High precision measurement of W boson mass

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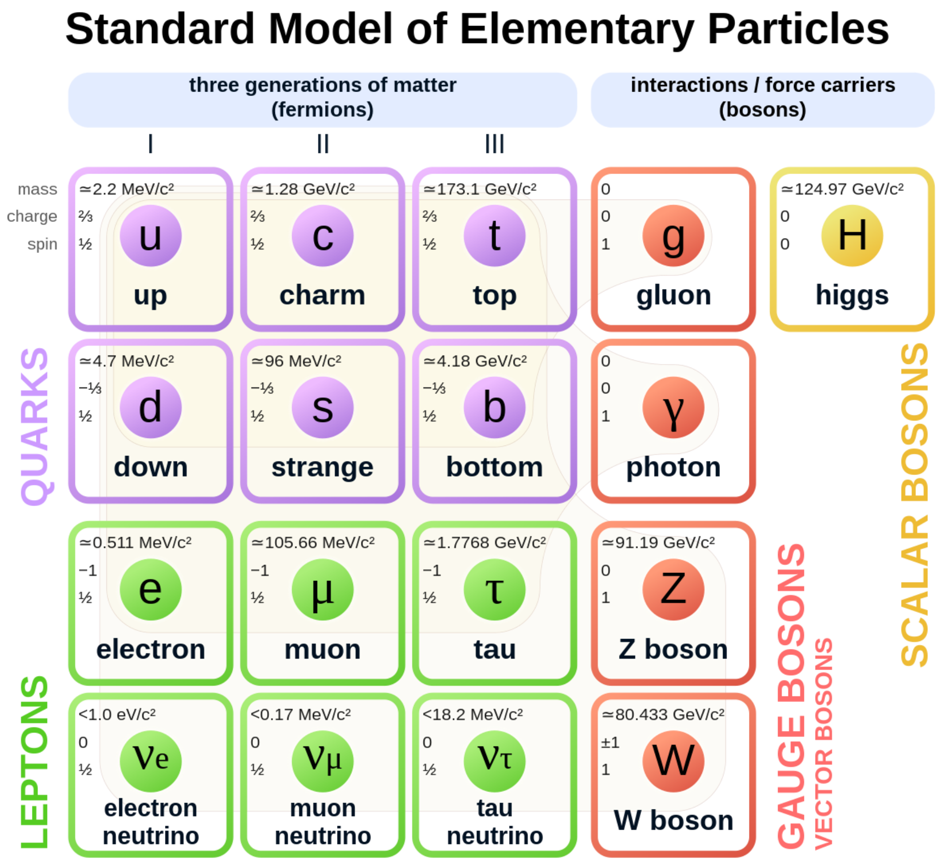
Introduction to Standard Model

Standard model introduction

Fundamental particles in nature and the particles that govern their interaction with each other.

- 6 quarks & 6 leptons: building blocks of matter
- 4 force-carrying particles
- 1 Higgs: Give masses to particles



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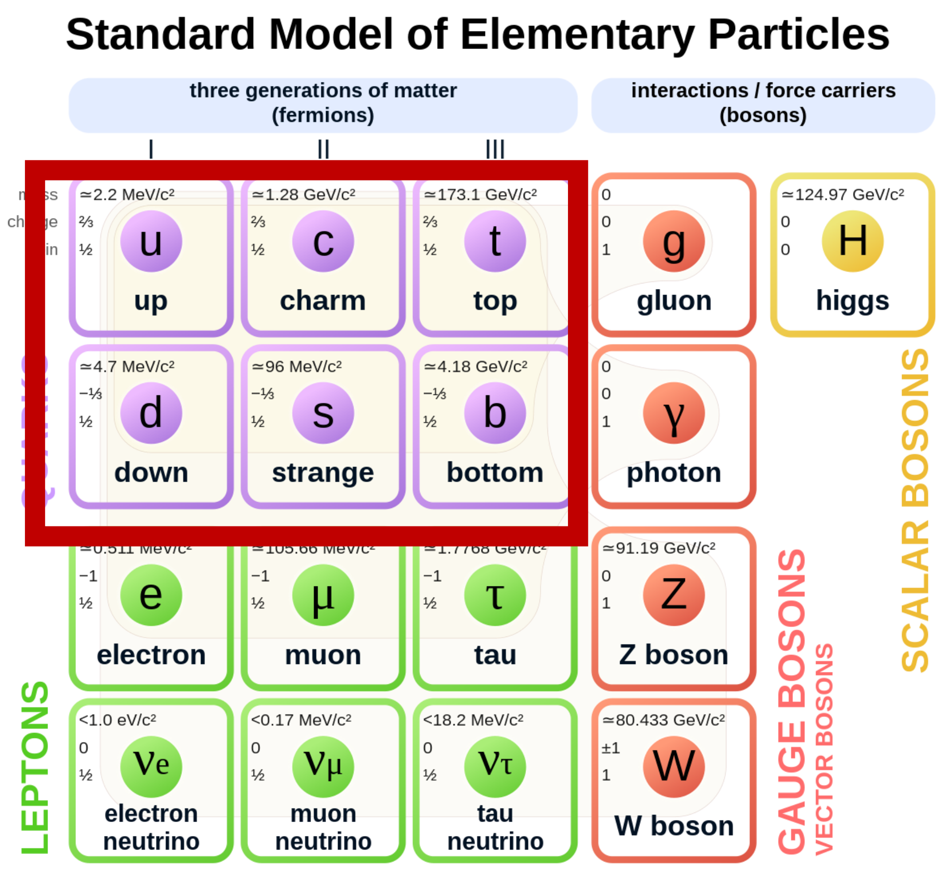
Quarks

- Six different types of quark
- Has color and can interact with each other through the strong force
- The building blocks of hadrons (protons and neutrons)



