Collider Particle Physics

- Chapter 9 -

Tevatron: top discovery and W mass measurement; top properties

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Chapter Summary

- ☐ Fermilab and the accelerator complex
- ☐ Top discovery
- ☐ W mass measurement at the Tevatron
- ☐ Top properties
- ☐ Top mass measurement (from LHC data)

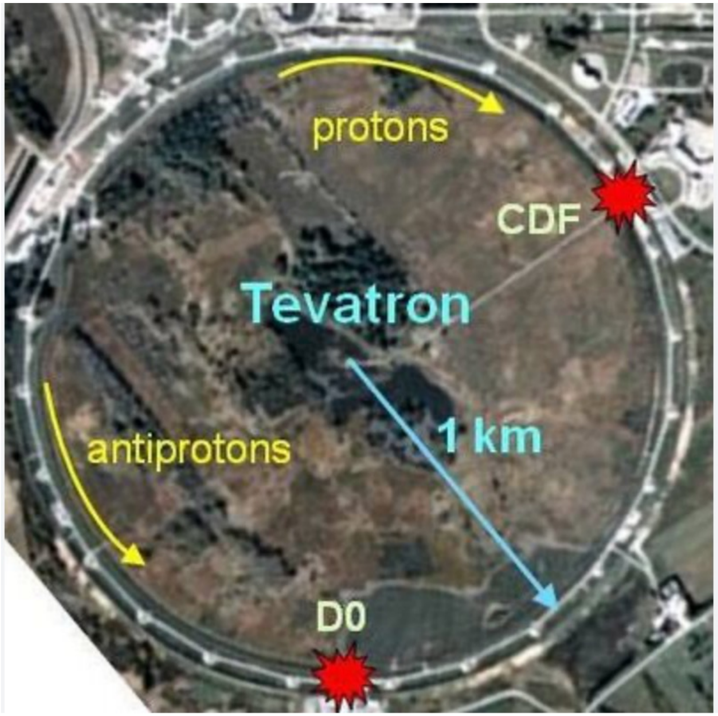
The accelerator

Fermilab and the accelerator complex

Fermilab and accelerators

Fermilab

- **National Accelerator Laboratory** founded 1967
  - Named after **Enrico Fermi** and dedicated ("Fermilab") in 1974
- Central facility: proton synchrotron "Main Ring"
  - 2π km circumference and initial energy of 200 GeV (1972)
  - Used for fixed target experiments
- Higher energy with **superconducting magnets**
  - **First** superconducting synchrotron
  - Initial name "Energy Doubler" or "Energy Saver". **512 GeV** (1983) ; then **800 GeV** (1984) and **900 GeV** (1986)
- **Antiproton source** added in 1985
  - Stochastic cooling **built on success of SppS at CERN**
  - First **collisions** at 1.6 TeV in 1985, 1.8 TeV in 1986: **TeVatron**
- **Run II (2001 – 2011)**
  - beam energy: **980 GeV**
  - main ring in another tunnel



Timeline

Main injector (warm magnets): Run I

Tevatron (superconducting magnets)

1983
W and Z bosons
discovered at
UA1 and UA2

1985
First collisions
at Tevatron

1988-1989
Tevatron Run 0

1989
LEP first
collisions

1992
Tevatron Run I
begins

1992
HERA
collisions
begin

1995
Top discovery

1996
Tevatron Run I
ends

2000
LEP collisions
end

2001
Tevatron Run II
begins

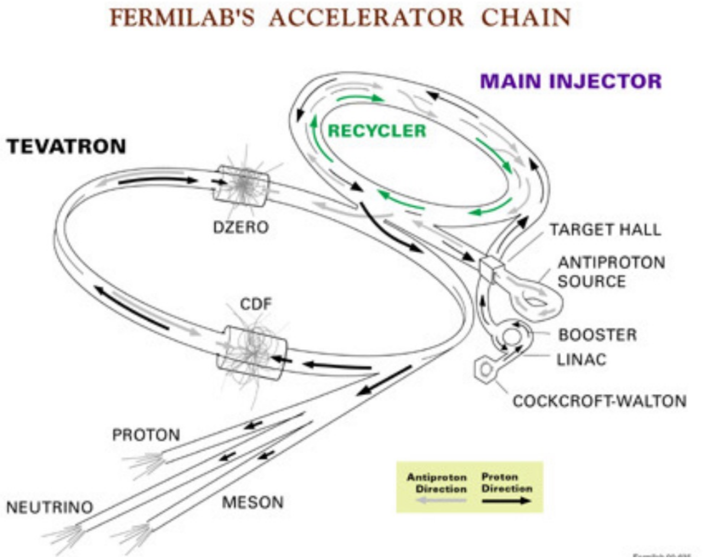
2007
HERA
collisions end

2008
LHC first
collisions

2011
Tevatron Run II
ends

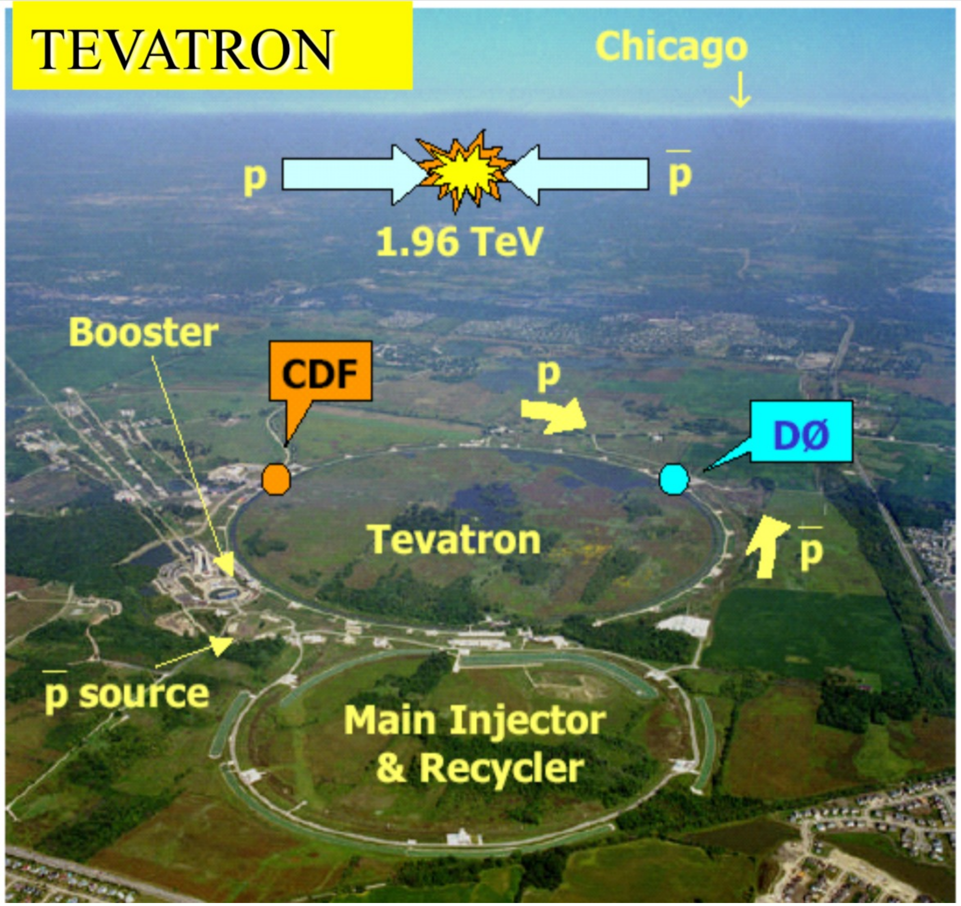
2012
Higgs boson
discovered at
ATLAS and CMS

Tevatron (Run II)



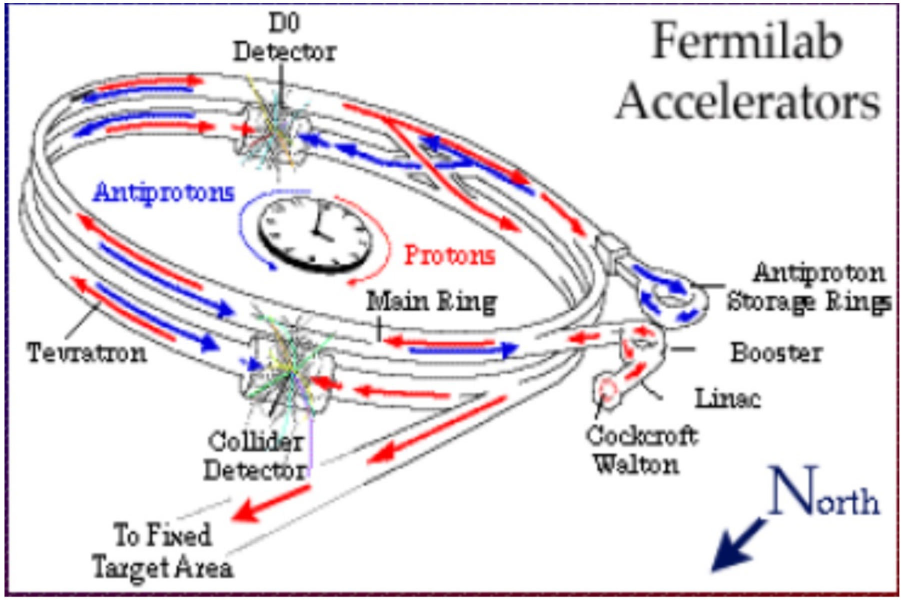
Fermilab is placed in natural areas, which are designated as a National Environmental Research Park. It is a federal area.

The Tevatron



RUN-2 Collider Upgrade

RUN-1 Collider: 1.8 TeV



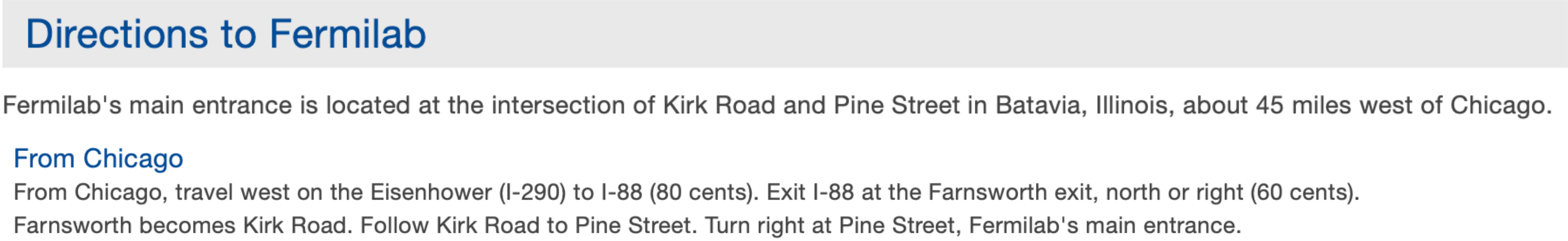
Main Ring and Collider in the same tunnel

Some of Fermilab inhabitants

Fermilab's first director brought bison to the lab in 1969 as a symbol of the history of the Midwestern prairie and the laboratory's research at the frontiers of particle physics.

First baby bison of 2021

How to get to Fermilab !

