A brief tour of the **Particle World**

(and your lecture programme)

Tara Shears, University of Liverpool

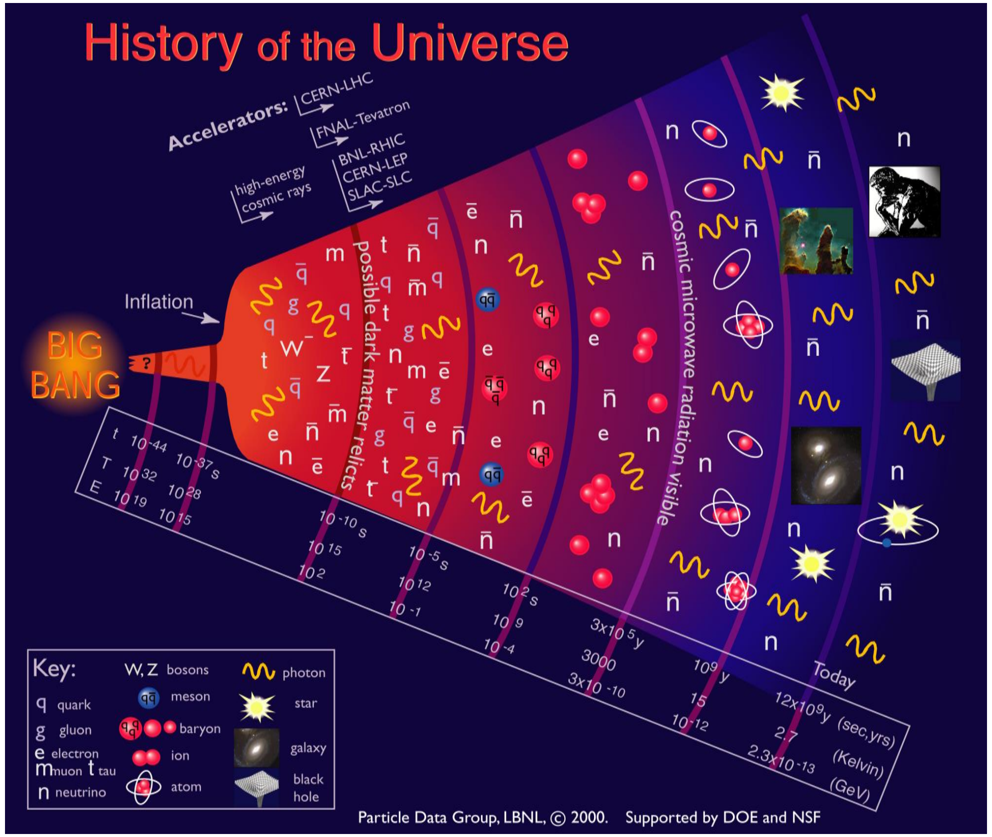
Overview

- What particle physics describes
- What we know (and what we don't)
  - The Standard Model: matter; forces; Higgs.
- Experiments; performing research
- Outstanding questions and mysteries …

… just a taster of what's waiting in your lectures

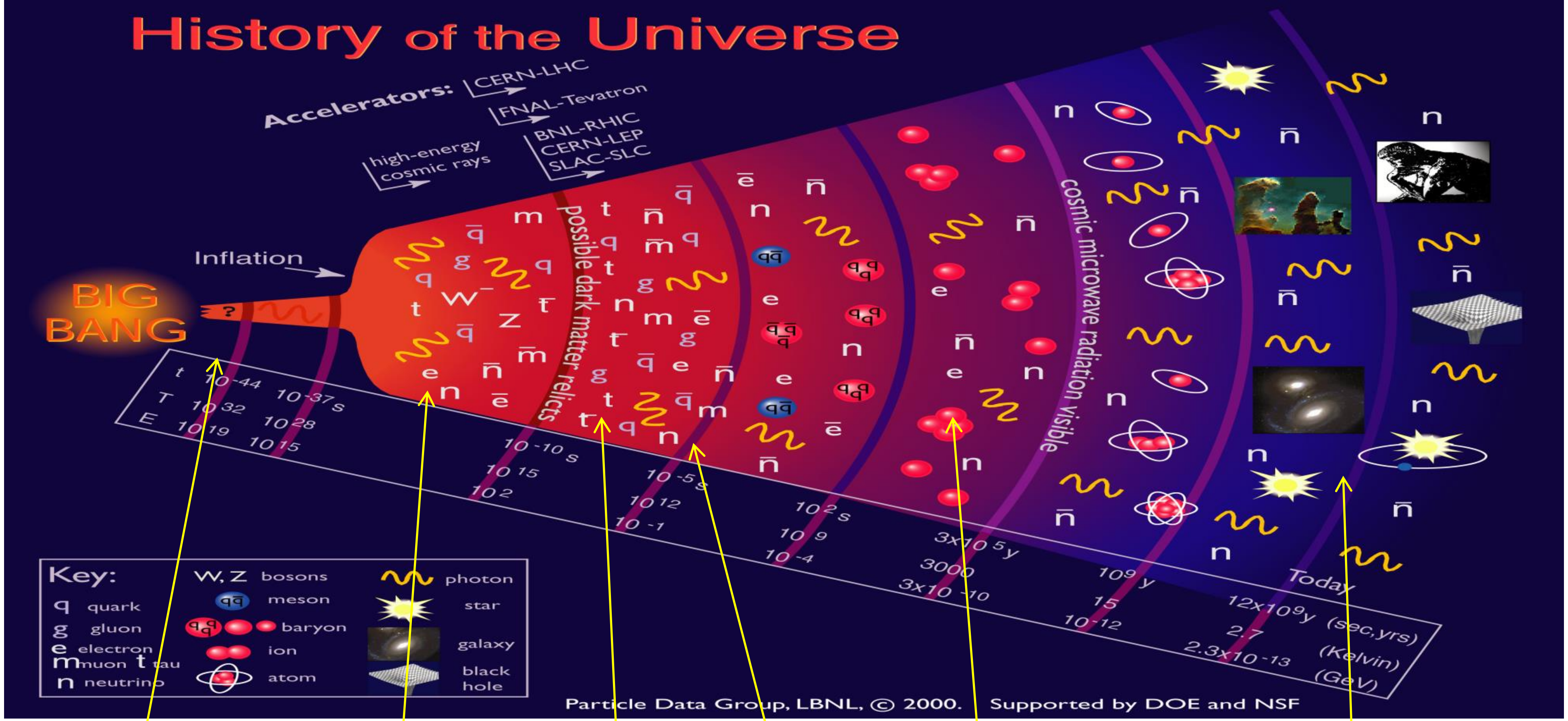
The Universe

BIG BANG



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

NOW



Cosmology
Q&A: 23/7/20

LHC

Nuclear physics
Q&A: 21/7/20

Cosmic rays

Astrophysics

Quark/gluon plasma
Heavy ions **Q&A: 29/7/20**

Plus ….
Antimatter **Q&A: 20/7/20**
Astroparticle physics **Q&A: 16/7/20**

Matter

u	c	t
d	s	b

quarks

e	μ	τ
ν_e	ν_μ	ν_τ

leptons

Mass →

Charge →

Spin →

2.4 MeV/c^2 2/3 1/2 u up	1.27 GeV/c^2 2/3 1/2 c charm	171.2 GeV/c^2 2/3 1/2 t top	quarks
4.8 MeV/c^2 -1/3 1/2 d down	104 MeV/c^2 -1/3 1/2 s strange	4.2 GeV/c^2 -1/3 1/2 b bottom	
0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	leptons
< 2.2 eV/c^2 0 1/2 ν_e e neutrino	< 0.17 MeV/c^2 0 1/2 ν_μ μ neutrino	< 15.5 MeV/c^2 0 1/2 ν_τ τ neutrino	

(more about the discoveries in Lecture 1, Particle World)

and … antimatter …

Einstein's equation of motion*: $E^2 = p^2c^2 + m^2c^4$

Two energy solutions for the same mass;

- Matter
- Antimatter

Every fermion has an antimatter version.

Same mass, opposite charge

eg. antiquark $\bar{q}$, antimuon μ^+, antineutrino $\bar{\nu}$

*(and others, more famously Dirac)

Electromagnetic

0 eV/c^2

0

1

γ

photon

U(1)

Strong (QCD)

8 x

0 eV/c^2

0

1

g

gluon

SU(3)

Weak

2 x

80.4 GeV/c^2

±1

1

W

W boson

,

91.2 GeV/c^2

0

1

Z

Z boson

SU(2)

Note:
No gravity!!

