“Elementary Particles”
Lecture 1

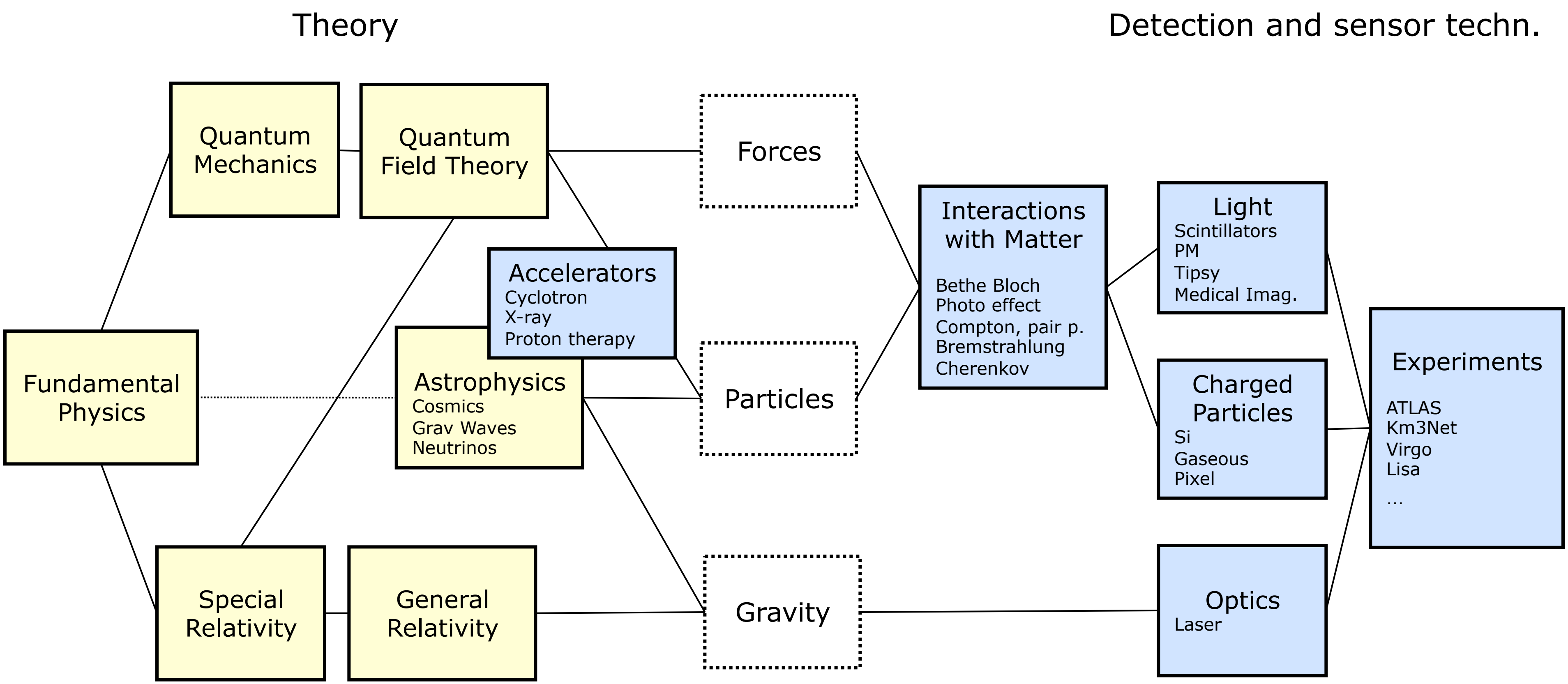
Niels Tuning

Harry van der Graaf

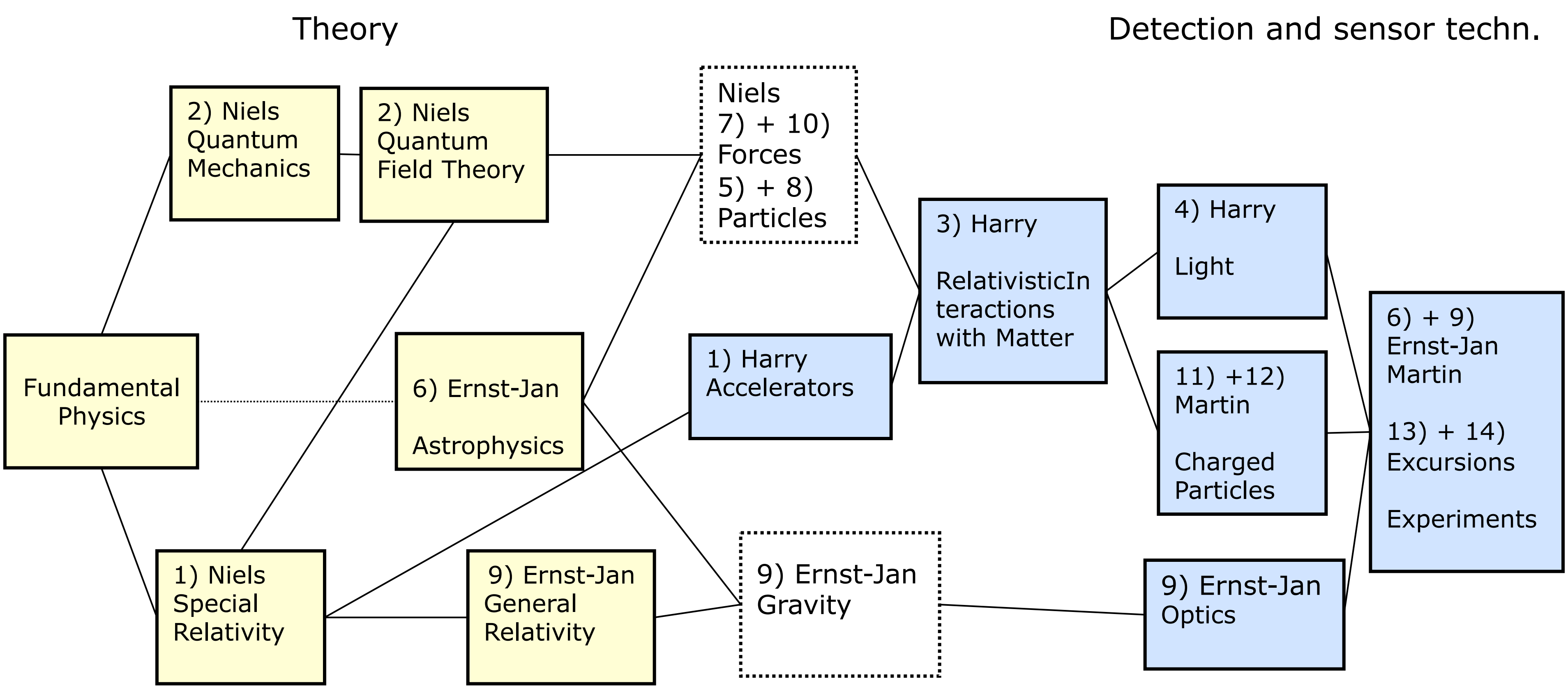
Martin Fransen

Ernst-Jan Buis

Plan


Theory
Detection and sensor techn.
Quantum Mechanics
Quantum Field Theory
Forces
Accelerators
Cyclotron
X-ray
Proton therapy
Fundamental Physics
Astrophysics
Cosmics
Grav Waves
Neutrinos
Particles
Interactions with Matter
Bethe Bloch
Photo effect
Compton, pair p.
Bremstrahlung
Cherenkov
Light
Scintillators
PM
Tipsy
Medical Imag.
Charged Particles
Si
Gaseous
Pixel
Experiments
ATLAS
Km3Net
Virgo
Lisa
…
Special Relativity
General Relativity
Gravity
Optics
Laser

Plan



Theory
Detection and sensor techn.
2) Niels
Quantum
Mechanics
2) Niels
Quantum
Field Theory
Niels
7) + 10)
Forces
5) + 8)
Particles
3) Harry
RelativisticIn
teractions
with Matter
4) Harry
Light
Fundamental
Physics
6) Ernst-Jan
Astrophysics
1) Harry
Accelerators
11) +12)
Martin
Charged
Particles
6) + 9)
Ernst-Jan
Martin
13) + 14)
Excursions
Experiments
1) Niels
Special
Relativity
9) Ernst-Jan
General
Relativity
9) Ernst-Jan
Gravity
9) Ernst-Jan
Optics

Schedule

1) 11 Feb: Accelerators (Harry) + Special relativity (Niels)
   - Layout, structure
   - Thomson Tube, vdGraaff, Cockroft Walton, cyclotron, synchrotron,
   - **(Synchrotron radiation (ESRF), neutron sites (ESS), WakeField accelerators, proton beam therapy ?)**
   - 4-vectors, Lorentz transformation, Special relativity
2) 18 Feb: Quantum Mechanics (Niels)
   - QM basics, wave function, Schrodinger, Klein-Gordon, Dirac equation, Rutherford scattering
3) 25 Feb: Interactions with Matter (Harry)
   - EM interactions, Bethe Bloch, Landau distributions, Ionisation in gas and Si
   - Three photon interactions (Photo effect, Compton, Pair Production)
   - Bremstrahlung, Cherenkov radiation. Equivalence of Pair Production and Brehmstrahlung
4) 3 Mar: Light detection? (Harry)
   - **Scintillators (including photon detectors, from ZiSulfide to Tipsy))**
   - **Calorimeters?**
5) 10 Mar: Particles and cosmics (Niels)
   - Cosmics, quark model, strangeness
6) 17 Mar: Astrophysics and Dark matter (Ernst-Jan)
   - Cosmic rays (Showers (**protons/gammas/neutrinos/dark matter**); Signals (Cherenkov radiation, fluorescence,radio); Experiments (PA/IceCube/Anatares/KM3NeT/TA); Cherenkov gamma-ray telescope(Magic/Hess/CTA))
   - Low background experiments (PMTs; Shielding; Experiments (Kamiokande/Xenon/DAMA)
   - Space based experiments (cosmic rays from space and spaceweather (AMS/ACE); Gamma/X-ray space based astrophysics, Optics/coded masks, Swift, Integral, XMM/Chandra, planetaire mission)
7) 24 Mar: Forces (Niels)
   - Symmetries, Gauge invariance, QED, weak and strong interaction

Schedule

8) 21 Apr: e^+e^- and ep scattering (Niels)
   - R (colors), running coupling, charm, gluon, tt, WZ, DIS

9) 28 Apr: Gravitational waves (Ernst-Jan)
   - Interferometry (Michelson, Sagnac; lasers, optics)
   - Ground based experiments (Virgo/LIGO/Karga/ET)
   - Spaced based experiments (LISA)
   - Multimessenger (Space+ground; triggers; Future, big questions)

10) 12 May: Higgs and big picture (Niels)
   - Higgs mechanism and Standard Model completion

11) 19 May: Charged particle detection (Martin)
   - **Gaseous detectors (from Geiger to GridPix)**
   - **Semiconductor (Si) detectors; pixel detectors**

12) 26 May: Applications: experiments and medical (Martin)
   - Pixels, ATLAS, 4D tracking
   - medical imaging, CT, spectral X-ray, PET scan

13) 2 Jun: Nikhef excursie
   - ATLAS? ALICE? Km3Net? Virgo? LHCb?

14) 8 Jun: CERN excursie
   - CERN lecture (H. Ten Kate); ATLAS underground; Synchro-cyclotron; LHCb; AD antimatter ?

Schedule

1) 11 Feb: Accelerators (Harry vd Graaf) + Special relativity (Niels Tuning)
2) 18 Feb: Quantum Mechanics (Niels Tuning)
3) 25 Feb: Interactions with Matter (Harry vd Graaf)
4) 3 Mar: Light detection (Harry vd Graaf)
5) 10 Mar: Particles and cosmics (Niels Tuning)
6) 17 Mar: Astrophysics and Dark Matter (Ernst-Jan Buis)
7) 24 Mar: Forces (Niels Tuning)

break

8) 21 Apr: e^+e^- and ep scattering (Niels Tuning)
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10) 12 May: Higgs and big picture (Niels Tuning)
11) 19 May: Charged particle detection (Martin Franse)
12) 26 May: Applications: experiments and medical (Martin Franse)

13) 2 Jun: Nikhef excursie
14) 8 Jun: CERN excursie

Plan

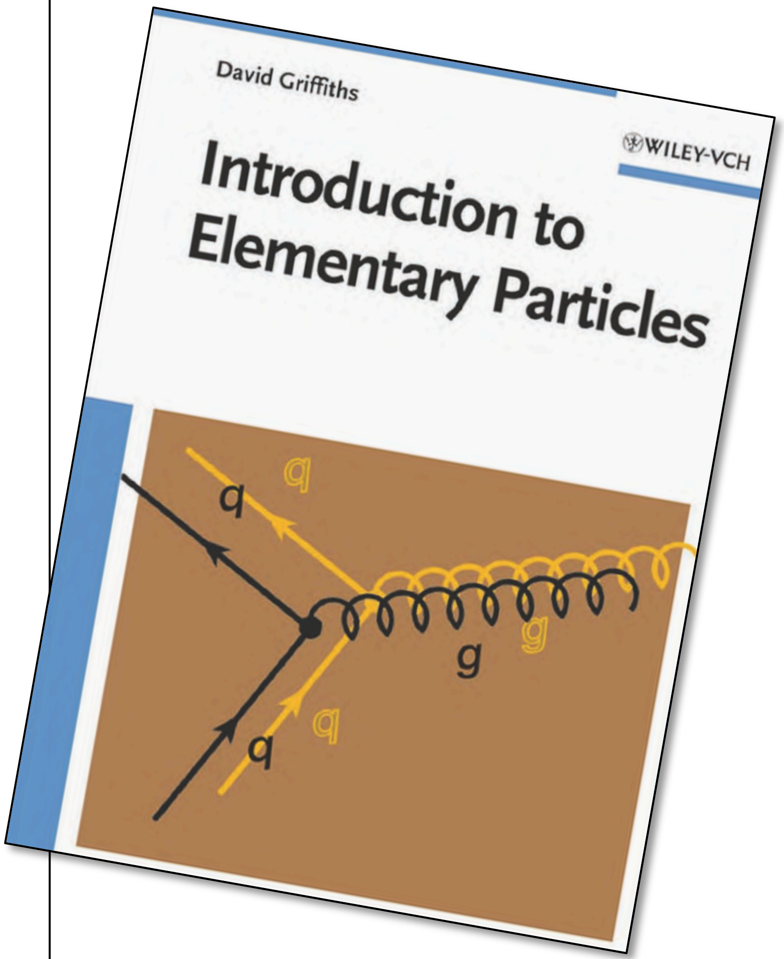
	1) Intro: Standard Model & Relativity	*11 Feb*
1900-1940	2) Basis	*18 Feb*
	1) Atom model, strong and weak force	
	2) Scattering theory	
1945-1965	3) Hadrons	*10 Mar*
	1) Isospin, strangeness	
	2) Quark model, GIM	
1965-1975	4) Standard Model	*24 Mar*
	1) QED	
	2) Parity, neutrinos, weak inteaction	
	3) QCD	
1975-2000	5) e^+e^- and DIS	*21 Apr*
2000-2015	6) Higgs and CKM	*12 May*

Books

• M. Thomson	"Modern Particle Physics"	(2013, 49 EUR)
• D. Griffiths	"Introduction to Elementary Particles"	(2008, 68 EUR)
• C. Tully	"Elementary Particle Physics in a Nutshell"	(2011, 65 EUR)
• F. Halzen & A.D.Martin	"Quarks and Leptons"	(1984, 68 EUR)

D. Griffiths "Introduction to Elementary Particles"

- Lecture 1:
  - ch.3 Relativistic kinematics
- Lecture 2:
  - ch.5.1 Schrodinger equation
  - ch.7.1 Dirac equation
  - ch.6.5 Scattering
- Lecture 3:
  - ch.1.7 Quarkmodel
  - ch.4 Symmetry/spin
- Lecture 4:
  - ch.7.4 QED
  - h.11.3 Gauge theories
- Lecture 5:
  - ch.8.2 e+e-
  - ch.8.5 e+p
- Lecture 6:
  - ch.11.8 Higgs mechanism



Outline of today

- Introduction
  - Start with the end... : Higgs!
  - The Standard Model
- How to calculate with high energies? A reminder.
  - Lorentz Transformation
  - Invariants
  - Colliding particles

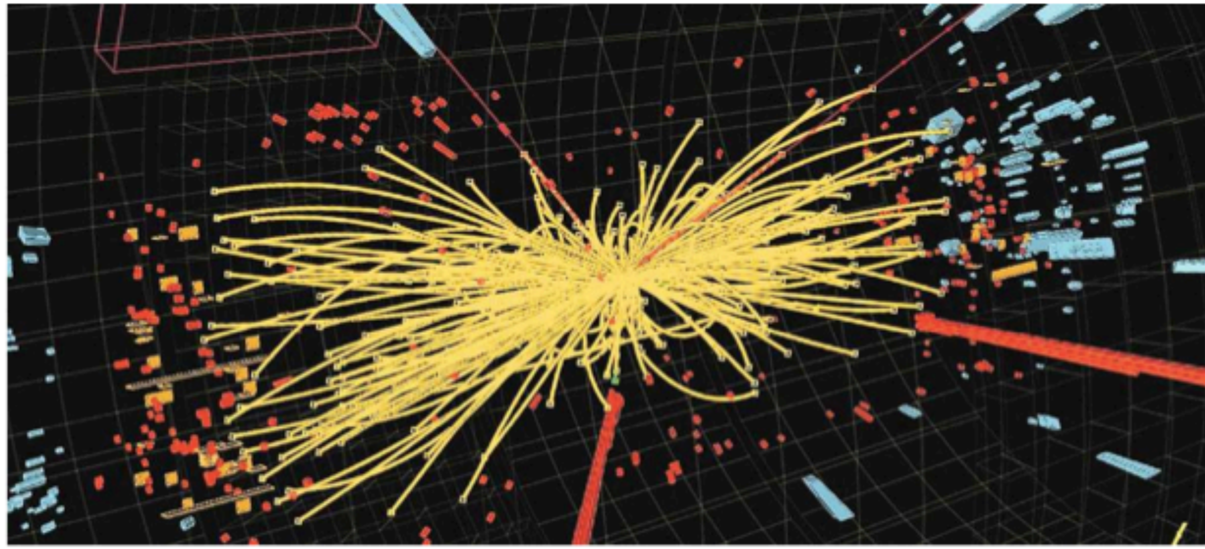
NRC HANDELSBLAD

Woensdag 4 juli 2012 Jaargang 42 no.233 Algemeen Handelsblad (1828) en Nieuwe Rotterdamsche Courant (1844) **Prijs € 2,–**

Kairo is synoniem met seksueel geweld
buitenland 10

Pininfarina gaf Ferrari een gezicht
het grote verhaal 12-13

Afstudeerfilms: lelijke kinderen, dolende zielen
film 18-19



Grafische weergave van de sporen van een proton-protonbotsing in een van de deeltjesdetectoren van CERN, het deeltjesversnellerinstituut bij Genève. Foto AFP / CERN

Historische stap in het onderzoek naar de bouwstenen waaruit heelal is opgebouwd

Higgsdeeltje 'vrijwel zeker' ontdekt

Door BRUNO VAN WAYENBURG

AMSTERDAM. Na twee uur spanningsrekkende praatjes komt CERN-directeur Rolf Heuer vanmorgen met dé mededeling: „We hebben een ontdekking, de waarneming van een nieuw deeltje, met de eigenschappen van een Higgs-boson".

