Nikhef

Radboud University
Nijmegen, the Netherlands

Four Tops results from ATLAS

Dr Clara Nellist

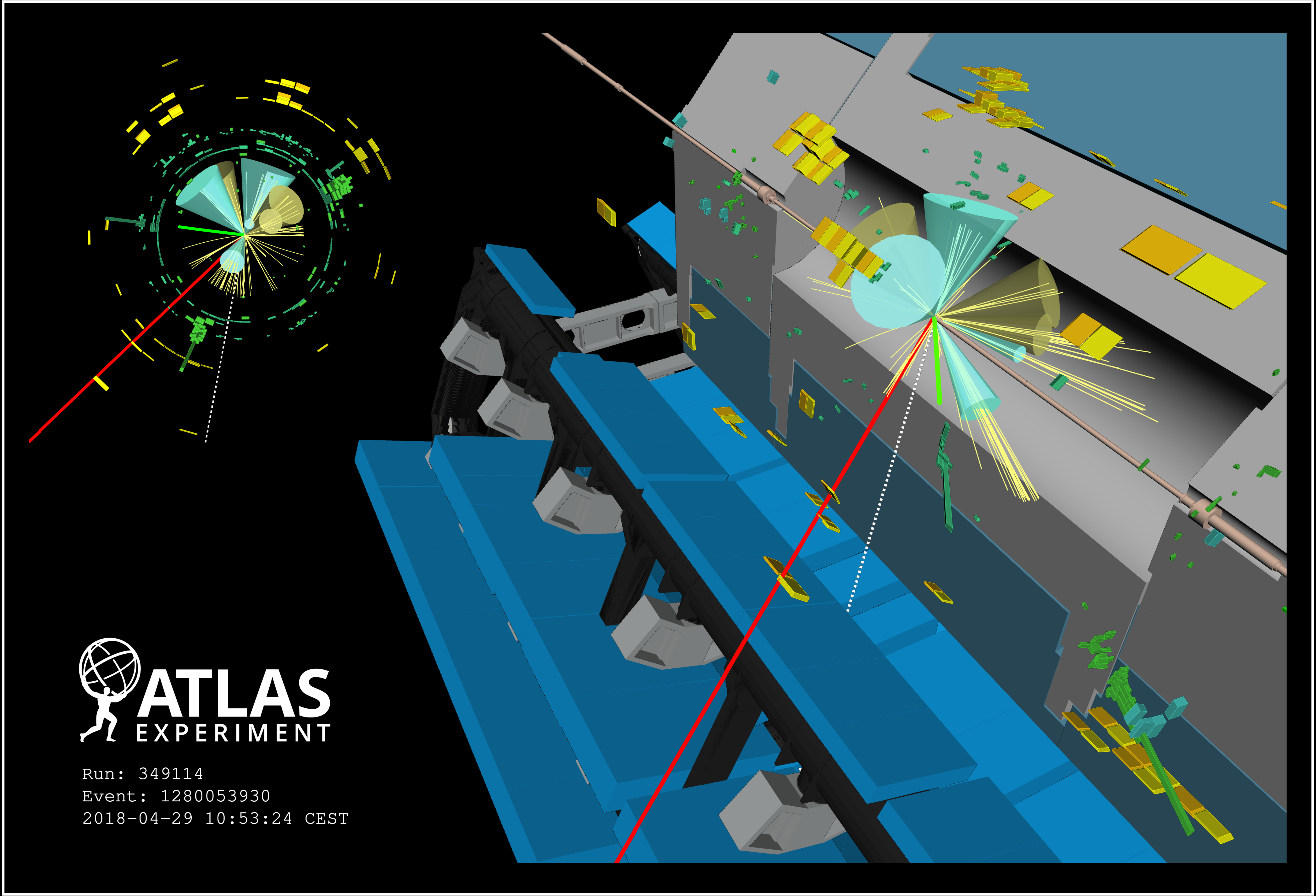
(she / her)

Excellence Initiative Fellow

Radboud University and NIKHEF

Online Particle Physics Seminar, Birmingham UK

07.10.2020



Added afterwards:

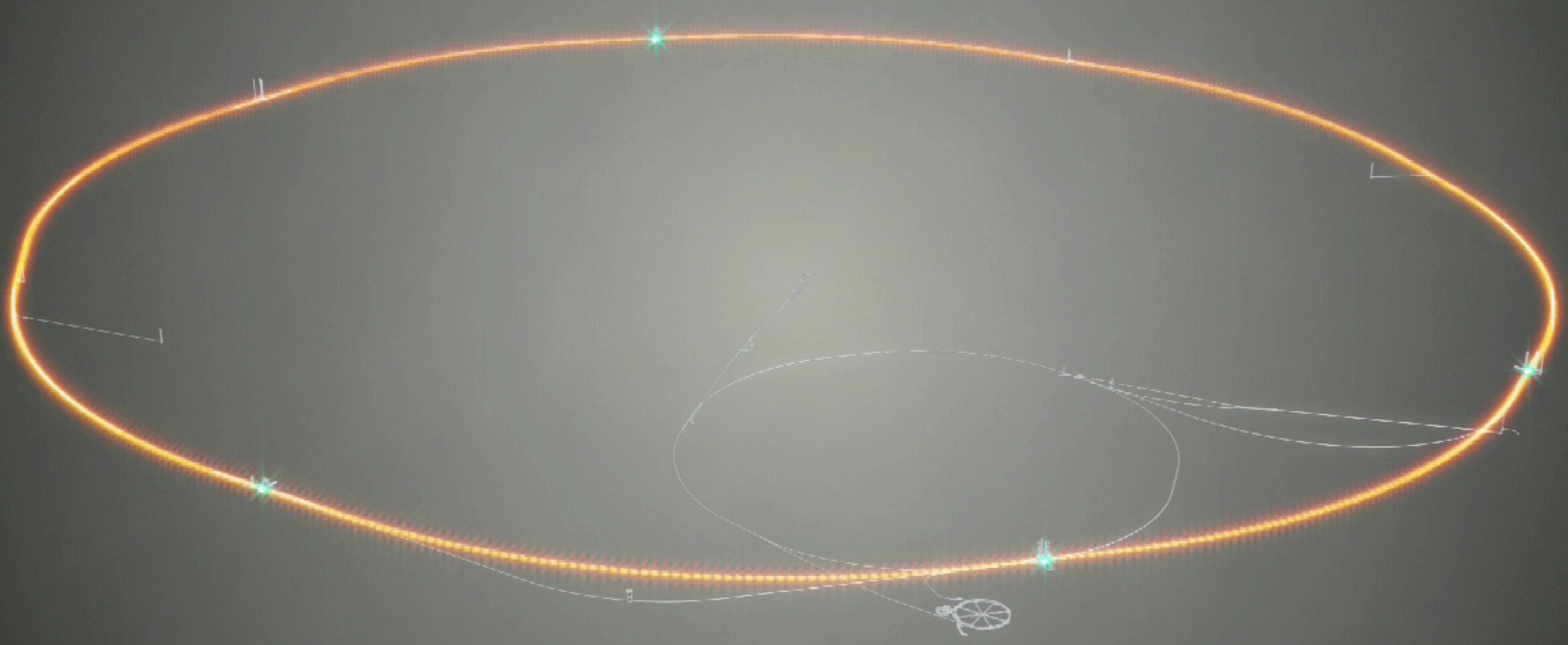
This presentation contained many videos. These cannot be embedded in a PDF, so I have instead added the link to the relevant CDS location for them. Let me know if you'd like advice to use them in a presentation too, I'm happy to help!

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

(I hope I got the right building, but this would have happened in real life too!)

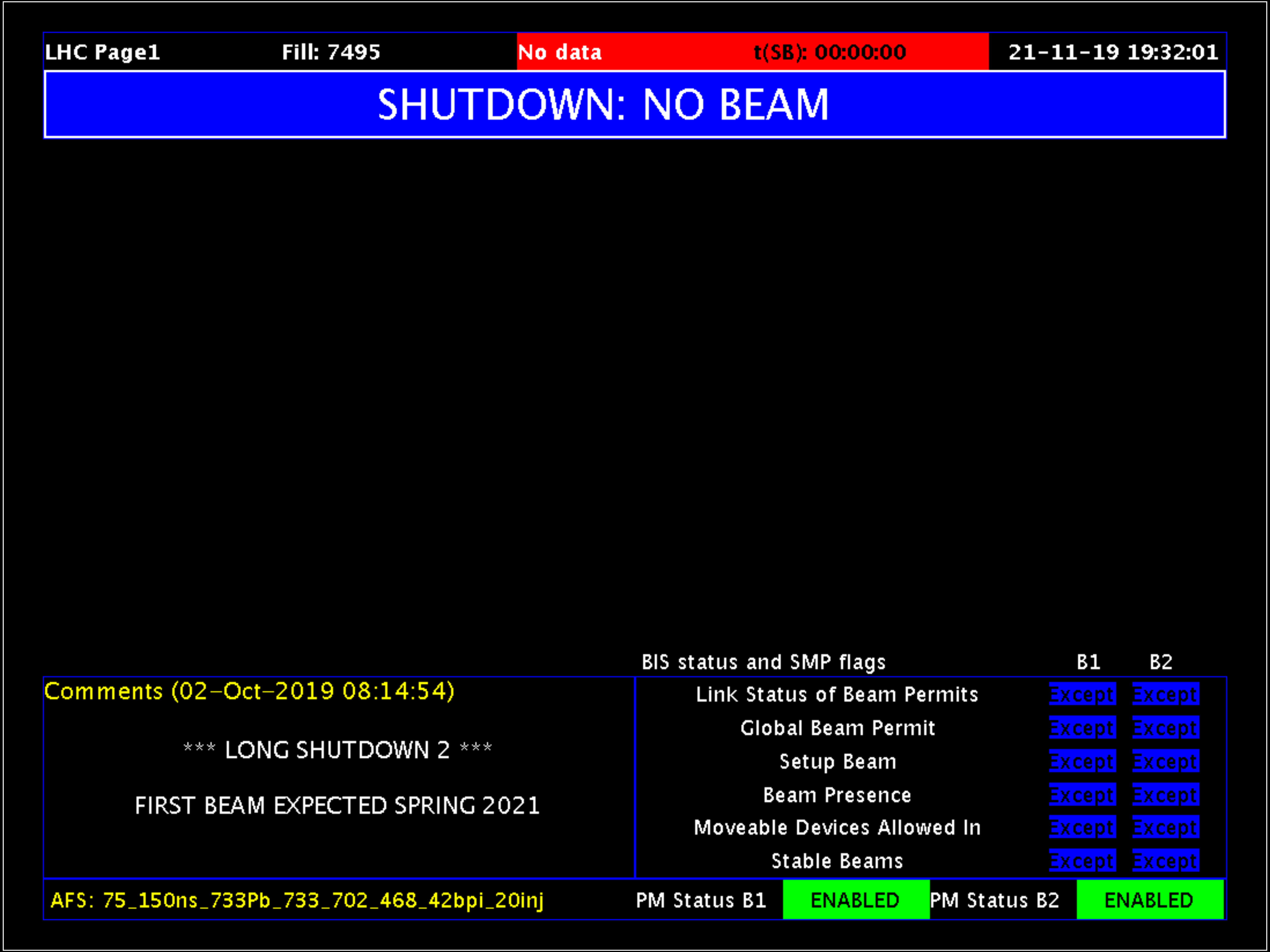
CERN

Video from: https://videos.cern.ch/record/1610170

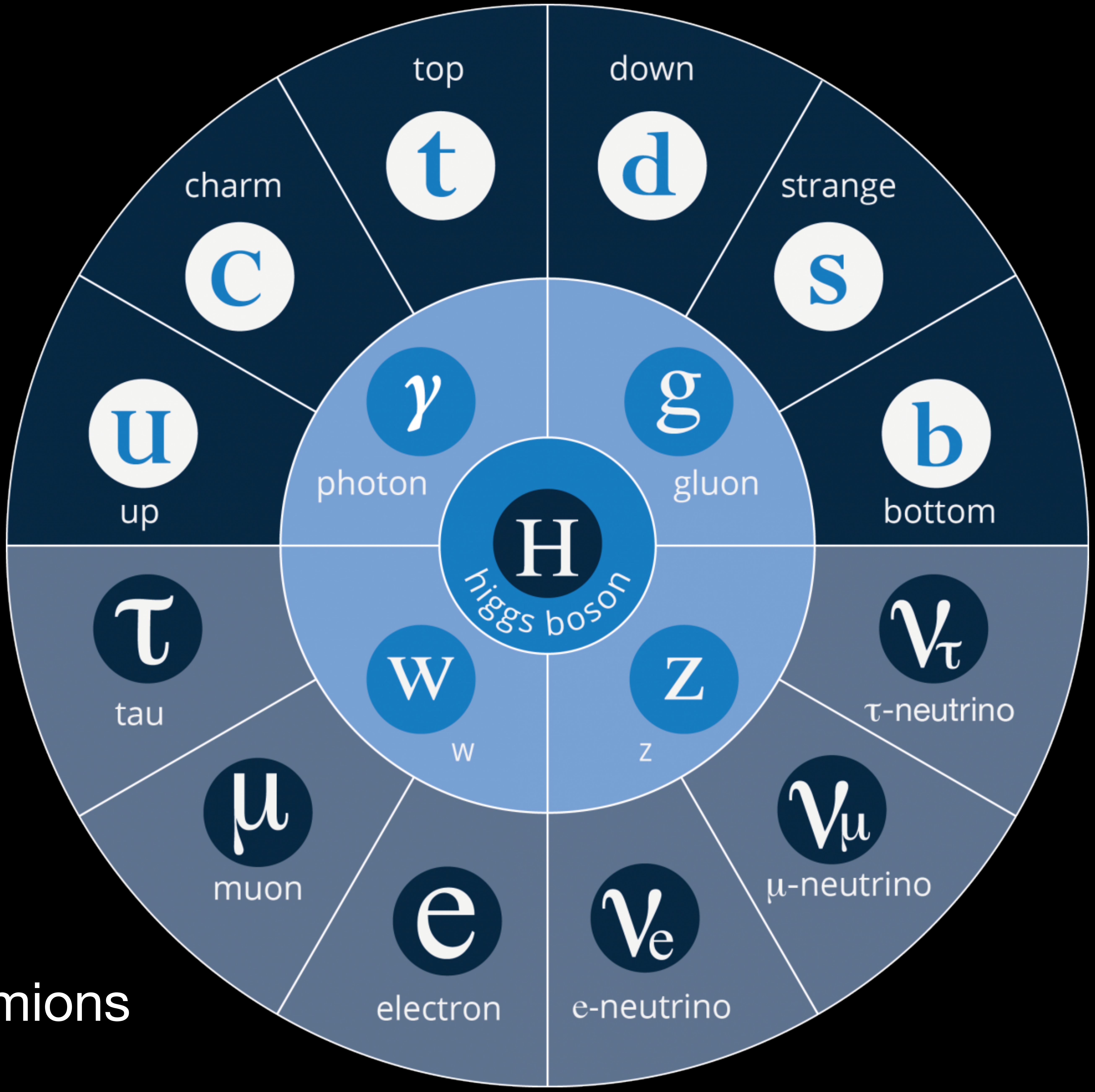


Video from: https://videos.cern.ch/record/1702939

Right now:


LHC Page1
Fill: 7495
No data
t(SB): 00:00:00
21-11-19 19:32:01
SHUTDOWN: NO BEAM
Comments (02-Oct-2019 08:14:54)
*** LONG SHUTDOWN 2 ***
FIRST BEAM EXPECTED SPRING 2021
BIS status and SMP flags
B1
B2
Link Status of Beam Permits
Global Beam Permit
Setup Beam
Beam Presence
Moveable Devices Allowed In
Stable Beams
Except
AFS: 75_150ns_733Pb_733_702_468_42bpi_20inj
PM Status B1
ENABLED
PM Status B2
ENABLED

The Standard Model



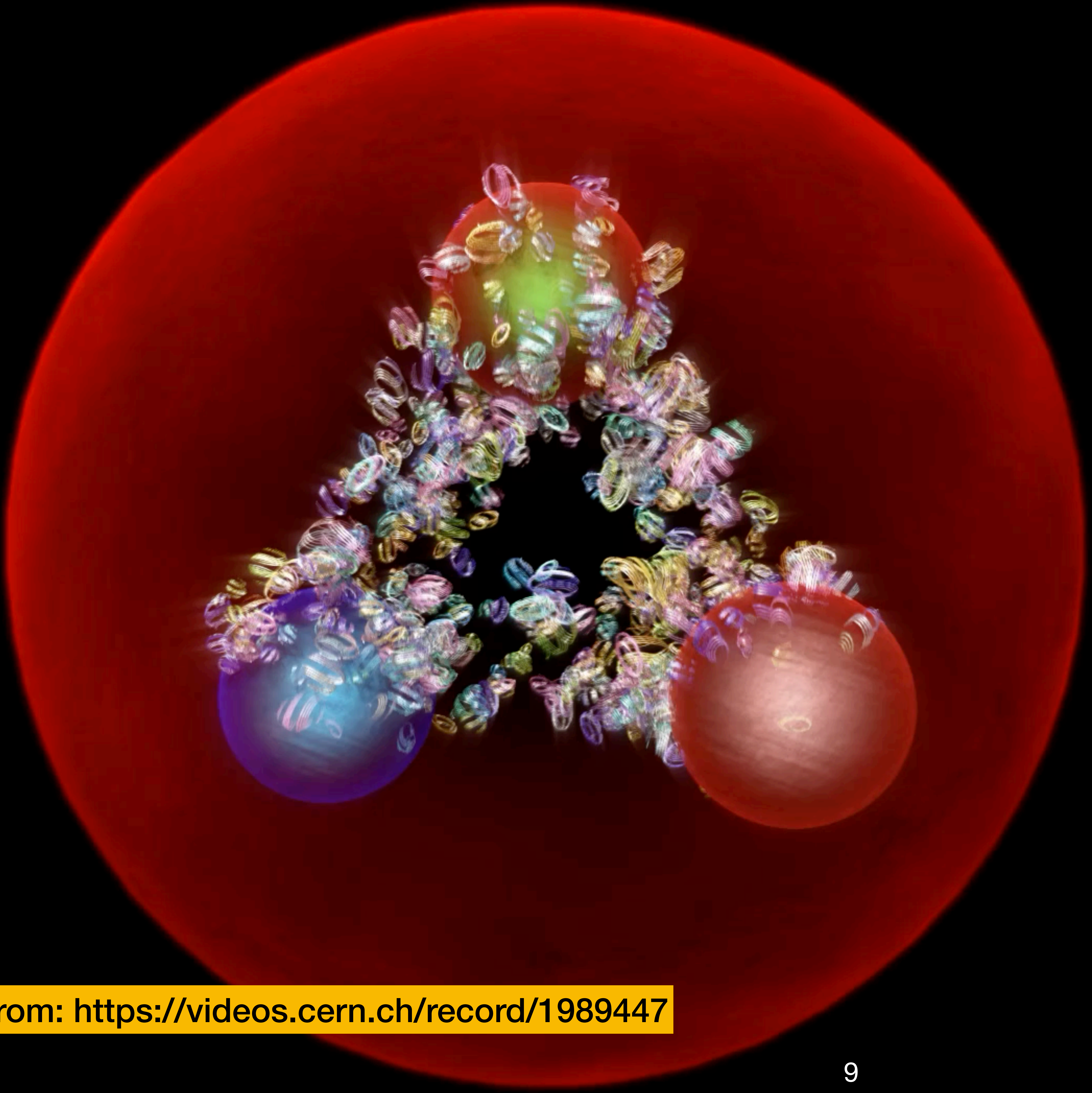
Quarks
Leptons
} Fermions

Bosons

Electromagnetism

The Strong Force

Weak-Nuclear Force



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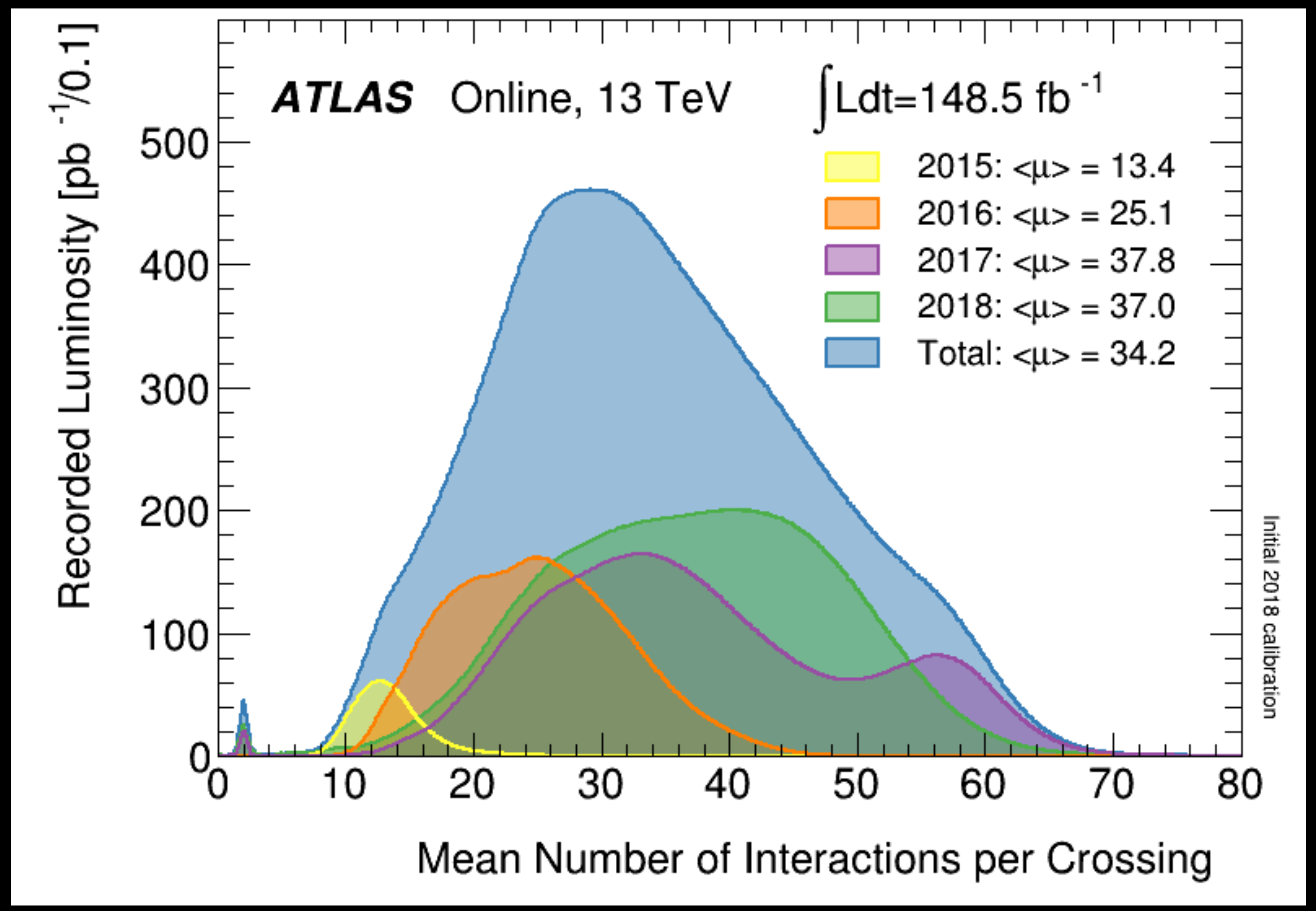
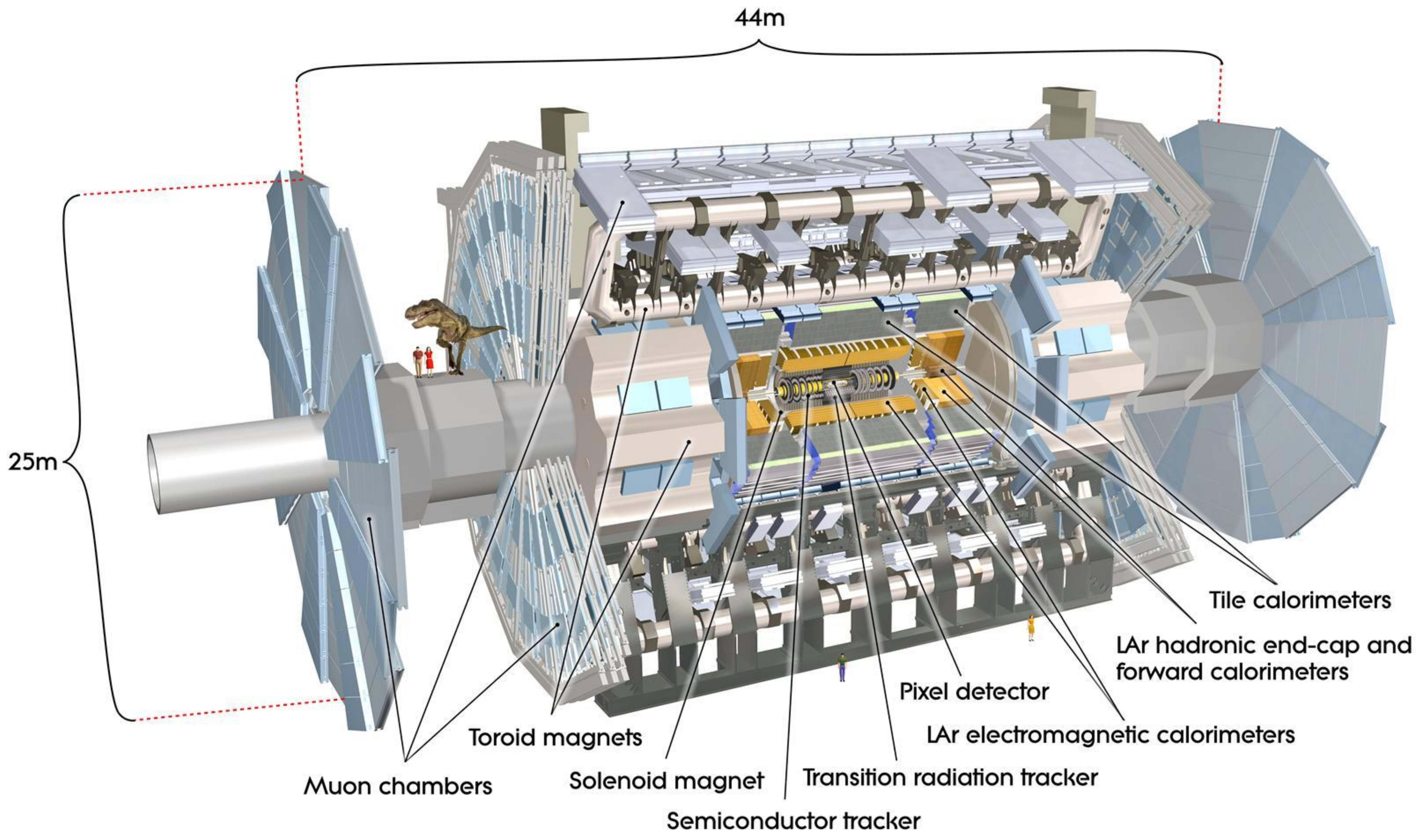
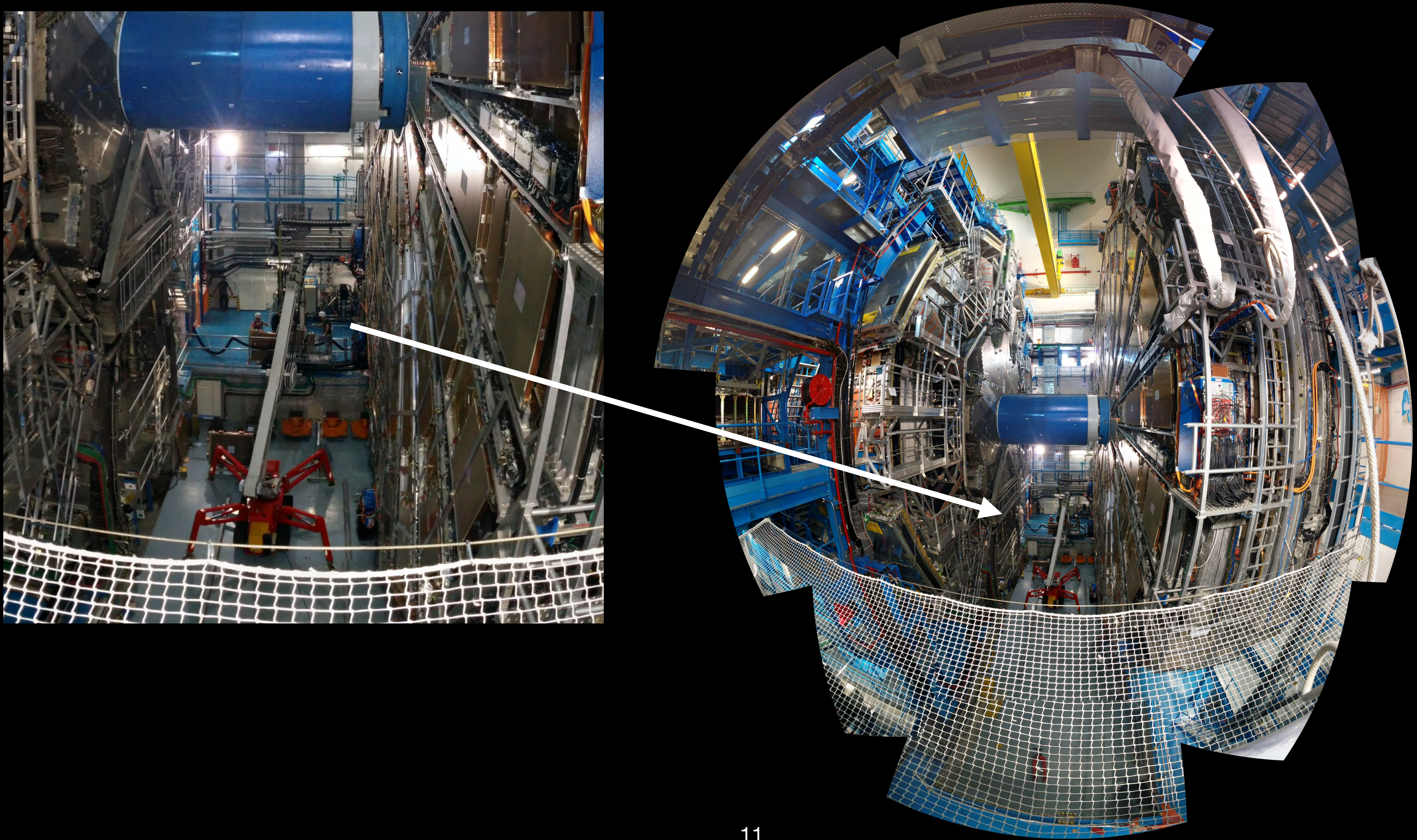



