Spin alignment in ultra-relativistic heavy ion collisions

J. Magnin

CBPF - Brazilian Center for Research in Physics

Rio de Janeiro - Brazil

Outline

- Quark-Gluon-Plasma
  - What the QGP is ?
  - How to produced QGP ?
- Spin alignment
  - Experimental results
  - A model for spin alignment
- Conclusions

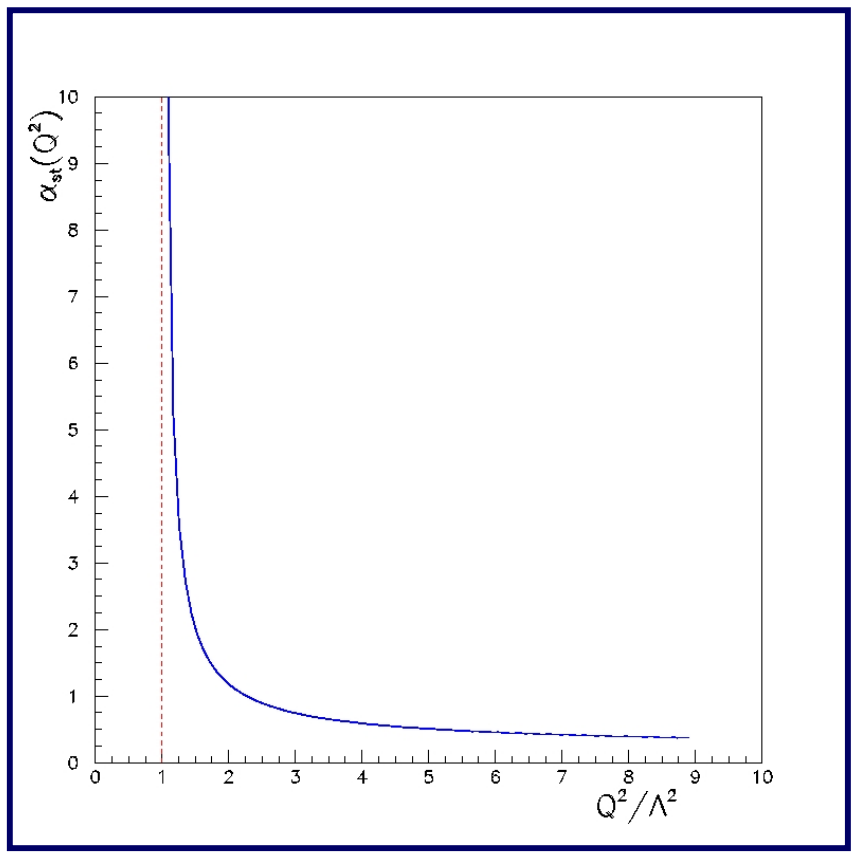
Quark-Gluon-Plasma

What Quark-Gluon-Plasma is ?

Asymptotic freedom

QCD has the property that the coupling constant goes to zero as the inverse of the logarithm of the energy scale:

$$\alpha_s\left(Q^2\right)=\frac{12\pi}{\left(33-2n_f\right)\ln\left(Q^2/\Lambda^2\right)}$$



Consequently:

• In hard processes (large Q^2) we can treat quarks and gluons as if they were free (non-interacting) entities.

• At a low Q^2 $\alpha\left(Q^2\right)$ is large and perturbative calculations are not allowed (soft processes).

Consequently:

• In hard processes (large Q^2) we can treat quarks and gluons as if they were free (non-interacting) entities.

• At a low Q^2 $\alpha(Q^2)$ is large and perturbative calculations are not allowed (soft processes).

Examples:

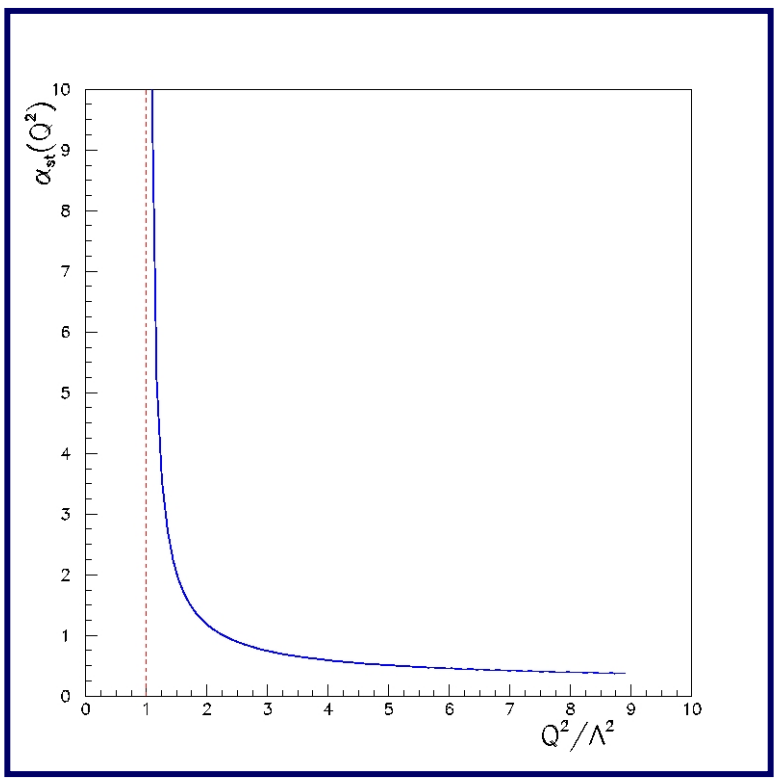
• DIS is a hard process

• Low energy properties of hadrons (mass spectrum, resonance widths, etc) are soft processes

Consequently:

• In hard processes (large Q^2) we can treat quarks and gluons as if they were free (non-interacting) entities.

• At a low Q^2 $\alpha\left(Q^2\right)$ is large and perturbative calculations are not allowed (soft processes).



Also, using that $\Delta p \Delta x \sim 1$

Large Q^2 → small distances

Small Q^2 → large distances

What if we include the temperature (T) into the game ?

What if we include the temperature (T) into the game ?

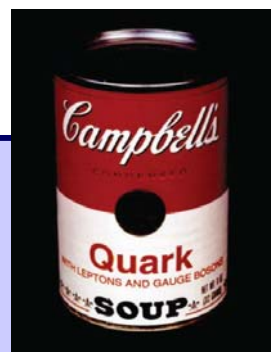
It can be demonstrated that if T is large enough, $\alpha(T^2) \sim 1/\ln(T^2/\Lambda^2)$ (See e.g. M. Chaichian, Acta Physica Polonica B27, 1703 (1996))

What if we include the temperature (T) into the game ?

