

Craftsmanship  
and Brainchildren  
of HEPP



Yuri Dokshitzer

1st CERN Baltic Conference

*Tartu 2021*



The only well-designed  
and efficiently functioning  
pan-European body

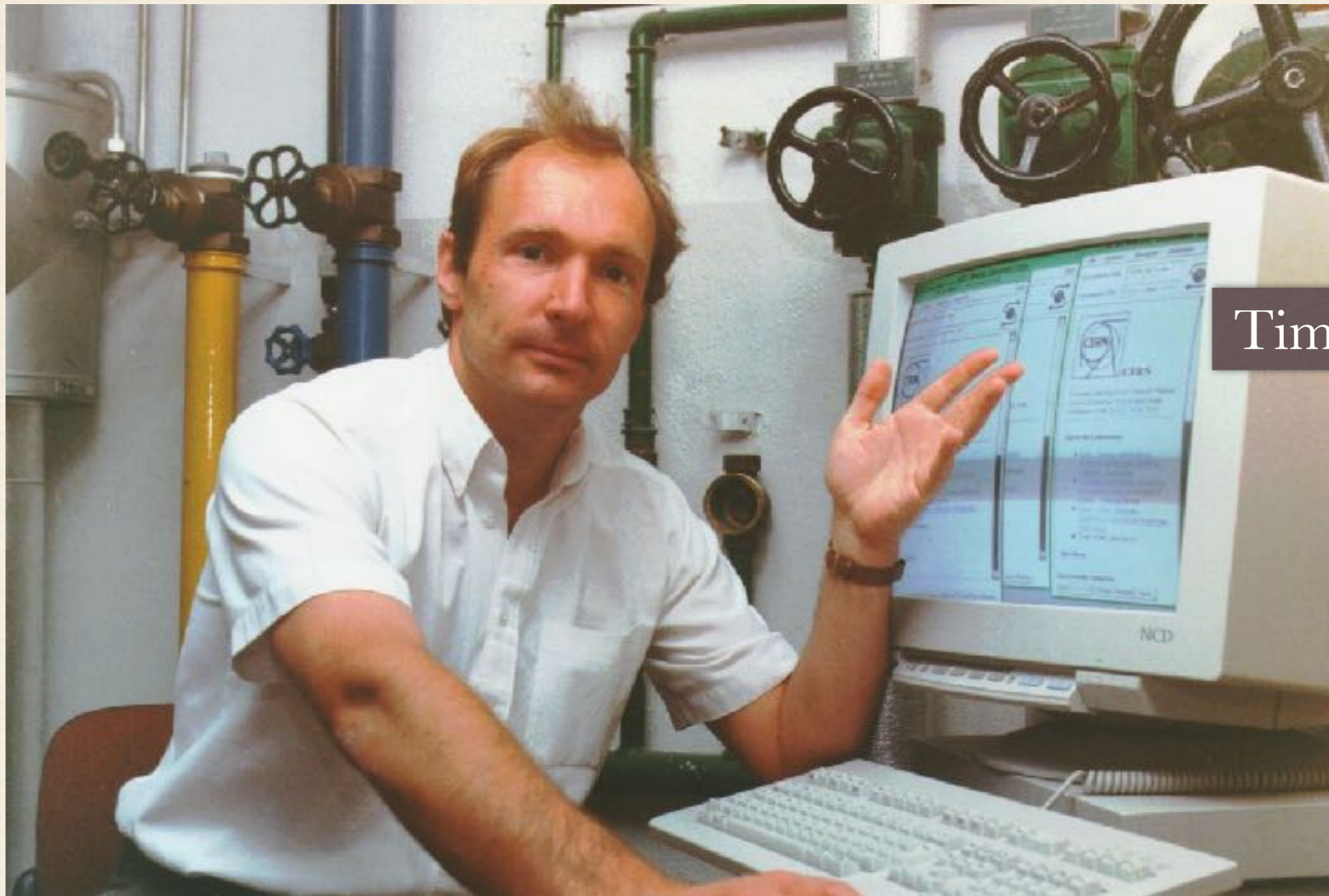
**CERN**

(with a proud obsolete name)

