Quark-Gluon Plasma @ LHC

- strongly or weakly coupled

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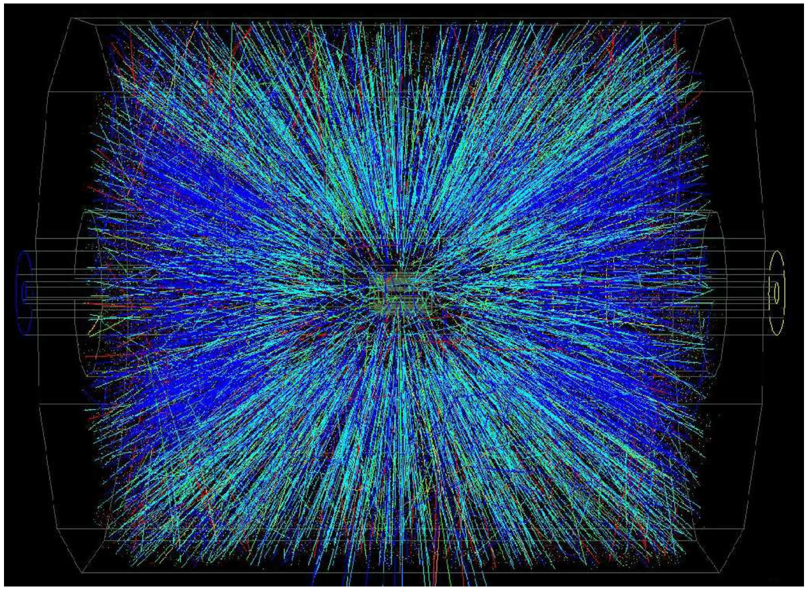
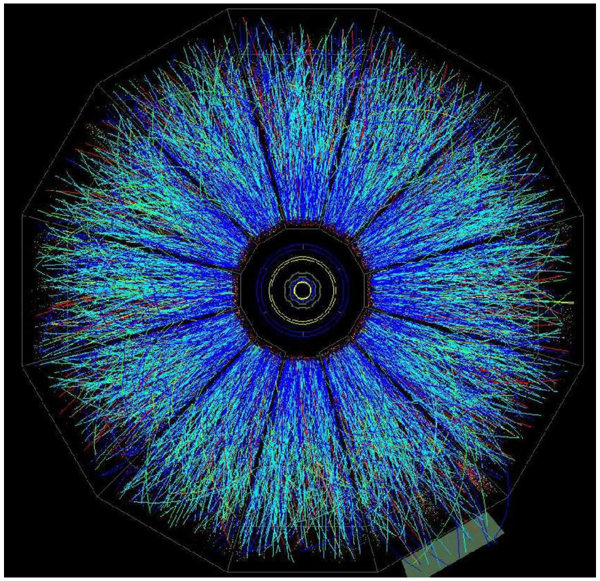
What we have learned @ RHIC