It can be demonstrated that if T is large enough, $\alpha(T^2) \sim 1/\ln(T^2/\Lambda^2)$ (See e.g. M. Chaichian, Acta Physica Polonica B27, 1703 (1996))

At T ~ 150 – 175 MeV

Soup of free quarks and gluons



Energy as a unit of temperature

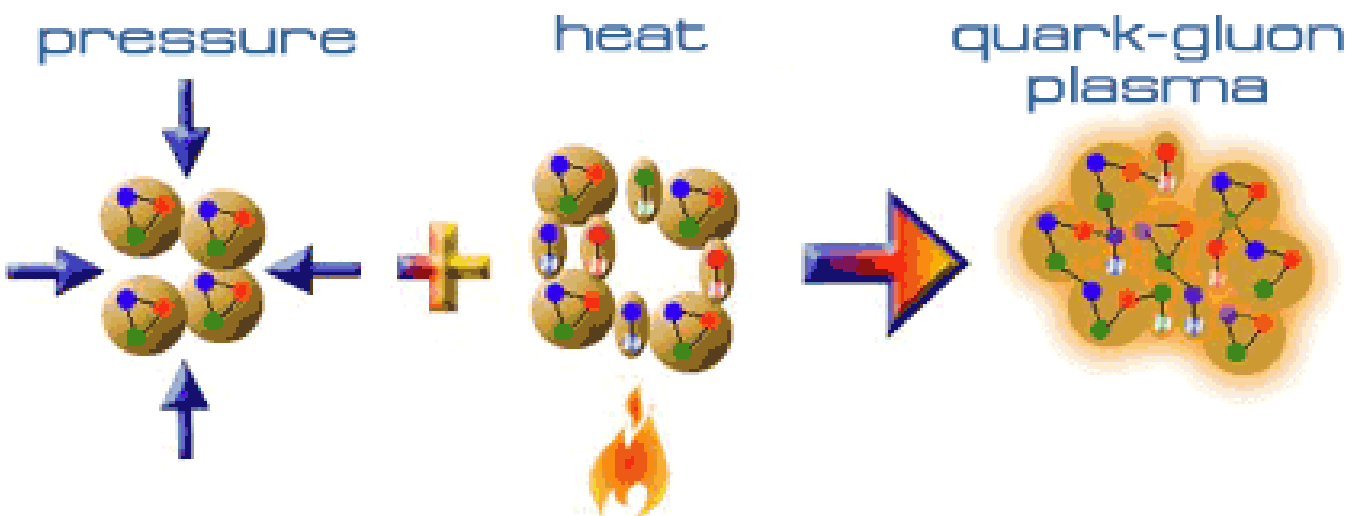
$$\frac{1\ \text{eV}}{k_B} = \frac{1.60217653 \times 10^{-19}\ \text{J}}{1.3806505 \times 10^{-23}\ \text{J/K}} = 11604.505\ \text{K}$$

150 – 175 MeV ~ (1.7 – 2.0) x 10^{12} K

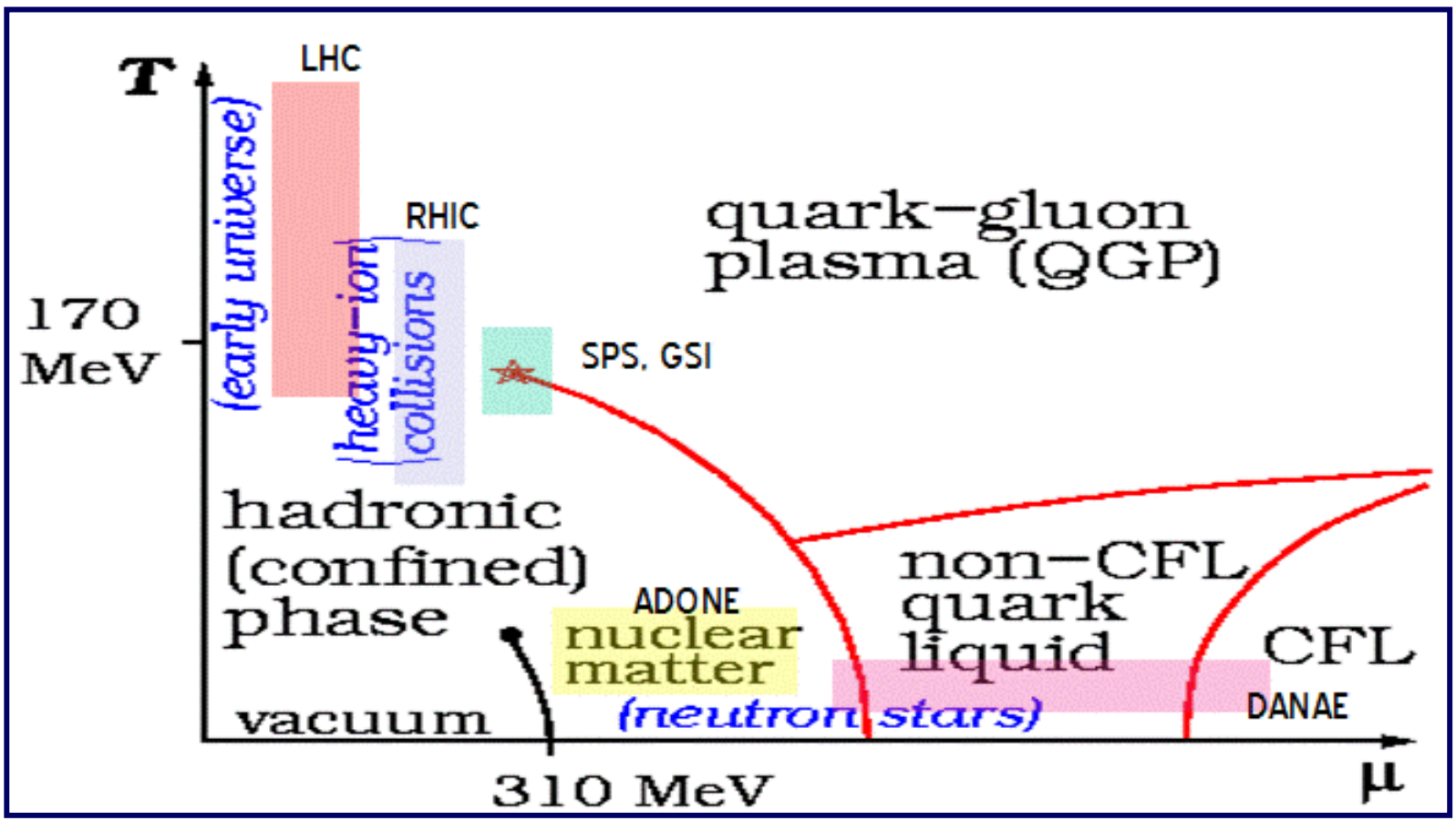
At T ~ 150 - 175 MeV

Soup of free quarks and gluons

The same effect can be obtained by increasing the pressure, P, or equivalently, by increasing the density at a constant volume

