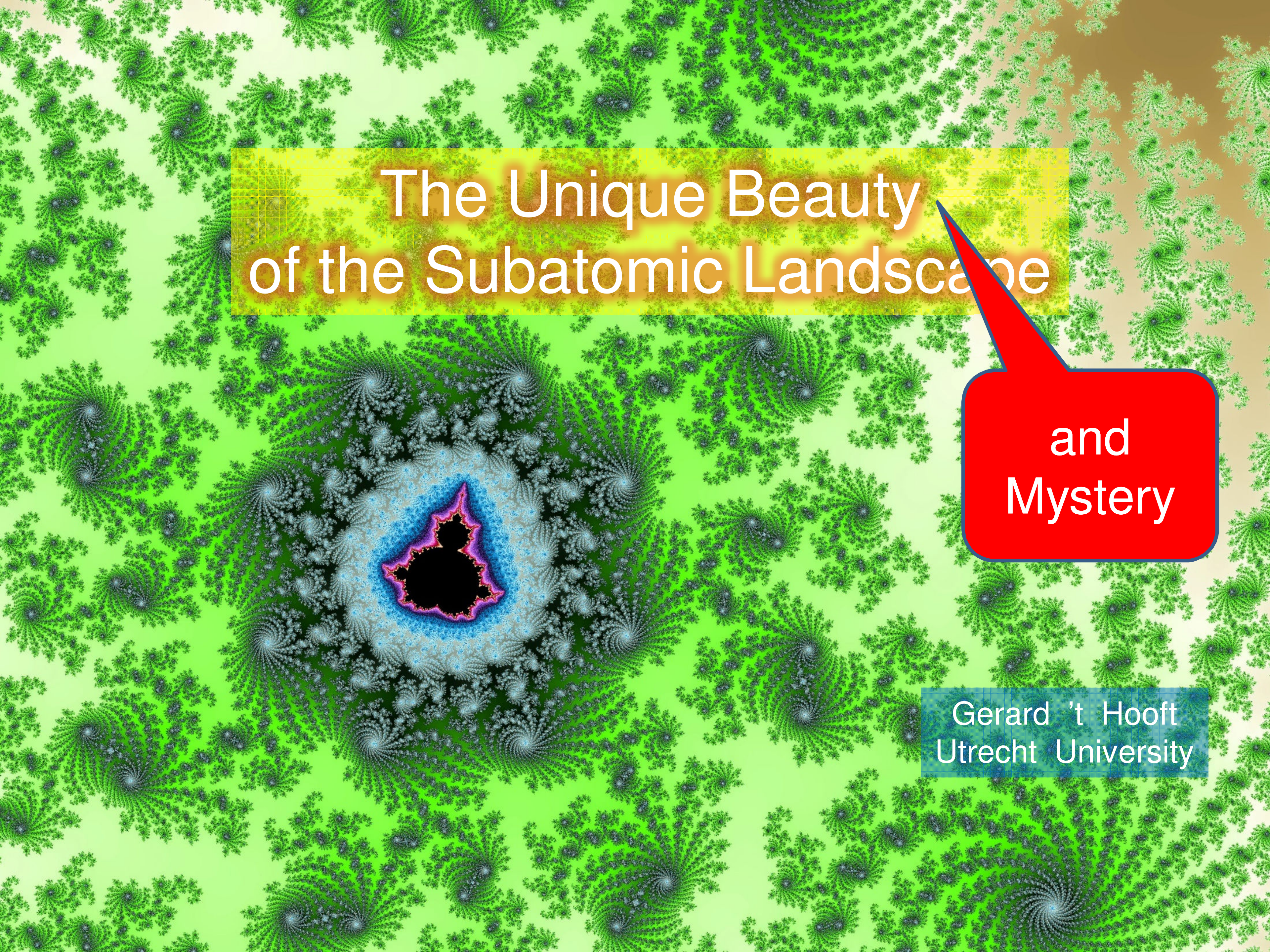

The Unique Beauty of the Subatomic Landscape

and Mystery

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Utrecht University

Recollections and reflections

Theme:

- Nature is more beautiful than we think

- Nature is smarter than we are

The landscape around 1965:

1969

photon γ

spin $= 1$

Leptons

$e^- \quad \nu_e$

$\mu^- \quad \nu_\mu$

spin $= \frac{1}{2}$

anti-
leptons

Hadrons

mesons

$\pi^+ \quad \pi^- \quad \pi^o$

$K^+ \quad K^-$

$K_L \quad K_S$

η

spin $= 0$

baryons

$P^+ \quad N$

Λ

$\Sigma^+ \quad \Sigma^o \quad \Sigma^-$

$\Xi^o \quad \Xi^-$

spin $= \frac{1}{2}$

anti-
baryons

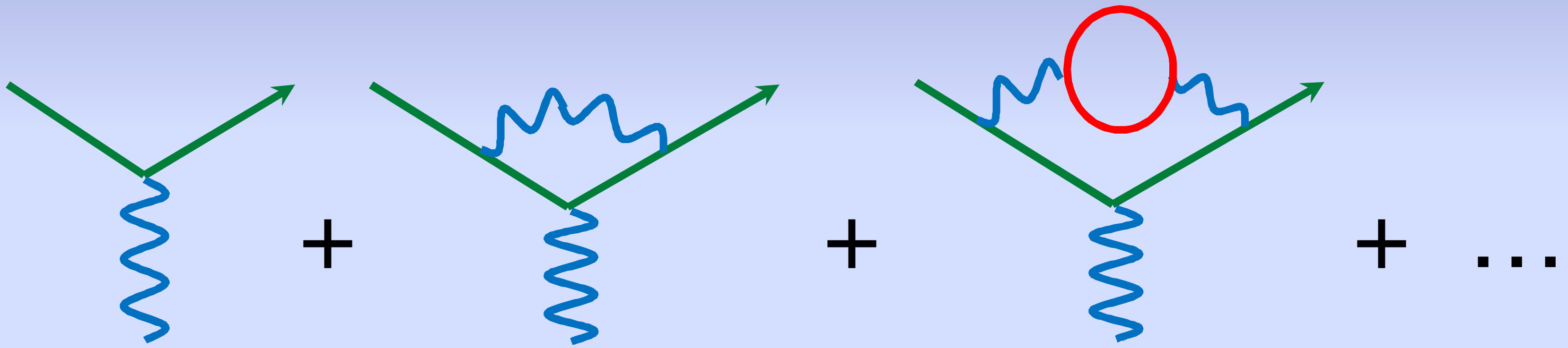
Ω^-

spin $= \frac{3}{2}$

anti-
Ω

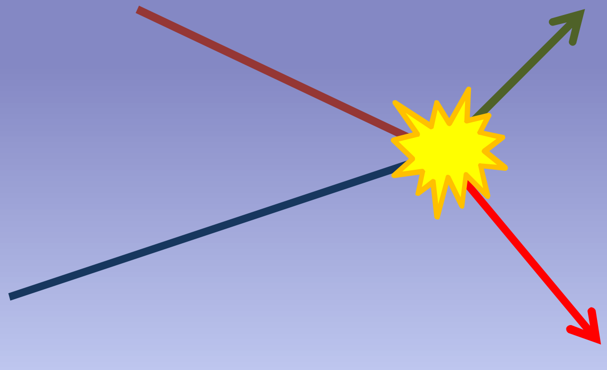
Quantum Electrodynamics (QED) was beautiful:

Renormalizable



$$g_e = 2.00231930436\ \ldots$$

But how did the *weak force* go ?



