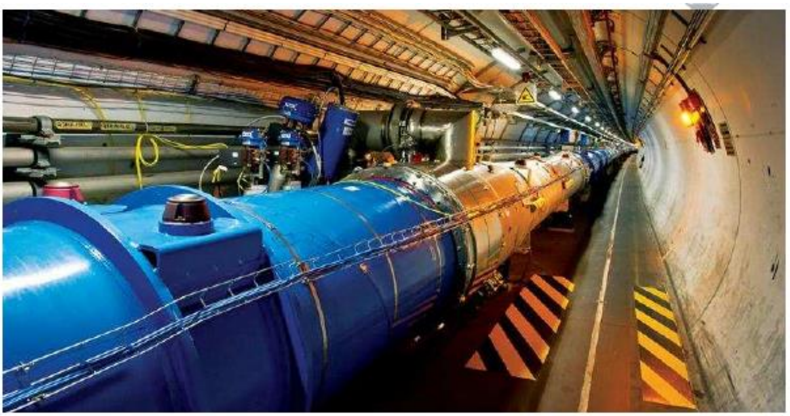
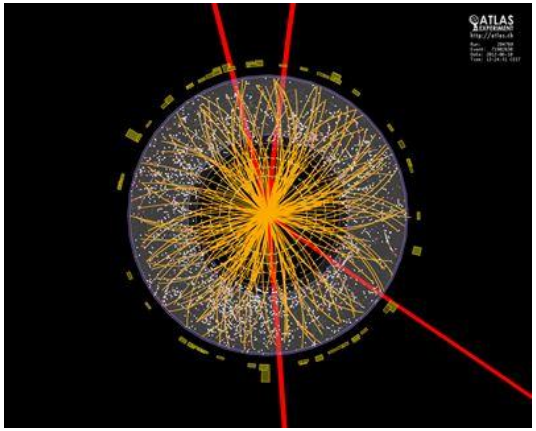
Introduction to High Energy Physics

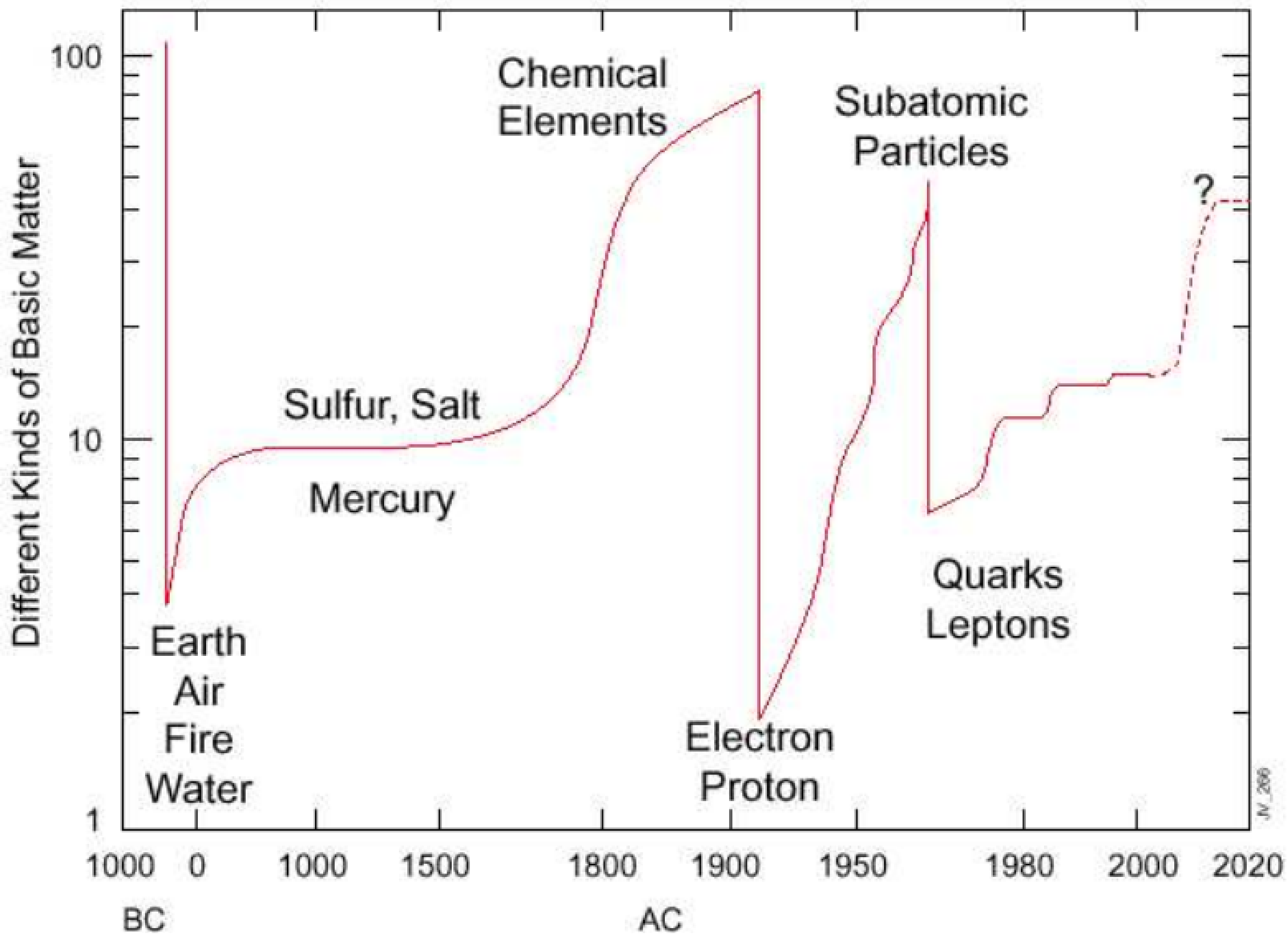
Prof. Vato Kartvelishvili



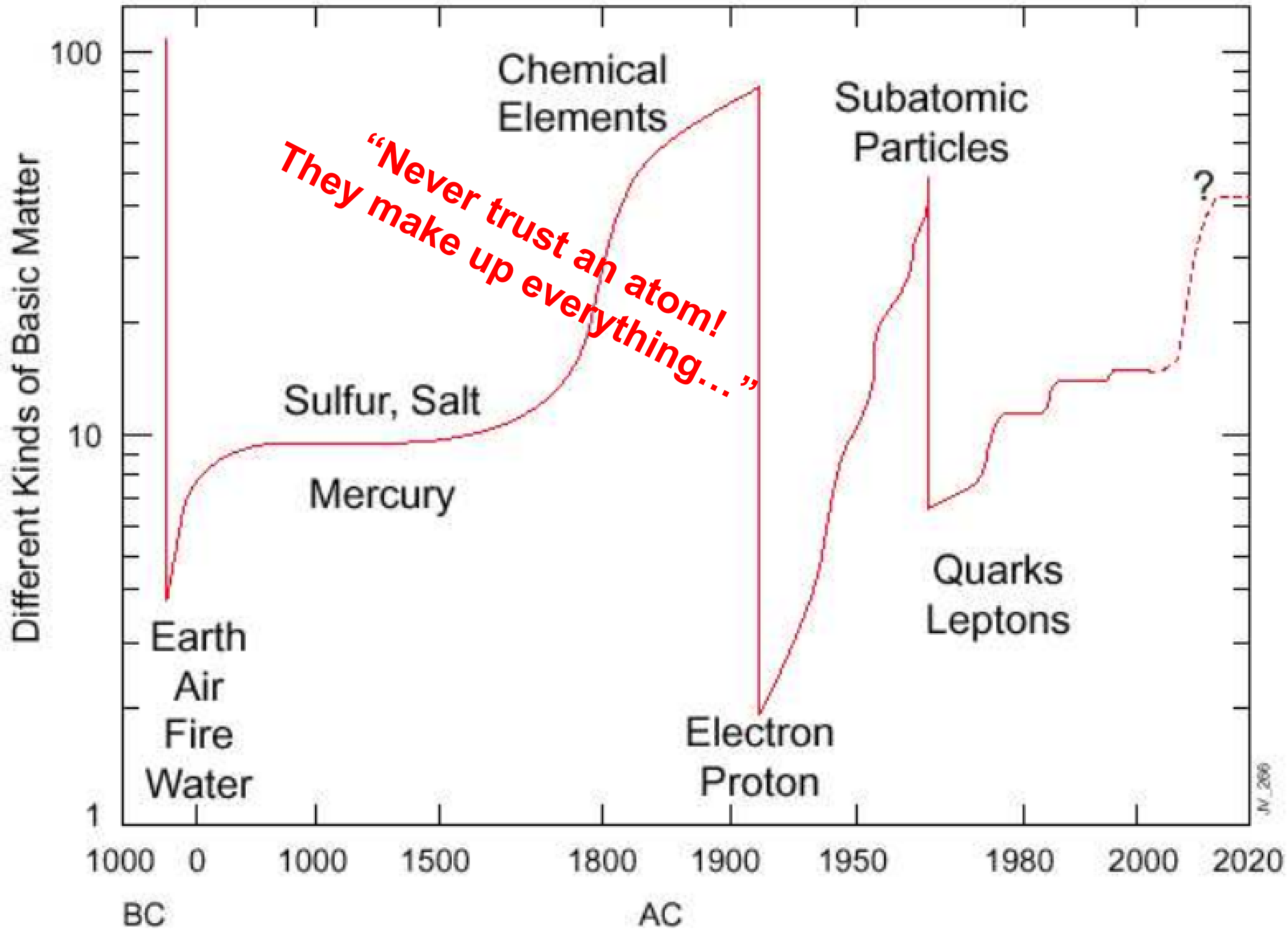
FGTSP Kutaisi
1 November 2024



Fundamental constituents of matter -- history



Fundamental constituents of matter -- history



"Never trust an atom!
They make up everything… "

Linking the mass scales

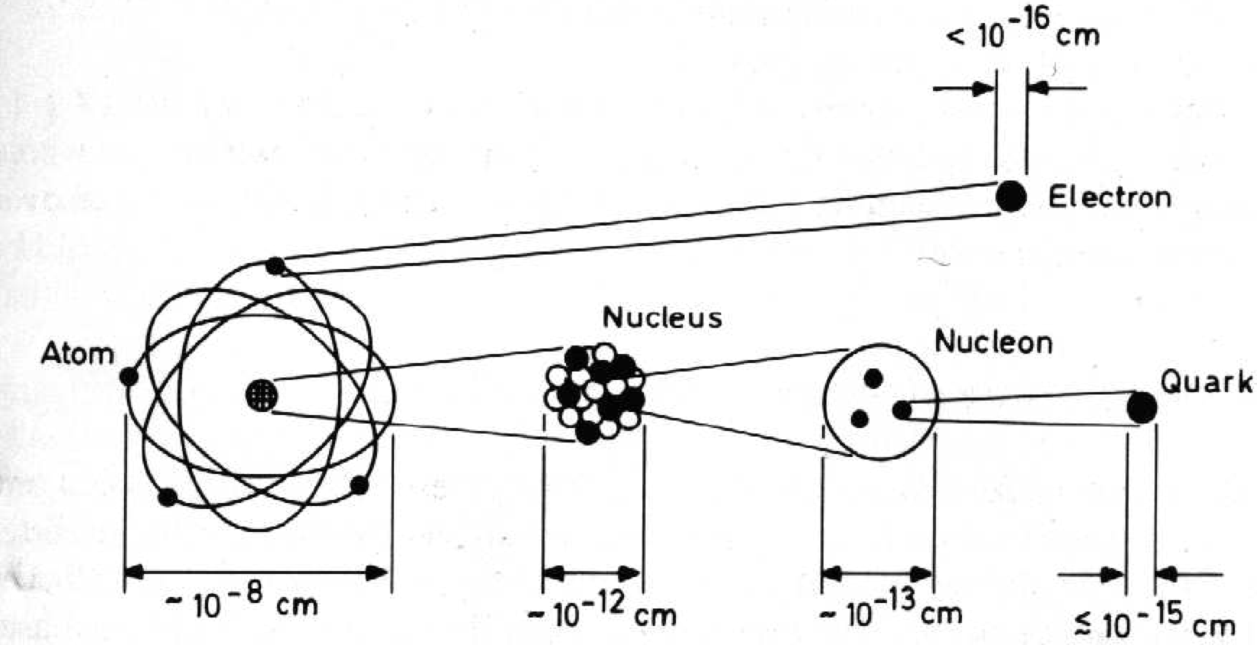
Avogadro number – link between the world of particles and your "normal" everyday world:

Any 1 gram of any matter contains 6 * 10^{23} nucleons (protons or neutrons)

That's a very large number -- 600'000 billion billion

Interactions and scales

'Elementary' Particles:
the smallest constituents
of matter (known so far):
leptons and quarks, and also
the interaction carriers:
photons γ, gluons g,
$W^{\pm}$ and Z^0 bosons.



Well-established models and theories at present exclude gravitational interactions:

1. quantum theory of gravity has not been built yet;
2. may (should!) be tied to properties of space-time at tiny scales;
3. too weak to matter for particles under 'usual' circumstances.

However, **weak, electromagnetic** and **strong** interactions are understood and described reasonably well.

Particle physics – What is it about?

‘Elementary’ Particles — $e, p, n, \nu, \mu, \tau, \gamma, W, Z \ldots$ and their interactions.

You should already know a few things about them.

Is Particle Physics a difficult subject?

