Introduction to Particle Physics and Cosmology

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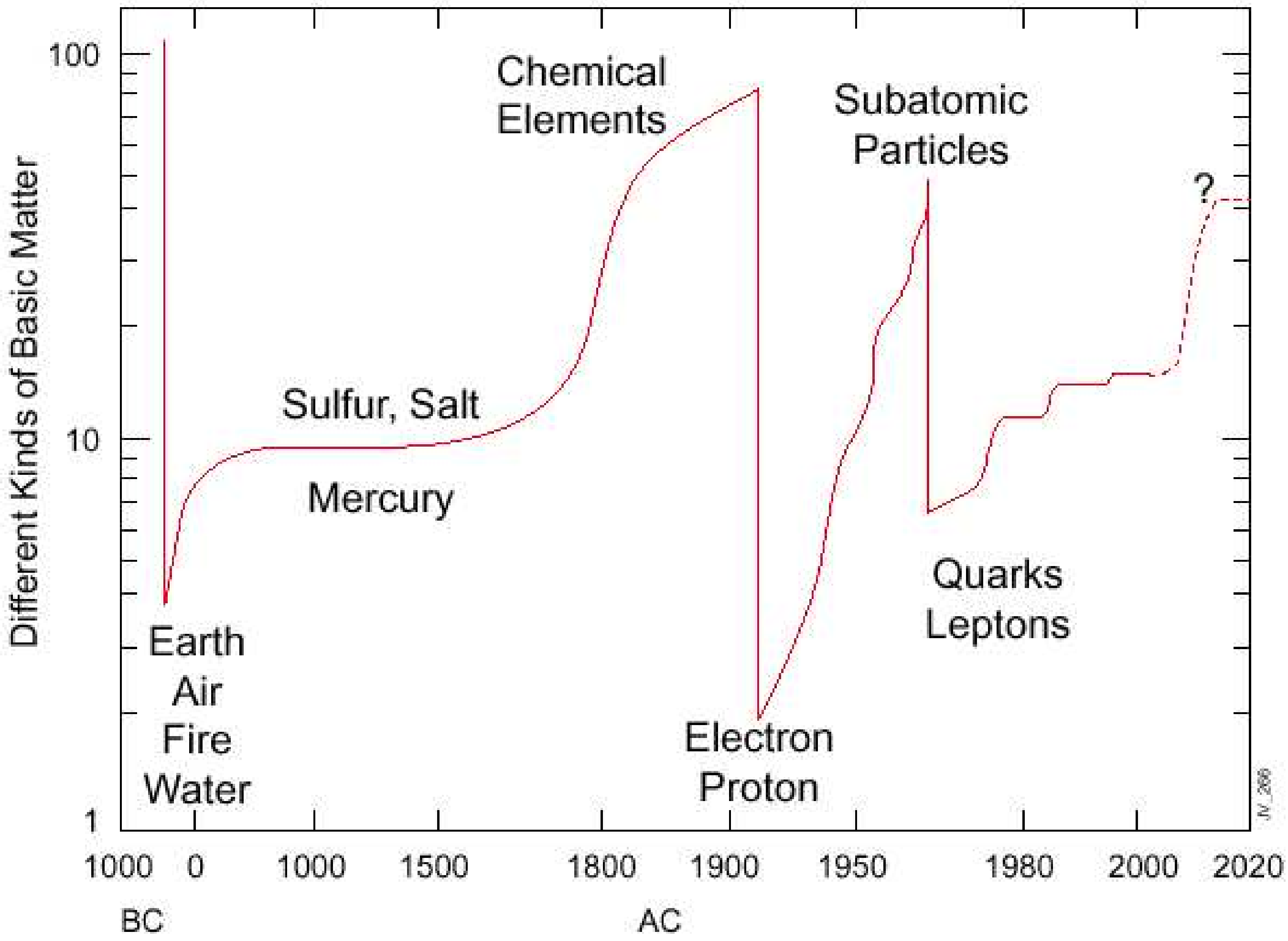
Outline

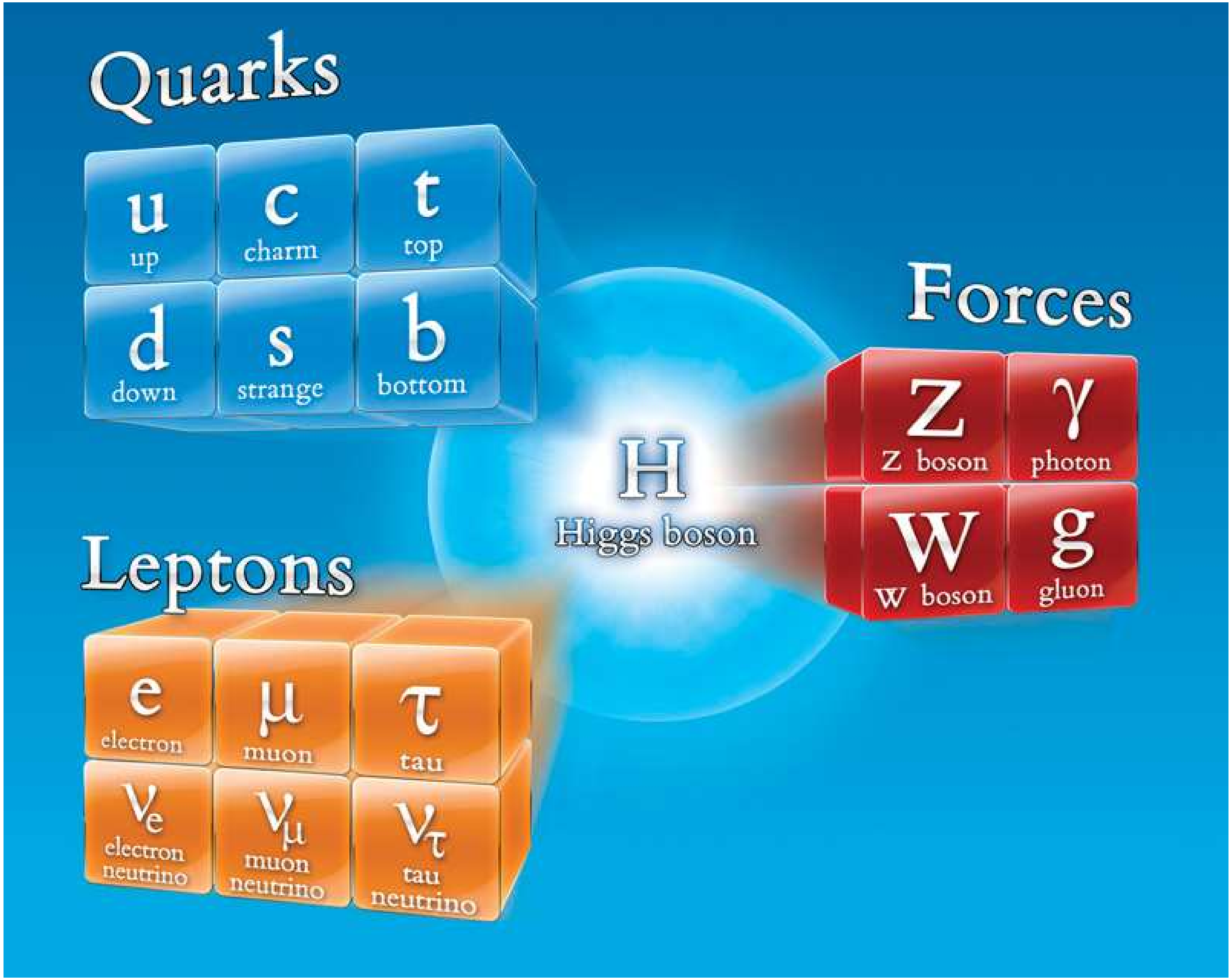
- Concepts and methods of particle physics
- The Standard Model (SM)
- CERN and its accelerator structure
- Large Hadron Collider (LHC)
- Proton-proton collisions, luminosity and triggers
- Lepton pair production: $J/\psi, \Upsilon, Z, \ldots$
- Other SM measurements: $t\bar{t}$, $W^{\pm}$, ZZ, ...
- Observation of the Higgs Boson
- Links with Cosmology
- Dark matter and dark energy
- Unanswered questions in particle physics and in cosmology
- Summary and outlook

Constituents of Matter



From http://teachers.web.cern.ch/teachers/archiv/HST2002/webgroup/mcclean/Introduction to Particle Physics.ppt

Fundamental constituents of the Standard Model



Particle Physics — What's This 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**.

Why does PP Seem So Hard Then?

- The world of particles is so far from our everyday experience, that all these simple properties and simple laws may look and seem unnatural and weird;

  What can we do?

  'Friendly' names: strangeness, charm, colour, top, bottom... Find analogies and simple rules

- Many mathematical methods used to describe the world of particles are quite advanced (Group Theory, Quantum Field Theory, Advanced Statistics ...)

  What can we do?

  Use simplified maths, skip derivations...

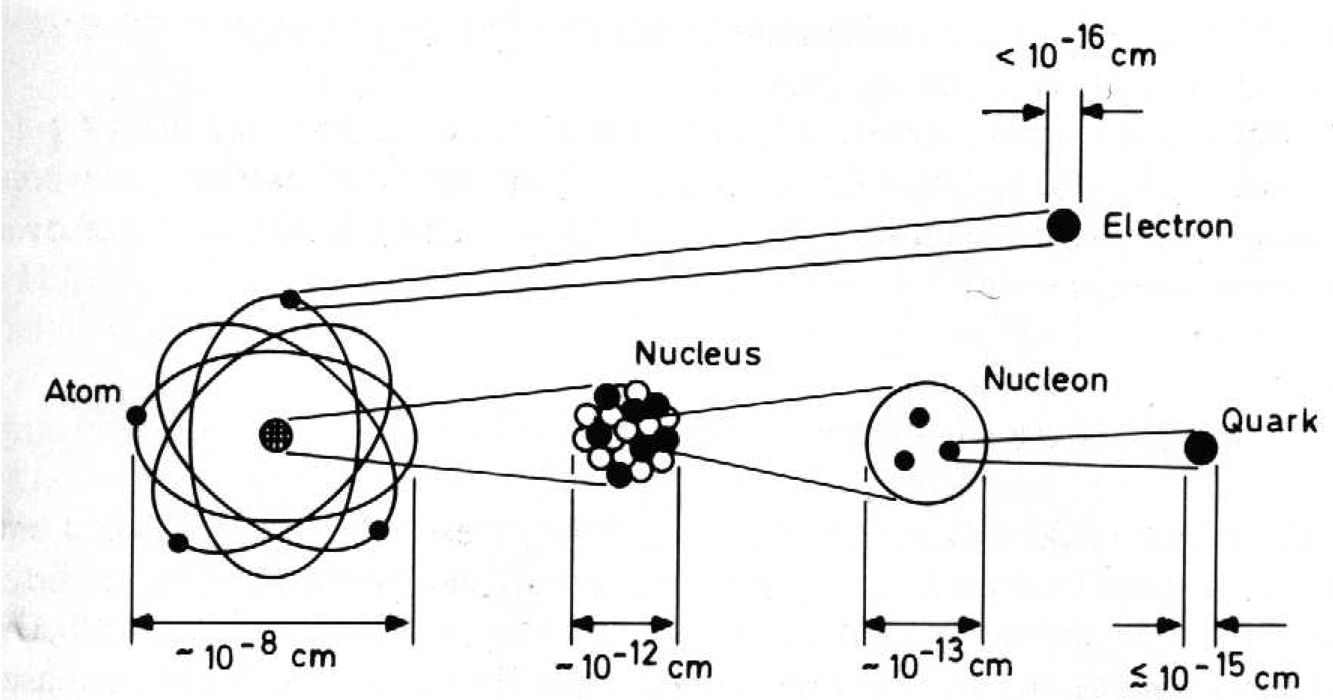
- Your intuition fails to work

  What can we do?

  Build our intuition by solving lots of various problems

What's the Scale?

'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.

Is SI System 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 it Even Simpler?

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

[energy] $\times$ [time] $=1$ and also [momentum] $\times$ [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 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:

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

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

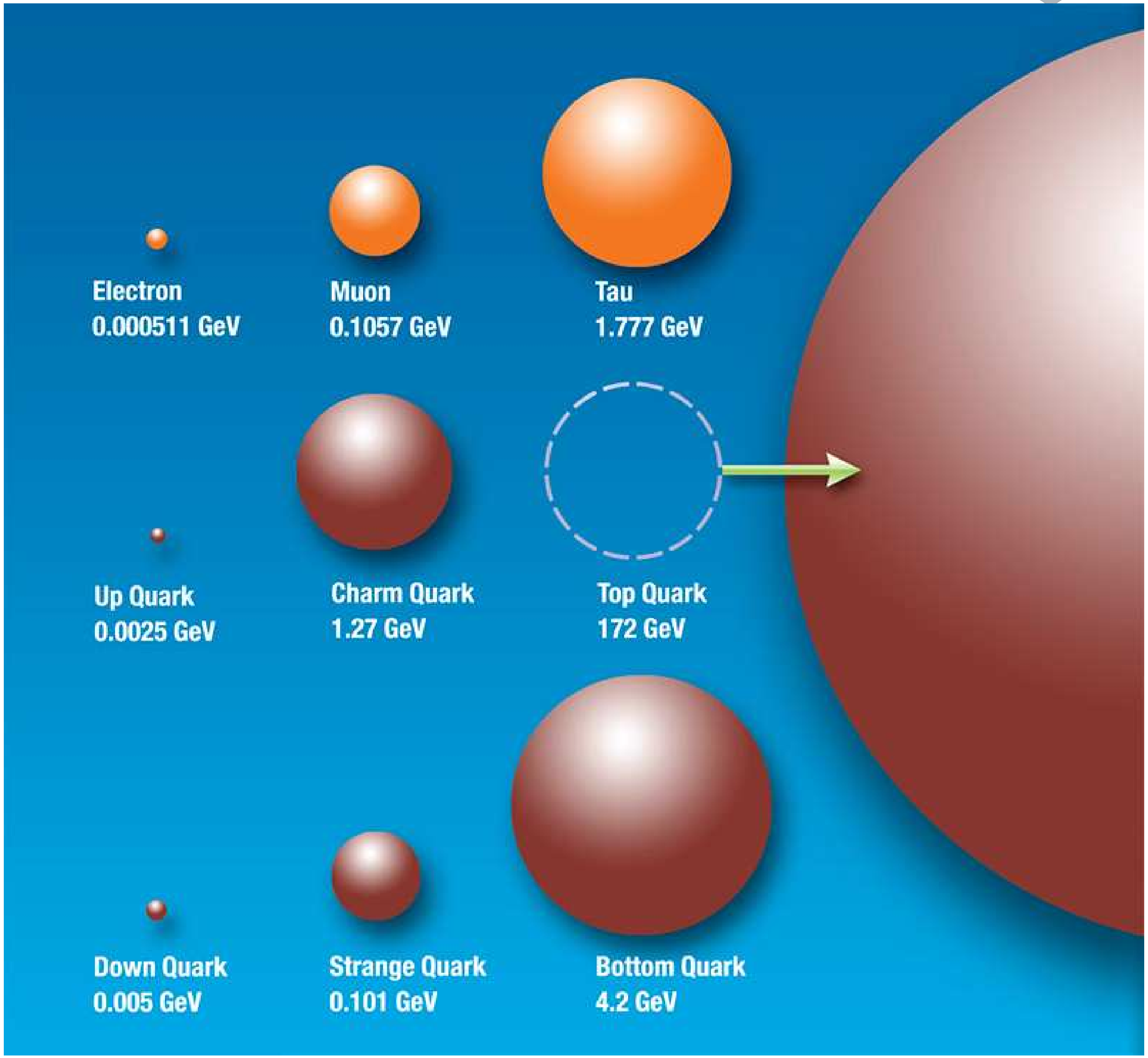
Generations and masses

Three "generations"

Getting heavier and heavier

Top quark especially heavy

No clue why...



CERN 'overview'

