Four Top Quarks: Evidence in ATLAS

Dr Clara Nellist

(she / her)

Excellence Initiative Fellow

Radboud University and NIKHEF

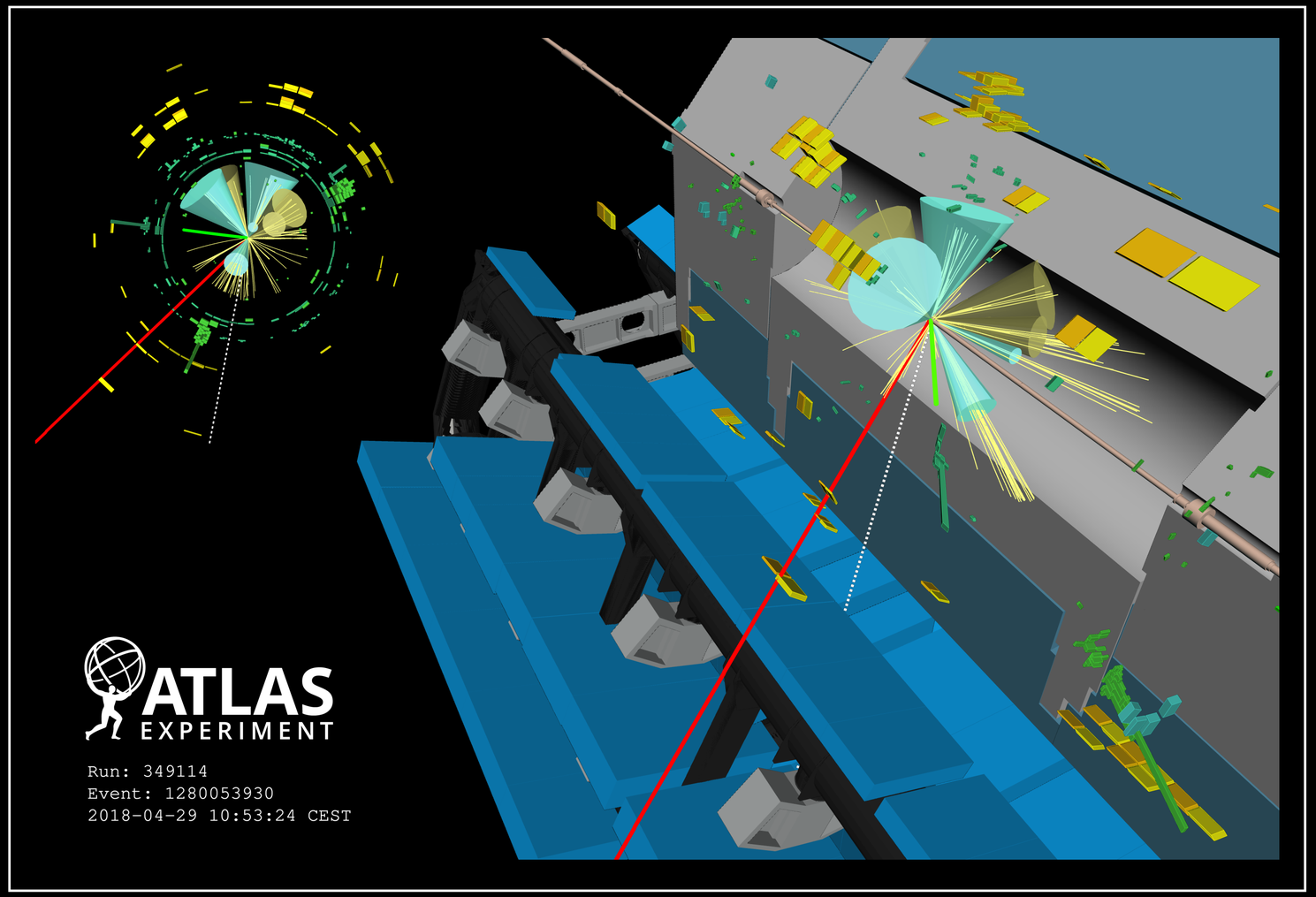
Online Particle Physics Seminar, Warwick UK

24.06.2021

Nikhef

Radboud University

Nijmegen, the Netherlands

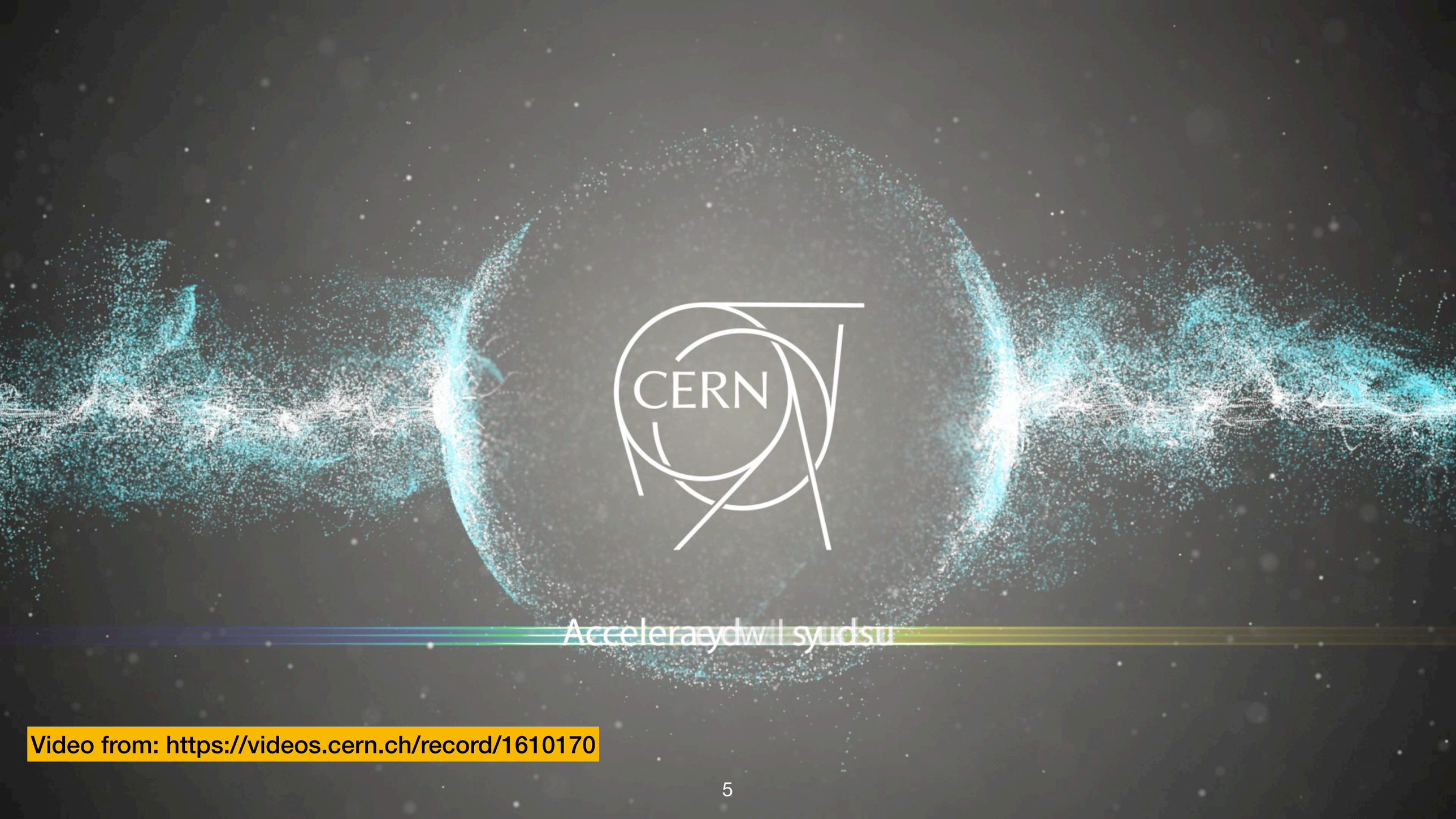


Added afterwards:

This presentation contained many videos. These cannot be embedded in a PDF, so I have instead added the link to the relevant CDS location for them. Let me know if you'd like advice to use them in a presentation too, I'm happy to help!

Sadly I can’t be there in person today, but here’s the selfie I would have taken.


CERN



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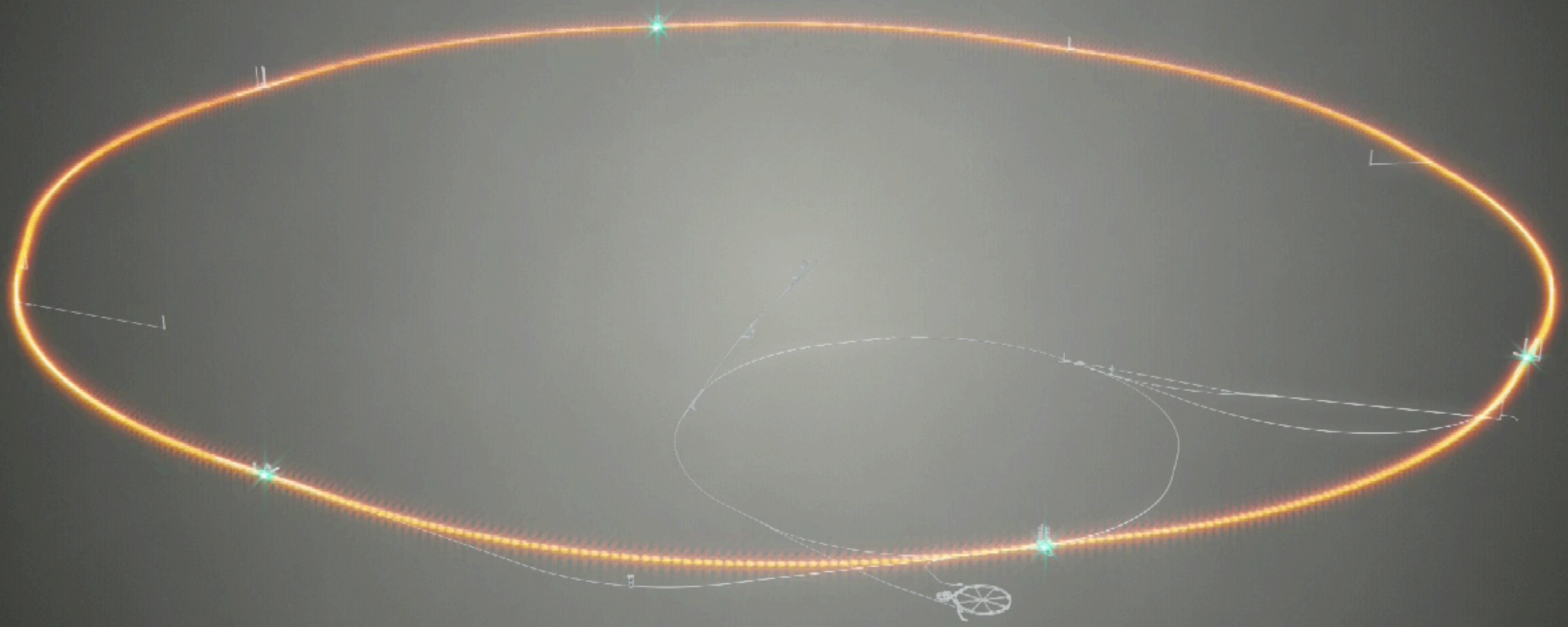

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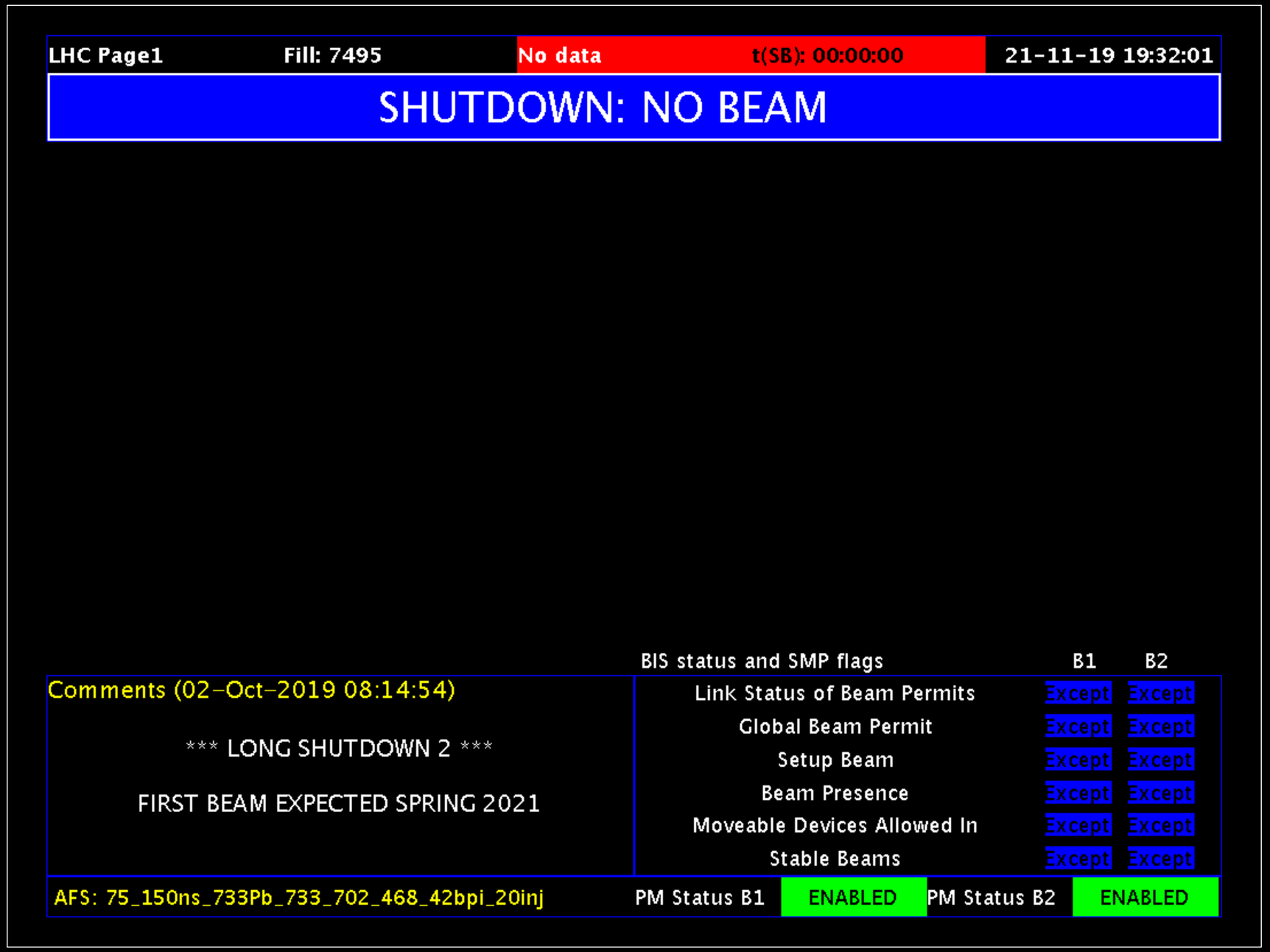
Right now:


LHC Page1
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21-11-19 19:32:01
SHUTDOWN: NO BEAM
BIS status and SMP flags
B1
B2
Comments (02-Oct-2019 08:14:54)
*** LONG SHUTDOWN 2 ***
FIRST BEAM EXPECTED SPRING 2021
Link Status of Beam Permits
Global Beam Permit
Setup Beam
Beam Presence
Moveable Devices Allowed In
Stable Beams
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PM Status B1
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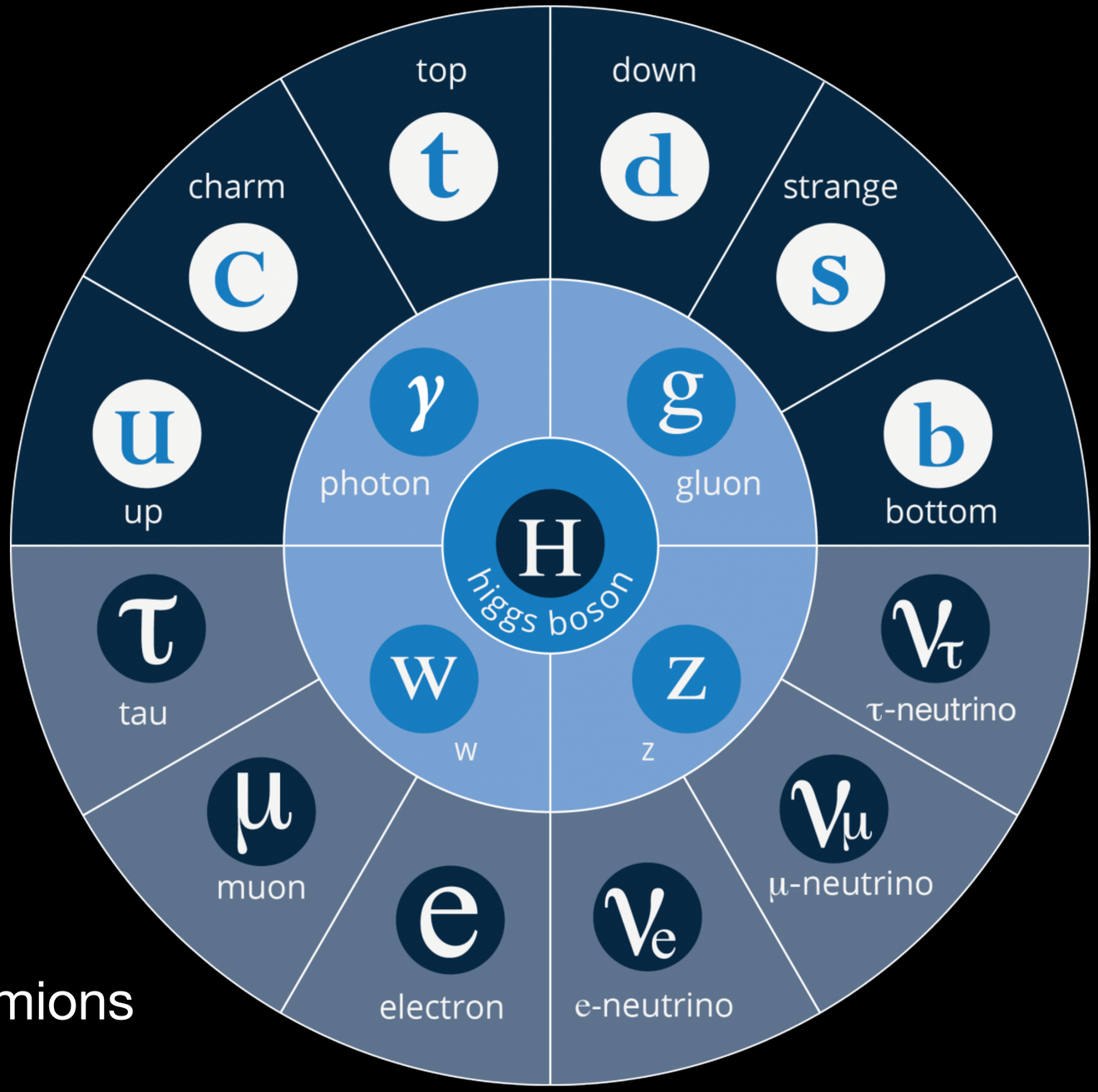
PM Status B2
ENABLED

