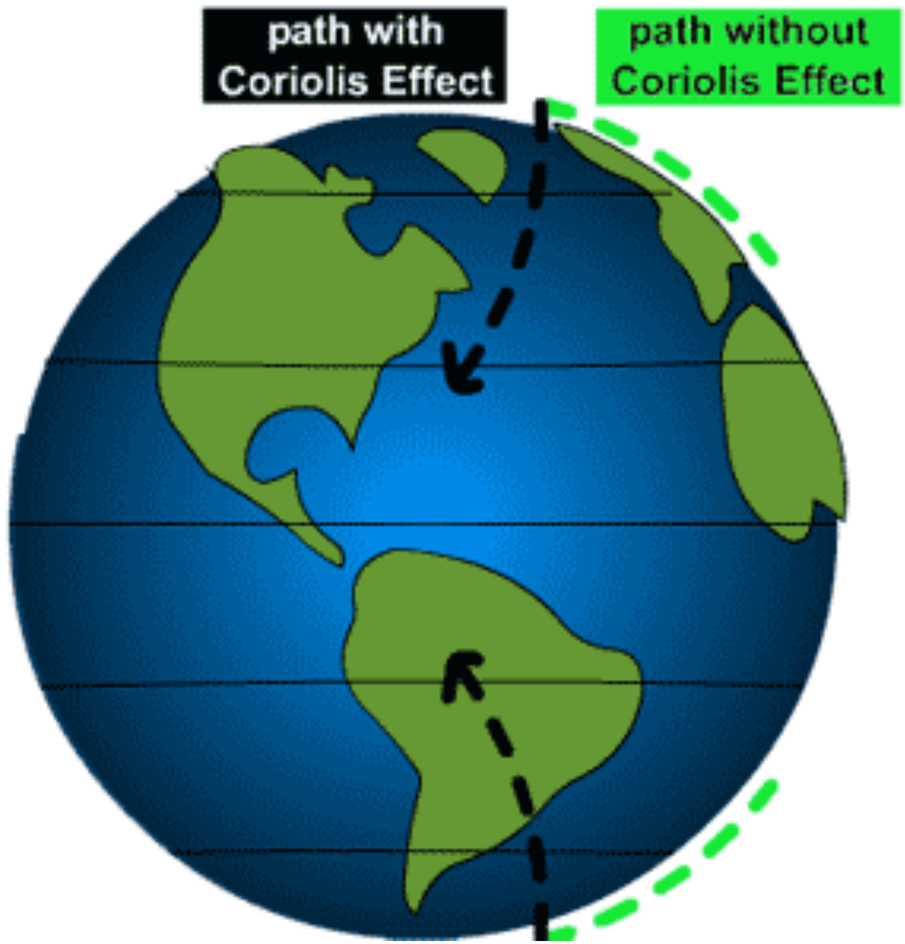
Towards a Fundamental Theory of Matter

Interchange between two electrons ⇔ rotate one by 360 deg.

Why Matter Occupies Volume

- $\psi(e_1, e_2) = -\psi(e_2, e_1)$
- But if two electrons occupied the same spot in space
- $\psi(e_1, e_2) = \psi(e_2, e_1)$
- Wave that both equal to itself and equal to negative of itself must be ZERO
- Pauli Exclusion Principle – identical particles like electrons, protons, neutrons cannot be at the same point in space at the same time
- This is a fundamental explanation for why matter is made up of fermions and why matter occupies volume

How to Predict Fundamental Forces



“fictitious” forces observed in accelerating frame of reference

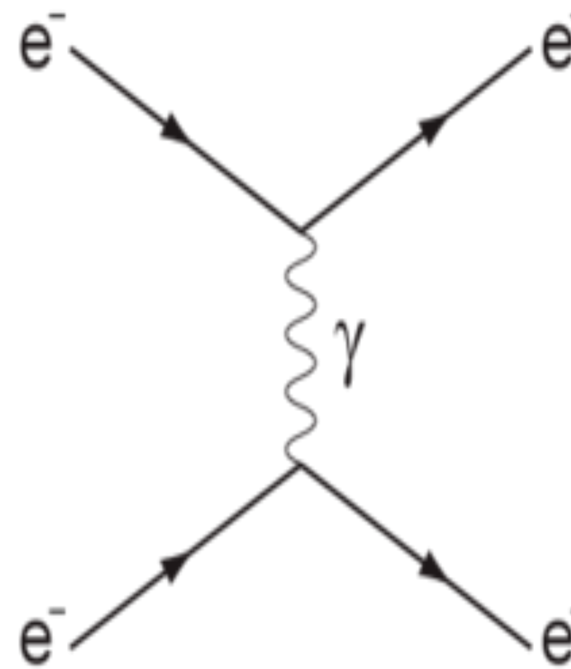
Manifestation of Coriolis Force

Hurricanes appear to rotate in Earth's frame of reference

Quantum Mechanics
force ⇔ particle exchange

Feynman Diagram: Force by Particle Exchange

Richard Feynman



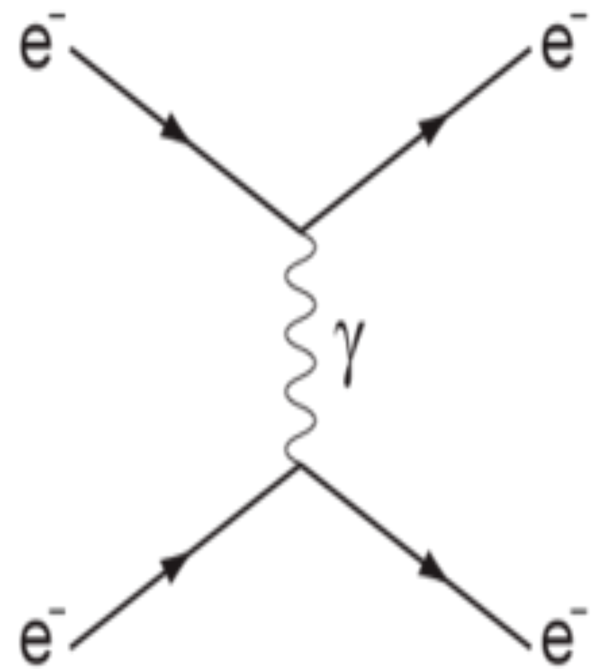
Electromagnetic force between two electrons mediated by "photon" exchange

Feynman Diagram: Force by Particle Exchange

The most precisely tested theory, ever:

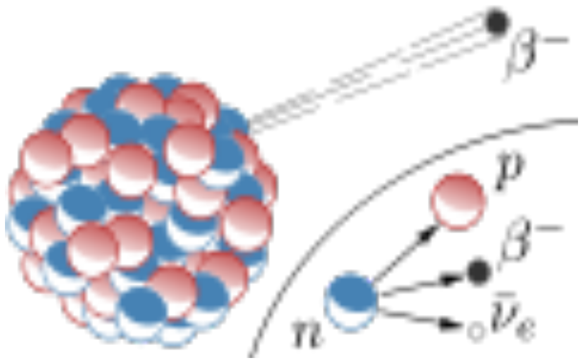
The quantum theory of the electric and magnetic forces, radio waves, light and X-rays:

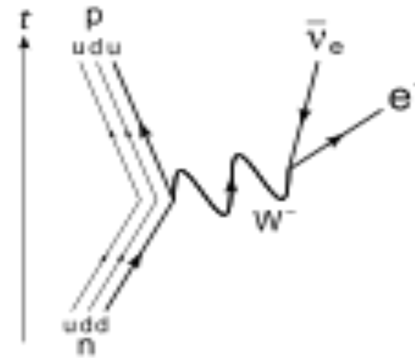
Measured and predicted magnetic moment of an electron agree within 0.3 parts per trillion accuracy



Electromagnetic force between two electrons mediated by "photon" exchange

Weak Nuclear Decay





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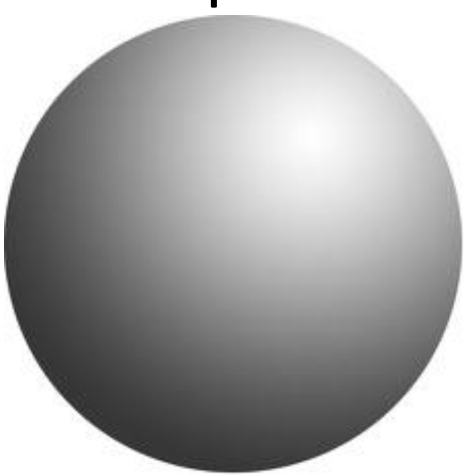
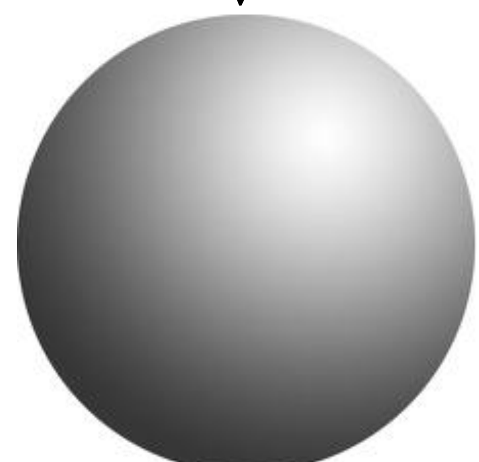


n

The force causing this interaction is described by particles making transitions on a "mathematical sphere"

ν



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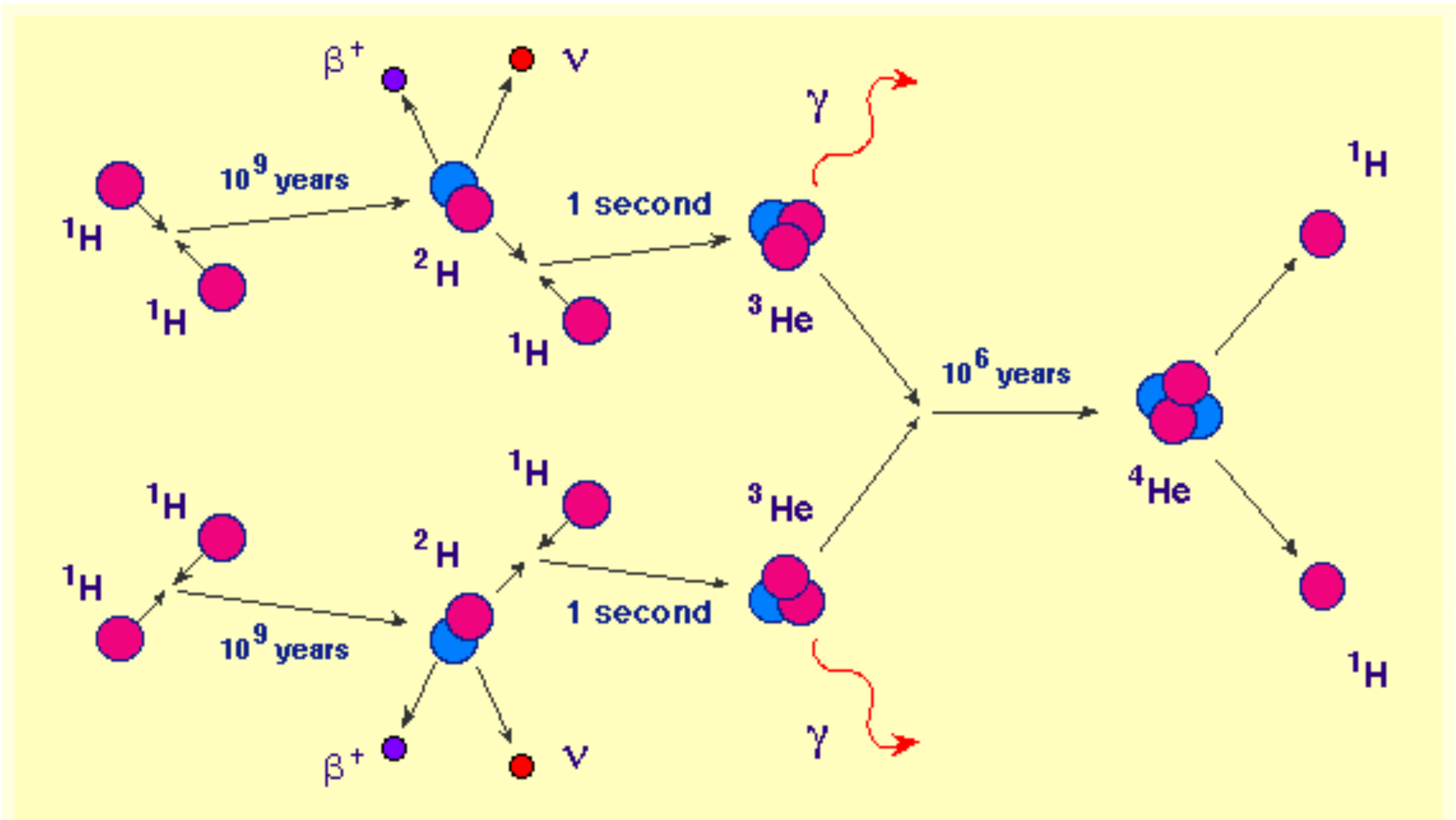
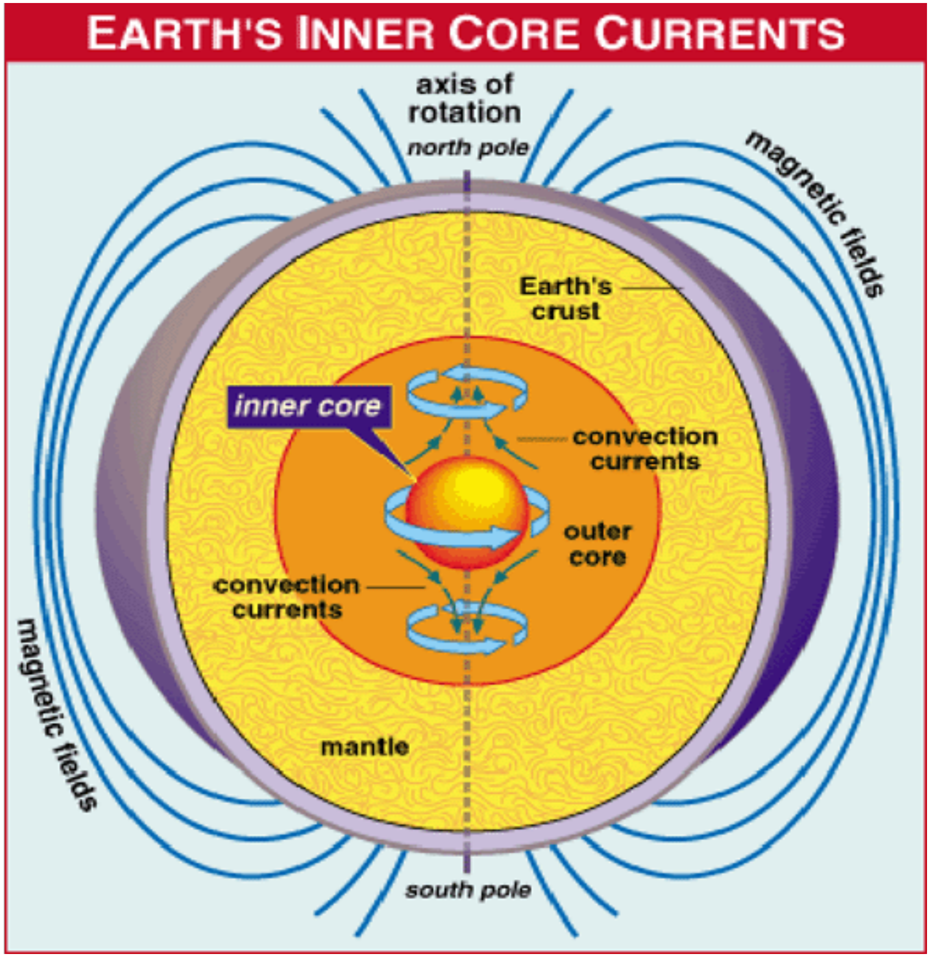
Nuclear Fusion in Sun's Core

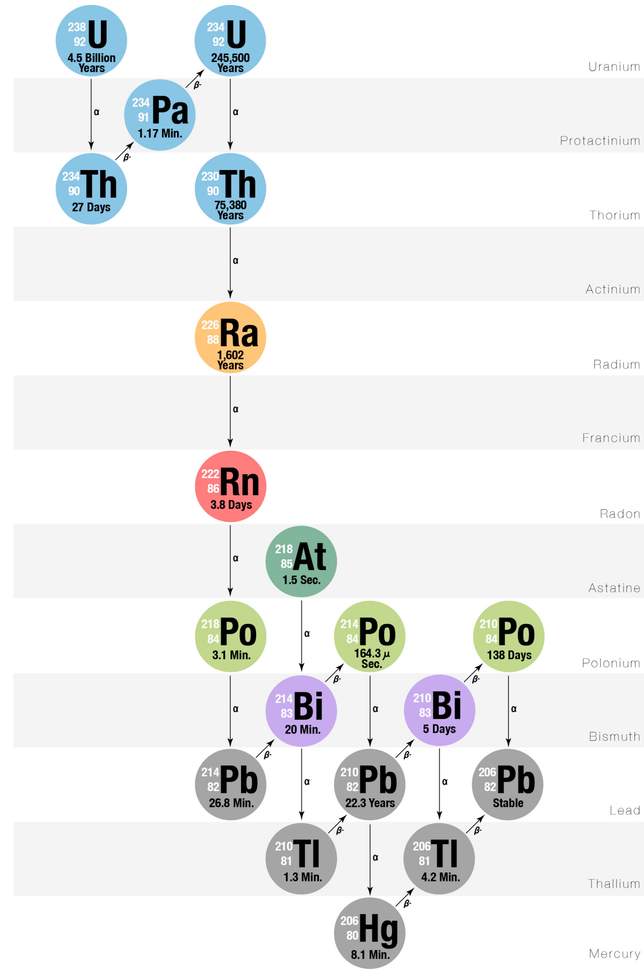


Main branch of the proton–proton chain.

Crucial role of W boson in hydrogen -> helium fusion in Sun's core

What Keeps the Earth's Core Molten?





Crucial role of W boson in keeping Earth core molten and generate protective magnetic shield against harmful solar radiation

Success and Problem of Force Theory

- Success: correct mathematical description of all properties of electromagnetic force and the weak nuclear force
- Another prediction: force-mediating particles must be massless
- Correct prediction for photon – mediator particle of electric and magnetic forces and all electromagnetic waves: radio, light, microwave, x-rays described by massless photons
- Problem: for the weak nuclear force causing nuclear beta-decay, the mediator particle, “W boson” is very heavy
- Question: How can we preserve the original theory and simultaneously impart mass to the W boson?

How does the W boson Acquire Mass?

- Fill all of space with "Higgs" field
- Particles propagating through "empty space" actually propagating though Higgs field
- Interaction of particles with Higgs field slows down the particle ⇔ imparting the property of mass to it

Light versus Heavy Particles –
like moving through water

Streamlined
⇒ Moves fast through water
⇒ analogous to light particle

Not streamlined
⇒ Moves slowly through water
⇒ analogous to heavy particle

How did we confirm the existence of the Higgs?

- Create ripples in the Higgs field

Ripples ⇔ Higgs boson

A Century of Particle Physics

- Success # 1: discovery of 6 quarks and 6 leptons
- 12 fundamental fermions: matter particles (and their antimatter counterparts) derived by combining quantum mechanics and special relativity

Quarks

$$\mathrm{u} < 1\ \mathrm{GeV} \quad \mathrm{c} \sim 1.5\ \mathrm{GeV} \quad \mathrm{t} \sim 175\ \mathrm{GeV}$$
$$\mathrm{d} < 1\ \mathrm{GeV} \quad \mathrm{s} < 1\ \mathrm{GeV} \quad \mathrm{b} \sim 4.5\ \mathrm{GeV}$$

But the intriguing pattern of mass values is not explained – just blamed on Higgs boson interactions

Leptons

$$\nu_e < 1\ \mathrm{eV} \quad \nu_\mu < 0.17\ \mathrm{MeV} \quad \nu_\tau < 24\ \mathrm{MeV}$$
$$\mathrm{e}\ 0.5\ \mathrm{MeV} \quad \mu\ 106\ \mathrm{MeV} \quad \tau\ 1.8\ \mathrm{GeV}$$

A Century of Particle Physics

- Success # 2: principle of gauge invariance for *predicting* the nature of fundamental forces
  - matter particles (quarks and leptons) transform in *curved* internal spaces
  - The equations of motion predict terms that describe particle interactions with force fields

Gauge sector $$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

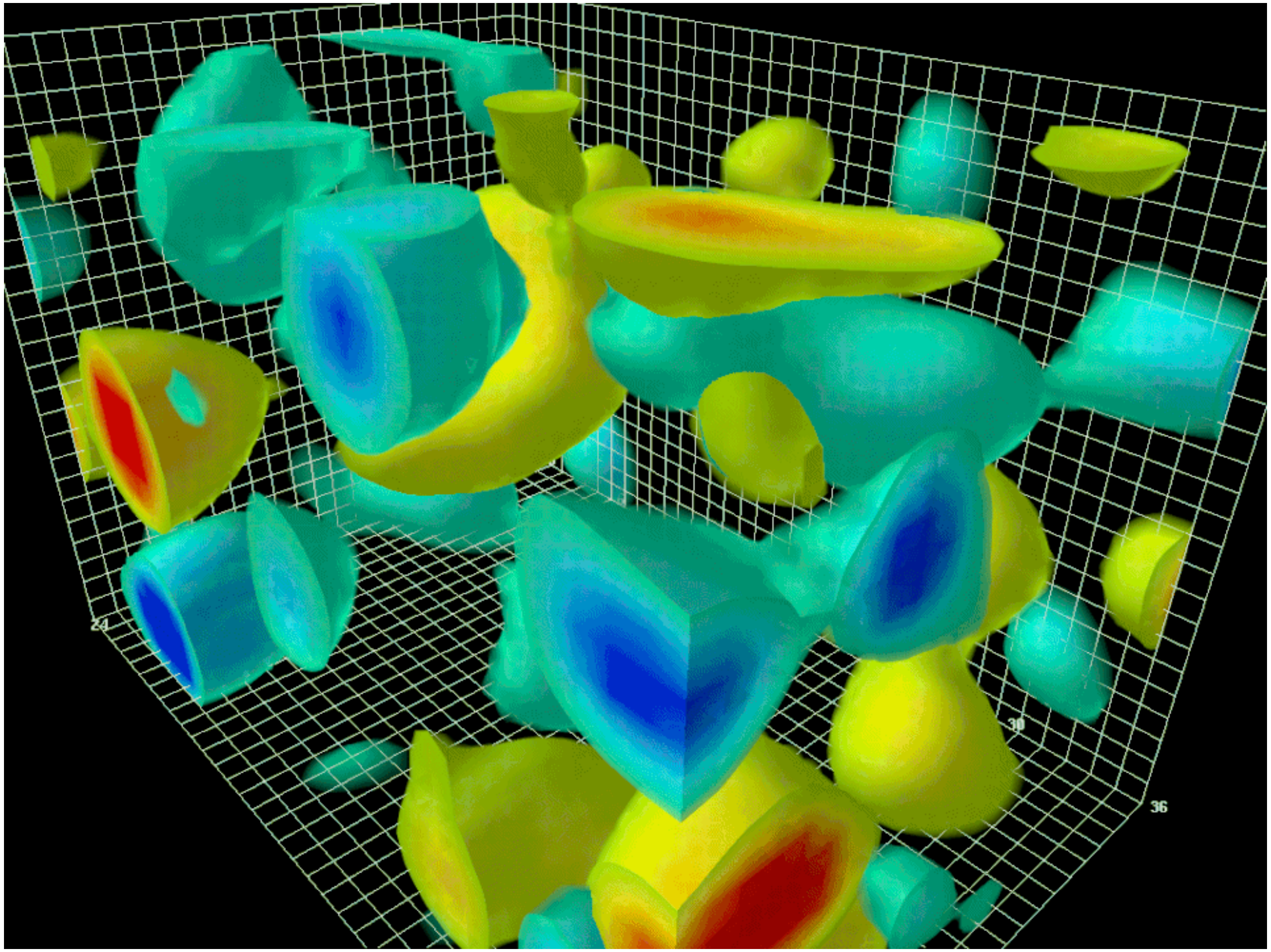
The Vacuum is a Quantum Foam

Implication of Heisenberg Uncertainty Principle

$$\Delta E \sim h \,/\, \Delta t$$

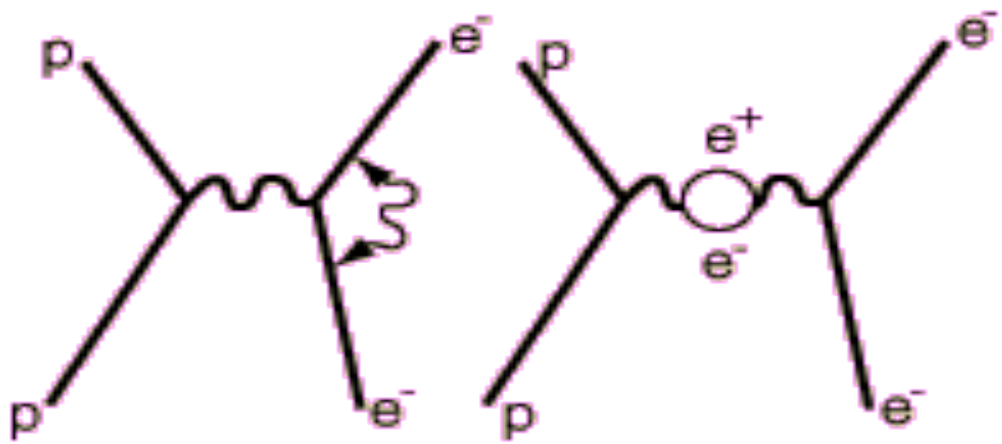
- Nature can "borrow" energy of amount ΔE for a short time Δt
- The shorter the time period of this "energy loan", the larger the amount of the loaned energy that is available
- Therefore the vacuum is a bubbling foam with high-energy particles popping up and disappearing

The Vacuum as a Quantum Foam

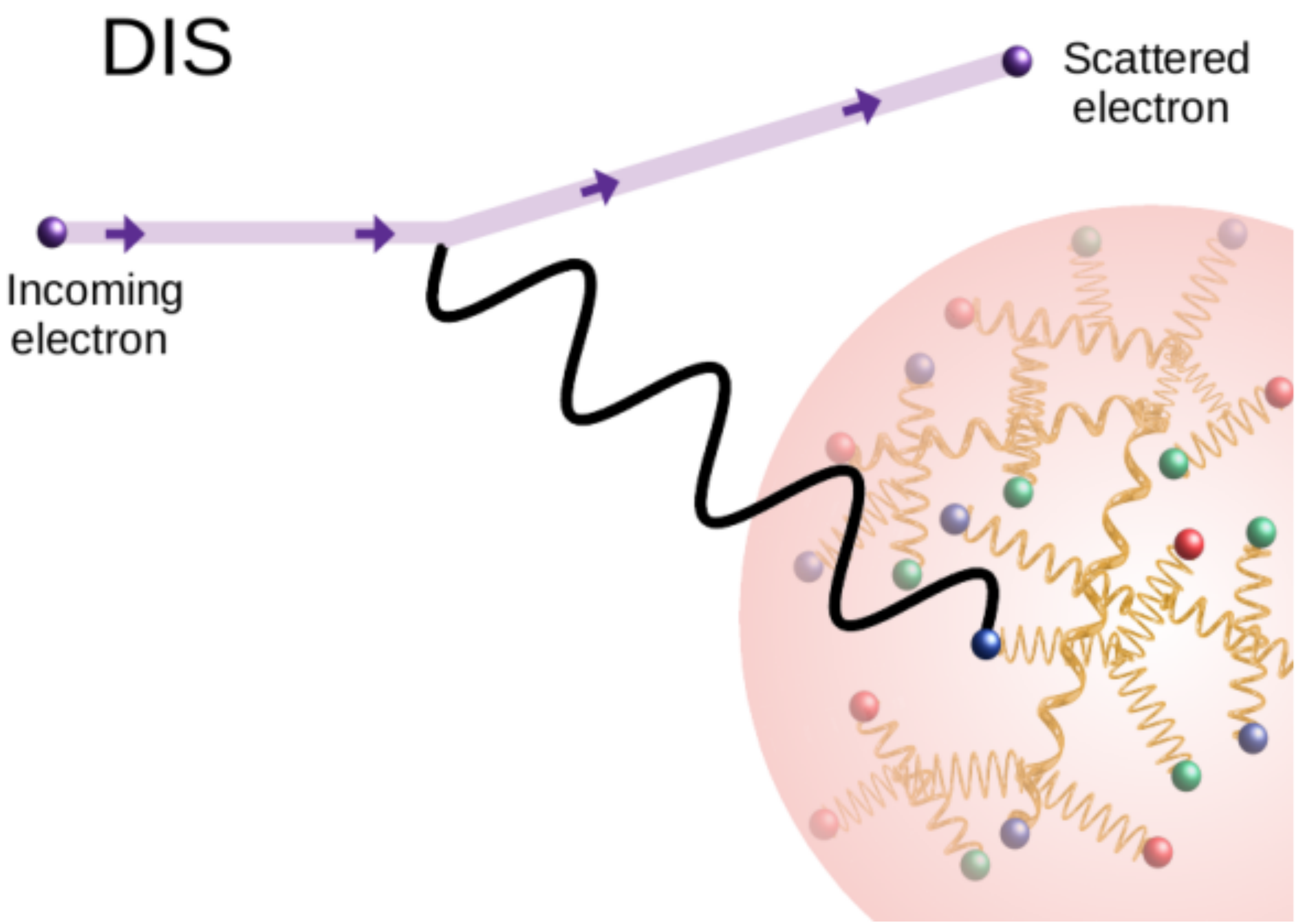


Detecting New Physics through Precision Measurements

- Willis Lamb (Nobel Prize 1955) measured the difference between energies of $^2S_{1/2}$ and $^2P_{1/2}$ states of hydrogen atom
  - Observed one part per million difference in their energies
  - States should have the same energy in the absence of vacuum fluctuations
- Harbinger of vacuum fluctuations to be calculated by Feynman diagrams containing quantum fluctuations
  - Modern quantum field theory of electrodynamics followed (Nobel Prize 1965 for Schwinger, Feynman & Tomonaga)

