



Particle physics

International teachers program

July 2018

part II
b&wf II

European Organisation for Nuclear Research

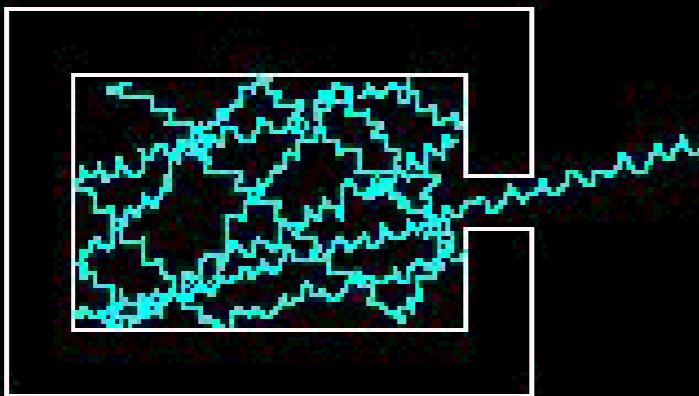
„Magic is not happening at CERN, magic is explained at CERN“ - Tom Hanks



Quanta - Black Body Radiation



Max Planck: 1900

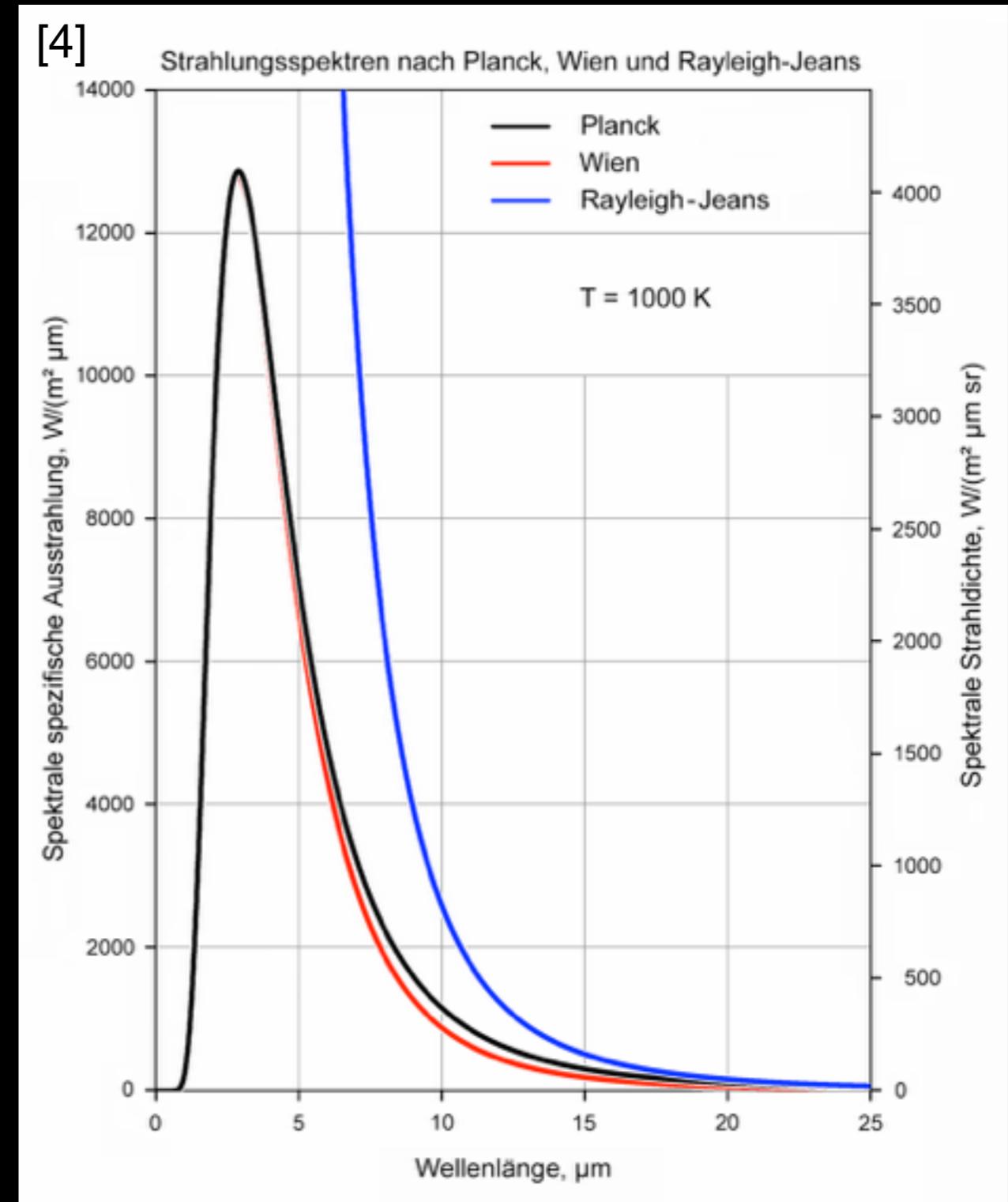


- Black body radiation only explicable introducing energy-quanta

- Oscillators in cavities (walls) will radiate energy as $\varepsilon = h\nu$
- Planck's law:

$$E(\nu, T) = \frac{h\nu}{e^{(h\nu/kT)} - 1}$$

- new fundamental constant: **h**

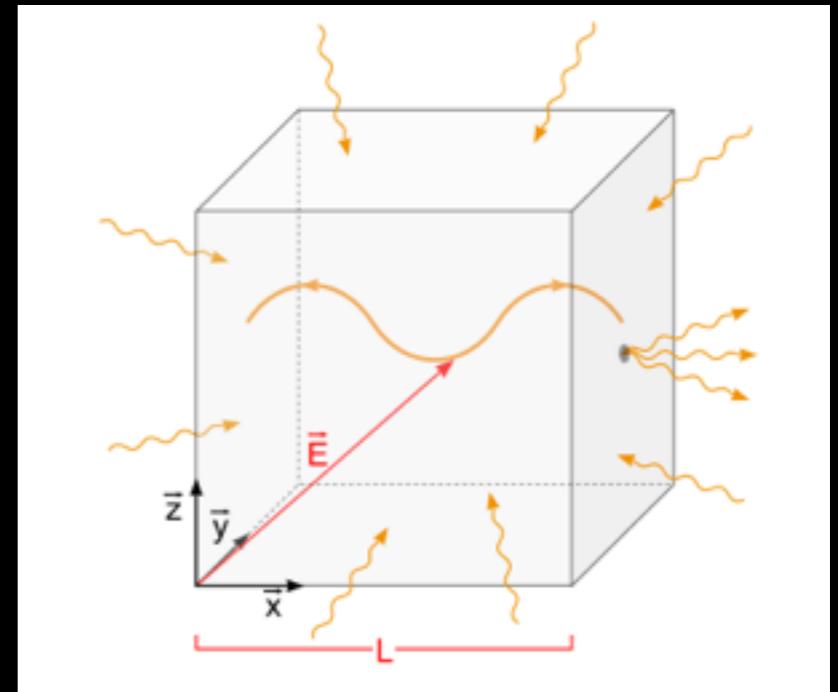


Plank's law - part II

- Standing em waves in box
 - boundary condition: knots must be at the wall

Density of allowed wave modes per frequency interval:

$$g(\nu)d\nu = \frac{8\pi}{c^3}\nu^2d\nu$$



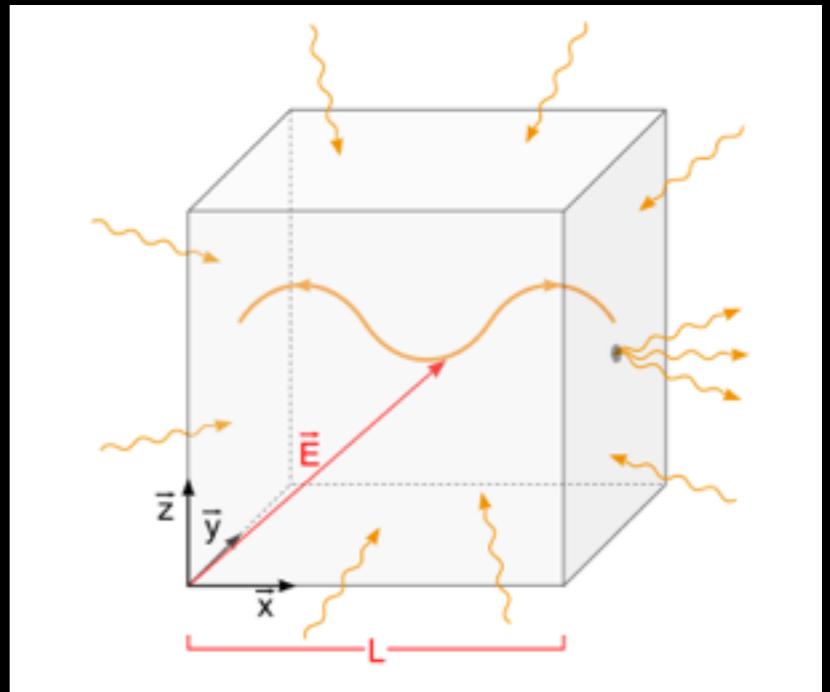
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$$g(\nu)d\nu = \frac{8\pi}{c^3}\nu^2d\nu$$



Every mode = harmonic oscillator

Thermal equilibrium \rightarrow mean energy of every oscillator = kT

Energy density in frequency interval = density of allowed states * mean energy:

$$U(\nu, T)d\nu = \frac{8\pi}{c^3}kT\nu^2d\nu$$

Rayleigh - Jeans

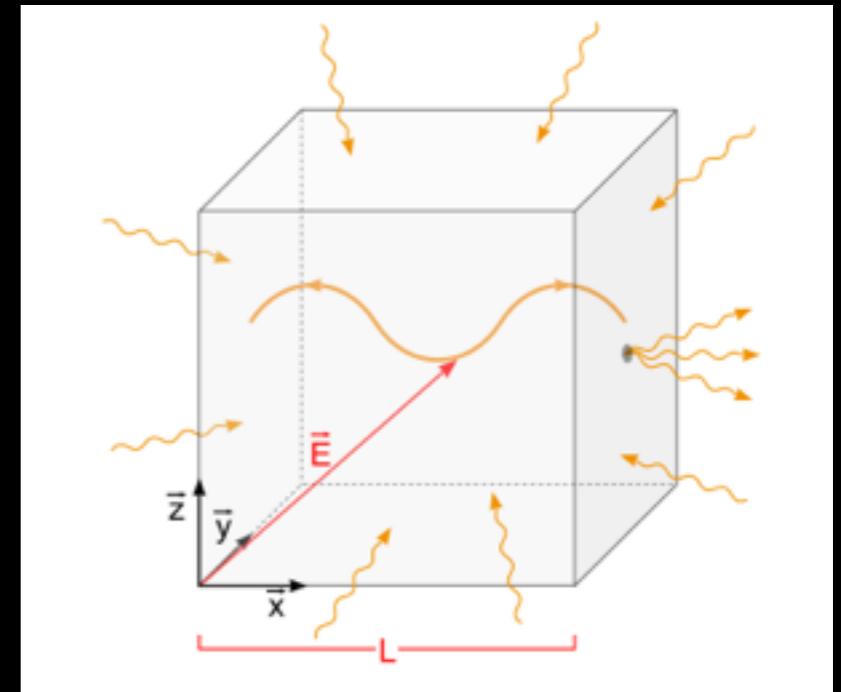
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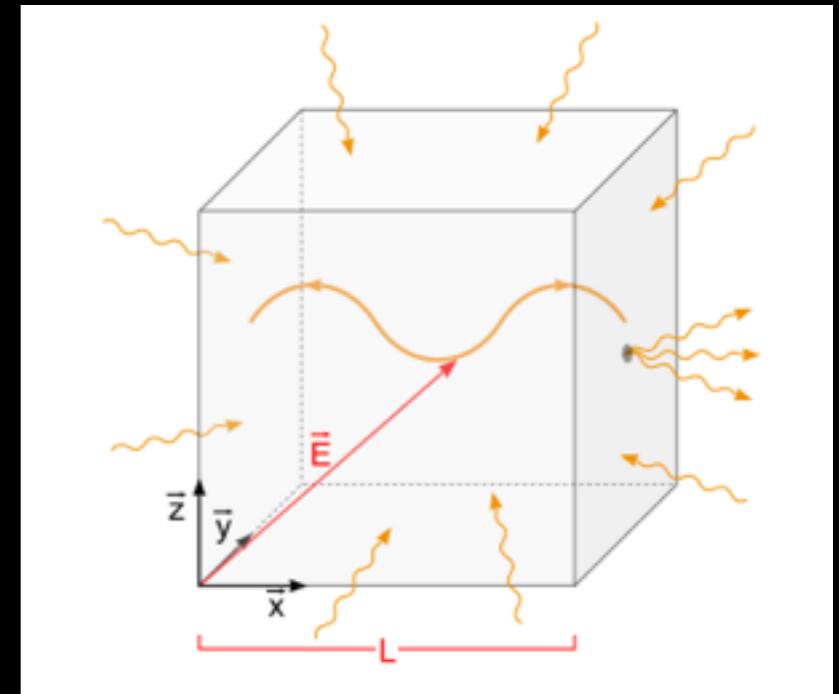
UV divergent: every mode has mean energy kT , but infinite amount of modes for high frequencies!!

Plank's law - part II

$$U(\nu, T)d\nu = \frac{8\pi}{c^3} kT\nu^2 d\nu \quad \text{Rayleigh - Jeans}$$

UV divergent: every mode has mean energy kT , but infinite amount of modes for high frequencies!!

- Postulate: change of energy only allowed in units of h
- Oscillators can only have energy states in integer multiples of $h\nu$!
- Minimum energy required: $h\nu$
- If $h\nu > kT$: oscillators will not radiate energy!
 - This explains the drop in the Energy spectrum for high frequencies
- From statistical thermodynamics follows



$$E(\nu, T) = \frac{h\nu}{e^{(h\nu/kT)} - 1}$$

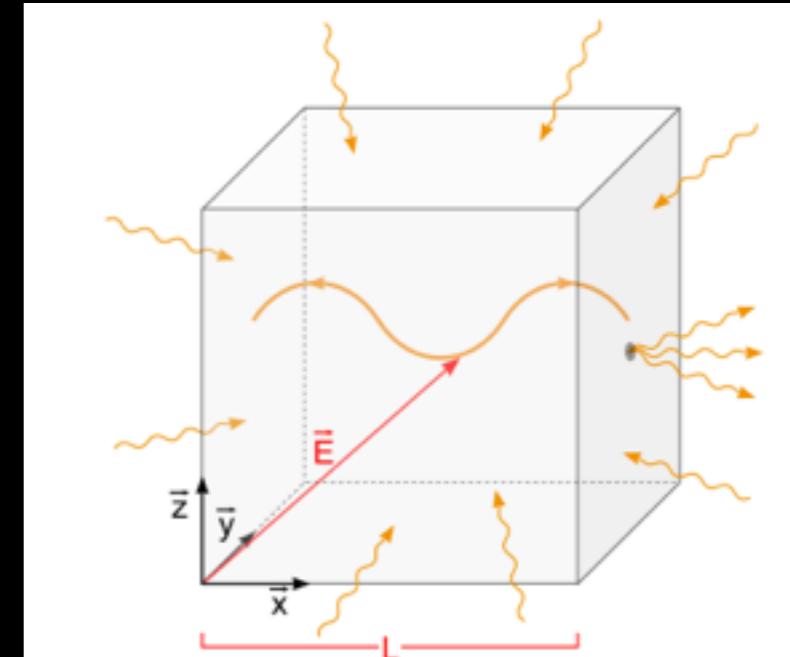
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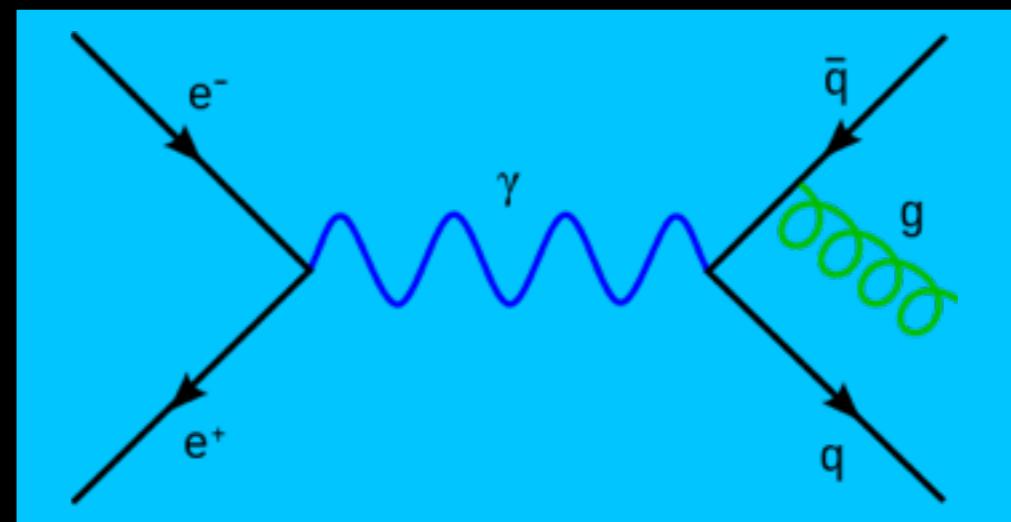
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$$E(\nu, T) = \frac{h\nu}{e^{(h\nu/kT)} - 1}$$

- Plank derived this description of the Energy spectrum from phenomenological observations. He then derived it using the Quantum principle within few months.

QFT & ,second quantization‘

- Second quantization:
 - Previously (Schrödinger): only observables are quantized (energy, momentum, ..)
 - Now: also fields quantized
 - => field quanta = gauge bosons, e.g. Photon for em field
- Originally introduced to handle many body problems
 - Instead of asking: In which state is a given particle
 - Wrong question because particles might be indistinguishable!
 - Now asking: how many particles are in a given state!
- Consequences:
 - Interactions are mediated by gauge bosons => virtual particles
 - Description of antiparticles with creation and annihilation operators
 - Description of ‘Vacuum fluctuations’ as lowest energy states of quantized fields



Are there any other
forces?
Jolcszi

How are protons and neutrons glued together?



- Force that is
 - Stronger than Coulomb repulsion
 - Short ranged (determines size of nucleus)

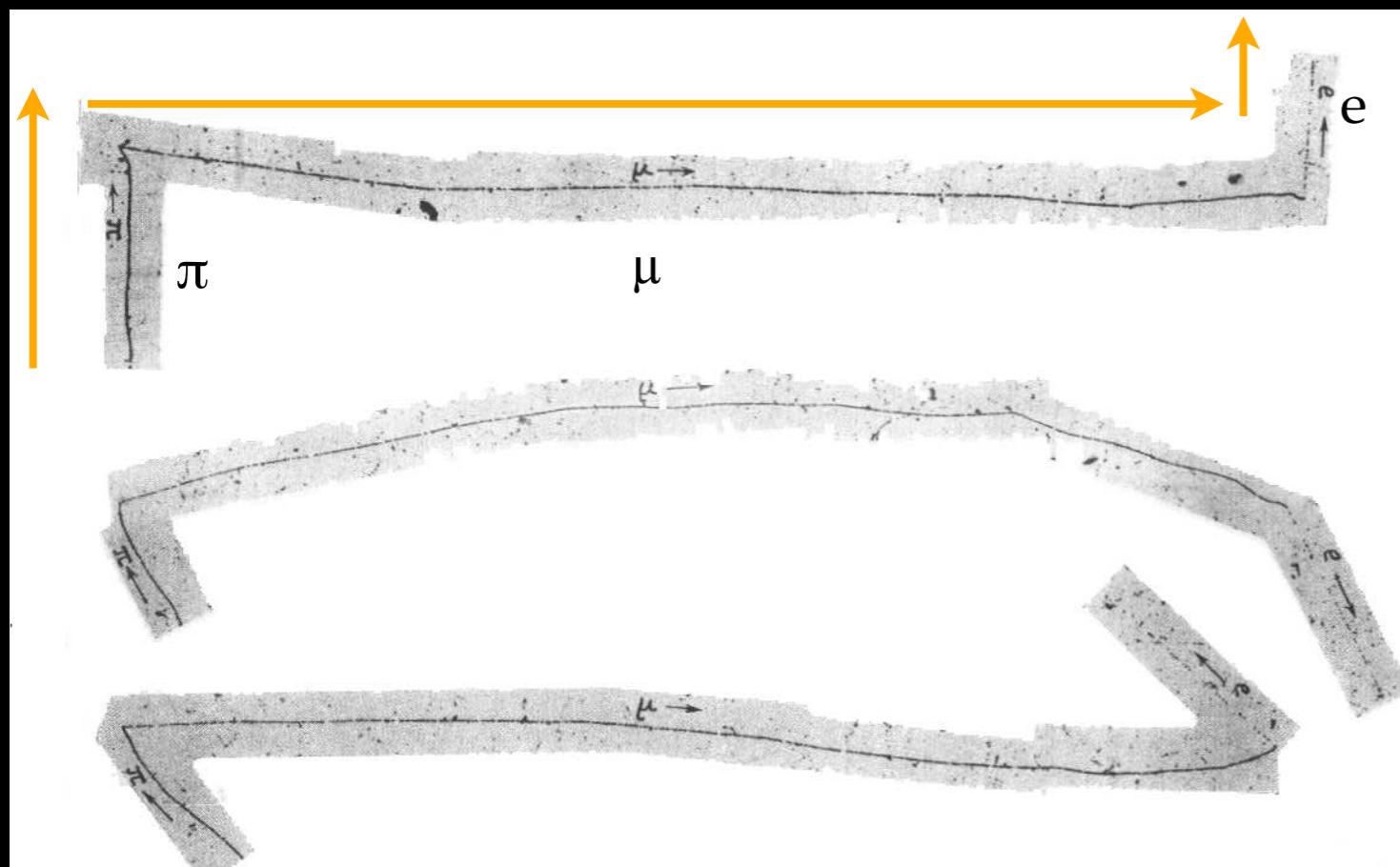
Yukawa: 1935

- Exchange of heavy particles: **Pions**
 - Predicted by Yukawa:

$$V_{\text{Coulomb}} = -g^2 \frac{1}{r}$$
$$V_{\text{Yukawa}} = -g^2 \frac{e^{-mr}}{r}$$

- Discovered in cosmic rays:

Powell / Perkins: 1947



$$M_{\text{Pion}} = 140 \text{ MeV}$$

$$\text{Range of force: } \Delta E \cdot \Delta t \approx \frac{\hbar}{2}$$

$$\sim 10^{-15} \text{ m}$$

- Small compared to radius of nuclei
- Explains const. binding energy per nucleon!

The world of particles ~1950



- Elementary particles: Elektron, Muon, Proton, Neutron, Photon, Pion
 - (Neutrino predicted in order to explain beta decay)
 - Concept of anti-particles
- Forces: electromagnetism, strong force
 - Interaction mediated via exchange particles
- Quantum mechanics & quantum field theory developed
- Complete description of: Electromagnetism using QED

more
elementary particles
GEMENEGOLD BOLLEFRES

Hadrons

- 1935: Pion predicted by Yukawa as exchange particle of strong force
 - Mass predicted from radius of nuclei: 100 - 200 MeV
- Frenetic search in cosmic rays (at high altitudes)
 - Discovery: 1947 (Powell / Perkins) (at the Pic du Midi / Pyrenees)
 - During this search μ discovered
- 1948: Pions artificially created using accelerators
 - Cyclotron at Berkley

Seek, and you shall find

- Fast development in accelerator technique
 - 1938: 80 keV - 1939: 19 MeV - 1946: 195 MeV - 1947: 6 GeV - 1960: 30 GeV
- Discovery of new particles
 - 'Resonances' in invariant mass spectrum of detected particles

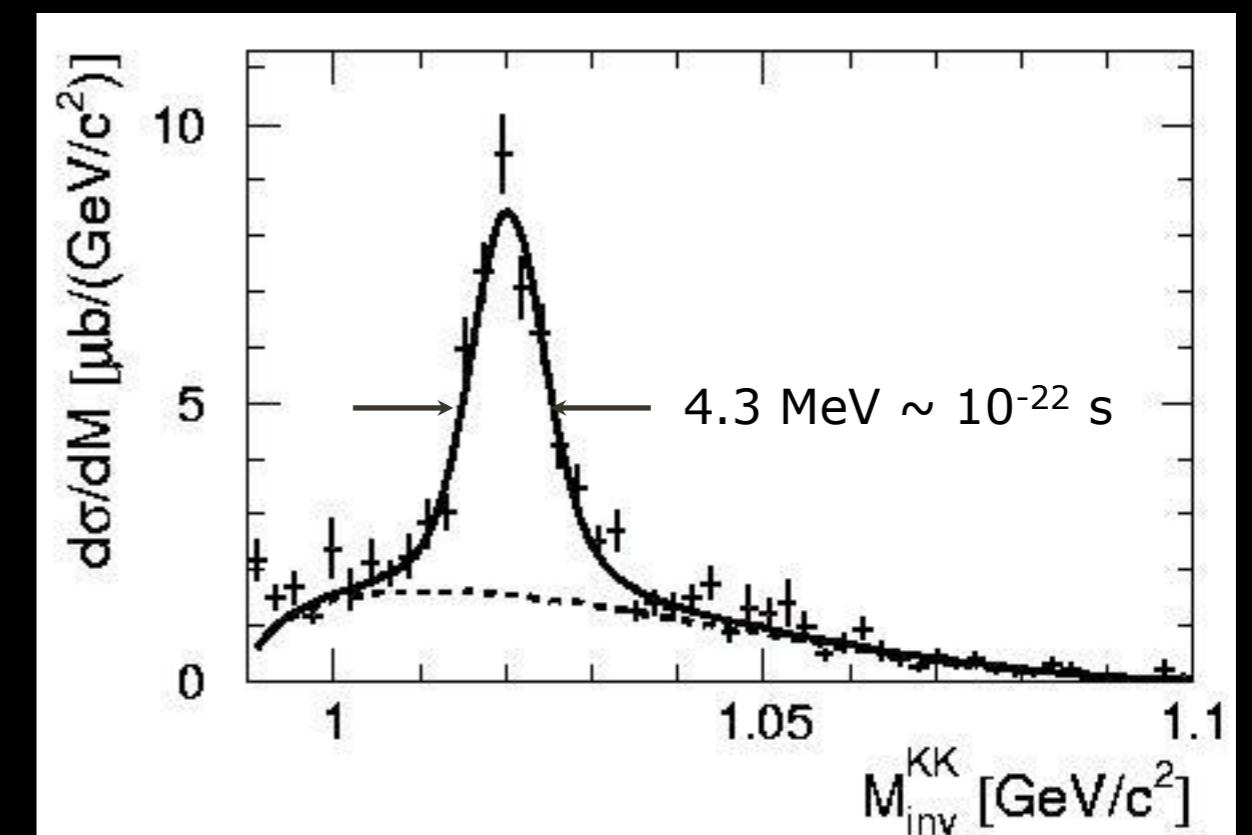
- Invariant mass M:

$$E^2 = (mc^2)^2 + \vec{p}^2 c^2$$

$$(mc^2)^2 = E^2 - \vec{p}^2 c^2$$

$$\rightarrow (Mc^2)^2 = \sum (E)^2 - \left(\sum \vec{p}c \right)^2$$

invariant under particle transformation!

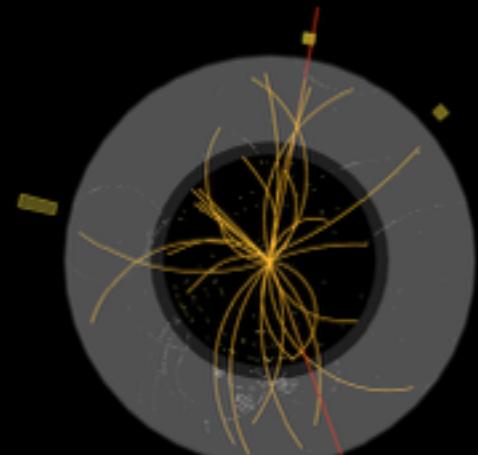


Intermezzo - Statistics & Particle Physics



Run: 154822, Event: 14321500

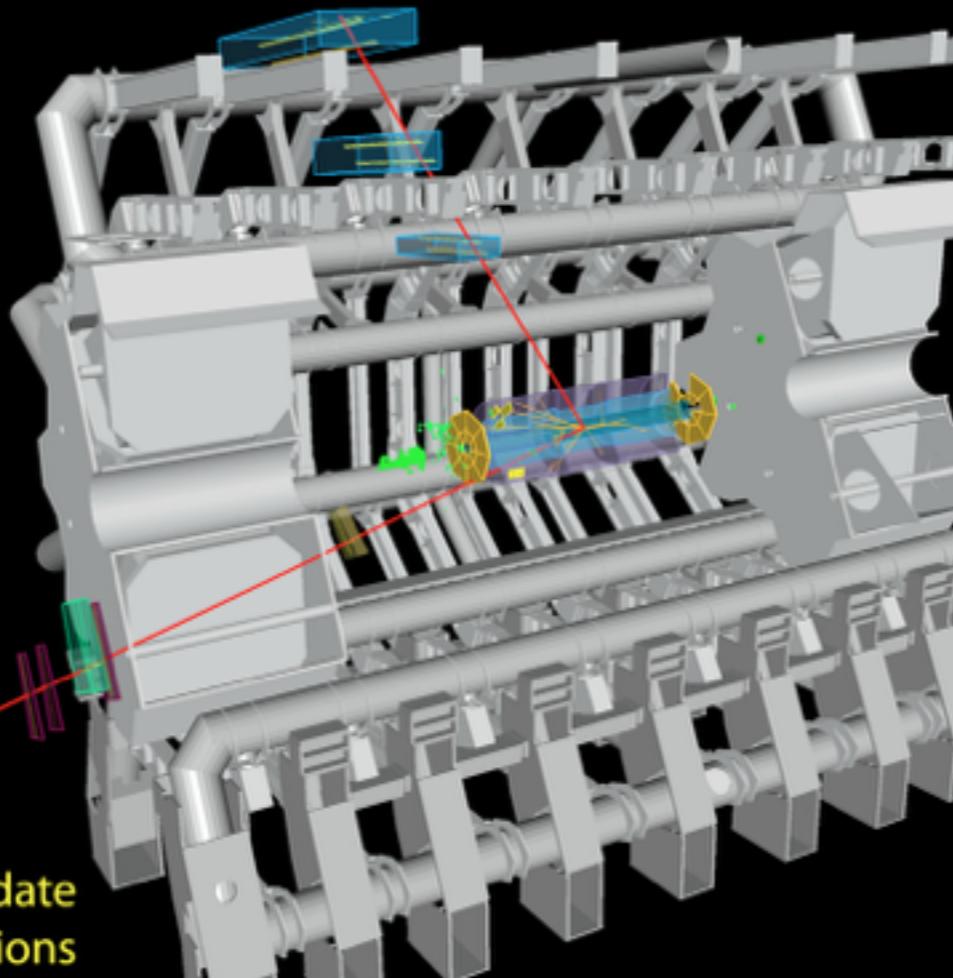
Date: 2010-05-10 02:07:22 CEST



$p_t(\mu^-) = 27 \text{ GeV}$ $\eta(\mu^-) = 0.7$
 $p_t(\mu^+) = 45 \text{ GeV}$ $\eta(\mu^+) = 2.2$

$M_{\mu\mu} = 87 \text{ GeV}$

Z \rightarrow $\mu\mu$ candidate
in 7 TeV collisions



Intermezzo - Statistics & Particle Physics

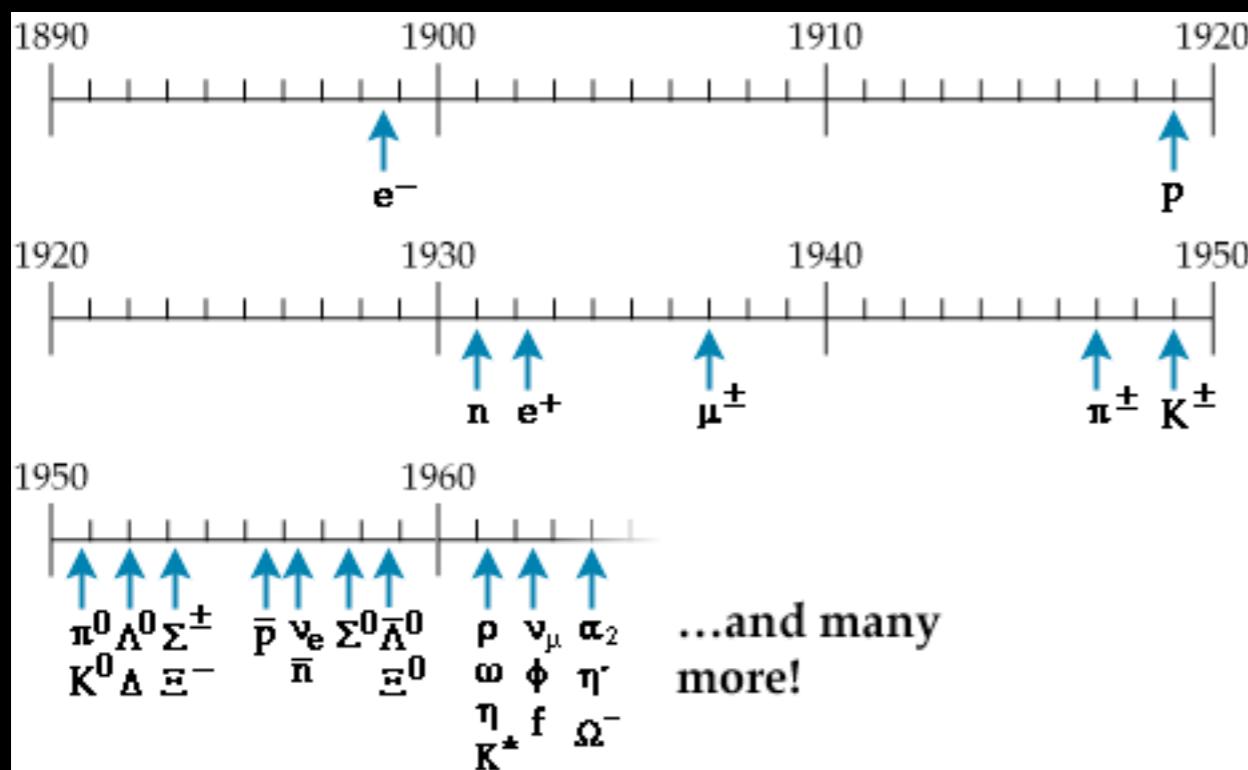


ATLAS
EXPERIMENT

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST

Seek, and you shall find more than expected

- Fast development in accelerator technique
 - 1938: 80 keV - 1939: 19 MeV - 1946: 195 MeV - 1947: 6 GeV - 1960: 30 GeV
- Discovery of many new particles ⇒ „particle zoo“



How to order this chaos?

Baryons

p^\pm (938.3), n (939.6), $N(1440)$, $N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$, $N(1720)$, $N(1875)$, $N(1900)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$, $\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$, $\Delta(2420)$, $\Lambda(1116)$, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$, $\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$, $\Lambda(2110)$, $\Lambda(2350)$, $\Sigma^+(1189)$, $\Sigma^0(1193)$, $\Sigma^-(1197)$, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$, $\Sigma(1750)$, $\Sigma(1775)$, $\Sigma(1915)$, $\Sigma(1940)$, $\Sigma(2030)$, $\Sigma(2250)$, $\Xi^0(1315)$, ...

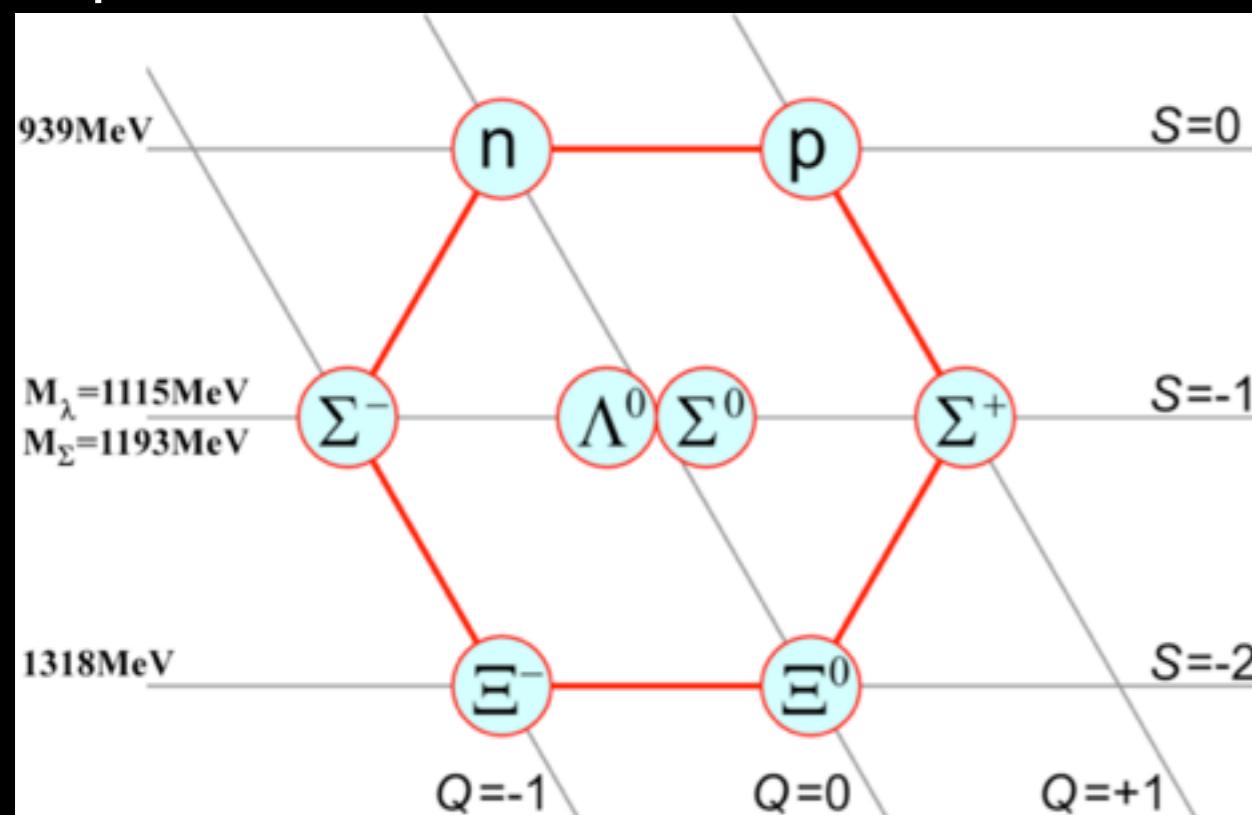
Mesons

π^\pm (139.6), π^0 (135.0), η (547.9), σ (400-550), ρ (770), ω (782.7), η' (957.8), f_0 (990), a_0 (980), ϕ (1019), h_1 (1170), b_1 (1229), a_1 (1230), f_2 (1275), f_1 (1282), η (1295), π (1300), a_2 (1318), f_0 (1370), π_1 (1400), η (1409), f_1 (1426), ω (1400-1450), a_0 (1474), ρ (1465), η (1476), f_0 (1505), f'_2 (1525), π_1 (1662), η_2 (1617), ω (1670), ω_3 (1667), π_2 (1672), ϕ (1680), ρ_3 (1689), ρ (1720), f_0 (1720), π (1812), ϕ_3 (1854), π_2 (1895), f_2 (1944), f_2 (2011), a_4 (1996), f_4 (2018), ϕ (2175), f_2 (2297), f_2 (2339), K^\pm (493.7), K^0 (497.6), K^0_S , K^0_L , $K^*(891.7)$, K_1 (1272), K_1 (1403), $K^*(1414)$, K^*_0 (1425), K^*_2 (1426), $K^*(1717)$, K_2 (1773), K^*_3 (1776), K_2 (1816), K^*_4 (2045), ...

