The Higgs Boson and Beyond at the Large Hadron Collider

Mike Hance (LBNL)

July 11, 2013

Particle Physics at the LHC

Today's Discussion:

- A few words about me
- Some basic particle physics
  - Fundamental particles and their interactions
  - Why the Higgs is important
  - What questions we're trying to answer at particle colliders

Short break here.

- The tools
  - The Large Hadron Collider
  - The ATLAS detector
- What we've learned in the past 5 years
  - There is a Higgs!
  - ...and other interesting things.
- Conclusion

About Me

About me

I went to high school in Connecticut, and then undergrad at Boston University.

- Majored in Physics and Math
- Research with the Intermediate Energy Group (physics)
  - Worked on scintillators and electronics for a muon-lifetime experiment
  - Great introduction to 'real' research
  - Travel to Switzerland for a few weeks over the summer
- Most useful things I did in college:
  1. Took two semesters of intro CS (programming)
  2. Found mentors early
  3. Found a research project that I could continue for several semesters
  4. Had fun!

About me

Graduate School at UPenn

- Two years of courses
- Research during the summers (and part-time in the second year)
- Full-time research after second year
  - This varies among universities and research topics
- I moved to CERN for three years after classes
  - Will mention some of the things I worked on later
- Back to the US to finish my dissertation

Post-doc at LBL

- Very similar to grad school, but with a little more autonomy and responsibility
- Typically lasts for 2-5 years in HEP

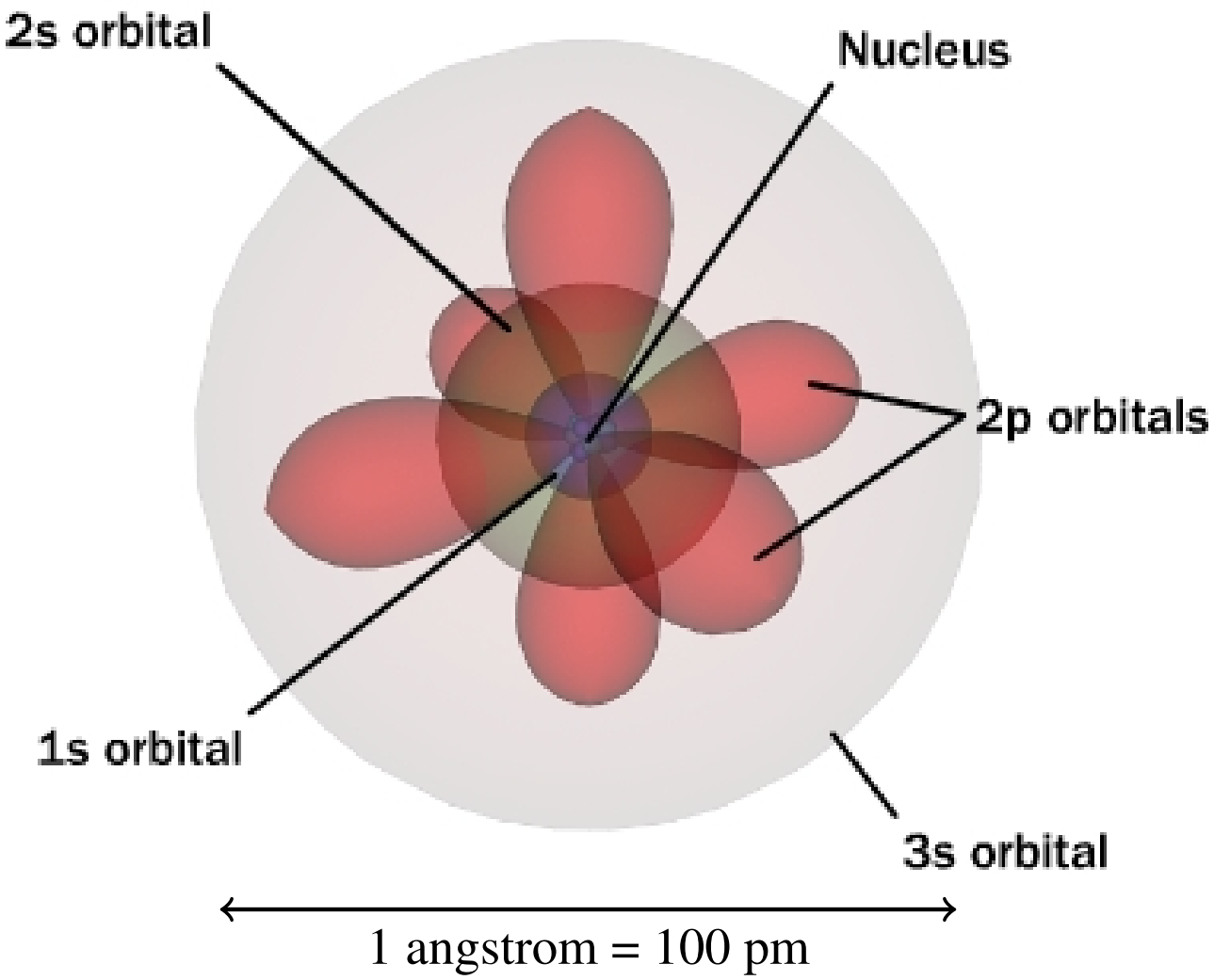
Particle Physics 101 (In 15 Minutes)

Some Useful Terms

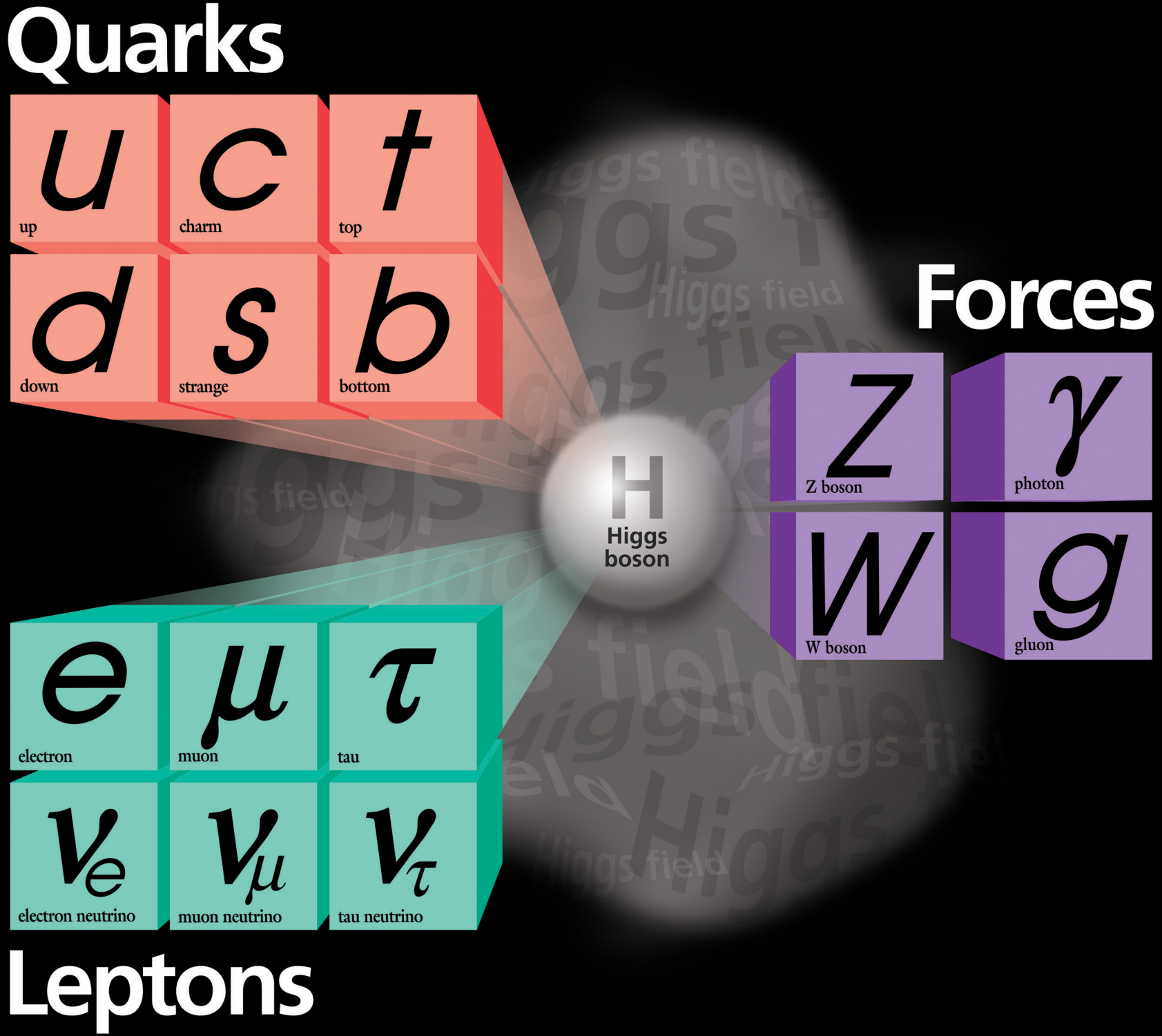
Some terms that will be useful today:

- **Cross section**: rate at which a given subatomic interaction occurs, abbrev. σ
- **barn**: a measure of cross section, abbrev. "b"
  - 1b = 10^{-28} m^2, 1 pb = 10^{-34} m^2
  - "Large cross section" – something that happens often (nb-pb)
  - "Small cross section" – rare process (fb)
- **Luminosity**: the rate at which particles collide in an accelerator
  - Expressed in units of 1/barns, e.g. 1000 pb^{-1} = 1 fb^{-1}
- **Integrated luminosity**: a measure of the amount of collisions recorded, abbrev. $\int \mathcal{L}$dt
- **electron Volt**: a unit of energy, abbrev. "eV"
  - $E = mc^2$, so is also a unit of mass (GeV$/c^2$) or momentum (GeV/c)
  - 1 proton has mass of roughly 1 GeV/c^2
- **Planck Mass**: what combination of fundamental constants ($\hbar, c, G$) gives units of mass?
  - $m_{\mathrm{P}} = \sqrt{\frac{\hbar c}{G}}$ = 2.18$\times 10^{-8}$ kg = 1.22 $\times$ 10^{19} GeV/c^2

Atoms are... big



- Usually a stable system
- Mass $\approx n \times 1.67 \times 10^{-27}$ kg $= n$ GeV/c^2
- Nucleons bound together
- Foundations of chemistry


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
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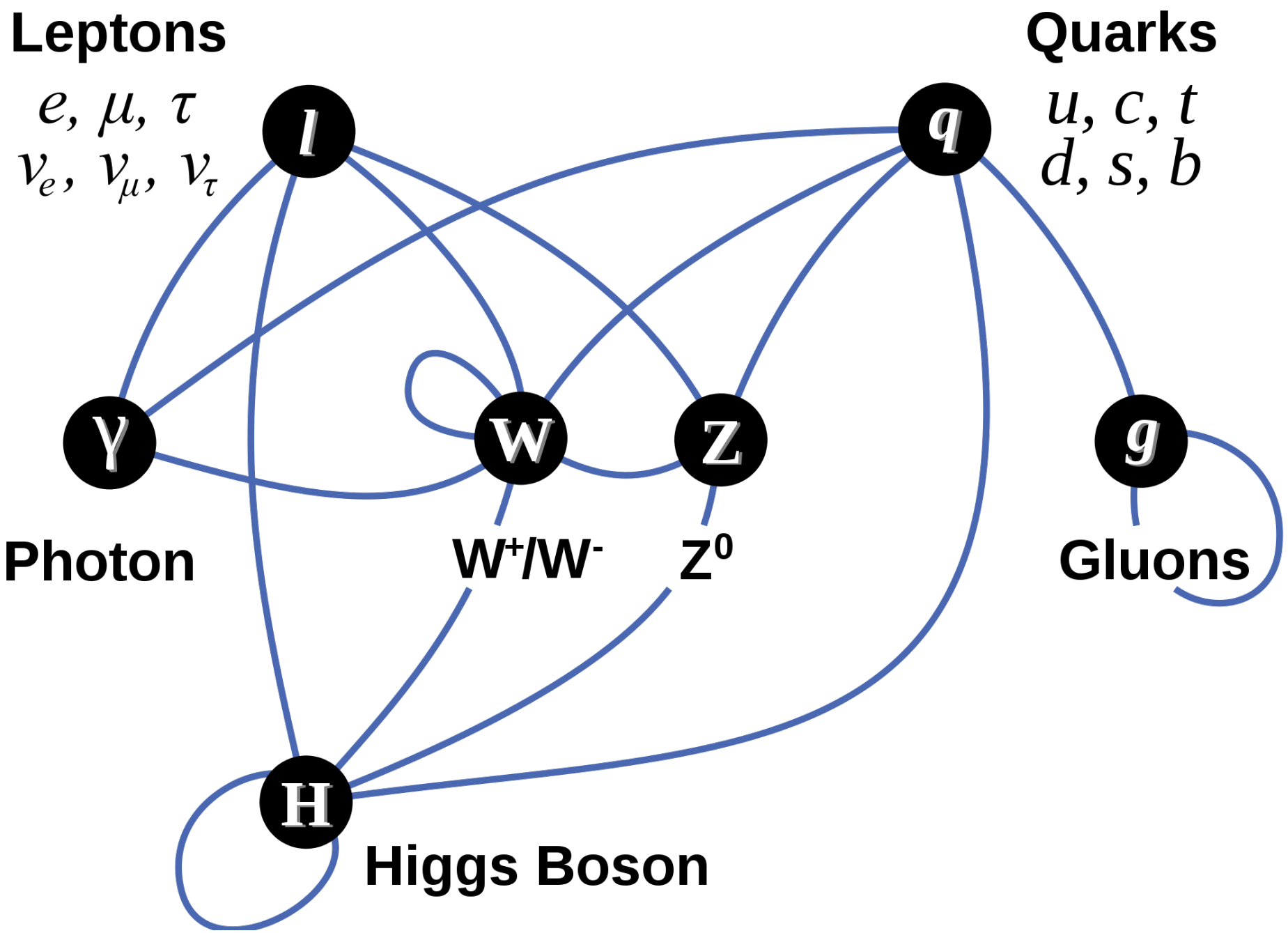
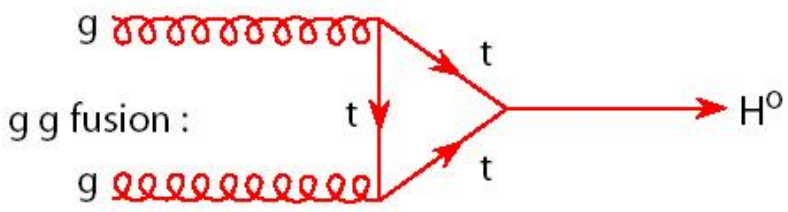
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons

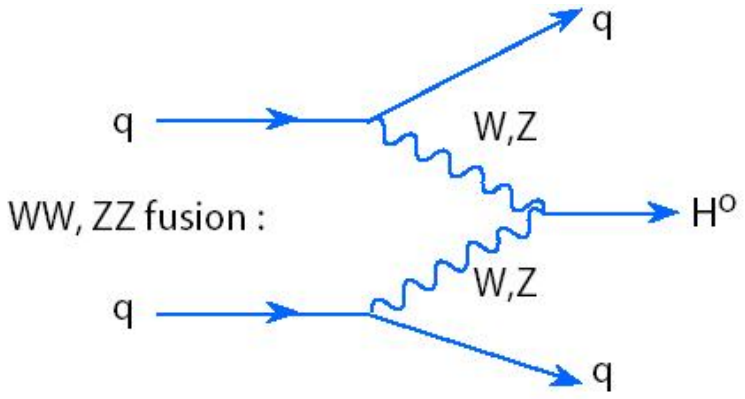

Leptons
e, μ, τ
ν_e, ν_μ, ν_τ
Quarks
u, c, t
d, s, b
l
q
γ
W
Z
g
Photon
W+/W-
Z0
Gluons
H
Higgs Boson

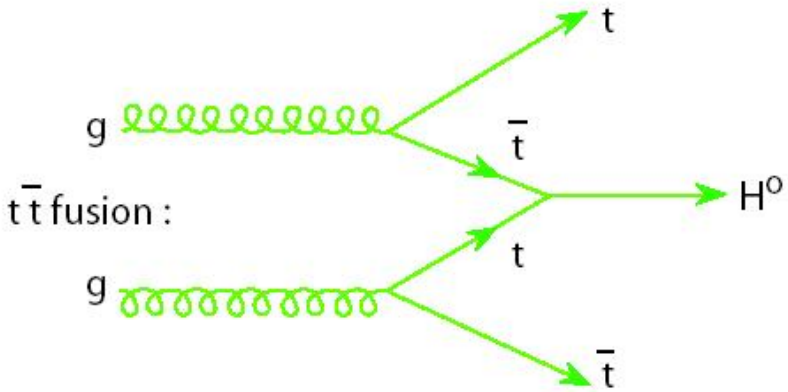
Discovering the Standard Model

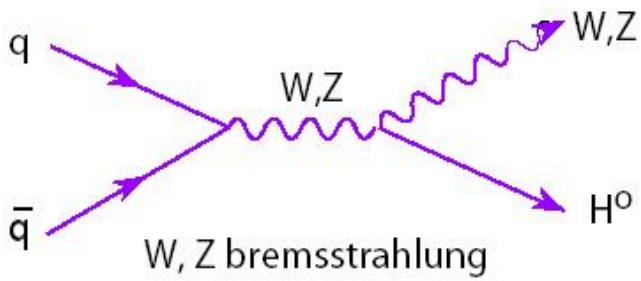
We've found all the pieces of the Standard Model... except perhaps one:

- Gluon observed in late 70's
- W and Z bosons first observed in 1980's
- All flavors of quarks and leptons have been found (last was t-quark in 1995)
- No signs of the Higgs until recently