Birdseye view of CERN and neighbourhood

Alps, lake Geneva, Geneva airport

LHC ring shown as the red line

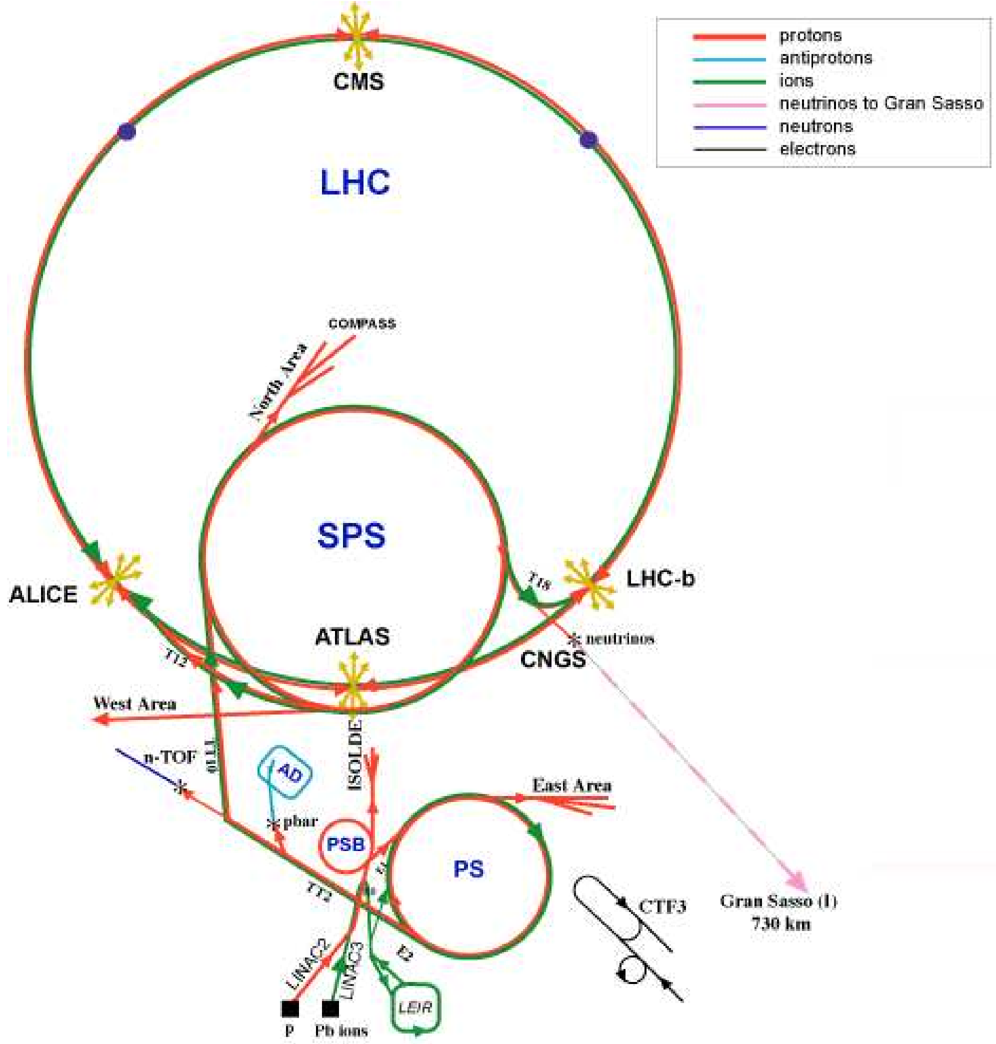
CERN accelerator complex

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

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

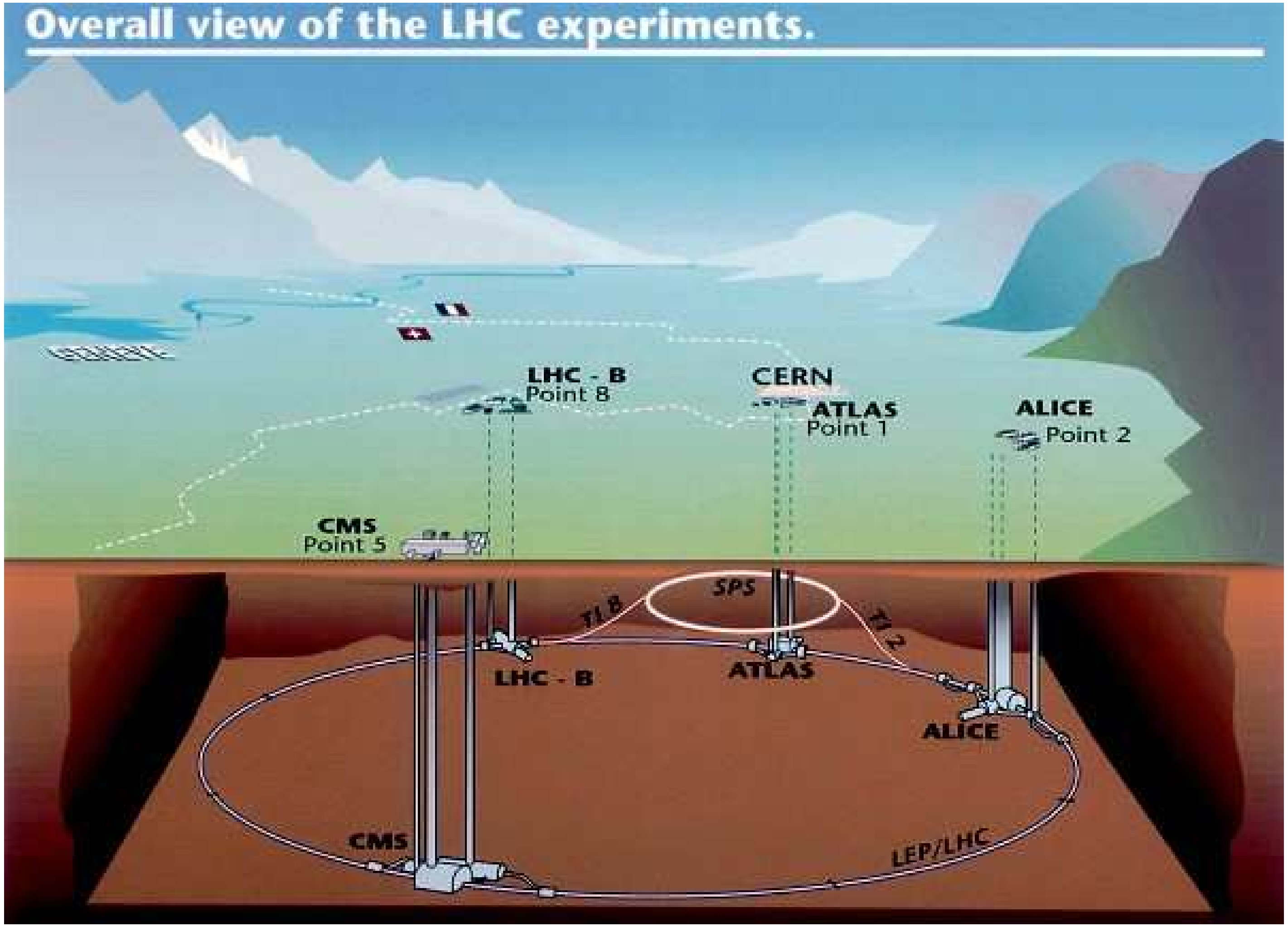
Lots of experiments, all very interesting and important

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



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

The Large Hadron Collider (LHC)



LHC is the flagship of CERN research programme, colliding two proton beams with energy of 13 TeV

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

Two multi-purpose experiments: ATLAS and CMS

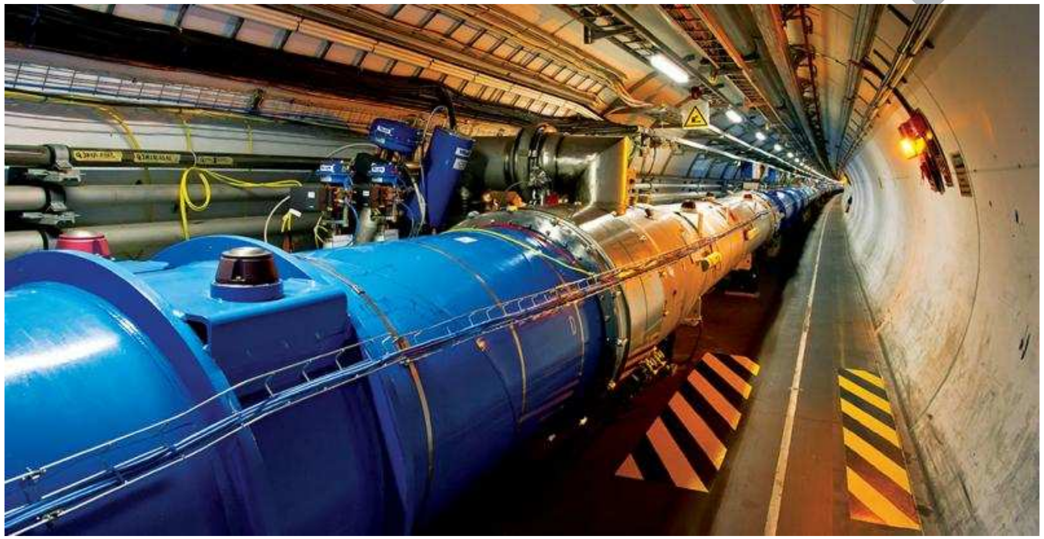
Others – such as LHCb and ALICE – are more specialised

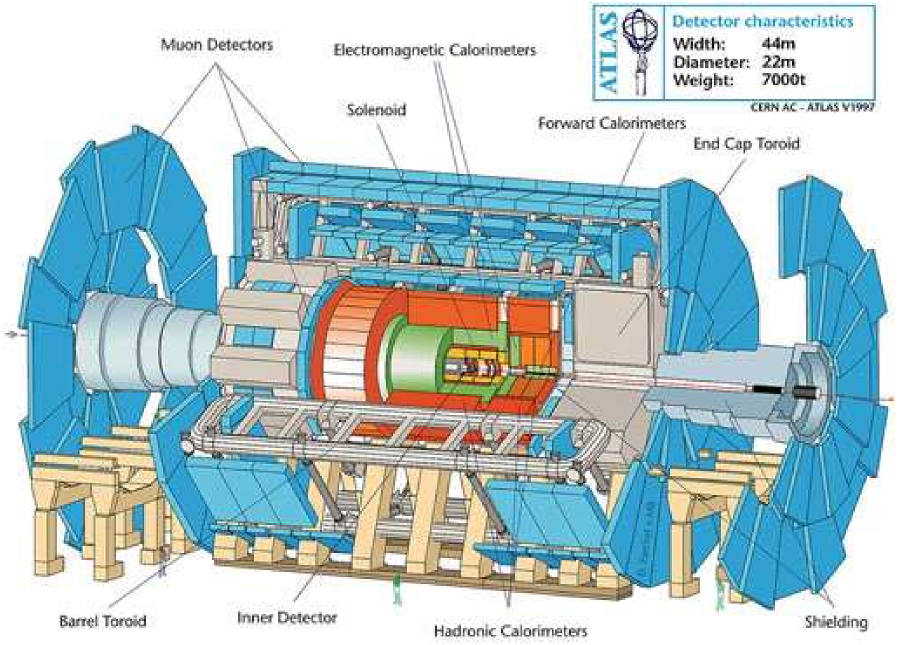
Tunnel 27 km long

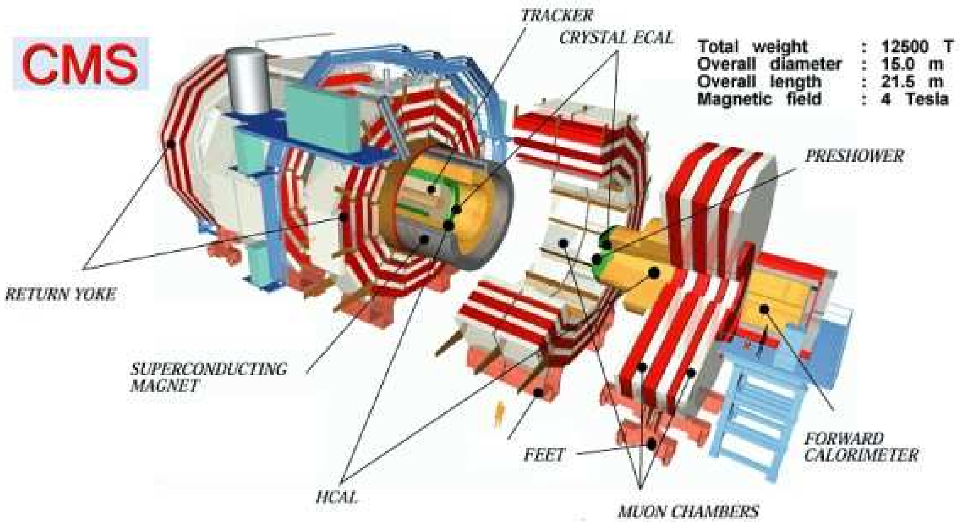
100 m under the surface

2000 magnets of various types

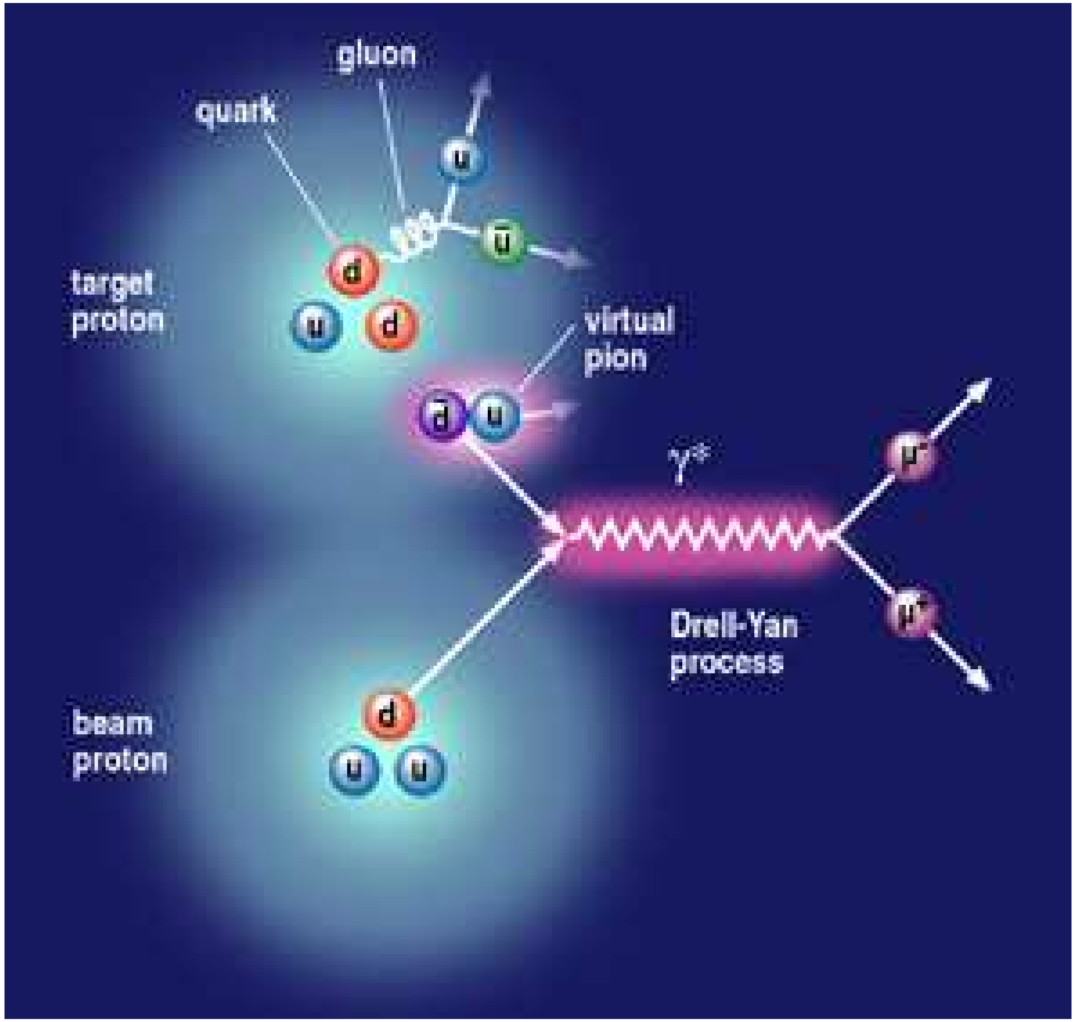
Two huge multi-purpose experimental installations: ATLAS and CMS







Is LHC really a proton - proton collider?



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

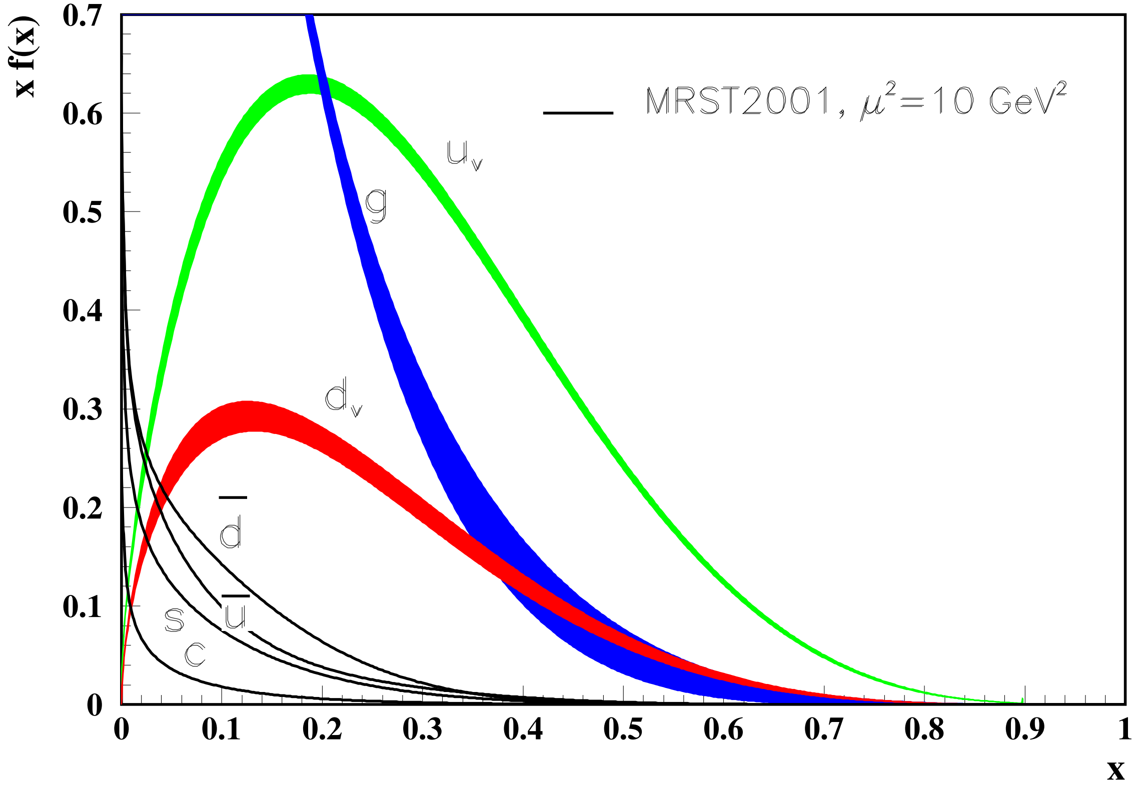
13 TeV of pp collision energy barely enough to produce a 2 TeV object...

Quark and gluon distributions in 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



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

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

Cross sections and units

- The intensity of various collisions is measured in terms of the cross section for particular reactions
- Cross section is the effective area which needs to be crossed by a test particle to get scattered
- Since early days of nuclear physics, measured in barns

$$1 \text{ barn} = 10^{-28} \text{ m}^2 = 100 \text{ fm}^2$$

  is about the size of lead or uranium nucleus
- Total cross section of proton-proton collisions is about 100 millibarn at 7 TeV
- Interesting processes like Higgs production have much smaller probabilities, and hence much smaller cross sections, measured in picobarns (10^{-12} barn) or femtobarns (10^{-15} barn) or even attobarns (10^{-18} barn)
- The smaller the cross section of a process, the fewer events you get
- Integrated luminosity of 100 pb^{-1} means that if the cross section is 1 pb, you will see 100 events

Luminosity

In early days of LHC:

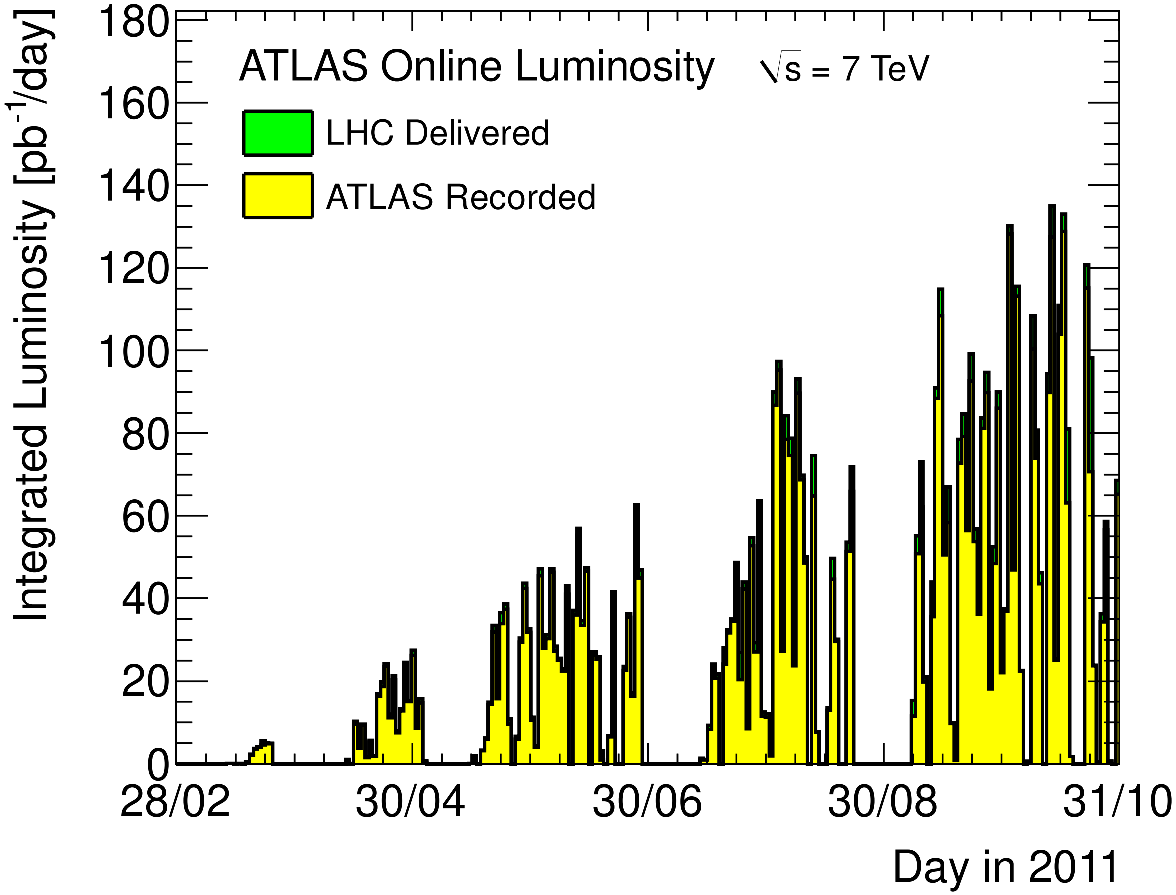
100's of collisions / sec

Now:

many millions / sec

No time for viewing

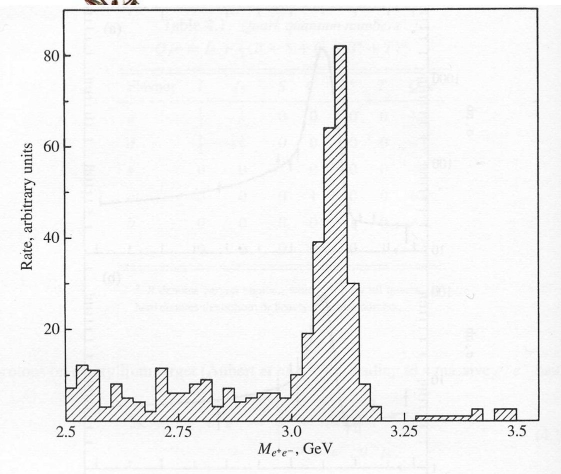
events one-by one...