44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Transition radiation tracker
Muon chambers
Solenoid magnet
Semiconductor tracker

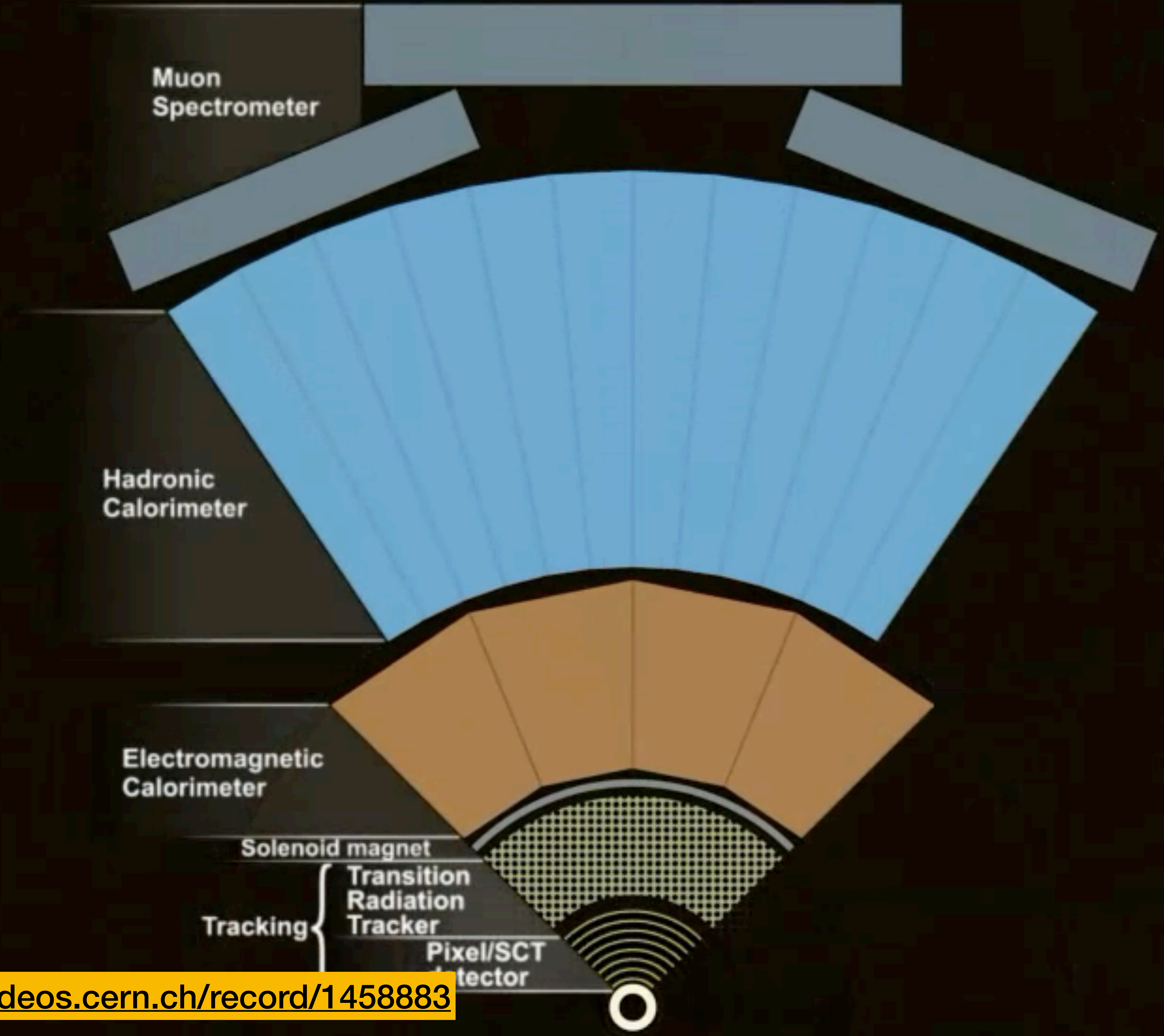


Status: November 2018

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



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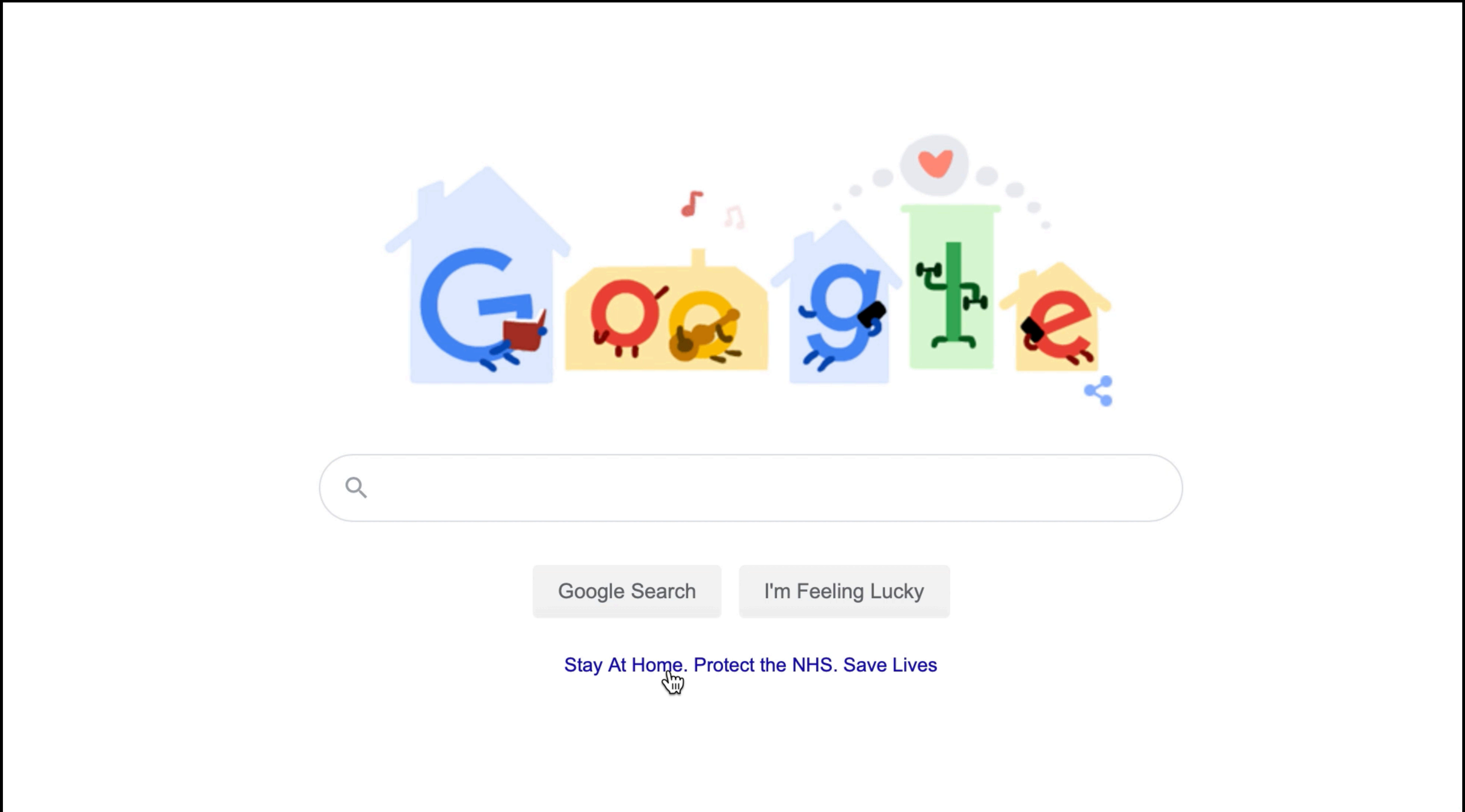
Video from: https://videos.cern.ch/record/1541893


Google Search
I'm Feeling Lucky
Stay At Home. Protect the NHS. Save Lives

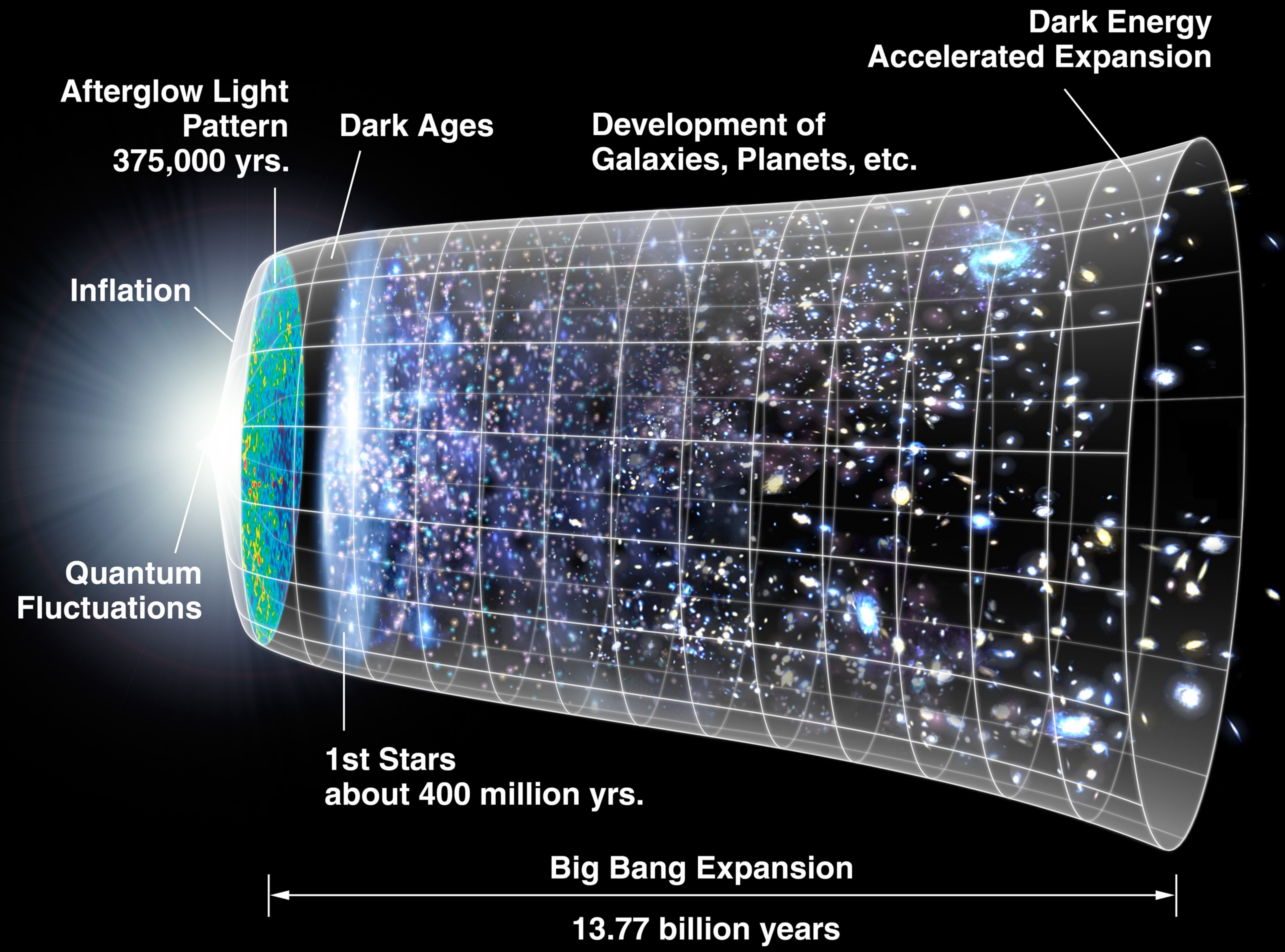

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Image: NASA

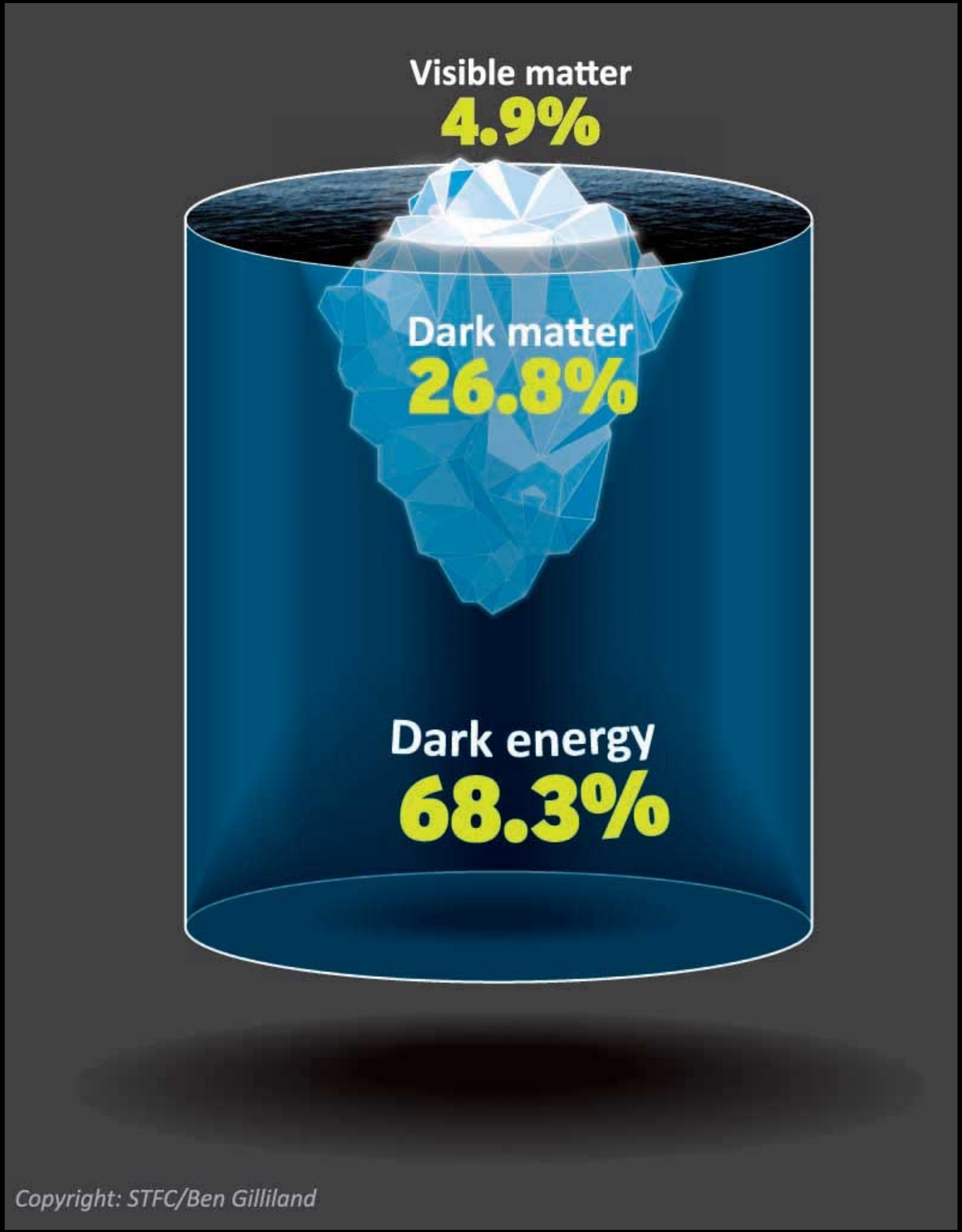
The Big Questions

- **The Higgs Boson**

Image: Jorge Cham / PhD Comics

The Big Questions

- The Higgs Boson
- Dark Matter



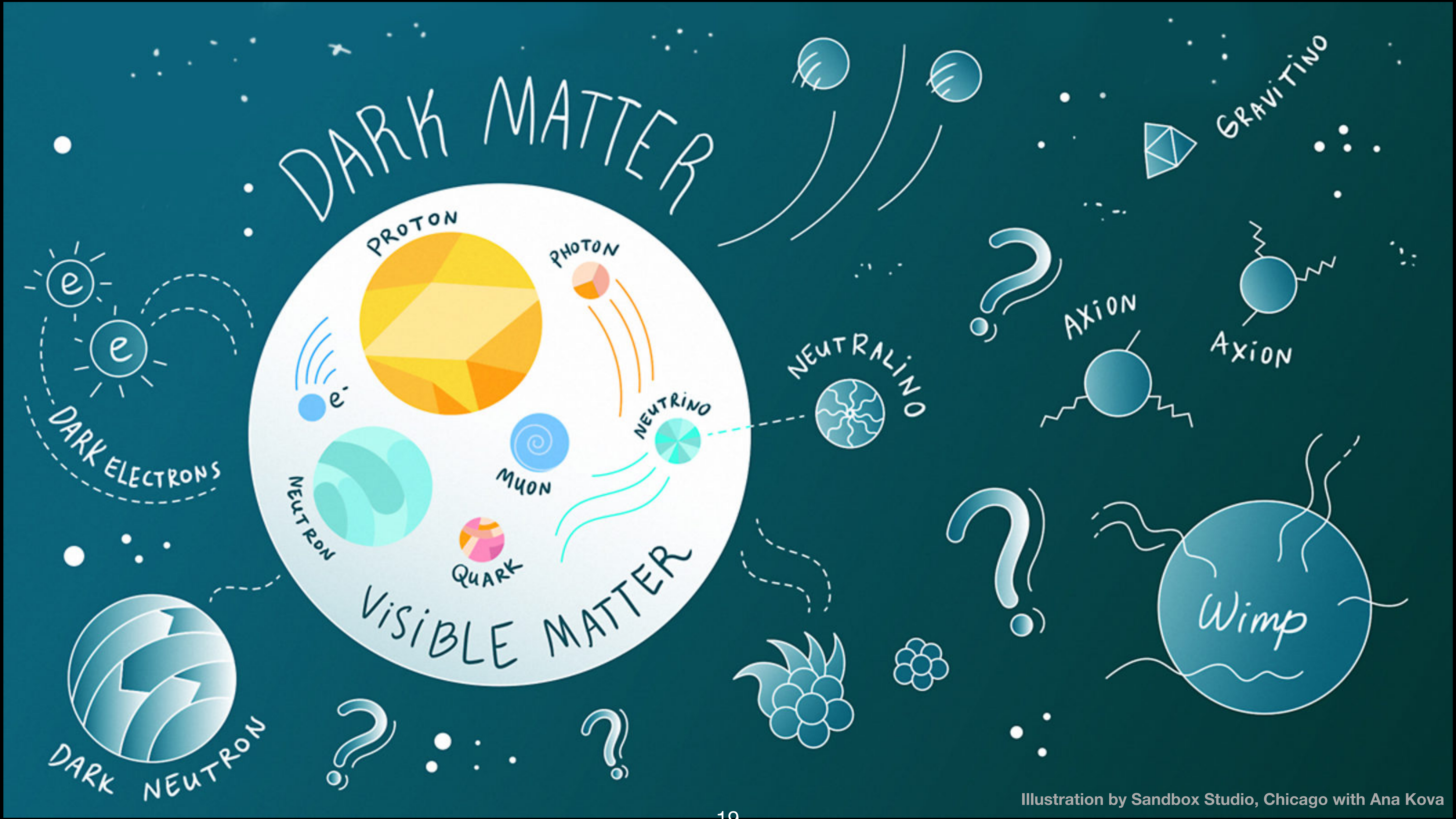
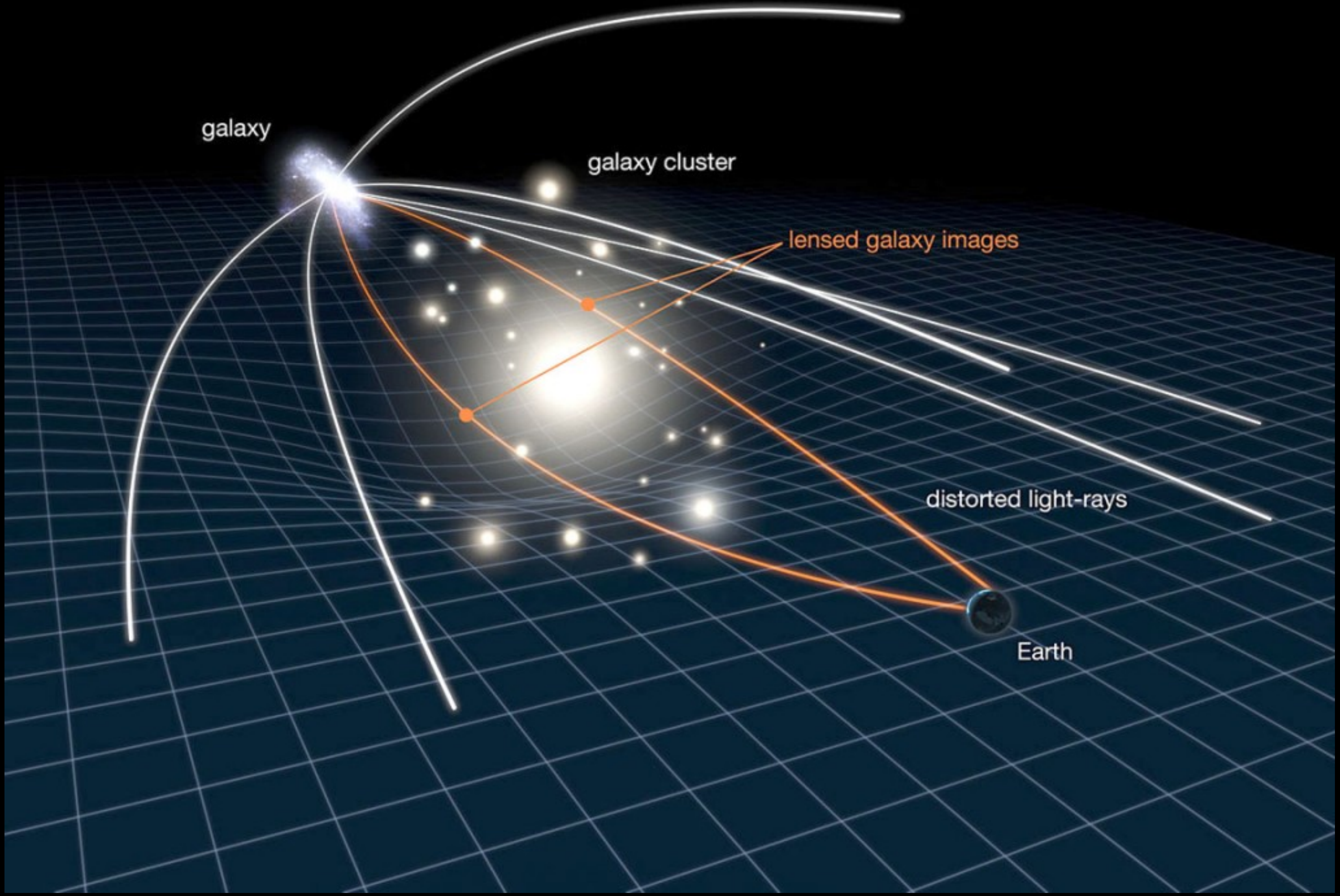


Illustration by Sandbox Studio, Chicago with Ana Kova

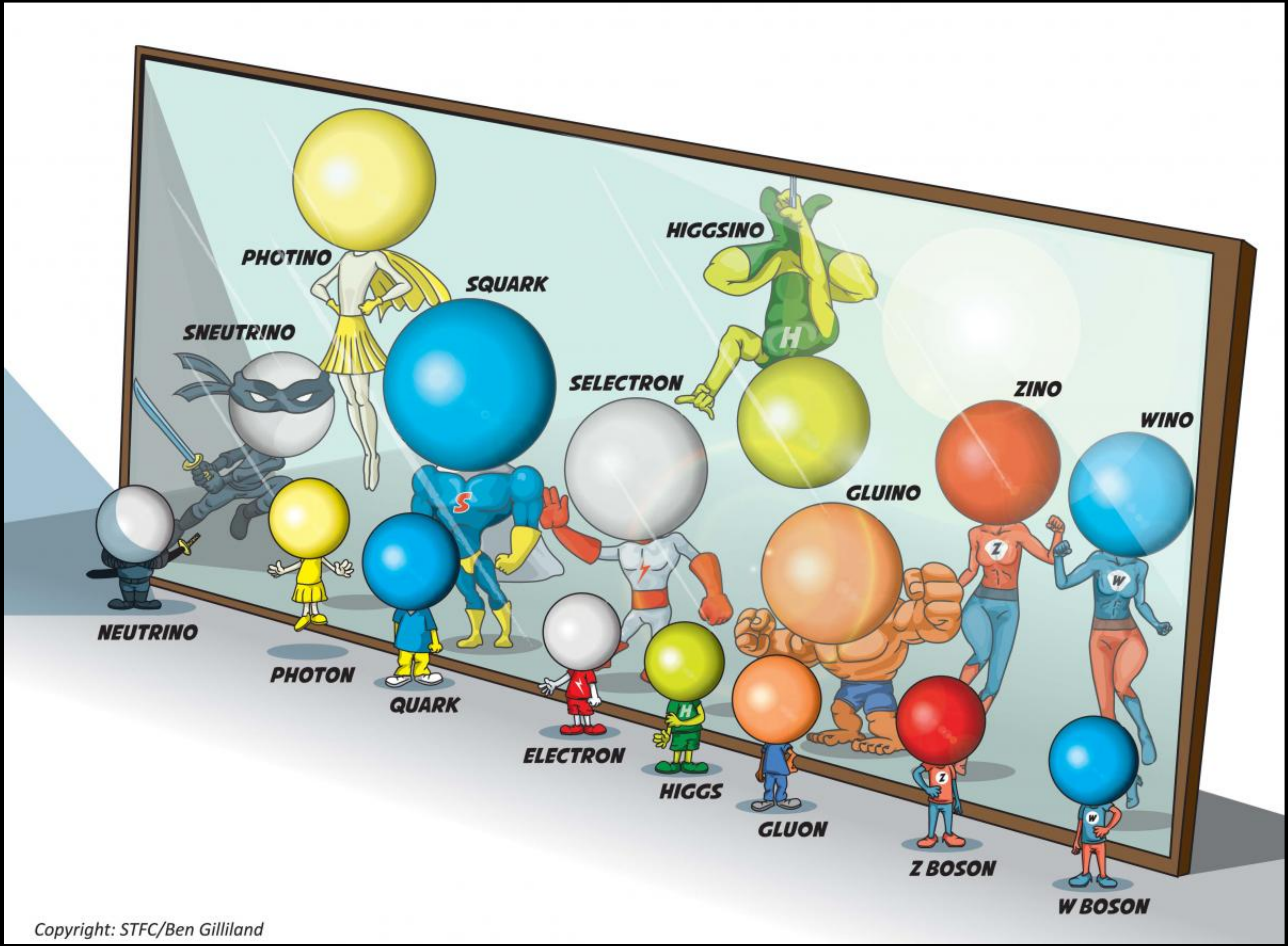


Gravitational lensing

Image: NASA/ESA

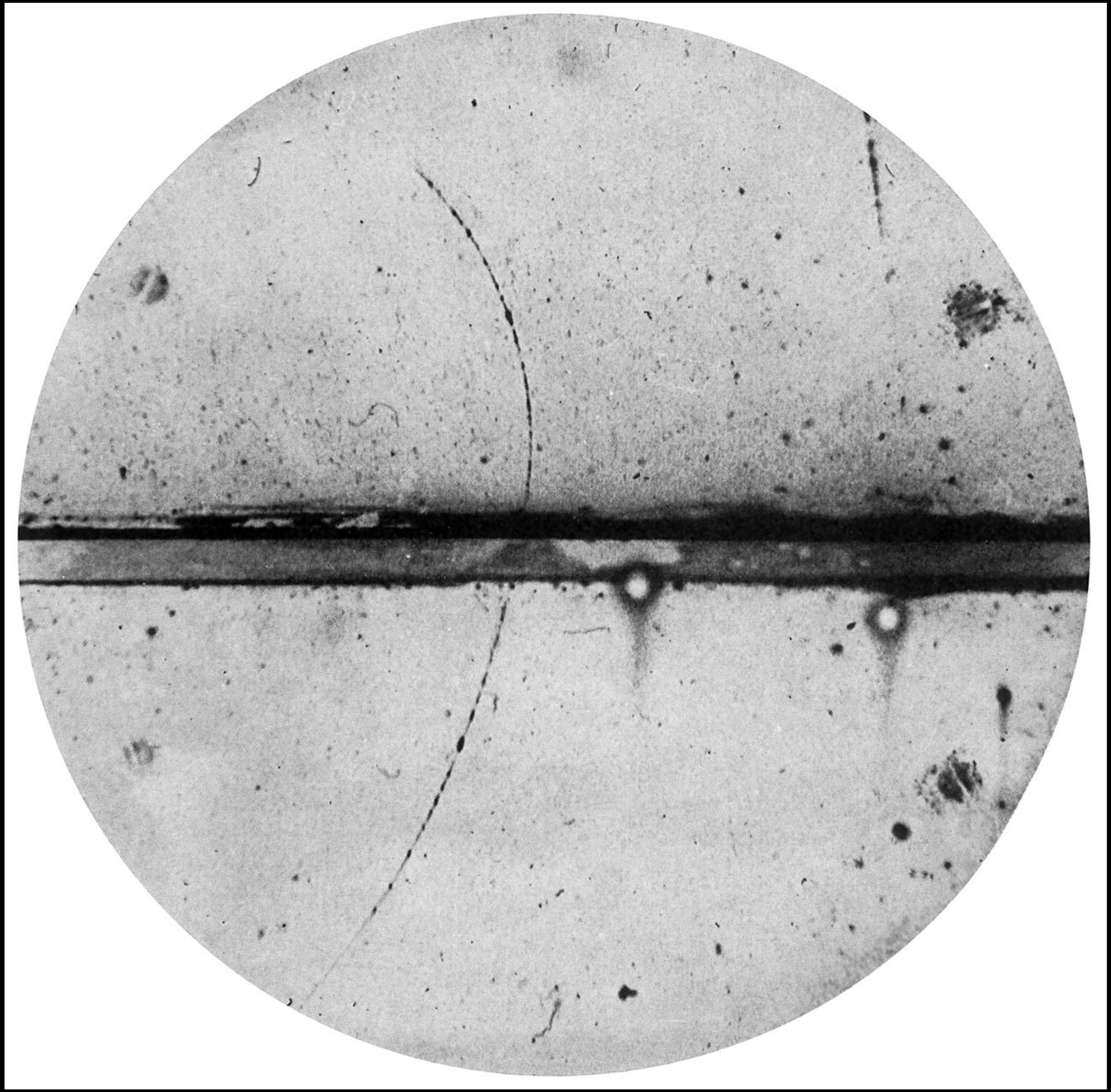
Supersymmetry

?