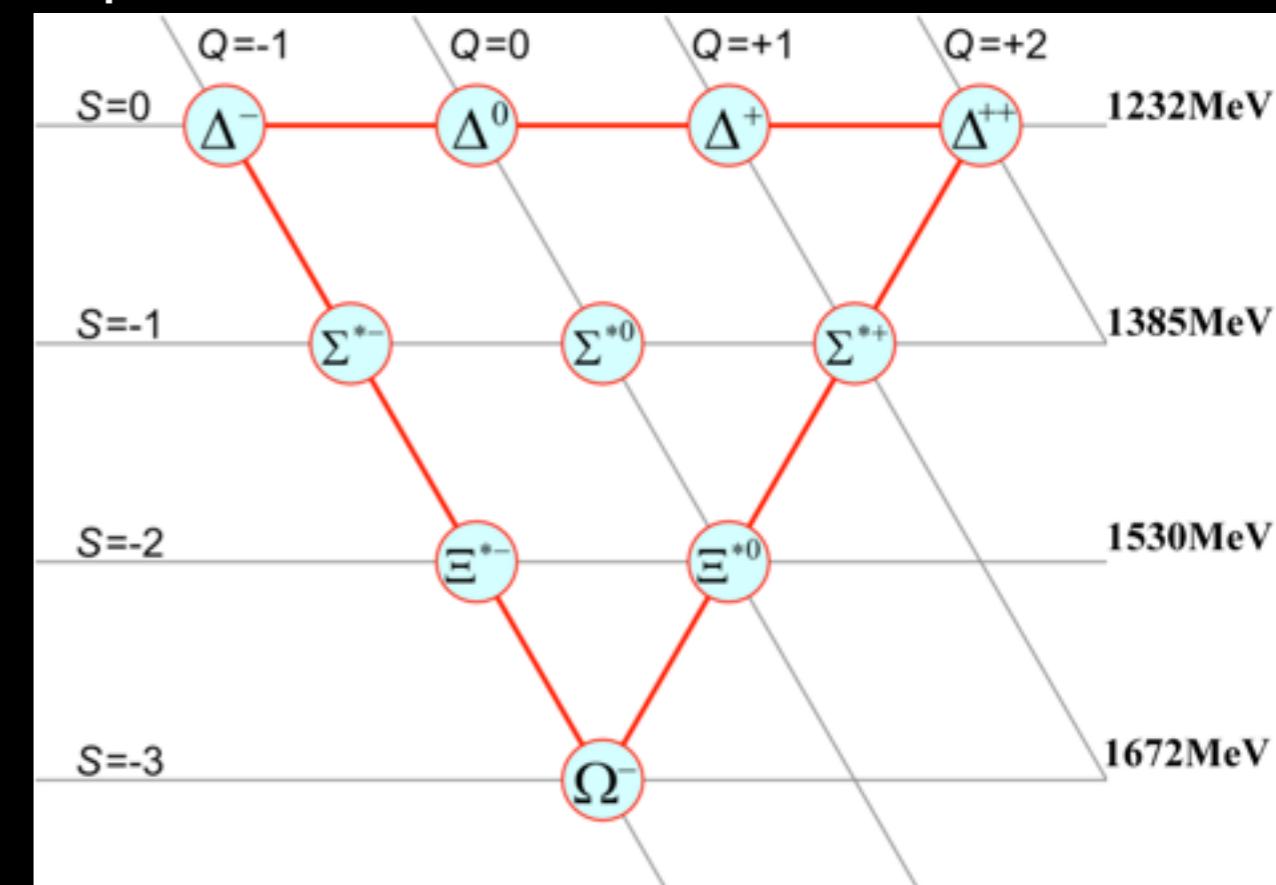
Hadron - Multiplets

- The quest for structures:

Spin = 1/2

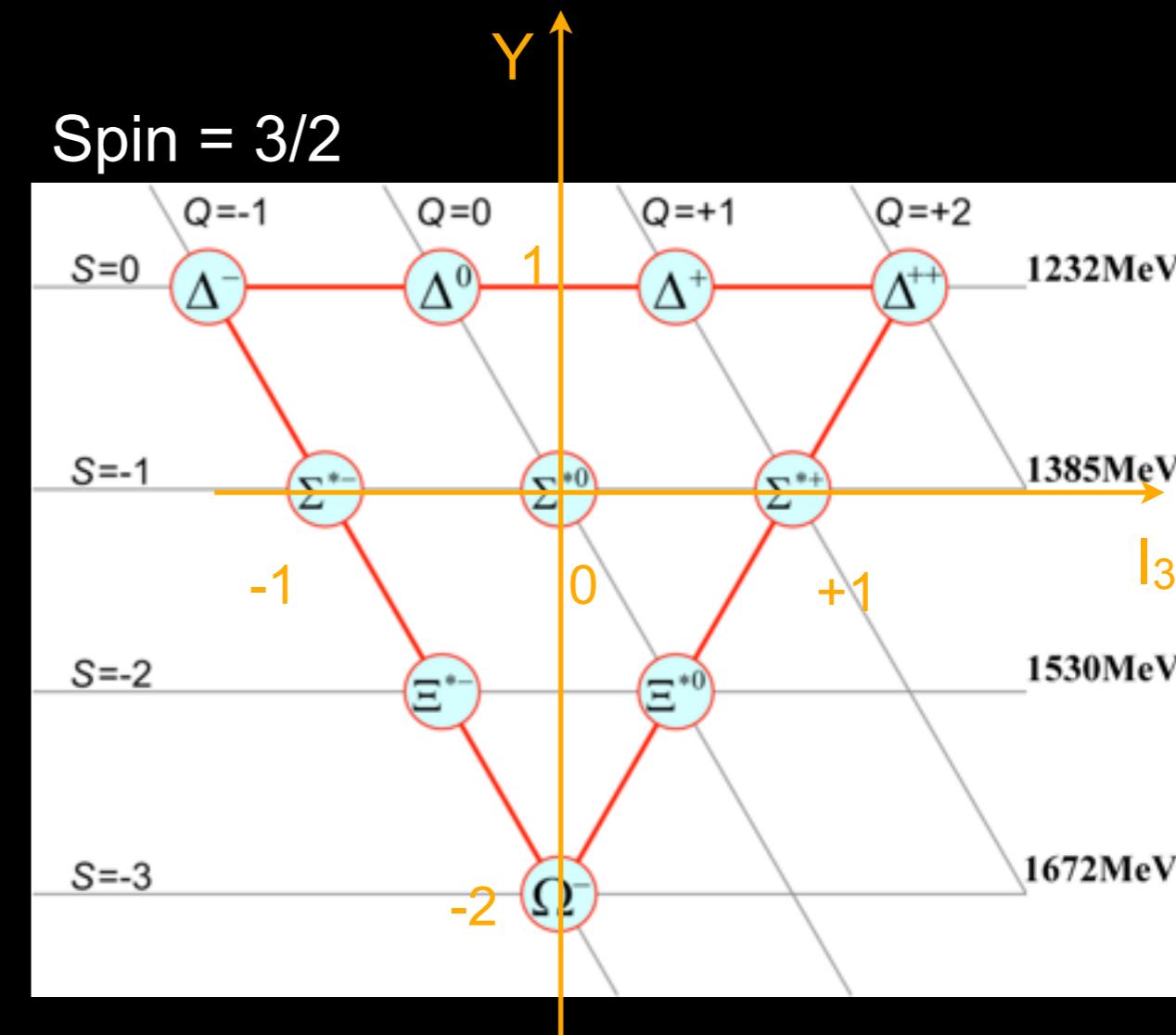
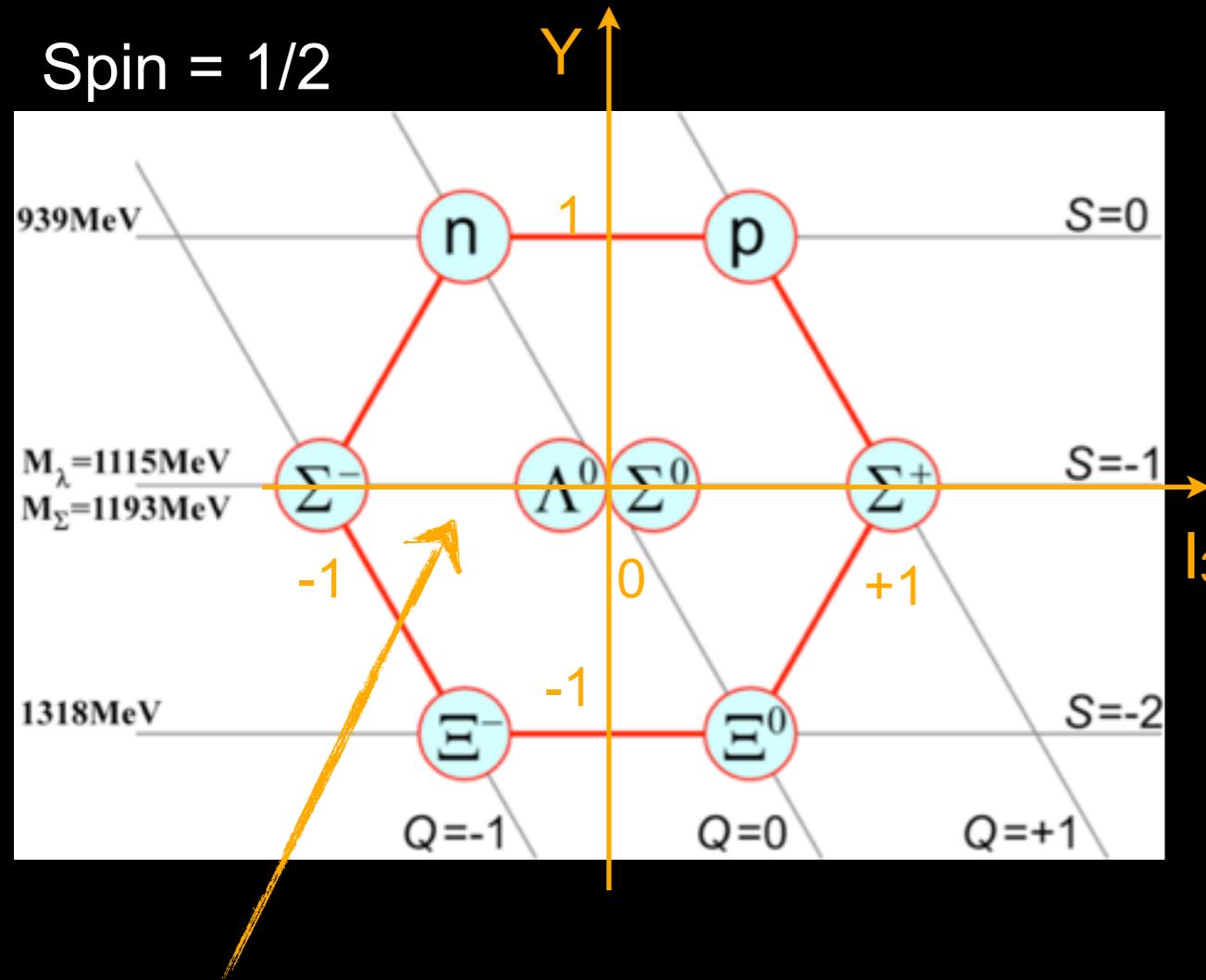


Spin = 3/2



Hadron - Multiplets

- The quest for structures:



Isospin:

Symmetry between p & n:
2 states of one „particle“

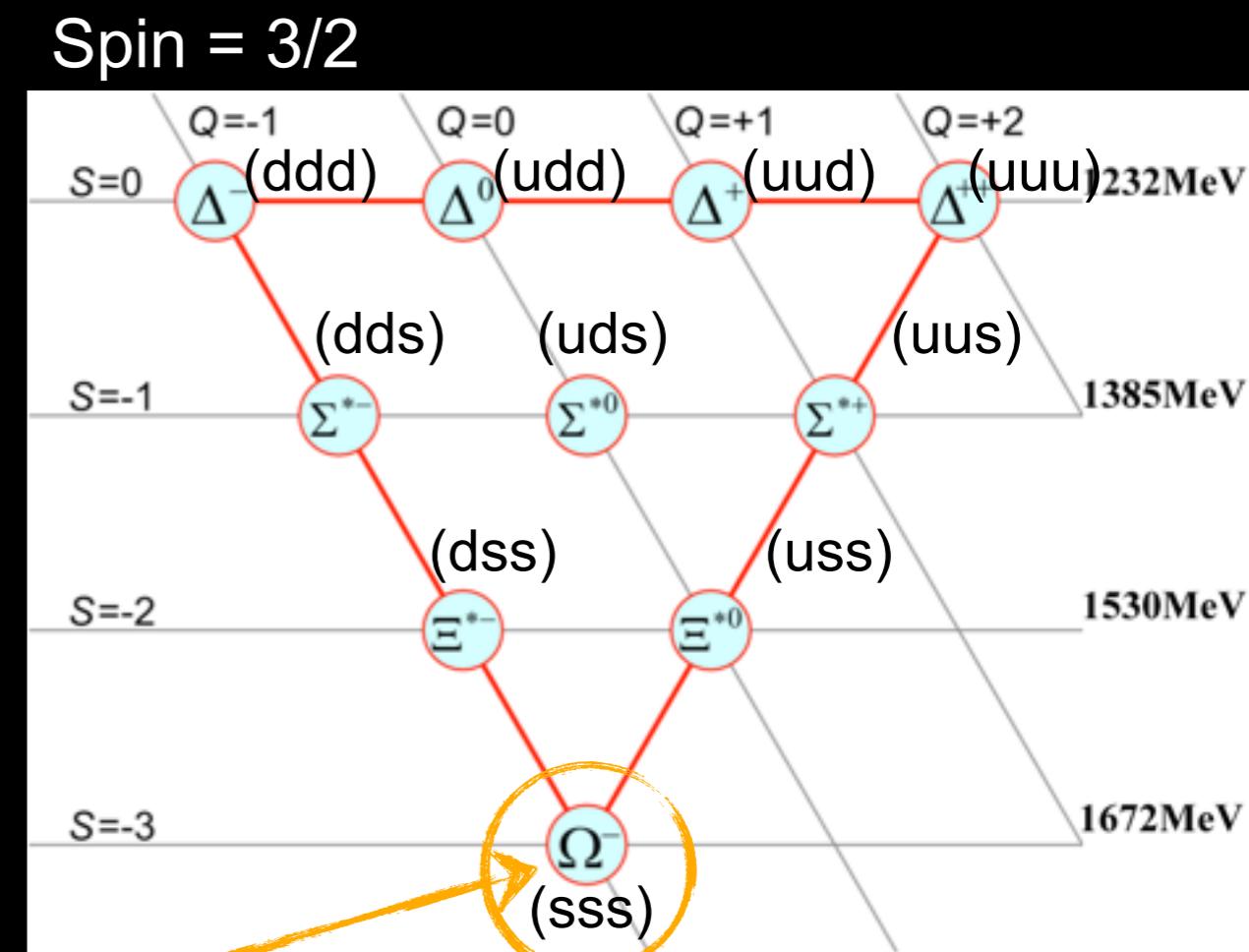
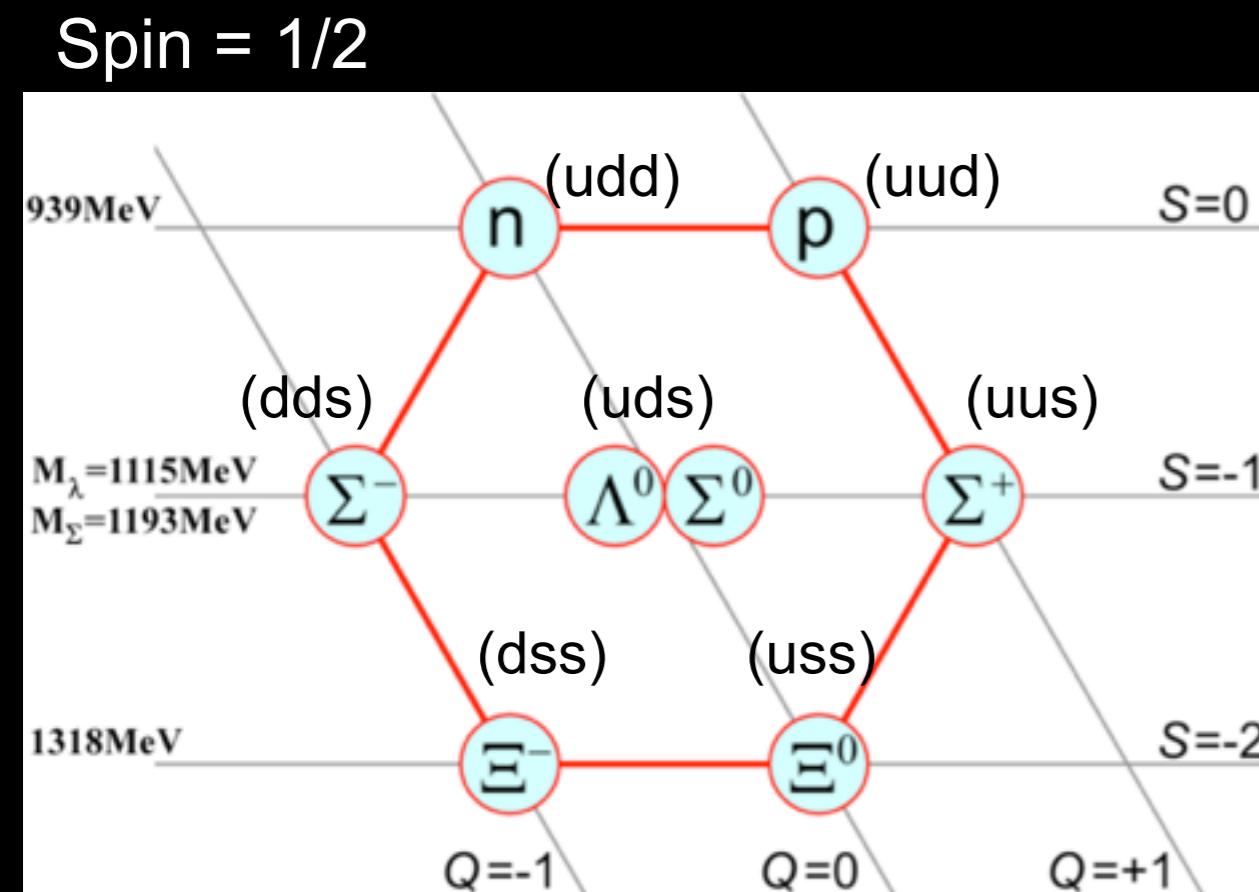
mathematical analogue with spin

Order through Internal Structure



- Postulate:
 - There exist **3 fundamental particles** which build up all hadrons (+ anti-particles)
 - Quarks:** up, down, strange

Gell-Mann /
Zweig: 1963

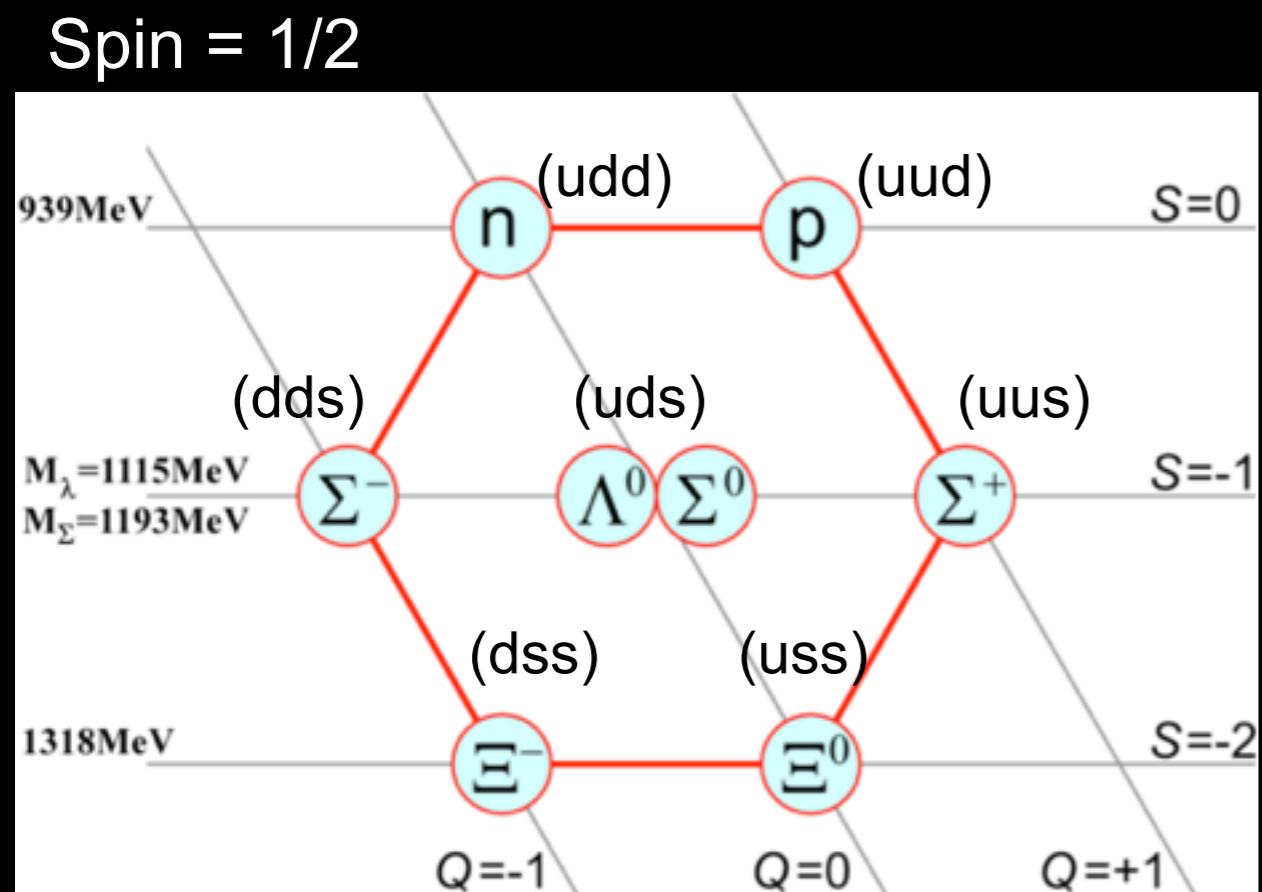


Predicted before experimental discovery

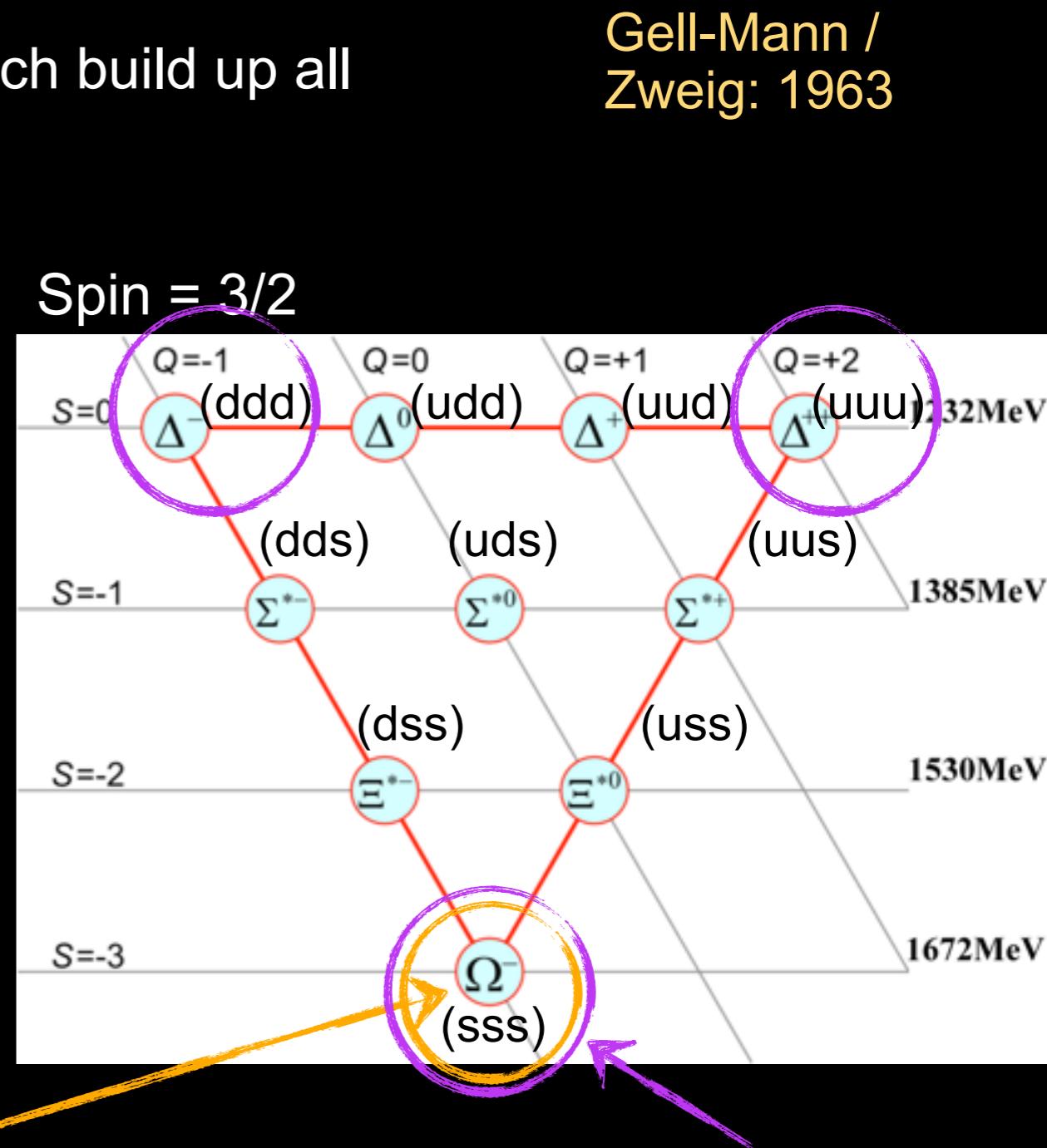
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Predicted before experimental discovery



Problem: violates Pauli exclusion principle: 2 identical quarks!
 ⇒ **color charge**

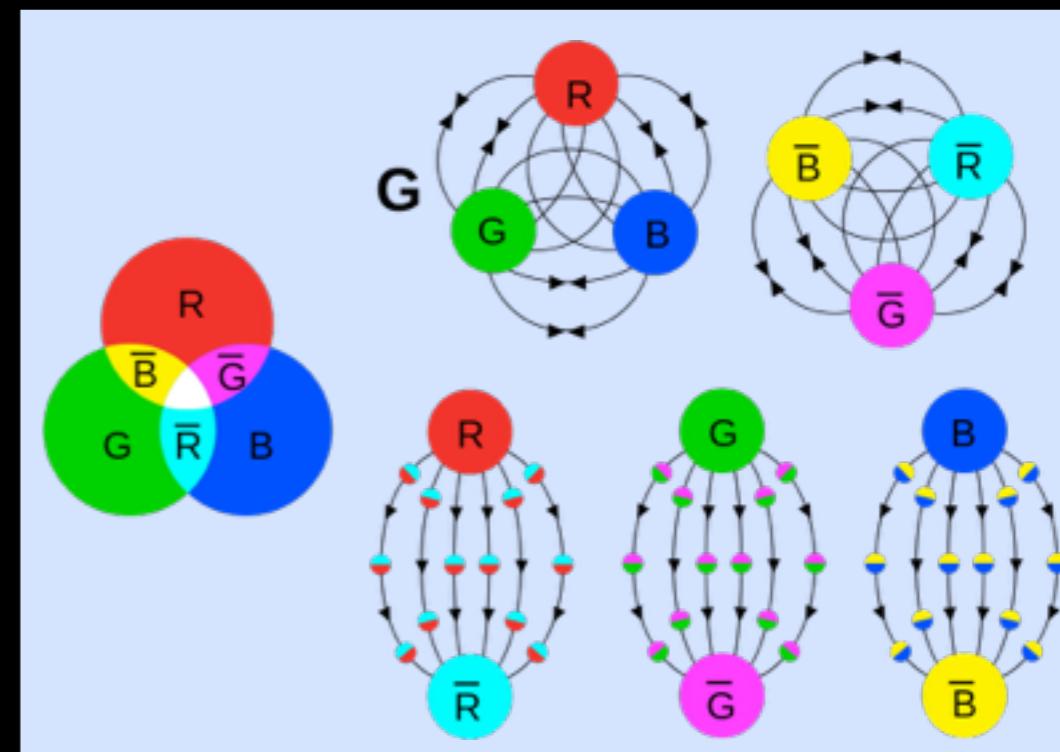
Quantum Chromo Dynamic



- Quarks carry additional charge (quantum number):
 - Color - 3 states necessary to explain multiplets (red, green, blue)
 - behaves vector-like
 - Color = charge of 'strong' interaction
 - Exchange particle: Gluon (massless)
 - Changes color of quarks
- ⇒ Carry color & anti-color

- Dogma of QCD:

- Only color neutral objects exist
 - Color + anti-color (Mesons)
 - red + green + blue (Baryons)

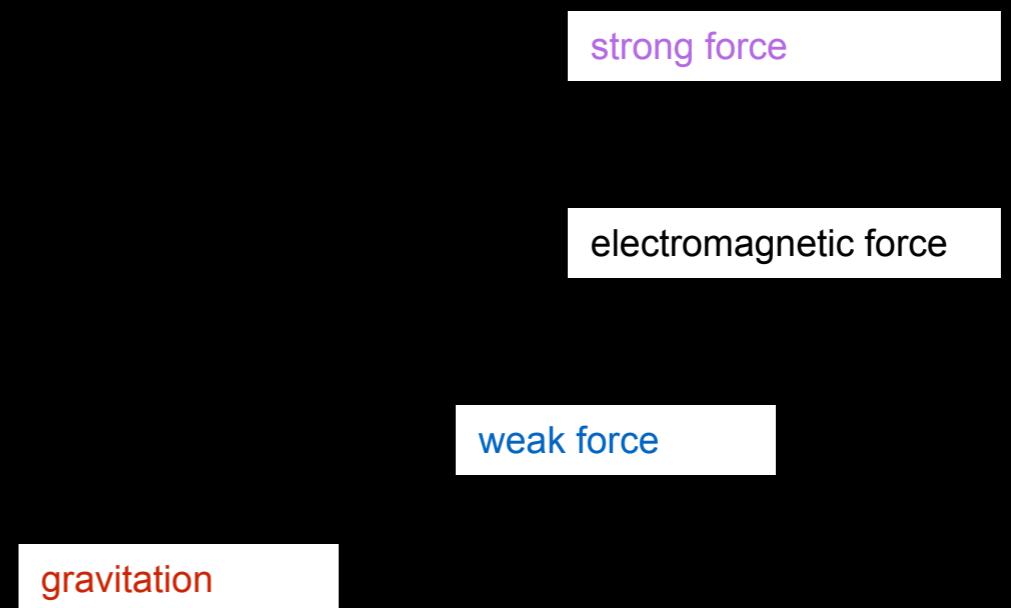
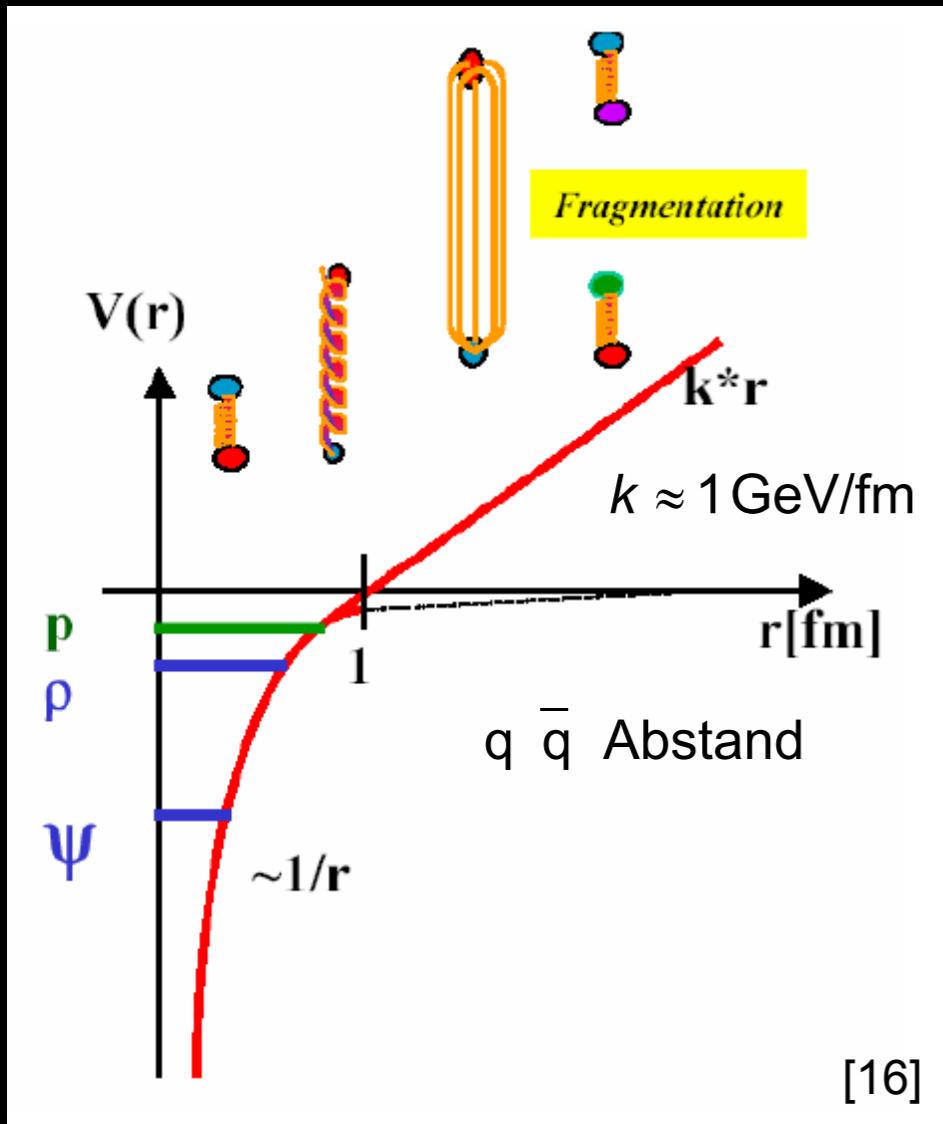
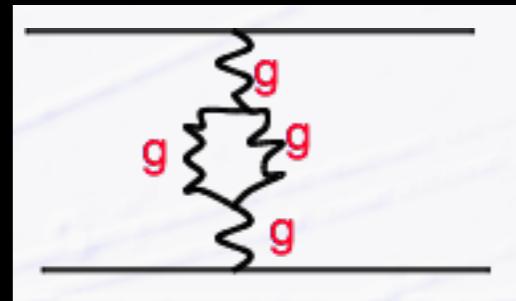


Gluons - plaguy glue

- Gluons carry color → interact with each other!

- Fundamental difference to QED

- Potential: $V(r) = -\frac{4}{3} \frac{\alpha_s^{eff}}{r} + kr$



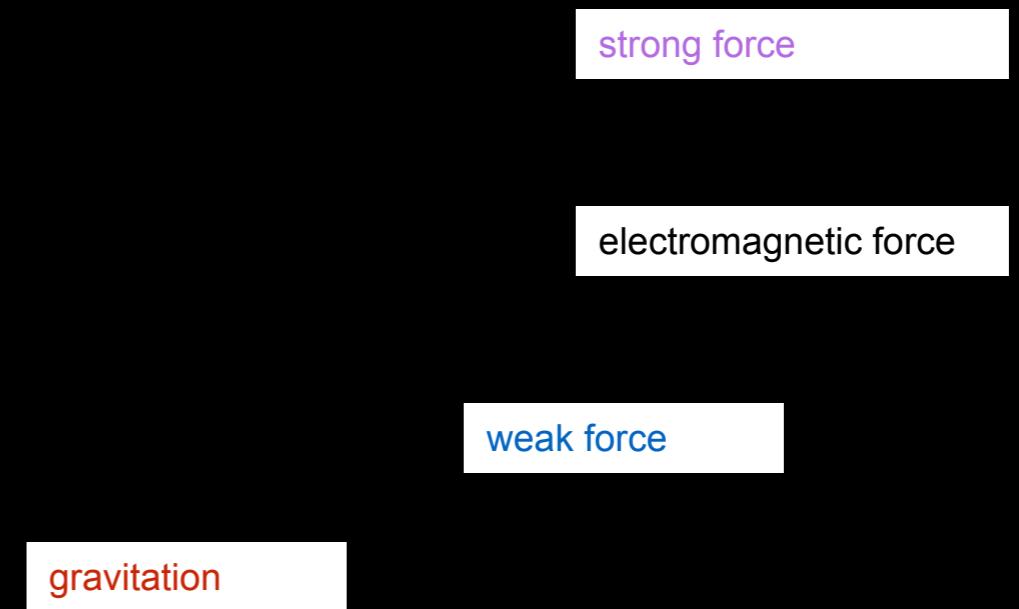
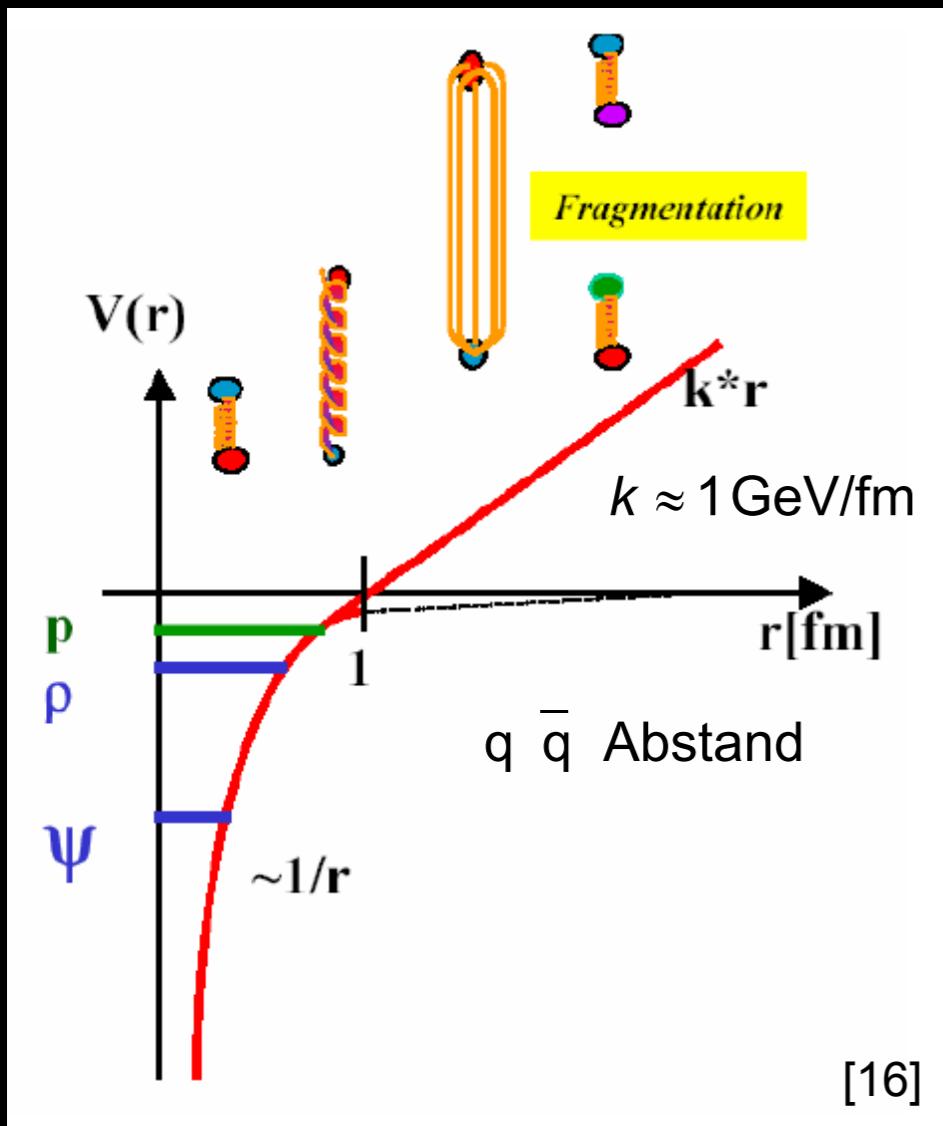
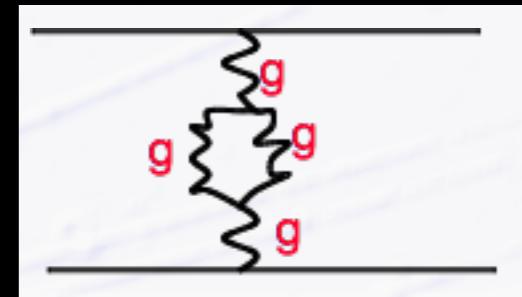
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,^{eff} - effective:
coupling depends
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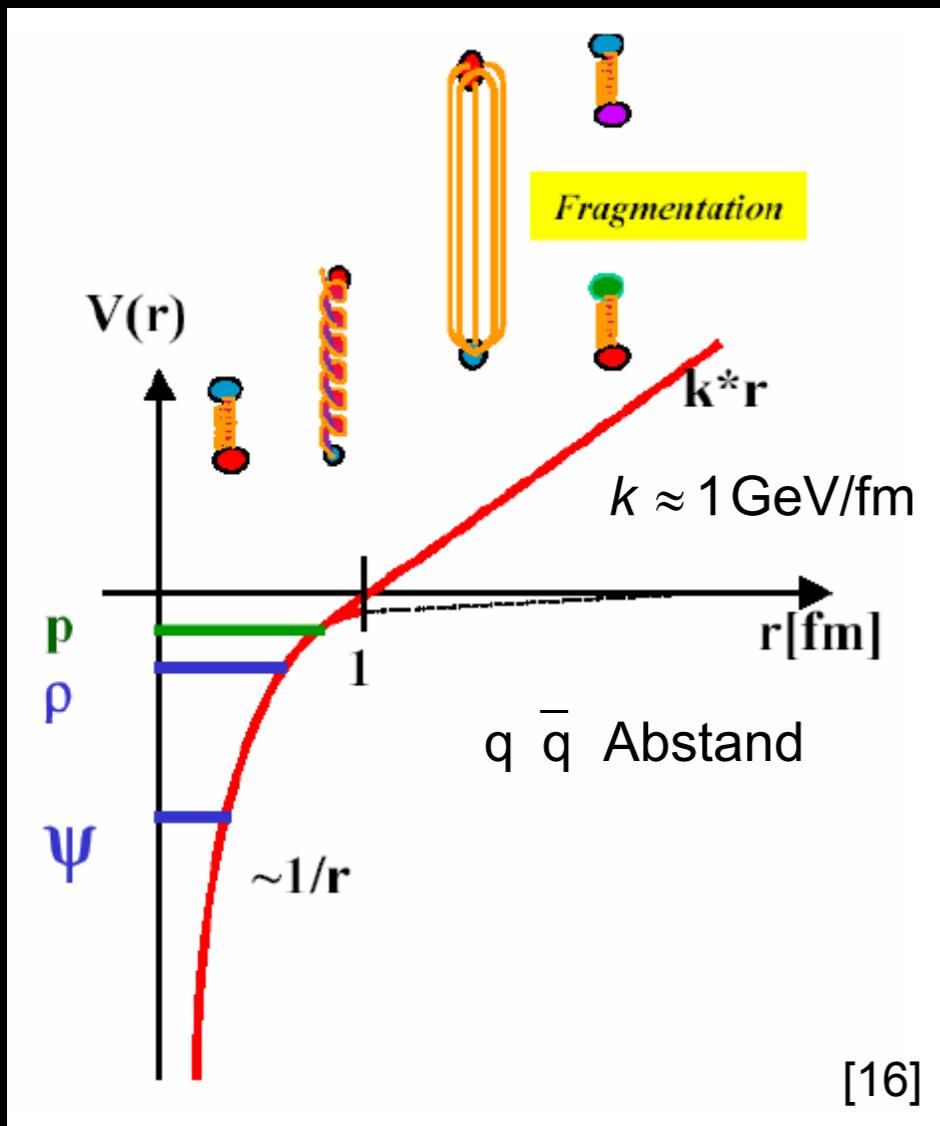
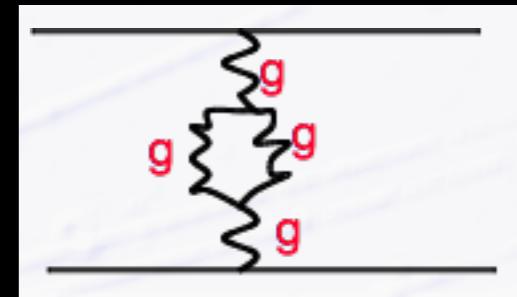
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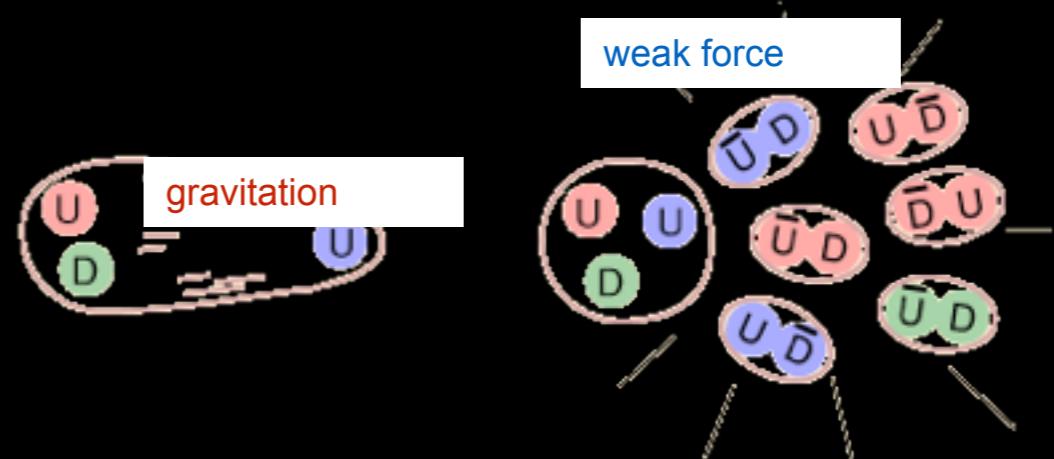
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- große Abstände
 - Potentielle Energie zwischen zwei quarks nimmt linear mit Abstand zu!
 $\sim 1 \text{ GeV pro fm}$
 - ,Confinement'



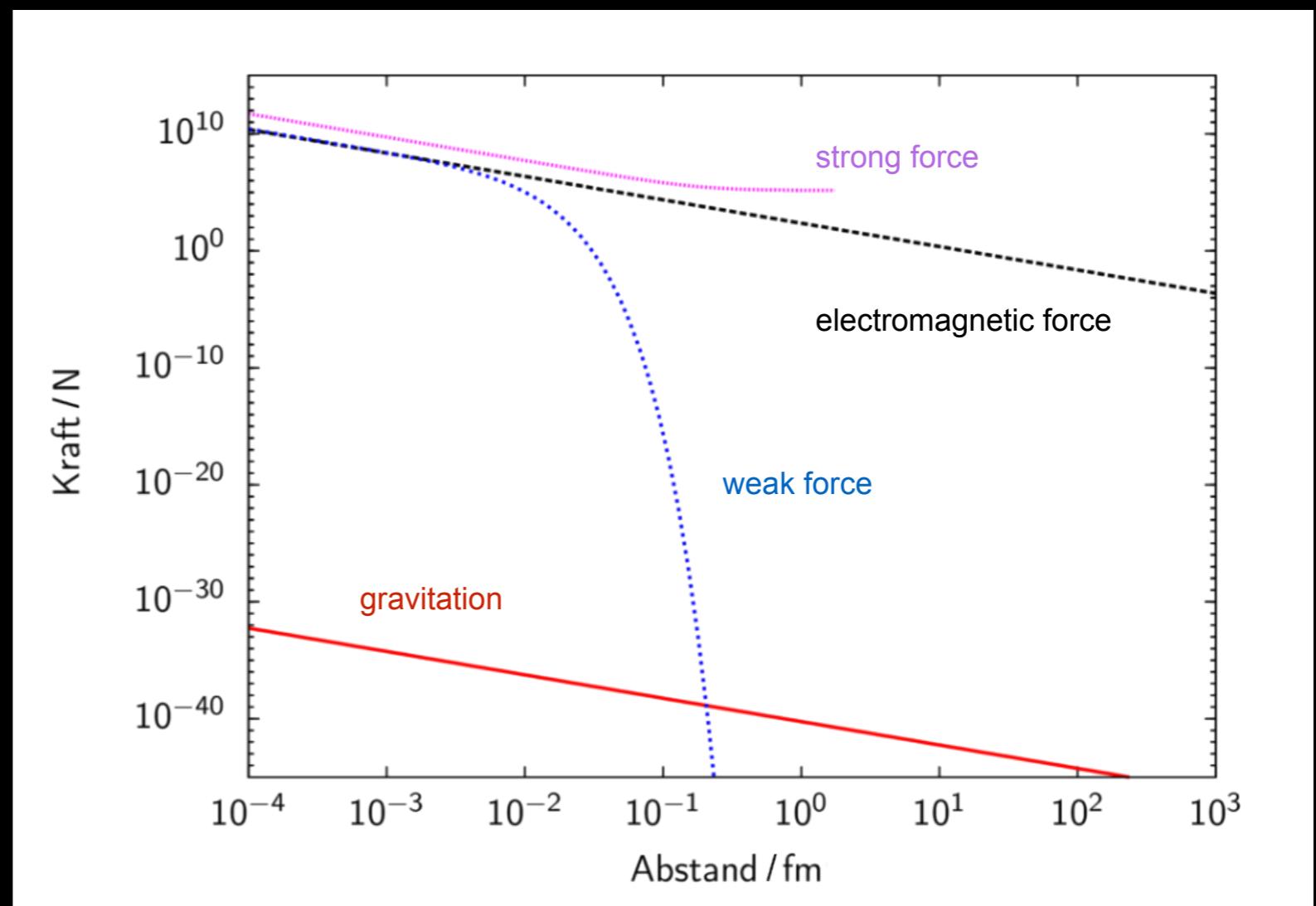
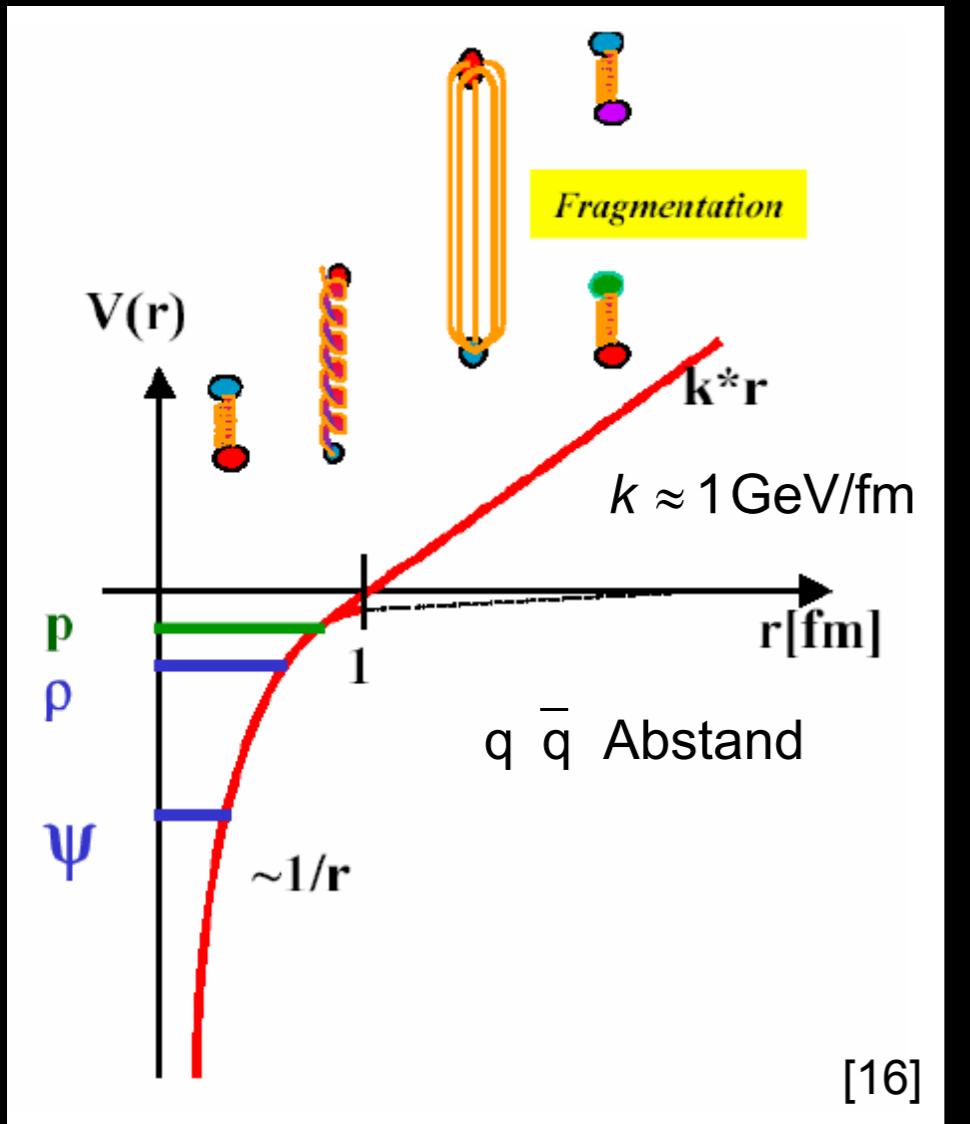
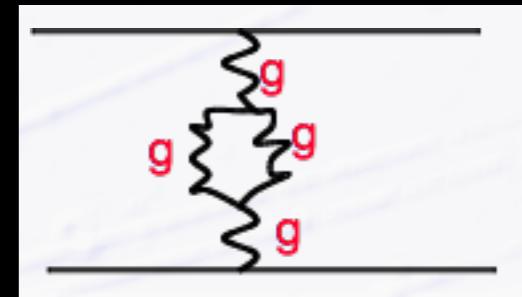
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Intermezzo: Color & other Charges

- Charges are the source of forces
- Every fundamental force requires corresponding charge
 - Only particles carrying specific charge take part in interaction

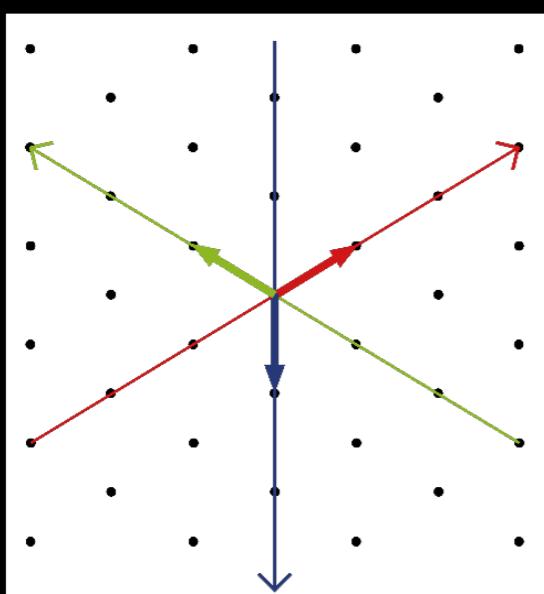
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electromagnetism	electric	$q = 1$ electron
weak force	weak	$I = 1/2$
strong force	color	$\vec{C} =$ red, green, blue

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- Charges are **additive**
 - E.g.: el. charge of nucleus = sum of proton charges
 - Similar for weak charge
 - What about color?



