AN INTRODUCTION TO PARTICLE PHYSICS

LECTURE 1/2

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OUTLINE

Lecture 1/2: "An introduction to particle physics"

Wonderland of particle physics

Scales and units

Particle kinematics

Standard Model of particles & interactions

Spontaneous breaking of symmetry: Higgs boson

Lecture 2/2: "An overview of physics at the LHC"

Rediscovering of the Standard Model at the LHC

Search for Higgs boson

Search for new physics: beyond the Standard Model

Supersymmetry?

Extra-Dimensions?

WONDERLAND OF ELEMENTARY PARTICLES

Particle physics: Wonderland of quantum objects with speeds nearly speed of light

It answers questions: What our Universe is made from?
What are the fundamental constituents of matter
and their interactions?

Physics of microworld: Elementary particles

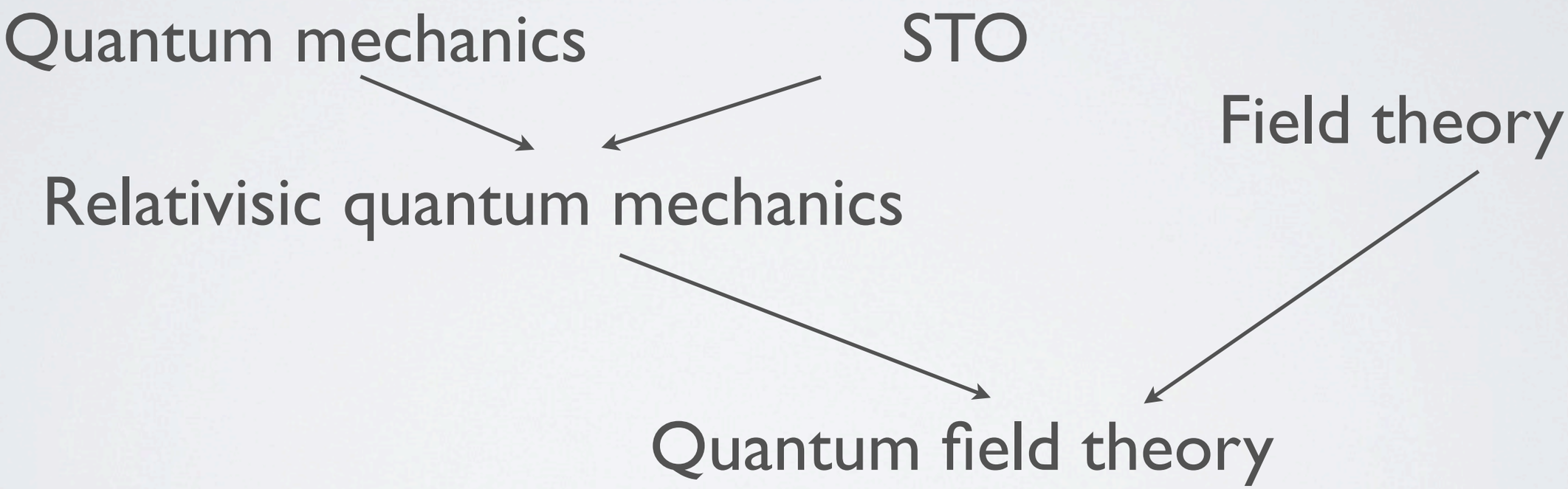
Big Bang theory

Physics of macroworld: Cosmology

Large Hadron Collider (LHC):
particle energies up to 10^{-10} sec after Bing Bang

WONDERLAND OF ELEMENTARY PARTICLES

Particle physics



PARTICLES: UNITS AND SCALES - 1

1 нм = 10^{-9} m		molecule
1 Фм = 10^{-15} m		proton
10^{-3} Фм = 10^{-18} m	≥	electron (HERA)
$5 \cdot 10^{-19}$ m	≥	quarks (LHC: CMS & ATLAS)

opportunity to probe at the LHC
particle substructure: ~ 10^{-6} Fm = 10^{-21} m

PARTICLES: UNITS AND SCALES - 2

typical strong interaction time scale = $3 \cdot 10^{-24}$ sec
photon covers 1 Fm = 10^{-15} m (proton size)

weak interaction time scale ~10^{-12} - 10^{-9}c

Energy scales:
1 эВ = $1.6 \cdot 10^{-19}$ J
molecules ~ 0.02 eV
photons ~ 2 eV
nuclear reactions: 1 МэВ = 10^6 эВ
proton structure: ГэВ = 10^9 эВ

LHC (1 stage): 3.5 TeV x 3.5 TeV
1 TeV = 10^{12} eV

PARTICLES: UNITS AND SCALES - 3

Probability of interaction ~ cross section ~ r^2

barn: 1 b = 10^{-24} cm^2

1 mb = 10^{-27} cm^2

1 nb = 10^{-33} cm^2

Luminosity (~ beam intensity): $cm^{-2} \cdot s^{-1}$

LHC 2010: 10^{32} $cm^{-2} \cdot s^{-1}$

2011: 10^{33} $cm^{-2} \cdot s^{-1}$

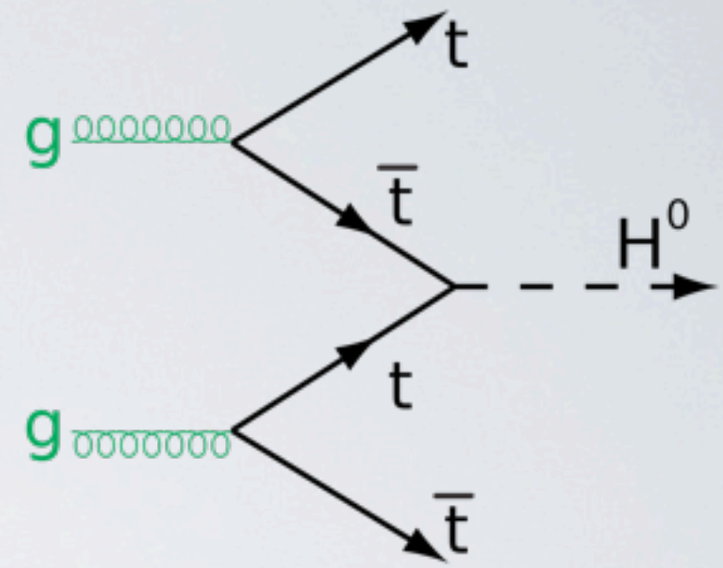
frequency of reactions = luminosity x cross section