EM force	**Weak force**	**Strong force**
Electric charge (1)	Weak charge (2)	Colour charge (3)
Massless photon	Massive $W^\pm$,Z	8 massless gluons
Coupling g	Coupling g_W	Coupling g_s
Abelian	Non-abelian	Non-abelian
Only charged particles couple	Only left handed particles couple	Only quarks couple
	quark mixing (3 generations, CP)	
	Neutrino mixing (3 generations, CP)	

Value unknown/ not predicted

(Lecture 2 Particle World)

July 4th 2012

126 GeV/c^2

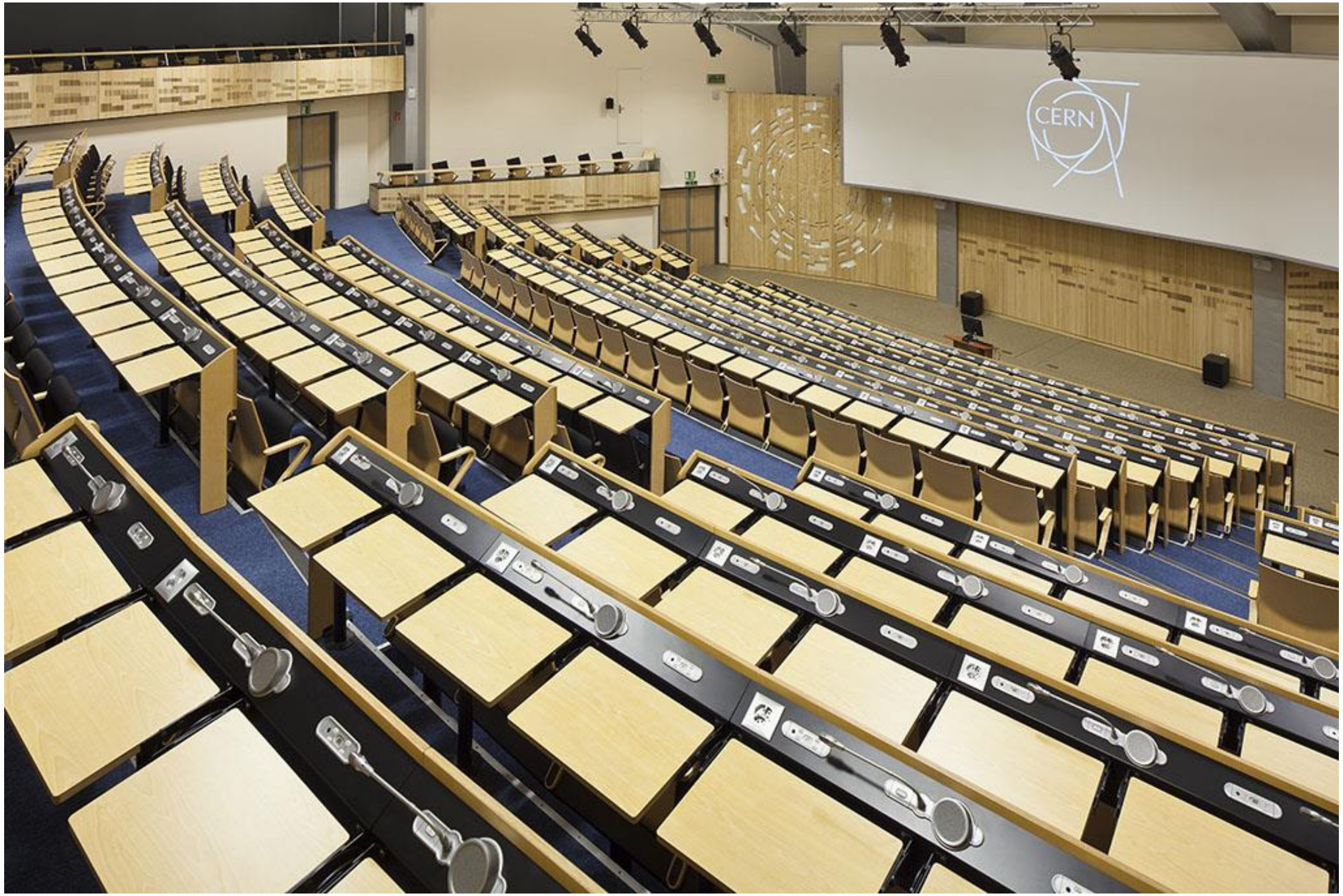
0

0

H

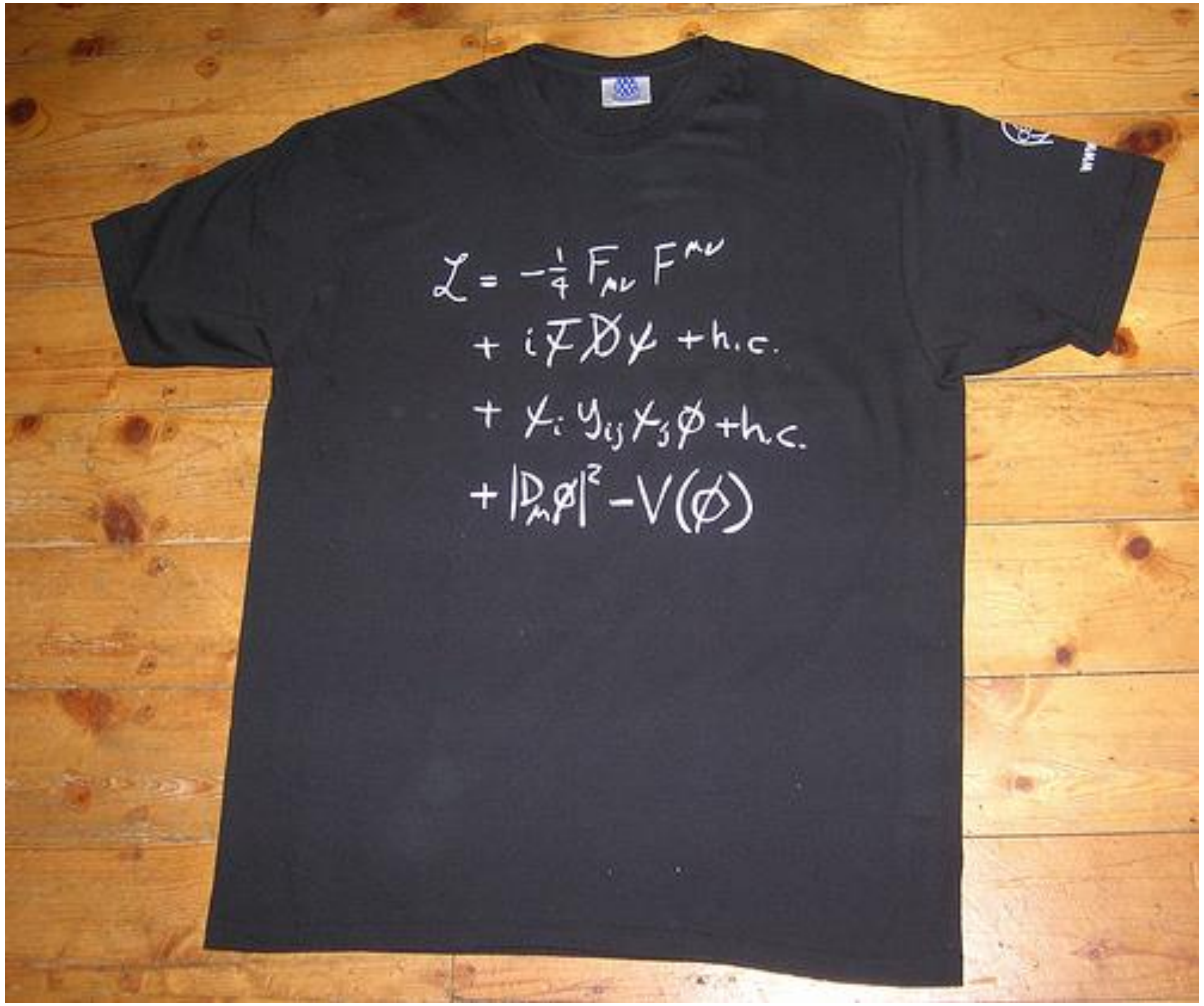
Higgs

~ 8 years later .. you would have been here ..



