Nikhef

Topical Lectures

Dr Clara Nellist

(she/her)

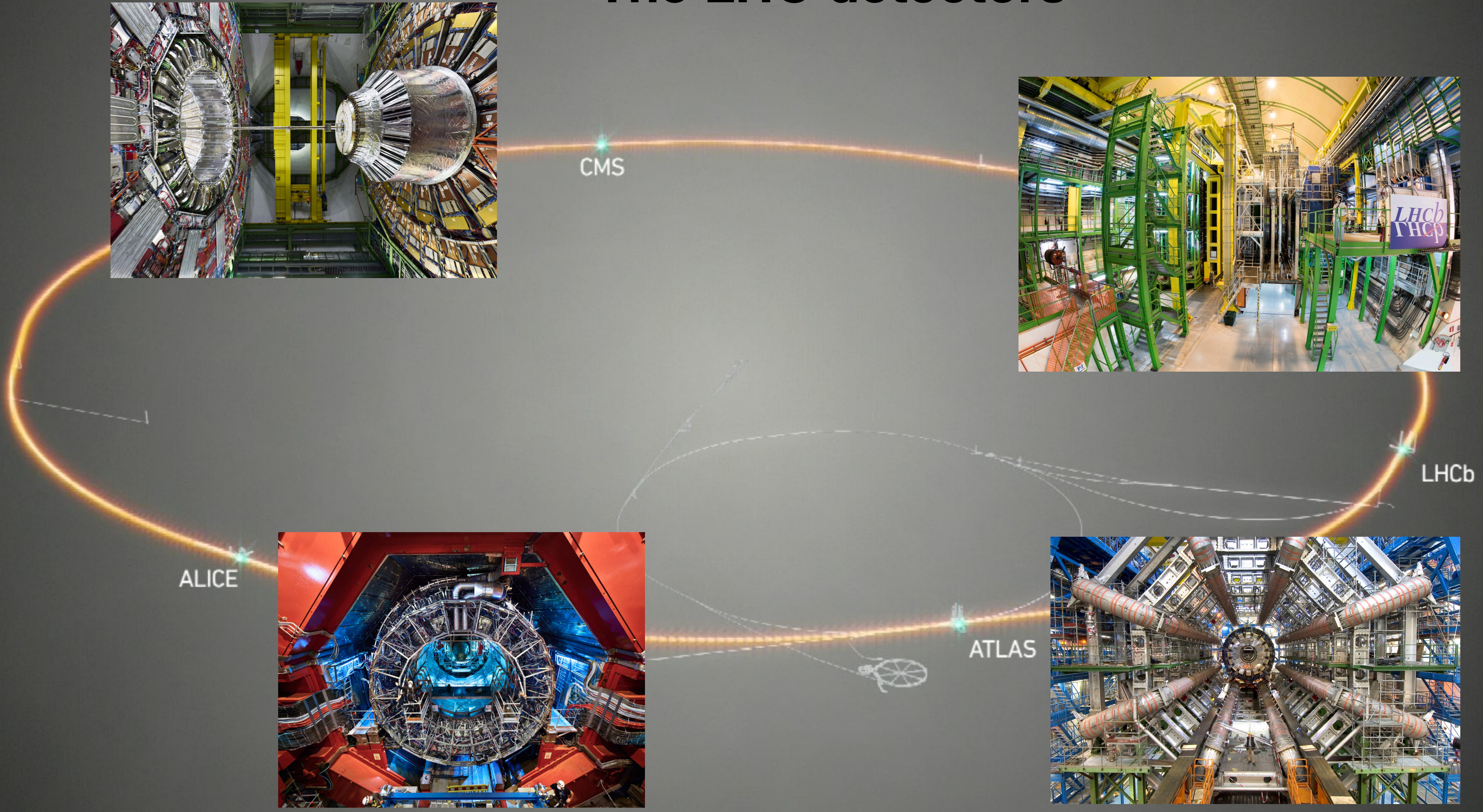
ATLAS EXPERIMENT

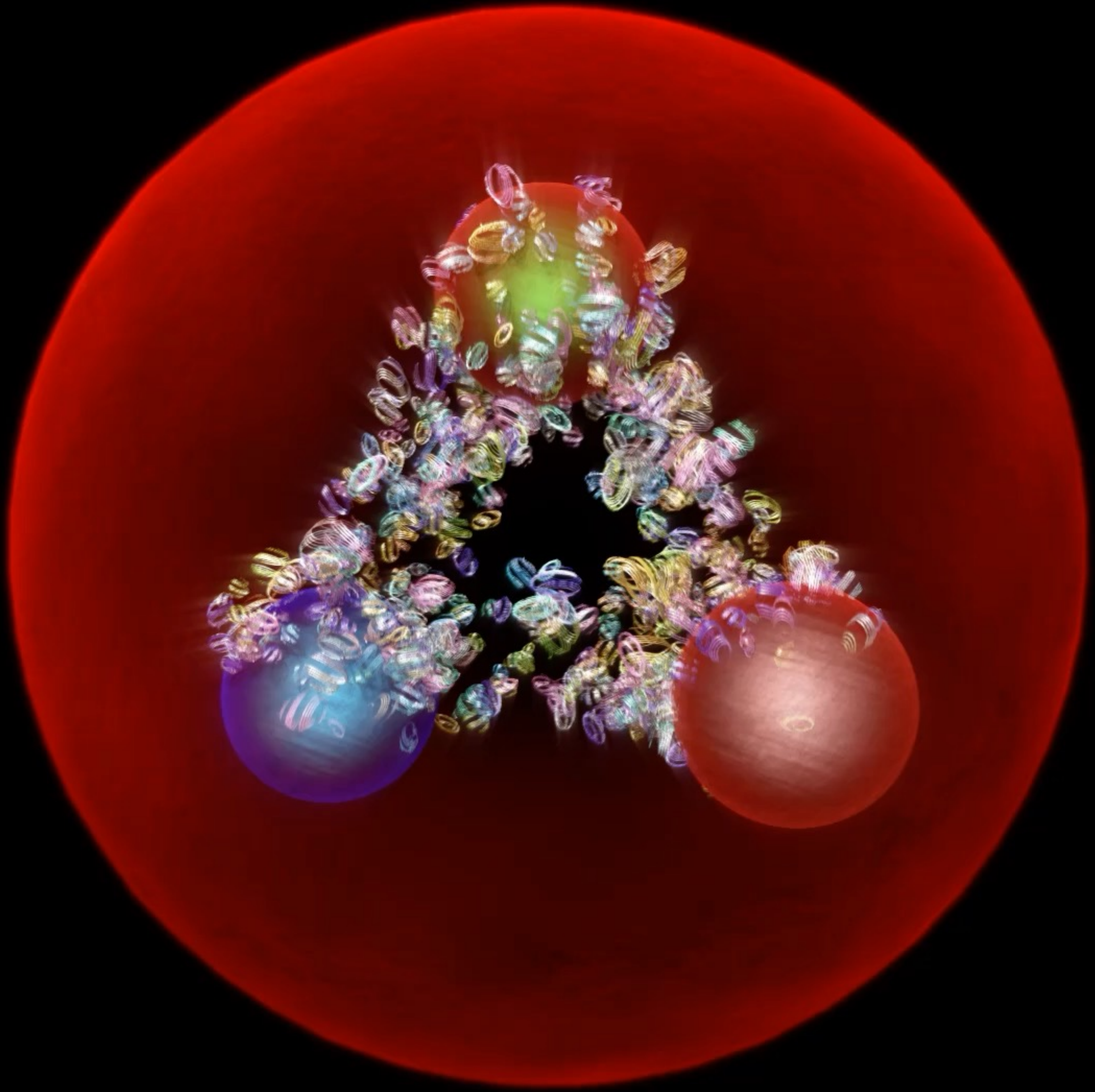
Universiteit van Amsterdam

Objective

- Want to give you an experimental overview of the top quark and why it's interesting (in < 1 hour!)
- Focus on the what we learn from studying the top quark at the LHC.
  - Won't go into the full details of the selections for every analysis.
  - Won't go into every kind of measurement.

The LHC detectors

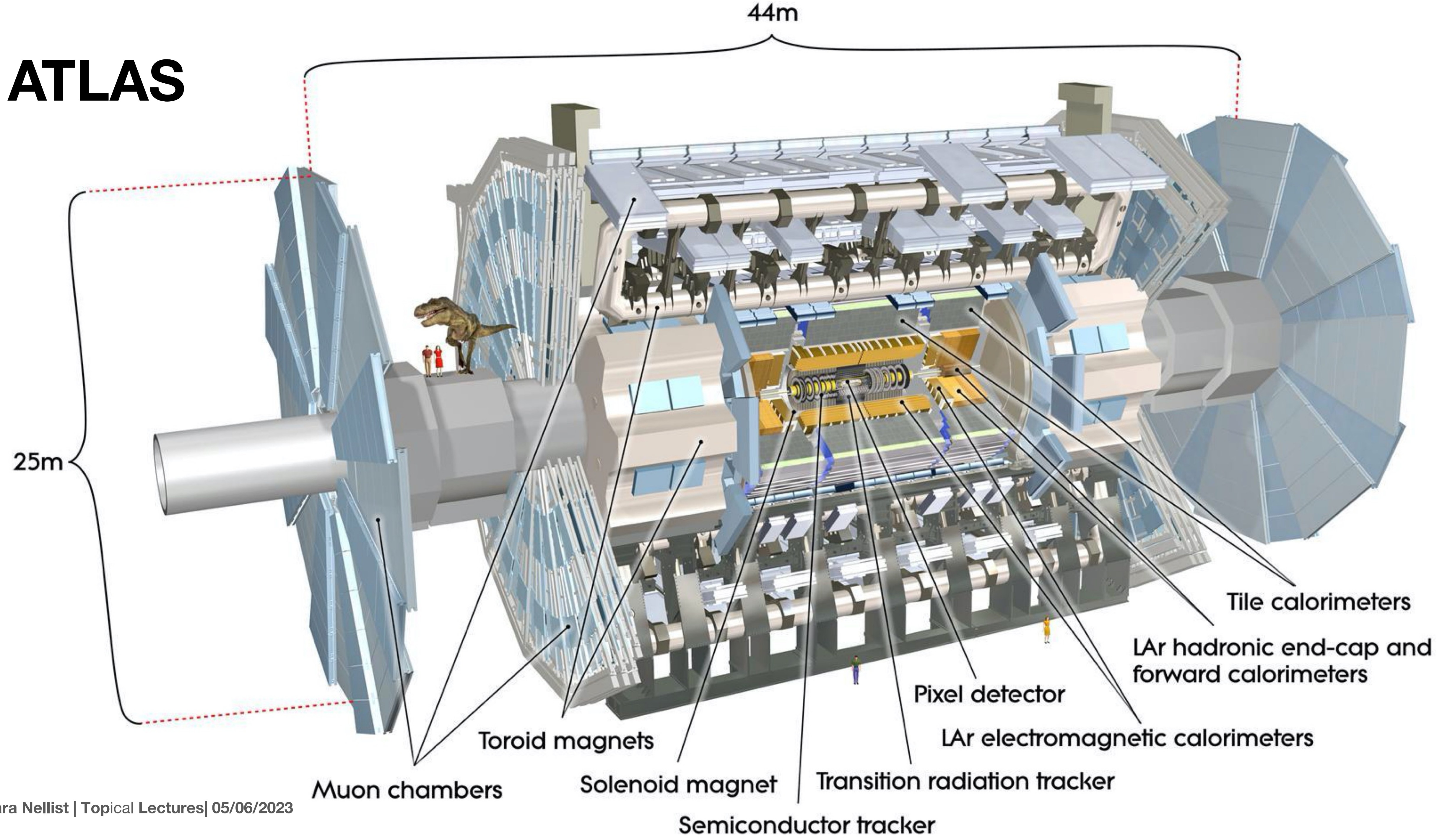




Colliding protons

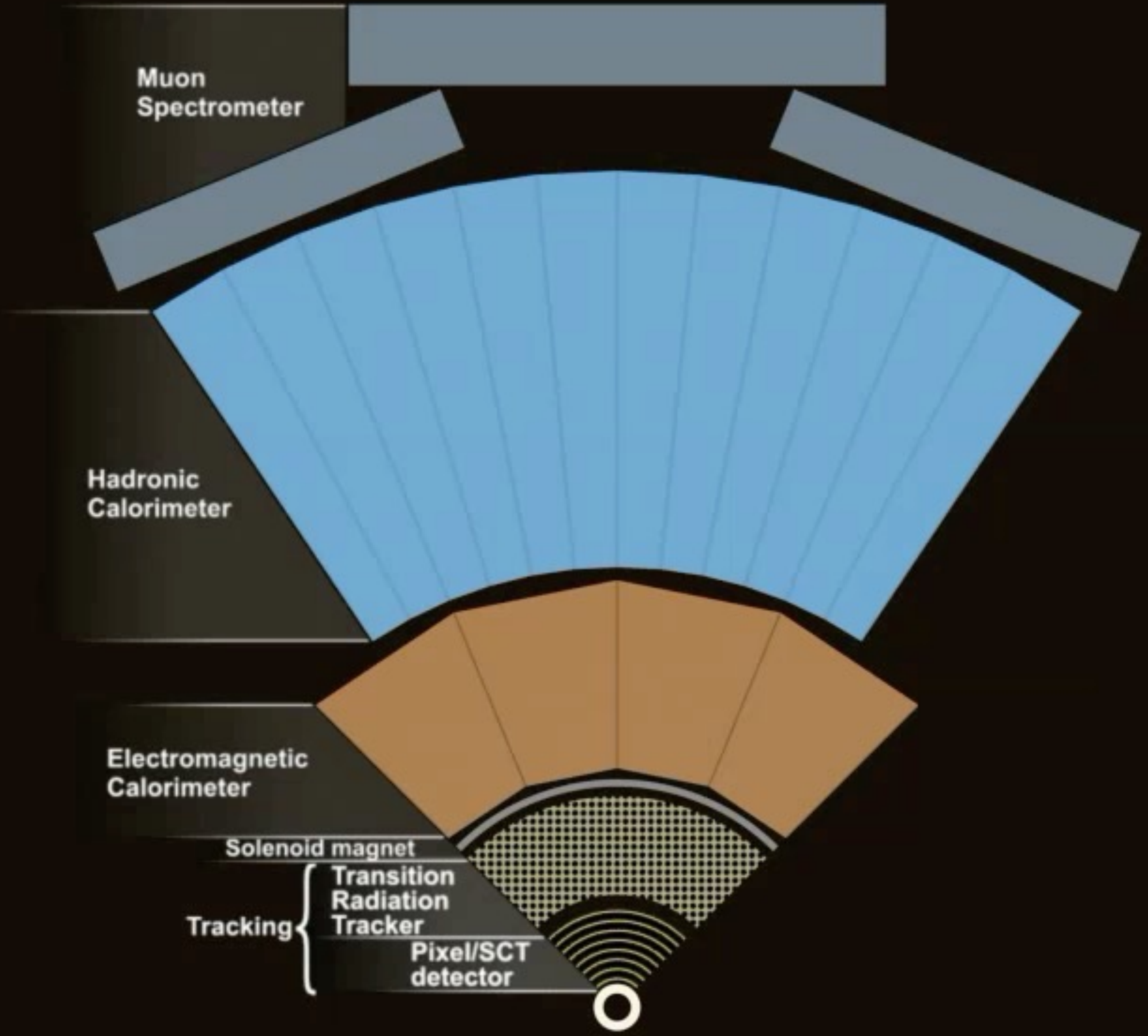
We wanted to explore a high range of masses: from 50 GeV to 1 TeV

ATLAS



44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

ATLAS Installation in the cavern 2004


Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector

Status: November 2018

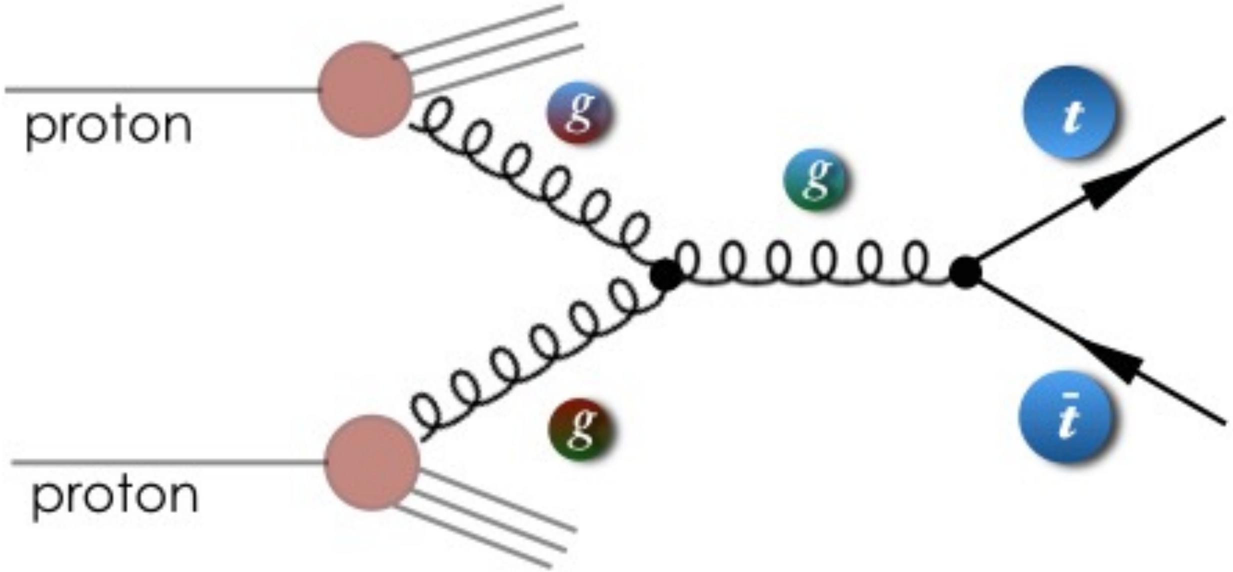
Albania
Algeria
Argentina
Armenia
Australia
Austria
Azerbaijan
Bangladesh
Belarus
Belgium
Bosnia and Herzegovina
Botswana
Brazil
Bulgaria
Burundi
Canada
Chile
China
Colombia
Costa Rica
Croatia
Cuba
Cyprus
Czech Republic
Denmark
Ecuador
Egypt
Finland
France
Georgia
Germany
Ghana
Greece
Honduras
Hong Kong
Hungary
Iceland
India
Indonesia
Iran
Iraq
Ireland
Israel
Italy
Japan
Jordan
Kazakhstan
Kenya
Kyrgyzstan
Latvia
Lebanon
Lithuania
Luxembourg
Madagascar
Malaysia
Malta
Mauritius
Mexico
Mongolia
Montenegro
Morocco
Nepal
Netherlands
New Zealand
Niger
Nigeria
Norway
Pakistan
Palestine
Peru
Philippines
Poland
Portugal
Romania
Russia
Saudi Arabia
Senegal
Serbia
Slovakia
Slovenia
South Africa
South Korea
Spain
Sri Lanka
Sudan
Swaziland
Sweden
Switzerland
Syria
Taiwan
Thailand
Tunisia
Turkey
Ukraine
UAE
UK
USA
Uruguay
Uzbekistan
Venezuela
Vietnam
Zambia
Zimbabwe

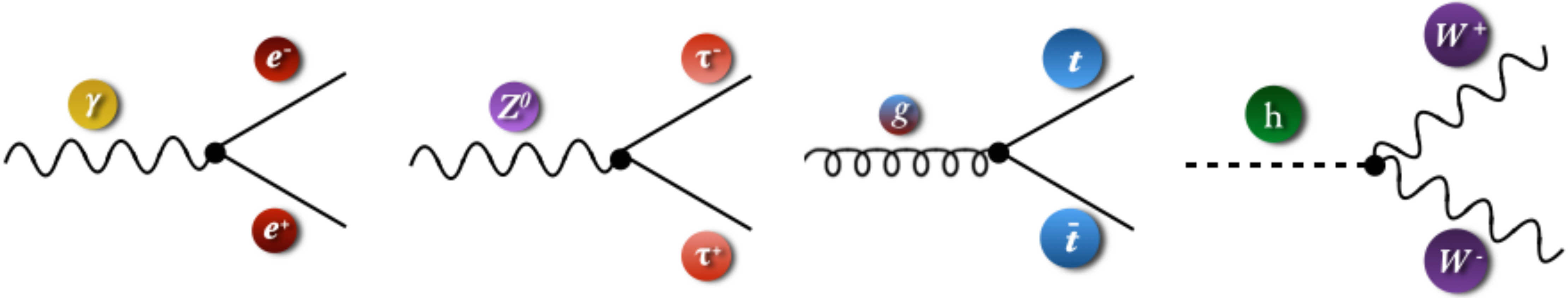
ATLAS Collaboration member nationalities

Over 5500 members of 103 nationalities

ATLAS EXPERIMENT

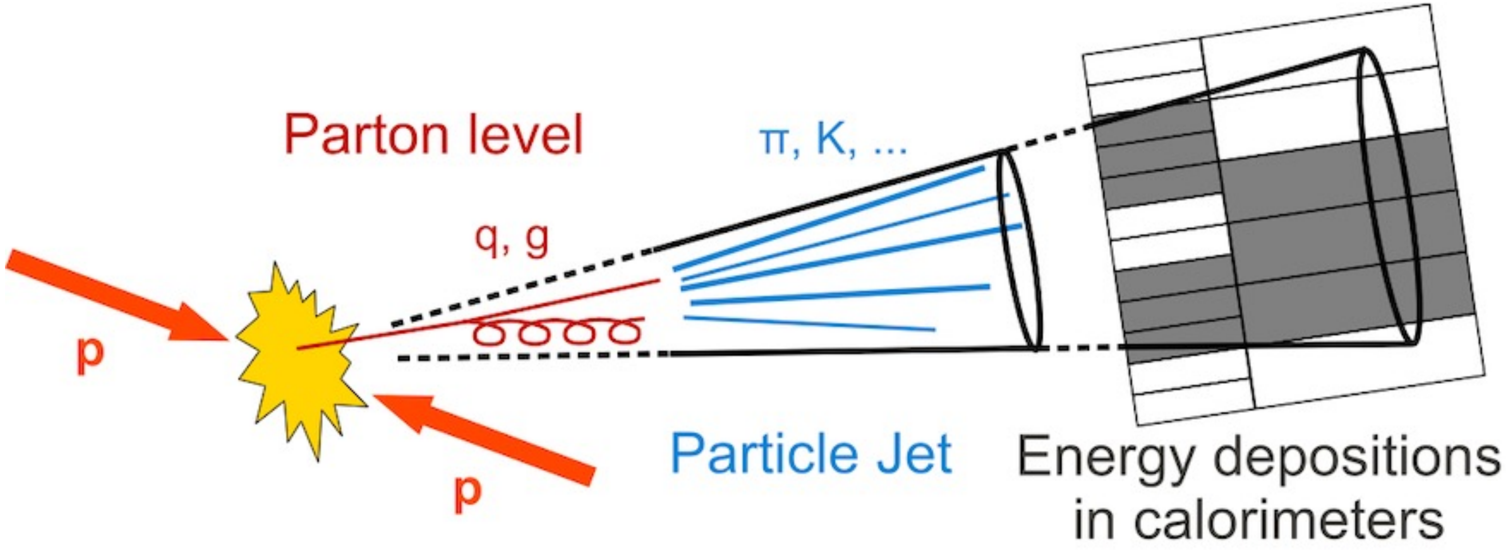
What is a Feynman diagram?