Full computing power of CERN only allows to reconstruct "just" a few hundred events per second

Very careful selection ("triggering") of potentially interesting events is required!

1974: discovery of J/ψ



$\Leftarrow$ **Discovery 1:** Ting's group

$$pN \to e^+e^-X$$

at $P_{\rm lab} = 30$ GeV/c

[Aubert et al., PRL, 6/11/1974]

Found a peak in e^+e^- inv.mass at 3.1 GeV, called it J.

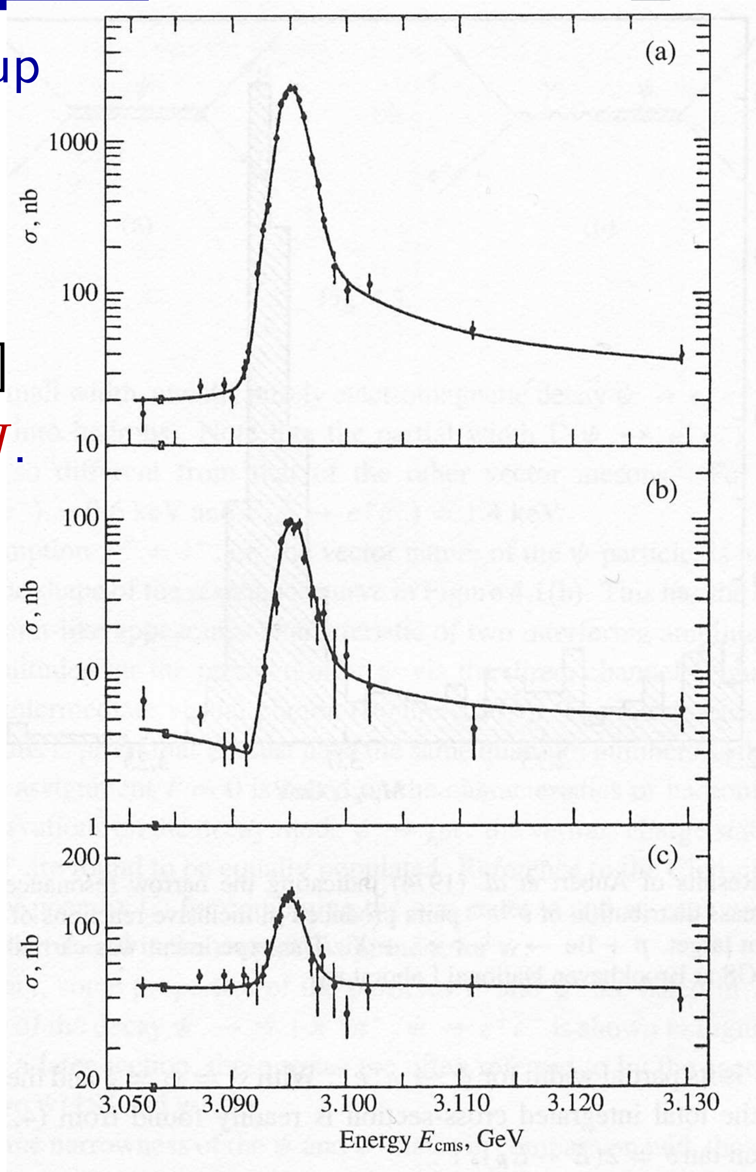
Discovery 2: Richter's group $\Rightarrow$

$$\begin{array}{llll} (a) & e^+e^- & \to & \text{hadrons} \\ (b) & e^+e^- & \to & \mu^+\mu^- \\ (c) & e^+e^- & \to & e^+e^- \end{array}$$

[Augustin et al., PRL, 7/11/1974]

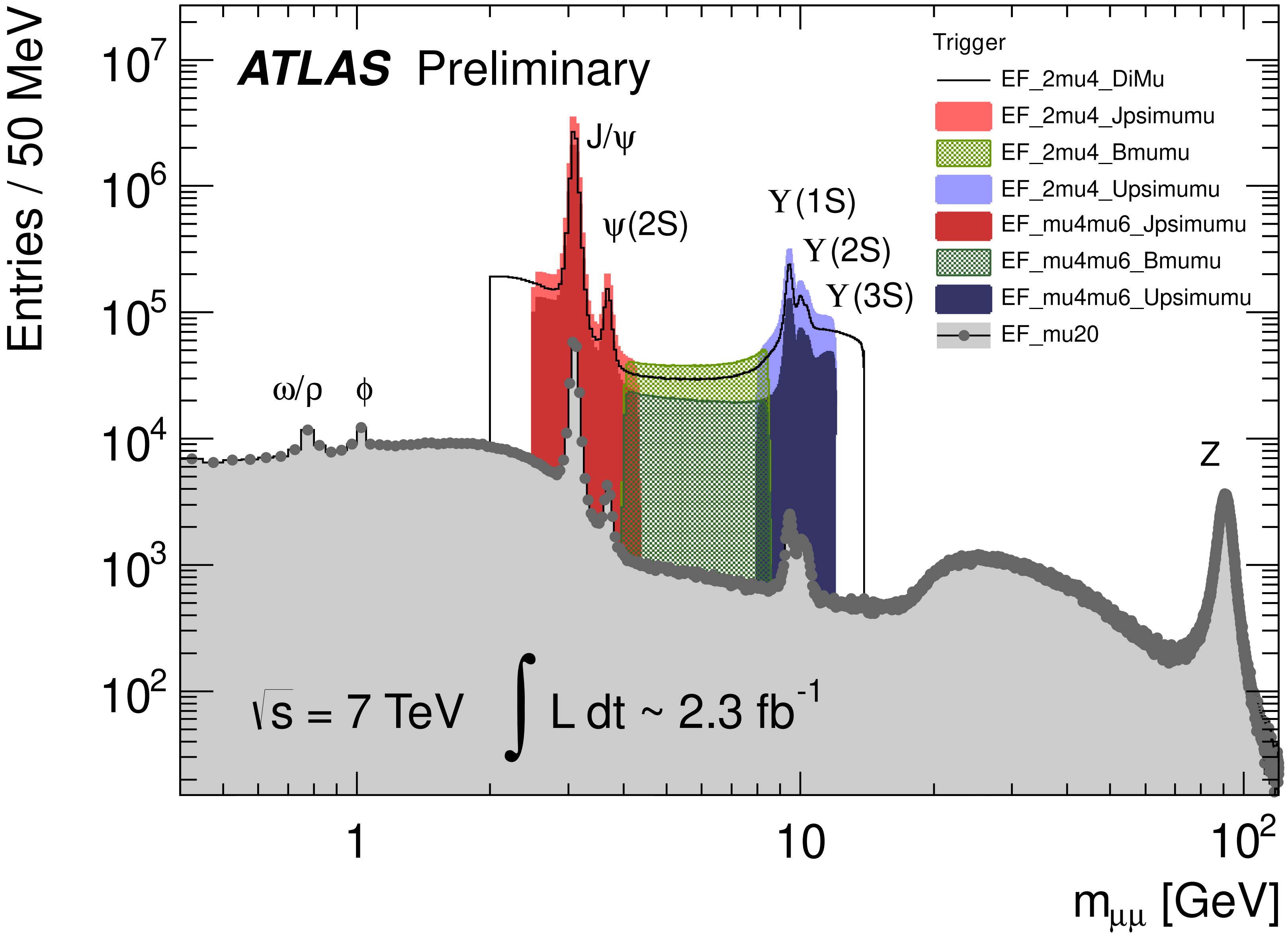
Found a peak in all these three cross-sections,

at the c.m.s. energy 3.1 GeV; called it ψ.

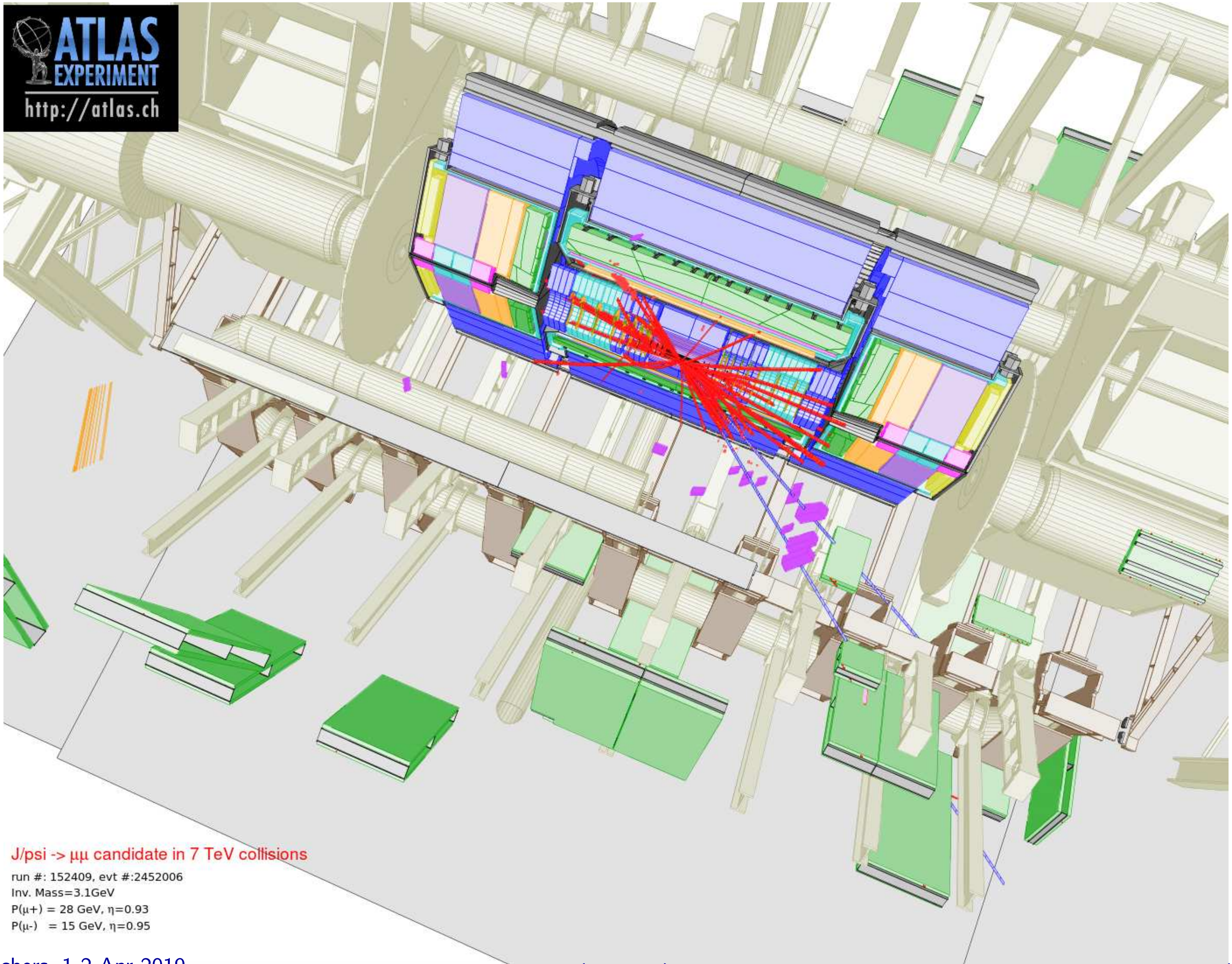


Now we know: J/ψ **is a bound state of charm-anticharm,** $c\bar{c}$.

History of 20th century Particle Physics in one plot



$$pp \to J/\psi(\to \mu^+\mu^-) + X$$



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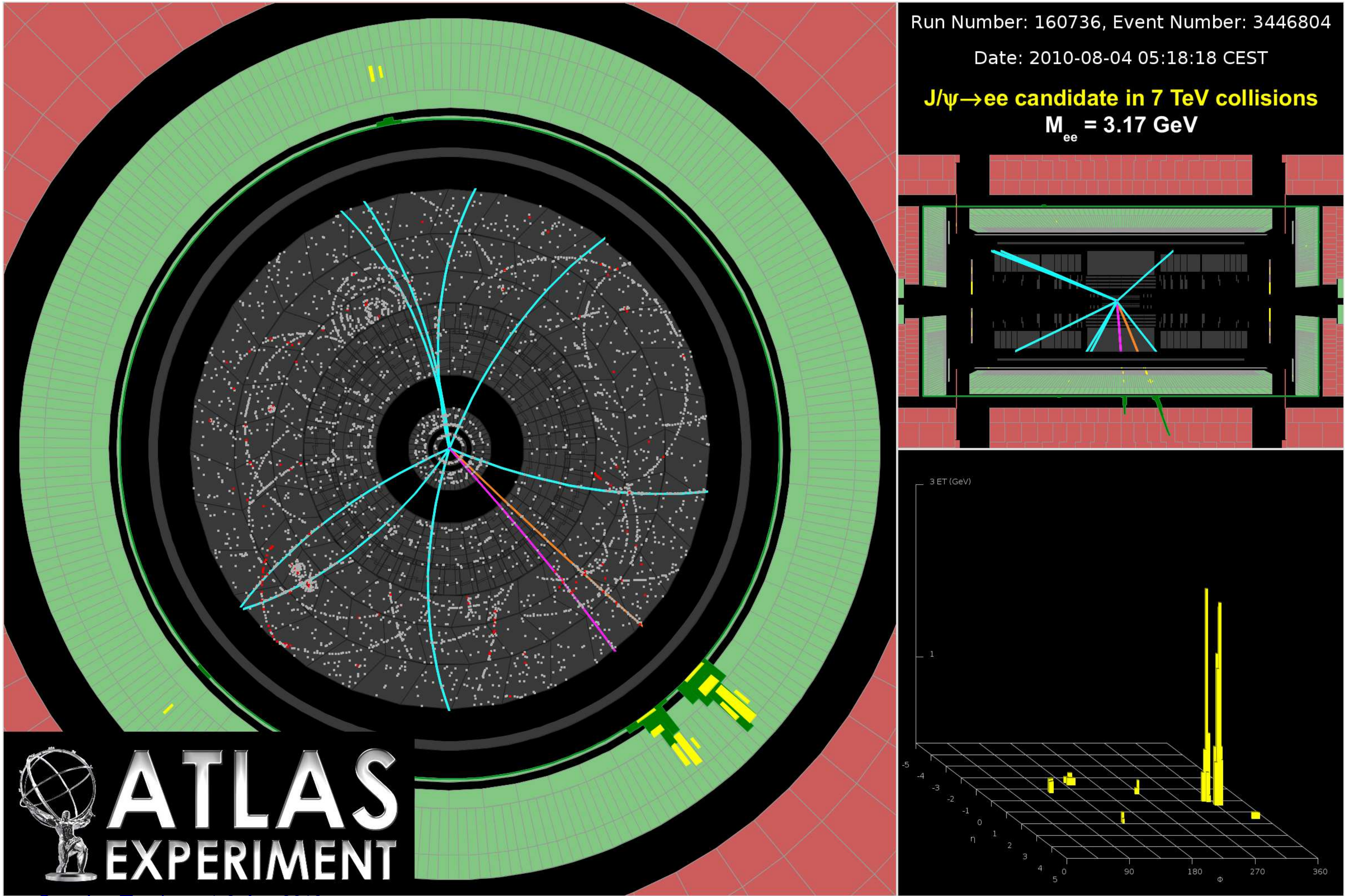
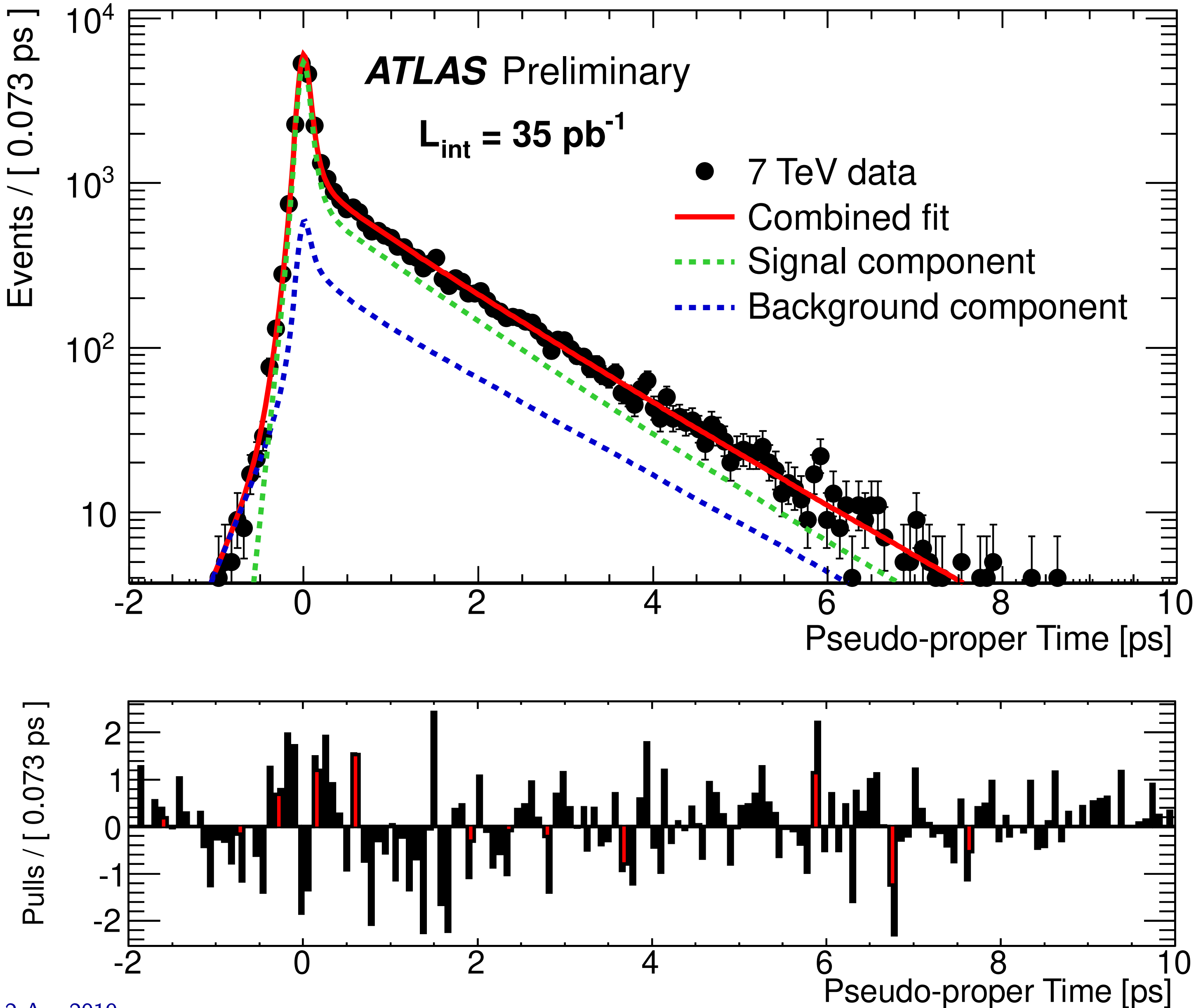
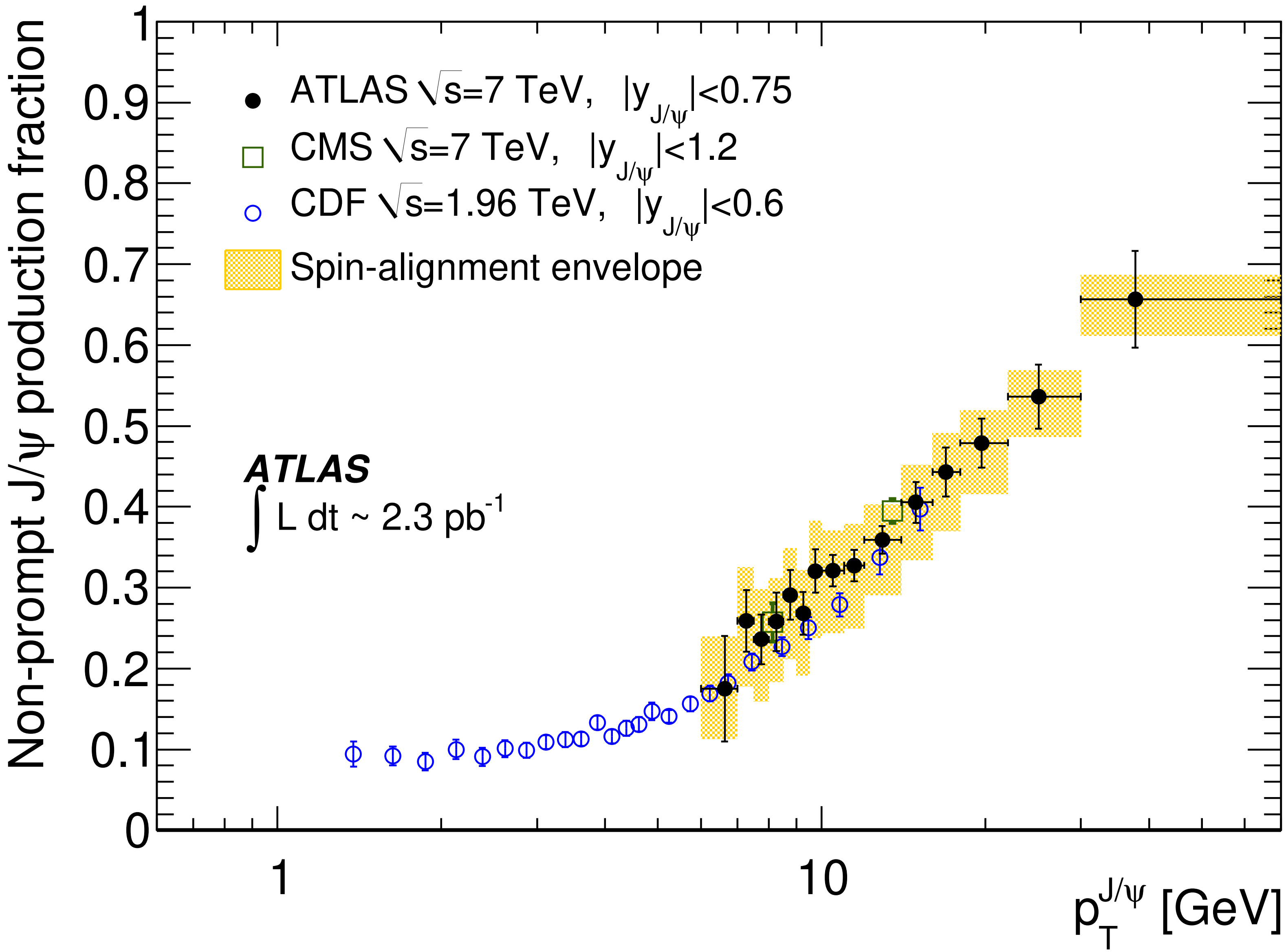


