Quantum vacuum and electromagnetism

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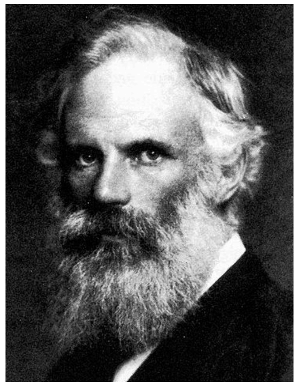
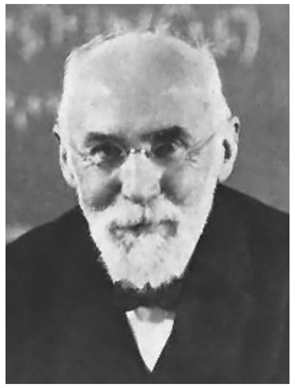
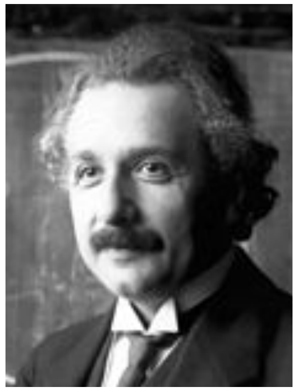
Prologue (I)

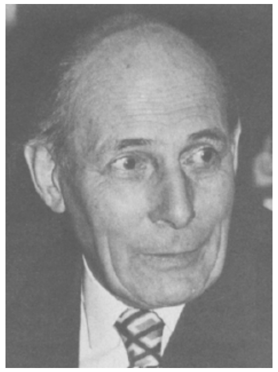




Maxwell's lucky strike

FitzGerald-Lorentz invariance ✓

field modes in quantum optics ✓

connection to high energy physics ?



Prologue (II)

beyond the electric field strength

$$E_S \simeq \frac{m^2c^3}{e\hbar} \simeq 5 \times 10^29\mathrm{W}/\mathrm{cm}^2$$

the vacuum is predicted to be nonlinear

Bohr, Sauter,
Heisenberg & Euler,
Schwinger ...

Maxwell Equations

0

E_S

electric field

linear

nonlinear

S.S. Bulanov et al., Phys.Rev.Lett. 104, 220404 (2010)

Prologue (III)

$$\Delta x \, \Delta p \geq \hbar/2$$

$$\Delta p \simeq mc \Rightarrow \Delta x \approx \frac{\hbar}{mc} = \lambda_{\mathrm{Compton}}$$

If – over a the distance of a Compton wavelength – the virtual particles are accelerated to their rest mass energy, they become real
pair production!

$$\boxed{eE \times \frac{\hbar}{mc} = mc^2}$$

Bohr (before 1931), Sauter 1931, Schwinger 1951

Warning!

VACUUM

Speculative!

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Regular Article

A sum rule for charged elementary particles

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The problem (I)

W. Heitler, "The quantum theory of radiation", p.113, 3rd edition, Oxford Univer
1954

We shall treat the polarization of the vacuum in detail in § 32, but the qualitative consequences are easily seen: A constant field merely leads to a constant polarization. The polarizability is field independent and thus all charges are changed by a universal constant factor (the 'dielectric constant' of the vacuum). Since there is no way of experimenting in an 'ideal vacuum' where this polarizability is absent, this effect is unobservable in principle (although the polarizability turns out to be infinite owing to the infinite number of pairs which contribute). An inhomogeneous field creates, in addition, a non-uniform polarization whose effects are observable (and finite). For example, an additional light wave will be scattered by the polarization dipoles, i.e. in the Coulomb field. Similarly, two light waves will be scattered by each other (§ 32).

The problem (II)

V. S. Weisskopf: Kongelige Danske Videnskabernes Selskab, Mathematisk-fysiske Meddelelser XIV, No.6, (1936)

Weisskopf's three problematic quantities

1.- ...
2.- ...
3.- A spatially and temporally constant and field independent electric and magnetic polarizability of the vacuum

These quantities relate to the field free vacuum.
It can be taken as self-evident that they can have no physical meaning.