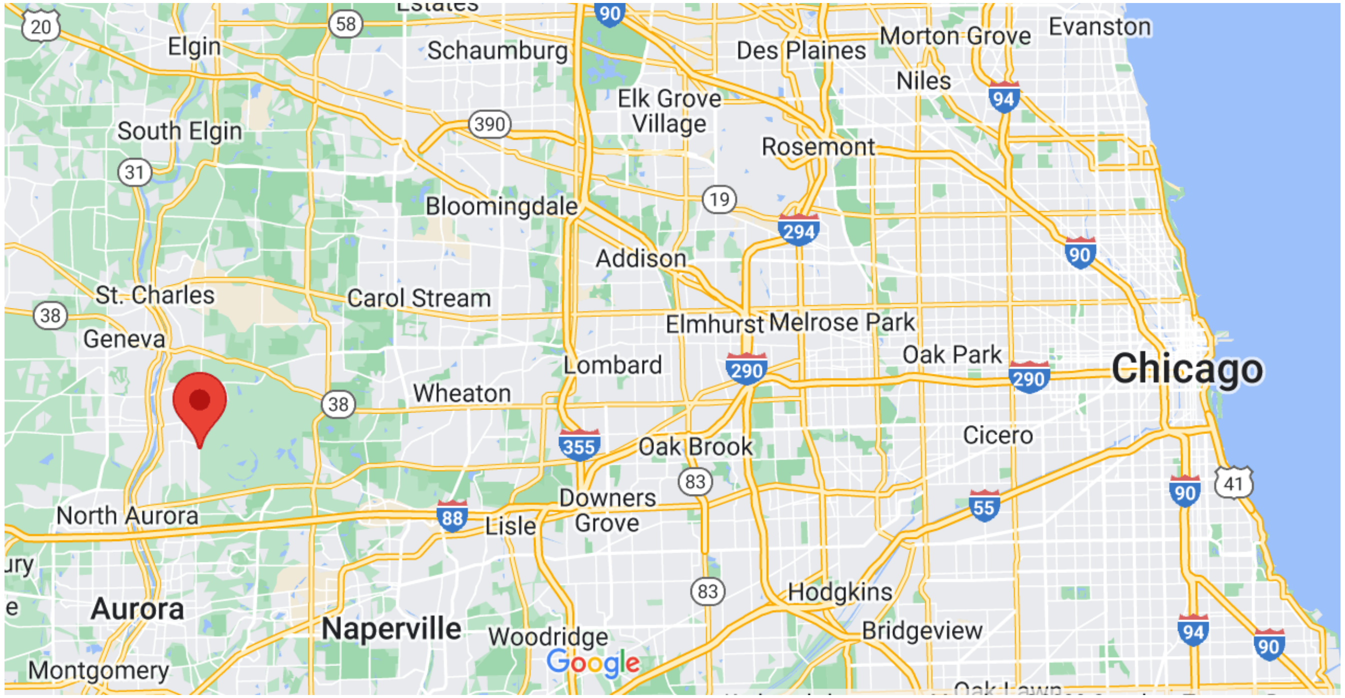


Directions to Fermilab

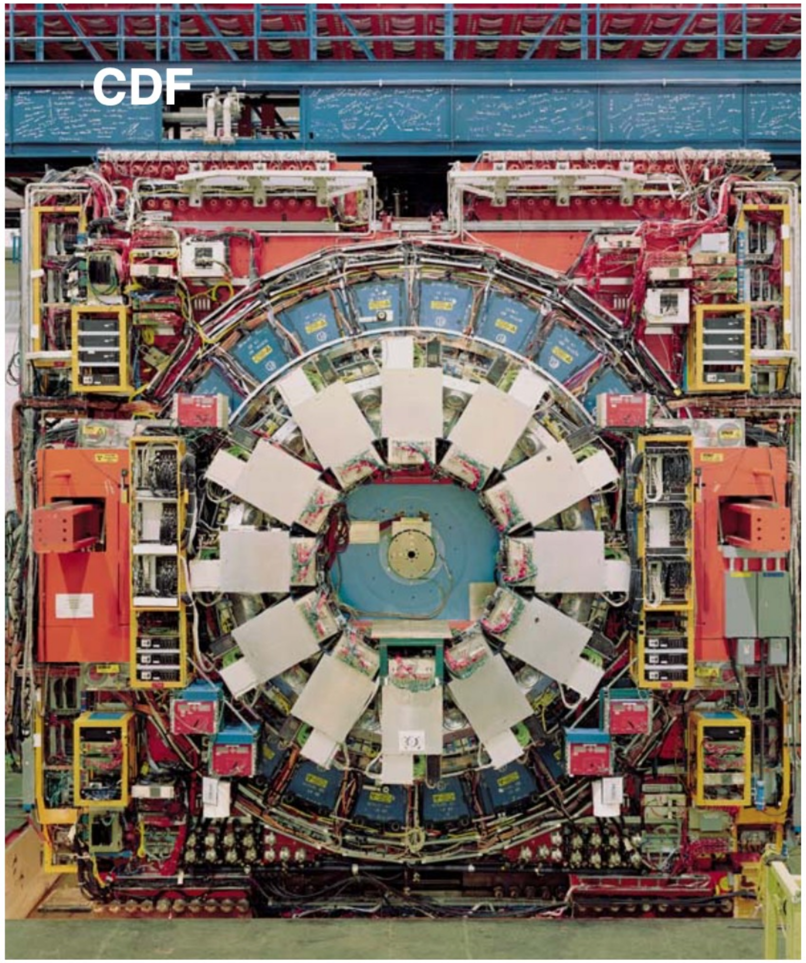
Fermilab's main entrance is located at the intersection of Kirk Road and Pine Street in Batavia, Illinois, about 45 miles west of Chicago.

From Chicago

From Chicago, travel west on the Eisenhower (I-290) to I-88 (80 cents). Exit I-88 at the Farnsworth exit, north or right (60 cents). Farnsworth becomes Kirk Road. Follow Kirk Road to Pine Street. Turn right at Pine Street, Fermilab's main entrance.



Tevatron experiments: CDF and D0



Early Tevatron results

- Tevatron first run 1988-1989
  - Retroactively named “Run 0”
  - 4 pb^{-1} lumi delivered to CDF
    - DØ still under construction at this time
- Ability to measure W and Z bosons?
  - Precision measurements *seemed* well out of reach
    - Limiting factor: calorimeter energy resolution
    - Breakthrough: **calibrating with E/p** (including tracker)
- SLC starting up around the same time
  - Who would be first to see Z bosons in the Western Hemisphere?

New York Times 19-Jul-1988

Search Quickens for Ultimate Particles

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

By MALCOLM W. BROWNE

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

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

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

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

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

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

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

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

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

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

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

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

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

Continued on Page C13

Fermi National Accelerator Laboratory

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

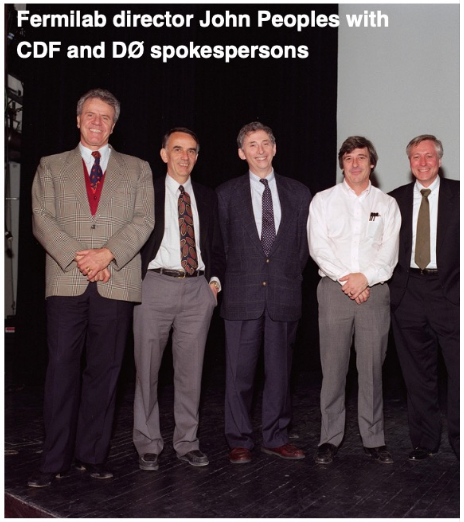
The Design of the Future?

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

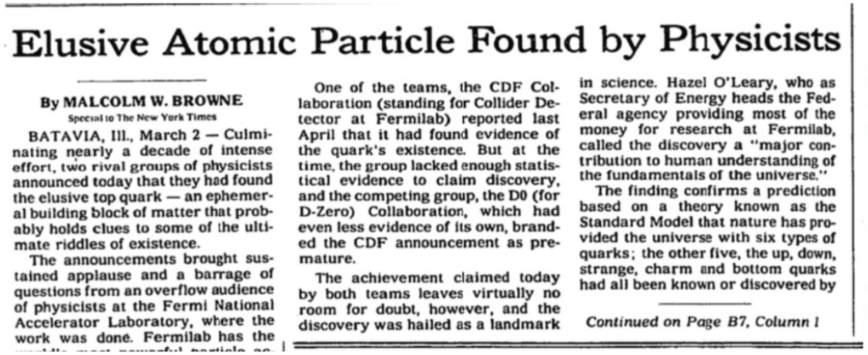
Steve Hart/The New York Times

Tevatron Run I (1992-1996): “top” result

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



Fermilab director John Peoples with CDF and DØ spokespersons



Elusive Atomic Particle Found by Physicists

By MALCOLM W. BROWNE

Special to The New York Times

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

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

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

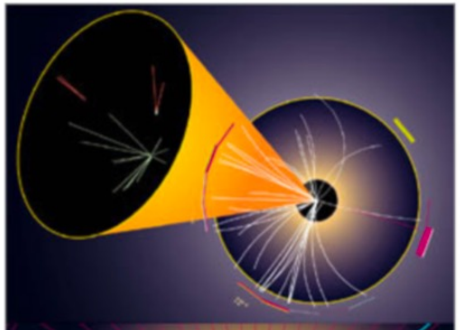
The achievement claimed today by both teams leaves virtually no room for doubt, however, and the discovery was hailed as a landmark in science. Hazel O'Leary, who as Secretary of Energy heads the Federal agency providing most of the money for research at Fermilab, called the discovery a "major contribution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

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

Continued on Page B7, Column 1

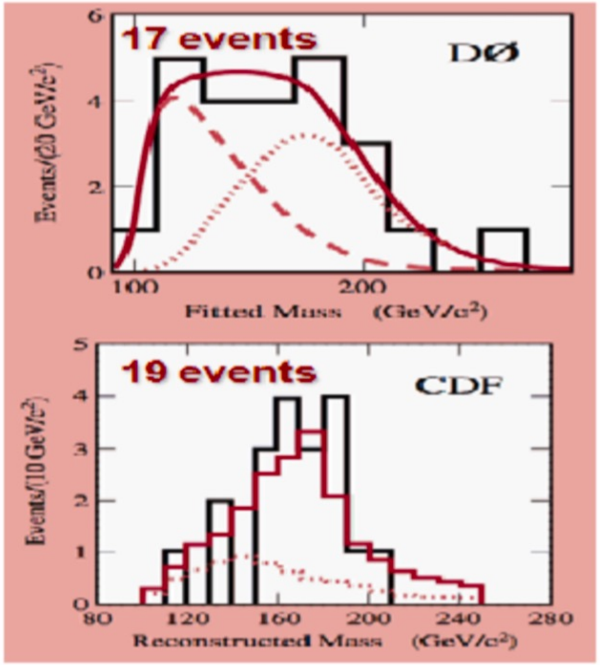
Top Quark Discovery: February 24th 1995

- February 24th, 1995: Simultaneous submission of “top-quark discovery” papers by CDF and D0 @ Tevavtron, Fermilab
  - ⋆ Luminosity collected at $\mathrm{D0}\ 50\,\mathrm{pb}^{-1}$
  - ⋆ $\mathrm{m_{top}} = 199 \pm 30\,\mathrm{GeV}$
  - ⋆ $\sigma_{t\bar{t}} = 6.4 \pm 2.2\,\mathrm{pb}$
  - ⋆ Background-only hypothesis rejected at $4.6\,\sigma$
  - ⋆ Luminosity collected at $\mathrm{CDF}\ 67\,\mathrm{pb}^{-1}$
  - ⋆ $\mathrm{m_{top}} = 176 \pm 13\,\mathrm{GeV}$
  - ⋆ $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}\,\mathrm{pb}$
  - ⋆ Background-only hypothesis rejected at $4.8\,\sigma$



CDF: the big cone is an electron from a W decay.

D0: two muons (in blue, one inside a jet), 4 jets and the neutrino (pink) identified as missing p_T



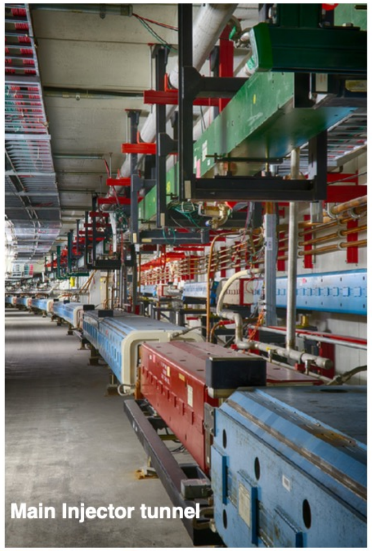
1995, CDF and DØ experiments, Fermilab

Top reconstructed mass

Tevatron Run II

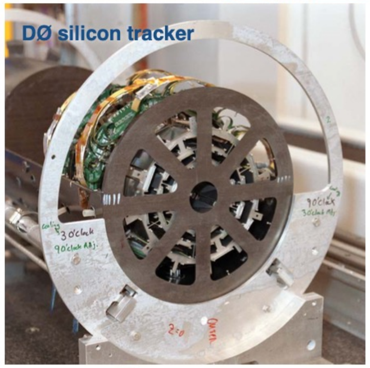
- Major upgrade after Run I ended (1996)
  - Increase in peak luminosity from 10^{30} cm^{-2} s^{-1} to over **4×10^{32} cm^{-2} s^{-1}**
  - Increase of beam energy from 900 GeV to **980 GeV**
- Construction of **Main Injector**
  - New 150 GeV accelerator stage
  - Essential in increase in luminosity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

Main Injector



Main Injector tunnel

CDF Central Outer Tracker installation



DØ silicon tracker

M_W at CDF

(chapter 1, second part in LHC slides)

W boson mass: toward unprecedented precision

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

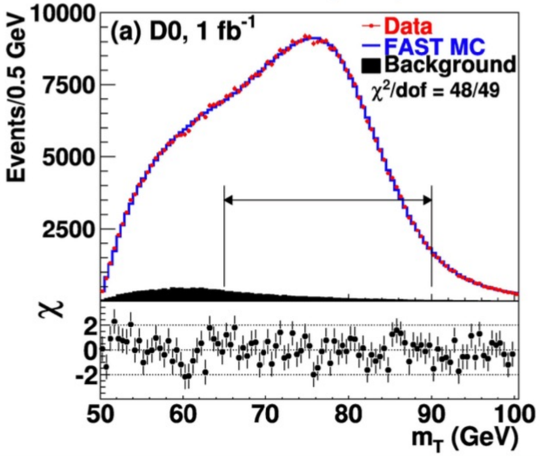

Unblinding first Run II W mass measurement at CDF
16 Dec 2006

First Run II measurements

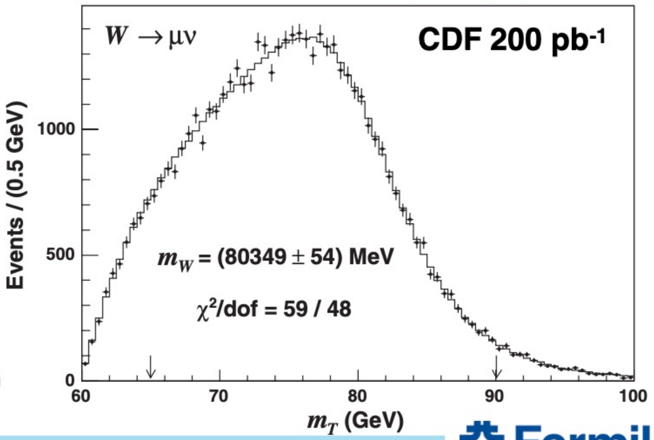
80413 ± 48 MeV (CDF, 2006)

80401 ± 43 MeV (DØ, 2009)

PRL **103** 141801 (2009)

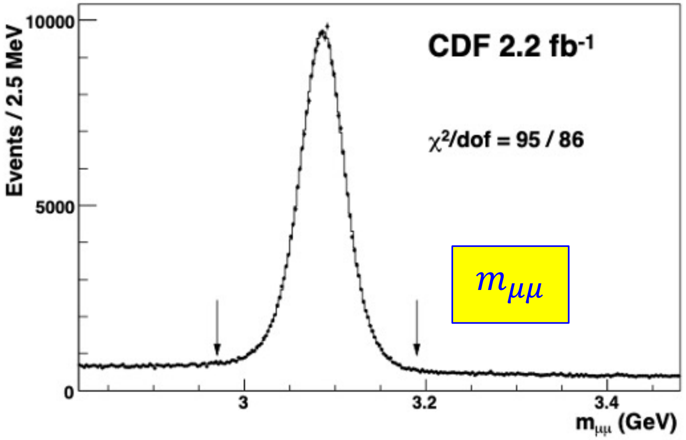


PRL **99** 151801 (2007)