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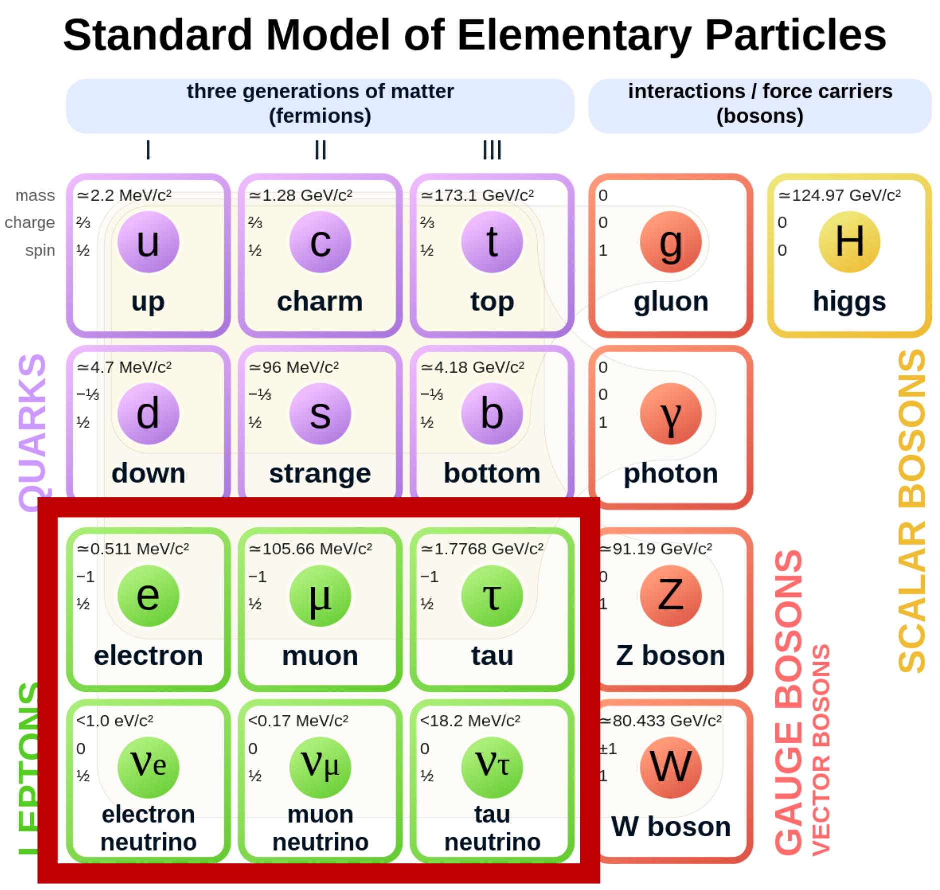
Lepton

- Six different types of leptons
- Neutrinos are a subgroup of the leptons
- Electron: weak and EM interaction
- Muon & Tau: heavier electron
- Neutrinos: only weak interaction → very hard to detect

* Electron and neutrino come in pairs

* Analogy to spin ½ particles



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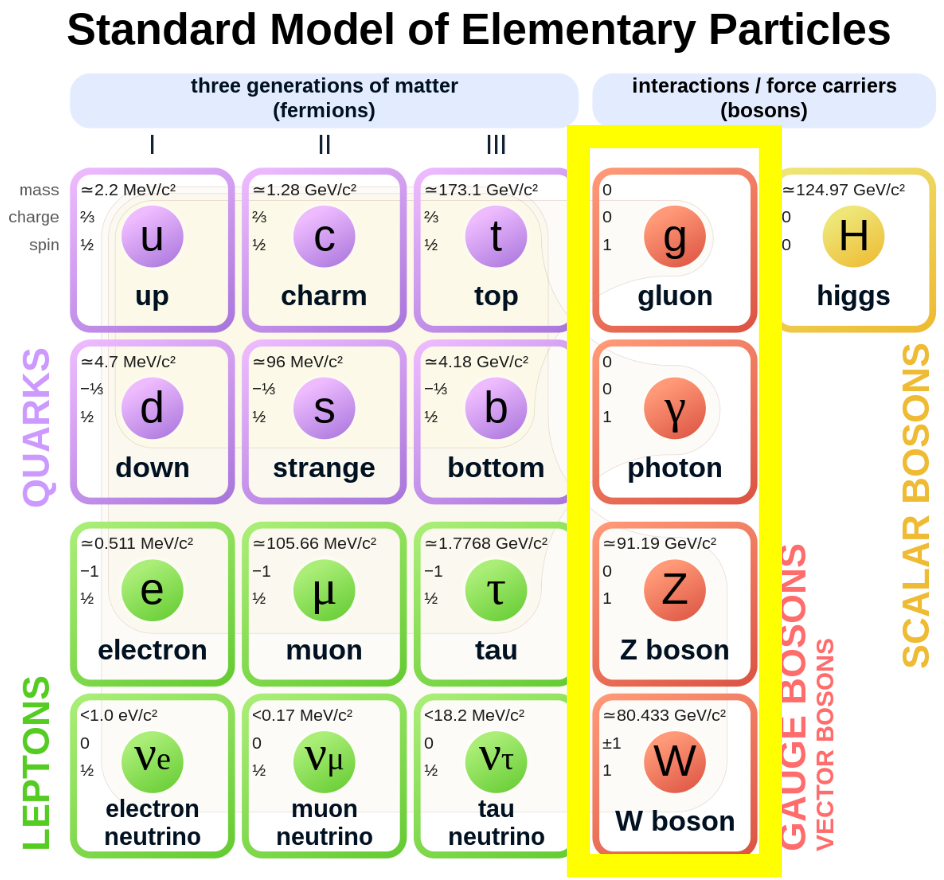
Bosons

- 4 fundamental forces of nature.
- 3 out of 4 are included in the SM of particle physics:
  - electromagnetic force
  - strong force
  - weak force.
- The Bosons are force carriers. (except Higgs)



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Electroweak Unification

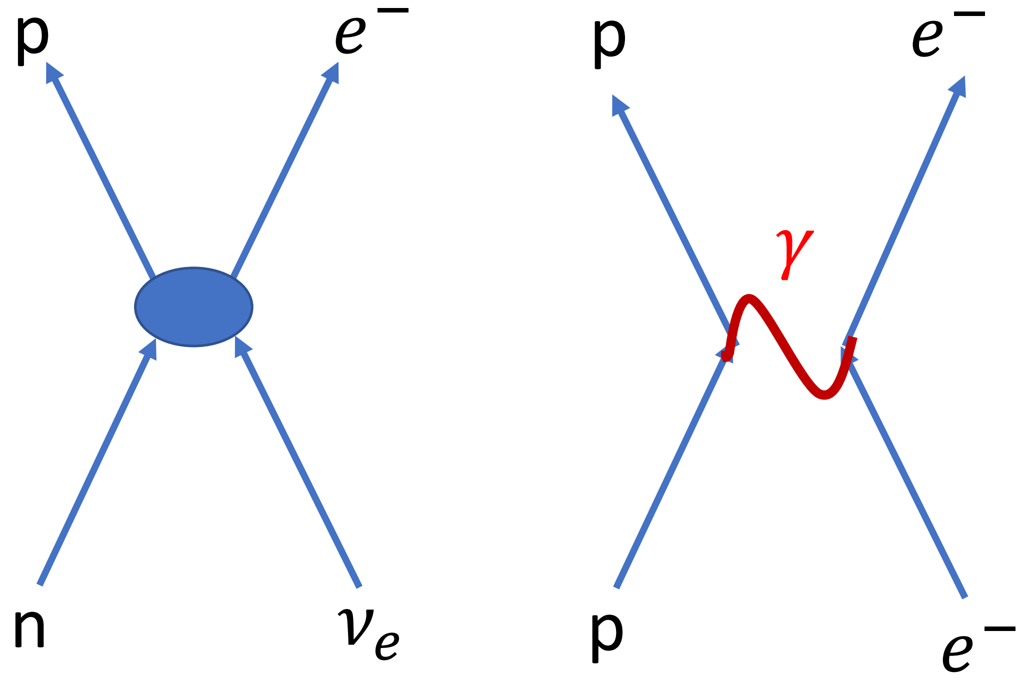
Weak and EM interaction

proton and neutron are very similar except for the charge.