Het Higgsdeeltje dus, het enige deeltje in het Standaardmodel van de natuurkunde waarvan het bestaan wel voorspeld was maar nog niet aangetoond.

Het is het deeltje dat andere deeltjes hun massa geeft.

Het is groot nieuws: de mededeling leidt tot een ontlading in de zaal bij het CERN, het deeltjesversnellerinstituut bij Genève. Het publiek van vooral natuurkundigen klapt en joelt.

Aanvankelijk aarzelend applaudisseren ook de onderzoekers en pers die samengekomen zijn in Nikhef, het instituut voor deeltjesfysica in Amsterdam.

Het lijkt er nu toch echt op dat ze, zij het virtueel, aanwezig zijn bij een historische aankondiging. Uit presentaties van Joe Incandela van de CMS-deeltjesdetector en van Gianotti van de ATLAS-detector, blijkt dat er maar een hele kleine kans op toeval is: minder dan 1 op de 3,5 miljoen. „Er is absoluut een nieuw deeltje ontdekt, dat valt niet meer te ontkennen", zegt ook Stan Bentvelsen, projectleider van de Nederlandse inbreng in het ATLAS-experiment, waarbij 45 onderzoekers betrokken zijn.

Om het Higgsdeeltje aan te tonen, moet je nieuwe deeltjes maken. Dat is peperduur, maar eenvoudig. Je laat in een deeltjesversneller deeltjes met vrijwel de lichtsnelheid met elkaar botsen. Hoe harder de botsing, hoe meer energie er wordt omgezet in nieuwe deeltjes. Zoals het Higgs-boson, dat in de jaren zestig voorspeld werd door zes theoretisch natuurkundigen. Het werd naar een van hen genoemd, Peter Higgs.

De Higgs is nodig om te verklaren hoe het komt dat alles massa heeft: doordat deeltjes worden afgeremd door het zogeheten Higgs-veld. Zo alomtegenwoordig als het uitgesmeerde Higgs is, zo ongrijpbaar is het als deeltje.

Zo gauw het ontstaat uit de enorme energie die vrijkomt bij een botsing, zo snel valt het ook weer uit elkaar in verschillende elementaire deeltjes. Alleen die brokstukken zijn, meteen na een botsing, goed te zien in de detectoren.

Maar veel vaker ontstaat er bij een botsing geen Higgs, maar een mix van al bekende deeltjes. Onderscheid maken tussen 'Higgs- en niet-Higgs-botsingen' is een kwestie van netjes meten en turven en zware statistiek.

Daarover gaat het allemaal, in de presentaties van Gianotti en Incandela.

In het deeltjesjagen gaat het om de sigma-waarde: een statistische maat voor de kans dat de gevonden botsingen, ook al lijken ze op een nieuw deeltje, toch een toevallige uitschieter zijn. De afspraak is dat je een deeltje pas mag claimen bij een sigma van 5: de kans dat het om een toevallige uitschieter zou gaan is dan 1 op de 3,5 miljoen. Incandela eindigt met een tergende 4,9, net geen 5. Maar Gianotti komt na eindeloze details uit op 5,0.

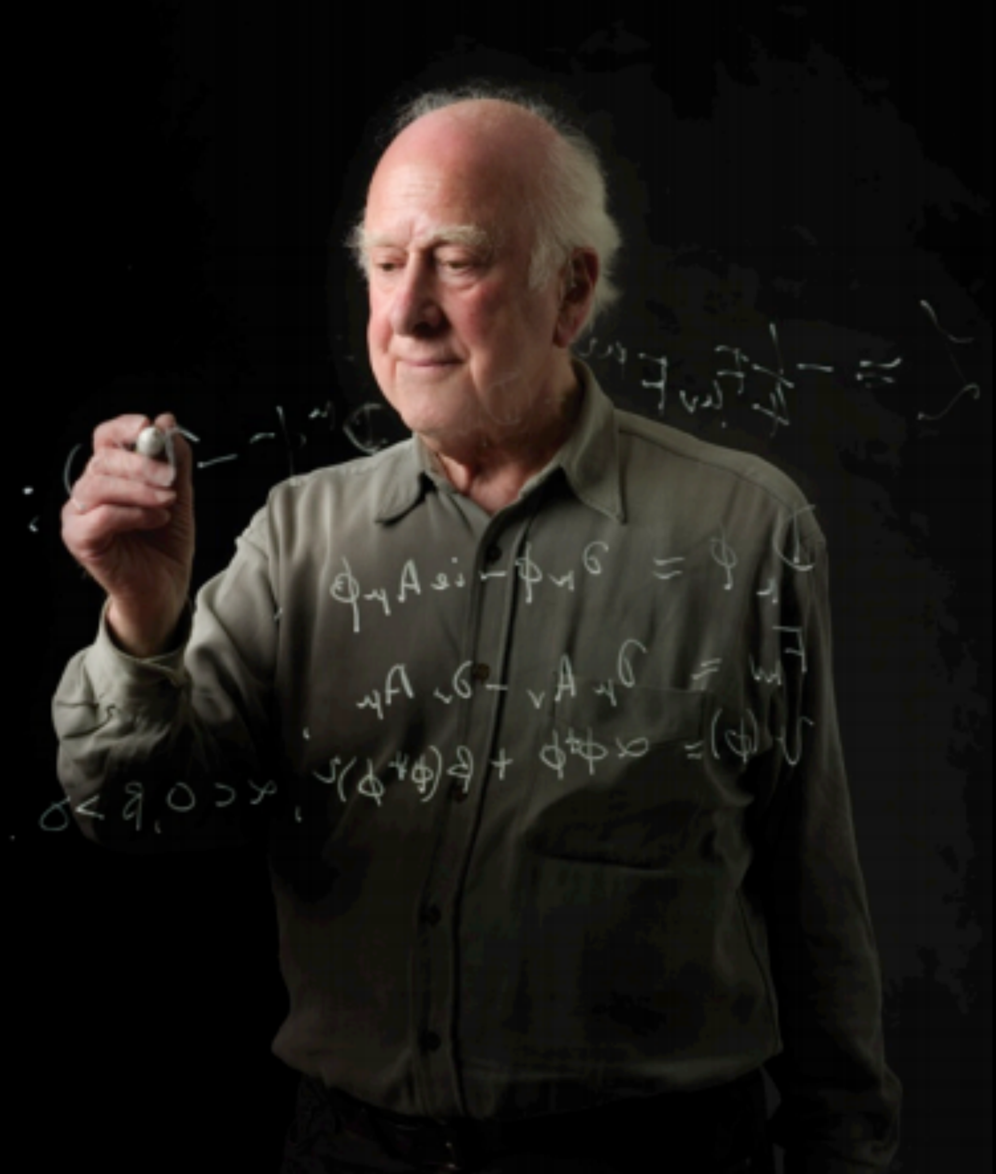
„Nu moeten we onderzoeken of het ook de Higgs is", zegt Bentvelsen. Daar lijkt het wel op. „Al vervalt het wel iets vaker in twee fotonen dan je zou verwachten."

Maar mocht het geen Higgs-boson zijn, of zelfs maar een licht afwijkend Higgs-boson, dan zou dat nog groter nieuws zijn. Want meer nog dan naar het Higgs-boson, snakken natuurkundigen naar 'nieuwe natuurkunde': metingen of deeltjes die eindelijk eens een keer niet overeenkomen met het Standaardmodel, is dus het devies. „Dit is pas het begin", concludeert ook Gianotti.

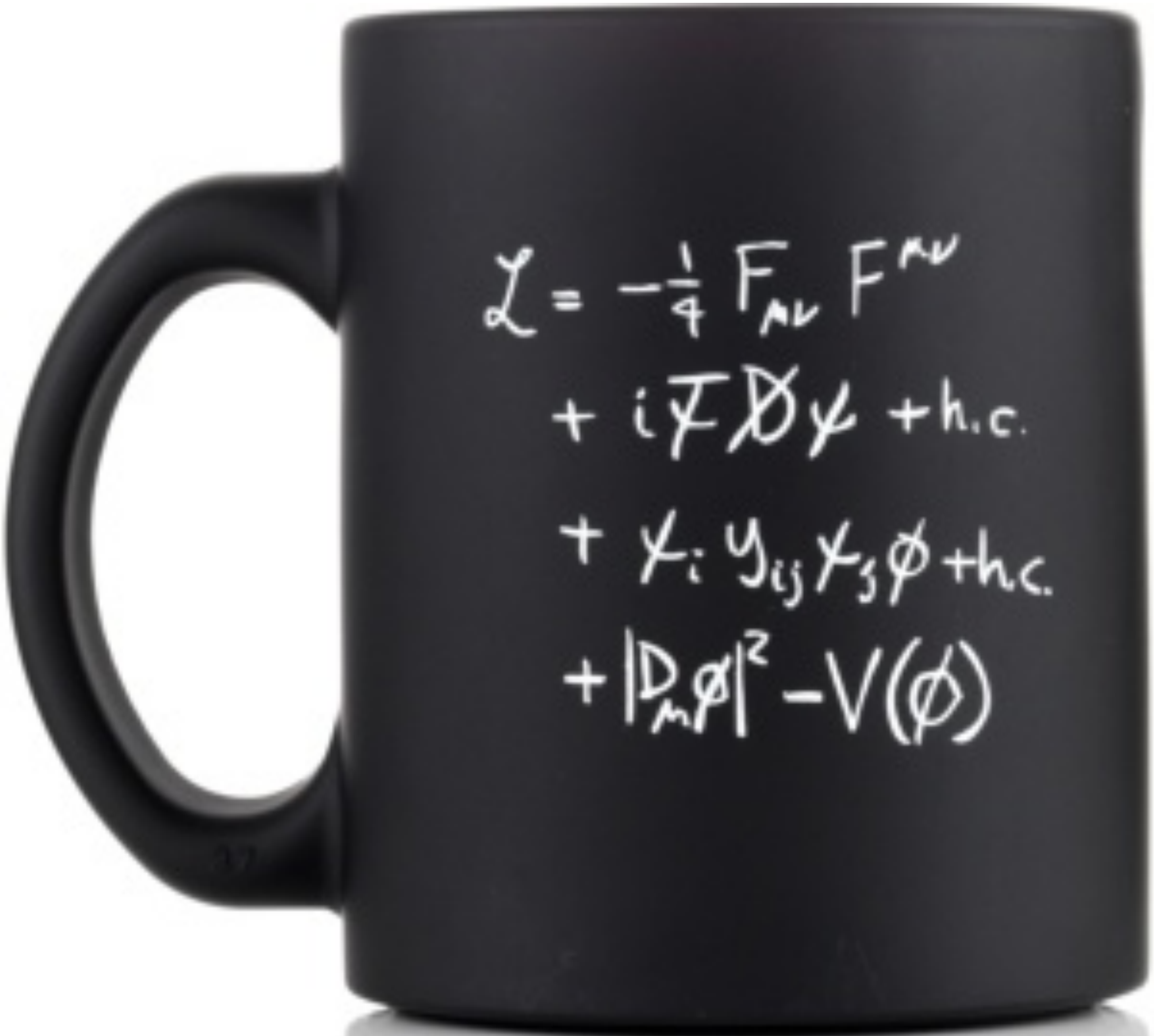
- Why is the Higgs particle so special?

- The Standard Model

Prof. P. Higgs



What are the rules for subatomic particles?



- Describes the behaviour of particles

Photons $F_{\mu\nu}$

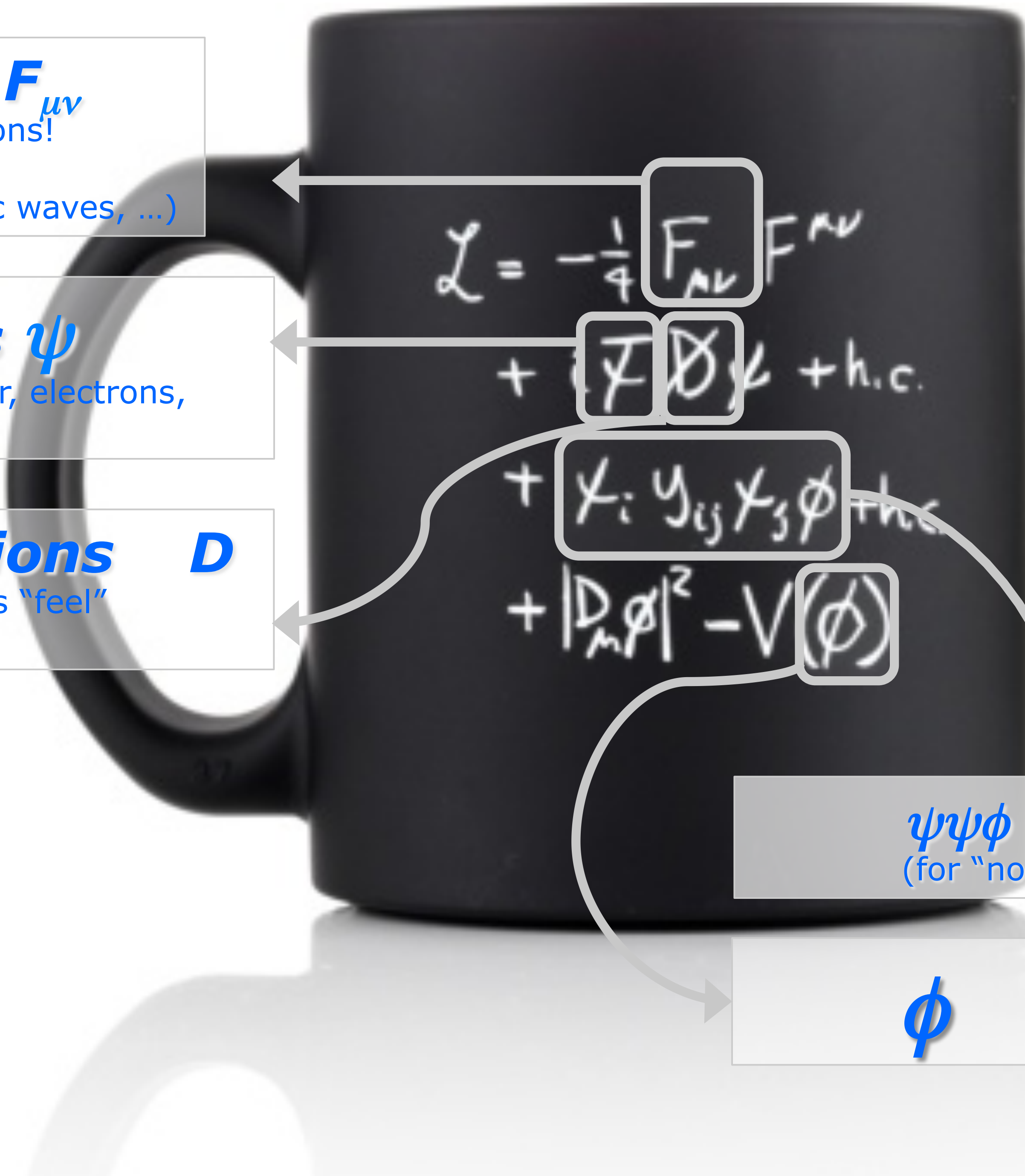
(Maxwell equations!
E-field, B-field,
electro-magnetic waves, …)

Particles ψ

(“normal” matter, electrons,
quarks, …)

Interactions D

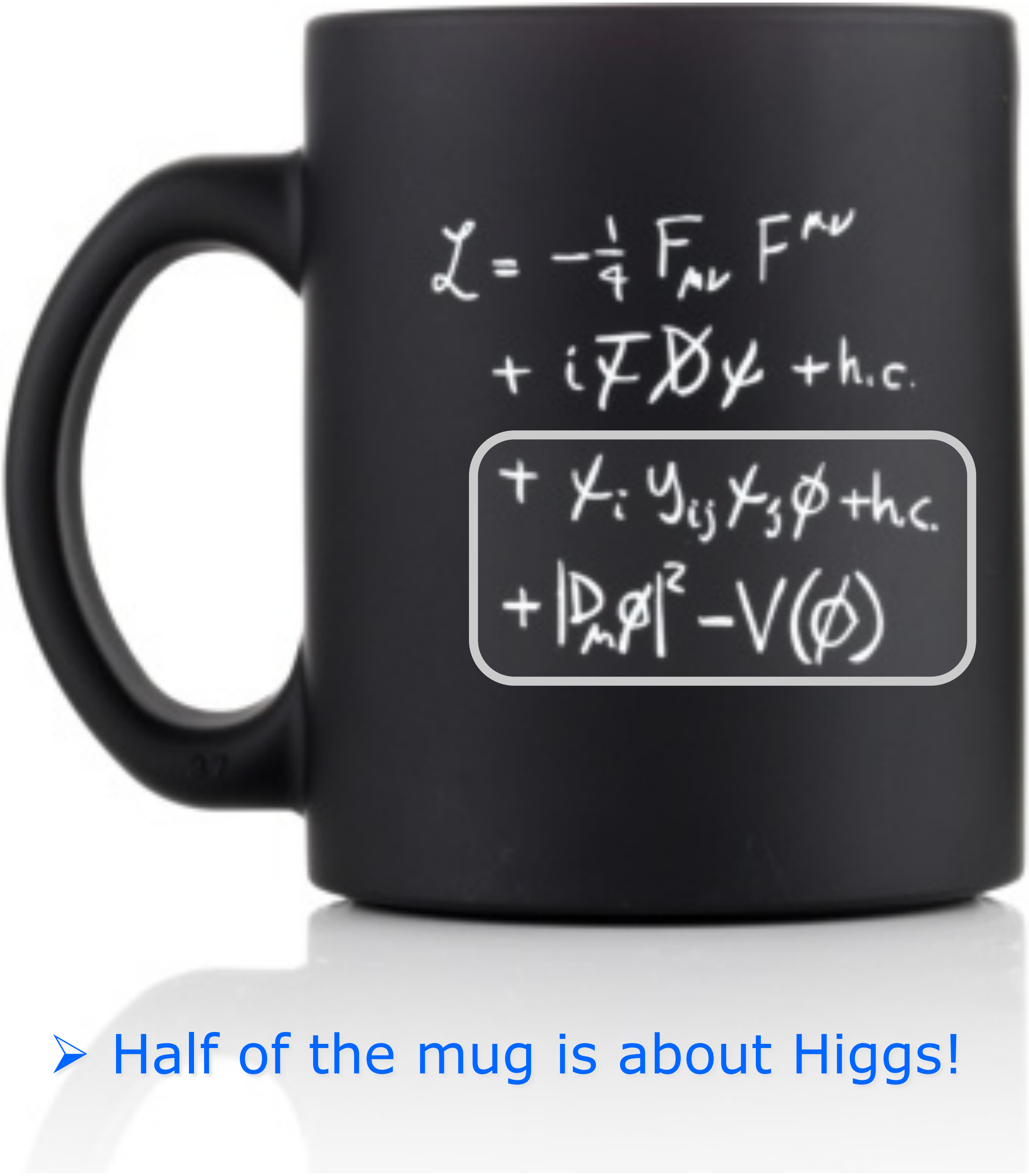
(how the partiles “feel”
eachother)