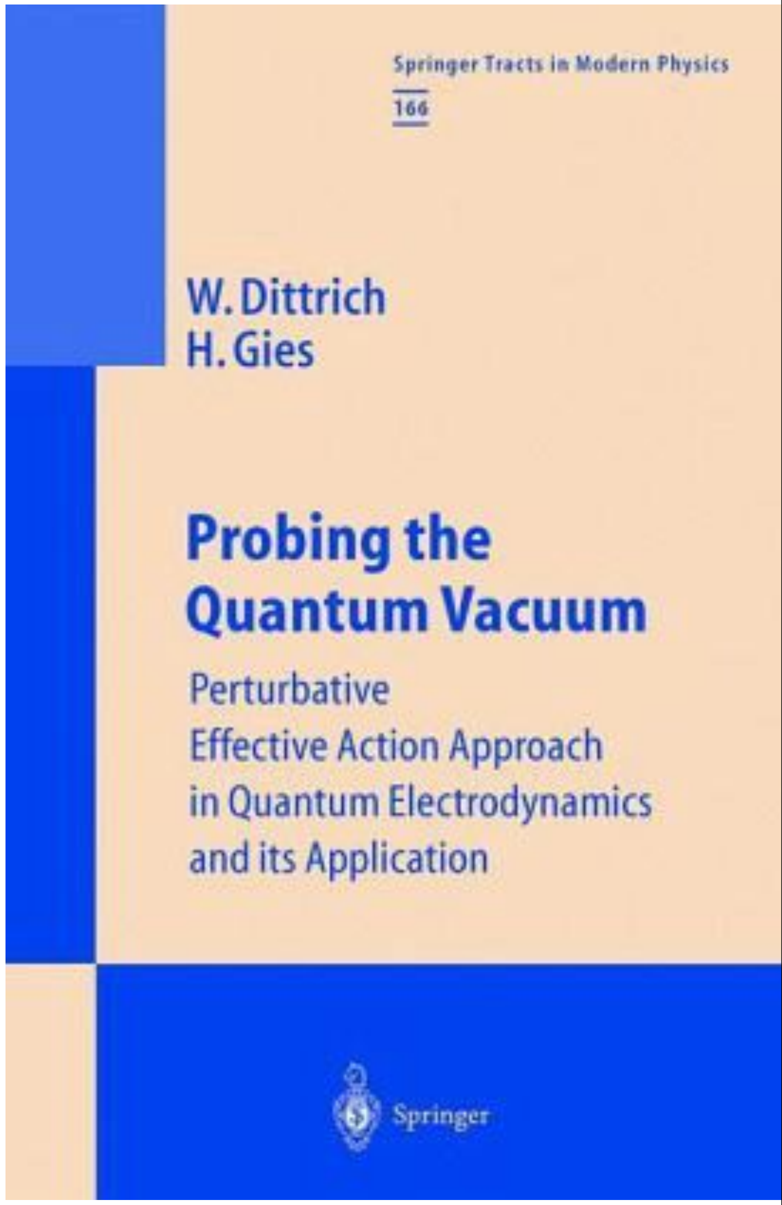
Probing the quantum vacuum

- Warning

$$c_{\mathrm{rel}} = \sqrt{\frac{E}{m}} \qquad\qquad c_{\mathrm{light}}$$

are not necessarily equivalent!

K. Scharnhorst, Phys. Lett. **B 236**, 354(1990)



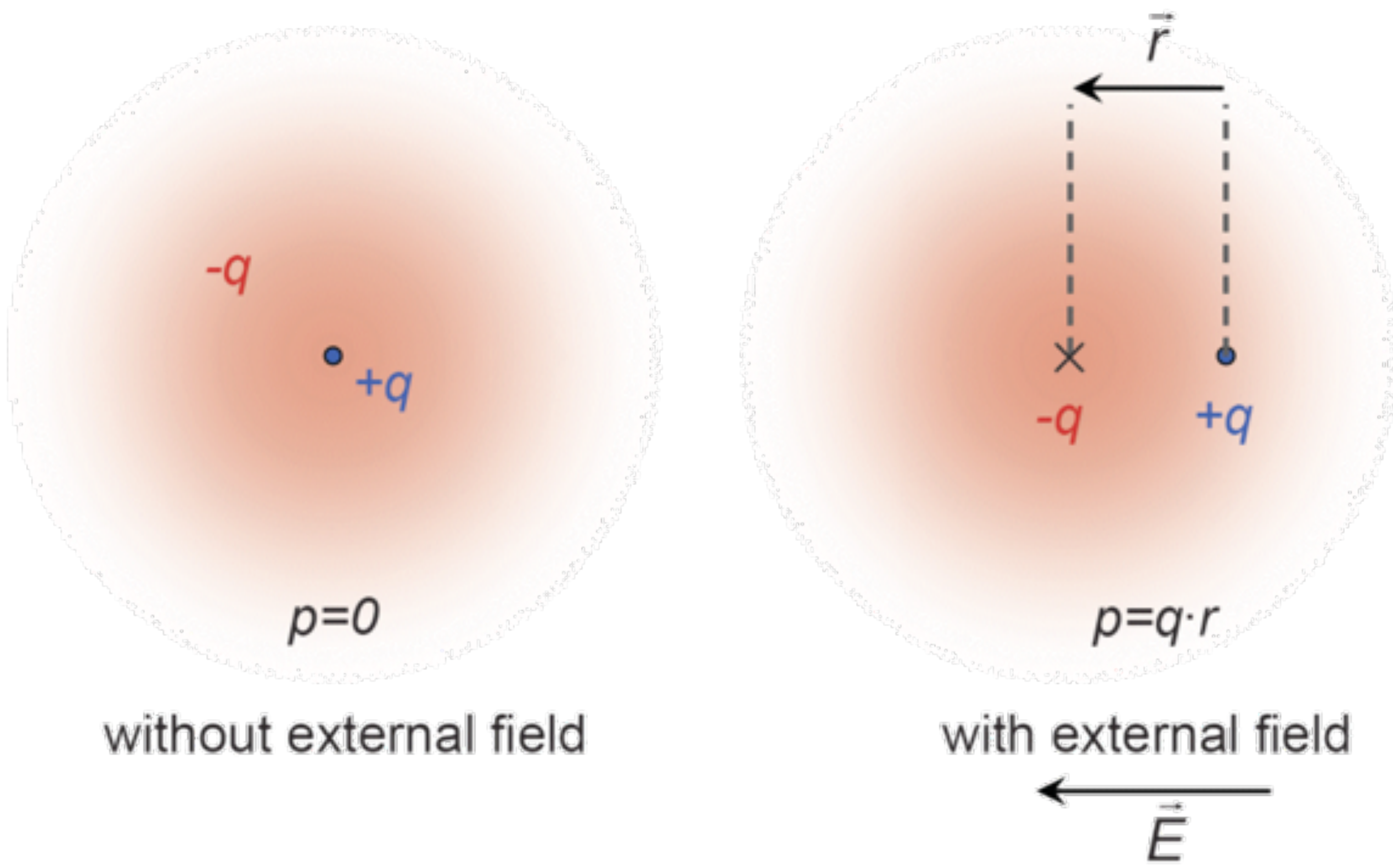
- We think of the vacuum as a dielectric and diamagnetic medium

