The Secret of Mass: Can we Evaporate the Vacuum at RHIC?

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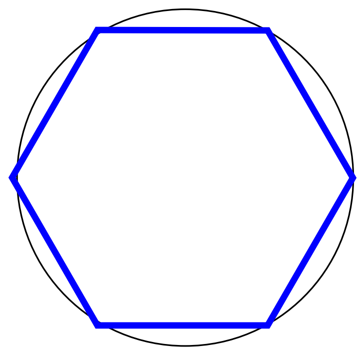
Outline

The Beauty of Nature: Symmetries

- What is a symmetry?
- Geometry: Certain operations like rotations or translations, do not change a figure ⇒ then we say "it's symmetric"!



- rotating the hexagon by an angle of 60° doesn't change it ⇒ Symmetry!

The Beauty of Nature: Symmetries
Elementary Particles
The Fundamental Interactions
Heavy-Ion Collisions and the Quark-Gluon Plasma

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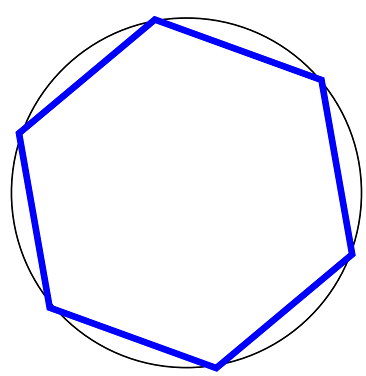

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Hendrik van Hees The Secret of Mass

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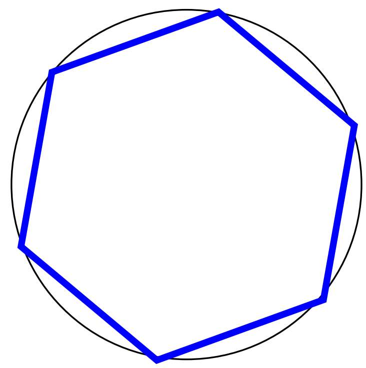

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The Beauty of Nature: Symmetries

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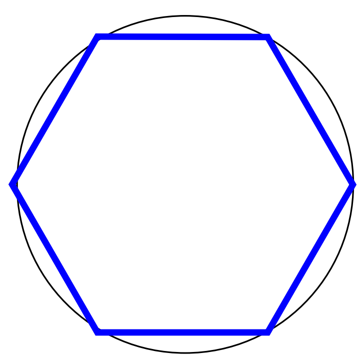

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Symmetry of Natural Laws and Conservation Laws

- Mathematician Emmy Noether found an important relation between symmetries and conservation laws
  - Equation, describing the behavior of an object in time, does not change under an operation (symmetry) $\Leftrightarrow$ a certain quantity stays constant in time (conserved quantity)
  - it works also the other way: conserved quantity $\Rightarrow$ equations obey a symmetry
- example 1: Natural Laws do not change with time (equations look the same at any time) $\Rightarrow$ Conservation of Energy
- example 2: Natural Laws do not change with position (equations of motion look the same at any place) $\Rightarrow$ Conservation of momentum

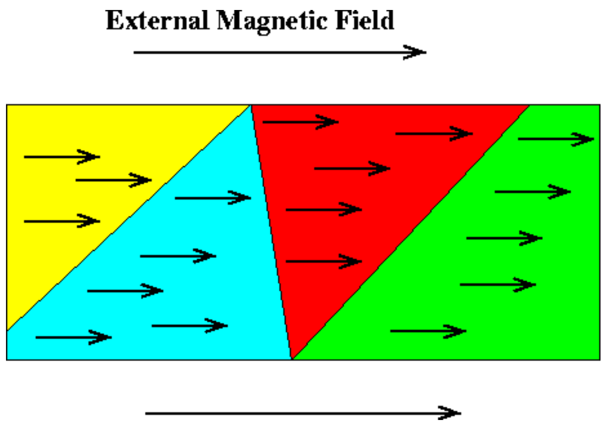
Spontaneous Symmetry Breaking

Emmy Noether

- Equations are symmetric, but not the state of lowest energy
- Conservation law still true, but symmetry not realized
- example: rotating a piece of iron, no change of laws for atoms
- it can be a magnet $\Rightarrow$ specifies a direction
- Heating the magnet, at a certain "critical temperature" iron becomes suddenly unmagnetic
- Phase transition $\Rightarrow$ Symmetry restored

