Hadron Modifications in Dense Nuclear Matter

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APCTP−BLTP JINR Workshop 2017

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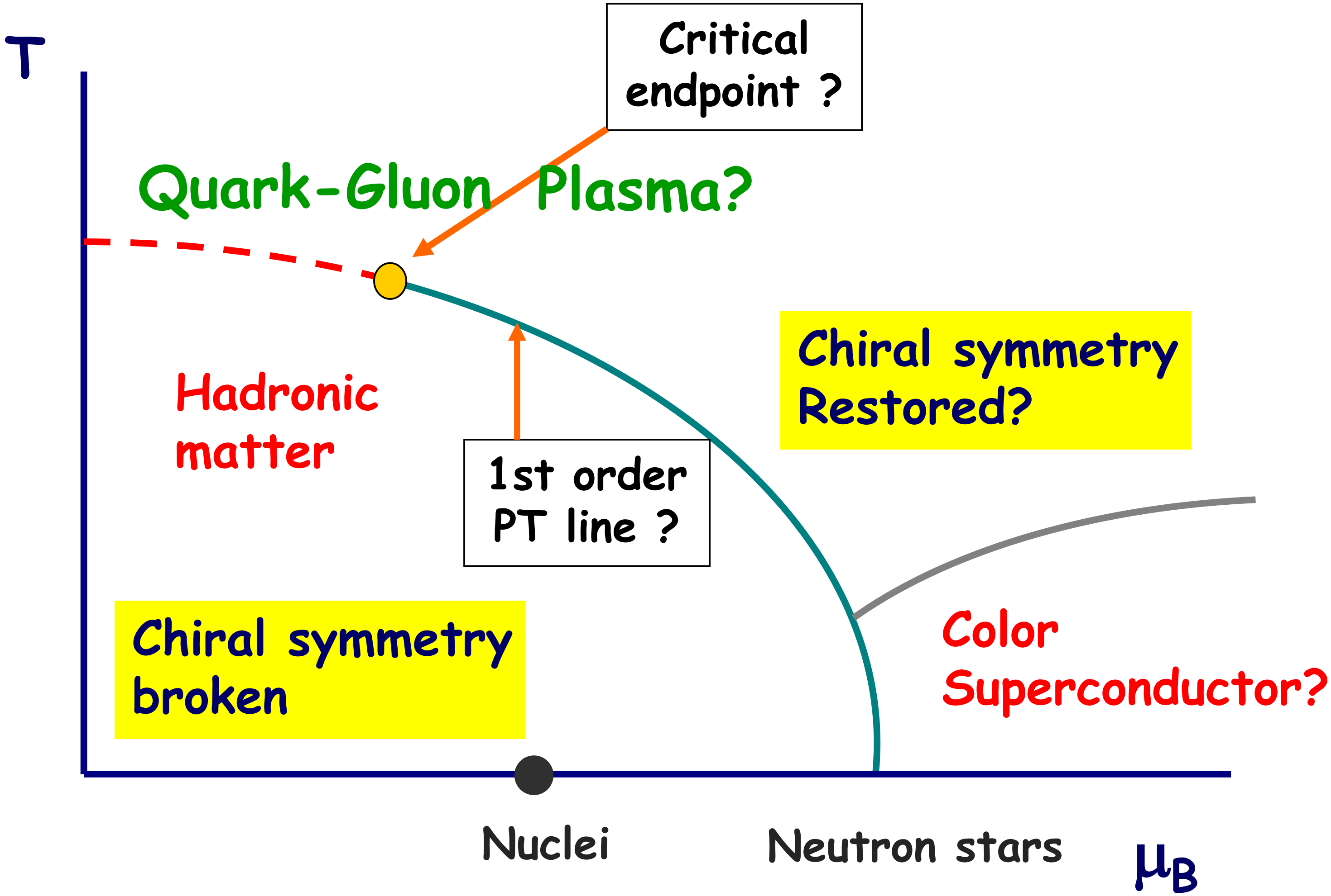
- The Model
  - Strongly correlated quark model (SCQM) of the hadron structure
  - Building the nuclear structure
- Hadron modifications in a dense nuclear matter
- Understanding of exp. effects in HIC
  - Enhanced strangeness production
  - Horn-effect
  - Enhancement of dilepton mass spectra in the range 0.2 – 0.6
- Conclusion

Motivation

- How nuclear matter behave under high compression?
- How hadron structures are modified in a dense matter?
- What observables are the possible signals of these modifications?

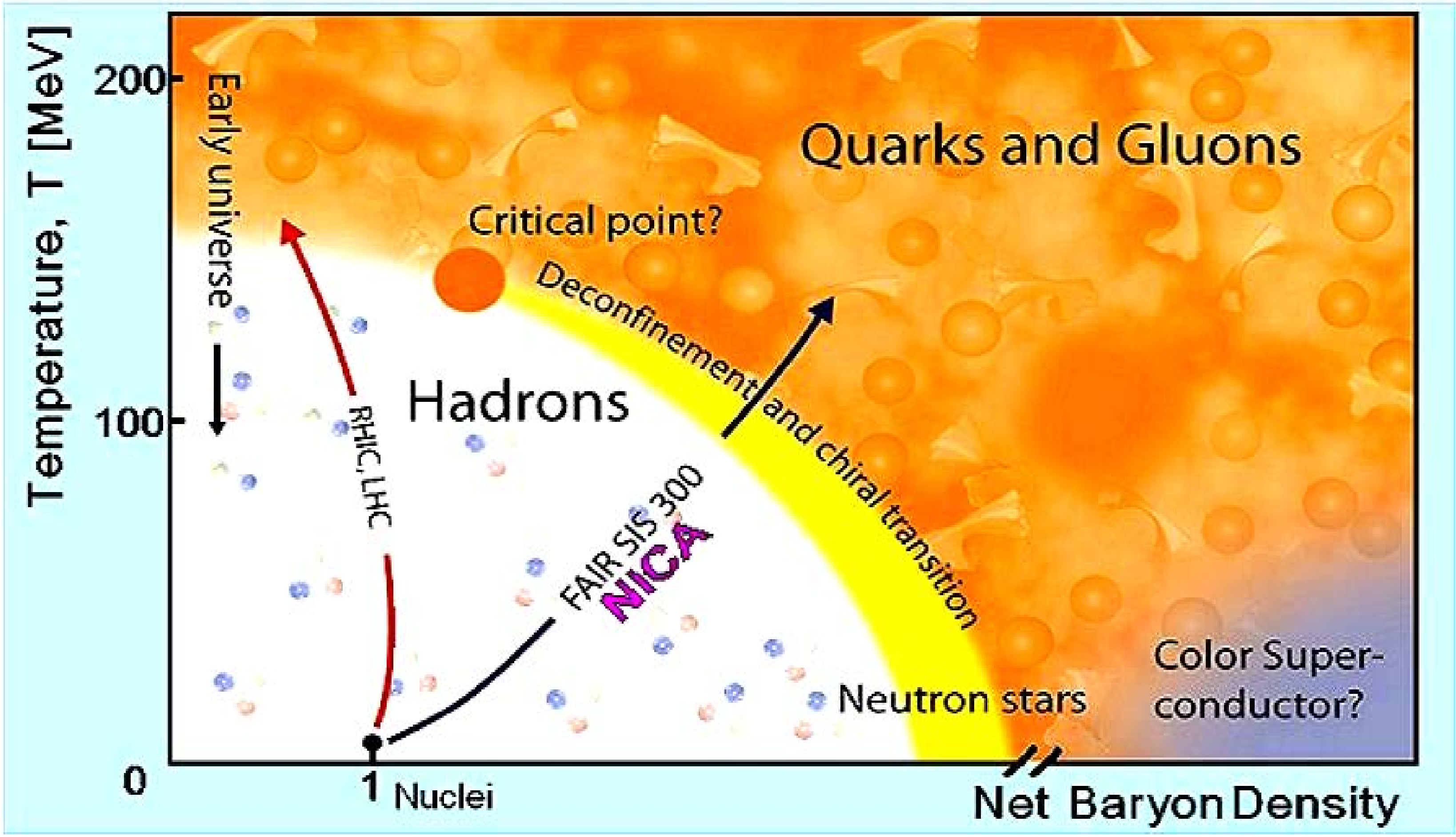
Motivation

- Does hadronic matter transit into QGP?



Motivation

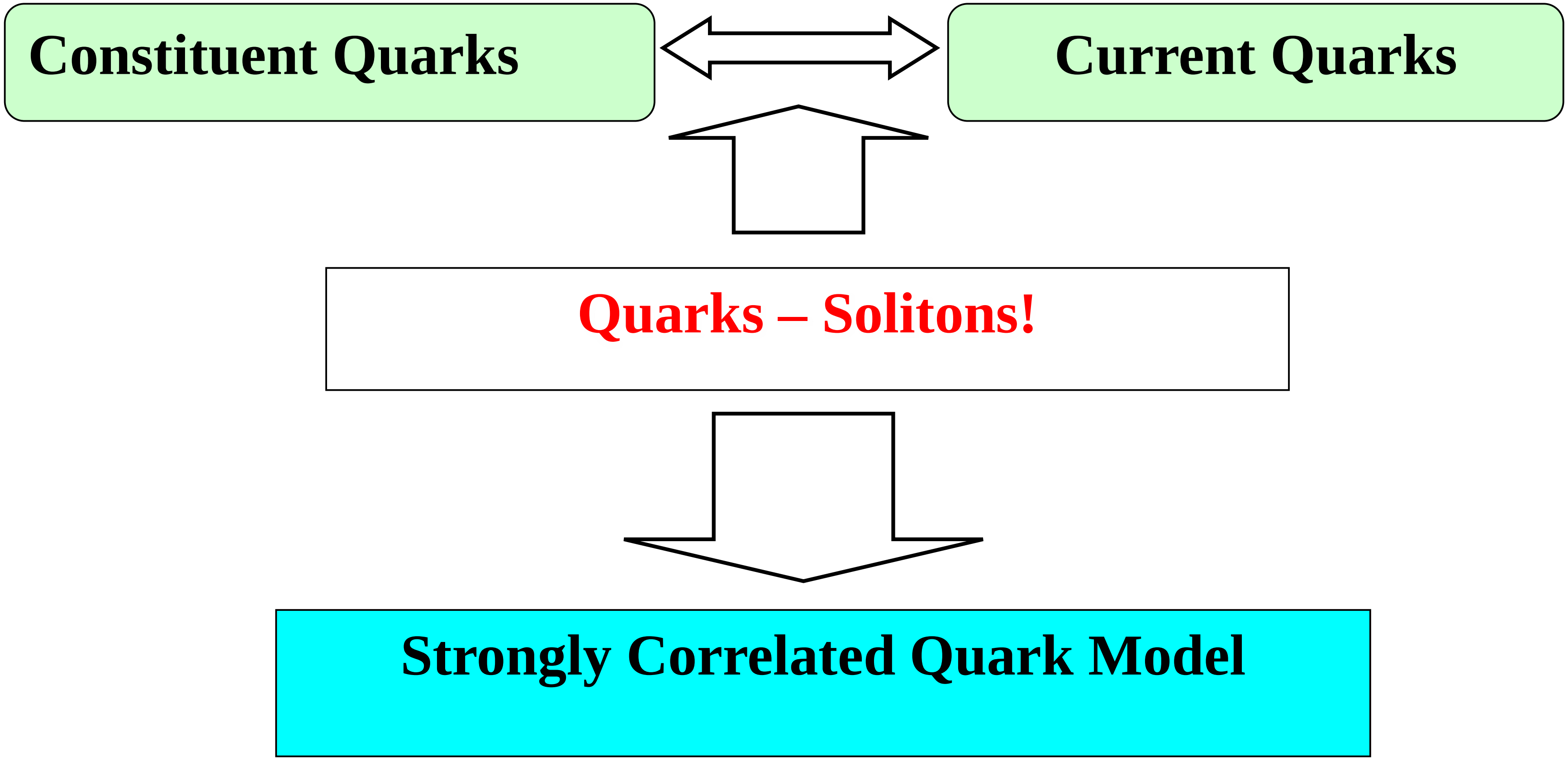
- Does hadronic matter transit into QGP?



Toy Model:

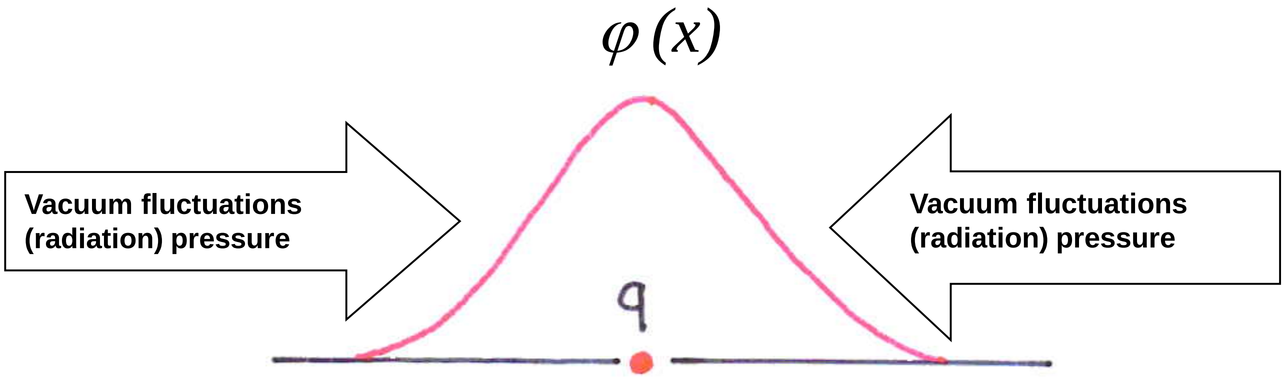
Strongly Correlated Quark Model

G. Musulmanbekov, 1995


Constituent Quarks
Current Quarks
Quarks – Solitons!
Strongly Correlated Quark Model