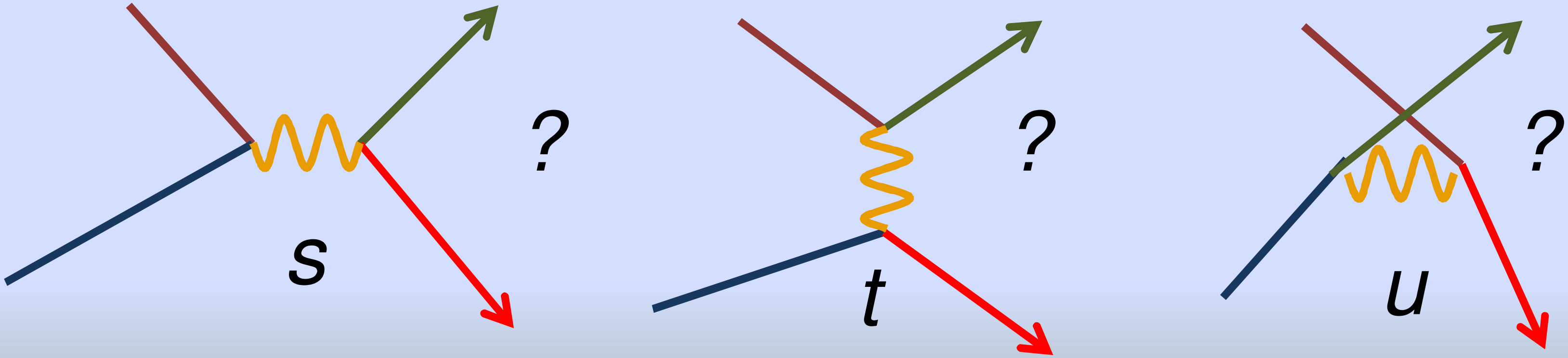
Gell-Mann, Feynman,
Sudarshan Marshak

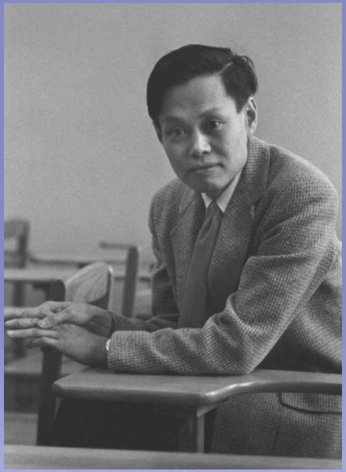
V - A

Too many lines at one point:

NOT RENORMALIZABLE

The **I**ntermediate **V**ector **B**oson:

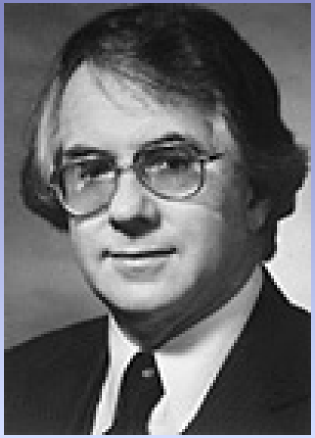


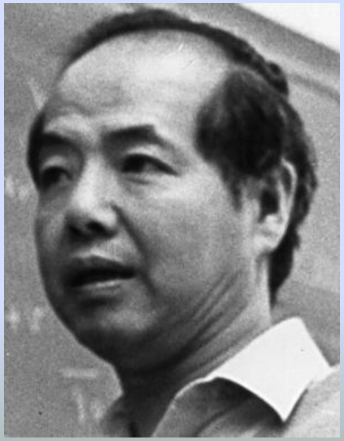

C.N. Yang


R. Mills

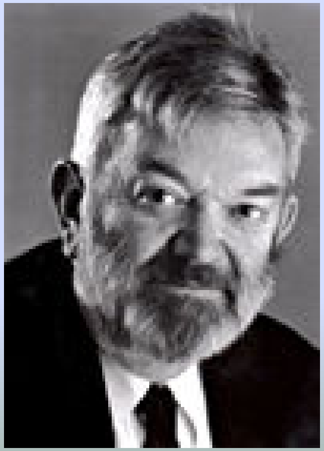

S. Weinberg


A. Salam

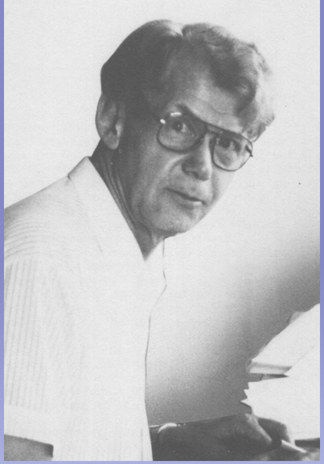

S. Glashow


T.D. Lee


R. Feynman


M. Veltman

How do we deal with the *mass* of the IVB ?