Ferromagnets

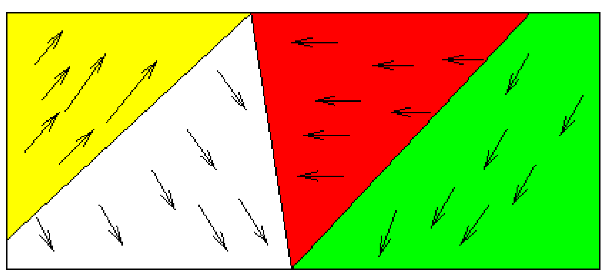
- Magnetizing Ferromagnet: Applying a magnetic field



- Little "elementary magnets" inside the magnet stay lined up even after switching off the magnetic field
- Ferromagnet itself becomes a magnet
- specifies direction in space ⇒ spontaneous breaking of rotational symmetry

Ferromagnets

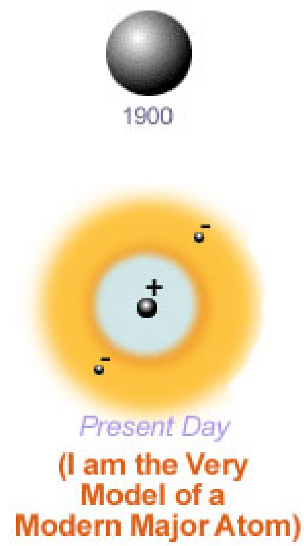
- heating up the ferro magnet rattles up the elementary magnets



- at a certain critical temperature: Alignment of elementary magnets lost (phase transition!)
- Iron rod is no longer a magnet!
- no direction specified anymore
- rotational symmetry restored

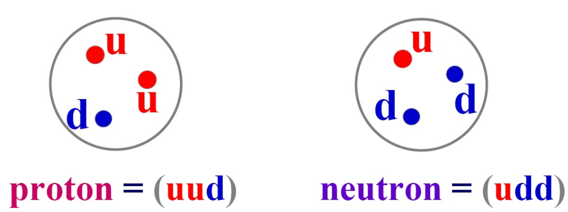
Elementary particles

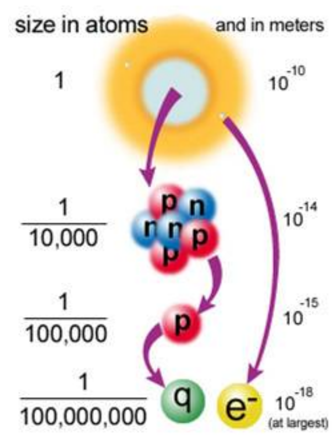
- Since ancient times scientists have asked: Are there indivisable smallest lumps of matter?
- Democritus (460-370 BC): "There is nothing but atoms and empty space (the void)."
- atom=Greek for indivisible
- Rutherford (1909-1911): most of the atom is "empty space"
- mass concentrated in the atomic nucleus



Subatomic particles

- electrons are elementary
- atomic nucleus is composed of nucleons=protons and neutrons
- nucleons made of up and down quarks

