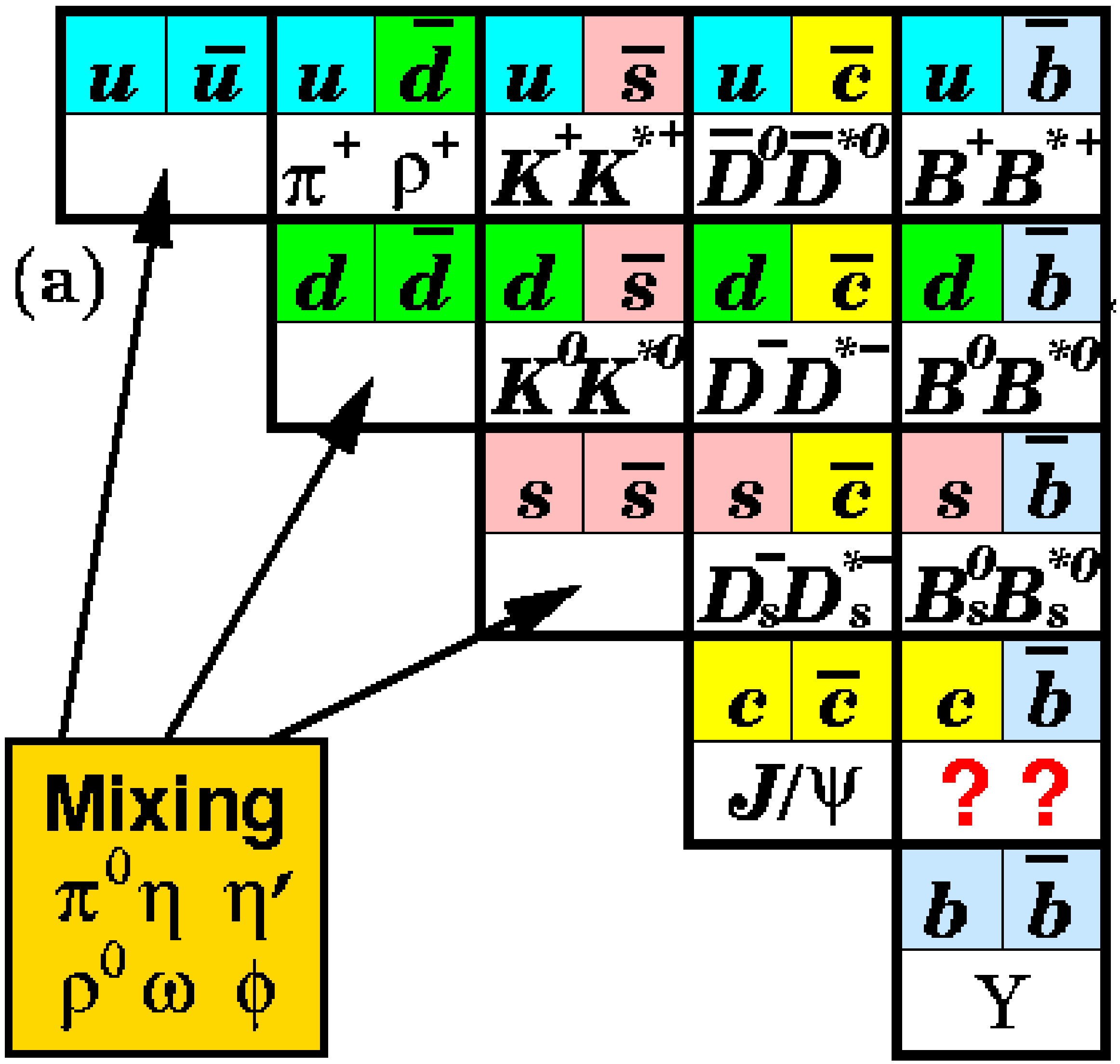
quarks, hadrons, mesons, baryons

- The quarks (and gluons) have never been observed in isolation (despite many searches); they are always bound in hadrons: mesons and baryons.
- mesons (q qbar): bound states of quark and antiquark (of same or different flavor). Color neutral. Integral spin. Can be their own antiparticle (eg, π^0).
- baryons (qqq): bound states of three quarks or three antiquarks (eg, proton, neutron, D, antiproton, antineutron). Color neutral (RGB="white" in $SU(3)_c$) and half-integral spin
- The "quark model" – most of the properties of the mesons and baryons (charge, spin, mass relations, lifetime …) can be understood in terms of the constituent "valence" quarks; and classified systematically using $SU(N)_{flavor}$.

