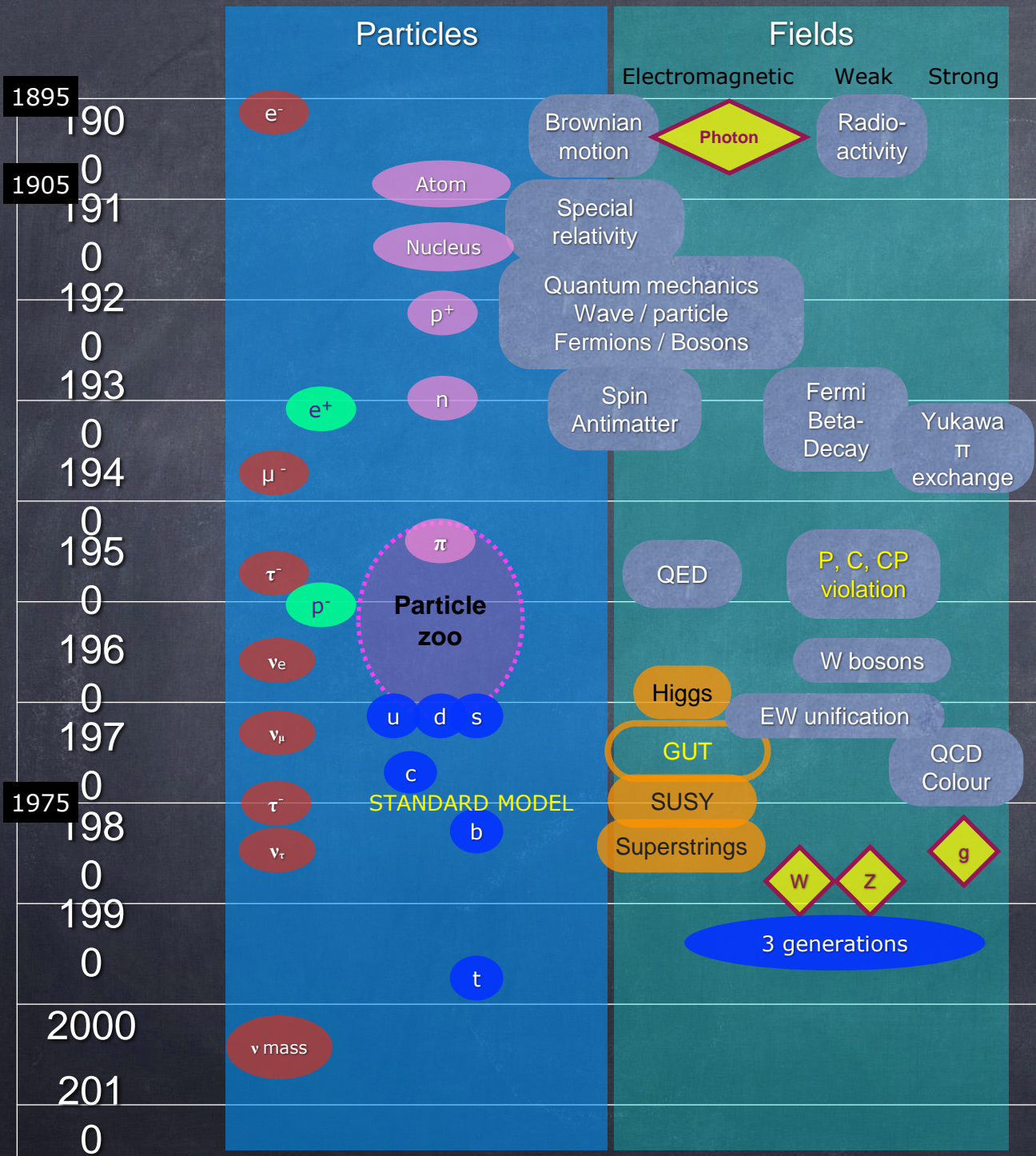


# **STRUCTURE OF MATTER**

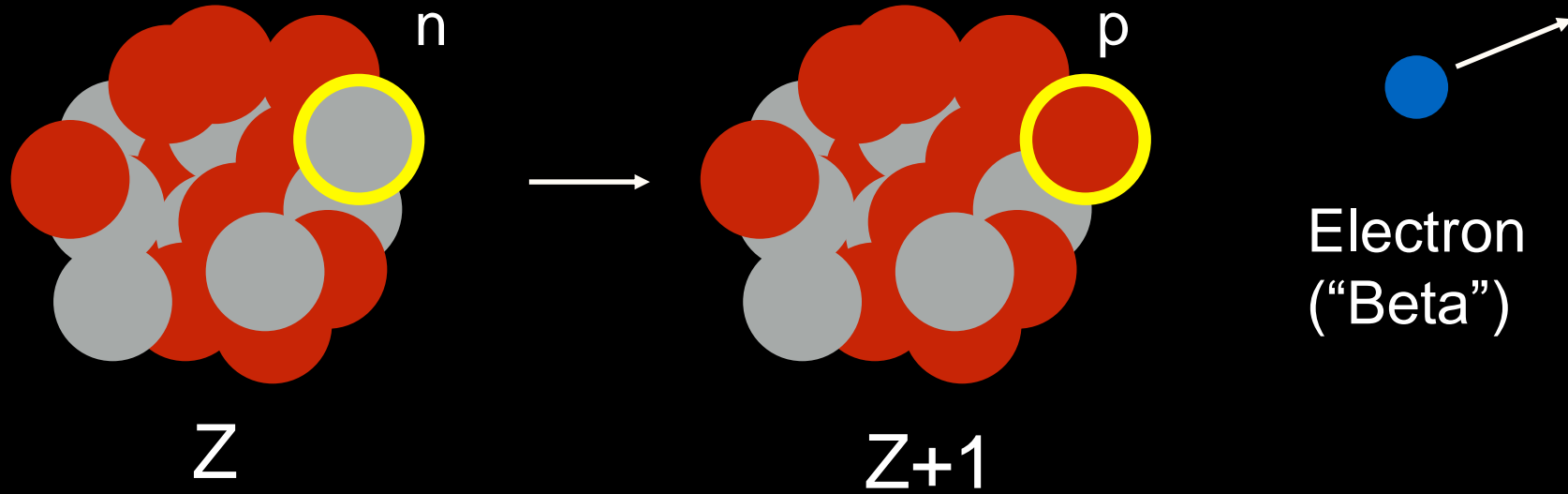
Discoveries and Mysteries

Part 2

Rolf Landua  
CERN

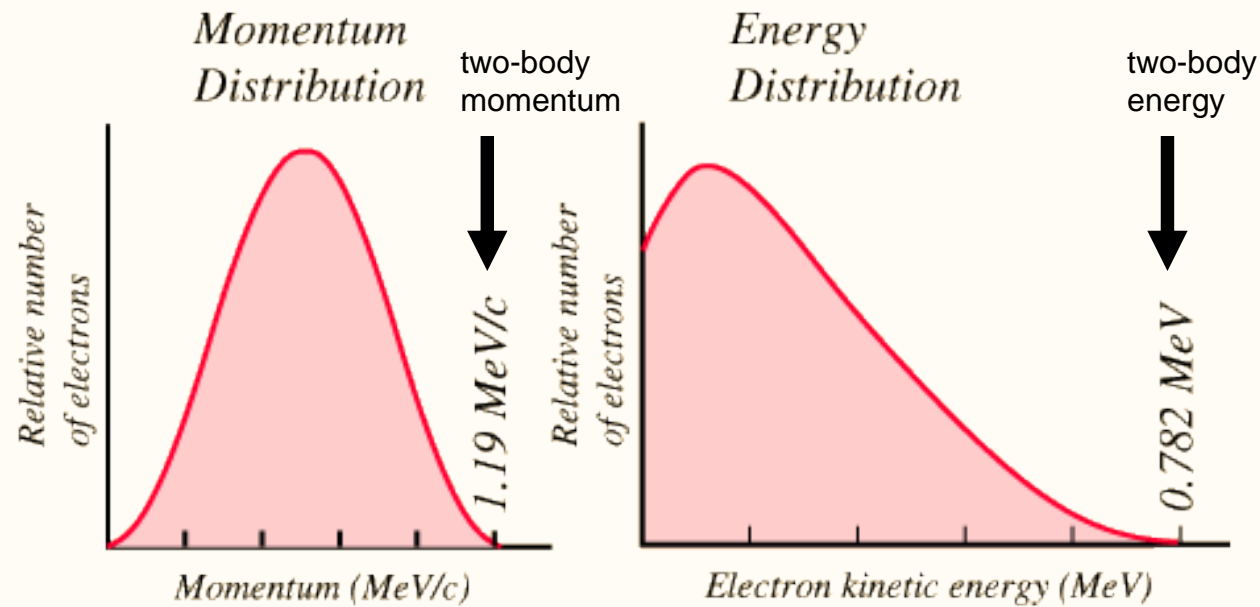


# WEAK INTERACTION



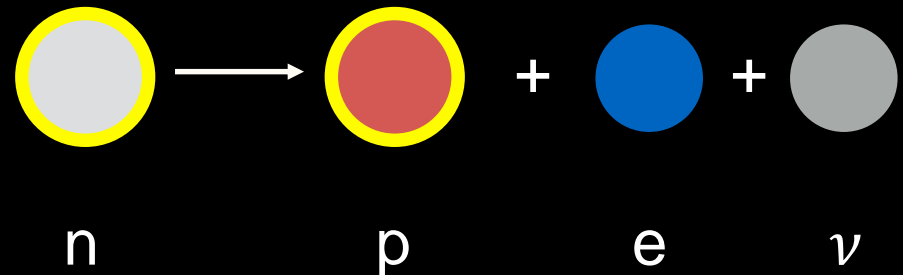
Henri Becquerel (1900): Beta-radiation = electrons

Two-body reaction? But electron energy/momentum is continuous:

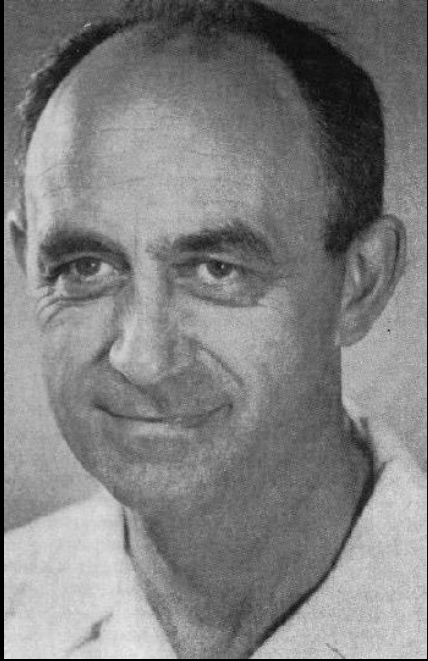


W. Pauli (1930) postulate:

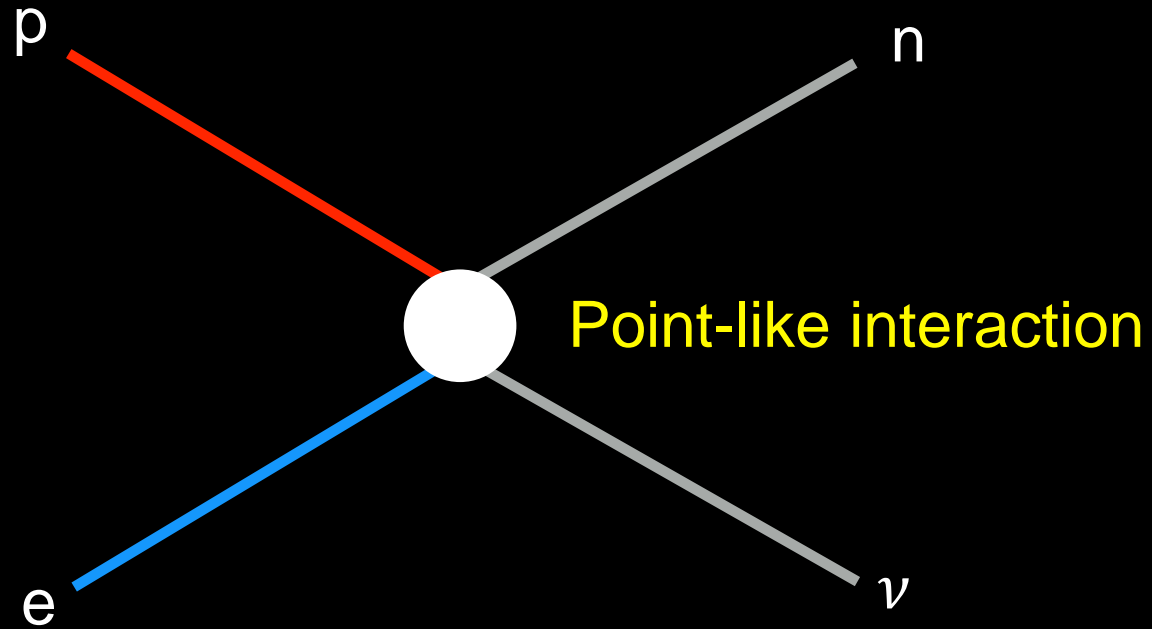
- there is a third particle involved
- neutral
- very small or zero mass
- "Neutrino" (Fermi)



# FERMI THEORY (1934)



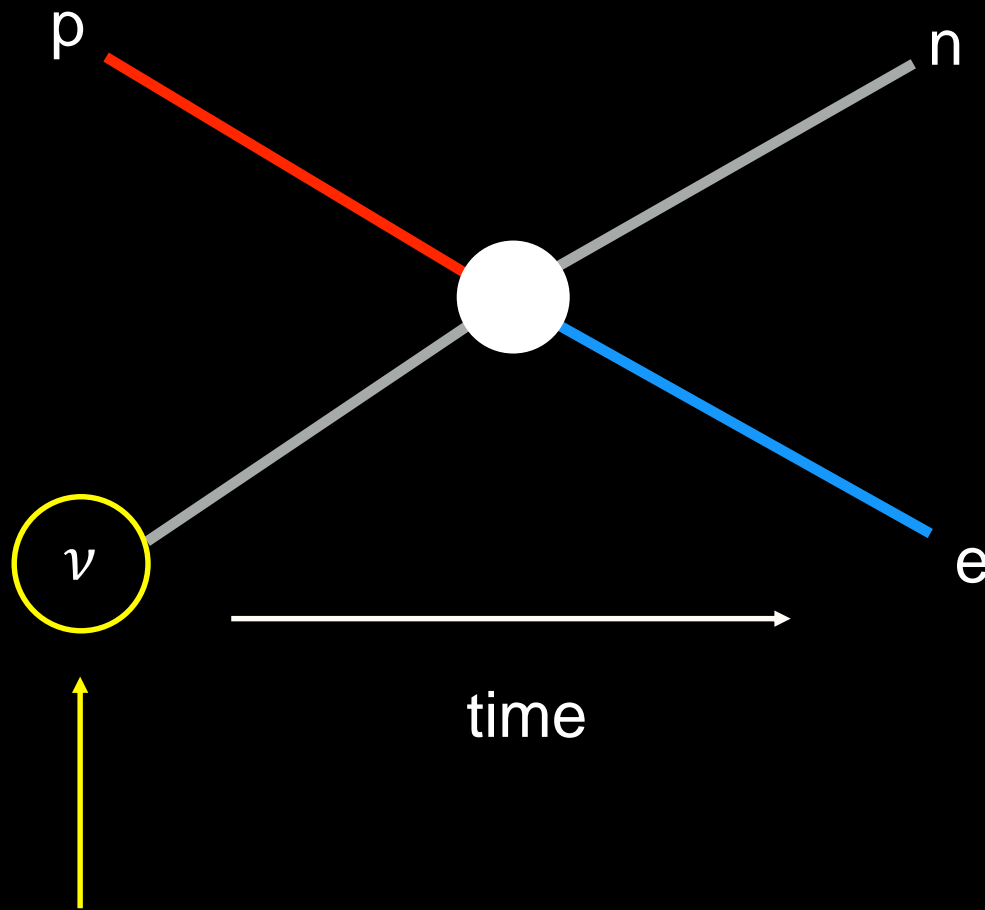
Enrico Fermi



$W =$  Overlap of the four wave functions  $\times$  Universal constant  $G$

$G \sim 10^{-5} / M_p^2 =$  "Fermi constant"

# FERMI: PREDICTION ABOUT NEUTRINO INTERACTIONS



$$\sigma = \frac{4}{\pi} G^2 E^2$$

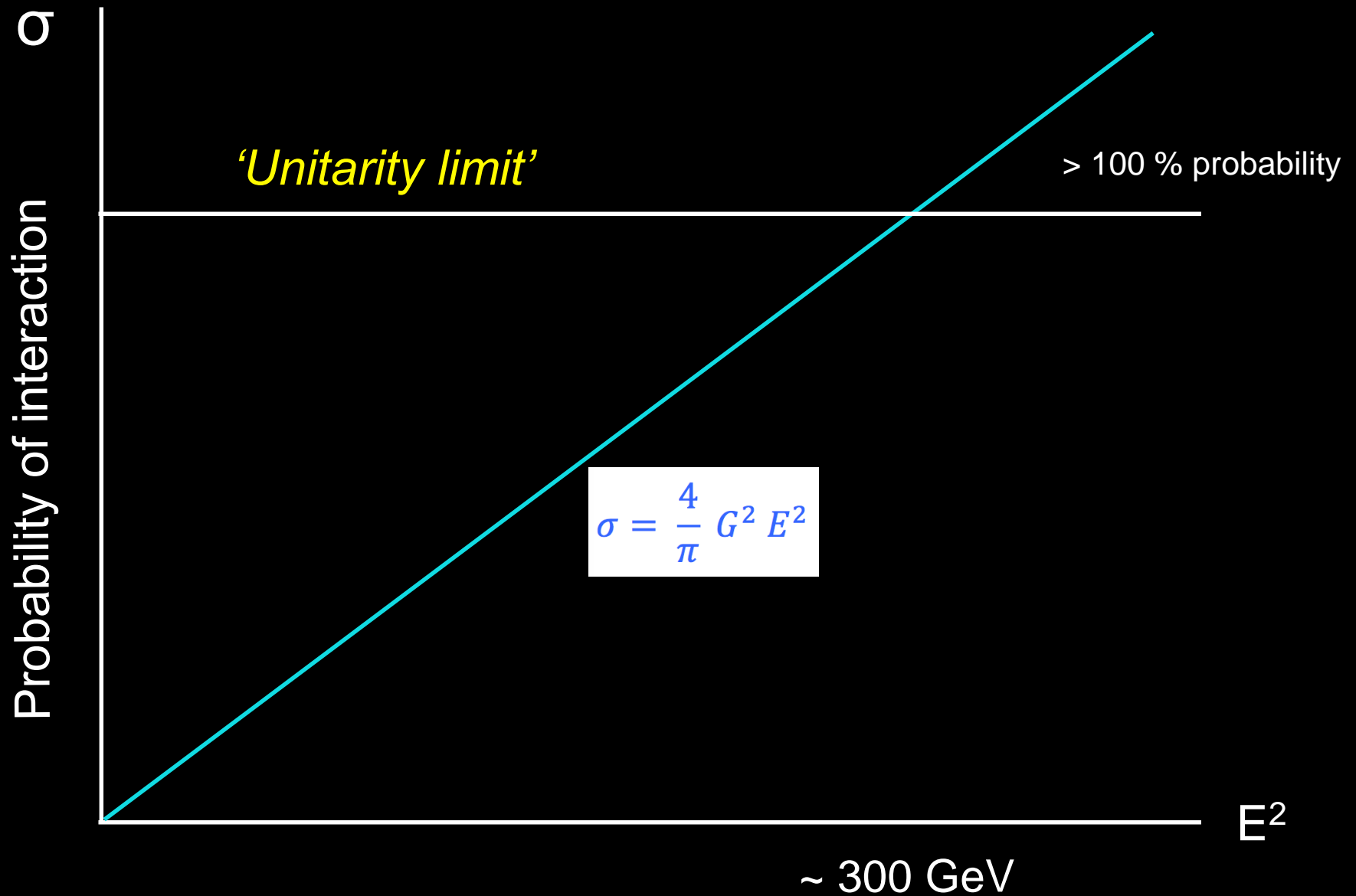
$$E = 1 \text{ MeV: } \sigma = 10^{-43} \text{ cm}^2$$

(Range:  $10^{20}$  cm  $\sim$  100 l.yr)

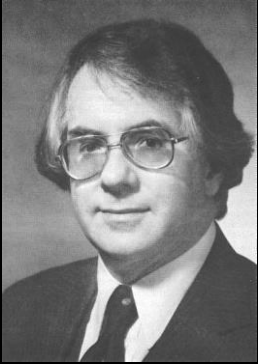
Reines, Cowan (1956):  
Neutrino 'beam' from reactor

Reactions prove existence of neutrinos

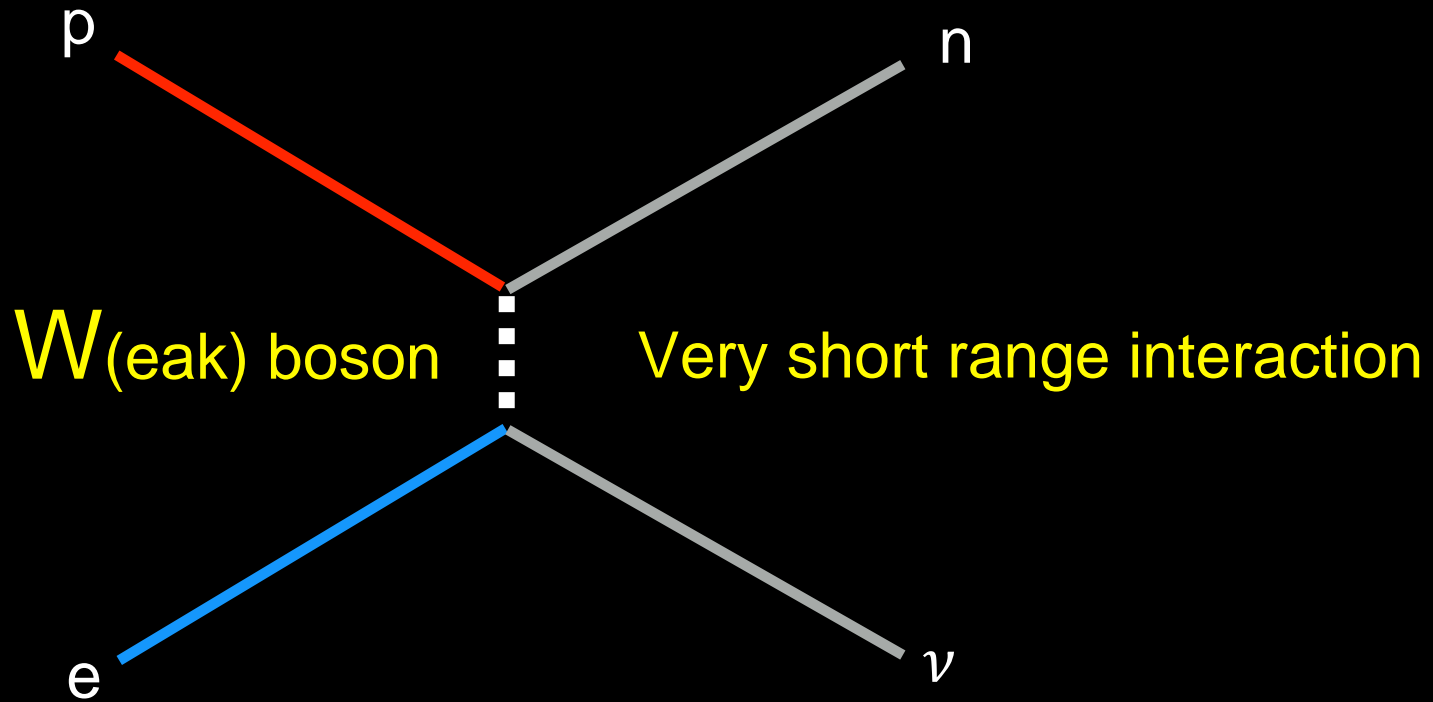
and then ..... THE PREDICTION FAILED !!