# CERN marvels

- ❖ precision mechanics                      micron precision @ km scale
- ❖ electrical engineering                      superconductivity, **I & B**
- ❖ cryogenics                                  create and maintain cosmic vacuum
- ❖ new materials                                radiation-*resistant* & radiation-*sensitive*
- ❖ new instruments and technologies                      medical imagery
- ❖ data acquisition and processing                      Fast & Very Big Data
- ❖ WWW





Tim Berners-Lee

online **Sotheby's** auction of the original code that have introduced **HTML, URL, HTTP**, etc, running from 23 to 30 June 2021



*Impatient Instigators & Capricious Consumers*

**Experiment**



**Theory**



*an eternal love-hate story*

# Cross-feed & Crossbreed

## Experiment

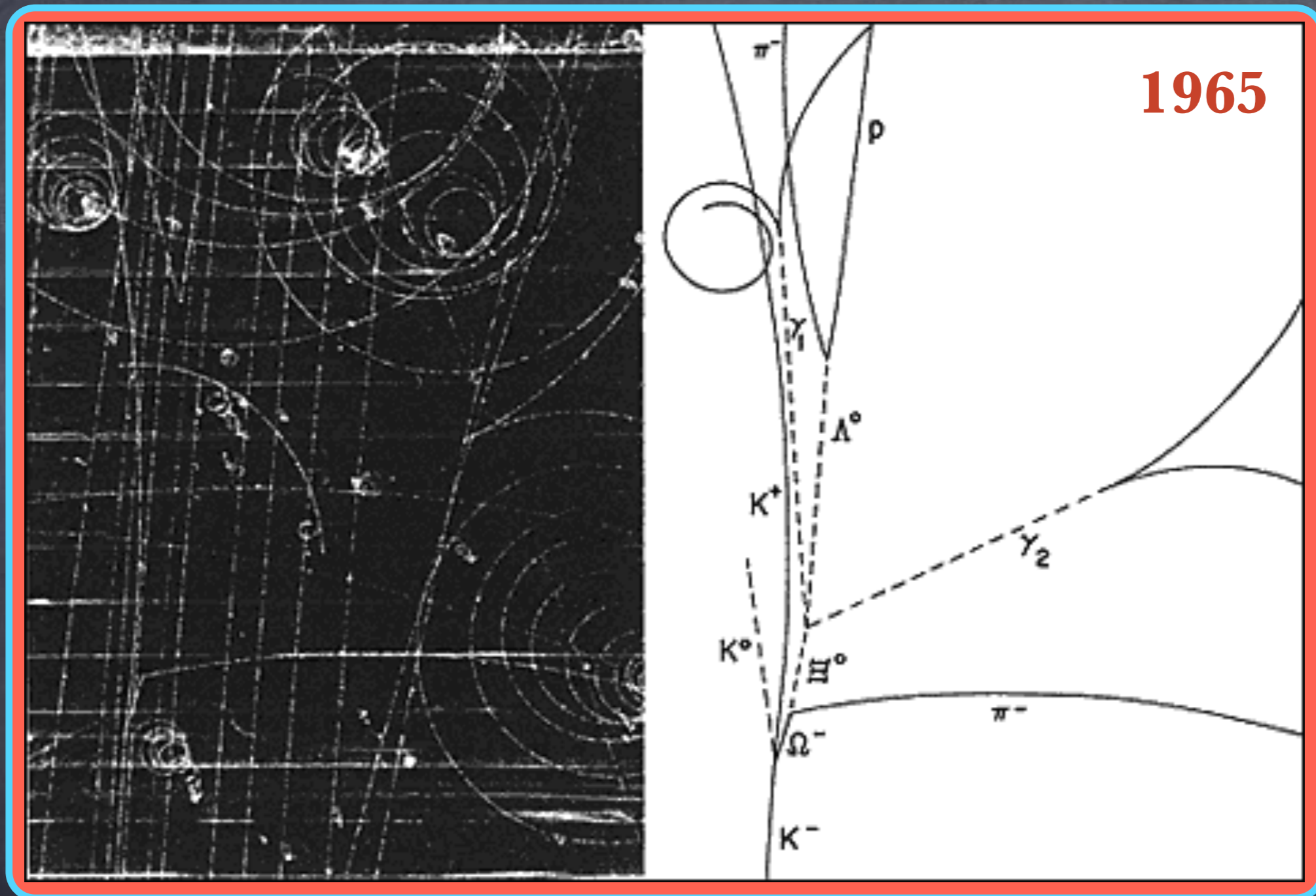


## Theory

speed of light <b>c</b>		Special Relativity
gravitating light		General Relativity
<b>muon</b> (1936)		2nd lepton generation
1949		<b>pion</b> (1935)
strange particles		quark model
$\Omega^-$ hyperon		SU(3) flavor symmetry
<b>tau</b> -lepton (1974)		3rd generation
HEPP		QCD
neutrino oscillations		neutrino masses (?)



*the 'Alpha' of the New Times : the discovery of 'Omega'*



- the first true 'Ahaa!' of the Quark model
- the final decisive 'Ahaa!' came with discovery of the 4th Quark - Charm - 10 years later