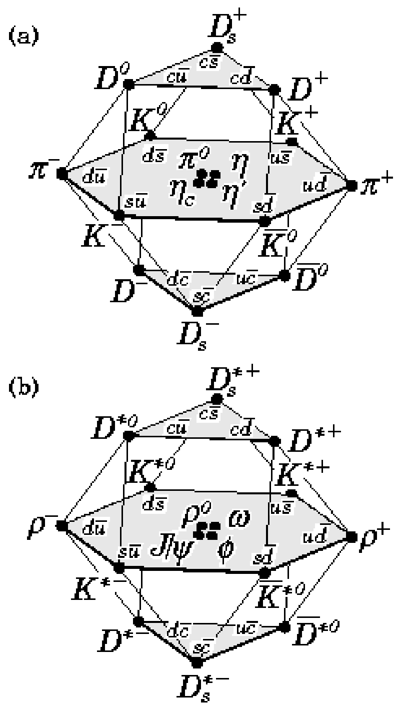
Quarks to mesons

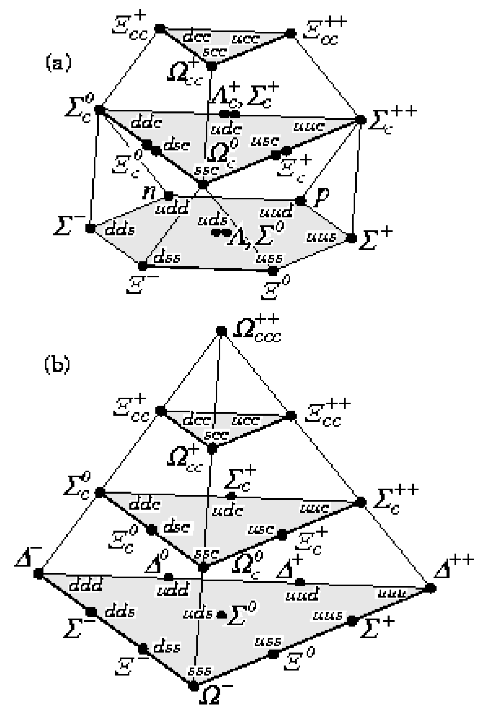


QUARKS TO MESONS AND BARYONS: "EIGHTFOLD WAY"

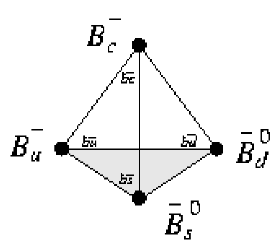
For first four quarks ($q = u, d, s, c$):

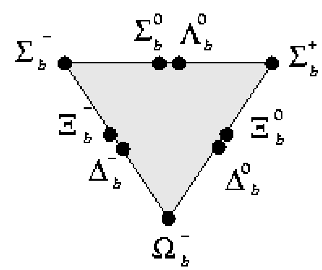
Mesons $= q\bar{q}$; baryons $= qqq$ or $= \bar{q}\bar{q}\bar{q}$





For the fifth quark ($q = b$):





Eightfold way

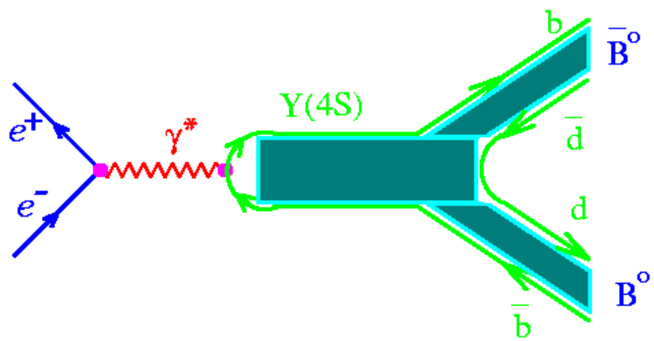
confinement, hadronization

- Quarks are “confined” in the hadrons.
  Color confinement has not been proven rigorously in QCD; it requires a non-perturbative calculation.
- An isolated quark has color charge.
  It feels a strong force with any nearby quarks.
  If there are none nearby, the energy in the field gets larger with distance:
  (Coulombic: $V \sim 1/r$. “Color string”: $V \sim r$).
- The energy in the field can be large enough to create qqbar pairs from the QCD vacuum (by $E = mc^2$),
  to neutralize the color charge of the original quark.
- This gets repeated until color-neutral objects are formed: hadronization.

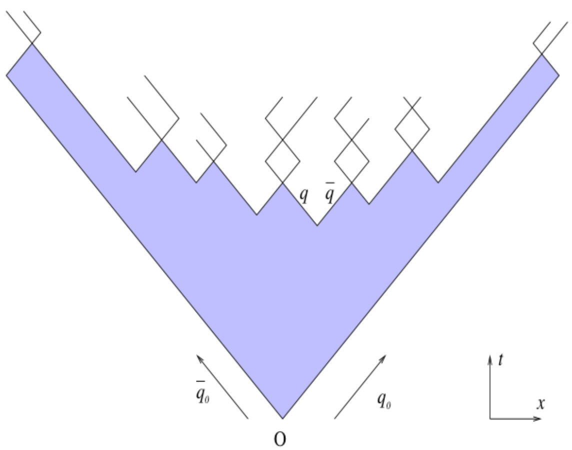
$e^+e^- \to B\bar{B}$ Production and decay