# GLASGOW REFORMULATES FERMIS THEORY (1958)



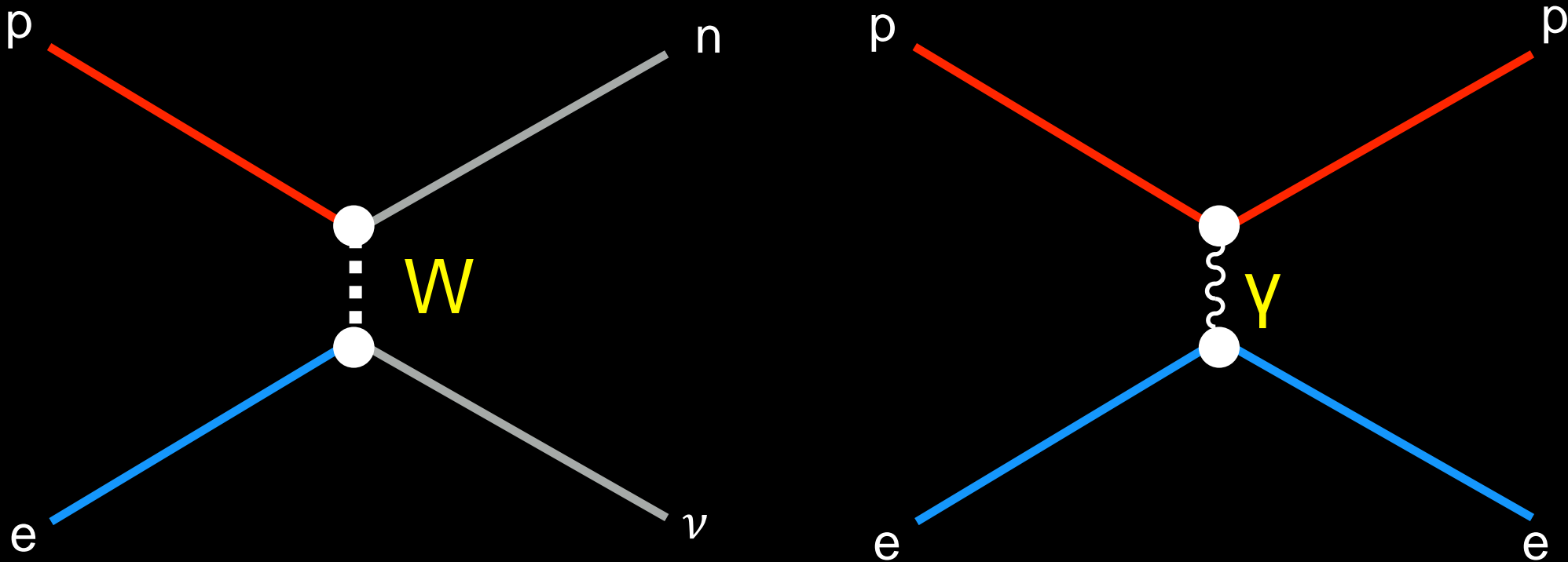
S. Glashow



If mass of W boson  $\sim 100$  GeV : theory o.k.



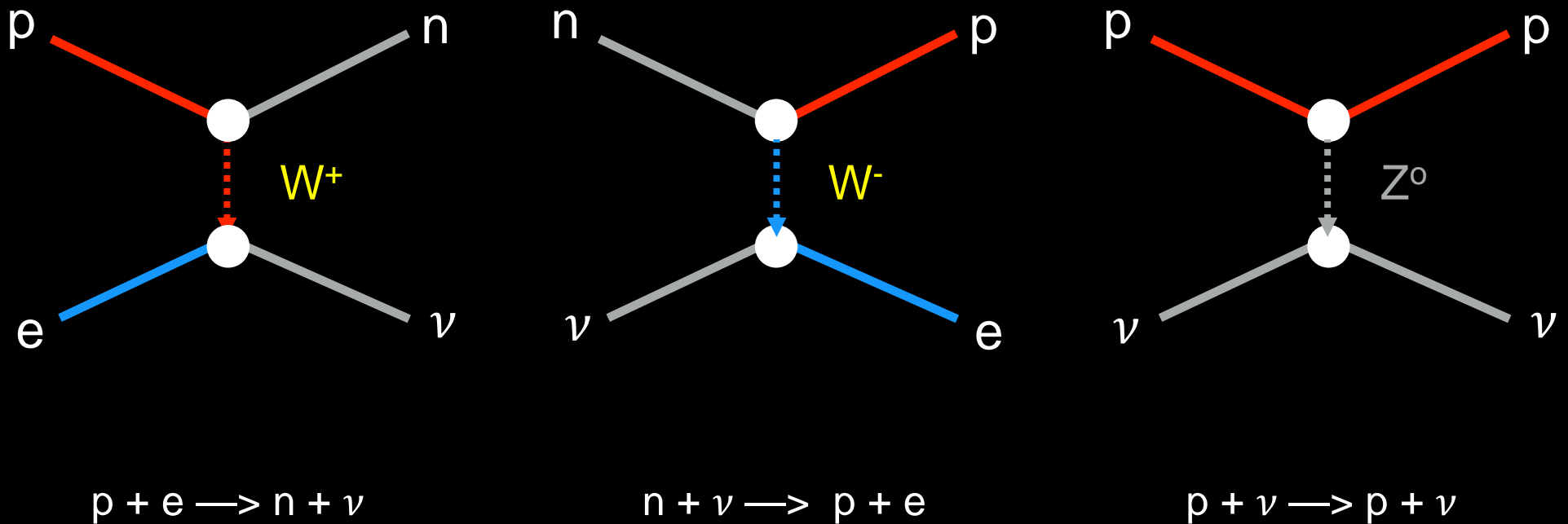
Interesting: at high energies, coupling of weak and e.m. interaction similar !



Leads to idea of ELECTRO-WEAK UNIFICATION  
(Glashow, Salam, Weinberg)

# ELECTRO-WEAK UNIFICATION

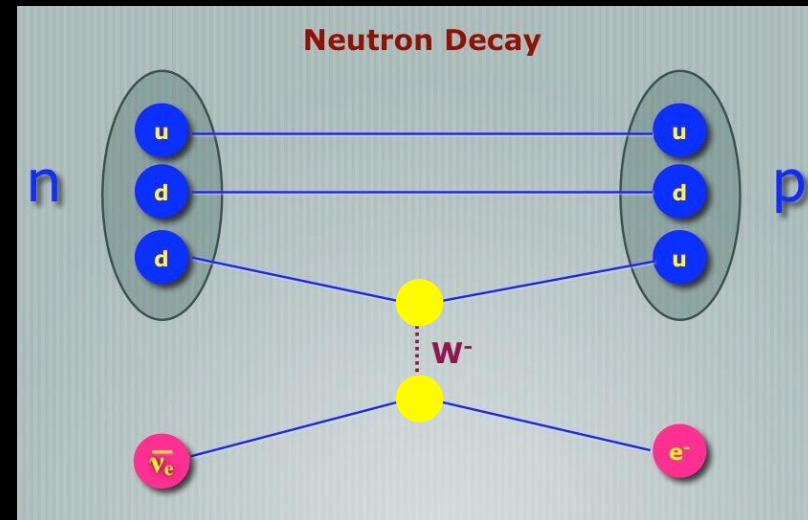
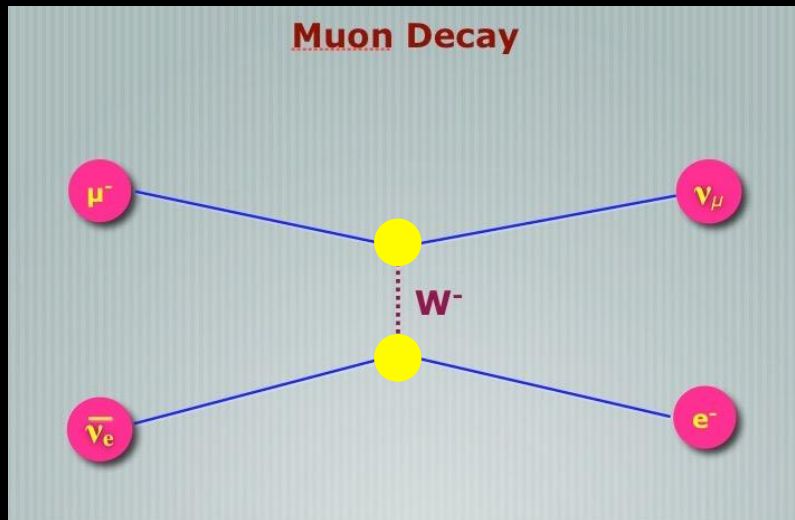
“Charged currents” ( $W^\pm$ ) and “Neutral Current” ( $Z^0$ )



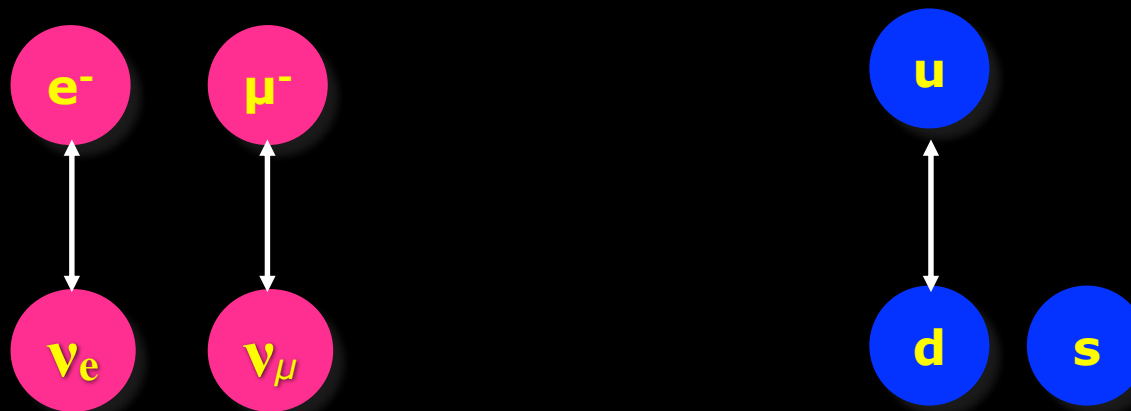
$Z^0$  is the ‘massive’ brother of the photon

Idea of “weak symmetry breaking” through ‘Higgs mechanism’

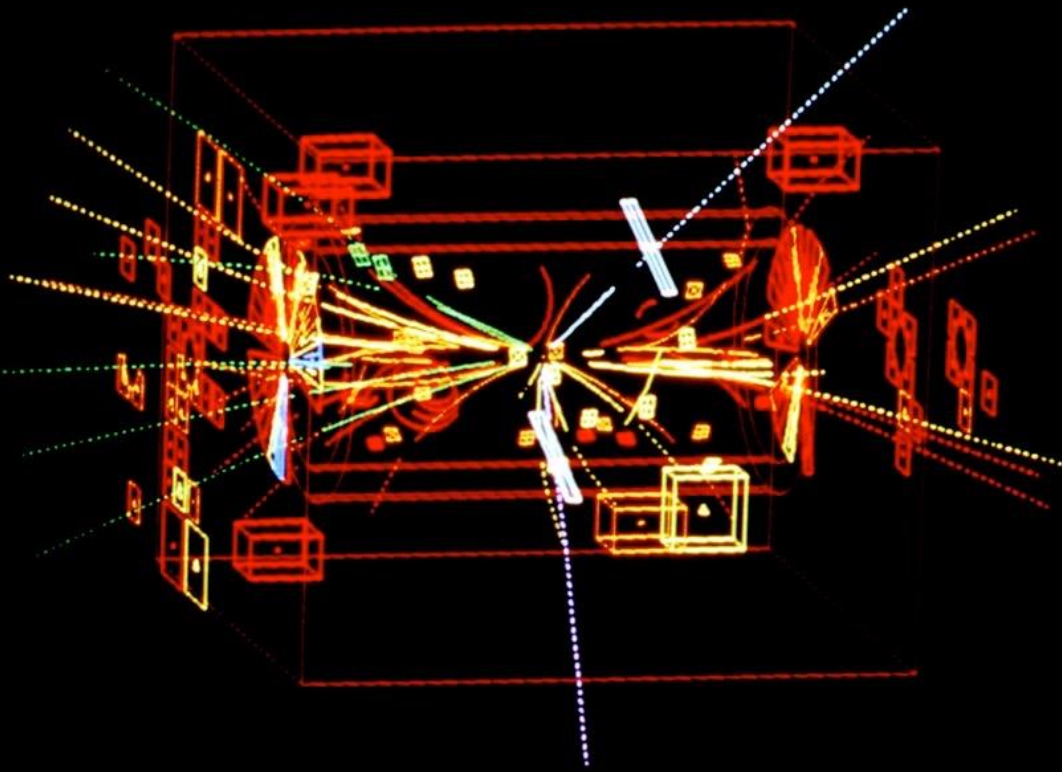
Interesting: electroweak interaction is (approx.) the same for leptons and quarks !



**“Universality\*” - transmitted by W, Z bosons, same strength!**



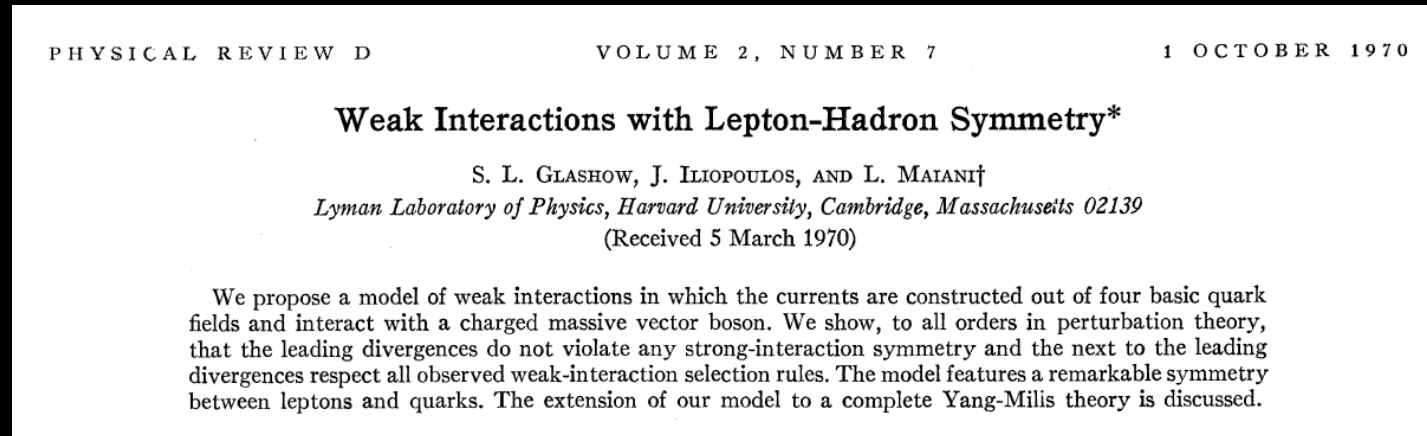
# DISCOVERY OF THE WEAK BOSONS AT CERN (1983)



(C. Rubbia, S. van der Meer)

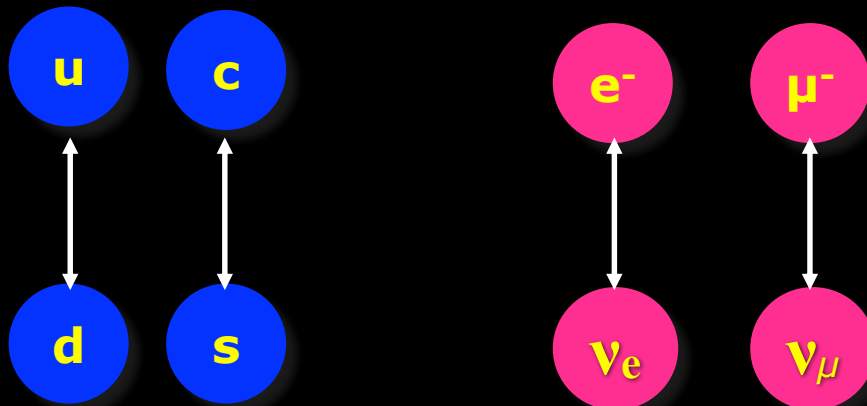
# THE CHARM QUARK

A legendary paper, predicting the 'charm' quark (Glashow, Iliopoulos, Maiani)



