Introduction to Particle Physics
- Top Quark Physics -

Teresa Barillari

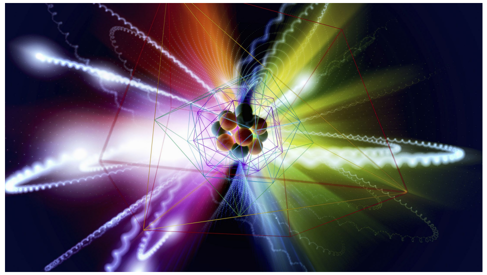
Max-Planck-Institut für Physik München (MPP)

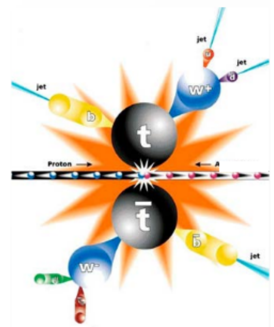
Rome, La Sapienza, December 20th, 2021

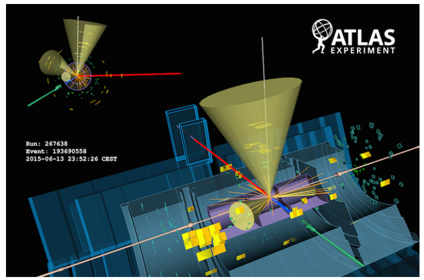
Max-Planck-Institut
für Physik

SAPIENZA
UNIVERSITÀ DI ROMA

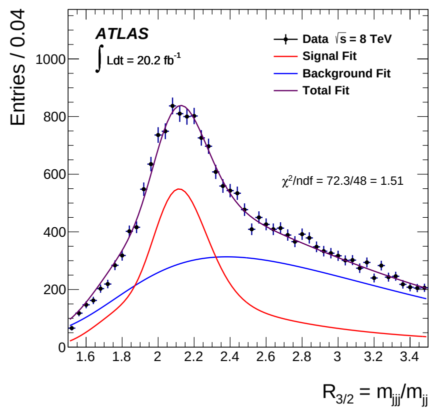
Overview



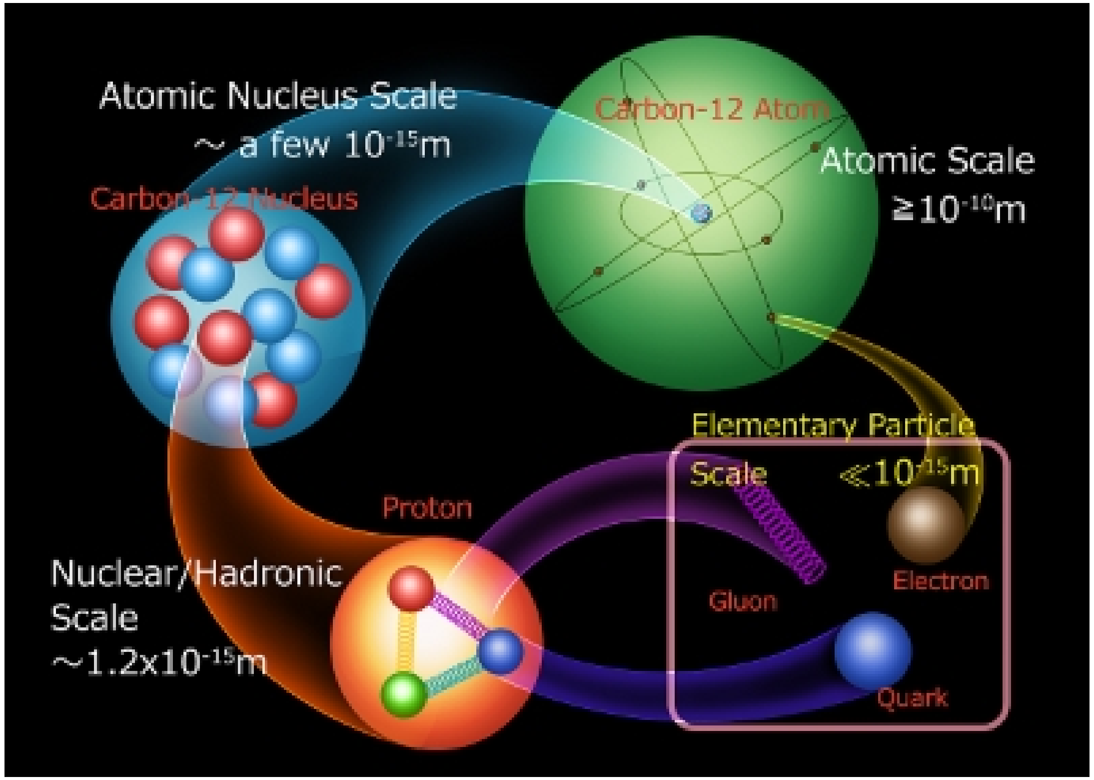


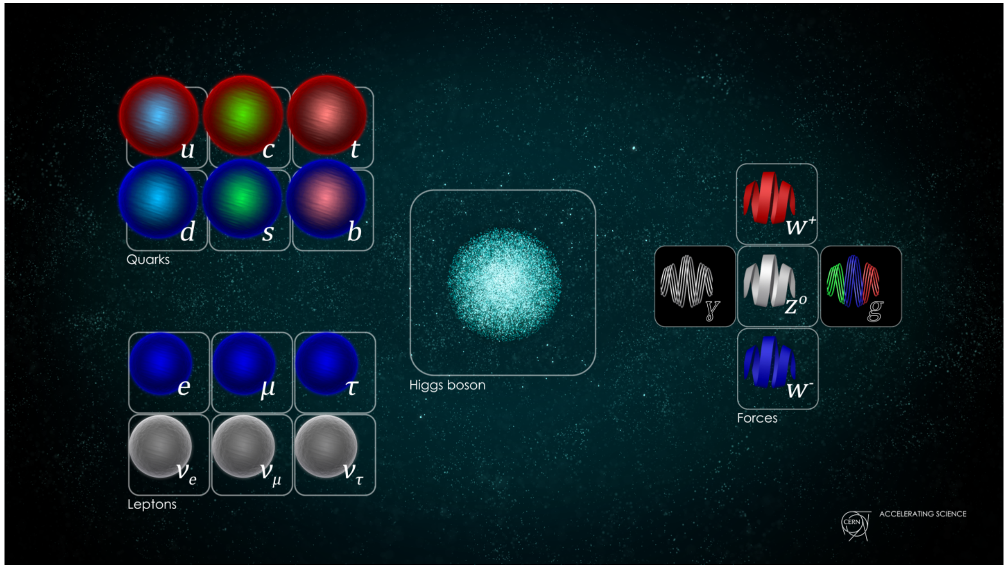


- The top quark: proprieties, mass, decay
- Top quark history
- Top-quark @ Tevatron & LHC
- Top quark physics
- $t\bar{t}$ cross section measurements
- Top quark mass measurements
- Conclusions

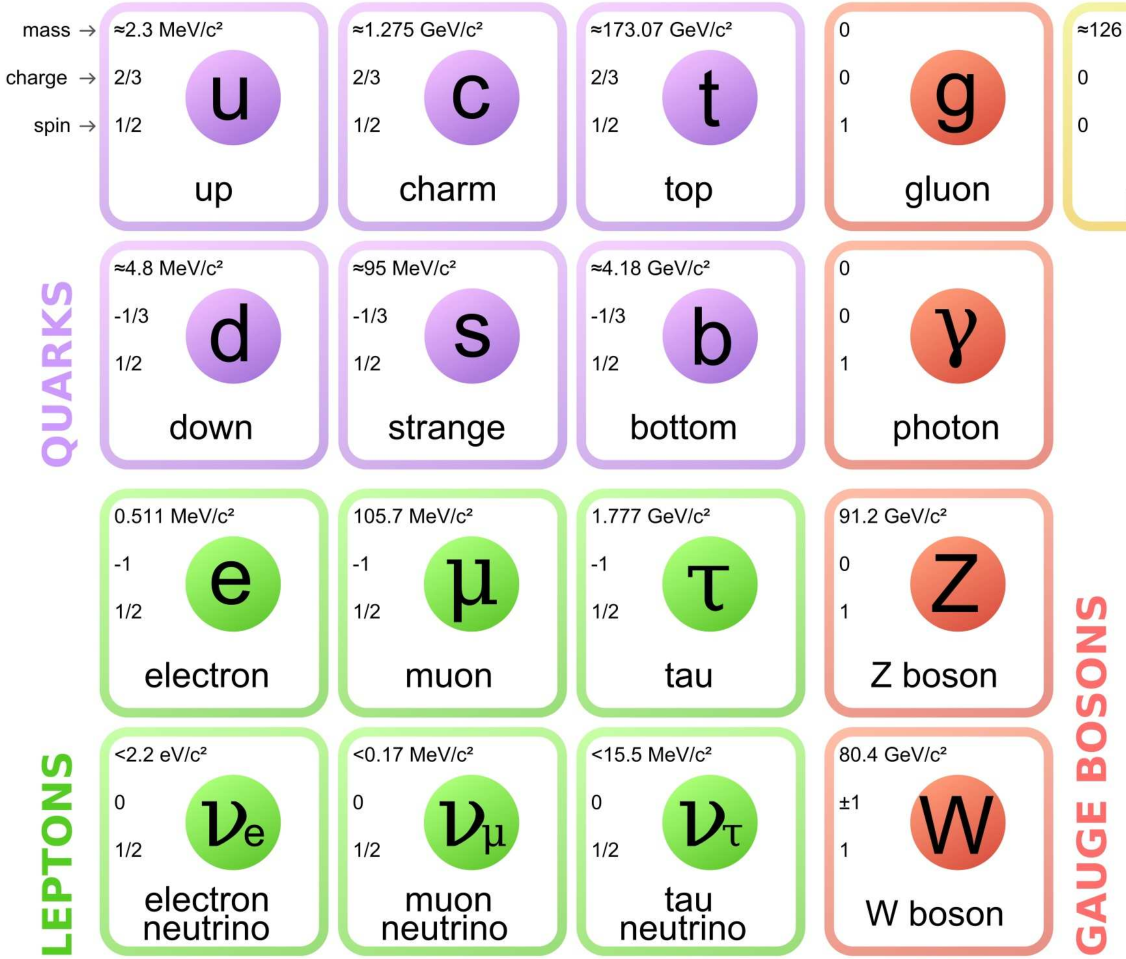


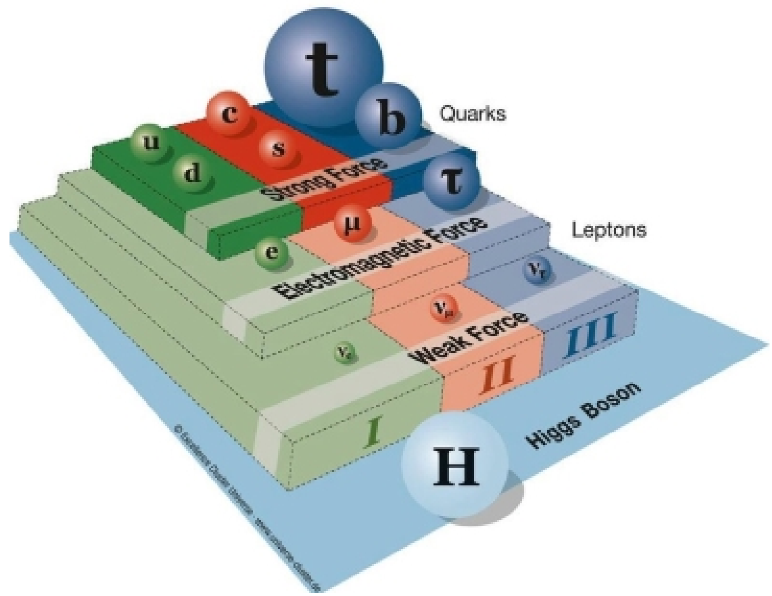
Atomic Nucleus & Elementary Particle Scale





