From Quarks to Real Life

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www-com.physik.hu-berlin.de/∼fjeger/QCDUS1.pdf

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Abstract

Understanding Hadrons like Protons, Neutrons or Pions in terms of quarks and gluons is an extraordinary challenge for particle theory. I try to give some account on status and perspectives in this field. QCD describing strong interactions in terms of quarks and gluons is kind of shadow world (looks like science fiction but is just another kind of reality) in terms of which we are challenged to explain reality: the world of hadrons basic to real life.

Quantum Chromodynamics
the theory of strong interactions

$SU(3)$ "color" gauge field theory[1], which describes the strong interactions of colored quarks and gluons.

QCD is a revolutionary theory in comparison with other known QFT's (QED, electroweak SM, etc.)

fields	non-perturbative	particles
in	$\Longleftrightarrow$	in
Lagrangian	relationship	physical states

[1] One component of the Standard Model: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \to SU(3)_c \otimes U(1)_{\rm em}$.

Gell-Mann, Fritzsch 1972 (color octet scheme)
Politzer 1973 (asymptotic freedom),
Gross, Wilczek 1973 (asymptotic freedom)
Gell–Mann, Fritzsch, Leutwyler 1973 (confinement postulate, the physics case)

D. Gross
H.D. Politzer
F. Wilczek
NP 2004

QCD Asymptotic Freedom (1973)

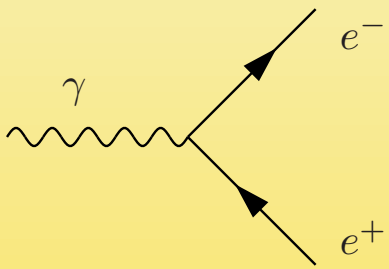
System	Radius	Q-value*	Remarks
Molecule			van der Waals
$\Downarrow$		10^{-10}	(residual e.m. force)
Atom	10^{-8}		
$\Downarrow$		10^{-4}	e.m., QED
Nucleus, Electron	10^{-12}		
$\Downarrow$		10^{-3}	nuclear power
Hadrons: Proton, Neutron	10^{-13}		("van der Waals")
$\Downarrow$		$10^{2} - 10^{-2}$	QCD, confinement
Quarks, Leptons	10^{-16}		
$\Downarrow$		$?10^{6}?$	hypercolor force
?? Preons ??			

Q-value* $\equiv \frac{\text{Binding energy}}{\text{Mass of the constituents}}$

❖ End of Reductionism? Radical change in pattern!

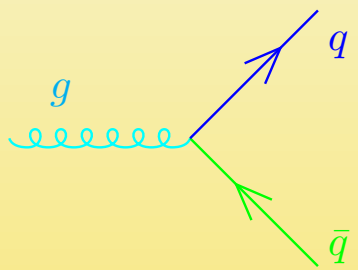
A local gauge theory, prototype QED.

QED electromagnetic interaction photon with charged particles, electrons,....



Abelian theory $U(1)$ phase transformations

QCD strong interactions gluons with quarks (colored)



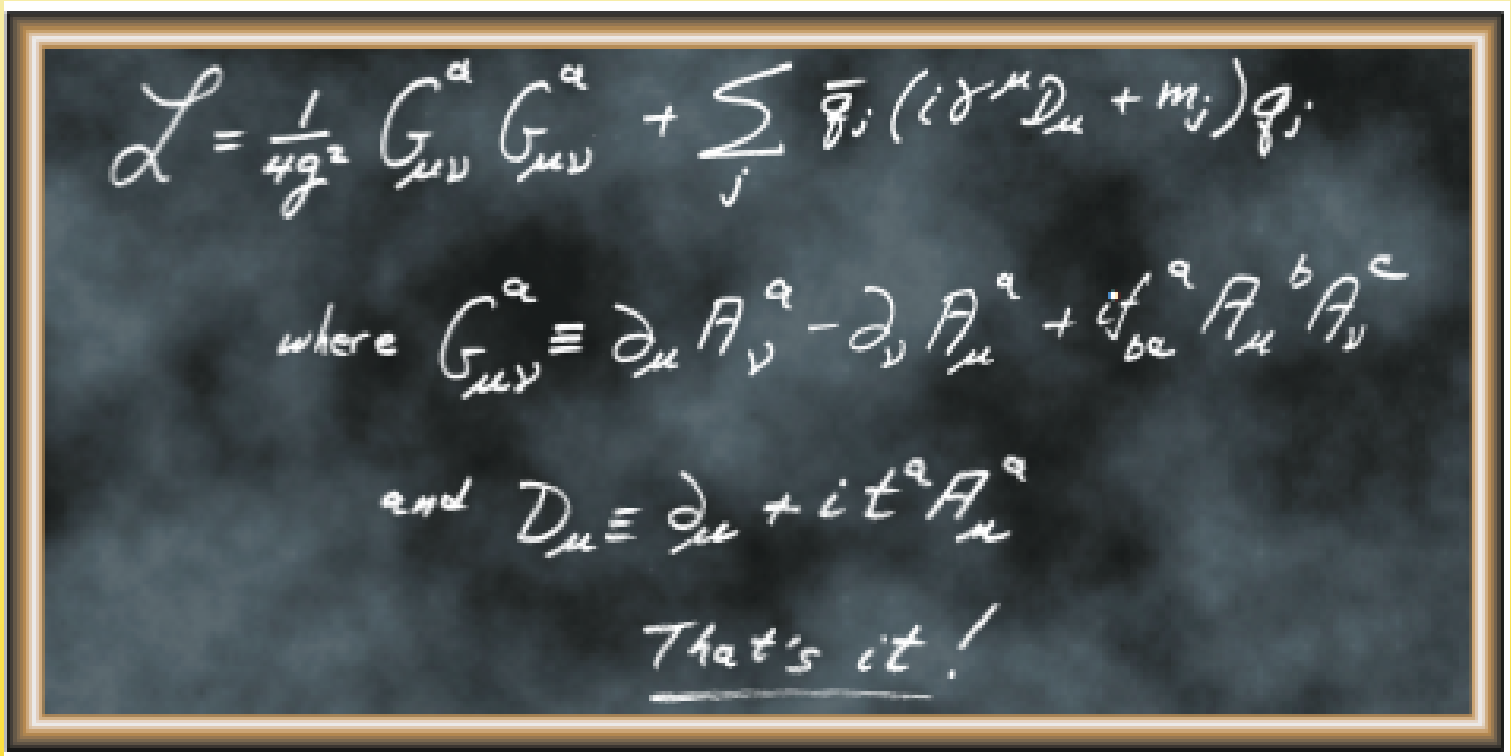
similar to QED, however, gluons carry color charge ➠ self interacting

That's what makes it interesting: responsible for Asymptotic Freedom

Completely fixed by local $SU(3)$ non-Abelian gauge invariance, equivalence principle applied to internal degrees of freedom: called "color"

Quarks: color triplets [fundamental rep. of SU(3)], Anti-quarks: color anti-triplets

➠ Lagrangian uniquely fixed

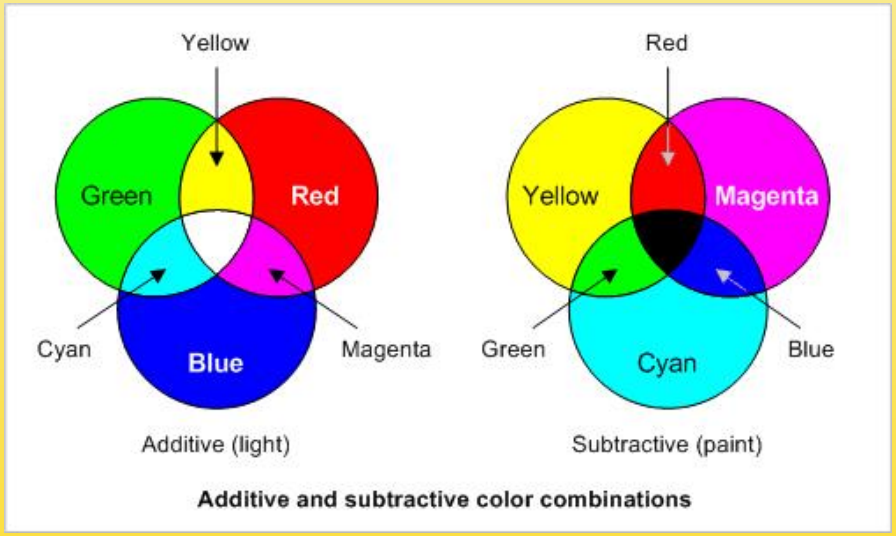


At first sight it appears outrageous to suggest that the equations of figure 1 or, equivalently, the pictures in the box, can describe the real world of the strongly

interacting particles. Frank Wilczek, Nobel Laureate, Physics Today 2004

In nature: hadrons only, color singlets, color unobservable! ➠ Confinement

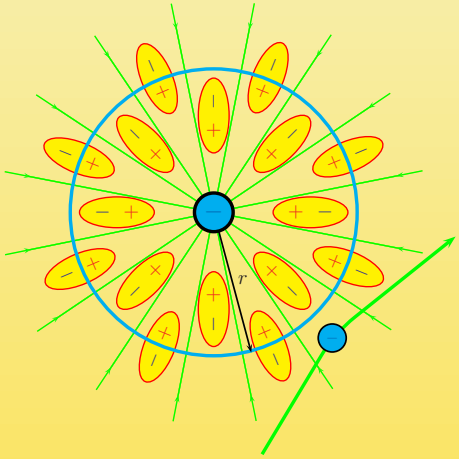
QUARKS are permanently confined inside HADRONS

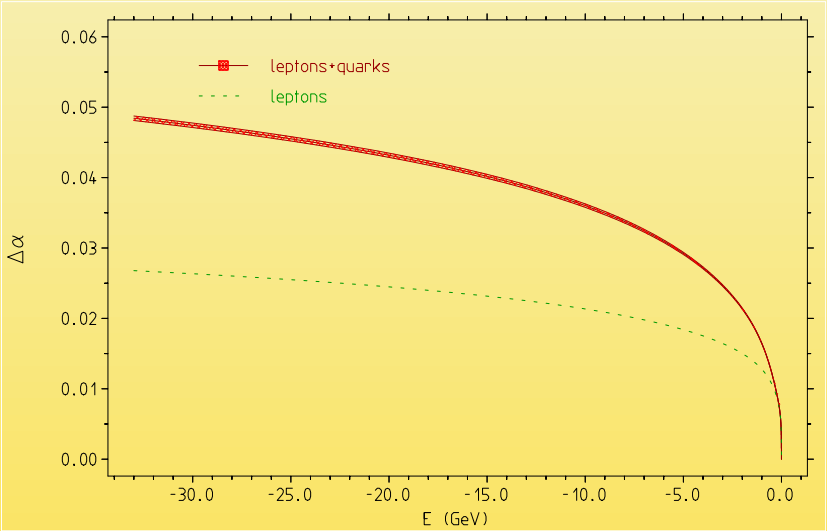


Hadrons are made of Quarks and Gluons

Asymptotic Freedom = Anti-Screening

QED: screening



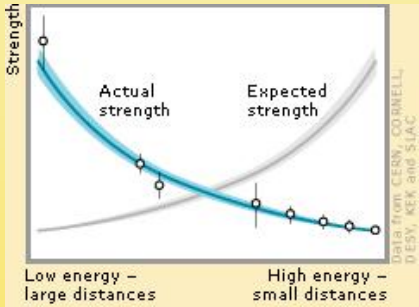


Vacuum polarization in QED causing charge screening by virtual pair creation and re–annihilation and shift of the effective fine structure constant $\Delta\alpha$ as a function of the energy

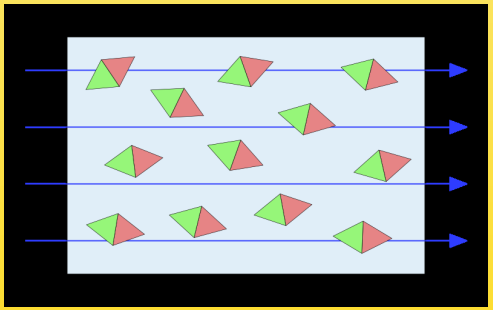
$$\alpha(E) = \frac{\alpha}{1-\Delta\alpha(E)}$$

1972: expected all QFT's are long distance free

1973: non-Abelian gauge theories are short distance free!



QCD anti-screening: magnetic analogue paramagnetism (Mn, Al, ...)



In relativistic QFT: $\varepsilon\mu = 1$ (units $c = 1$)

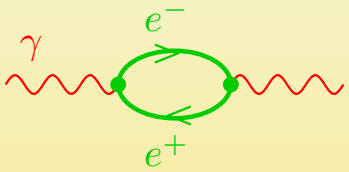
gluons make vacuum paramagnetic $\mu > 1$ hence $\varepsilon < 1 \Rightarrow$ anti-screening!

$$\delta\mu_{\rm gluon} = \ (-1/3 + (2 \times s_g)^2)\, q^2 = \ 11/3\, q^2$$
$$\delta\mu_{\rm quark} = -(-1/3 + (2 \times s_q)^2)\, q^2 = -2/3\, q^2$$
$$s_g = 1\ ;\ \ s_q = 1/2$$

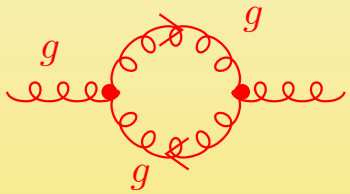
❖ contribution to ε from particle of charge q is $-\frac{1}{3}\, q^2$ (ordinary dielectric or diamagnetic screening)

❖ spin s ➠ permanent dipole moment γs with $\gamma = 2$ contributes $(\gamma s)^2$ to μ

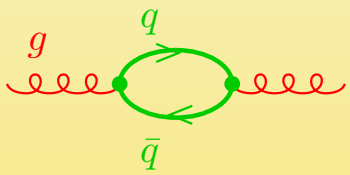
QED:



QCD:



$+$



fermion loops $\rightarrow$ -1 $\Rightarrow$ screening contribution

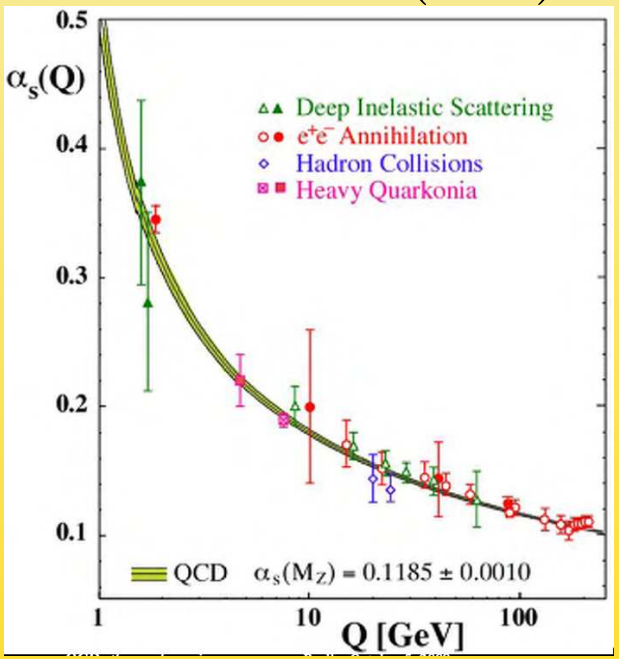
boson loops $\Rightarrow$ anti-screening contribution

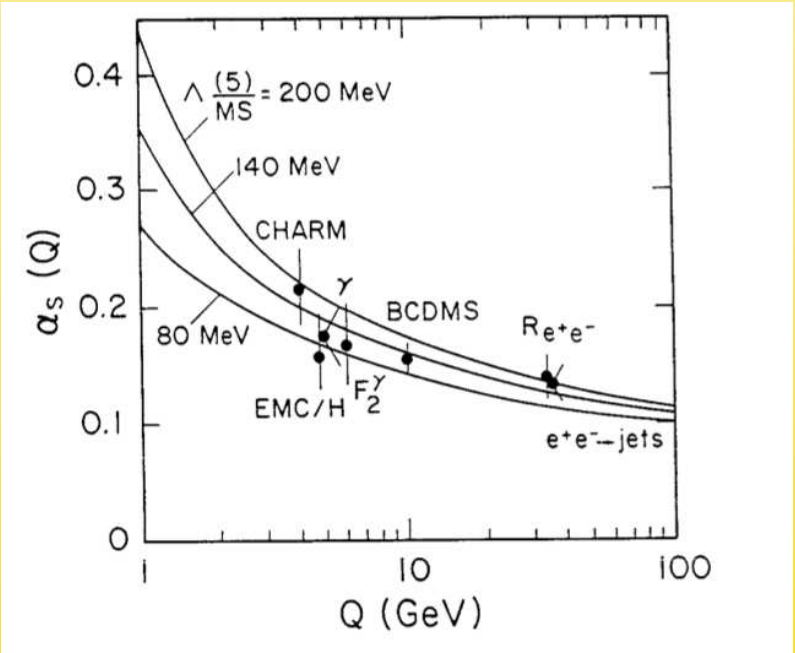
(actually more complicated, more diagrams, individually gauge dependent)

Asymptotic Freedom: QCD running coupling

- Asymptotic freedom: weak coupling at high energies

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$





Status of α_s [Bethke 2009](left) compared with 1989 pre LEP status (right) $\alpha_s^{(5)}(M_Z) = 0.11 \pm 0.01$ (corresponding to $\Lambda^{(5)}_{\overline{\rm MS}} = 140 \pm 60$ MeV).[Altarelli 89].