The Big Questions

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

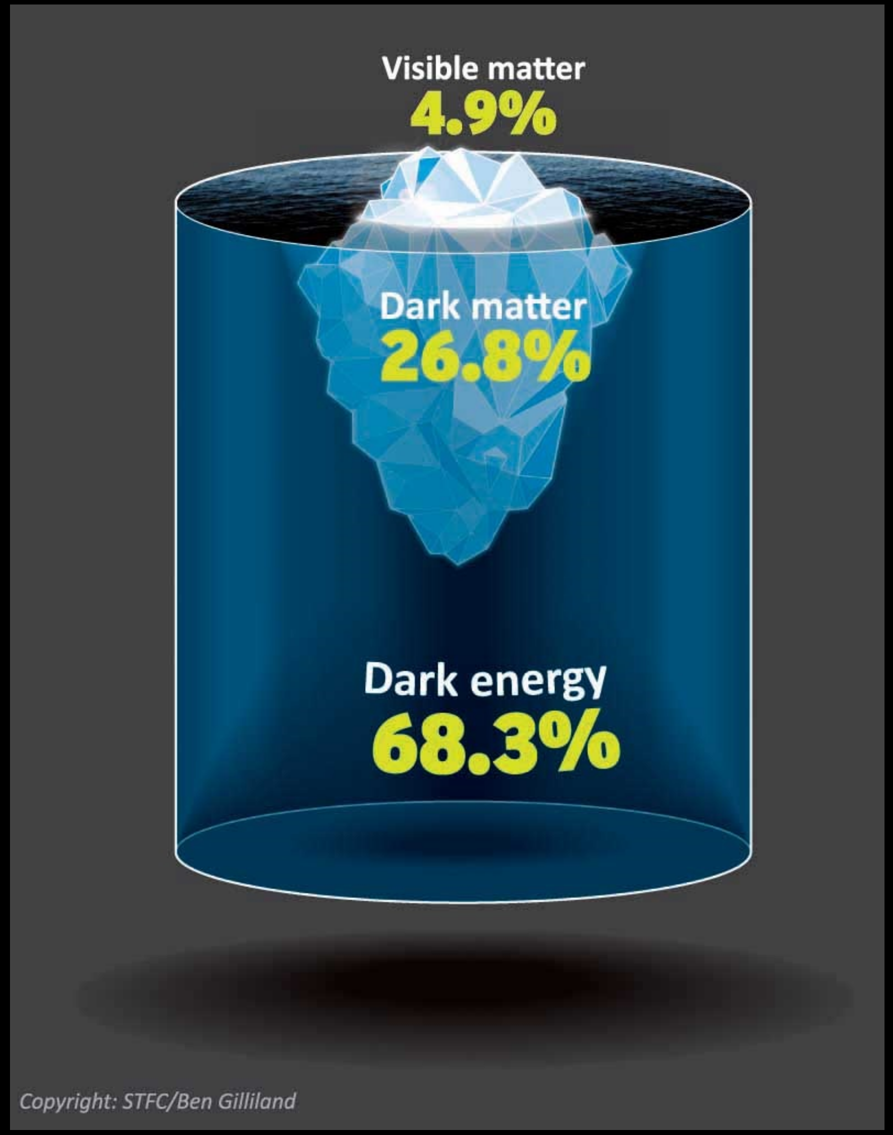


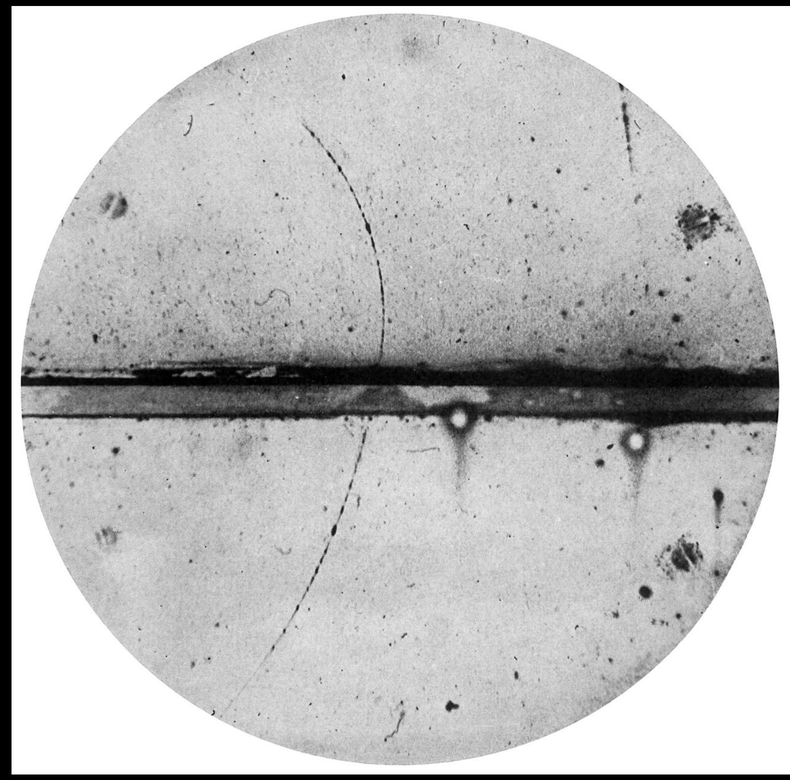
The Big Questions

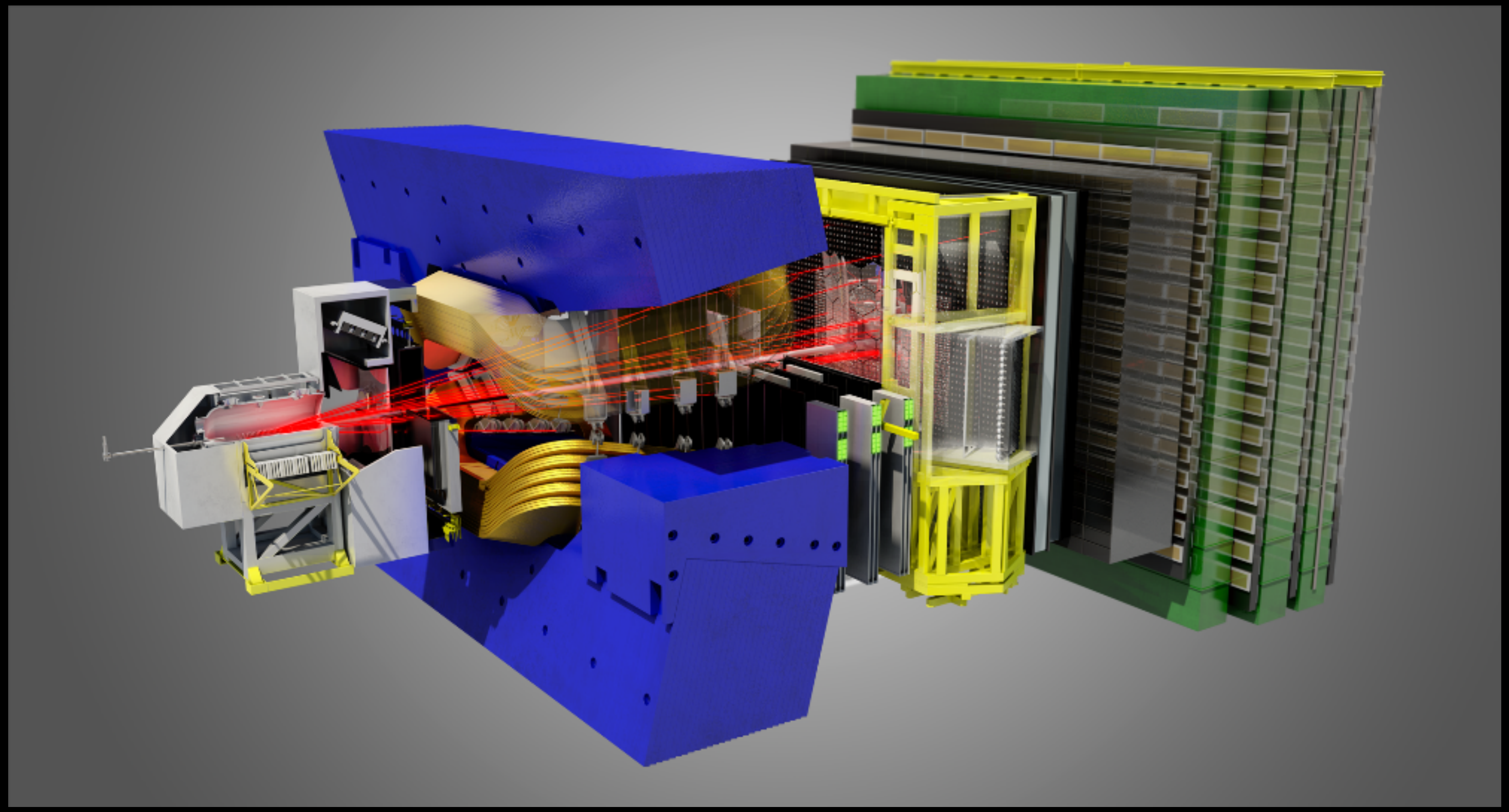
- The Higgs Boson
- Dark Matter
- Matter-Antimatter asymmetry
- **Strength of Gravity**

The Big Questions

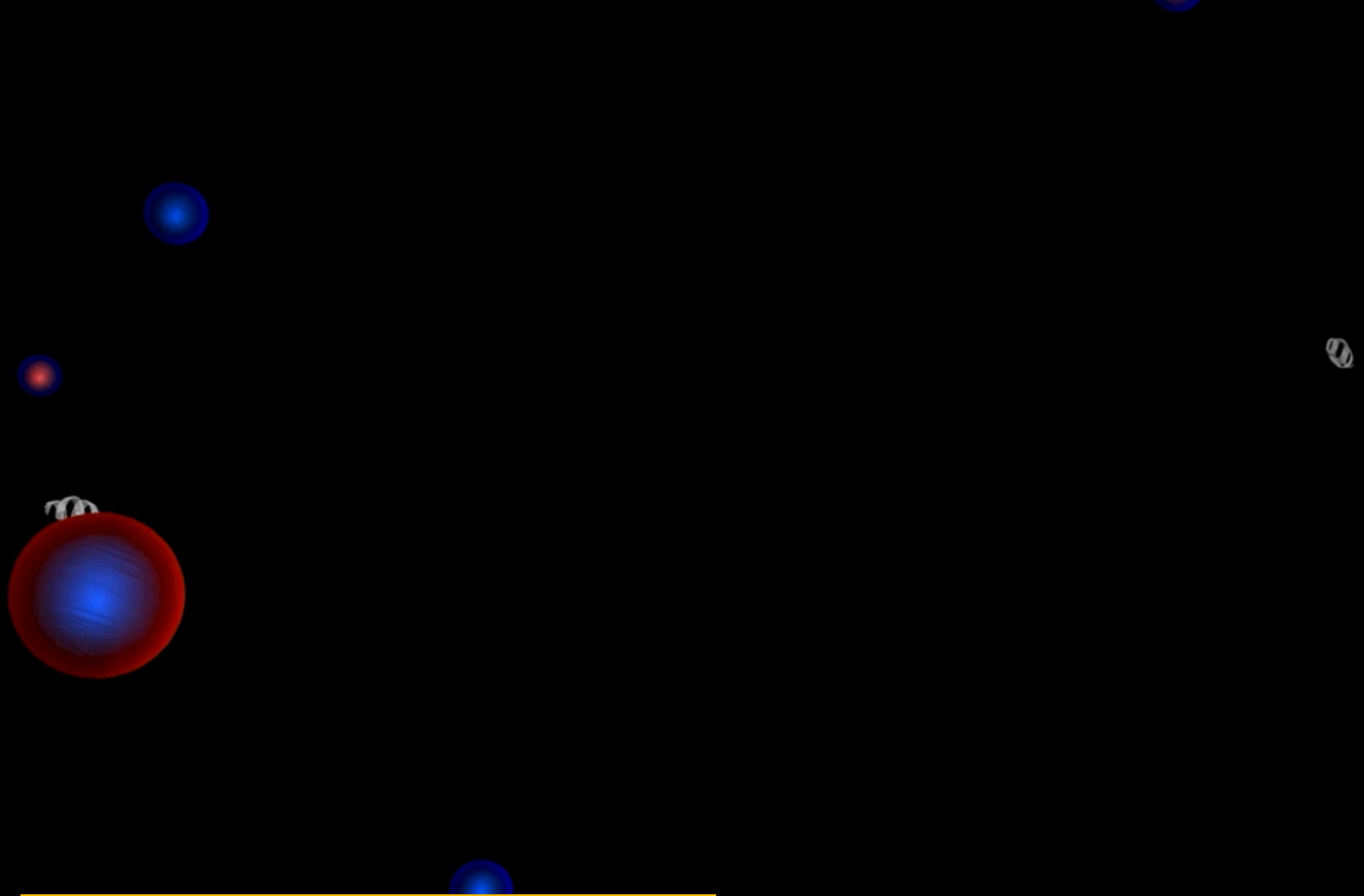
- The Higgs Boson
- Dark Matter
- Matter-Antimatter asymmetry
- ~~Strength of Gravity~~







THE HIGGS BOSON



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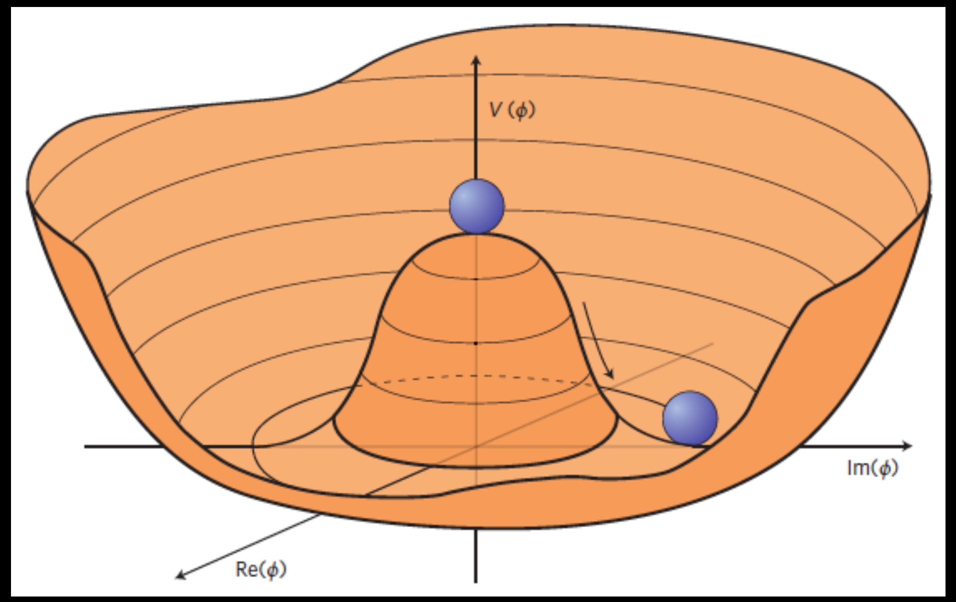
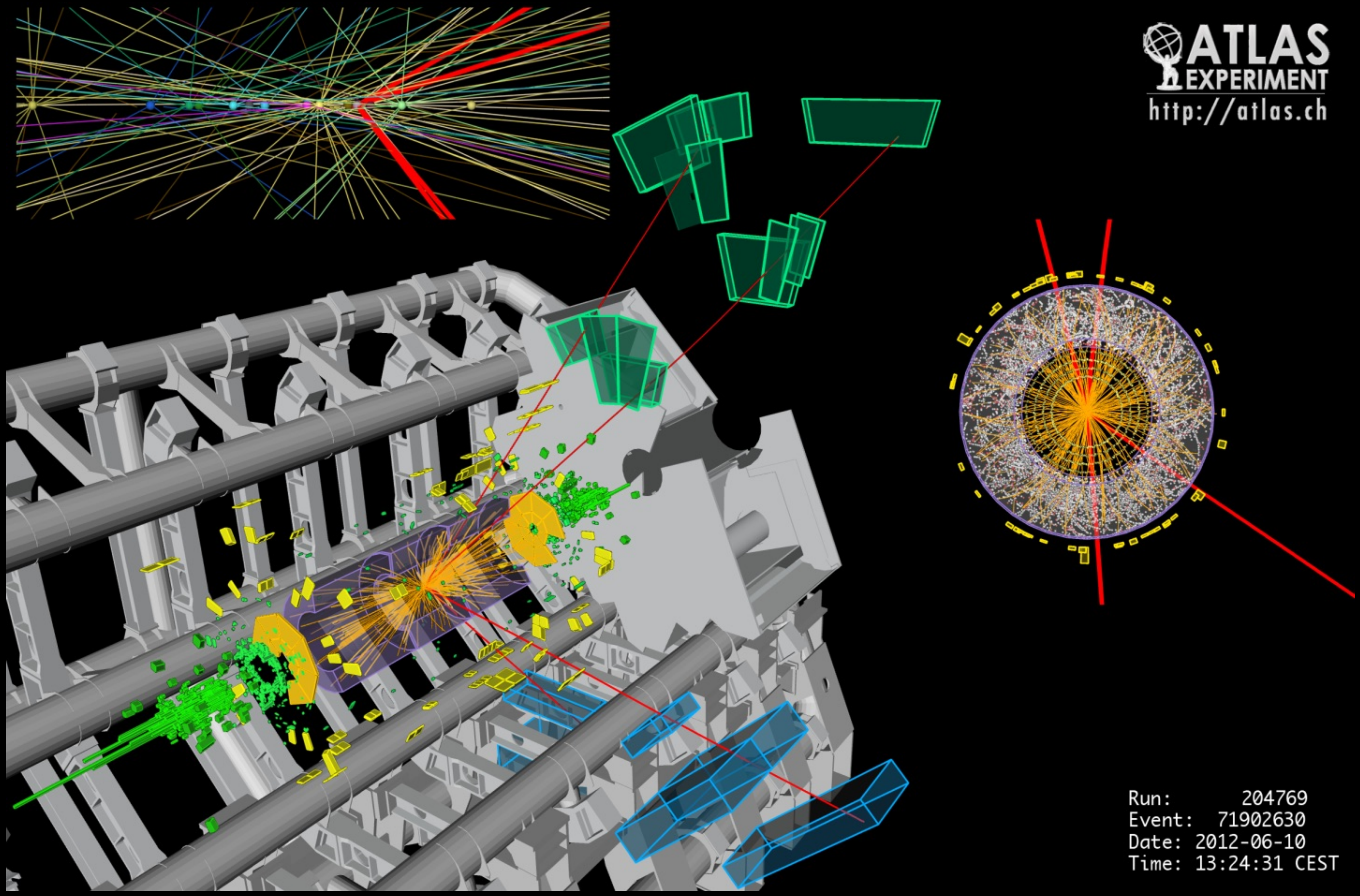
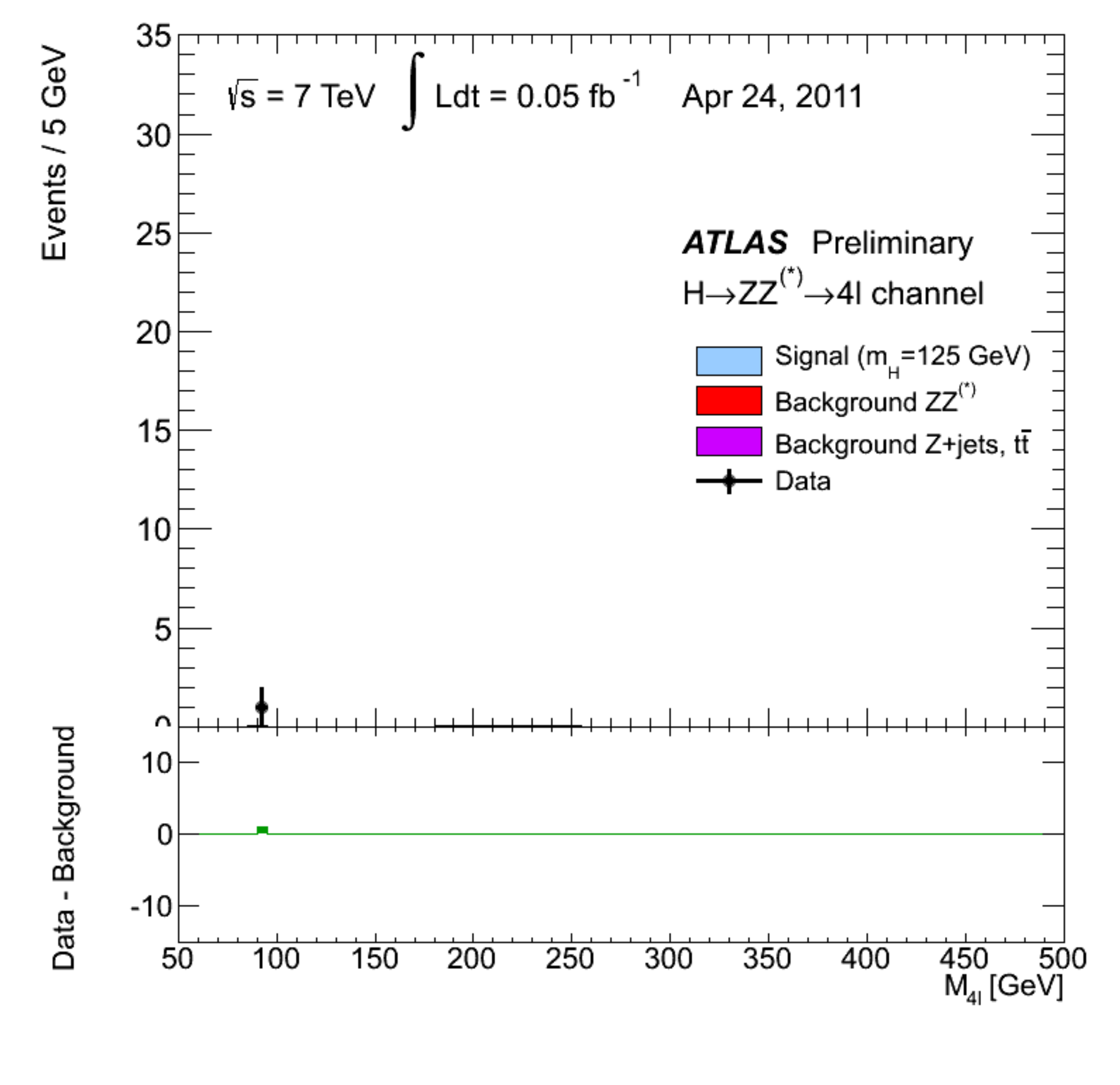



ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

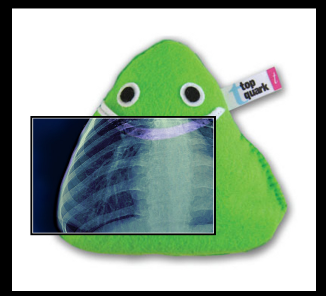

√s = 7 TeV ∫ Ldt = 0.05 fb-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]
35
30
25
20
15
10
5
10
0
-10
50
100
150
200
250
300
350
400
450
500

Physicists Find Elusive Particle Seen as Key to Universe

By DENNIS OVERBYE JULY 4, 2012

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson. Pool photo by Denis Balibouse

The top quark



By James St. John - Gold nugget (Australia)