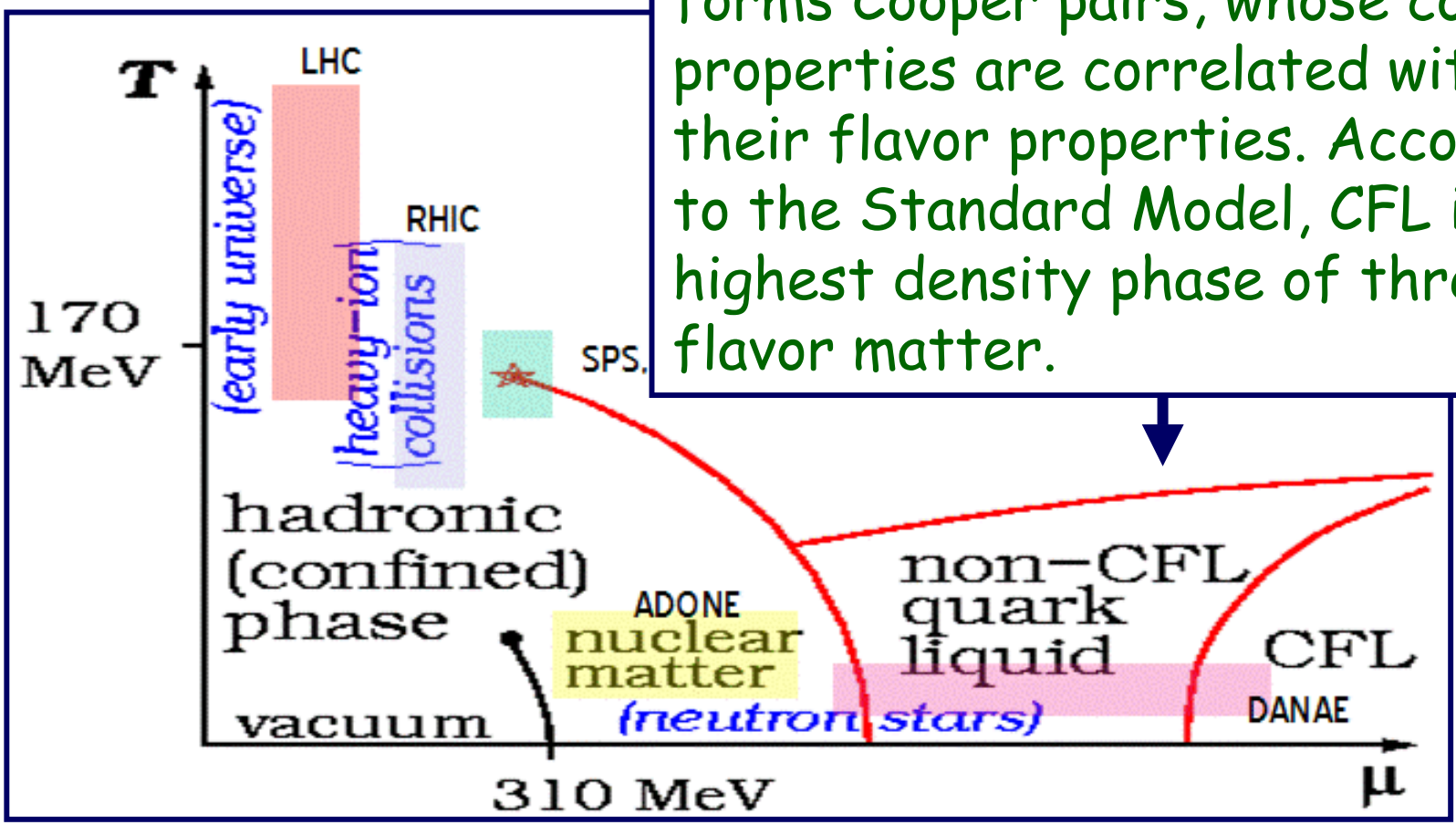


The phase transition of QCD

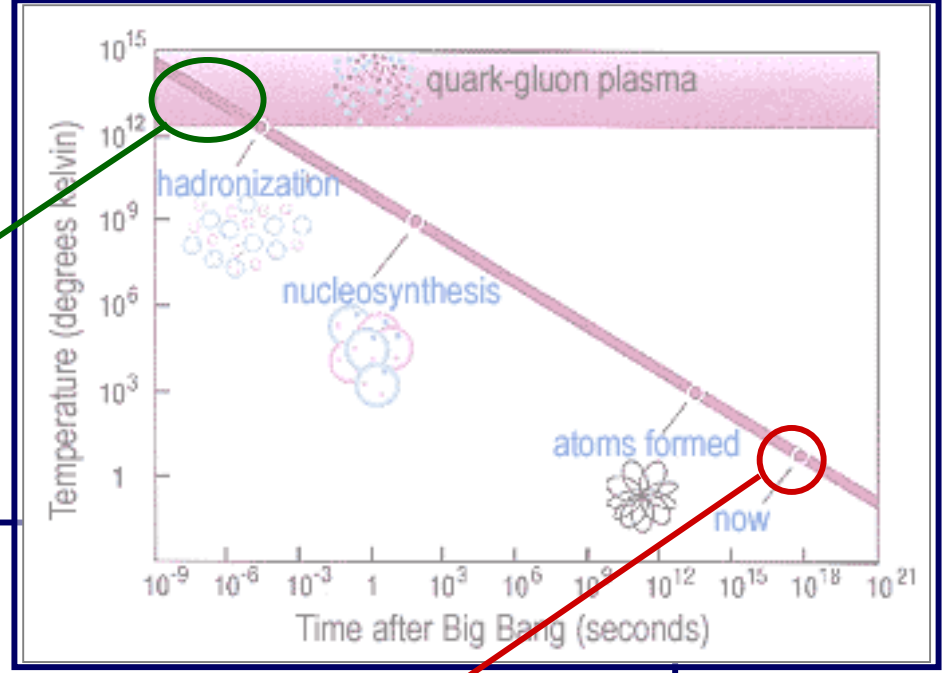


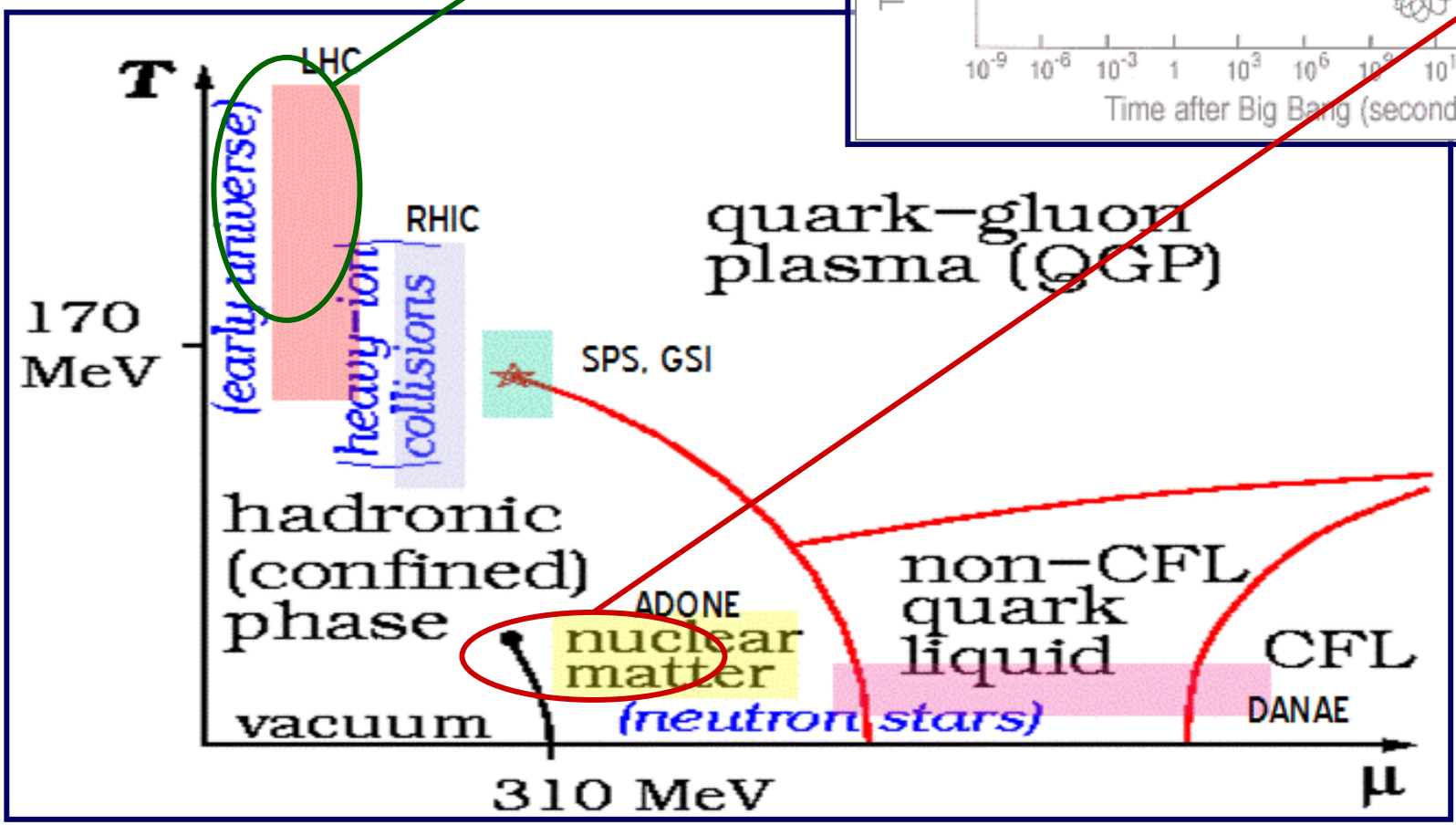
The phase transition of QCD

Color-Flavor-Locking (CFL): quarks forms Cooper pairs, whose color properties are correlated with their flavor properties. According to the Standard Model, CFL is the highest density phase of three flavor matter.



The phase transition of QCD

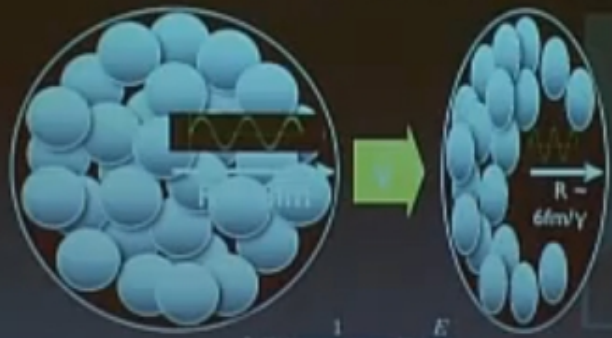




How to produce QGP (in laboratory)

- **Heavy ion collisions**:
  - heavy ions = atoms (heavy) with their outer cloud of electrons removed.
  - if conditions are right, the collision melts protons and neutrons liberating their constituent quarks and gluons.
  - right after the collision the energy density is so high that the plasma is produced.
  - as the plasma cools quarks and gluons start to group in hadrons.

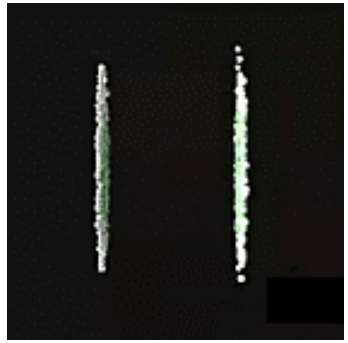
"Lorentz Contraction"

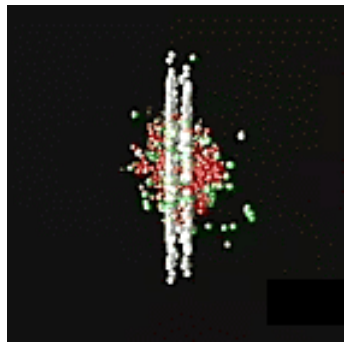


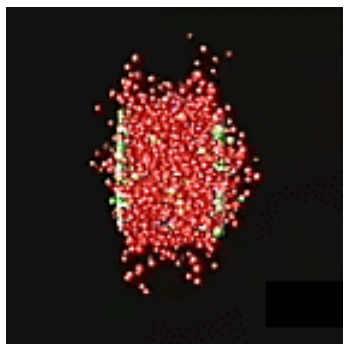
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{E}{mc^2}$$

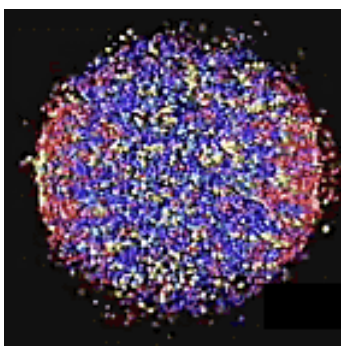
Objects with v~c appear "contracted"

At RHIC, we accelerate gold ions to 99.995% of the speed of light -- a ~100x compression!









1 fm = 10^{-15} m

How much energy in each collision?

$$1.6 \times 10^{-19} \frac{J}{eV} \times 197 \times 200GeV \sim 6\mu J$$