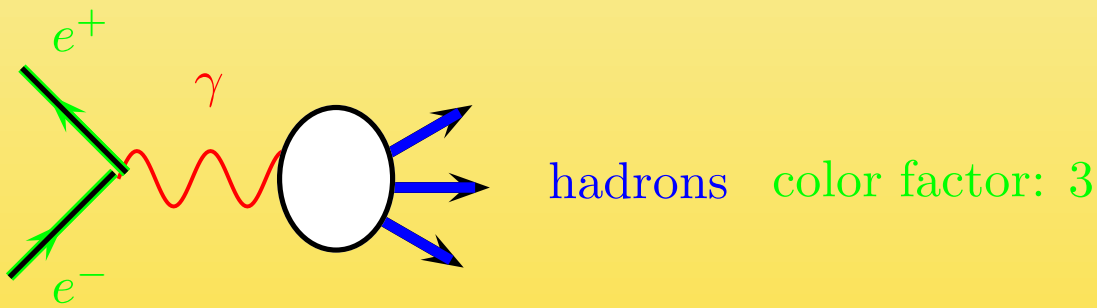
- perturbative QCD (pQCD) applies for $\sqrt{s} \geq M_\tau$
- basis for applicability of perturbative QCD hadron production and deep inelastic scattering (scaling) !!!
- tool: Renormalization Group [μ renormalization scale]

$$\boxed{\mu \frac{\mathrm{d}}{\mathrm{d}\mu} g_s(\mu) = \beta\left(g_s(\mu)\right)}$$

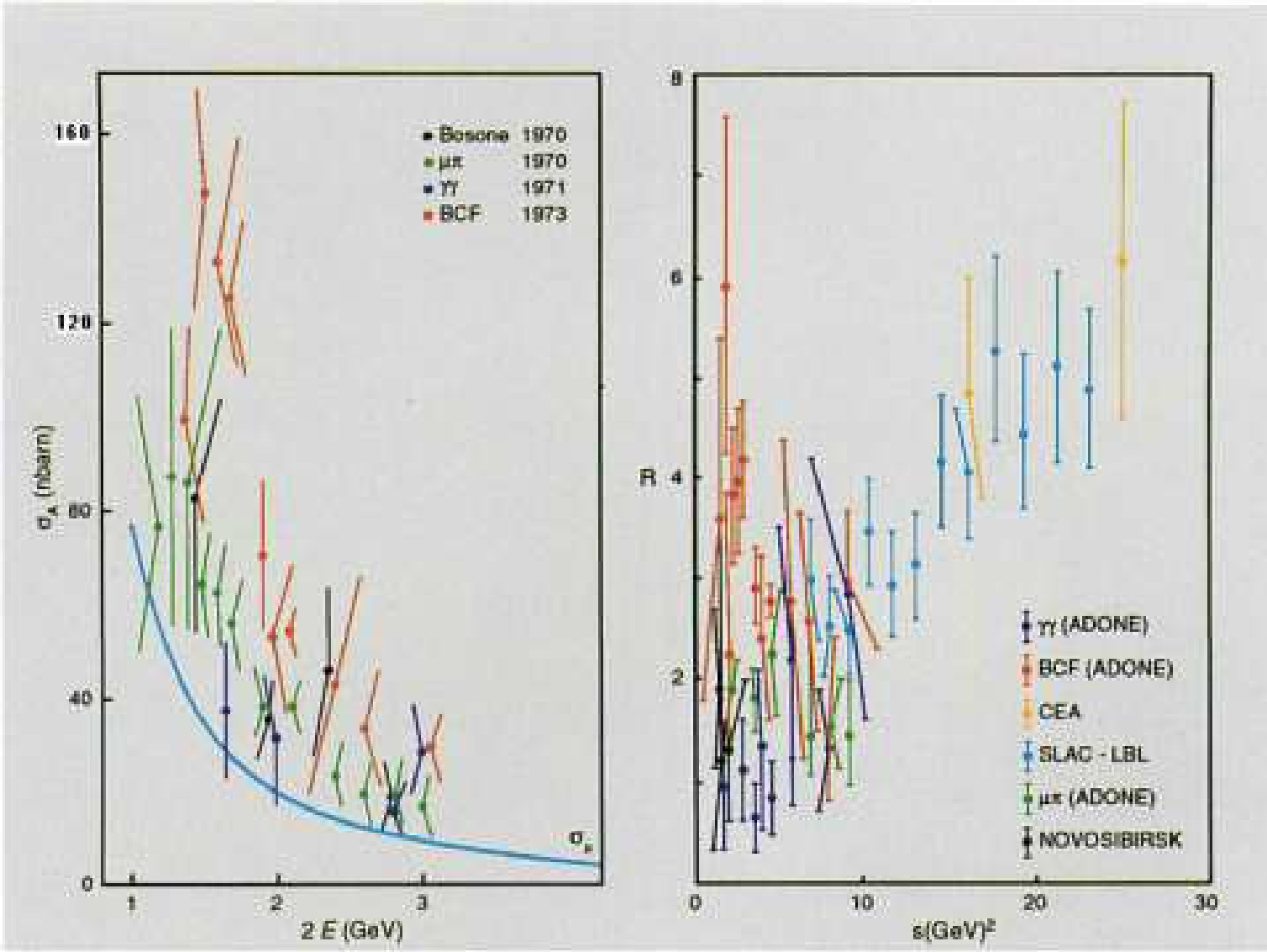
$$\beta(g) = -\frac{g^3}{16\pi^2}\left(\frac{11}{3}N_c - \frac{4}{3}\frac{N_F}{2}\right)$$

Theory meets Reality I: Hard Processes vs perturbative QCD

1. $e^+e^- \to$ hadrons : unitarity crisis 1973
Predicted cross–section by far too low!

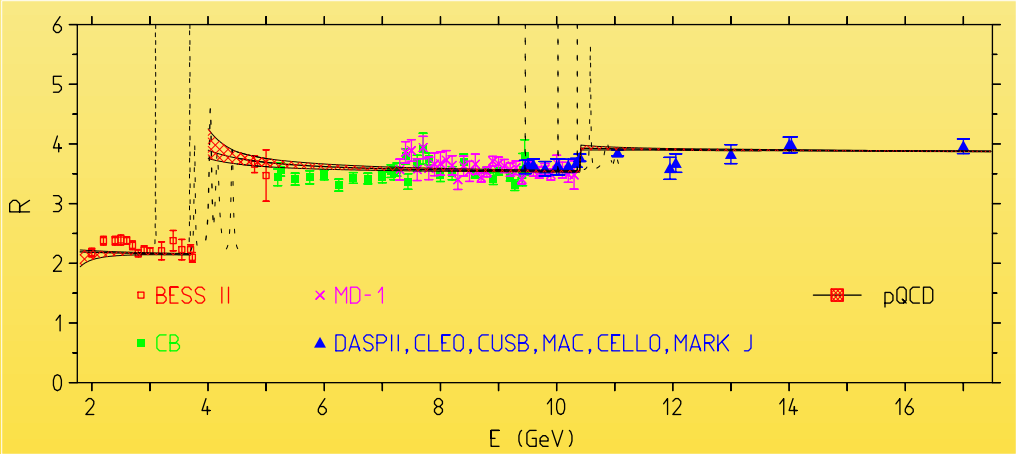


Rochester Conf. London 1974: 21 theory explanations (one QCD Fritzsch&Leutwyler, the only one not mentioned in John Ellis Conf. summary!)


Bosone 1970
μπ 1970
γγ 1971
BCF 1973
σA (nbarn)
2 E (GeV)
R
s(GeV)²
γγ (ADONE)
BCF (ADONE)
CEA
SLAC - LBL
μπ (ADONE)
NOVOSIBIRSK

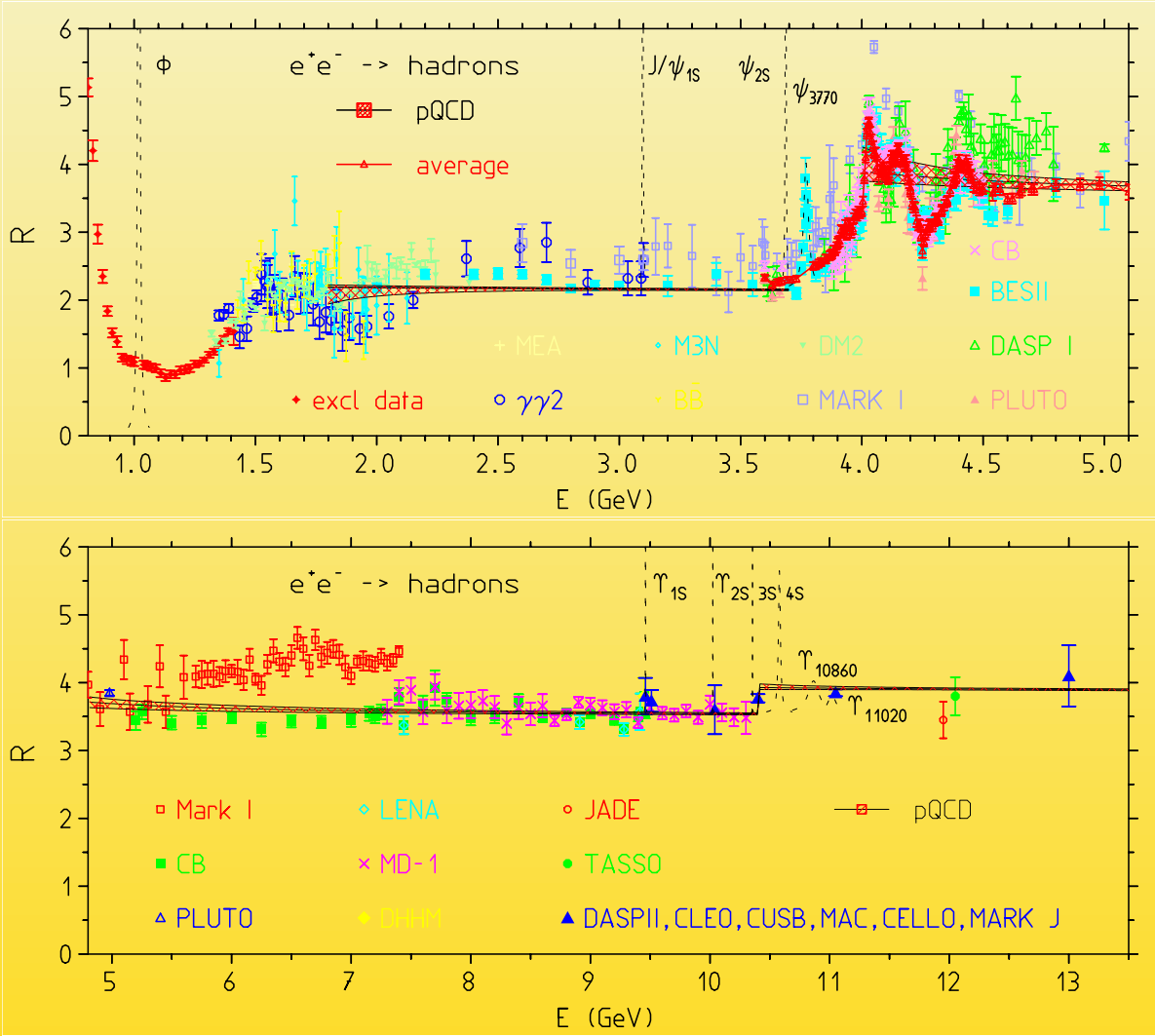
QCD lowest order: Free quark model calculation

N_f	3	4	5
quarks	uds	$udsc$	$udscb$
R	2	$3\,\frac{1}{2}$	$3\,\frac{2}{3}$
range	1.8 - 3.73 GeV	4.8 - 10.52 GeV	11.20 - (2 m_t-10.0) GeV



Test of pQCD prediction of R with some more recent data in the non-resonant regions. The spikes show the sharp J/ψ ($\bar{c}c$) and Υ ($\bar{b}b$) resonances.

Including all data = hadrons vs theory = quarks+gluons: (time-like!)



Testing pQCD via the Adler function

- use old idea: Adler function: Monitor for comparing theory and data

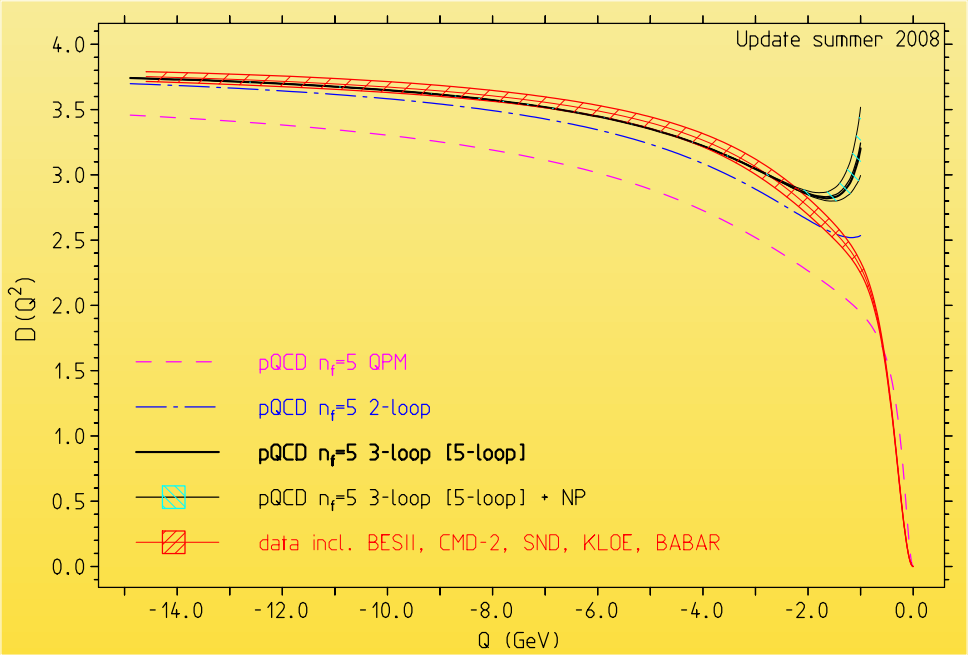
$$D(-s) \doteq \frac{3\pi}{\alpha}\, s\, \frac{d}{ds}\Delta\alpha_{\rm had}(s) = -\left(12\pi^2\right)\, s\, \frac{d\Pi'_\gamma(s)}{ds}$$

$$\Rightarrow \qquad D(Q^2) = Q^2 \int\limits_{4m_\pi^2}^{\infty} ds\, \frac{R(s)}{(s+Q^2)^2}$$

pQCD $\leftrightarrow R(s)$	pQCD $\leftrightarrow D(Q^2)$
very difficult to obtain in theory	smooth simple function in Euclidean region

"Experimental" Adler–function versus theory (pQCD + NP)

Error includes statistical + systematic here (in contrast to most R-plots showing statistical errors only)! Quark+gluons vs hadrons (red band)



(Eidelman, F.J., Kataev, Veretin 98, FJ 08 update)

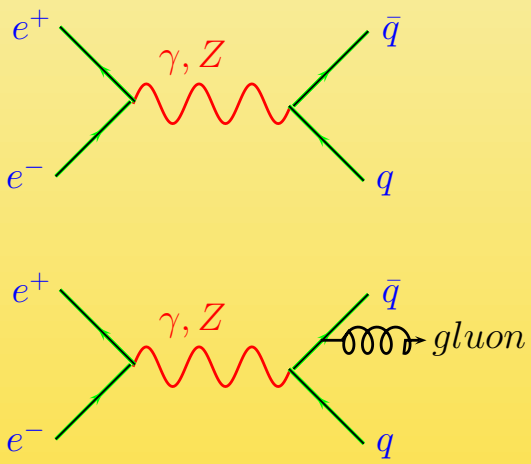
theory based on results by Chetyrkin, Kühn et al.

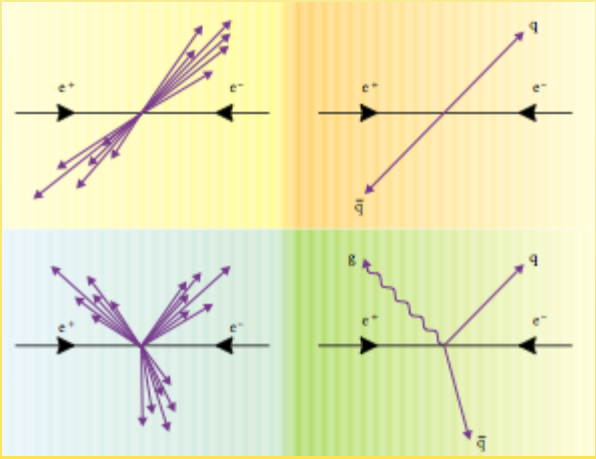
Conservative conclusion:

- time-like approach: pQCD works well in "perturbative windows"
  3.00 - 3.73 GeV, 5.00 - 10.52 GeV and 11.50 - ∞
  Kühn,Steinhauser

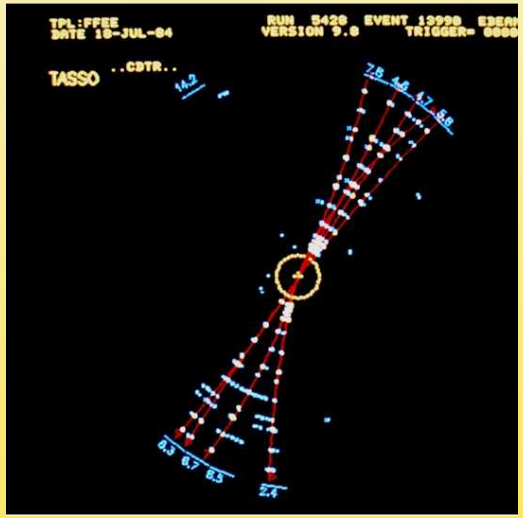
- space-like approach: pQCD works well for $\sqrt{Q^2 = -q^2} > 2.5$ GeV (see plot)

2. $e^+e^- \to$ hadrons : jet–production





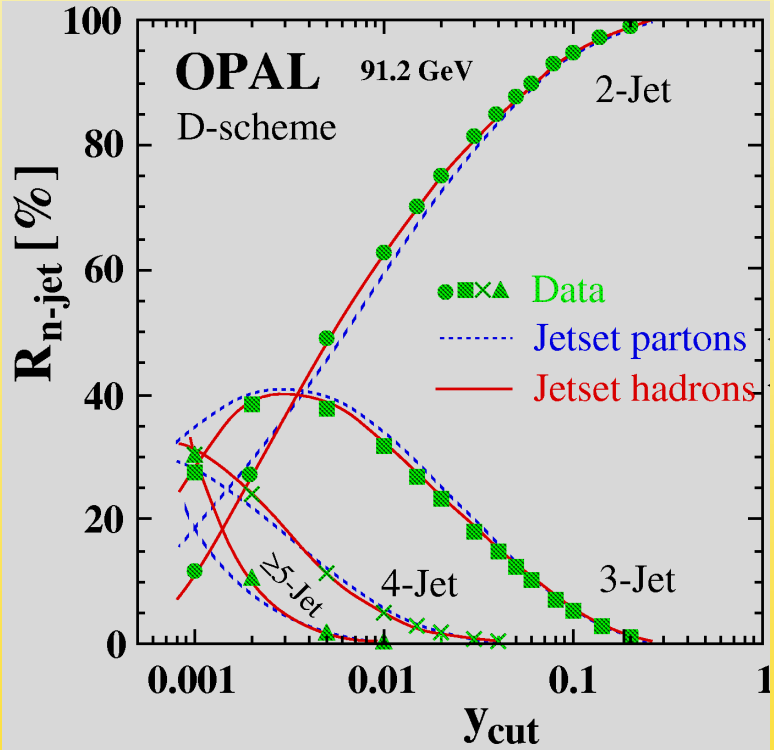
Inclusive cross sections at high energy are well described by perturbative QCD (weak effective coupling). Energetic quarks and gluons hadronize as jets.