Standard Model of Elementeray Particles





Top-Quark Mass

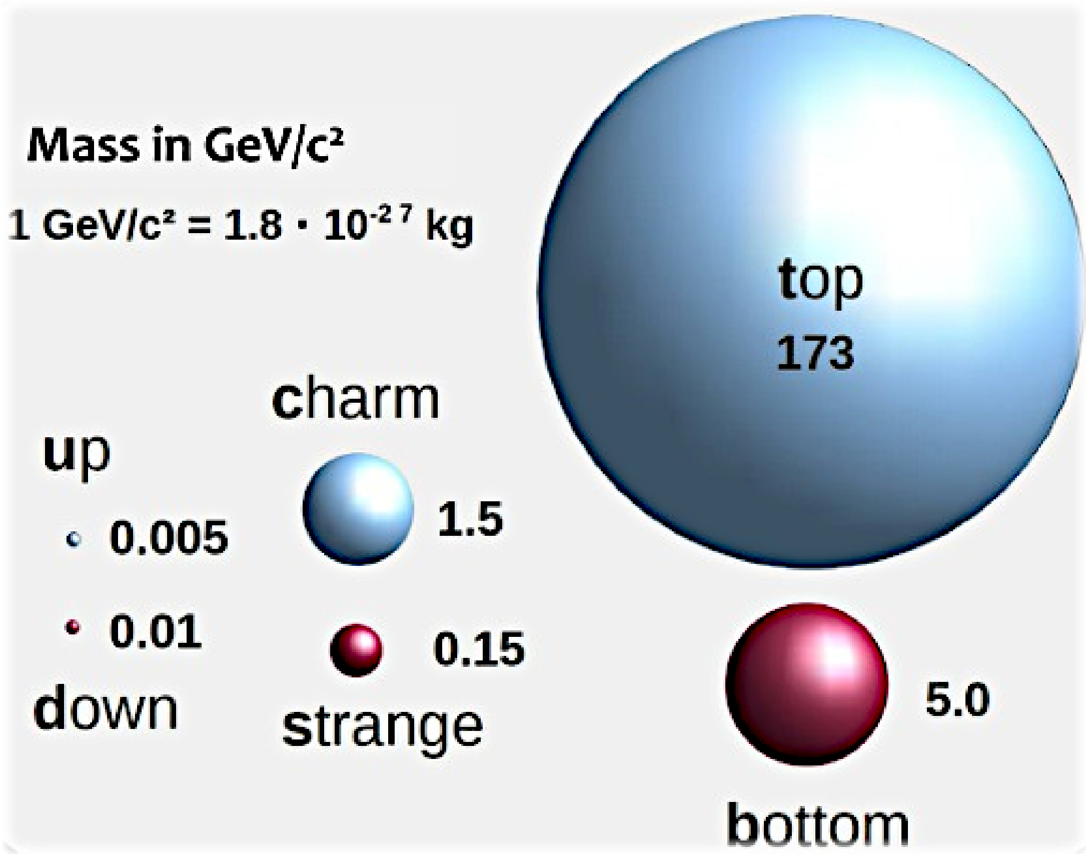
- The top quark is the heaviest known elementary particle, $m_{top} \approx 173\,GeV$
- It is outperforming the Higgs mass by $\sim$ 40%
- But also for comparison:

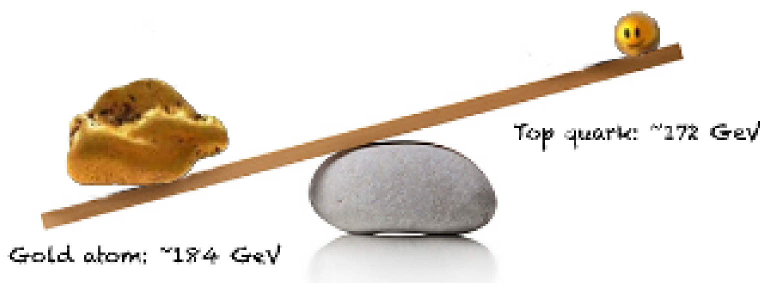
  $M_W = 80.425 \pm 0.038\,GeV$

  $M_{Z^0} = 91.1876 \pm 0.0021\,GeV$

  $M_g = 0$

  $M_\gamma \approx 0$ i.e. 6×10^{-26}

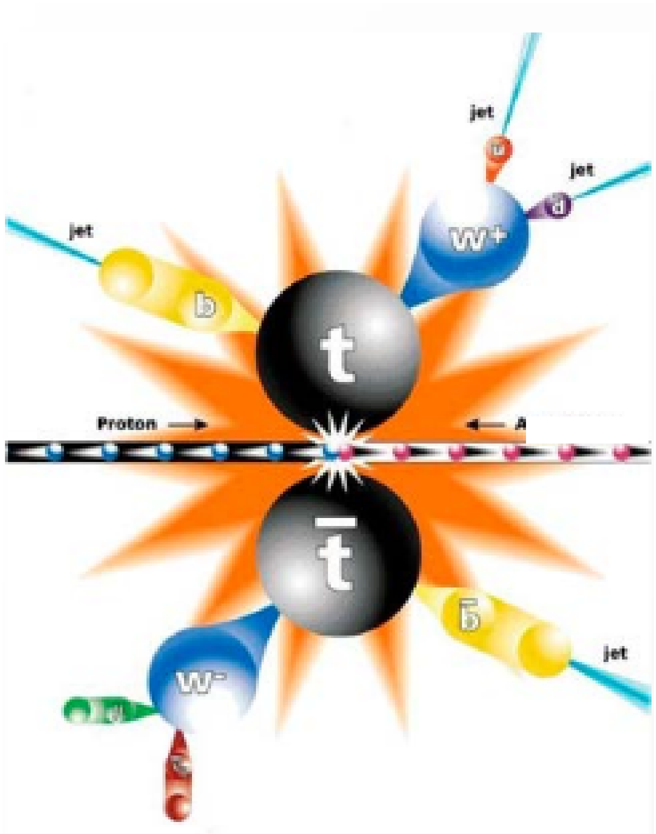




- It has a mass comparable to the mass of a gold atom

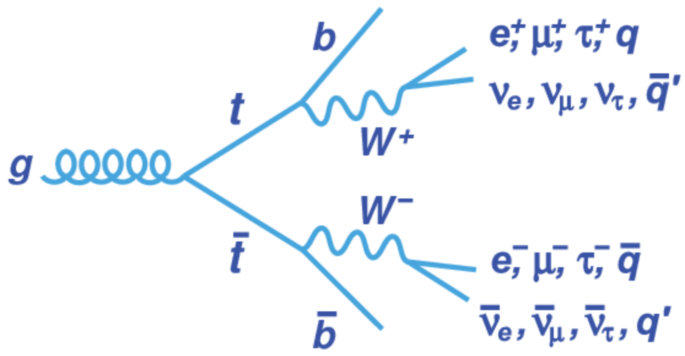
Top quark proprieties

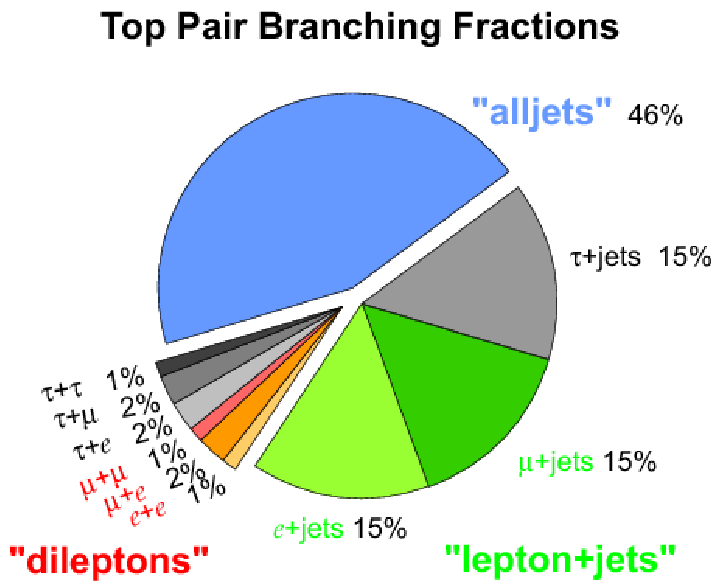
- The top quark has charge $Q = +2/3\mathrm{e}$ and weak isospin $\mathrm{T3} = +1/2$
- The top -quark is the partner of the bottom quark in the third generation quark doublet
- Yukawa coupling $\mathrm{Y_t} \sim 1$
- It decays before hadronizing
  - ⋆ Hadronization timescale: $\tau_{\mathrm{had}} \sim \times 10^{-23}\,\mathrm{s}$
  - ⋆ Top quark lifetime: $\tau_{\mathrm{top}} \sim 5 \times 10^{-25}\,\mathrm{s}$
  - ⋆ Bottom quark lifetime: $\tau_{\mathrm{bottom}} \sim \times 10^{-12}\,\mathrm{s}$
- Due to its short lifetime, it offers the unique opportunity to study the properties of a “bare” quark which are transferred to its decay products, e.g. its spin information