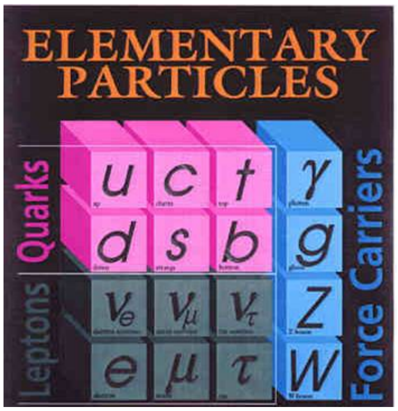


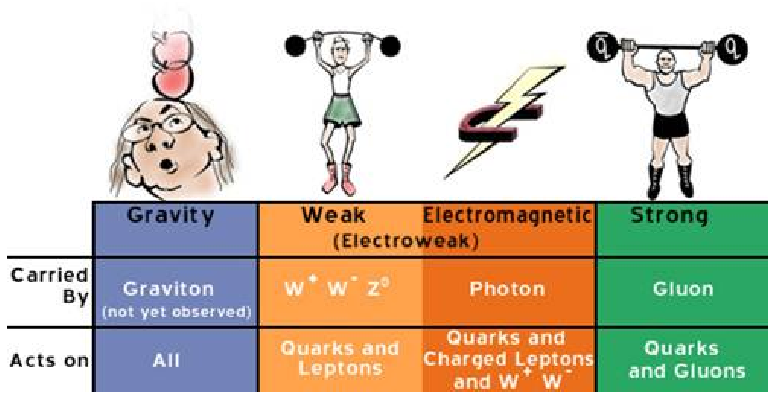


- up quark: charge $+2/3$, mass $m_u = 3$ MeV$/c^2$
  down quark: charge $-1/3$, mass $m_d = 6$ MeV$/c^2$
  electron: charge -1, mass $m_e = 0.5$ MeV$/c^2$
- BUT: nucleon mass $m_p = m_n = 940$ MeV$/c^2$

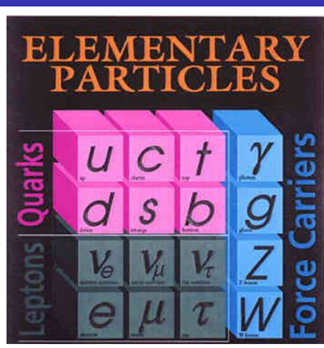
Elementary Particles and Fundamental Interactions

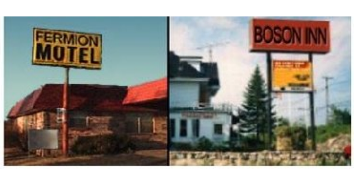
- What holds the particles together (forming matter)?
- Fundamental forces or interactions (see Professor Fries's talk!)
- Laws ruled by symmetries!
- e.g. electric charge conserved $\Leftrightarrow$ "Force Carrier" (wave fields $\leftrightarrow$ particles) for electromagnetic interaction Photon

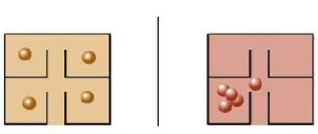




Matter particles vs. Force Carriers







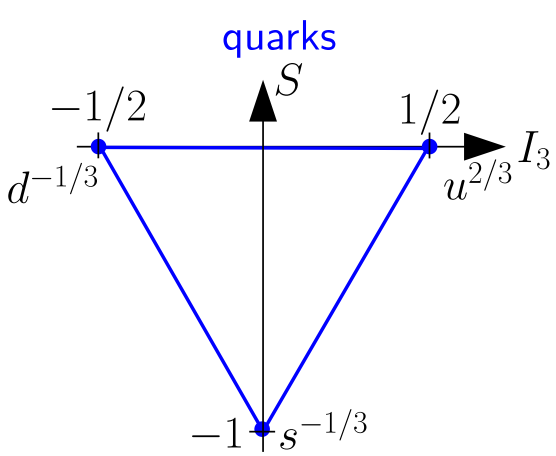
- Elementary Matter Parcitlces:
  Quarks and Leptons
  spin $s = 1/2$
- Elementary Force particles
  gluons, photons (γ), W, Z
  Spin $s = 1$
- Fermions: only one identical fermion per room!
  Space-time symmetries:
  particles with half-integer spin
- Bosons: identical bosons prefer to stay together!
  Space-time symmetries:
  particles with integer spin

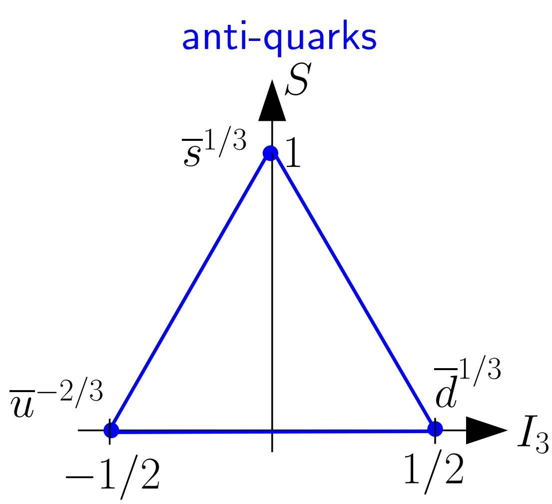
The Eightfold Way

- in the 1950-1960'ies a whole zoo of particles has been discovered using accelerators (see Prof. Cagliardi's Talk!)
- most of them: hadrons: particles participating in strong interaction
- Gell-Mann, Zweig, Ne'eman (1961): all the hadrons can be understood by assuming that they are composed of spin-$1/2$ particles with electric charges $-1/3$ and $2/3$
- Gell-Mann: How to name them? Quarks!
- Symmetry principles brought order in the chaos:
- three quarks (up, down, strange)
- Murray Gell-Mann
  Nobel Prize in Physics (1969)

