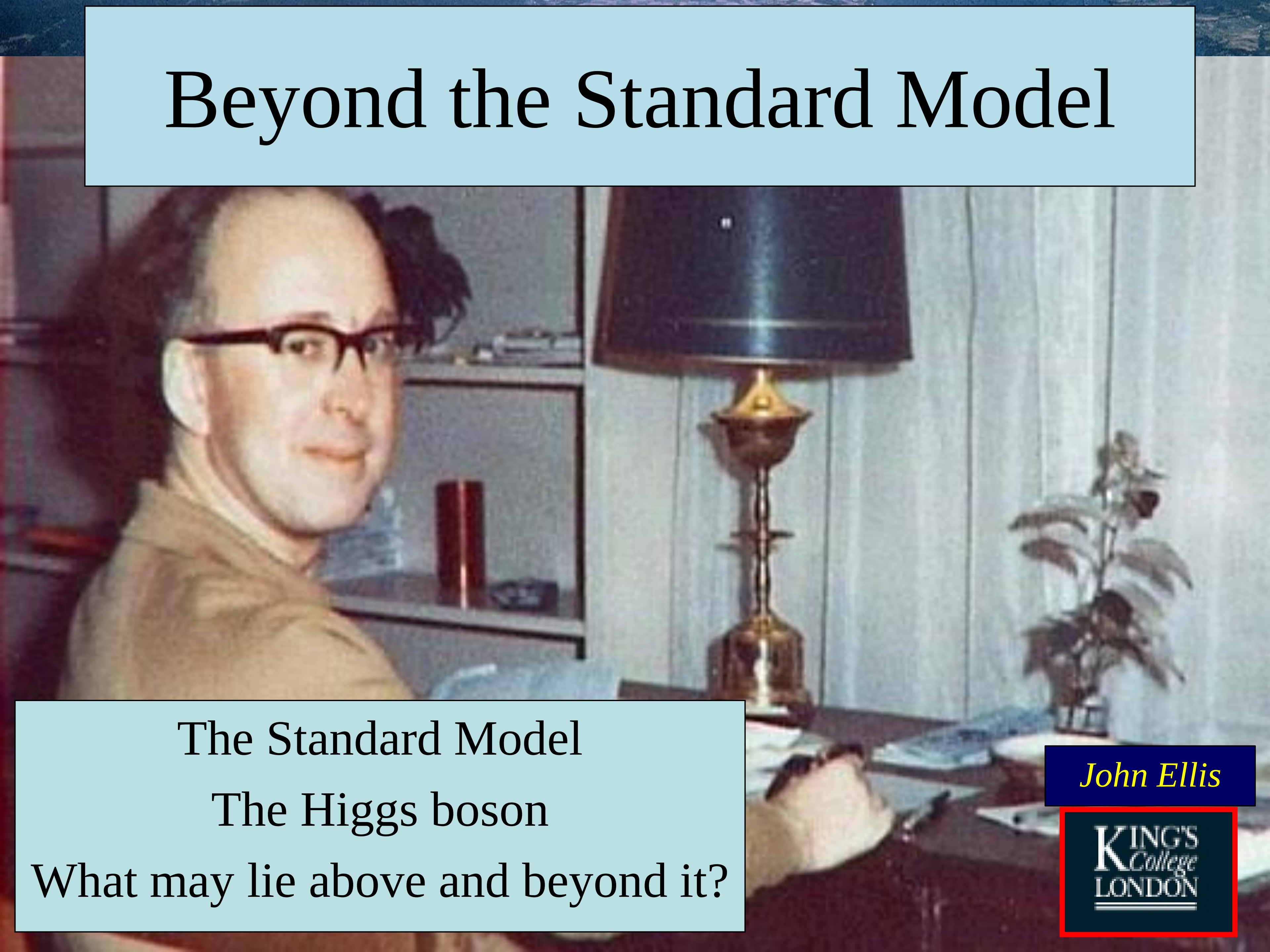
Beyond the Standard Model

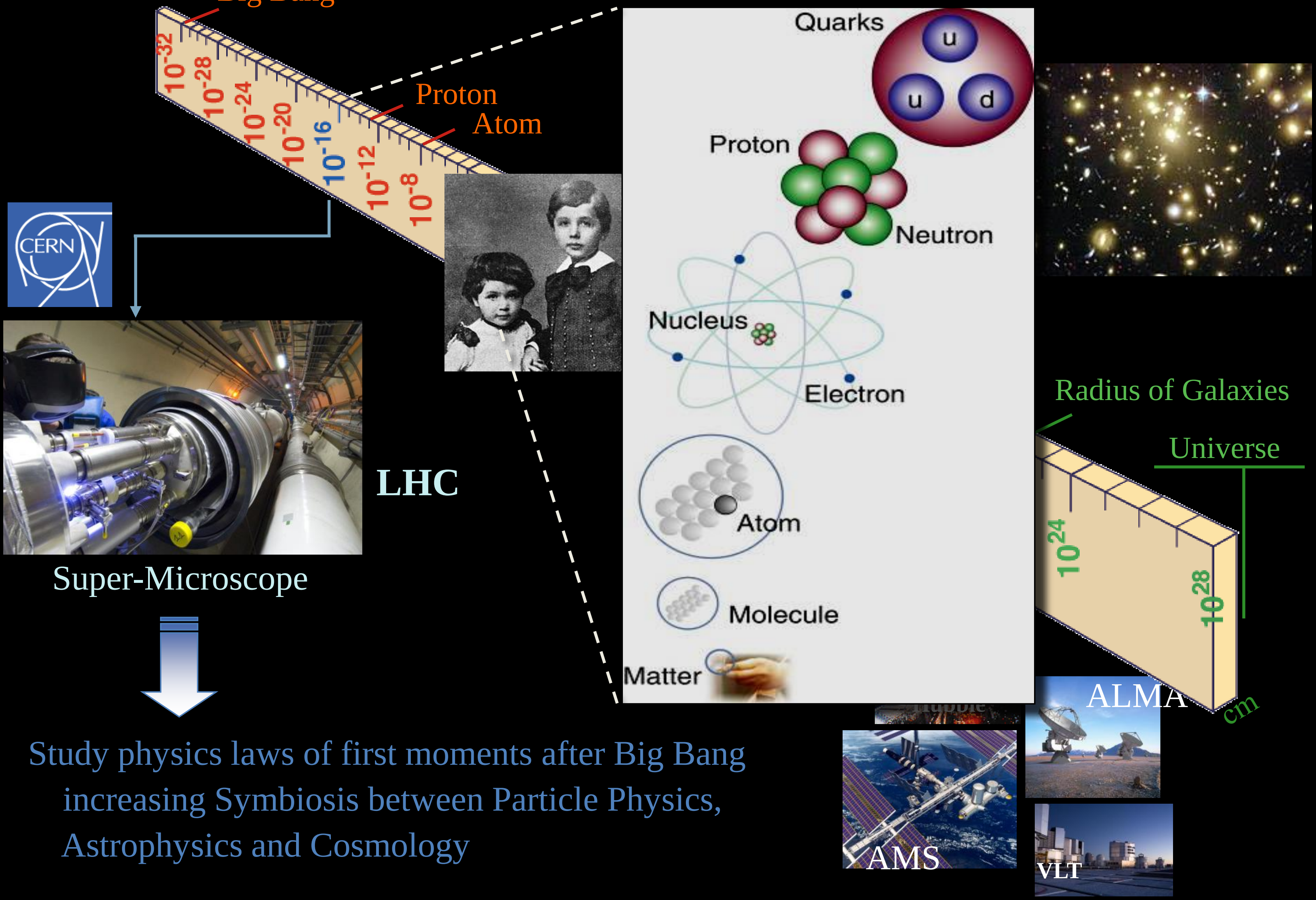


The Standard Model

The Higgs boson

What may lie above and beyond it?

John Ellis



LHC

Super-Microscope

Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

“Where do we come from?

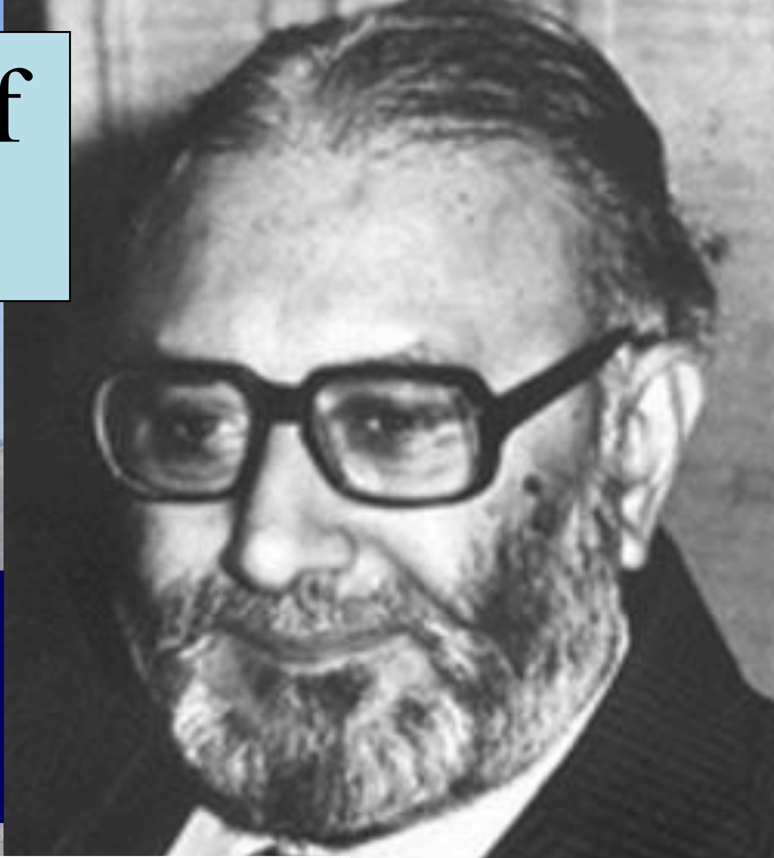
What are we?

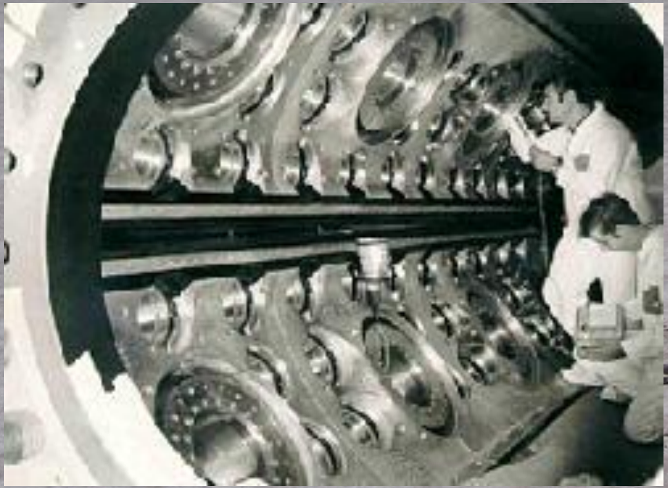
Where are we going?”

The aim of particle physics, CERN & the LHC:
What is the Universe made of?

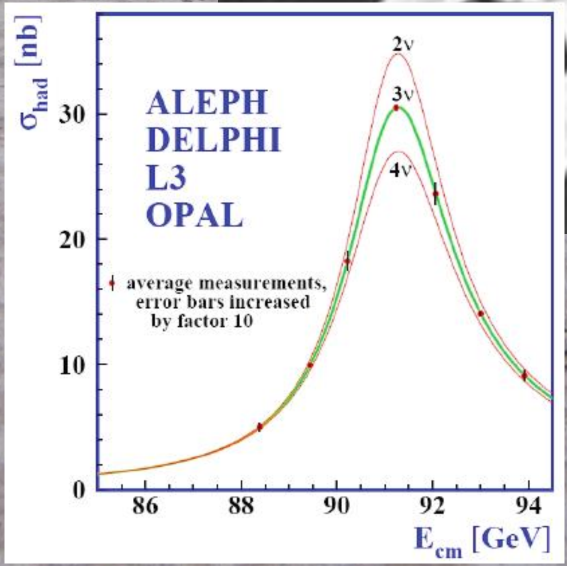
The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow & Weinberg





Crucial tests in Experiments at CERN, etc.



In agreement with all confirmed laboratory experiments

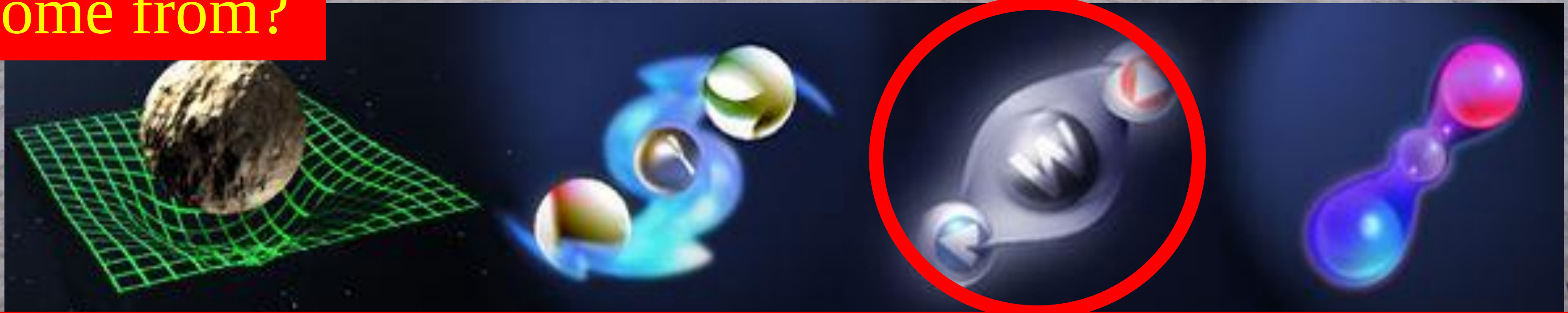
The ‘Standard Model’

= Cosmic DNA

The matter particles

Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Gauguin’s Questions in the Language of Particle Physics

- What is matter made of?
  - – Why do things weigh?

- What is the origin of matter?

LHC Run 2

- What is the dark matter that fills the U

LHC Run 2

- How does the Universe evolve?
- Why is the Universe so big and old?

LHC Run 2

- What is the future of the Universe?

LHC Run 2

Our job is to ask - and answer - these questions

Structure of the Standard Model

- Special relativity
- Quantum mechanics
- Field theory
- Quantum field theory
- Three fundamental forces:
  - strong, weak and electromagnetic
- Each associated with a local (gauge) symmetry
- Leads to interactions between matter and force particles
- Massless photon & gluons and **massive W, Z**

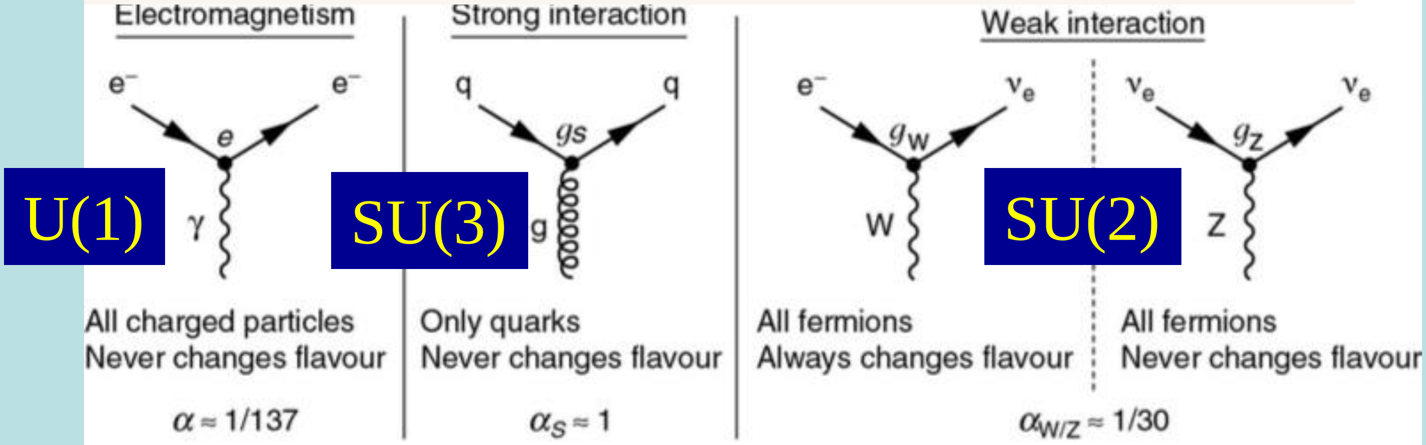
Beyond U(1) Gauge Symmetry

- Generalize phase to matrix:

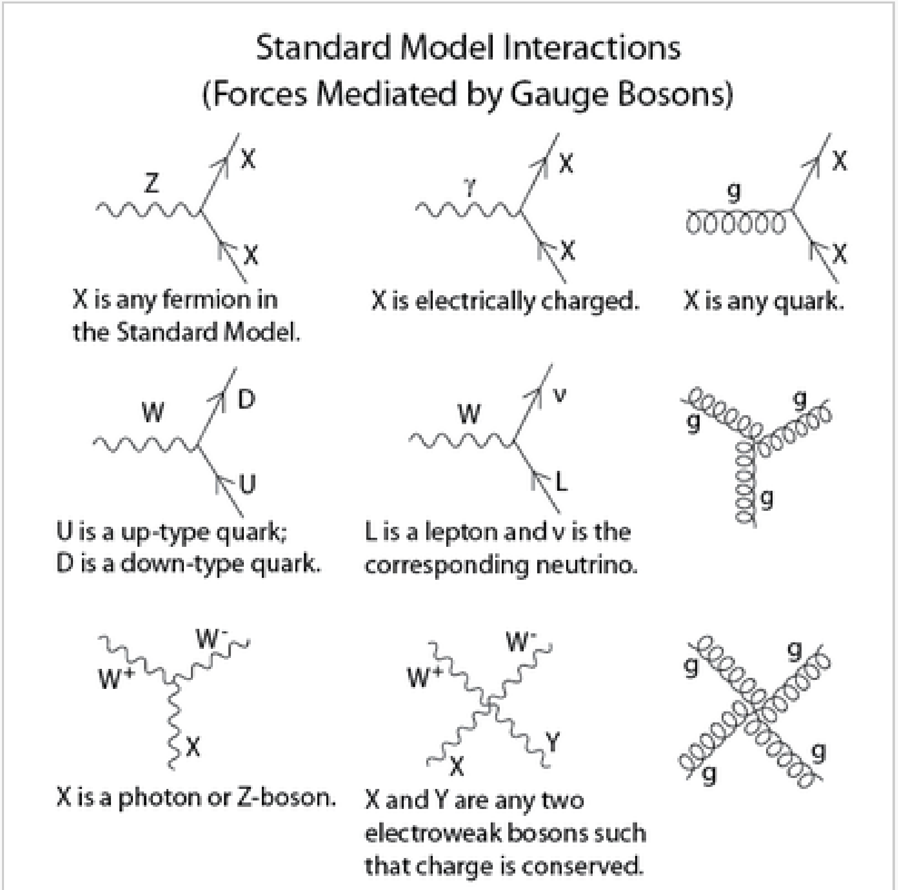
$$\Psi_i \to U_i^j \Psi_j \qquad D_\mu \Psi \to U D_\mu \Psi \qquad D_\mu = \partial_\mu + igT_a G^a_\mu$$

- Representation matrix $[T_a, T_b] = i f_{ab}{}^c T_c$
- Standard Model covariant derivative:

$$D_\mu = \partial_\mu \overset{\text{U(1)}}{-\, i\frac{Y}{2} g_1 B_\mu} \overset{\text{SU(2)}}{-\, i g_2 \frac{\sigma_j}{2} W^j_\mu} \overset{\text{SU(3)}}{-\, i g_3 \frac{\lambda_a}{2} G^a_\mu}$$



Standard Model Interactions



Standard Model Interactions
(Forces Mediated by Gauge Bosons)

X is any fermion in the Standard Model.

X is electrically charged.

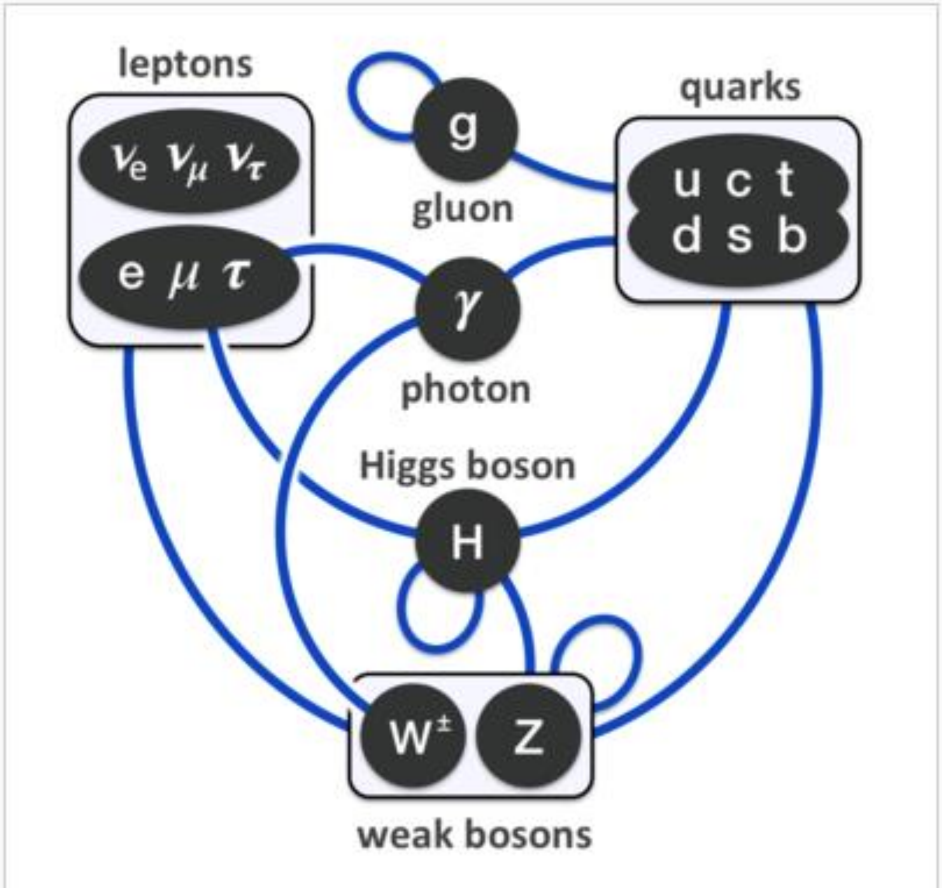
X is any quark.

U is a up-type quark; D is a down-type quark.

L is a lepton and v is the corresponding neutrino.

X is a photon or Z-boson.

X and Y are any two electroweak bosons such that charge is conserved.



Feynman Diagrams

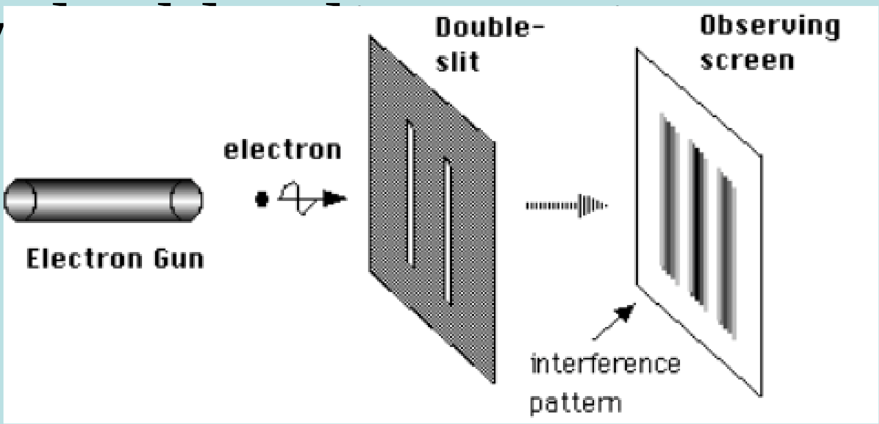
- Quantum mechanics = sum over all paths
- Exemplified by

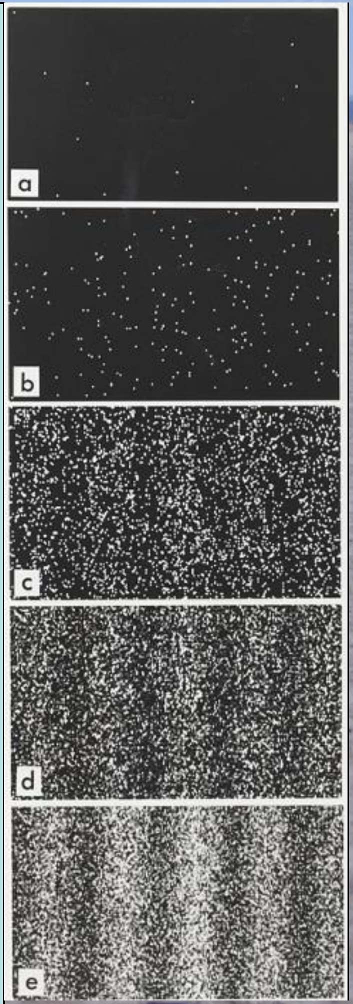
  photons &

  electrons:

  interference

  (one by one)



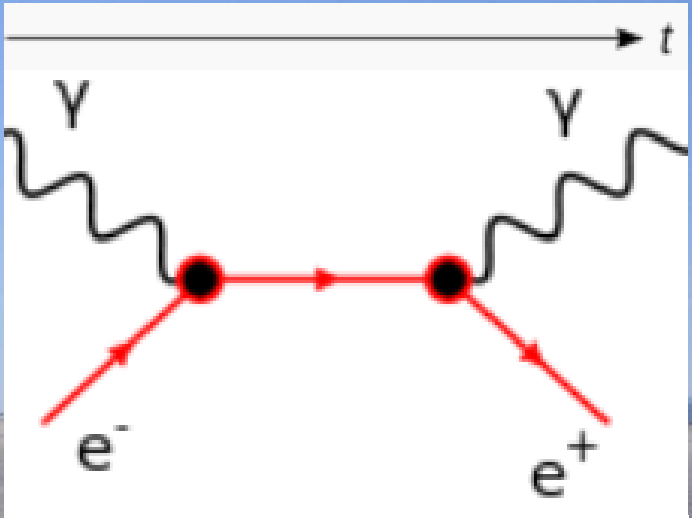


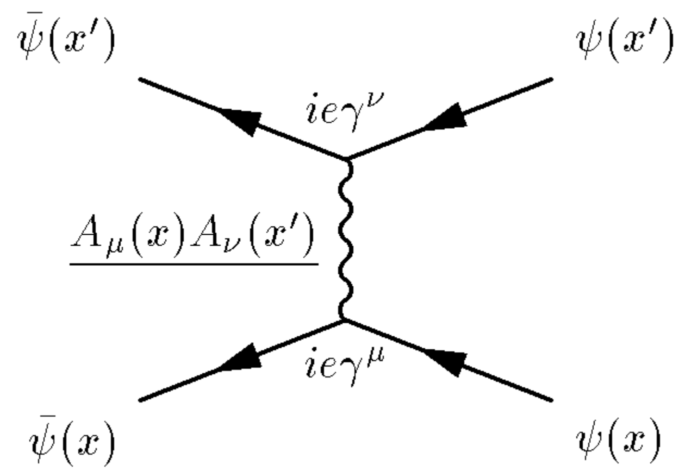
- Possible in$e\bar{\Psi}\gamma^{\mu}A_{\mu}\Psi = j^{\mu}A_{\mu}$l from L:

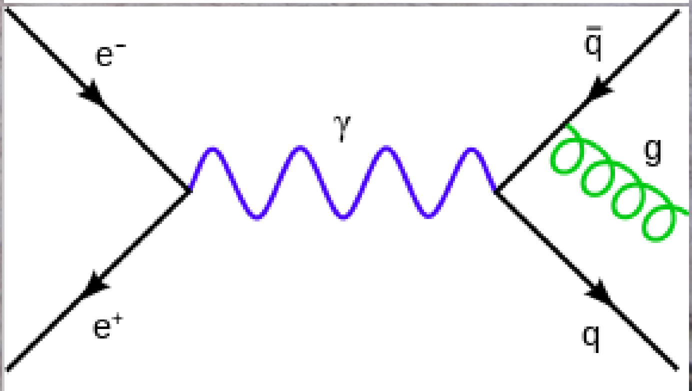
- Write all possible paths = diagrams

Diagrams for Simple Processes

- Photon scattering on electron (Compton)
  - photoelectric effect
- Scattering process
  - with detailed factors
- Electron-positron annihilation to quark + antiquark + gluon

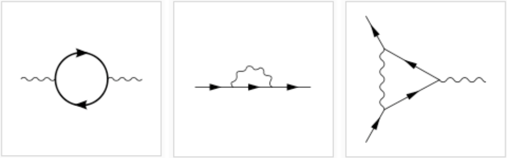


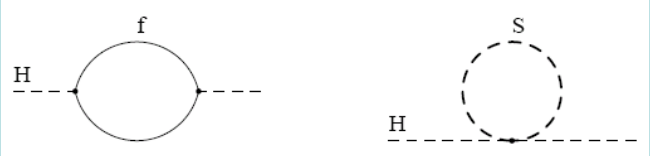




Higher-Order Diagrams

- Loops of virtual quantum particles

QED: 

Higgs: 

- Also called radiative corrections
- Calculations often give infinite results
- May be controlled to give finite answers for physical quantities by “renormalization”
- Examples of renormalizable (sensible) theories
  - Quantum electrodynamics (1940s)
  - Gauge theories (1970s)

The Problem of Mass

- Massless gauge bosons:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\gamma^{\mu}D_{\mu}\Psi + m\bar{\Psi}\Psi$$

- Invariant under gauge transformations

$$A_{\mu} \longrightarrow A'_{\mu} = A_{\mu} + \partial_{\mu}\lambda$$

- Massive W, Z: add mass term ‘by hand’?

$$\Delta\mathcal{L} \sim -m^{2}A_{\mu}A^{\mu}$$

- Not gauge-invariant
- Calculations give nonsensical answers

Problem solved by Higgs et al

BUT

Why do Things Weigh?

Newton:

Weight proportional to Mass

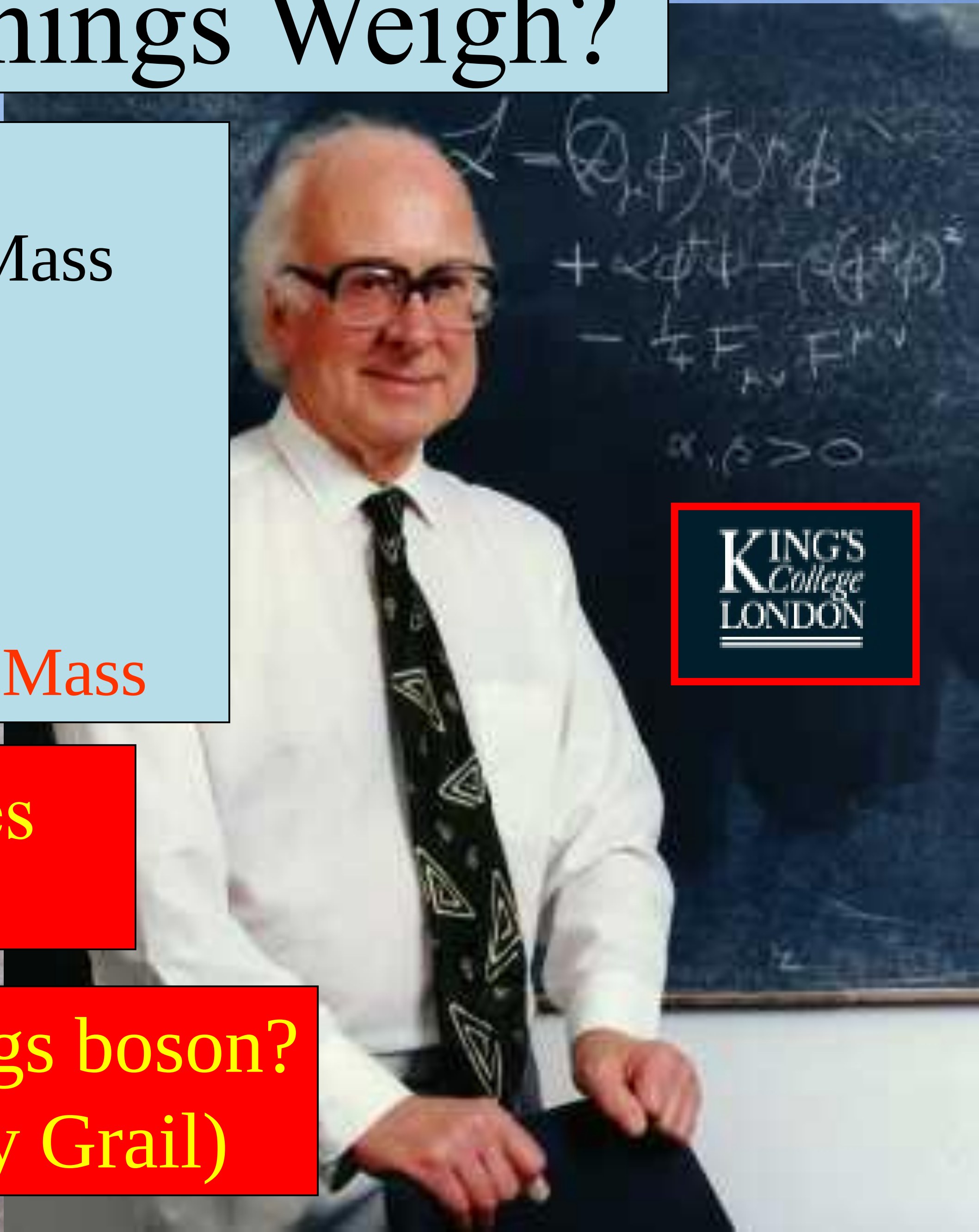
Einstein:

Energy related to Mass

Neither explained origin of Mass

Where do the masses come from?

Are masses due to Higgs boson?
(the physicists' Holy Grail)



KING'S College LONDON

Think of a Snowfield

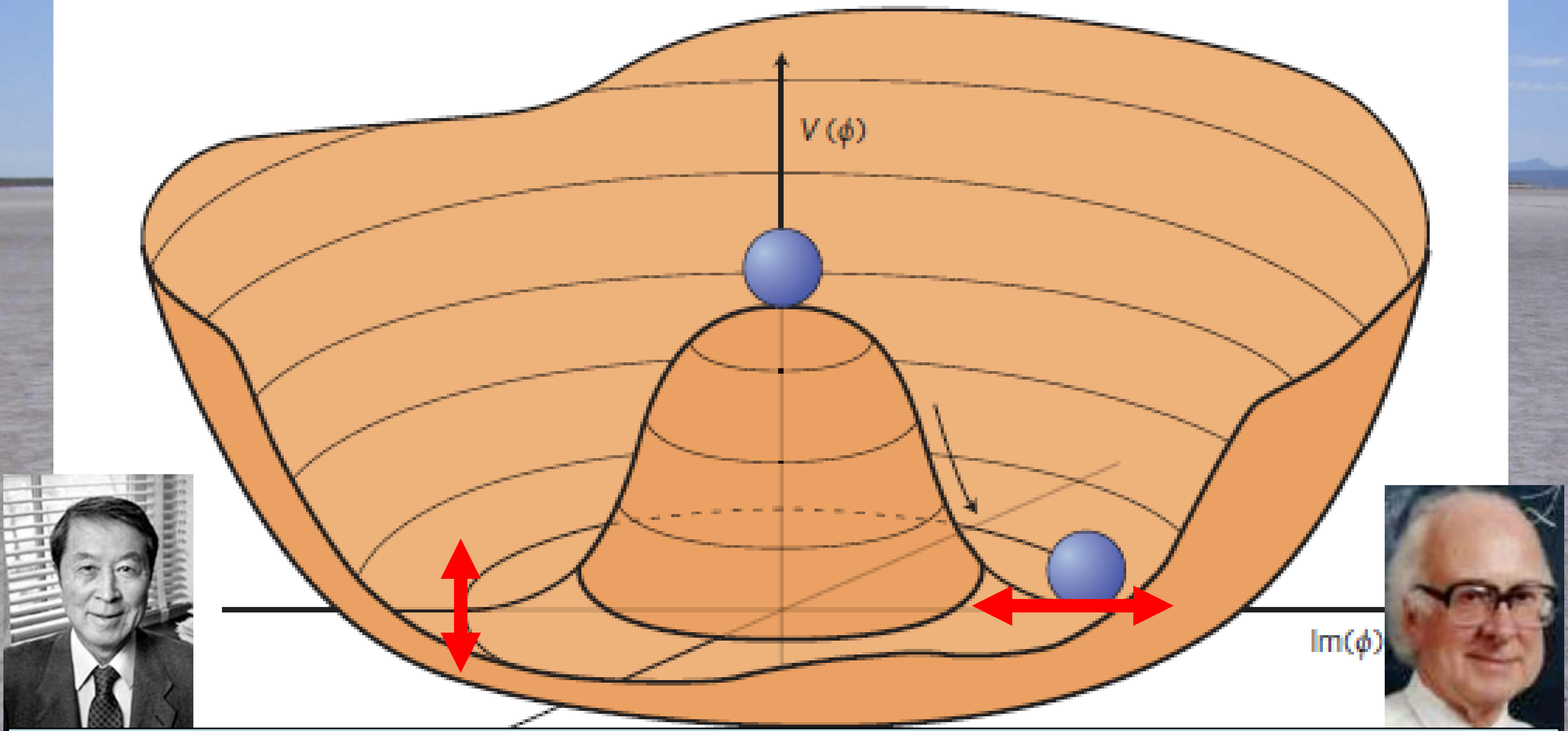
Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

Hiker sinks deep,
moves very slowly:
Particle with large mass

The LHC looks for
the snowflake:
the Higgs Boson

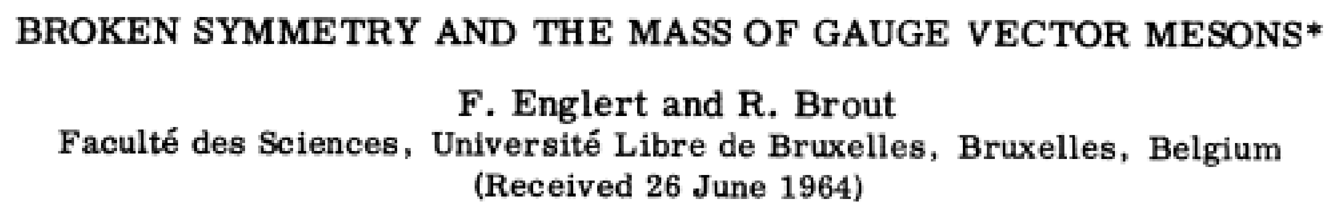
Nambu **EB, H, GHK** **and Higgs**



Spontaneous symmetry breaking: massless Nambu-Goldstone boson **‘eaten’ by massless gauge boson**

Accompanied by massive particle

The (NGA)EBHGHKMP Mechanism

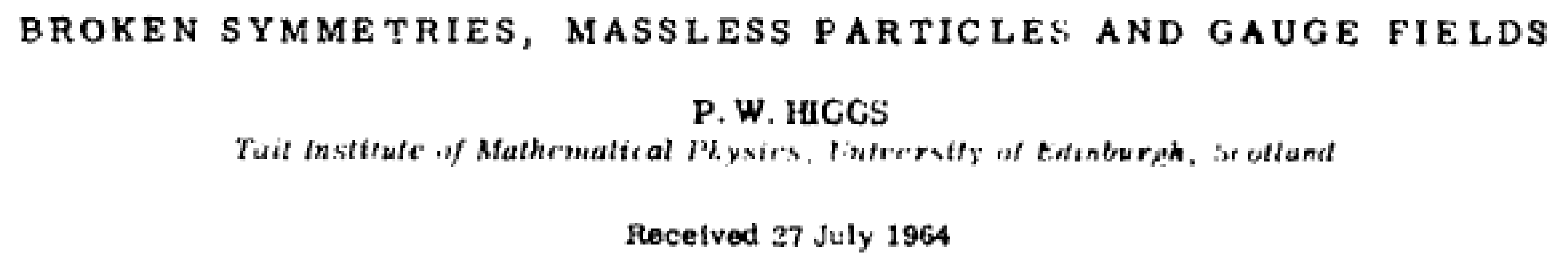


BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

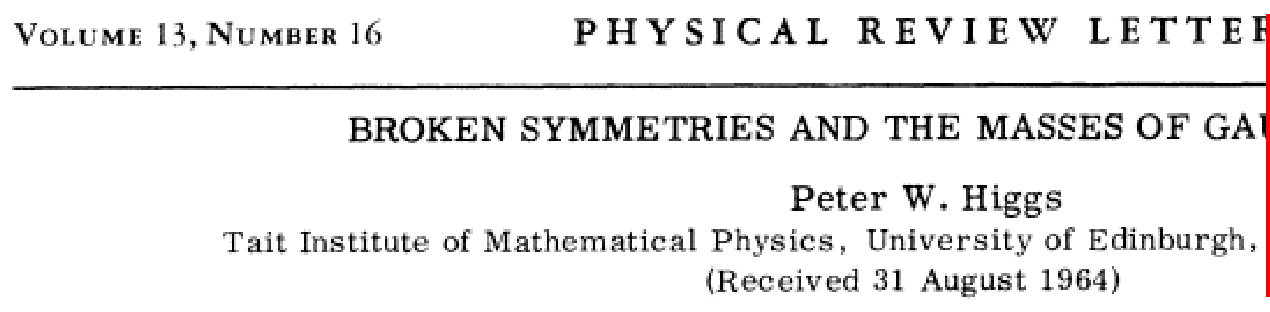


BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTE

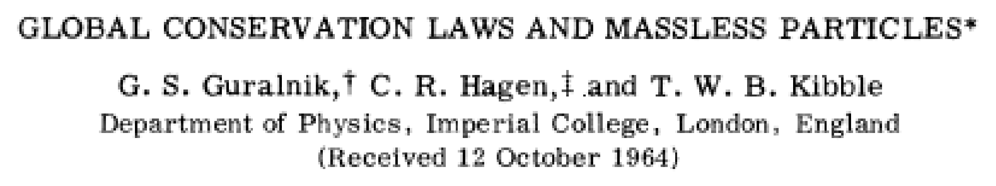
BROKEN SYMMETRIES AND THE MASSES OF GA

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh,

(Received 31 August 1964)

The only one
who mentioned a
massive scalar boson

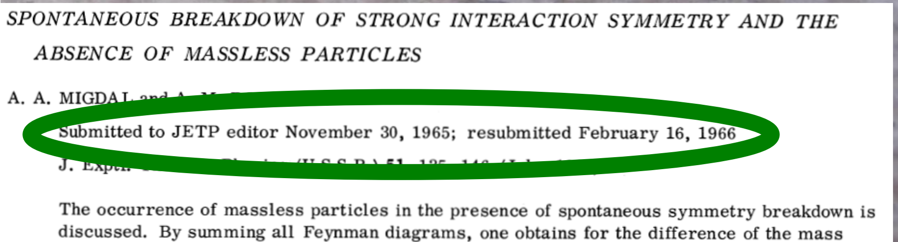


GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,[†] C. R. Hagen,[‡] and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 1964)



SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

A. A. MIGDAL and

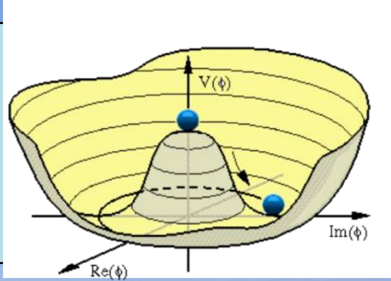
Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966

J. Exptl.

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

1964

Brout-Englert-Higgs Mechanism



- Lagrangian

$$\mathcal{L} = \left(D_\mu \phi\right)^+ \left(D^\mu \phi\right) - V(|\phi|) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \quad D_\mu = \partial_\mu - ieA_\mu$$

- Gauge transformation

$$\phi'(x) = e^{i\alpha(x)}\, \phi(x) = e^{i\alpha(x)}\, e^{i\theta(x)} \eta(x)$$

$$A'_\mu(x) = A_\mu(x) + \frac{1}{e} \partial_\mu \alpha(x)$$

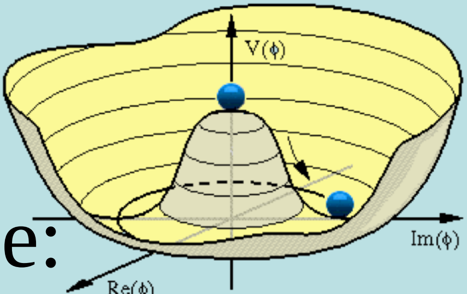
- Choose $\alpha(x) = -\theta(x)$: $\quad \phi'(x) = \eta(x)$
- Rewrite Lagrangian: $\mathcal{L} = |(\partial - ieA'_\mu)\eta|^2 - V(\eta) - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu}$

$$\begin{aligned}\mathcal{L} &= |(\partial_\mu - ieA'_\mu)(v + \tfrac{1}{\sqrt{2}} H)|^2 - \tfrac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - V \\ &= \underbrace{-\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + v^2 e^2\, A'_\mu A'^\mu}_{\text{massive A-field, } m_A \sim ev} + \underbrace{\frac{1}{2}[(\partial_\mu H)^2 - m_H^2 H^2]}_{\text{neutral scalar, } m_H \neq 0} + \cdots\end{aligned}$$

The Brout-Englert- Higgs Mechanism

- Postulated effective potential:

$$V[\phi] = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



- Minimum energy at non-zero value:

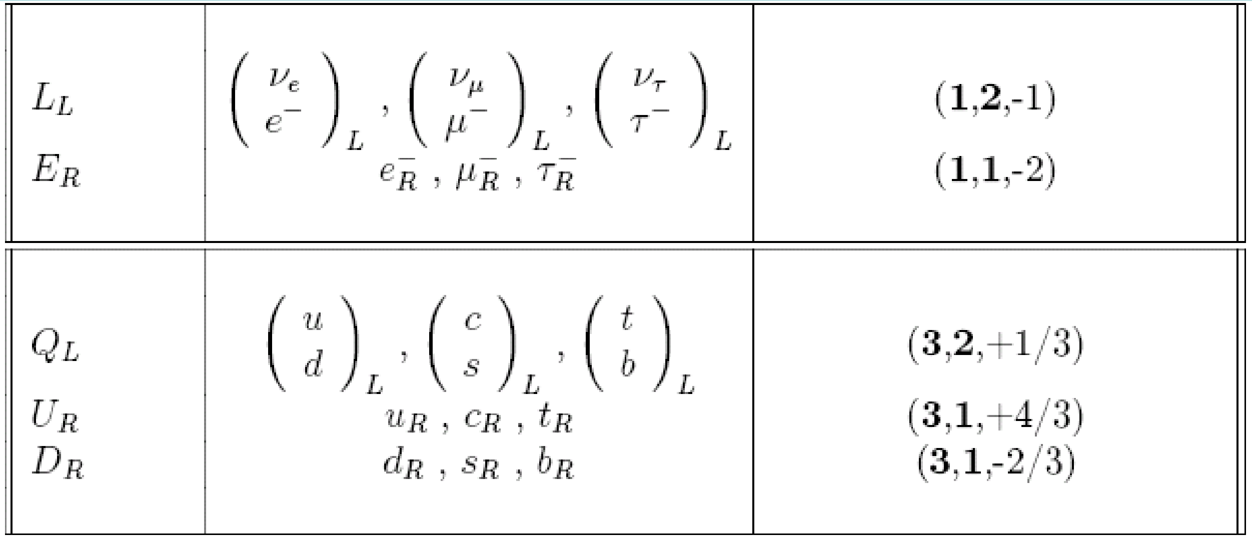
$$\phi_0 =< 0|\phi|0 >= \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ +v \end{array}\right) \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

➔➔π
η➔σ

- Components of Higgs field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π m = 0, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$ **Higgs boson**
- After gauging: $M_W = \frac{g\,v}{2}$ **Massive gauge boson**
- Couple to fermions: non-zero masses: $M_f = y_f \frac{v}{\sqrt{2}}$

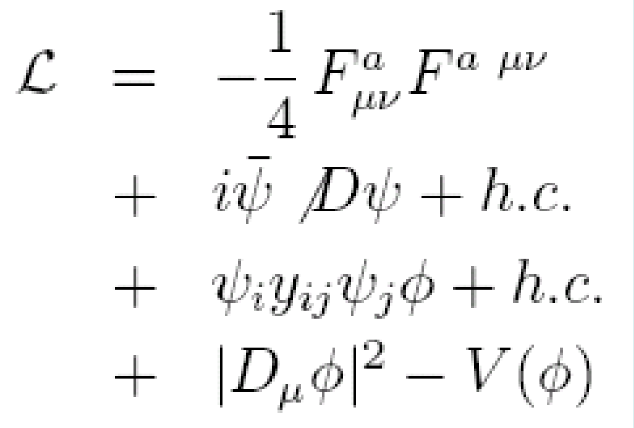
Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:



L_L	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L , \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L , \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},\text{-}1)$
E_R	$e^-_R \, , \, \mu^-_R \, , \, \tau^-_R$	$(\mathbf{1},\mathbf{1},\text{-}2)$
Q_L	$\begin{pmatrix}u\\ d\end{pmatrix}_L , \begin{pmatrix}c\\ s\end{pmatrix}_L , \begin{pmatrix}t\\ b\end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	$u_R \, , \, c_R \, , \, t_R$	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	$d_R \, , \, s_R \, , \, b_R$	$(\mathbf{3},\mathbf{1},\text{-}2/3)$

- Lagrangian:



$$\begin{aligned}\mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu}\\ &+ i\bar{\psi} \not{D}\psi + h.c.\\ &+ \psi_i y_{ij} \psi_j \phi + h.c.\\ &+ |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

gauge interactions

matter fermions

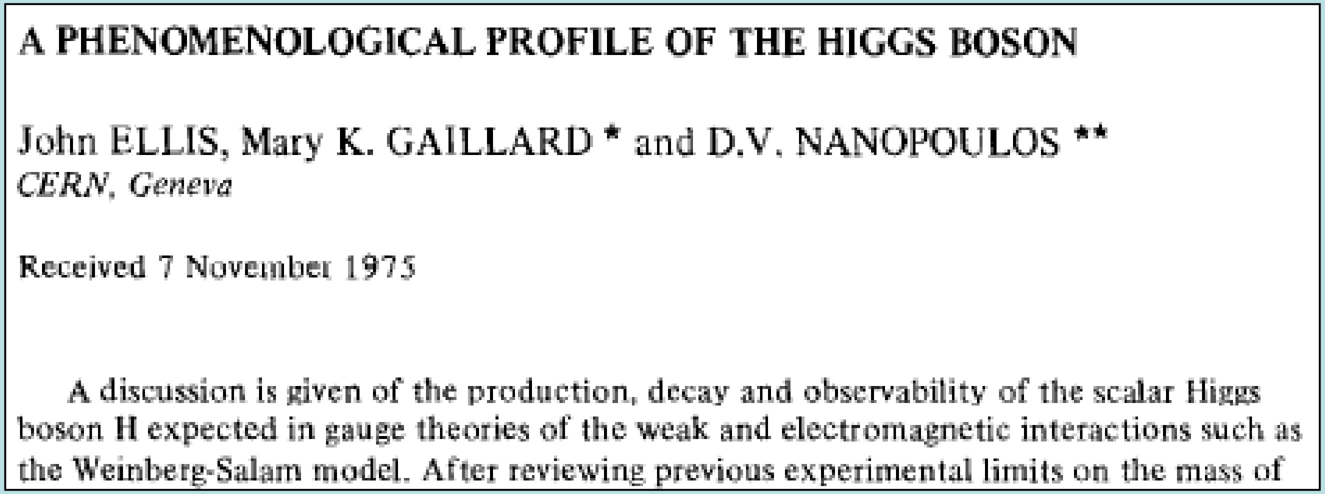
Yukawa inte

Higgs poten

Untested before 2012

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

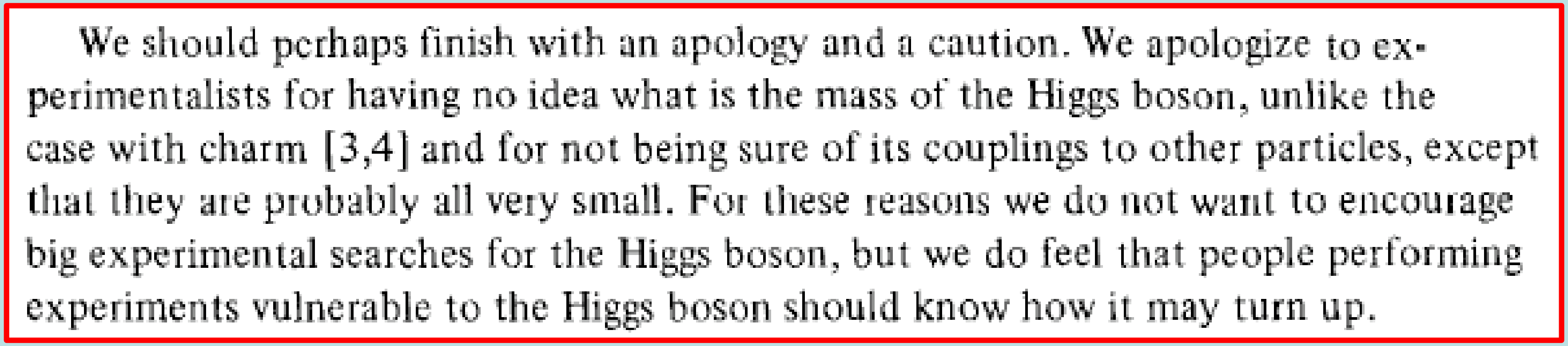


A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Before 2012

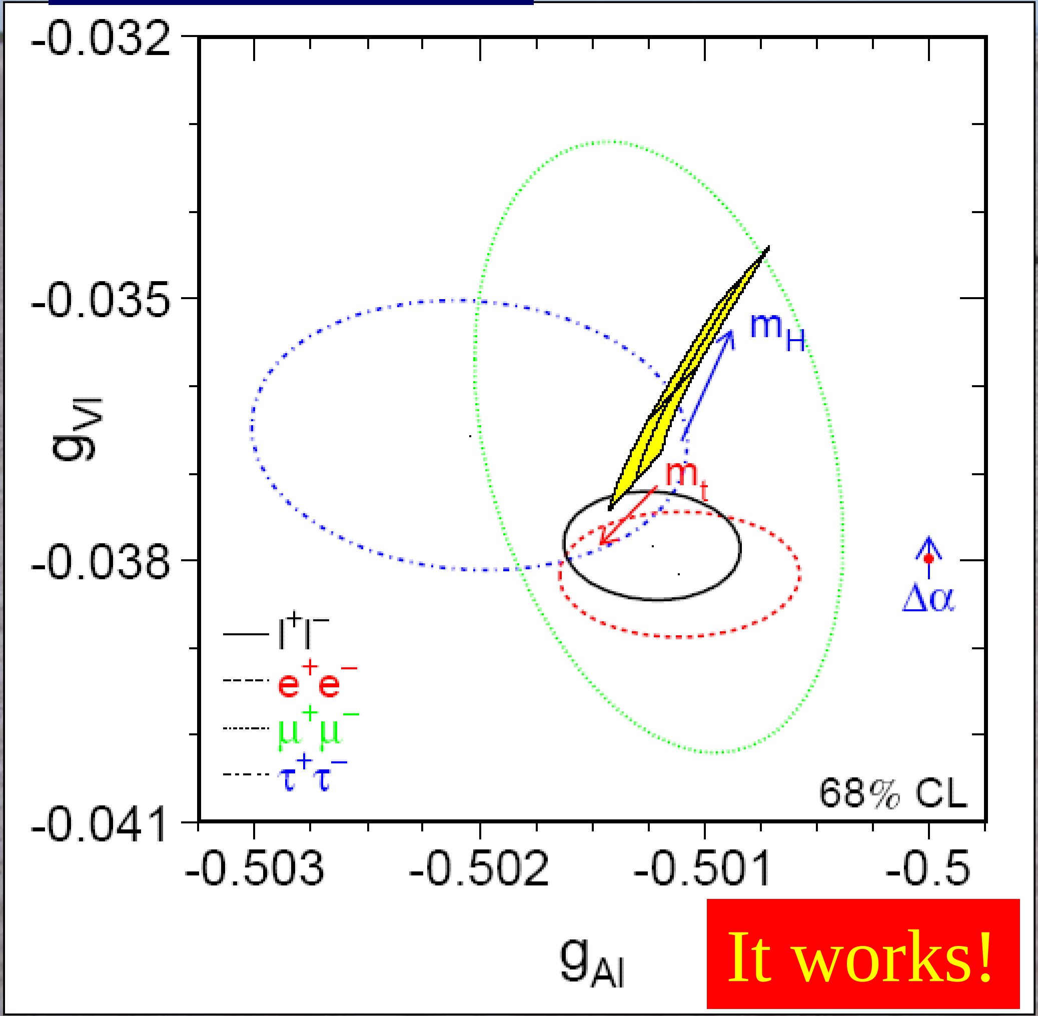
Status of the Standard Model

- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing < ~ 180 GeV
- Leaves many unanswered questions:

mass? flavour? unification?

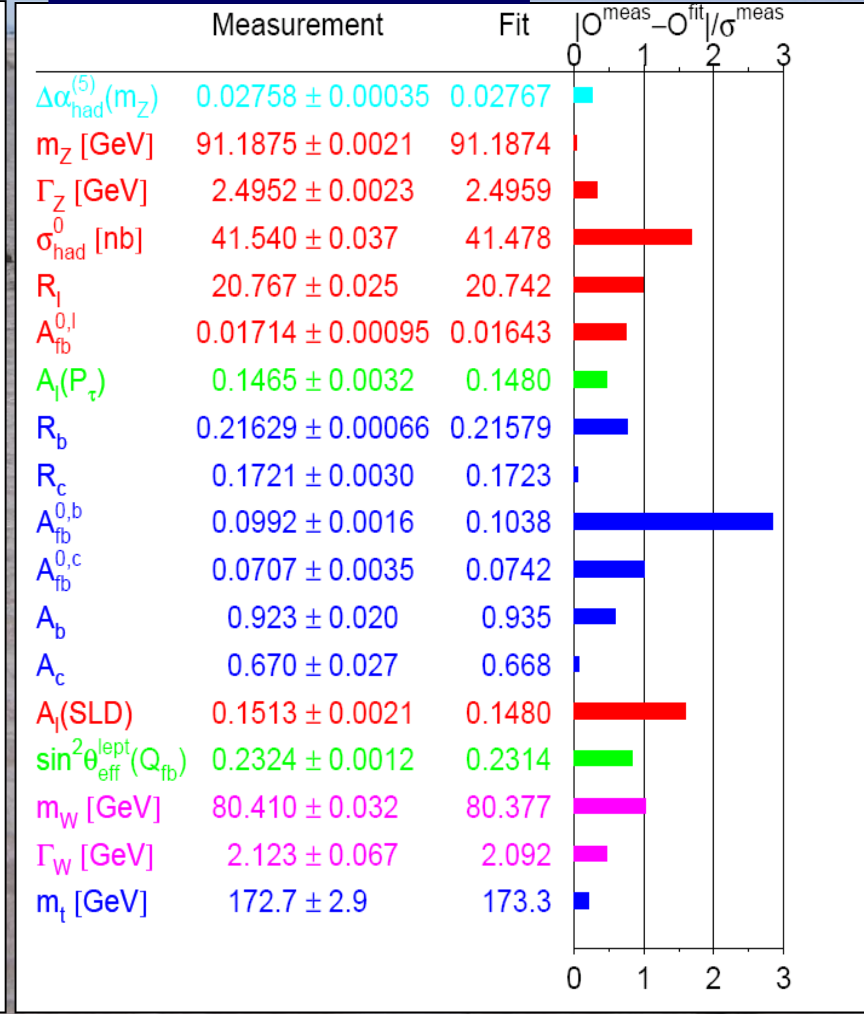
Precision Tests of the Standard Model

Lepton couplings



It works!

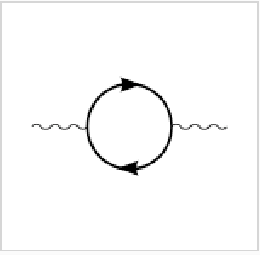
Pulls in global fit



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3

2011

Constraints on Higgs Mass



- Electroweak observables sensitive via quantum loop corrections:

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\mathrm{G}_F}(1+\Delta r)$$

- Sensitivity to top, Higgs masses:

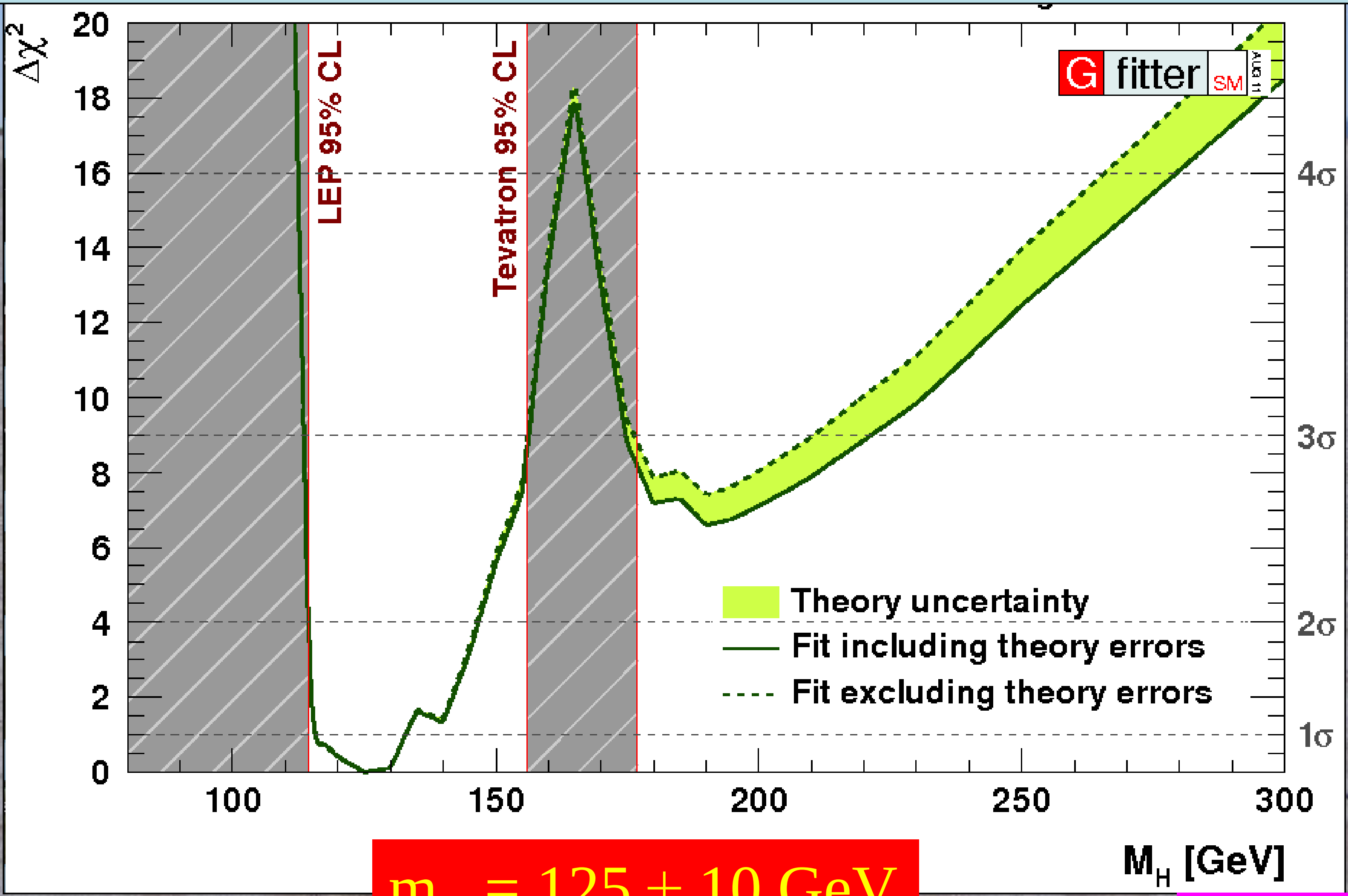
$$\frac{3\mathrm{G}_F}{8\pi^2\sqrt{2}} m_t^2 \qquad \frac{\sqrt{2}\mathrm{G}_F}{16\pi^2} m_W^2 \left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2} + \ldots\right),\ M_H >> m_W$$

- Preferred Higgs mass: **$m_H \sim 100 \pm 30$ GeV**
- Compare with lower limit from direct search at LEP:

$m_H > 114$ GeV

and exclusion around **(160, 170 GeV)** at TeVatron

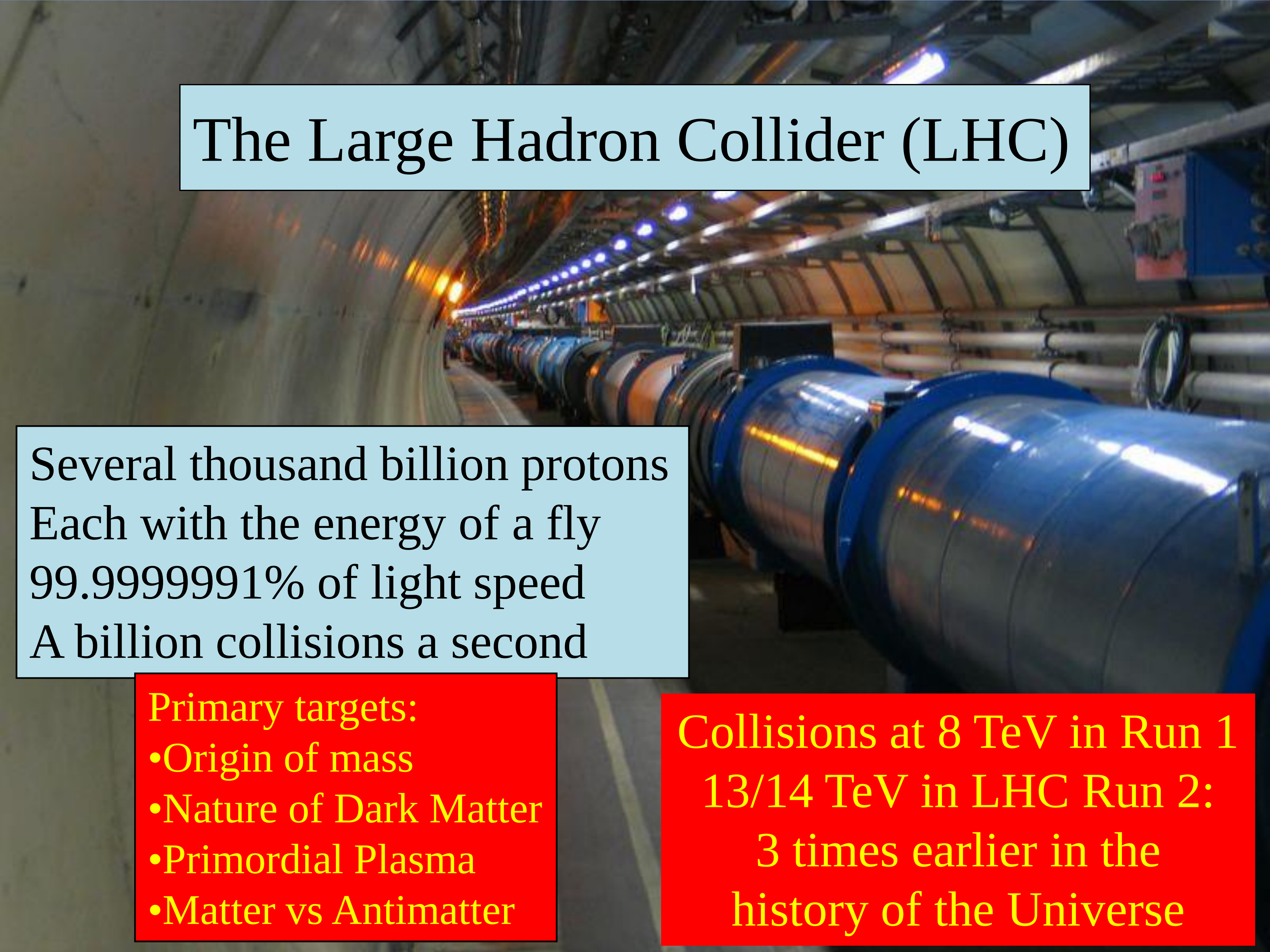
2011: Combining Information from Previous Direct Searches and Indirect Data



$m_H = 125 \pm 10$ GeV

Gfitter collaboration

The Large Hadron Collider (LHC)

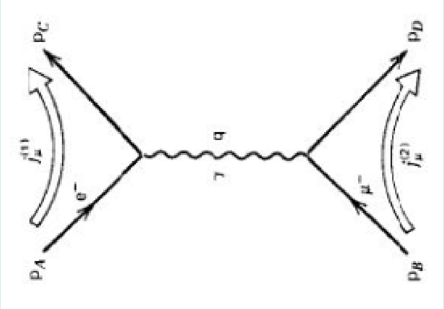


Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
A billion collisions a second

Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

Collisions at 8 TeV in Run 1
13/14 TeV in LHC Run 2:
3 times earlier in the
history of the Universe

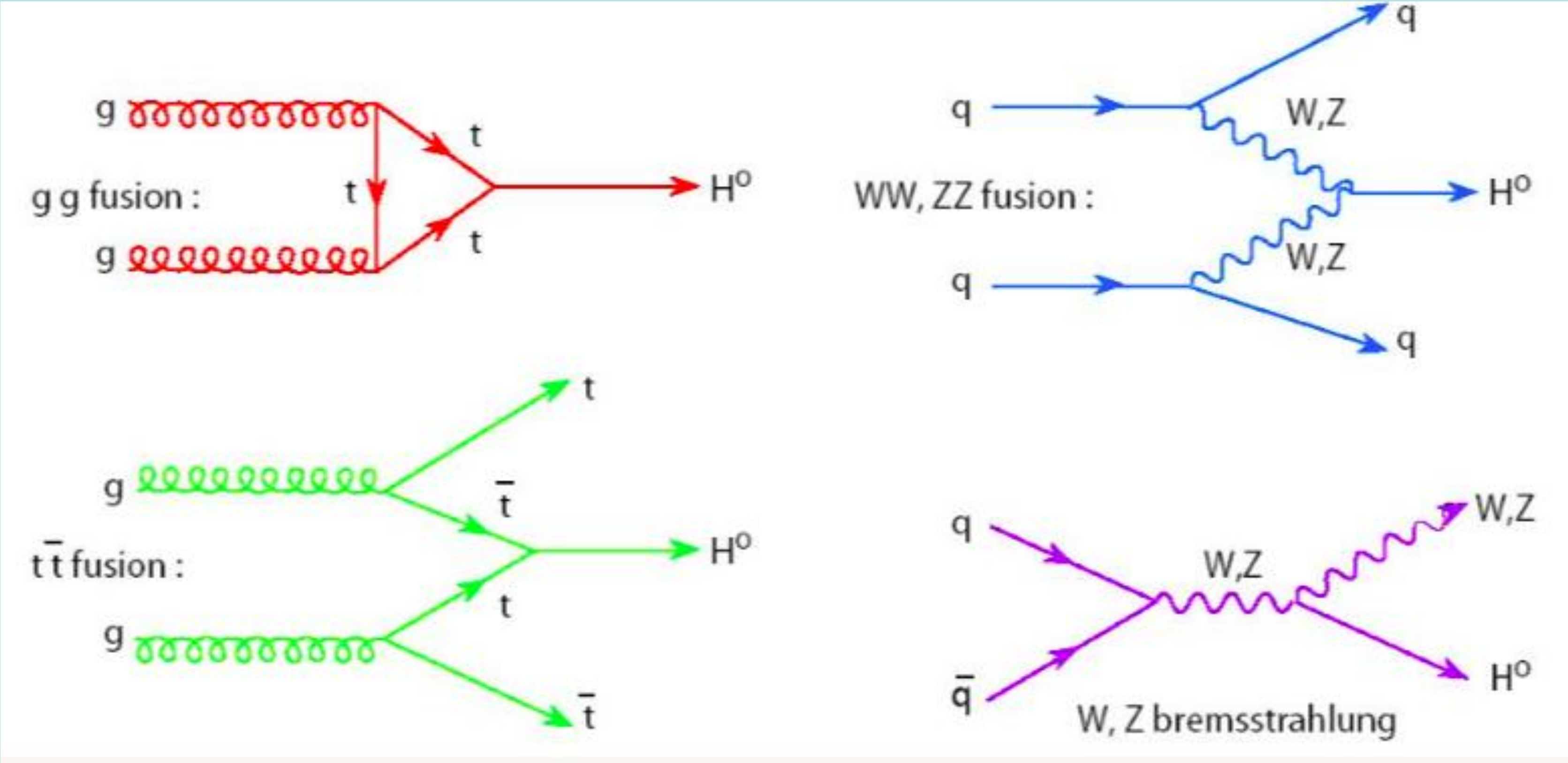
Simple Cross-Section

- Electron-positron annihilation to muons
- Cross-section: $\Big|$  $\Big|^2$

- Factors of electric charge: $\sigma \propto e^4 \sim \alpha^2$
- Dimensional analysis: cross-section ~ $[L]^2$
- Centre-of-mass energy √s: $\sigma \sim \frac{\alpha^2}{s}$
- With numerical factors: $\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}$

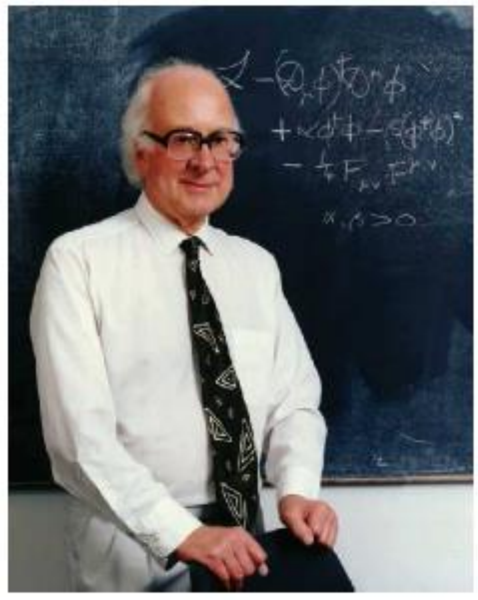
Higgs Production at Large Hadron Collider

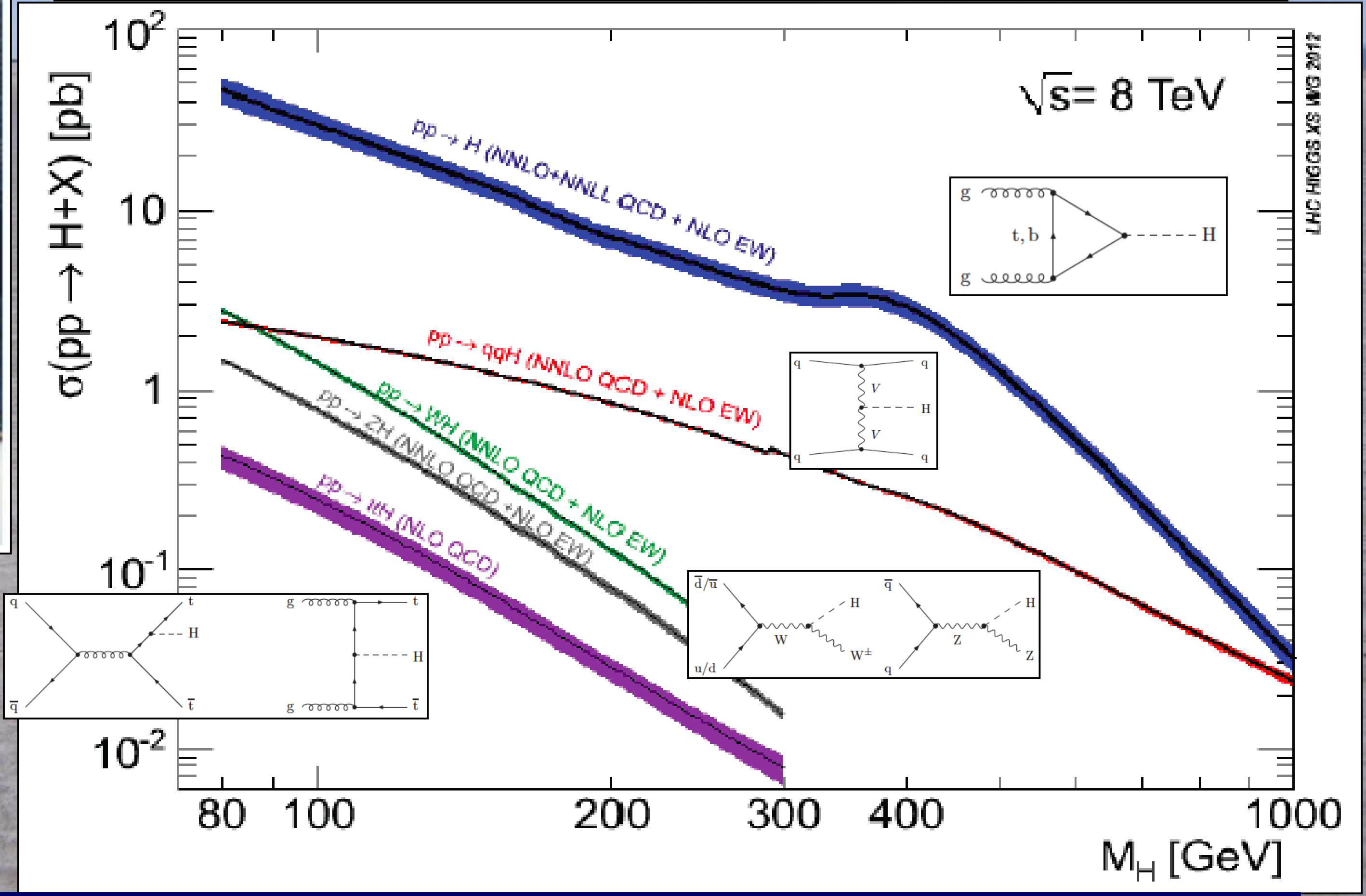
- Produced by collisions of constituents of protons: quark, antiquarks, gluons:



A la recherche du
Higgs perdu …

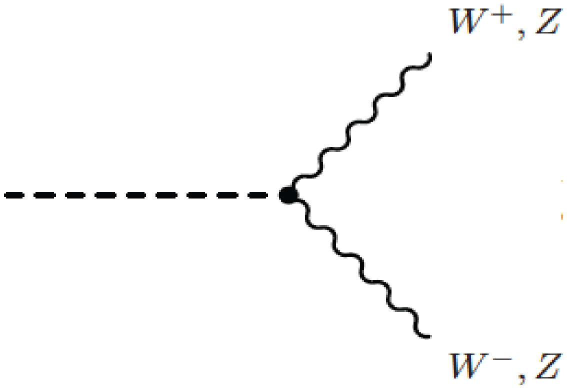
Higgs Production at the LHC



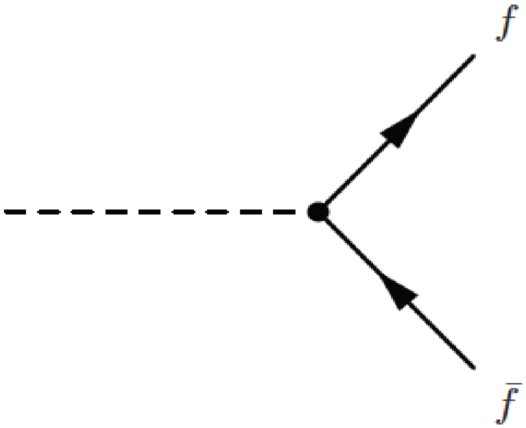


Many production modes measurable if M_h ~ 125 GeV

Summary: Higgs Boson Couplings



$$g_2 M_W \;, \quad g_2 \frac{M_Z}{c_W}$$



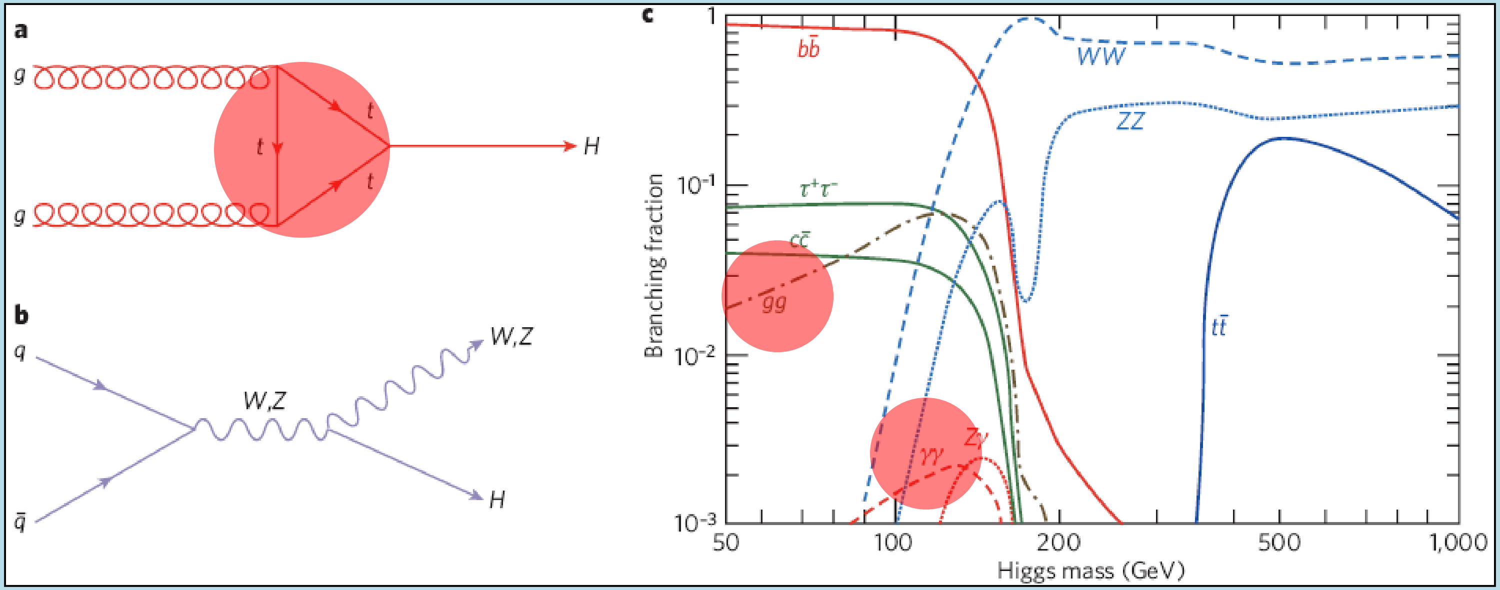
$$\frac{m_f}{v} \;=\; \frac{g_2\, m_f}{2M_W}$$

$$\Gamma(H \to f\bar{f}) \;=\; N_c \frac{G_F M_H}{4\pi\sqrt{2}}\, m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

$$\Gamma(H \to VV) \;=\; \frac{G_F M_H^3}{8\pi\sqrt{2}}\, F(r) \left(\frac{1}{2}\right)_Z, \quad r = \frac{M_V}{M_H}$$

Higgs Decay Branching Ratios

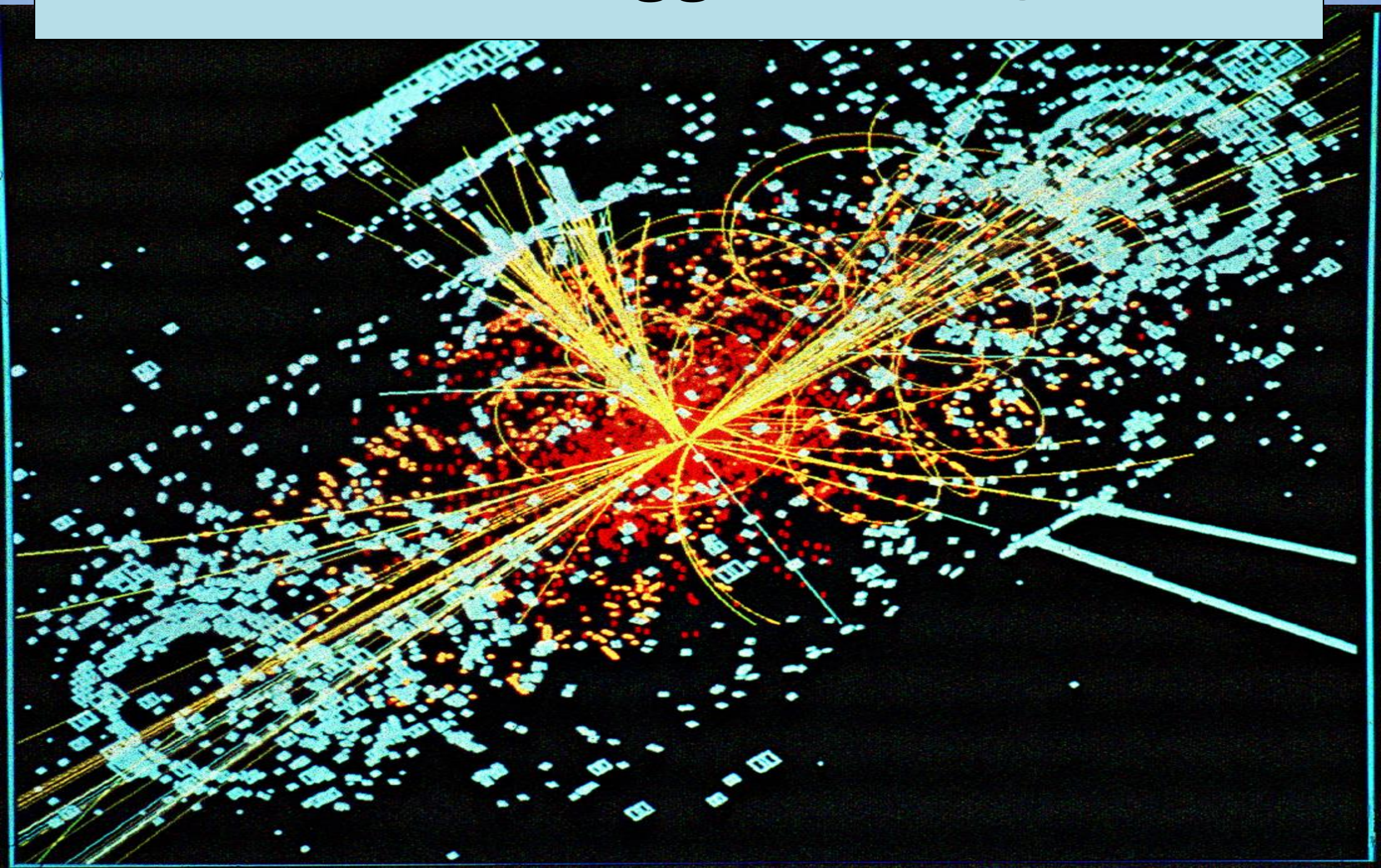
- Couplings proportional to masses (?)