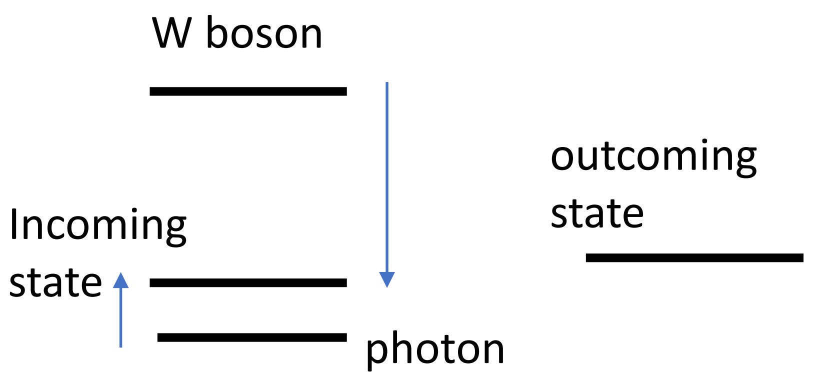
Similarity between weak and EM interaction?

However, weak interaction:
- Short range
- Extreme weak

Extremely massive force carriers may save the argument.



Massive force carriers



Strength of the perturbation $\sim \frac{1}{|E_{carrier} - E_{incom}|}$

W and Z bosons are significantly massive

- W ~ 80 GeV/c^2 and Z ~ 91 GeV/c^2
- Proton mass ~ 0.9 GeV/c^2 , 100 times larger!

High mass → large energy difference → small effect of perturbation → weak interaction

High mass → more channels to decay → short-lived → short-range interaction

Electroweak unification

- Why EM and weak interaction is similar?
- Because they are the same interaction!

At high energy level, the mass of force carriers becomes not so important:

Weak interaction → Electroweak interaction ← electromagnetic interaction

Electroweak interaction

The break of this unification is caused by the Higgs mechanism:

The Higgs field give mass to Z & W boson only

Electroweak Mixing

Under the electroweak unification, the force carriers:

- One Vector-like set of bosons $\overrightarrow{W} = \begin{bmatrix} W^+ \\ W^0 \\ W^- \end{bmatrix}$
- One scalar-like set of boson B^0
- Both sets have different coupling constants, α and β

Remember the electron and neutrino pairs in SM, analog to spin of electron.

$\overrightarrow{W}$ is like the Spin operator of electron $\vec{S}$

W^+ and W^- corresponds to S^+ and S^-

Electroweak mixing

$W^0 \rightarrow \mathrm{Z}$ while $B^0 \rightarrow \gamma$?

- The neutral part of the $\vec{W}$ and B^0 mix together while the Higgs mechanism happens
- $\begin{bmatrix} \beta B^0 \\ \alpha W^0 \end{bmatrix} \rightarrow \begin{bmatrix} \beta B^0 cos\theta_w + \alpha W^0\ sin\theta_w \\ -\beta B^0 sin\theta_w + \alpha W^0\ cos\theta_w \end{bmatrix}$ Like a rotation with angle θ_w

- $\beta B^0 cos\theta_w + \alpha W^0\ sin\theta_w \rightarrow \mathrm{g_e}\gamma$ & $-\beta B^0 sin\theta_w + \alpha W^0\ cos\theta_w \rightarrow \mathrm{g_z} Z$
- $\alpha W^{\pm} \rightarrow \mathrm{g_w} W^{\pm}$

Electroweak mixing

- The mixing also appears in the mass relation of W & Z

$$M_W = M_Z\, cos\theta_W$$

Deducing M_W from M_Z and θ_W!

The theoretical relation

- M_Z measured by other accelerator measurements
- θ_W can be derived from the coupling constants g_w and g_e
- Finally,

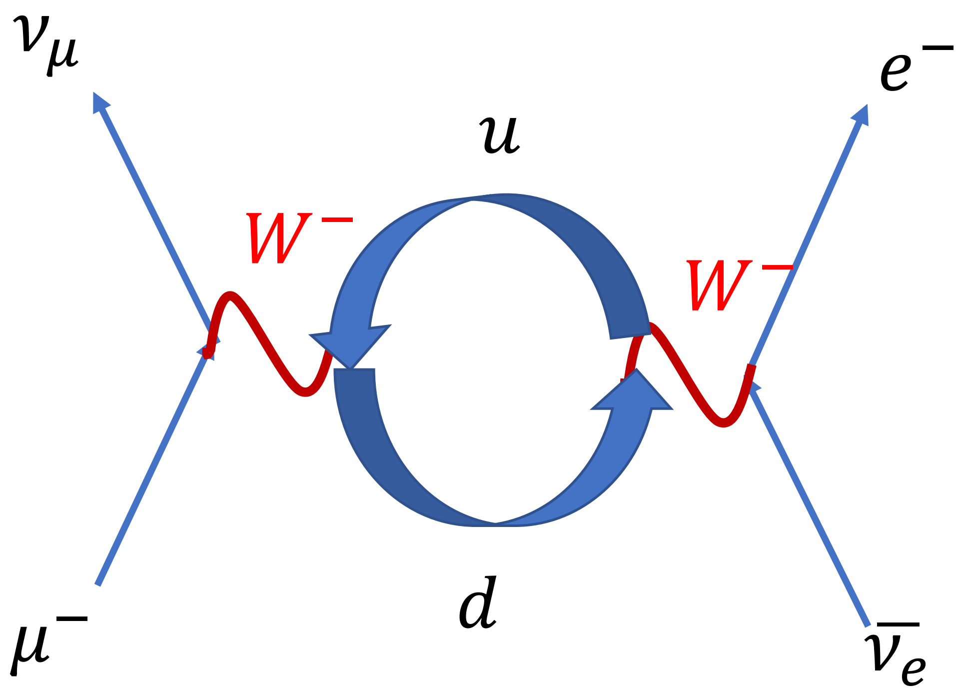
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}$$

Equivalent to $M_W = M_Z \, cos\theta_W$

- $\alpha \propto g_e^2$
- $G_F \propto g_w^2/M_W^2$
- $\alpha/\ G_F$ related to θ_W

Almost there…

- G_F is derived from muon lifetime $\tau_\mu \sim \frac{1}{G_F^2}$
- Not only the first order contribute…
- But higher order calculation is very technical