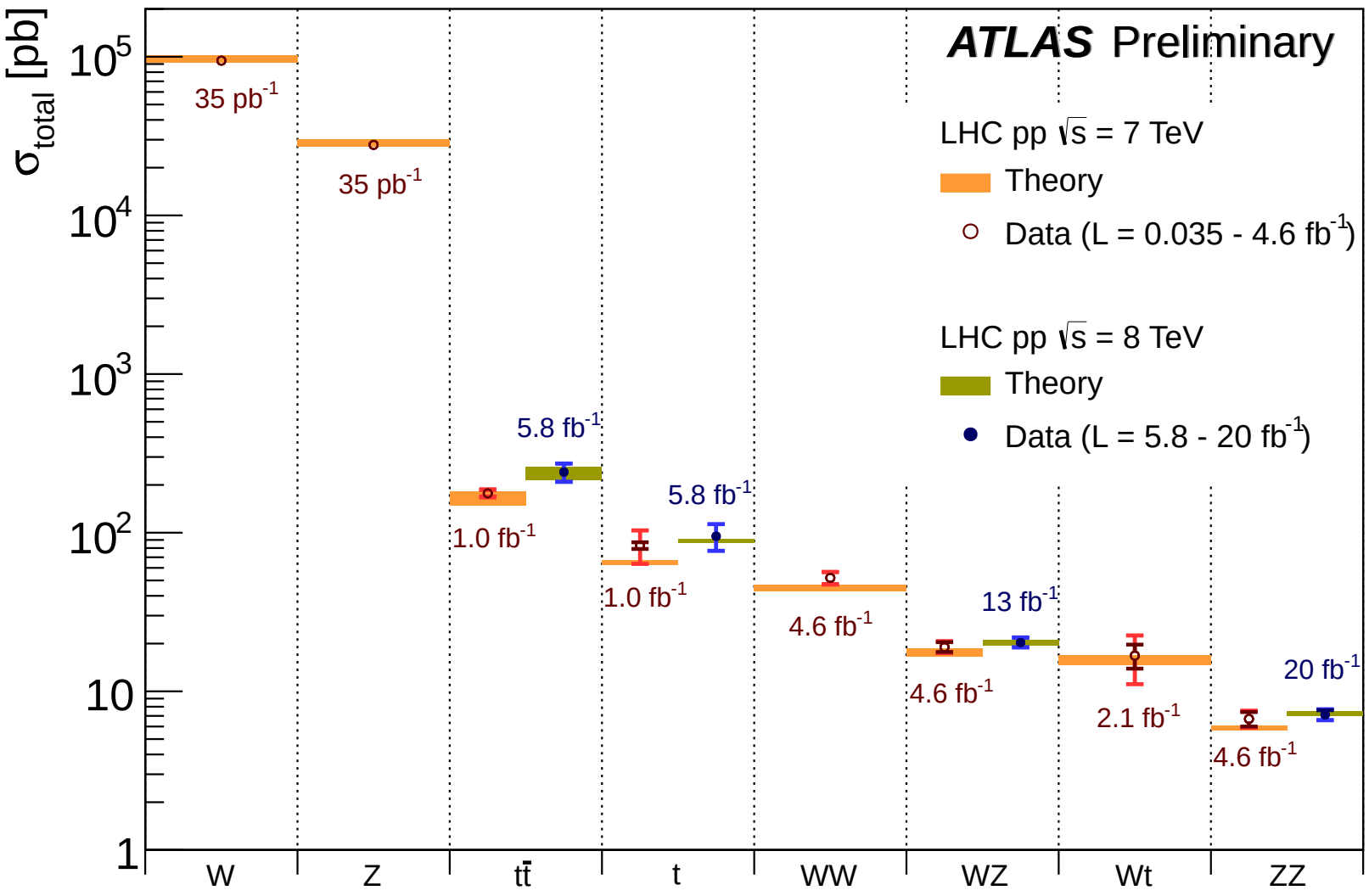








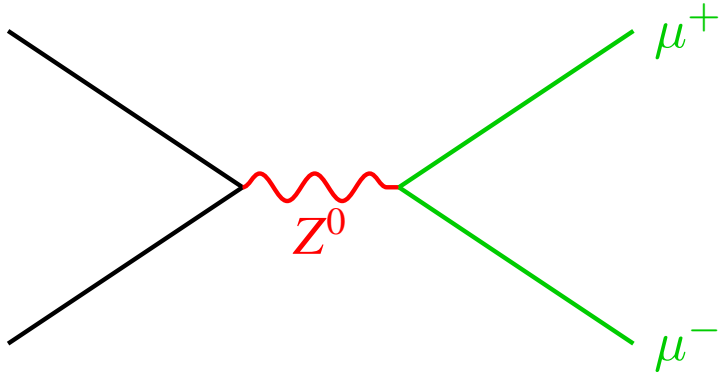
Discovering the Standard Model



Finding Heavy Particles

One way to find heavy particles is to look for *mass resonances*.

- $E = mc^2$ is only really true for particles at rest
- $E^2 = m_0^2 c^4 + \vec{p}^2 c^2$ in special relativity



- $m_Z = \sqrt{E_Z^2 - (||\vec{p_Z}||c)^2}/c^2$
- Let $c = 1$
- $m_Z = \sqrt{(E_{\mu^+} + E_{\mu^-})^2 - ||\vec{p}_{\mu^+} + \vec{p}_{\mu^-}||^2}$

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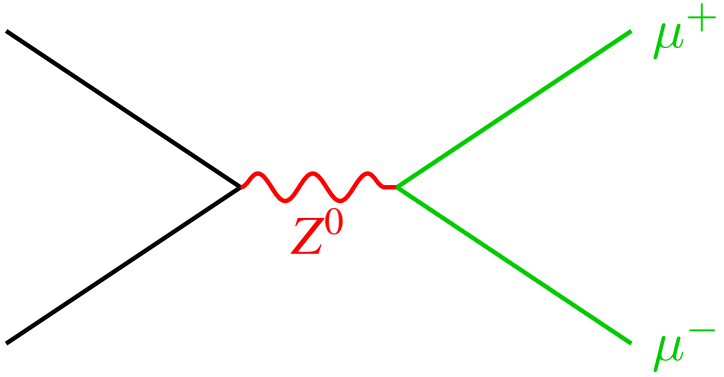

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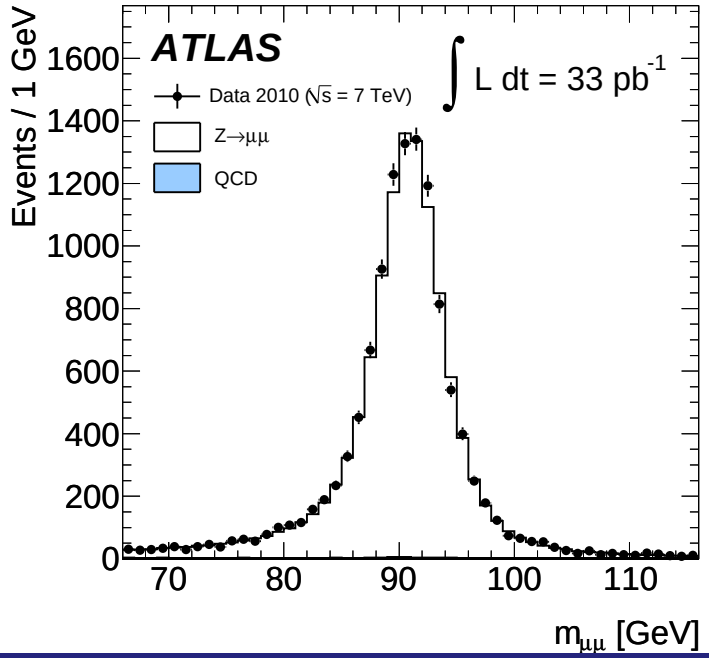
So, by measuring muon properties, we can reconstruct the Z-boson mass and momentum

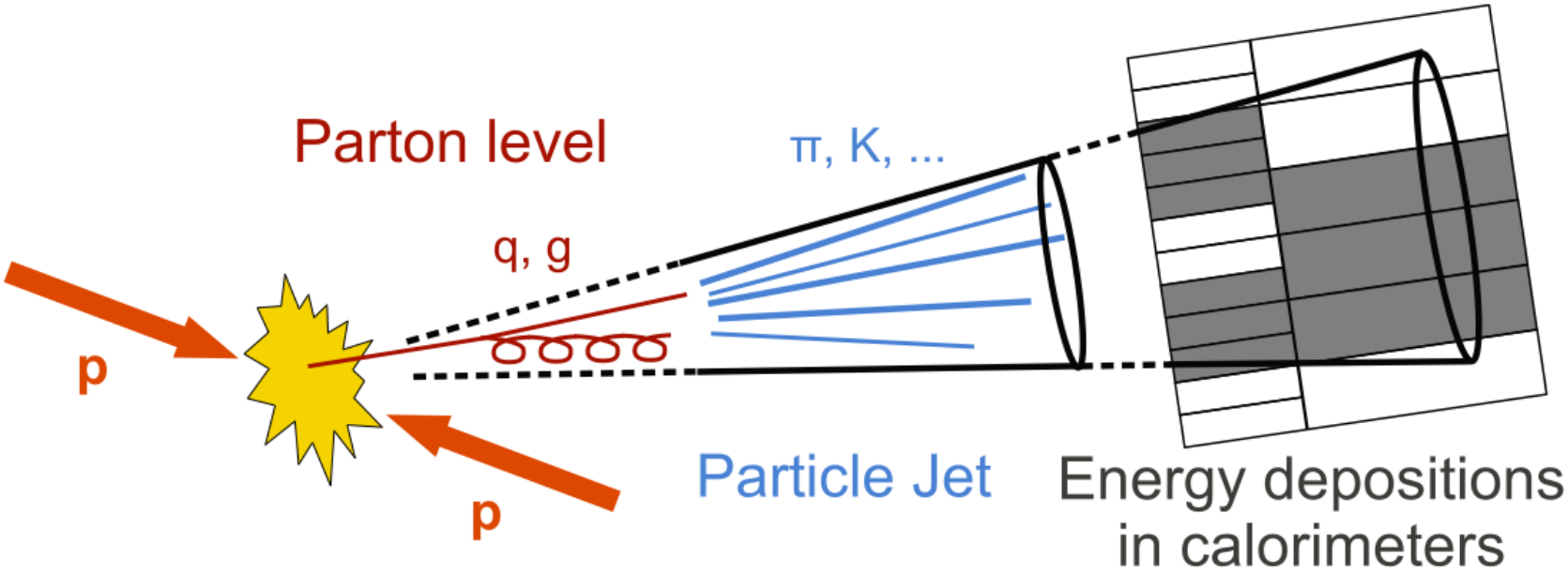
- Conservation of momentum
- Basis for many, many analyses



Jets

Quarks and gluons don't land in the detector intact – they fragment almost immediately

- Strong force prevents us from seeing "bare" partons

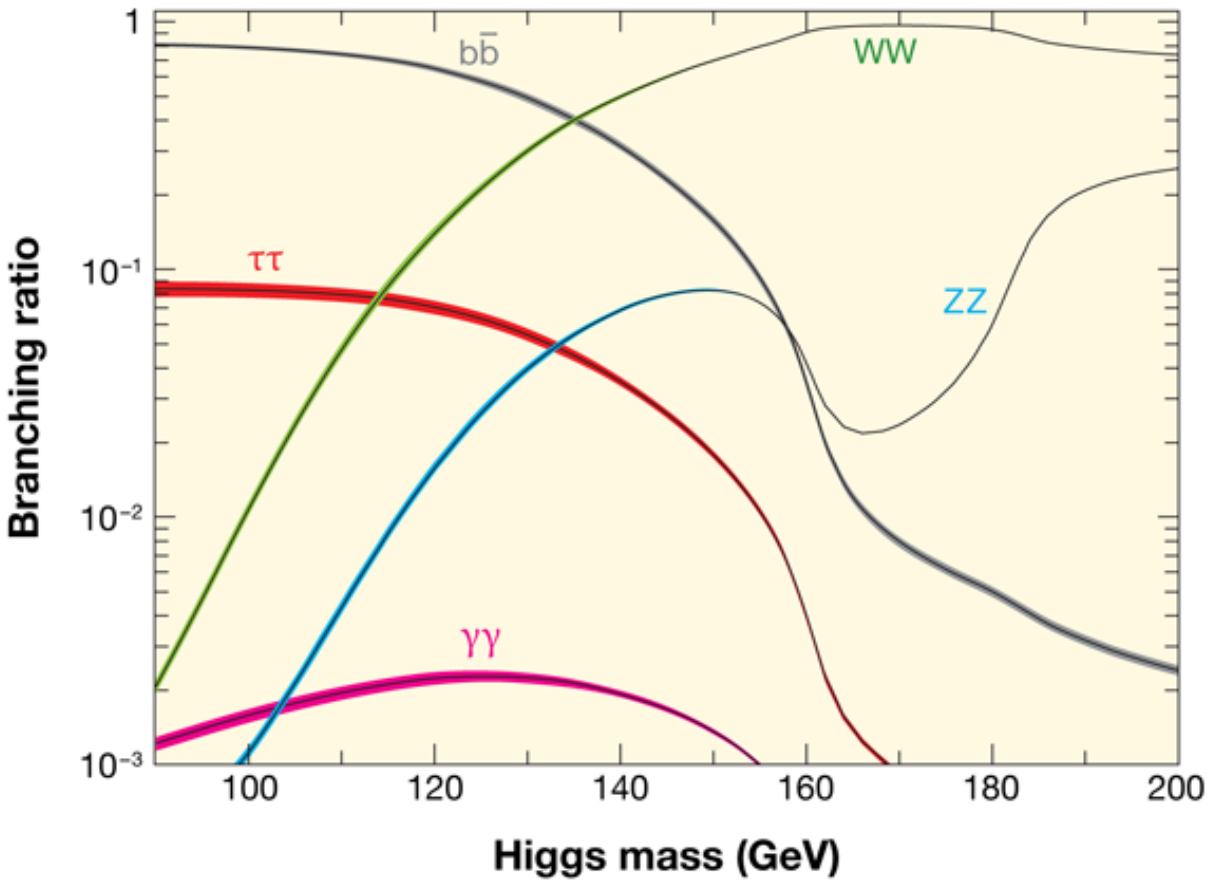


Many things produce jets:

- Can be partons bouncing off of each other
- $\approx$70% of W- and Z-bosons decay into jets

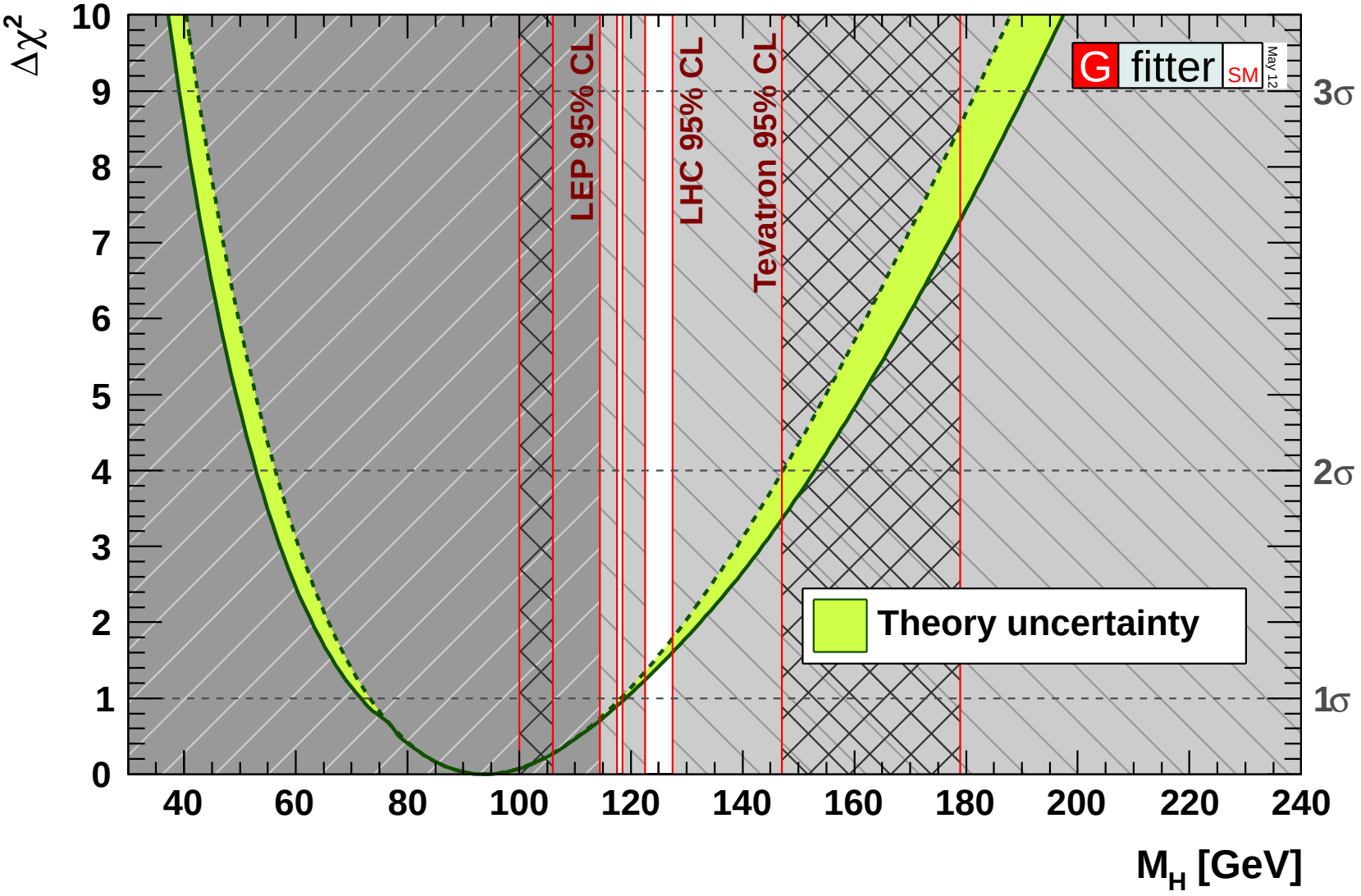
Easy to find jets, hard to measure their energies.

How do we look for the Higgs?



- Finding the Higgs is tricky!
- Trade-off between most common decays (lots of background) and rare decays (smaller backgrounds)

How do we look for the Higgs?



What can't the Standard Model do?