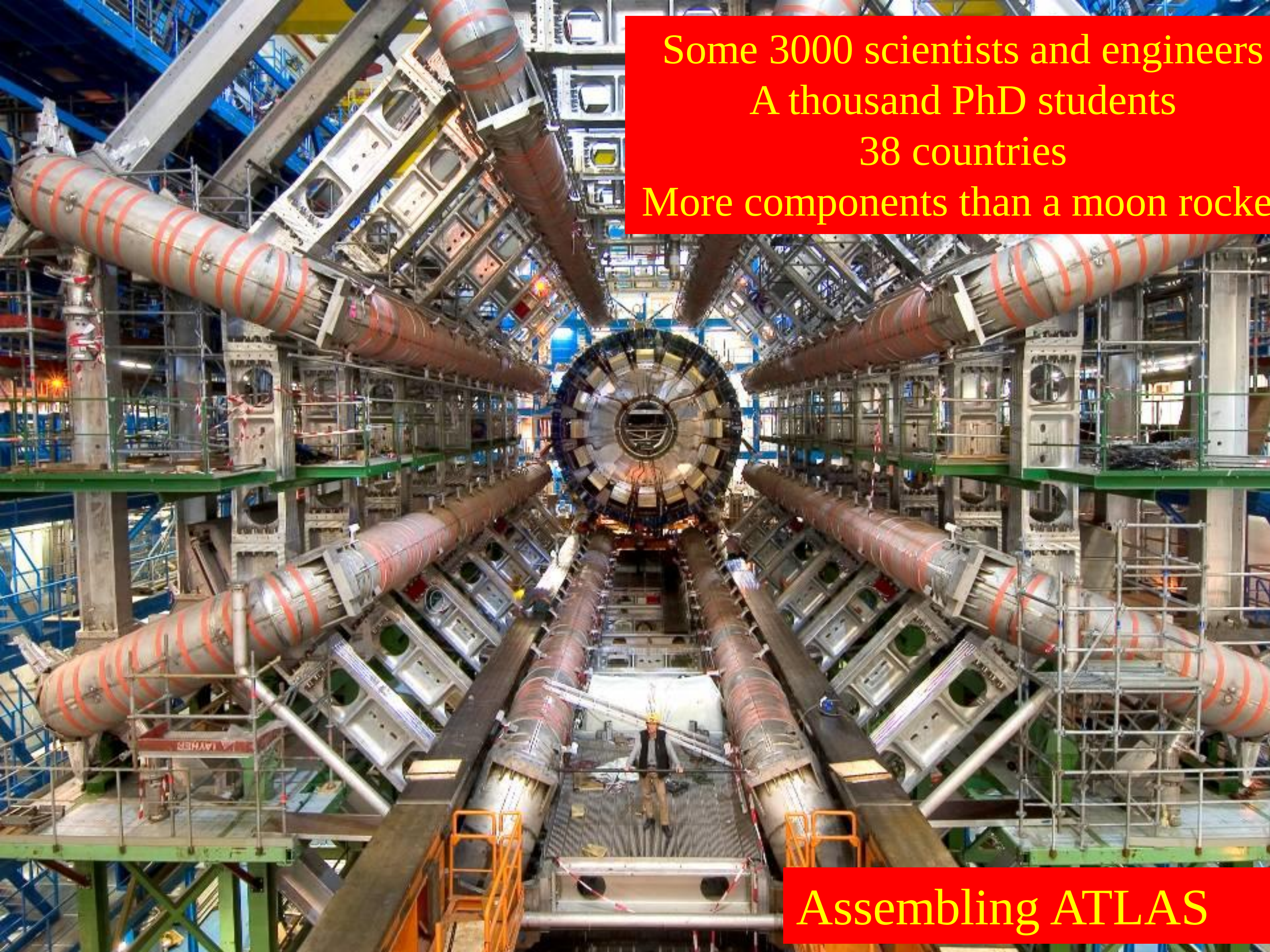


- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if M_h ~ 125 GeV

A Simulated Higgs Event @ LHC





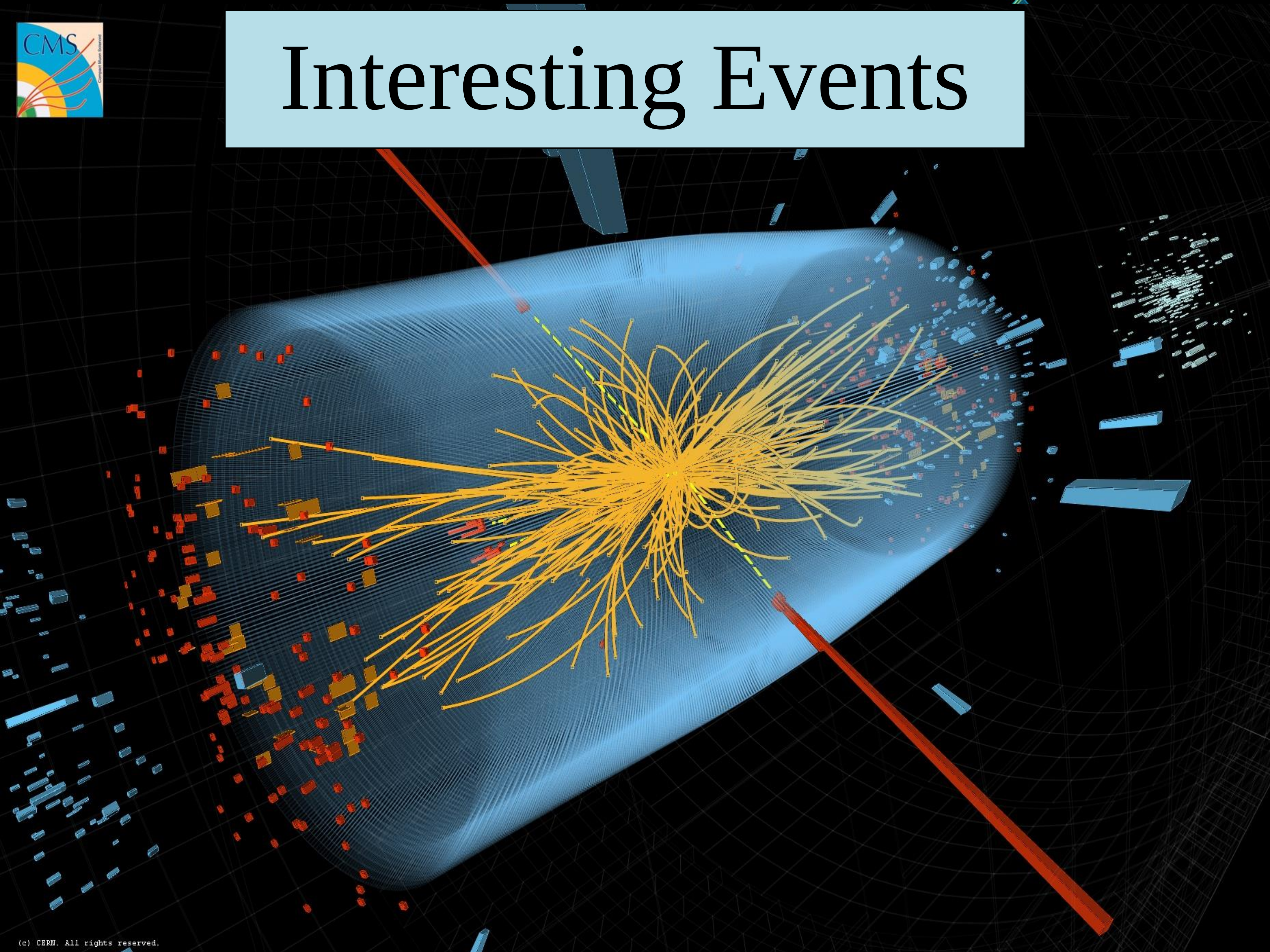
Some 3000 scientists and engineers
A thousand PhD students
38 countries
More components than a moon rocke

Assembling ATLAS

How the Higgs Boson was finally revealed?

Mass Higgsteria

Interesting Events



July 4th 2012
The discovery of a new particle

International Herald Tribune

Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

Oil Backed Up, Iranians Put It On Idled Ships

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

The Economist

A giant leap for science

Finding the Higgs boson

ヒッグス粒子 発見か

新素粒子検出 年内に結論

日米欧2チーム

Milhares de moradores de bairros sociais em risco de perderem RSI

CIÊNCIA "PARTÍCULA DE DEUS" EXISTE. MAS A HISTÓRIA NÃO ACABA AQUI

Le Monde

Science : la matière dévoilée

The Gazette

'God particle' discovery has scientists giddy. Page A2

EL PAIS

Hallada la partícula clave para la comprensión del universo

В ТЕАТРЫ БУДУТ ПУСКАТЬ ПО МОБИЛЬНЫМ ТЕЛЕФОНАМ

ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ

«КРЕМЛЕВСКИЕ» САМОЛЕТЫ ПРИШЛОСЬ МЕНЯТЬ НА ПЕРЕПРАВЕ

МЕТРО СПУСТЯТ НА ВОДУ

ALGEMEEN DAGBLAD

EINDELIJK GELIJK NA 48 JAAR

Frankfurter Allgemeine

ZEITUNG FÜR DEUTSCHLAND

Masse macht's

CHINA DAILY

IMPORTANT MATTER Scientists claim to have discovered 'God particle'

THE TIMES OF INDIA

Big bang moment: Scientists may have found 'God particle'

THE HINDU

Elusive particle found, looks like Higgs boson

CERN physicists hail evidence of game-changing discovery of subatomic particle

CORRIERE DELLA SERA

La particella che può svelare i segreti dell'universo

gazeta WYBORCZA.PL

Cząstkę Higgsa fizycy najpierw wymyślili, potem szukali 40 lat

BOSKA MASA

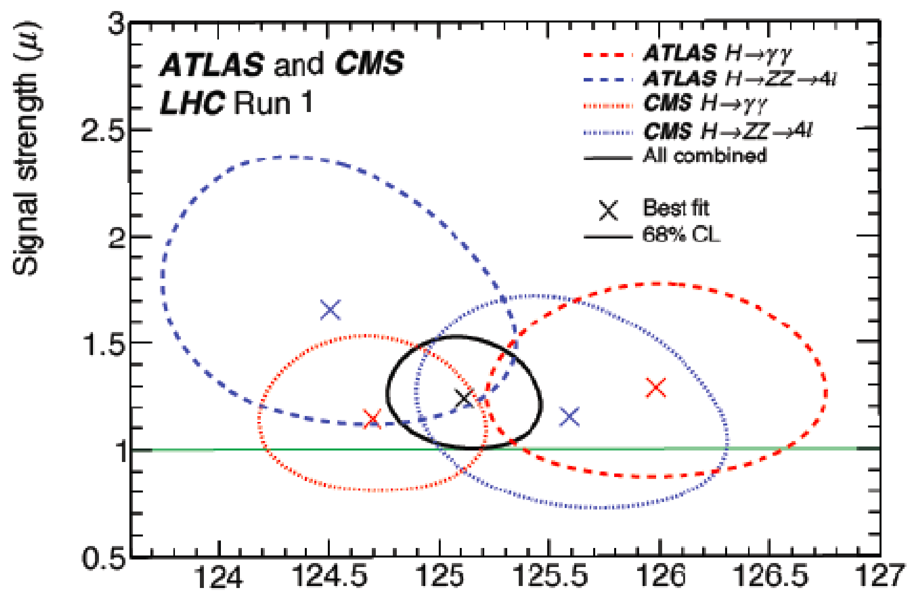
আনন্দবাজার পত্রিকা

বিজ্ঞানের 'ঈশ্বর' দর্শন

'পেয়েছি, যা খুঁজছিলাম'

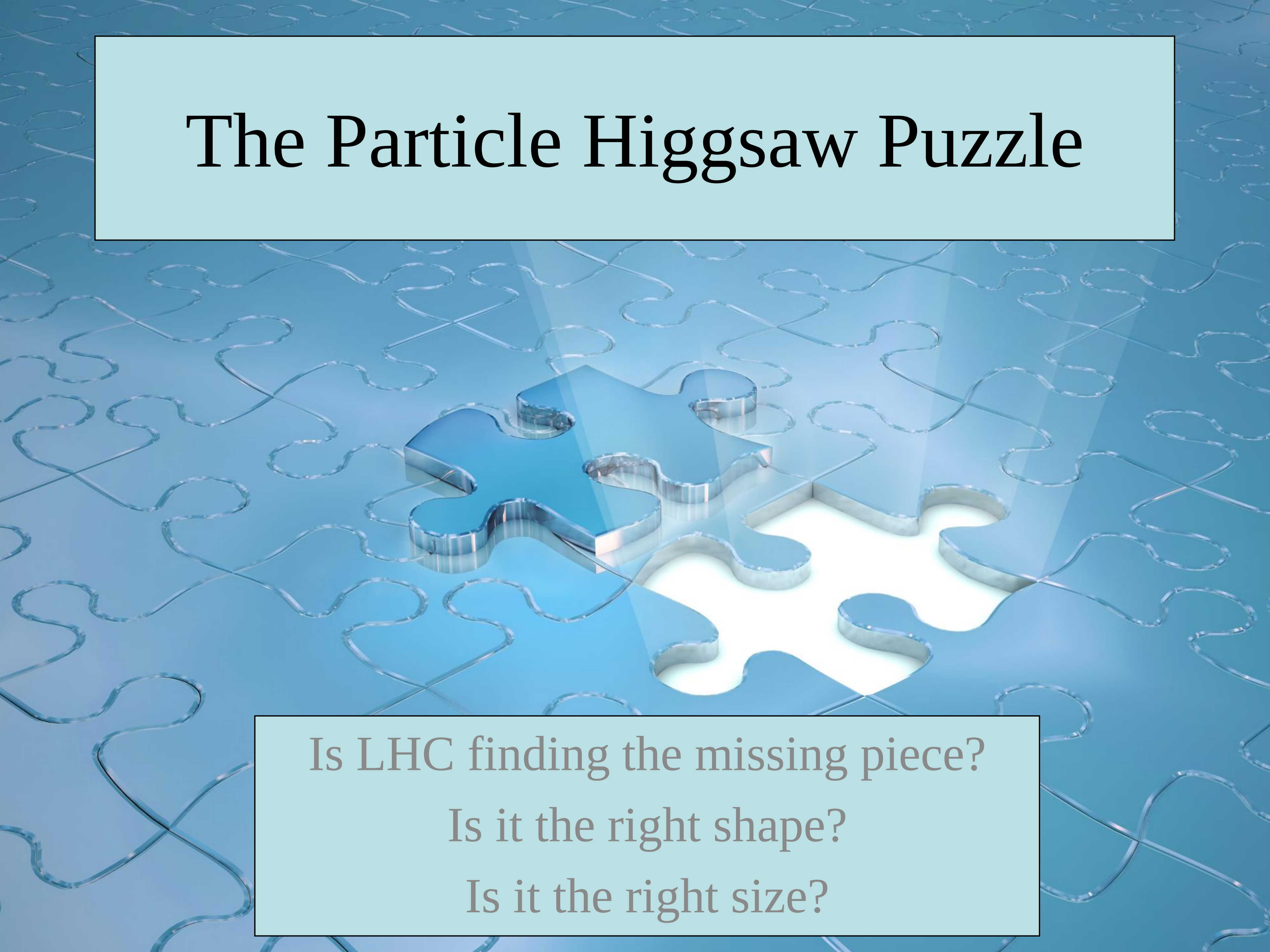
Higgs Mass Measurements

- ATLAS + CMS ZZ* and γγ final states



- Statisti $125.09 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{syst})$
- Allows precision tests
- **Crucial for stability of electroweak vacuum**

The Particle Higgsaw Puzzle



Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

What is it ?

- Does it have spin 0 or 2?

- Is it scalar or pseudoscalar?

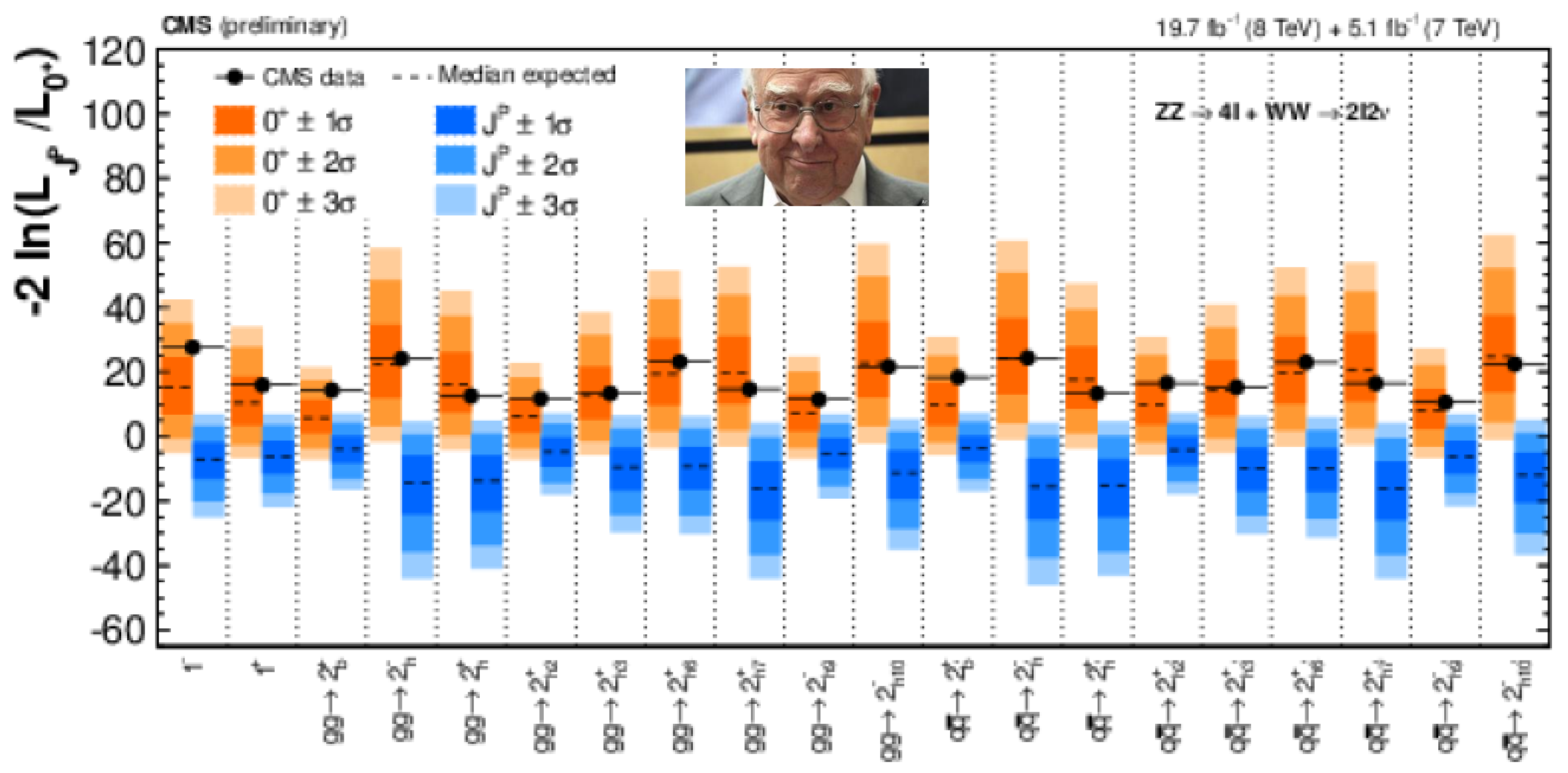
- Is it elementary or composite?

- Does it couple to particle masses?

- Quantum (loop) corrections?

- What are its self-couplings?

The ‘Higgs’ has Spin 0



- Alternative spin-parity hypotheses disfavoured

What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?

- Does it couple to particle masses?

- Quantum (loop) corrections?

- What are its self-couplings?

What is it ?

- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?

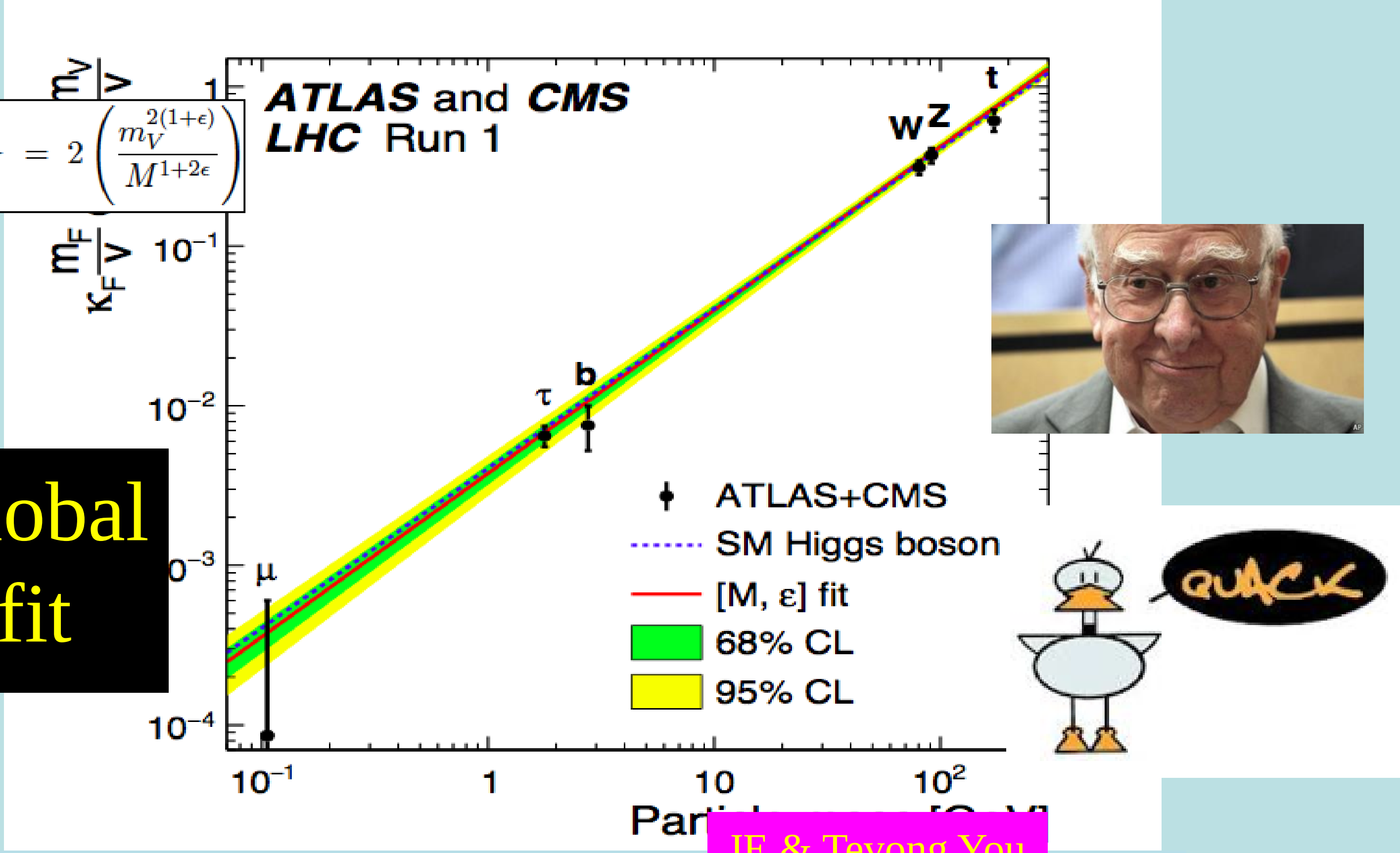
- Quantum (loop) corrections?

- What are its self-couplings?

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$



Global fit

JE & Tevong You

- **Blue** dashed line = Standard Model

What is it ?

- Does it have spin 0 or 2?
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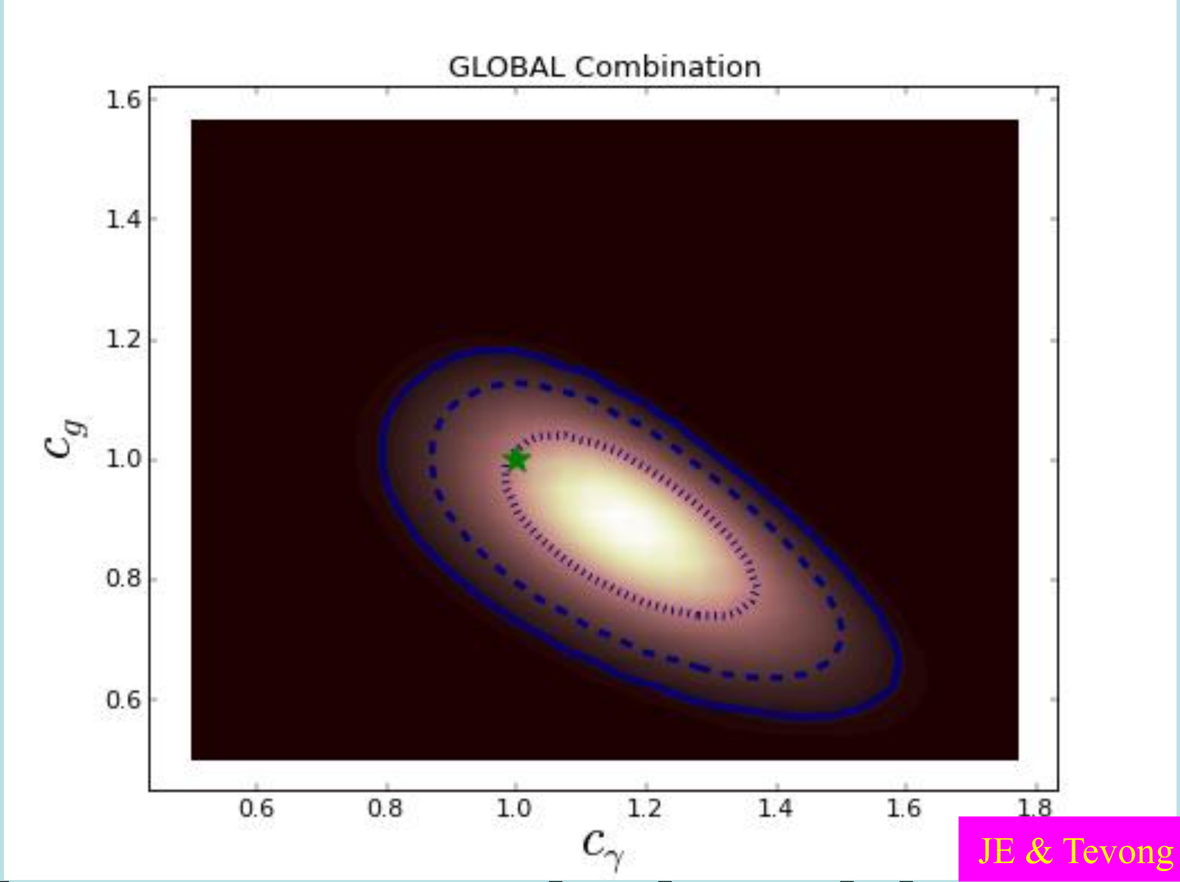
  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**
- Quantum (loop) corrections?

- What are its self-couplings?

Loop Corrections ?

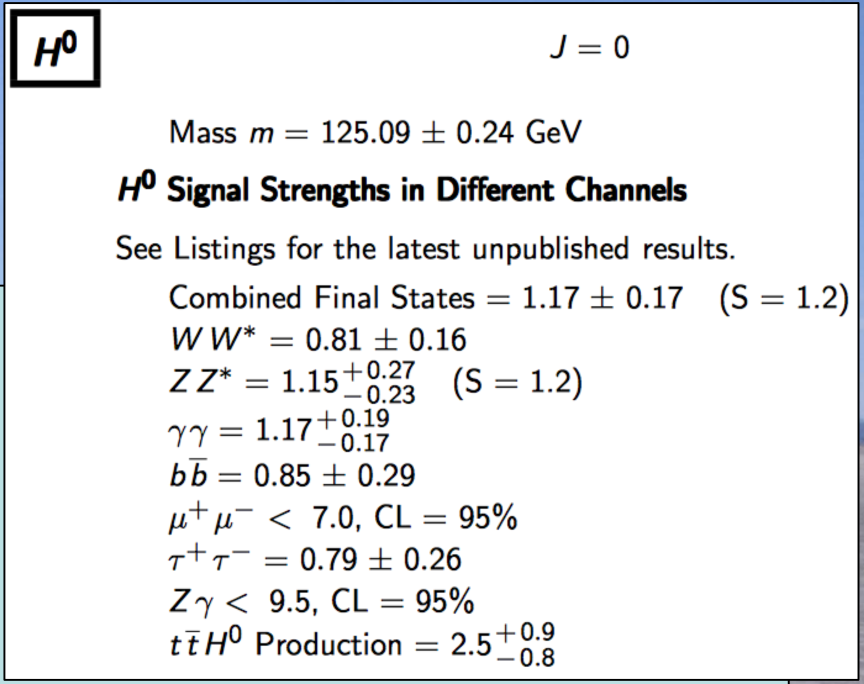
- Combination of data on γγ, gluon-gluon couplings



JE & Tevong You, arXiv:1303.3879

- Loop diagrams ~ Standard Model?

What is it ?



H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV

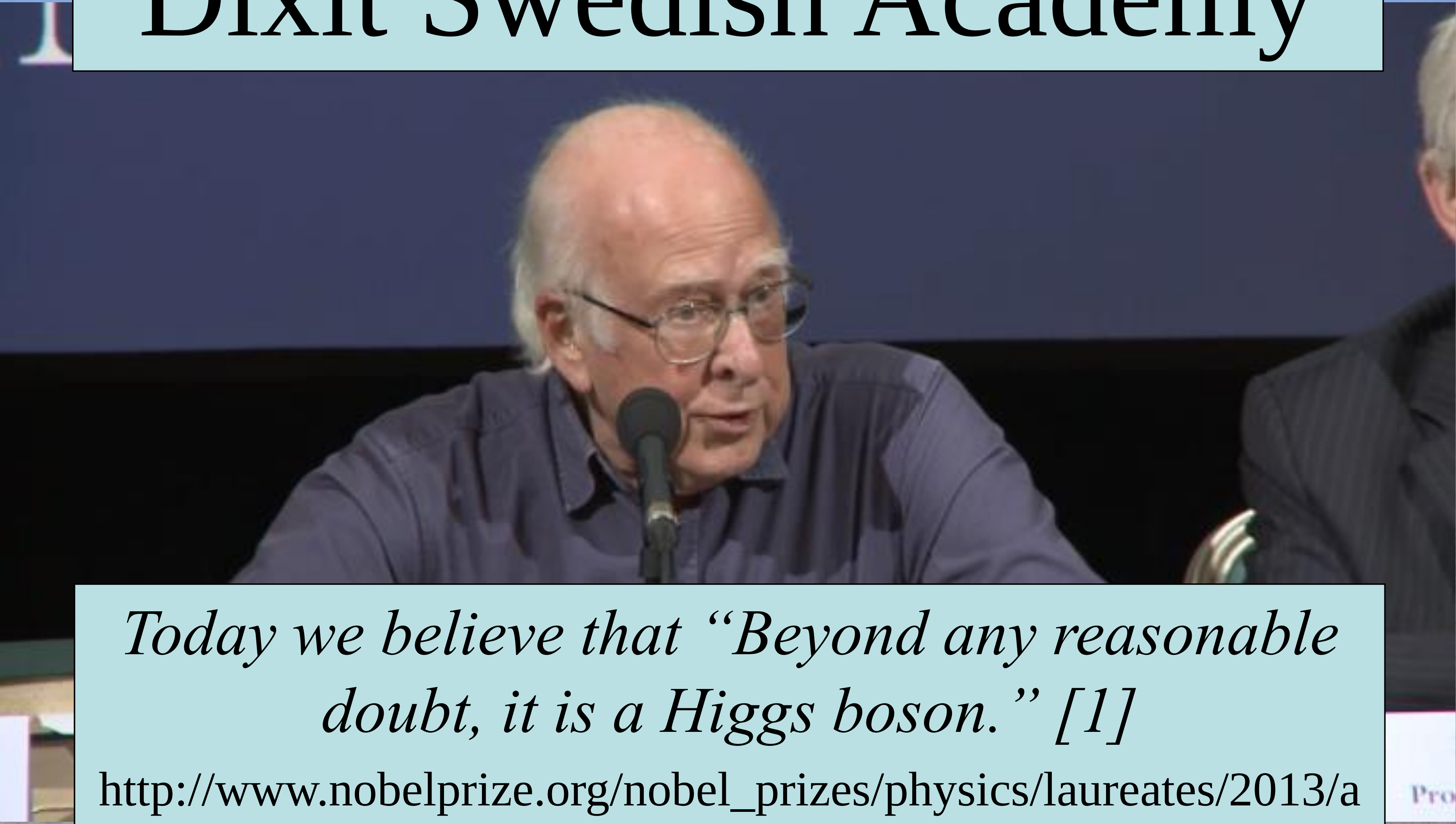
H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$WW^* = 0.81 \pm 0.16$
$ZZ^* = 1.15^{+0.27}_{-0.23}$ (S = 1.2)
$\gamma\gamma = 1.17^{+0.19}_{-0.17}$
$b\bar{b} = 0.85 \pm 0.29$
$\mu^+\mu^- < 7.0$, CL = 95%
$\tau^+\tau^- = 0.79 \pm 0.26$
$Z\gamma < 9.5$, CL = 95%
$t\bar{t}H^0$ Production $= 2.5^{+0.9}_{-0.8}$

- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**
- Quantum (loop) corrections?
  - **γγ, gg couplings ~ Standard Model**
- What are its self-couplings?

Dixit Swedish Academy



Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879

Without Higgs …

… there would be no atoms

- Electrons would escape at the speed of light

… weak interactions would not be weak

- Life would be impossible: there would be no nuclei, everything would be radioactive

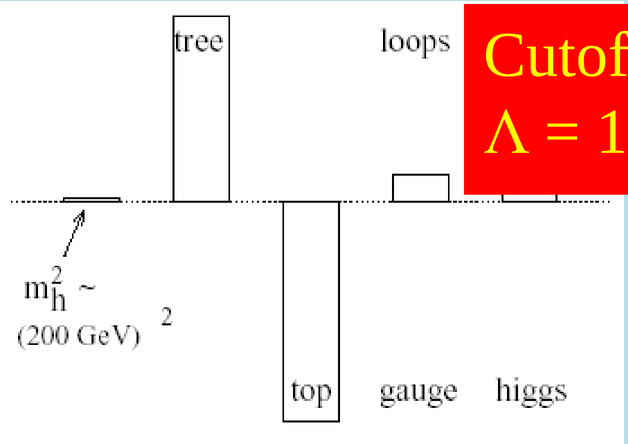
How does the Higgs trick work?

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff

Λ = 10 TeV

Cut-off Λ ~ 1 TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed $m_t > 200$ GeV

New technicolour force?

- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

Phenomenological Framework

- Assume custodial symmetry:

$$SU(2) \times SU(2) \rightarrow SU(2)_V \qquad (\rho \equiv M_W/M_Z \cos\theta_w \sim 1)$$

- Parameterize gauge bosons by 2 × 2 matrix Σ:

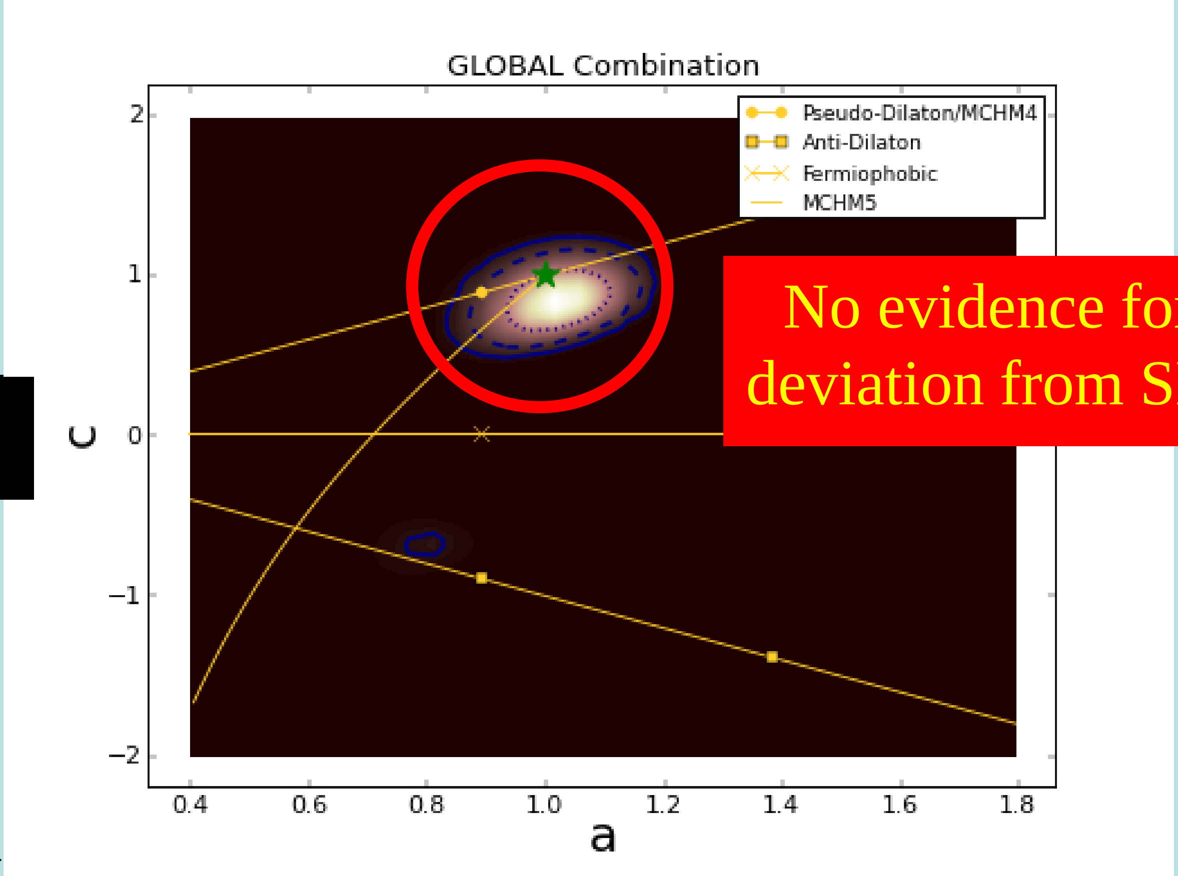
$$\begin{aligned}\mathcal{L} = {} & \frac{v^2}{4}\mathrm{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+\ldots\right) - m_i\bar{\psi}^i_L\Sigma\left(1+c\frac{h}{v}+\ldots\right)\psi^i_R + \text{h.c.}\\ & + \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \quad ,\end{aligned}$$

$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right) \quad \mathcal{L}_\Delta \;=\; -\left[\frac{\alpha_s}{8\pi}b_sG_{a\mu\nu}G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

- Coefficients *a = c = 1* in Standard Model

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*



No evidence for deviation from SM

Global

- Stand

JE & Tevong You, arXiv:1303.3879

No BSM? Beware Historical Hubris

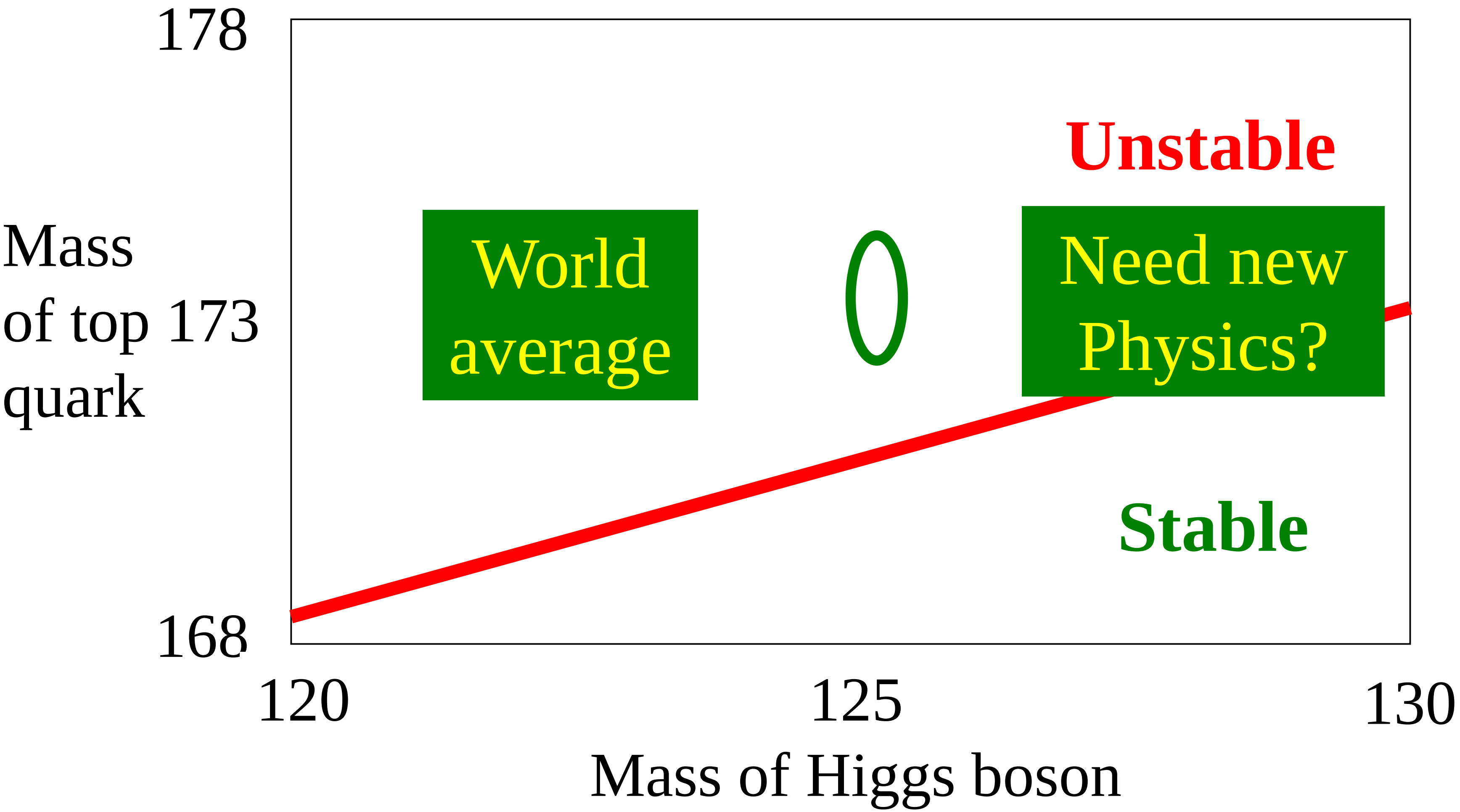
- ***"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"* - Spanish Royal Commission, rejecting Christopher Columbus proposal to sail west, < 1492**
- *"The more important fundamental laws and facts of physical science have all been discovered"* – Albert Michelson, 1894
- *"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"* - Lord Kelvin, 1900
- *"Is the End in Sight for Theoretical Physics?"* – Stephen Hawking, 1980

- « Empty » space is u LHC Run 2
- Dark matter LHC Run 2
- Origin of matter LHC Run 2
- Masses of neutrinos
- Hierarchy problem LHC Run 2
- Inflation LHC Run 2
- Quantum gravity SUSY
- …

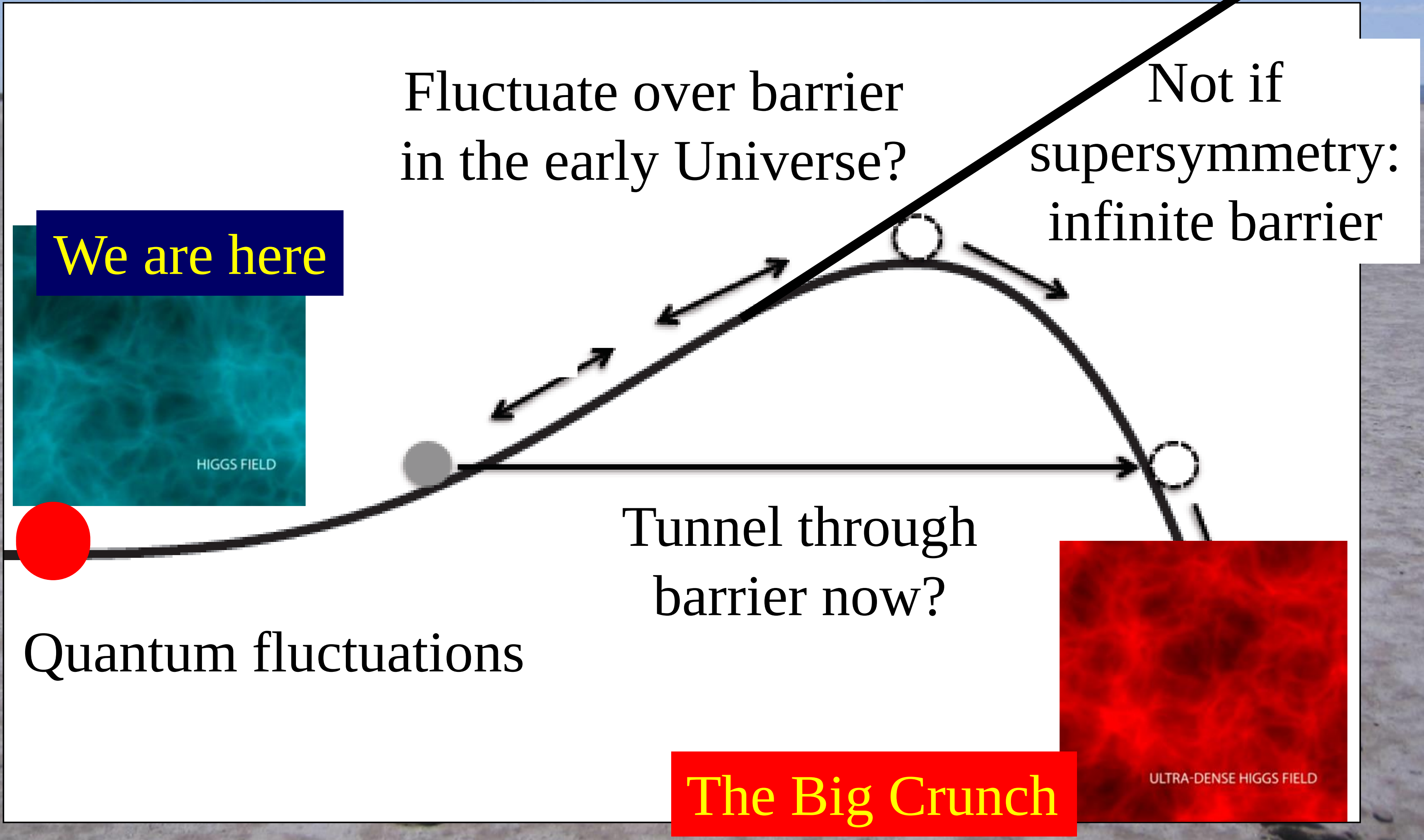
The Standard Model

Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark



Should it have Collapsed already?