The Standard Model



Quarks

Leptons

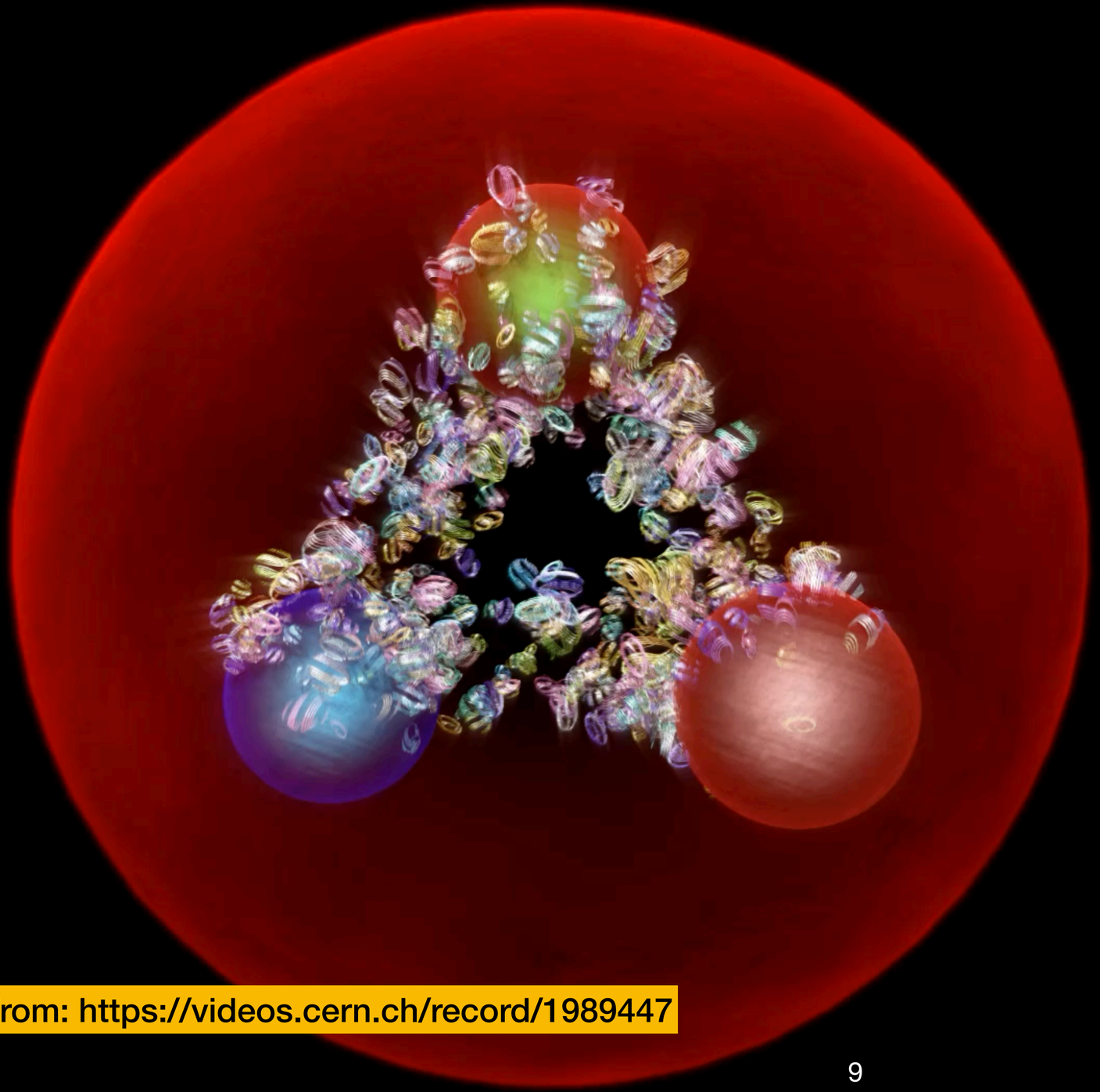
} Fermions

Bosons

Electromagnetism

The Strong Force

Weak-Nuclear Force



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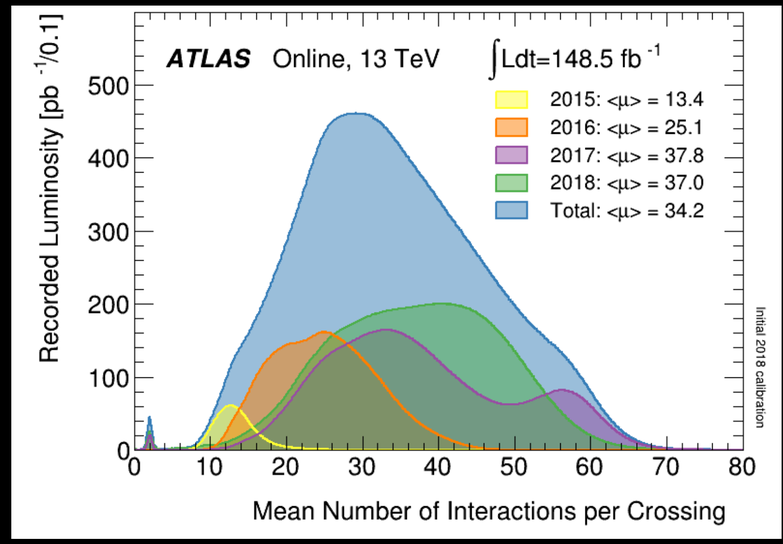
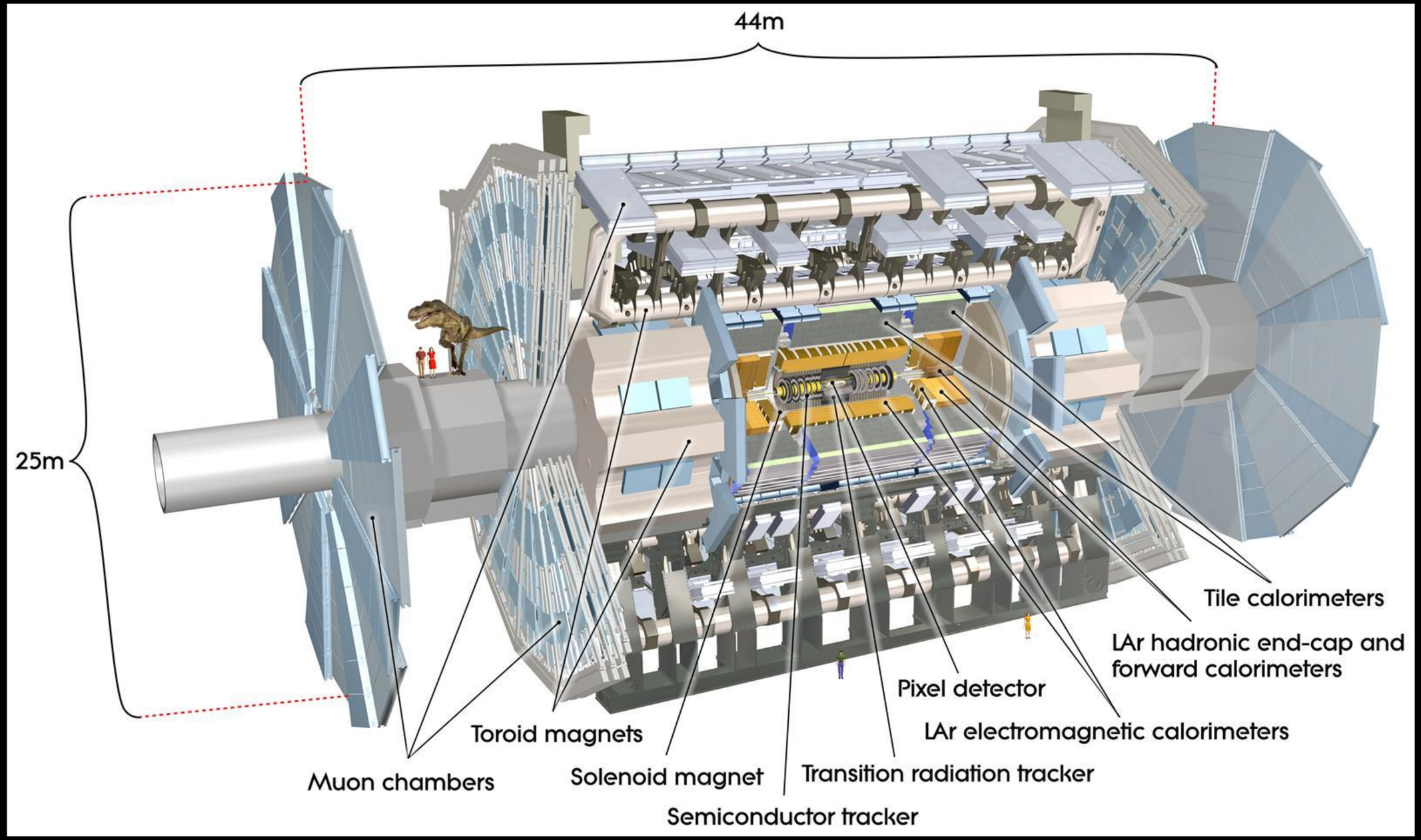
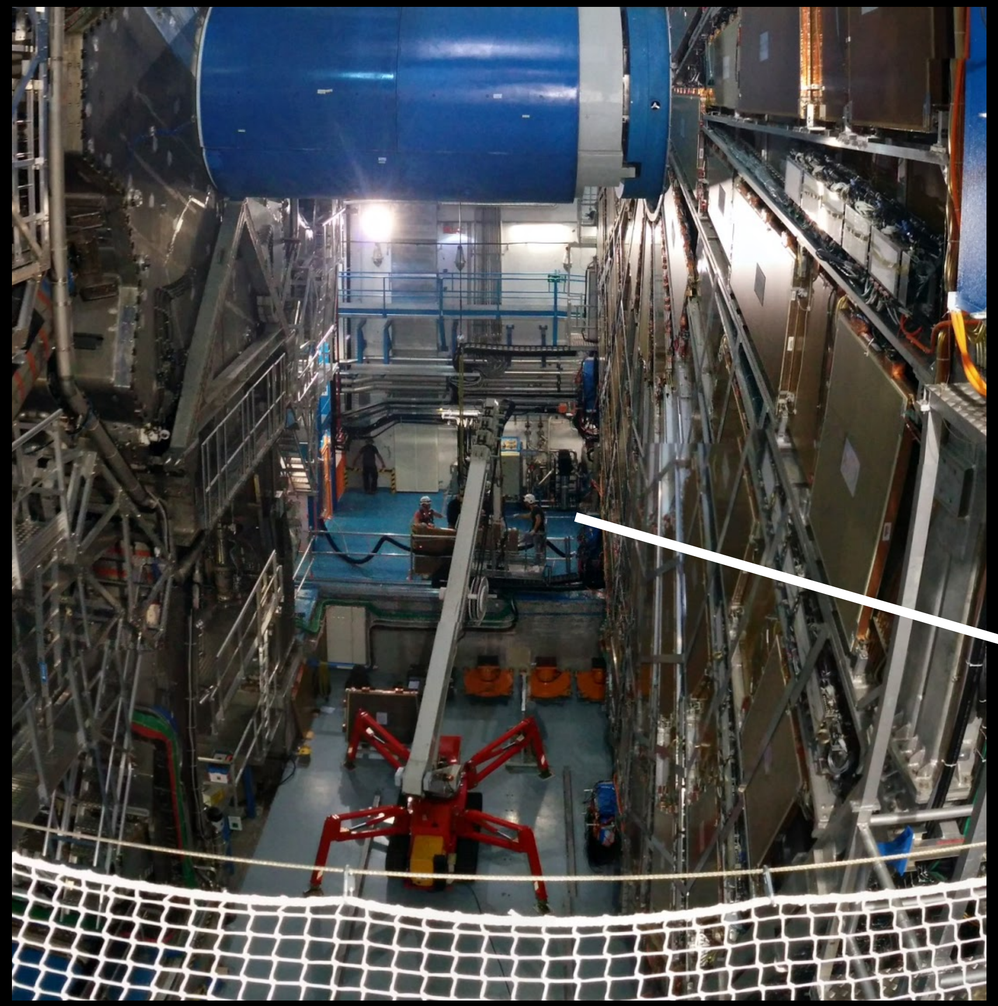
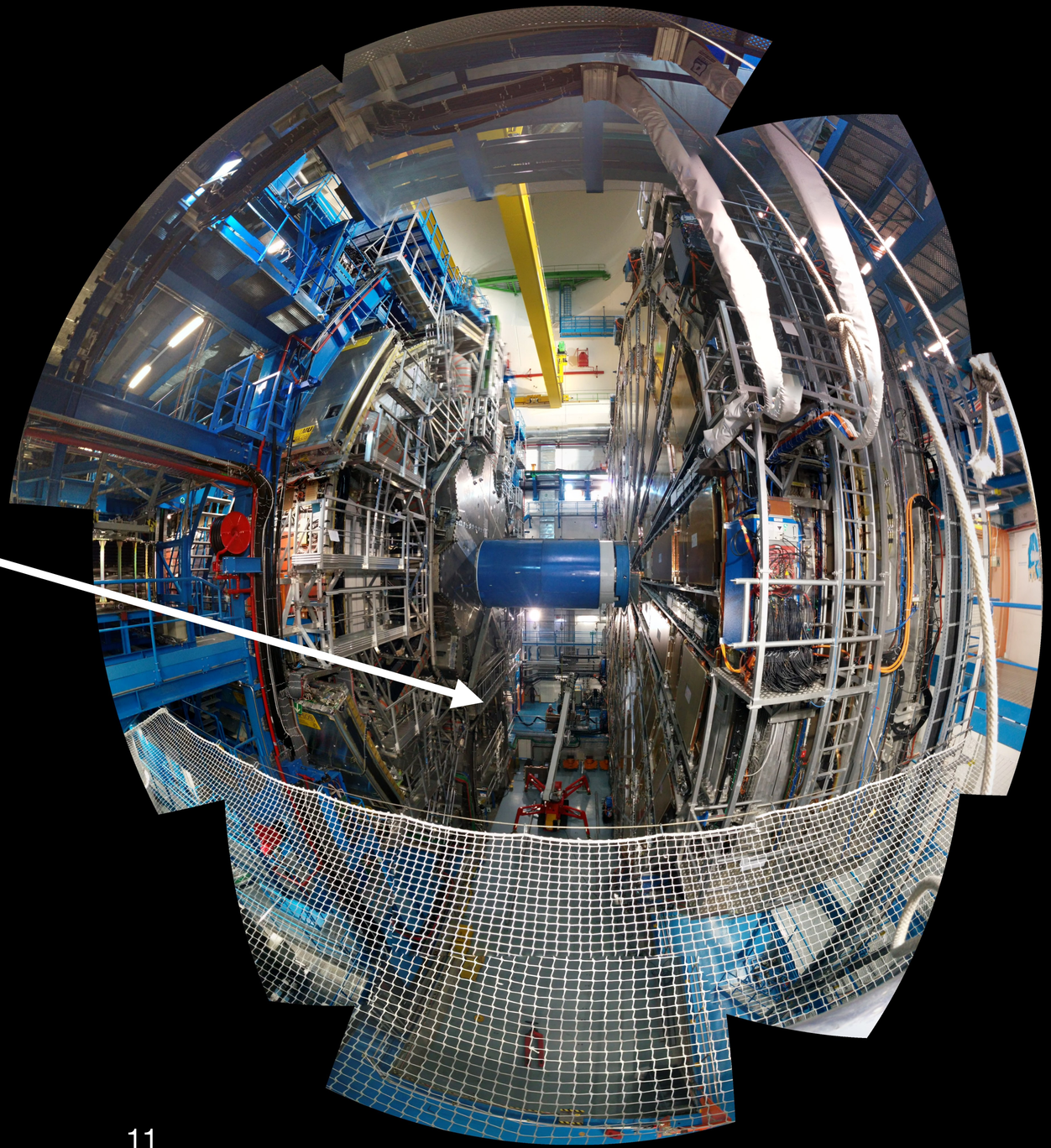



44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker





Status: November 2018

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Algeria
Argentina
Armenia
Australia
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Azerbaijan
Bangladesh
Belarus
Belgium
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Botswana
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Bulgaria
Burundi
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Costa Rica
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Honduras
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Israel
Italy
Japan
Jordan
Kazakhstan
Kenya
Kyrgyzstan
Latvia
Lebanon
Lithuania
Luxembourg
Madagascar
Malaysia
Malta
Mauritius
Mexico
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Morocco
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Netherlands
New Zealand
Niger
Nigeria
Norway
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Peru
Philippines
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Romania
Russia
Saudi Arabia
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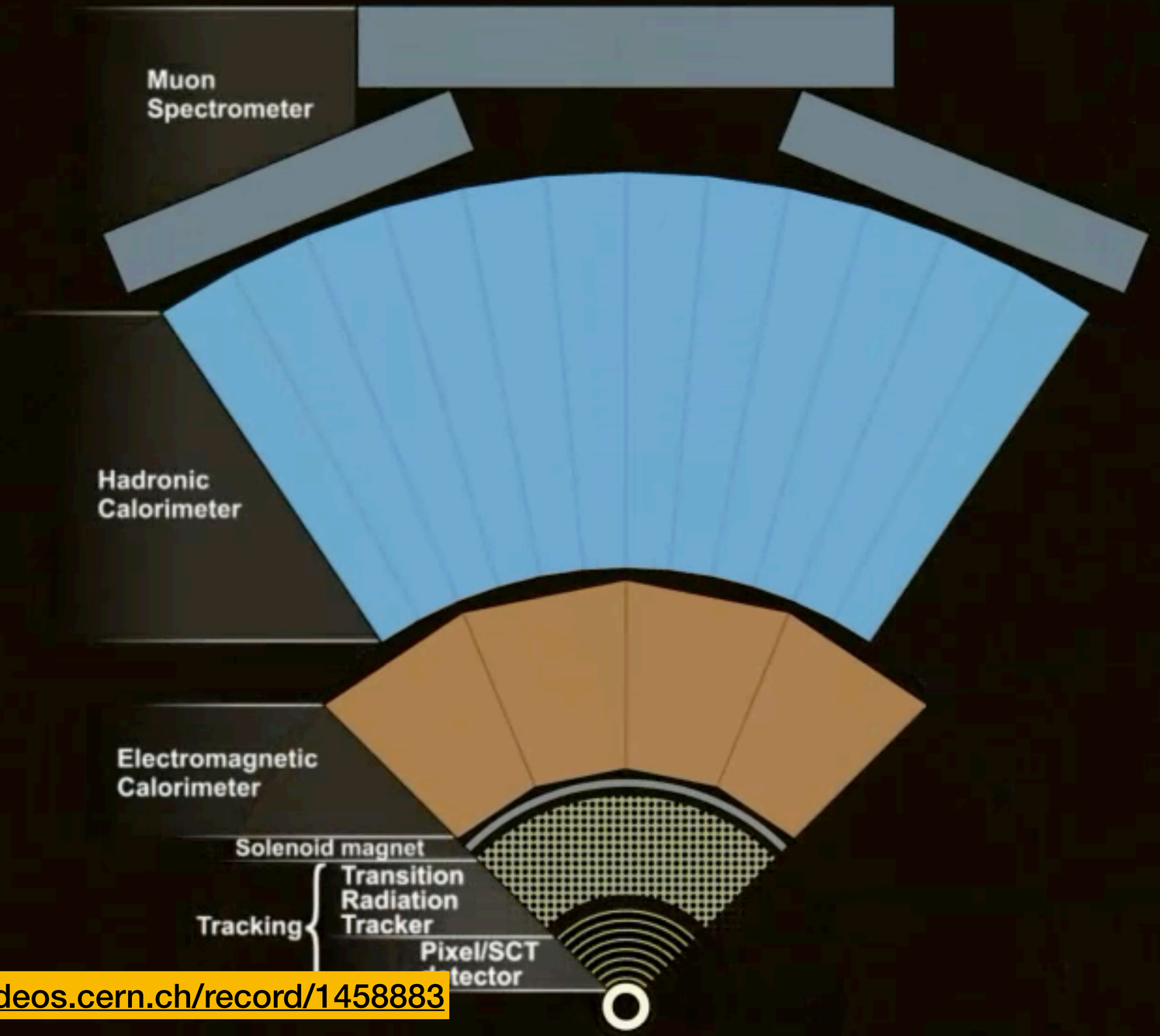
South Africa
South Korea
Spain
Sri Lanka
Sudan
Swaziland
Sweden
Switzerland
Syria
Taiwan
Thailand
Tunisia
Turkey
Ukraine
UAE
UK
USA
Uruguay
Uzbekistan
Venezuela
Vietnam
Zambia
Zimbabwe