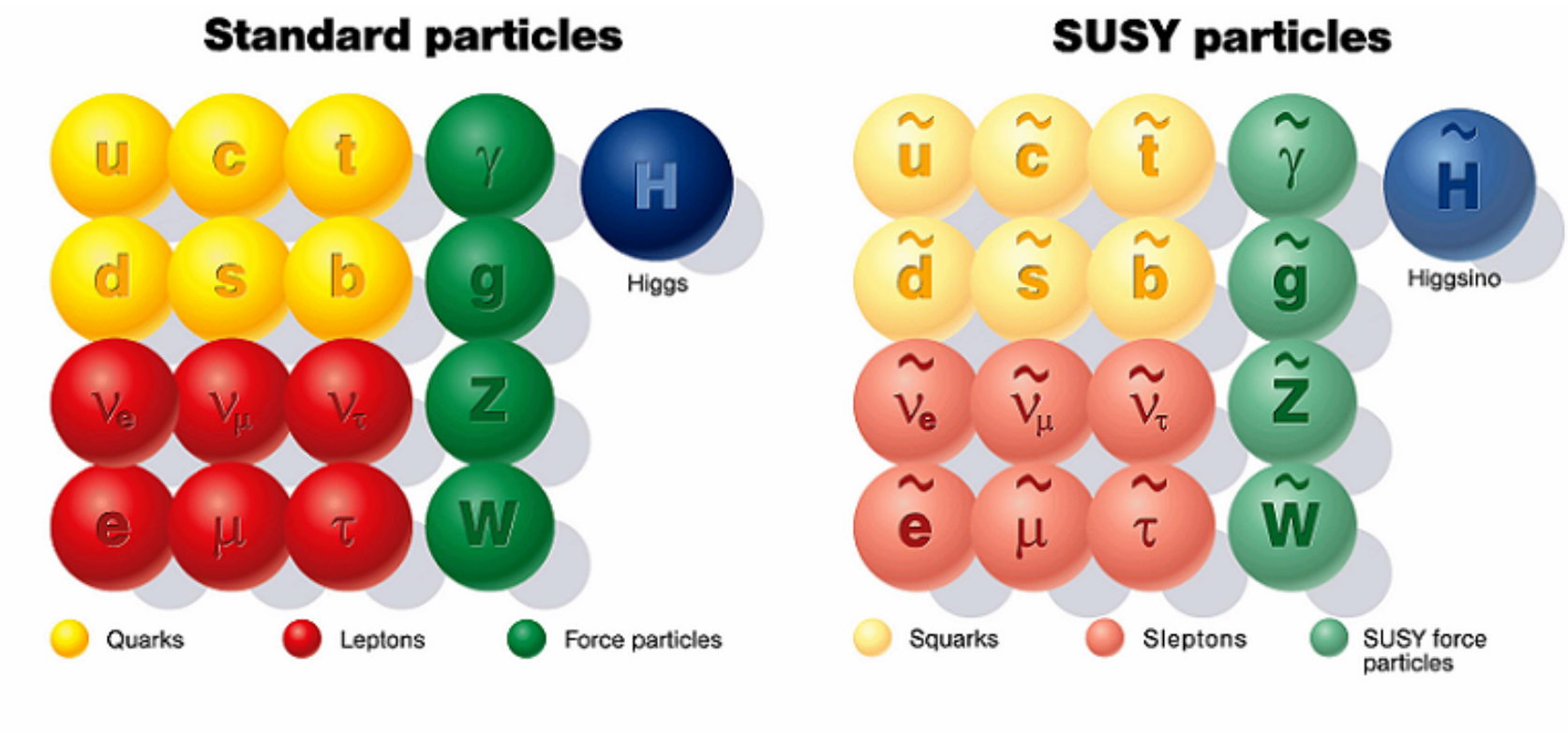
Assuming we find the Higgs, the Standard Model will be "complete". Then what?

- Why is gravity so weak at short distances? How does gravity behave at the quantum level?
  - Black holes
  - Big bang
- What is dark energy?
- What is dark matter?
- Why is the Higgs mass so light compared to the Planck mass?

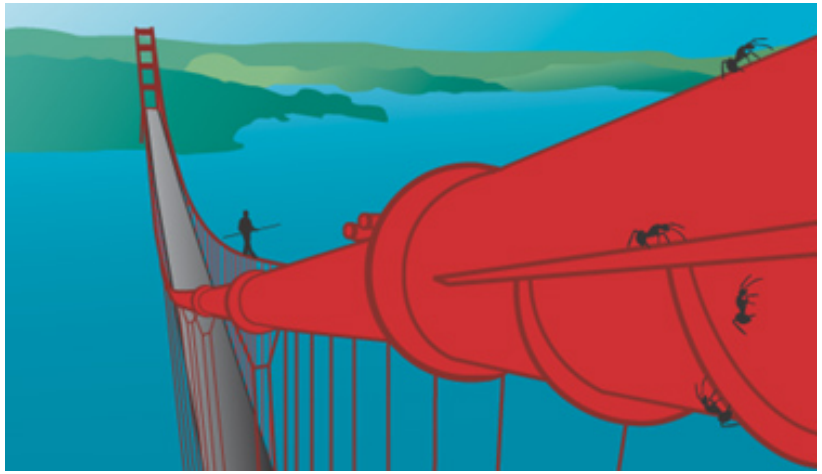
Need *new theories* to explain what happened at the Big Bang to produce the universe we see today.

- Supersymmetry (SUSY)?
- (Large) Extra Dimensions?
- Something completely unexpected?

Supersymmetry



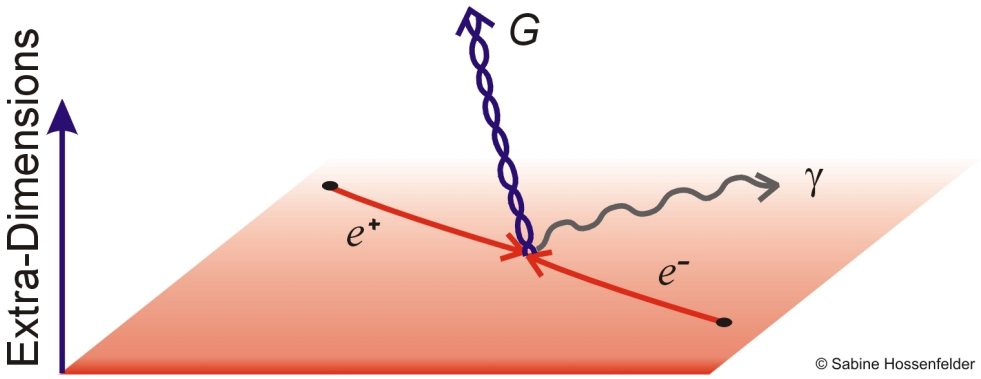
Extra Dimensions



New dimensions could be very small, but still big enough to change how particles behave

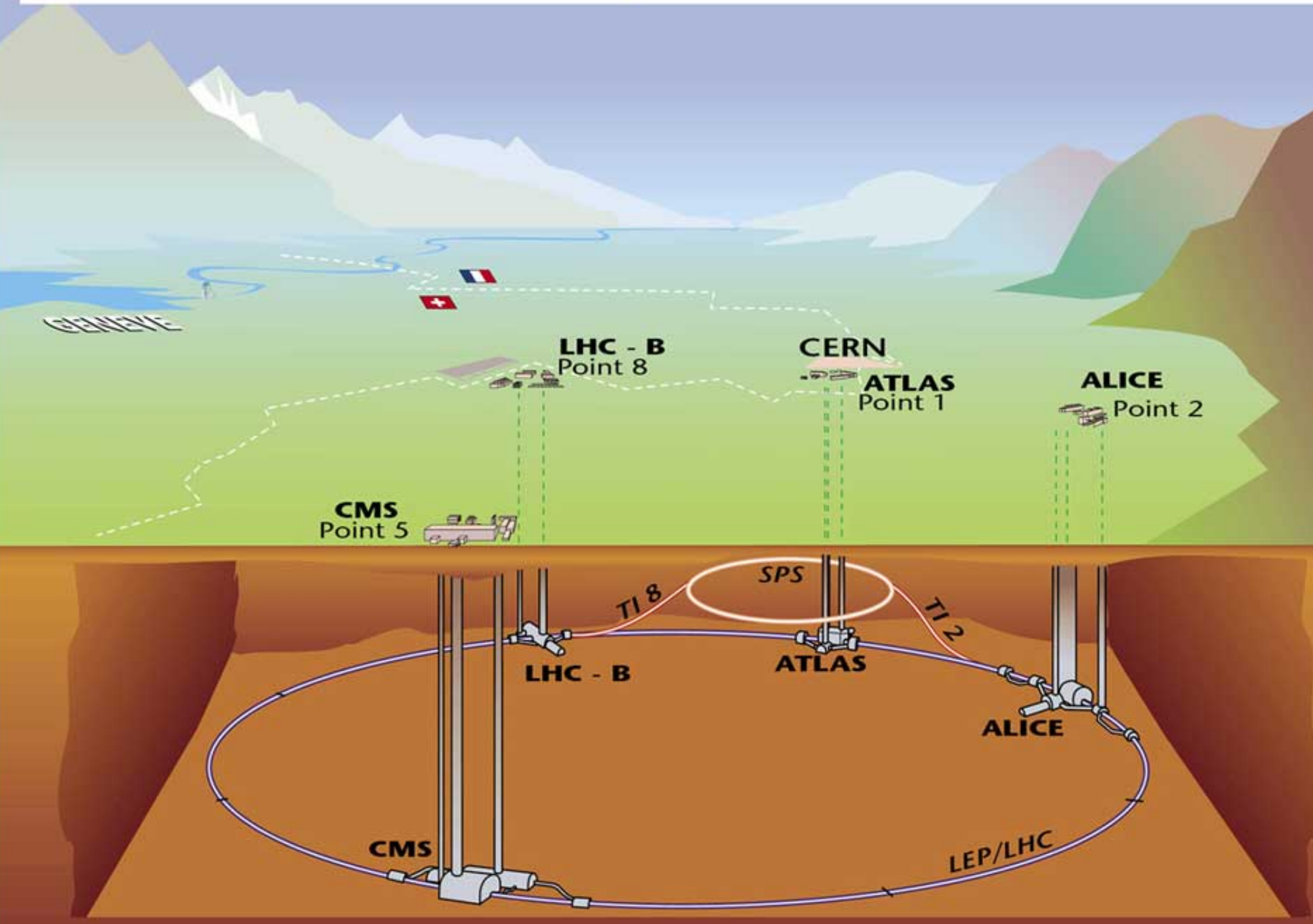
Look for extra dimensions via *missing energy*

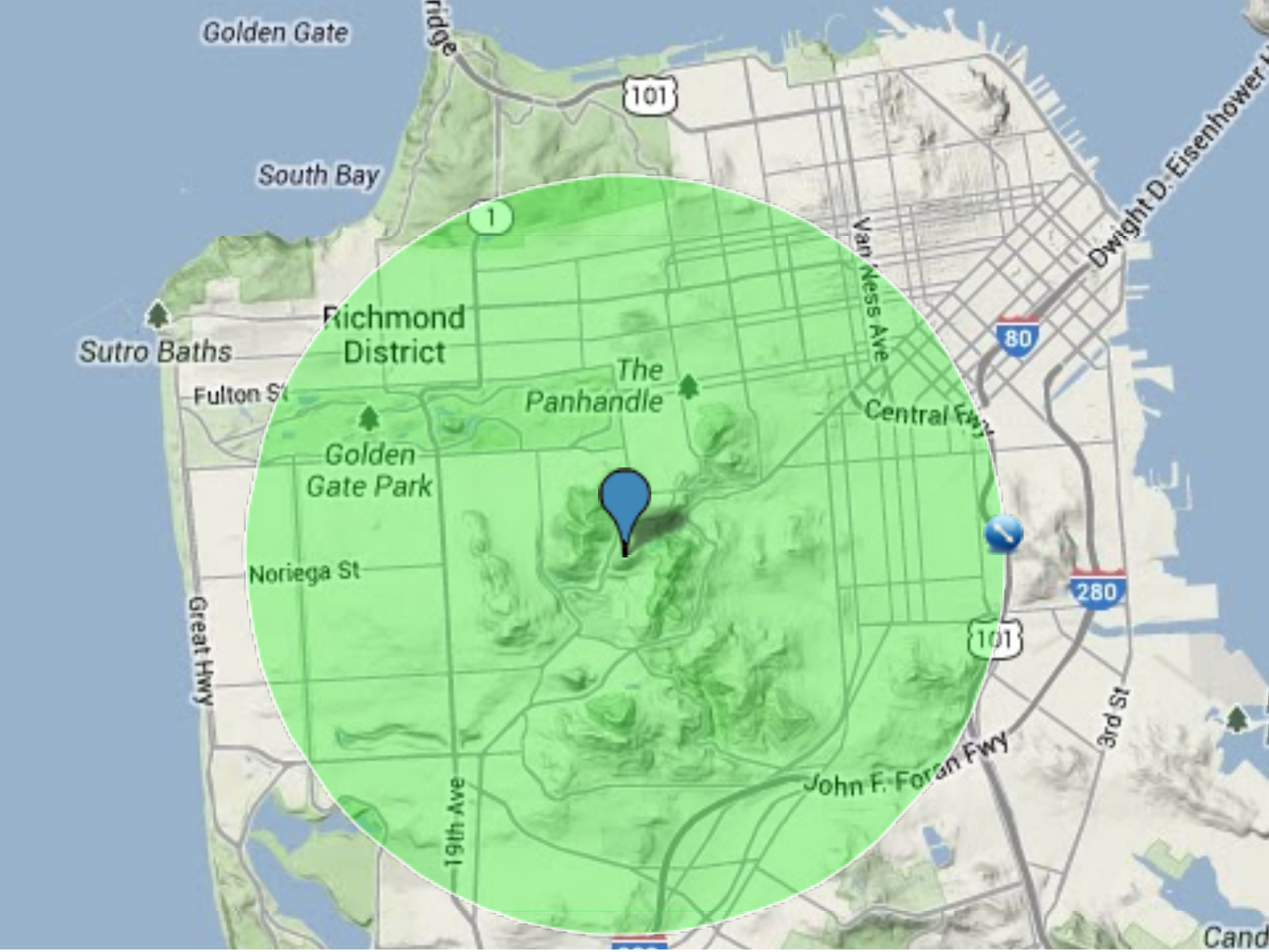
- New particles carry energy into bulk
- Very distinct events!



The Tools

Overall view of the LHC experiments.

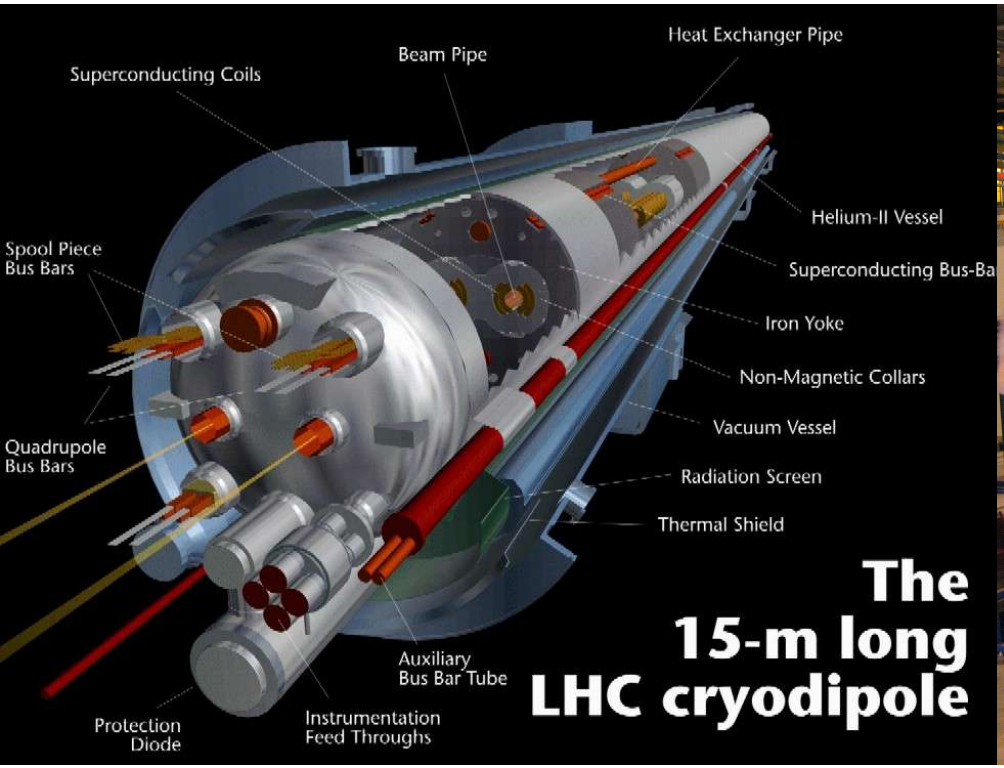


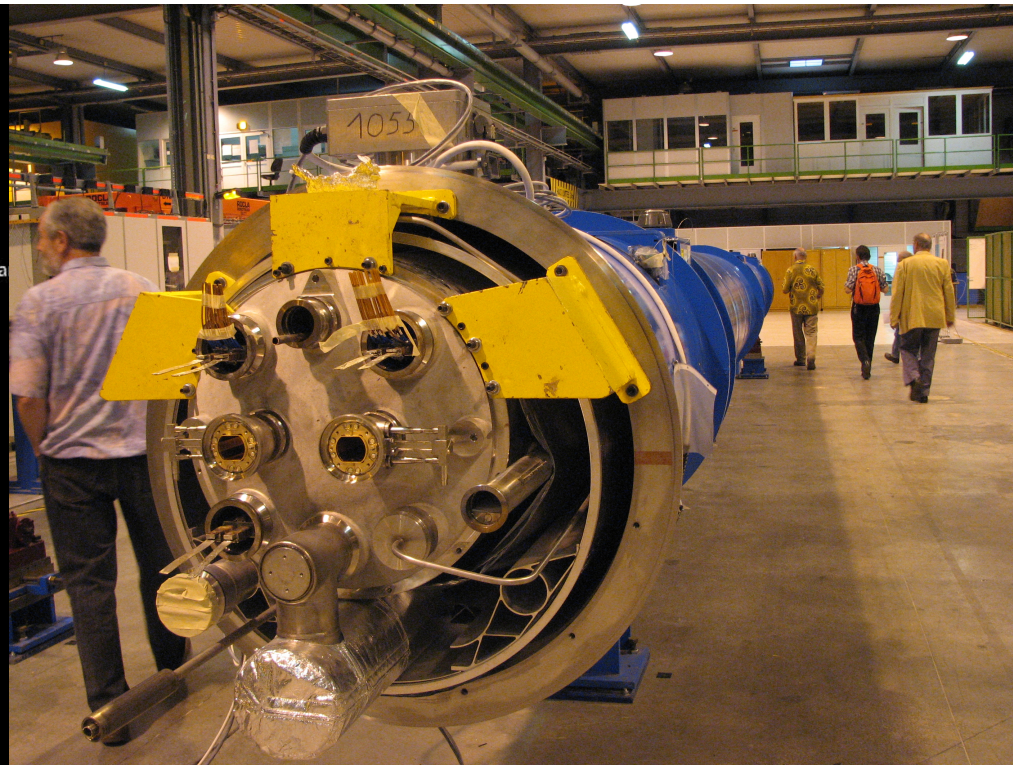

Golden Gate
South Bay
101
Dwight D. Eisenhower
Richmond District
Sutro Baths
Fulton St
The Panhandle
Golden Gate Park
Van Ness Ave
Central Fwy
80
Noriega St
280
101
Great Hwy
3rd St
John F. Foran Fwy
19th Ave