- Color charge can be seen as 2D vector

$$p(u^{\textcolor{red}{\nearrow}} u^{\textcolor{green}{\nwarrow}} d^{\textcolor{blue}{\downarrow}})$$

$$\vec{C}_{u^{\textcolor{red}{\nearrow}}} + \vec{C}_{u^{\textcolor{green}{\nwarrow}}} + \vec{C}_{d^{\textcolor{blue}{\downarrow}}} = \textcolor{red}{\nearrow} + \textcolor{green}{\nwarrow} + \textcolor{blue}{\downarrow} = \vec{0}.$$

- E.g.: **Proton**:
- Sum of color vectors = 0 (**white**)

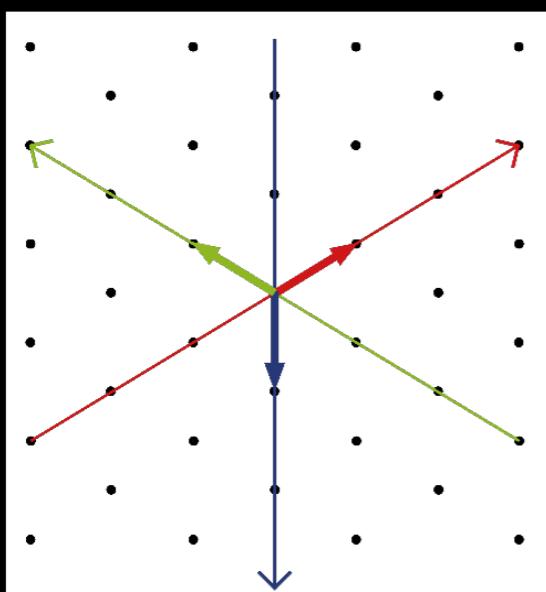
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- Charges are **additive**
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- Charges are conserved
 - In all reactions



- Color charge can be seen as 2D vector

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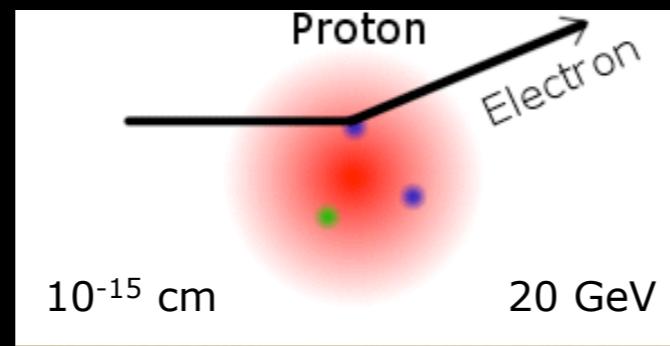
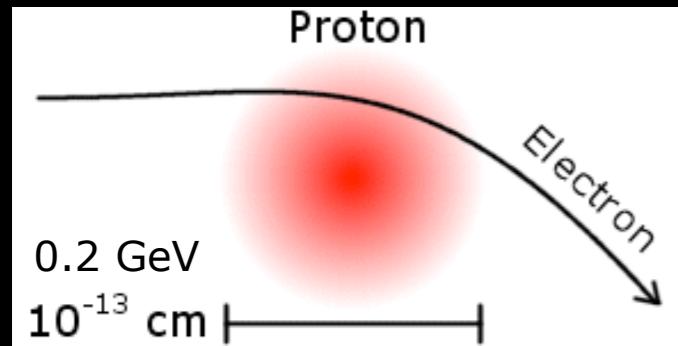
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Discovery of the quarks



Electrons scattered off protons

Friedmann, Kendall,
Taylor: 1969

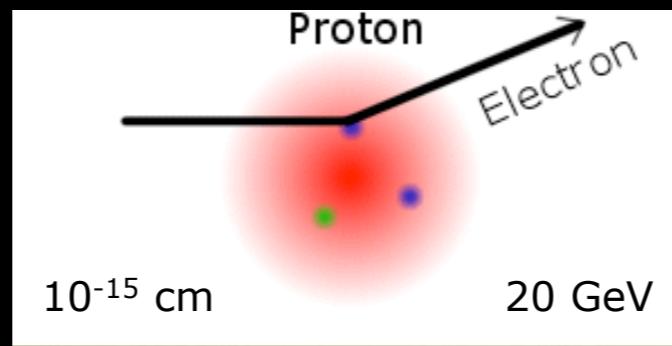
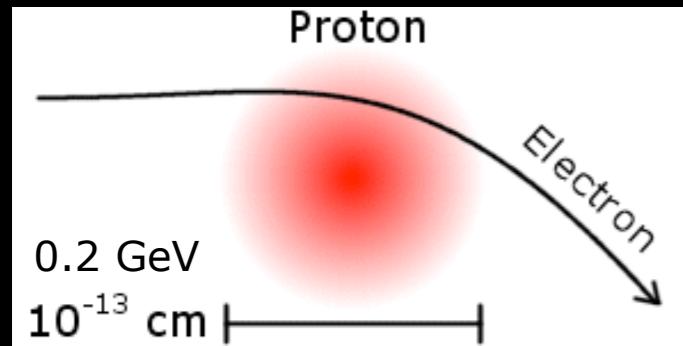


- Elastic scattering:
 - Sensitive to radius of proton
- Inelastic scattering:
 - Scattering off constituents!
- Relativistic events
 - Characterised via momentum transfer² = q^2 , instead of scattering angle
 - $(\Delta E + m_p c^2)^2 = (\Delta \vec{p})^2 c^2 + (m_W c^2)^2$
 - $m_W = m_p$: elastic scattering

Discovery of the quarks

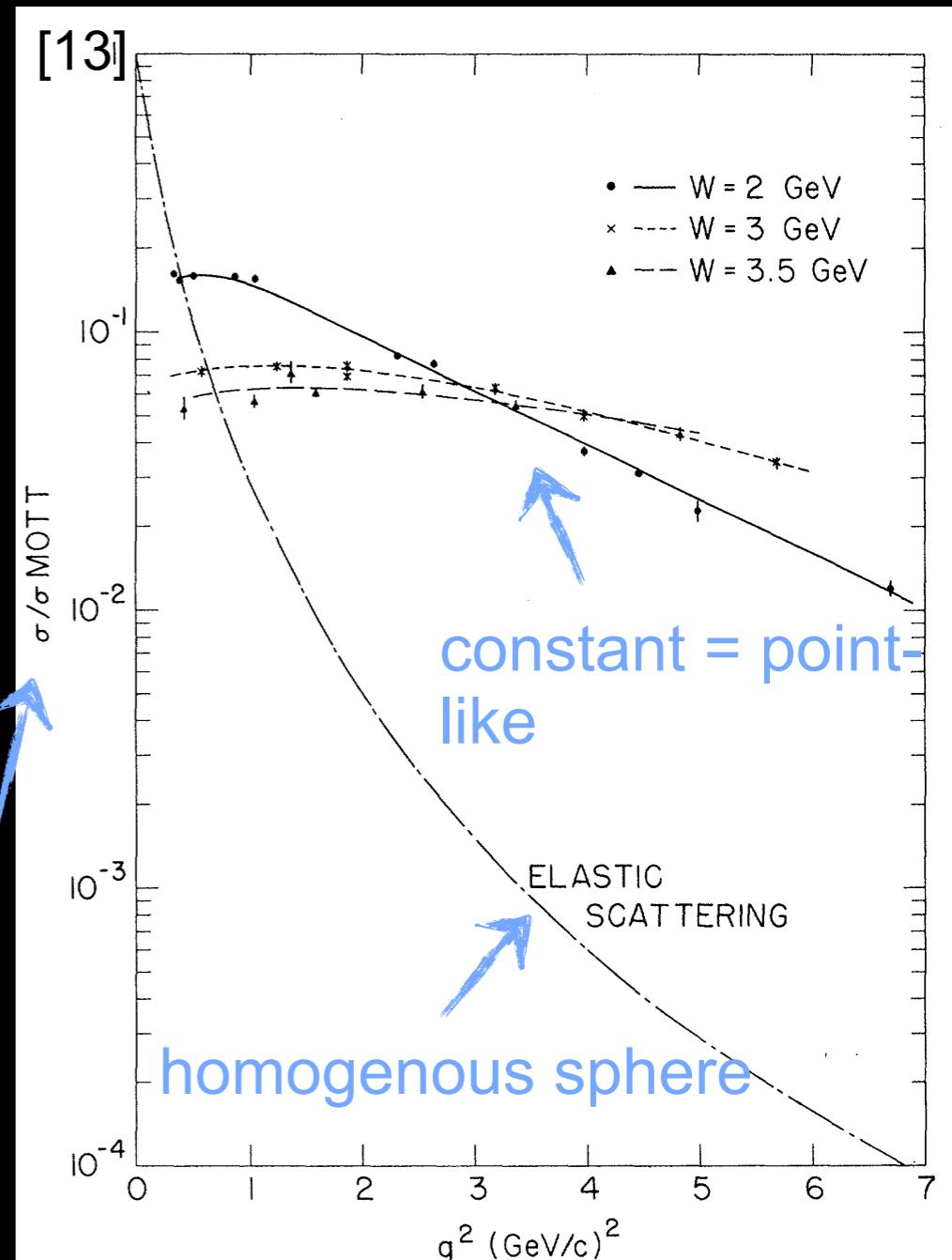


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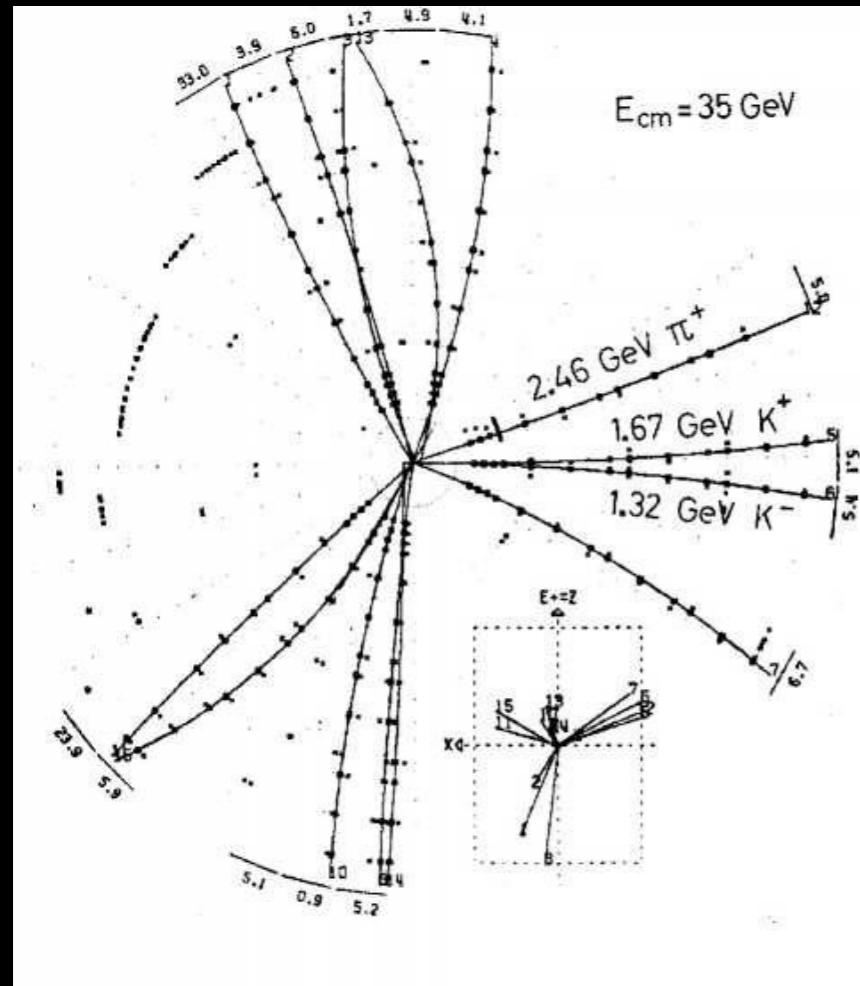
Formfactor F

Discovery of the Gluons



- Creation of quark anti-quark pairs
 - 3rd „jet“ emerges from gluon radiation

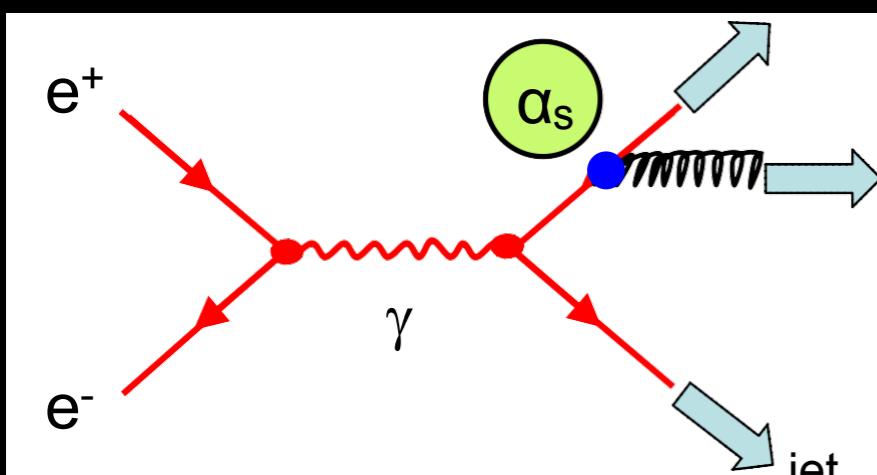
Desy (Petra): 1979



- Measurement of the strong coupling constant:

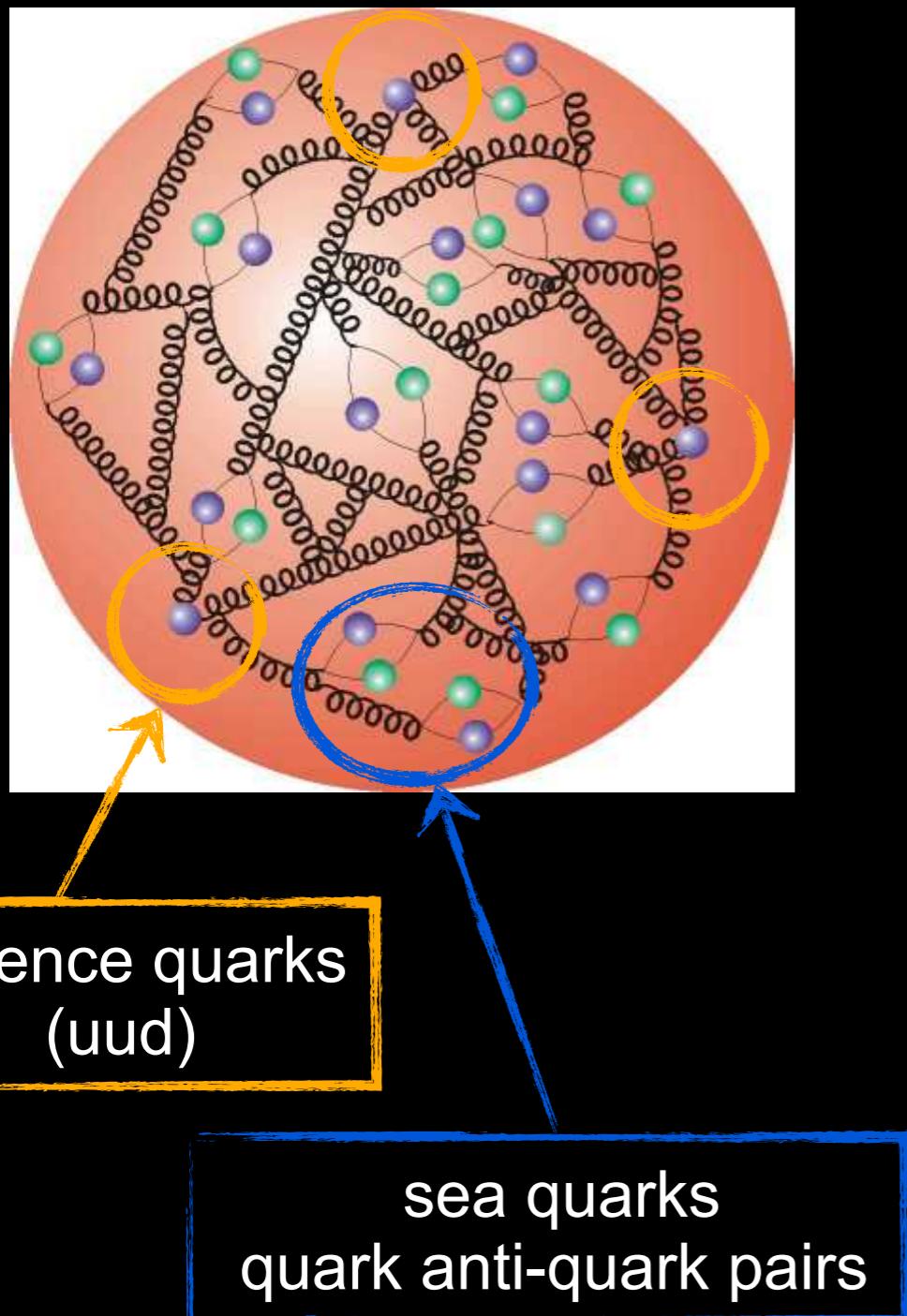
$$\alpha_s \sim \frac{\# \text{ 3 jet events}}{\# \text{ 2 jet events}}$$

- Experiments at the Petra e^+e^- accelerator at DESY
 - Experiments TASSO, Pluto, Mark-J, JADE

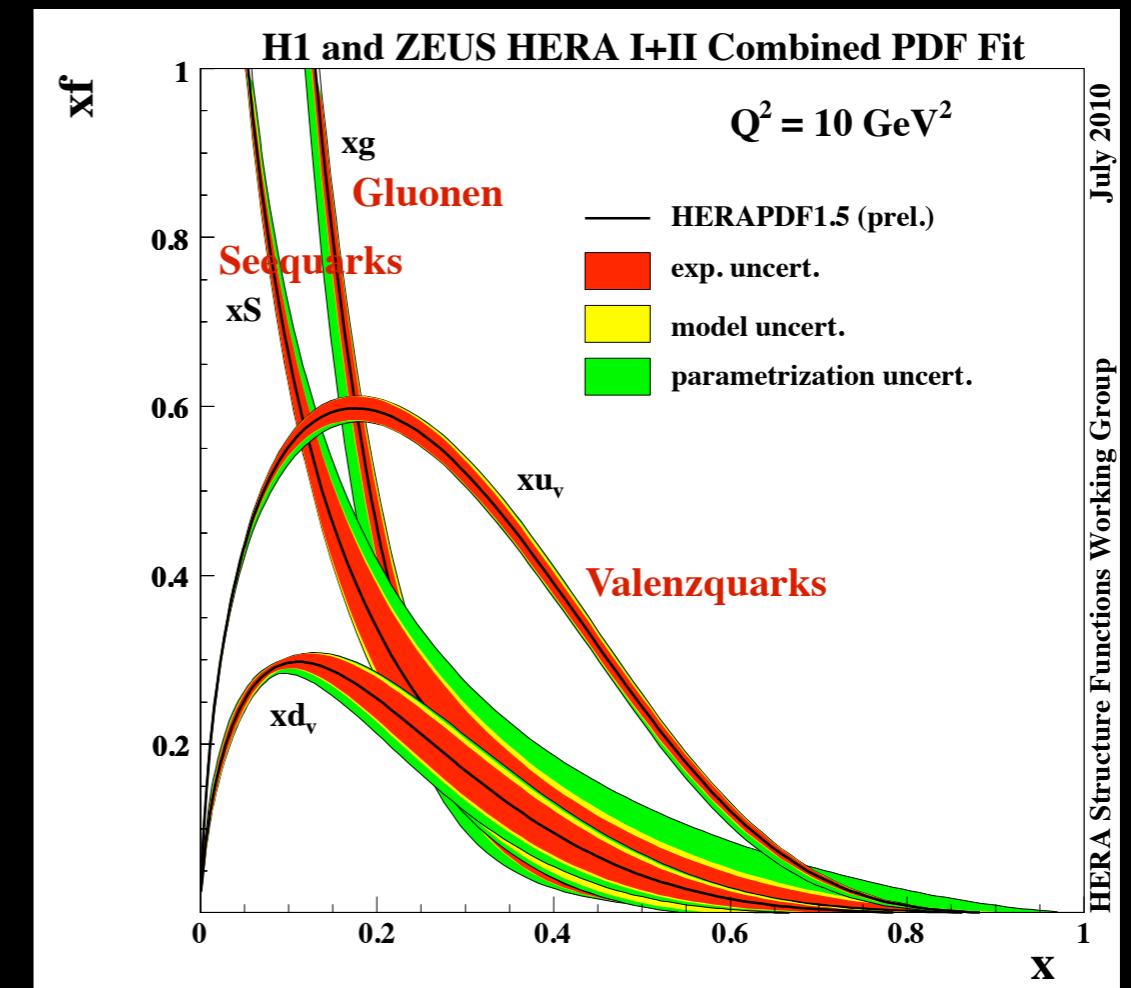


The Proton - todays view

- Complex many particle system
- Quarks, anti-quarks, gluons



- High energetic collisions:
 - Collisions of individual 'partons'
 - Which momentum carry partons?
- PDFs (Parton density function)

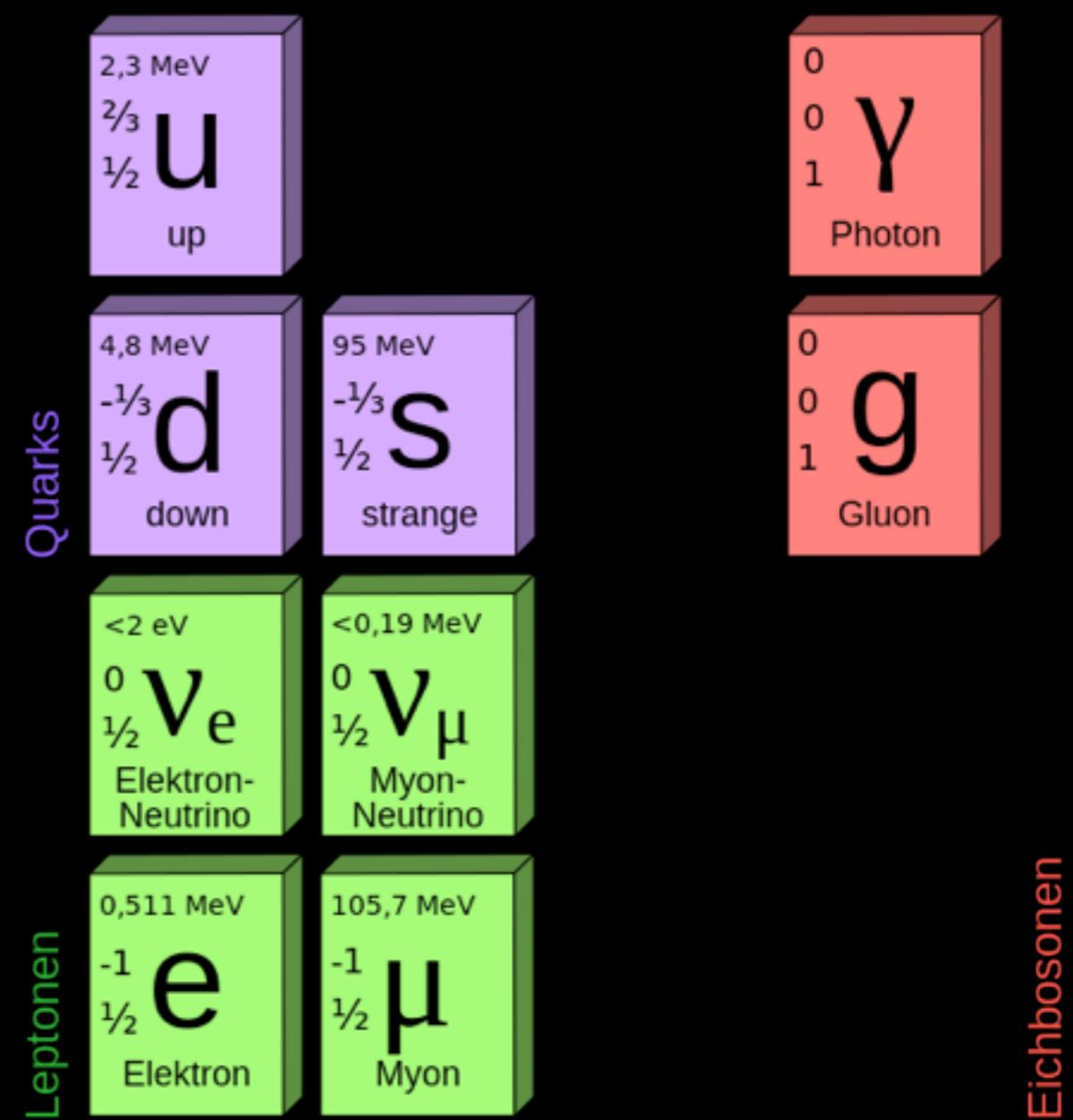


x: Fractional momentum of parton on proton momentum (Björken x)

What we covered so far

- Elementary particles

- Constituents of matter
 - Fermions ($S=1/2$)
- Force carries
 - Bosons ($S=1$)

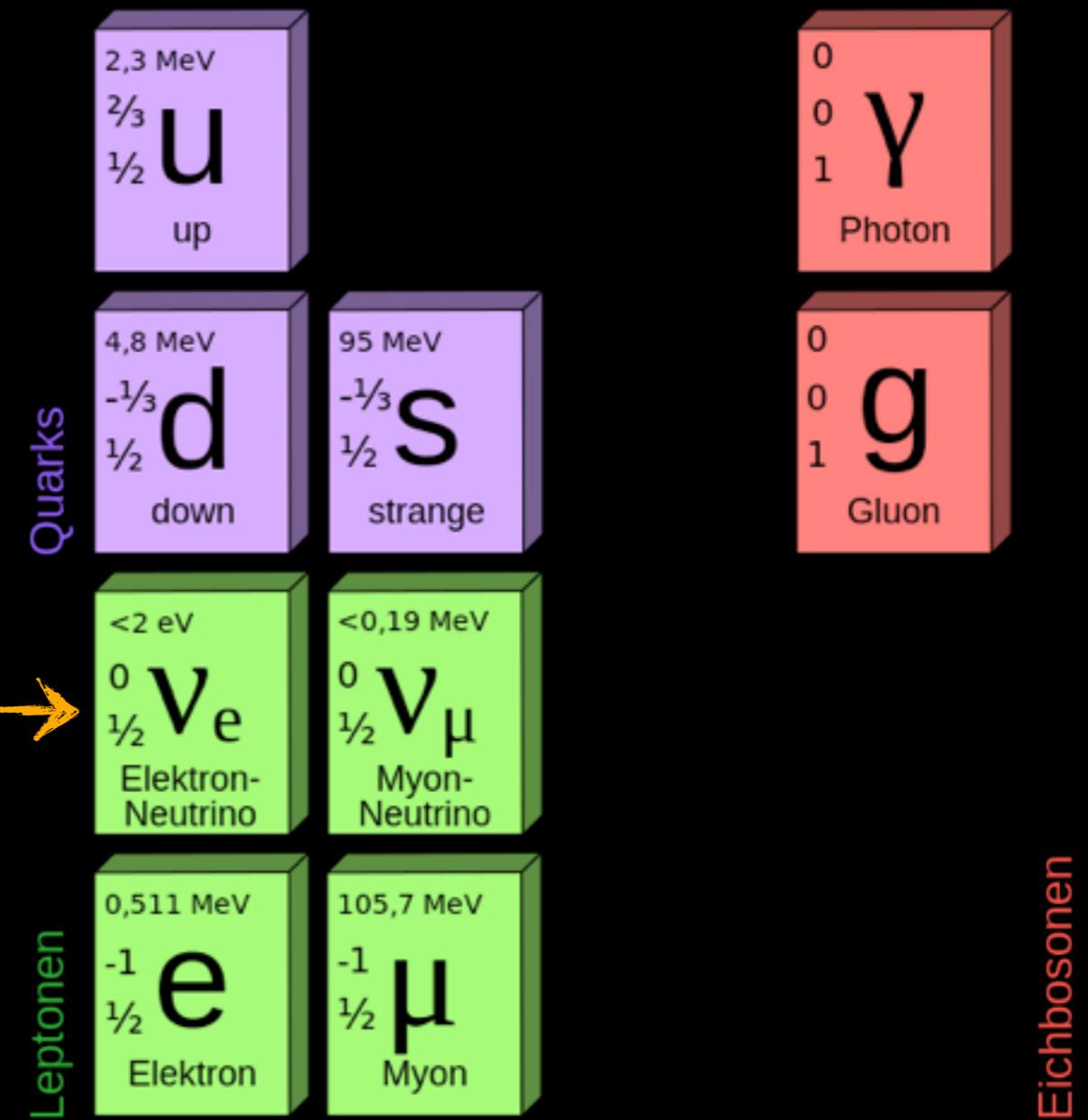


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Neutrinos: neglected so far



weak interaction

Radioactivity



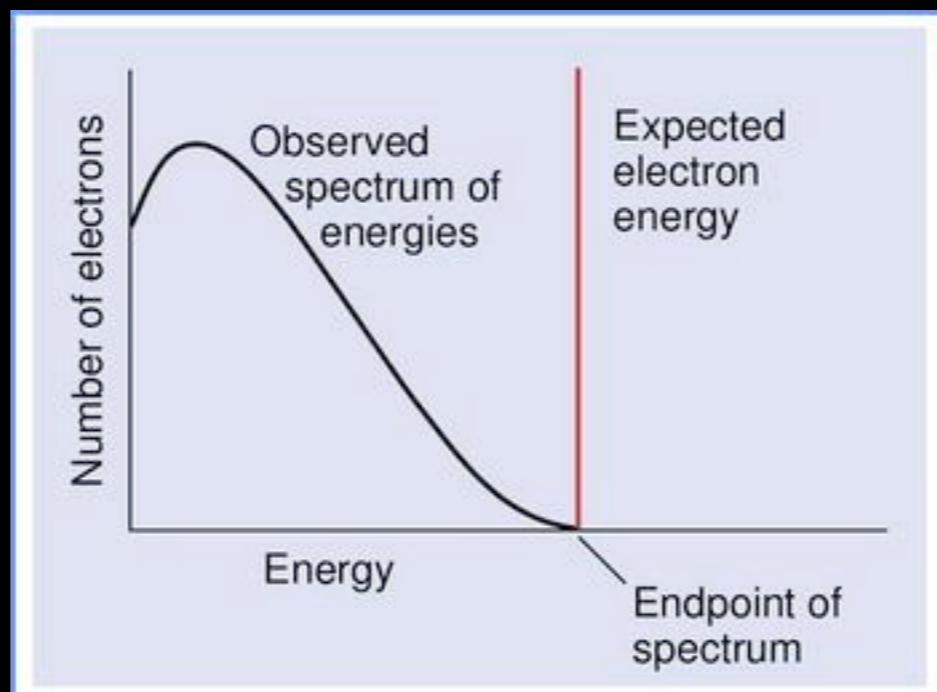
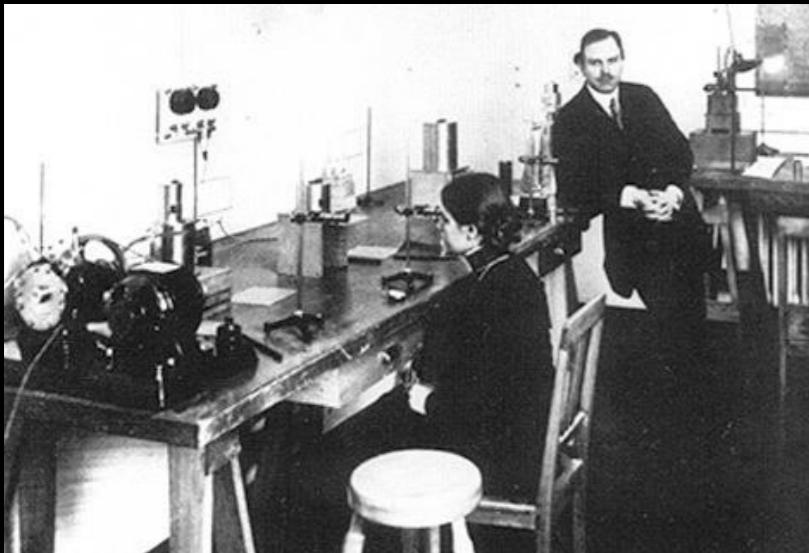
- Back to beginning of 20th century
 - 1895: Wilhelm Röntgen discovered **x-rays**
 - 1896: Henri Becquerel discovered **radiation from uranium crystals**
 - 1898: Marie & Pierre Curie: **radiation from pitch (U + Polonium)**
- It took 35 years to get basic understanding of these phenomena

β -Decay

- β - decay of atoms

Meitner, Hahn: 1911

Visible: $A_z \rightarrow A_{z+1} + e^-$



- **Violation of energy conservation?**

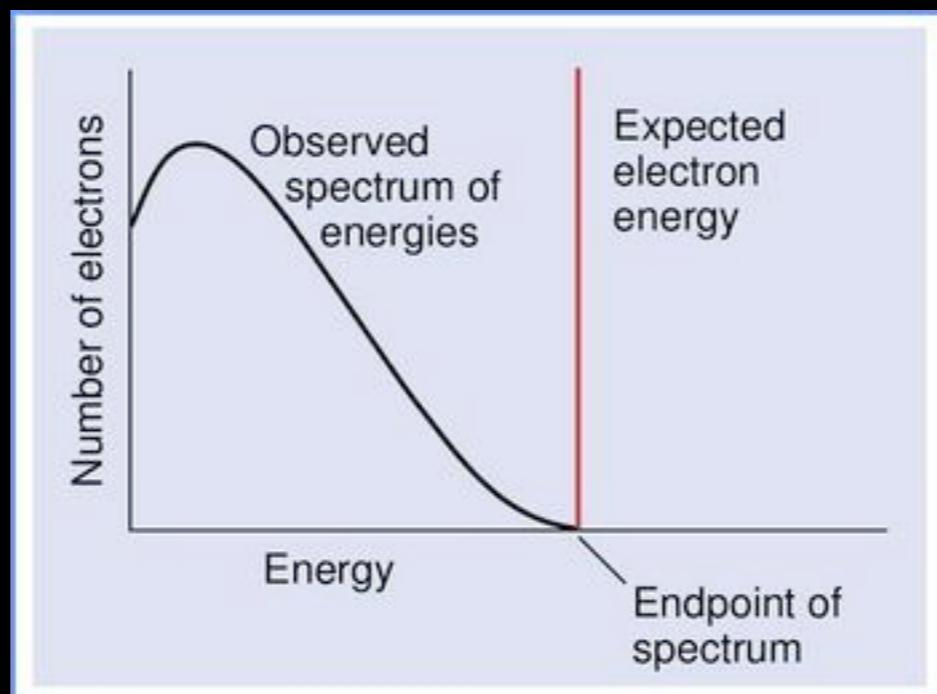
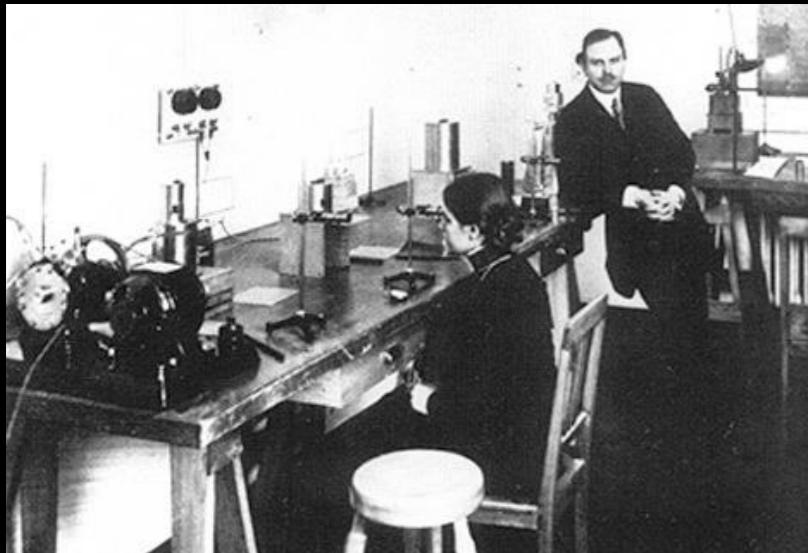
Pauli: 1930

β -Decay

- β - decay of atoms

Meitner, Hahn: 1911

Visible: $A_z \rightarrow A_{z+1} + e^-$



- **Violation of energy conservation?**

Pauli: 1930

- Solution: additional very light particle produced in decay

Postulate: $A_z \rightarrow A_{z+1} + e^- + \bar{\nu}$

Neutrino (little neutron)
Direct observation 1956.