We are here

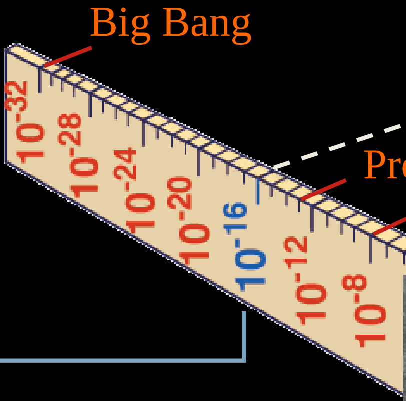
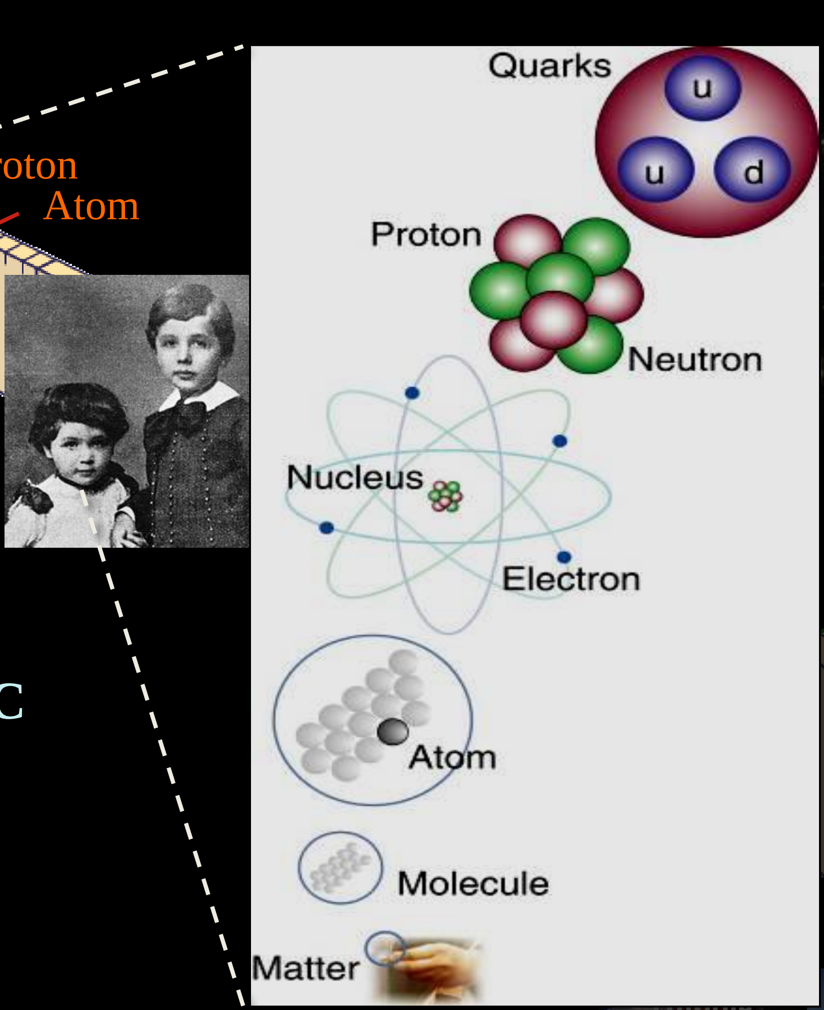
Fluctuate over barrier in the early Universe?

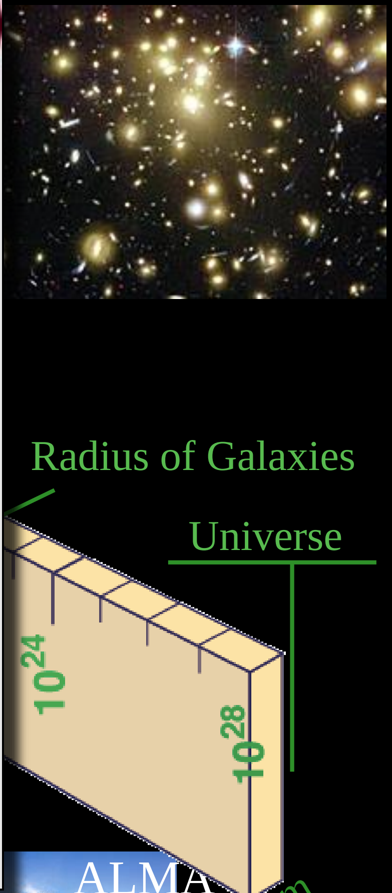
Not if supersymmetry: infinite barrier

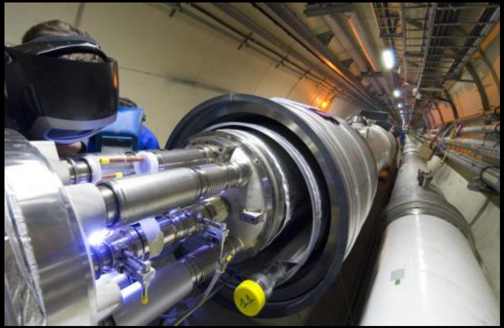
Quantum fluctuations

Tunnel through barrier now?

The Big Crunch





LHC

Super-Microscope

Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

The Young Universe

- Age: **t → zero**
- Size: **a → zero**
- Temperature: **T → high**

  $T \sim 1/a$, $t \sim 1/T^2$
- Energies: **$E \sim T$**
- Orders of magnitude:

  $t \sim$ 1 second

  $T \sim$ 10,000,000,000 degrees

  $E \sim$ 1 MeV ~ mass of electron

Need particle physics to describe the very early Universe

The Dark Matter Hypothesis

- Motivated by Fritz Zwicky’s observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a

  stronger gravitational field

  than provided by the visible matter
- **Dark matter?**

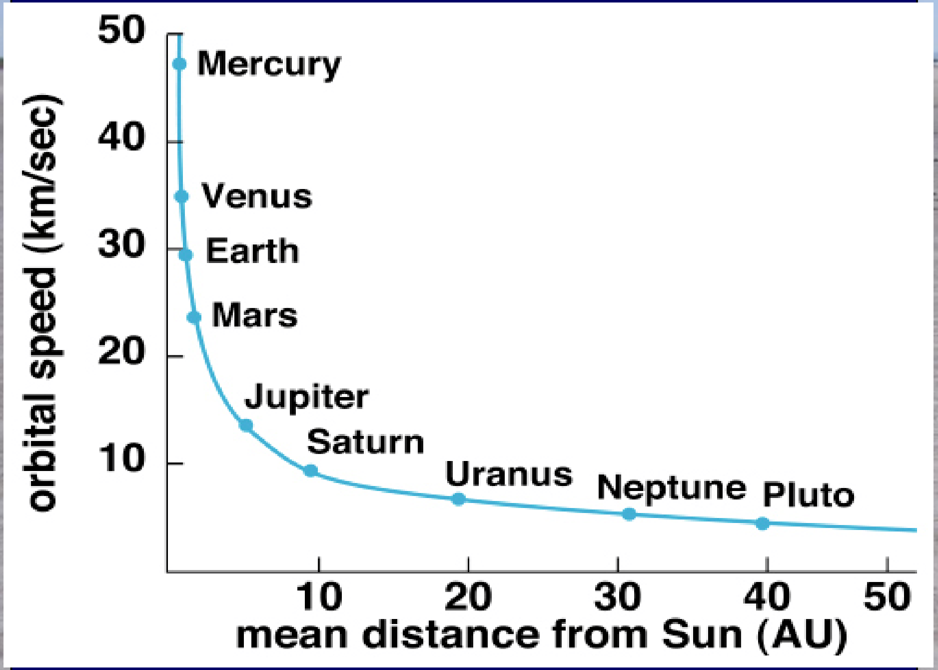
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations aslo required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**

Scanned at the American Institute of Physics

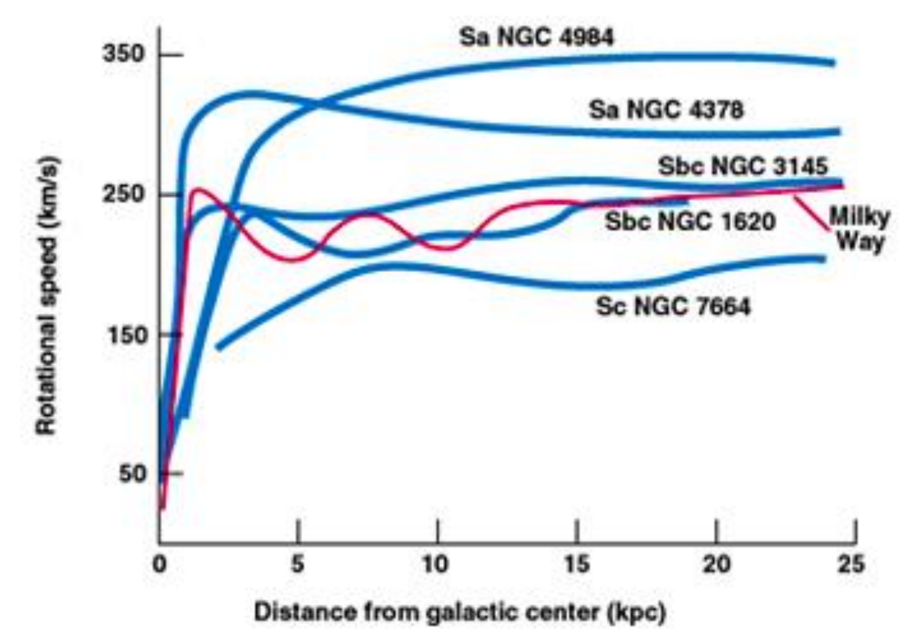
Rotation Curves

- In the Solar System



- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies



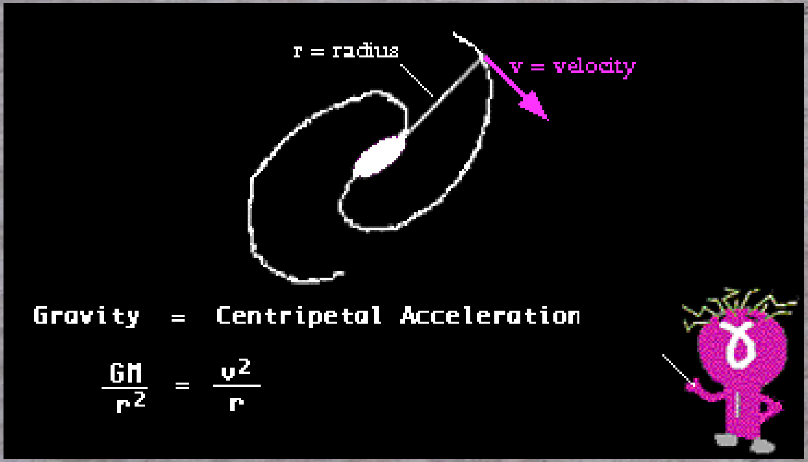
- The velocities do not decrease with distance
- Dark matter spread out

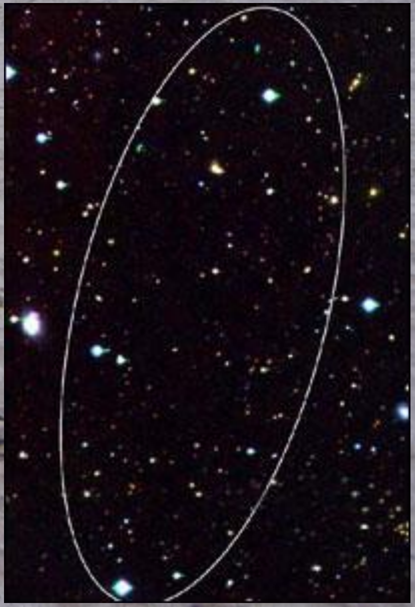
Evidence for Dark Matter

Galaxies rotate more rapidly than allowed by centripetal force due to visible matter

X-ray emitting gas held in place by extra dark matter

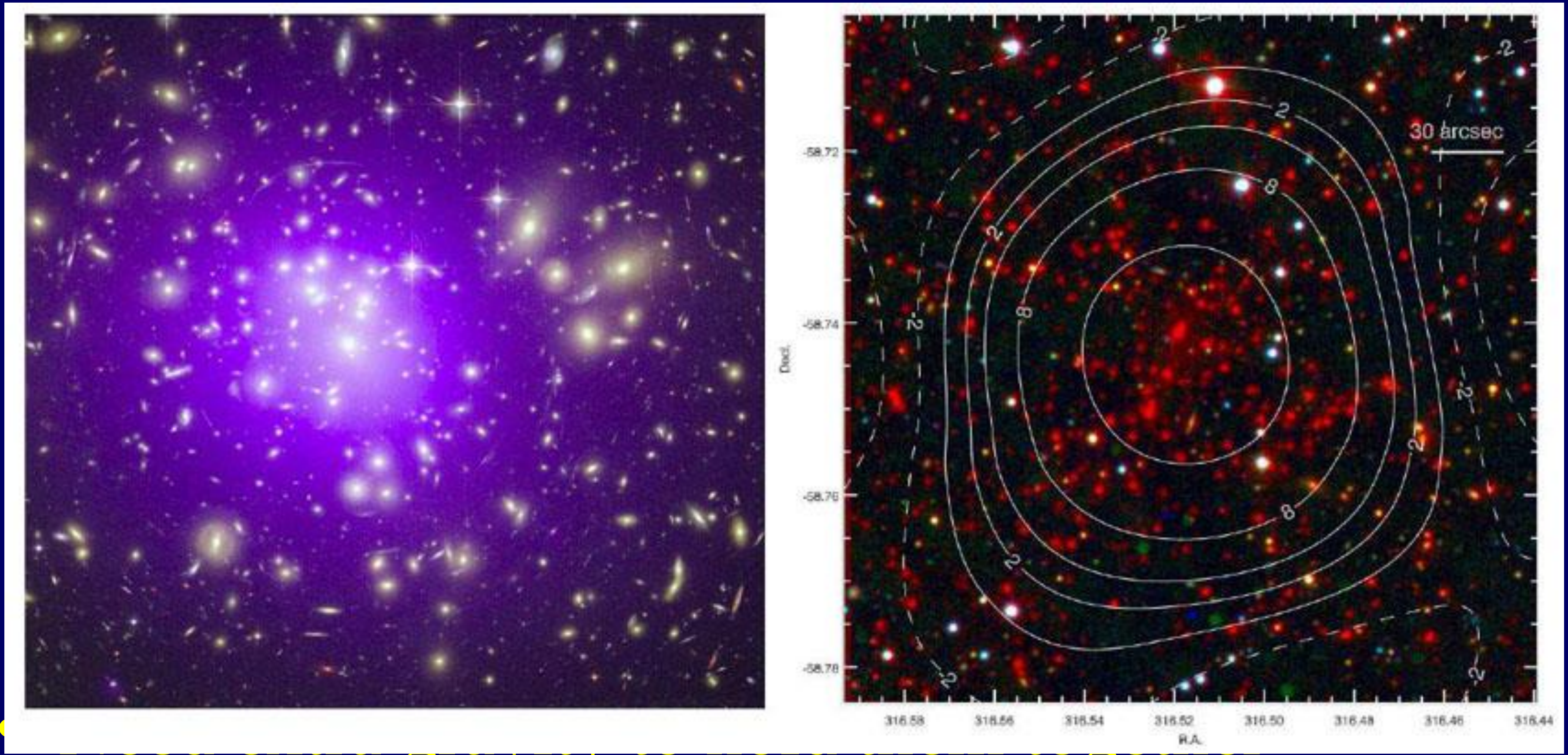
Even a 'dark galaxy' without stars





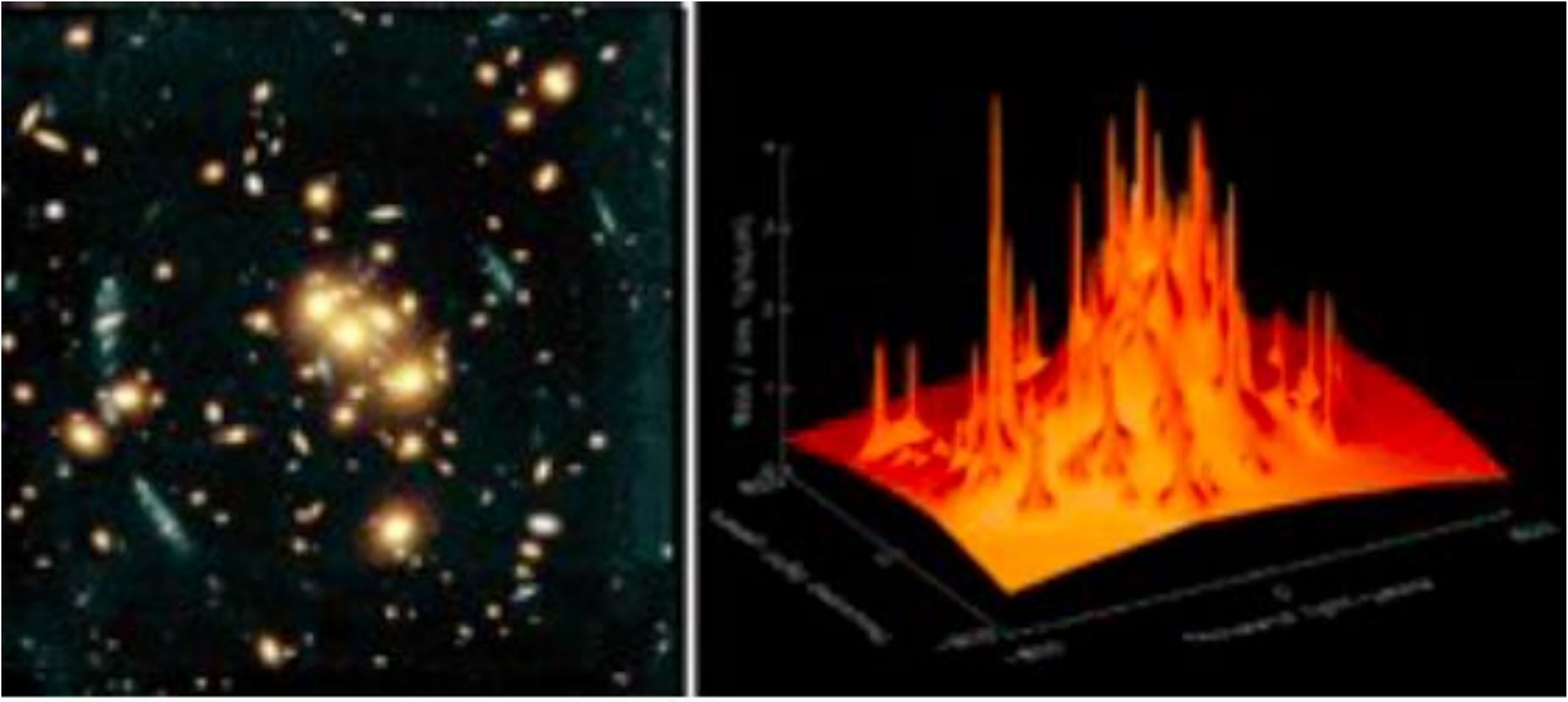
X-Rays from Galaxy Clusters

- High temperature and pressure



Gravitational Lensing

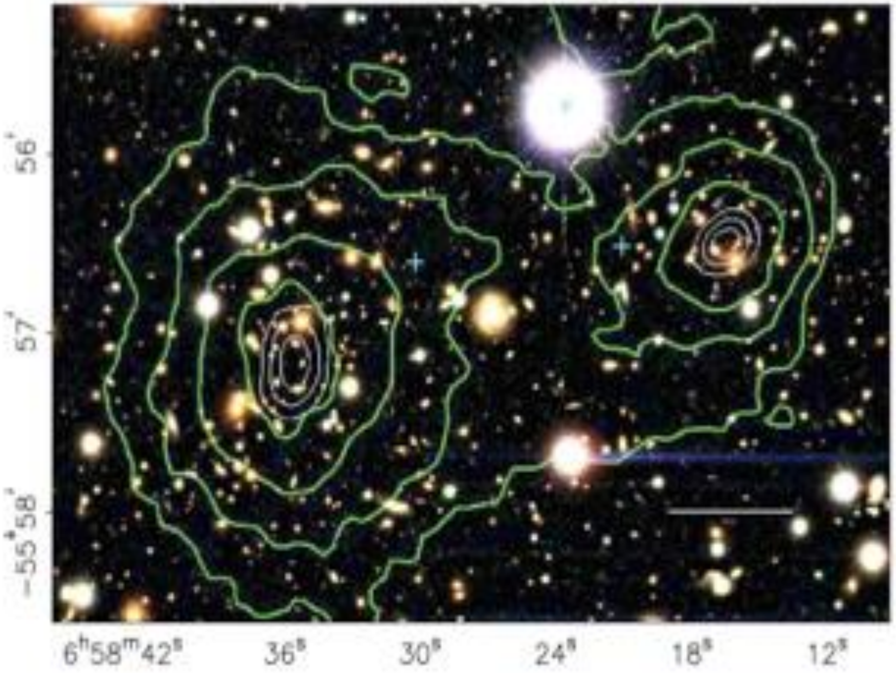
- Reveal all the matter



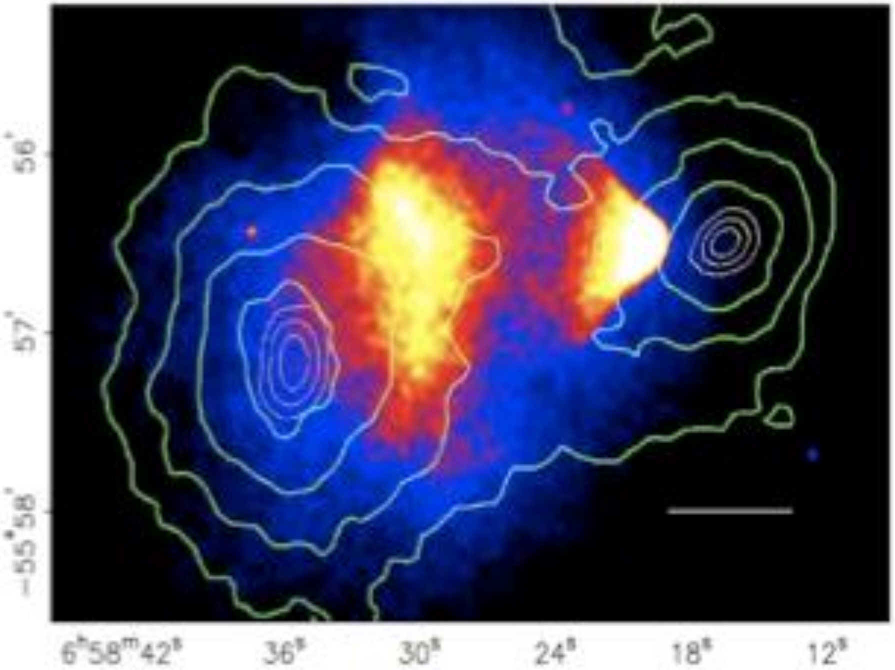
- Galaxies = peaks on a background of dark matter

More Evidence for Dark Matter

Collision between
2 clusters of galaxies:
Dark matter passes through



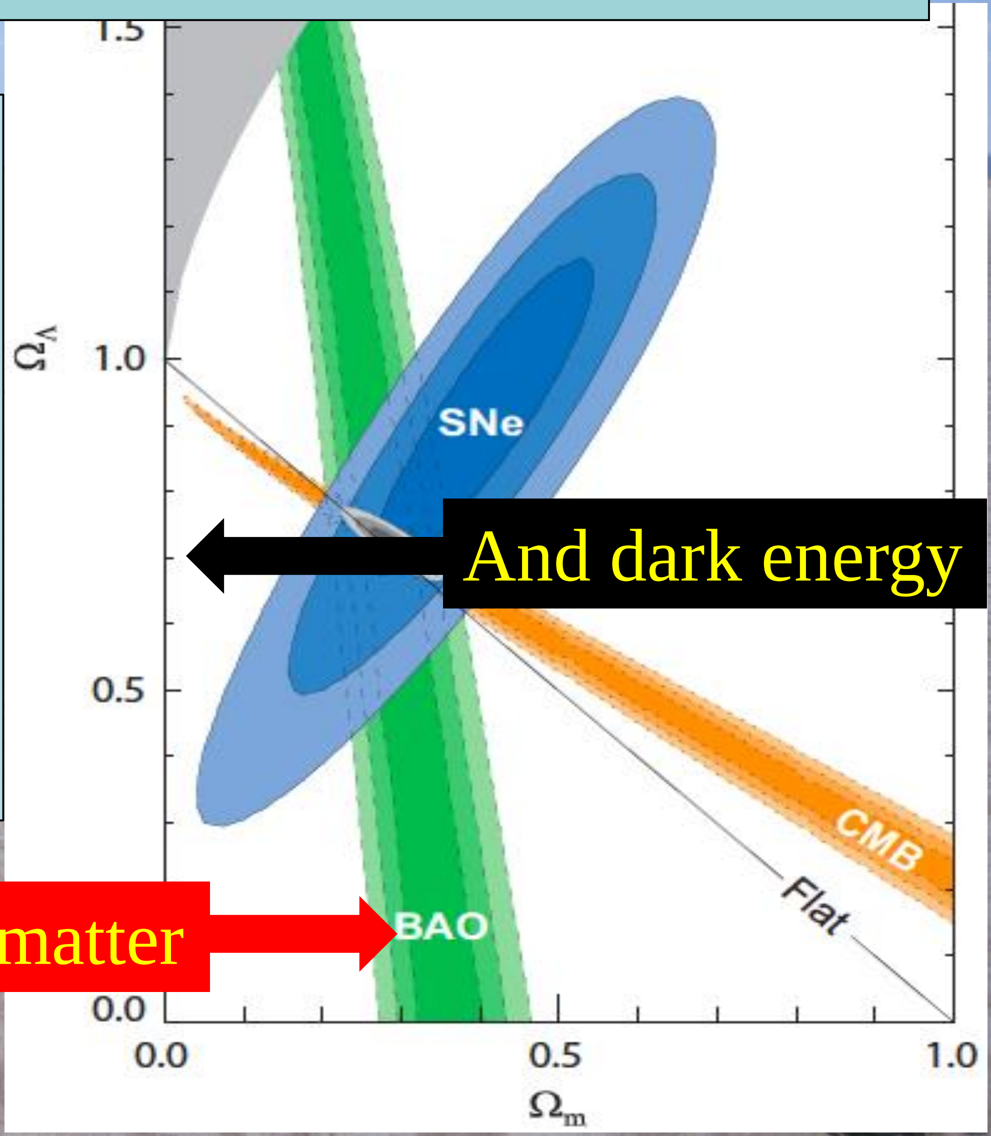
Collision between
2 clusters of galaxies:
Gas interacts, heats and stops



Clowe et al, 2006

The Content of the Universe

- According to
  - **Microwave background**
  - Supernovae
  - Structures (galaxies, clusters, …) in the Universe



And dark energy

There is dark matter

Dark Energy

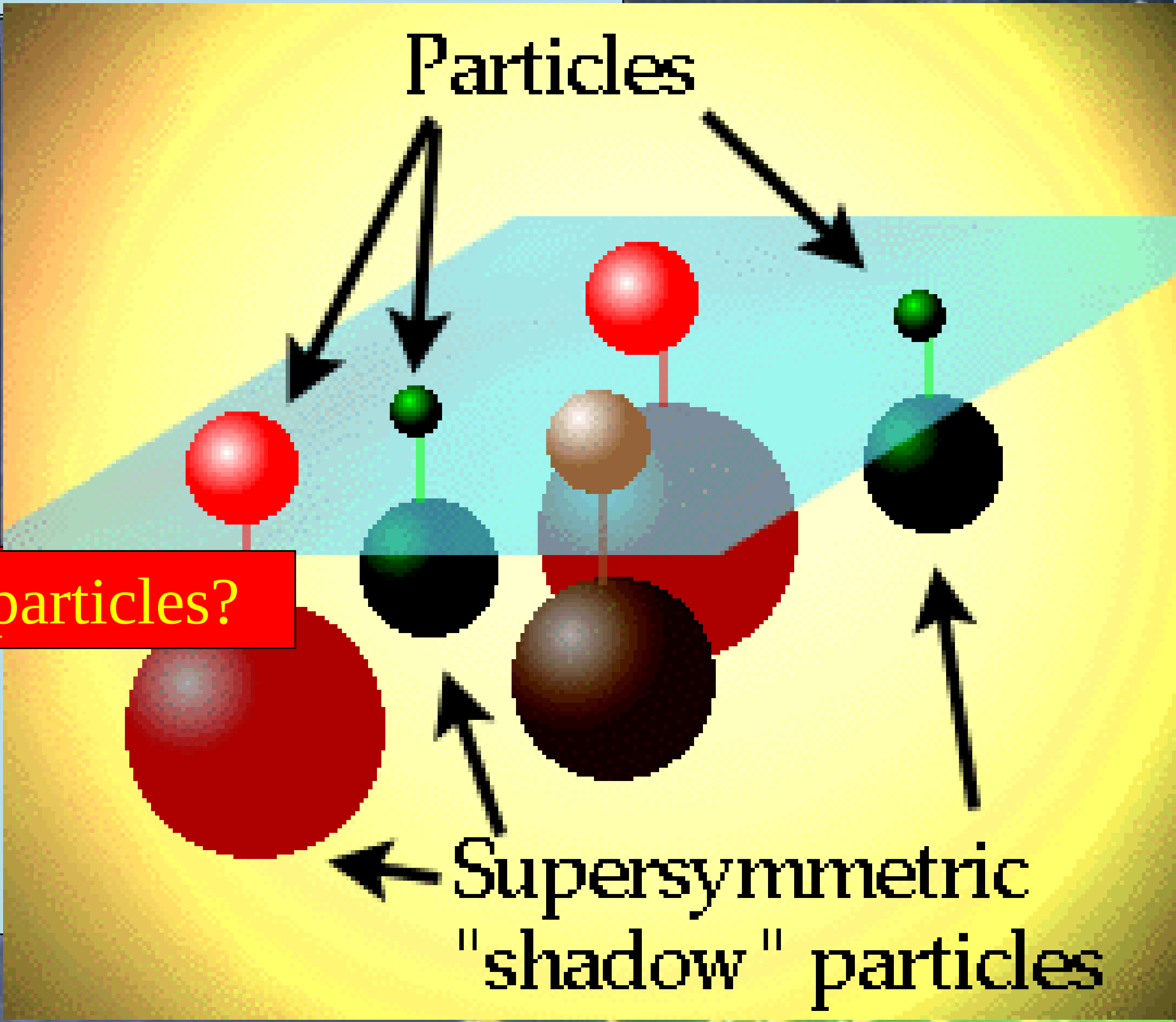
- Energy density spread throughout space
- Not clustered like matter in galaxies, etc.
- Apparently ~ constant for billions of years
- Expect in many theories of fundamental physics
- Mystery is why it is so small

Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible Dark Matter

Supersymmetric particles?

Searching for them at the LHC



What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- Stabilize electroweak vacuum
- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values
- Naturalness, GUTs, string, …, dark matter

Why Supersymmetry (Susy)?

- **Hierarchy problem: why is $m_W << m_P$?**

  ($m_P \sim 10^{19}$ GeV is scale of gravity)
- Alternatively, why is

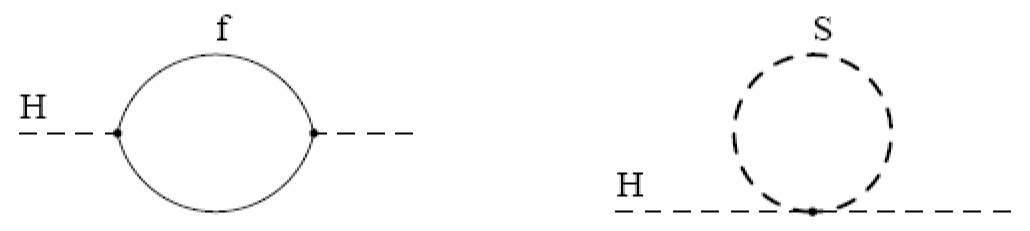
  $G_F = 1/ m_W^2 >> G_N = 1/m_P^2$?
- Or, why is

  $V_{Coulomb} >> V_{Newton}$? $e^2 >> G\, m^2 = m^2 / m_P^2$
- **Set by hand? What about loop corrections?**

  $\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$
- **Cancel boson loops ⇔ fermions**
- Need $| m_B^2 – m_F^2| < 1\ \text{TeV}^2$

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

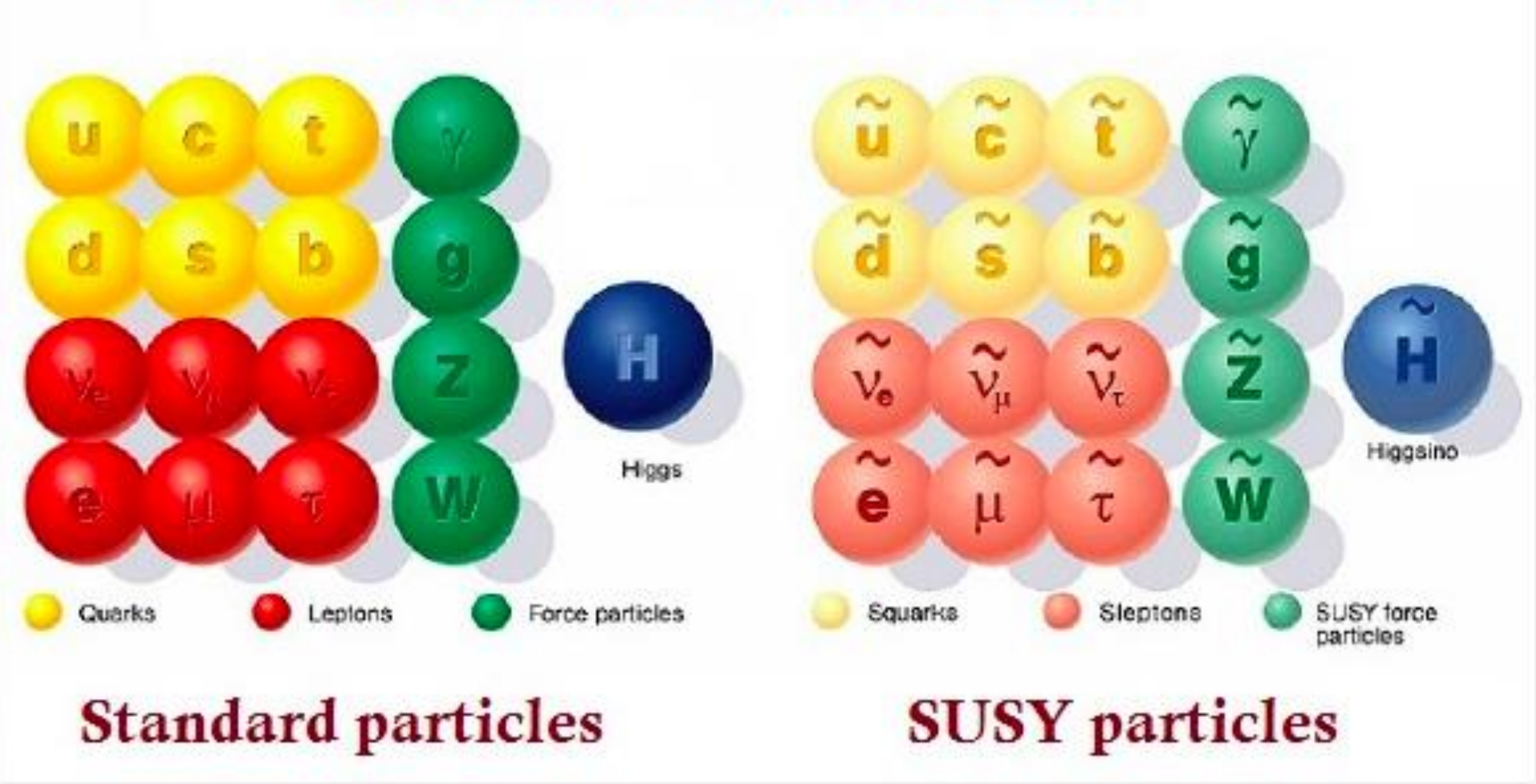
$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + \ldots]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + \ldots]$$

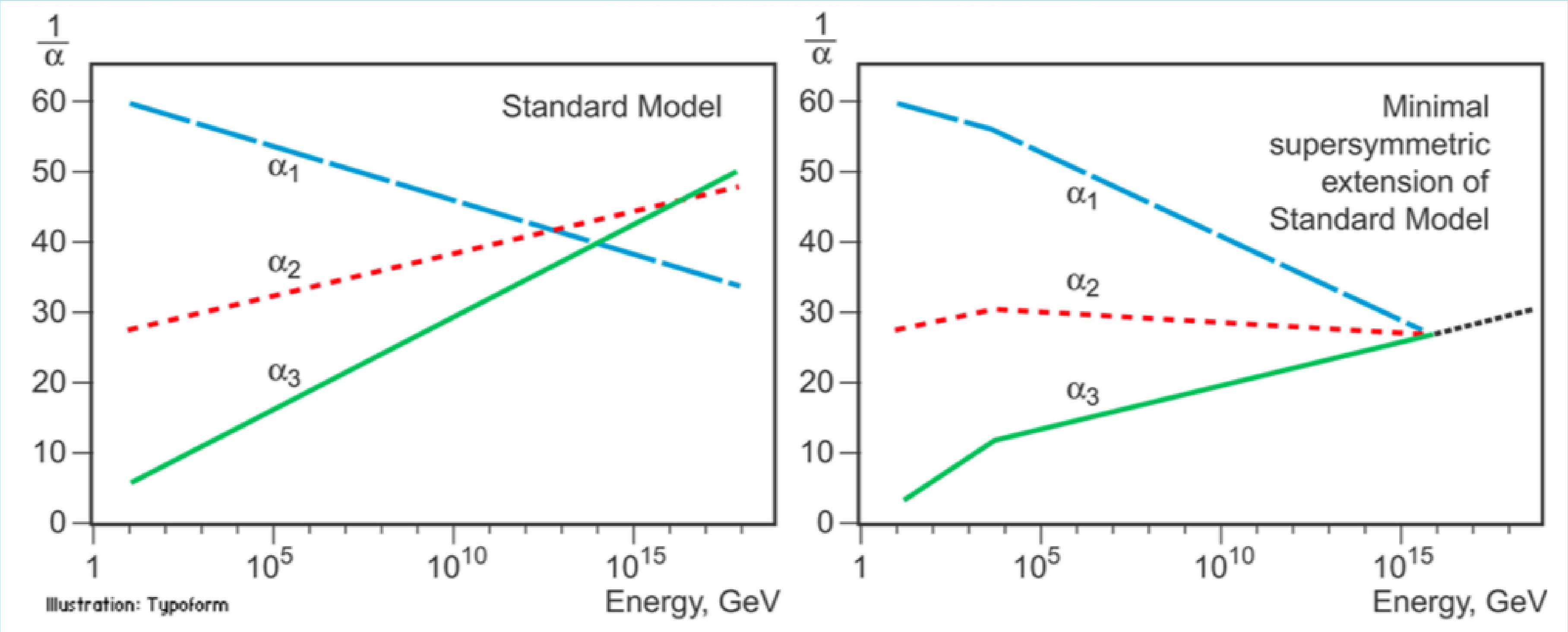
- Leading divergence cancelled if

Su $\lambda_S = y_f^2$ x 2 **ry!**

Minimal Supersymmetric Extension of the Standard Model



Unification of Gauge Couplings



- **Impressive!**
- **Over-ambitious? Hubristic?**

Magnetic Monopoles?