The LHC Magnets

The LHC machine is a 17-mile ring of magnets:

- Uses superconducting NbTi wires to create dipole fields
- Superconductivity needs cold temperatures – 100 tons of liquid helium at 1.9 Kelvin
- Fields of up to 8.3 T





The LHC in Numbers

For the 2012 run, some stats on the accelerator:

- 8 TeV collisions
- Bunches of protons colliding at 40 MHz
- 20 fb^{-1} of data per experiment
- O(100) petabytes of data stored

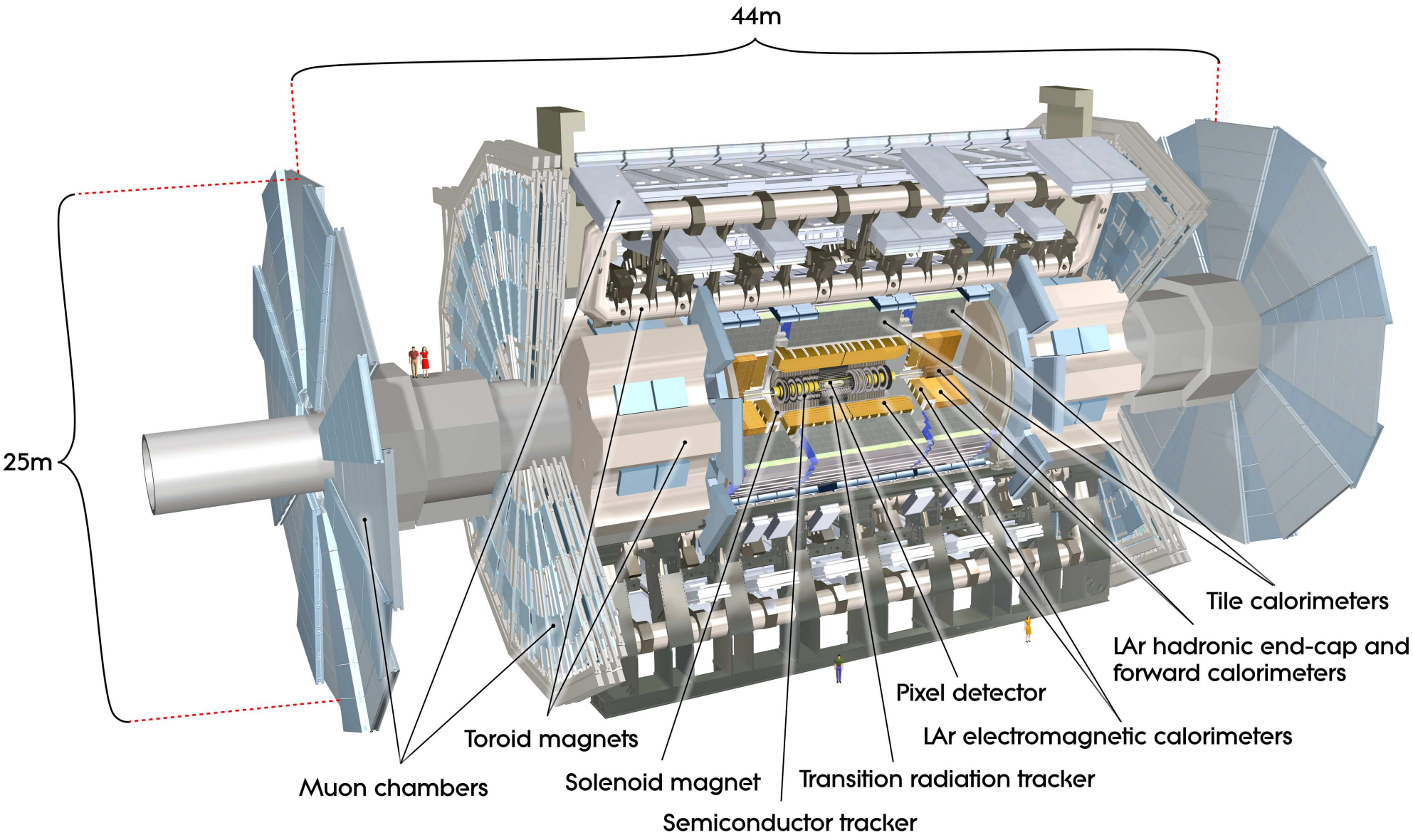
After the current shutdown:

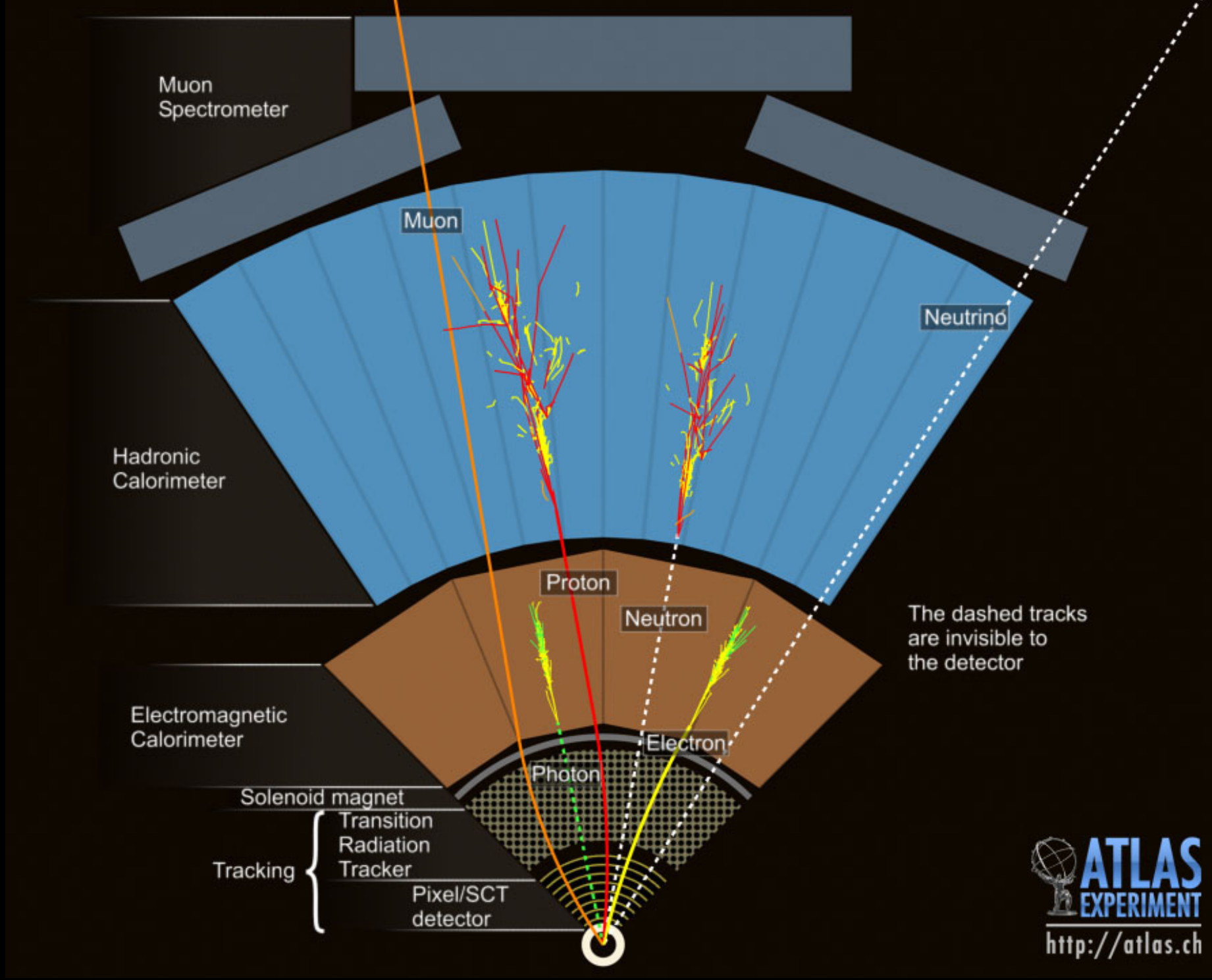
- 14 TeV collisions
- 3000 fb^{-1} of data per experiment by 2030

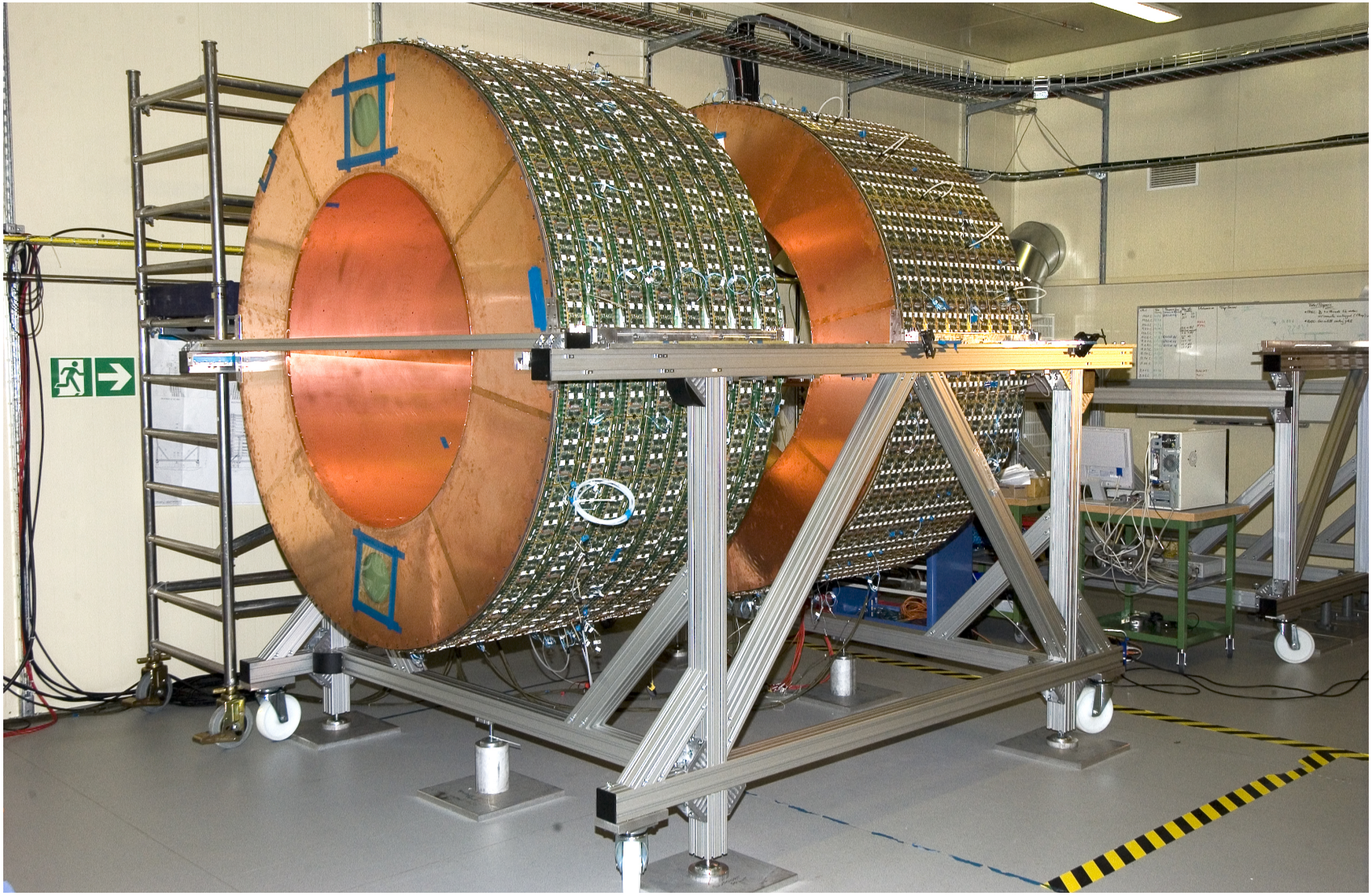
Four main experiments:

- **ATLAS** - multipurpose experiment, $\approx$ 3000 collaborators
- **CMS** - multipurpose, $\approx$ 3000 collaborators
- **ALICE** - heavy ion physics, $\approx$ 1200 collaborators
- **LHCb** - bottom-quark physics, $\approx$ 620 collaborators

A Toroidal LHC ApparatuS




Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch



The ATLAS Pixel Detector
March 2006 Status
MODULES
GLOBAL MECHANICAL STRUCTURES
Test Setups for
ATLAS
OPEN HOUSE • 2012

How do we do science at the LHC?

Two general types of investigations:

- **Measurements** of known quantities
  - e.g. mass of top quark, Z-boson cross section, etc.
  - Limit *uncertainty* on measurement as much as possible

How do we do science at the LHC?

Two general types of investigations:

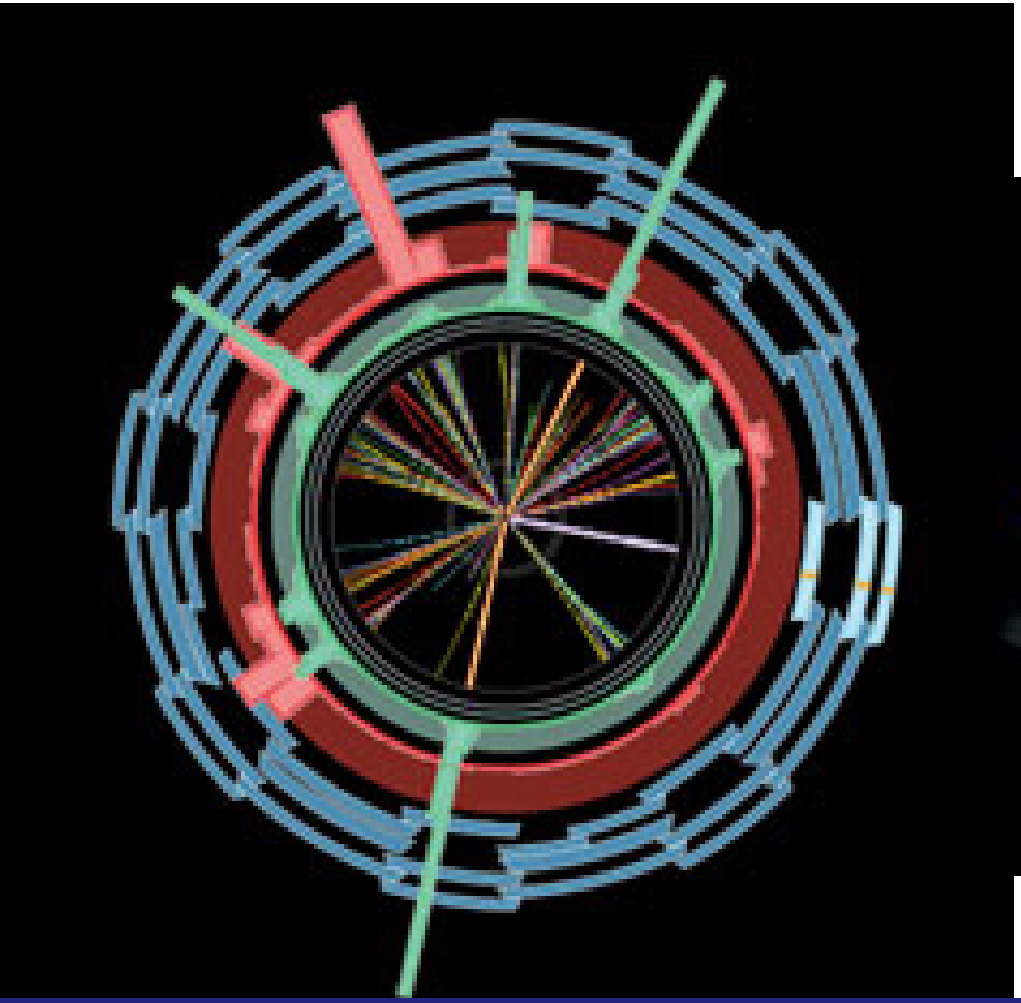
- **Measurements** of known quantities
  - e.g. mass of top quark, Z-boson cross section, etc.
  - Limit *uncertainty* on measurement as much as possible
- **Searches** for unobserved phenomena
  - Looking for SUSY or extra dimensions
  - Can focus on a specific model (SUSY) or signature (events with two muons)
  - Two possible outcomes:
    - We discover new physics!
    - We only see what the Standard Model predicts, so we can infer the absence of new physics

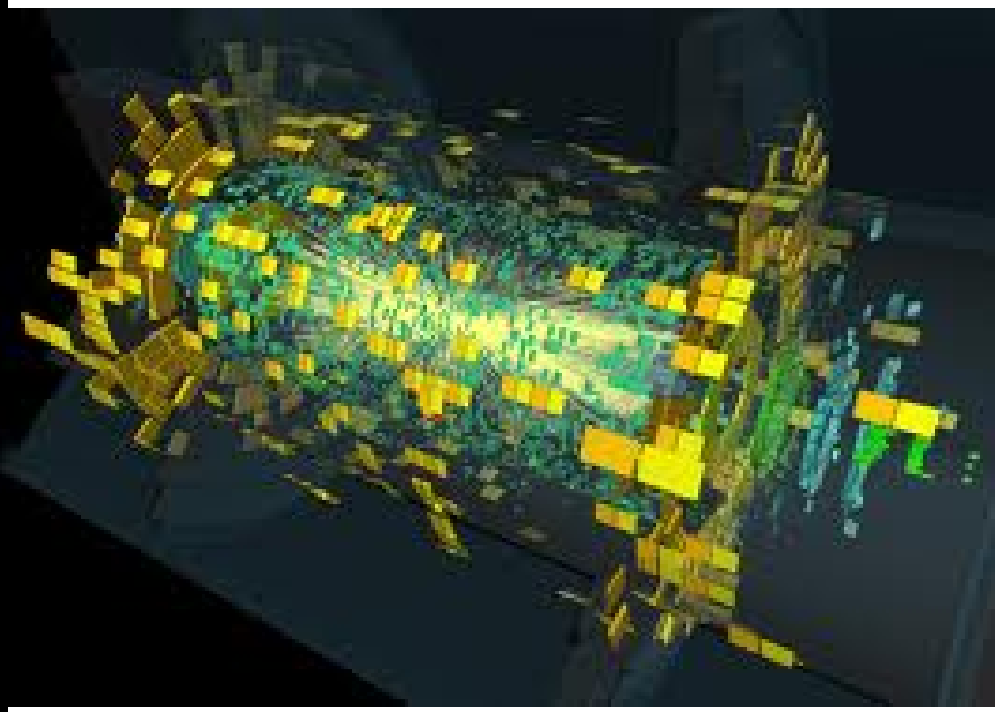
Both are critical components of the overall physics program at the LHC!