Au-Au collisions @ $\sqrt{s} = 100 + 100$ GeV/NN





STAR experiment

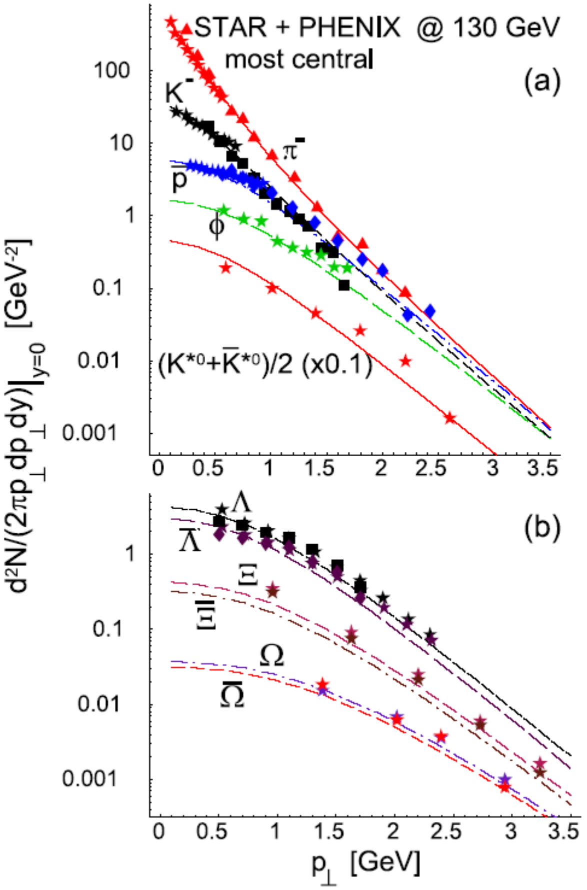
Equilibrium

Matter produced at RHIC appears to be in local thermal equilibrium

Late stage equilibrium

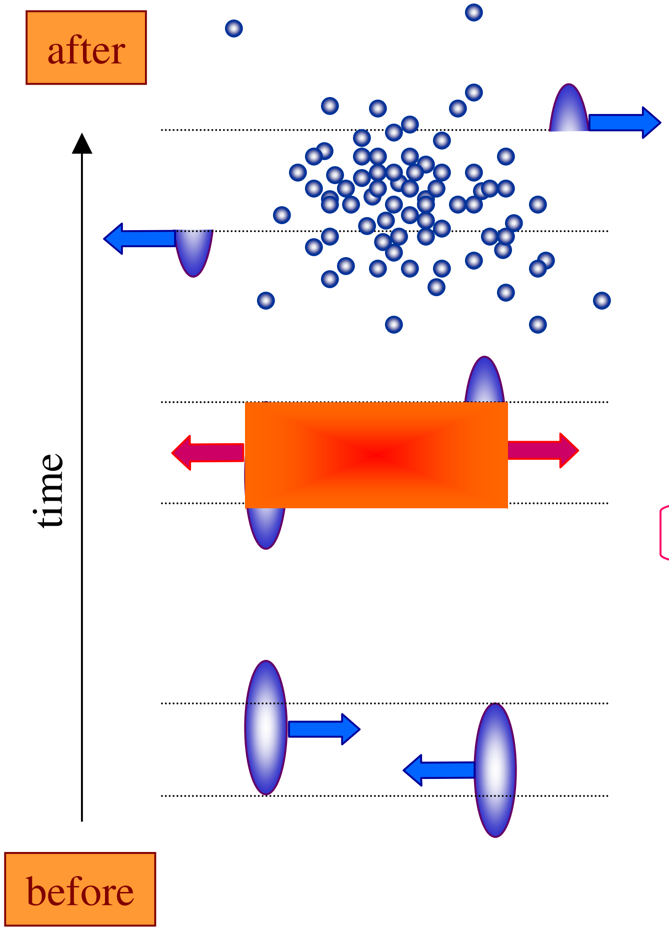
Au-Au @ 130 GeV within Cracow Thermal Model

