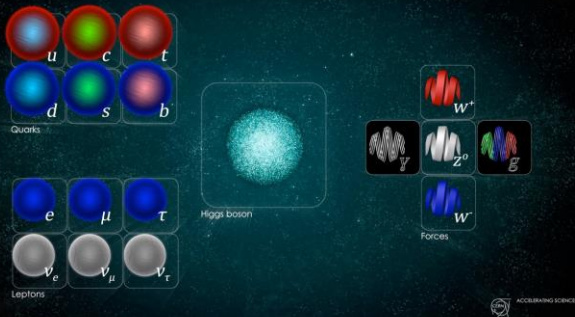


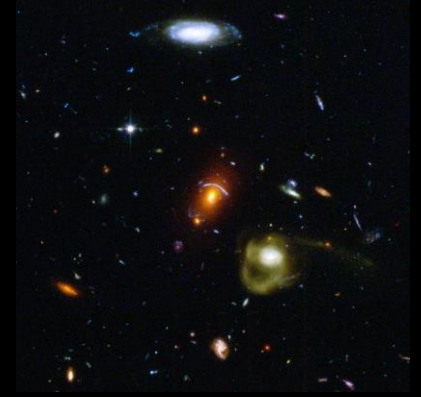
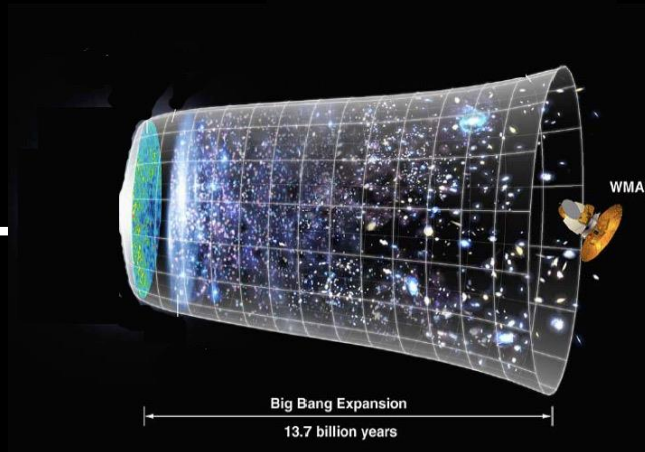
# Particle physics of the 21<sup>st</sup> century

Particle  
physics

+ Cosmology = Universe ?



+



No !

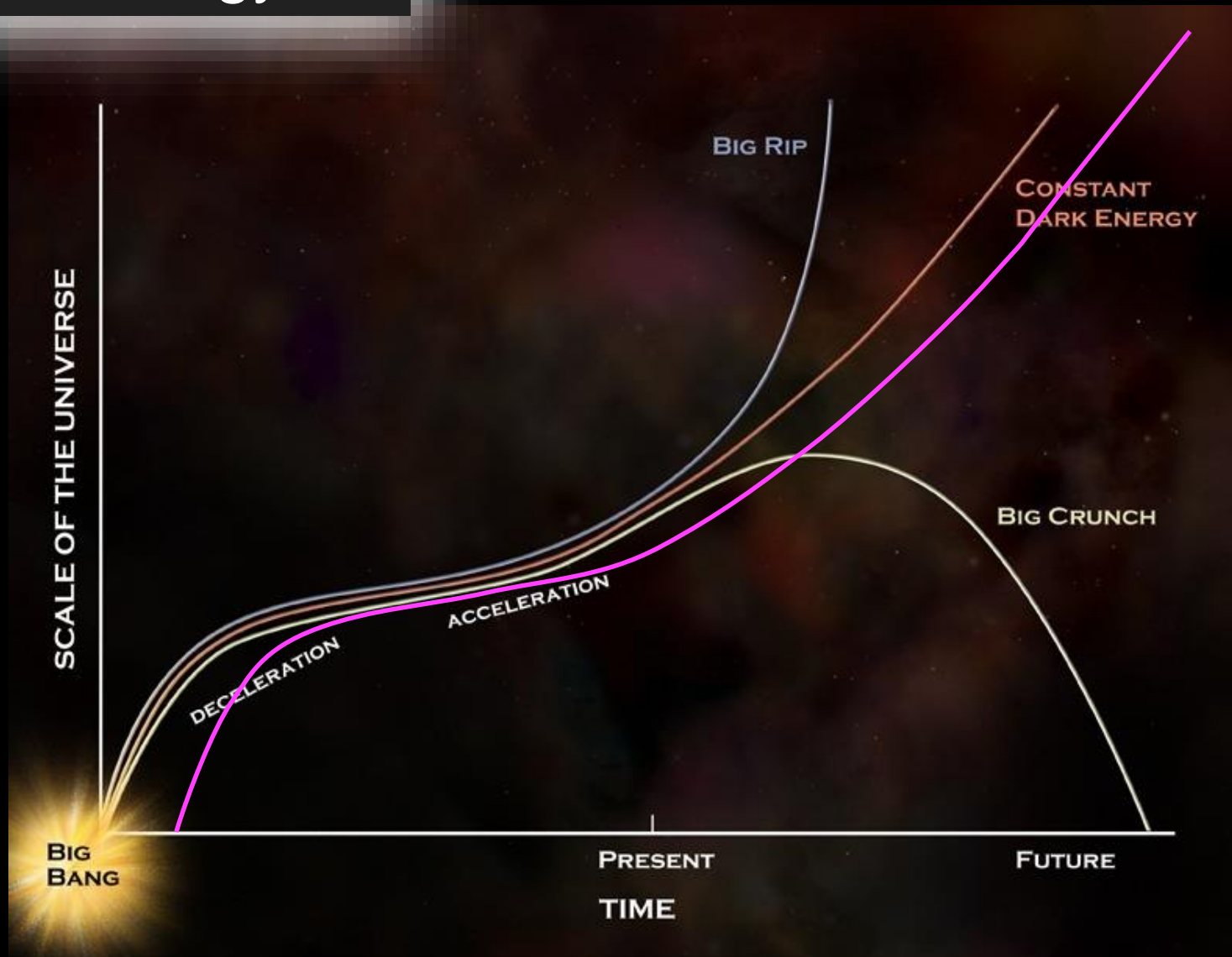
Less than 5% of the energy content of  
the universe are understood!

# Dark matter ...?



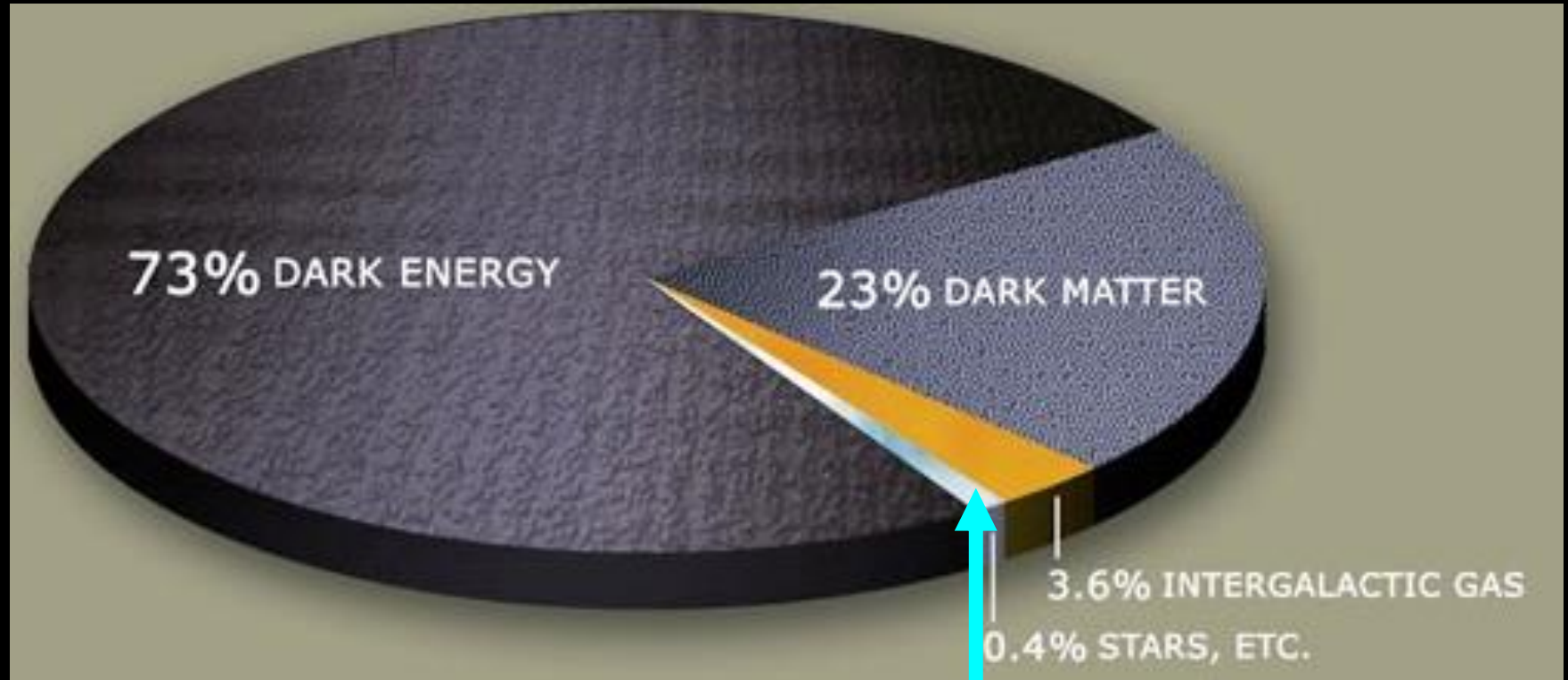
Galaxies rotate too fast

# Dark energy ...?



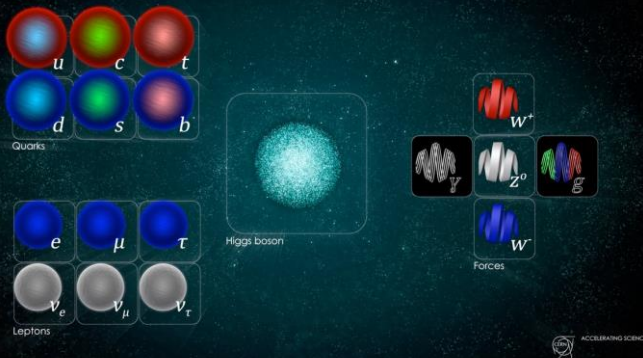
The expansion of the Universe accelerates ...