Fermi's Theory

- Observation:

- Transformation of matter particles
- Weak force (long lifetimes compared to em decays)
- Short ranged

Fermi: 1934

⇒ **new interaction!** (1934 only gravity & EM known)

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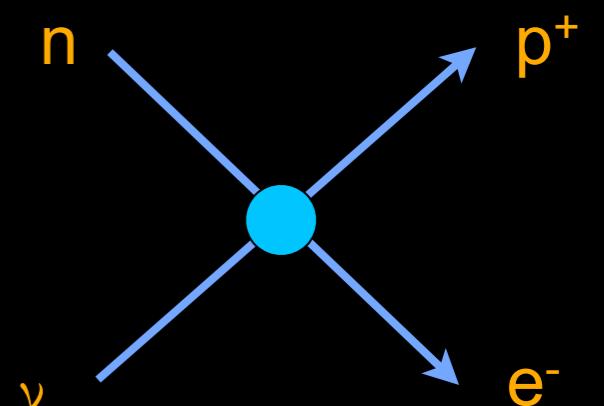
Fermi: 1934

⇒ **new interaction!** (1934 only gravity & EM known)

- Phenomenological interpretation by Enrico Fermi:

- Point-like interaction of 4 particles
- Weak: G_F 10^{-5} relativ to EM interaction
- Analogy: 2 currents of particles: p,n / e, ν

⇒ Calculation of β^- - decays & cross sections possible

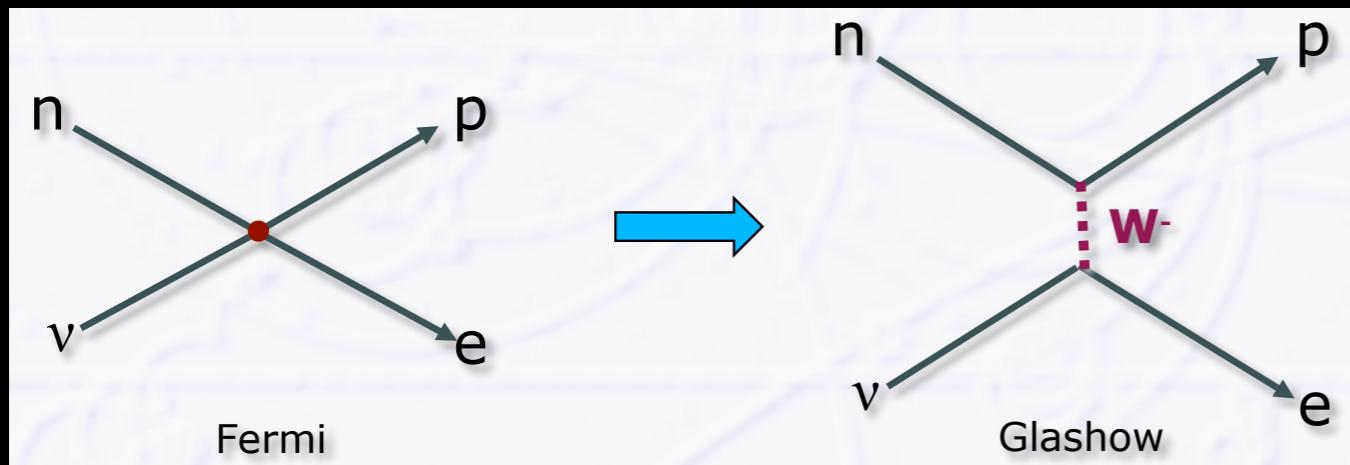


Conservation of Probability

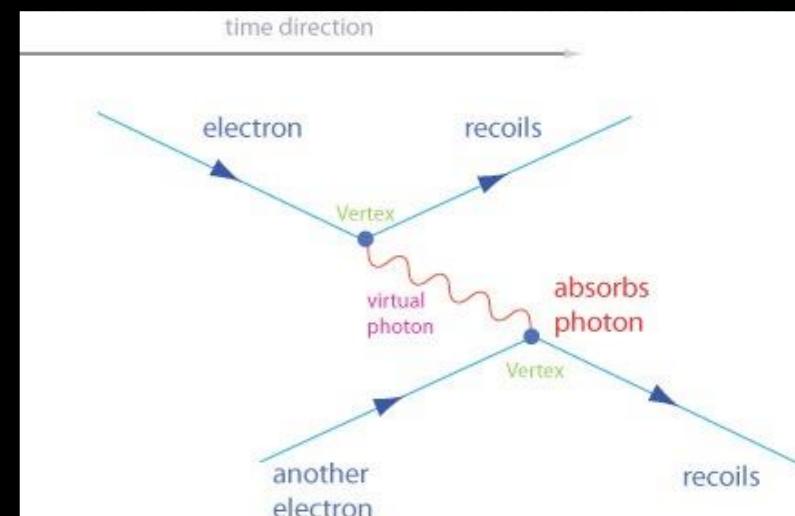
- Huge problem in ~ 1950
 - Cross section for the reaction $p + \nu \sim (G_F E_\nu)$
 - **Violates unitarity** for $E > 300$ GeV (probability > 1)

- A way out:
 - Weak interaction is transmitted via heavy force carriers
 - (Photons already known as exchange particles of em interaction)

Glashow: 1958



Electron scattering



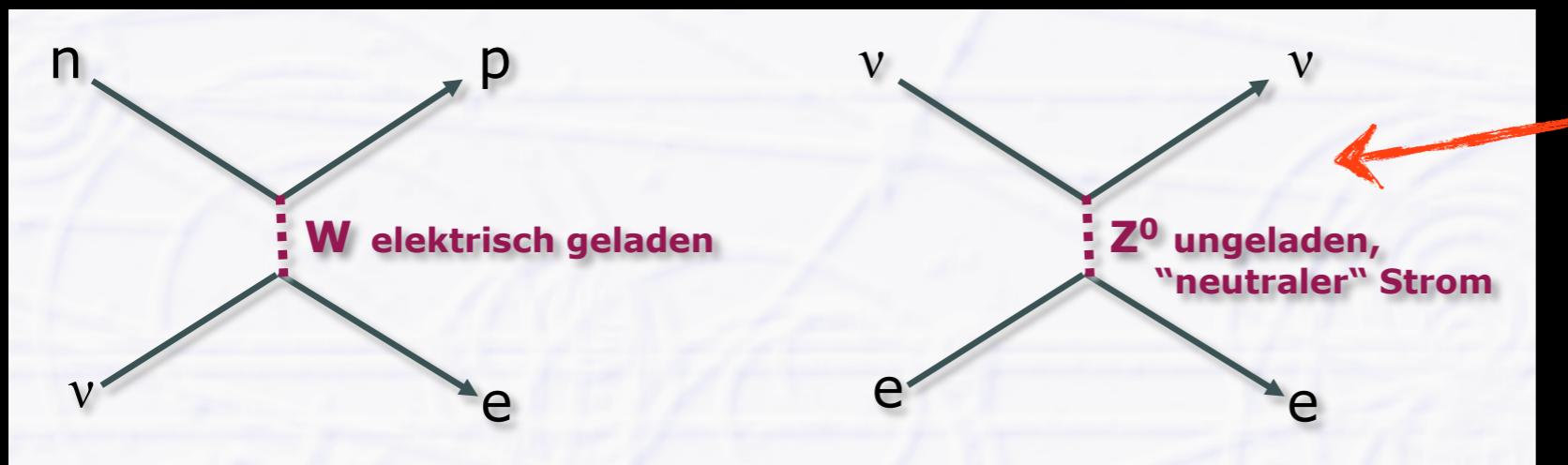
- Large mass of W - particle explains short range ($\sim 10^{-18}$ m) and small cross section of weak interaction

Electroweak Interaction



- Realisation: electromagnetic & weak interactions are manifestations of **same underlying force**
- Unified in **electroweak interaction!**
- New „weak“ charge: carried by quarks & leptons

Glashow, Salam,
Weinberg: 1968

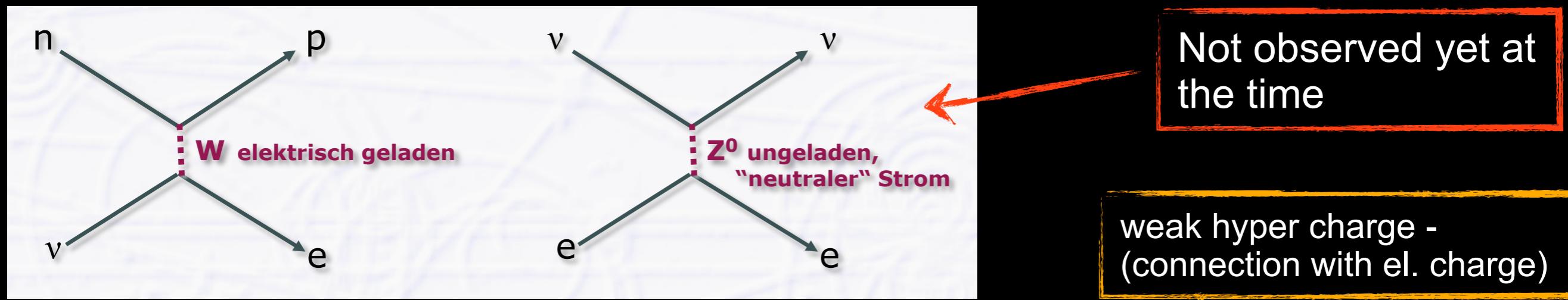


- 2 el. charged exchange particles: W^+ , W^- (massive)
- 2 neutral exchange particles: γ (mass less), Z^0 (massive)

Electroweak Interaction

- Unified in **electroweak** interaction!
 - New „weak“ charge: carried by quarks & leptons

Glashow, Salam,
Weinberg: 1968



- New symmetry belonging to this approach ($SU(2) \times U(1)$)
 - Symmetry only realized at large energies (~ 250 GeV):
 - Same coupling for weak & em. interactions!
 - At low energies:
 - Symmetry „spontaneously“ broken
- W&Z Bosons gain mass via interaction with Higgs field
 - more on that later

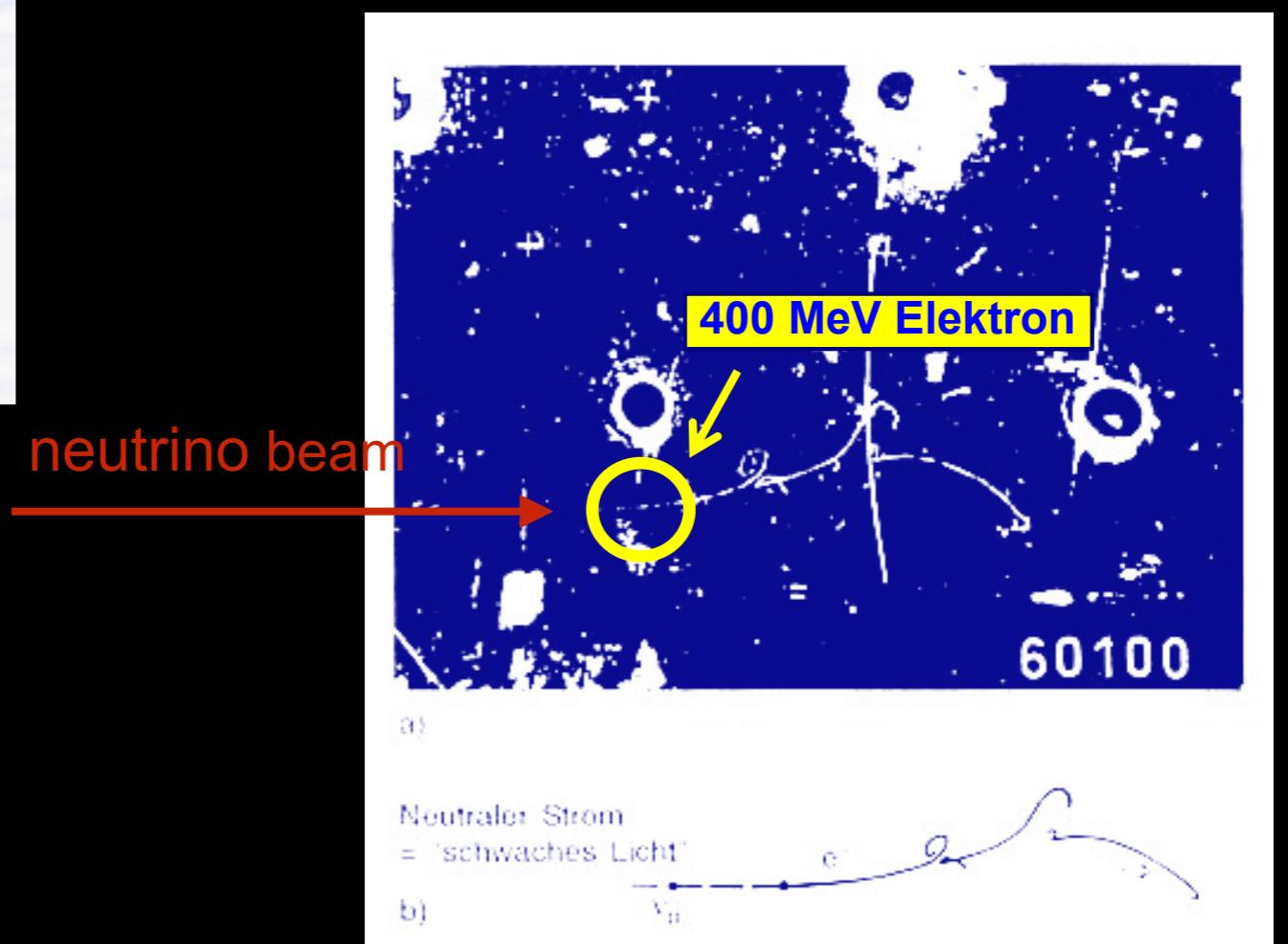
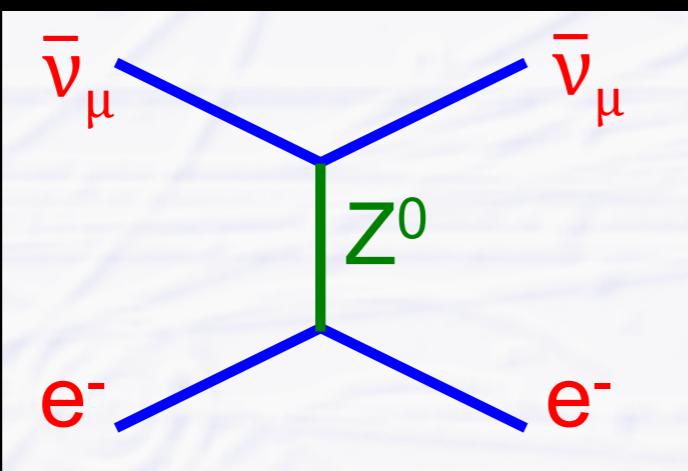
Discovery of neutral currents



- Indirect observation of Z^0

CERN: 1973

- Elastic scattering of neutrino on electron from atomic shell



Experimental Discovery of W & Z Bosons



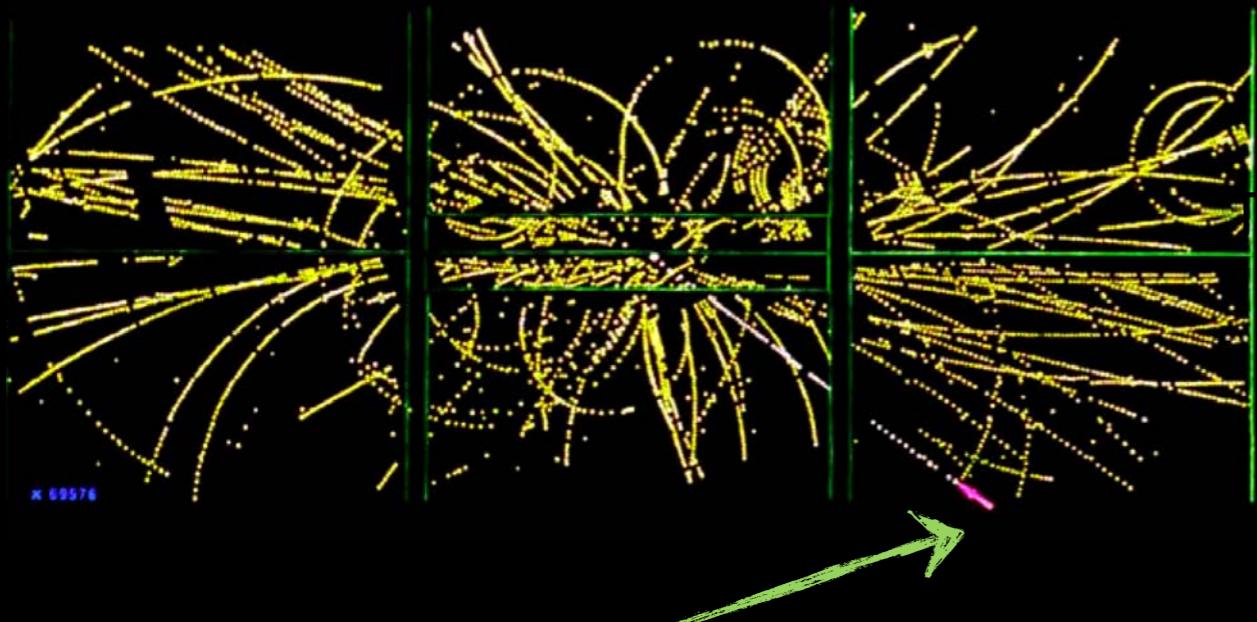
- SPS Accelerator in collision mode:

CERN: 1983

- Proton - anti-proton collision ($p\bar{p}$ S)

- Experimente UA1 & UA2

$$p\bar{p} \rightarrow W_- + X \rightarrow e^- \bar{\nu}_e + X$$



High energy electron



Rubio, van der Meer

Experimental Discovery of W & Z Bosons



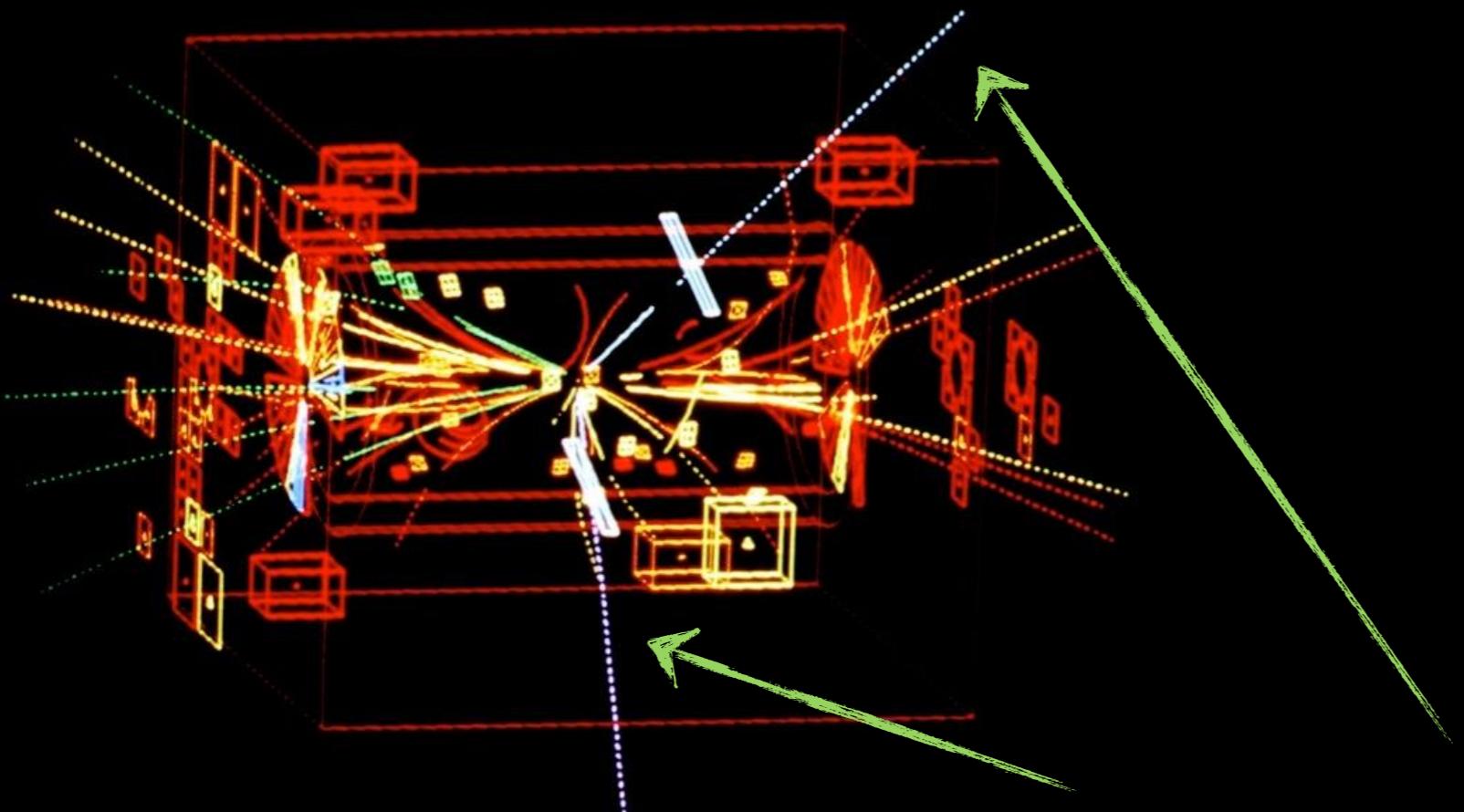
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High energy electrons

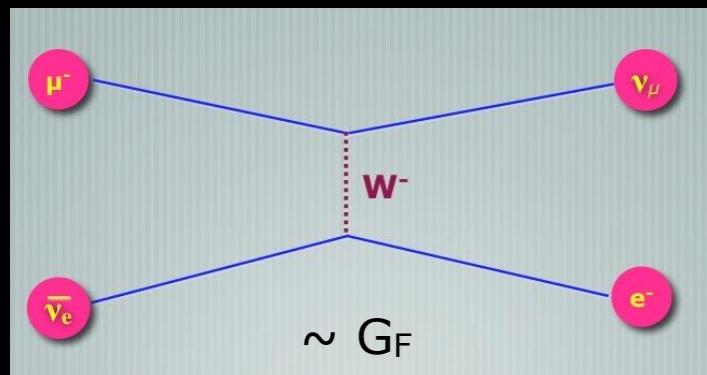


Rubio, van der Meer

Electroweak theory

- Quarks: u, d, s
- Weak interactions

Muon decay

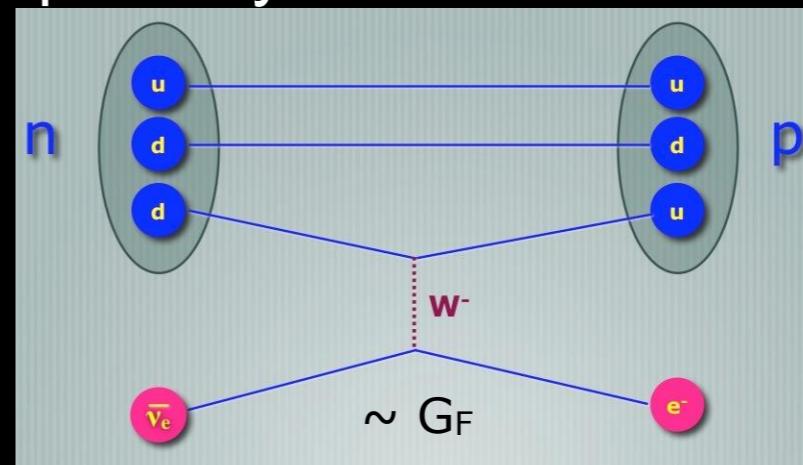


- Leptons: $\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$



weak isospin 1/2 doublets!

β -decay

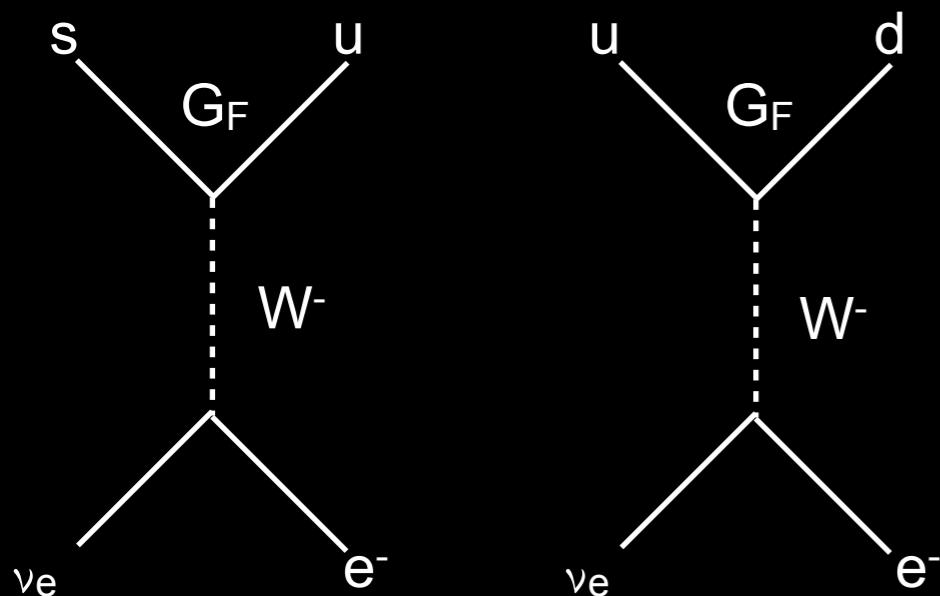


- Coupling strength should be **identical**: same weak charge for quarks & leptons
- measured to be slightly different!

Electroweak theory



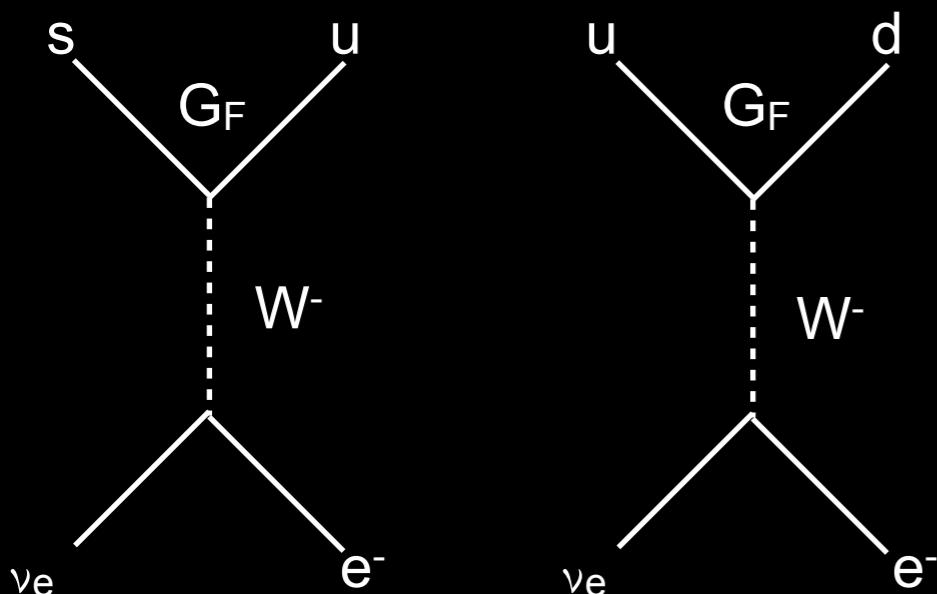
Observation in other particle reactions



Electroweak theory



Observation in other particle reactions

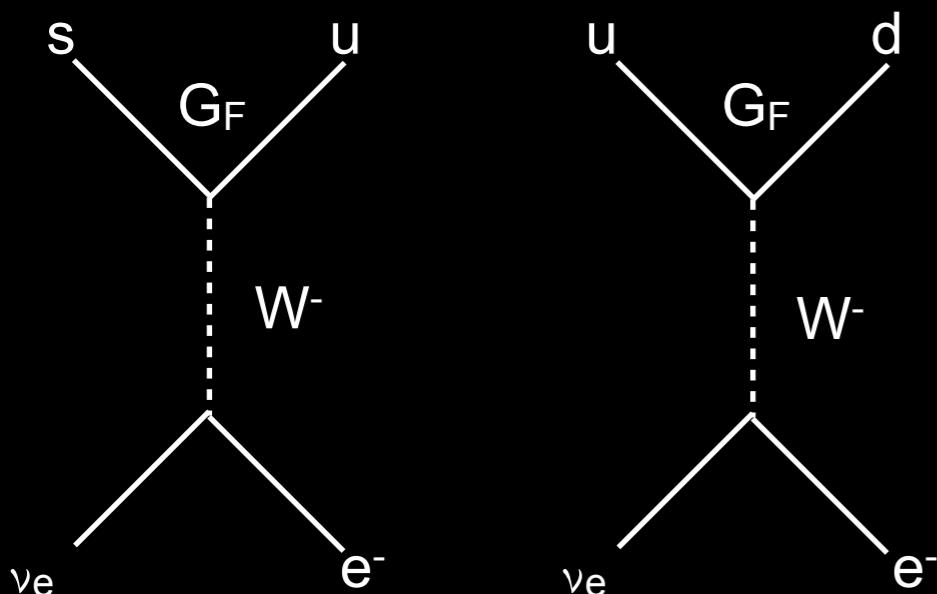


Both reactions should have identical rate!

Electroweak theory



Observation in other particle reactions



Both reactions should have identical rate!

$$\frac{(sdd) \quad (udd)}{(udd) \quad (uud)} \sum^- \rightarrow n + e^- + \bar{\nu}_e \sim 20$$
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Electroweak theory

- Quarks (u,d,s) are **eigenstates** under the **strong force!**
 - Interact via strong force
- Remember: Particles are waves!
 - Can superimpose, interfere, mix (similar to electric signals!)
- Mix of strong quark eigenstates takes part in weak interaction

Eigenstates of strong force != Eigenstates under weak force

Cabibbo: 1963
(5 Jahre nach
Einführung des W
Bosons)

Electroweak theory

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Eigenstates of strong force != Eigenstates under weak force

- Base transformation:
$$\begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \end{pmatrix} = \begin{pmatrix} \cos \theta_C |d\rangle + \sin \theta_C |s\rangle \\ -\sin \theta_C |d\rangle + \cos \theta_C |s\rangle \end{pmatrix}$$
- Eigenstates of weak interaction
 - Quarks:
$$\begin{pmatrix} |u\rangle \\ \cos \theta_C |d\rangle + \sin \theta_C |s\rangle \end{pmatrix} (-\sin \theta_C |d\rangle + \cos \theta_C |s\rangle)$$
 - Leptons:
$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$$

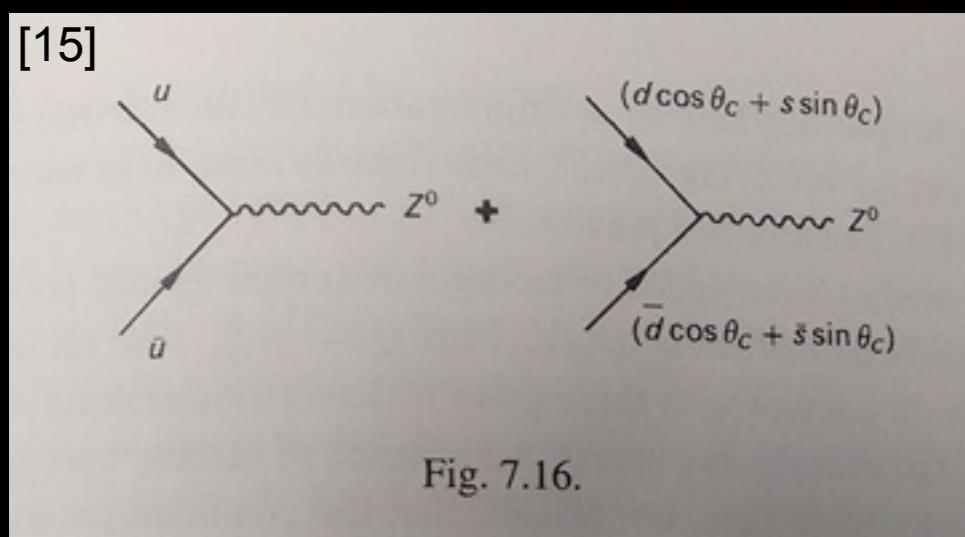
weak isospin doublets

This solves previous mystery!

Further measurements - further surprises ...

- Neutral currents (Z^0 exchange) - no flavor change observed!

$$\frac{(u\bar{s})}{(u\bar{s})} \frac{K^+ \rightarrow \pi^+ + \nu + \bar{\nu}}{(u\bar{u})} \leq 10^{-5}$$



$$^{15} \underbrace{\bar{u}\bar{u} + (\bar{d}\bar{d} \cos^2 \theta_c + \bar{s}\bar{s} \sin^2 \theta_c)}_{\Delta S = 0} + \underbrace{(\bar{s}\bar{d} + \bar{d}\bar{s}) \sin \theta_c \cos \theta_c}_{\Delta S = 1}$$

„Flavor“ change:
not observed!

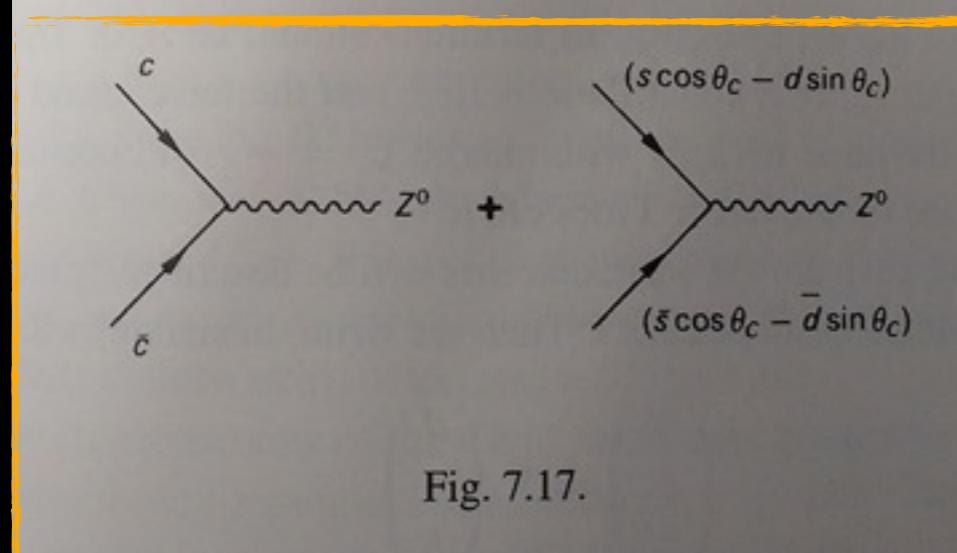
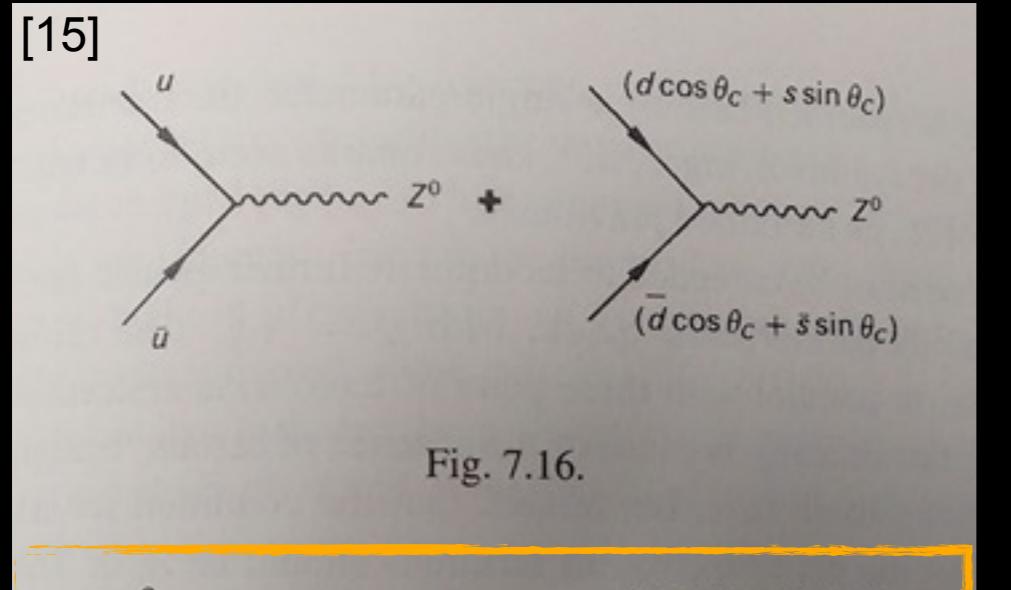
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Glashow, Iliopoulos,
Maiani: 1970

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→ GIM mechanism



New particle: „charm“ quark

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[15]

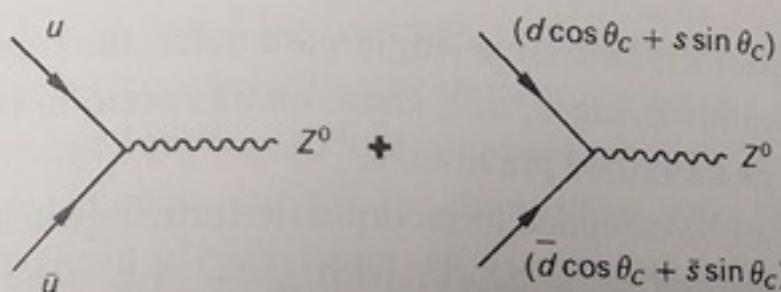


Fig. 7.16.

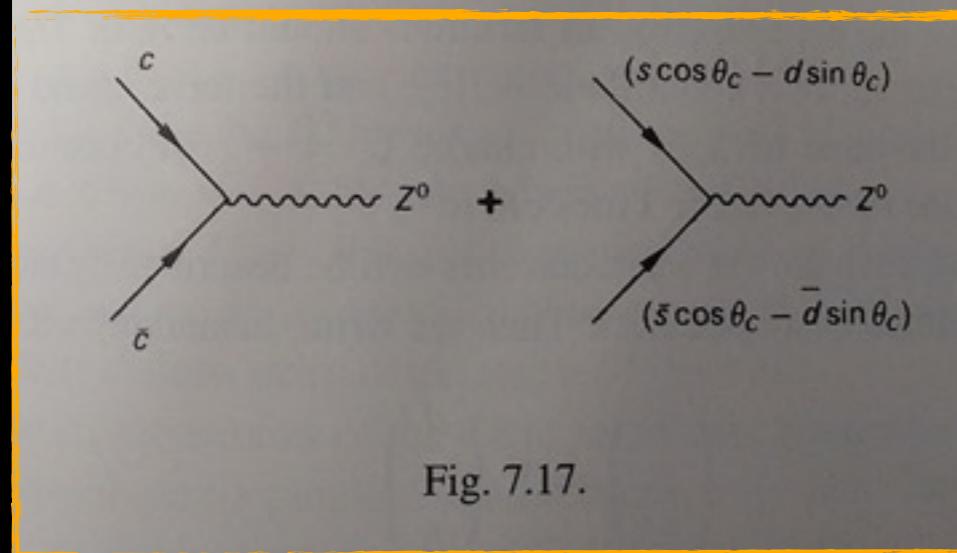


Fig. 7.17.

[15]

$$\underbrace{u\bar{u} + c\bar{c} + (d\bar{d} + s\bar{s}) \cos^2 \theta_c + (s\bar{s} + d\bar{d}) \sin^2 \theta_c}_{\Delta S = 0}$$

$$+(s\bar{d} + \bar{s}d - \bar{s}d - s\bar{d}) \sin \theta_c \cos \theta_c$$

$$\Delta S = 1$$

„Flavor“ change: = 0

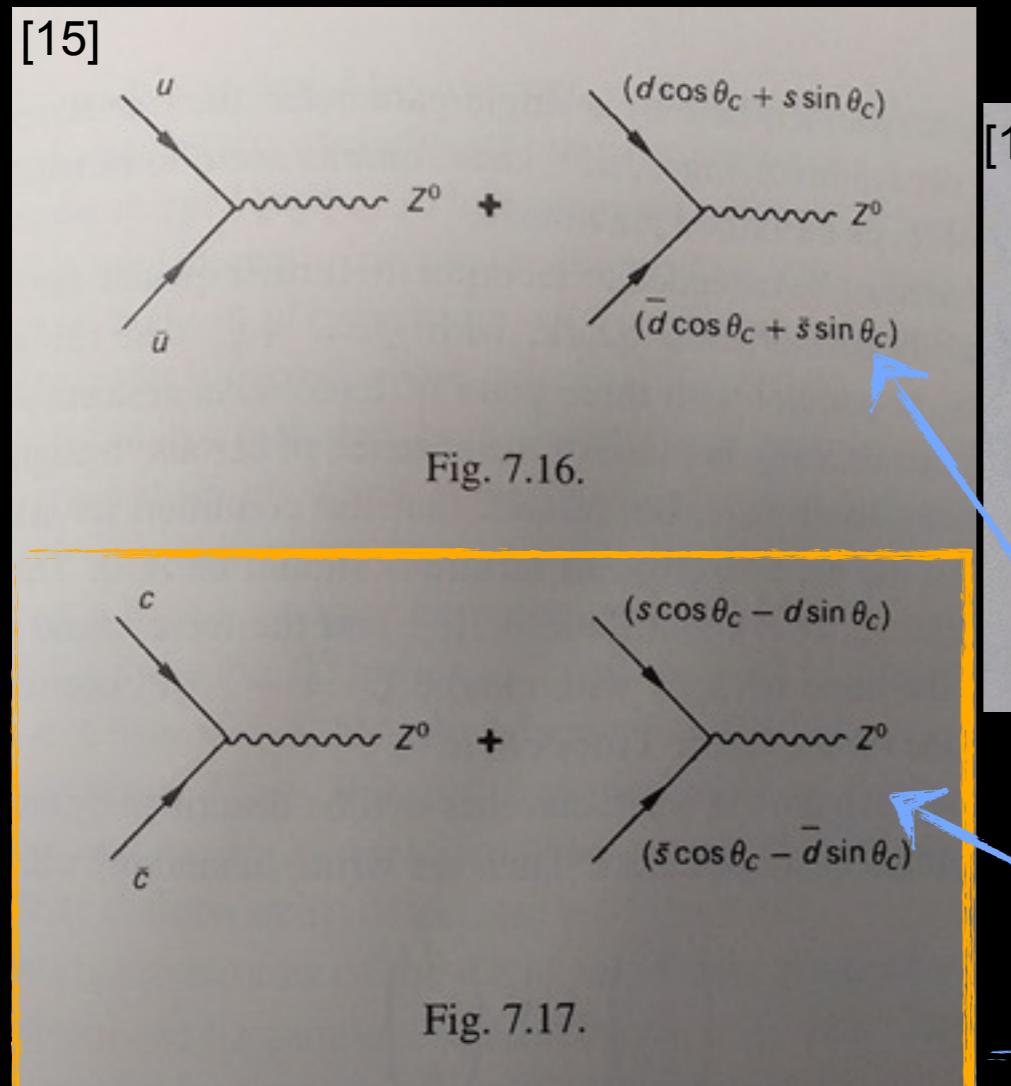
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„Flavor“ change: = 0

Quantum mechanical: interference of diagrams

Further measurements - further surprises ...

weak eigenstates

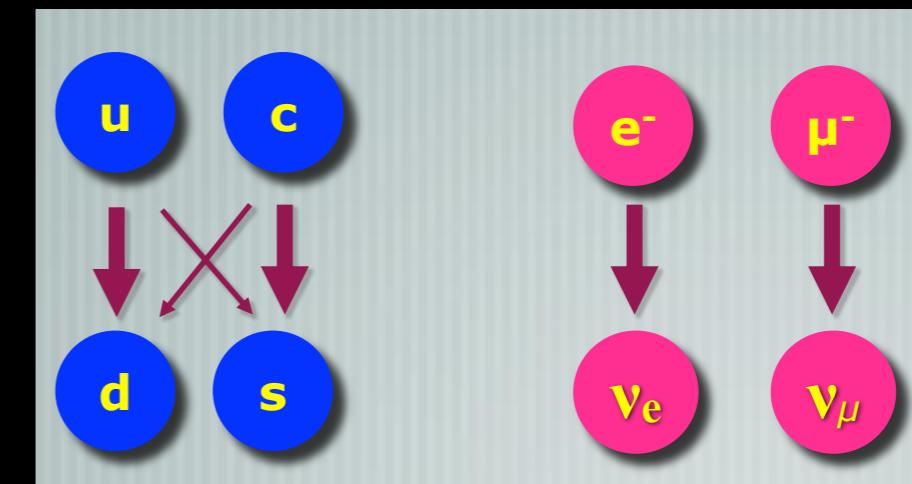
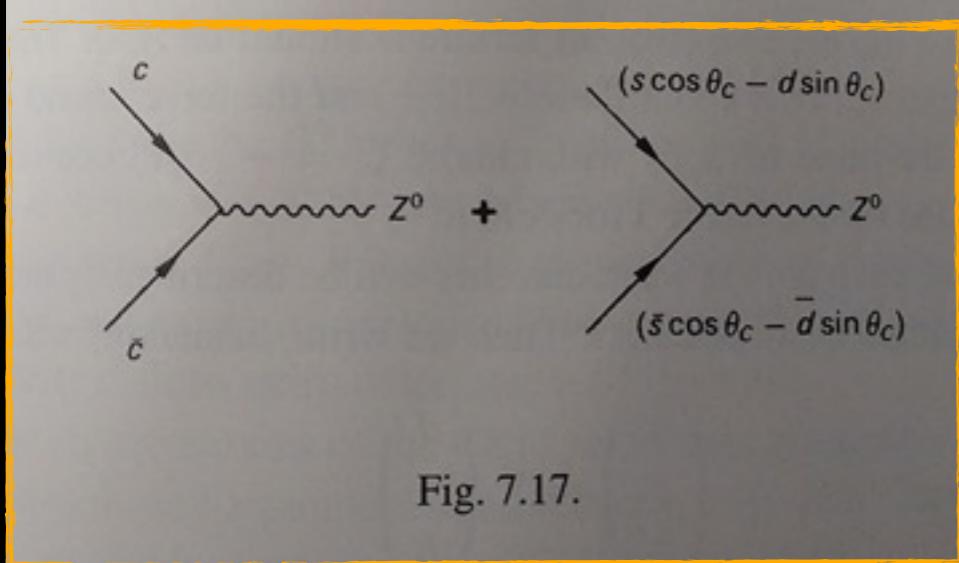
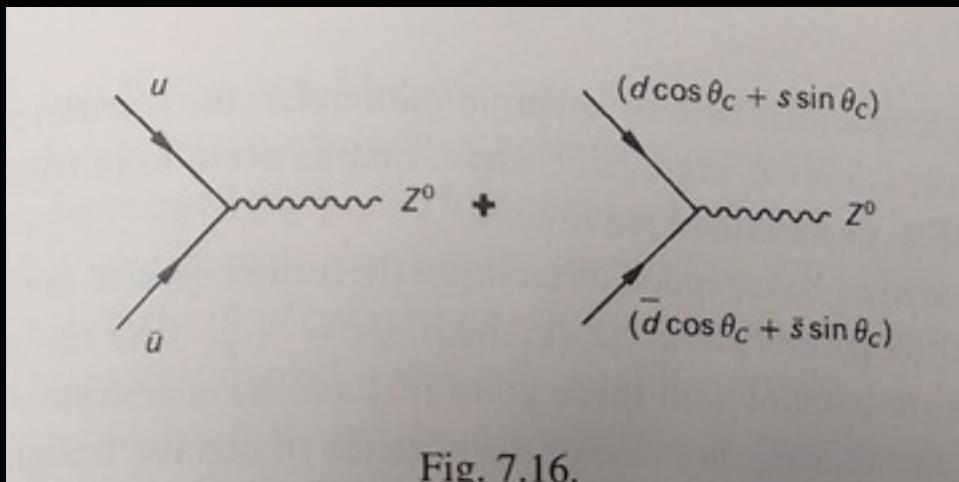
$$\left(\begin{array}{c} |u\rangle \\ \cos\theta_C|d\rangle + \sin\theta_C|s\rangle \end{array} \right) \left(\begin{array}{c} |c\rangle \\ -\sin\theta_C|d\rangle + \cos\theta_C|s\rangle \end{array} \right)$$