Compared to other areas of physics (nuclear, solid state, bio-. . .) and other sciences (botany, chemistry, zoology, medicine) PP is actually **very simple**:

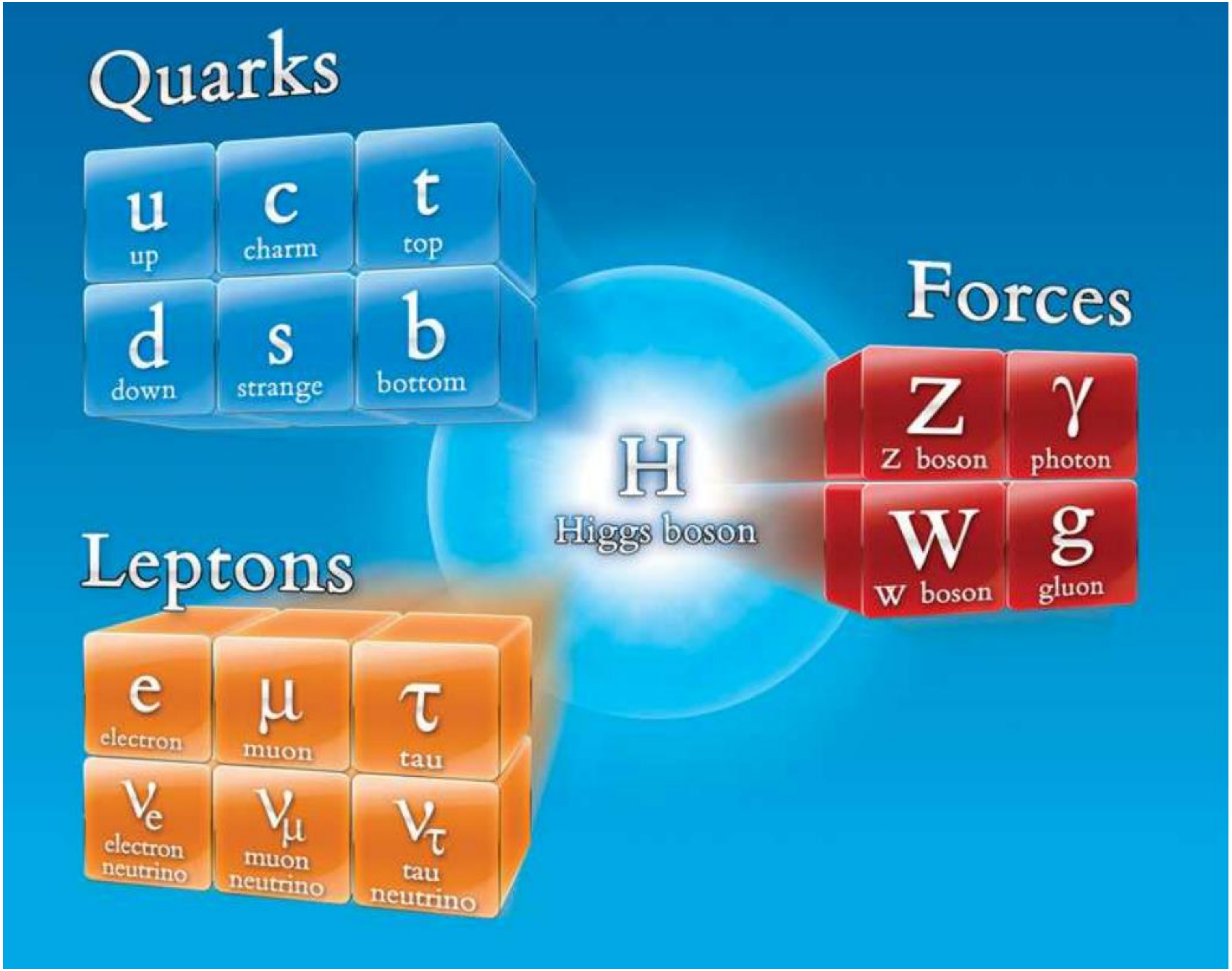
✦ Particles have (relatively) few properties (‘quantum numbers’).

✦ These properties usually have few discrete values.

✦ Particles obey very simple, relatively few, well-defined laws.

✦ All elementary particles of the same type are **absolutely identical**.

Constituents of the Standard Model



What do particle physicists do?

THEORISTS:

- come up with mathematical models which describe experimental observations better and better, starting from more and more general principles and following the maths
- calculate various measurable quantities with better and better uncertainty to confront with experimental data

EXPERIMENTALISTS:

- measure those measurable quantities with better and better precision
- look for phenomena which the theory is unable to describe

If and when there is a mismatch -- we need a bigger theory!

Is SI system of units useful in particle physics?

Main properties of particles: mass m, charge e, spin s.

For an electron in SI system:

$$\begin{aligned} m_e &= 9.109 \times 10^{-31}\ \mathrm{kg} \\ e &= -1.602 \times 10^{-19}\ \mathrm{C} \\ s_z &= \pm\hbar/2 = \pm(1/2) \times 1.055 \times 10^{-34}\ \mathrm{J \cdot s} \end{aligned}$$

Particle physicists **do not** use SI system. Instead, a particle physicist would write:

$$\begin{aligned} m_e &= 0.51\ \mathrm{MeV}/c^2 \\ e &= -1\ \text{proton charge} \\ s_z &= \pm 1/2 \end{aligned}$$

The last equation suggests: in particle physics

$$\hbar = 1.055 \times 10^{-34}\ \mathrm{J \cdot s} = 1$$

which, for one thing, states that in particle physics the product of units of [energy] and [time] is dimensionless.

Can we make things even simpler?

So, it's natural to choose units such that $\hbar = 1$. This means that

[energy] × [time] $=1$ and also [momentum] × [distance] $=1$

Now, remember the relativistic relation between Energy E, momentum $\mathbf{p}$ and mass m:

$$E^2 = \mathbf{p}^2\, c^2 + m^2\, c^4$$

Relativistic particles move with speeds close to speed of light. Carrying all these huge factors like $(300000000 \text{ m/s})^2$ around will be avoided in a system of units where $c = 1$, which simply means that [new unit of time] is [old unit of time]$/c$.

The choice $\hbar = 1$ and $c = 1$ would mean that

- Energy, momentum and mass are measured in the same units
- Angular momentum is dimensionless
- Time and distance are measured in the same units
- Energy is inverse of time
- One needs just **one** dimesional unit, which is usually chosen as the unit of energy
- In Particle Physics this is 1 GeV

Natural system of units

The system of units with $\hbar = 1$ and $c = 1$ is called the Natural system:

$$\begin{aligned} \text{1 unit of length} &= 1\ \mathrm{GeV}^{-1} \simeq 0.1978\ \mathrm{fm} \\ \text{1 unit of time} &= 1\ \mathrm{GeV}^{-1} \simeq 0.6588 \cdot 10^{-24}\ \mathrm{s} \\ \text{1 unit of energy} &= 1\ \mathrm{GeV} \\ \text{1 unit of momentum} &= 1\ \mathrm{GeV} \qquad \text{sometimes } \mathrm{GeV}/c \\ \text{1 unit of mass} &= 1\ \mathrm{GeV} \qquad \text{sometimes } \mathrm{GeV}/c^2 \end{aligned}$$

Note: 1 GeV = 1000 MeV and $(1\ \mathrm{GeV})^{-1} = (1000\ \mathrm{MeV})^{-1}$, but $1000\ \mathrm{GeV}^{-1} = 1\ \mathrm{MeV}^{-1}$

One more unit: **barn b** for cross section: $1\ \mathrm{b} = 10^{-24}\ \mathrm{cm}^2$.

One barn is far too big a unit for particle physics:

$$1\ \mathrm{b} = 10^3\ \mathrm{mb} = 10^6\ \mu\mathrm{b} = 10^9\ \mathrm{nb} = 10^{12}\ \mathrm{pb} = 10^{15}\ \mathrm{fb}$$

The cross sections of most interesting processes in particle physics are usually measured in femtobarns fb.

Rare processes have smaller cross sections, and vice-versa.

Collisions – the way to go!

One way to study particle properties is to collide them

Even in bird-watching, there are collisions involved:

- Photons (particles of light) from the Sun collide with the bird and get scattered, some of those scattered photons get into your eyes

- After all, a photon is just another type of an elementary particle!

We collide particles and observe what happens, trying to make sense of the results

Naked eyes are not fast or sensitive or versatile enough –- we need sophisticated detectors

Large Hadron Collider at CERN

Birdseye view of CERN and neighbourhood

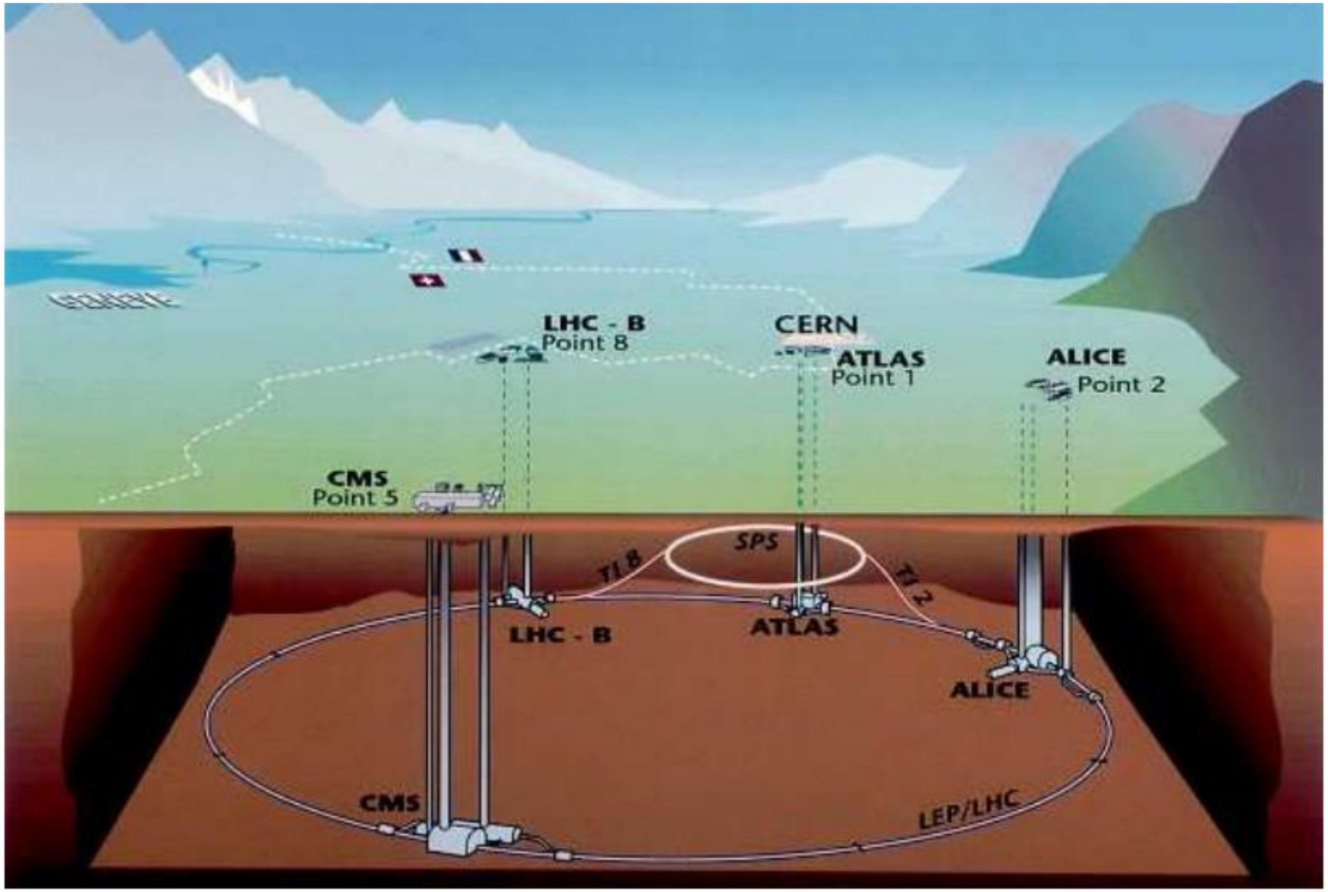
Alps, lake Geneva, Geneva airport

LHC ring shown as the red line

Schematic view – not to scale!

LHC is the flagship of CERN research programme, colliding two proton beams with energy of up to 14 TeV

One of the largest and most complicated engineering constructions in human history



Two multi-purpose experiments: ATLAS and CMS

Others – such as LHCb and ALICE – are more specialised

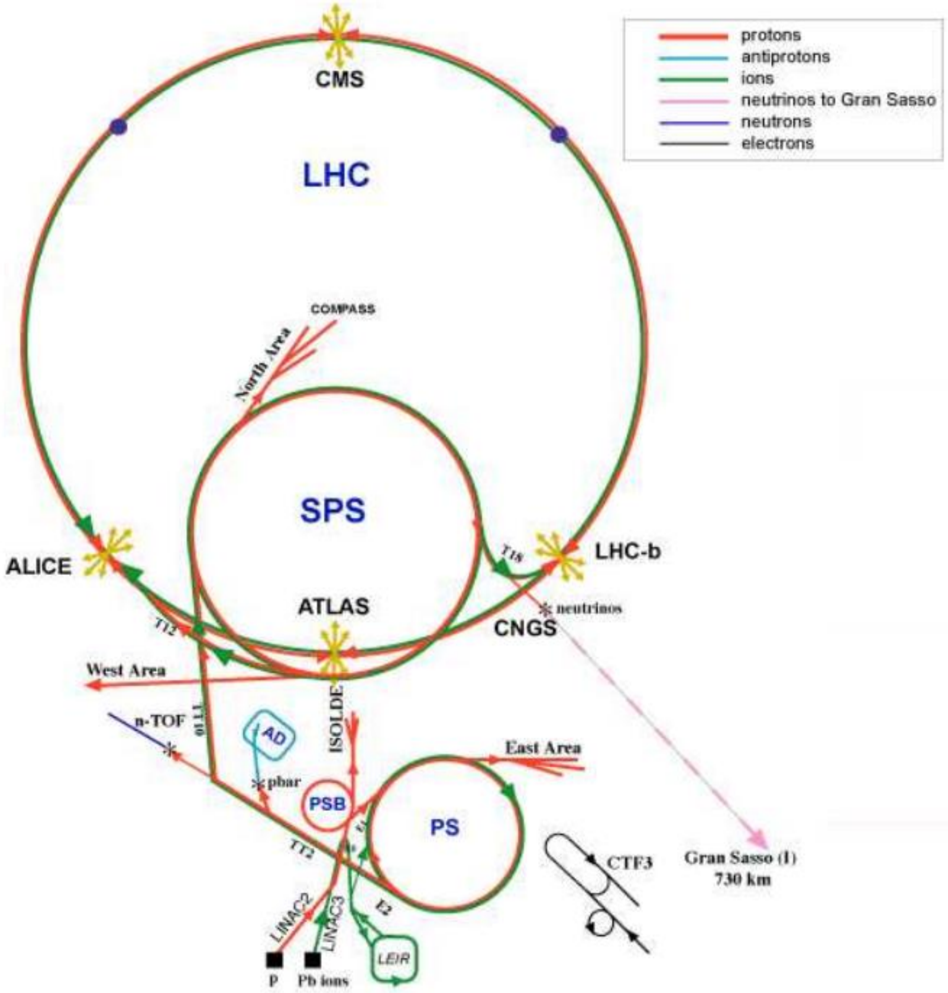
CERN accelerator complex

A very long chain of accelerators, culminating in the Large Hadron Collider (LHC)

Producing beams of protons, ions, antiprotons. . . even neutrinos!