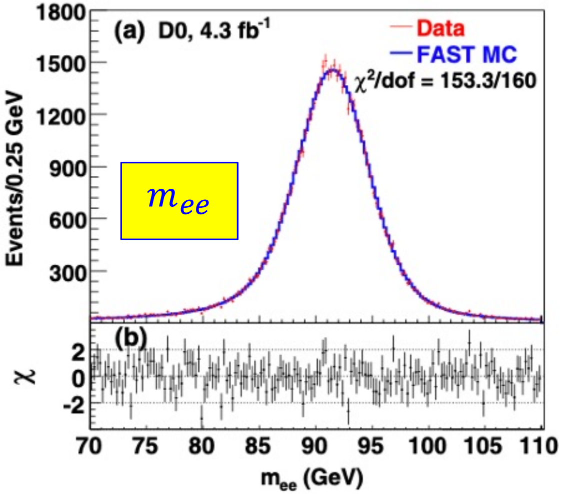


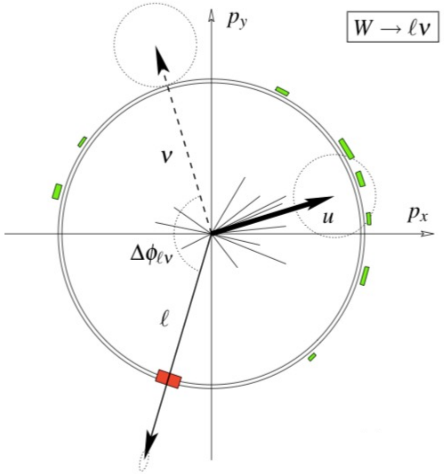
nb. CDF e+μ, DØ e only

W boson mass: calibration of the energy scale

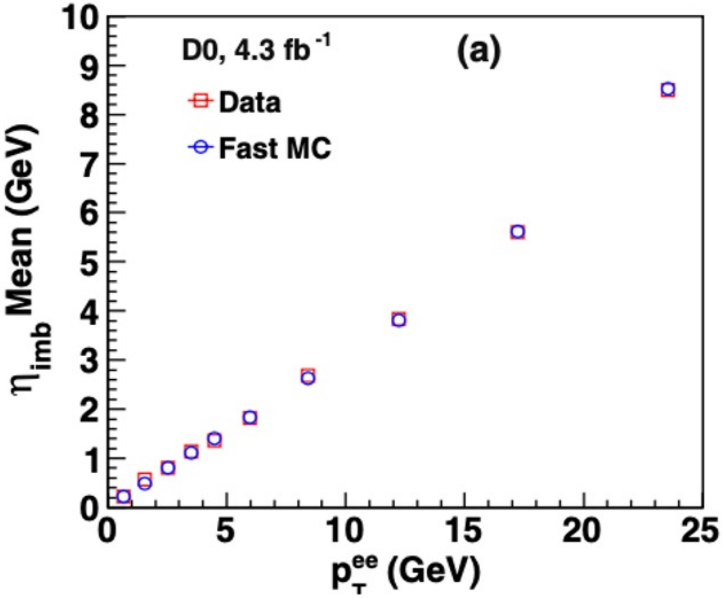


Calibrating with well-know resonances: J/Ψ, Υ, Z at CDF; Z at D0

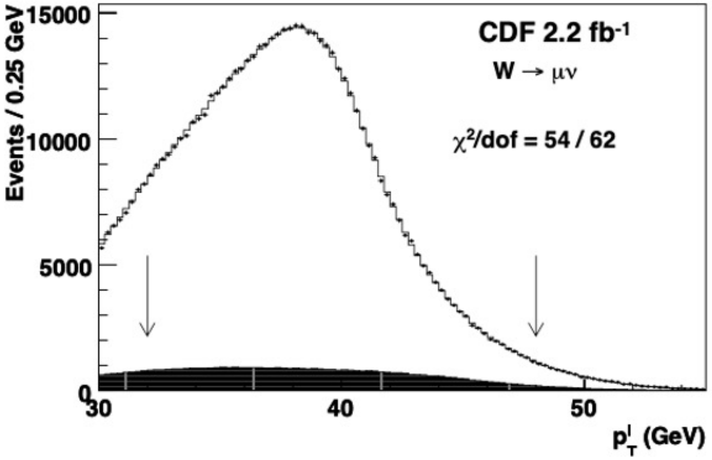




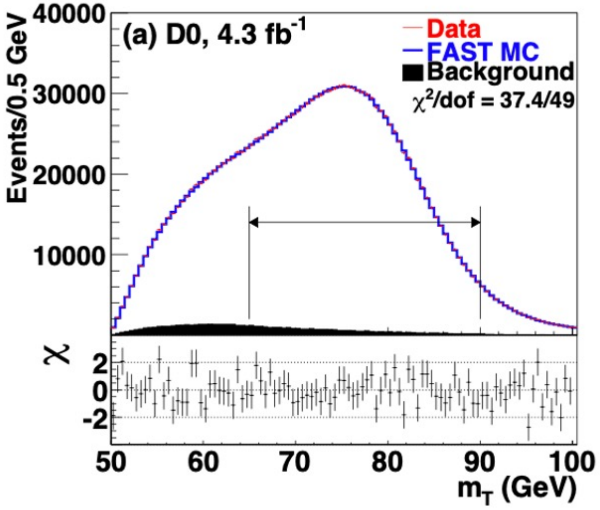
Calibrating hadronic recoil with Z (no neutrino)



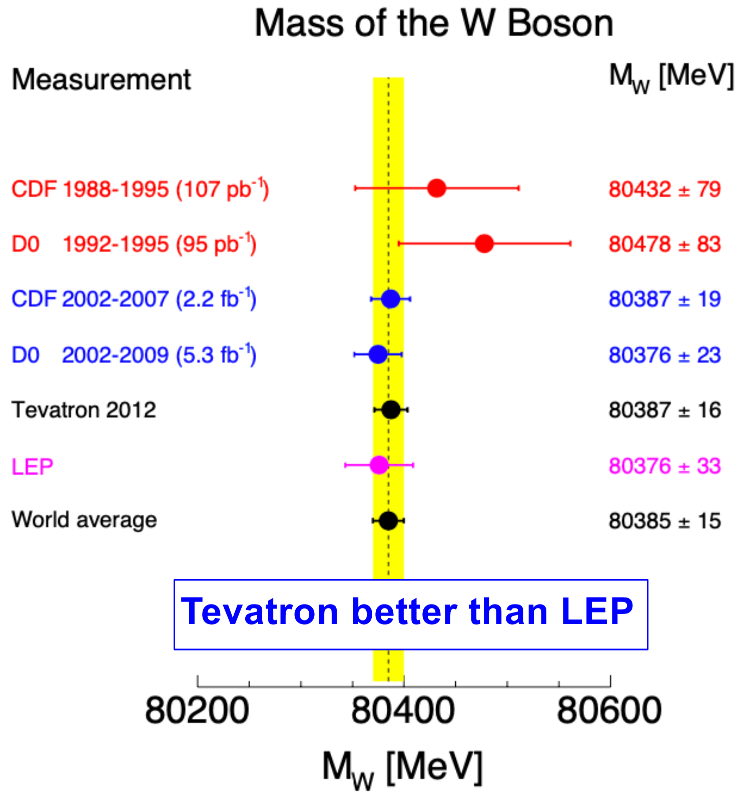
W boson mass: achieving unprecedented precision



Lepton transverse momentum



Invariant transverse mass

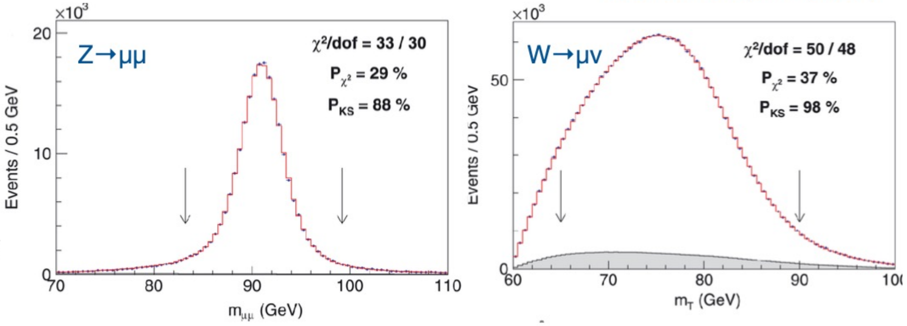


Tevatron better than LEP

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

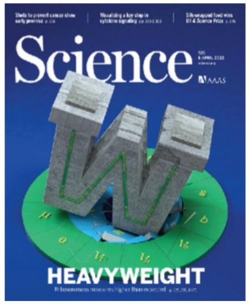
W boson mass: one final surprise?

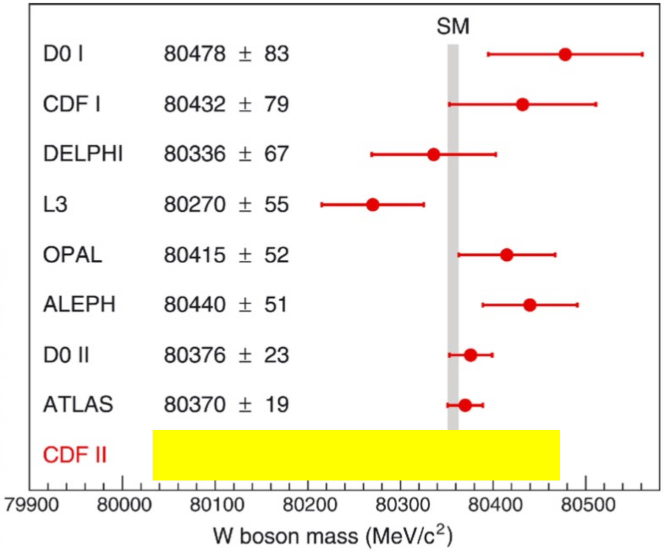
- CDF goal with the **full** Tevatron dataset
  - Once again exceed world average precision
  - < 10 MeV total uncertainty
    - Nearly every systematic uncertainty constrained by data


Science **376**, 170 (2022)

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

- **M_W =** Wait for the LHC lectures

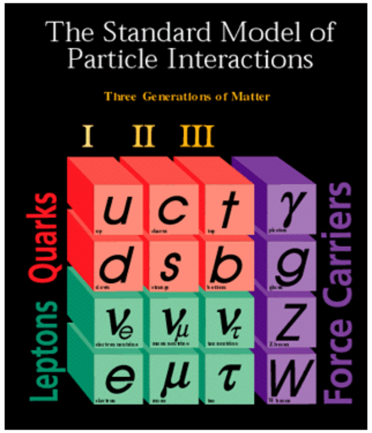




Top properties

Experimental results come from LHC data

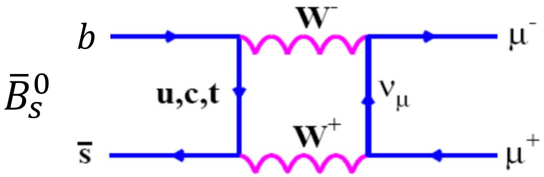
The ”needs” for top quark



The existence of the Top Quark is predicted by the SM and it is required to explain a number of observations.

Top quark has been discovered at the Tevatron in 1995

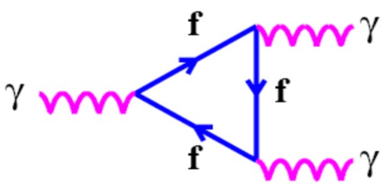
Example: negligible BR of the decays $B_s^0 \longrightarrow \mu^+\mu^-$



In the Standard Model the top quark cancels the contributions from the u and c quarks

All SM predictions without the top quark wouldn’t agree with the experimental data

Example: Electro-magnetic anomalies



This triangle diagram leads to infinities in the theory unless

$$\sum_f Q_f = 0$$

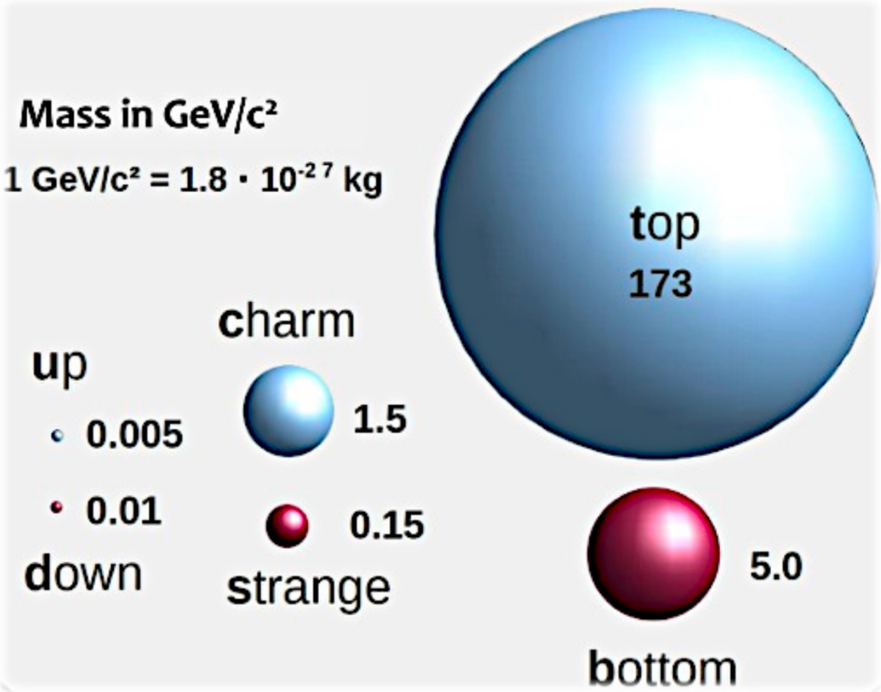
where the sum is over all fermions (and colours)

$$\sum_f Q_f = [3 \times (-1)] + [3 \times 0] + [3 \times 3 \times \tfrac{2}{3}] + [3 \times 3 \times (-\tfrac{1}{3})] = 0$$