ATLAS Collaboration member nationalities

Over 5500 members of 103 nationalities

ATLAS EXPERIMENT



Video from: https://videos.cern.ch/record/1458883

Video from: https://videos.cern.ch/record/1541893

Google Search I'm Feeling Lucky

Stay At Home. Protect the NHS. Save Lives

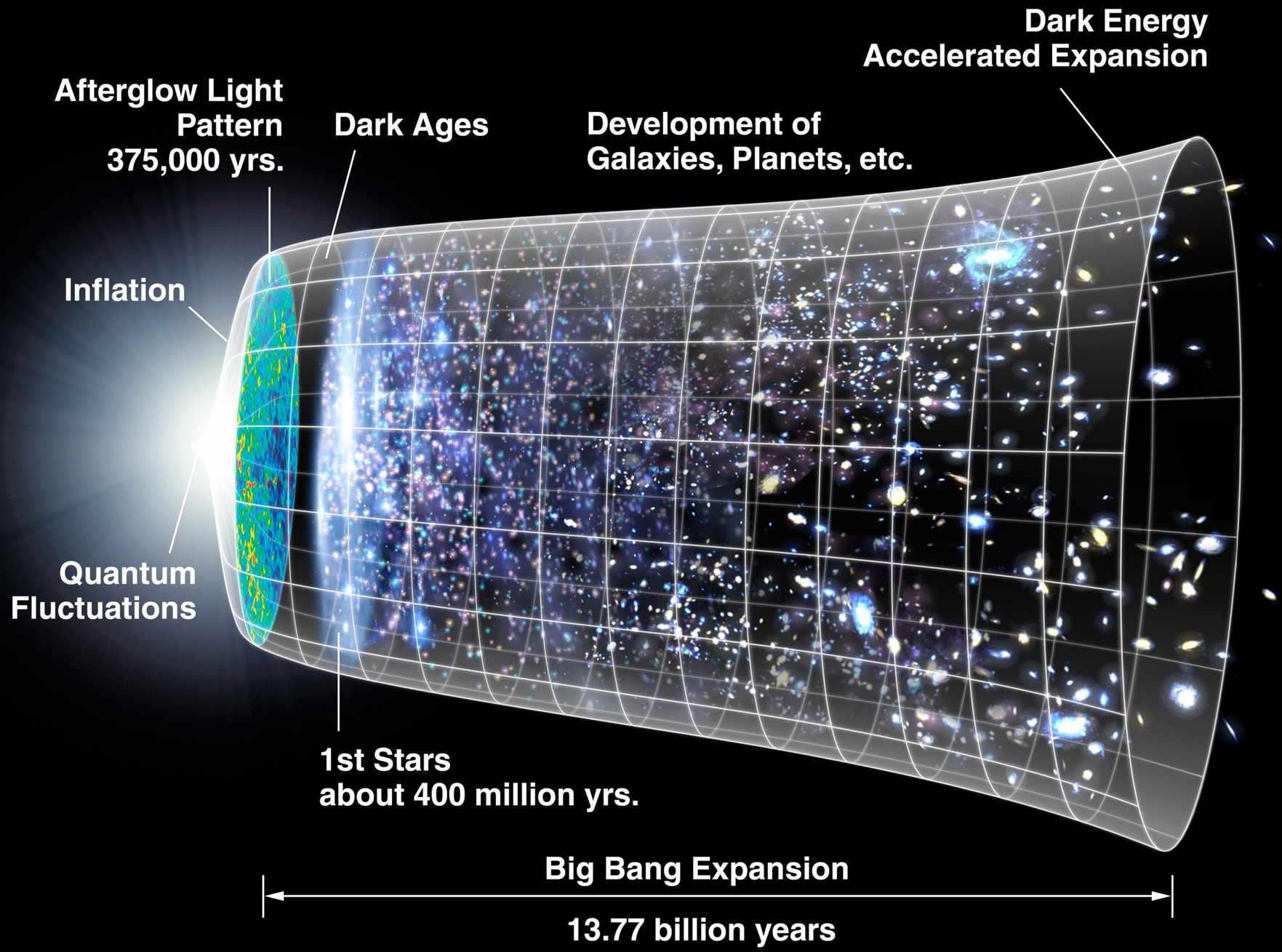

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Image: NASA

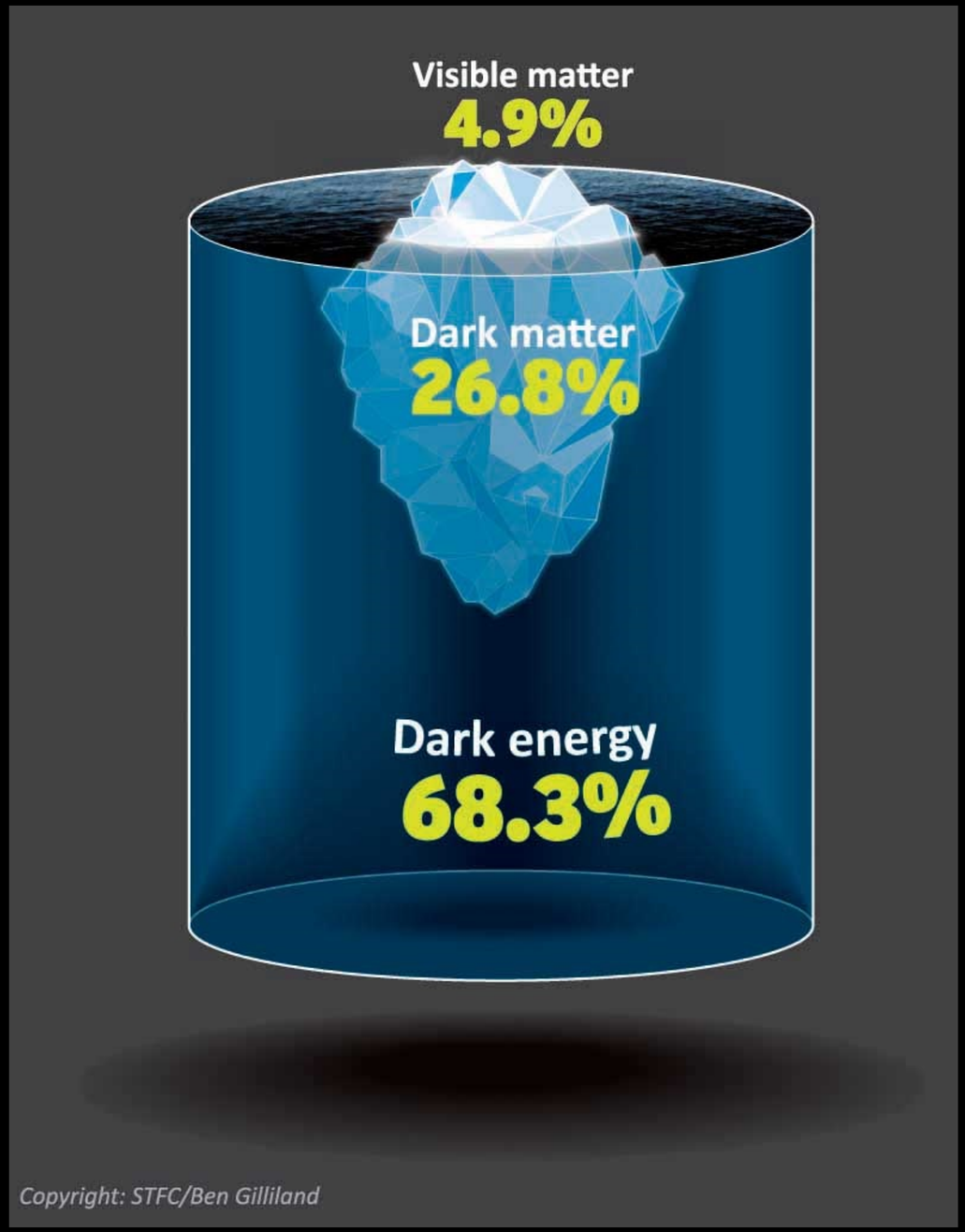
The Big Questions

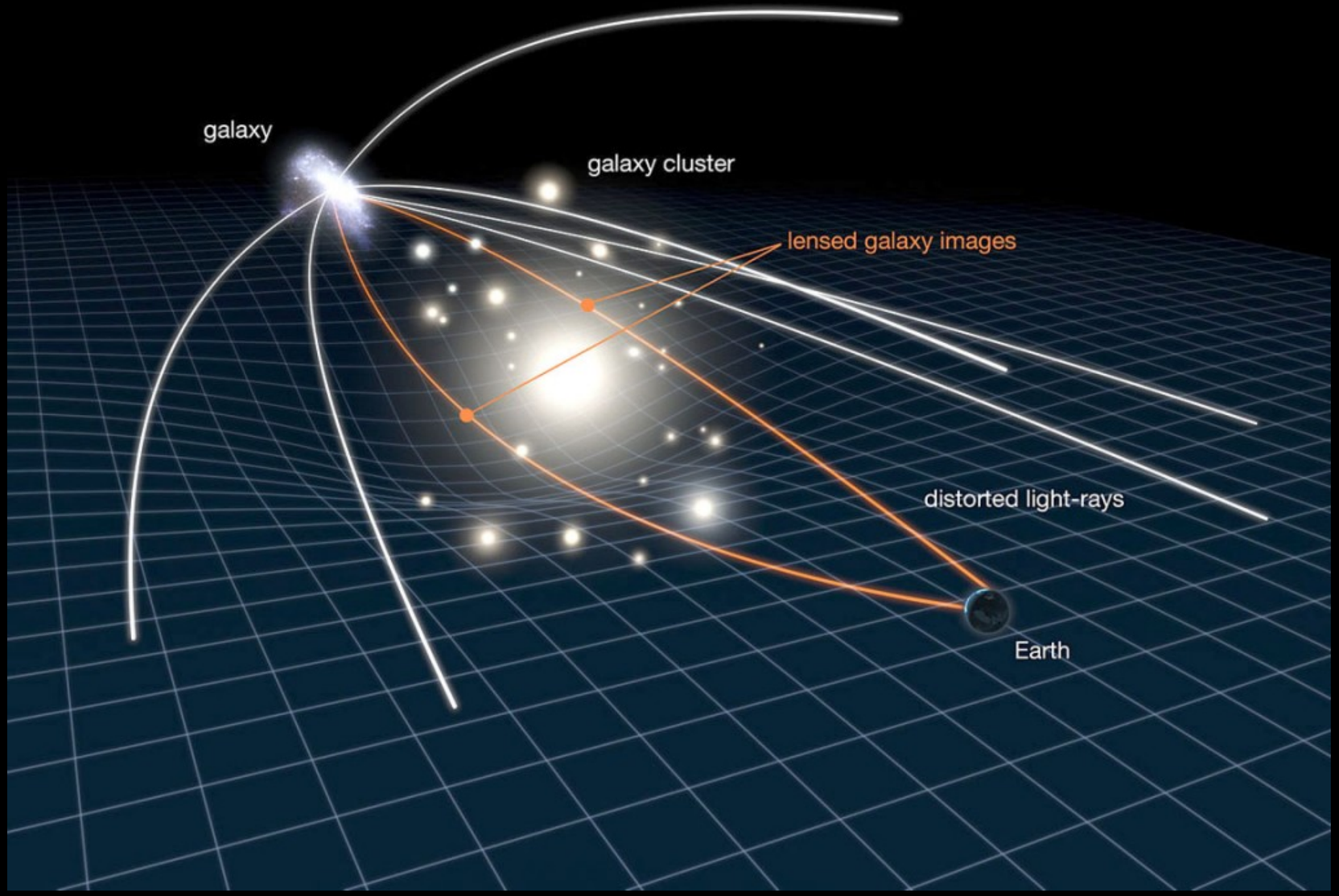
- The Higgs Boson

Image: Jorge Cham / PhD Comics

The Big Questions

- The Higgs Boson
- **Dark Matter**



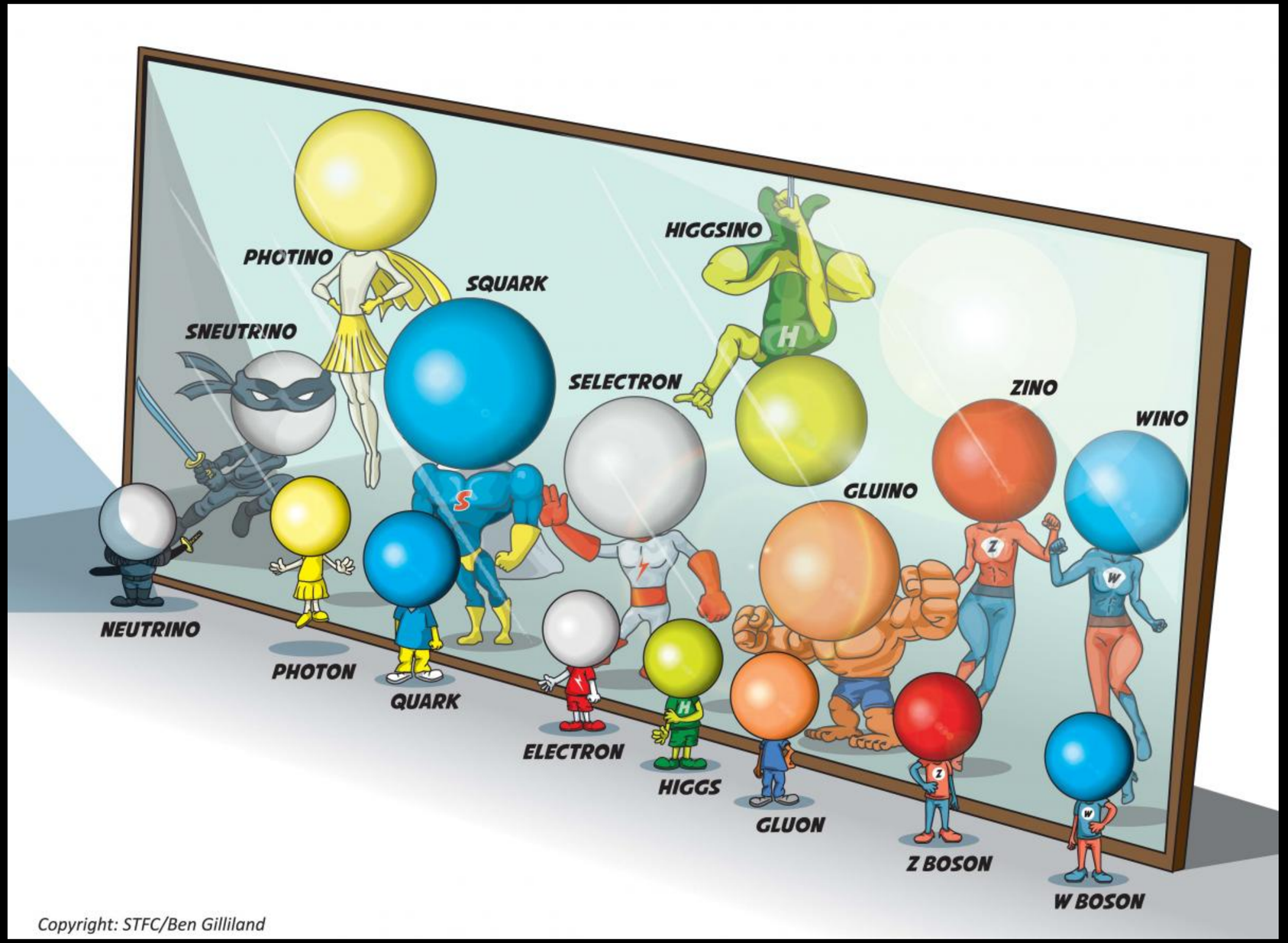


Gravitational lensing

Image: NASA/ESA

Supersymmetry

?



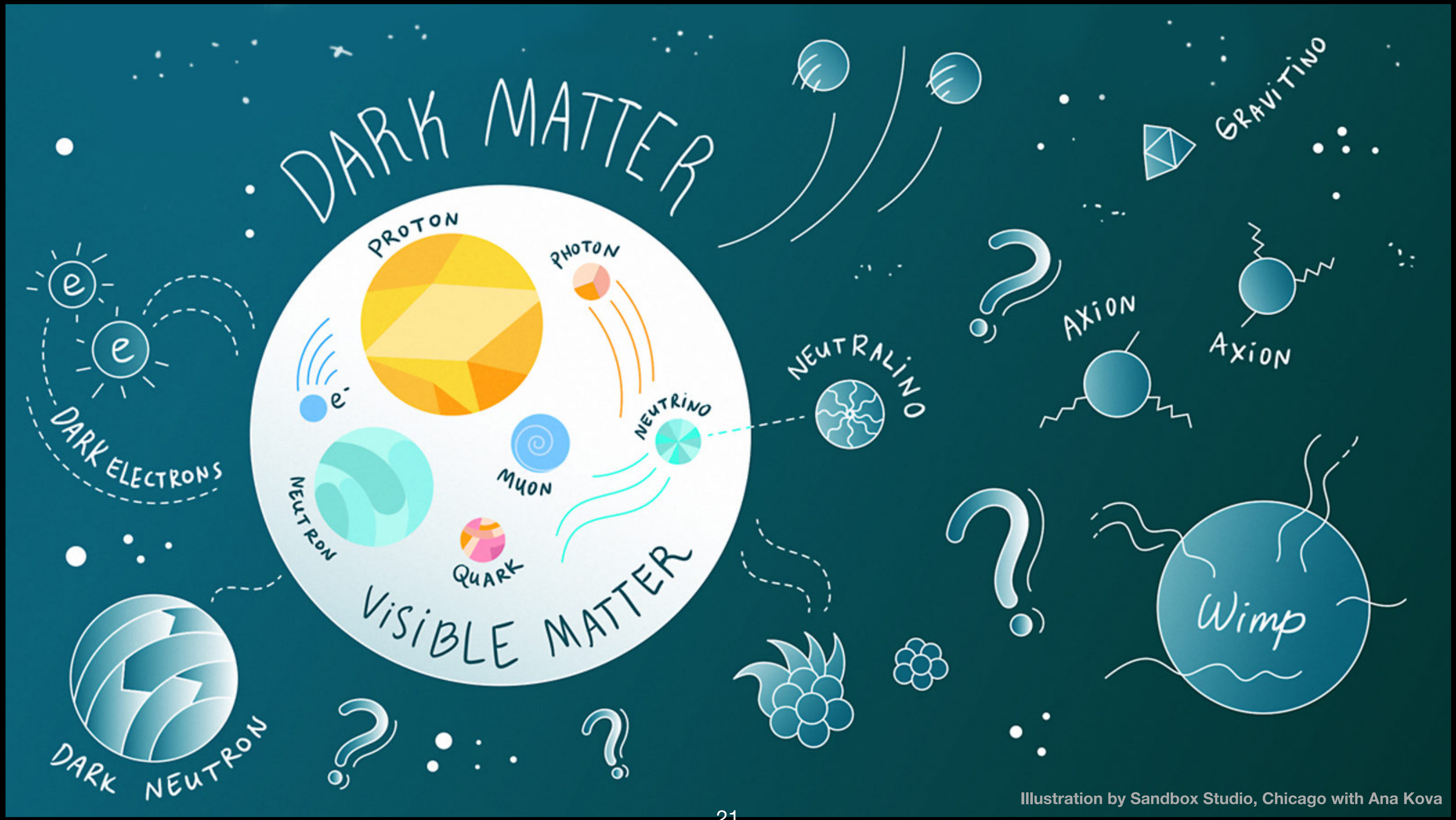
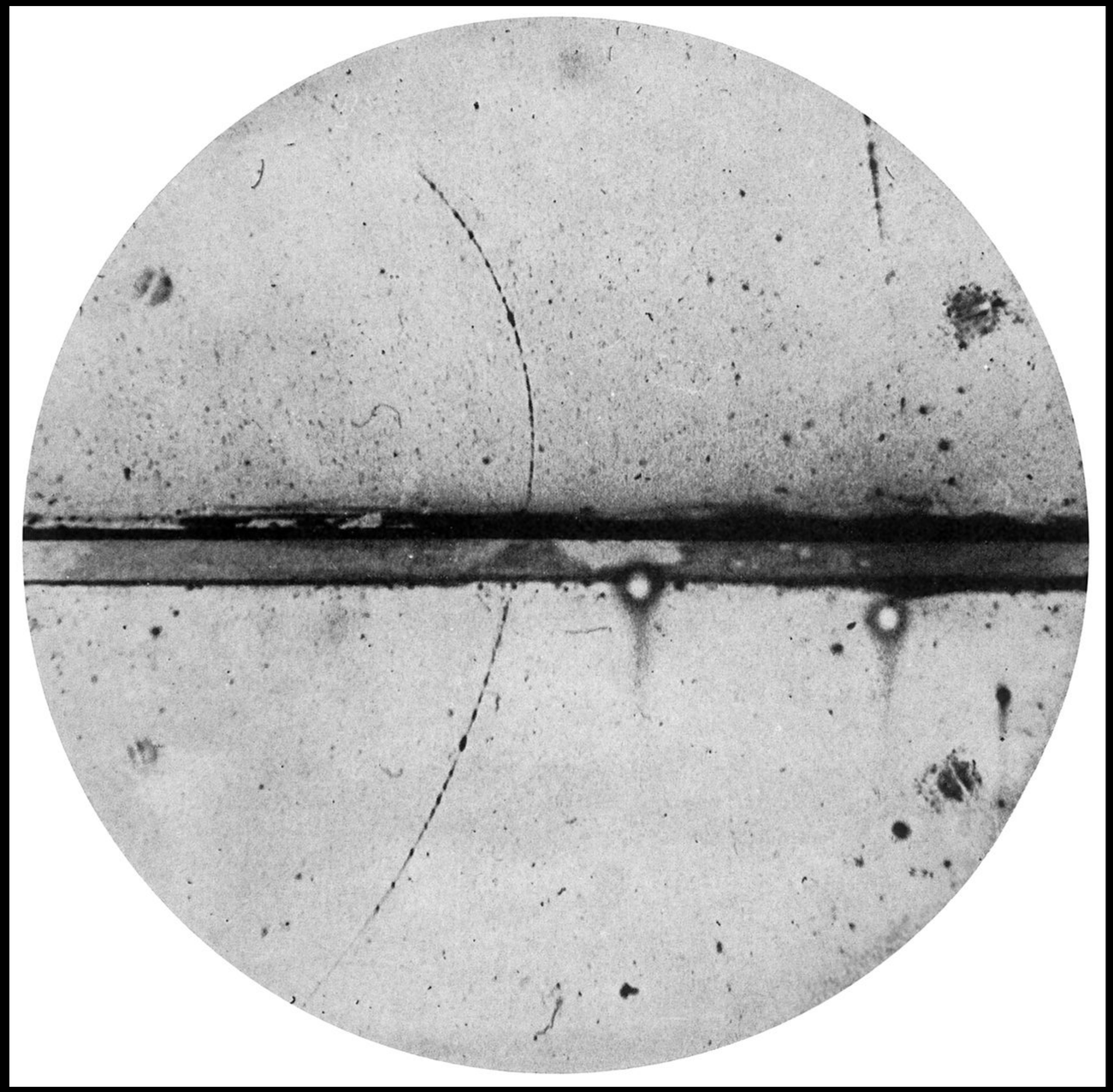


Illustration by Sandbox Studio, Chicago with Ana Kova

The Big Questions

- The Higgs Boson
- Dark Matter
- **Matter-Antimatter asymmetry**

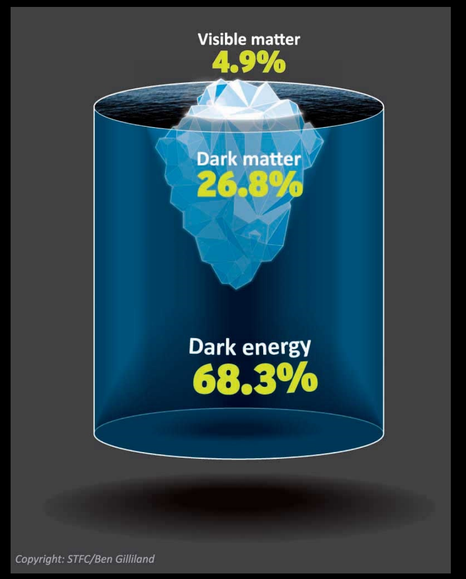


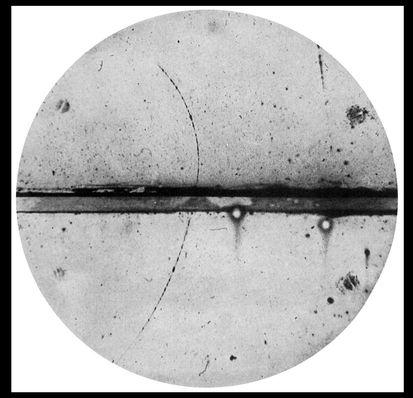
The Big Questions

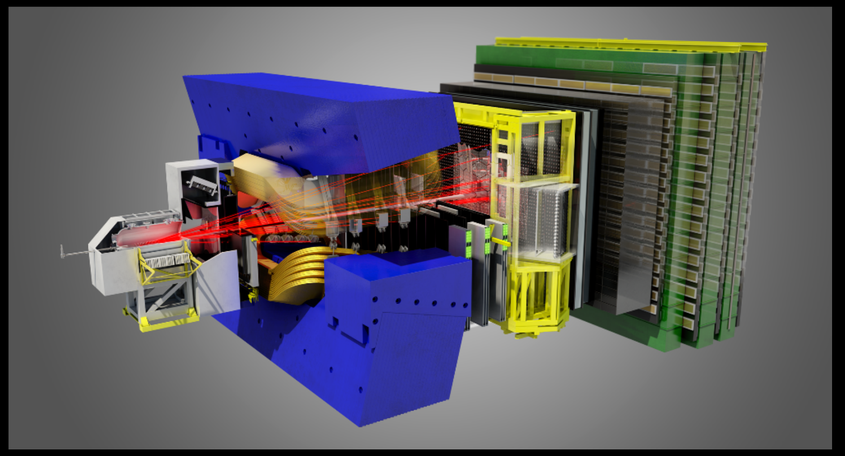
- The Higgs Boson
- Dark Matter
- Matter-Antimatter asymmetry
- **Strength of Gravity**

The Big Questions

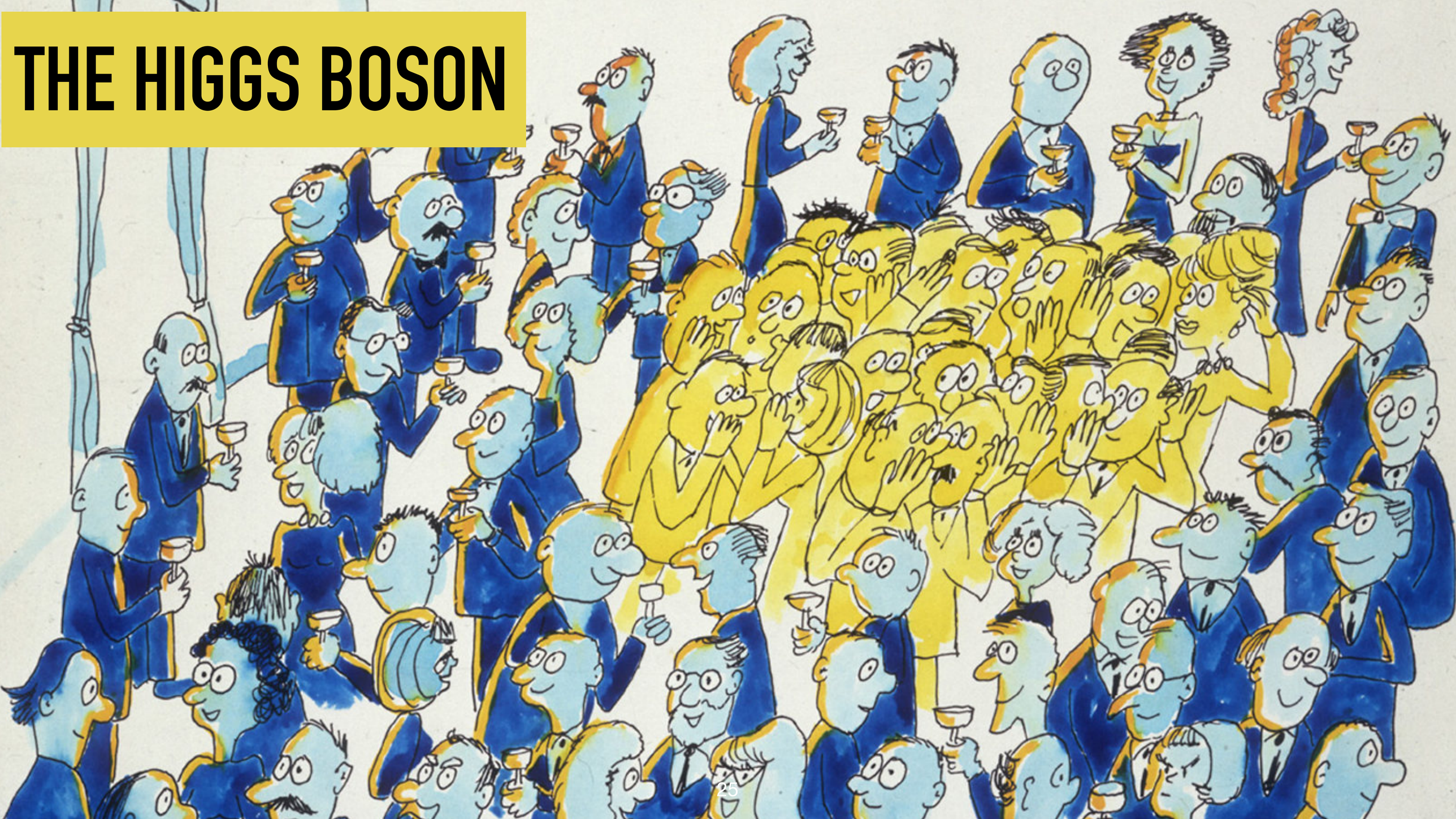
- The Higgs Boson
- Dark Matter
- Matter-Antimatter asymmetry
- ~~Strength of Gravity~~