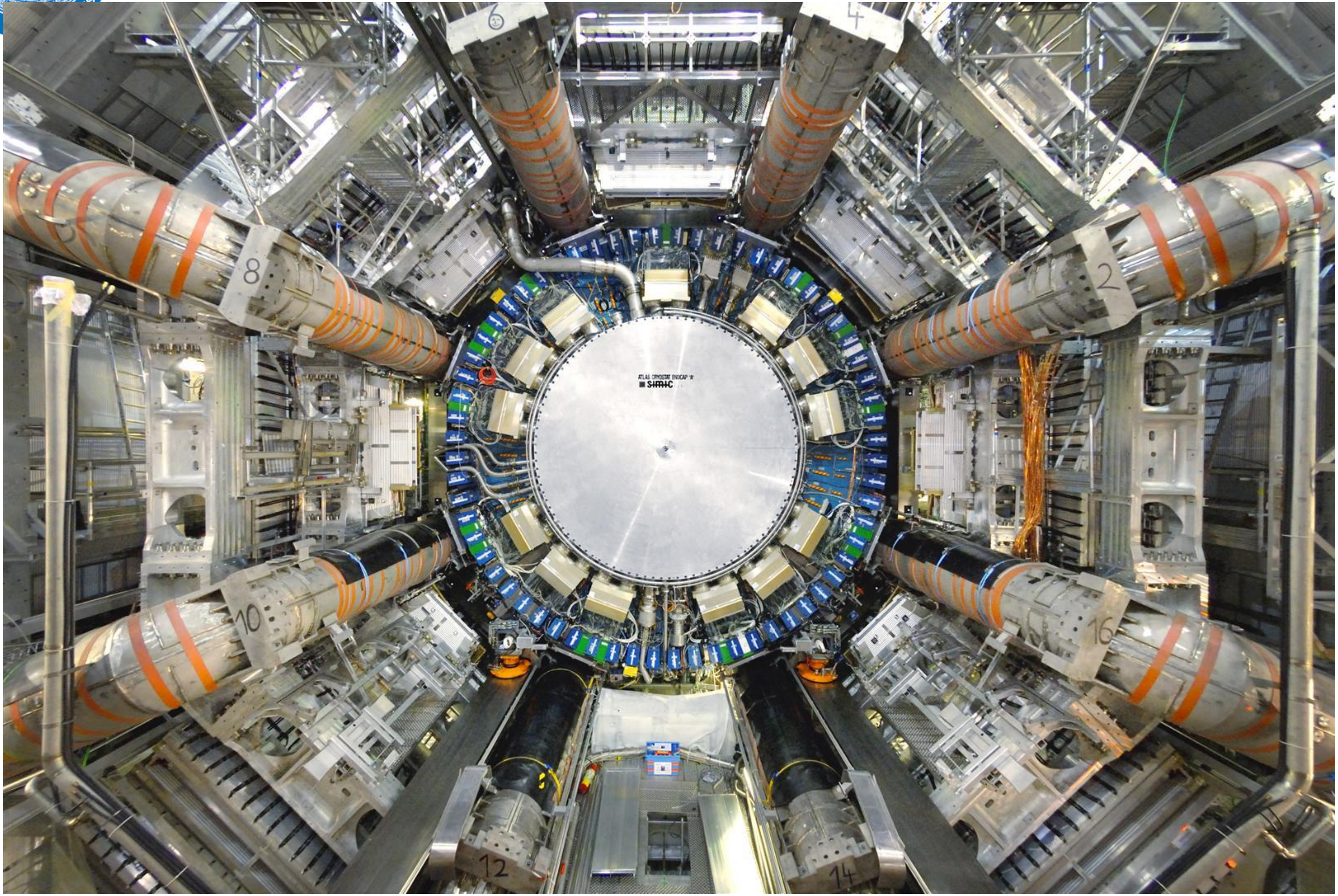
Lots of experiments, all very interesting and important

I will only touch the one I know better. . .



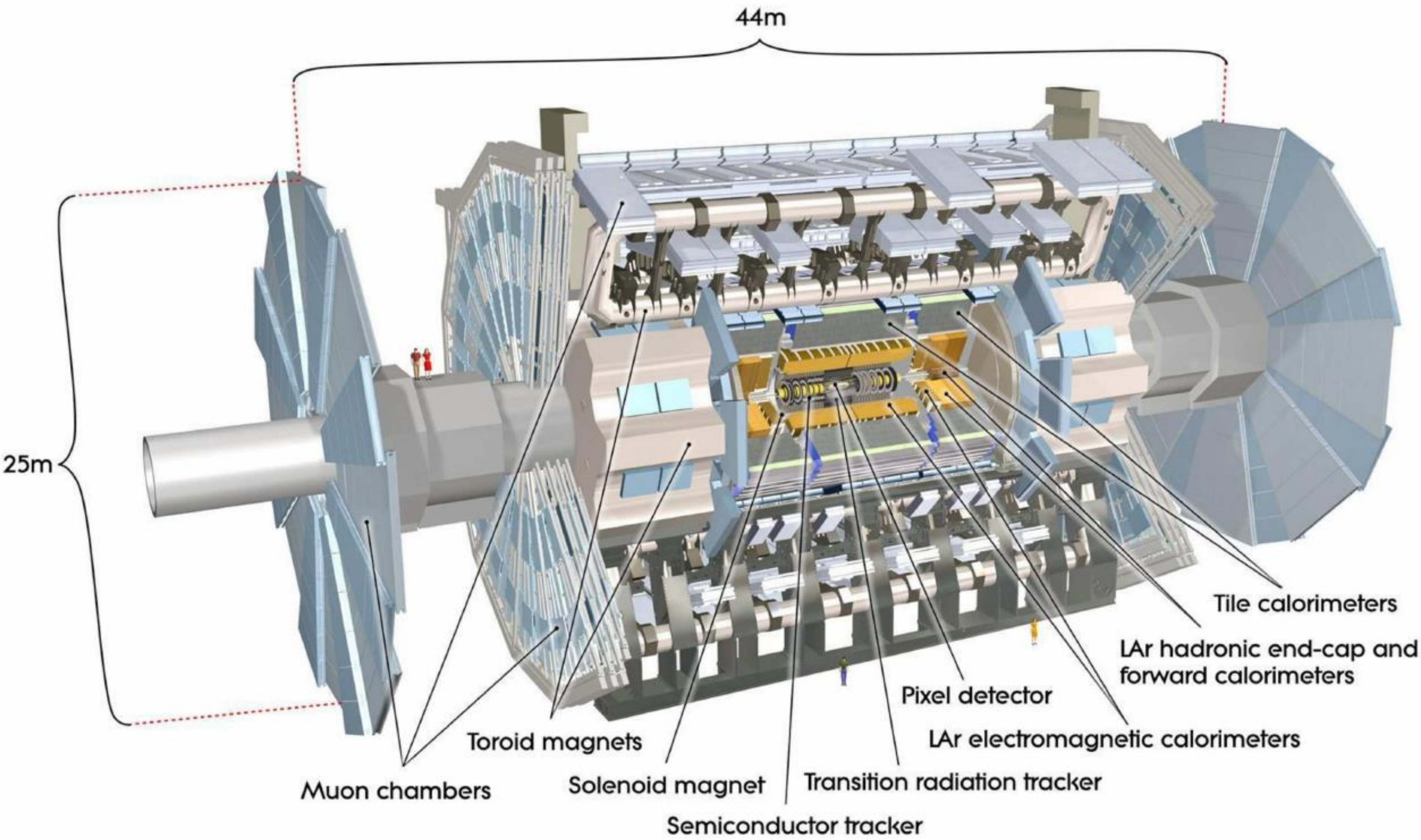
CNGS	CERN neutrino to Le Gran Sasso	**PSB**	proton synchrotron booster
AD	antiproton decelerator	**ISOLDE**	on line isotope mass separator
PS	proton synchrotron	**LEIR**	low energy ion ring

ATLAS detector – insider view



Geography of ATLAS collaboration

ATLAS detector – schematic view



Are proton-proton collisions weird?

Collide two oranges at low energy – you get two oranges

At higher energies they will get squashed, some pulp, some juice…

You will never get any cherries, apricots, apples, or water-melons

Collide two protons at low energy – you get two scattered protons

At higher energies, you will still always get two pristine protons – and often a lot of other stuff: pions, kaons, Z and W bosons, top-antitop quark pairs, and an occasional Higgs boson…

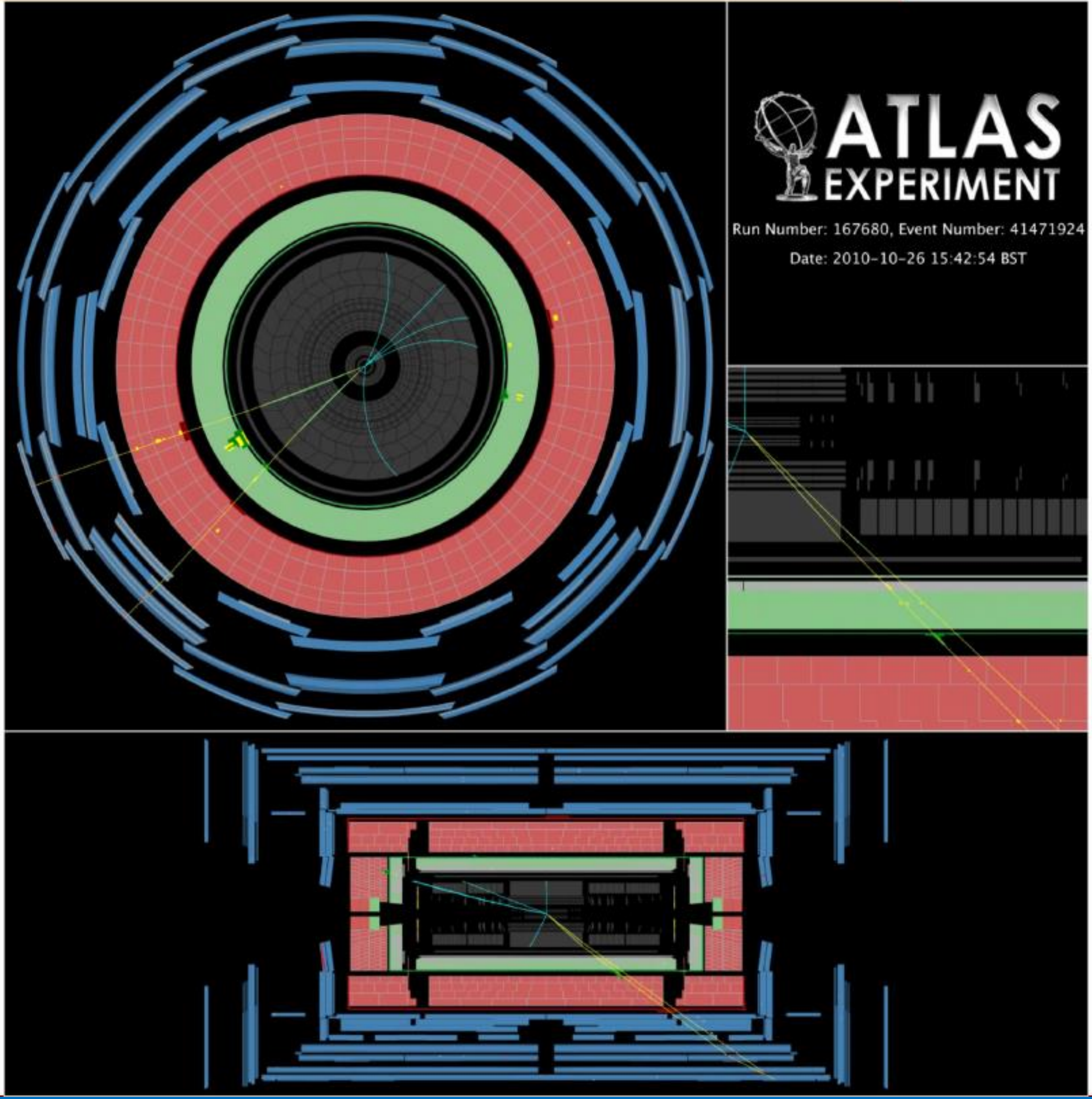
ATLAS event display: $\chi_c \rightarrow J/\psi(\mu^+\mu^-)\,\gamma$ candidate