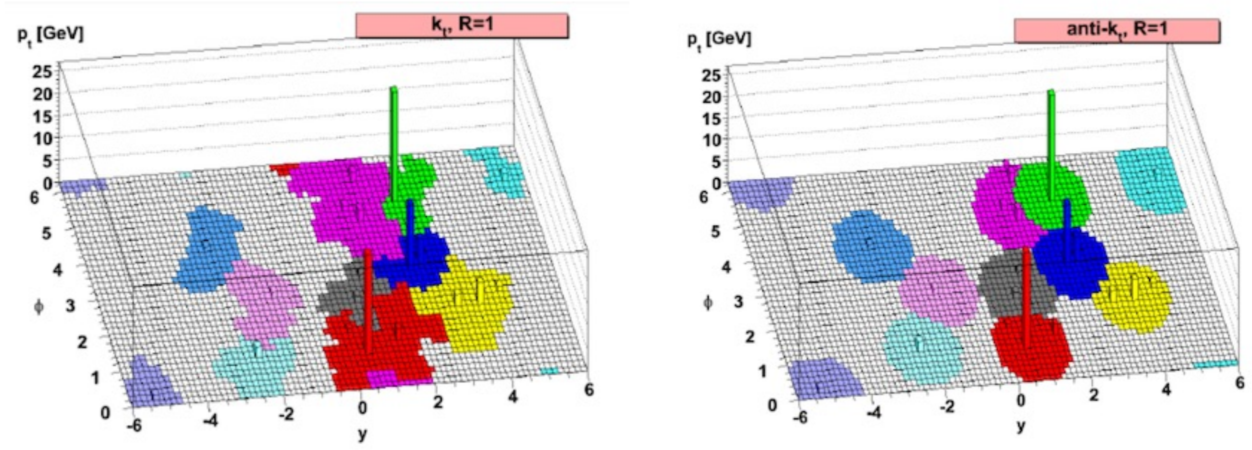


Images: T. G. McCarthy

Jets



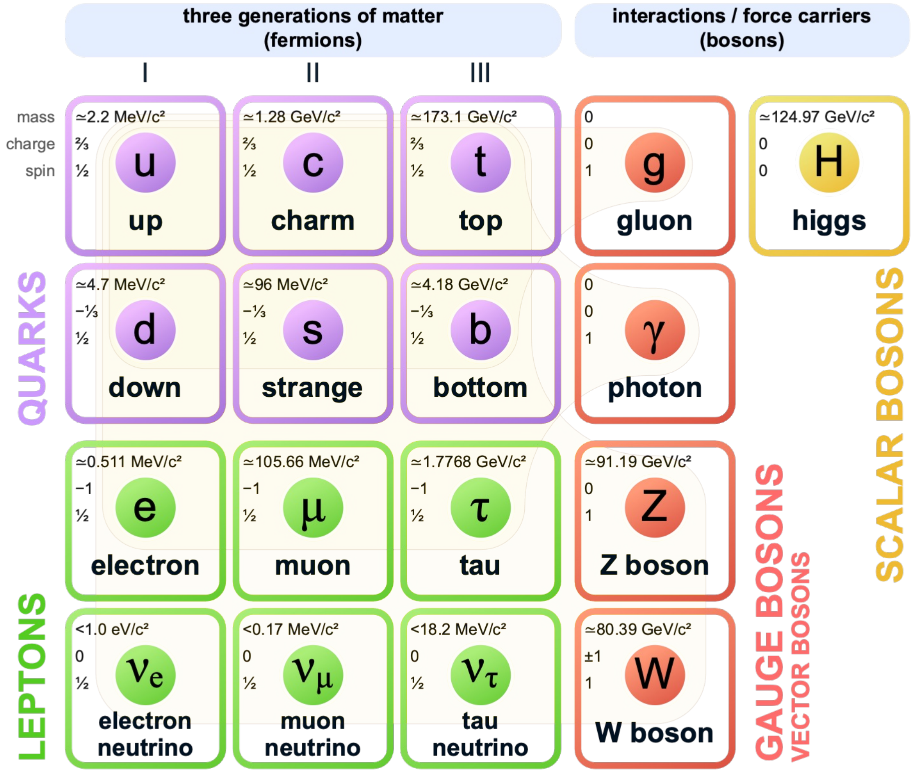
- Partons (quarks and gluons) carry colour charge and therefore don't like to be alone.
- Energy deposits in the calorimeter can be grouped together and declared a jet.



- Jet Vertex Tagging allows us to ignore (some) jets from pile-up by looking at tracks associated with the jets.

The Big Questions

Image: Jorge Cham / PhD Comics



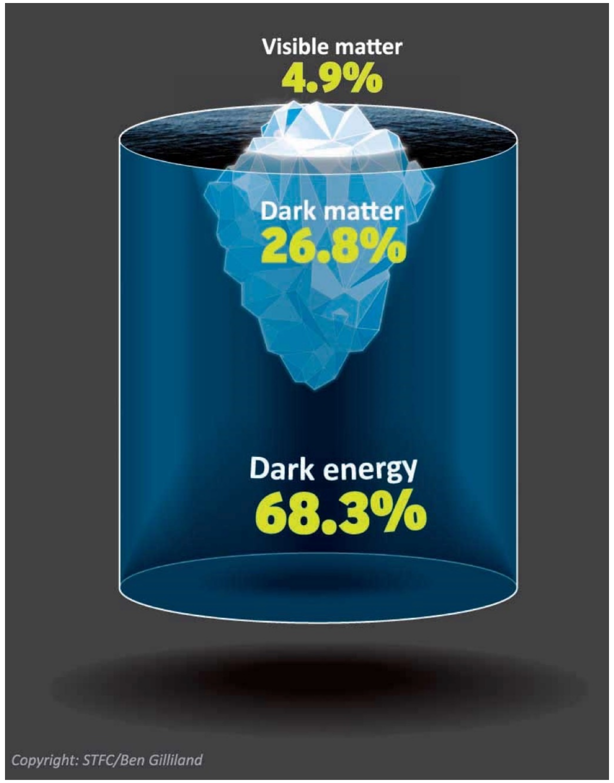
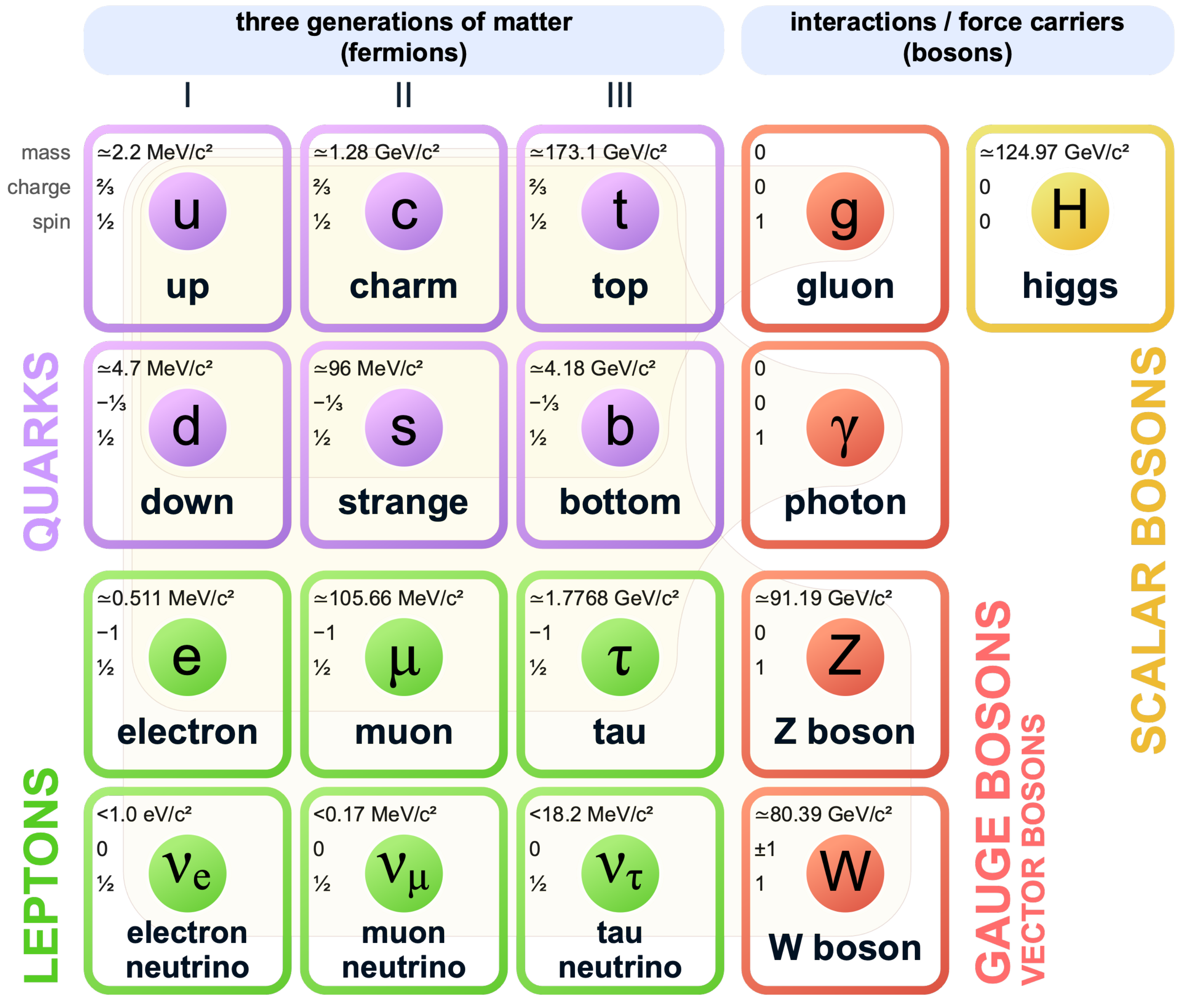


Illustration by Carolina Deluca / ATLAS © CERN

The Standard Model

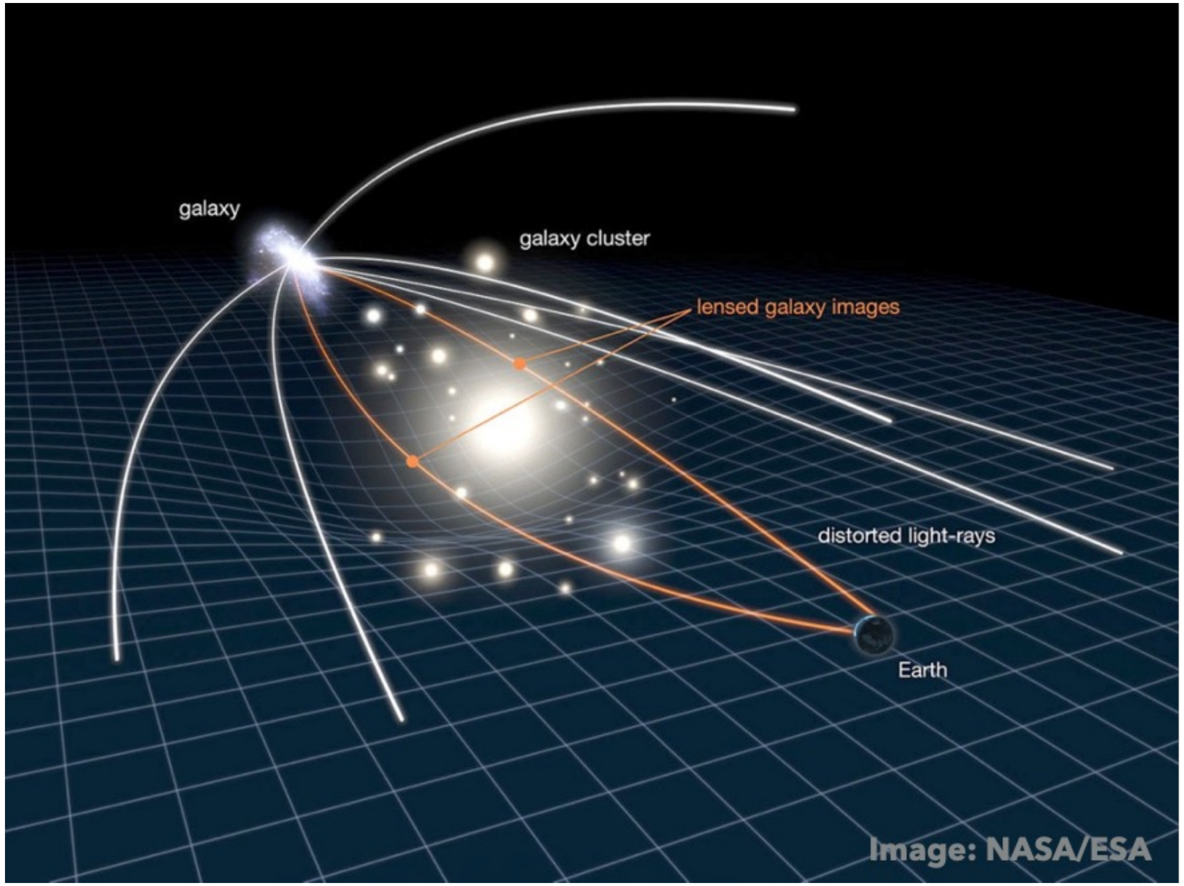


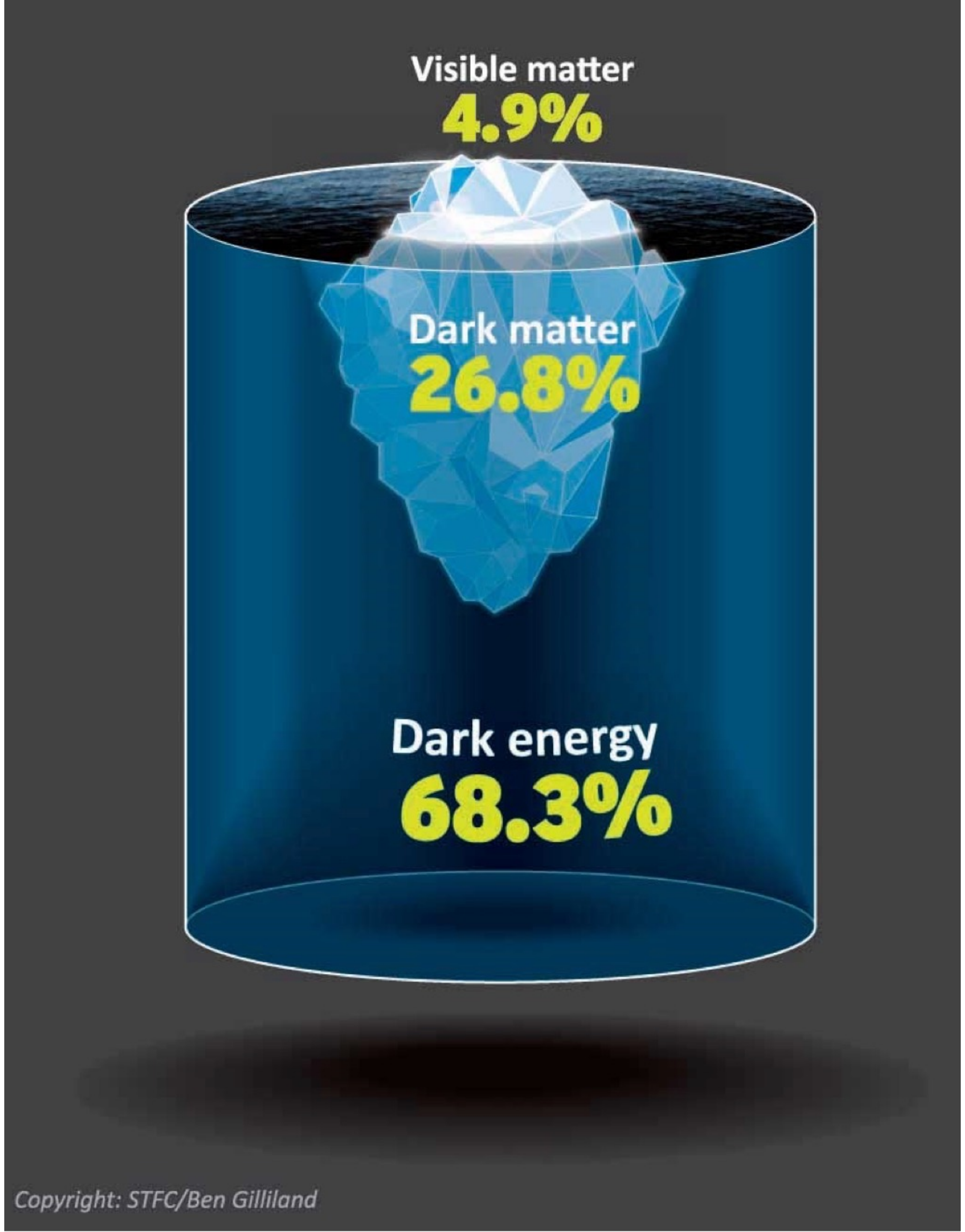
The discovery of a new boson!

The Higgs boson – a major success of the first LHC run.

This will be covered by Robin later

The search for new particles (dark matter?)



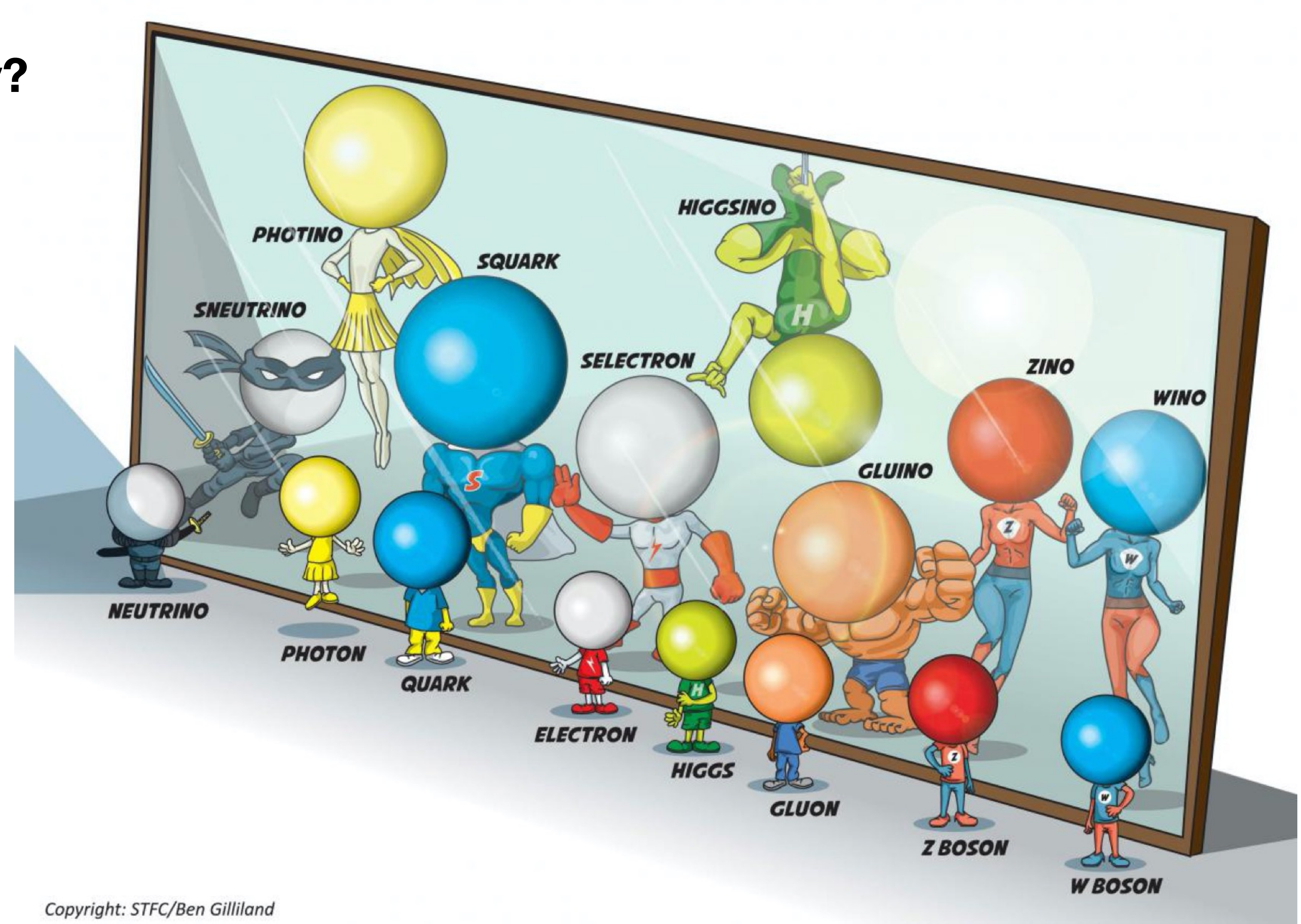


The search for

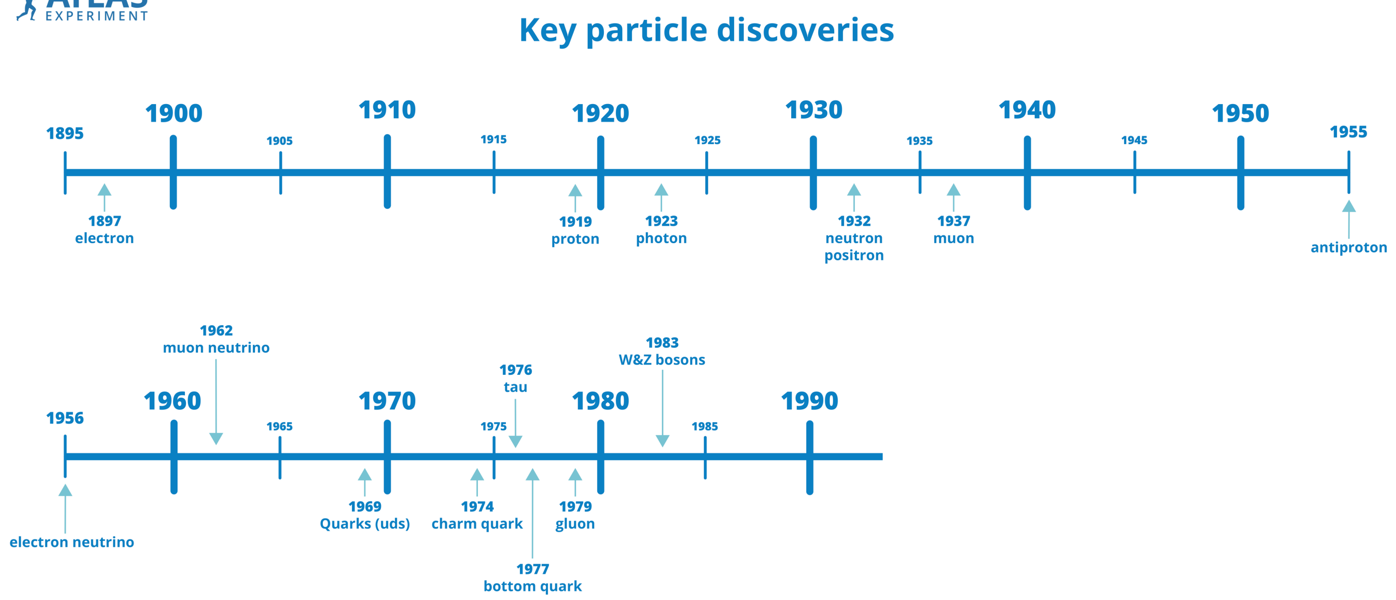
Illustration by Sandbox Studio, Chicago with Ana Kova for Symmetry magazine