Simulation

For either measurements or searches, rely a lot on *simulation*.

- Rather than building multiple LHC's and detectors in the real world, use computers to model them
- We can then inject fake events into our simulated detector to see how it responds





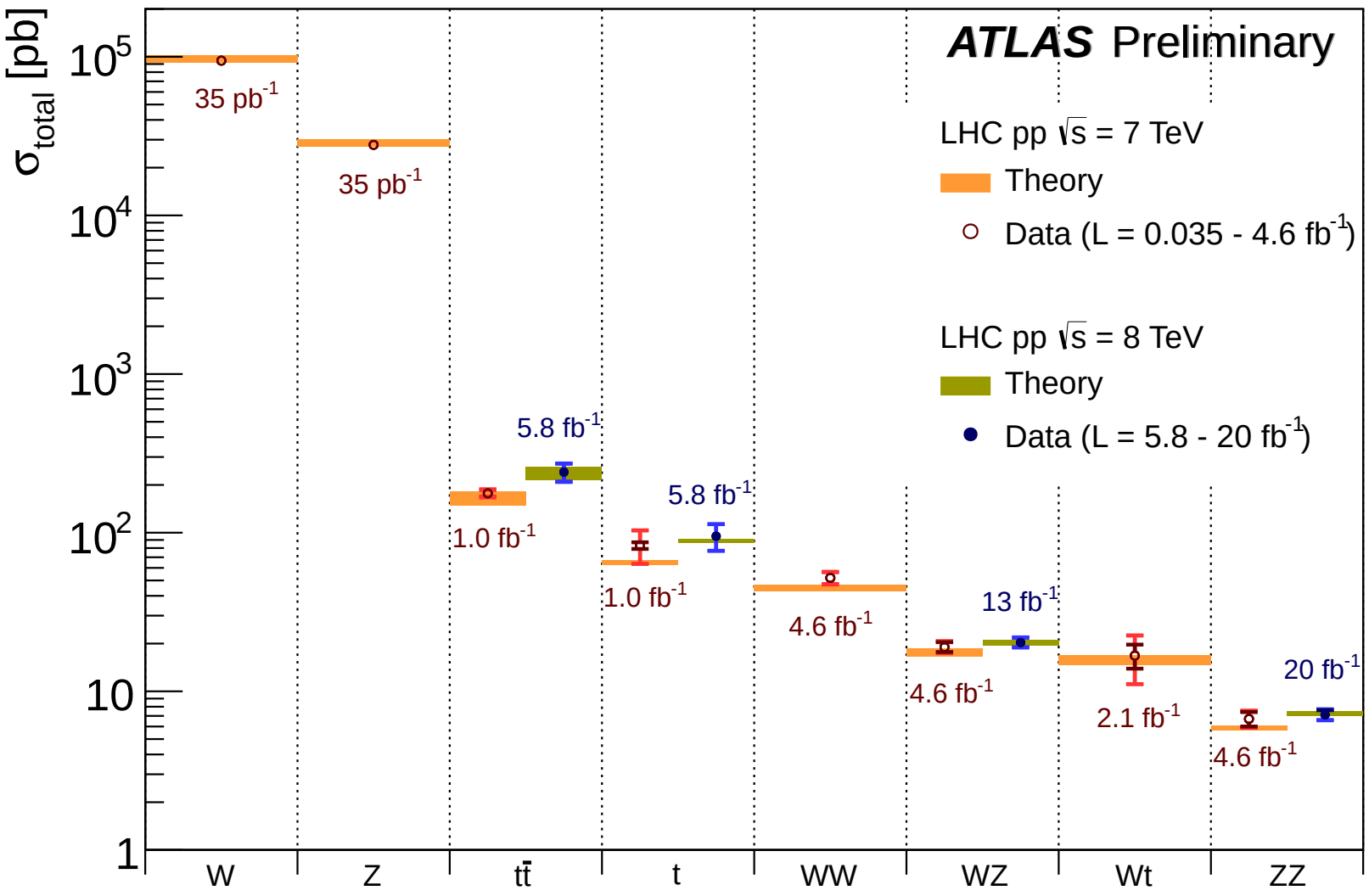
Computing

It takes a lot of computers to handle 100 PB!

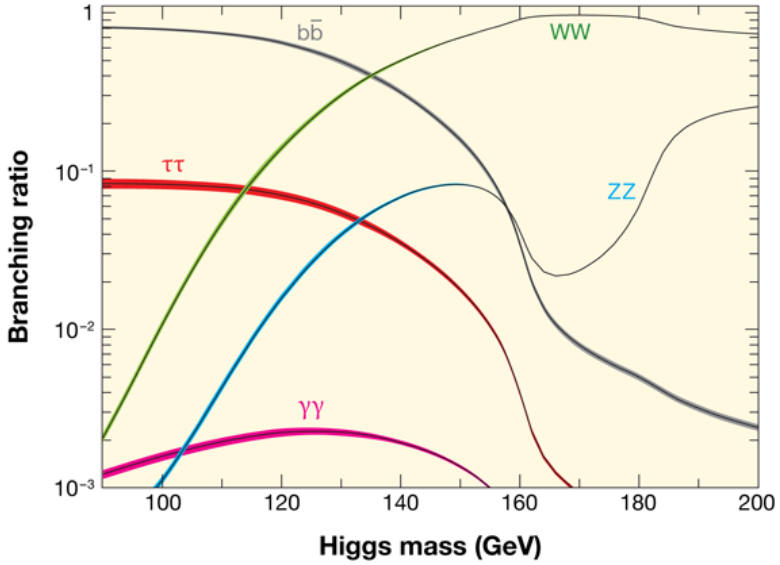
- Computing farms all over the world
- Lots of different technologies at work:
  - Most computers run Linux (Windows and IOS are for phones)
  - Data analysis: programming languages like `C++` and `python`
  - Information management: making data easily available to many people, security issues, data privacy
  - Low-level hardare: getting computers to talk with custom detector components

So, what have we found?

(Re)-discovering the Standard Model



What about the Higgs?

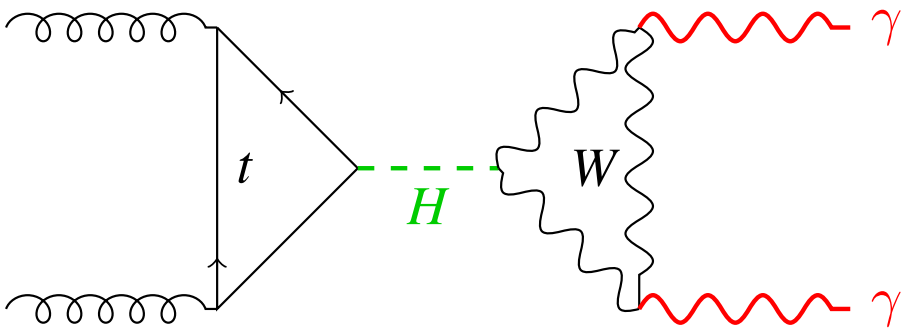


Look for Higgs in all possible decays

- Roughly 45 Higgs bosons produced in each pb^{-1} of data
- Can't afford to waste any of them!

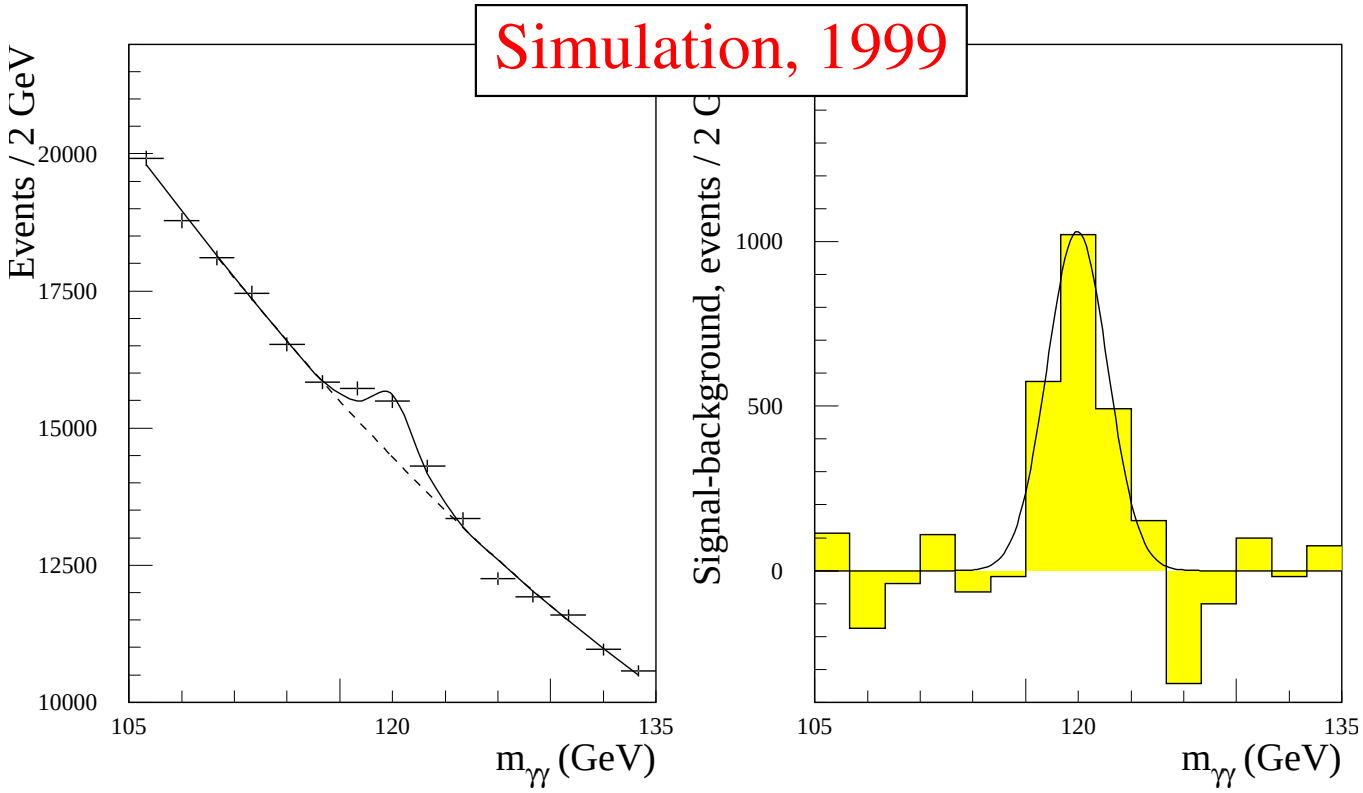
- Most popular decay is bb – difficult!
  - b's show up as jets, there are a lot of those, and it's hard to measure their energies
- Then WW, $\tau\tau$, and ZZ – also hard
  - Most of the time, these particles also produce jets!
- $\gamma\gamma$ is last, but promising

What about the Higgs?

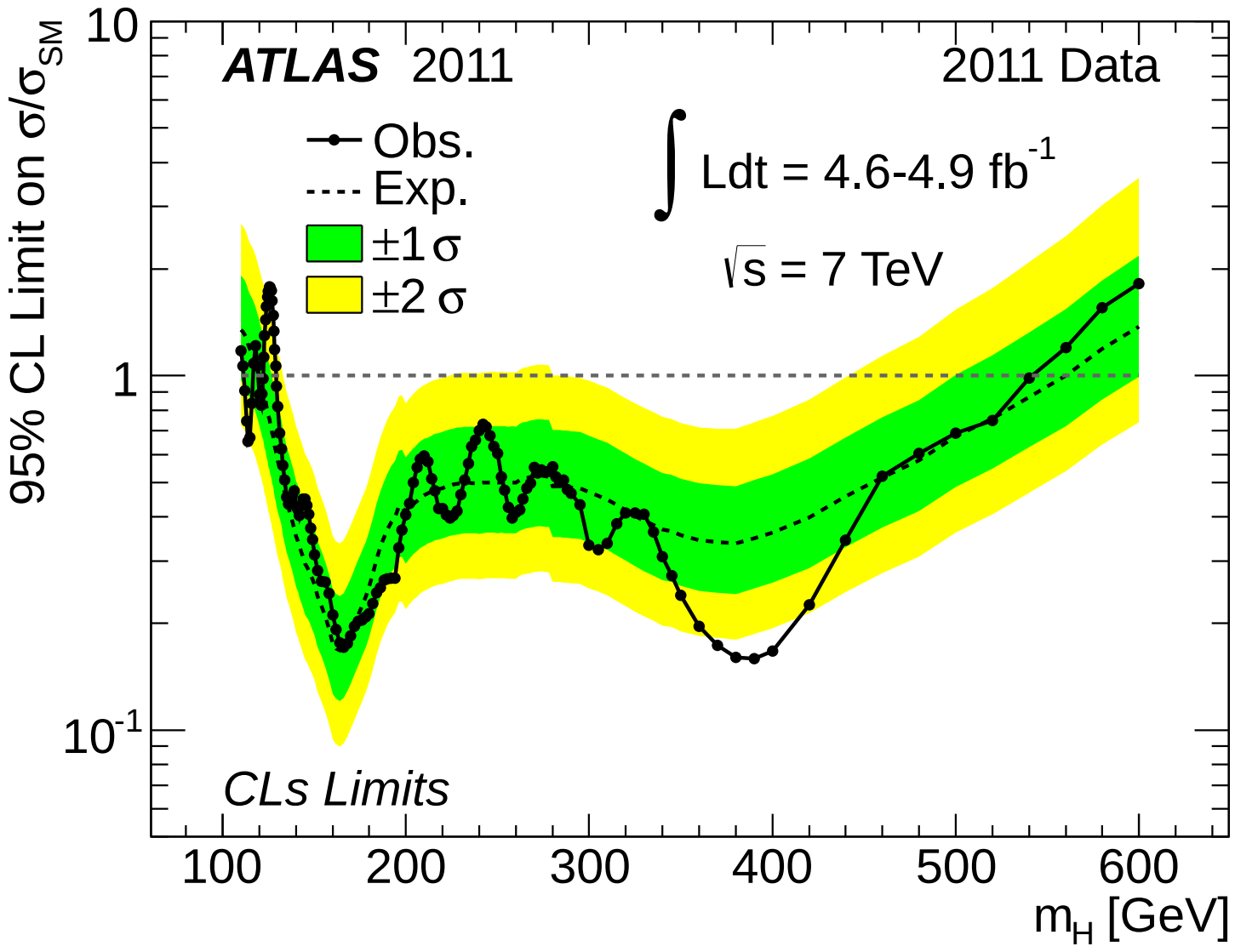


Higgs decay to diphotons is rare, but powerful

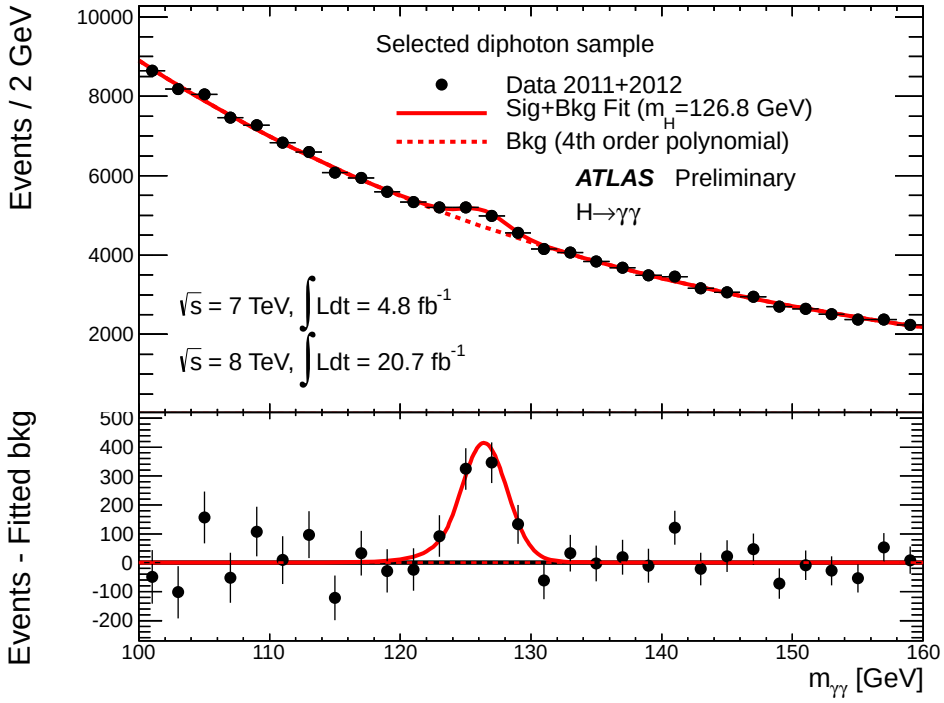
- BR$\approx 10^{-3}$
- But ATLAS can measure photons very accurately
- Use photons to figure out invariant mass