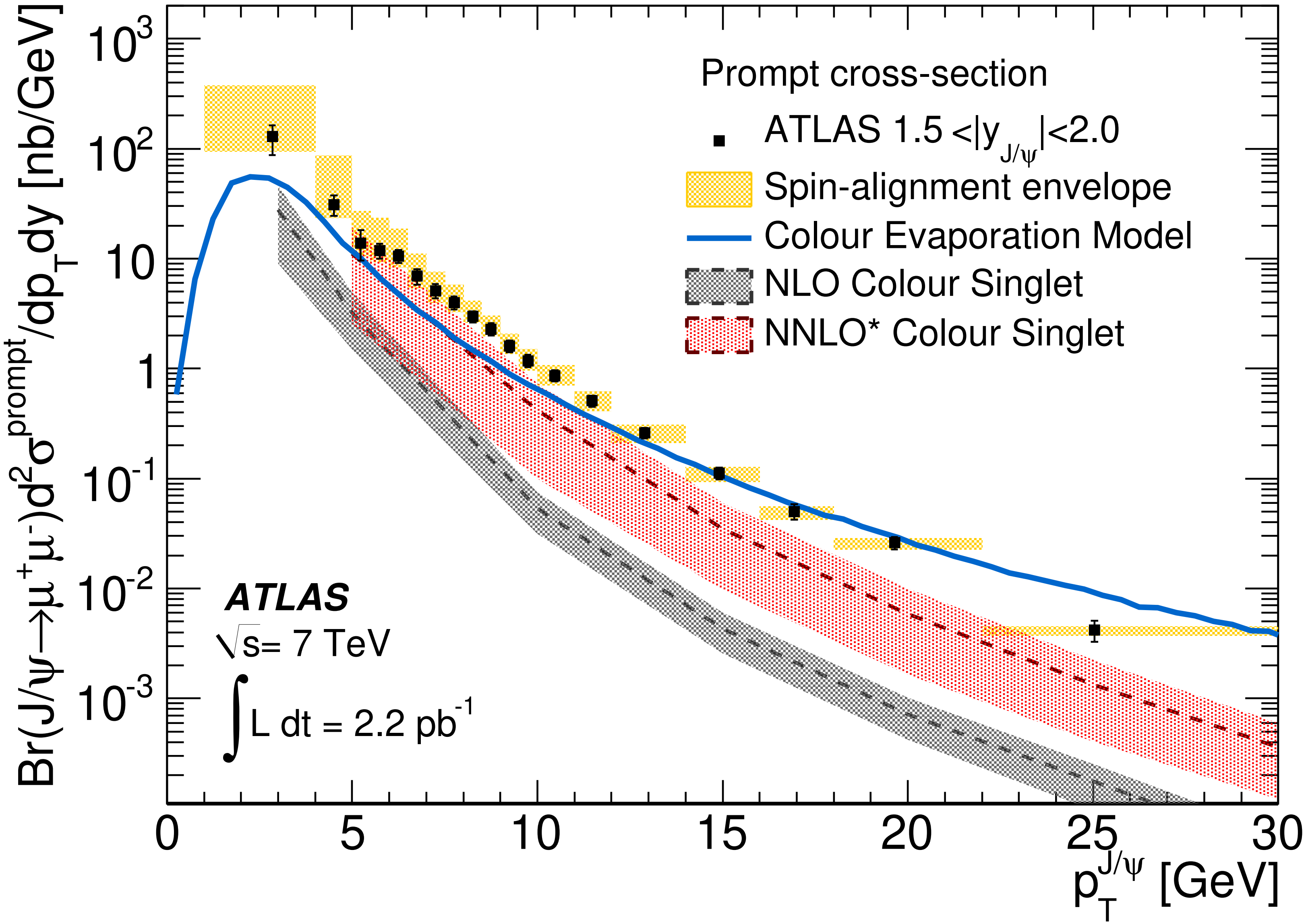
Proper Decay Time of the J/ψ vertex



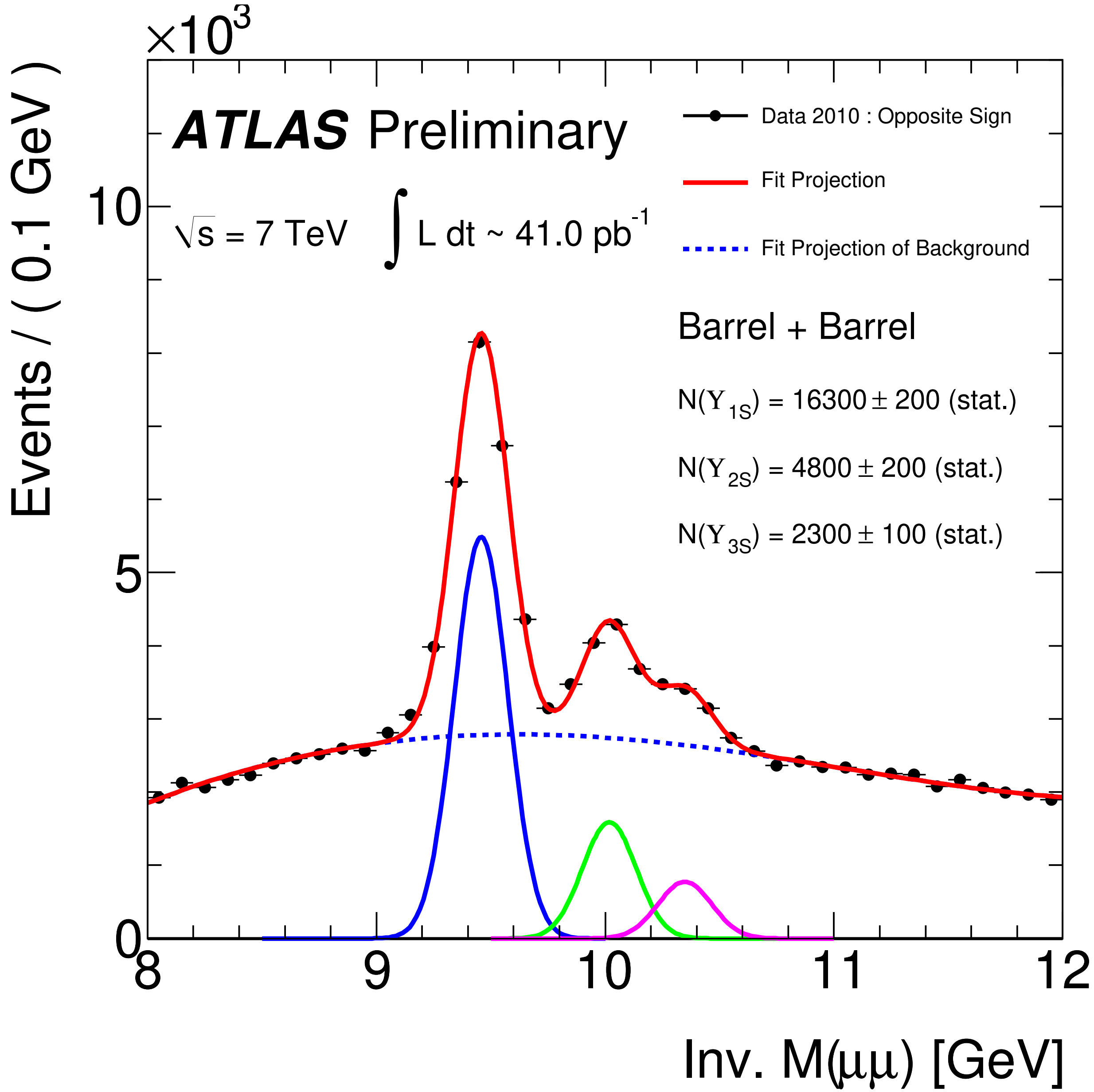
Fraction of non-promptly produced J/ψ



p_T dependence of prompt J/ψ



$b\bar{b}$ bound states: Υ system



Spectroscopy of $b\bar{b}$ mesons

Spectroscopy similar to hydrogen atom

$\Upsilon(1S)$: ground state

$\Upsilon(2S, 3S)$: radial excitations

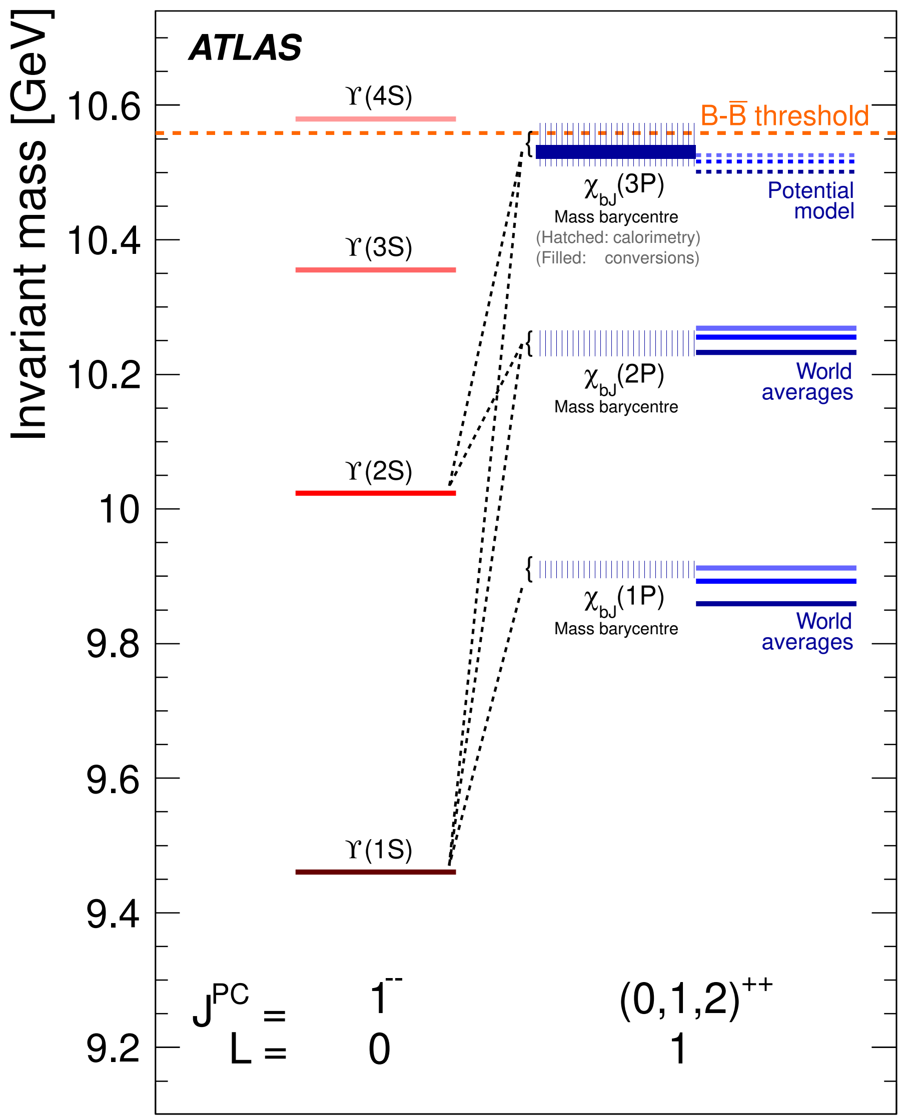
Three families of χ_b:

orbital excitations, $L = 1$

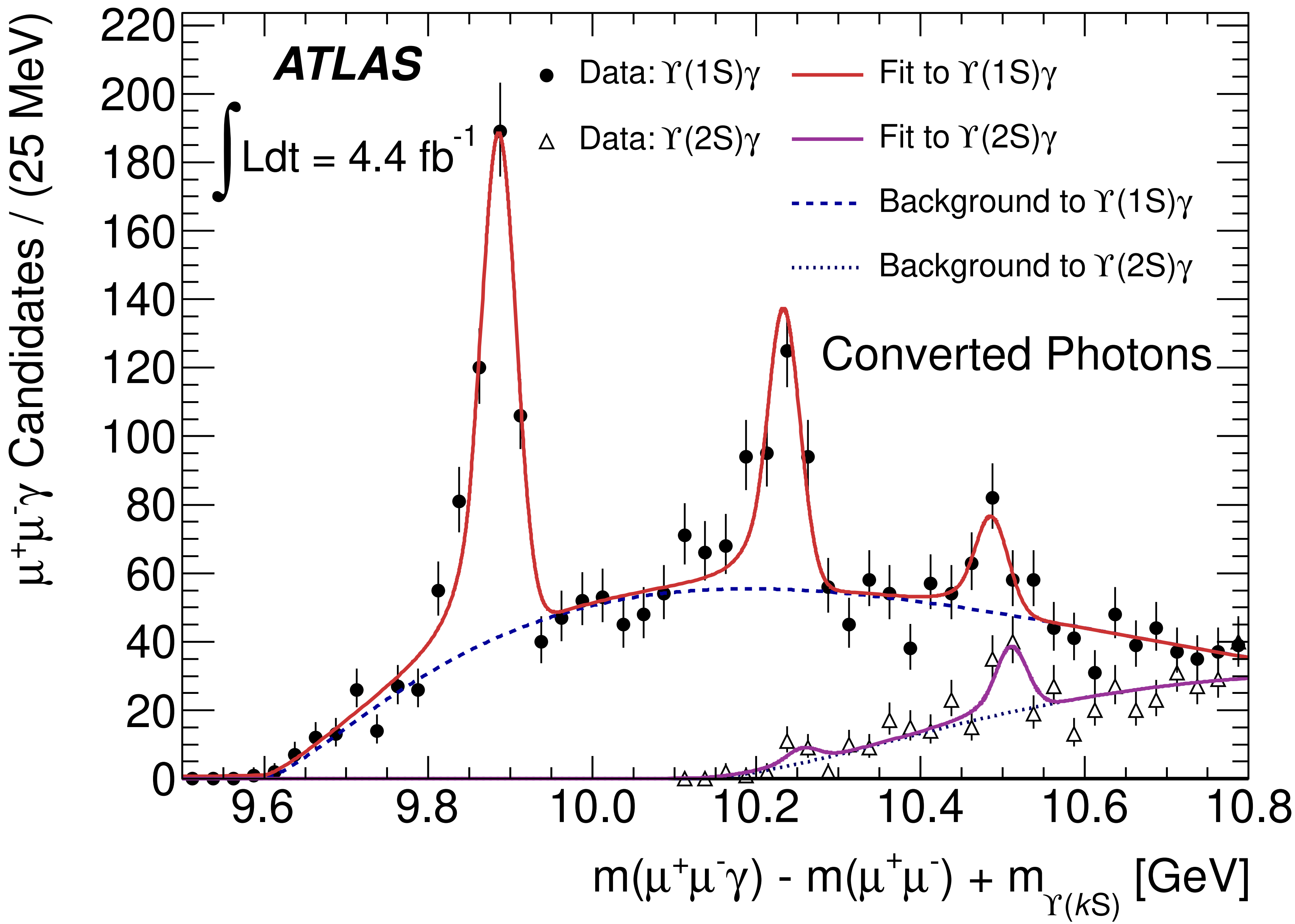
Until 22 December 2011, only

$\chi_b(1P)$ and $\chi_b(2P)$ were observed

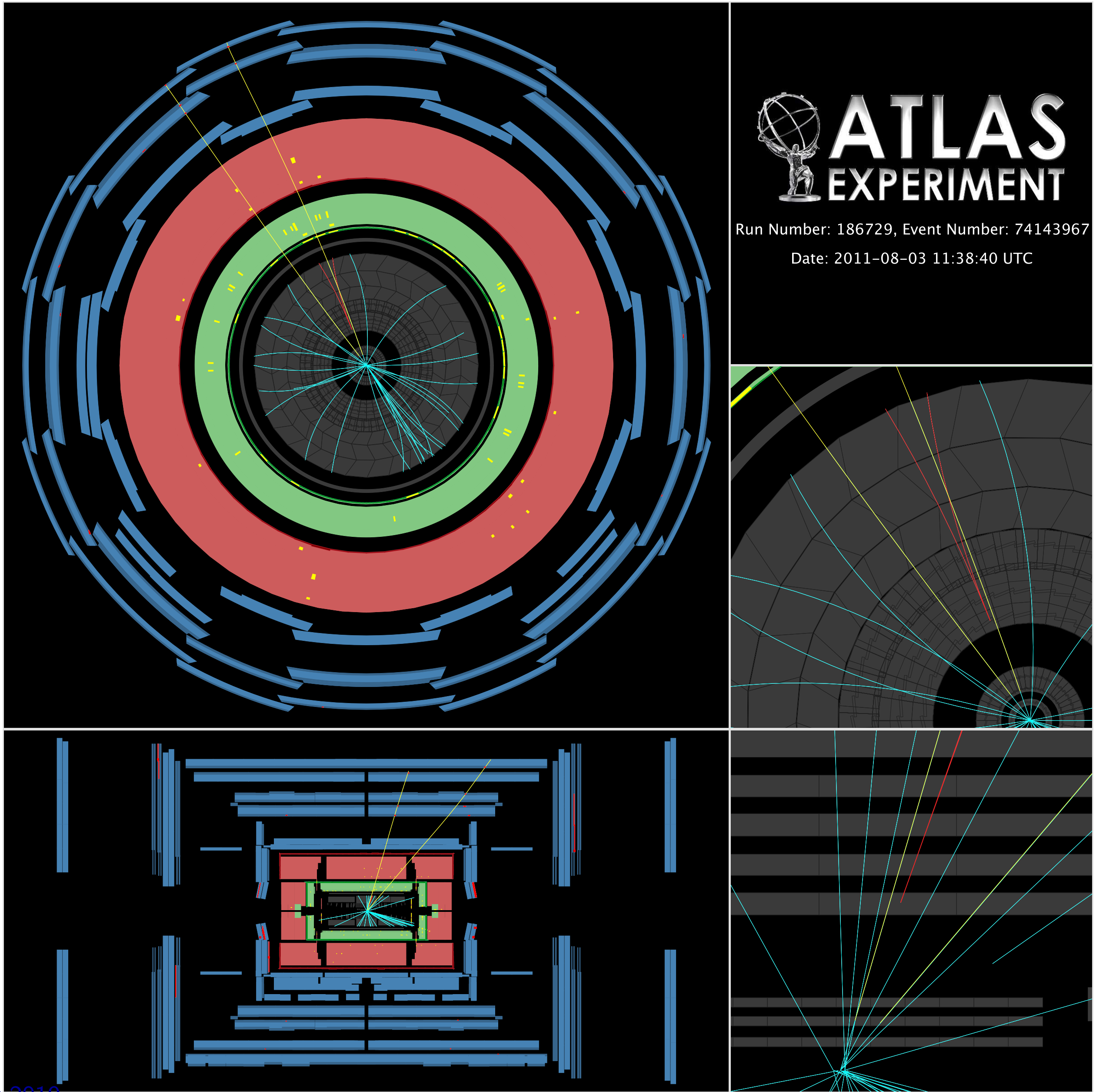
Observed bottomonium radiative decays in ATLAS, L = 4.4 fb^{-1}



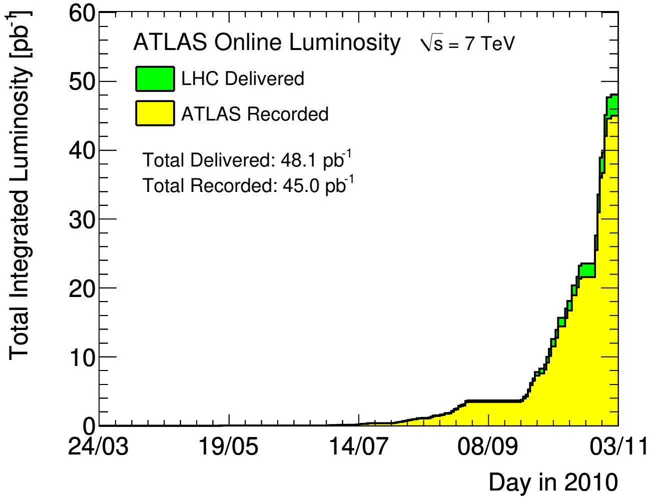
All three χ_b peaks as seen by ATLAS

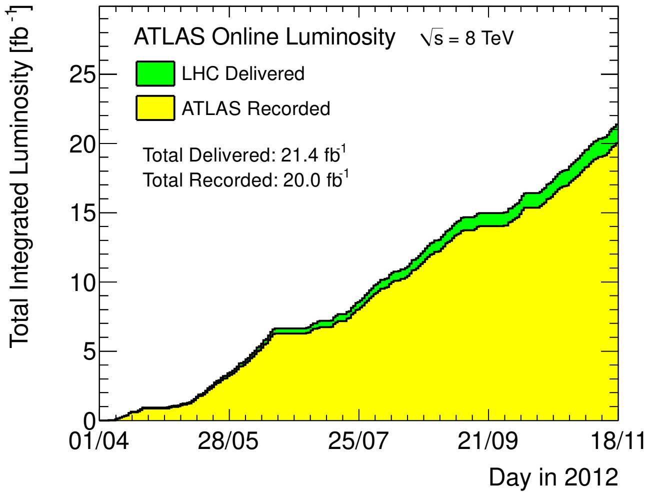


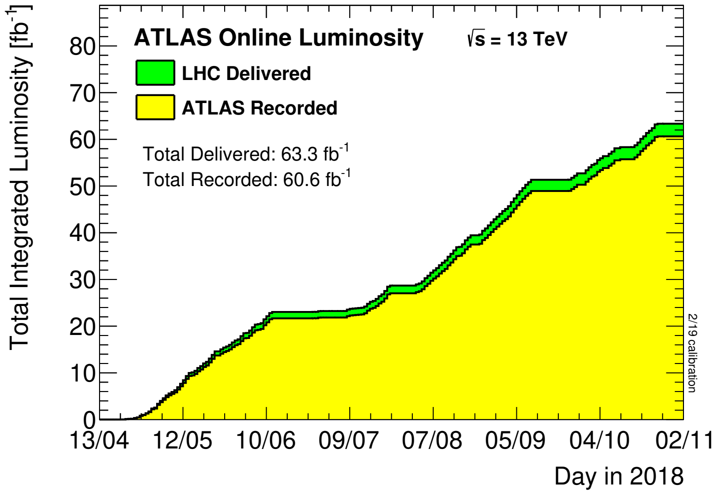
Event with $\chi_b(3P)$ candidate



Integrated luminosity in 2010, 2012, 2018





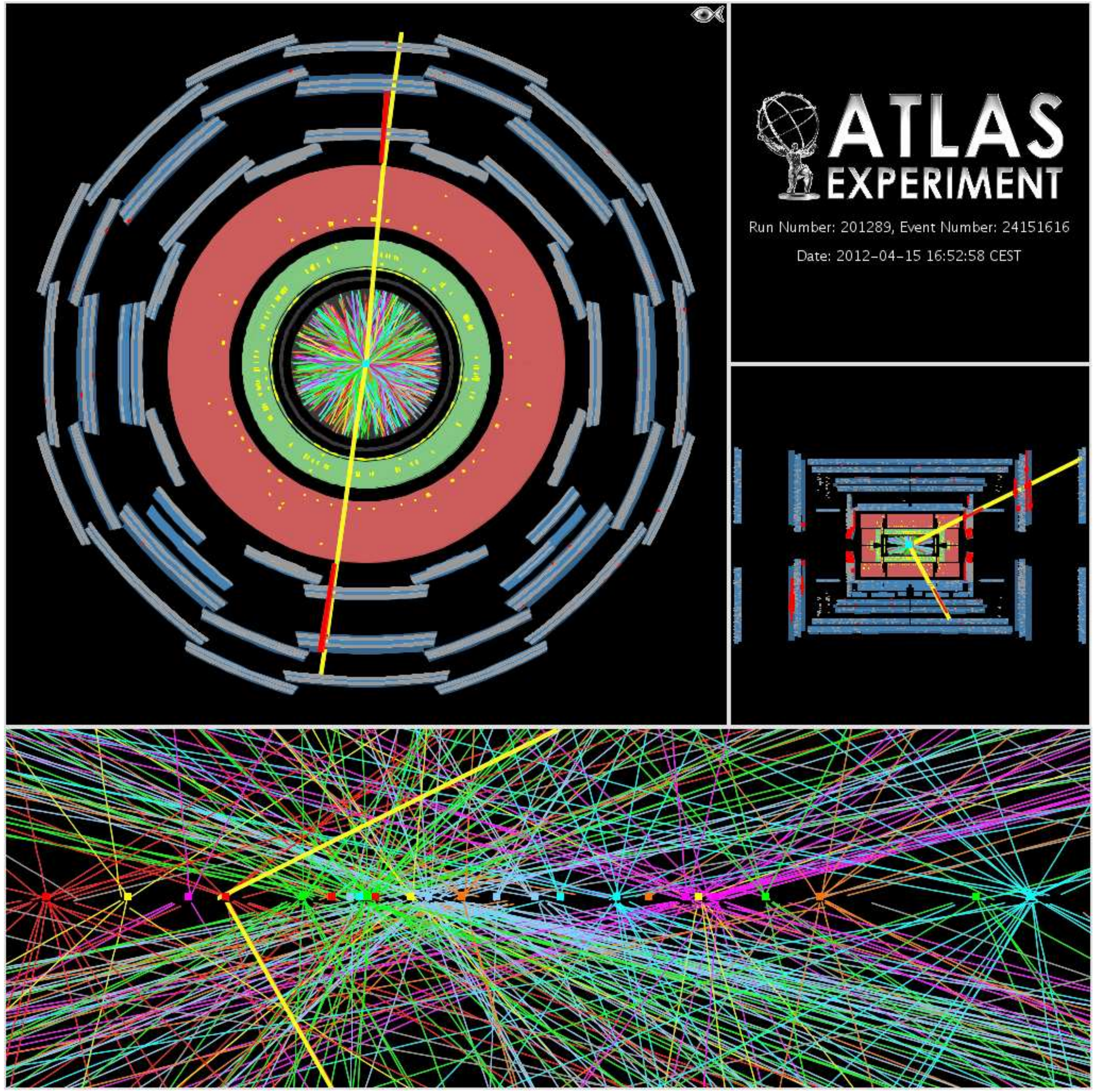


Look at the scales on y-axes: $1\ \text{fb}^{-1} = 1000\ \text{pb}^{-1}$

Dramatic progress over the years, meaning that one can now access less and less frequent processes...

...and at a higher and higher energy!