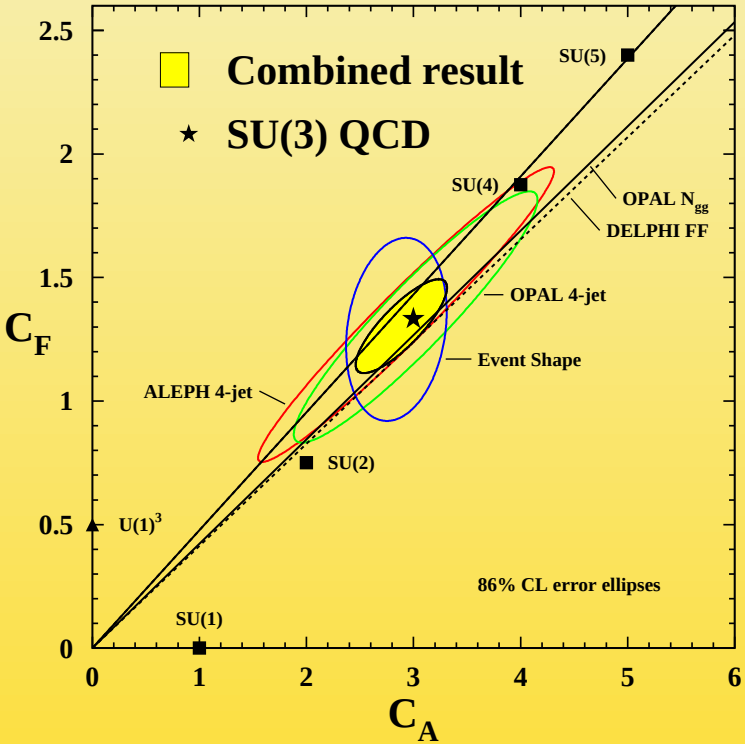


Discovery of the gluon (gluon-jet in 3-jet-event) by Tasso at DESY 1979

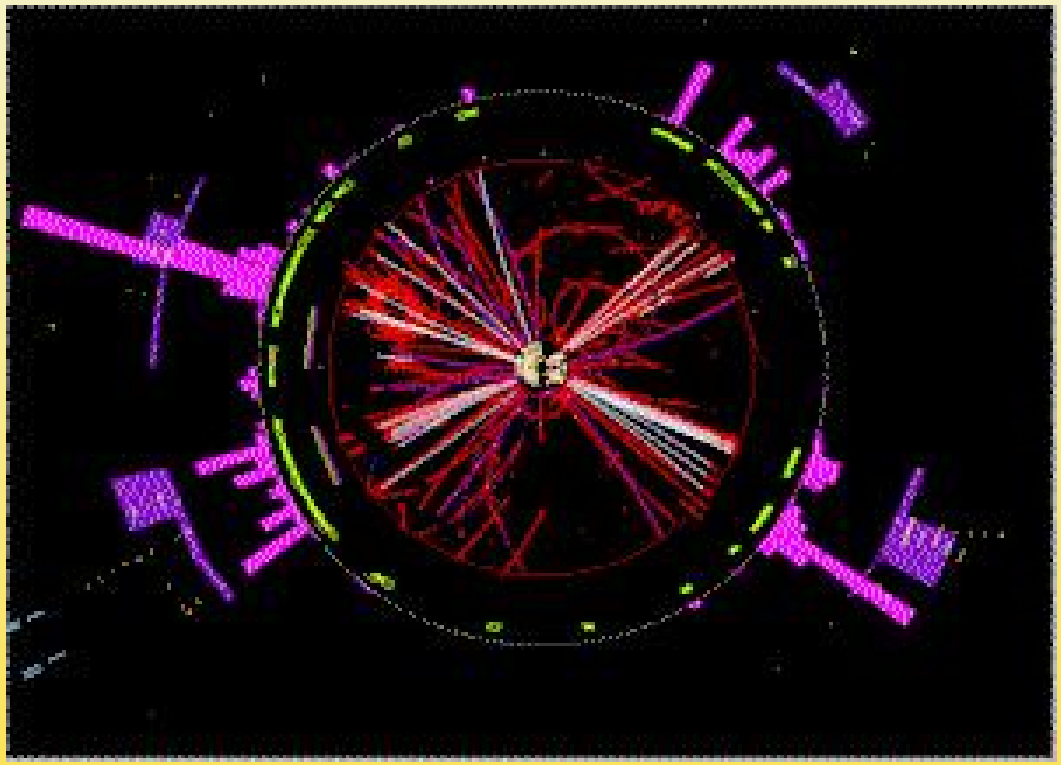
Note: hadronization details not under control of theory!

QCD group structure from 4-jet cross sections

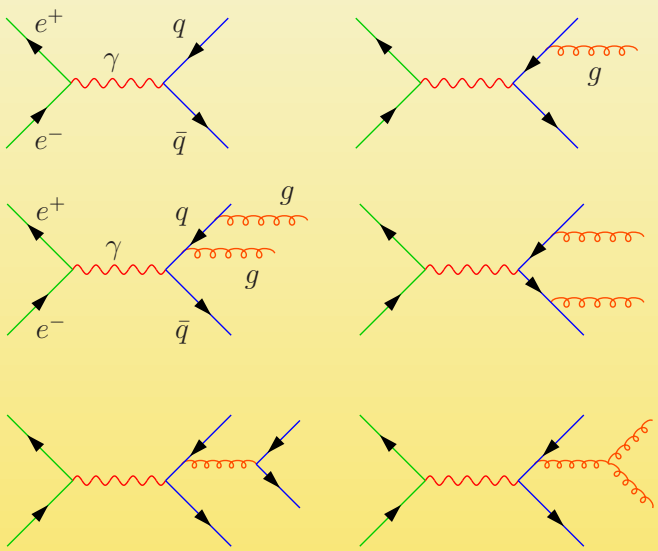




We have been measuring the QCD Gauge Group !!!



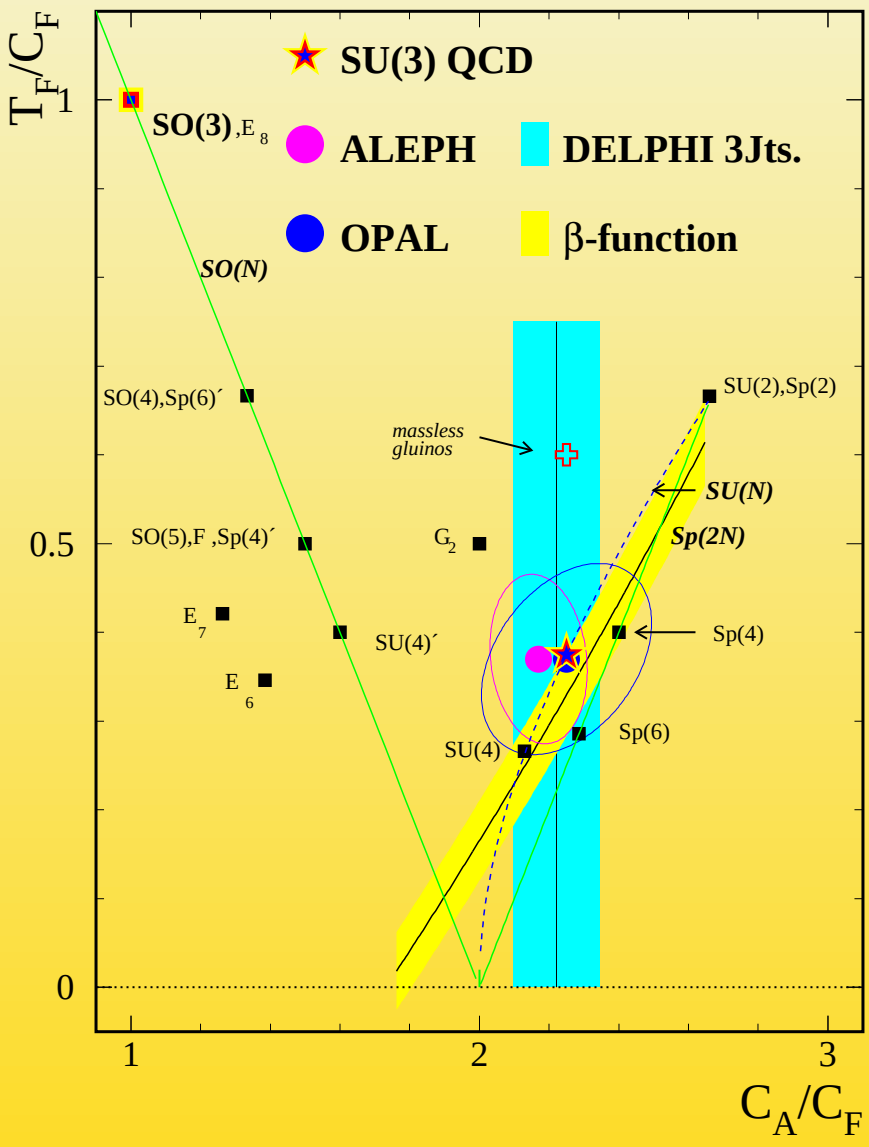
Four jet event from OPAL/LEP CERN



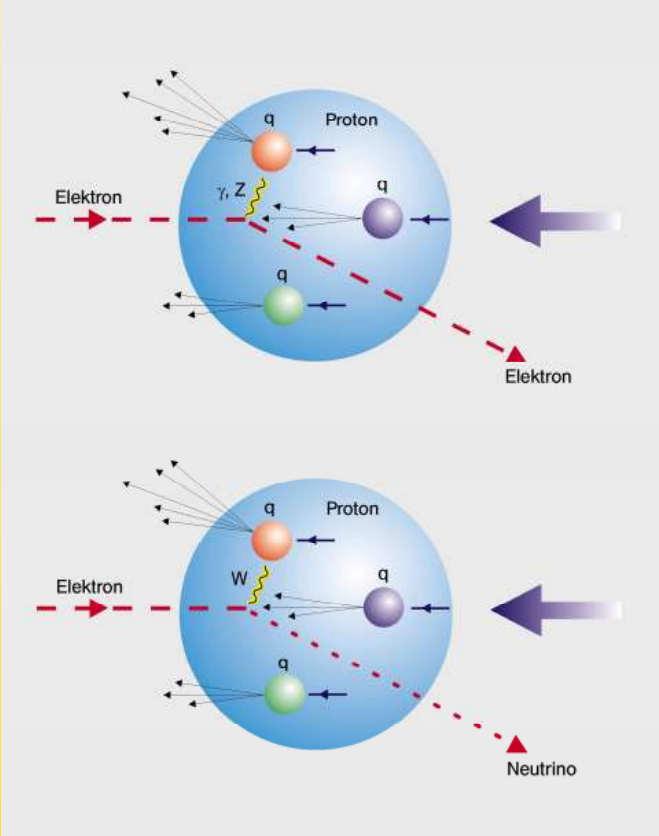
Feynman diagrams for perturbative jet cross-section calculations in QCD

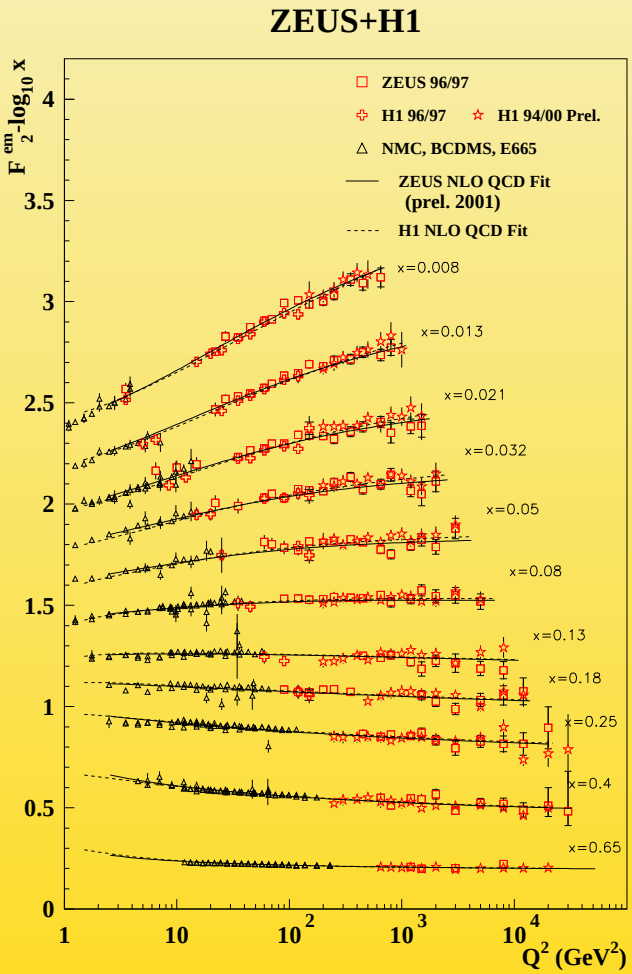
Final states: $q\bar{q}\,(2jets),\ q\bar{q}g\,(3jets)$ **and** $q\bar{q}, q'\bar{q}'\,(4jets),\ q\bar{q}g\,g\,(4jets)$

[only typical cases shown, gluons to be attached to quarks in all possible ways]


SU(3) QCD
ALEPH
DELPHI 3Jts.
OPAL
β-function
SO(3),E 8
SO(N)
SO(4),Sp(6)´
SO(5),F ,Sp(4)´
E 7
E 6
SU(4)´
massless gluinos
G 2
SU(2),Sp(2)
SU(N)
Sp(2N)
Sp(4)
Sp(6)
SU(4)
T F/C F
C A/C F
0
0.5
1
1
2
3

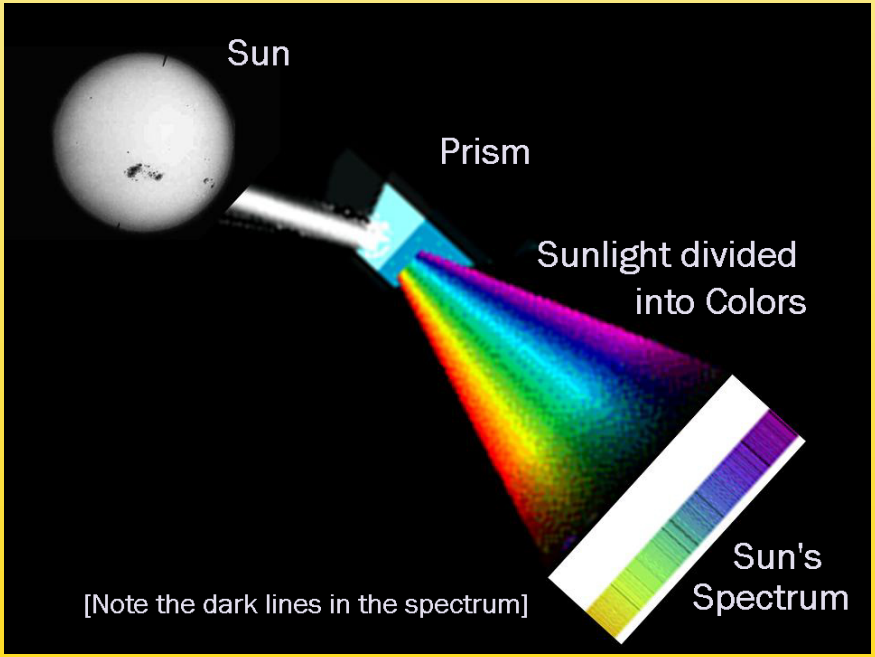
4. $ep \to eX$: Deep inelastic scattering (DIS) [Bjorken scaling]