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \equiv \mathbf{P}_0 + \mathbf{P}$$

$$\mathbf{H} = \frac{1}{\mu_0}\mathbf{B} - \mathbf{M} \equiv \mathbf{M}_0 - \mathbf{M}$$

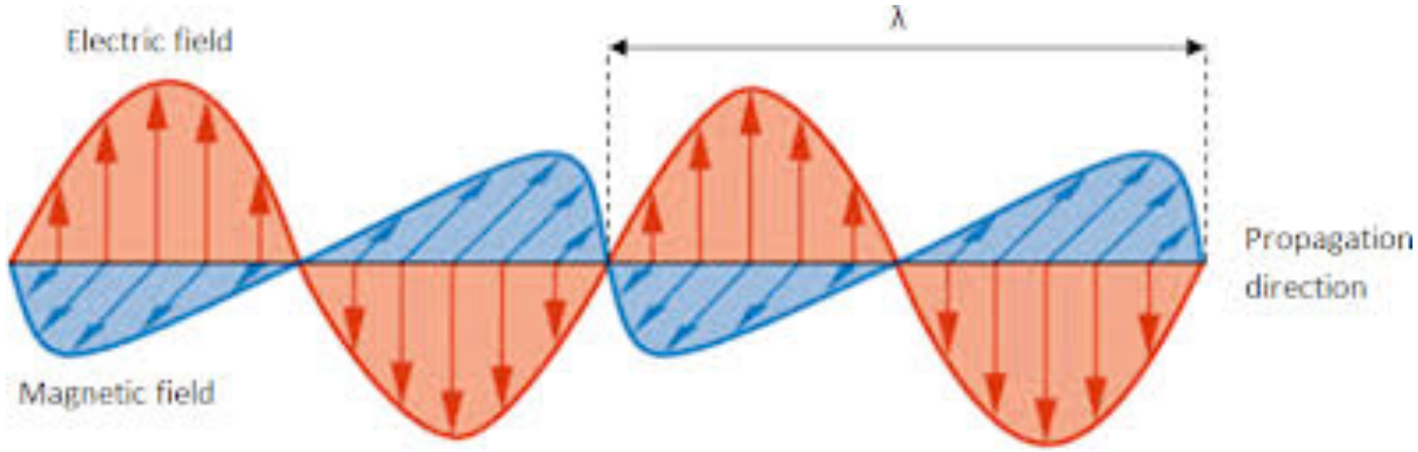
derive ε_0, μ_0 from properties of the vacuum

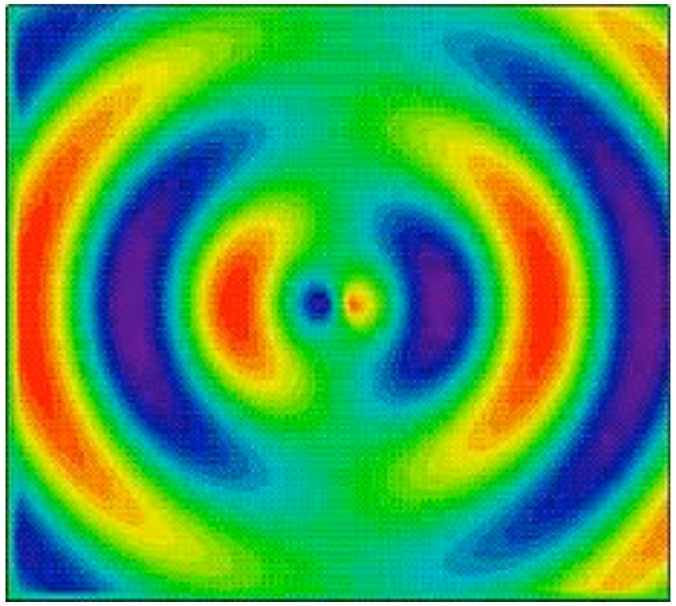
Dielectrics: the naive picture (I)