Cross section views perpendicular and parallel to the beam line

Two muon tracks spanning the Inner Detector and the Muon System

A photon tower in Eclectromagnetic Calorimeter

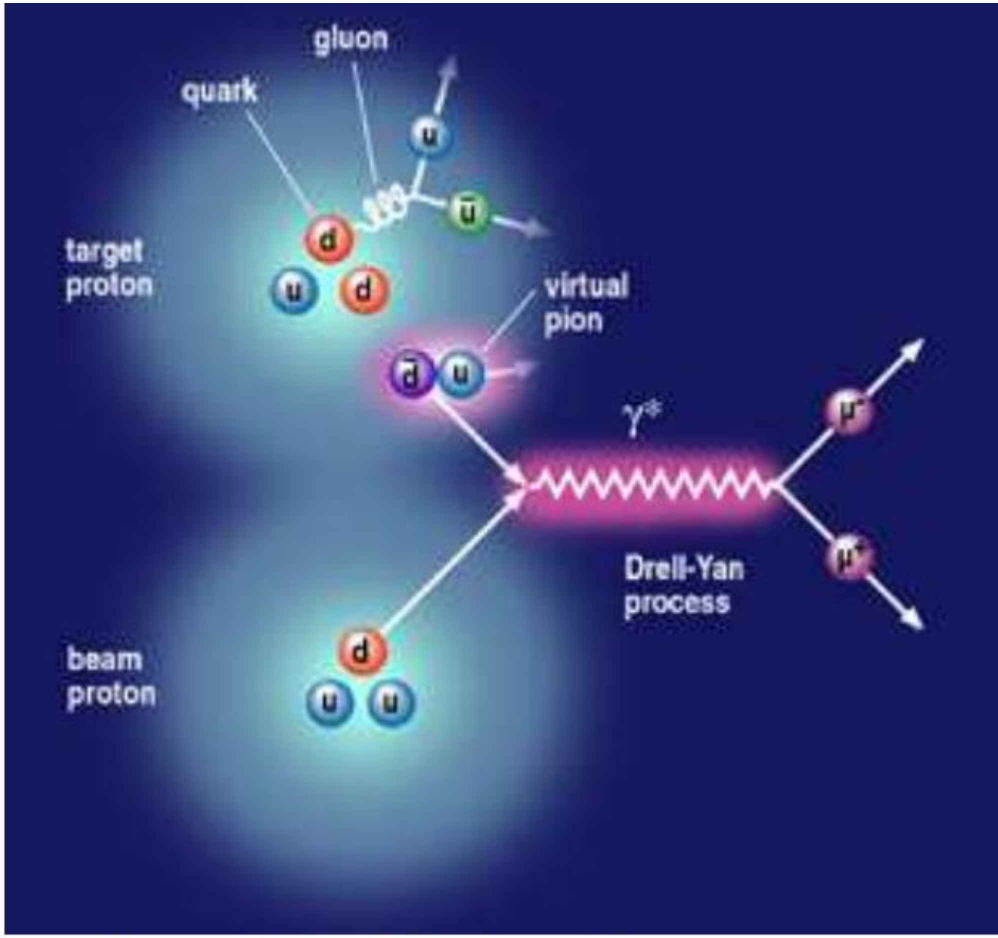
Invariant mass in the χ_c region



Are we really colliding protons?

Protons are composite – consist of quarks gluons and even some antiquarks

Here a quark and an antiquark collide to create a muon-antimuon pair



High energy of constituents is needed to produce something new and interesting

A proton is a bunch of quarks and gluons, each carrying a fraction of energy

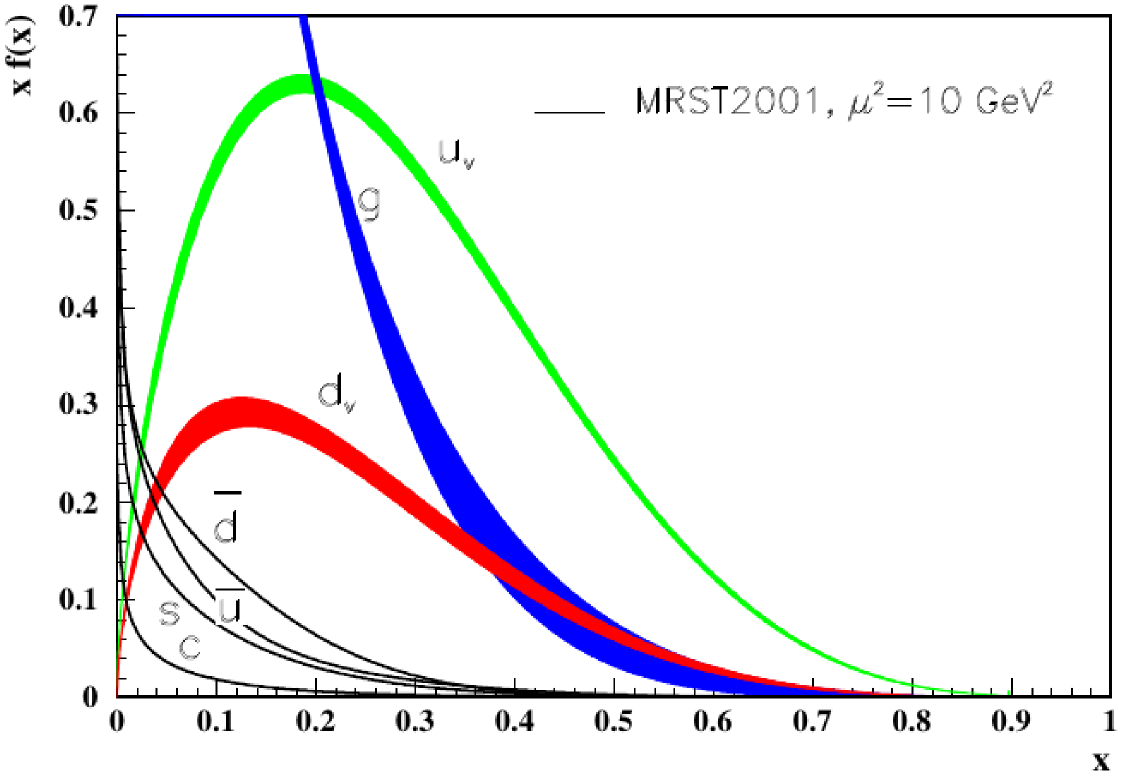
14 TeV of pp collision energy barely enough to produce a 2 TeV object. . .

Quarks and gluons inside a proton

Only 30% of proton energy is carried by the three constituent uud quarks

Most of proton energy is carried by gluons

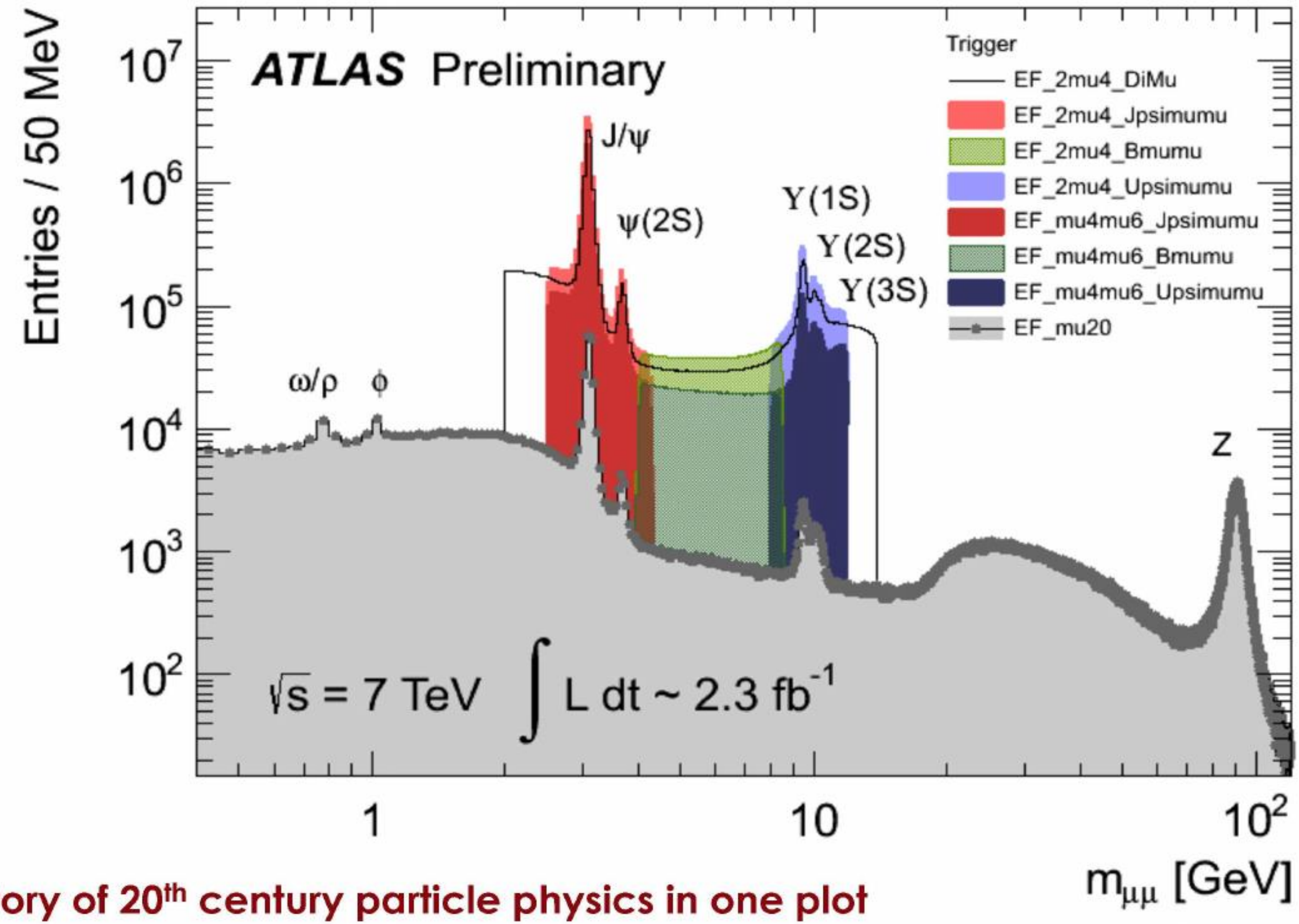
The “sea” of quark-antiquark pairs is also important