# Quantum Field Theory

QFT



Relativistic  
Quantum  
Multi-Body

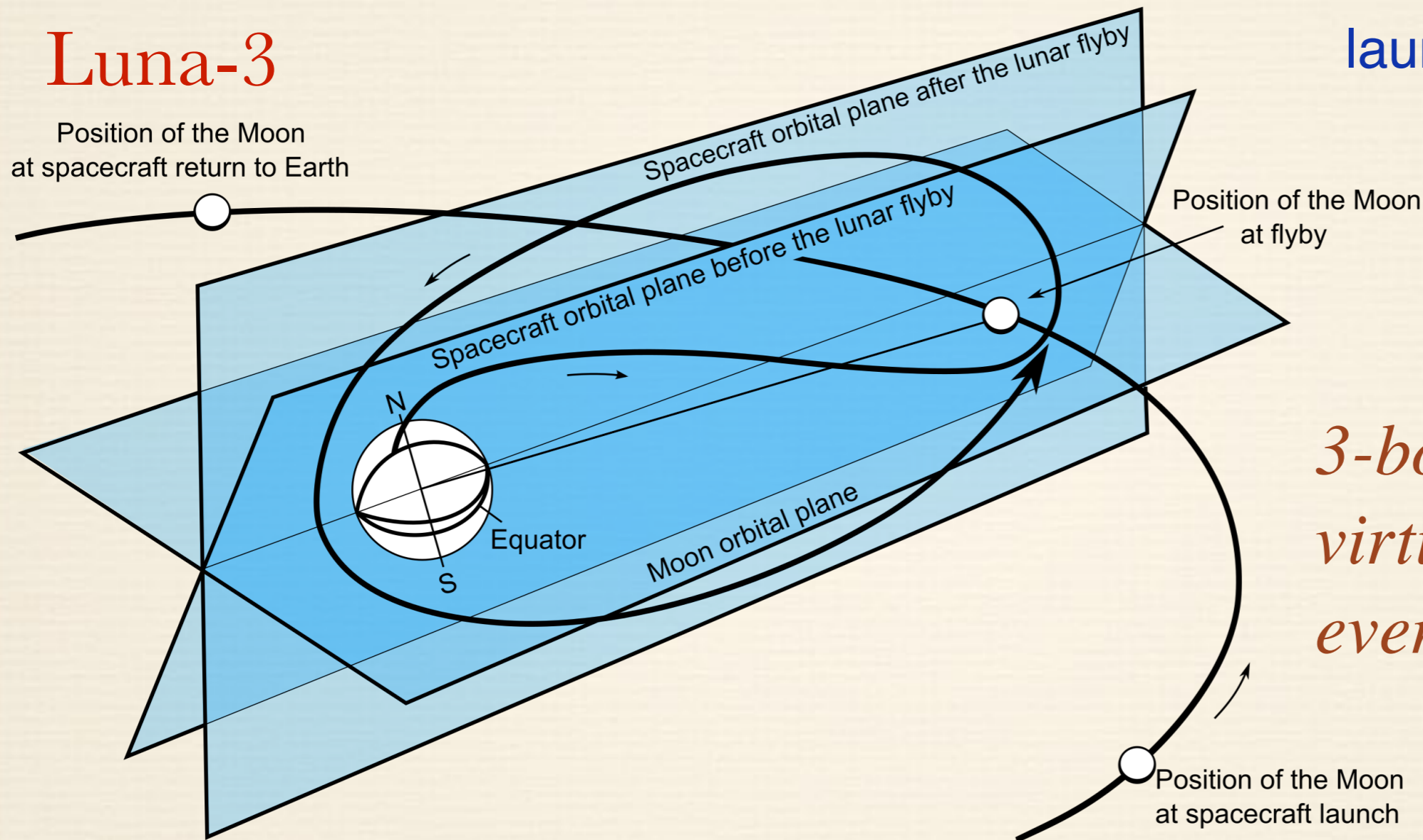
*dynamics*



# 1, 2, 3, - many

## Luna-3

launched 4.10.1959



*3-body dynamics  
virtually unknown  
even **classically***

“an **eternal** manmade Moon satellite!”

**in a few days the orbiting capsule  
fell on the surface of the Moon!..**

*“vertical Moon” - lifetime 52 days*



# Quantum

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## Photoelectric Effect

Energy of electrons kicked off irradiated surface of a metal increases with the frequency of light.

The *number* of electrons does increase with *intensity* of light, but the *energy* does not!

Light gets absorbed as a *particle* with  $E_\gamma = h\nu$  - “**photon**”

The role of quantum physics - to teach humility:

get used to live with - study, interpret, predict -

*bizarre* phenomena involving *unimaginable* objects



# Relativistic

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another weird fact

- dependence of properties of **space**  
and **time** on the velocity of the observer  
also took a good century to get used to.

To digest and accept such an anti-intuitive consequence  
of **Special Relativity** as ***shrinkage of time***  
became so much easier nowadays

when we carry the proof in the pocket on a daily basis!



## GPS and Relativity

**Orbital clocks move with velocity**  $v = 14000\text{km/hour} \approx 4\text{km/sec}$

$$(v/c)^2 \approx 2 \cdot 10^{-10}$$