Minimal Supersymmetric Extension of Standard Model (MSSM)

Double up the known particles:

$$\begin{pmatrix}\frac{1}{2}\\ 0\end{pmatrix}\ e.g.,\ \begin{pmatrix}\ell\ (lepton)\\ \tilde{\ell}\ (slepton)\end{pmatrix}\ or\ \begin{pmatrix}q\ (quark)\\ \tilde{q}\ (squark)\end{pmatrix}$$

$$\begin{pmatrix}1\\ \frac{1}{2}\end{pmatrix}\ e.g.,\ \begin{pmatrix}\gamma\ (photon)\\ \tilde{\gamma}\ (photino)\end{pmatrix}\ or\ \begin{pmatrix}g\ (gluon)\\ \tilde{g}\ (gluino)\end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

Higgs Bosons in Supersymmetry

- Need 2 complex Higgs doublets

  (cancel anomalies, form of SUSY couplings)
- 8 – 3 = 5 physical Higgs bosons

  Scalars h, H; pseudoscalar A; charged $H^{\pm}$
- Lightest Higgs < MZ at tree level:

$$M^2_{\mathrm{H,h}} = \frac{1}{2}\left[M^2_{\mathrm{A}} + M^2_{\mathrm{Z}} \pm \sqrt{(M^2_{\mathrm{A}} + M^2_{\mathrm{Z}})^2 - 4M^2_{\mathrm{Z}}M^2_{\mathrm{A}}\cos^2 2\beta}\,\right]$$

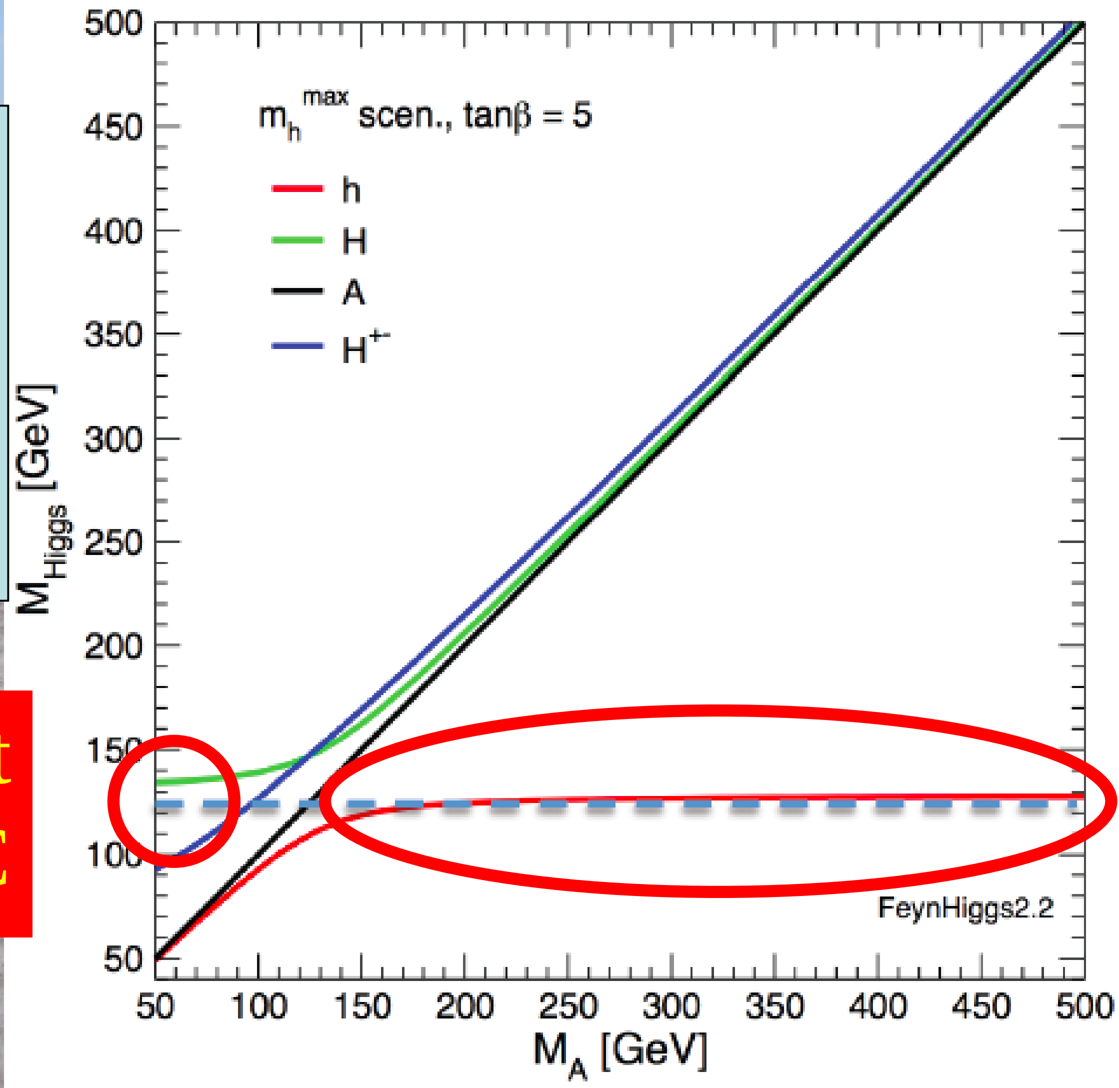
- Important radiative corrections to mass:

$$G_\mu m^4_{\mathrm{t}} \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m^2_{\mathrm{t}}}\right) \qquad \Delta M_{\mathrm{H}}\big|_{\mathrm{TH}} \sim 1.5\ \mathrm{GeV}$$

MSSM Higgs Masses & Couplings

Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close



Consistent With LHC

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

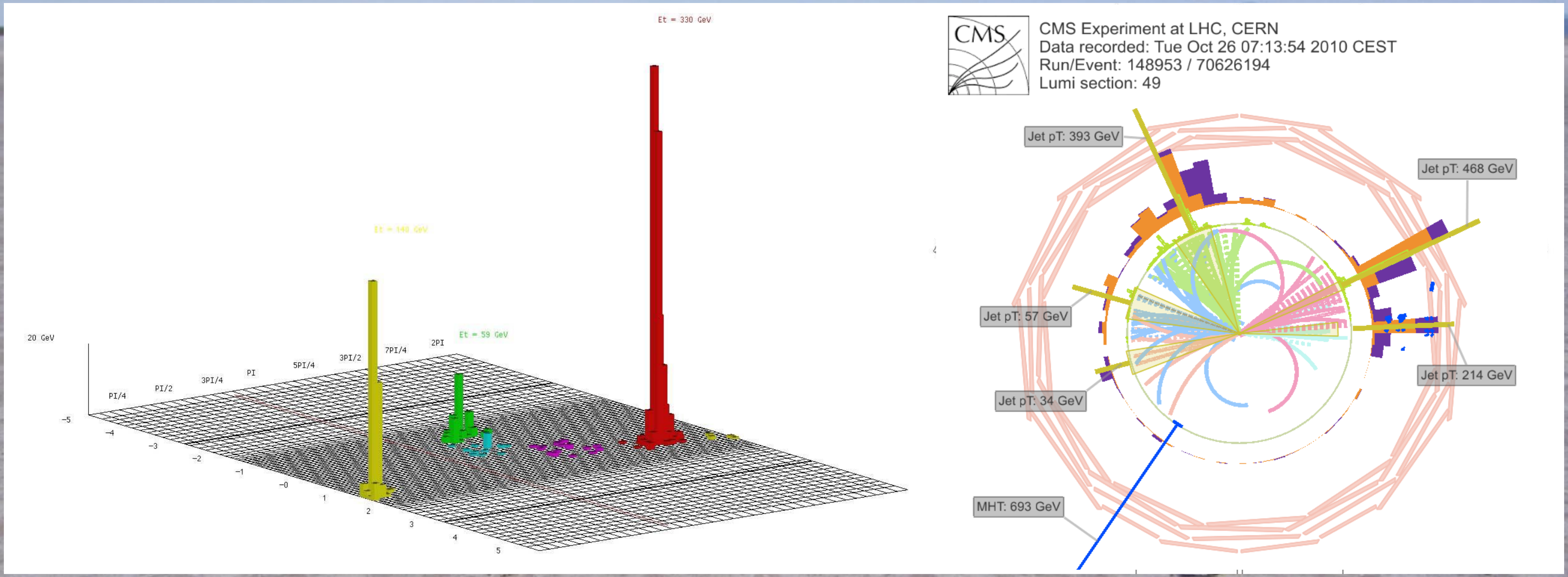
  Heavier sparticles → lighter sparticles

- **Lightest supersymmetric particle (LSP) stable**

Lightest Sparticle as Dark Matter?

- No strong or electromagnetic interactions
  - **Otherwise would bind to matter**
  - **Detectable as anomalous heavy nucleus**
- Possible weakly-interacting scandidates
  - **Sneutrino**
    - (Excluded by LEP, direct searches)
  - **Lightest neutralino χ** (partner of Z, H, γ)
  - **Gravitino**
    - (nightmare for detection)

Looking for Dark Matter @ LHC



Missing transverse energy

carried away by dark matter particles

General Interest in Antimatter Physics

Physicicists cannot make enough for
Star Trek or Dan Brown!

Where does the Matter come from?

Dirac predicted existence of antimatter:

- same mass
- opposite internal properties:
  - electric charge, …

Discovered in cosmic rays

Studied using accelerators

Used in medical diagnosis

Matter and antimatter not quite equal and opposite: WHY?

Is this why the Universe contains matter, not antimatter?

Will experiments reveal how matter was created?

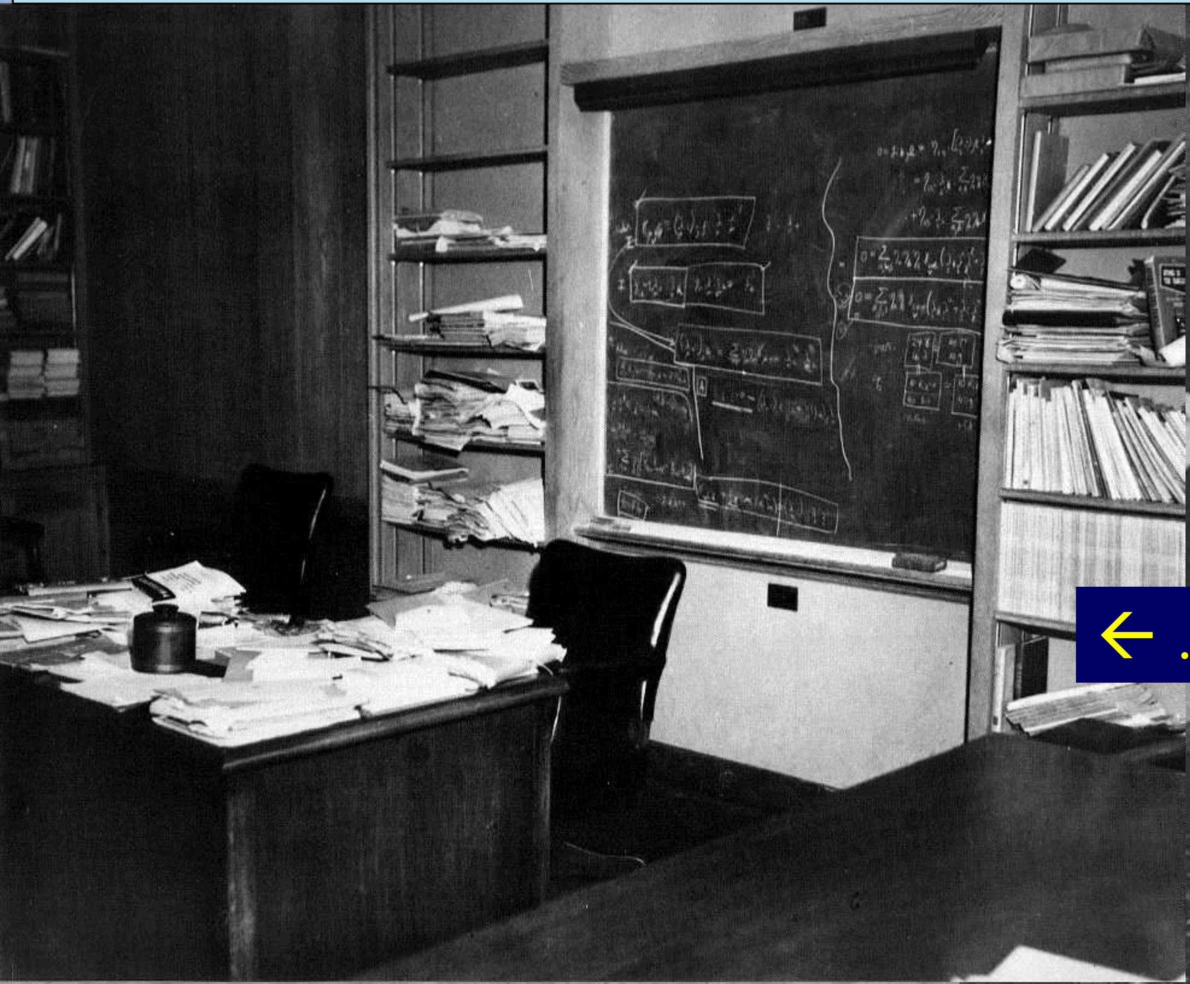
How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter
  observed in the laboratory
- Need interactions able to create matter
  predicted by theories
  not yet seen by experiment
- Need the expansion of the Universe
  a role for the Higgs boson?

Will we be able to calculate using laboratory data?

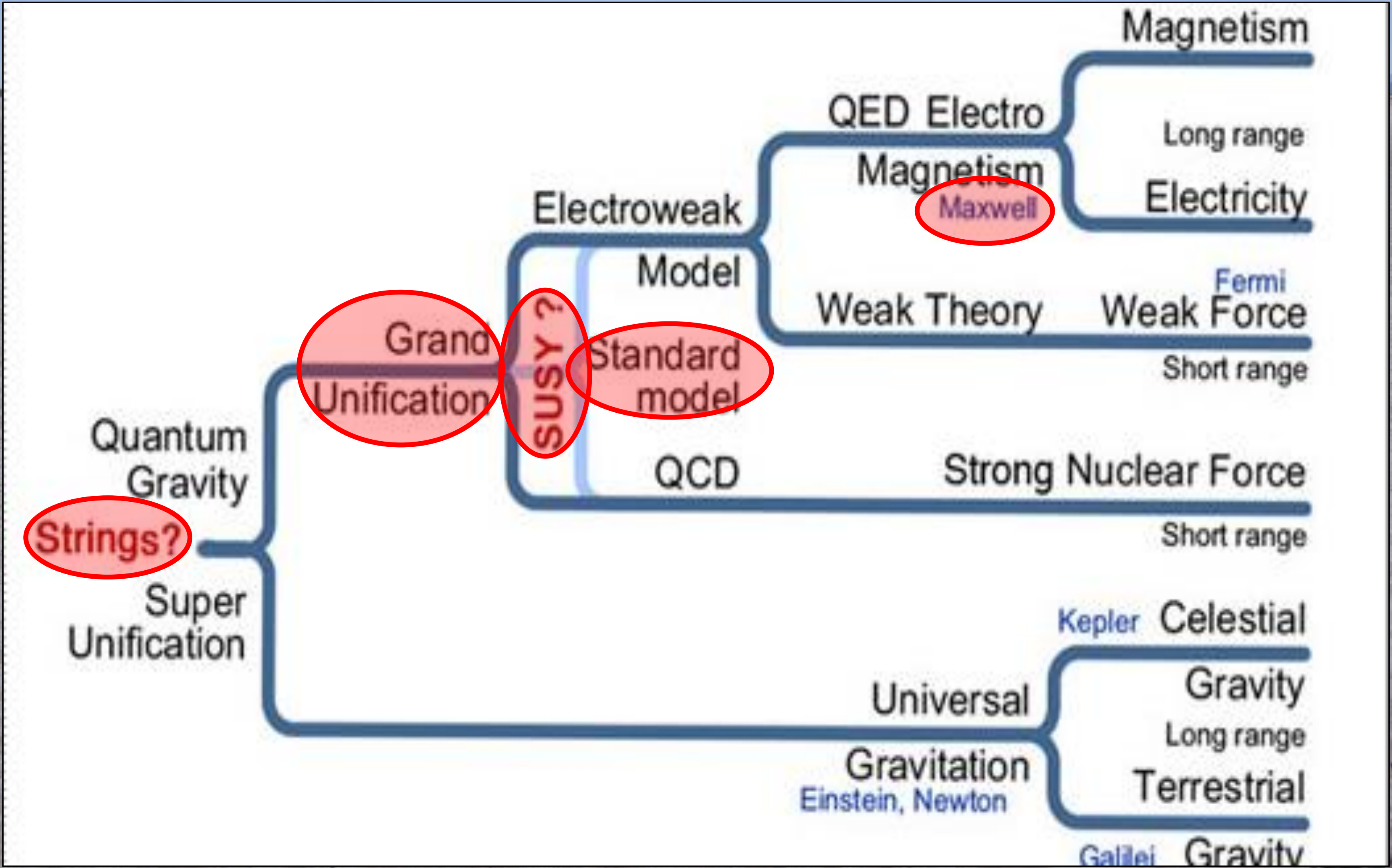
Unify Fundamental Interactions:
Einstein’s Dream …



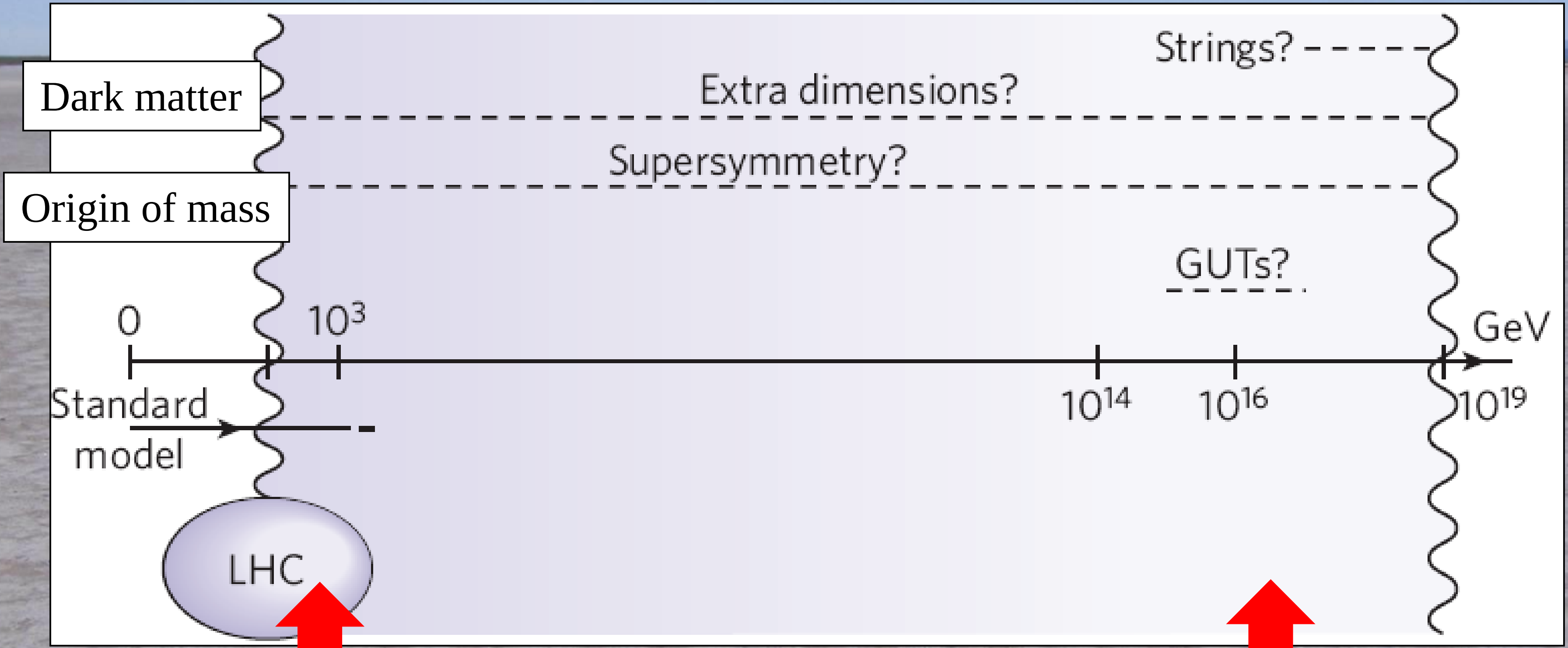
← … but he never succeeded

Unification via extra dimensions of space?

The Unification Trail



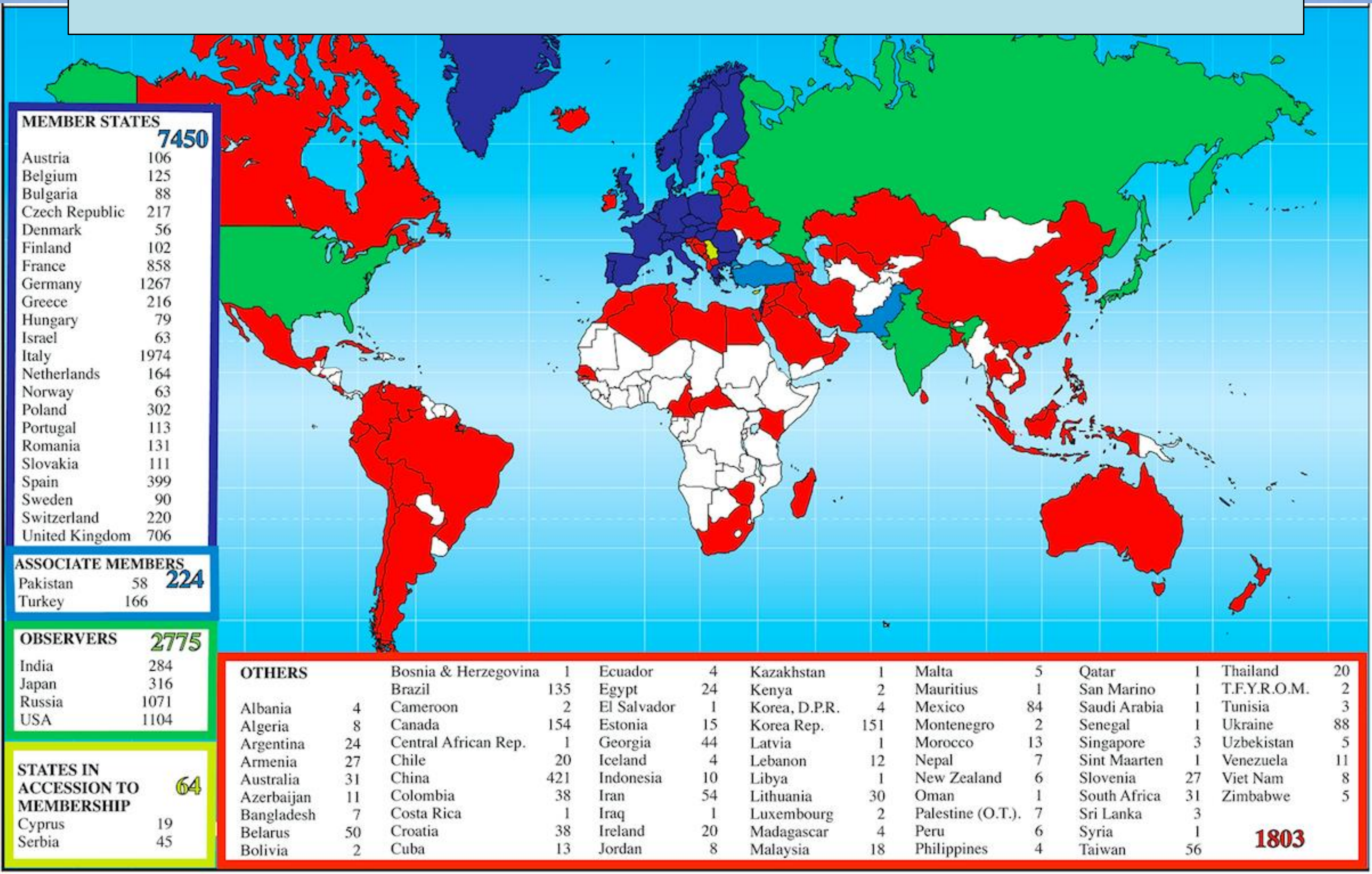
At what Energy is the New Physics?



A lot accessible to the LHC

Some accessible only via astrophysics & cosmology

Scientists working at CERN



MEMBER STATES 7450

Austria	106
Belgium	125
Bulgaria	88
Czech Republic	217
Denmark	56
Finland	102
France	858
Germany	1267
Greece	216
Hungary	79
Israel	63
Italy	1974
Netherlands	164
Norway	63
Poland	302
Portugal	113
Romania	131
Slovakia	111
Spain	399
Sweden	90
Switzerland	220
United Kingdom	706

ASSOCIATE MEMBERS 224

Pakistan	58
Turkey	166

OBSERVERS 2775

India	284
Japan	316
Russia	1071
USA	1104

STATES IN ACCESSION TO MEMBERSHIP 64

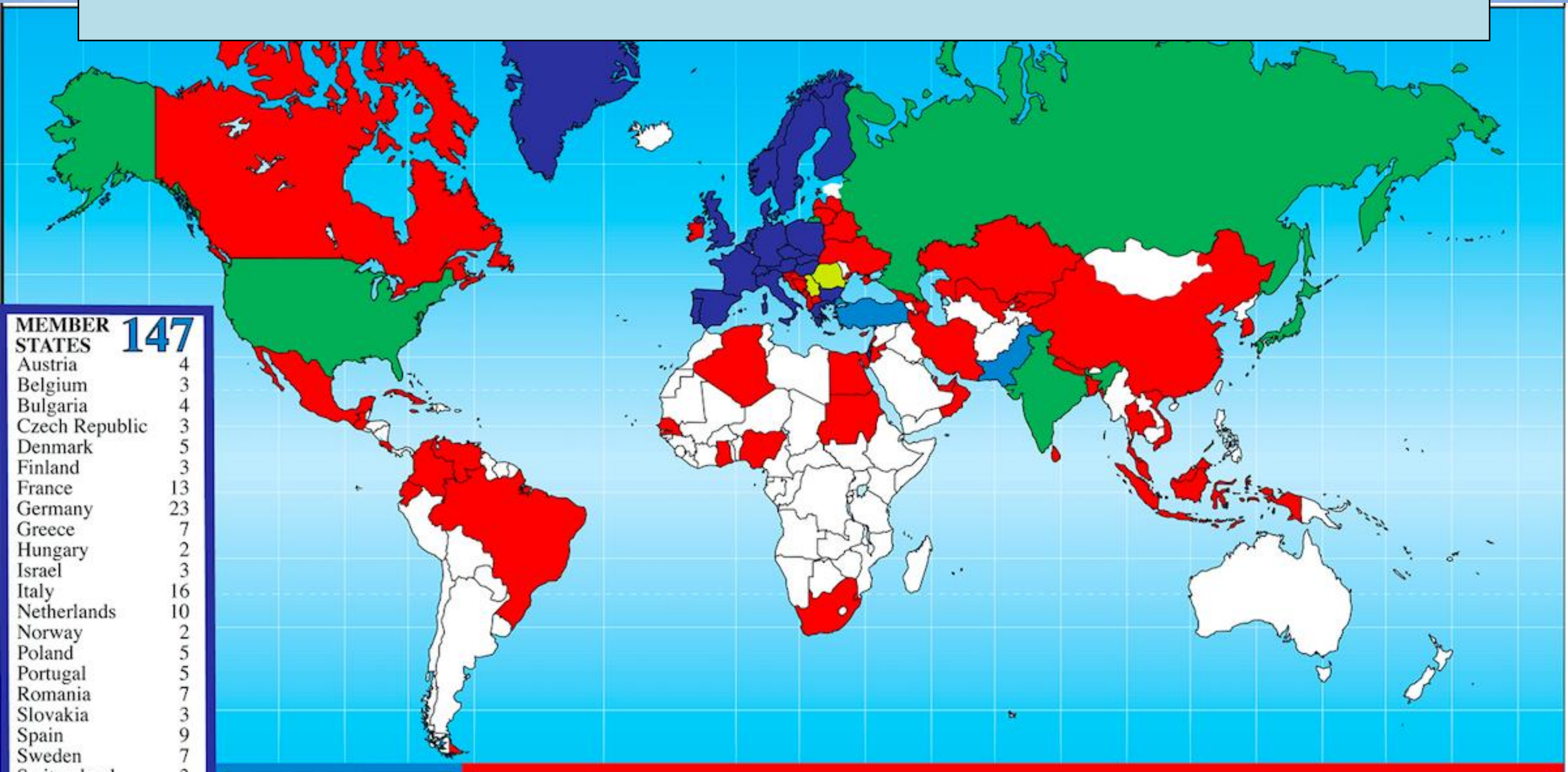
Cyprus	19
Serbia	45

OTHERS

Albania	4
Algeria	8
Argentina	24
Armenia	27
Australia	31
Azerbaijan	11
Bangladesh	7
Belarus	50
Bolivia	2
Bosnia & Herzegovina	1
Brazil	135
Cameroon	2
Canada	154
Central African Rep.	1
Chile	20
China	421
Colombia	38
Costa Rica	1
Croatia	38
Cuba	13
Ecuador	4
Egypt	24
El Salvador	1
Estonia	15
Georgia	44
Iceland	4
Indonesia	10
Iran	54
Iraq	1
Ireland	20
Jordan	8
Kazakhstan	1
Kenya	2
Korea, D.P.R.	4
Korea Rep.	151
Latvia	1
Lebanon	12
Libya	1
Lithuania	30
Luxembourg	2
Madagascar	4
Malaysia	18
Malta	5
Mauritius	1
Mexico	84
Montenegro	2
Morocco	13
Nepal	7
New Zealand	6
Oman	1
Palestine (O.T.).	7
Peru	6
Philippines	4
Qatar	1
San Marino	1
Saudi Arabia	1
Senegal	1
Singapore	3
Sint Maarten	1
Slovenia	27
South Africa	31
Sri Lanka	3
Syria	1
Taiwan	56
Thailand	20
T.F.Y.R.O.M.	2
Tunisia	3
Ukraine	88
Uzbekistan	5
Venezuela	11
Viet Nam	8
Zimbabwe	5

1803

Students at CERN this Summer



MEMBER STATES	147
Austria	4
Belgium	3
Bulgaria	4
Czech Republic	3
Denmark	5
Finland	3
France	13
Germany	23
Greece	7
Hungary	2
Israel	3
Italy	16
Netherlands	10
Norway	2
Poland	5
Portugal	5
Romania	7
Slovakia	3
Spain	9
Sweden	7
Switzerland	3
United Kingdom	12

OBSERVERS	49
India	16
Japan	5
Russia	9
USA	19

ASSOCIATE MEMBERS	7
Pakistan	4
Turkey	3

CANDIDATES FOR ACCESSION	5
Serbia	5

OTHERS	97
Albania	1
Algeria	3
Azerbaijan	2
Bangladesh	1
Belarus	1
Bosnia	2
Brazil	1
Canada	5
China	11
Colombia	1
Costa Rica	3
Croatia	2
Cuba	1
Cyprus	2
Ecuador	1
Egypt	4
Georgia	1
Ghana	1
Guatemala	1
Indonesia	3
Iran	2
Ireland	1
Jamaica	1
Jordan	2
Kazakhstan	1
Korea	1
Kyrgyzstan	1
Latvia	1
Lebanon	2
Lithuania	1
Madagascar	1
Malaysia	3
Malta	4
Mexico	1
Montenegro	2
Nepal	1
Nigeria	2
Oman	1
Palestine	2
Qatar	1
Singapore	1
Slovenia	1
South Africa	2
Sri Lanka	1
Sudan	1
Thailand	3
T.F.Y.R.O.M.	3
U.A.E.	1
Ukraine	3
Uzbekistan	1
Venezuela	1
Viet Nam	1

Innovation
Education
CERN
uniting people
Research

The Mission of CERN

- Push forward the frontiers of knowledge

  E.g. the secrets of the Big Bang … what was r like wit in the first moments of the Universe's existence?

- Develop new techn log and detectors

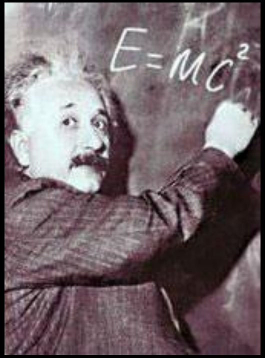
  Information technology - th

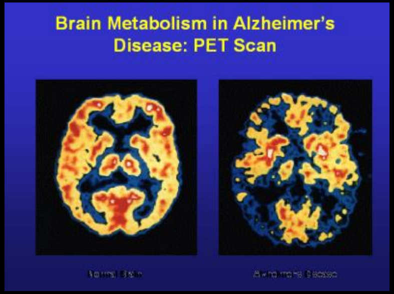
  Medicine - diagnosis an

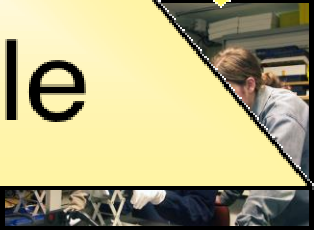
- Train scien

- Unite people from different countries and cultures

Innovation
Education
CERN
uniting people
Research







CERN’s Education Activities

Scientists at CERN
Academic Training Programme

Latin American School of HEP
Viña del Mar, Chile, 2007

Young Researchers
CERN School of High Energy Physics
CERN School of Computing
CERN Accelerator School

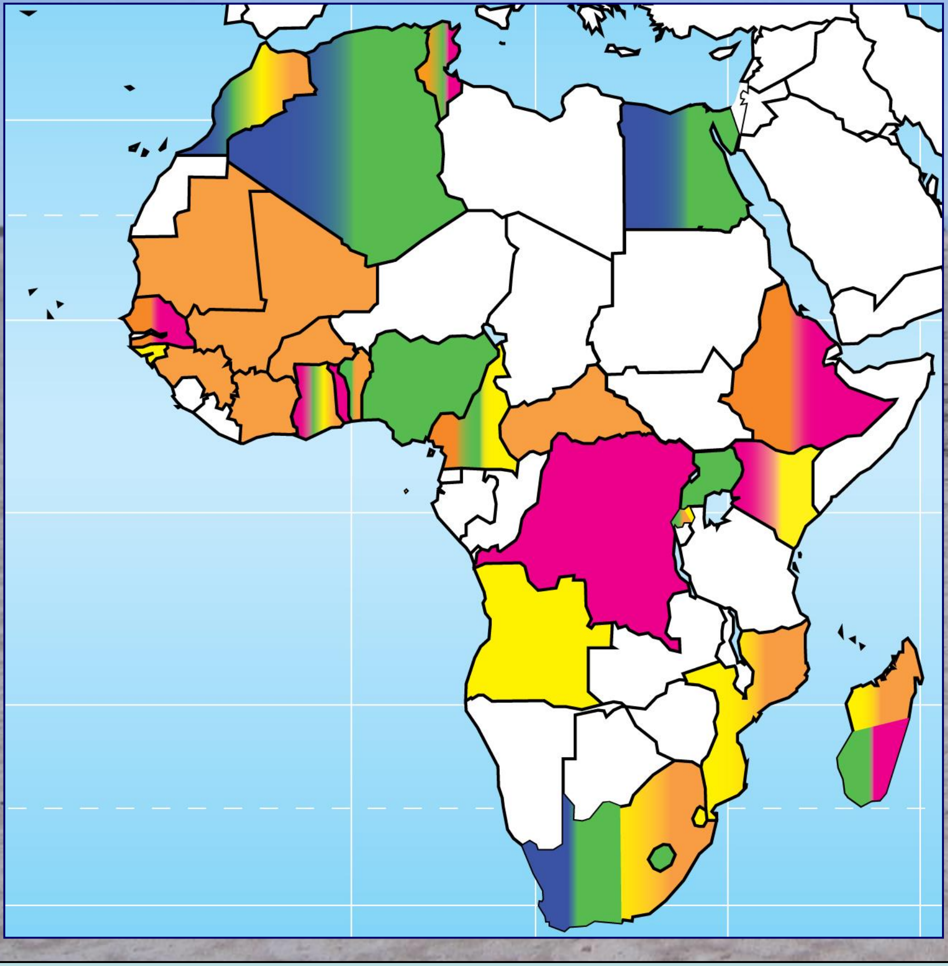
CERN School of Computing
Uxbridge, UK, 2010

Physics Students
Summer Students Programme

CERN Teacher Schools
International, National Programmes

African Schools of Physics
2010/12/14/16, …

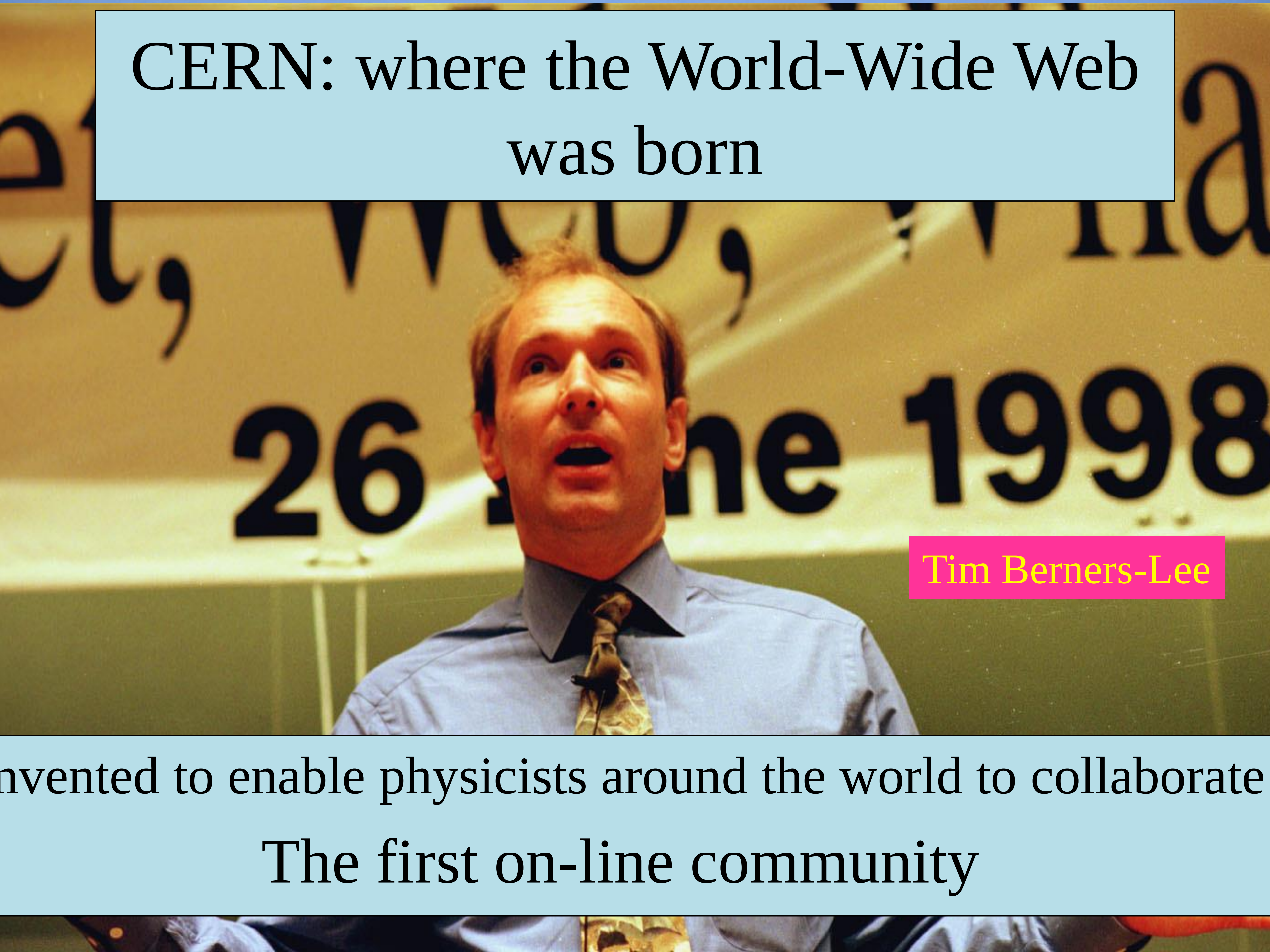
Africa – CERN Collaboration



- **Participation in LHC:**
  - **Morocco, South Africa, Egypt, Algeria, Tunisia, …**
- Governmental co-operation agreements
- Other scientific contacts
- IT contacts
- Summer students
- High-school teachers
- Digital libraries

Training & education agreements with Mozambique, Rwanda
Expressions of interest for participation of students in LHC experiments by universities in Madagascar, Ghana