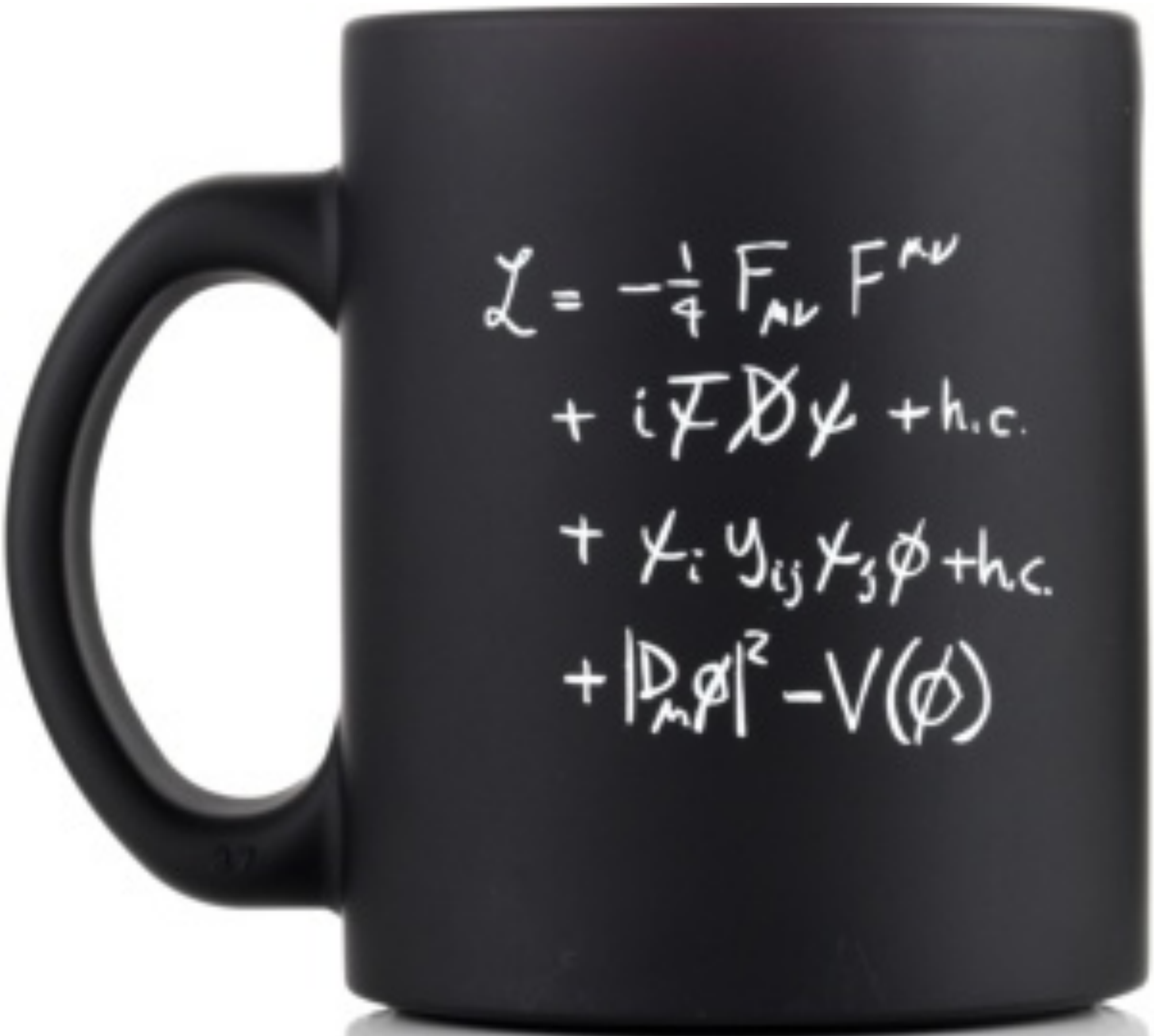
$\psi\psi\phi$ Mass

(for “normal” particles)

ϕ Higgs



- Half of the mug is about Higgs!



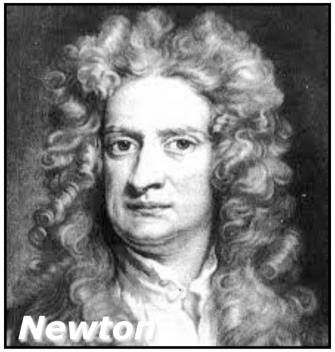
For sale in the CERN shop…

Higgs and Mass?

- Mass is "exchange rate" between force and acceleration

  But… what ***is*** it ?

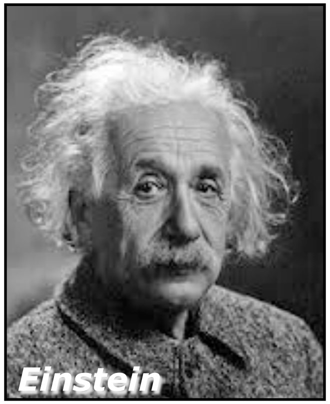
$$F = m \times a$$



- Mass is energy

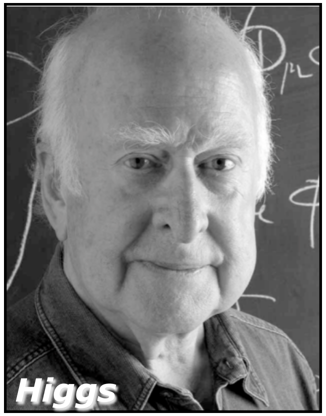
  But… where does it ***come from*** ?

$$E = m \times c^2$$



- Mass is friction with Higgs field!

$$m: \ \psi\psi\phi$$



“Wij zwemmen in een oceaan van Higgs deeltjes,

… alsof we vissen zijn en nu hebben vastgesteld dat er water om ons heen is.”

Prof. Robbert Dijkgraaf

Outline of today

- Introduction
  - Start with the end... : Higgs!
  - The Standard Model
- How to calculate with high energies? A reminder.
  - Lorentz Transformation
  - Invariants
  - Colliding particles

The Standard Model

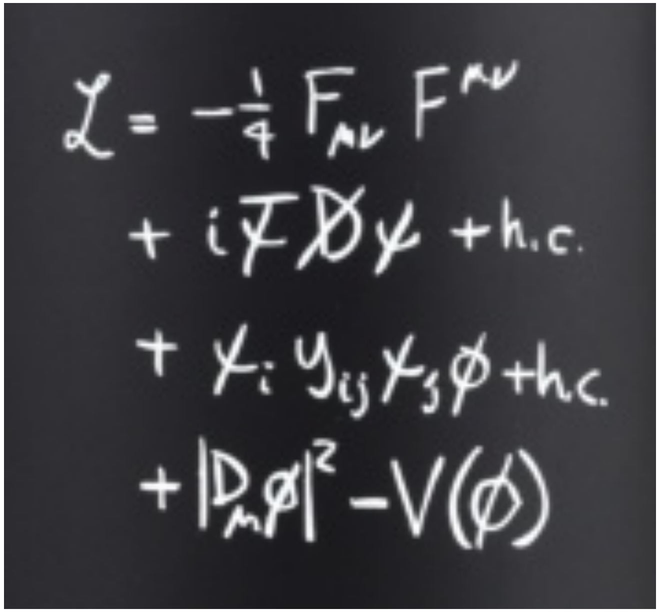
These lectures deal with the

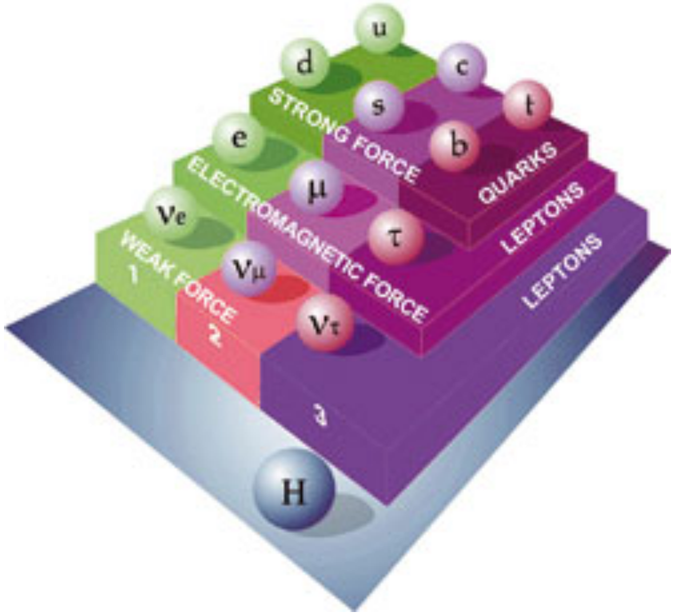
- Formalism
- Concepts

on

- Particles
- Interactions

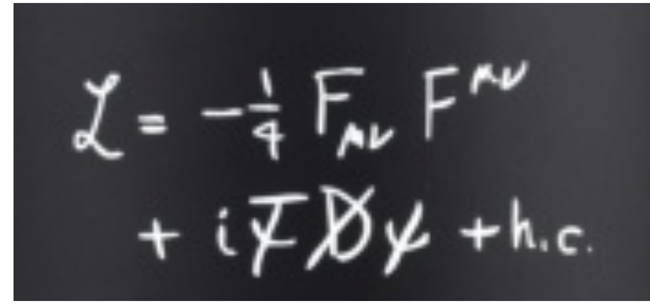
jointly known as the <u>*Standard Model*</u>

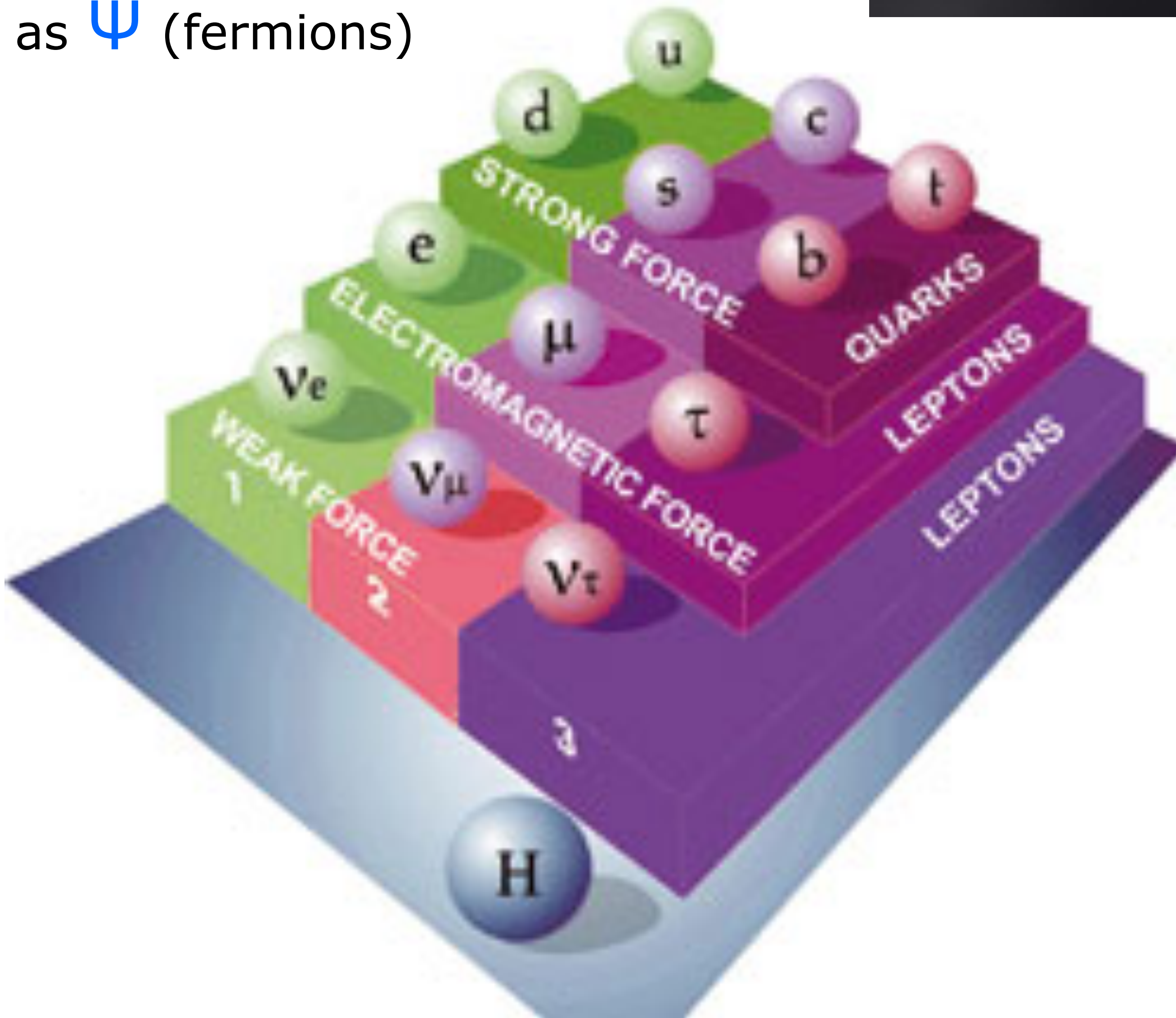




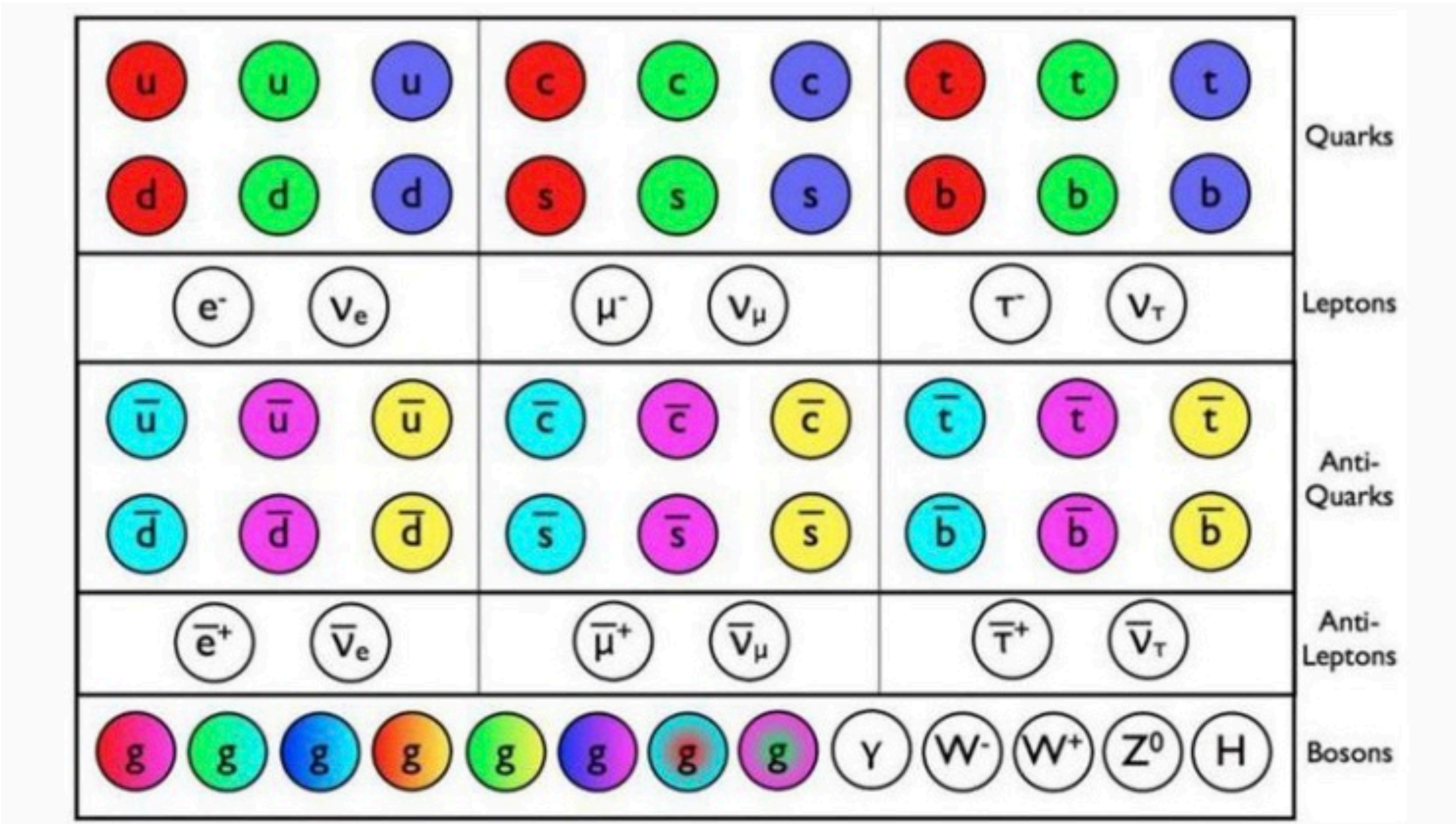
The Standard Model

All “matter” particles are described here as ψ (fermions)