Simple example of hadronization: BB production and decay

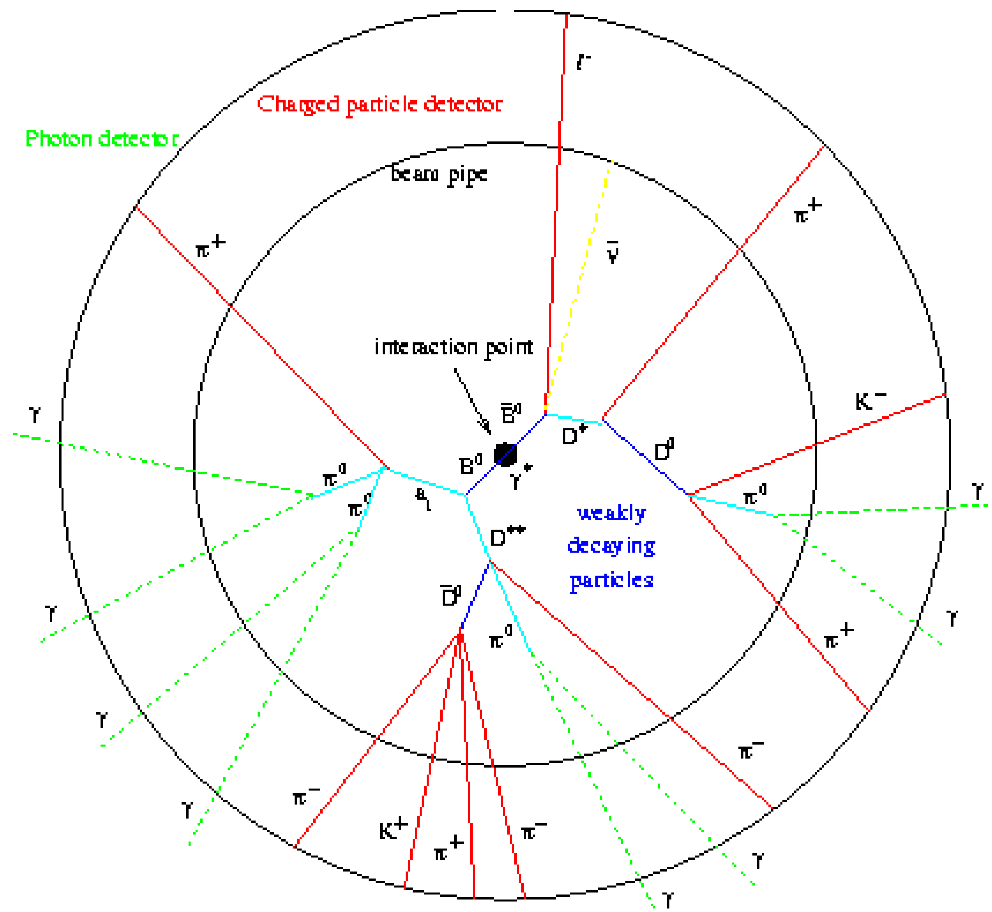
Production:



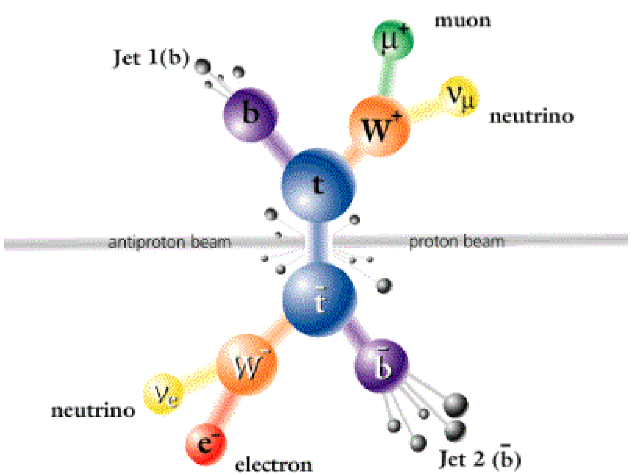
Decay:



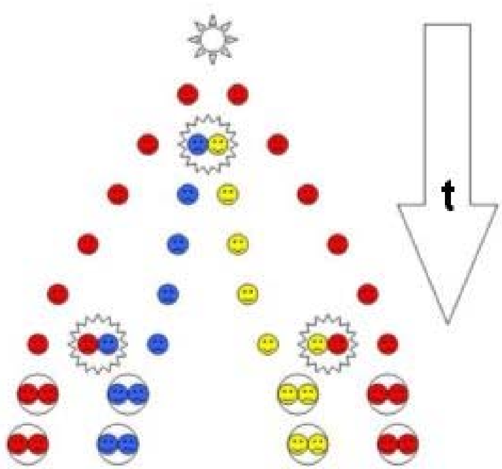
1: *String fragmentation and mesons production in $t-x$ space*



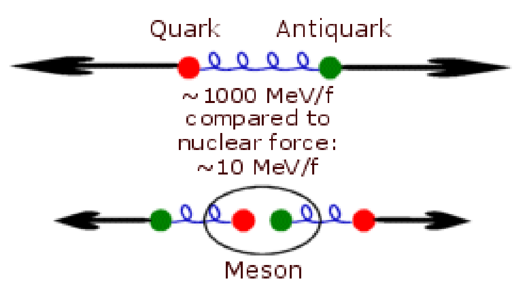
Parton showers, fragmentation, hadronization



"hard" (high-energy, parton-level) scattering process

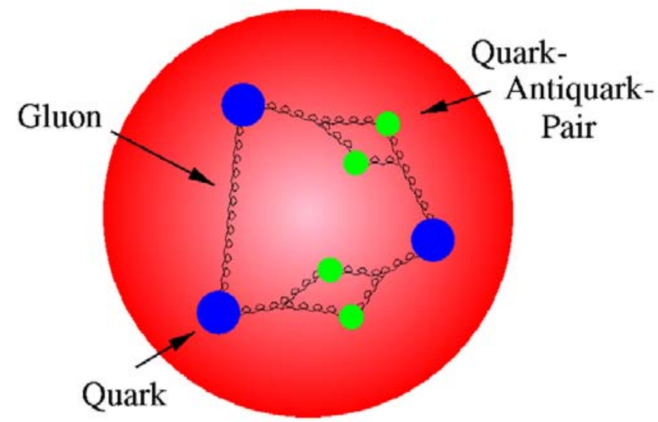


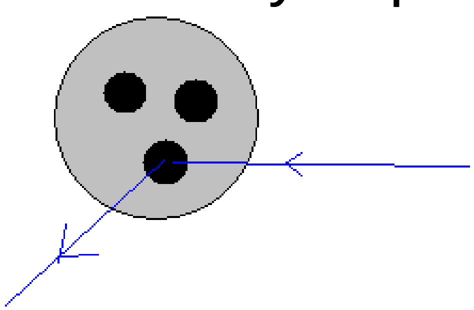
parton shower,
fragmentation into colorless hadrons
(hadronization)



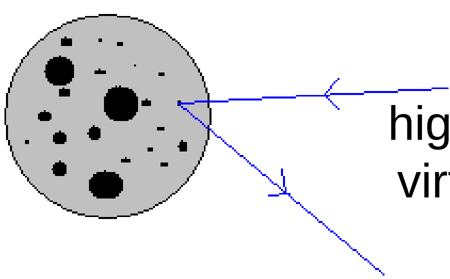
Structure of the proton

- The “valence quark model” only predicts the gross features of the hadrons (charge, spin, …)
- The strong interaction endows the hadrons with rich structure, which depends on the energy at which you probe it.