Top quark production

- Main top decay: $\mathrm{t} \to \mathrm{Wb}$ ($> 99.8\%$)
- The Ws and Wd decays suppressed relatively to Wb by the square of the CKM matrix elements $\mathrm{V_{ts}}$ and $\mathrm{V_{td}}$
- Leading $\mathrm{t\bar{t}}$-production process final states divided in three classes:
  - ⋆ All-jets (46.2%):
    $\mathrm{t\bar{t}} \to \mathrm{W^+bW^-\bar{b}} \to \mathrm{q\overline{q'}bq''\overline{q'''}b}$
  - ⋆ Lepton+jets (43.5%):
    $\mathrm{t\bar{t}} \to \mathrm{W^+bW^-\bar{b}} \to \mathrm{q\overline{q'}b}\ell^-\bar{\nu}_\ell\mathrm{\bar{b}}$
  - ⋆ Dilepton (10.3%):
    $\mathrm{t\bar{t}} \to \mathrm{W^+bW^-\bar{b}} \to \ell^+\nu_\ell\mathrm{b}\ell^-\bar{\nu}_\ell\mathrm{\bar{b}}$





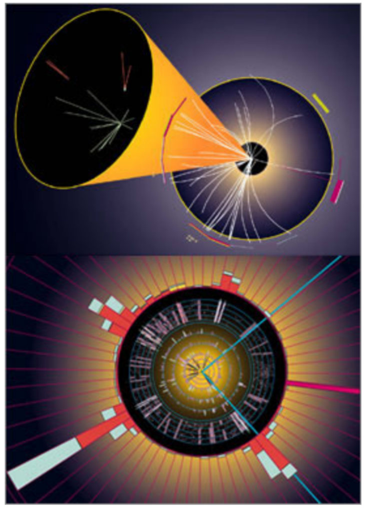
History of particles discovery

Quarks	Up/Down	1964/68	SLAC	1980 Nobel Prize
	Strange	1964/68	SLAC	1990 Nobel Prize
	Charm	1974	SLAC/BNL	1976 Nobel Prize
	Bottom	1977	Fermilab	
	Top	1995	Fermilab	
Leptons	Electron	1897	Thomson	1906 Nobel Prize
	e-Neutrino	1956	Reactor	1995 Nobel Prize
	Muon	1937	Cosmic Rays	
	Mu-Neutrino	1962	BNL	1988 Nobel Prize
	Tau	1976	SLAC	1995 Nobel Prize
	Tau-Neutrino	2000	Fermilab	first direct evidence
Bosons	Photon	1905	Planck/Einstein	1918/1921 Nobel Prize
	Gluon	1979	DESY	1995 EPS Prize
	W/Z	1983	CERN	1984 Nobel Prize
	Higgs	2012	CERN	2013 Nobel Prize

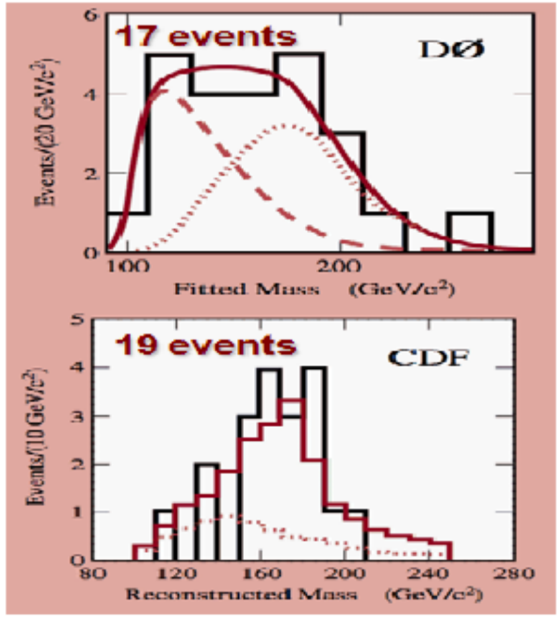
- In 2008 Makoto Kobayashi, and Toshihide Maskawa got the Nobel Prize for “the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature”, postulated in 1973

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 $4.8\,\sigma$



The first image shows a pair of top quarks reconstructed in the Collider Detector at Fermilab (CDF). Each top quark decays to a W boson and a b quark. The pink tower in the wide view identifies a positron (an anti-electron) from one W decay; the inset shows displaced decays of two b particles (red tracks). The second image shows a pair of top quarks reconstructed in the DZero experiment at Fermilab. This end view shows the final decay products: two muons (turquoise), a neutrino (pink), and four jets of particles. The height of the boxes denotes the amount of energy deposited in the detector in each wedge.



1995, CDF and DØ experiments, Fermilab

History of the Top Quark Discovery

Table 2. History of the search for the top quark at e^+e^- and at hadron colliders. The quoted uncertainties for the top quark mass from the 1995 discovery publications are statistical and systematic uncertainties, respectively

Year	Collider	Particles	References	Limit on m_t
1979–84	PETRA (DESY)	e^+e^-	[50]–[63]	> 23.3 GeV/c^2
1987–90	TRISTAN (KEK)	e^+e^-	[64]–[68]	> 30.2 GeV/c^2
1989–90	SLC (SLAC), LEP (CERN)	e^+e^-	[69]–[72]	> 45.8 GeV/c^2
1984	$Sp\bar{p}S$ (CERN)	$p\bar{p}$	[75]	> 45.0 GeV/c^2
1990	$Sp\bar{p}S$ (CERN)	$p\bar{p}$	[76, 77]	> 69 GeV/c^2
1991	TEVATRON (FNAL)	$p\bar{p}$	[78]–[80]	> 77 GeV/c^2
1992	TEVATRON (FNAL)	$p\bar{p}$	[81, 82]	> 91 GeV/c^2
1994	TEVATRON (FNAL)	$p\bar{p}$	[84, 85]	> 131 GeV/c^2
1995	TEVATRON (FNAL)	$p\bar{p}$	[42]	$= 174 \pm 10^{+13}_{-12}$ GeV/c^2
			[43]	$= 199^{+19}_{-21} \pm 22$ GeV/c^2

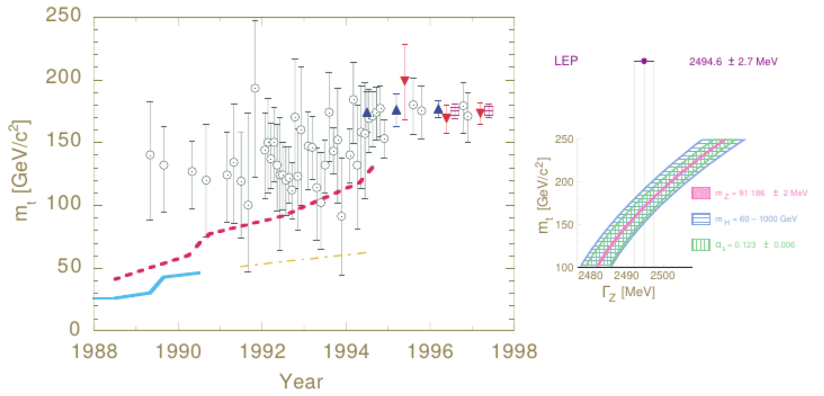
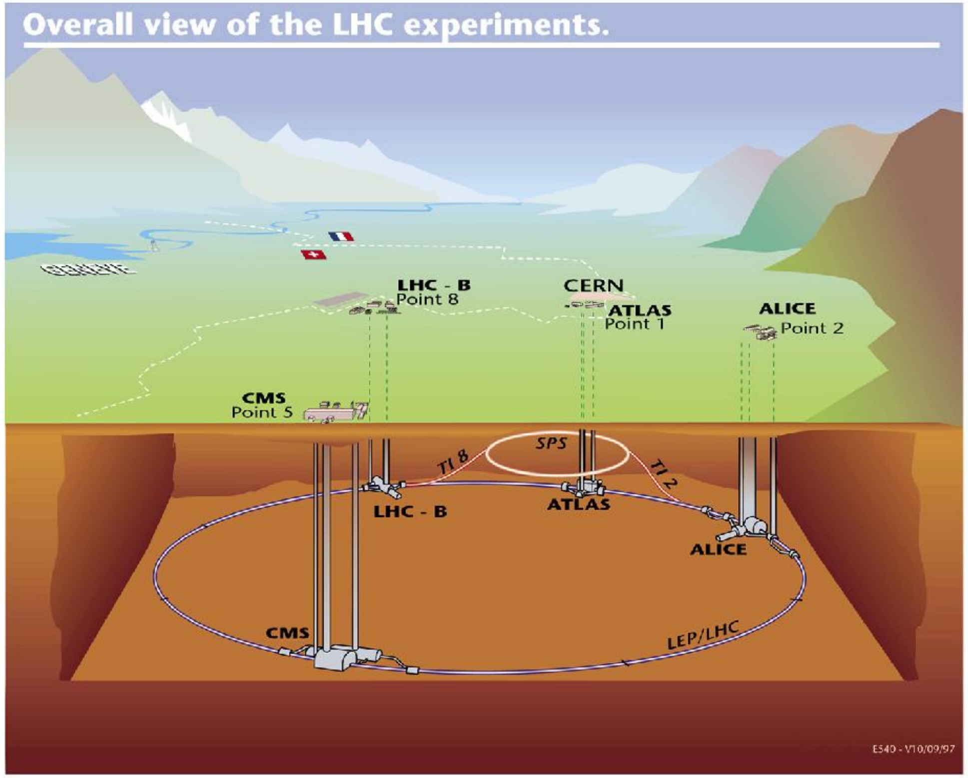


Figure 1: Indirect determinations of the top-quark mass from fits to electroweak observables (open circles) and 95% confidence-level lower bounds on the top-quark mass inferred from direct searches in e^+e^- annihilations (solid line) and in $\bar{p}p$ collisions, assuming that standard decay modes dominate (broken line). An indirect lower bound, derived from the W-boson width inferred from $\bar{p}p \to (W \text{ or } Z) +$ anything, is shown as the dot-dashed line. Direct measurements of m_t by the CDF (triangles) and DØ (inverted triangles) Collaborations are shown at the time of initial evidence, discovery claim, and today. The current world average from direct observations is shown as the crossed box. For sources of data, see Ref. [3]. *Inset:* Electroweak theory predictions for the width of the Z^0 boson as a function of the top-quark mass, compared with the width measured in LEP experiments (Ref. [4]).

