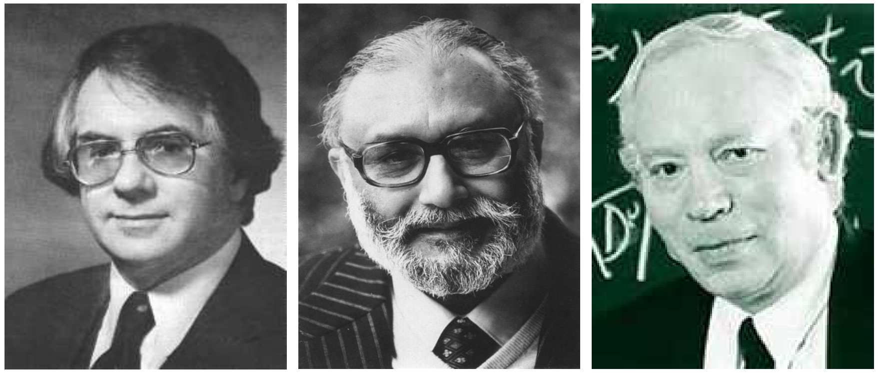
part II: **Weak Interactions**

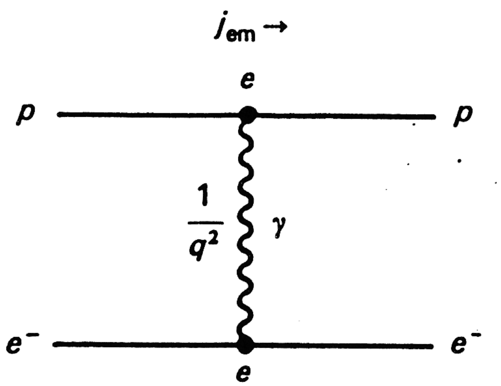
The Theory of GLASHOW, SALAM and WEINBERG ~ 1959-1968

more details:
lecture H. Kim

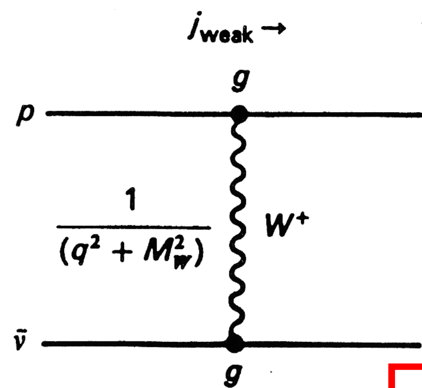


(Nobel 1979)

Theory of the unified weak and electromagnetic interaction, transmitted by exchange of "intermediate vector bosons"



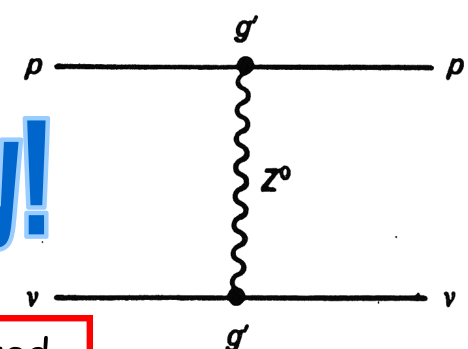
(a) Electromagnetic scattering



(b) Weak scattering (charged current)

heavy!

mass generated by Higgs field



(c) Weak scattering (neutral current)

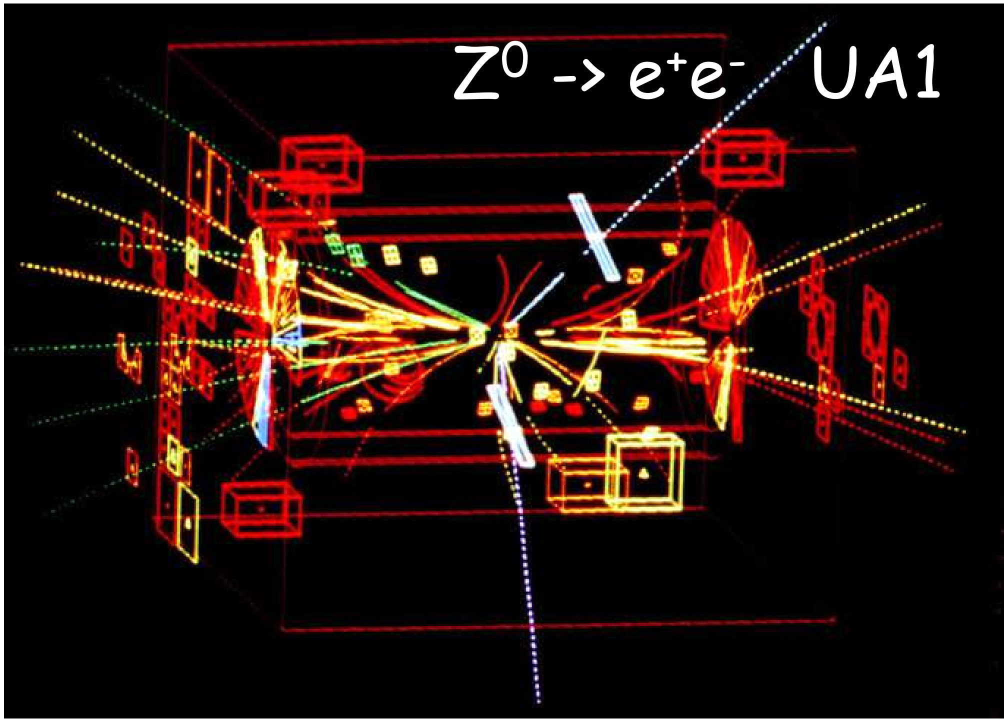
Discovery of the W and Z (1983)

- To produce the heavy W and Z bosons (m ~ 80-90 GeV) need high energy collider!
- 1978-80: conversion of SPS proton accelerator at CERN into proton-antiproton collider
  challenge: make antiproton beam!
- success!
  -> first W and Z produced 1982/83

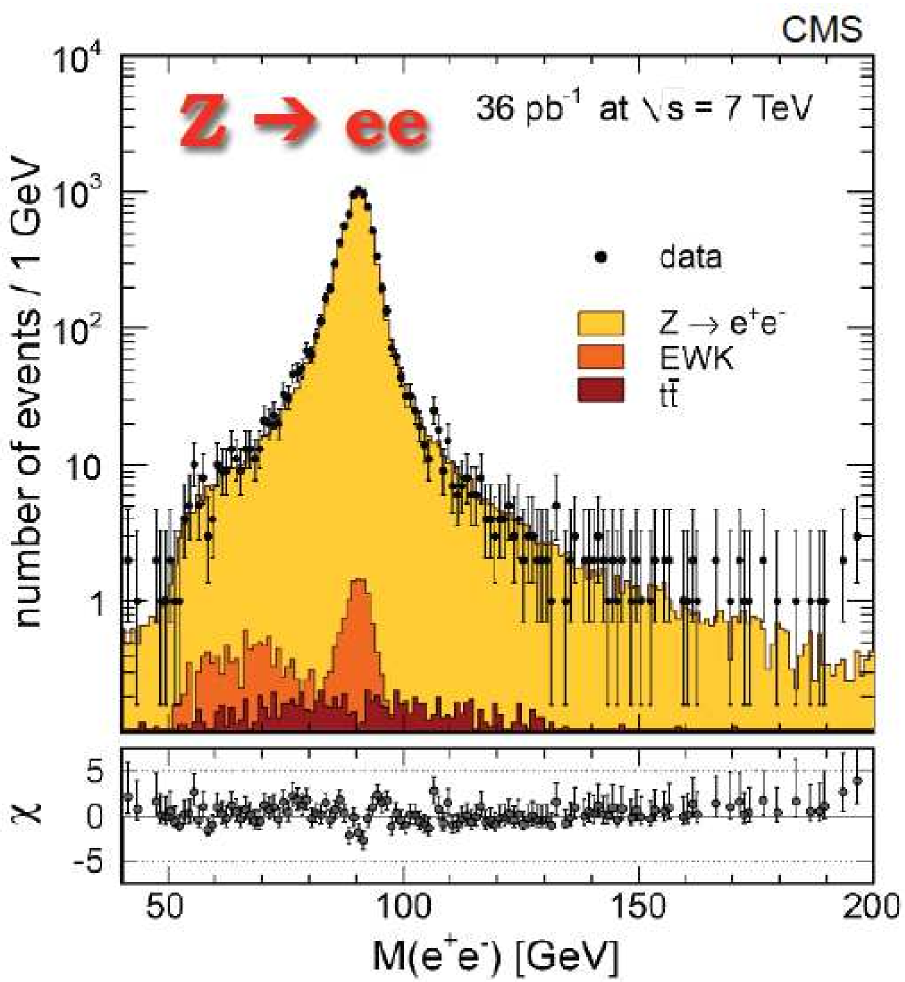
(Nobel 1984)

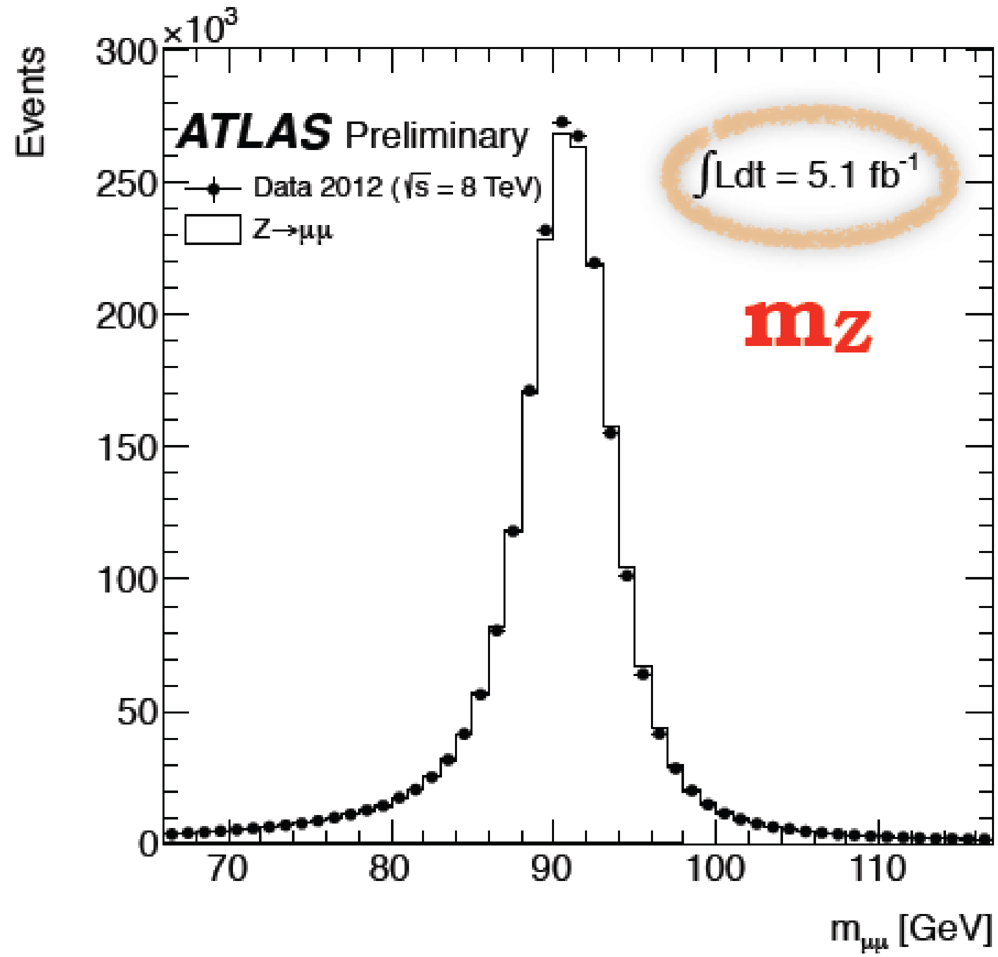
Carlo Rubbia

Simon van der Meer



Z production at LHC





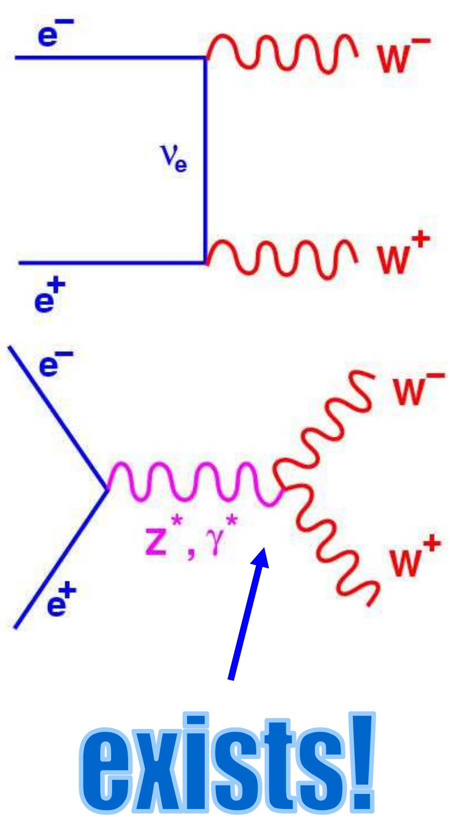
Now millions of events …

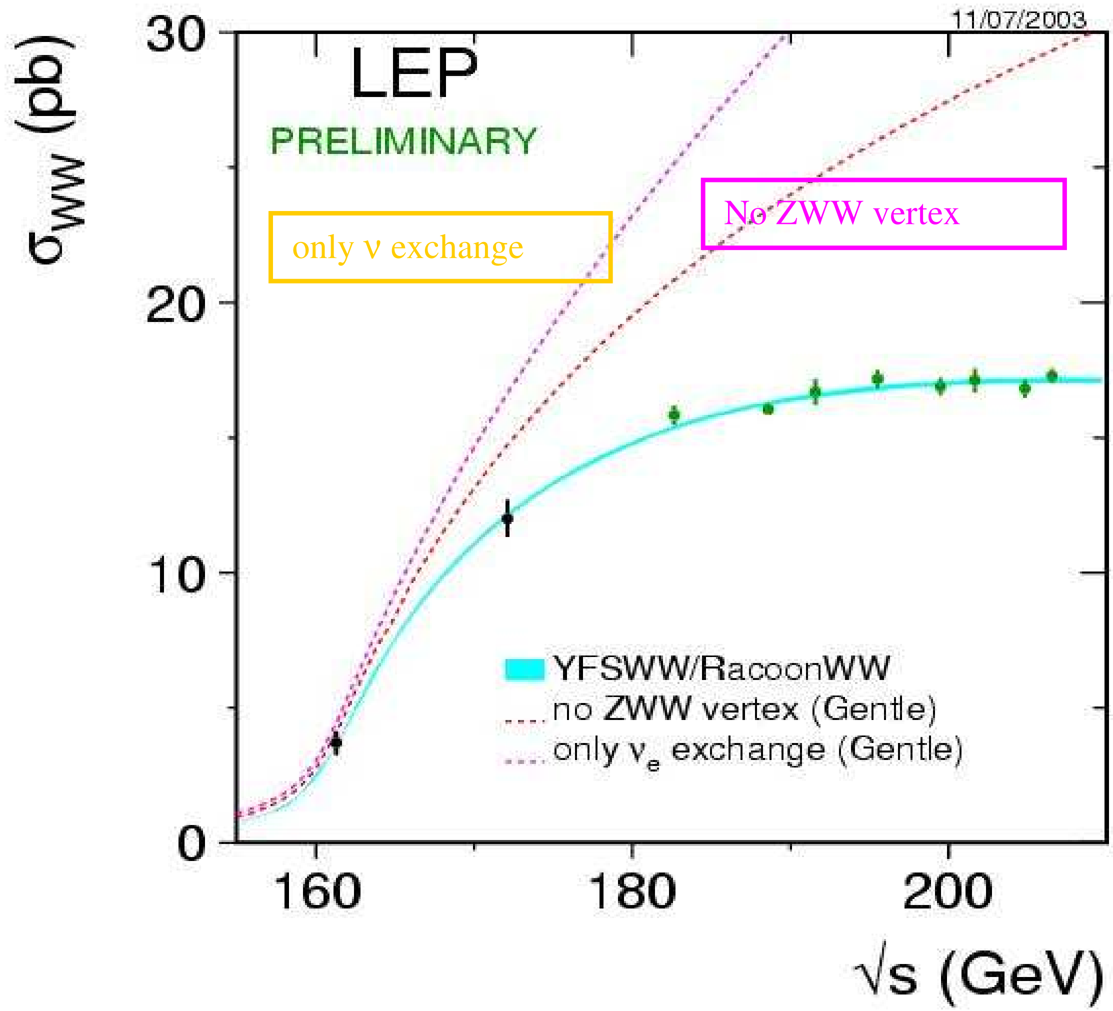
yesterday's signal is today's background and tomorrow's calibration

Three Boson Coupling @ LEP

W/Z bosons carry electroweak charge (like colour for gluons)

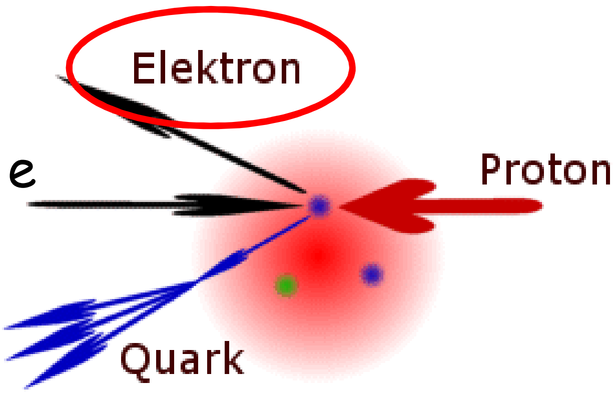
-> measure rate of W pair production at LEP II

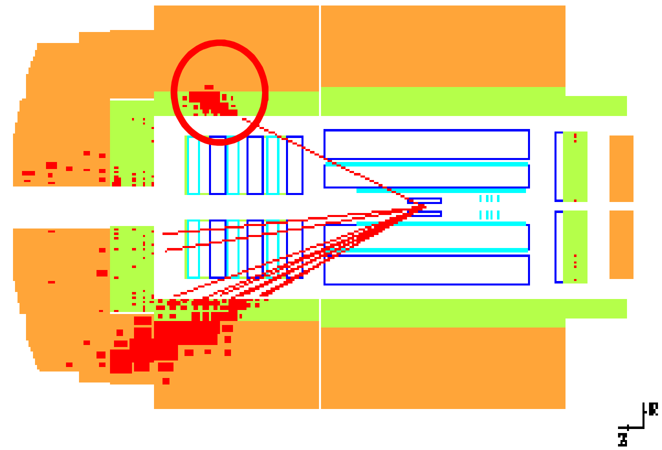


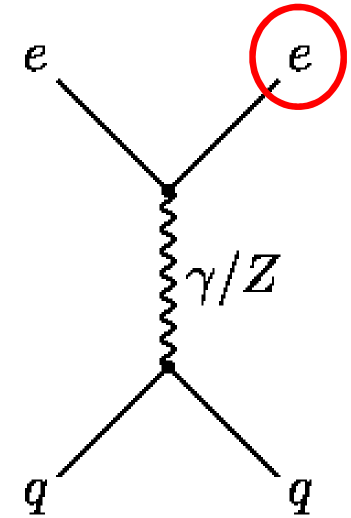


Electroweak Physics at HERA

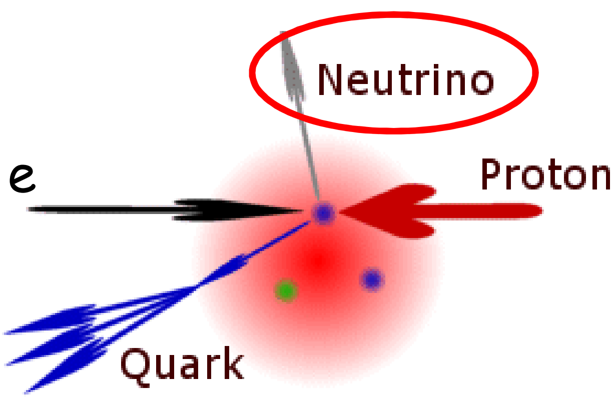
Neutral Current (NC) interactions

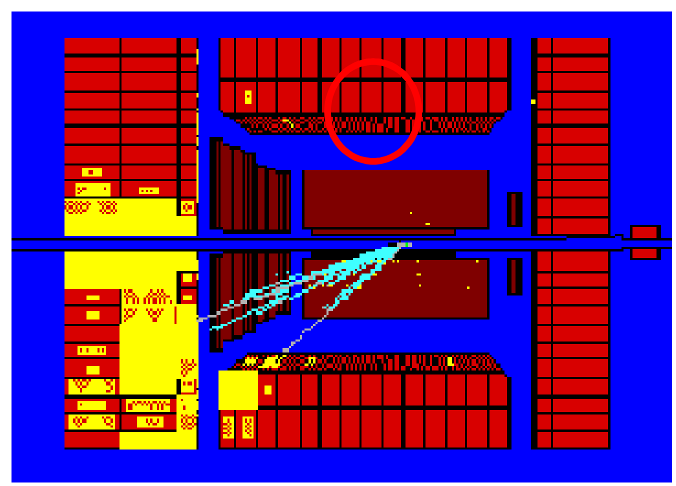


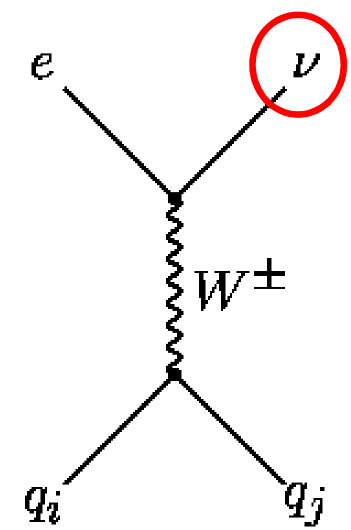




Charged Current (CC) interactions

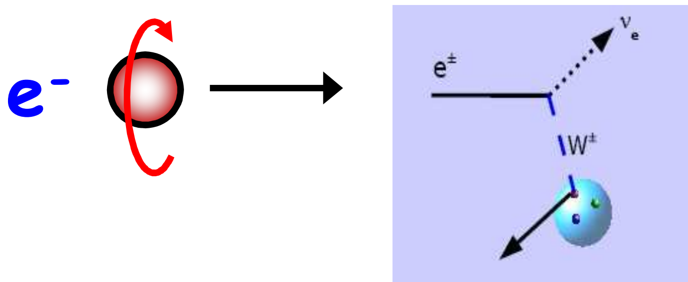




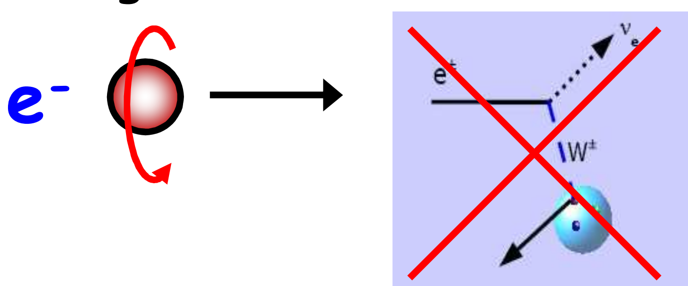


Weak interactions are "left-handed"