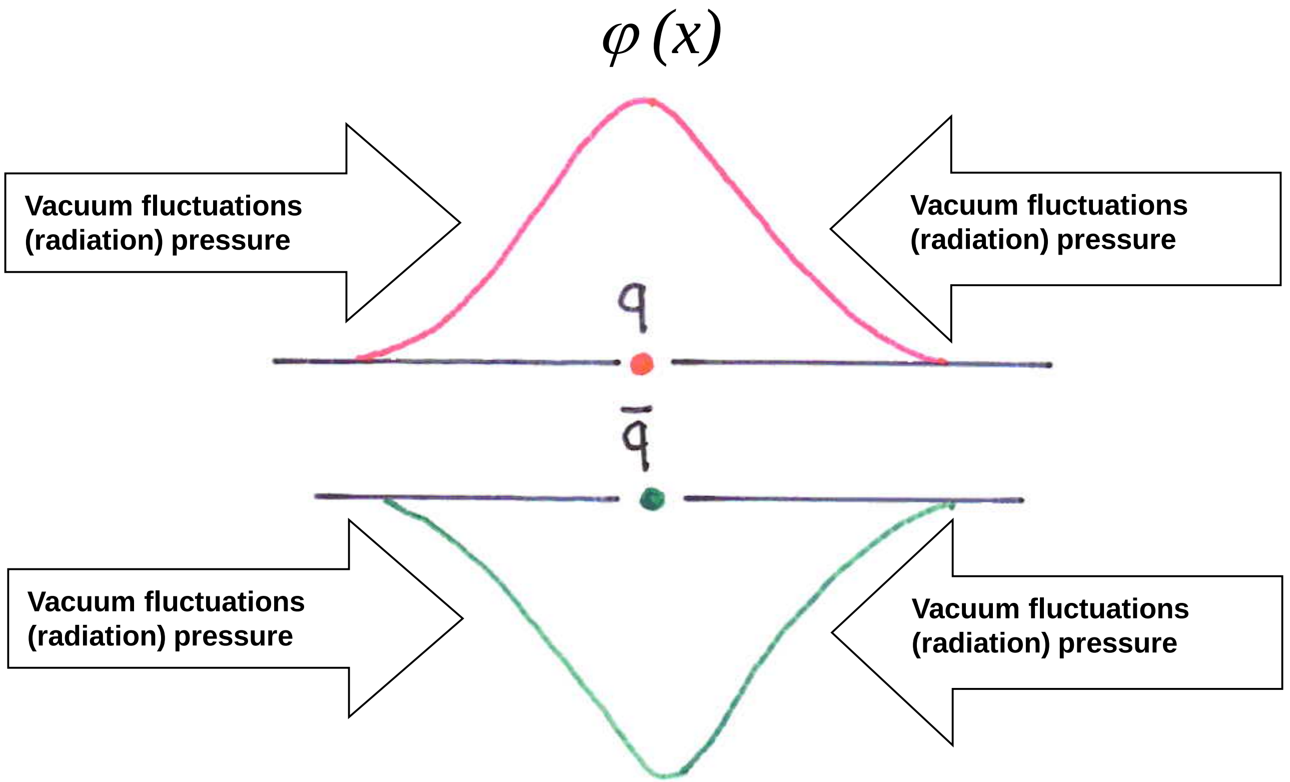
Strongly Correlated Quark Model

(SCQM)



Strongly Correlated Quark Model

(SCQM)



Strongly Correlated Quark Model

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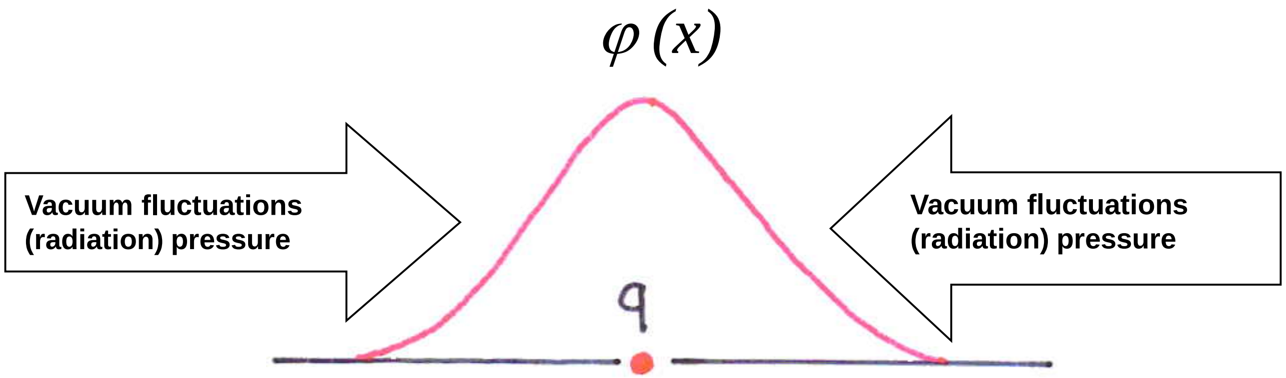


Vacuum polarization around single quark

⇩

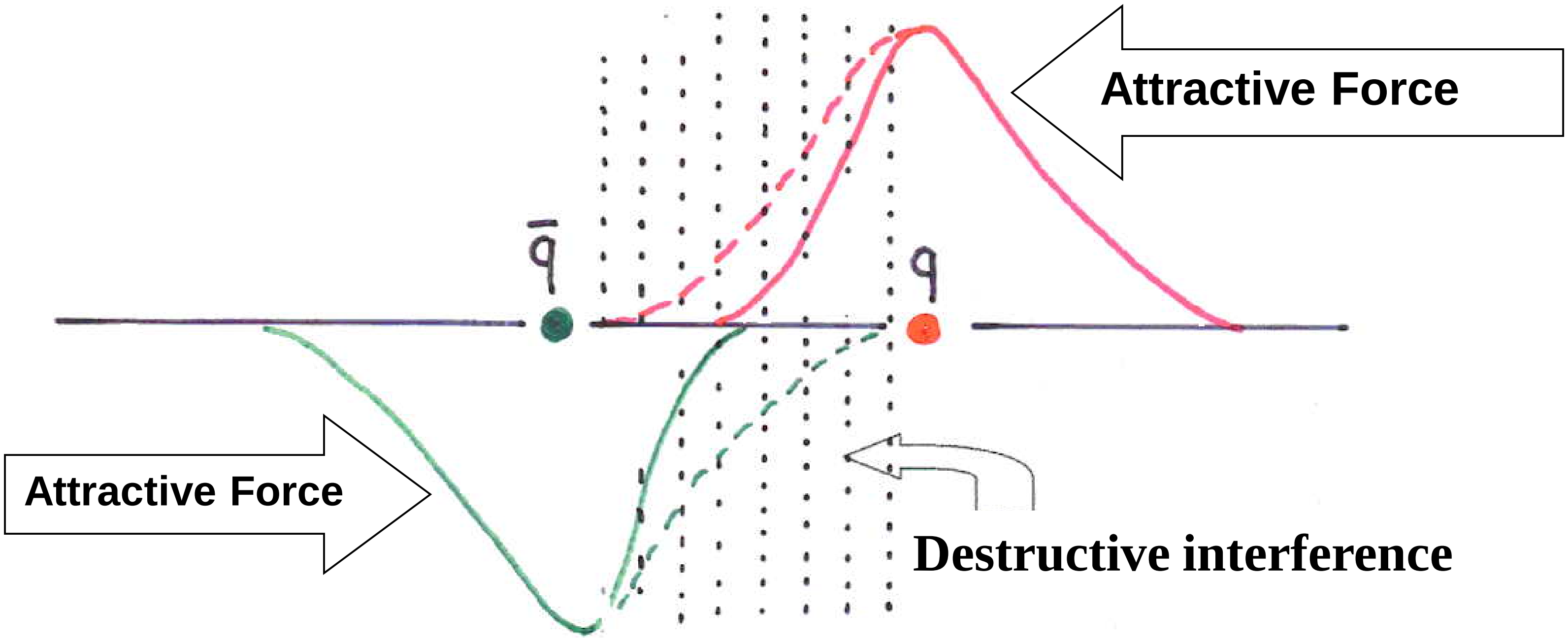
Quark and Gluon Condensate

What is Chiral Symmetry and its Breaking?

- Chiral Symmetry
  $SU(2)_L \times SU(2)_R$ for $\psi_{L,R} = u, d$
- The order parameter for symmetry breaking is quark or *chiral* condensate:
  $<\psi\psi> \simeq -(250\ \text{MeV})^3, \quad \psi = u,d$
- As a consequence massless valence quarks (u, d) acquire dynamical masses which we call constituent quarks
  $$M_C \approx 350 - 400\ \text{MeV}$$

Strongly Correlated Quark Model

(SCQM)



The Strongly Correlated Quark Model

Hamiltonian of the Quark – AntiQuark System

$$H = \frac{m_{\bar{q}}}{(1-\beta_{\bar{q}}^{\;2})^{1/2}} + \frac{m_q}{(1-\beta_q^{\;2})^{1/2}} + V_{\bar{q}q}(2x)$$

$m_{\bar{q}}$, m_q are the current masses of quarks,

***β = β(x)* –** the velocity of the quark (antiquark),

$V_{\bar{q}q}$ **-** *is the quark–antiquark potential.*

$$H = \left[\frac{m_{\bar{q}}}{(1-\beta_{\bar{q}}^{\;2})^{1/2}} + U(x)\right] + \left[\frac{m_q}{(1-\beta_q^{\;2})^{1/2}} + U(x)\right] = H_{\bar{q}} + H_q$$

$U(x) = \frac{1}{2} V_{\bar{q}q}(2x)$ is the potential energy of a single quark/antiquark.

Constituent Quarks – Solitons

SCQM ≡ Breather Solution of Sine- Gordon equation

$$\partial_\mu \partial^\mu \phi(x,t) + \sin\phi(x,t) = 0$$

Breather – oscillating soliton-antisoliton pair:

$$\phi(x,t)_{s-as} = 4\tan^{-1}\left[\frac{\sinh\left(ut/\sqrt{1-u^2}\right)}{u\cosh\left(x/\sqrt{1-u^2}\right)}\right]$$

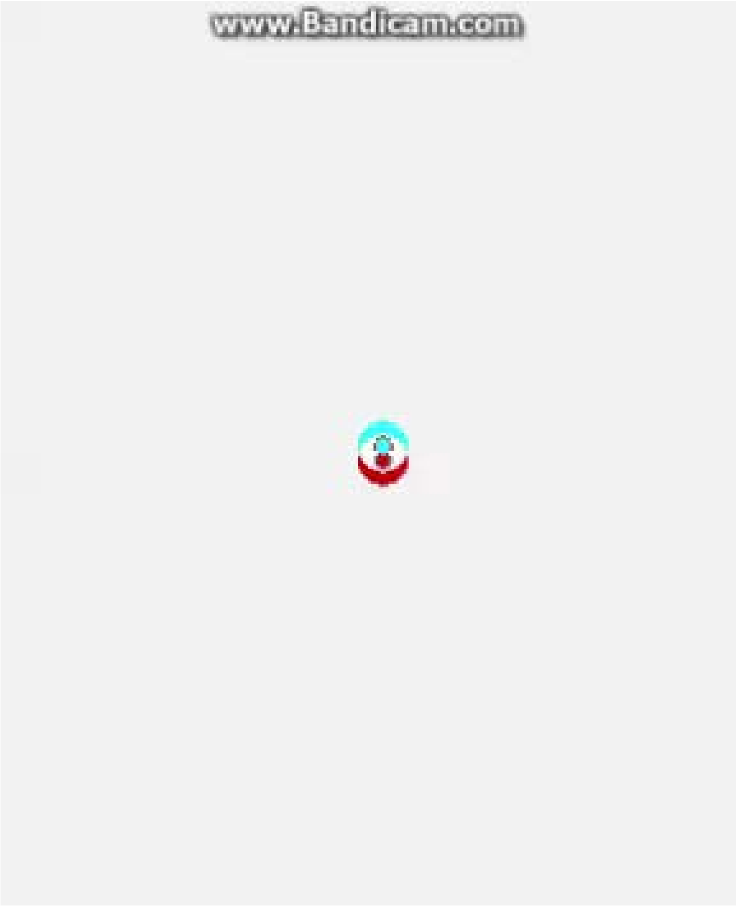
$$\varphi(x,t)_{s-as} = \frac{\partial\phi(x,t)_{s-as}}{\partial x}$$

is identical to our quark-antiquark system;

Breather – quark-antiquark pair
Meson

$\varphi(x,t)$ $\varepsilon(x,t)$

quark-antiquark pair
Meson

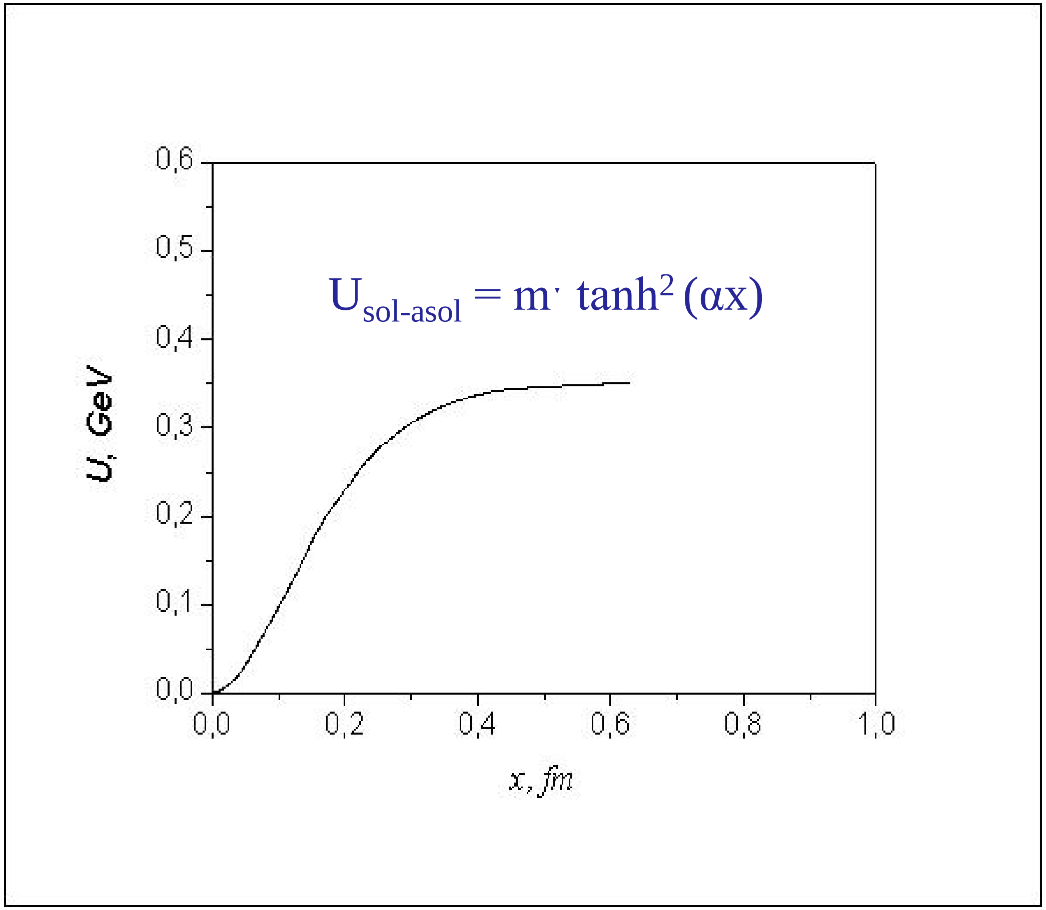


Quark Potential

Potential in soliton-antisoliton system: $U_{sol\text{-}asol} = m \cdot \tanh^2(\alpha x)$