$$M^2 = x_1 \times x_2 \times (13\ TeV)^2$$

$$d\sigma \sim f_1(x_1) \times f_2(x_2) \times \hat{\sigma}(M^2)$$

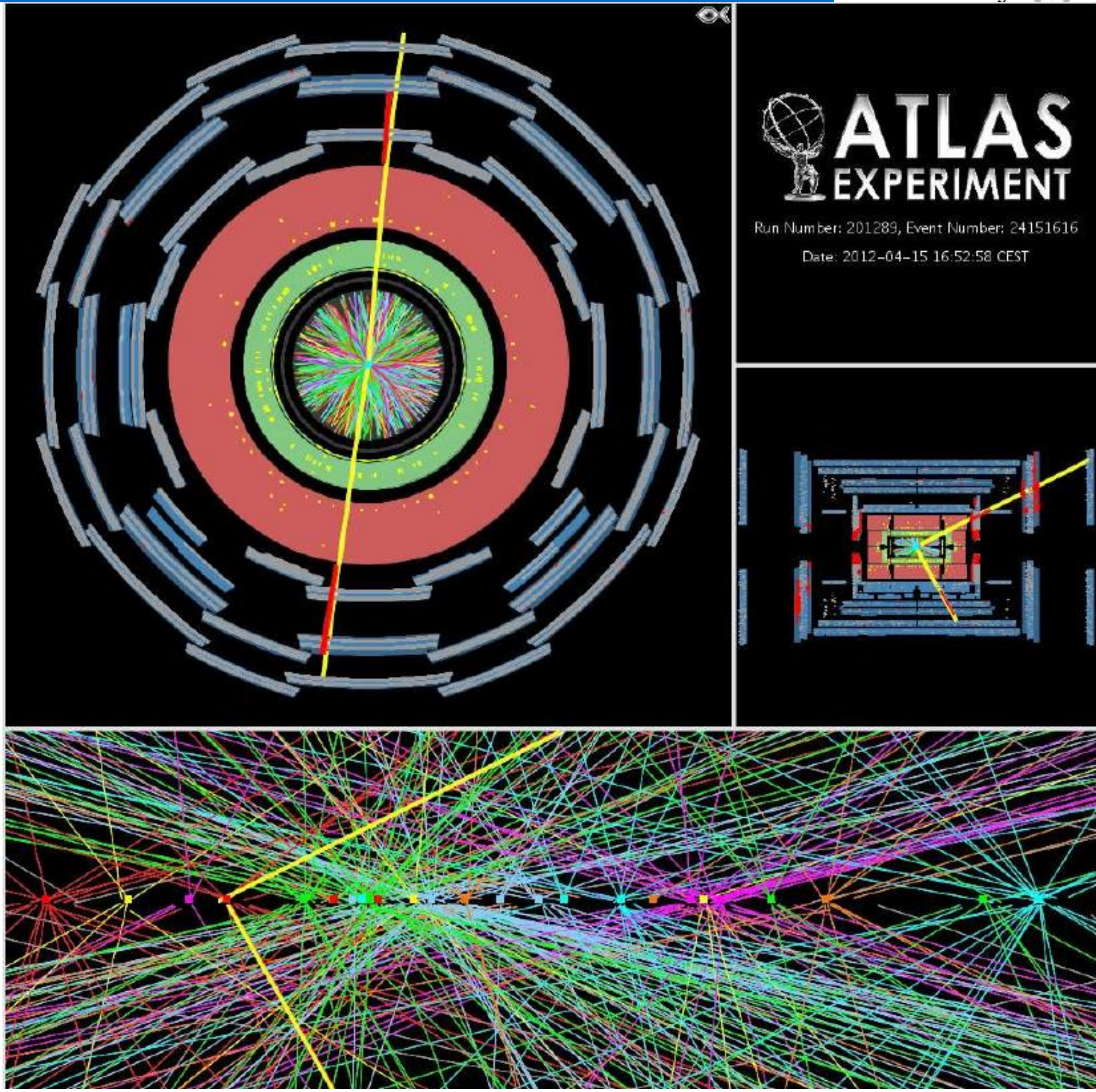
Resonances in dimuon system



History of 20th century particle physics in one plot

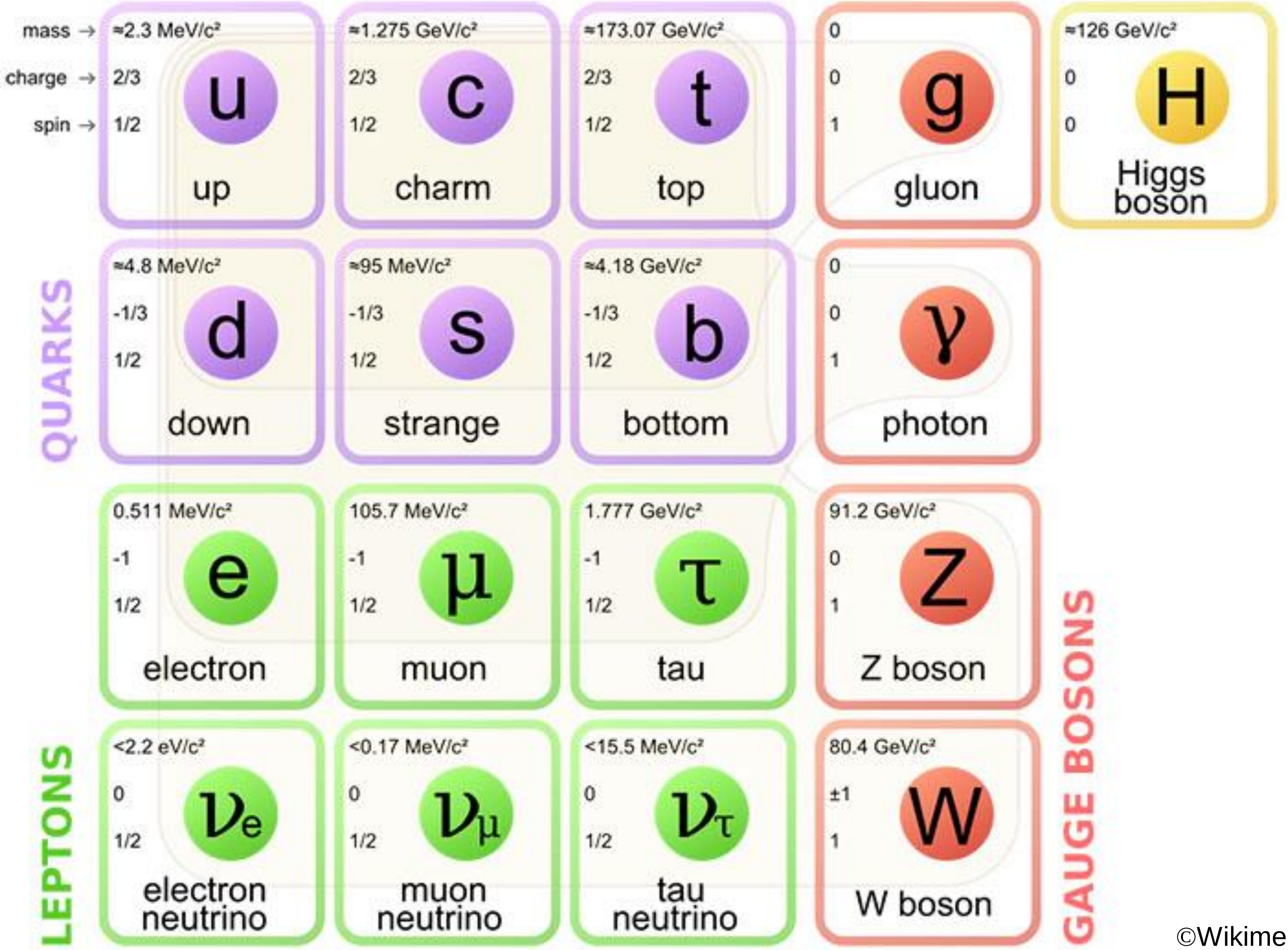
Z boson production candidate

There are 20+ collisions
in one bunch crossing,
with a $Z \rightarrow \mu^+\mu^-$ candidate
produced in one of them.



CERN overview video

Fundamental constituents of the Standard Model



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	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	91.2 GeV/c^2 0 1 Z Z boson	
	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

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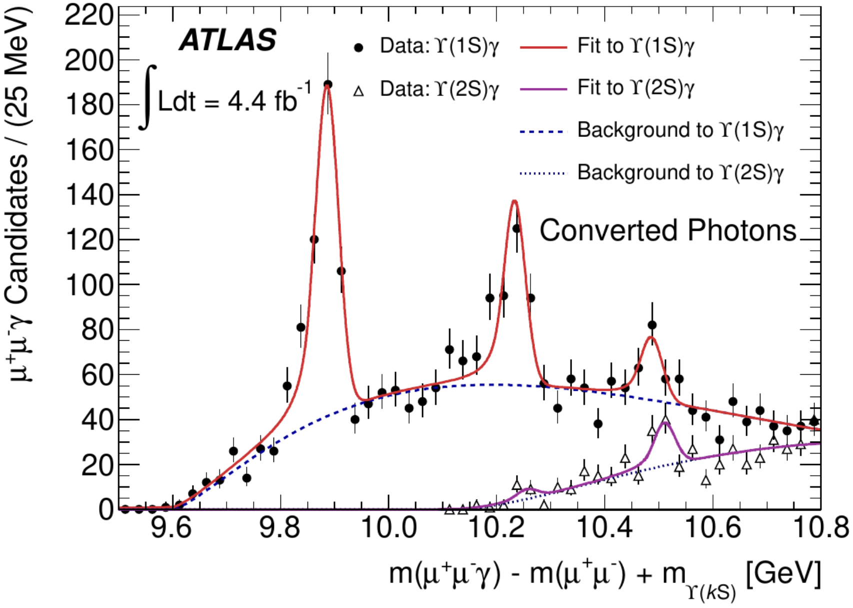
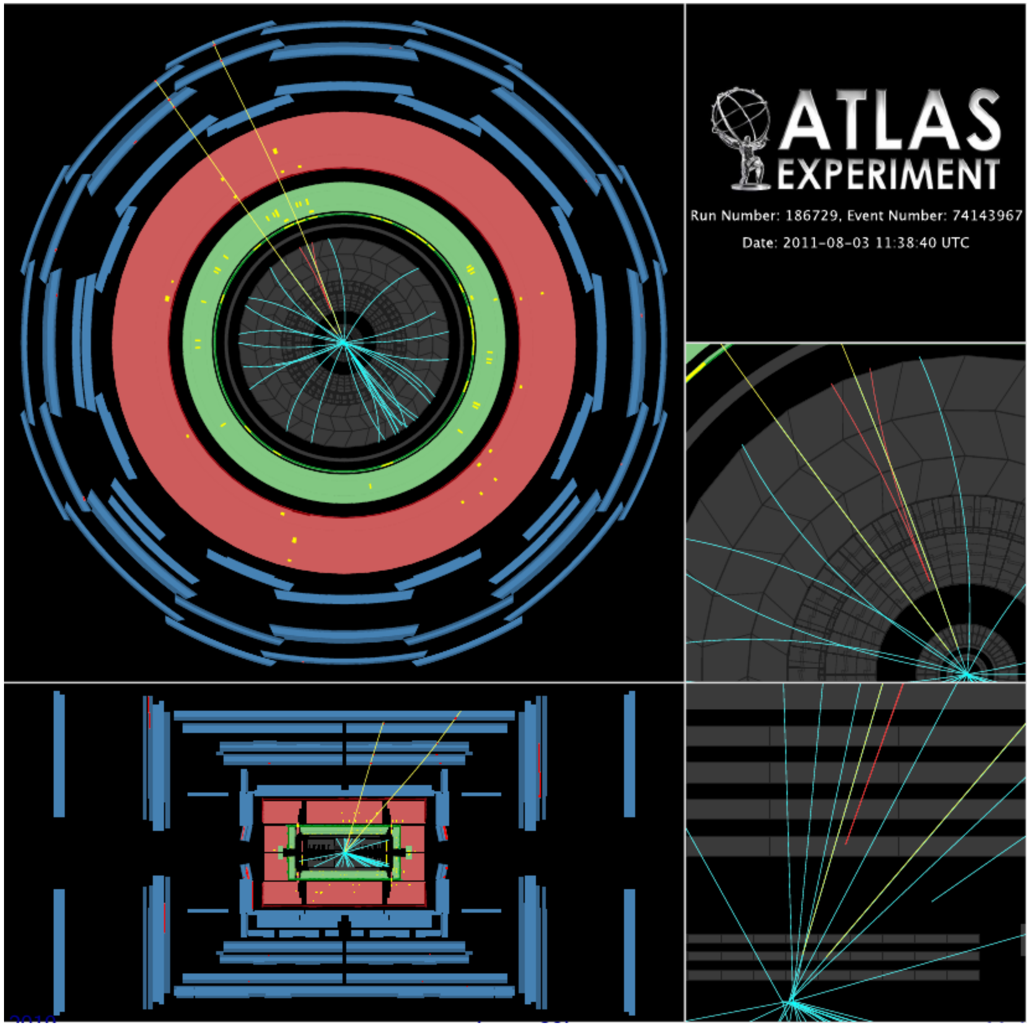
First LHC discovery -- $\chi_b(3P)$

Excited bound state of a b quark and a b antiquark

Discovered by our group at Lancaster





Media reaction back in 2011

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22 December 2011 Last updated at 10:59

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LHC reports discovery of its first new particle

By Jonathan Amos
Science correspondent, BBC News

The Large Hadron Collider (LHC) on the Franco-Swiss border has made its first clear observation of a new particle since opening in 2009.

It is called Chi_b (3P) and will help scientists understand better the forces that hold matter together.

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Large Hadron Collider has first confirmed sighting of new particle (but it's not the Higgs)

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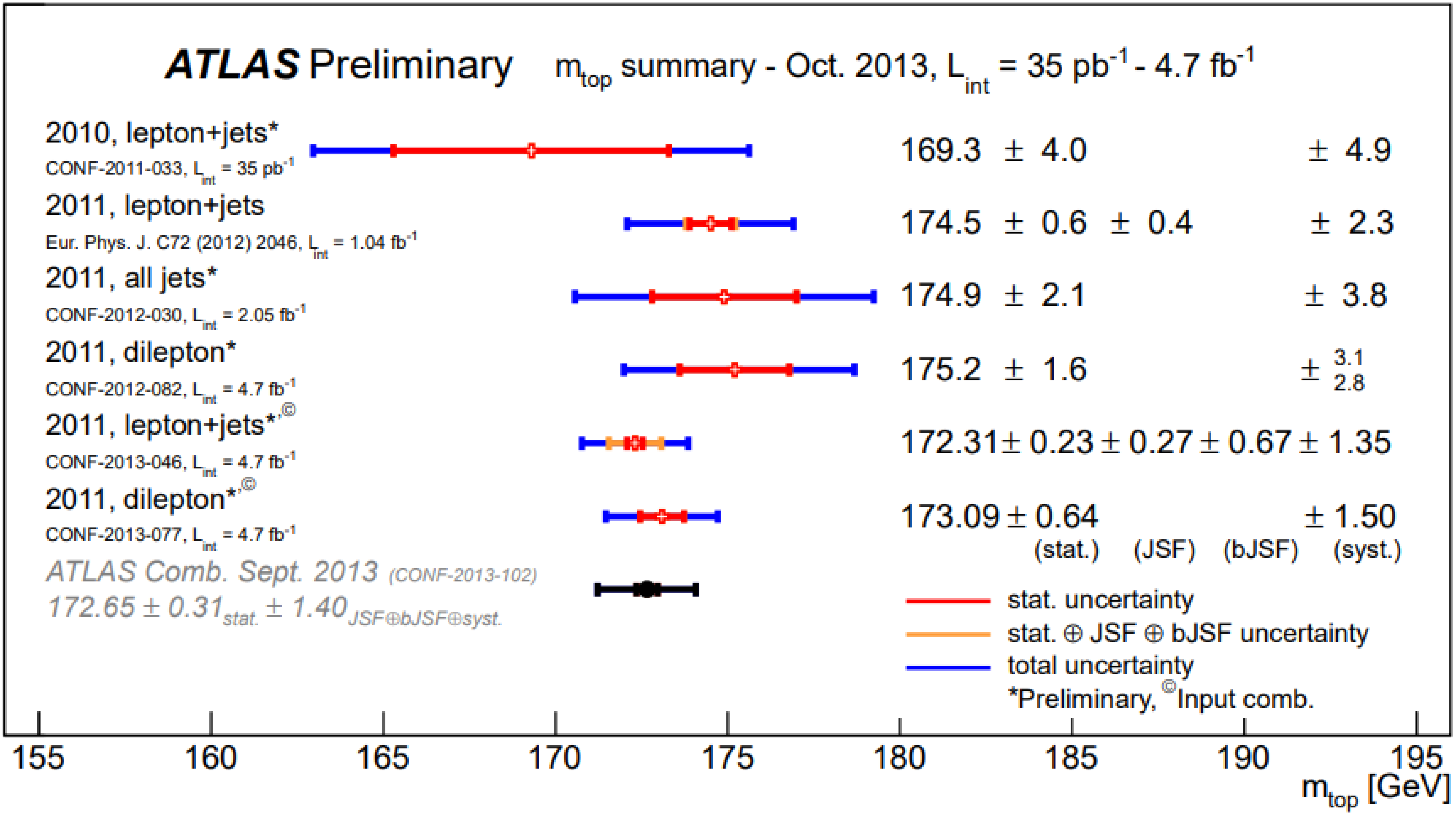
SCIENCE