- lefthanded electrons interact (CC)

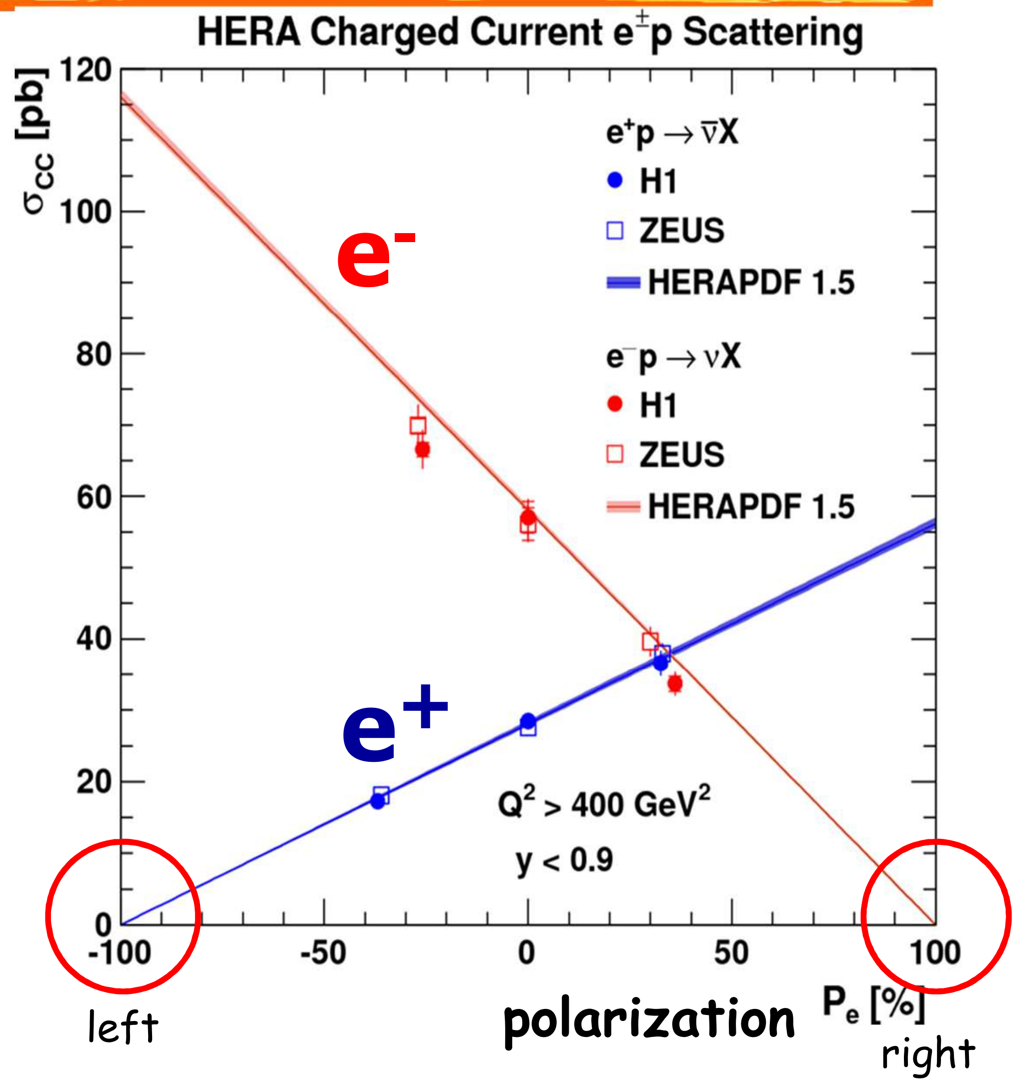


- righthanded electrons do not!



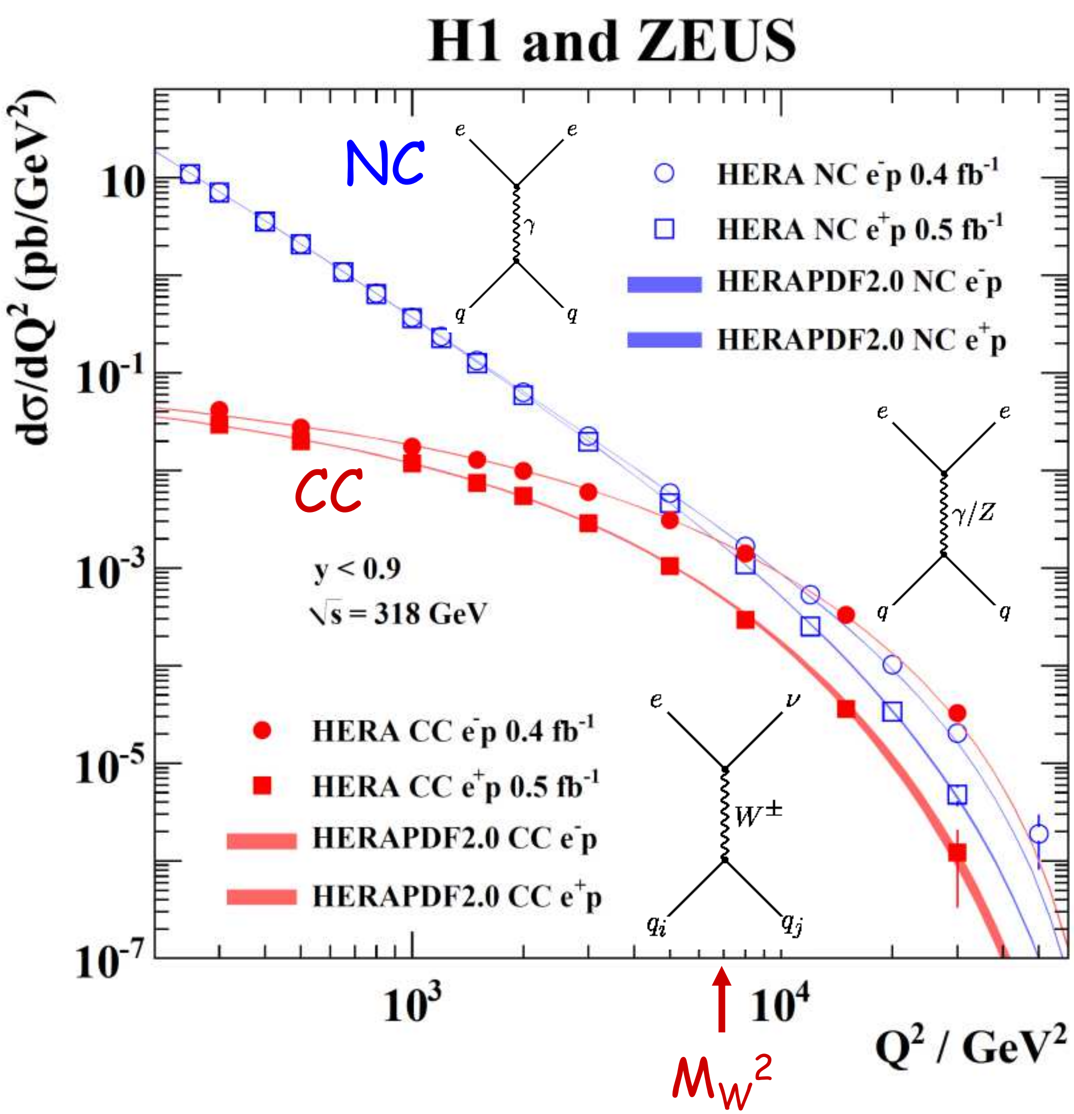
- cross section linearly proportional to polarization

$$\sigma_{polCC}^{e^{\pm}p} = (1 \pm P_e) \cdot \sigma_{unpolCC}^{e^{\pm}p}$$



It works!

Electroweak Unification

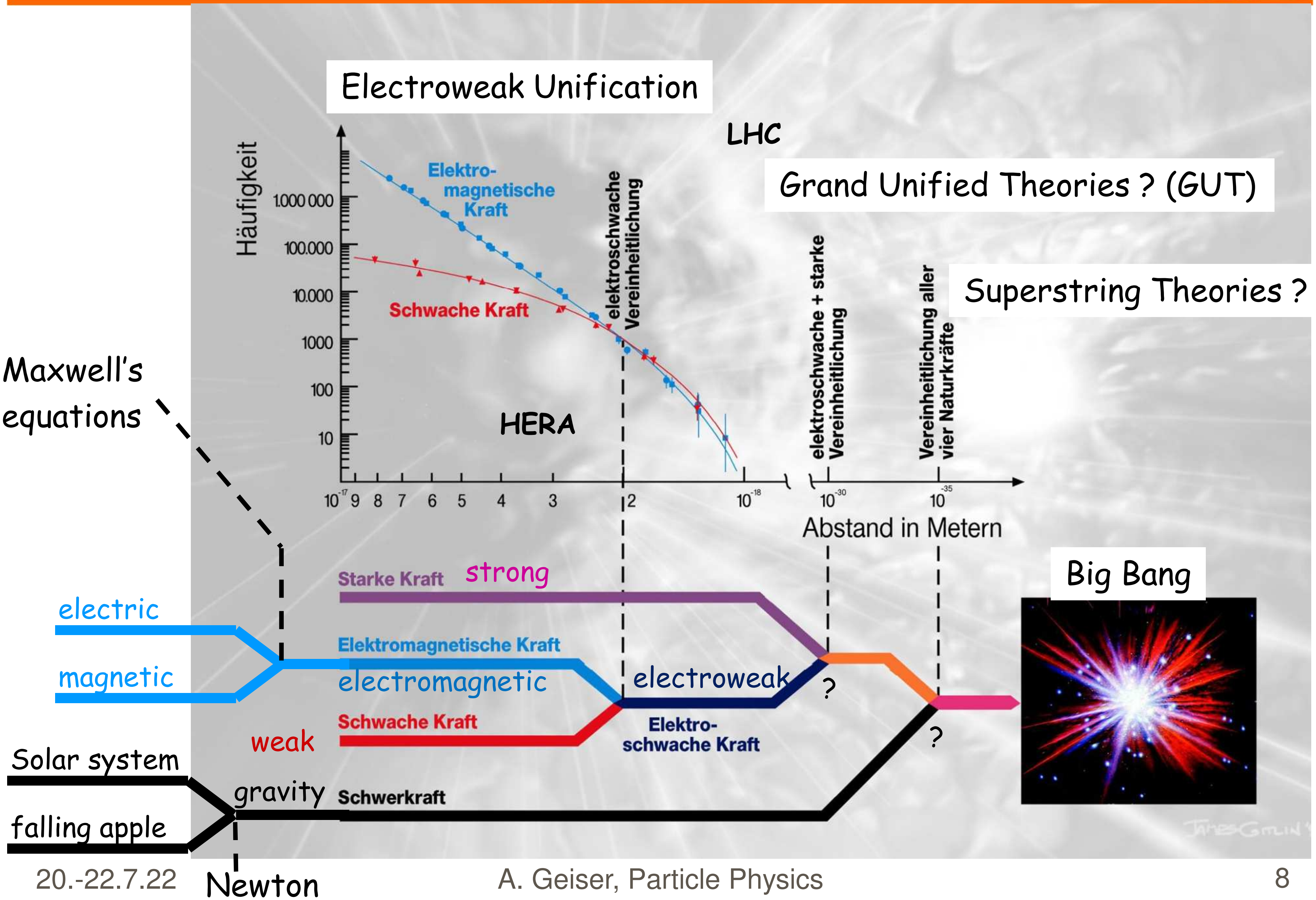


Strengths of weak and electromagentic forces become similar at scale $Q^2 \sim M_W^2$

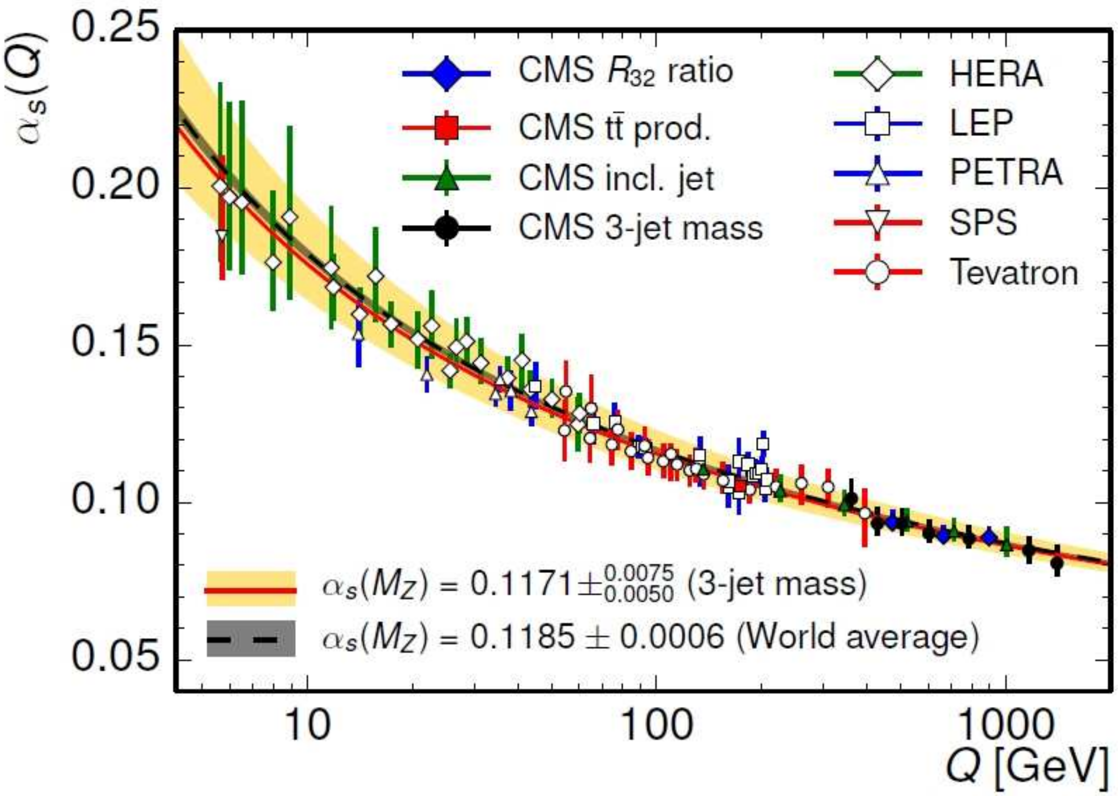
$$\frac{d^2\sigma_{NC}}{dQ^2\,dx} \sim \alpha^2 \quad \frac{1}{Q^4} \quad \frac{1}{x}\Phi_{NC}(x,Q^2)$$

$$\frac{d^2\sigma_{CC}}{dQ^2\,dx} \sim G_F^2 \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{1}{x}\Phi_{CC}(x,Q^2)$$

The Quest for Unification of Forces

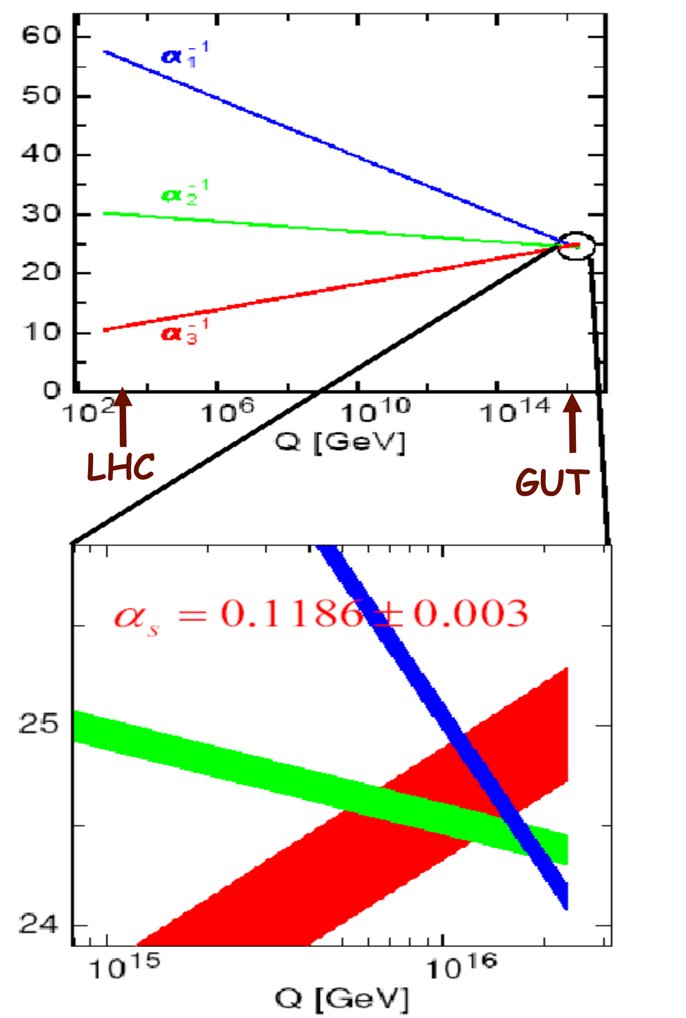


α_s running and Grand Unification



?

with SUSY (see later):



hep-ph/0407067 B.Allanach ... P.Zerwas

Antimatter

P.A.M. Dirac

(Nobel 1933)

relativistic Schrödinger equation
(Dirac equation)
two solutions:

one with positive, one with negative energy

Dirac: interpret negative solution as **antiparticle**

C.D.Anderson

(Nobel 1936)

1932 antielectrons (positrons) found in conversion of energy into matter

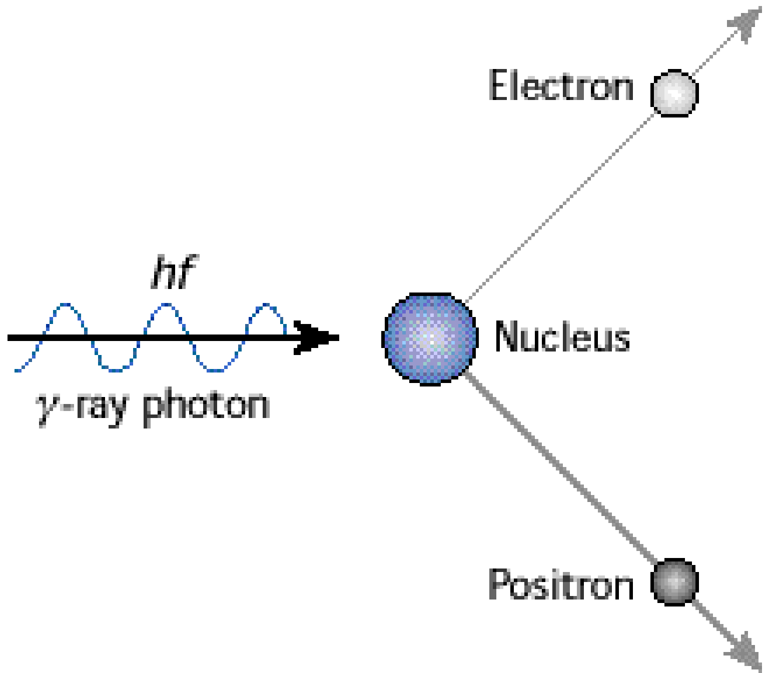
1995 antihydrogen consisting of antiprotons and positrons produced at CERN

In principle: antiworld can be built from antimatter
In practice: produced only in accelerators and in cosmic rays

Why???