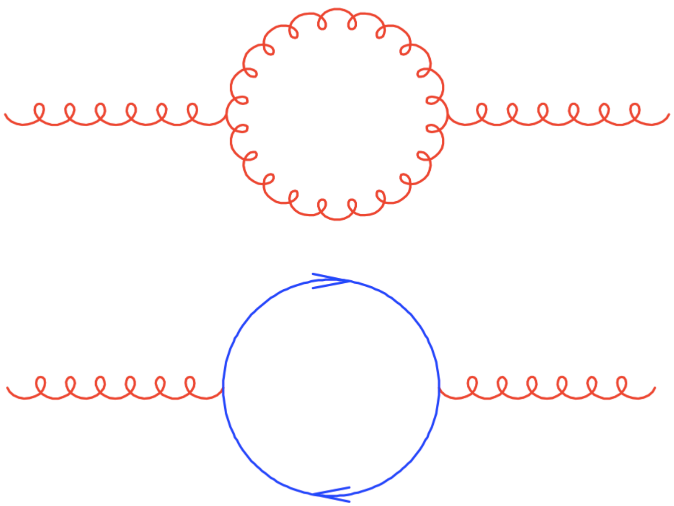


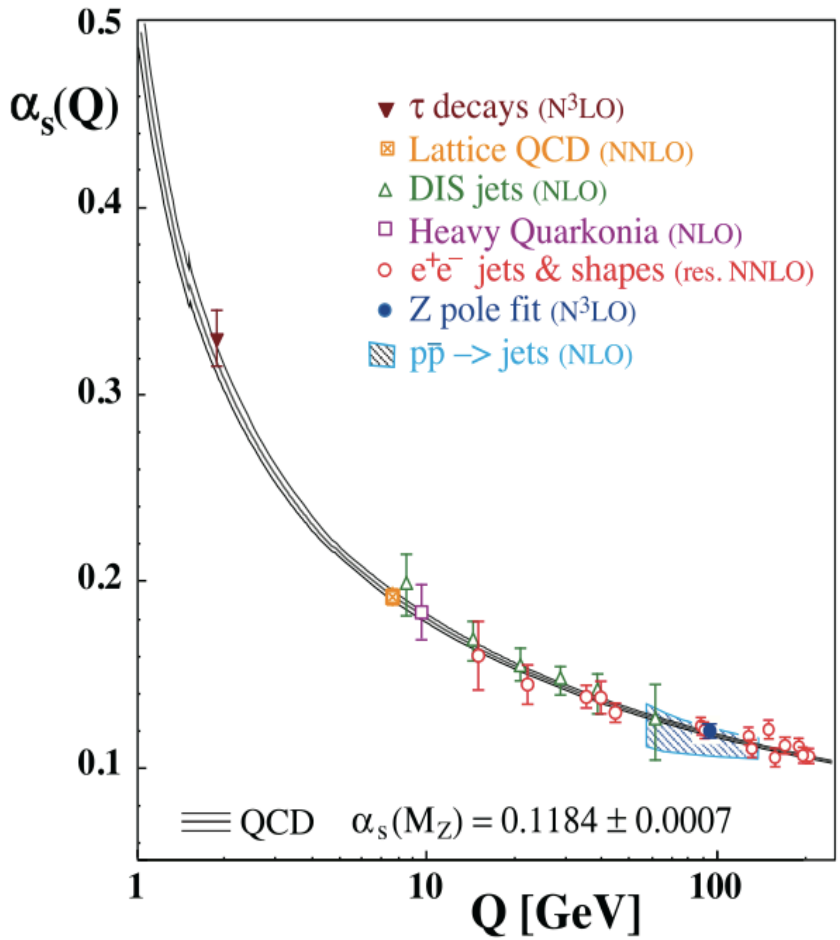
From Atoms to Quarks



DIS = Deep Inelastic Scattering

Test of Quantum Fluctuations at High Energy





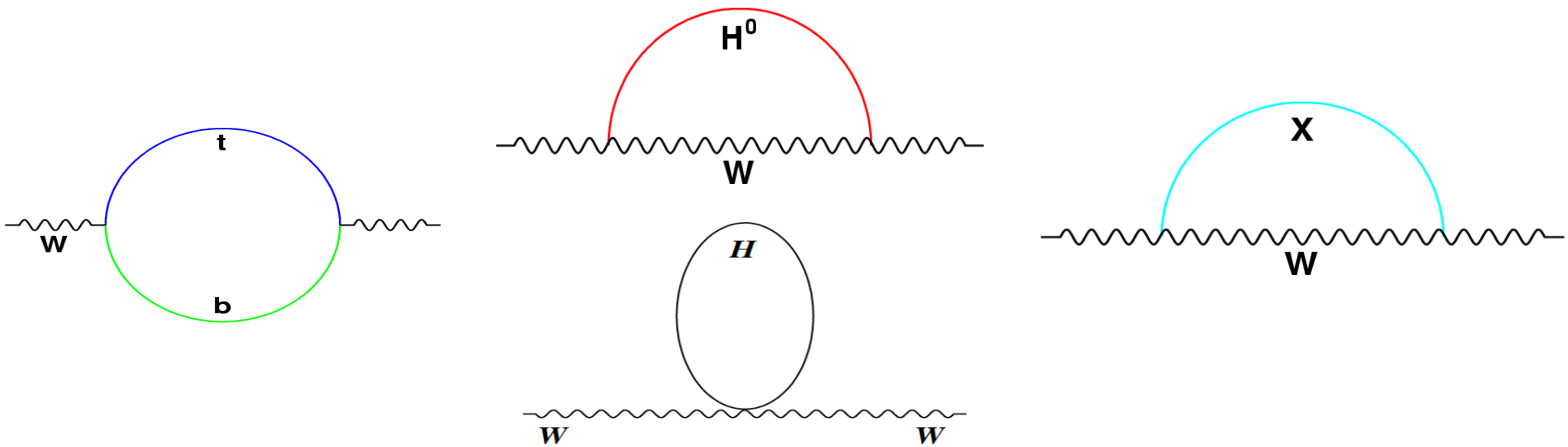
(Gross & Wilczek, Politzer, 1973

Changing strength of the strong force with energy has been confirmed experimentally

The Vacuum Quantum Foam and the W boson Mass

Motivation for Precision Measurement of W boson Mass

- Quantum fluctuations due to top quark and Higgs boson and (potentially) undiscovered particles



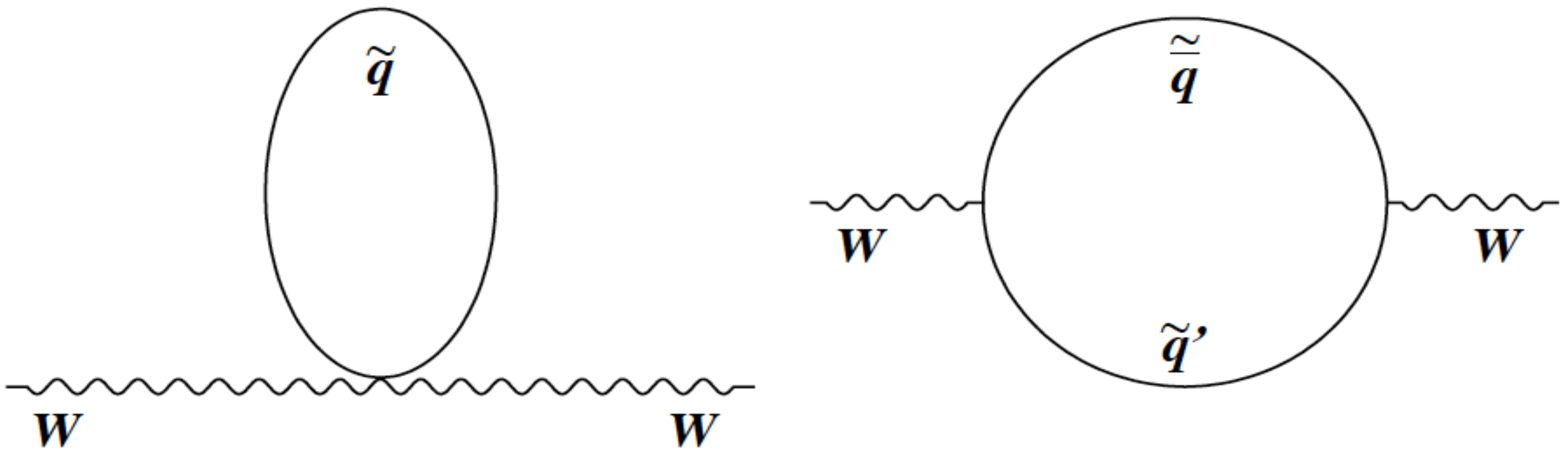
Standard Model calculation of the quantum fluctuations:

- Since we know top quark and Higgs boson masses, comparing measured and calculated values of W boson mass tells us about new particles "X" beyond the Standard Model

Motivation for Precision Measurement of W boson Mass

- The mass of the W boson is precisely calculable in Standard Model theory
  - The Higgs boson was the last missing component of the model
- The W boson mass is calculated to accuracy of 0.01%
  - Standard Model expectation
  - $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ MeV
  - A target for comparison to experimental measurement

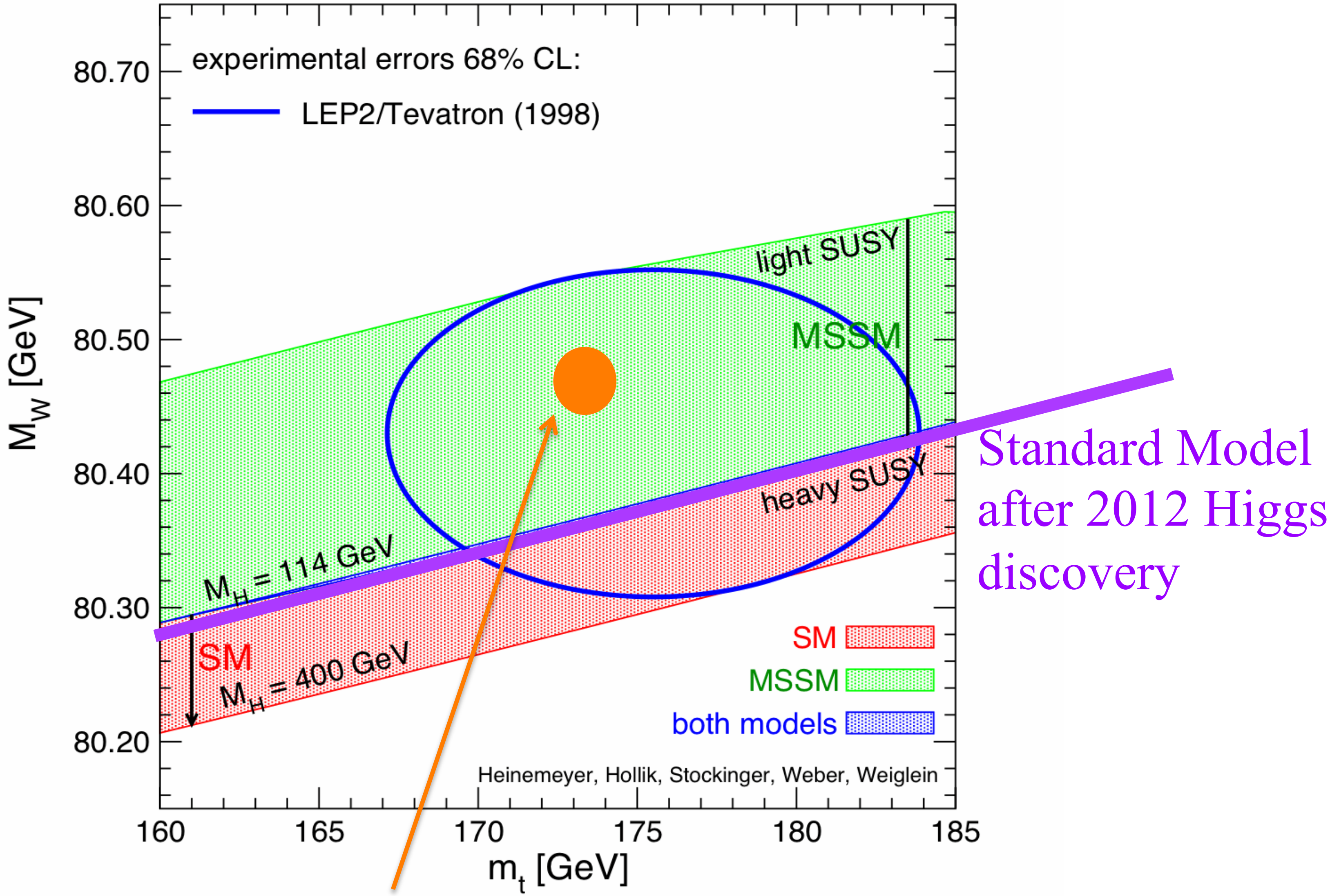
Quantum Fluctuations from Supersymmetric Particles



- Quantum fluctuations involving supersymmetric particles contribute to the W boson mass

- Supersymmetric particle could constitute dark matter

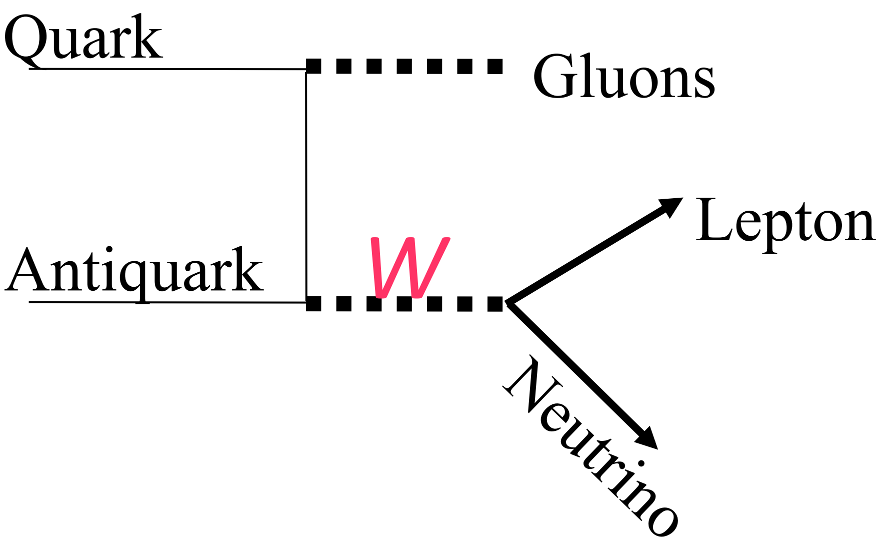
2022 Status of M_W *vs* M_{top}



Science **376**, 170 (April 7, 2022); DOI: 10.1126/science.abk1781

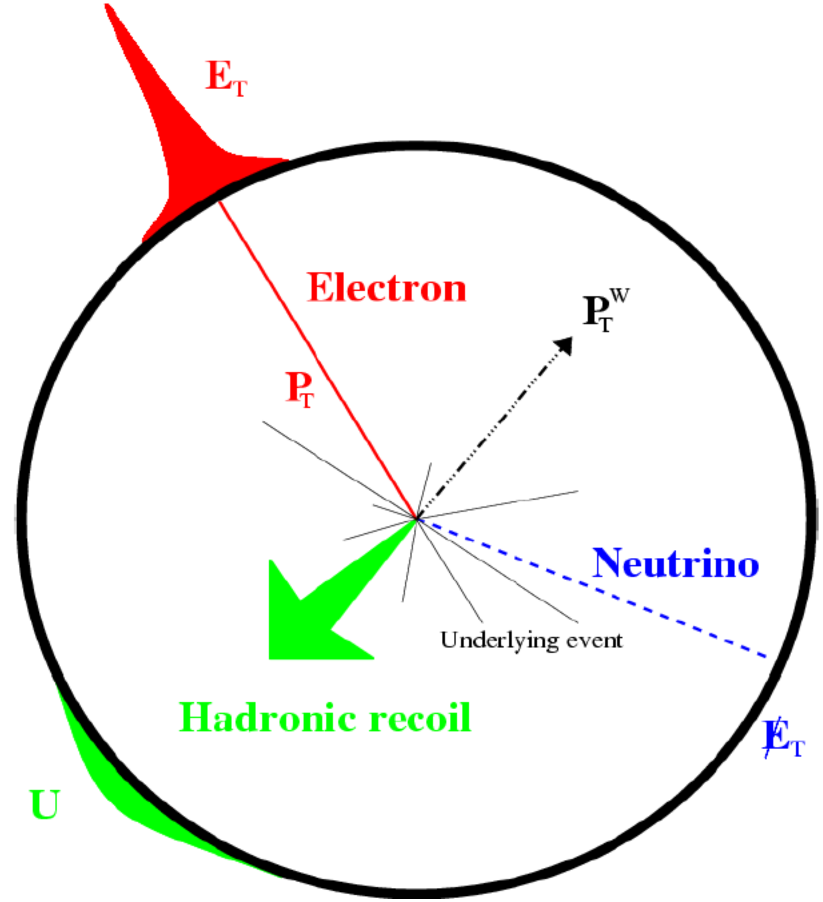
How to Measure the W boson Mass to 0.01% accuracy

W Boson Production in Proton-Antiproton Collisions



Quark-antiquark annihilation produces W boson

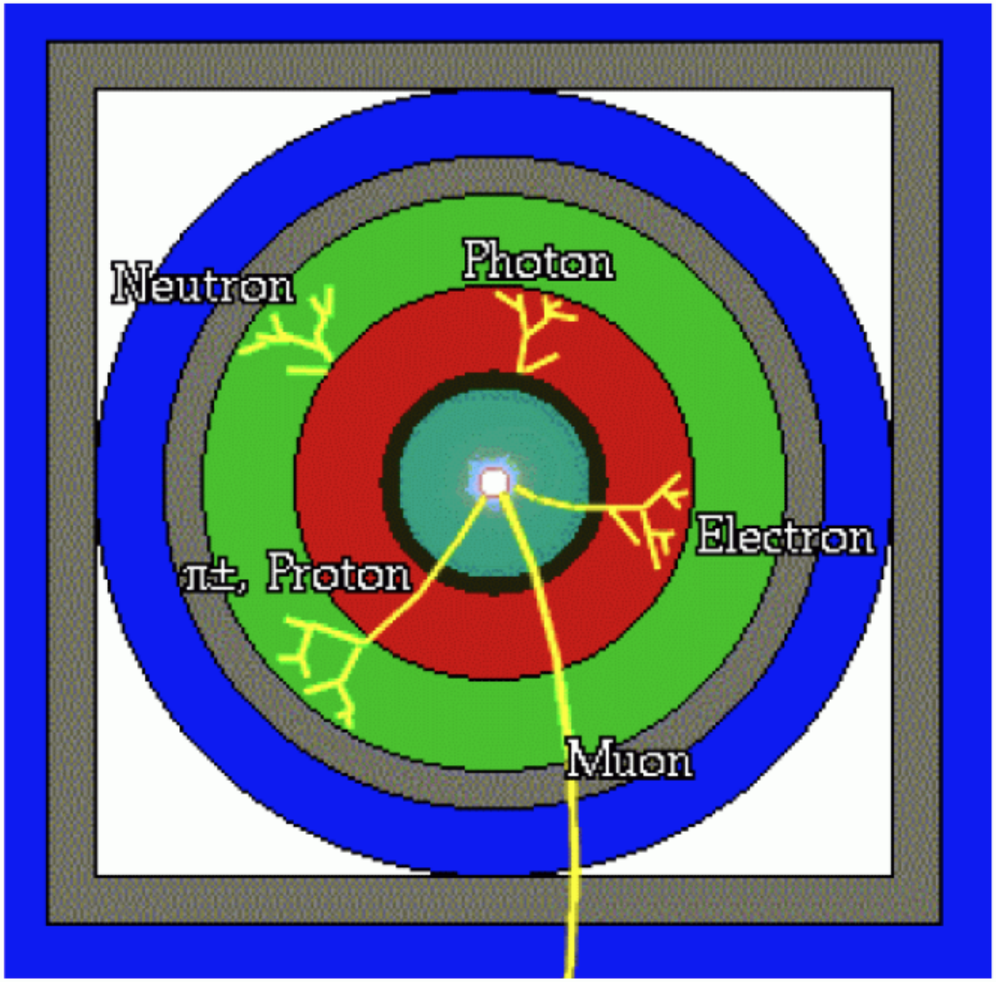
W boson decays to neutrino, accompanied by electron or muon



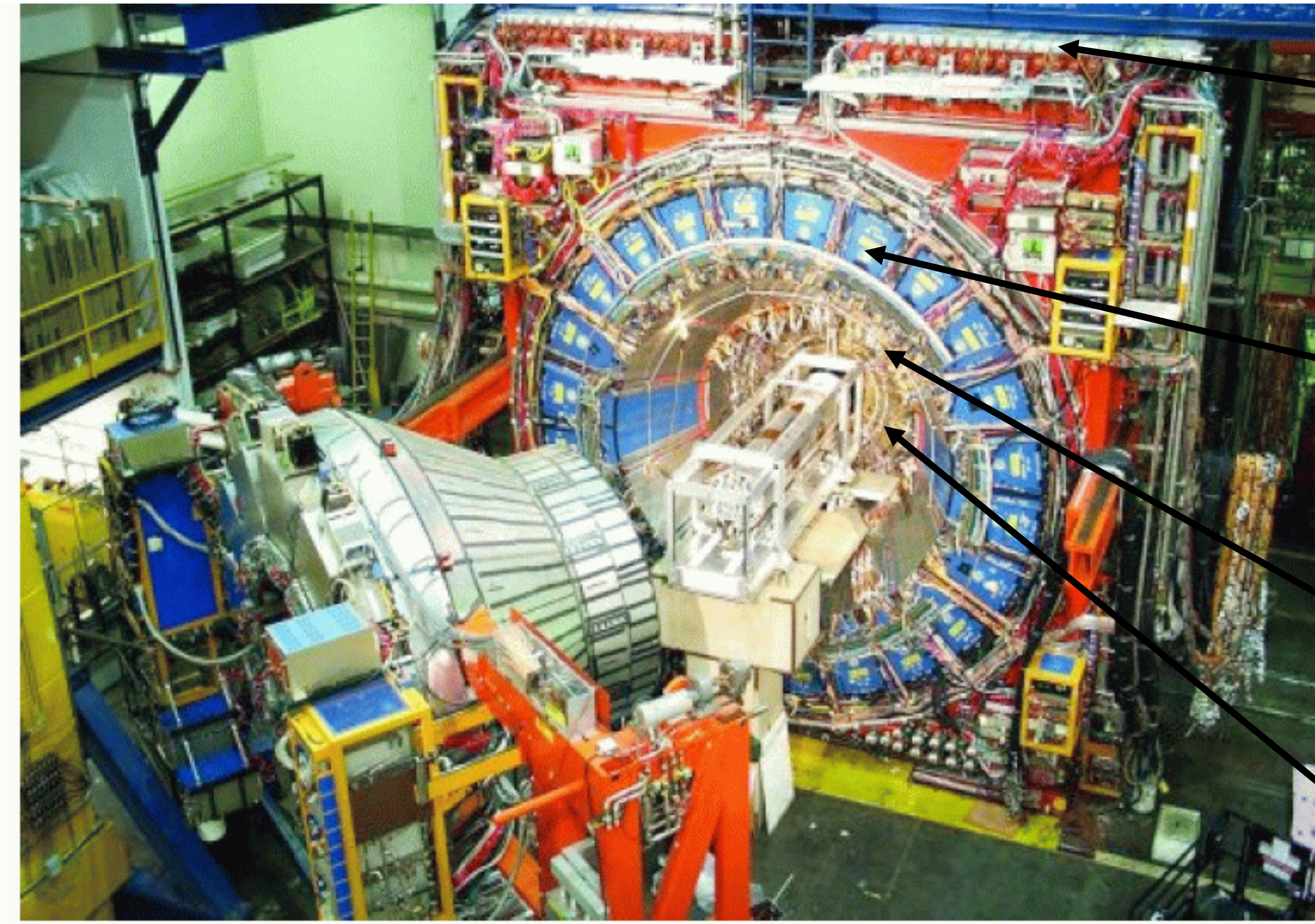
Lepton (electron or muon) momentum carries most of *W* mass information, can be measured precisely (achieved 0.004%)

Particle Detector Design

- Concentric cylinders of different kinds of detector technologies
- Decay products of unstable particles identified



Collider Detector at Fermilab (CDF)



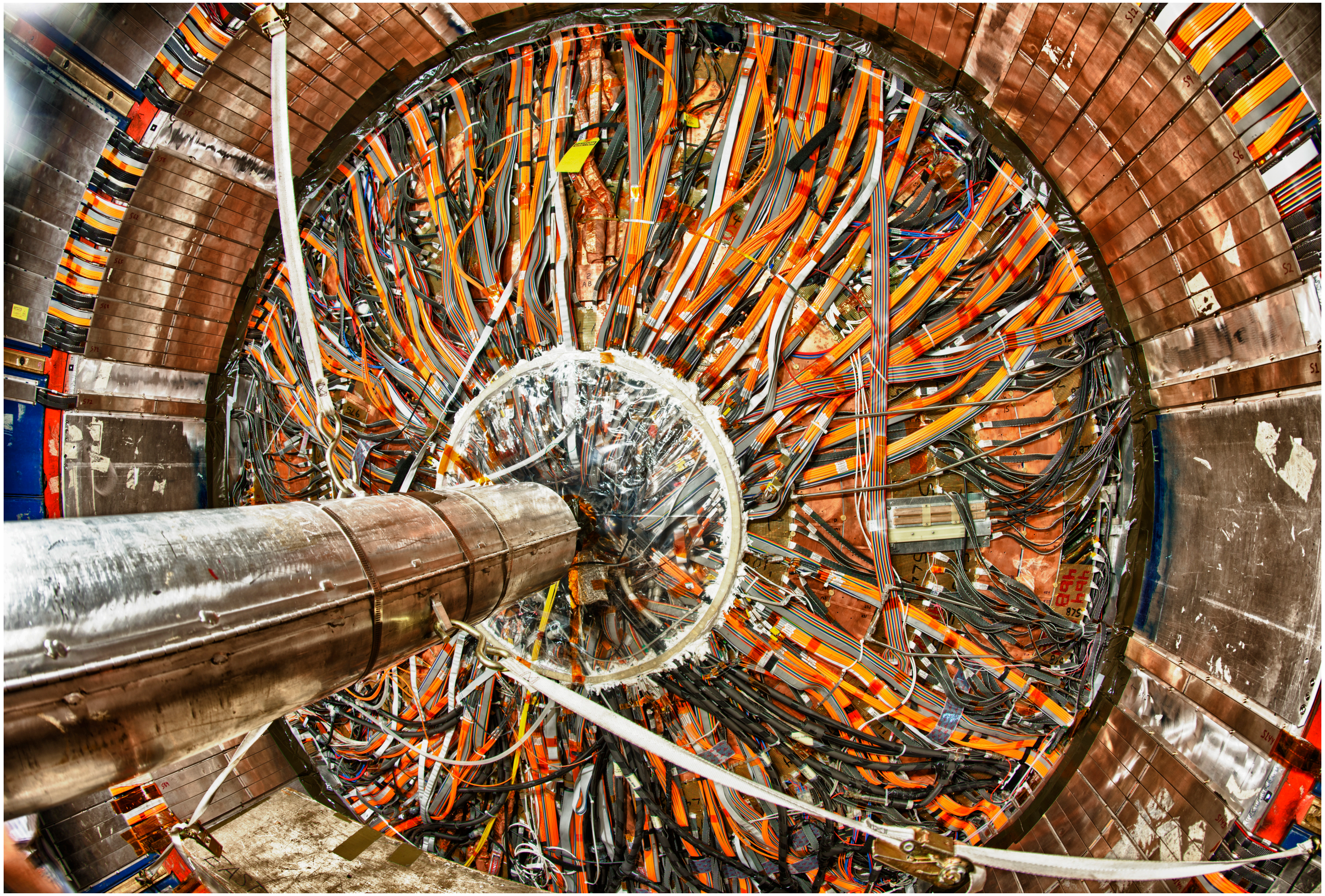
Muon detector

Central hadronic calorimeter

Central EM calorimeter

Drift chamber

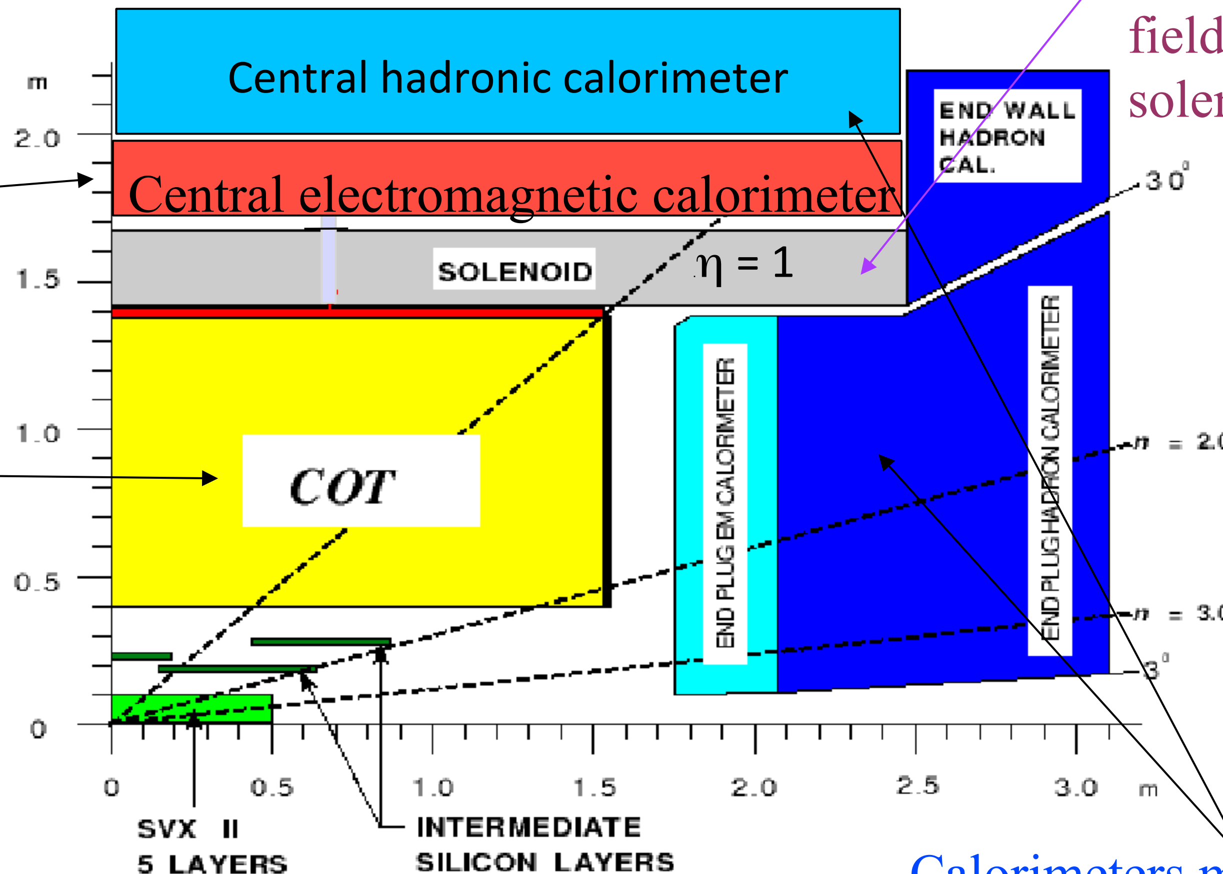
Collider Detector at Fermilab (CDF)