Top quark mass

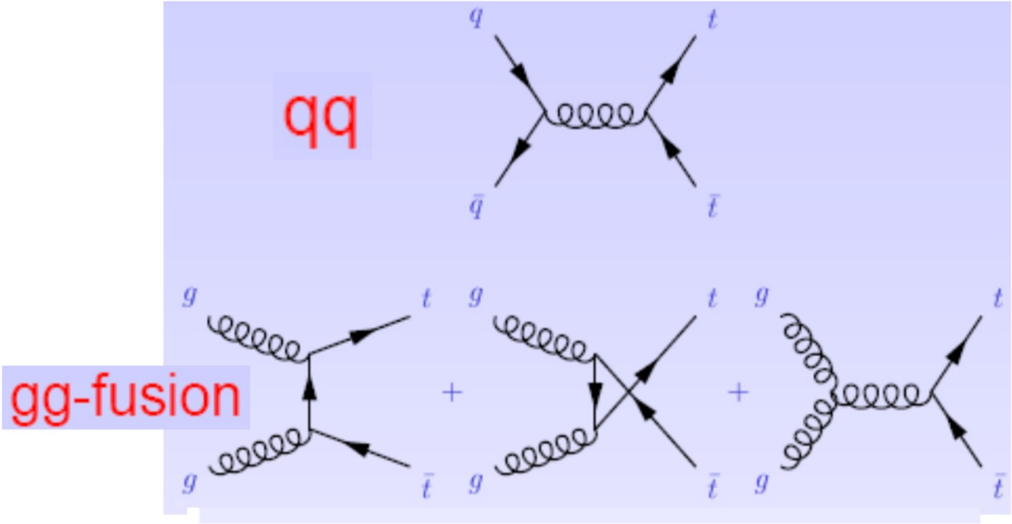
- The top quark is the heaviest known elementary particle, $m_{\mathrm{top}} \approx 173\,\mathrm{GeV}$
- It is outperforming the Higgs mass by $\sim 40\%$
- But also for comparison:

$$M_W = 80.425 \pm 0.038\,\mathrm{GeV}$$
$$M_{Z^0} = 91.1876 \pm 0.0021\,\mathrm{GeV}$$
$$M_g = 0$$
$M_\gamma \approx 0$ i.e. 6×10^{-26}



- It has a mass comparable to the mass of a gold atom

Top (pair) production at the hadron colliders



Old calculation … just for comparison

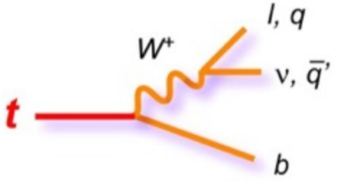
	Run 1 1.8 TeV	Run II 1.96 TeV	LHC 14 TeV
qq gg	90% 10%	85% 15%	5% 95%
σ (pb)	5 pb	7 pb	600 pb

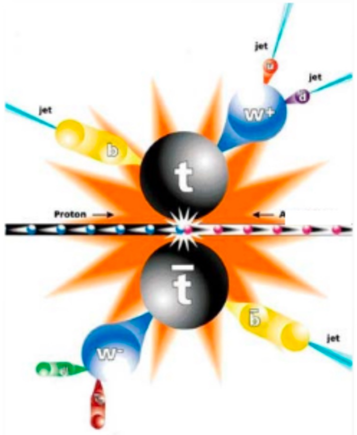
At LHC the gluon fusion is the dominant channel

No competition in term of number of top pairs produced between LHC and Tevatron.
In what follows all results about top properties are coming from LHC.

Top quark decay

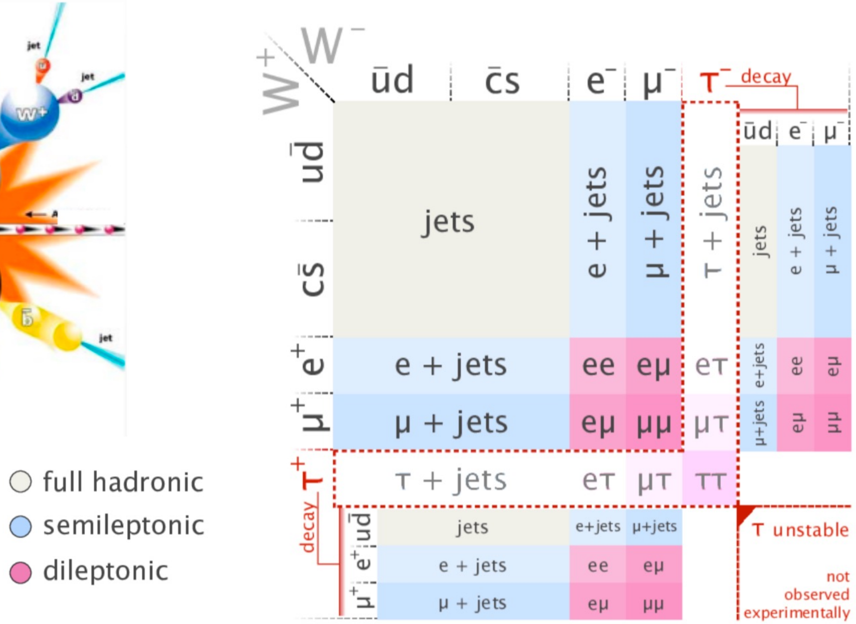
- ❑ top quark, being heavier than W, decays mostly into a W and a b quark:





- ❑ Due to the very high mass, the top quark lifetime is very short: $\tau_{top} \approx 5 \cdot 10^{-25}\ s$
- ❑ It is shorter than the typical hadronisation timescale: $\tau_{hadr} \approx 10^{-23}\ s$.
- ❑ Therefore top quark decays before hadronising (no topponium bound state); it offers a unique opportunity to study the properties of a "bare" quark which are transferred to its decays products, e.g. its information.
- ❑ **Very recently a new research line became very active: the entanglement between the two top.**

- ❑ The final states dipends on the different W decays, but a b quark is always present:



W^+ \ W^-	$\bar{u}d$	$\bar{c}s$	e^-	μ^-	τ^-	τ^- decay $\bar{u}d$	τ^- decay e^-	τ^- decay μ^-
$u\bar{d}$	jets		e + jets	μ + jets	τ + jets	jets	e + jets	μ + jets
$c\bar{s}$								
e^+	e + jets		ee	eμ	eτ	e+jets	ee	eμ
μ^+	μ + jets		eμ	μμ	μτ	μ+jets	eμ	μμ
τ^+	τ + jets		eτ	μτ	ττ			
τ^+ decay $u\bar{d}$	jets		e+jets	μ+jets				
τ^+ decay e^+	e + jets		ee	eμ				
τ^+ decay μ^+	μ + jets		eμ	μμ				

τ unstable

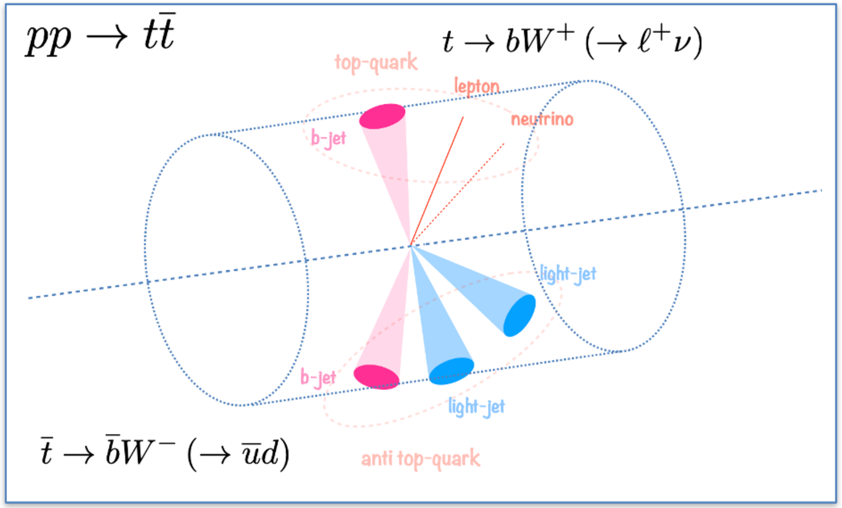
not observed experimentally

○ full hadronic
○ semileptonic
○ dileptonic

$$Br(W \to \ell\nu) = 10.9\,\%$$
$$Br(W \to \mathrm{u}\bar{\mathrm{d}}, \mathrm{c}\bar{\mathrm{s}}) = 67.4\,\%$$

top pair signature

- A $t\bar{t}$ events contains:
  - ⋆ At least 2 b-quark jets
- and
  - ⋆ Either 2 charged lepton and missing transverse energy (E_T^{miss}) (neutrinos)
  - ⋆ Or 1 charged lepton, E_T^{miss} and at least 2 more jets
  - ⋆ Or at least 4 more jets
- All detector components used to identify the above leptons (mostly electrons and muons), jets, b-quark jets, E_T^{miss}



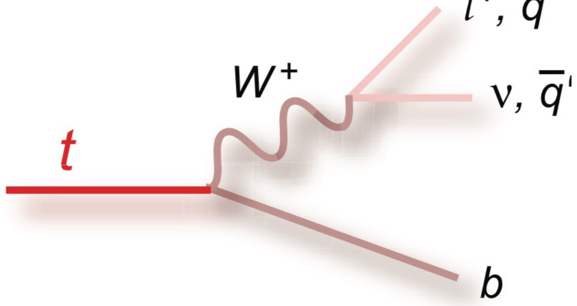
Example: semi-leptonic topology

Reconstruction level typical selection

- One identified and isolated lepton (electron or muon) ET/ pT> 25 GeV and with in |eta|<2.5.
- Missing transverse momentum in excess of 20 GeV.
- Four jets wit ET> 35 GeV and |eta|<2.5.
- Two jets tagged as b-jets.

Top quark physics

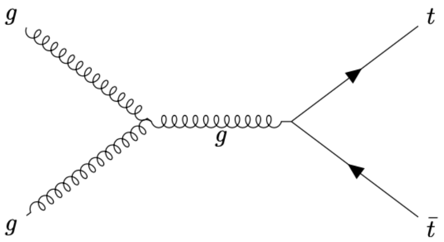
- **Top proprieties**
  - ⋆ Mass, width, charge, spin, ...
- **Top production**
  - ⋆ $t\bar{t}$ cross-section, production dynamics, spin polarization
- **Top decay**
  - ⋆ V_{tb}, brancing ratios, rare decays, W helicity

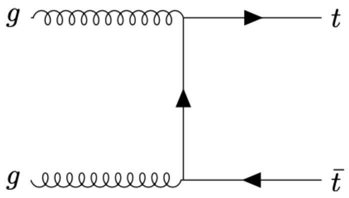


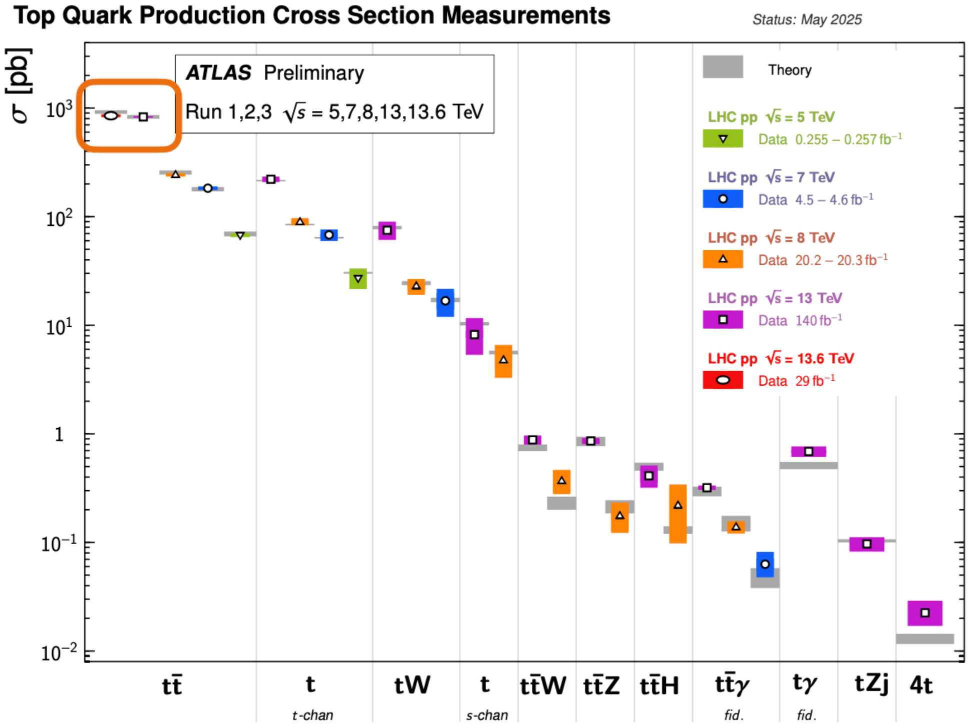
- Top quark allows tests of the participating forces
- Top quark plays an important role in the search for new physics beyond the SM (BSM) (new particles decaying to top quark)
- Top quark events are background to many physics processes

Top pair production cross section at LHC

- LHC is a top-quark factory
  - $\sigma_{t\bar{t}} \sim 834$ pb at $\sqrt{s} = 13$ TeV (Run-2)
  - $\sigma_{t\bar{t}} \sim 924$ pb at $\sqrt{s} = 13.6$ TeV (Run-3)
- O(100) million top-quark pairs produced in Run 2!!
- Dominant production channel at the LHC: gluon fusion







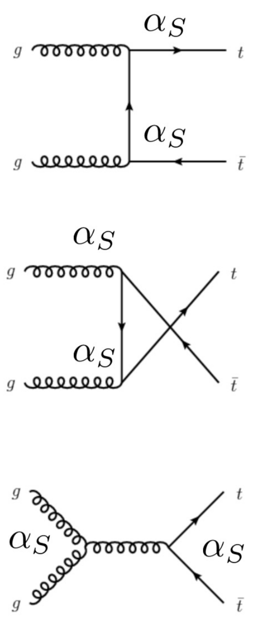
ATLAS Top Cross section summary plots

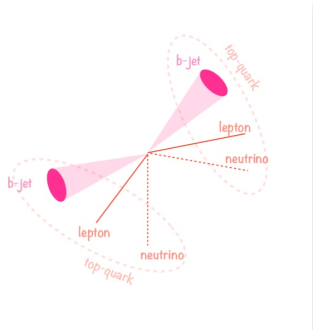
Top pair production cross section measurements

Main production diagrams

At tree level leading order

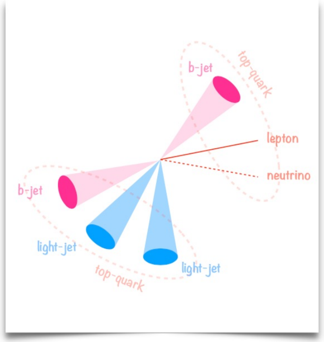
$$O(\alpha_S^2)$$





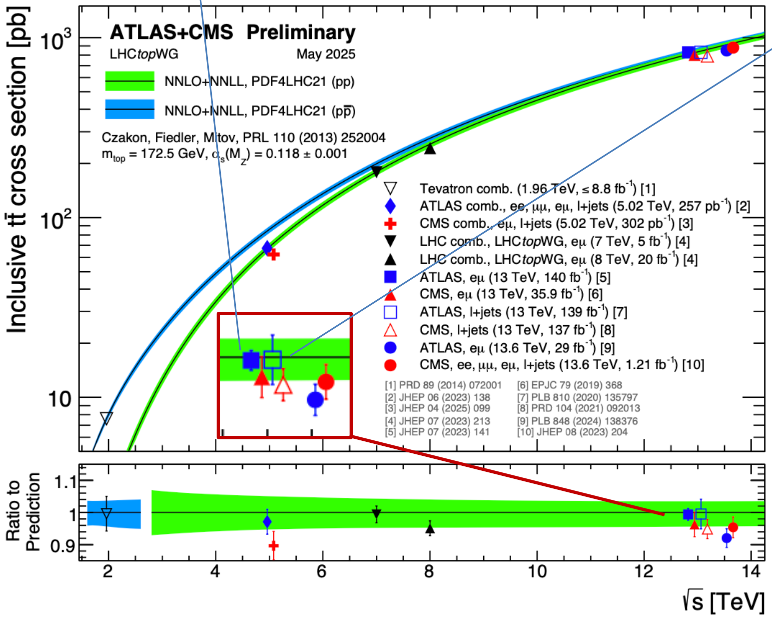
Di-lepton topology:

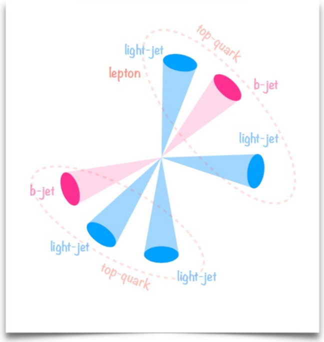
Precise determination of cross section in the different flavour electron-muon channel in particular. Excellent signal to background ratio. Lower stats (4%).