W. Troost, CERN Report, 1975;

P. Vinsarelly, Acta Phys. Aust. Suppl., 1976

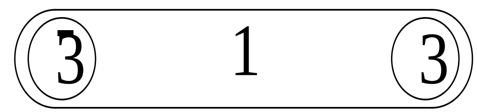


Generalization to the 3 – quark system (baryons)

$SU(3)_{Color}$

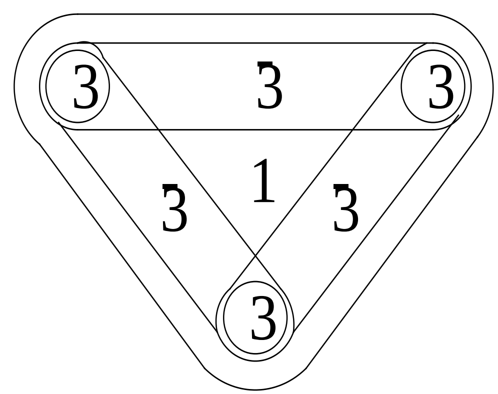
$q \Rightarrow SU(3) \Leftrightarrow RGB \qquad \bar{q} \Rightarrow SU(\bar{3}) \Leftrightarrow CMY$

$\bar{q}q \Rightarrow$



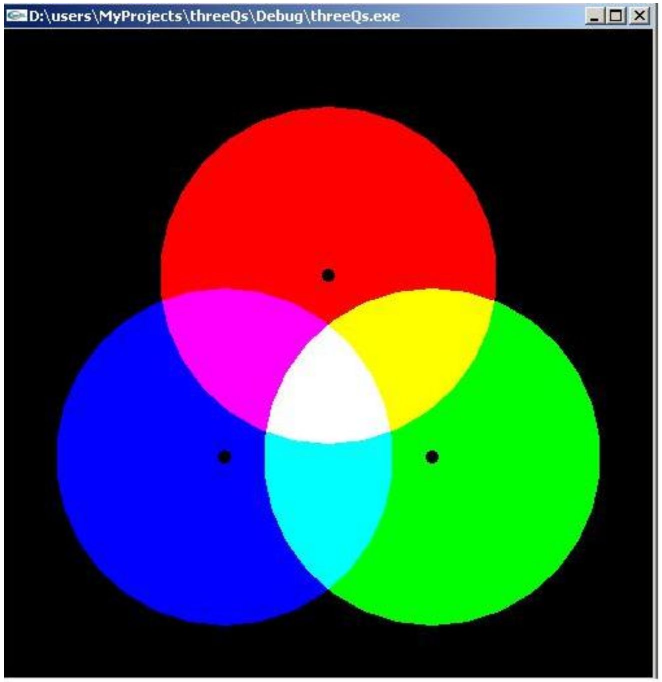
$qq \rightarrow 3 \times 3 = 6 \oplus \bar{3} \Rightarrow \bar{q} \rightarrow qq$

$qqq \Rightarrow$

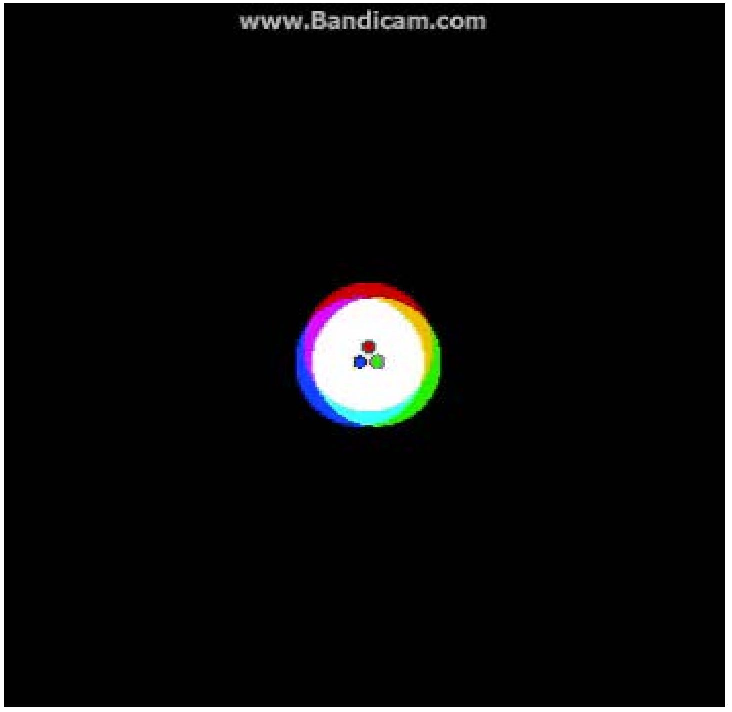


Baryon – 3-color quark system

$SU(3)_{color} \Longleftrightarrow RGB$



Nucleon

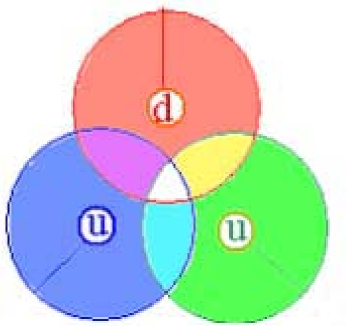


$SU(3)_{color}$ - singlet

Interplay between constituent and current quark states

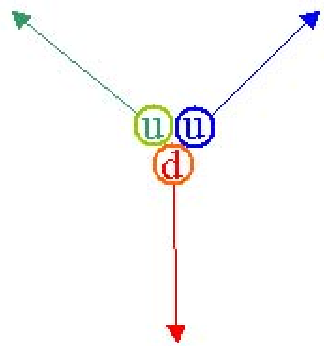
Chiral Symmetry Breaking $\Longleftrightarrow$ Restoration

t = 0
$x = x_{max}$



Constituent quaks

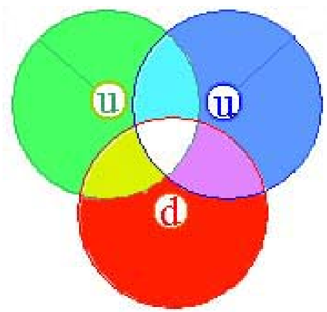
$t = T/4$
$x = 0$



current quarks

Asymptotic freedom

$t = T/2$
$x = -x_{max}$

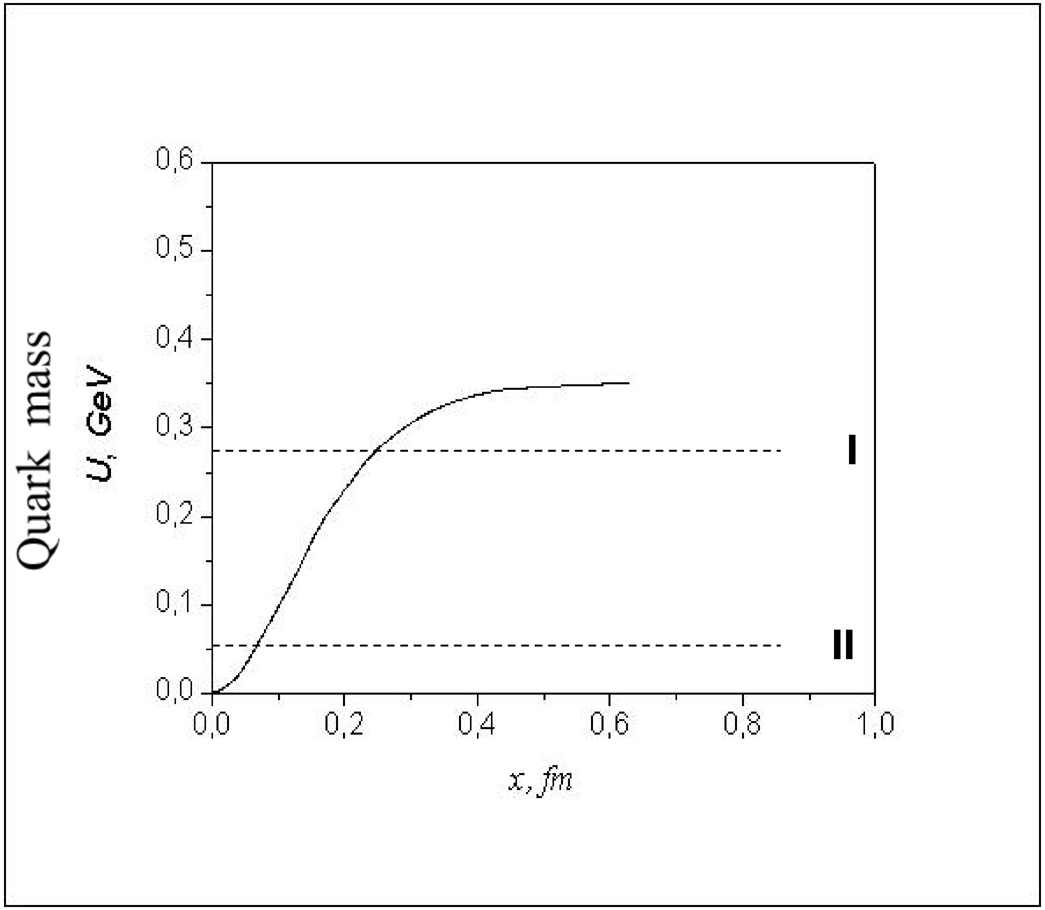


Constituent quarks

During the valence quarks oscillations:

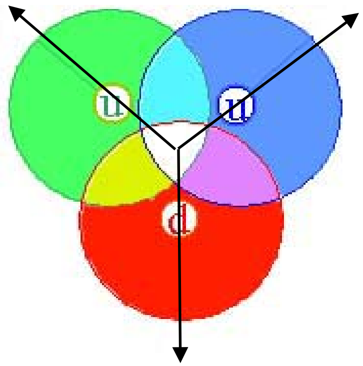
$$|B\rangle = a_1 |q_1 q_2 q_3\rangle + a_2 |q_1 q_2 q_3 \bar{q} q\rangle + a_3 |q_1 q_2 q_3 g\rangle + \ldots$$

Quark Potential



U(x) > I – constituent quarks
U(x) < II – current (relativistic) quarks

Nucleon



Quark color wave function

$$\psi(x)_{Color} = \sum_{i=1}^{3} a_i(x)\left|c_i\right\rangle$$

Where $\left|c_i\right\rangle$ **are orthonormal states with *i, j* = R,G,B**

$$\left\langle c_i \middle| c_j \right\rangle = \delta_{ij}$$

Nucleon wave function

$$\psi(x)_{Color} \to \frac{1}{\sqrt{6}} \sum_{ijk} e_{ijk} \left|c_i\right\rangle \left|c_j\right\rangle \left|c_k\right\rangle$$

Parameters of SCQM for the Nucleon

- Parameters of Quark potential **$U_{sol\text{-}asol} = m \cdot \tanh^2(\alpha x)$**

1. Mass of Consituent Quark

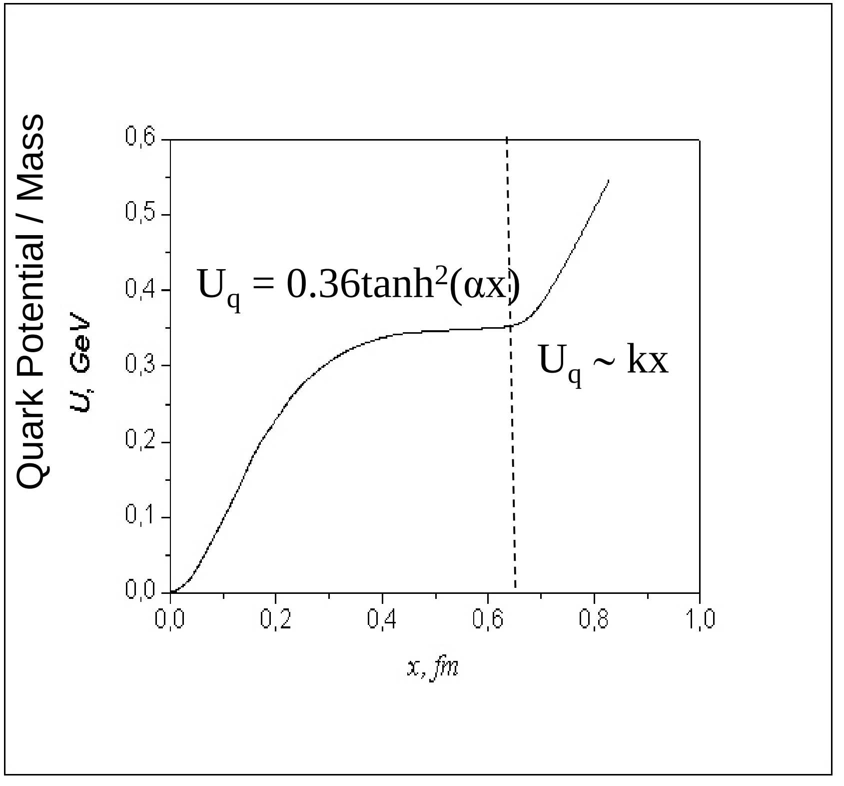
$$m = M_{Q(\overline{Q})}(x_{\max}) = \frac{1}{3}\left(\frac{m_\Delta + m_N}{2}\right) \approx 360 MeV,$$

2. Amplitude of VQs oscillations : $\alpha = x_{max} = 0.64\ fm$,

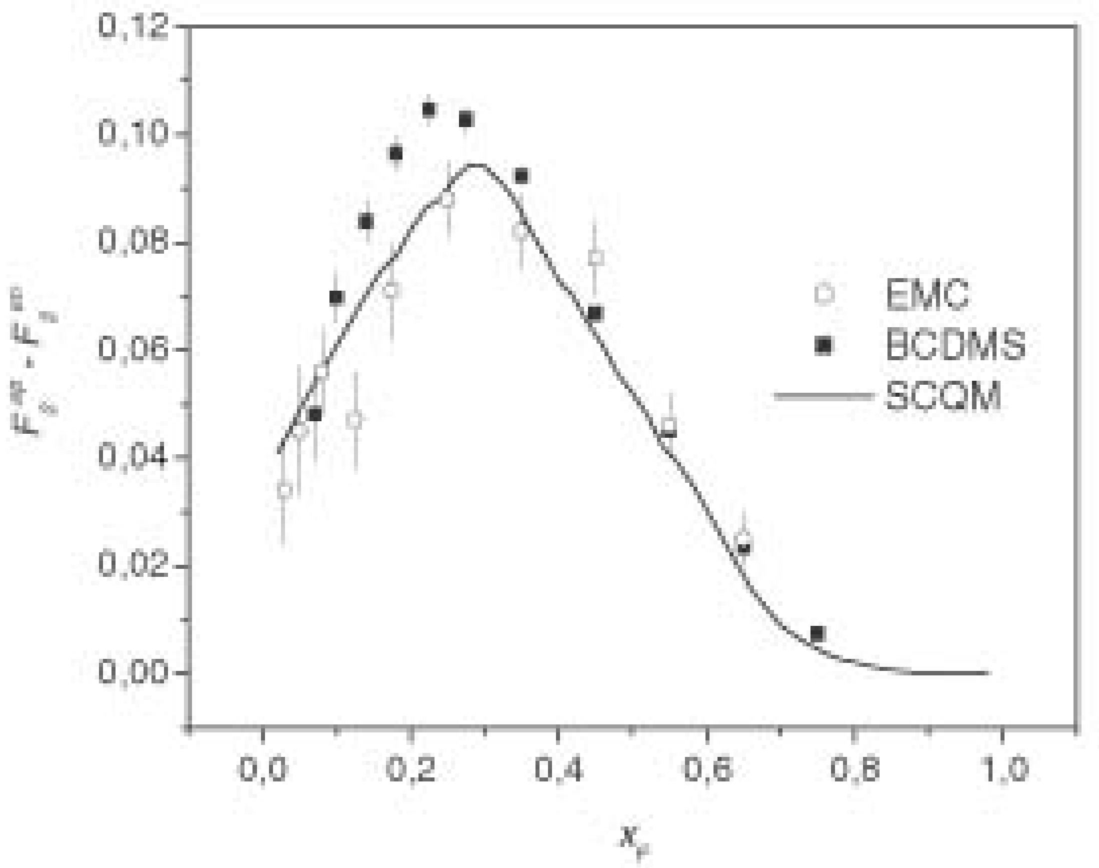
- Constituent quark sizes (parameters of gaussian distribution): $\sigma_{x,y} = 0.24\ fm$, $\sigma_z = 0.12\ fm$
- Parameters 2 and 3 are derived from the calculations of Inelastic Overlap Function (IOF) and σ_{tot} in $\bar{p}\,p$ and *pp* – collisions.