Pair Production

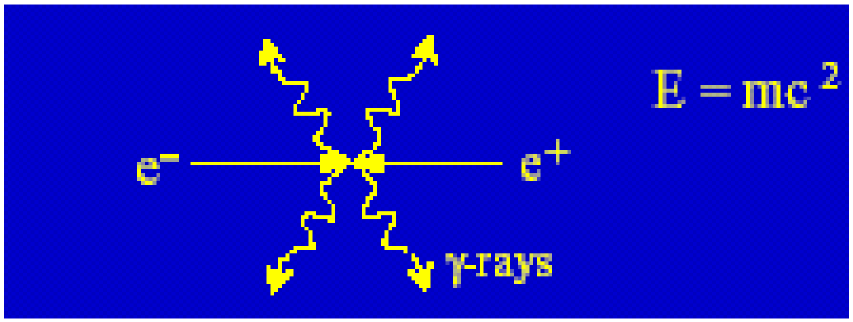
e.g. $\gamma \rightarrow e^{+} + e^{-}$

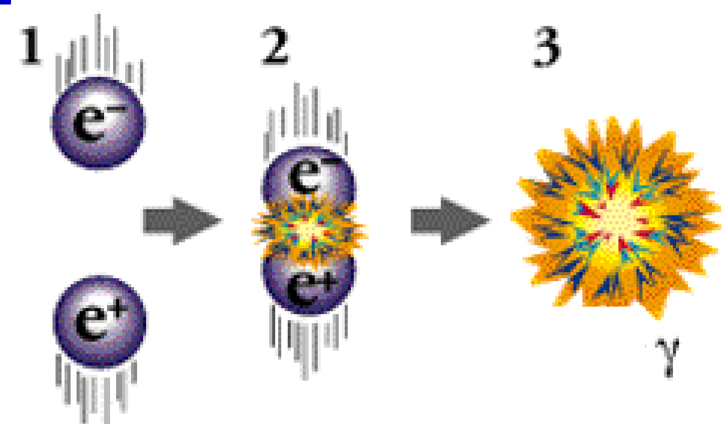


Equal amounts of matter and antimatter are produced when radiation is converted to matter

Annihilation

$$e^{+} + e^{-} \rightarrow 2hf$$



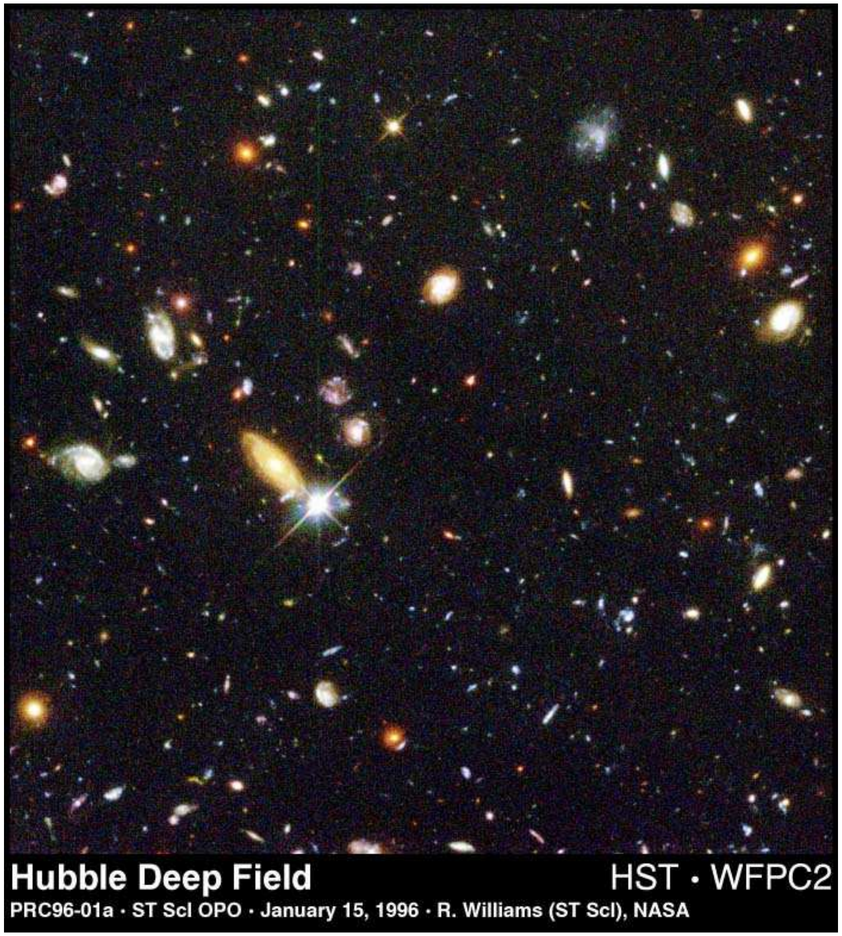


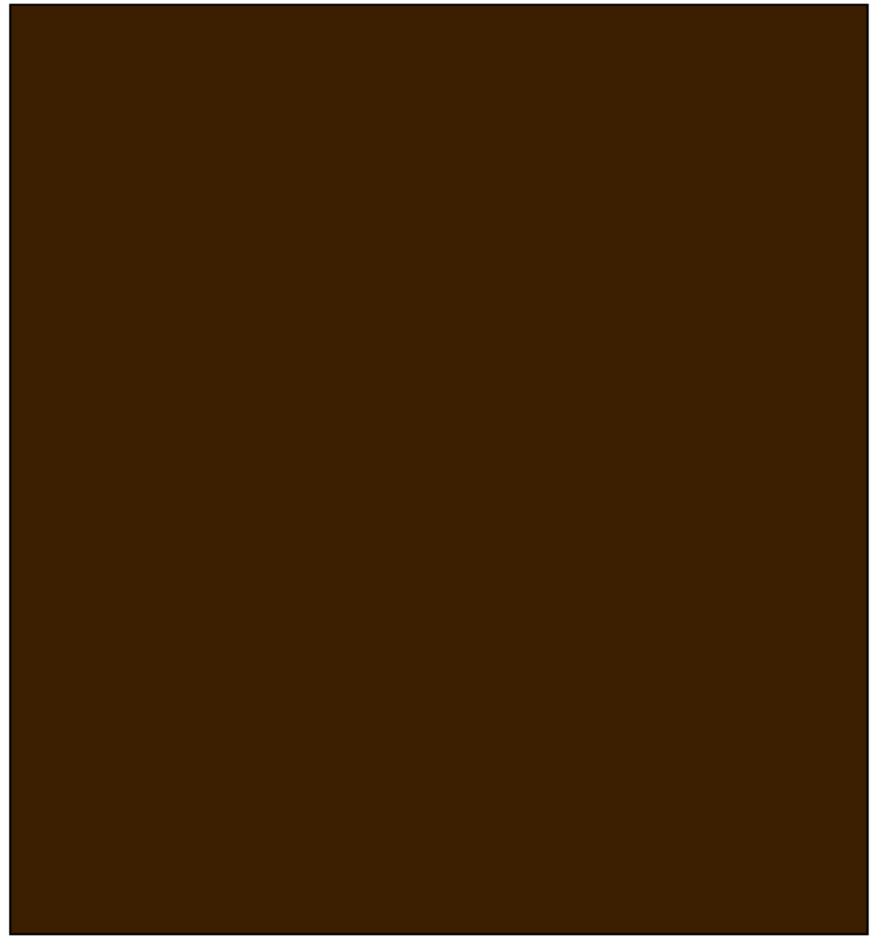
Antimatter can be produced.
It annihilates with matter to produce radiation

The Matter Antimatter Puzzle

Why does the Universe look like

this | not | that?



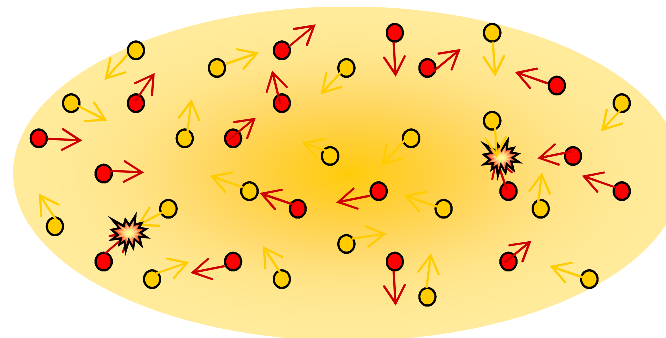


As far as we can see in universe, no large-scale antimatter.

-> need CP violation!

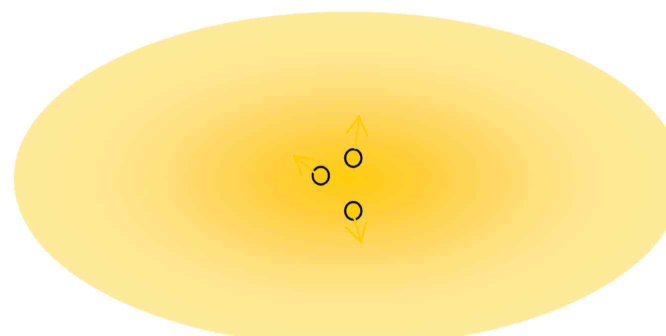
The Matter Antimatter Puzzle

Early Universe



-> particles, anti-particles and photons in thermal equilibrium
- colliding, annihilating, being re-created etc.

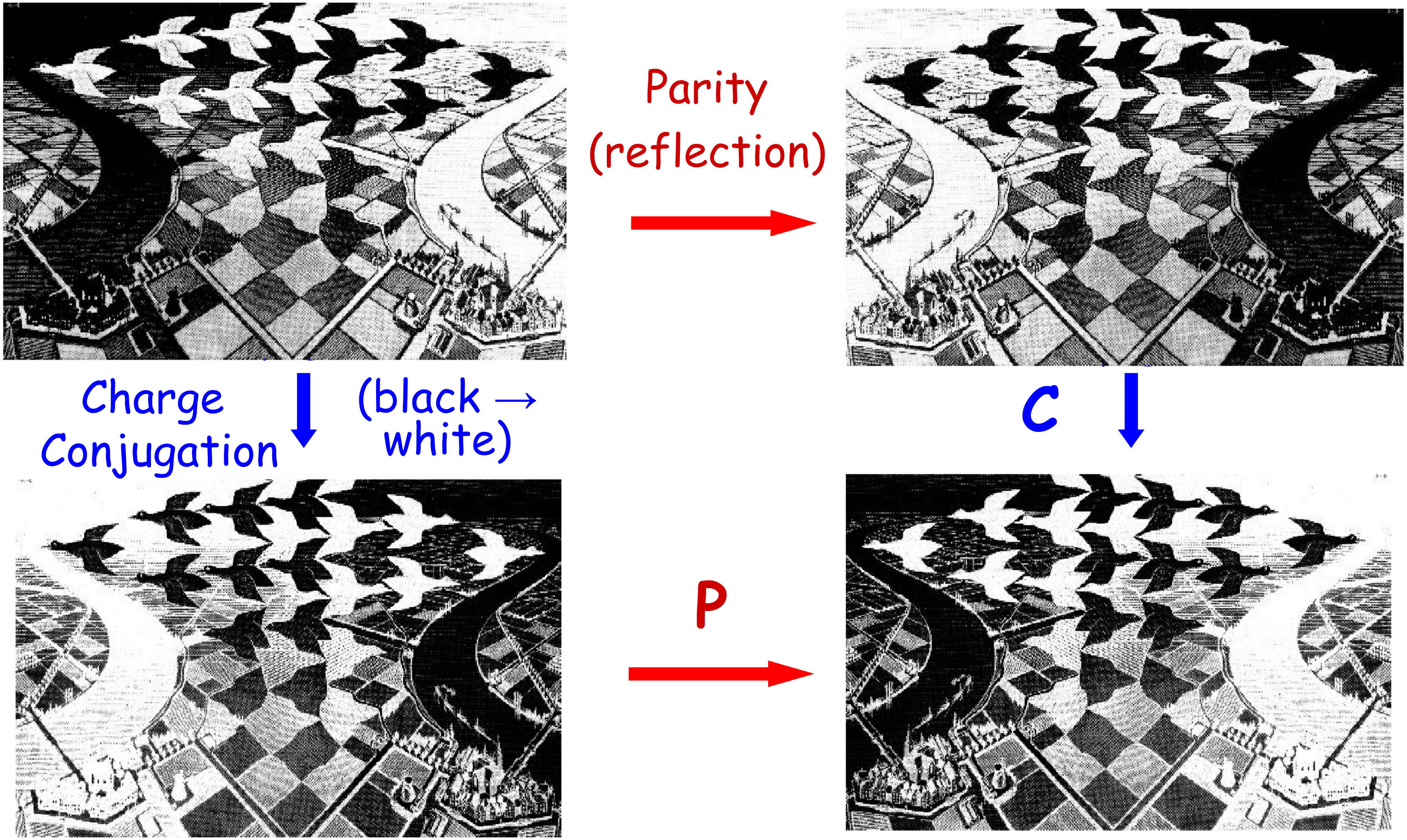
Slight difference in fundamental interactions between matter and antimatter ("CP violation") ?
-> matter slightly more likely to survive



Ratio of baryons (e.g. p, n) to photons today tells us about this asymmetry - it is about $1:10^9$

CP symmetry

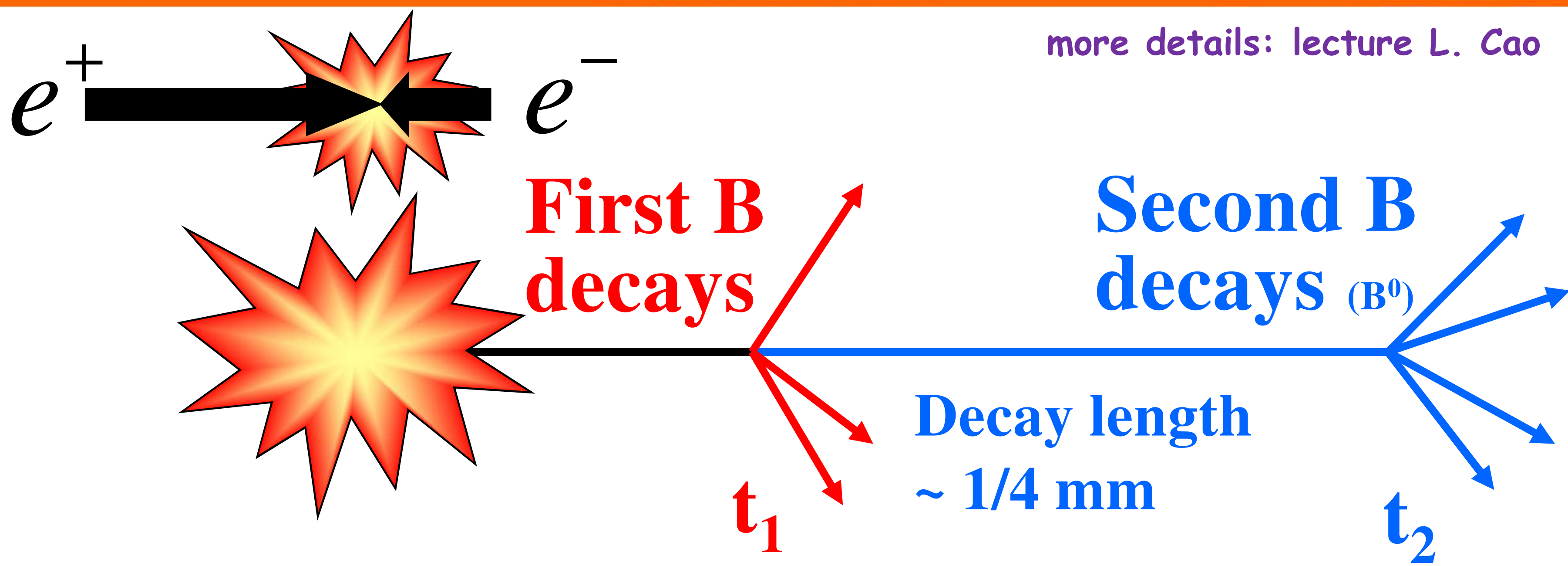
graphics: M.C. Escher

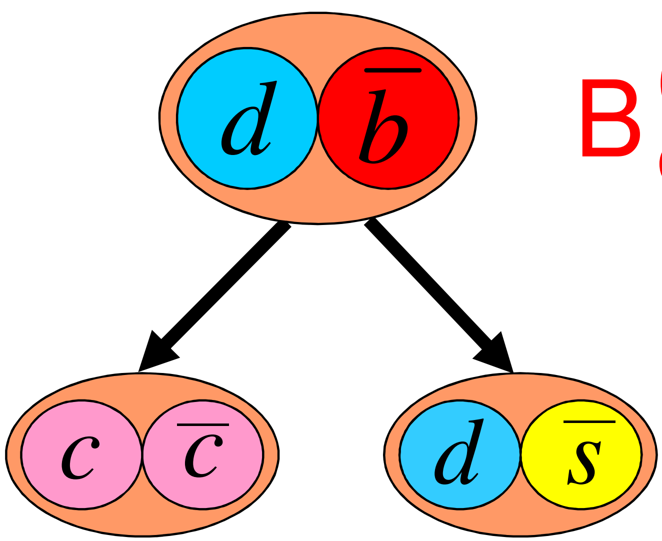


Like weak interaction, symmetric under CP (at first sight!)
Can there be small deviations from this symmetry?

CP violation in B meson decays

more details: lecture L. Cao





B_d^0 (or $\overline{B}_d^0$)

$$Asymmetry(t) = \frac{\overline{B}^0 - B^0}{\overline{B}^0 + B^0}$$

Simply count decays as function of t!

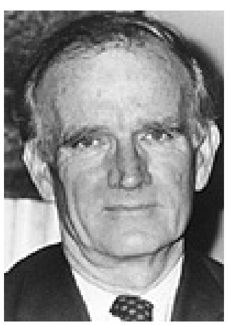
CP violation in B meson decays

Example: measurement from BaBar at SLAC

(also Belle at KEK)

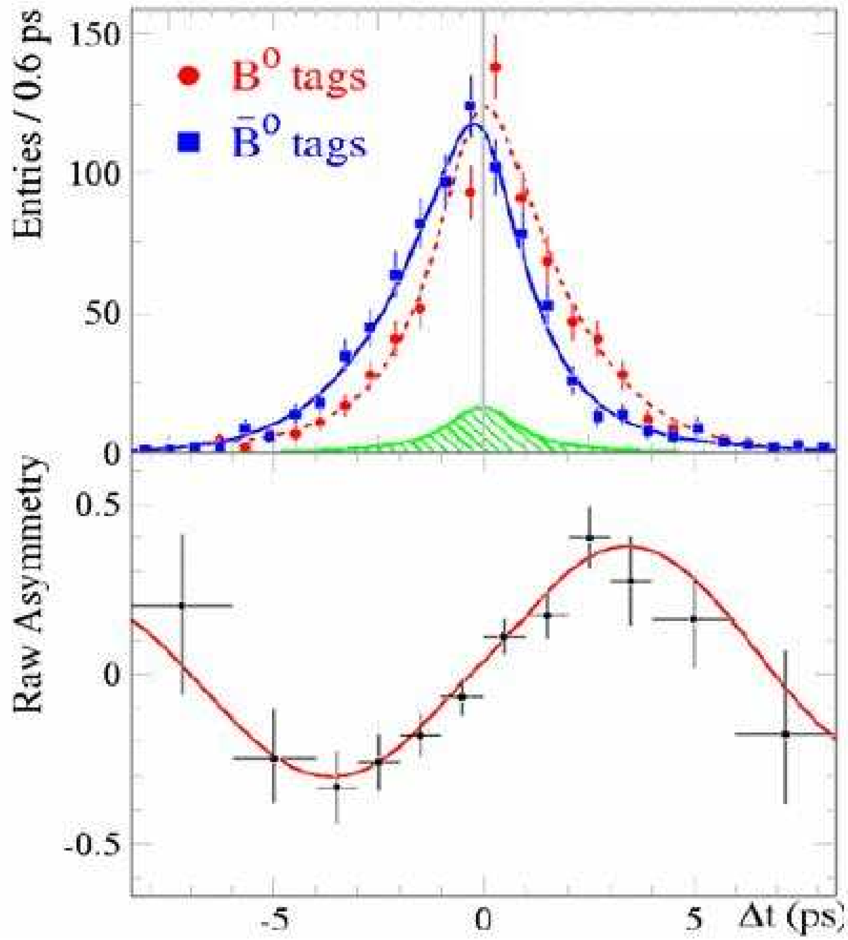
B and anti-B are indeed different

(also found earlier for K decays:)



Val L. Fitch

James W. Cronin (Nobel 1980)



data taking stopped

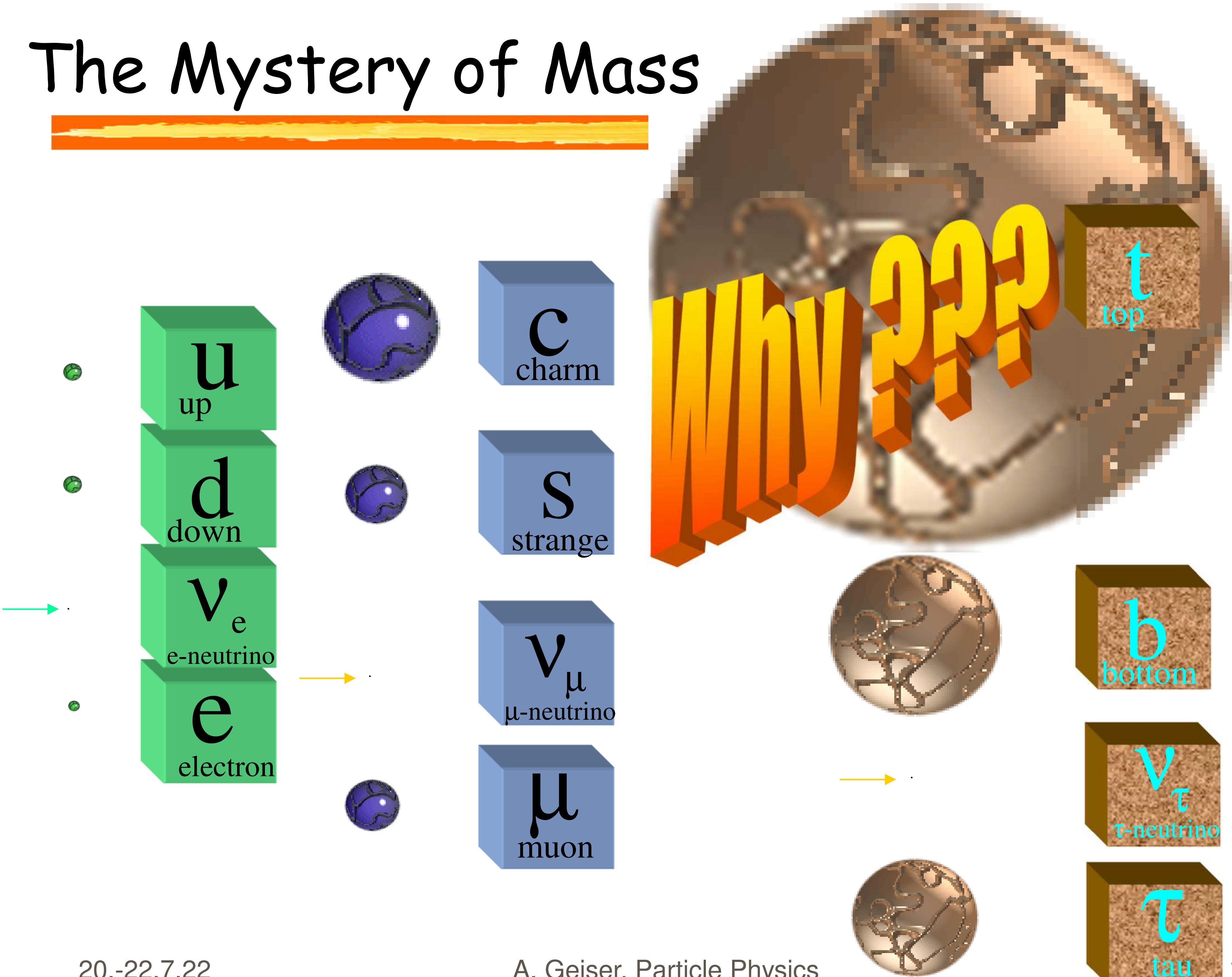
Belle/**Belle II continuing (DESY!)**

Weak Interactions violate CP!