Quadrant of Collider Detector at Fermilab (CDF)

calorimeter provides precise electron energy measurement

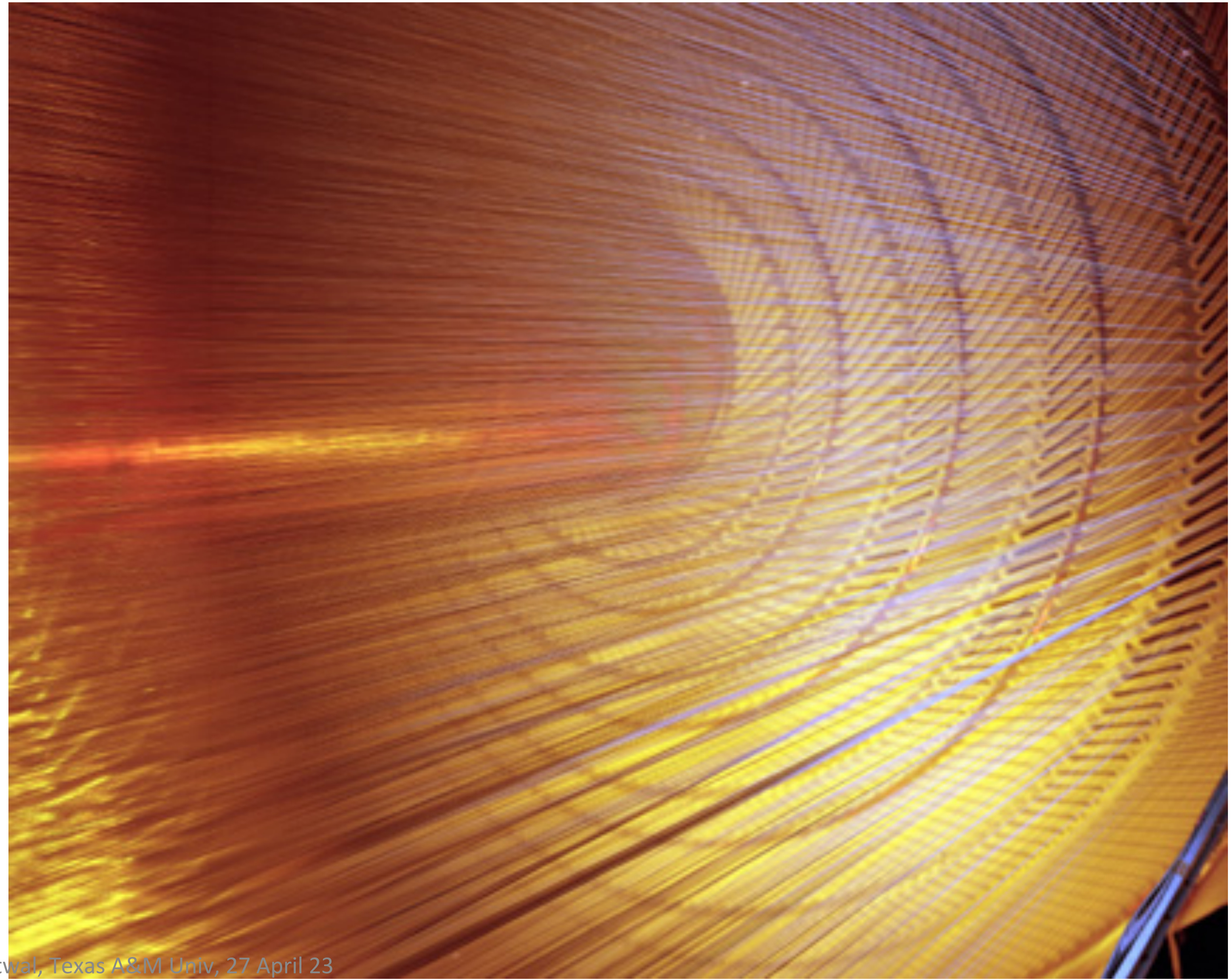
drift chamber provides precise particle momentum measurement



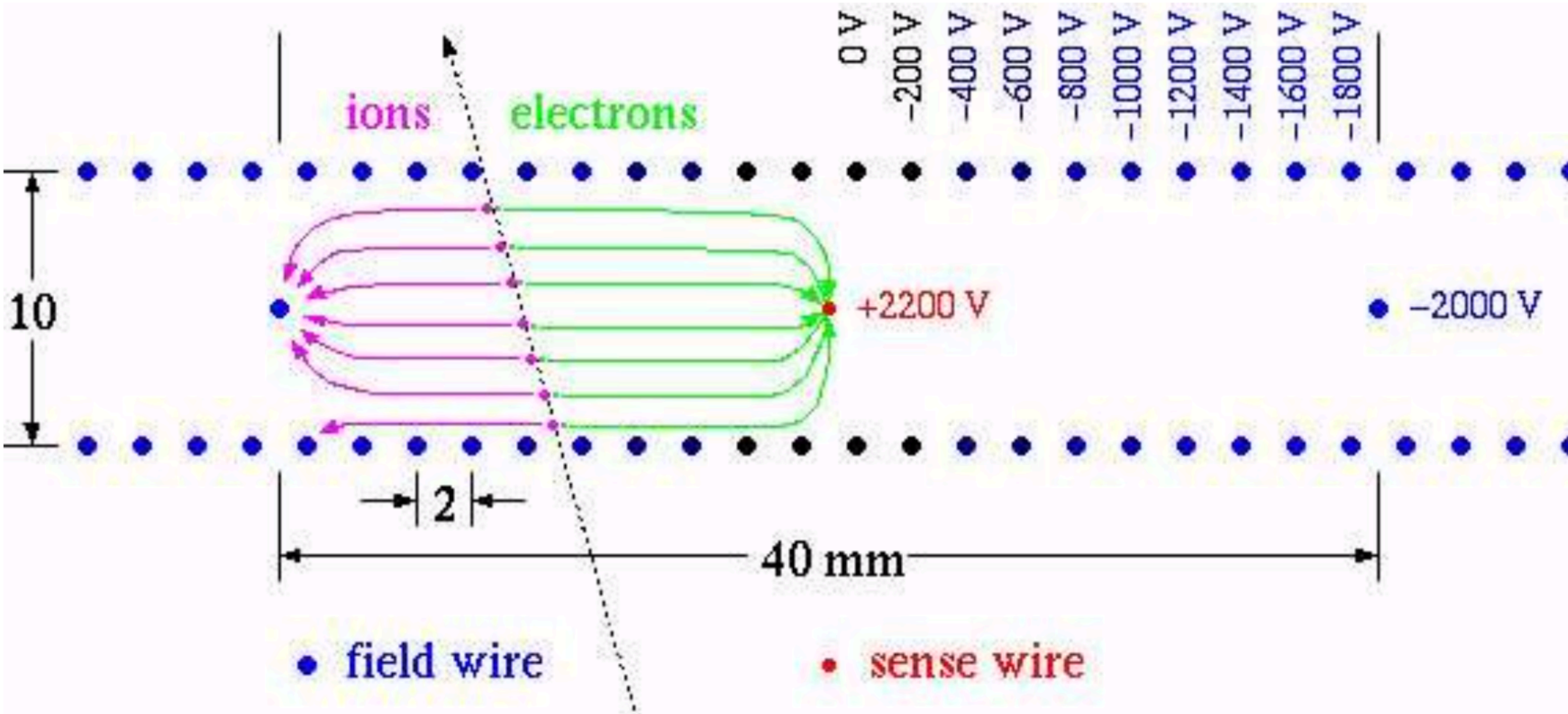
Axial magnetic field from solenoid

Calorimeters measure all other particles

CDF Particle Detector – Drift Chamber



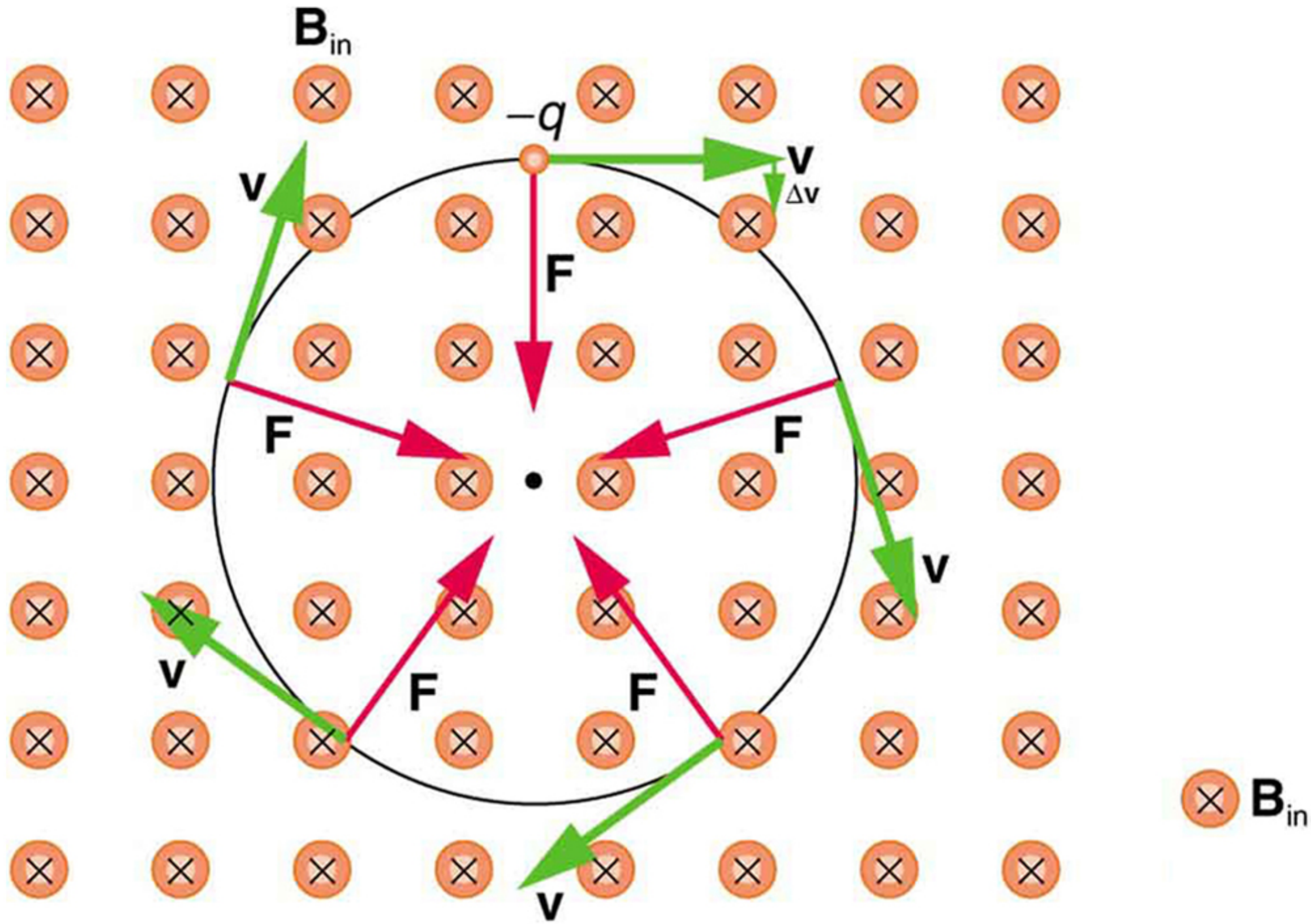
Drift Chamber Operation



Records the position of the charged particle as it passes near the high-voltage sense wire

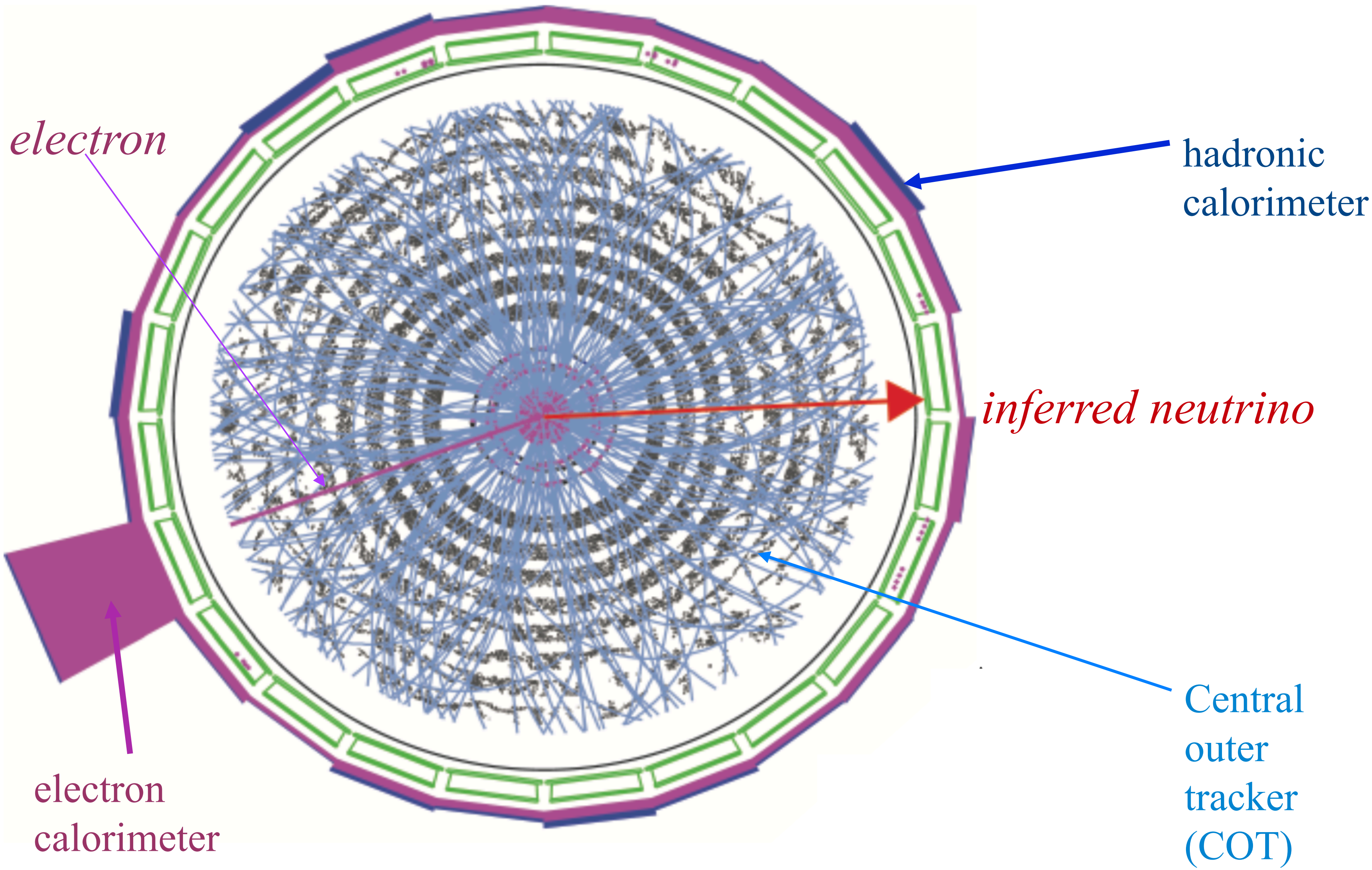
drift time x drift velocity = drift distance

Charged Particle in Magnetic Field



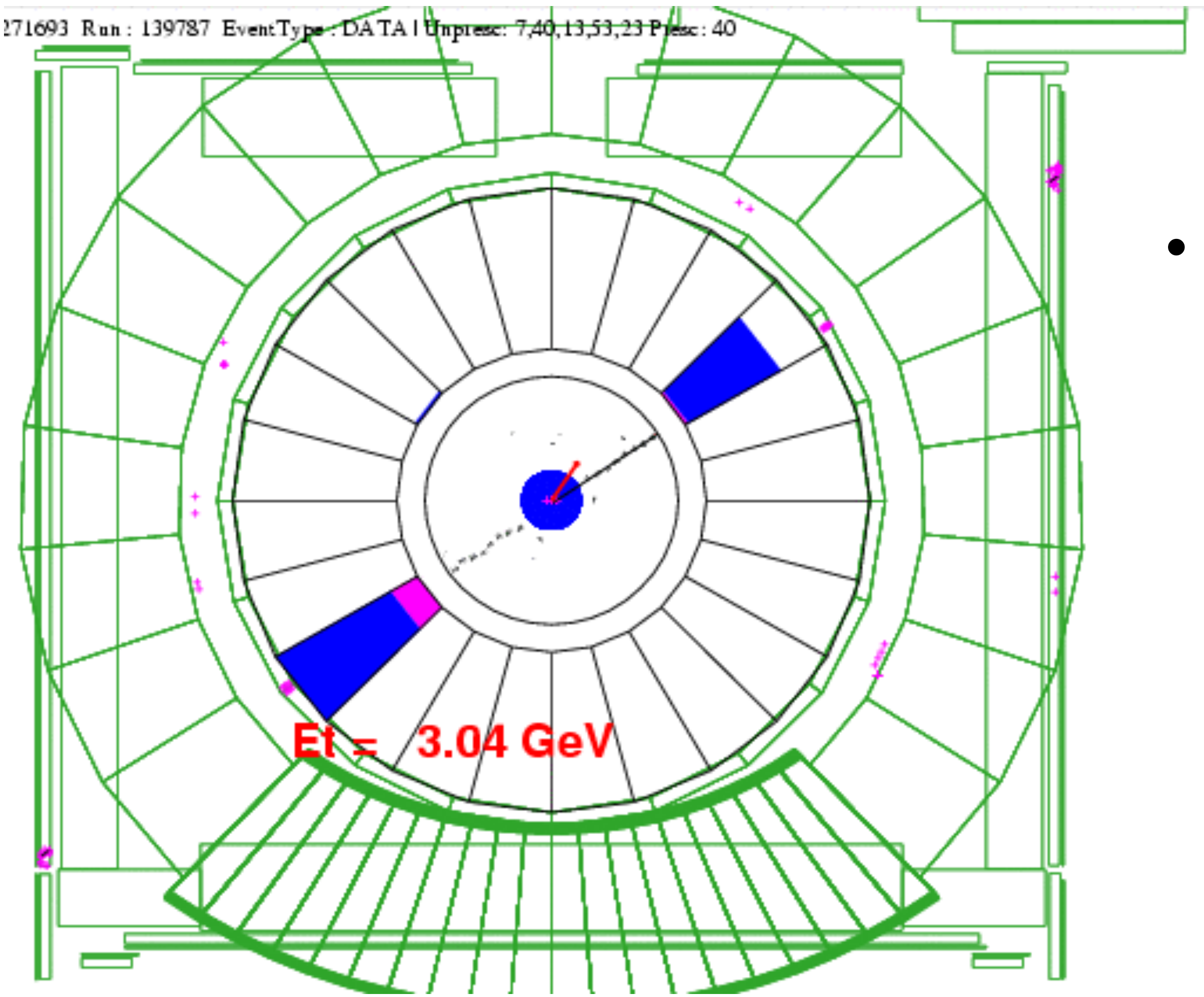
Circular trajectory of a charged particle in a perpendicular magnetic field

W boson Production Event



Measurement of Drift Chamber Wire Positions

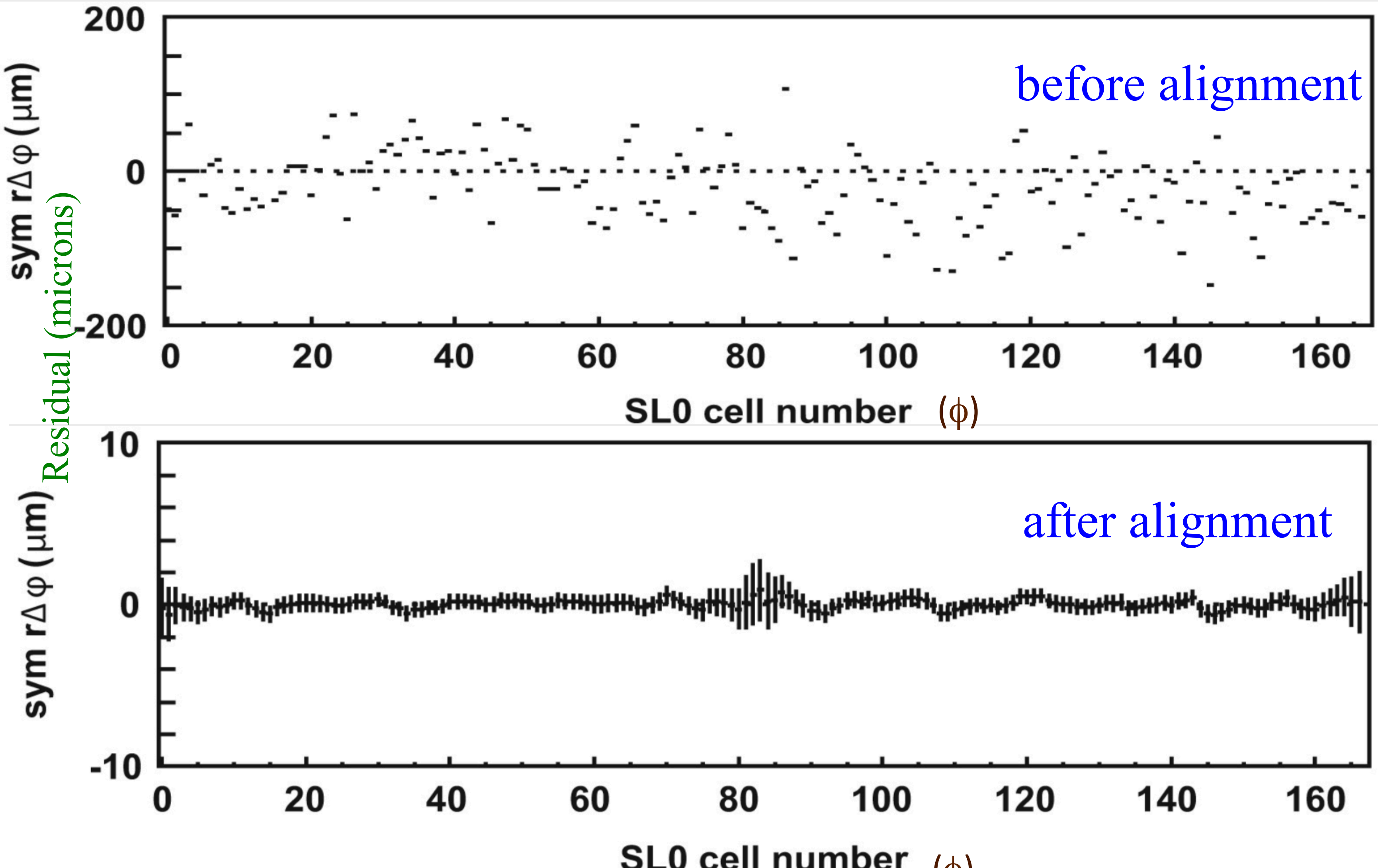
- Use cosmic rays for wire-by-wire position measurements



- Fit points on both sides simultaneously to a single helix
(Ashutosh V. Kotwal , H. Gerberich and C. Hays, NIMA 506, 110 (2003)

Accuracy of Position Measurements

(Ashutosh V. Kotwal & Chris Hays, *NIM A* 762 (2014) pp 85-99)



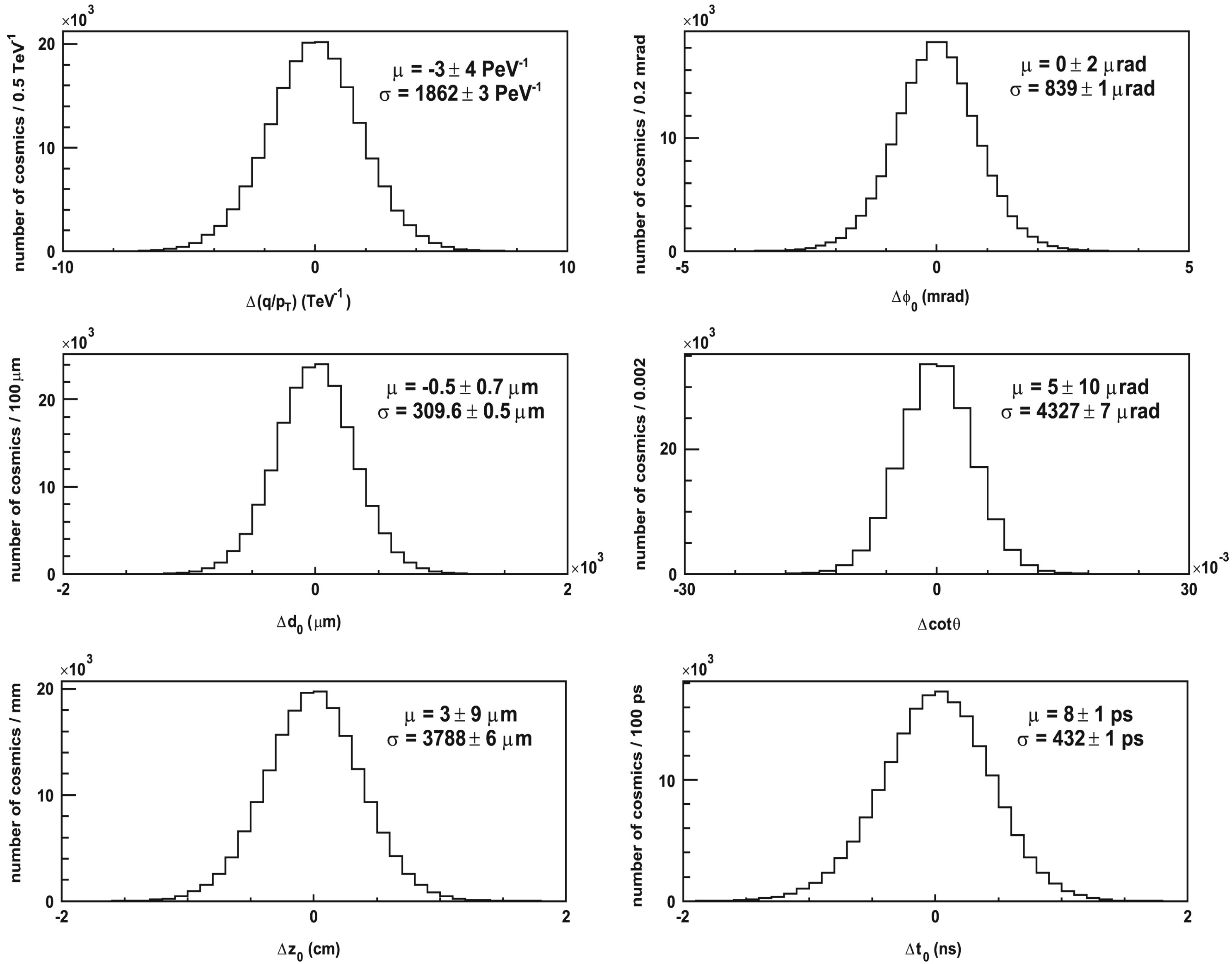
- Final position accuracy of 1 μm (initially 50 μm)

Consistency of alignment procedure

(Ashutosh V. Kotwal & Chris Hays, *NIM A* 762 (2014) pp 85-99)

Fit separate helices to cosmic ray tracks

Compare track parameters of the two tracks: a measure of track parameter bias



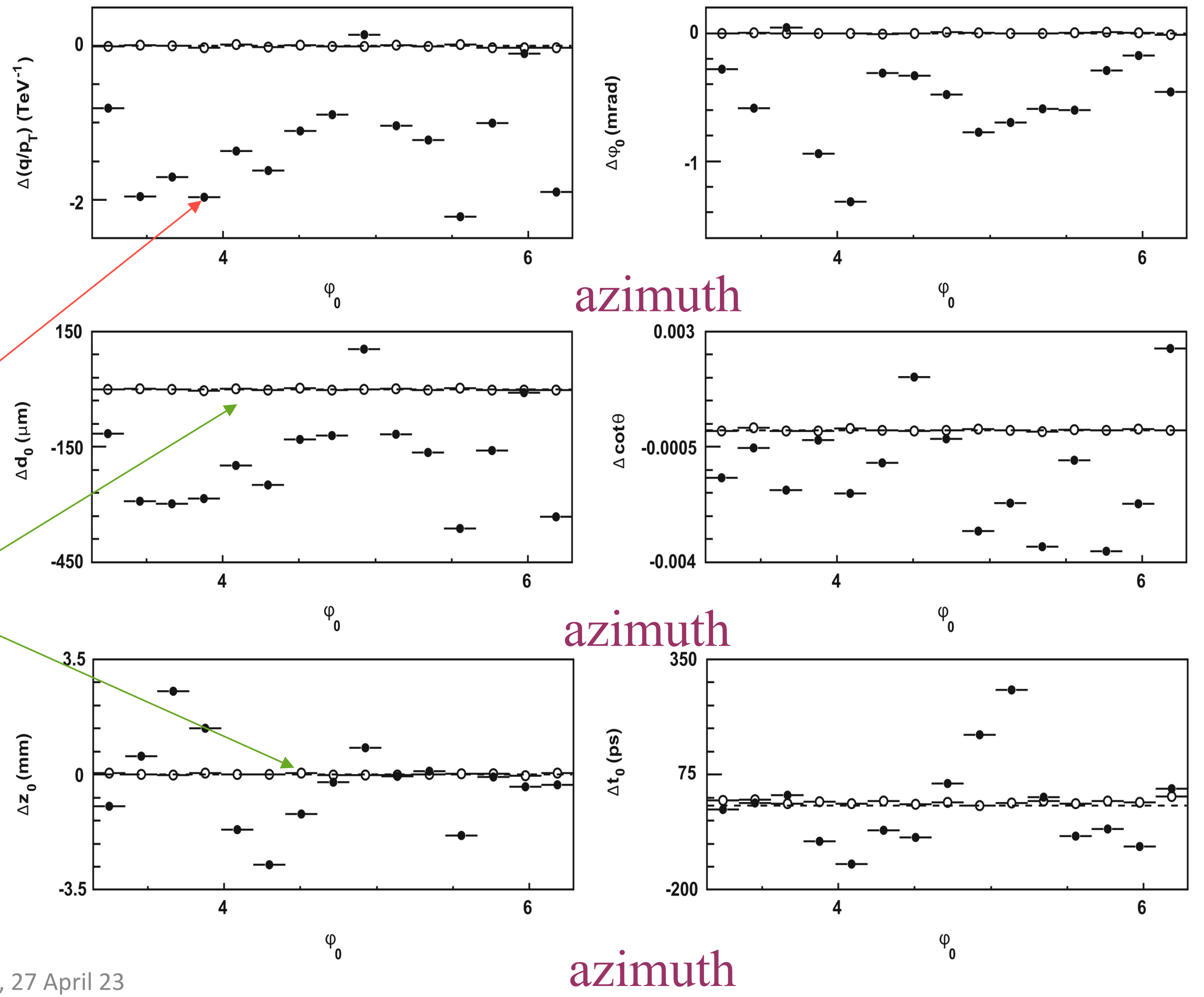
Consistency of alignment procedure

(Ashutosh V. Kotwal & Chris Hays, *NIM A* 762 (2014) pp 85-99)

track parameter bias versus azimuth

solid = before alignment

open = after alignment



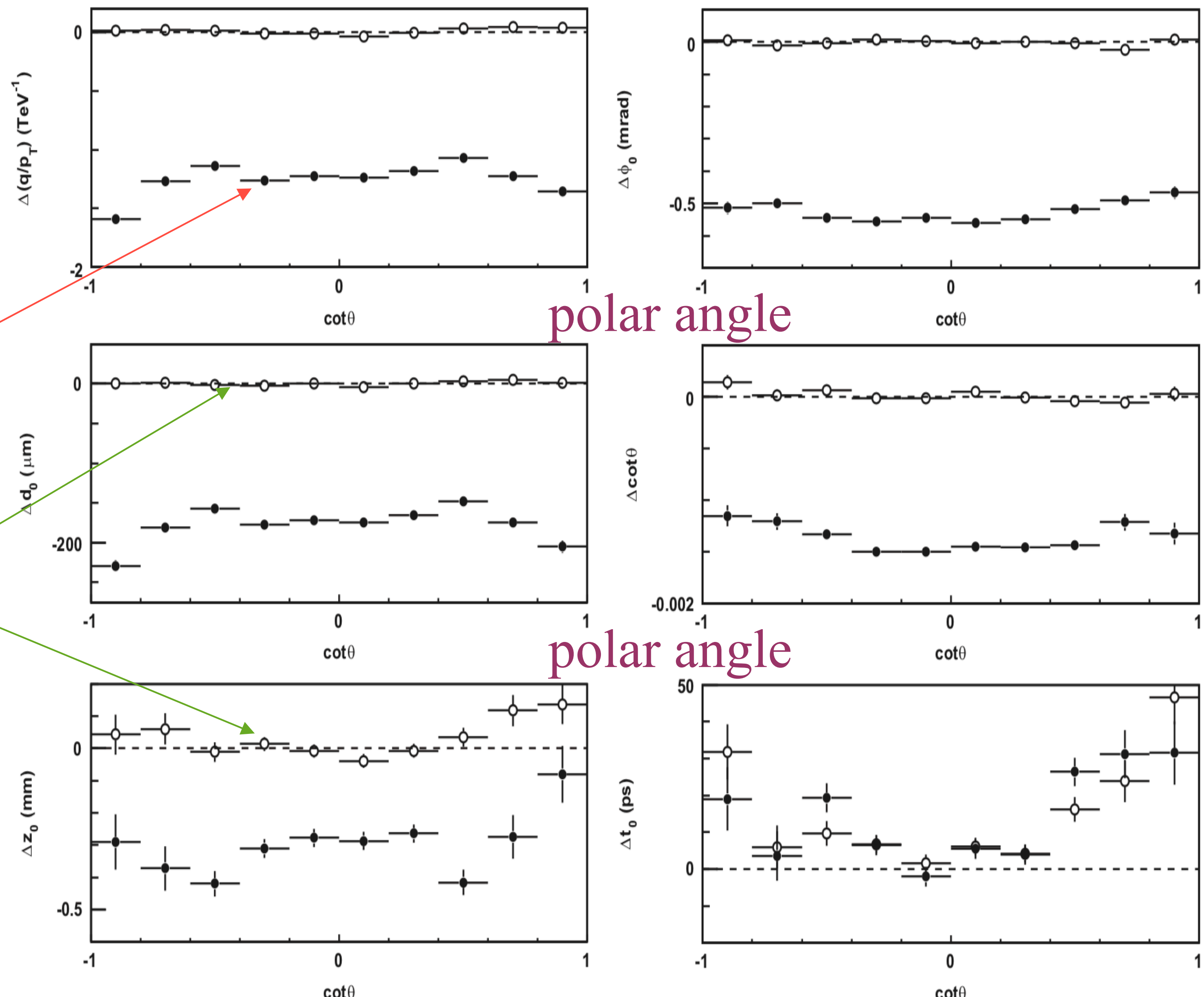
Consistency check of alignment procedure