The Eightfold Way

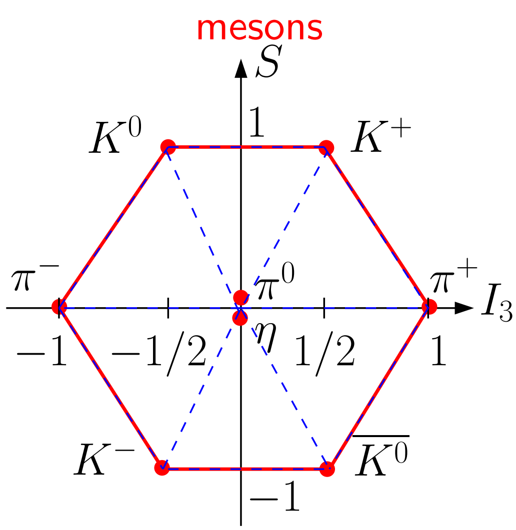
- symmetry two quantum numbers: Isospin and Strangeness
- Isospin and Strangeness conserved in strong interactions

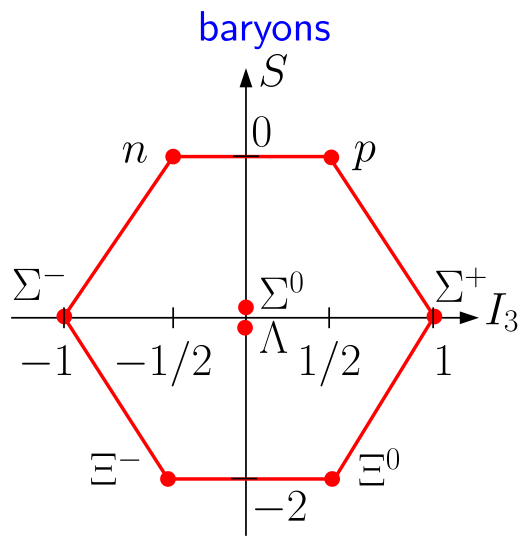




The Eightfold Way

- Mesons: "add" a quark and an anti-quark (ex: $|\pi^-\rangle = |d\bar{u}\rangle$)
- Baryons: "add" three quarks (ex: $|p\rangle = |uud\rangle$)





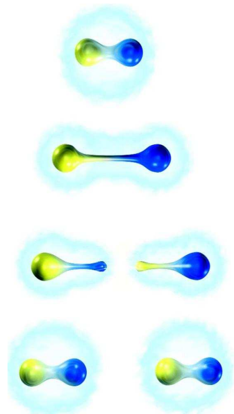
Color

- Trouble: get only all observed hadrons if one puts three quarks in the same state!
- BUT: quarks must have spin $1/2$
- they must be fermions (who don't like to be in the same room of the fermion motel!)
- but the model works: predicted $|\Omega^-\rangle = |sss\rangle$ was found
- Solution: Each quark comes in three "colors"
- All quarks of the same kind are the same except they can differ in the color quantum number ⇒ Symmetry!

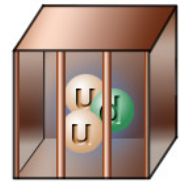
Quantum Chromo Dynamics

- More trouble: Nobody has seen free quarks yet!

I want free quarks!
⇒ break up a meson



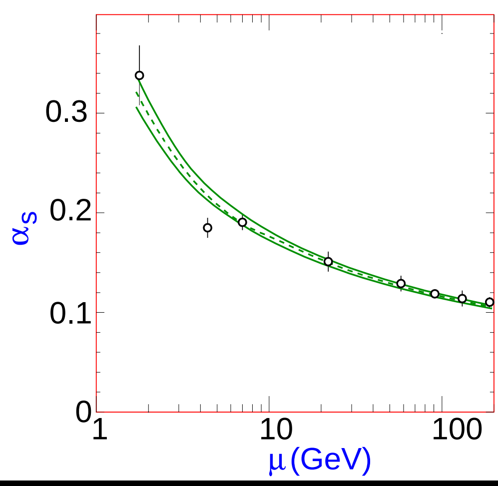
cannot break the meson, but I produce more hadrons!



