Quark-Gluon Plasma
and Heavy Ion Collisions

II – Collective effects, Hydrodynamics, Phenomenology

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General outline

- I : Physics of the QGP, Field theory at finite T
- II : Collective effects, Hydrodynamics, Phenomenology

Lecture II

- Collective phenomena
- Relativistic hydrodynamics
- Phenomenology

Collective phenomena in the QGP

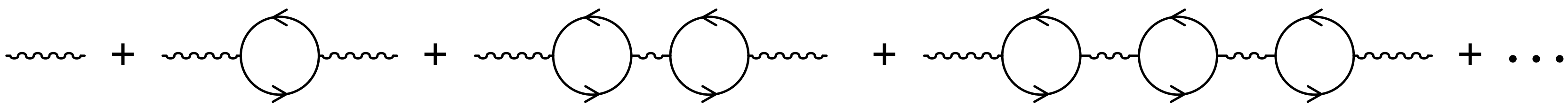
Collective phenomena

- Phenomena involving many elementary constituents
- Long wavelength compared to the typical distance between constituents
- Small frequency or energy
- Major collective phenomena :
  - Quasi-particles
  - Debye screening
  - Landau damping
  - Collisional width

Dressed propagator

- In order to assess how the medium affects the propagation of excitations, one must compute the photon (gluon) polarization tensor $\Pi^{\mu\nu}(x,y) \equiv \big\langle J^\mu(x) J^\nu(y) \big\rangle$

- The photon (or gluon for QCD) self-energy can be resummed on the propagator. Diagrammatically, this amounts to summing :



- The properties of the medium can be read off the analytic properties of this resummed propagator (cuts, poles, ...)

Dressed propagator

- Reminder : the photon polarization tensor $\Pi^{\mu\nu}$ is transverse. At $T = 0$, this implies :

$$\Pi^{\mu\nu}(P) = \left(g^{\mu\nu} - \frac{P^\mu P^\nu}{P^2}\right)\,\Pi(P^2)$$

  - this is due to gauge invariance and Lorentz invariance
  - Exercise : this property ensures that the photon remains massless at all orders of perturbation theory

- This formula is not valid at $T > 0$, because there is a preferred frame (in which the plasma velocity is zero)

  $\triangleright$ the tensorial decomposition of $\Pi^{\mu\nu}$ is more complicated, and the photon acquires an effective mass

Dressed propagator

- At finite T, the tensorial decomposition of $\Pi^{\mu\nu}$ is :

$$\Pi^{\mu\nu}(P) = P_T^{\mu\nu}(P)\,\Pi_T(P) + P_L^{\mu\nu}(P)\,\Pi_L(P)$$

with the following projectors (in the plasma rest frame)

$$P_T^{ij}(P) = g^{ij} + \frac{p^i p^j}{\vec{\boldsymbol{p}}^2}\;, \quad P_T^{0i}(P) = 0\;, \quad P_T^{00}(P) = 0$$

$$P_L^{ij}(P) = -\frac{(p^0)^2 p^i p^j}{\vec{\boldsymbol{p}}^2 P^2}\;, \quad P_L^{0i}(P) = -\frac{p^0 p^i}{P^2}\;, \quad P_L^{00}(P) = -\frac{\vec{\boldsymbol{p}}^2}{P^2}$$

- Therefore, we have

$$\Pi^{\mu}{}_{\mu}(P) = 2\Pi_T(P) + \Pi_L(P) \quad , \quad \Pi^{00}(P) = -\frac{\vec{\boldsymbol{p}}^2}{P^2}\,\Pi_L(P)$$

- This leads to the following propagator :

$$D^{\mu\nu}(P) = P_T^{\mu\nu}(P)\,\frac{1}{P^2 - \Pi_T(P)} + P_L^{\mu\nu}(P)\,\frac{1}{P^2 - \Pi_L(P)}$$

Dressed propagator - Exercise

- Check the following properties of the tensors $P_{T,L}^{\mu\nu}$:

$$P_T{}^{\mu}{}_{\mu} = 2$$

$$P_L{}^{\mu}{}_{\mu} = 1$$

$$P_T{}^{\mu}{}_{\alpha}\, P_T^{\alpha\nu} = P_T^{\mu\nu}$$

$$P_L{}^{\mu}{}_{\alpha}\, P_L^{\alpha\nu} = P_L^{\mu\nu}$$

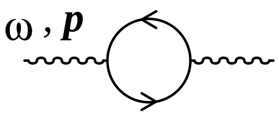
$$P_T{}^{\mu}{}_{\alpha}\, P_L^{\alpha\nu} = 0$$

Dressed propagator

- The calculation of $\Pi^{\mu}{}_{\mu}$ and Π^{00} can be done for a discrete Matsubara frequency ω_p, and one performs the analytic continuation $i\omega_p \to p_0$ afterwards

- Because one is after the long distance properties of the plasma, one also makes the approximation $|\vec{\boldsymbol{p}}| \ll |\vec{\boldsymbol{k}}|$ (Hard Thermal Loops : Braaten, Pisarski - 1990)

- For instance, the fermionic contribution to the spatial part Π^{ij} of the polarization tensor reads :



$$= -\frac{g^2 N_{\rm f} T}{2} \int \frac{d^3\vec{\boldsymbol{k}}}{(2\pi)^3}\, \widehat{\boldsymbol{v}}^i_{\boldsymbol{k}}\, \frac{\partial n_F(\vec{\boldsymbol{k}})}{\partial \boldsymbol{k}^l} \left[\delta^{jl} - \frac{\widehat{\boldsymbol{v}}^j_{\boldsymbol{k}} \widehat{\boldsymbol{v}}^l_{\boldsymbol{k}}}{\omega - \widehat{\boldsymbol{v}}_{\boldsymbol{k}} \cdot \vec{\boldsymbol{p}} + i\epsilon}\right]$$

($\widehat{\boldsymbol{v}}_{\boldsymbol{k}} \equiv \vec{\boldsymbol{k}}/|\vec{\boldsymbol{k}}|$, $N_{\rm f}$= number of quark flavors)

  - Note : with the gluon loop, the only change is $N_{\rm f} \to N_{\rm f} + 2N_{\rm c}$

Quasi-particles

- The functions $\Pi_{T,L}(P)$ read :

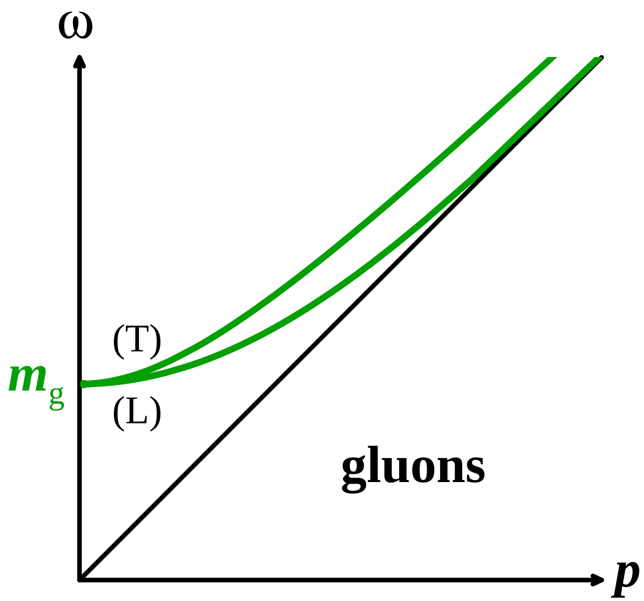
$$\Pi_T(P) = \frac{e^2T^2}{6}\Big[\frac{p_0^2}{p^2} + \frac{p_0}{2p}\Big(1-\frac{p_0^2}{p^2}\Big)\ln\Big(\frac{p_0+p}{p_0-p}\Big)\Big]$$

$$\Pi_L(P) = \frac{e^2T^2}{3}\Big[1-\frac{p_0^2}{p^2}\Big]\Big[1-\frac{p_0}{2p}\ln\Big(\frac{p_0+p}{p_0-p}\Big)\Big]$$

- Quasi-particles correspond to poles in the propagator. Their dispersion relation is the function $p_0 = \omega(\vec{\boldsymbol{p}})$ that defines the location of the pole
- The inverse of the imaginary part of p_0 is the lifetime of the quasi-particles (If $\mathrm{Im}(p_0) = 0$, they are stable). In order to be able to talk about quasi-particles, one must have $\mathrm{Im}(p_0) \ll \mathrm{Re}(p_0)$

Quasi-particles

- Dispersion curves of particles in the plasma :