(AVK & CH, *NIM A* 762 (2014) pp 85-99)

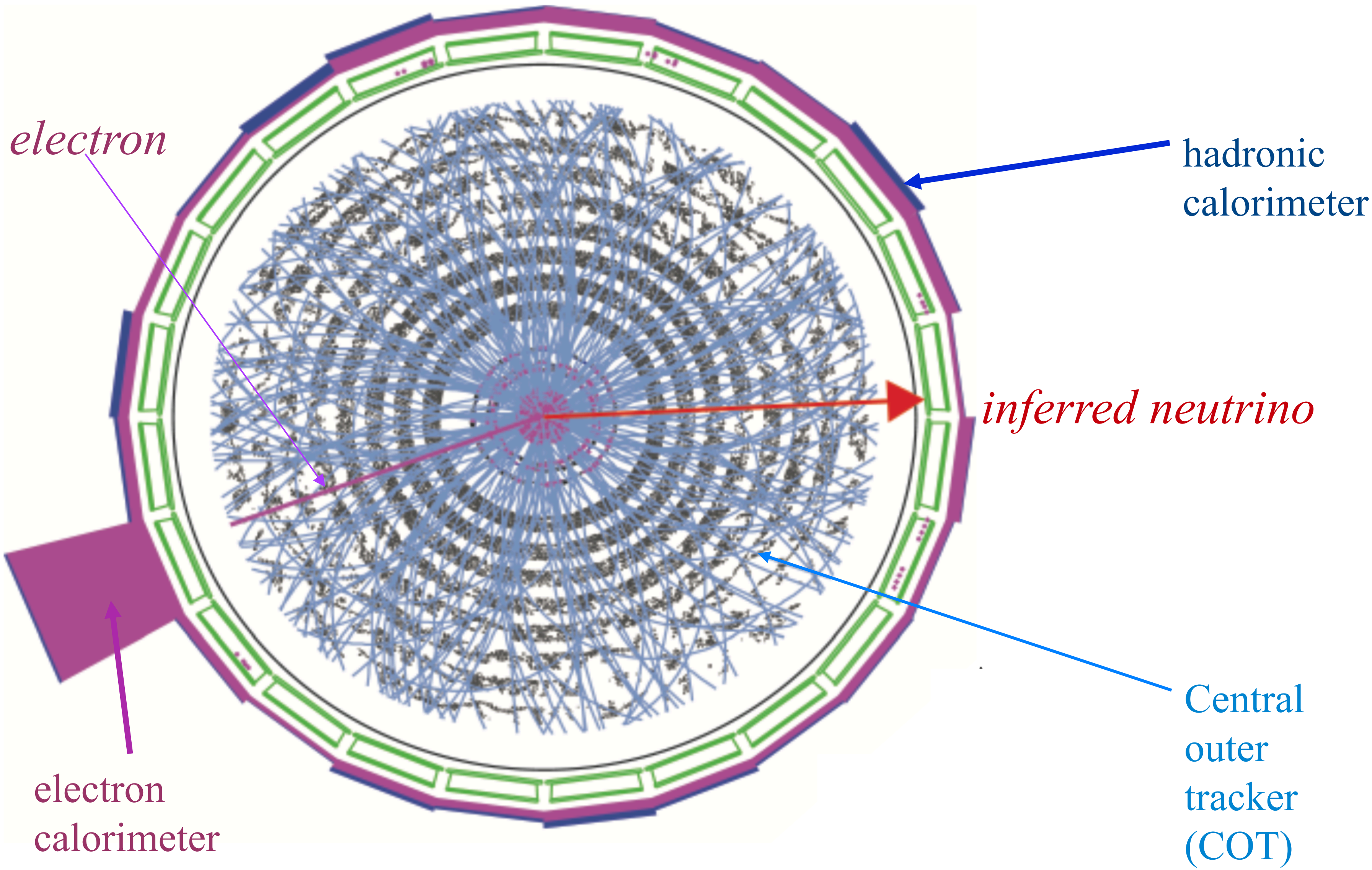
track parameter bias versus polar angle

solid = before alignment

open = after alignment



W boson Production Event

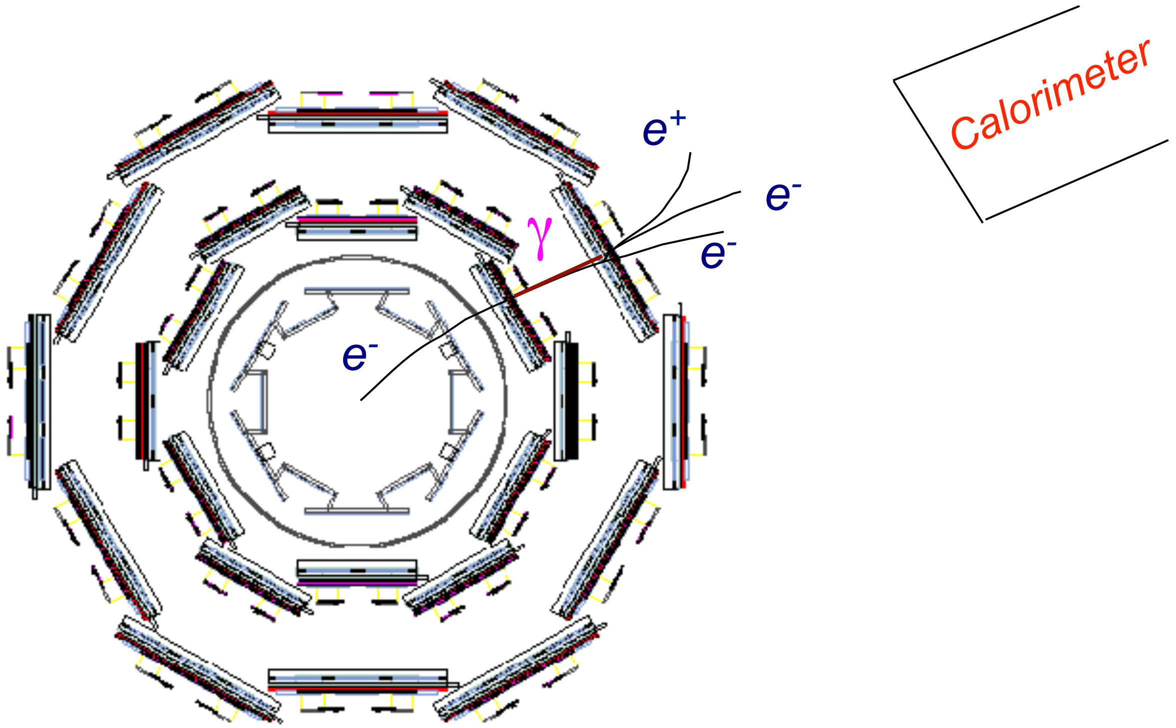


Custom Monte Carlo Detector Simulation

- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - particles propagated through a high-resolution map of material properties
  - At each material interaction, calculate
    - Ionization energy loss according to detailed formulae and Landau distribution
    - Generate bremsstrahlung photons using detailed cross section and spectrum calculations
    - Simulate photon conversion and Compton scattering
    - Propagate bremsstrahlung photons and conversion electrons
    - Simulate multiple Coulomb scattering, including non-Gaussian tail
  - Simulate position measurements and perform full helix fit as with data

Custom Monte Carlo Detector Simulation

- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - particles propagated through a high-resolution 3-D lookup table of material properties for silicon detector and drift chamber



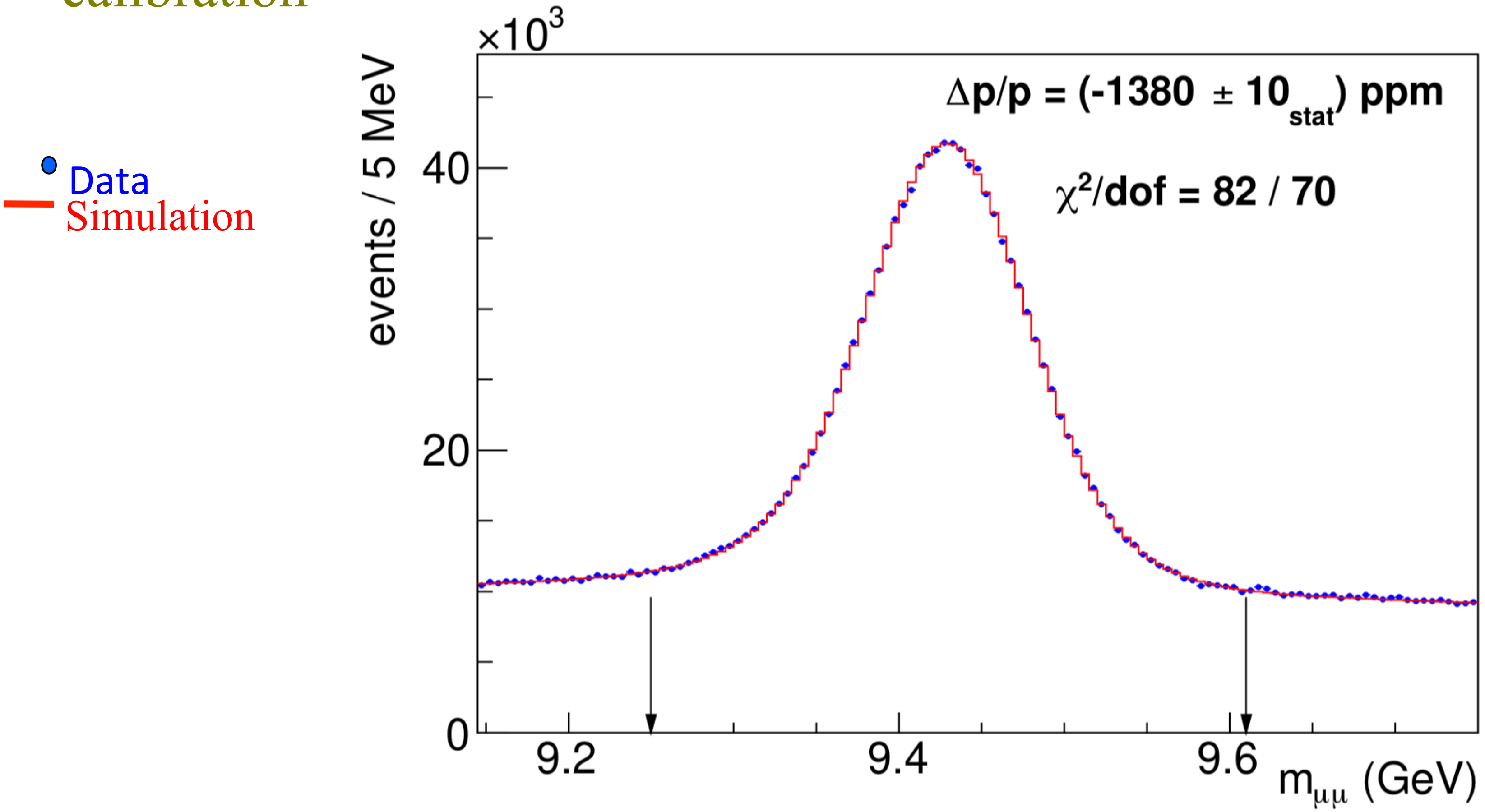
Strategy

- *Maximize the number of internal constraints and cross-checks*
- *Driven by three goals:*
- *1) Robustness: constrain the same parameters in as many different ways as possible*
- *2) Precision: combine independent measurements after showing consistency*
- *3) minimize bias: blinded measurements of M_Z and M_W*

Momentum Calibration

- Well-known Υ (Upsilon) particle mass is measured and compared to previously known mass value

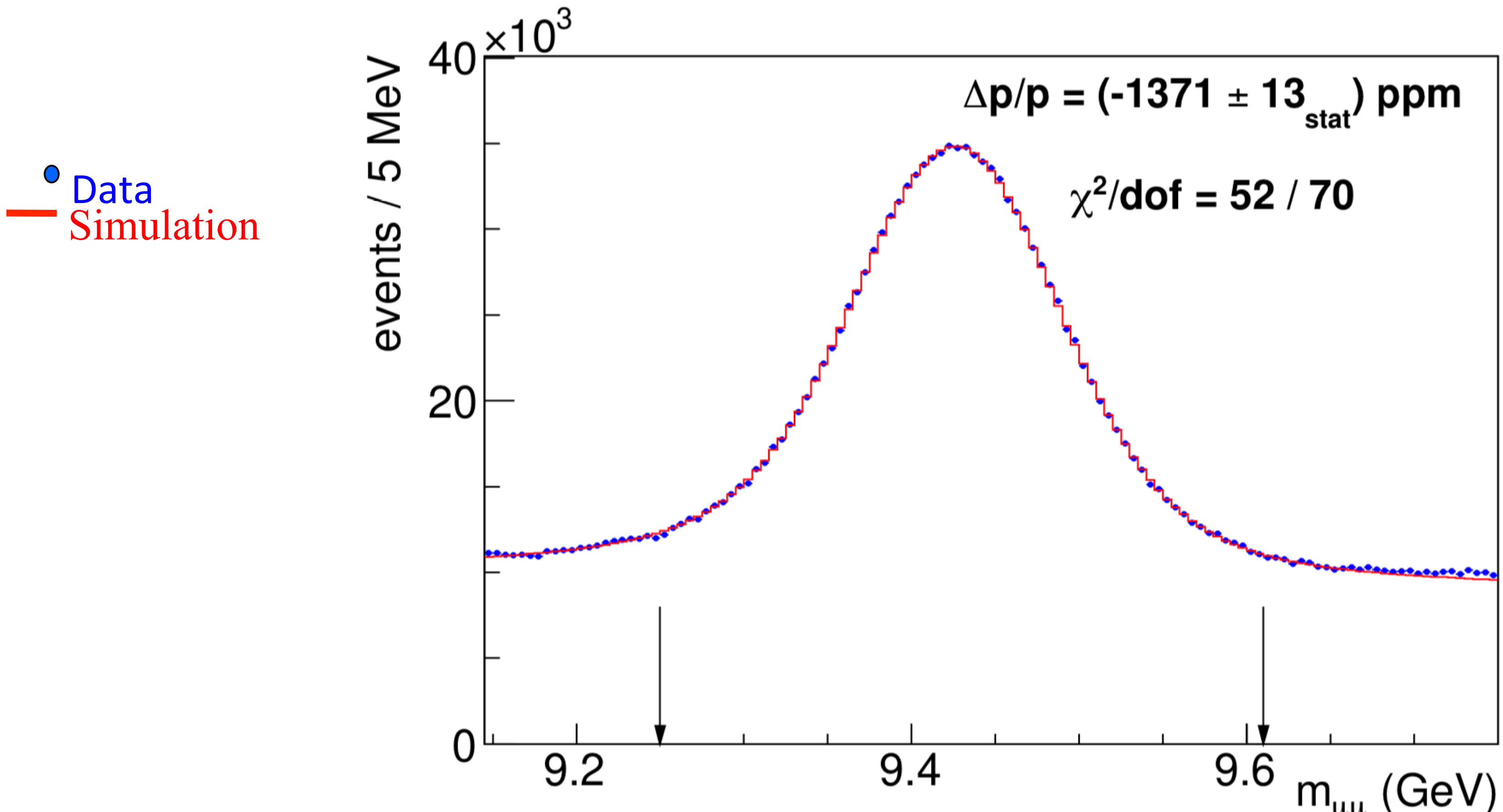
Achieved precision of 25 parts per million on momentum calibration



Momentum Calibration

- Well-known Υ (Upsilon) particle mass is measured and compared to previously known mass value

Achieved consistency between two methods of track reconstruction



Momentum Calibration

- Well-known J/ψ particle mass is measured and compared to previously known mass value
  - In bins of $1/p_T(\mu)$ to simultaneously measure and correct for ionization energy loss

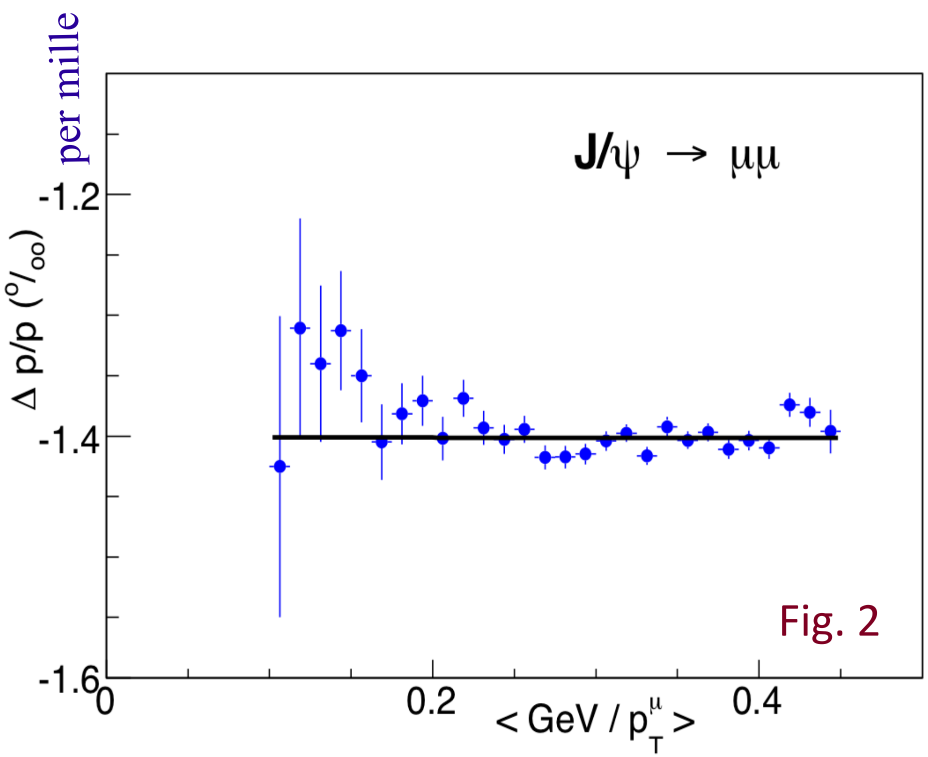


Fig. 2

$J/\psi \longrightarrow \mu\mu$ mass fit (bin 8)

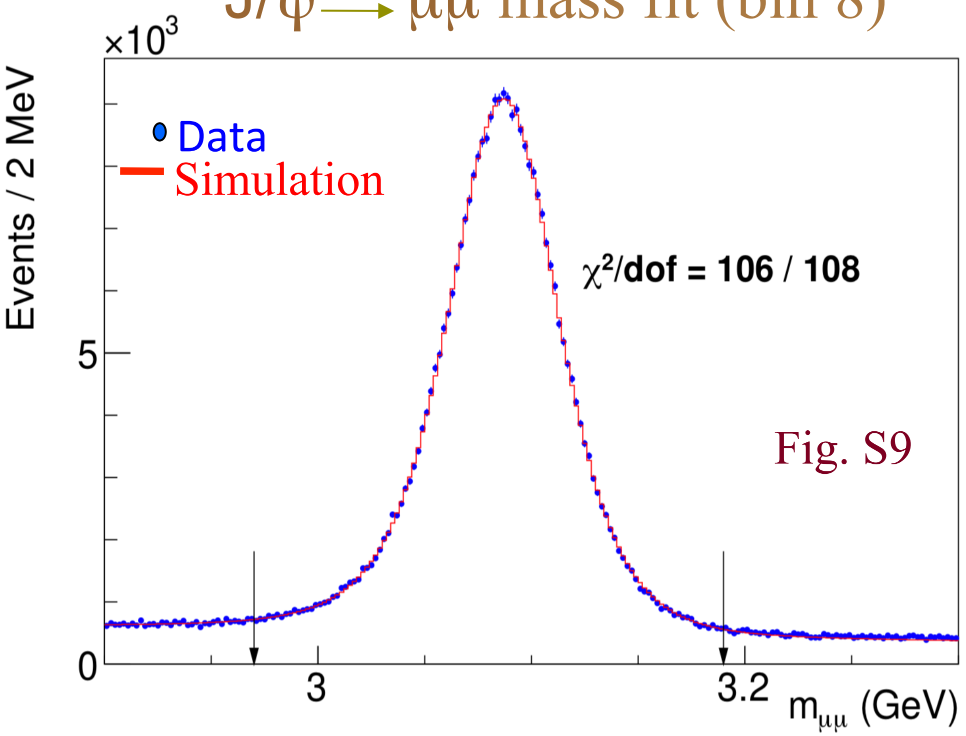


Fig. S9

Momentum Calibration Uncertainties

Systematic uncertainties on momentum (parts per million)

Source	J/ψ (ppm)	Υ (ppm)	Correlation (%)
QED	1	1	100
Magnetic field non-uniformity	13	13	100
Ionizing material correction	11	8	100
Resolution model	10	1	100
Background model	7	6	0
COT alignment correction	4	8	0
Trigger efficiency	18	9	100
Fit range	2	1	100
$\Delta p/p$ step size	2	2	0
World-average mass value	4	27	0
Total systematic	29	34	16 ppm
Statistical NBC (BC)	2	13(10)	0
Total	29	36	16 ppm

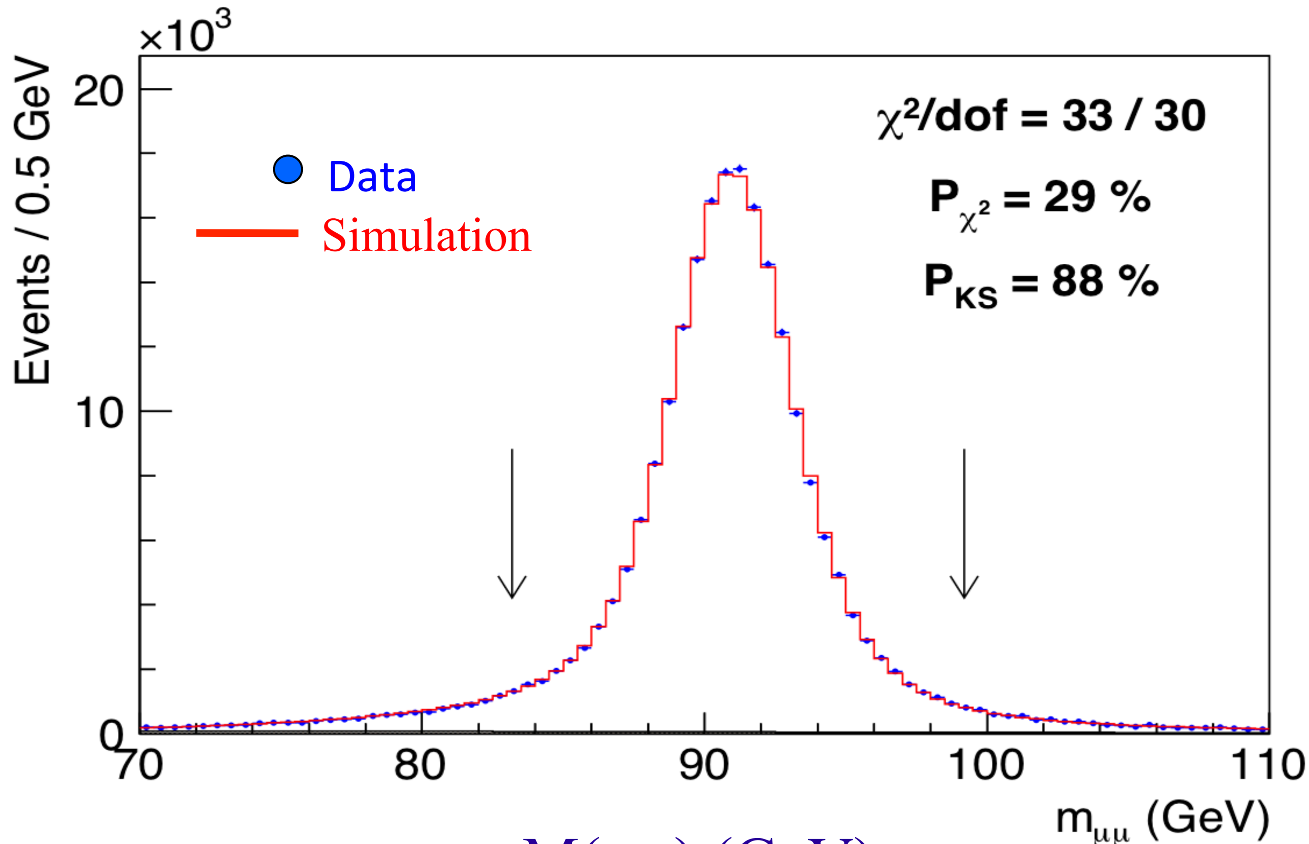
Table S2

$\Delta M_{W,Z} = 2$ MeV

Proof of Momentum Calibration

- We measure the Z boson mass and it agrees with previous measurement of 91188 MeV from CERN electron-positron collider

- We measure M_Z = 91192.0 ± 7.5 MeV



M(μμ) (GeV)

Momentum Calibration

- Final calibration using the J/ψ, ϒ and Z bosons for calibration

- Combined momentum calibration correction:

$\Delta p/p$ = (-1389 ± 25) parts per million

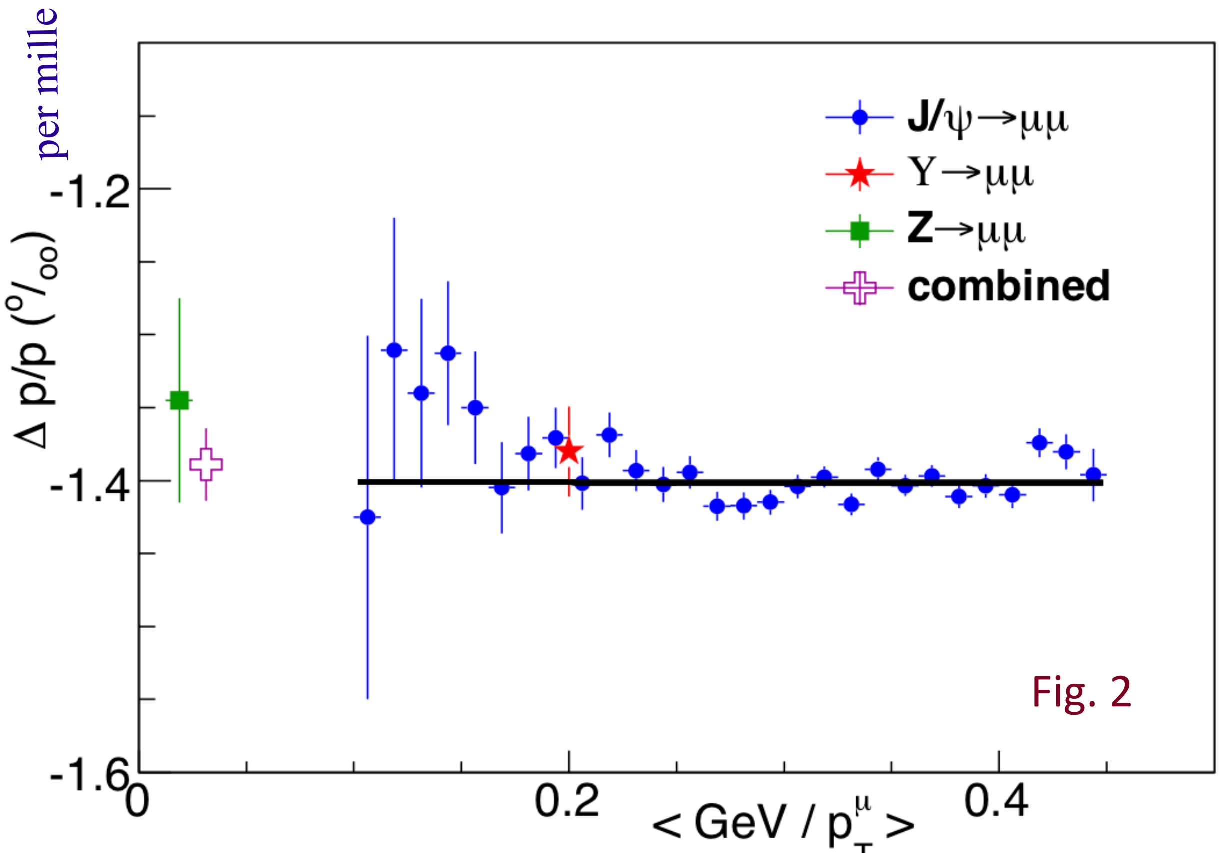
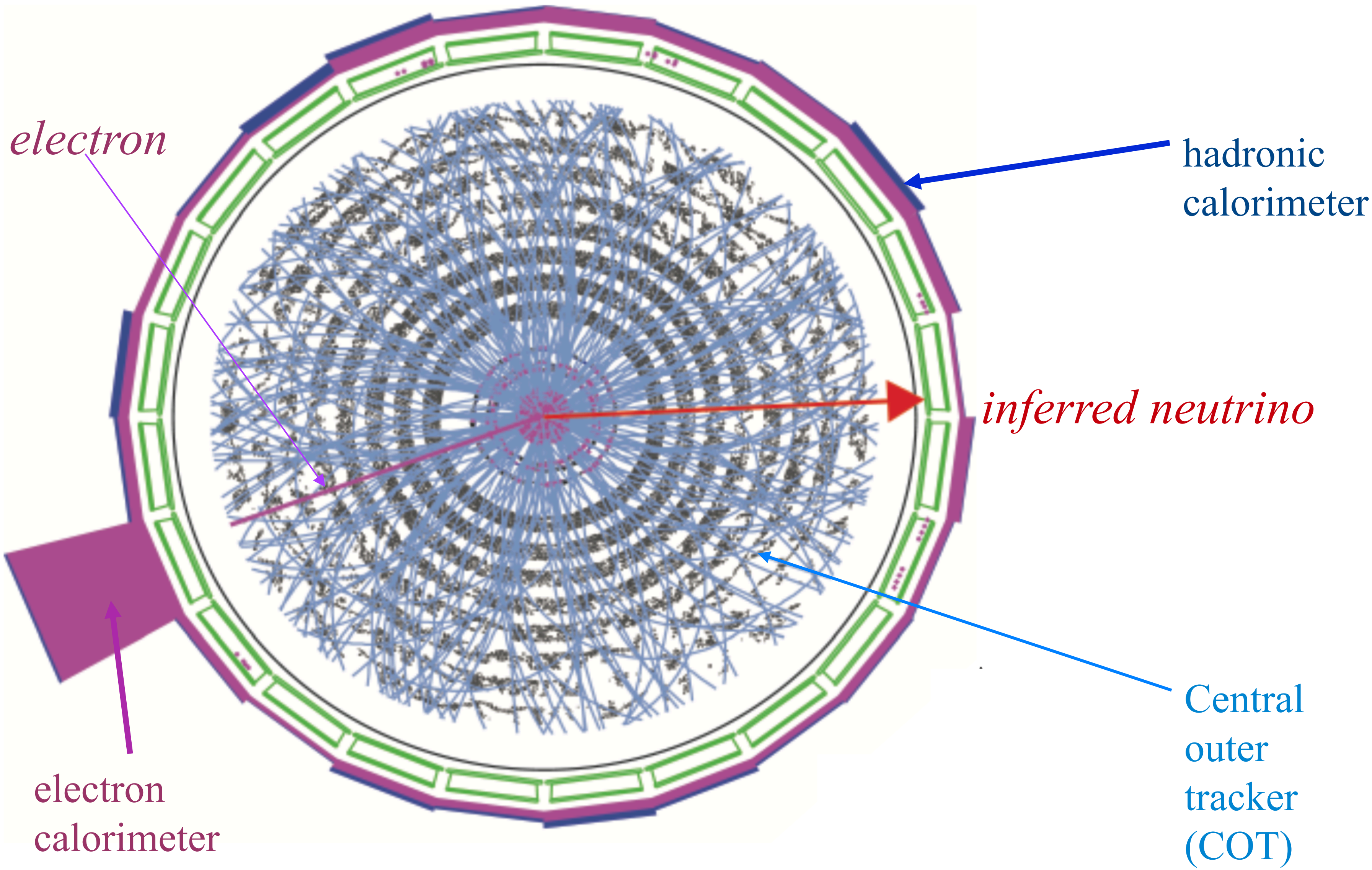


Fig. 2

ΔM_W = 2 MeV

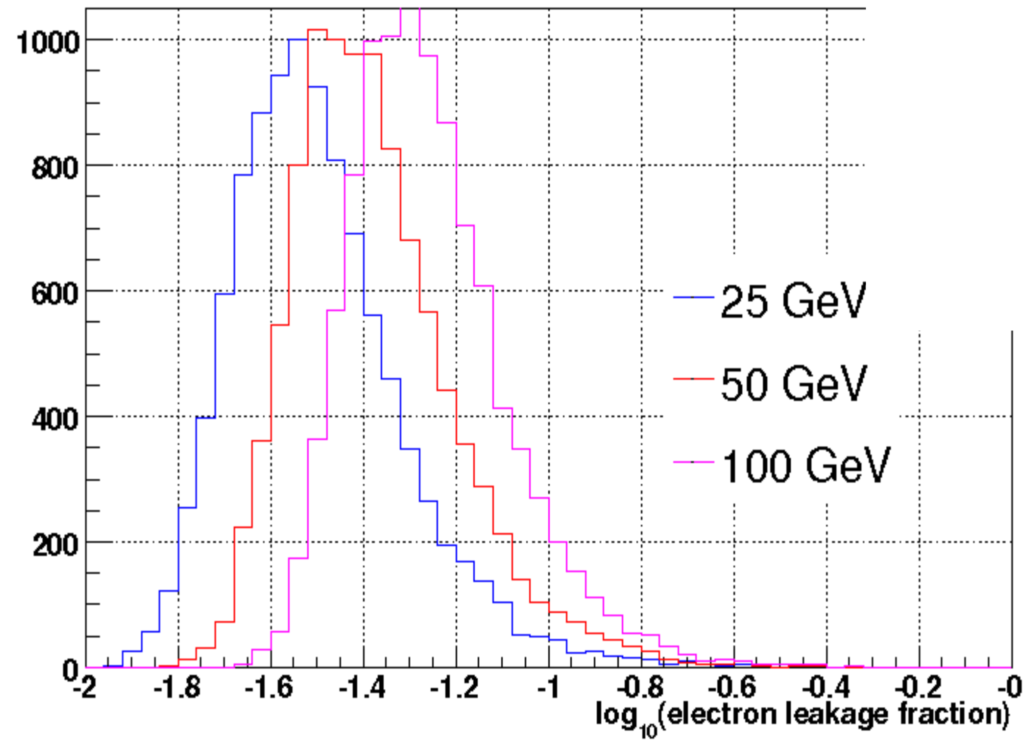
W boson Production Event



Calorimeter Simulation for Electrons and Photons

- Energy response calculated using detailed GEANT4 simulation of calorimeter

  - Leakage of energy
  - Absorption in upstream
  - Dependence on incident angle and energy



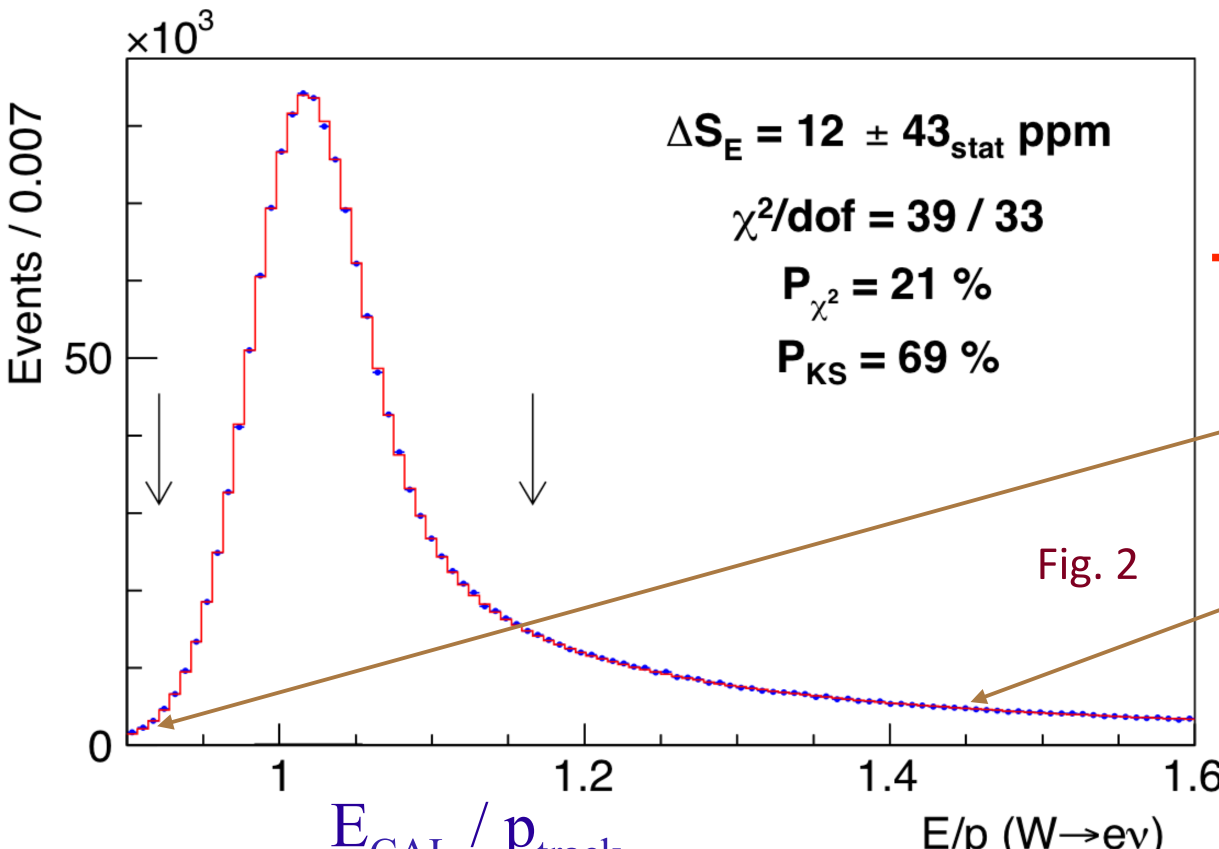
(AVK & CH, *NIM A* 729 (2013) pp 25-35)

- Parameters in the calculation are extracted from data

Electron and Photon Calorimeter Calibration

- E/p peak from $W \longrightarrow e\upsilon$ decays provides measurement of calorimeter energy response, with the following uncertainties:

$\Delta S_E = (43_{stat} \pm 30_{non\text{-}linearity} \pm 34_{X0} \pm 45_{Tracker})$ parts per million



$\Delta M_W = 6$ MeV

Data

Simulation

Low tail used for tuning calorimeter thickness

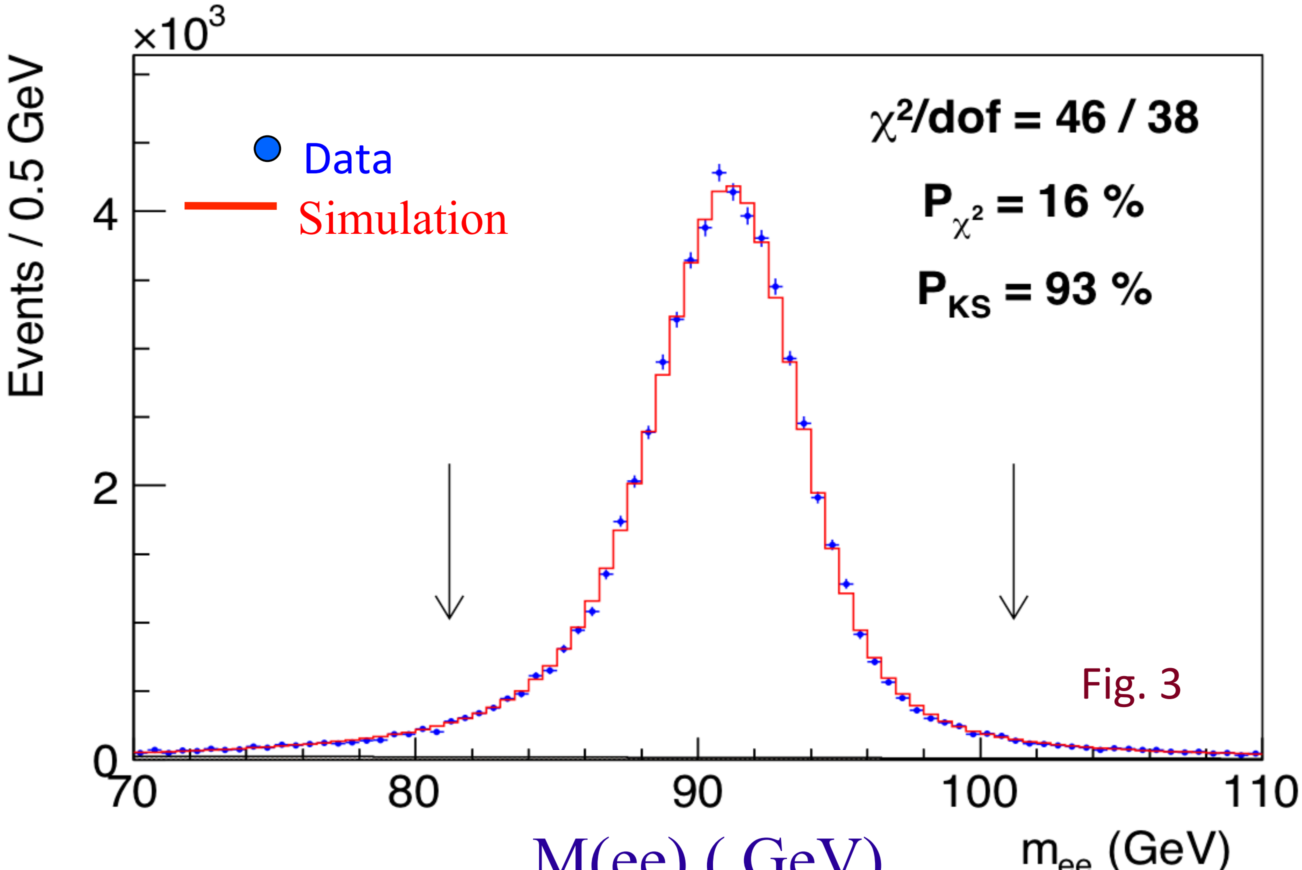
High tail of used for tuning model of radiative material

E_{CAL} / p_{track}

Proof of Calorimeter Calibration using Z boson mass Measurement

Consistent with previous measurement from CERN (91188 MeV)

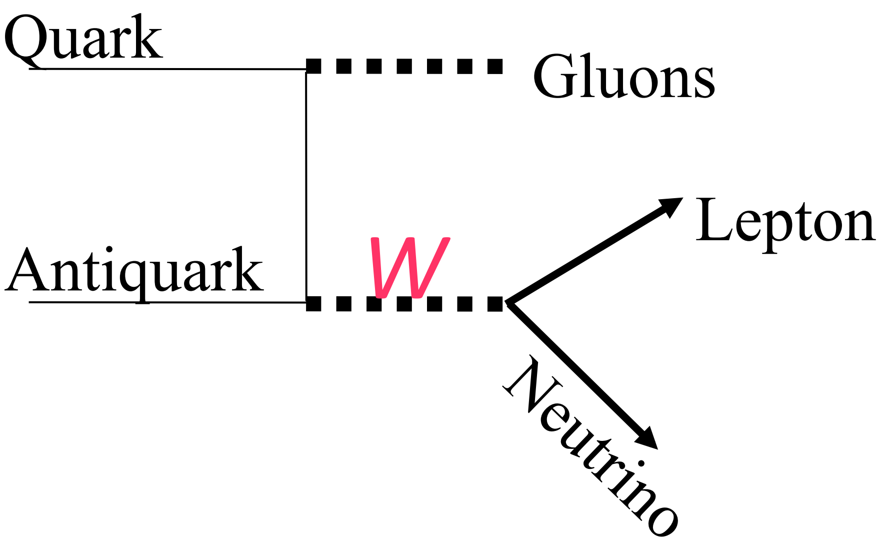
$M_Z = 91194.3 \pm 13.8_{stat} \pm 6.5_{calorimeter} \pm 2.3_{momentum} \pm 3.1_{QED} \pm 0.8_{alignment}$ MeV

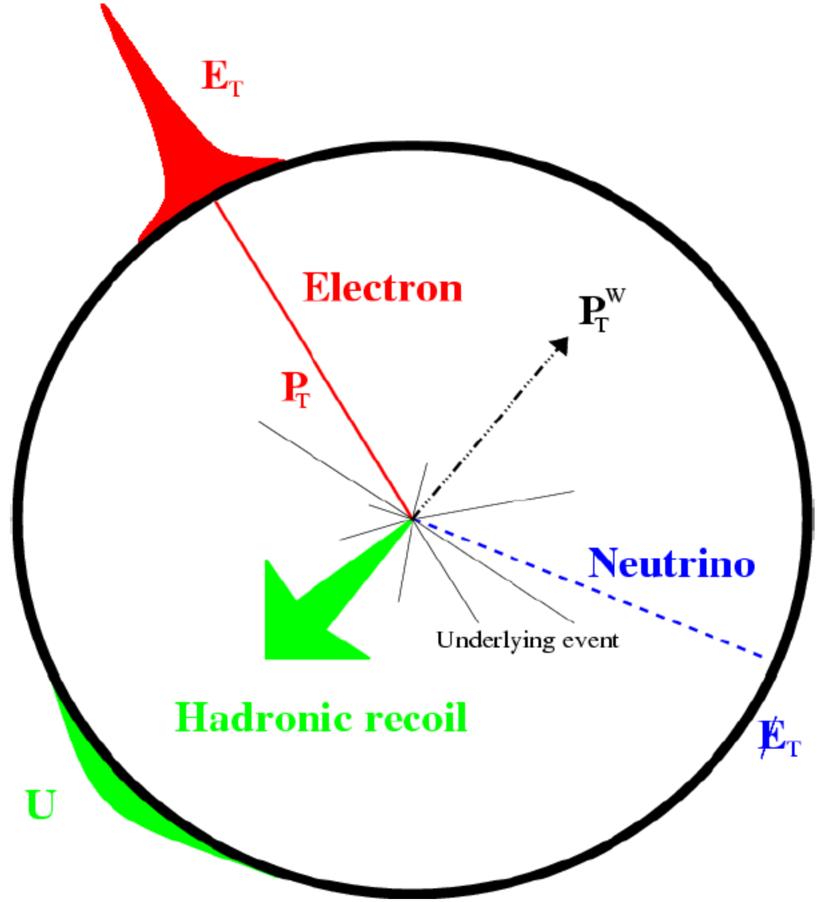


M(ee) (GeV)

ΔM_W = 5.8 MeV

W Boson Production in Proton-Antiproton Collisions





Quark-antiquark annihilation produces W boson

W boson decays to neutrino, accompanied by electron or muon

Lepton (electron or muon) momentum carries most of *W* mass information, can be measured precisely (achieved 0.004%)

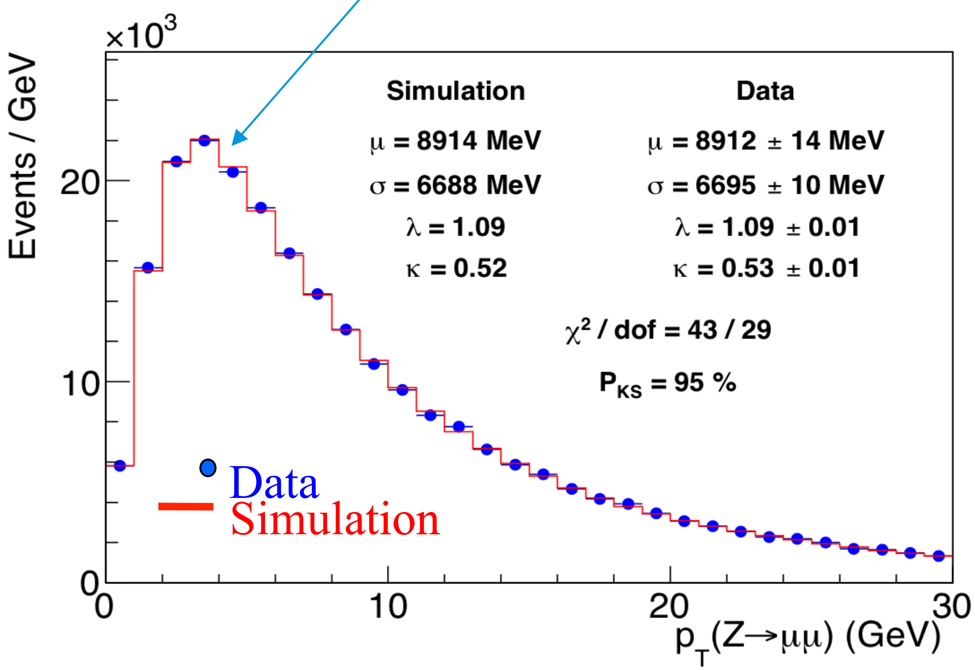
Constraining Boson p_T Spectrum with Data

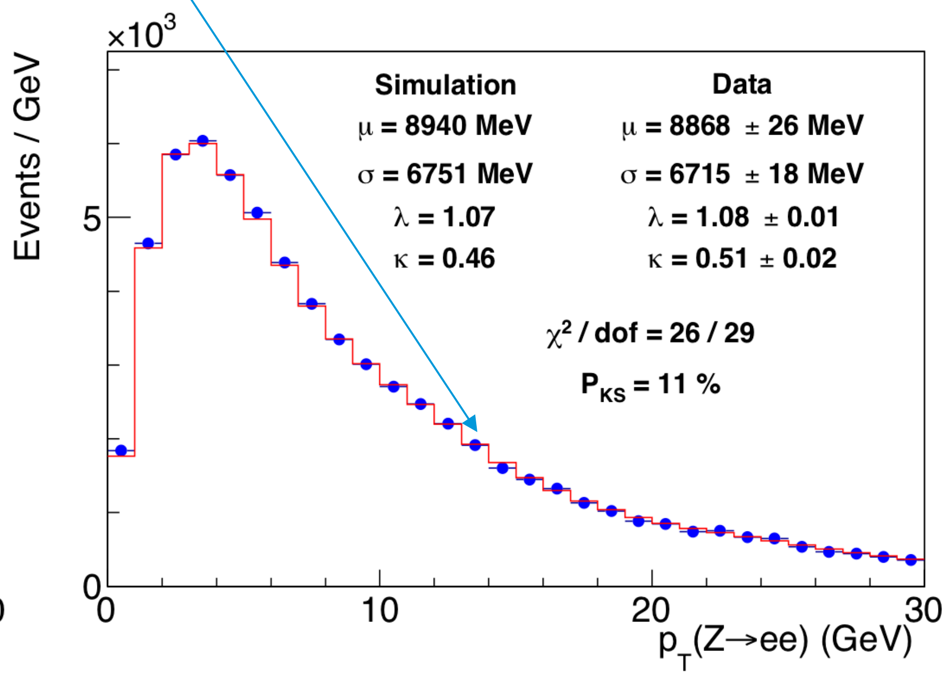
- Fit the non-perturbative parameter g_2 and QCD coupling α_S in theoretical production model to $p_T(ll)$ data spectra:

ΔM_W = 1.8 MeV

Position of peak in boson p_T spectrum depends on g_2

Tail to peak ratio depends on α_S



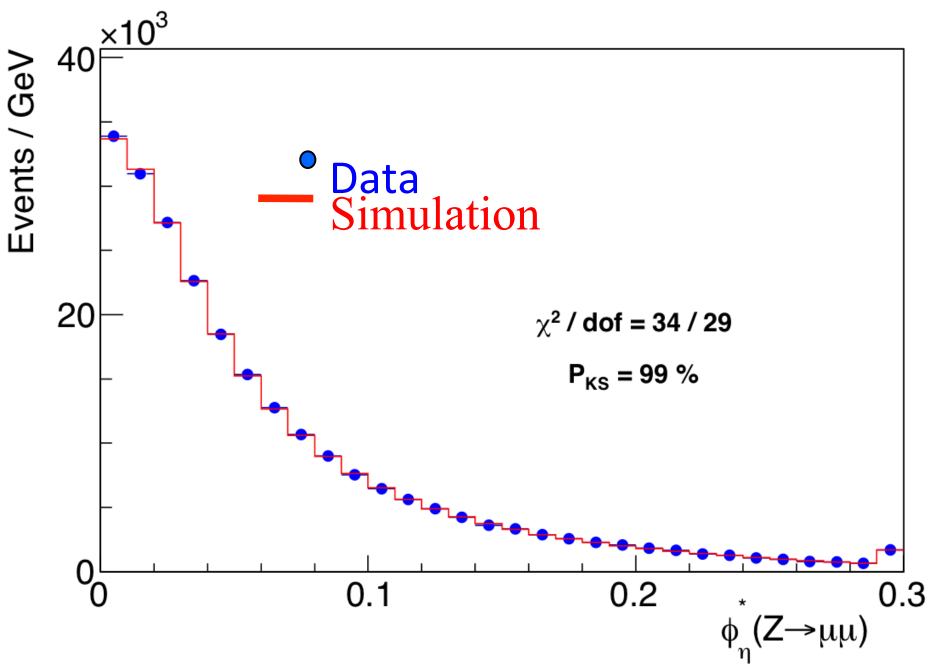


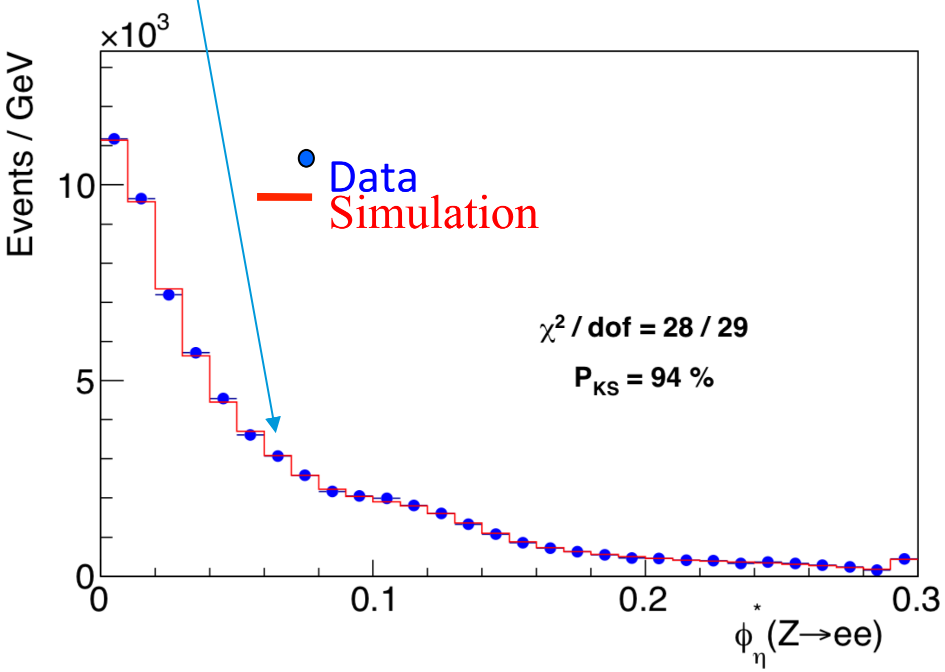
Constraining Boson p_T Spectrum with Data

- NEW: Use azimuthal opening angle between leptons as a check of the $p_T(ll)$ spectrum modeling:

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi^{\ell\ell}}{2}\right) \mathrm{sech}\left(\frac{\eta^- - \eta^+}{2}\right)$$

Acceptance effect modeled in simulation

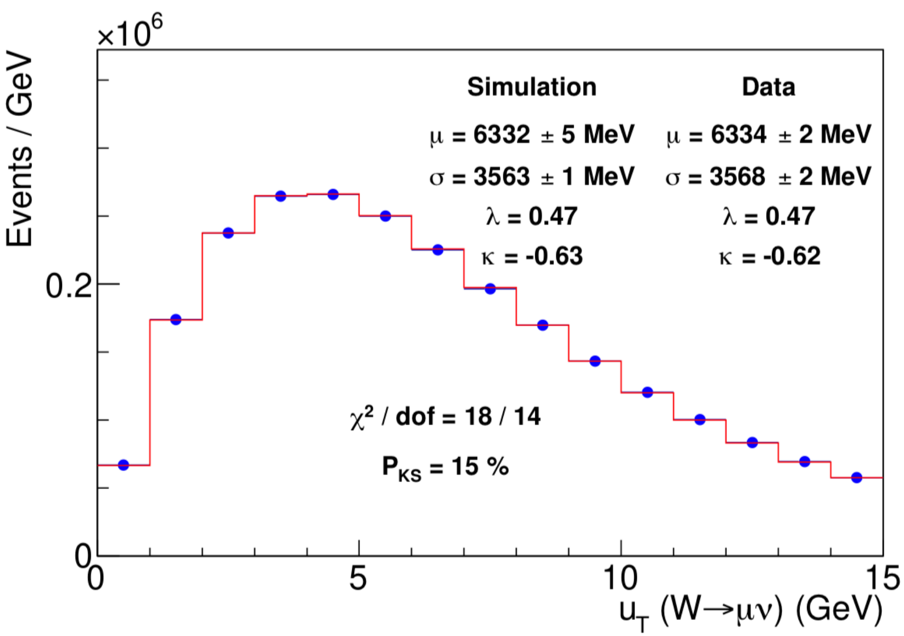




Additional Constraint on $p_T(W)$ Model with *W* boson data

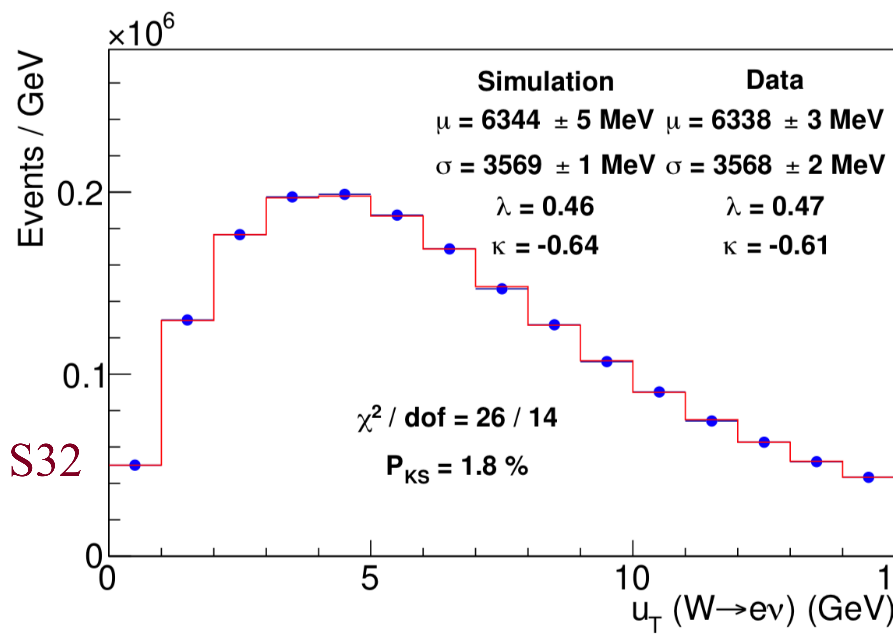
- NEW: In addition to the $p_T(Z)$ data constraint on the boson p_T spectrum, the theoretical calculation of the $p_T(W)$ spectrum is also constrained by using the $p_T(W)$ data