CERN: where the World-Wide Web was born

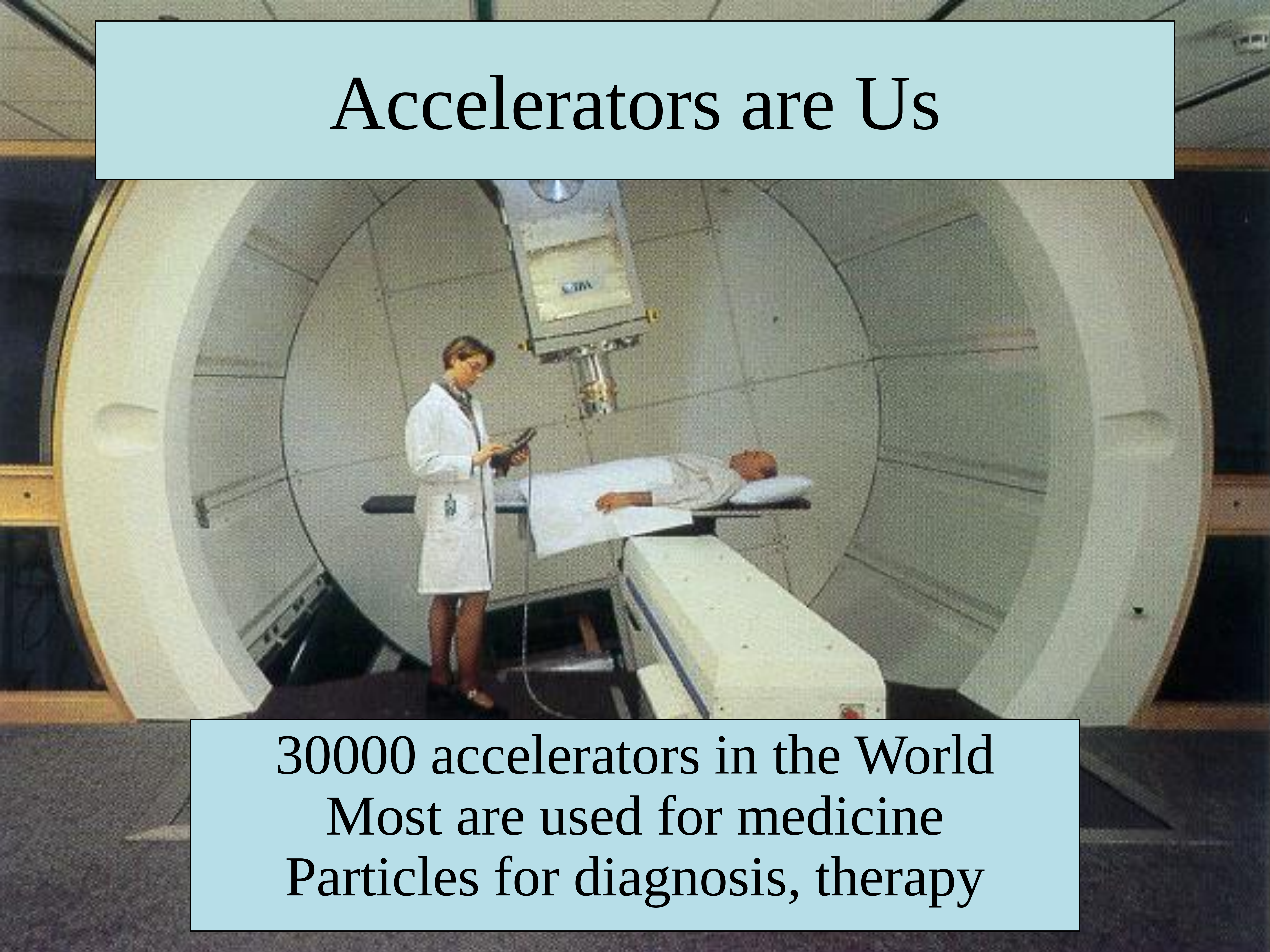


Tim Berners-Lee

nvented to enable physicists around the world to collaborate

The first on-line community

Accelerators are Us

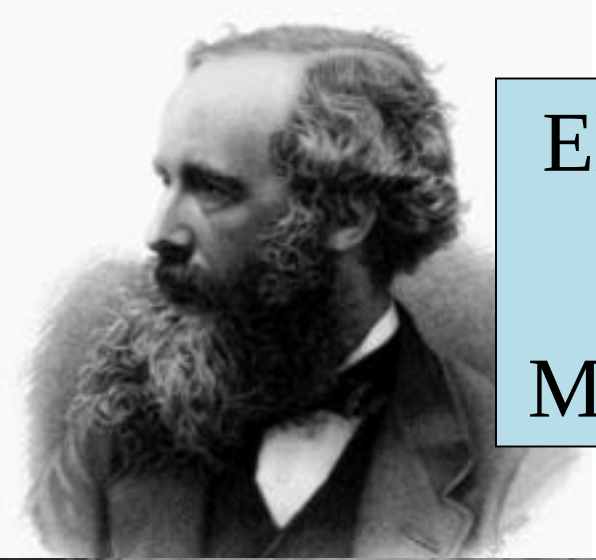


30000 accelerators in the World
Most are used for medicine
Particles for diagnosis, therapy

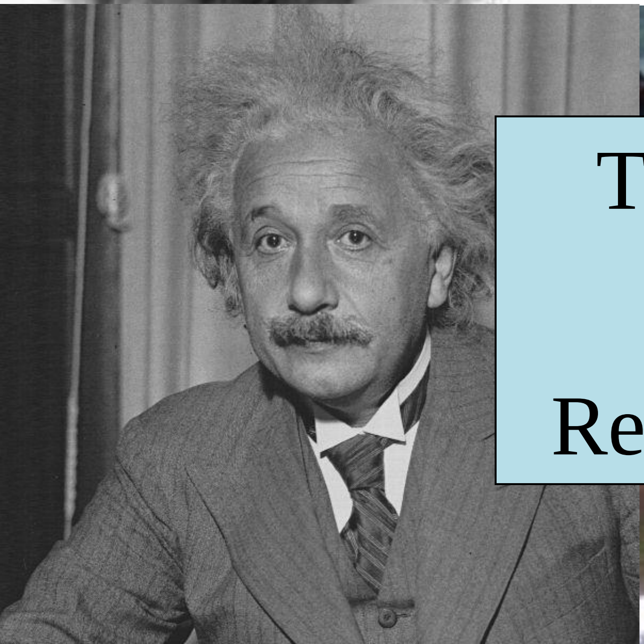
Largest Computer System in the World

200,000 computers all over the world
linked to analyse data from CERN
Grid is new advance in decentralised computing -
from laboratory that invented the World-Wide Web

Innovation is based on Fundamental Science

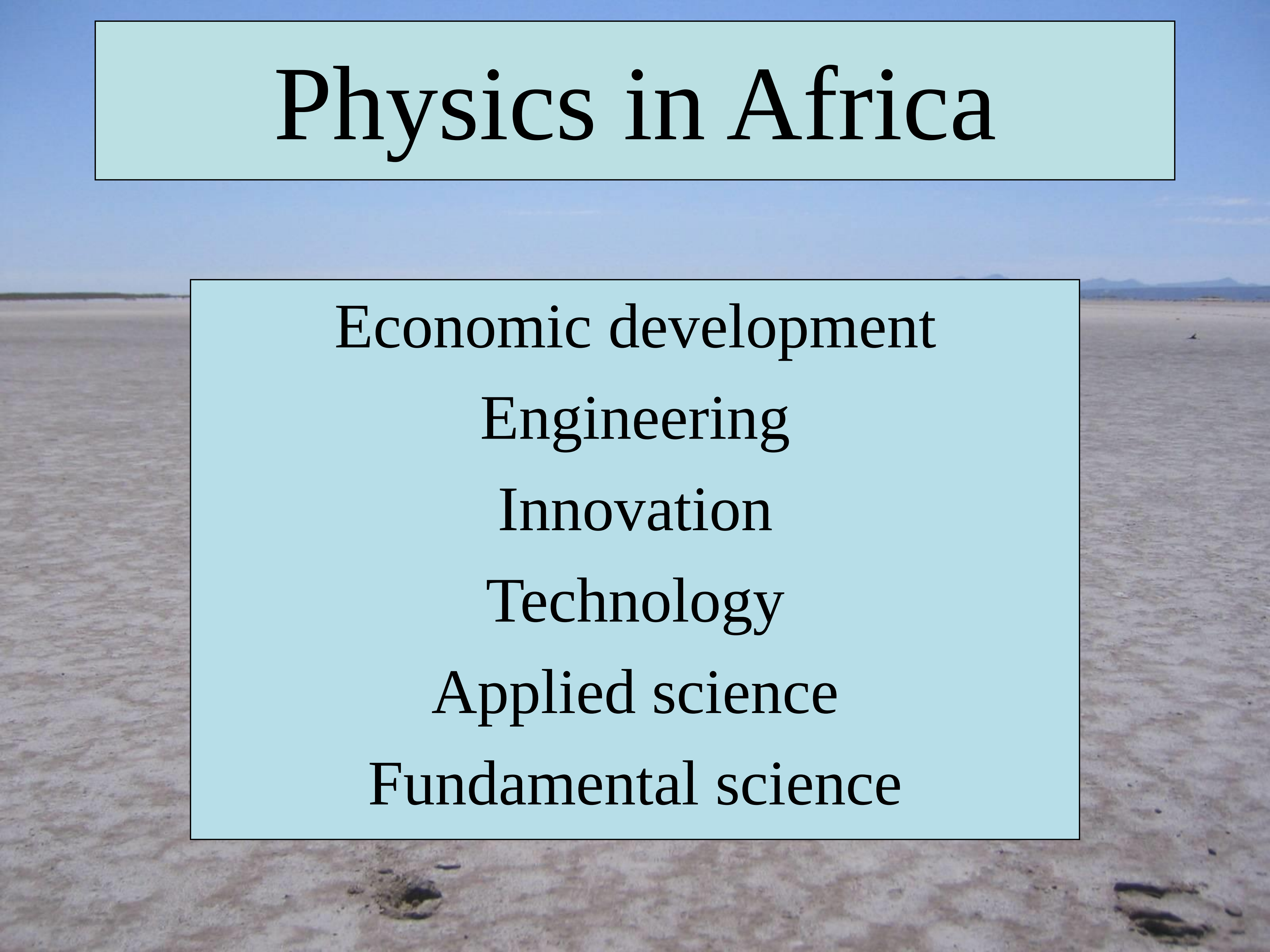


Electricity
and
Magnetism



Theory
of
Relativity

Physics in Africa



Economic development

Engineering

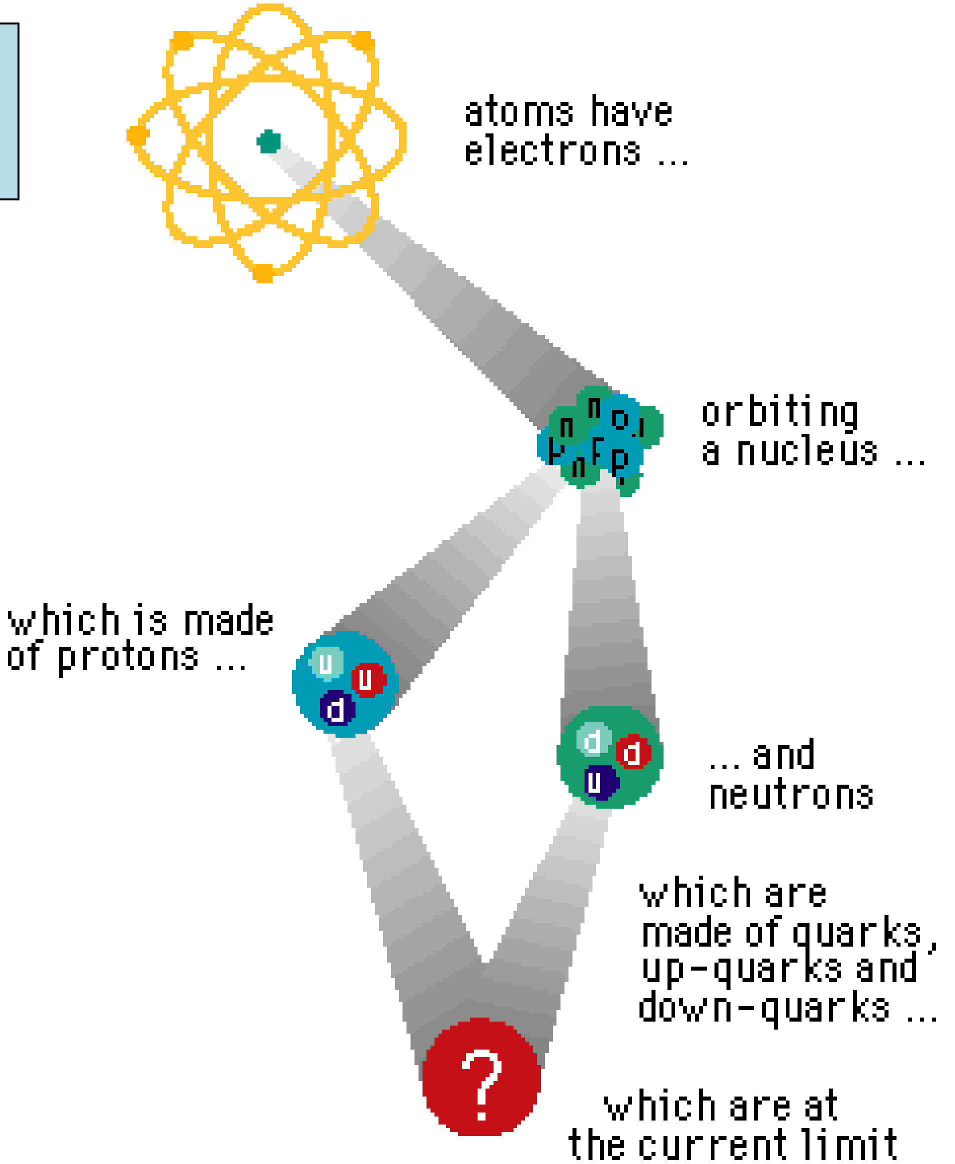
Innovation

Technology

Applied science

Fundamental science

Inside Matter

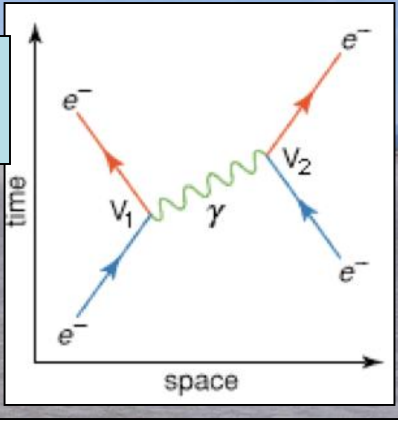


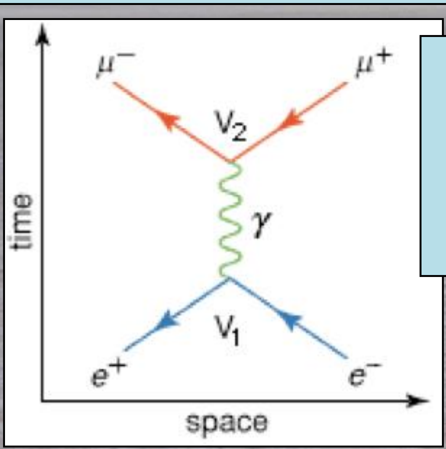
All matter is made of the same constituents

What are they?
What forces between them?

Discoveries of Force Particles

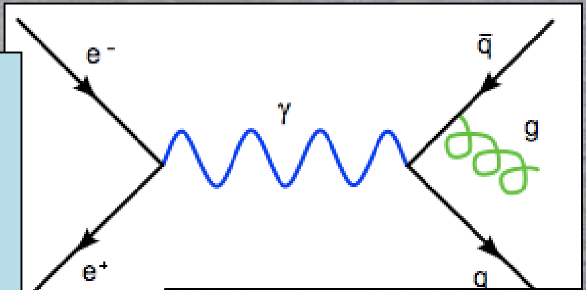
Photon exchange in electromagnetism

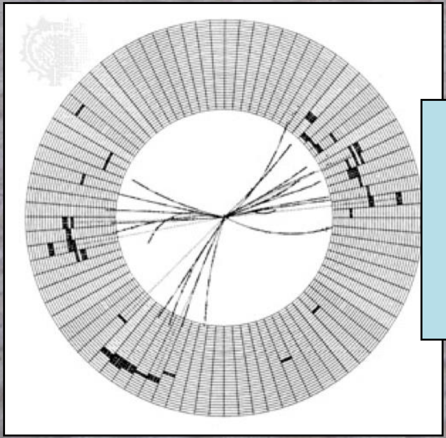




Electron-positron annihilation

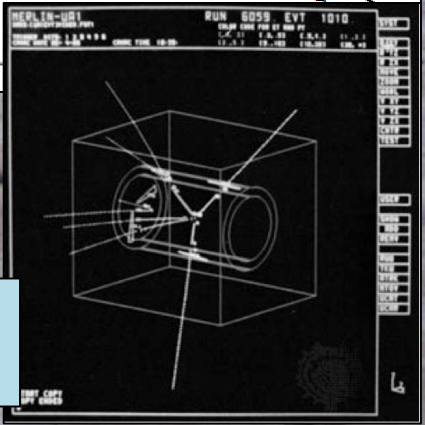
With radiation of a gluon





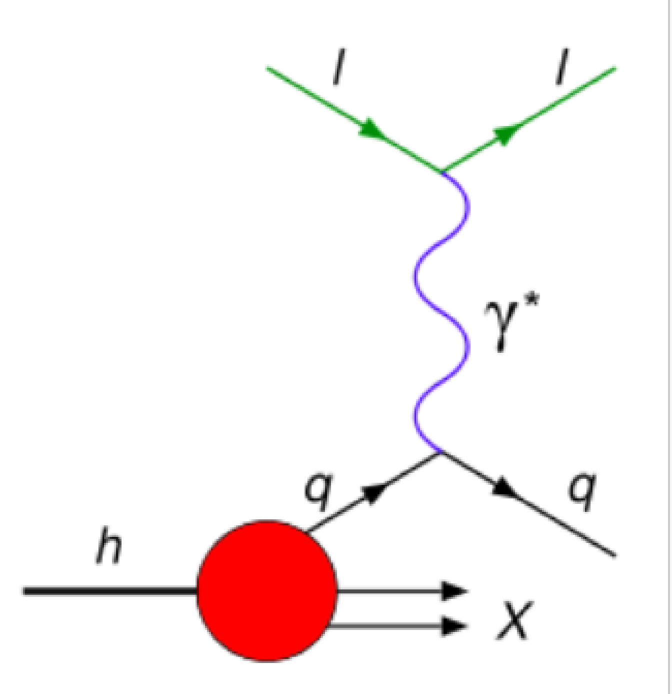
Experimental evidence for gluon

Evidence for weak boson



Strong Interactions

- Nuclei made of protons and neutrons
- Many other strongly-interacting particles
- Understood as composed of quarks
- Physical reality of quarks confirmed by deep inelastic scattering experiments
- Quarks seem almost free
- at short distances



Gauge Interactions of the Standard Model

- Three separate gauge group factors:
  - SU(3) × SU(2) × U(1)
  - Strong × electroweak
- Three different gauge couplings:
  - g_3, g_2, g'
- Mixing between the SU(2) and U(1) factors:

$$\begin{pmatrix} Z^\mu \\ A^\mu \end{pmatrix} = \begin{pmatrix} \cos(\theta_W) & \sin(\theta_W) \\ -\sin(\theta_W) & \cos(\theta_W) \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}$$

$$\sin^2(\theta_W) = \frac{g'^2}{g'^2 + g^2}$$

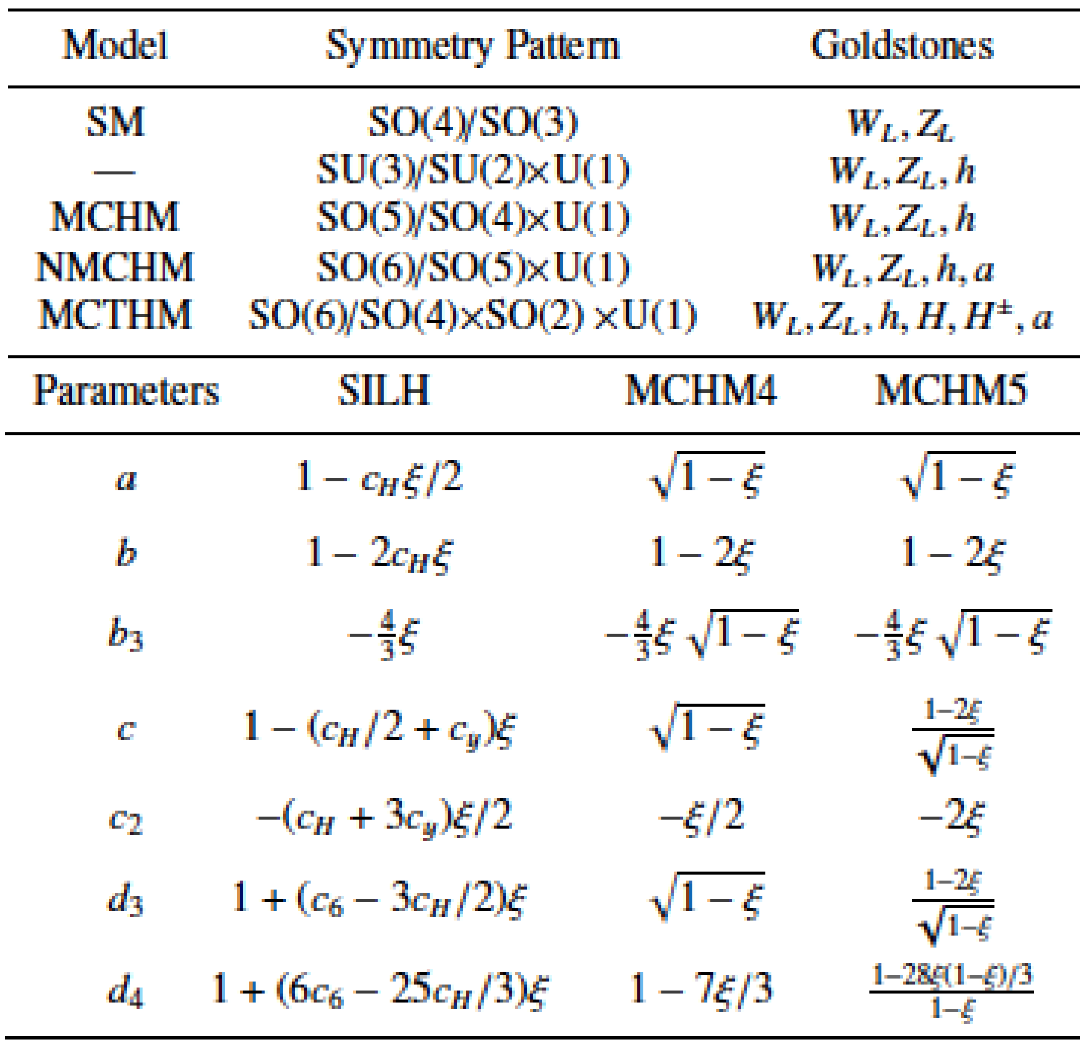
- Experimental value: $\sin^2\theta_W = 0.23120 \pm 0.00015$

Clue for Grand Unification and supersymmetry

Examples of Higgs as Pseudo-Goldstone Boson

- Sample models:
- Dependences of couplings on model parameters:
- **To be measured!**
- Translation to experimental parameters:

$a = \kappa_V, \; c = \kappa_F$

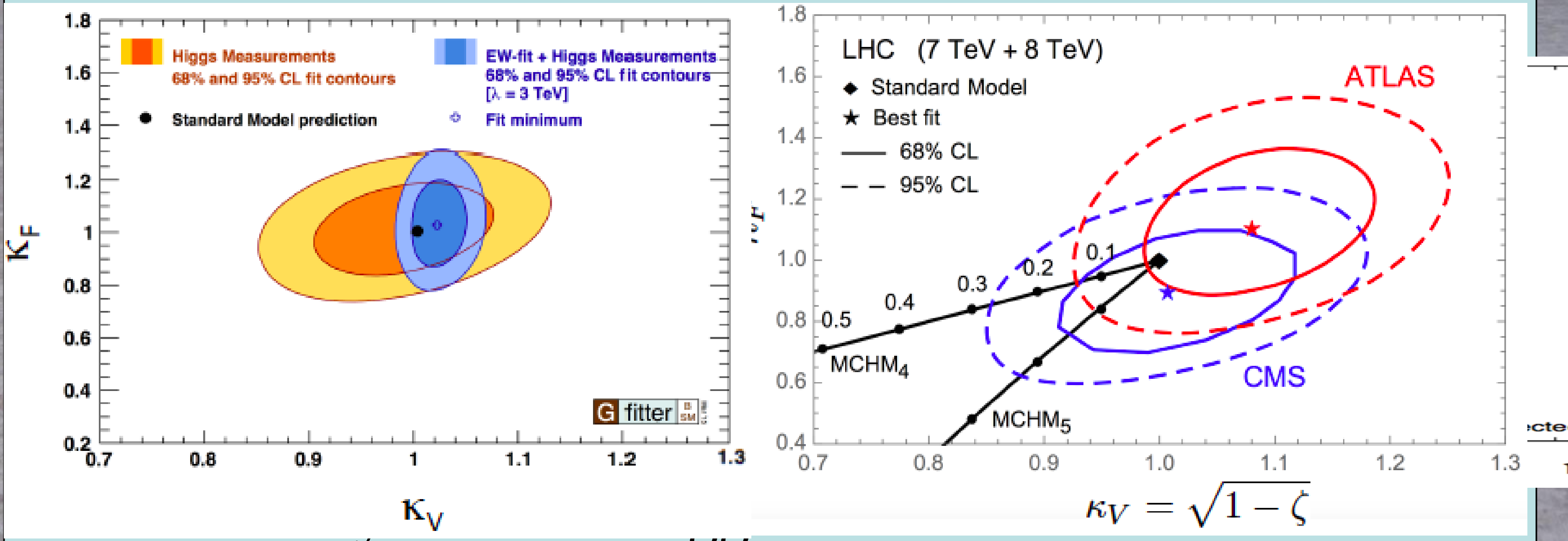


Model	Symmetry Pattern	Goldstones
SM	SO(4)/SO(3)	W_L, Z_L
—	SU(3)/SU(2)×U(1)	W_L, Z_L, h
MCHM	SO(5)/SO(4)×U(1)	W_L, Z_L, h
NMCHM	SO(6)/SO(5)×U(1)	W_L, Z_L, h, a
MCTHM	SO(6)/SO(4)×SO(2) ×U(1)	$W_L, Z_L, h, H, H^\pm, a$

Parameters	SILH	MCHM4	MCHM5
a	$1 - c_H\xi/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
b	$1 - 2c_H\xi$	$1 - 2\xi$	$1 - 2\xi$
b_3	$-\frac{4}{3}\xi$	$-\frac{4}{3}\xi\sqrt{1-\xi}$	$-\frac{4}{3}\xi\sqrt{1-\xi}$
c	$1 - (c_H/2 + c_y)\xi$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_2	$-(c_H + 3c_y)\xi/2$	$-\xi/2$	-2ξ
d_3	$1 + (c_6 - 3c_H/2)\xi$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
d_4	$1 + (6c_6 - 25c_H/3)\xi$	$1 - 7\xi/3$	$\frac{1-28\xi(1-\xi)/3}{1-\xi}$

Global Analysis of Higgs-like Models

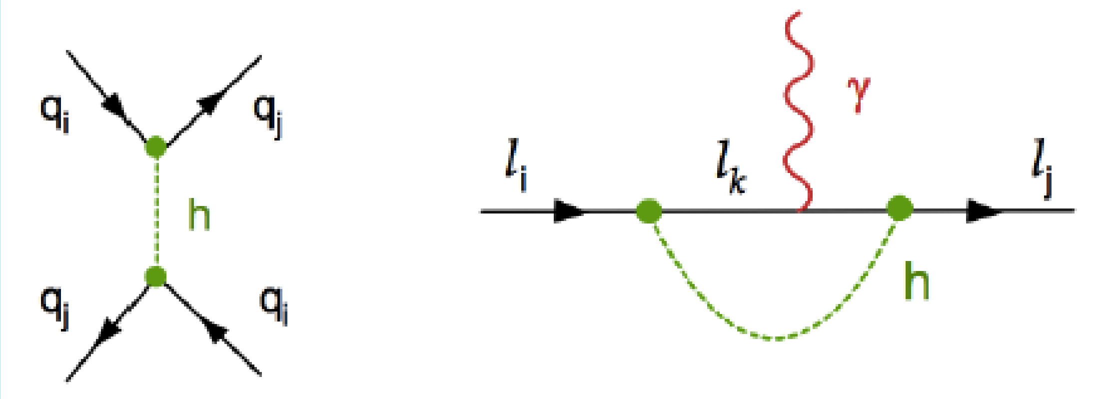
- Rescale couplings: to bosons by κ_V, to fermions by κ_f
- Standard Model: $\boldsymbol{\kappa_V = \kappa_f = 1}$



- **Must tune composite models to look like SM**

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



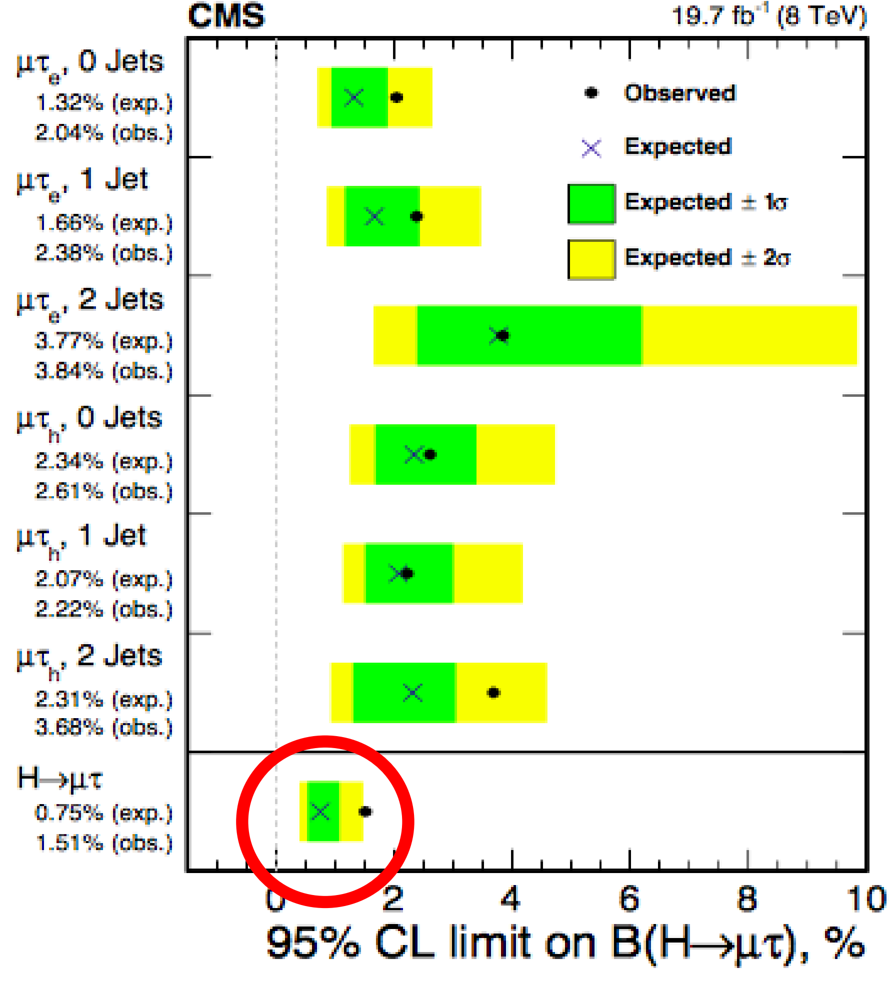
- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

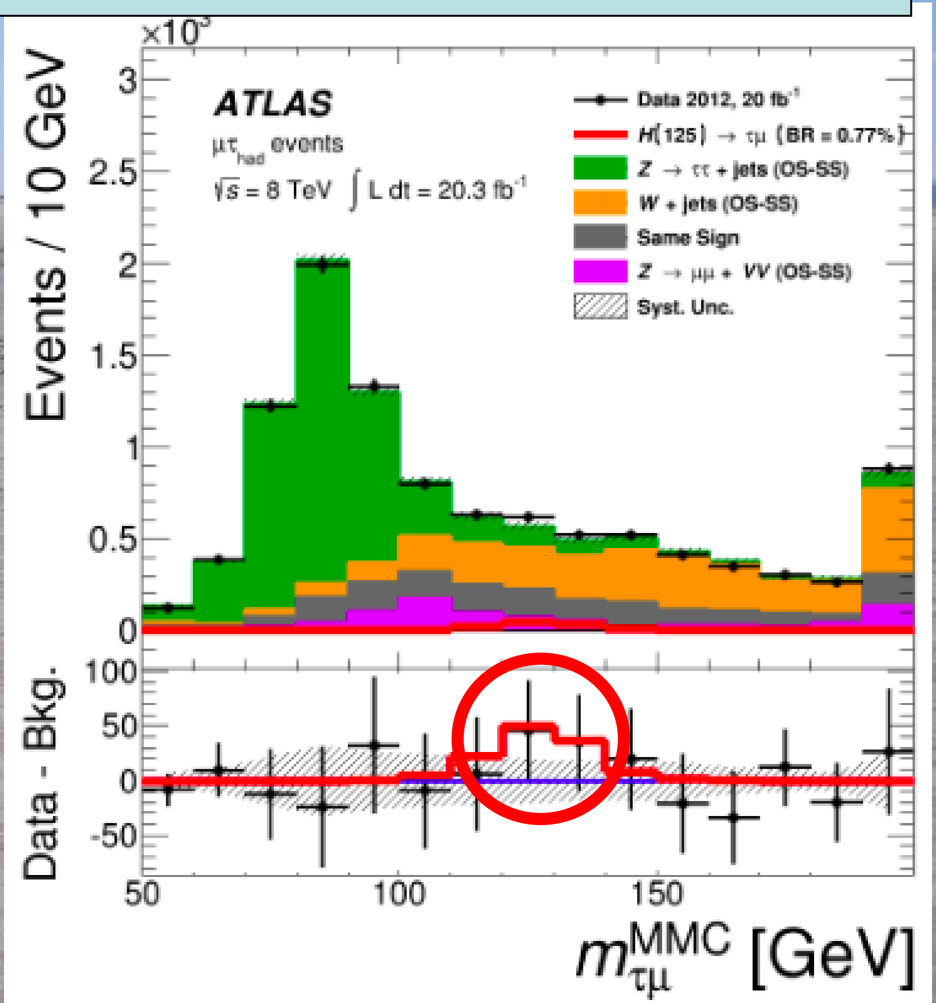
BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704

must be $< 2 \times 10^{-5}$

Flavour-Changing Higgs Coupling?



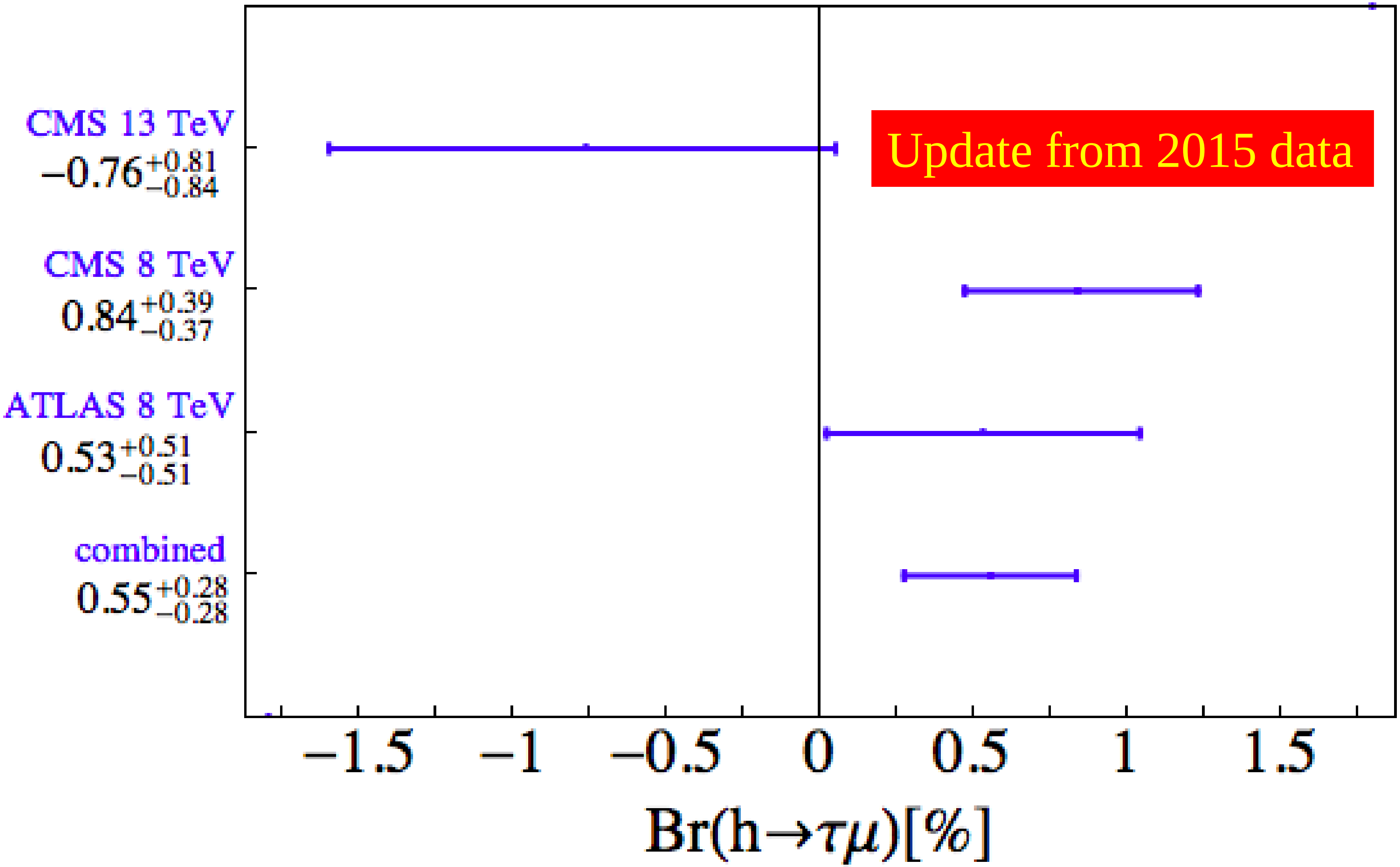


$\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$

Also: BR(eτ) < 0.69%, BR(eμ) < 0.036%

$\mathrm{Br}(H \to \mu\tau) = (0.77 \pm 0.62)\%$

Flavour-Changing Higgs Coupling?



Update from 2015 data

The Strong Interactions

- Quantum chromodynamics: gluon fields acting on quarks:

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu$$

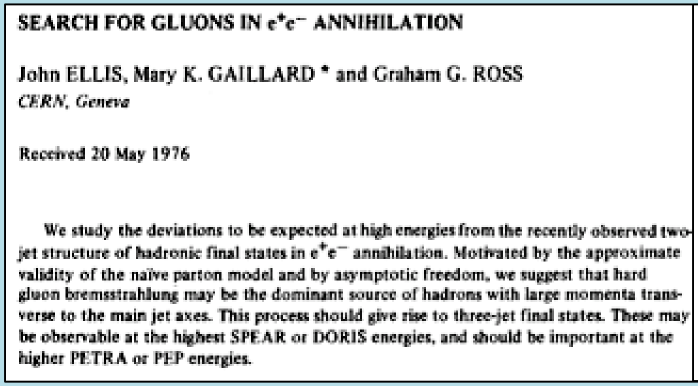
- Only theory able to explain ‘asymptotically free’ quarks confined inside nuclear particles

$$\alpha_s(k^2) \stackrel{\mathrm{def}}{=} \frac{g_s^2(k^2)}{4\pi} \approx \frac{1}{\beta_0 \ln(k^2/\Lambda^2)}$$

- Many proofs of existence of quarks
- **But how to prove existence of gluons?**

Gluon Radiation in e^+e^- Annihilation

- Discovery method suggested by JE, Mary Gaillard, Graham Ross:

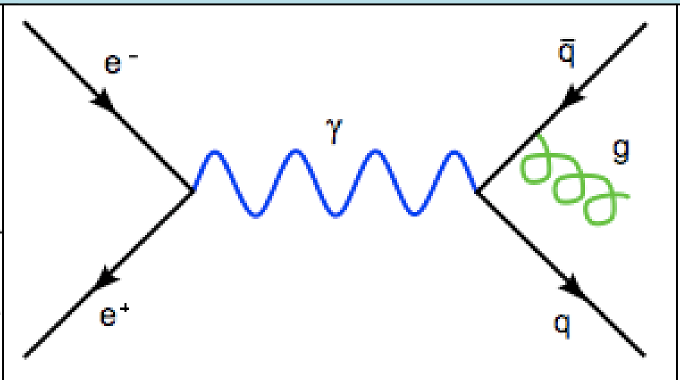


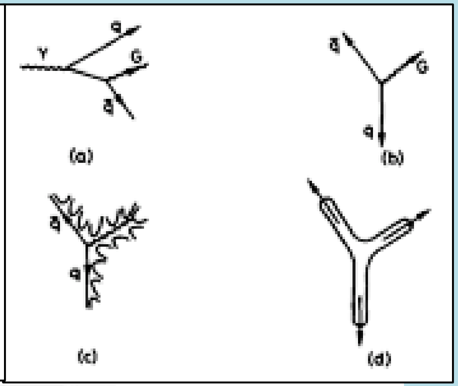
SEARCH FOR GLUONS IN e^+e^- ANNIHILATION

John ELLIS, Mary K. GAILLARD * and Graham G. ROSS
CERN, Geneva

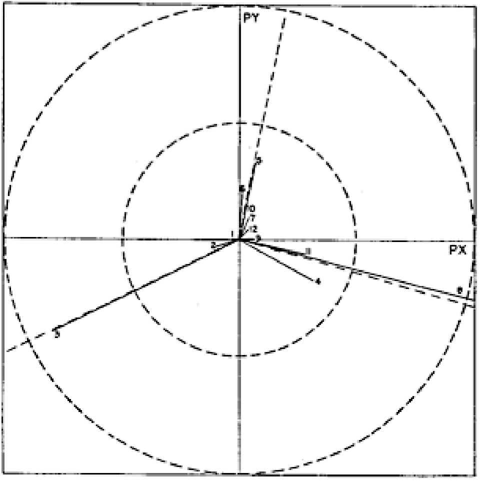
Received 20 May 1976

We study the deviations to be expected at high energies from the recently observed two-jet structure of hadronic final states in e^+e^- annihilation. Motivated by the approximate validity of the naive parton model and by asymptotic freedom, we suggest that hard gluon bremsstrahlung may be the dominant source of hadrons with large momenta transverse to the main jet axes. This process should give rise to three-jet final states. These may be observable at the highest SPEAR or DORIS energies, and should be important at the higher PETRA or PEP energies.