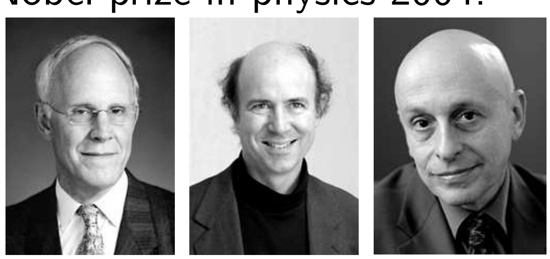
- quarks confined in hadrons
- 1973: Gross and Wilczek, Politzer
- build theory based on color symmetry!
- force becomes stronger for longer distances
- reason: force carriers themselves have color

Quantum Chromo Dynamics

- from color symmetry of quarks (color charge conserved)
- force carriers: gluons (spin 1)
- matter particles: quarks (spin $1/2$)
- theory called Quantum Chromo Dynamics (QCD) (Greek: chromos=color)
- force becomes weaker at small distances/high energy



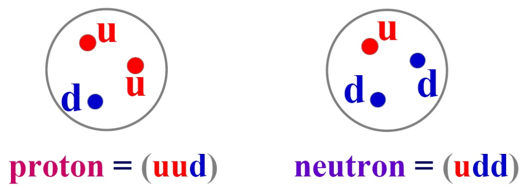
Nobel prize in physics 2004:



Gross, Wilczek, Politzer

Reminder: Mass problem

- atomic nucleus is composed of nucleons=protons and neutrons
- nucleons are composed of
  up and down quarks



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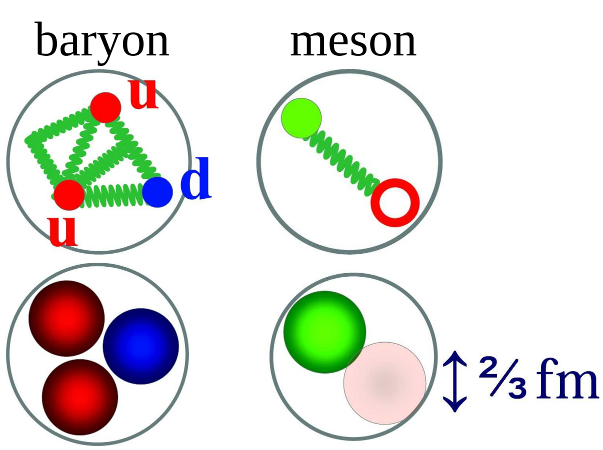
Constituent Quarks

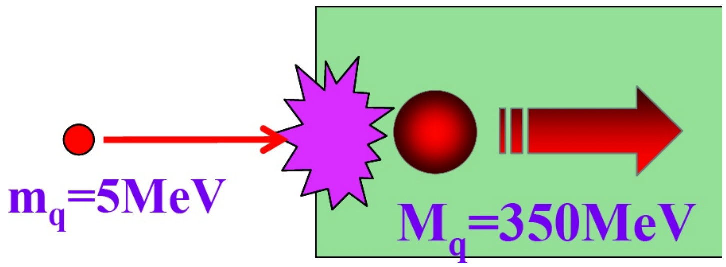


- Quarks inside hadron
- cloud of gluons around
- effectively: extended object
- constituent quark
- $M_{\text{con}} = 350$ MeV$/c^2$
- $m_d = 6$ MeV$/c$,
  $m_u = 3$ MeV$/c$

Where does the Constituent-Quark Mass come from?