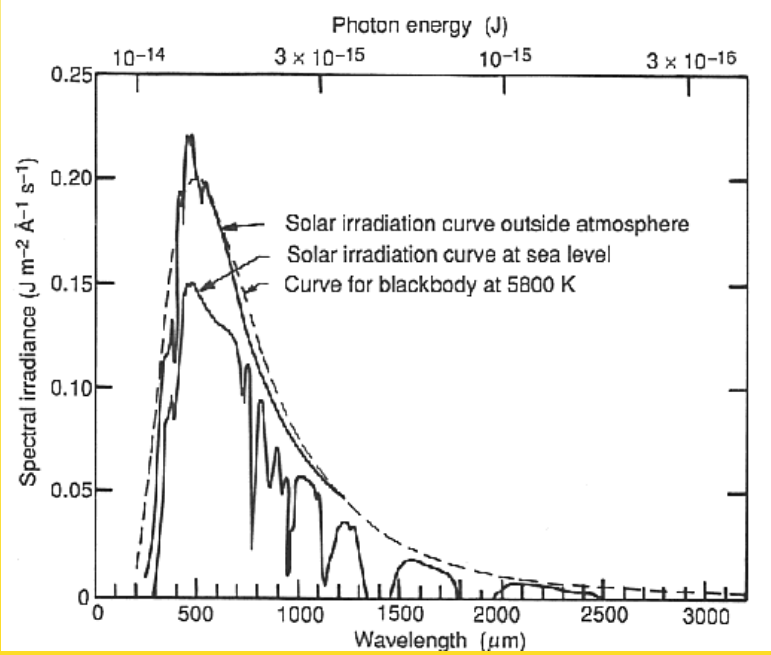


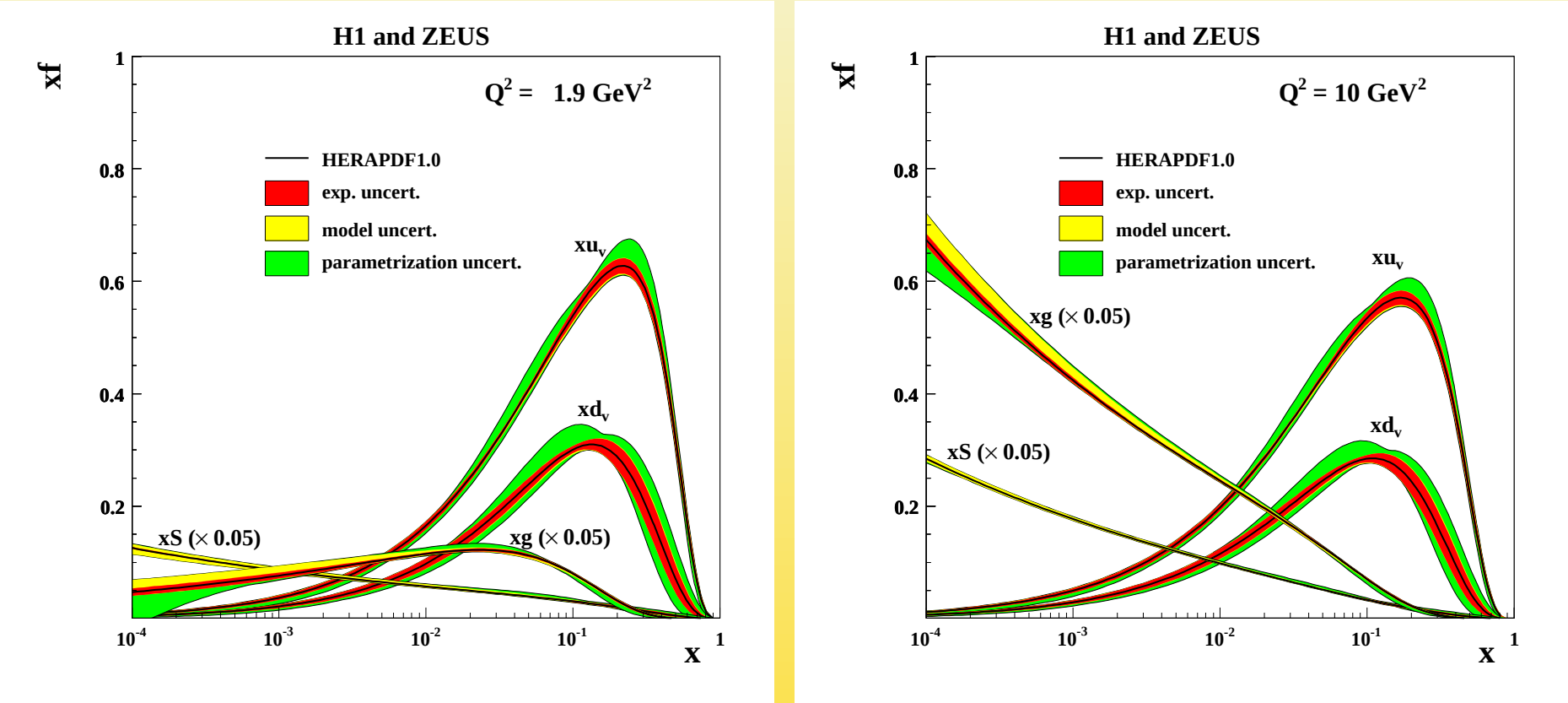


Spectra decomposition of proton into color components the quarks and gluons

Prototype spectral decomposition of solar light





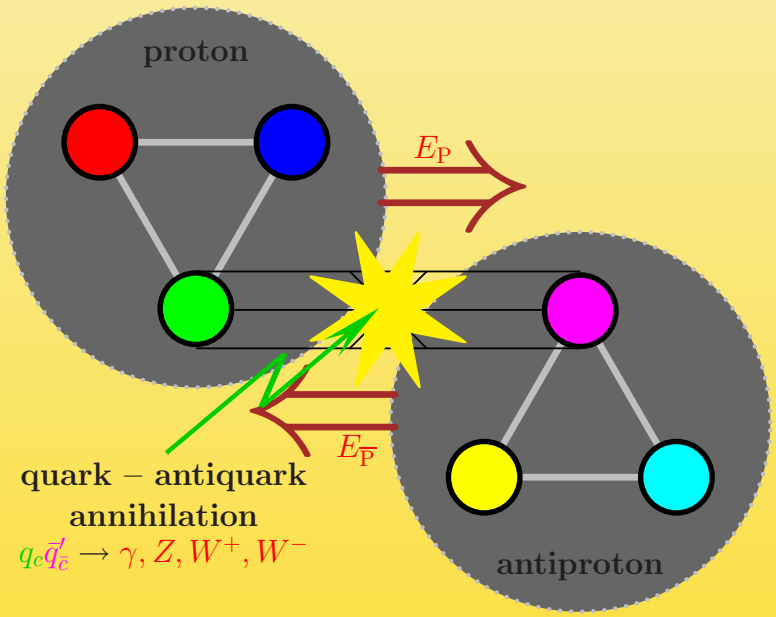


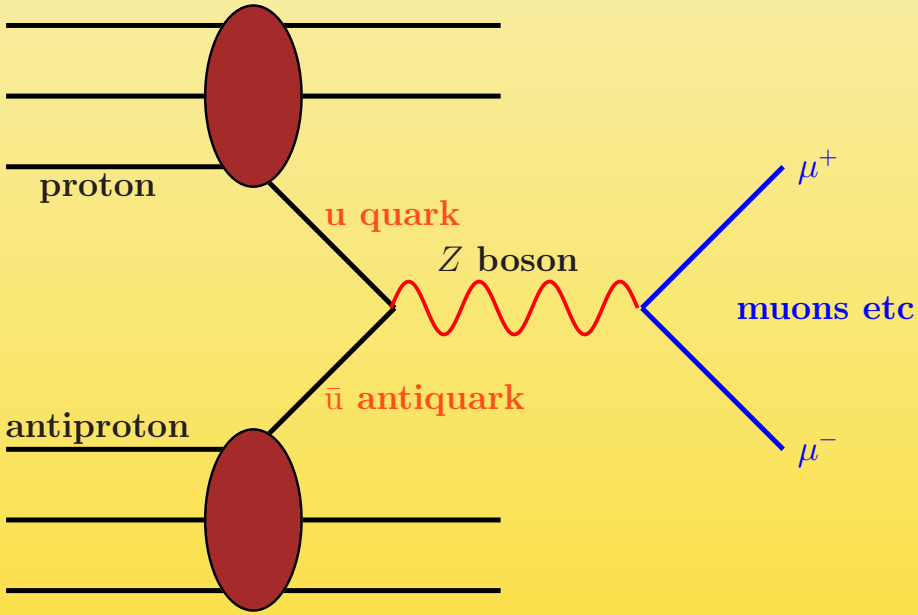
Quark distribution inside proton: x is the fraction of proton energy carried by the parton=quarks, gluons

HERA/DESY 2009

Another Proof for Quarks and Gluons in Protons

CERN Proton - Antiproton collider SPS





p $\bar{\rm p}$ fragments hadronize into hadronic junk

$$s_{q\bar{q}} = s_{p\bar{p}}\, x_q\, x_{\bar{q}}$$

($s = E^2_{\text{center of mass}}$, x_q momentum fraction carried by quark)

What beam energy needed to produce W and Z bosons: $M_W \sim 80$ GeV, $M_Z \sim 90$ GeV ?

In fact 50% of the momentum of a high energetic proton is carried by gluons!

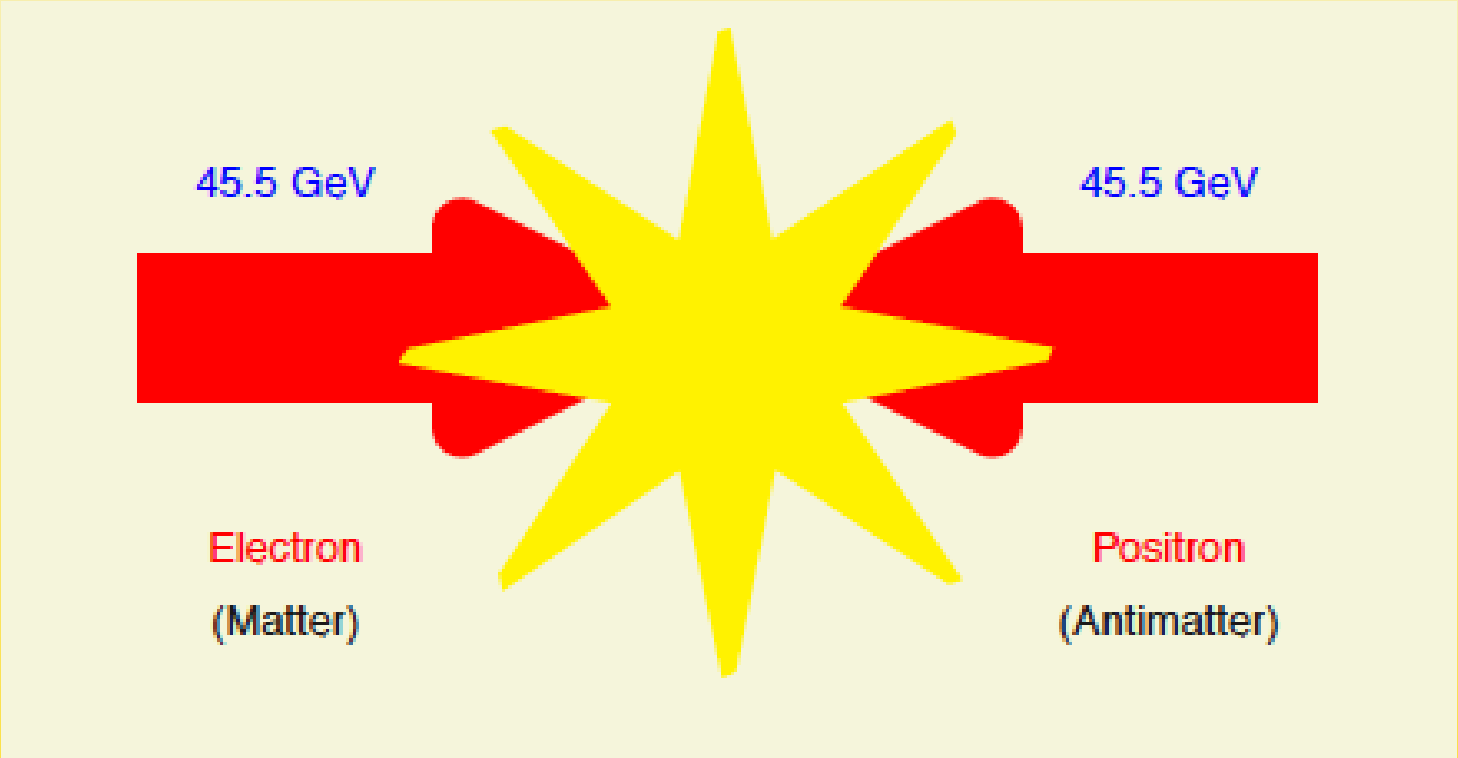
➠ a valence quark in average only carries $1/6$ of the proton momentum!

The CERN SPS operated with 270 GeV energy per beam: center of mass $E_{\rm tot}$ 540 GeV ➠ 540/6=90 GeV $q\bar{q} \to Z$ ✓

1983 Discovery of W and Z particles, which mediate weak force

Carlo Rubbia and Simon van der Meer , Nobel Prize 1984 !

In contrast e^+e^- machine LEP: Z physics at LEP I $E_{\rm beam} \sim 45$ GeV for same physics!



LEP II $E_{\rm LEP\ max} = 200$ GeV now: LHC $E_{\rm LHC\ max} = 14000$ GeV

Gain for physics: factor $\frac{1}{6}\frac{E_{\rm LHC\ max}}{E_{\rm LEP\ max}} \sim 12$ in energy; however, also gluon fusion

QCD Strings

In QCD long distance = size of hadron ! Perturbation expansion useless!

How could a $q\bar{q}$–potential look like?

These two limits suggest a model:

$$V(r) = -\frac{a}{r} + V_0 + \sigma\, r\ .$$

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1) At large distances confinement requires a linearly rising potential as known from the Regge behavior of excited hadrons: $V(r) \propto r$. Such behavior is supported by strong coupling expansions as well as by numerical simulations in lattice regulated QCD.

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$$\boxed{V(r) = -\frac{a}{r} + V_0 + \sigma\, r\ .}$$

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1) At large distances confinement requires a linearly rising potential as known from the Regge behavior of excited hadrons: $V(r) \propto r$. Such behavior is supported by strong coupling expansions as well as by numerical simulations in lattice regulated QCD.
2) At short distances, by virtue of asymptotic freedom, we expect a Coulomb like potential mediated by the massless gluon: $V(r) \propto -1/r$.

These two limits suggest a model:

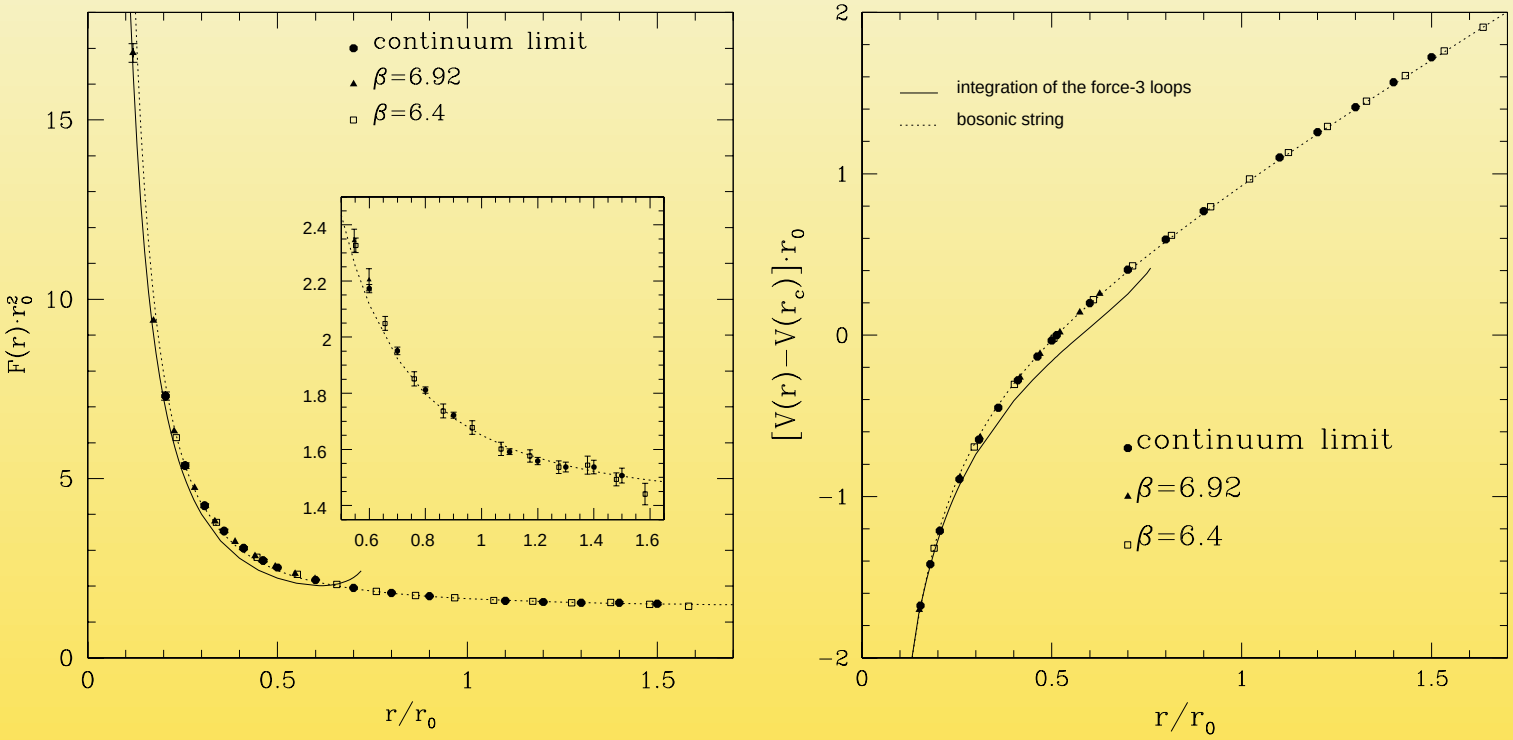
$$\boxed{V(r) = -\frac{a}{r} + V_0 + \sigma\, r\ .}$$

In fact: effective nucleon interaction via pion exchange: Yukawa Potential (also called a 'screened Coulomb potential') is a potential of the form

$$\text{“Real life”: } V(r) = -g^2 \frac{\mathrm{e}^{-mr}}{r} \simeq m = m_\pi \sim 134 \text{ MeV}$$

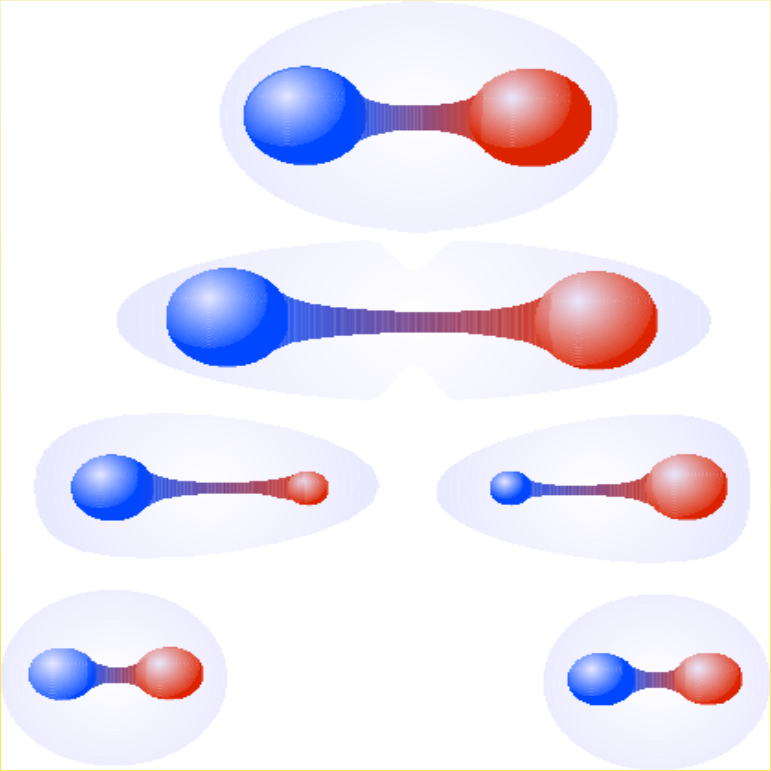
mass gap (like superconductor!)