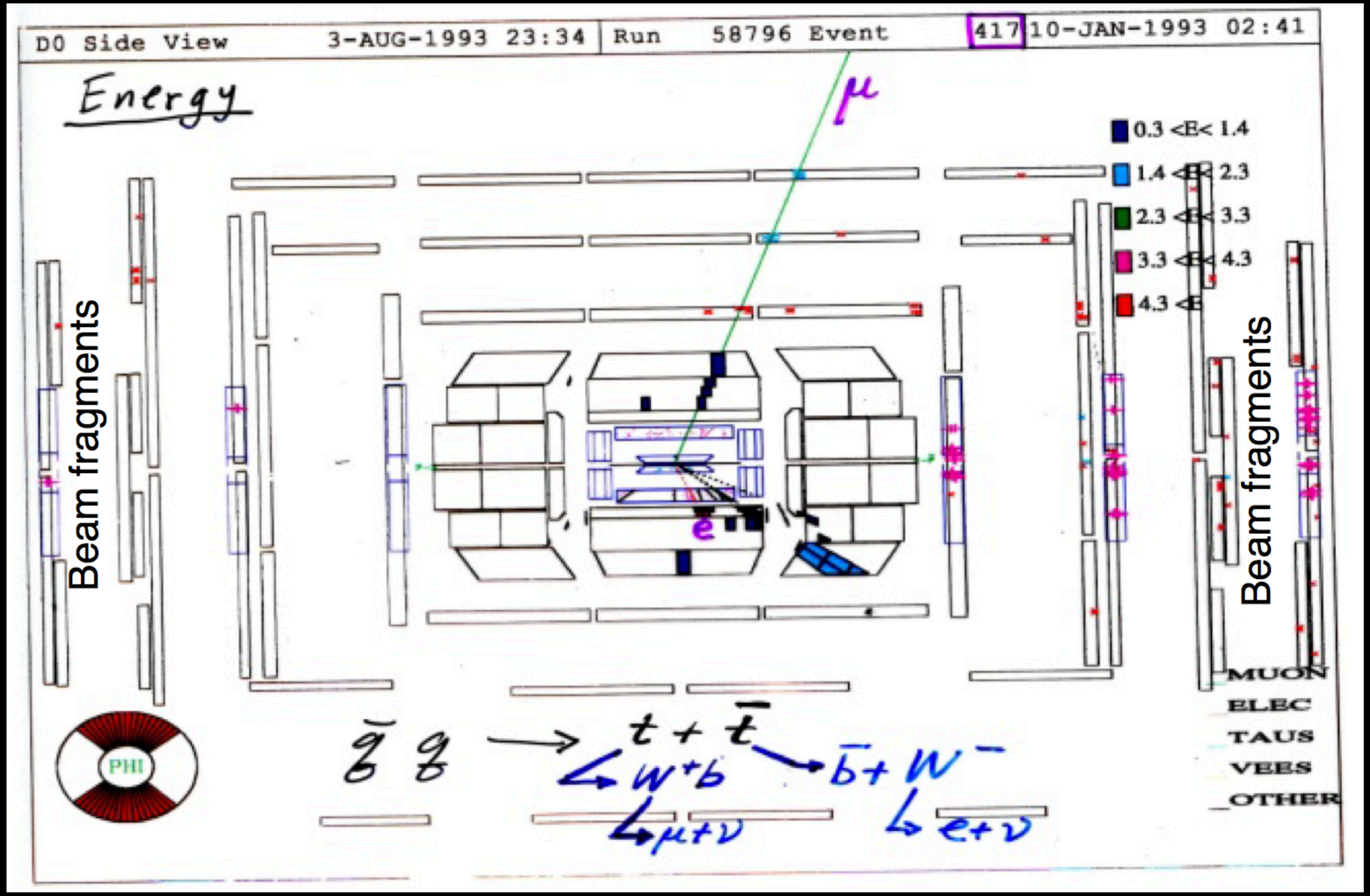
Massive

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

$$\frac{1}{m(t)} << \frac{1}{\Gamma(t)} << \frac{1}{\Lambda_{QCD}}$$

Very short lifetime

Discovered in 1995



Can tell us about the stability of the Universe

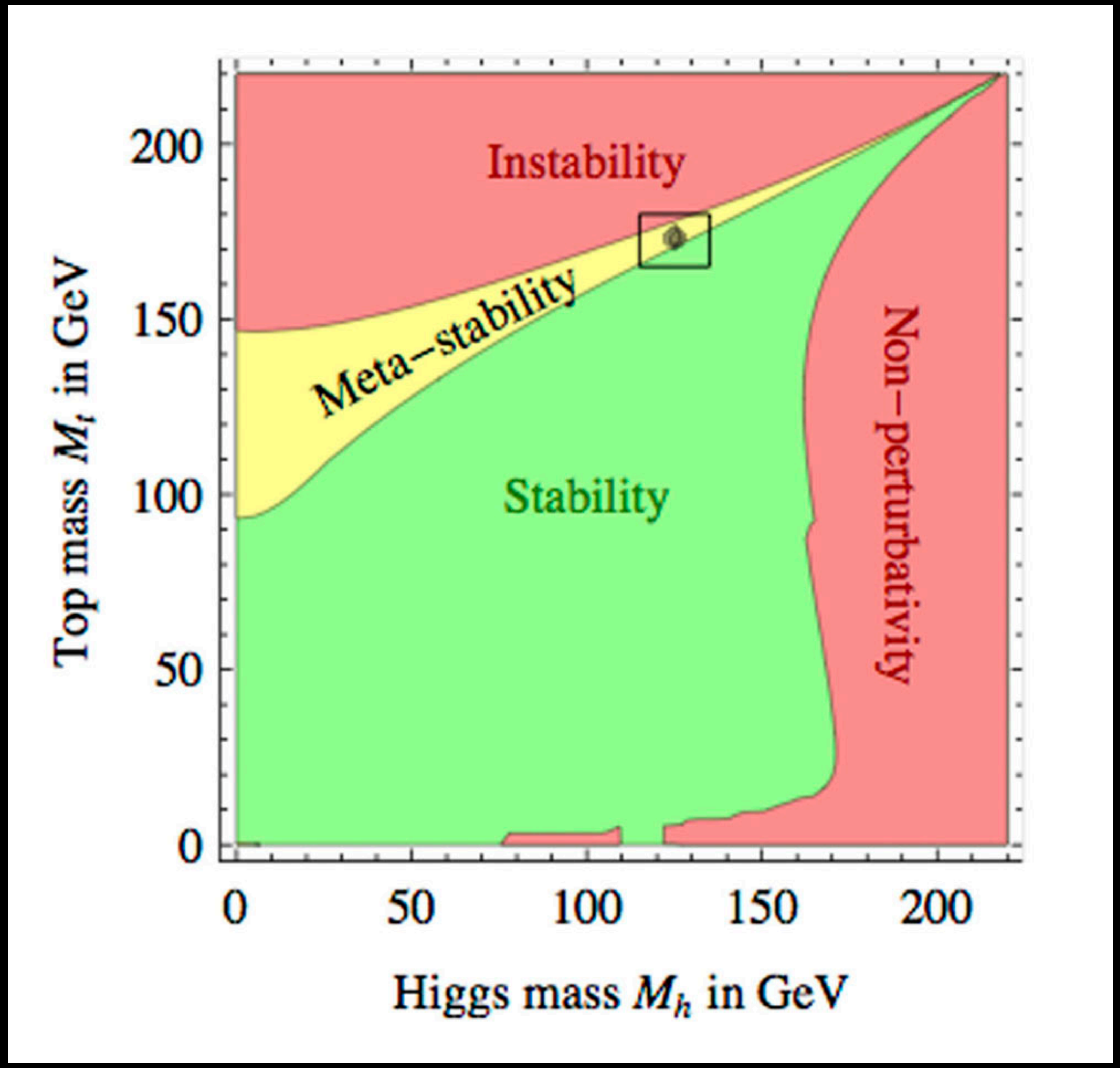
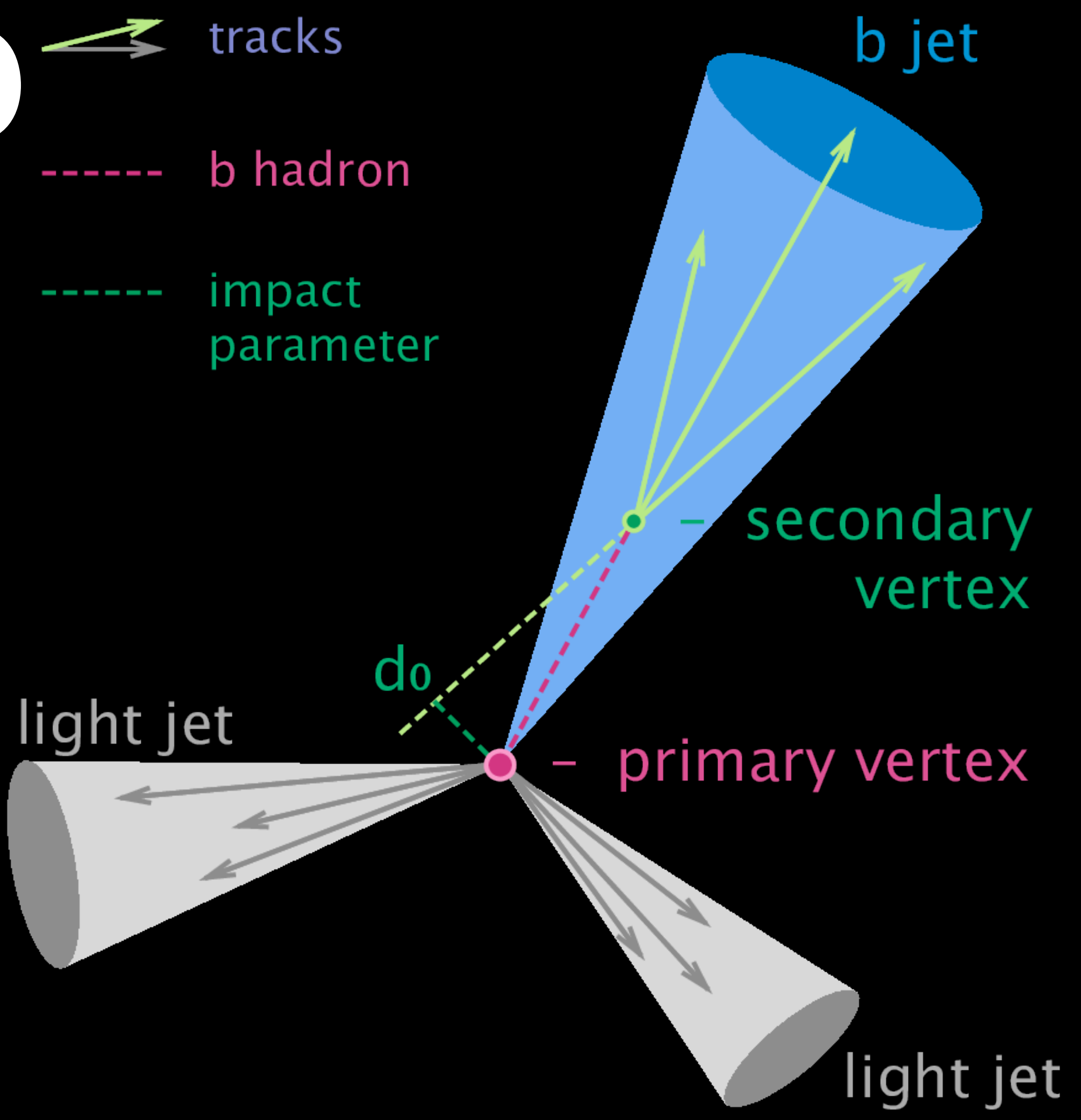
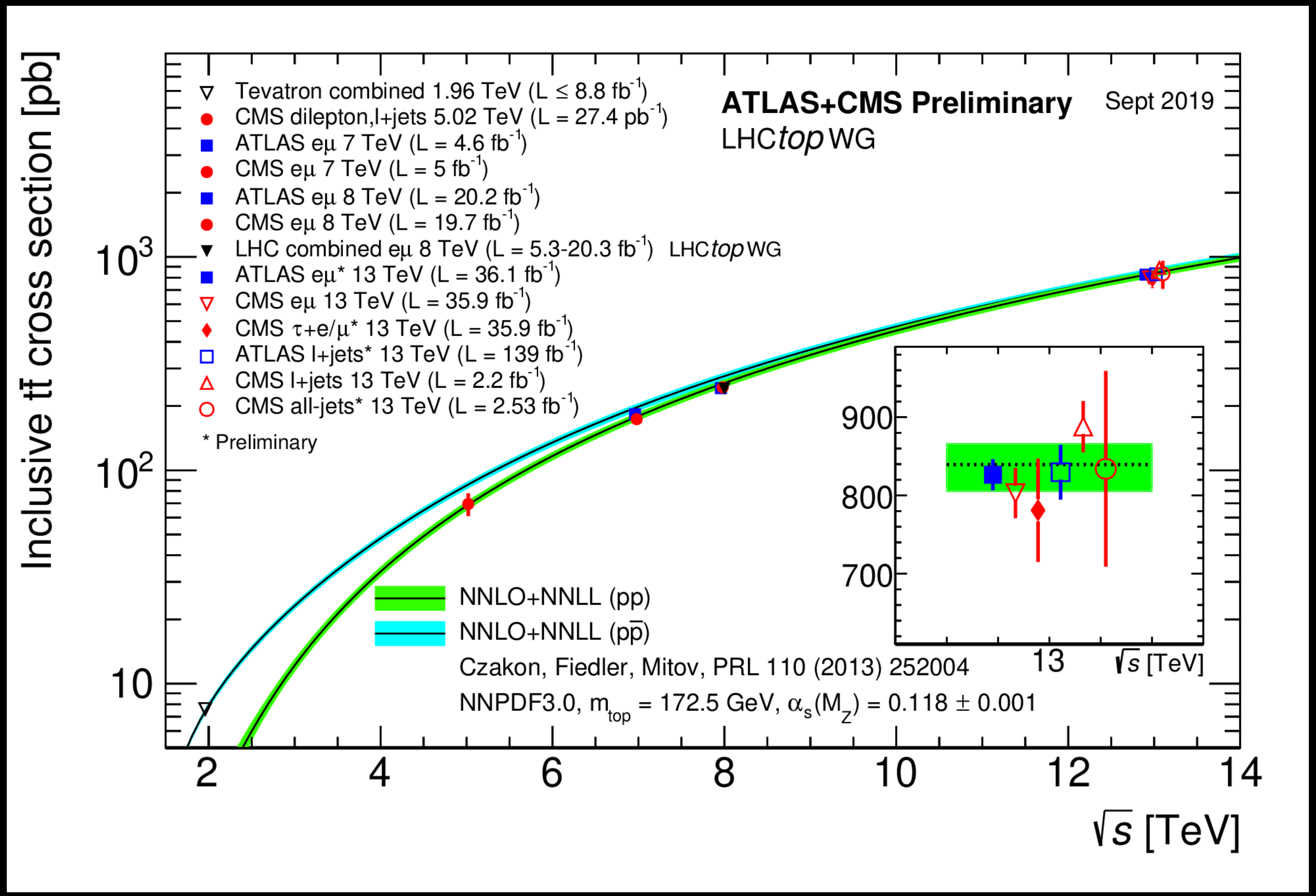


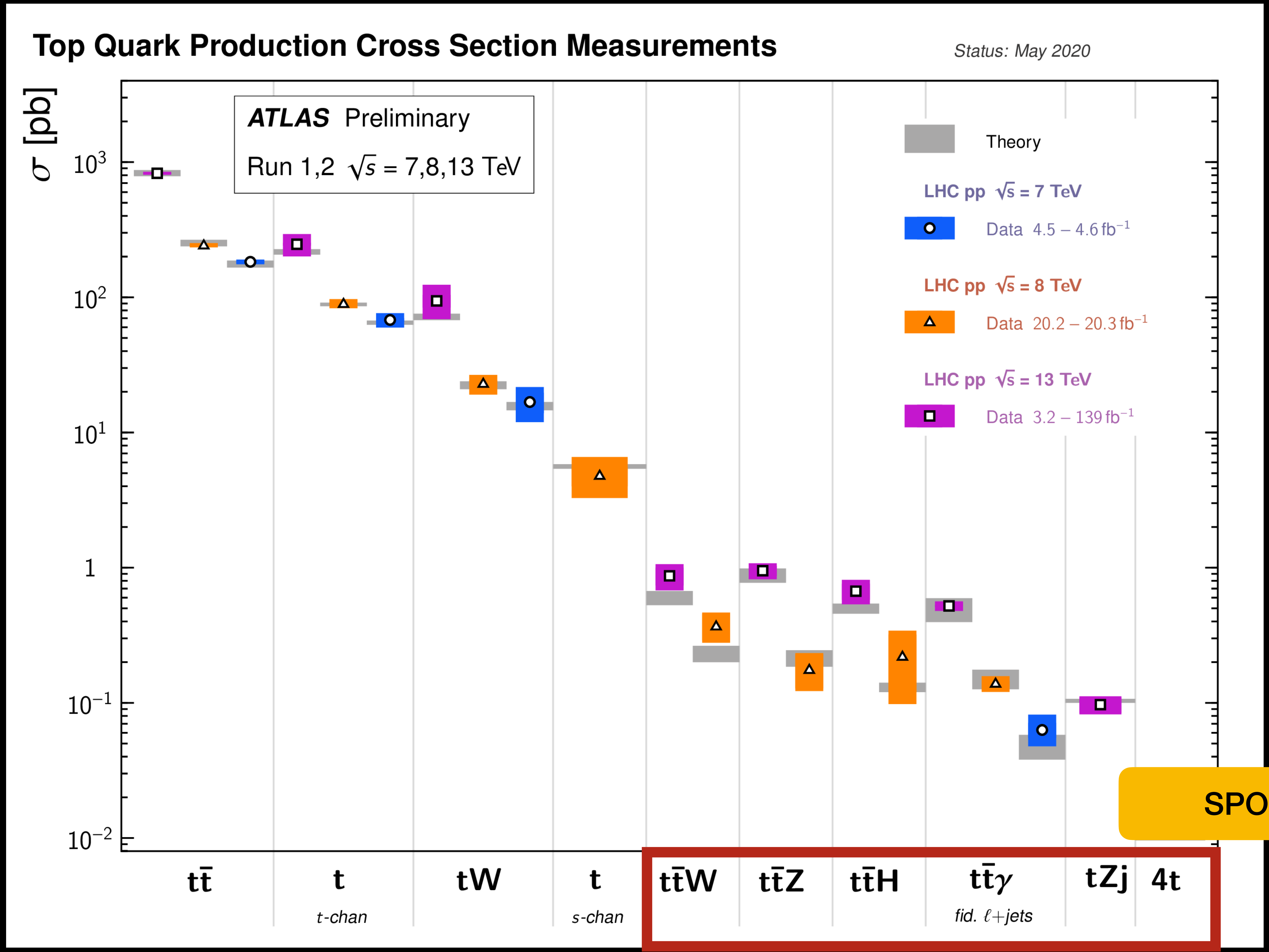
Photo: Reidar Hahn, Fermilab

The top quark



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

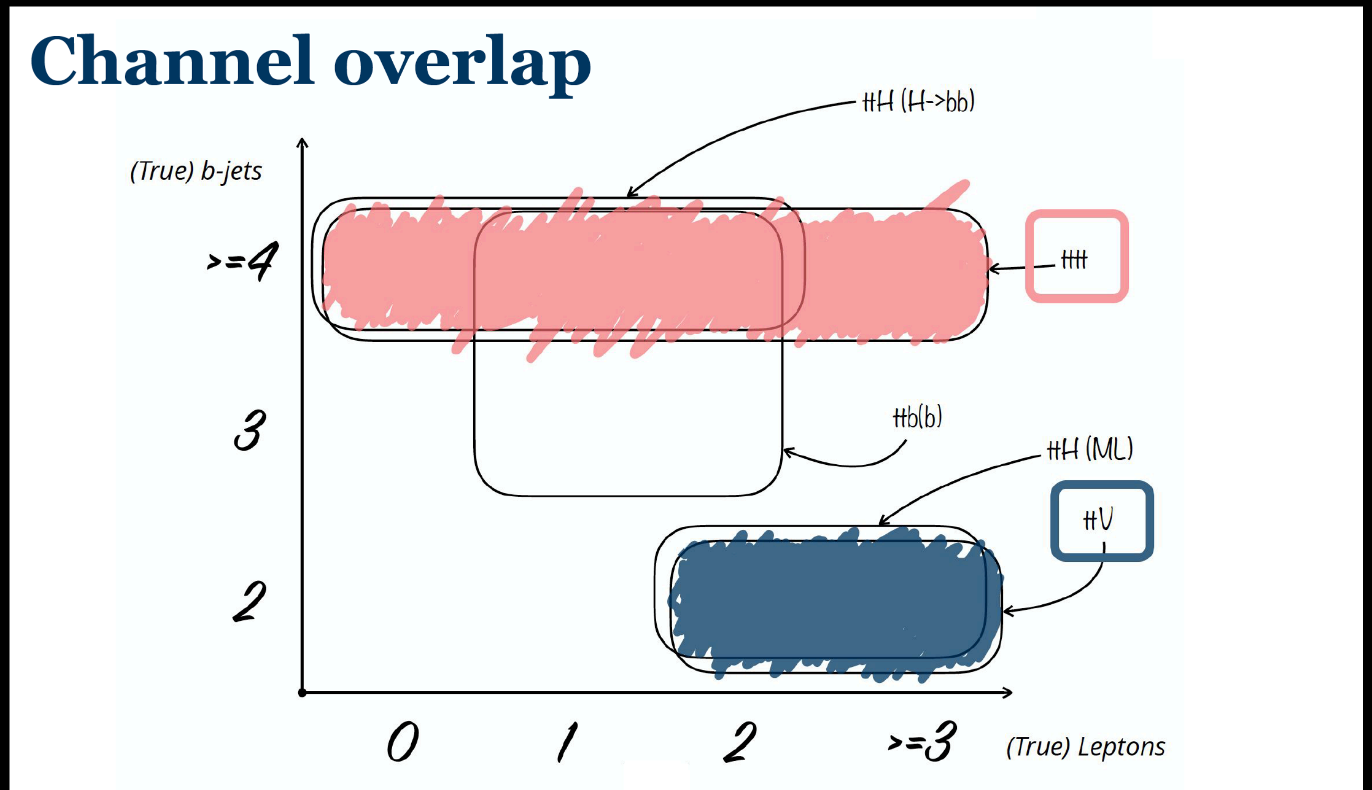


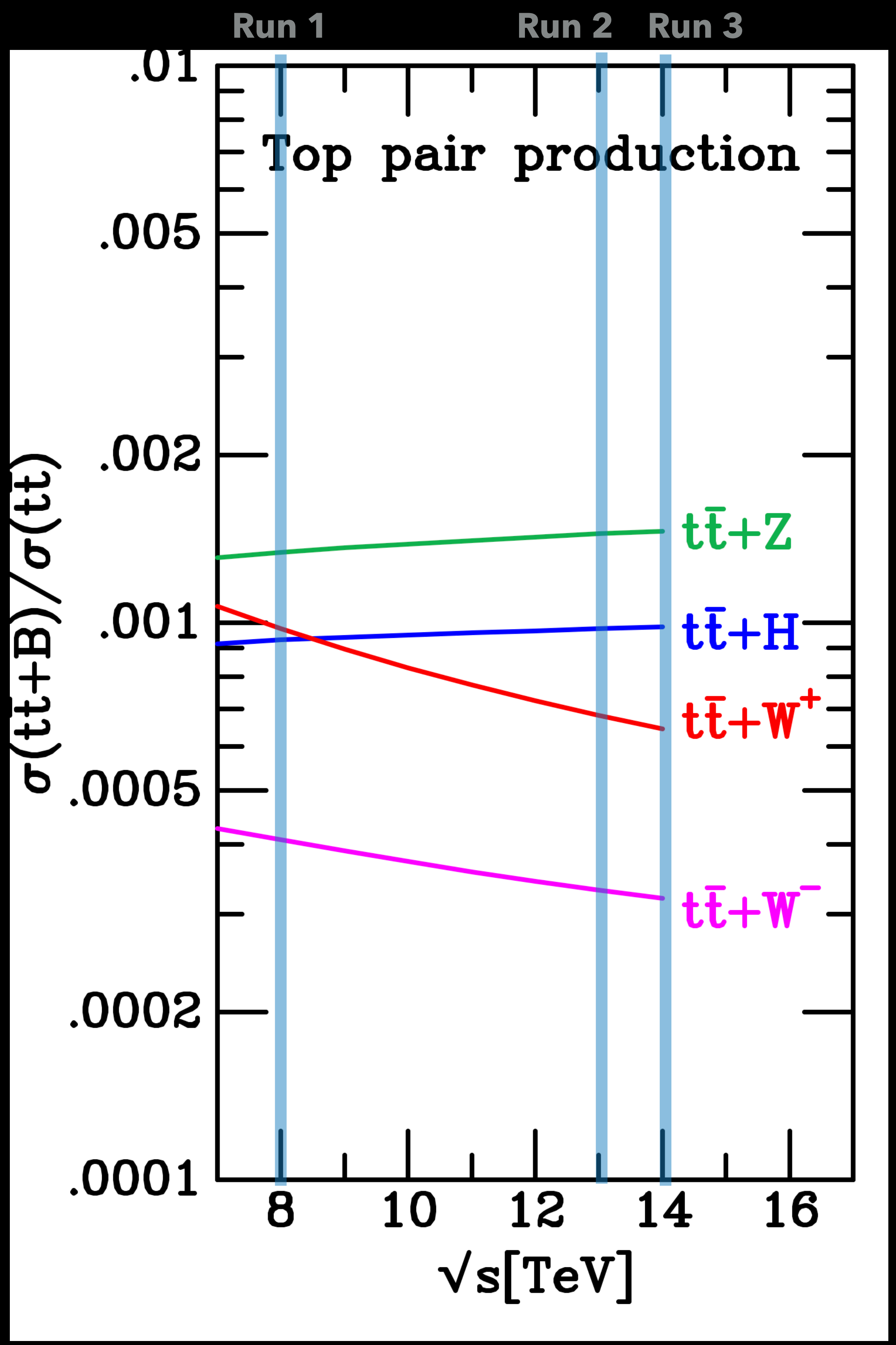


SPOILER!

Plays well with others

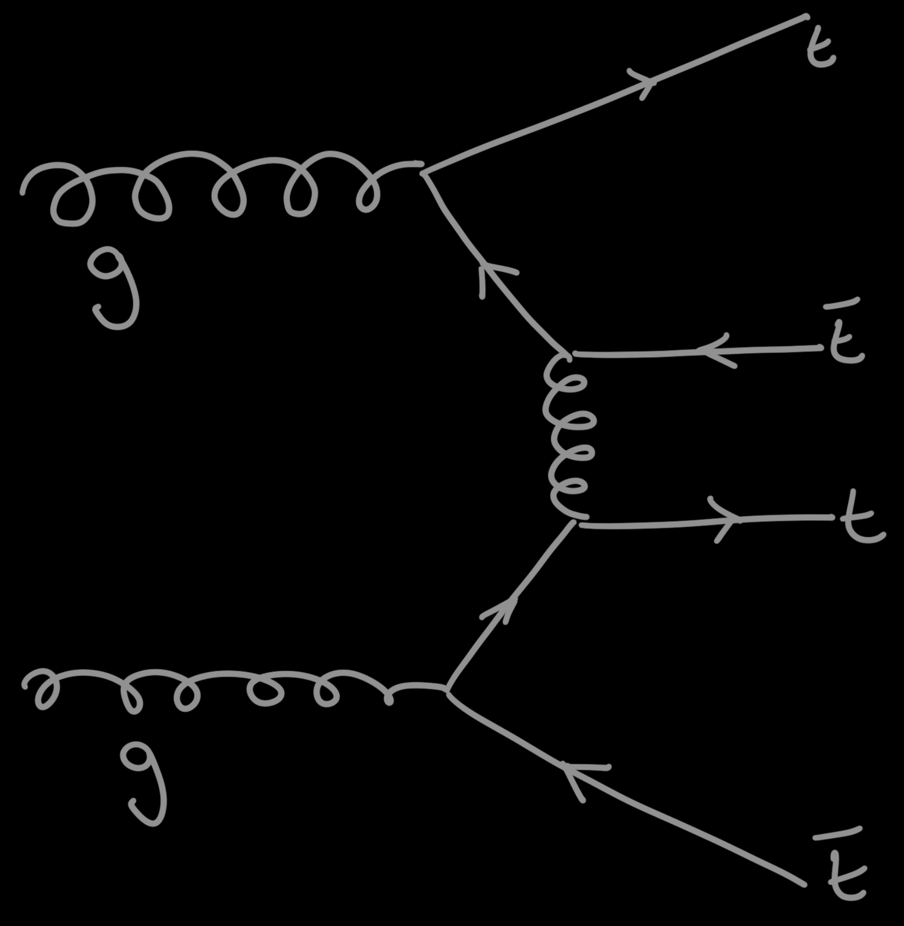
- To understand the top quark and validate the Standard Model, we need to look at **how it interacts with other particles**.
  - Higgs Boson - Yukawa coupling
  - Photons - Determine the charge of the top quark
  - Heavy gauge bosons: Z and W - Direct probe of the weak couplings of the top quark.
  -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