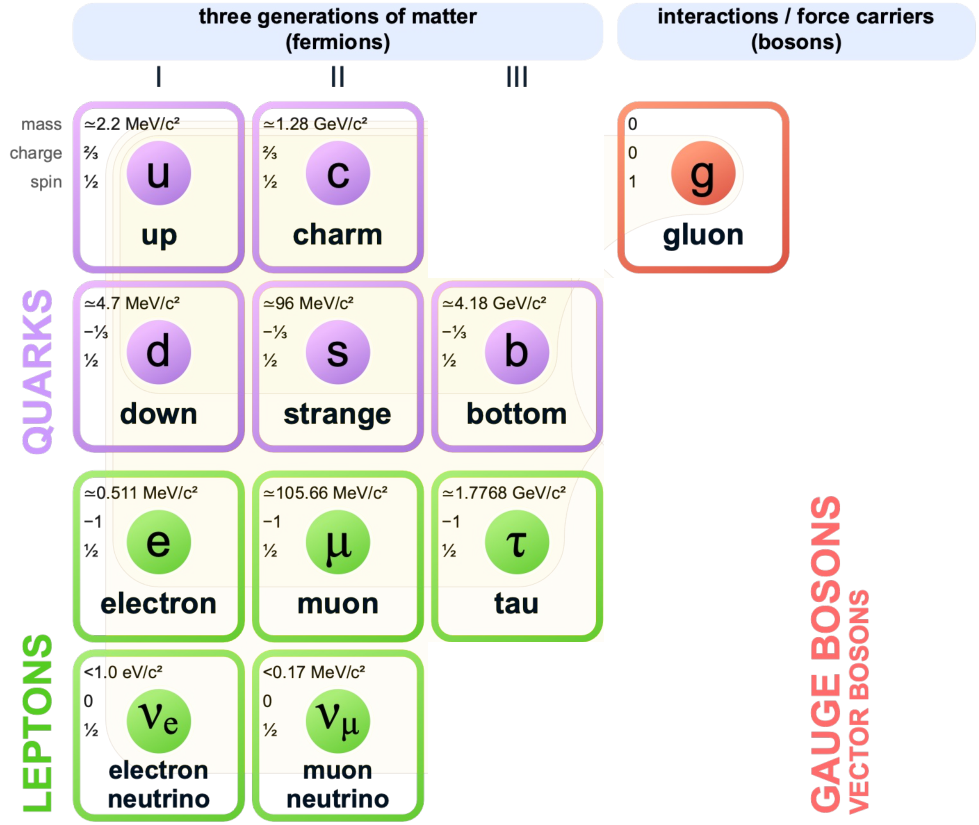
Dark Matter

Supersymmetry?



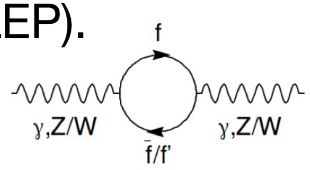
The road to the top quark

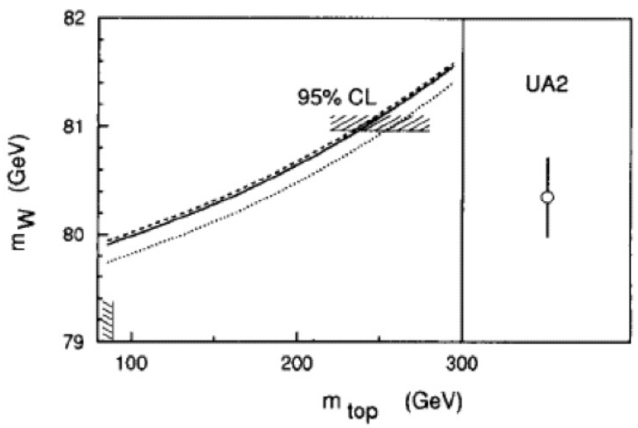




- Once the tau lepton and the b-quark had been discovered, there was the assumption that **there must be an up-type quark in the third generation.**

- **Limits on the mass** were set from loops within diagrams for W & Z bosons (from Sp$\bar{p}$S and LEP).
  - $m_{top} = 160\ ^{+50}_{-60}$ GeV

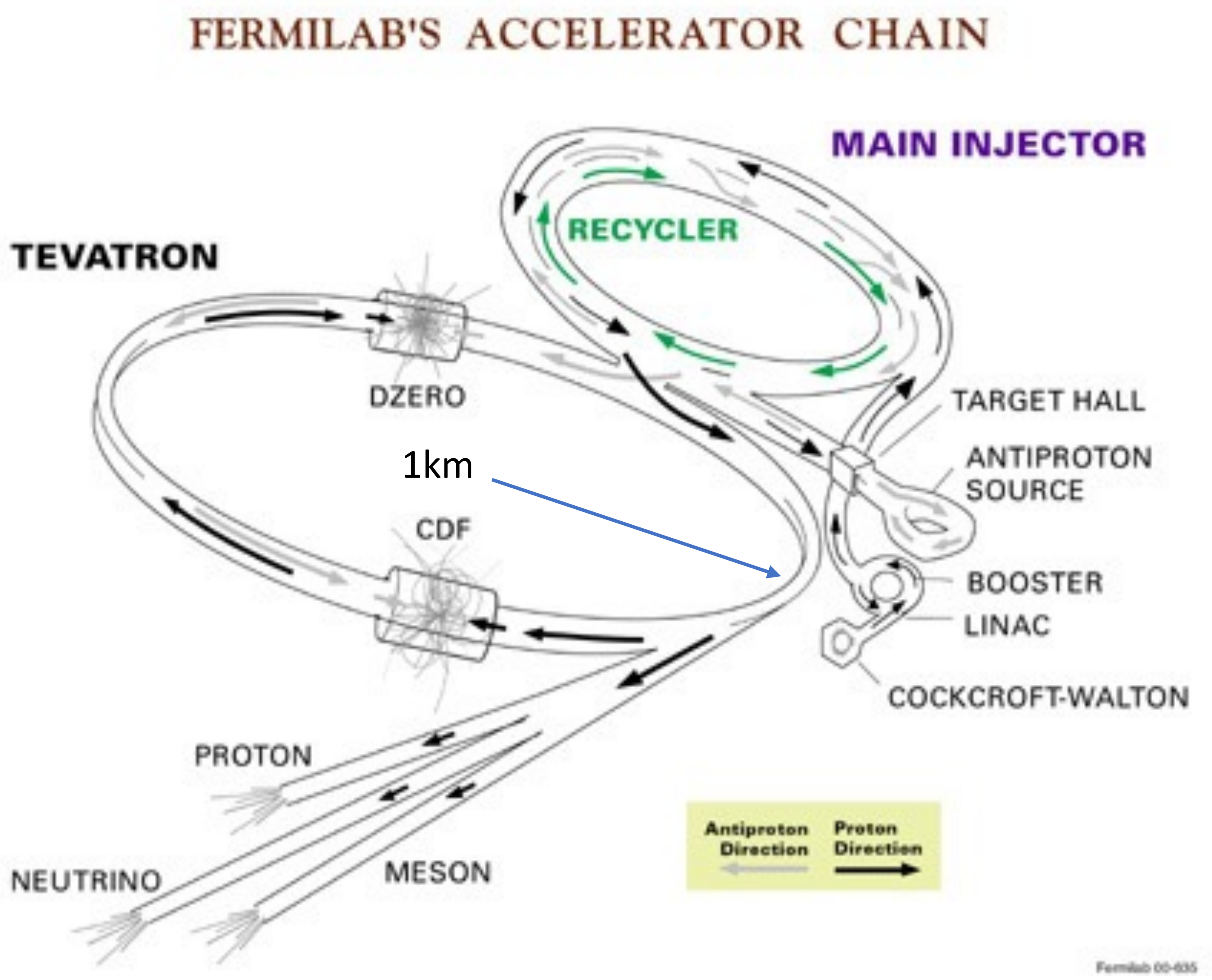


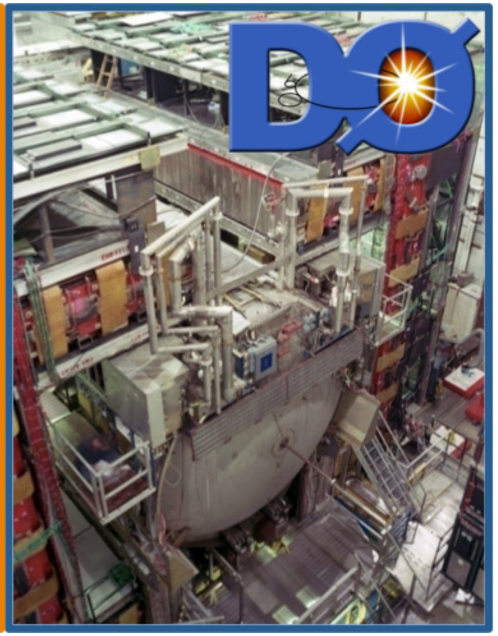


Slide credit: A. Knue https://cern.ch/5gkk5

In steps the Tevatron

30 miles west of Chicago, USA





Experimental teams of about 600 physicists each.

Discovered in **1995** by D0 and CDF at Fermilab in the US.

CoM Energy: **1.8 TeV**

Looked at ~2×10^{12} proton-antiproton collisions

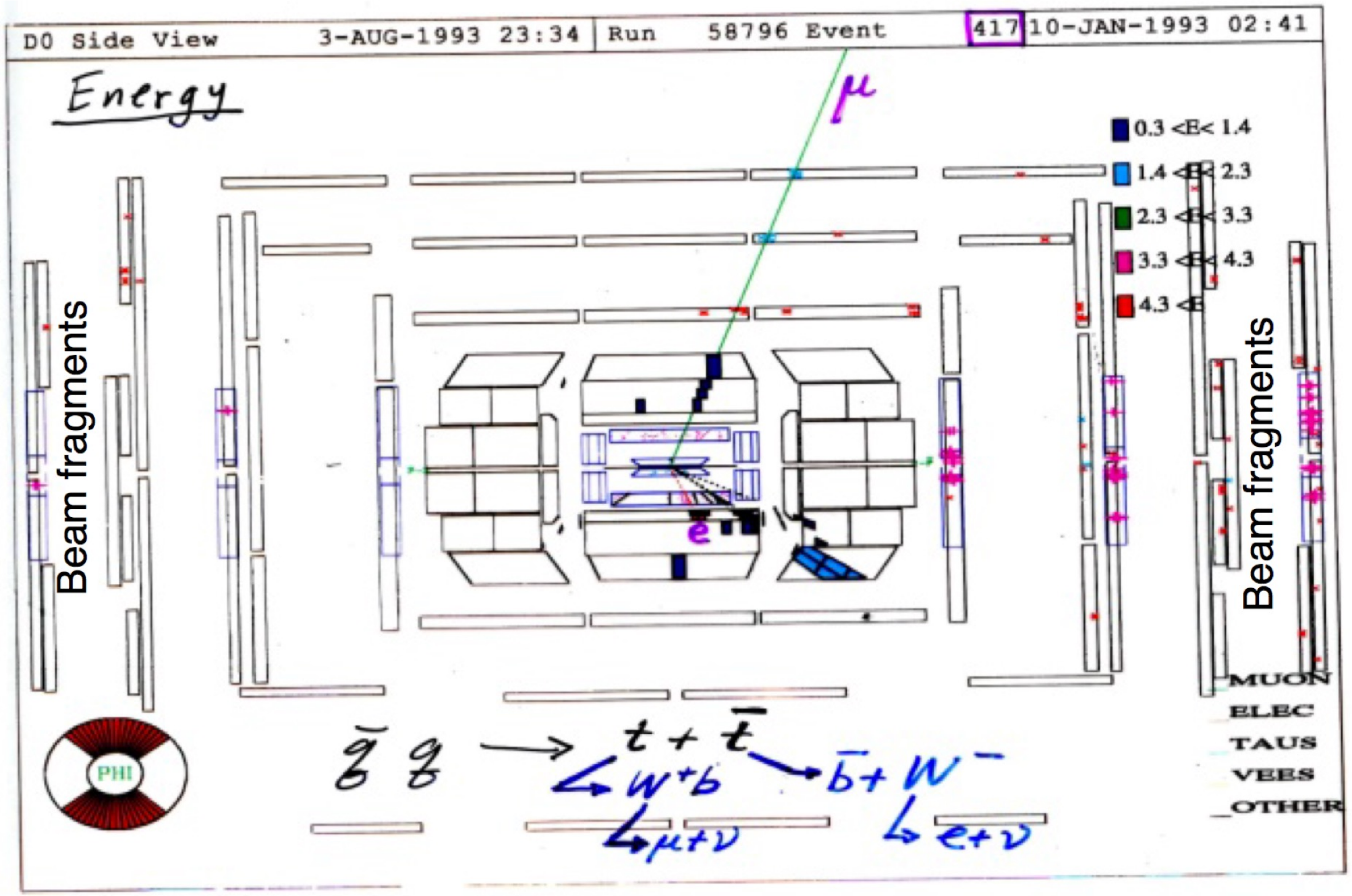
Events with a W bosons (leptonic decay) and 3 or more jets (with at least one b-tag)

CDF, PRL 74, 2626 (1995)
D0, PRL 74, 2632 (1995)

Photo: Reidar Hahn, Fermilab

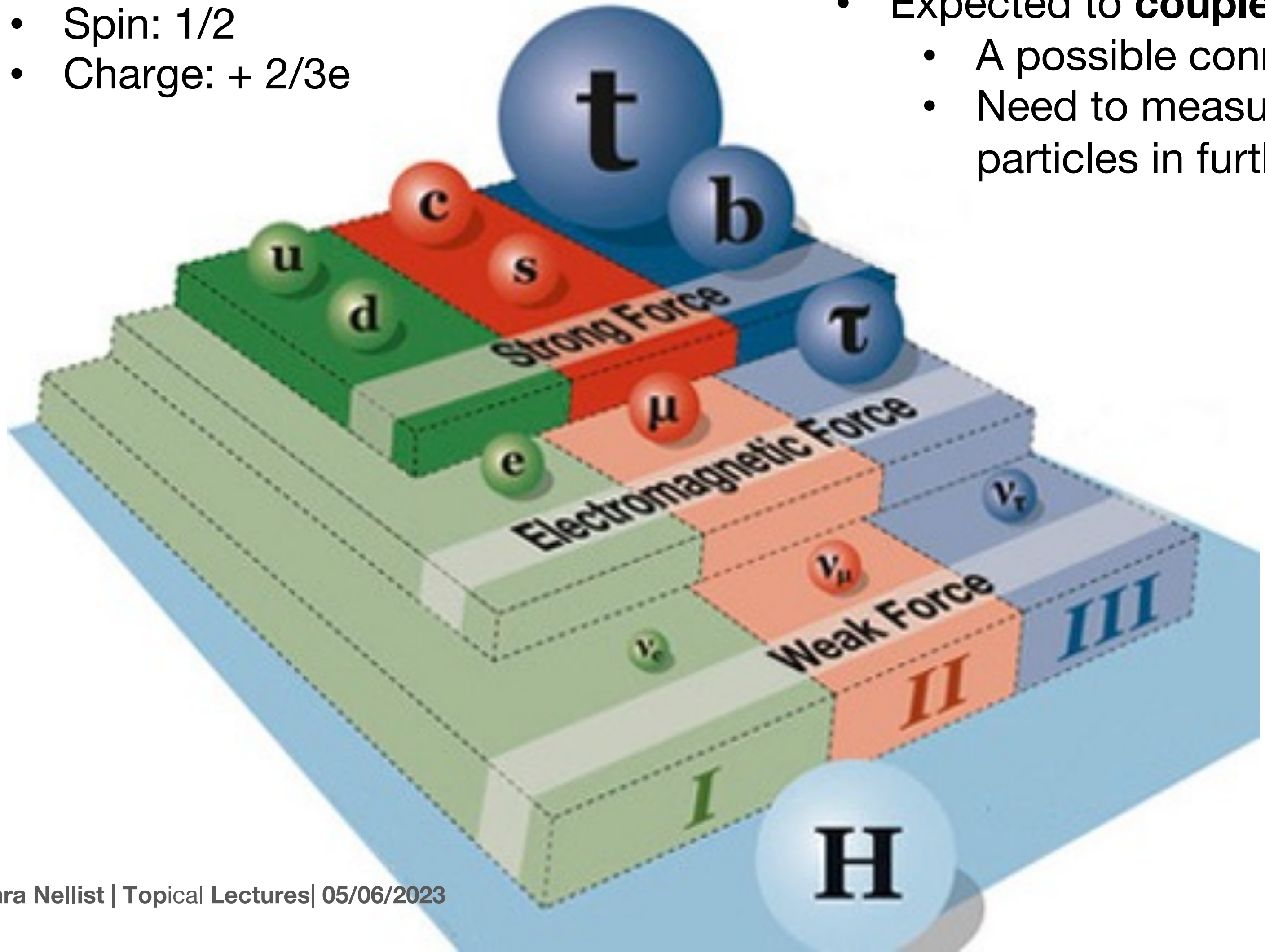
The top quark

Discovered in **1995** by D0 and CDF at Fermilab in the US.



The top quark

- Spin: 1/2
- Charge: + 2/3e

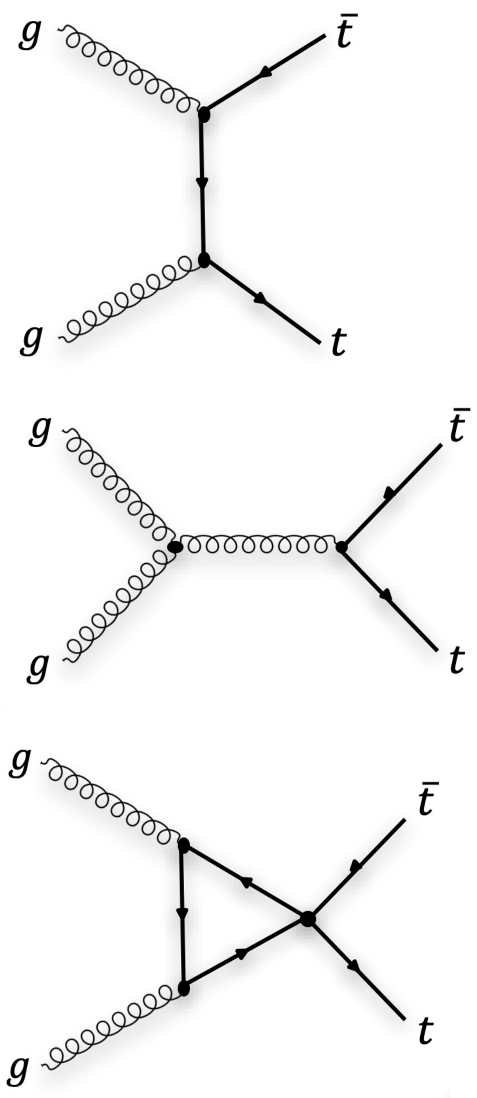


- The **heaviest fundamental particle.**
  - **~170 GeV** (but we don't know why it's so heavy).
  - **Very short lifetime**.
- The weak iso-spin partner of the b quark
- Expected to **couple strongly to the Higgs boson** (~1).
  - A possible connection to new physics!
  - Need to measure its properties and interactions with other particles in further detail to find out!