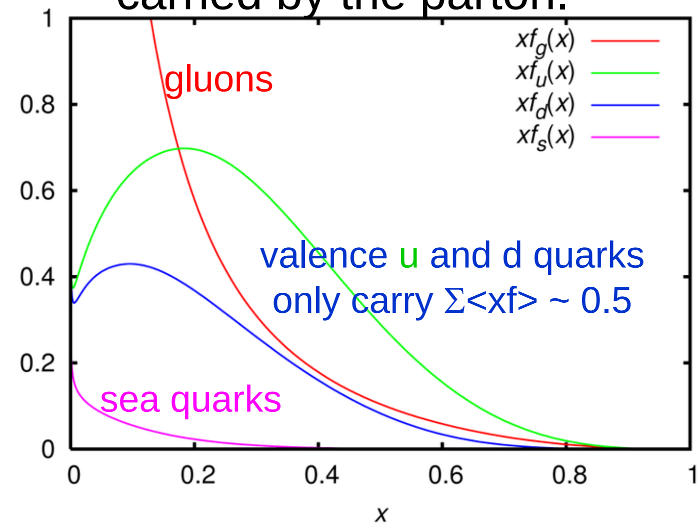
low energy scattering:
valence quarks carry
~1/2 energy of the proton



high energy (hard) scattering:
virtual “sea” quarks & gluons
carry the other half

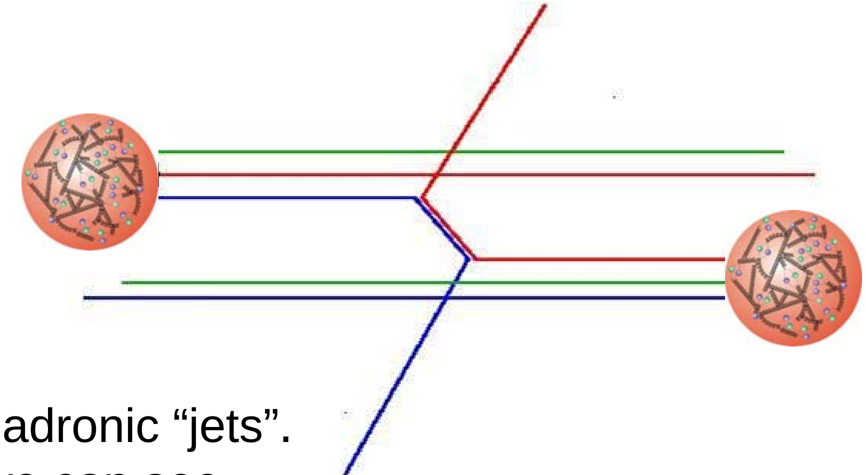
Parton Distribution Functions

Feynman x: fraction of energy carried by the parton.

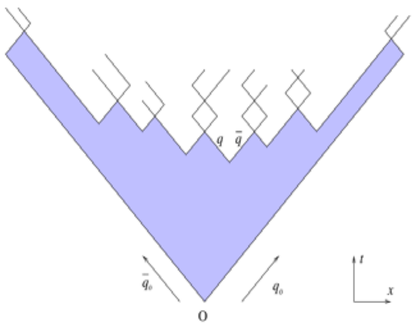


pp collisions at the LHC

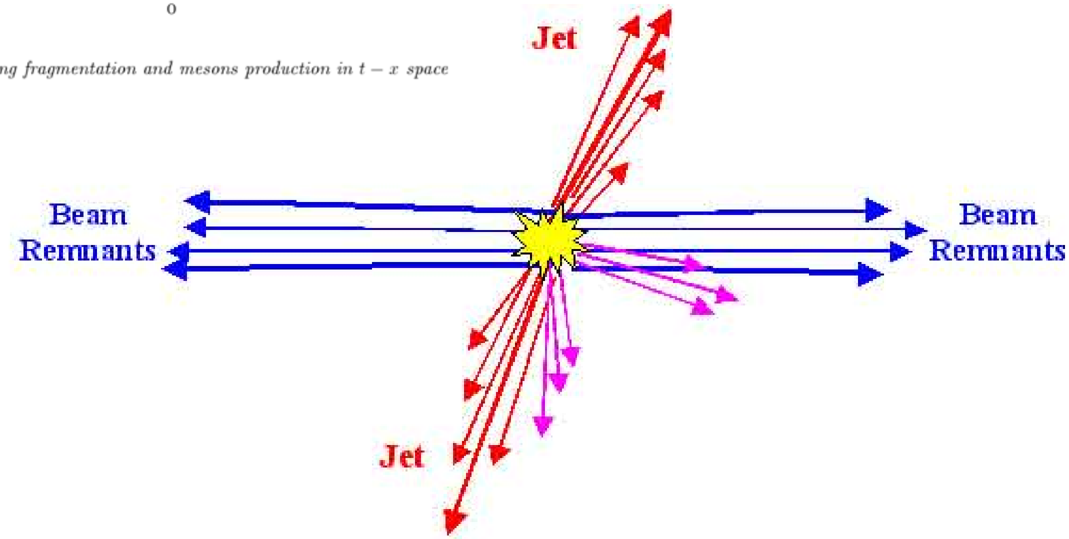
“hard” (high-energy, parton-level)
scattering process