M. Kobayashi T. Maskawa

(Nobel 2008)

The Mystery of Mass



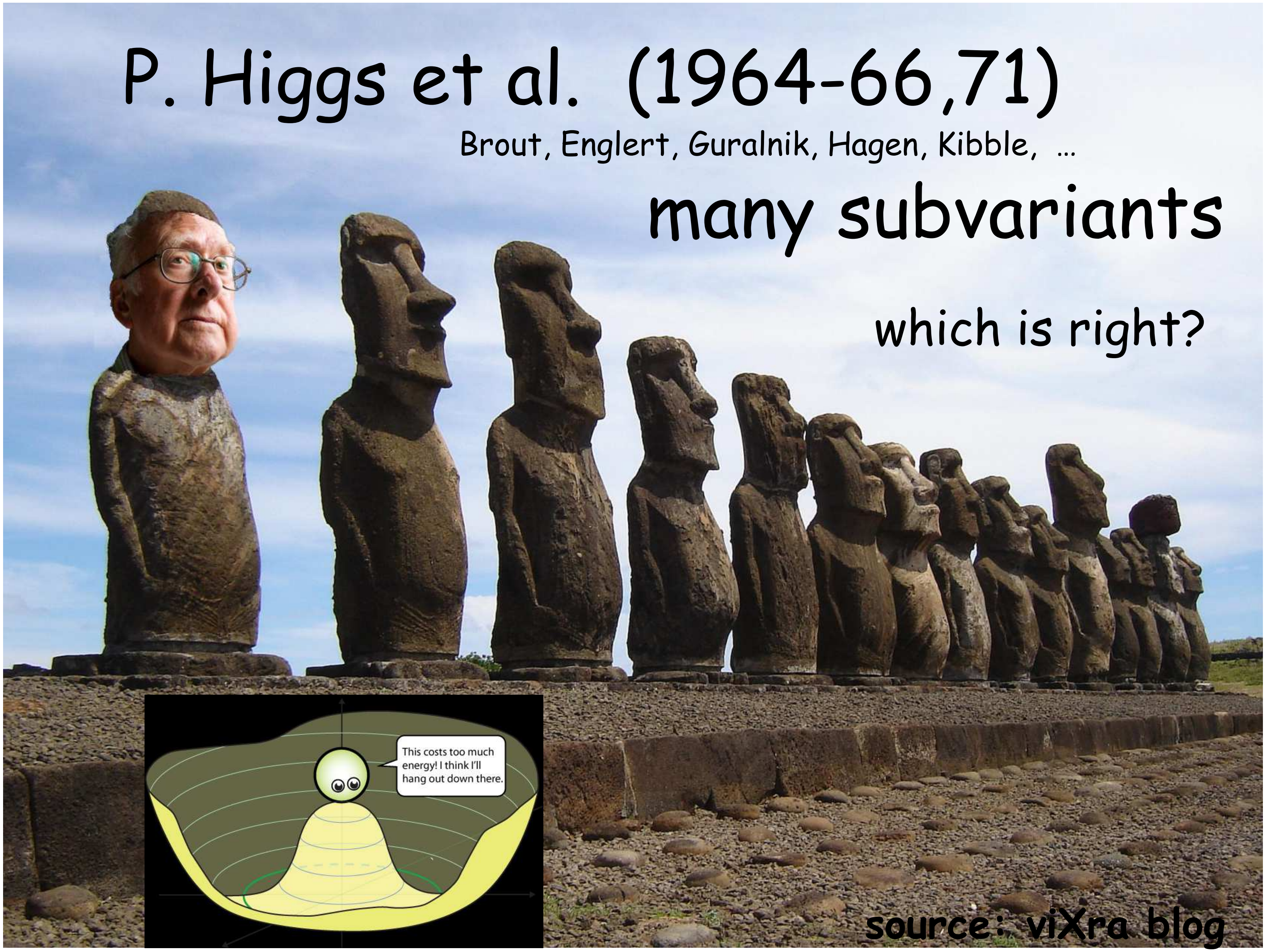
The Mass (BEH) Mechanism

P. Higgs et al. (1964-66,71)

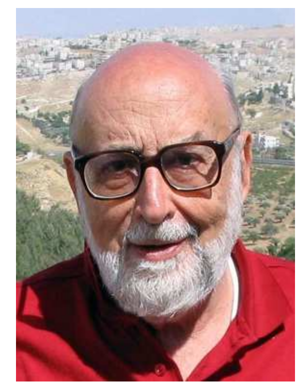
Brout, Englert, Guralnik, Hagen, Kibble, ...

many subvariants

which is right?



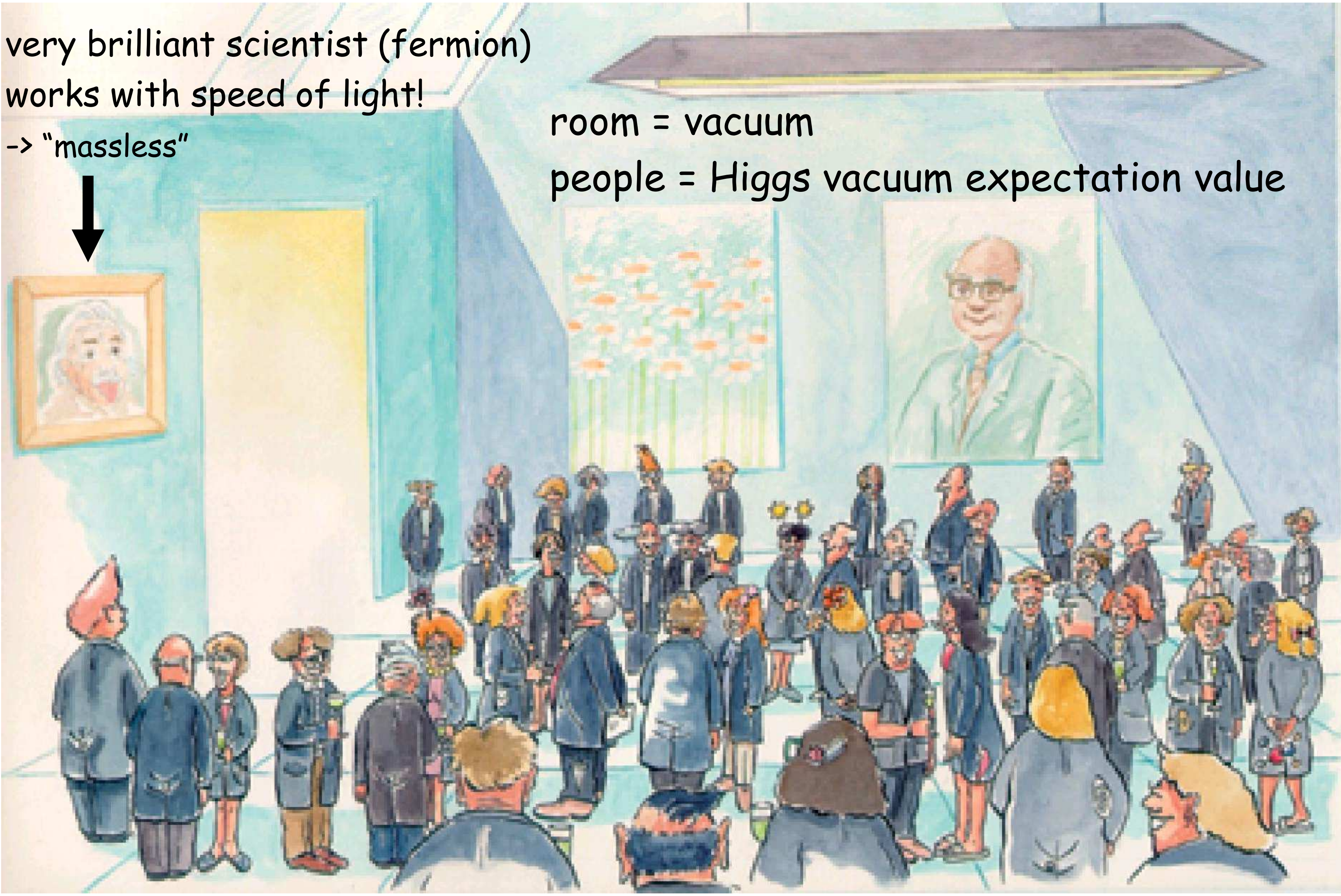
Peter Higgs



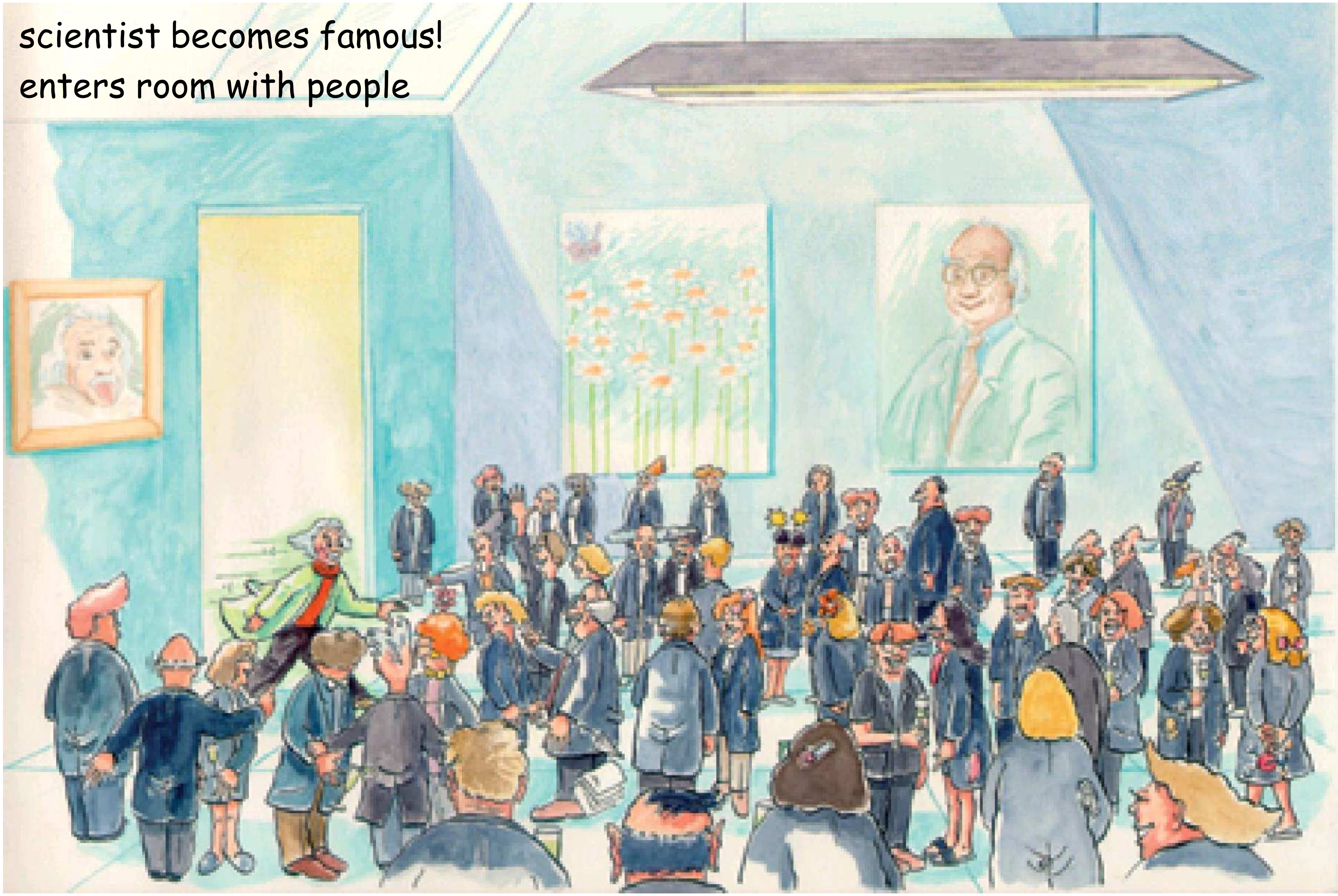
François Englert

(Nobel 2013)

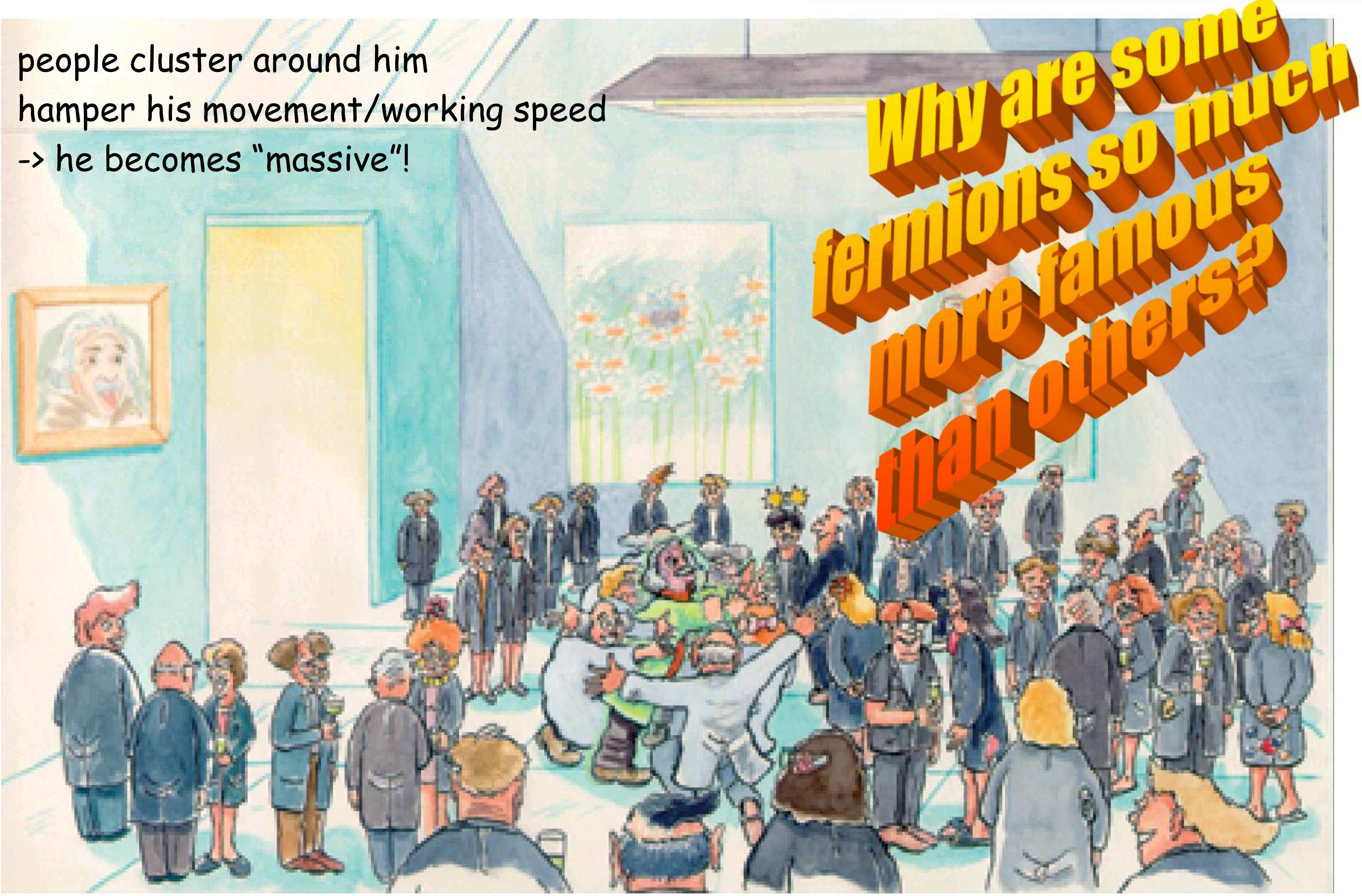
Fermion Mass from Higgs field?



Fermion Mass from Higgs field?

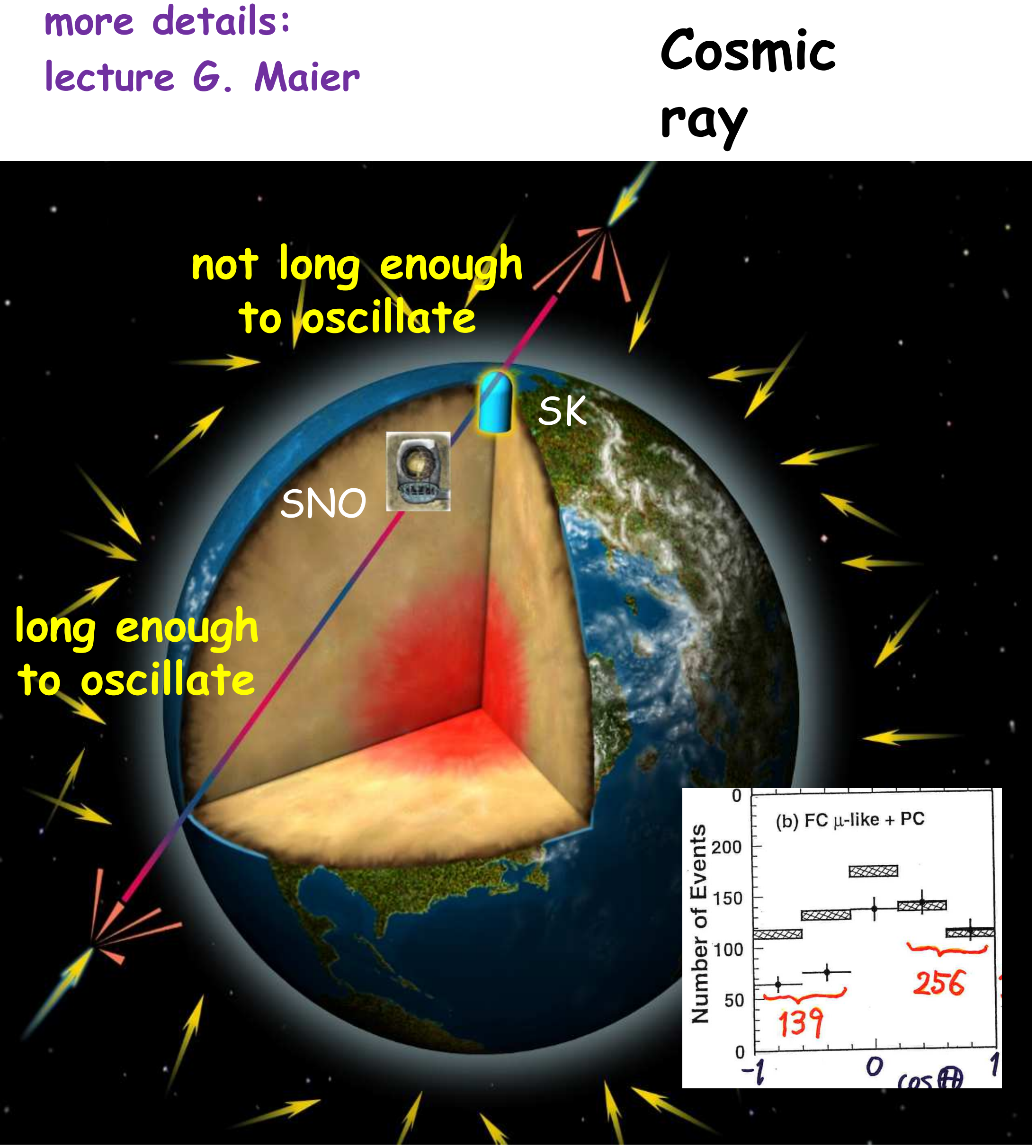


Fermion Mass from Higgs field?