The “dark Universe”: 96 % of its energy content are hidden in ‘dark energy’ and ‘dark matter’



You are here

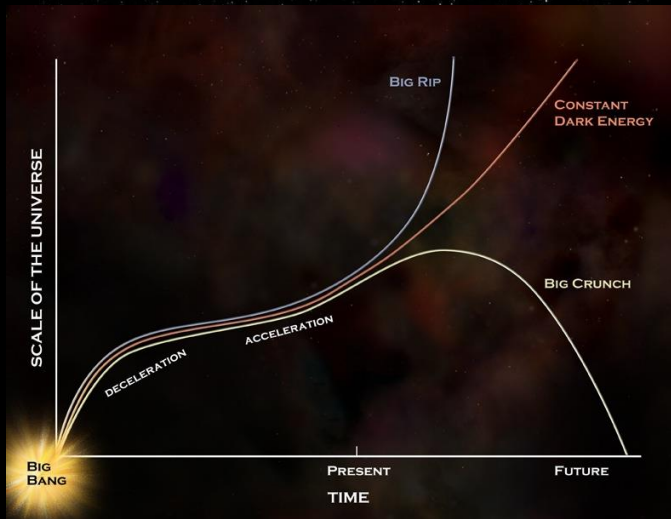
# The big questions:



How do particles obtain their mass?



What is dark matter?



What is dark energy?

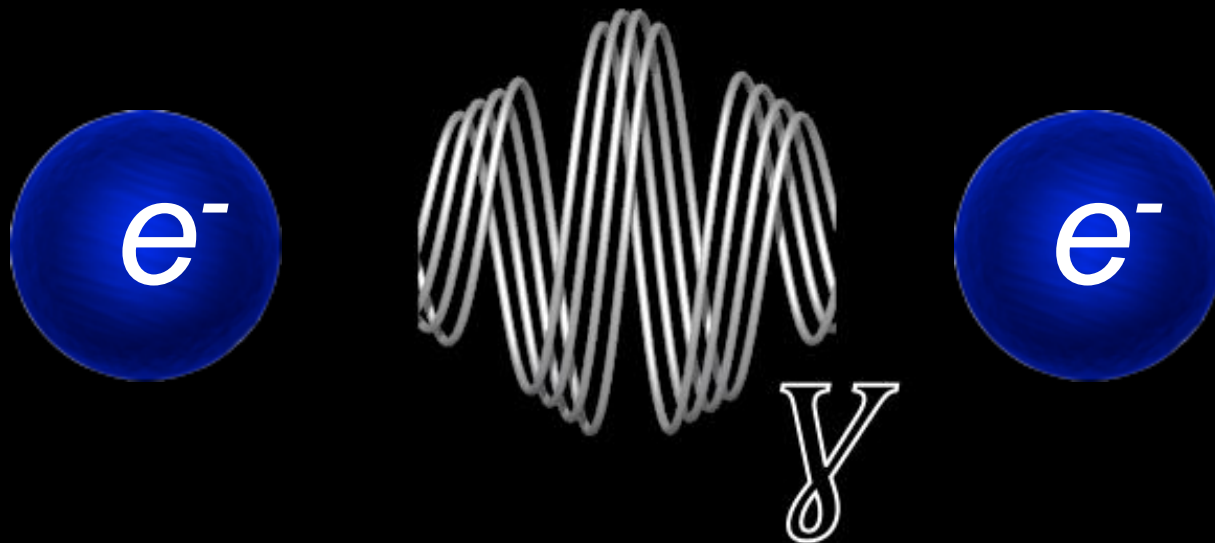
# Voyage to the smallest scales of matter



Anything you can see and touch is made of three particles:

**Up-Quark, Down-Quark, Electron.**

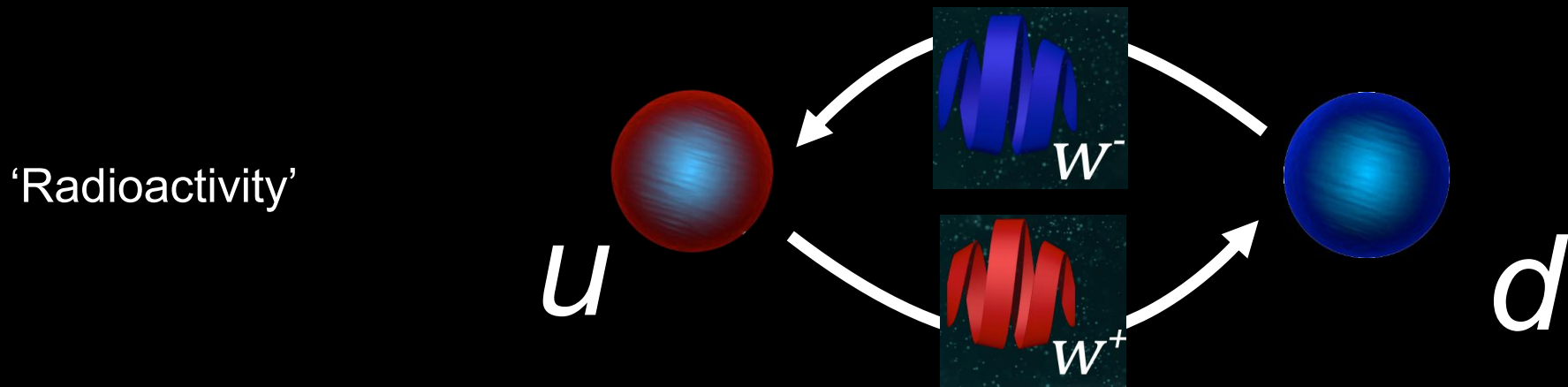
Forces are transmitted by the exchange of messenger particles ('bosons', spin = 1)



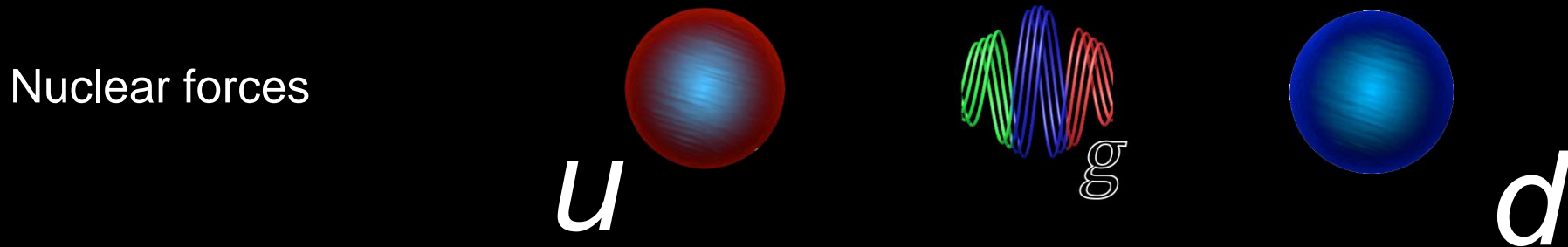
Electromagnetic interaction: Photons



Two forces have a very short range:



Weak force: **W-** and **Z-bosons**



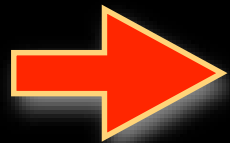
Strong force: **gluons**

How do we know?