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Rotation in 'flavor' space

New particle: „charm“ quark



Further measurements - further surprises ...



weak eigenstates

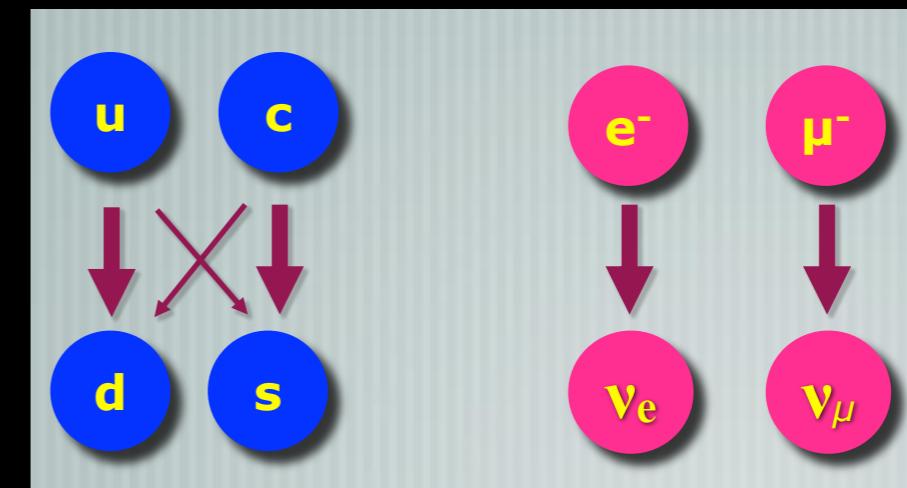
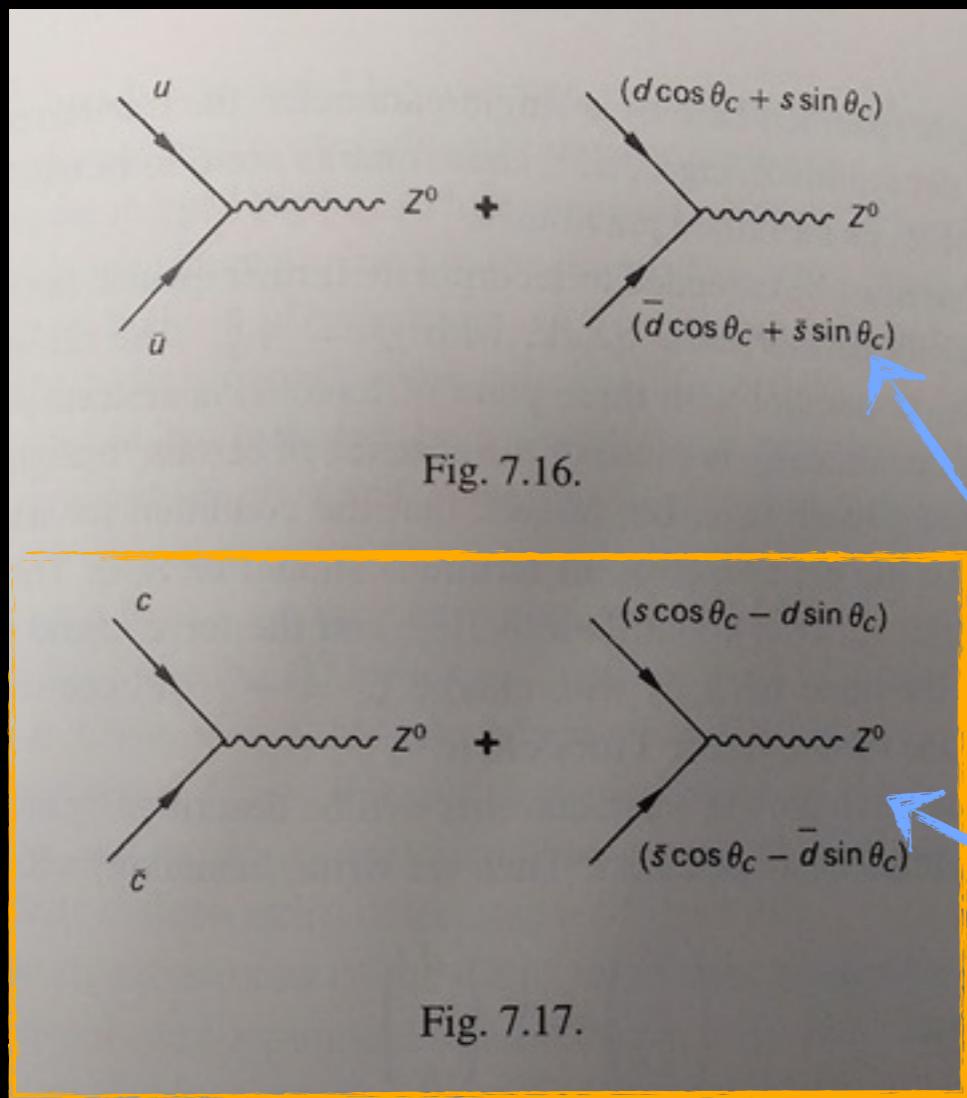
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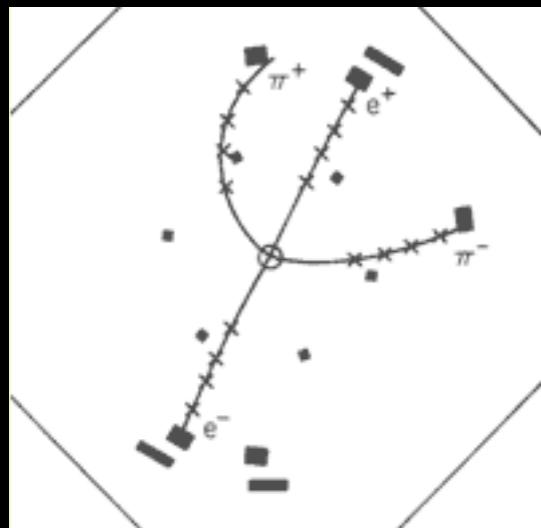
Quantum mechanical: interference of diagrams

Discovery of the charm quark

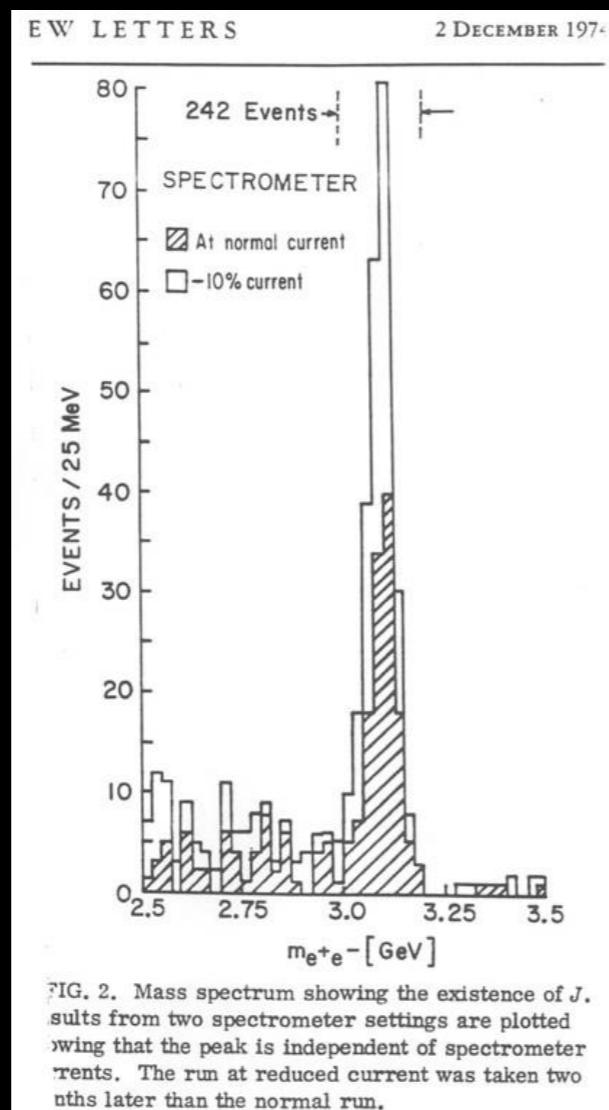
- Dedicated experiments
 - Simultaneously found by 2 independent groups

Richter (Slac) &
Ting (Brookhaven):
November 1974

Richter: Ψ



Ting: J



Particle labeled J/Ψ !

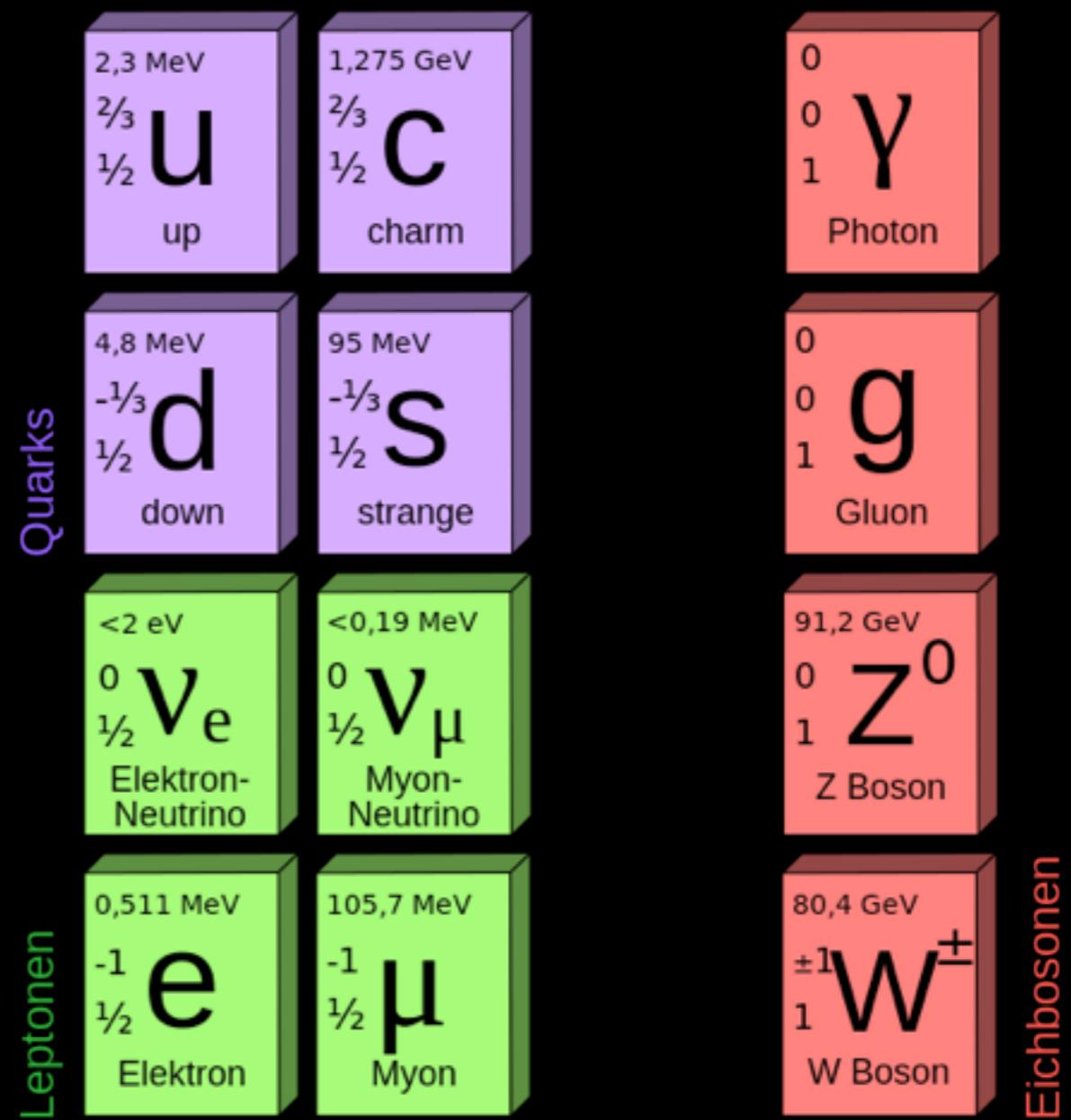
- Bound state of charm & anti-charm quarks
- Decay exclusively via weak interaction
- long lived! (10^{-20} sec)
- => narrow resonance (mass peak)

What we learned so far



- Elementary particles

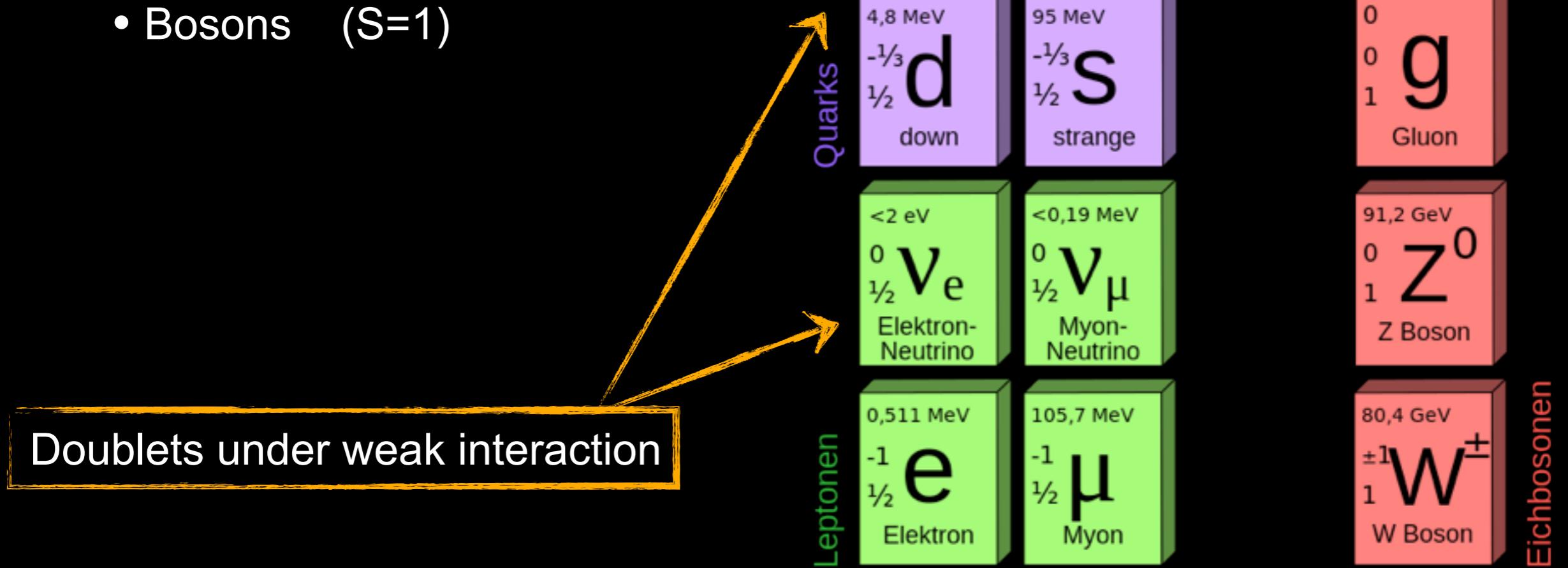
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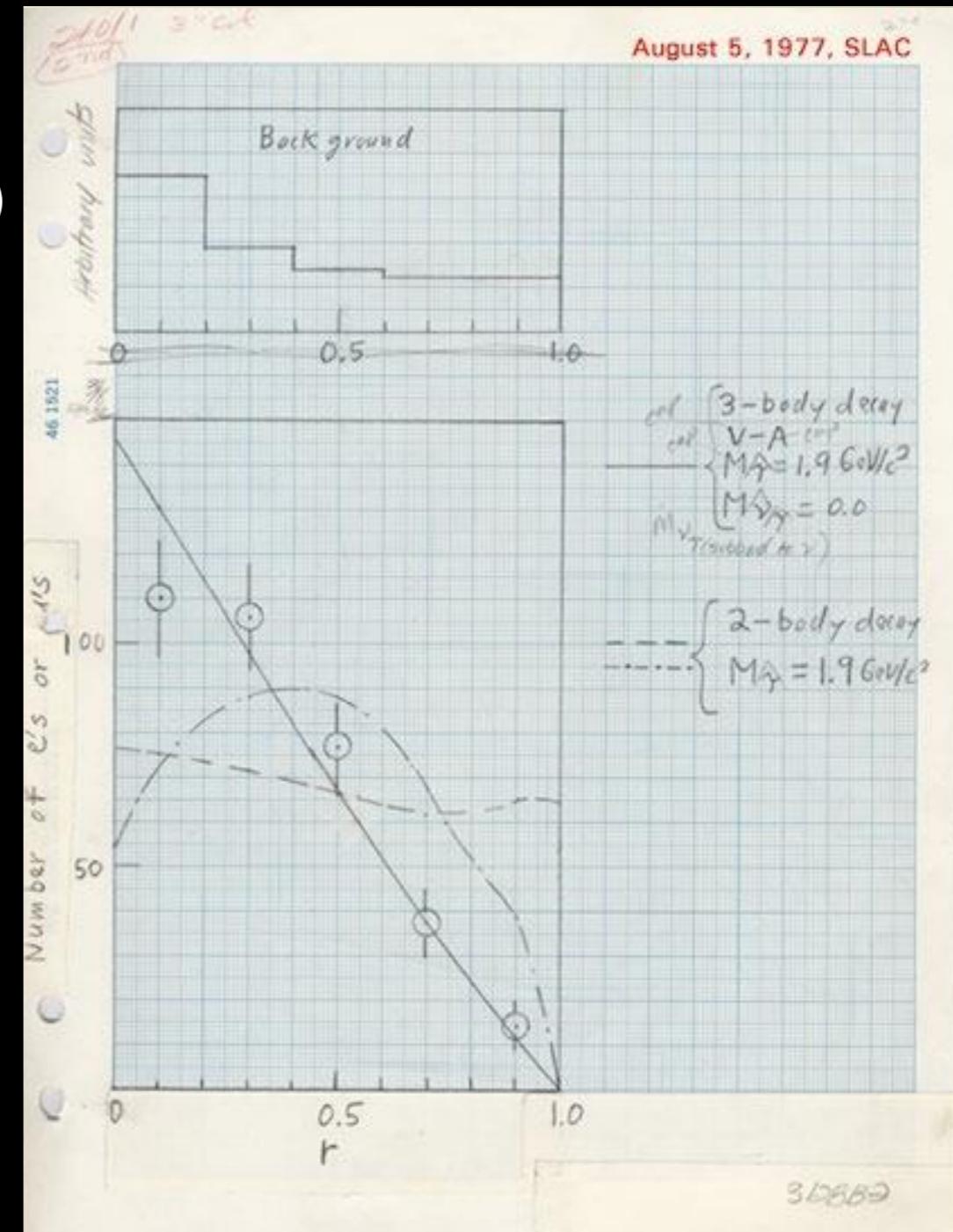
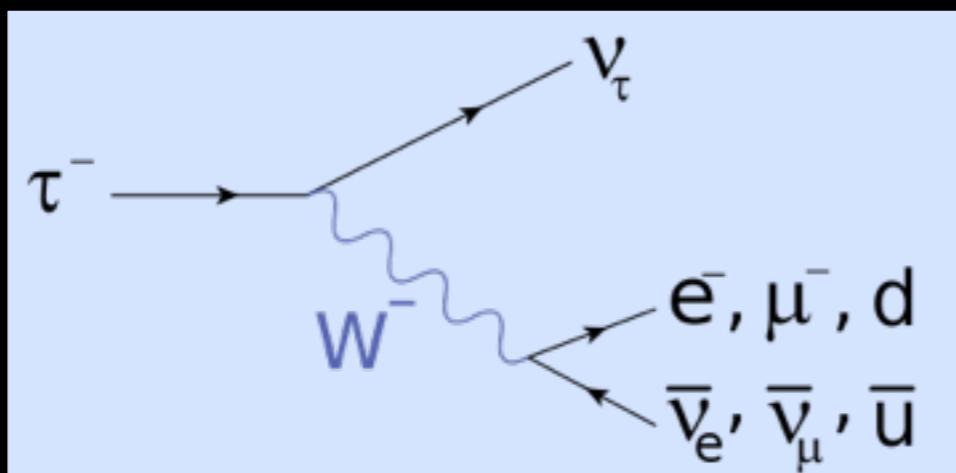
What else?

- Discovery of a 3rd lepton

SLAC: 1975

- Called tauon: τ
- Yet another, heavy copy of electron ($3500 m_e$)

- Requires existence of another neutrino
- As well as 2 additional quarks



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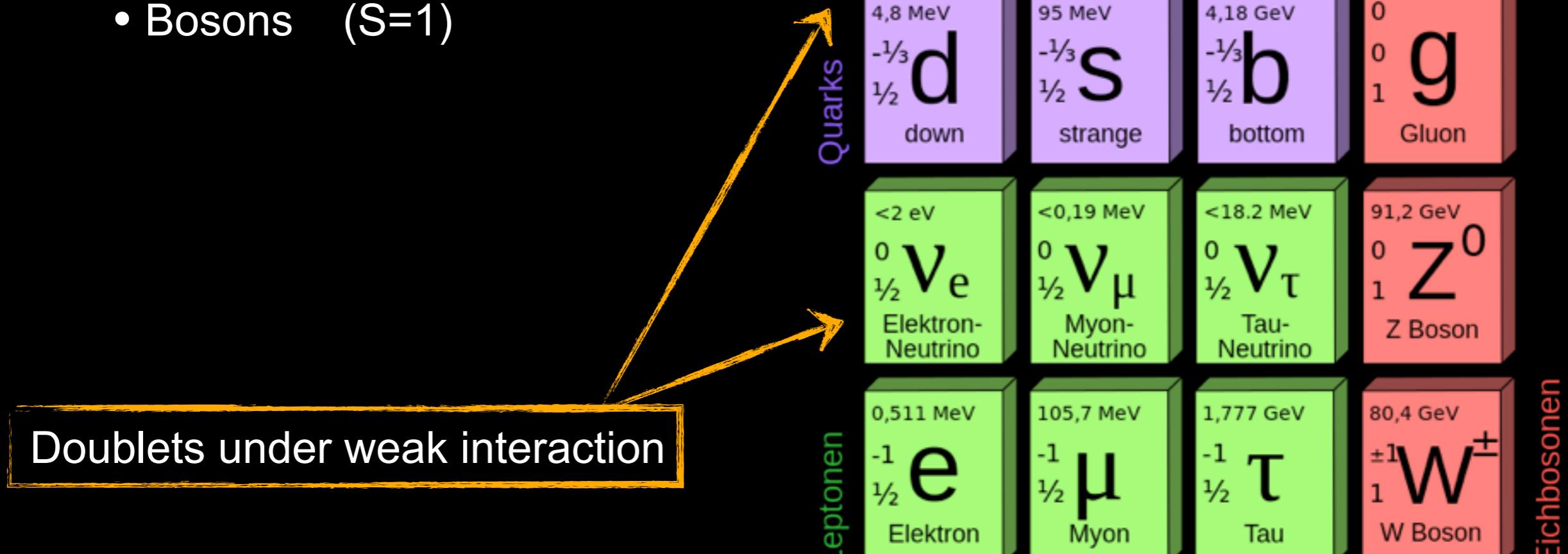
	1.	2.	3.	generation
Quarks	2,3 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1,275 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	173,07 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 Photon
	4,8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	95 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4,18 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 Gluon
Leptonen	<2 eV 0 $\frac{1}{2}$ ν_e Elektron-Neutrino	<0,19 MeV 0 $\frac{1}{2}$ ν_μ Myon-Neutrino	<18,2 MeV 0 $\frac{1}{2}$ ν_τ Tau-Neutrino	91,2 GeV 0 1 Z^0 Z Boson
Eichbosonen	0,511 MeV -1 $\frac{1}{2}$ e Elektron	105,7 MeV -1 $\frac{1}{2}$ μ Myon	1,777 GeV -1 $\frac{1}{2}$ τ Tau	80,4 GeV ± 1 1 W^+ W Boson

Bottom & Top discovered @ Fermilab
 1977 1995

What we learned so far

- Elementary particles

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Bottom & Top discovered @ Fermilab
1977 1995

3 Generations ...



- Weak interaction: Base transformation by 3x3 matrix

Cabibbo, Kobayashi, Maskawa:
(Nobelpreis 2008)

- Transitions within & between generations

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Diagram illustrating CKM matrix elements and their connections to various particle transitions:

- V_{ud} : e.g. $n \rightarrow p \bar{e} v$
- V_{cd} : e.g. $D \rightarrow \pi \ell \nu$
- V_{td} : e.g. $K_L \rightarrow \pi \ell \nu$
- V_{us} : e.g. $B \rightarrow D \ell \nu$
- V_{cs} : e.g. $B \rightarrow \pi \ell \nu$
- V_{ts} : e.g. $t \rightarrow W b$
- V_{ub} : e.g. $D \rightarrow K \ell \nu$
- V_{cb} : e.g. $B \rightarrow D \ell \nu$
- V_{tb} : e.g. $t \rightarrow W b$

BB oszillations

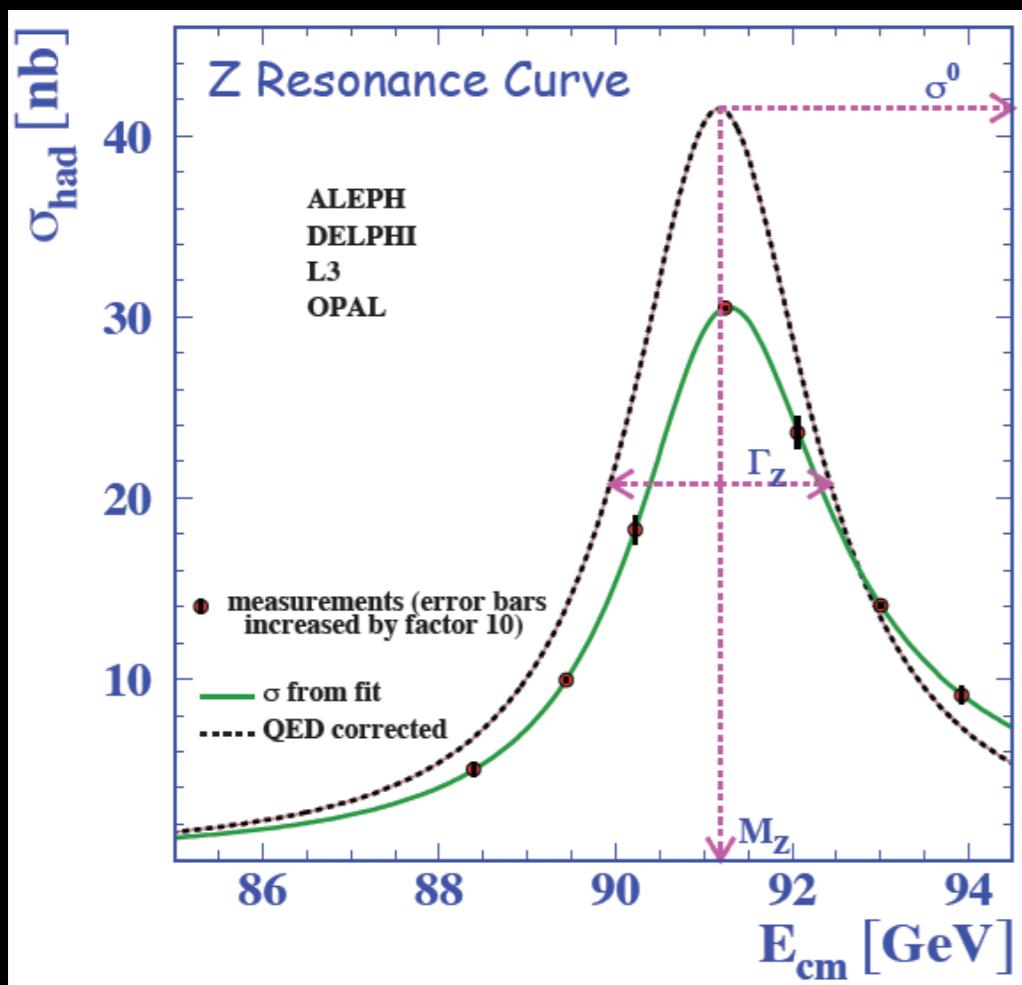
- Free parameters: 3 angles + 1 complex phase
- Essential to explain 'CP' violation:
 - CP violation: physic laws can distinguish between matter & anti-matter!
 - Requires at least 3 generations
 - Initial trigger to postulate a 3rd generation

Are there more than 3 generations

- Study of Z boson in detail:

Mass distribution: Breit-Wigner curve
 → harmonic oscillator

Measured in reaction: $e^+ e^- \rightarrow Z \rightarrow e^+ e^-$



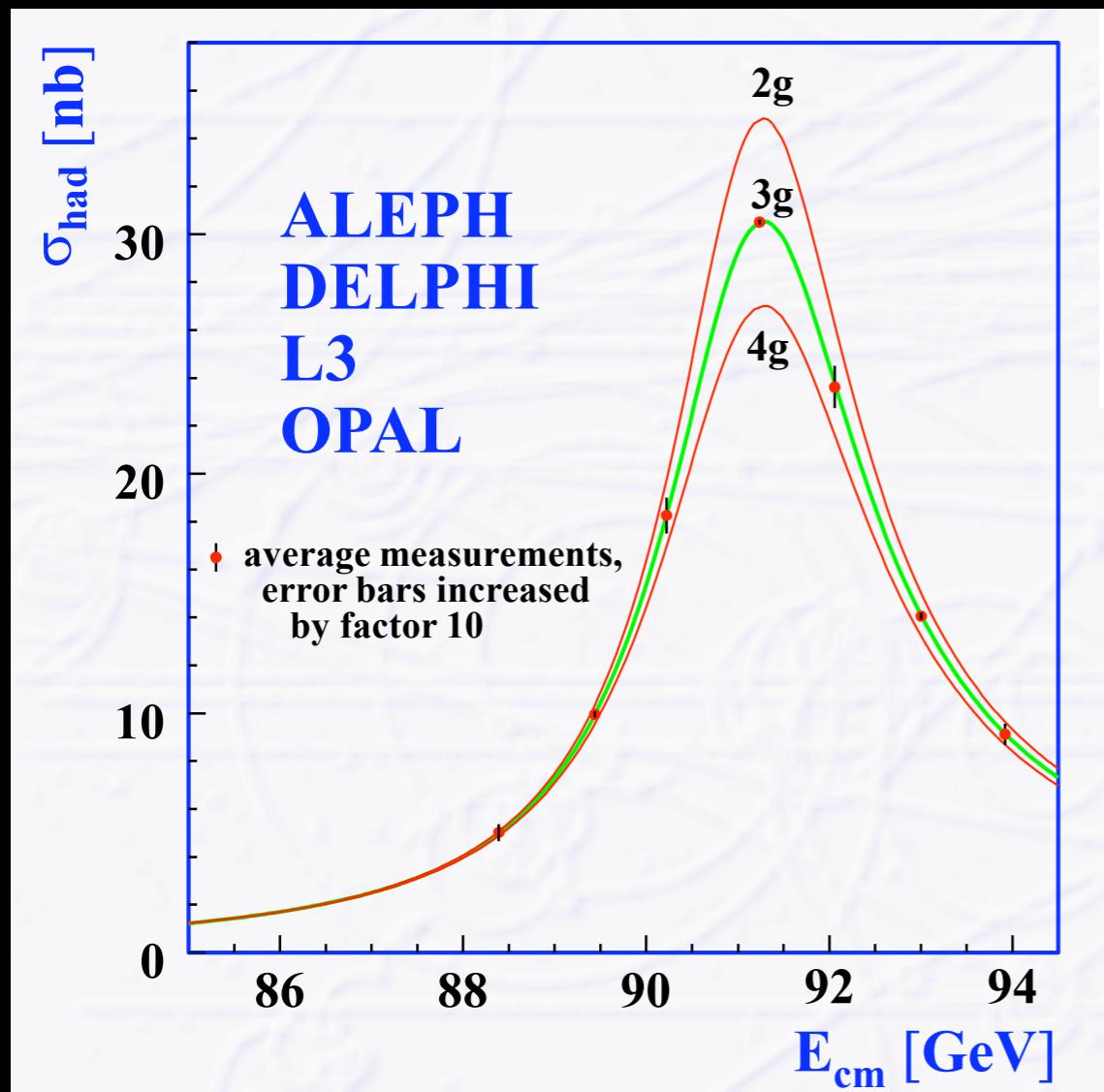
Exact shape depends on

- Vacuum fluctuations
- Radiation of photons
- Virtual photons between electrons

Gibt es mehr als 3 Familien? - Nein

- Untersuchung des Z-Teilchens im Detail:

Measured in reaction: $e^+ e^- \rightarrow Z \rightarrow e^+ e^-$



Exact shape depends on

- Vacuum fluctuations
- Radiation of photons
- Virtual photons between electrons
- Number of **light** neutrino flavours
 - Width depends on accessible decay channels

Standard model of particle physics



• Elementary particles

- Constituents of matter
 - Fermions ($S=1/2$)
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1. 2. 3. generation

Quarks	2,3 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1,275 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	173,07 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 γ Photon	125,9 GeV 0 0 H Higgs Boson
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Doublets under weak interaction

Quarks

Leptonen

Eichbosonen

Questions?

Higgs
boson

Higgs

- Higgs mechanism has essential role in theory of electroweak interactions
- Why is Higgs mechanism so import for particle physics?

Higgs,
Englert,
Brout: 1964

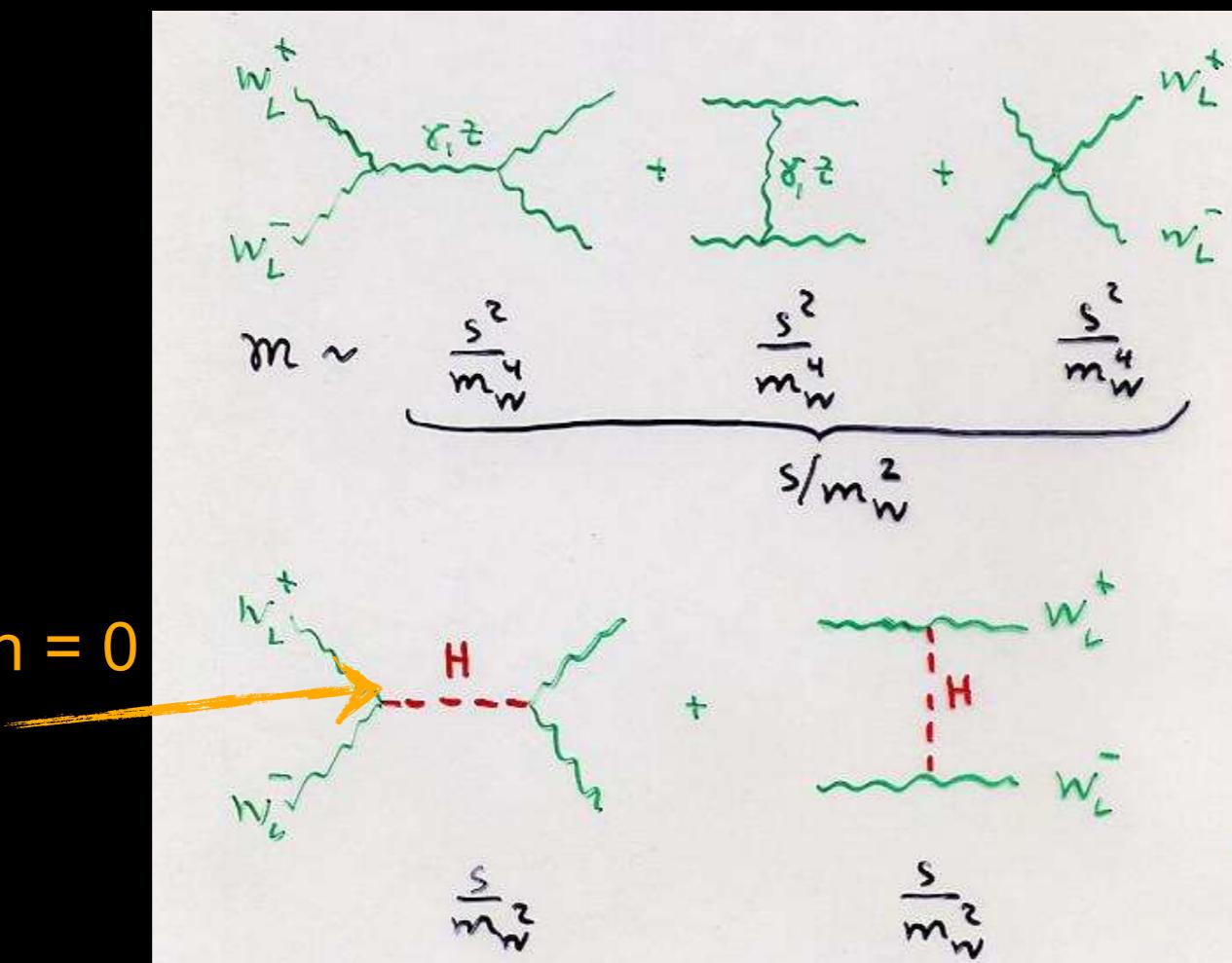
- All **gauge bosons massless** in standard model!
 - However, W & Z Bosons are massive particles!
 - Conservation of probability!

Higgs

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Scattering of longitudinally polarised W bosons:

Interaction probability > 1 for large Q^2 !

Destructive interference
→ probability < 1

Has to be
,scalar': Spin = 0

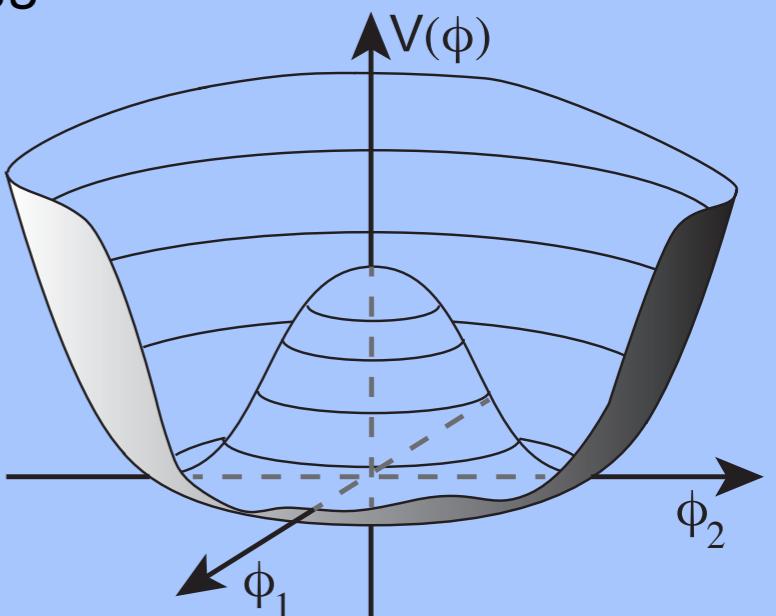
Masses of gauge bosons

- All gauge bosons are massless within theory!
- If mass added explicitly: **breakdown of theory!!**
- → Gauge invariance is lost
- Dynamic emergence of mass:
 - Interaction with scalar field
 - Field spreads through entire universe
 - Leads to mass terms in equations

- Symmetry of potential minimum ,spontaneously' broken
- Breaking of electroweak symmetry!
 - Manifestation of electromagnetism & weak interactions
- Similar processes known from solid state physics (superconductivity)

$$V(\phi^\dagger \phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad m, \lambda \in \mathbb{R}.$$

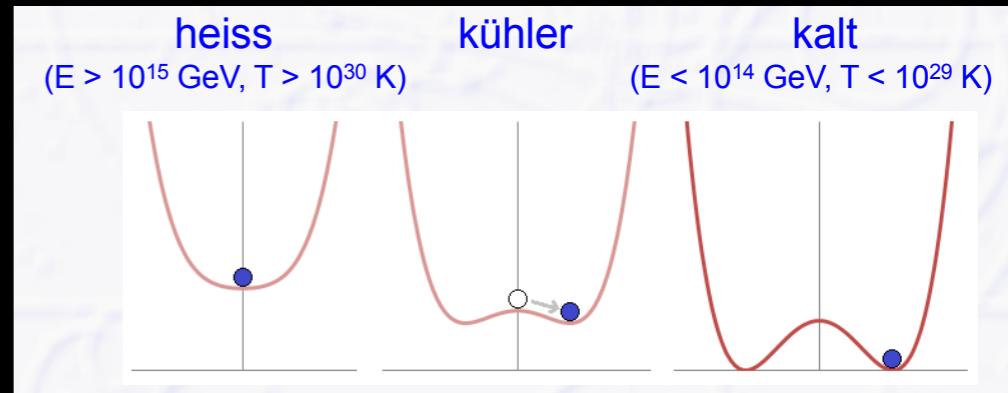
Higgs - Potential



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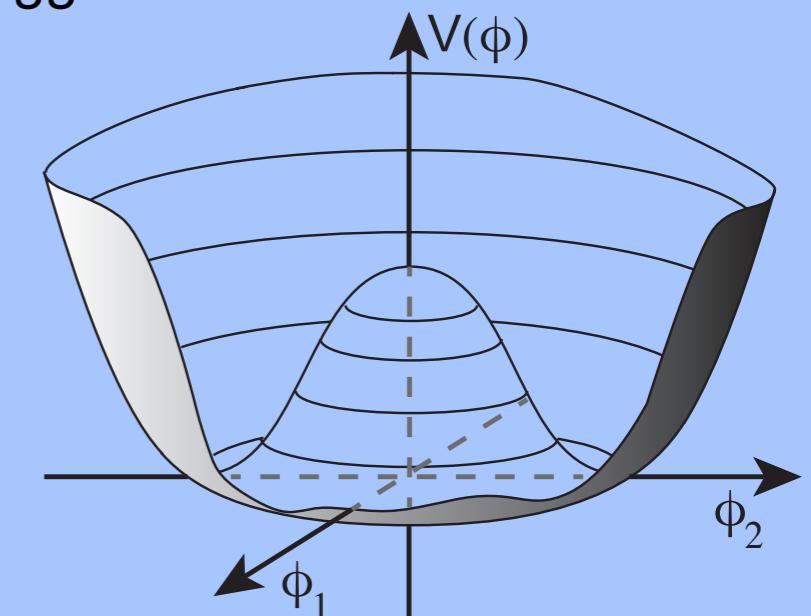


Large energy density

Low energy density

$$V(\phi^\dagger \phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad m, \lambda \in \mathbb{R}.$$