Quarks

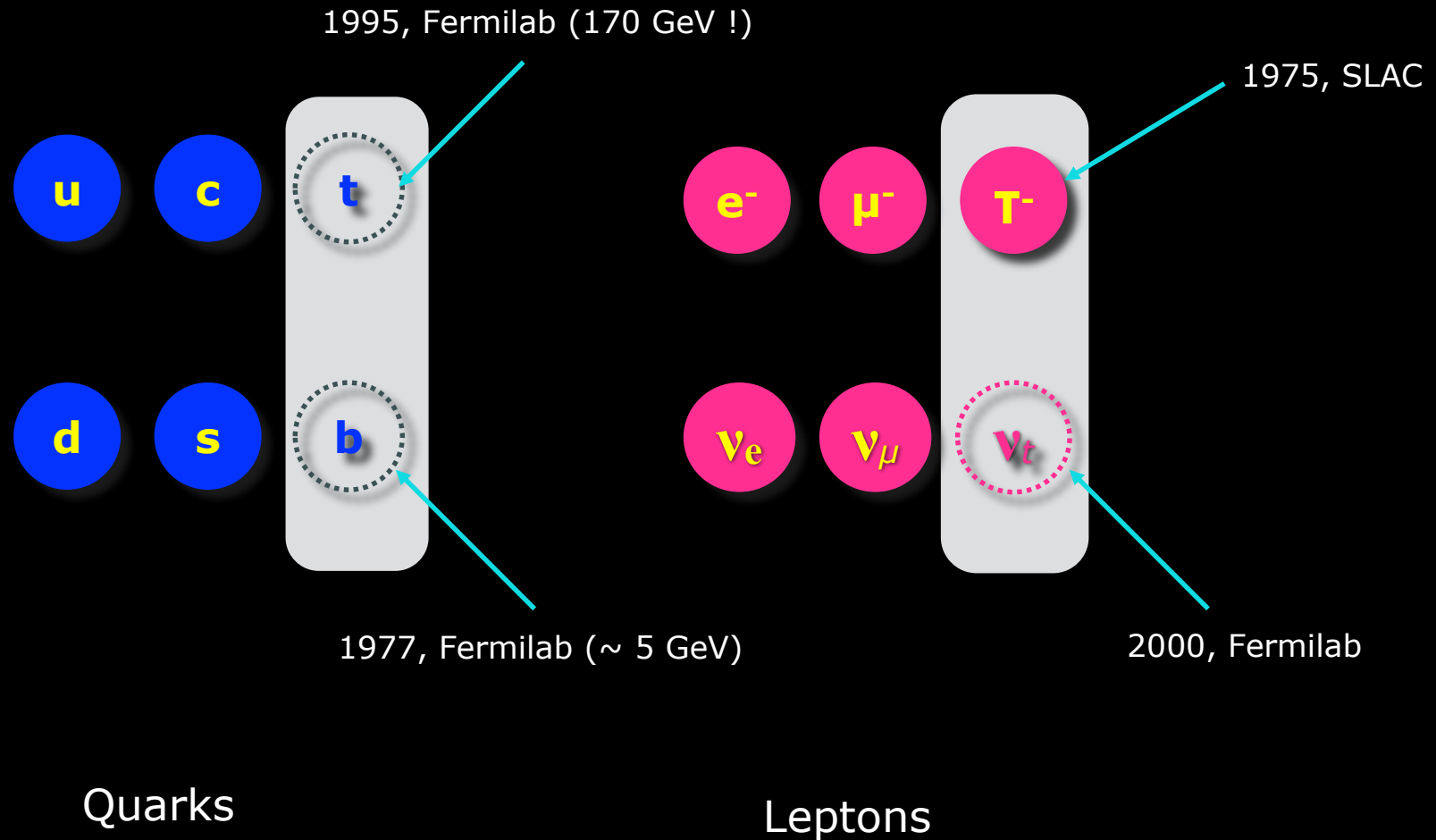
Leptons



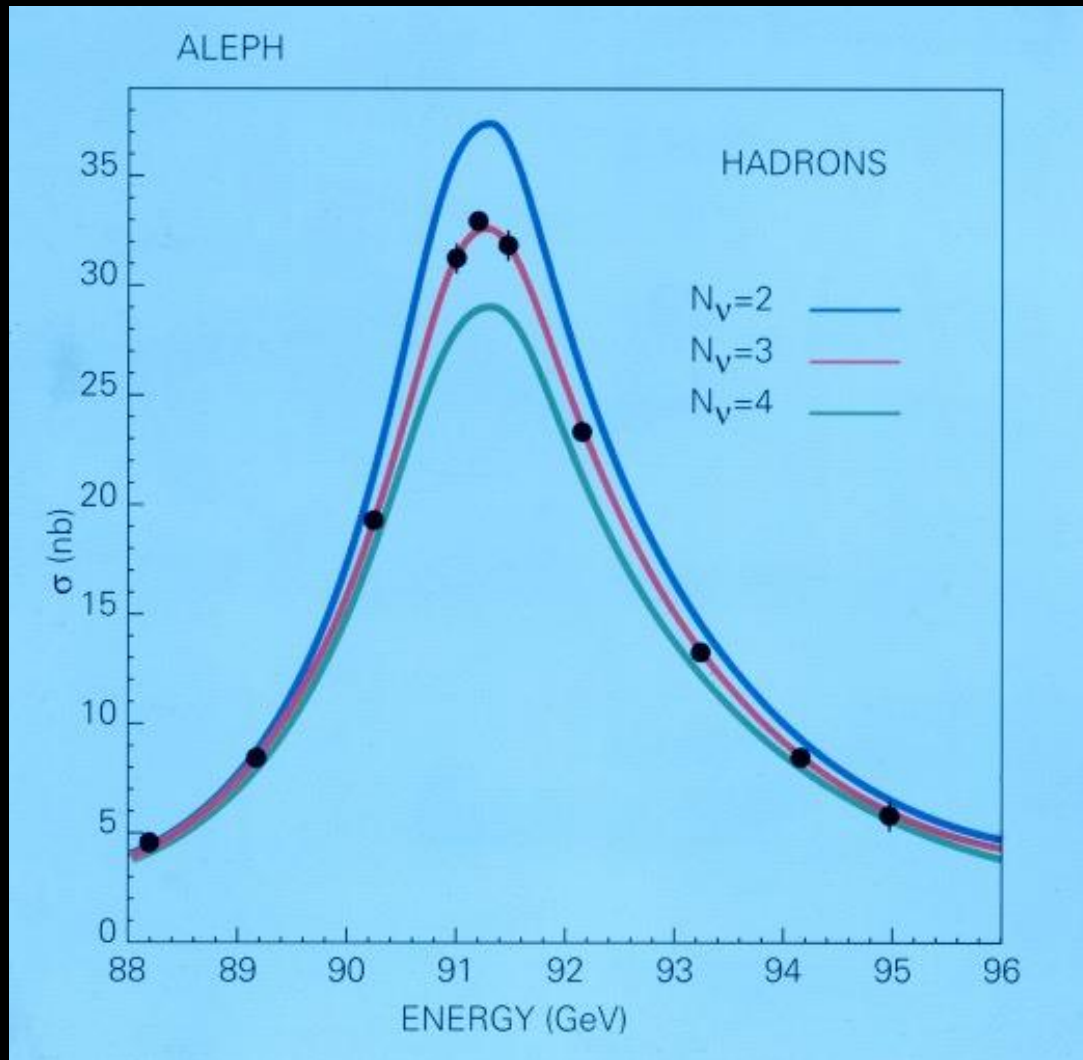
The charm quark was discovered  
( $J/\psi$  meson = charm-anticharm bound state)  
in November 1974

# Surprise, surprise: enter the THIRD FAMILY

*A new lepton (called "tau") is discovered ( heavy brother of e and  $\mu$  )*

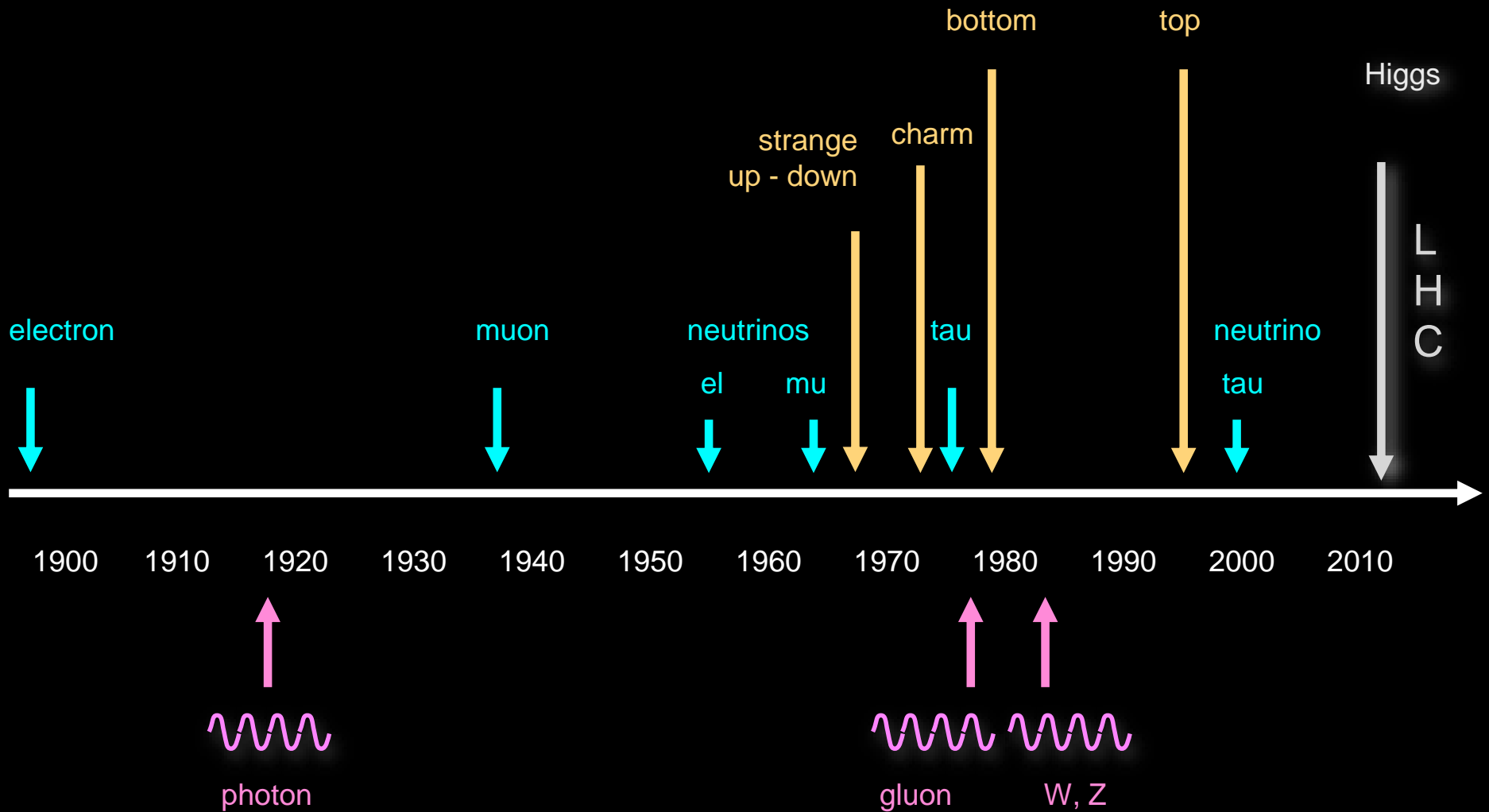


# There are exactly 3 families



LEP measures the decay width of the  $Z^0$  particle

# Experiments at accelerators have discovered the whole set of fundamental particles



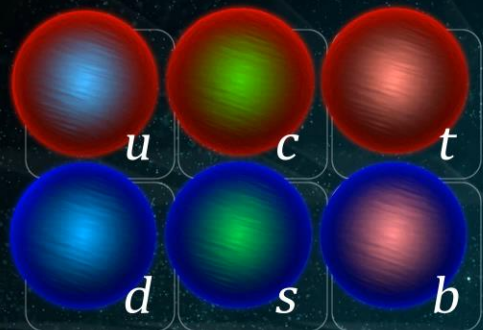




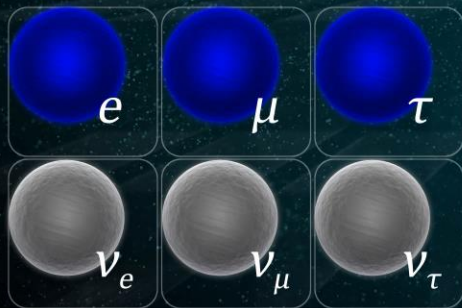
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# The Higgs boson discovery

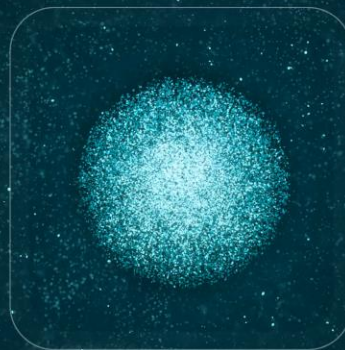
# Standard model: 'Periodic system' of particles



Quarks



Leptons



Higgs boson

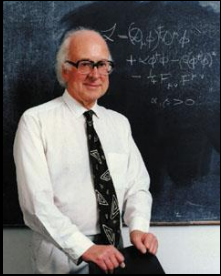


Forces



# The Brout-Englert-Higgs (BEH) field idea

the entire Universe is filled with a homogeneous field  
particles interacting with this field obtain inertia (=rest mass)  
the BEH field interaction is proportional to the mass of the particle



Sir Peter Higgs

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



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'



A rumour is spreading among the guests ...



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

*The BEH field ...*

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

# Animation: Higgs mechanism



the theory is correct - then there should be an "excitation" of the Higgs field, called the "Higgs boson". Does it exist?

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



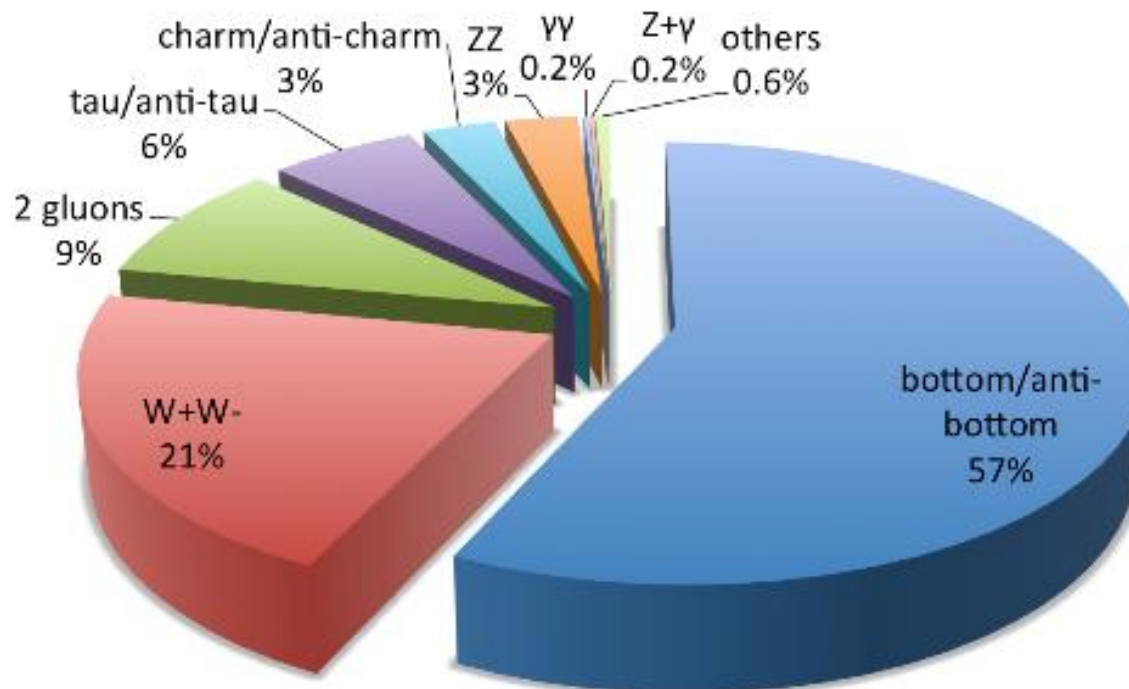
... but this happens on average once per 10,000,000,000 ( $10^{10}$ ) collisions !

# Higgs decay?

## Key prediction

Decay probability is proportional to the mass of the daughter particles

Decays of a 125 GeV Standard-Model Higgs boson

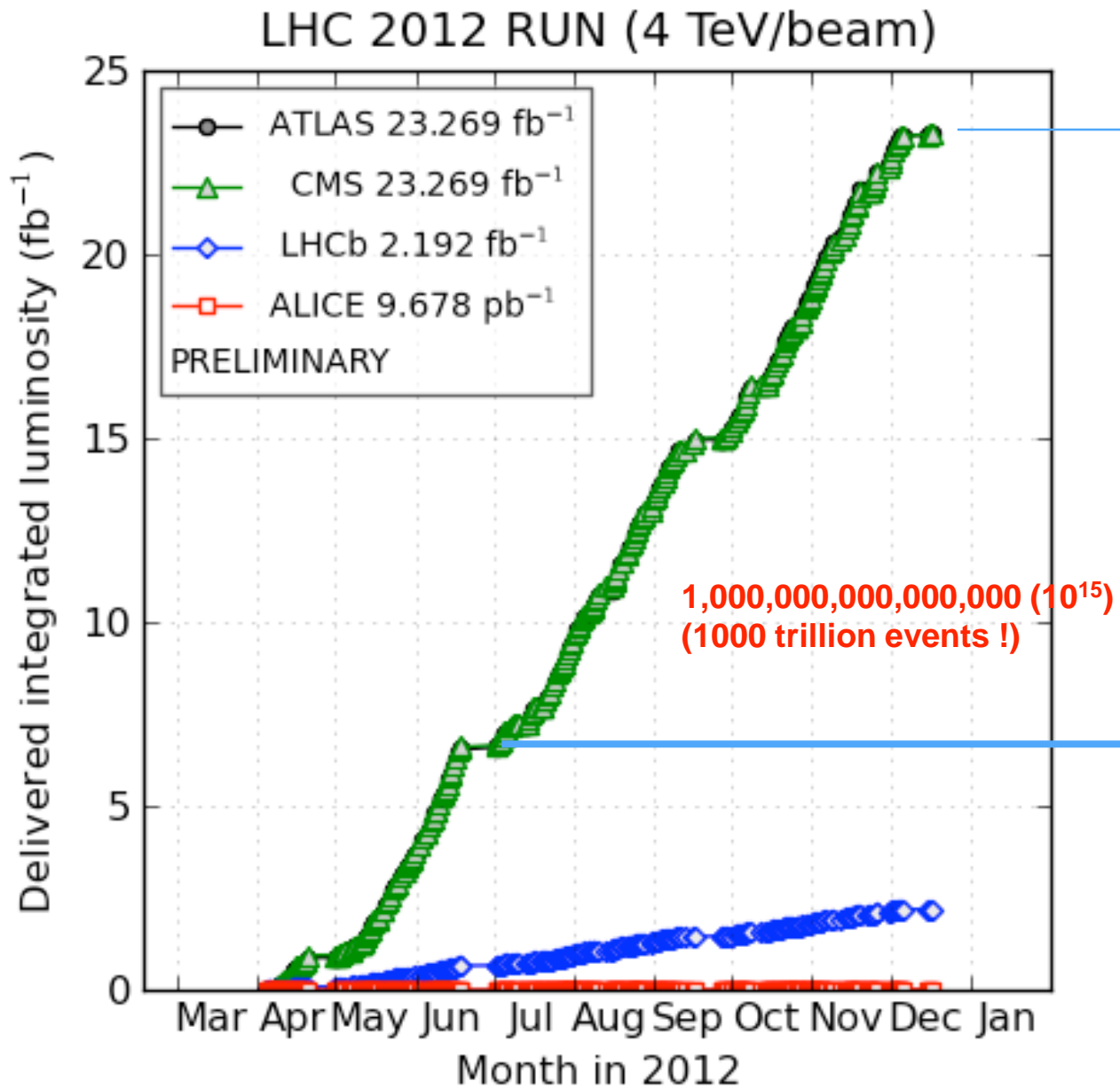


The Higgs boson can decay in two photons ...