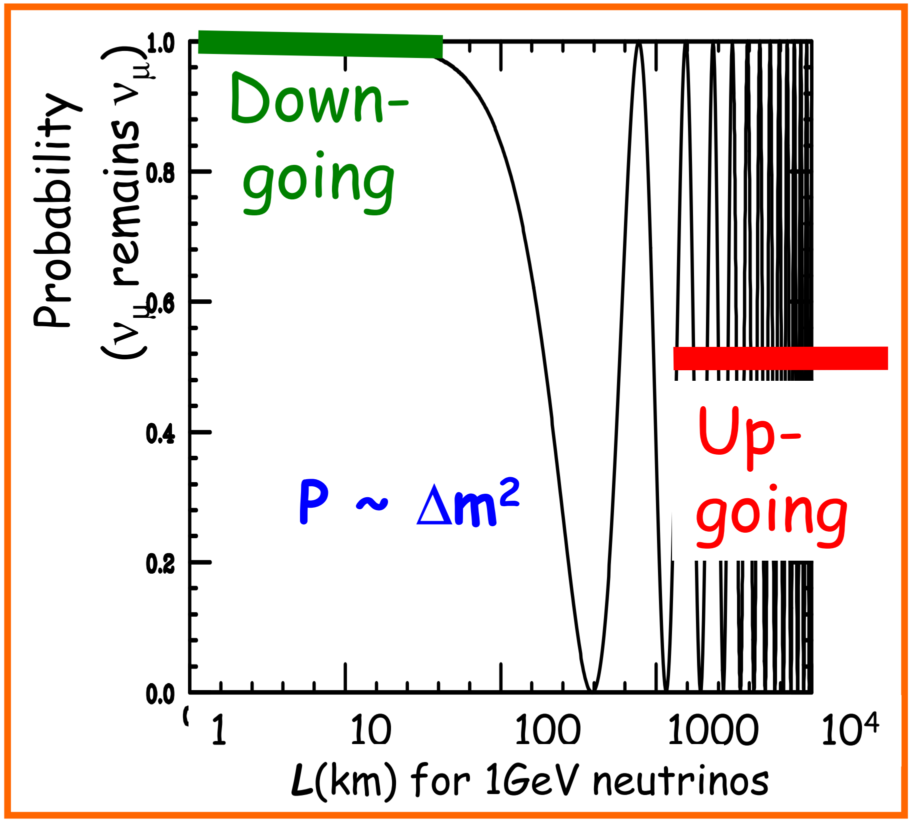


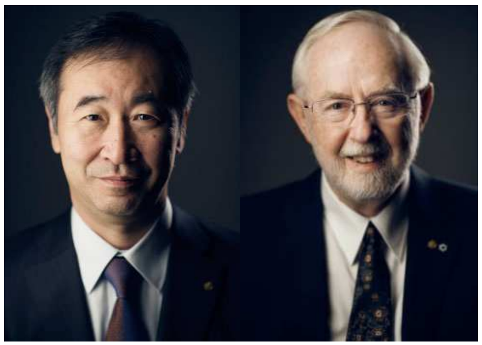
Neutrino oscillations: neutrinos are massive!

more details:
lecture G. Maier



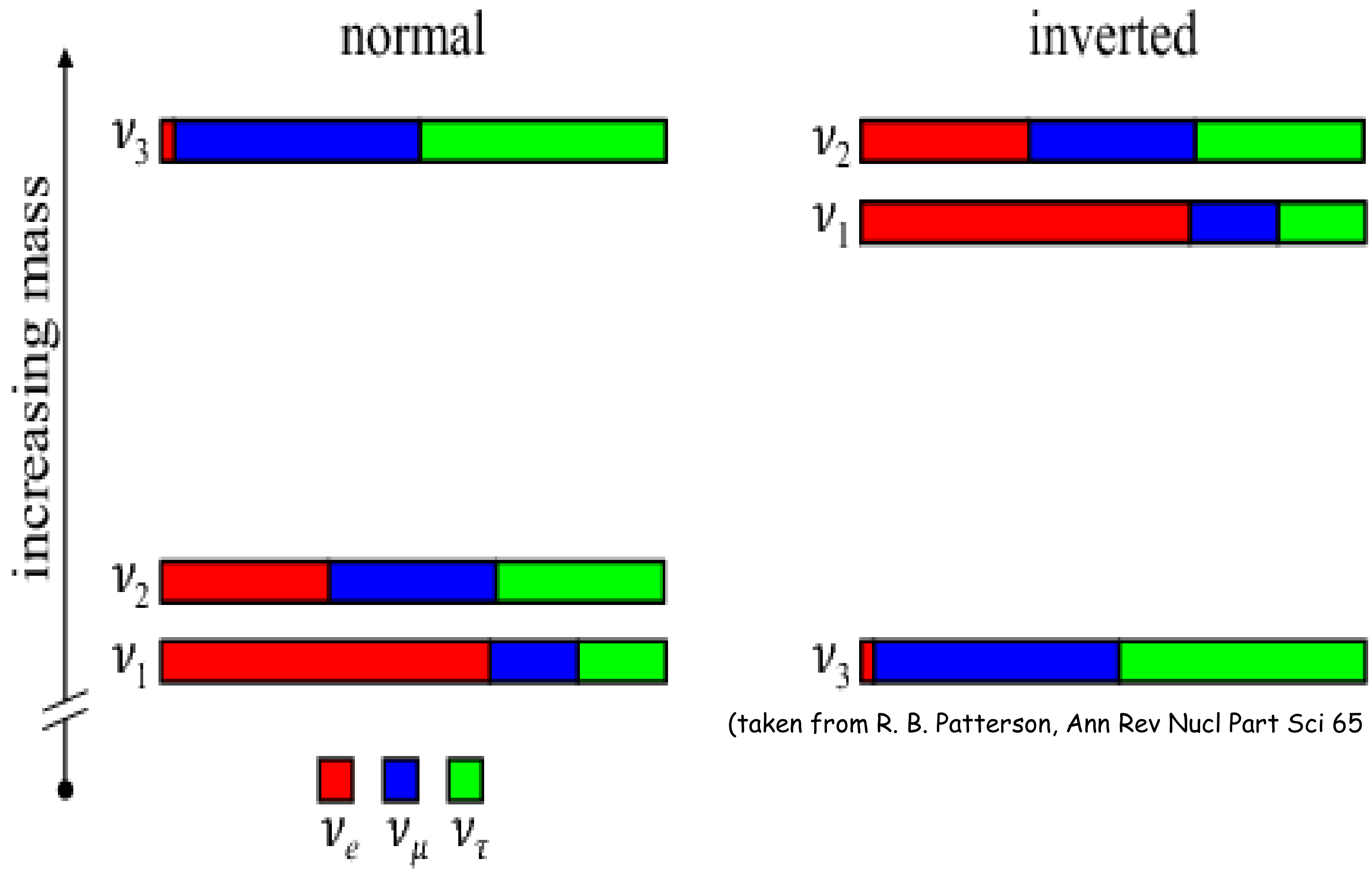
1998





Takaaki Kajita Arthur McDonald
(Nobel 2015)

What do we know about Neutrino mass?



< 2.2 eV

> 1 meV

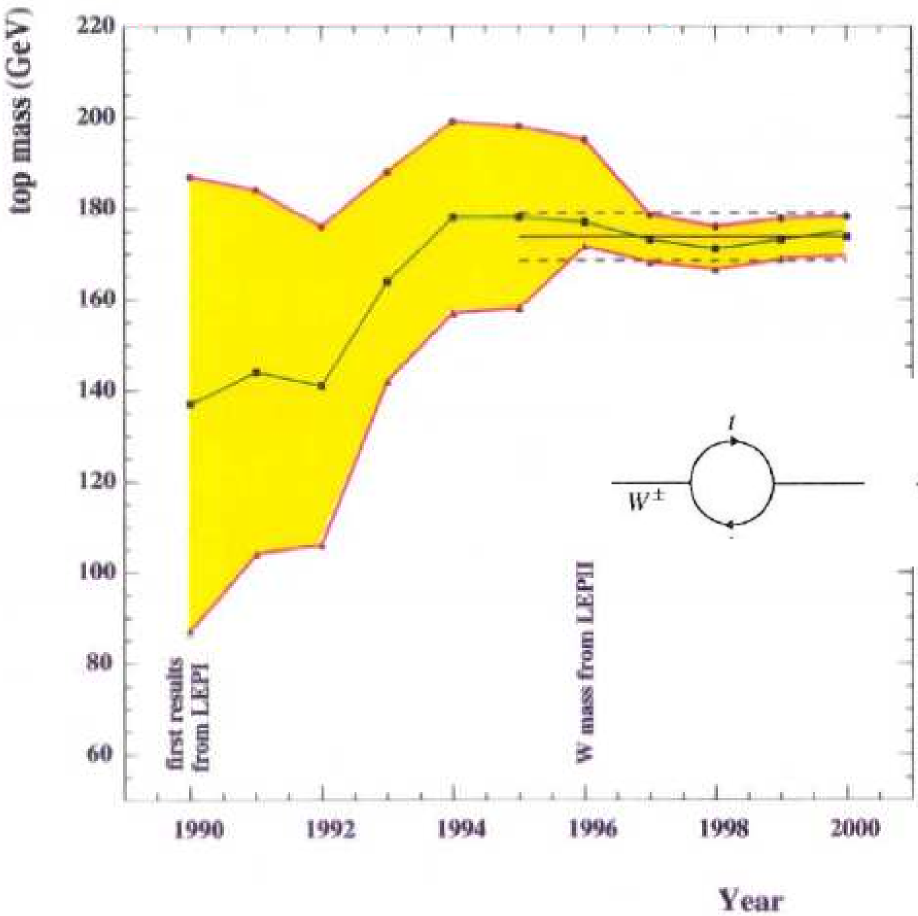
(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

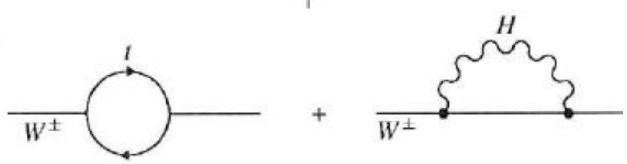
- are the masses of Dirac type (generated by Higgs)?
  or of Majorana type (ν's are their own antiparticles,
  masses have non-Standard Model origin)?
- CP violation?

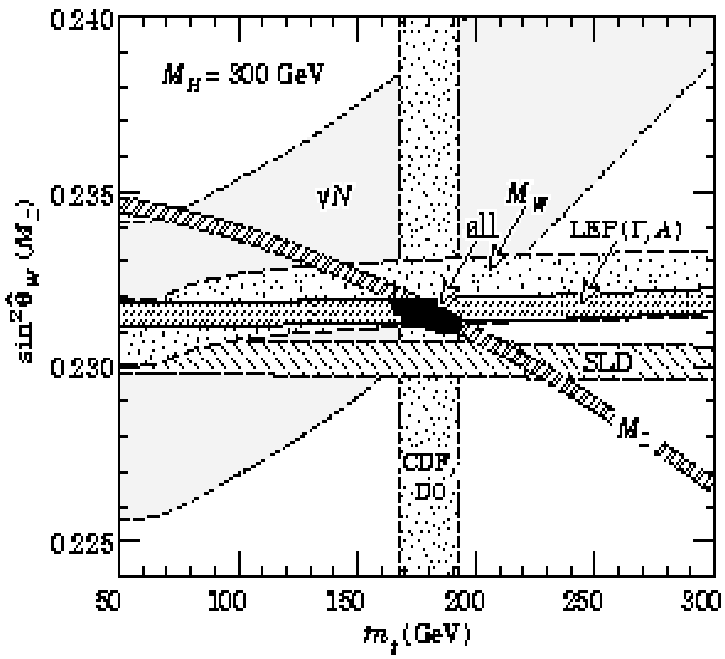
possibly first evidence
for physics
beyond Standard Model

The quest for the top quark

Electroweak precision measurements at LEP/CERN sensitive to top quark mass and Higgs mass (indirect effects) already before top discovery



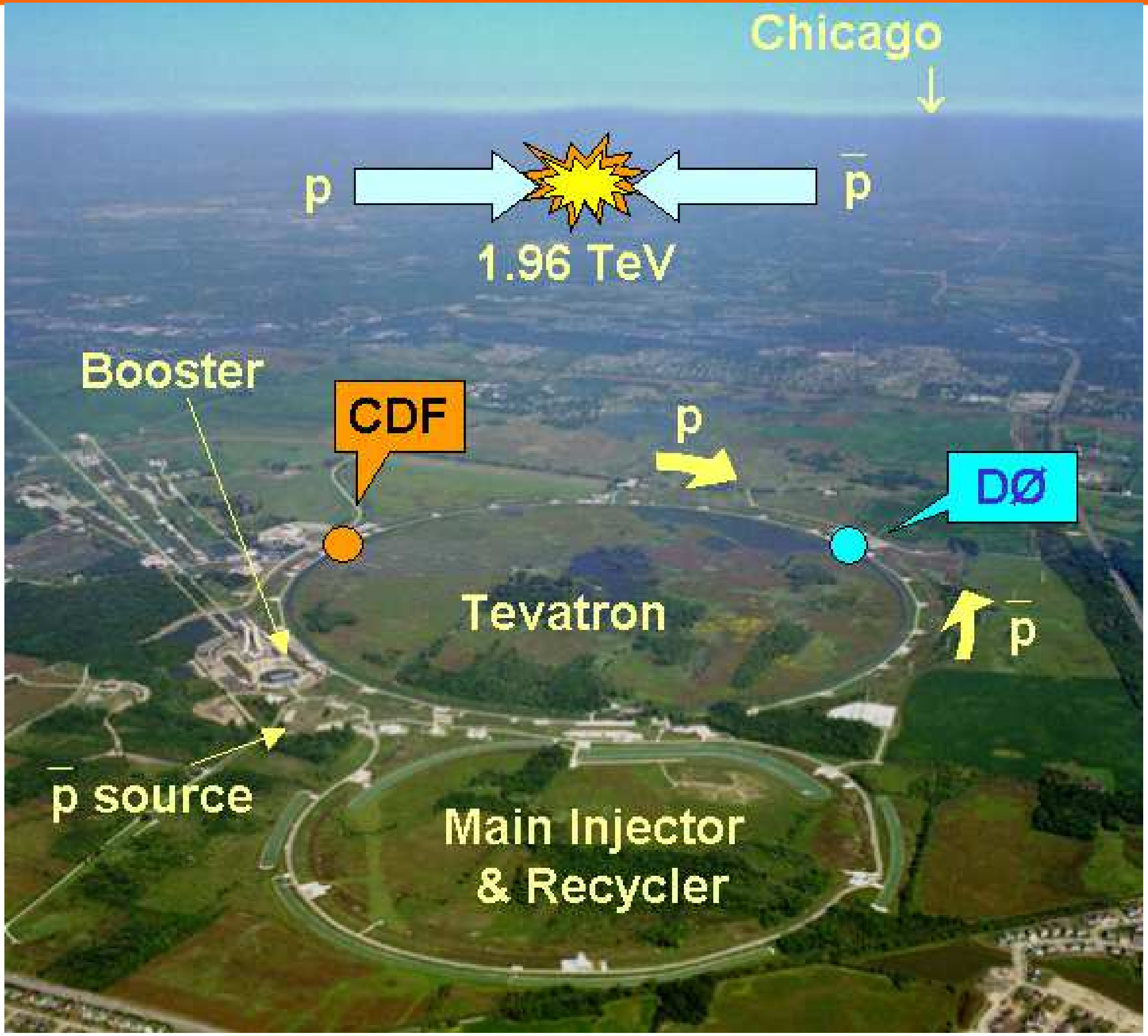




$$\propto \left(\frac{M_t}{M_W}\right)^2, \ln\left(\frac{M_h}{M_W}\right)$$

-> $M_t \sim 170$ GeV

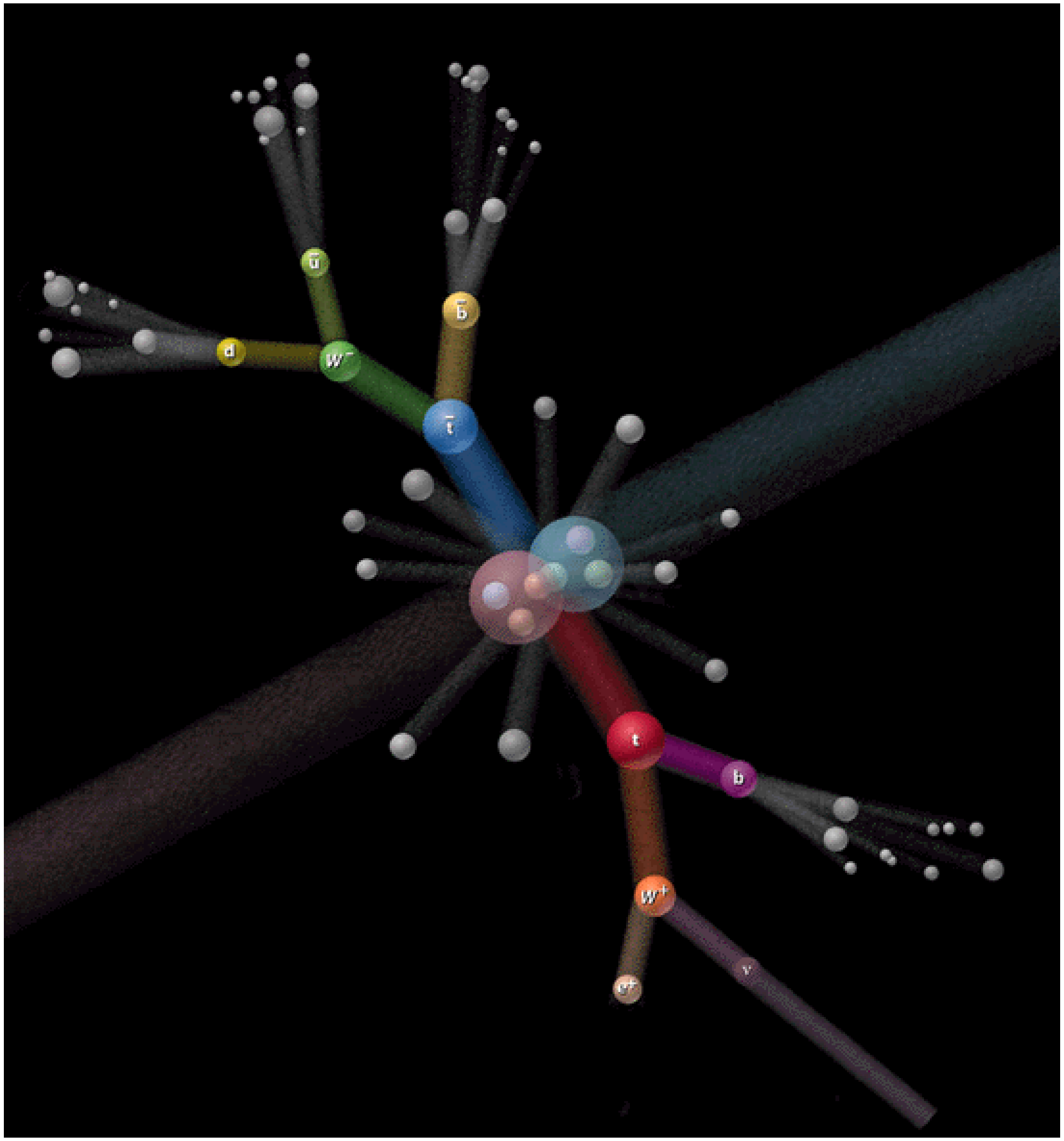
The Tevatron (Fermilab)



data taking ended in 2011

analysis still ongoing

Top quark discovery (Fermilab 1995)



Top quark actually found where expected!

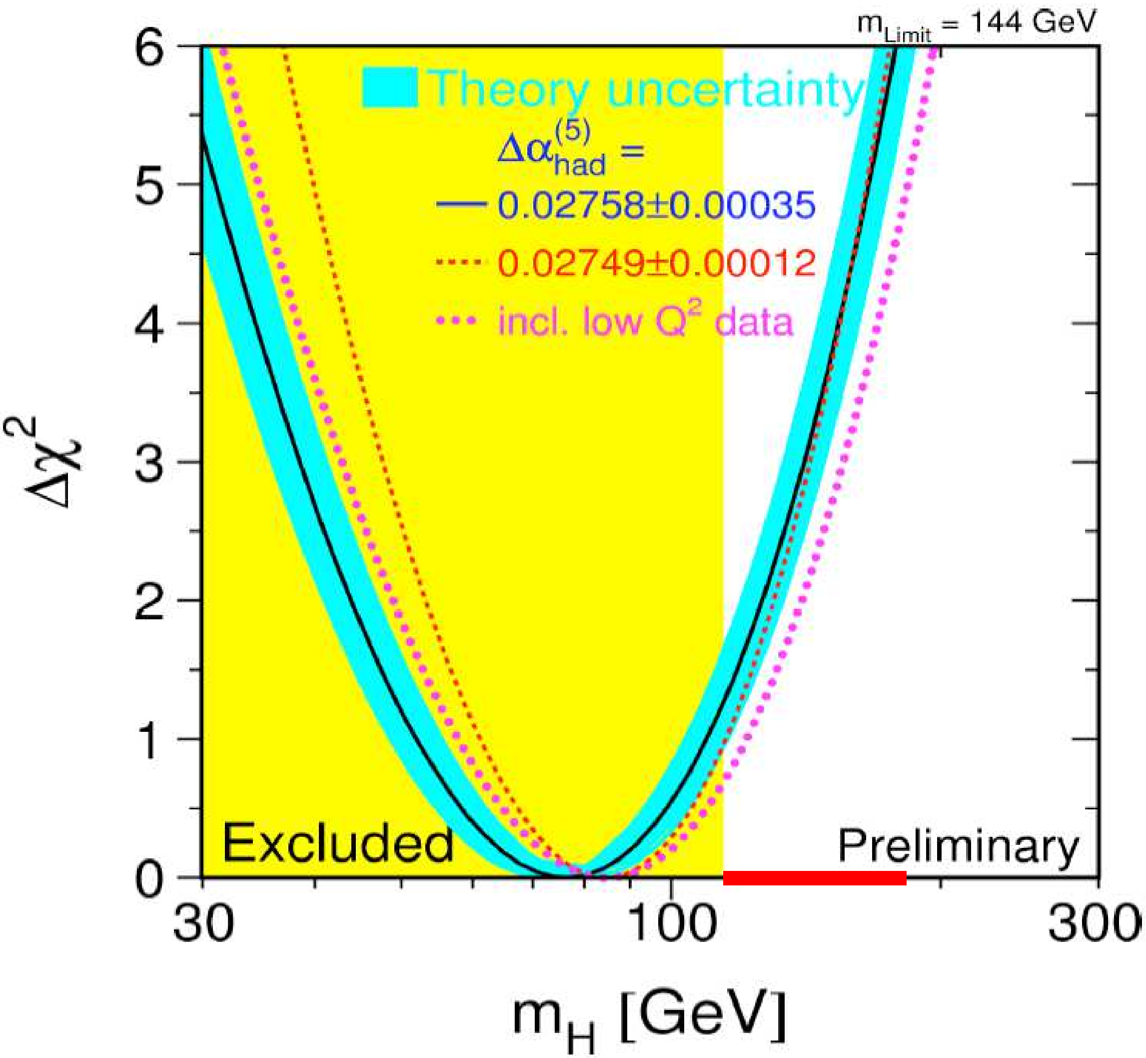
Tevatron at Fermilab (CDF + D0)

measured mass value: (PDG18)

M_{top} = 173.0 ± 0.4 GeV

it works!