Consider two mosquitos colliding...

$$2 \times \frac{1}{2} mv^2 = (2.5mg) \times (2.5km/h)^2 = 1.2\mu J$$

Spin alignment

Experimental results

PHYSICAL REVIEW C 77, 061902(R) (2008)

Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

Star Collaboration

We present the first spin alignment measurements for the $K^{*0}(892)$ and $\phi(1020)$ vector mesons produced at midrapidity with transverse momenta up to 5 GeV/c at $\sqrt{s_{NN}} = 200$ GeV at RHIC. The diagonal spin-density matrix elements with respect to the reaction plane in Au + Au collisions are $\rho_{00} = 0.32 \pm 0.04$ (stat) $\pm$ 0.09 (syst) for the K^{*0} ($0.8 < p_T < 5.0$ GeV/c) and $\rho_{00} = 0.34 \pm 0.02$ (stat) $\pm$ 0.03 (syst) for the ϕ ($0.4 < p_T < 5.0$ GeV/c) and are constant with transverse momentum and collision centrality. The data are consistent with the unpolarized expectation of 1/3 and thus no evidence is found for the transfer of the orbital angular momentum of the colliding system to the vector-meson spins. Spin alignments for K^{*0} and ϕ in Au + Au collisions were also measured with respect to the particle's production plane. The ϕ result, $\rho_{00} = 0.41 \pm 0.02$ (stat) ± 0.04 (syst), is consistent with that in $p+p$ collisions, $\rho_{00} = 0.39 \pm 0.03$ (stat) ± 0.06 (syst), also measured in this work. The measurements thus constrain the possible size of polarization phenomena in the production dynamics of vector mesons.