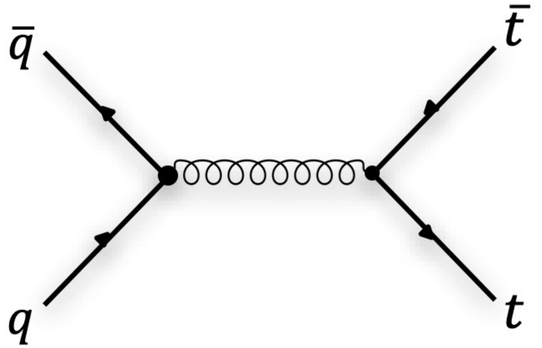
Production time		Lifetime		Hadronisation time
$\frac{1}{m(t)}$	$<<$	$\frac{1}{\Gamma(t)}$	$<<$	$\frac{1}{\Lambda_{QCD}}$
~4 x 10^{-27} s		**~4 x 10^{-25} s**		**~3 x 10^{-24} s**

Top quark production (LHC)

Pairs



90% Gluon-gluon fusion

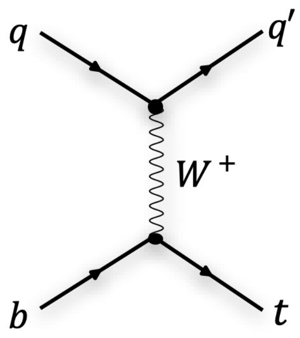


10% quark-antiquark annihilation

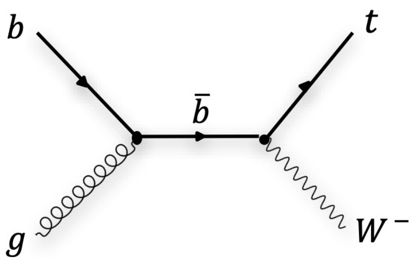
+ some others

Single top

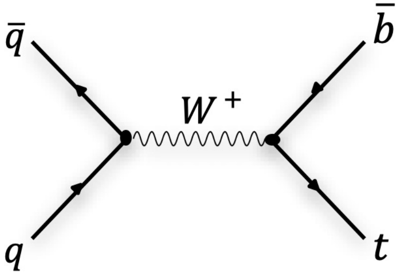
t-channel



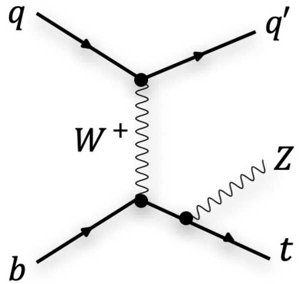
tW-associated production

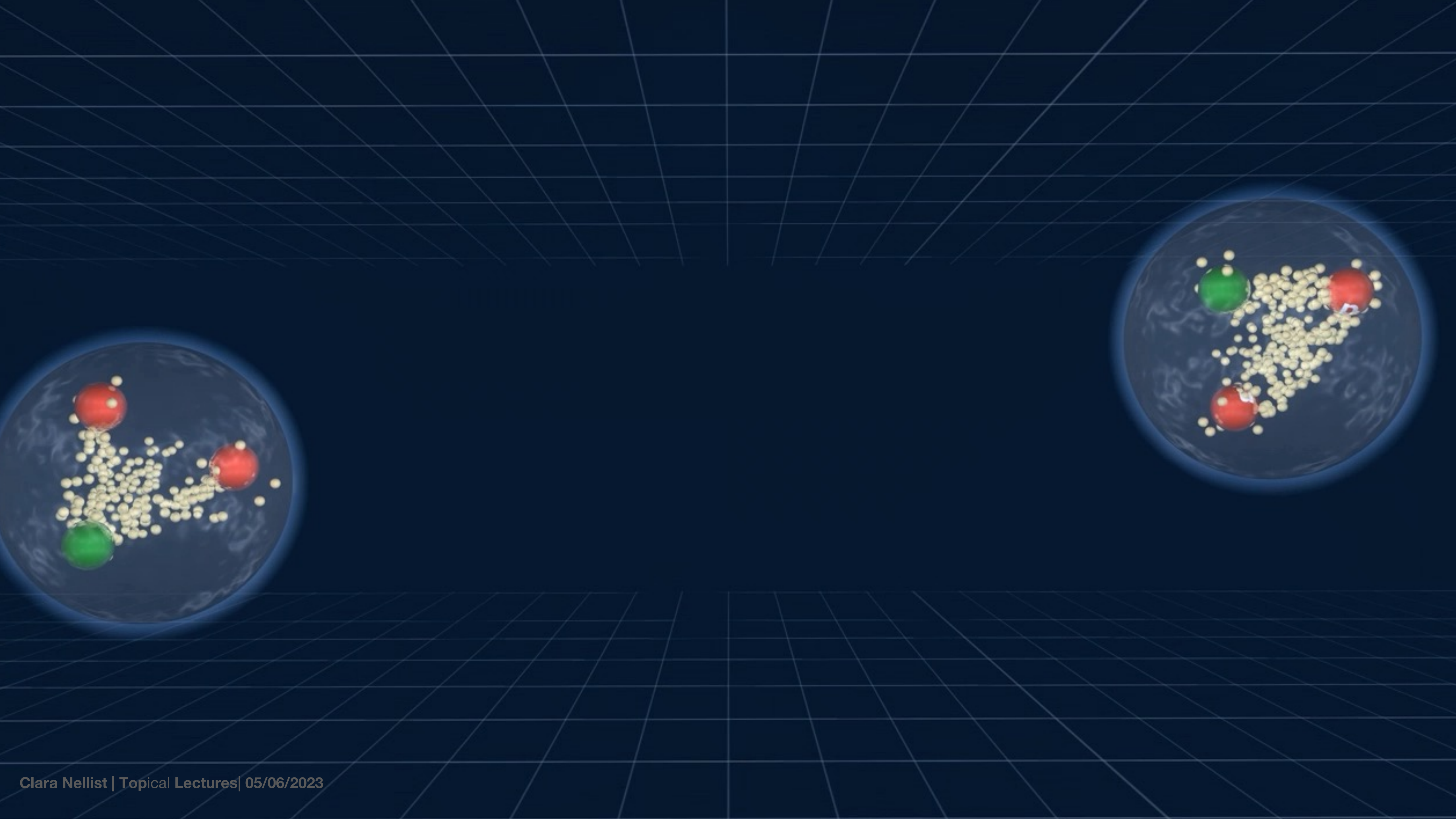


s-channel

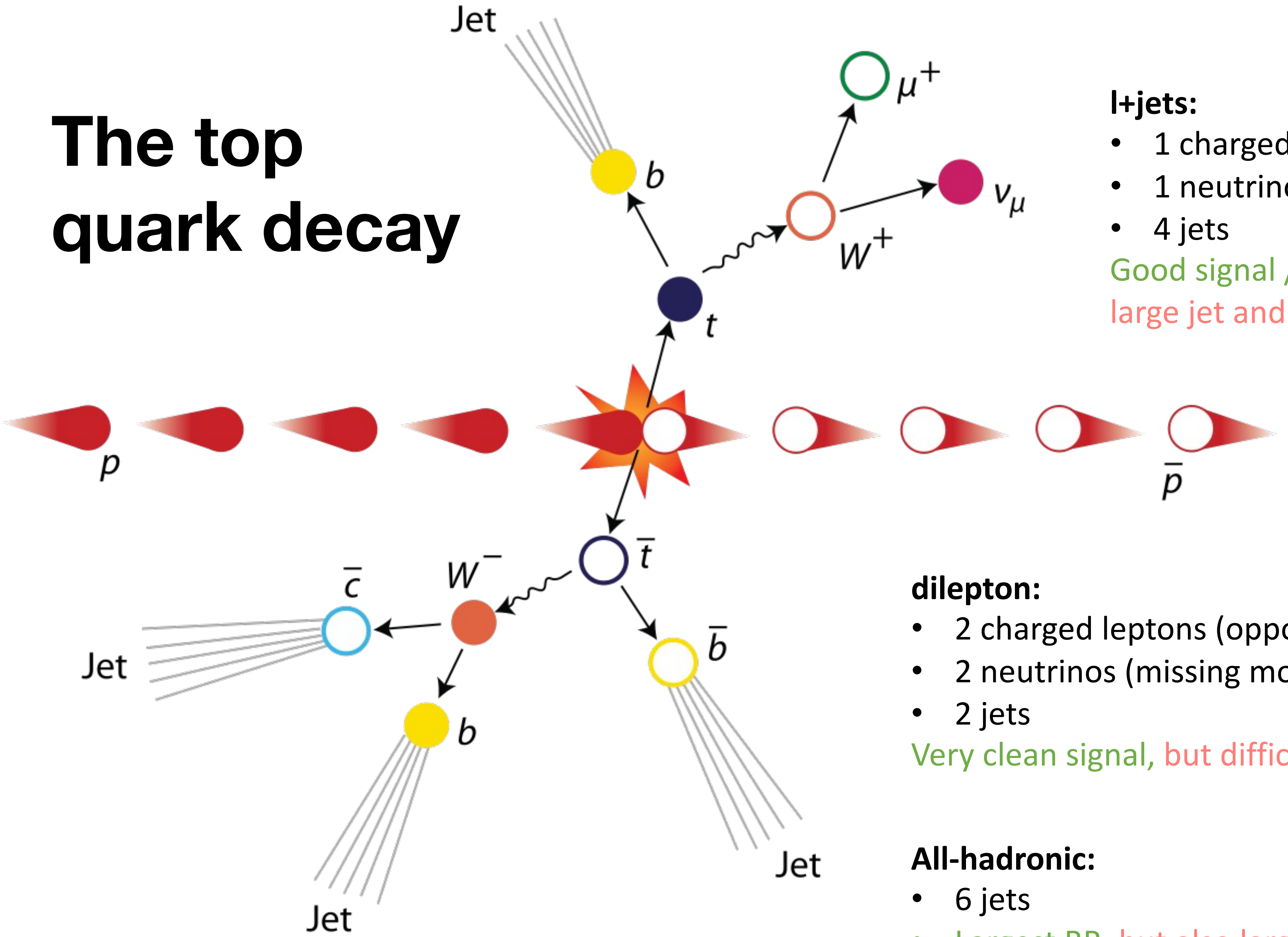


tZ production





The top quark decay



$|V_{tb}|^2 \sim 1$

l+jets:

- 1 charged lepton
- 1 neutrino (missing momentum)
- 4 jets

Good signal / background, but there are large jet and modelling uncertainties.

dilepton:

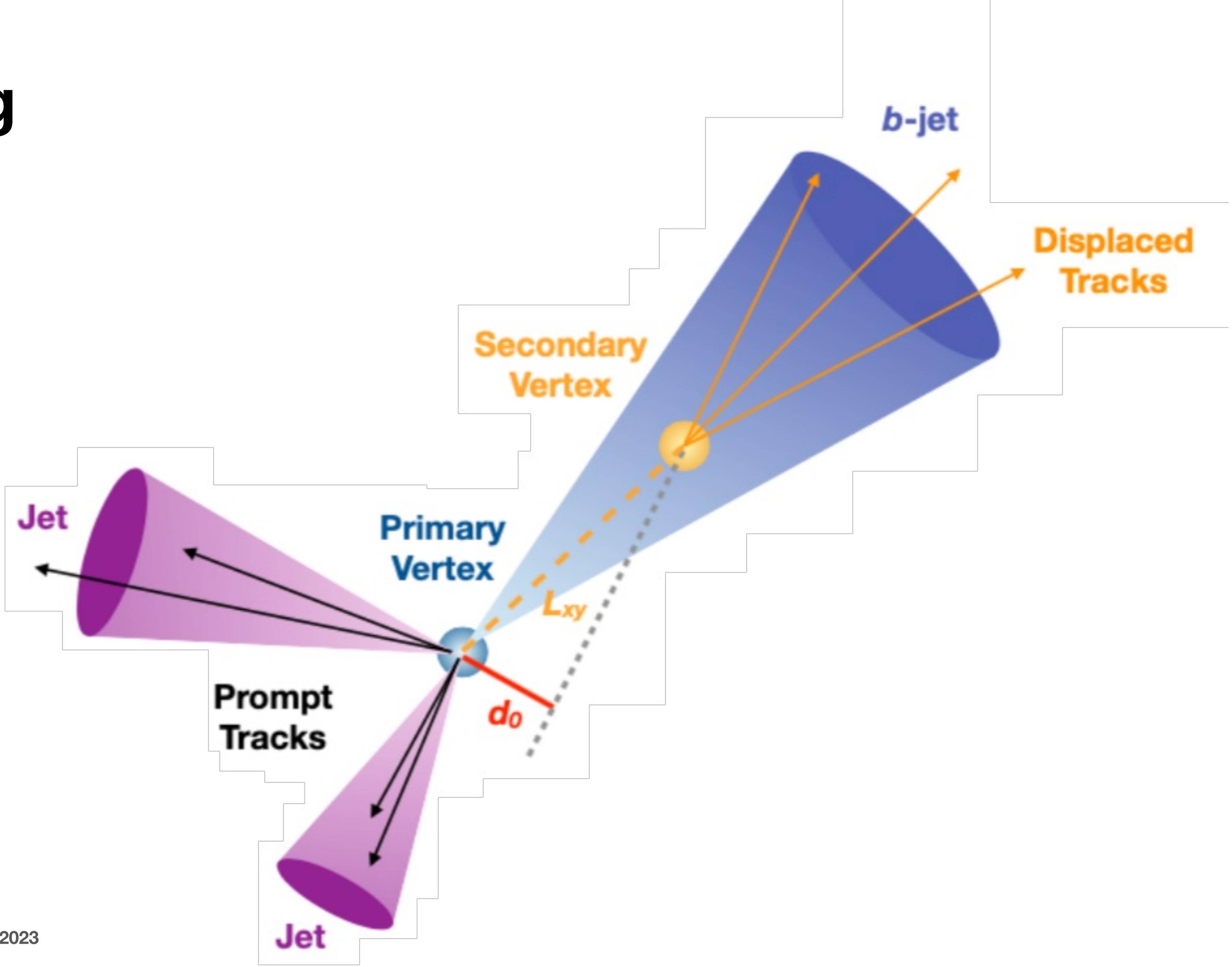
- 2 charged leptons (opposite charge)
- 2 neutrinos (missing momentum)
- 2 jets

Very clean signal, but difficult to reconstruct the kinematics.

All-hadronic:

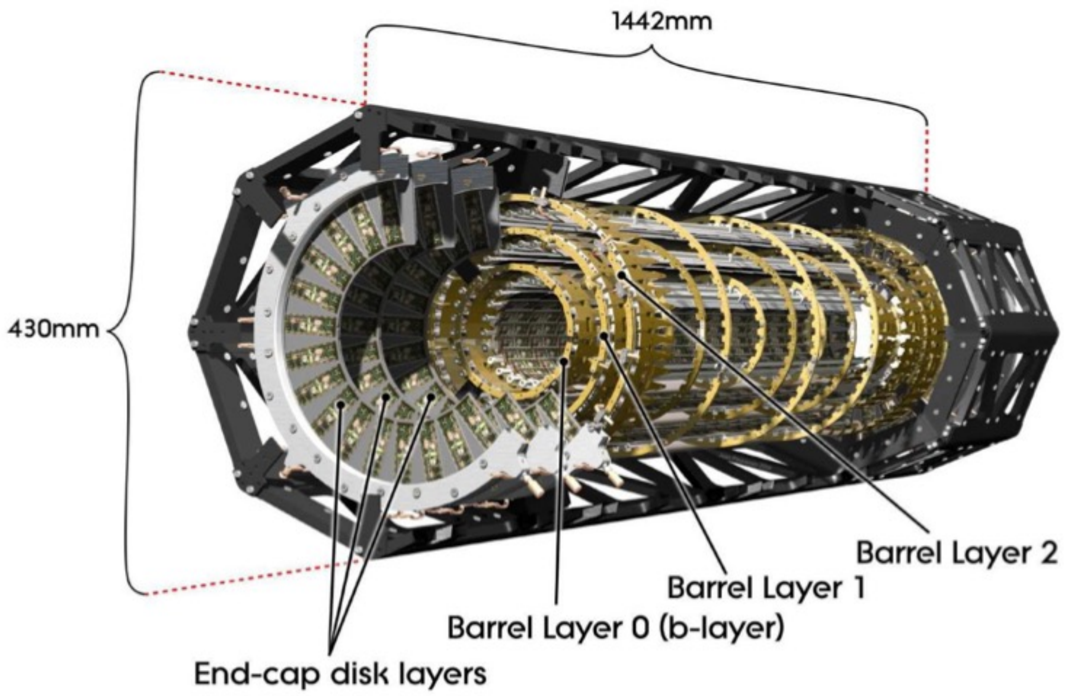
- 6 jets
- Largest BR, but also large multi-jet background.

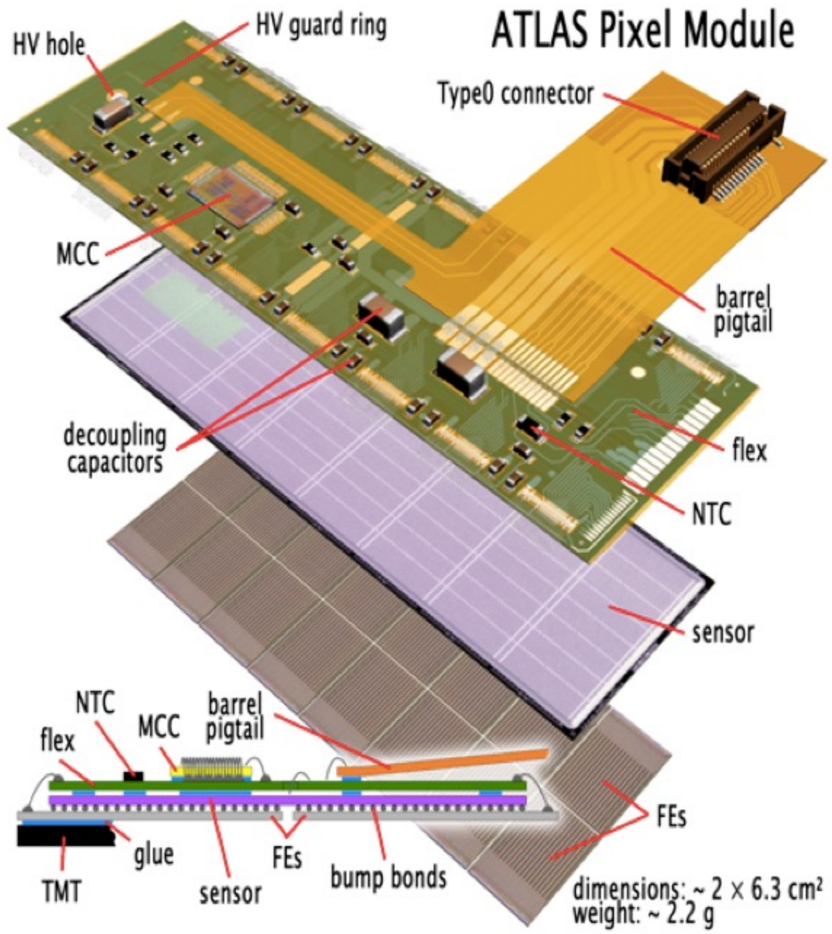
B-tagging

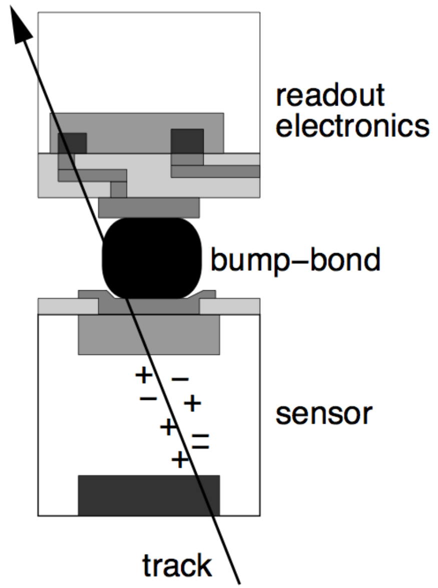


b-jet
Displaced Tracks
Secondary Vertex
Jet
Primary Vertex
L_{xy}
Prompt Tracks
d_0
Jet

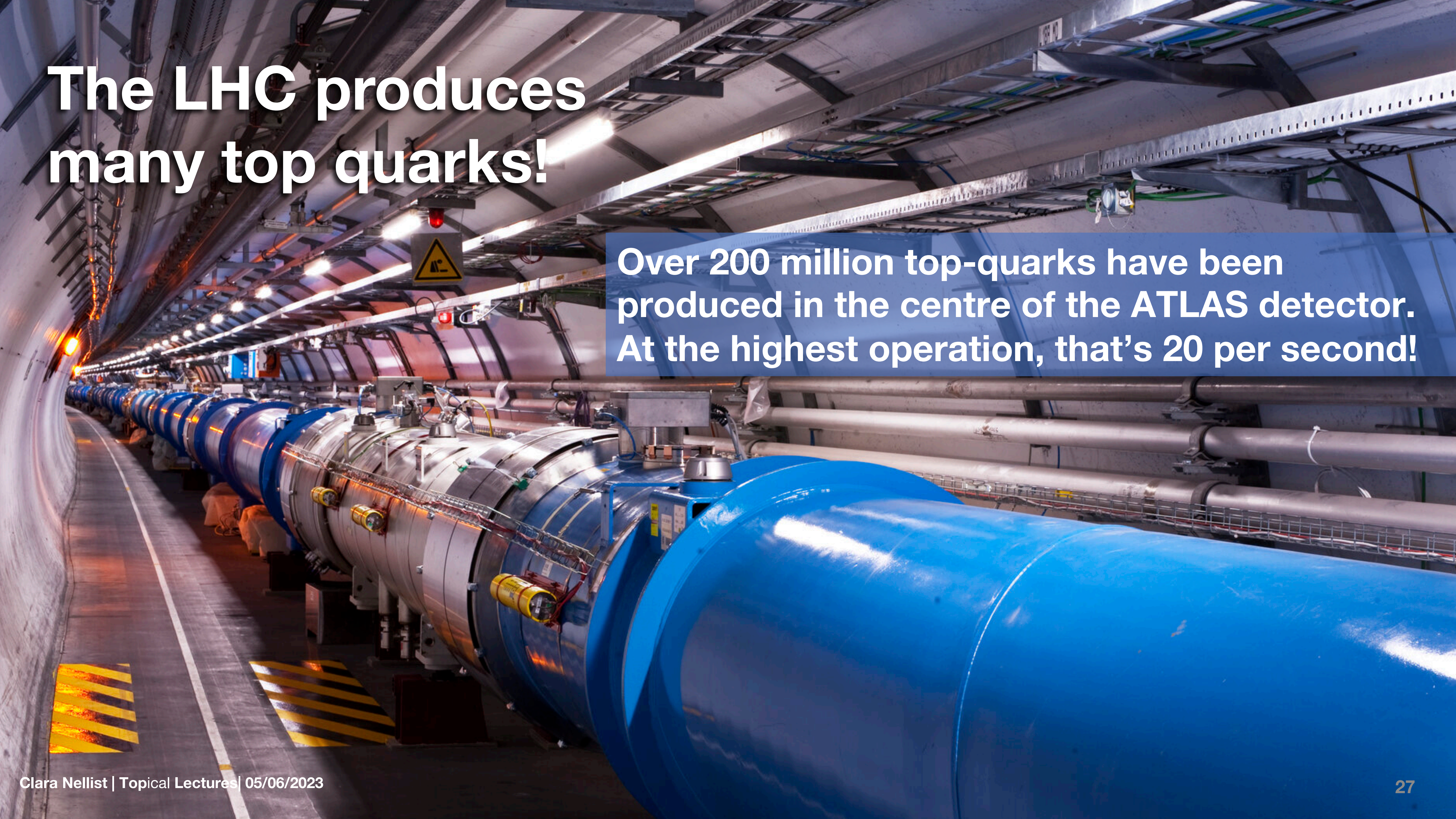
Requires a very precise pixel detector







The LHC produces many top quarks!



Over 200 million top-quarks have been produced in the centre of the ATLAS detector. At the highest operation, that's 20 per second!

LHC Run 1 and 2 history and some selected highlights

- Run 1
  - Rediscovery of the top quark
  - First associated production (ttγ)
  - Spin correlations
- Run 2
  - Searches for FCNC
  - Boosted differential tt analyses
  - Observation of tttt and of tγ
  - Energy asymmetry & single-top polarization measurements

As the data increases, we have improved precision measurements and searches, but systematic uncertainties have now begun to dominate.