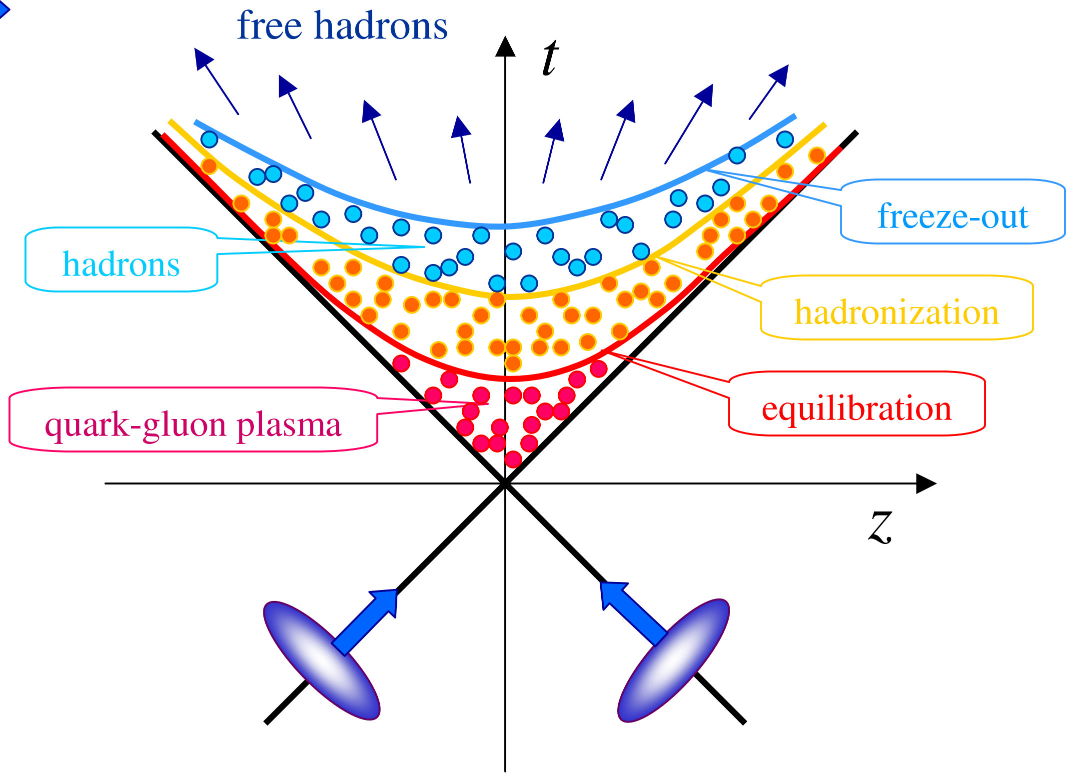
	Model	Experiment
Fitted thermal parameters		
T [MeV]	165±7	
μ_B [MeV]	41±5	
μ_S [MeV]	9	
μ_I [MeV]	-1	
χ^2/n	0.97	
Ratios used for the fit		
π^-/π^+	1.02	1.00 ± 0.02 [47], 0.99 ± 0.02[48]
$\overline{p}/\pi^-$	0.09	0.08 ± 0.01 [49]
K^-/K^+	0.92	0.88 ± 0.05 [50], 0.78 ± 0.12 [51] 0.91 ± 0.09 [47], 0.92 ± 0.06 [48]
K^-/π^-	0.16	0.15 ± 0.02 [50]
K_0^*/h^-	0.046	0.060 ± 0.012 [50, 52] later: 0.042 ± 0.011 [41]
$\overline{K_0^*}/h^-$	0.041	0.058 ± 0.012 [50, 52] later: 0.039 ± 0.011 [41]
$\overline{p}/p$	0.65	0.61 ± 0.07 [49], 0.54 ± 0.08 [51] 0.60 ± 0.07 [47], 0.61 ± 0.06 [48]
$\overline{\Lambda}/\Lambda$	0.69	0.73 ± 0.03 [50]
$\overline{\Xi}/\Xi$	0.76	0.82 ± 0.08 [50]
Ratios predicted		
ϕ/h^-	0.019	0.021 ± 0.001 [53]
ϕ/K^-	0.15	$0.1 - 0.16$ [53]
Λ/p	0.47	0.49 ± 0.03 [54, 55]
Ω^-/h^-	0.0010	0.0012 ± 0.0005 [56]
Ξ^-/π^-	0.0072	0.0085 ± 0.0020 [57]
Ω^+/Ω^-	0.85	0.95 ± 0.15 [56]



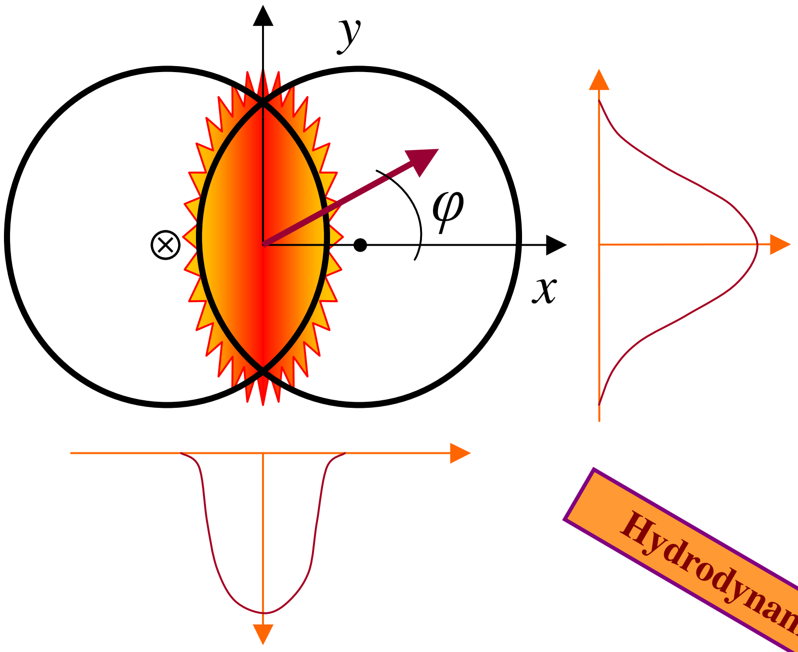
W. Broniowski, A. Baran and W. Florkowski, Acta Phys. Polon. **B33**, 4235 (2002)