$$t = \frac{t_s}{\sqrt{1 - (v/c)^2}} \approx (1 + 10^{-10})t_s$$

**amounts to  $7 \mu\text{s/day}$  slowdown.**

**The story does not end here, though**

**20000 km above the Earth *gravity is 4 times weaker*, and the clock ticks *faster* due to Einstein's *General Relativity!***

**The net effect:  $45 - 7 = 38 \mu\text{s/day}$ .**

**Without account for Relativistic effects GPS would become useless in about 2 minutes! (10 km/day accumulated error)**



# Relativity: **velocity and beyond**

**Chemistry** (atoms & molecules)  $v_e \sim \alpha_{e.m.} \simeq 1/137$

**Nuclear Physics**  $v_\pi \sim m_\pi/M_p \simeq 1/7$

**Particle World** intrinsically, essentially **relativistic**  
and not only because typical velocities are large...

The key feature of **Relativistic Dynamics** - **antiparticles!**

you want to study, start probing  
you come closer and see instead

$$\begin{array}{c} e^- \\ e^- e^+ e^- \end{array}$$

**Extra headache:** not just “multi” but *indefinitely* multi- !



# Elementary Particles (as of today)

## FERMIONS

matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	$<1 \times 10^{-8}$	0
$e$ electron	0.000511	-1
$\nu_\mu$ muon neutrino	$<0.0002$	0
$\mu$ muon	0.106	-1
$\nu_\tau$ tau neutrino	$<0.02$	0
$\tau$ tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$u$ up	0.003	2/3
$d$ down	0.006	-1/3
$c$ charm	1.3	2/3
$s$ strange	0.1	-1/3
$t$ top	175	2/3
$b$ bottom	4.3	-1/3

g

## BOSONS

+  $\gamma, W^\pm, Z^0$  (spin=1) +  $H$  (spin=0)