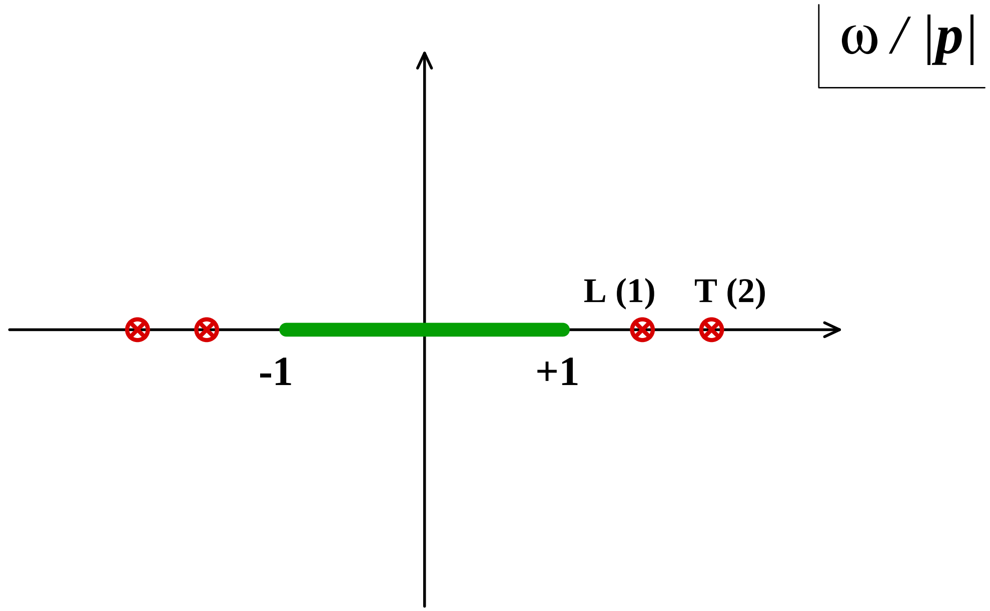
- Thermal masses due to interactions with the other particles in the plasma :

$$m_{\rm q} \sim m_{\rm g} \sim gT$$

- At this order, the quasi-particles are stable

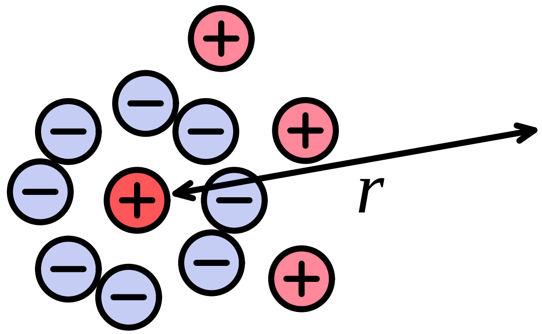
Singularities

- In the complex plane of $\omega/|\vec{p}|$, the dressed propagator has poles (quasi-particles) and a cut (Landau damping) :



Debye screening

- A test charge polarizes the particles of the plasma in its vicinity, in order to screen its charge :



$$V(r) = \frac{\exp(-m_{\mathrm{debye}}\, r)}{r}$$

- The Coulomb potential of the test charge decreases exponentially at large distance. The effective interaction range is :

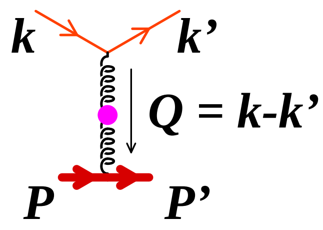
$$\ell \sim 1/m_{\mathrm{debye}} \sim 1/gT$$

- Note : static magnetic fields are not screened by this mechanism (they are screened over length-scales $\ell_{\mathrm{mag}} \sim 1/g^2T$)

Debye screening

- Place a quark of mass M at rest in the plasma, at $\vec{r} = 0$
- Scatter another quark off it. The scattering amplitude reads

$$\mathcal{M} = \left[g\overline{u}(\vec{k}^{\prime})\gamma_\mu u(\vec{k})\right]\left[g\overline{u}(\vec{P}^{\prime})\gamma_\nu u(\vec{P})\right] \sum_{\alpha=T,L} \frac{P_\alpha^{\mu\nu}(Q)}{Q^2 - \Pi_\alpha(Q)}$$



  - If $\vec{P} = 0$ (test charge at rest), only $\alpha = L$ contributes
  - From $(P+Q)^2 = M^2$, we get a $2\pi\delta(q_0)/2M$

- For the scattering off an external potential A^μ, the amplitude is $\mathcal{M} = \left[g\overline{u}(\vec{k}^{\prime})\gamma_\mu u(\vec{k})\right] A^\mu(Q)$

- Thus, the potential created by the test charge at rest is :

$$A^\mu(Q) = g\frac{\overline{u}(\vec{P}^{\prime})\gamma_\nu u(\vec{P})}{2M} \frac{2\pi\delta(q_0)P_L^{\mu\nu}(0,\vec{q})}{\vec{q}^2 + \Pi_L(0,\vec{q})} = \frac{2\pi g\delta^{\mu 0}\delta(q_0)}{\vec{q}^2 + \Pi_L(0,\vec{q})}$$

Debye screening

- By a Fourier transform, we obtain the Coulomb potential :

$$A^0(t,\vec{\boldsymbol{r}}) = g\int \frac{d^3\vec{\boldsymbol{q}}}{(2\pi)^3}\;\frac{e^{i\vec{\boldsymbol{q}}\cdot\vec{\boldsymbol{r}}}}{\vec{\boldsymbol{q}}^2 + \Pi_L(0,\vec{\boldsymbol{q}})}$$

- If we are in the vacuum, $\Pi_L = 0$, and the Fourier transform gives the usual Coulomb law :

$$A^0_{\rm vac}(t,\vec{\boldsymbol{r}}) = g\int \frac{d^3\vec{\boldsymbol{q}}}{(2\pi)^3}\;\frac{e^{i\vec{\boldsymbol{q}}\cdot\vec{\boldsymbol{r}}}}{\vec{\boldsymbol{q}}^2} = \frac{g}{4\pi|\vec{\boldsymbol{r}}|}$$

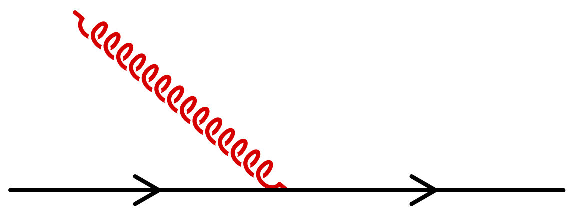
- In a plasma, $\Pi_L(0,\vec{\boldsymbol{q}}) = \frac{g^2T^2}{3} \equiv m_D^2$. The Fourier transform can also be done exactly

$$A^0(t,\vec{\boldsymbol{r}}) = g\int \frac{d^3\vec{\boldsymbol{q}}}{(2\pi)^3}\;\frac{e^{i\vec{\boldsymbol{q}}\cdot\vec{\boldsymbol{r}}}}{\vec{\boldsymbol{q}}^2 + m_D^2} = \frac{g}{4\pi|\vec{\boldsymbol{r}}|}\;e^{-m_D|\vec{\boldsymbol{r}}|}$$

▷ the potential is unmodified at $r \ll 1/m_D$, but exponentially suppressed at large distance

Landau damping

- The self-energies $\Pi_{L,T}(p_0,\vec{\boldsymbol{p}})$ have an imaginary part when $|p_0| \le |\vec{\boldsymbol{p}}|$. This implies that the propagation of space-like modes is attenuated
- A wave propagating through the plasma is damped because its quanta may be absorbed by particles of the plasma :



- The characteristic frequency of this damping is :

$$\omega_c \sim gT$$

Relativistic hydrodynamics

Energy-momentum tensor

- Noether's theorem states that for each continuous symmetry of the Lagrangian, there is an associated conserved current J^μ, such that $\partial_\mu J^\mu = 0$

- As a consequence, the quantity

$$Q(t) \equiv \int d^3\vec{\boldsymbol{x}}\; J^0(t,\vec{\boldsymbol{x}})$$

  is time independent. Proof :

$$\begin{aligned}\partial_t Q(t) &= \int d^3\vec{\boldsymbol{x}}\;\partial_t J^0(t,\vec{\boldsymbol{x}}) = -\int d^3\vec{\boldsymbol{x}}\;\vec{\boldsymbol{\nabla}}_{\boldsymbol{x}}\cdot\vec{\boldsymbol{J}}(t,\vec{\boldsymbol{x}}) \\ &= -\oint d^2\vec{\boldsymbol{S}}\cdot\vec{\boldsymbol{J}}(t,\vec{\boldsymbol{x}}) = 0\end{aligned}$$

- Note : the spatial vector $\vec{\boldsymbol{J}}$ describes the flow of the quantity Q across a surface

Energy-momentum tensor

- In a theory invariant under translations in time and position, the energy and the momentum are conserved quantities
- For each direction ν, there is a conserved current, denoted $T^{\mu\nu}$, called the energy-momentum tensor, that obeys

$$\partial_\mu T^{\mu\nu} = 0$$

- The integral over space of the zero component gives the 4-momentum of the system

$$P^\nu = \int d^3\vec{\boldsymbol{x}}\; T^{0\mu}(t, \vec{\boldsymbol{x}})$$

- The vector $T^{i\mu}$ (i=1,2,3) represents the flow of the component μ of momentum. For $\mu = 0$, this is an energy flow. For $\mu = 1, 2, 3$, this is a 3-momentum flow and it is thus related to pressure

Energy-momentum tensor

- Consider a fluid cell at rest, of volume δV. It has an energy $\delta P^0 = \epsilon\,\delta V$ and a 3-momentum $\delta\vec{\boldsymbol{P}} = 0$. This can be achieved if the energy momentum tensor has the following components :

$$T^{00} = \epsilon \quad , \quad T^{0i} = 0$$

- The flow of momentum P^i across an element of surface $d\vec{\boldsymbol{S}}$ is $dP^i = dS^j T^{ji}$. From the definition of the pressure p, this must be equal to $p dS^i$. Hence $T^{ij} = p\delta^{ij}$.