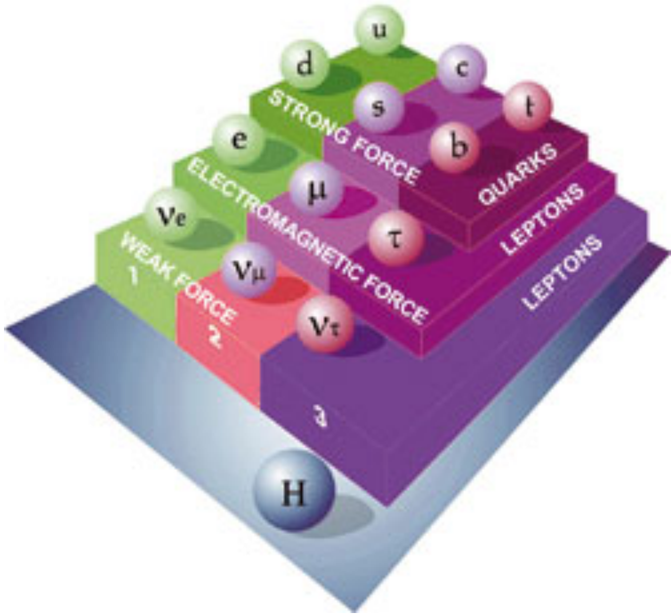


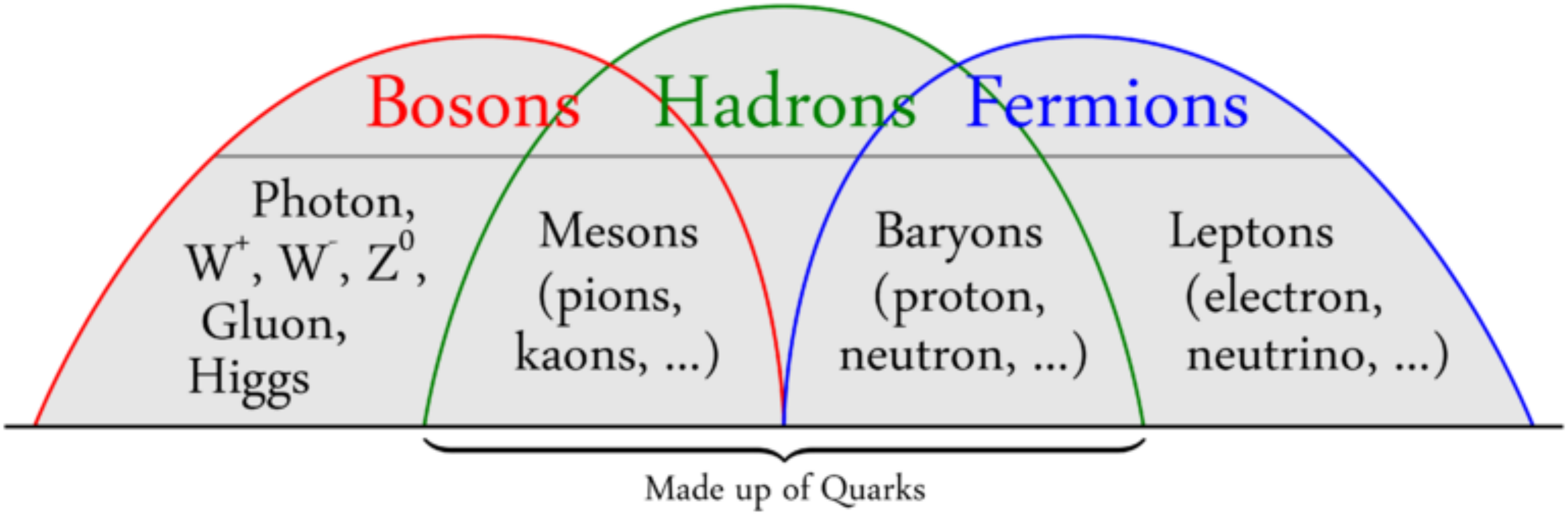
The Standard Model



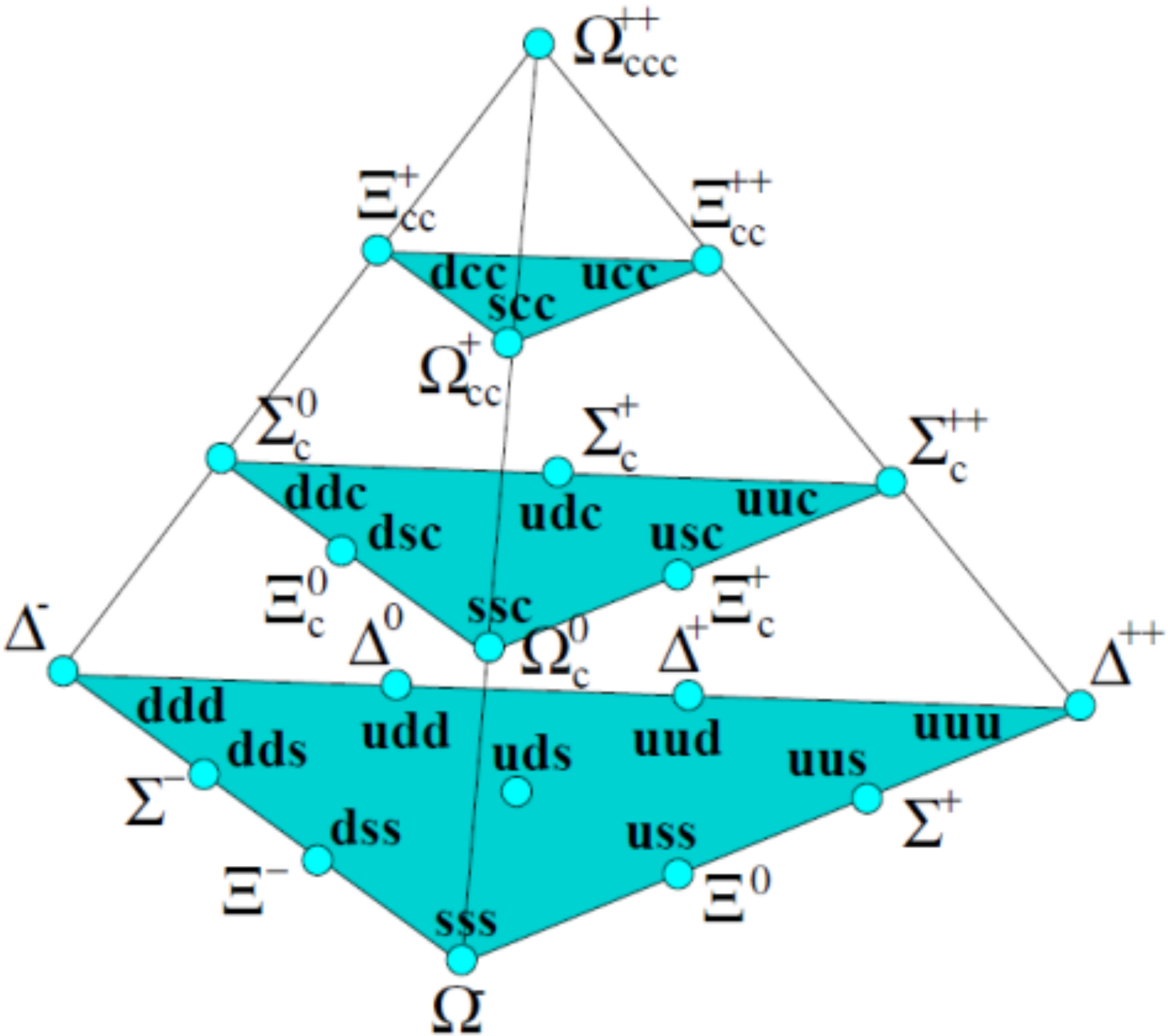
Particles

- Quarks and leptons…:





Particles…



Ω_{ccc}^{++}
Ξ_{cc}^{+}
Ξ_{cc}^{++}
dcc
ucc
scc
Ω_{cc}^{+}
Σ_c^0
Σ_c^+
Σ_c^{++}
ddc
udc
uuc
dsc
usc
Ξ_c^0
Ξ_c^+
ssc
Ω_c^0
Δ^-
Δ^0
Δ^+
Δ^{++}
ddd
udd
uud
uuu
dds
uds
uus
Σ^-
Σ^+
dss
uss
Ξ^-
Ξ^0
sss
Ω

Particles

Three generations:

	I	II	III	Charge
quarks	u	c (1976)	t (1995)	+2/3 e
	d	s (1947)	b (1978)	-1/3 e
leptons	e (1895)	μ (1936)	τ (1973)	-1 e
	ν_e (1956)	ν_μ (1963)	ν_τ (2000)	0 e

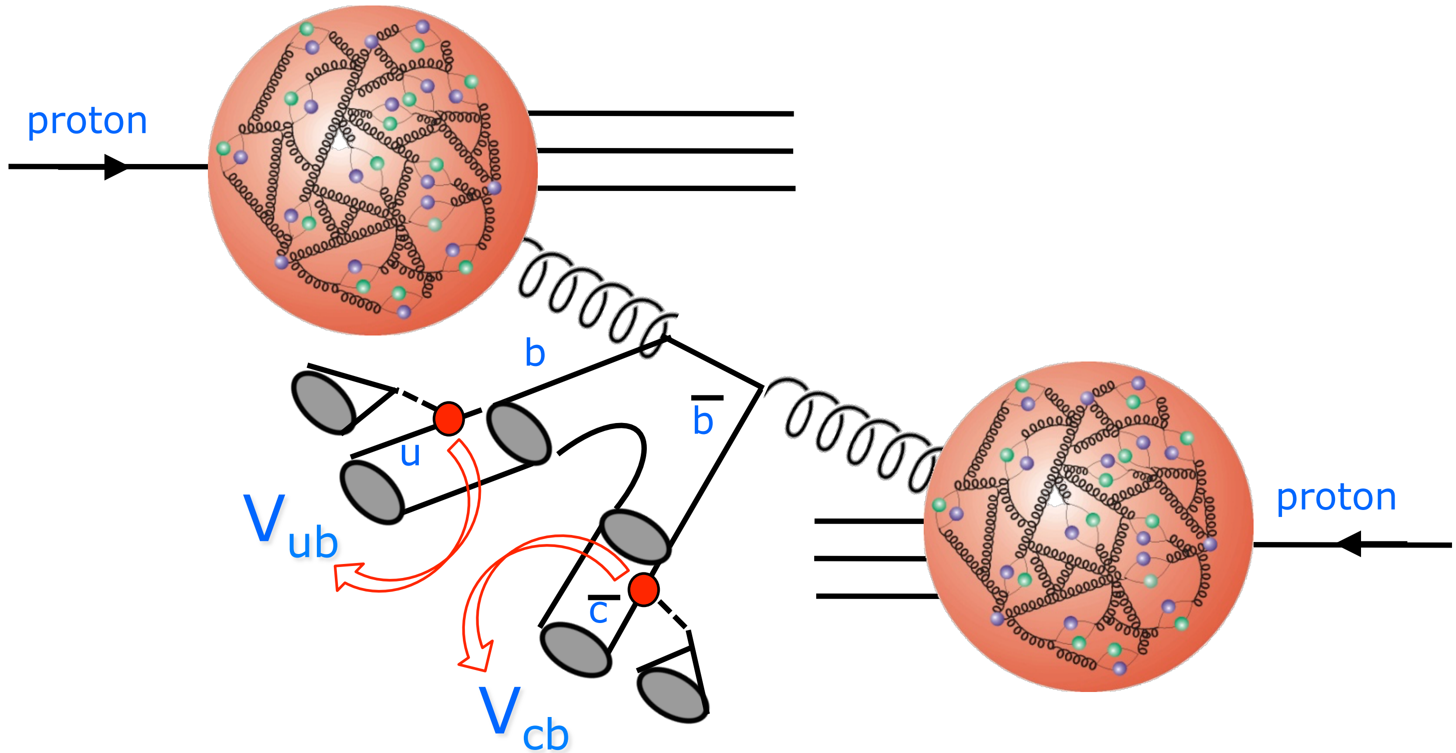
Particles and Anti-particles

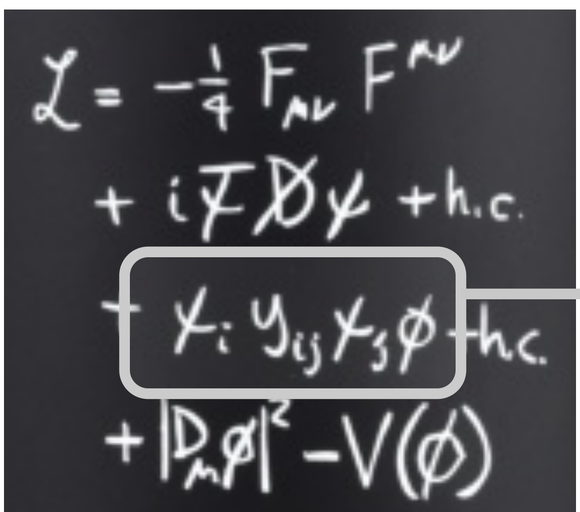
Three generations

	I	II	III	Charge	Charge	I	II	III
quarks	u	c (1976)	t (1995)	+2/3 e	-2/3 e	$\bar{u}$	$\bar{c}$	$\bar{t}$
	d	s (1947)	b (1978)	-1/3 e	+1/3 e	$\bar{d}$	$\bar{s}$	$\bar{b}$
leptons	e (1895)	μ (1936)	τ (1973)	-1 e	+1 e	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$
	ν_e (1956)	ν_μ (1963)	ν_τ (2000)	0 e	0 e	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

Where did the anti-matter go?

Personal Intermezzo

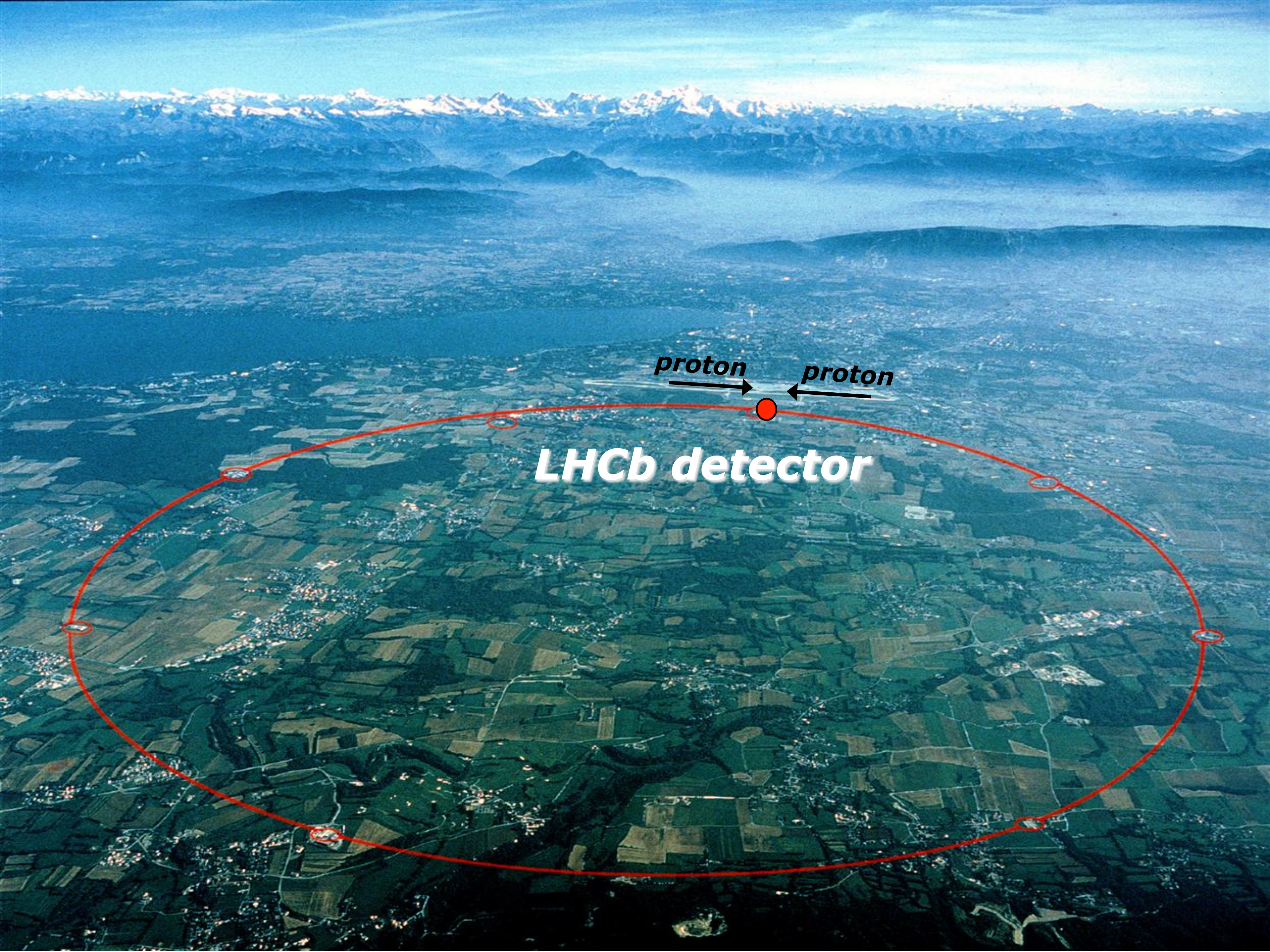




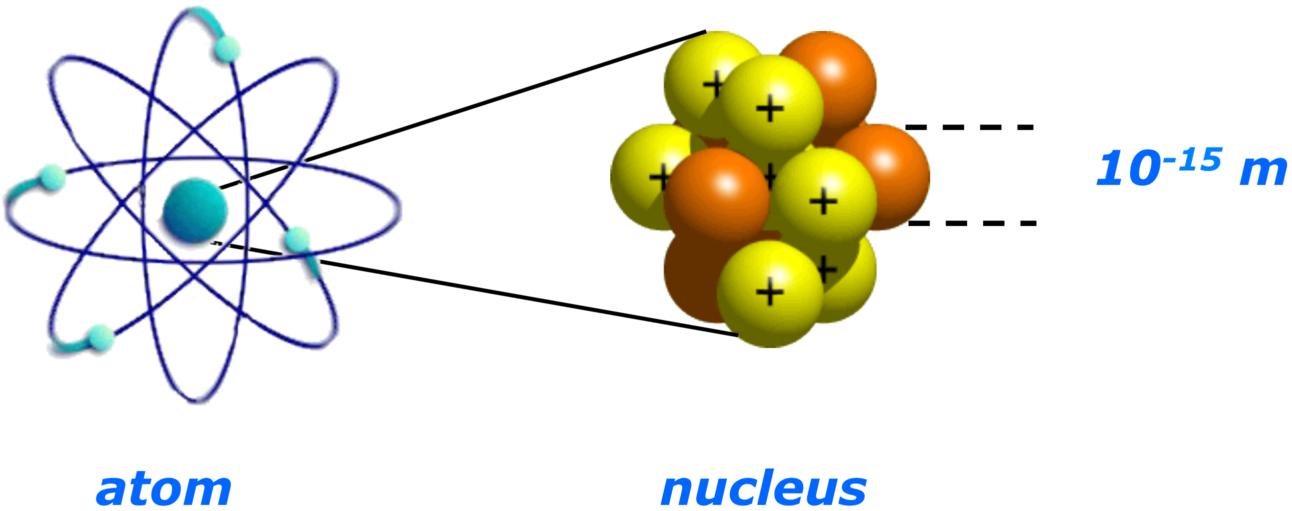
Y_{ij} → V_{cb}, V_{ub}

Difference between matter and anti-matter


LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km


proton
proton
LHCb detector

What energy is needed?