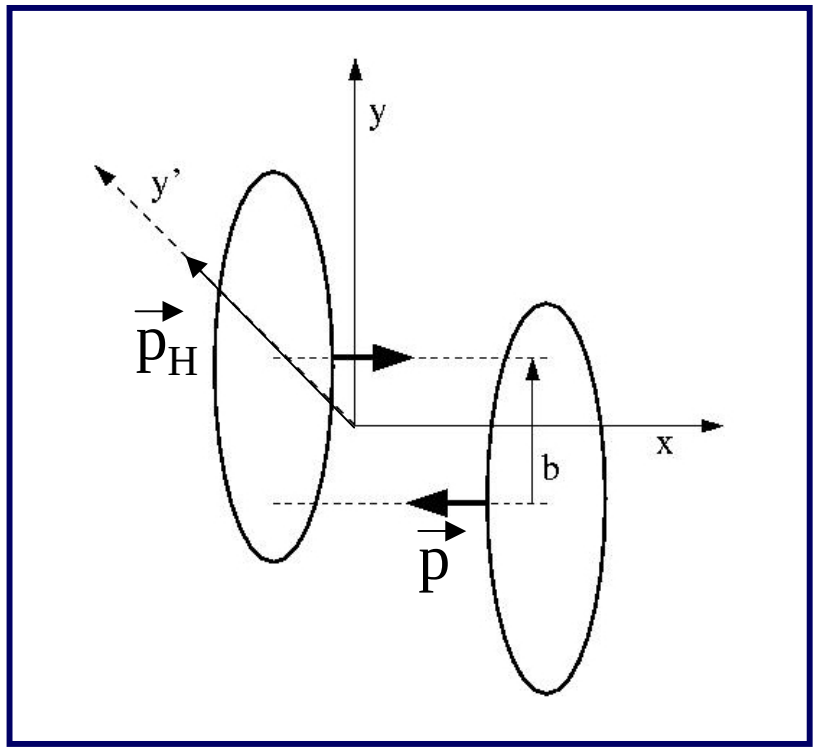
See also Star Collaboration, J. Phys. G: Nucl. Part. Phys. 35, 044068 (2008); J. Phys. G: Nucl. Part. Phys. 34, S331 (2007)

Reaction plane:

$$\vec{n}_b = \frac{\vec{p} \times \vec{b}}{|\vec{p} \times \vec{b}|}$$

Production plane:

$$\vec{n}_H = \frac{\vec{p} \times \vec{p}_H}{|\vec{p} \times \vec{p}_H|}$$

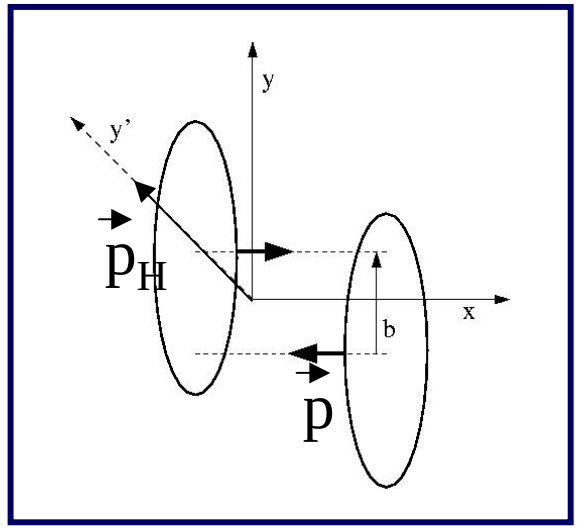


Spin alignment:

- described by a spin-density matrix ρ
- ρ = Hermitian matrix with unit trace
- deviation of ρ_{mm} (m = -1, 0, 1) from 1/3 signals net spin alignment
- vector mesons decay strongly, then diagonal elements ρ_{-1-1} and ρ_{11} are degenerate. ρ_{00} is the only independent observable

Vector mesons:

- formed by a quark and anti-quark
- spin 1 (m = -1, 0, 1)
- $K^{*0}(892) = d\bar{s}$
- $\phi(1020) = c_1(u\bar{u}) + c_2(d\bar{d}) + c_3(s\bar{s})$



ρ_{00} measured from the angular distribution of the decay products

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times [(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$

θ^* = angle between $\vec{n}_b$ ($\vec{n}_H$) and one of the decay products

Star results:

- K* and ϕ produced in $\sqrt{s_{nn}}$ = 200 GeV Au + Au collisions at RHIC
- $\vec{p}_T^{(K^*,\phi)} < 5$ GeV/c

w.r.t the reaction plane:

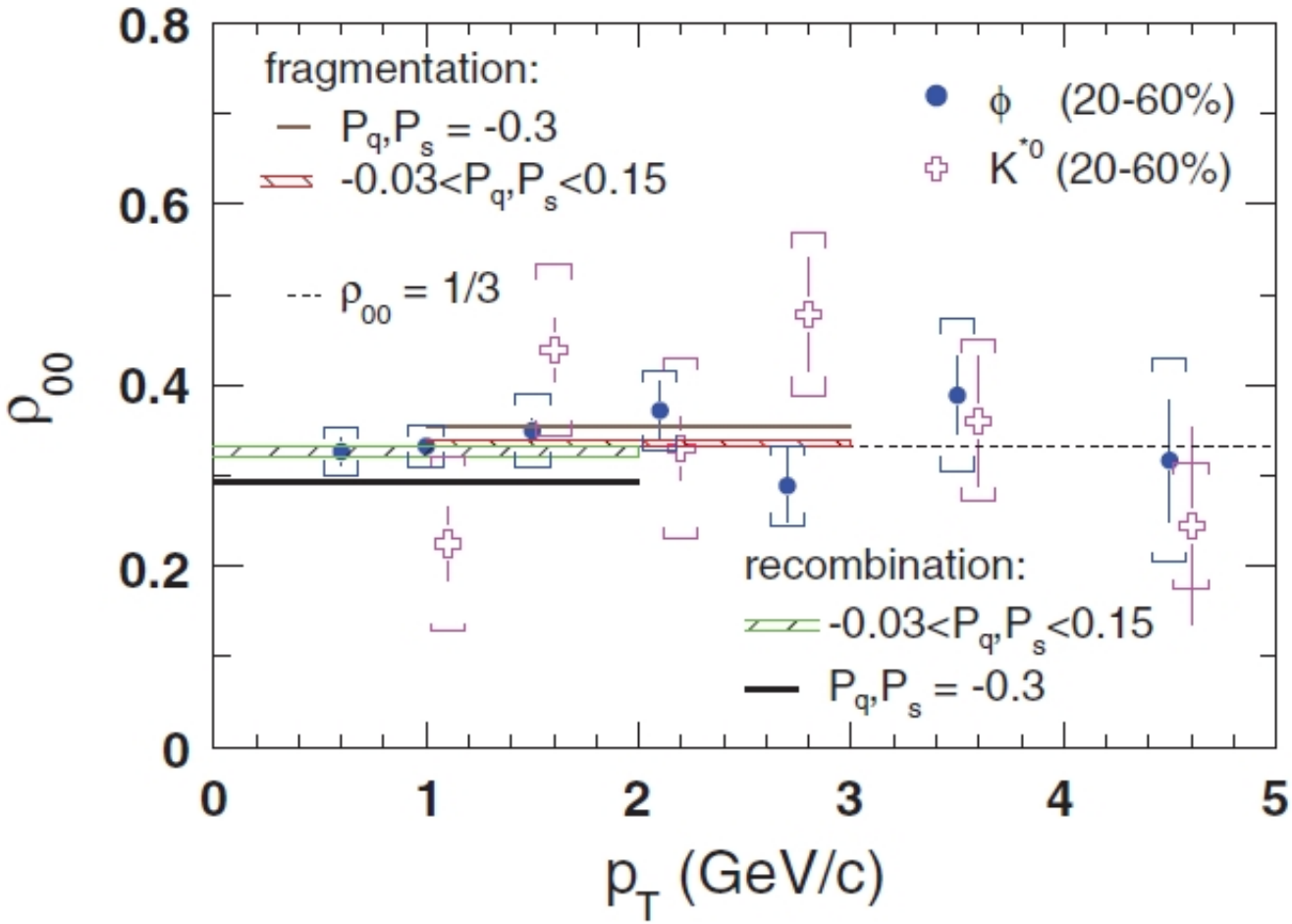
$K^{*0}(892) \rightarrow \rho_{00} = 0.32 \pm 0.04\ (stat) \pm 0.09\ (sys)$