"The wave packet solution of time-dependent Schrodinger equation for harmonic oscillator moves in exactly the same way as corresponding classical oscillator"
E. Schrodinger, 1926

Quark Potential



Structure Function of Valence Quarks in Proton



SCQM $\Longrightarrow$ The Local Gauge Invariance Principle

Destructive Interference of color fields ≡ Phase rotation of the quark w.f. in color space:

$$\psi(x)_{Color} \rightarrow e^{ig\theta(x)}\psi(x)$$

Phase rotation in color space $\Longrightarrow$ quark dressing (undressing) ≡ the gauge transformation

$$A^{\mu}(x) \rightarrow A^{\mu}(x) + \partial^{\mu}\theta(x)$$

Therefore, during quark oscillation its

color charge

momentum

mass

are continuously varying function of time.

Relation SCQM to QCD

We reduce interaction of color quarks via **non-Abelian** fields to its **E-M** analog:

$$A_a^{\mu}(x) \rightarrow A^{\mu}(x)$$

$$F_a^{\mu\nu} = \partial^{\mu} A_a^{\nu} - \partial^{\nu} A_a^{\mu} - \lambda f^{abc} A_b^{\mu} A_c^{\nu} \rightarrow F_{ch}^{\mu\nu} = \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu}$$

Spin in SCQM

Conjecture: spin of constituent quark is entirely analogous to the angular momentum carried by classical circularly polarized wave:

$$\mathbf{J_Q} = \mathbf{J_g} = \int_a^\infty d^3r \left[\mathbf{r} \times (\mathbf{E} \times \mathbf{B})\right]$$

Classical analog of electron spin – *F.Belinfante 1939; R. Feynman 1964; H.Ohanian 1986; J. Higbie 1988.*

Electron surrounded by proper **E** and **B** fields creates circulating flow of energy:

$$\mathbf{S} = \varepsilon_0 c^2 \mathbf{E} \times \mathbf{B}$$

Total angular momentum created by this Pointing's vector

$$\mathbf{s} = \mathbf{L} = (\ldots)\int_a^\infty d^3r \left[\mathbf{r} \times (\mathbf{E} \times \mathbf{B})\right]$$

is associated with the entire spin angular momentum of the electron.

Spin in SCQM

1. Now we accept that

$$A^{\mu} = \{\varphi, \mathbf{A}\}$$

and intersecting $\mathbf{E_{ch}}$ and $\mathbf{B_{ch}}$ create around VQ color analog of Pointing's vector (circulating flow of energy)

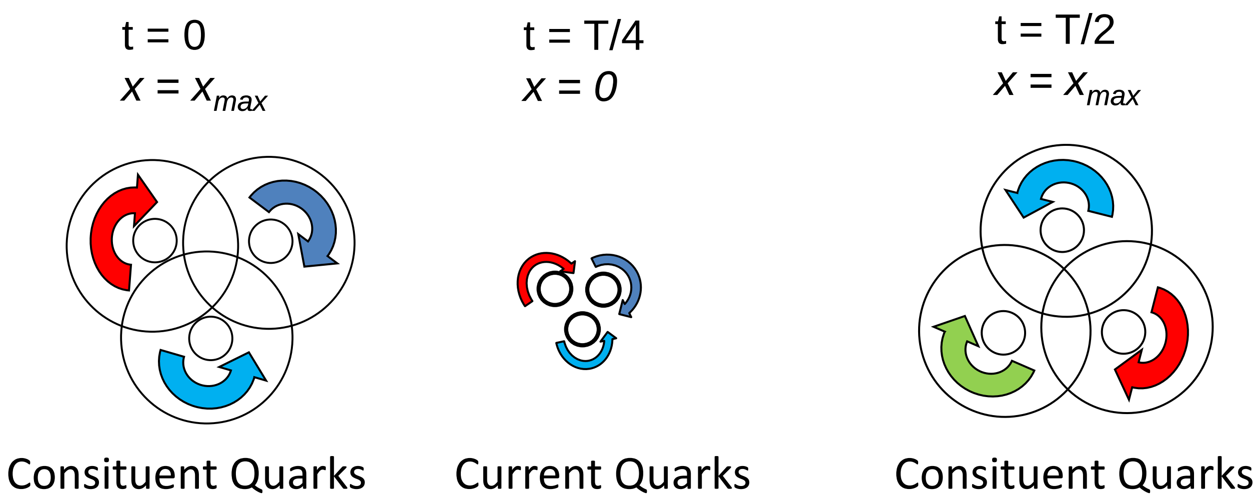
$$\mathbf{S = \varepsilon_0 c^2 E_{ch} \times B_{ch}}.$$

2. Total angular momentum created by this Pointing's vector

$$\mathbf{s_Q} = \mathbf{L_g} = (...) \int_a^{\infty} d^3 r \left[\mathbf{r} \times (\mathbf{E_{ch}} \times \mathbf{B_{ch}})\right]$$

is associated with the intrinsic spin of the constituent quark.

Quarks – Oscillating Vortices



- In the current quark state E_{ch} and B_{ch} are concentrated in a **small radius shell** around VQ.
- And so is for the vortices around VQs.

Quark Arrangement inside Nuclei

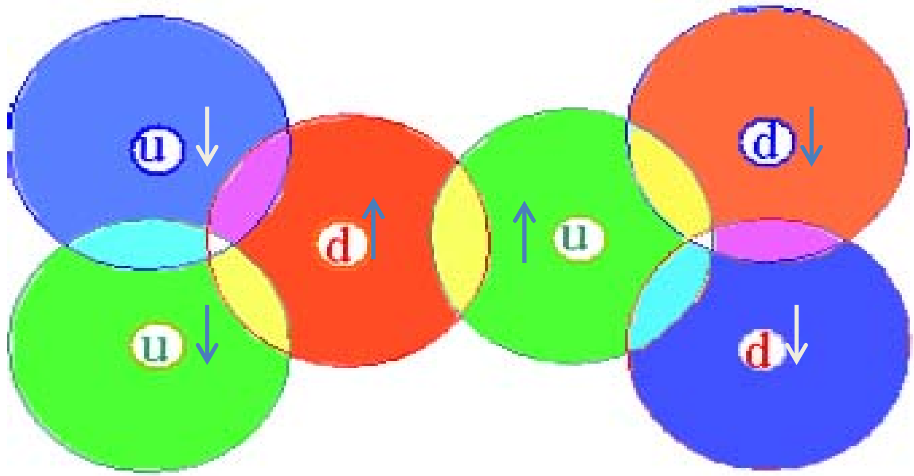
Nuclear Models

Strongly Correlated Quark Model

↓

Crystal-like arrangement of Nuclear Structure

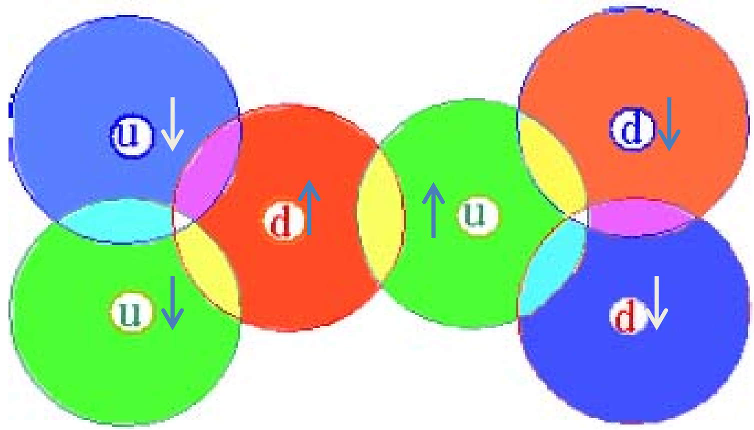
Two Nucleon System in SCQM



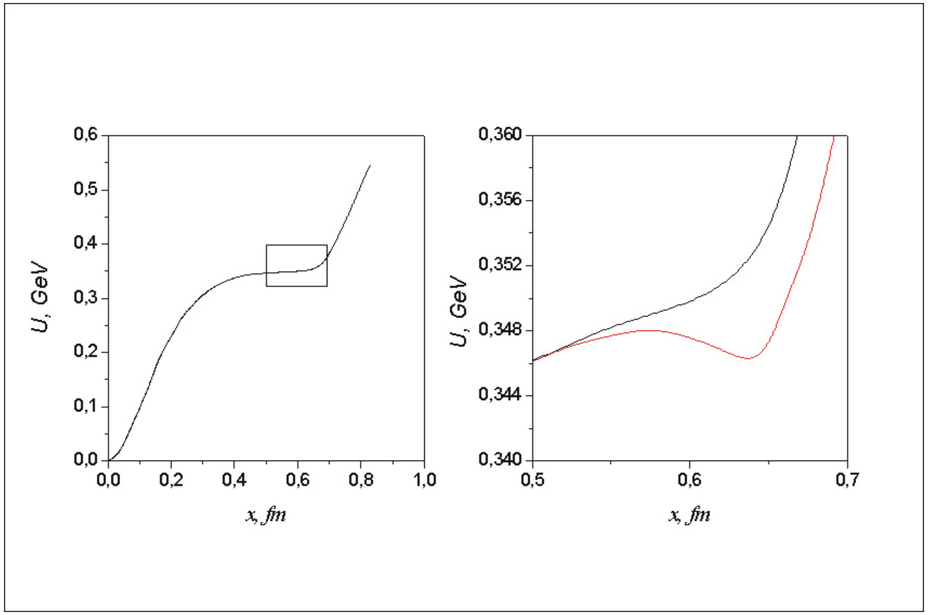
Selection rules for binding two quarks of neighboring nucleons at a junction:

- $SU(3)_{Color}$ – of different colors
- $SU(2)_{Flavor}$ – of different flavors
- $SU(3)_{Spin}$ – of parallel spins