Precision @ LEP, and Higgs



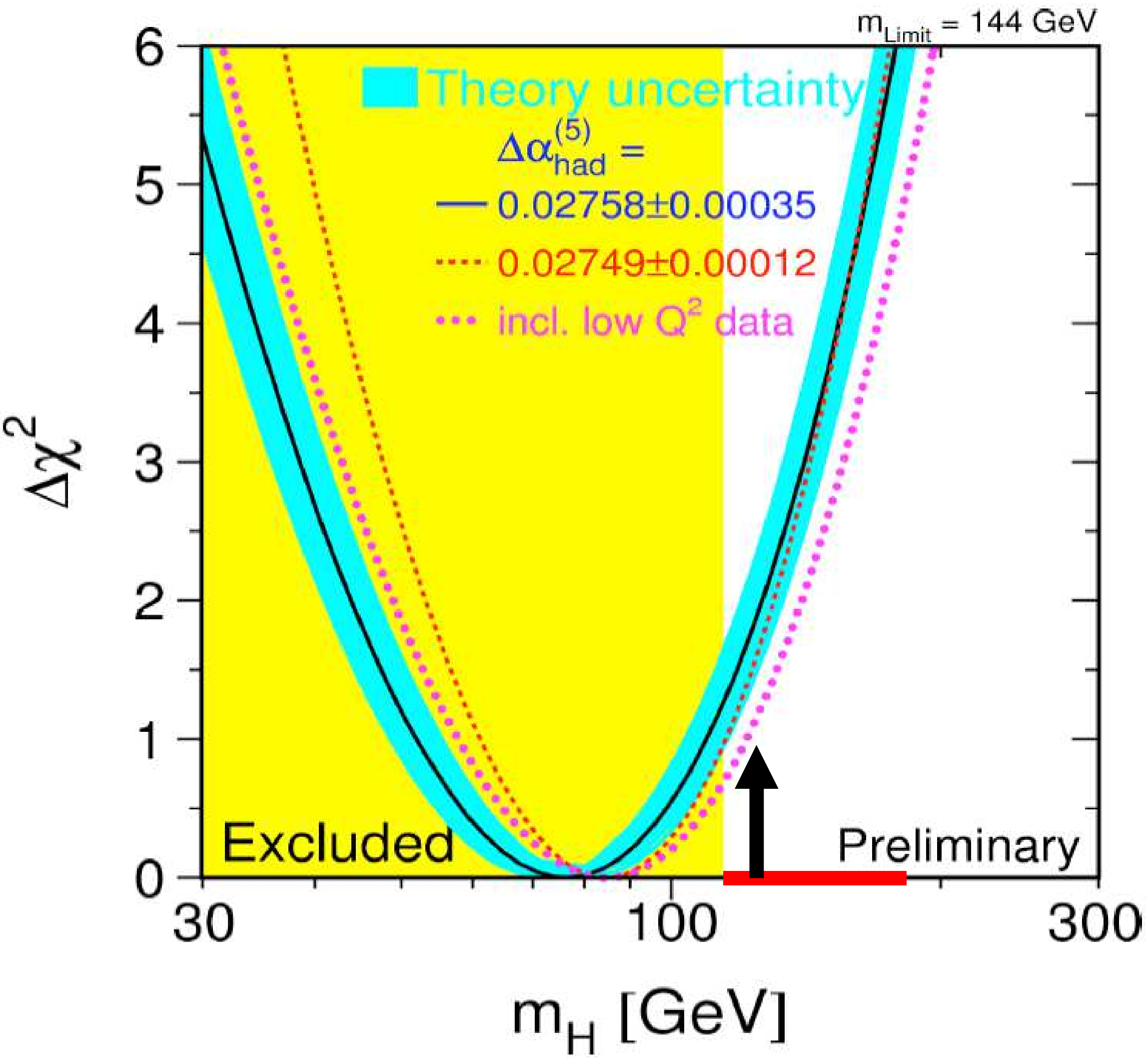
insert measured top mass into precision measurements at LEP
-> now sensitive to Higgs mass

m_H < 182 GeV at 95% CL

LEP direct lower limit:

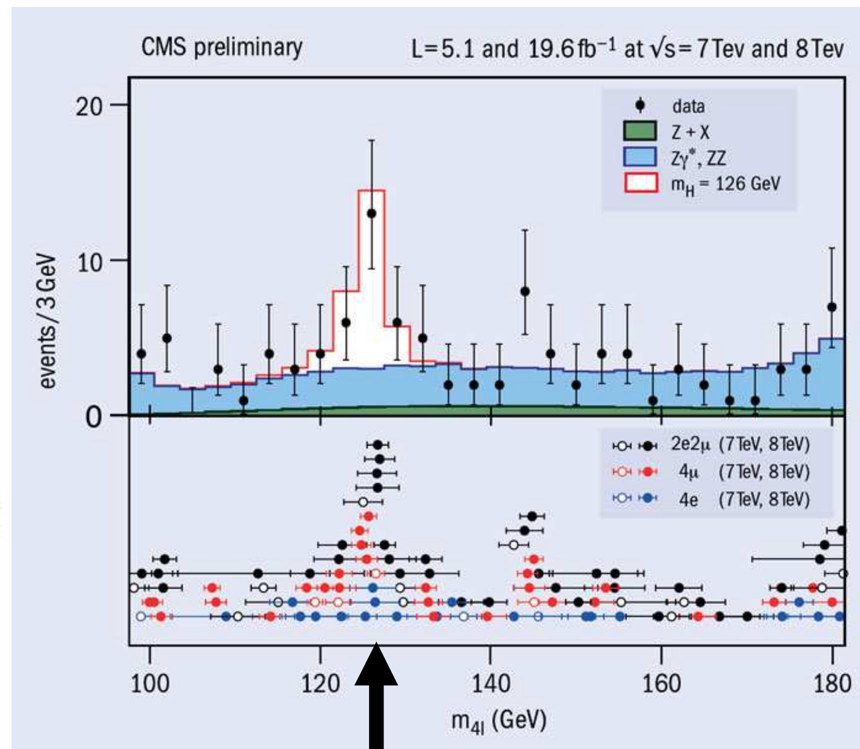
m_H > 114 GeV at 95% CL

Precision @ LEP and Higgs at LHC



and there it was!

H->ZZ*-> 4 leptons



$m_H = 125.7 \pm 0.4$ GeV

Special Fundamental Physics Prize 2013

for their leadership role in the scientific endeavour
that led to the discovery of the new Higgs-like particle
by the ATLAS and CMS collaborations at CERN's Large Hadron Collider.

by the Milner Foundation

Peter Jenni, ATLAS

Tejinder Singh Virdee, CMS

Lyn Evans, LHC

Fabiola Gianotti, ATLAS

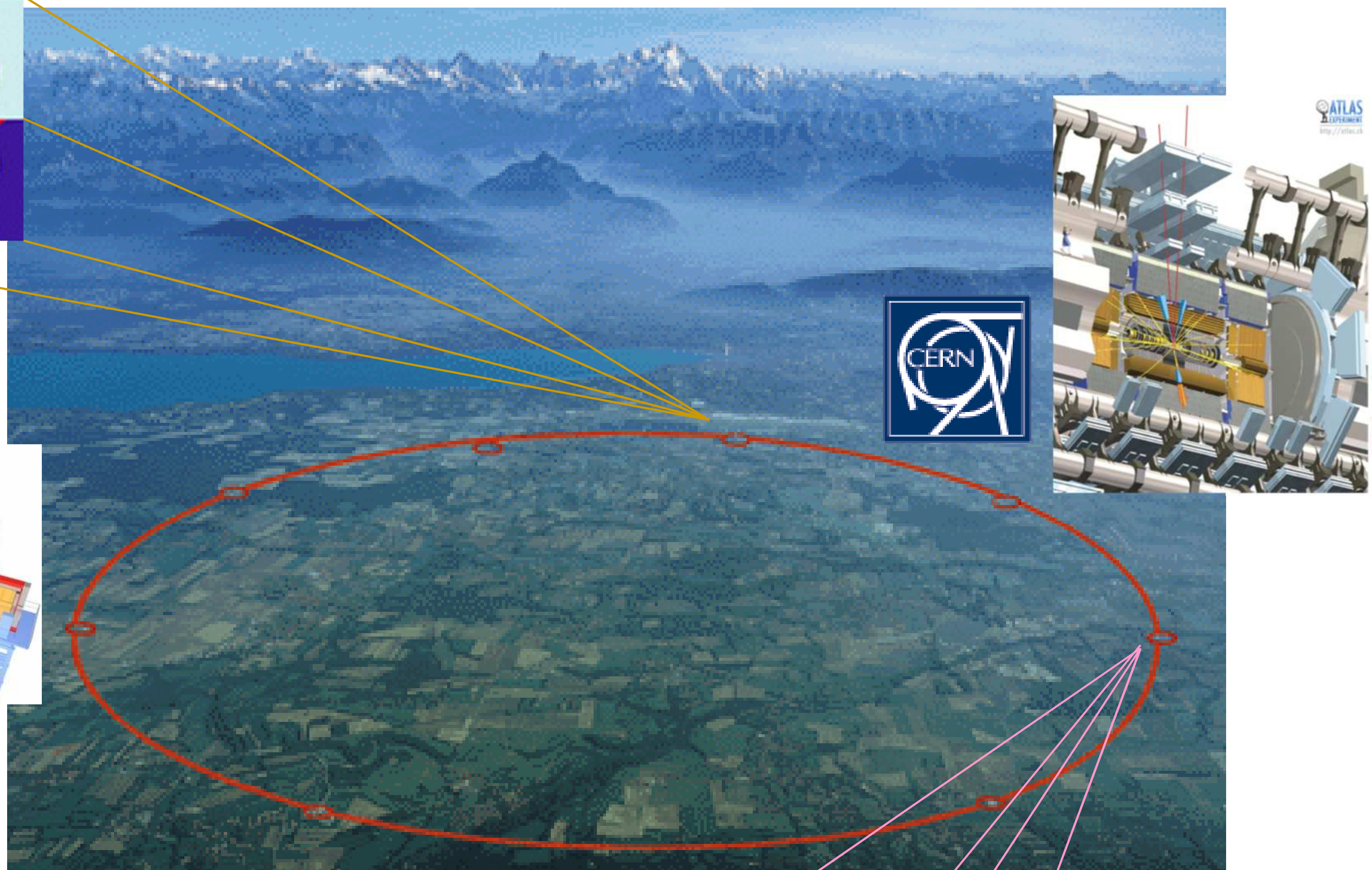
Joe Incandela, CMS

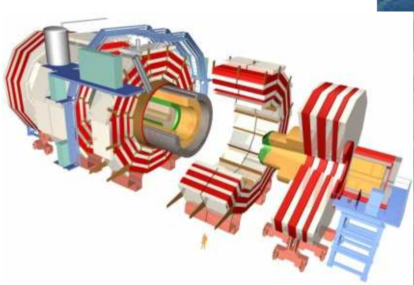
Michel Della Negra CMS

Guido Tonelli, CMS

The LHC Project

recently running pp collisons @ 13.6 TeV

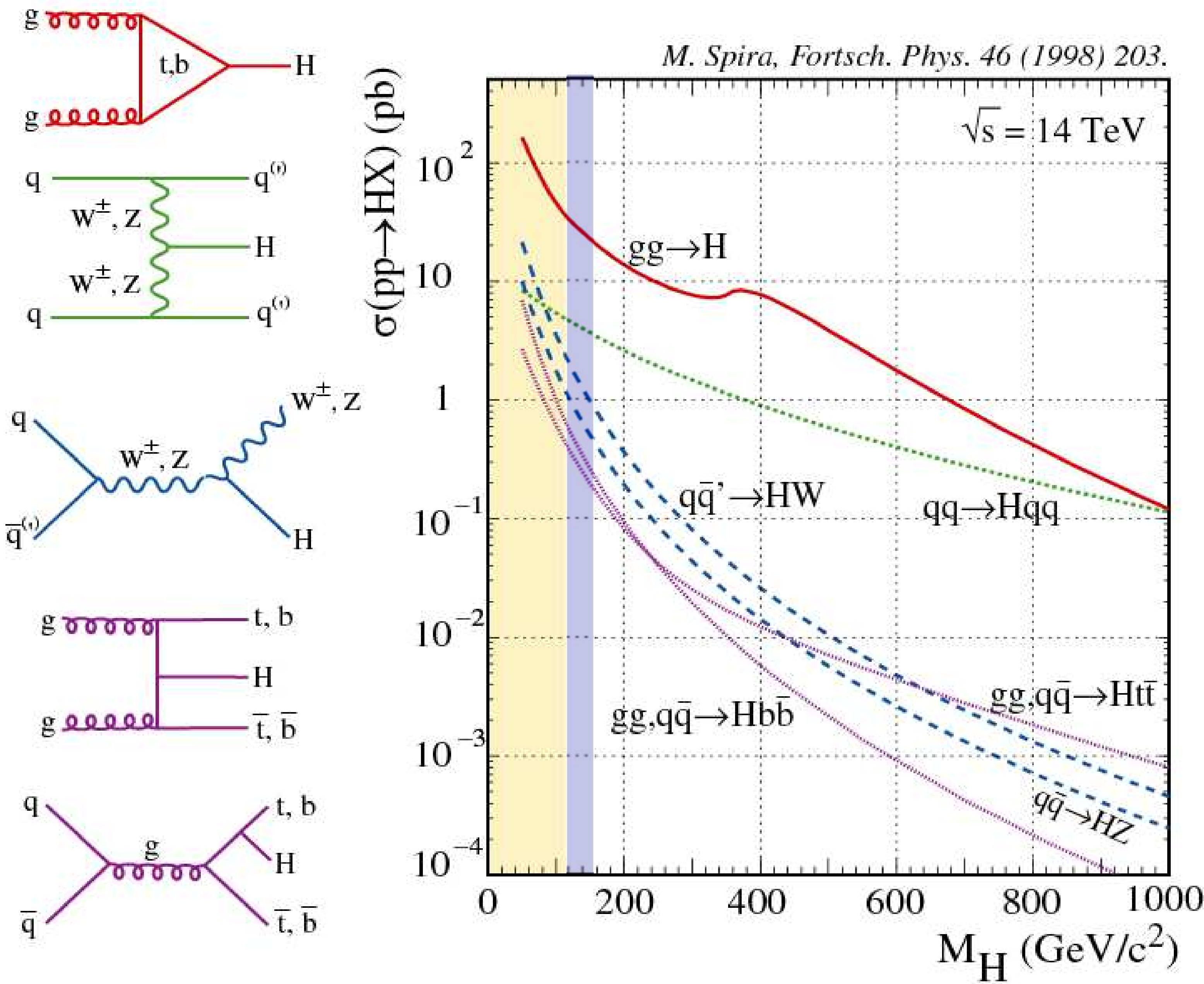




more details: lecture C. Seitz

Higgs production at LHC

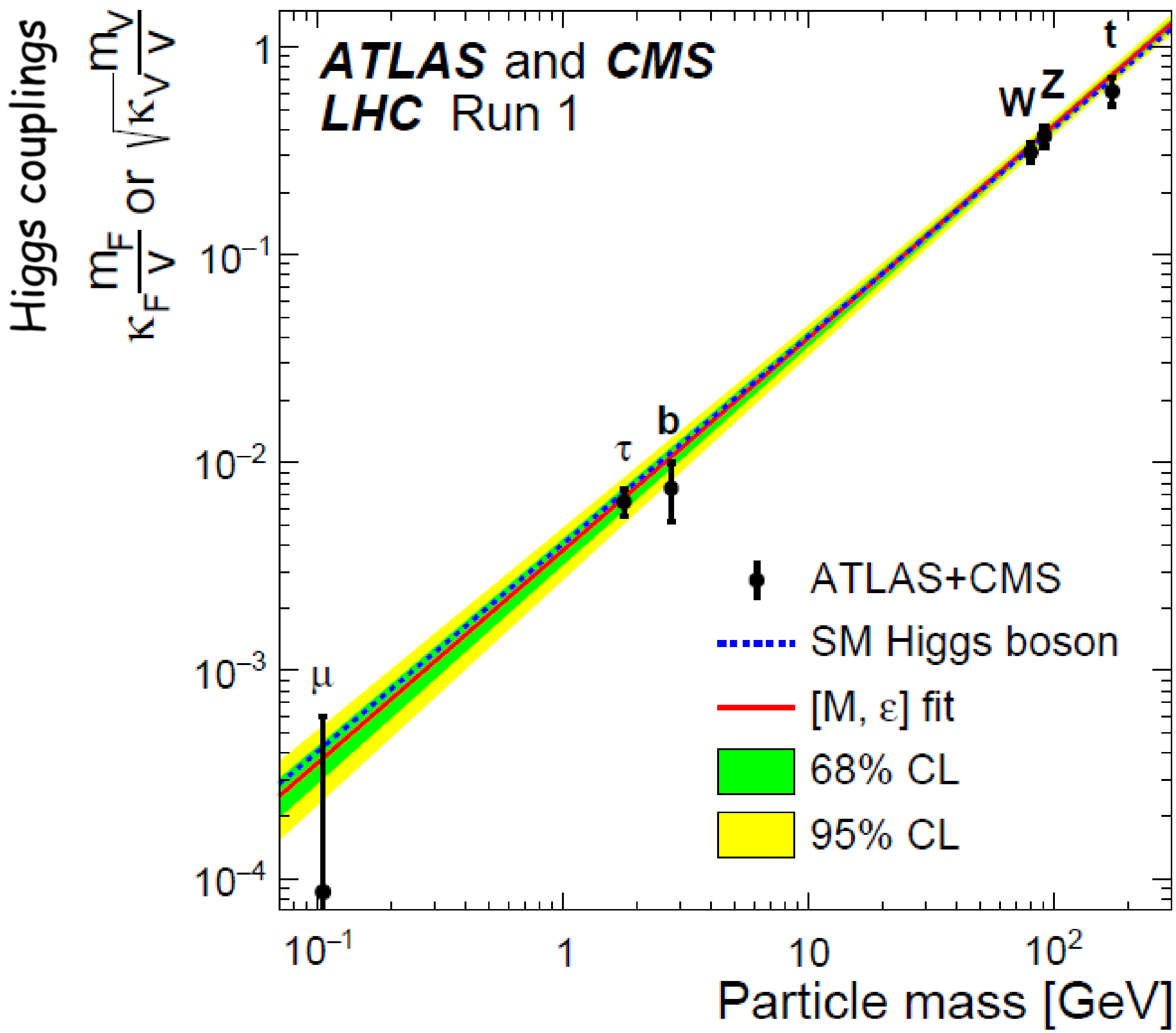
measure
as many as
possible
to
check
Higgs
properties



Direct measurements of Higgs Yukawa couplings

examples

ATLAS and CMS, JHEP08 (2016) 045

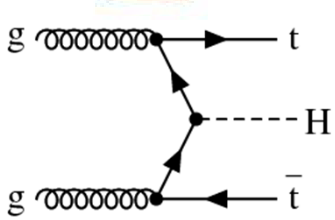


(Run 2 not yet combined)

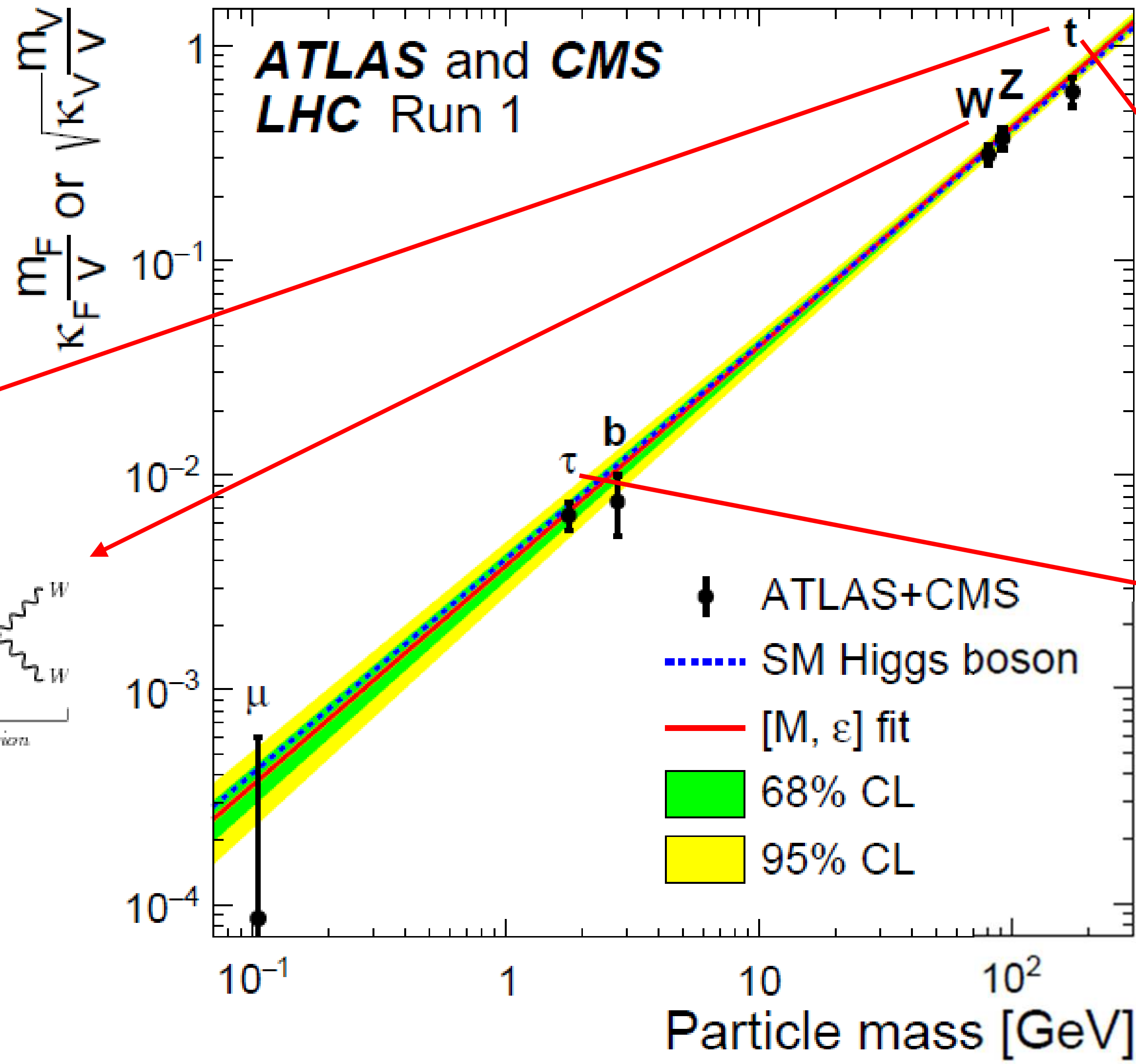
Direct measurements of Higgs Yukawa couplings

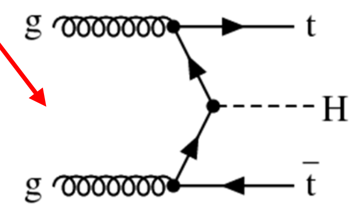
examples

ATLAS and CMS, JHEP08 (2016) 045

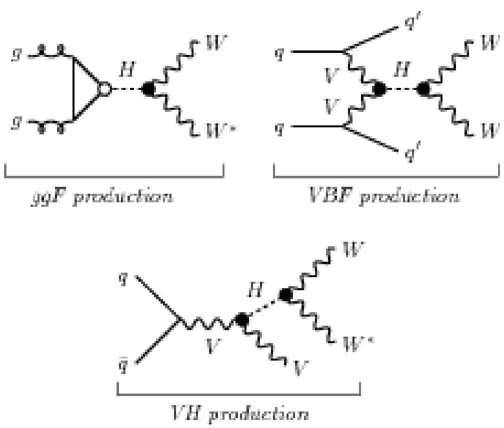


5.8 σ observed
(June 2018)



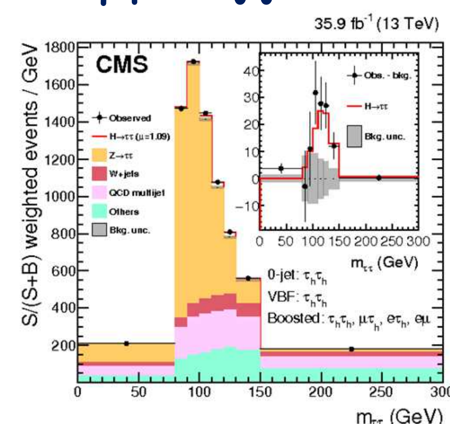


5.2 σ observed
(April 2018)