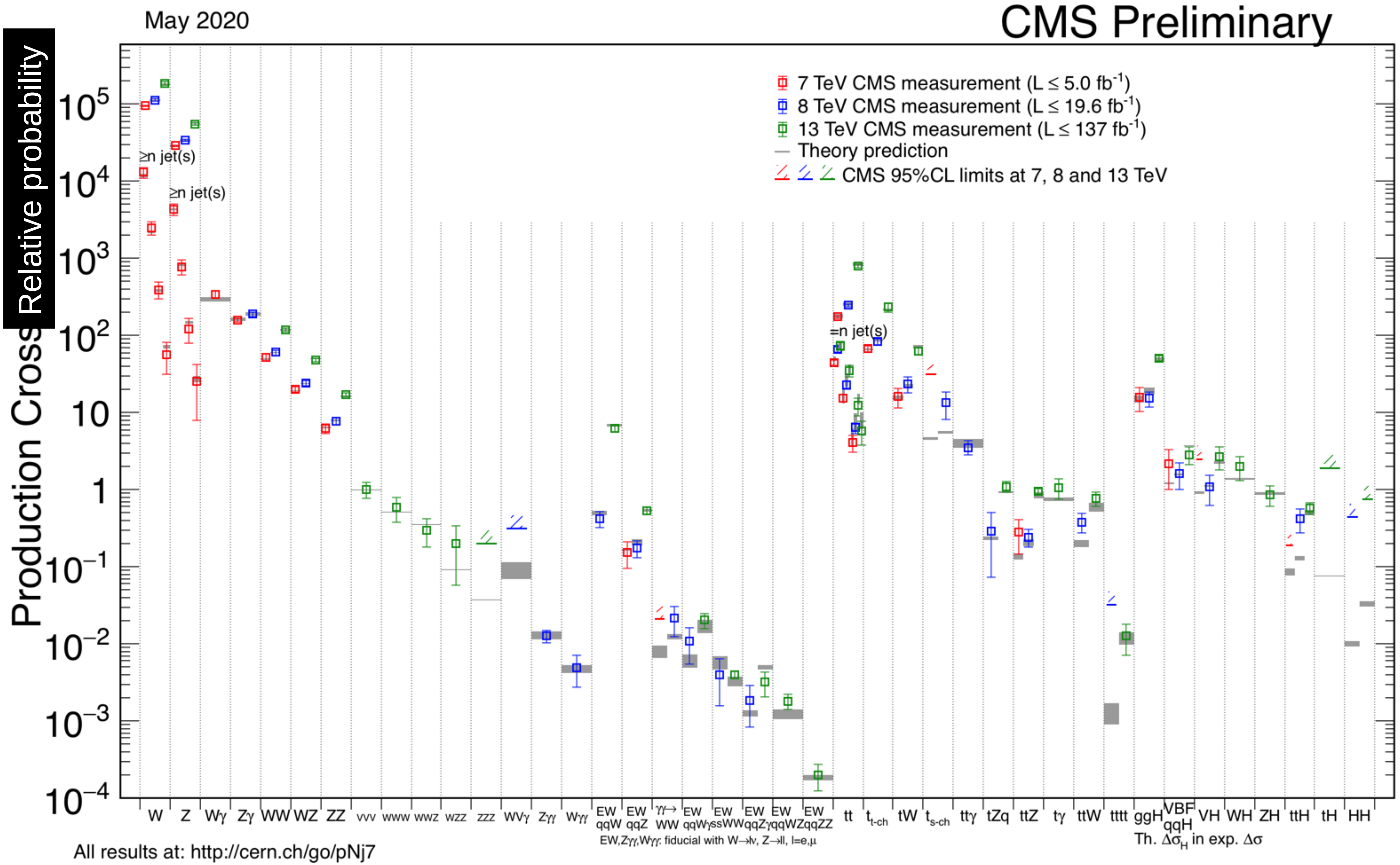
Standard Model

- **Standard Model** (SM)
- Quantum field theory based on lagrangians
- We use the SM to predict experimental observations



Standard Model **Q&A 22/7/20**
HEP theory concepts **Q&A 17/7/20**

Relative probability



Successes

Consistent with experiment

No significant deviations seen

Predictions (eg Higgs) proven

BUT

Incomplete (eg. no gravity)

Few explanations

Many ad-hoc additions to fit experimental data

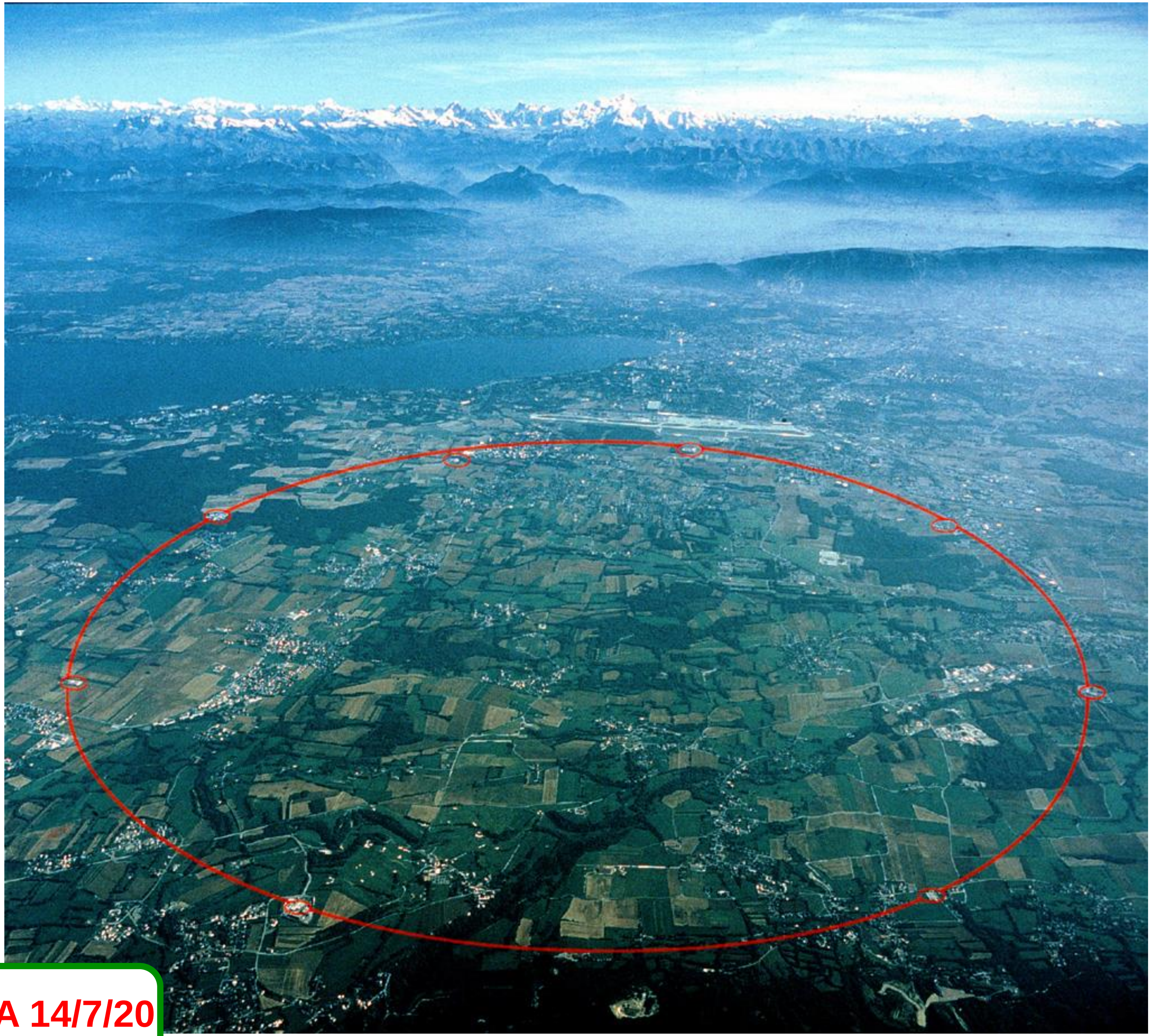
Many mysteries…

Need to find a breakdown to move forward.
Need experiments.