$$E=mc^2$$

Energy can become matter

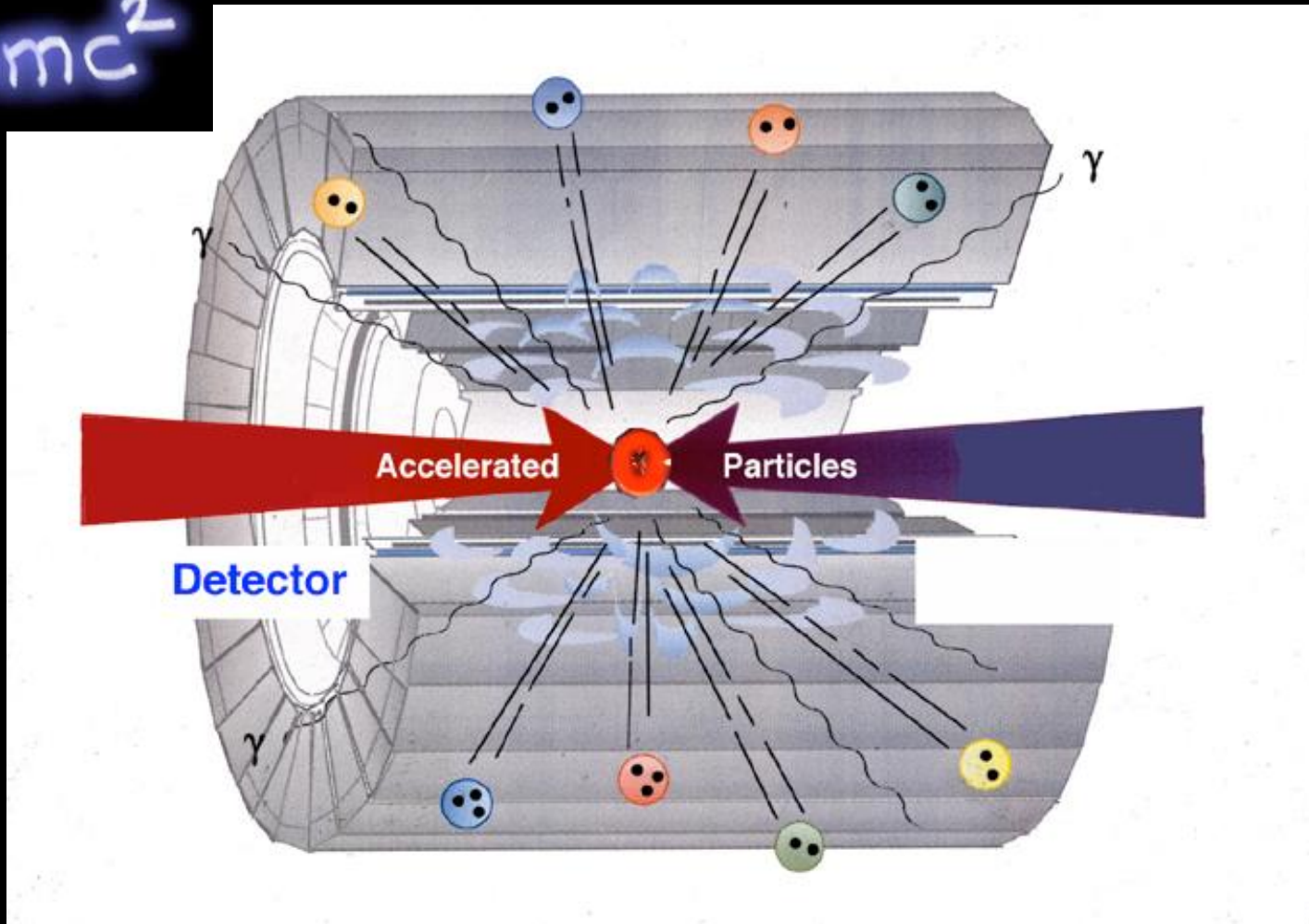
**How? Concentrate lots of energy on small scale**