5.9 σ observed
(December 2014)

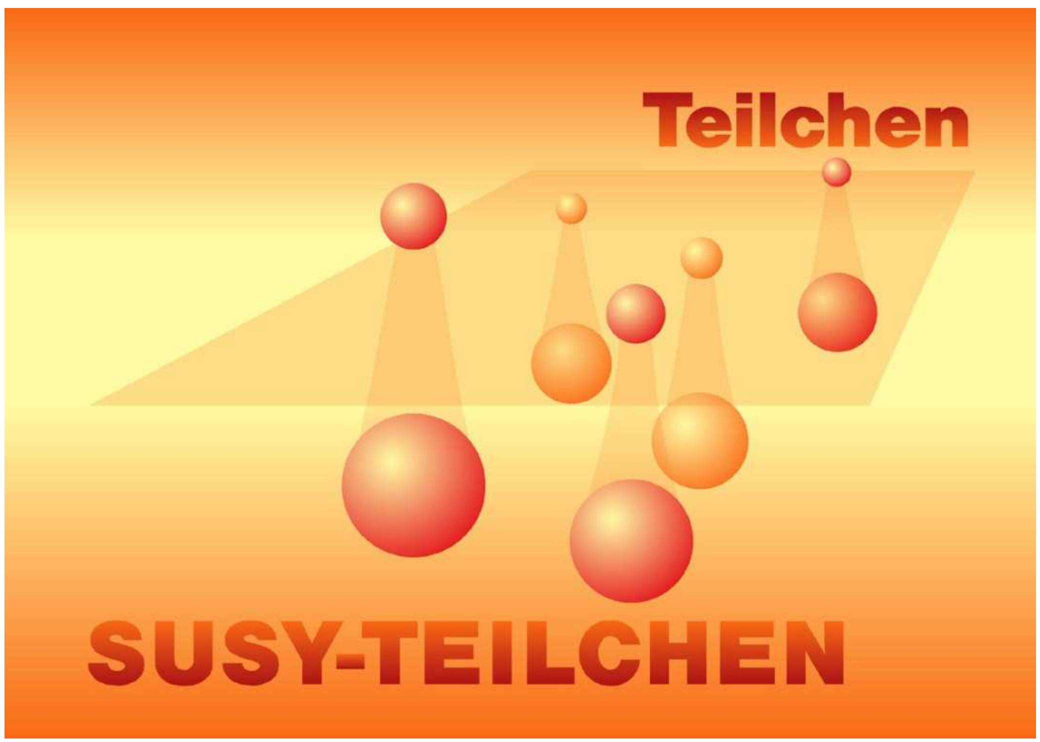
H -> ττ



5.9 σ observed
(August 2017)

Supersymmetry

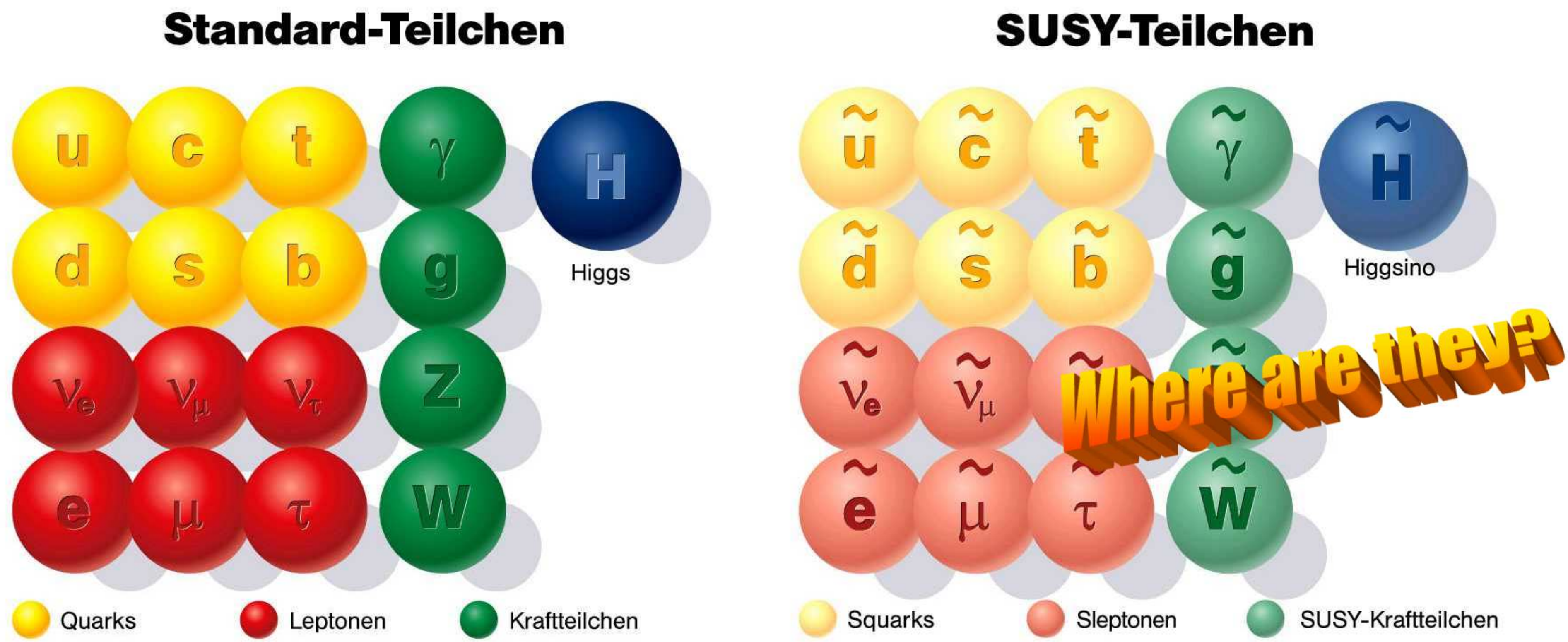
- A way to solve theoretical problems with Unification of Forces: Supersymmetry
- For each existing particle, introduce similar particle, with spin different by 1/2 unit



more details:
lecture H. Kim

Supersymmetry

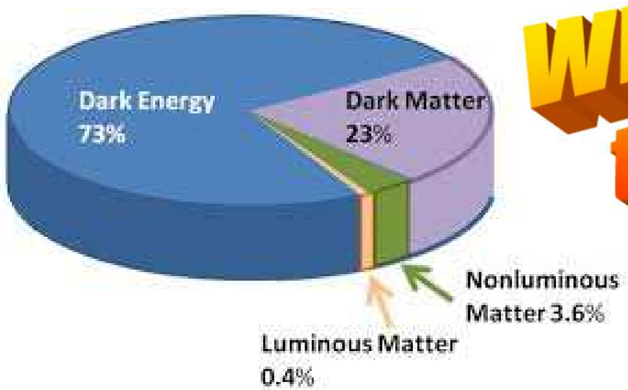
- double number of particles:



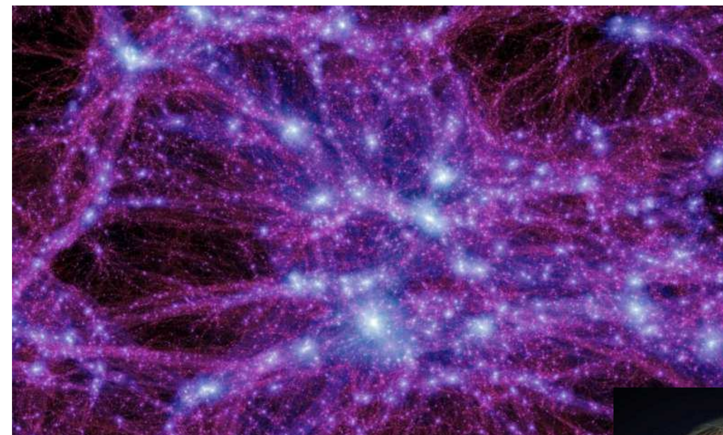
- not seen at LEP, HERA, Tevatron ... -> must be heavy!
- **(still) hope to see them at LHC ! ?**

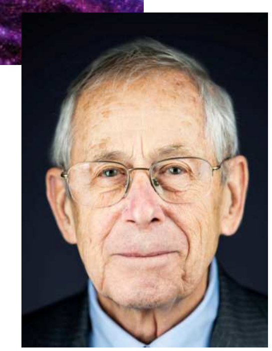
Dark matter and dark energy

structure of matter distribution and its motion throughout the universe:



What are they?





James Peebles
(Nobel 2019)

- some potential dark matter particles (e.g. from supersymmetry) can be probed at LHC
- others (e.g. axions) through dedicated experiments (e.g. ALPS@DESY)

more details: lecture A. Lindner

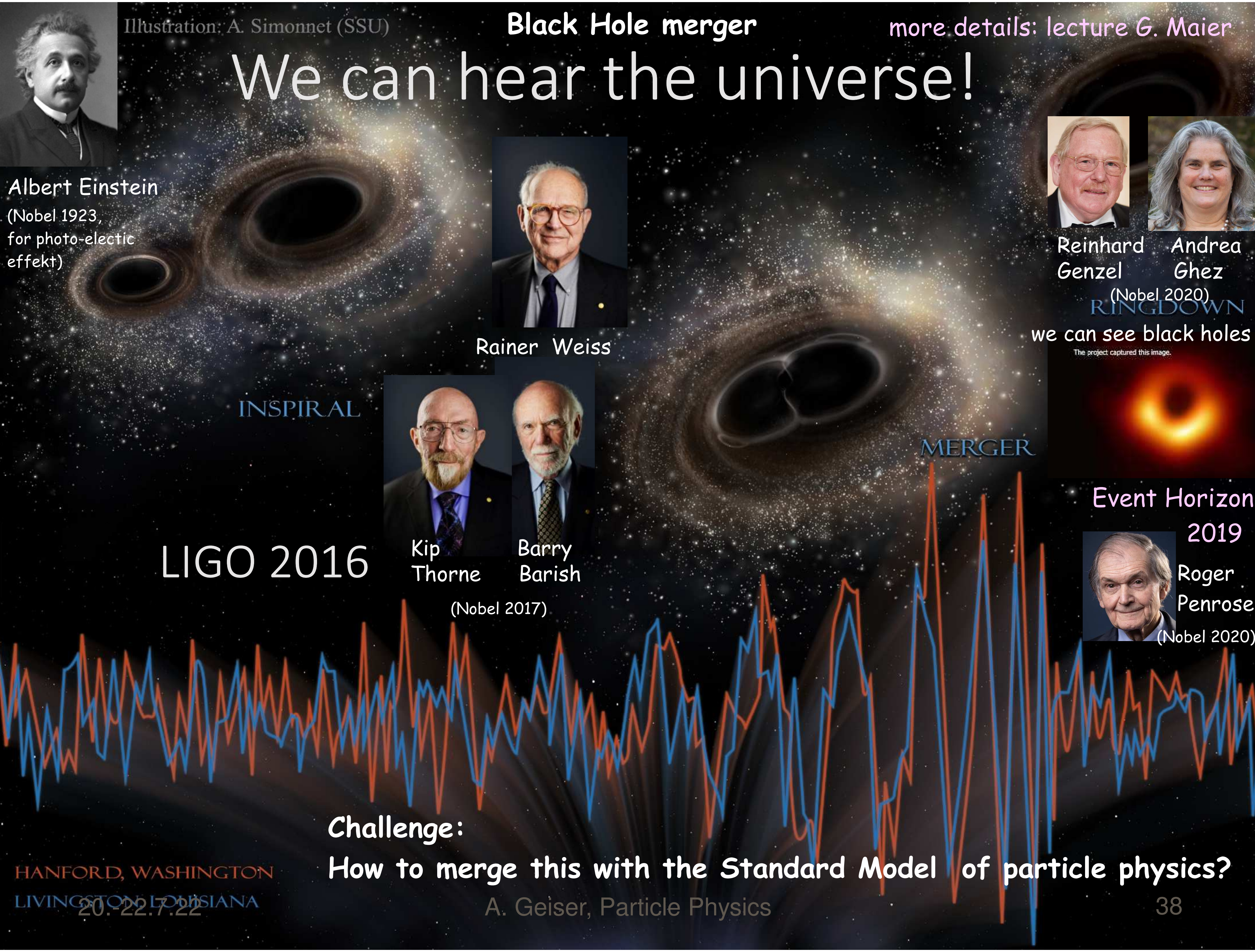
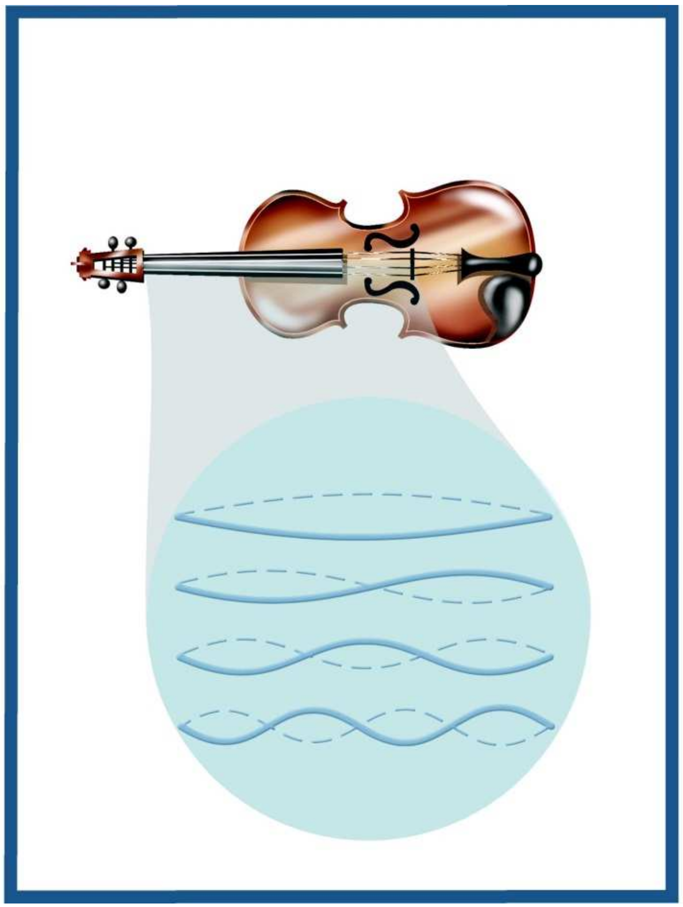
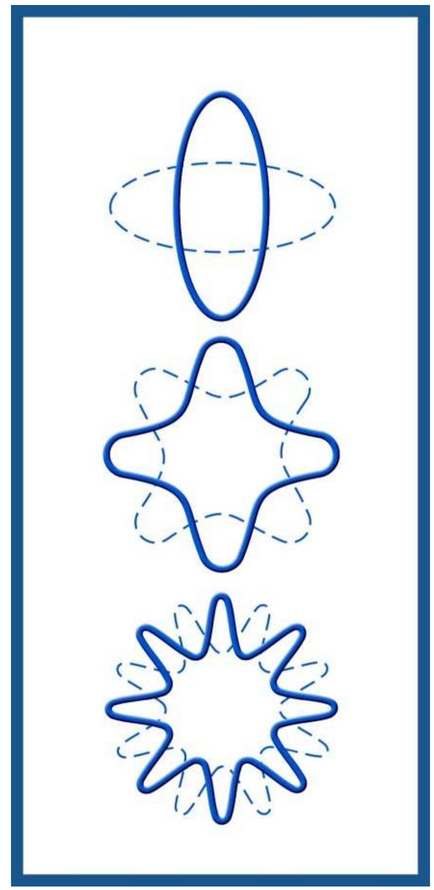


Illustration: A. Simonnet (SSU)
Black Hole merger
more details: lecture G. Maier
We can hear the universe!
Albert Einstein
(Nobel 1923, for photo-electic effekt)
Rainer Weiss
Reinhard Genzel
Andrea Ghez
(Nobel 2020)
RINGDOWN
we can see black holes
The project captured this image.
INSPIRAL
MERGER
Event Horizon 2019
LIGO 2016
Kip Thorne
Barry Barish
(Nobel 2017)
Roger Penrose
(Nobel 2020)
Challenge:
How to merge this with the Standard Model of particle physics?
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

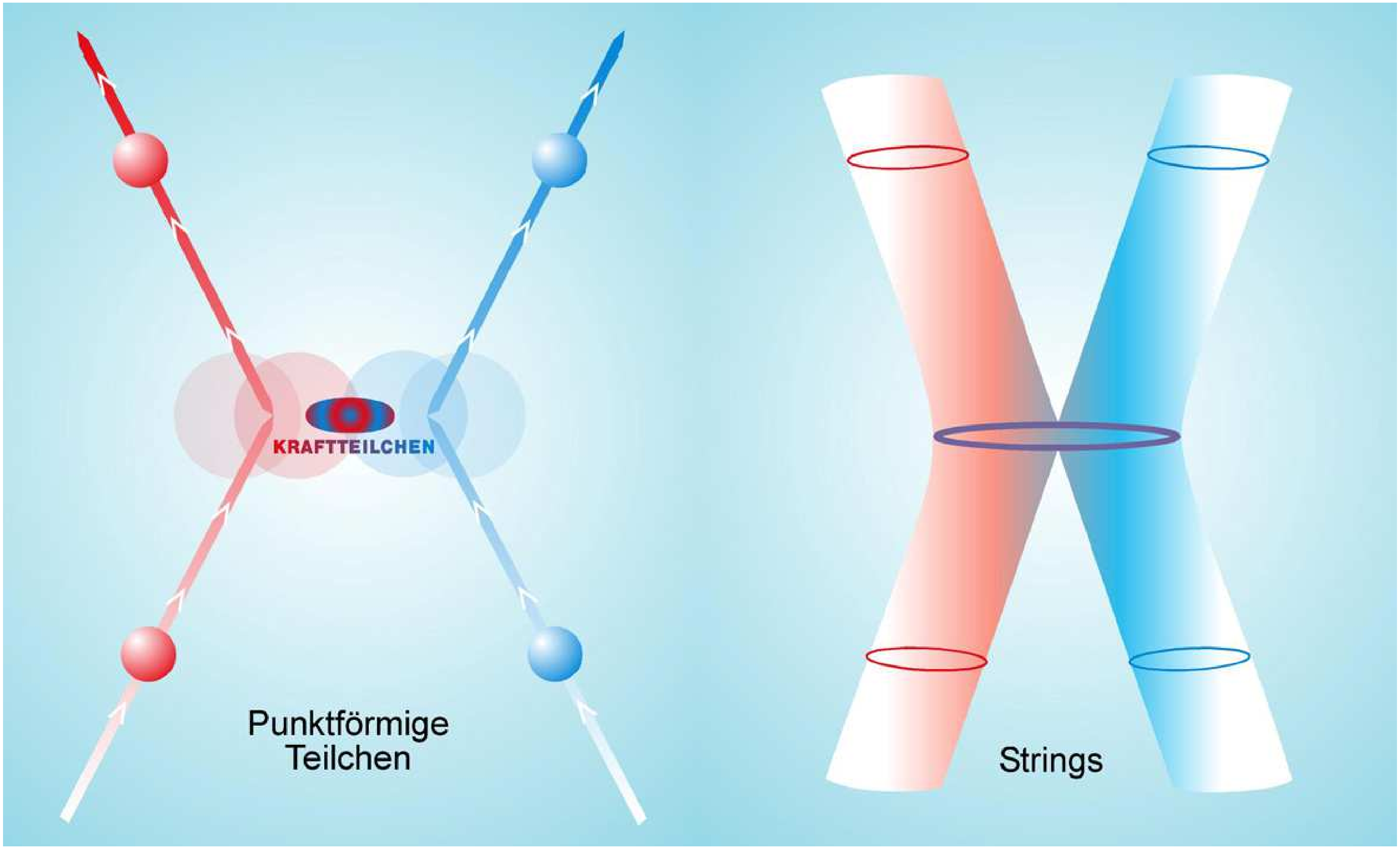
Unification and Superstrings

To include gravity in unification of forces, need Superstrings (Supersymmetric strings)



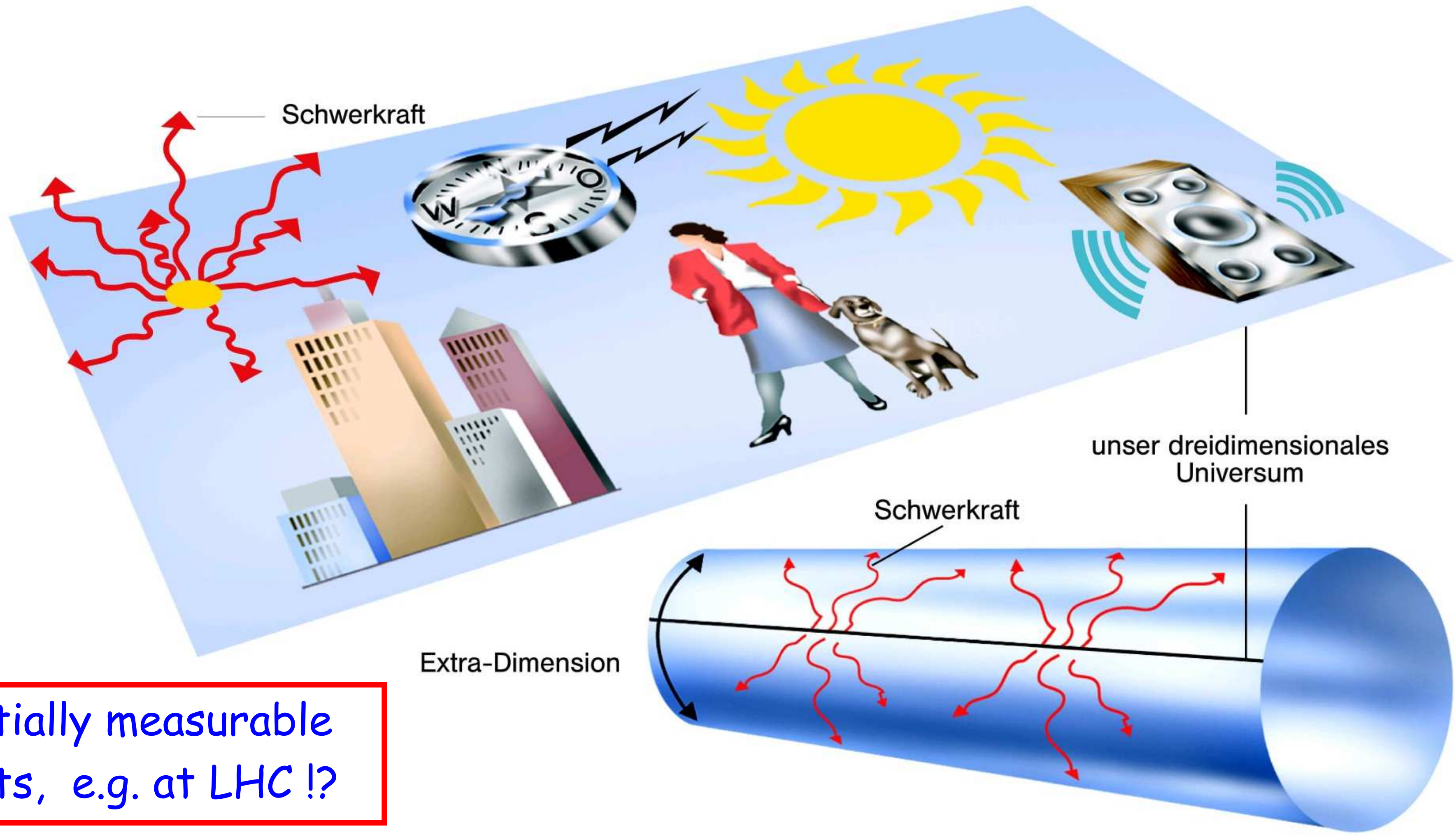


Superstring interaction



Extra Dimensions?