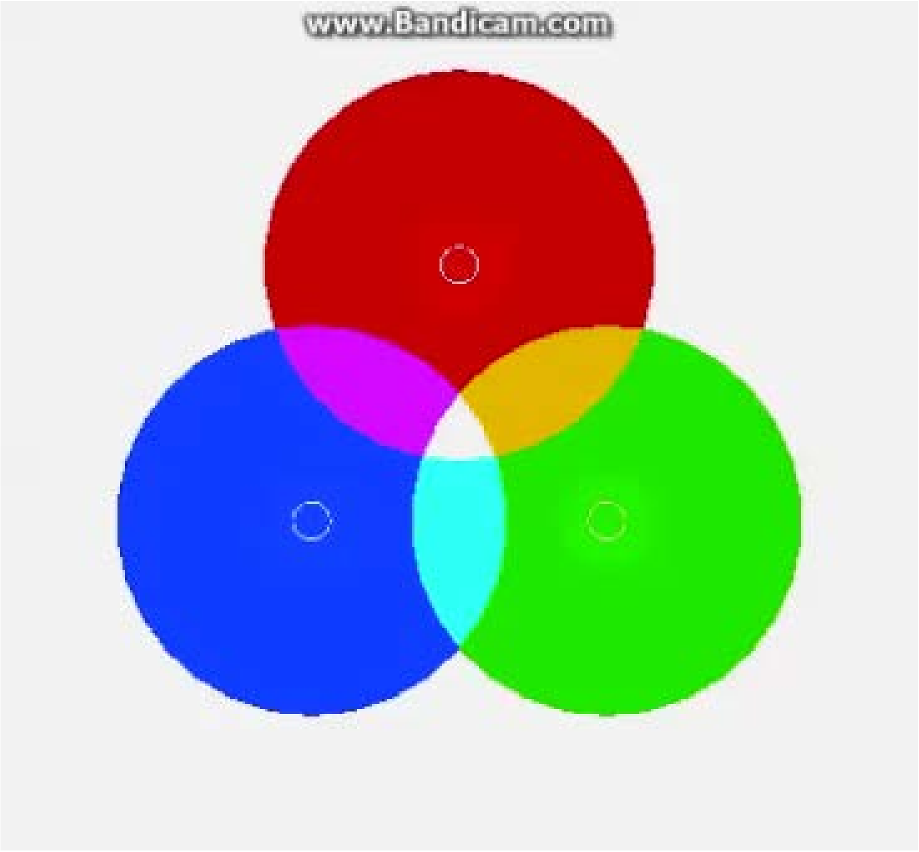
Two Nucleon System in SCQM



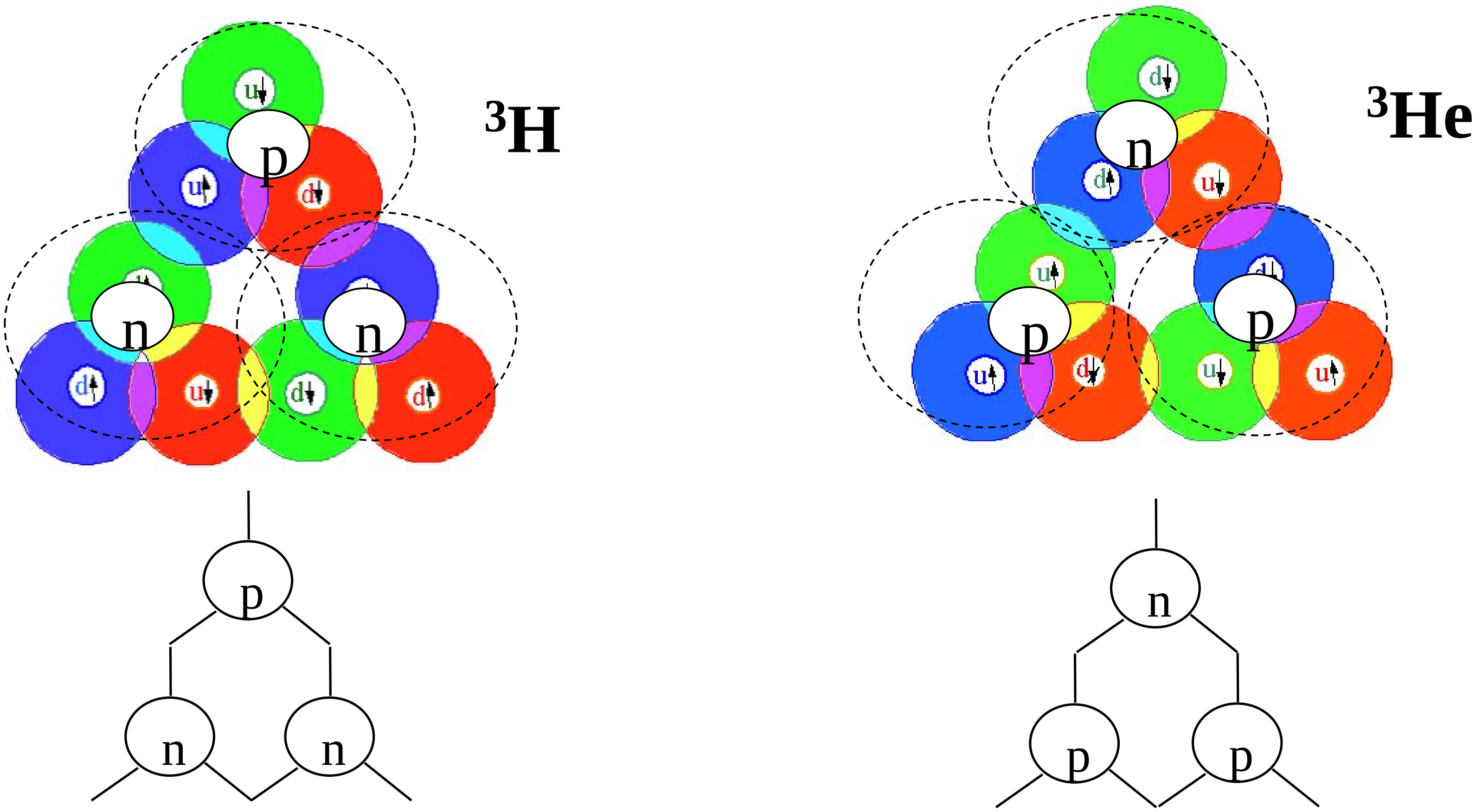
Quark Potential Inside Nuclei



Quarks inside nucleus



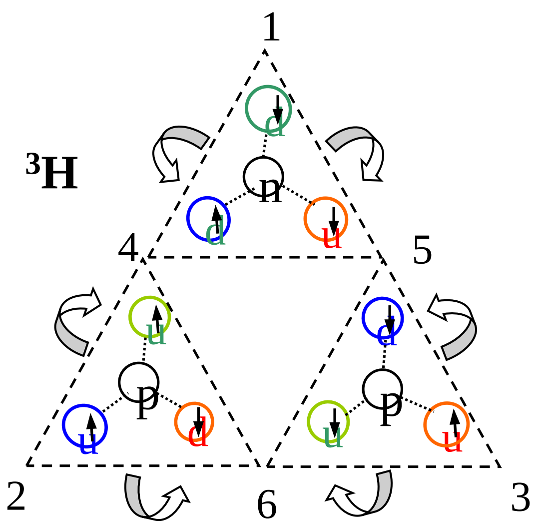
Three Nucleon Systems in SCQM



Quark loop → 3 – body force

The closed shell n = 0, nucleus ^4He

^3He + neutron or ^3H + proton

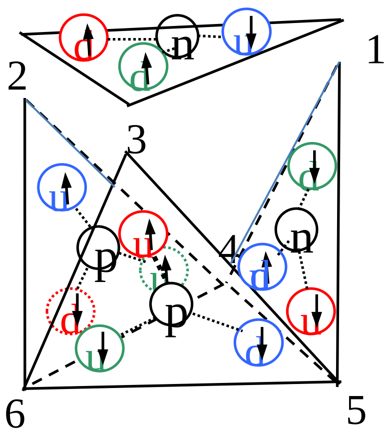


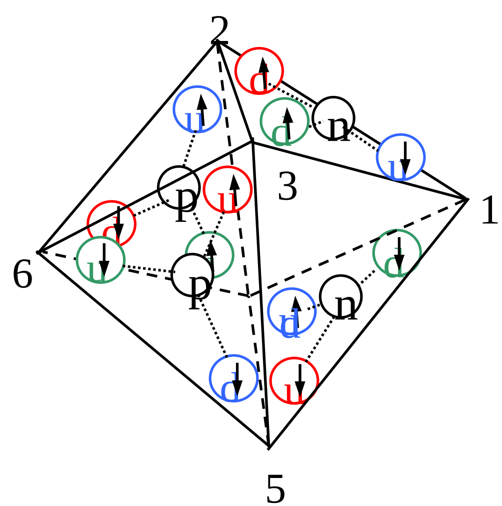
Junctures

1 ←→ 1

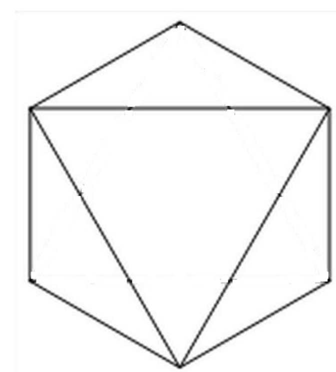
2 ←→ 2

3 ←→ 3





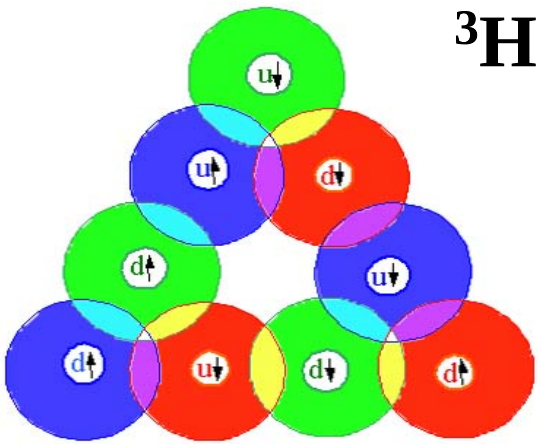
Shell Closure



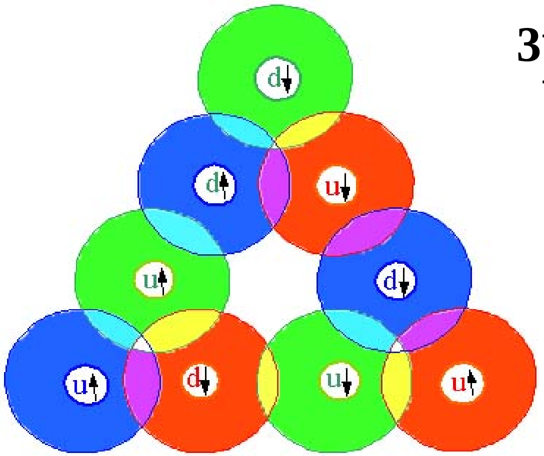
Binding Energy of Stable Nuclei Experiment

Nucleus	E_B, MeV per junction	Number of quark loops	Free quark ends	Nuclear forces
d	1.1	no	4	2-body (attr. + repul.)
^3H	2.83	1	3	2-body + 3-body (attr.)
^3He	2.57	1	3	2-body + 3-body (attr.)
^4He	7.07	4	0	2-body + 4-body (attr.)

Three Nucleon Systems in SCQM

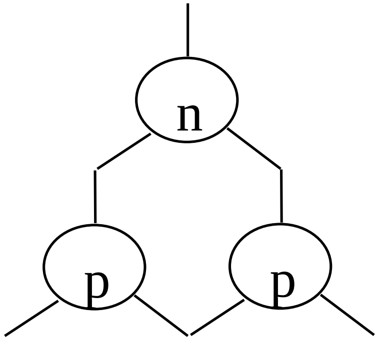


^3H

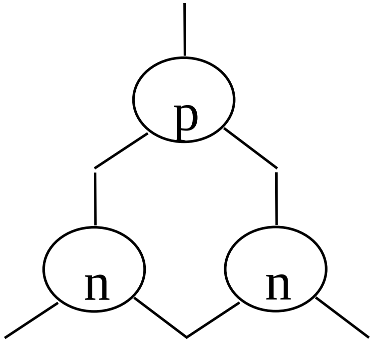


^3He

Quark Loops



^3He – block

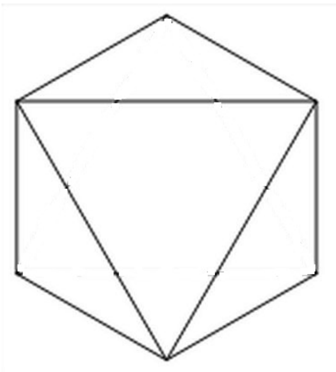


^3H – block

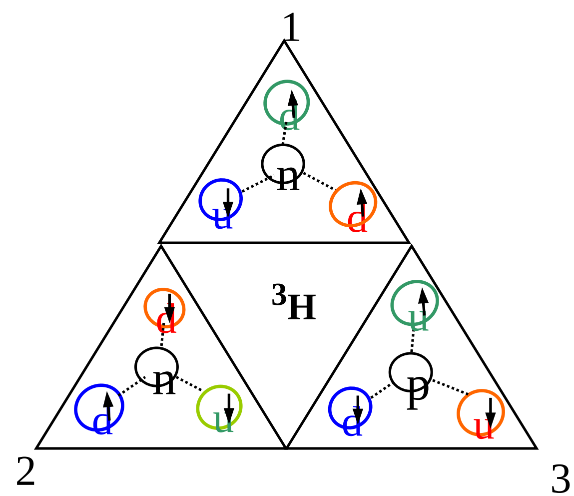
Basic building blocks of Nuclear Structure