Higgs boson:

cross section (m_H = 200 GeV at 7 TeV) ≈ 7 nb

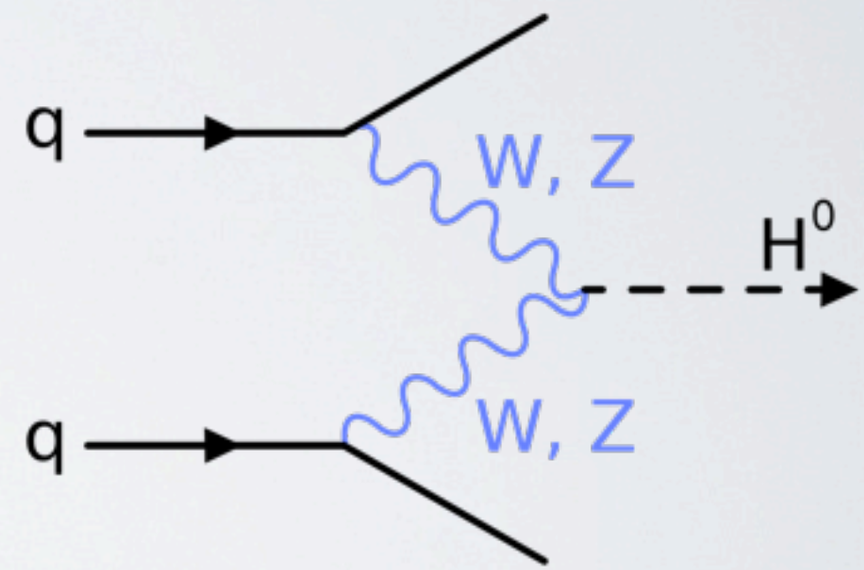
1 event per 2.5 min

CROSS SECTIONS: FEYNMAN DIAGRAMS



Calculation of cross section for particle interactions:

cross section = |process amplitude|^2



probability amplitude ⇔ Feynman diagrams

PARTICLE KINEMATICS

special theory of relativity (STO) $E=\gamma mc^2=\gamma m$

hereafter $c=1$

proton mass = 0.94 GeV
electron mass = 0.5 MeV

Lorentz transformation

4D-rotations in Minkowski space

4-vector length: invariant

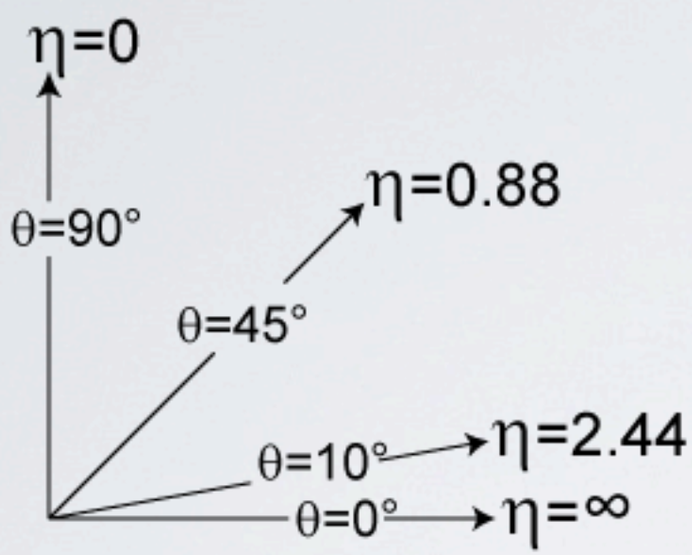
pseudo-Euclidean space: $p = (E, \vec{p}) \rightarrow p^2 = E^2 - \vec{p}^2 = m^2$

mass of decayed particle: $m^2 = (E_1+E_2)^2 - (p_1+p_2)^2$

(PSEUDO)RAPIDITY

angle $\vartheta \longrightarrow$ pseudorapidity $\eta = -\log[\tan(\vartheta/2)]$

$$\eta = \log[(|\vec{p}| + p_L)/(|\vec{p}| - p_L)]$$



rapidity: $y = \log[(E+p_L)/(E-p_L)] \rightarrow$ Lorentz boost invariant

if $E >> m$: $y \longrightarrow \eta$

rapidity in STO: $\psi = \log[(E+|\vec{p}|)/(E-|\vec{p}|)]$

$\cos(\vartheta), \sin(\vartheta) \longrightarrow \cosh(\psi), \sinh(\psi)$

WHY COLLIDERS?

G.I. Budker (INP, Novosibirsk): collider idea

$$p = p_1 + p_2$$

C.M.S.