Mass generation

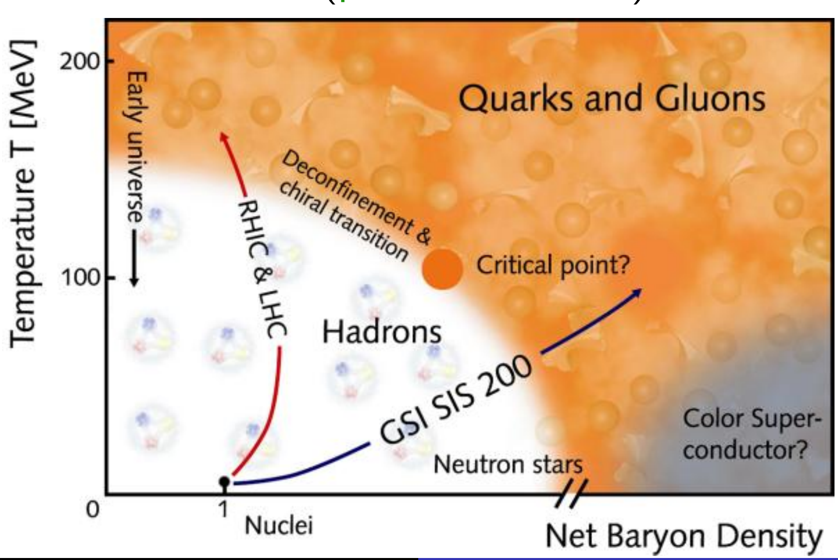
- Strong force at low energies very strong ⇒ forms $q\bar{q}$ pairs
- pairs are bosons! ⇒ all like to stay in vacuum state (at lowest possible energy)
- about 5 pairs per fm^{-3} (1 fm$=10^{-15}$ m!)



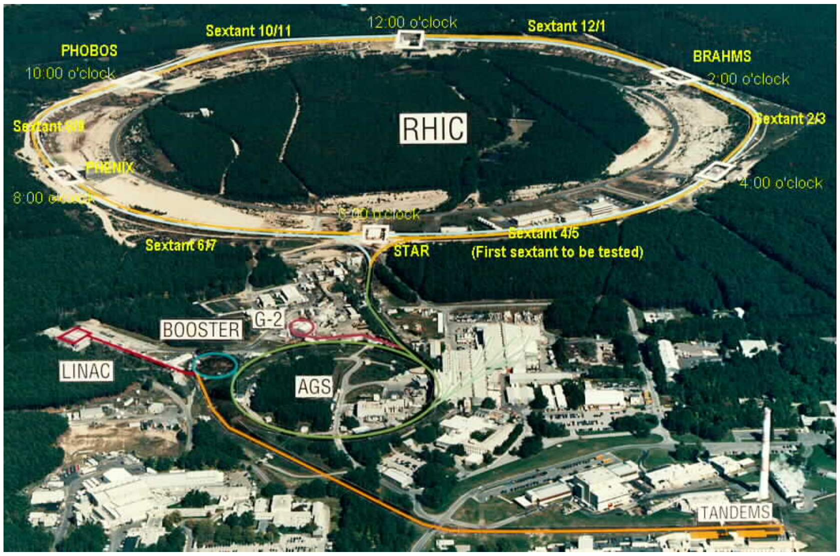
- Quarks become massive, because of very dense vacuum!
- How can we check this?
- Can we evaporate the vacuum?

How to evaporate the vacuum?

- lots of quarks and gluons close together
- dense and hot environment ⇒ strong force becomes weaker!
- QCD at high temperatures and densities
- $\bar{q}q$ condensate disolves (phase transition!)

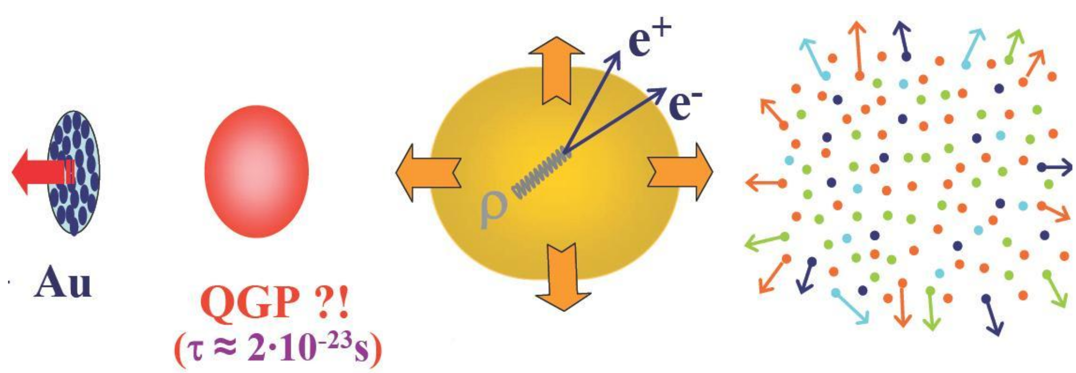


Use our favorite tool: Heavy-Ion Colliders!