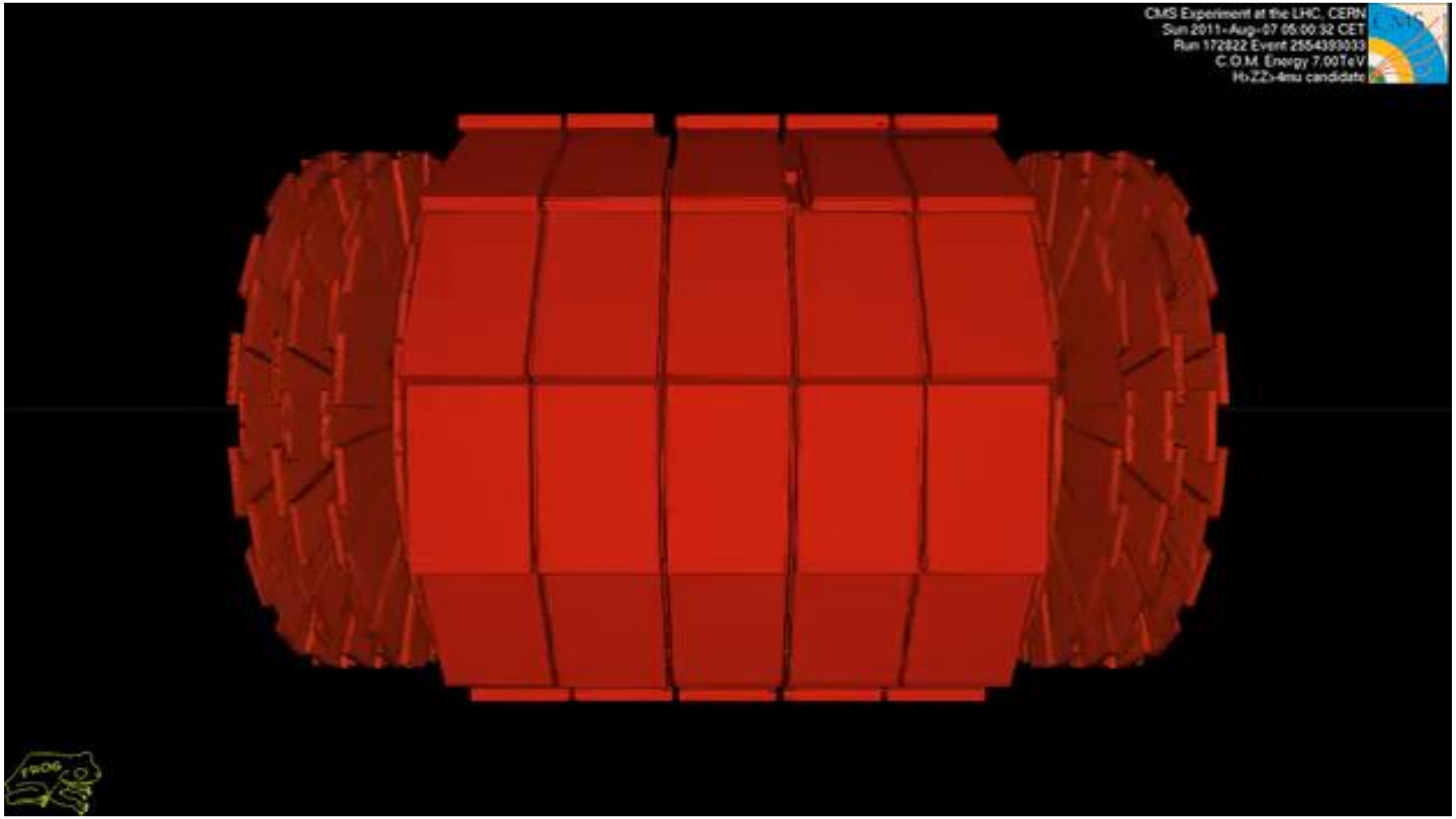
Accelerators

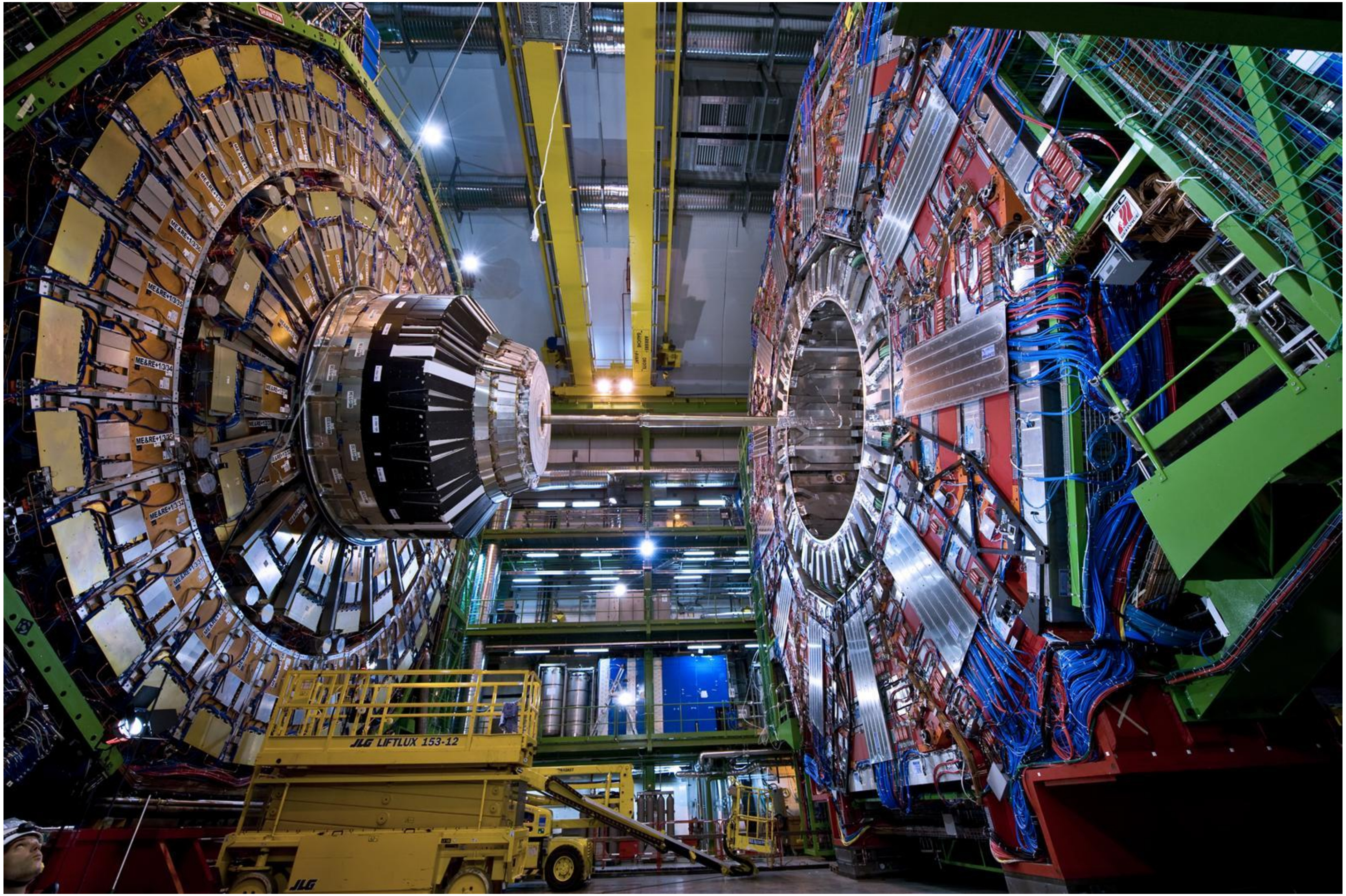
Eg. Large Hadron Collider:

- High energy (√s=14 TeV)
- Circular
- Proton beams
- Up to 10^8 collisions/s



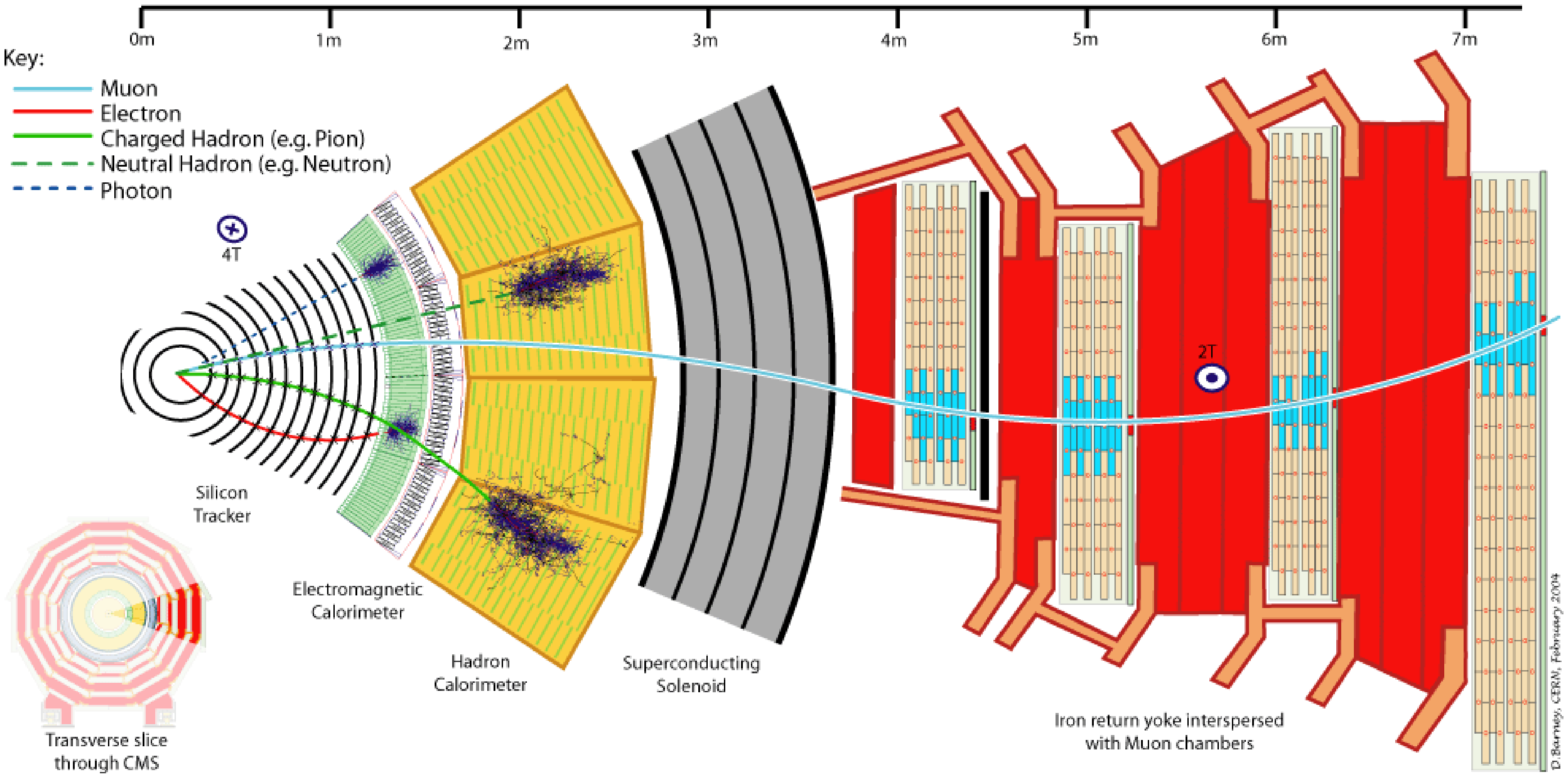
Particle Accelerators and Beam Dynamics **Q&A 14/7/20**
Accelerator Technology Challenges **Q&A 15/7/20**


CMS Experiment at the LHC, CERN
Sun 2011-Aug-07 05:00:32 CET
Run 172822 Event 2554393033
C.O.M. Energy 7.00TeV
H>ZZ>4mu candidate
FROG



Detectors **Q&A: 10/7/20**

(+lecture 3, Particle World)