Scenario of relativistic heavy-ion collisions





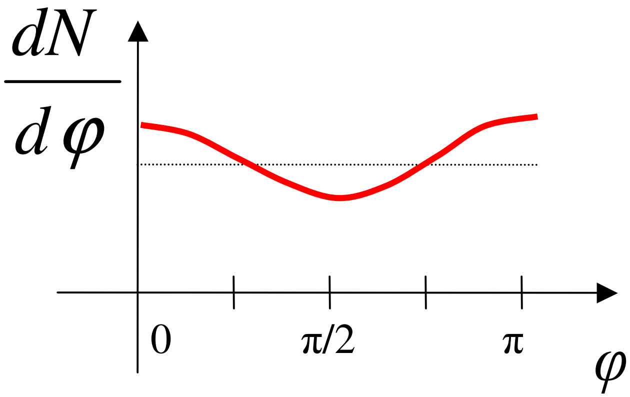
Elliptic Flow & Early Stage Equilibrium



$$\left(\frac{\partial}{\partial t}+\mathbf{v}\nabla\right)\mathbf{v}=-\frac{\nabla p}{\rho}$$

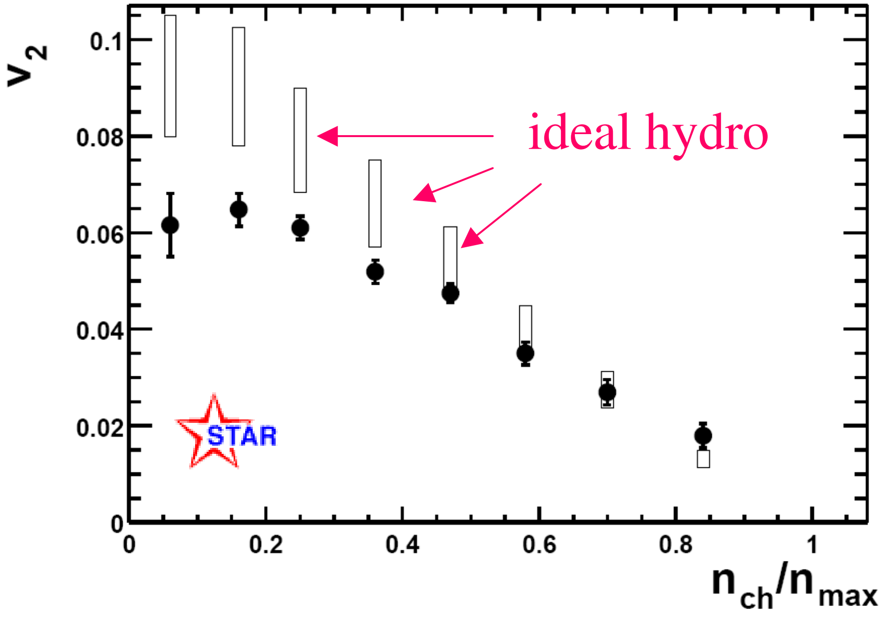
Hydrodynamics

Hydrodynamics requires local thermodynamical equilibrium!



Elliptic Flow & Early Stage Equilibrium

Au-Au @ 130 GeV



ideal hydro

peripheral collisions

central collisions

$$\frac{dN}{d\varphi} = \frac{1}{2\pi}\left[1 + \sum_{n=0}^{\infty} v_n \cos(n(\varphi - \varphi_R))\right]$$