but only with a probability of 0.2 %

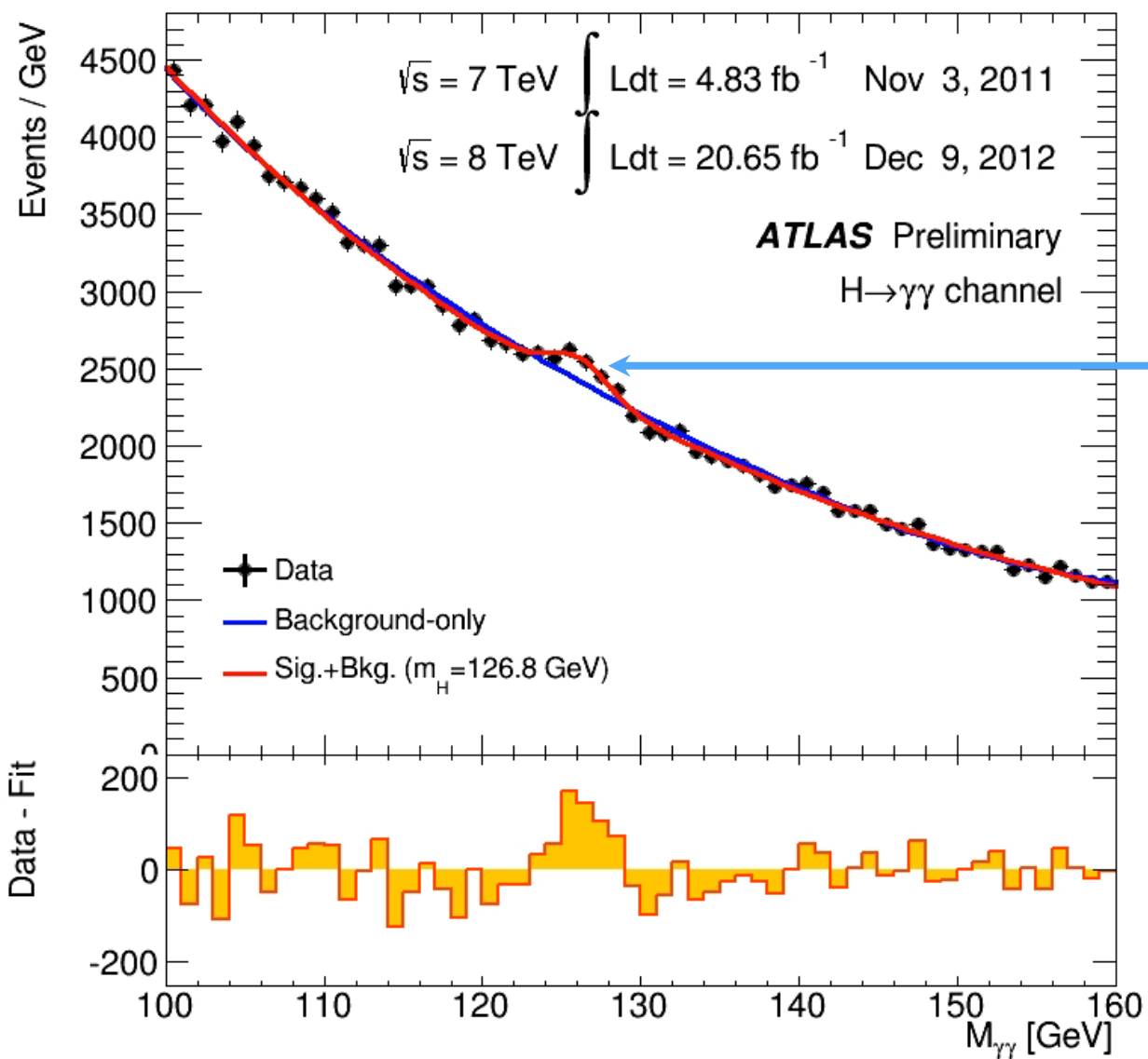


# The CERN hunt for the Higgs boson



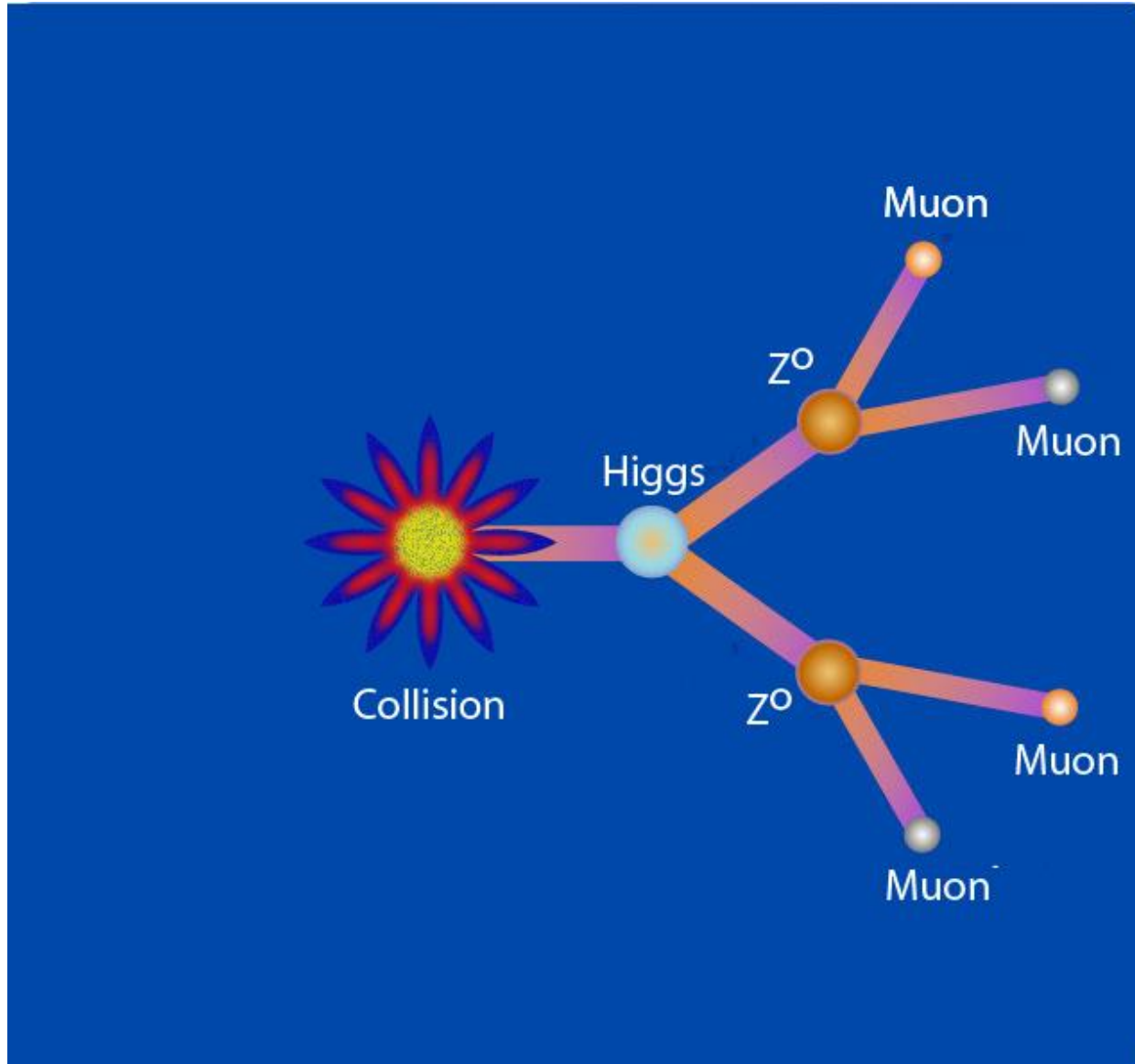
(generated 2013-01-29 18:28 including fill 3453)

# The evolution of the histogram with two-photon events

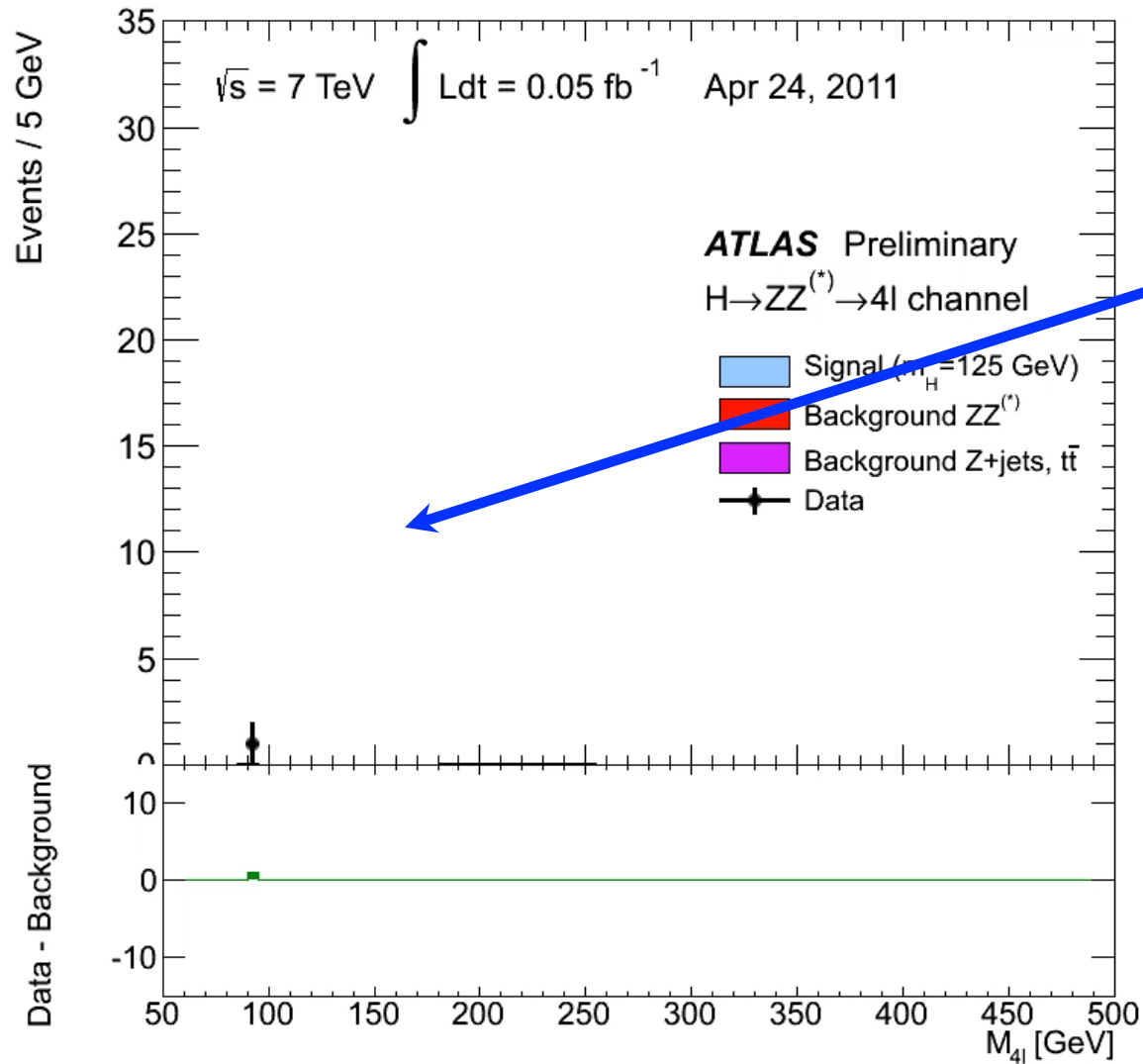


Higgs boson

# Higgs decay into four muons



# The evolution of the histogram with four leptons



Higgs boson

The  
Economist

JULY 7TH - 13TH 2012

Economist.com

In praise of charter schools  
Britain's banking scandal spreads  
Volkswagen overtakes the rest  
A power struggle at the Vatican  
When Lonesome George met Nora

# A giant leap for science



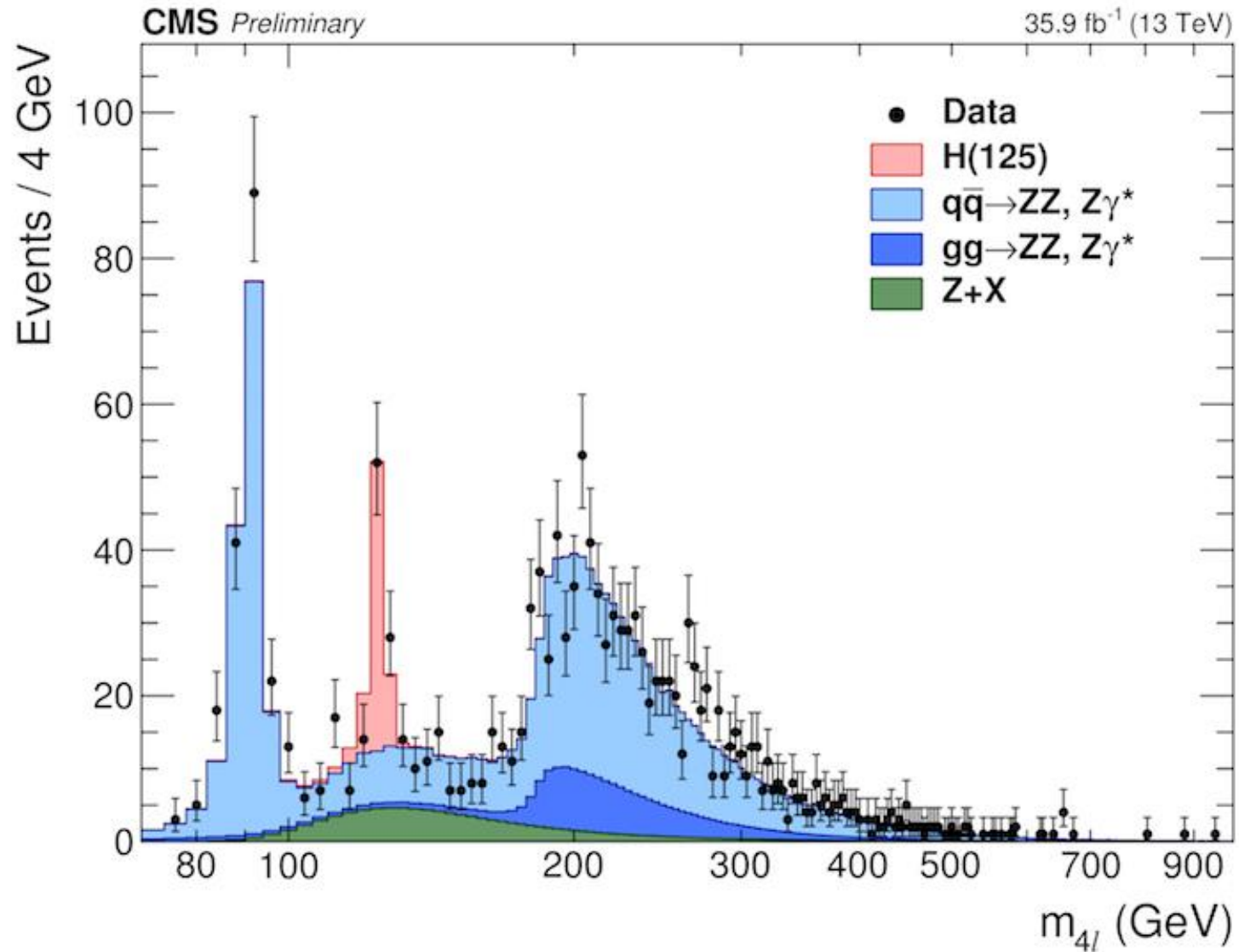
Finding the  
Higgs boson

## *What does this mean?*

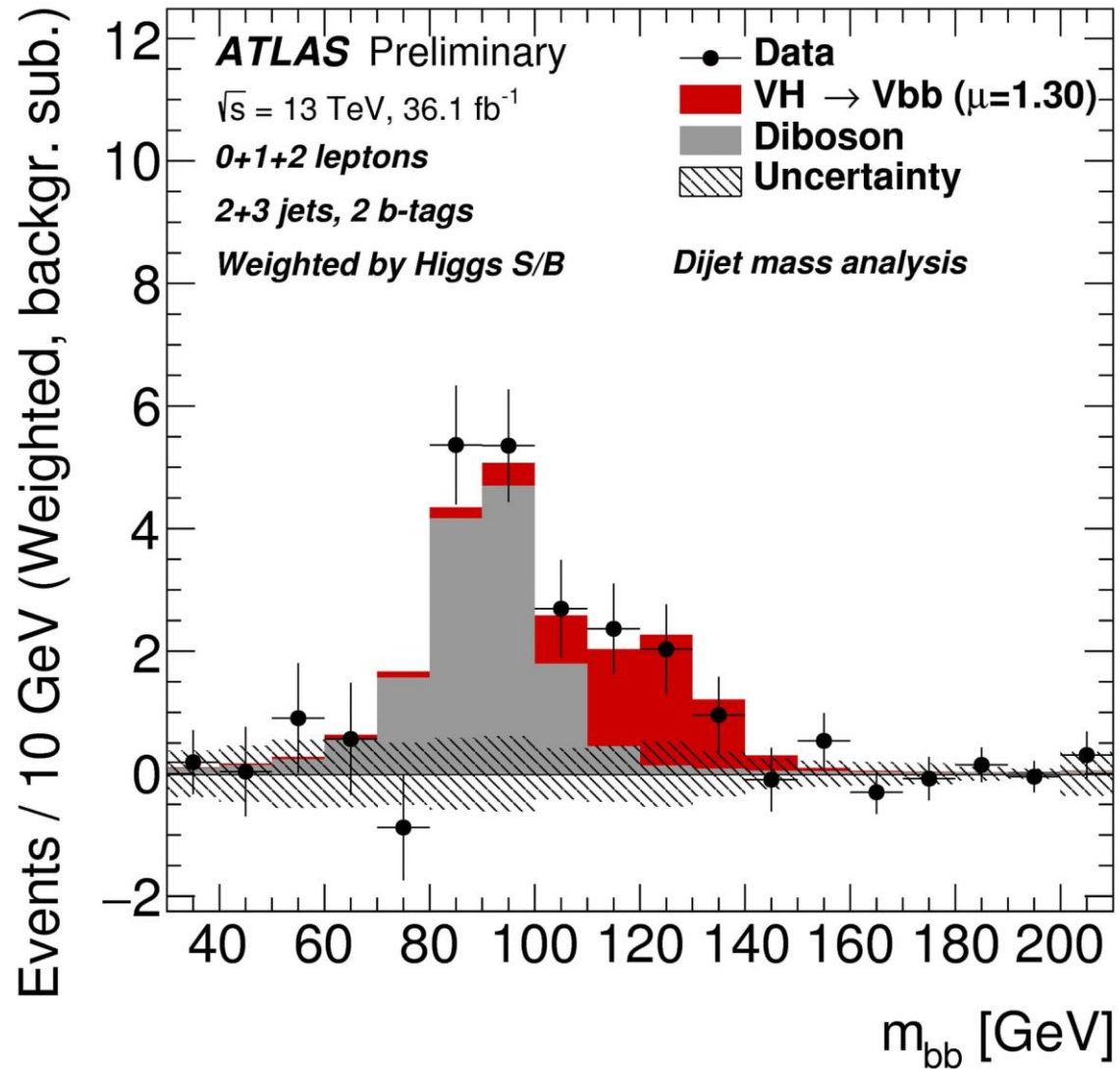
- the Higgs boson exists, therefore ...
- the Brout-Englert-Higgs field exists
- we know how particles obtain their mass
- the “Standard model” is complete
  
- empty space is not ‘empty’
- perhaps a connection to ‘dark energy’ ?

*Even more:*

# Higgs decay into four leptons



# Higgs decay into $b\bar{b}$





# Higgs boson ID: Mass, Width, Production, Decay

---

**Mass:** free parameter of BEH theory ( $\sim$  self-coupling of BEH field)

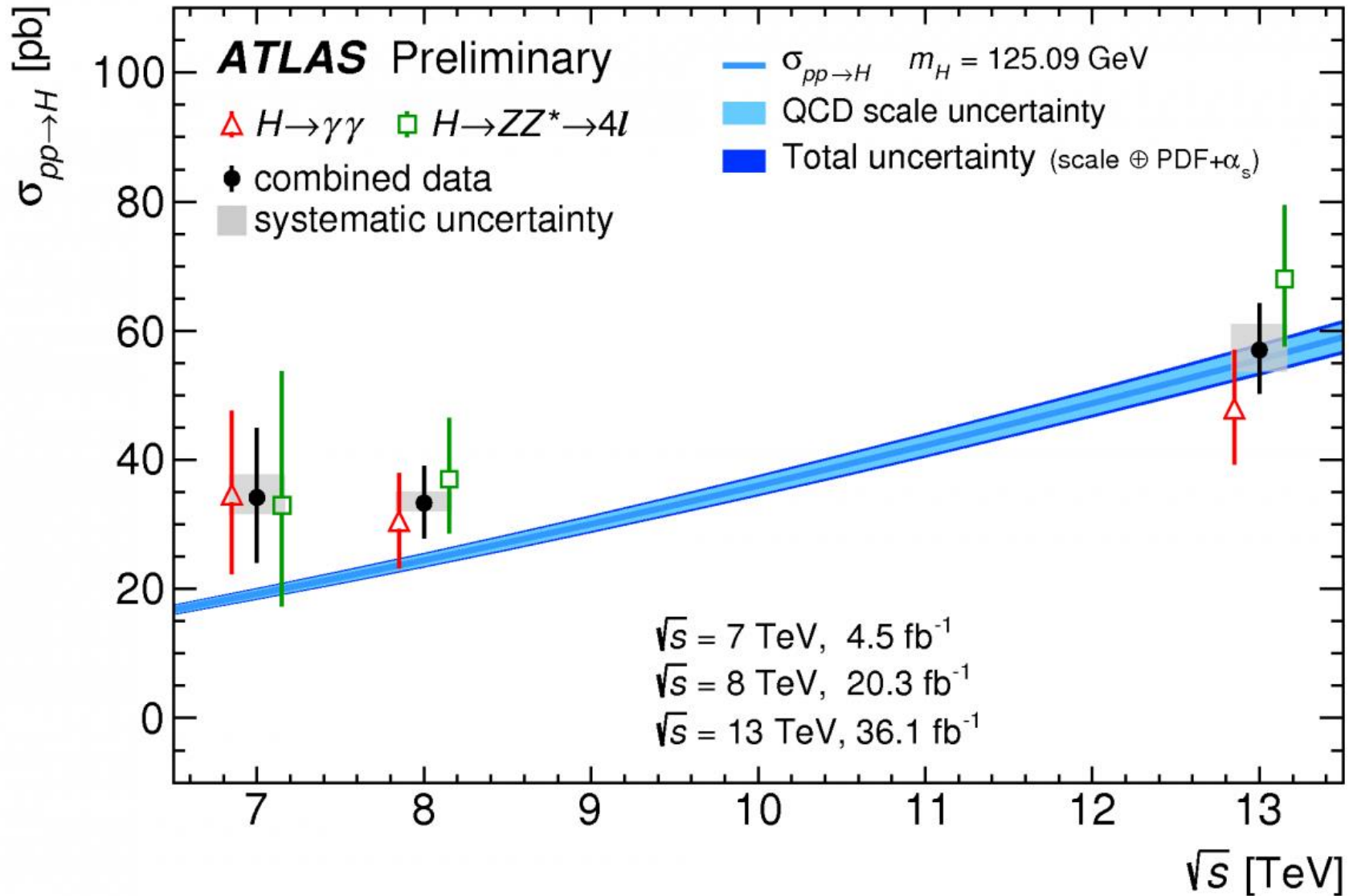
$$M_H = 125.09 \pm 0.21 \text{ GeV}$$

But: once the Higgs boson mass is known, the other parameters are predicted:

- 1) **Lifetime** ( $1.5 \cdot 10^{-22}$  s, width  $\sim 4$  MeV; too small to be measured)
- 2) **Production cross-section in p-p collisions at different energies**
- 3) **Decay probability**