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

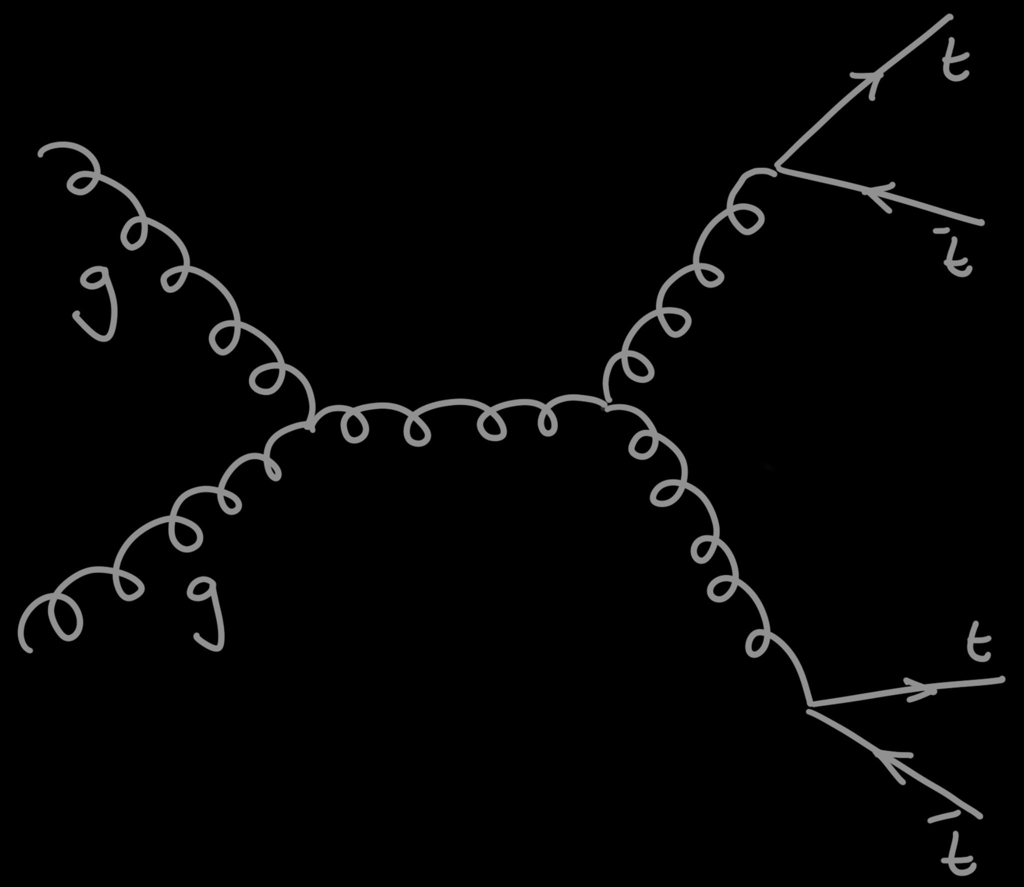
4tops signature

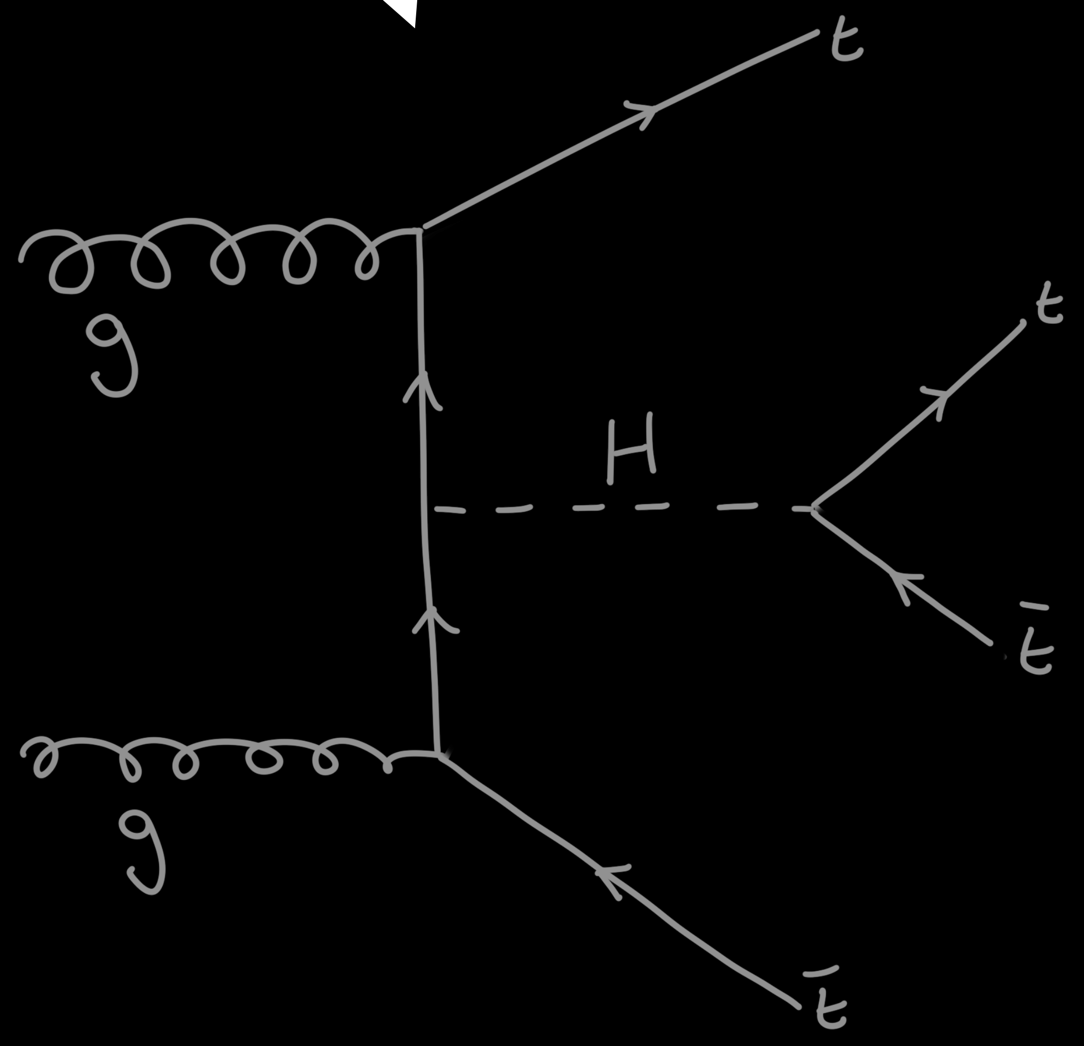


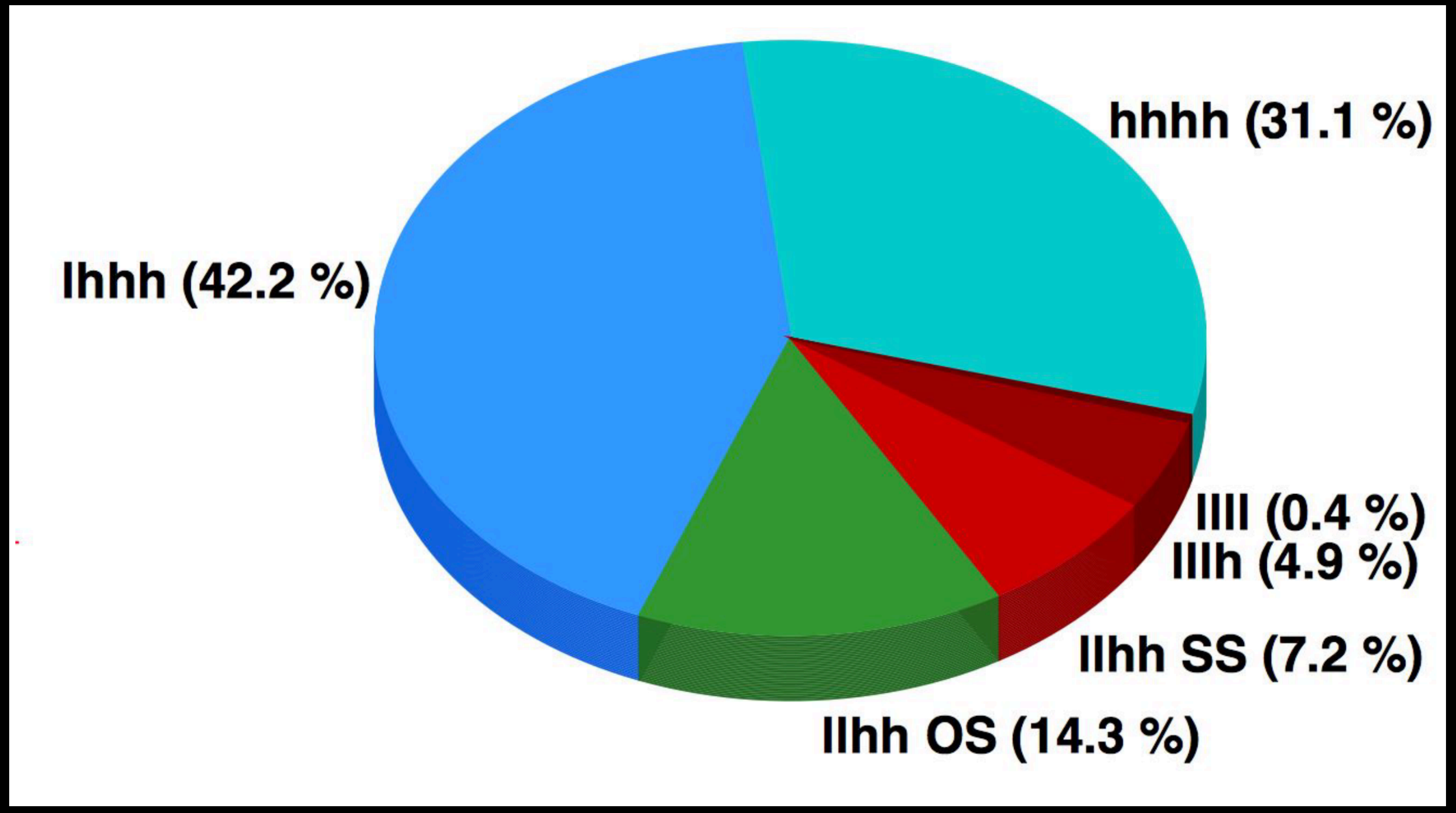
Using the full Run 2 pp dataset, ~140 fb^{-1} at 13 TeV.

Once for every 70 000 top quark pairs.

Top Yukawa coupling.



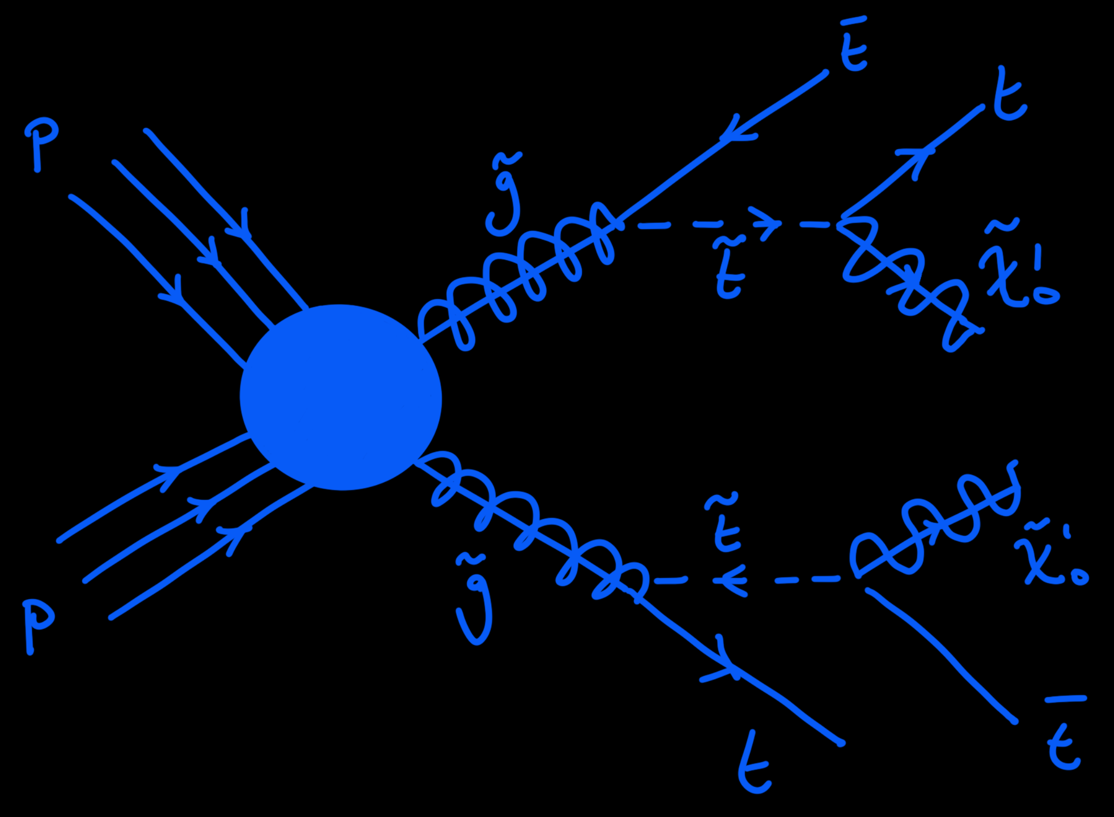




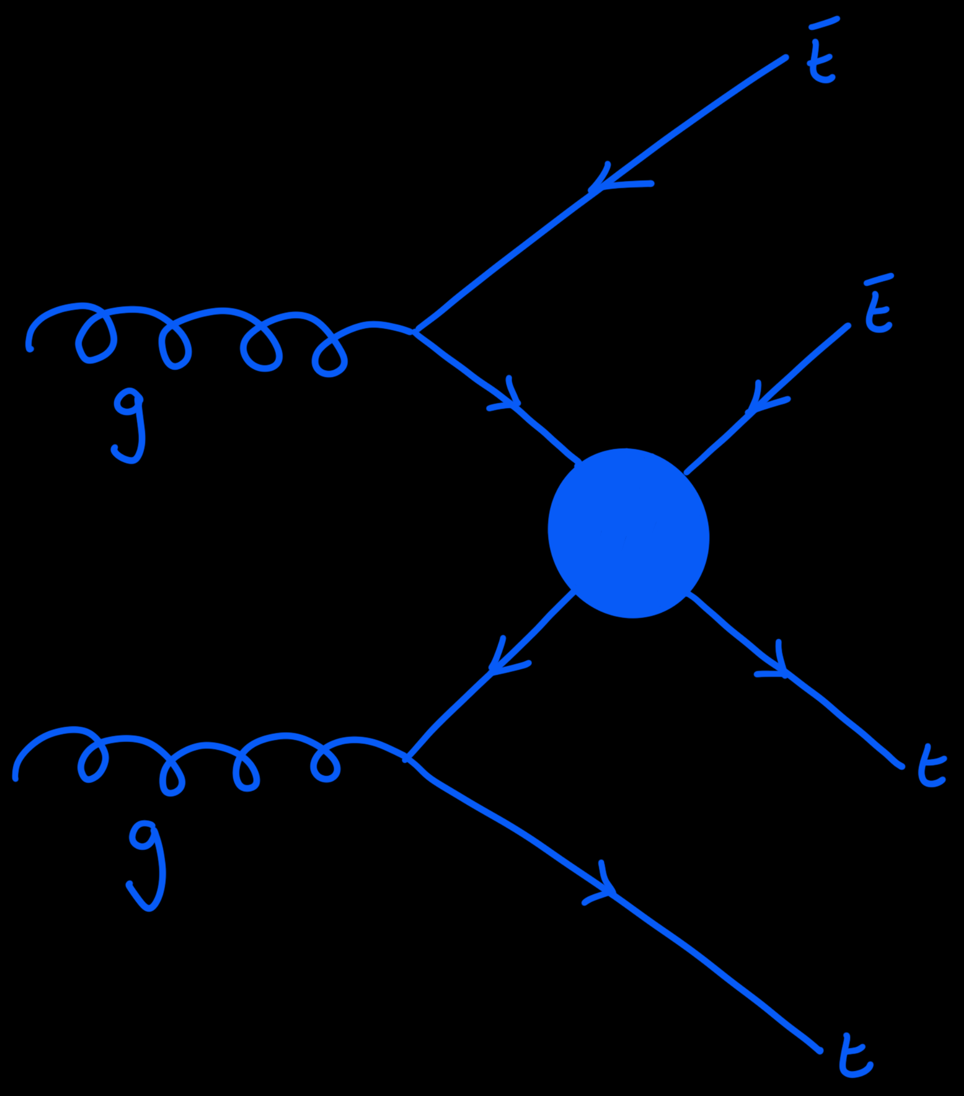
The predicted cross-section is:
SM NLO QCD+EW: **12.0** +2.0 –2.5 fb
[JHEP02(2018)031]

This analysis focuses on the **multi lepton channel**:
- Low branching fraction (12%)
- Cleaner signal.

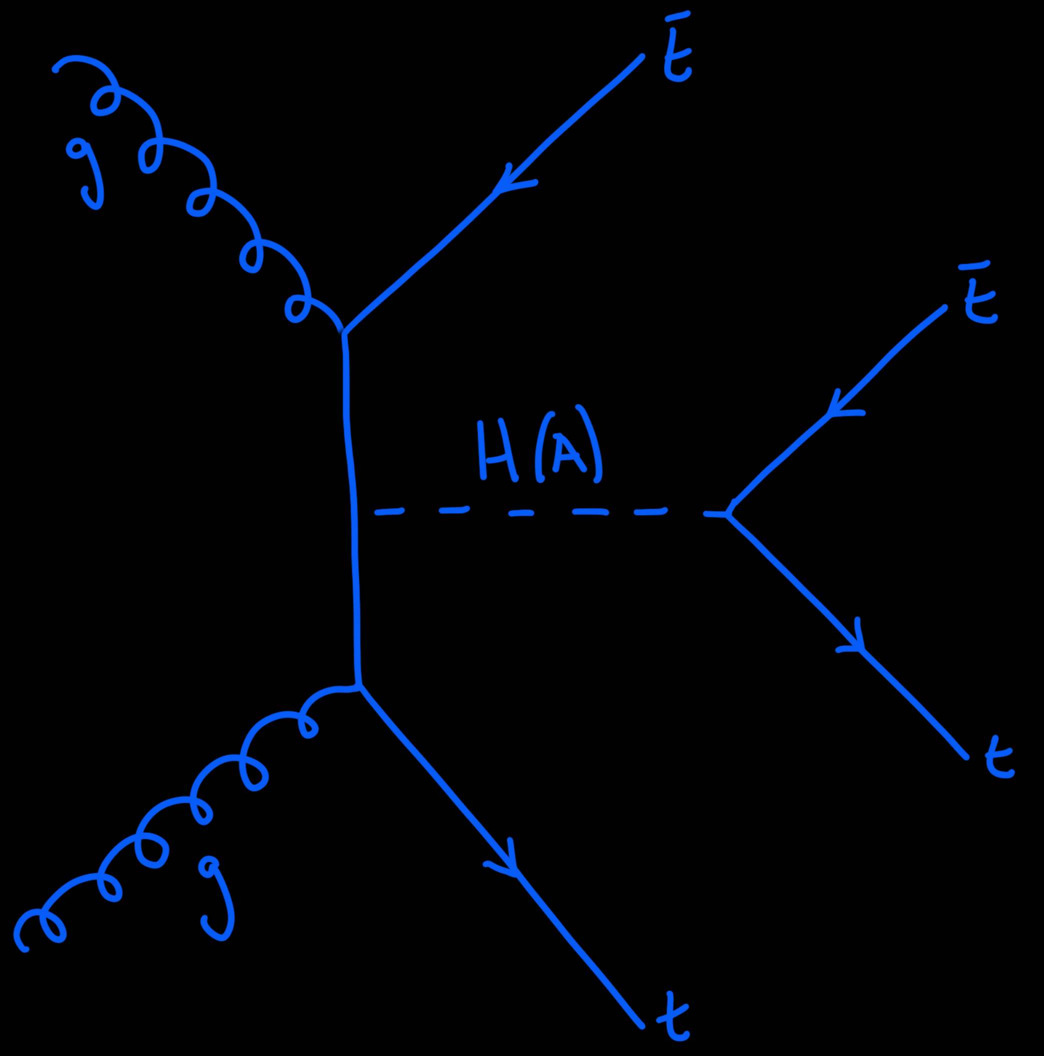
Dark matter models to consider



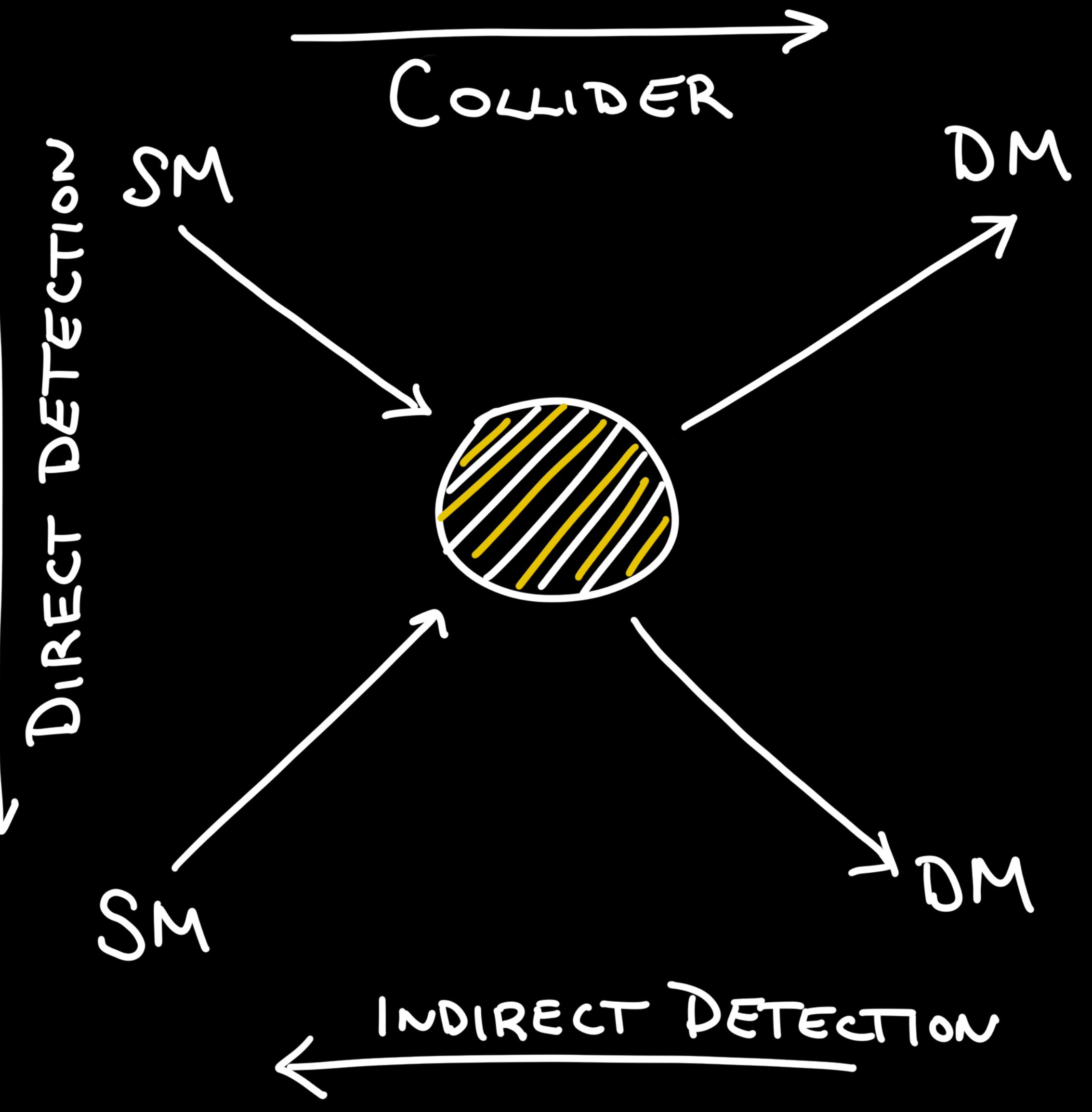
SUSY (gluino/ sgluino pair, for example)



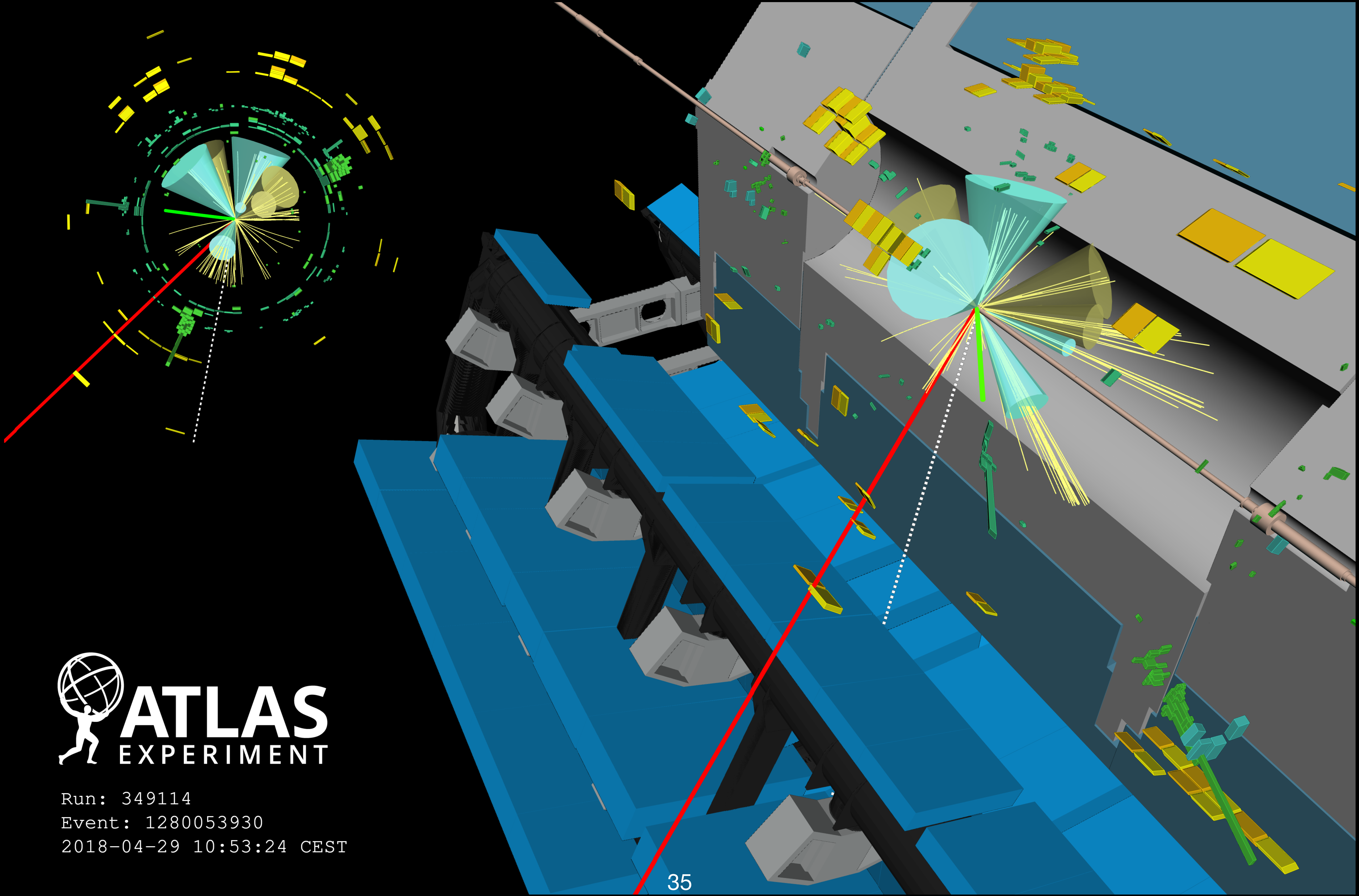
Contact Interaction



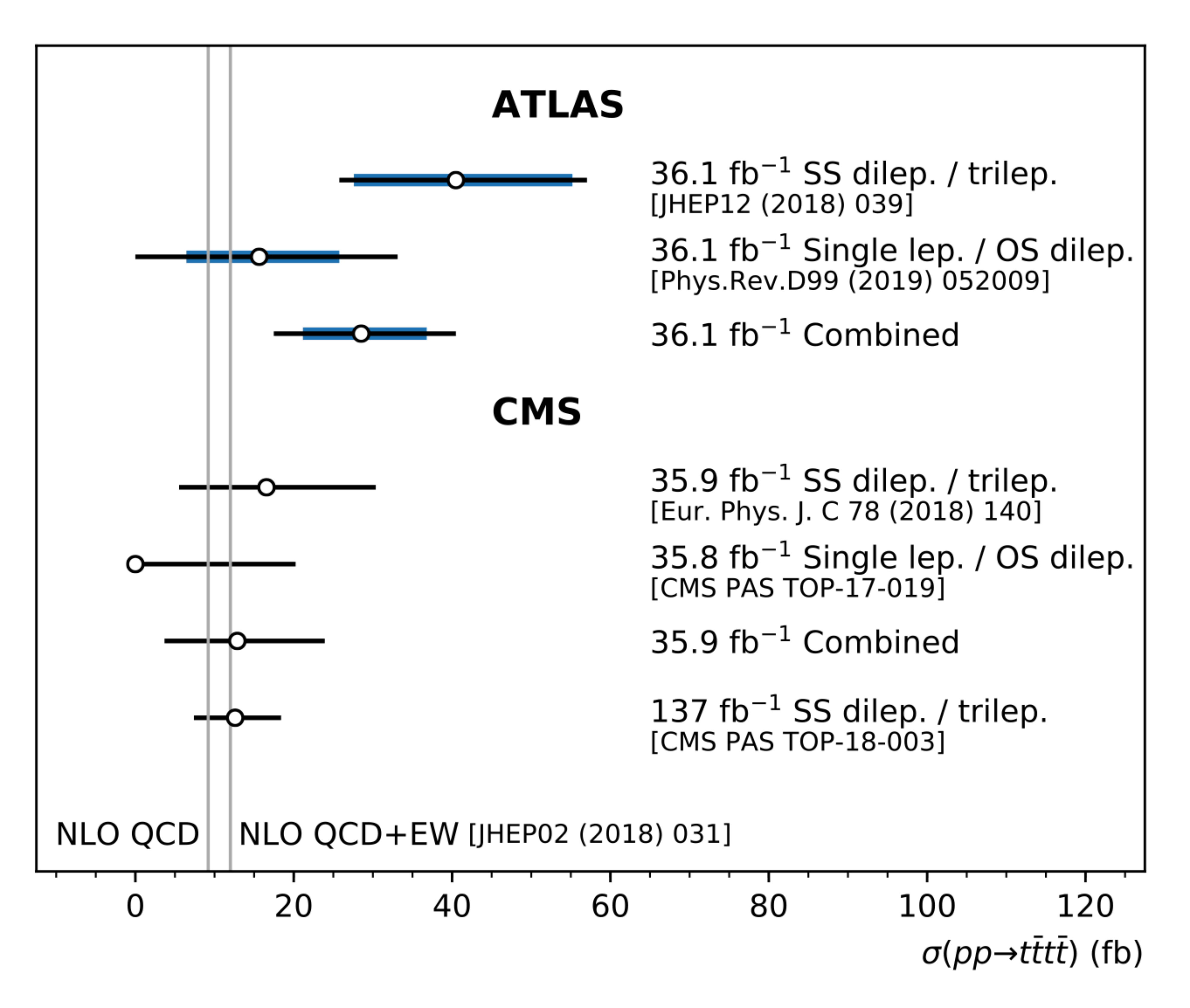
2HDM



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)

$\mu = 4.4 +1.8 -1.6$

3σ observed (0.8σ expected)

CMS

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

12.6 +5.8 - 5.4 fb

$\mu = 1.05 +0.48 -0.43$

2.6σ observed (2.7σ expected)

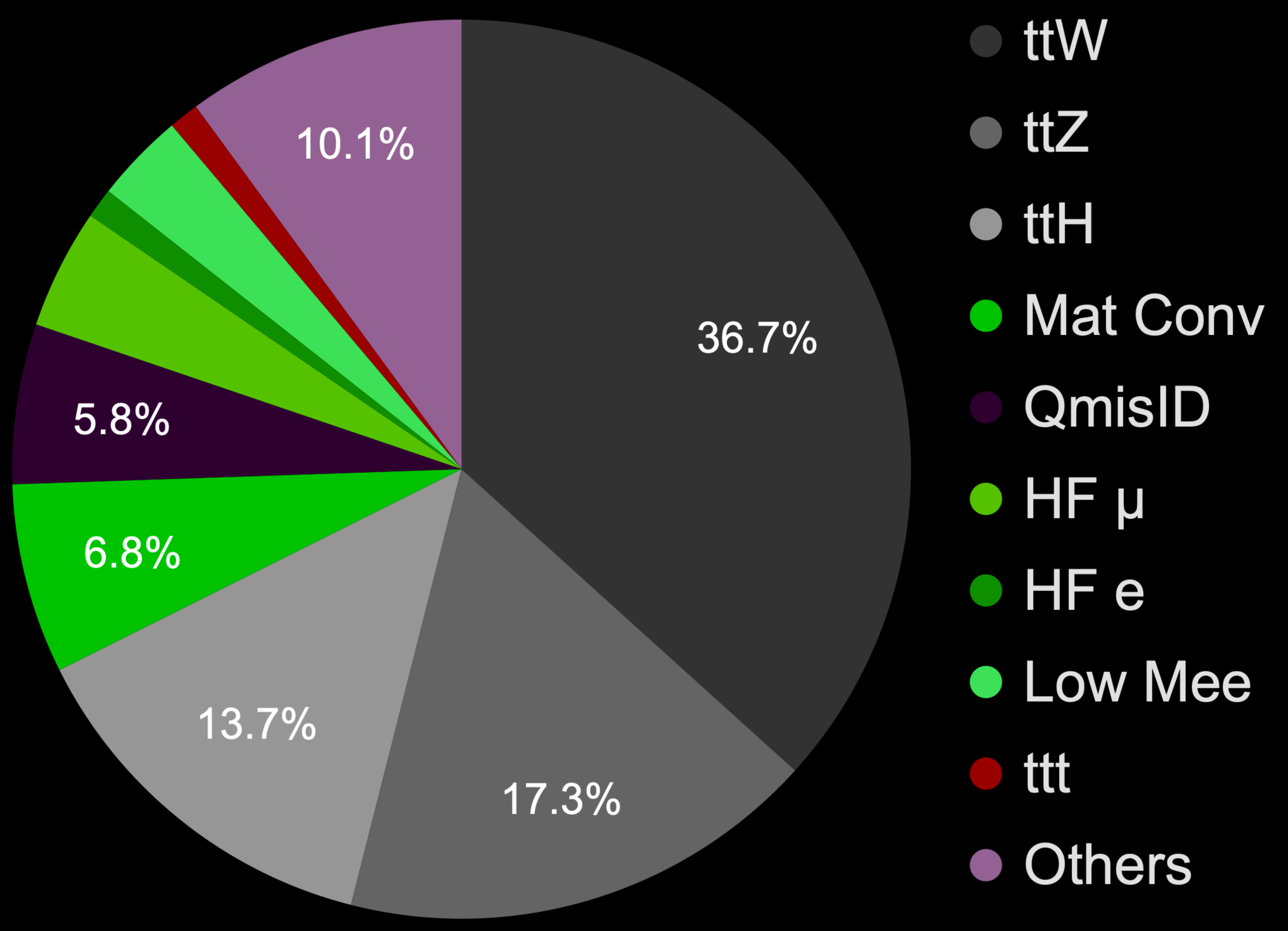
[Eur. Phys. J. C 80 (2020) 75]