- Therefore, in the local rest frame of the fluid :

$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

Energy-momentum tensor

- In an arbitrary frame where the fluid 4-velocity is v^μ, the energy-momentum tensor can only be built from the symmetric tensors $g^{\mu\nu}$ and $v^\mu v^\nu$. In the local rest frame ($v^\mu = (1,0,0,0)$), we must recover the previous expression. Therefore :

$$T^{\mu\nu} = (p+\epsilon)\, v^\mu\, v^\nu - p\, g^{\mu\nu}$$

- Note : this expression is valid only for an ideal fluid, with no dissipative phenomena. In a viscous fluid, there can be a transport of momentum due to the friction of fluid layers that move at different velocities. This is taken into account by additional terms in $T^{\mu\nu}$ that are proportional to the derivatives $\partial_i v^j$, multiplied by the viscosity η.

CERN

Ideal hydrodynamics

- The fundamental equation of non viscous hydrodynamics is simply the conservation of the energy-momentum,

$$\partial_\mu T^{\mu\nu} = 0$$

- In the non-relativistic limit,
  - $v^\mu \approx (1, \vec{\boldsymbol{v}})$
  - ϵ becomes the mass density ρ
  - the pressure p is much smaller than the energy density ϵ

  It is easy to check that the above equation is equivalent to the continuity equation for mass and to Euler's equation :

$$\nu = 0 \; : \qquad \partial_t \rho + \vec{\boldsymbol{\nabla}}_{\boldsymbol{x}} \cdot (\rho \vec{\boldsymbol{v}}) = 0$$

$$\nu = i \; : \qquad \partial_t (\rho v^i) + \partial_j (\rho v^i v^j) + \partial_i p = 0$$

  Note : the second equation can be cast into the more familiar form

$$\rho \left[\partial_t + \vec{\boldsymbol{v}} \cdot \vec{\boldsymbol{\nabla}}_{\boldsymbol{x}} \right] \vec{\boldsymbol{v}} + \vec{\boldsymbol{\nabla}}_{\boldsymbol{x}} \, p = 0$$

Ideal hydrodynamics

- In hydrodynamics, the unknown functions are :
  - $p(t,\vec{\boldsymbol{x}}), \epsilon(t,\vec{\boldsymbol{x}})$
  - $v^\mu(t,\vec{\boldsymbol{x}})$ (3 unknowns only, since $v_\mu v^\mu = 1$)
- $\partial_\mu T^{\mu\nu} = 0$ gives only 4 equations
- An additional constraint comes from the equation of state of the matter under consideration, as a relation between the local pressure p and energy density ϵ
- An initial condition $p_0(\vec{\boldsymbol{x}}), \epsilon_0(\vec{\boldsymbol{x}}), \vec{\boldsymbol{v}}_0(\vec{\boldsymbol{x}})$ must be specified at a certain time t_0. Since the relativistic Euler equation contains only first derivatives in time, this is sufficient to obtain the solution at any time $t > t_0$.

Sound propagation

- Consider a small perturbation on top of a static fluid :

$$p = p_0 + p'$$
$$\epsilon = \epsilon_0 + \epsilon'$$

- The Euler equation, linearized in the perturbations, read :

$$\partial_t \epsilon' + (p_0 + \epsilon_0) \vec{\boldsymbol{\nabla}}_{\boldsymbol{x}} \cdot \vec{\boldsymbol{v}}' = 0$$
$$(p_0 + \epsilon_0) \partial_t \vec{\boldsymbol{v}}' + \vec{\boldsymbol{\nabla}}_{\boldsymbol{x}}\, p' = 0$$

- Differentiate the 1st equation with respect to time, and eliminate the velocity $\vec{\boldsymbol{v}}'$. We get :

$$\partial_t^2 \, \epsilon' = \vec{\boldsymbol{\nabla}}_{\boldsymbol{x}}^2 \, p'$$

- For small perturbations, write $\epsilon' = (\partial\epsilon/\partial p)_0 \, p'$. Therefore,

$$\frac{1}{c_s^2} \partial_t^2 \, p' = \vec{\boldsymbol{\nabla}}_{\boldsymbol{x}}^2 \, p' \qquad \text{with} \quad c_s^2 \equiv \left(\frac{\partial p}{\partial \epsilon}\right)_0$$

Phenomenology

Initial energy density

- Bjorken estimate :

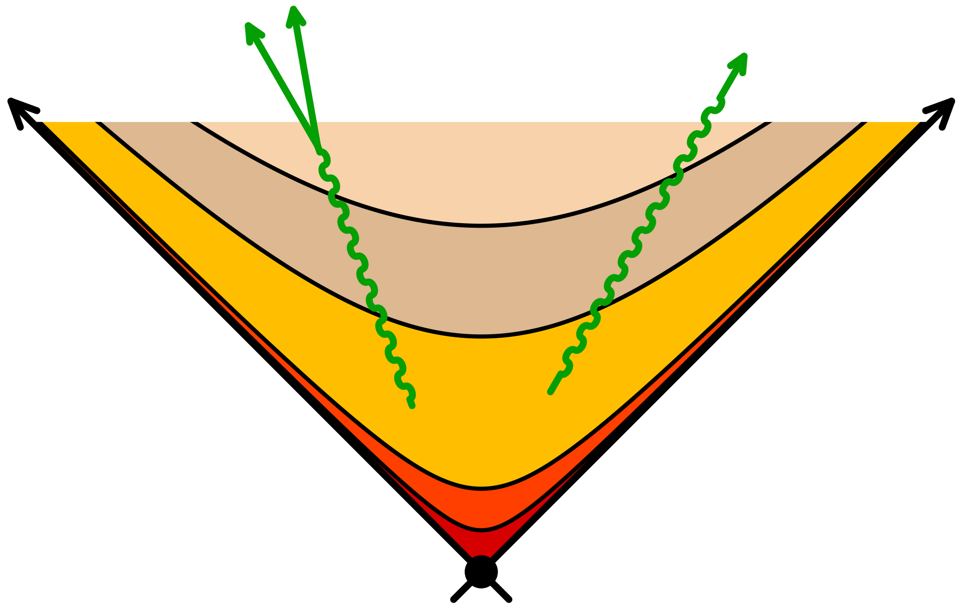
$$\epsilon_0 \approx \frac{1}{S_\perp \tau_0} \frac{dE_\perp}{dy}$$

- $dE_\perp/dy \approx 620$ GeV at RHIC ($\sqrt{s} = 200$ GeV, gold nuclei)
- $S_\perp \approx 140$ fm^2 for central collisions
- $\tau_0 \approx 0.15$ fm

$$\triangleright \quad \epsilon_0 \approx 30 \text{ GeV/fm}^3$$

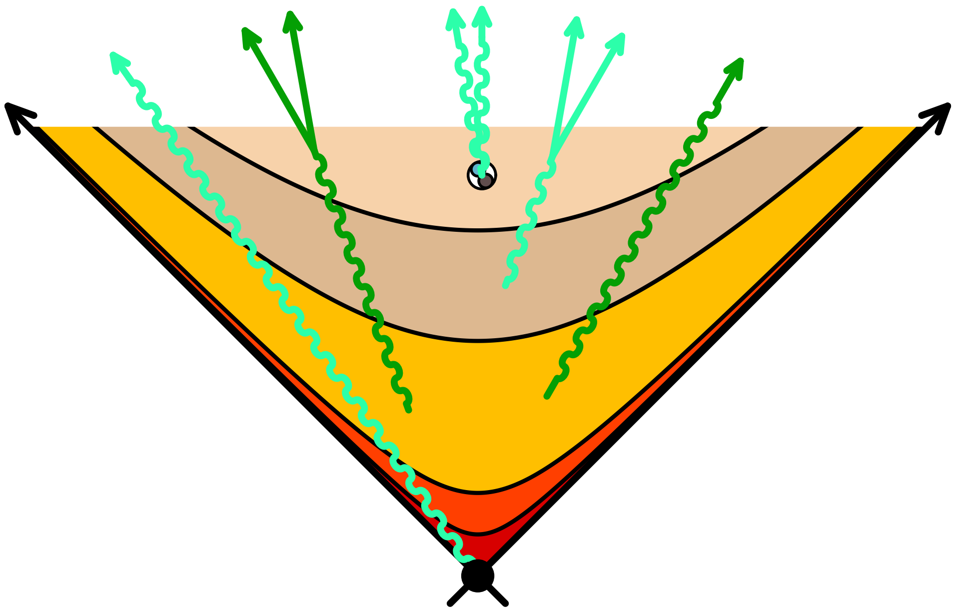
- Reminder : lattice QCD predicts deconfinement at $\epsilon_{\rm crit} \sim 1$ GeV/fm^3
- Note : things look less impressive in terms of the temperature since $\epsilon \sim T^4 \Rightarrow T/T_{\rm crit} \sim 30^{1/4} \sim 2.3$