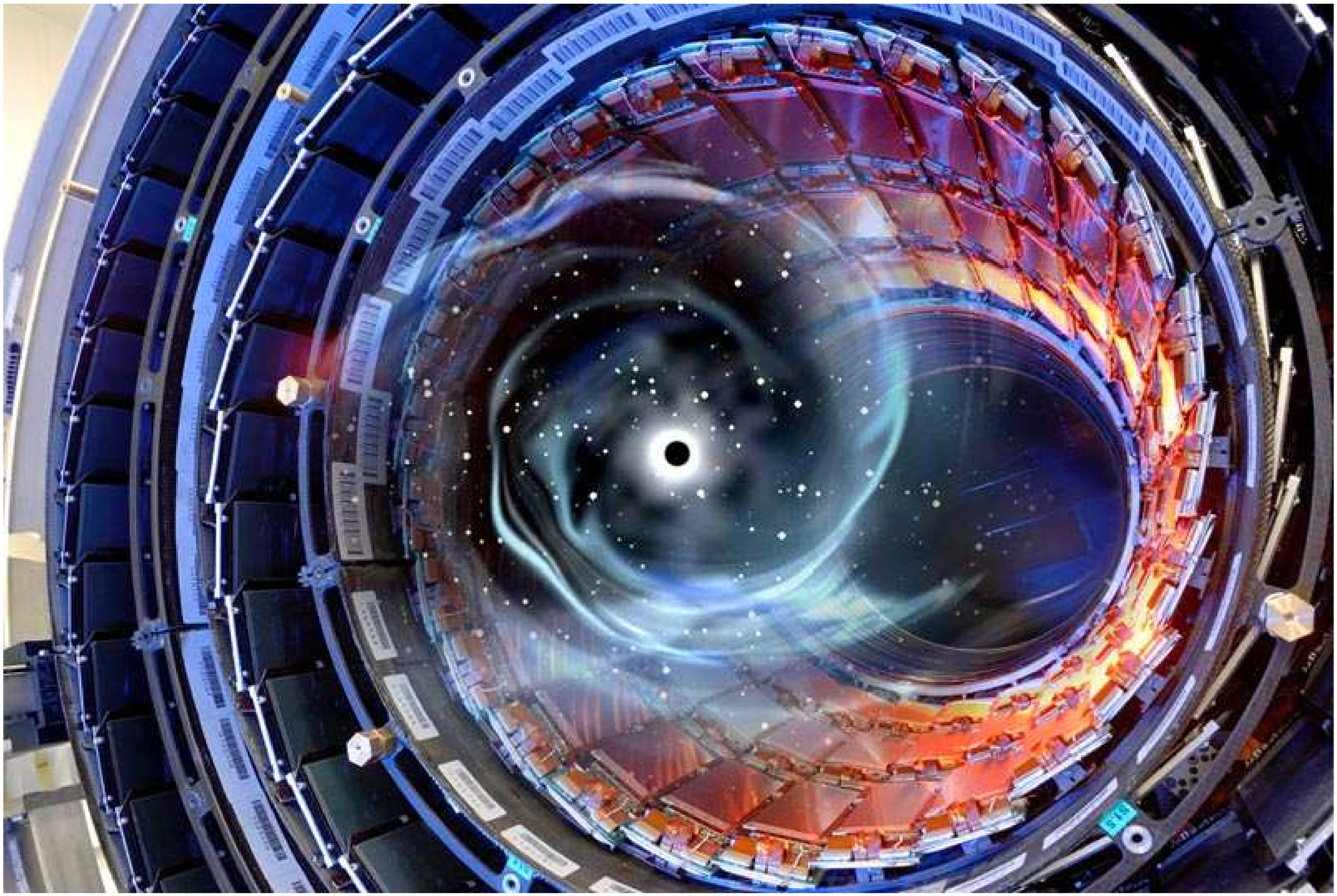
- Superstrings require more than 3+1 dimensions (10 or 11)
- additional "extra" dimensions -> "curled up" (?)



potentially measurable effects, e.g. at LHC !?

extra dimensions -> micro black holes?

extremely short-lived - no indications so far



The case for an e+e- Linear Collider

more details: lecture K. Büßer

- Historically, hadron (proton) and electron colliders have yielded great symbiosis:

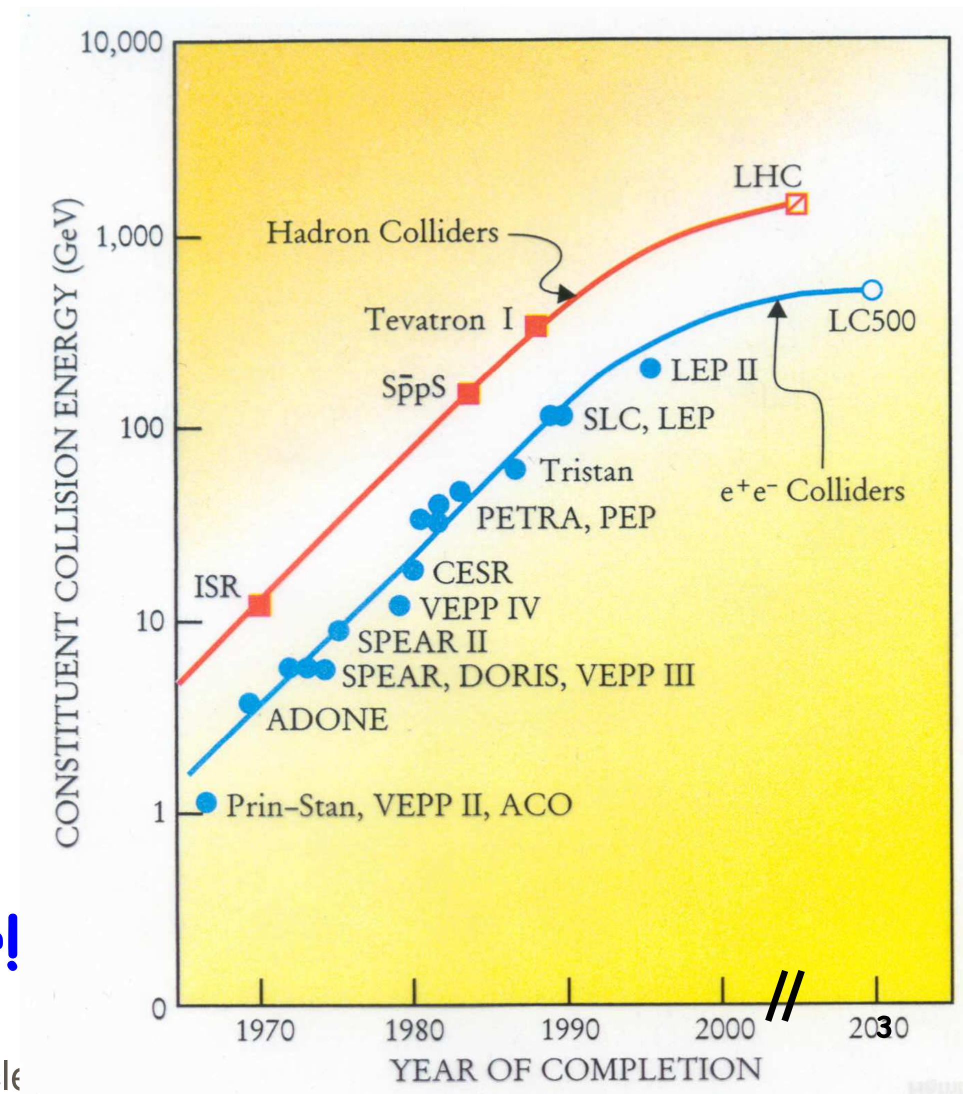
- hadron colliders:
  discoveries at highest energies

- electron colliders:
  discoveries and precision measurements

- latest example:
  Tevatron/LEP (top),
  now Higgs at LHC

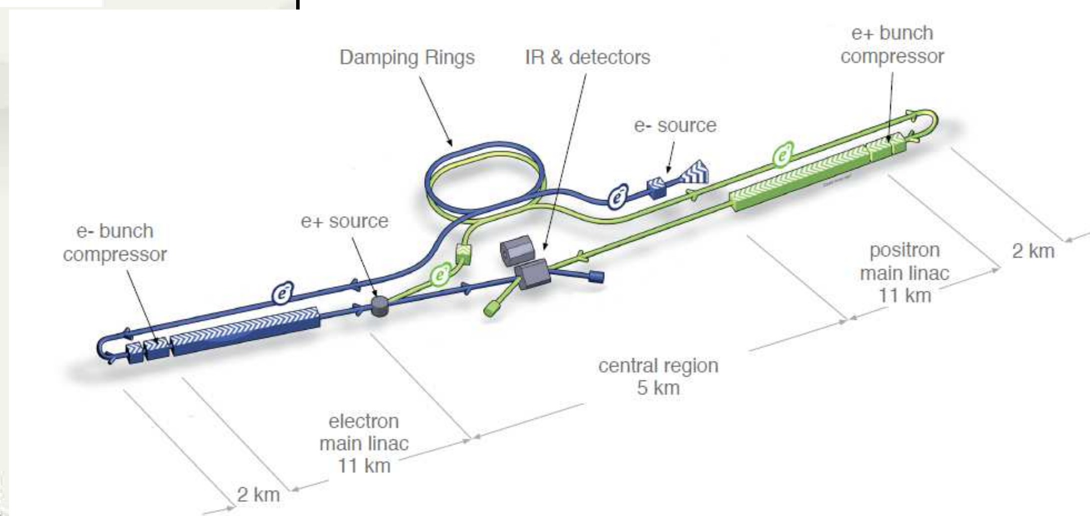
⇒ **International Linear Collider!**

decision unfortunately further delayed



The ILC

"NEW DIRECTIONS IN SCIENCE ARE LAUNCHED BY NEW TOOLS MUCH MORE OFTEN THAN BY NEW CONCEPTS. THE EFFECT OF A CONCEPT-DRIVEN REVOLUTION IS TO EXPLAIN OLD THINGS IN NEW WAYS. THE EFFECT OF A TOOL-DRIVEN REVOLUTION IS TO DISCOVER NEW THINGS THAT HAVE TO BE EXPLAINED." FREEMAN DYSON, Imagined Worlds

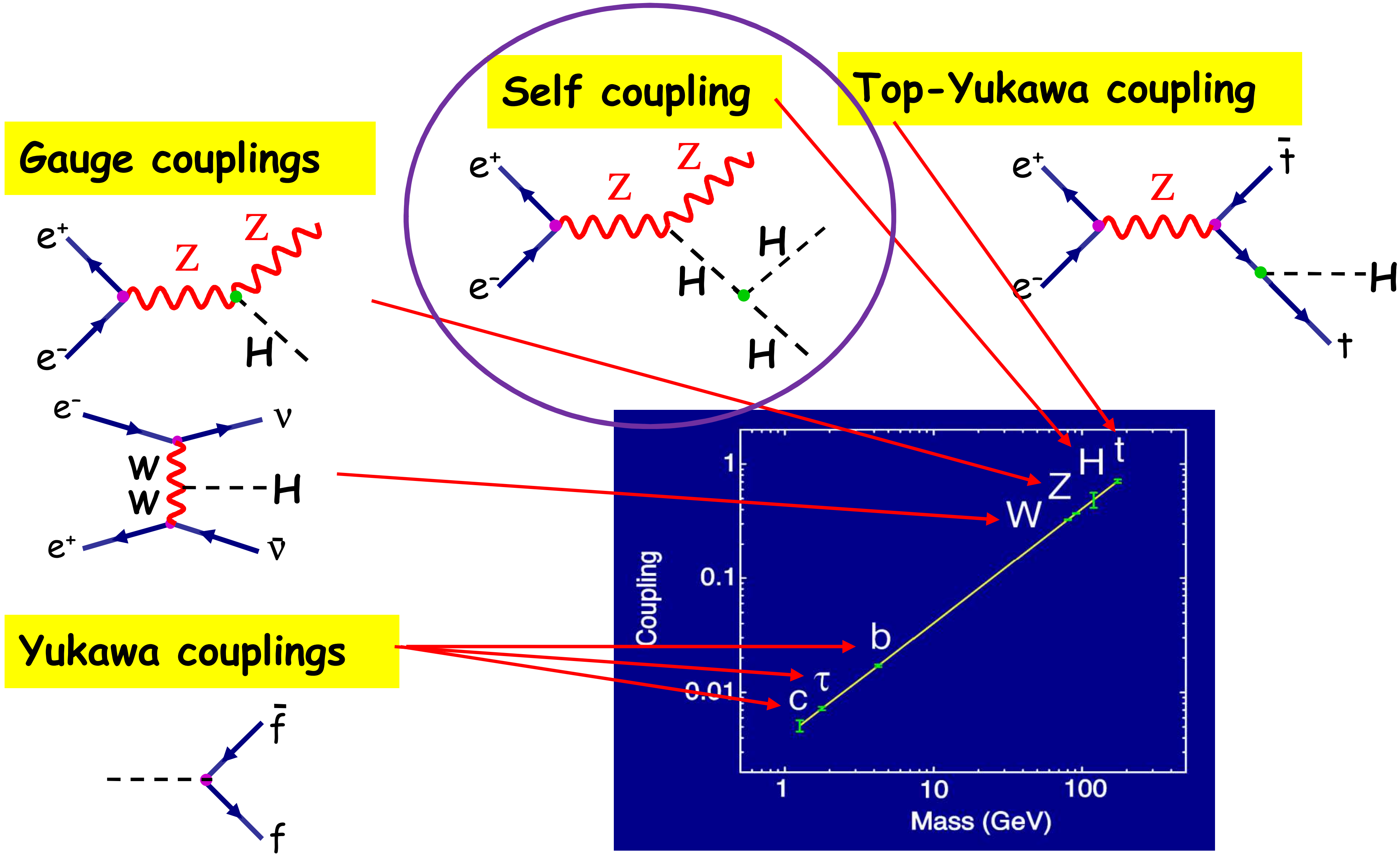


Technical Design Report released (June 2013)

Hosting in Japan being discussed

(+ alternatives, e.g. CLIC, CEP, FCC-ee)

Example: Higgs Physics at the ILC

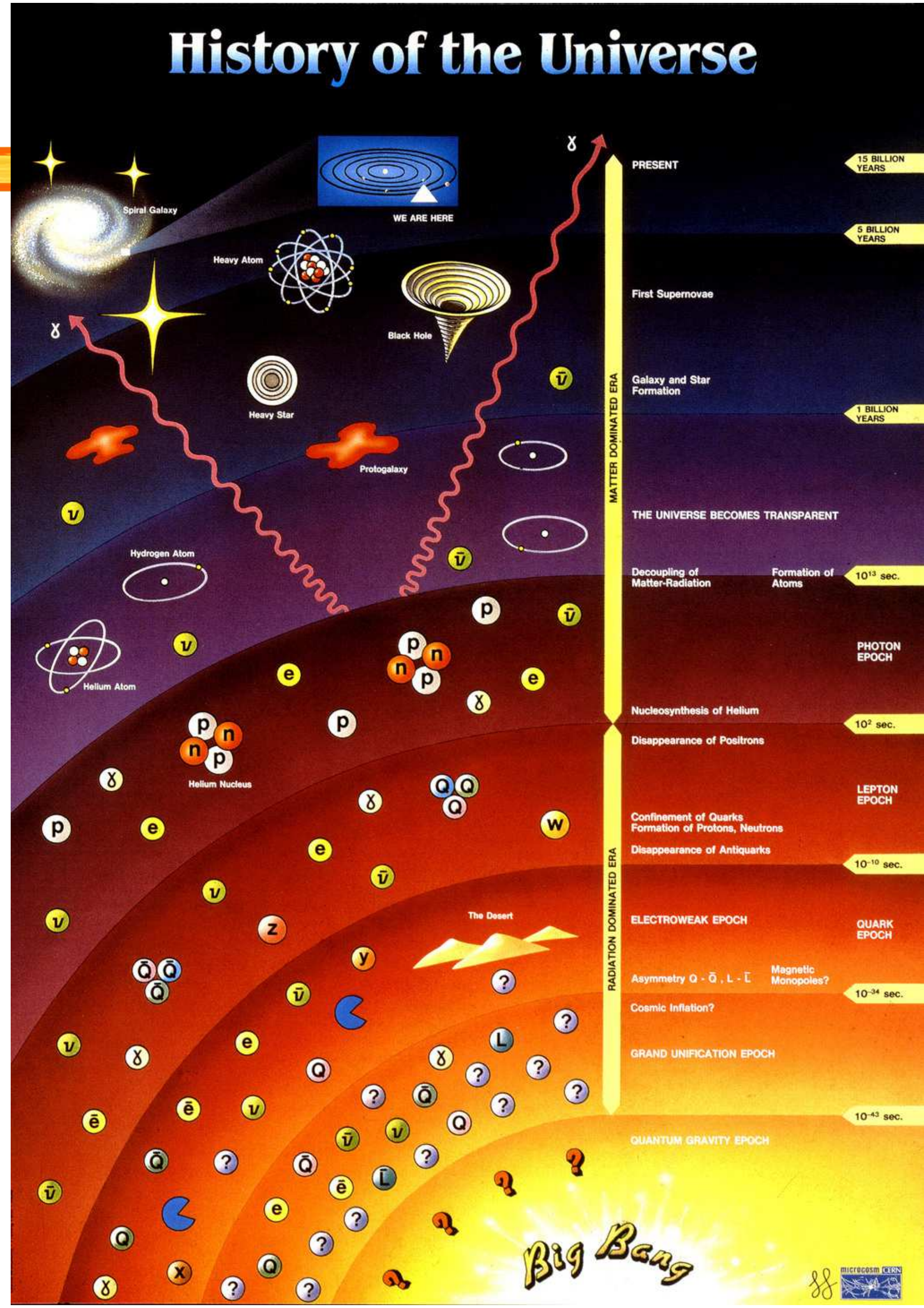


all measurable with very high precision!

Cosmology

Direct link between Particle Physics and Cosmology

increasing energy
-> going further
backwards in time
in the universe
-> getting closer to
the Big Bang



The Big Bang

Galaxy formation

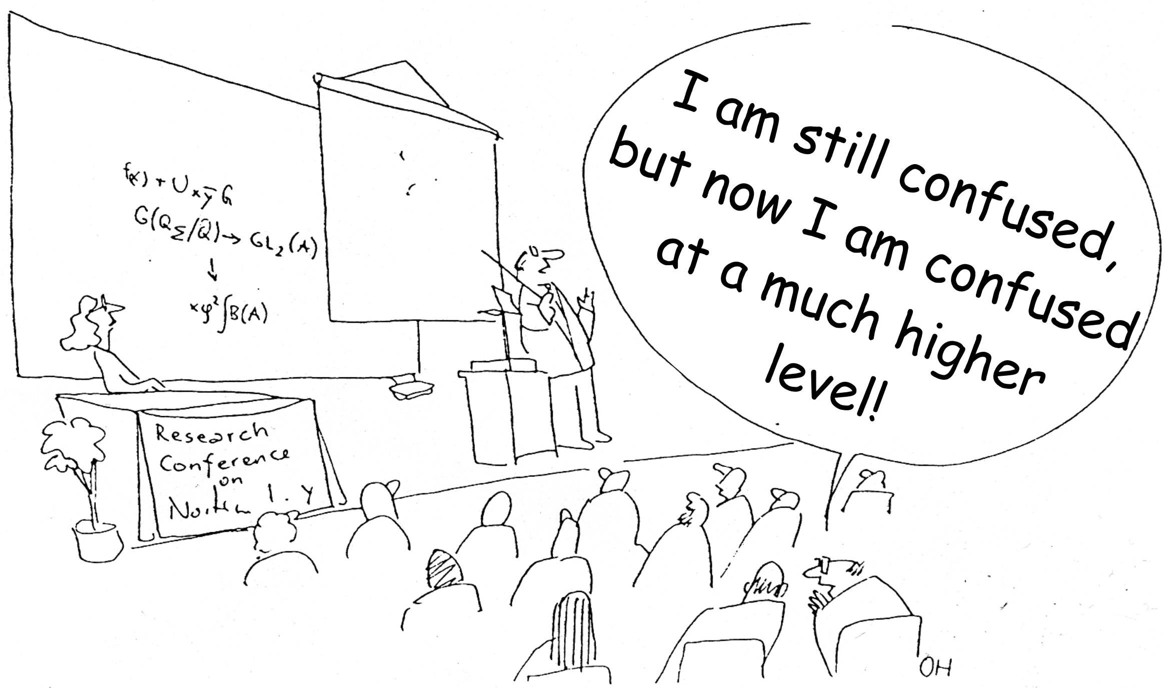
1000 M years

Galaxies begin to form

Urknall

Elementary Particle Physics is exciting!

- We already know a lot, but many open issues



- Exciting new insights expected for the coming decade (e.g. HL-LHC, Belle II) !

Join the Fun!

contact: Achim.Geiser@desy.de