K. Symanzik

"Spontaneous symmetry breaking does not affect renormalizability"

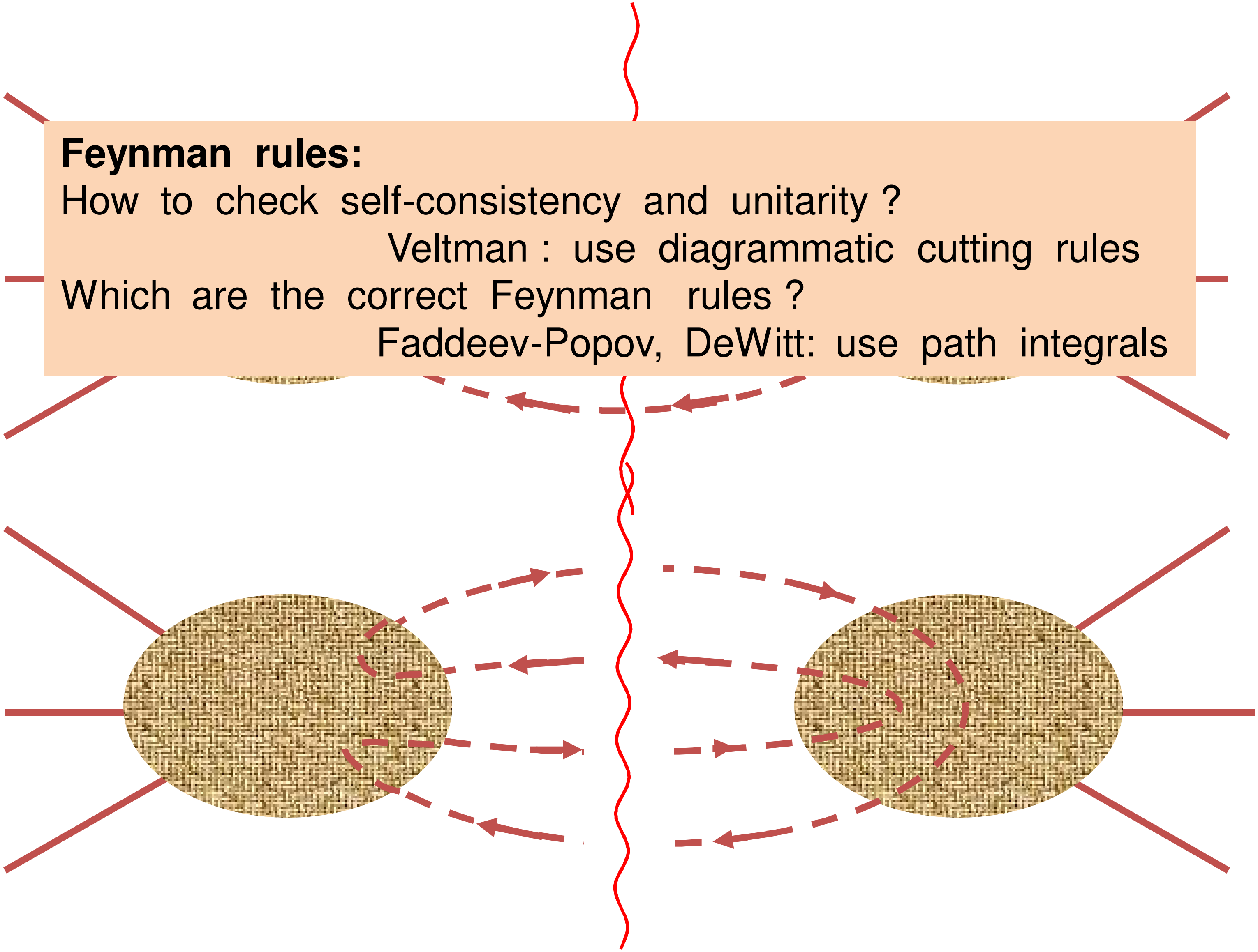
"You have to understand the small distance structure of a theory"

What is the small distance structure of a massive Yang-Mills theory ?