Semi-leptonic topology:

Best compromise between statistics (30%) and signal to background ratio.





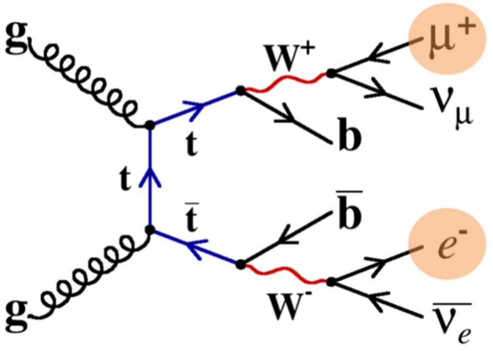
Full hadronic topology:

Largest stats (50%) but larger multi-jet background and large combinatorial.

Top pair production cross section measurements

$t\bar{t} \rightarrow bW^{+}\bar{b}W^{-} \rightarrow b\mu^{+}\nu_{\mu}\,\bar{b}e^{-}\bar{\nu}_{e}$

Ideal channel: very little background and enough statistics



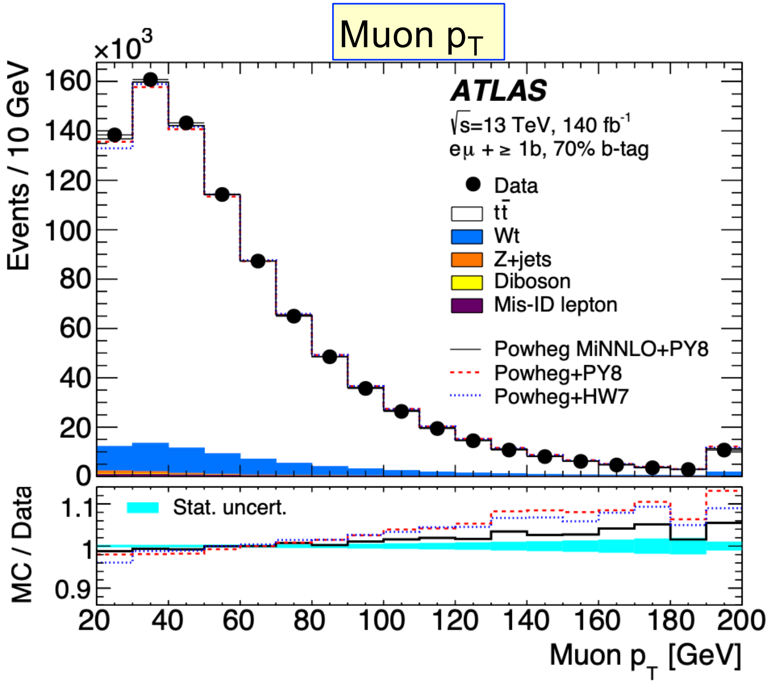
Final state

2 b-jets plus one electron and one muon with **opposite** charge

Event selection

- Pick events using single-lepton triggers
  - Leading lepton p_T ranging from 21 to 27 GeV in 2015-2018 data
  - Relaxed sub-leading lepton p_T > 20 GeV — increase acceptance
- Reconstruct jets with anti-k_t algorithm with R=0.4
  - p_T > 25 GeV, b-tagging using DL1r algorithm (70% b-efficiency)

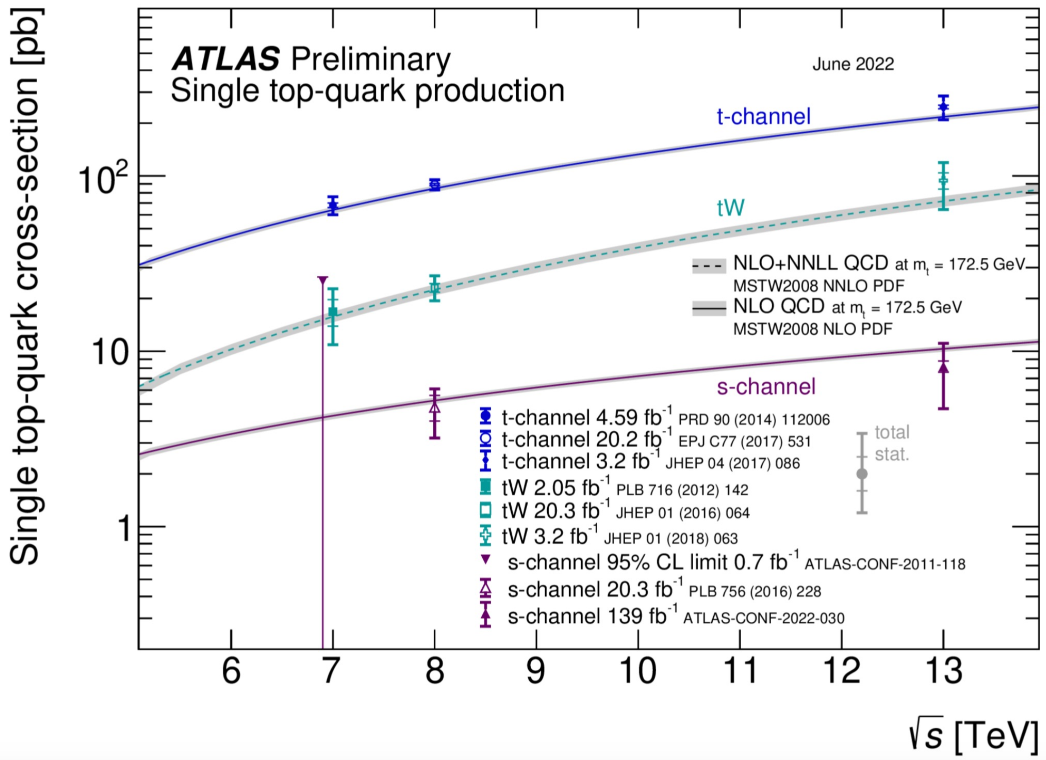
Muon p_T

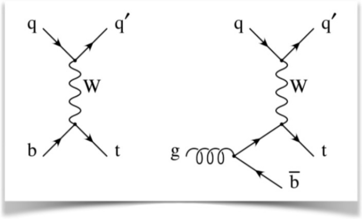


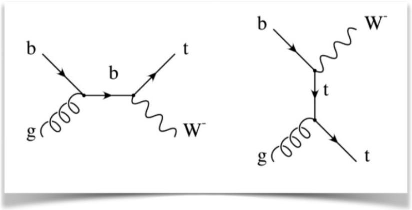
most precise 13 TeV measurement by ATLAS in the eμ final state (JHEP 07 (2023) 141)

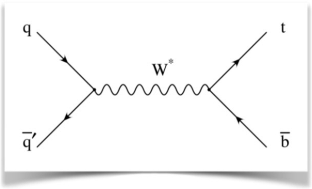
$\sigma_{t\bar{t}}$ = 829 ± 1 (stat) ± 13 (syst) ± 8 (lumi) ± 2 (beam) pb

Single top production cross section









- Can be used to measure $|V_{tb}|$
  - ⋆ Example: $|V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo.}(V_{tb}=1)}}$
  - ⋆ $|V_{tb}| = 1.02 \pm 0.4(\text{meas.}) \pm 0.02(\text{theo.})$

top mass measurement

Experimental results come from LHC data

top mass definition

- ☐ **Direct measurement:**
  - rely on parton shower simulation;
  - build templates that depend on the top quark mass (m_t) parameter in the simulation
  - yield small uncertainties
  - relation to a theoretically well defined mass has an uncertainty of O(0.1 – 1 GeV)

- ☐ **Indirect measurement through cross section measurement:**
  - any quantitative statement about the value of a quark mass requires a precise reference to the mass scheme in which the mass is defined;
  - the most used is the pole-mass scheme, where the renormalised top-quark mass coincedes with the pole of the top quark propagator: m_t^{pole}

$$\frac{i}{\not{p} - m_0} \Rightarrow \frac{i}{\not{p} - \underbrace{m_0\left(\Lambda\right)}_{\text{'bare' mass}} - \underbrace{\delta m_0\left(\Lambda\right)}_{\text{divergent}} - \underbrace{\Sigma' m_0\left(\Lambda\right)}_{\text{finite}}} := \frac{i}{\not{p} - m^{\text{pole}}}$$

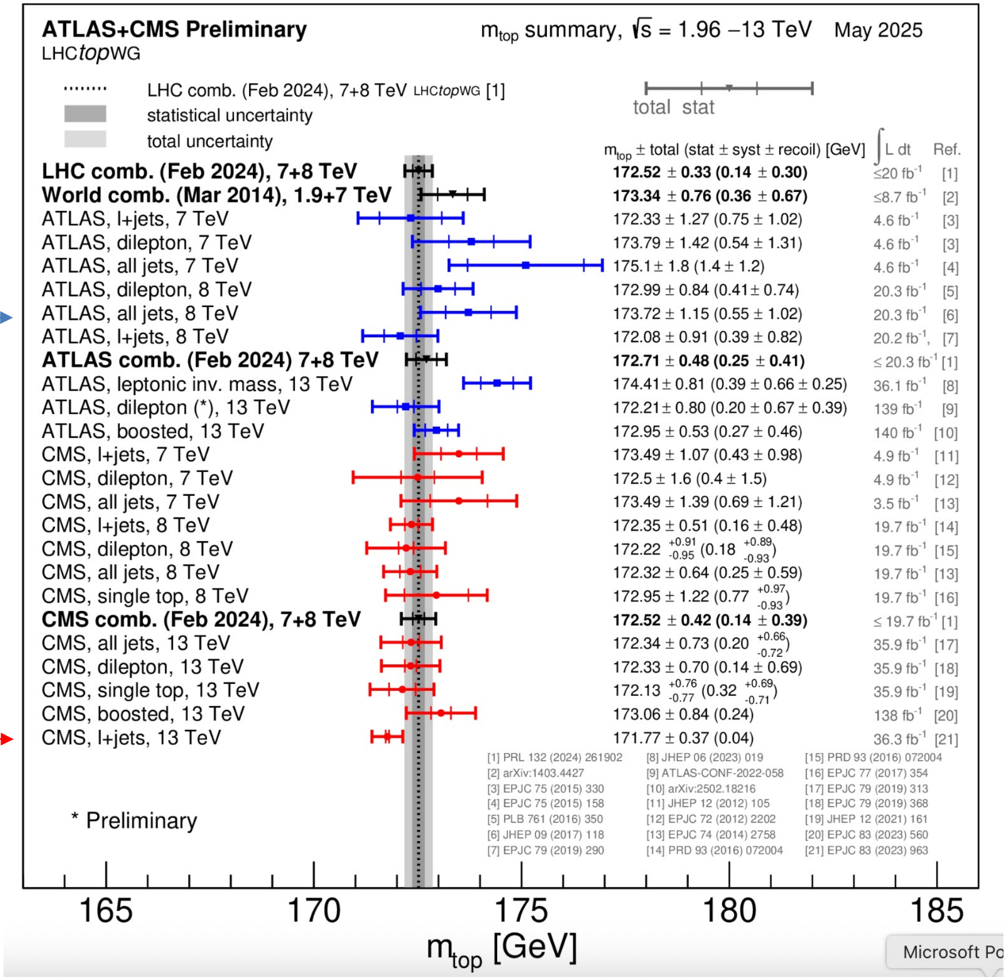
    - it is extracted via differential cross sections
    - non perturbative corrections must be added
    - unfolding procedure yield typically bigger uncertainty than direct measurement