$\phi(1020) \rightarrow \rho_{00} = 0.34 \pm 0.02\ (stat) \pm 0.03\ (sys)$

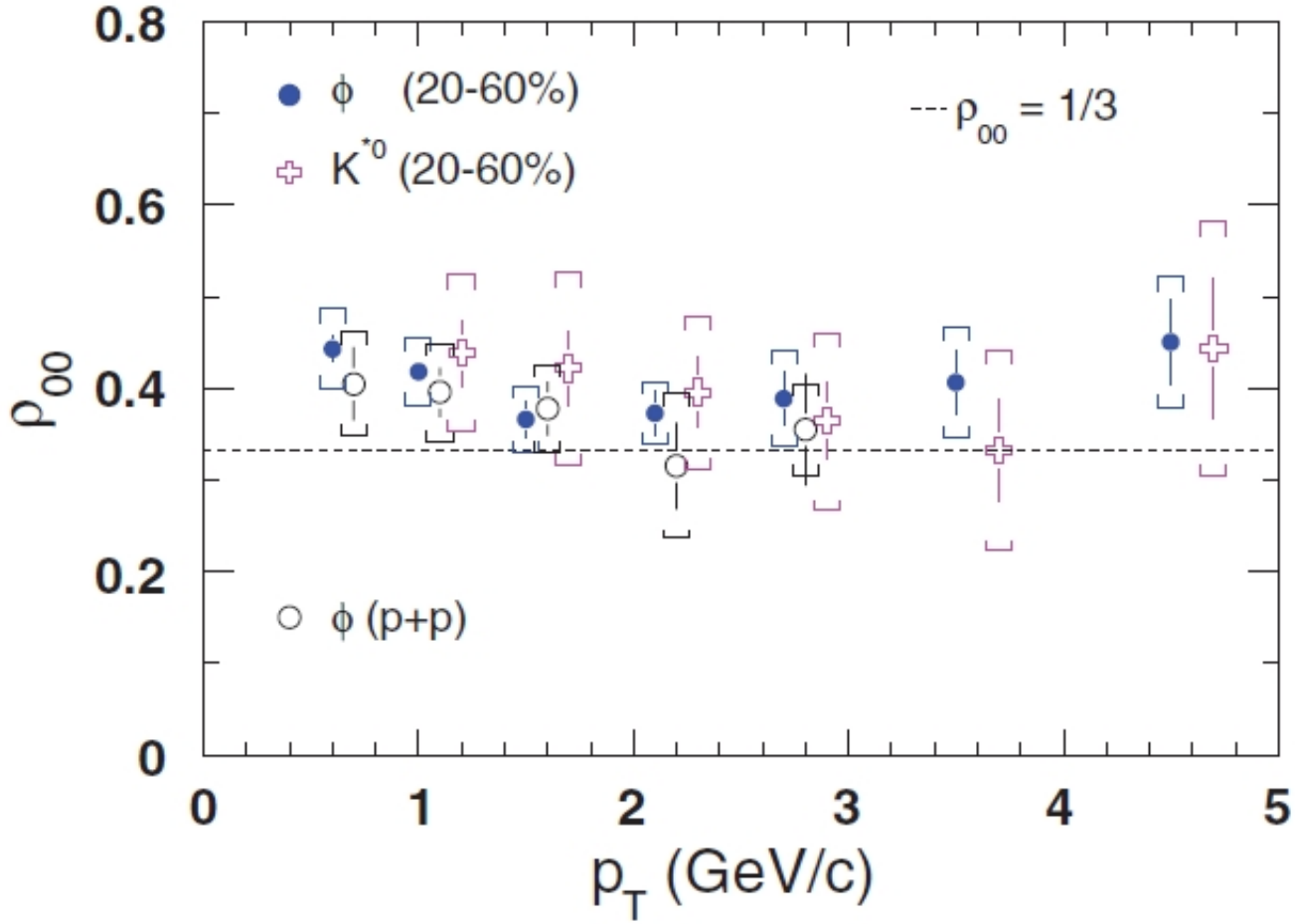
w.r.t the production plane:

$K^{*0}(892) \rightarrow \rho_{00} = 0.42 \pm 0.03\ (stat) \pm 0.09\ (sys)$

$\phi(1020) \rightarrow \rho_{00} = 0.41 \pm 0.02\ (stat) \pm 0.04\ (sys)$



ρ_{00} w.r.t. the reaction plane as a function of p_T (Phys. Rev. ***C77***, 061902R (2008)). Consistent with no net spin alignment.



ρ_{00} w.r.t. the production plane as a function of p_T (Phys. Rev. ***C77***, 061902R (2008)). Consistent with net spin alignment.

A model for spin alignment

ArXiV: 0906.4295

- Assume that quarks hadronize by recombination and,
- Assume that the spin of a quark is oriented in the hadronization process.