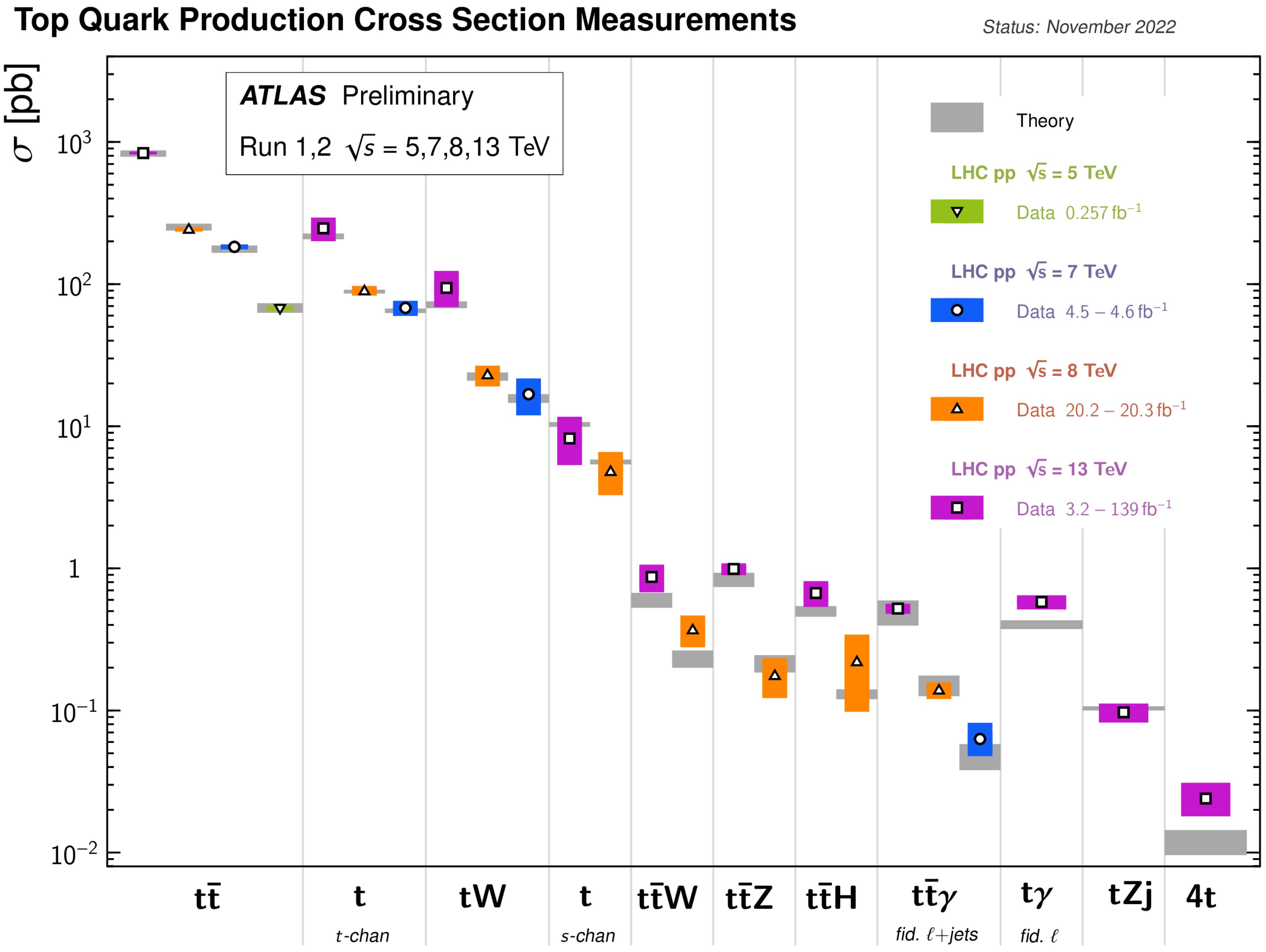
Ref: https://indico.cern.ch/event/1139204/contributions/4860537/attachments/2438911/4177515/TopWorkshop2022.pdf

Top quark production

Another test of the Standard Model is to measure the rates at which top quarks are produced.

Single-top t-channel
- ~30 million collisions in ATLAS Run 2
- Probe of the electroweak interaction
- Top polarized: **sensitive to new physics**

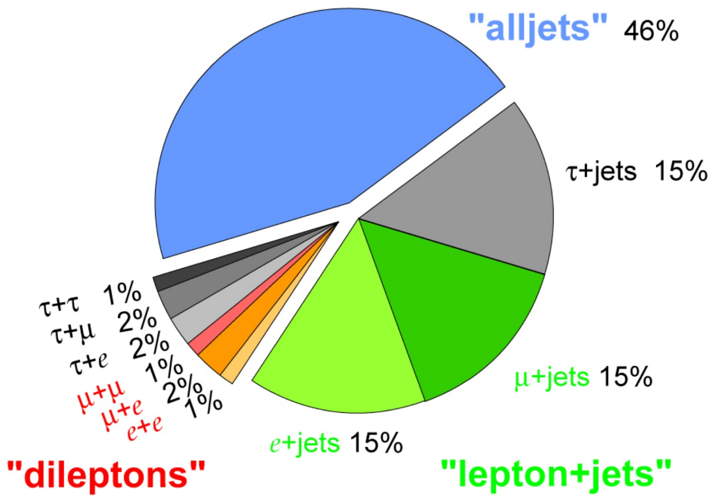
Four top quarks at once is very rare
=> **challenging**

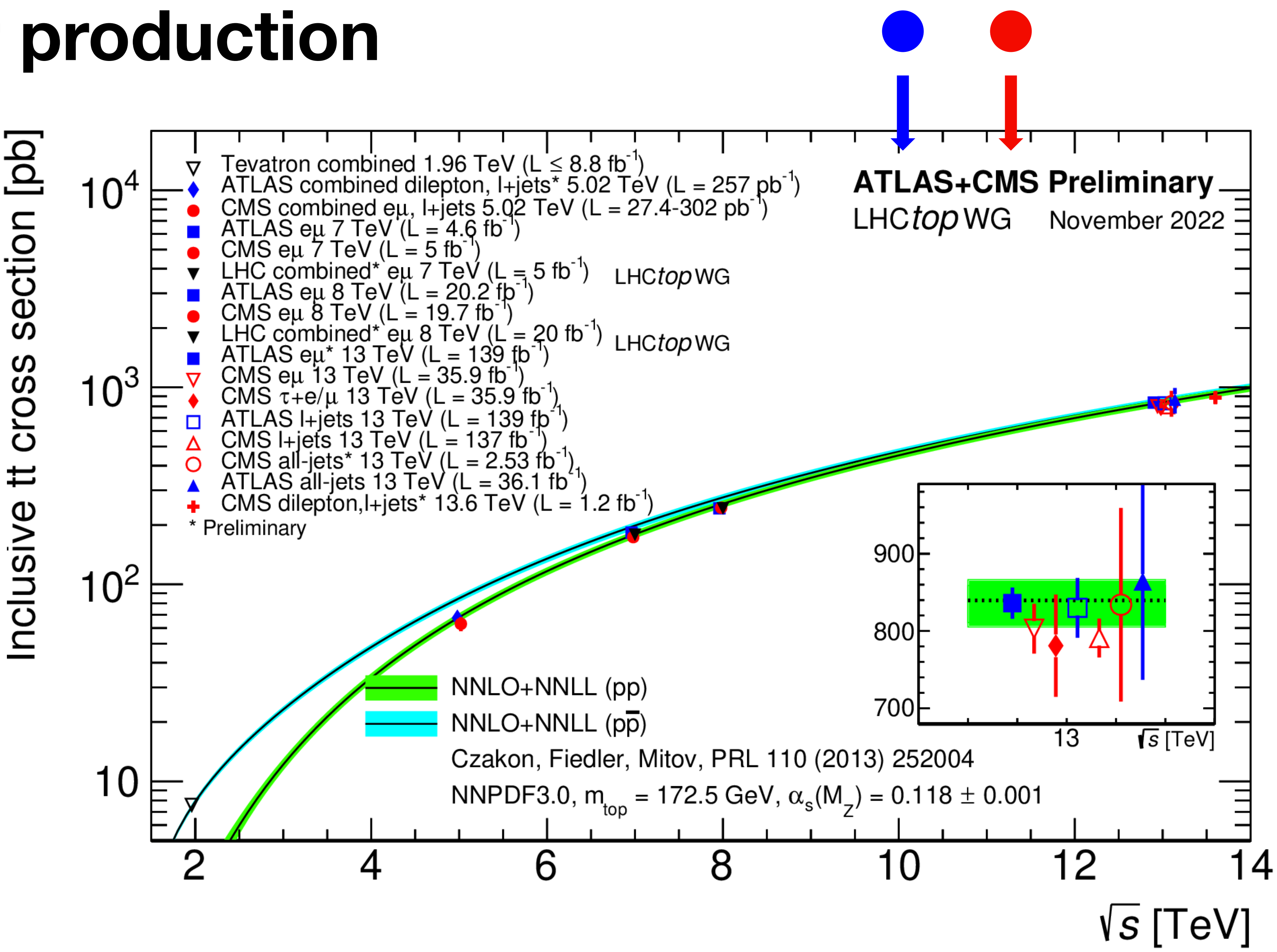


Top quark pair production

Note:

Another test of the Standard Model is to measure the rates at which top quarks are produced.

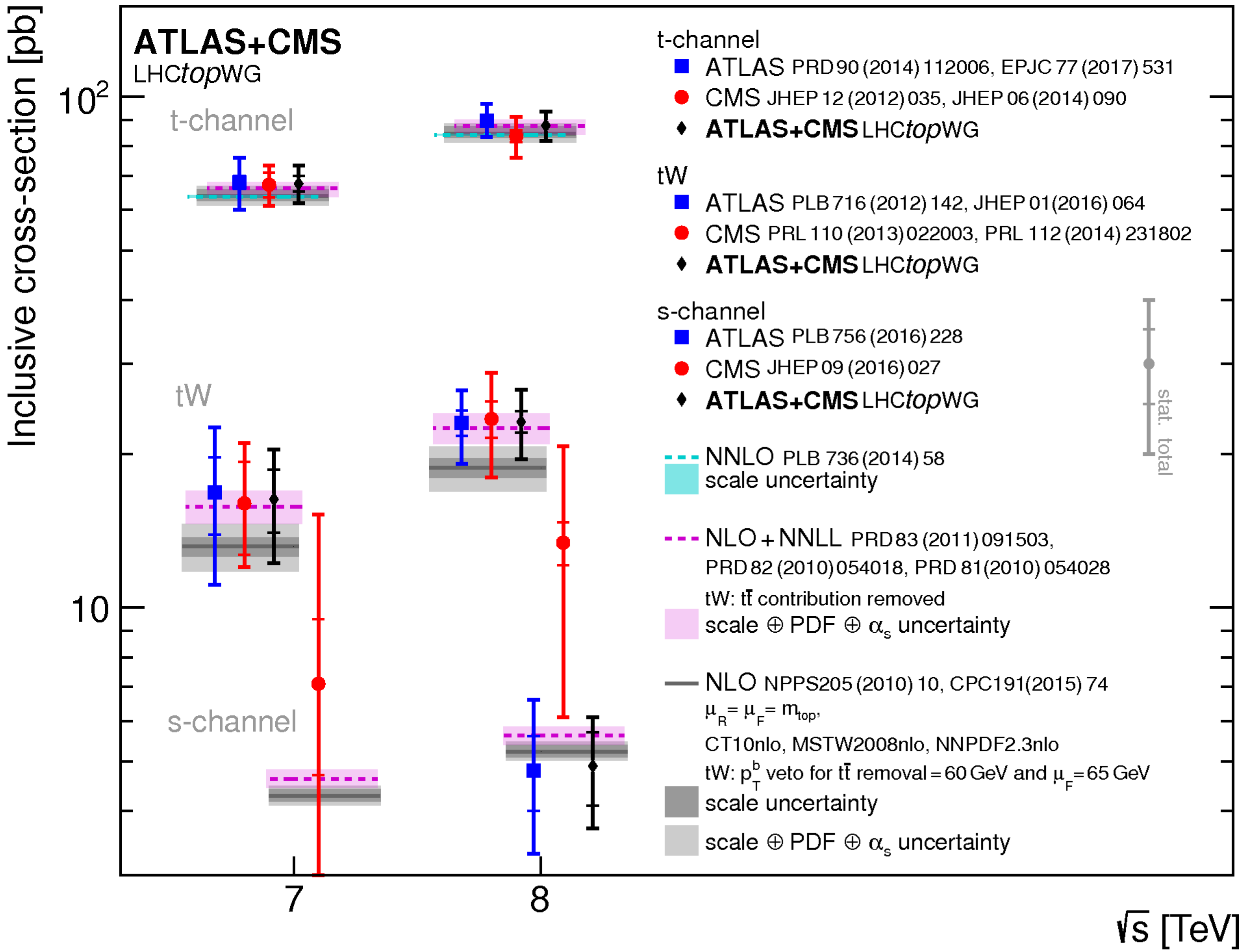




There is a very impressive agreement between prediction and measurements

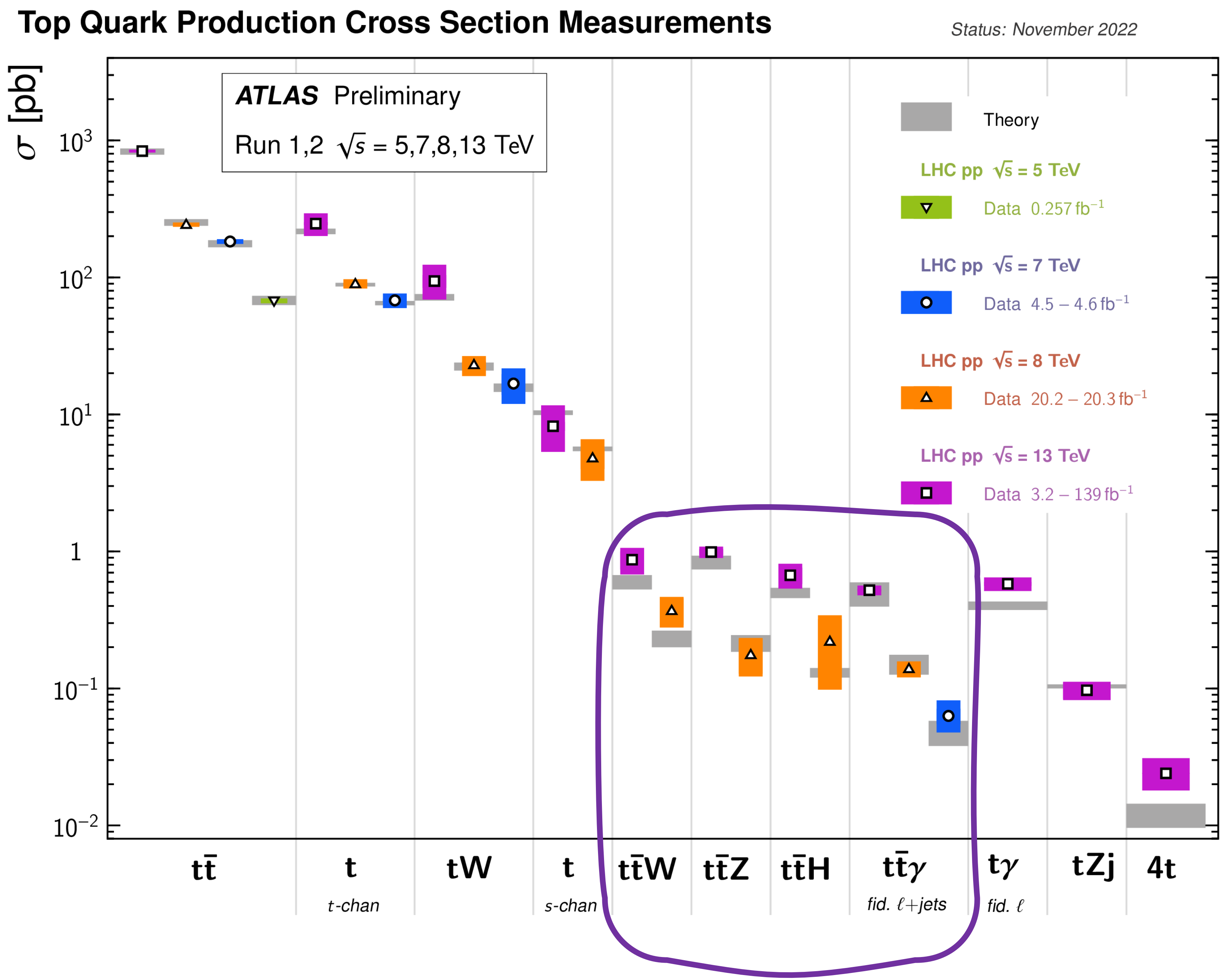
Single top quark production

Another test of the Standard Model is to measure the rates at which top quarks are produced.

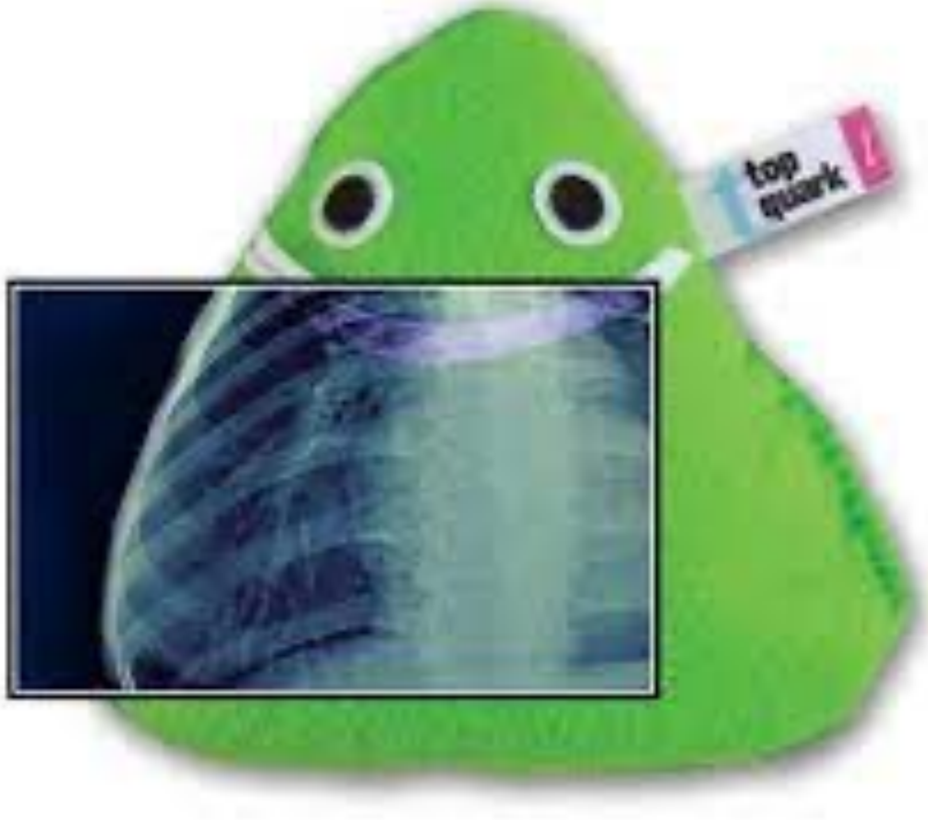


tt+X production

- To understand the top quark and validate the Standard Model, we need to look at how it interacts with other particles.
  - Higgs Boson - Yukawa coupling
  - Photons - Determine the charge of the top quark
  - Heavy gauge bosons: Z and W - Direct probe of the weak couplings of the top quark.
  - Four tops - High sensitivity to New Physics.

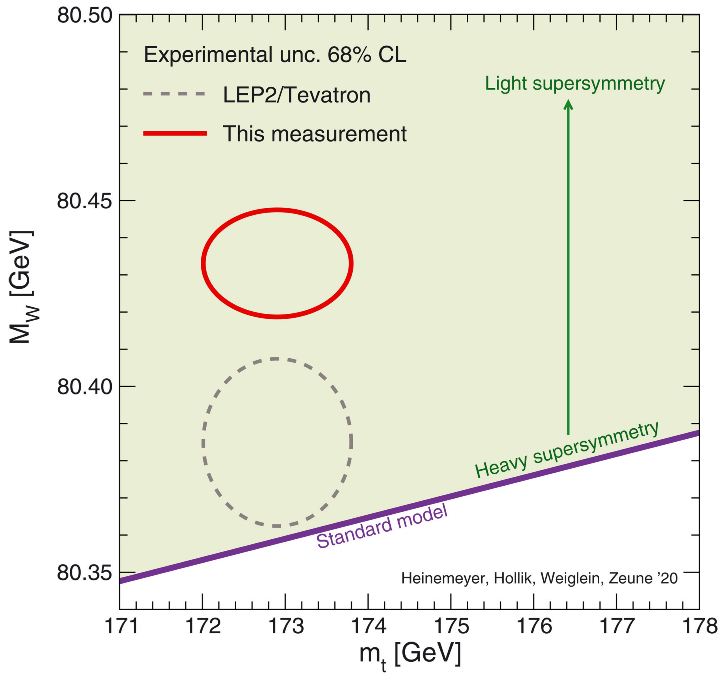


Top Properties



Top Mass

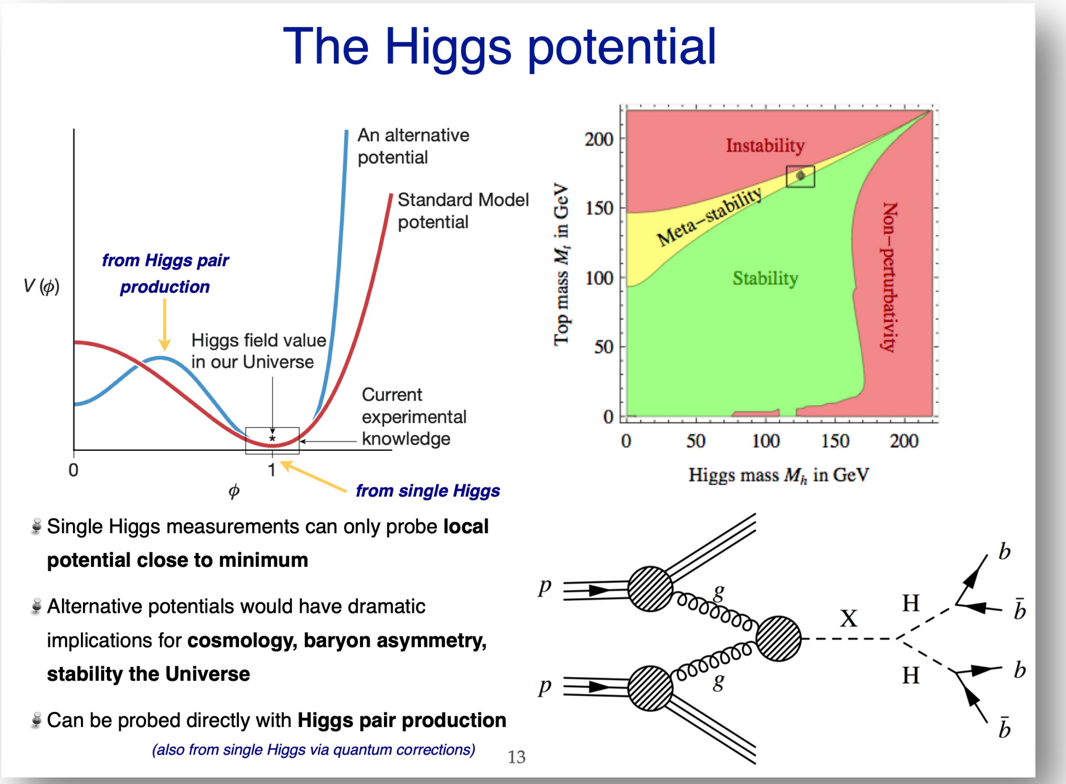
- Properties of the top quark are well predicted
  - ⇒ precision test of the SM
  - Mass measurement is also a probe of the consistency of the SM



The stability of the universe depends on it!