Thermal photons



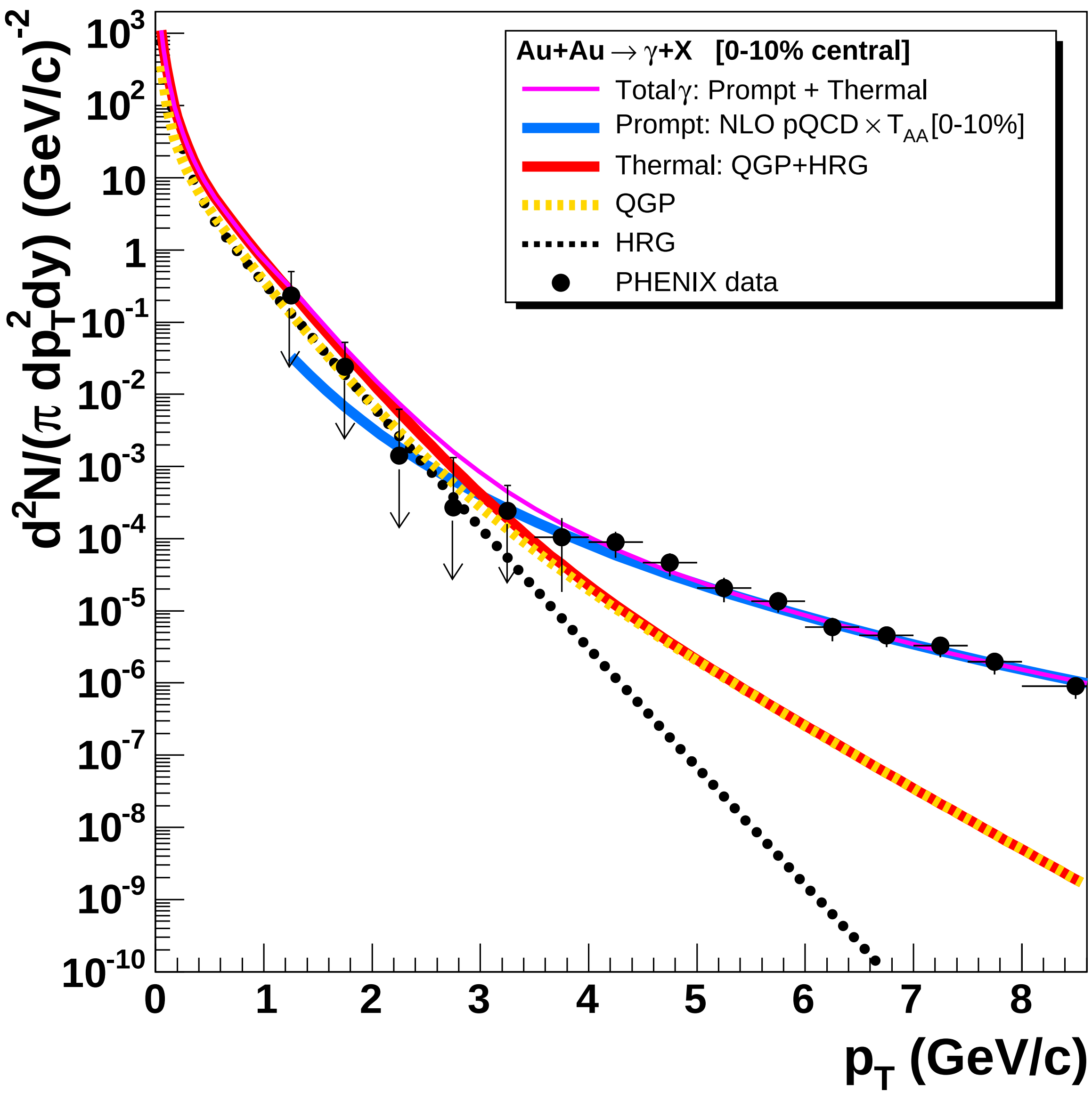
- Photons produced by the QGP :
  - Rate determined by physics at the scale g^2T
  - Very sensitive to the temperature : $dN_\gamma/dtd^3\vec{\boldsymbol{x}} \sim T^4$

Thermal photons

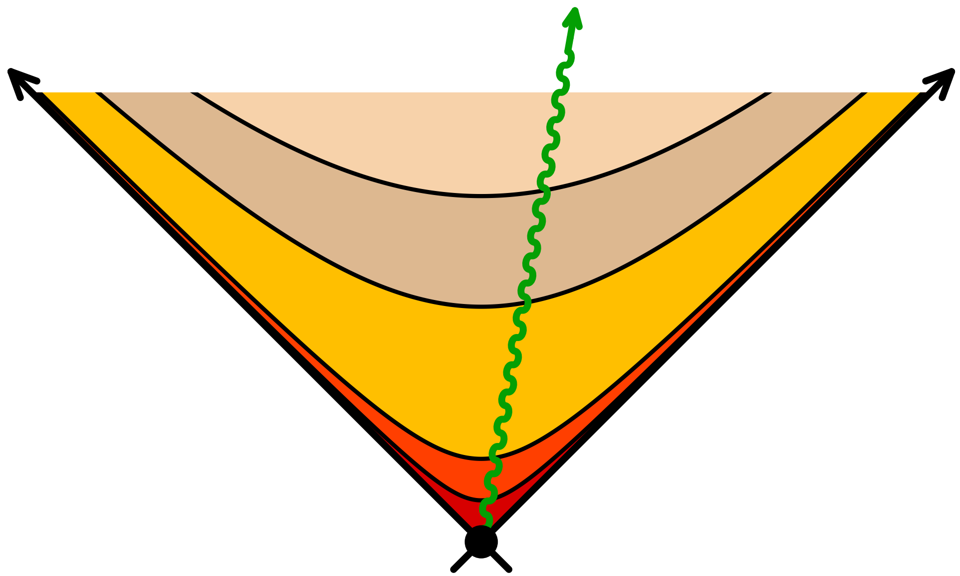


- Photons produced by the QGP :
  - Rate determined by physics at the scale g^2T
  - Very sensitive to the temperature : $dN_\gamma/dtd^3\vec{\boldsymbol{x}} \sim T^4$
- But very important background...
  - initial photons
  - photons produced by in-medium jet fragmentation
  - photons produced by the hadron gas
  - meson decays

Direct photons at RHIC



QGP “opacity”



- High $p_\perp$ jets are produced at the initial impact
  - Not very interesting by themselves...

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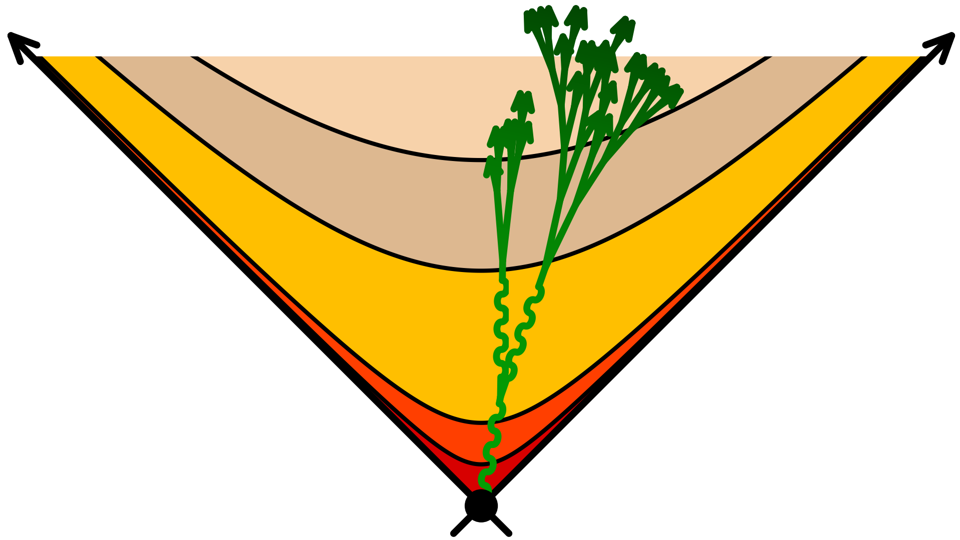
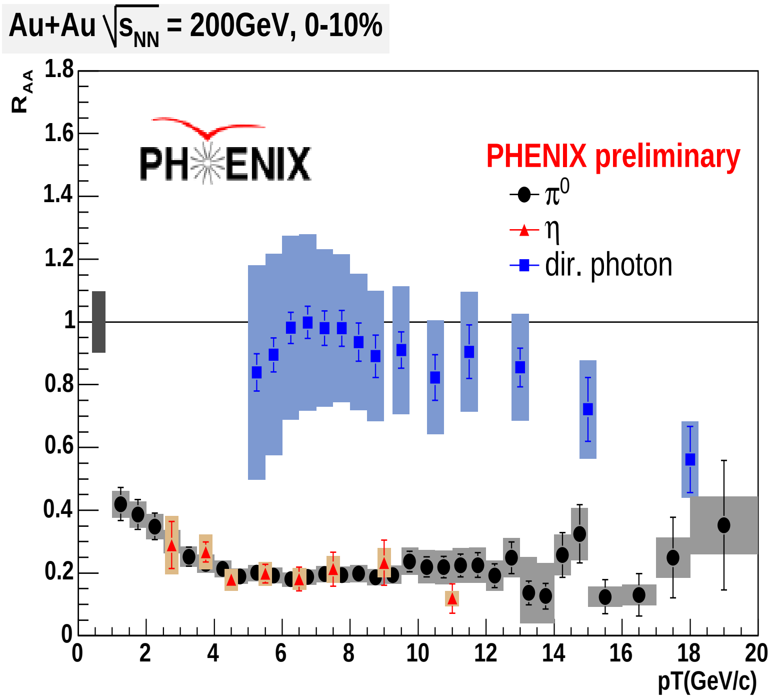
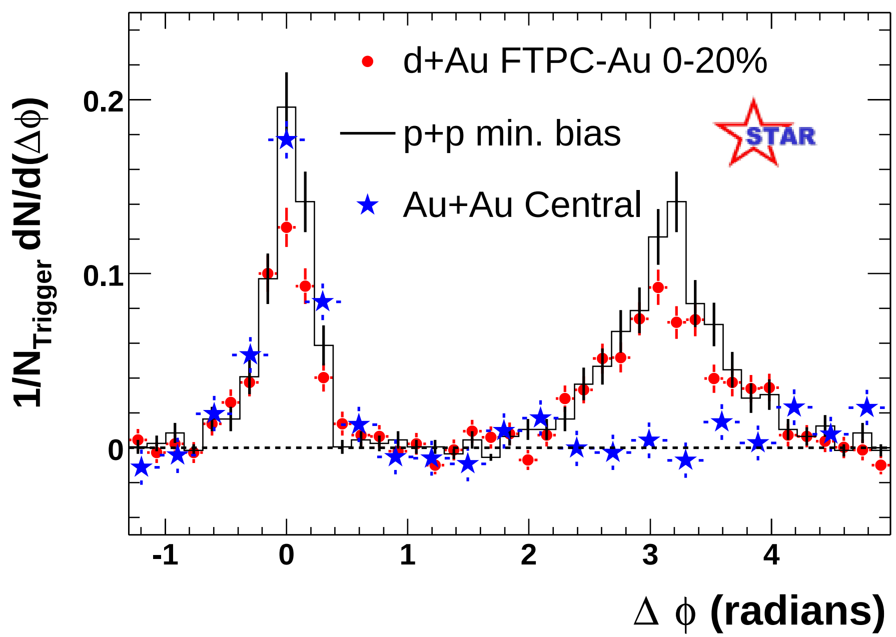