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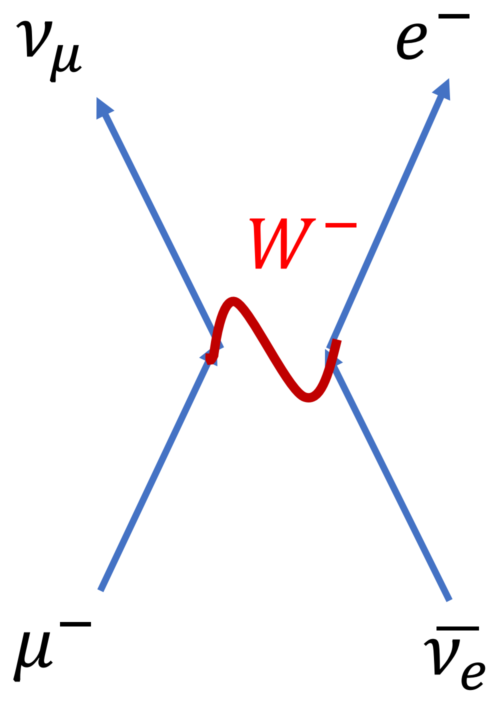


The final formula

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

The higher order correction term Δr

Different theoretical groups have calculated different values

Only refer to the result done by *Review of Particle Physics* later

Introduction to experimental particle physics

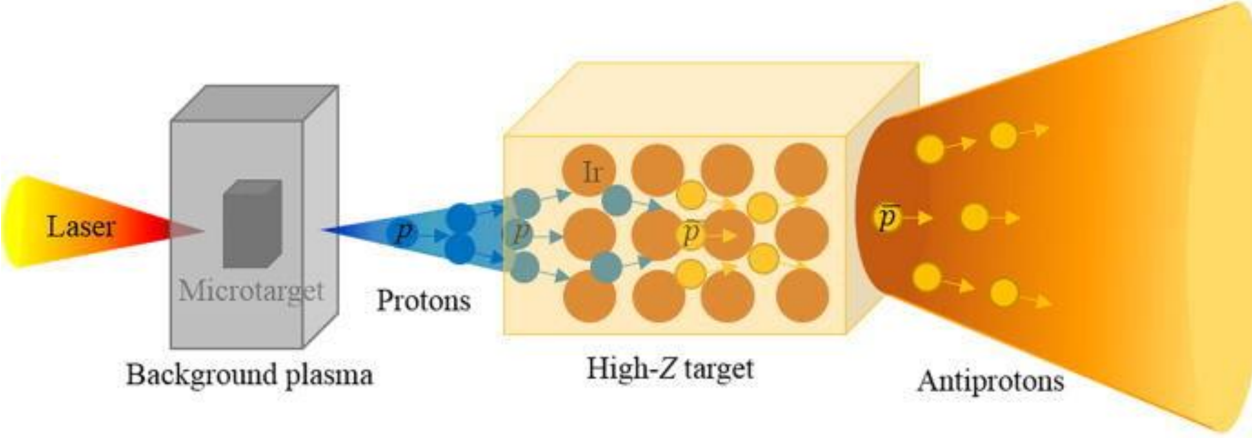
Main Stages

- Create protons/anti-protons from Hydrogen, accelerate to nearly c
- Smash protons/ anti-protons at the center of the detector (‘events’)
- Track the out-going particles from the detected ‘hits’ on detectors
- Identify types of particles
- Reconstruct decay structure
- Filter meaningful events
- Analyze statistical properties

Pre-collision process

- Creation of proton
  - Hydrogen broke down to proton and electron under large electric field.
- Creation of anti-proton
  - High energy protons colliding with nuclei in the targeted metal produce proton-antiproton pairs.

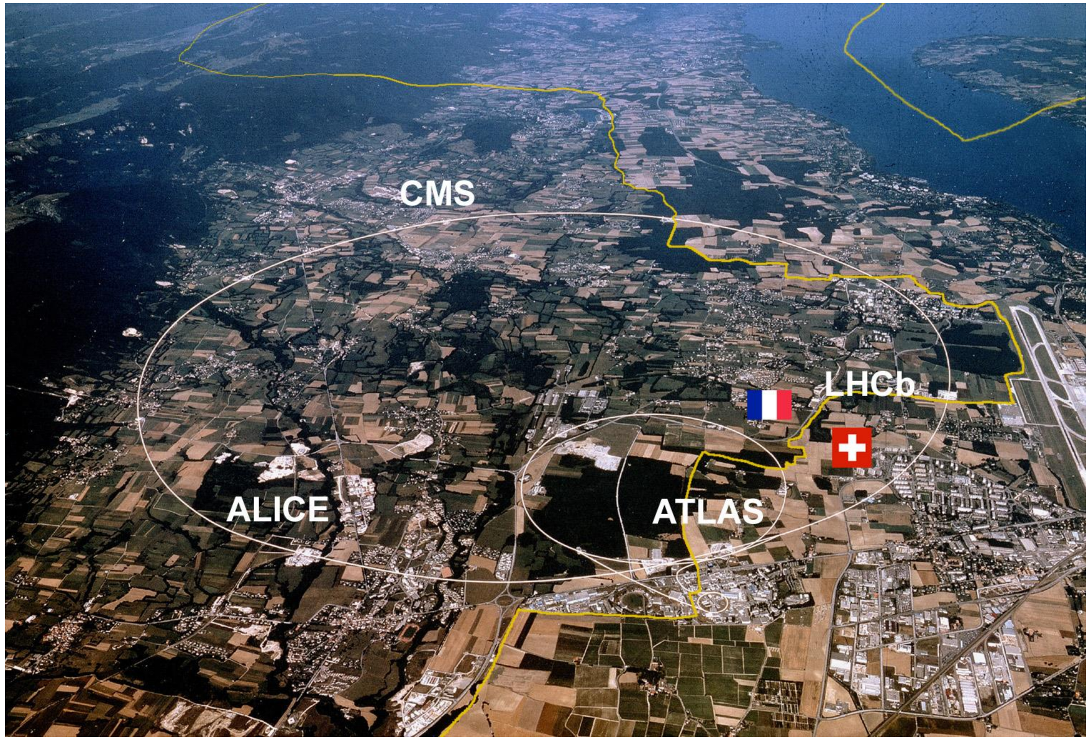
(Credit: taking_a_closer_look_at_LHC)