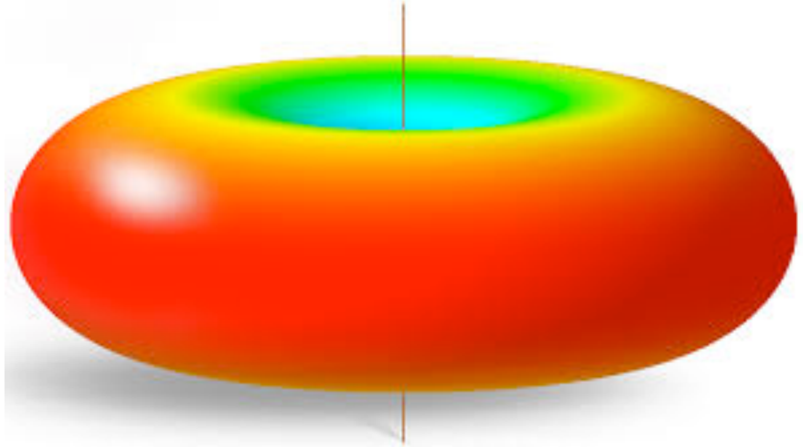


$$\text{polarization} = \frac{\text{dipole moment}}{\text{volume of dipole}}$$

Dielectrics: the naive picture (II)







The ether

- Absolute reference system
- Incompressible
- Huge stiffness
- Not opposing to the motion of bodily matter
- Experiments cannot detect the relative motion respect to the ether!