- correlation with detector response is taken into account



$p_T(W)$, muon channel

Fig. S32

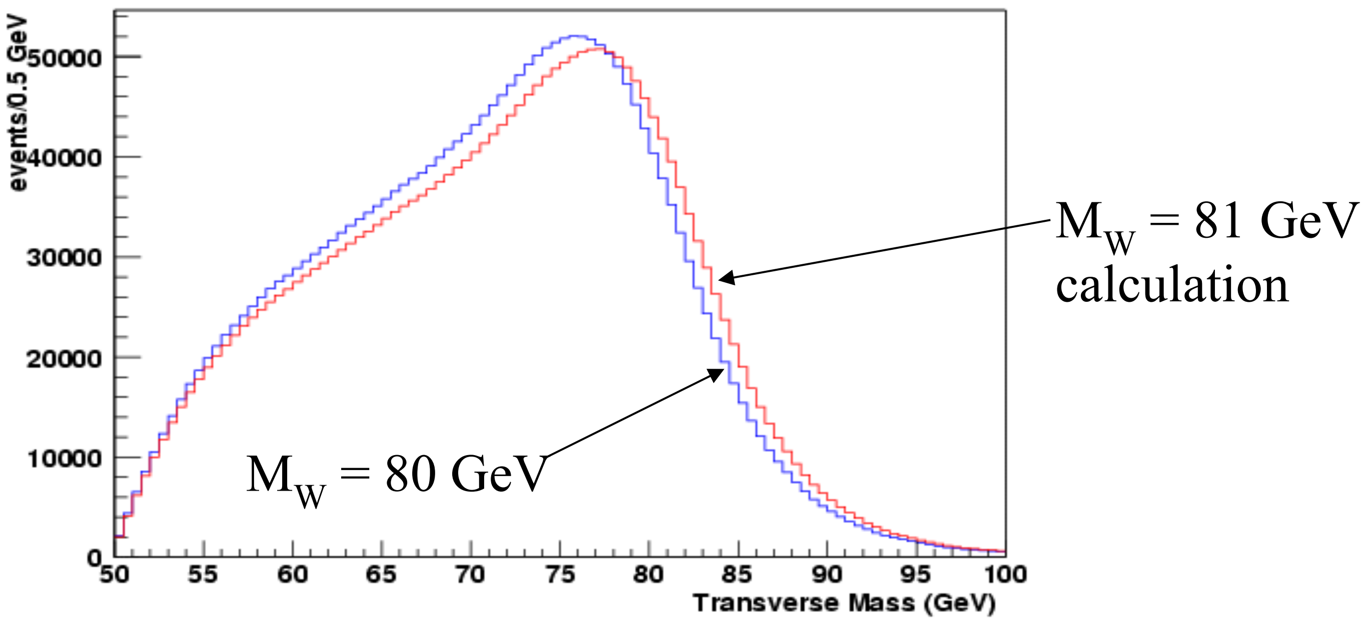


$p_T(W)$, electron channel

• Data
— Simulation

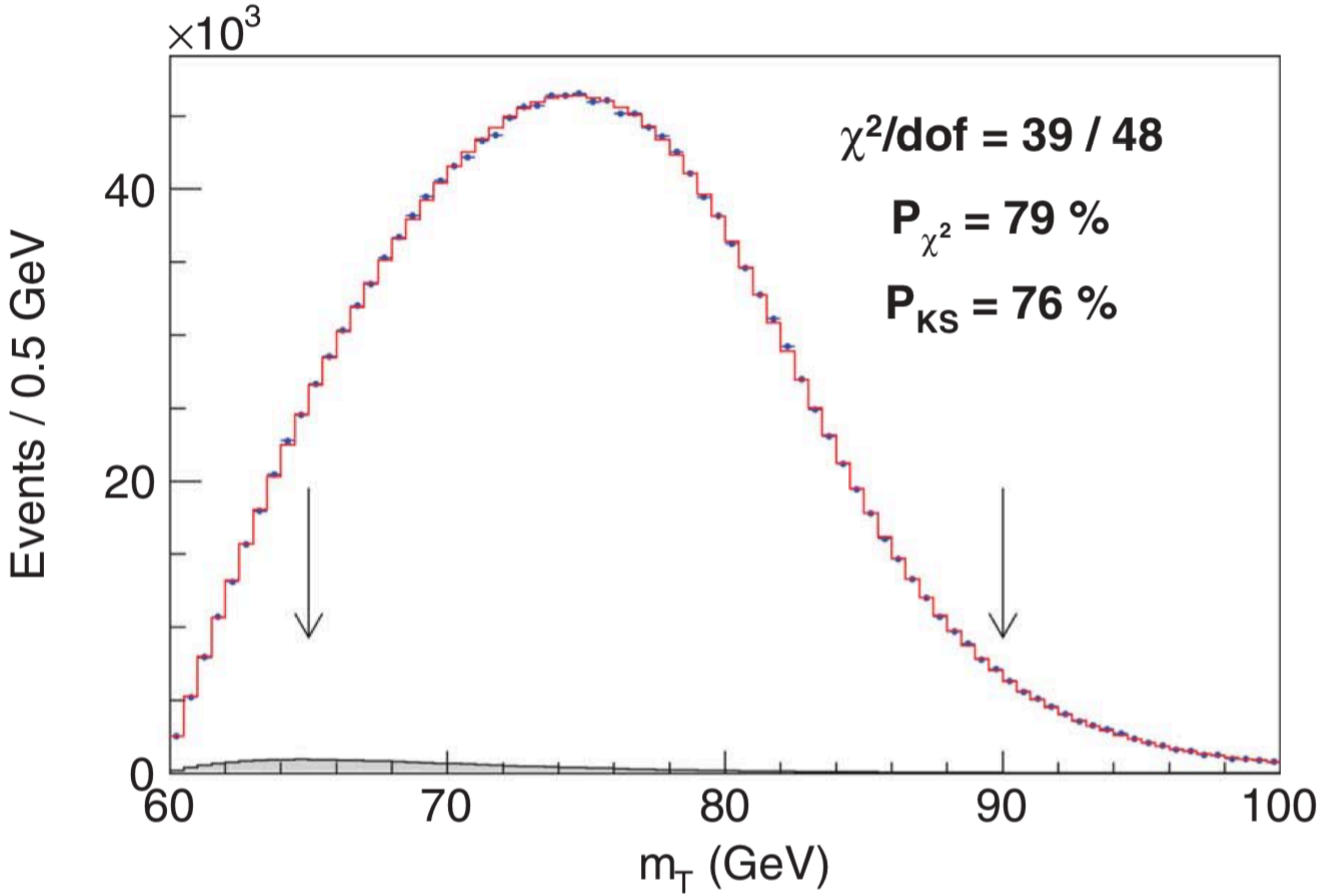
Matching Calculated and Observed Distributions

- We perform a very accurate calculation of the momentum of the electron or muon emanating from the W boson decay
- We perform a very accurate comparison of this momentum distribution between the observed data and the calculation

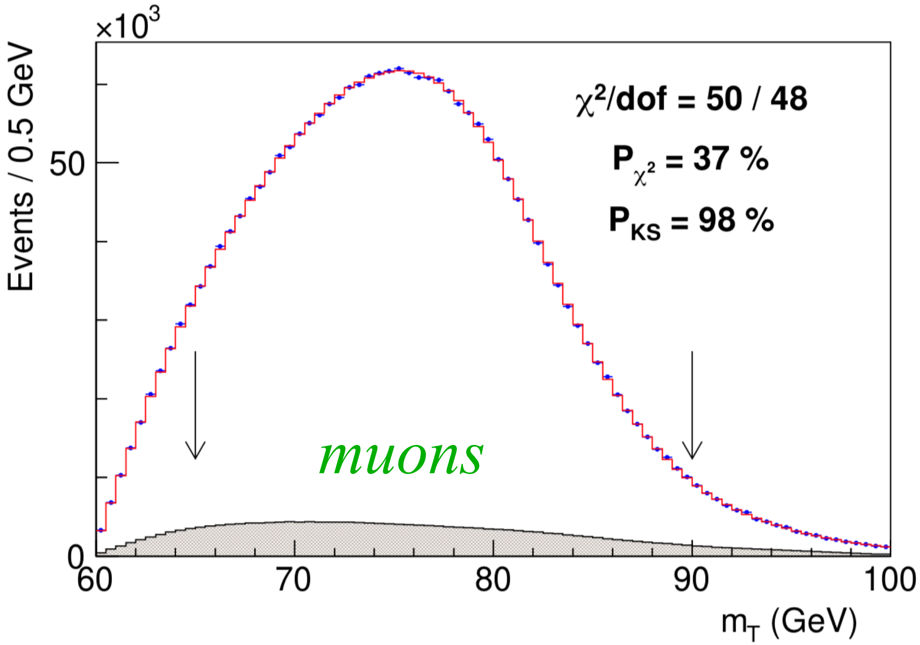


- We used advanced statistical methods to quantify this comparison and infer the W boson mass

Fit to Electron Momentum Distribution from *W* boson decay



W Boson Mass Fits



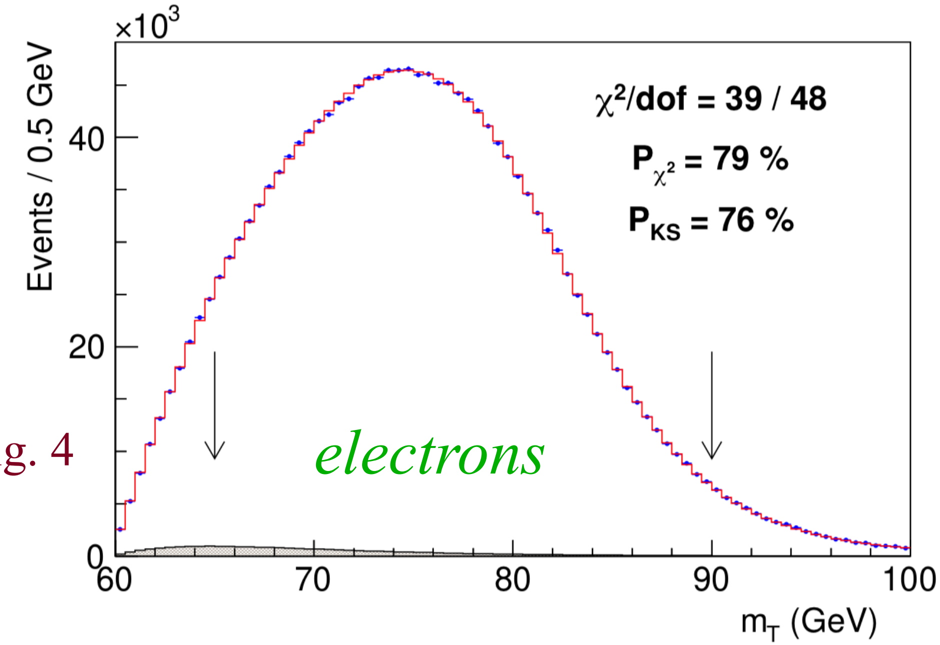
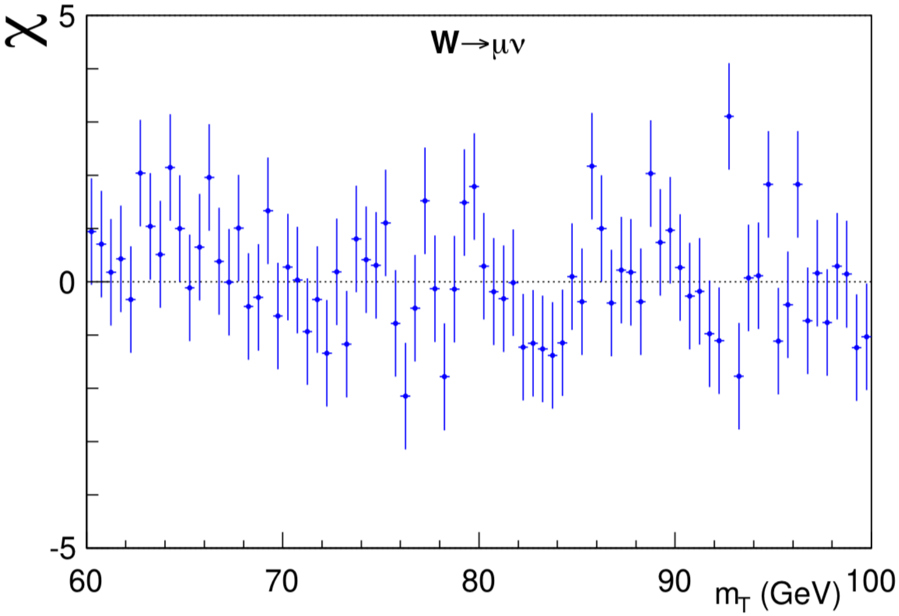


Fig. 4



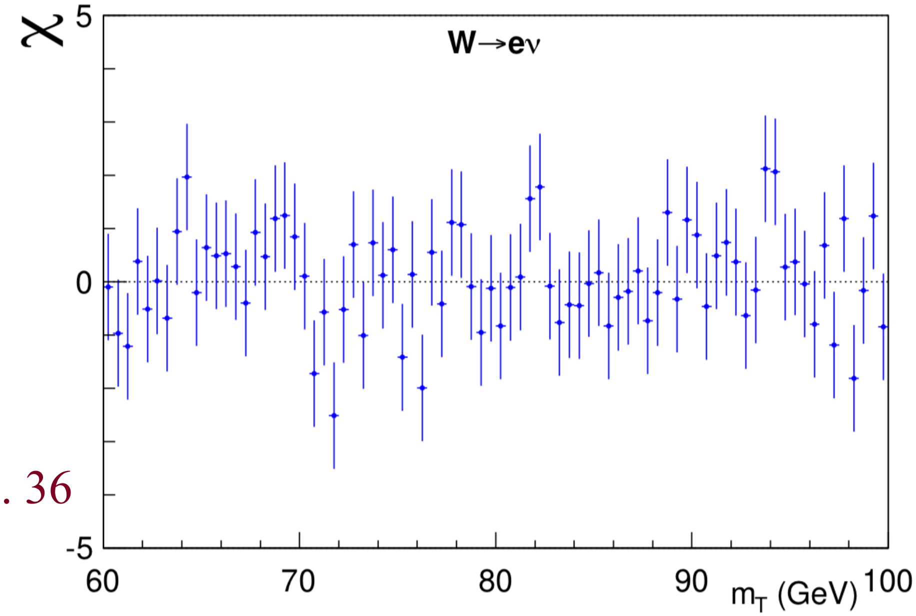


Fig. 36

Summary of *W* boson Mass Fits

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

Table 1

Consistency between two channels and three kinematic fits

Combinations of Fit Results

Combination	m_T fit Electrons	m_T fit Muons	p_T^ℓ fit Electrons	p_T^ℓ fit Muons	p_T^ν fit Electrons	p_T^ν fit Muons	Value (MeV)	χ^2/dof	Probability (%)
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

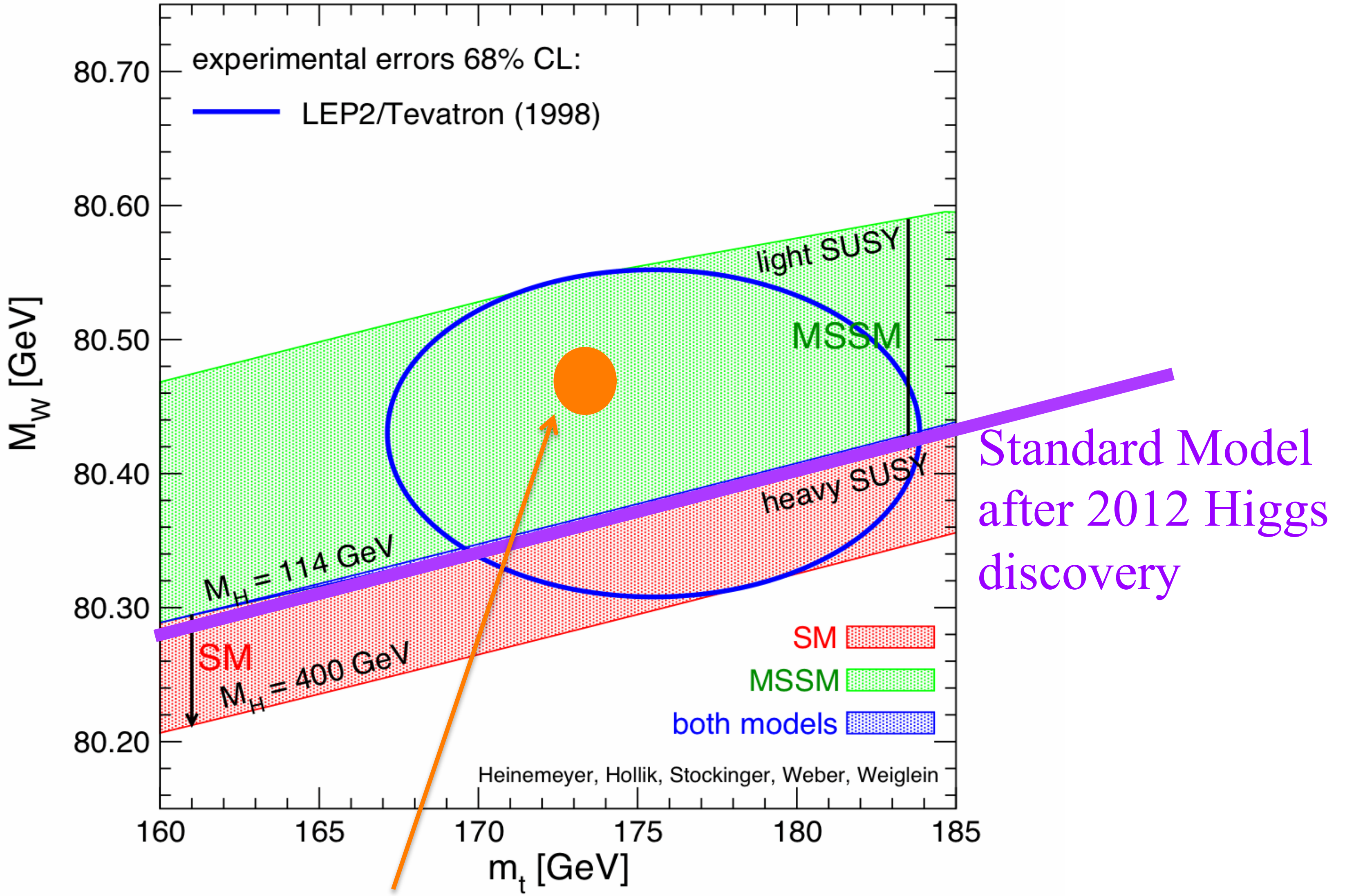
- Combined electrons (3 fits): $M_W = 80424.6 \pm 13.2$ MeV, $P(\chi^2) = 19\%$
- Combined muons (3 fits): $M_W = 80437.9 \pm 11.0$ MeV, $P(\chi^2) = 17\%$
- All combined (6 fits): $M_W = 80433.5 \pm 9.4$ MeV, $P(\chi^2) = 20\%$

New CDF Result Uncertainties

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

Table 2

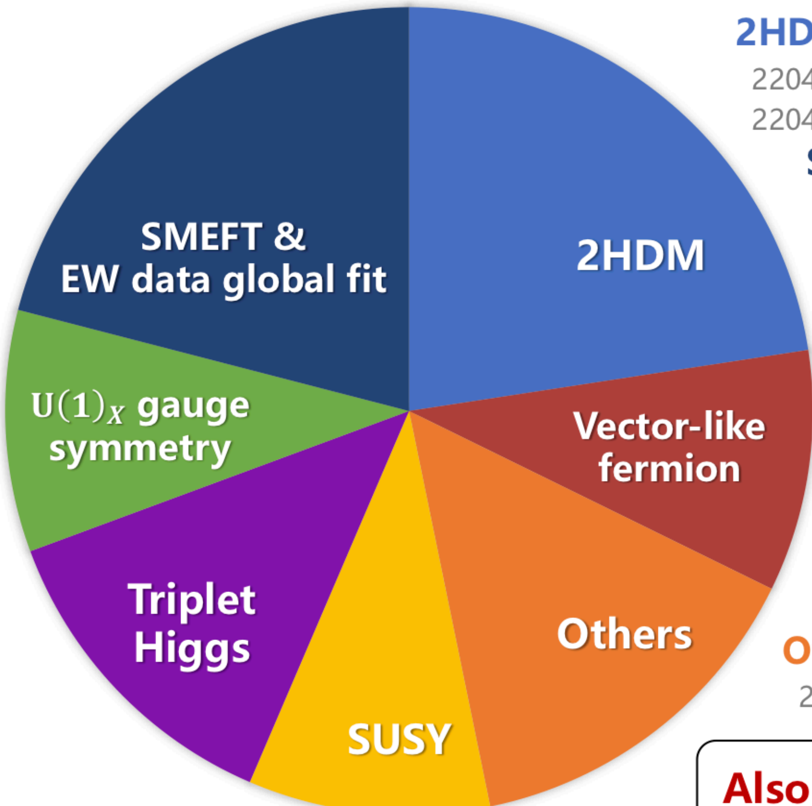
2022 Status of M_W *vs* M_{top}



Science **376**, 170 (April 7, 2022); DOI: 10.1126/science.abk1781

Epilogue

CDF W mass



Total number: 62*

2HDM: 14
2204.03693/03767/04834/04688/06485/05085/05269/05303
2204.05975/09001/05728/08406/08390/10338

SMEFT & EW data global fit: 13
2204.04805/05260/05284/05267/05992/05965/05965/08546
2204.08440/10130/04191/05283/04204

Triplet Higgs: 8
2204.05031/05760/07144/07511/07844/08266/10274/10315

SUSY: 6
2204.04286/04356/04202/05285/06541/07138

$\mathrm{U}(1)_X$ gauge symmetry: 6
2204.07100/08067/09487/09024/09585/10156

Vector-like fermion: 6
2204.07022/07411/08568/09477/09671/05024

Others: 9 (Non-unitarity, leptoquark, singlet scalar, …)
2204.04559/04672/04770/04514/05302/06327/03996/05942/09031

* Preprints as of April 25th are counted.

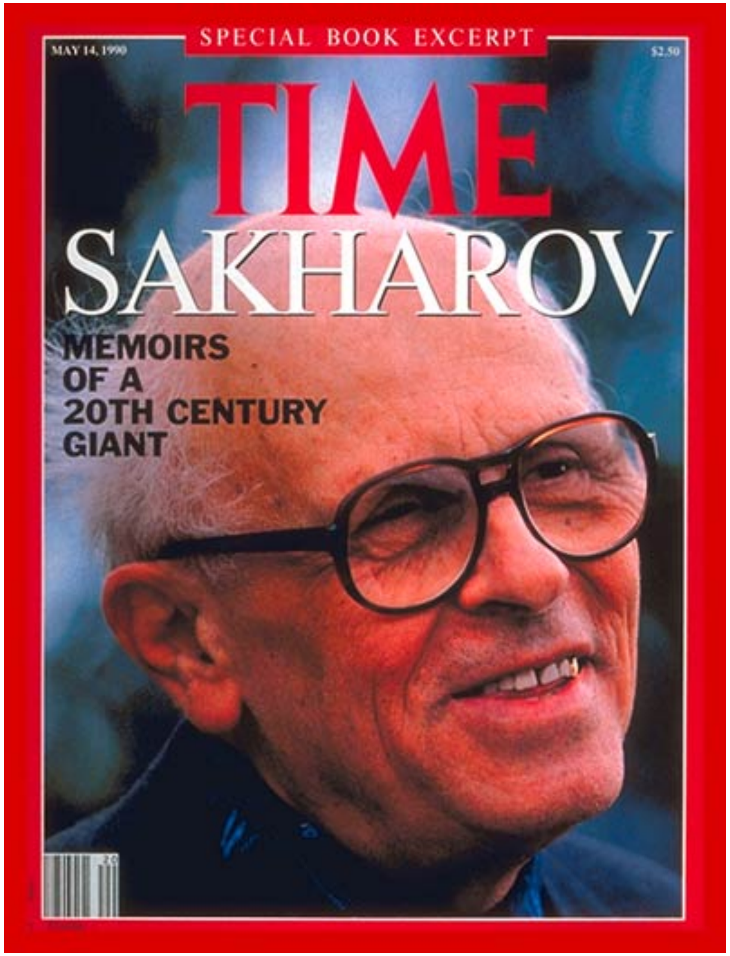
Also related to
dark matter, neutrino masses/seesaw, flavor violation, muon g-2, flavor anomalies, gravitational waves, …

The Heavyweight W boson
&
The Mystery of the Missing AntiMatter

Matter-AntiMatter Symmetry

- Laws of nature have been proven to be (almost) exactly identical for matter and antimatter
- There should be equal amounts of matter and antimatter in the Universe
- Where is the *MISSING* antimatter?
- *WE* need an excess of matter over antimatter in order for galaxies, stars, planets and *us* to exist…

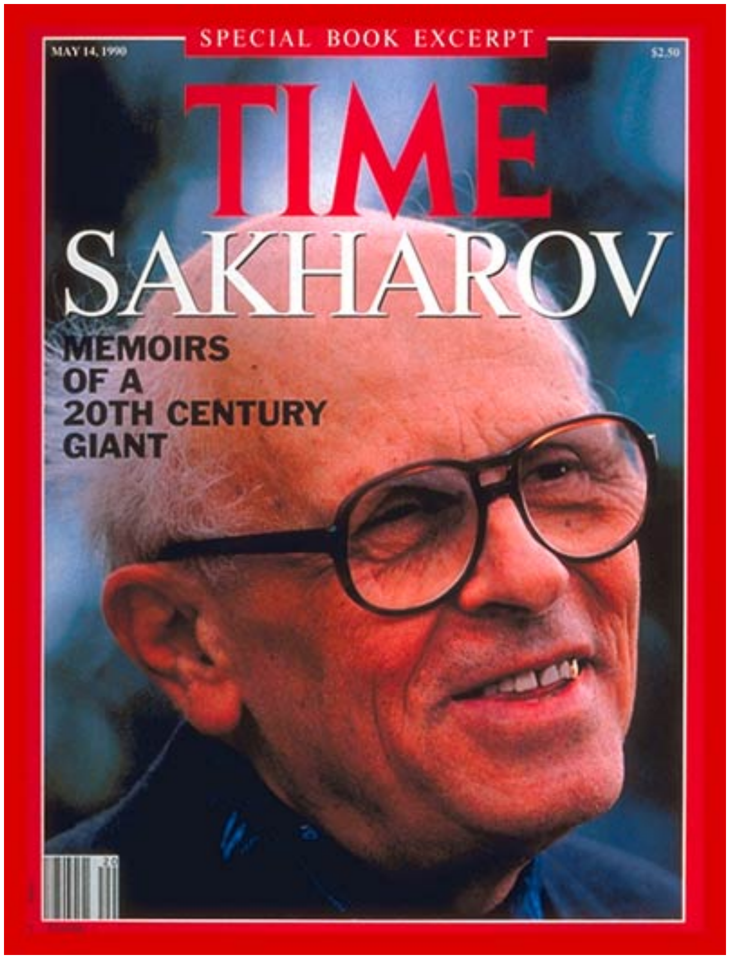
Sakharov Conditions for Matter Excess



Andrei Sakharov calculated three conditions that must exist in early Universe for creation of matter excess

The Standard Model of Particle Physics satisfies only one of these conditions

Sakharov Conditions for Matter Excess



If the Higgs boson had a partner

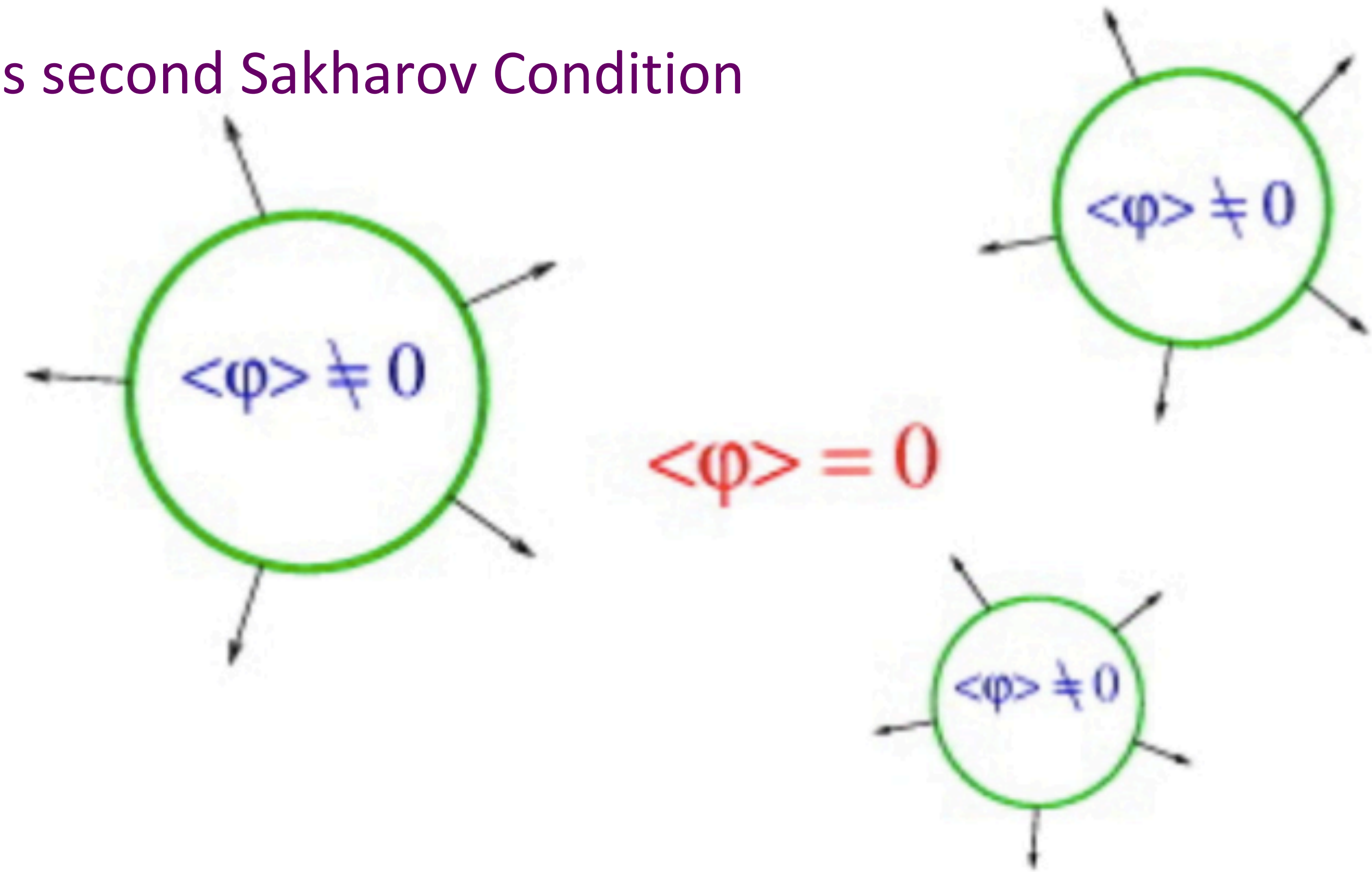
i.e. a second Higgs-like particle existed…

The second Sakharov condition can be satisfied !