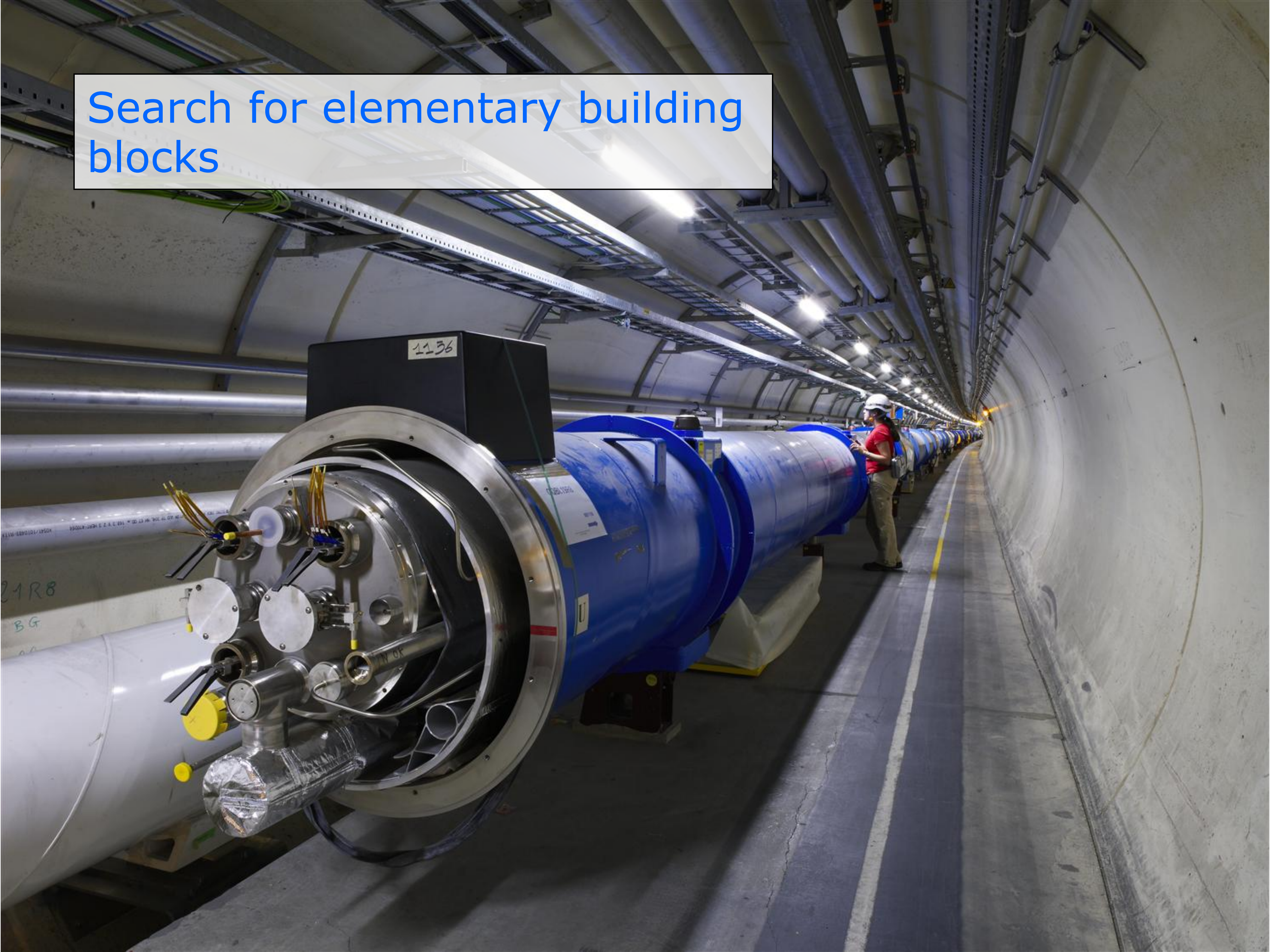


Object	Grootte	Energie
Atoom	10^{-10}m	10keV
Kern	10^{-14}m	10MeV
Nucleon	10^{-15}m	0.1GeV
Quark	<10^{-18}m	>1GeV

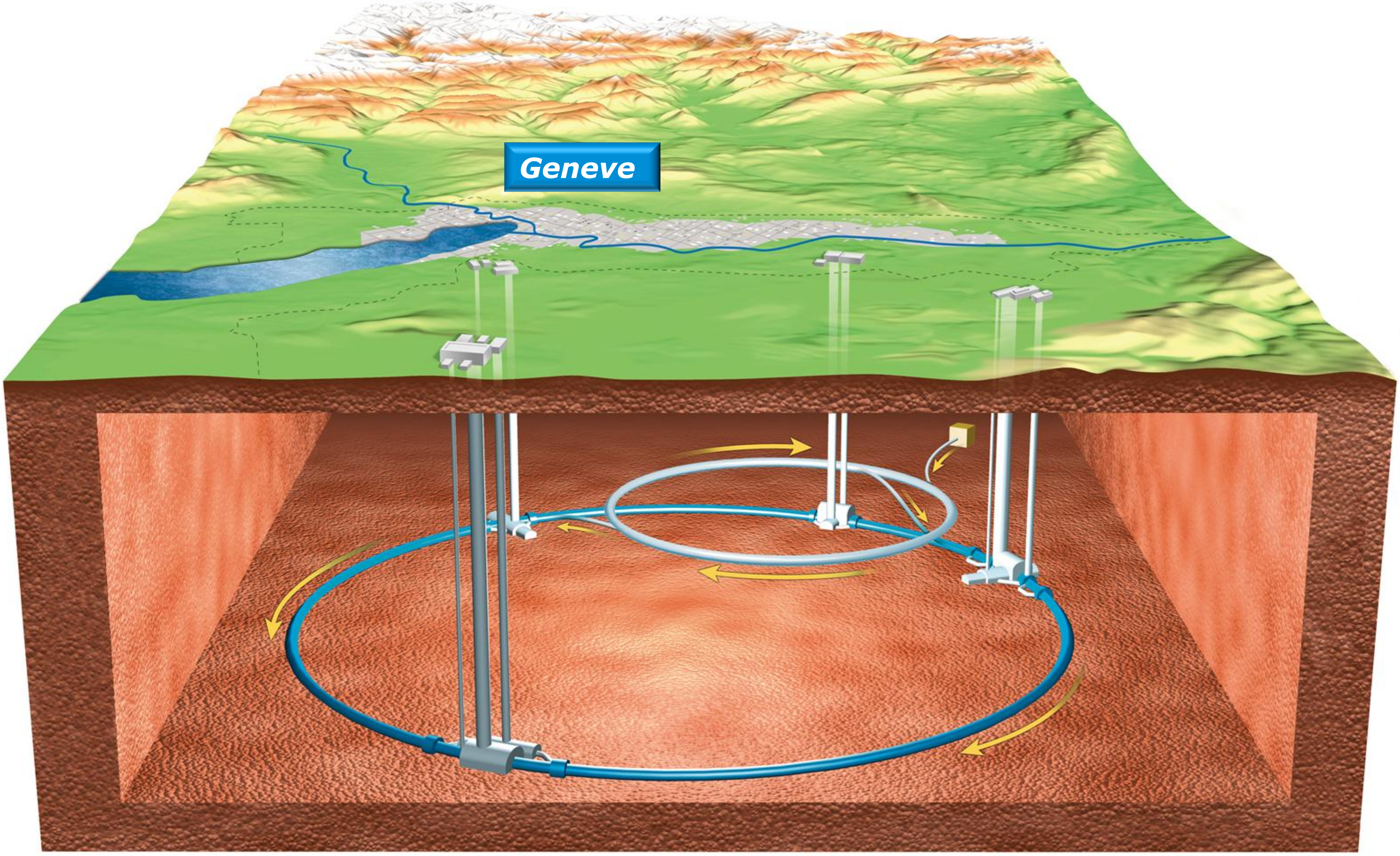
How to make energies around 100.000.000 eV or more ?

Energy of 1 e^- that passes a potential difference of 1 V: 1 eV
Energy of mass of 1 proton: $m = E/c^2$: 1 GeV

Search for elementary building blocks



LHC accelerator



LHC

Energy limited by field of 1232 dipole magnets: B= 8.4 T

Klassiek botsen

Quantummechanisch botsen

proton

proton

$$E = mc^2$$

Create new particles if
energy is large enough
(and if they exist...)

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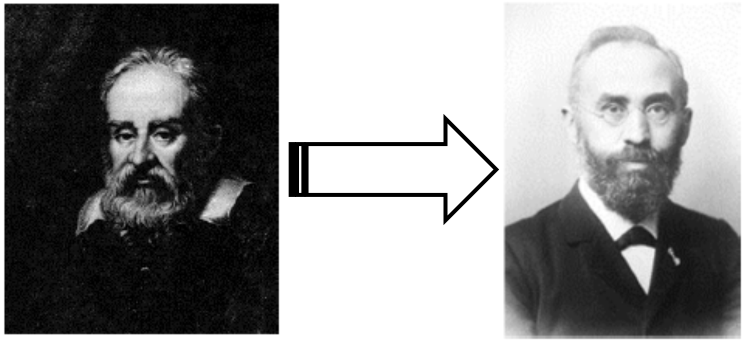
Summary special relativity



Galileo Galilei — Hendrik Antoon Lorentz

- Lorentz transformation
- Length contraction & Time dilatation
- Adding velocities

- Relativistic energies
- Relativistic kinematics
- Collision
- Decay

Lorentz transformation

1) Speed of light constant
2) Every (inertial) coordinate system equivalent

Albert Einstein

$x=ct$ becomes $x'=ct'$

Lorentz transformation

Albert Einstein

1) Speed of light constant
2) Every (inertial) coordinate system equivalent

➢ Find transformation rules:

Galilei: Lorentz: x=ct becomes x’=ct’ :

$$Newton: \quad x' = x - vt \quad wordt: \quad x' = \gamma(x - vt) \quad \rightarrow \quad x' = ct' = \gamma(ct - vt)$$

$$Newton: \quad x = x' + vt' \quad wordt: \quad x = \gamma(x' + vt') \quad \rightarrow \quad x = ct = \gamma(ct' + vt')$$

➢ Find γ :

$$ct' = \gamma(ct - vt)$$

$$ct = \gamma(ct' + vt')$$

$$\Rightarrow \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Lorentz transformation

Albert Einstein

1) Speed of light constant
2) Every (inertial) coordinate system equivalent

- Find transformation rules:

Galilei:	Lorentz:	x=ct becomes x' =ct' :
$Newton: \quad x' = x - vt$	$wordt: \quad x' = \gamma(x - vt)$	$x' = ct' = \gamma(ct - vt)$
$Newton: \quad x = x' + vt'$	$wordt: \quad x = \gamma(x' + vt')$	$x = ct = \gamma(ct' + vt')$

- Find γ :

$$ct' = \gamma(ct - vt)$$
$$ct = \gamma(ct' + vt')$$

$$\Rightarrow \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$x' = \gamma(x - vt)$$
$$x = \gamma(x' + vt')$$

Consequences: Lorentz contraction

- Stick with length L_0 in system S' :
  - moving relative to system S with speed v
  - Observer in S sees length L
  - At same time *t* in fixed frame: $t_1 = t_2$

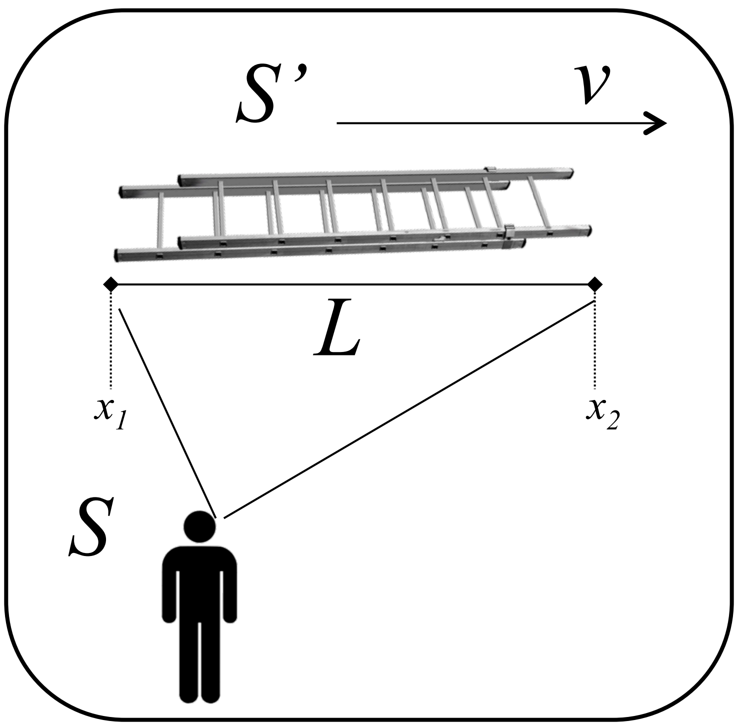
$$L_0 = x'_2 - x'_1$$
$$t = 0: \quad x'_2 = \gamma x_2; \quad x'_1 = \gamma x_1$$

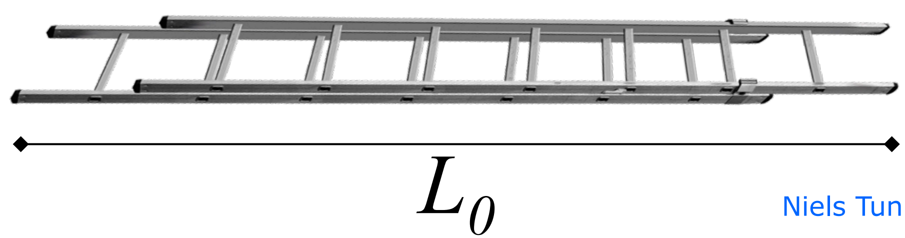
(Length L_0 as seen in moving frame S', is at rest)

➢ Length L is factor $1/\gamma$ smaller in rest frame S:

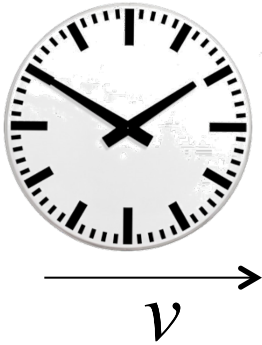
$$L = x_2 - x_1 = \frac{x'_2 - x'_1}{\gamma} = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

(Length L as seen in frame S, is difference between coordinates x_2 and x_1 in frame S.)