The Persistence of Ether

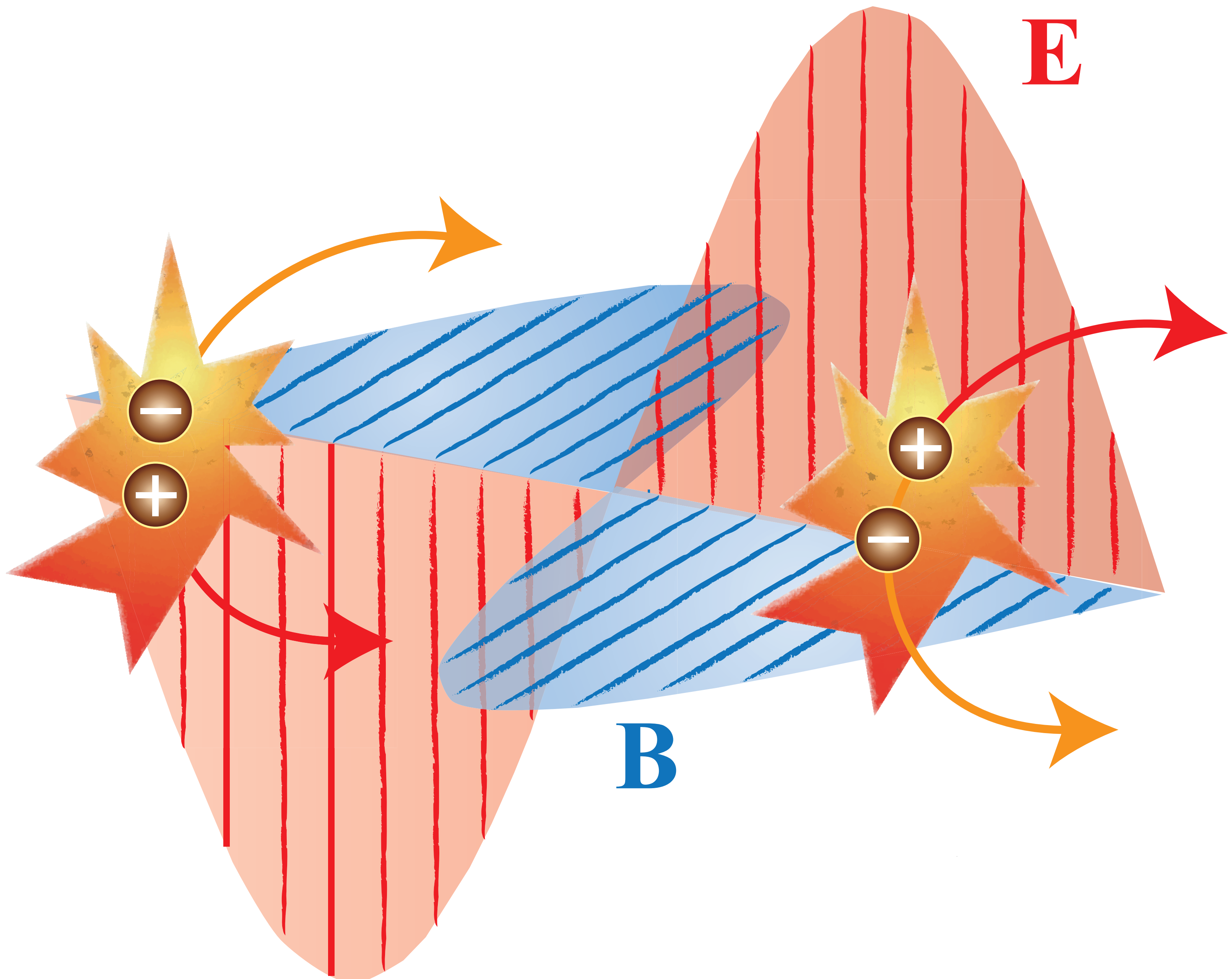
Frank Wilczek

Quite undeservedly, the ether has acquired a bad name. There is a myth, repeated in many popular presentations and textbooks, that Albert Einstein swept it into the dustbin of history. The real story is more complicated and interesting. I argue here that the truth is more nearly the opposite: Einstein first purified, and then enthroned, the ether concept. As the 20th century has progressed, its role in fundamental physics has only expanded. At present, renamed and thinly disguised, it dominates the accepted laws of physics. And yet, there is serious reason to suspect it may not be the last word.

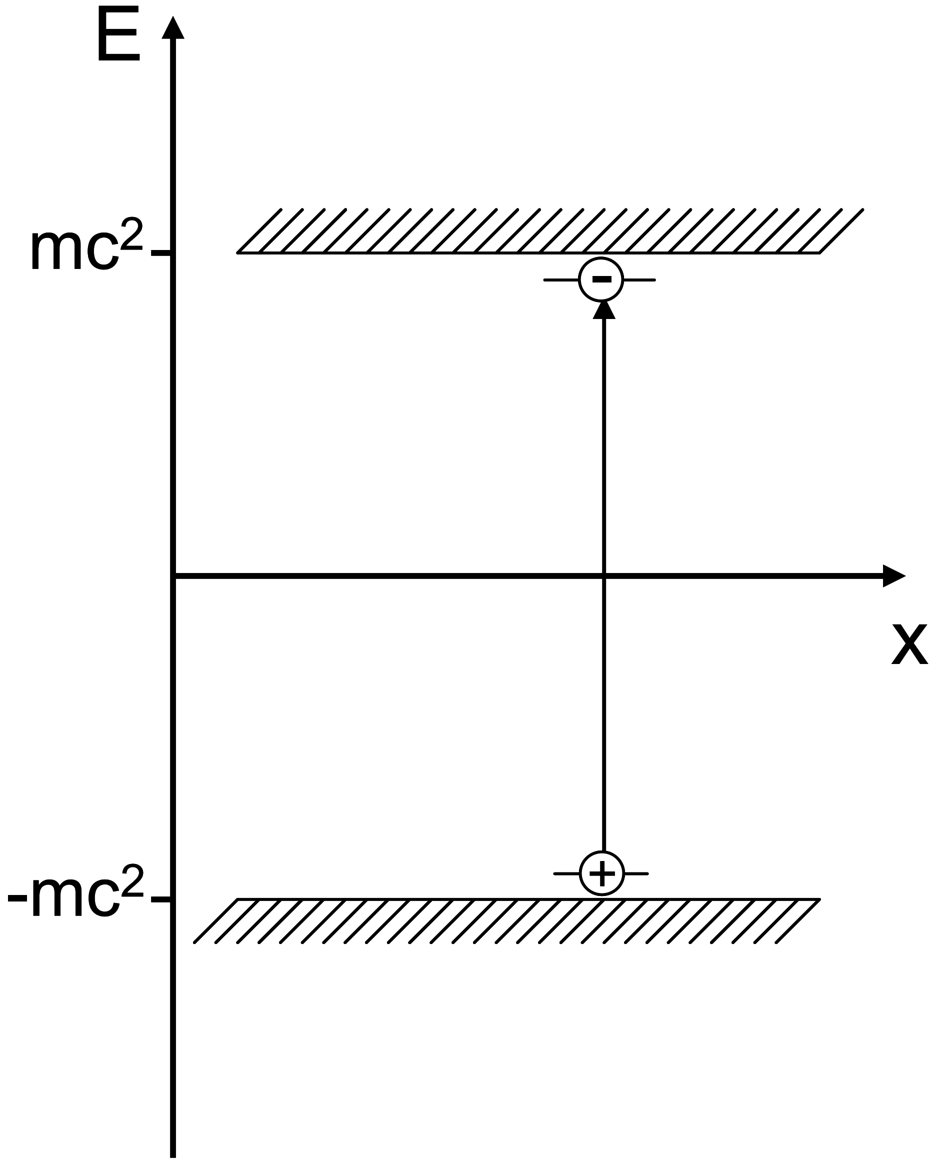
perimenter, who revived the idea that space was filled with a medium having physical effects in itself. His intuition led him to devise experiments looking

tual readjustments, the mathematics required to bring the equations of mechanics—that is, the motion of particles in response to given forces—into a form consistent with special relativity, is not hard. Einstein developed it swiftly and painlessly. The remaining foundational piece of classical physics, the theory of gravity, posed a greater challenge. Although Newton's extremely economical, and extensively battle-tested, formulations deployed forces depending on the present distance between particles, special relativity taught that observers moving relative to one another would have different notions of distance, and that

The quantum vacuum



The quantum vacuum (II)