- High $p_\perp$ jets are produced at the initial impact
  - Not very interesting by themselves...
- Radiative energy loss when they travel through the QGP
  - Sensitive to the energy density of the medium
  - Depends on the path length as L^2
  - Important modification of the azimuthal correlations

QGP "opacity"

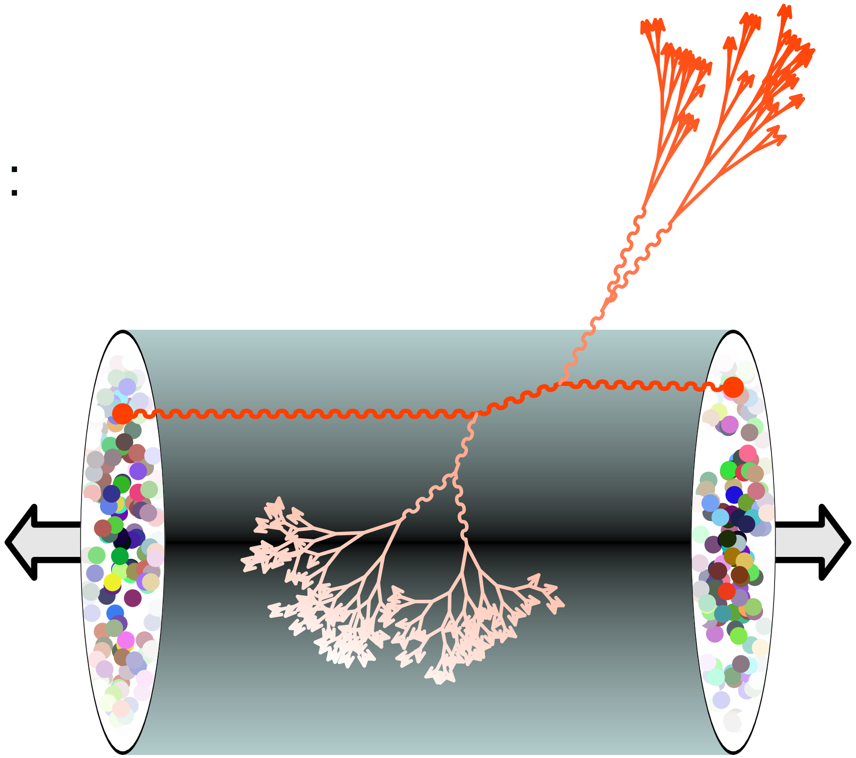




- Hadrons are strongly suppressed
  - Mesons involving heavy quarks (e.g. D) are also suppressed
  - Photons are not suppressed
- The correlation at 180^o disappears in AA collisions

QGP “opacity”

- Interpretation :

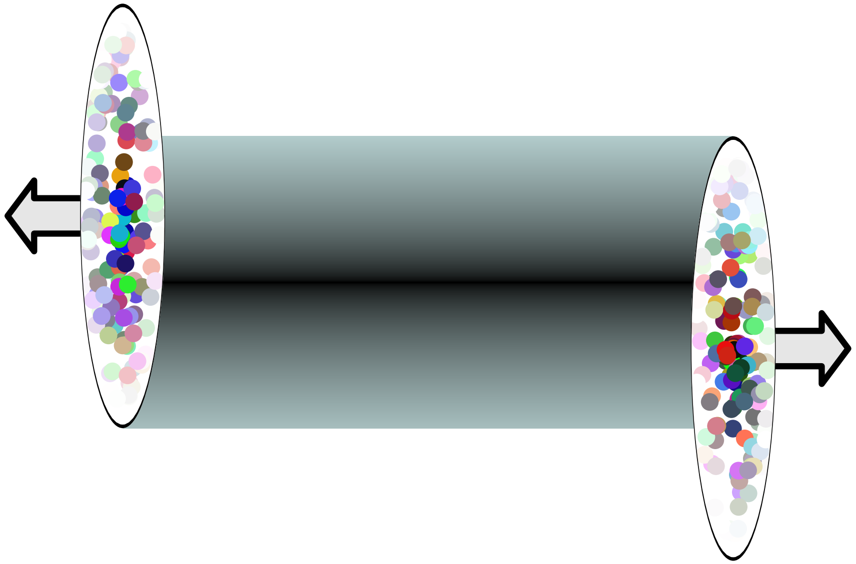


- Jets escape only if they are produced near the edge and are directed outwards
- The opposite jet is totally absorbed

  ▷ confirms the very large energy density

Collective flow

- Consider a non-central collision :



Collective flow

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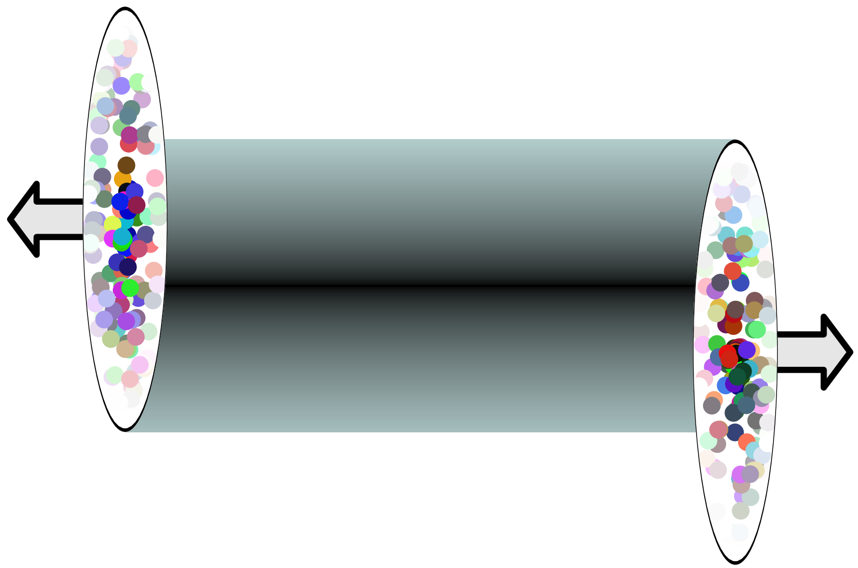

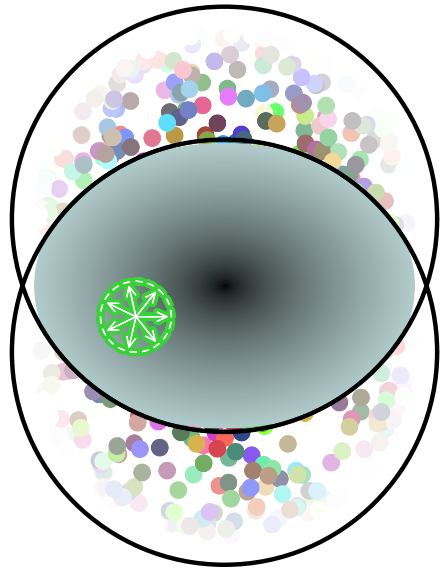

  - Initially, the momentum distribution of particles is isotropic in the transverse plane, because their production comes from local partonic interactions

Collective flow

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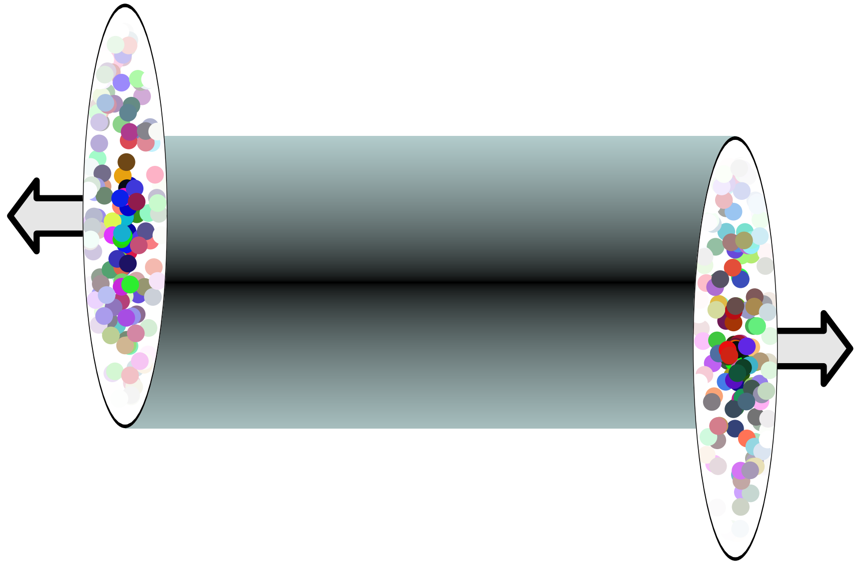