Consequences: Time dilatation



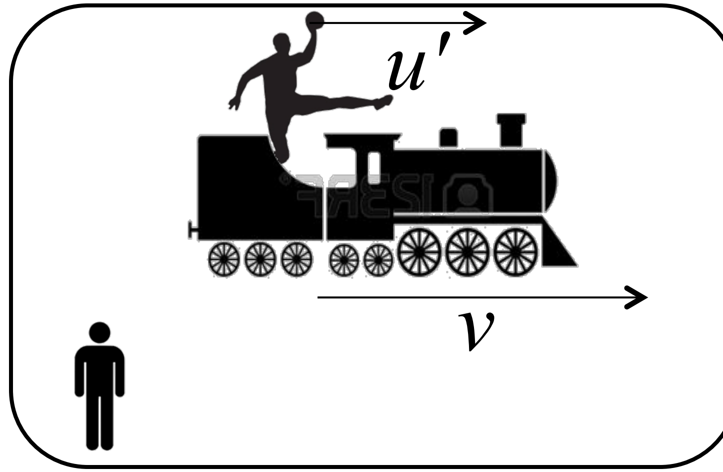
- Clock is moving in frame S' with relative speed v
- Suppose clock is emitting light pulses
  - Time interval between pulses in frame S': $\Delta t' = t_2' - t_1'$
  - Light pulses are emitted from same point *x'* in moving frame: $x_1' = x_2'$

- What sees the observer at rest in frame S?
  - First pulse: $t_1 = \gamma(t_1' + v x_1'/c^2)$
  - Second pulse: $t_2 = \gamma(t_2' + v x_2'/c^2)$
  - Hence: $\Delta t = t_2 - t_1 = \gamma(t_1' - t_2' + \underbrace{v/c^2 (x_1' - x_2')}_{=0}) = \gamma \Delta t'$

$$\boxed{\Delta t = \gamma \Delta t'}$$

➢ Clock period is seen factor γ longer for observer at rest

Adding velocities



- Time and space transformation:

$$x = \gamma\left(x' + vt'\right) \qquad\longrightarrow\qquad dx = \gamma\left(dx' + v\,dt'\right)$$

$$t = \gamma\left(t' + \frac{vx'}{c^2}\right) \qquad\longrightarrow\qquad dt = \gamma\left(dt' + \frac{v\,dx'}{c^2}\right)$$

- Hence observer in frame S sees velocity u_x:

$$u_x = \frac{dx}{dt} = \frac{\gamma\left(dx' + v\,dt'\right)}{\gamma\left(dt' + \frac{v\,dx'}{c^2}\right)} \overset{/dt'}{=} \frac{\left(u'_{x'} + v\right)}{\left(1 + u'_{x'}\frac{v}{c^2}\right)}$$

(Galilei: u = u' + v)

- Ex: If train goes fast ($v=c$), then velocity u_x seen by observer:
  $u_x = (u'+c)/(1+u'/c) = c$

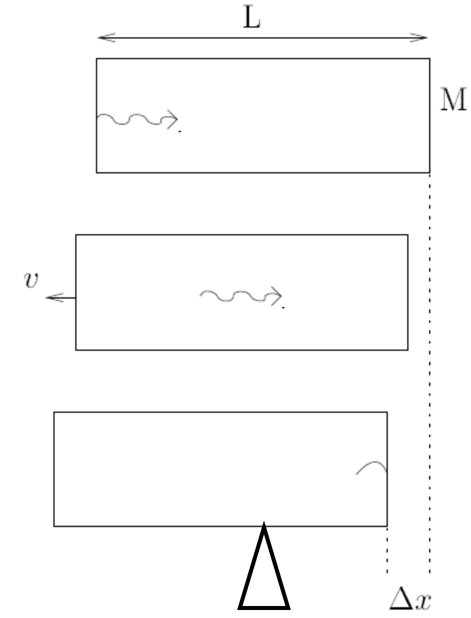
E=mc^2

1) Photon is emitted from box

2) Momentum conservation: box moves

3) Photon is absorbed by box: box stops

Einstein's box:



NB: Centre-of-mass of entire system remains at rest

- Photon must carry a "*mass equivalent to the energy of the photon, m*"
  - Box: mass *M* over length *Δx*: $M\Delta x$
  - Photon: mass *m* over length *L*: mL
  - System at rest: $(M\Delta x + mL)=0$

$$\Delta x = v\Delta t$$

$$v = \frac{p_{box}}{M} = -\frac{p_{photon}}{M} = -\frac{E_{photon}}{Mc}, \Delta t = \frac{L}{c}$$

$$\Delta x = -\frac{E_{photon}L}{Mc^2}$$

$$\left(M\Delta x + mL\right) = 0 \Rightarrow$$

$$L(-\frac{E}{c^2} + m) = 0 \Rightarrow$$

$$E = mc^2$$

Relativistic energies

- Momentum:
  - In rest: $p = m_0 v$ (or at *low speeds*, to satisfy Newtonian dynamics)
  - Moving mass: $p = \gamma m_0 v$ (Relativistic momentum must be conserved in all frames)
- Einstein: equivalence between energy and mass
  - In rest: $E = m_0 c^2$
  - Moving mass: $E = \gamma m_0 c^2$

$$E = pc^2/v \rightarrow v/c = pc/E$$

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{1}{\sqrt{1 - p^2c^2/E^2}}$$

$$E = \gamma m_0 c^2$$

➢ E:

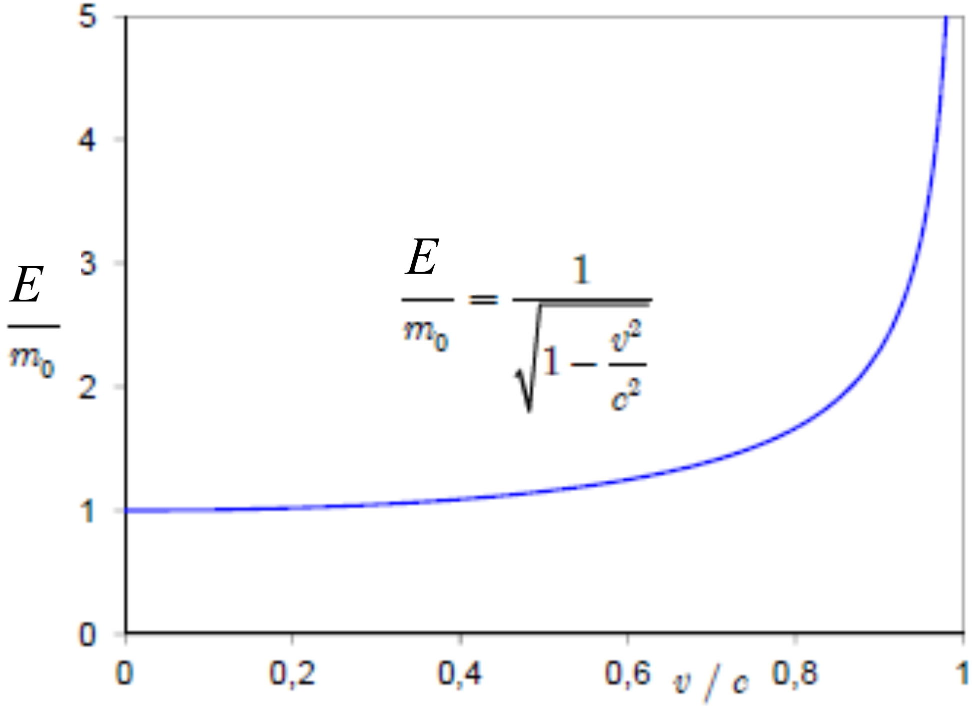
$$E_{tot} = \frac{m_0 c^2}{\sqrt{1 - \frac{(\vec{p}c)^2}{E_{tot}^2}}}$$

$$E_{tot}{}^2 - \vec{p}^2 c^2 = m_0^2 c^4$$

- Btw, a Taylor expansion gives classical kinetic energy:

$$E = mc^2\left(1 + \frac{1}{2}\frac{v^2}{c^2} + \frac{3}{8}\frac{v^4}{c^4} + \cdots\right) = mc^2 + \frac{1}{2}mv^2 + \frac{3}{8}m\frac{v^4}{c^2} + \cdots$$

Relativistic energies



$$E = \gamma m_o c^2$$

4-vectors

- Write *(t, x)* as 4-vector x^μ:

$$x^0 \equiv ct, \quad x^1 \equiv x, \quad x^2 \equiv y, \quad x^3 \equiv z$$

$$x^\mu = \begin{pmatrix} x^0 \\ x^1 \\ x^2 \\ x^3 \end{pmatrix}, \quad (\mu = 0, 1, 2, 3)$$

- Nicely symmetric form of Lorentz transformation:

$$\begin{aligned} x'^0 &= \gamma\left(x^0 - \beta x^1\right) \\ x'^1 &= \gamma\left(x^1 - \beta x^0\right) \\ x'^2 &= x^2 \\ x'^3 &= x^3 \end{aligned} \quad \textbf{met} \quad \beta \equiv \frac{v}{c}, \quad \gamma \equiv \frac{1}{\sqrt{1-\beta^2}}$$

$$x'^\mu = \sum_{\nu=0}^{3} \Lambda^\mu_\nu x^\nu \quad \left(\mu = 0, 1, 2, 3\right)$$

"Boost" in x-direction:

$$\Lambda = \begin{pmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Invariants ("fixed length")

- Write *(t, x)* as 4-vector x^μ:

$$x^0 \equiv ct, \quad x^1 \equiv x, \quad x^2 \equiv y, \quad x^3 \equiv z$$

$$x^\mu = \begin{pmatrix} x^0 \\ x^1 \\ x^2 \\ x^3 \end{pmatrix}, \quad \left(\mu = 0, 1, 2, 3\right)$$

- Covariant and contravariant 4-vector related through metric g:

$$x_\mu = g_{\mu v} x^v$$

$$x_0 = x^0, x_1 = -x^1, x_2 = -x^2, x_3 = -x^3$$

$$g_{\mu v} \equiv \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- Any pair of 4-vectors is invariant as:

$$a^\mu b_\mu = a_\mu b^\mu = a^0 b^0 - a^1 b^1 - a^2 b^2 - a^3 b^3 \ \textbf{invariant}$$

  - (similar to the *length* of a vector in Euclidean space)

Spacetime

- Special relativity
  - Flat ("Minkowski") spacetime

$$g_{\mu\nu} \equiv \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- General relativity
  - Curved spacetime

$$g_{\mu\nu} = \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}$$

Spacetime

- General relativity
  - Curved spacetime

$$g_{\mu\nu} = \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}$$

  - Line element (invariant) $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$
  - Christoffel symbols:

$$\Gamma^\lambda{}_{\mu\nu} = \frac{1}{2} g^{\lambda\rho} \left(\frac{\partial g_{\rho\mu}}{\partial x^\nu} + \frac{\partial g_{\rho\nu}}{\partial x^\mu} - \frac{\partial g_{\mu\nu}}{\partial x^\rho} \right)$$

  - Riemann curvature tensor:

$$R^\rho{}_{\sigma\mu\nu} = \partial_\mu \Gamma^\rho{}_{\nu\sigma} - \partial_\nu \Gamma^\rho{}_{\mu\sigma} + \Gamma^\rho{}_{\mu\lambda} \Gamma^\lambda{}_{\nu\sigma} - \Gamma^\rho{}_{\nu\lambda} \Gamma^\lambda{}_{\mu\sigma}$$

  - Einstein equations:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$T_{\mu\nu}$: Energy-momentum tensor

Intermezzo: Use of 4-vectors

- 4-vectors
  - Use for relativistic kinematics in particle collisions
  - Use for quantum-field description of matter fields:

The famous Dirac equation:

$$\begin{aligned}(i\gamma^\mu \partial_\mu - m)\ \psi &= 0 \\ \text{with}:\ \gamma^\mu = (\beta, \beta\vec{\alpha}) &\equiv \text{Dirac } \gamma\text{−matrices}\end{aligned}$$

Remember!

- μ : Lorentz index
- 4x4 γ matrix: Dirac index

Less compact notation:

$$\left[\begin{pmatrix} 1\!\!1 & 0 \\ 0 & -1\!\!1 \end{pmatrix} \frac{i\partial}{\partial t} - \begin{pmatrix} 0 & \sigma_1 \\ -\sigma_1 & 0 \end{pmatrix} \frac{i\partial}{\partial x} - \begin{pmatrix} 0 & \sigma_2 \\ -\sigma_2 & 0 \end{pmatrix} \frac{i\partial}{\partial y} - \begin{pmatrix} 0 & \sigma_3 \\ -\sigma_3 & 0 \end{pmatrix} \frac{i\partial}{\partial z} - \begin{pmatrix} 1\!\!1 & 0 \\ 0 & 1\!\!1 \end{pmatrix} m\right] \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Energy-momentum 4-vector

- Example of invariant: rest mass ("*invariant mass*")

$$p^\mu = \left(\frac{E}{c}, p_x, p_y, p_z\right)$$

$$\Rightarrow$$

$$p_\mu p^\mu = \frac{E^2}{c^2} - \mathbf{p}^2 = m^2 c^2$$

$$E_{tot}{}^2 - \vec{p}^2 c^2 = m_0^2 c^4$$

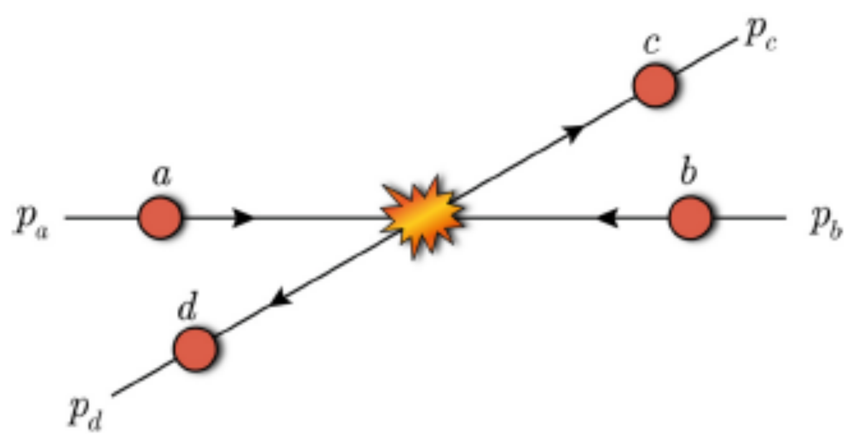
- Lorentz transformation on energy-momentum 4-vector:

$$x'^\mu = \sum_{\nu=0}^{3} \Lambda^\mu_\upsilon x^\upsilon \quad (\mu = 0, 1, 2, 3)$$

$$\begin{pmatrix} \frac{E'}{c} \\ p_x' \\ p_y' \\ p_z' \end{pmatrix} = \begin{pmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \frac{E}{c} \\ p_x \\ p_y \\ p_z \end{pmatrix}$$

Calculate with 4-vectors: colliding particles

- Elastic collission of two particles *a* and *b*: *a* + *b* → *c* + *d*
- Take c=1 ("*natural units*")
- Invariant mass of initial state: $(p_a + p_b)^2 = m_{ab}^2$



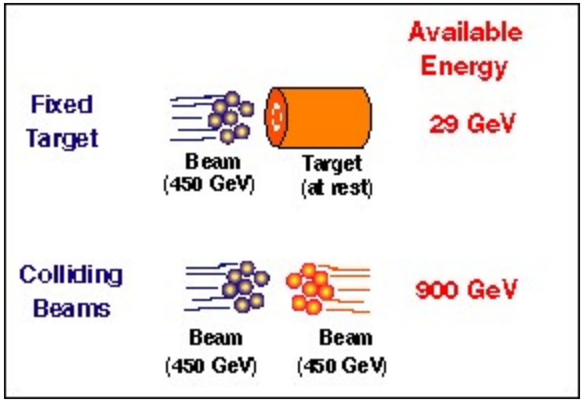
- Invariant mass of initial state = invariant mass of final state:

  = "center-of-mass energy" , **√s**:

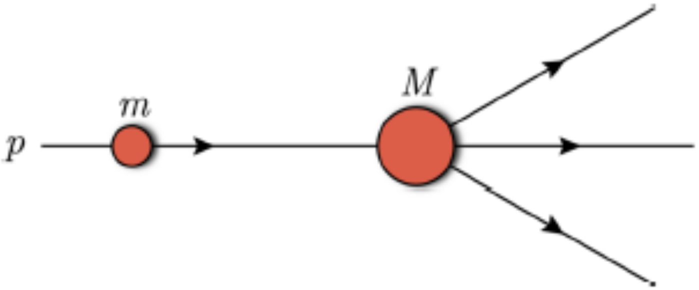
$$s = (p_a + p_b)^2 = (p_c + p_d)^2$$
$$= m_c^2 + m_d^2 + 2(E_c E_d - \vec{p}_c \cdot \vec{p}_d) \geq (m_c + m_d)^2$$

“Fixed target” vs “colliding beams”

- Calculate center-of-mass energy for beam of 450 GeV protons:



1) Fixed target:



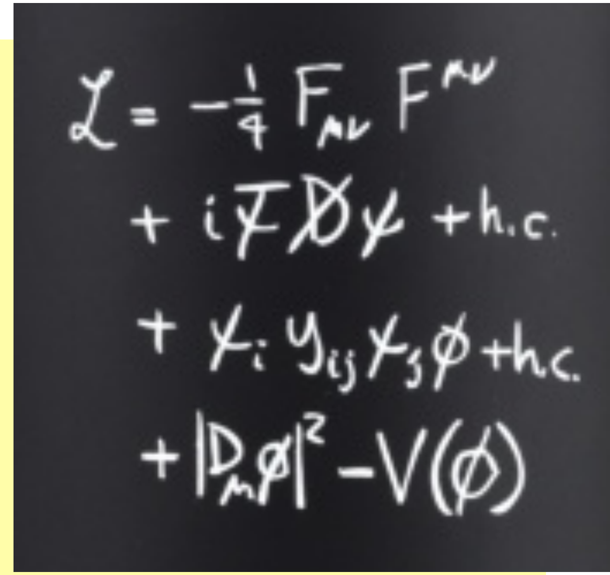
$$s = (p + P)^2 = m^2 + M^2 + 2EM$$

2) Colliding beams:

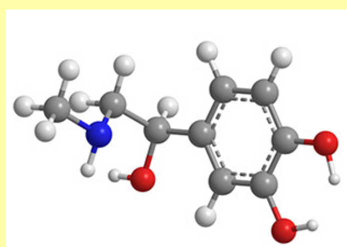
$$s = (p_1 + p_2)^2 = 2m^2 + 2(E^2 + \vec{p}^2)$$
$$= 2m^2 + 2E^2 + 2(E^2 - m^2) = 4E^2$$

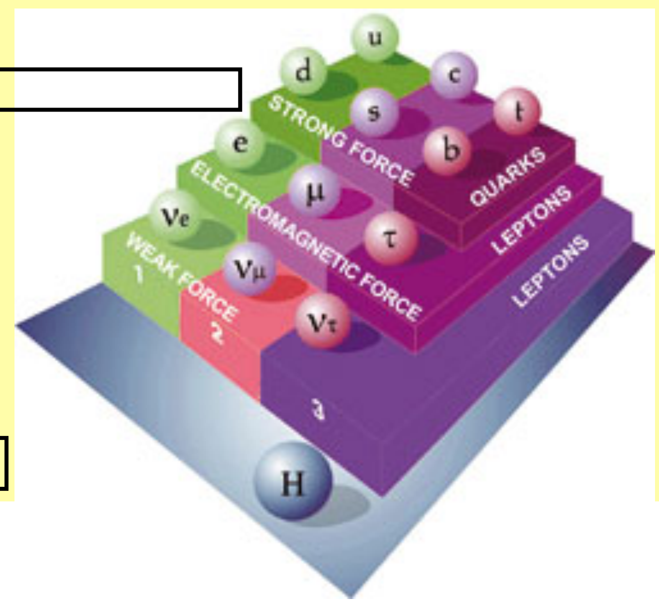
Summary: Standard Model

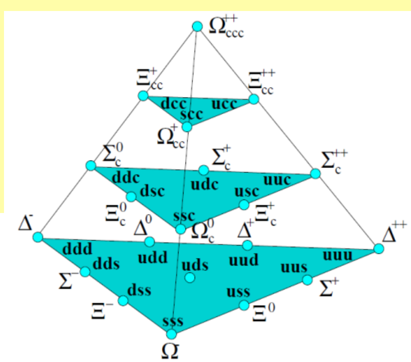
- Standard Model Lagrangian



- Standard Model Particles







Summary: Relativity

- Theory of relativity
  - Lorentz transformations ("boost")
  - Calculate energy in colissions

$$x'^0 = \gamma\left(x^0 - \beta x^1\right)$$
$$x'^1 = \gamma\left(x^1 - \beta x^0\right)$$
$$x'^2 = x^2$$
$$x'^3 = x^3$$

met

$$\beta \equiv \frac{v}{c}$$
$$\gamma \equiv \frac{1}{\sqrt{1-\beta^2}}$$

- 4-vector calculus

$$x^\mu = \begin{pmatrix} x^0 \\ x^1 \\ x^2 \\ x^3 \end{pmatrix}, \quad \left(\mu = 0, 1, 2, 3\right)$$