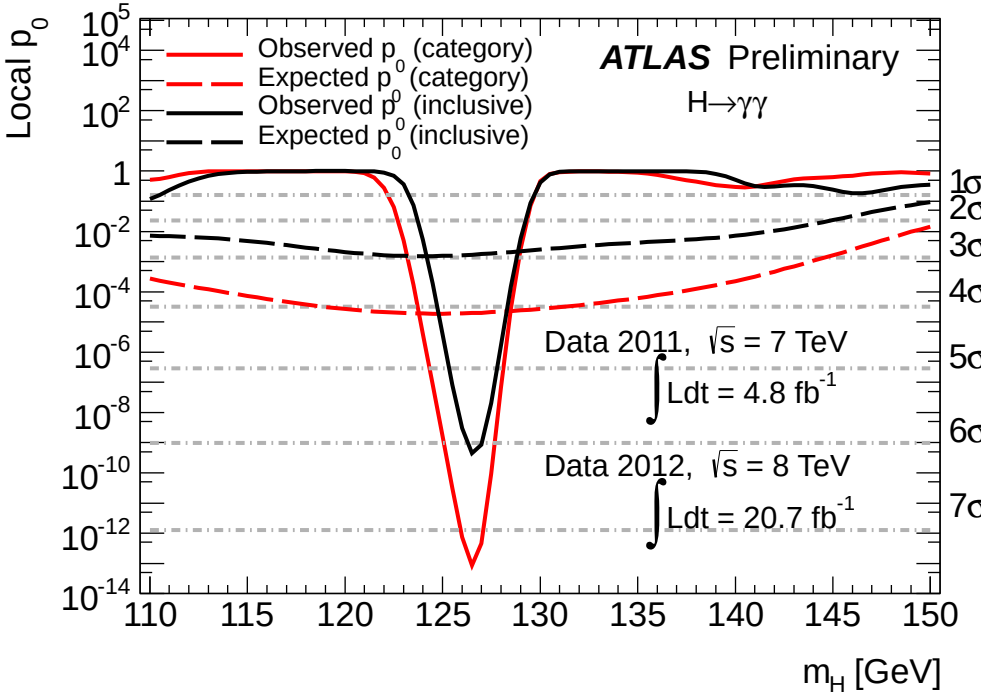


What we knew after 2011



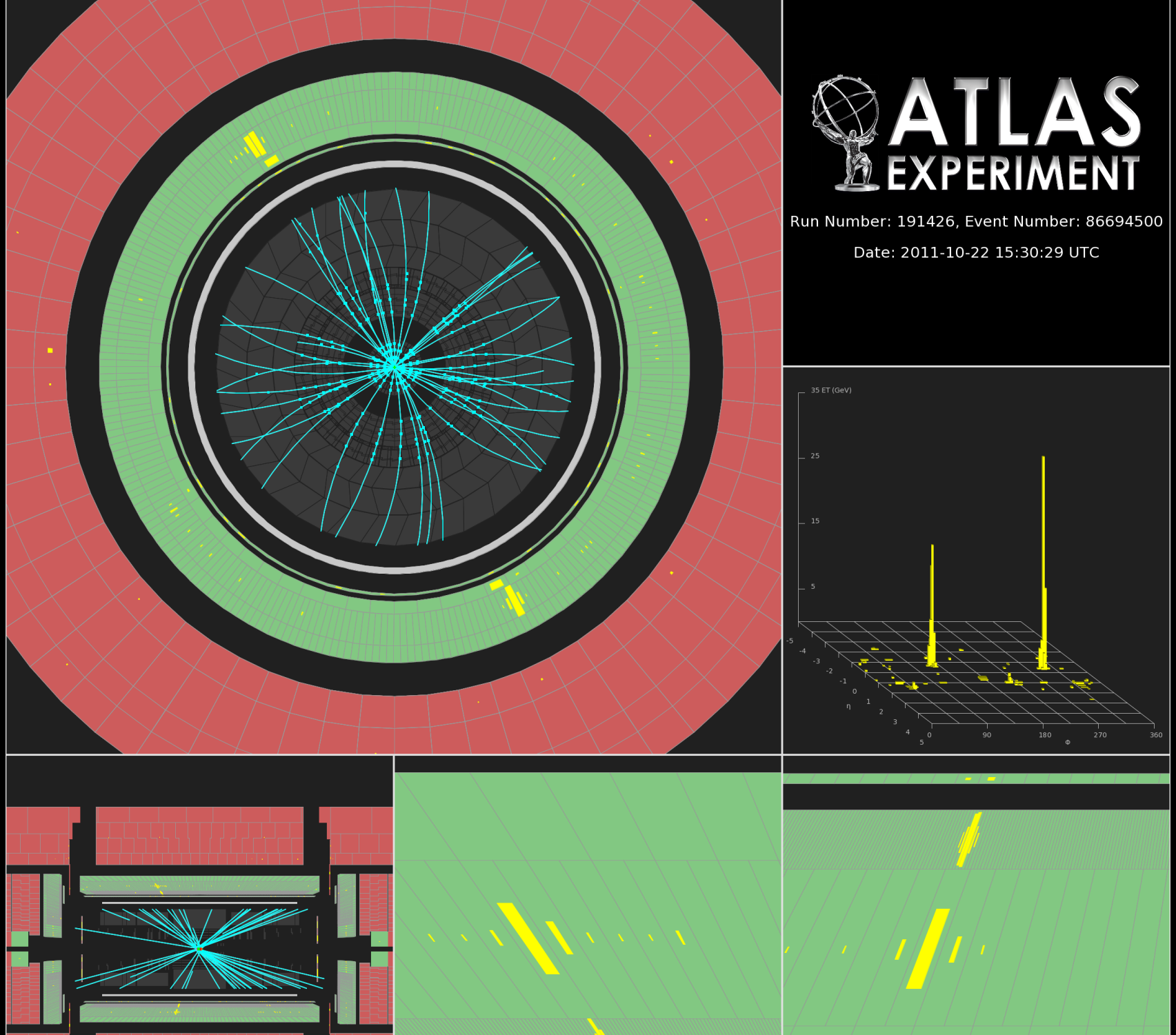
What we saw in 2012





It looks just like we expected!

- Still not total confirmation yet, still need to look at other properties
- A lot of work left to be done on the Higgs, but this is a major scientific achievement!


ATLAS
EXPERIMENT
Run Number: 191426, Event Number: 86694500
Date: 2011-10-22 15:30:29 UTC
35 ET (GeV)
25
15
5
-5
-4
-3
-2
-1
0
1
2
3
4
5
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90
180
270
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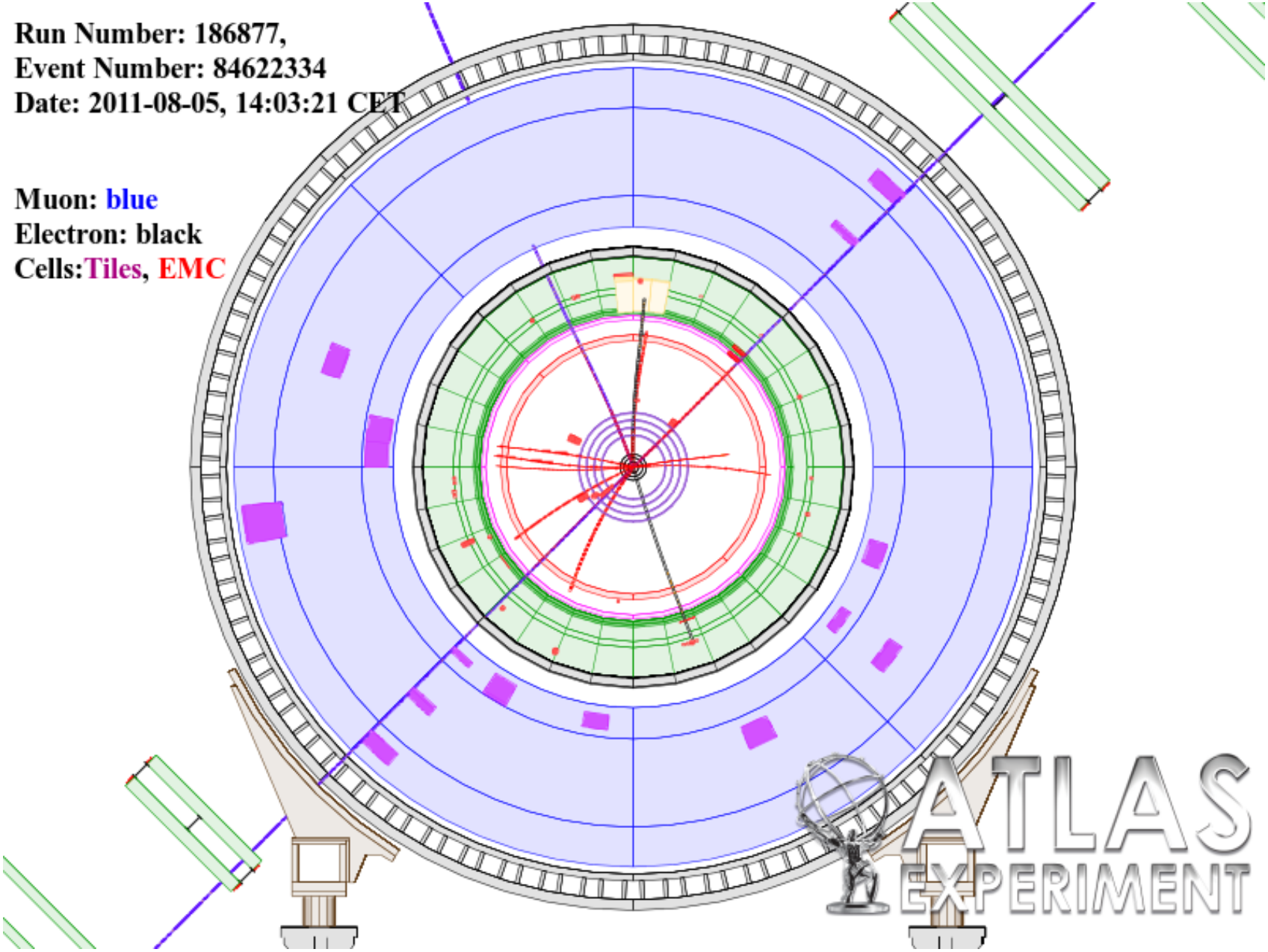
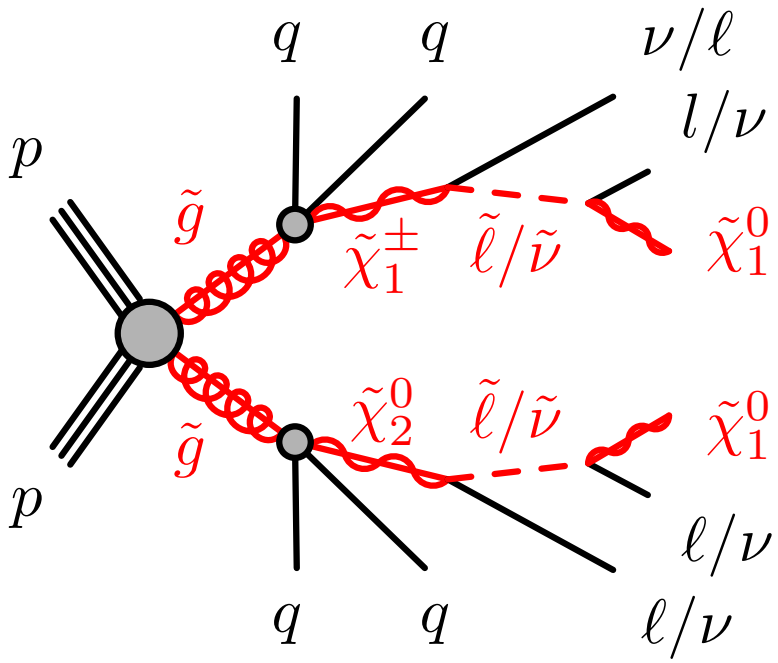

Run Number: 186877,
Event Number: 84622334
Date: 2011-08-05, 14:03:21 CET
Muon: blue
Electron: black
Cells:Tiles, EMC
ATLAS
EXPERIMENT

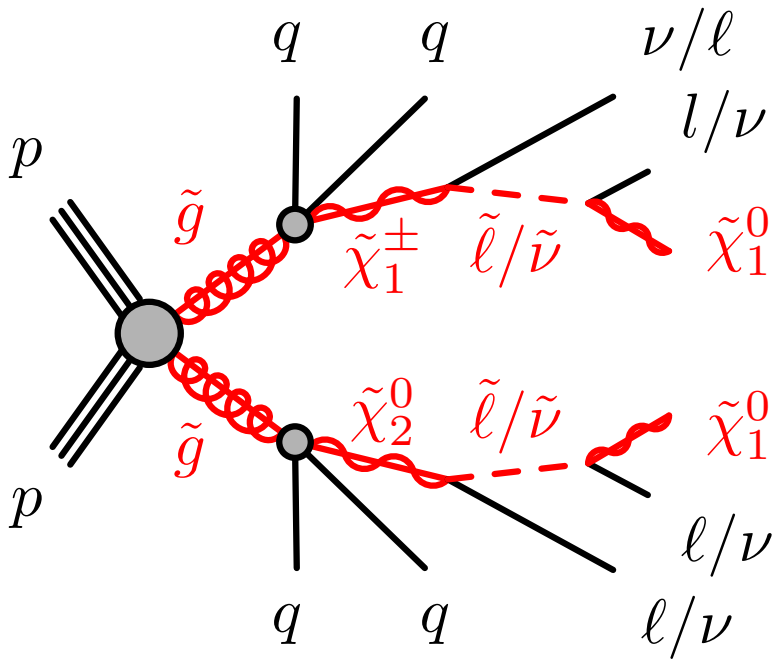
And SUSY?



SUSY often produces very spectacular events

- Lots of energetic particles
- Missing energy from neutrinos and χ_1^0

And SUSY?



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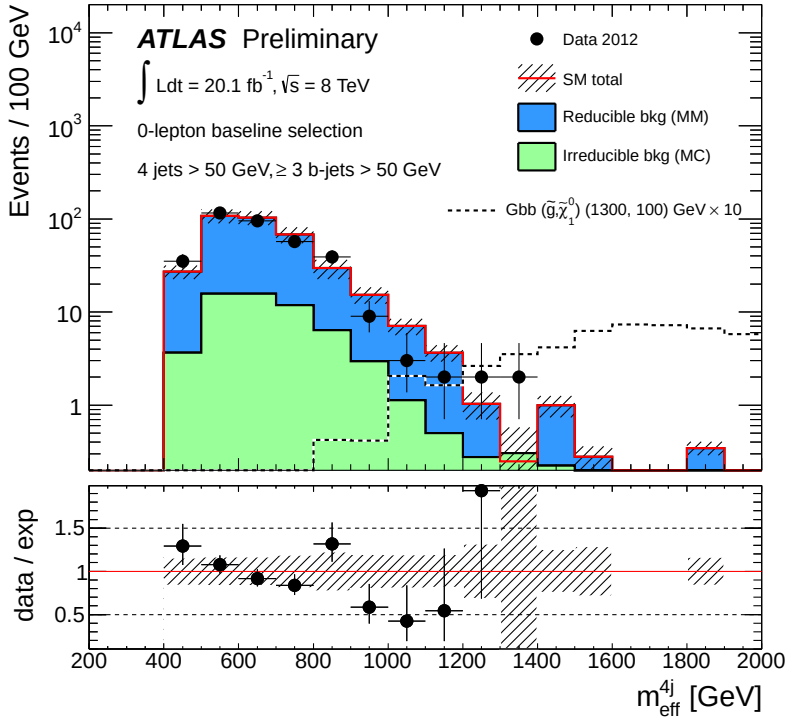
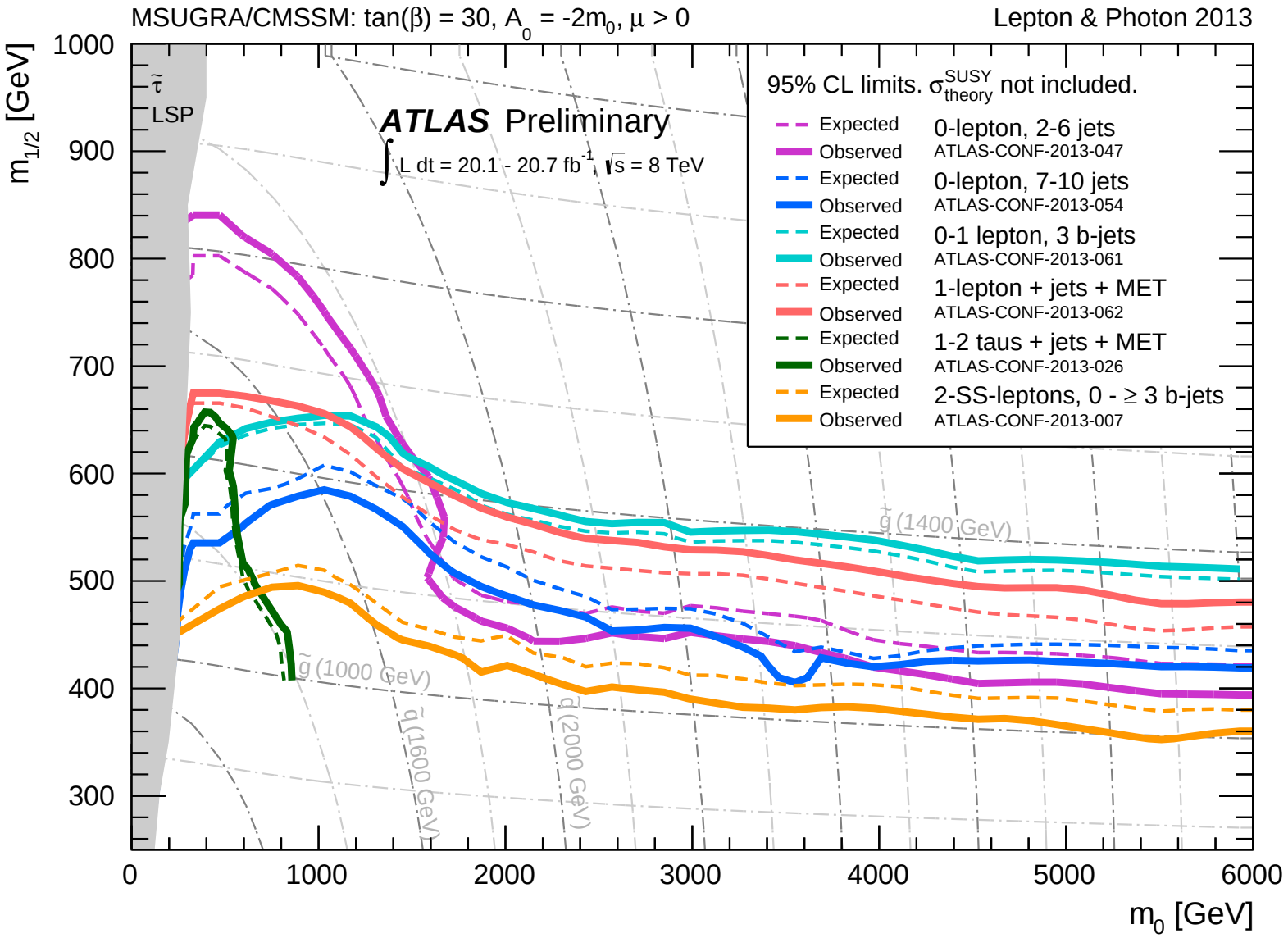


No signs of SUSY yet

- Ruled out the easiest-to-see models
- Plenty of ways it could still be hiding!