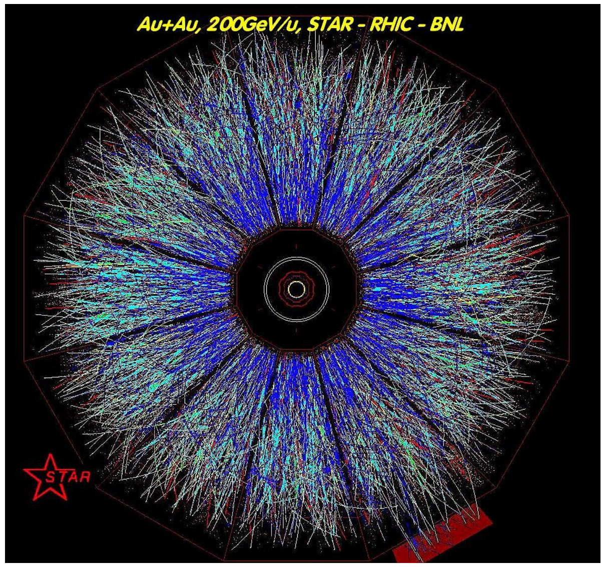
- RHIC: Accelerate gold nuclei to 200 GeV per nucleon
- collide them head-on!
- Hope to create the Quark-Gluon Plasma!

The “Little Bang” in the Lab



- What are probes from hot and dense stage?
- Answer: decays of $\rho(770)$ meson to electrons and positrons!

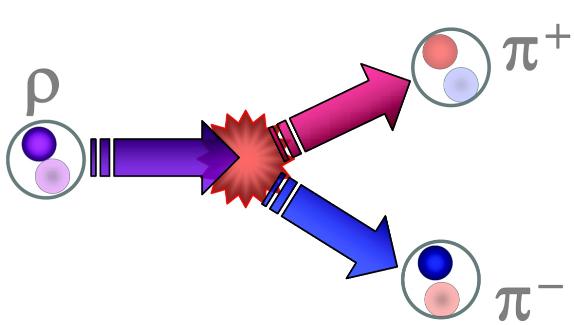
The “Little Bang” in the Lab

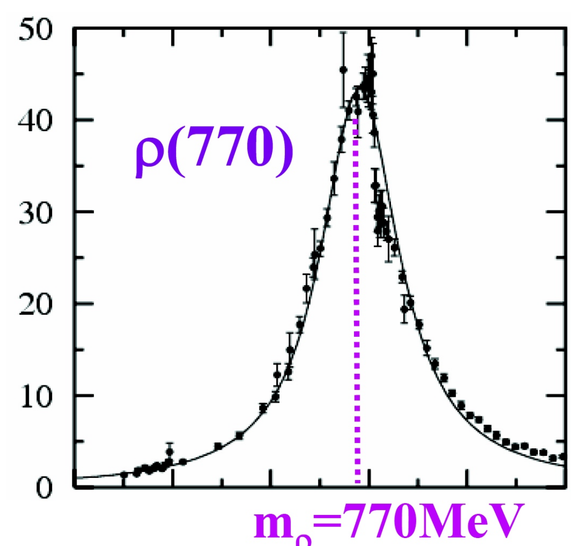


- Challenge: Find the rare events!
- See Prof. Mioduszewski’s talk from last week!

The ρ meson in the vacuum

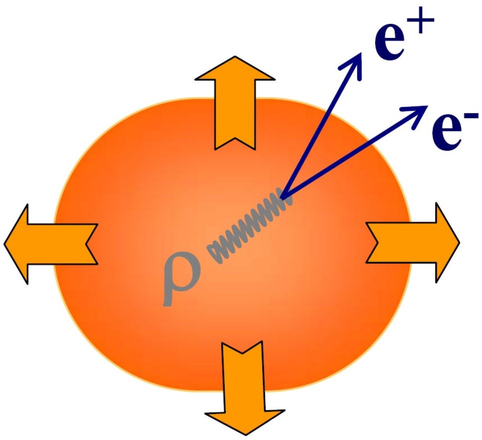
- mass of the ρ mesons: $m_\rho = 770\ \text{MeV}/c^2$
- $m_\rho \approx 2M_{\text{constituent quarks}}$
- its lifetime is about $1.3\ \text{fm}/c = 3.3 \cdot 10^{-24}$sec
- It decays inside the hot and dense matter!