Direct top quark mass summary

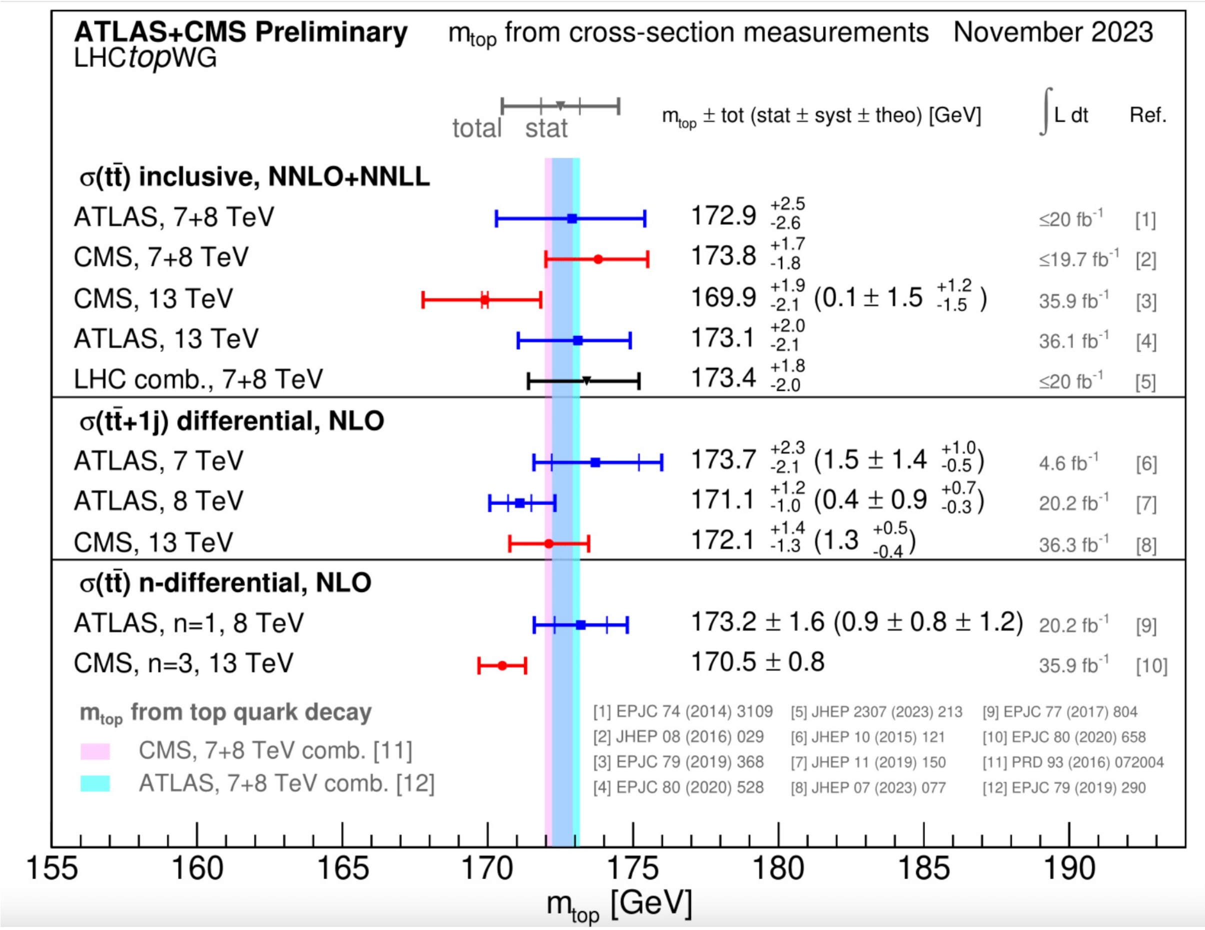
- LHC combination (**7 + 8 TeV**) : 172.52 ± 0.33 GeV
- ATLAS comb. (**7 + 8 TeV**): 172.71 ± 0.48 GeV
- CMS comb. (**7 + 8 TeV**) : 172.52 ± 0.42 GeV

I'll show an example of the Atlas measument with all jets in the final state

Best single measurement is coming from CMS 13 GeV (Run2) data with lepton + jets in the final state.



Top quark mass from tt cross-section summary



Measurements from cross sections will be limited by prediction uncertainties and luminosity error.

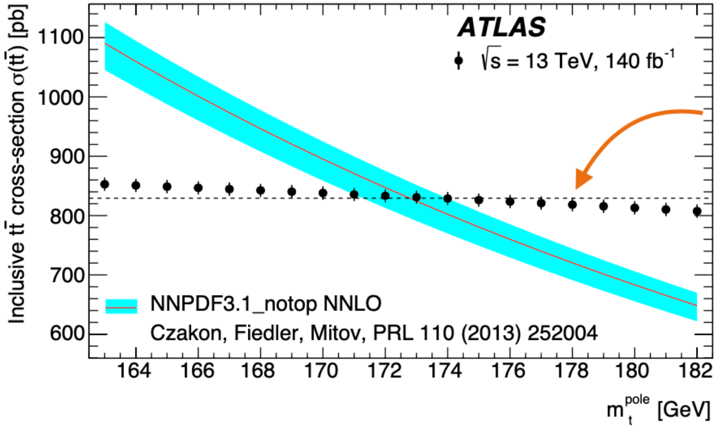
Some of the uncertainties can be reduced by measuring the differential cross section of the tt production in association with a jet in the final state. This is a promising channel for the top mass measurement.

Top quark pole mass determination

Inclusive cross-section results

Top-quark pole mass (m_t^{pole}) extraction

Predicted $\sigma_{t\bar{t}}$ depends strongly on top quark mass

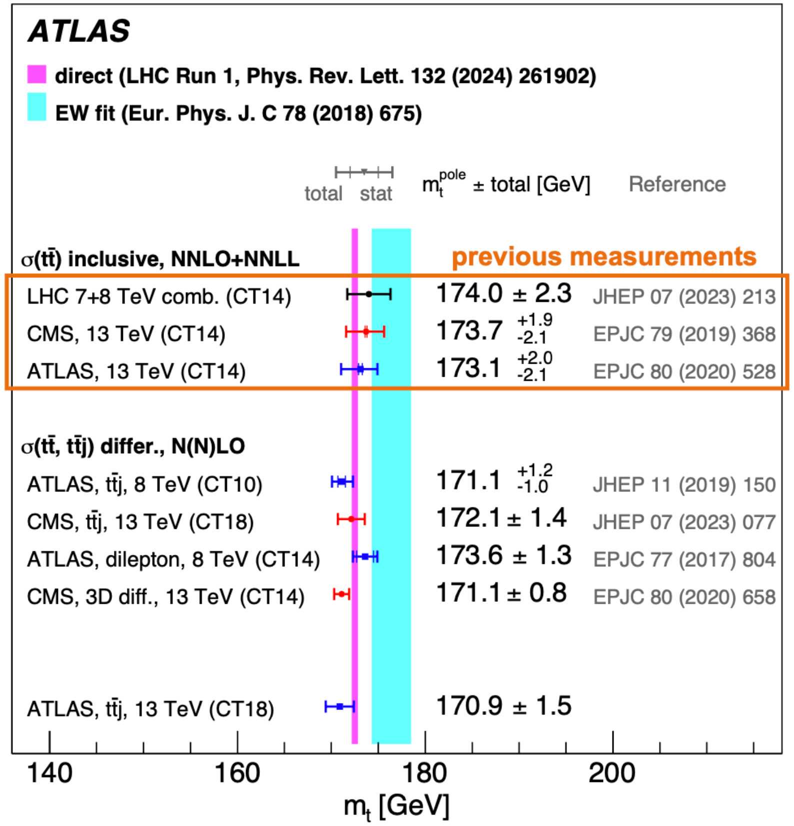


$$\frac{1}{\sigma}\frac{d\sigma}{dm_t} = -0.3\%\ /\ \text{GeV}$$

Small dependence on m_t

PDF set	NNPDF3.1_notop	CT14
Result [GeV]	$172.79^{+1.52}_{-1.70}$	$173.00^{+1.84}_{-2.04}$
Experimental	0.55	0.55
PDF+α_s	$^{+1.00}_{-0.89}$	$^{+1.50}_{-1.48}$
QCD scales	$^{+1.00}_{-1.48}$	$^{+1.01}_{-1.49}$

Plot from arXiv:2507.02632



Most precise m_t^{pole} measurement from **inclusive cross-section**

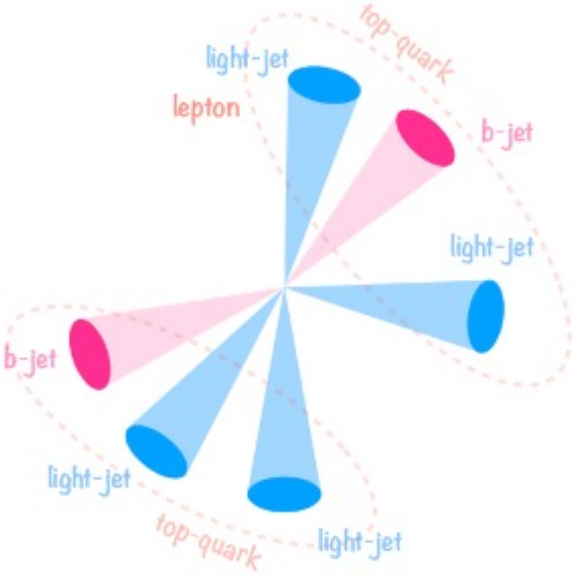
(from a very recent Atlas result on the tt cross-section)

Atlas top mass direct measurement: event selection

Example taken from:

Top-quark mass measurement in the all-hadronic $t\bar{t}$ decay channel at $\sqrt{s} = 8$ TeV with the ATLAS detector (published in 2017)

Fully hadronic final state



	Event yields (thousands)	
Cut	Data	$t\bar{t}$ all-hadronic (MC)
Initial	850450	2338 ± 1
$N_{\mathrm{PV}_{>4\,\mathrm{tracks}}}$ & no isolated e/μ At least 5 tracks in the primary vertex	33476	308.7 ± 0.6
Trigger: 5 jets with $p_{\mathrm{T}} > 55\,\mathrm{GeV}$ & ≥ 6 good jets	16110	241.4 ± 0.5
No 2 good jets (j_i, j_k) within $\Delta R(j_i, j_k) < 0.6$ Only isolated jets	7646	142.9 ± 0.4
≥ 5 good jets with $p_{\mathrm{T}} > 60\,\mathrm{GeV}$	3303	51.4 ± 0.2
$E_{\mathrm{T}}^{\mathrm{miss}} < 60\,\mathrm{GeV}$ No neutrinos	3021	46.3 ± 0.2
$\Delta\phi(b_i, b_j) > 1.5$ Angular separation between the 2 b-jets	1737	30.9 ± 0.2
$\chi^2 < 11$ See next slide	645.8	22.3 ± 0.1
$N_{b_{\mathrm{tag}}} \geq 2$ At least 2 b-jets	21.9	6.61 ± 0.08
$\langle\Delta\phi(b, W)\rangle < 2$ Angular separation between b and W	12.9	4.40 ± 0.07

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Final purity: $(58.8 \pm 0.2)\%$

Reconstruction of the final state top-antitop

- ❑ In the final state we have six jets, among which two must be b-jets: $t\bar{t} \to bWbW \to b_1 j_1 j_2\, b_2 j_3 j_4.$

- ❑ In order to associate 3 jets to a top and the othes to the the second top, a χ^2 is built:

$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})^2}{\sigma^2_{\Delta m_{bjj}}} + \frac{(m_{j_1 j_2} - m_W^{\mathrm{MC}})^2}{\sigma^2_{m_W^{\mathrm{MC}}}} + \frac{(m_{j_3 j_4} - m_W^{\mathrm{MC}})^2}{\sigma^2_{m_W^{\mathrm{MC}}}}.$$

- ❑ Here, two of the jets are associated with the b-quarks from the top decays (b_1 and b_2), the other four are assumed to be light quarks from the W decays. No explicit b-tagging information is used.

$$\Delta m_{bjj} = m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4}$$ where $m_{b_2 j_3 j_4}$ is the invariant mass of the three jets

- ❑ This method considers all possible permutations of the six (or more) reconstructed jets in each event. The one resulting in the lowest χ^2 is kept. A low χ^2 value indicates a permutation of jets consistent with the $t\bar{t}$ hypothesis.

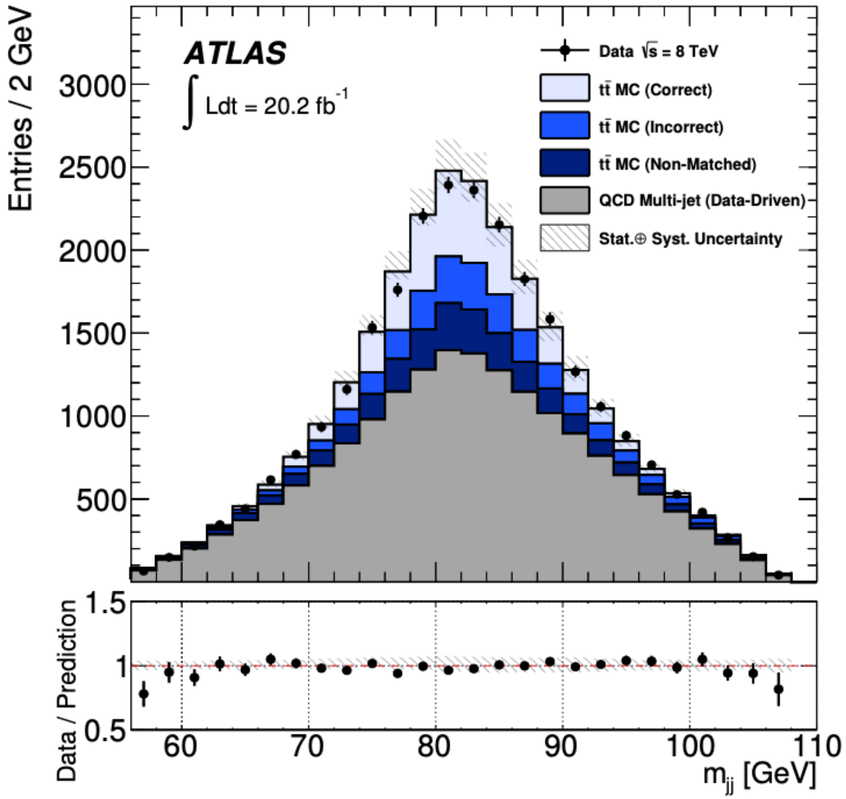
- ❑ In each combination the reconstructed mass of the two jets from the W decays are compared with the mean value of the mass distribution of correctly reconstructed W in simulated signal MC events (M_W^{MC}).