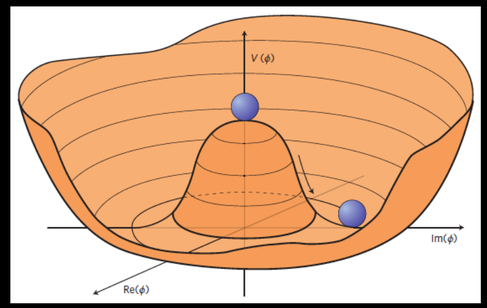






THE HIGGS BOSON





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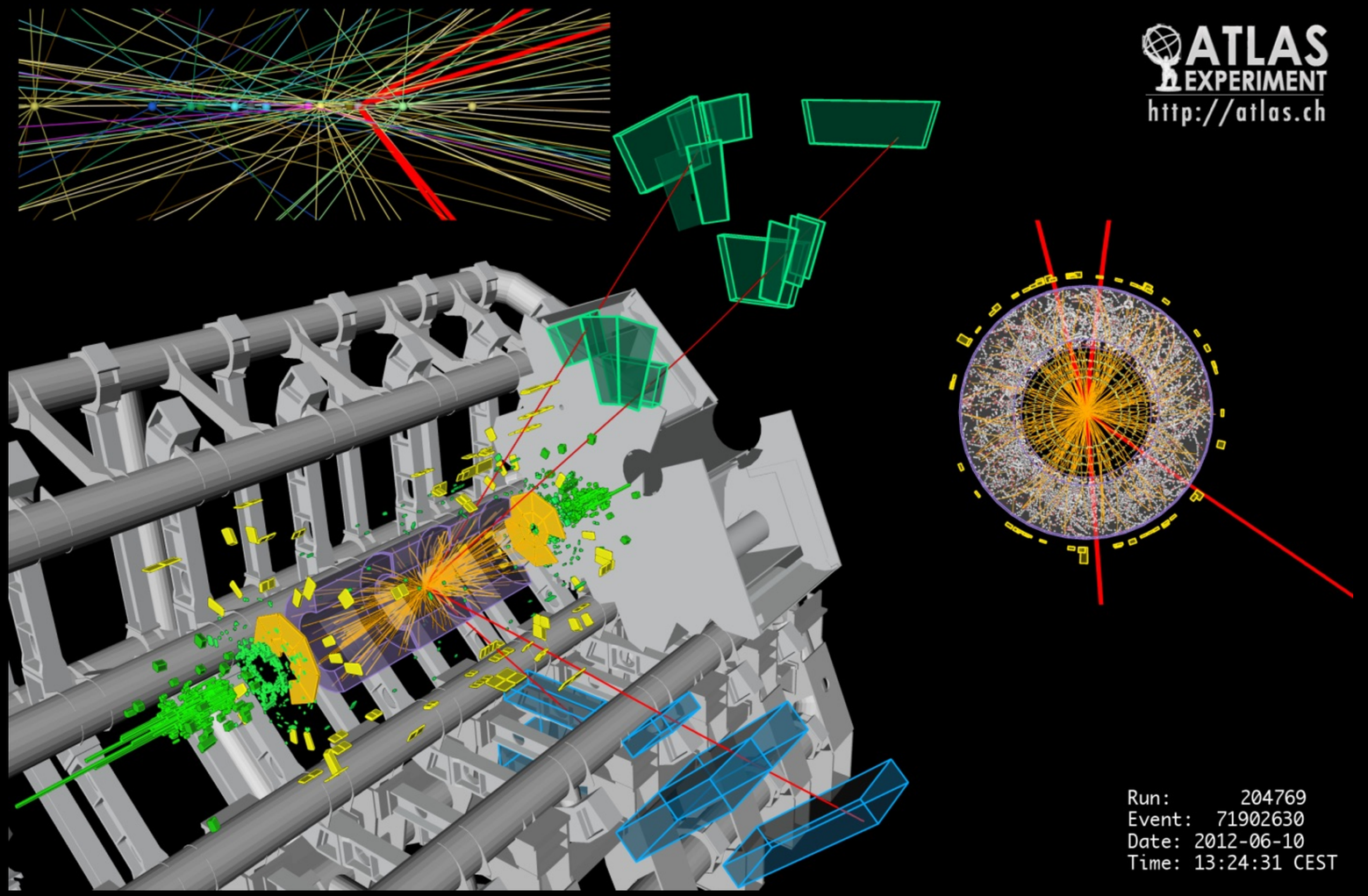
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EXPERIMENT
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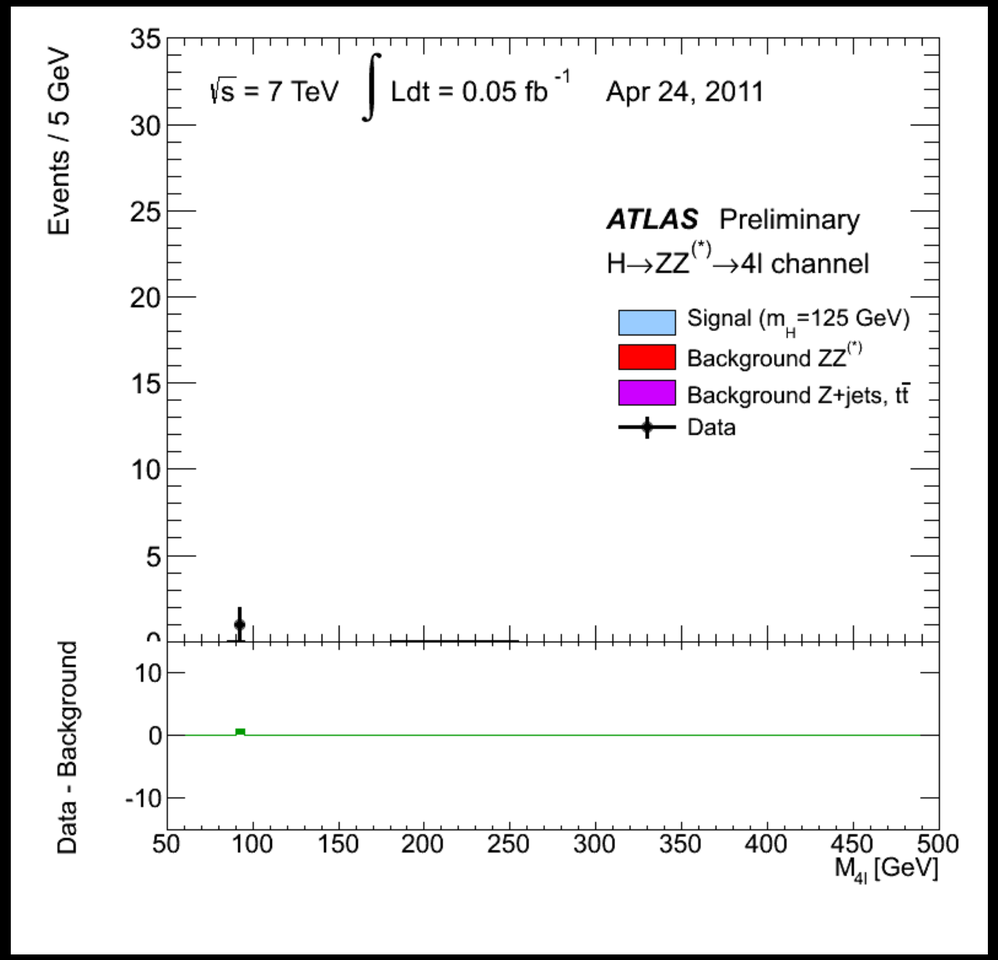
Time: 13:24:31 CEST


Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M4l [GeV]

Physicists Find Elusive Particle Seen as Key to Universe

By **DENNIS OVERBYE** JULY 4, 2012

Scientists in Geneva on Wednesday ap
boson. Pool photo by Denis Balibouse

The top quark

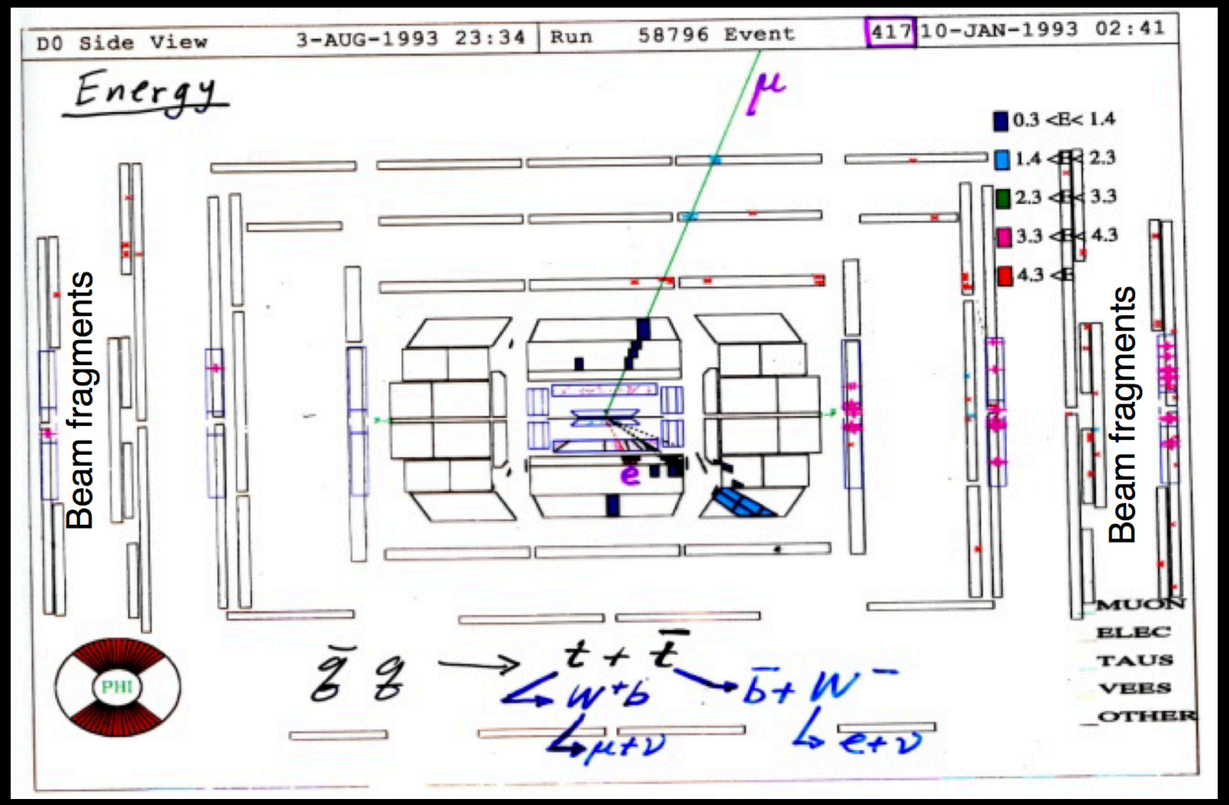
By James St. John - Gold nugget (Australia)

Massive

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

Very short lifetime

Discovered in 1995



Can tell us about the stability of the Universe

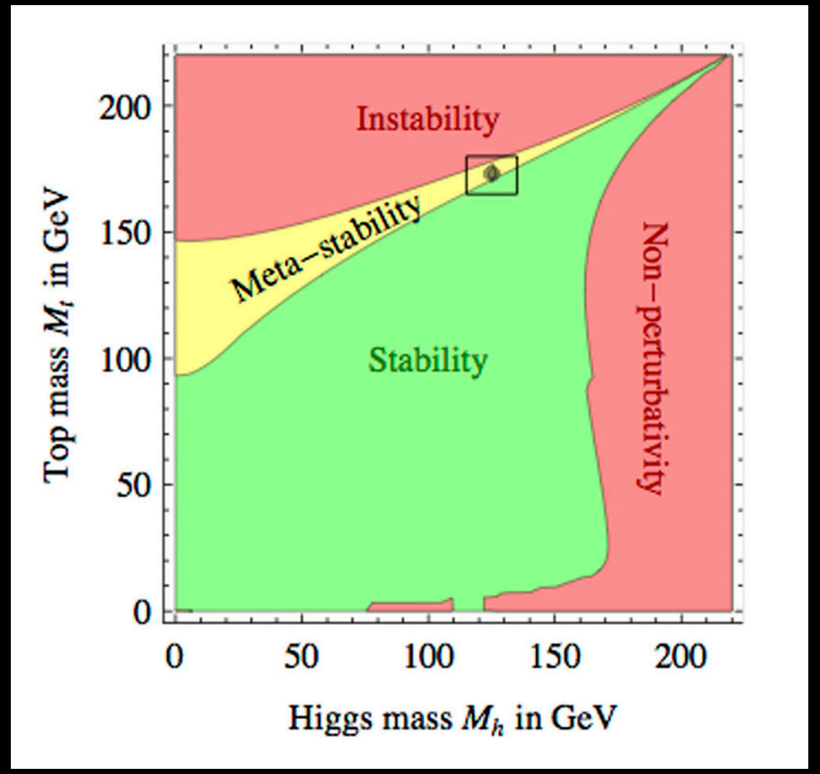
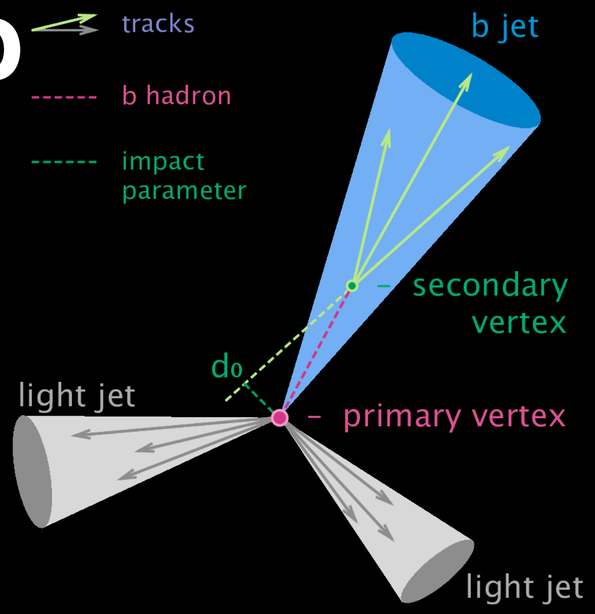
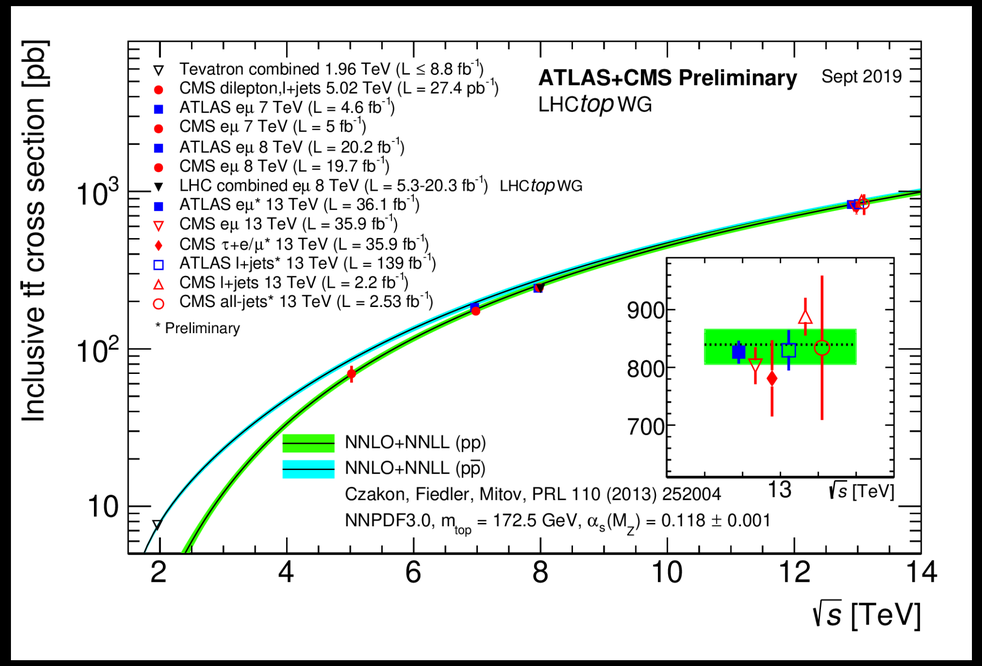


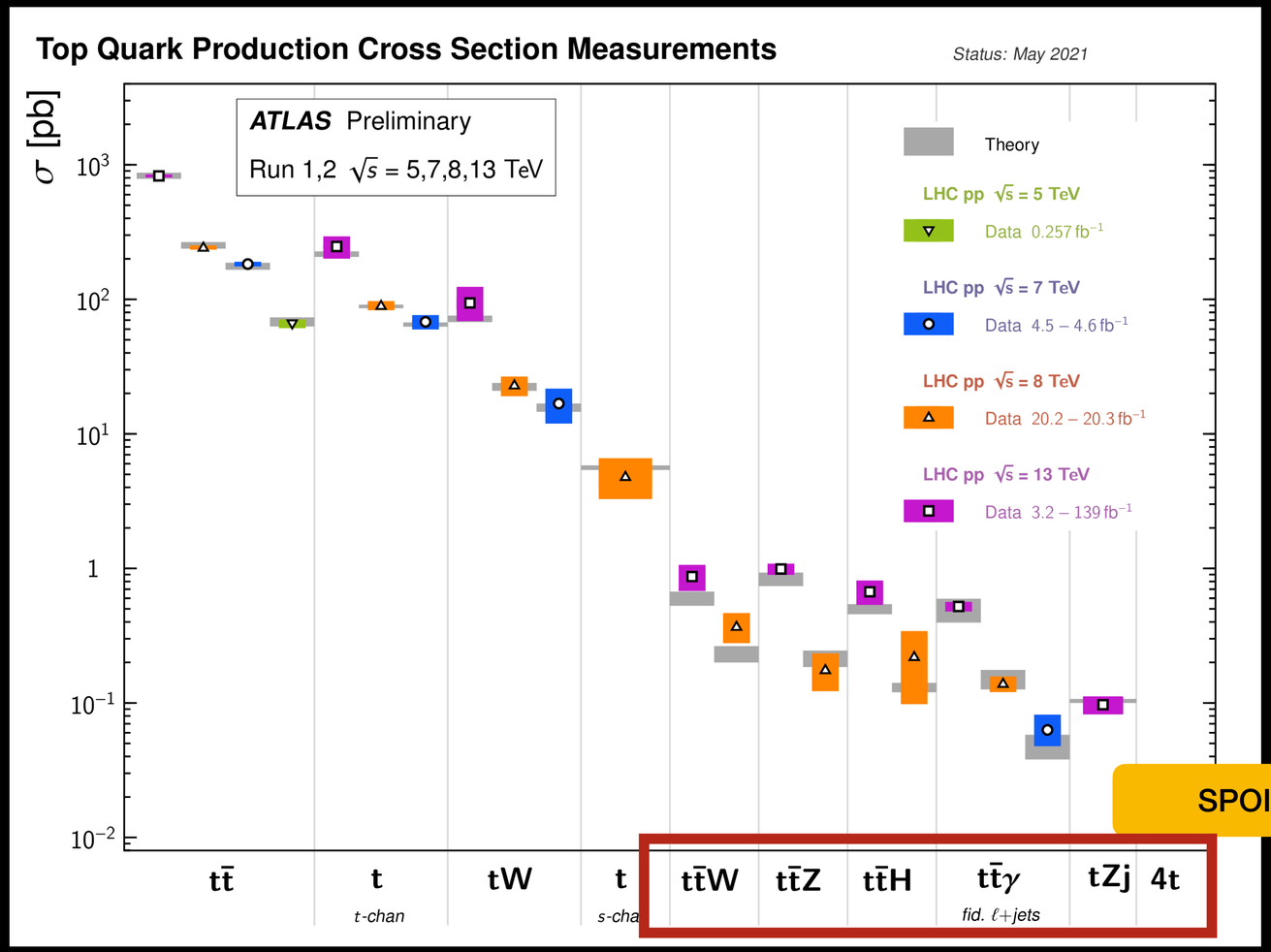
Photo: Reidar Hahn, Fermilab

The top quark



Decays to a W-boson and a b-quark ~100% of the time.

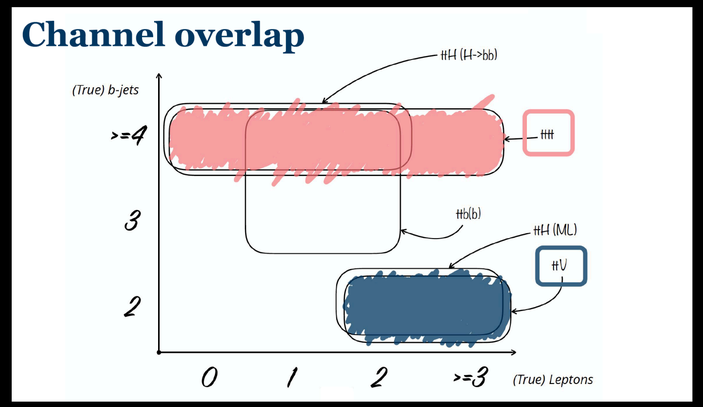


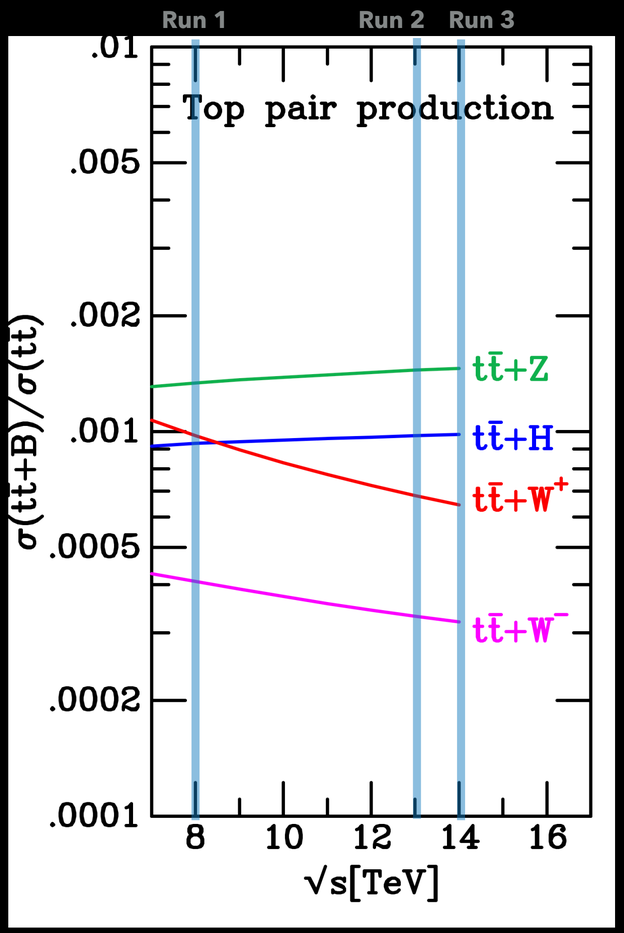


SPOILER!