**Particle collision at high kinetic energy**

# Energy becomes matter

$$E=mc^2$$

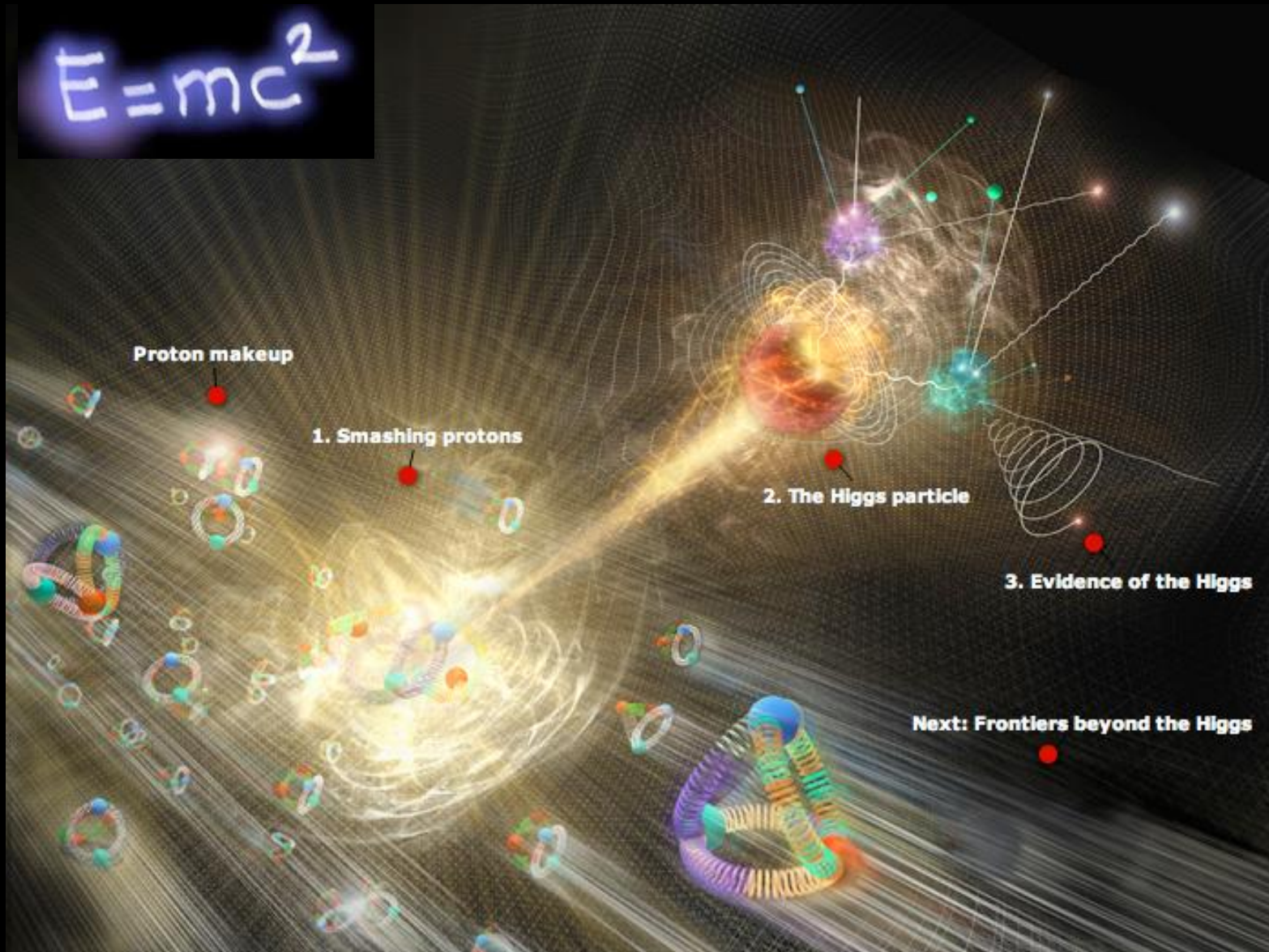


# Simple analogy

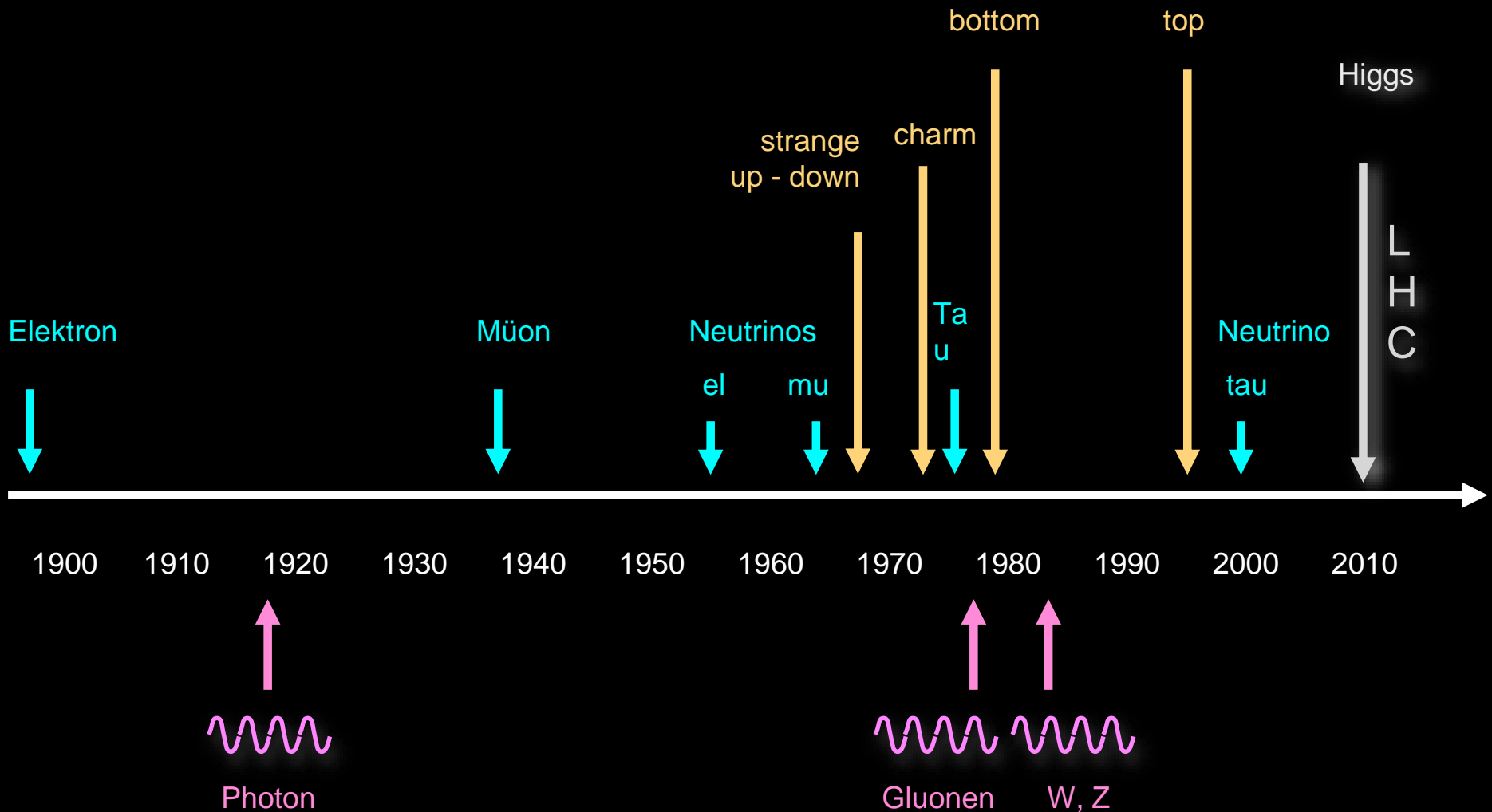
$$E=mc^2$$



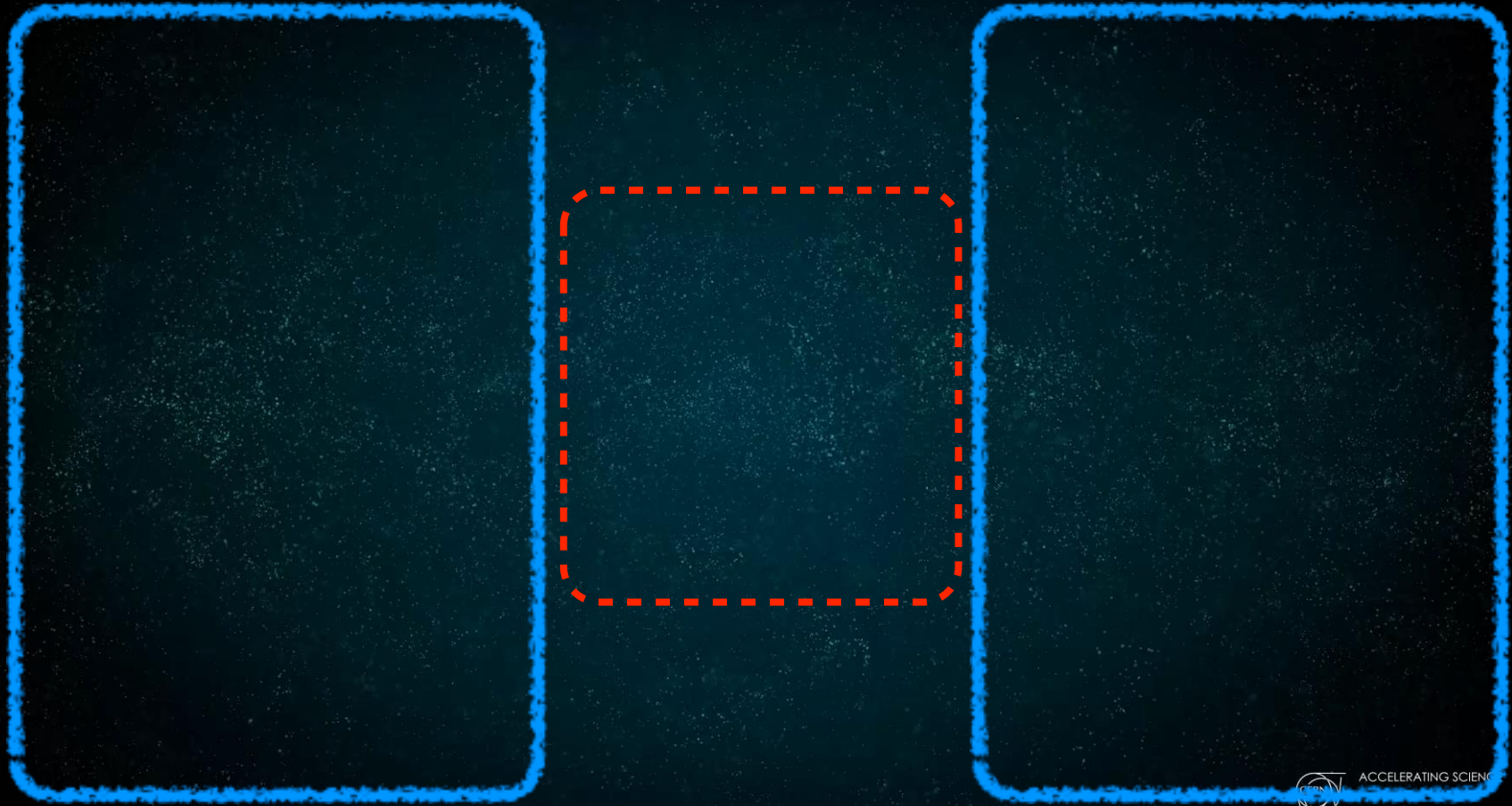
# Produce short-lived particles and observe their decay products



# Experiments at accelerators have discovered all particles of the “Standard Model”



# Standard model = 'periodic system' of elementary particles



Particles

Higgs

Fields

# How do particles obtain their respective masses?

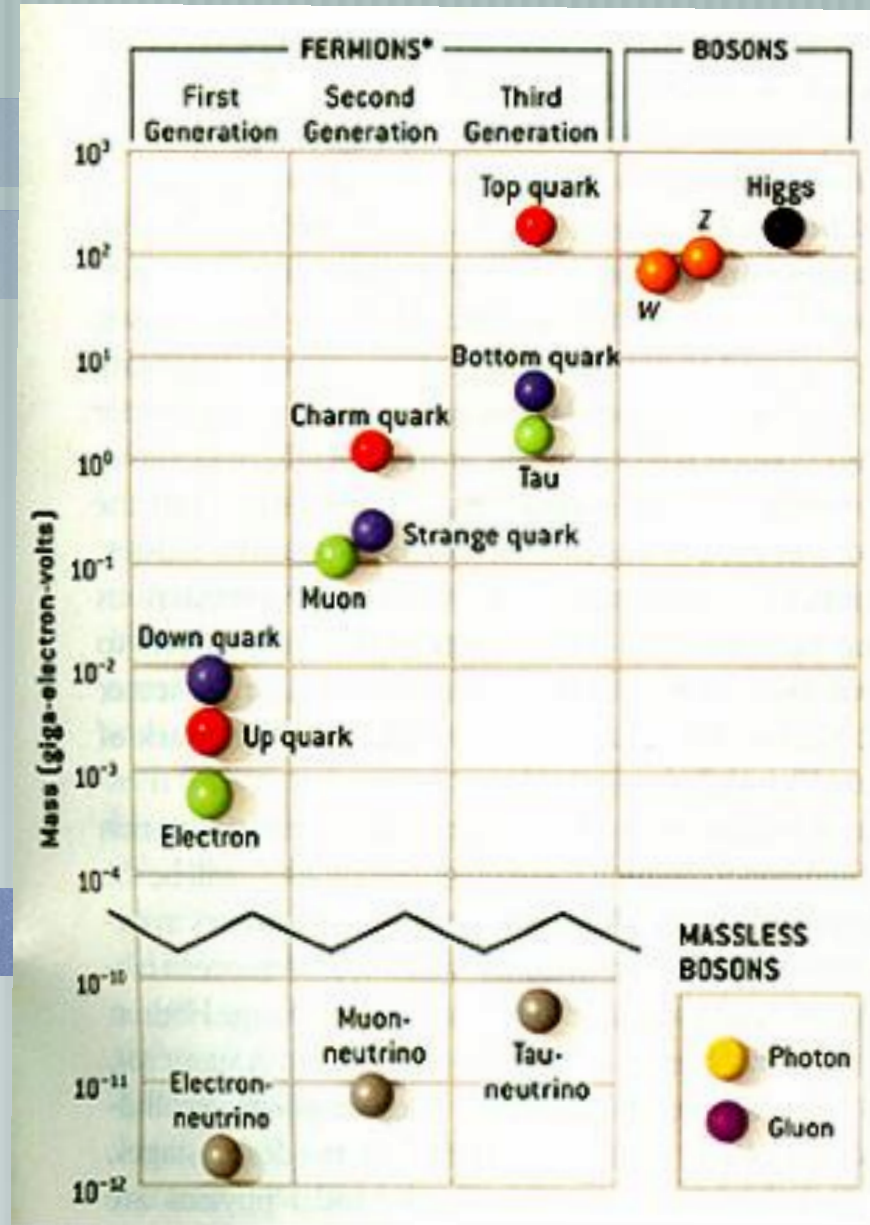
1 TeV →

100 GeV →

1 GeV →

1 MeV →

0.01 eV →





# The mystery of mass

Massless particles have to move with the speed of light

THEY CANNOT FORM SOLID OBJECTS

# The Brout-Englert-Higgs field idea

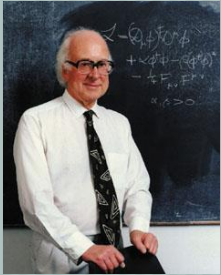
The Brout-Englert-Higgs field idea:

the entire Universe is filled with a homogeneous field

massless particles interacting with this field obtain inertia (=rest mass)

the BEH field interaction is proportional to the mass of the particle

## The 'cocktail party' explanation of the Higgs mechanism



Sir Peter Higgs



A cocktail party ...

*The BEH field ....*



.. a famous person wants to traverse the room...