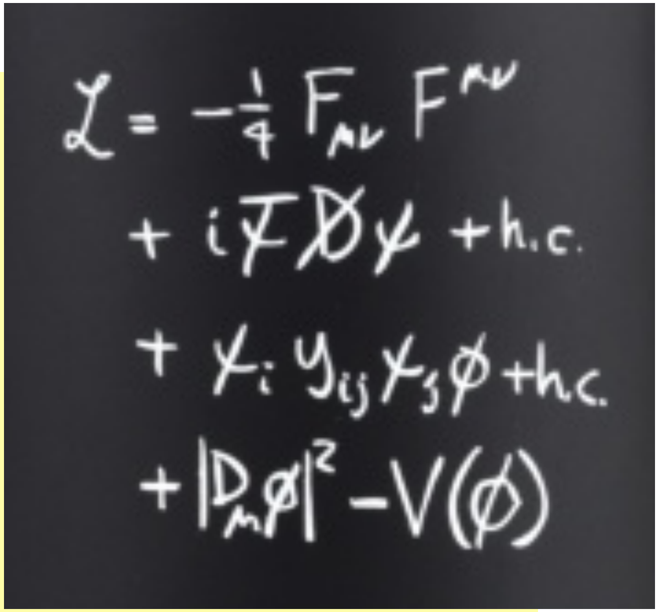
$$p_\mu p^\mu = (E/c)^2 - |\vec{p}|^2 = (E^2 - c^2|\vec{p}|^2)/c^2 = (m_0 c^4)/c^2$$

- High energies needed to make (new) particles

$$s = \left(p_1 + p_2\right)^2 = 2m^2 + 2\left(E^2 + \vec{p}^2\right)$$
$$= 2m^2 + 2E^2 + 2\left(E^2 - m^2\right) = 4E^2$$

Next: QM

- Introduce “matter particles”
  - spinor ψ from Dirac equation



- Introduce “force particles”

- Introduce basic concepts of scattering processes

Plan

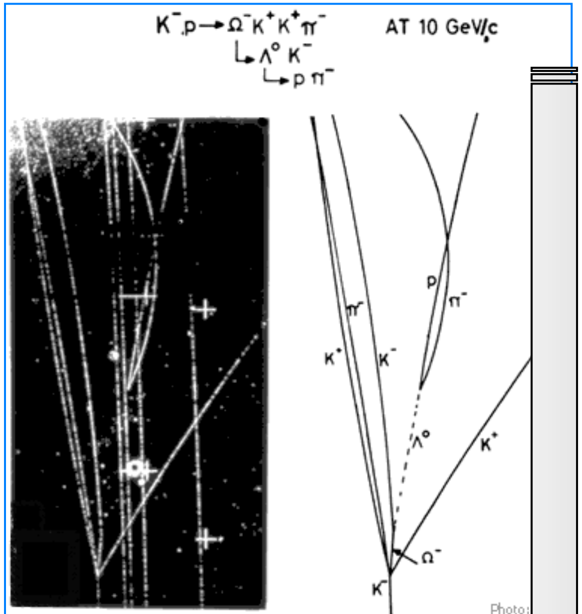
	1) Intro: Standard Model & Relativity	***12 Feb***
1900-1940	2) Basis	***19 Feb***
	1) Atom model, strong and weak force	
	2) Scattering theory	
1945-1965	3) Hadrons	***12 Mar***
	1) Isospin, strangeness	
	2) Quark model, GIM	
1965-1975	4) Standard Model	***19 Mar***
	1) QED	
	2) Parity, neutrinos, weak inteaction	
	3) QCD	
1975-2000	5) e^+e^- and DIS	***7 May***
2000-2015	6) Higgs and CKM	***21 May***

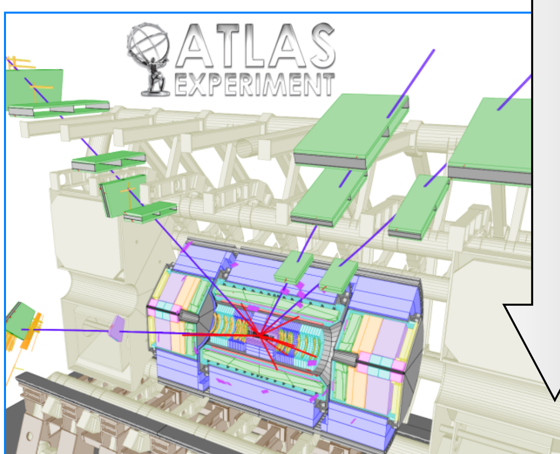
Backup slides: on accelerators

How do you create enough energy?

Accelerators

From bubble chamber to LHC





Discoveries made with the help of Accelerators:

1950

The Bevatron began to operate in **1954** and the **antiproton** was discovered in **1955**.

The Nobel Prize in Physics 1959

Segrè Chamberlain

1960

The inner structure of **nucleons** (protons and neutrons) was discovered at SLAC in **1969**.

The Nobel Prize in Physics 1990

Friedman Kendall Taylor

1970

Discovery of **J/Ψ particle** (composed of charm quarks) was discovered at Brook-haven and SLAC in **1974**.

The Nobel Prize in Physics 1976

Richter Ting

1980

The **tau lepton** was discovered at SLAC in **1976**.

The Nobel Prize in Physics 1995

Perl

1990

The **W and Z particles** were discovered at the proton-antiproton collider at CERN in **1983**.

The Nobel Prize in Physics 1984

Rubbia van der Meer

The first direct evidence for the **top quark** was announced at the Tevatron at Fermilab in **1995**.

2000

- 2012: Higgs discovered

The Nobel Prize in Physics 2013

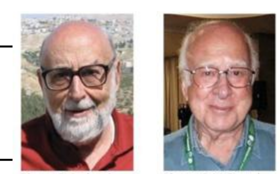


Photo: Pnicolet via Wikimedia Commons
François Englert

Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

Cockcroft-Walton

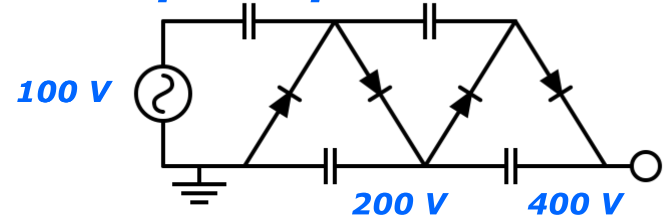
Bart Hommels

Cockcroft

Walton

Cavendish lab Cambridge

Operation principle



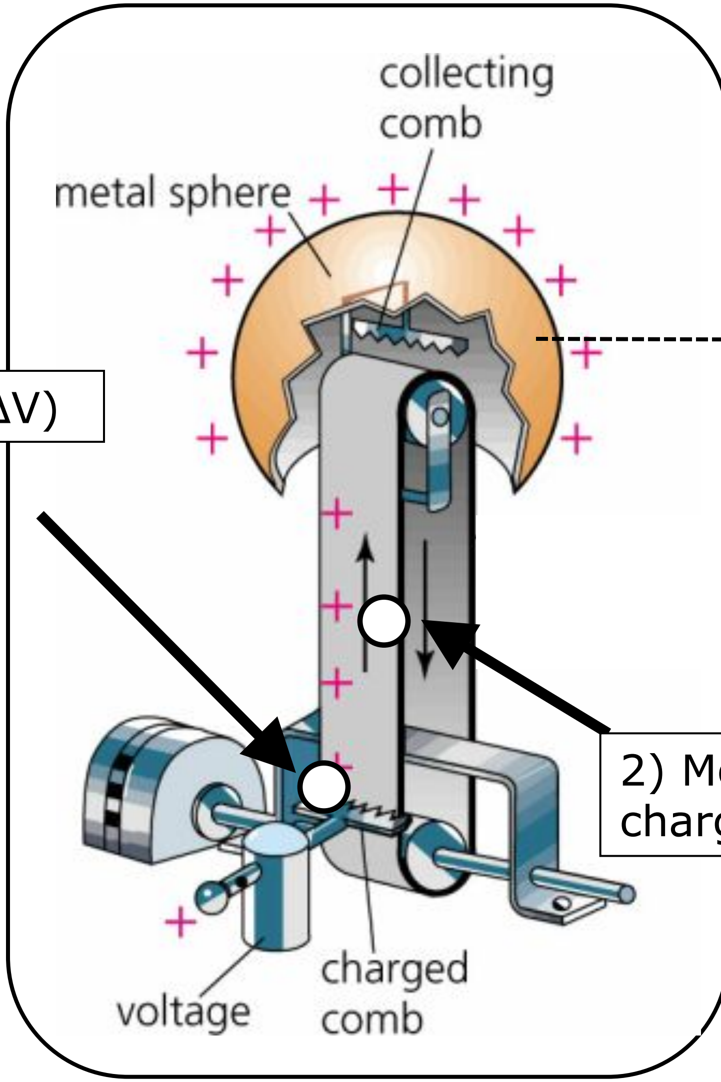
1932: 800 kV 0.8 MeV:
energy threshold to split atoms

Li + p → He + something

1951: Nobelprize

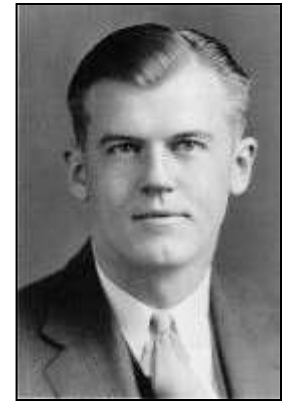
Van de Graaff

High voltage electro static generator



1) Gas ionizes (ΔV)