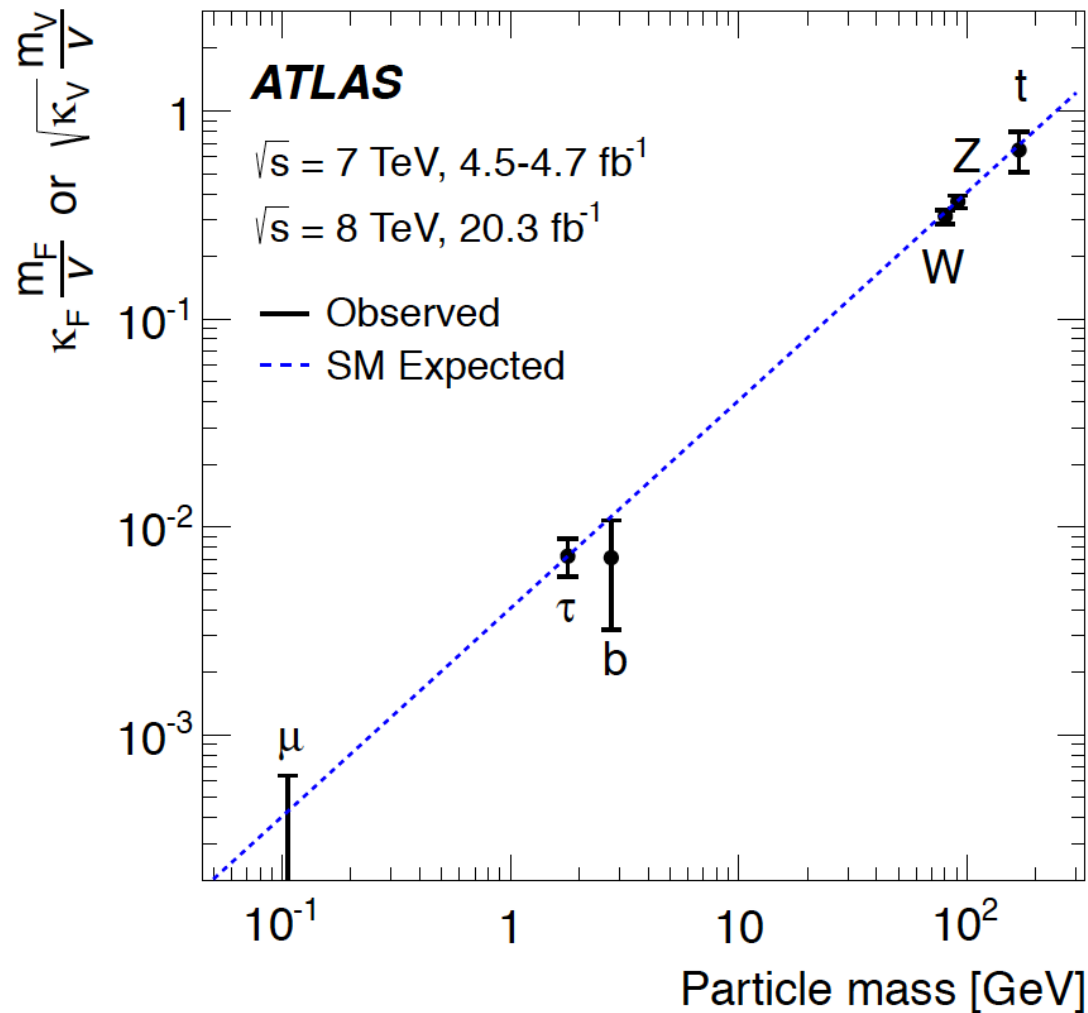


# Higgs production cross-section: as predicted by S.M.



Perfect agreement - as predicted by S.M.

# Higgs decay rate proportional to particle mass ?



Perfect linear dependence - as predicted by S.M.



---

# What about new particles?

# Finding new particles .... X(750) saga

**December 2015:**

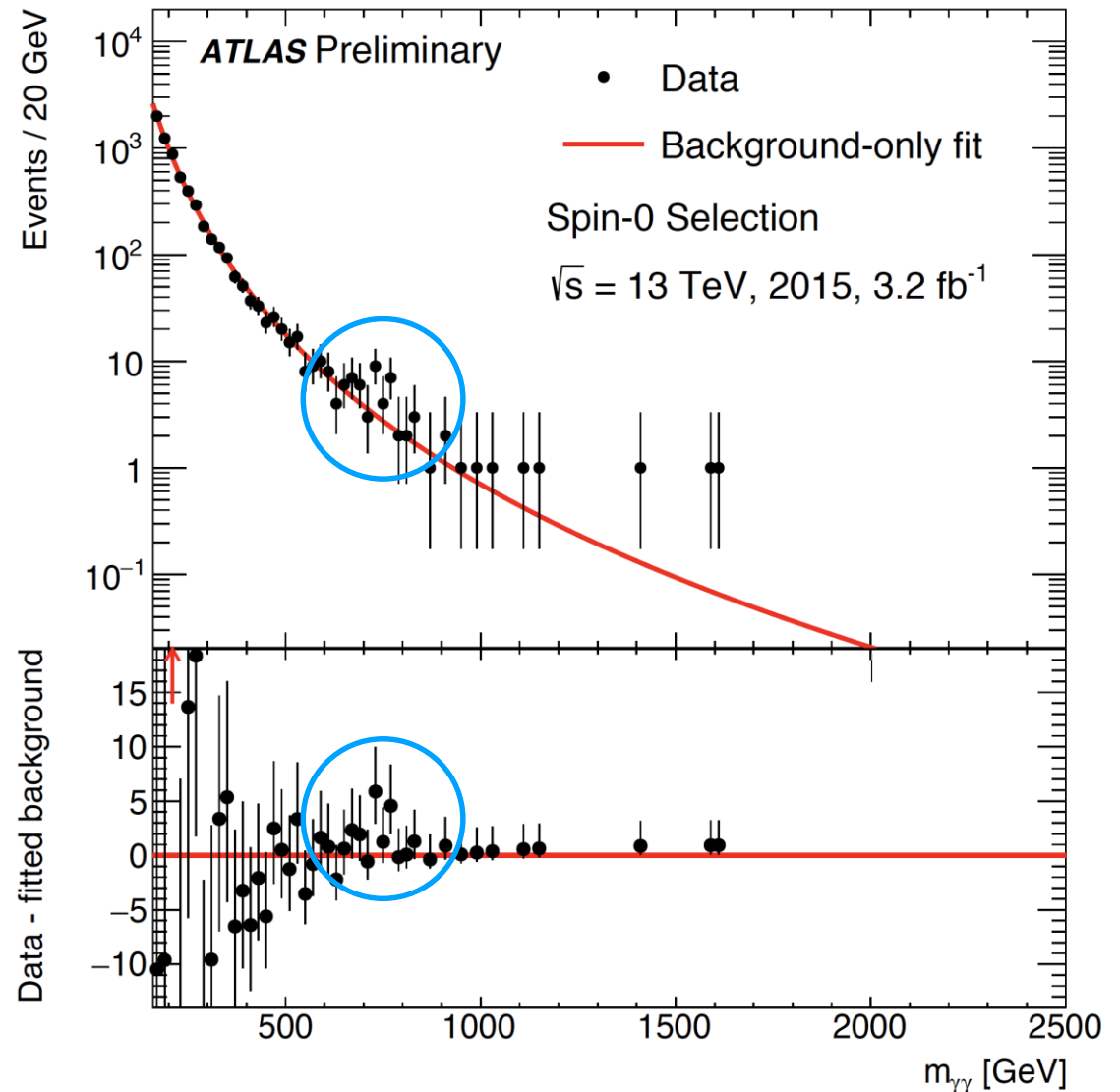
ATLAS presents ~3-sigma bump

$M \sim 750$  GeV

Decay into 2 photons

(CMS also sees 'something' at this mass)

( $3.2 \text{ fb}^{-1}$  at 13 TeV)



# ... or not: the end of the X(750) saga

**2016:**

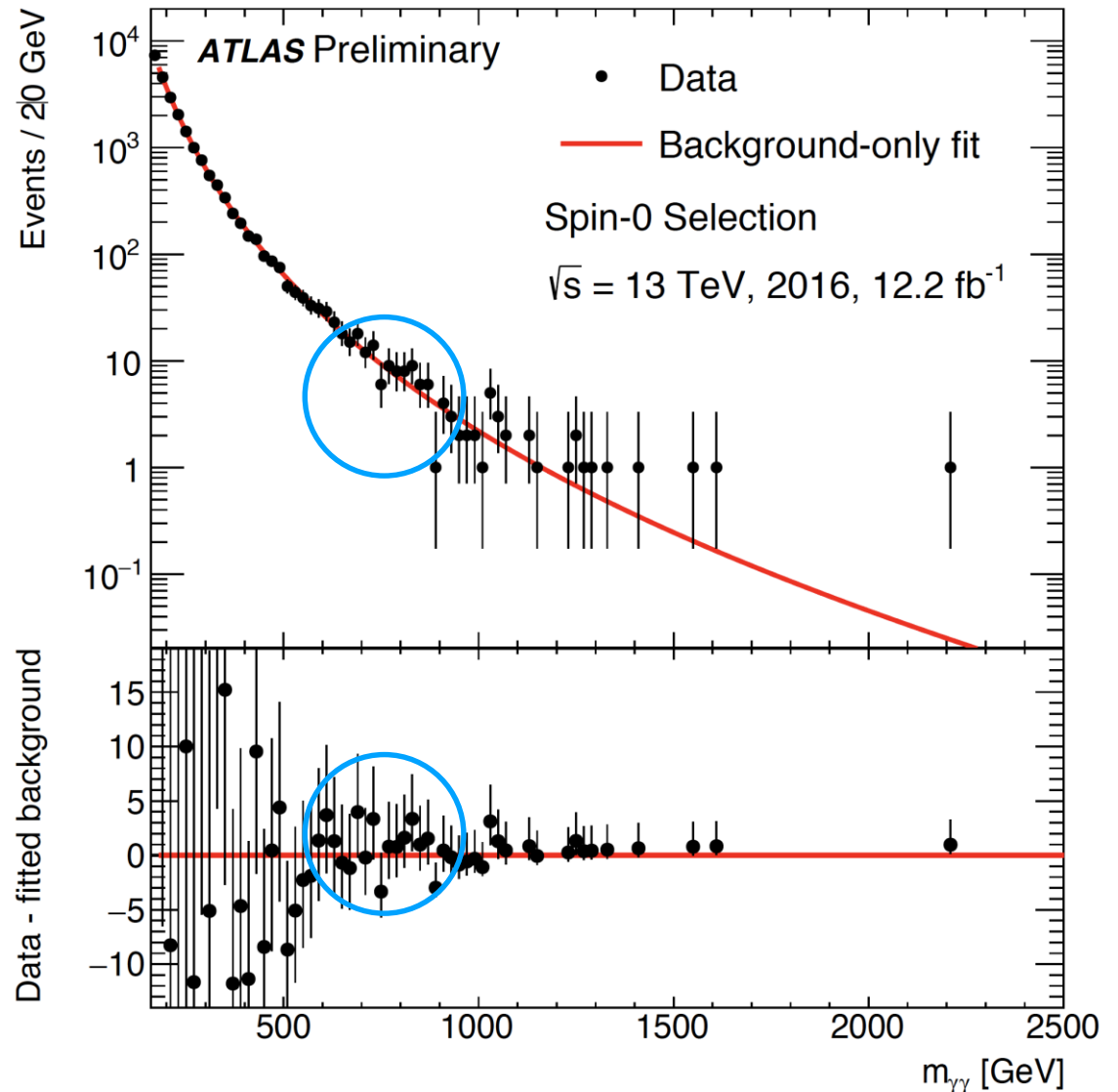
ATLAS publishes plot with 4x data

**NO BUMP !**

(12.2 fb<sup>-1</sup> at 13 TeV)

**as statistics increases,  
significance decreases ...**

*It was 'just' a statistical fluctuation.*



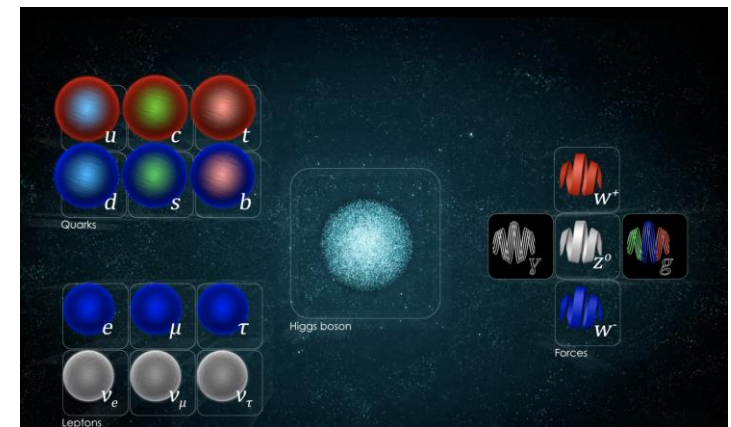


# What next ?

---

The known Unknowns: the Standard Model

# How did Nature choose this ‘Standard Model’ ?



Cook book recipe  
for a ‘Goldilocks’ universe

Describes a ‘tasty’ universe  
including friendly stars, life

Drives theorists nuts ...

# The Standard Model is not exactly 'elegant'

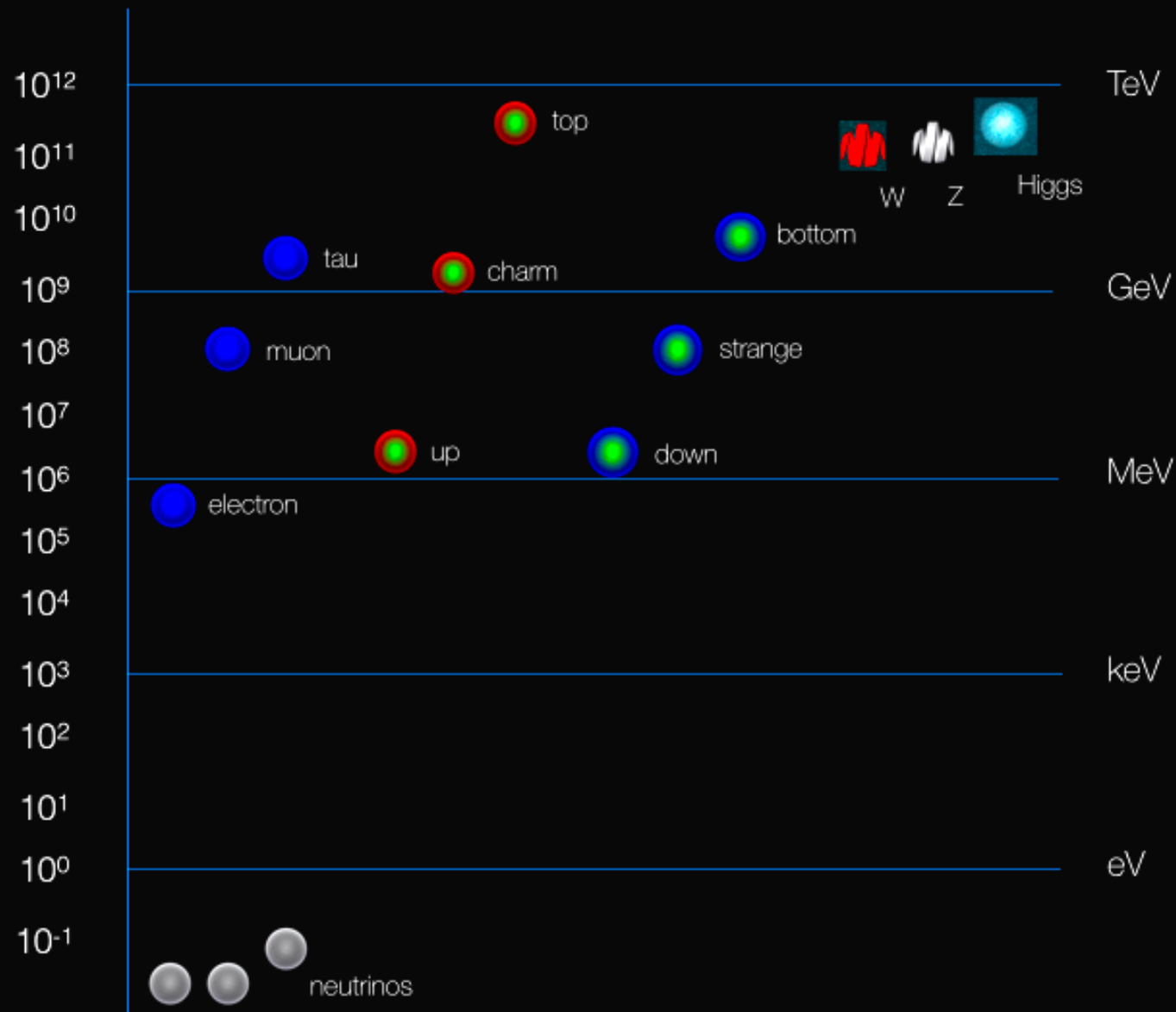
$\mathcal{L}_{SM} =$

$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \\
& \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \\
& \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
& \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[ \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - igs_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
& \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - Z_\mu^0 Z_\nu^0 W_\nu^+ W_\mu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - \\
& A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + \\
& H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + \\
& 2(\phi^0)^2 H^2] - gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \\
& \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \\
& \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \\
& \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
& \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \\
& \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma^\mu \partial + m_e^\lambda) e^\lambda - \\
& \bar{\nu}^\lambda \gamma^\mu \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma^\mu \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\mu \partial + m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \\
& \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
& 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \\
& \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \\
& \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \\
& \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
& \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
& \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + \\
& igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
& \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igM s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
& \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

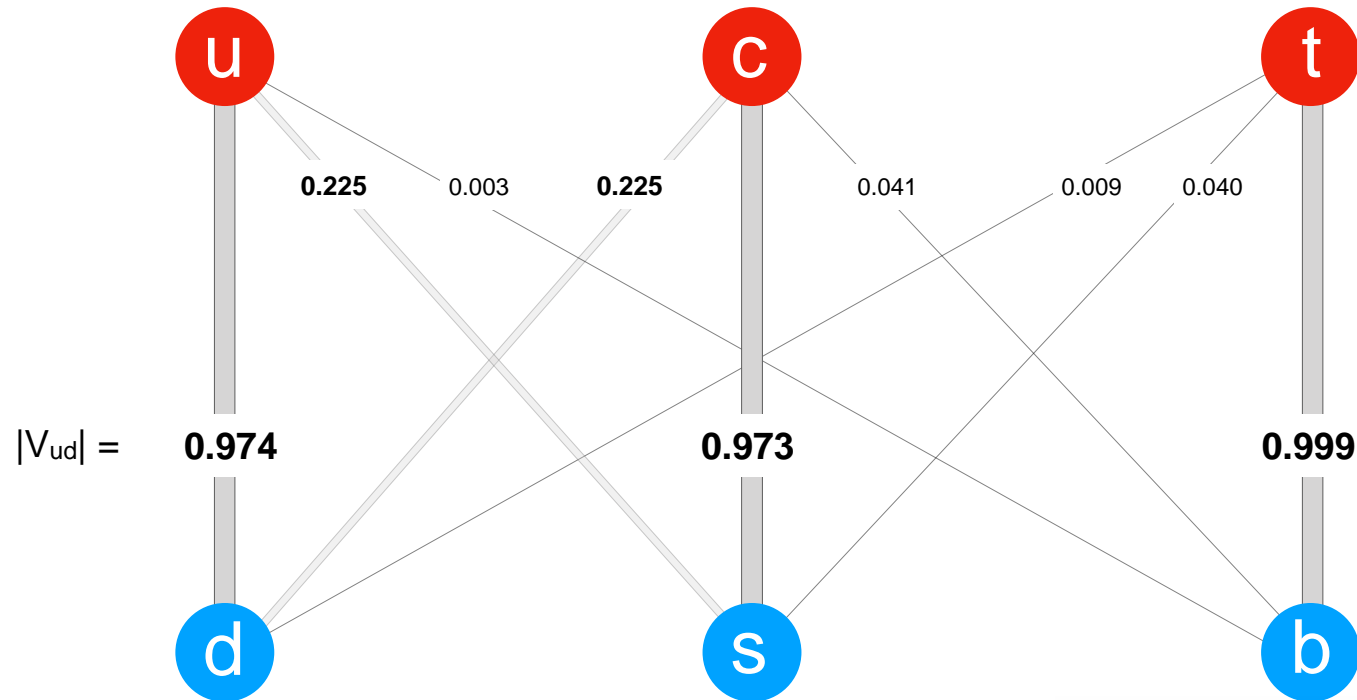


# Why **these** masses of elementary particles?

Mass of particles  
[eV]



# Quark mixing in weak interactions ?



$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

weak eigenstates
CKM matrix
mass eigenstates

4 free parameters  
 (3 mixing angles, 1 phase)  
 Origin of CP violation in S.M.