$(E_1+E_2, \vec{p}_1+\vec{p}_2) = (2E, \vec{0})$

$p^2 = 4\,(E)^2$

$E = E_1 = E_2$

fixed target

$(E^L + m, \vec{p}^L + \vec{0})$

$p^2 = (E^L + m)^2 - (\vec{p}^L)^2 =$

$= 2mE^L + 2m^2 \approx 2mE^L$

$E^L \approx 2\,(E)^2 / m$

$s = (p_1+p_2)^2 \qquad \sqrt{s} = \sqrt{(p_1+p_2)^2}$

Tevatron: 1 TeV x 1 TeV $\longrightarrow$ $E^L = 2 \cdot 10^3$ ТэВ $\quad 2 \cdot 10^3$

LHC: 3.5 TeV x 3.5 TeV $\longrightarrow$ $E^L = 2 \cdot 10^4$ ТэВ $\quad 6 \cdot 10^3$

LHC: 7 TeV x 7 TeV $\longrightarrow$ $E^L = 10^5$ ТэВ $\quad 1.4 \cdot 10^4$

STANDARD MODEL: NON-ABELIAN GAUGE THEORY

Quantum chromodynamics (strong interactions): SU(3)

Standard Model: U(1)xSU(2)xSU(3)

Standard Model of electroweak interactions: U(1)xSU(2)

Electromagnetic interactions: U(1)

Weak interactions: SU(2)

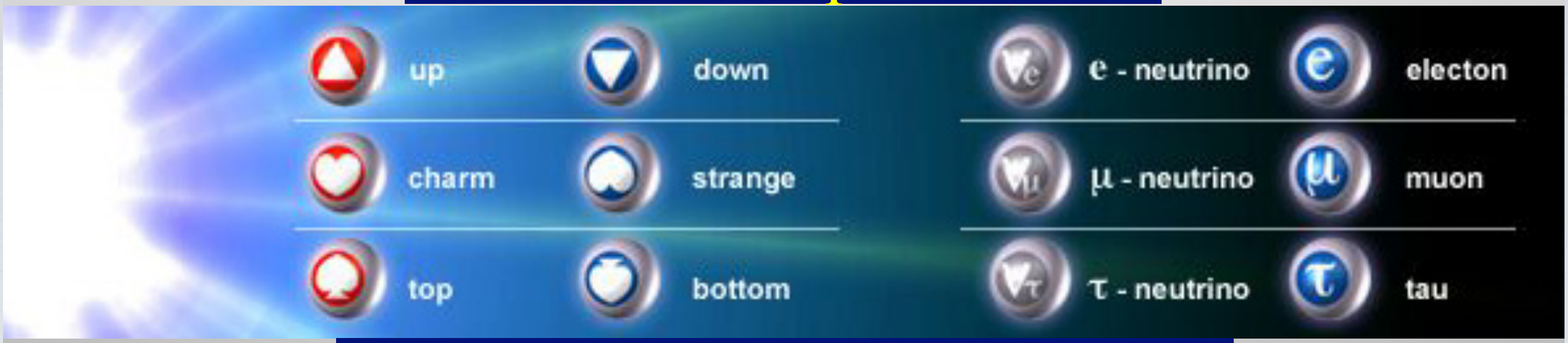
Electricity

Magnetism

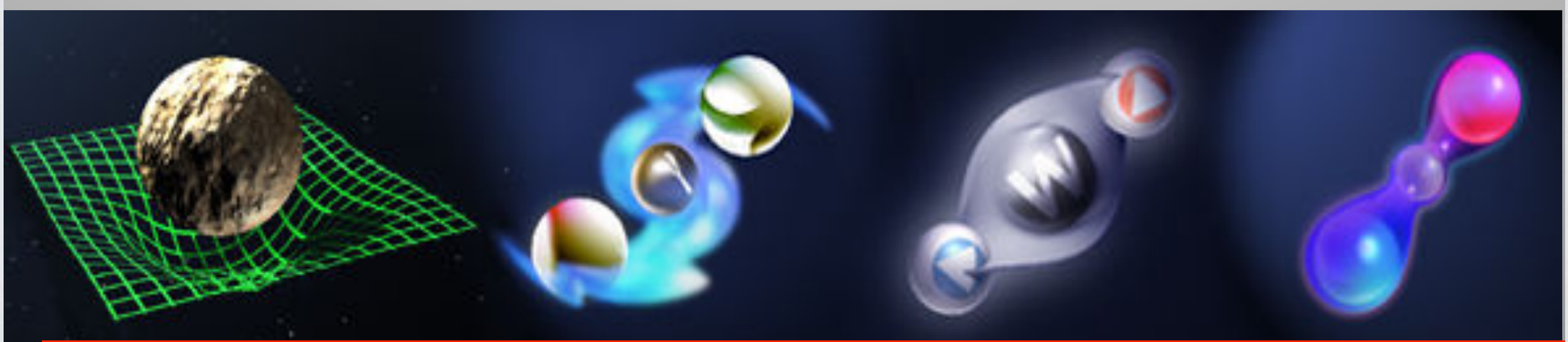
STANDARD MODEL: ELECTROWEAK & QCD

= Cosmic DNA

The matter particles



The fundamental interactions



Gravitation | electromagnetism | weak nuclear force | strong nuclear force

QUARKS AND HADRONS

leptons - “leptos” (Greek: light):
EM & weak interactions

hadrons - “hadros” (Greek: heavy):
EM, weak & strong interactions

baryon: three quarks
meson: quark-antiquark

Quantum Chromodynamis (QCD)

quarks: 6 flavors (flavours)
3 colors (strong charges)
fractional electric charges
gluons: 8 colors electrically neutral