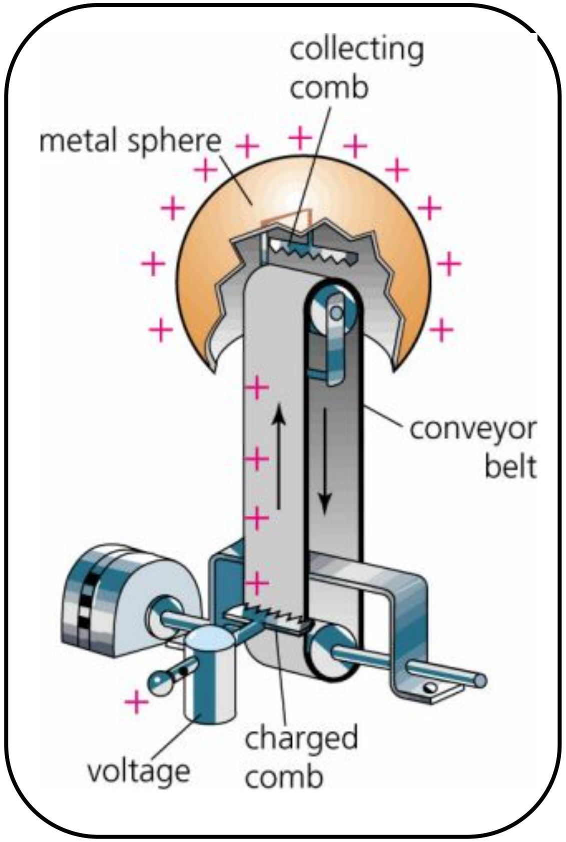
2) Moving belt transports charge

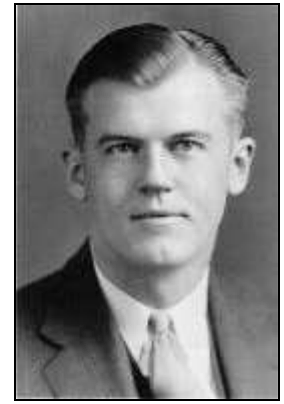


Robert van de Graaff

Harry van der Graaf

Van de Graaff





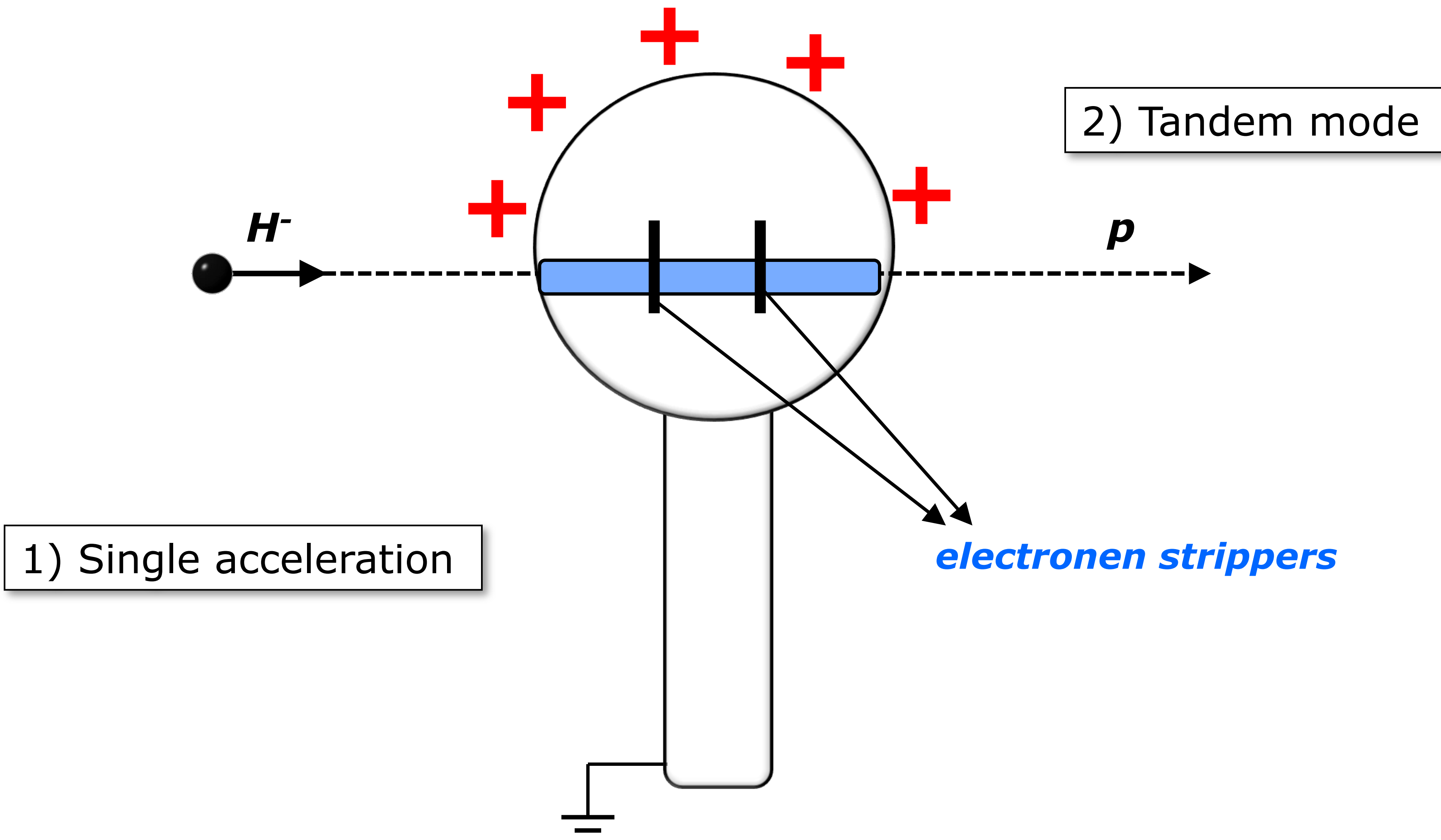
Robert van de Graaff

Harry van der Graaf

1929: 80,000 volt
1931: 1,000,000 volt
1933: 7,000,000 volt

Nowadays: ***Oak Ridge*** ***25 MeV***
Vivitron ***35 MeV***

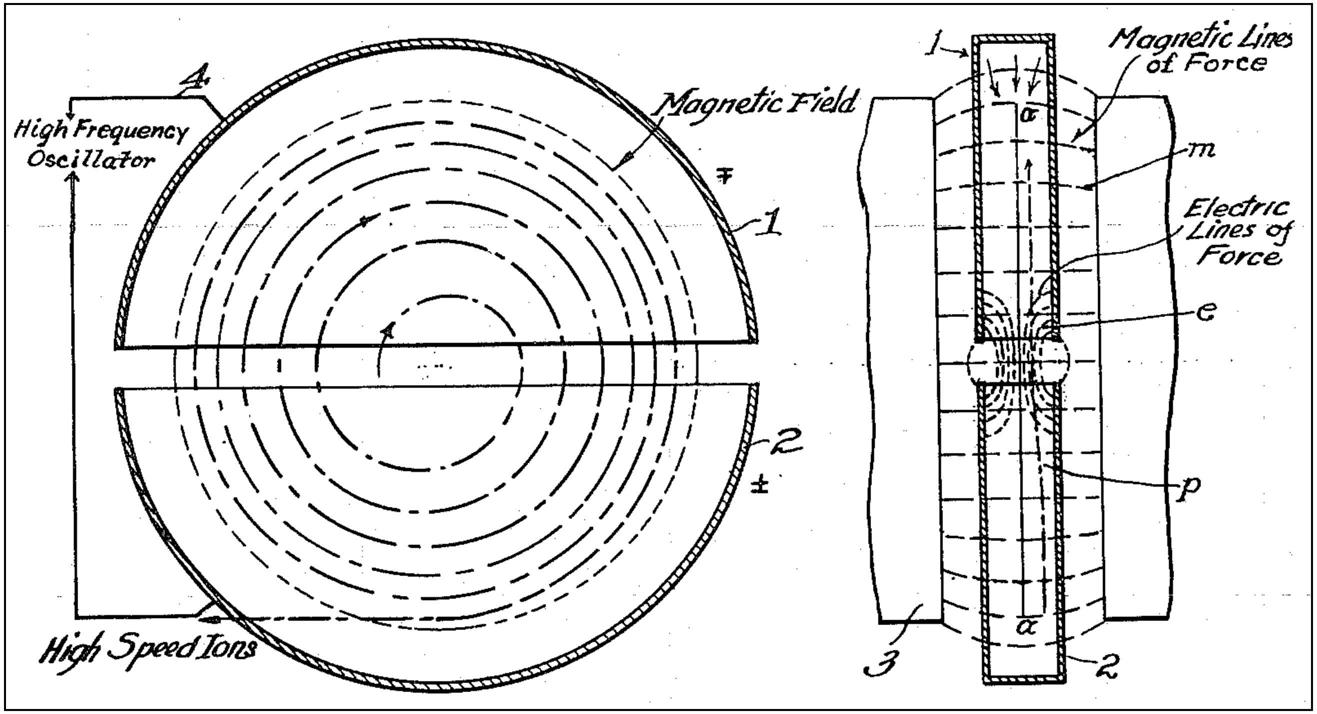
Van de Graaff



Cyclotron

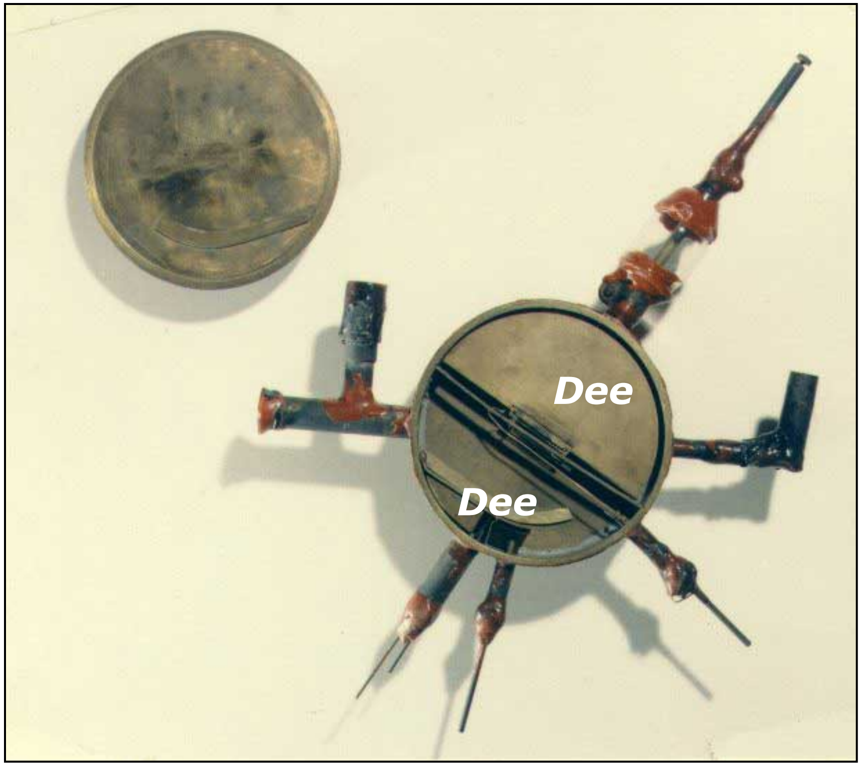
Ernest "atom smasher" Lawrence

Nobelprijs 1939



First cyclotron 1930

Cyclotrons in real life



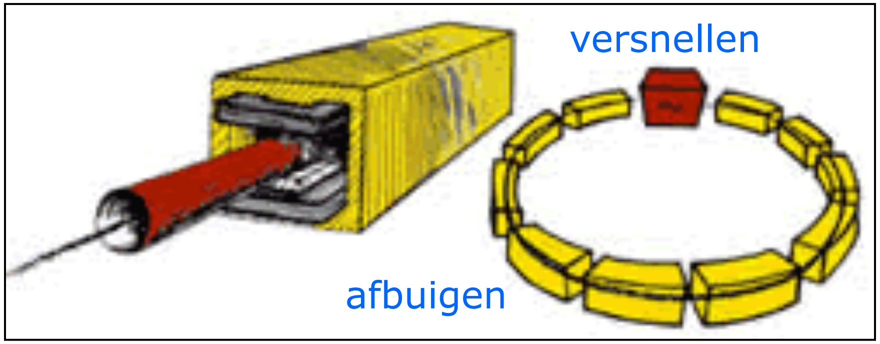
1931: r = 12 cm
→ 1 MeV protons

1974: B = 0.46 [T], r = 9 [m]
→ 520 MeV protons

Synchrotron

M. Oliphant

In a synchrotron, particles move in fixed orbit



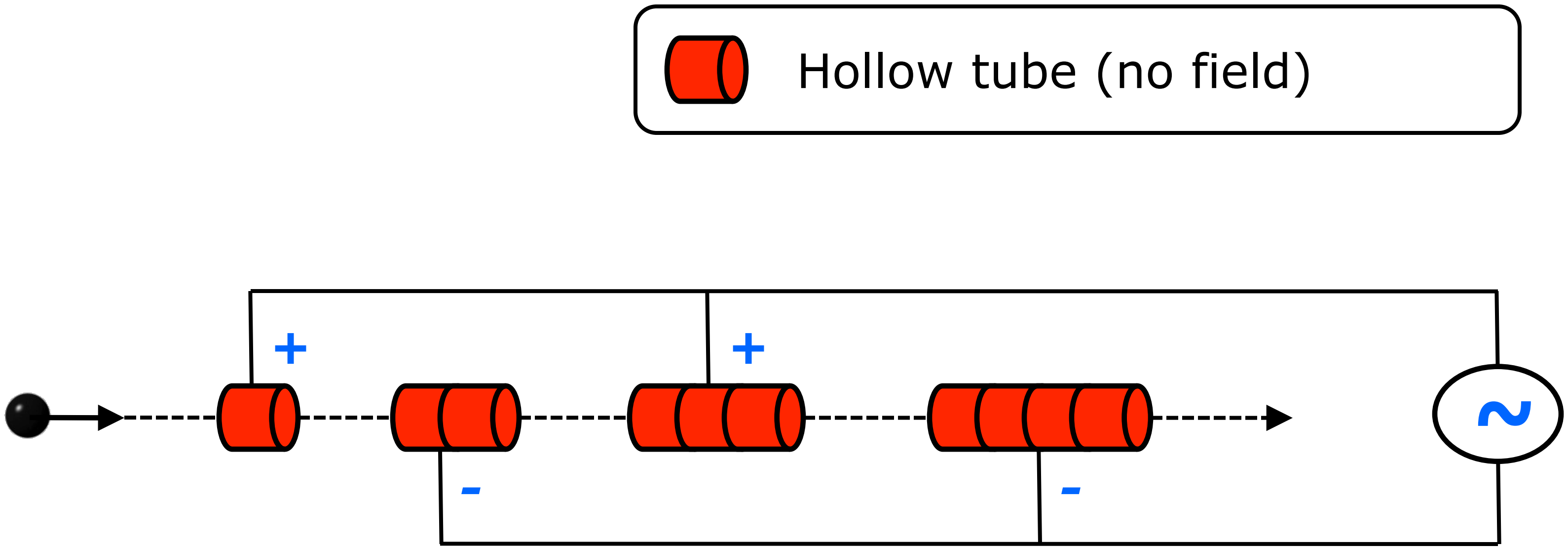
$$r = \frac{p}{qB}$$

Accelerate: higher E → higher p
r constant: also higher B

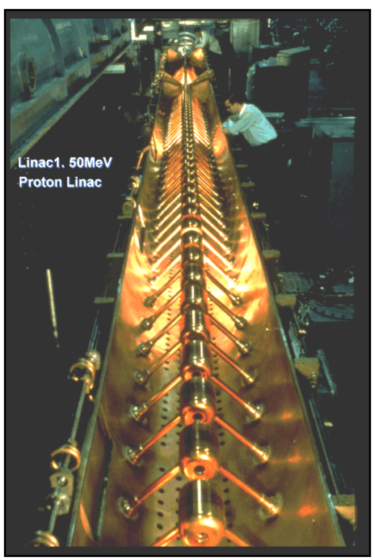
Known synchrotrons:

- Bevatron	
- Tevatron (Fermilab)	collider
- LEP (CERN)	collider
- LHC (CERN)	collider

Linac (principle)



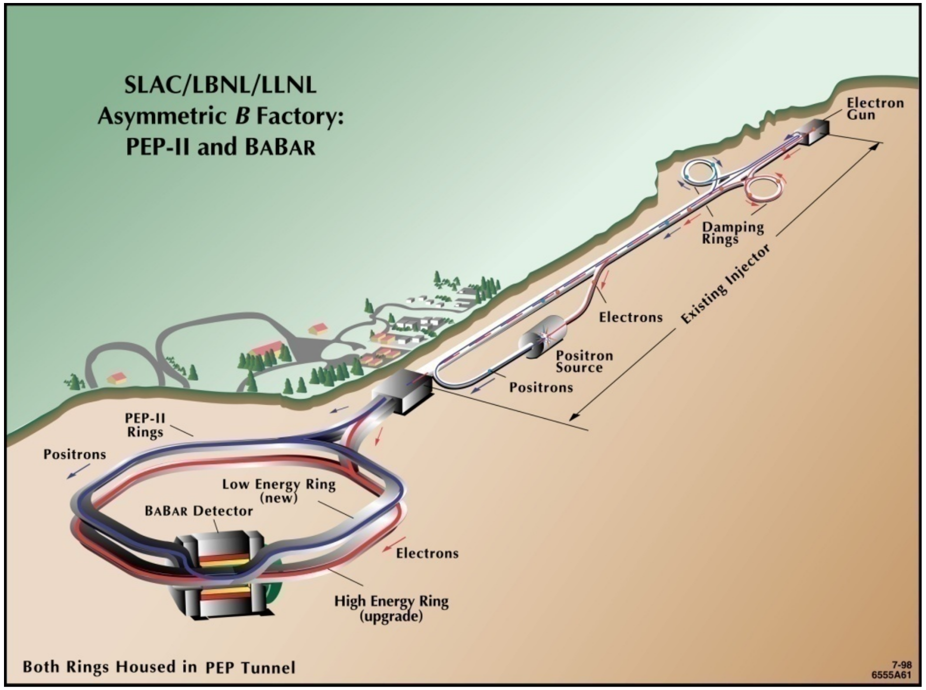
Equal frequency, larger velocity
→ (space between) tubes increasingly larger



Linac typically first step in acceleration chain
Typical: ~50m, ~100 MeV

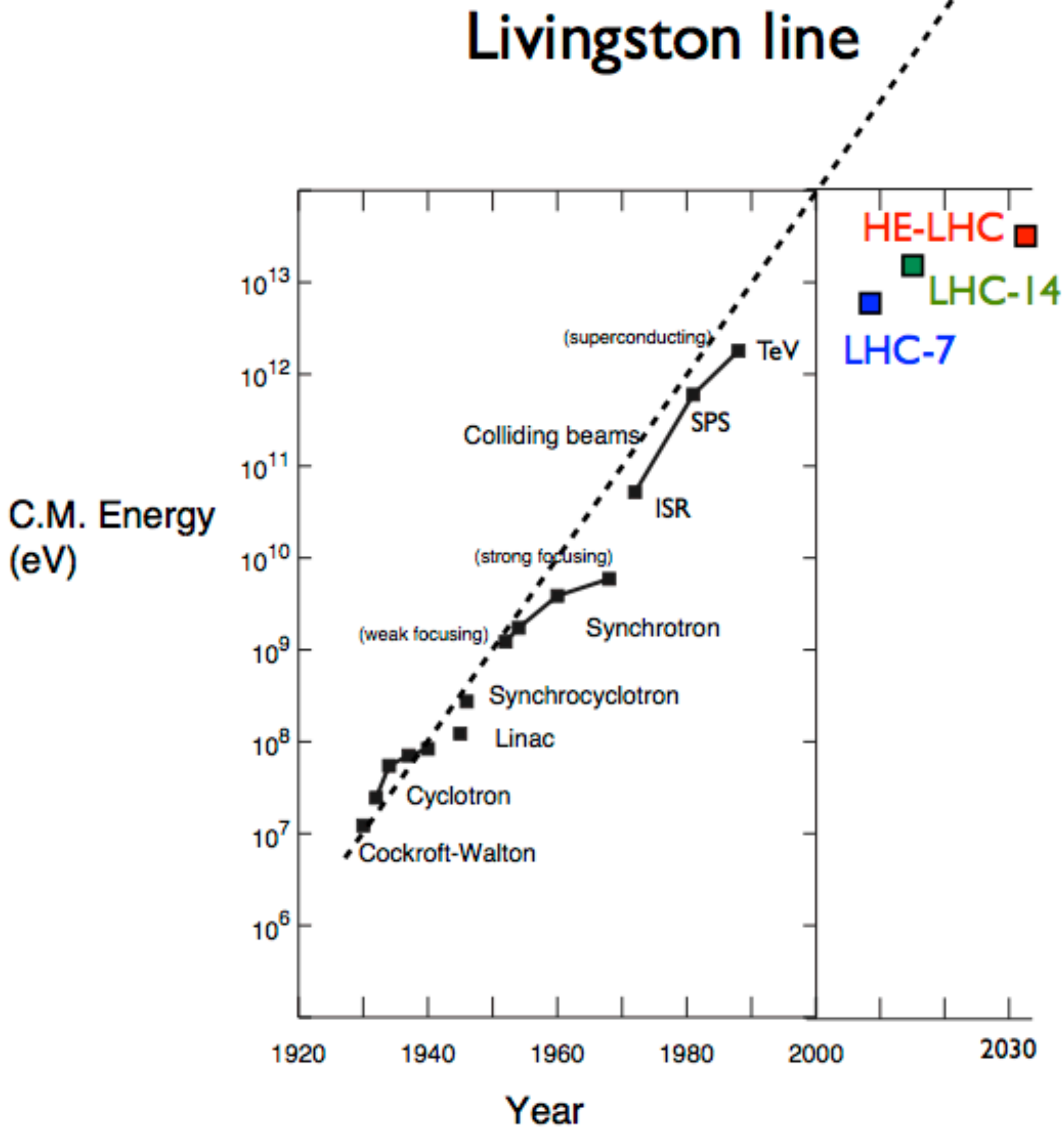
Linac's & traveling wave guide

Big Linac's



SLAC: Stanford Linear Accelerator Center (San Francisco)
3.2 km long → 50 GeV electrons

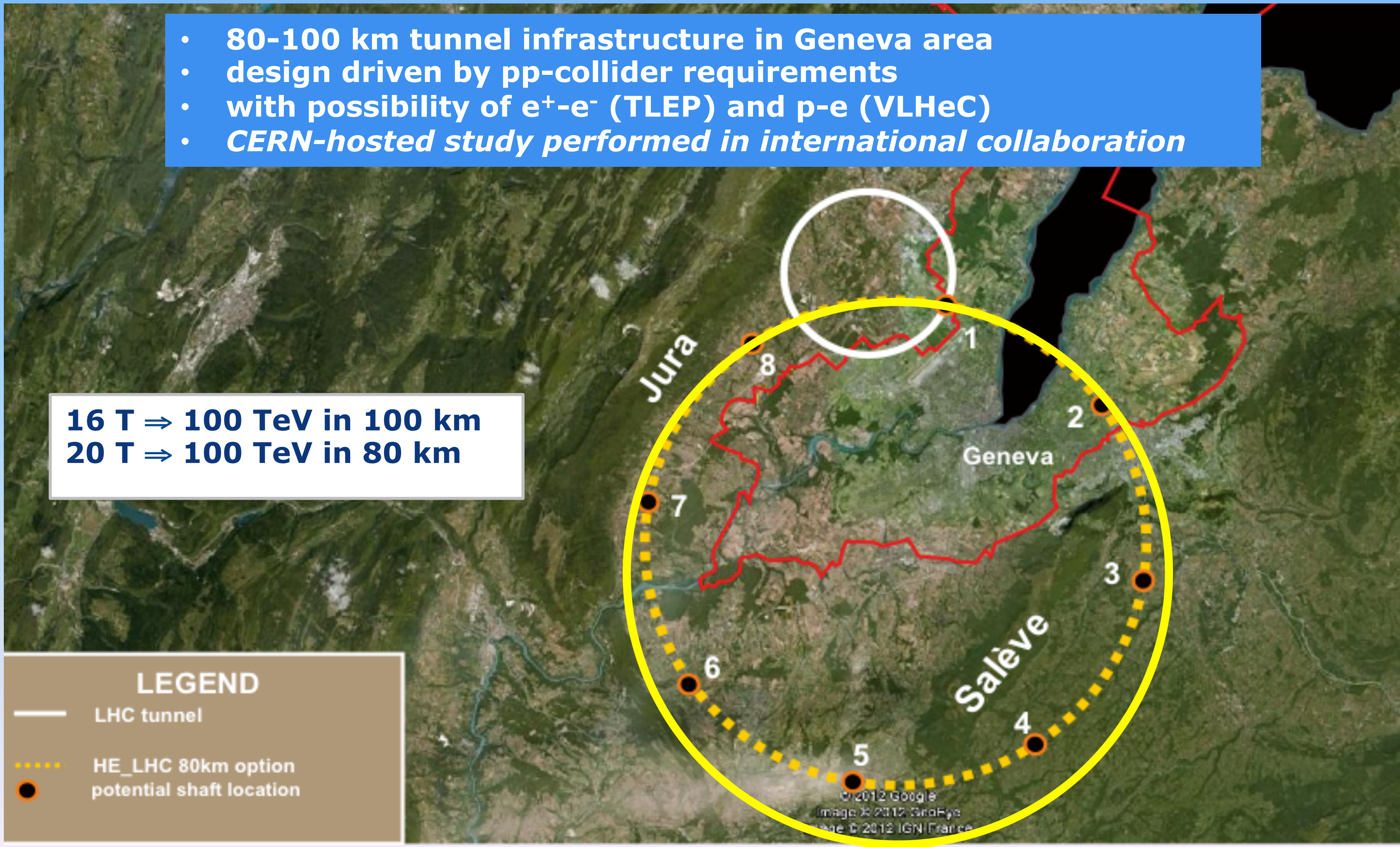
Livingston line



Future Circular Collider (FCC) ???

- **80-100 km tunnel infrastructure in Geneva area**
- **design driven by pp-collider requirements**
- **with possibility of e^+-e^- (TLEP) and p-e (VLHeC)**
- ***CERN-hosted study performed in international collaboration***

16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km



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