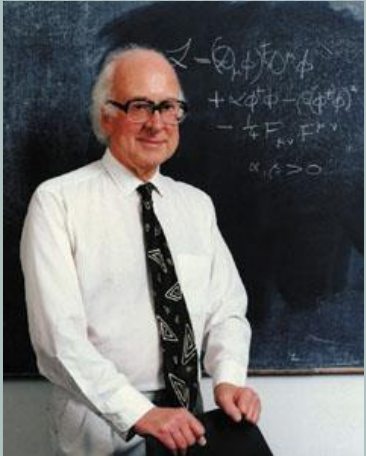
*... a massless particle enters...*



.. but the guests cluster around and slow down its movement...

*... the interaction with the BEH field produces the inertia of the particle ...*

# The 'Higgs boson'



Sir Peter Higgs



A rumour is spreading among the guests ...

*The BEH field ...*



.. they cluster together to exchange the information among themselves...

*... is excited by an energy concentration and forms an excitation by self-interaction ...*

# Animation: the Higgs mechanism



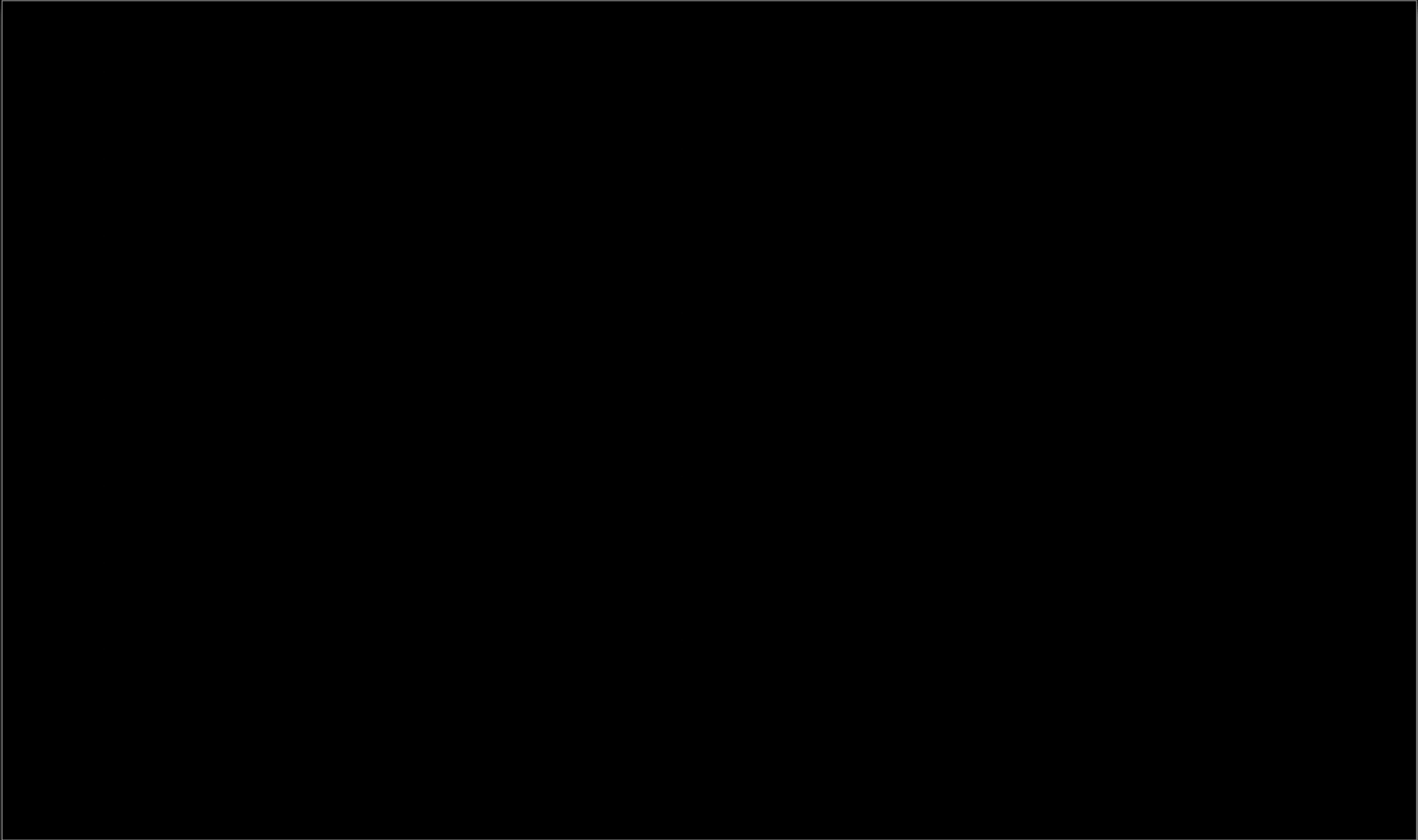
# Exciting the Brout-Englert-Higgs field: the “Higgs boson”



... but this happens on average once per 10,000,000,000 ( $10^{10}$ ) collisions !

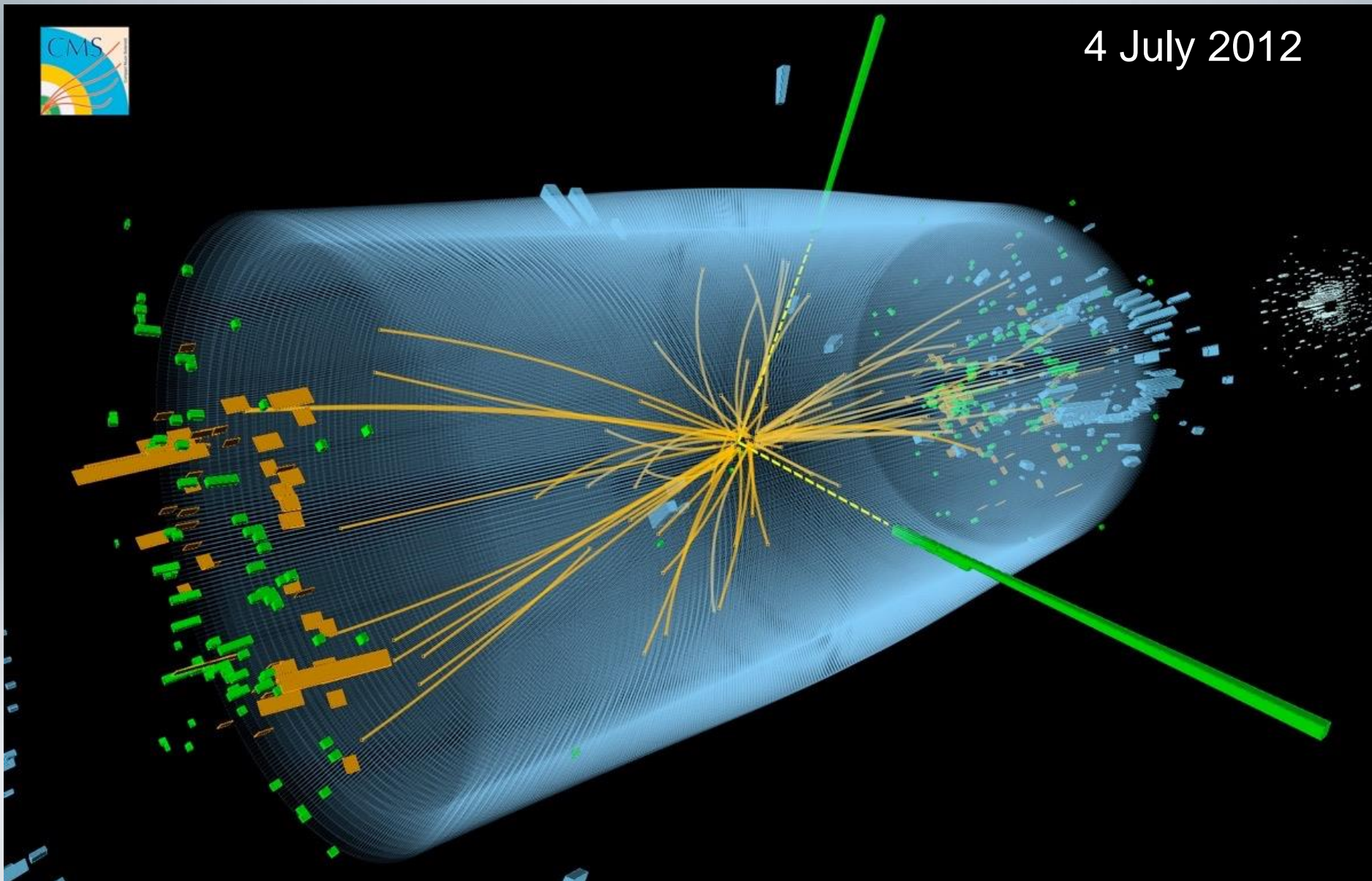
# The Higgs boson can decay in two photons

...