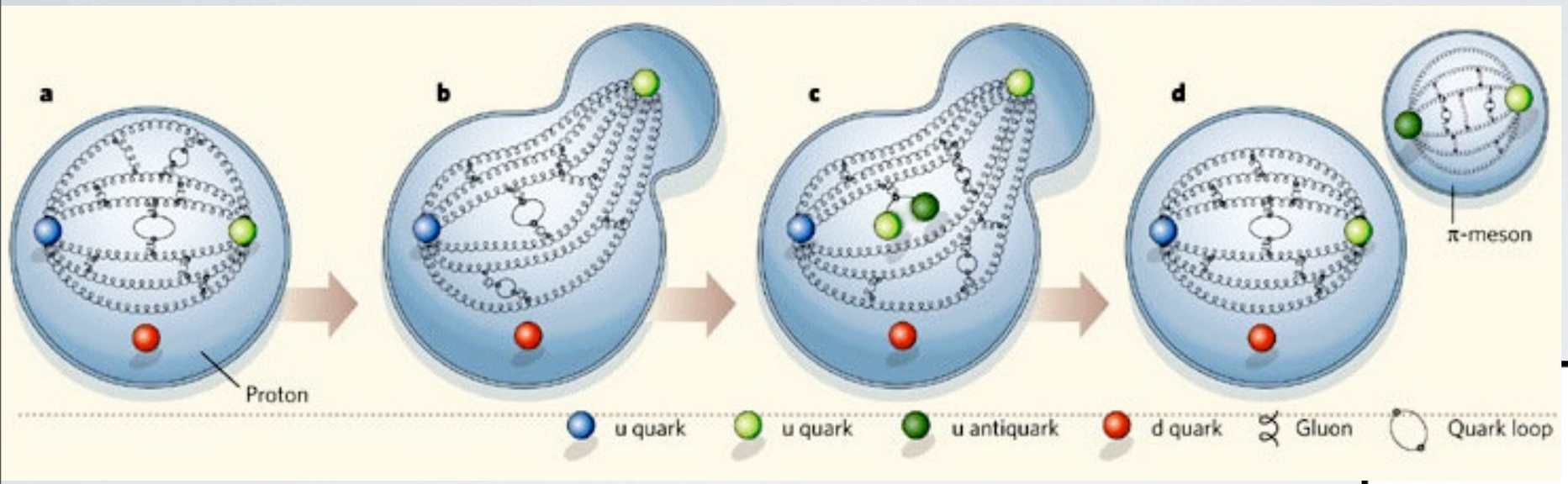
QUARKS: ETYMOLOGY

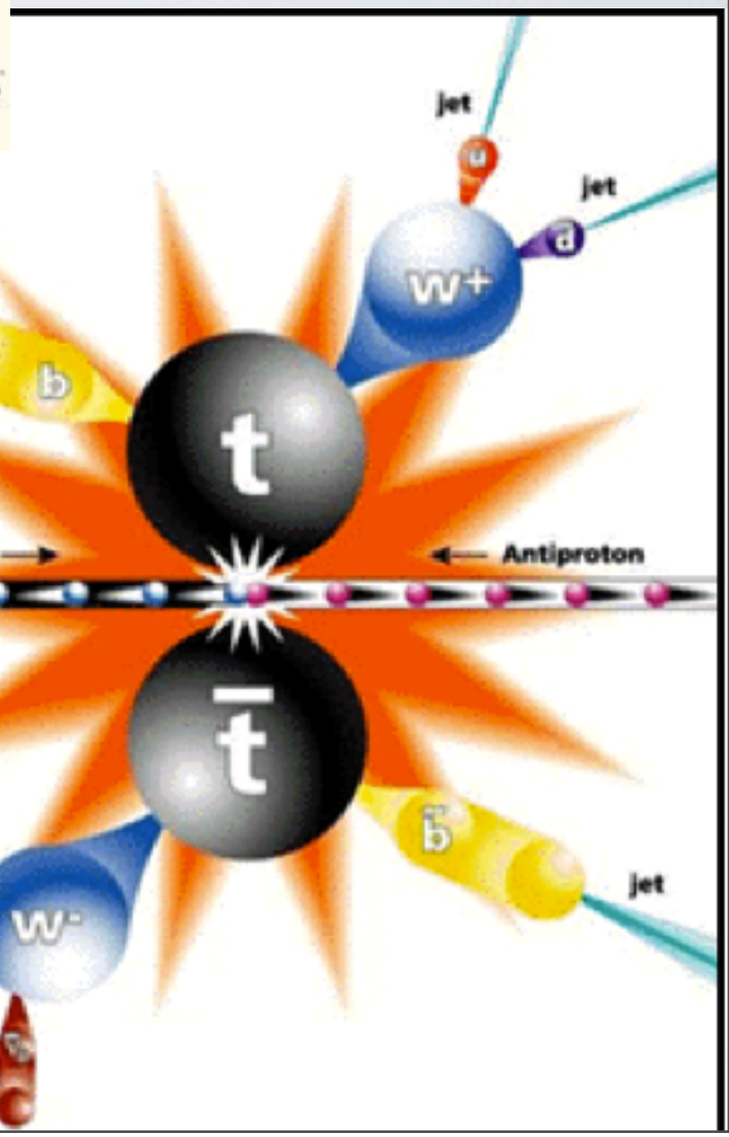
M. Gell-Mann: "quarks" (1964)
S. Zweig: "aces"

James Joyce "Finnegan's wake":
"... Three quarks for muster Mark! ... "

V.M. Shekhter: quark etymology in
"Why we love quarks?" (1974)

QUANTUM CHROMODYNAMICS: ASYMPTOTIC FREEDOM AND CONFINEMENT





Hadrons are very hard,
but they very fragile:
like, e.g., magnets

MASSIVE ELECTROWEAK BOSONS?

Gauge symmetry: massless gauge bosons
mass violates gauge invariance!