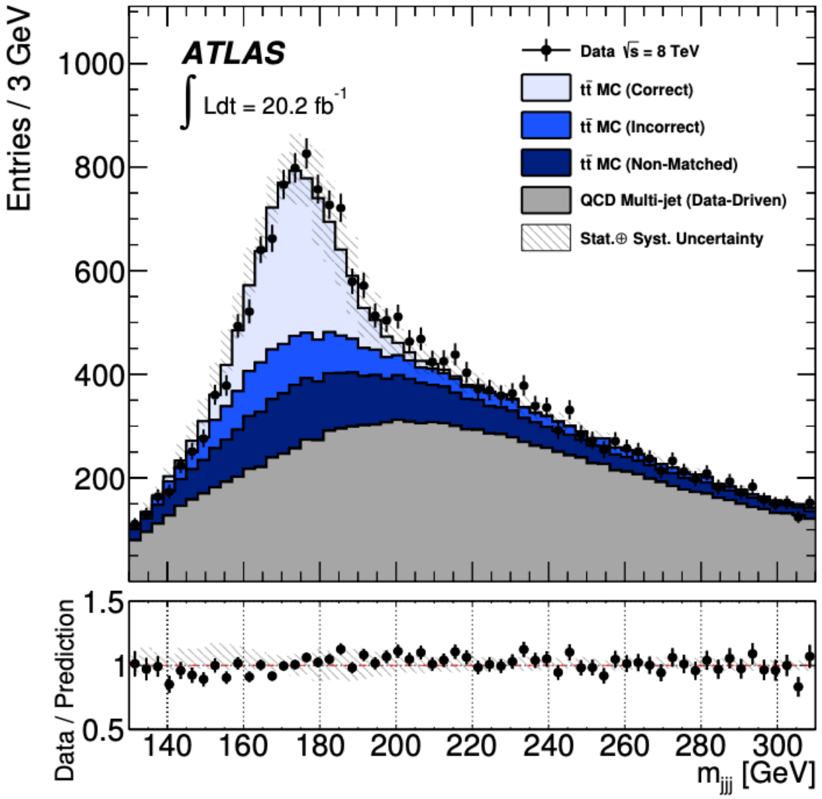
- ❑ The widths are obtained from a fit to the MC signal events:

$\sigma_{\Delta m_{bjj}} = 21.60 \pm 0.16\ (\mathrm{stat.})\ \mathrm{GeV}$ $\sigma_{m_W^{\mathrm{MC}}} = 7.89 \pm 0.05\ (\mathrm{stat.})\ \mathrm{GeV}$ and $M_W^{MC} = 81.18 \pm 0.04\ (\mathrm{stat.})\ \mathrm{GeV}$

Di-jet and three-jet mass distributions

“W mass”





MC correct means that the three jets assignement to a top decay is correct, otherwise is said to be incorrect. If at least a quark is not matched to any jet, it is said Non-Matched.

The $t\bar{t}$ simulation corresponds to $m_{\text{top}} = 172.5\,\text{GeV}$.

Top quark mass determination

❑ **The top mass is NOT equal to the three jet invariant mass:**

- **large error due to the jet energy resolution;**
- **large error due to the jet energy scale**

❑ **It is obtained from a comparison data - Montecarlo of the quantity:**

$$R_{3/2} = \frac{m_{jjj}}{m_{jj}}$$

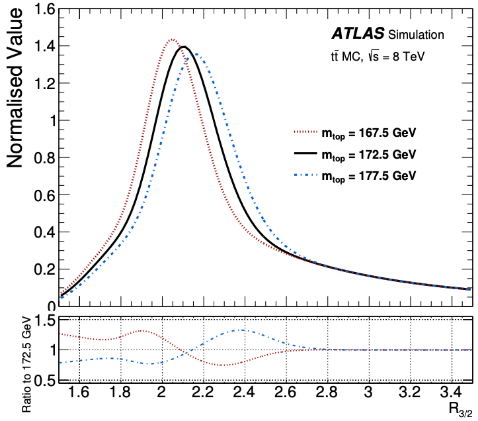
$m_{jjj} =$ three jet invariant mass (top mass)

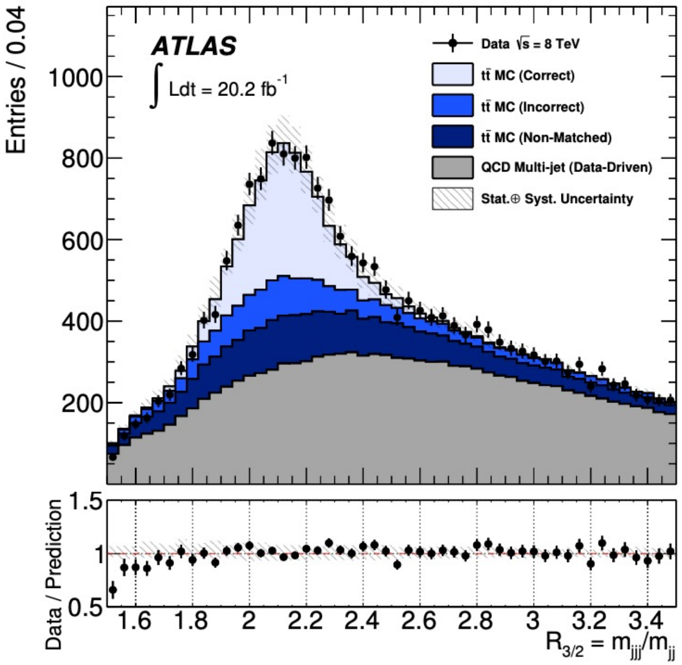
$m_{jj} =$ di-jet invariant mass (W mass)

❑ **In the ratio many systematics uncertainties cancel.**

❑ **To extract a measurement of the top quark mass, a template method with a minimum χ^2approach is employed:**

- **the data distribution is compared with MC distributions generated with three top mass: 167.5, 172.5 and 175 GeV;**
- **then an interpolation is used to obtain the top mass with the best agreement with the data.**





Top quark mass measurement: pdf function

- ❑ The top quark contribution to the histogram is parameterised by a probability distribution function (pdf) which is the sum of a Novosibirsk function for the signal and a Landau function that describes the combinatorial background.
- ❑ The 6 parameters of the distributions depend on the top value, in particular the peak and width of the N. function.

The Novosibirsk function is a continuous probability density function that is used to model asymmetric peaks in high-energy physics.

$$f(x;\sigma,x_0,\Lambda)=\exp\left[-\frac{1}{2}\frac{(\ln q_y)^2}{\Lambda^2}+\Lambda^2\right]$$

$$q_y(x;\sigma,x_0,\Lambda)=1+\frac{\Lambda(x-x_0)}{\sigma}\times\frac{\sinh\left(\Lambda\sqrt{\ln 4}\right)}{\Lambda\sqrt{\ln 4}}$$

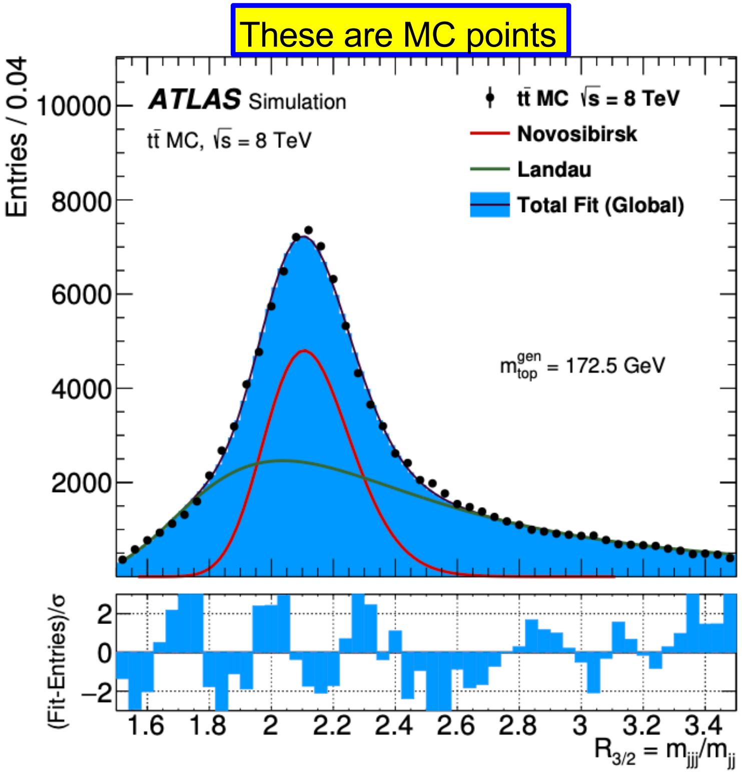
x_0: peak position; σ : width, Λ : tail, plus a normalisation constant N

Landau distribution

$$f(x;\mu,c)=\frac{1}{\pi c}\int_0^{\infty}\exp(-t)\cos\left(t\left(\frac{x-\mu}{c}\right)+\frac{2t}{\pi}\log\left(\frac{t}{c}\right)\right)dt$$

The location parameter μ is the location of the distribution,

while the scale parameter [c] determines the width of the distribution,


These are MC points

Top quark mass measurement: fit procedure

- The fit is done in two steps, first the $R_{3/2}$ distributions from $t\bar{t}$ simulation samples are fitted separately to determine the six parameters for each template mass. The MC simulation shows that each of these parameters depends linearly of the input m_{top}.
- In the next step, the parameters are fitted to obtain the offsets and slopes of the linear m_{top} dependencies.
- These values are then used as inputs to a combined, simulateous fit to determine the pdf, namely the probability P_S and P_B to have the signal and the background in a given bin of the $R_{3/2}$ distribution of the data.
- The final (simplified) χ^2 function to estract m_{top} is the following:

$$\chi^2 = \sum_{\text{bin } i}^{N_{\text{bin}}} \frac{(n_i - \mu_i)^2}{n_i}$$

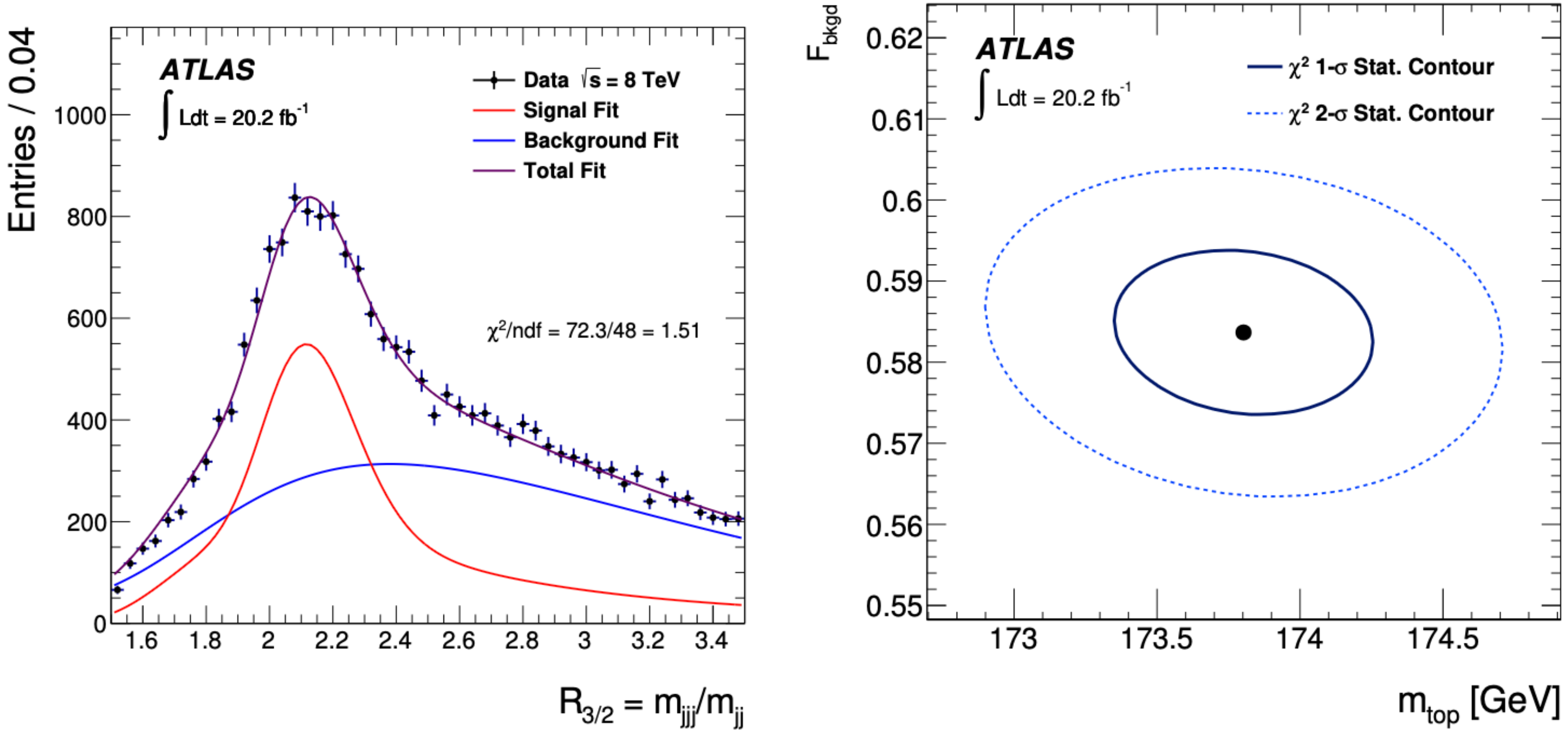
N_{bin}: number of bins in the data distribution
n_i: number of data in the bin i
μ_i: number of expected data from MC in the bin i

$$\mu_i\left(m_{\text{top}}, \underbrace{F_{\text{bkgd}}}_{\text{background fraction}}\right) = \underbrace{w_{\text{bin}}}_{\text{bin width}} \underbrace{N_d}_{\text{Total number of data}} \left[\left(1 - F_{\text{bkgd}}\right) \underbrace{P_{\text{S}}}_{\text{Signal probability}} \left(R_{3/2,i} | m_{\text{top}}\right) + F_{\text{bkgd}} \underbrace{P_{\text{B}}}_{\text{background probability}} \left(R_{3/2,i}\right)\right]$$

- The mass of the top and the background fraction are fitted simultaneously.