(Please note: measuring this doesn't affect the stability)

As you saw from Juan:



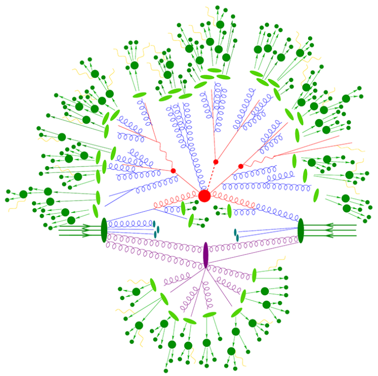
Top Mass

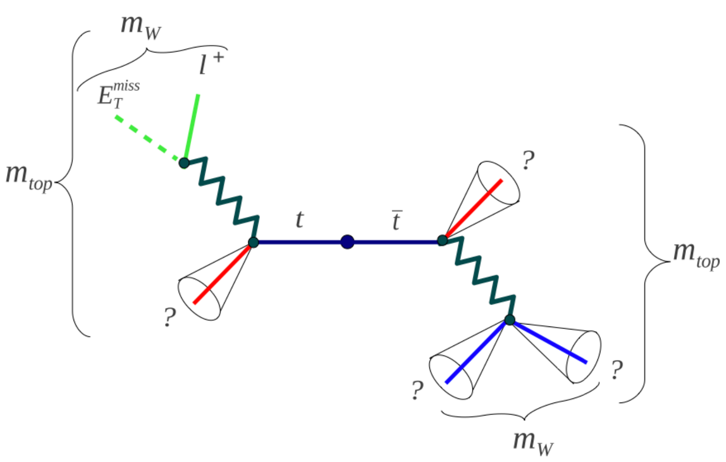
How to directly measure the mass?

1. Monte Carlo simulation

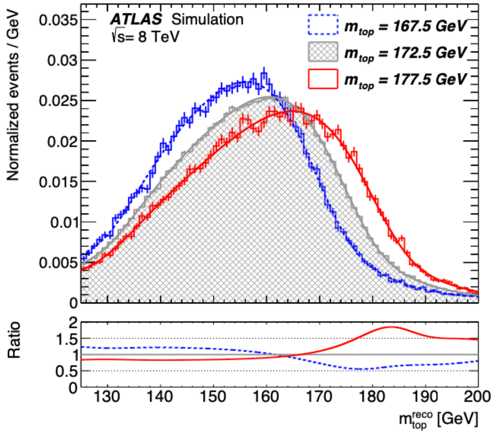
2. Select events

3. Reconstruct event

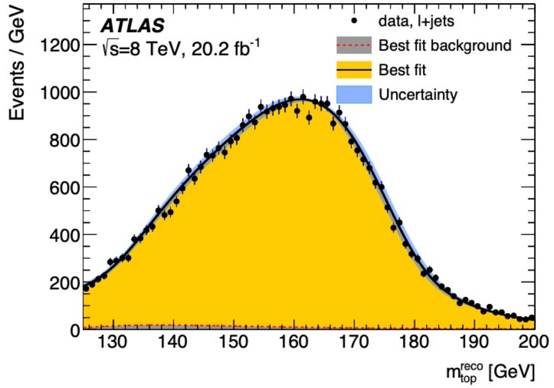




4. Templates for different masses

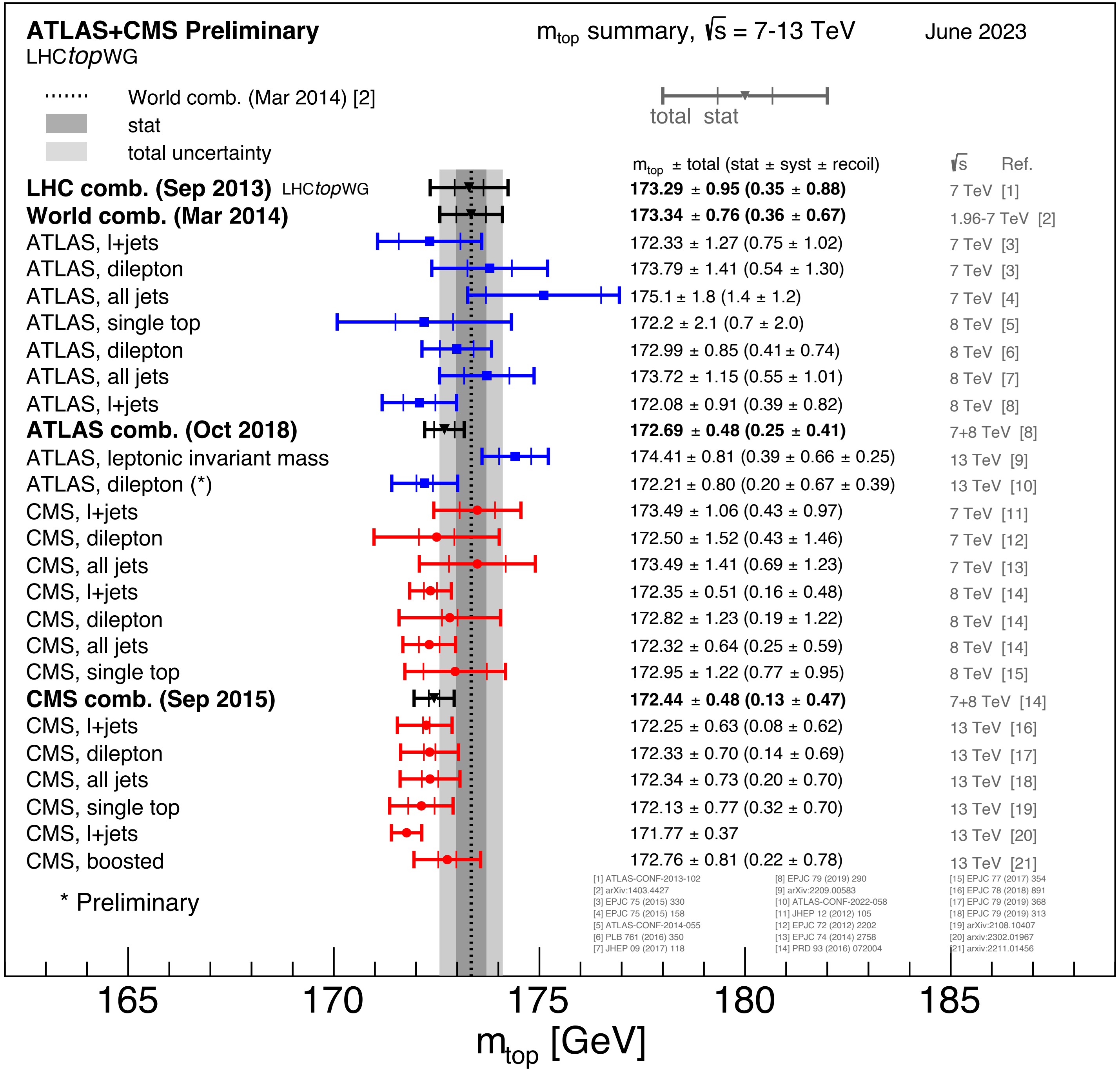


5. Obtain top mass from fit to data



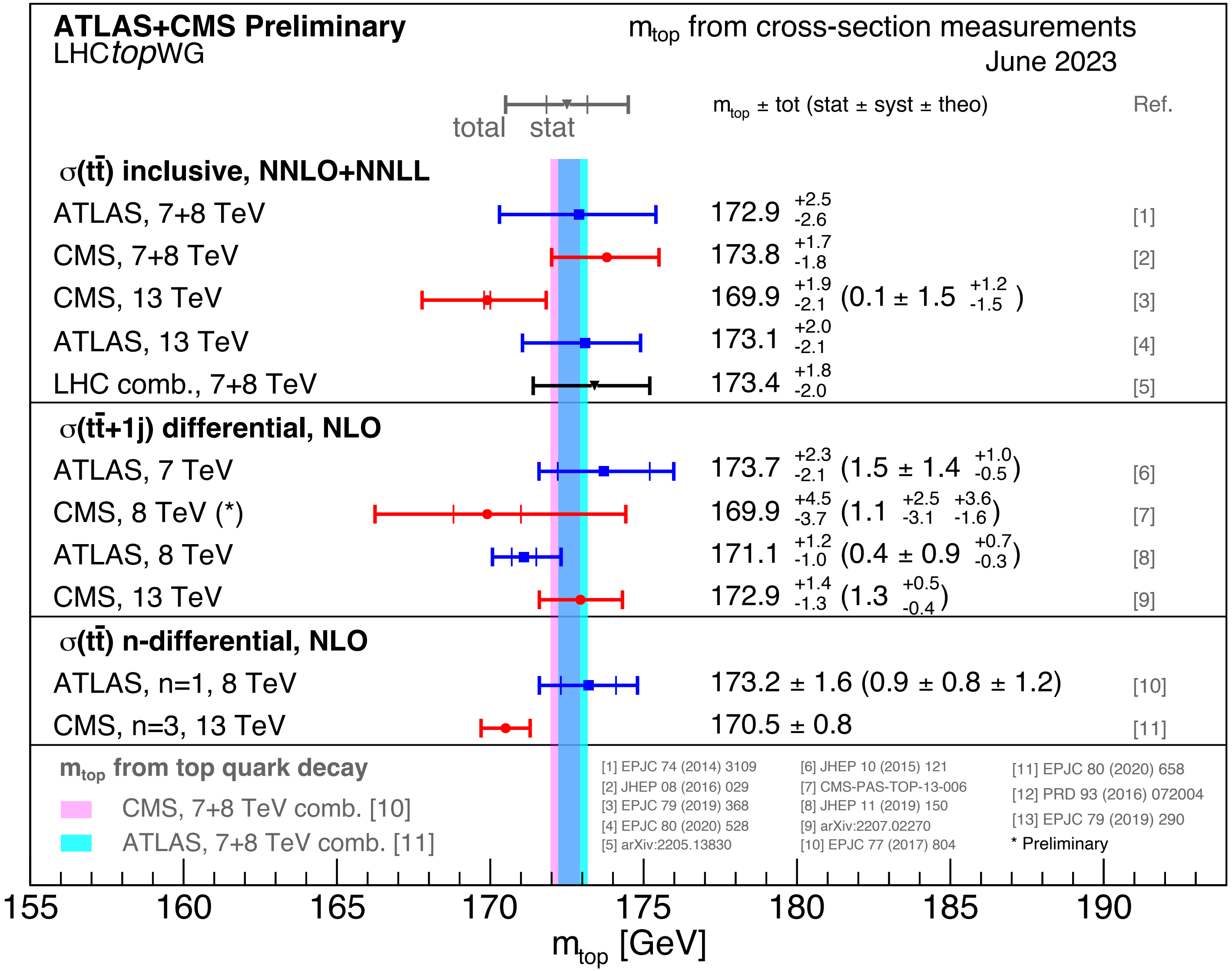
Slide credit: A. Knue
https://cern.ch/5gkk5

Top Mass


ATLAS+CMS Preliminary
LHCtopWG
m_top summary, √s = 7-13 TeV
June 2023
World comb. (Mar 2014) [2]
stat
total uncertainty
total stat
m_top ± total (stat ± syst ± recoil)
√s Ref.
LHC comb. (Sep 2013) LHCtopWG 173.29 ± 0.95 (0.35 ± 0.88) 7 TeV [1]
World comb. (Mar 2014) 173.34 ± 0.76 (0.36 ± 0.67) 1.96-7 TeV [2]
ATLAS, l+jets 172.33 ± 1.27 (0.75 ± 1.02) 7 TeV [3]
ATLAS, dilepton 173.79 ± 1.41 (0.54 ± 1.30) 7 TeV [3]
ATLAS, all jets 175.1 ± 1.8 (1.4 ± 1.2) 7 TeV [4]
ATLAS, single top 172.2 ± 2.1 (0.7 ± 2.0) 8 TeV [5]
ATLAS, dilepton 172.99 ± 0.85 (0.41 ± 0.74) 8 TeV [6]
ATLAS, all jets 173.72 ± 1.15 (0.55 ± 1.01) 8 TeV [7]
ATLAS, l+jets 172.08 ± 0.91 (0.39 ± 0.82) 8 TeV [8]
ATLAS comb. (Oct 2018) 172.69 ± 0.48 (0.25 ± 0.41) 7+8 TeV [8]
ATLAS, leptonic invariant mass 174.41 ± 0.81 (0.39 ± 0.66 ± 0.25) 13 TeV [9]
ATLAS, dilepton (*) 172.21 ± 0.80 (0.20 ± 0.67 ± 0.39) 13 TeV [10]
CMS, l+jets 173.49 ± 1.06 (0.43 ± 0.97) 7 TeV [11]
CMS, dilepton 172.50 ± 1.52 (0.43 ± 1.46) 7 TeV [12]
CMS, all jets 173.49 ± 1.41 (0.69 ± 1.23) 7 TeV [13]
CMS, l+jets 172.35 ± 0.51 (0.16 ± 0.48) 8 TeV [14]
CMS, dilepton 172.82 ± 1.23 (0.19 ± 1.22) 8 TeV [14]
CMS, all jets 172.32 ± 0.64 (0.25 ± 0.59) 8 TeV [14]
CMS, single top 172.95 ± 1.22 (0.77 ± 0.95) 8 TeV [15]
CMS comb. (Sep 2015) 172.44 ± 0.48 (0.13 ± 0.47) 7+8 TeV [14]
CMS, l+jets 172.25 ± 0.63 (0.08 ± 0.62) 13 TeV [16]
CMS, dilepton 172.33 ± 0.70 (0.14 ± 0.69) 13 TeV [17]
CMS, all jets 172.34 ± 0.73 (0.20 ± 0.70) 13 TeV [18]
CMS, single top 172.13 ± 0.77 (0.32 ± 0.70) 13 TeV [19]
CMS, l+jets 171.77 ± 0.37 13 TeV [20]
CMS, boosted 172.76 ± 0.81 (0.22 ± 0.78) 13 TeV [21]
* Preliminary
[1] ATLAS-CONF-2013-102
[2] arXiv:1403.4427
[3] EPJC 75 (2015) 330
[4] EPJC 75 (2015) 158
[5] ATLAS-CONF-2014-055
[6] PLB 761 (2016) 350
[7] JHEP 09 (2017) 118
[8] EPJC 79 (2019) 290
[9] arXiv:2209.00583
[10] ATLAS-CONF-2022-058
[11] JHEP 12 (2012) 105
[12] EPJC 72 (2012) 2202
[13] EPJC 74 (2014) 2758
[14] PRD 93 (2016) 072004
[15] EPJC 77 (2017) 354
[16] EPJC 78 (2018) 891
[17] EPJC 79 (2019) 368
[18] EPJC 79 (2019) 313
[19] arXiv:2108.10407
[20] arxiv:2302.01967
[21] arxiv:2211.01456
165
170
175
180
185
m_top [GeV]

Top Mass

- Alternative methods of measuring mass:
  - Design cross-section measurement to be insensitive to mass.
  - Then compare to well-defined predictions



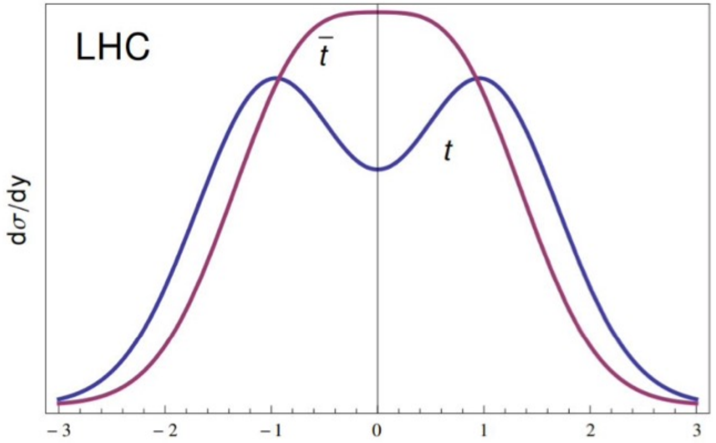
Charge Asymmetry

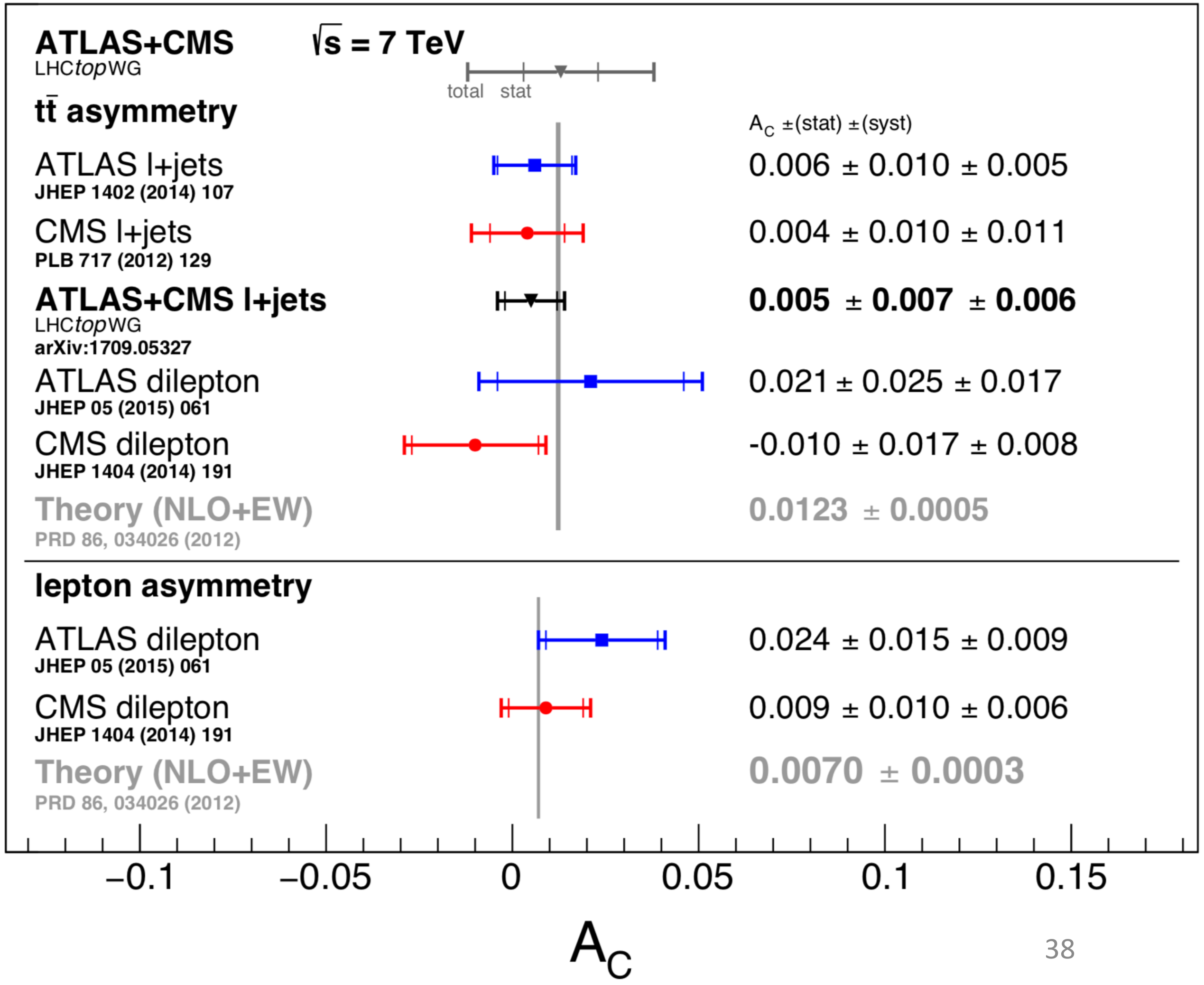
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$
$$(\Delta|y| = |y_t| - |y_{\bar{t}}|)$$

Top and anti-top quarks are not produced equally with respect to the beam direction.

Top quarks are produced preferentially in the centre of the LHC's collisions, while anti-top quarks are produced preferentially at larger angles.

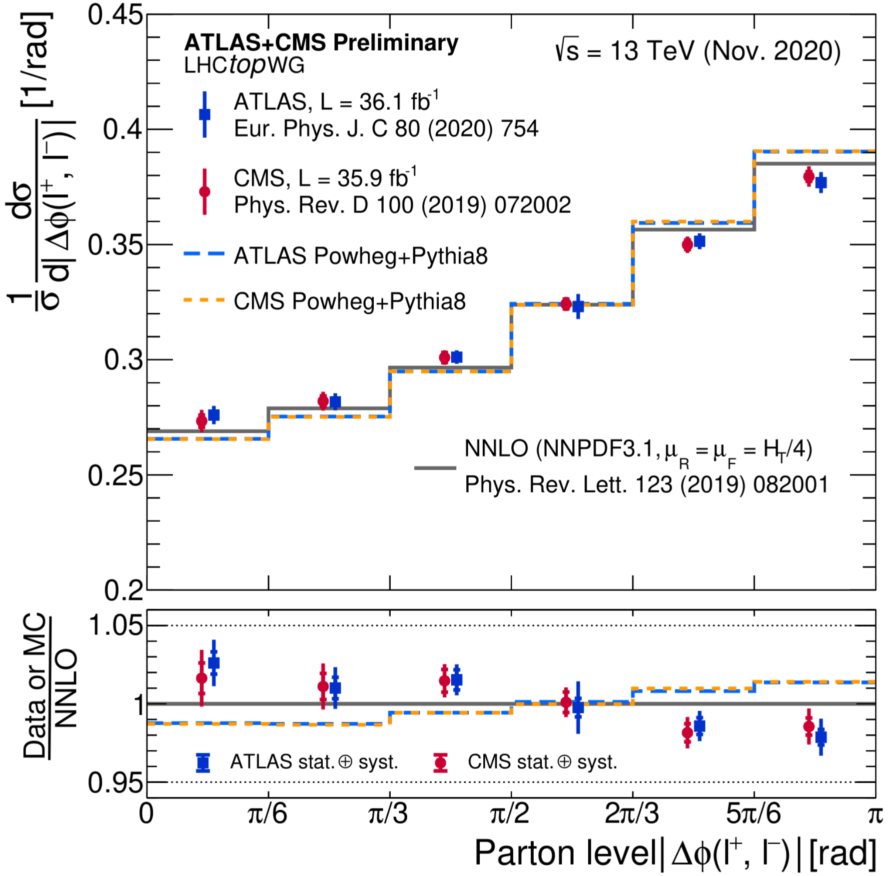
This is known as a 'charge asymmetry' and is a test of the Standard Model.