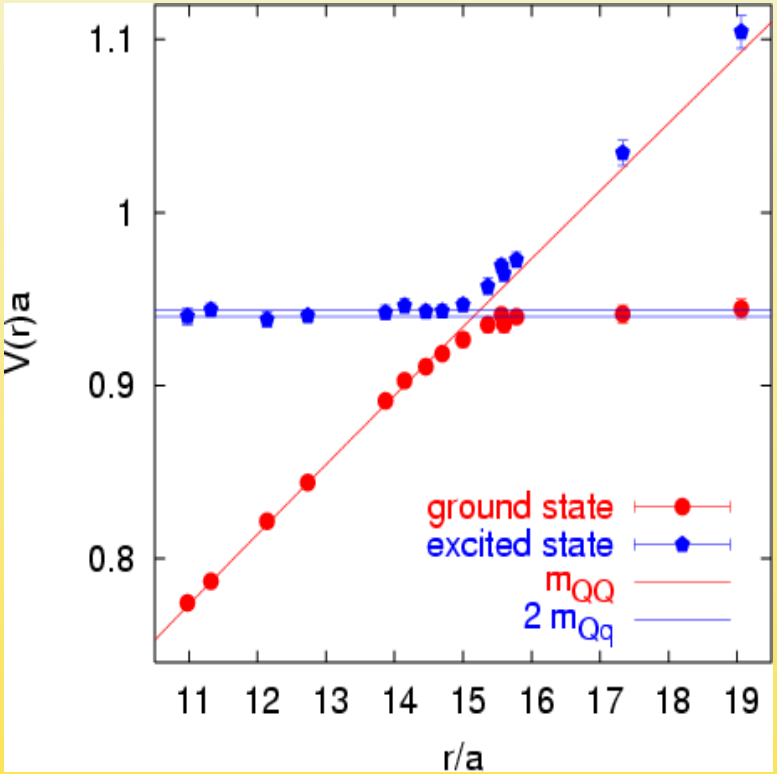
Hideki Yukawa 1930's



The force and the static potential from LQCD. The dashed line represents the bosonic string model and the solid line the prediction of perturbation theory.
Sommer, Necco

Tested in Quarkonium spectra! in fact strings break up by hadro-production:





- QCD completely new type of force
- normal forces between bodies get smaller the more they are separated

- for quarks and gluons the contrary is true: the force acting remains constant with distance ➠ absolute prison = confinement (separation energy grows linearly with distance)

- quarks can be separated in color neutral bags = hadrons

- strong residual force (like van der Waals in QED) very short ranged

- real challenge: explain the short range force = real life in terms of long range dominated one!

Theory meets Reality II: Hadron Spectrum

Spectrum: Hadrons$\equiv$ color singlet states

Mesons $(q_1\bar{q}_2)$,

Baryons (q_1, q_2, q_3),

Antibaryons $(\bar{q}_1, \bar{q}_2, \bar{q}_3)$,

Glueballs.

- Hadrons are elementary composite systems

100% non-perturbative $\Rightarrow$ lattice QCD

Perturbative QCD does not know about spontaneous breaking of chiral symmetry!

Yoichiro Nambu, NP 2008

Spontaneous Symmetry Breaking
in Particle Theory

Mimicking and adapting BCS theory of superconductivity to hadron physics

- Chiral symmetry (chiral limit) must be spontaneously broken
- Vacuum cannot be empty
- Predicts pions as Nambu-Goldstone bosons
- Predicts nucleon masses to be generated dynamically,
  in chiral limit: 100% strong interaction dynamics

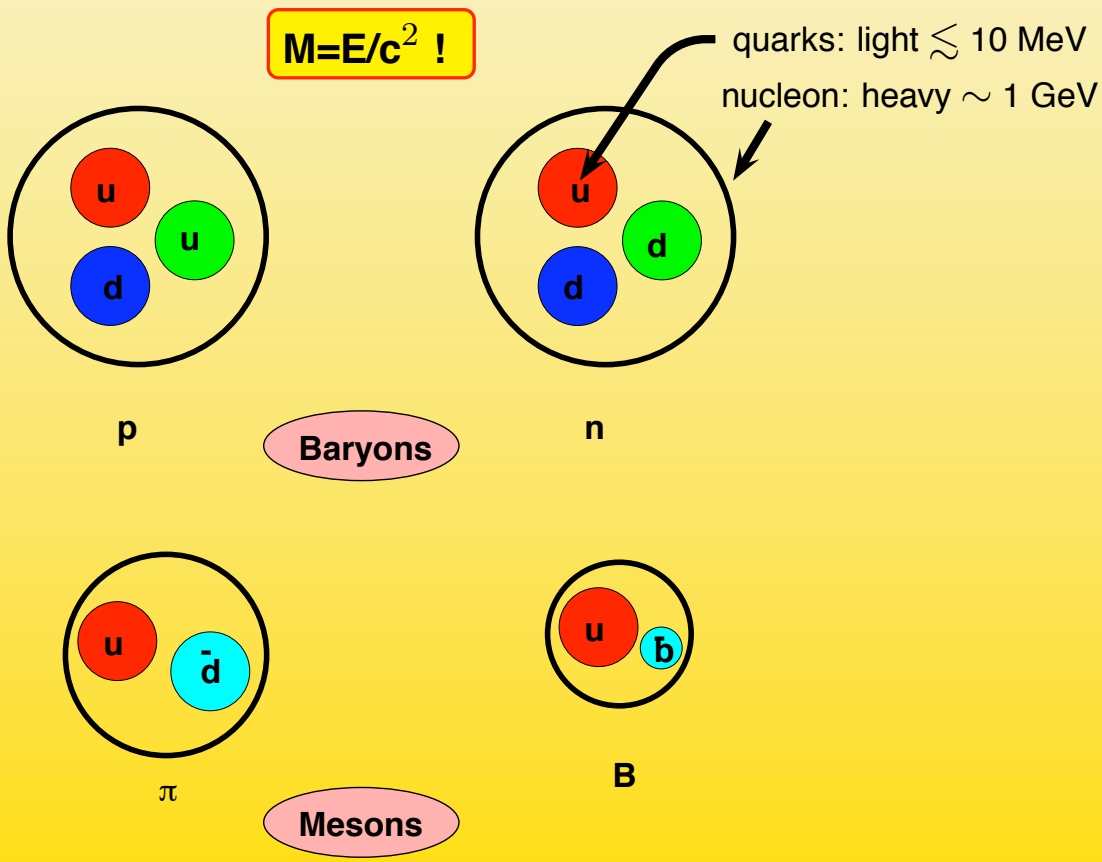
In other words:

- Parity violation: Vector and Axialvector currents!
- Chiral symmetry: $SU_V(2) \otimes SU_A(2) \to SU_V(2)$
- Quark condensates!
- Nambu-Goldstone bosons = Pions
- Low energy effective theory: Chiral Perturbation Theory!

➠ Hadron mass spectrum intrinsic non-perturbative

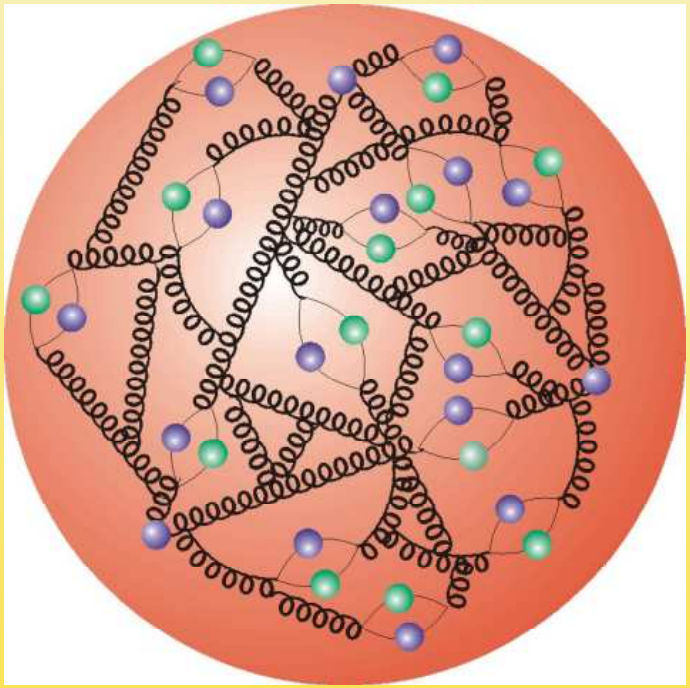
Hadrons are made of Quarks and Gluons

QUARKS are permanently confined in HADRONS



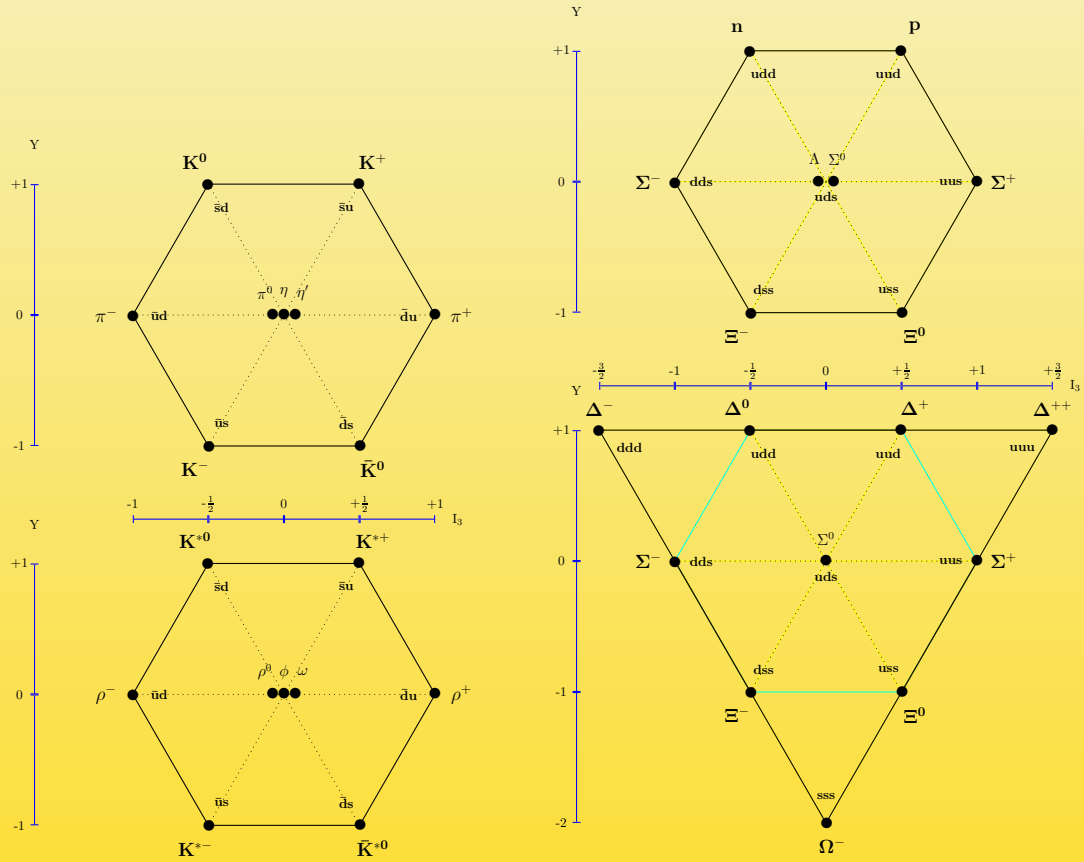
Hadrons are elementary composite systems [Wigner state]

Quantum fluctuations inside the Proton:

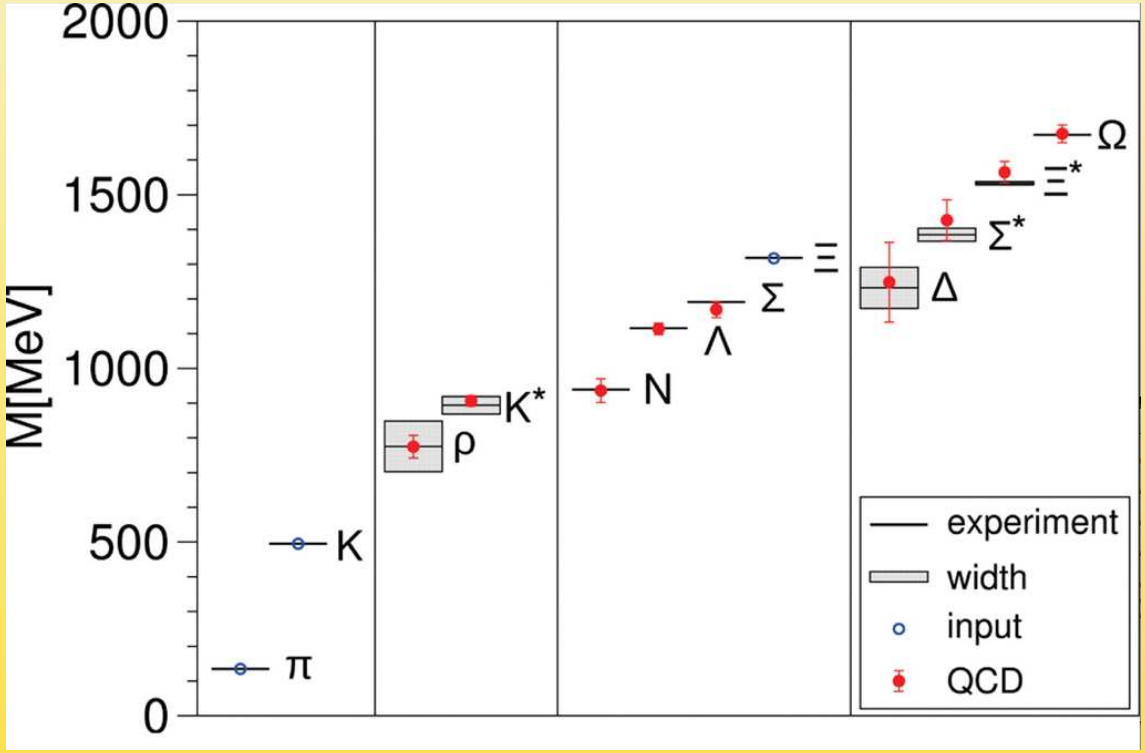


In spite of its complex structure: it is a representations of $SL(2, C)$ (Wigner particles), i.e. has definite mass, spin 1/2, and charge 1

Lowest $SU(3)_{\text{Flavor}}$ Hadron Multiplets



QCD hadron spectrum as calculated in lattice QCD:

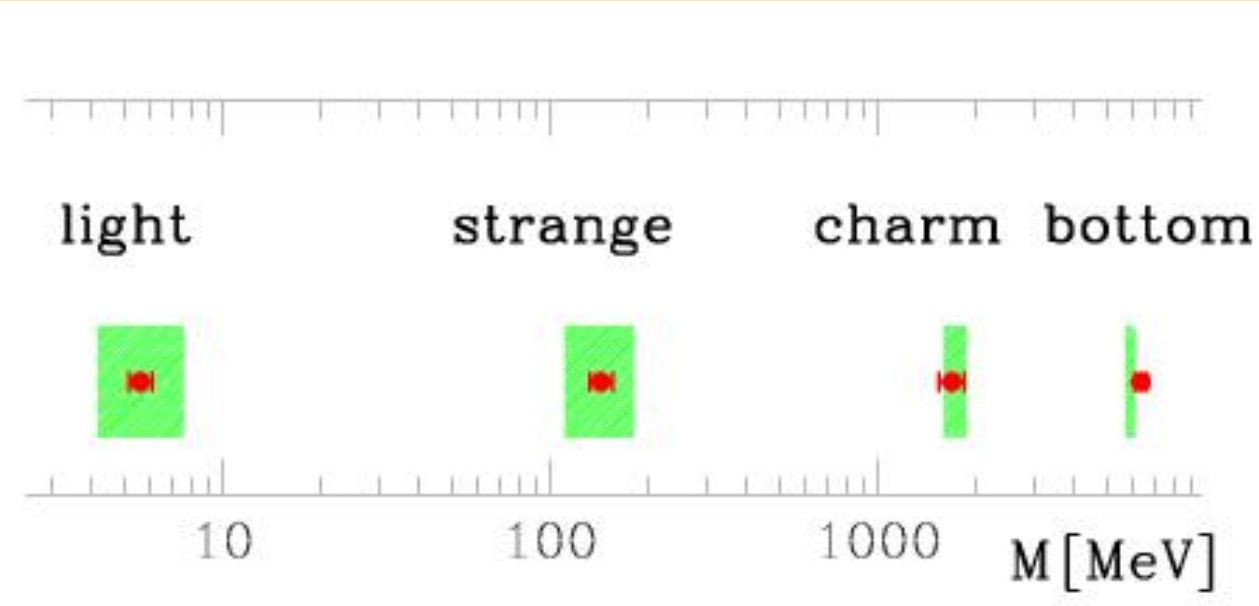


[from Dürr et al. Science 322 (2008) 1224]

Proton mass calculated from first principles!