Higgs - Potential



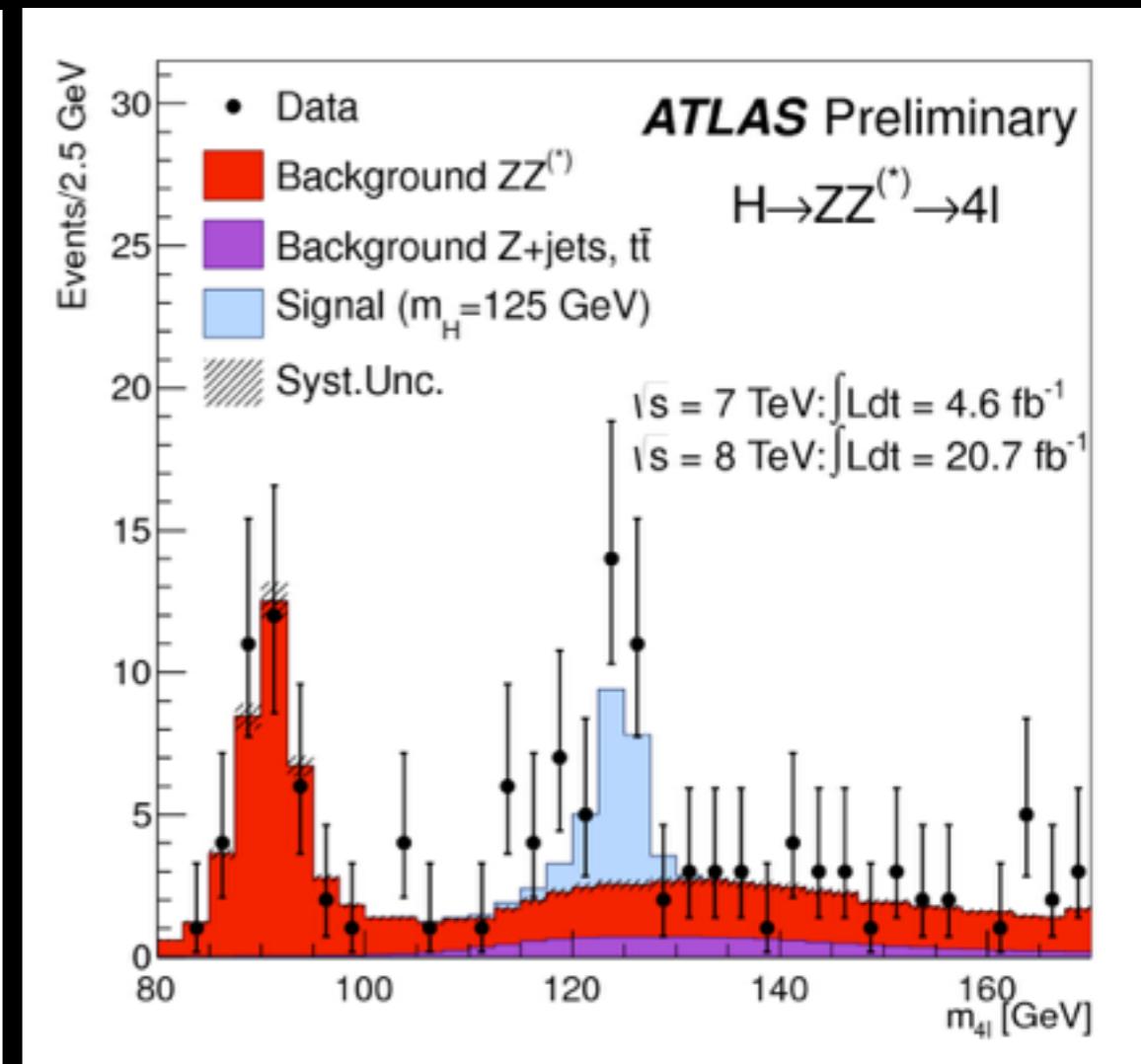
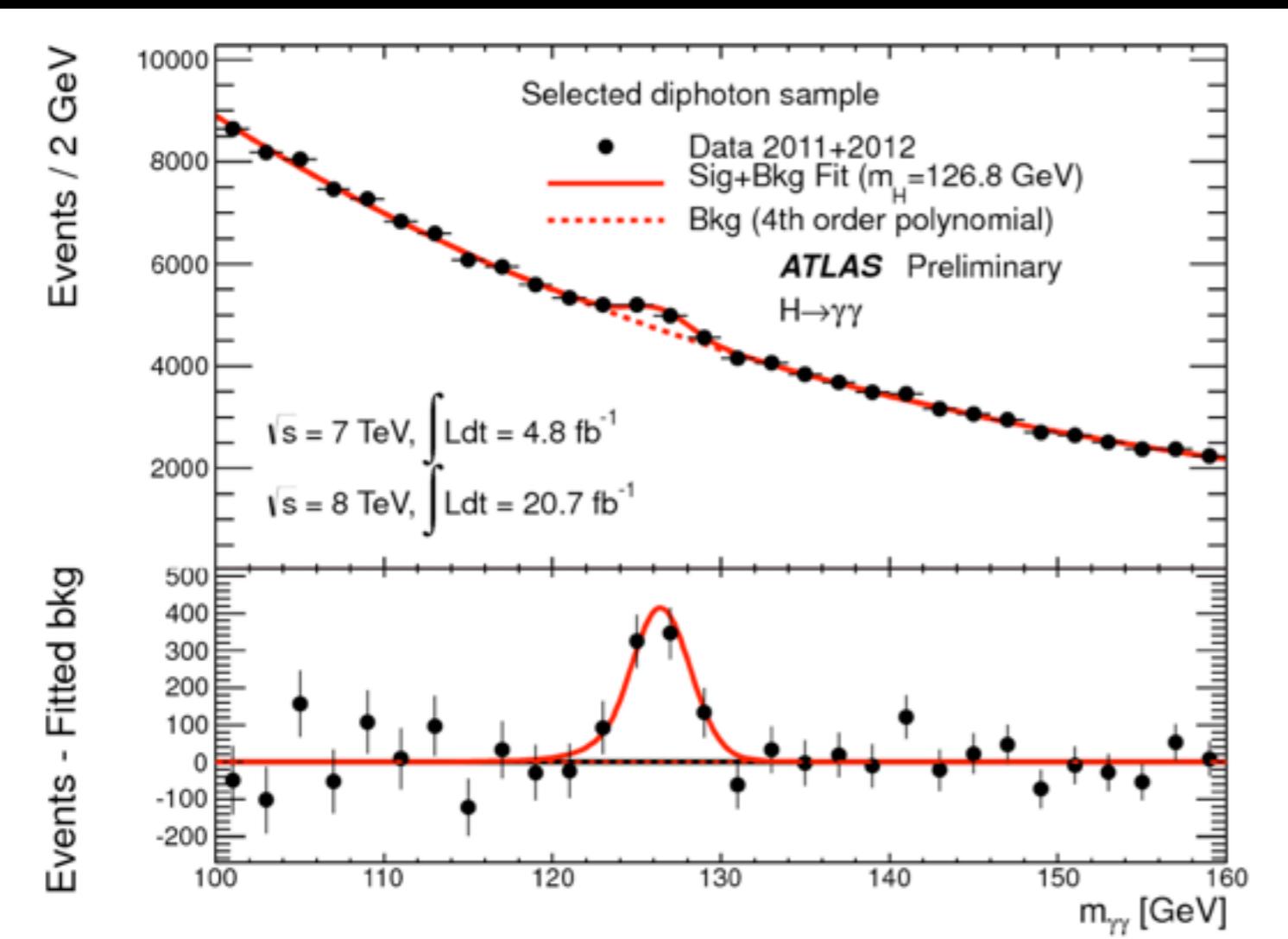
The Higgs particle

- Higgs mechanism requires **particle with spin = 0** (scalar)
 - Boson of higgs field, mediator of interactions with Higgs field

The Higgs particle

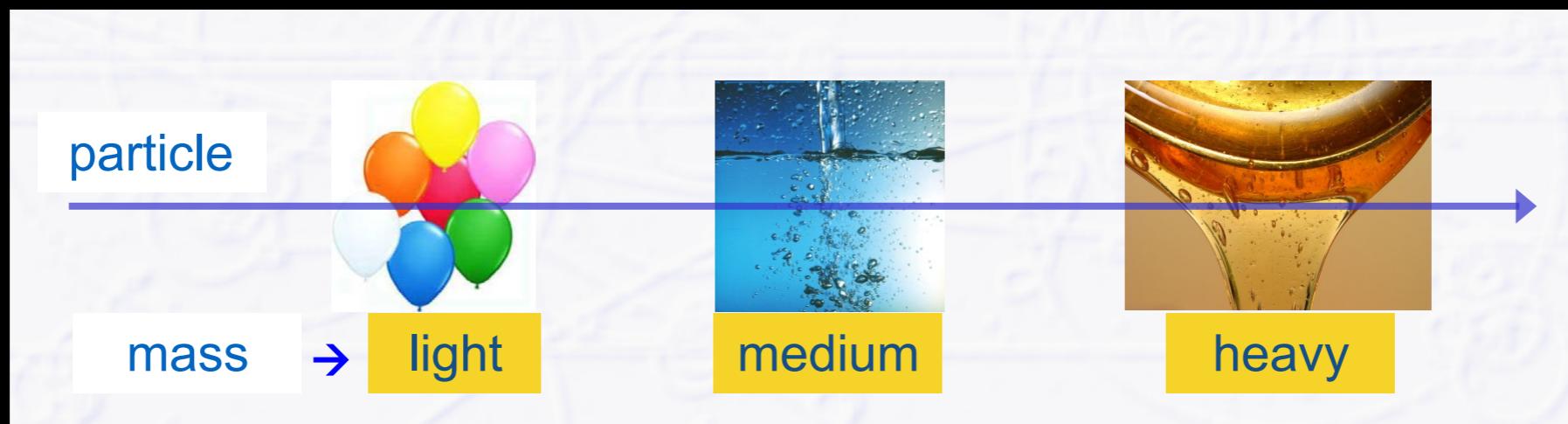
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CERN
(ATLAS &
CMS): 2012



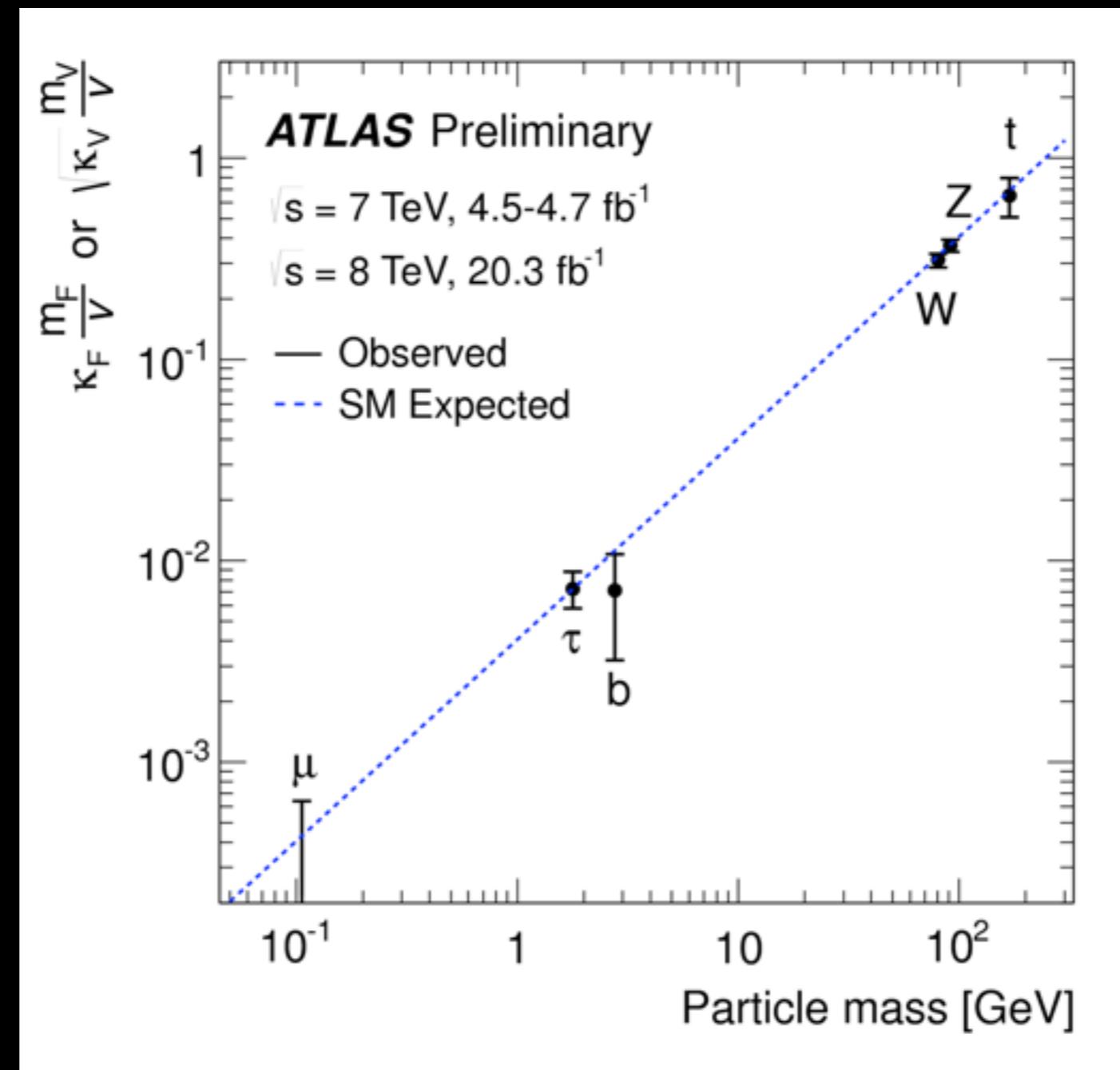
How the particles grew massive

- Mass of particles depends on coupling strength with Higgs field:
- Directly responsible for masses of **vector bosons**: $g_V \sim m_V^2$
- Broken symmetry → goldstone bosons → available degrees of freedom absorbed in 3 massive and 1 massless gauge boson (\Rightarrow base rotation)
- What about fermions?
 - Yukawa interaction with Higgs field
 - **Explicitly added**
 - $g_F \sim m_F$



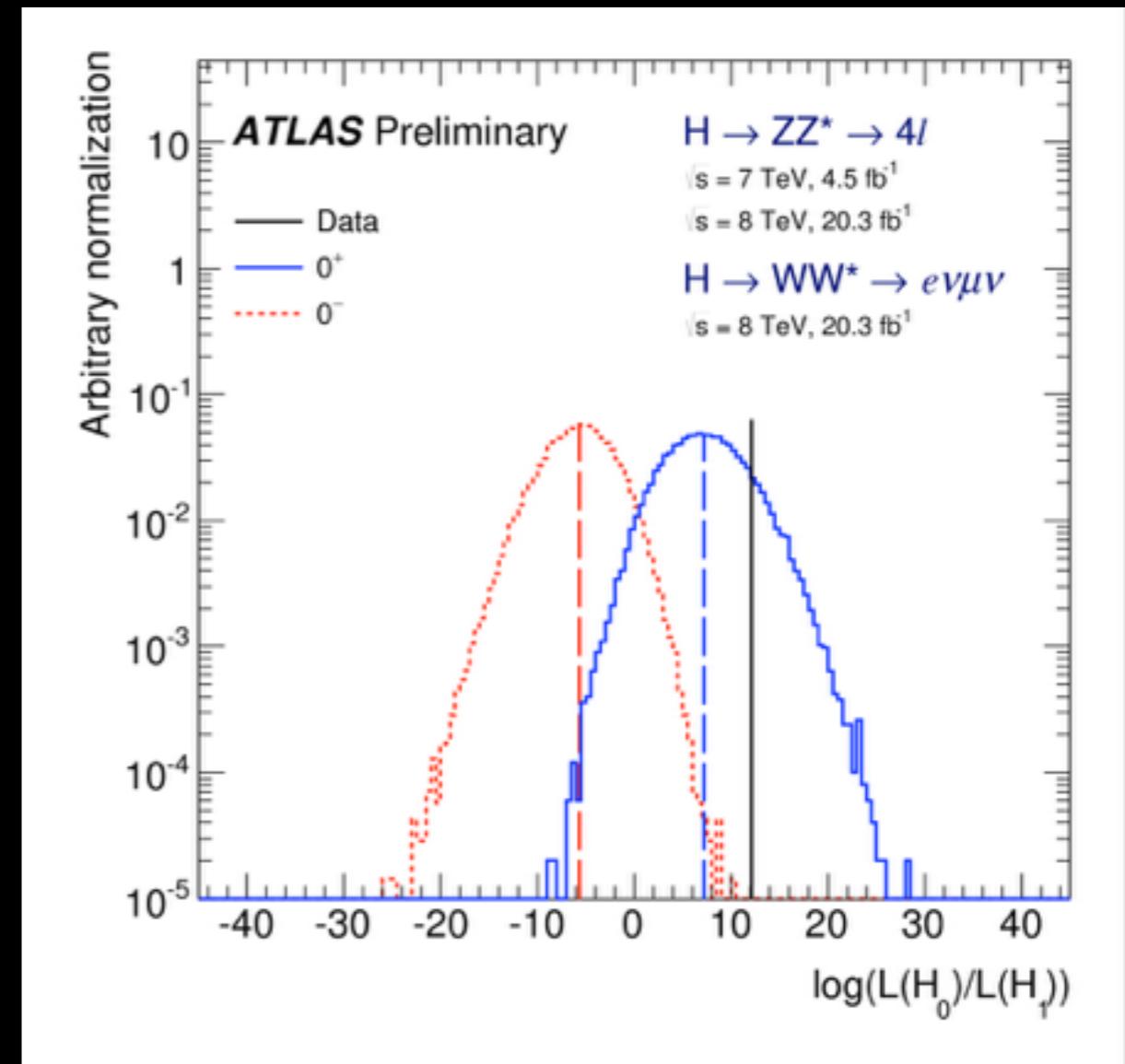
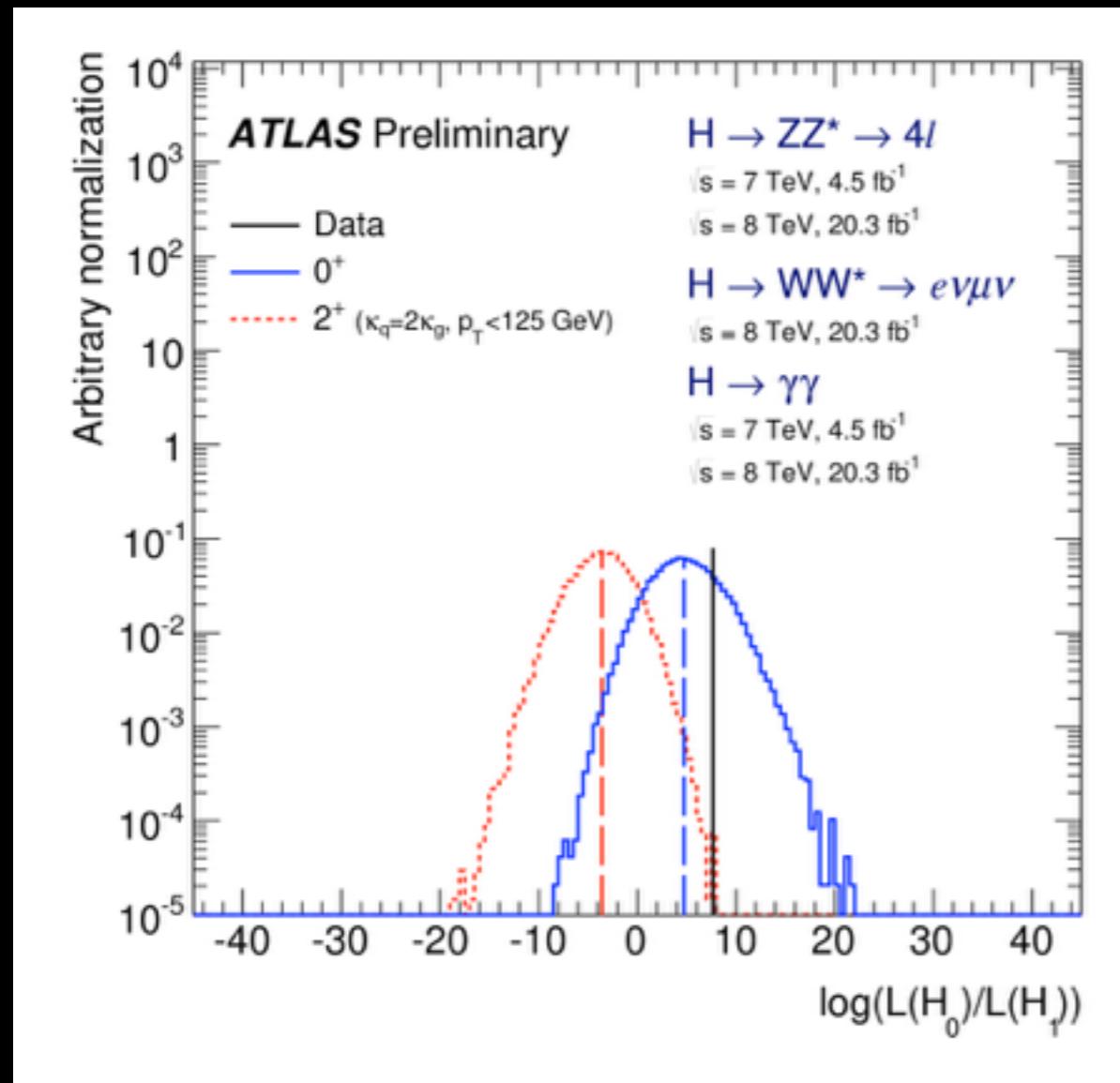
Higgs coupling - mass dependence

- Coupling or $\sqrt{\text{coupling}}$
- V & F on straight line



Properties of the Higgs boson - Spin & Parity

- Is it really the standard model Higgs particle?
- Spin:
 - integer, as decaying to $\gamma\gamma$
- Parity:
 - Even or Odd?



- Comparison of measurement with various predictions!
- Agreement displayed as 'likelihood'
- Many 'pseudo experiments' => random fluctuations of predictions

Standard model of particle physics



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Doublets under weak interaction

Quarks

Leptonen

In summary

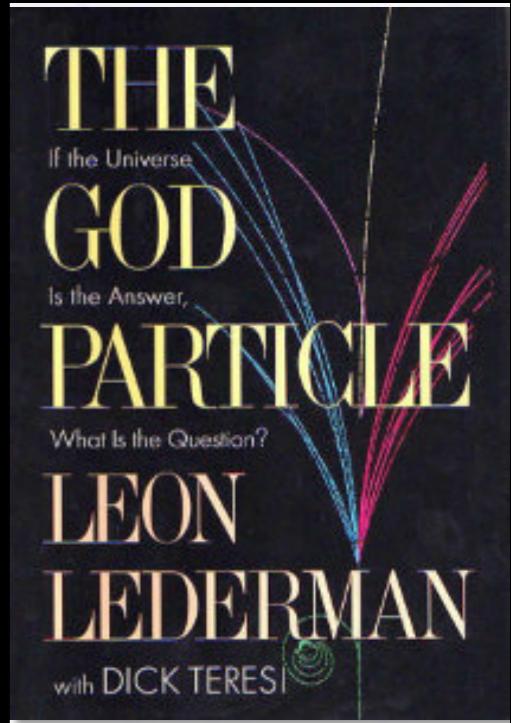
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- Breaking of electroweak symmetry consistently described
- Massive & Massless gauge bosons
 - Difference between gauge boson masses

In summary

- Masses are dynamically generated
- Unification of electromagnetic & weak interactions
- Breaking of electroweak symmetry consistently described
- Massive & Massless gauge bosons
 - Difference between gauge boson masses
- Why is fermion mass $\neq 0$?
- Why are fermion masses so different from each other?
- What determines „mass hierarchy“? [2 MeV (u) -- 173 GeV (t)]

One more statement on the Higgs particle

- Leon Lederman (ex director general of Fermilab), Nobelprice 1988
 - Published book on particle physics & the Higgs particle (1993)
 - Introduced „God particle“
- But why?

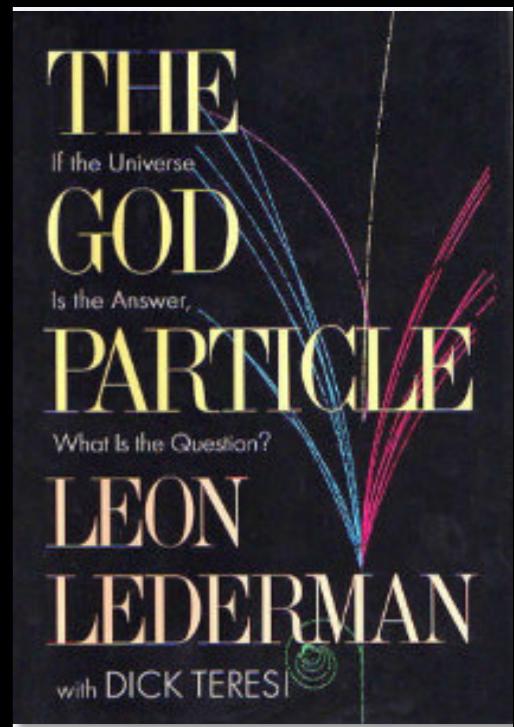


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"so central to the state of physics today, so crucial to our final understanding of the structure of matter, yet so elusive"

but "the publisher wouldn't let us call it the **Goddamn Particle**, though that might be a more appropriate title, given its villainous nature and the expense it is causing."



Neutrinos

↳ [Introduction](#) ↳ [Properties](#)

Sources of neutrinos

- Sun / Supernovae: Nuclear fusion



- Nuclear reactors: fission
 - β - decay of spallation products and neutrons $\rightarrow \nu_e$
- Atmosphere:
 - Decaying muons from cosmic rays $\rightarrow \nu_\mu, \nu_e$
- Accelerators:
 - Muon decays $\rightarrow \nu_\mu, \nu_e$

Neutrino oscillations

- Detection of stellar neutrinos in Homestake experiment: Davis Jr.: 1960ies
 - Measured neutrino flux 50% of expectation from sun's luminosity

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 - What happens to the neutrinos within the earth?
- Neutrinos can oscillate from one flavour to another!
 - Note: only electron & muon neutrinos are detected in those experiments

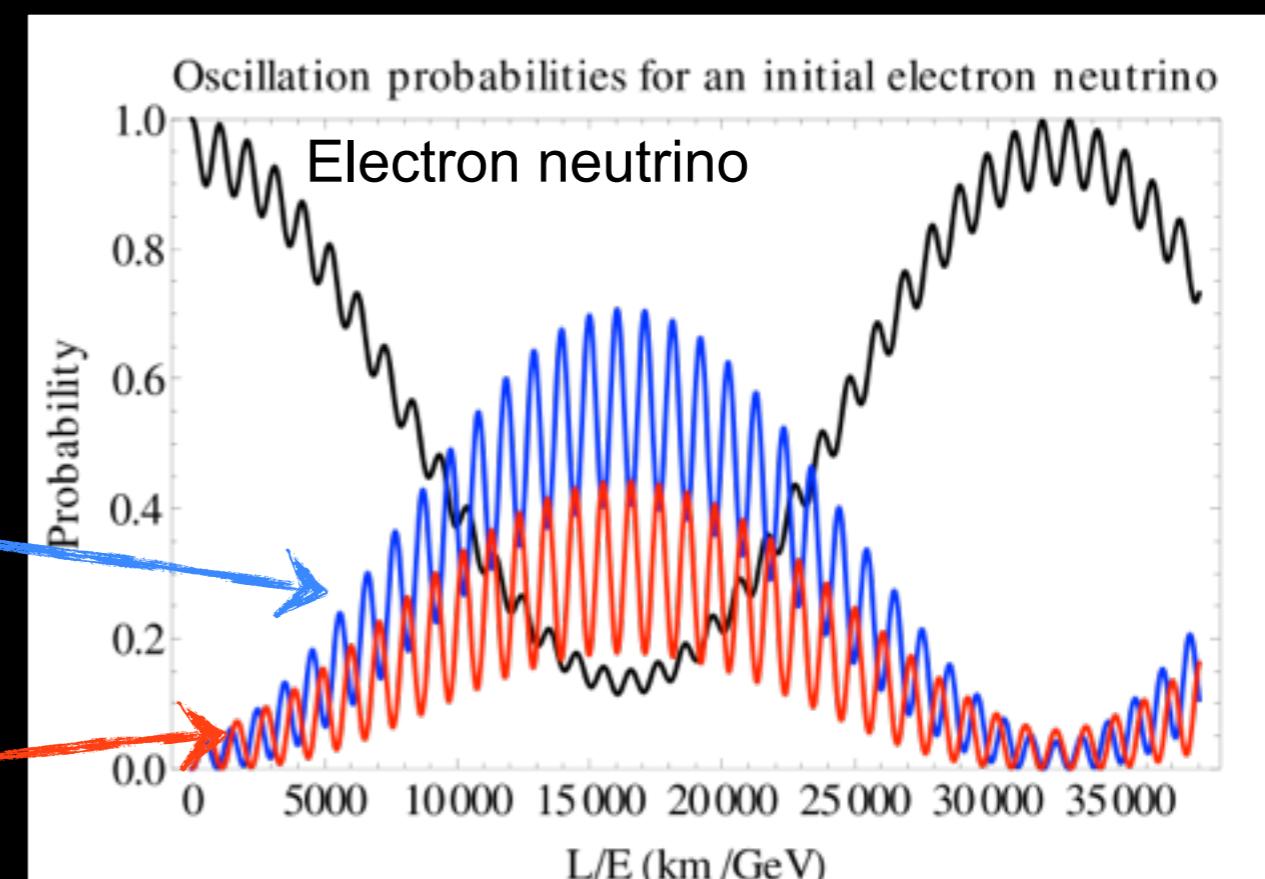
Neutrino oscillations

- Analogy to quark sector => Maki-Nakagawa-Sakata-Matrix
- **Mass eigenstates \neq flavour eigenstates**
- Mixing allowed \rightarrow oscillations
- Requires: $m_\nu > 0$ & $m_{\nu 1} \neq m_{\nu 2} \neq m_{\nu 3}$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos \Theta_m & \sin \Theta_m \\ -\sin \Theta_m & \cos \Theta_m \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix},$$

Muon neutrino

Tau neutrino



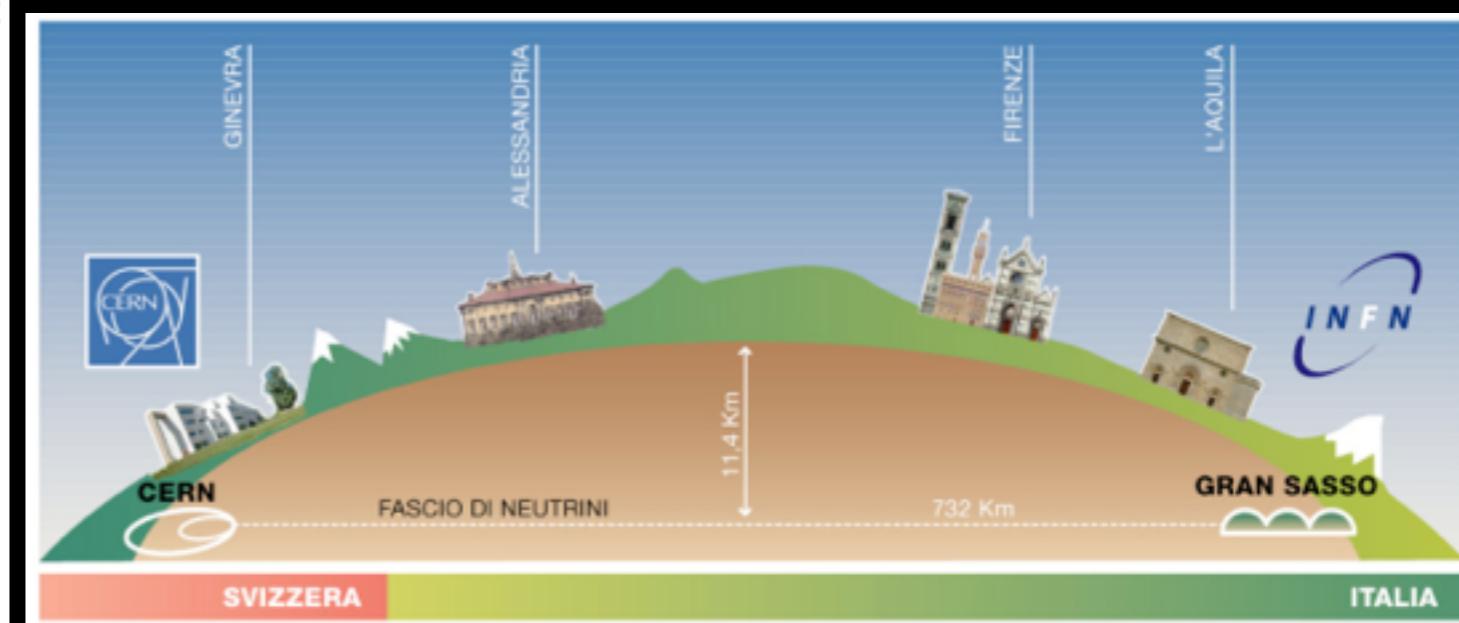
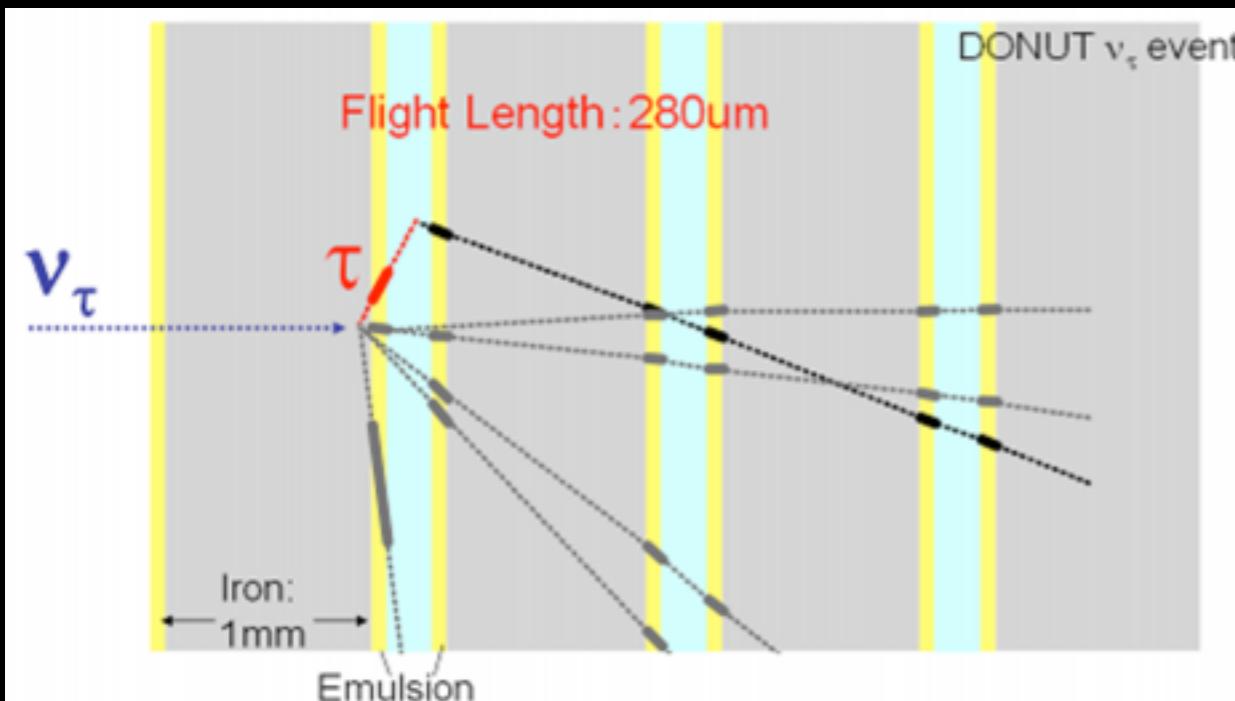
$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta(0) | \nu_\alpha(L) \rangle|^2 \approx \sin^2 \left(\frac{\Delta m^2 c^4}{4E} \frac{L}{\hbar c} \right) \cdot \sin^2 (2\Theta_m)$$

Neutrino oscillations - detection

- Various reactor and accelerator based experiments
 - Detectors in varying distance to sources
 - Double Chooz, KamLand, DayaBay / T2K, Opera, Minos
 - Measurement: disappearance of neutrino flux

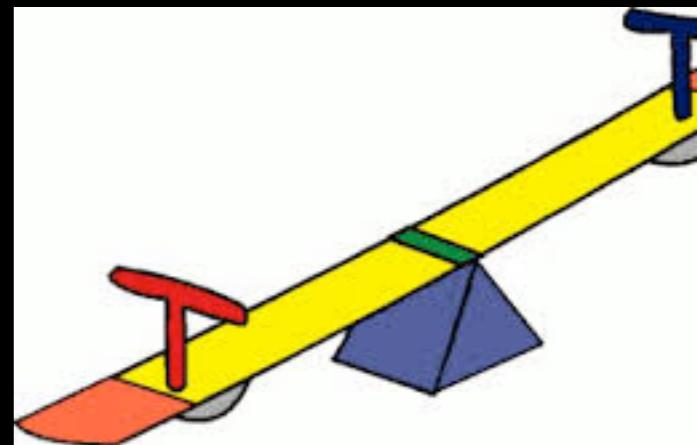
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- **Opera:** Detected appearance of tau-neutrinos! Opera: 2010-2014
- Neutrino beam (μ , e) from CERN sent 740km to Gran Sasso (IT)
- Detection of tau-neutrinos in neutrino beam (5x)



How do neutrinos gain mass?

- And why is mass so little? (< 2eV)
- Like fermions: coupling to Higgs field?
 - Requires left & right handed neutrinos
 - Only left-handed neutrinos observed!
- Other mechanism?
- One option: **See-Saw mechanism:**
 - Neutrinos are Majorana particles (their own anti-particles)
 - In addition very heavy right handed neutrinos (sterile Neutrinos)
 - Require very small mass for known neutrinos
- Violated lepton number conservation & B-L
 - Possible explanation of the existence of matter via lepto-genesis



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Leptonen

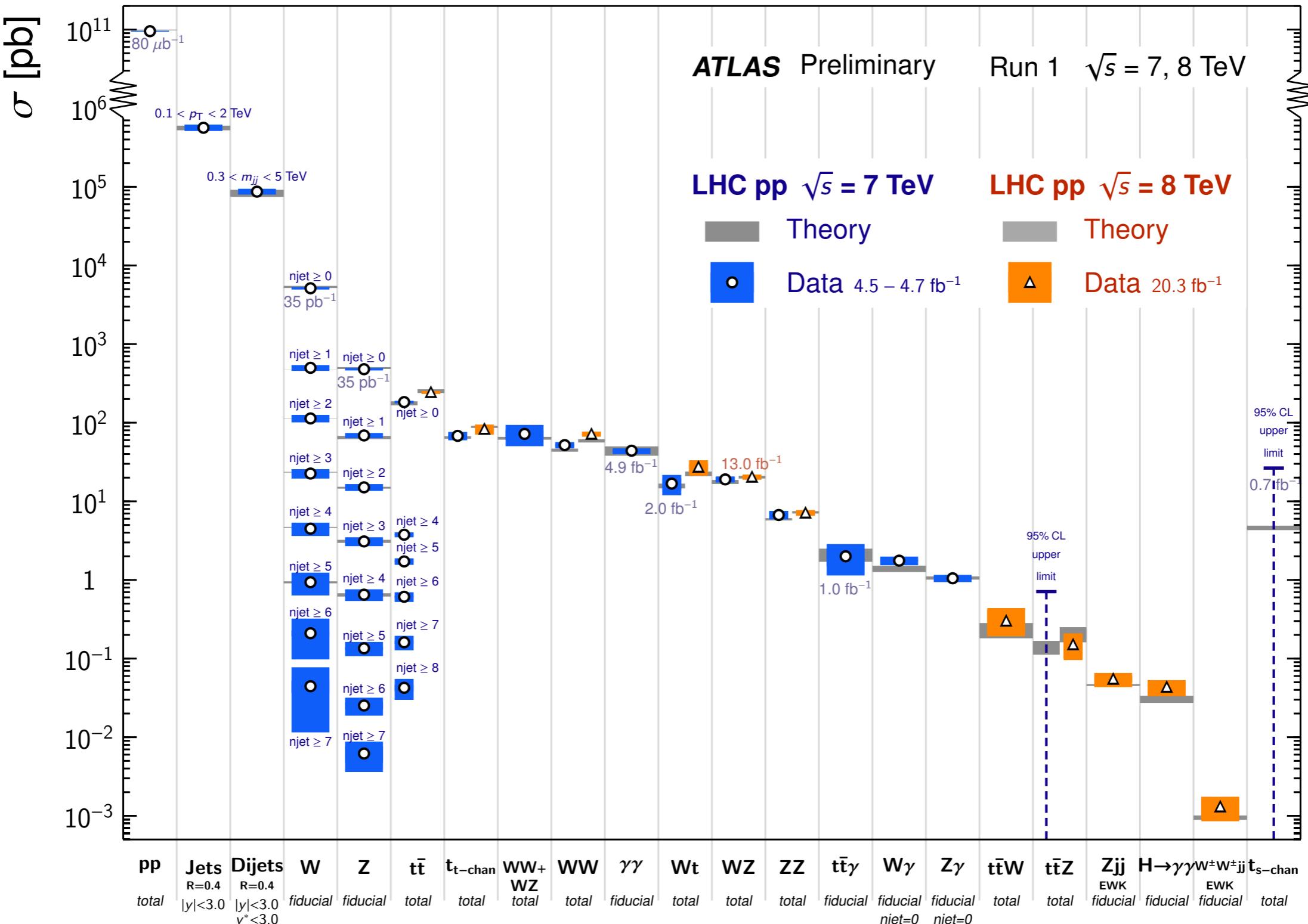
Sucsess of SM



Quarks, Leptonen, Neutrinos

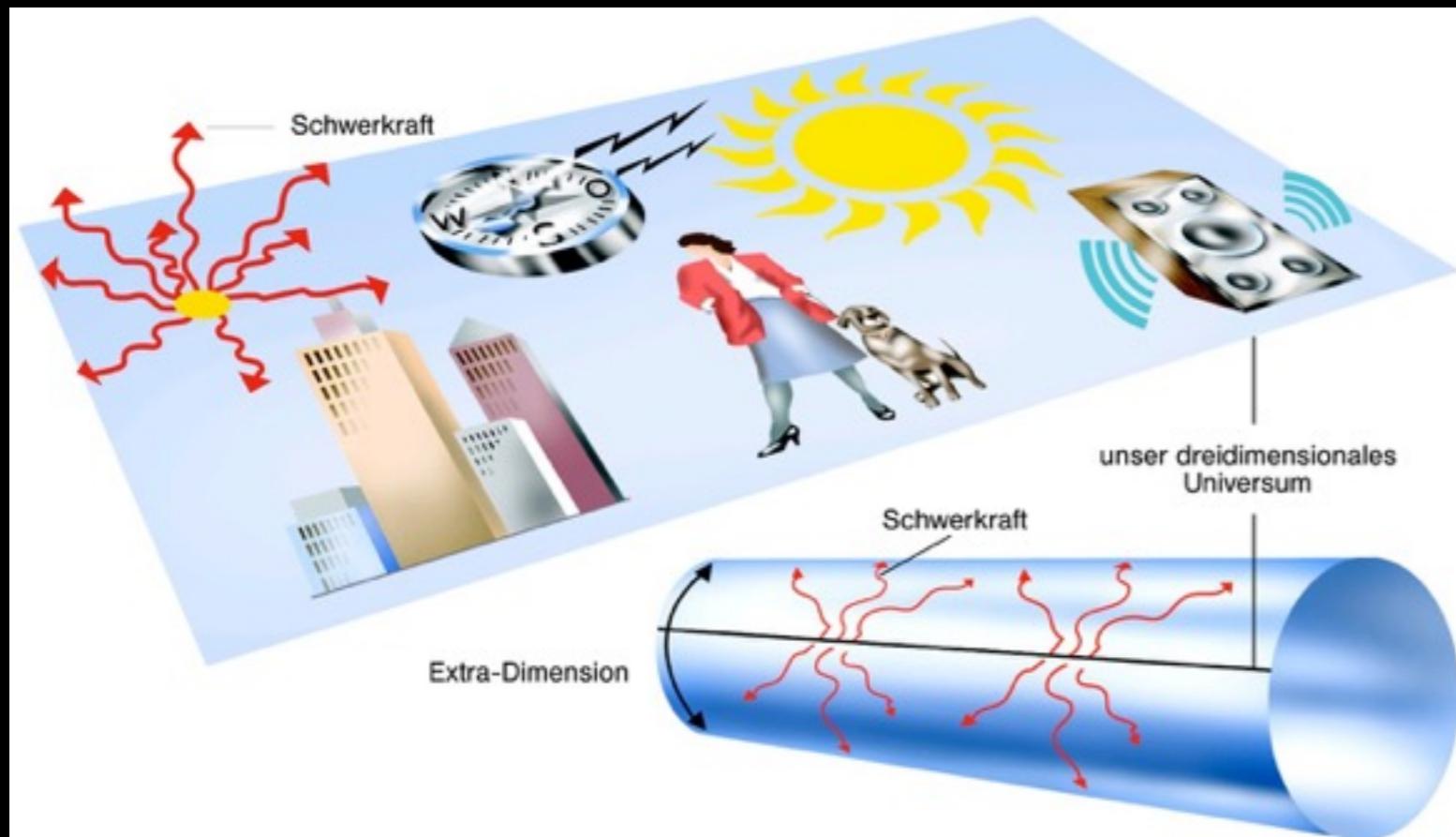
Standard Model Production Cross Section Measurements

Status: July 2014



A few loose ends ...