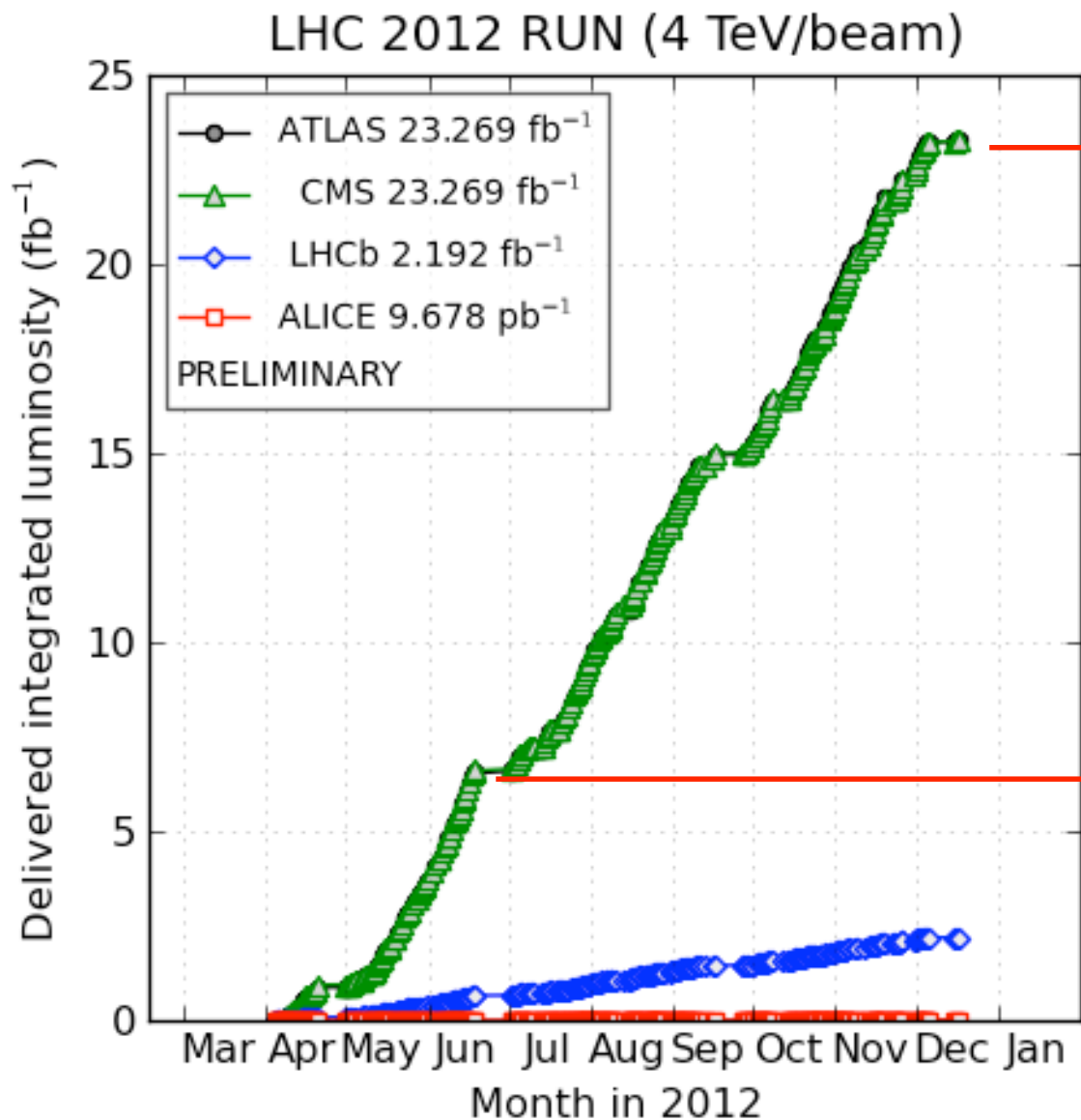


but only with a probability of 0.2 %

# How do we know that it is the Higgs boson ?



# 2011 - 2012 : Data taking with LHC



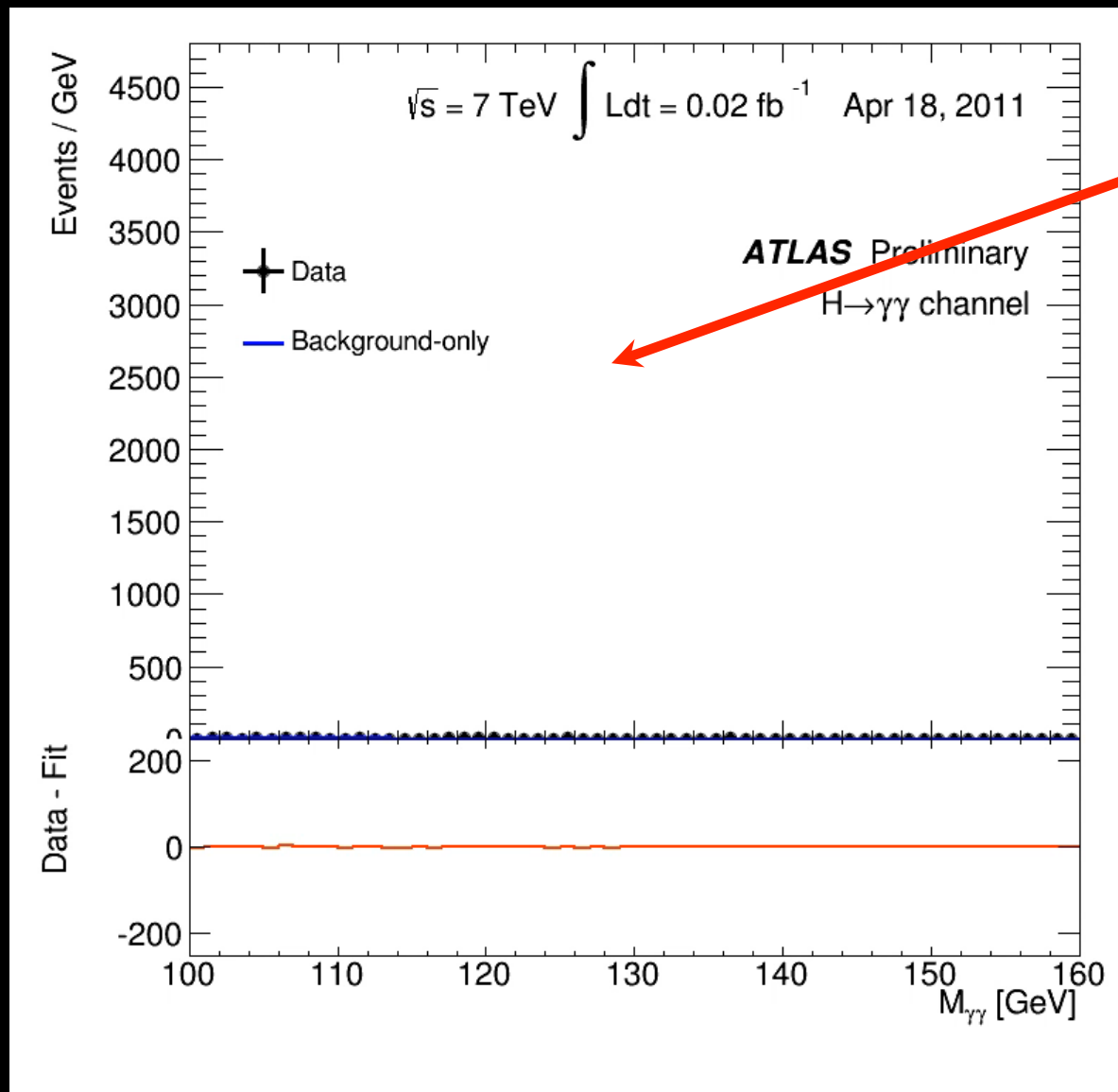
15.12.2012

3,000,000,000,000,000 ( $3 \cdot 10^{15}$ )  
(3000 trillion events !)