Identify particles by characteristic signatures in experiment

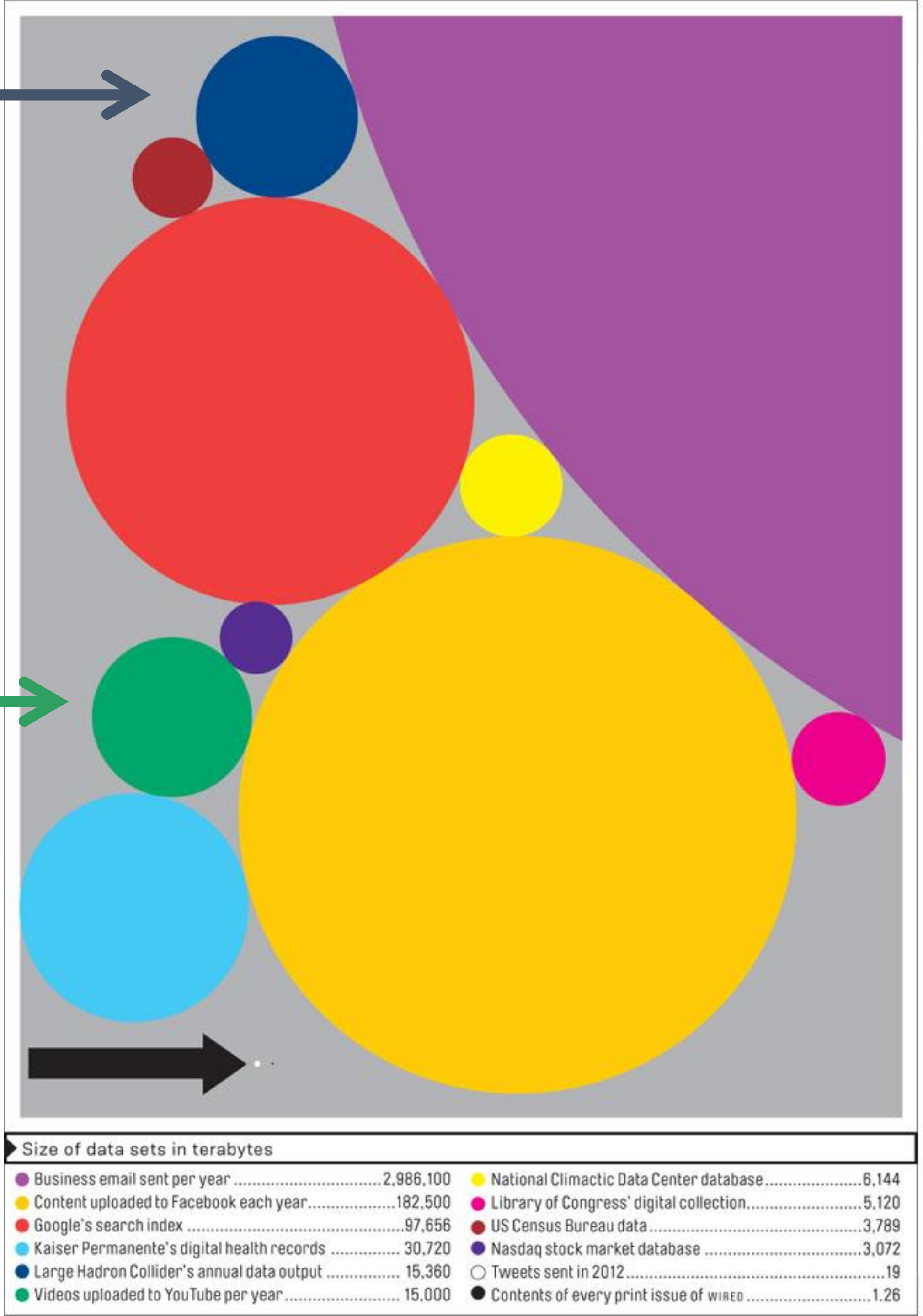
Add computers: calculate particle paths and energies

Add theory: infer what fundamental process happened

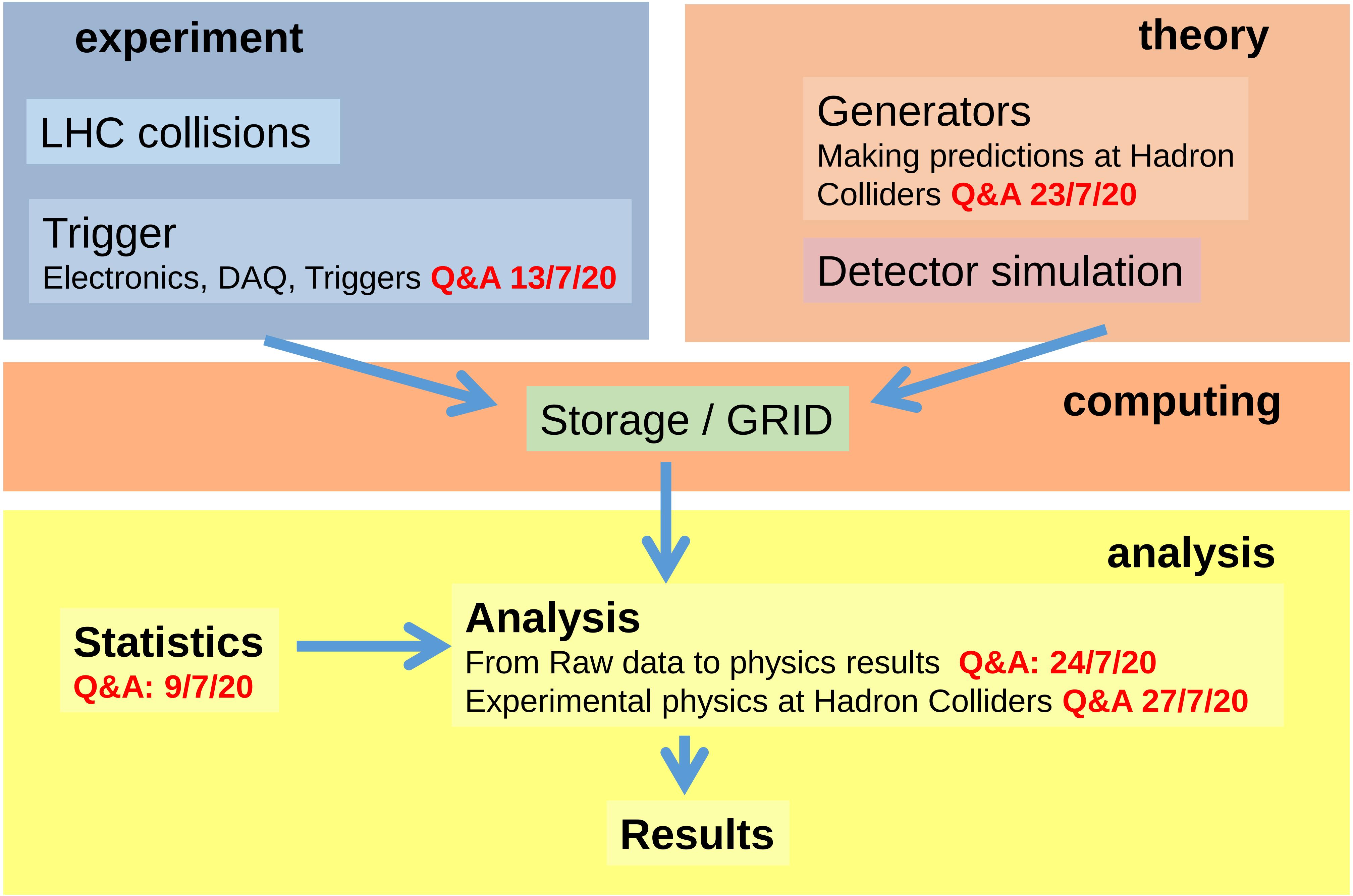
LHC
15 360 TB/yr

Big data …….

Videos uploaded to YouTube
15 000 TB/yr



(http://www.wired.com/2013/04/bigdata/)