The gauge symmetry becomes *exact,* and the longitudinal mode of the vector boson behaves as a *scalar particle* – the *Higgs* !

Only the Brout – Englert - Higgs mechanism can generate renormalizable massive vector particles such as the Intermediate Vecor Bosons of the weak interactions.

Now work out the details: will the renormalized theory be unitary ? What are the Feynman rules? What are the counter terms?



Feynman rules:

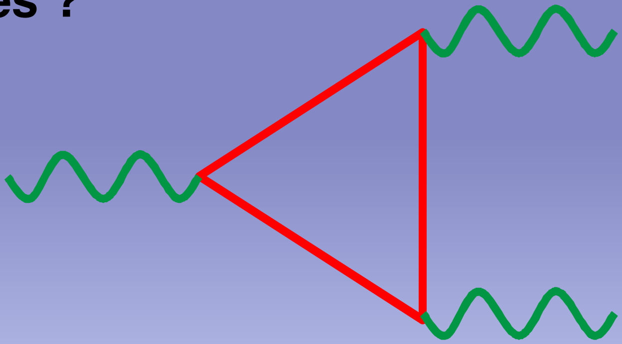
How to check self-consistency and unitarity ?

Veltman : use diagrammatic cutting rules

Which are the correct Feynman rules ?

Faddeev-Popov, DeWitt: use path integrals

Will there be anomalies ?



The $\pi^0 \rightarrow \gamma\gamma$ decay was known to violate the symmetry laws of the Lagrangian that generates its Feynman rules.
Such an anomaly could jeopardize the renormalizability of massive vector theories. How can we assure that such anomalies stay harmless ? Should the small-distance behavior provide answers?

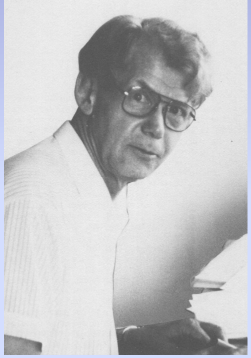
This was an important reason for studying the *scaling behavior of gauge theories*. What is their small-distance structure?

If they stay regular, should the absence of 1-loop anomalies then not be sufficient to guarantee their absence at higher loops?

Indeed, in 1971, our Feynman rules could be used to calculate what happens if you **scale** all momenta k_μ by a factor λ. Pure gauge theories behave fine (they are now called "*asymptotically free*")

In modern words: $\beta(g) < 0$

An elementary calculation. Why was that nowhere published before ?



Did nobody take notice of off - shell physics ?

Anyway, there are problems when there are fermions or scalars around, and I was not able to prove that asymptotic freedom would ensure absence of higher order anomalies . . .

There was a better approach:

Add to the theory a 5th dimension! Take $k_5 = \Lambda$ and use diagrams with this k_5 going around in a loop as regulator diagrams. This works to renormalize all 1-loop diagrams without anomalies

But what about higher loop diagrams? It would be elegant if you could use 6, 7, or more dimensions. **But this did not work !**

A last, desparate attempt:

Take $4+\varepsilon$ dimensions and use ε as a regulator:
Dimensional renormalization !

We were led to the following *beautiful* discoveries:

All quantized field theories are **renormalizable** iff they contain
- vector fields in the form, of Yang-Mills fileds,
- scalar fields and spinor fields in the form of representations of the YM gauge groups,

where the scalar fields may give mass to the vector particles via the Brout-Englert-Higgs mechanism,

Although also composite spin 0 particles can give mass: the **proton** owes its mass to a meson quadruplet, $[\sigma, \pi^{\pm}, \pi^{0}]$ (quark bound states).

and where the ABJ anomalies cancel out.