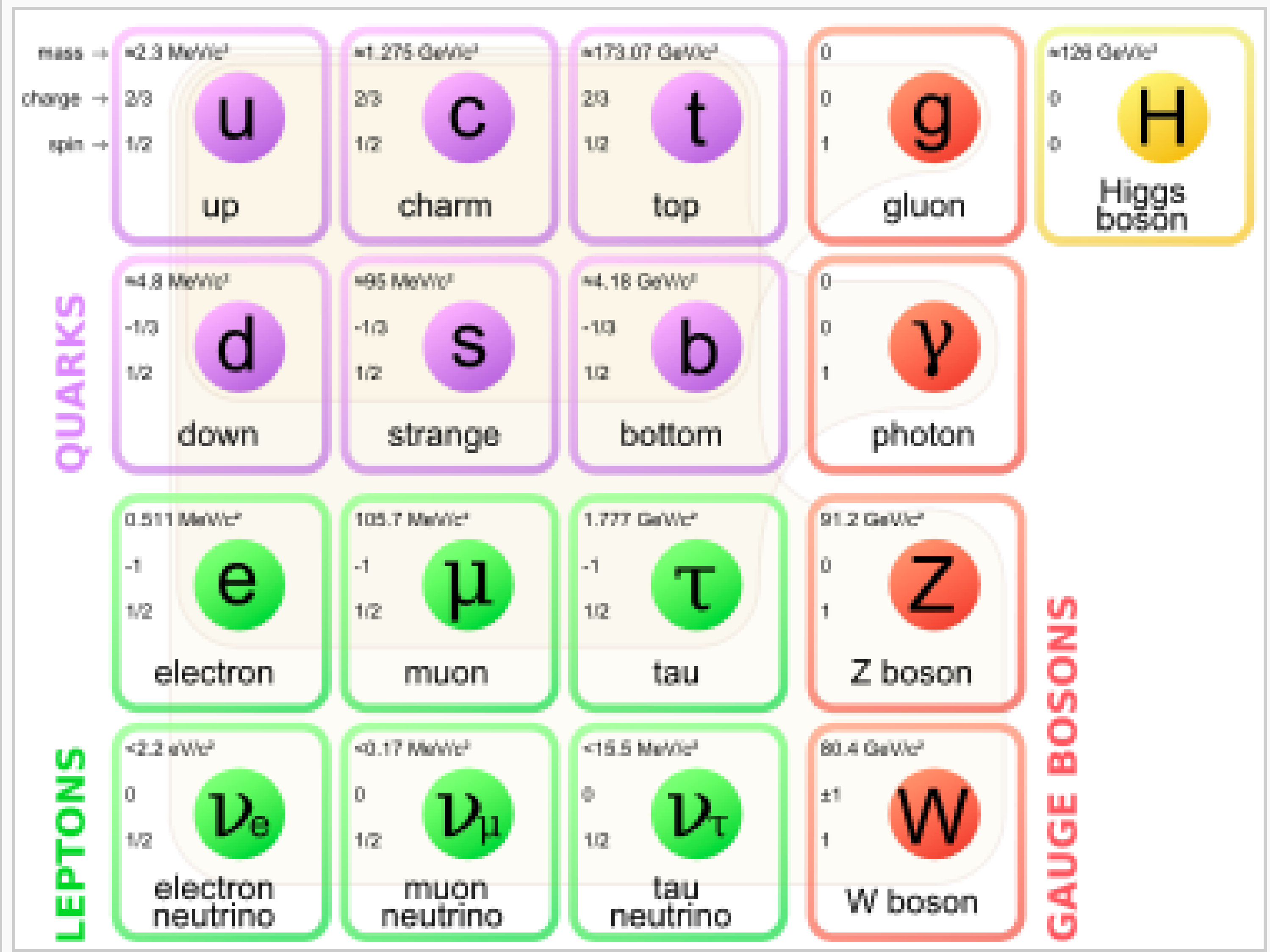


- Jets of hadrons produced by gluons DESY (Hamburg) in 1978



- **Second force particle discovered**

Standard Model of Particles

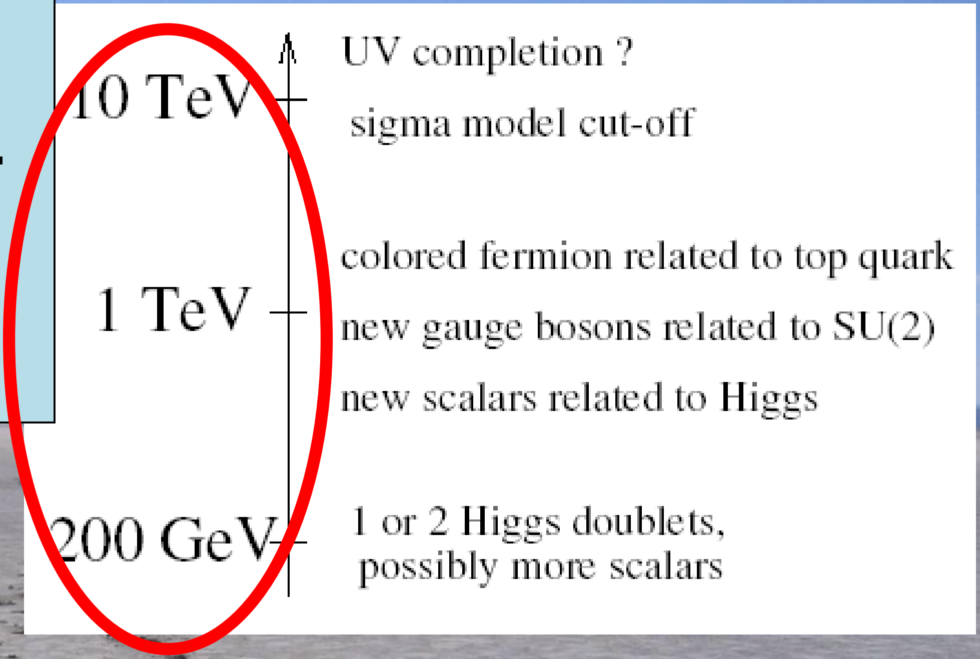


mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson	
QUARKS	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon		
	0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	GAUGE BOSONS	
LEPTONS	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson		

The Large Hadron Collider @ CERN

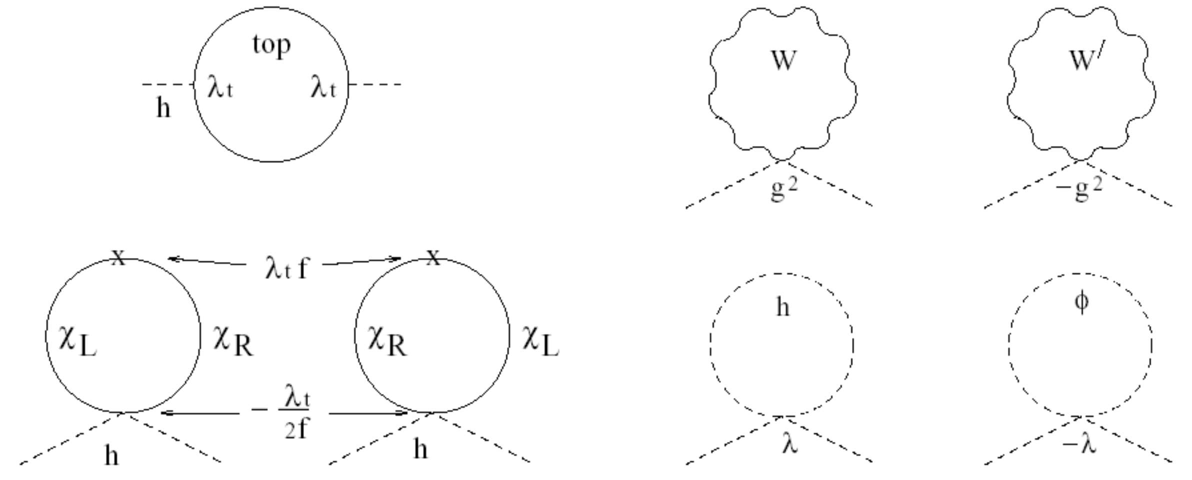
The world’s biggest scientific laboratory

Higgs as a Pseudo-Goldstone Boson

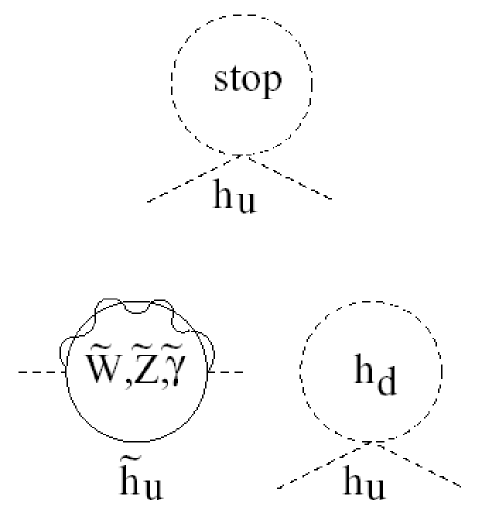


‘Little Higgs’ models
(breakdown of larger symmetry)

Loop cancellation mechanism



Little Higgs



Supersymmetry

Triangle Diagrams for gg ➔Spin-0 ➔γγ

- Effective vertices:

$$\mathcal{L}_{\rm eff}^{H} = \frac{e}{v} c_{H\gamma\gamma}\, H F_{\mu\nu} F^{\mu\nu} + \frac{g_s}{v} c_{Hgg}\, H G_{\mu\nu} G^{\mu\nu}$$

$$\mathcal{L}_{\rm eff}^{A} = \frac{e}{v} c_{A\gamma\gamma}\, A F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_s}{v} c_{Agg}\, A G_{\mu\nu} \tilde{G}^{\mu\nu} \,,$$

- Decay rates:

$$\Gamma(\Phi \to gg) = \frac{G_\mu \alpha_s^2 M_\Phi^3}{64\sqrt{2}\pi^3} \left| \sum_Q \hat{g}_{\Phi QQ} A_{1/2}^{\Phi}(\tau_Q) \right|^2 \,,$$

$$\Gamma(\Phi \to \gamma\gamma) = \frac{G_\mu \alpha^2 M_\Phi^3}{128\sqrt{2}\pi^3} \left| \sum_F \hat{g}_{\Phi FF} N_c e_F^2 A_{1/2}^{\Phi}(\tau_F) \right|^2$$

- Vertex form factors:

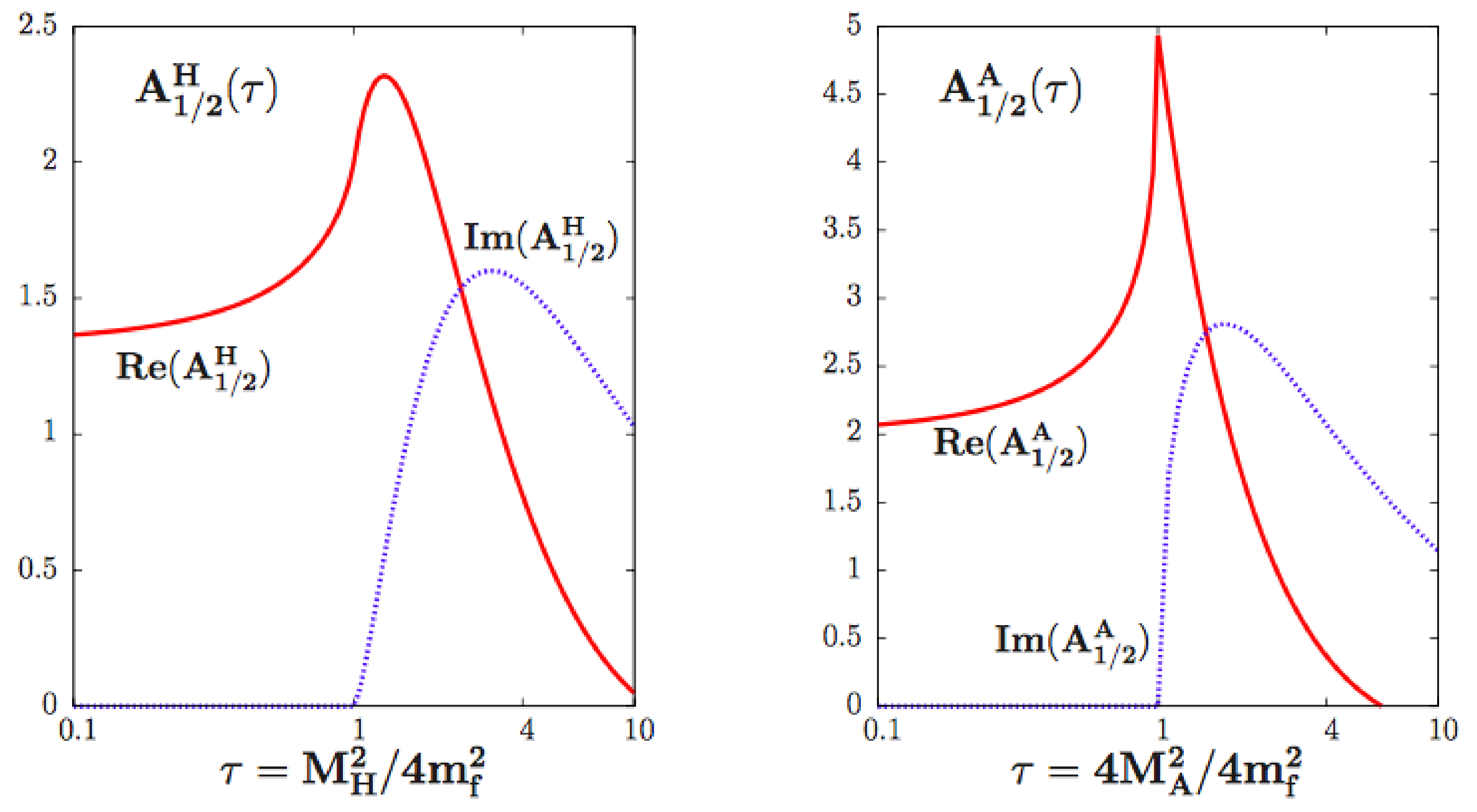
$$A_{1/2}^{H}(\tau) = 2\left[\tau + (\tau - 1) f(\tau)\right] \tau^{-2} \,, \quad A_{1/2}^{A}(\tau) = 2\tau^{-1} f(\tau)$$

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau} & \text{for } \tau \le 1 \,, \\ -\dfrac{1}{4}\left[\log \dfrac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \text{for } \tau > 1 \,. \end{cases}$$

- Vanish for fermion mass << spin-0 mass

Triangle Diagrams for gg ➔Spin-0 ➔γγ

- Form factors for triangle diagrams

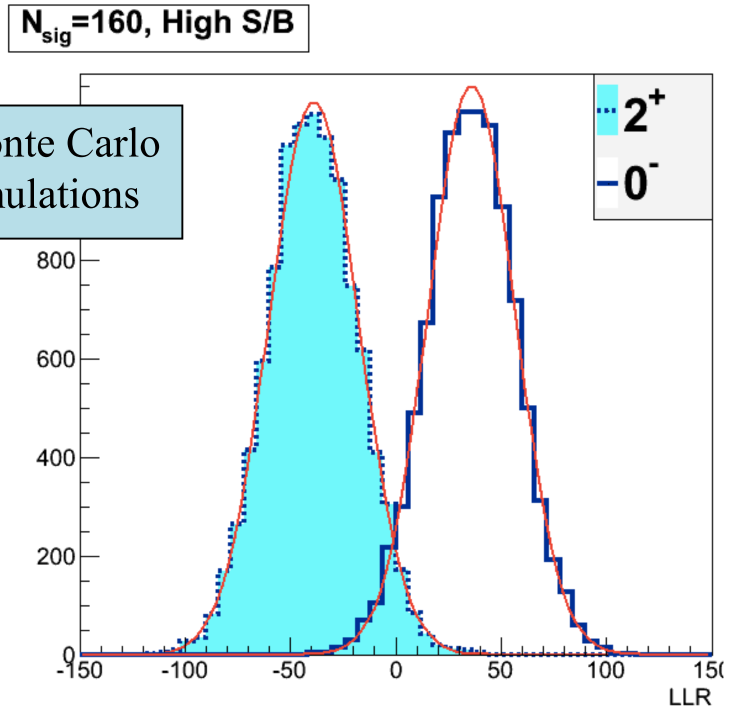


- Vanish for fermion mass << spin-0 mass

Does the 'Higgs' have Spin Two ?

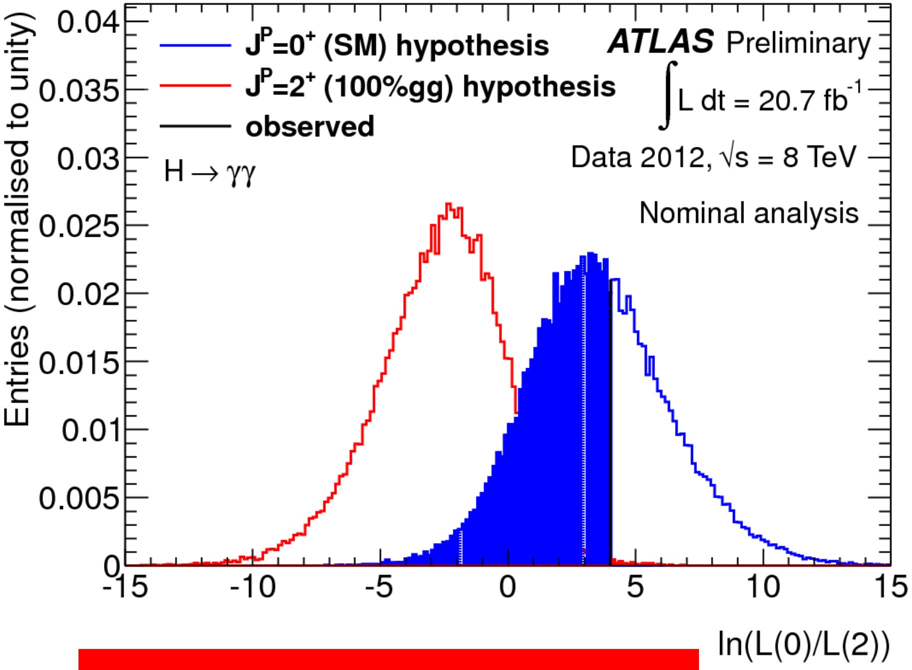
- Discriminate spin 2 vs spin 0 via angular distribution of decays into γγ

JE & Hwang: arXiv:1202.6660



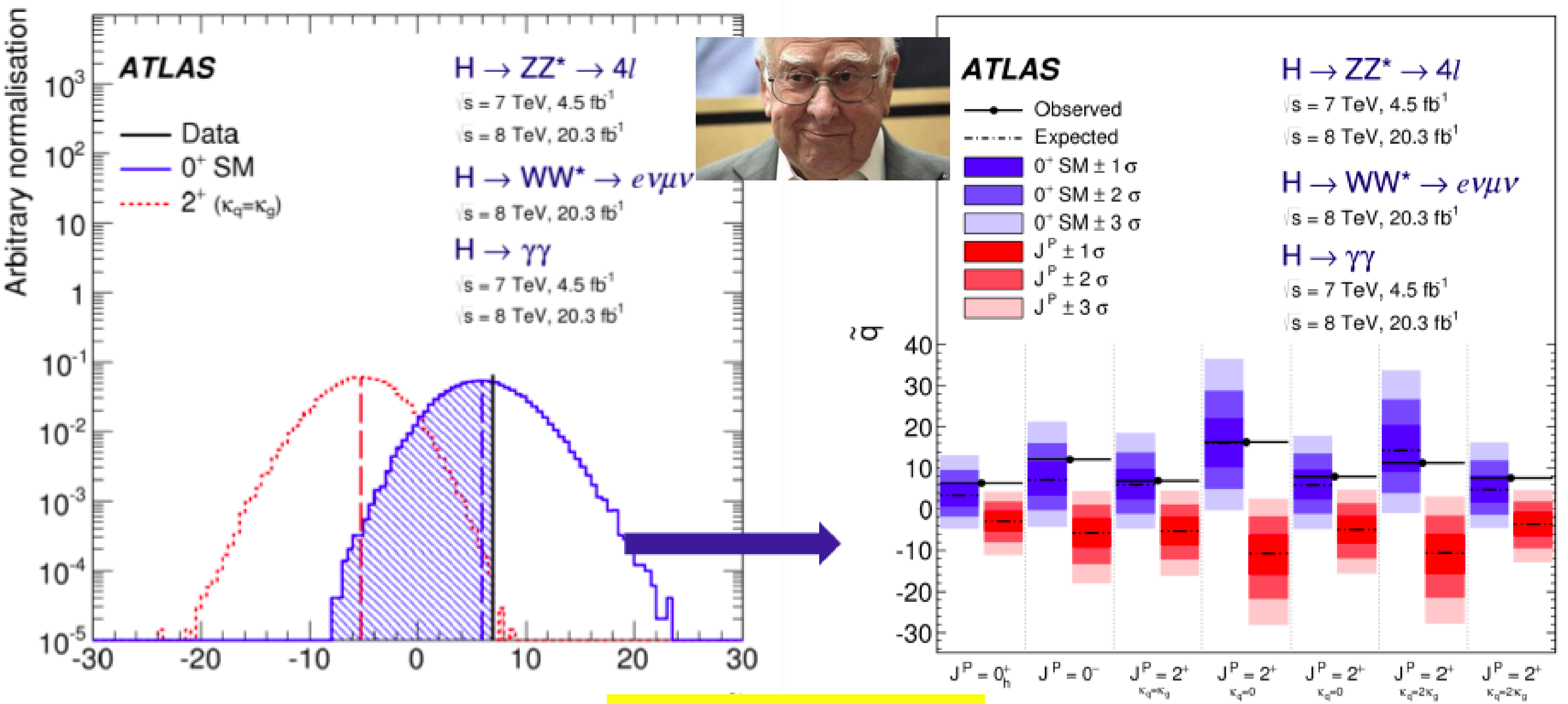
Monte Carlo simulations

JE, Fok, Hwang, Sanz & You: arXiv:1210.5229



2^+ disfavoured @ 99%

H Spin-Parity Tests: 0^+ AOK



arXiv:1506.05669

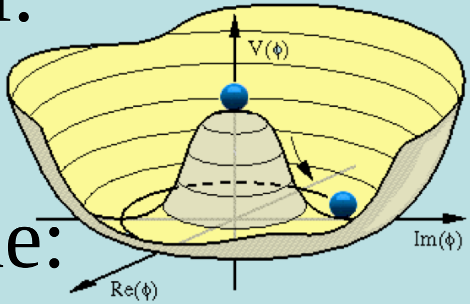
- Alternative spin-parities disfavoured > 99.9%

1964

The Higgs Mechanism

- Postulate effective Higgs potential:

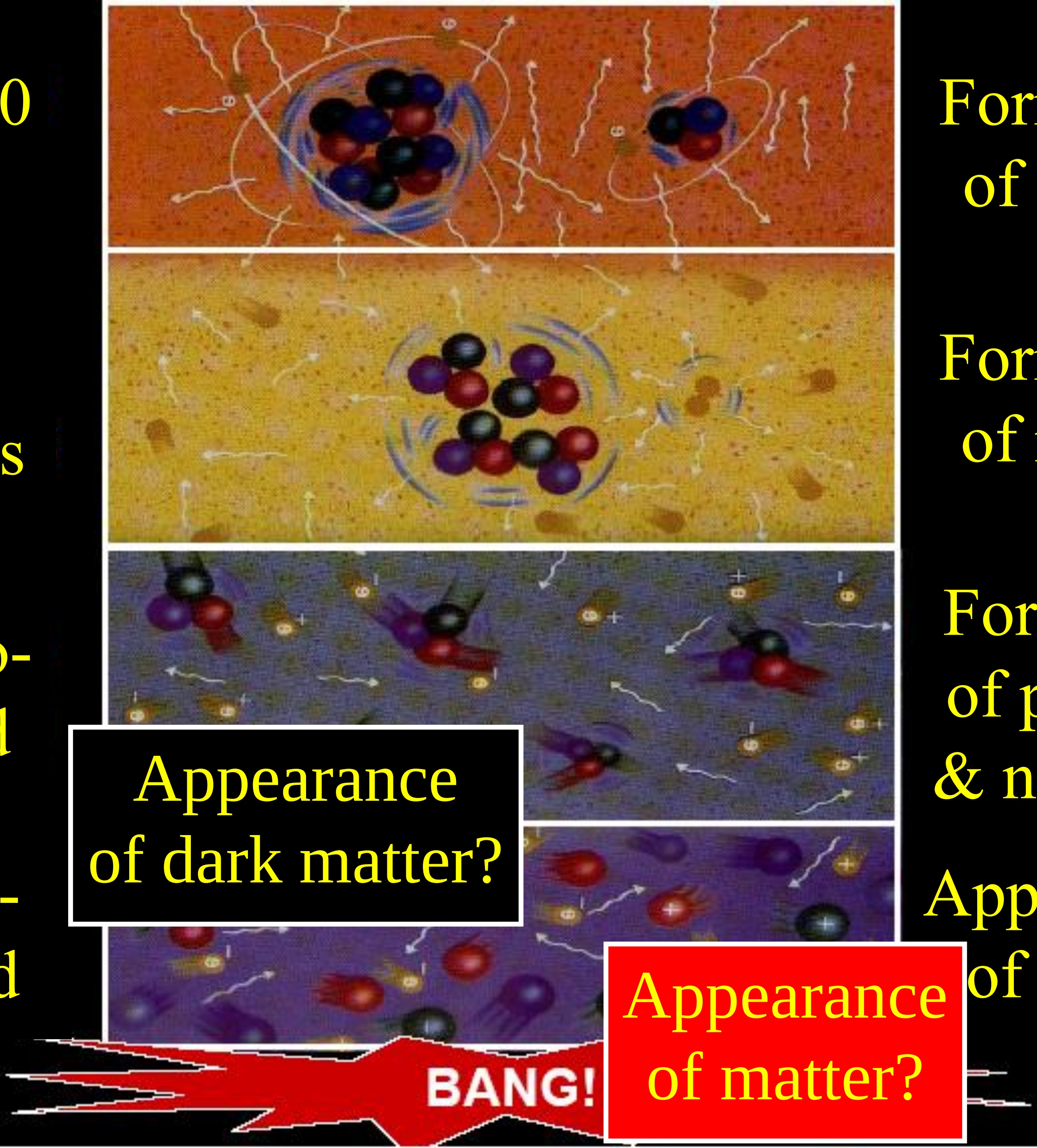
$$V[\phi] = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



- Minimum energy at non-zero value:

$$\phi_0 =< 0|\phi|0 >= \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ +v \end{array}\right) \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

- Components of Higgs field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π massless, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$
- Couple to fermions: on-zero masses: $M_f = y_f\,\frac{v}{\sqrt{2}}$
- After gauging: $M_W = \frac{g\,v}{2}$

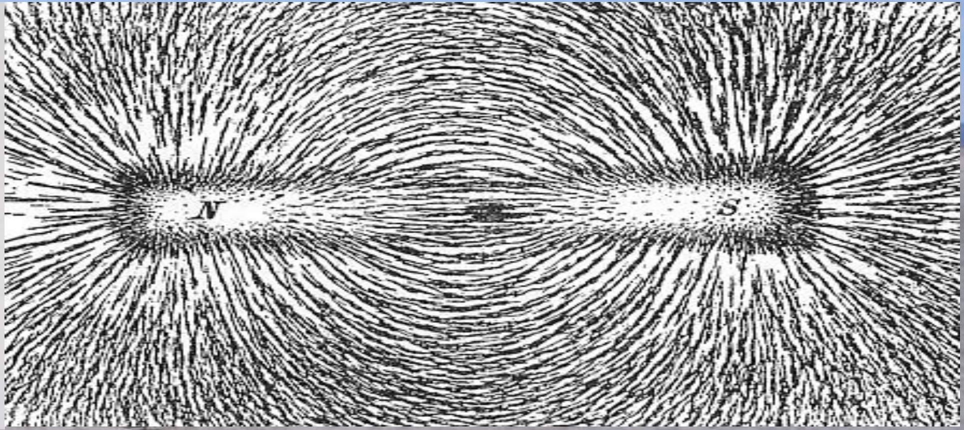


300,000 years	Formation of atoms
3 minutes	Formation of nuclei
1 micro-second	Formation of protons & neutrons
1 pico-second	Appearance of mass?

Appearance of dark matter?

Appearance of matter?

Electricity and Magnetism



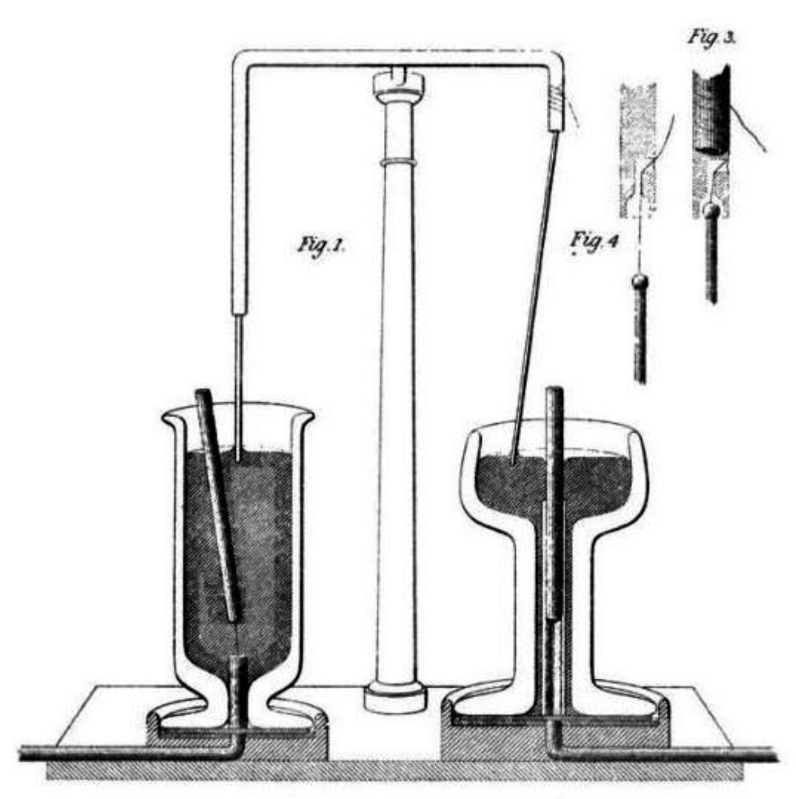
- Electricity:
  - Named using the Greek word for amber
  - Fish, lightning, …
  - Static electricity and electric currents

- Magnetism:
  - Named for the region of Greece where lodestones were found
  - Used for navigation from 12th century

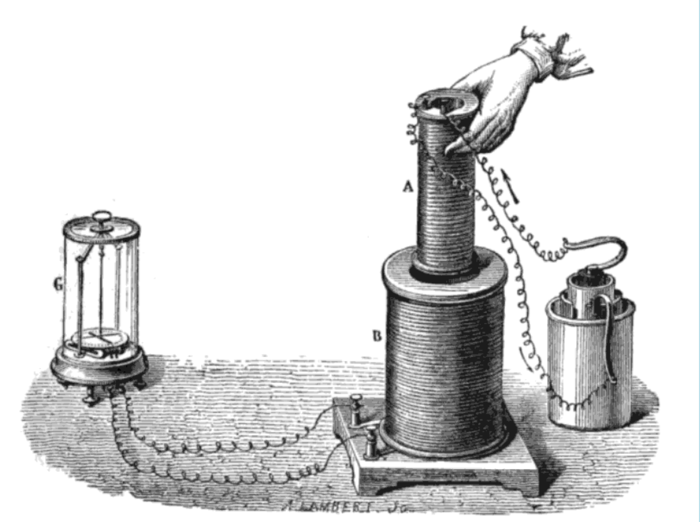
Who could have foreseen their importance for development?

Michael Faraday

- Invented the electric motor

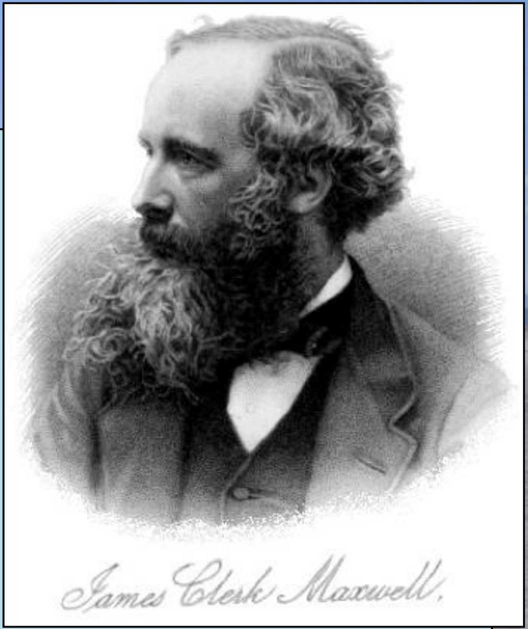


- Discovered induction



Einstein’s study had pictures of Newton, Faraday and Maxwell

James Clerk Maxwell


James Clerk Maxwell.

- Professor at King’s 1860 – 1865
- The first colour photograph
- Unified theory of electricity and magnetism
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light
- …

One scientific epoch ended and another began with James Clerk Maxwell - *Albert Einstein*

Maxwell’s Equations

- Prototype for describing particle interactions:

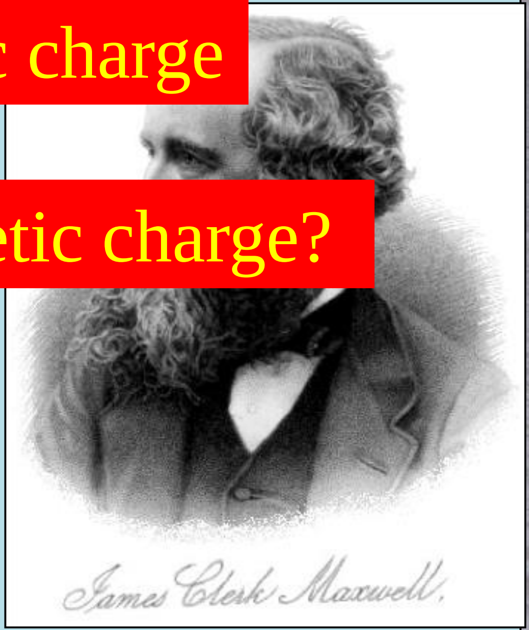
  unified electricity & magnetism

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{B} &= \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}
\end{aligned}
$$

Electric charge

Magnetic charge?

- Basis for Einstein’s theories of relativity

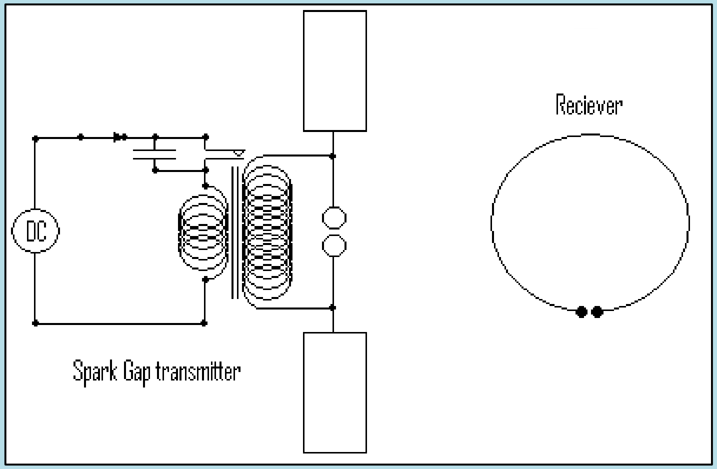


There is every probability that you will soon be able to tax it!

Maxwell to William Gladstone, then Chancellor of the Exchequer, when he asked about the practical worth of electricity

Electromagnetic Waves

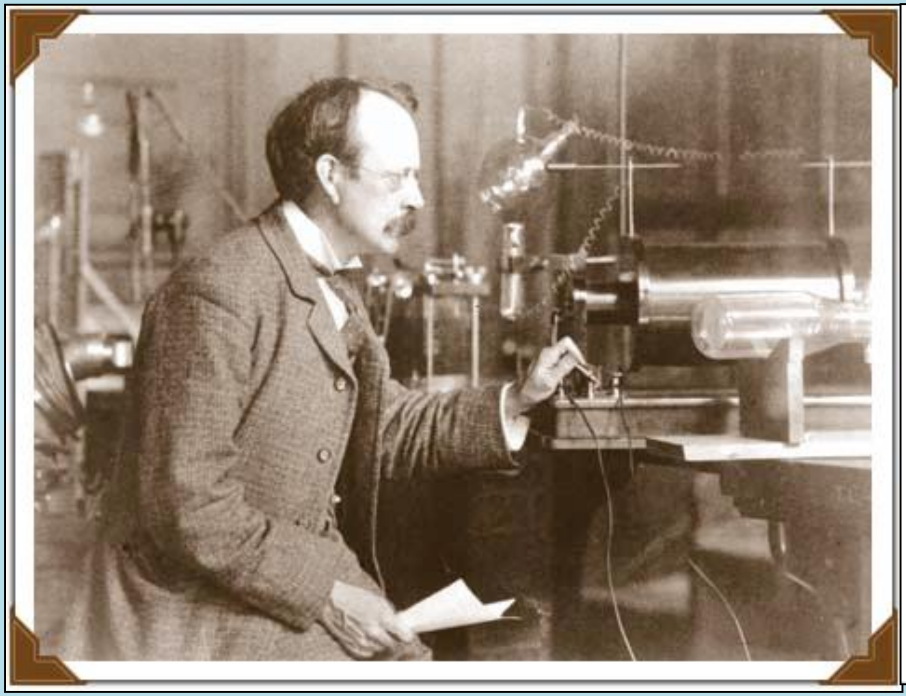
- Proposed by Maxwell
- Discovered by Hertz

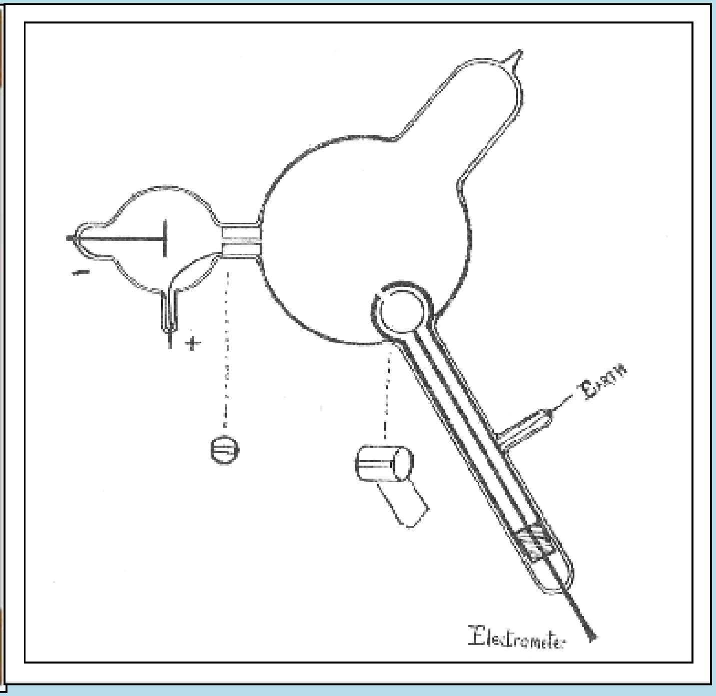


- A lot to answer for ….
- **Nobody knows where fundamental physics may lead**

The First Elementary Particle

- Discovered by J.J. Thomson in 1897





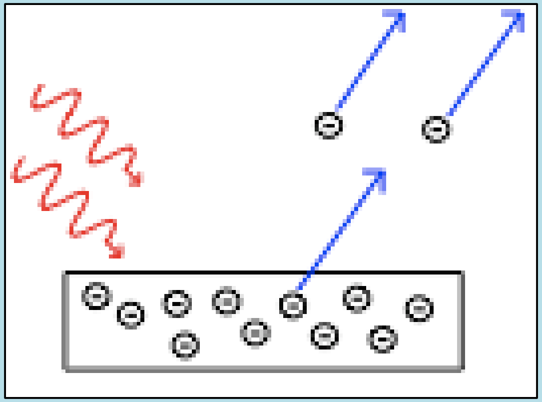
- **The electron** – the basis of the electronic industry
- Old-style TV sets used beams of electrons

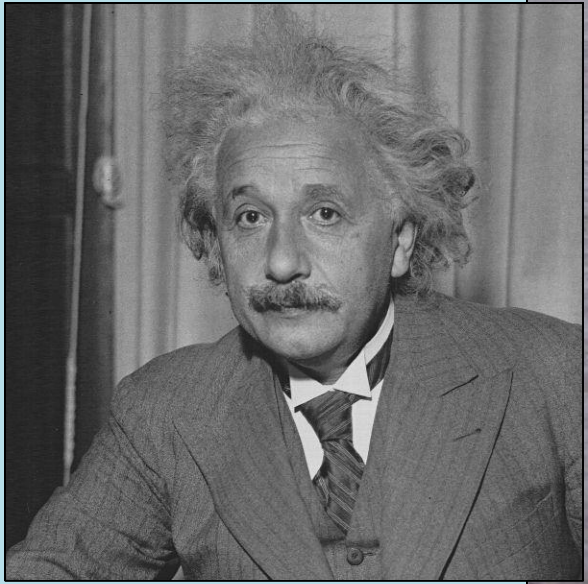
Photon: the Particle of Light

- Quantum hypothesis introduced by Planck:

$$\boxed{E = hf}$$

- Physical reality postulated by Einstein to explain photoelectric effect

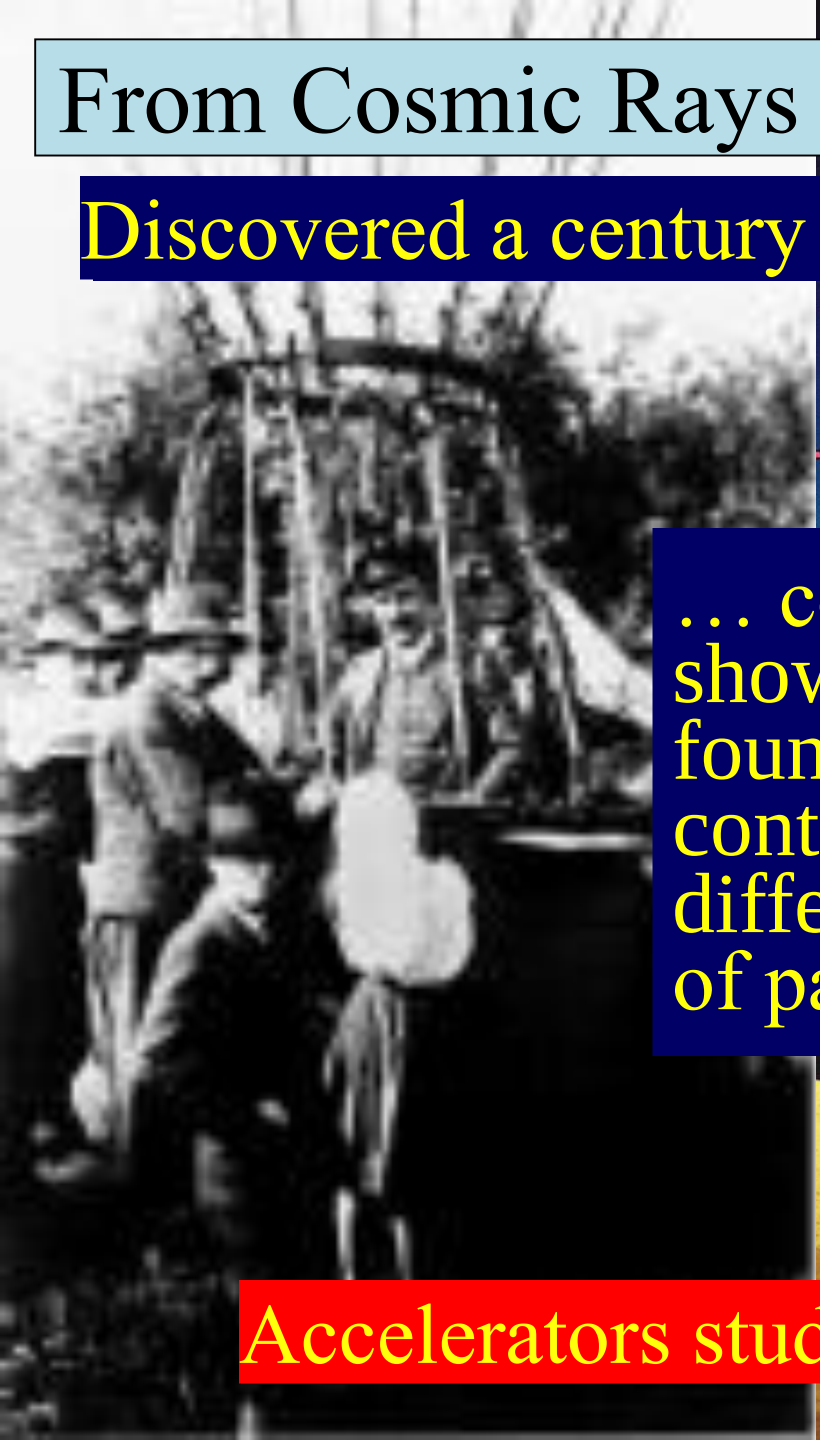


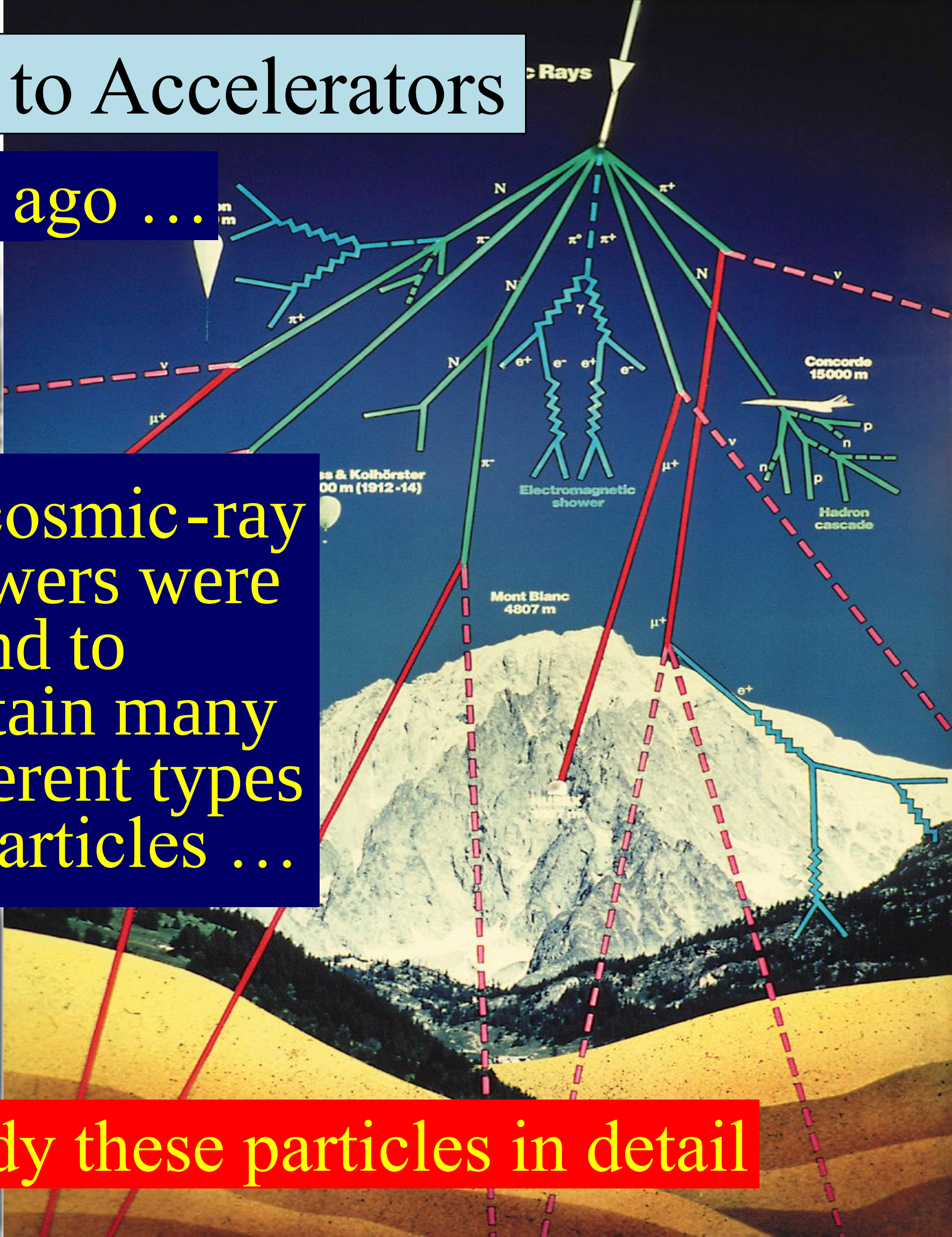


- **The reason for his Nobel Prize**

From Cosmic Rays to Accelerators

Discovered a century ago …





… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

Leptons: Particles without Strong Interactions

- 1905: First example: electron
- 1930: Continuous energy spectrum in β decay explained by missing neutrino (observed in 1956)
- 1936: Muon discovered in cosmic rays