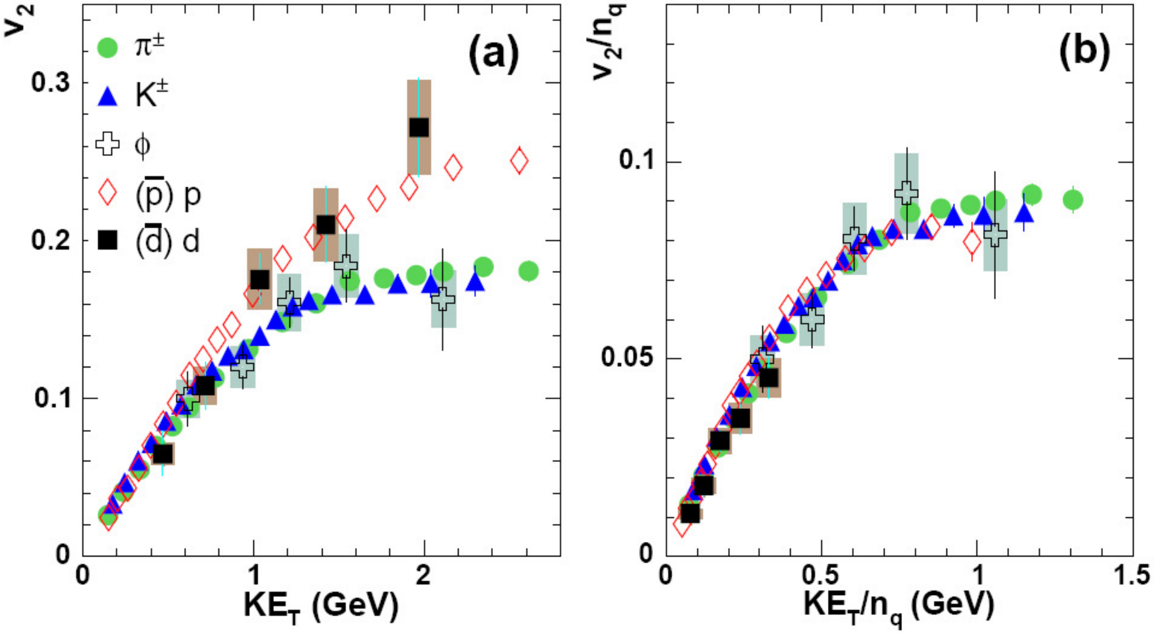
Ideal hydro works very well for central collisions

K.H. Ackermann et al. [STAR Collaboration], Phys. Rev. Lett. **86**, 402 (2001)

Elliptic Flow & Early Stage Equilibrium

Au-Au @ 200 GeV

$$\frac{dN}{d\varphi} = \frac{1}{2\pi}\left[1 + \sum_{n=0}^{\infty} \mathrm{v}_n \cos\left(n(\varphi - \varphi_R)\right)\right]$$