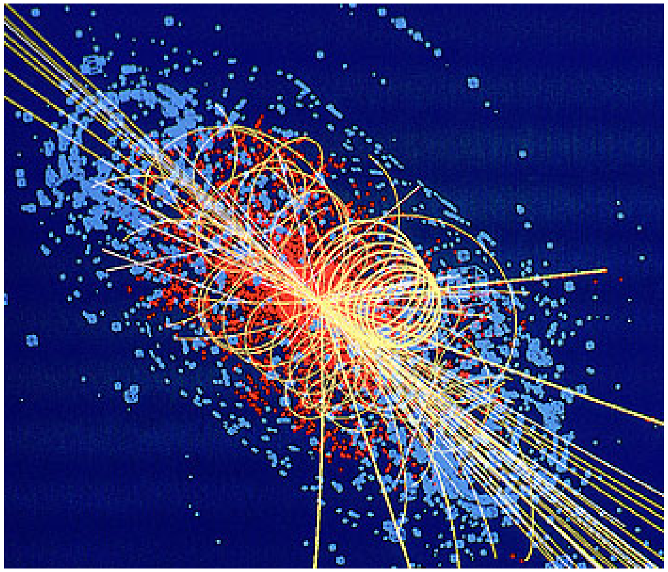


fragmentation into hadronic “jets”.
The jets are all we can see
of the hard-scattered quark or gluon



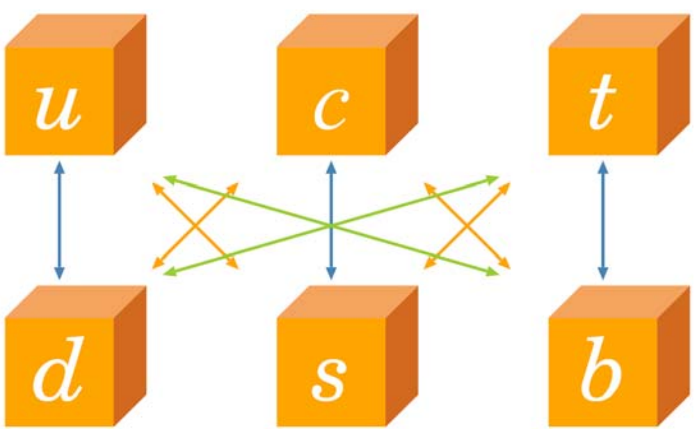
1: *String fragmentation and mesons production in $t - x$ space*





Quark Mixing, CP violation

- What is the origin of the quantum mechanical mixing between the fermions? How do the neutrinos mix? What sets the values of the quark mixing matrix and the neutrino mixing matrix?
- Why is there CP violation in the quark mixing matrix? Is there CP violation in the neutrino mixing matrix?
- There is an (almost) exact symmetry in the Standard Model between matter and antimatter, and they are always produced and destroyed in pairs. Why is the matter in the universe not balanced with an equal amount of antimatter? The small amount of CP violation in the Standard model is not enough… or is it? Might neutrino mass and mixing hold the key? Or is there more CP violation in the undiscovered physics beyond the SM?



NEUTRINOS

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

QUARKS

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Heavy fermions in the Standard Model

- The first 3 quarks (u, d, s) have $m_q \ll \Lambda_{QCD}$ - LIGHT
  mass can be neglected: $SU(3)_f$, "eightfold way"
  perturbation expansion in quark mass/momentum
  $\Longrightarrow$ chiral perturbation theory, $SU(3)_L \times SU(3)_R$

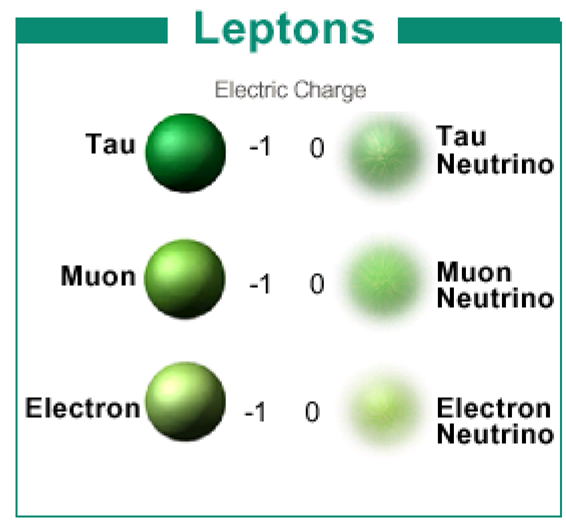
- the next 3 quarks (c, b, t) have $m_q \gg \Lambda_{QCD}$ - HEAVY
  bound state properties (mass, decay rates, ...)
  are independent of mass or spin of heavy quark;
  $\Longrightarrow$ $SU(2n_f)$ Heavy Quark Effective Theory
  (HQET, Isgur & Wise)
  perturbation expansion parameter: $1/m_q$

- Third generation quarks and leptons (τ, ν_τ):
  highest sensitivity to interesting phenomena:
  CP violation, top, Higgs, 4th generation, ...

- UNIVERSALITY:
  Are all 12 quarks and leptons truly fundamental, pointlike objects, with identical couplings to the gauge bosons?
  Why three families? Why the bizarre mass spectrum?