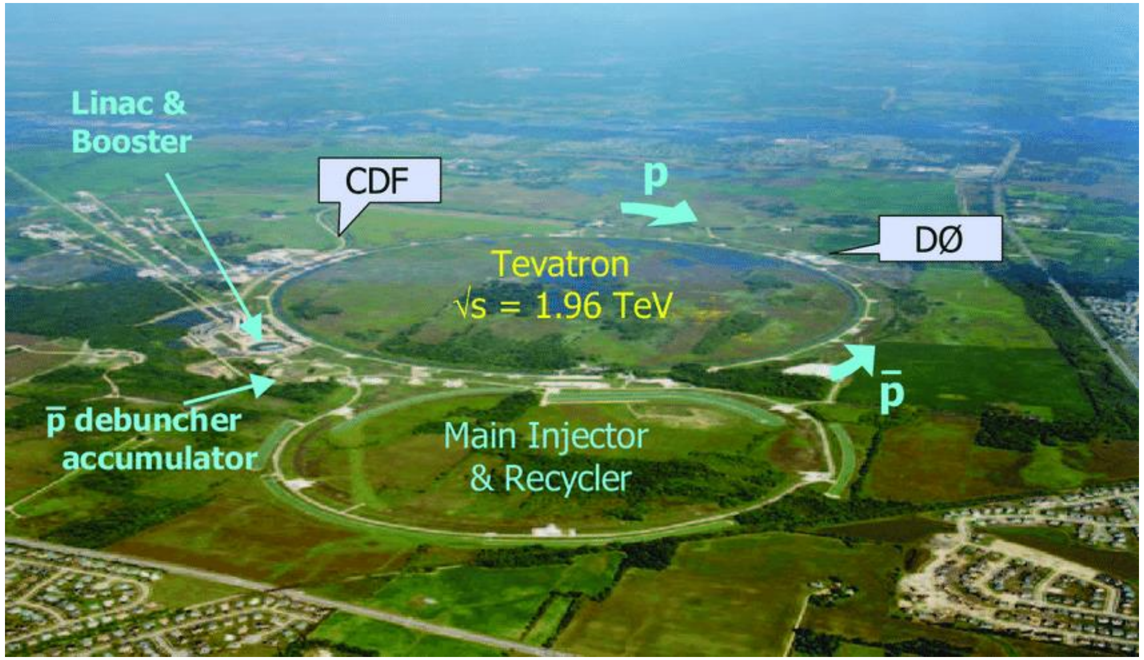
Physics of Plasmas **25**, 023111 (2018)

Pre-collision process

- Creation of proton
  - Hydrogen broke down to proton and electron under large electric field.
- Creation of anti-proton
  - High energy protons colliding with nuclei in the targeted metal produce proton-antiproton pairs.
- Hadron Accelerator
  - Large Hadron Collider (CERN, Europe)
  - Tevatron (Fermilab, U.S.)



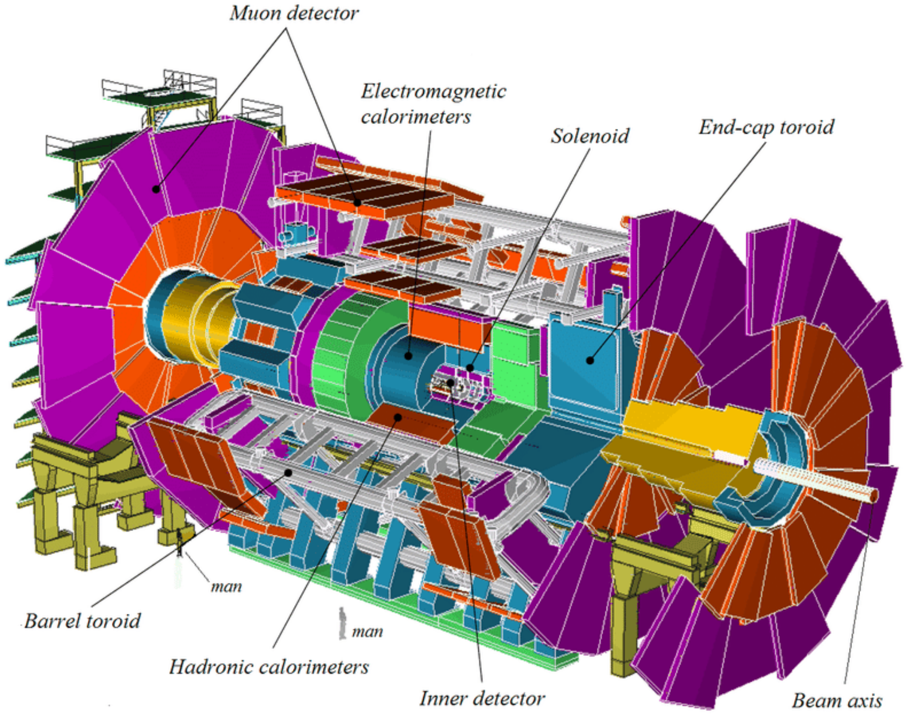
(Credit: IEEE Spectrum)



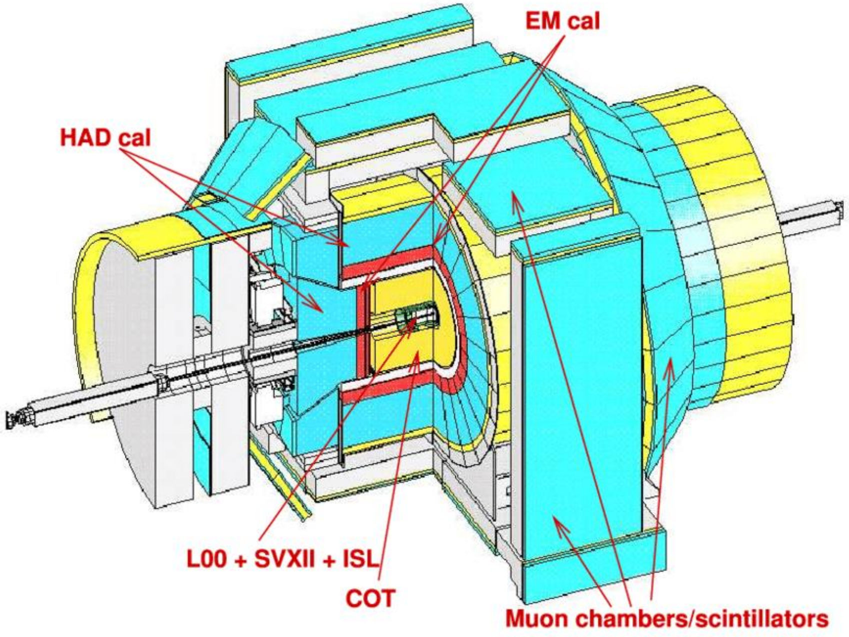
(Incandela et al., 1926)

Post-collision process

- Mechanically designed detectors
  - ATLAS at CERN (Europe)
  - CDF at Fermilab (U.S)