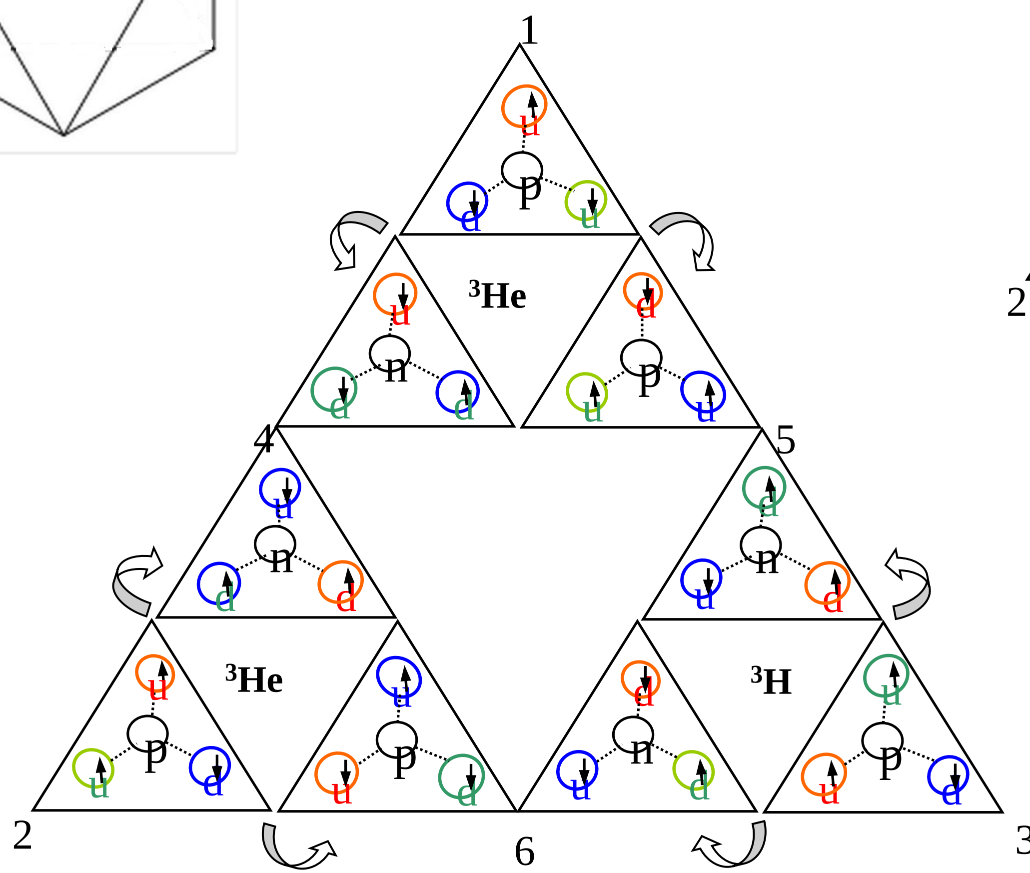
The closed shell n = 1, ^{16}O

Shell Closure



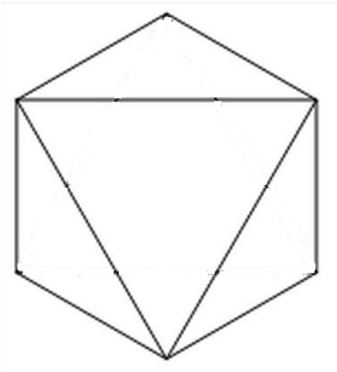
Face of ^{16}O octahedron



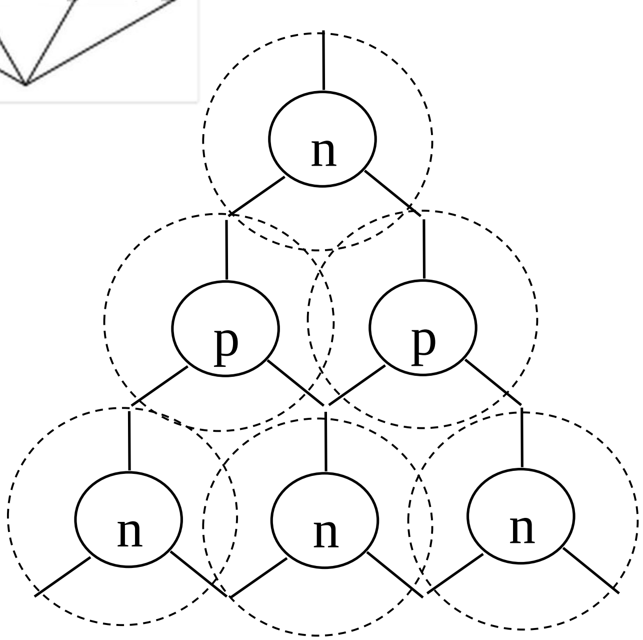


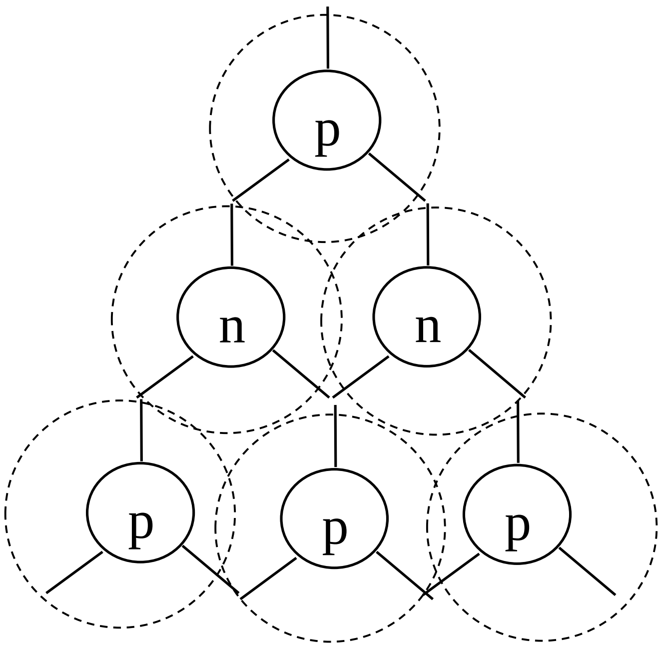
The closed shell n = 2, ^{40}Ca

Shell Closure



Faces of ^{40}Ca octahedron



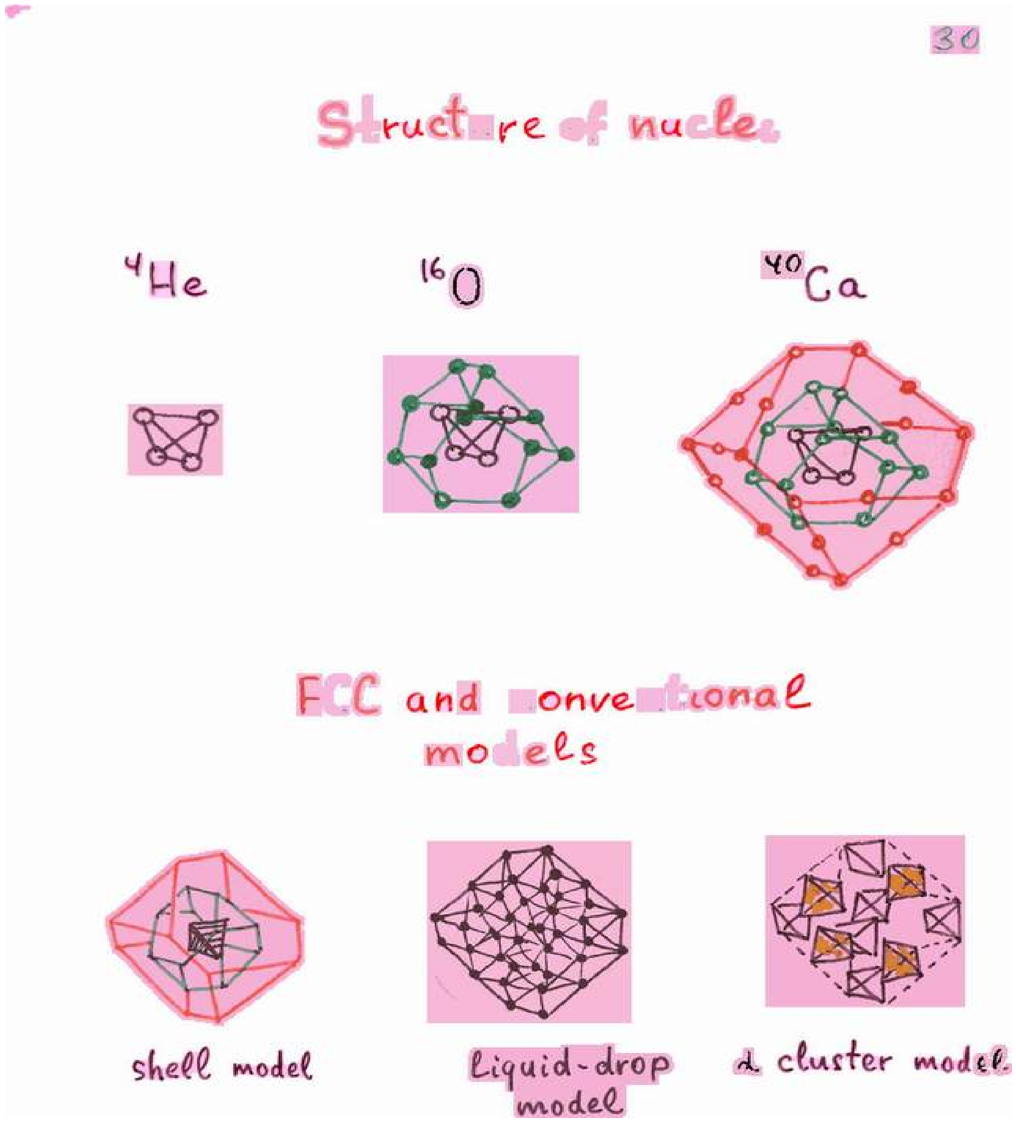


Resume on nuclear symmetry

- Nucleon are located on the sites of face-centered cubic lattice.
- Nuclei with a closure shells has a shape of tetrahedron (s-shell) and truncated tetrahadron/octahadron (p, d, f, …-shells).
- Nucleons are arranged in alternating (antiferromagnetic) spin, isospin layers.
- SCQM leads to Face-Centered-Cubic (FCC) Lattice symmetry of nuclear structure!

Face – Centered – Cubic Lattice Model (FCC)

(N. Cook, 1987)



FCC Lattice Model

Particle in 3D box

$$-(h^2/2m)(d^2\Psi/dr^2) + V(r)\,\Psi(r) = E\,\Psi(r)$$

For harmonic oscillator potential cartesian coordinate system

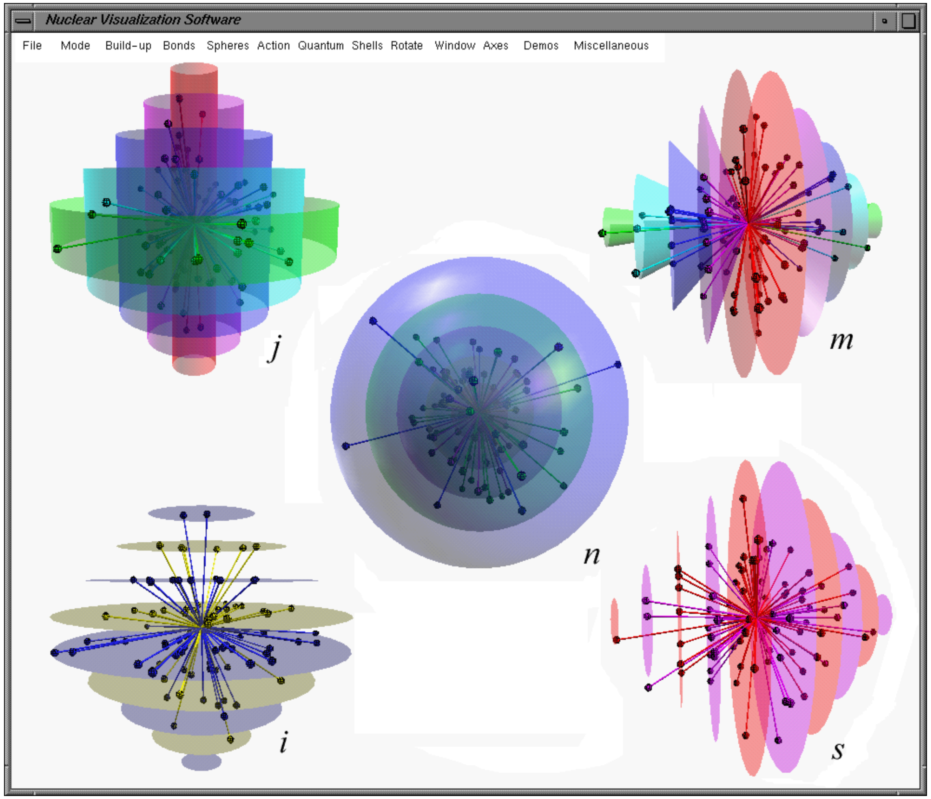
$$E_N = h\omega_0(n_x + n_y + n_z + 3/2) = h\omega_0(N + 3/2)$$

$$N = 0, 1, 2, 3, \ldots$$

Different combinations of $\mathbf{n_x}$, $\mathbf{n_y}$ and $\mathbf{n_z}$ that give the same total **N** – value denote spatially distinct " degenerate" states, with the same energy.

If the origin of the coordinate system is taken as the center of the central tetrahedron, then the closure of each consecutive, symmetrical (x=y=z) geometrical shell in the lattice composes precisely the numbers of nucleons in the shells derived from the three-dimensional Schrodinger equation.

Face – Centered – Cubic Lattice



$$\mathbf{n} = (x + y + z - 3)/2 = (r \sin\theta \cos\phi + r \sin\theta \sin\phi + r \cos\theta - 3) / 2$$

$$\mathbf{j} = l + s = (x + y - 1) / 2 = (r \sin\theta \cos\phi + r \sin\theta \sin\phi - 1) / 2$$

$$\mathbf{m} = x / 2 = (r \sin\theta \cos\phi) / 2$$

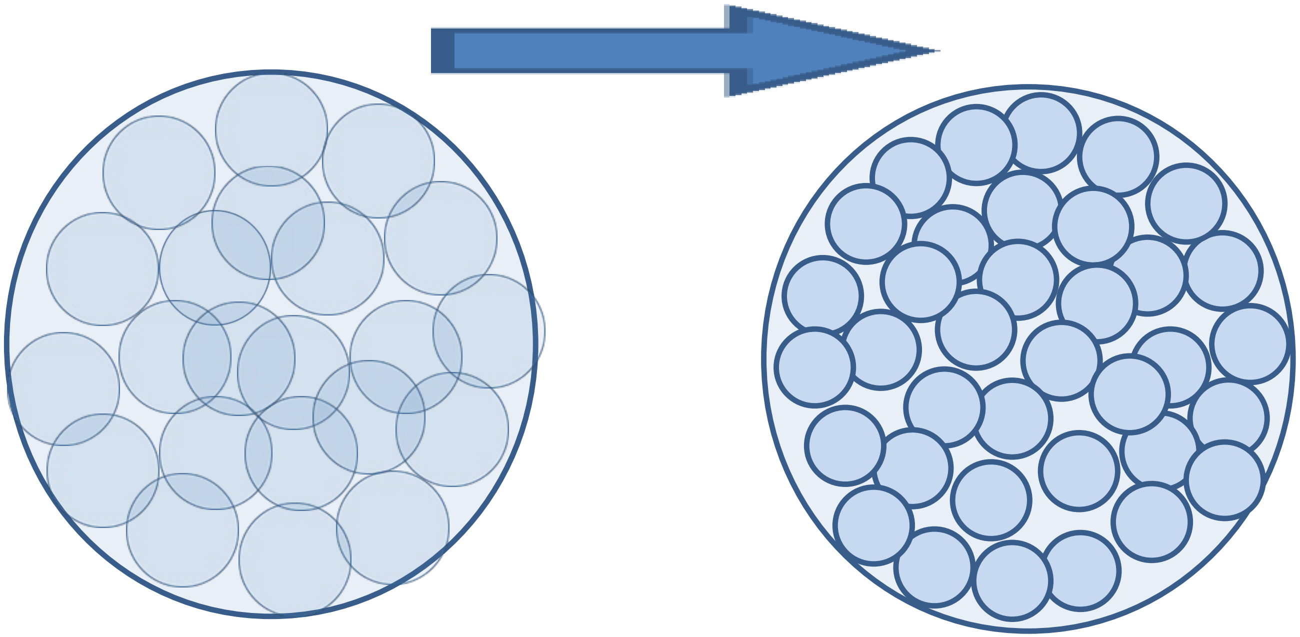
Resume on Nucleus structure

1. Quarks play an explicit role in formation of the nuclear structure.
2. Quarks and nucleons inside nuclei are correlated.
3. Quark loops are building blocks of nuclear binding.
4. Quark loops are the sources of the **pairing effect**.
5. Close **link between the nodes of a lattice** with **quantum numbers** of **Shell Model**.
6. **Nuclei possess crystal-like structure**:
   - Nucleon centers are arranged according to FCC lattice
   - Even-even nuclei are composed of **virtual α-clusters**
   - Closed Shells ≡ Octahedral Faces
   - All nuclei are deformed, even with shell closure!
7. 'Halo' nuclei **– fruits of quark-loop bindings**