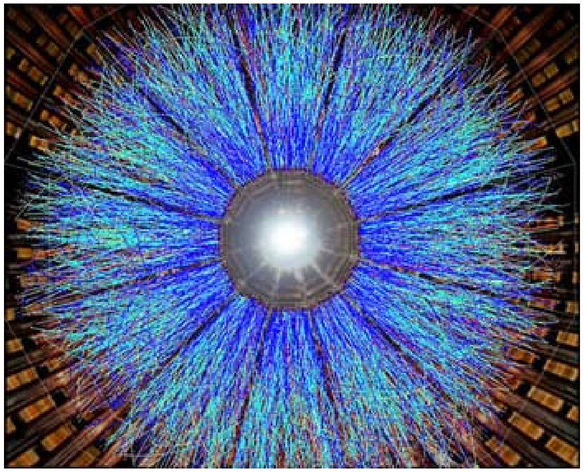
Mysteries in EW theory

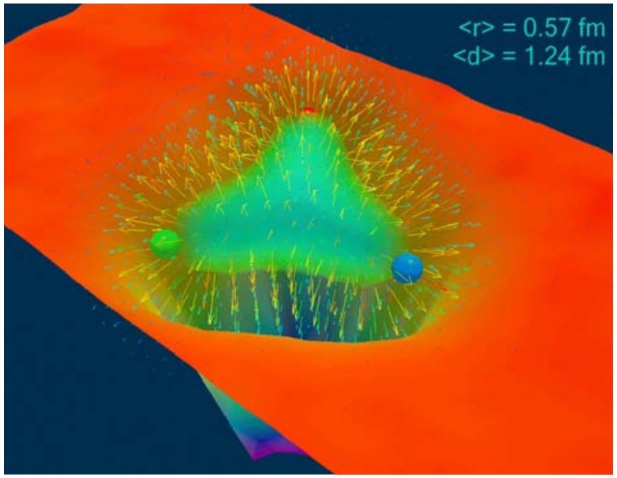
- Why are atoms so remarkably neutral? Why is charge quantized? Quarks and leptons must be deeply related…
- If quark flavor can change, and if quarks and leptons are related (in families), can quarks change into leptons (and vice versa)?
- Does a Grand Unified Theory unite them? Does the proton decay? Why is the proton so long-lived?

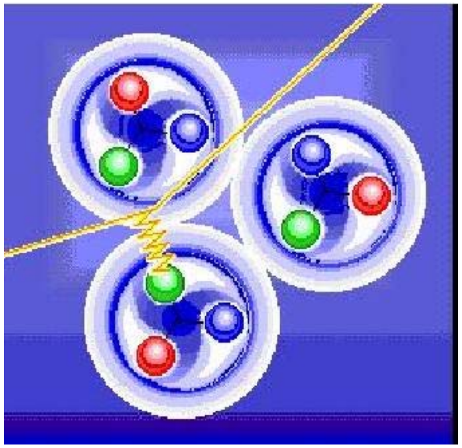


The Strong interaction

- How can we understand the strong interaction (QCD) at low energy, where perturbation theory breaks down? Can we "solve" the problem non-perturbatively, eg "on the lattice", or by invoking clever symmetries or dualities?
- how can we understand quark confinement?
- Can we understand the structure of the proton? This little ball of energy, quarks and gluons, lives (by construction) in the regime where the strong interaction is strong (non-perturbative).
- What is the nature of QCD at high temperature? Do quarks and gluons exist in a new phase of matter (QGP)? What is its nature?
- Why is the CP-violating θ term in the QCD Lagrangian (so close to) zero? Is there an axion?