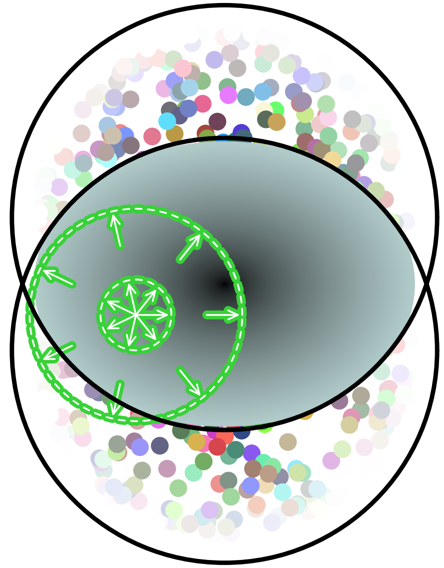

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Collective flow

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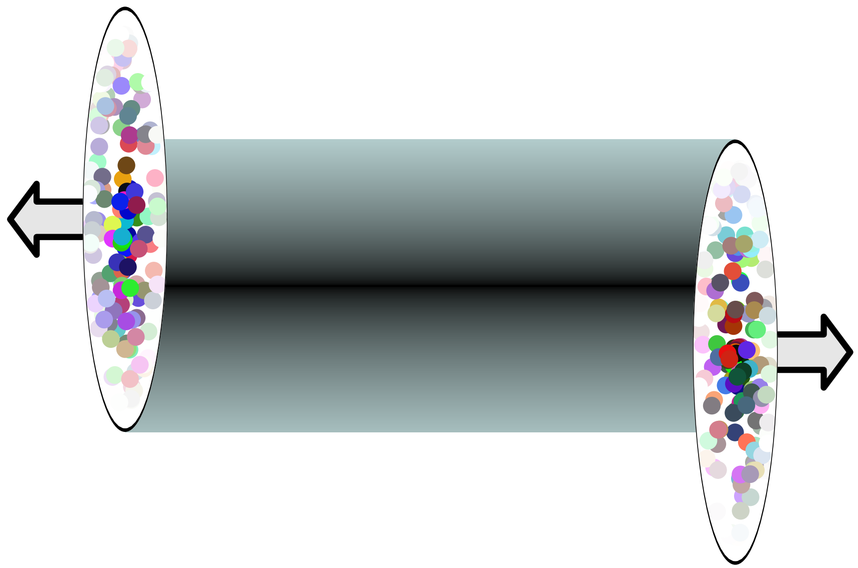
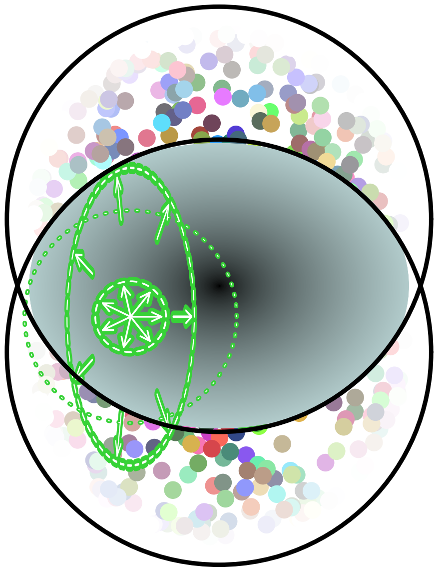




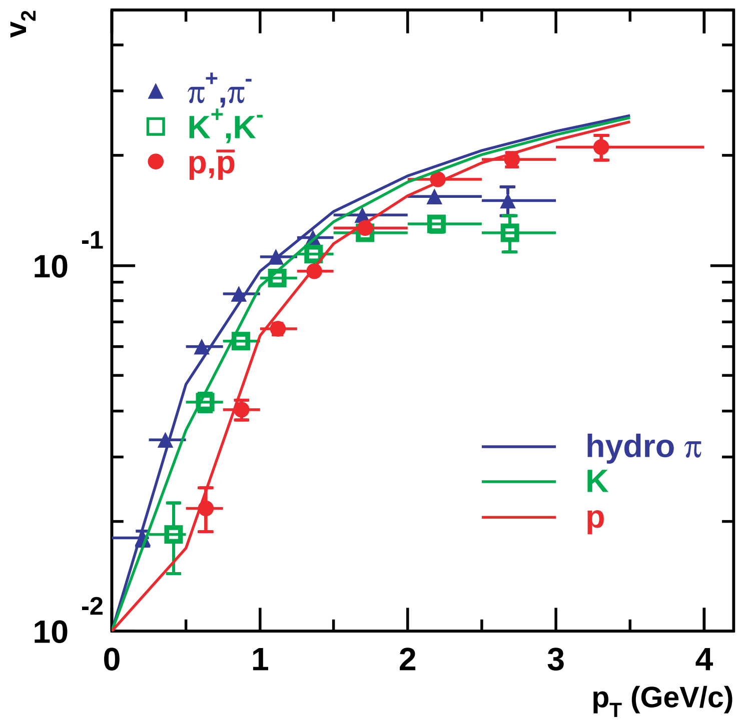
- Initially, the momentum distribution of particles is isotropic in the transverse plane, because their production comes from local partonic interactions
- If these particles were escaping freely, the distribution would remain isotropic at all times
- If the system has a small mean free path, pressure gradients are anisotropic and induce an anisotropy of the distribution

Collective flow and ideal hydrodynamics

- Observable: 2^{nd} harmonic of the azimuthal distribution

$$dN/d\varphi \sim 1 + 2v_1 \cos(\varphi) + 2v_2 \cos(2\varphi) + \cdots$$

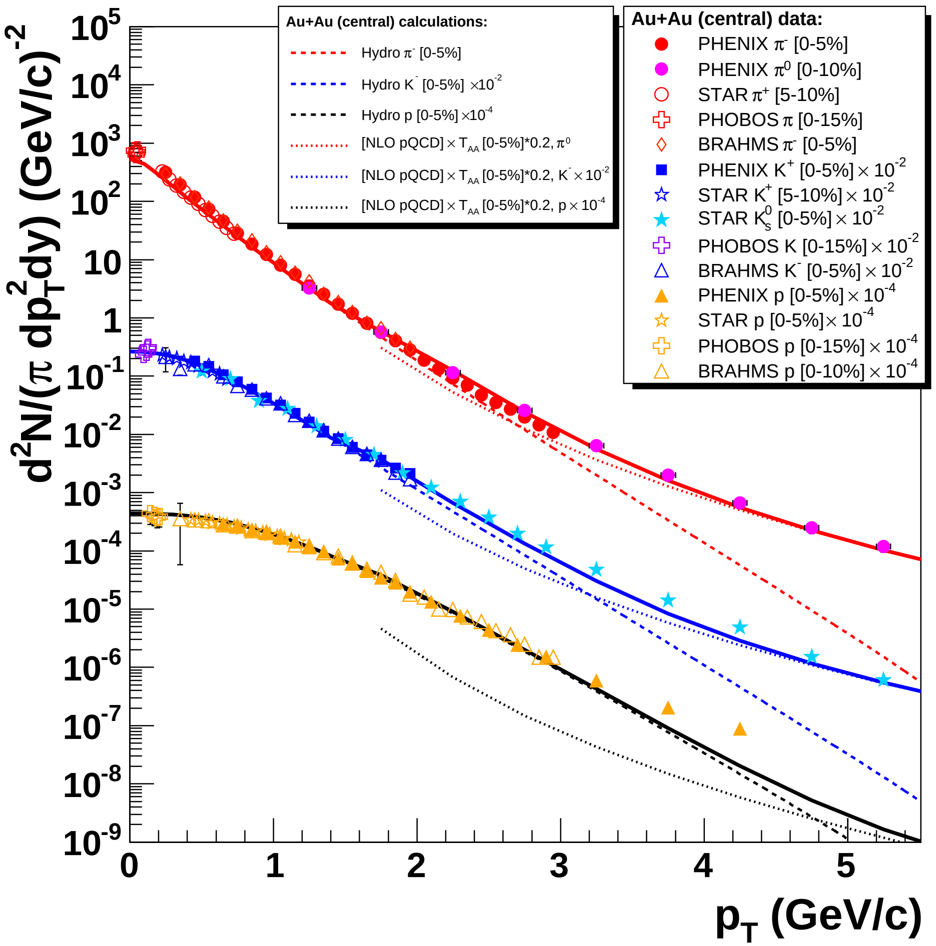
  ▷ v_2 measures the ellipticity of the momentum distribution



- Note : even heavy quarks seem to follow this flow

Another success of hydrodynamics

- Hydrodynamics reproduces the hadron spectra at low $p_\perp$



Is the QGP a perfect fluid?