A model for spin alignment

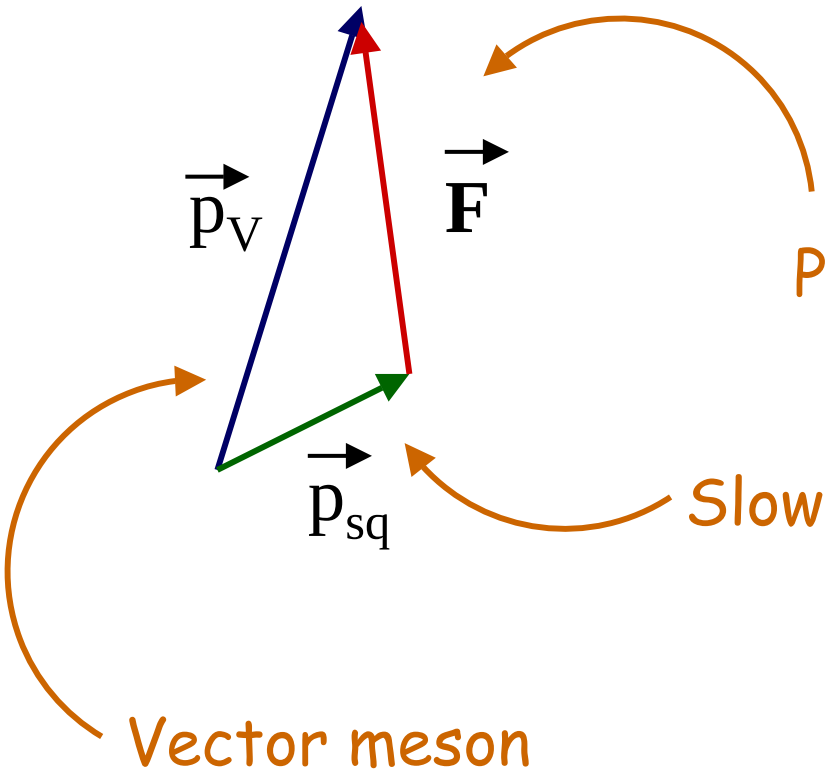
ArXiV: 0906.4295

- Assume that quarks hadronize by recombination and,
- Assume that the spin of a quark is oriented in the hadronization process.

Thomas precession: **(Phys. Rev. D24, 2419 (1981))**

✓ ***Slow quarks preferentially recombine with their spin down in the scattering plane***

✓ ***Fast quarks preferentially recombine with their spin up in the scattering plane***



$$\mathcal{H}_{int} = \vec{S} \cdot \vec{\omega}_T$$

s = slow
f = fast

Quark polarization

$$\mathcal{P}^{s,f} = \mp \frac{\omega_T^{s,f}}{\Delta E}$$

Thomas frequency

$$\boldsymbol{\omega}_T = \left(\frac{\gamma}{1+\gamma}\right) \mathbf{F} \times \boldsymbol{\beta}$$

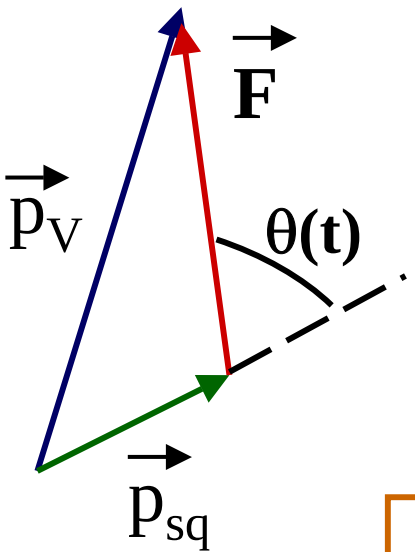
± because s and f quarks acquire opposite polarization

Main ingredients (I)

$$\mathbf{F} = \frac{\Delta \mathbf{p}}{\Delta t}$$

Change in momentum of the quark in the hadronization

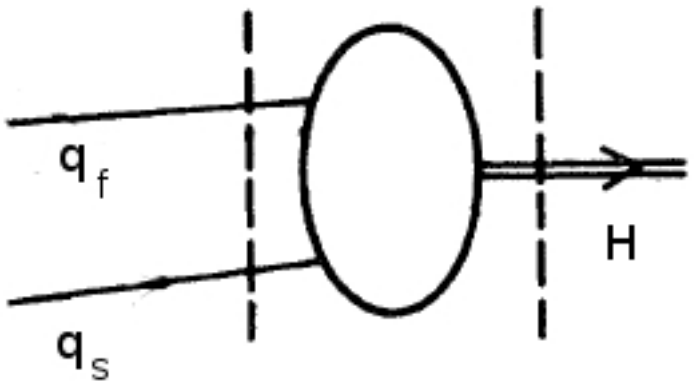
time for the hadron to be formed (~ 1fm)



$$\omega_T^{s,f} \propto \frac{\Delta p^{s,f}}{\Delta t}\beta^{s,f}\left(\int_{\Delta t} dt \sin\theta^{s,f}/\Delta t\right)$$
$$\simeq \frac{\Delta p^{s,f}}{\Delta t}\beta^{s,f}\langle\sin\theta\rangle^{s,f}$$

Main ingredients (II)

$$\mathcal{P}^{s,f} = \mp \frac{\omega_T^{s,f}}{\Delta E}$$



$$\Delta E = E_{qs} + E_{qf} - E_H$$

z = momentum fraction of the hadron wrt the fast quark,
$z = p^H/p_f$; $0 < z < 1$

y = rapidity of the hadron

$$\Delta E = \left\{ \left(\frac{1-z}{z} \right) p_\perp^H + \left[\frac{z(m^f)^2 - (m^H)^2}{2p_\perp^H} \right] + m^s \cosh y^H \right\}$$