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

Backgrounds

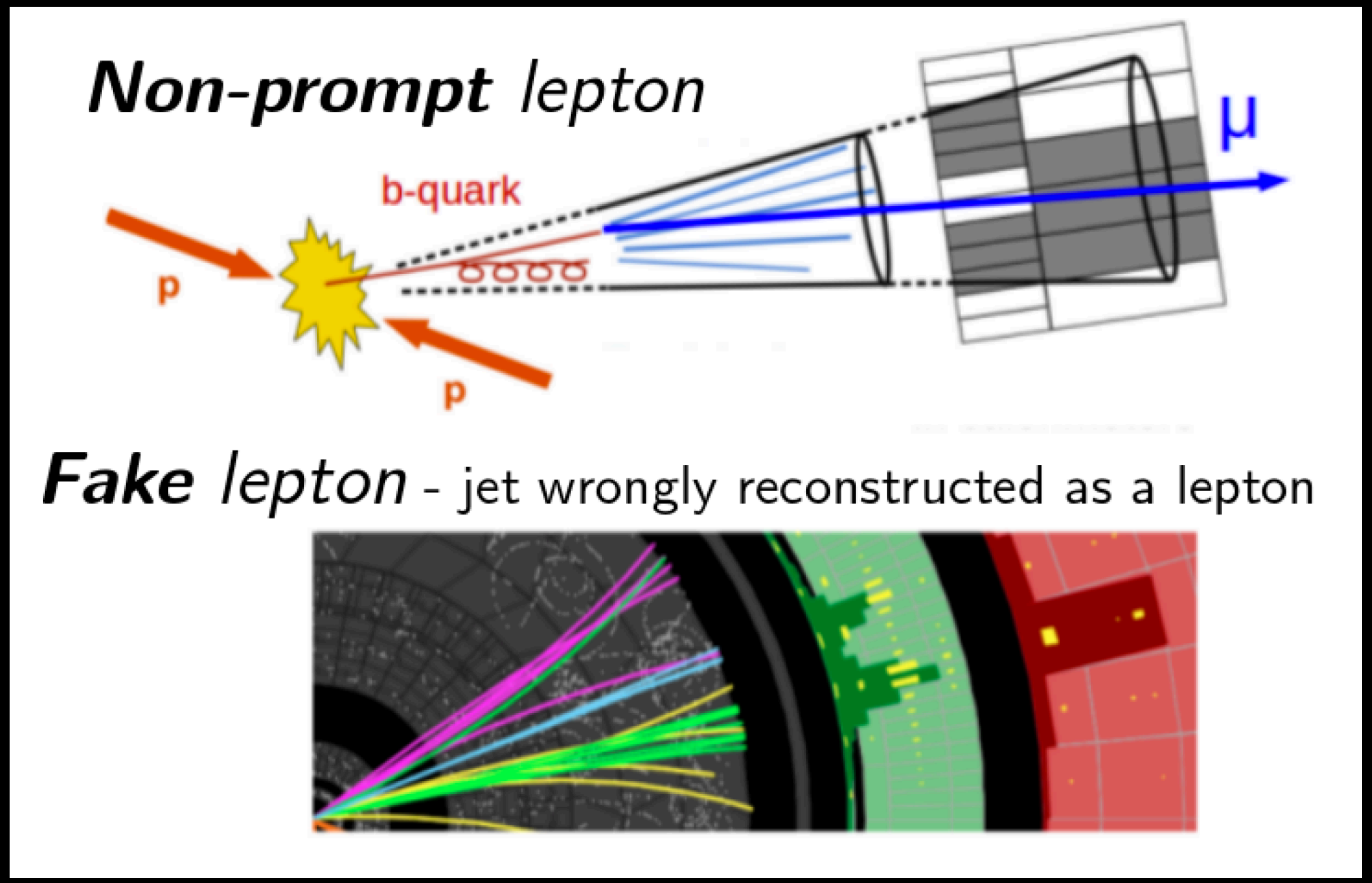
- Irreducible:
  - Main:
    - $t\bar{t}W$+jets, $t\bar{t}Z$+jets and $t\bar{t}H$+jets processes.
  - Smaller:
    - diboson / triboson production
    - $V\,H$ production in association with jets
    - Rare processes ($t\bar{t}WW$, tWZ, tZq, $t\bar{t}t$)

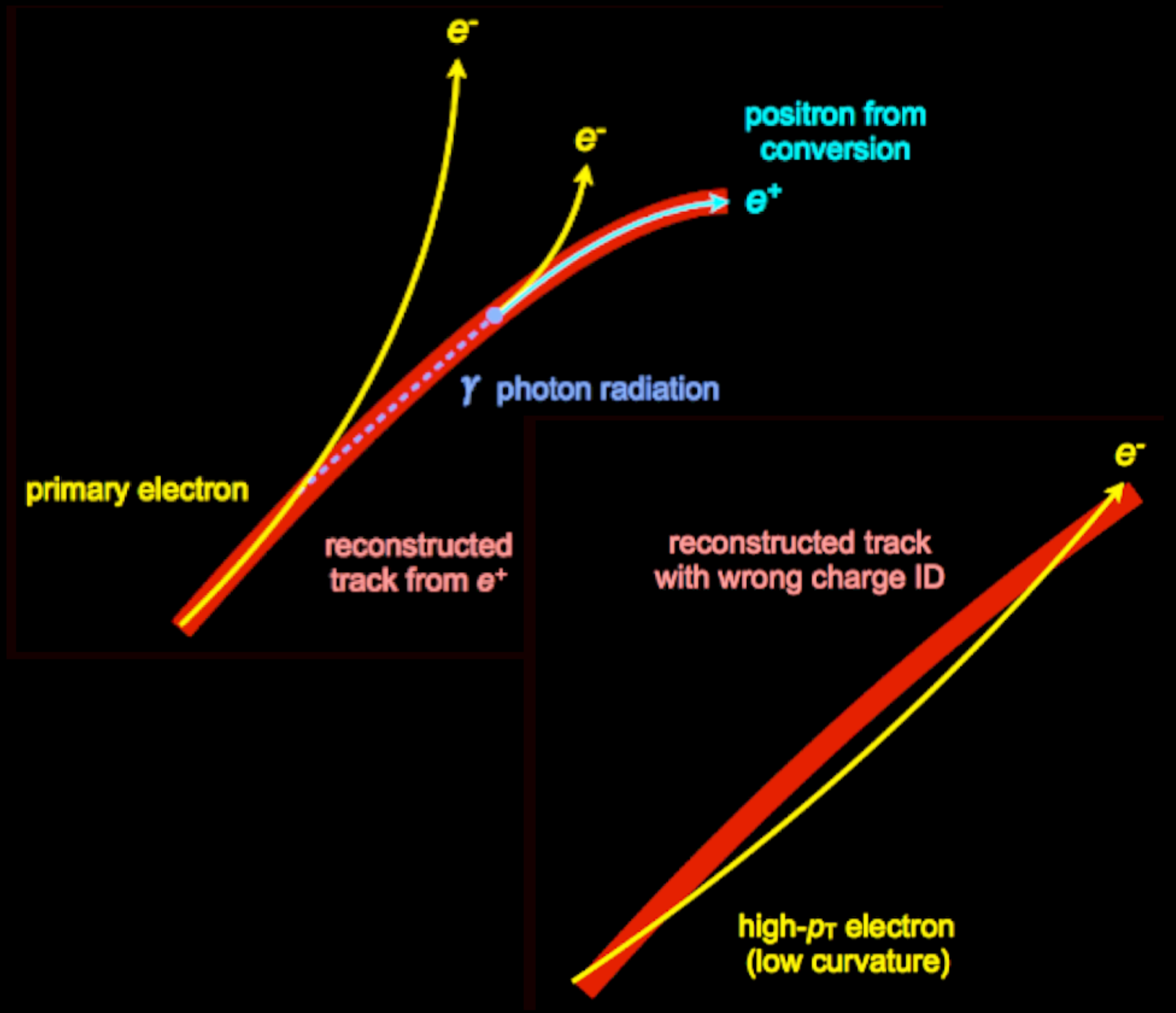
Evaluated using MC simulation normalised to their SM cross sections (except $t\bar{t}$W)



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

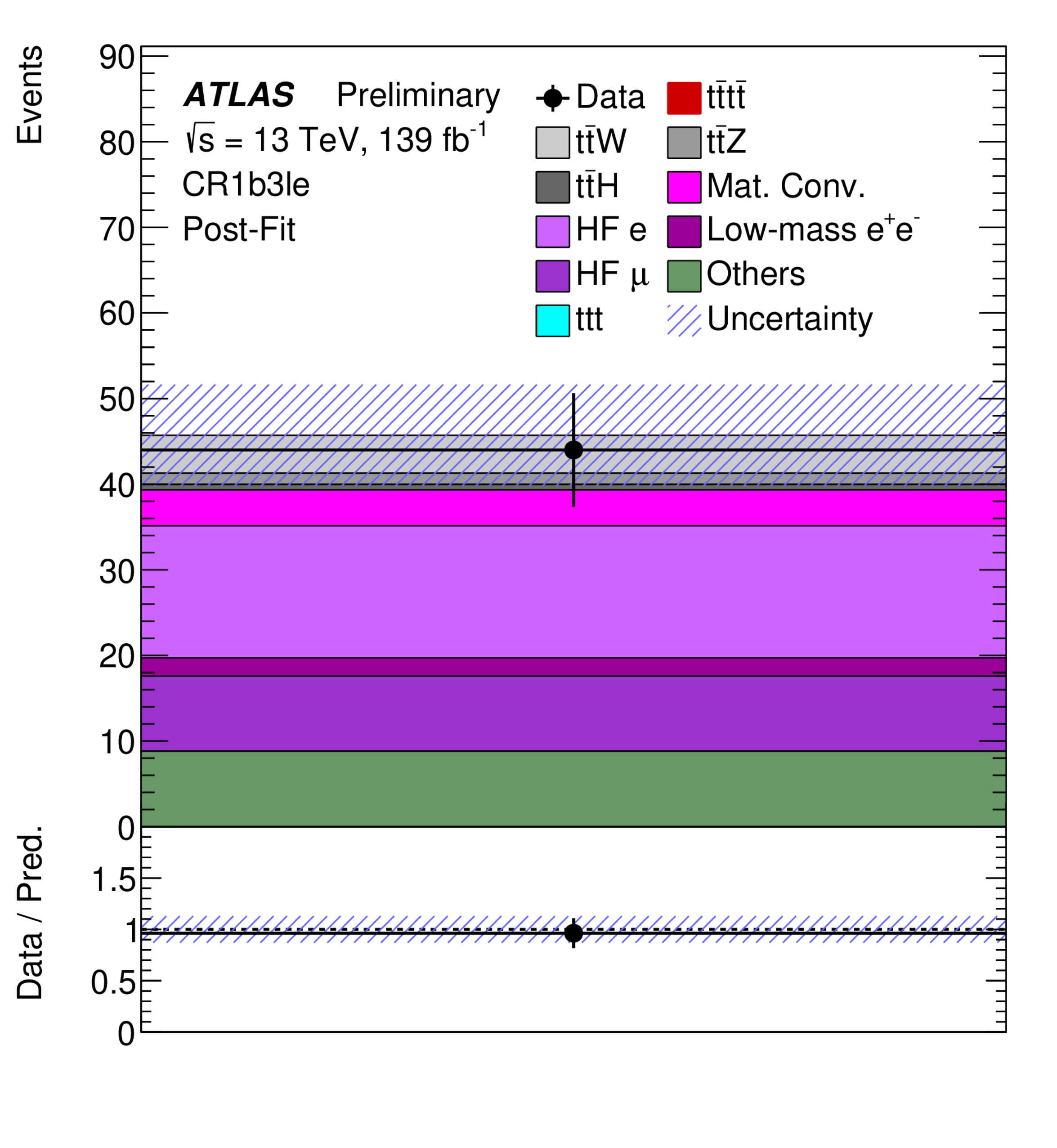


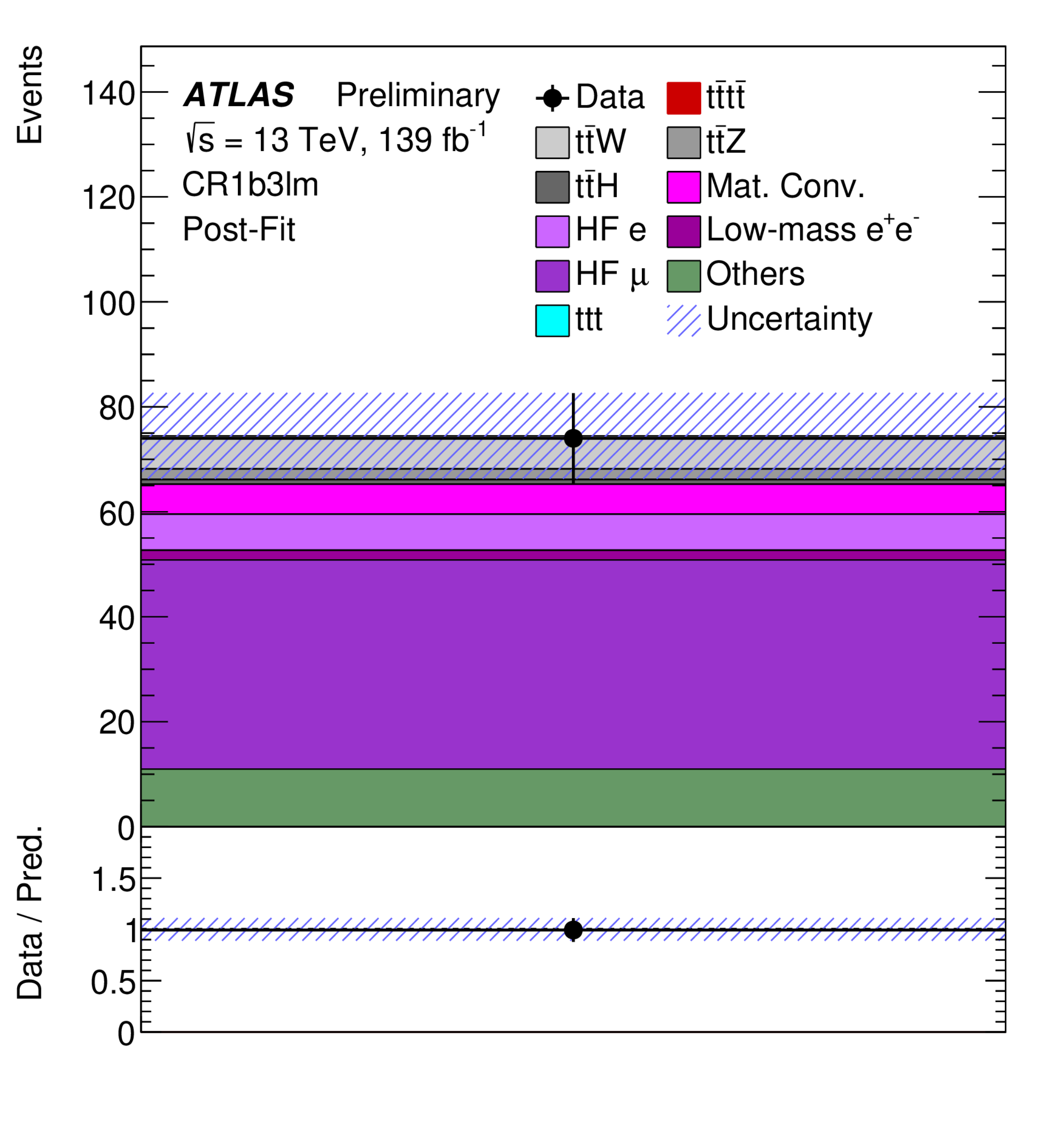


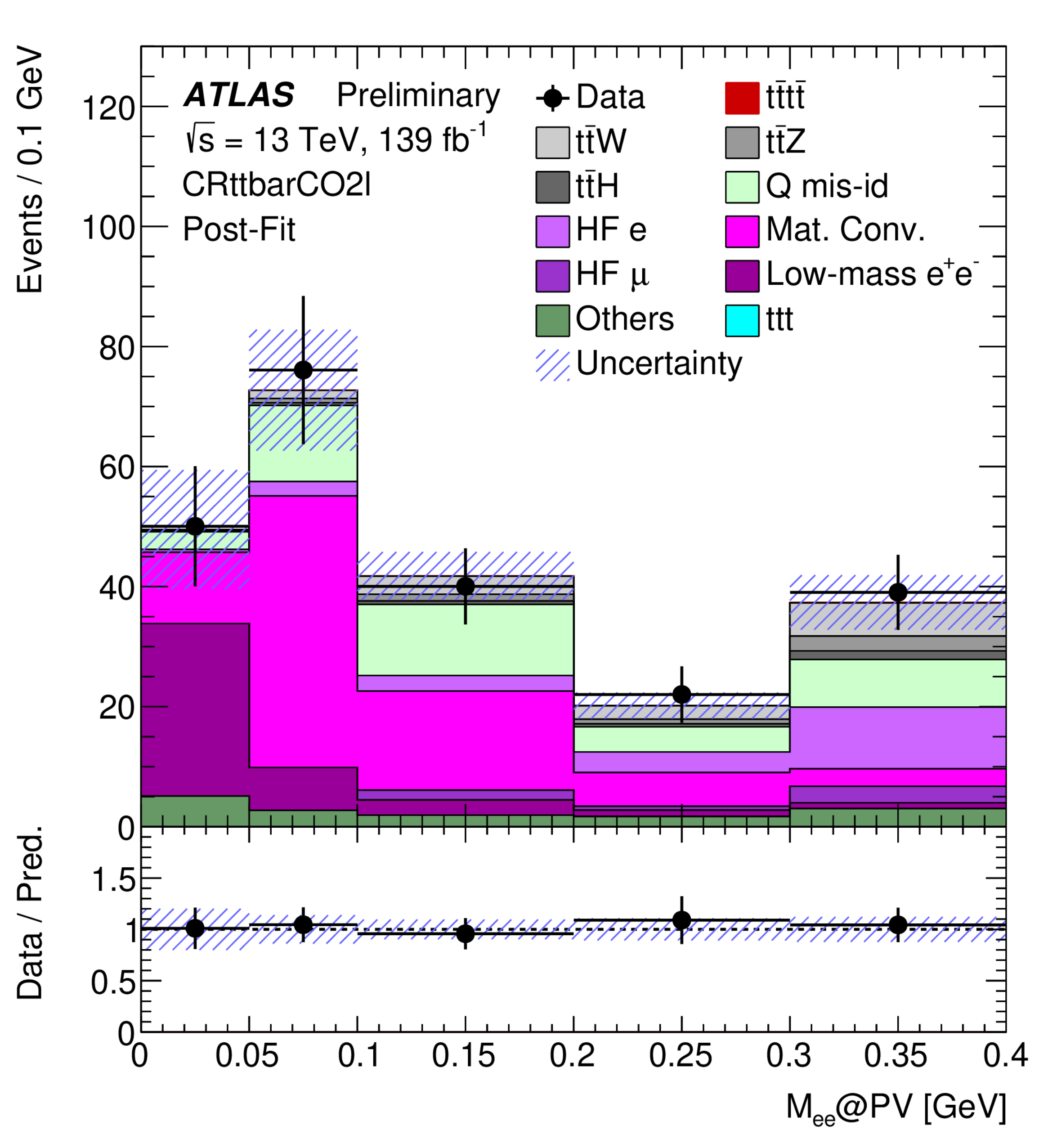
Template fit

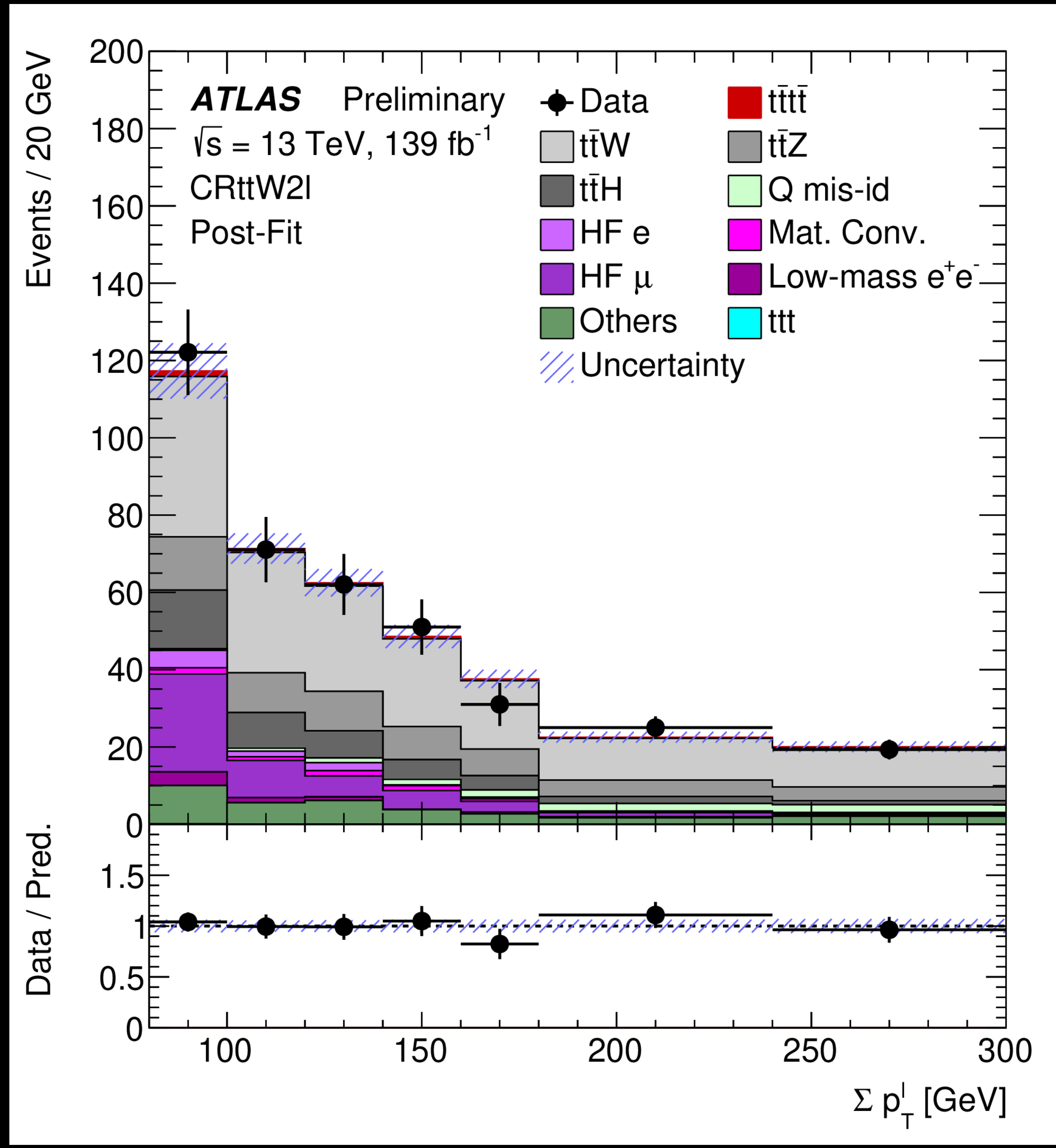
Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } M_{ee}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

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.