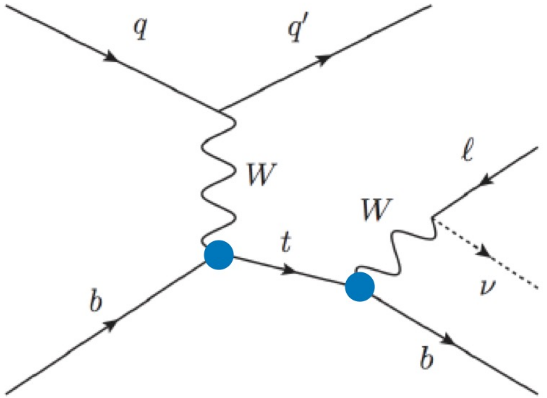
Spinning tops

- Since the top quark decays before hadronization, can study 'bare' properties.
- The spins of the top quark and the anti-top quark in a pair can be preferentially aligned or anti-aligned, depending on their production mechanism.



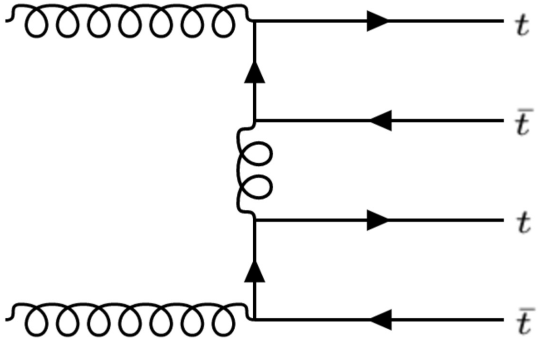
- Single-top t-channel – here in Nikhef!
  - ~30 million collisions in ATLAS Run 2
  - Probe of the electroweak interaction
  - Top is polarized due to left-handed W-coupling
  - Top spin points in the direction of the spectator-quark (q')
  - Top polarized: **sensitive to new physics**
- Systematically limited channel

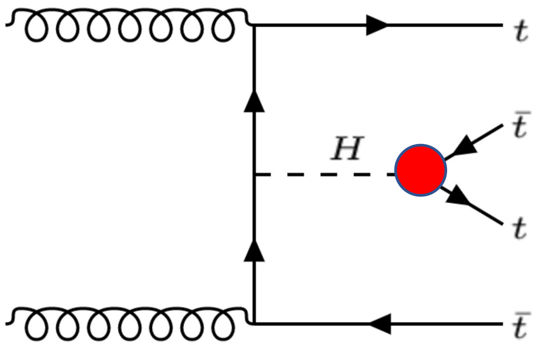
  => need to increase sensitivity and improve reconstruction.



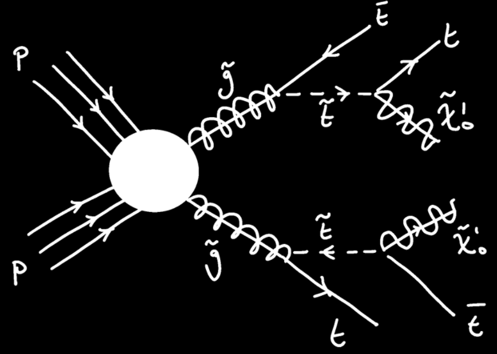
Four top quarks produced at once!

- The **rarest** process including top quarks measured at the LHC so far!
  - One event for every 70,000 top-quark pairs.
- **Heaviest** particle final state ever seen at the LHC
  - Provides physicists with a **unique opportunity** to study the top quark's relationship to the Higgs boson.

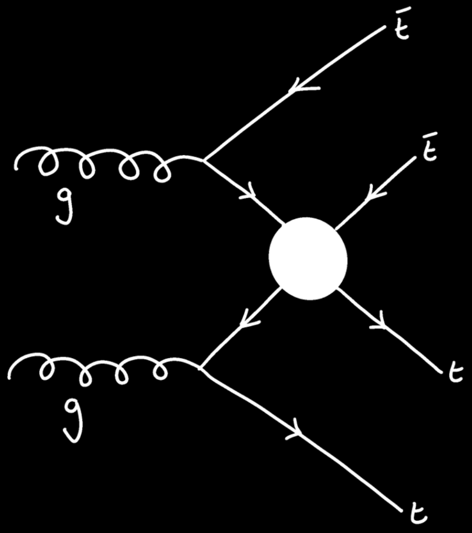




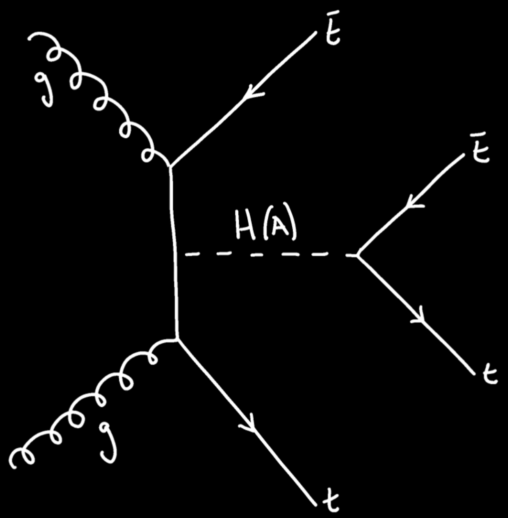
SUSY (gluino/sgluino pair, for example)



Contact Interaction



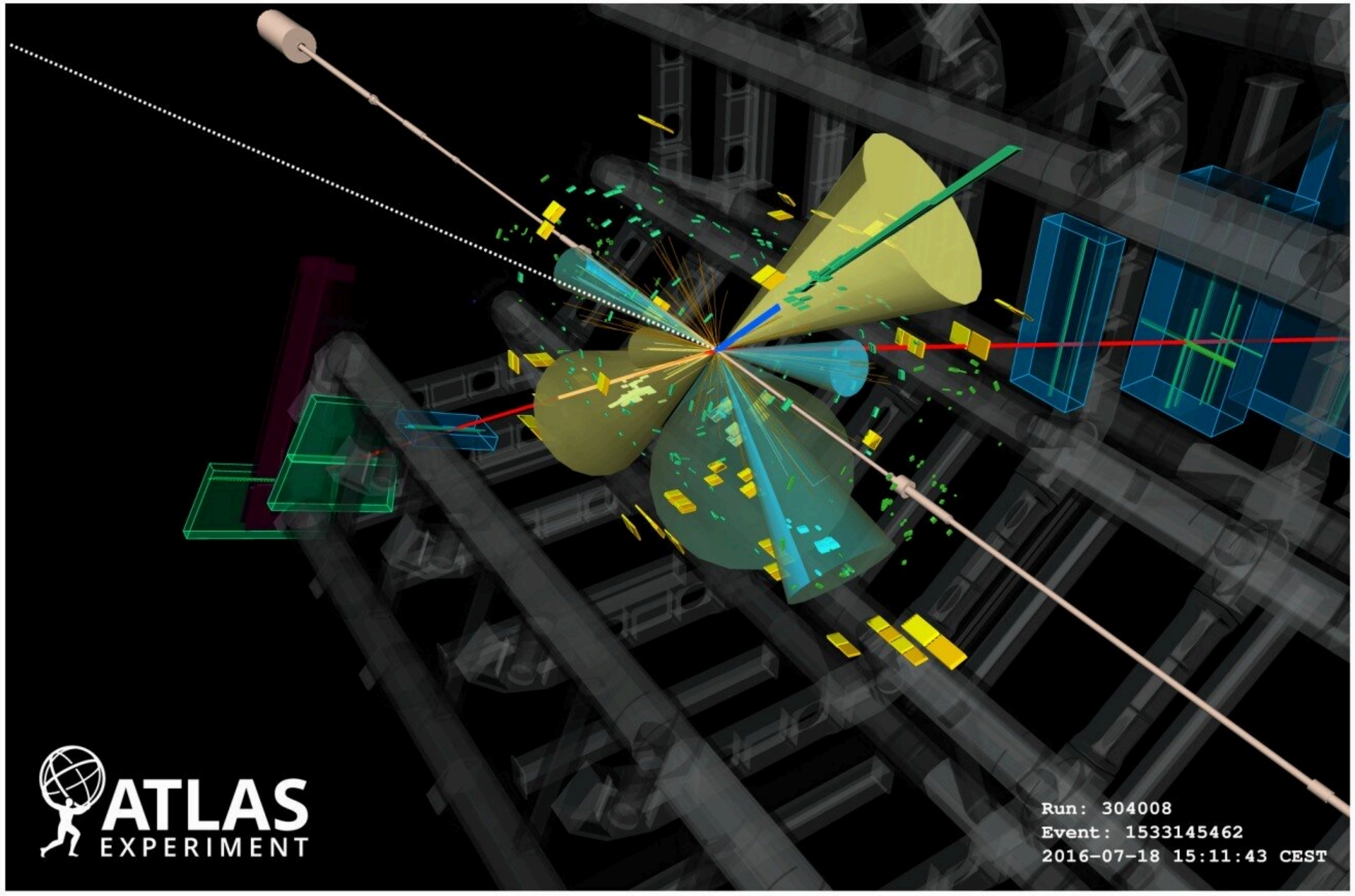
2HDM

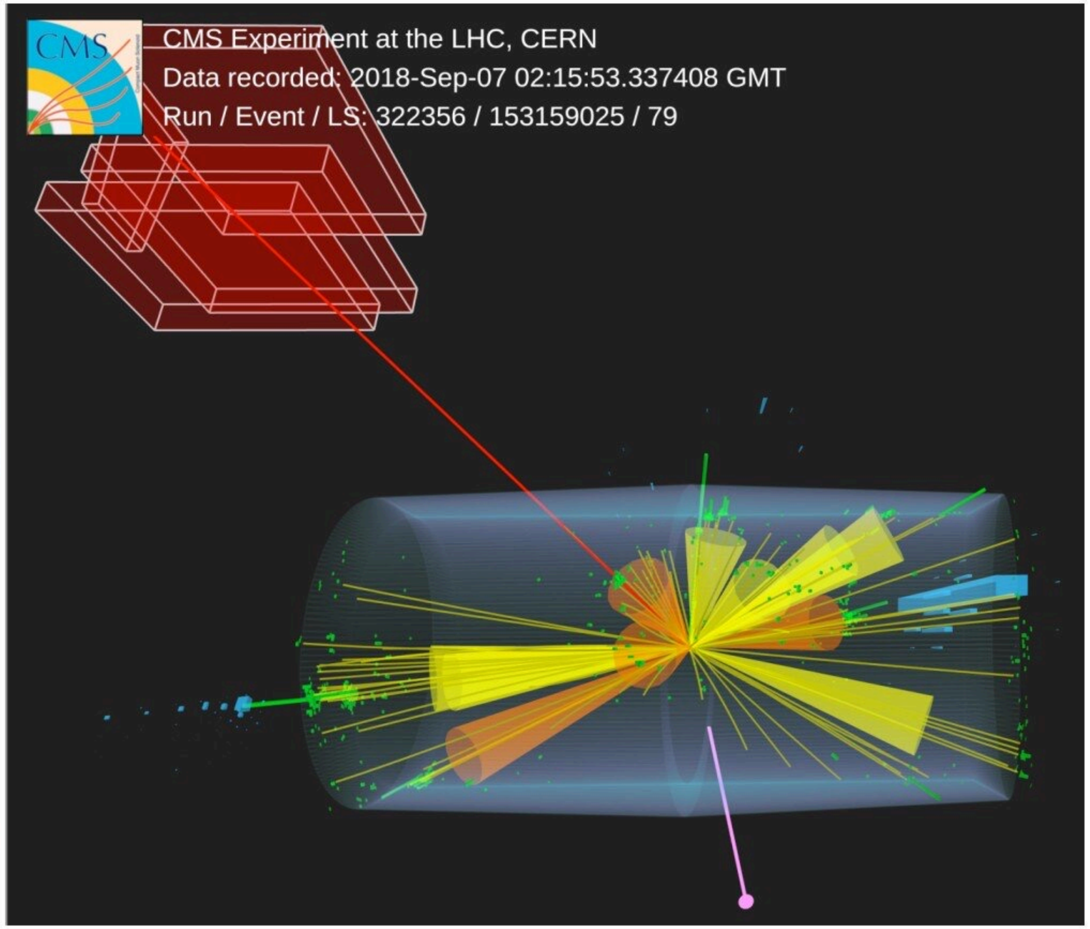


Production rate could be **enhanced** by various new BSM theories

- ➢ providing a unique **window** to search for new physics.

Four top quarks produced at once!





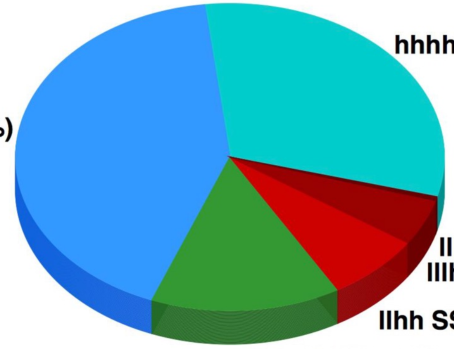
Four top production cross-section

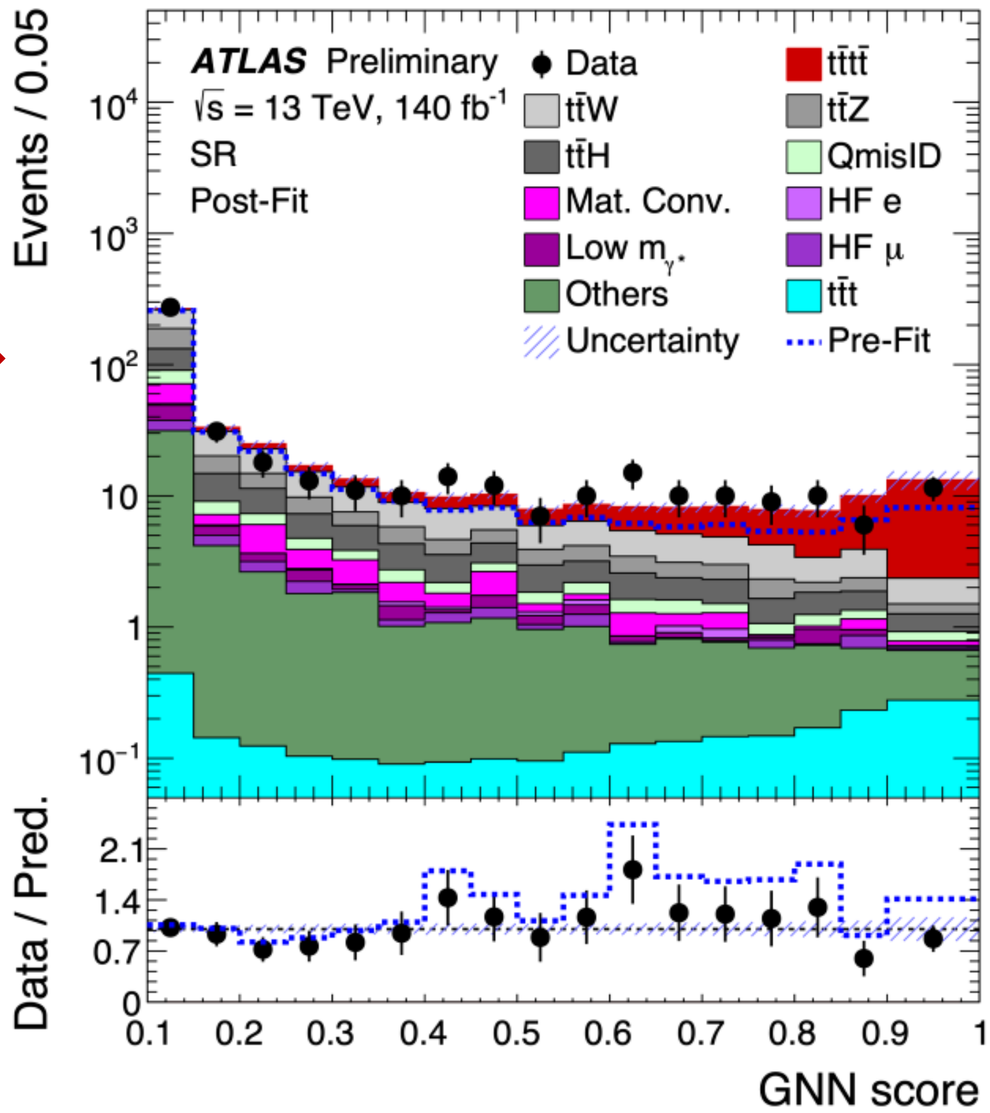
A maximum likelihood fit is performed with all systematic uncertainties included.

The predicted cross-section is:
SM NLO QCD+EW: **12.0** +2.0 –2.5 fb [JHEP02(2018)031]

Signature: from 0-4 charged leptons and up to 12 jets produced by the quarks!

Multi-lepton channel (2LSS/3L):
Low branching fraction (13%).
Cleaner signal.
Single lepton / dilepton opposite sign (1L/2LOS):
Higher branching fraction (57%).
Suffers from a large irreducible background.





Four top production cross-section

The signal strength (measured XS / SM prediction):

$$\mu = 1.9 \pm 0.4(\text{stat})\,^{+0.7}_{-0.4}(\text{syst}) = 1.9\,^{+0.8}_{-0.5}.$$

Therefore the measured cross-section is:

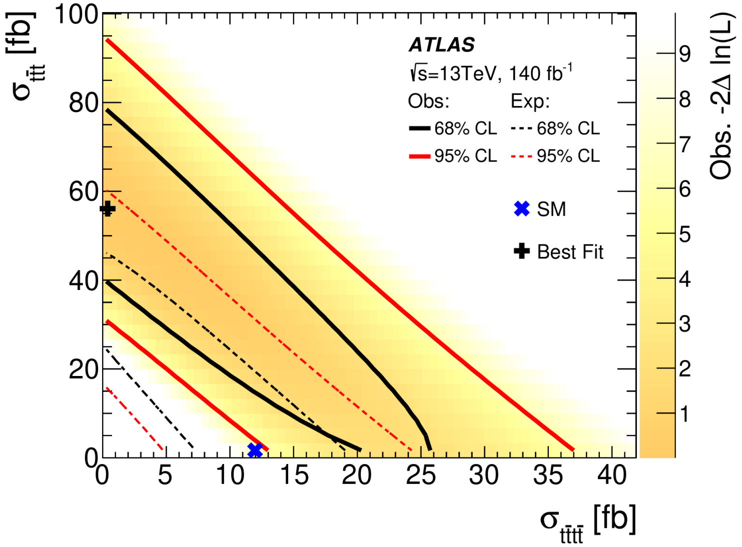
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\text{ fb} = 22.5\,^{+6.6}_{-5.5}\text{ fb}.$$

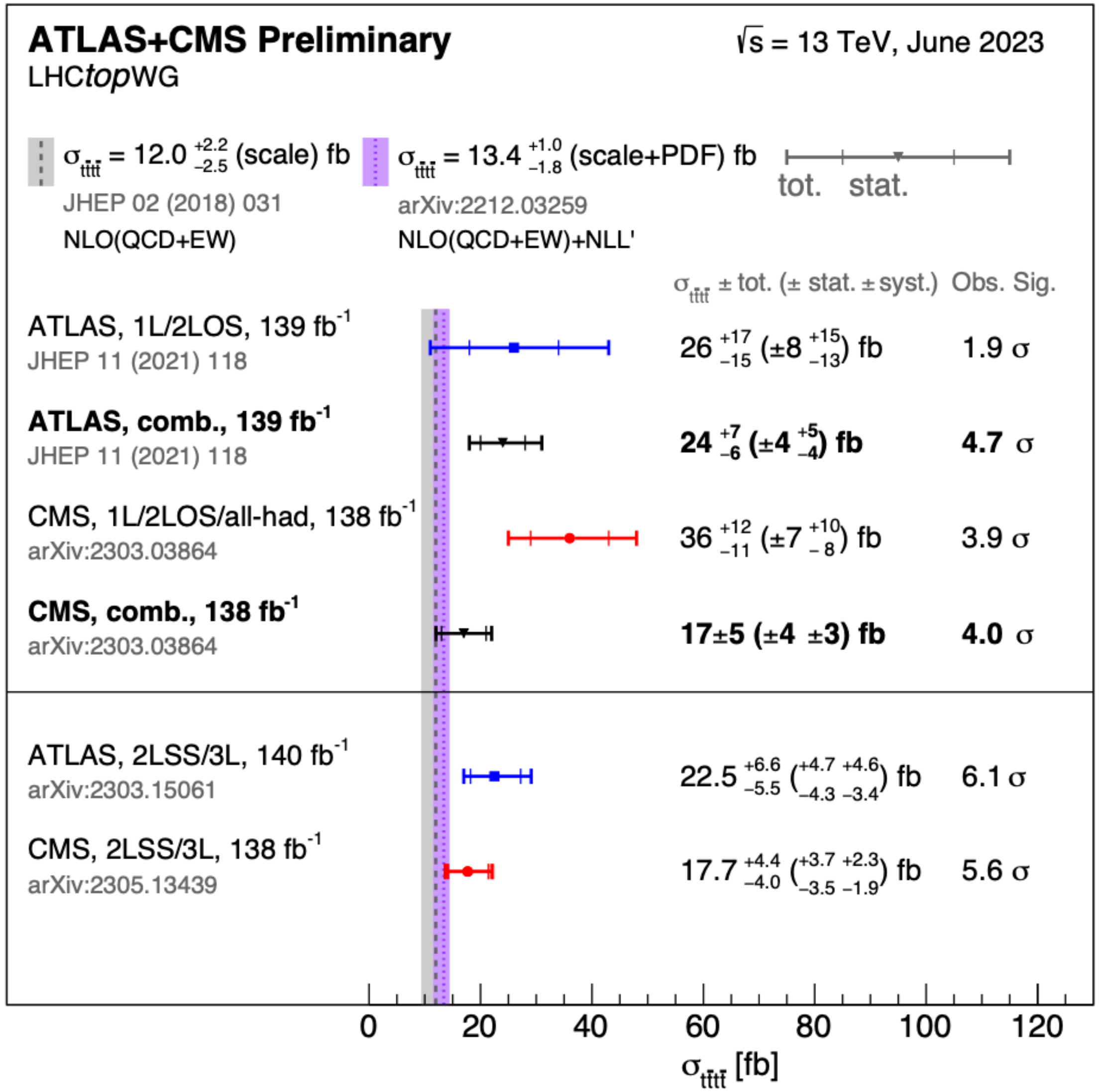
Gives us an observed (expected) significance of:

- 6.1 (4.3) standard deviations
  => OBSERVATION!