Large Hadron Collider discovers a new particle: the Chi-b(3P)

By Mark Brown | 22 December 11

Phys.Rev.Lett. 108 (2012) 152001

Top quark mass measurement progress



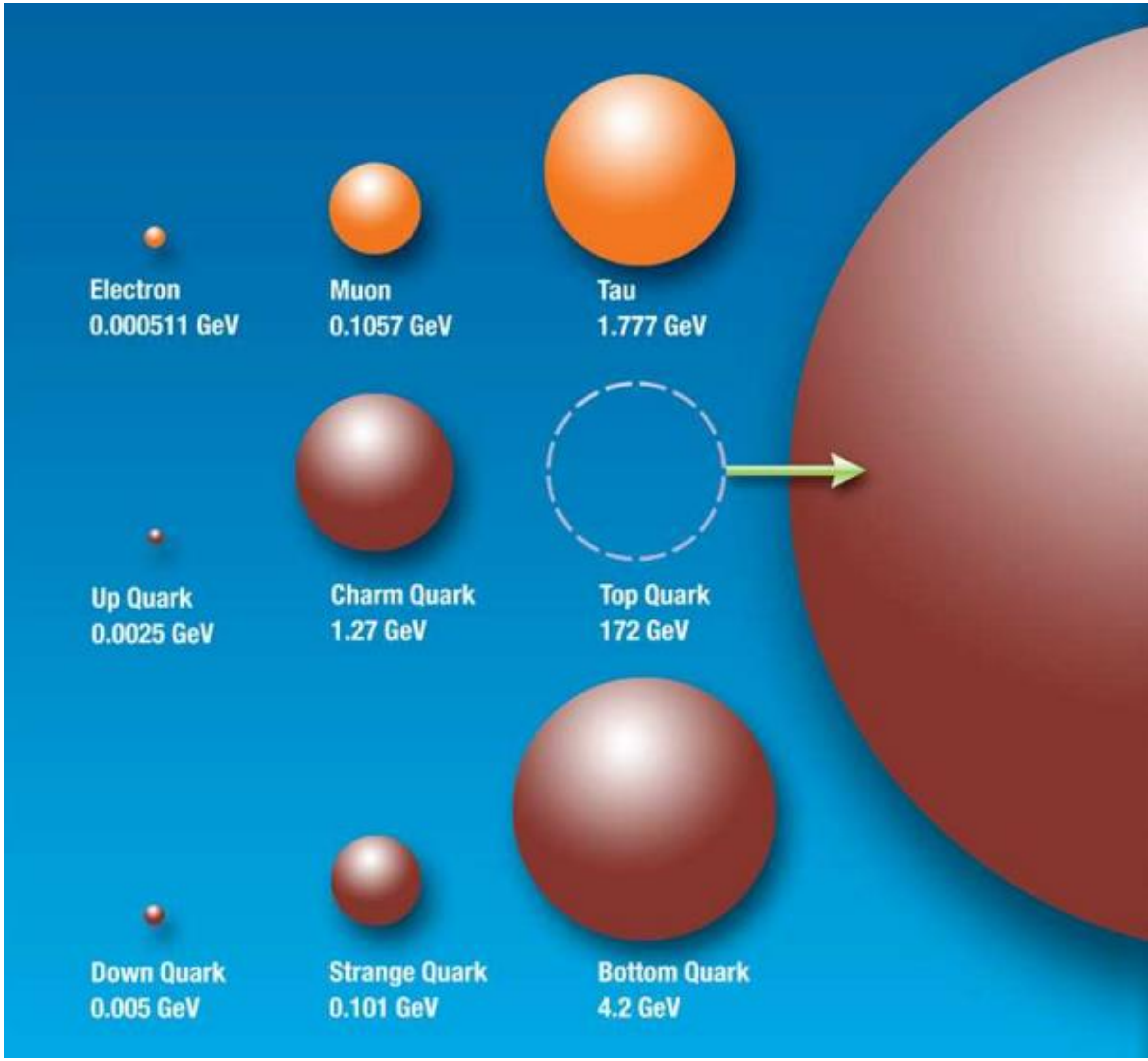
Generations and masses

Three “generations of fermions

Each is much heavier than the previous

The top quark is especially heavy

Nobody really knows why…



Physical theories: how things work

The development cycle of physical theories:

1. Find (or create!) a mathematical concept/model/theory which has the appropriate structure and properties relevant to your area of physics.
2. Formulate your problem in terms of this mathematical theory.
3. Solve the mathematical problem (nothing to do with physics whatsoever!)
4. Try to understand and interpret the solution.
5. If/when this solution becomes unsatisfactory (new data, higher precision), go to 1.

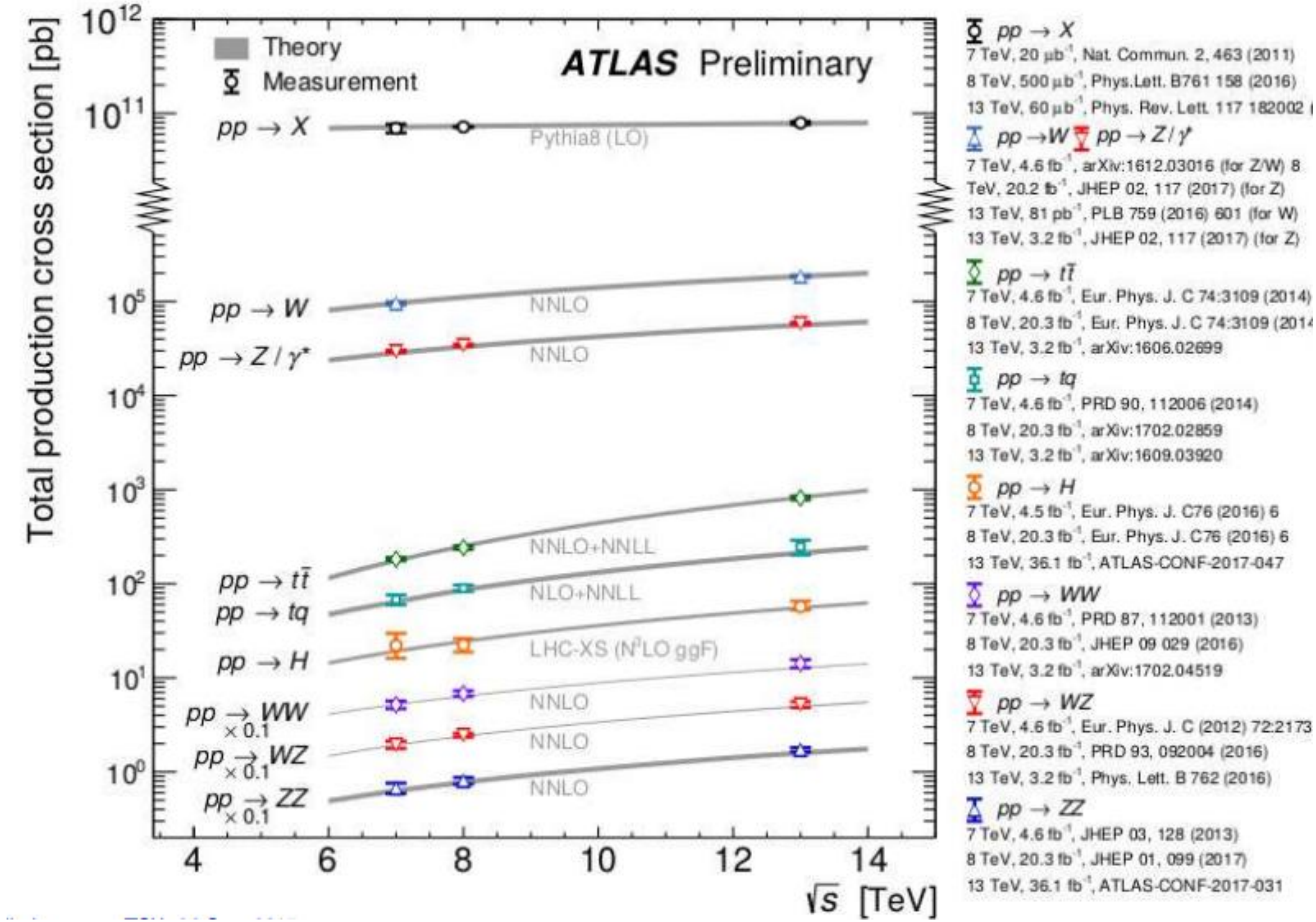
History of physics knows many examples illustrating this cycle (Newton, Shrödinger, Bohr, Heisenberg, Einstein, Dirac, Feynman. . .)

With the Standard Model of elementary particles, we are somewhere at point 4, in search for 5. . .

A big chunk of step 1 in many areas of physics is the Group Theory (sometimes well-hidden!)

Lesson to learn: Do the math first, think later!

SM predictions versus experiment



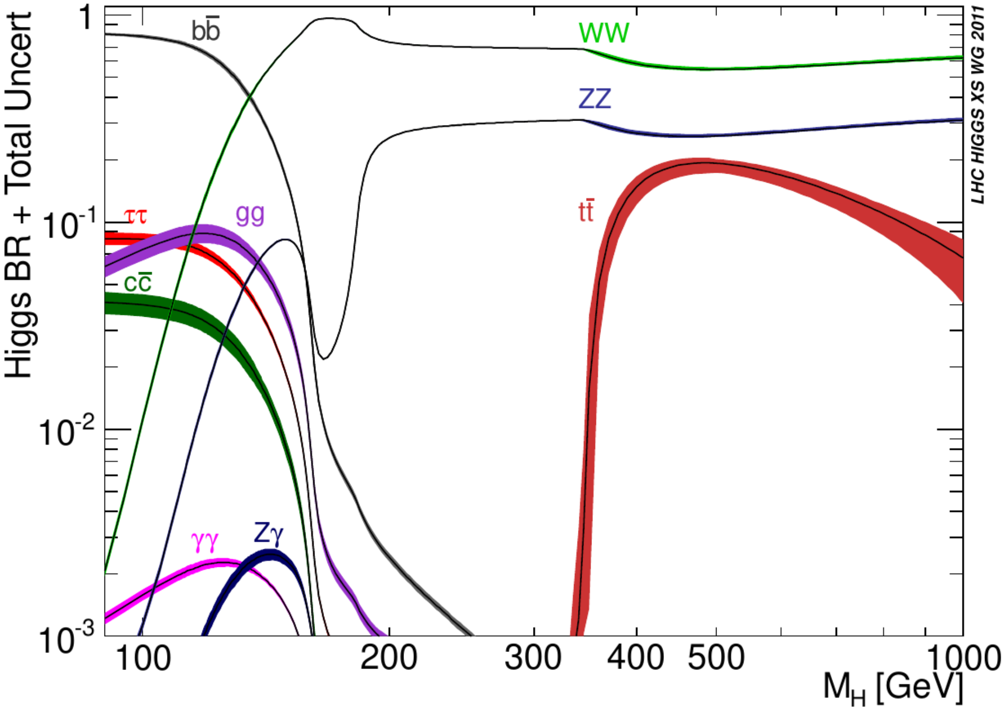
Properties of the Higgs boson

Introduced by theorists well before you were born – to make the Standard Model much more appealing mathematically

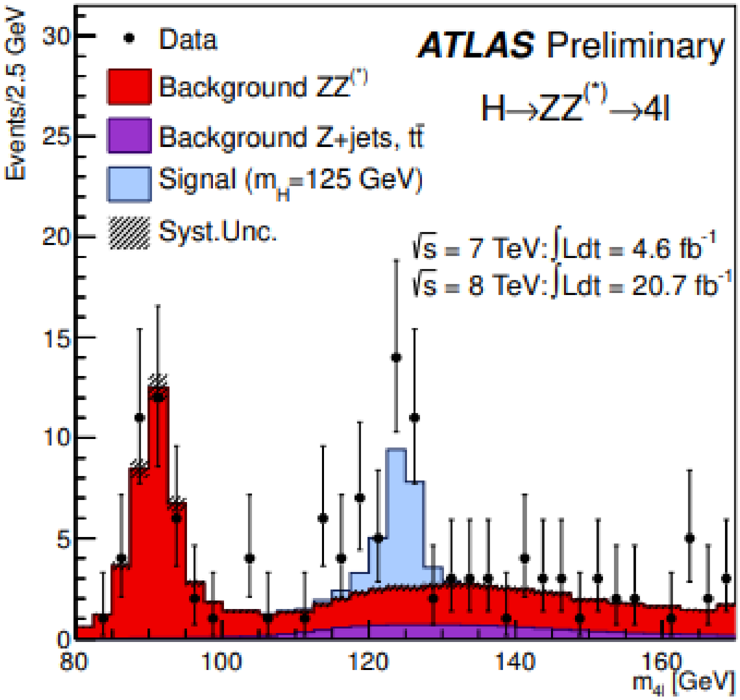
Rock-solid predictions for all its properties – except the mass…

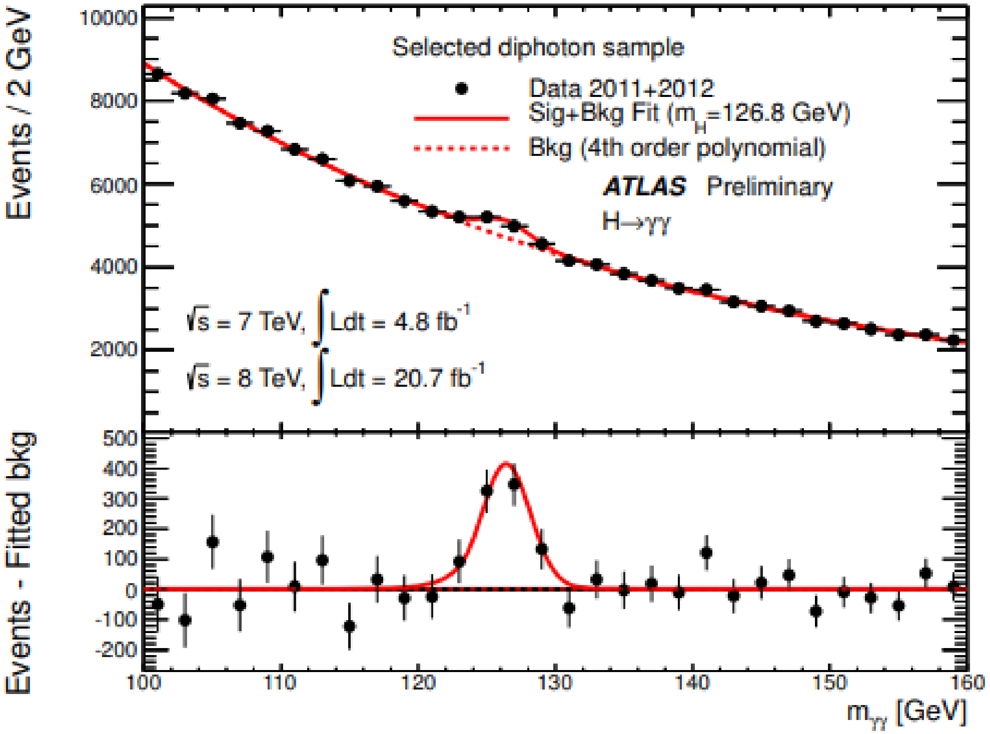
It took almost 50 years – and construction of the LHC and its two general-purpose detectors, ATLAS and CMS, to discover…

… in the most interesting place!