The ρ meson in the fireball

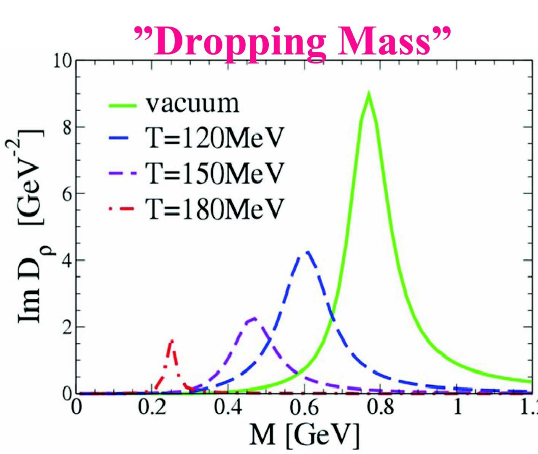
- how to measure the ρ mass inside the fireball?
  - could look at the decay pions
  - energy-momentum conservation $\Leftrightarrow$ ρ mass $(E = mc^2!)$
  - but pions interact strongly with the "junk" around them $\Rightarrow$ Signal gets destroyed!
- solution: rarely the ρ's decay into an e^+e^- or $\mu^+\mu^-$ pair

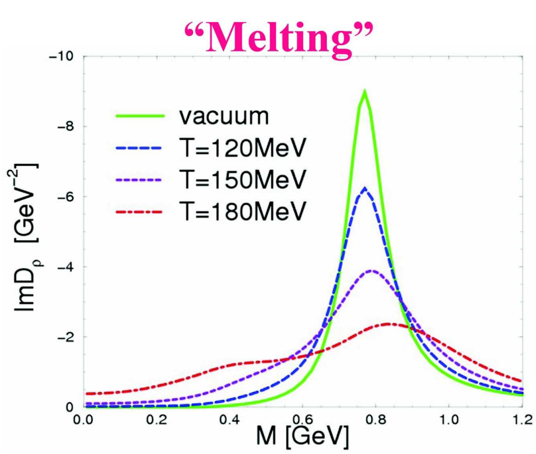


- $e^\pm$ and $\mu^\pm$ are leptons
- they do not interact strongly
- signal undistorted
- get the mass of the ρ inside the fireball

What do the Theoreticians predict?

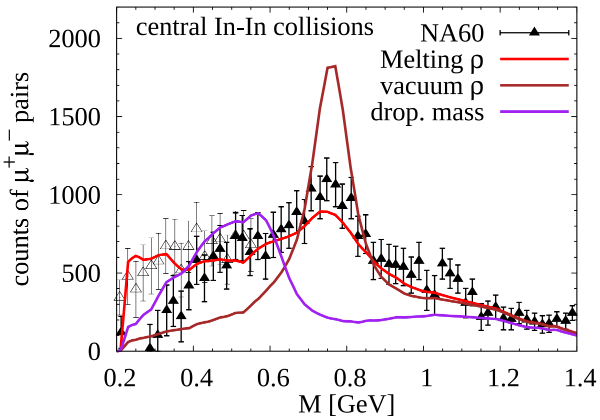
- some theoreticians predicted "dropping ρ mass"
- quark condensate melts, not much else happens to the ρ
- others simulated interactions of the ρ in the hot gas
- ρ becomes a broad mass distribution ("melting ρ")





What is right?

- Only experiment can answer!
- most recent data from NA60 Experiment at CERN
- look for $\mu^+\mu^-$ pairs ("dileptons")



Curves from recent calculation [Ralf Rapp, HvH 2006] "Melting ρ" favored compared to dropping ρ mass

- need more detailed theoretical studies
- going on also at Texas A&M!
- We begin to understand the origin of mass!

Summary

- Natural Laws ↔ Symmetries ↔ Conservation Laws
- Atom → Nucleus → Nucleons → quarks (elementary!)
- Quarks always confined to Hadrons (baryons and mesons)
  - strong force described by QCD (based on color symmetry!)
  - Confinement only partially understood from QCD
- Quarks acquire a large mass within hadrons
  - vacuum is a "dense liquid" of $\bar{q}q$ and gluon condensates
  - spontaneous symmetry breaking
  - more than 98% of the visible mass in the universe
- Collisions of Heavy Nuclei at High Energies
  - Heat the vacuum and evaporate the condensates
  - deconfine quarks and gluons
  - dissolve mass into energy
  - dileptons (e^+e^- or $\mu^+\mu^-$) from decays of ρ mesons
  - study the origin of mass

Very exciting physics ahead!