Spinger Nature,2007, Vol. 28 ISBN : 978-3-540-71059-2

arXiv:hep-ph/9704332v1

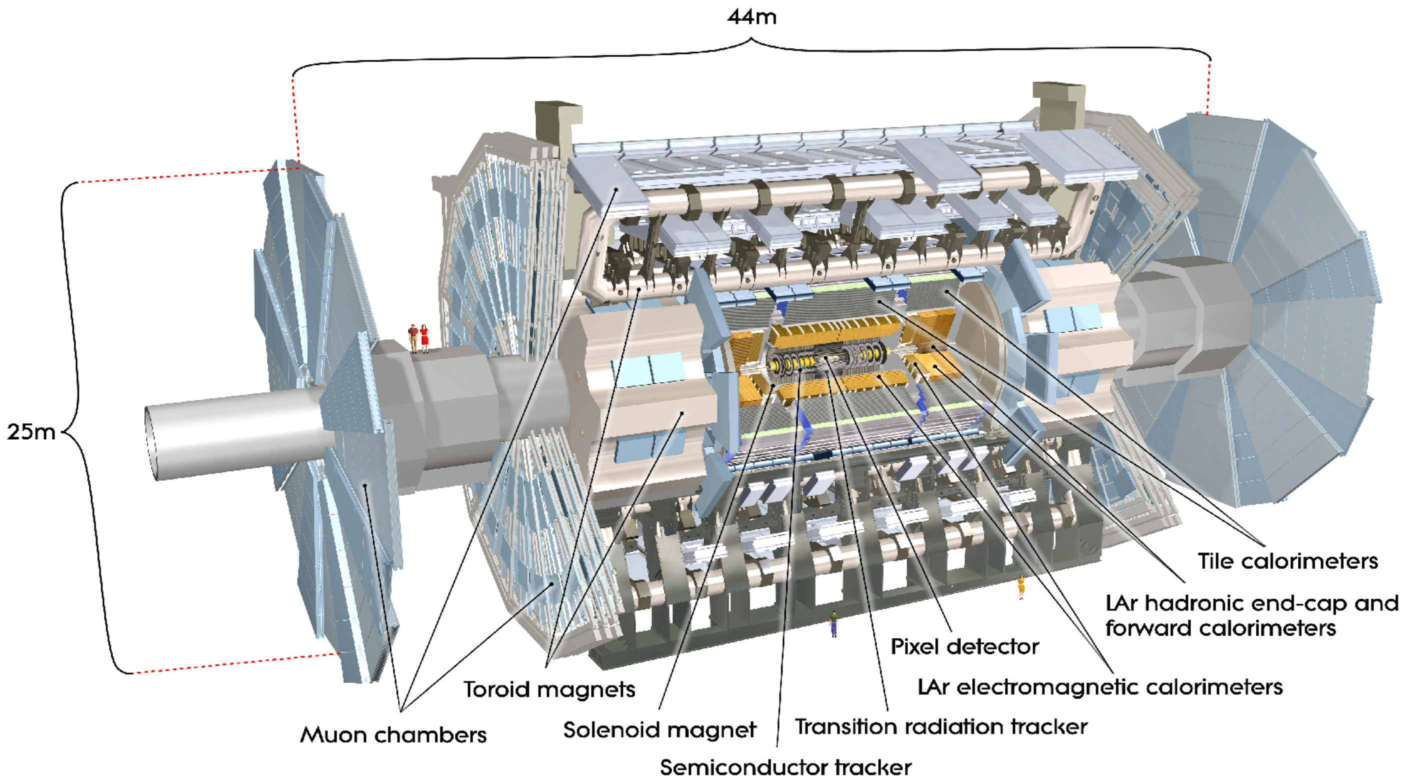
From Tevatron to LHC



	Tevatron	LHC
Location:	Fermilab, USA	CERN, Geneva, CH
Collider name:	Tevatron	Large Hadron Collider (LHC) and High Lumi. Large Hadron Collider (HL-LHC)
Start - end:	1987 - 2011	2008 (restart 2010) - $\sim$ 2035
Collisions:	protons and antiprotons ($p\bar{p}$)	protons-protons (pp)
$\sqrt{s}$:	$1.8\,\mathrm{GeV} \rightarrow 1.96\,\mathrm{GeV}$	$14\,\mathrm{TeV}$ ($7\,\mathrm{TeV}$ - $8\,\mathrm{TeV}$ Run1, $13\,\mathrm{TeV}$ Run2)
Top quark experiments:	**CDF**, **DO**	**ATLAS**, **CMS**

ATLAS Detector at LHC

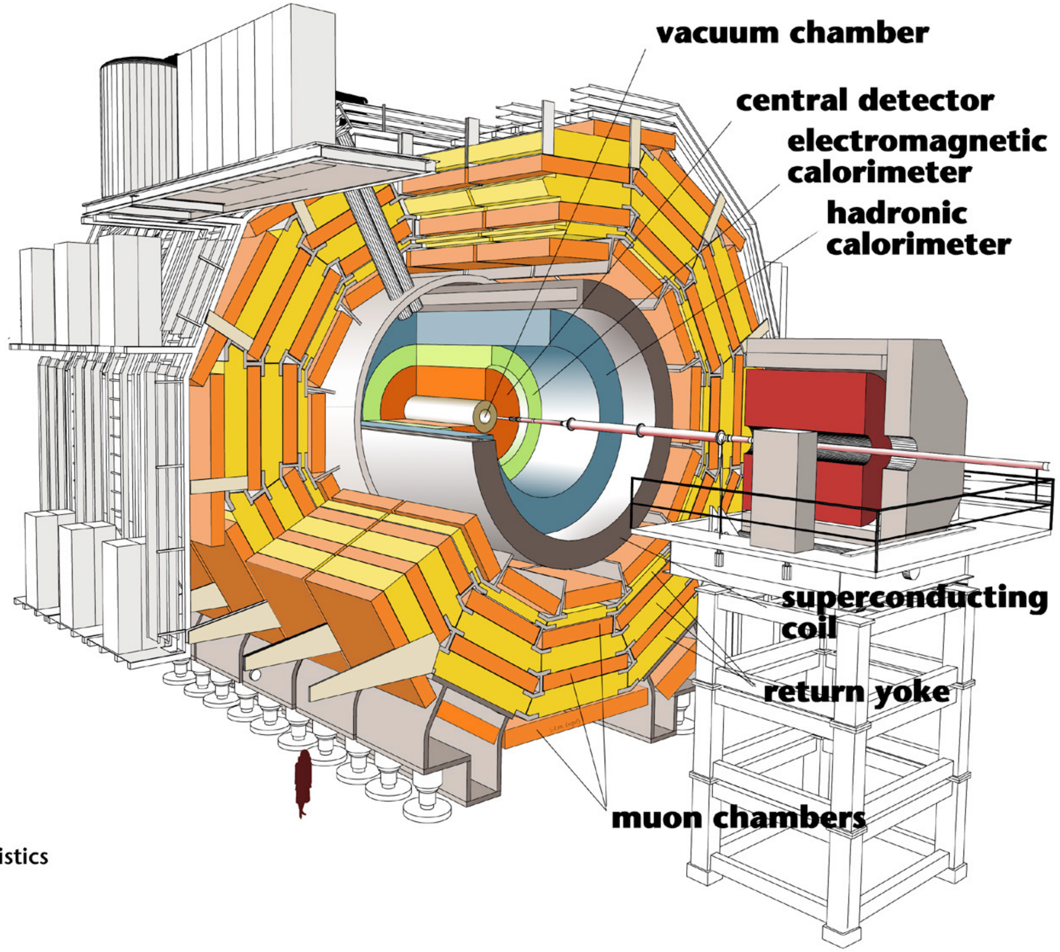
- **A T**oroidal **L**HC **A**pparatu**S** (**A**TLAS), at the (**L**HC): layout and detectors



- Overall weight 7000 Tonnes
- 40 Countries + CERN, 180 Institutions
- About 2700 scientific authors
- $\sim$ 1200 PhD students and $\sim$ 520 Master / Diploma students

CMS Detector at LHC

- **C**ompact **M**uon **S**olenoid (**C**MS), at the (**L**HC): layout and detectors



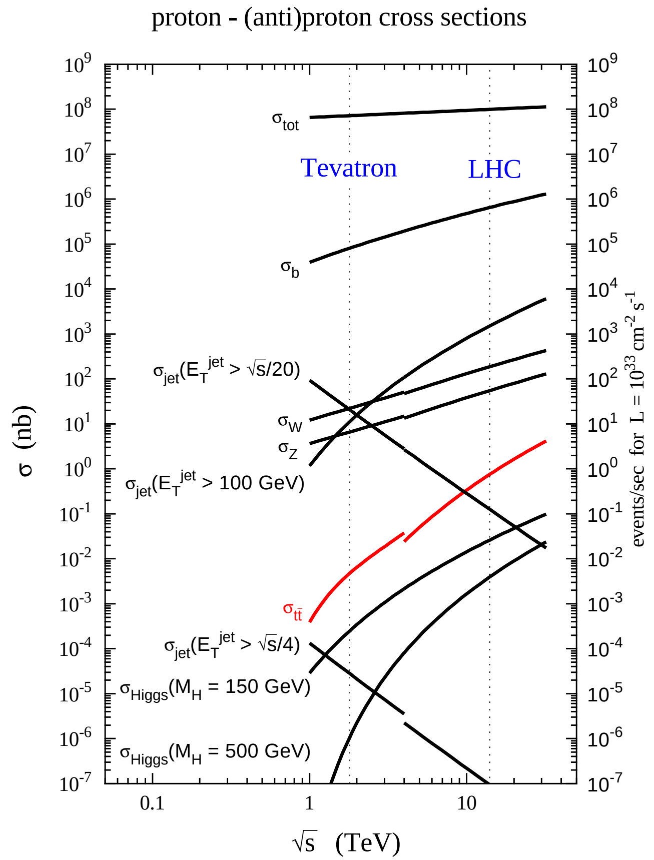
Detector characteristics

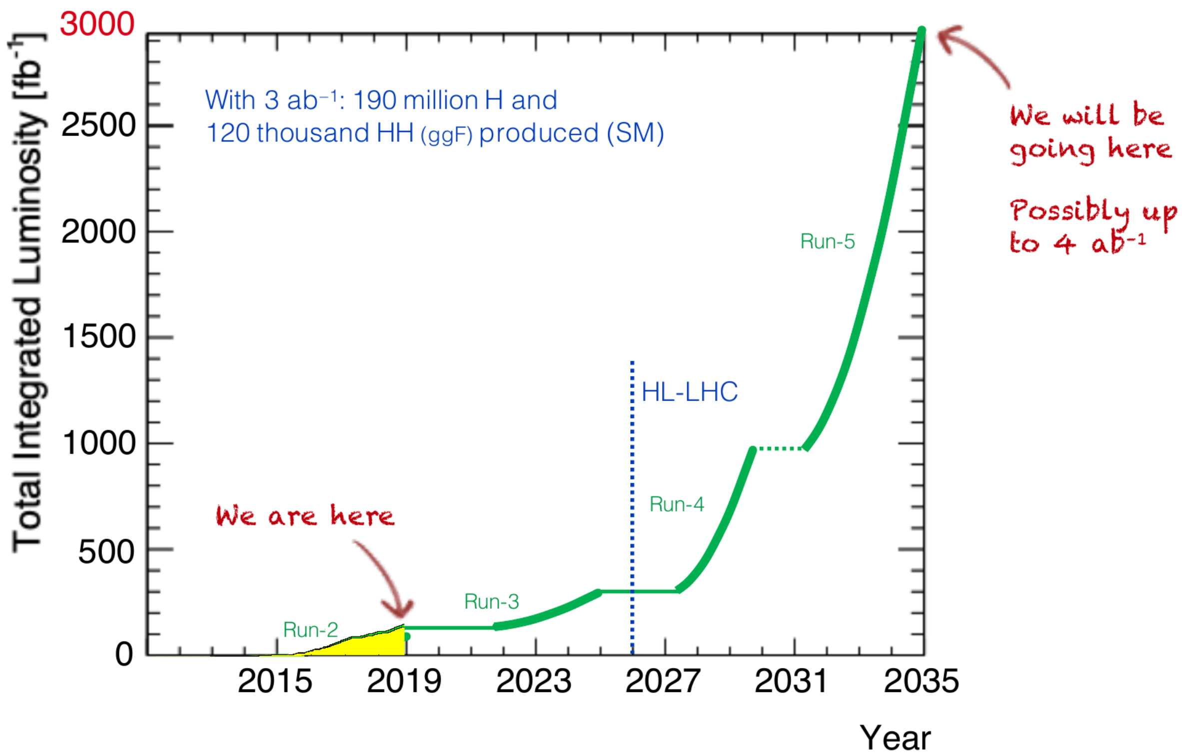
Width: 22m
Diameter: 15m
Weight: 14'500t