# What lies behind the Standard Model?

Strength of the three interactions

-  $\alpha_{em}, \theta_w, \alpha_s$

Higgs field v.e.v. and Higgs boson mass

-  $v, m_H$

CKM matrix parameters (weak mixing of quarks)

-  $\theta_{12}, \theta_{23}, \theta_{13}, \delta_{13}$

Quark and lepton masses

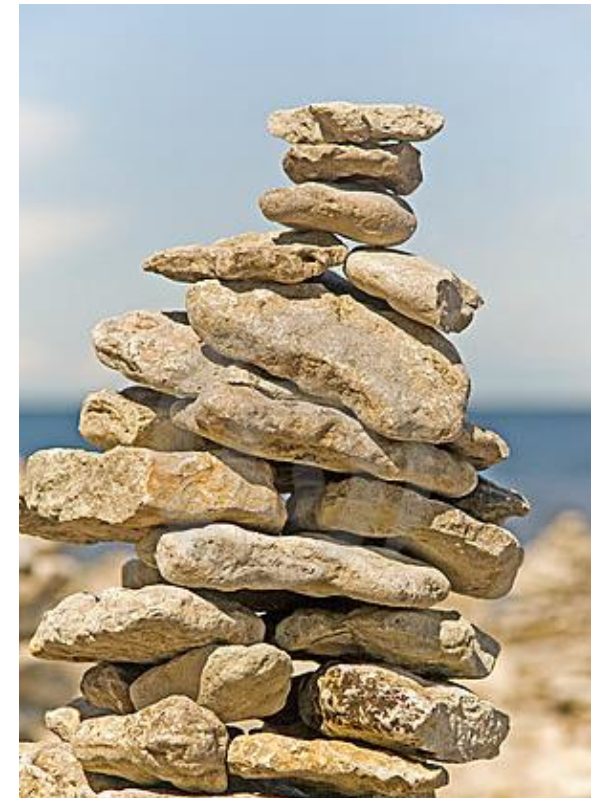
-  $m_u, m_d, m_c, m_s, m_t, m_b, m_\tau, m_\mu, m_e$

Neutrino masses and mixing angles

-  $m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, \theta_{12}, \theta_{23}, \theta_{13}, \delta_{13}$

QCD vacuum angle

-  $\theta_{QCD}$



**Why is Nature so stable?**

26 free parameters  
why these values?



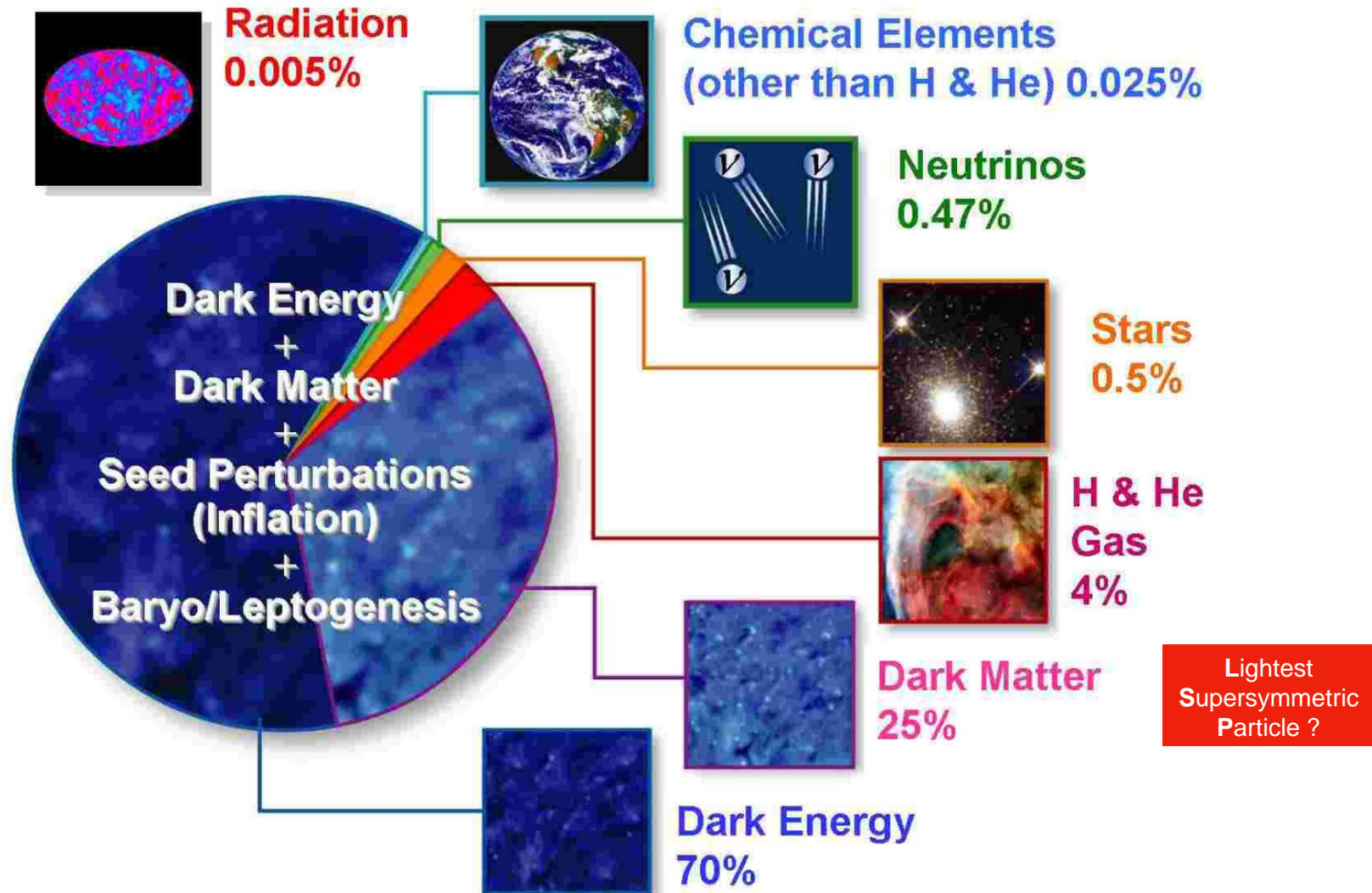
# Known problems of the Standard Model

---

- Origin of 3 families of particles ('periodic table')
- Origin of forces (three forces, different strengths)
- Origin of different particle masses, mixing angles
- Neutrino masses, mixing angles
- Antimatter disappearance after Big Bang
- Higgs mass relatively light (metastable universe)

# Known problems with the Universe

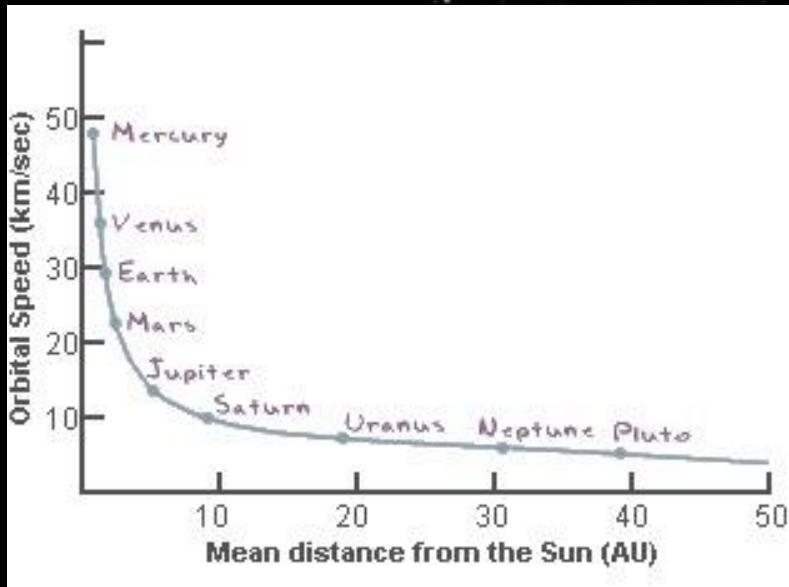
The strange toppings on the cosmic pizza



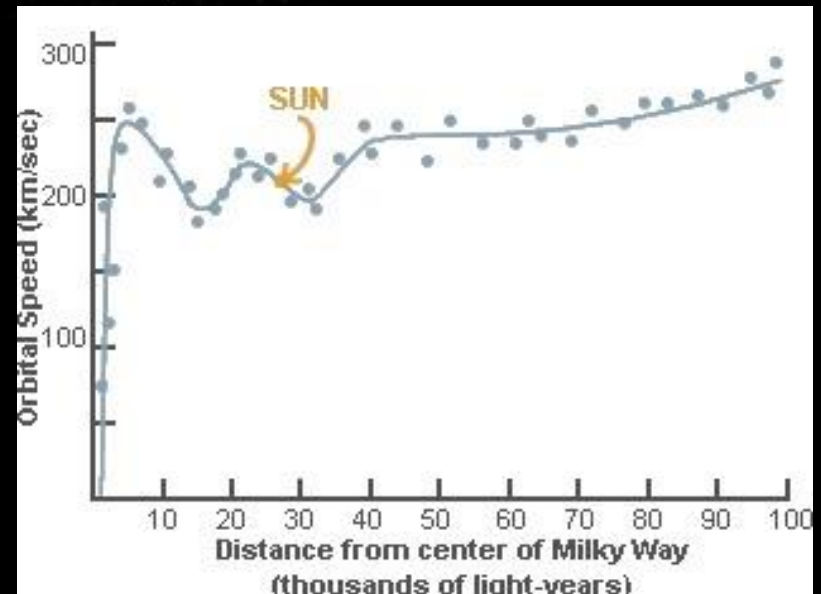
# EVIDENCE FOR "DARK MATTER"



Orbital speed vs Distance from center  
(Kepler - expect  $r^{-1/2}$  dependence)



One central mass (Sun)



Milky Way

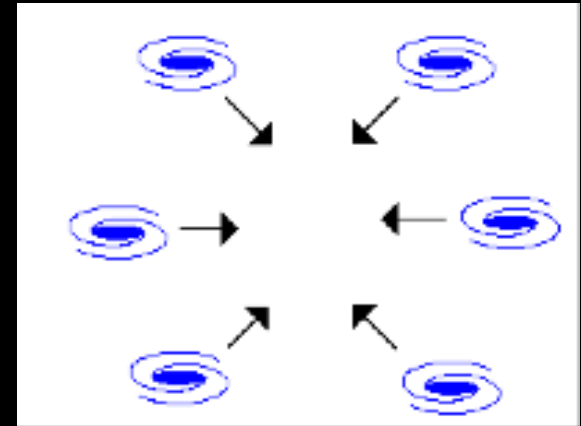
# MORE EVIDENCE FOR "DARK MATTER"



**Gravitational Lens in Abell 2218**

HST • WFPC2

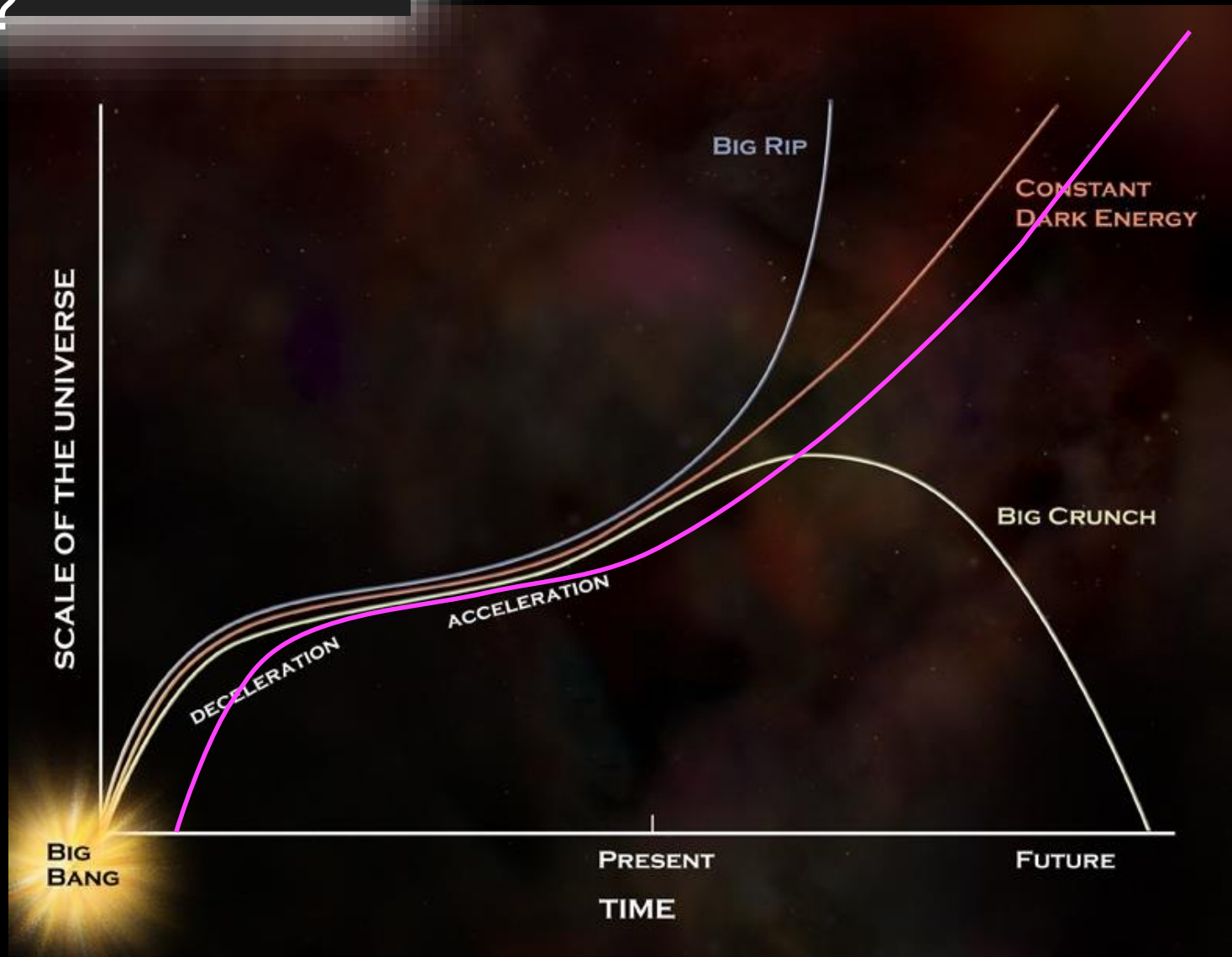
PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA



GRAVITATIONAL LENSING

# Dark energy

...?



The expansion of the Universe accelerates ...





# What next ?

---

- a) Extra dimensions ? Strong gravity at small distances ?
- b) Supersymmetric particles ?
- c) New fundamental interactions ?
- d) New generations of quarks/leptons ?
- e) Leptoquarks ?
- f) Something completely new ?

# Interlude: the Planck scale

## Boundary for quantum theory, gravity, and space-time

System of units based on three fundamental constants (G, c, h)  
Dimensionally independent - length, time, and mass (energy)

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-35} \text{ m}$$

$$T_P = \sqrt{\frac{\hbar G}{c^5}} = 0.54 \times 10^{-43} \text{ s}$$

$$M_P = \sqrt{\frac{\hbar c}{G}} = 2.2 \times 10^{-8} \text{ kg}$$

$$E_P = M_P c^2 = 1.2 \times 10^{19} \text{ GeV}$$

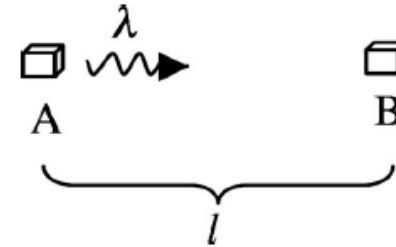


Fig. 3. A light pulse is sent from A and reflected back from B. Its energy causes a distortion of the spacetime between A and B and hence affects the length  $\ell$ .

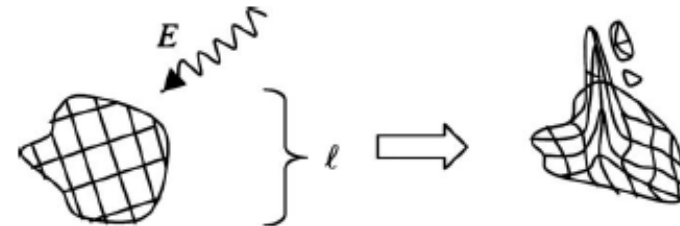
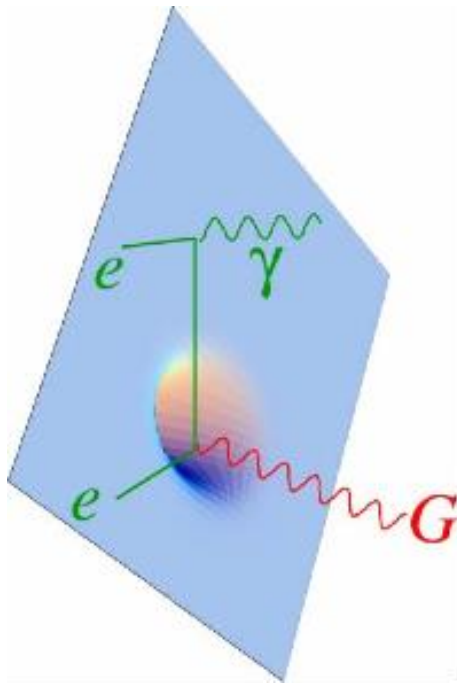


Fig. 5. A region of space of size  $\ell$  to be measured in time  $\ell/c$ . As the size approaches the Planck length, there can occur wild variations in the geometry, including such things as black holes and wormholes.



## Randall-Sundrum type models

More than 3 macroscopic dimensions of space ?

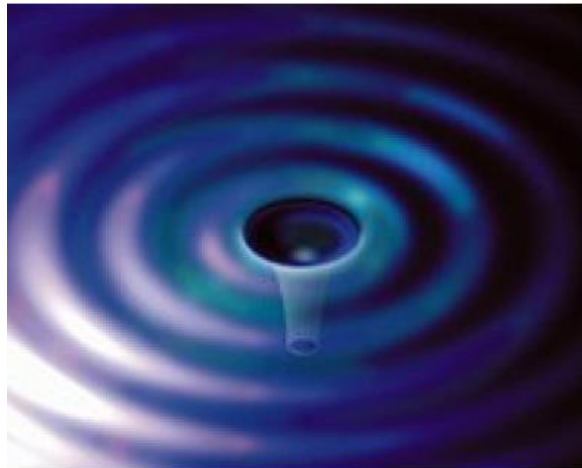
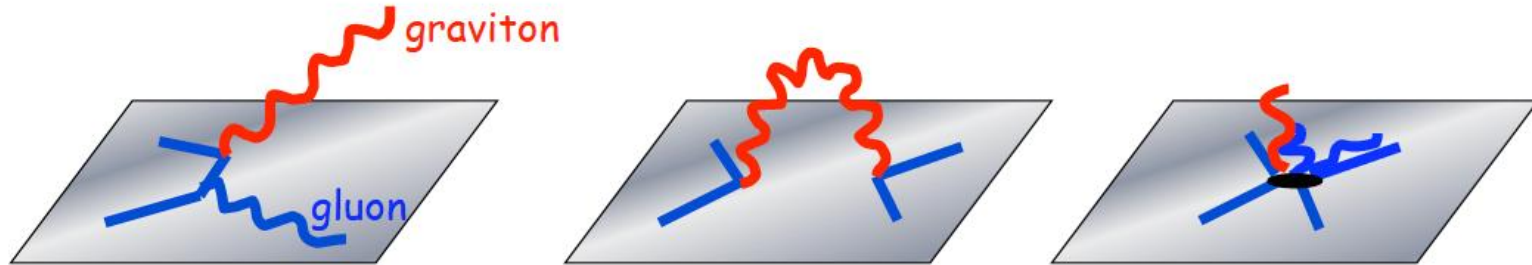
Is the graviton propagating in 4- or more dimensions of space?

Does gravity become very strong at small dimensions ?

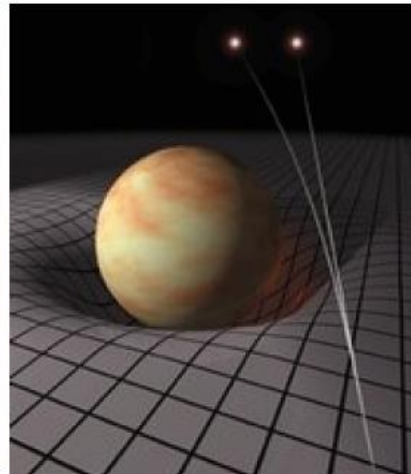
Micro-black holes ?

# Gravity and extra dimensions ?

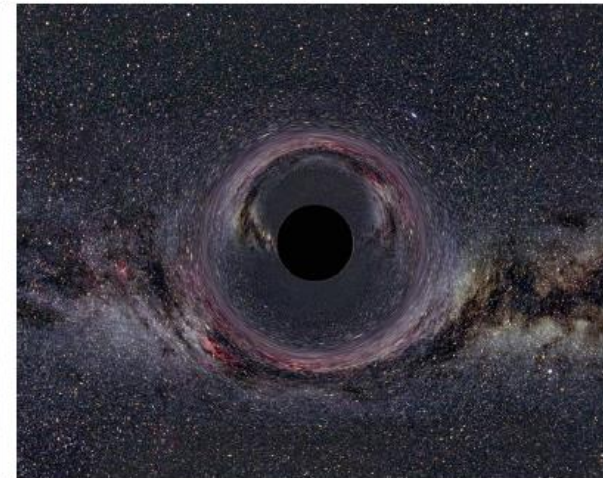
## Probing gravity at the LHC?