experiment

LHC collisions

Trigger

Electronics, DAQ, Triggers **Q&A 13/7/20**

theory

Generators

Making predictions at Hadron Colliders **Q&A 23/7/20**

Detector simulation

computing

Storage / GRID

analysis

Statistics

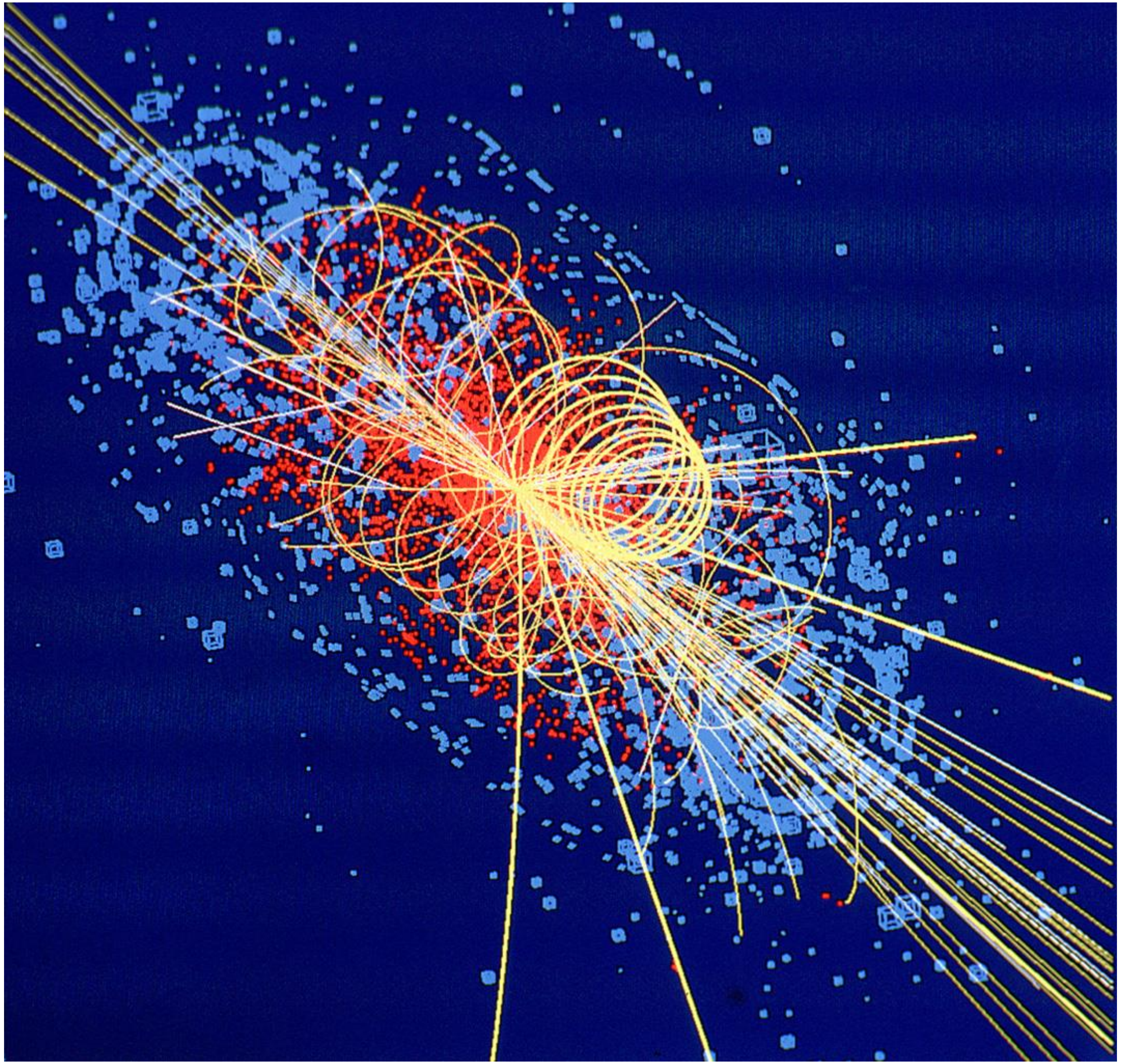
Q&A: 9/7/20

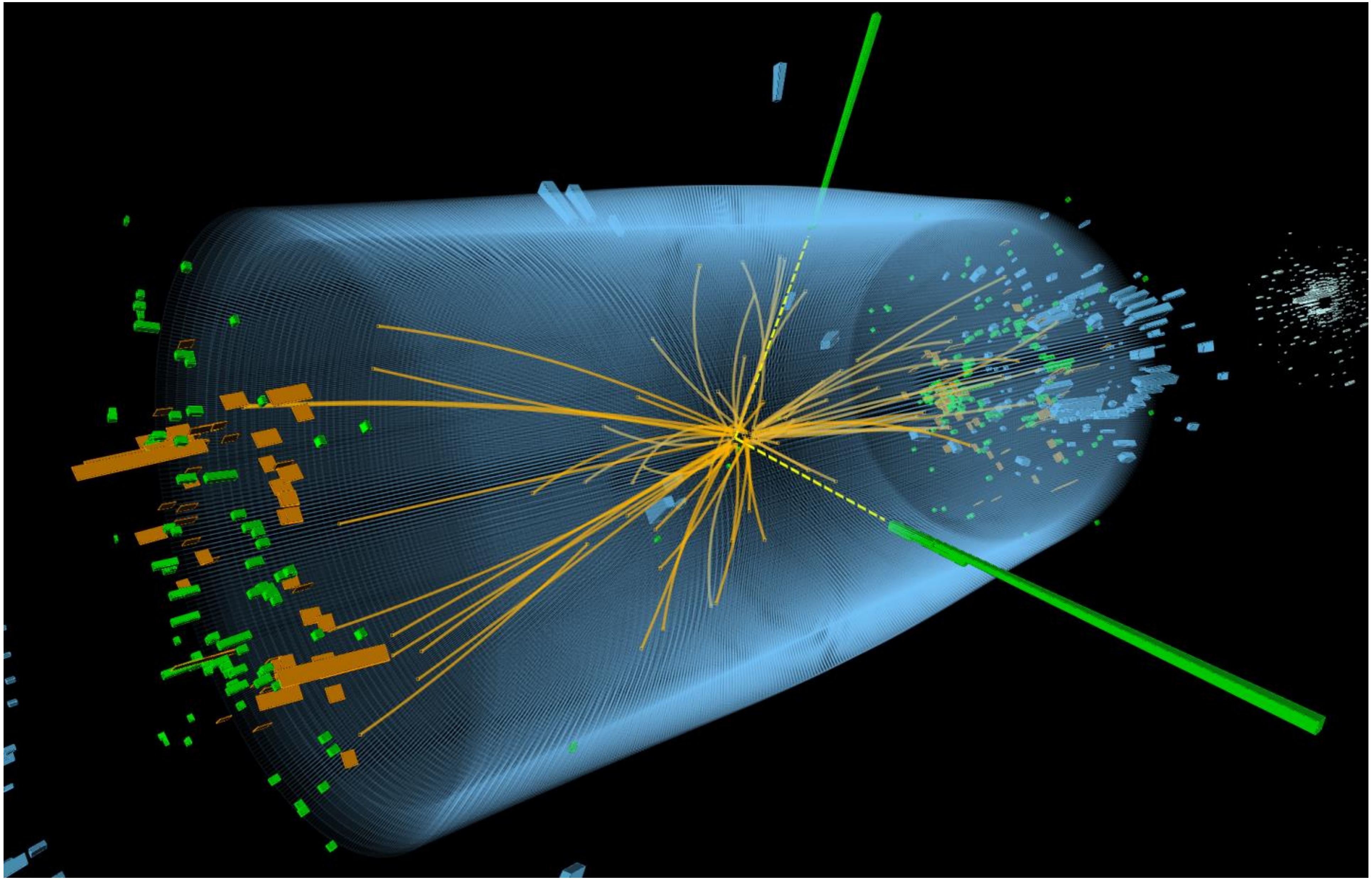
Analysis

From Raw data to physics results **Q&A: 24/7/20**

Experimental physics at Hadron Colliders **Q&A 27/7/20**

Results





Future facilities?

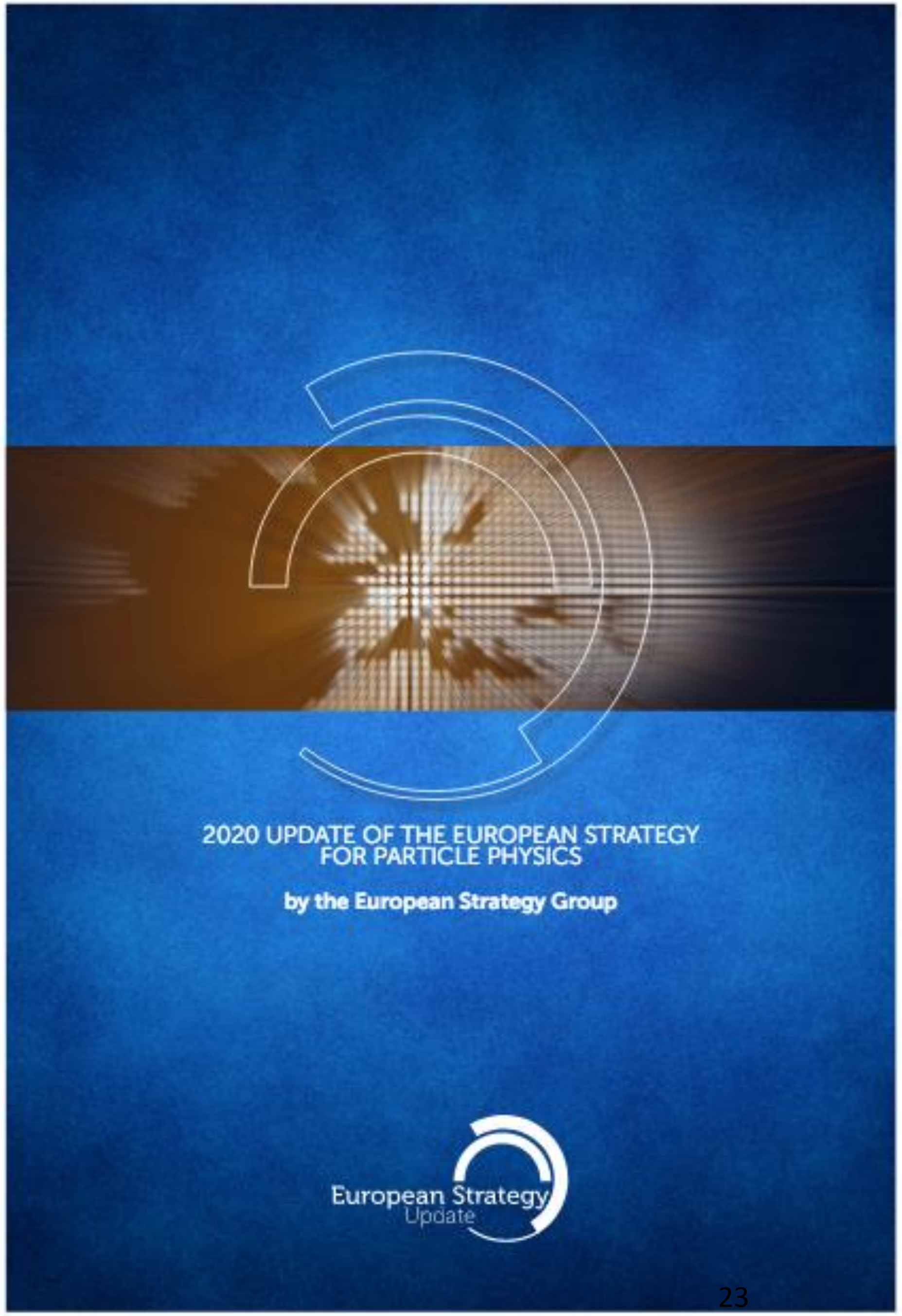
Too many open questions to stop here.