Spontaneous breaking of symmetry
in electroweak interactions

SYMMETRY SPONTANEOUS BREAKING

N.N. Bogolyubov: Spontaneous breaking of symmetry

Y.Nambu: Spontaneous breaking of symmetry in particle physics

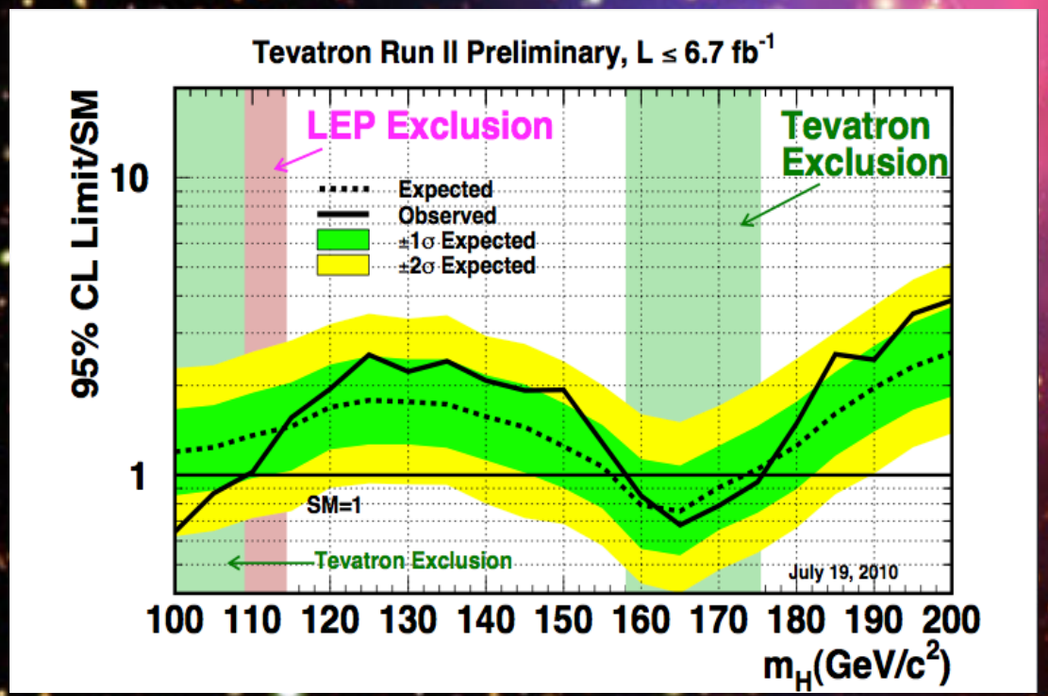
F. Englert & Brout, P. Higgs (1964):
Spontaneous breaking of symmetry in electroweak interactions

The Origin of Mass

Some particles have mass, some do not

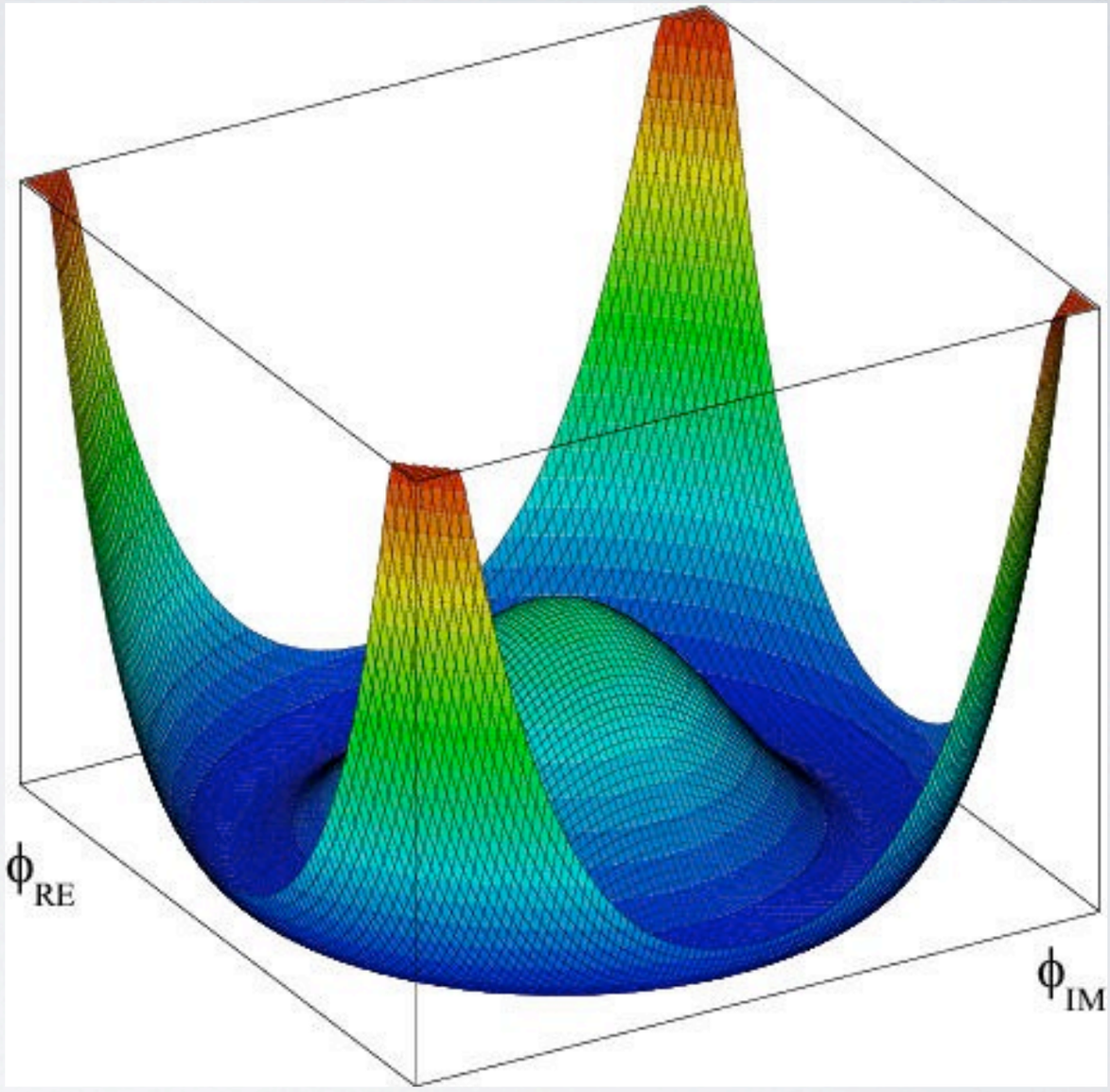
Where do the masses come from?