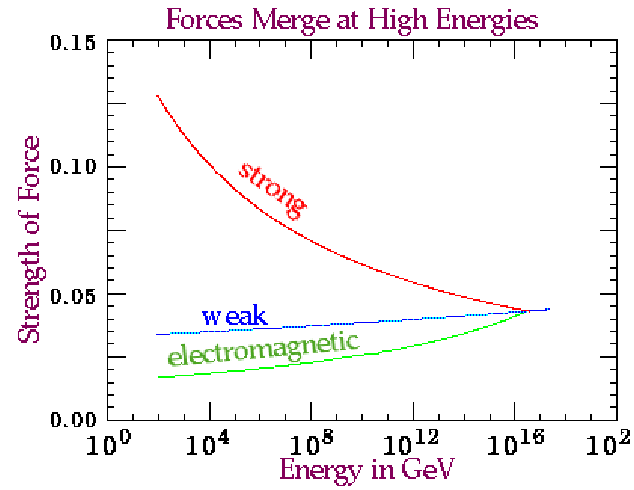


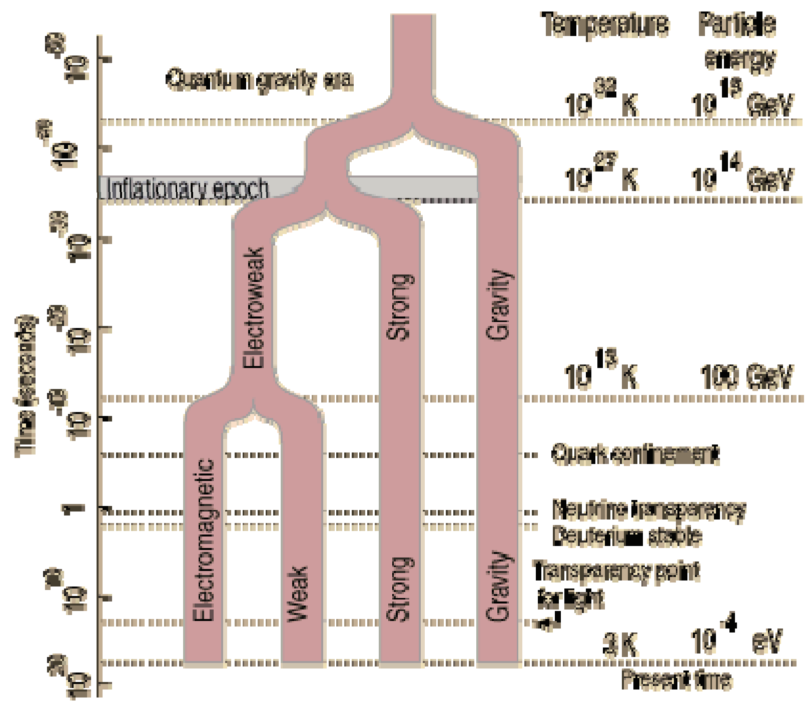




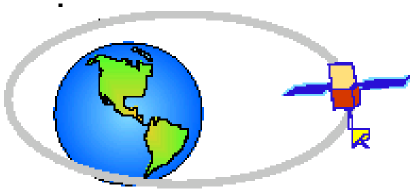
Beyond SM Mysteries

- The symmetries that describe the SM interactions are very similar in mathematical detail. This very strongly suggests that they are embedded in a higher “broken” symmetry which governs the strong, EM and weak interactions in a unified way (Grand Unified Theories, GUTs). Almost all theorists believe in GUTs. Is it real?
- How can we incorporate gravity into our quantum theory? Why is it so hard to quantize gravity?
- An even grander symmetry unifies fermions and bosons, incorporates GUTs, and throws in gravity as well. Does supersymmetry exist in nature?
- String theory and beyond (M-theory) incorporates all of the above. Is it relevant in the physical world? How can we understand it? How can we test it?





Unification of forces



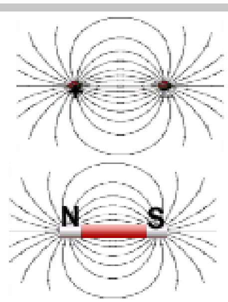
Terrestrial mechanics

Celestial mechanics

Universal Gravitation

Inertial vs. Gravitational mass

(I. Newton, 1687)



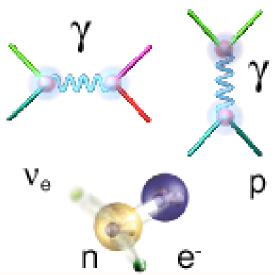
Electricity

Magnetism

Electromagnetism

Electromagnetic waves (photon)

(J.C. Maxwell, 1860)



Electromagnetism

Weak force

Electroweak

Intermediate bosons W, Z

(1970-83)

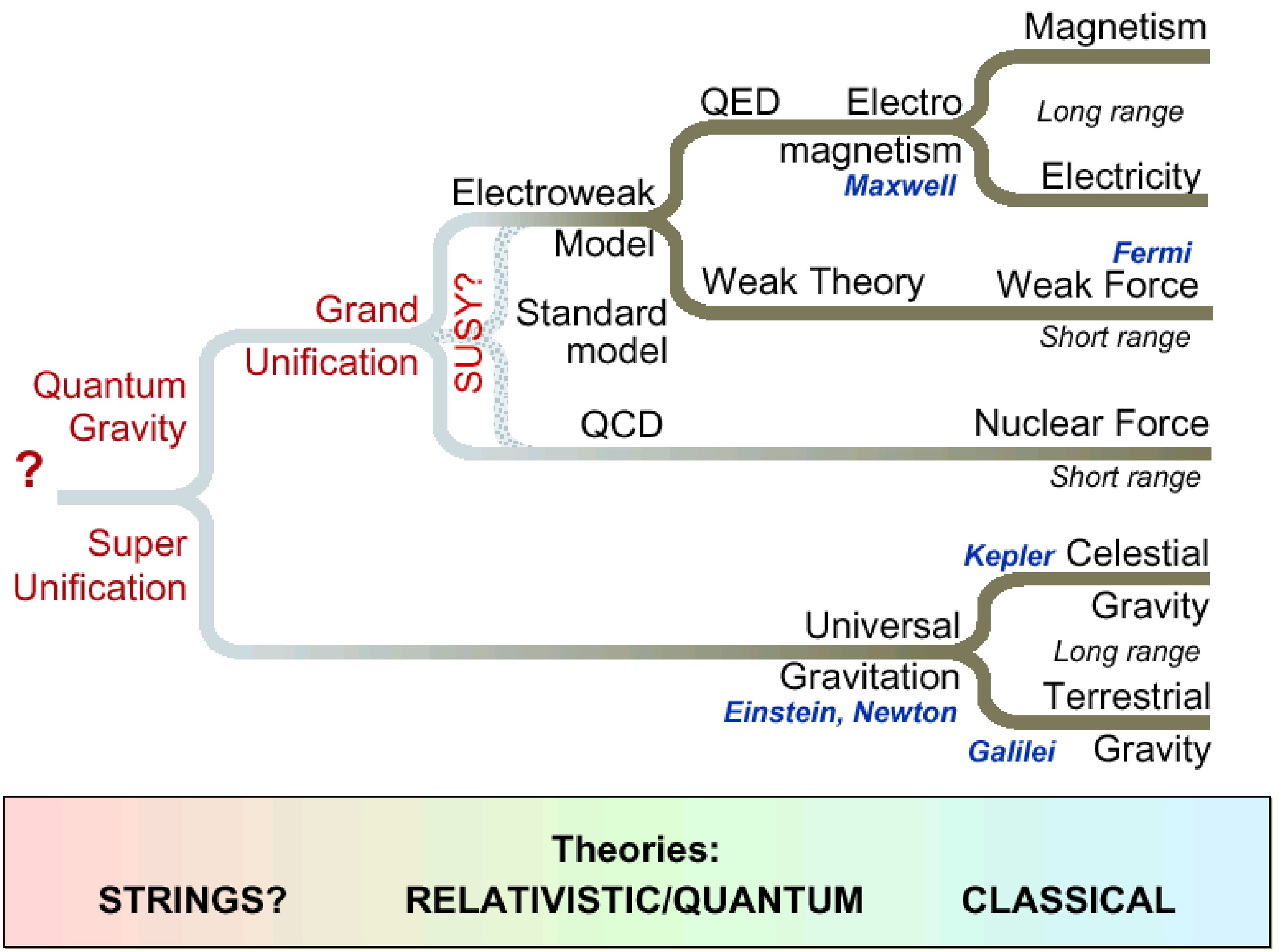
?