Plays well with others

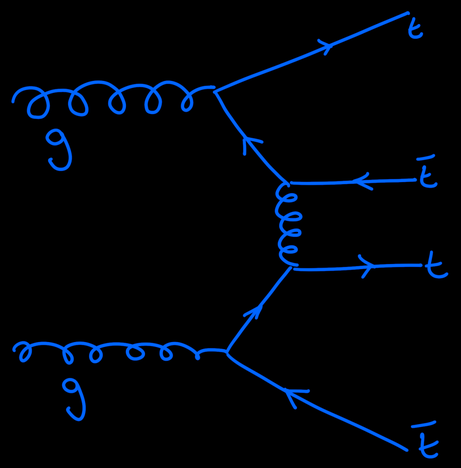
- To understand the top quark and validate the Standard Model, we need to look at **how it interacts with other particles**.
  - Higgs Boson - Yukawa coupling
  - Photons - Determine the charge of the top quark
  - Heavy gauge bosons: Z and W - Direct probe of the weak couplings of the top quark.
  -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



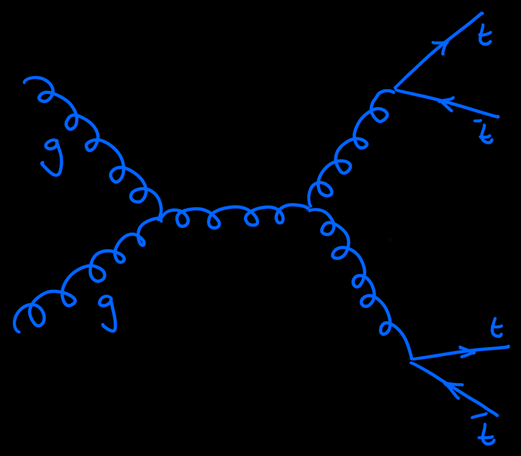


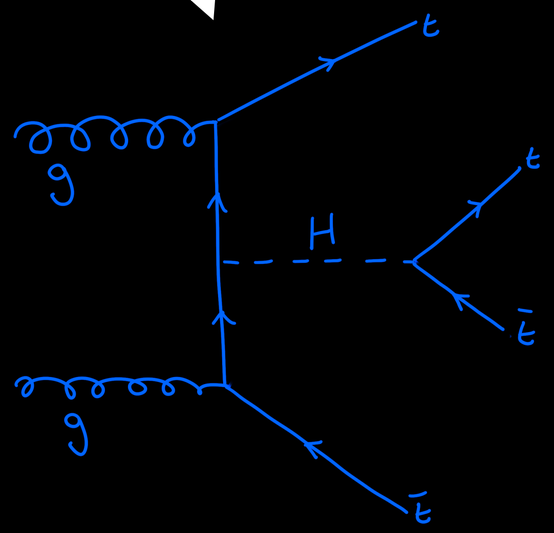
Note: many of these measurements have only just been observed by the ATLAS and CMS Collaborations

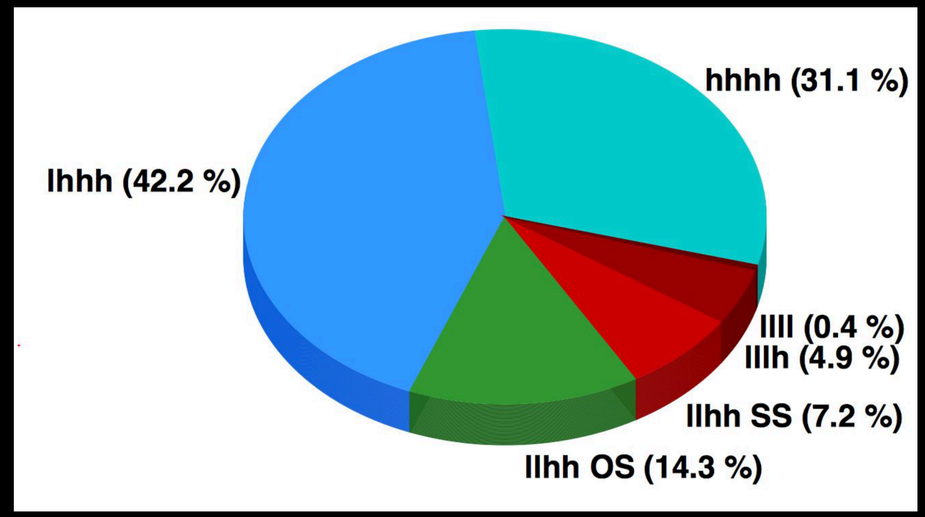
4tops signature



- Using the full Run 2 pp dataset, ~140 fb^{-1} at 13 TeV.
- Once for every 70 000 top quark pairs.
- Top Yukawa coupling.







The predicted cross-section is:

SM NLO QCD+EW: **12.0** +2.0 –2.5 fb [JHEP02(2018)031]

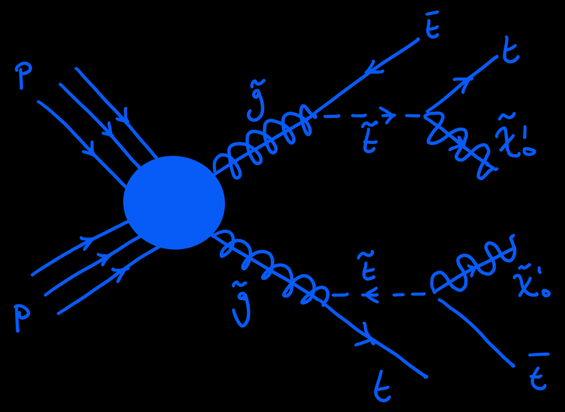
Multi-lepton channel (2LSS/3L):

- Low branching fraction (13%).
- Cleaner signal.

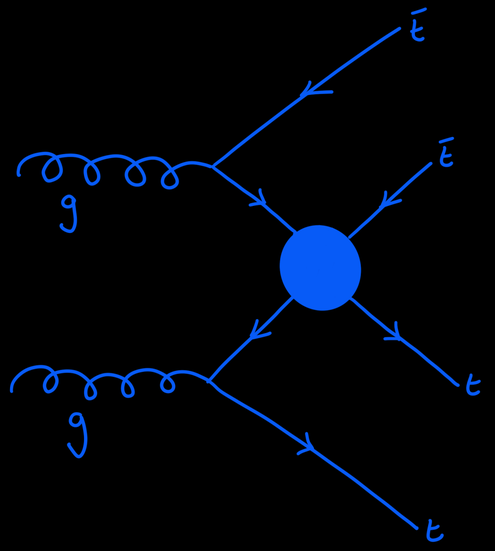
Single lepton / dilepton opposite sign (1L/2LOS):

- Higher branching fraction (57%).
- Suffers from a large irreducible background.

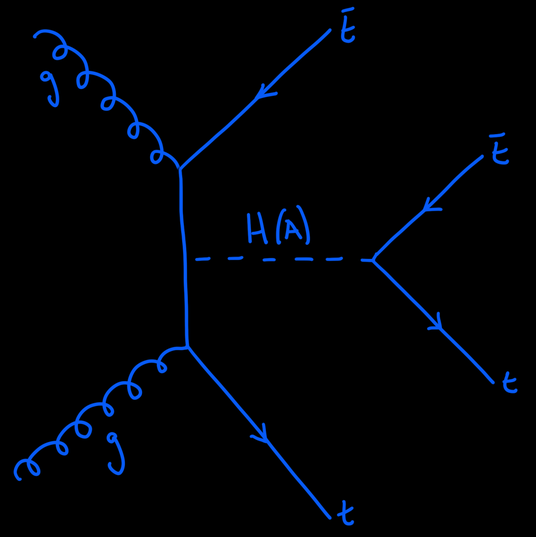
Dark matter models to consider



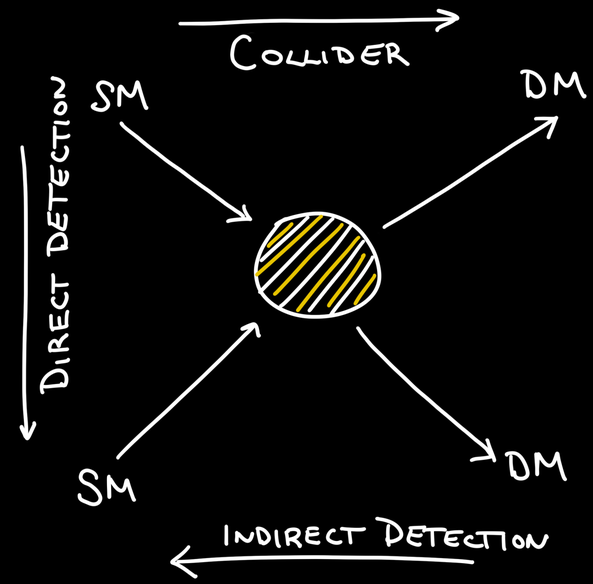
SUSY (gluino/ sgluino pair, for example)



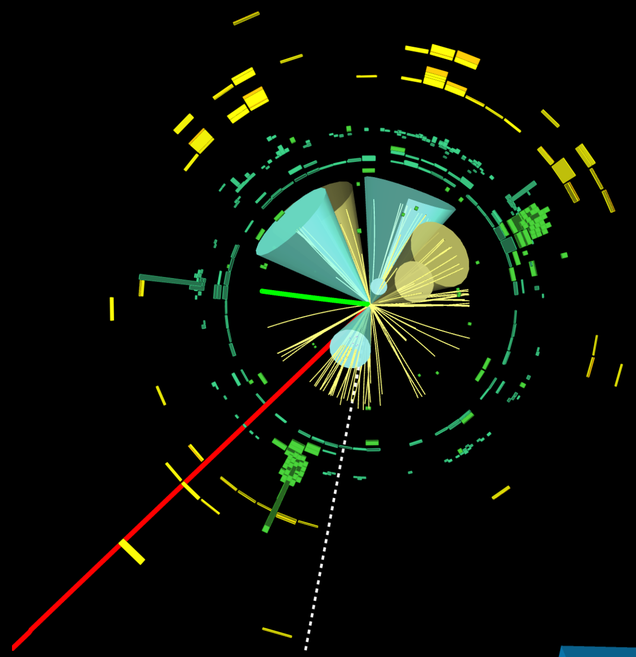
Contact Interaction

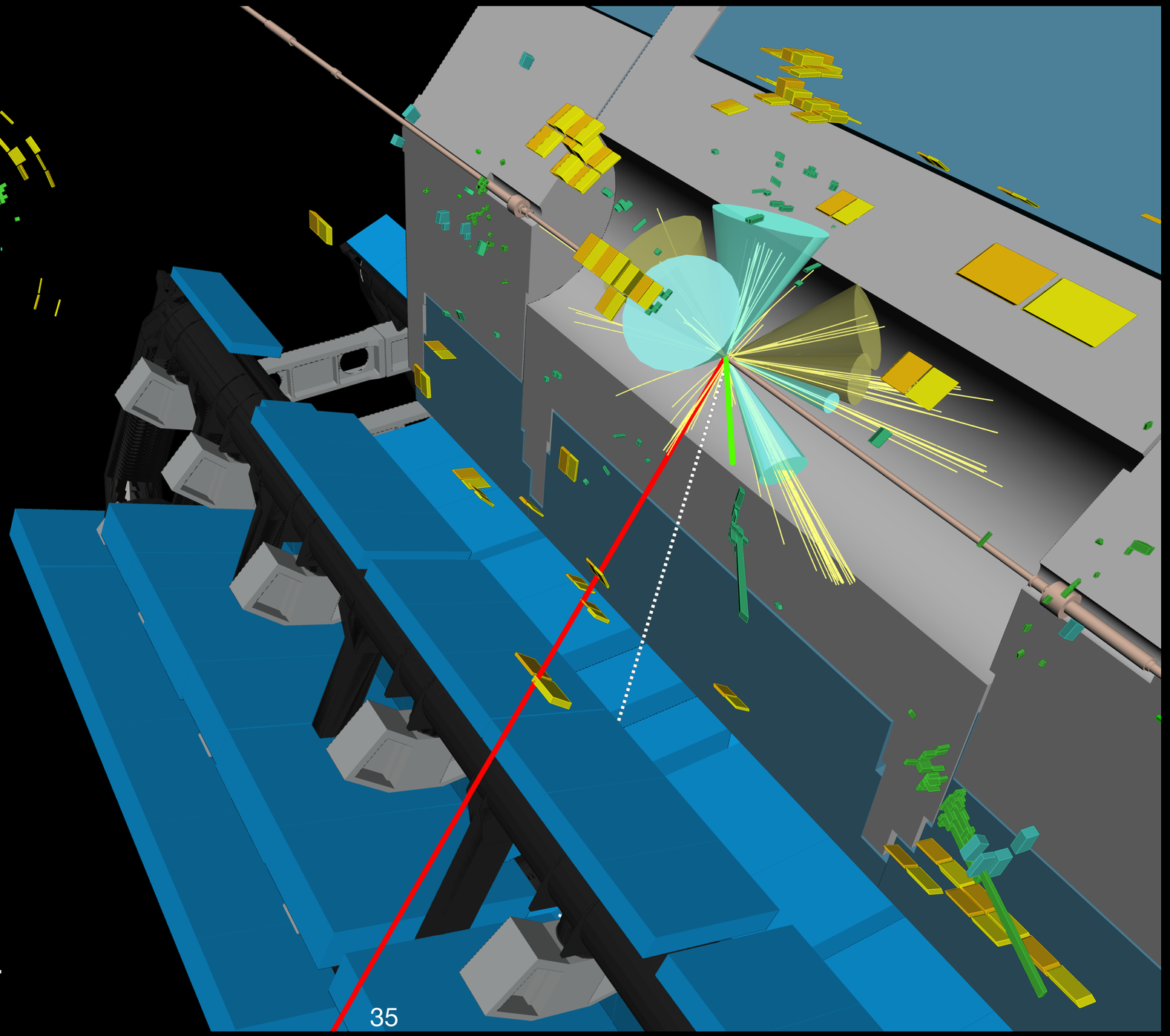


2HDM



Could produce an enhancement of the SM four top cross-section, but more data and further investigation required.

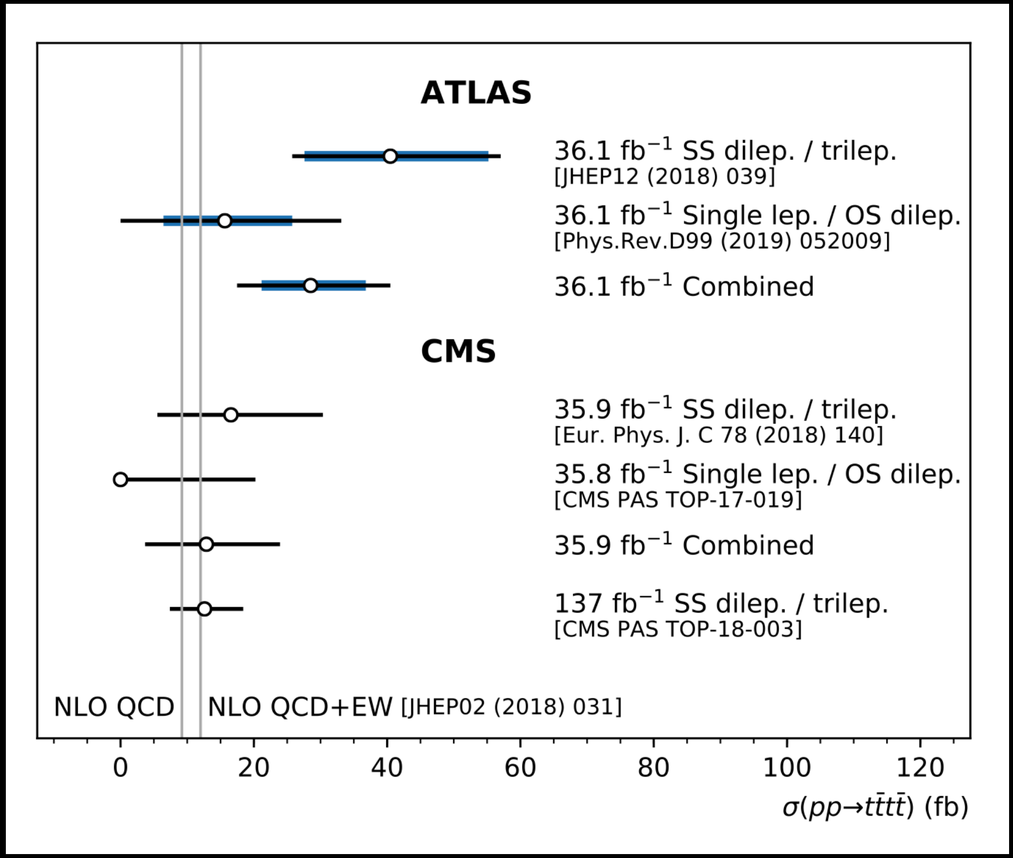




ATLAS EXPERIMENT

Run: 349114
Event: 1280053930
2018-04-29 10:53:24 CEST

Previous results



Multi-lepton channels:

ATLAS EXPERIMENT

[Phys. Rev. D 99, 52009]

Partial Run 2 data (36 fb^{-1})

XS upper limit: 69 (29) fb (95% CL)

μ = 4.4 +1.8 -1.6

3σ observed (0.8σ expected)

CMS

Full Run 2 data (137 fb^{-1})

12.6 +5.8 - 5.4 fb

μ = 1.05 +0.48 -0.43

2.6σ observed (2.7σ expected)

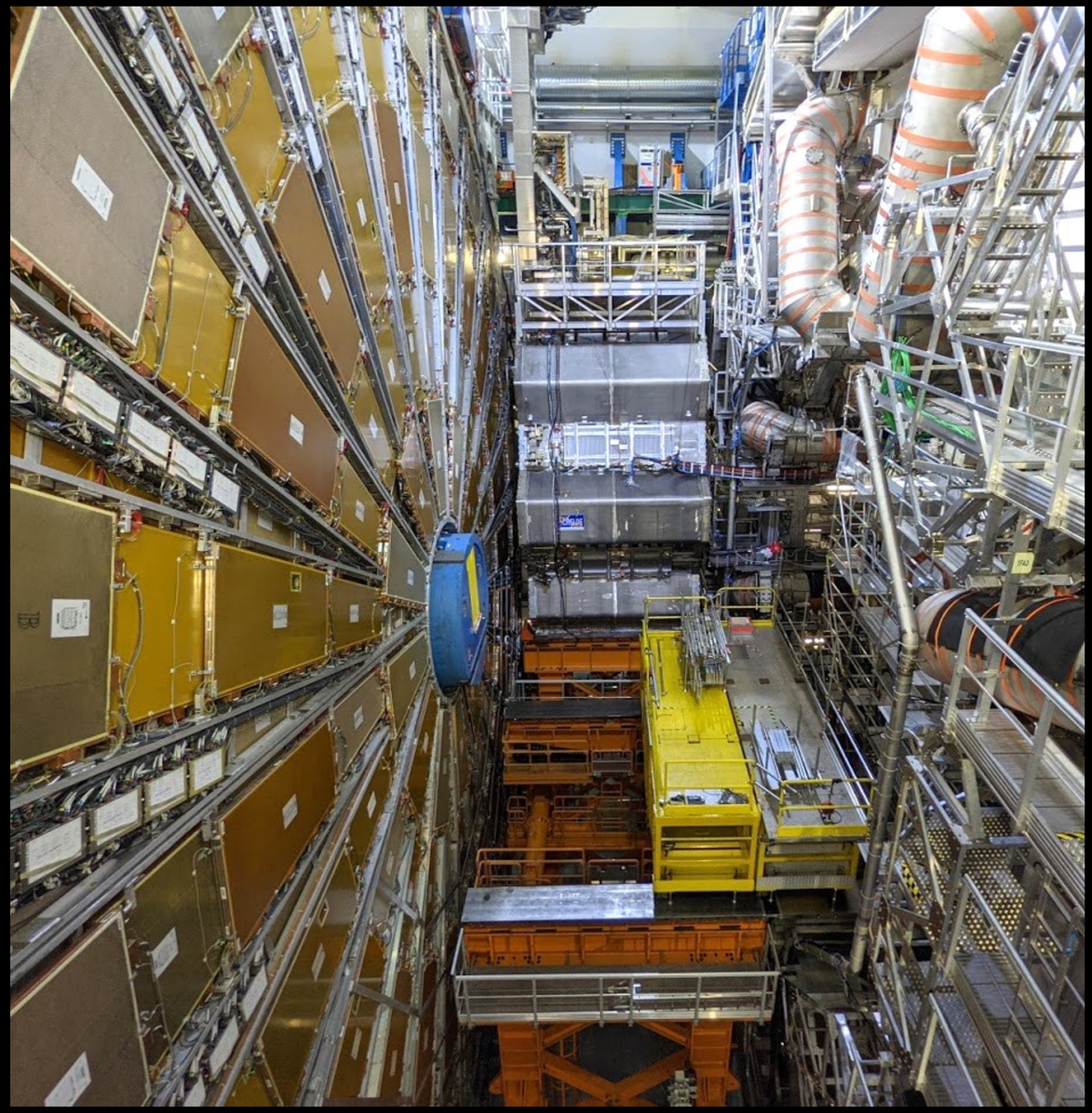
[Eur. Phys. J. C 80 (2020) 75]

$\mu=\sigma_{obs}/\sigma_{SM}$

Multi-lepton channel (2LSS/3L)

Basic selection:

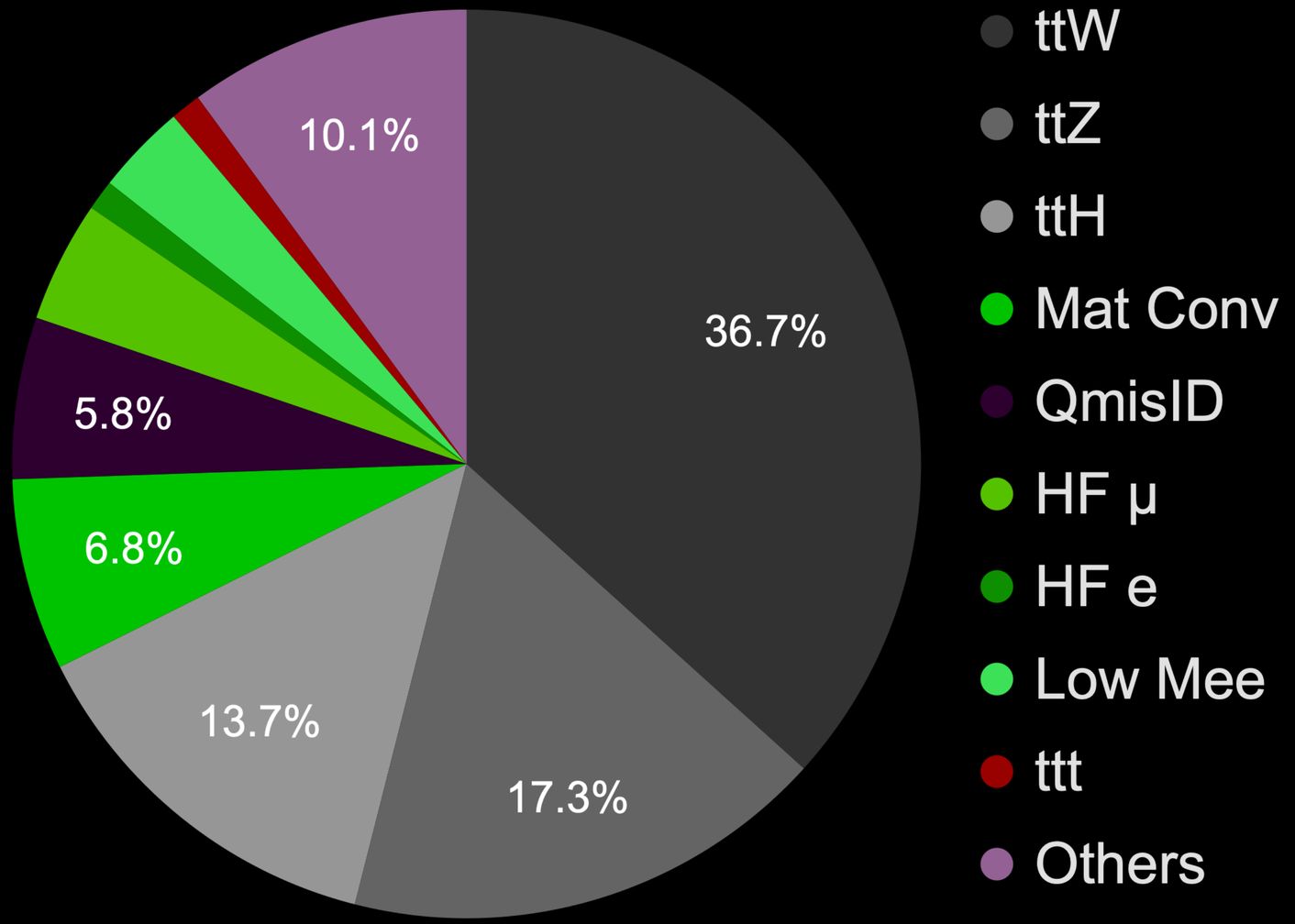
- ≥4 jets, ≥1 b-jets
- $|m_{ll} - m_Z| > 10$GeV
  - 3L, opposite sign, same flavour



Backgrounds

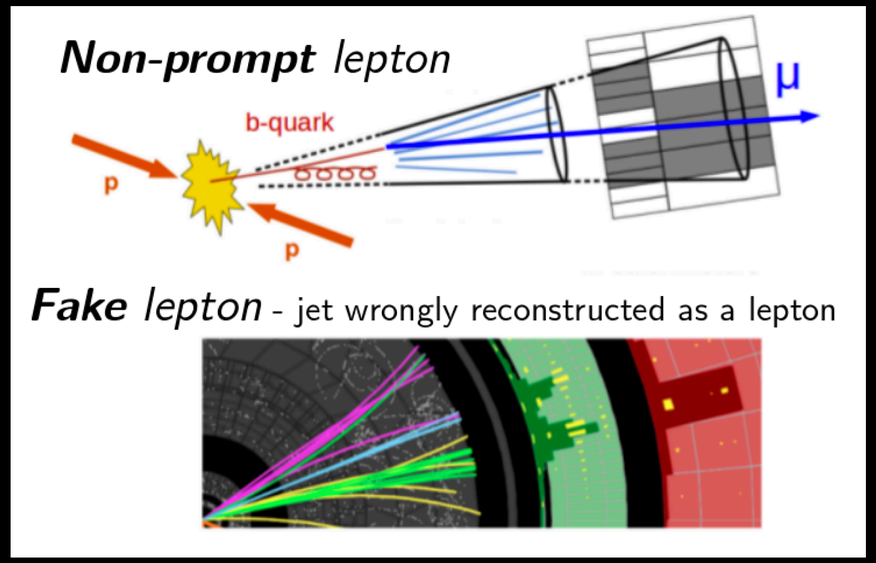
- Irreducible:
  - Main:
    - $t\bar{t}W$+jets, $t\bar{t}Z$+jets and $t\bar{t}H$+jets processes.
  - Smaller:
    - diboson / triboson production
    - *V H* production in association with jets
    - Rare processes ($t\bar{t}WW$, *tWZ*, *tZq*, $t\bar{t}t$)

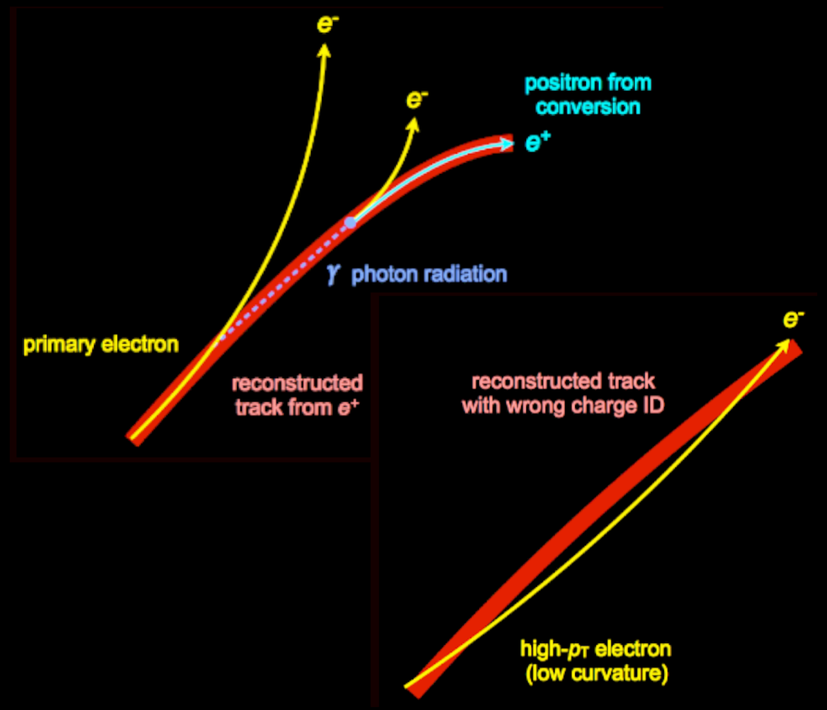
Evaluated using MC simulation normalised to their SM cross sections (except $t\bar{t}W$)



Backgrounds

- Reducible:
  - mainly $t\bar{t}$+jets and tW+jets production
    - Fake/non-prompt leptons.
      - Leptons from heavy flavour decay
      - Electrons from photon conversion in the material of the detector.
      - Virtual photon which produces e+e- pair.
      - Template method
    - QmisId - 2LSS
      - Data-driven method

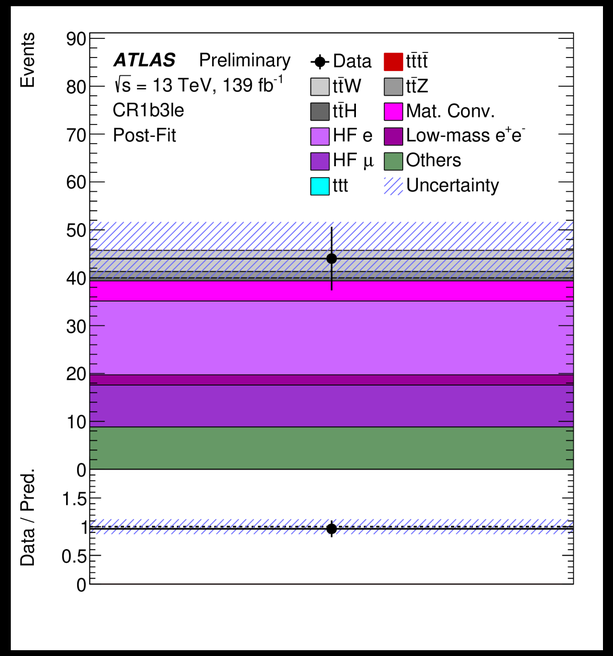


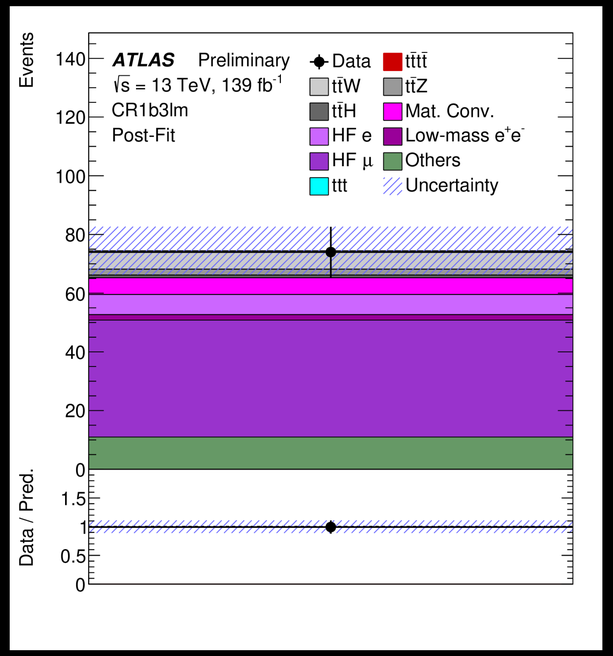


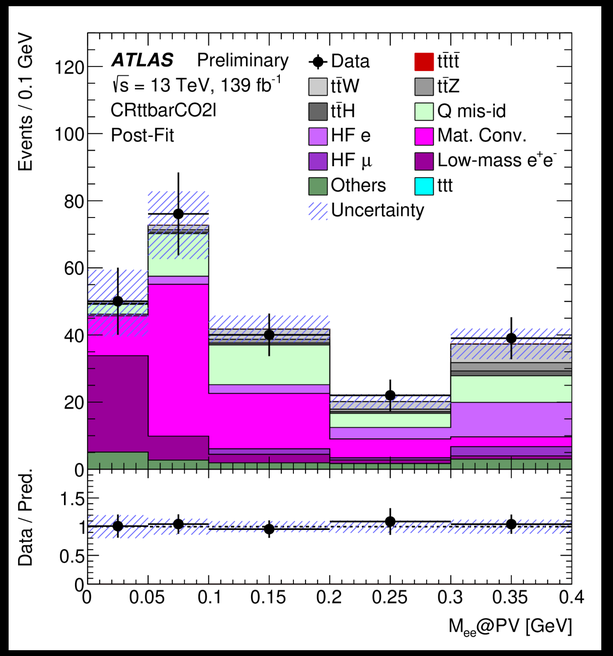
Template fit

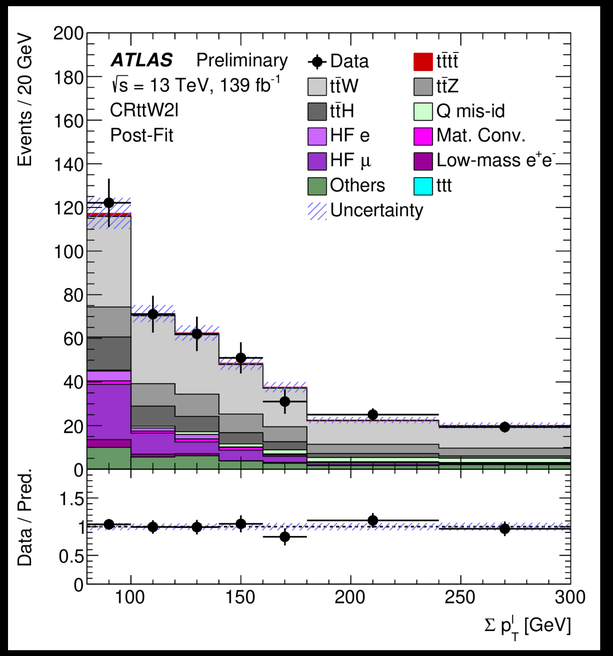
Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } M_{ee}}$	$NF_{\text{HF e}}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

Invert the selections to increase the purity of a background in a dedicated control region to be able to determine the normalisation factor. The shapes are modelled from simulation.



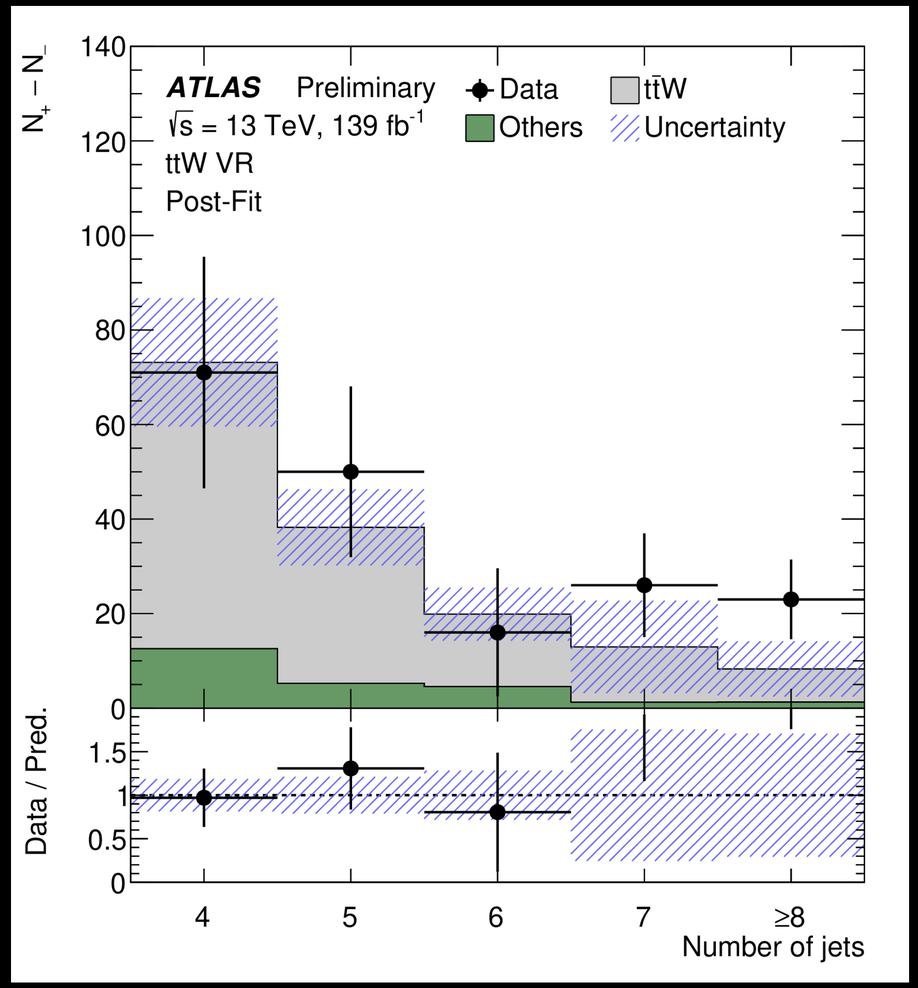


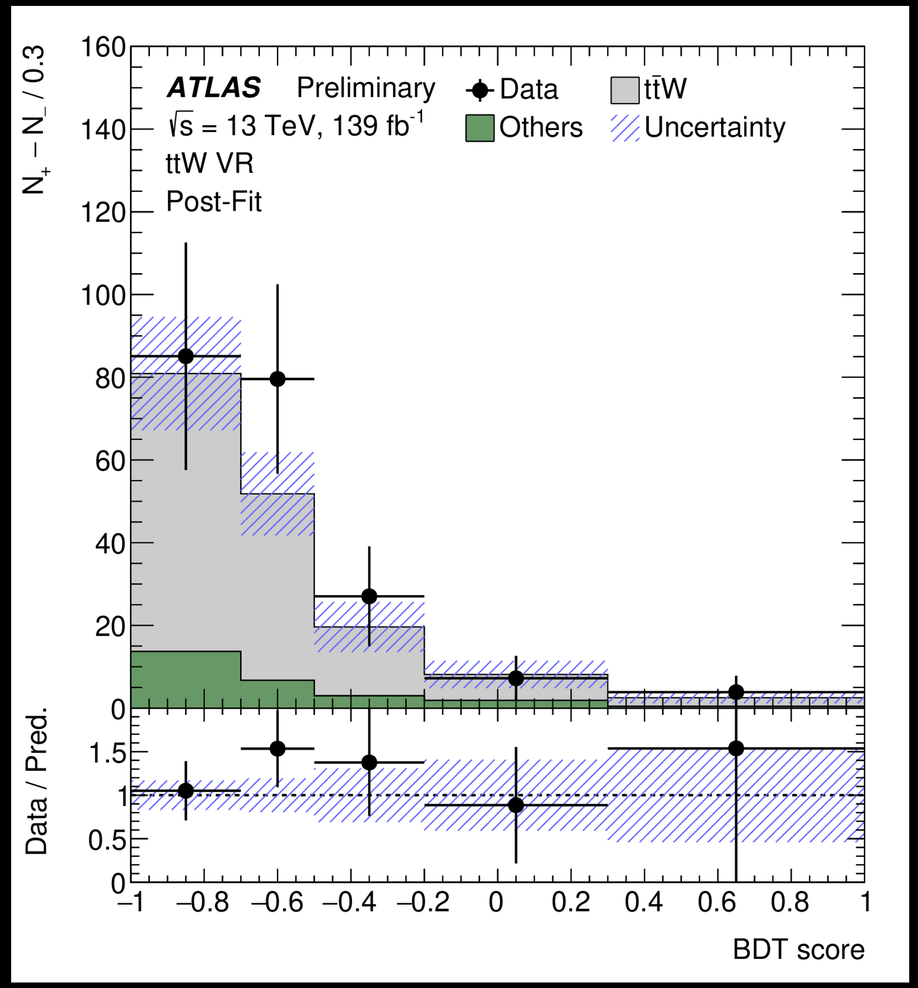




ttW Validation

Using ttW charge asymmetry (ttW^+:ttW^- approximately 2:1)





Uncertainty: 125% (300%) assigned to events with =7 (≥8) jets

Boosted Decision Tree Classification

Input to distinguish the signal included:

- the high numbers of jets
- their quark-flavour origin (b-jets)
- the energies and angular distributions of the measured particles

Training is inclusive.

Four tops sample was LO.

Variables and hyperparameters were optimised.

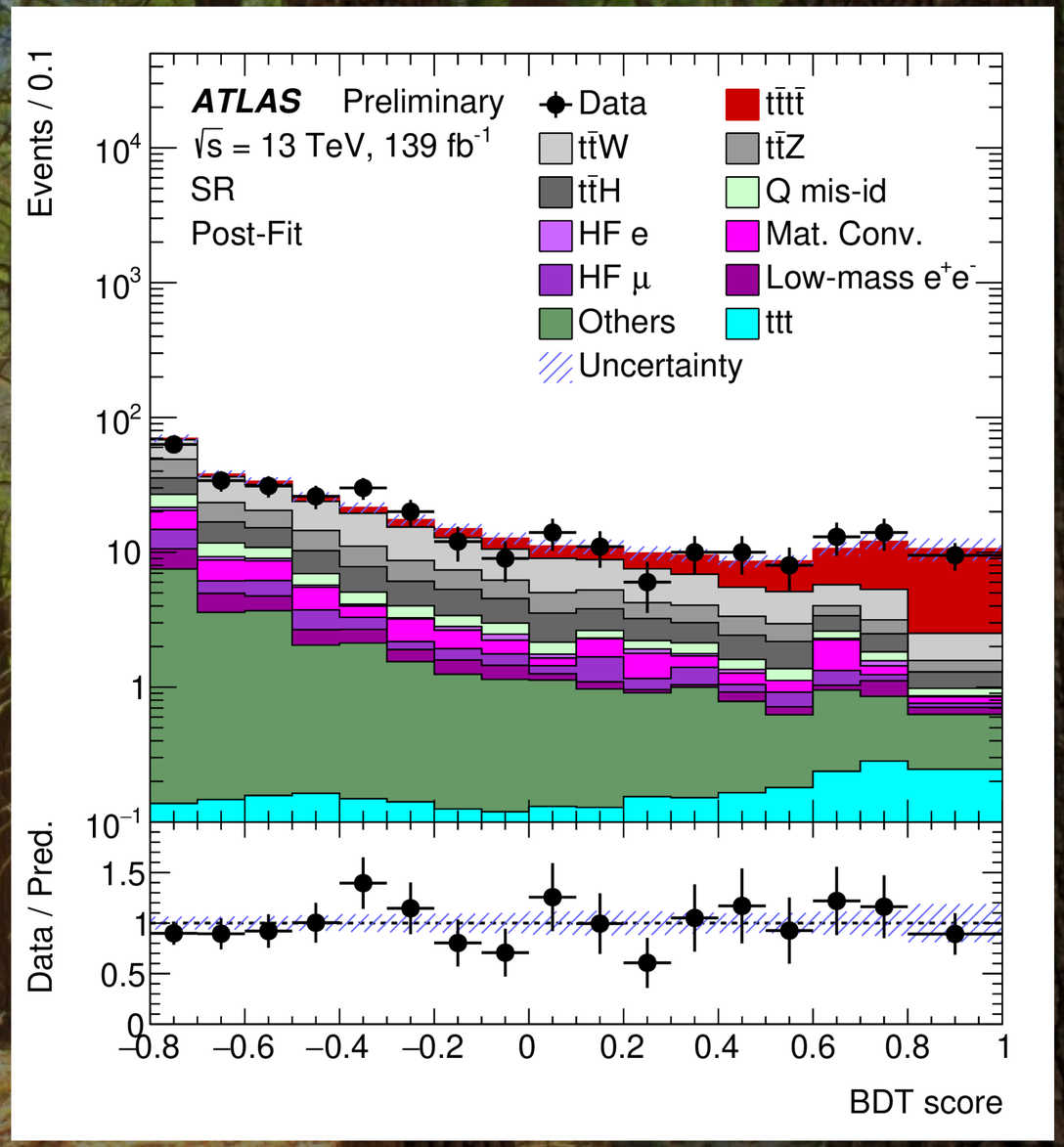


Image: N. A. Tonelli

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$ modelling	+0.26	−0.27
$t\bar{t}t$ modeling	+0.10	−0.07
Non-prompt leptons modeling	+0.05	−0.04
$t\bar{t}H$ modelling	+0.04	−0.01
$t\bar{t}Z$ modelling	+0.02	−0.04
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Other experimental uncertainties	+0.03	−0.01
Jet flavour tagging (c-jets)	+0.03	−0.01
Total systematic uncertainty	+0.69	−0.46
Statistical	+0.42	−0.39
Non-prompt leptons normalisation(HF, material conversions)	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.82	−0.62

Result 2LSS/3L:

Simultaneous fit in 4 CRs and the SR.