This gives elementary particles of **spin 0, ½ and 1**.

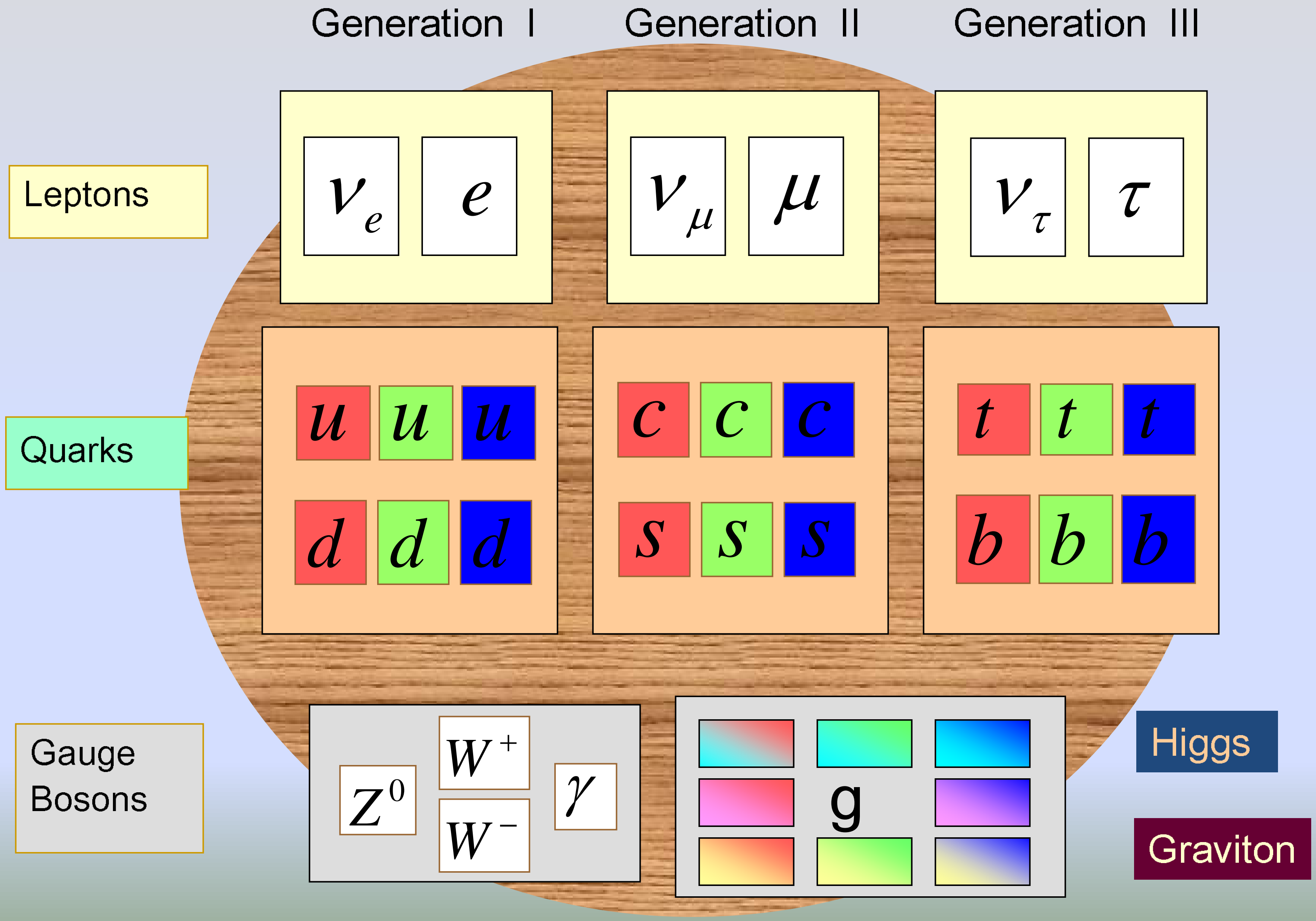
No *other* field theories are renormalizable.