- 50 Countries + CERN, 200 Institutions
- About 5000 particle physicists, engineers, technicians, students and support staff

Top quark @ LHC

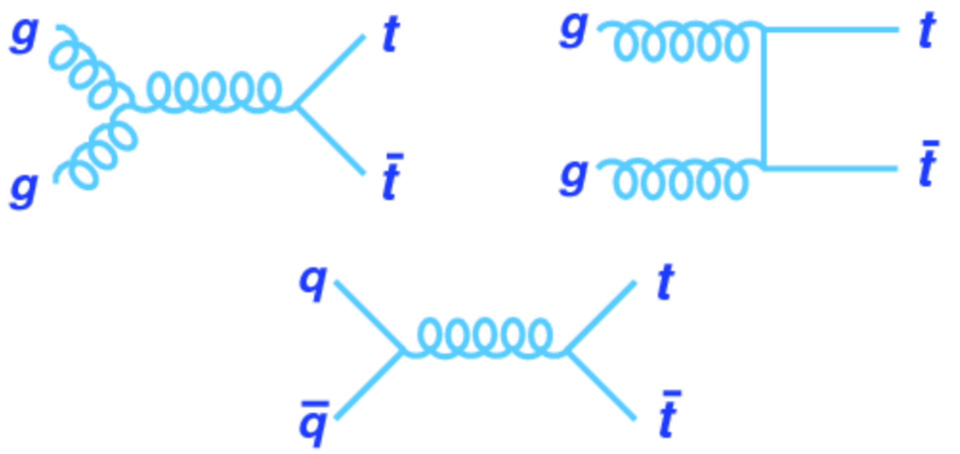
- LHC (and the HL-LHC) is a top quark factory
- Total cross section for $t\bar{t}$-production is about a factor of 100 larger at LHC than at Tevatron (figure down-left)
- $\sigma_{t\bar{t}}(14.0\,\mathrm{TeV}) = 800\,\mathrm{pb}$: $2\,t\bar{t}$ events per second
- Perfect place for m_{top} precision measurements
- Huge additional potential still to come





Top quark production @ LHC

- Production mechanisms at LHC
  - ⋆ Top quarks produced in pairs ($t\bar{t}$) through the strong interaction: gluon-gluon fusion dominant $t\bar{t}$ production process at LHC ($\sim 85\%$) and quark-anti quark annihilation ($\sim 15\%$). See top-right Feynman diagrams @ LO
  - ⋆ Single top production possible by virtue of the electroweak interaction, with a smaller production cross-section; t-channel and tW production processes dominant at the LHC. See bottom-right Feynman diagrams @ LO



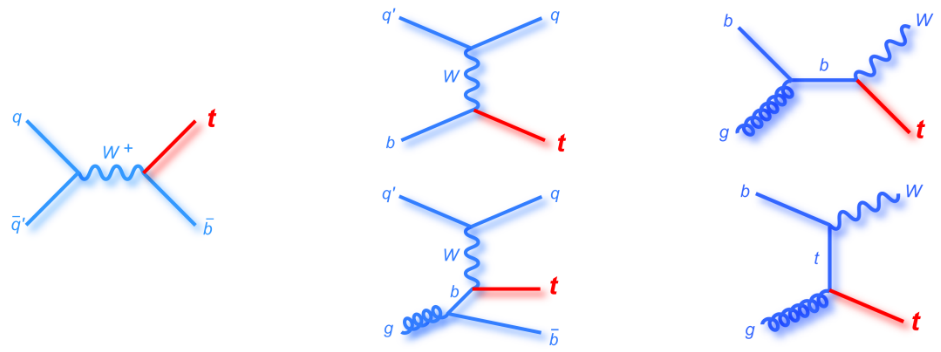
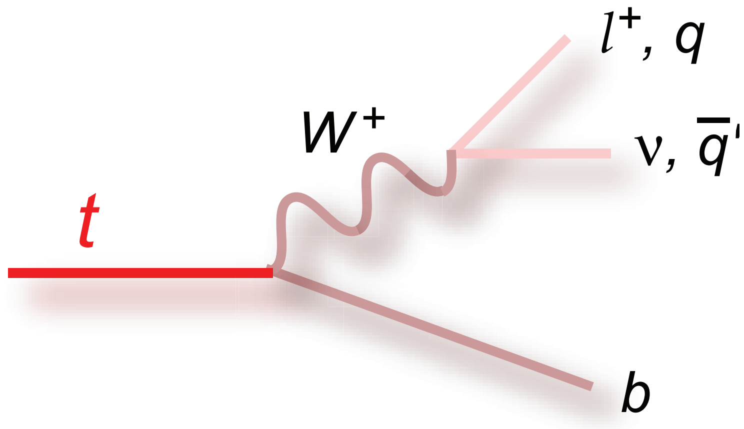


Figure 1 – Feynman diagrams of single top quark production for s-channel (left), t-channel (center) and tW production (right) respectively

Top quark physics

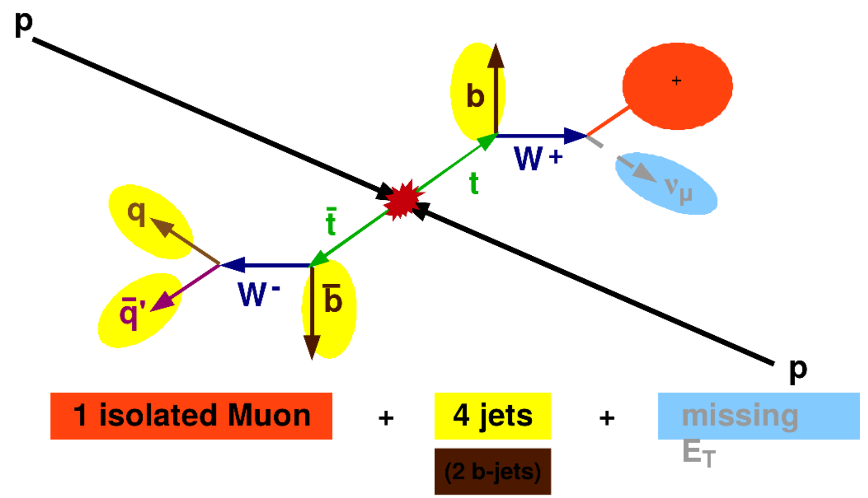
- **Top proprieties**
  - ⋆ Mass, width, charge, spin, ...
- **Top production**
  - ⋆ $t\bar{t}$ cross-section, production dynamics, spin polarization
- **Top decay**
  - ⋆ V_{tb}, brancing ratios, rare decays, W helicity



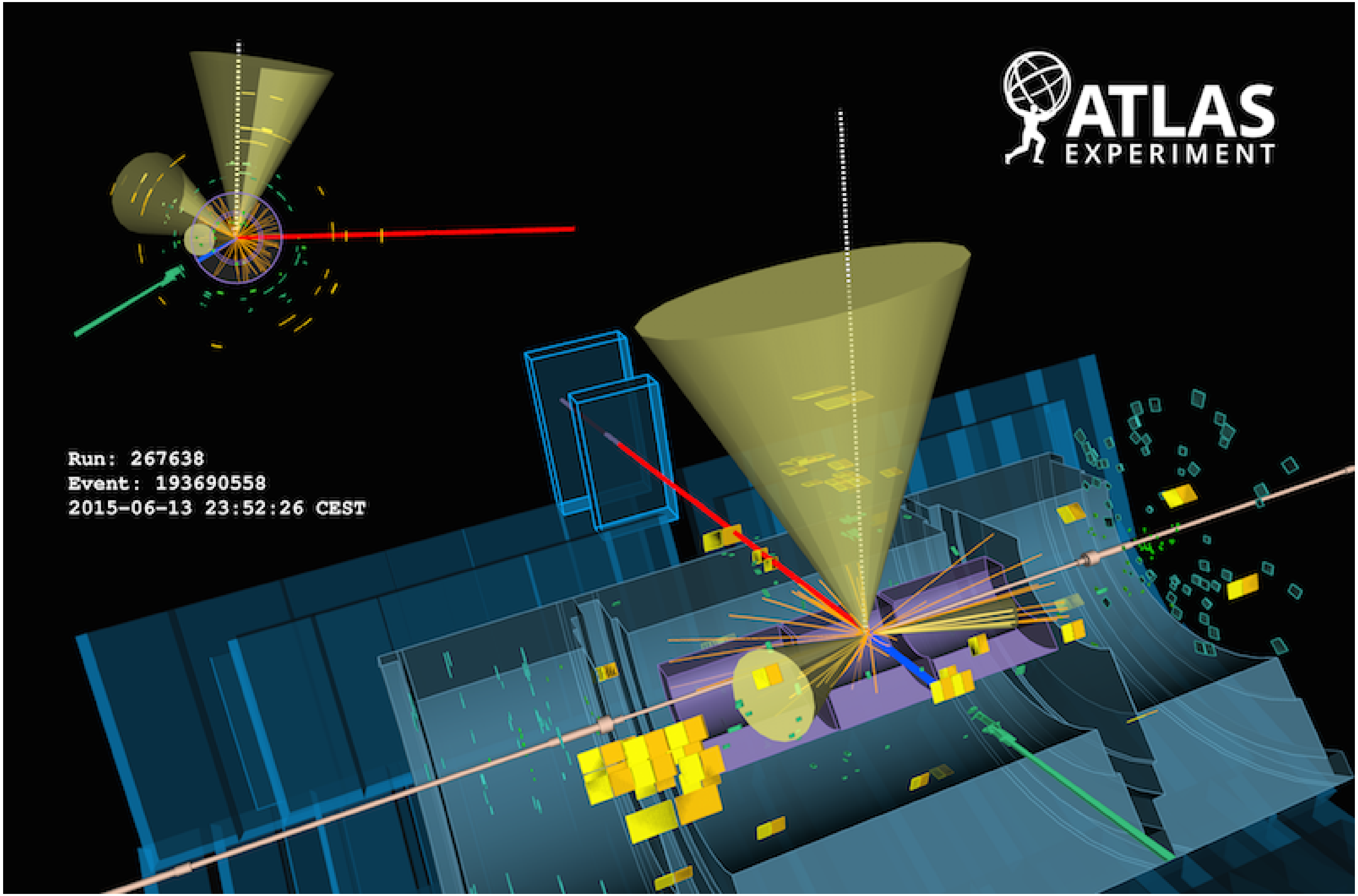
- Top quark allows tests of the participating forces
- Top quark plays an important role in the search for new physics beyond the SM (BSM) (new particles decaying to top quark)
- Top quark events are background to many physics processes