Measured four top signal strength:
μ = 2.0 +0.9 - 0.6

[+0.4 -0.4(stat) +0.6 -0.3 (theory) +0.4 -0.3(syst)]

Cross section:

$\sigma(tttt) = 24\ ^{+5}\ -5(\text{stat})\ ^{+5}\ -4(\text{syst})$ fb

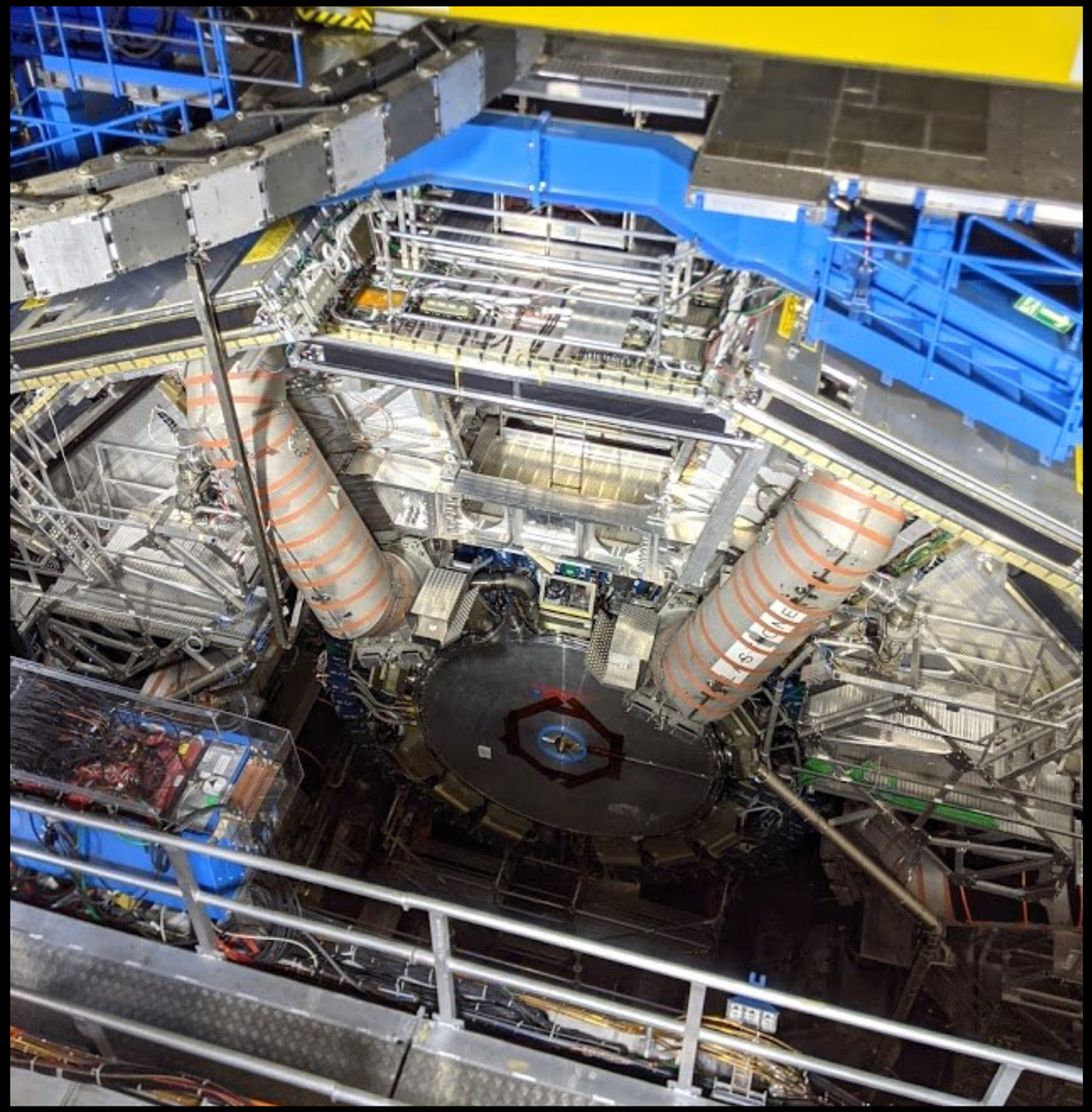
Evidence: 4.3σ (2.4σ expected)

1.7σ consistent with the Standard Model.

Single lepton / dilepton opposite sign (1L/2LOS)

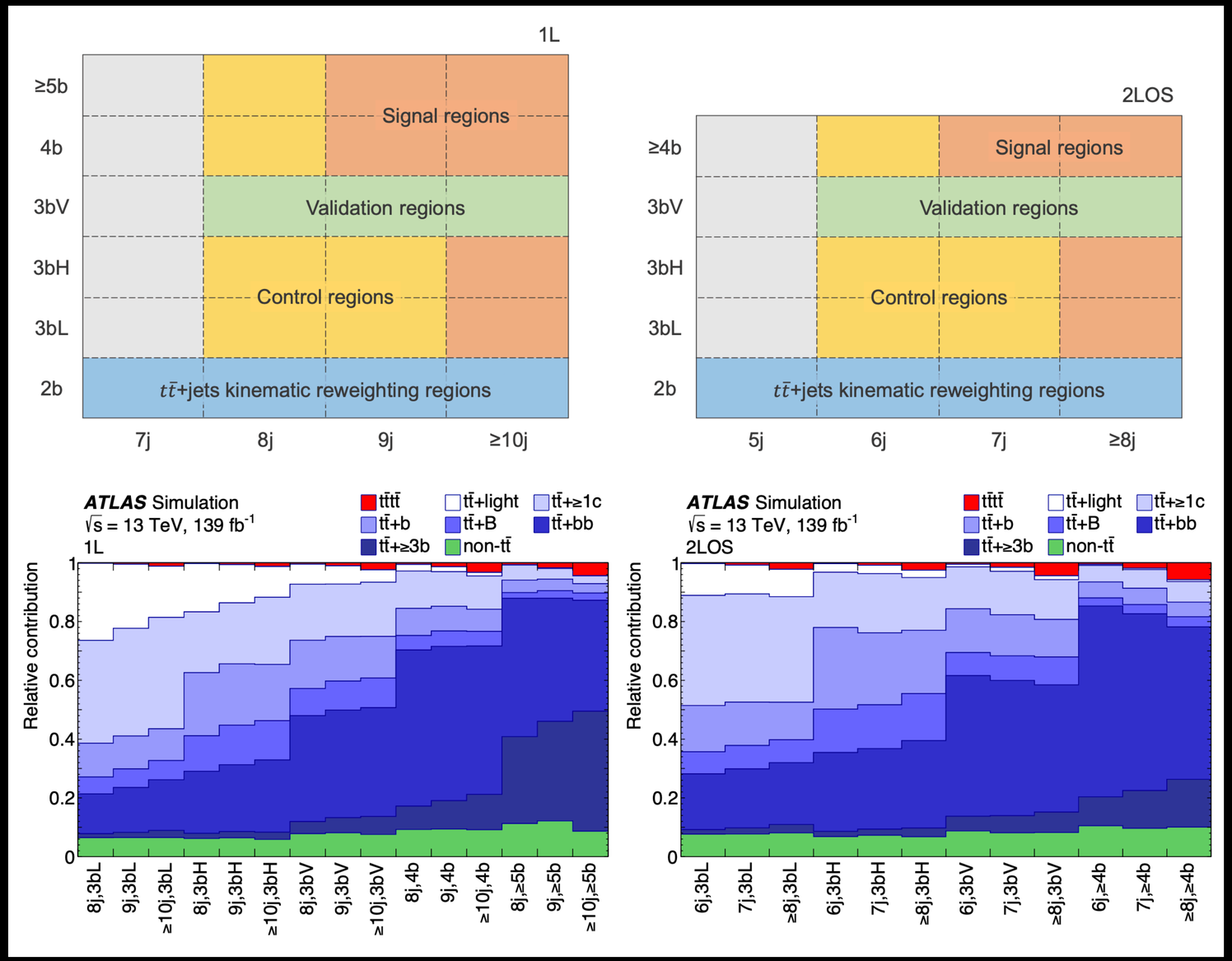
Basic selection:

≥ 2 *b*-jets, (1l, ≥ 7 jets) or (2lOS, *Z*-veto, ≥ 5 jets)



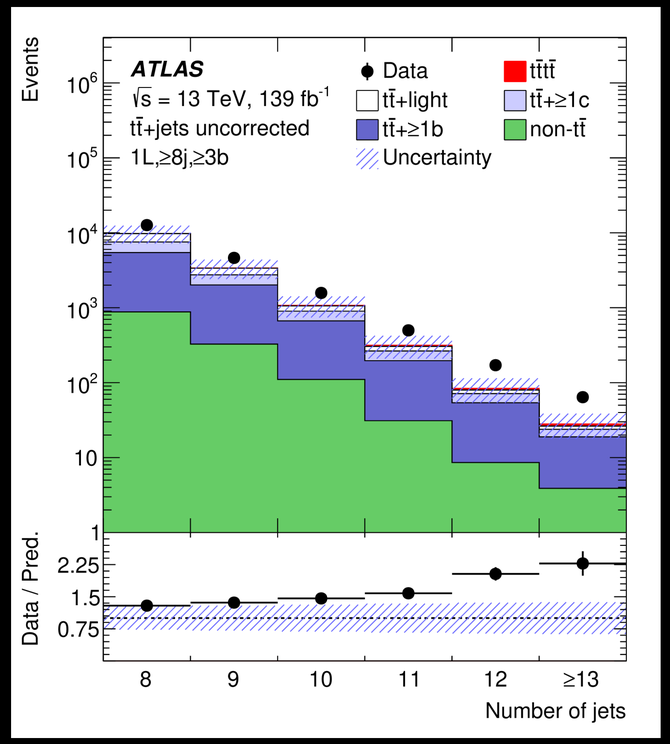
Selection and backgrounds

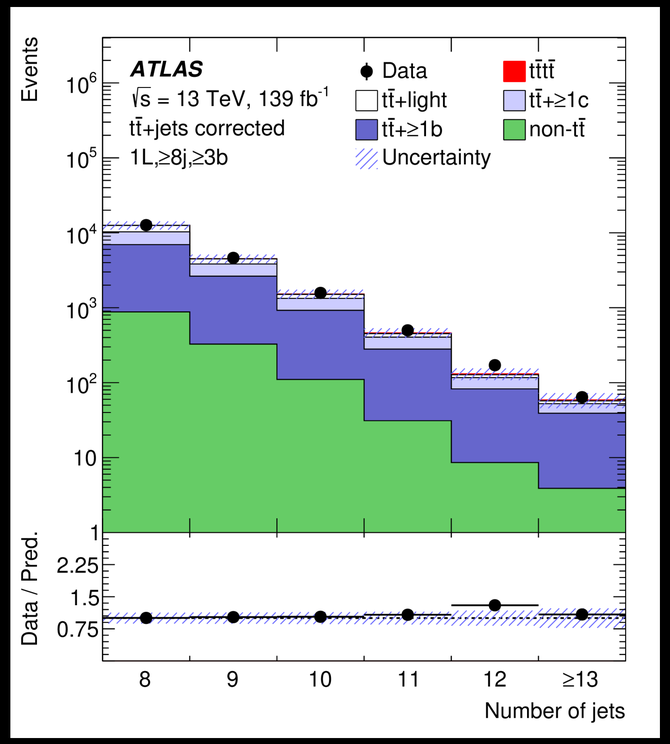
- Jet multiplicity and jet flavour are used to enhance signal sensitivity, and dedicated control regions are used to constrain the dominant backgrounds.
  - 21 regions are used in the profile likelihood fit.
- The phase-space is contaminated by a large tt+jets background.
- Other backgrounds (<8%):
  - ttW, ttZ, ttH, single top-quark or W/Z +jets.
  - Di-boson and rare processes (tZq,tWZ, $t\bar{t}$ WW and $t\bar{t}$t) <1%.



Modelling of tt+jets background

- Perform a 3-step sequential kinematic reweighting on $t\bar{t}$ MC from **2b-tagged** region and apply to higher b-jet multiplicities.
  - 1L and 2LOS channels separately.
  - Uncertainties in the derived reweighting factors are propagated as systematic uncertainties in the $t\bar{t}$+jets background.





Boosted Decision Tree Classification

Similar to the 1LOS channel, a BDT was used to discriminate signal from background.

Simultaneous fit in SRs (BDT shape) and in CRs (H_T shape).

Name	Description
$\sum b$-tag	Sum of pseudo-continuous b-tagging score over the six jets with the highest score
N_{jets}	Number of jets
$\Delta R_{bb}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets
$H_{\text{T}}^{\text{all}}$	Scalar sum of all jet and lepton transverse momenta
C^{all}	Centrality ($\sum_i p_{\text{T}i} / \sum_i E_i$) of the leptons and jets
$p_{\text{T}}^{\text{lead}}$	Transverse momentum of the leading jet
$\Delta R_{b\ell}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets and leptons
$\Delta R_{jj}^{\text{avg}}$	Average ΔR between all pairs of jets
m_{jjj}	Invariant mass of the closest triplet of jets
$E_{\text{T}}^{\text{miss}}$	Missing transverse momentum
m_{T}^{W}	W reconstructed transverse mass $m_T(\ell, E_{\text{T}}^{\text{miss}})$ (1L)
$N_{\text{LR-jets}}$	Number of large-R jets with a mass above 100 GeV
$\sum d_{12}$	Sum of the first k_t splitting scale d_{12} of all large-R jets
$\sum d_{23}$	Sum of the second k_t splitting scale d_{23} of all large-R jets

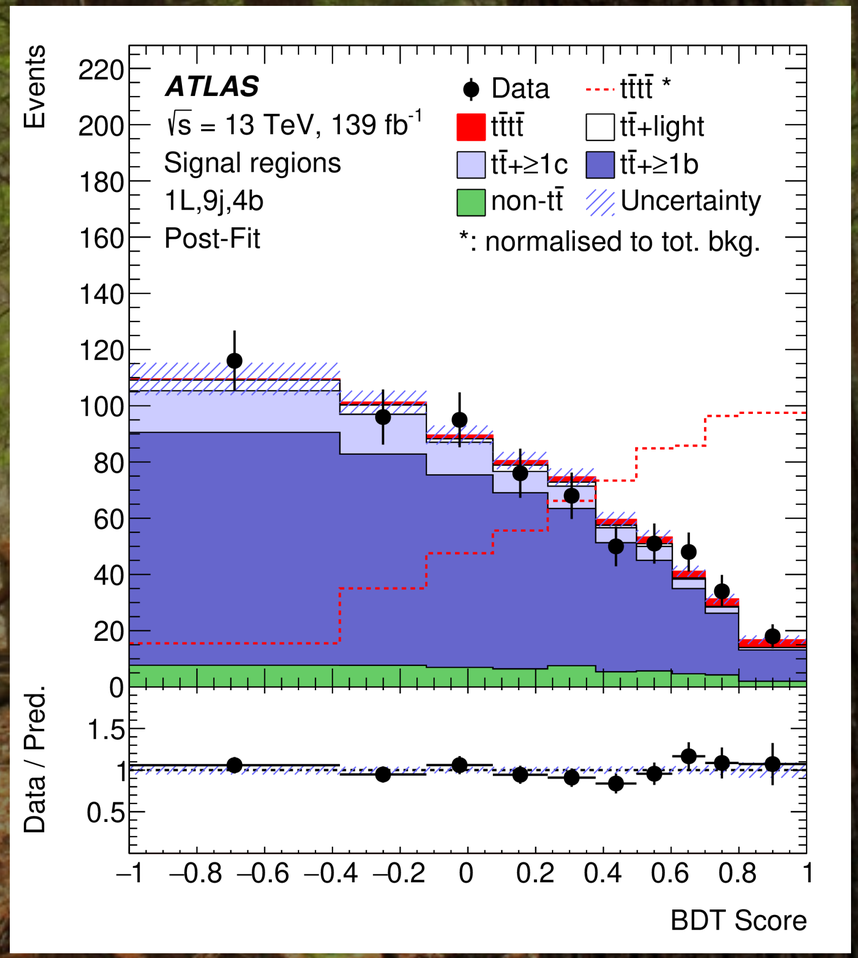


Image: N. A. Tonelli

Result 1L/2LOS:

Simultaneous fit in 21 regions.

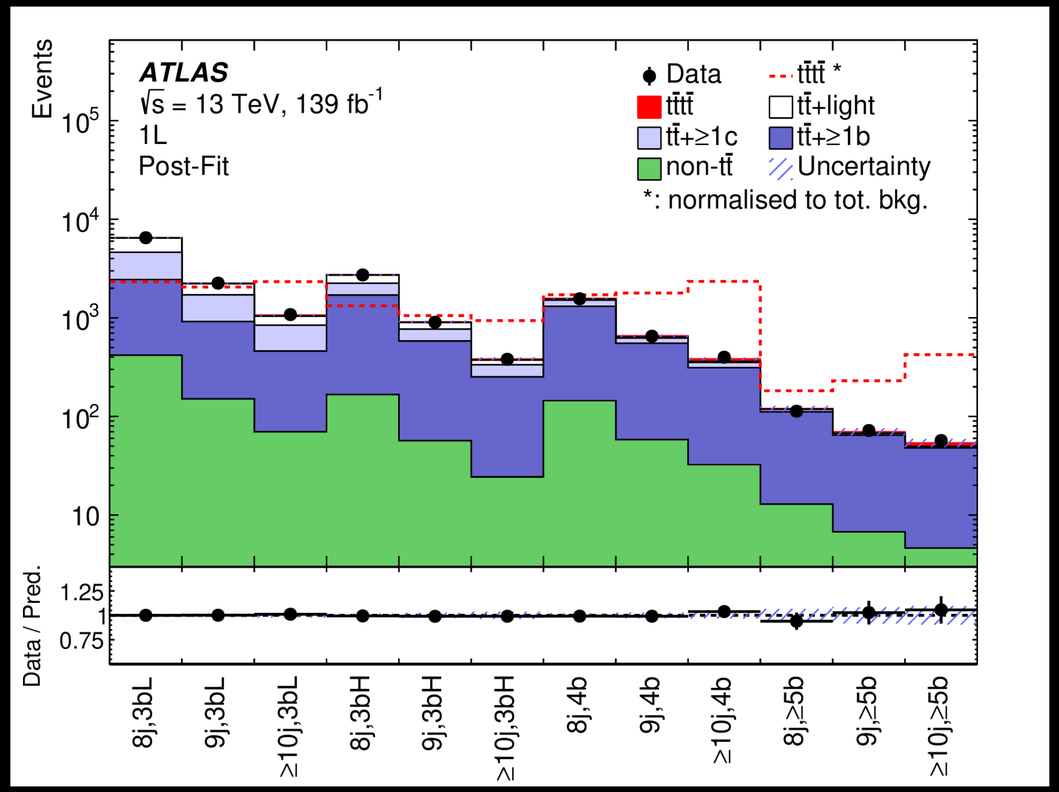
Good agreement observed between data and post-fit prediction in all fitted regions.

Measured four top signal strength:
$\mu = 2.2 \pm 0.7\ (\text{stat})\ ^{+1.5}_{-1.0}\ (\text{syst})$

Cross section:

$\sigma(tttt) = 26 \pm 8\ (\text{stat})\ ^{+15}_{-13}\ (\text{syst})$ fb

Significance: 1.9σ (1.0σ expected)



Combination

ATLAS Full Run 2 Data

Combined fit

- A simultaneous profile likelihood fit in all regions of both analyses
  - all systematic uncertainties included.

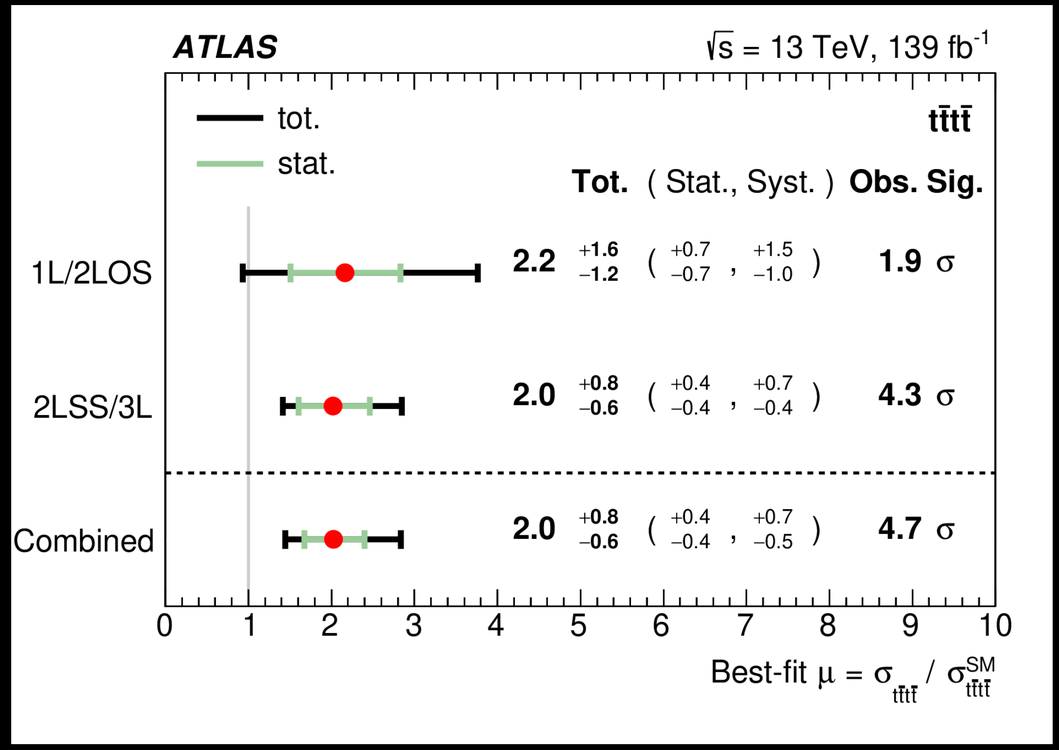
- Signal strength:

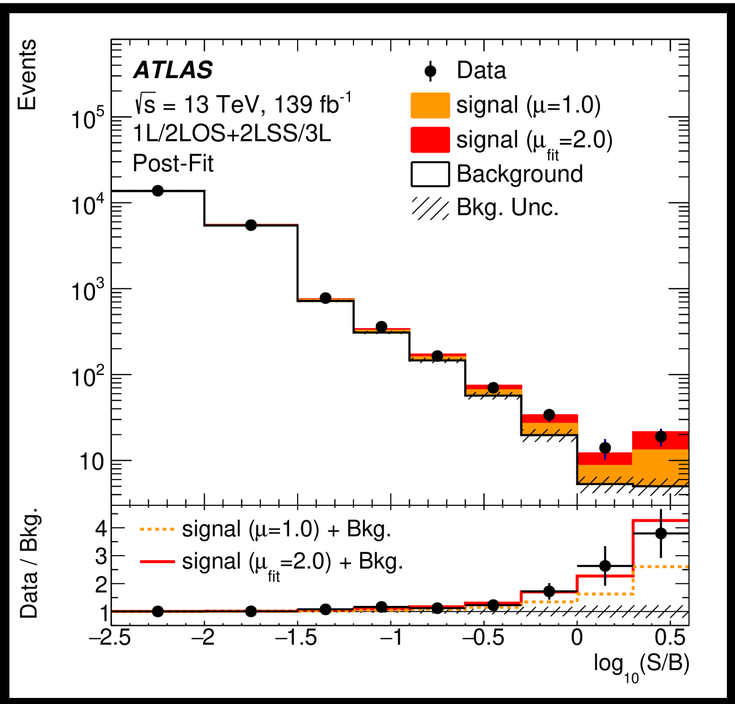
$$\mu = 2.0 \pm 0.4\,(\text{stat.})\,^{+0.7}_{-0.5}\,(\text{syst.}) = 2.0\,^{+0.8}_{-0.6}.$$