Renormalizability means nothing more than that the effective coupling strengths run logarithmically when we scale the momenta. If we want them to run to zero at high energies, this gives much more stringent conditions, which are met nearly but not entirely by the SM :

ASYMPTOTIC FREEDOM

The more modern landscape:

The Standard Model



	Generation I	Generation II	Generation III
Leptons	ν_e e	ν_μ μ	ν_τ τ
Quarks	u u u d d d	c c c s s s	t t t b b b

Gauge Bosons

Z^0 W^+ W^- γ

g

Higgs

Graviton

This model explains in a magnificent way all observed strong, weak and electromagnetic interactions

It predicted/predicts totally new phenomena:

- Instanton effects in the strong and the weak force:
  - mass splittings in the pseudoscalar and the scalar sector of QCD
  - baryon number non-conservation during early Big Bang

- Running coupling strengths
  - strong force gets weaker at higher energies
  - 3 forces unite at extremely high energies

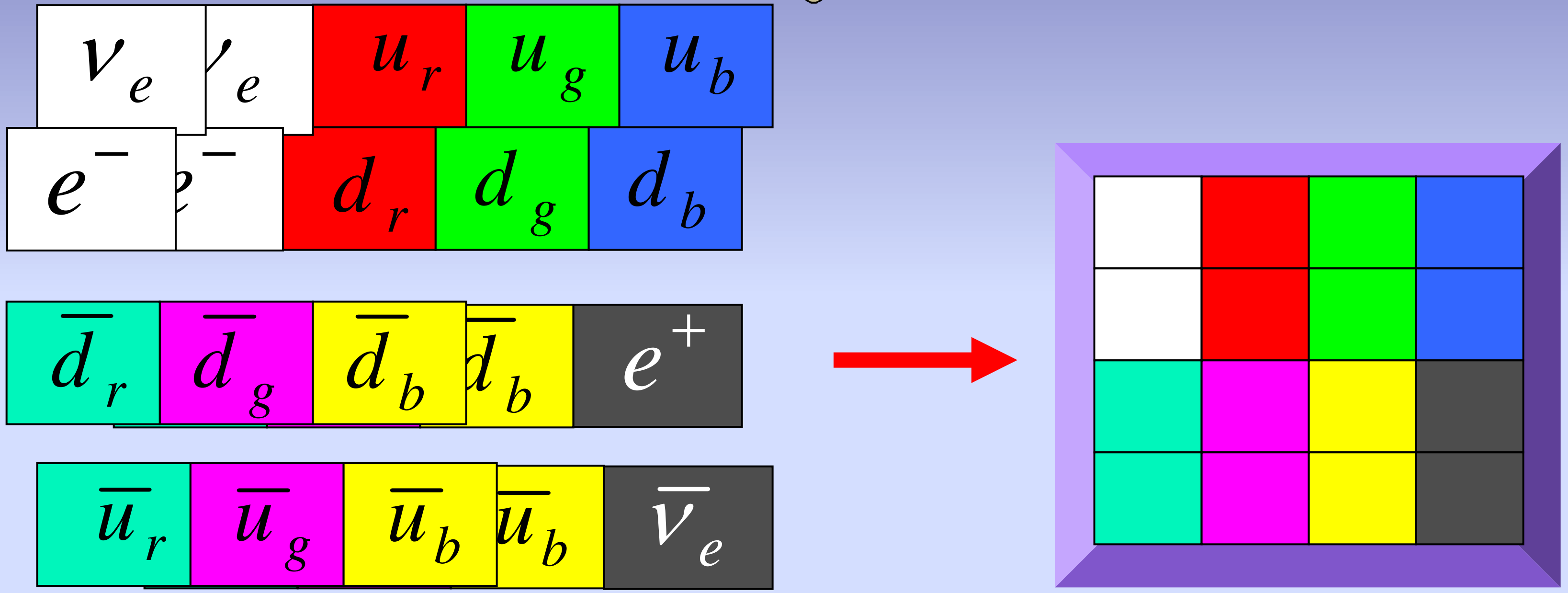
- Anomalies must always cancel out
  - whenever new forces or fermionic particles (new generations) are added to the scheme.