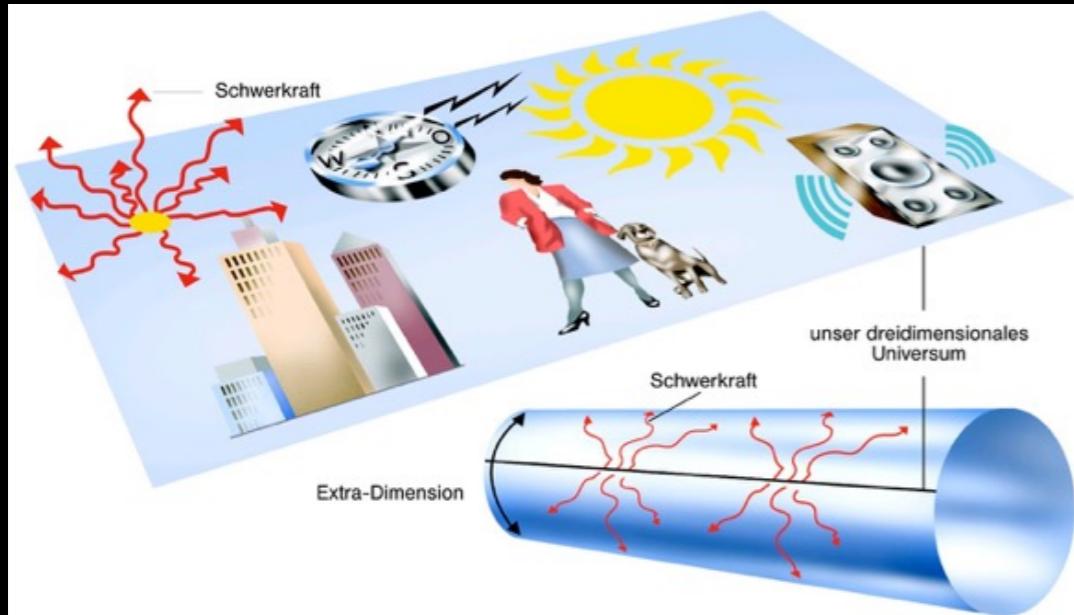
- Gravitation lässt sich nicht innerhalb des SM beschreiben
 - **Theoretisches Problem:** Allgemeine Relativitätstheorie und Quantenmechanik konnten bisher nicht zusammengefügt werden
- Wieso ist Gravitation so schwach?
 - Dominiert makroskopische Objekte
 - Auf Teilchenebene vernachlässigbar!
 - 10^{-38} mal so stark wie elektromagnetische Wechselwirkung!



- Zusätzliche Dimensionen?

- Wieso ist Gravitation so schwach?

- Zusätzliche Dimensionen?



- Vorhersage von ‚schwarzen Löchern‘
 - Teilchen die am LHC erzeugt werden könnten
- Streuung an kompaktifizierten Extra-Dimensionen
 - Kaluza-Klein Tower / Anregungen (= stehende Wellen in Extra-Dimension)

Bisher nicht beobachtet :(

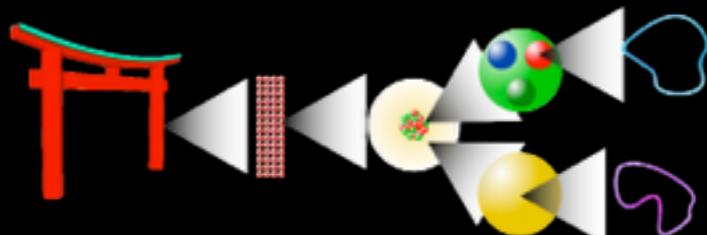
Gravitation - String Theorie



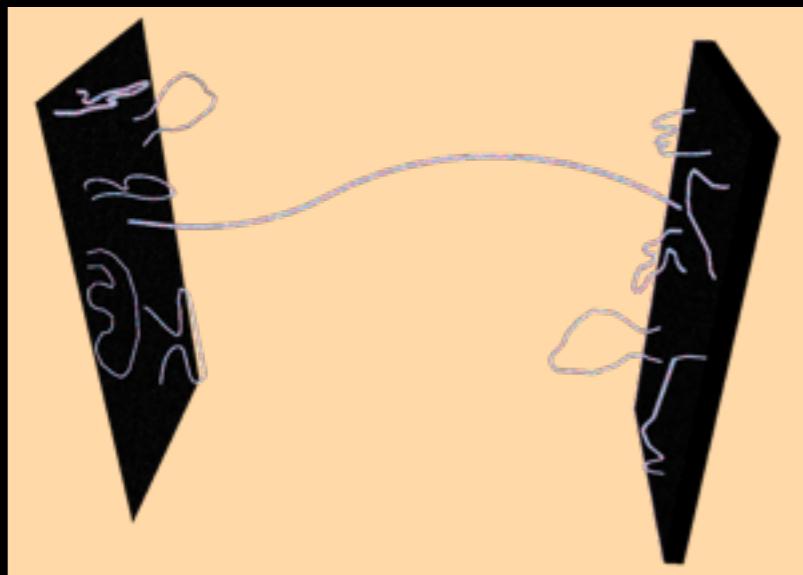
- Ein fundamentales Objekt:

- String (Saite)

- Größe ~ Planck Länge: 10^{-35} m



ab ~1980 bis
heute



- Können offen oder geschlossen sein
- Angeheftet auf „Welt-Brane“
- Schwingungsmoden entsprechen beobachtbaren Teilchen
- Branen leben in 11 dimensionalen Raum
- M-Theorie

- Sehr einfacher, eleganter Ansatz

- Vereinheitlichung aller bekannten Kräfte (beinhaltet Quanten-Gravitation)

- Unglaublich schwer zu berechnen. Bisher keine überprüfbaren Vorhersagen

Wo ist die Antimaterie?

- Bekannte Asymmetrie zwischen Materie und Antimaterie kann beobachtete Materie im Universum nicht erklären.
- CP - Verletzung der schwachen Wechselwirkung
 - Teilchen und Anti-Teilchen werden Leicht unterschiedlich behandelt
 - LHCb untersucht dies (u.a.)
- Muss Wechselwirkungen außerhalb des Standardmodells geben!



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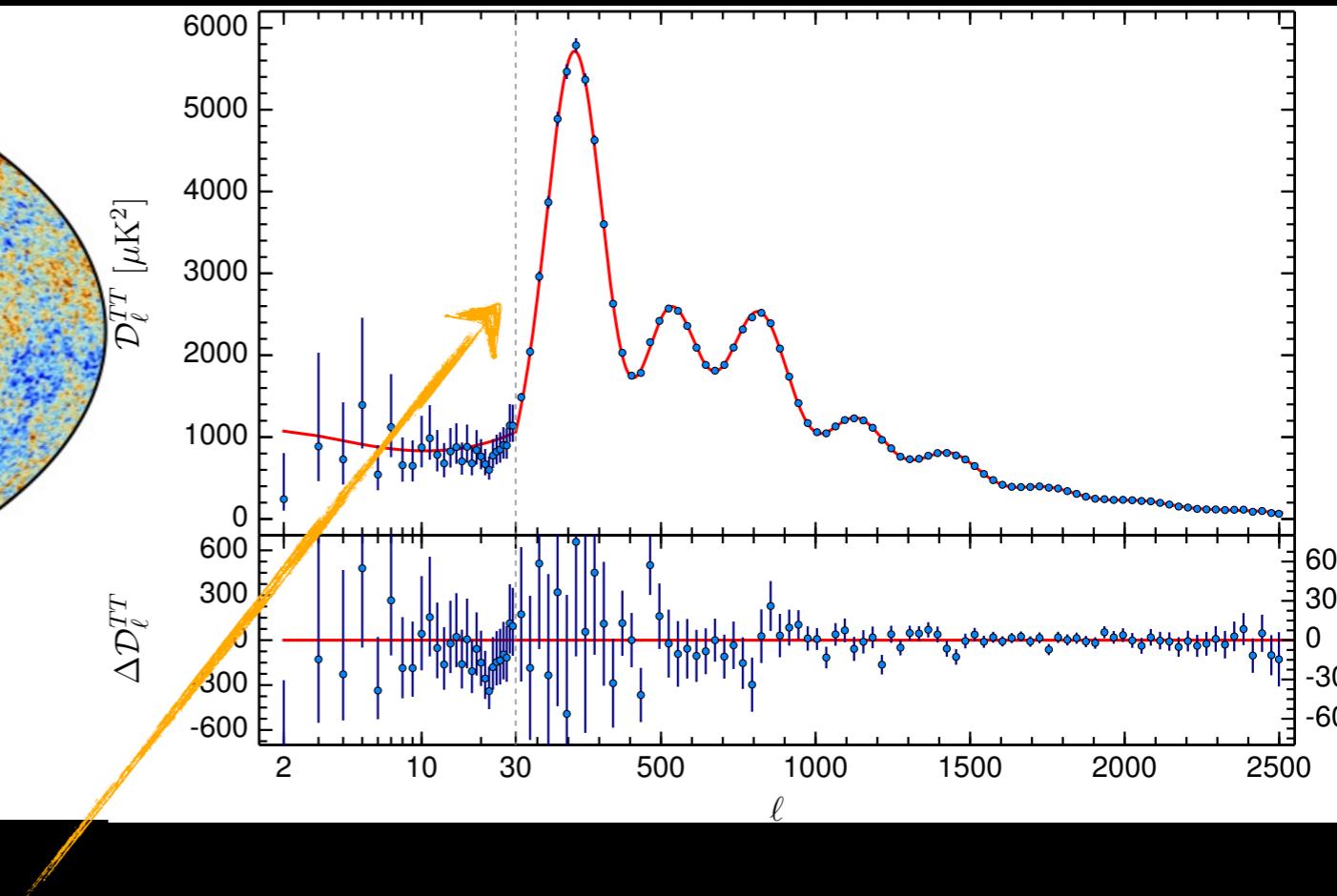
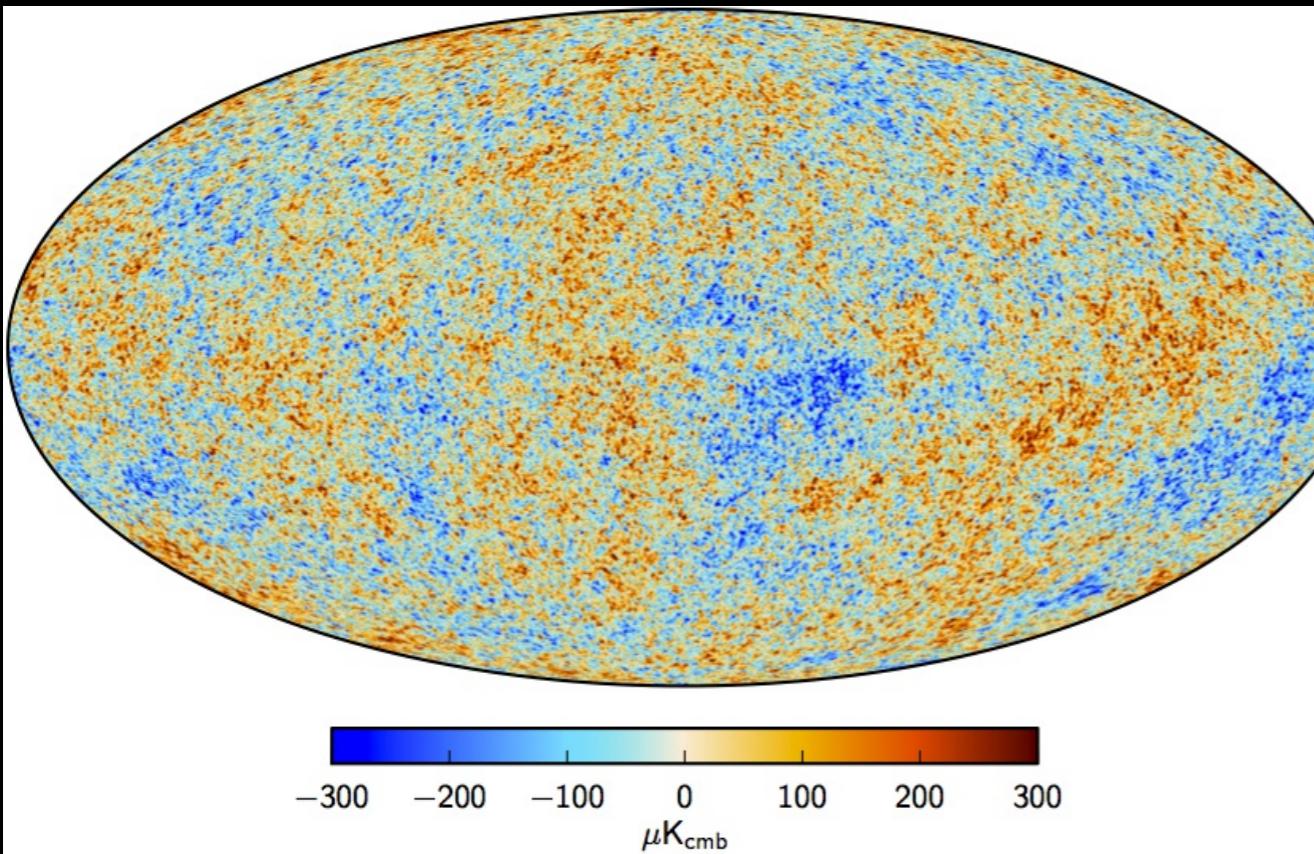
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 - => Wie viel Energie ist im Universum?



Bekannte Teilchen - Antiteilchen Asymmetrie:
Erzeugte Menge an Materie / Antimaterie im Urknall > totale Energiedichte

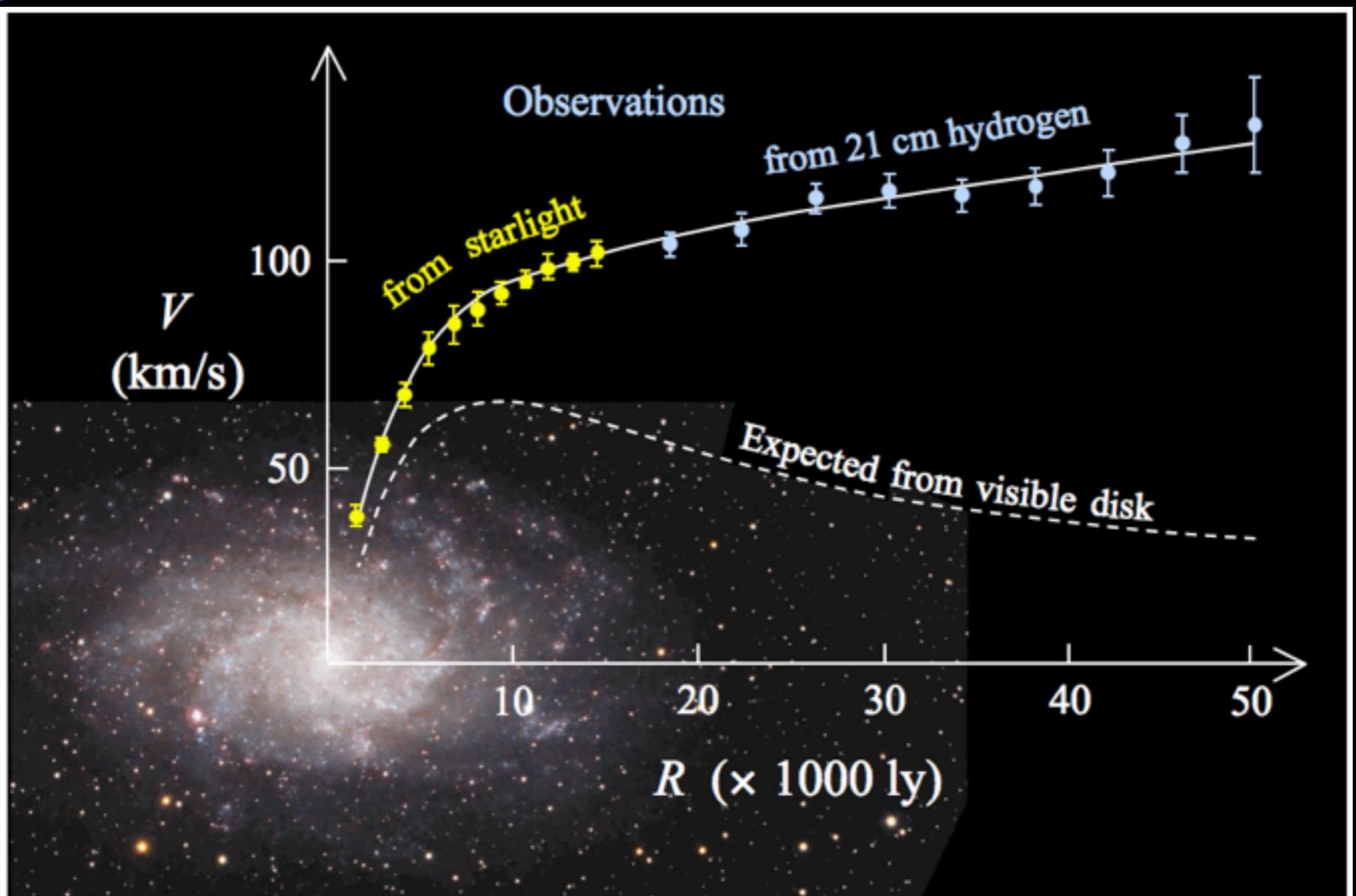
Intermezzo - Kosmologie

- Beobachtungen der kosmischen Hintergrundstrahlung:
 - Universum kühlt ab => Neutrale Atome => Durchsichtig
 - Strahlung von diesem Zeitpunkt: Durchquert Universum, Wellenlänge durch Ausdehnung des Raums gedehnt: Röntgen → Mirkowellen

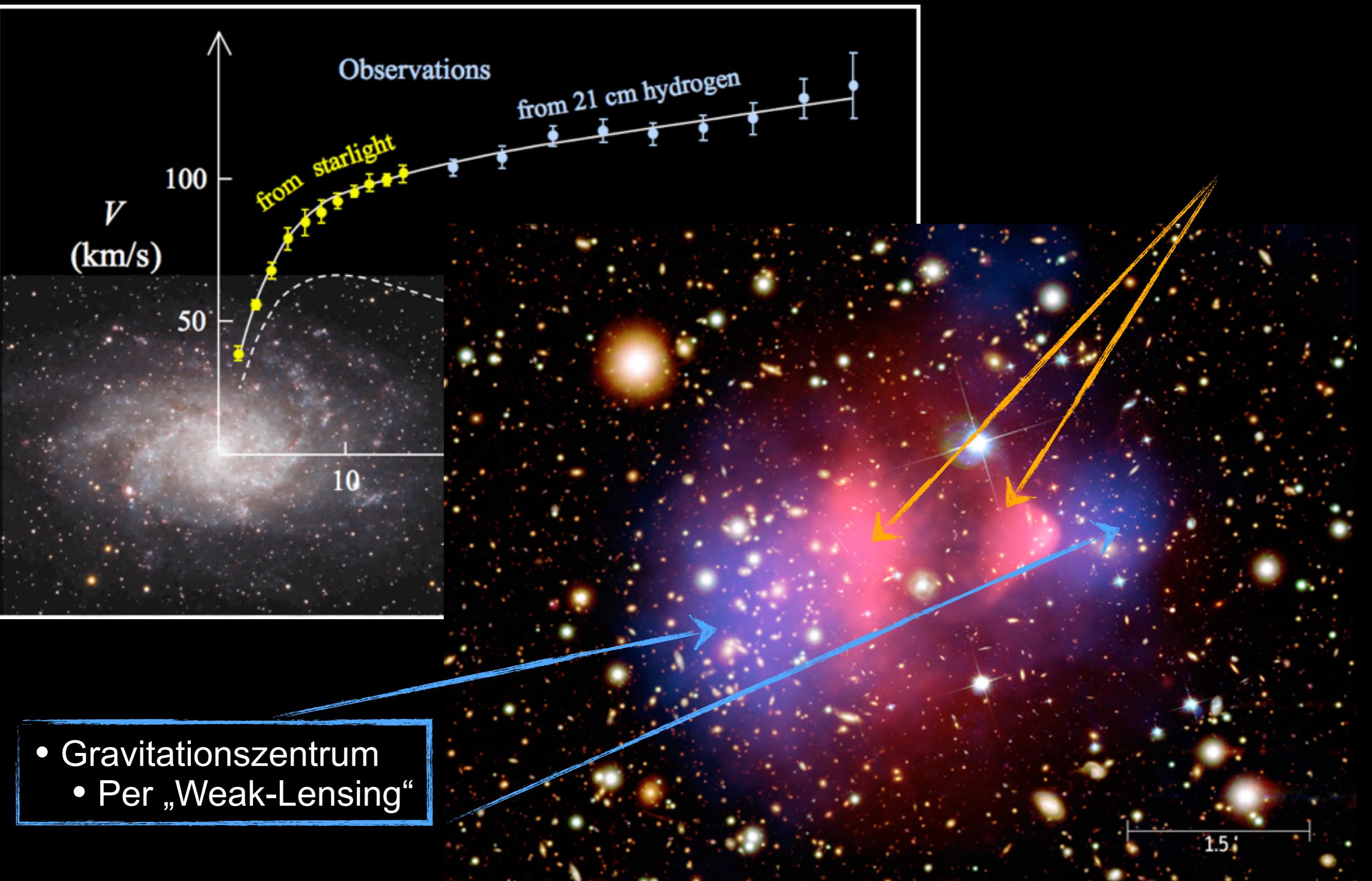


- Fit des Λ CDM Modells an Daten. Parameter: Baryon-Dichte, Materie-Dichte, Raumkrümmung,

Apropos Dunkle Materie

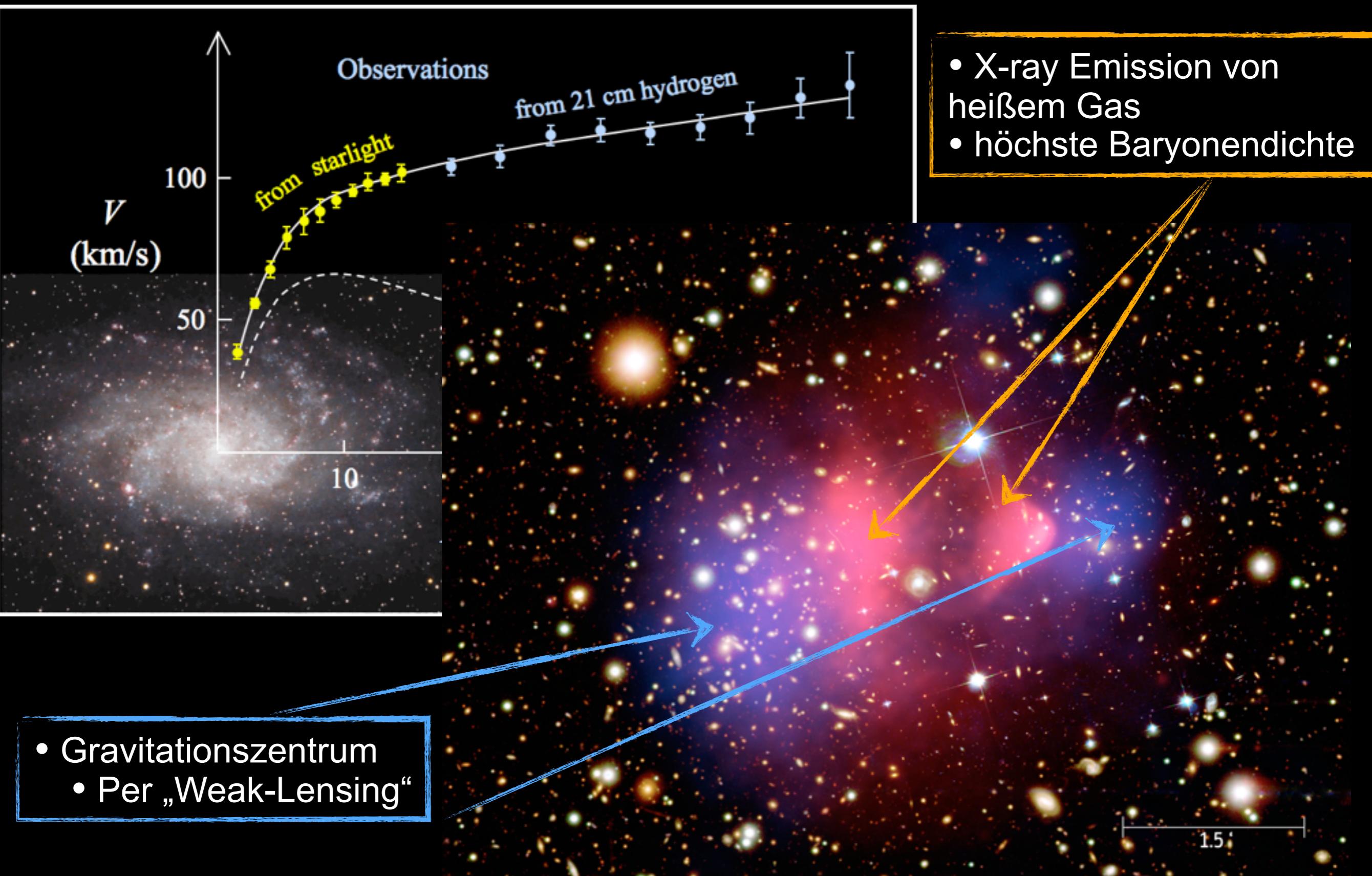


Apropos Dunkle Materie



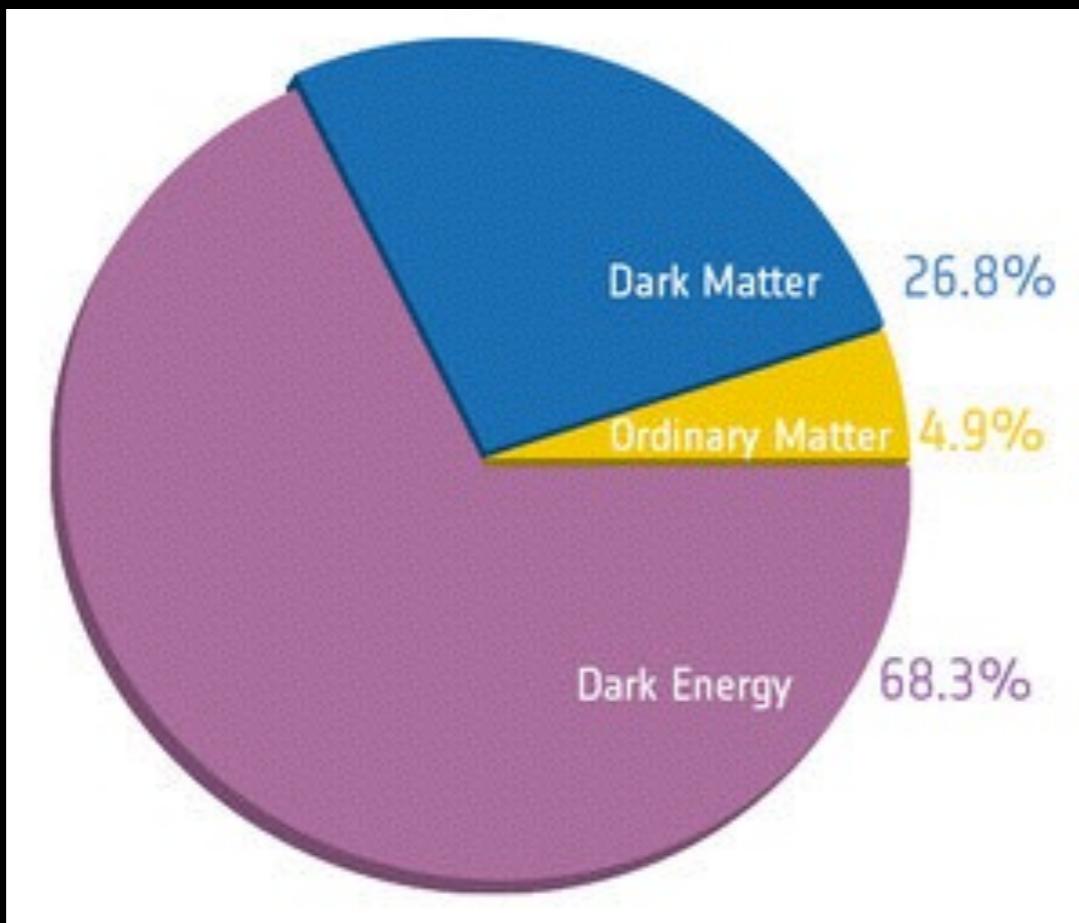
- Gravitationszentrum
 - Per „Weak-Lensing“

Apropos Dunkle Materie



Apropos Dunkle Materie

Planck: 2015



Dunkle Materie ?

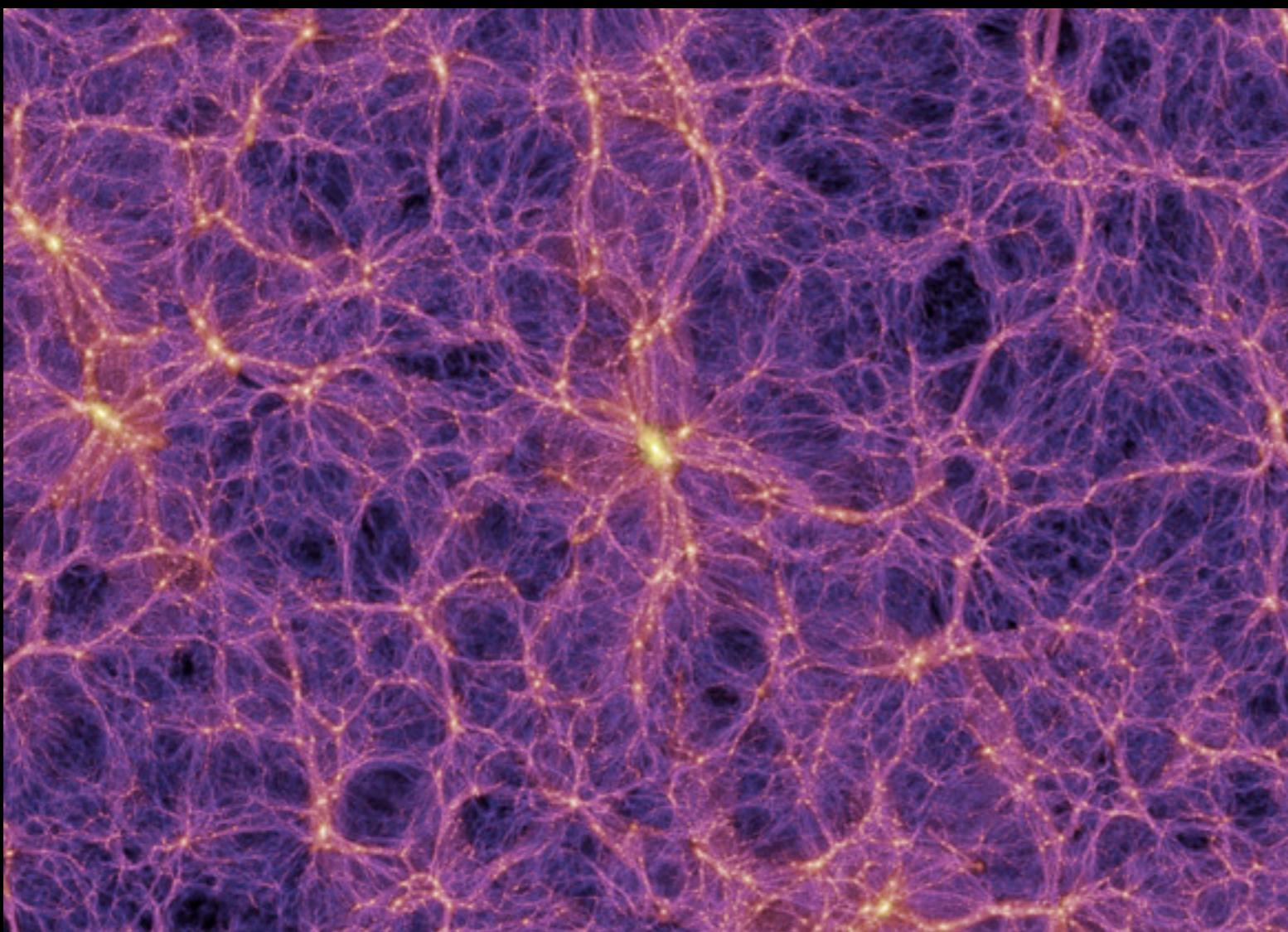
Baryonen

Dunkle Energie ???

- Mehrere Kandidaten + Erweiterungen des SM zur Beschreibung DM

Dunkle Materie

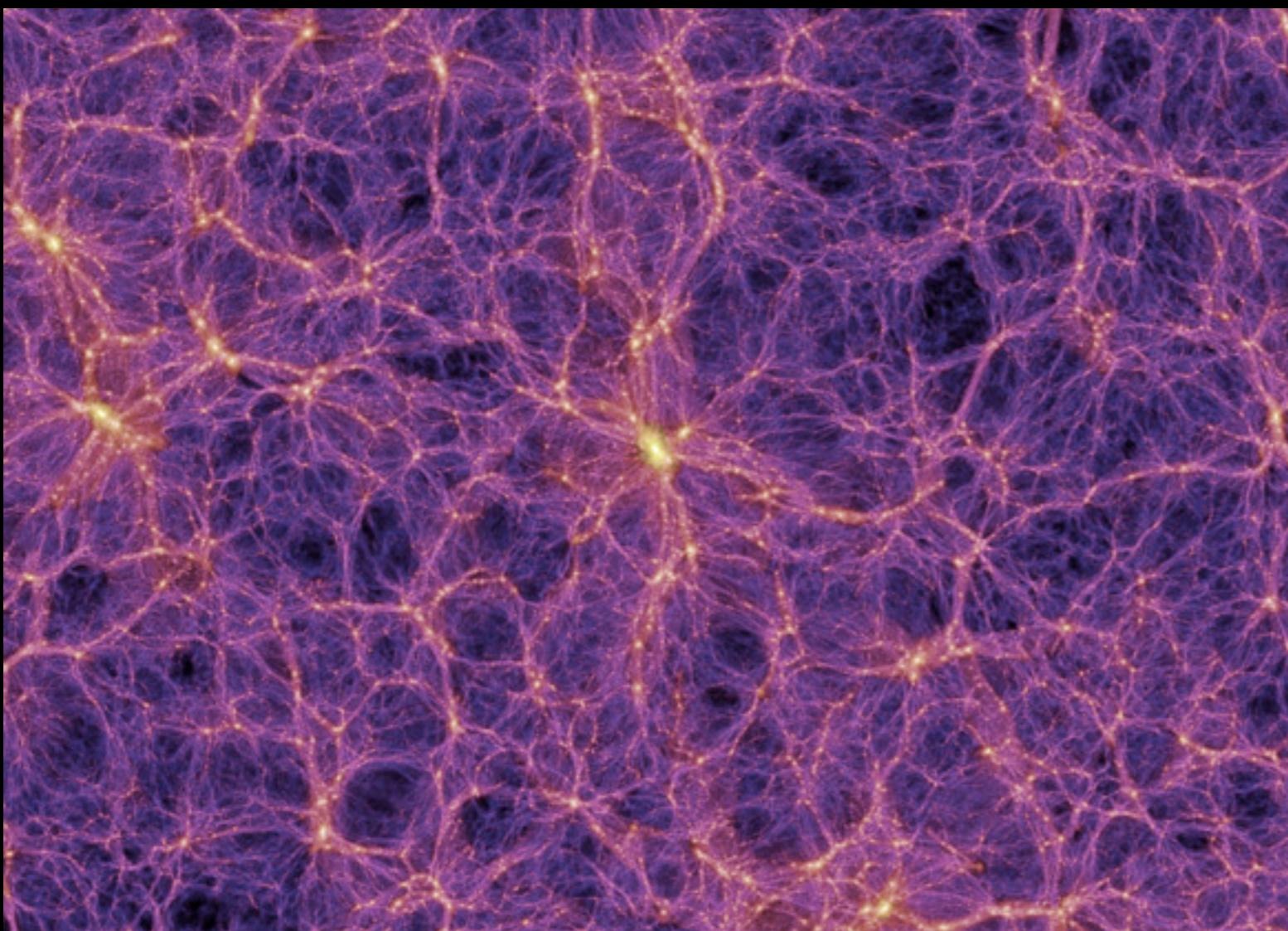
- Eigenschaften:
 - Massiv (Gravitation)
 - Wechselwirken schwach



Dunkle Materie



- Eigenschaften:
 - Massiv (Gravitation)
→ Neutrinos?
 - Wechselwirken schwach



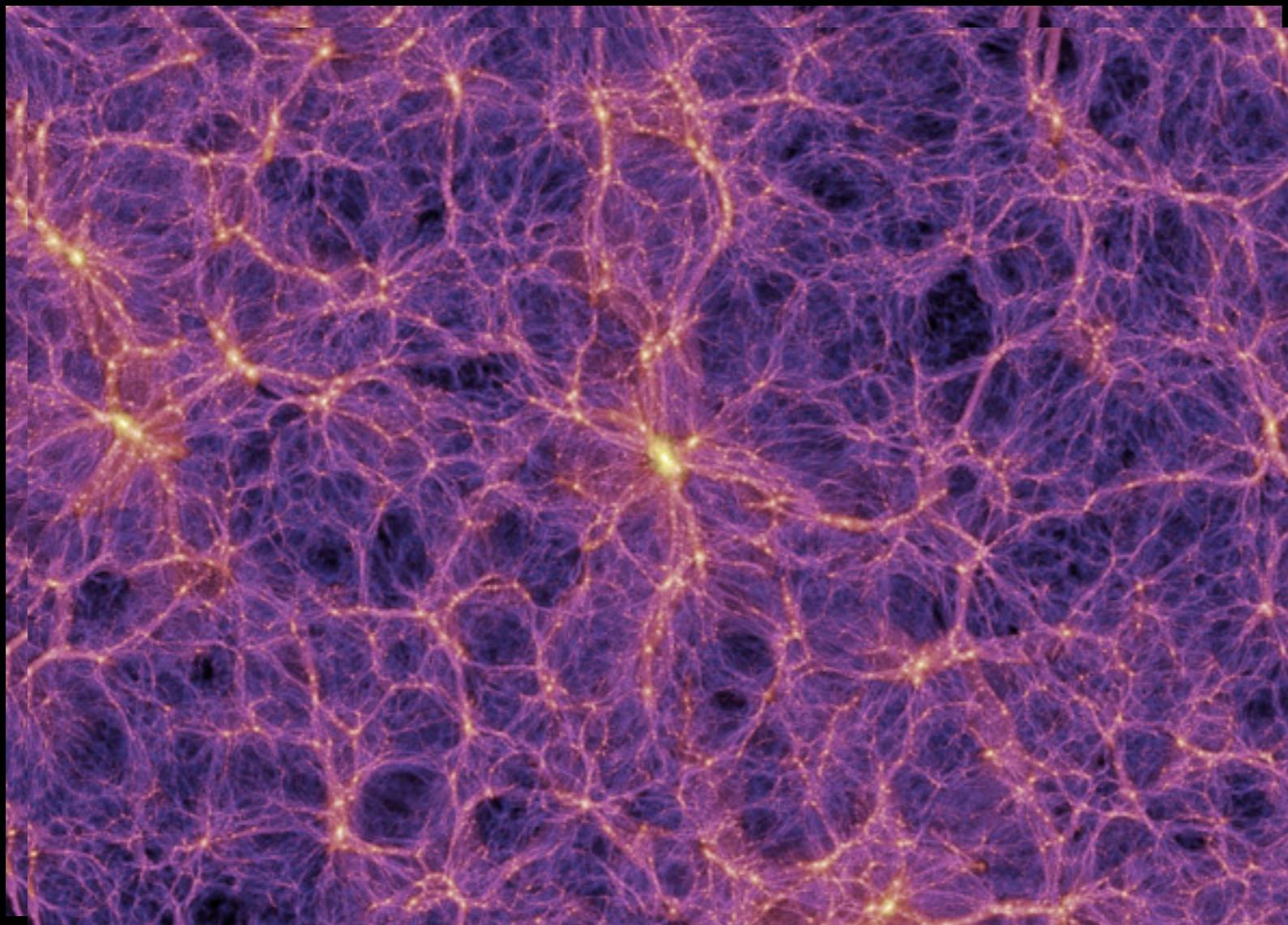
Dunkle Materie



- Eigenschaften:
 - Massiv (Gravitation)
 - Wechselwirken schwach

→ Neutrinos?

Nein! Nur nicht-relativistische Teilchen tragen zur Strukturbildung bei!