Probing shorter distances
reveals
deeper regularities

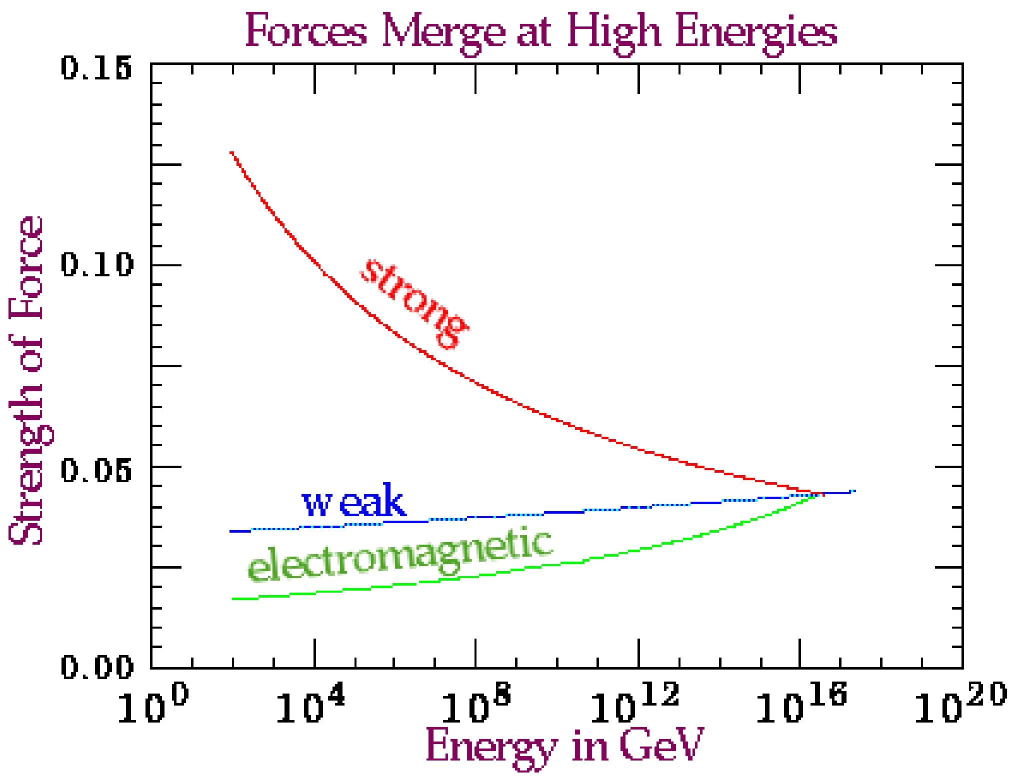
UNIFIED DESCRIPTIONS

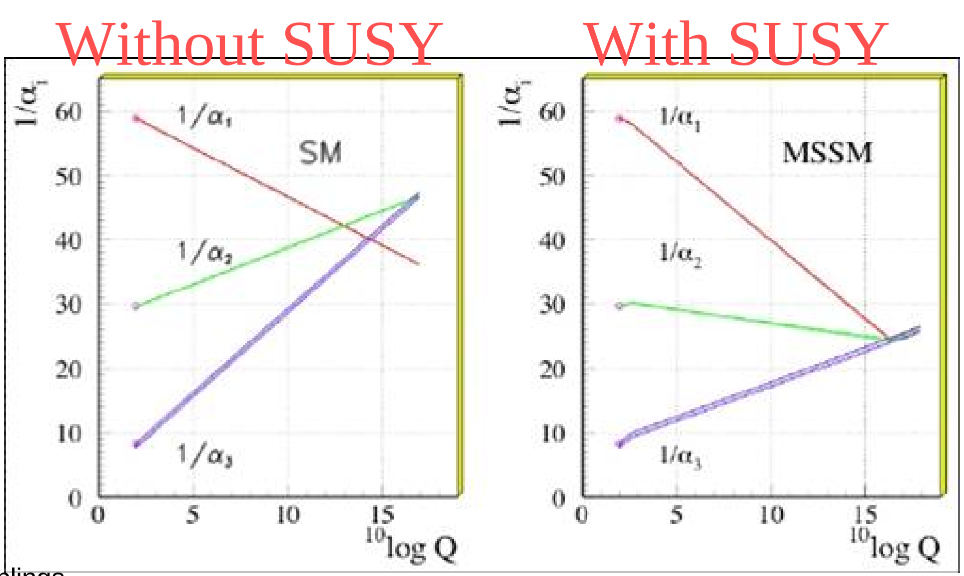
Unification of forces

Summary of forces



Unification summary





- In QFT, couplings are not constant, but "run" with energy / distance scale.
- GUTs are inspired by the fact that the force couplings merge to one value (with the help of SUSY) at the GUT scale ~ 10^{16} GeV
- More importantly, the QFT mathematical description of the strong, weak, and EM forces are very similar, and can be combined into a single theory (so far, not the right one).
- Gravity remains the odd one out! Must go beyond QFT (string theory?) to include it.