$Z \to \mu^+\mu^-$ candidate at high luminosity



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

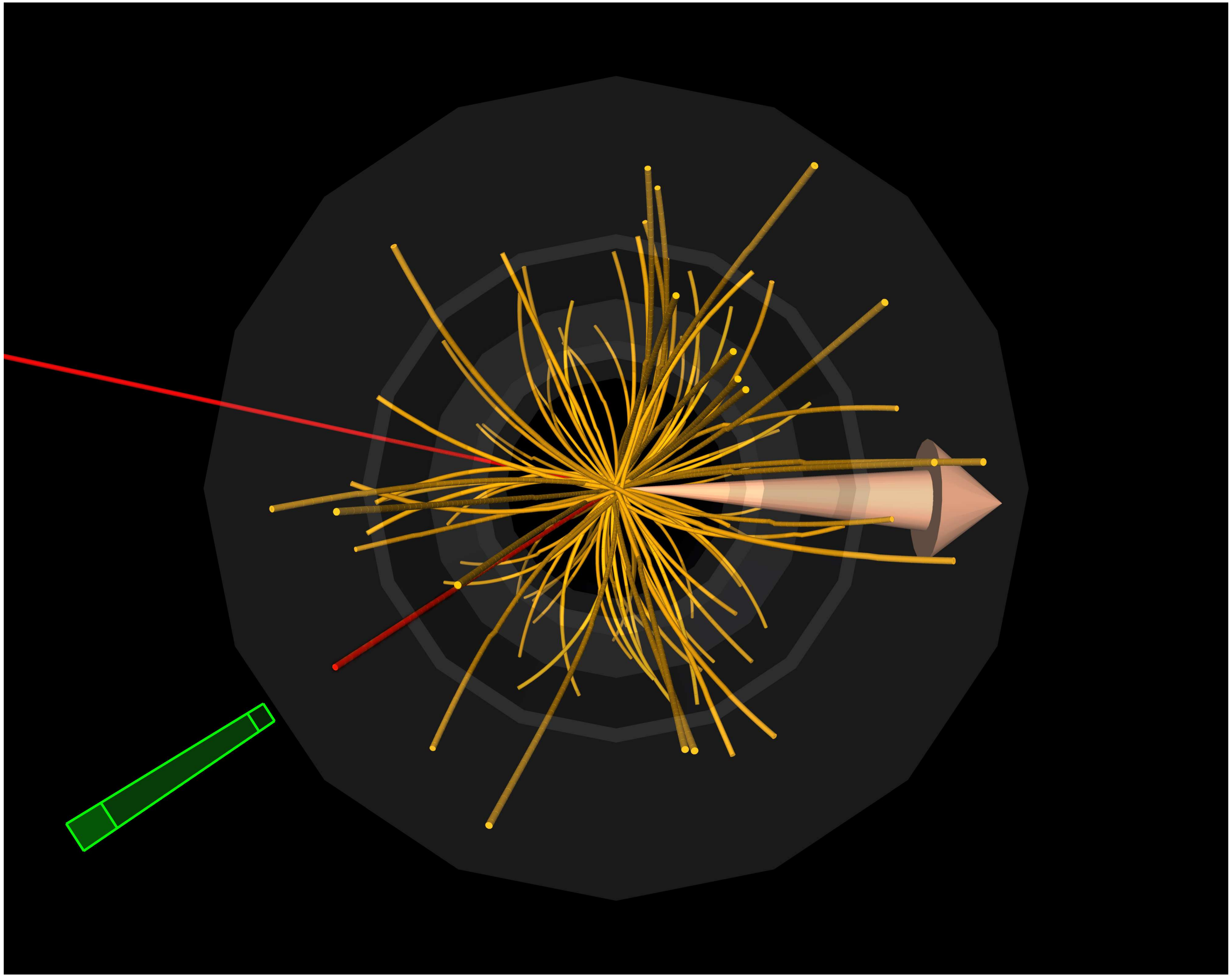
W^+W^- pair production

$W^+ \to \mu^+ \nu_\mu$

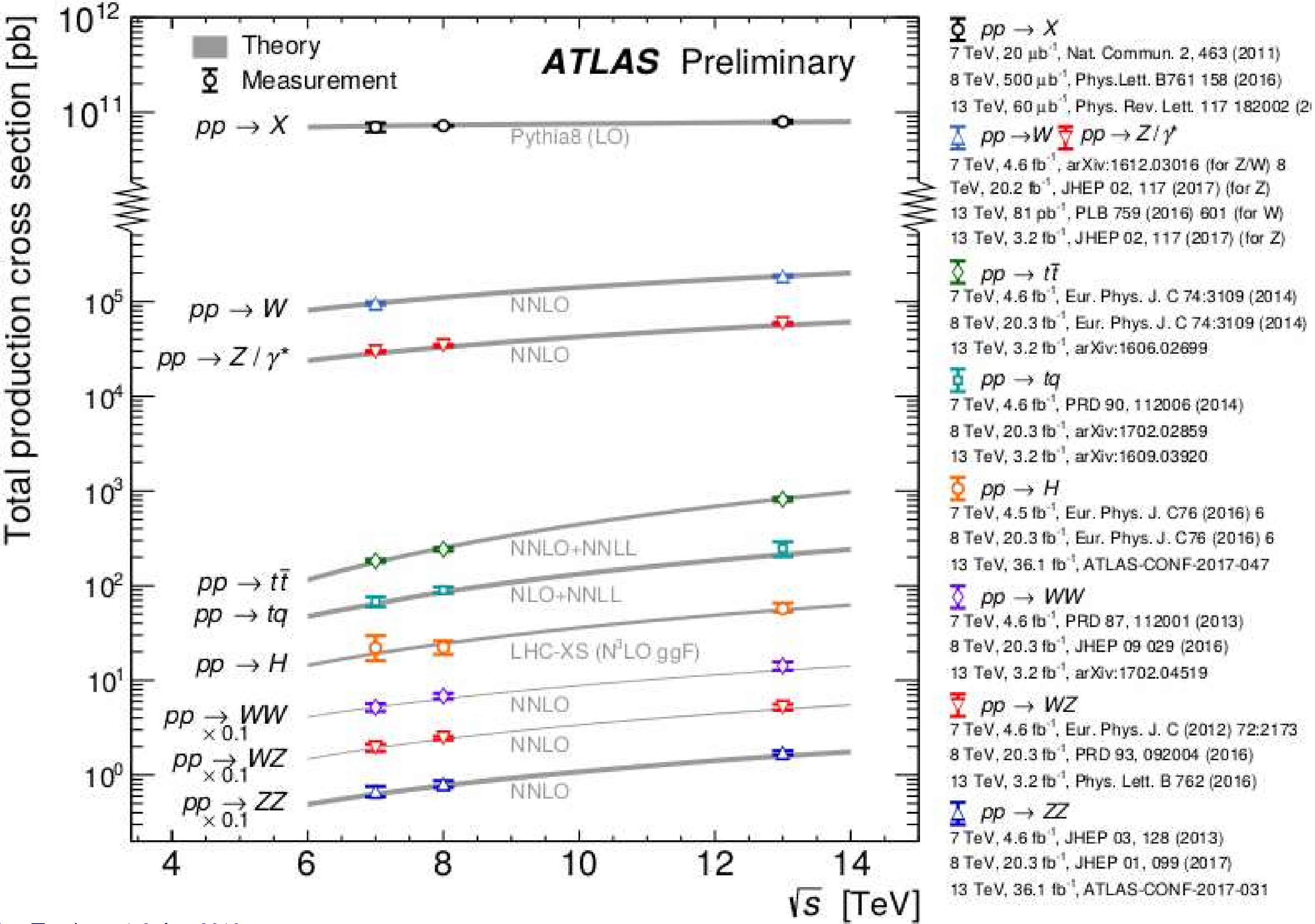
$W^- \to e^- \bar{\nu}_e$

Neutrinos escape detection

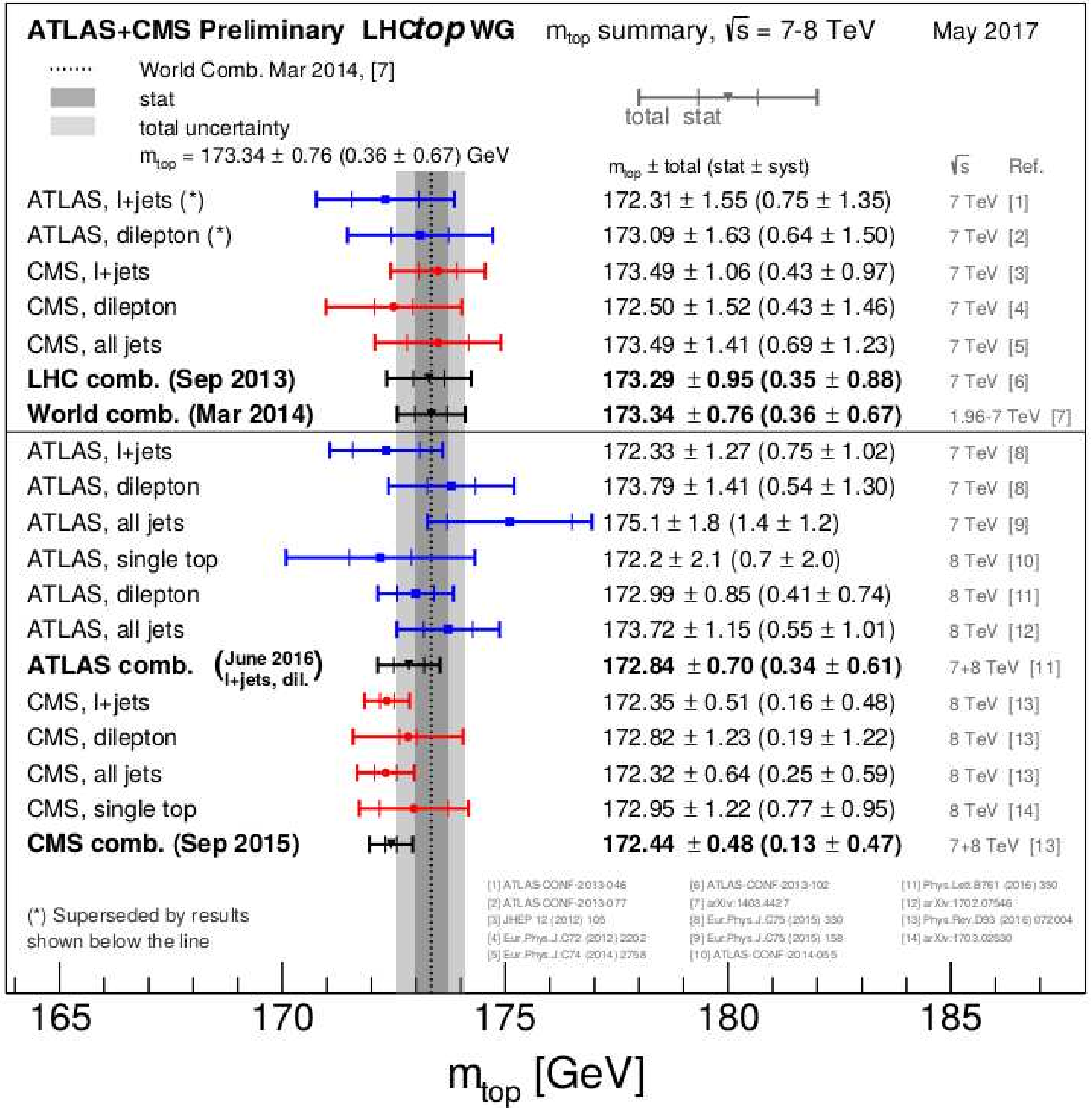
$\Rightarrow$ missing P_T



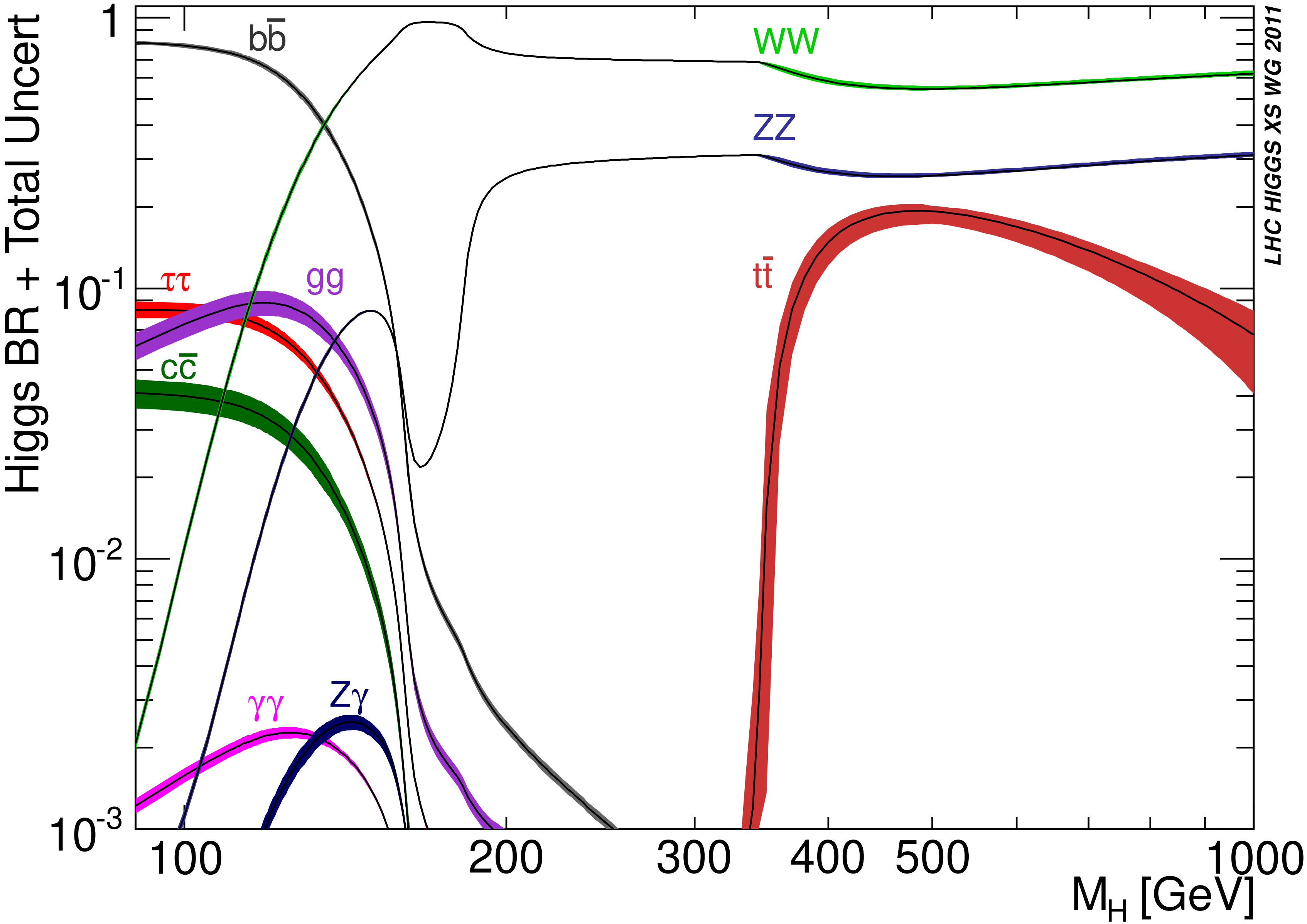
Standard Model cross sections vs theory



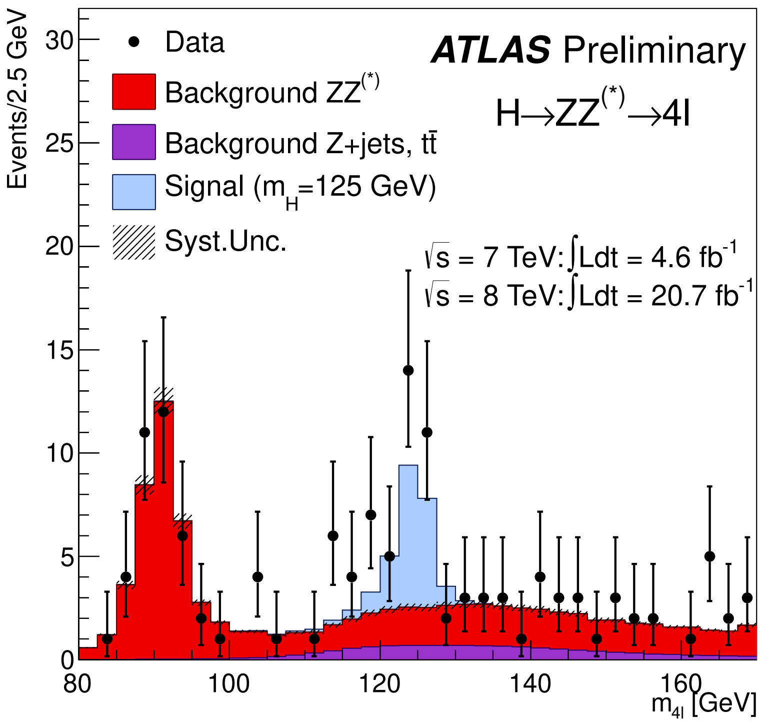
Top quark mass measurement

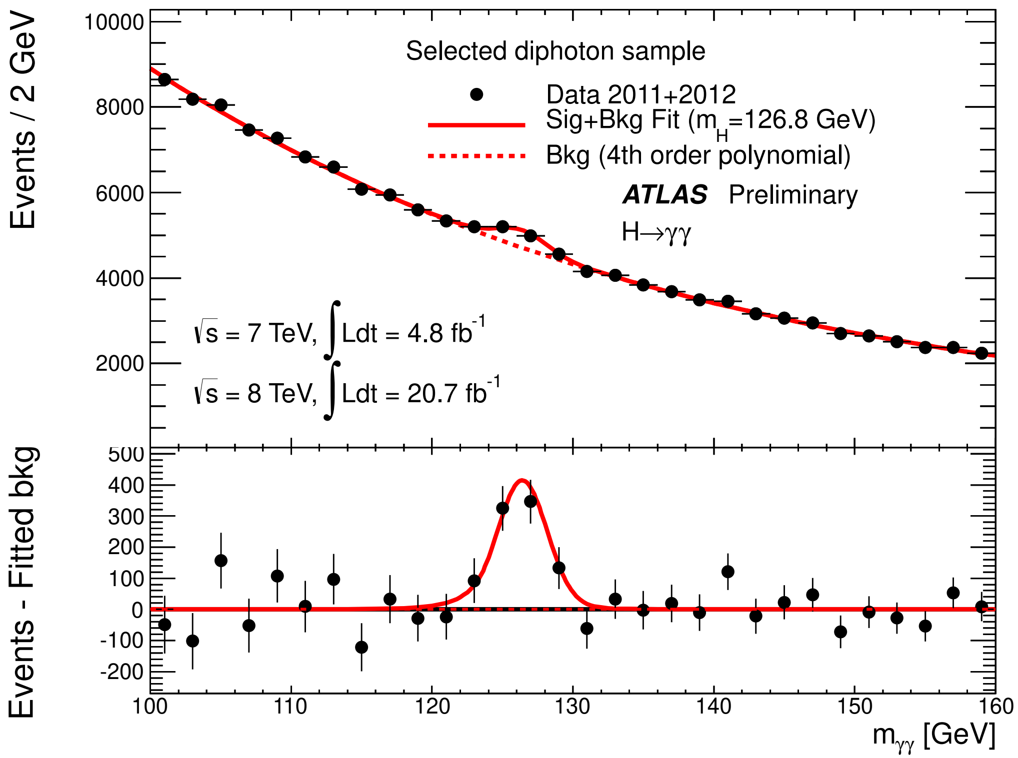


Decay modes of the Standard Model Higgs Boson

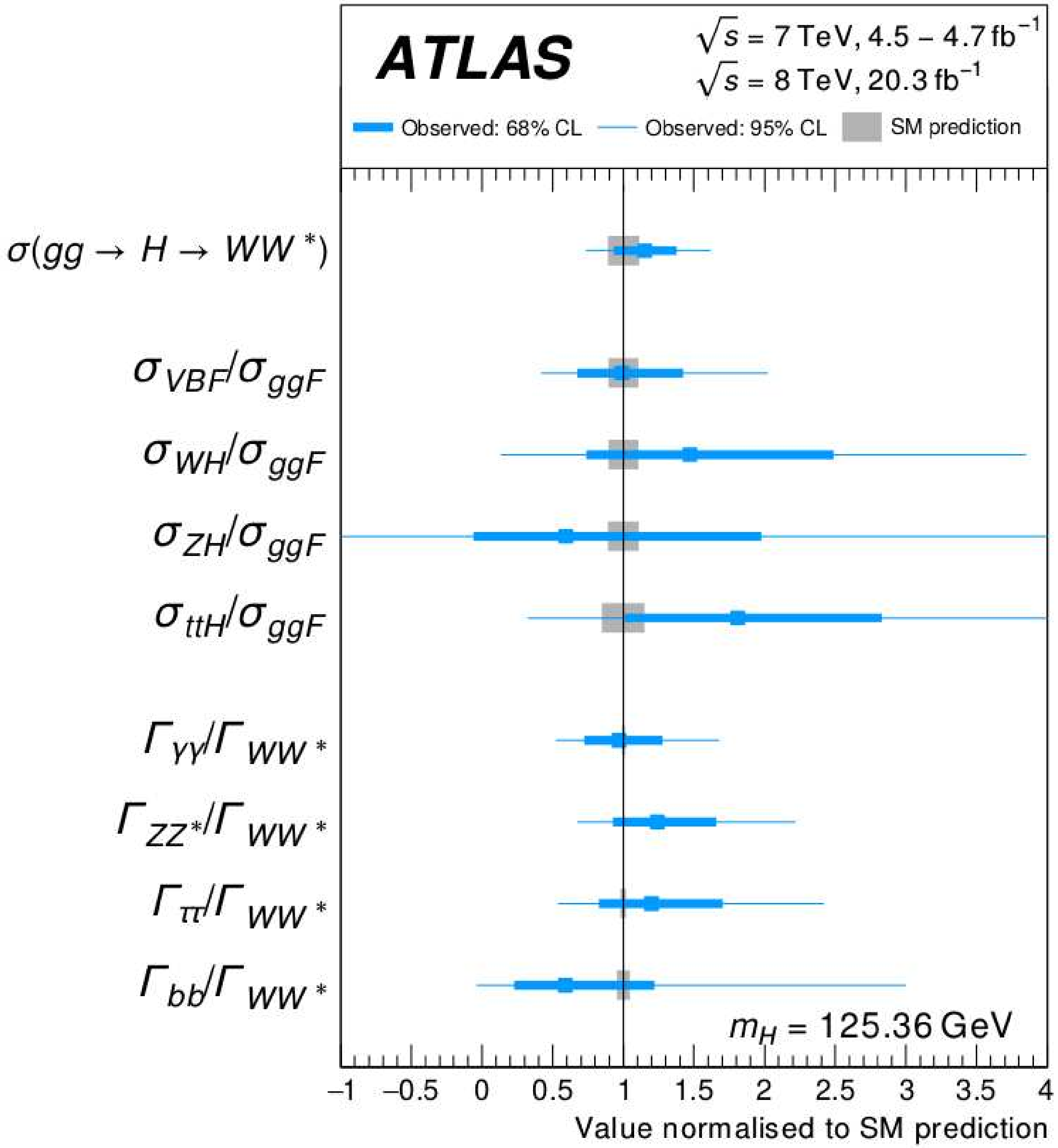


Higgs boson observation





Higgs decay Branching Ratios vs SM



Questions to the Standard Model

There are three types of interactions in the Standard Model, and the variety of gauge bosons, the interaction carriers: γ for electromagnetic,$W^{\pm}, Z^0$ for weak, g for strong.

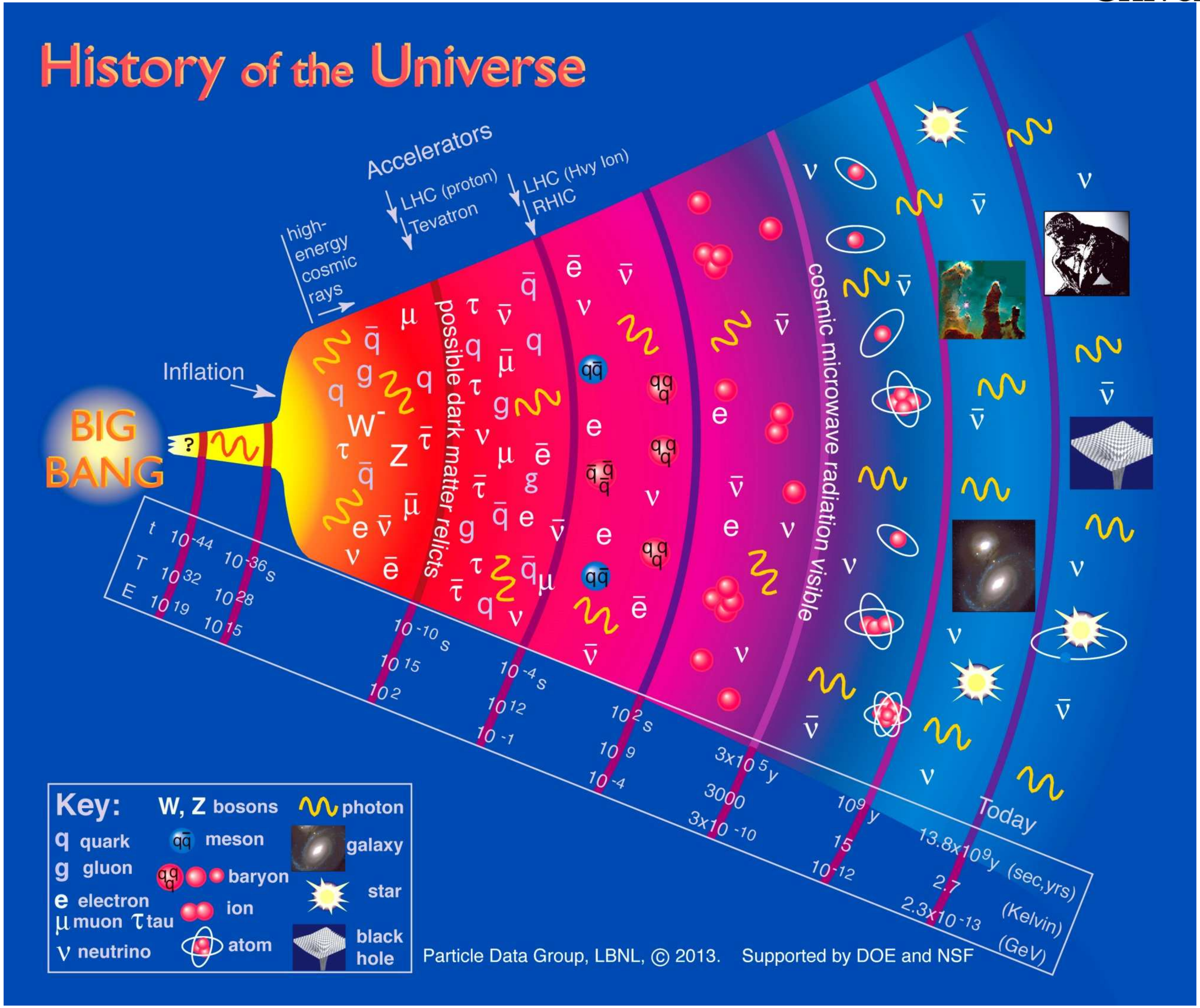
- ✦ Why are these three types so different – and the fourth, gravity, even more so?
- ✦ Why are there three generations of quarks and leptons?
- ✦ Why fractional electric charges of quarks?
- ✦ Why are the fermion masses so different?
- ✦ What determines the mixing of various generations?

These and many more questions cannot be answered within SM.

We need a bigger theory. . .

Cosmology: source of inspiration

- Universe is made up of $\sim 10^{11}$ galaxies; each galaxy contains $10^{10} - 10^{12}$ stars
- Cosmology: science about the history of the Universe
- Assumption: laws of physics have not changed along the way
- Method 1: observe the Universe evolution NOW and try to extrapolate backward
- Method 2: assume some starting point (the Big Bang) and extrapolate forward
- The overall established picture in modern cosmology is arguably as stable and solid as the Standard Model in Particle Physics, but it also has its unanswered questions
- The hope (from both camps) is that the answers may be shared!