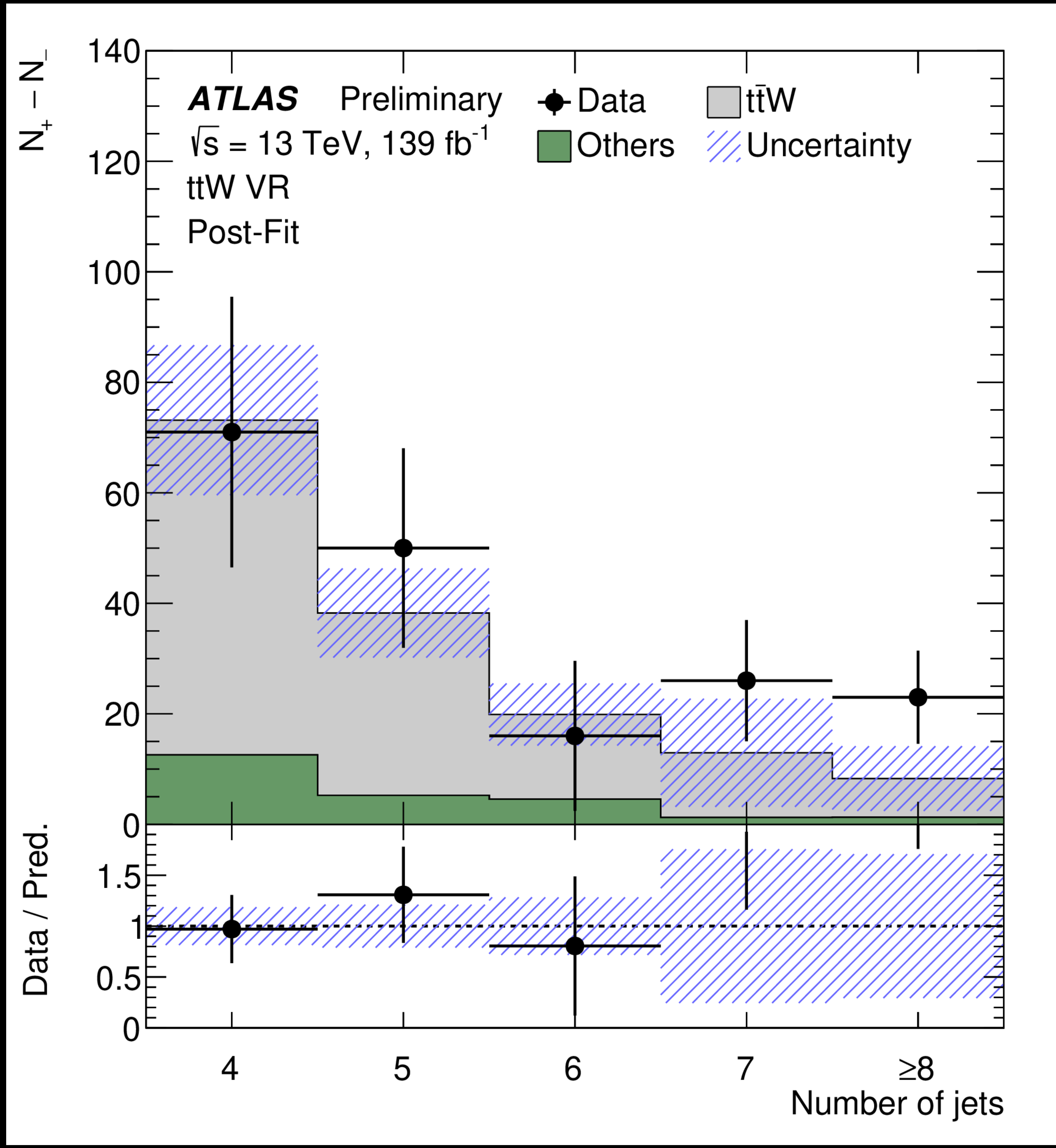


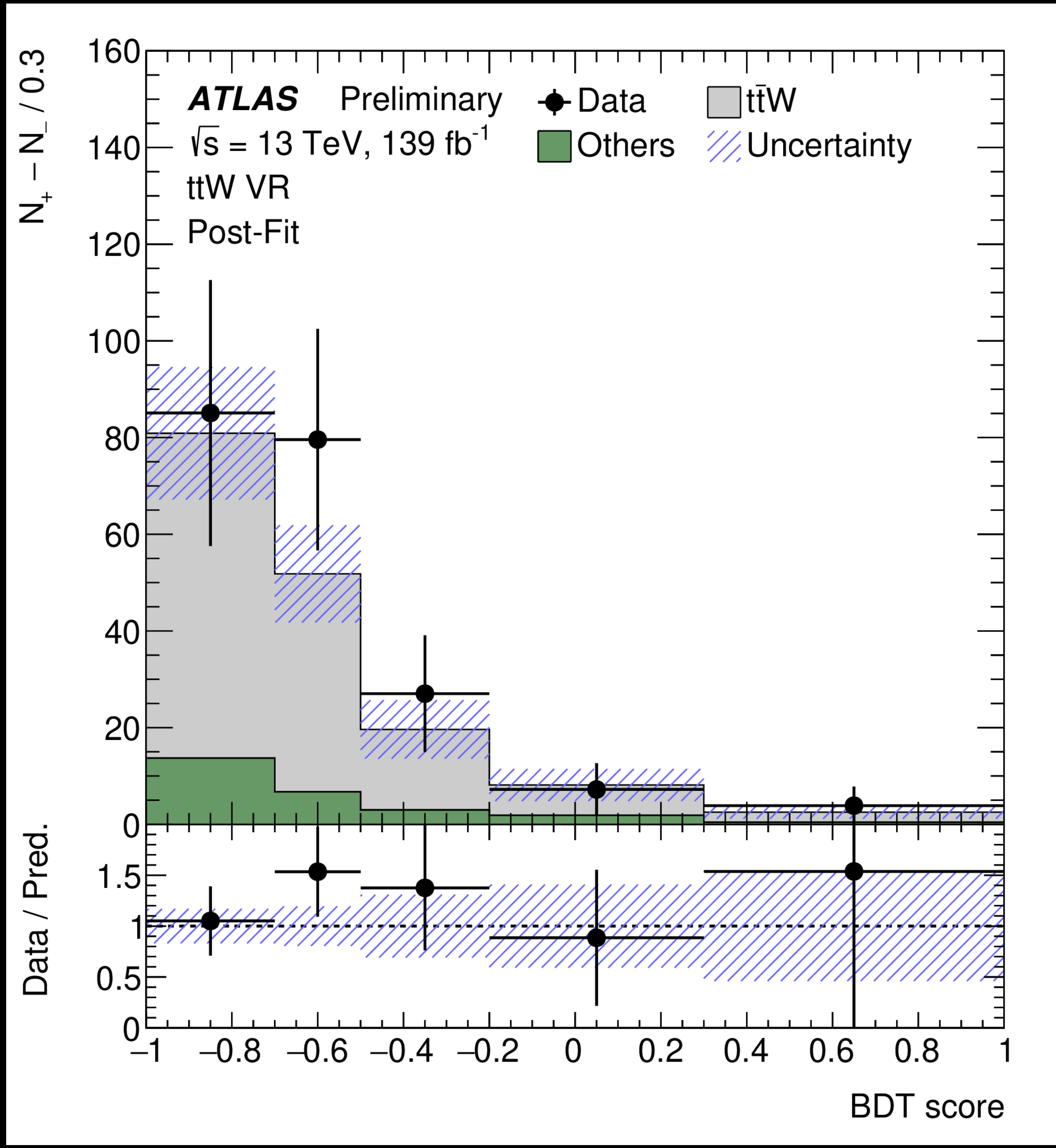




ttW Validation

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



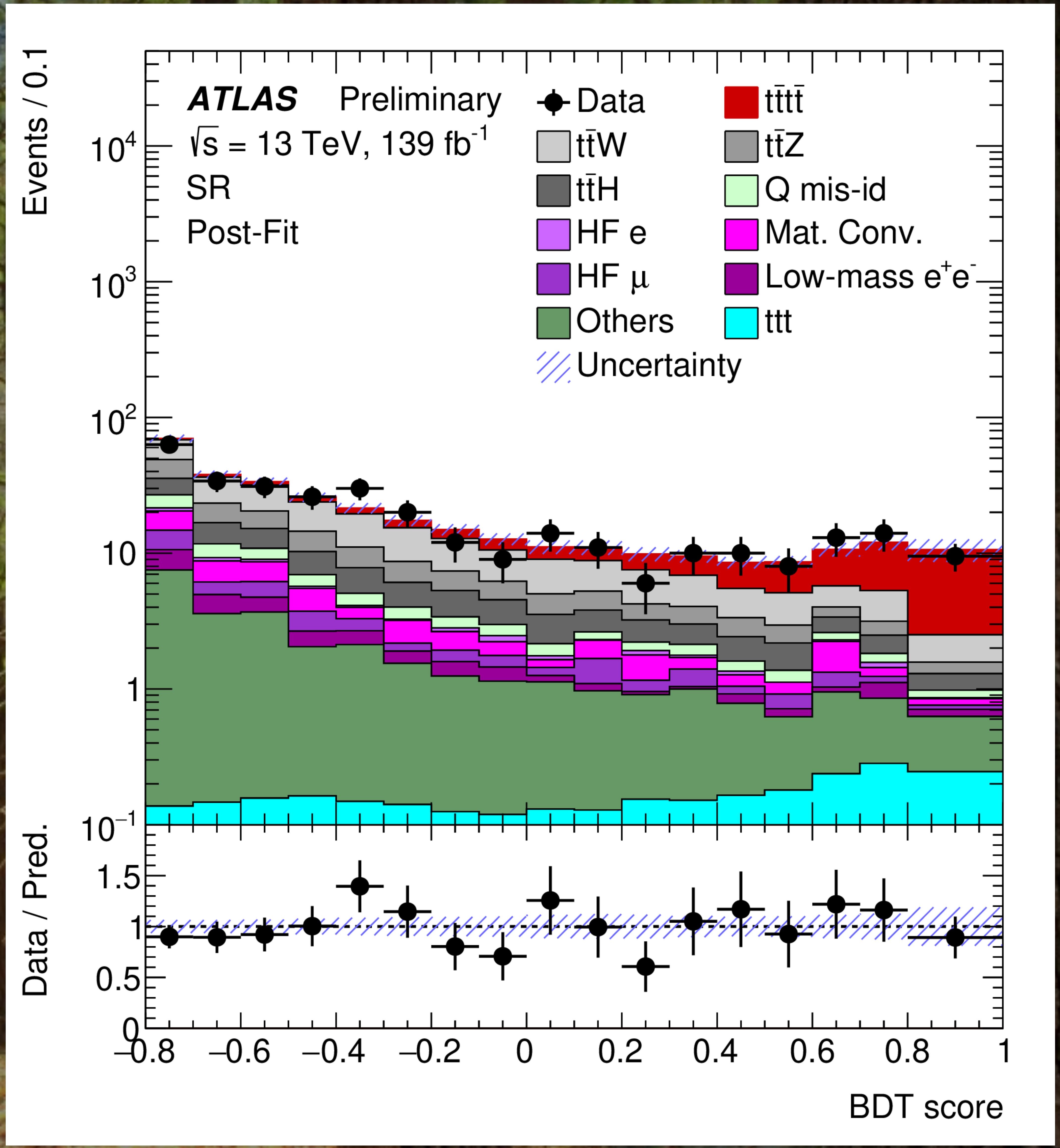


Uncertainty: 125% (300%) assigned to events with =7 (≥8) jets

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:

Simultaneous fit in 4 CRs and the SR.

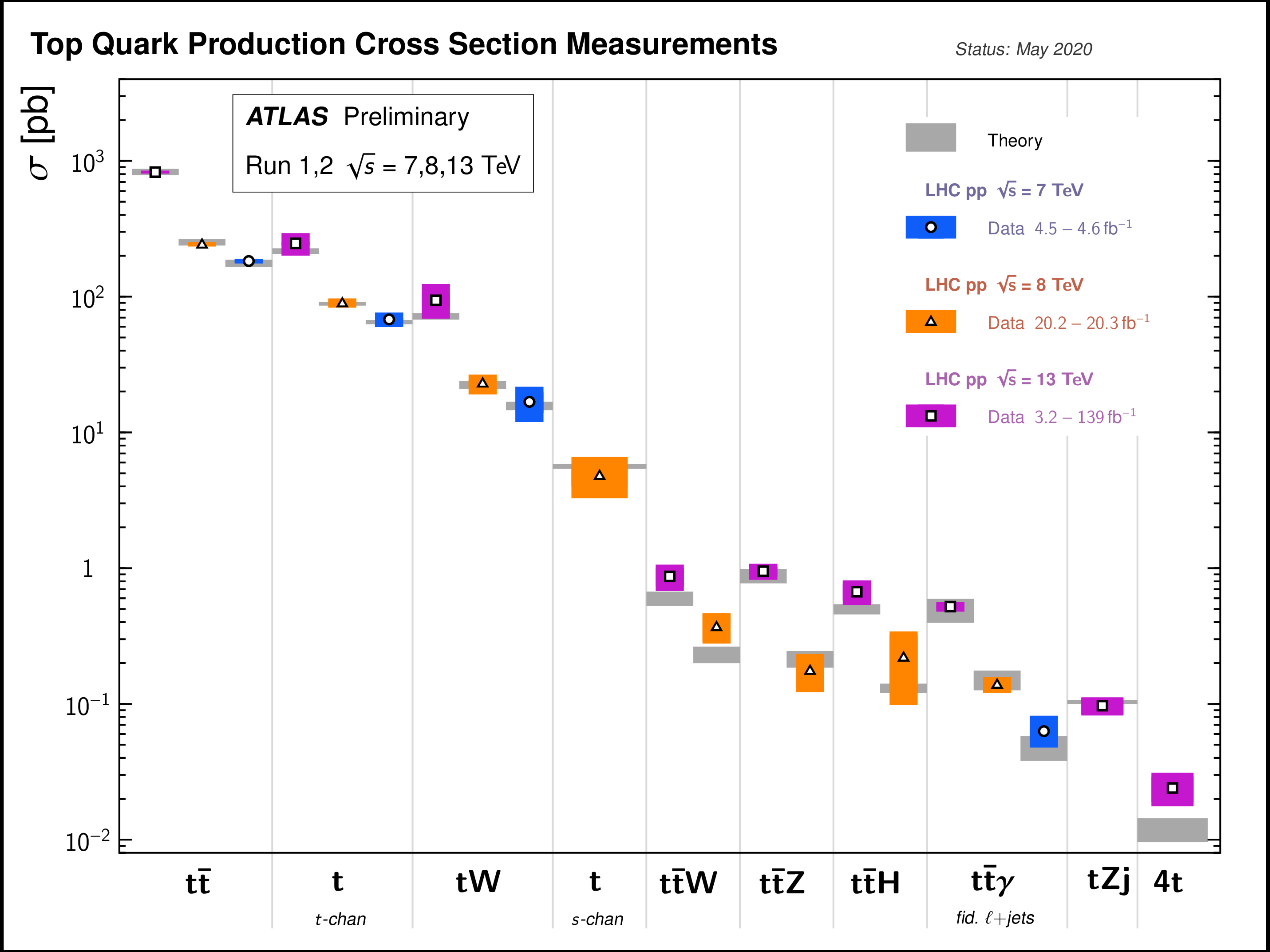
Measured four top signal strength:
μ = 2.0 +0.9 - 0.6

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

Cross section: σ(tttt) = 24 +5 - 5(stat) +5 -4(syst) fb

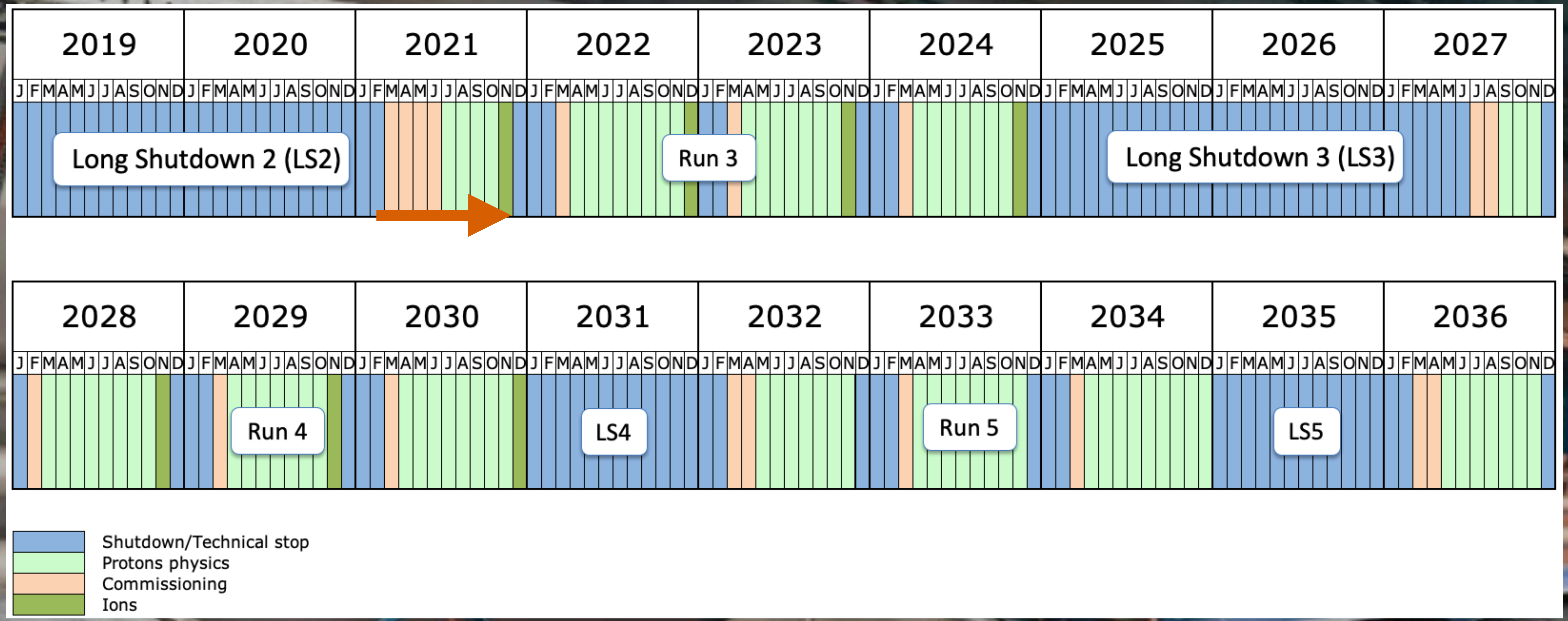
Evidence: 4.3σ (2.4σ expected)

1.7σ consistent with the Standard Model.


Top Quark Production Cross Section Measurements
Status: May 2020
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
tt̄
t
t-chan
tW
t
s-chan
tt̄W
tt̄Z
tt̄H
tt̄γ
fid. ℓ+jets
tZj
4t

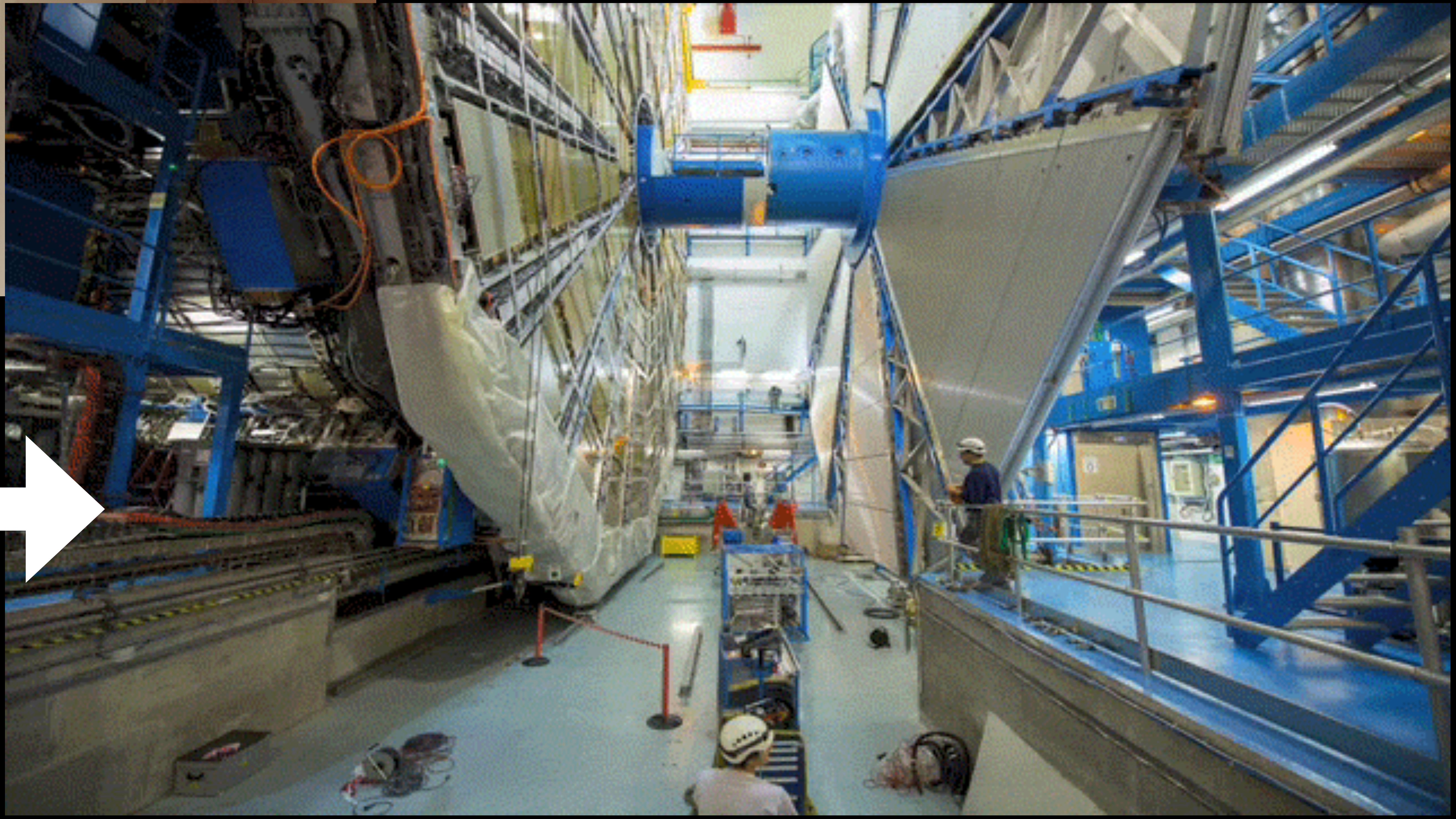
THE ROAD AHEAD

Forest Road in Oregon by Michael Matti



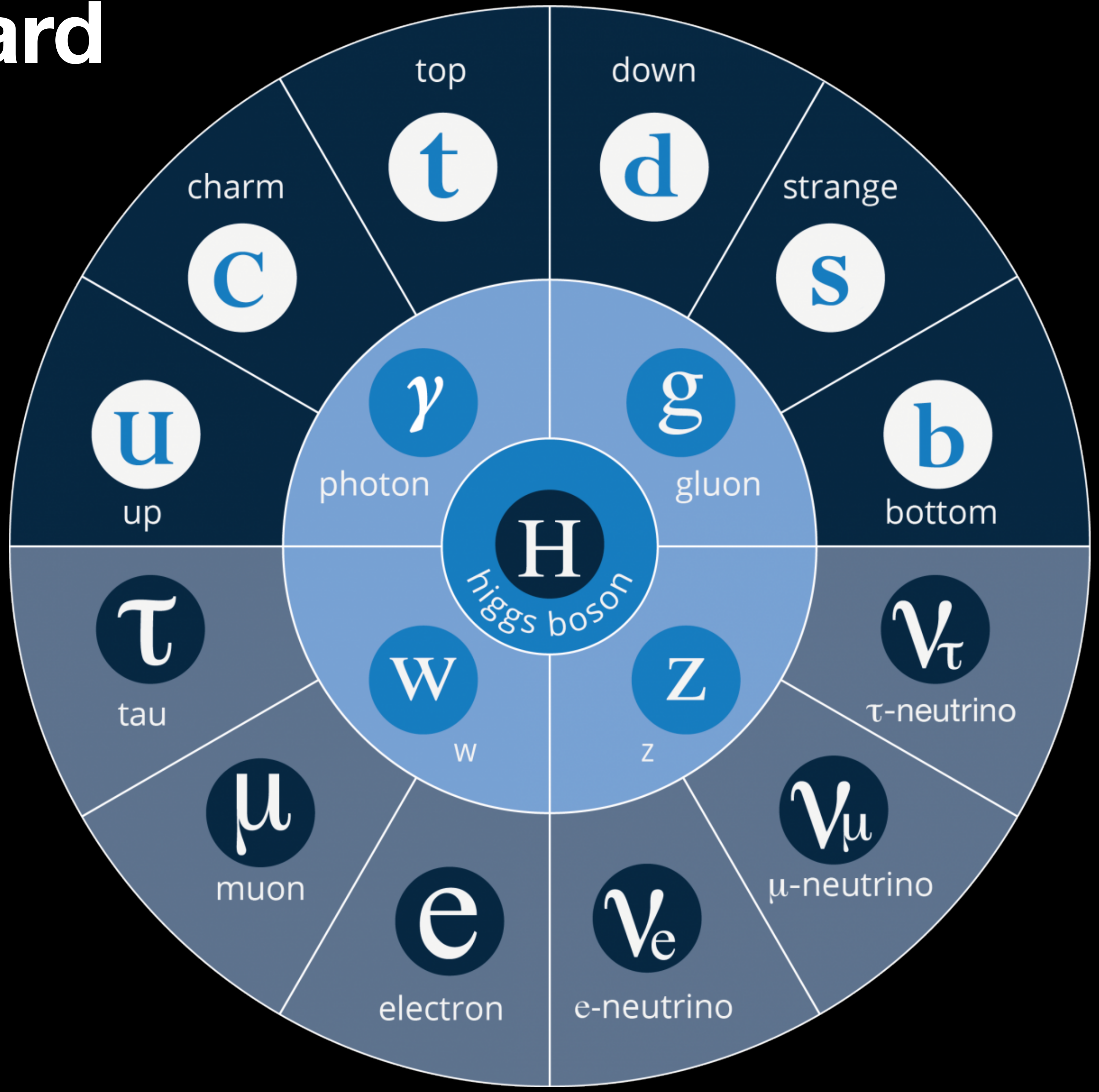
The LHC schedule

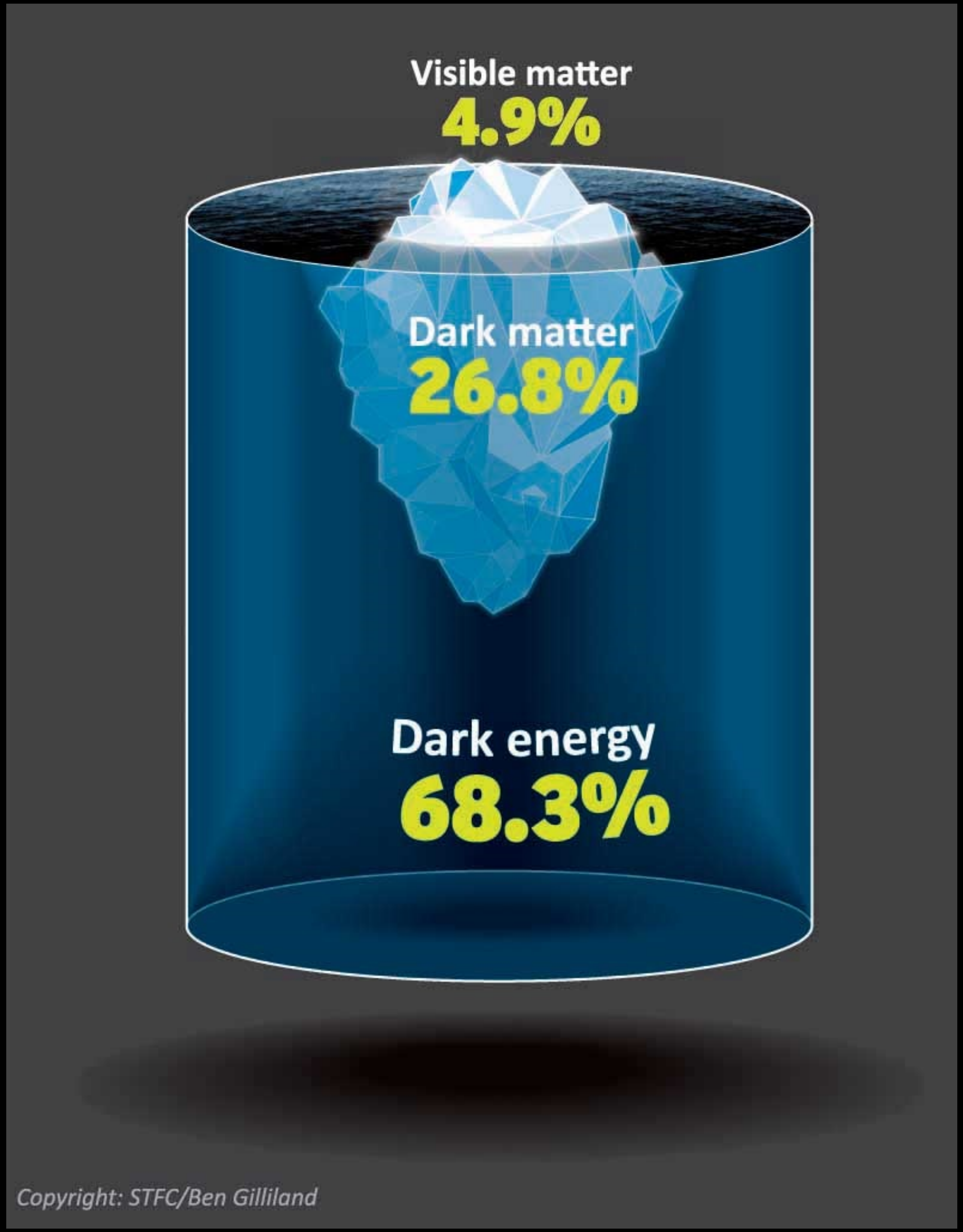
Due to COVID19, the start of Run 3 has been delayed to early-2022, but this is subject to change depending on the evolution of the situation.



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

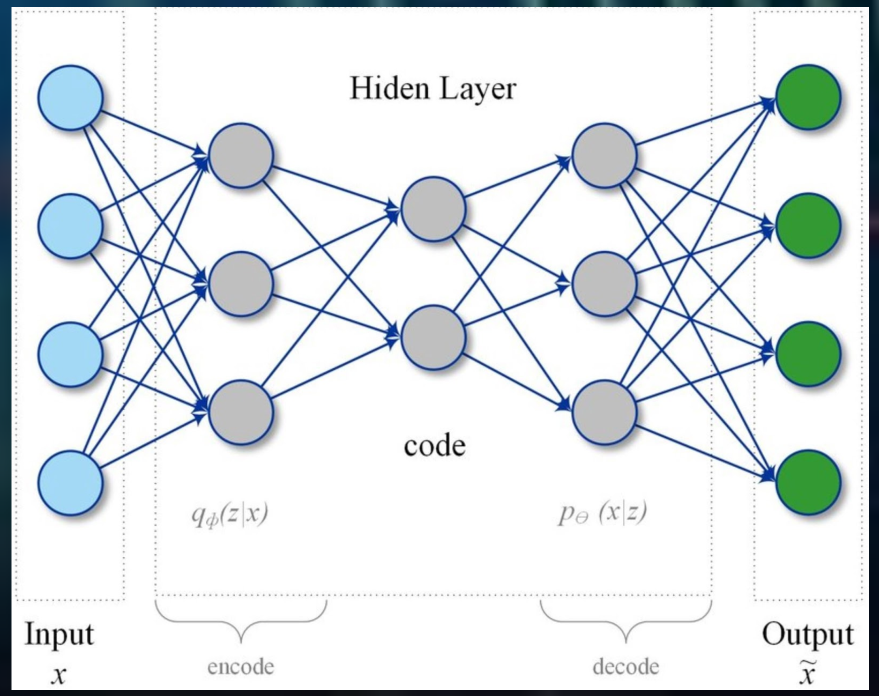
Precision measurements of the Standard Model





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.