And, there is intrinsic beauty:

$$SU(3)\times SU(2)\times U(1)\rightarrow SU(5)\rightarrow SO(10)$$

Grand Unification

(left rotating)



ν_e ν_e u_r u_g u_b

e^- e^- d_r d_g d_b

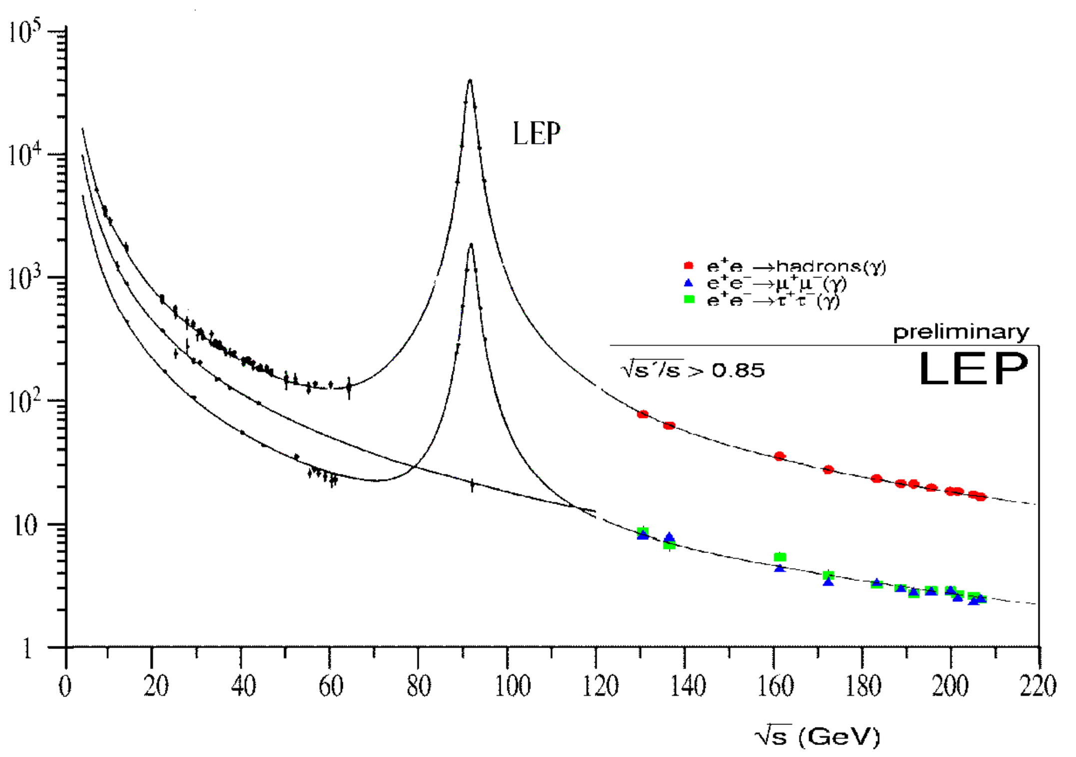
$\bar{d}_r$ $\bar{d}_g$ $\bar{d}_b$ $\bar{d}_b$ e^+

$\bar{u}_r$ $\bar{u}_g$ $\bar{u}_b$ $\bar{u}_b$ $\bar{\nu}_e$

× 3 generations

Who would have suspected such a powerful theory in the 1960s?

None of this could have been possible without the magnificent achievements of the experimental laboratories,
In particular CERN



During the most exciting periods when these discoveries were made, the CERN theory group was very strongly involved

What will the landscape of the 21st century be like ?

Will it be as beautiful as today’s or more beautiful?

Will it include super symmetry, or super strings?

Will it be a

THEORY of EVERYTHING

?

THANKS to CERN

Total cross sections