Top quark reconstruction

- 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}
- Top quarks events can be used to understand the performance of the detector
- Reconstruct $t\bar{t}$ events in data and Monte Carlo (MC) events using e.g. kinematics fits



A $t\bar{t}$ candidate event at 13 TeV in ATLAS @ LHC



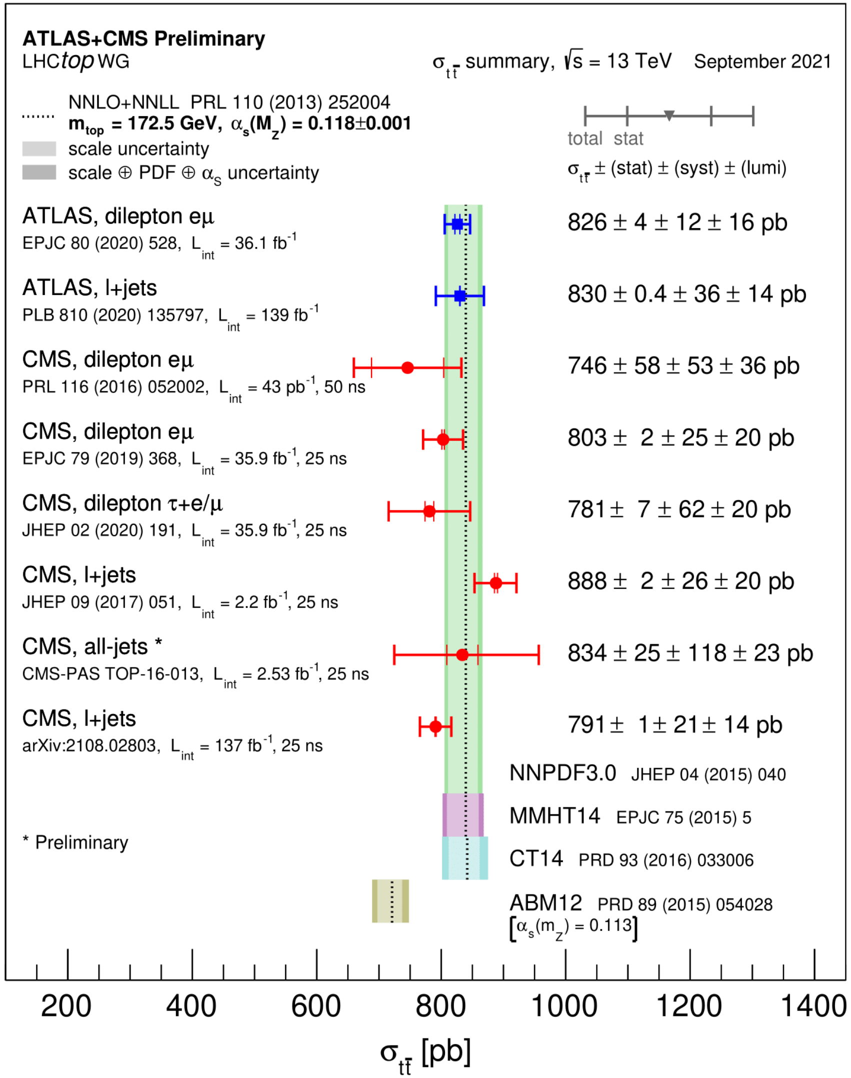
Top quark cross-section

- Cross-section measurements conceptually simple to measure, though the devil is in the details

$$\sigma = \frac{N_{meas} - N_{bkg}}{\mathcal{L}\, A\, \epsilon}$$

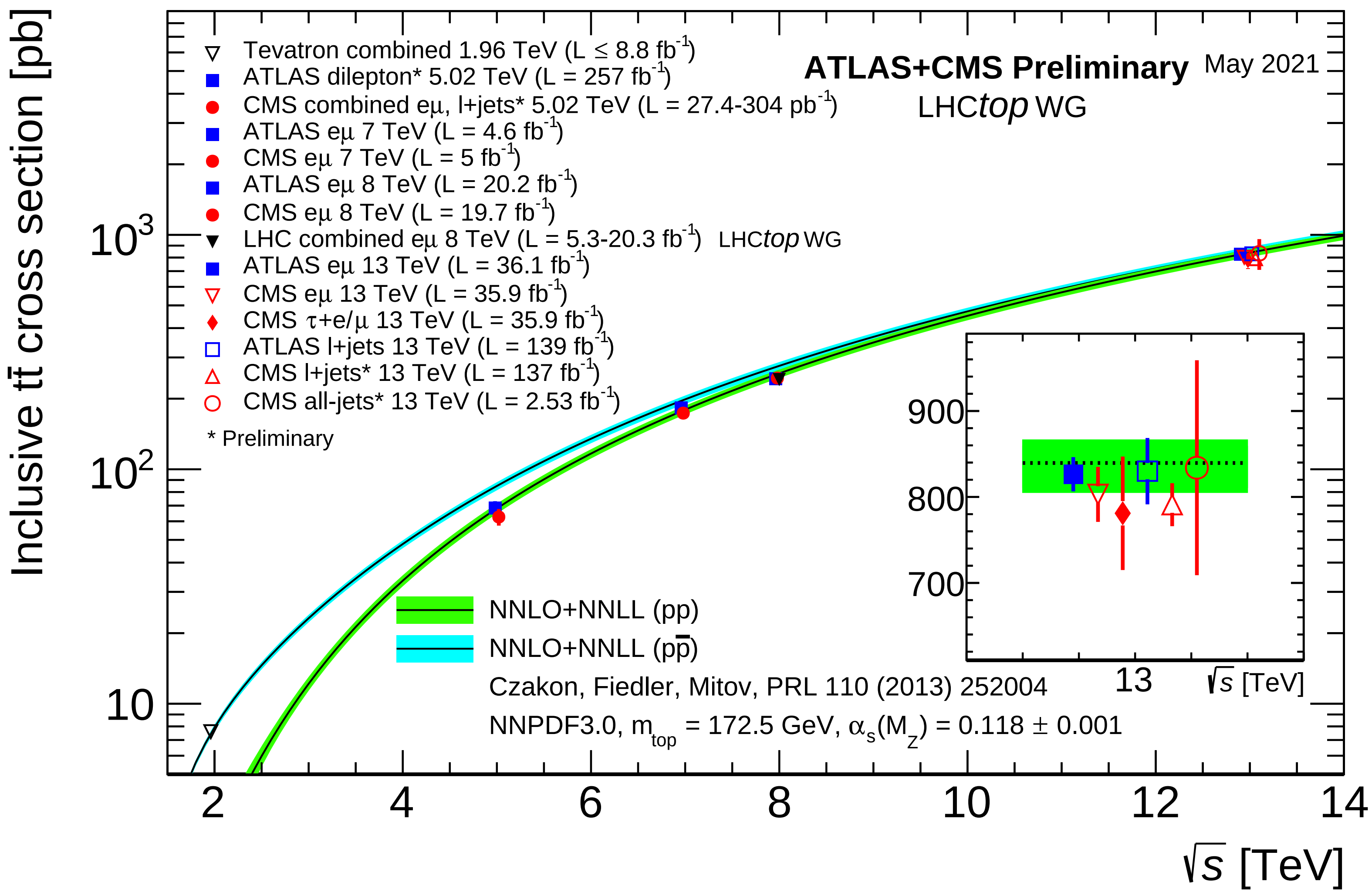
- Where: N_{meas} number of measured events, N_{bkg} number of background events from data driven methods or MC, $\mathcal{L}$ measured integrated luminosity, A and ϵ are the detector acceptance obtained with MC and the trigger efficiency

- Measured cross sections are compared with the predictions, to test models, e.g. the SM



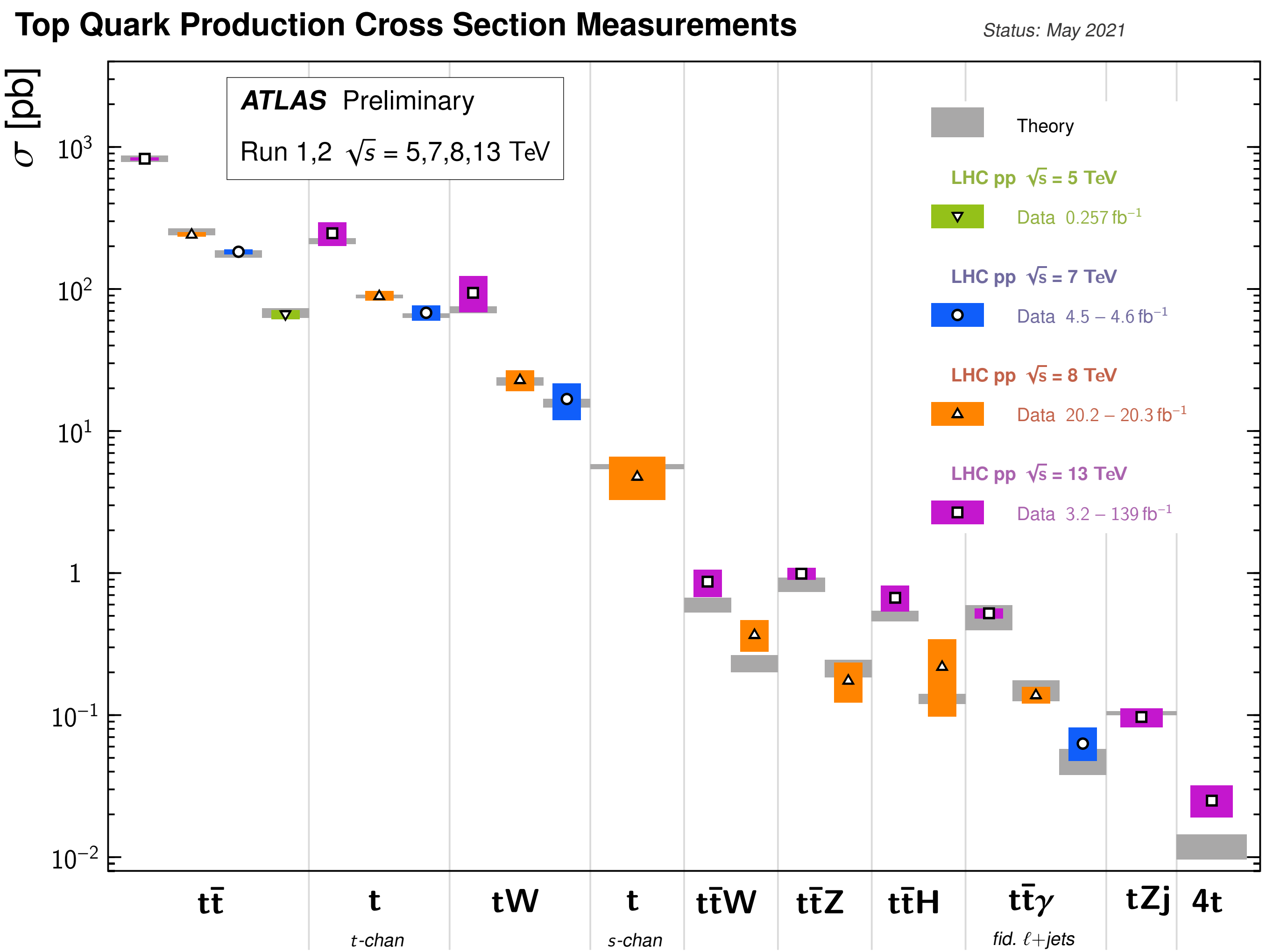
Top quark cross-section @ Tevatron and LHC