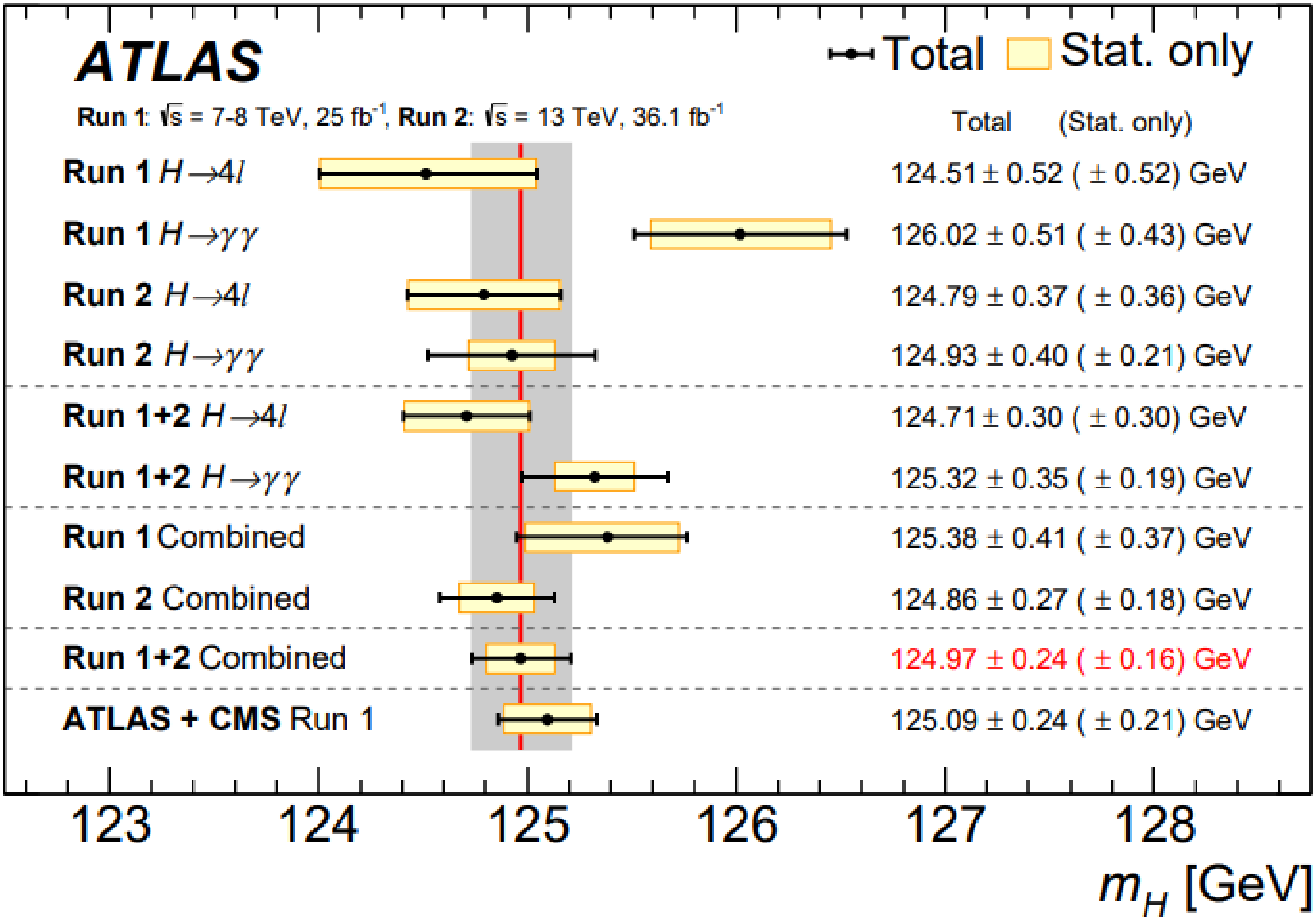


First observation of the Higgs boson



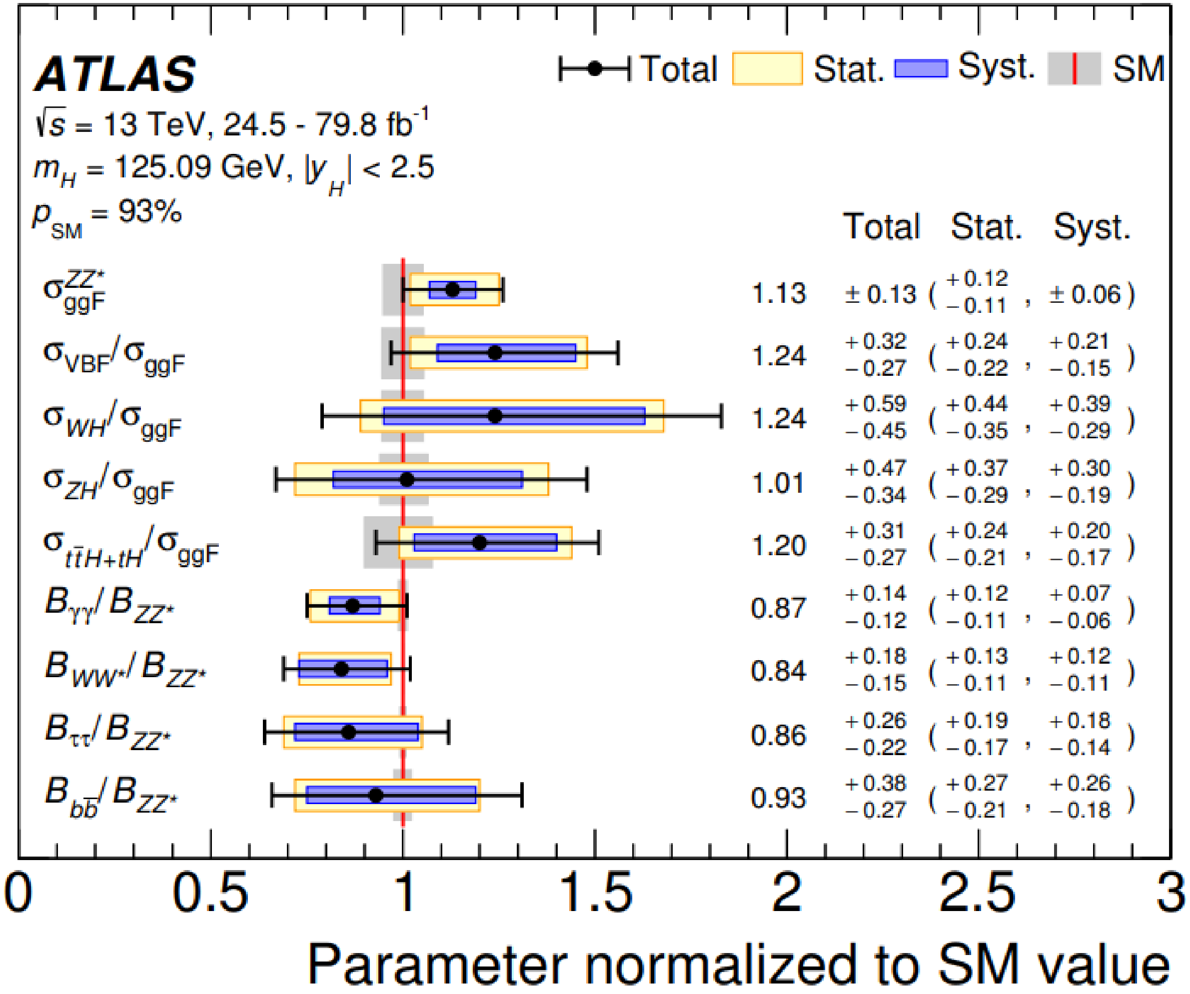


Higgs boson mass measurements



Higgs couplings vs SM predictions

Once the Higgs mass has been measured, the Standard Model has very specific – and fairly precise – predictions for the couplings of the Higgs field with various types of fermions and bosons



So far (sadly) no significant deviations have been found, but uncertainties are still quite lagre…

Questions to the Standard Model

The (gauge) symmetry group of the Standard Model is $SU(2) \times U(1) \times SU(3)$

Hence three types of interactions, and the variety of gauge bosons, the interaction carriers: $\gamma, W^{\pm}, Z^0, g$

- Why are these three types so different – and the fourth, gravity, even more so?
- Why three generations?
- Why fractional electric charges of quarks?
- Why are the fermion masses so different?
- What determines the mixing of various generations?

These and many more questions cannot be answered within SM.

We need a bigger theory. . .

Beyond the Standard Model

- Is there a bigger symmetry group, which will become visible at higher energies?
  $\Rightarrow$ Grand Unification

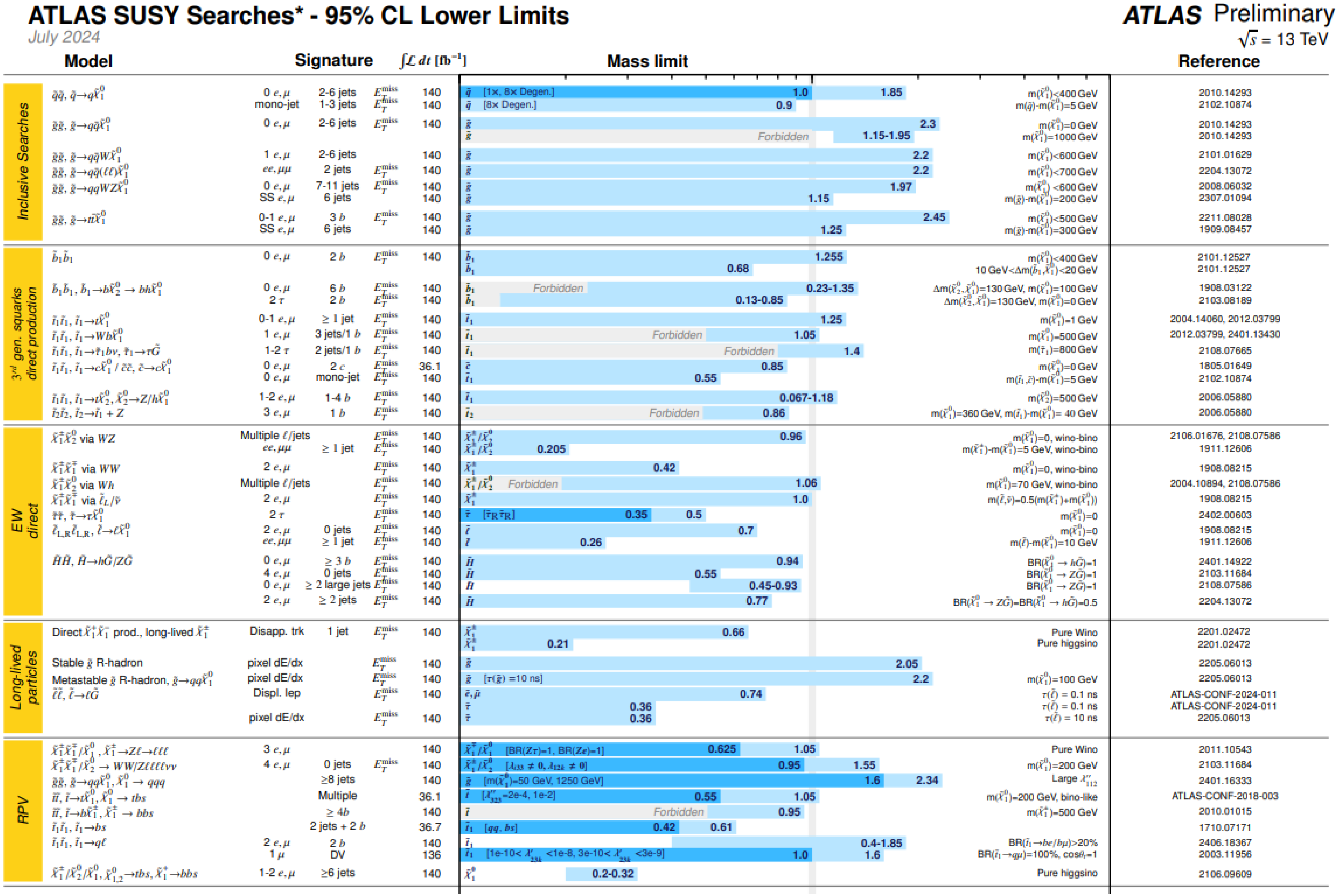
- Or maybe the Poincaré-Lorentz invariance group can be extended to include anticummutation relations?
  $\Rightarrow$ Supersymmetry

- Or maybe our space-time has more than 3+1 dimensions, some of which are "compactified" ?
  $\Rightarrow$ Large extra dimensions

These, and many other, theories exist — and predict some observable effects.