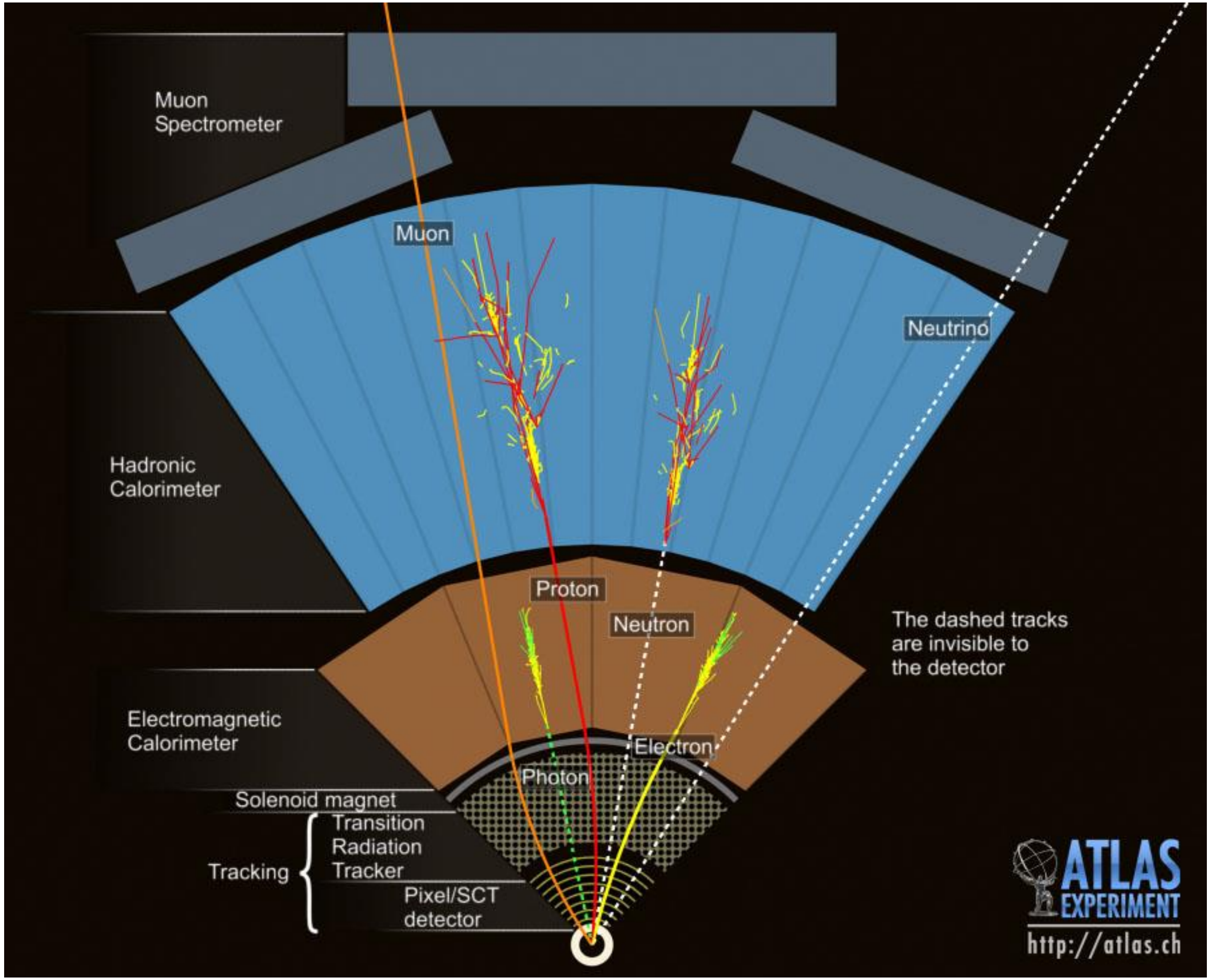
(Ky et al., 2015)



(Roberto, 2022)

Post-collision process

- Mechanically designed detectors
  - ATLAS at CERN (Europe)
  - CDF at Fermilab (U.S)
- Particles hit the detector and leave traces
- Based on their traces, particles can be identified

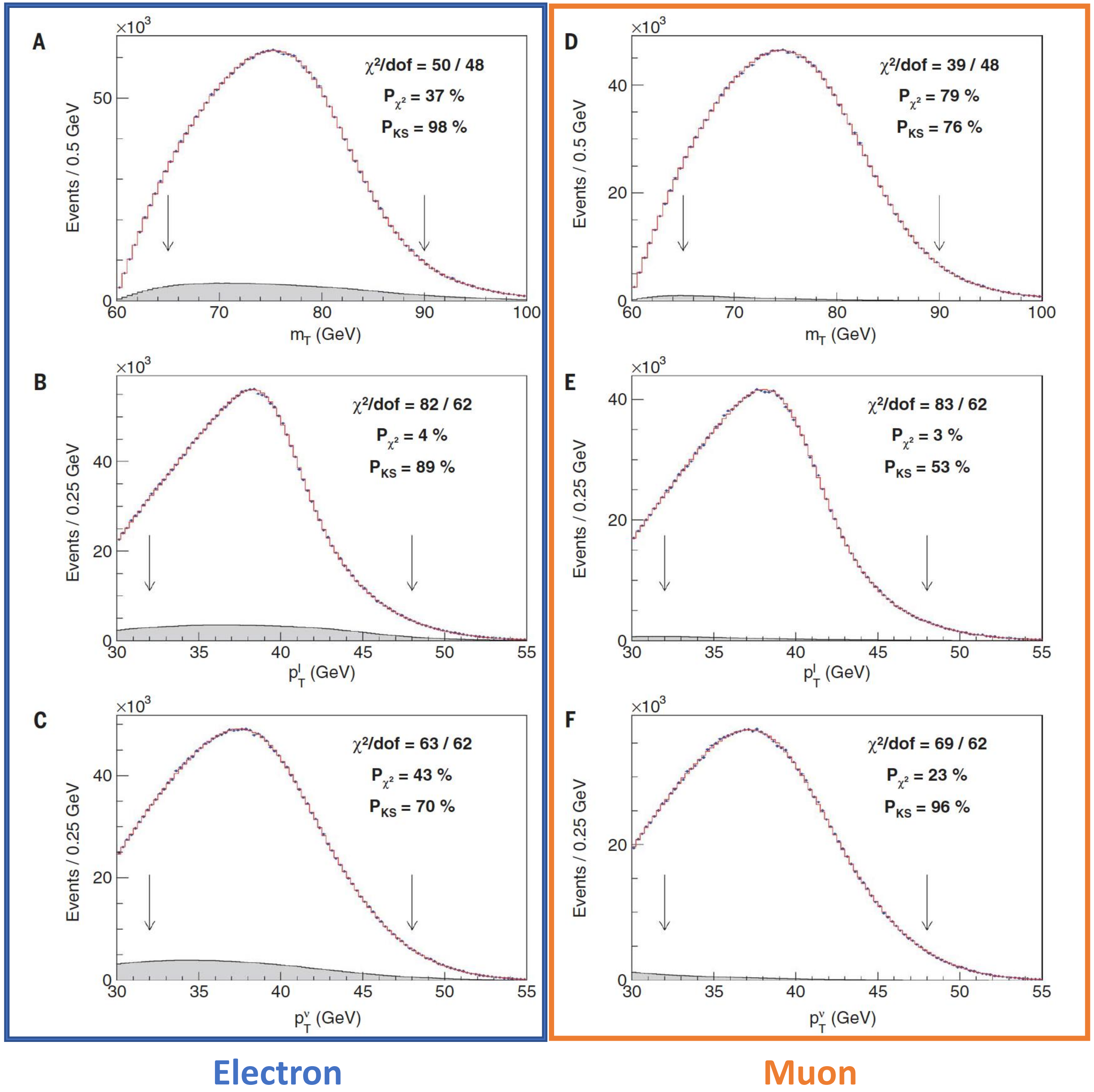


(Credit: Stanford ATLAS)