- Note: a perfect fluid is a fluid with a very small viscosity, that can be described with Euler equations (ideal hydrodynamics)
- The elliptic flow coefficient v_2 measured at RHIC is well reproduced by ideal hydrodynamics, that has no viscosity
  - In hydrodynamics, the relevant parameter is the dimensionless ratio η/s of the shear viscosity to the entropy density
  - It has been concluded from there that the QGP must have a very small ratio η/s
- In the weakly coupled QGP, η/s is all but small...

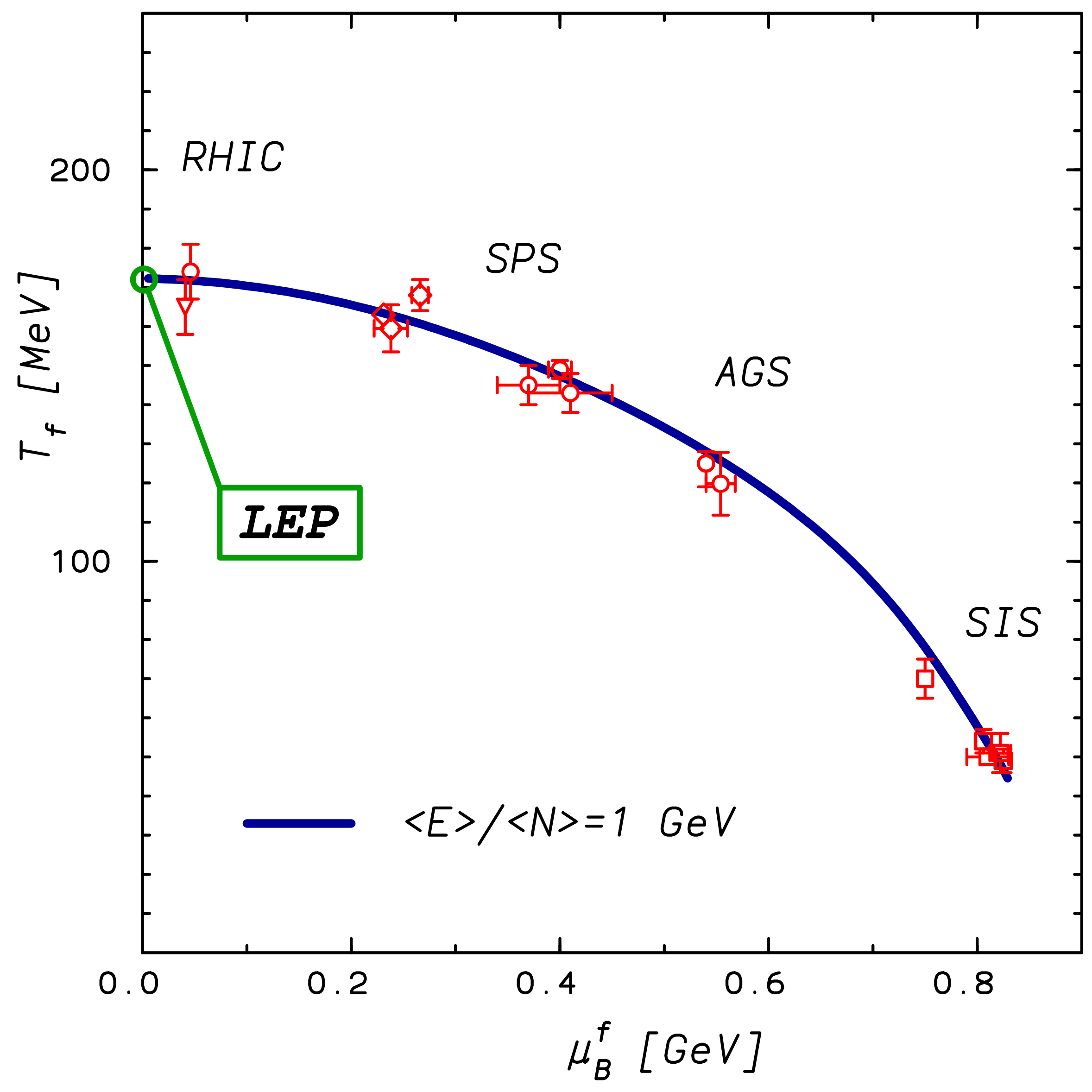
Statistical models

- One assumes that particles are produced by a thermalized system with temperature T and baryon chemical potential μ_B
- The number of particles of mass m per unit volume is :

$$\frac{dN}{d^3\vec{\boldsymbol{x}}} = \int \frac{d^3\vec{\boldsymbol{p}}}{(2\pi)^3} \, \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B Q)/T} \pm 1}$$

- These models reproduce the ratios of particle yields with only two parameters
- The same models also work for e^+e^- collisions
  - Standard explanation: randomly filling a phase space leads to exponential distributions
  - However, this argument alone does not explain why the value of T that comes out is the same as in nucleus-nucleus collisions
    ▷ dynamical arguments (about the properties of the vacuum?) may be involved here...