Gravitational wave  
jet +  $\cancel{E}_T$



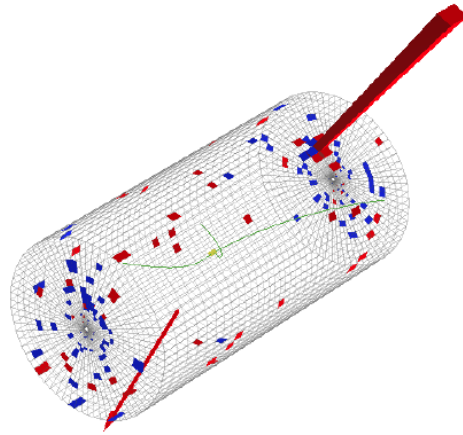
Gravitational deflection  
dijet



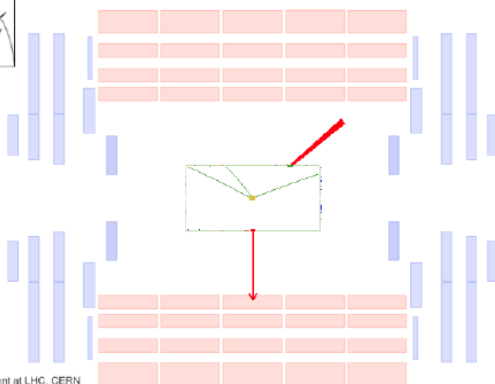
Black hole  
multiparticle event

Gravitational phenomena into collider arena

## Monophoton event



CMS Experiment at LHC, CERN  
Data recorded: Sun Apr 24 22:57:52 2011 CDT  
Run/Event: 163374 / 314736281  
Lumi section: 604

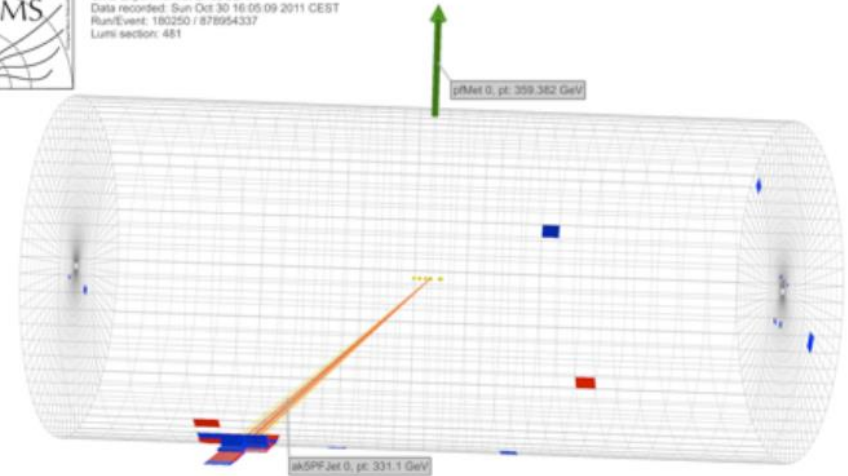


CMS Experiment at LHC, CERN  
Data recorded: Sun Apr 24 22:57:52 2011 CDT  
Run/Event: 163374 / 314736281  
Lumi section: 604

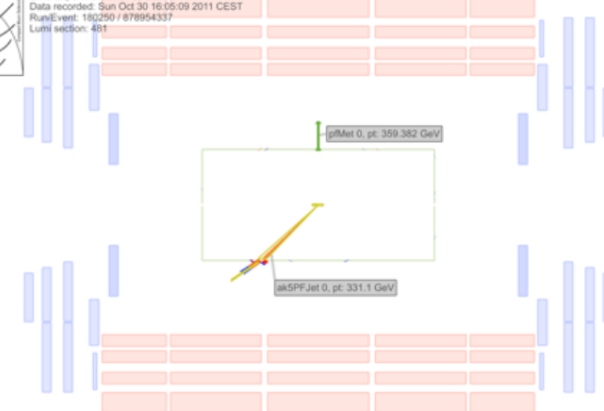
## Monojet event



CMS Experiment at LHC, CERN  
Data recorded: Sun Oct 30 16:05:09 2011 CEST  
Run/Event: 180250 / 878954337  
Lumi section: 481



CMS Experiment at LHC, CERN  
Data recorded: Sun Oct 30 16:05:09 2011 CEST  
Run/Event: 180250 / 878954337  
Lumi section: 481



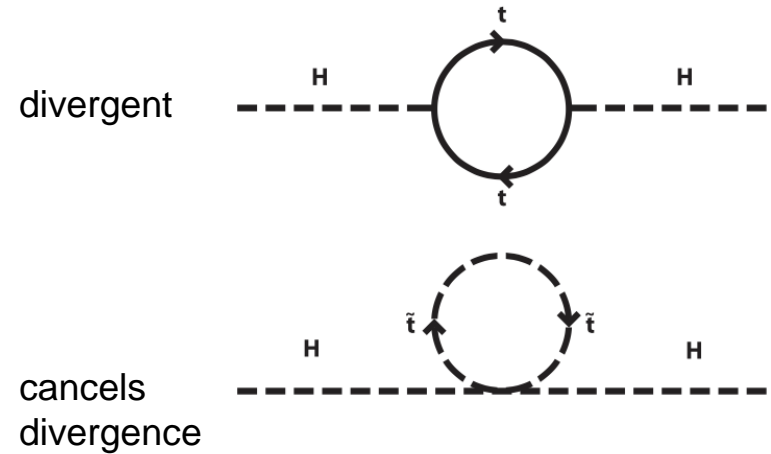
# Supersymmetry vs dark matter ?

Hierarchy problem:

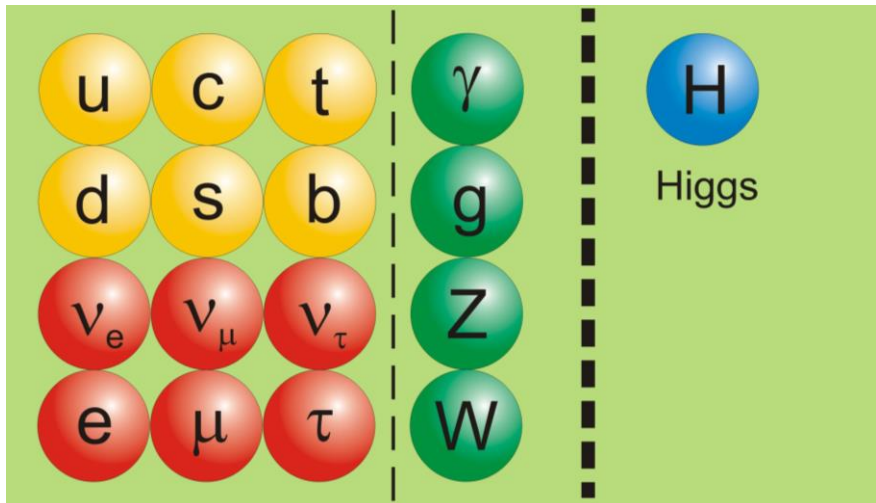
Higgs mass ( $10^2$  GeV)  $\ll$  Planck Scale ( $10^{19}$  GeV)

Possible solution:  
Supersymmetry

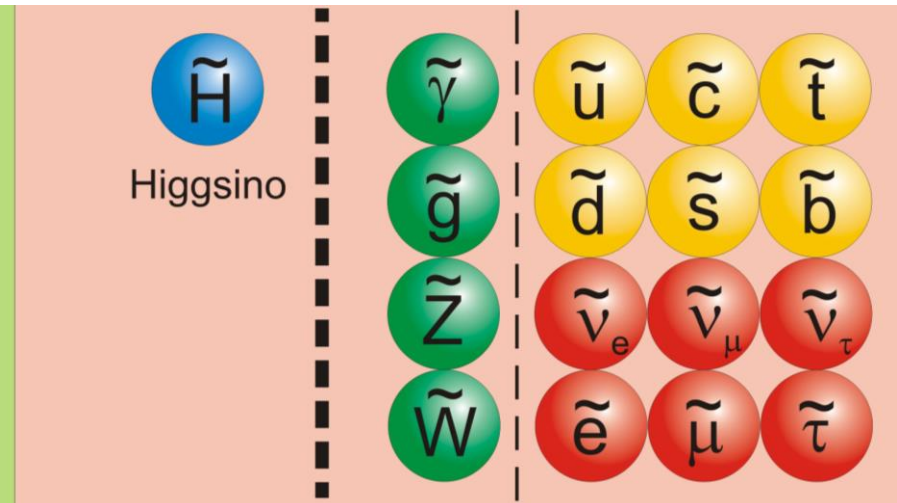
Fermions	Bosons
Spin 1/2	Spin 0, Spin 1
electron	selectron (S=0)
quark	squark (S=0)
photino	photon (S=1)
gluino	gluon (S=1)
gaugino (Wino, Zino)	W, Z (S=1)



Known particle spectrum



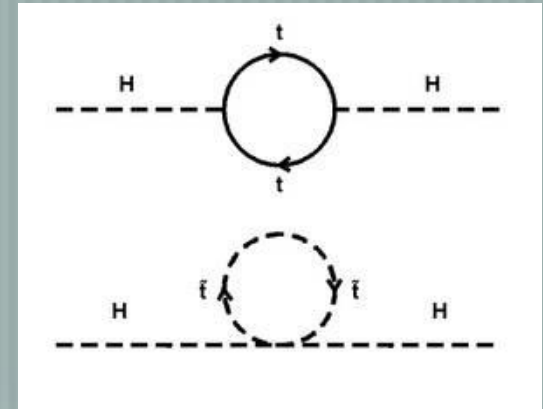
supersymmetric partners



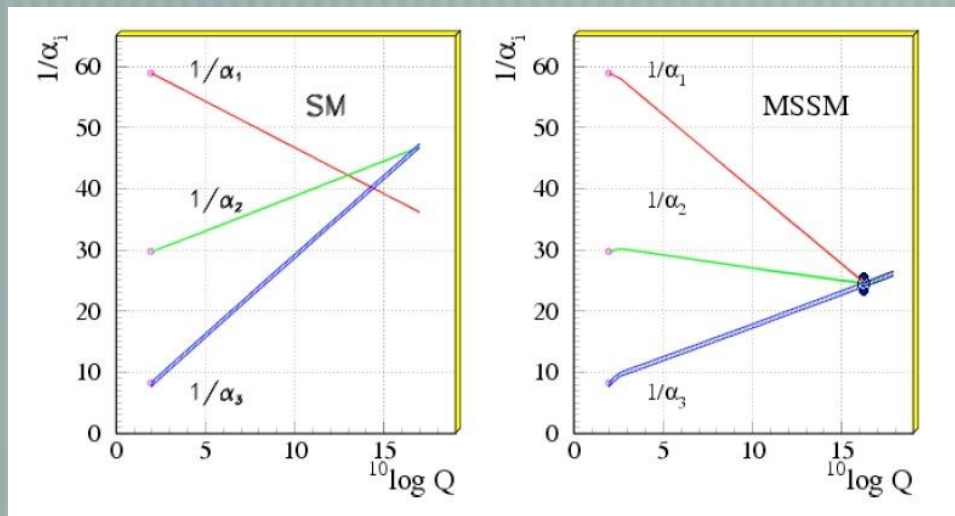
# Why SUSY?

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 ??**



# No sign of SUSY ... yet

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

Status: March 2016

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$  TeV

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{miss}$ [ $\mathcal{L} dt(\text{fb}^{-1})$ ]	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference
<b>Inclusive Searches</b>	MSUGRA/CMSSM	0-3 $e, \mu/1-2 \tau$	2-10 jets/3 $b$	Yes 20.3	$\tilde{g}, \tilde{g}$	1.85 TeV	$m(\tilde{g})=m(\tilde{g})$ 1507.05525
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes 3.2	$\tilde{q}$	980 GeV	$m(\tilde{\chi}_1^0)=0$ GeV, $m(1^{st} \text{ gen. } \tilde{q})=m(2^{nd} \text{ gen. } \tilde{q})$ 1503.03290
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes 3.2	$\tilde{q}$	610 GeV	$m(\tilde{g}), m(\tilde{\chi}_1^0) < 5$ GeV <i>To appear</i>
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q(\ell\ell/\nu\nu/\nu\nu)\tilde{\chi}_1^0$	2 $e, \mu$ (off-Z)	2 jets	Yes 20.3	$\tilde{q}$	820 GeV	$m(\tilde{\chi}_1^0)=0$ GeV 1503.03290
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes 3.2	$\tilde{g}$	1.52 TeV	$m(\tilde{\chi}_1^0)=0$ GeV 1503.03290
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	1 $e, \mu$	2-6 jets	Yes 3.3	$\tilde{g}$	1.6 TeV	$m(\tilde{\chi}_1^0) < 350$ GeV, $m(\tilde{\tau}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ 1501.03555
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	2 $e, \mu$	0-3 jets	- 20	$\tilde{g}$	1.38 TeV	$m(\tilde{\chi}_1^0)=0$ GeV 1602.06194
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	0	7-10 jets	Yes 3.2	$\tilde{g}$	1.4 TeV	$m(\tilde{\chi}_1^0)=100$ GeV 1407.0603
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes 20.3	$\tilde{g}$	1.63 TeV	$\tan\beta > 20$ 1507.05493
	GMSB ( $\tilde{\ell}$ NLSP)	$\gamma$	-	Yes 20.3	$\tilde{g}$	1.34 TeV	$c\tau(\text{NLSP}) < 0.1$ mm 1507.05493
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes 20.3	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0) < 950$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu < 0$ 1507.05493
	GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes 20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0) < 850$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu > 0$ 1503.03290
GGM (higgsino NLSP)	2 $e, \mu$ (Z)	2 jets	Yes 20.3	$\tilde{g}$	900 GeV	$m(\text{NLSP}) > 430$ GeV 1502.01518	
Gravitino LSP	0	mono-jet	Yes 20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-1}$ eV, $m(\tilde{g})=m(\tilde{g})=1.5$ TeV	
<b>3<sup>rd</sup> gen. &amp; med.</b>	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{\chi}_1^0$	0	3 $b$	Yes 3.3	$\tilde{g}$	1.78 TeV	$m(\tilde{\chi}_1^0) < 800$ GeV 1602.09058
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$	Yes 3.3	$\tilde{g}$	1.76 TeV	$m(\tilde{\chi}_1^0)=0$ GeV <i>To appear</i>
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$	Yes 20.1	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0) < 300$ GeV 1407.0600
<b>3<sup>rd</sup> gen. squarks direct production</b>	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes 3.2	$\tilde{b}_1$	840 GeV	$m(\tilde{\chi}_1^0) < 100$ GeV ATLAS-CONF-2015-066
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 $e, \mu$ (SS)	0-3 $b$	Yes 3.2	$\tilde{b}_1$	325-540 GeV	$m(\tilde{\chi}_1^0)=50$ GeV, $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_1^0)+100$ GeV 1602.09058
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	1-2 $e, \mu$	1-2 $b$	Yes 4.7/20.3	$\tilde{t}_1$	117-170 GeV	$m(\tilde{\chi}_1^0)=1$ GeV, $m(\tilde{\chi}_1^\pm)=55$ GeV 1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 $e, \mu$	0-2 jets/1-2 $b$	Yes 20.3	$\tilde{t}_1$	90-198 GeV, 205-715 GeV	$m(\tilde{\chi}_1^0)=1$ GeV 1509.08616, ATLAS-CONF-2016-00
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/ $c$ -tag	Yes 20.3	$\tilde{t}_1$	90-245 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0) < 85$ GeV 1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 $b$	Yes 20.3	$\tilde{t}_1$	150-600 GeV	$m(\tilde{\chi}_1^0) > 150$ 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	$\tilde{t}_2$	290-610 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV 1403.5222
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1 $e, \mu$	6 jets + 2 $b$	Yes 20.3	$\tilde{t}_2$	320-620 GeV	$m(\tilde{\chi}_1^0)=0$ GeV 1506.08616	
<b>EW direct</b>	$\tilde{\chi}_{1,2}^+ \tilde{\chi}_{1,2}^- \rightarrow \tilde{e}\tilde{e}$	2 $e, \mu$	0	Yes 20.3	$\tilde{\chi}$	90-335 GeV	$m(\tilde{\chi}_1^0)=0$ GeV 1403.5294
	$\tilde{\chi}_{1,2}^+ \tilde{\chi}_{1,2}^- \rightarrow \tilde{\nu}\tilde{\nu}$	2 $e, \mu$	0	Yes 20.3	$\tilde{\chi}$	140-475 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
	$\tilde{\chi}_{1,2}^+ \tilde{\chi}_{1,2}^- \rightarrow \tilde{\tau}\tilde{\tau}$	2 $\tau$	-	Yes 20.3	$\tilde{\chi}$	355 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
	$\tilde{\chi}_{1,2}^+ \tilde{\chi}_{1,2}^- \rightarrow \tilde{\ell}_L \nu_{\tilde{\ell}_L}^0(\tilde{\nu})$	3 $e, \mu$	0	Yes 20.3	$\tilde{\chi}$	715 GeV	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$ 1402.7029
	$\tilde{\chi}_{1,2}^+ \tilde{\chi}_{1,2}^- \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 $e, \mu$	0-2 jets	Yes 20.3	$\tilde{\chi}$	425 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)=0, \text{ sleptons decoupled}$ 1403.5294, 1402.7029
	$\tilde{\chi}_{1,2}^+ \tilde{\chi}_{1,2}^- \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/WW/\tau\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 $b$	Yes 20.3	$\tilde{\chi}$	270 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)=0, \text{ sleptons decoupled}$ 1501.07110
	$\tilde{\chi}_{2,3}^0 \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R \ell$	4 $e, \mu$	0	Yes 20.3	$\tilde{\chi}$	635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^\pm)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ 1405.5086
	$\tilde{\chi}_{2,3}^0 \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R \ell$	4 $e, \mu$	0	Yes 20.3	$\tilde{\chi}$	635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^\pm)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ 1507.05493
	GGM (wino NLSP) weak prod.	1 $e, \mu + \gamma$	-	Yes 20.3	$\tilde{W}$	115-370 GeV	$c\tau < 1$ mm
<b>Long-lived particles</b>	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	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm)=0.2$ ns 1310.3675
	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes 18.4	$\tilde{\chi}_1^\pm$	495 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm) < 15$ ns 1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes 27.9	$\tilde{g}$	850 GeV	$m(\tilde{\chi}_1^0)=100$ GeV, $10 \mu\text{s} < c\tau(\tilde{g}) < 1000$ s 1310.6584
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	3.2	$\tilde{g}$	1.54 TeV	$m(\tilde{\chi}_1^0)=100$ GeV, $\tau > 10$ ns <i>To appear</i>
	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	$10 < \text{clan}_{\tilde{\tau}} < 50$ 1411.6795
	GMSB, $\tilde{\chi}_1^0 \rightarrow \tilde{G}$ , long-lived $\tilde{\chi}_1^0$	2 $\gamma$	-	Yes 20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model 1409.5542
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow e\tilde{\nu}/e\tilde{\mu}/\mu\tilde{\nu}$	displ. $e\ell/e\mu/\mu\tilde{\nu}$	-	- 20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740$ mm, $m(\tilde{g})=1.3$ TeV 1504.05162
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	displ. vtx + jets	-	- 20.3	$\tilde{\chi}_1^0$	1.0 TeV	$6 < c\tau(\tilde{\chi}_1^0) < 480$ mm, $m(\tilde{g})=1.1$ TeV 1504.05162	
<b>RPV</b>	LFV $pp \rightarrow \tilde{\nu} + X, \tilde{\nu} \rightarrow e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	20.3	$\tilde{\nu}$	1.7 TeV	$A_{311}=0.11, A_{132/133/233}=0.07$ 1503.04430
	Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 $b$	Yes 20.3	$\tilde{g}, \tilde{g}$	1.45 TeV	$m(\tilde{g})=m(\tilde{g}), c\tau_{LSP} < 1$ mm 1404.2500
	$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 $e, \mu$	-	Yes 20.3	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), A_{121} \neq 0$ 1405.5086
	$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tilde{\nu}_\tau, e\tau\tilde{\nu}_e$	3 $e, \mu + \tau$	-	Yes 20.3	$\tilde{\chi}_1^\pm$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), A_{133} \neq 0$ 1405.5086
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}$	0	6-7 jets	- 20.3	$\tilde{g}$	917 GeV	$\text{BR}(\tilde{g})-\text{BR}(\tilde{b})=\text{BR}(c)=0\%$ 1502.05686
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$	0	6-7 jets	- 20.3	$\tilde{g}$	980 GeV	$m(\tilde{\chi}_1^0)=600$ GeV 1502.05686
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b\tilde{s}$	2 $e, \mu$ (SS)	0-3 $b$	Yes 20.3	$\tilde{g}$	880 GeV	1404.2500
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	0	2 jets + 2 $b$	- 20.3	$\tilde{t}_1$	320 GeV	1601.07453	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	2 $e, \mu$	2 $b$	- 20.3	$\tilde{t}_1$	0.4-1.0 TeV	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$ ATLAS-CONF-2015-015	
<b>Other</b>	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 $c$	Yes 20.3	$\tilde{c}$	510 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV 1501.01325