Explanation of Profs P. Higgs R. Brout en F. Englert
⇒ A new field and particle



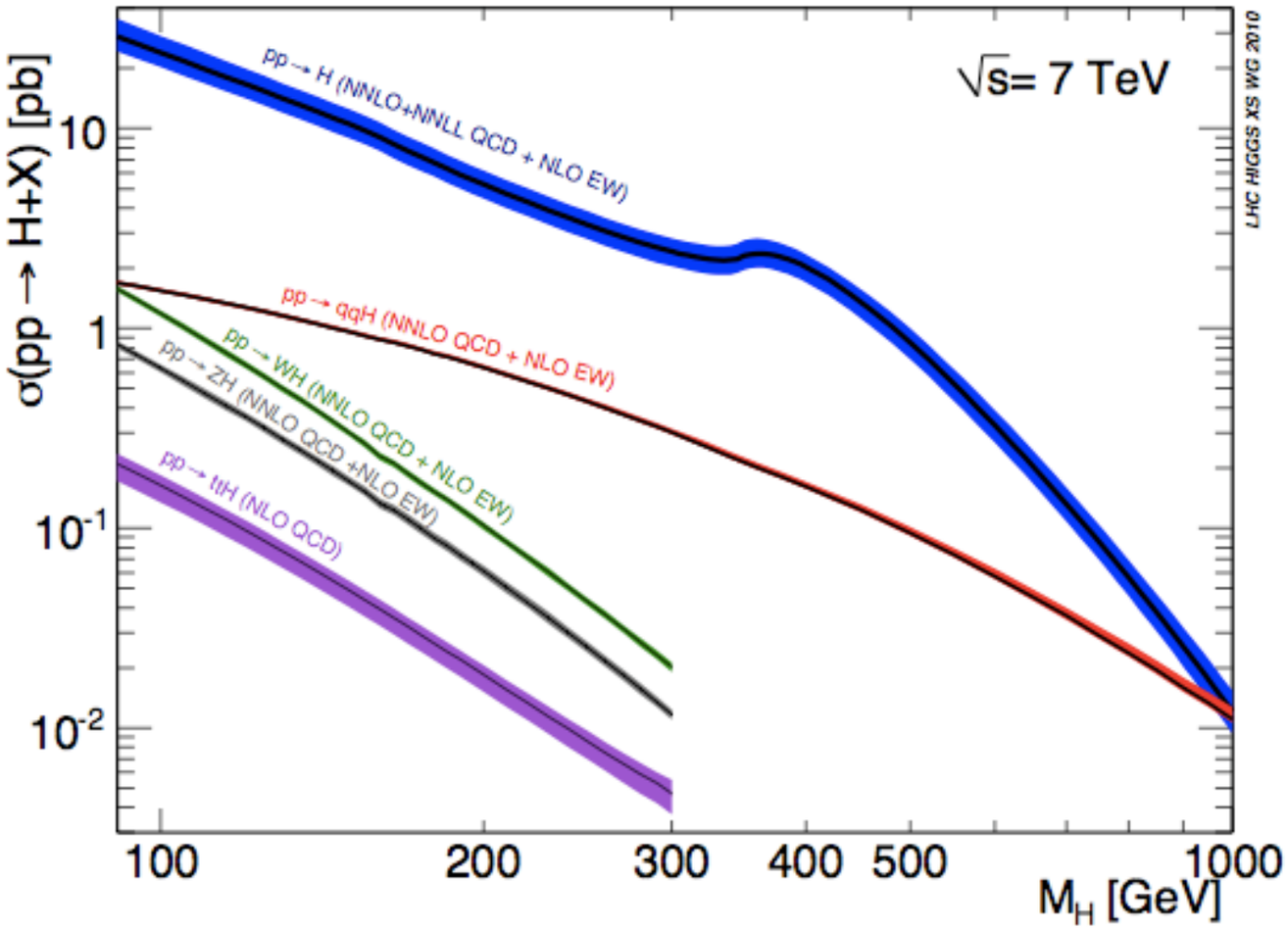
The key question:
Where is the Higgs?