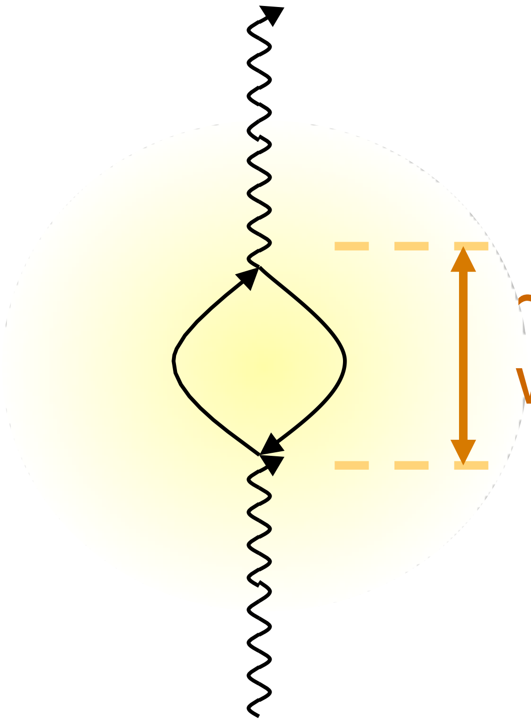


$$\langle d\rangle = e\langle x\rangle = \frac{e^2}{m\omega_0^2}\zeta E = \frac{e^2\hbar^2\zeta}{2m^3c_{\rm rel}^4}E$$

$$\hbar\omega_0 = 2mc_{\rm rel}^2$$

Transient creation of the dipole

The quantum vacuum (III)



$\frac{\hbar}{mc_{rel}}$

$$V = \eta \left(\frac{\hbar}{mc_{\rm rel}} \right)^3$$

The quantum vacuum (IV)

$$P_0 = \frac{d}{V} = \frac{e^2 \zeta}{2 c_{\mathrm{rel}} \hbar \eta} E$$

Mass drops out!

al... ementary ... ontribute?

determine number of elementary particles (discovered and undiscovered)

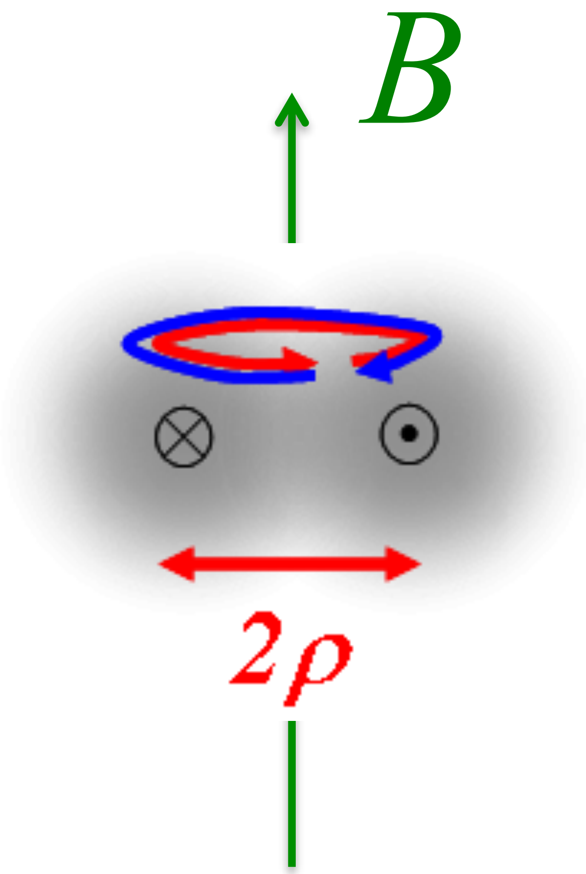
$e \quad \mu \quad \tau$

$(u \; d \; c \; s \; t \; b \;) * 3$

$W^{+/-}$ ...

$$\varepsilon_0 = \frac{\zeta}{2 c_{\mathrm{rel}} \hbar \eta} \left(\sum_{j}^{\mathrm{e.\,p.}} q_j^2 \right)$$