- Figure shows LHC & Tevatron $t\bar{t}$ cross-section measurements compared to the NNLO QCD calculation and NNLL resummation



Top quark cross-section in ATLAS

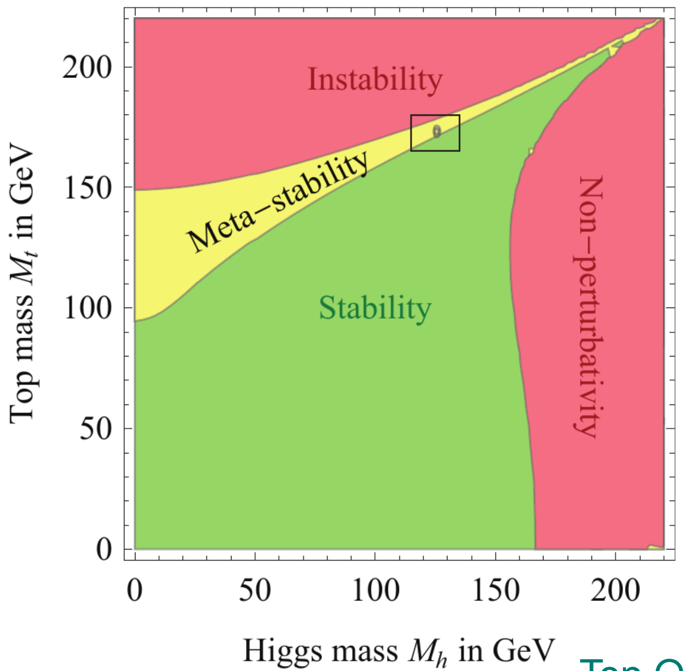
- Figure shows top-quark cross-section measurements compared to theoretical. expectation (NLO or higher)



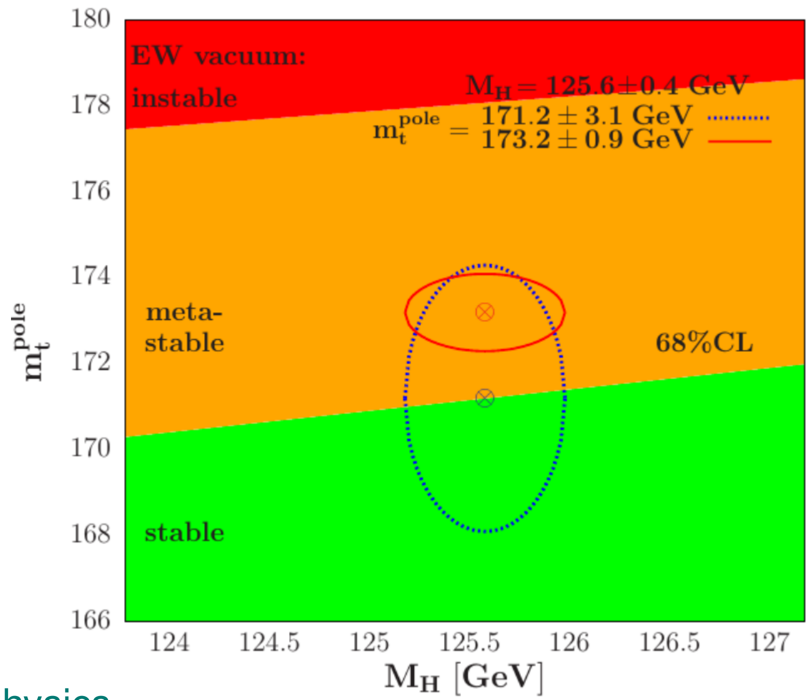
Top quark mass

- The top-quark mass, m_{top}, is a fundamental parameter of the Standard Model (SM)
- Precise determinations of the SM parameters (m_{top}, m_W, m_H, ...) 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, $m_{top}^{pole} - m_H$, plane; (right) ellipses for the $1\,\sigma$ uncertainties in the $m_{top}^{pole} - m_H$ plane confronted with the SM vacuum expectations;

arXiv:1205.6497v2



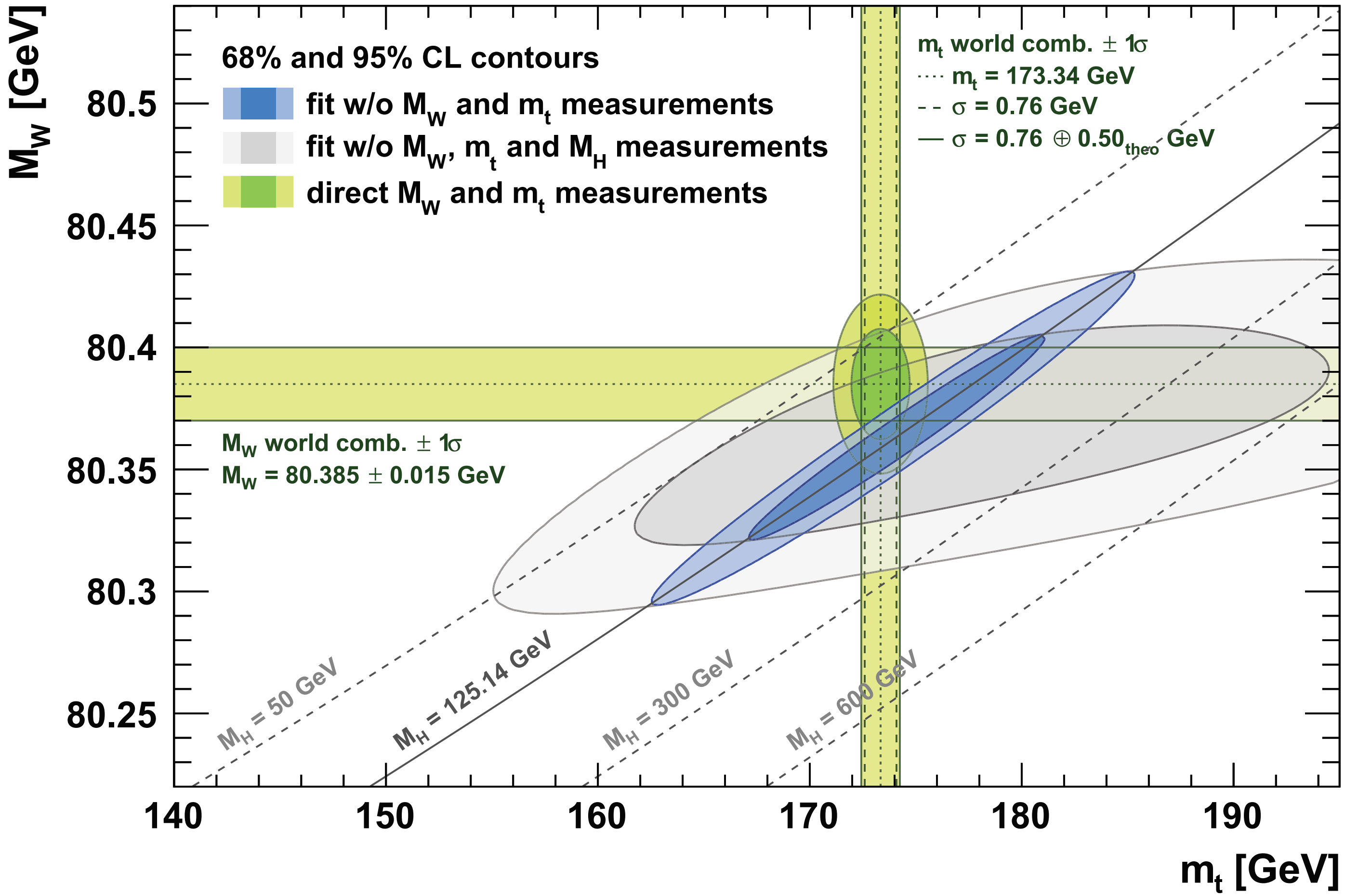
arXiv.1207.0980v3



Electroweak fits

- Plot show: electroweak fits at NNLO: contours at 68% and 95% CL obtained from scans of mass of the W, m_W, versus m_{top}