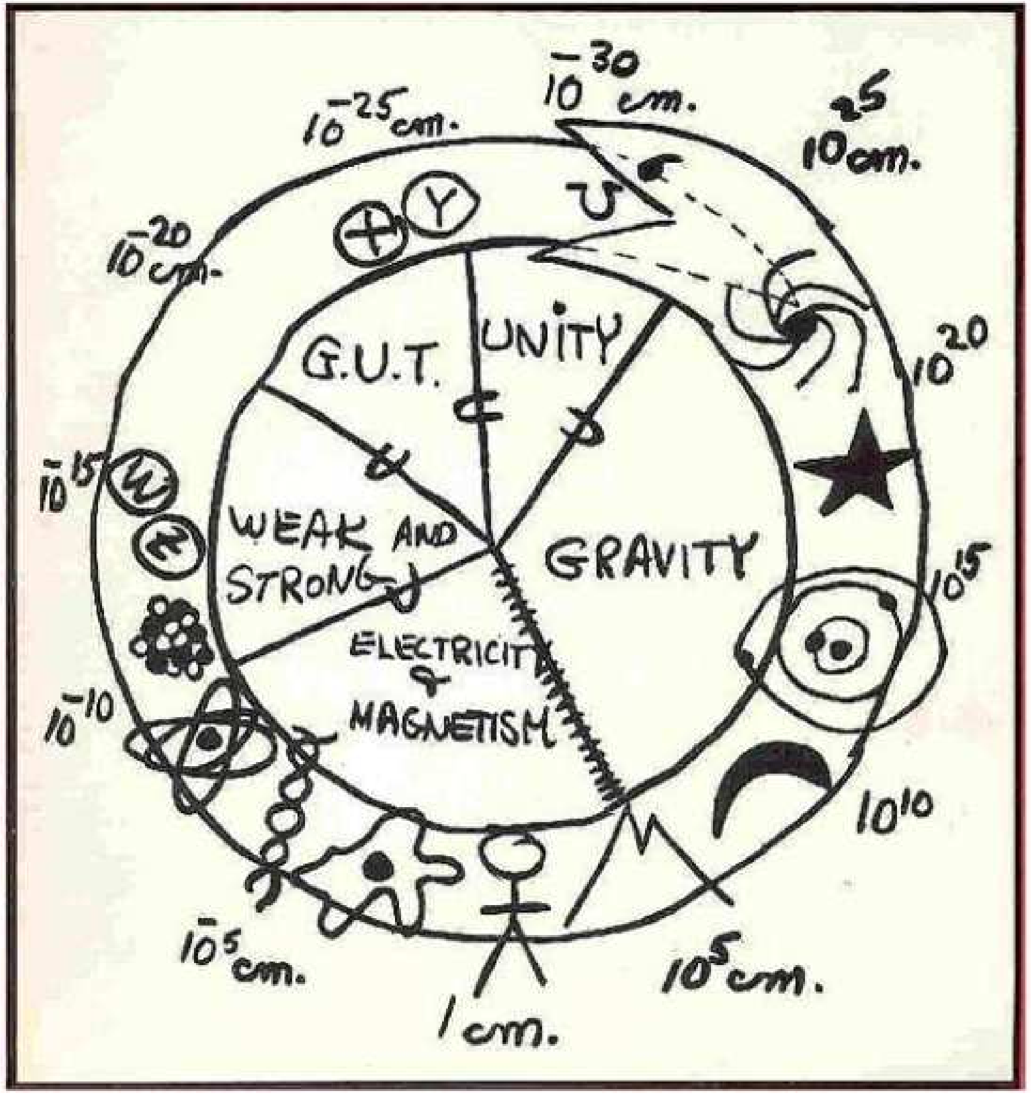

History of the Universe
Accelerators
LHC (proton)
Tevatron
LHC (Hvy Ion)
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-36 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-4 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
13.8x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

Glashow's serpent

As usual, "natural" system of units:

- $\hbar = 1, \; c = 1, \; k_B = 1$
- distance $\sim$ time
- Energy $\sim 1/$distance
- Temperature $\sim$ Energy
- Hence, Planck's mass

$$M_p = \sqrt{\frac{\hbar c}{G_N}} \quad = \quad 10^{19} \text{ GeV}$$
$$\sim \quad 10^{-25} \text{ cm}$$



Expanding Universe

Experimental fact: Universe is expanding

Light from distant galaxies is red-shifted (Doppler effect)

The larger the distance, the more the shift (can be measured precisely)

The light wave expands with space, hence the shift towards lower frequency

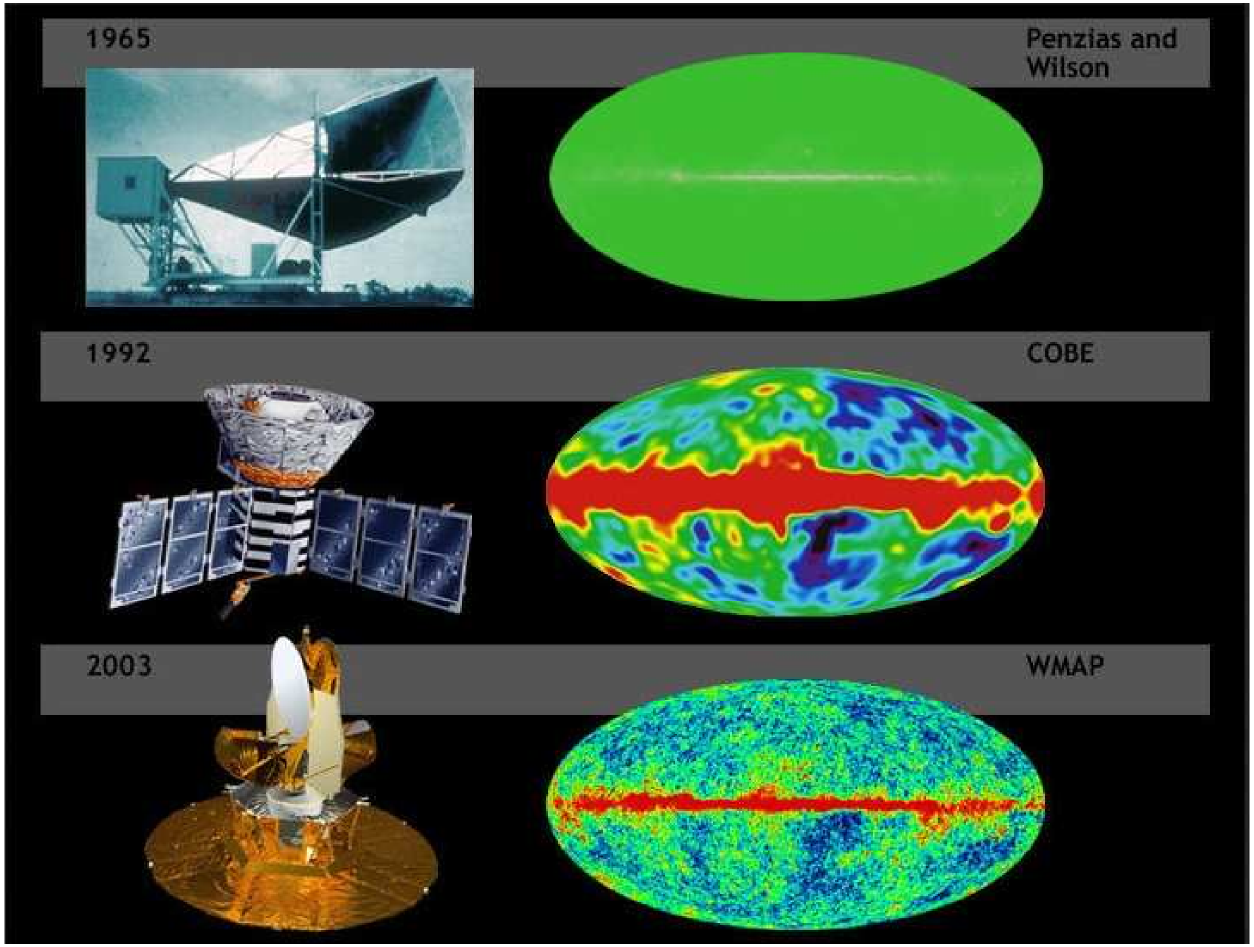
Hubble constant: 70 km/s per Megaparsec

Once, the Universe was 3000 times smaller – and 3000 times hotter than today

Cosmic Microwave Background 2.7 K today: photons wandering in space since then

Almost isotropic (same in all directions) – but NOT EXACTLY!

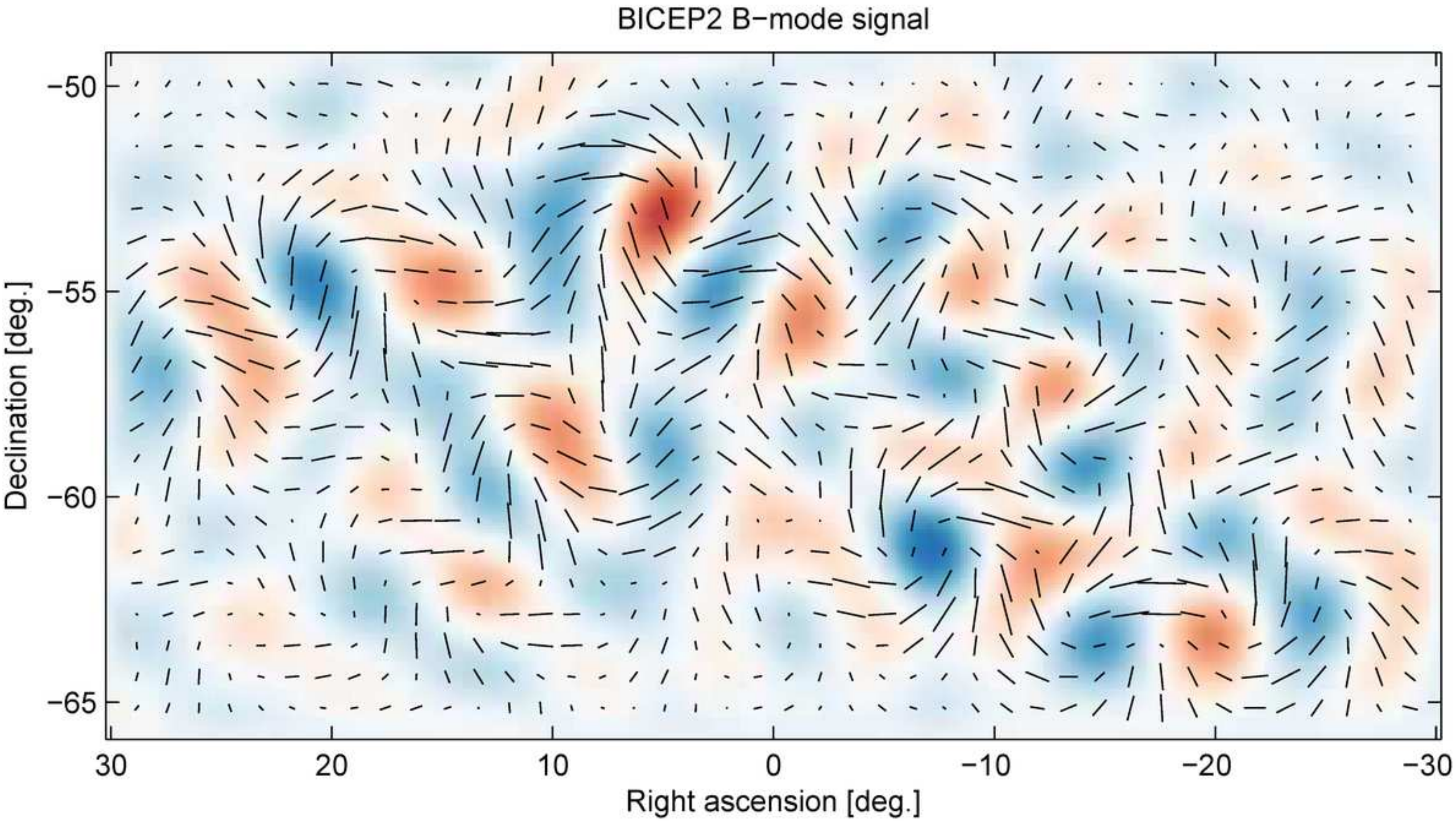
CMB anisotropy



Ripples from times 300 000 years ago, at the level of 10^{-3}

These small non-uniformities may be signals from the seeds of galaxy formation

Polarisation fluctuations



Possible signs of gravitational waves from the Big Bang?

Bariogenesis

Once the Universe was a billion times smaller and hotter than today

Light chemical elements were formed: $He^4,\ D,\ He^3,\ Li,\ \ldots$

Relative abundance of these elements can be predicted by theory

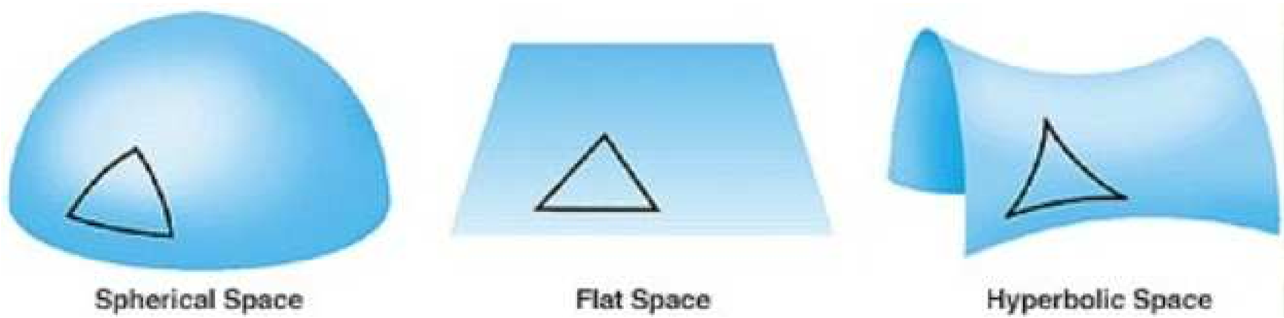
Depends on density of matter and number of types of particles

Does not seem to be enough to stop expansion, or even to form the galaxies like ours:

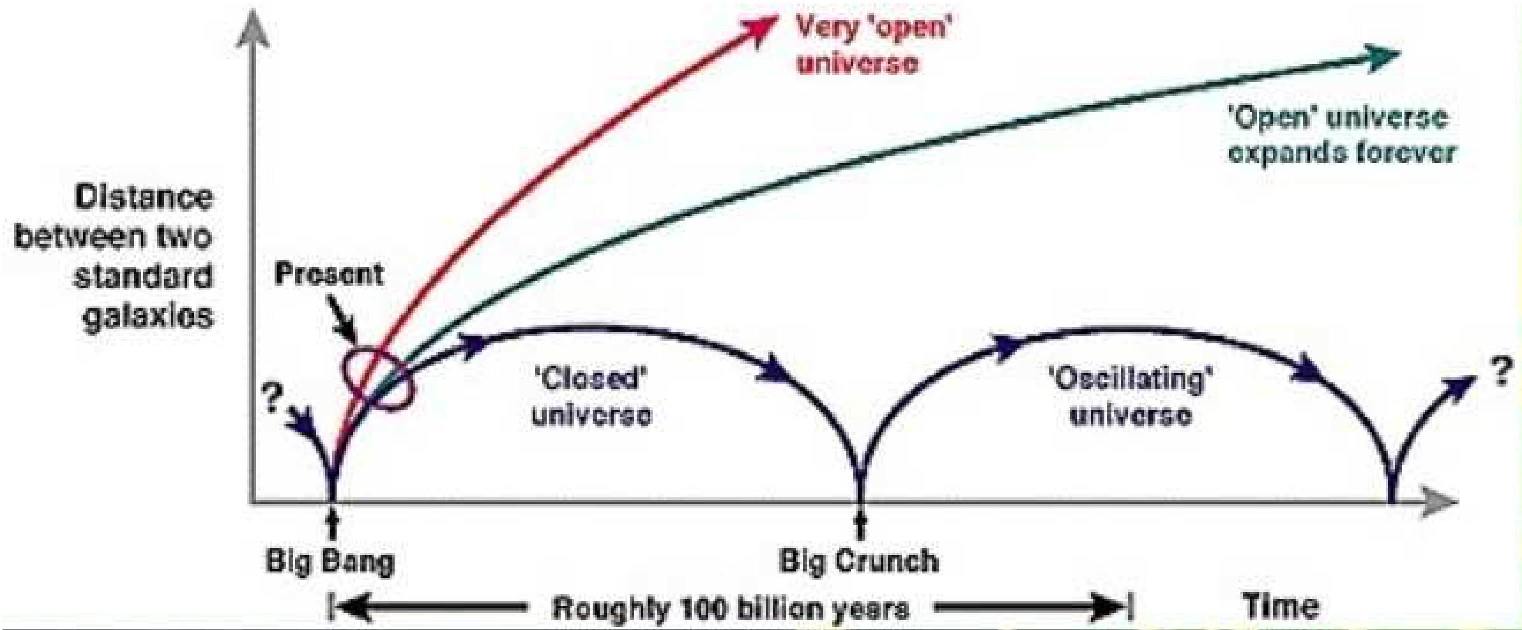
Cosmological inflation

Basic idea: very early, about maybe 10^{-35} s after the Big Bang, the expansion was exponentially fast

Can explain why the universe looks almost flat now



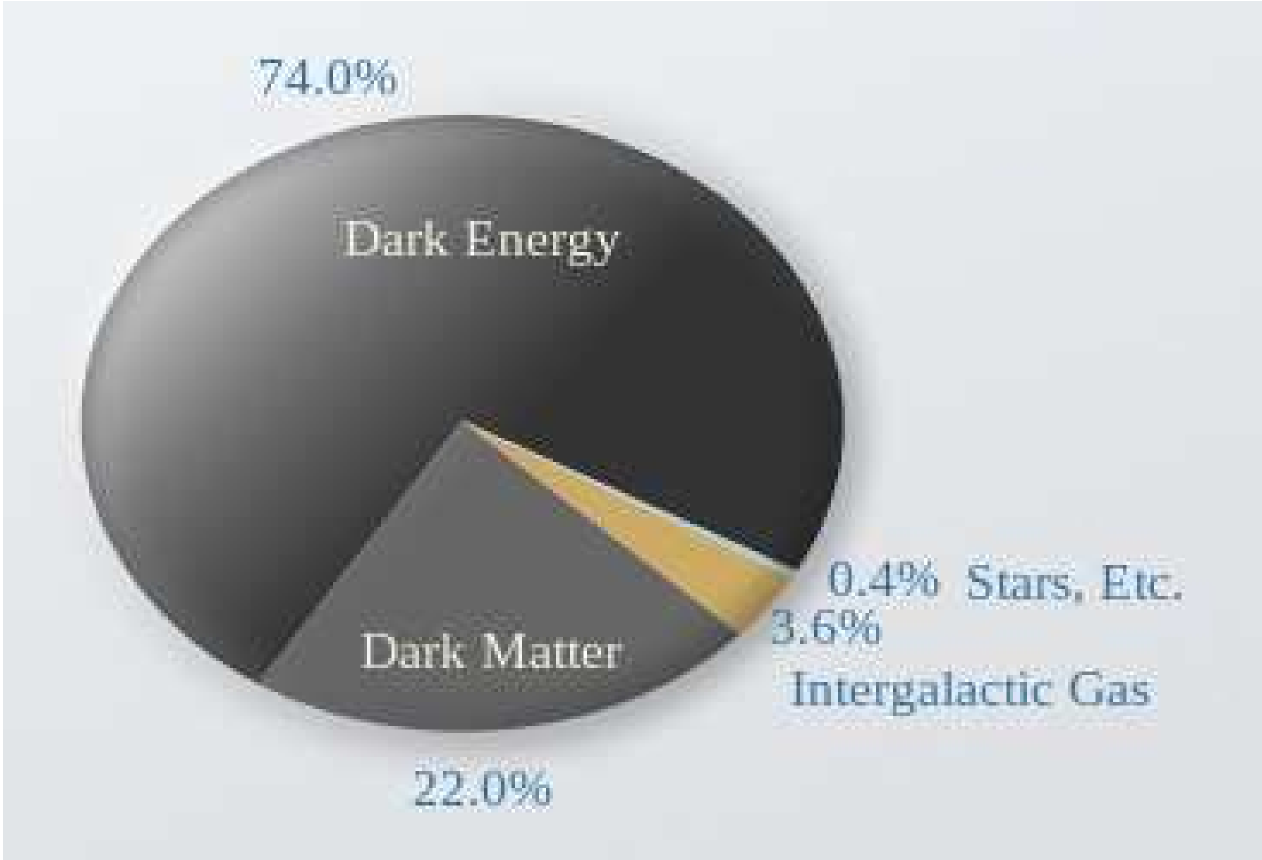
Fate of the Universe depends on this:



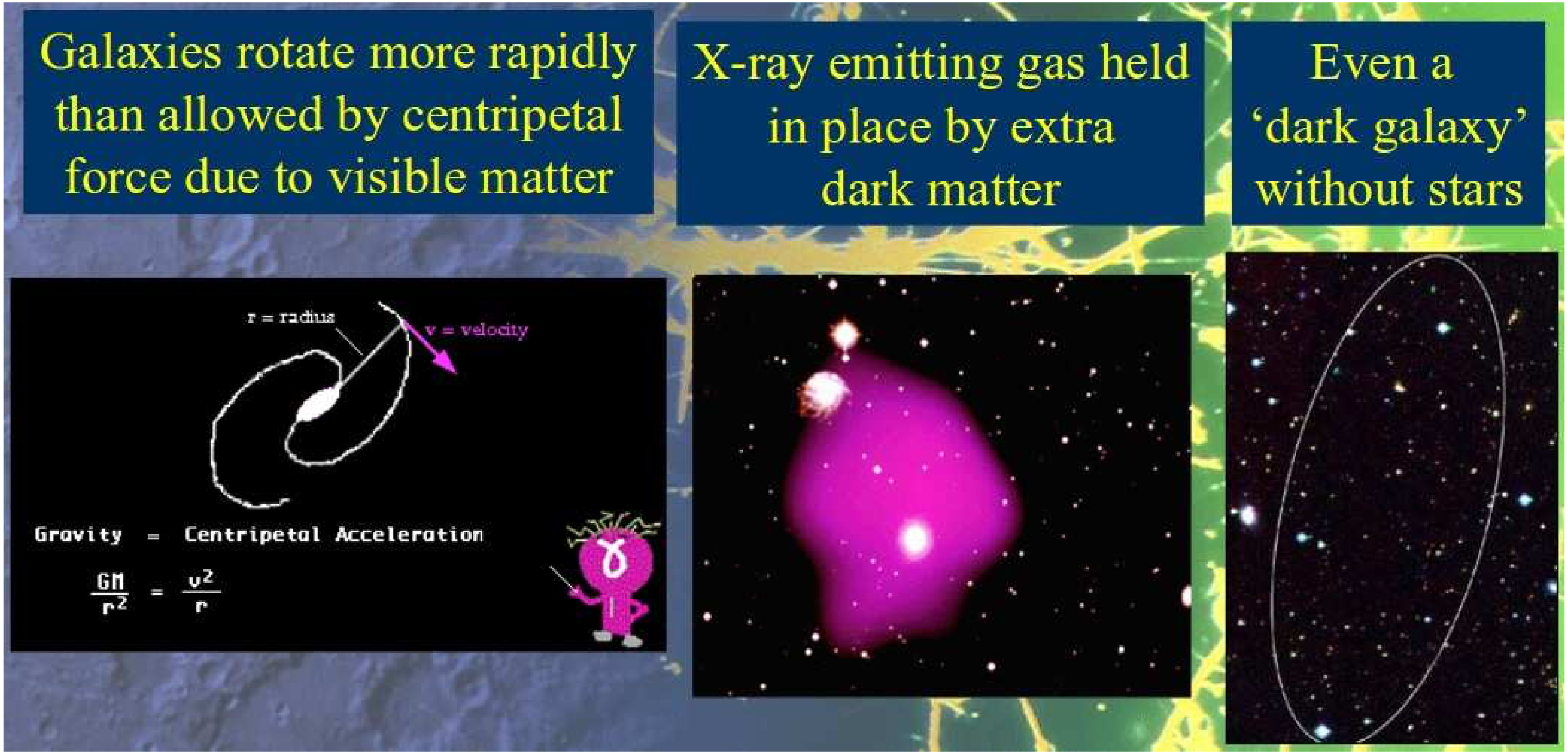
There is some critical value of the energy density which keeps the balance between expansion and contraction of the universe.

$\Omega = 1$ corresponds to a flat universe – close to what we see today

Latest measurements show that there are different components to this density:

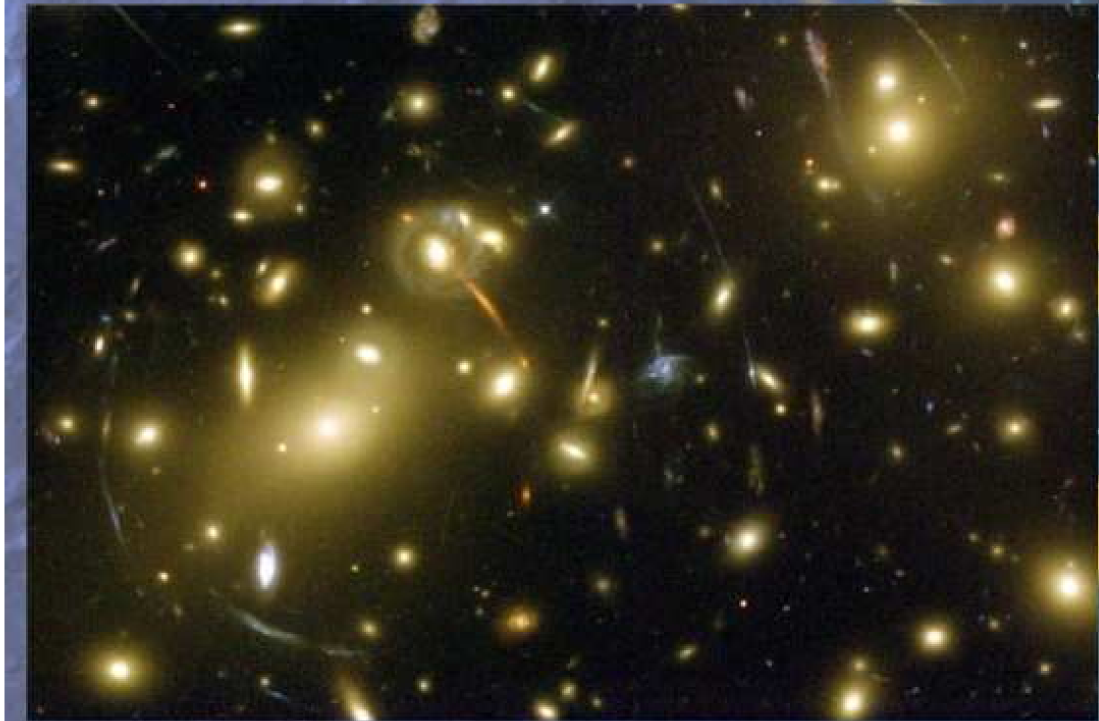


Evidence for Dark Matter – I

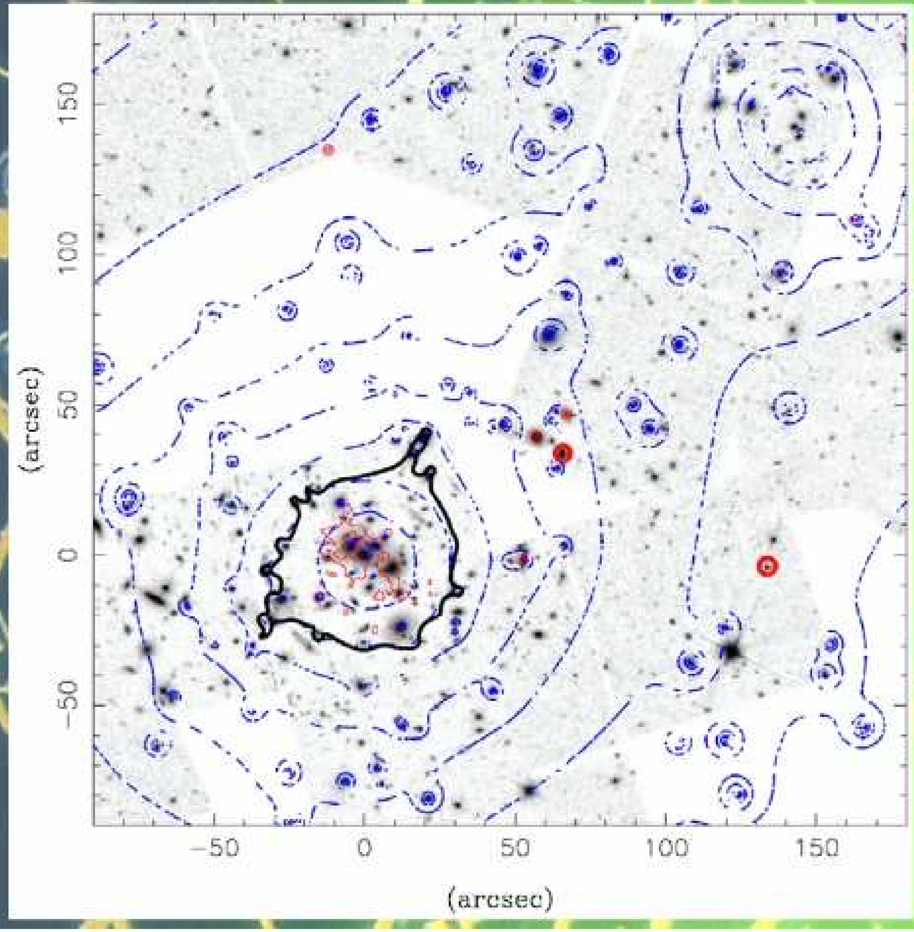


Evidence for Dark Matter – II

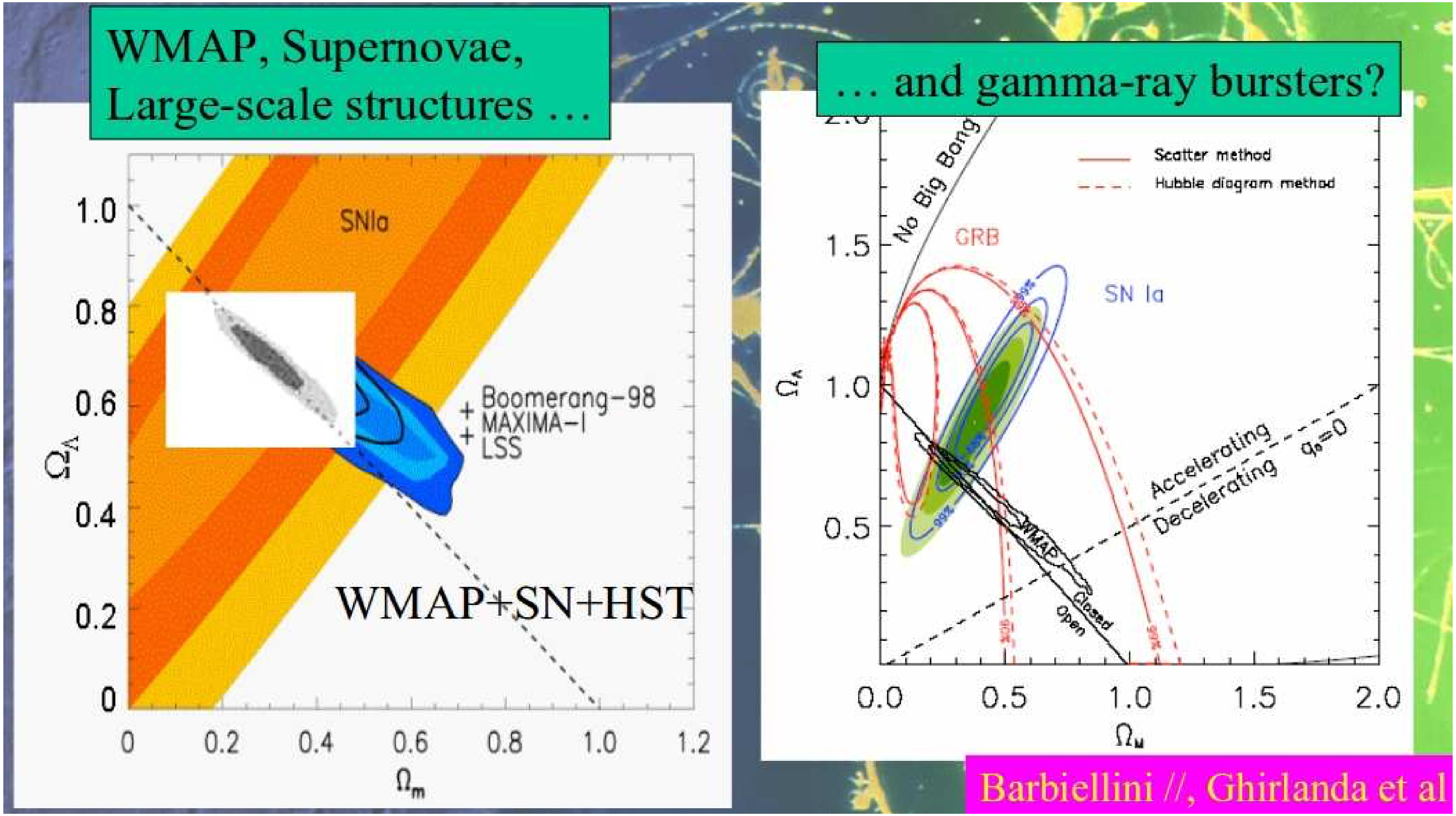
Light bent by gravitational field of dark matter



Contours of mass density



Experimental data on components of Ω



Unresolved questions in Cosmology

- Why is the Universe so big and old?
  - ~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?
  - almost flat: density nearly critical
- Where did the matter come from?
  - 1 proton for every 1,000,000,000 photons
- How did structures form?
  - ripples + invisible dark matter?
- What is the dark matter?
- What is the dark energy?

The hope is that Particle Physics can help answer at least some of these!

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: lower limits

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

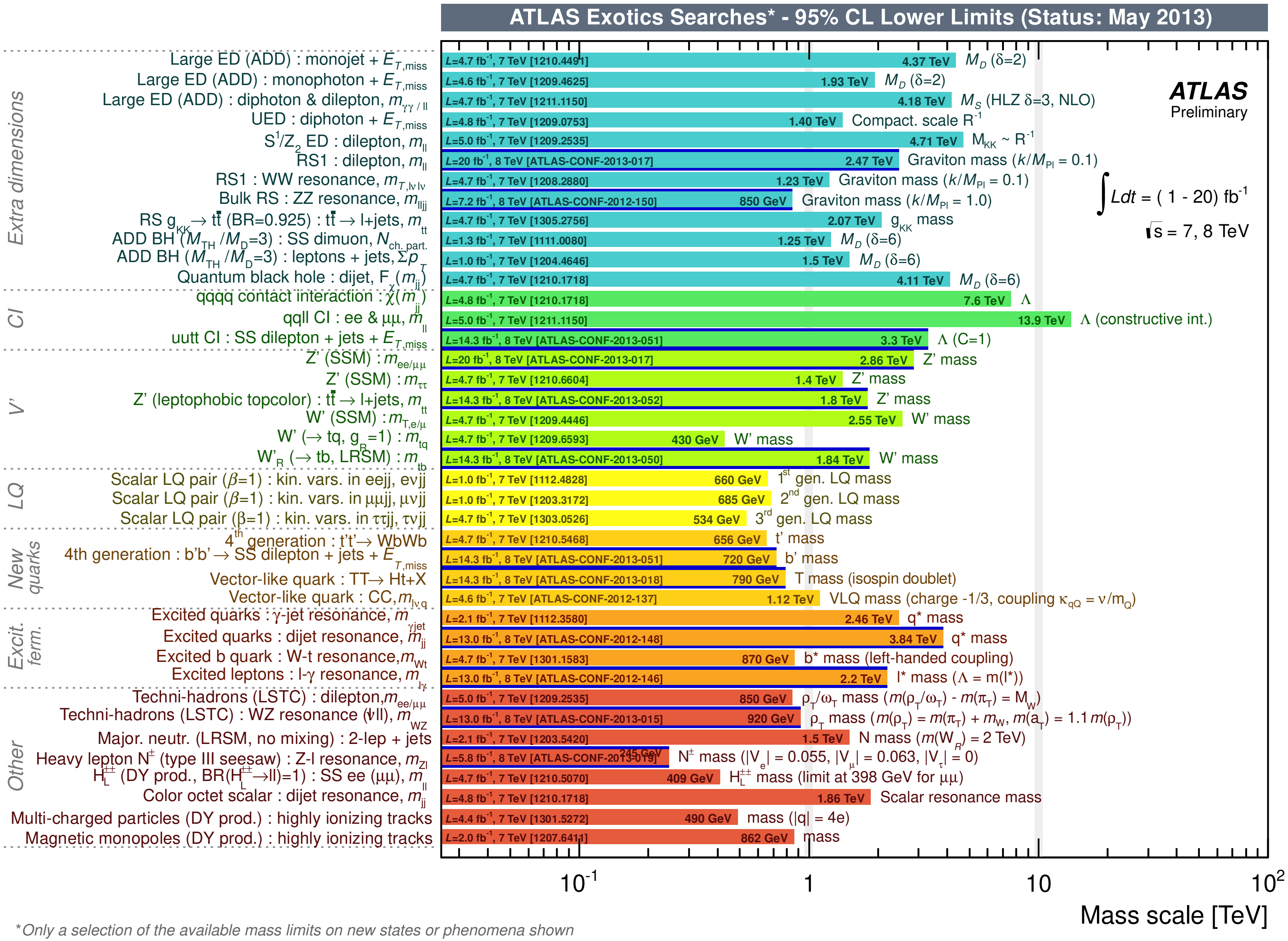
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	m($\tilde{G}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 285 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq 0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq 0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} 1 **Mass scale [TeV]**

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

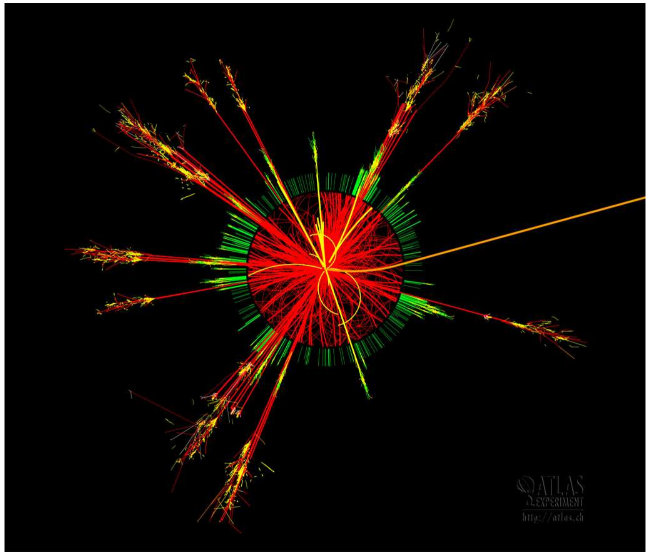
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Exotics searches: lower limits



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!



Web Resources

1. Lancaster Particle Physics Package for A-level students:
   http://www.hep.lancs.ac.uk/package/
   Some basic stuff - worth a look or two (feedback welcome)

2. Paricle Physics in the UK website, plenty of info and links:
   http://hepweb.rl.ac.uk/ppUK/

3. FNAL (Fermi National Accelerator Laboratory), home of the Tevatron:
   http://www.fnal.gov/

4. CERN (European Centre for Nuclear Research), home of LEP and LHC:
   http://public.web.cern.ch/public/

5. The ultimate resource: Particle Data Group website
   http://pdg.lbl.gov
   The official reference for all particle data. Many useful review articles, too