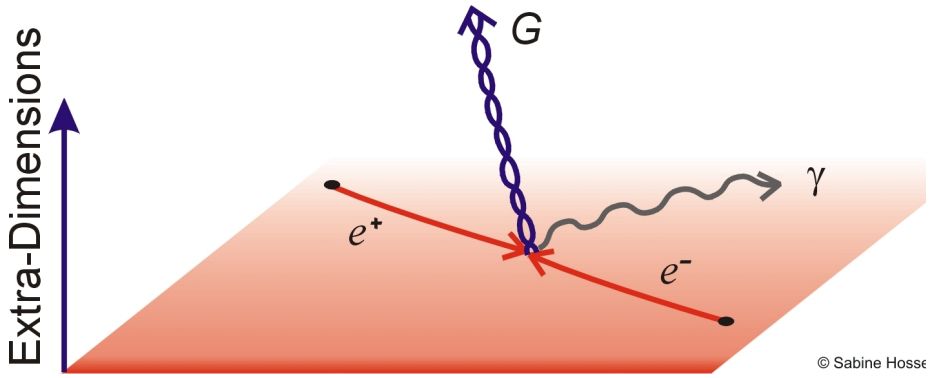
SUSY is Hiding....

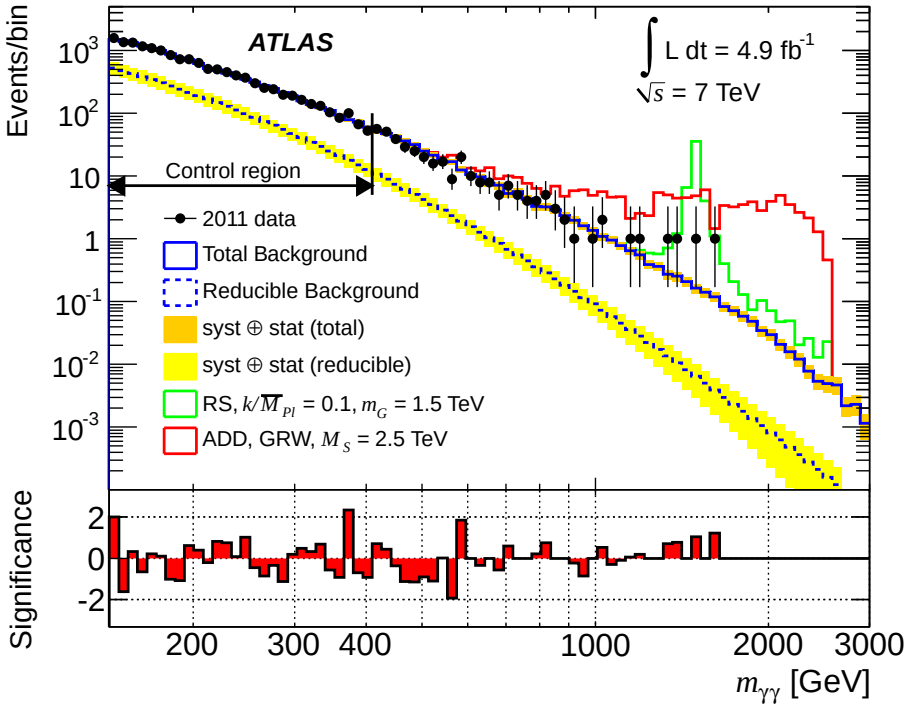


Extra Dimensions?

A few ways to look for extra dimensions:

- One way: look for events with two energetic photons
- Like the Higgs, but much higher energy

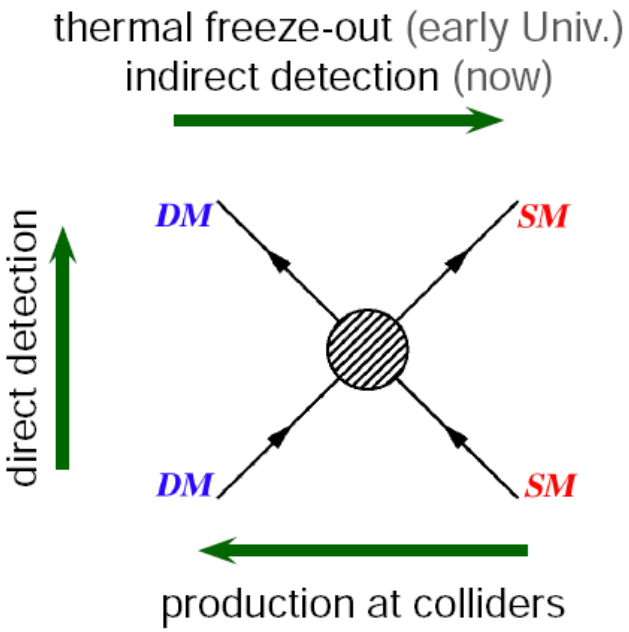




Dark Matter

Two ways to look for dark matter at the LHC:

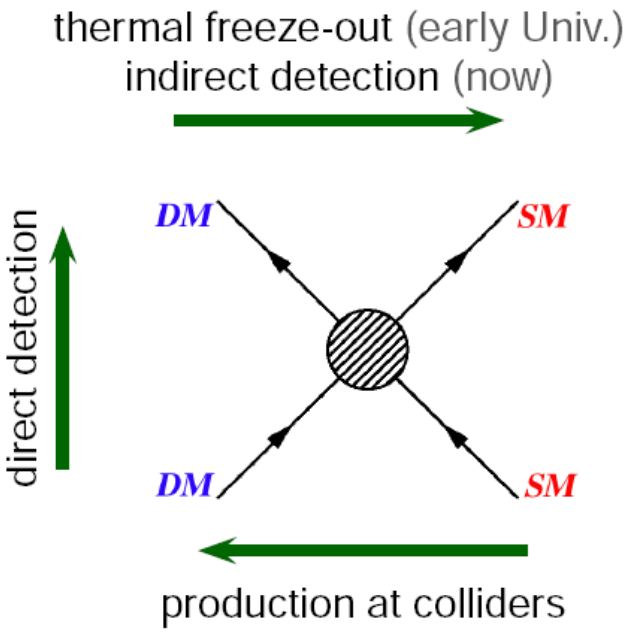
- Look for SUSY
- Look for generic dark matter

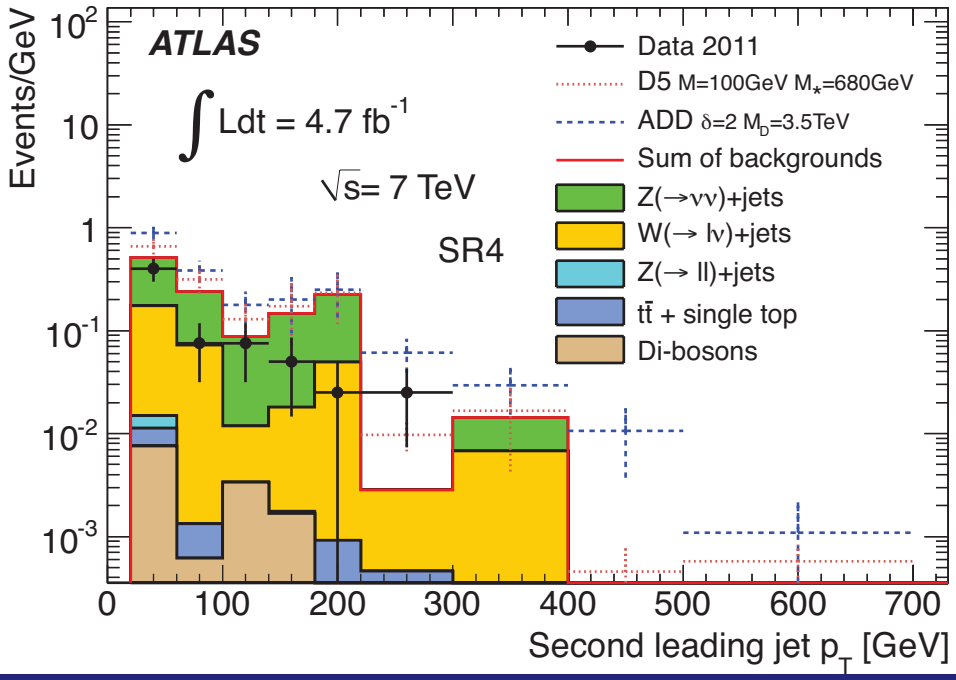


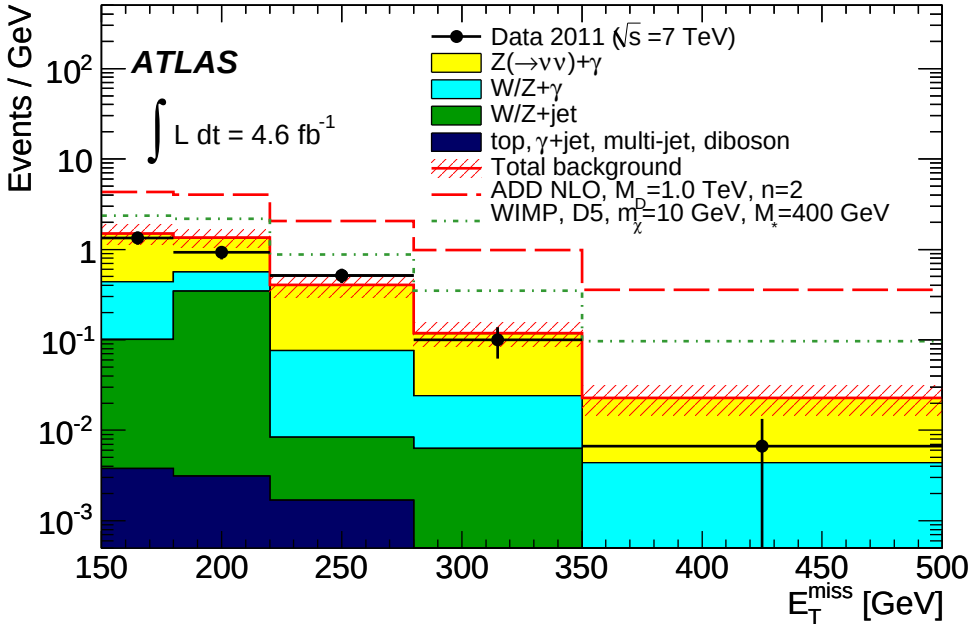
Dark Matter

Two ways to look for dark matter at the LHC:

- Look for SUSY
- Look for generic dark matter







Future Plans

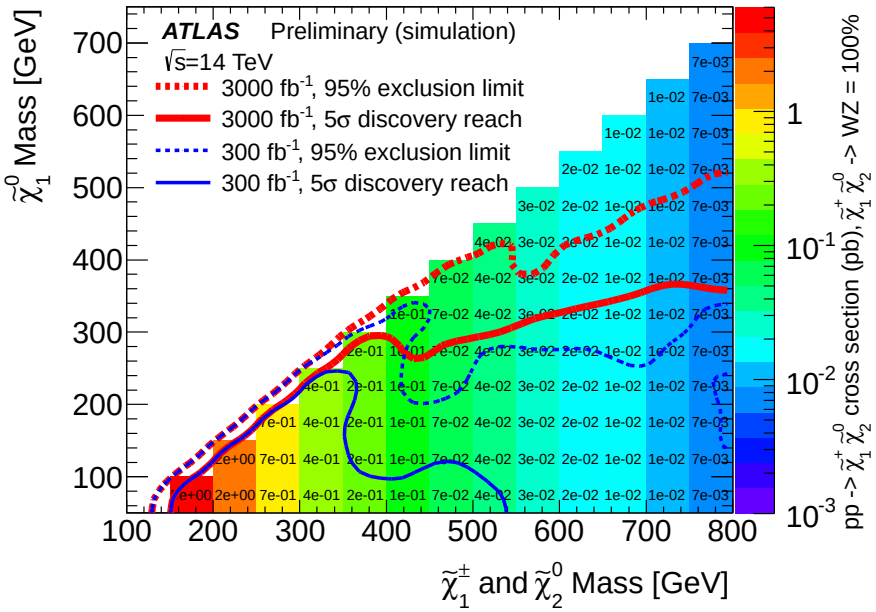
Future Plans

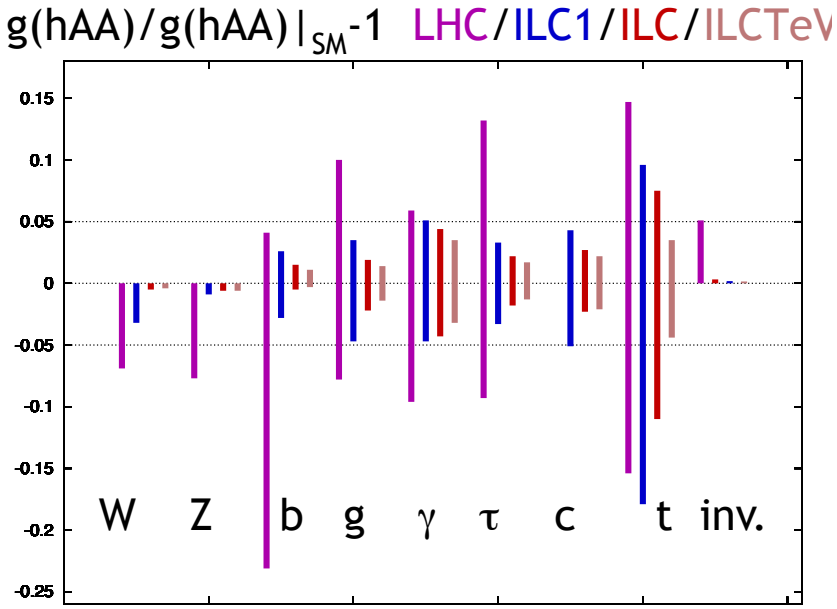
Currently in a 2-year shutdown

- Fix magnets for high energy
- Fix detector
- Add new subdetectors
- Upgrade/fix software

Restart in 2015 at 13 TeV

- What we learn at 13 TeV will influence what we do next
  - Will there be anything new?
  - Will we need to build a new (bigger) accelerator?

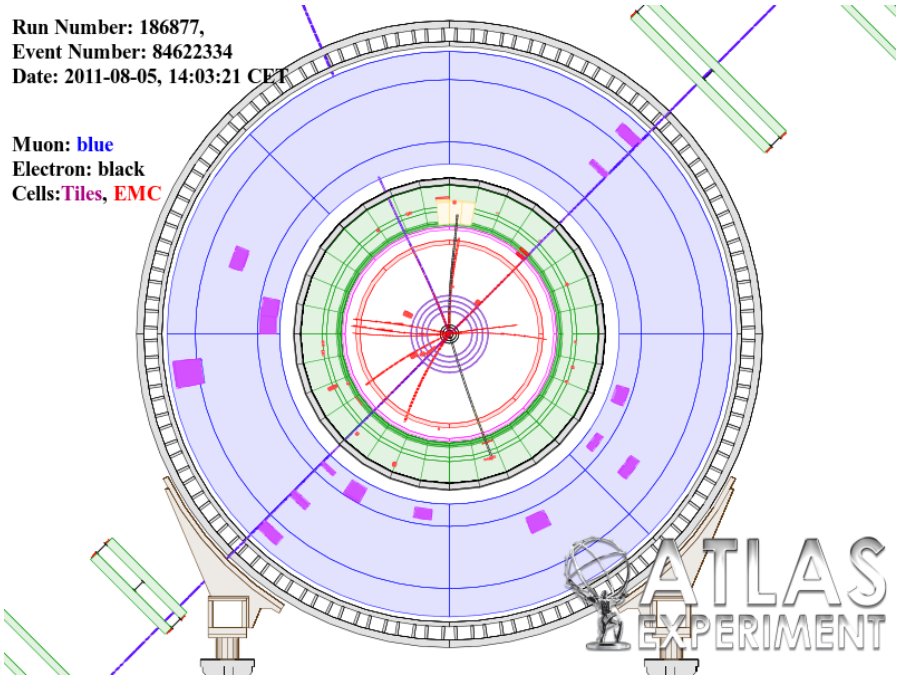


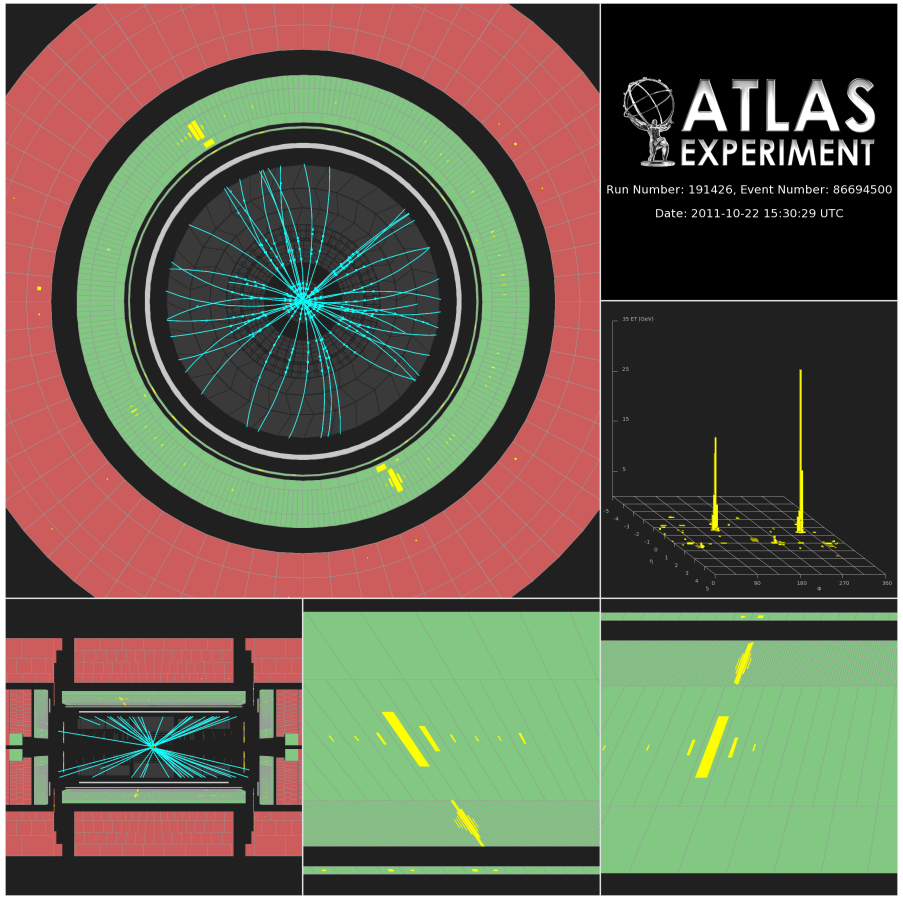


Conclusions

We're in a golden age of high energy physics!