main ingredients I + II = quarks polarized in the hadronization process

The spin of quarks and ρ_{00}

$$\rho^q = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix}$$

$$\rho^q \otimes \rho^{\bar{q}}$$

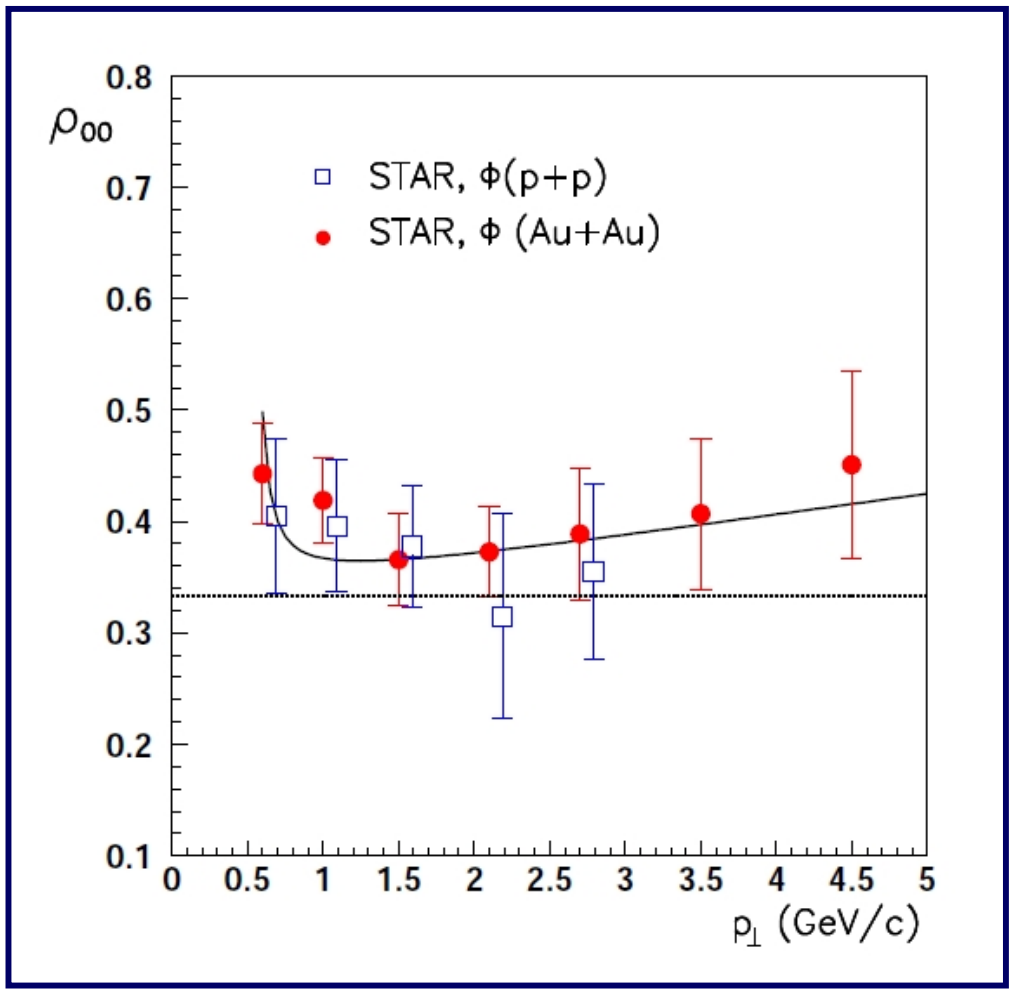
extract the spin 1 part

$$\rho^V = \begin{pmatrix} \frac{(1+P_q)(1+P_{\bar{q}})}{3+P_q P_{\bar{q}}} & 0 & 0 \\ 0 & \frac{1-P_q P_{\bar{q}}}{3+P_q P_{\bar{q}}} & 0 \\ 0 & 0 & \frac{(1-P_q)(1-P_{\bar{q}})}{3+P_q P_{\bar{q}}} \end{pmatrix}$$

$$\rho_{00} = \frac{1 - \mathcal{P}^s \mathcal{P}^f}{3 + \mathcal{P}^s \mathcal{P}^f}$$

ϕ is $s\bar{s}$, then is irrelevant which one is fast or slow

- ✓ m_ϕ = 1020 MeV
- ✓ m_s = 500 MeV
- ✓ Δt = 1 fm
- ✓ y^H = 1

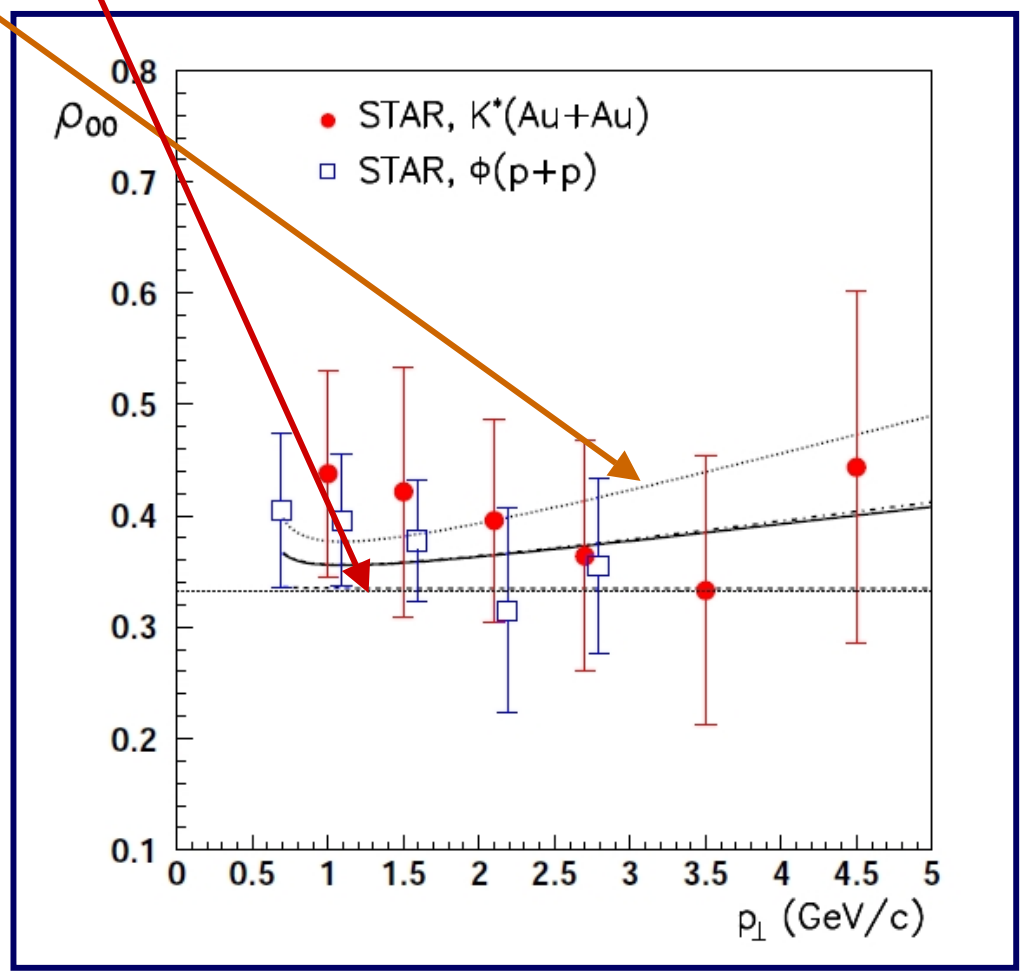


$$\rho_{00}^{K^*} = \frac{1}{2}\left(\rho_{00}^{f=\mathrm{s},\ s=\mathrm{d}} + \rho_{00}^{f=\mathrm{d},\ s=\mathrm{s}}\right)$$

$$\mathcal{P}^s\mathcal{P}^f \rightarrow \frac{\mathcal{P}^{s=\mathrm{s}}\mathcal{P}^{f=\mathrm{d}} + \mathcal{P}^{s=\mathrm{d}}\mathcal{P}^{f=\mathrm{s}}}{2}$$

$K^{*0} = \bar{s}d$

- ✓ m_{K*} = 892 MeV
- ✓ m_s = 500 MeV
- ✓ m_d = 300 MeV
- ✓ Δt = 1 fm
- ✓ y^H = 1



Conclusions

✓ Data on the vector mesons ϕ and K^{*0} spin alignment wrt the production plane are well described by the model in both, Au + Au and p + p interactions.

✓ The underlying hadronization mechanism is recombination of a slow and a fast quarks.

✓ Quark polarization is produced during the hadronization , at the quark level, by the Thomas precession mechanism.

✓ The momentum of the hadron provides a fixed direction which allows to define whether a quark accelerates or decelerates

✓ In the reaction plane there is no such fixed direction, since the impact parameter vector changes from one reaction to another, then $\rho_{00} = 1/3$ (no polarization)

The End