- Cross section:

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4\,(\text{stat.})\,^{+5}_{-4}\,(\text{syst.})\,\text{fb} = 24\,^{+7}_{-6}\,\text{fb}.$$

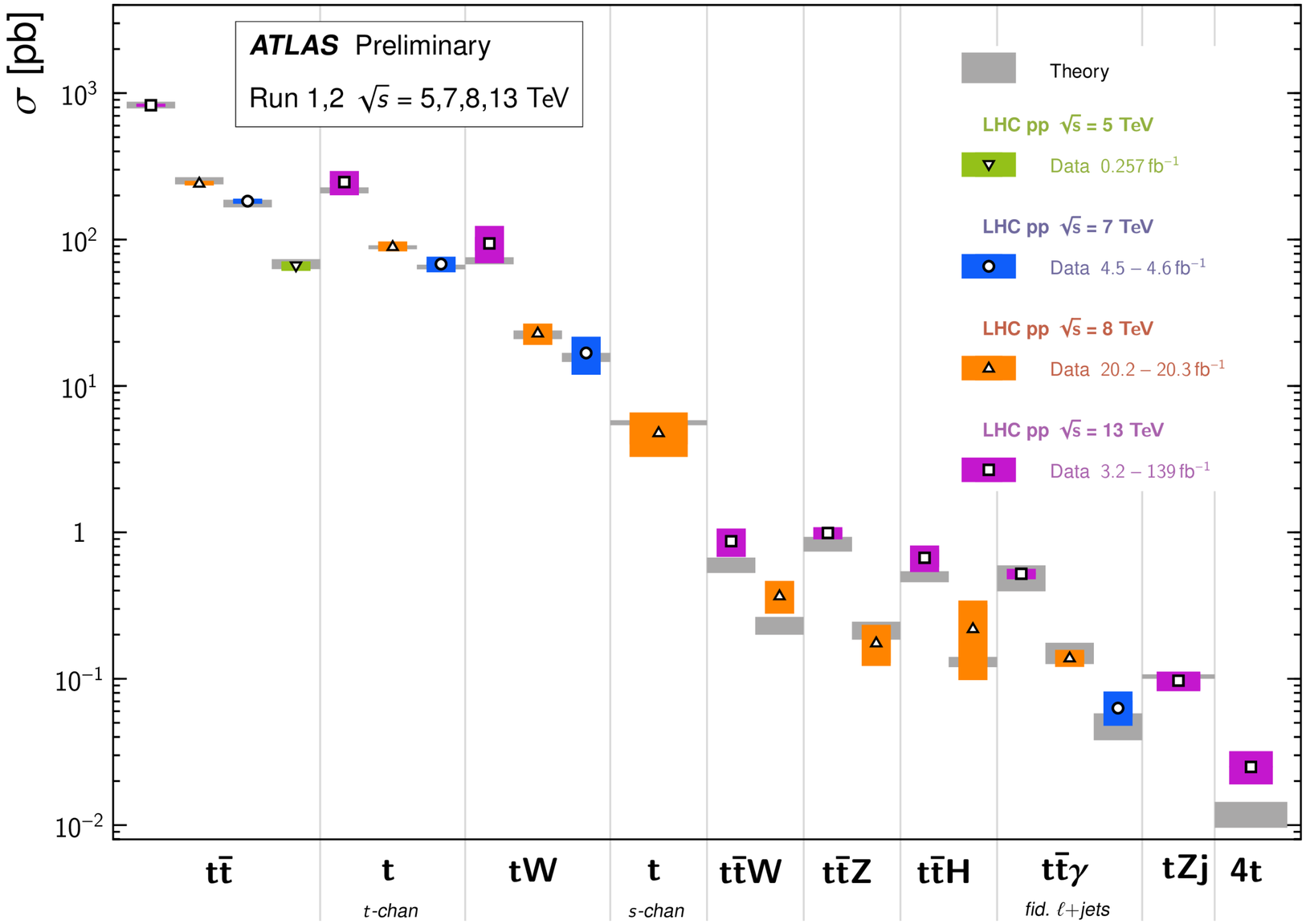
Evidence: 4.7σ (2.6σ expected)

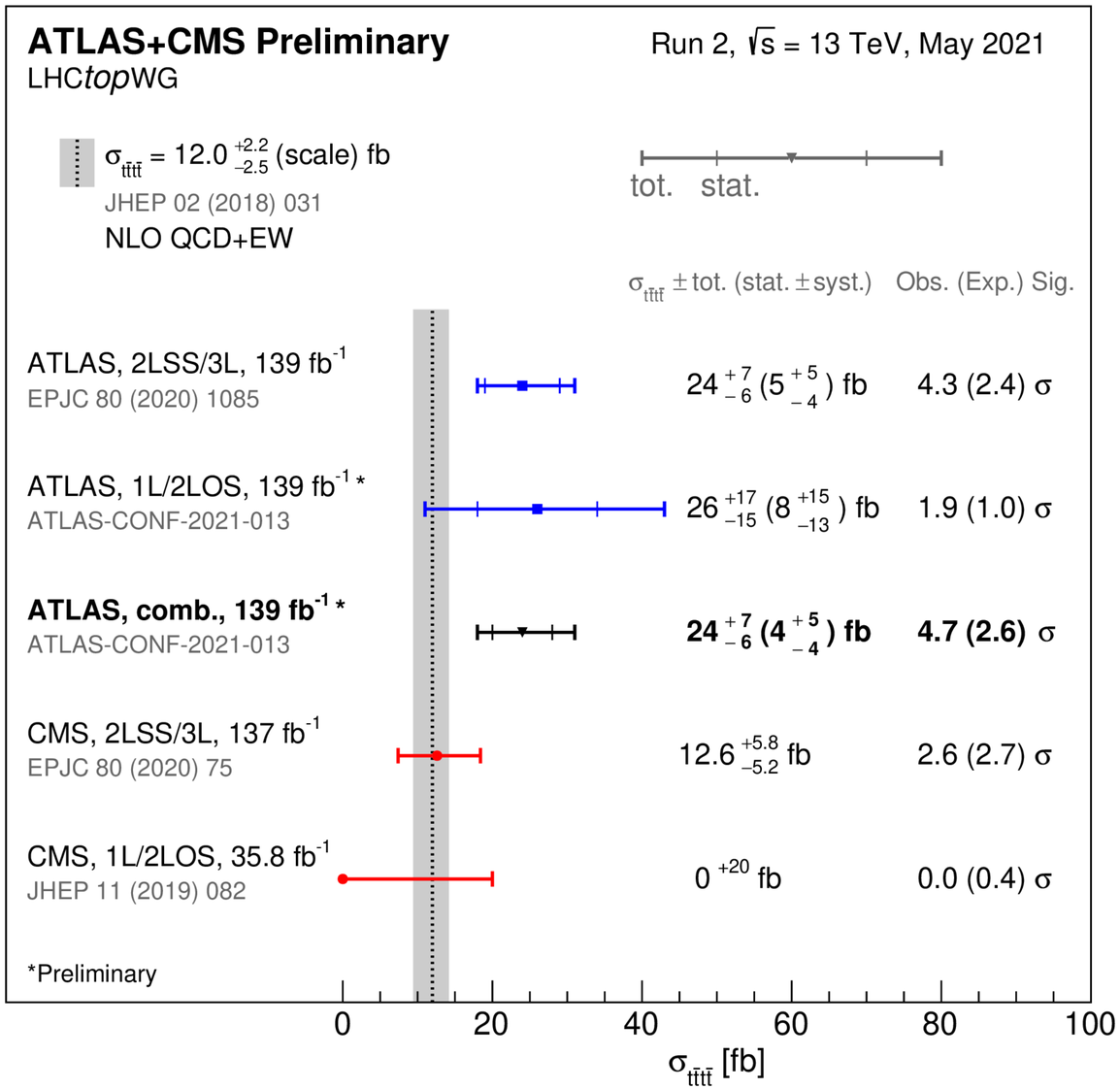




Top Quark Production Cross Section Measurements

Status: May 2021





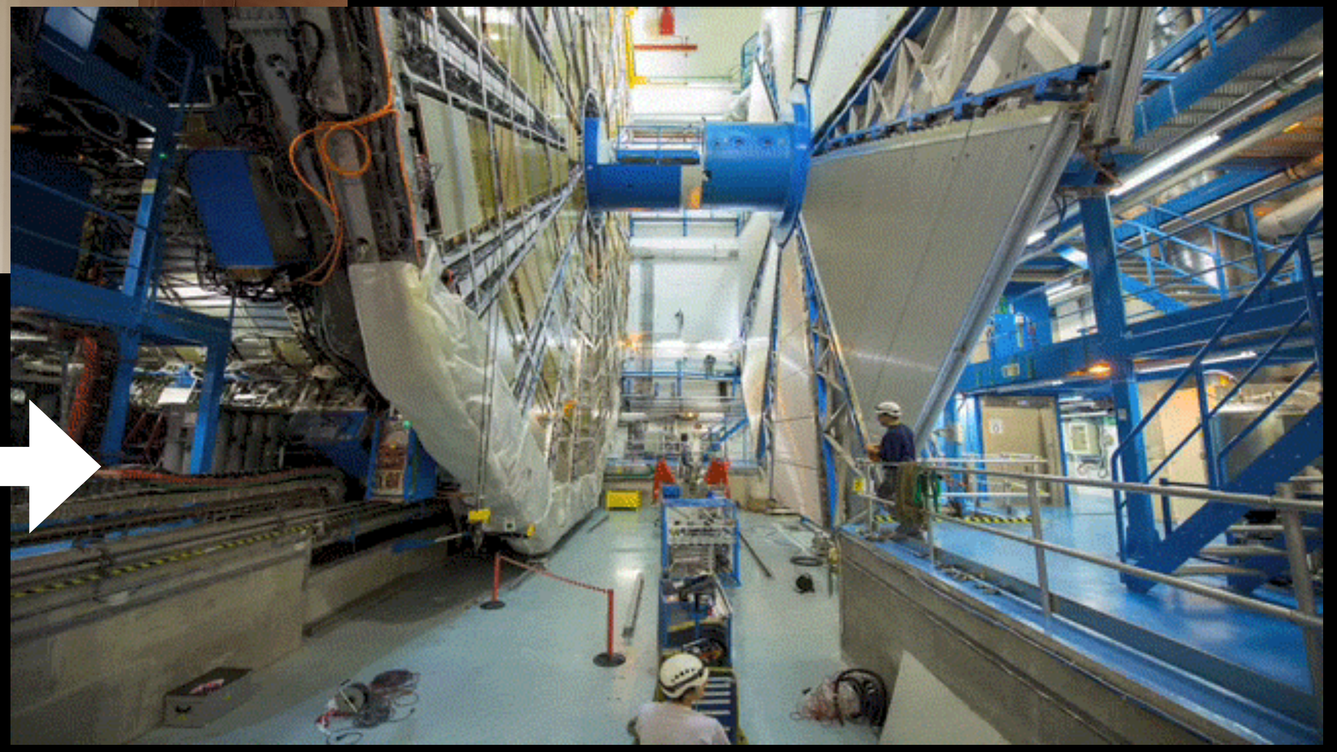
The cross section measurements are compared to the NLO QCD and EW theoretical calculation. The theory band represents uncertainties due to renormalisation and factorisation scales

THE ROAD AHEAD

Forest Road in Oregon by Michael Matti

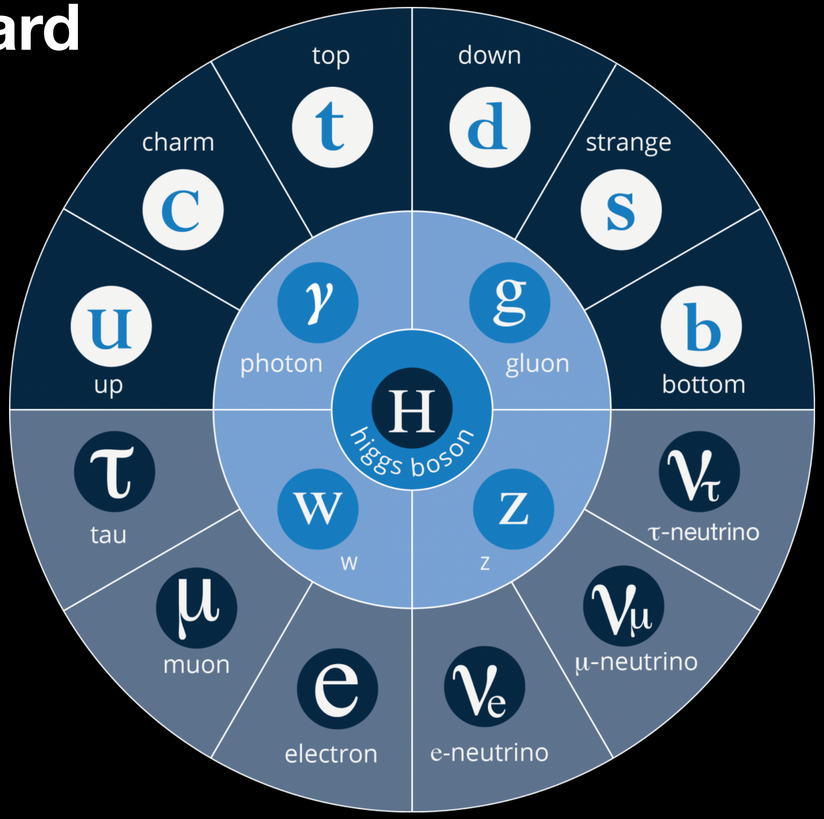
The LHC schedule

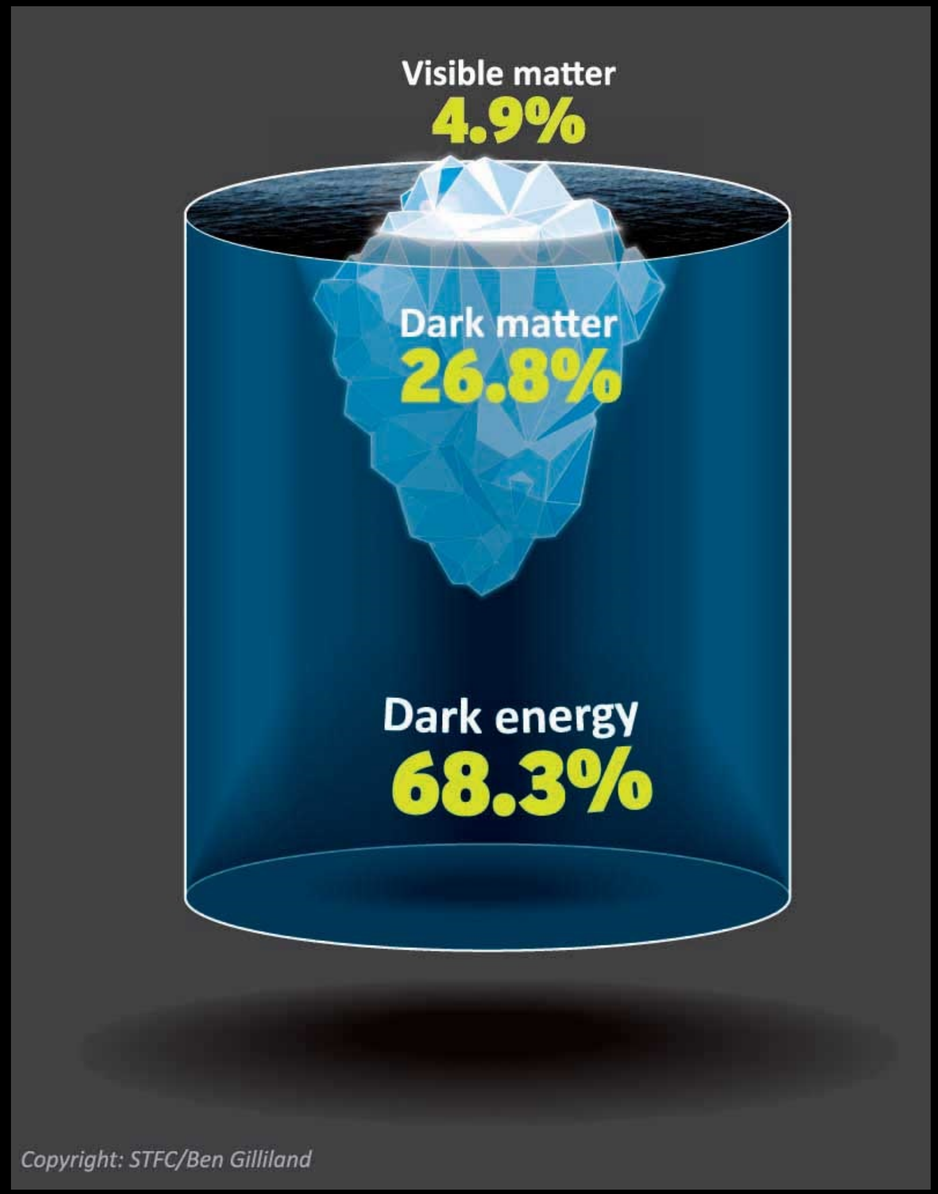
Due to COVID19, the start of Run 3 has been delayed to early-2022.



GIF from:https://cds.cern.ch/record/2283032

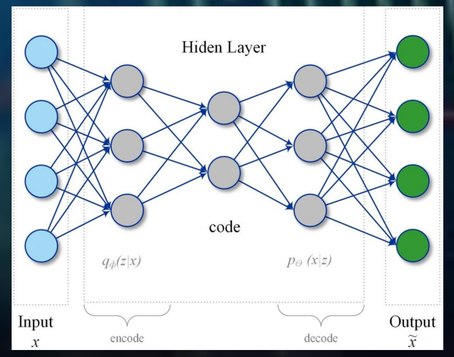
Precision measurements of the Standard Model





Could lead to hints of dark matter…

Searching for new physics processes hidden in a lot of data using machine learning…



… like a lighthouse to show the way.

But that’s not it…

Communication of results

An essential component of the long-term success of scientific research is communicating the results and methodology to the wider public. Social media is a vital new tool for this endeavour.

33.8k followers

91.3k followers

29.7k followers

643 followers

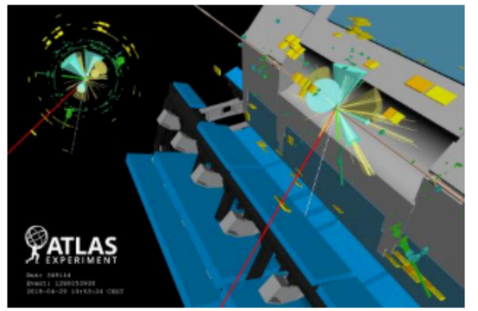
7.2k subscribers

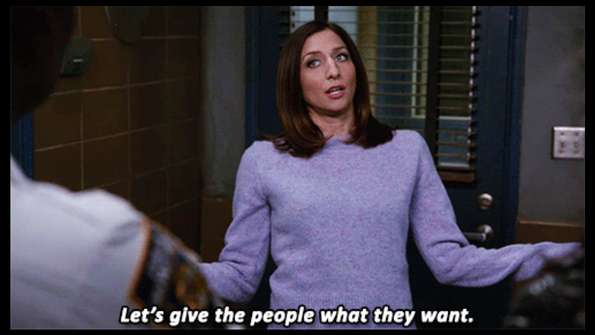
Physics Briefing

ATLAS finds evidence of spectacular four-top quark production

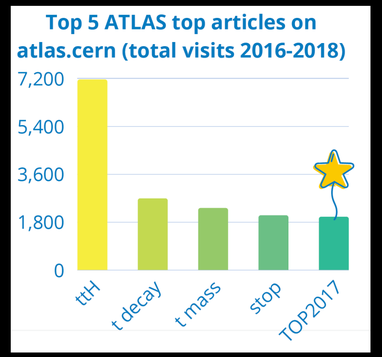
26th May 2020 – In a new result released today, the ATLAS Collaboration announced strong evidence of the production of four top quarks. This rare Standard Model process is expected to occur only once for every 70 thousand pairs of top quarks created at the LHC and has proven extremely difficult to measure.

Read more →





atlas.cern

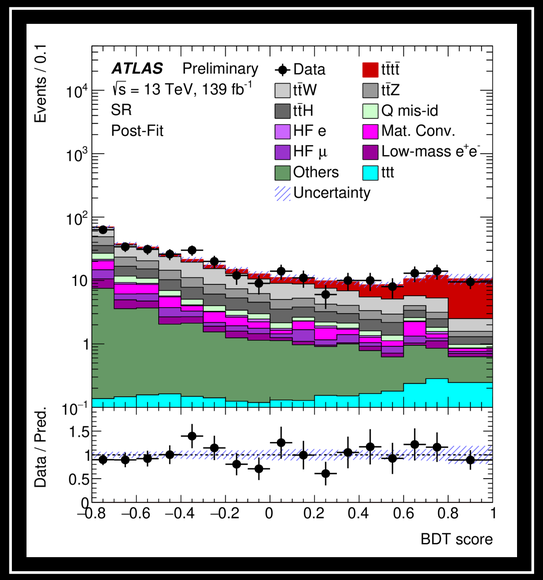


Please ensure you go through internal approval and publication before talking about your result online...

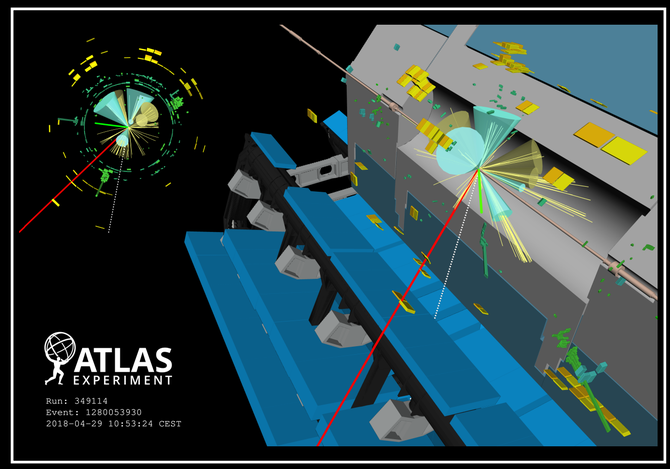
Nikhef

Radboud University

Nijmegen, the Netherlands



Four Top Quarks: Evidence in ATLAS



Thank you!

Dr Clara Nellist

Excellence Initiative Fellow

Radboud University and NIKHEF

Online Particle Physics Seminar, Warwick UK

24.06.2021