Physicists are searching for them, in a hope to answer some of the questions. . .

Supersymmetry searches



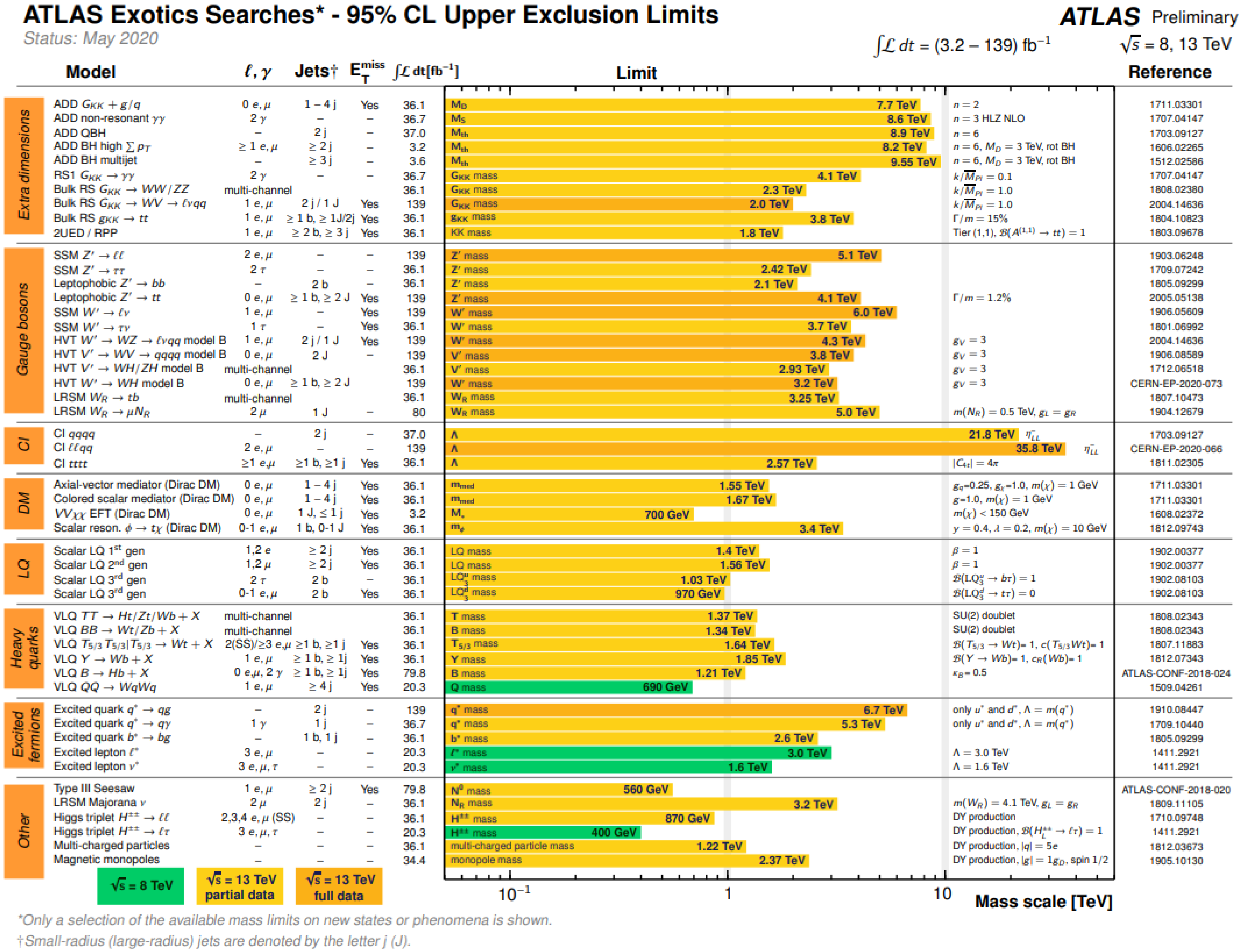
ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit				Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{q}$	[1×, 8× Degen.]	1.0 1.85	$m(\tilde{\chi}^0_1)$<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	140	$\tilde{q}$	[8× Degen.]	0.9	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{g}$		2.3	$m(\tilde{\chi}^0_1)$=0 GeV	2010.14293
						$\tilde{g}$	Forbidden	1.15-1.95	$m(\tilde{\chi}^0_1)$=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		140	$\tilde{g}$		2.2	$m(\tilde{\chi}^0_1)$<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	E_T^{miss}	140	$\tilde{g}$		2.2	$m(\tilde{\chi}^0_1)$<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	140	$\tilde{g}$		1.97	$m(\tilde{\chi}^0_1)$ <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$		1.15	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	140	$\tilde{g}$		2.45	$m(\tilde{\chi}^0_1)$<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$		1.25	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	140	$\tilde{b}_1$		1.255	$m(\tilde{\chi}^0_1)$<400 GeV	2101.12527
						$\tilde{b}_1$		0.68	10 GeV<$\Delta m(\tilde{b}_1,\tilde{\chi}^0_1)$<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	140	$\tilde{b}_1$	Forbidden	0.23-1.35	$\Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1)$=130 GeV, $m(\tilde{\chi}^0_1)$=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	140	$\tilde{b}_1$		0.13-0.85	$\Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1)$=130 GeV, $m(\tilde{\chi}^0_1)$=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{t}_1$		1.25	$m(\tilde{\chi}^0_1)$=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden	1.05	$m(\tilde{\chi}^0_1)$=500 GeV	2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden	1.4	$m(\tilde{\tau}_1)$=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$		0.85	$m(\tilde{\chi}^0_1)$=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	140	$\tilde{t}_1$		0.55	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}^0_1)$=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	E_T^{miss}	140	$\tilde{t}_1$		0.067-1.18	$m(\tilde{\chi}^0_2)$=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	140	$\tilde{t}_2$	Forbidden	0.86	$m(\tilde{\chi}^0_1)$=360 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$		0.96	$m(\tilde{\chi}^0_1)$=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$		0.205	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		E_T^{miss}	140	$\tilde{\chi}^\pm_1$		0.42	$m(\tilde{\chi}^0_1)$=0, wino-bino	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden	1.06	$m(\tilde{\chi}^0_1)$=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	140	$\tilde{\chi}^\pm_1$		1.0	$m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		E_T^{miss}	140	$\tilde{\tau}$	[$\tilde{\tau}_R\tilde{\tau}_R$]	0.35 0.5	$m(\tilde{\chi}^0_1)$=0	2402.00603
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	140	$\tilde{\ell}$		0.7	$m(\tilde{\chi}^0_1)$=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\ell}$		0.26	$m(\tilde{\ell})$-$m(\tilde{\chi}^0_1)$=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}	140	$\tilde{H}$		0.94	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	2401.14922
		4 e,μ	0 jets	E_T^{miss}	140	$\tilde{H}$		0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	140	$\tilde{H}$		0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	E_T^{miss}	140	$\tilde{H}$		0.77	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=BR($\tilde{\chi}^0_1\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}^\pm_1$		0.66	Pure Wino	2201.02472
						$\tilde{\chi}^\pm_1$		0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$		2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns]	2.2	$m(\tilde{\chi}^0_1)$=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	140	$\tilde{e},\tilde{\mu}$		0.74	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
						$\tilde{\tau}$		0.36	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$		0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$	[BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	[$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$]	0.95 1.55	$m(\tilde{\chi}^0_1)$=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		≥8 jets		140	$\tilde{g}$	[$m(\tilde{\chi}^0_1)$=50 GeV, 1250 GeV]	1.6 2.34	Large λ''_{112}	2401.16333
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2]	0.55 1.05	$m(\tilde{\chi}^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		140	$\tilde{t}$	Forbidden	0.95	$m(\tilde{\chi}^\pm_1)$=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		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		140	$\tilde{t}_1$		0.4-1.85	BR($\tilde{t}_1\to be/b\mu$)>20%	2406.18367
		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
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	≥6 jets		140	$\tilde{\chi}^0_1$		0.2-0.32	Pure higgsino	2106.09609



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.2 - 139)\ \text{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

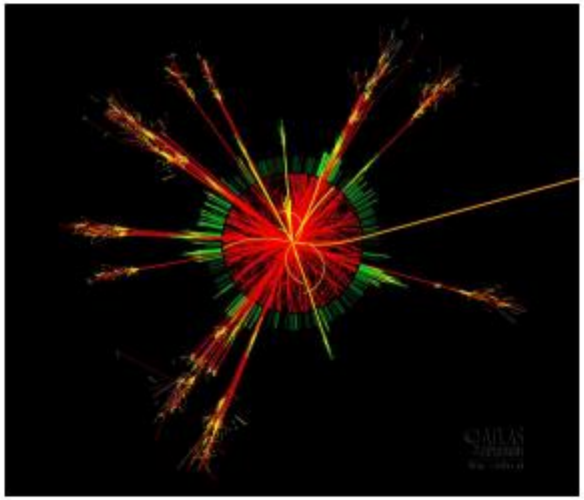
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	CERN-EP-2020-066
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(\text{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(\text{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Summary and outlook

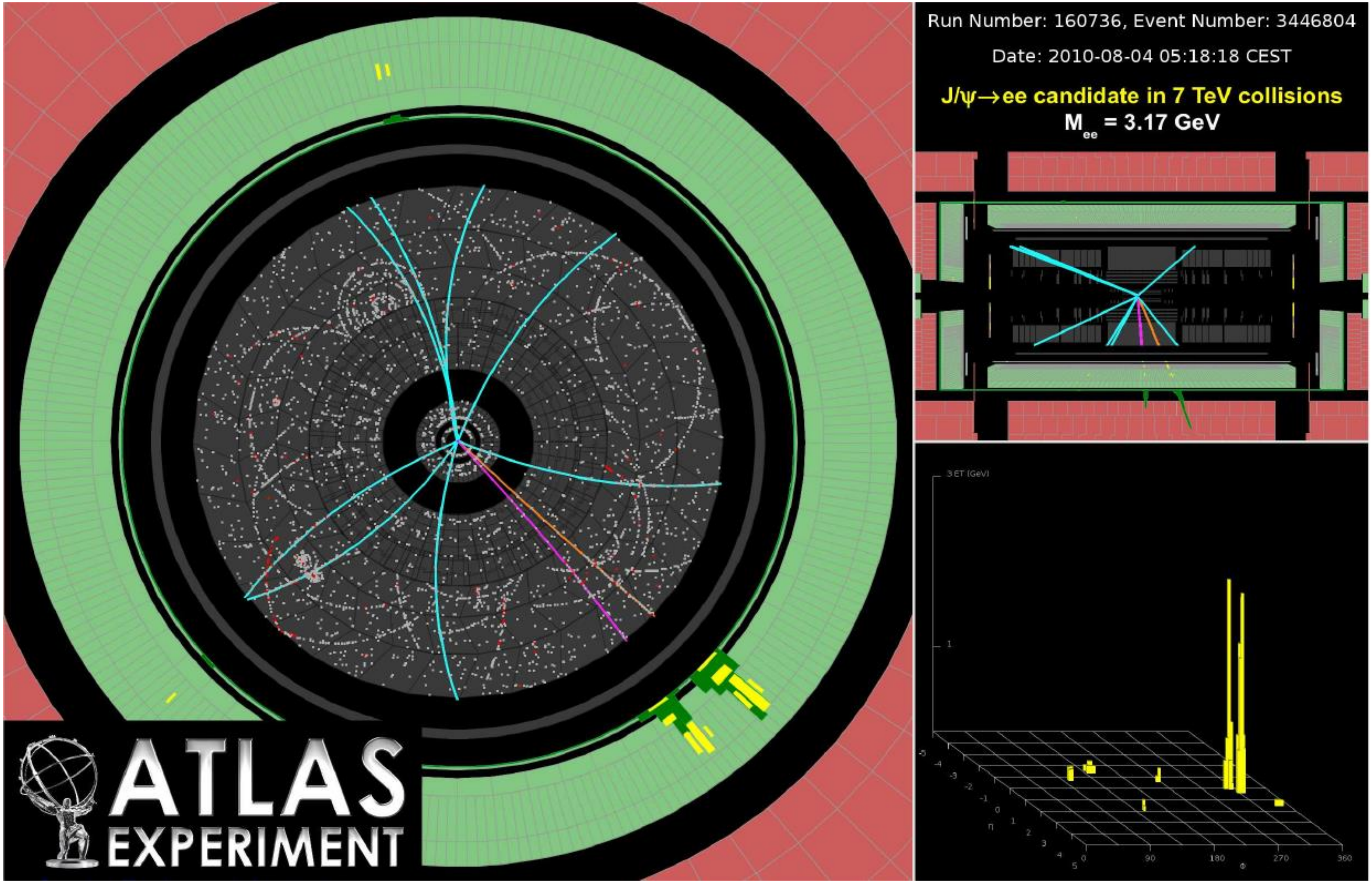
- Huge amount of work has been done by CERN experiments
- Antimatter has been created and studied in some detail
- The Higgs boson discovered in 2012 so far looks like the Standard Model Higgs
- The Standard Model is standing strong – no SUSY, no sign of any exotics either. . .
- Some data still to be analysed, and much more data is still to come
- Hoping for many fascinating discoveries in the near future!



THANKS FOR LISTENING!

ANY QUESTIONS?

Hadronic production of charmonium



CERN overview video