arXiv:1407.3792v1

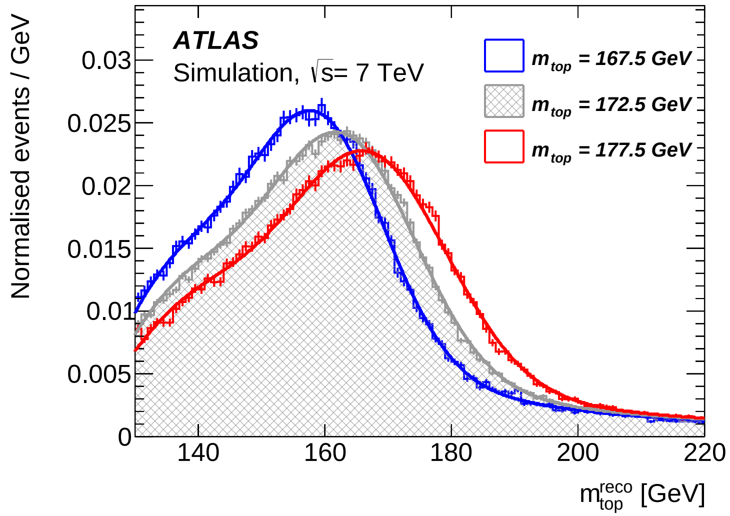


Top-quark mass measurements

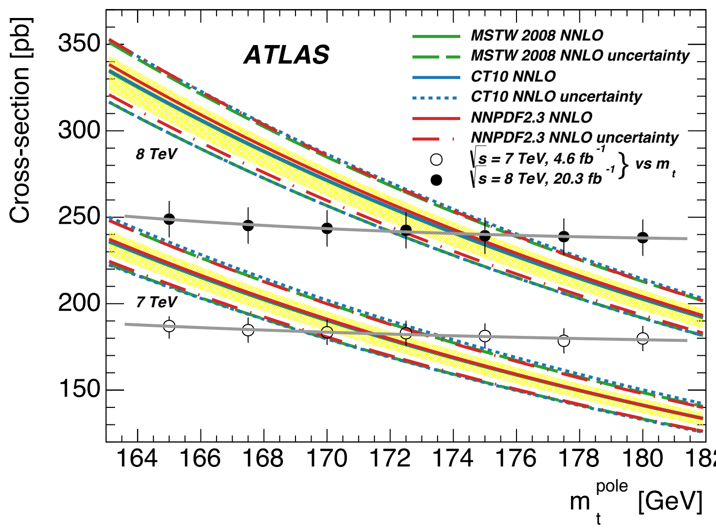
- Direct m_{top} measurements:
  - ⋆ Reconstruct $t\bar{t}$ events in data and MC
  - ⋆ Reduce backgrounds to obtain a clean sample
  - ⋆ Reconstruct the final state
  - ⋆ Use sophisticated technique to extract the m_{top}, using e.g. a kinematic fit

- 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}

Eur. Phys. J. C75 (2015) 330



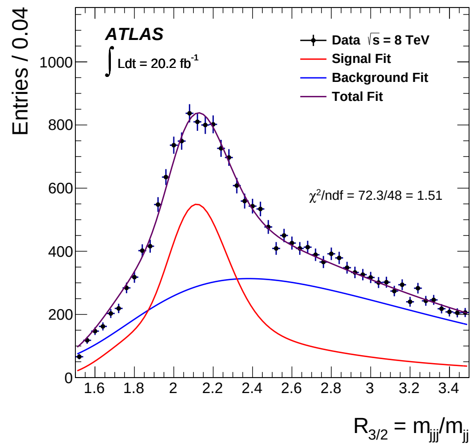
Eur. Phys. J. C74 (2014) 3109

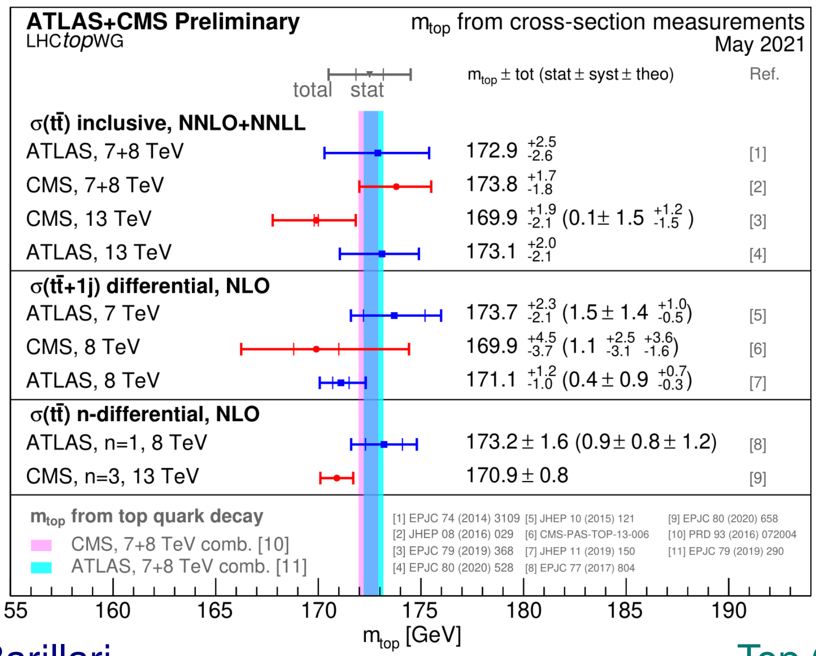


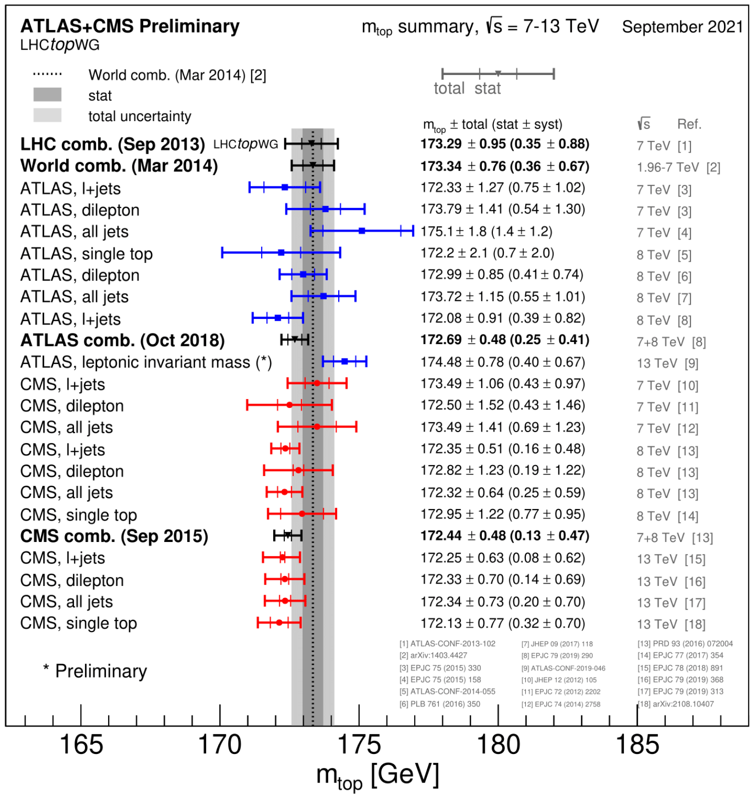
Top quark mass summary

- Direct m_{top} measurements
  - ★ Most precise from LHC combinations
  - ★ ATLAS: $m_{top} = 172.69 \pm 0.48_{tot}$ GeV
  - ★ CMS: $m_{top} = 172.44 \pm 0.48_{tot}$ GeV
- Indirect m_{top} measurements
  - ★ Most precise from CMS @ 13 TeV
  - ★ CMS: $m_{top}^{pole} = 170.9 \pm 0.8_{tot}$ GeV
  - ★ ATLAS: $m_{top}^{pole} = 171.2^{+1.2}_{-1.0\,tot}$ GeV

JHEP 09 (2017) 118

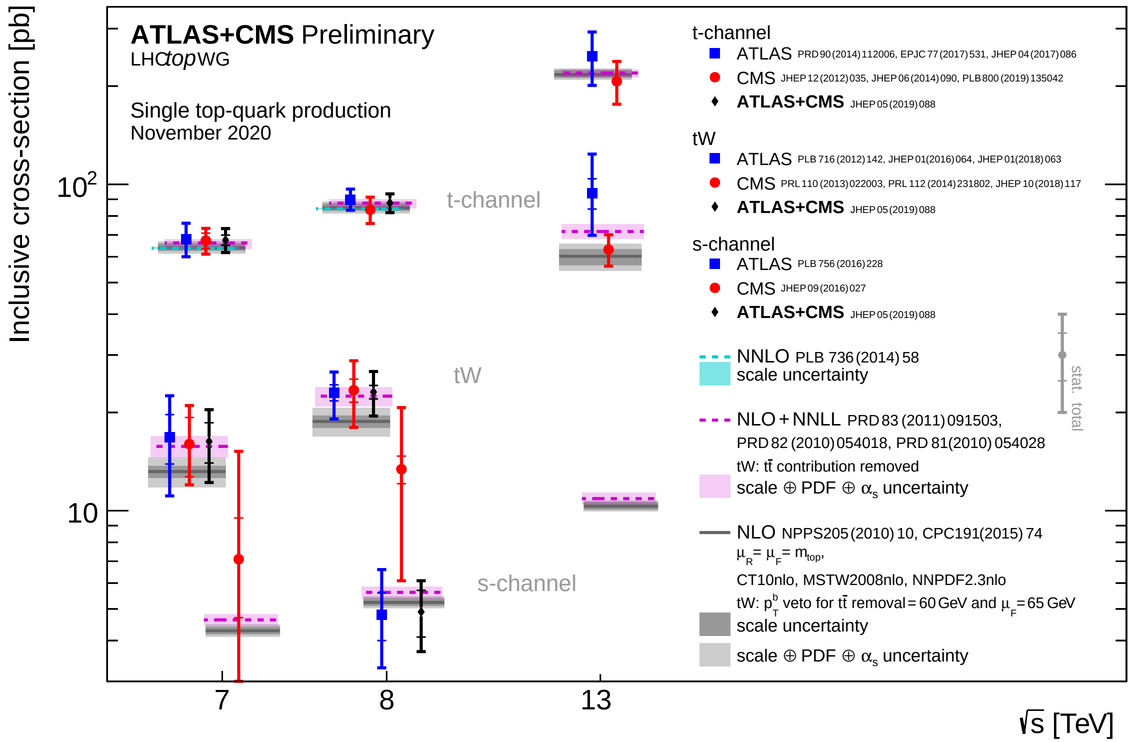






Single top production summary

- Cross-section similar or much smaller than the one for the top-quark pairs ($t\bar{t}$ cross-section), much more difficult to distinguish from the background
- It needs sophisticated analysis, e.g. boosted decision trees
- Can be used to measure $|V_{tb}|$
  - ⋆ Example: $|V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo.}(V_{tb}=1)}}$
  - ⋆ $|V_{tb}| = 1.02 \pm 0.4(\text{meas.}) \pm 0.02(\text{theo.})$, see JHEP 05 (2019) 088.



Conclusions

- Top quark predicted for long time and discovered at the Fermilab Tevatron
- Top quark has a large mass, after Higgs discovery test consistency, can be a link to physics BSM
- Since the discovery with few events, top quark physics evolved into precision physics @ LHC
- Direct m_{top} measurements reached $\mathcal{O}(0.5\,\mathrm{GeV})$ precision
- Indirect m_{top}^{pole} measurements reached $\mathcal{O}(0.8\,\mathrm{GeV})$ precision
- So far no tension between the results
- Many analyses using data at $13\,\mathrm{TeV}$ @ LHC in preparation, using different and alternative reconstruction methods
- Huge additional potential still to come