Dunkle Materie

- Eigenschaften:

- Massiv (Gravitation)
- Wechselwirken schwach
- ~Nichtrelativistisch
 - Ansätze mit ‚heißer‘ dunkler Materie existieren

- Kandidatenliste:

- WIMPs (Lightest Supersymmetric Particle?)
- Axionen
- Sterile Neutrinos

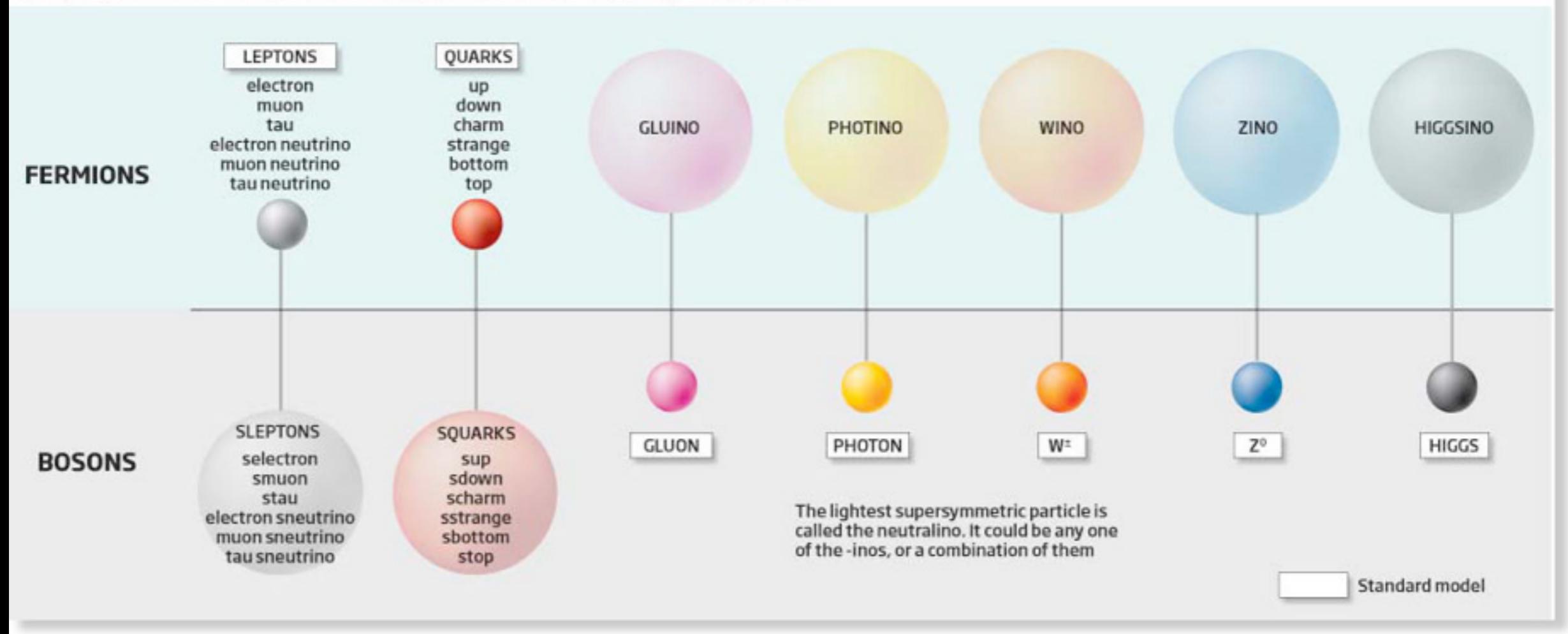
Supersymmetrie

- Neue Symmetrie:
 - Jedem Boson ($S=0,1$) wird ein neues Fermion ($S=1/2$) zugeordnet, und umgekehrt

Particle zoo

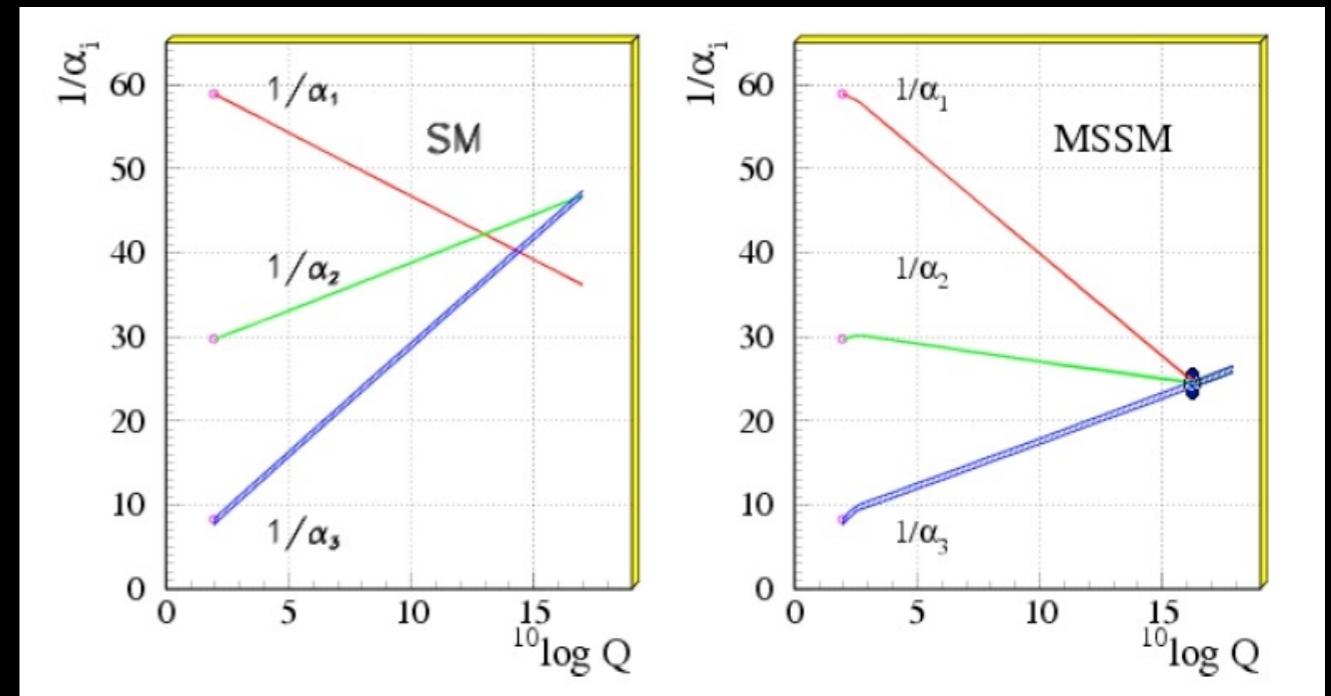
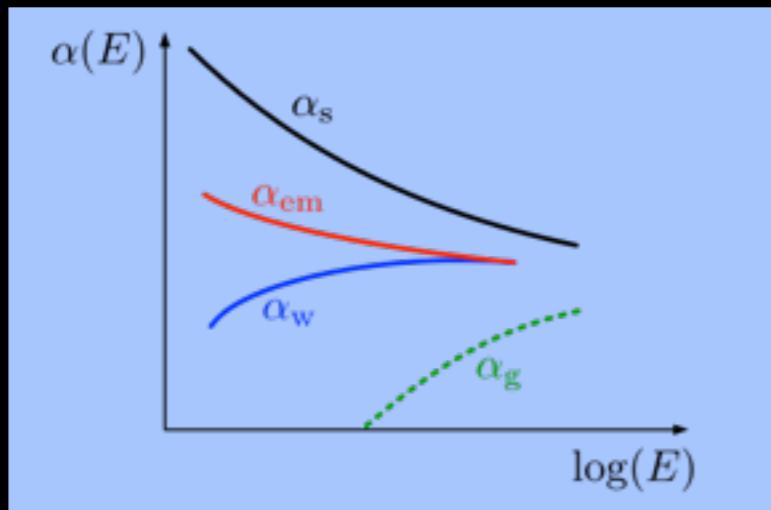
©NewScientist

Particles are divided into two families called bosons and fermions. Among them are groups known as leptons, quarks and force-carrying particles like the photon. Supersymmetry doubles the number of particles, giving each fermion a massive boson as a super-partner and vice versa. The LHC is expected to find the first supersymmetric particle



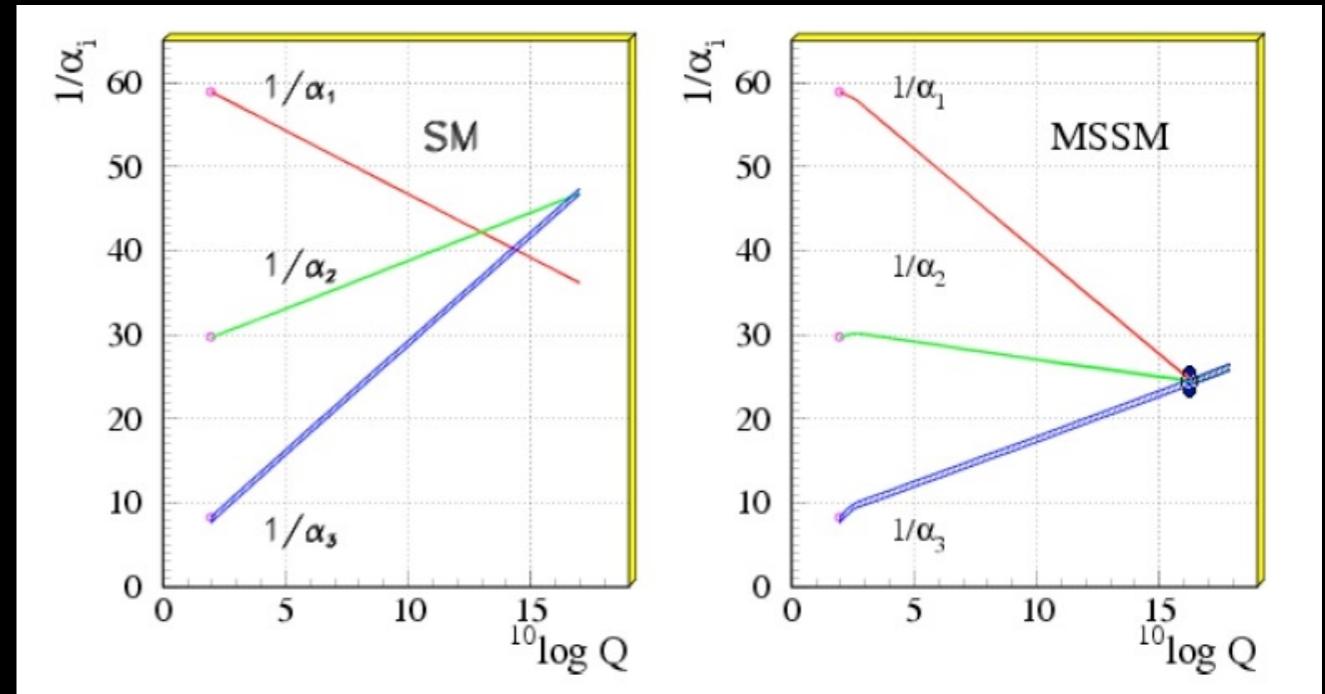
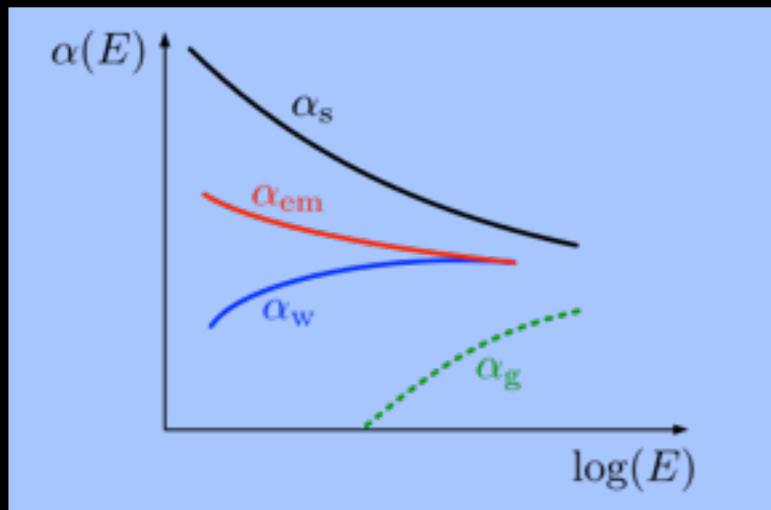
Supersymmetrie

- „Komplettiert“ SM → alle Symmetrien ausgeschöpft
- Neue Teilchen beeinflussen das „Laufen“ der Kopplungen
 - Große Vereinheitlichung möglich



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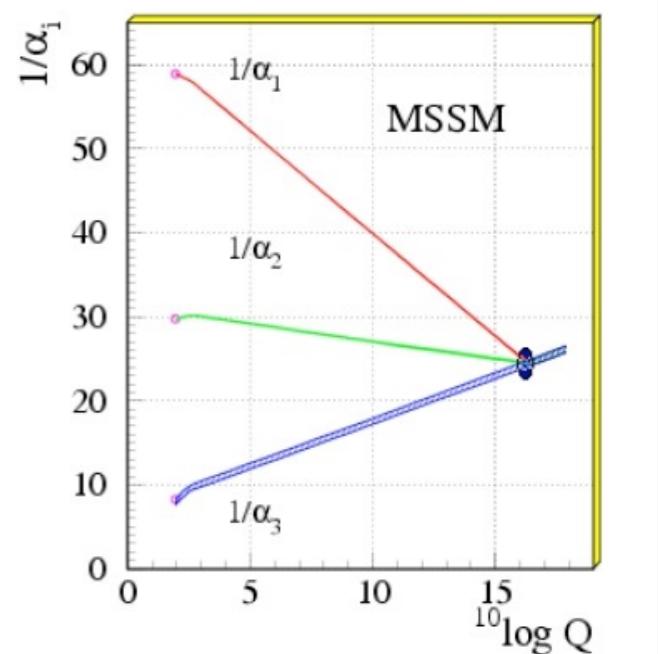
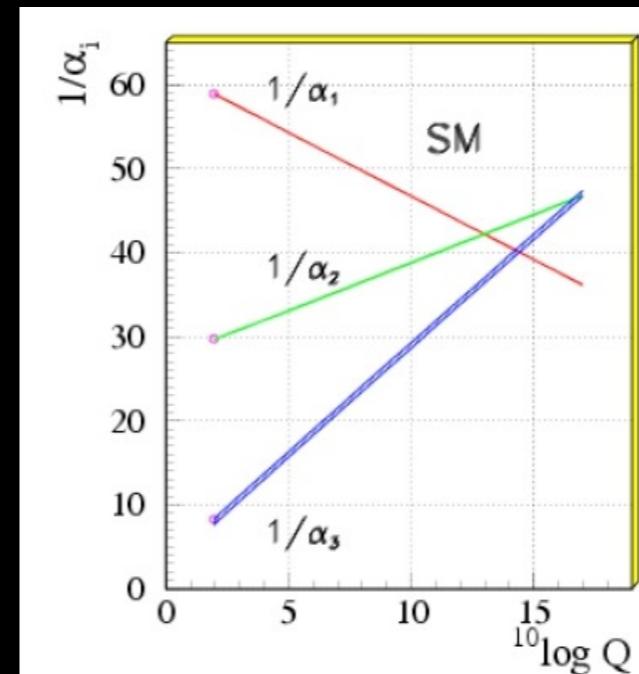
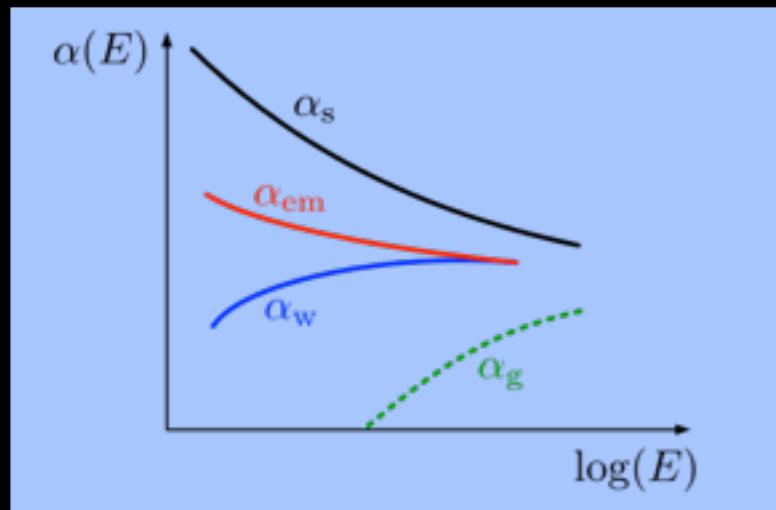


- Neue Erhaltungsgröße: R-Parität (+1 für Teilchen, -1 für Superpartner)
 - Leichtestes Supersymmetrisches Teilchen kann nicht zerfallen!
 - Kandidat für Dunkle Materie

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- Parameterraum für Supersymmetrie riesig
 - Parameter bestimmen Teilchenmasse, sind (fast) beliebig
 - Nicht ausschließbar

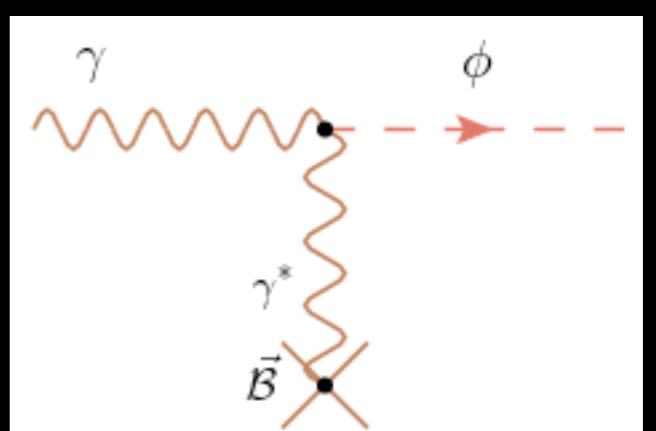
Axionen

- Lösen das „starke CP Problem“
- QCD erlaubt CP verletzende Reaktionen. Stärke beschrieben durch Parameter θ
 - CP Verletzung → Elektrisches Dipolmoment des Neutron
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- Einführung eines weiteren komplexen, skalaren Feldes
 - Mit dazugehöriger Symmetrie, die spontan gebrochen ist (Analog zum Higgs Mechanismus)
 - θ wird ‚dynamisch‘ exakt 0
 - Neues, massives Teilchen: **Axion**
 - Kandidat für dunkle Materie

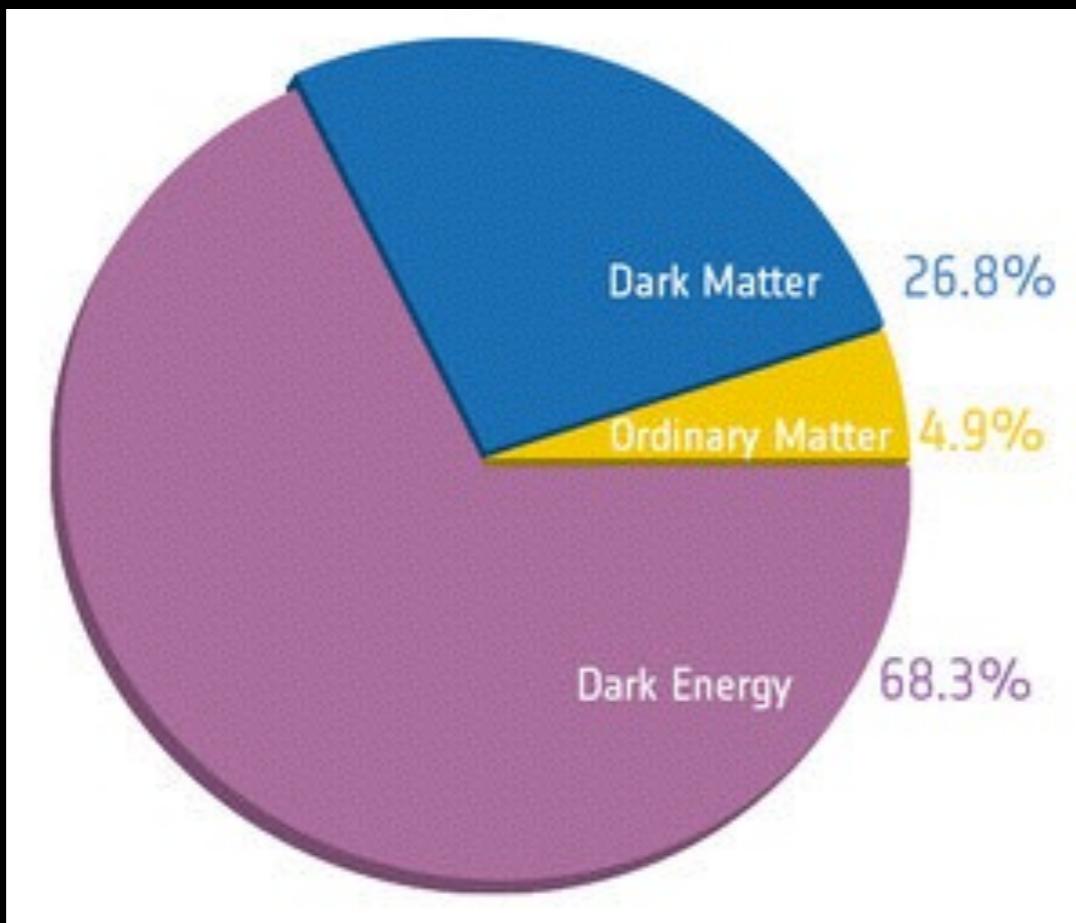
Peccei, Quinn:
1977



Primakov Effekt

Alles dunkle ist spannend

Planck: 2015



Dunkle Materie ?

Baryonen

Dunkle Energie ???

- Dunkle Energie ist völlig unerklärt
 - Zusammenhang mit Inflation?
 - Vakuumfluktuationen?
 - Quintessenz ?

Viele Ungelößte Probleme

- Gravitation lässt sich nicht innerhalb des SM beschreiben
 - Wieso ist Gravitation so schwach?
- Wieso gibt es keine Antimaterie im Universum?
- Der Dunkle Sektor? (Dunkle Materie, Dunkle Energie)
- Was ist die Natur der Neutrinos?
- Wieso gibt es 3 Familien?
- Wieso haben Teilchen unterschiedliche Masse?
-
-

https://en.wikipedia.org/wiki/List_of_unsolved_problems_in_physics

The End

Literaturverzeichnis

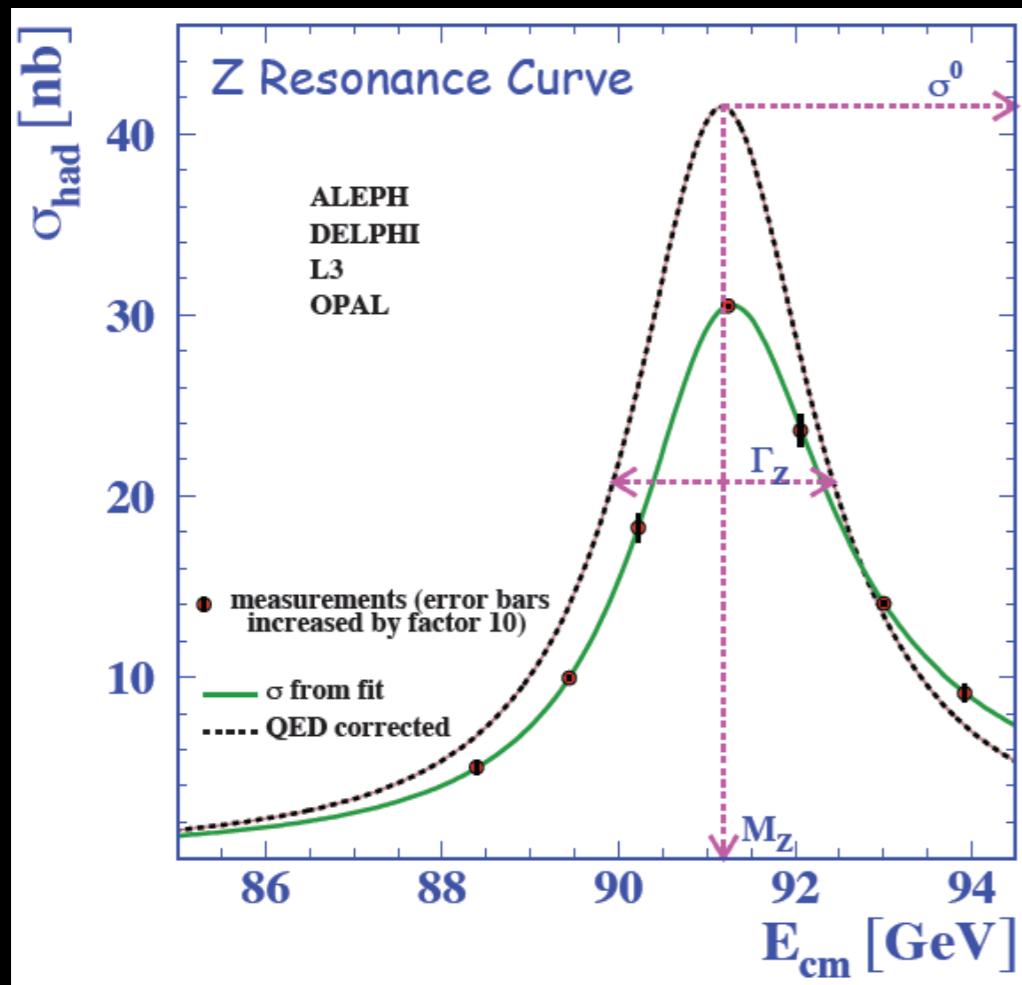
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- [3] Von Kurzon - Eigenes Werk, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=32422326>
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A.S. Barabash (Moscow, ITEP) et al.. Nov 2012. 8 pp. Phys.Inst. 39 (2012) 300-304 <http://arxiv.org/abs/1211.1471v2>
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Gibt es mehr als 3 Familien?

- Untersuchung des Z-Teilchens im Detail:

Breit-Wigner Kurve
→ harmonischer Oszillator

Gemessen in Reaktion: $e^+ e^- \rightarrow Z \rightarrow e^+ e^-$



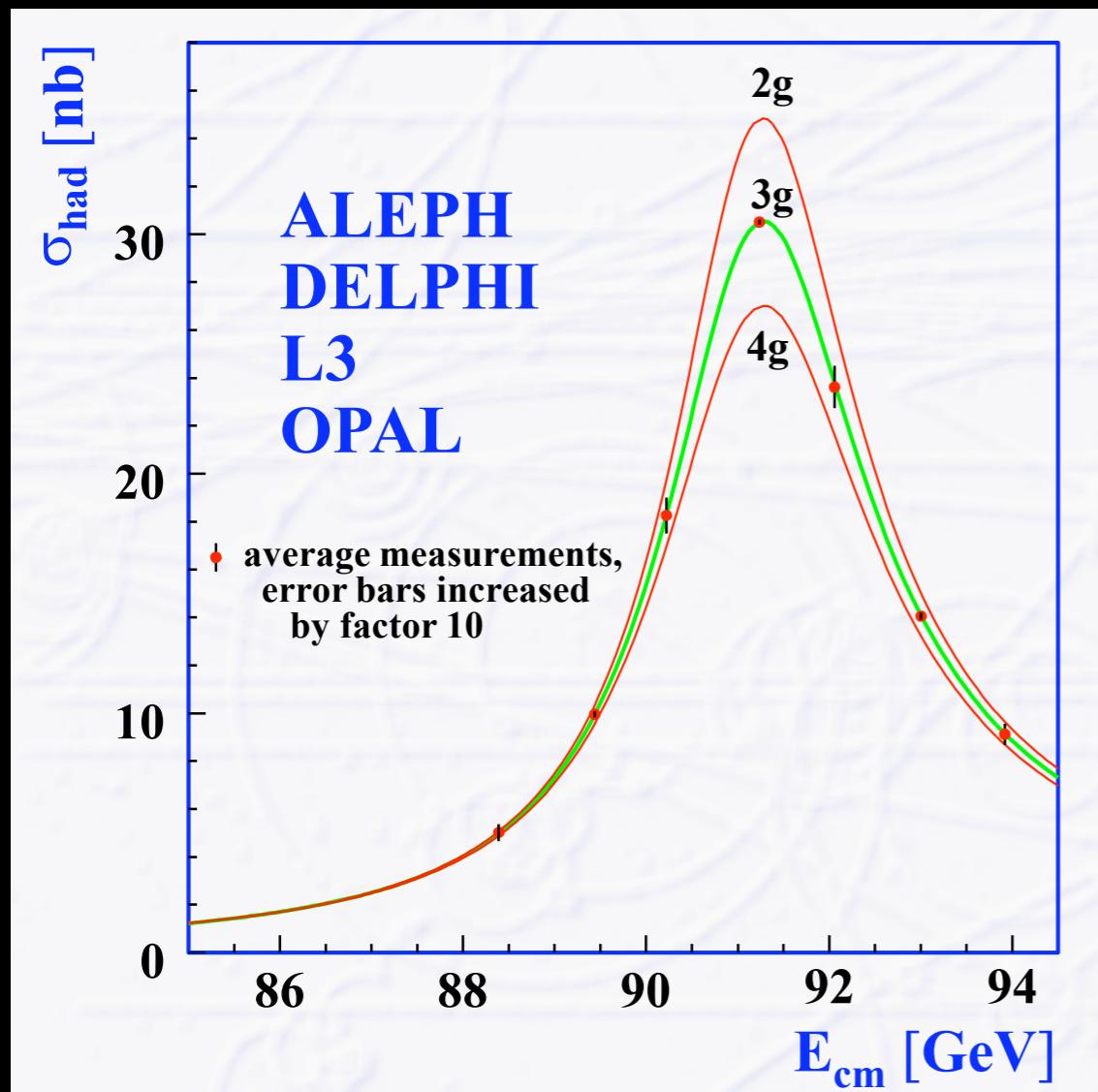
Exakte Form abhängig von

- Vakuumfluktuationen
- Abstrahlung von Photonen
- Virtuelle Photonen zwischen Leptonen

Gibt es mehr als 3 Familien? - Nein

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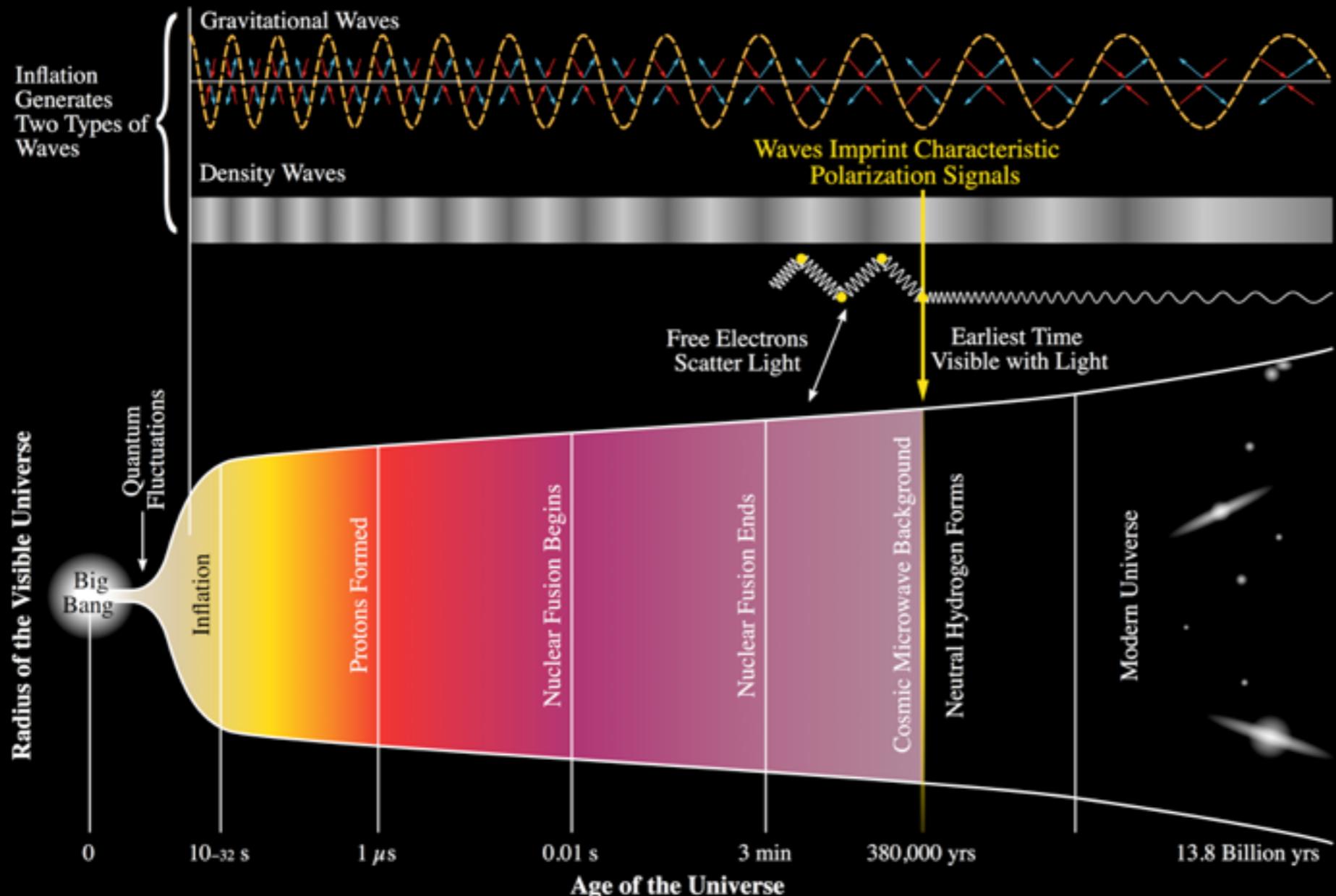
Exakte Form abhängig von

- Vakuumfluktuationen
- Abstrahlung von Photonen
- Virtuelle Photonen zwischen Leptonen
- Anzahl der **leichten** Neutrino 'Flavour'

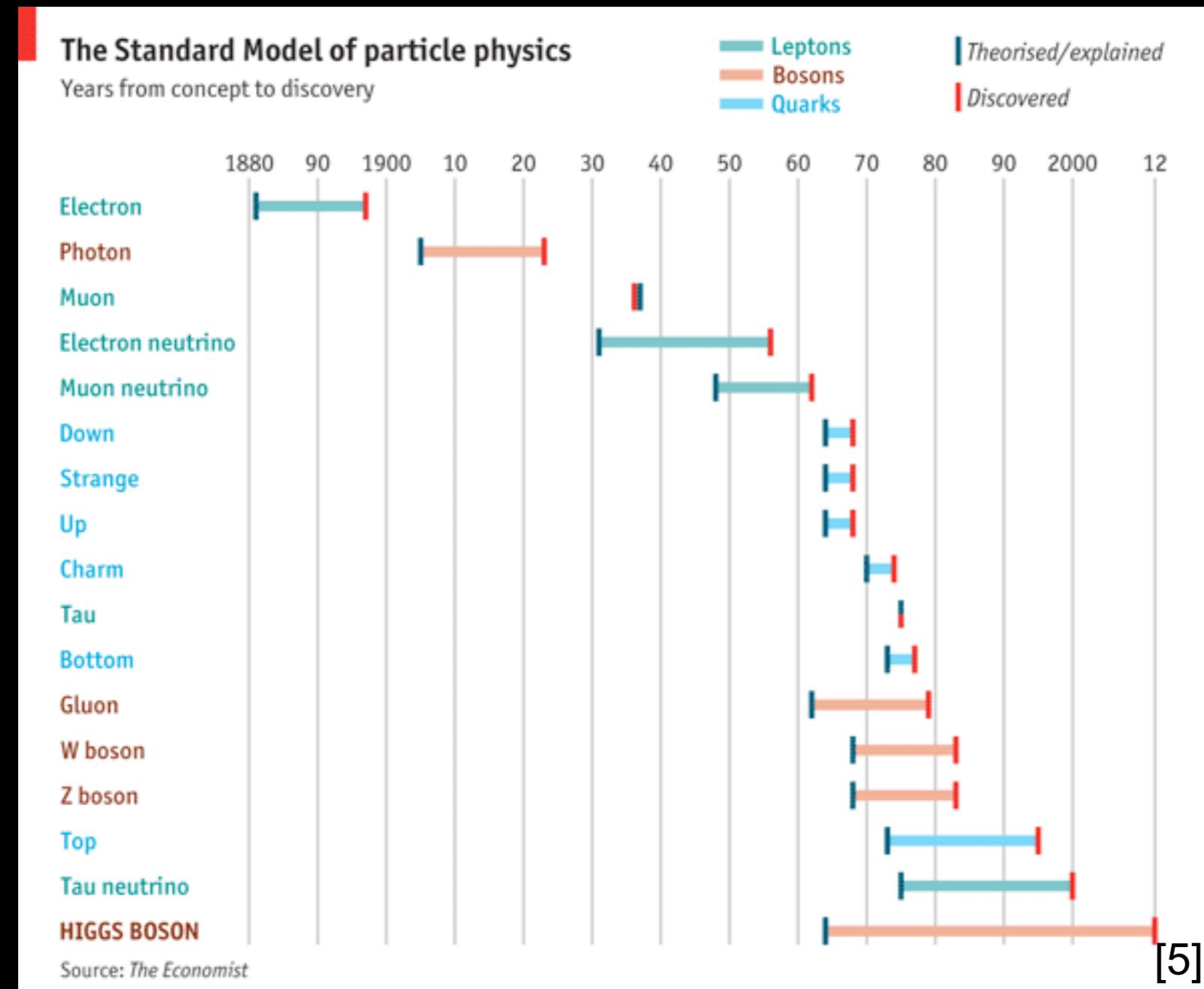
Inflation



History of the Universe



Überschrift



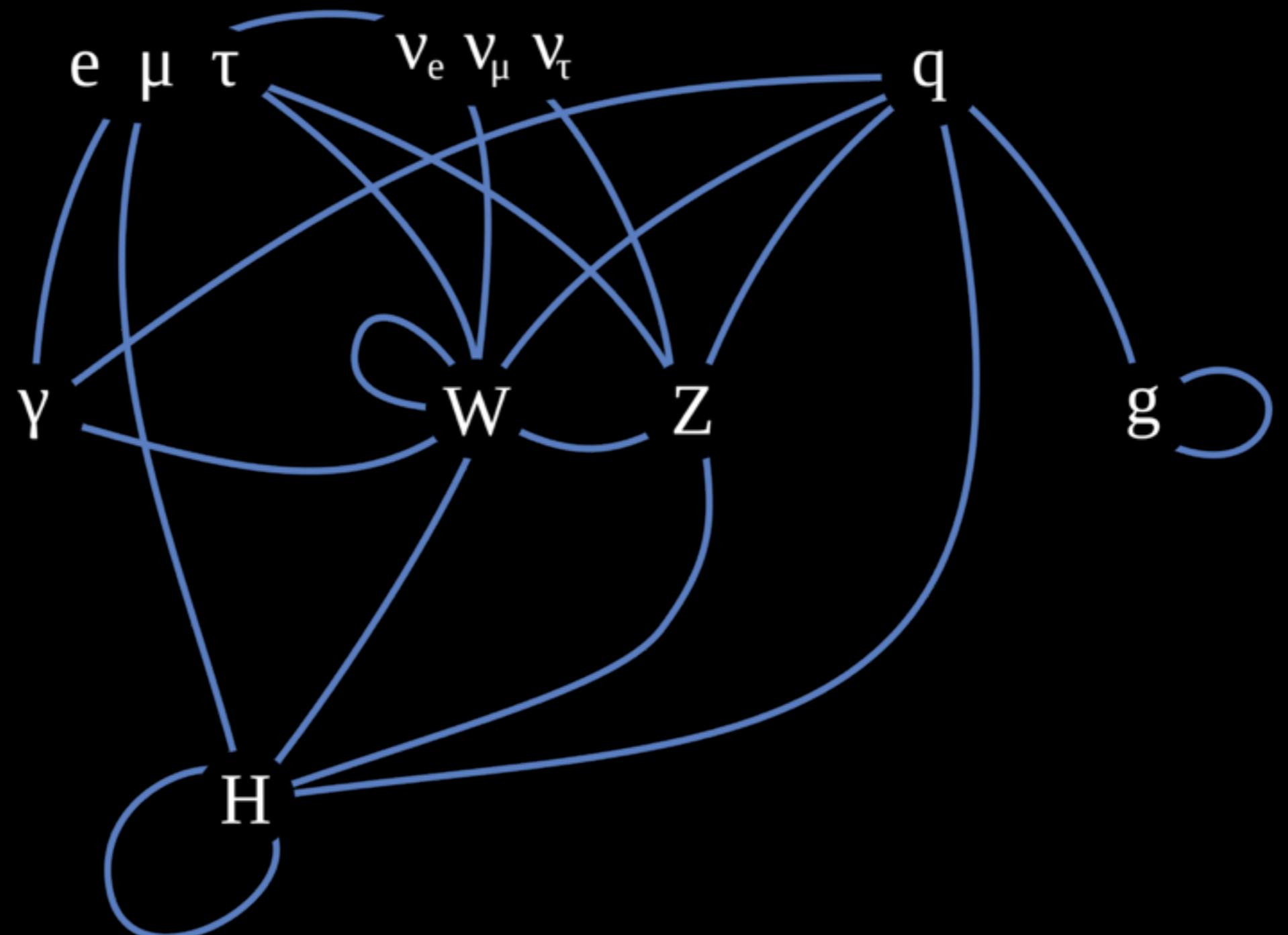
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- Ja
- Allgemein: Teilchen die keine Ladung haben sind ihre eigenen Anti-teilchen
 - Ladungen: Elektrisch, Schwach, Farbe

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- Ladungen: Elektrisch, Schwach, Farbe
 - $W^+ W^-$ sind Anti-Teilchen zueinander
 - Z^0 & Photon sind ihre Eigenen Anti-Teilchen
 - Vektor-Boson-Fusion: $W^+ + W^- \rightarrow Z^0$; $Z^0 + Z^0 \rightarrow H$
 - Gluonen besitzen Farbe & Anti-Farbe: Teilchen-Antiteilchen Paare
- Bosonen gehorchen Bose-Statistik:
 - können einzeln erzeugt und Vernichtet werden!
- Fermionen gehorchen Fermi-Statistik
 - können nur Paarweise erzeugt / Vernichtet Werden
 - Leptonzahl / Baryonzahl Erhaltung

Überschrift

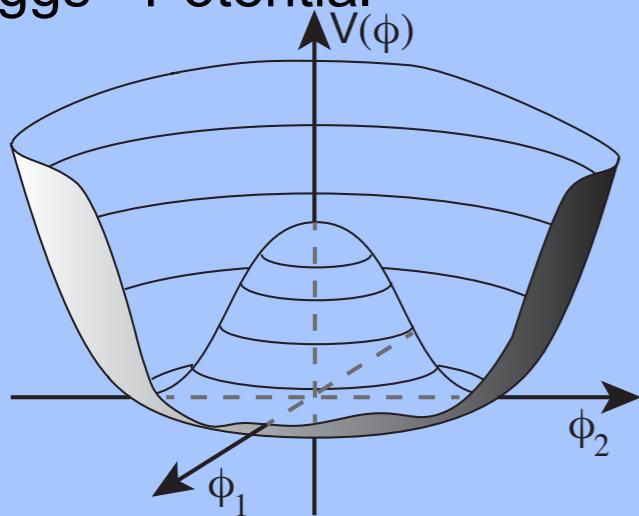


Stabilität des Universums

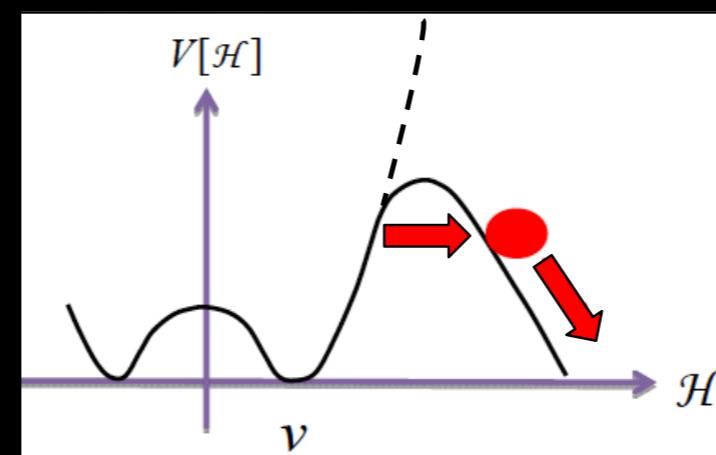
- Entspricht Vakuum Energie des Higgs Feldes **lokalen** oder **globalen Minimum?**
 - Falls lokal, gibt es Zustand geringerer Energie?
 - Könnte Universum in diesen Zustand Tunneln?
- Abhängig von Higgs & Top Masse

$$V(\phi^\dagger \phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad m, \lambda \in \mathbb{R}.$$

Higgs - Potential

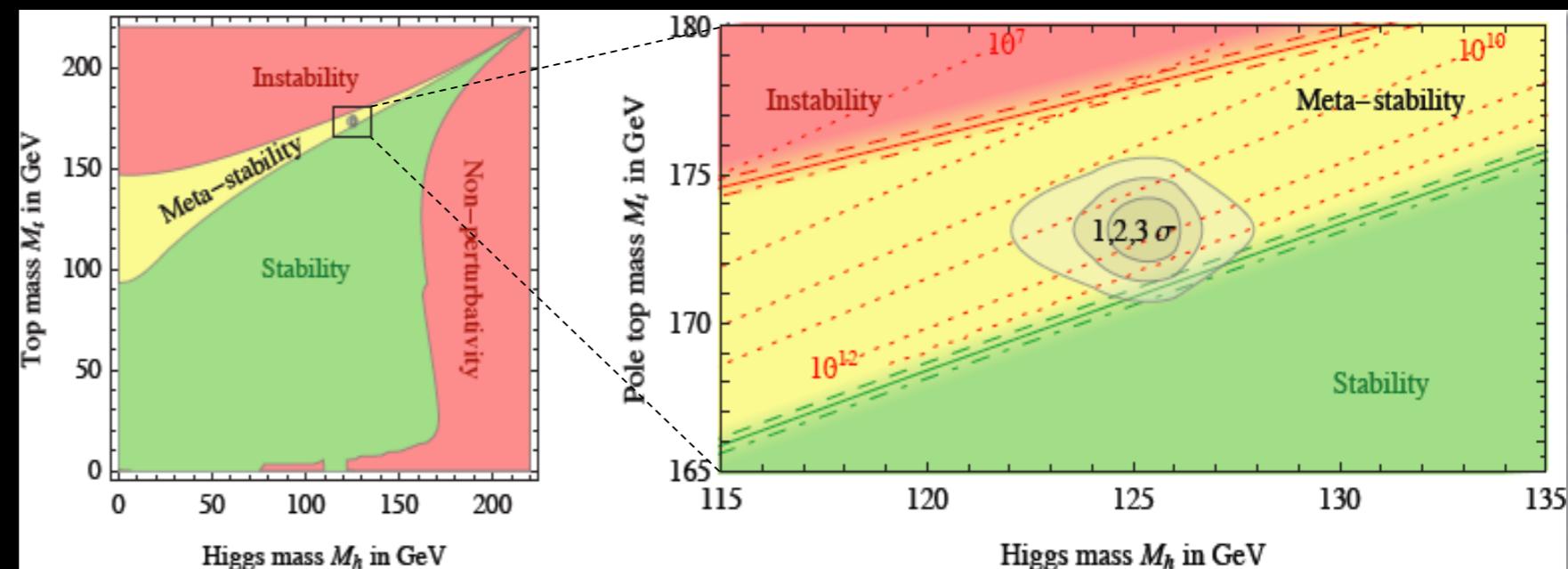
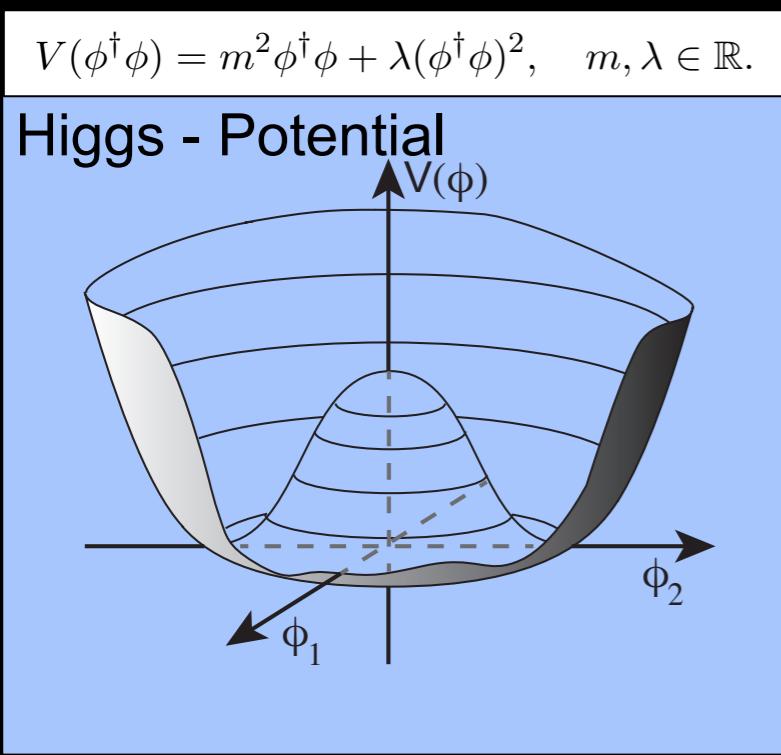


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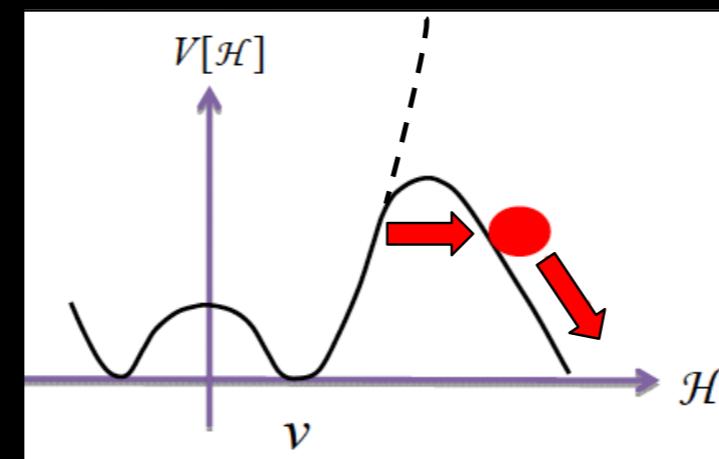


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?



• Tunnelzeit $\sim 10^{100}$ Jahre