The magnetic response



$$d_{\mathrm{magn}} = 2iA = 2(e\nu)(\pi\varrho^2) = \frac{e^2}{m}\varrho^2 B$$

$$\varrho^2 = \xi\left(\frac{\hbar}{m_j c_{\mathrm{rel}}}\right)^2$$

$$M_0 = \frac{\xi c_{\mathrm{rel}} e^2}{\eta\hbar}$$

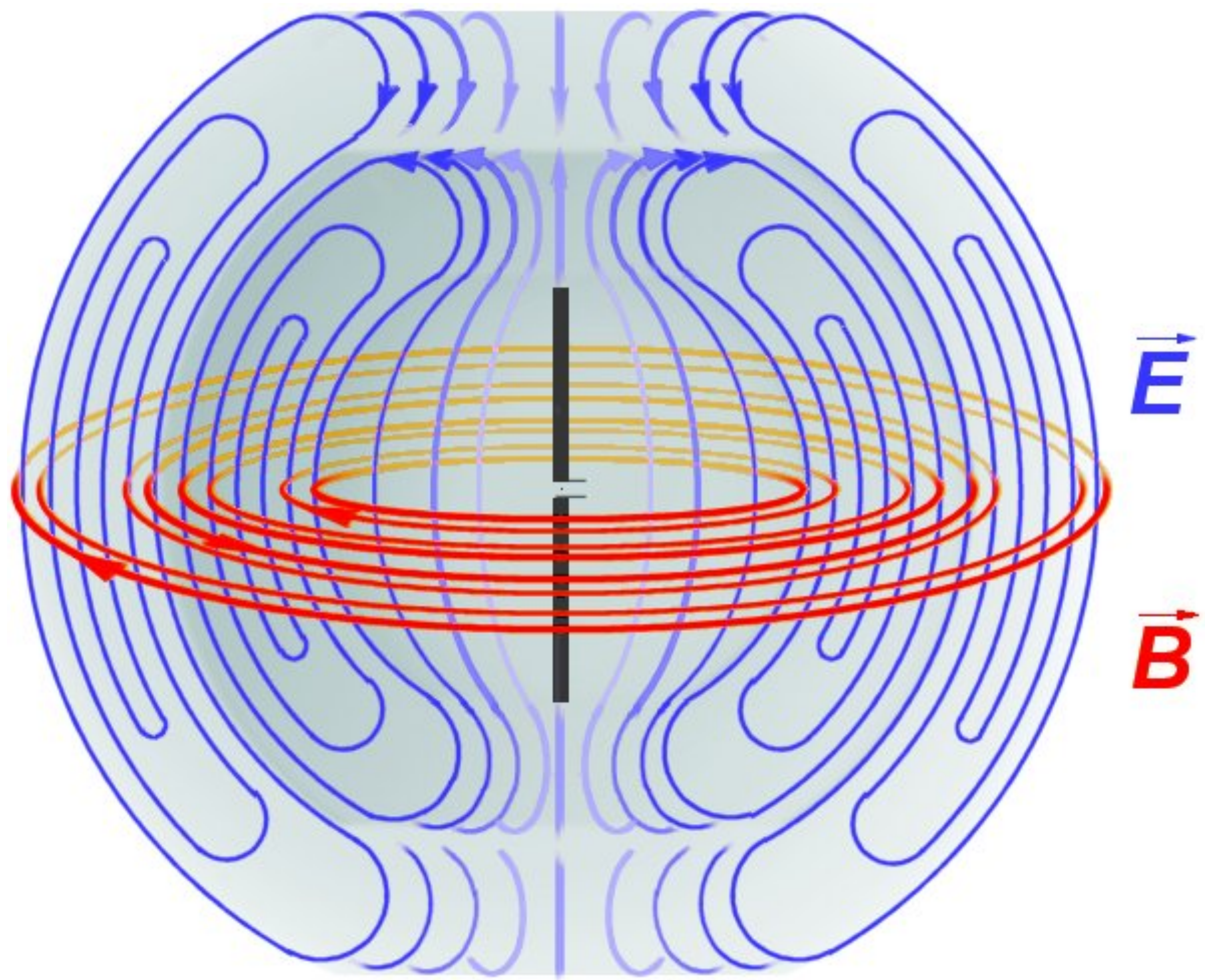
$$\frac{1}{\mu_0} = \frac{\xi c_{\mathrm{rel}}}{\eta\hbar}\left(\sum_j^{\mathrm{e.\,p.}} q_j^2\right)$$

Vacuum impedance

Vacuum impedance determines the power radiated by a dipole

$$P = e^2\omega^2 \left(\frac{d}{\lambda}\right)^2 \frac{\pi}{3} Z_0$$

$$Z_0 = 376.7 \text{ Ohms}$$



Vacuum impedance

$$c_{\rm light} = 1/\sqrt{\varepsilon_0\mu_0} \quad \Rightarrow \quad c_{\rm light} = c_{\rm rel}\sqrt{\frac{2\xi}{\zeta}}$$