- New neutrino facility?
- New high energy machine?
- New linear collider?

June 19 2020: European Strategy for Particle Physics released

Physics at lepton colliders
Future collider projects **Q&A: 6/8/20**

https://cds.cern.ch/record/2720129/files/Update%20European%20Strategy.pdf



2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy
Update

The known unknowns

- Higgs – still don’t know a lot about it
- Gravity?
- Antimatter?
- Dark matter, dark energy?
- A unified theory?

+ unknown unknowns…..

Gravity

Can’t describe it in SM

Can include it in string theory – not very testable (yet)

Large extra dimensions could be observed at LHC (no sign so far…)

?

String theory **Q&A 30/7/20**

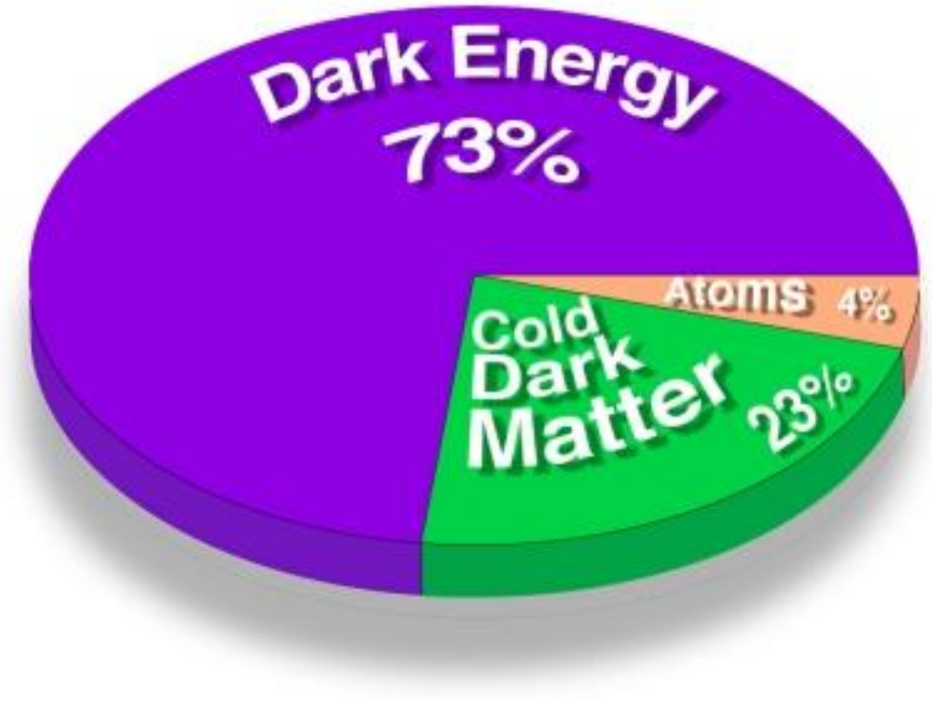
CP violation

Consistent picture in SM but can we explain matter – antimatter asymmetry of the universe?

Does the answer lie in new physics?

?

Antimatter **Q&A 20/7/20**
Flavour physics **Q&A 4/8/20**



Source: Robert Kirshner
Source: NASA/WMAP Science Team

Standard Model

Dark energy:

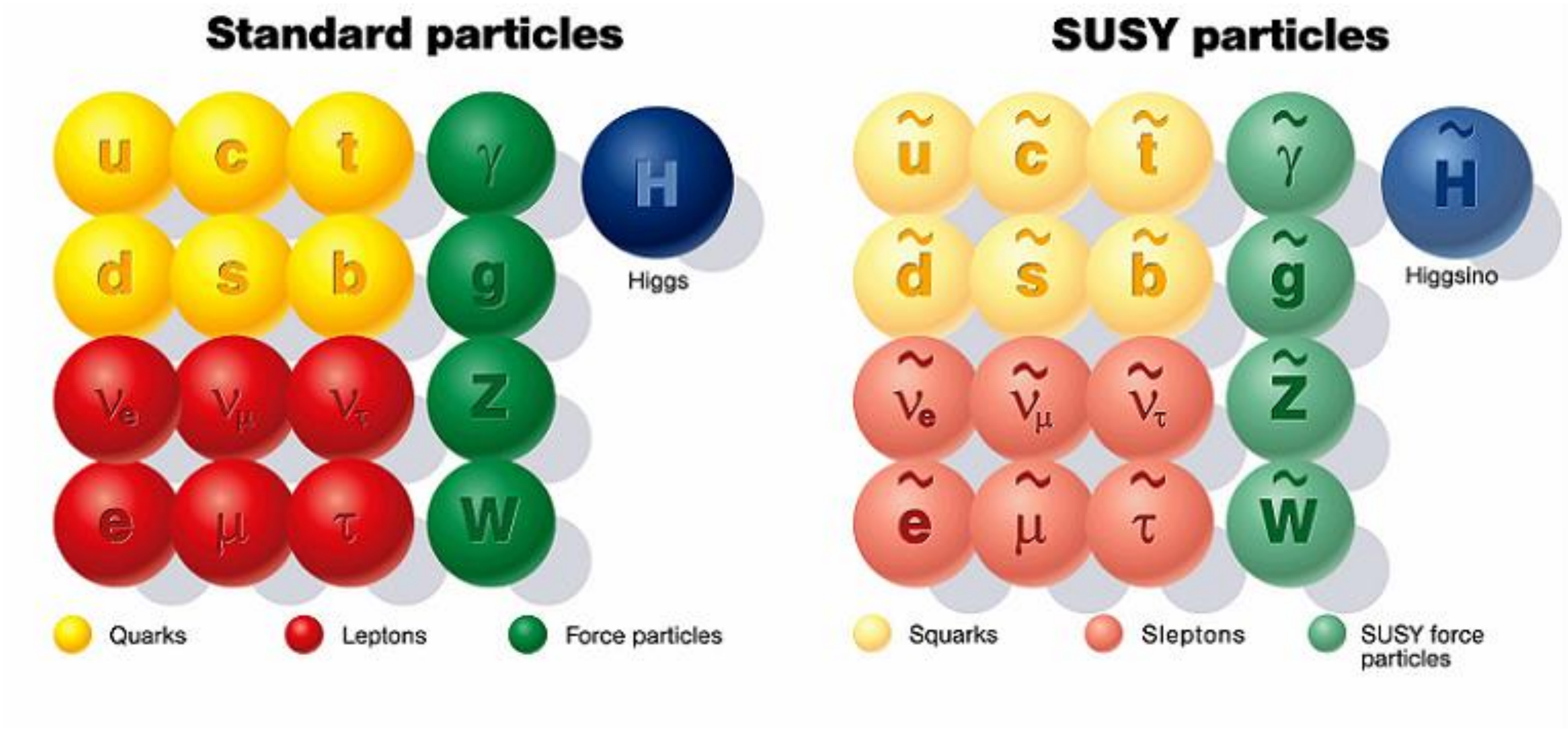
?

Dark matter?

Try Supersymmetry (SUSY).

Lightest supersymmetric particle is a dark matter candidate (massive and unobservable)

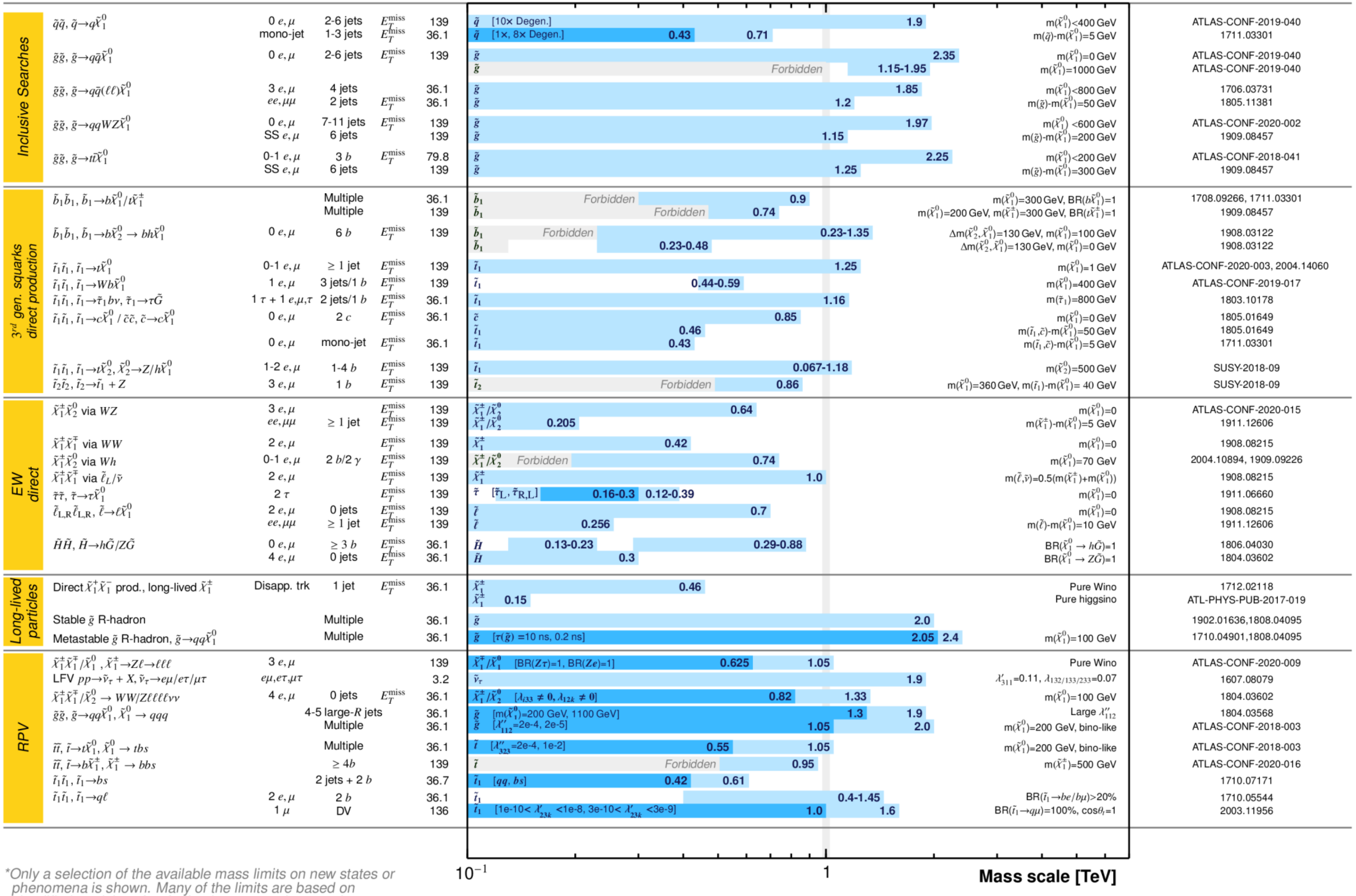
Beyond the Standard Model **Q&A 31/7/20**