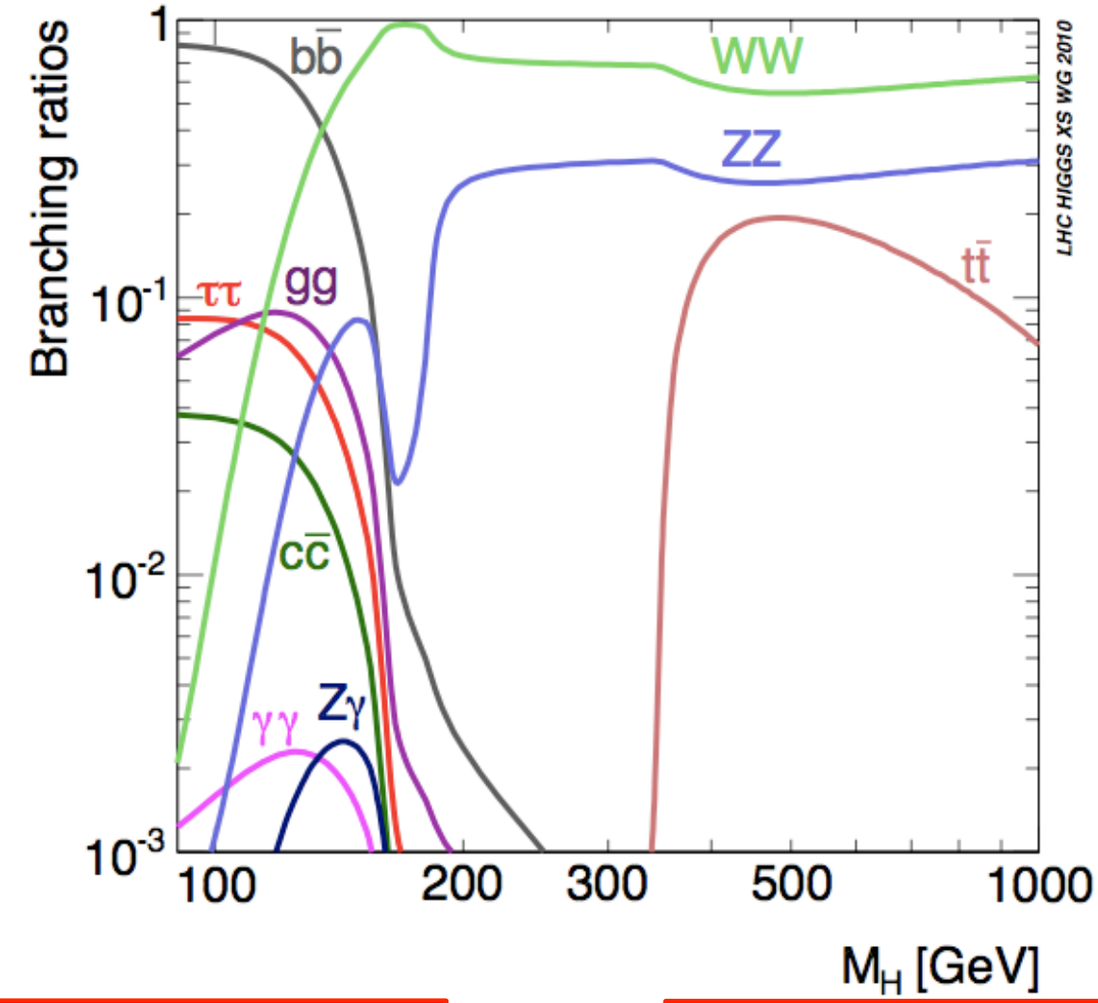
SYMMETRY SPONTANEOUS BREAKING



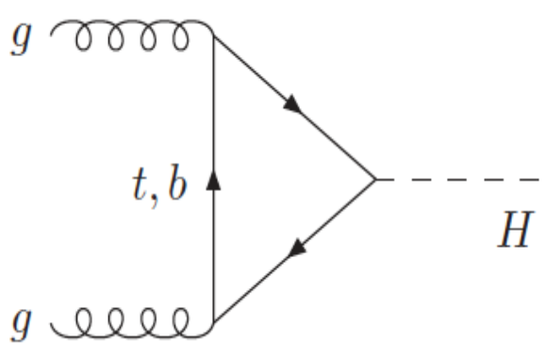
F. Englert & Brout
P. Higgs (1964):
Spontaneous breaking of symmetry in electroweak interactions