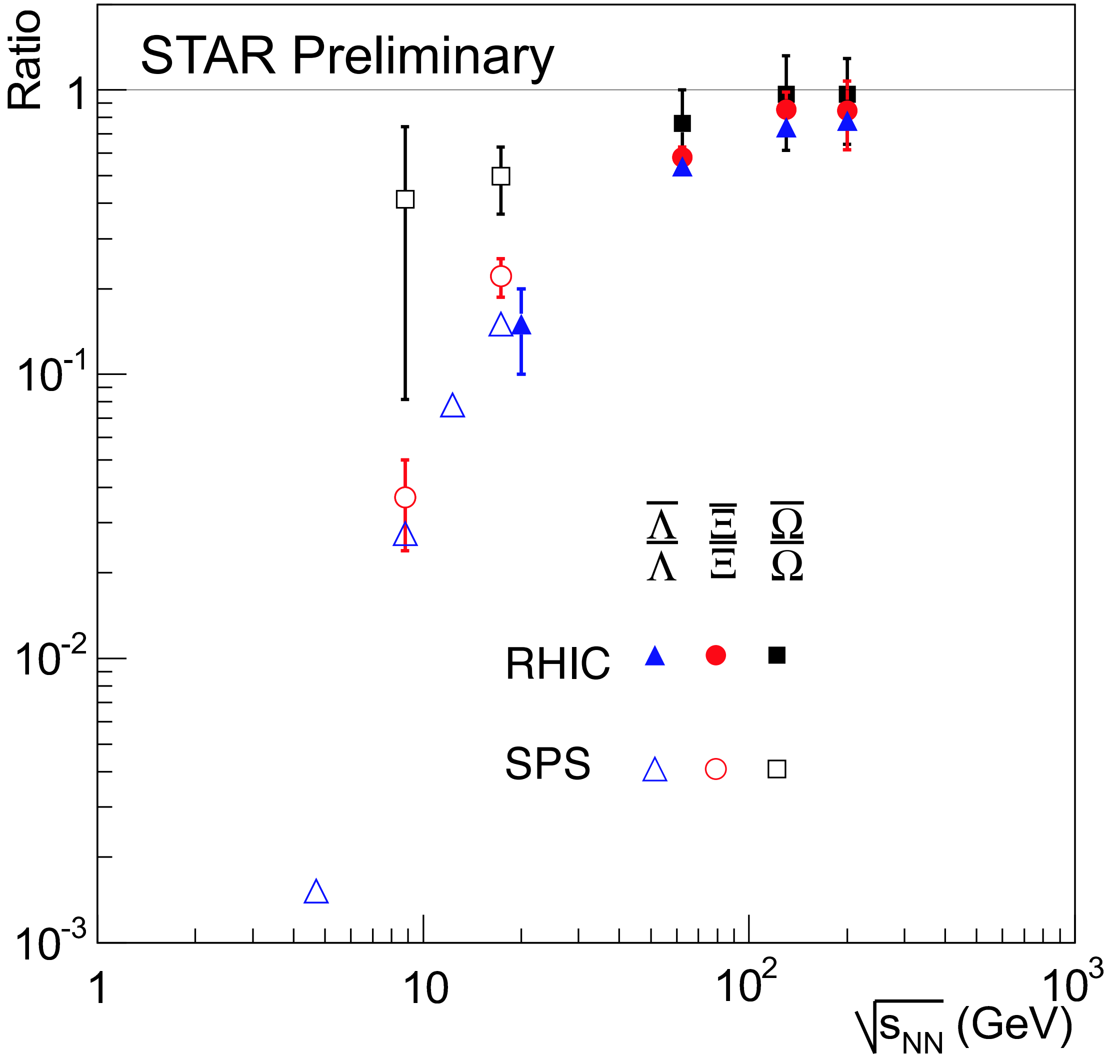
Freeze-out parameters



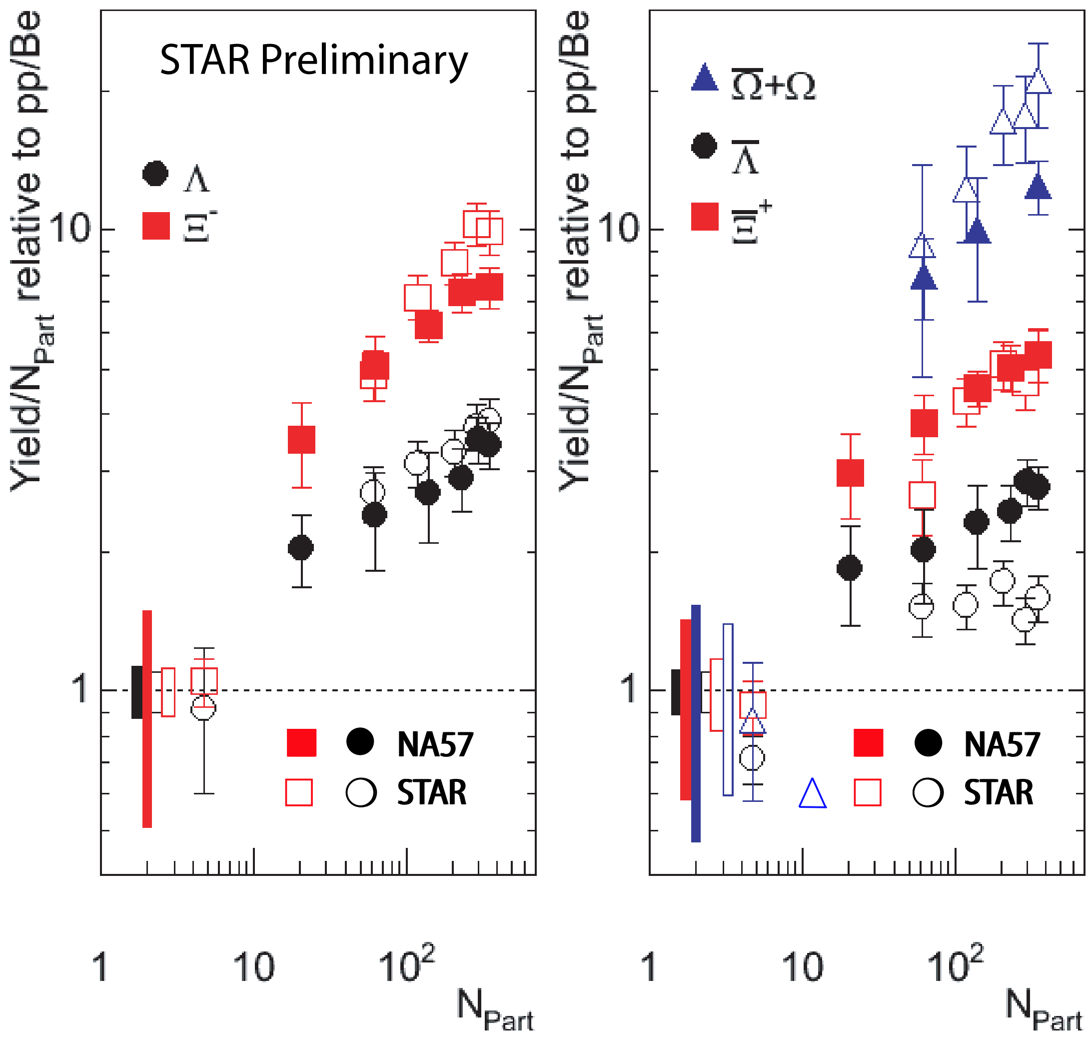
Strangeness enhancement

- In a nucleon, the distribution of strange quarks is smaller than that of u, d quarks (valence) by a factor of the order of $\alpha_s \sim 0.2$–0.3
  ▷ In pp collisions, less strange particles are produced than non-strange particles
- In the QGP, the average energy of u, d quarks and of the gluons is of the order of the temperature
  ▷ if T is large enough (compared to the mass of the strange quark), then the processes $u\bar{u} \to s\bar{s}$, $d\bar{d} \to s\bar{s}$, $gg \to s\bar{s}$ are not inhibited by the kinematical threshold due to the mass of the s quark
- In this case, the population of strange quarks will become identical to that of light quarks
  ▷ the production of strange hadrons will be enhanced compared to proton-proton collisions
- The interpretation of data based on statistical models works also for strange particles at RHIC

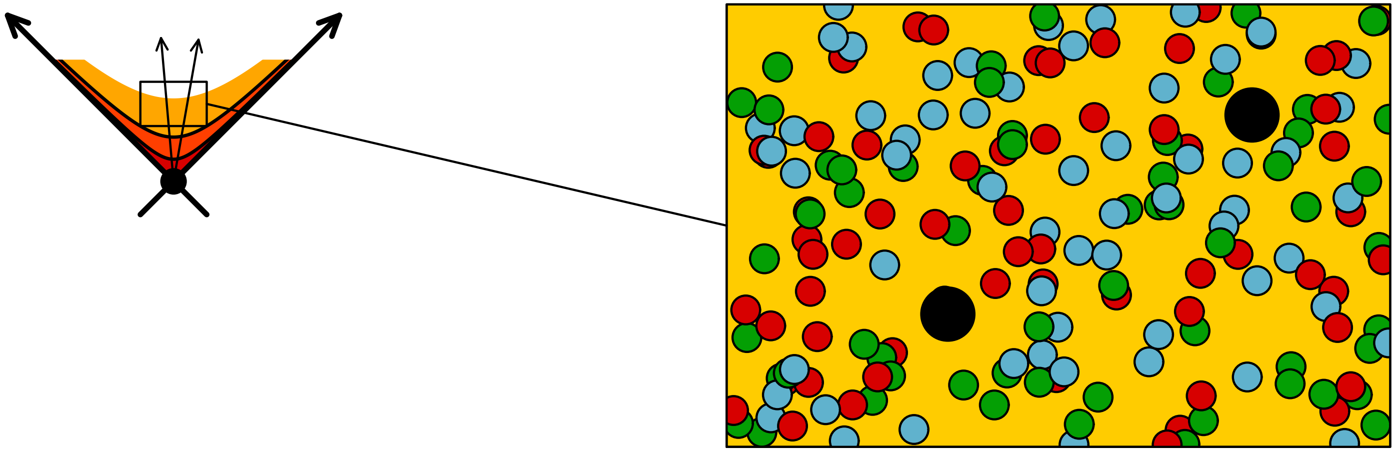
Strangeness enhancement



Strangeness enhancement



J/Psi suppression



- Debye screening prevents the $Q\overline{Q}$ pair from forming a bound state Matsui, Satz (1986)
  - each heavy quark pairs with a light quark in order to form a D meson
- The inter-quark potential can be calculated using lattice QCD
- Possible observable : $[J/\psi]$ / $[\text{Open charm}]$
  ▷ complication : there is also a suppression in proton-nucleus collisions, due to multiple scattering

J/Psi suppression

- What do we do with this potential?
  - Shröedinger equation for a $Q\overline{Q}$ bound state :

$$\left[2m_Q + \frac{1}{m_Q}\vec{\nabla}^2 + U(r,T)\right]\Psi = M(T)\Psi$$

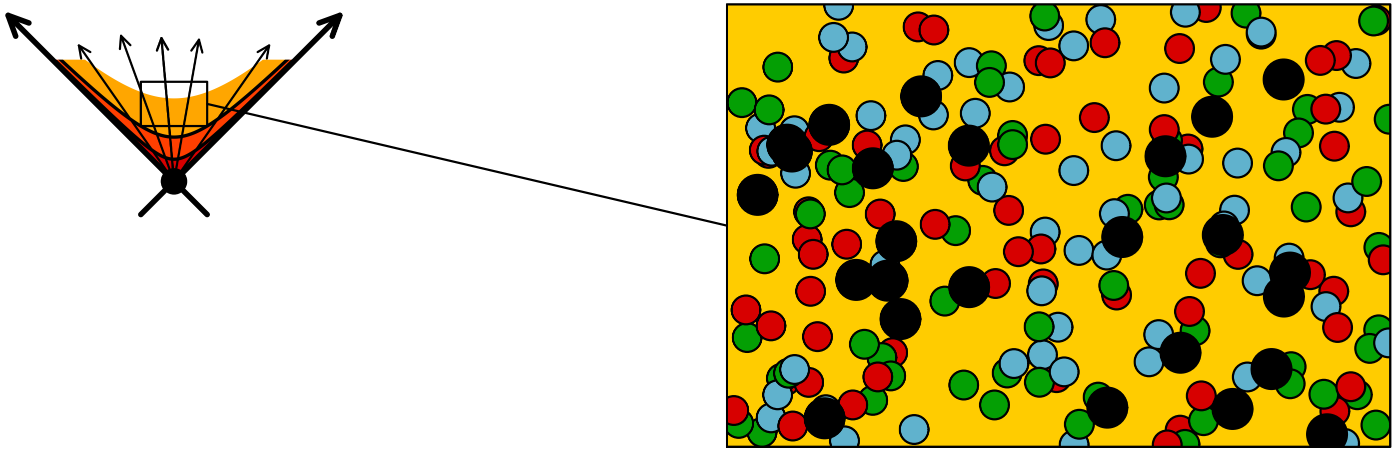
  - Non-relativistic
  - Assumes that there are only two-body interactions

- Dissociation temperatures :

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'
T_d/T_c	2.0	1.1	1.1	4.5	2.0	2.0

▷ the $Q\overline{Q}$ states are not dissolved immediately above the critical temperature

... or enhancement ?



- Many $Q\overline{Q}$ pairs may be produced in each AA collision
  Braun-Munzinger, Stachel (2000)
  Thews, Schroedter, Rafelski (2001)
  - A Q from one pair may recombine with a $\overline{Q}$ from another pair
- Avoids the conclusion of Matsui and Satz’s scenario, provided that the average distance between heavy quarks is smaller than the Debye screening length
- May lead to an enhancement of J/ψ production

J/Psi measurements at RHIC