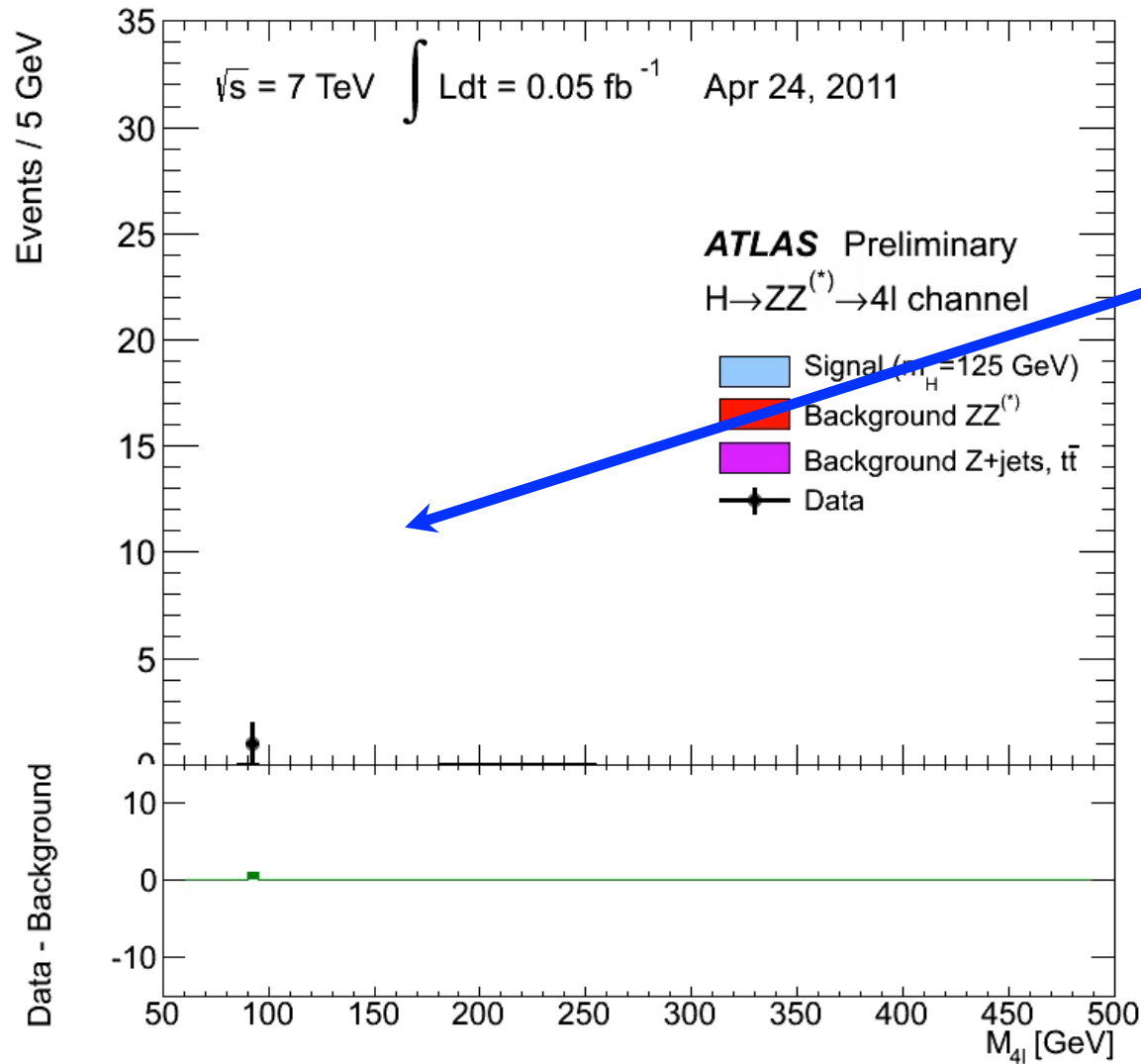
4.7.2012



# The evolution of the histogram with two-photon events



# The evolution of the histogram with four leptons

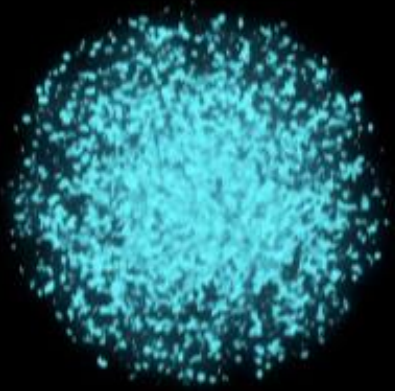


Higgs boson

# Update 14.3.2013: CERN Press Release

## More data confirm: new particle = Higgs boson

Higgs boson decay



$\gamma\gamma$



$Z^0 - Z^0$



Tau- Antitau

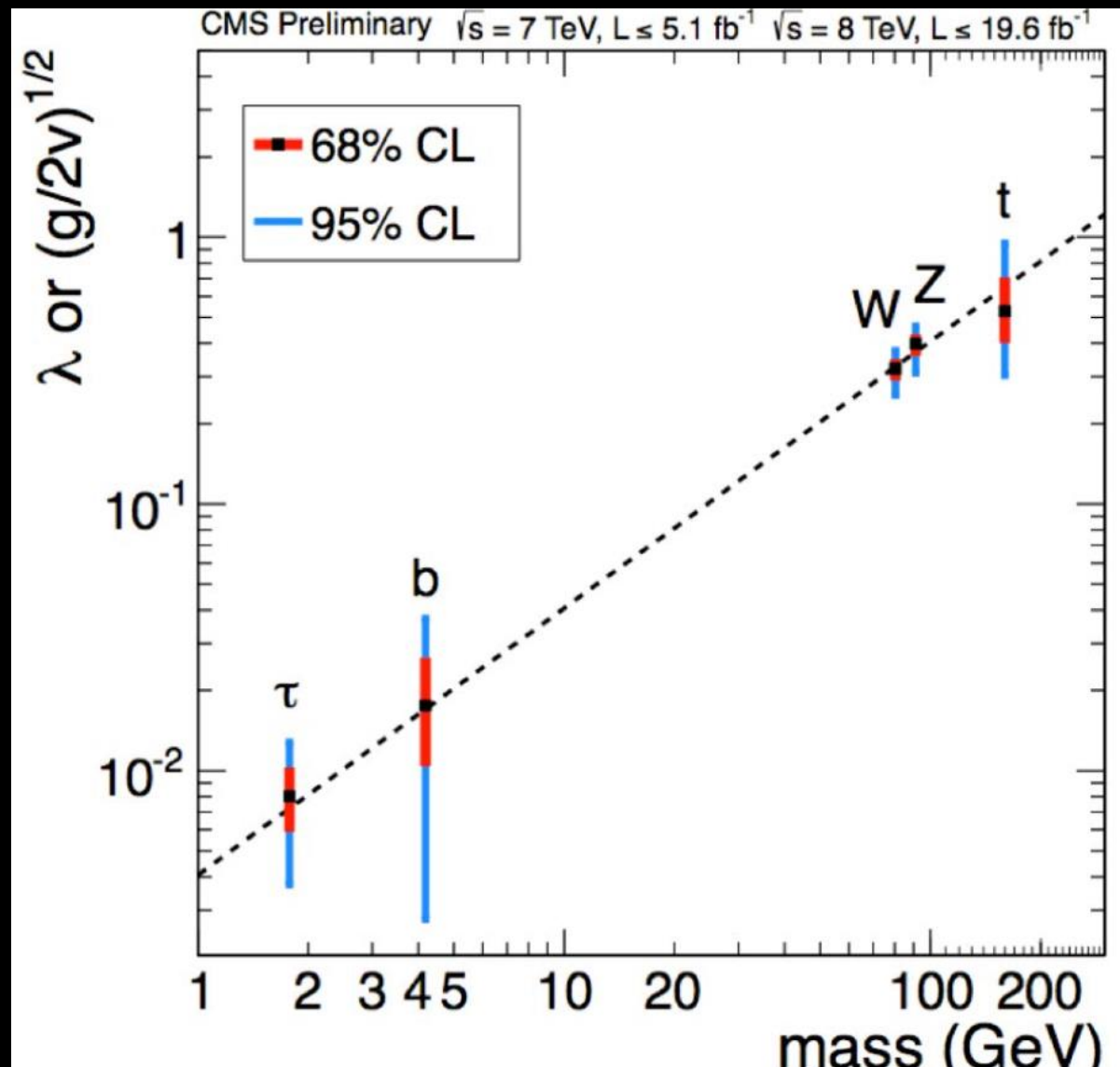


Bottom - Antibottom

Theoretical expectations compatible with observations

# Vorhersagen der Theorie sind konsistent mit den Messungen

Higgs-Boson-Zerfallswahrscheinlichkeit  $\sim$  Masse der Zerfallsteilchen





## *What does this mean?*

- the Higgs boson exists, therefore ...
- the Brout-Englert-Higgs field exists
- we know how particles obtain their mass
- the “Standard model” is complete

## *Even more:*

- empty space is not ‘empty’
- perhaps a connection to ‘dark energy’ ?

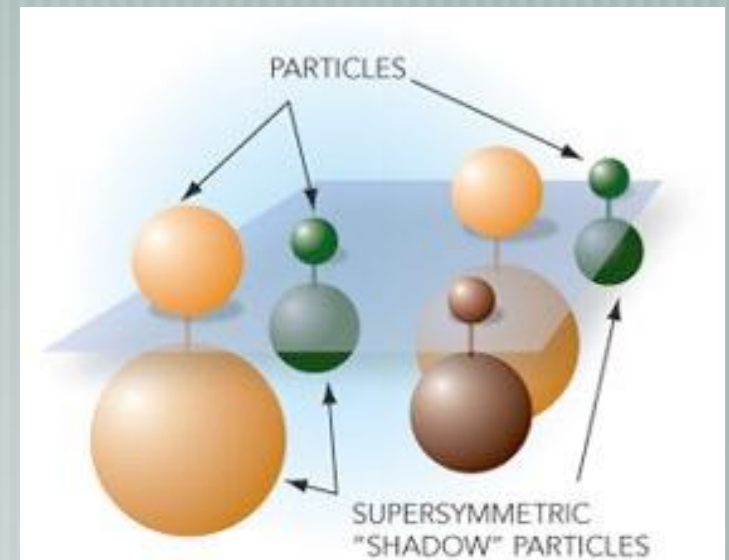
# SUPERSYMMETRY

**A connection between particles (spin 1/2) and fields (spin 1) ?**

FERMIONS (quarks, electrons, neutrinos) interact through the exchange of BOSONS (gluons, photon, W/Z bosons)

**“SUPERSYMMETRY” predicts a complete symmetry between FERMIONS AND BOSONS: each fermion has a boson partner, and vice versa:**

Spin 1/2	Spin 0, Spin 1
electron	selectron (S=0)
quark	squark (S=0)
photino	photon (S=1)
gluino	gluon (S=1)
gaugino (Wino, Zino)	W, Z (S=1)

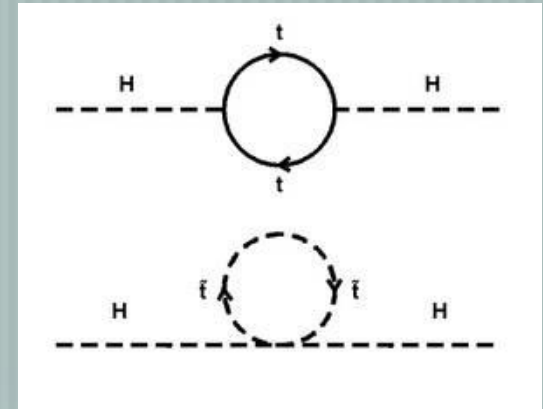


But: no such SUSY partner has ever been seen. So ... if they exist, they must have a large mass (> 1 TeV)