# abstractions and shortcomings of QFT

**point-like objects  
engaged in local (point) interactions**



*- the only framework known today  
enabling us to derive verifiable predictions*

**Prise to pay - divergencies :**  
**mass** and interaction constant (**charge**)  
*not calculable*



*A sneaky way out:*

cannot calculate in a sensible manner? - don't!

Try to express everything in terms of physical  
(measurable) ***masses*** and ***charges***.

If/when you succeed - your theory is

***renormalisable,***

ready for making high-accuracy predictions.

*How bad a situation?*

*depends on your ambitions*



# Non-renormalisable QFTs

Specific phenomena in a limited range of parameters

## *Effective QFTs*

small-energy  $\pi - N$  interactions

critical phenomena

effective d.o.f. (e.g. phonons)

+ stock markets etc (“financial physics”)

NB: George Zweig, James Simons, Patrizio Vinciarelli, Alexandre Migdal...

Example of *non*-renormalisable dynamics

- **Quantum Gravity**

... *alas*

Otherwise, all QFTs we need *are* renormalisable

**SM** QFTs

*real world*

(QED  $\rightarrow$  GWS) + QCD

model QFTs

*playing ground*

**BSM, Grand Unification  
Super-Symmetry**

A technical proof that “*God, though sophisticated, is not malicious*” (c)

Moreover, in order to keep **SM** renormalisable, theorists needed, successively,

4th quark (charm)

← to kill divergence in kaon oscillations

3rd quark generation (t,b)

← to cure “axial anomaly” (#quarks = #leptons)

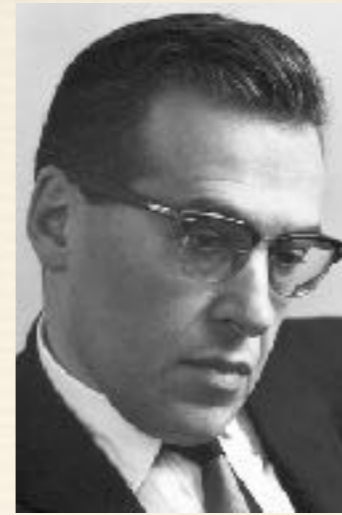
the Higgs boson

← to make Z and W massive without spoiling



Quantum Electrodynamics  
Feynman-Schwinger-Tomonaga

**QED**



**1965**

Electro-Weak Interactions  
or **GWS** theory  
Glashow-Weinberg-Salam



**1979**

Quantum Chromodynamics  
Gross-Wilczek-Politzer

NB: NP not for **QCD** but for  
“**Asymptotic Freedom**” -



**2004**

the most unexpected and marvellous property of quark-gluon interactions

Polarisation of QED vacuum makes  
the electric charge “run” with photon virtuality

$$\alpha \rightarrow \alpha(k^2)$$

**L.Landau 1954**

Electric charge *increases*  
at small distances (large momentum transfers).