Also quark masses calculated in LQCD [Alpha Collab.]

Exploiting as input chiral symmetry breaking pattern of low lying meson spectrum!



Proton 98% gluonic binding energy! Mass of us! Almost all Baryonic Mass of the Universe!

What about Dark Matter?

Normal matter: 98% binding energy $M = E/c^2$. Baryonic matter in the universe almost 100% pure binding energy, completely non-perturbative phenomenon.

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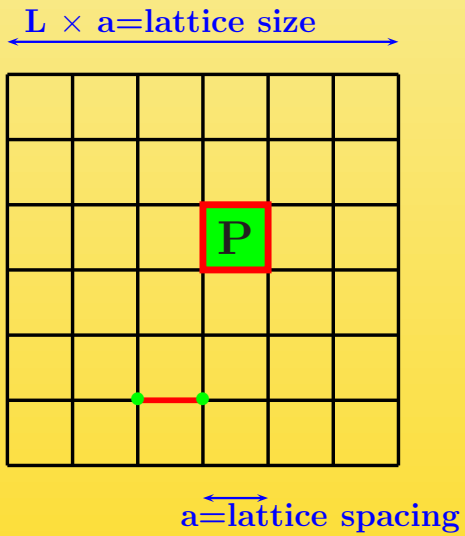
Dark matter problem: why do we suppose that some elementary particle like neutralino should be responsible for it? I think dark matter could as well be just condensed energy.

Non-perturbative Approach the QCD: Lattice Gauge Theory

Rules of the Game

space–time continuum $\longrightarrow$ discretization $\longrightarrow$ space–time lattice

$$x_\mu = a n_\mu \quad , \quad n_\mu \in Z$$



- **QUARK FIELD** $\Psi(x)$: **3×4 complex**
  on lattice sites

— **GLUON FIELD** $\mathbf{U}(x,y)$: **3×3 complex**
on lattice links $\in SU(3)$

P PLAQUETTE: **Tr** [UUUU]

Prototype: F. Wegeners Z_2 Gauge Link model 1969, Wilson 1973

fields are statistically distributed with weight function

$$e^{-S(U,\Psi,\bar{\Psi})}$$

where

S=“ACTION” = energy × time

$$S = \sum_{\mathrm{P}} \mathrm{Tr}[UUUU] + \sum_{<xy>} \bar{\Psi}_x M(U)_{xy} \Psi_y$$

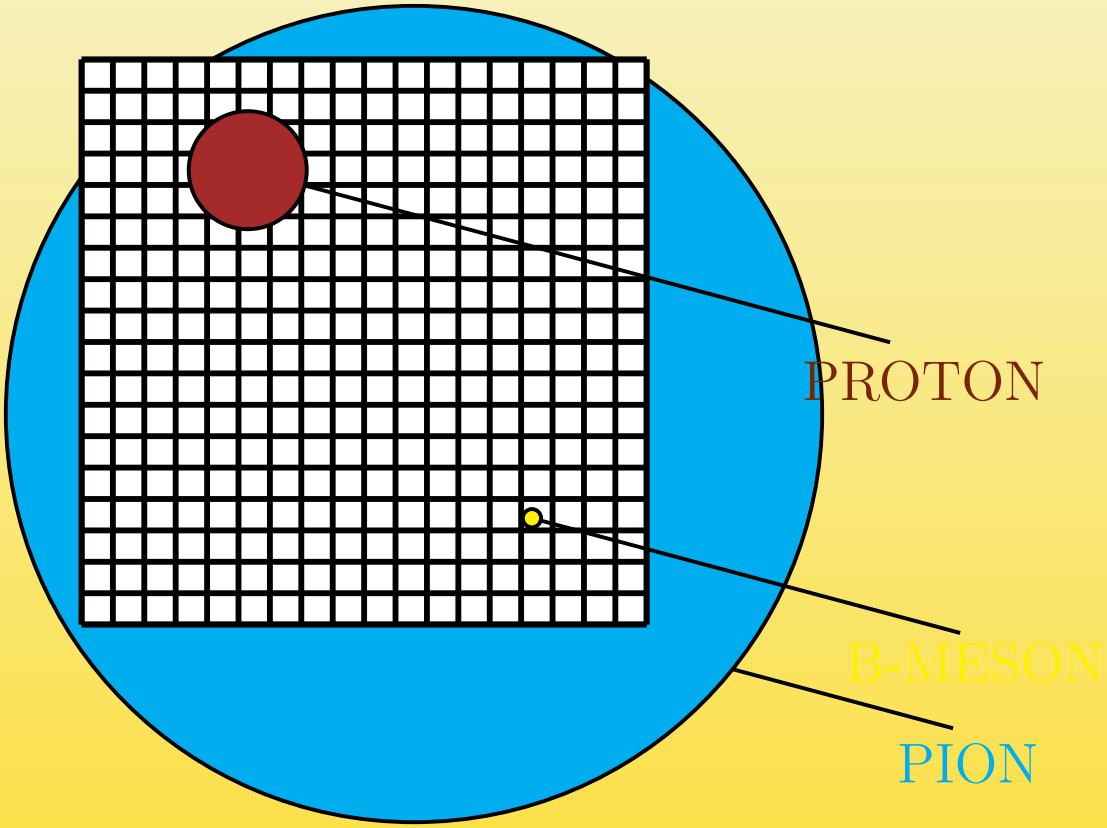
$$\frac{1}{g_0^2} \sum_{\mathrm{P}} \mathrm{Tr}\{1 - U(P)\}$$

$$a^4 \sum_x \bar{\Psi}_x (\not{D} + m) \Psi_x$$

OBSERVABLES
(physical quantities)

$$< \mathcal{O} >= \frac{1}{Z} \int \cdots \int \prod_x d\Psi_x d\bar{\Psi}_x \prod_{<xy>} dU_{xy} \times$$

$$\mathcal{O}(U, \Psi, \bar{\Psi})\, e^{-S(U,\Psi,\bar{\Psi})}$$


PROTON
B-MESON
PION

What makes real life hard :

Dynamics of a quantum mechanical $N(\to \infty)$–body problem

- **dimensionality 4 (3 space, 1 time)**
- **many local degrees of freedom**
  - Quarks: in 3 colors, 2 to 6 "Flavors"
    and 4 spin–degrees of freedom
  - Gluons: 8 color states
    and 2 spin–degrees of freedom

- **fermions in comparison to bosons much more difficult to simulate (technically "new territory")**

- **statistical method requires large samples to be accurate; accuracy $\sim \frac{1}{\sqrt{N}}$; problem of auto-correlations**

- **Extrapolations necessary (volume, lattice distance, parameters)!**

DIMENSION OF INTEGRALS:

$$\mathrm{D}{=}80 \times \mathrm{L}^3 \times \mathrm{T} \simeq 13 \times 10^9 \quad (L = T = 64)$$

(32 real parameters of the U's, 2 $\times$12 real parameters for Ψ and the same number for $\bar{\Psi}$ = 80 real entries per site)

DIMENSION OF FERMION MATRICES:

$$\mathrm{N}{=}12 \times \mathrm{L}^3 \times \mathrm{T} \simeq 20 \times 10^7 \quad (L = T = 64)$$

complex N$\times$N matrix (2N $\sim$ 50×10^6 real entries)

"Rough estimate calculation" at 10% statistical error level: requires 100 configurations and 6$\times$100 quark propagators (6 different mass values)

Methods

- **Monte Carlo integration with Metropolis updating algorithm**
(M. Metropolis et al. 1953)
- **Conjugate gradient algorithm for sparse matrix inversion**
(E. Stiefel et al. 1957)

substantial progress requires efforts towards:

- better algorithms and methods of analysis
- much faster computers

❂break through with multi Teraflop machines!

Status Germany:

PETAFLOP machine JUGENE at Jülich Supercomputing Center, May 2009

1 Petaflop = 1000 Teraflops!

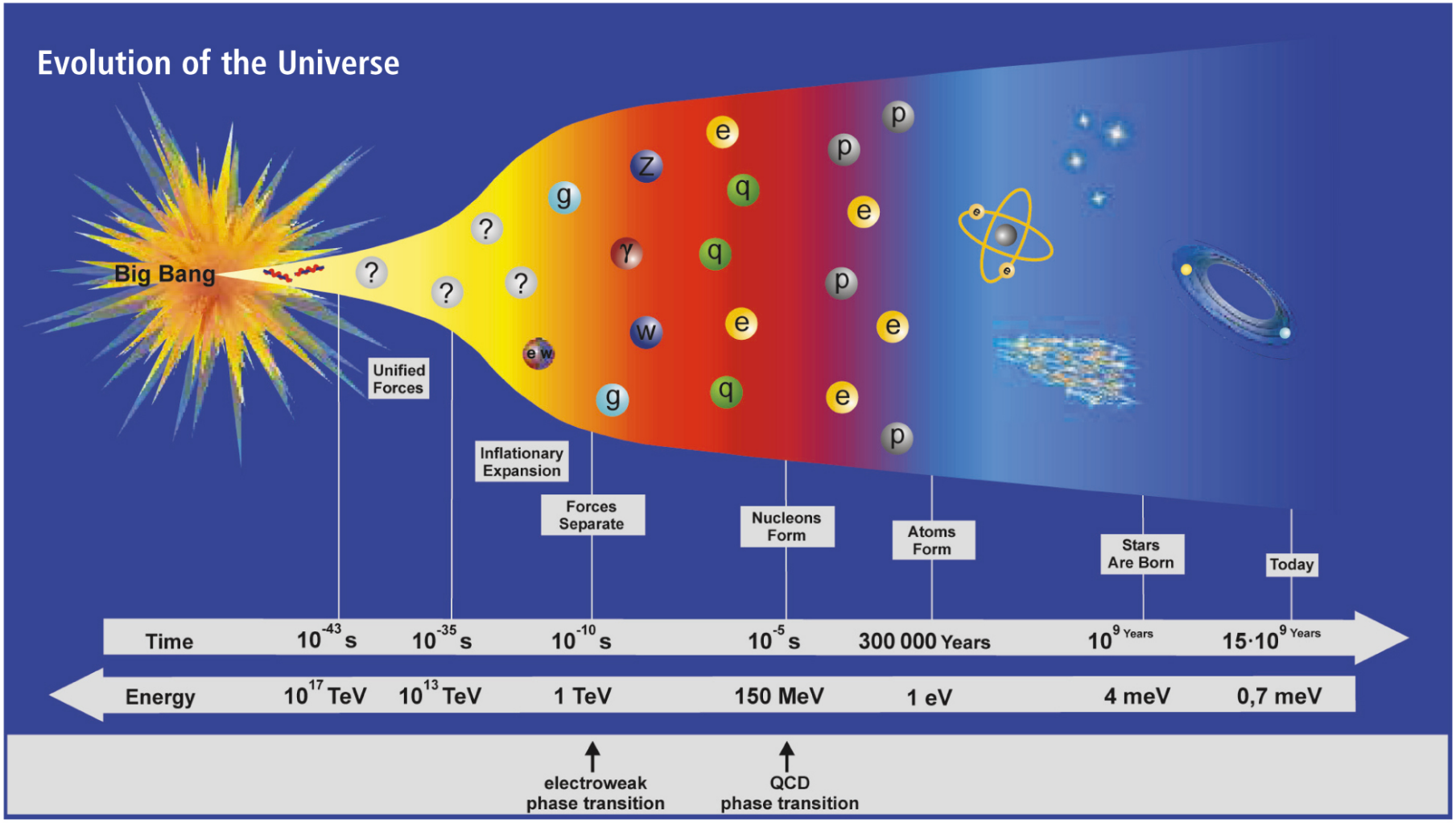
System: FZJ-JSC IBM Blue Gene/P, 4th world wide (1. to 3. in US)

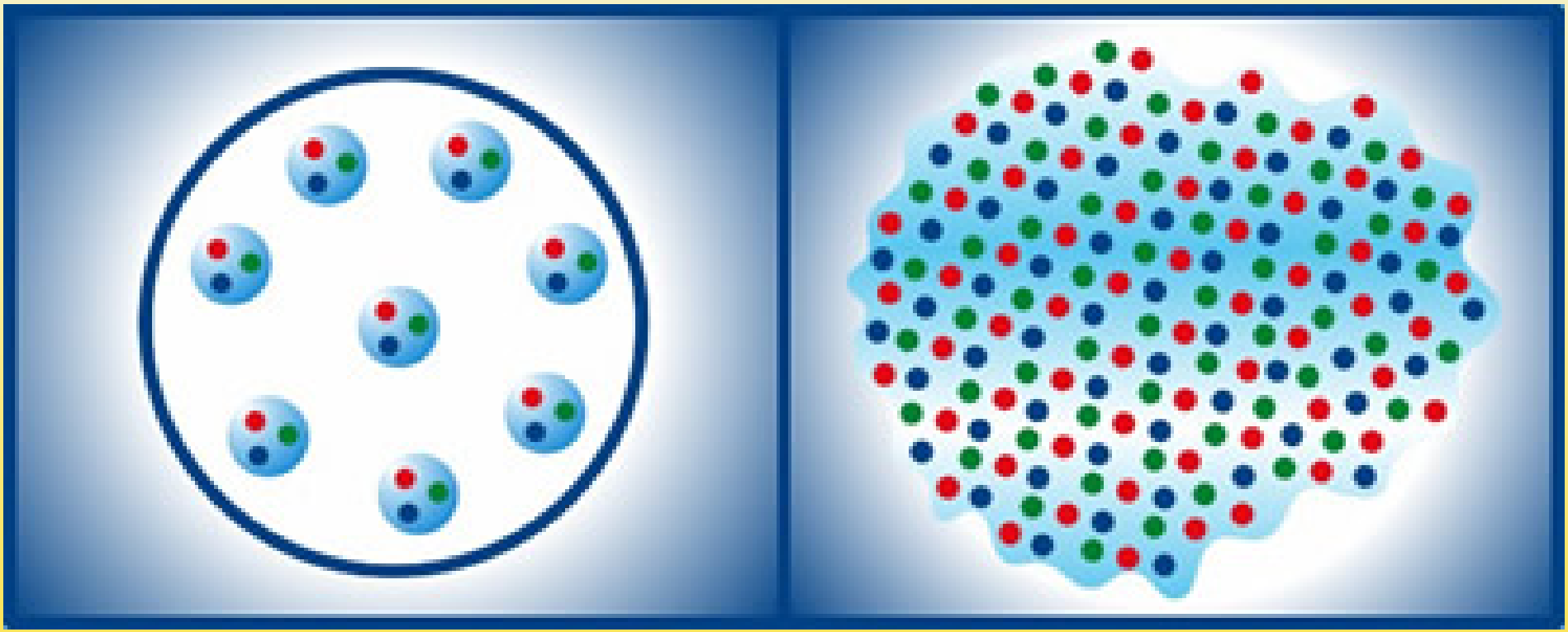
- 72 Racks with 32 nodecards x 32 compute nodes (total 73728)
- Compute node: 4-way SMP processor
- Processor type: 32-bit Power PC 450 core 850 MHz
- Processors: 294912
- Overall peak performance: 1 Petaflops
- Linpack: 825.5 Teraflops
- Main memory: 2 Gbytes per node (aggregate 144 TB)

- I/O Nodes: 600
- Networks:
  - Three-dimensional torus (compute nodes)
  - Global tree / Collective network (compute nodes, I/O nodes)
  - 10 Gigabit Ethernet / Functional network (I/O Nodes)
  - Power Consumption: max. 35 kW per rack