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

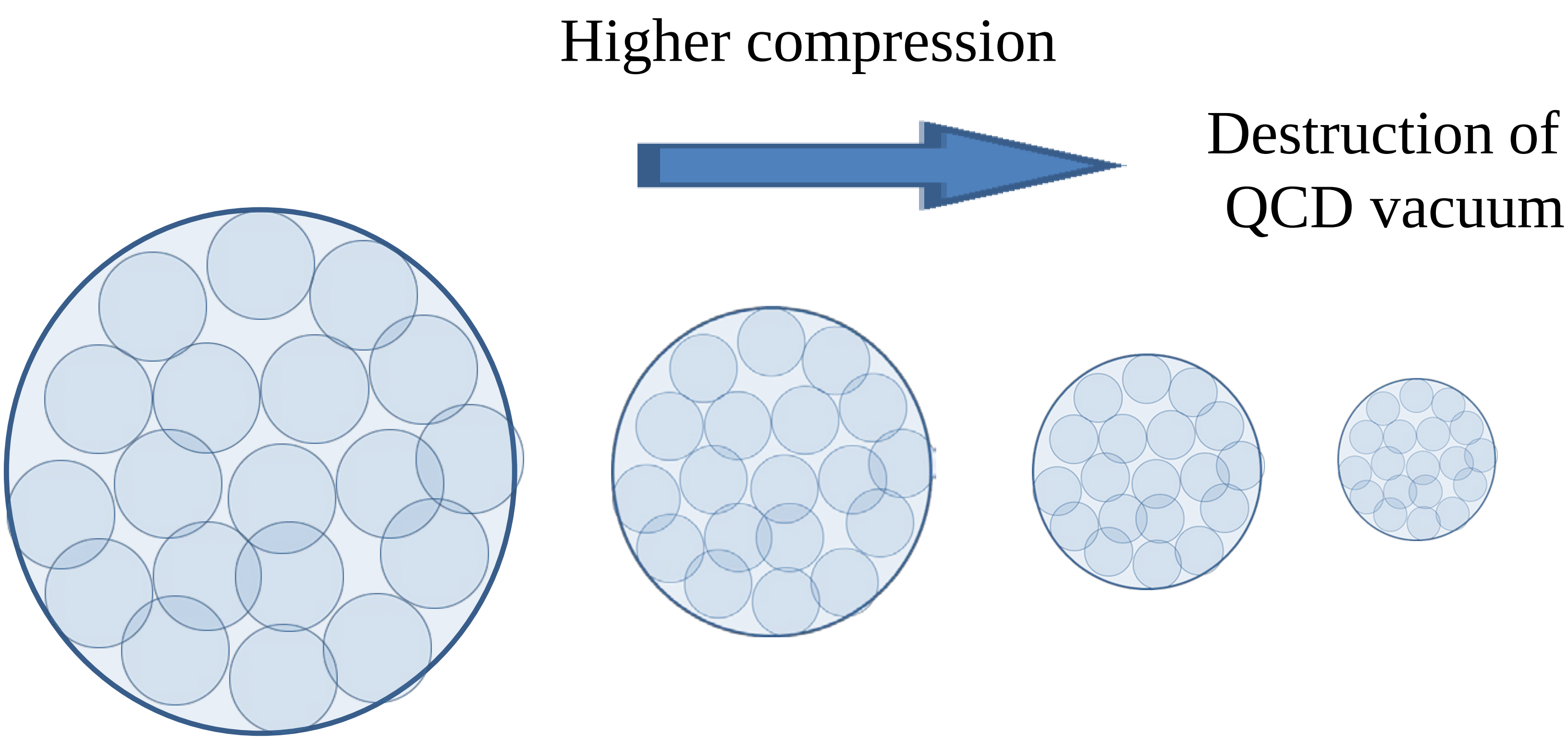
Higher compression



Destruction of QCD vacuum in intersection volume

Hadron modifications in a dense nuclear matter

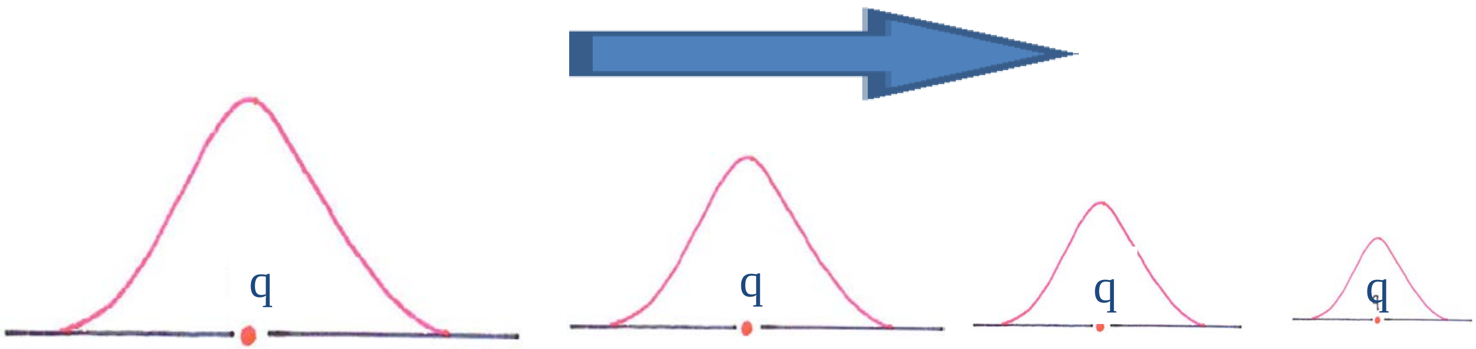
1. Baryonic matter under compression



Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression

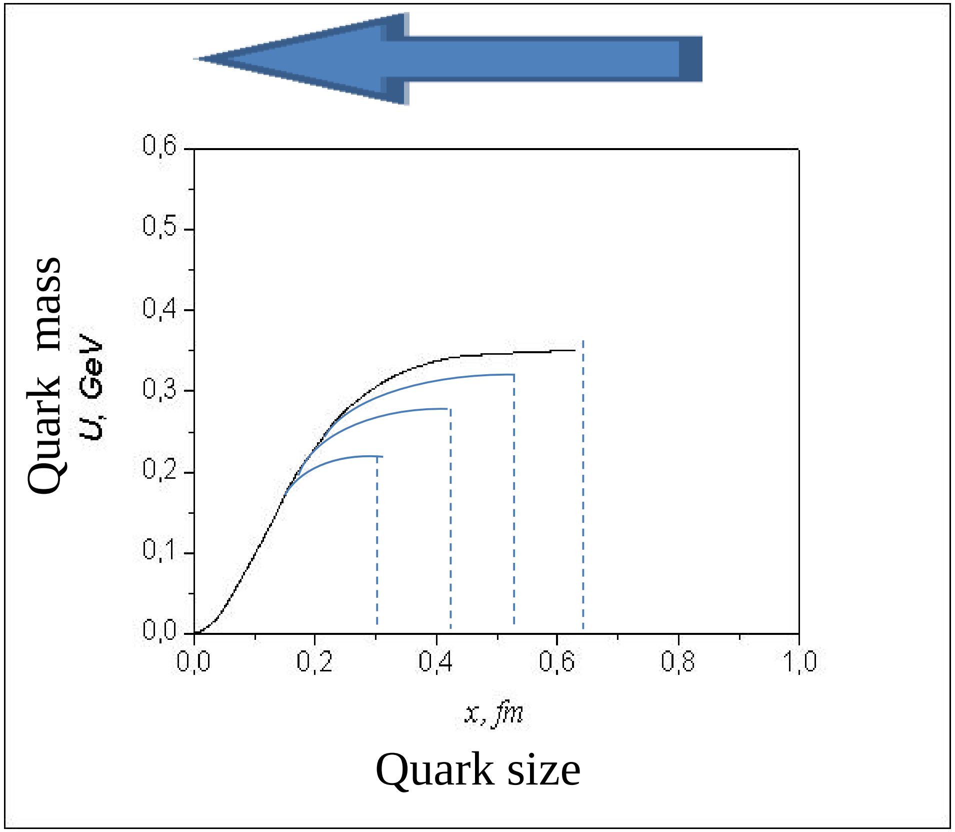


Quark color field

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression



Decreasing quark/nucleon dimension

Decreasing quark/nucleon mass

Nucleons may collapse after all!

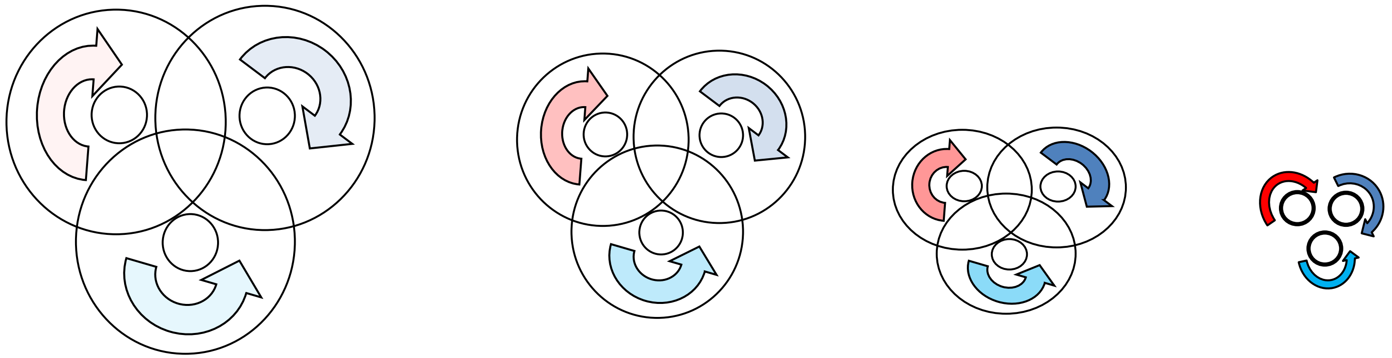
Scenario to avoid collapse

Higher compression

Hadronic liquid

$$n, p \Rightarrow \Delta$$

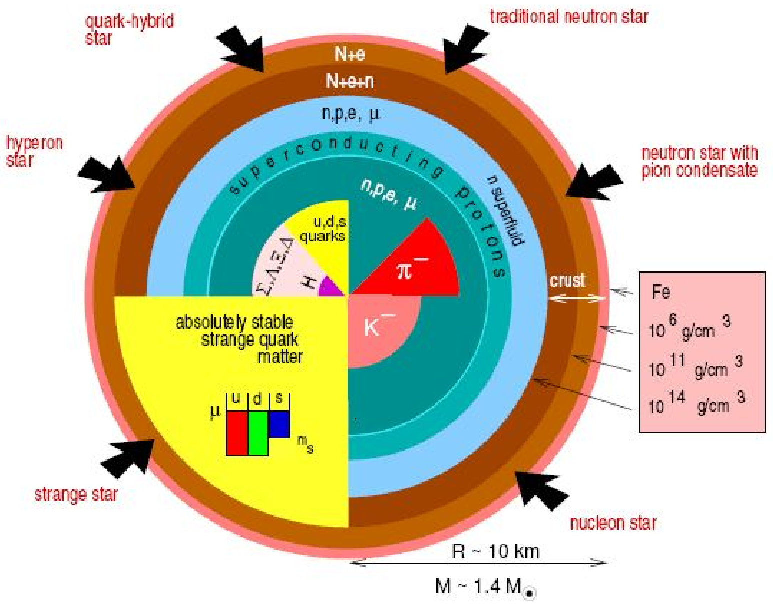
$$u, d \Rightarrow s, c, \ldots \quad n, p \Rightarrow \Lambda, \Sigma, \Xi, \Omega, \ldots$$



Neutron star

Gravitational compression

NS core



compression

Neutrons?

Δ- isobars

Hyperons

...

Hadron modifications in a dense nuclear medium

1. Hadronic matter at high density and temperature

Particle production in a hot and dense fireball

- π–production is suppressed
- vector mesons: $\rho, \omega, \varphi, K^{*}, \ldots$ - incompressible (effective cores)
- ρ, ω – ‘**melting**’: mass dropping and width-widening;
  dilepton spectra
- Fireball ‘cooling’ → increased π – yield

Hadrons in a high dense and temperature medium

Model Consequences

1. **Baryons** transform to isobars then to hyperons
2. **π–production** is suppressed
3. Particle generation inside hot and dense fireball is realized mainly via **vector mesons** $\boldsymbol{\rho, \omega, \varphi, K^*}$**, …**
4. $\boldsymbol{\rho, \omega}$ – '**melting**': mass dropping and width-widening;

5. **Fireball evolution:**

   Hadron-Resonance Liquid → Hadron-Resonance Gas

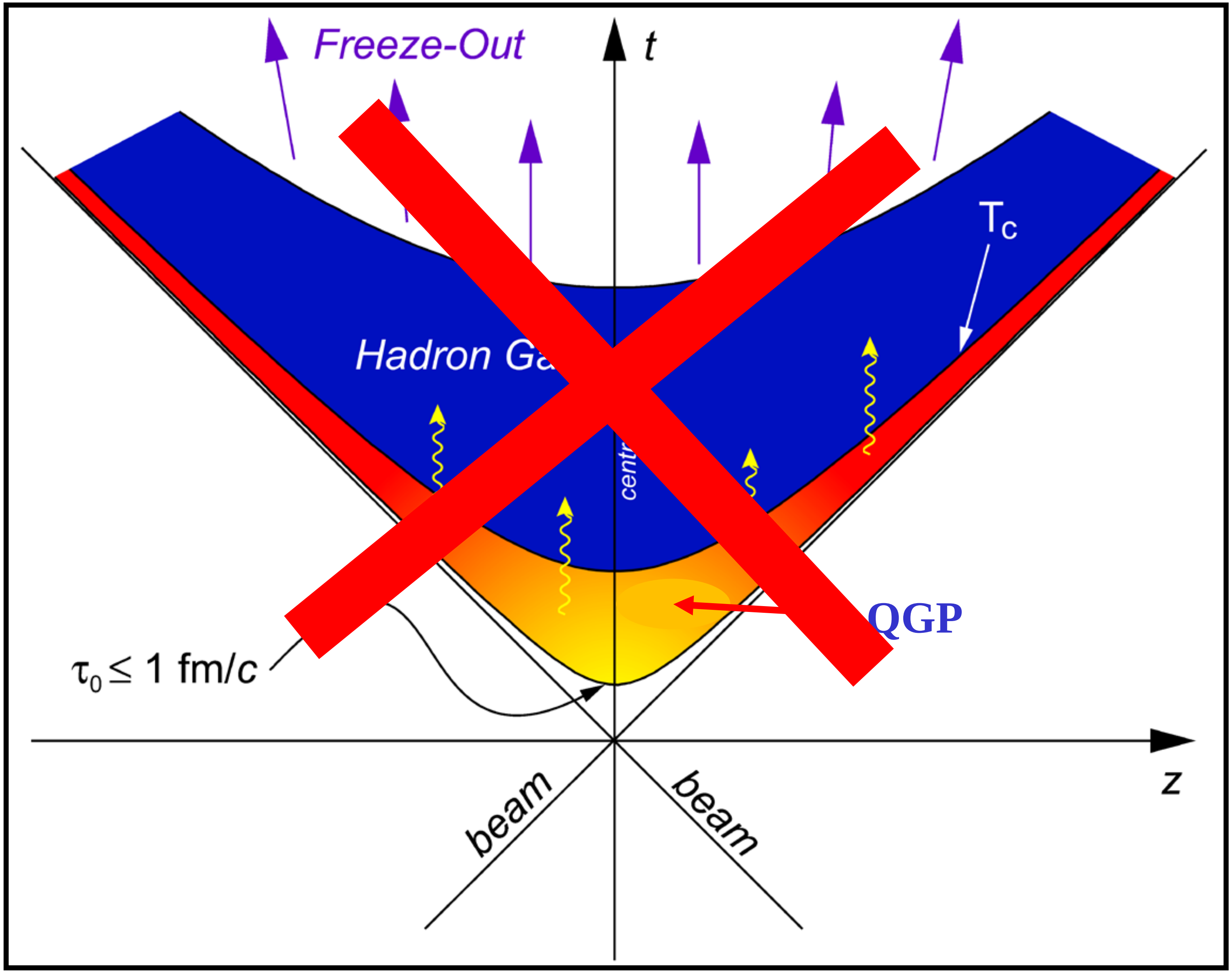
Hadrons in a high dense and temperature medium