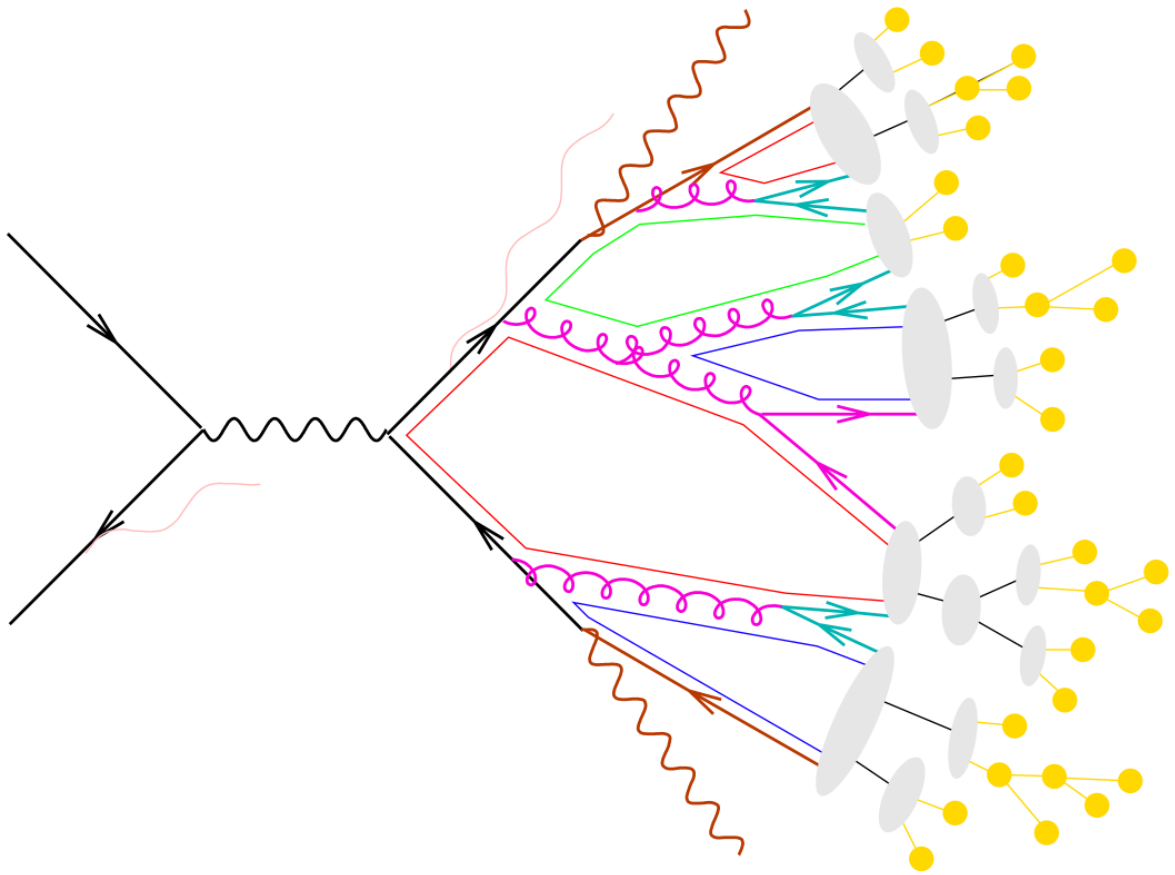
- We see a Higgs consistent with the Standard Model
- ... but we know nature must have more in store for us! What is it?
- So far, no signs of anything new at the LHC
  - But there's a lot more data to be taken at higher energies
  - Plenty of time to see new physics!





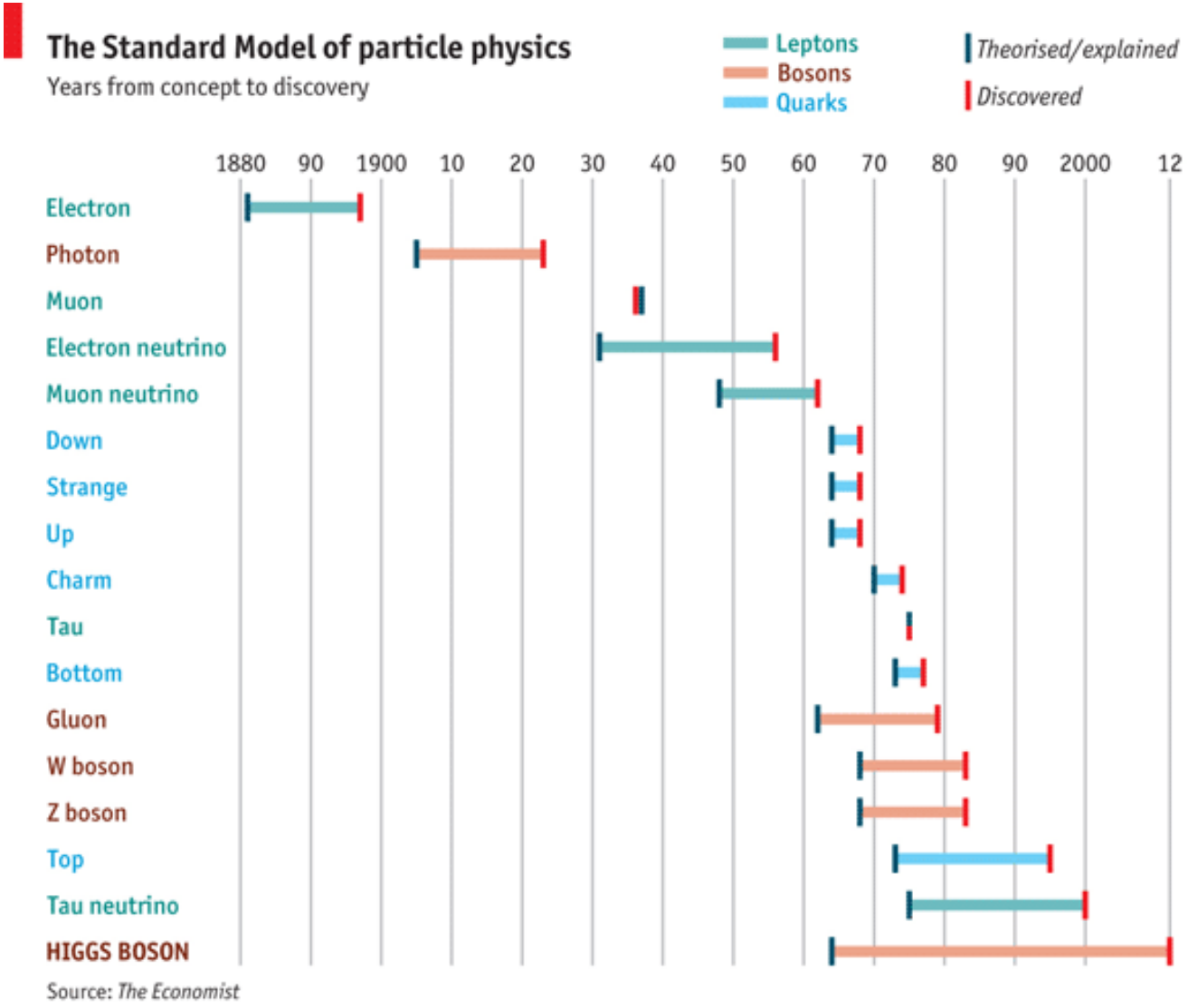
Bonus Slides!

Parton Shower

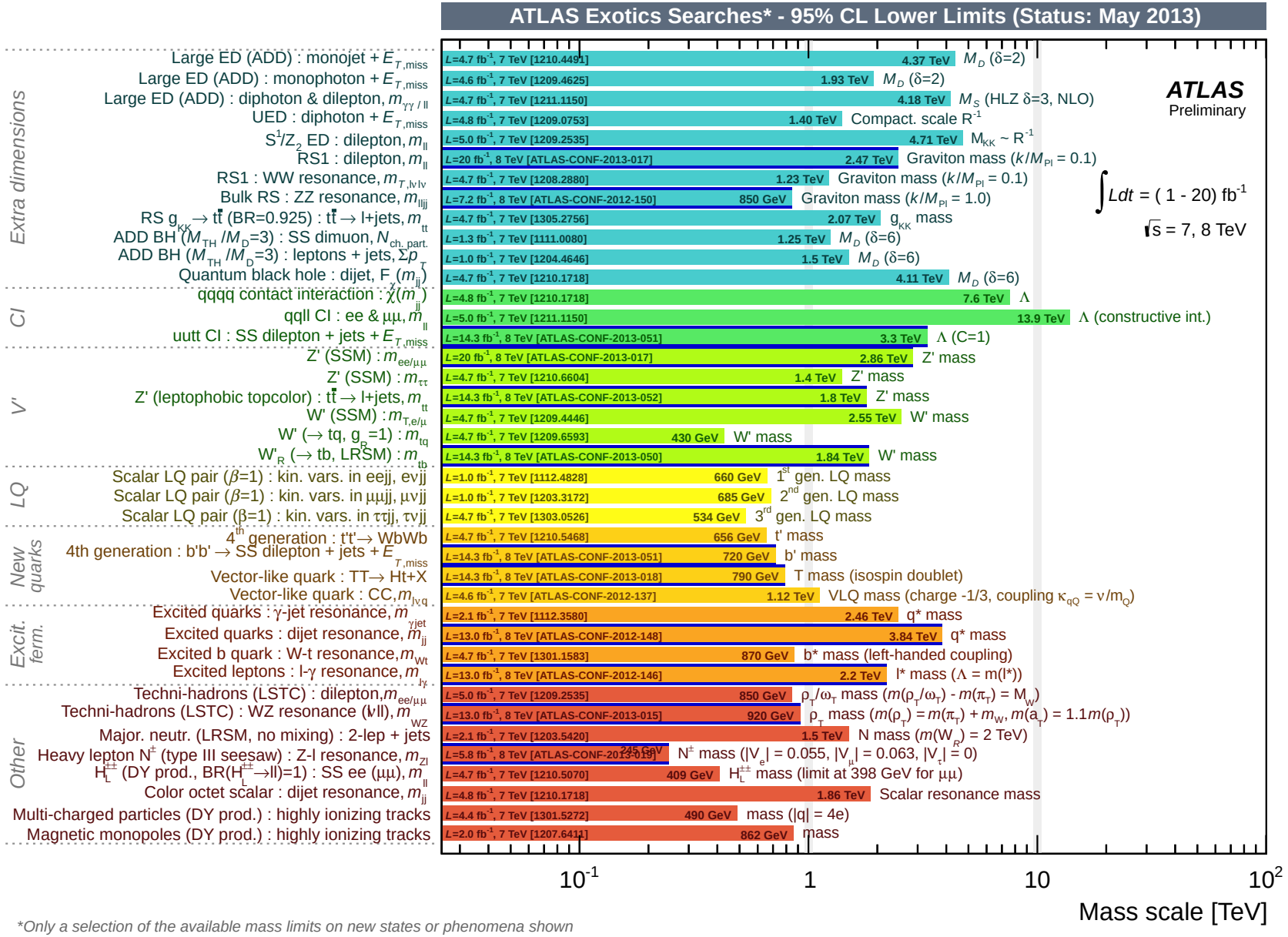


- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \to bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\to$ hadrons
- hadronic decays

History


The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist

Exotics



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

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LP 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.4 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

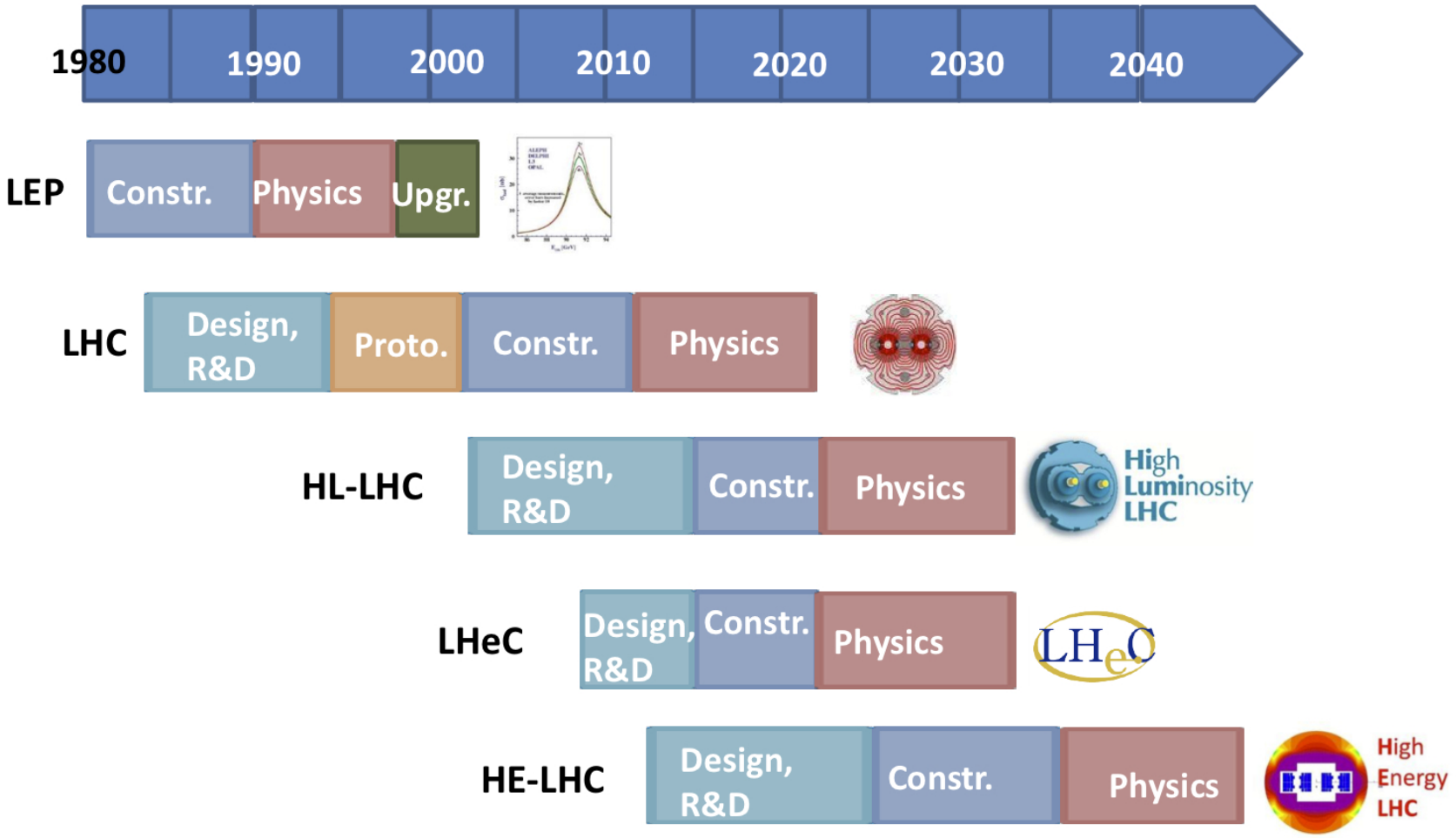
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	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
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$)<650 GeV	ATLAS-CONF-2013-007
	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	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	m($\tilde{\chi}_1^0$)>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	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($\tilde{H}$)>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
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	m($\tilde{\chi}_1^0$) <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3rd 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	$\tilde{b}_1$ 100-630 GeV	m($\tilde{\chi}_1^0$)<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 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	$\tilde{t}_1$ 220 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 150-440 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^{\pm}$)=10 GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(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	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	m($\tilde{\chi}_1^0$)>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	m($\tilde{t}_1$)=m($\tilde{\chi}_1^0$)+180 GeV	ATLAS-CONF-2013-025
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	$\tilde{\ell}$ 85-315 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 125-450 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 600 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($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0 Z^*\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 315 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	0	1 jet	Yes	4.7	$\tilde{\chi}_1^{\pm}$ 220 GeV	1<τ($\tilde{\chi}_1^{\pm}$)<10 ns	1210.2852
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 857 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$	1-2 μ	0	-	15.9	$\tilde{\tau}$ 385 GeV	5<tanβ<50	ATLAS-CONF-2013-058
	Direct $\tilde{\tau}\tilde{\tau}$ prod., stable $\tilde{\tau}$ or $\tilde{\ell}$	1-2 μ	0	-	15.9	$\tilde{\tau}$ 395 GeV	m($\tilde{\tau}$)=m($\tilde{\ell}$)	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{g}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e, μ	0	-	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 $e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	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

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

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

*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.

Future


1980
1990
2000
2010
2020
2030
2040
LEP
Constr.
Physics
Upgr.
LHC
Design, R&D
Proto.
Constr.
Physics
HL-LHC
Design, R&D
Constr.
Physics
High Luminosity LHC
LHeC
Design, R&D
Constr.
Physics
LHeC
HE-LHC
Design, R&D
Constr.
Physics
High Energy LHC