  "Who ordered that?" (Rabi)

- 1962: Two species of neutrino: (e, ν_e), (μ, ν_μ)
- 1975: Another heavy charged lepton τ
- 2000: Third neutrino: (τ, ν_τ)
- 1990s: Large mixing between neutrino species

The Discovery of Antimatter

- Existence predicted by Dirac
- The antiparticle of the electron (the positron) was discovered in cosmic rays by Anderson

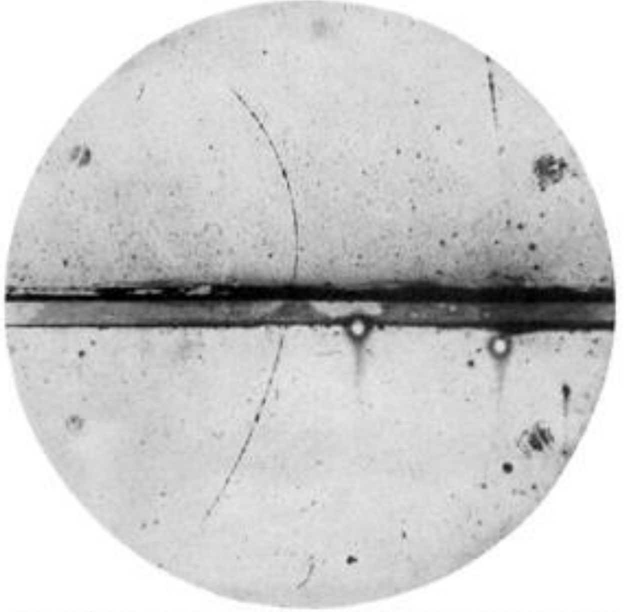


Fig. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

- The same mass as the electron, opposite electric charge
- Used in medical diagnosis (PET scanners)

Weak Interactions

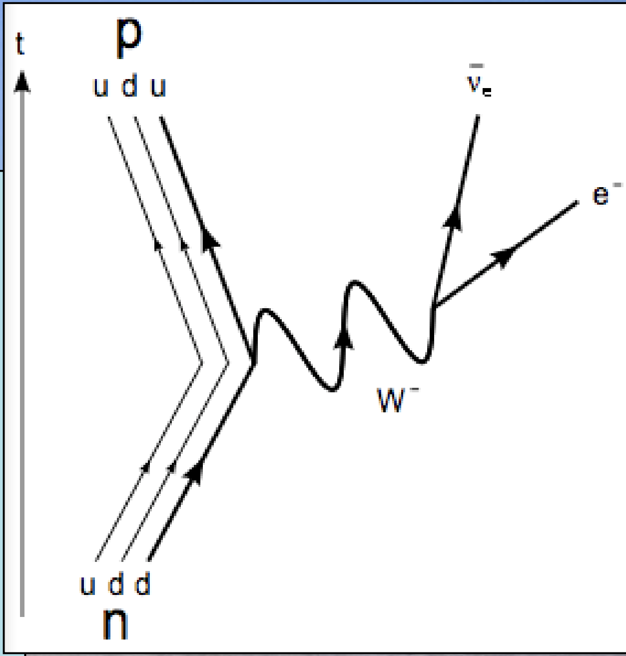
Responsible for radioactivity

Theory modelled on Maxwell

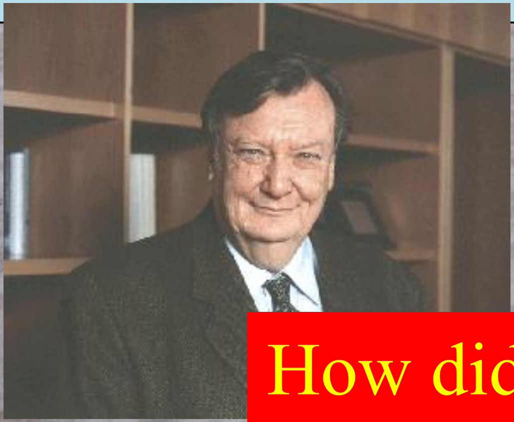
BUT

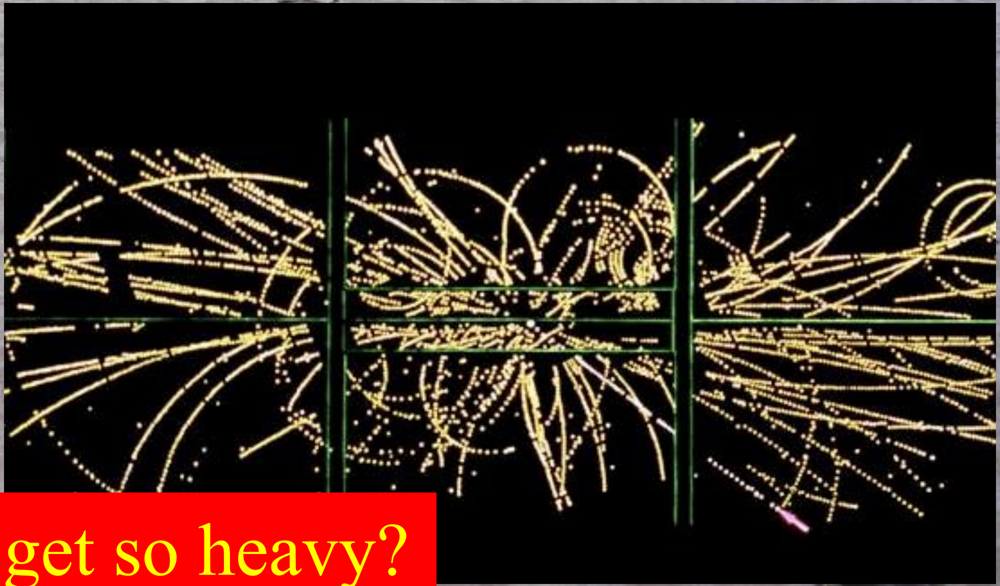
W boson - carrier of weak interactions

Predicted to weigh ~ 80 GeV



Discovered at CERN in 1983 by Carlo Rubbia et al

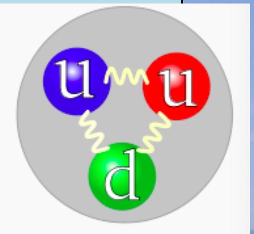


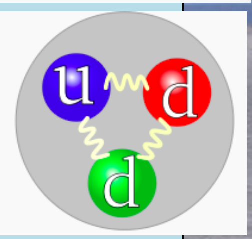


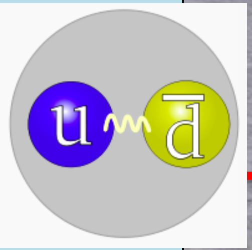
How did it get so heavy?

Hadrons: Particles with Strong Interactions

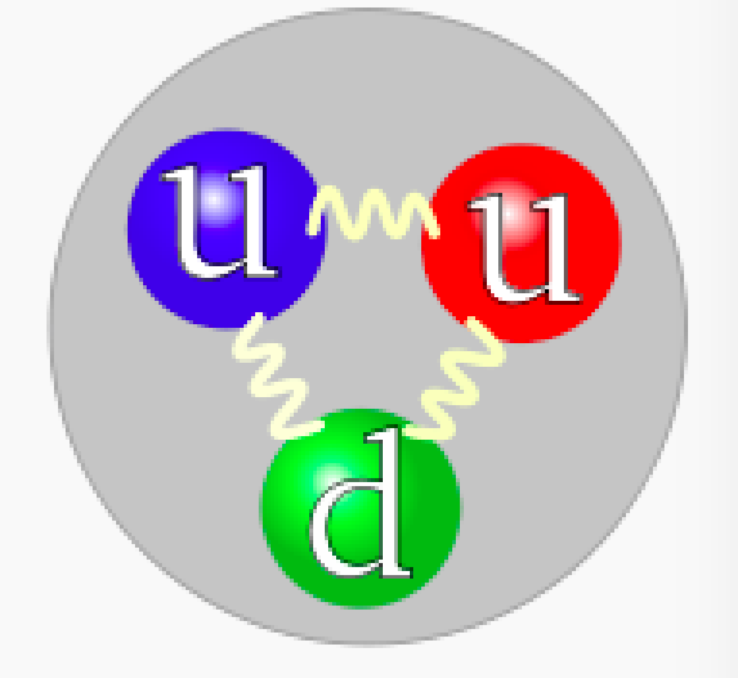
- 1917: Proton (hydrogen nucleus in nuclei)
- 1931: Neutron discovered by Chadwick
- 1935: Pion prediction by Yukawa
- 1947: Pion discovery by Powell et al
- 1947: Kaon in cosmic rays
- 1950s: Other strange particles
- 1950s: Excited states (resonances)
- 1964: Quark model
- 1973: Quantum Chromodynamics postulated
- 1974: Charm quark
- 1977: Bottom quark
- 1995: Top quark



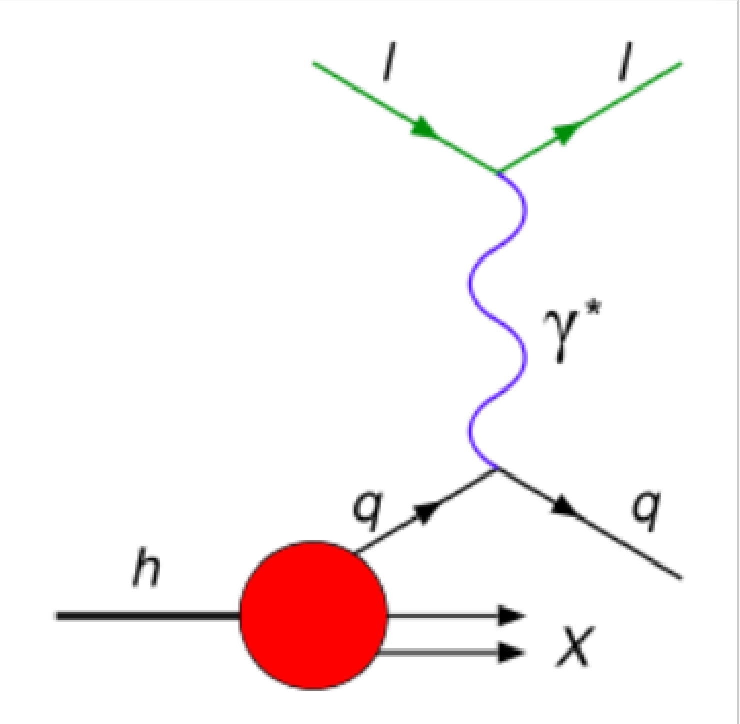




The Strong Interactions

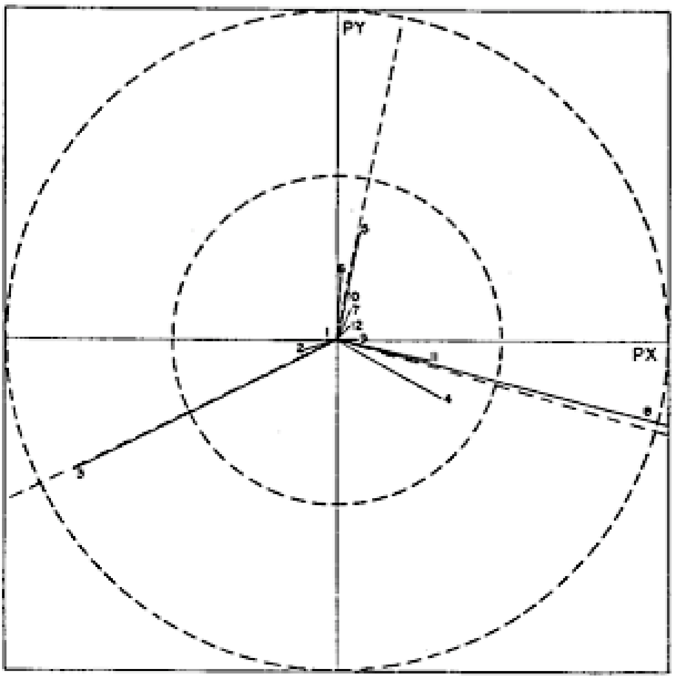


- Nuclei composed of protons & neutrons
- Protons and neutrons composed of 3 quarks held together by gluons
- Quark model provides understanding of many aspects of hadron spectroscopy
- Physical reality proven by deep inelastic electron and neutrino scattering



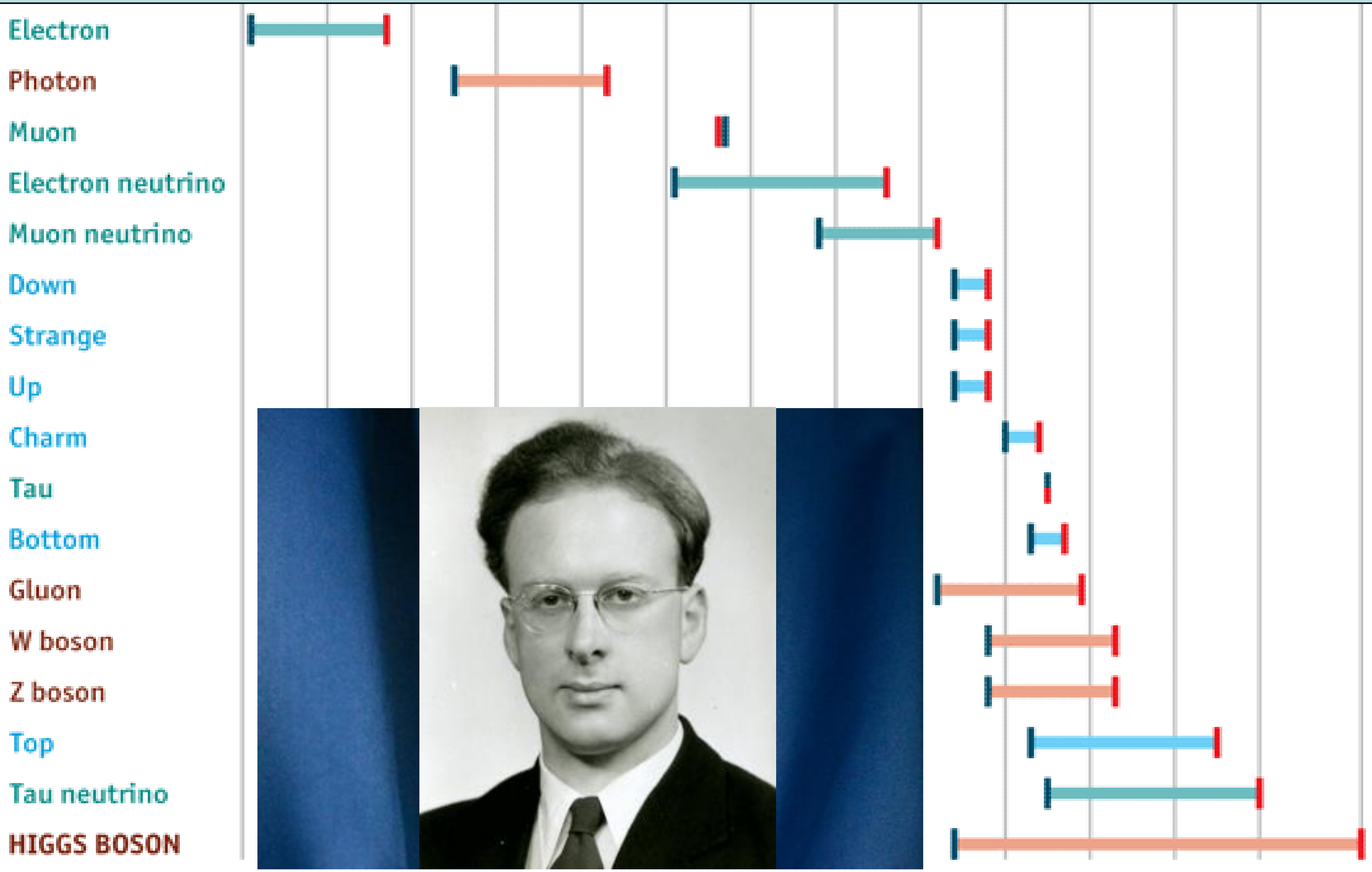
Strong Nuclear Force

- Holds quarks together inside protons inside nuclei
- Modelled after Maxwell’s theory
- Carried by ‘gluon’ particles
- First direct evidence in 1979
- Using method suggested by JE, Mary Gaillard, Graham Ross in 1976
- **Second force particle to have been discovered**



Standard Model Particles:

Years from Proposal to Discovery



Source: *The Economist*

Units

- Use units in which $\boxed{\hbar = (G_N =) c = 1}$
- First identity relates energy and time:

$$1 = 1.0546 \times 10^{-34}\text{Joules} \,.\, s = 6.582 \times 10^{-16}\ \text{eV.s}$$

- Third identity relates distance and time:

$$1 = 3 \times 10^{8}\text{ms}^{-1} \quad \Rightarrow \quad 1\text{s} \equiv 2.998 \times 10^{8}\text{m}$$

- Relation between mass and distance:

$$1\text{kg} \equiv 7.424 \times 10^{-28}\text{m}$$

- Typical particle energies:

$$\text{MeV} = 10^{6}\ \text{eV},\ \text{GeV} = 10^{9}\ \text{ev}, \text{TeV} = 10^{12}\ \text{eV}$$

- (Planck scale: $G_N = 1$ ➔energy 10^{19} GeV = 1)

Special Relativity

- Proper time: $\delta\tau^2 = t^2 - x^2 - y^2 - z^2$
- Invariant mass: $m^2 = E^2 - p^2$
- Minkowski metric:

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- Lorentz transformation:

$$\bar{t} = \gamma(t - vx)\ , \qquad \bar{x} = \gamma(x - vt)\ , \qquad \bar{y} = y\ , \qquad \bar{z} = z$$

- Lorentz factor: $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$ $\quad E = m\gamma$

Quantum Mechanics

- Definite predictions replaced by probabilities
- Probabilities determined by complex wave functions (amplitudes):

$$P = |\psi|^2$$

- Cannot determine simultaneously

(position, momentum): $\Delta x \, \Delta p \geq h/2\pi$

(energy, time): $\Delta E \, \Delta t \geq h/2\pi$

- $[x, p] = ih/2\pi$, $[E, t] = ih/2\pi$; $E \to i\partial_t$,$p_j \to -i\partial_j$

Wave Equations

- Schrödinger equation

$$E = \frac{p_j^2}{2m}, \quad E \to i\partial_t, \quad p_j \to -i\partial_j$$

$$\Rightarrow \quad i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[\frac{-\hbar^2}{2\mu}\nabla^2 + V(\mathbf{r},t)\right]\Psi(\mathbf{r},t)$$

- Klein-Gordon equation for spin 0:

$$E^2 = p_j^2 + m^2 \quad \Rightarrow \quad \partial_\mu\partial^\mu\Psi + m^2\Psi = 0$$

- Dirac equation for spin ½:

$$(i\gamma^\mu\partial_\mu + m)\Psi = 0$$ (antimatter)

- Derived from Lagrangian: $L = \int d^3x \mathcal{L}(\phi, \partial_\mu\phi)$
- Action: $S = \int dt L = \int d^4x \mathcal{L}$

Lagrangian Formulation

- $L = \int d^3x \mathcal{L}(\phi, \partial_\mu \phi)$ & $\partial_\mu \left(\frac{\delta \mathcal{L}}{\delta(\partial_\mu \phi)} \right) - \frac{\delta \mathcal{L}}{\delta \phi} = 0$
- Lagrangian for spin 0:

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - m^2 \phi^* \phi$$

- To get Klein-Gordon equation:

Use $\left(\frac{\delta \mathcal{L}}{\delta(\partial_\mu \phi)} \right) = \partial^\mu \phi^*$ to obtain $\partial_\mu \partial^\mu \phi + m^2 \phi = 0$

- Lagrangian density for Maxwell’s equations:

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - j^\mu A_\mu$ where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

(A_μ vector potential, j_μ current)

Maxwell’s Equations

- Electric and magnetic fields in terms of A_μ:

  $E_i = \partial_0 A_i - \partial_i A_0$ $B_1 = \partial_2 A_3 - \partial_3 A_2$
- Field strength: $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
- Maxwell’s equations:
  - Identity:

$$\partial_\rho F_{\mu\nu} + \partial_\mu F_{\nu\rho} + \partial_\nu F_{\rho\mu} = 0 \rightarrow \dot{\mathbf{B}} + \nabla \times \mathbf{E} = 0$$

  - Lagrange equations:

$$\partial^\mu F_{\mu\nu} = 0 \rightarrow \dot{\mathbf{E}} - \nabla \times \mathbf{B} = 0$$

$$\partial^\mu F_{\mu\nu} = 0 \rightarrow \nabla \cdot \mathbf{E} = 0$$

Charges, Currents and Symmetries

- Symmetry: charge Q = $\int$ j_0 dt conserved if current $j^\mu \equiv \left(\frac{\delta\mathcal{L}}{\delta(\partial_\mu\Psi)}\Psi\right)$ conserved: $\partial_\mu\left(\frac{\delta\mathcal{L}}{\delta(\partial_\mu\Psi)}\Psi\right) = 0$
- Global or local symmetry?

  e.g., U(1) phase: $U(\alpha) = e^{i\alpha}$ local? $\alpha = \alpha(x_\nu)$
- Maxwell's equations have local U(1)

$$A_\mu \longrightarrow A'_\mu = A_\mu + \partial_\mu\lambda(x,y,z,t) \rightarrow F'_{\mu\nu} = F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- Extend to matter via covariant derivative:

$$\partial_\mu \to D_\mu \equiv \partial_\mu - ieA_\mu \rightarrow D_\mu\Psi \to e^{i\alpha(x)}D_\mu\Psi : \lambda = \frac{1}{e}\alpha$$

- Lagrangian of QED: $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu\Psi + m\bar{\Psi}\Psi$

Lagrangian of QED

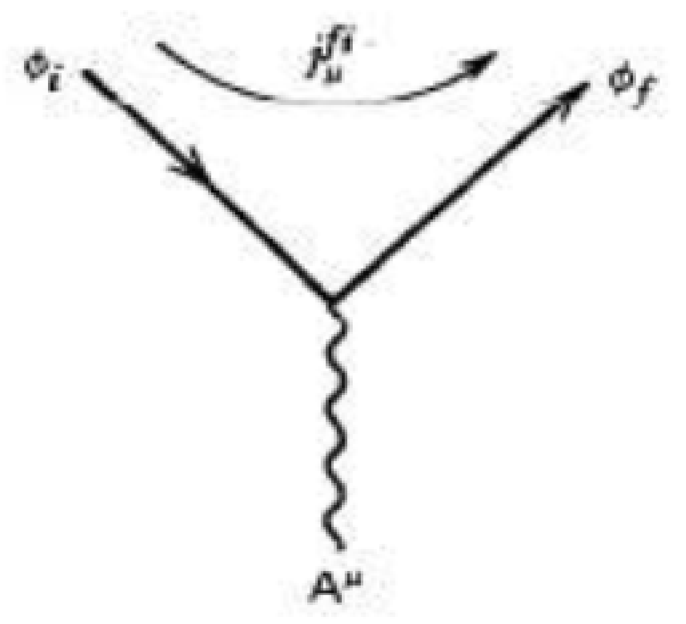
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\gamma^{\mu}D_{\mu}\Psi + m\bar{\Psi}\Psi$$

Maxwell’s equations + photoelectric effect + fermion mass

- U(1) gauge invariance

$$A_\mu \longrightarrow A'_\mu = A_\mu + \partial_\mu \lambda$$

$$\partial_\mu \to D_\mu \equiv \partial_\mu - ieA_\mu$$



- Fermion-fermion-photon interaction
- Consequence of gauge symmetry

Feynman Diagrams

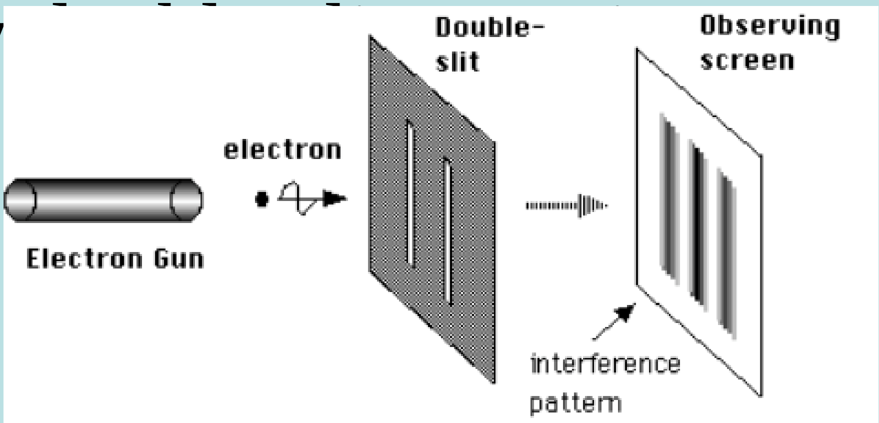
- Quantum mechanics = sum over all paths
- Exemplified by

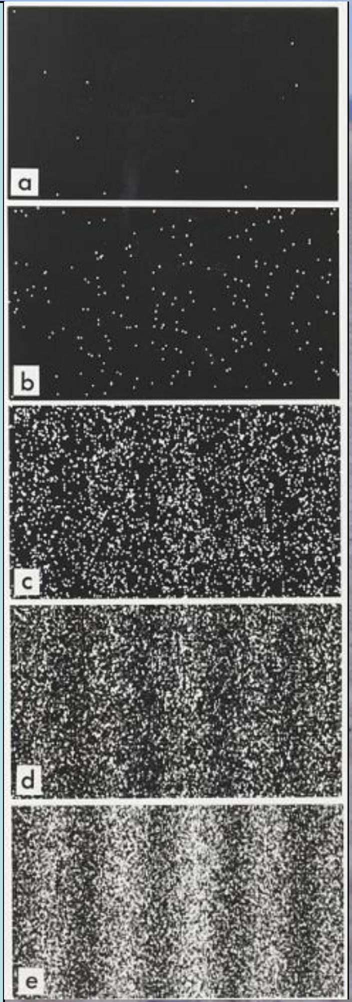
  photons &

  electrons:

  interference

  (one by one)



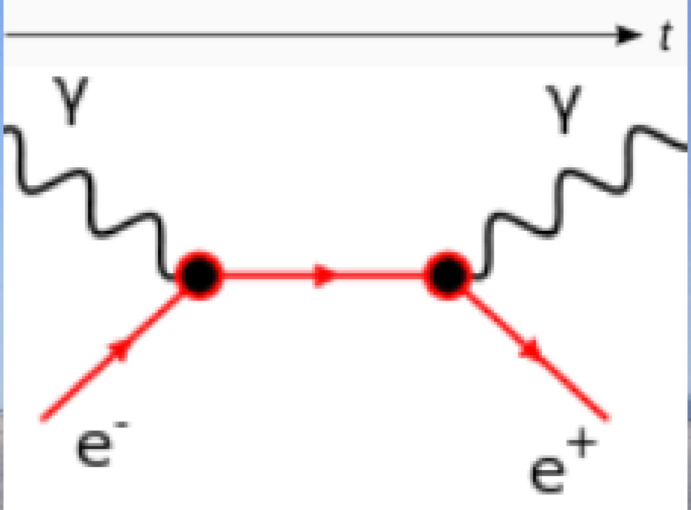


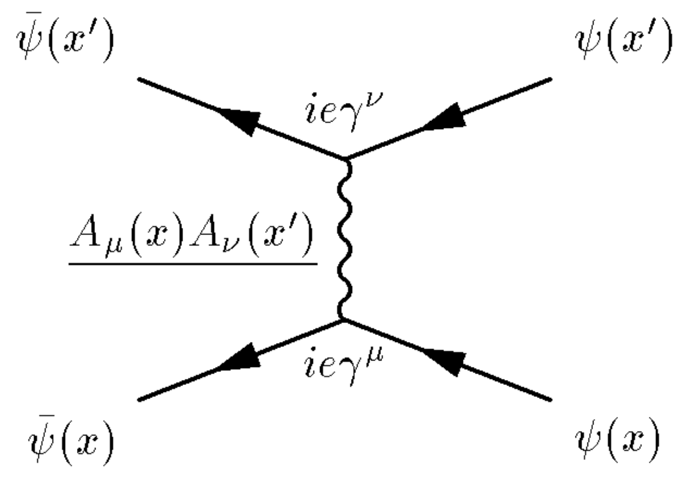
- Possible in $e\bar{\Psi}\gamma^{\mu}A_{\mu}\Psi \;=\; j^{\mu}A_{\mu}$ l from L:

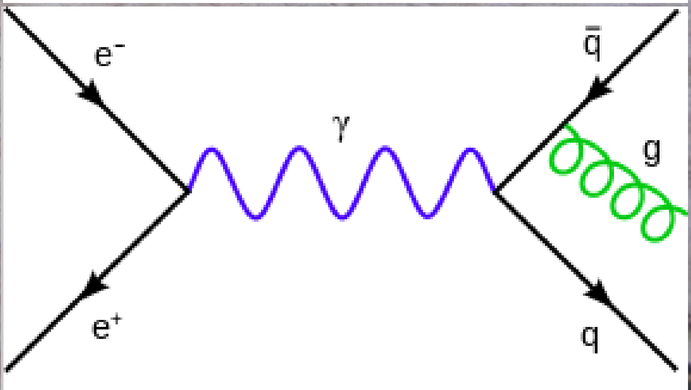
- Write all possible paths = diagrams

Diagrams for Simple Processes

- Photon scattering on electron (Compton)
  - photoelectric effect
- Scattering process
  - with detailed factors
- Electron-positron annihilation to quark + antiquark + gluon







Quantum Electrodynamics

- Lagrangian of QED:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

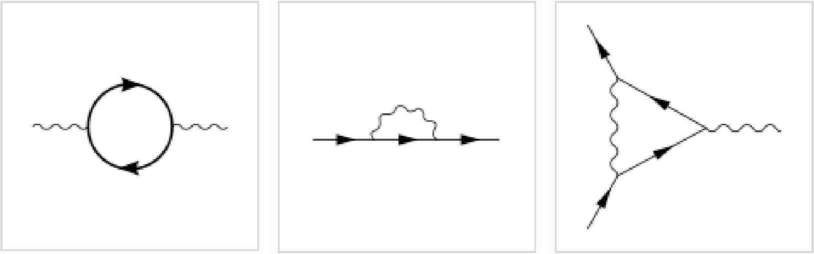
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- Equations of motion:

$$\partial_\mu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\psi)}\right) - \frac{\partial\mathcal{L}}{\partial\psi} = 0$$

$$\partial_\nu F^{\nu\mu} = e\bar{\psi}\gamma^\mu\psi$$

- Renormalizable quantum field theory
- Successful accurate predictions in perturbation theory:
  - – 10^{-12} for anomalous magnetic moment of electron, **but muon?**



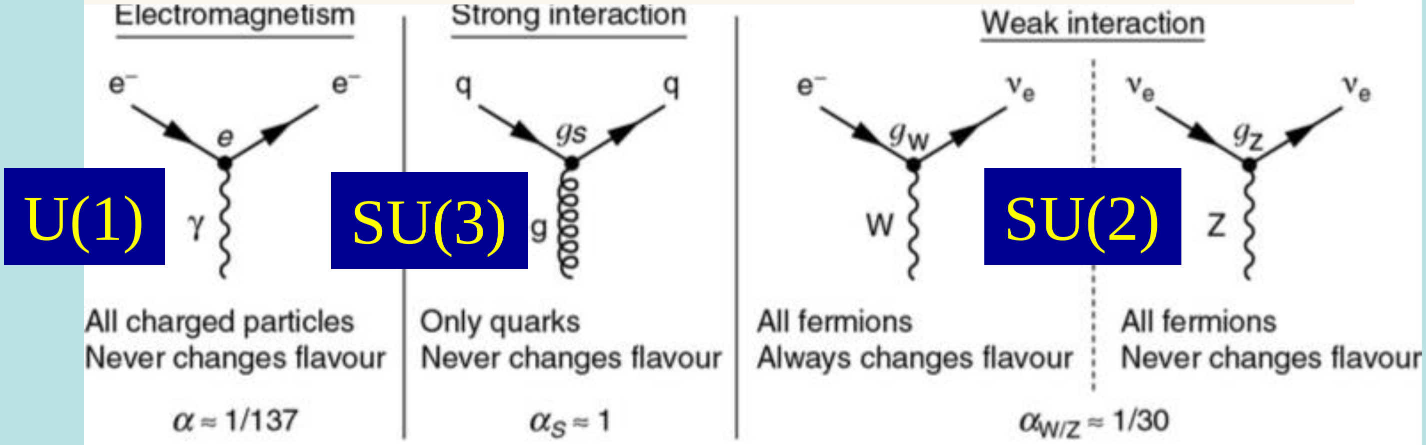
Beyond U(1) Gauge Symmetry

- Generalize phase to matrix:

$$\Psi_i \to U_i^j \Psi_j \qquad D_\mu \Psi \to U D_\mu \Psi \qquad D_\mu = \partial_\mu + i g T_a G^a_\mu$$

- Representation matrix $[T_a, T_b] = i f_{ab}{}^c T_c$
- Standard Model covariant derivative:

$$D_\mu = \partial_\mu \overset{\text{U(1)}}{- i \frac{Y}{2} g_1 B_\mu} \overset{\text{SU(2)}}{- i g_2 \frac{\sigma_j}{2} W^j_\mu} \overset{\text{SU(3)}}{- i g_3 \frac{\lambda_a}{2} G^a_\mu}$$



Quantum Chromodynamics

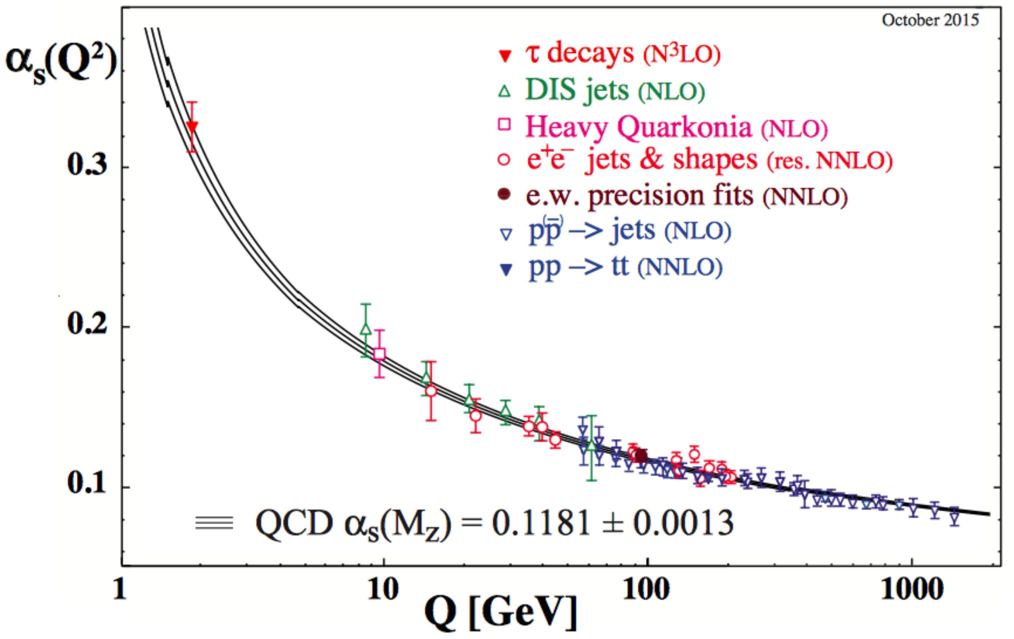
- Theory of the strong interactions
- Quarks interact by exchanging massless gluons
- Lagrangian similar to QED

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- Gluon field strength: $G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc} \mathcal{A}^b_\mu \mathcal{A}^c_\nu$
- Trilinear and quartic self-interactions of gluons
- Strong interaction weaker at small distances
- “Asymptotic freedom”

Asymptotic Freedom

- QCD: strong force weaker at higher energies (shorter distances)
- Confirmed by many experiments:



- Stronger at larger distances: quarks confined

Quantum Electrodynamics

- Lagrangian of QED:

$$\boxed{\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}} \quad \boxed{F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu}$$

- Equations of motion:

$$\boxed{\partial_\mu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\psi)}\right) - \frac{\partial\mathcal{L}}{\partial\psi} = 0} \quad \boxed{\partial_\nu F^{\nu\mu} = e\bar{\psi}\gamma^\mu\psi}$$

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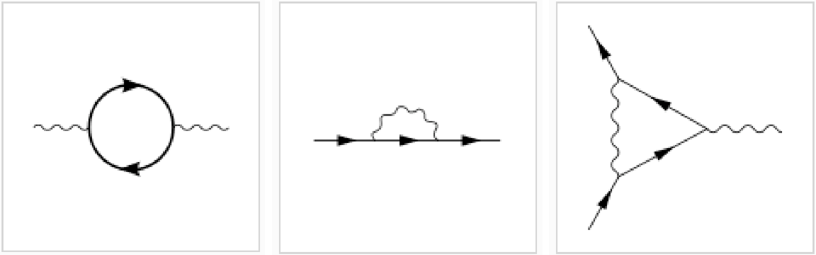


Weak Interactions

- Interactions of lepton doublets: $L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$
- Charged-current interactions:

$$\mathcal{L}_{cc} = \frac{-g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \nu_{L\alpha} \gamma_\mu l_{L\alpha} W^\mu \ + \ h.c.$$

- Neutral-current interactions:

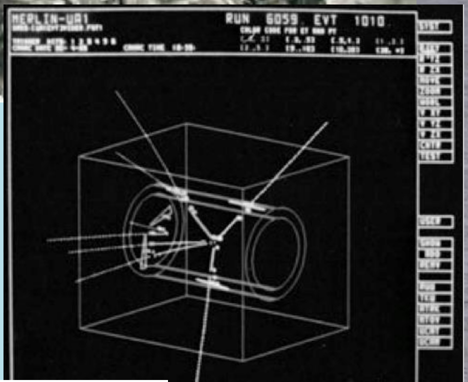
$$\mathcal{L}_{nc} = \frac{-g}{2\cos\theta_W} \sum_{\alpha=e,\mu,\tau} \nu_{L\alpha} \gamma_\mu l_{L\alpha} Z^\mu \ + \ h.c$$

- Mixing between quark types (flavours):

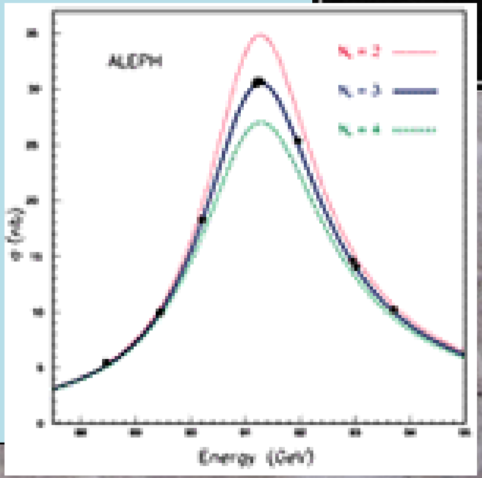
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Also fundamental constants

Neutral-Current Weak Interactions



- Discovered at CERN in 1973 by Gargamelle Collaboration
- **Breakthrough leading to the Standard Model**
- Carrier particle (Z boson) discovered at CERN in 1983 by Rubbia et al
- Measured in great detail at CERN in 1990s
- **Accurate confirmation of the Standard Model**



Does the ‘Higgs’ have Spin Zero ?

750?

- Polar angle distribution for $X_2 \rightarrow W^+W^-$
- Polar angle distribution for $X_0 \rightarrow W^+W^-$

  (for $\varphi = \pi$)

JE, Hwang: arXiv:1202.6660