Triple top quarks:

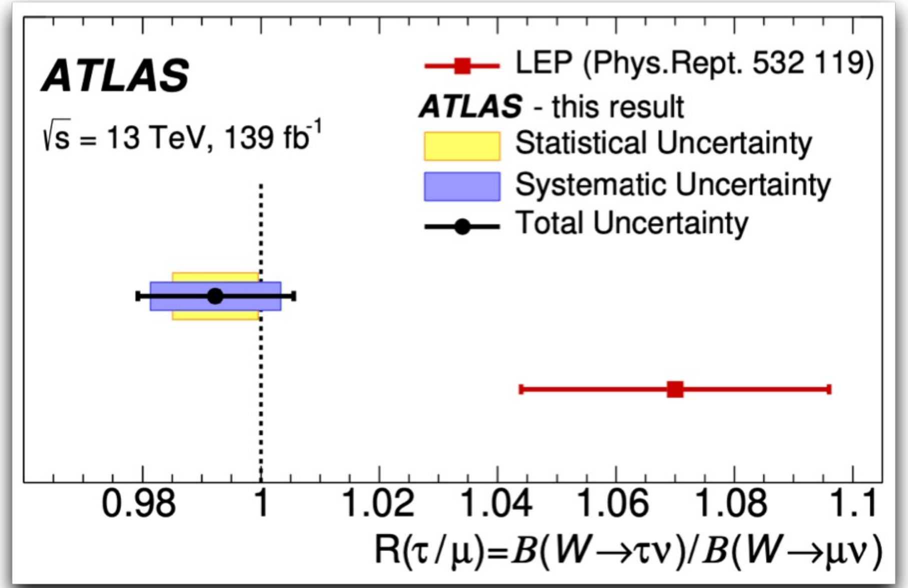
- always produced in association with other particles
- split into the $tt\bar{t}W$ & $tt\bar{t}q$ processes





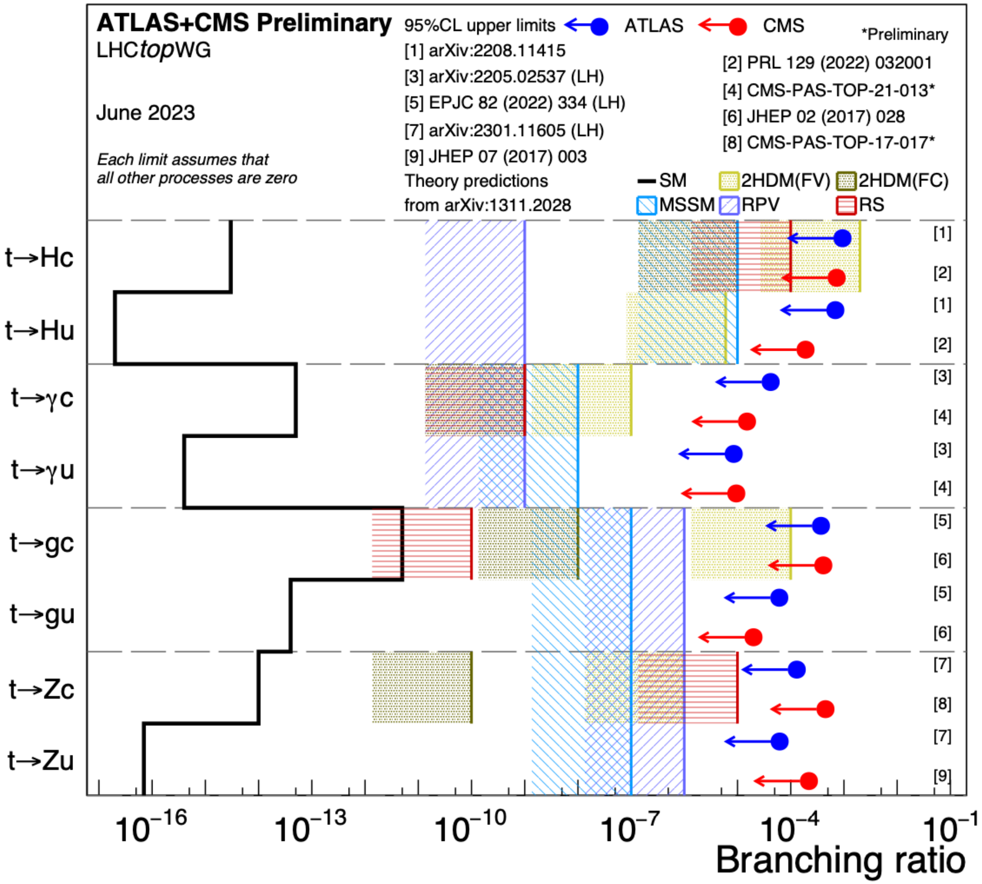
Lepton Flavour Universality

- In the Standard Model, leptons coupling to W&Z bosons is not dependent on mass.
  - ⇒ Lepton flavour should be universal.
  - ⇒ But we want to test it!
- We measure the ratio of two decays and see how far it is from 1.



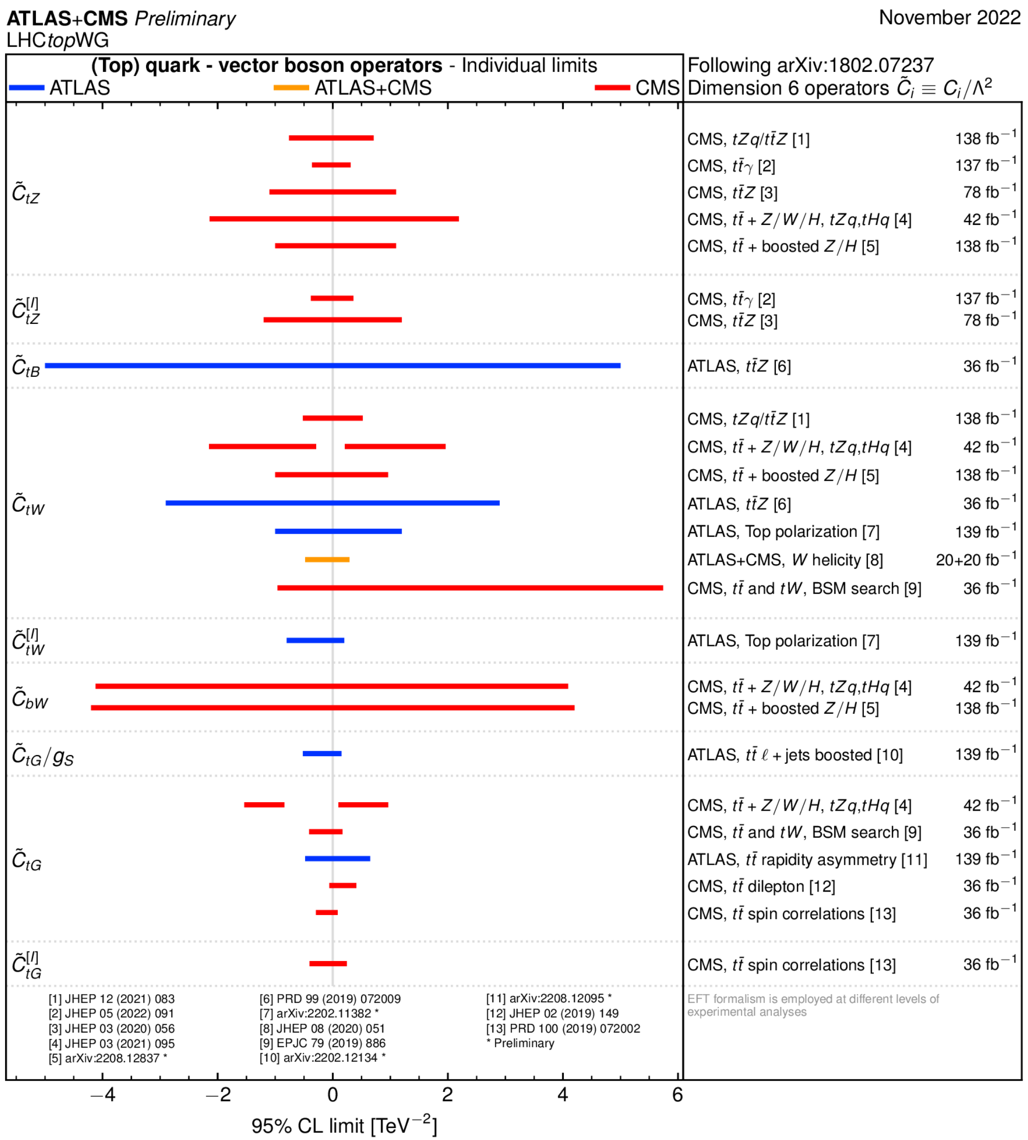
Flavour Changing Neutral Current

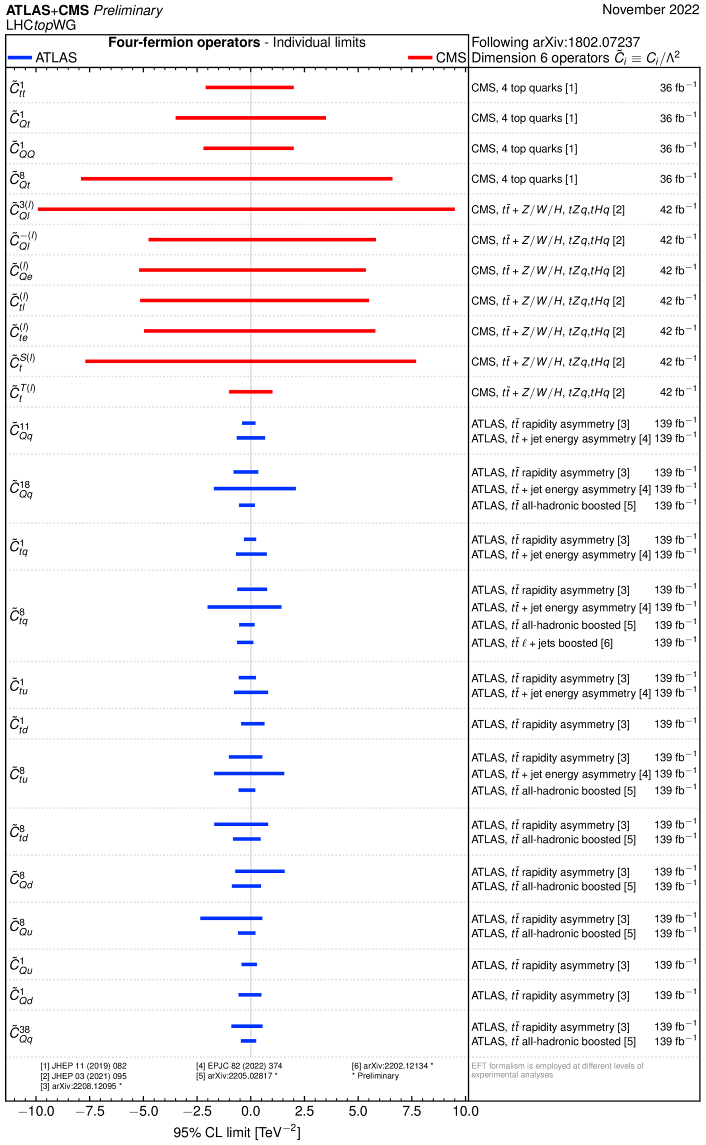
- Changing the flavour of a particle without changing the charge.
  - => If they occur, it's a clear indication of new physics.



Effective Field Theory (EFT) with tops

- Allows us to test for new physics in a model independent way
- Plenty of EFT activity going on at the LHC with top quarks
- Comparisons are already a reality
- Combinations in progress between CMS and ATLAS



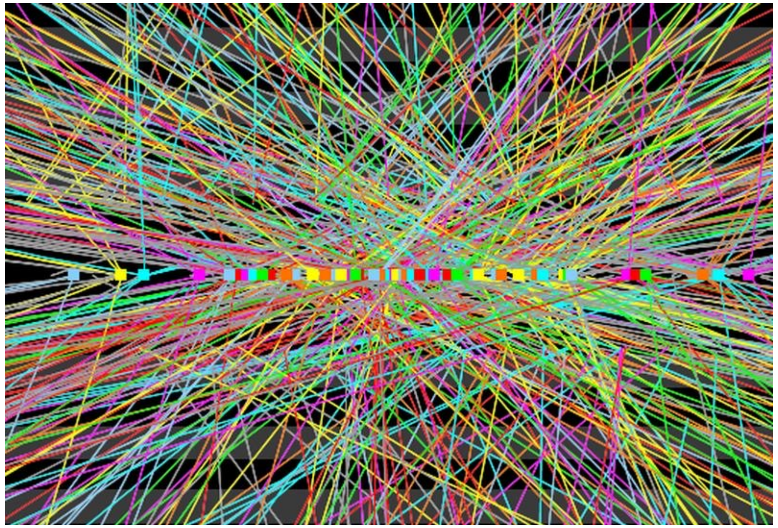


The LHC schedule

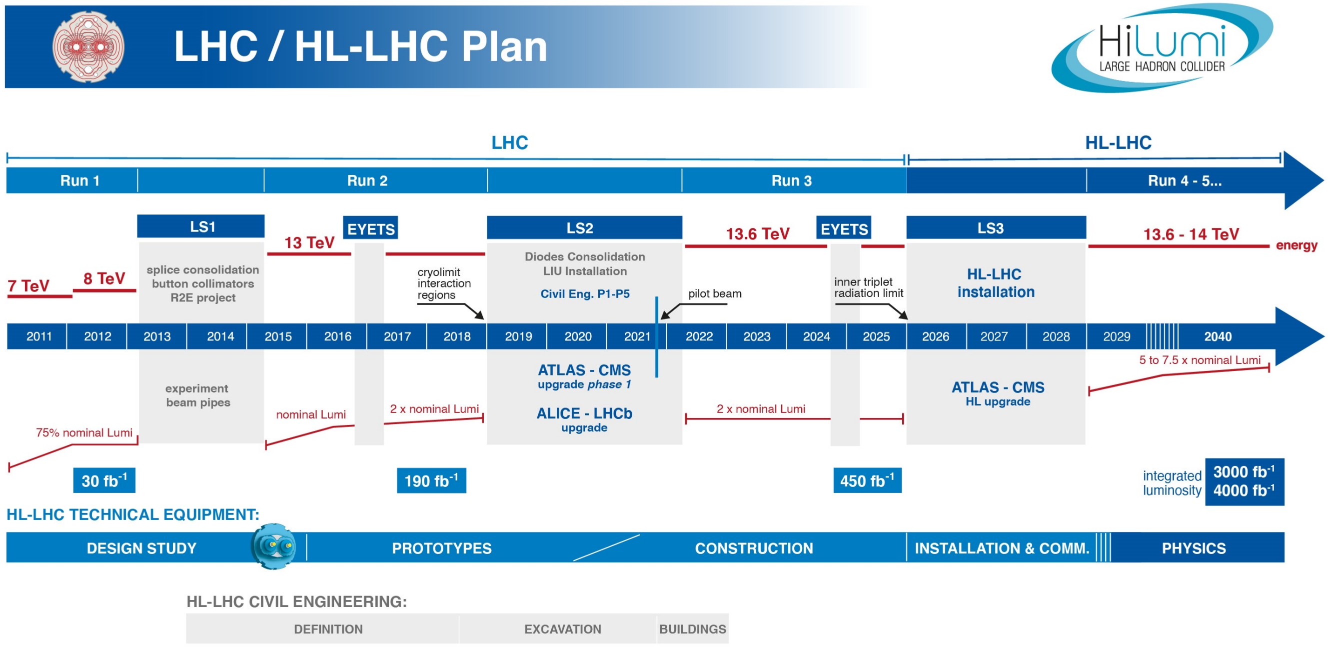
Have only taken ~ 10% of planned data so far

More on this from Ewen this afternoon.

Tops at the the HL-LHC?



- Increase the integrated luminosity by a factor of 10 beyond the LHC design luminosity
  - Integrated luminosity 3000-4000fb^{-1}
  - Expected pile-up (PU)
    140-200 collisions per bunch crossing



- Increased data is going to greatly benefit the measurement of rare processes.
- Pile-up is going to be a huge challenge
- ATLAS upgrades:
  - Completely new tracking detector (ITk)
    - Extended to $|\eta|=4.0$
  - Timing detector (HGTD)
    - Time resolution of 30 ps

The future is top!

- The top quark is 28 this year!
  - And yet there's still so much to learn about & from this particle.

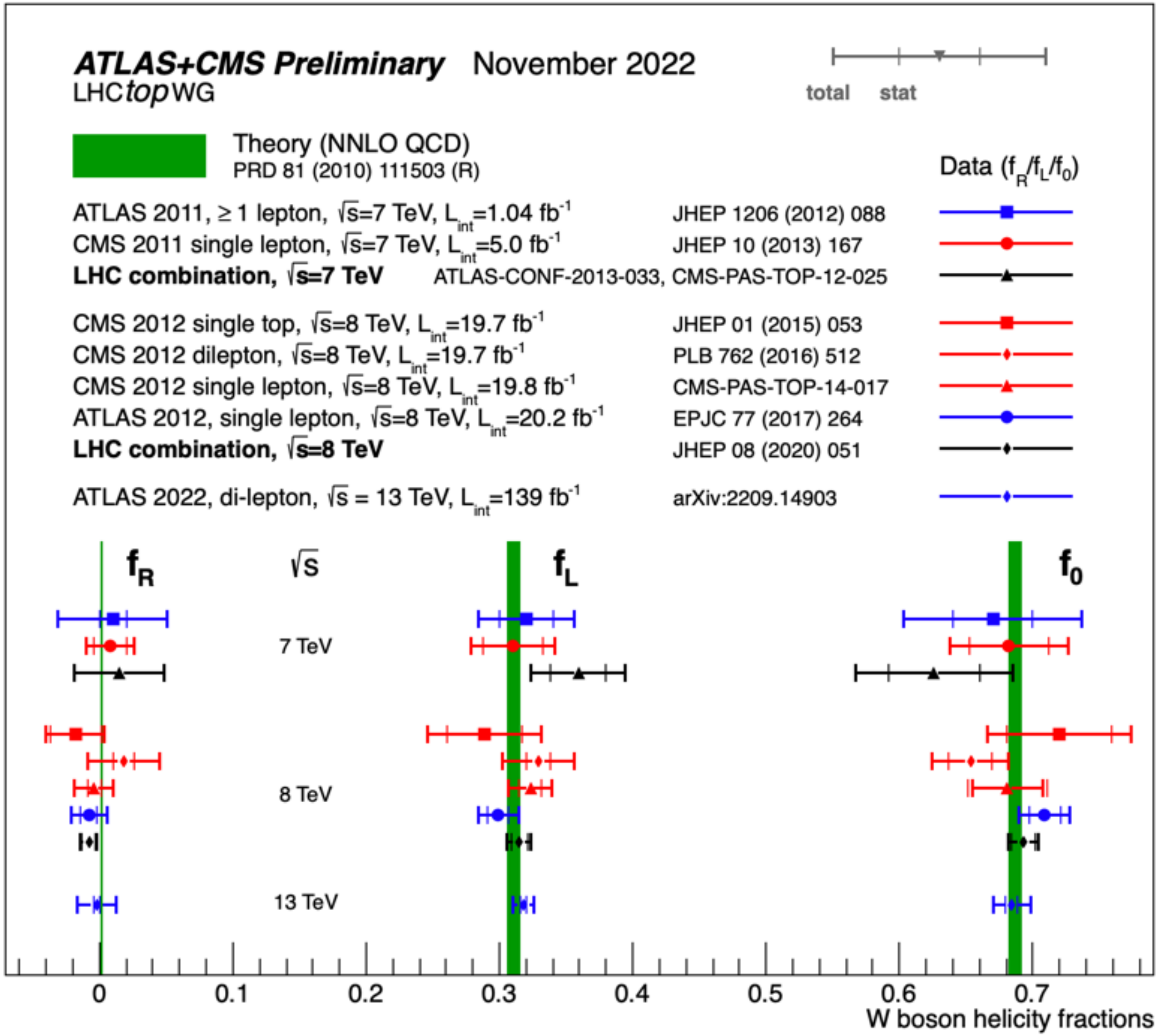
- So far there has been no concrete sign of new physics in top data, but plenty of analyses with machine learning and EFT measurements still to come.

thank you!

Backup

Here's one I prepared earlier

W-helicity


ATLAS+CMS Preliminary November 2022
LHCtopWG
total stat
Theory (NNLO QCD)
PRD 81 (2010) 111503 (R)
Data (f_R/f_L/f_0)
ATLAS 2011, ≥ 1 lepton, √s=7 TeV, L_int=1.04 fb^-1 JHEP 1206 (2012) 088
CMS 2011 single lepton, √s=7 TeV, L_int=5.0 fb^-1 JHEP 10 (2013) 167
LHC combination, √s=7 TeV ATLAS-CONF-2013-033, CMS-PAS-TOP-12-025
CMS 2012 single top, √s=8 TeV, L_int=19.7 fb^-1 JHEP 01 (2015) 053
CMS 2012 dilepton, √s=8 TeV, L_int=19.7 fb^-1 PLB 762 (2016) 512
CMS 2012 single lepton, √s=8 TeV, L_int=19.8 fb^-1 CMS-PAS-TOP-14-017
ATLAS 2012, single lepton, √s=8 TeV, L_int=20.2 fb^-1 EPJC 77 (2017) 264
LHC combination, √s=8 TeV JHEP 08 (2020) 051
ATLAS 2022, di-lepton, √s = 13 TeV, L_int=139 fb^-1 arXiv:2209.14903
f_R
√s
f_L
f_0
7 TeV
8 TeV
13 TeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
W boson helicity fractions