Standard particles
u c t γ
d s b g
H
Higgs
ν_e ν_μ ν_τ Z
e μ τ W
Quarks
Leptons
Force particles
SUSY particles
$\tilde{u}$ $\tilde{c}$ $\tilde{t}$ $\tilde{\gamma}$
$\tilde{H}$
Higgsino
$\tilde{d}$ $\tilde{s}$ $\tilde{b}$ $\tilde{g}$
$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$ $\tilde{Z}$
$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$ $\tilde{W}$
Squarks
Sleptons
SUSY force particles

ATLAS SUSY Searches* - 95% CL Lower Limits

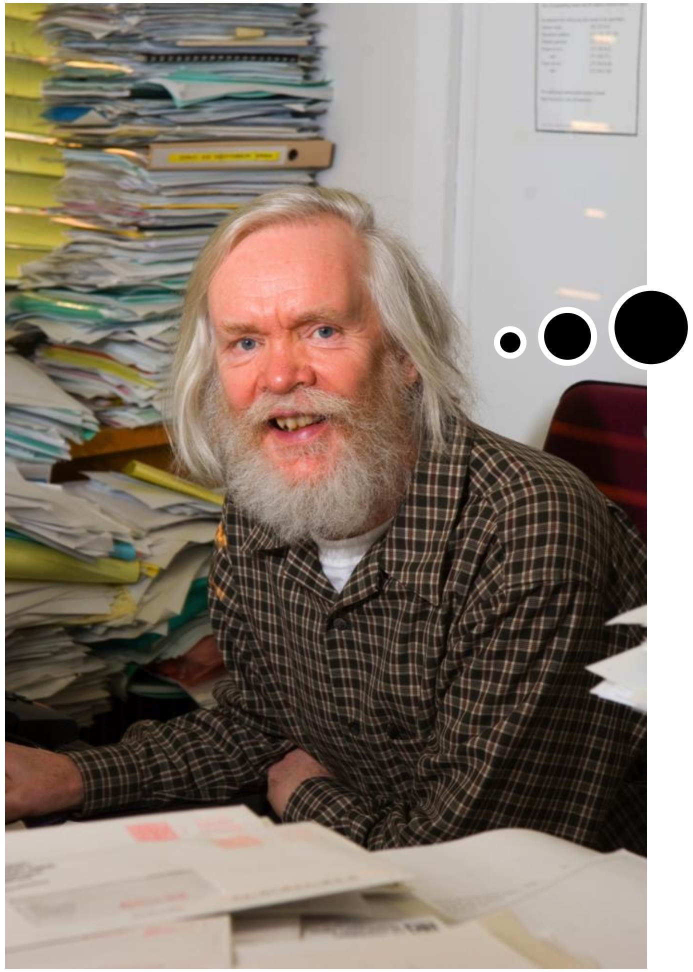
May 2020

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$	[10× Degen.] 1.9	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$	[1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$	2.35	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$	1.97	m($\tilde{\chi}_1^0$) <600 GeV	ATLAS-CONF-2020-002
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde{b}_1$	Forbidden 0.74	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1909.08457
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
						$\tilde{b}_1$	0.23-0.48	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	1908.03122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{t}_1$	1.25	m($\tilde{\chi}_1^0$)=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	0.44-0.59	m($\tilde{\chi}_1^0$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	139	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	SUSY-2018-09
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	SUSY-2018-09
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	3 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.64	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.205	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.42	m($\tilde{\chi}_1^0$)=0	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden 0.74	m($\tilde{\chi}_1^0$)=70 GeV	2004.10894, 1909.09226
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$	[$\tilde{\tau}_{\text{L}}$, $\tilde{\tau}_{\text{R,L}}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}_1^0$)=0	1911.06660
	$\tilde{\ell}_{\text{L,R}}\tilde{\ell}_{\text{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$	0.15	Pure higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901,1808.04095
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$	[BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	ATLAS-CONF-2020-009
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	[$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$	[m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$	[λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\to bbs$		$\geq 4b$		139	$\tilde{t}$	Forbidden 0.95	m($\tilde{\chi}_1^\pm$)=500 GeV	ATLAS-CONF-2020-016
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



Absence of evidence is
not necessarily
evidence of absence..

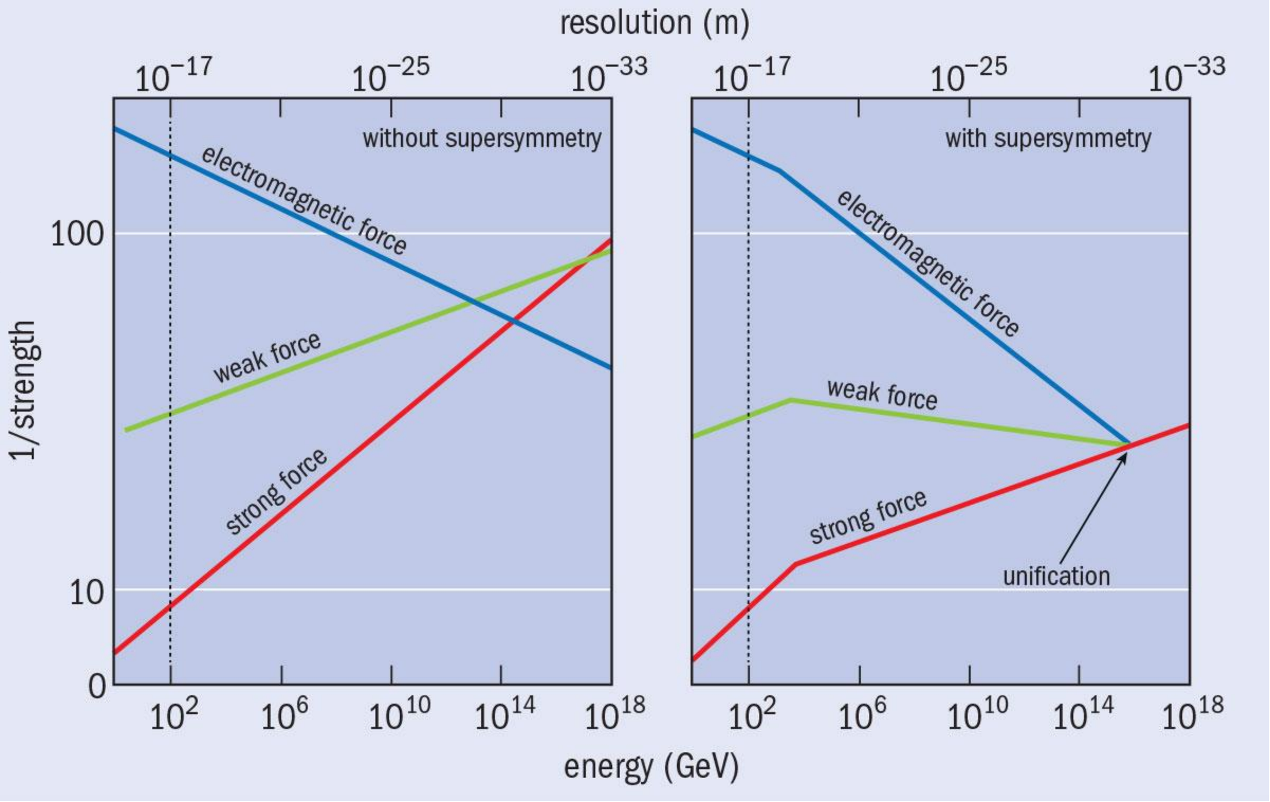
Professor John Ellis, SUSY enthusiast

What’s fundamental?

Forces
- Why so many?
- Do they unify? (SUSY?)

Particles

- Why so many?
- Why are their masses so different?



?

Conclusions

Particle physics describes the smallest structures in the Universe

Theory: the Standard Model

- Works fabulously well
- Is fabulously frustrating

Many big mysteries to solve.

(ps. Not just particle physics …. Physics and Medical Applications **Q&A 3/8/20**)