Events analysis

- **Meaningful events** are selected based on E_{min} of outgoing particles
- Distributions of several variables are fitted to extract the **desired physical observable**

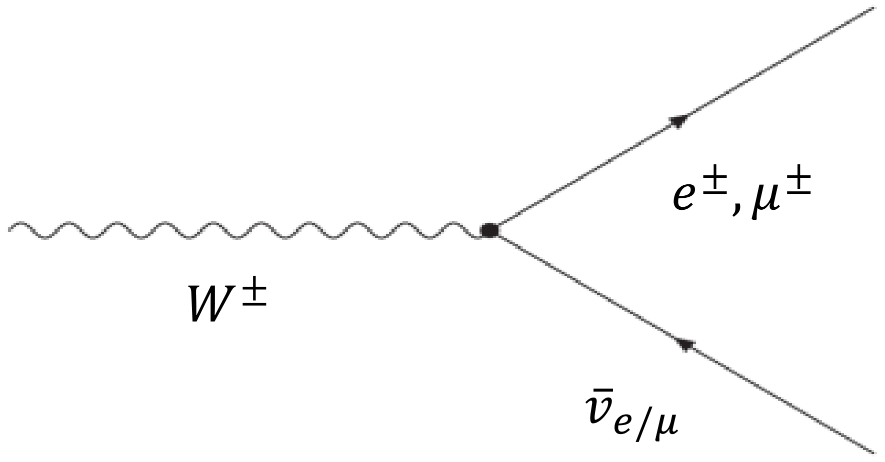
CDF Collaboration et al., Science 376, 170–176 (2022)

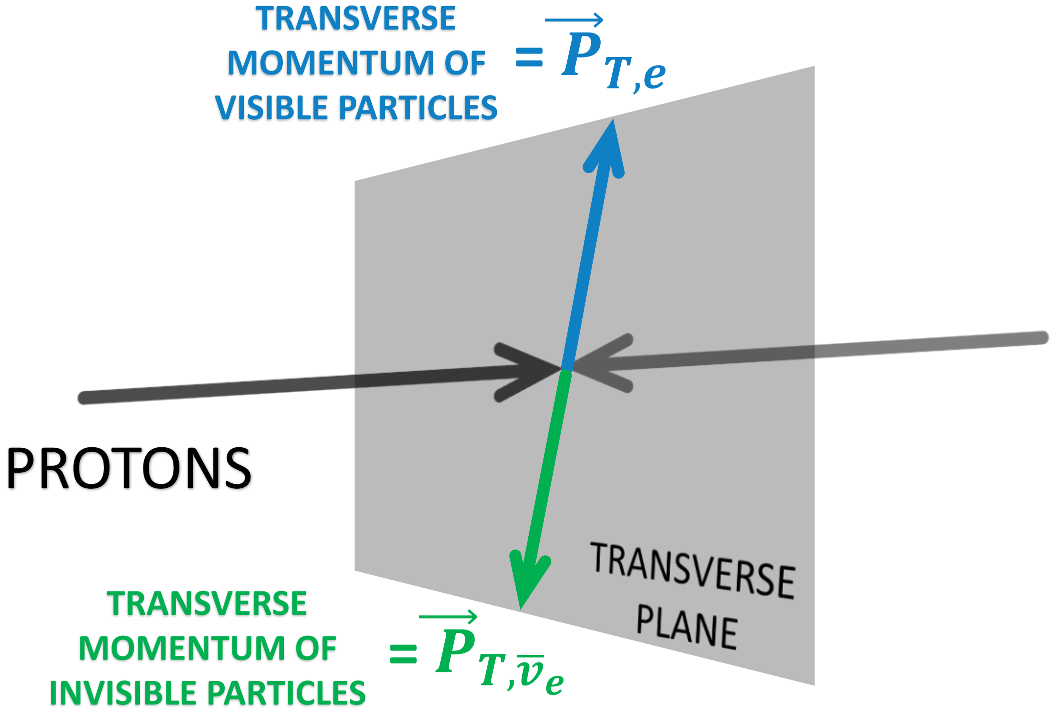


W boson mass measurement

Events & Challenges

- Leptonic decay
  - $W \rightarrow e + v_e$;
  - $W \rightarrow \mu + v_\mu$;
  - Electron: e; Muon: μ; Neutrino: v
- Undetectable Neutrino momentum
  - Charge Neutral
  - Conservation of total transverse momentum





$$\overrightarrow{P}_{T,\bar{\nu}_e} = -\overrightarrow{P}_{T,ee}$$

Comparison of different experiments

Large Hadron Collider (LHC) [CERN]

- Proton-proton collision
- Result: $m_W = 80370 \pm 19\ \mathrm{MeV/c^2}$
- Discrepancy: $< 1\sigma$ significance

Eur. Phys. J. C (2018) 78:110

Collider Detector at Fermilab II (CDF II)

- Proton-antiproton collision
- Result: $m_W = 80433 \pm 9\ \mathrm{MeV/c^2}$
- Discrepancy: $\sim 7\sigma$ significance