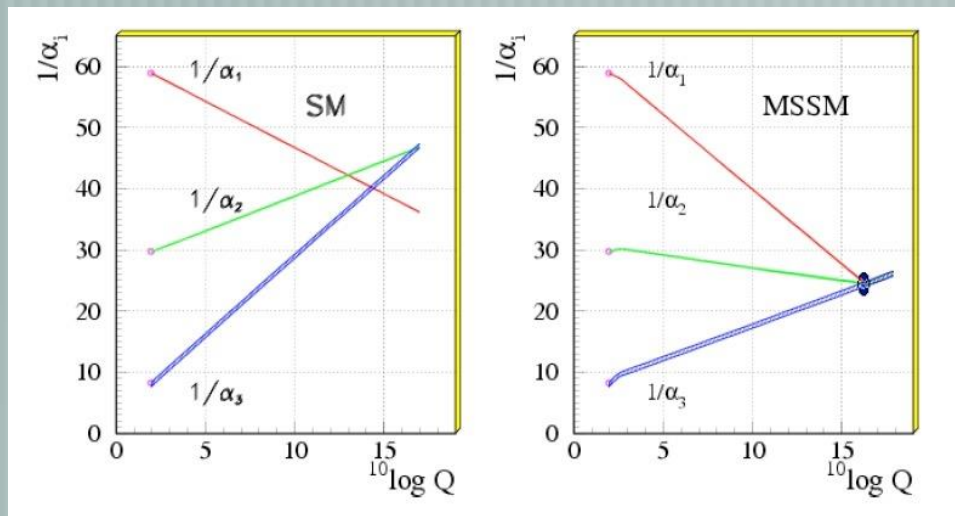
# Why SUSY?

1) A fundamental space-time-symmetry

2) "Protection of the Higgs boson mass ( $M \sim 10^2$  GeV) from vacuum fluctuations up to Planck mass ( $\sim 10^{19}$  GeV)



3) Predicts unification of electroweak and strong interaction at  $\sim 10^{17}$  GeV

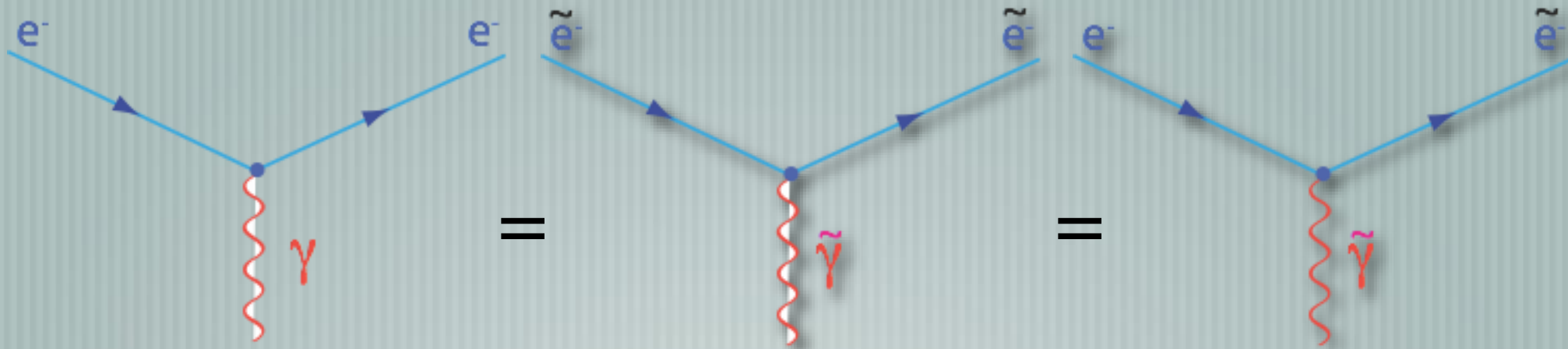


4) May explain the cosmological matter-antimatter asymmetry

5) **Lightest supersymmetric particle = dark matter ??**

# Supersymmetry - easy to calculate:

Particles and 'Super-Partners' can simply be exchanged



$e$  = electron

$\tilde{e}$  = selectron

$\odot$  = photon

$\tilde{\odot}$  = photino



# Desperately seeking SUSY ...

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

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

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} d\mathcal{I} [\text{fb}^{-1}]$	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
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1405.7875
	$\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	1 $\gamma$	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) = m(c)$	1411.1559
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_1^0$	1 $e, \mu$	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}, m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1501.03555
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 $e, \mu$	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1501.03555
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta > 20$	1407.0603
	GGM (bino NLSP)	2 $\gamma$	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0) > 50 \text{ GeV}$	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0) > 50 \text{ GeV}$	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0) > 220 \text{ GeV}$	1211.1167
GGM (higgsino NLSP)	2 $e, \mu$ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\text{NLSP}) > 200 \text{ GeV}$	ATLAS-CONF-2012-152	
Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$	1502.01518	
3 <sup>rd</sup> gen. $\tilde{g}$ med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 $b$	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	1407.0600
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0) < 350 \text{ GeV}$	1308.1841
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^{\pm}$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	1407.0600
	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^{\pm}$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	1407.0600
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0) < 90 \text{ GeV}$	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^{\pm}$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^0)=2m(\tilde{\chi}_1^{\pm})$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$	1-2 $e, \mu$	1-2 $b$	Yes	4.7	$\tilde{t}_1$ 110-167 GeV, 230-460 GeV	$m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=55 \text{ GeV}$	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 215-530 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 $e, \mu$	1-2 $b$	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	1407.0583, 1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0) < 85 \text{ GeV}$	1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1403.5294
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \tilde{\ell}\nu(\tilde{\ell}\nu)$	2 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}\nu(\tilde{\tau}\nu)$	2 $\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \tilde{\ell}\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 $e, \mu$	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 $e, \mu$	0-2 jets	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/WW/\tau\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 $b$	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0$ , sleptons decoupled	1501.07110
	$\tilde{\chi}_{2,3}^0\tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R\ell$	4 $e, \mu$	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 $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=160 \text{ MeV}, \tau(\tilde{\chi}_1^{\pm})=0.2 \text{ ns}$
Stable, stopped $\tilde{g}$ R-hadron		0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
Stable $\tilde{g}$ R-hadron		trk	-	-	19.1	$\tilde{g}$ 1.27 TeV	-	1411.6795
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$		1-2 $\mu$	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	$10 < \tan\beta < 50$	1411.6795
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$		2 $\gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	$2 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}$ , SPS8 model	1409.5542
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$ (RPV)		1 $\mu$ , displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	$1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$	ATLAS-CONF-2013-092
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 $e, \mu$	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda_{511}^{\prime}=0.10, \lambda_{132}=0.05$	1212.1272
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda_{511}^{\prime}=0.10, \lambda_{1(2)33}=0.05$	1212.1272
	Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{LSP} < 1 \text{ mm}$	1404.2500
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 $e, \mu$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda_{121} \neq 0$	1405.5086
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda_{133} \neq 0$	1405.5086
	$\tilde{g} \rightarrow q\tilde{q}$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	$\text{BR}(\tau)=\text{BR}(b)=\text{BR}(c)=0\%$	ATLAS-CONF-2013-091
$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b s$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{g}$ 850 GeV	-	1404.250	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 $c$	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1501.01325

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

$10^{-1}$

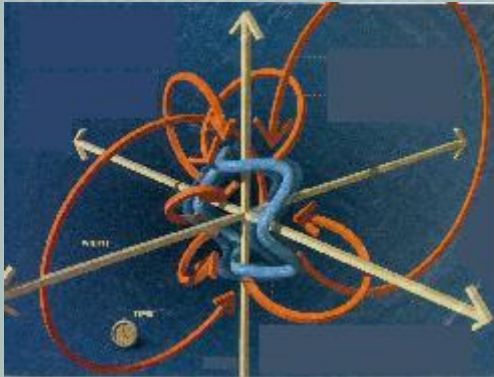
1

Mass scale [TeV]

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

# MORE MYSTERIES

## What is a particle?



## Superstrings in 9+1 dimensions?

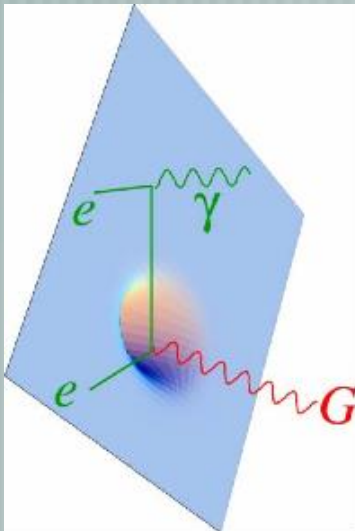
Little strings of string energy vibrating in a 9+1 dimensional space ?

$L \sim 10^{-35}$  m (Planck length)

Standard model particles: different vibration modes, open/closed strings  
GRAVITON-like particle contained (unification of SM and gravity?)

BUT: why did 6 dimensions disappear? how did they disappear?  
is there a unique way to go from 10 to 4 dimensions?

## Quantum Gravitation



More than 3 macroscopic dimensions of space?

Is the graviton propagating in 4- or more dimensions of space?

Micro-black holes ?

# Mysteries of the 21st century

1900 - 2000: Phantastic progress in understanding matter and the Universe

We know what matter is made of.

We know the principle steps in the evolution of the Universe.

## Some of the big physics questions of the 21st century

What is the structure of empty space: the BEH field? dark energy?

What is dark matter?

What is the origin/nature of particle families? Why three? What are particles?

Where is the connection between quarks and leptons (identical electroweak charges!!)

How did the antimatter disappear?

The origin and value of the constants of Nature? Is life in the Universe an 'accident' ?

# The Large Hadron Collider - 2015 13 TeV - 1 billion events/sec



**New discoveries are waiting !**