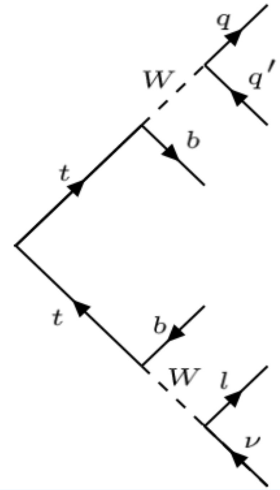
Top quark mass measurement: result

$$m_{\rm top} = 173.72 \pm 0.55\ ({\rm stat.}) \pm 1.01\ ({\rm syst.})\ {\rm GeV}.$$

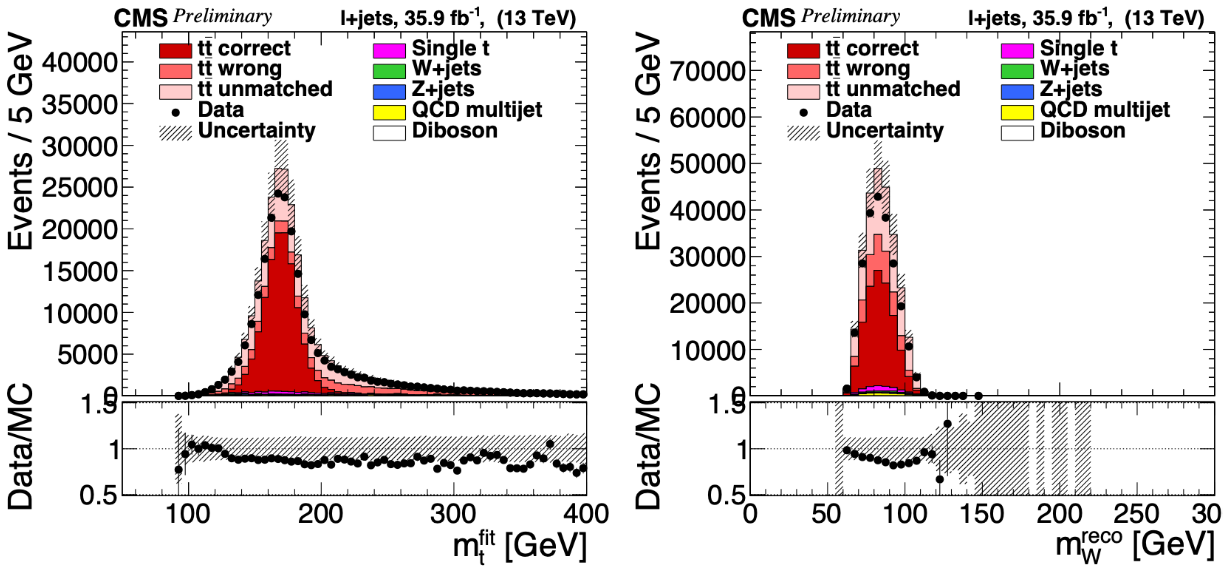


CMS direct measurement: l + jets final state

Event selection



- 36 fb^{-1} of $\sqrt{s}$ =13TeV pp-collision data recorded by CMS in 2016
- trigger on single isolated muons and electrons
- anti-$k_t^{R=0.4}$ jets with $p_T > 30$ GeV, $|\eta| < 2.4$
- at least two b-tagged jets via *DeepJet* (WP: 1% mis-tag)



- ▶ m_t^{fit} main observable
- ▶ m_W^{reco} reduces jet energy correction (JEC) uncertainties

The fitting procedure is similar to what has been described for the Atlas measurement

$$m_t^{\text{MC}} = 171.77 \pm 0.38\,\text{GeV},\ \text{this includes } \sigma_{\text{stat}} = 0.04\,\text{GeV}$$

Top quark mass measurement: recap

- Direct m_{top} measurements:
  - ⋆ Reconstruct $t\bar{t}$ events in data and MC
  - ⋆ Reduce backgrounds to obtain a clean sample
  - ⋆ Reconstruct the final state
  - ⋆ Use sophisticated technique to extract the m_{top}, using e.g. a kinematic fit
- Indirect m_{top}^{pole} measurements
  - ⋆ Instead of fitting to MC distributions "folded" with the detector response unfold the data to e.g parton-level
  - ⋆ Caveat: Larger uncertainties on both theory and experiment
  - ⋆ Measure cross section as function of m_{top}^{pole} in LO, NLO and NNLO and determine m_{top}^{pole}

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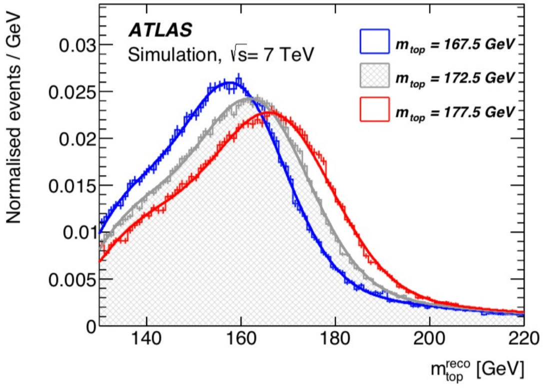
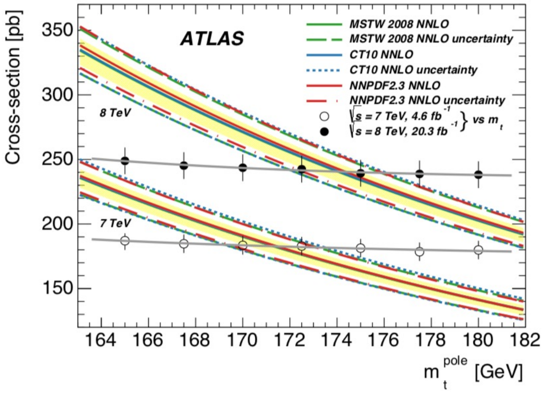


Eur. Phys. J. C74 (2014) 3109



Digression on the mass measurement

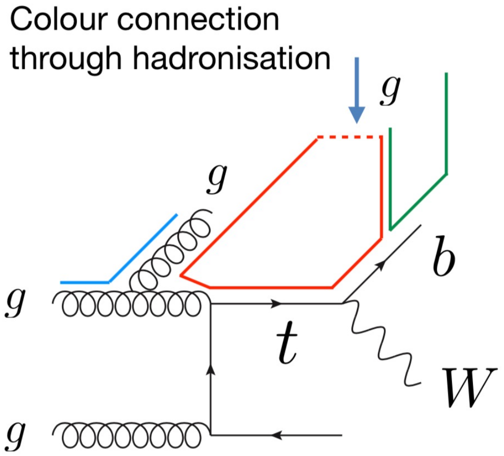
The relation between the Monte Carlo template used to fit the mass spectrum and the Field Theoretical parameter of the pole mass is not straightforward.

The top is coloured, so it is impossible to unambiguously associate every object in the final state to it!

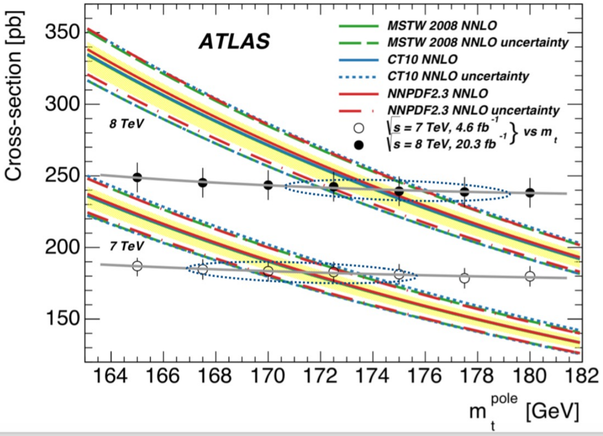
These ambiguities lead to an uncertainty on the top mass measurement varying between 1 GeV and 200 MeV.

The pole mass can be measured using observables that are not dependent on the detailed reconstruction of the top system.

e.g. the pole mass can be measured using the top production cross section (at the cost of introducing a dependence on the production prediction).



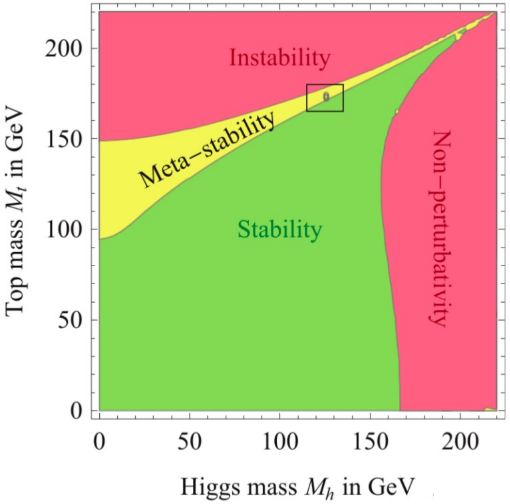
Colour connection through hadronisation



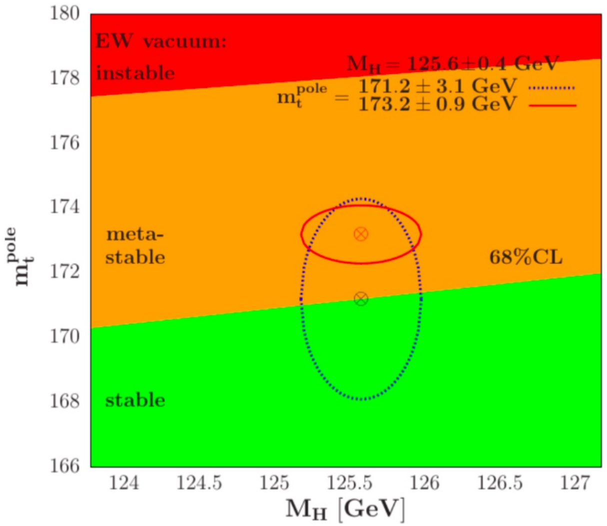
Top quark mass … and the Universe

- The top-quark mass, $\mathrm{m_{top}}$, is a fundamental parameter of the Standard Model (SM)
- Precise determinations of the SM parameters ($\mathrm{m_{top}}, \mathrm{m_W}, \mathrm{m_H}, \ldots$) allow to challenge consistency tests of the SM and to look for signs of new physics beyond the SM (BSM)
- Plots show: (left) Regions of absolute stability, meta-stability and instability of the SM vacuum in the top-quark pole mass and the Higgs mass, $\mathrm{m_{top}^{pole}} - \mathrm{m_H}$, plane; (right) ellipses for the $1\,\sigma$ uncertainties in the $\mathrm{m_{top}^{pole}} - \mathrm{m_H}$ plane confronted with the SM vacuum expectations;

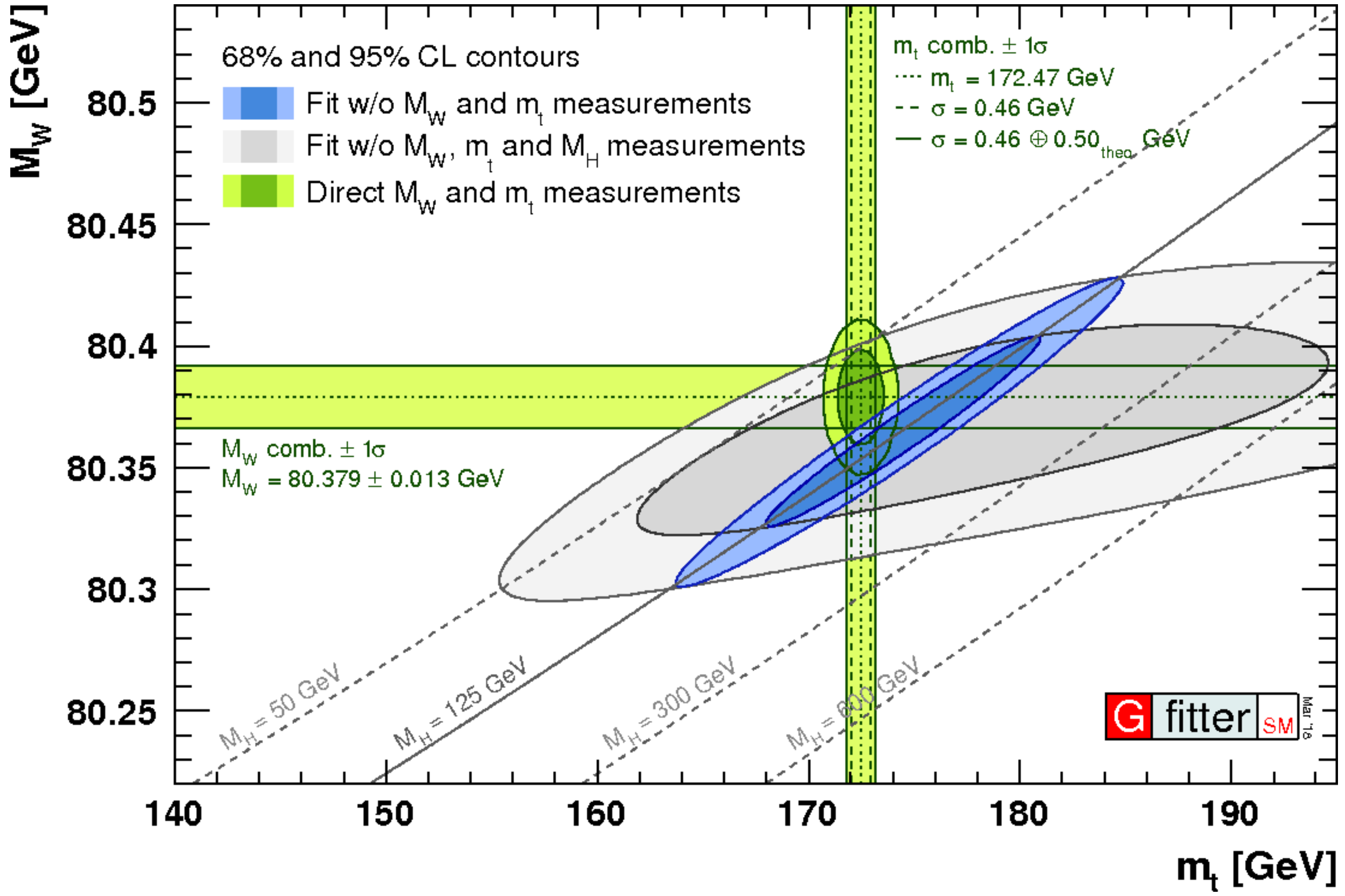
arXiv:1205.6497v2



arXiv.1207.0980v3



Electroweak fits



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End of chapter 9