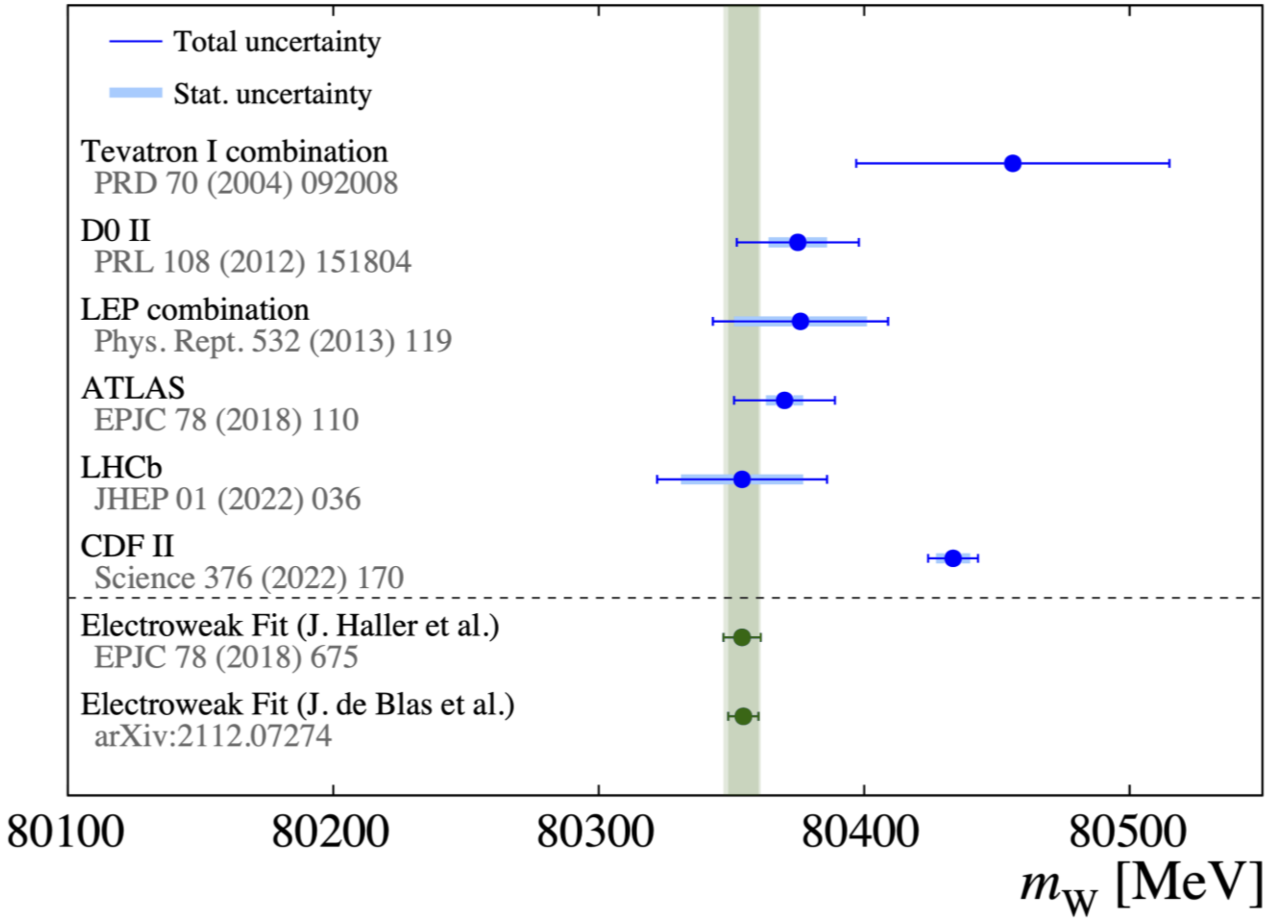
CDF Collaboration et al., Science 376, 170–176 (2022)

Why CDF II is more precise?

- Proton-antiproton collision
  - →Smaller Parton momentum uncertainty (Parton: proton, neutron, etc.)
  - →Smaller M_W *uncertainty*
- Cosmic-ray muon rejection
  - Done by powerful computer algorithm
- More sophisticated statistical correction, incorporating with improved understanding of the distribution function

Results comparison

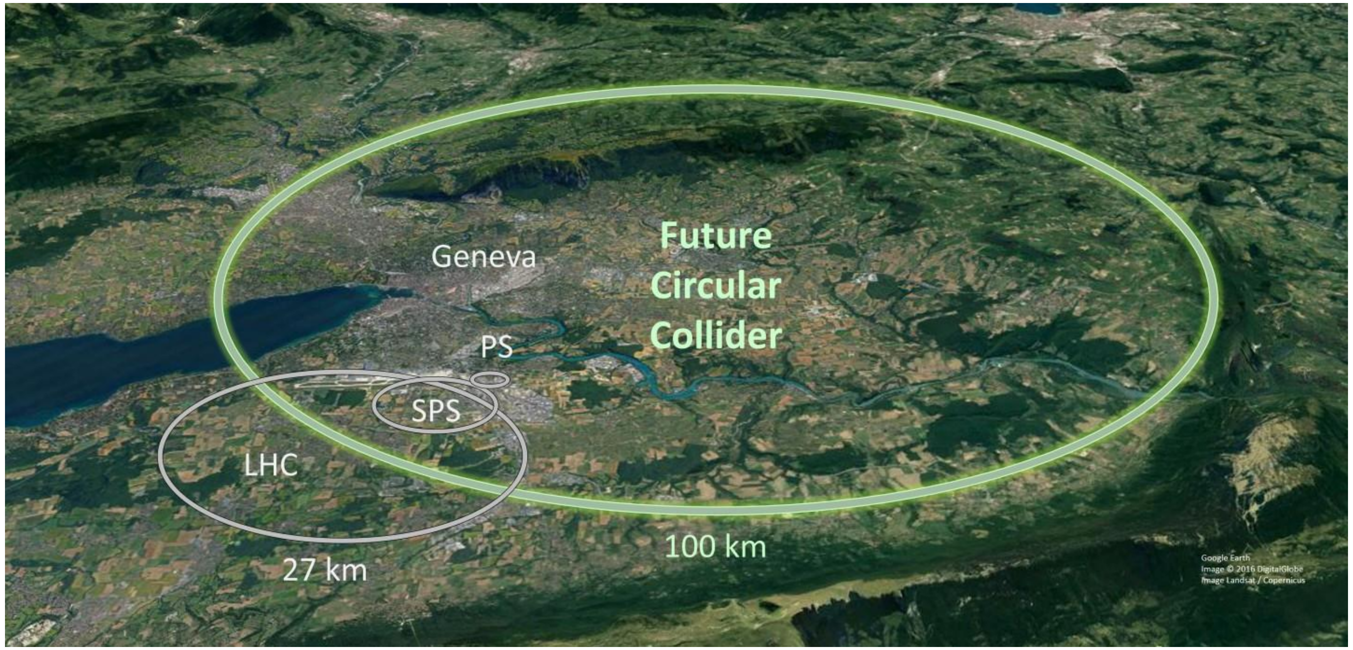
- CDF II
  - Unprecedented precision
  - Relatively larger discrepancy (7σ)
- Possible explanations
  - Systematic error in CDF II
  - NEW PHYSICS!!!



(Credit: CERN Courier)

Future outlook

- Veracity of this discrepancy will probably remain a mystery in the foreseeable future
  - Lack of independent measurement with comparable precision
  - More powerful colliders and detectors are in construction
  - No guarantee of similar result with comparable precision in the future



(Credit: CERN)

Conclusion

- The result is very important if it is correct!
- However, both experimental part and theoretical part can make mistakes

If everything is correct within SM,

- New particles? Which enter the Δr calculation
- New theories invoke Supersymmetry?

ALL ARE UNKOWN!

Reference

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