IBM
Blue Gene/P

Quark-Gluon Plasma: The Stuff of the Early Universe



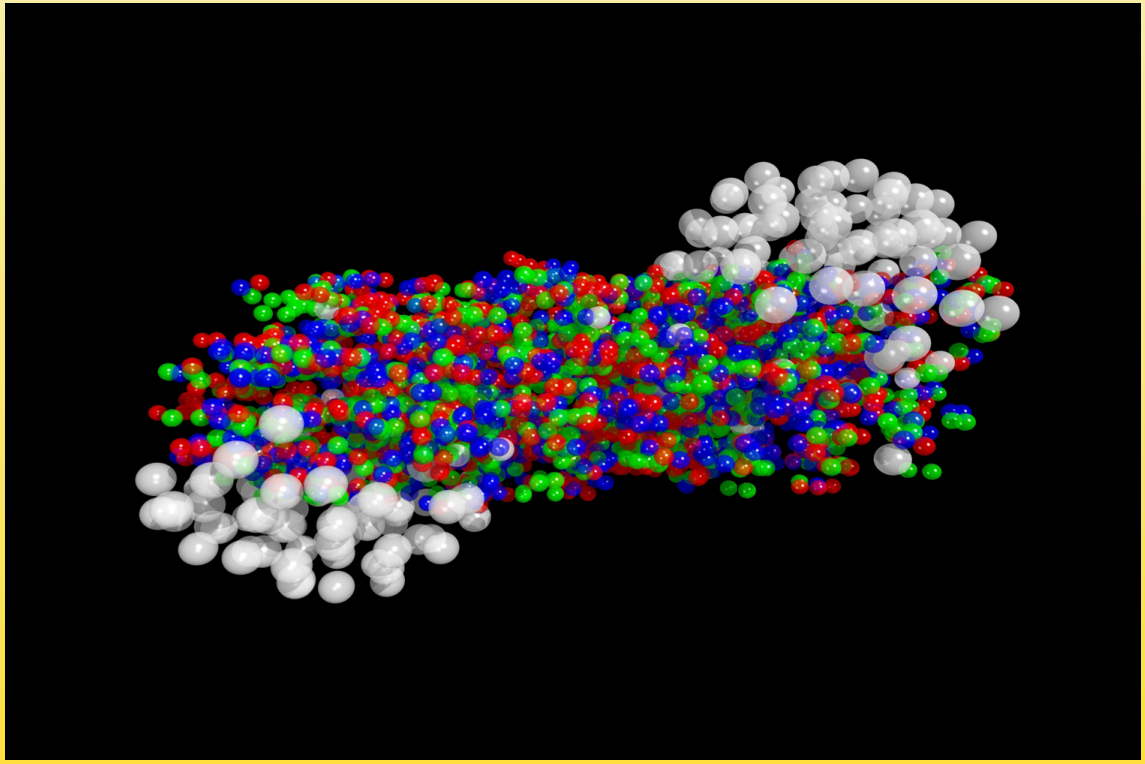


QCD under extreme conditions:

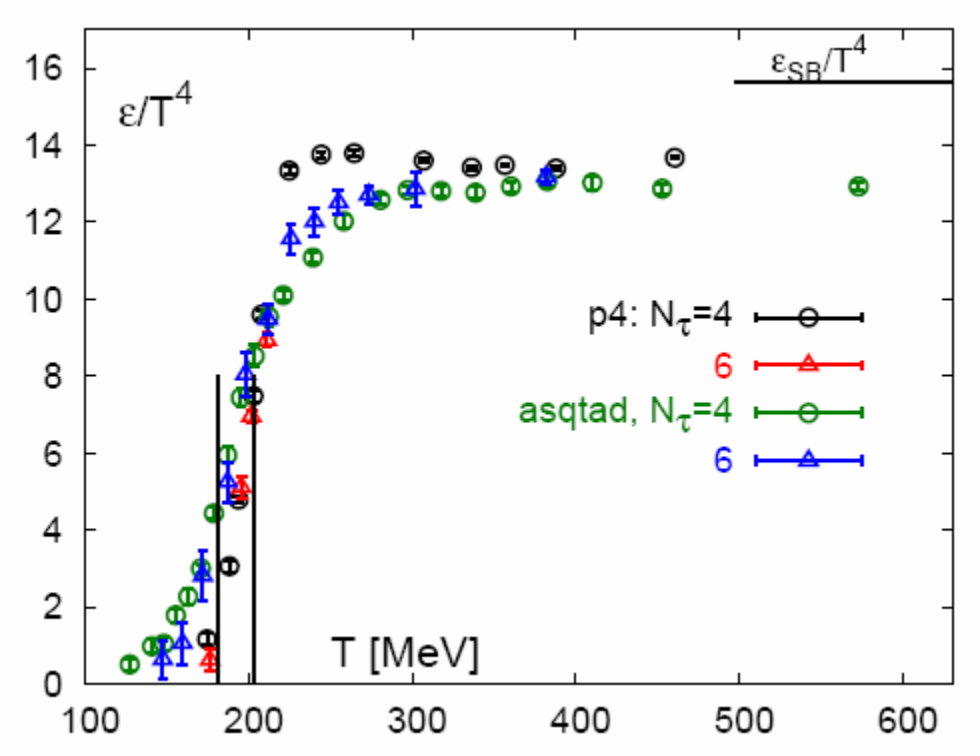
- High temperature matter: early universe
- High density matter: in neuron stars and other supernova remnants

- Laboratory test to come: heavy ion collisions RICH/Brookhaven, LHC/Geneva

Nuclei in collision:



QCD phase transition: insulator $\leftrightarrow$ metal, hadrons get "ionized"



Physics of the early universe:

➠ Entropy per co-moving volume is conserved

➠ All entropy is in relativistic species Expansion covers many decades in T, so typically either $T \gg m$ (relativistic) or $T \ll m$ (frozen out)

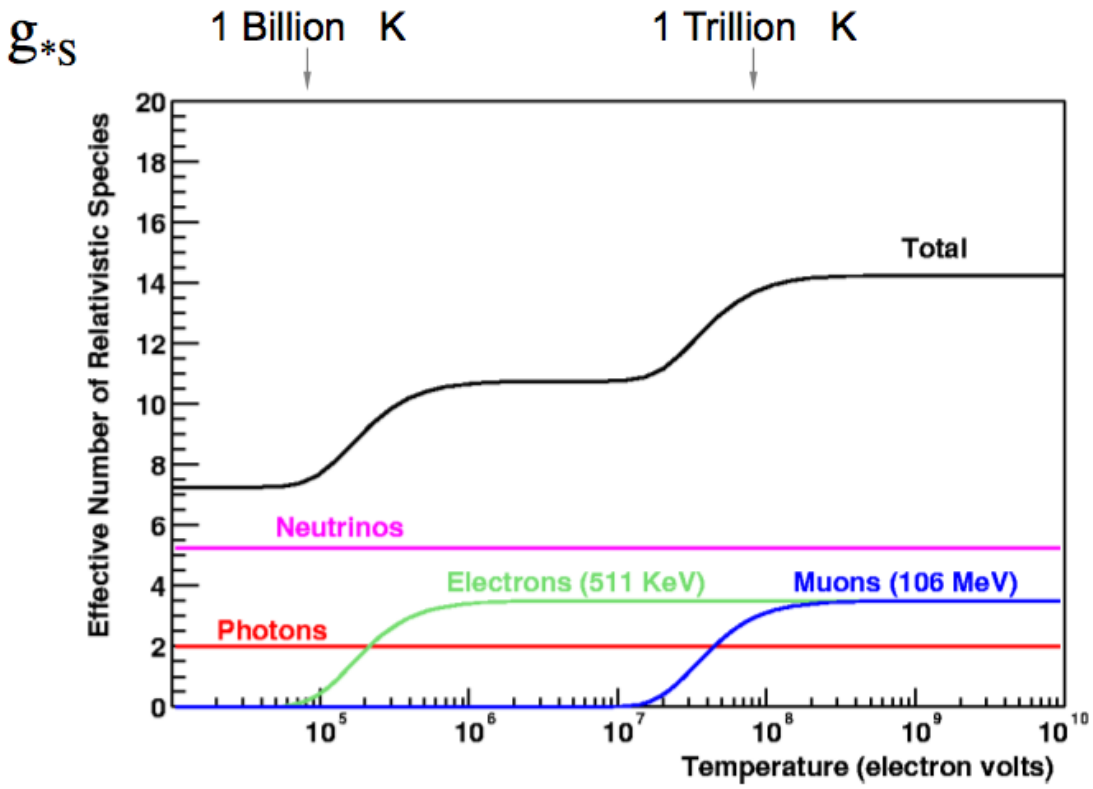
➠ All chemical potentials are negligible

Entropy S in co-moving volume $(D_c)^3$ preserved

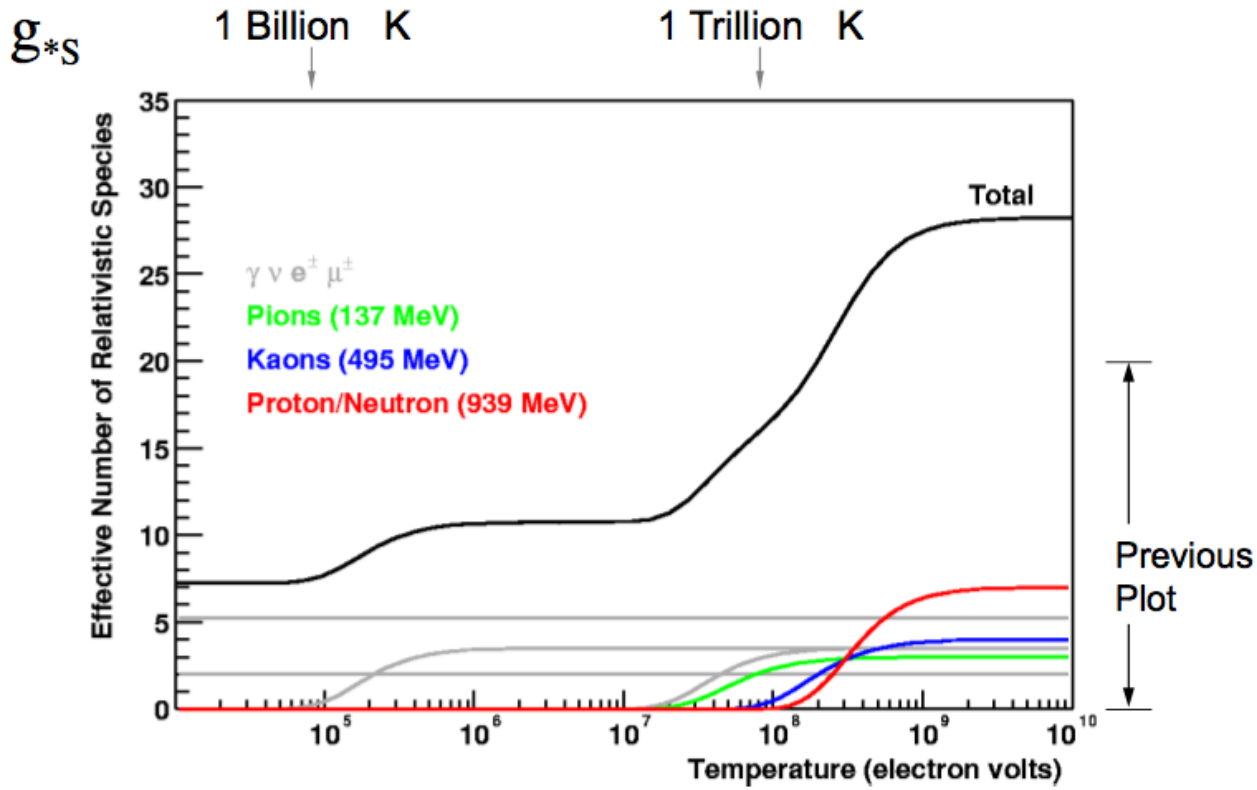
g_{*S} effective number of relativistic species

Entropy density $\frac{S}{V} = \frac{S}{D_c^3}\frac{1}{a^3} = \frac{2p^2}{45} g_S^* T^3$

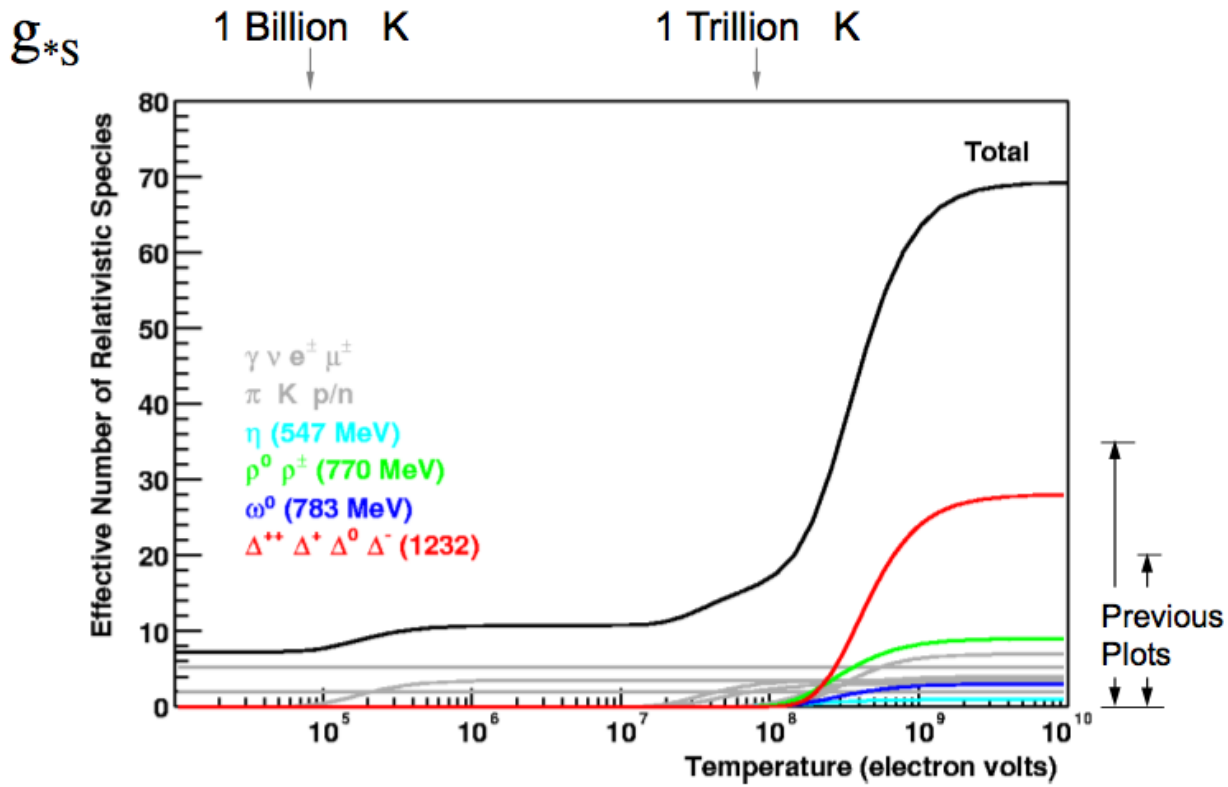
➠ $T = (g_{*S})^{-1/3}\ \frac{1}{a}$



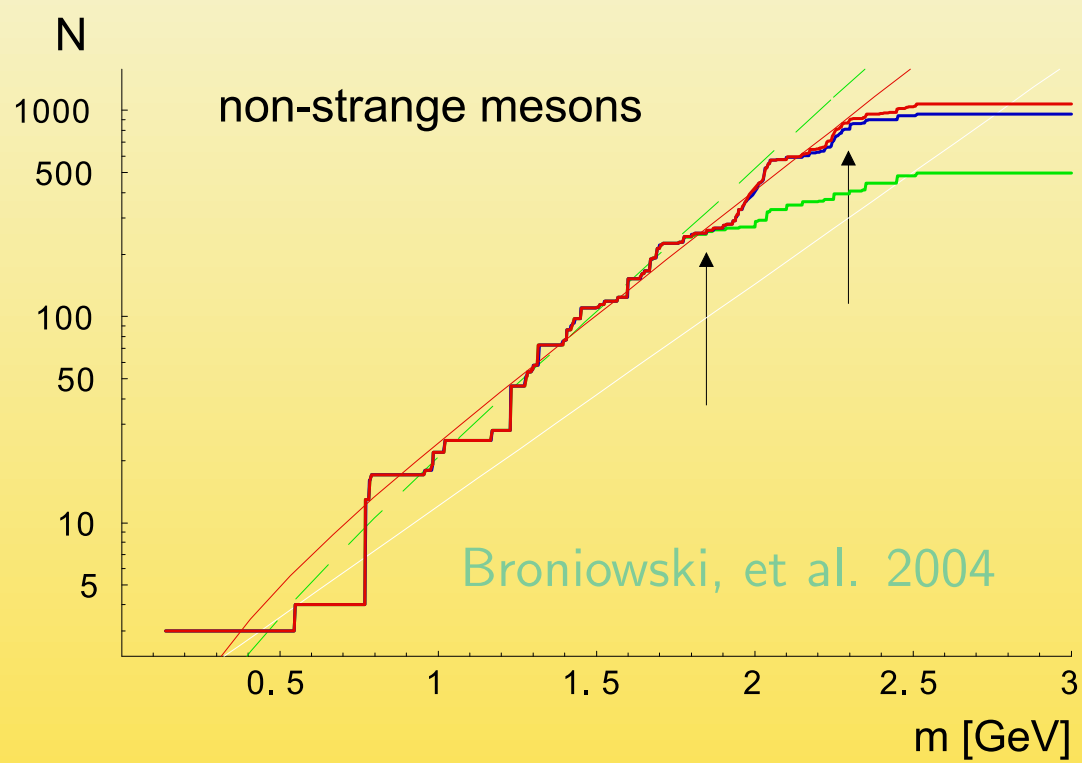
Start with light particles, no strong nuclear force



Now add *hadrons* = feel strong nuclear force



Keep adding more hadrons....



How many hadrons?

Density of hadron mass states dN/dM increases exponentially:

$$\frac{dN}{dM} \sim M^a \exp M/T_{\rm H} \; (T_{\rm H} \sim 2 \times^\circ K = 170 \text{ MeV})$$

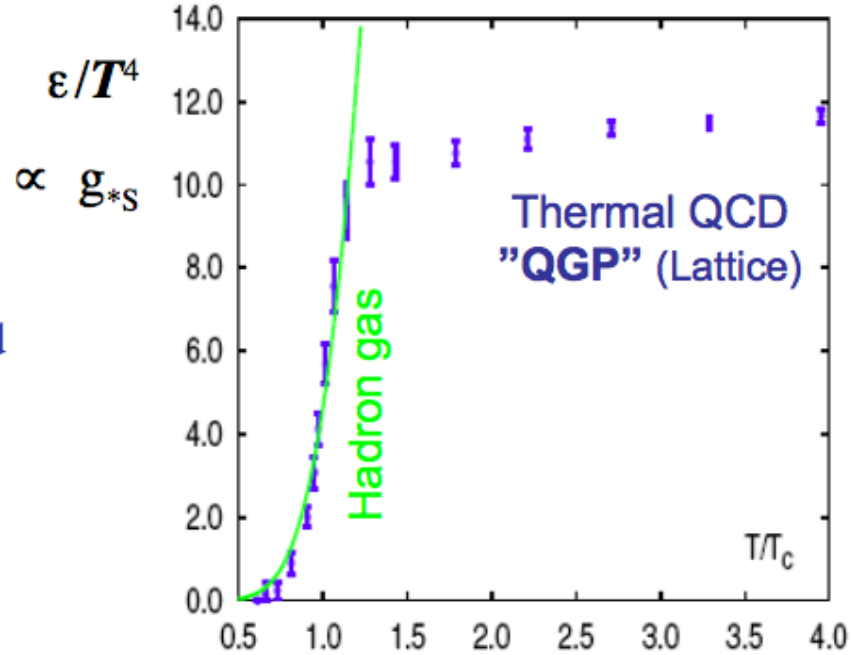
QCD to the rescue!