1. **Hadrons – topological solitons?**

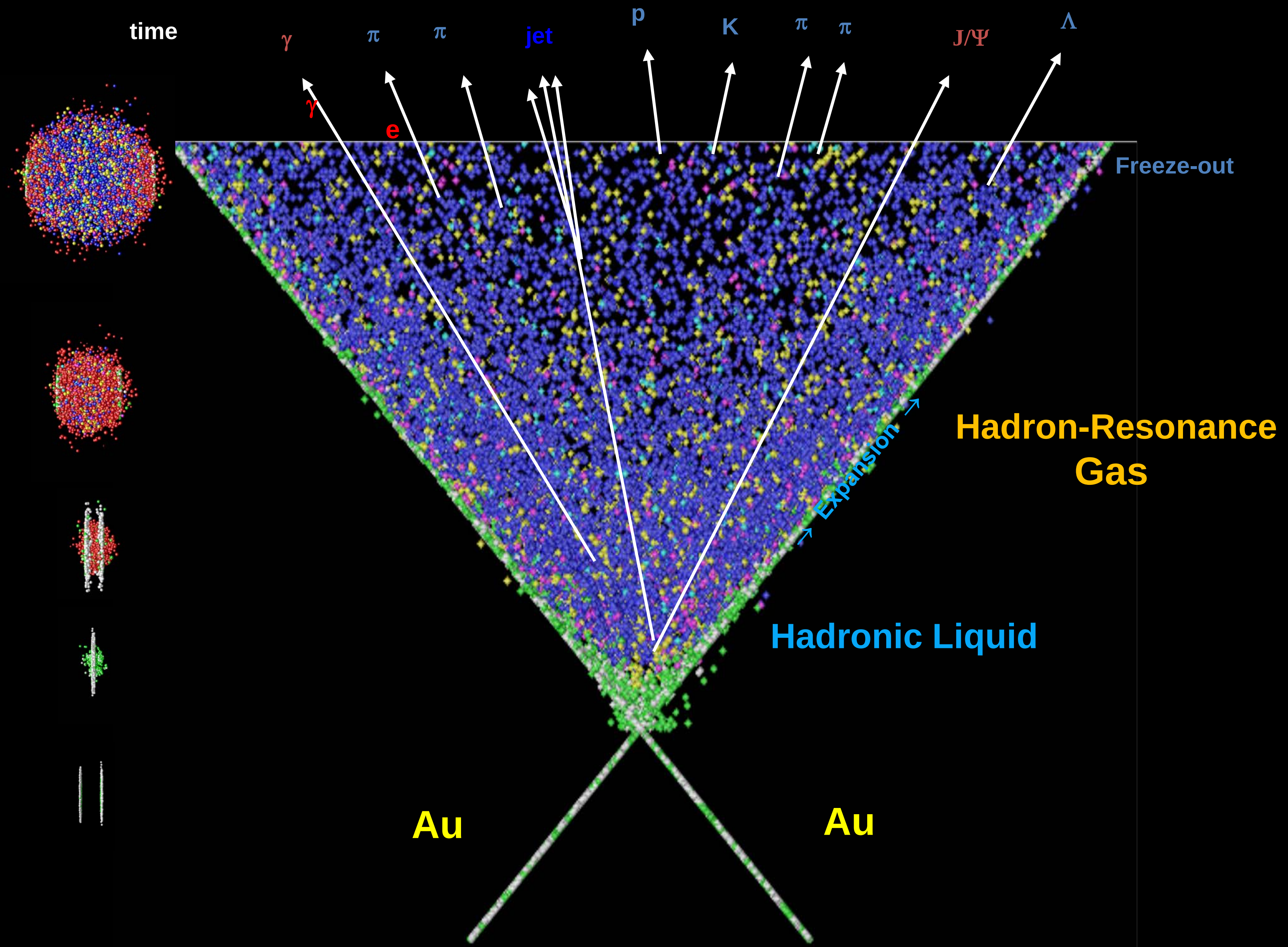
2. Conservation of topological charge

3. Deconfinement **is forbidden** → no room for QGP

Space-time Evolution of HIC



Space-time Evolution of HIC



Experiments

Energy range: $\sqrt{s} = 3 - 11$ *GeV* ***most interesting!***

- **Enhanced yield of K^+, φ, (multi)strange baryons**

experiments: KaoS, AGS, NA49 at low energies of SPS

- **Horn-effect – irregular behaviour of K^+/π^+**

experiments: NA49, STAR (BES RHIC)

- **Dilepton production**

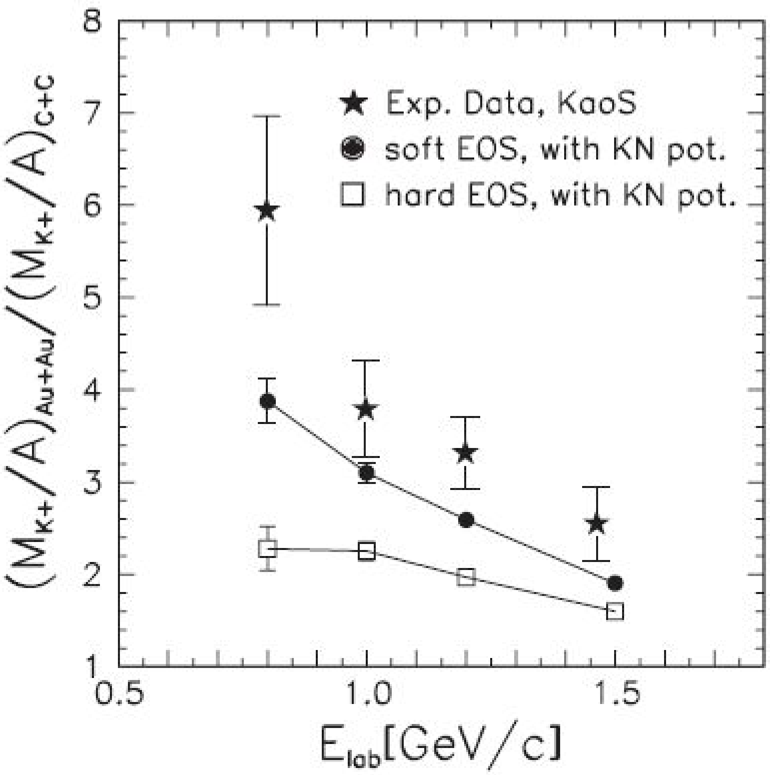
experiments: DLS, HADES, CERES, PHENIX

- **Projects:** FAIR/CBM, NICA/MPD, BM&N

Enhanced yield of K^+ in subthreshold kaon production

KaoS at SIS

Transport models with NN-interactions
- **underestimate yield of K^+ by a factor of 6**
- **overestimate yield of K^-**



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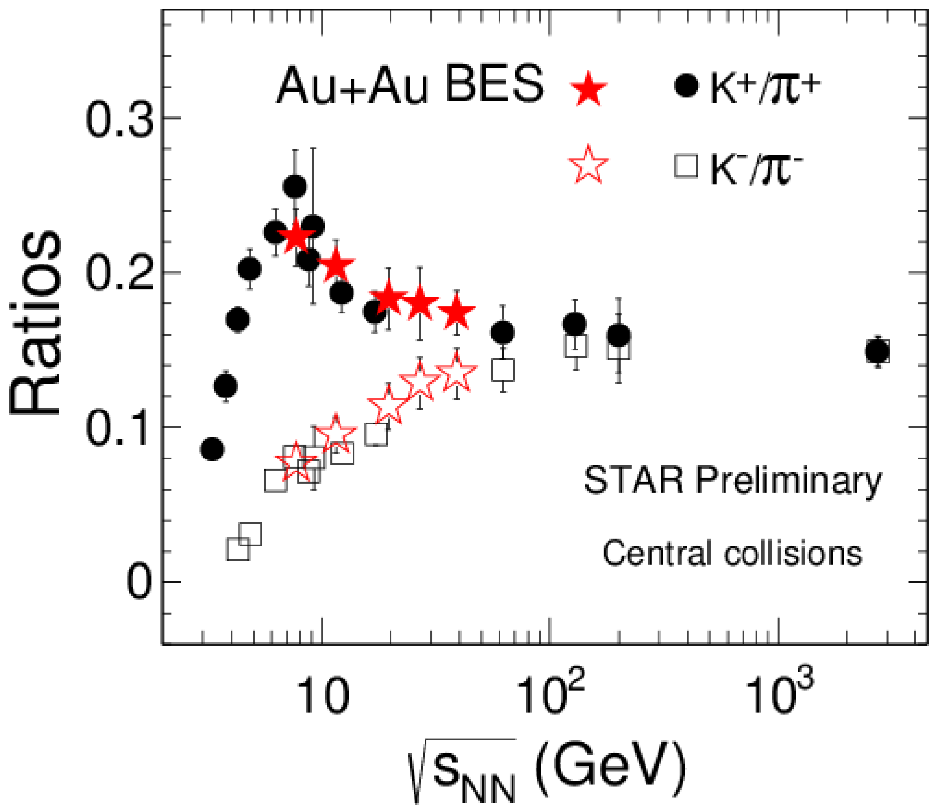
RQMD:
- K^+ N repulsive potential
- K^- N attractive potential
- Momentum dependent Skyrme forces
- Compression parameter
  - ✓ soft ~ 200 MeV
  - ✓ hard ~ 380 MeV

Enhansement of stangeness

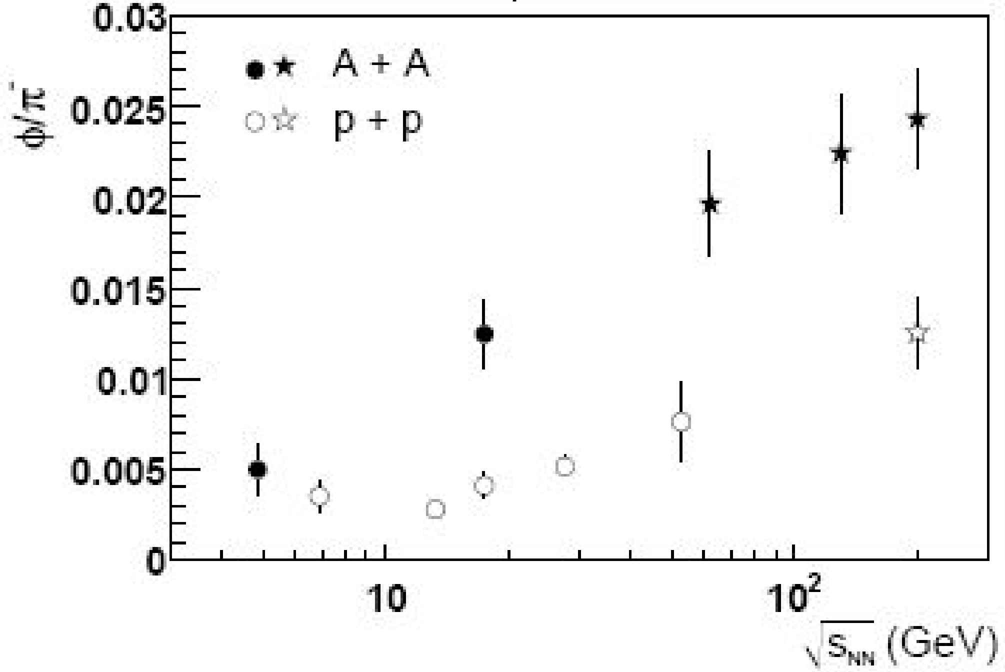
- Clear evidence for "horn" structure in K^+/π^+ at ~30 A GeV !
- Non-horn structure in K^-/π^-



Enhancement of strangeness

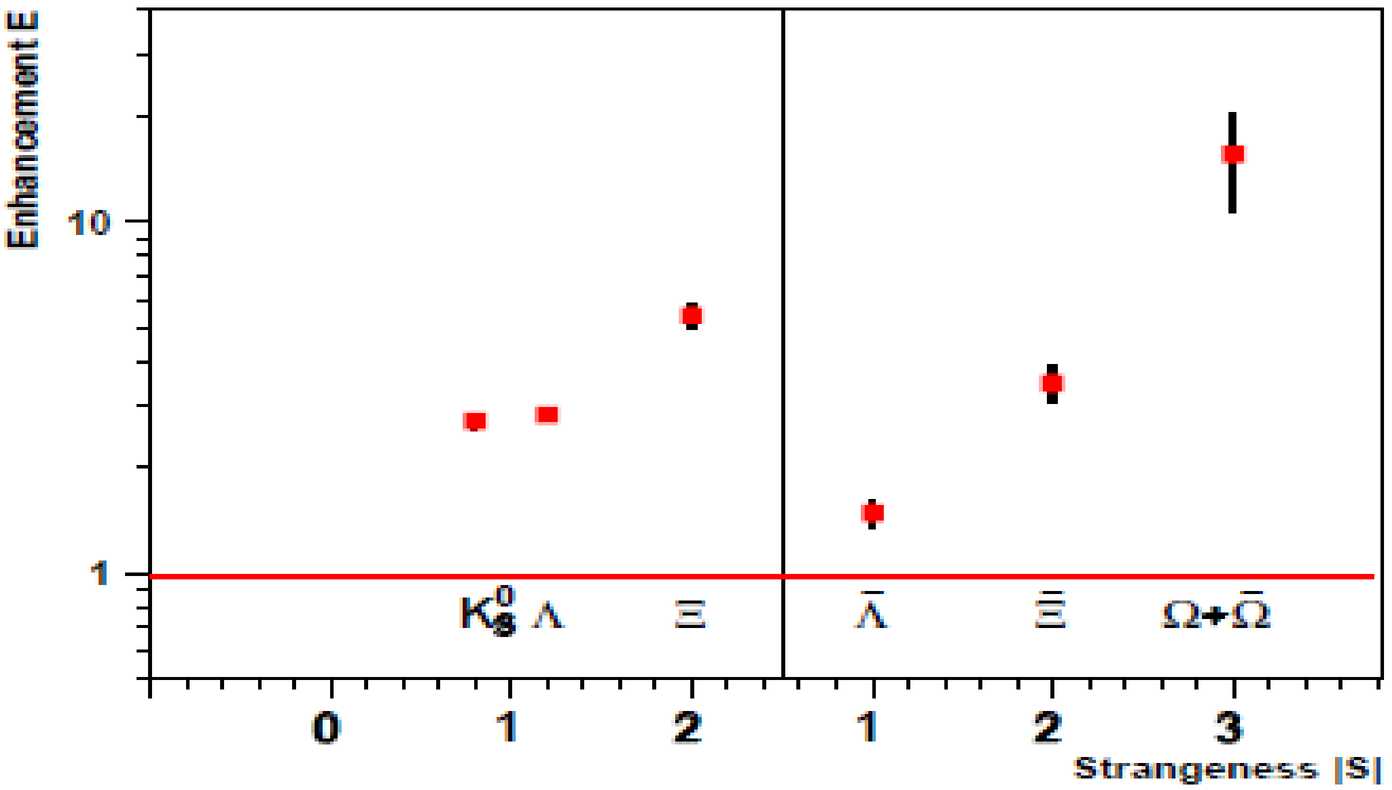
φ-mesons

φ/π⁻



Enhanced yield of hyperons

PbPb vs pBe SPS



Thank you for your attention!