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

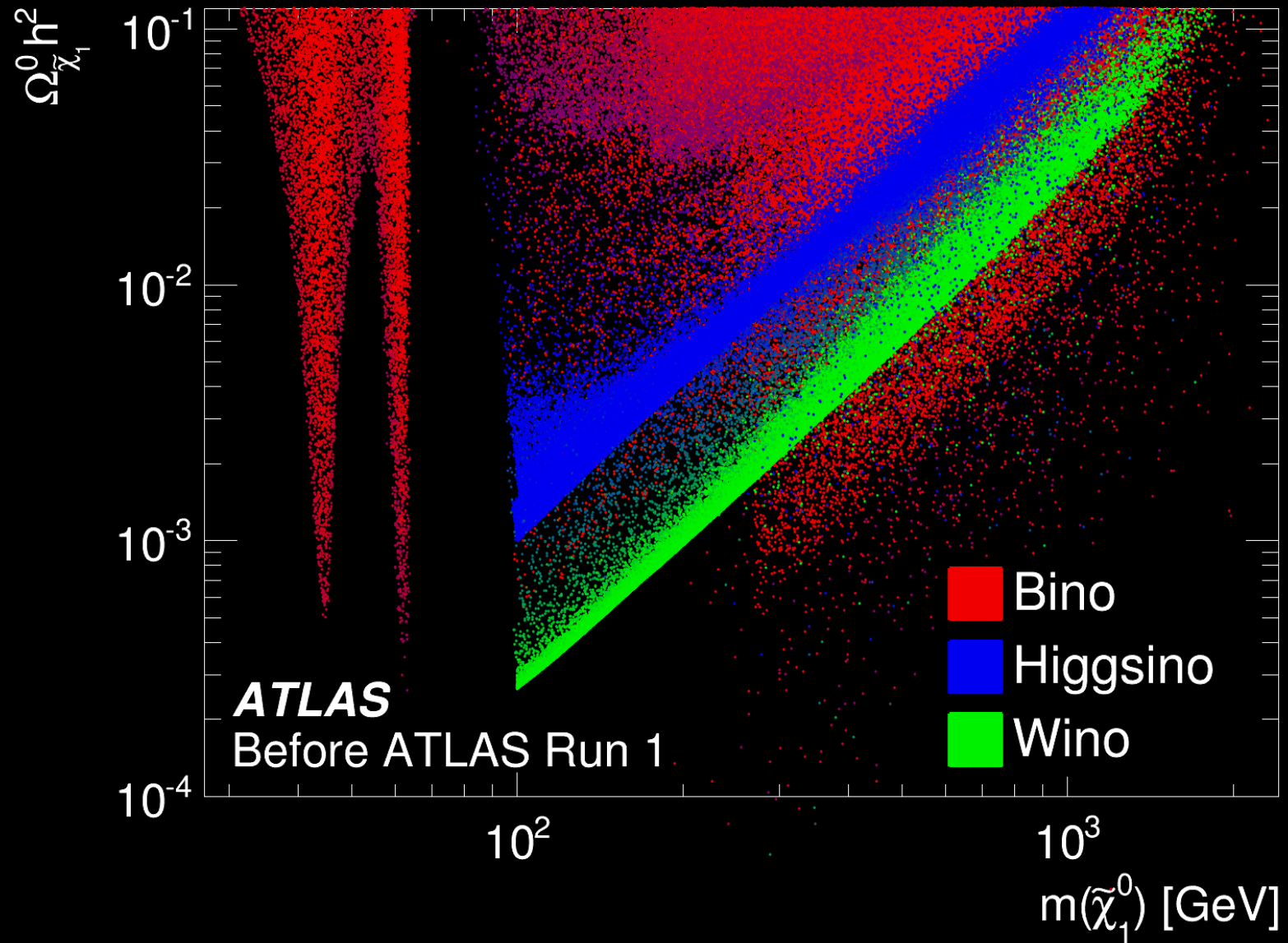
10<sup>-1</sup>

1

Mass scale [TeV]



# Excluding SUSY models





# Prospects of particle physics

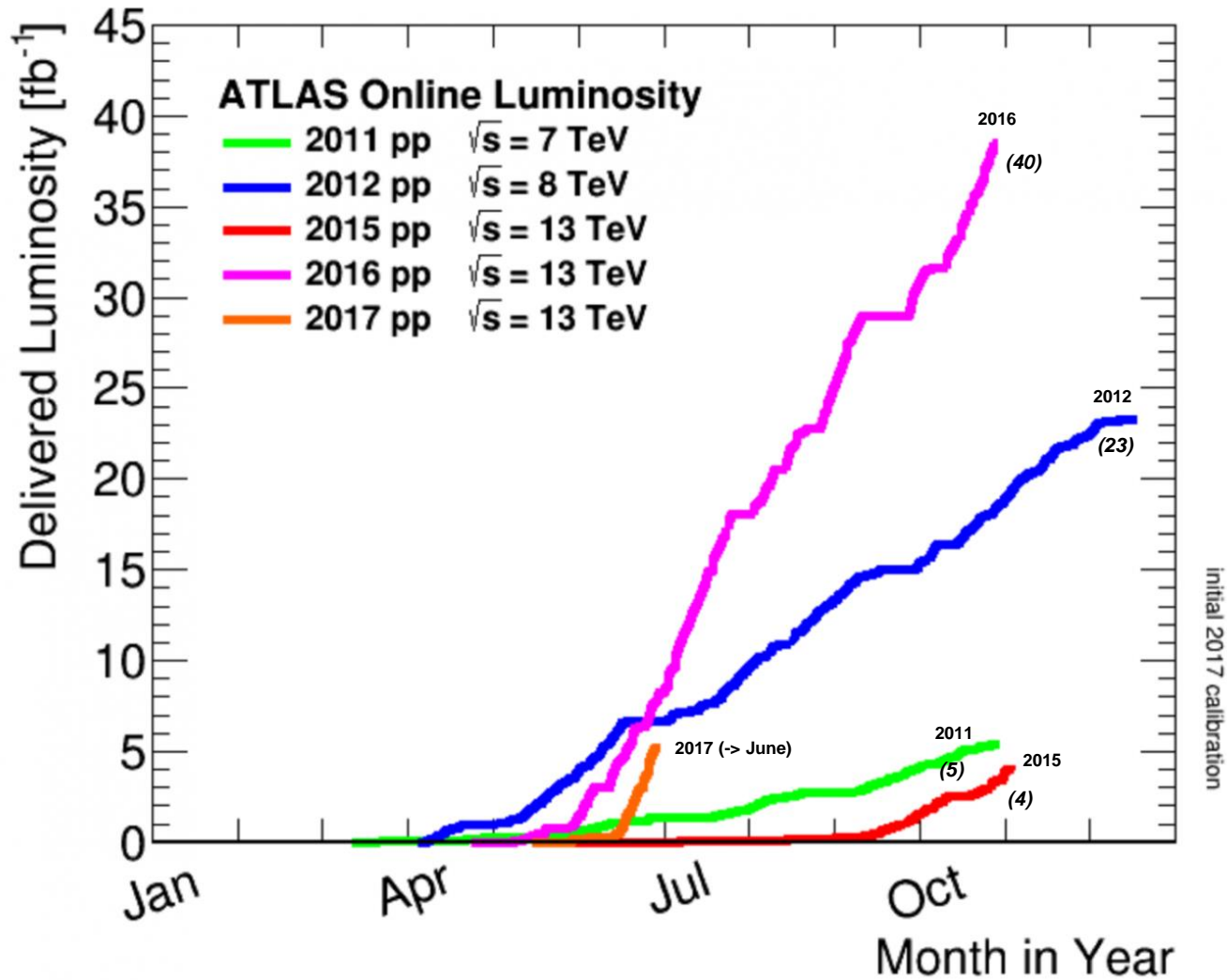
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- Higher luminosity (until 2035)
- Higher energy (afterwards)



# Goal: maximize number of collision events (“integrated luminosity”)

ATLAS and CMS each  $\sim 70 \text{ fb}^{-1} = 5.6 \cdot 10^{15}$  p-p collisions

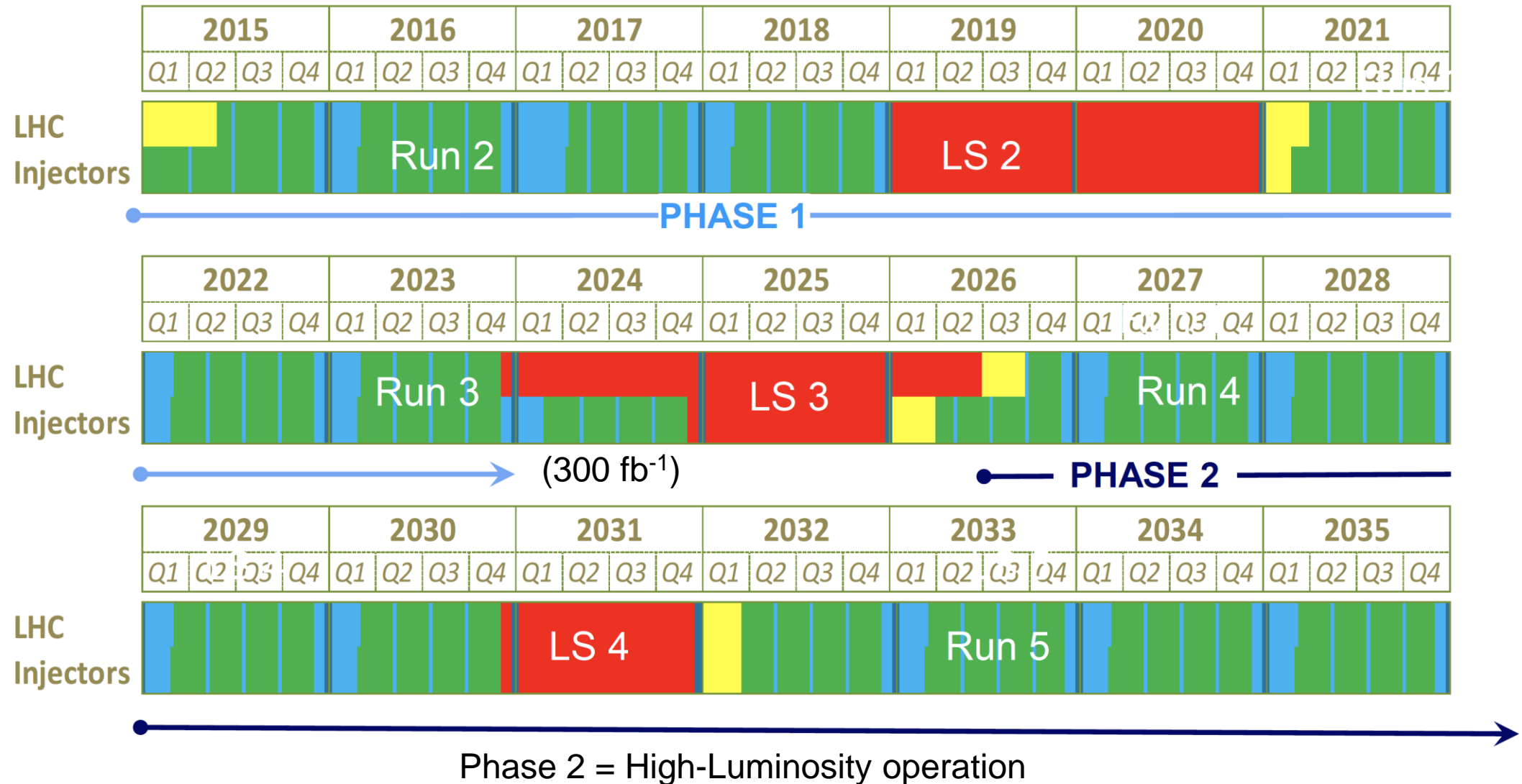


$1 \text{ fb}^{-1} = 80 \cdot 10^{12}$  p-p collisions



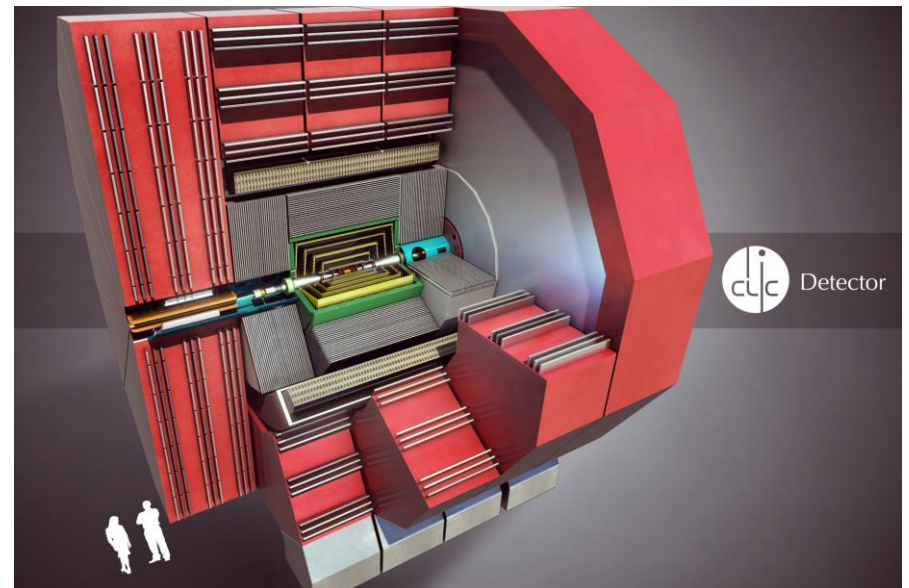
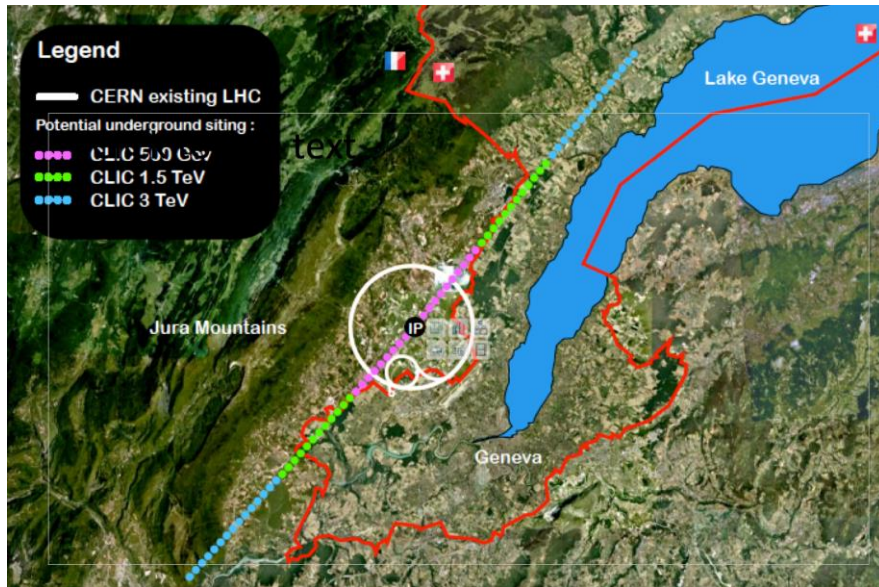
# CERN Schedule 2015 - 2035 with Hi-Lumi phase

Final goal: 3000 fb<sup>-1</sup>

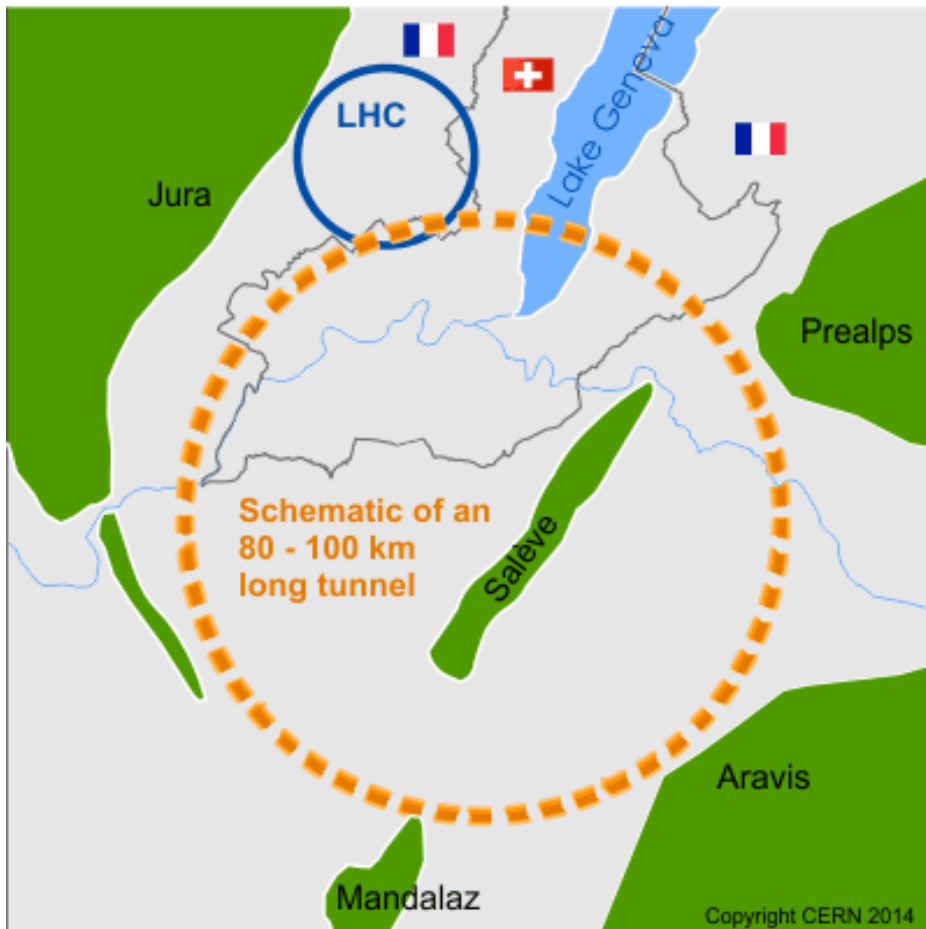


# Linear Collider

## CLIC: 3 TeV $e^+ e^-$ Collider ?



# Future circular collider - project study (FCC)



Conceptual design report ~ late 2018

## Circular collider in new tunnel

80- 100 km circumference

Circular proton-proton collider  
**100 TeV** collision energy (p+p)

Circular electron-positron collider (VLEP)  
(**350 GeV c.m.** energy, t-tbar threshold)

Lepton-Hadron collider (like HERA)  
(**50 TeV p + 100 GeV e**)

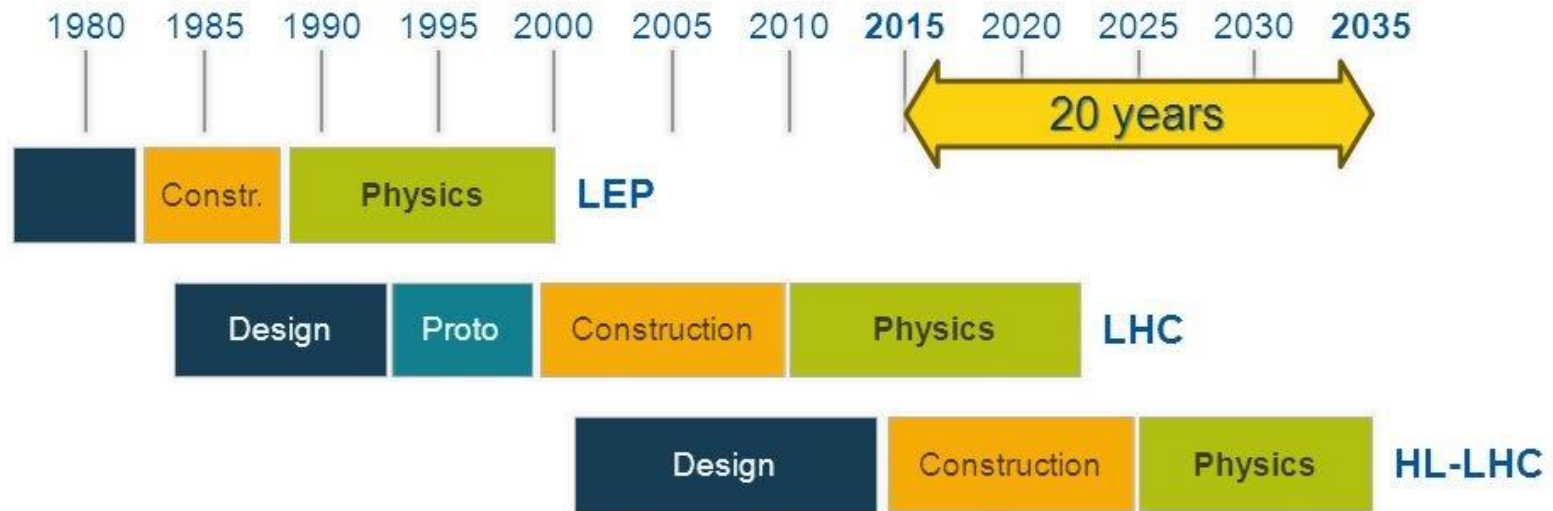
## Alternatively:

30 TeV p-p collider in LHC tunnel ?  
(**16 T magnets**)



# How to get there ?

## CERN Circular Colliders + FCC



Future Collider



# 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 - 2017



**New discoveries are waiting !**