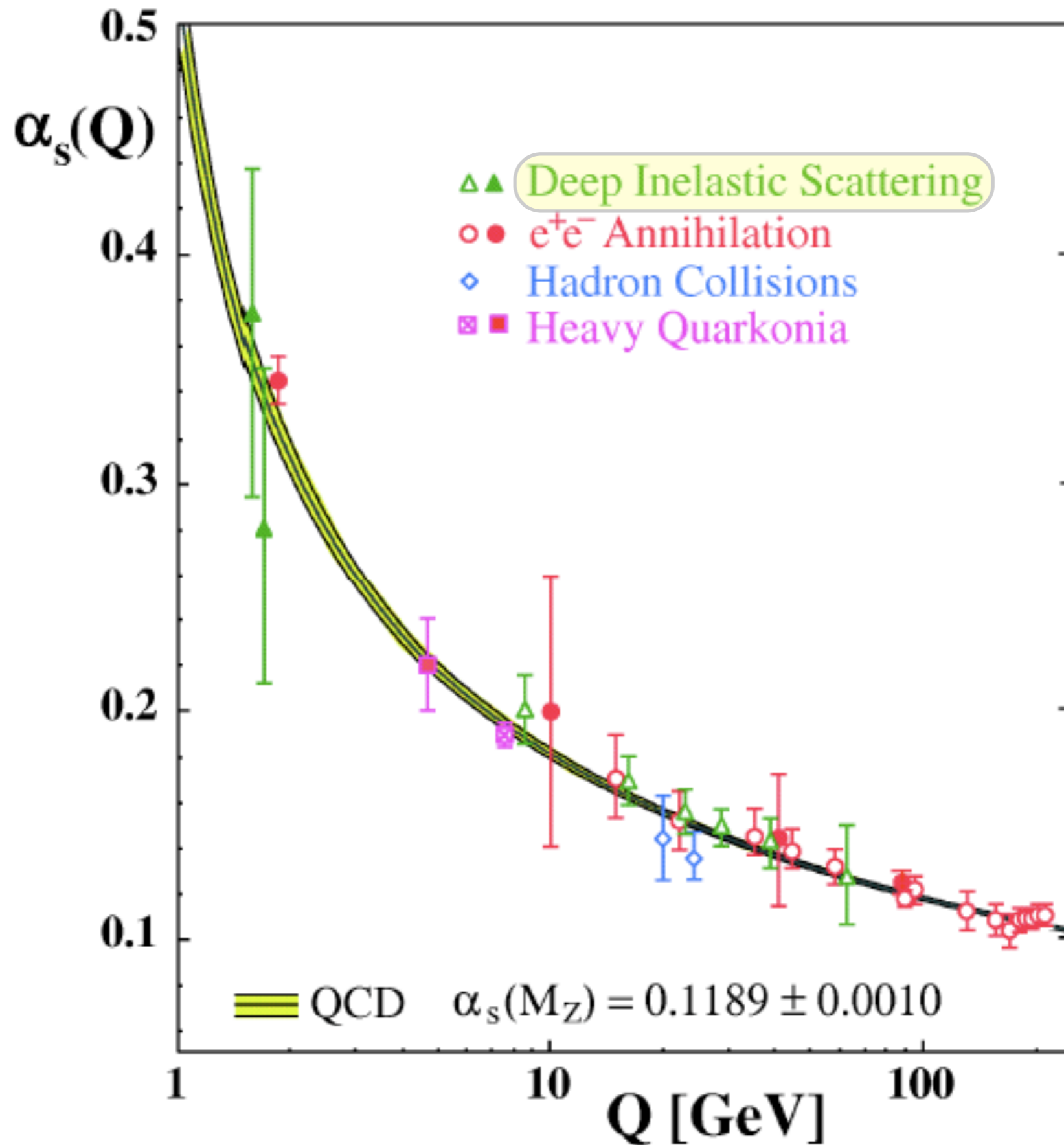
For many years such a behaviour was believed to be general,  
common for all QFTs, as it follows from the basic properties:  
*relativity* (crossing), *causality* (cause vs effect) and *unitarity* (probability)

In QCD, on the contrary, effective charge was found  
to *fall* with increase of momentum transfer!

This allows theorists to keep under *quantitative control*  
what happens with “QCD partons” - quarks and gluons -  
at small space-time intervals: *Hard Processes*.



# Summary of the QCD coupling measurements



**Asymptotic Freedom**

High precision predictions in electro-week sector

Controlling hard lepton-hadron and h-h interactions

{ Evolution of quark-gluon

{ Distribution of hadrons in

Structure of hadron flows

First glance at confinement

Errors, misconcepts, productive quarrels  
→ breathtaking discoveries.



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red that?" (c)

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**To be  
continued...**