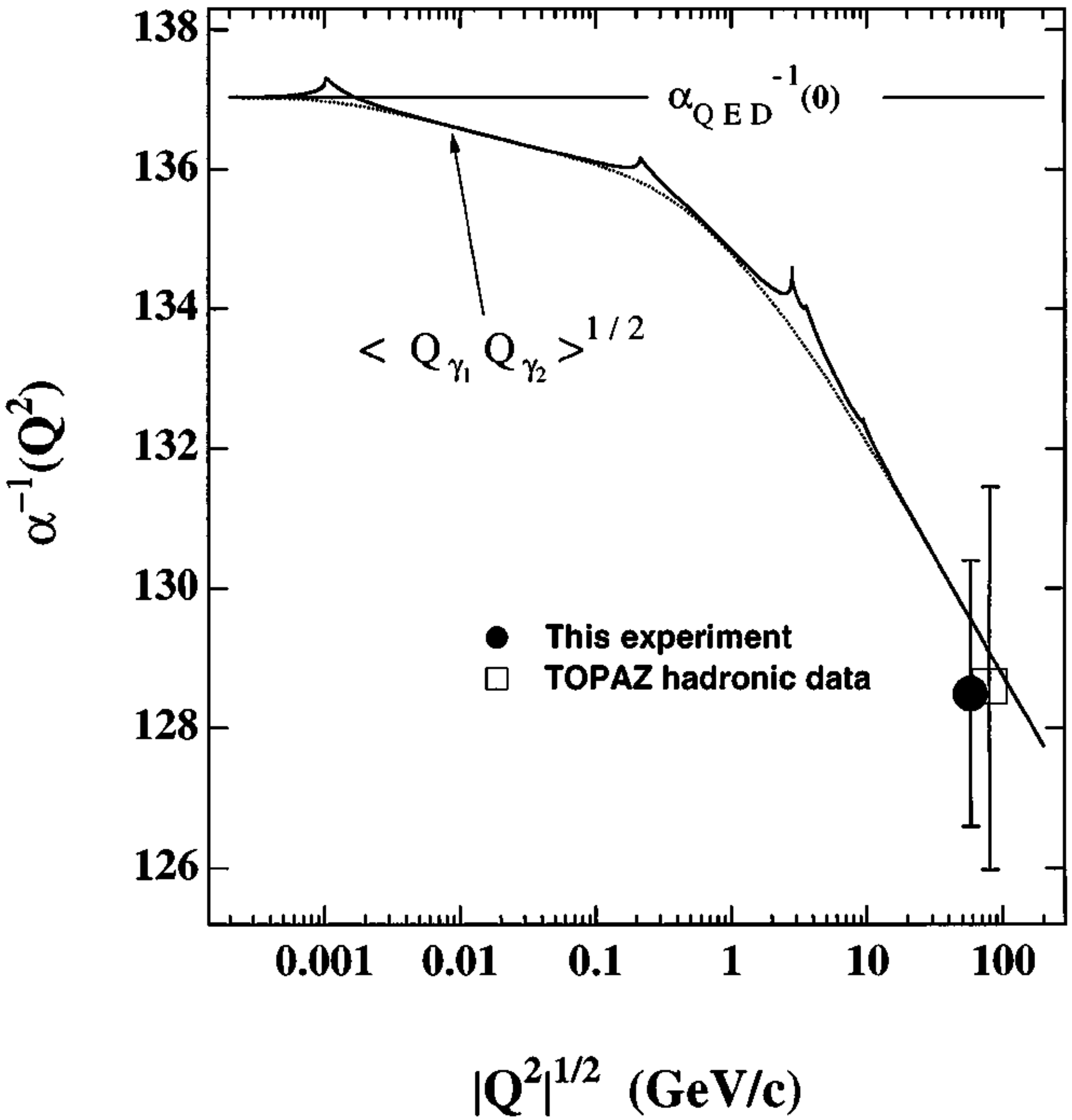
$$\frac{\zeta}{\xi} = 2$$

$$Z_0 = \frac{2\eta\hbar}{\zeta}\left(\sum_j^{\rm e.\,p.} q_j^2\right)^{-1} = 8218[\Omega]\frac{\eta}{\zeta}\left(\sum_j^{\rm e.\,p.}\frac{q_j^2}{e^2}\right)^{-1}$$

$$\boxed{\sum_j^{\rm e.\,p.}\frac{q_j^2}{e^2} = \frac{2\hbar}{e^2 Z_0\zeta} = 21.82\frac{\eta}{\zeta}}$$

$$\eta \simeq 0.48 - 2.06$$

The running fine structure constant



$$\alpha = \frac{e^2}{4\pi c\hbar\epsilon_0}$$

$$\alpha_0^{-1} = 137.04 = \text{constant} \sum_j^{\text{e. p.}} \frac{q_j^2}{e^2}$$

$$\alpha_{58\,\text{GeV}}^{-1} = 128.5 \pm 2.5$$

$$= \text{constant} \sum_j^{\text{e. p.}>58\,\text{GeV}} \frac{q_j^2}{e^2}$$

The running fine structure constant

$$\frac{\alpha_0^{-1}}{\alpha_{58\,\mathrm{GeV}}^{-1}} = \frac{\sum_{\mathrm{all}}}{\sum_{>58\,\mathrm{GeV}}} = \frac{137.04}{128.05 \pm 2.5}$$

$$\sum_{\mathrm{all}} = 104 \begin{cases} +43 \\ -24 \end{cases}$$

Conclusions

• Our simple model predicts a finite number of charged elementary particles and that it relates this number to low-energy properties of the electromagnetic field

• The value predicted by the model is determined by the relative properties of the electric and magnetic interaction of light with the quantum vacuum and is independent of the number of elementary particles.

• We have shown an intimate relationship between the properties of the quantum vacuum and the constants in Maxwell's equations.

"It is deplorable that fewer and fewer students nowadays study Heitler's classical treatise on the quantum theory of radiation. As a result, we see a number of sophisticated, yet uneducated, theoreticians who are conversant in LSZ formalism of Heisenberg field operators but do not know why an excited atom radiates”