Higgs Condensation after Big Bang
aided by Higgs-like Partner

Higgs droplets form and expand, filling the whole Universe

Satisfies second Sakharov Condition



Higgs-like partner's existence increases the W boson mass by the observed 0.1%

Summary

- The *W* boson mass is sensitive to new laws of nature through quantum fluctuations

- New measurement is twice as precise as previous measurements

  - $M_W = 80433.5 \pm 9.4$ MeV

- Significant difference from Standard Model calculation of $M_W = 80{,}357 \pm 6$ MeV

  - significance of 7.0σ ($>5\sigma$ is considered scientific discovery)
  - The Higgs boson is not the end of the story

Thank you for your attention !

W Boson Mass Measurements from Different Experiments

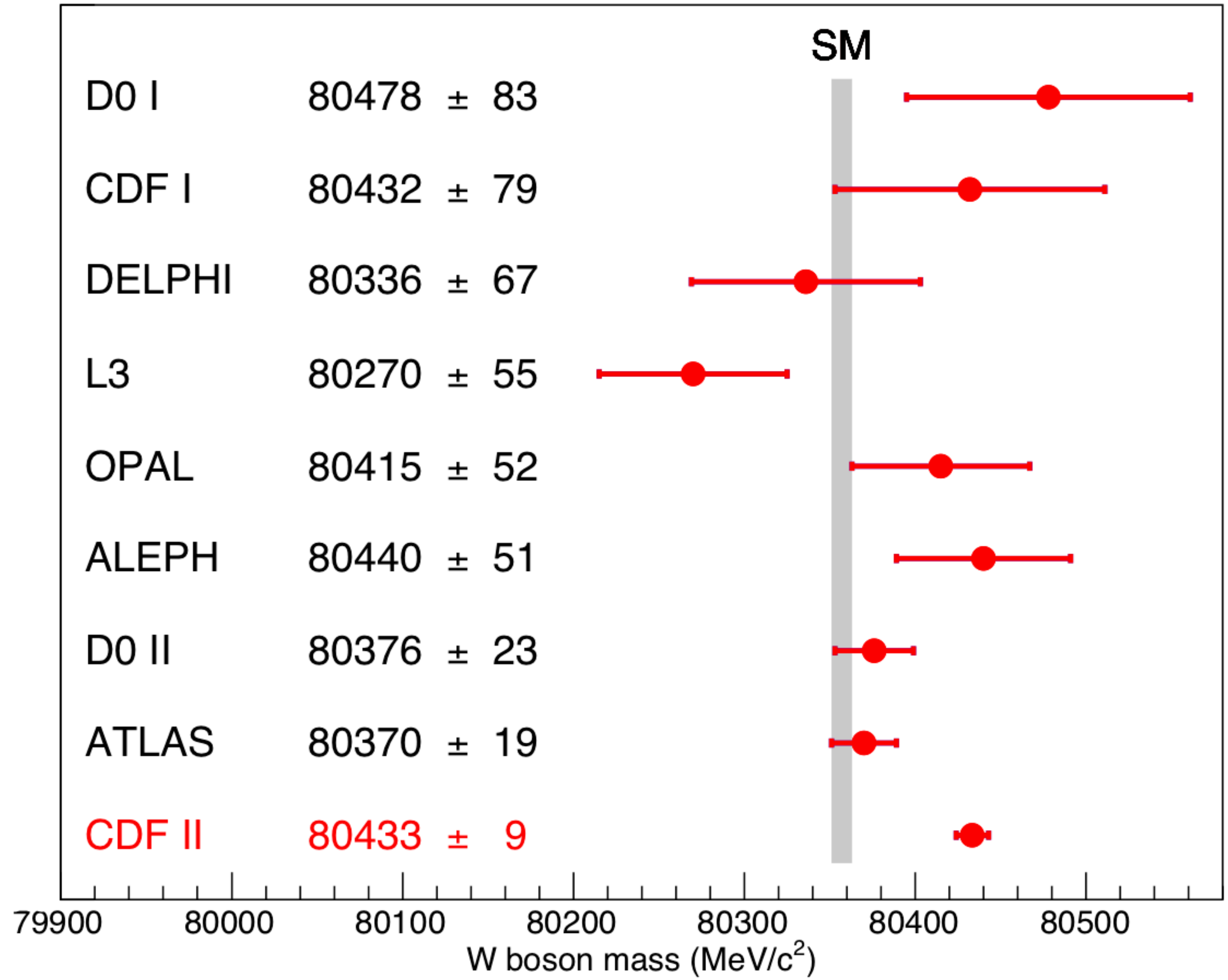
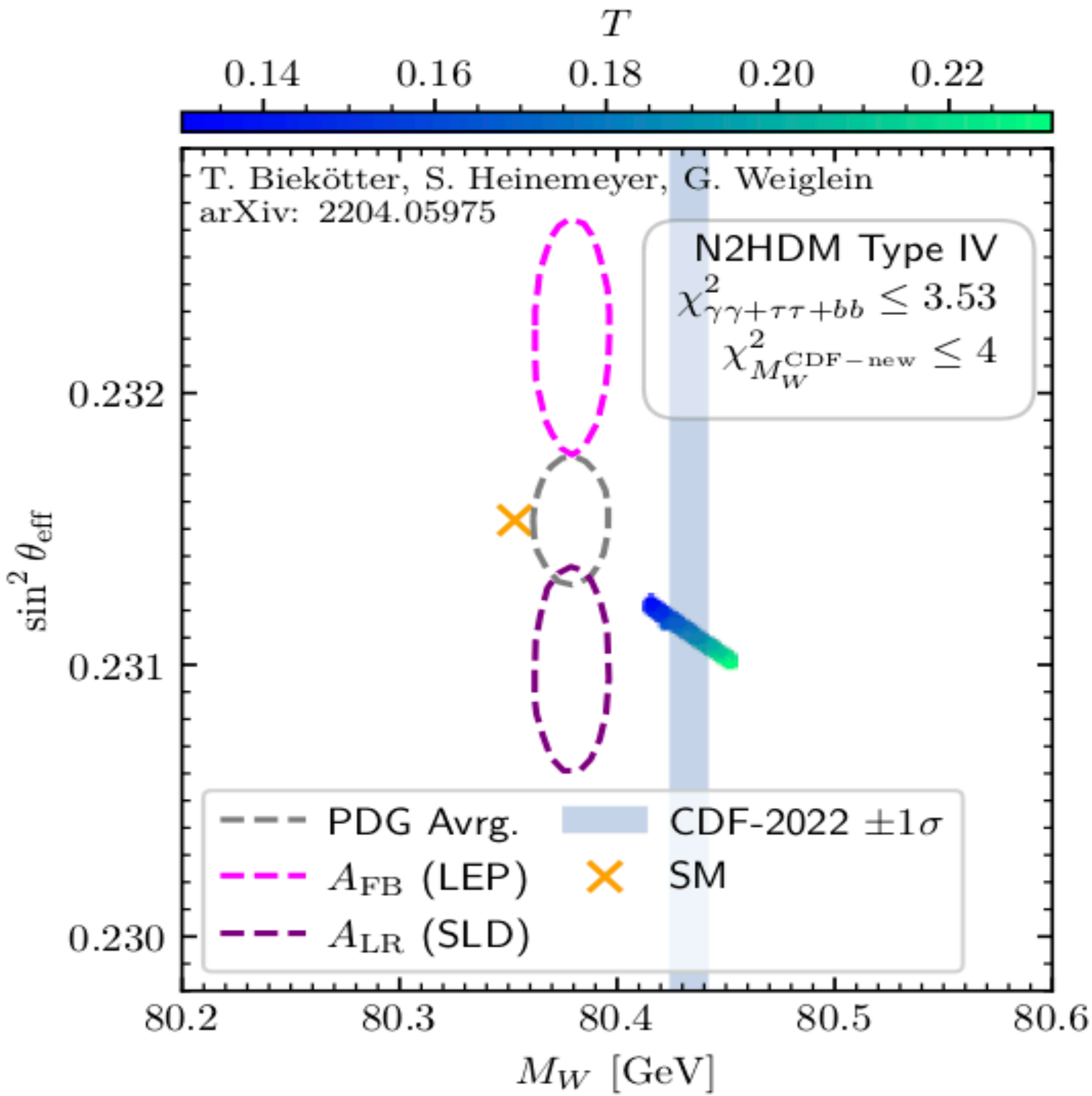


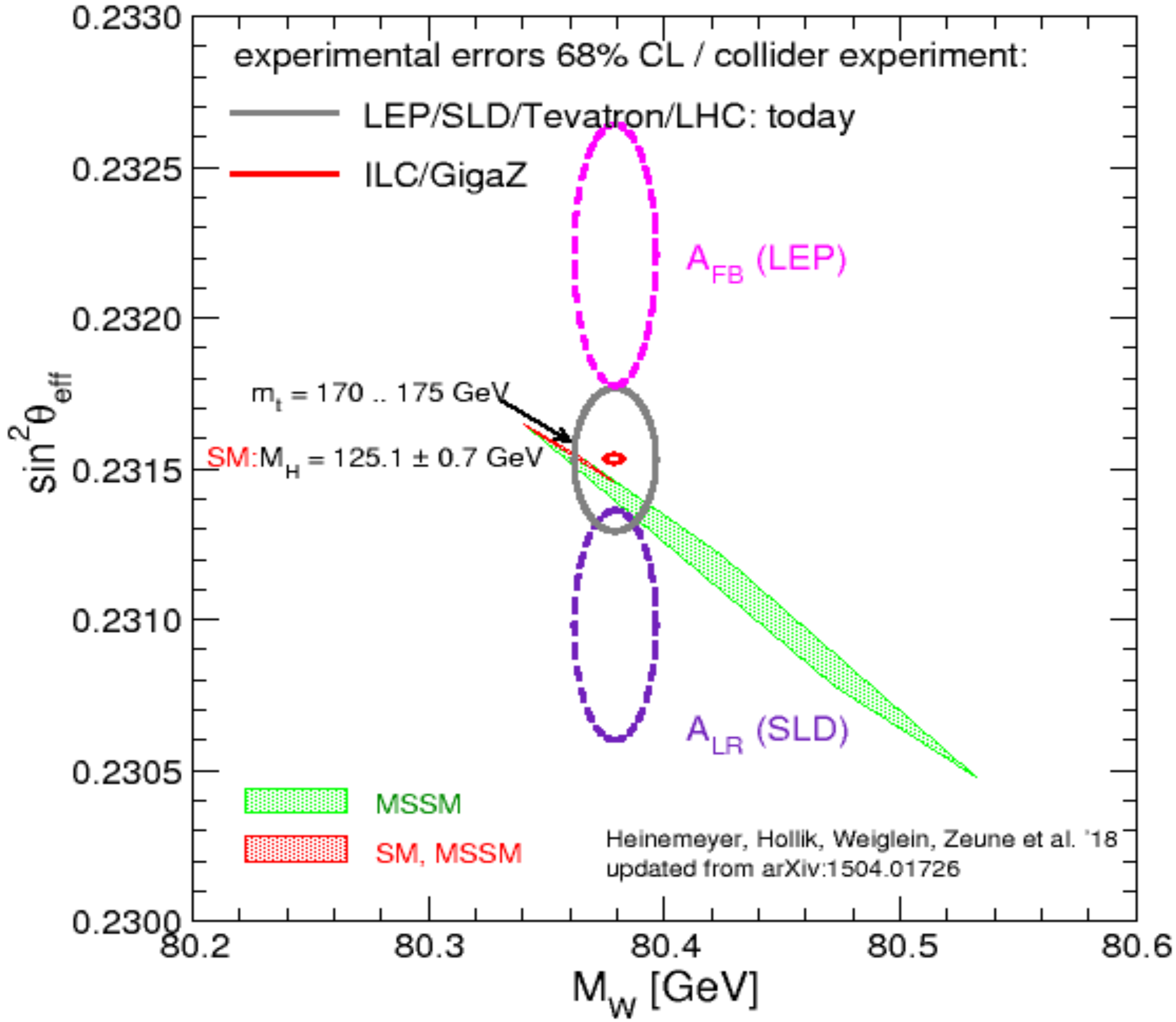
Fig. 5

SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ (PDG 2020)

LHCb measurement : $M_W = 80{,}354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ [*JHEP* **2022,** 36 (2022)]



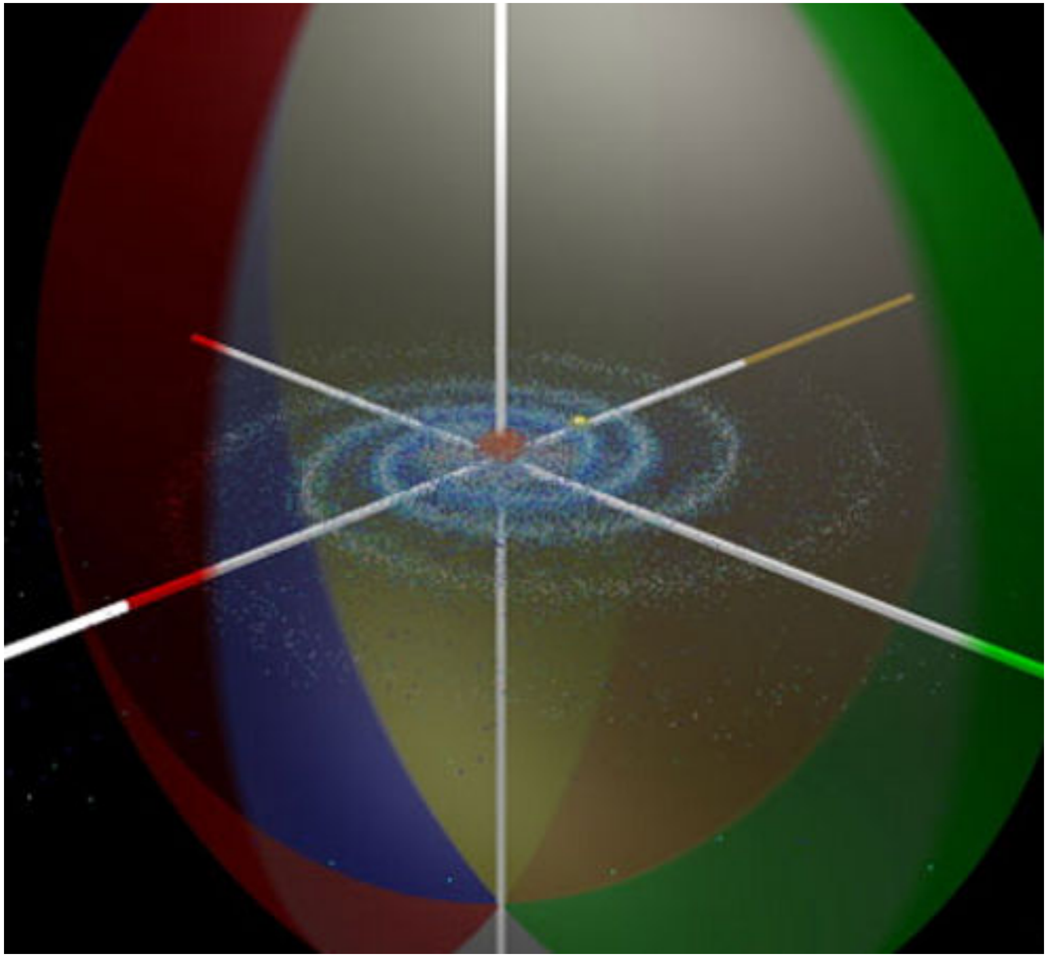
T
0.14
0.16
0.18
0.20
0.22
T. Biekötter, S. Heinemeyer, G. Weiglein
arXiv: 2204.05975
N2HDM Type IV
$\chi^2_{\gamma\gamma+\tau\tau+bb} \leq 3.53$
$\chi^2_{M_W^{\mathrm{CDF-new}}} \leq 4$
0.232
0.231
0.230
$\sin^2\theta_{\mathrm{eff}}$
PDG Avrg.
A_{FB} (LEP)
A_{LR} (SLD)
CDF-2022 $\pm 1\sigma$
SM
80.2
80.3
80.4
80.5
80.6
M_W [GeV]



experimental errors 68% CL / collider experiment:
LEP/SLD/Tevatron/LHC: today
ILC/GigaZ
A_FB (LEP)
A_LR (SLD)
m_t = 170 .. 175 GeV
SM:M_H = 125.1 ± 0.7 GeV
MSSM
SM, MSSM
Heinemeyer, Hollik, Weiglein, Zeune et al. '18
updated from arXiv:1504.01726
sin²θ_eff
M_W [GeV]
0.2330
0.2325
0.2320
0.2315
0.2310
0.2305
0.2300
80.2
80.3
80.4
80.5
80.6

Dark Matter, Galaxy Formation and the Quantum Foam

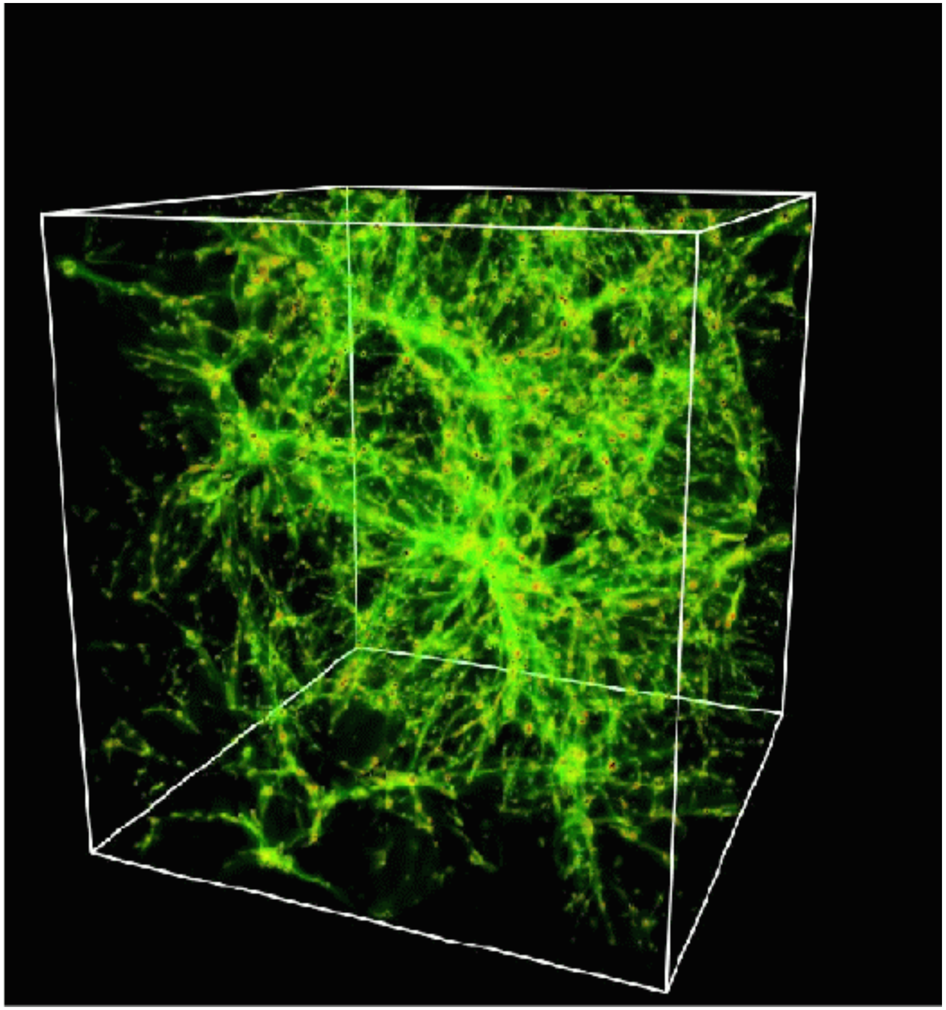
Halo of Invisible Dark Matter around Galaxies



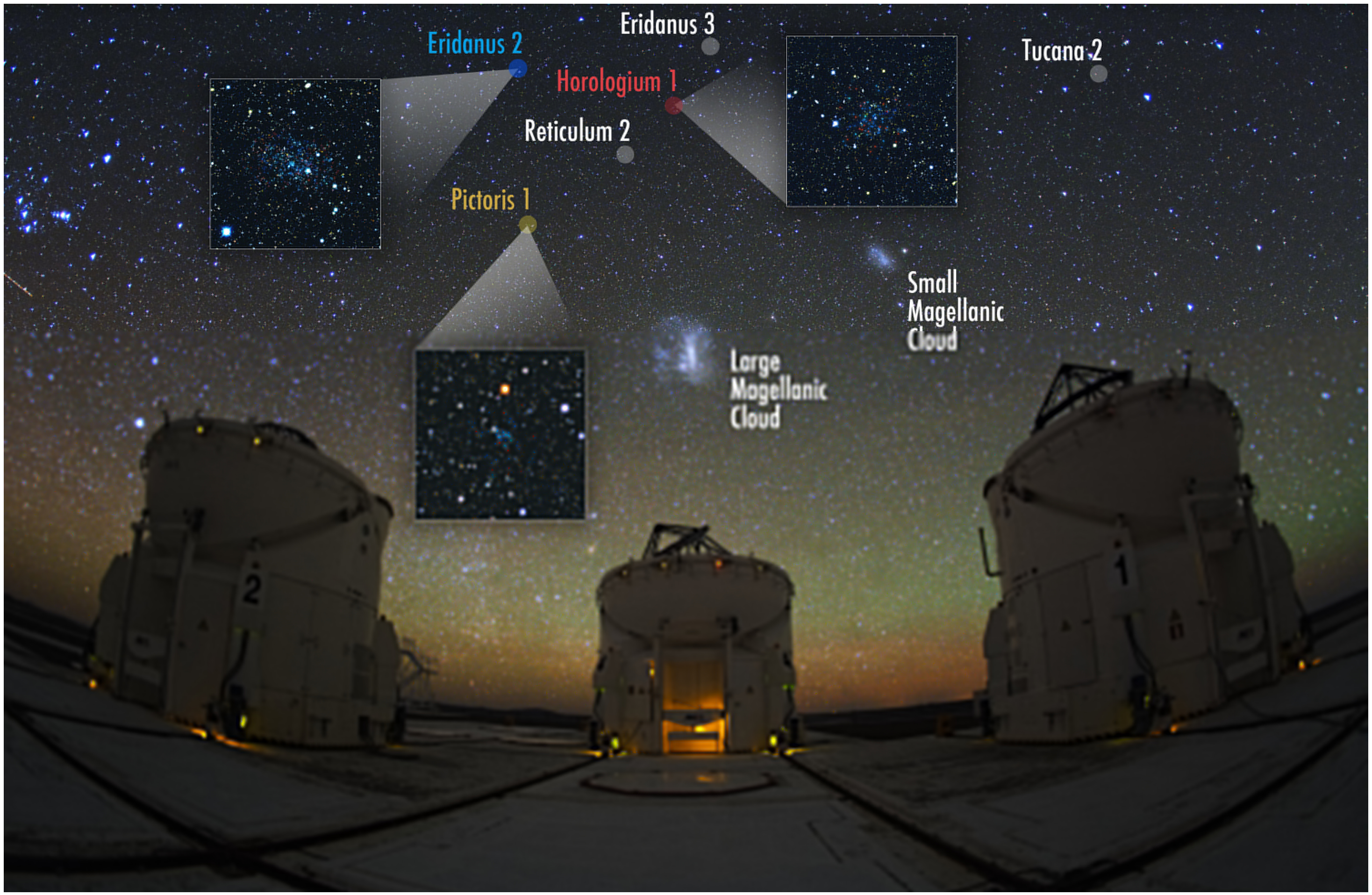
Four times as much dark matter as visible matter

Mapping out the Dark Matter

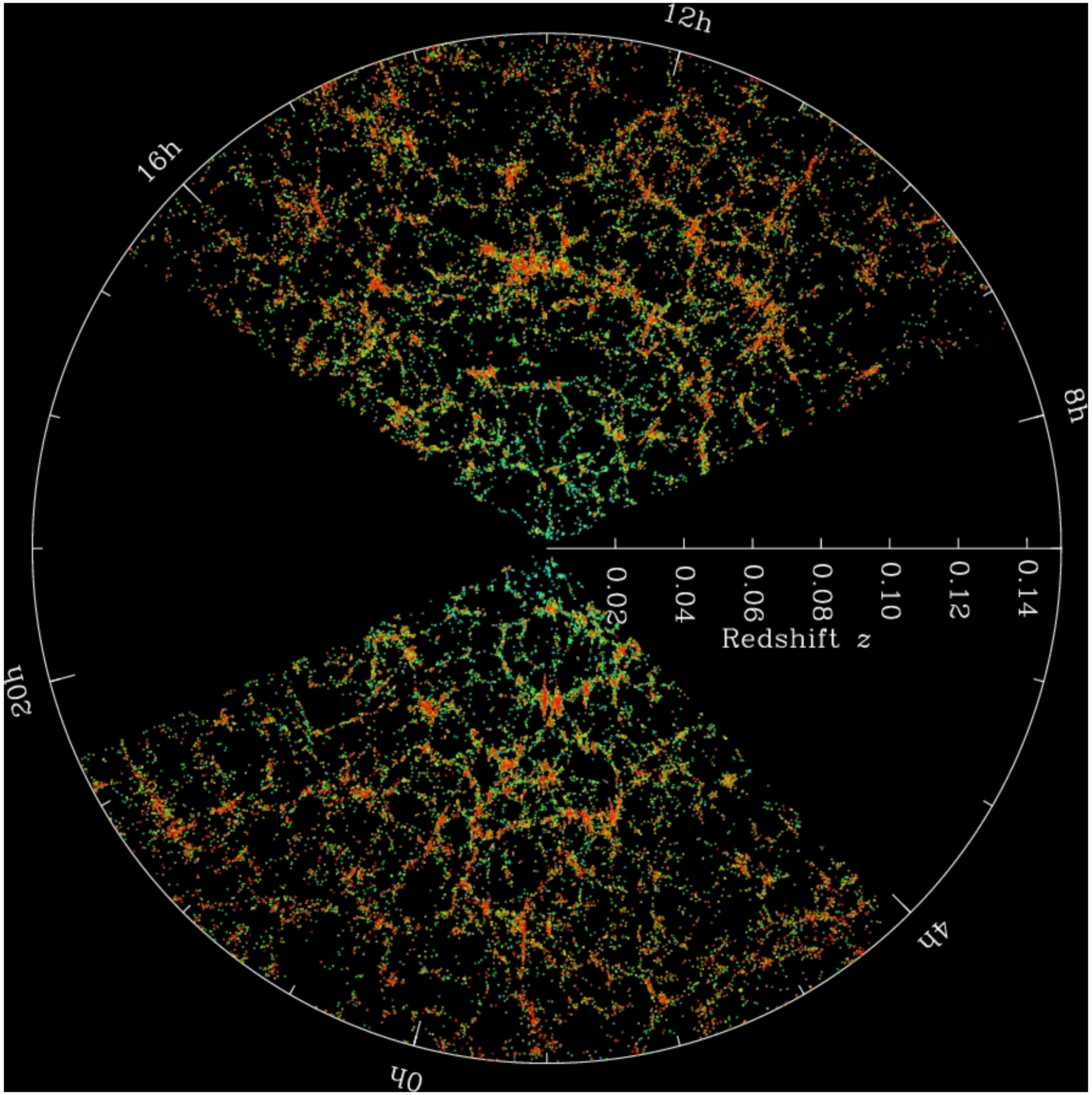
- *A lot* of dark matter is required to hold galaxies together
- It cannot all be made of protons
- It must be neutral, stable, heavy
- It must be some new form of matter – new fundamental particles



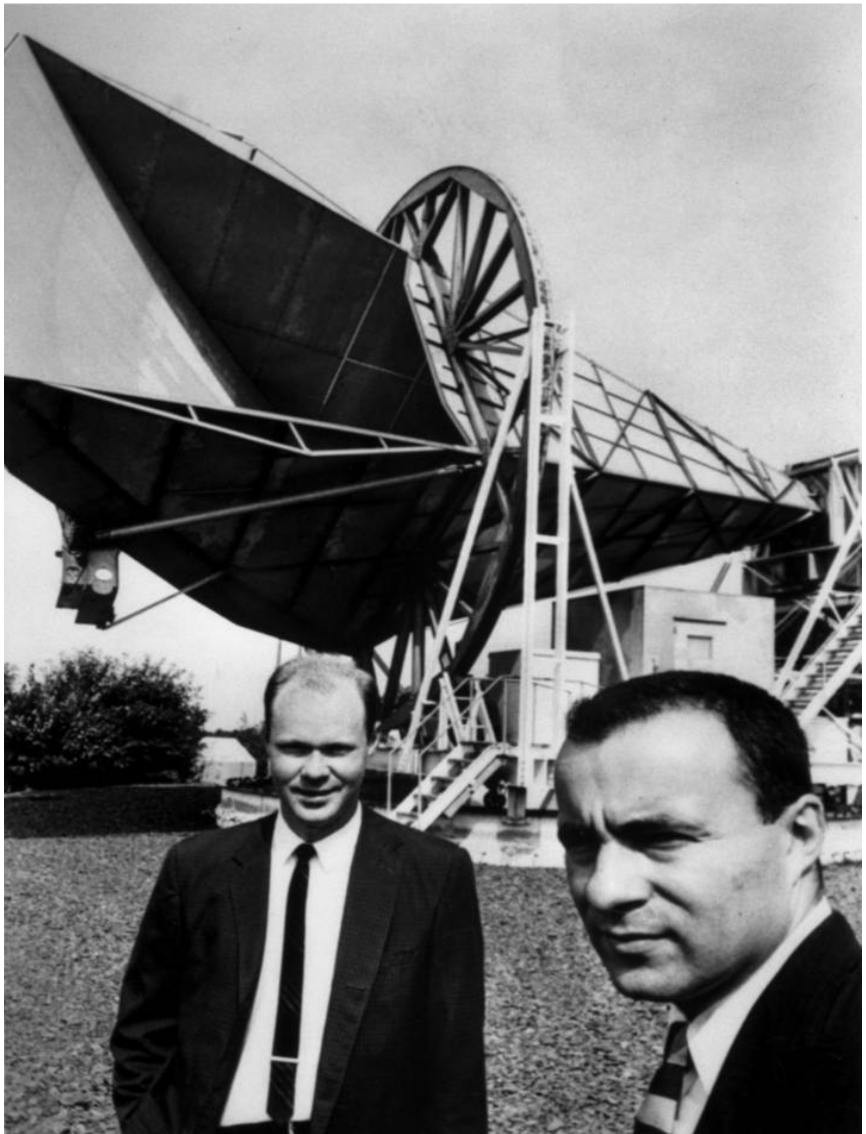
Newly Discovered Dark Matter Galaxies



3D Distribution of Galaxies



Cosmic Microwave Background

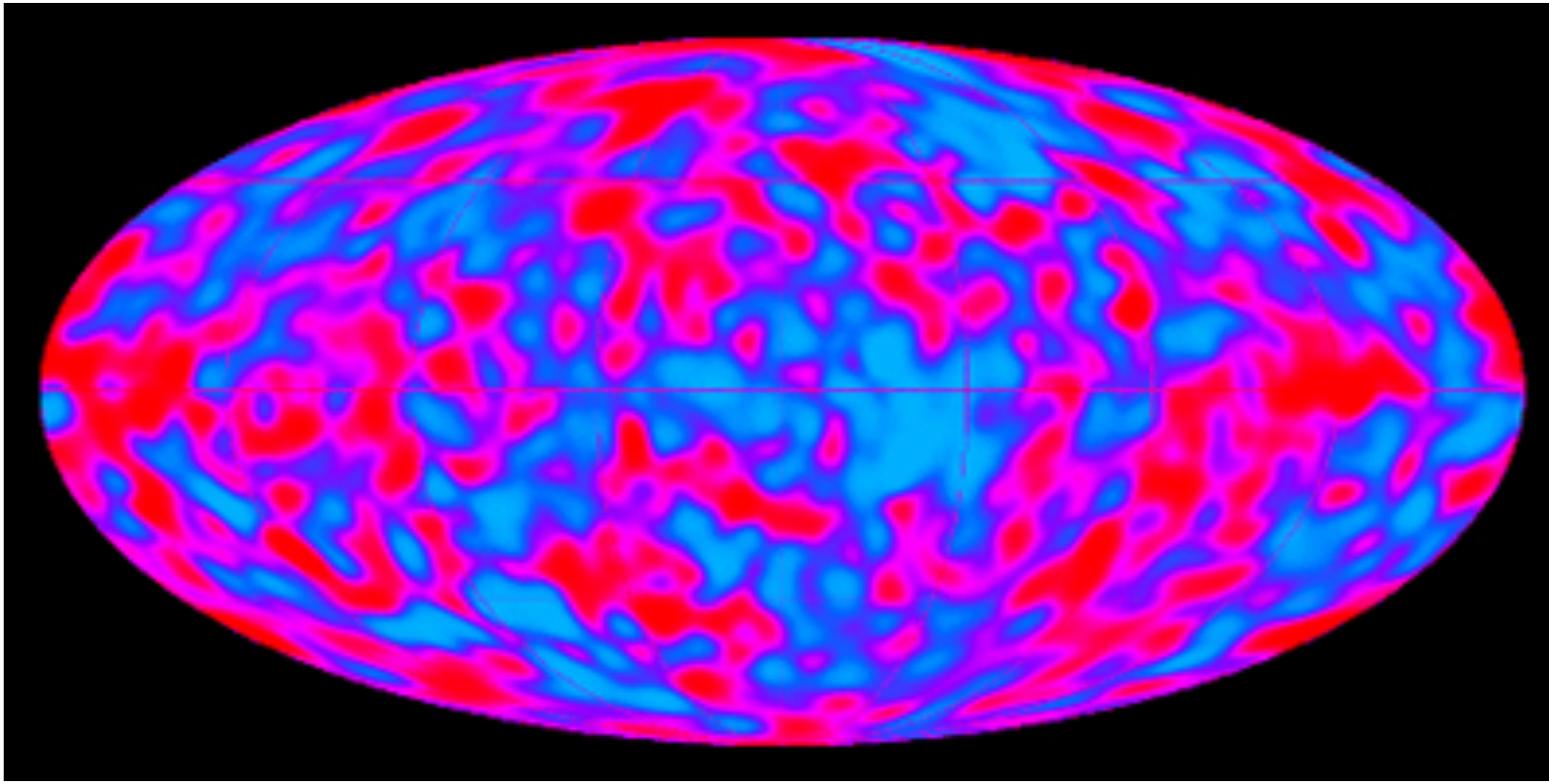


Penzias and Wilson (Bell Labs) discovered in 1964 a constant microwave radiation coming uniformly from all points in the sky