ATLAS EXPERIMENT

33.2k followers

90.2k followers

22.4k followers

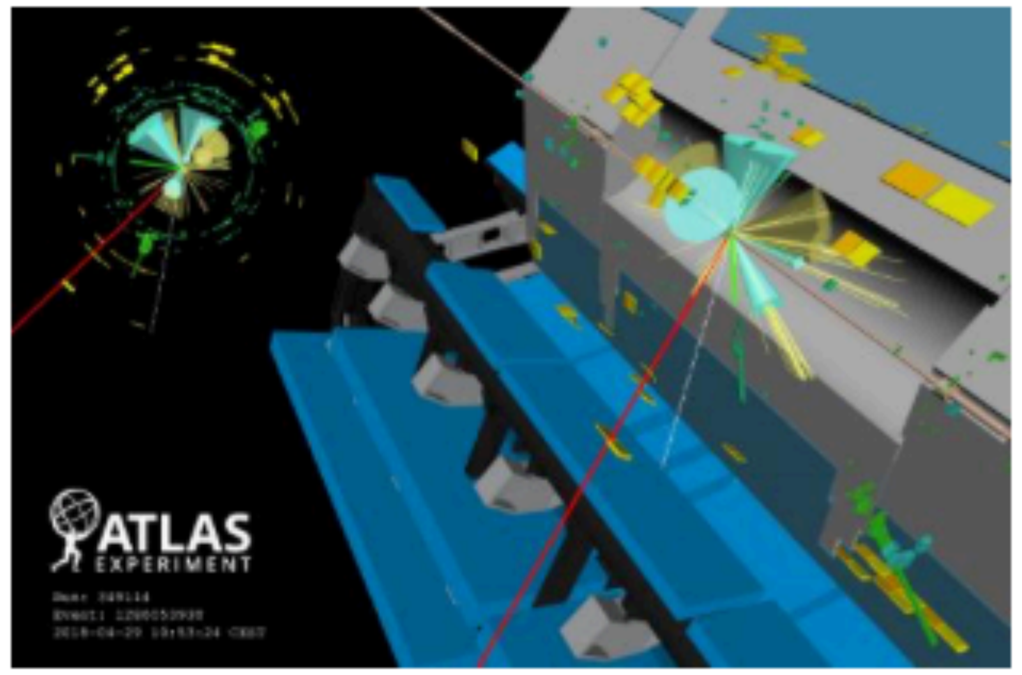
6.3k subscribers

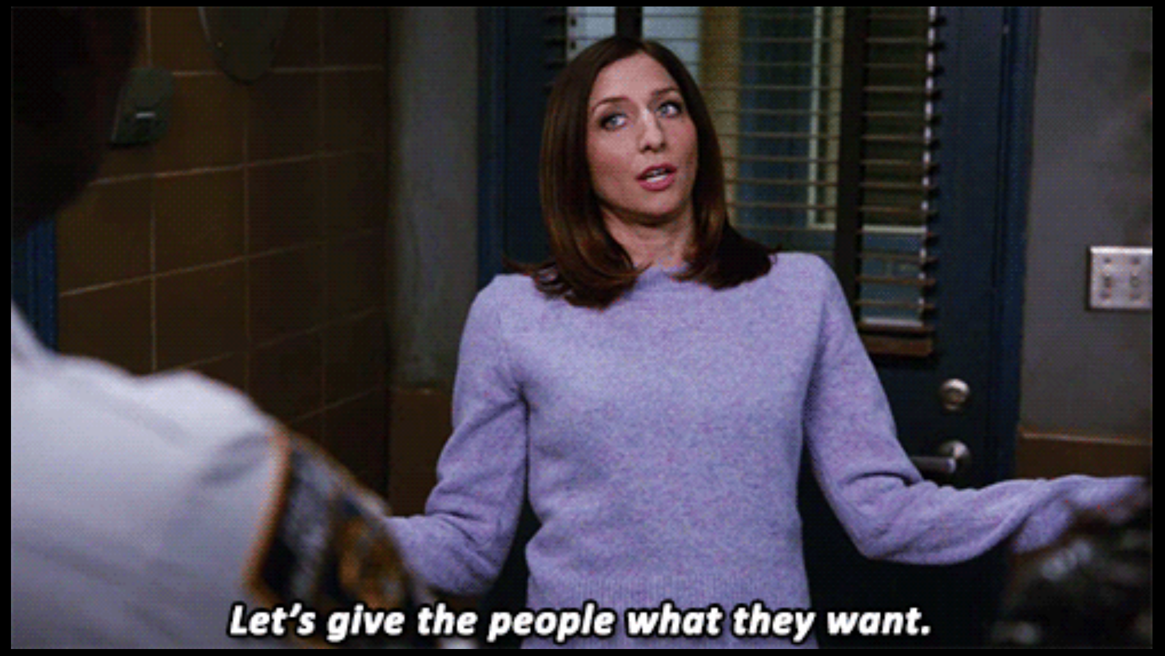
Physics Briefing

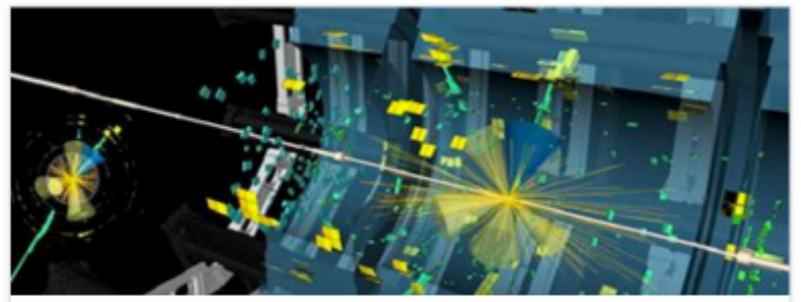
ATLAS finds evidence of spectacular four-top quark production

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 Experiment at CERN
4 June ·

Press Statement: ATLAS observes direct interaction of Higgs boson with top quark

CERN and Bologna, Italy, 4 June 2018. The ATLAS Collaboration at CERN has announced the observation of Higgs bosons produced together with a top-quark pair. Observing this extremely rare process is a significant milestone for the field of High-Energy Physics. It allows physicists to test critical parameters of the Higgs mechanism in the Standard Model of particle physics.

The result exploits the fu...

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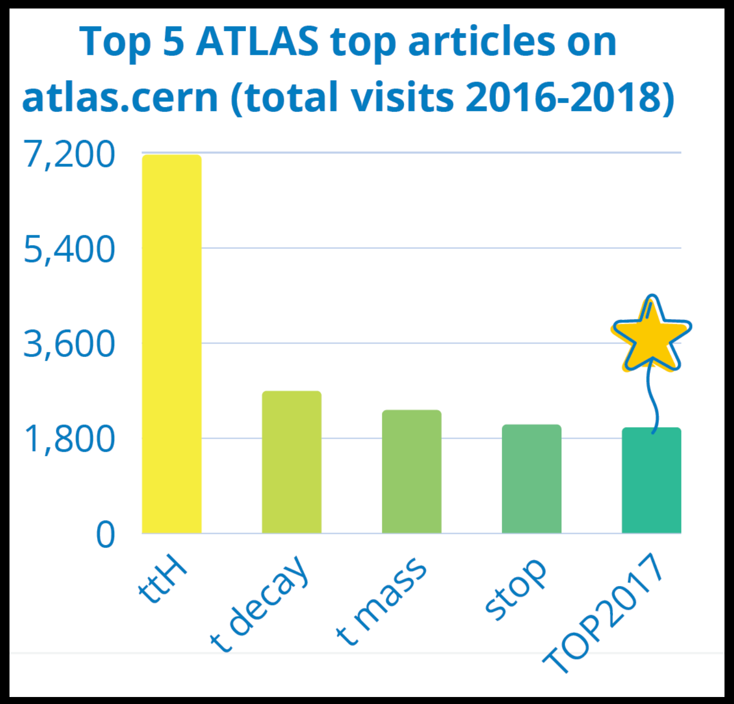
atlas.cern

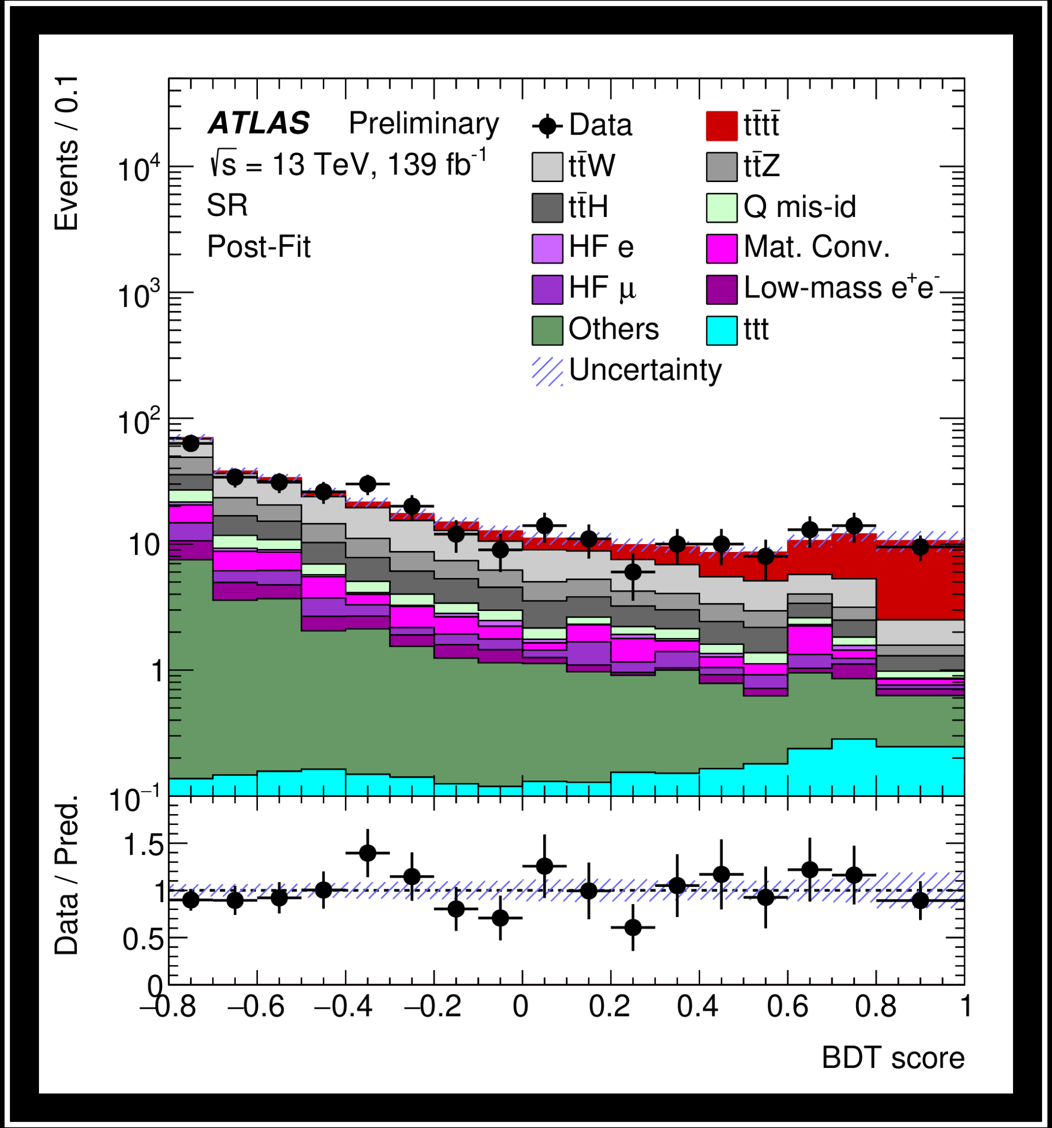


Please ensure you go through internal approval and publication before talking about your result online...

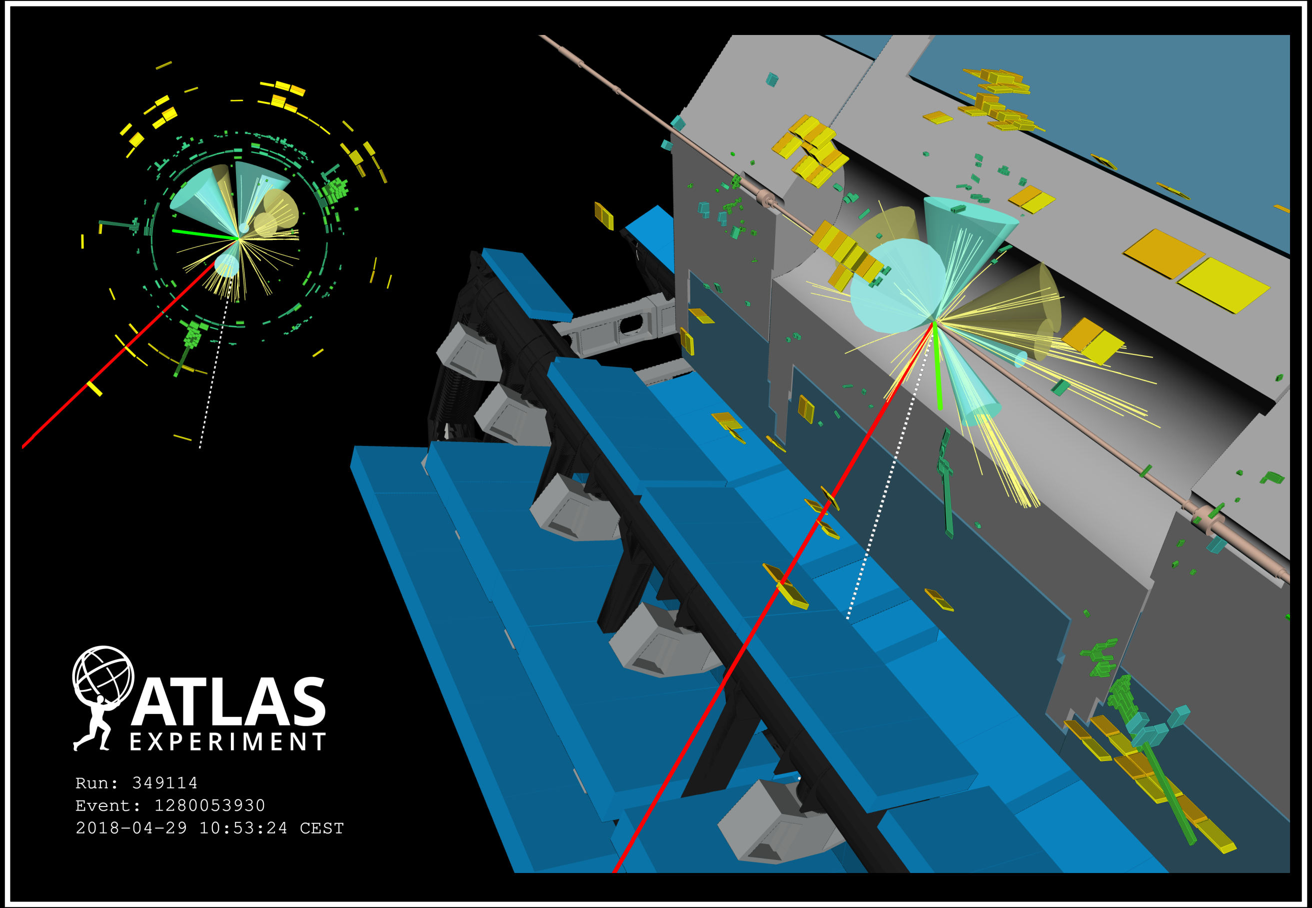
Nikhef

Radboud University

Nijmegen, the Netherlands



Four Tops results from ATLAS



Thank you!

Dr Clara Nellist

Excellence Initiative Fellow

Radboud University and NIKHEF

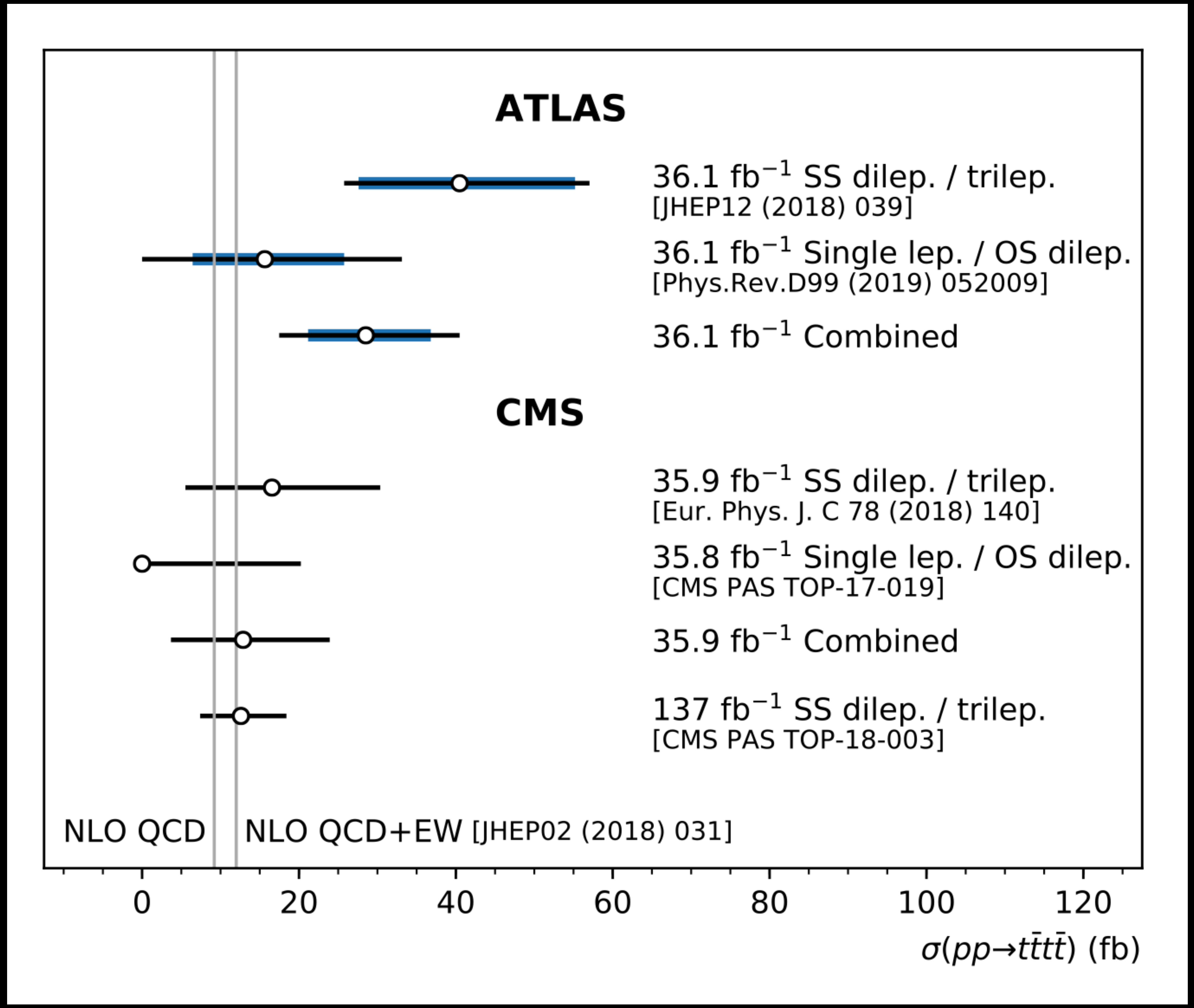
Online Particle Physics Seminar, Birmingham UK

07.10.2020

Backup

Previous results

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



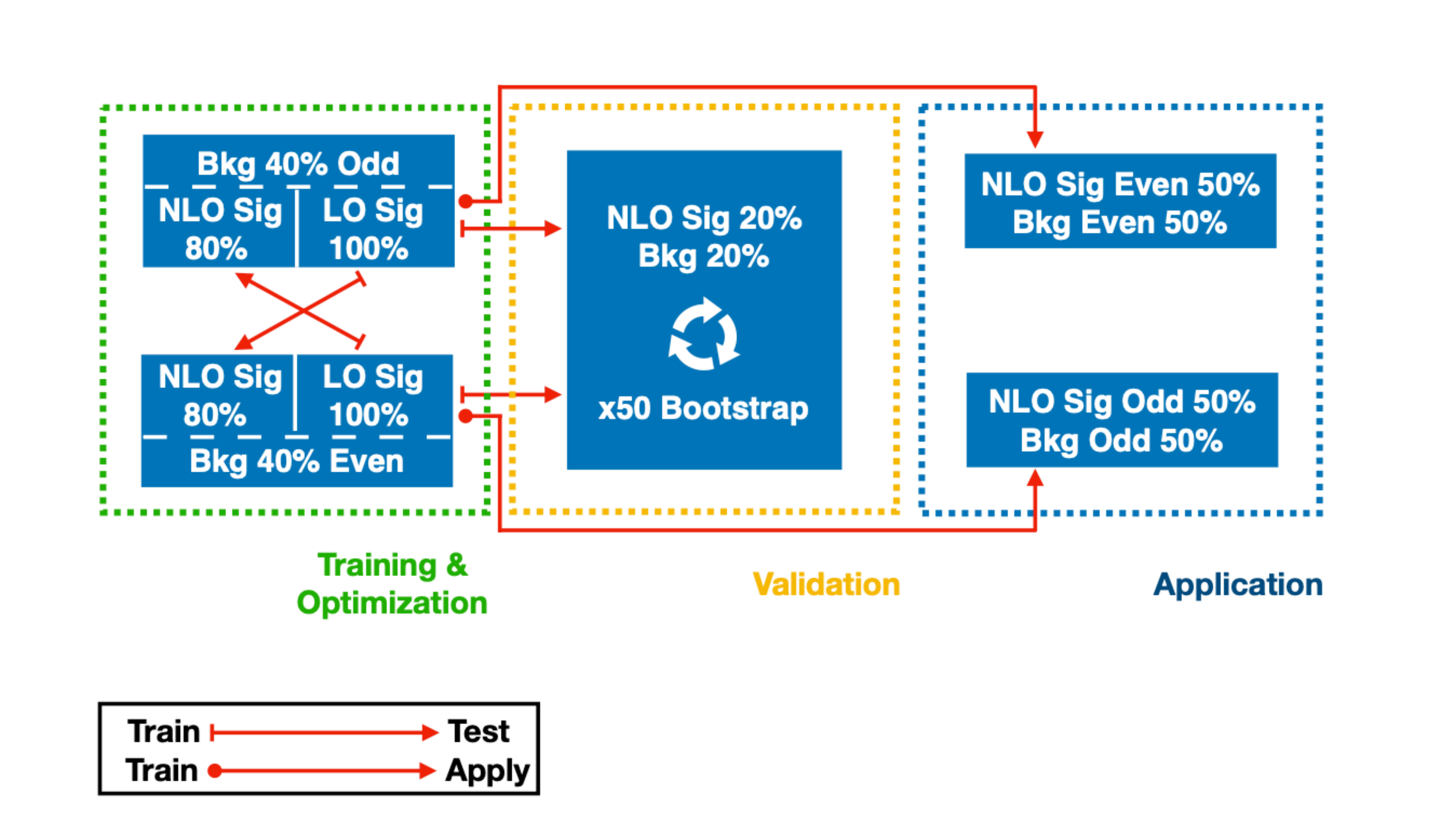
1LOS channels:

ATLAS EXPERIMENT

Partial Run 2 data (36 fb^{-1})
μ = 1.7 +1.9 -1.7
1σ observed (0.6σ expected)

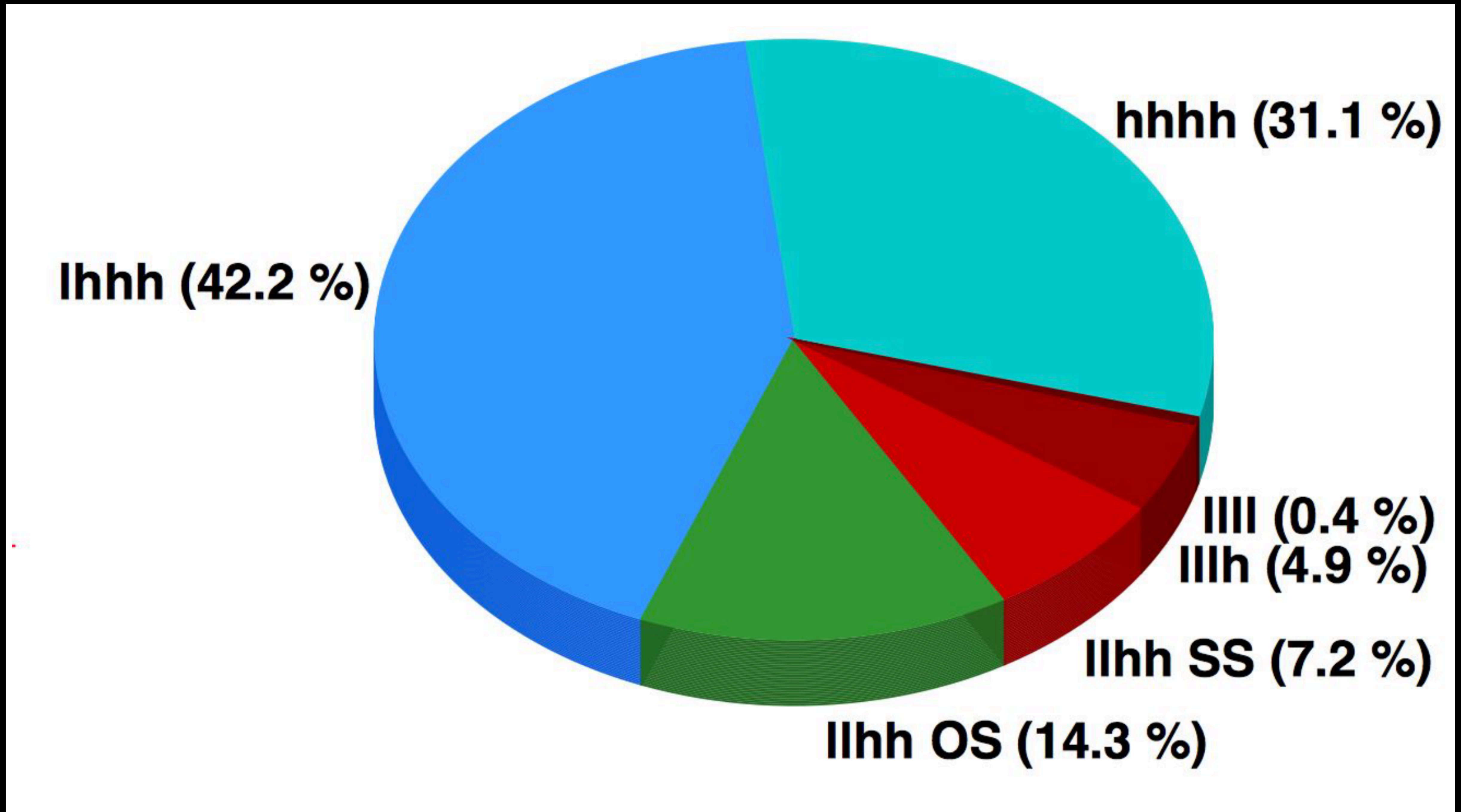
CMS

Partial Run 2 data (36 fb^{-1})
μ = 0.0 +2.2
0σ observed (0.4σ expected)

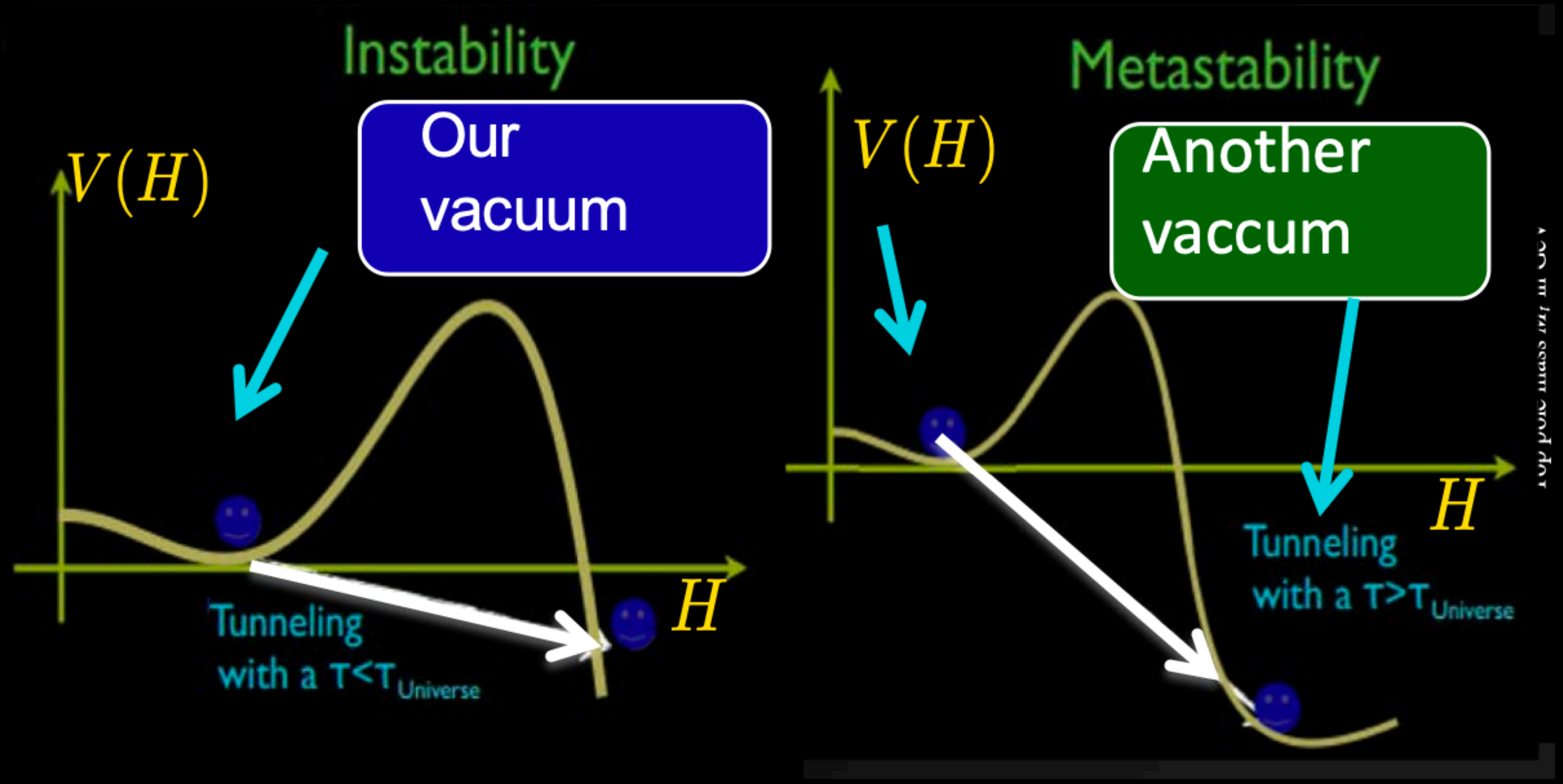

Bkg 40% Odd
NLO Sig 80%
LO Sig 100%
NLO Sig 80%
LO Sig 100%
Bkg 40% Even
NLO Sig 20%
Bkg 20%
x50 Bootstrap
NLO Sig Even 50%
Bkg Even 50%
NLO Sig Odd 50%
Bkg Odd 50%
Training &
Optimization
Validation
Application
Train
Test
Train
Apply

Selection:

Two same-sign leptons or at least 3 leptons
>= 6 jets (pT > 25GeV)
>= 2 b-jets (77% WP)
HT> 500 GeV



Reminder: top quark decays to a W-boson and a b-quark ~100% of the time.


Instability
Our vacuum
V(H)
H
Tunneling
with a T<TUniverse
Metastability
Another vaccum
V(H)
H
Tunneling
with a T>TUniverse