HIGGS BOSON: PRODUCTION AND DECAYS

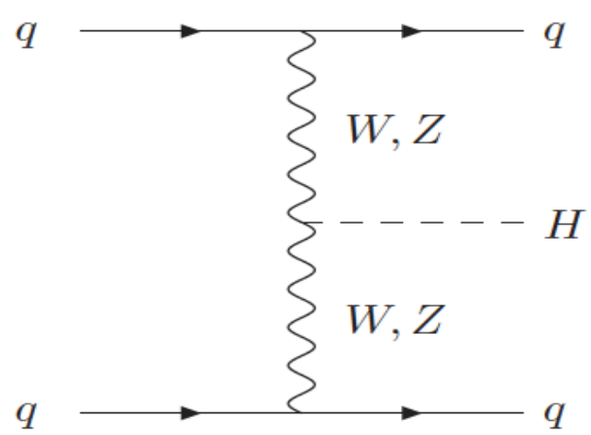




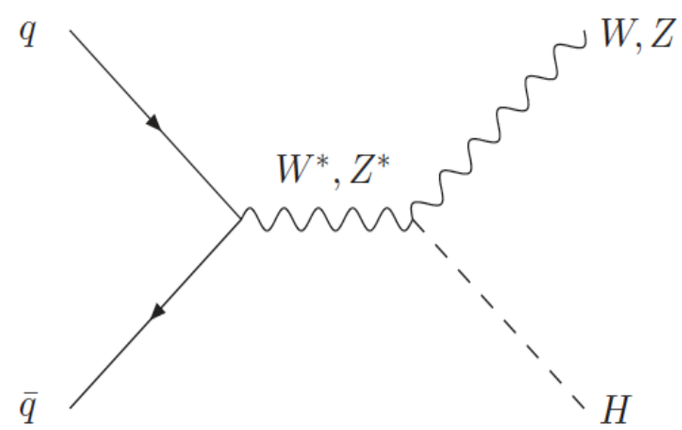
gluon-fusion



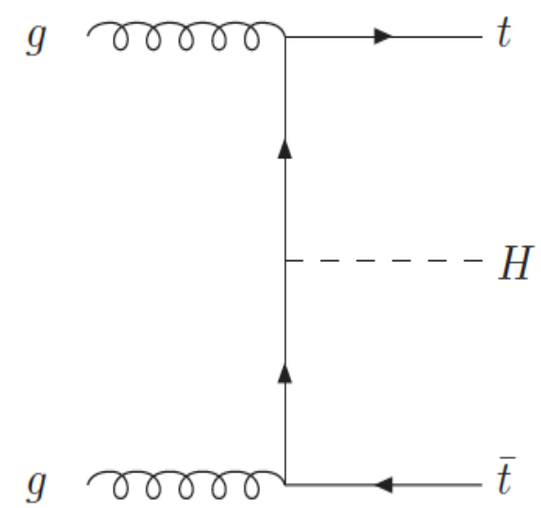
VBF



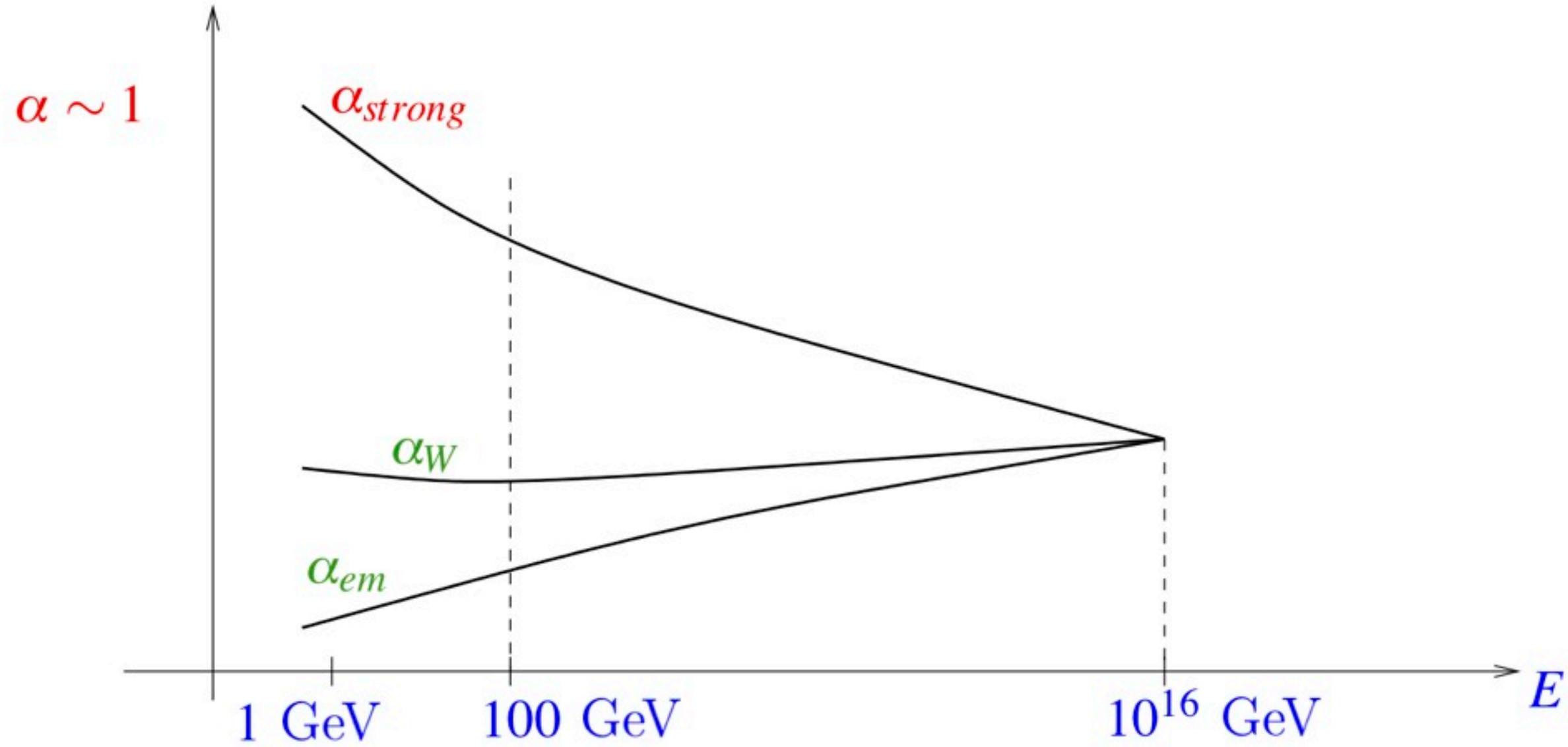
VH



ttH



ENERGY SCALES OF STANDARD MODEL



HIGGS BOSON: PRESERVING UNITARITY

High-energy scattering of longitudinal vector bosons:
$W_L W_L$ cross section diverges, if no Higgs boson

longitudinal components of vector bosons behave as scalars
Higgs boson contribution compensate the divergence

STANDARD MODEL: PARAMETERS

The Standard Model is defined by
a fixed set of parameters:

gauge couplings (α_{EM}, α_S, $\sin\vartheta_W$): 3
masses: m_W, m_{quarks}, $m_{leptons}$, m_{Higgs}: 14
CKM mixings and CP-odd phase: 4
Higgs boson self-coupling λ_{Higgs}: 1

total: 22

Everything else can be derived:

gauge weak coupling $g = \alpha_{EM} / \sin\vartheta_W$
$m_Z = m_W / \cos\vartheta_W$

etc.

USEFUL LINKS

Popular physics site of “Dynasty”: elementy.ru

CERN Schools of High Energy Physics Proceedings

High energy physics software: hepforge.org:
Monte Carlo event generators,
particle process calculation software, etc.