This radiation was emitted at the beginning of the Universe

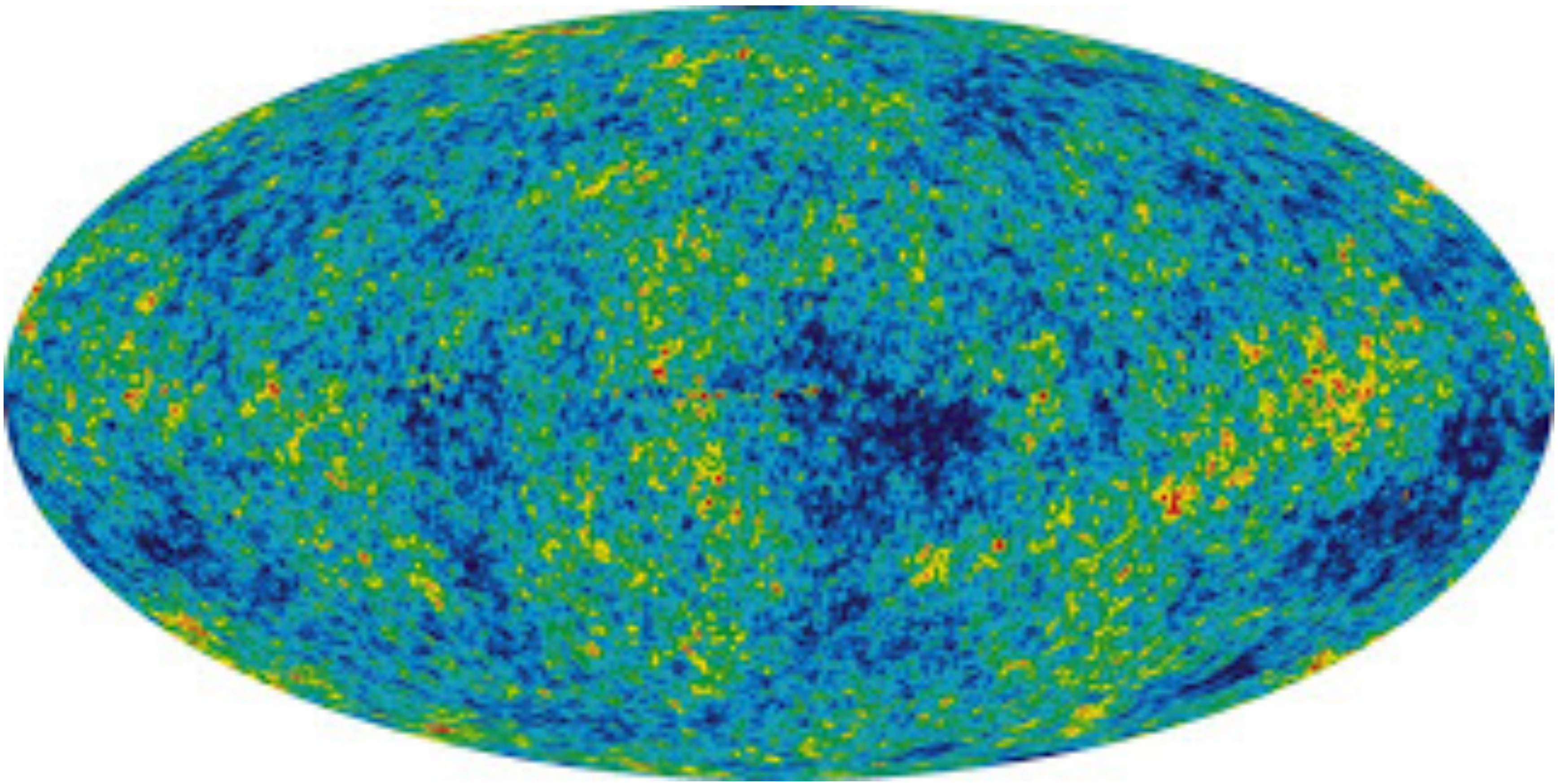
Nobel-prize winning discovery

Cosmic Microwave Background Fluctuations



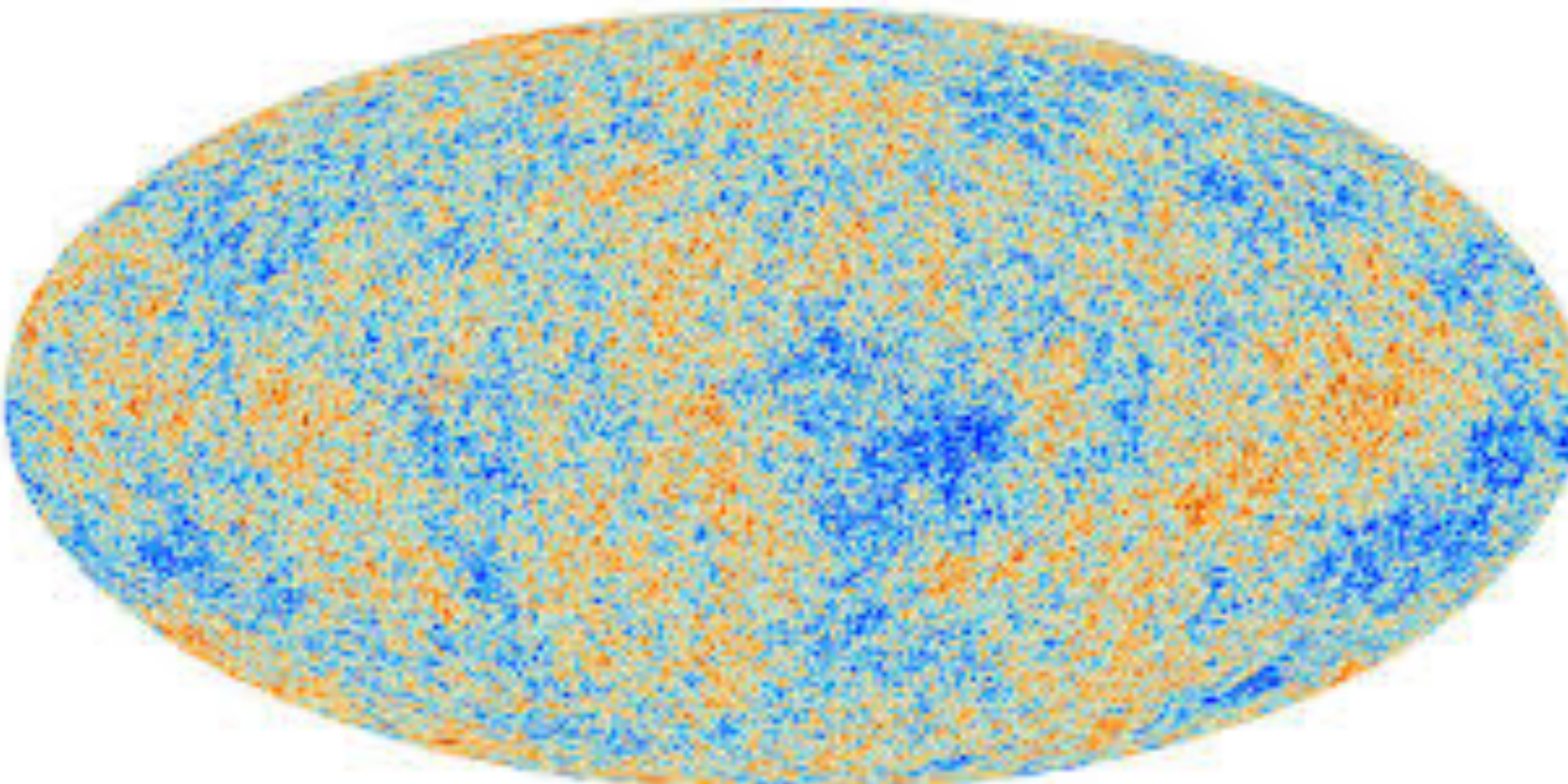
Full sky measurement of variation of microwave radiation
0.001% variation with direction in sky, measured by COBE satellite
(Nobel-prize winning discovery)

Cosmic Microwave Background Fluctuations



Full sky measurement of variation of radiation
Improved direction precision measured by WMAP satellite

Cosmic Microwave Background Fluctuations



Full sky measurement of variation of radiation
Further improved direction precision measured by PLANCK satellite

Origin of Galaxies Requires Dark Matter

- Quantum fluctuations at the Big Bang cause density variations
  - We are seeing the imprint of these density variations on the earliest light
- Density variations seeded the accretion of dark matter
- Dark matter accretion causes accretion of visible matter
  - Leading to galaxies we see today

Improvements over 2012 Analysis (Table S1 of Paper)

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

Table S1

Quantified shifts in 2012 result due to updates in PDF and track reconstruction

Improvements over 2012 Analysis

- The statistical precision of the measurement from the four times larger sample is improved by almost a factor of 2
- To achieve a commensurate reduction in systematic uncertainties, a number of analysis improvements have been incorporated
- These improvements are based on using cosmic-ray and collider data in ways not employed previously to improve
  - the COT alignment and drift model and the uniformity of the EM calorimeter response
  - the accuracy and robustness of the detector response and resolution model in the simulation
  - theoretical inputs to the analysis have been updated
- Upon incorporating the improved understanding of PDFs and track reconstruction, our previous measurement is increased by 13.5 MeV to 80,400.5 MeV
  - consistency of the latter with the new measurement is at the percent probability level

W Mass Fit Window Variation, m_T Fit

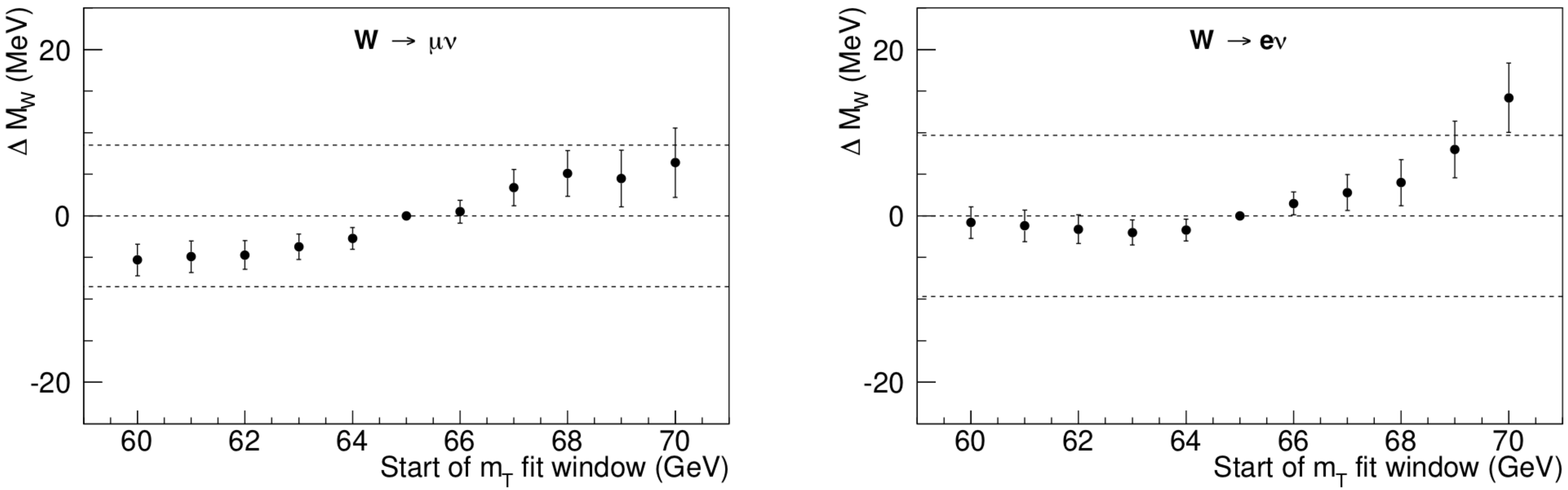
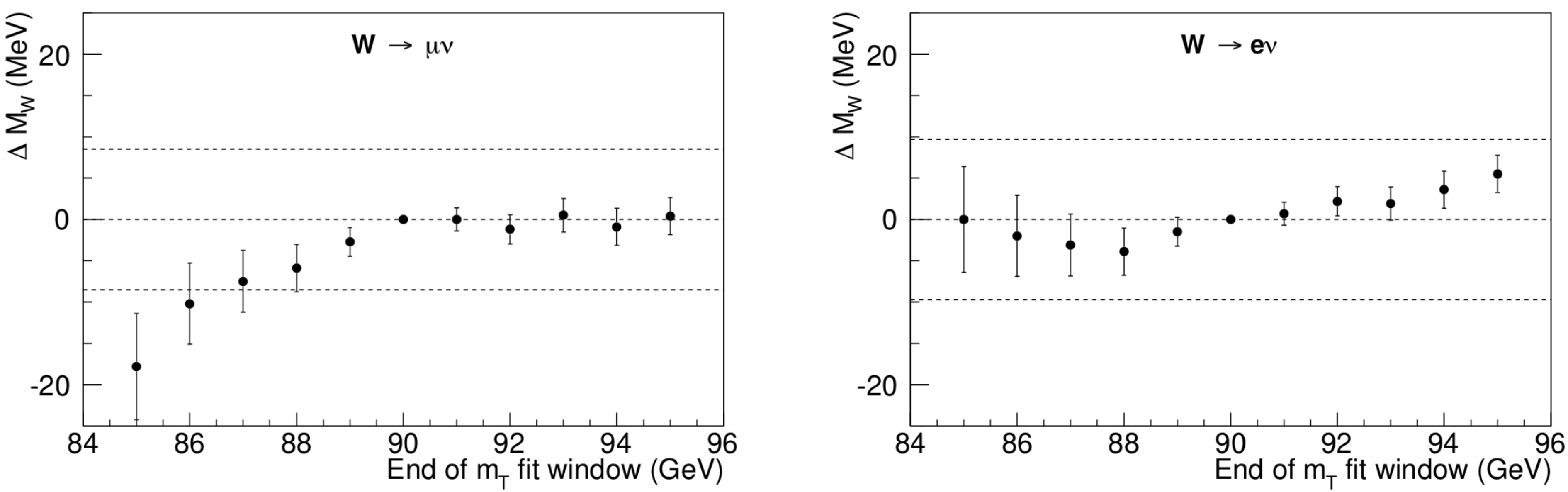


Fig. S39



W Mass Fit Window Variation, $p_T(l)$ Fit

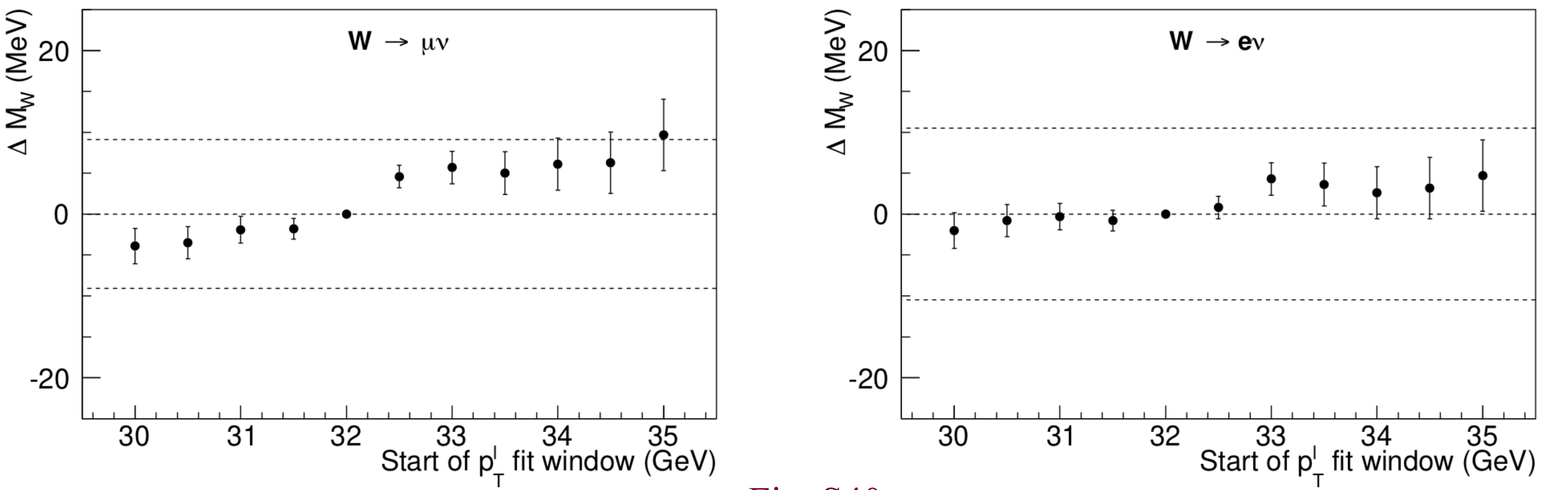
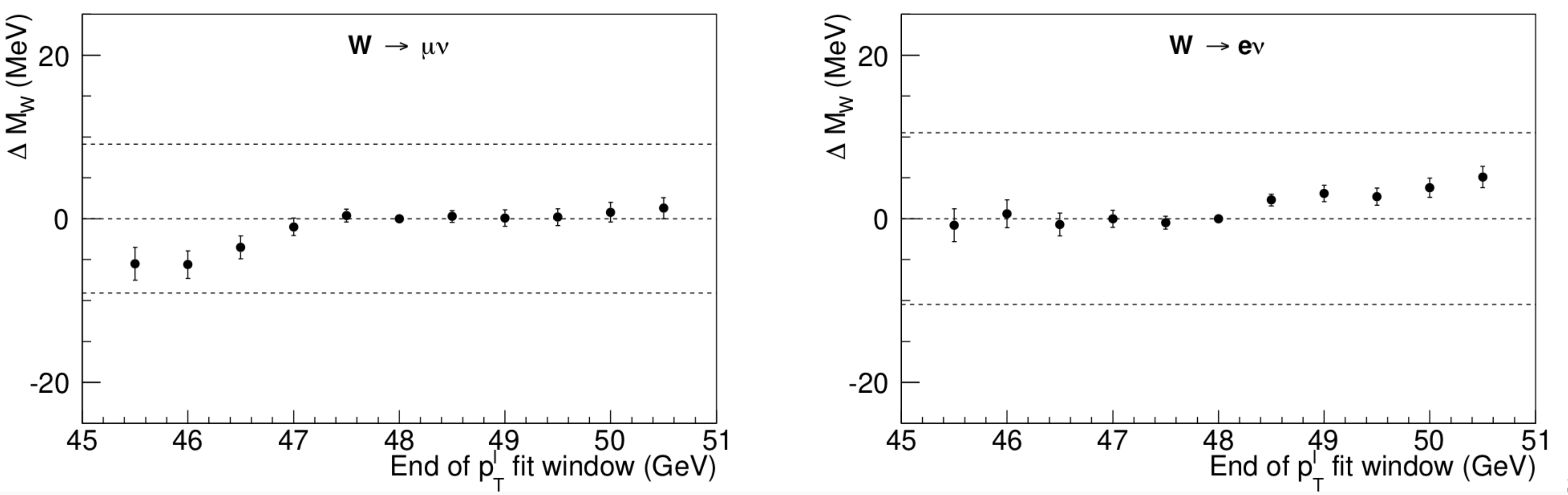


Fig. S40



W Mass Fit Window Variation, $p_T(\upsilon)$ Fit

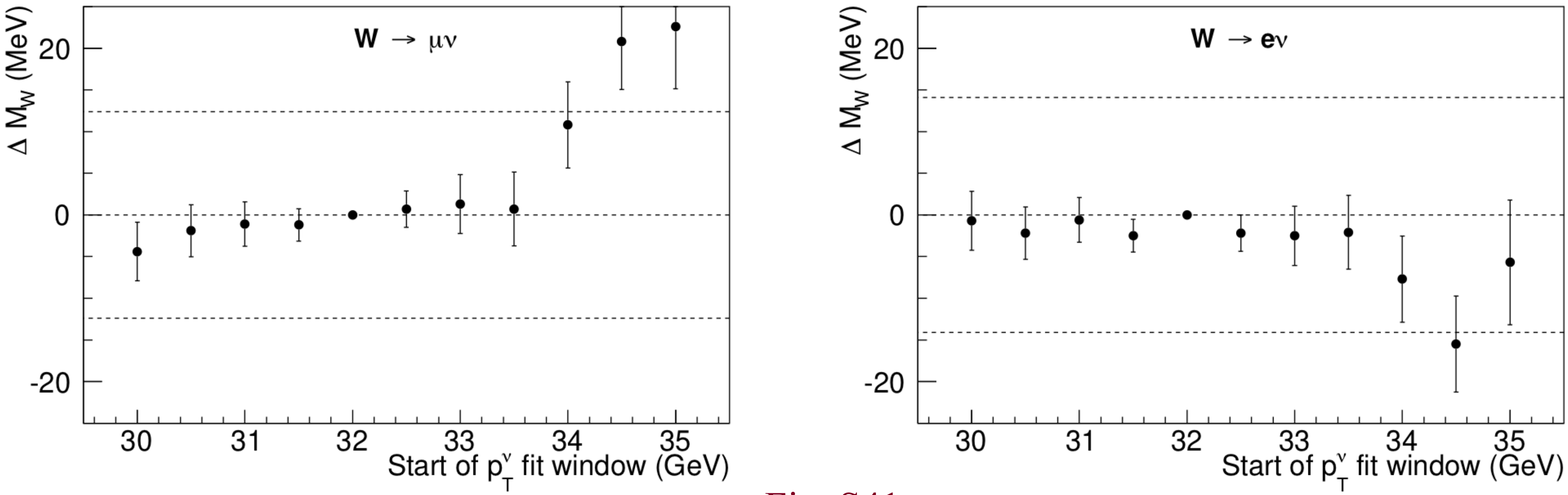
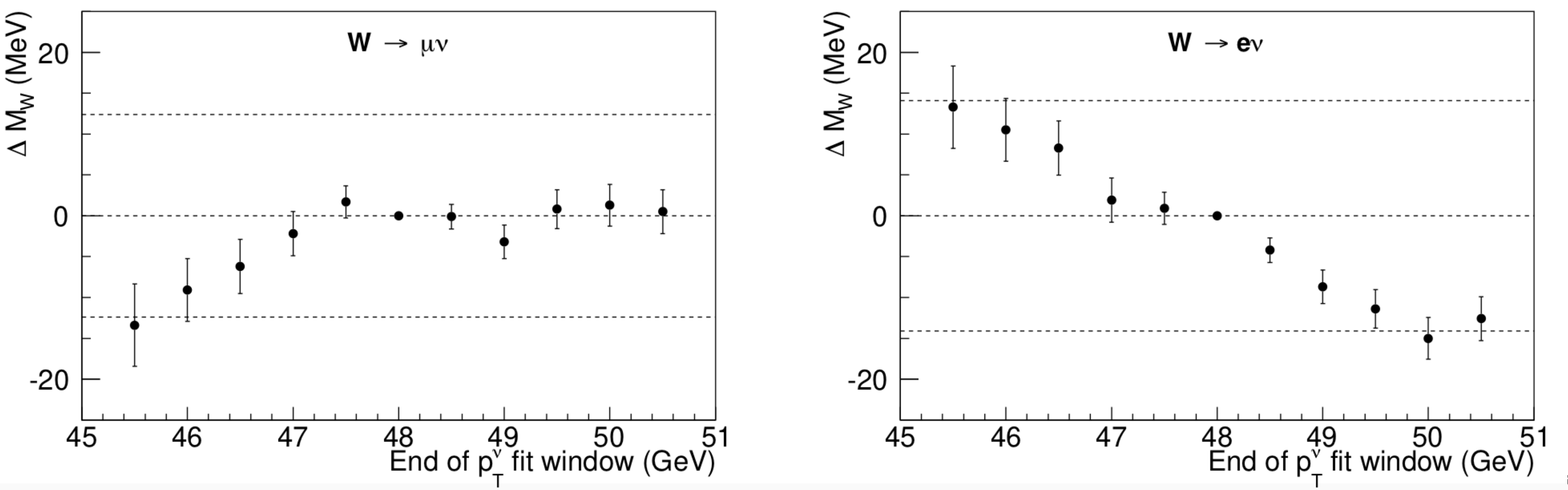


Fig. S41



Updates to 2012 Result (2.2 fb^{-1})

- Shift from CTEQ6 to NNPDF3.1 PDF used for central value = +3.5 MeV

- In the 2.2 fb^{-1} analysis, an additional systematic uncertainty was quoted to cover an inconsistency between the NBC and BC $\Upsilon \rightarrow \mu\mu$ mass fits.
- In this analysis we resolve the inconsistency caused by the beam-constraining procedure, eliminating the additional systematic uncertainty and increasing the measured M_W value by ≈ 10 MeV.
- The beam-constraining procedure in the CDF track reconstruction software extrapolates the tracks found in the COT inward to the transverse position of the beamline. This extrapolation can and should take into account the energy loss in the material inside the inner radius of the COT (the beampipe, the silicon vertex detector and its services) to infer and update the track parameters at the beam position before applying the beam constraint.
- This update had been deactivated in the reconstruction software used for the previous analysis. By activating this updating feature of the extrapolator, the flaw in the BC $\Upsilon \rightarrow \mu\mu$ mass is corrected, which changes the momentum scale derived from it.

Subsample Fit Stability

TABLE S10: Differences (in MeV) between W-mass p_T^ℓ-fit results and Z-mass fit results obtained from subsamples of our data with equal statistics. For the spatial and time dependence of the electron channel fit result, we show the dependence with (without) the corresponding cluster energy calibration using the subsample E/p fit.

Fit difference	Muon channel	Electron channel
$M_W(\ell^+) - M_W(\ell^-)$	$-7.8 \pm 18.5_{\mathrm{stat}} \pm 12.7_{\mathrm{COT}}$	$14.7 \pm 21.3_{\mathrm{stat}} \pm 7.7^{\mathrm{E/p}}_{\mathrm{stat}}$ $(0.4 \pm 21.3_{\mathrm{stat}})$
$M_W(\phi_\ell > 0) - M_W(\phi_\ell < 0)$	$24.4 \pm 18.5_{\mathrm{stat}}$	$9.9 \pm 21.3_{\mathrm{stat}} \pm 7.5^{\mathrm{E/p}}_{\mathrm{stat}}$ $(-0.8 \pm 21.3_{\mathrm{stat}})$
$M_Z(\mathrm{run} > 271100) - M_Z(\mathrm{run} < 271100)$	$5.2 \pm 12.2_{\mathrm{stat}}$	$63.2 \pm 29.9_{\mathrm{stat}} \pm 8.2^{\mathrm{E/p}}_{\mathrm{stat}}$ $(-16.0 \pm 29.9_{\mathrm{stat}})$

$\Upsilon \longrightarrow \mu\mu$ mass fit – stability w.r.t. time and instantaneous luminosity

Table S2. The BC $\Upsilon \to \mu\mu$ sample is divided into two equal size sub-samples to check the stability of the momentum scale versus time and versus instantaneous luminosity. The momentum scales are consistent within the statistical uncertainty; the difference between the later and earlier datasets is $(\frac{\Delta p}{p})_{\mathrm{later}} - (\frac{\Delta p}{p})_{\mathrm{earlier}} = (23 \pm 22_{\mathrm{stat}})$ ppm and the difference between the higher and lower instantaneous-luminosity datasets is $(\frac{\Delta p}{p})_{\mathrm{higher}} - (\frac{\Delta p}{p})_{\mathrm{lower}} = (22 \pm 22_{\mathrm{stat}})$ ppm (the later dataset has a higher average instantaneous luminosity).

The Future of the M_W Measurement

- The experiments at the LHC have collected and are collecting a lot of data.
  - While W bosons are produced slightly differently at the LHC (*pp* collider) than the Tevatron ($p\bar{p}$ collider), the LHC experiments have the opportunity to make this measurement.

- If built, a new electron-positron collider can also measure the W boson mass very precisely.

- The LHC as well as smaller, specialized experiments are sensitive to the kinds of new particles and interactions that can influence the W boson mass.
  - If there is new physics which could explain the tension of our result with the SM expectation, this new physics could show up directly in these experiments.

- CDF has analyzed and published on the full dataset. We have incorporated a lot of new ideas in this round of analysis. If we get more ideas, we will pursue them systematically.