Replace Hadrons (messy and numerous)

by Quarks and Gluons (simple and few)

D. Gross
H.D. Politzer
F. Wilczek
American

QCD Asymptotic Freedom (1973)

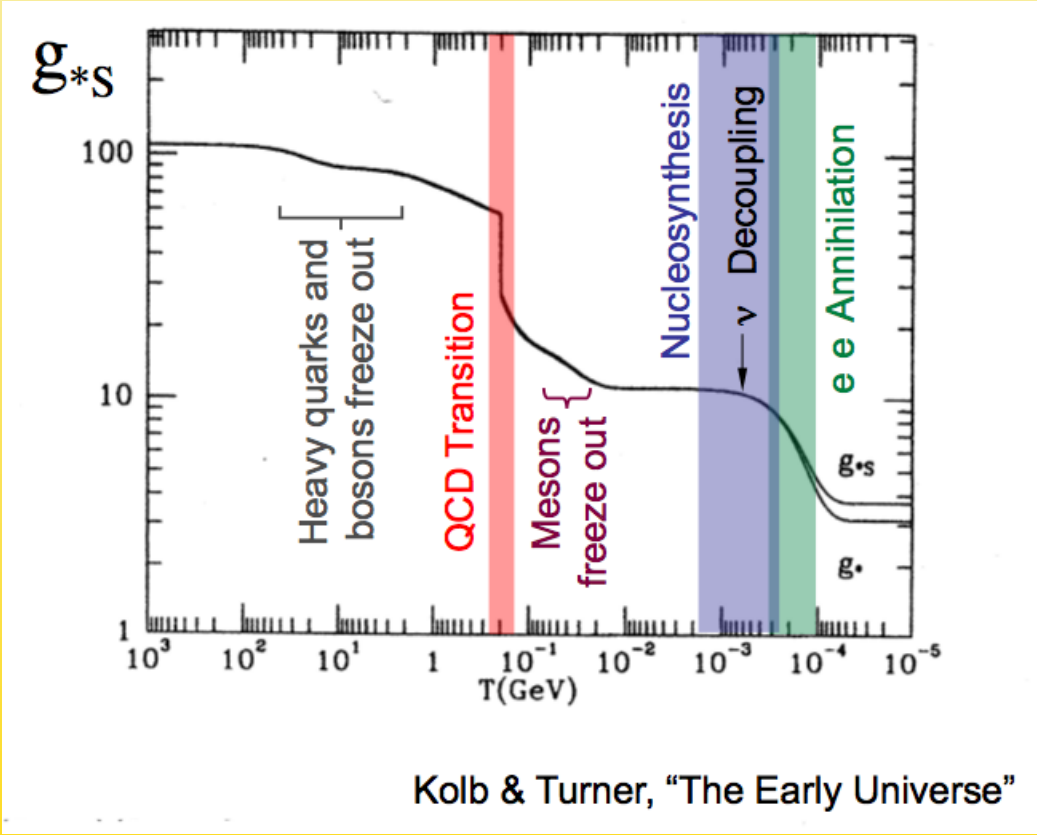


Karsch, Redlich, Tawfik, Eur.Phys.J.**C29**:549-556,2003

"In 1972 the early universe seemed hopelessly opaque…conditions of ultrahigh temperatures…produce a theoretically intractable mess. But asymptotic freedom renders ultrahigh temperatures friendly…"
Frank Wilczek, Nobel Lecture (RMP 05)

from P. Stankus, APS 09

Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted to form a quark-gluon plasma. David Gross, Nobel Lecture (RMP 05)



Cosmological phase transition....

...when the universe cools down below 175 MeV

10^{-5} seconds after the big bang...

Quarks and gluons form baryons and mesons

before: simply not enough volume per particle available

related baryogenesis? hadrons condense (get masses), others phase transitions earlier?

Electroweak phase transition T= 150 GeV ($\sim 1/\sqrt{\sqrt{2}G_F}$ G_F Fermi constant)

$\sim 6 \times 10^{-12}$ seconds after big bang

fermions, W and Z bosons get mass

Standard model: cross over transition baryogenesis if 1st order bubble formation "out of vacuum"

QCD at High temperature, at high T less order more symmetry (magnets crystals):

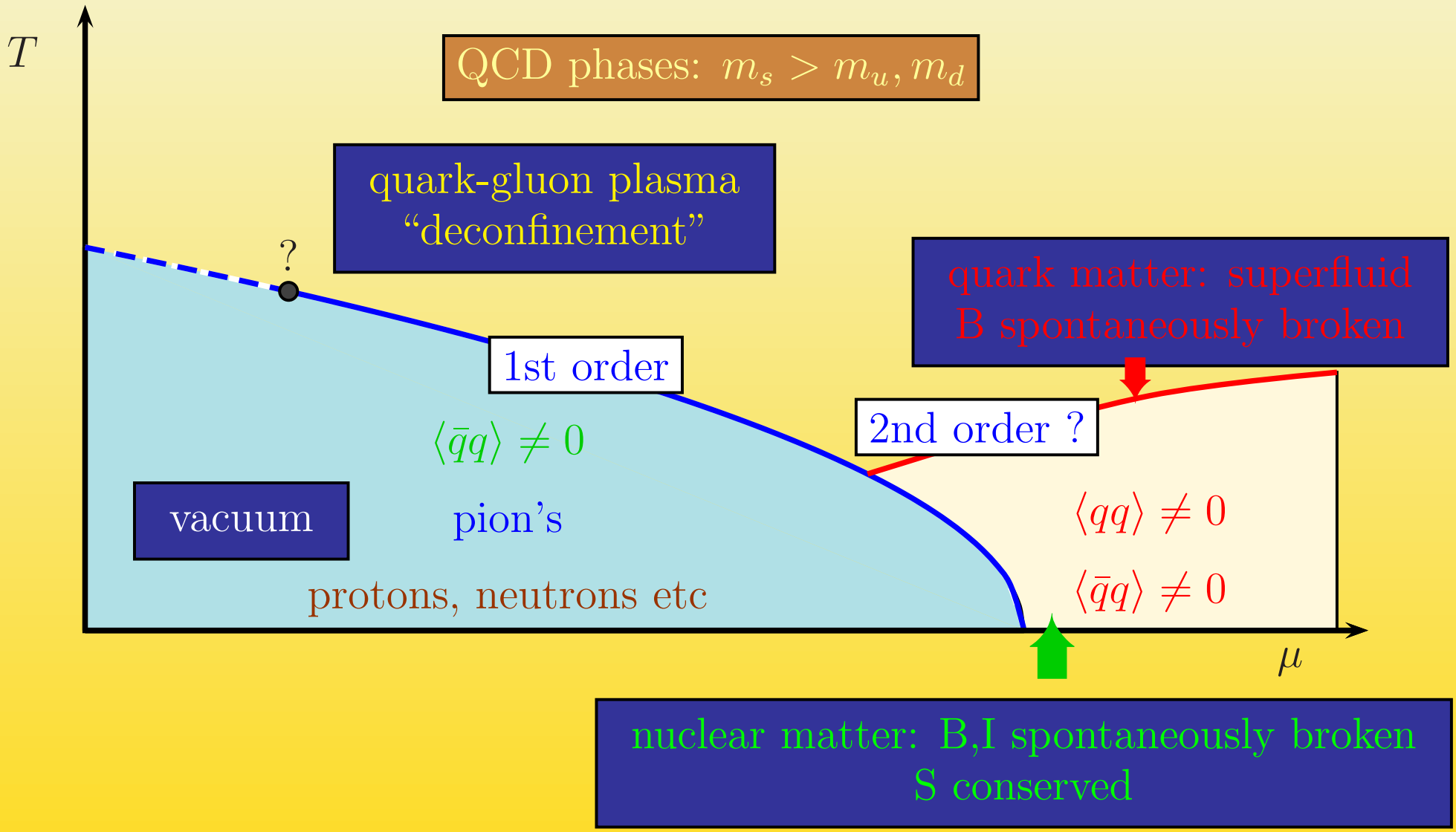
- Quark-gluon plasma
- Chiral symmetry restored (no pions, no quark condensates)
- "Deconfinement" (no linear heavy quark potential at large distances)
- Lattice QCD simulations: both effects happen at the same temperature

QCD - phase transition

Quark-gluon plasma		Hadron gas	
❖ Gluons:	$8 \times 2 = 16$	❖ Light mesons:	8
❖ Quarks:	$9 \times 7/22 = 12.5$	❖ (Pions:	3)
❖ DOF:	28.5	❖ DOF:	8
Chiral symmetry		Chiral symmetry broken	

Large difference in number of degrees of freedom !

Strong increase of density and energy density at T_c !


T
QCD phases: $m_s > m_u, m_d$
quark-gluon plasma
"deconfinement"
?
1st order
$\langle \bar{q}q \rangle \neq 0$
vacuum
pion's
protons, neutrons etc
quark matter: superfluid
B spontaneously broken
2nd order ?
$\langle qq \rangle \neq 0$
$\langle \bar{q}q \rangle \neq 0$
μ
nuclear matter: B,I spontaneously broken
S conserved

❖ Is B broken spontaneously? Could it be responsible for matter-antimatter asymmetry? Likely not: need $B - L$ conserved!

❖ What about dark matter? Is it frozen energy? Is there a phase transition like in baryonic sector? and, and, and ?

Summary

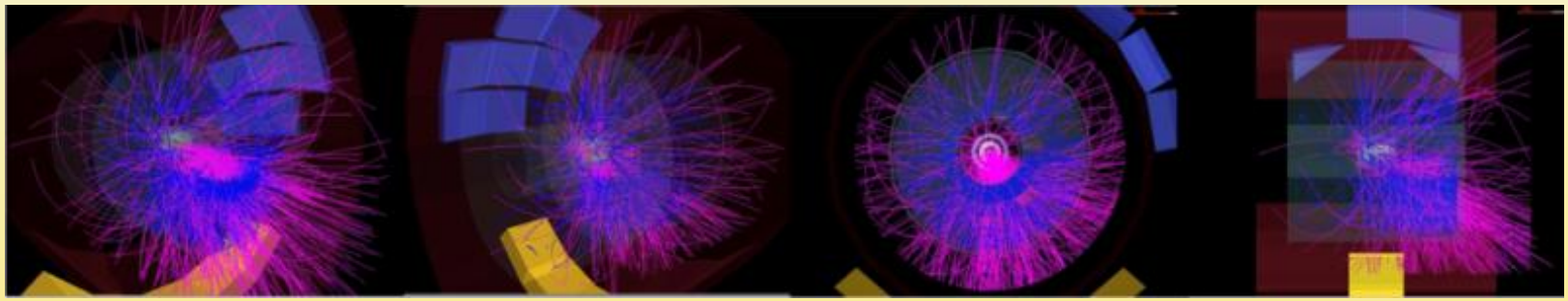
- QCD new type of QFT: particle $\leftrightarrow$ fields intrinsically non-perturbative, confinement & asymptotic freedom
- Baryonic matter (98%) binding energy (induced by interaction, frozen energy, condensed energy bags)
- Triggered development of new theoretical approaches and tools
- Big progress in understanding strong interaction in quantitative way
- Typically progress very slow very hard and elaborate
- Sub-spectacular physics!
- Remains the big challenge of particle theory
- Debris of hadrons produced at higher and higher energies ends in simple quark-gluon plasma (early universe)

- Extend our understanding of early cosmology from QCD phase transition (175 MeV; about 2×10^{-5} seconds back to the electroweak scale [200 GeV; about 6×10^{-12} seconds A.B.B.])

- QCD not only able to make post-dictions, e.g. quark-gluon plasma, in flavor physics hadronic matrix elements mandatory for precision physics (but that's another topic)

A real big challenge for QCD: the LHC


CERN, Geneva
LHC

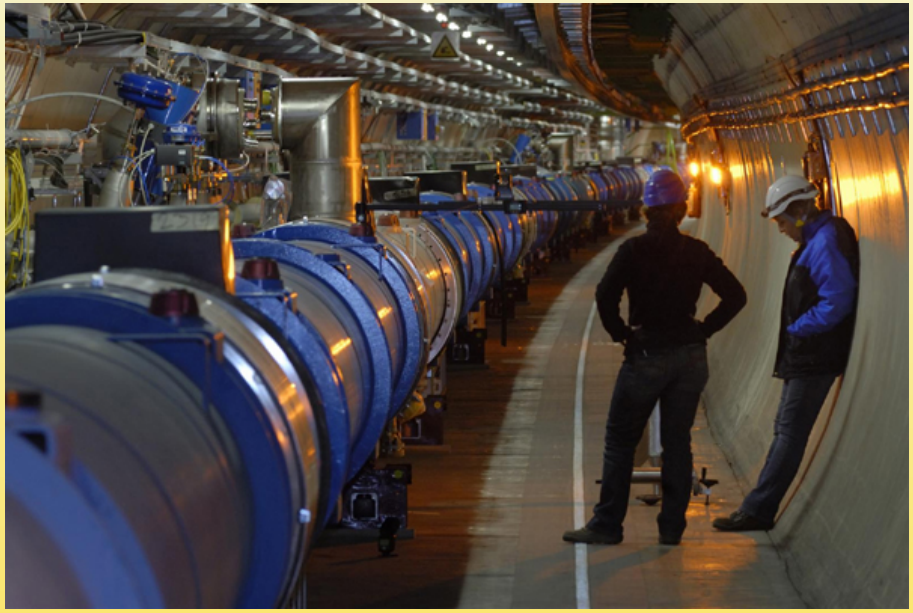


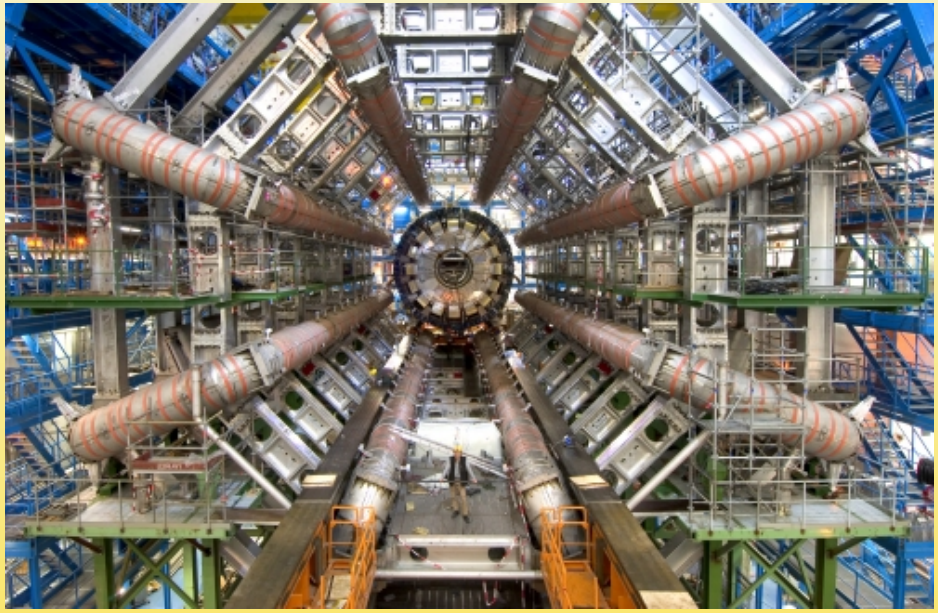
❒ In fact: LHC is designed to look for states and new forms of matter which existed in the early universe but have not yet be seen!

❒ At least find the guy responsible for electroweak symmetry breaking, the Higgs boson, which gives mass to quarks leptons and the weak gauge bosons

"Hunting for the ghost in the LHC tunnel"

❒ LHC 27 km beam line: is operated at a temperature of only 1.9 K (-271°C) the coldest spot in the universe and producing hottest spots since 10^{-15} seconds A.B.B.





ALICE detector should shed new light on QCD quark gluon plasma

- Will it be possible to see the quark-gluon plasma ? and to measure the QCD phase-transition temperature experimentally?
- So far we rely on non-perturbative lattice QCD Monte Carlo simulation

To do list

- Need much better understanding of hadronization effects
- What about quark-hadron duality:
  - exact in large N_c-limit, but limit not really under quantitative control, infinite series of narrow vector states etc.
  - whether it works depends on observable, e.g. works for Adler function, fails in light-by-light scattering etc
  - no quantification of where it works at what precision
- Need much better low energy effective theory (resonance Lagrangian approach)
- Substantial problems on experimental side, often data not in agreement within quoted errors
  - $\pi^+\pi^-$ production in e^+e^- annihilation

- big discrepancy in iso-vector form factor from hadronic τ-decays
- range [1 to 2] GeV only data at 20% syst error from 1970's
- off-shell $\pi^0\gamma\gamma$ form factor etc

- Parton distribution functions status unsatisfactory for LHC applications

- Lattice QCD still enormous effort needed to do what can be done and what is needed:
  - masses of quarks and hadrons and decay constants
  - flavor physics hadronic matrix elements (often not observable directly!)
  - low energy constants in effective theory etc.
  - parton distribution functions

- Peta-flop machines provide $\longrightarrow$ new quality!

No lack of real work to be done for our young people! Do it!

Thanks

Thanks for your attention!

Dziękuję bardzo!