$$KE_T \equiv \sqrt{p_T^2 + m^2} - m$$

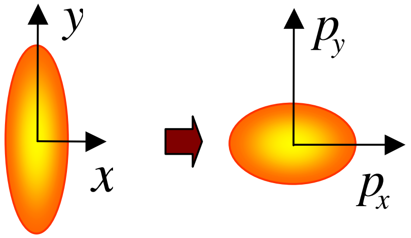
n_q – number of constituent quarks

Elliptic flow is generated
at quark phase

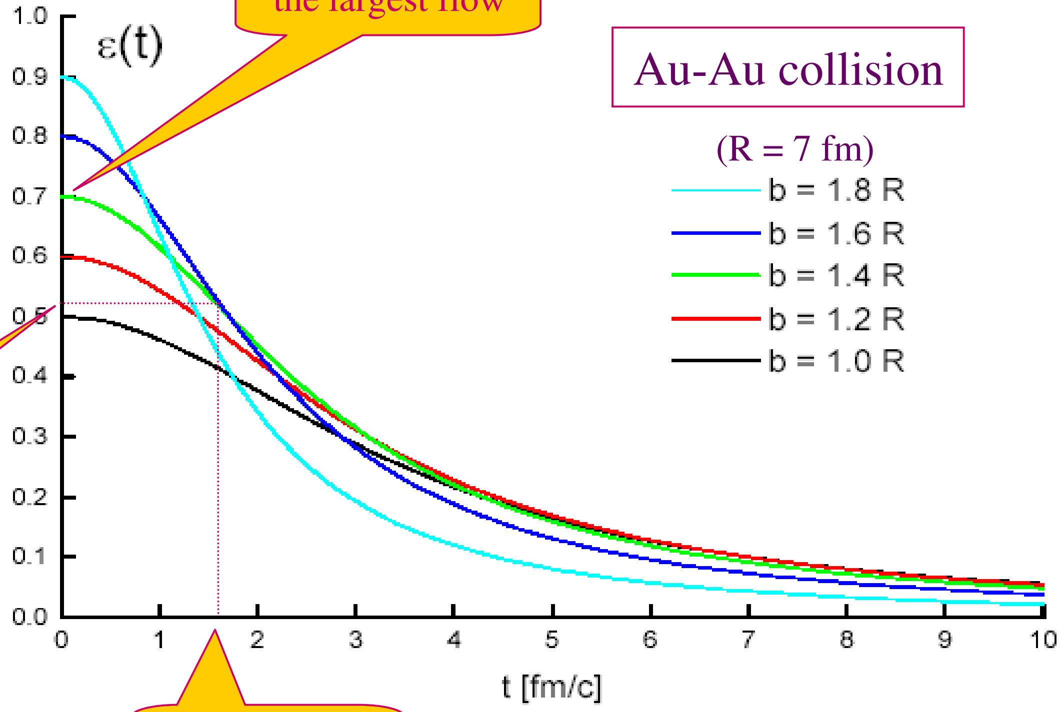
S. Afanasiev et al. [PHENIX Collaboration], Phys. Rev. Lett. **99**, 052301 (2007)

Equilibration Time

$$v_2 \sim \varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$



Eccentricity decay due to the free streaming



Au-Au collision

(R = 7 fm)

the largest flow

$0.75\ v_2$

$t_{eq} = 1.5$ fm/c

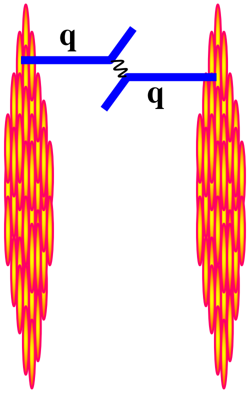
Equilibration is fast!

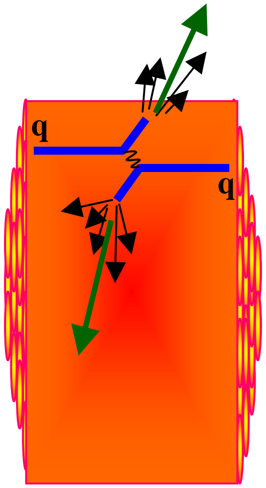
W. Jas and St. Mrówczyński, Phys. Rev. **C76**, 044905 (2007)

Opaqueness

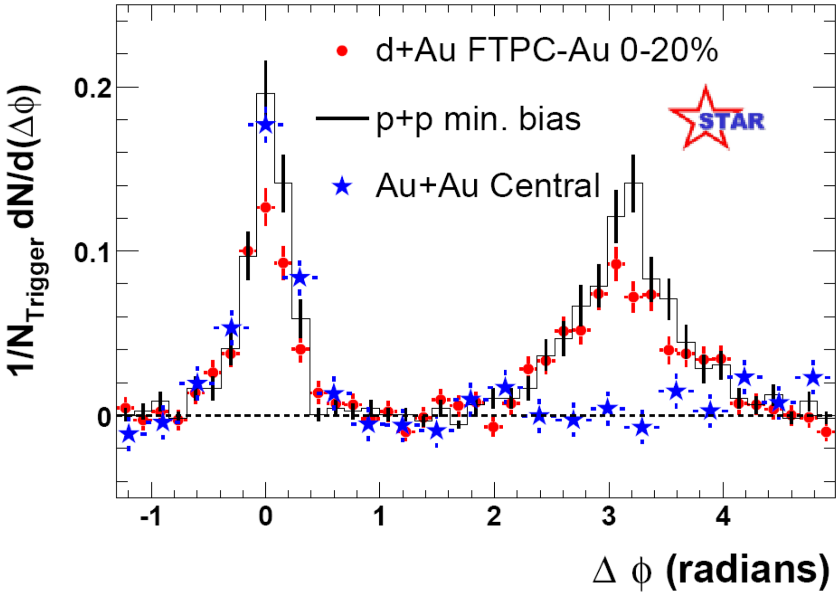
Matter produced at RHIC
appears to be very opaque

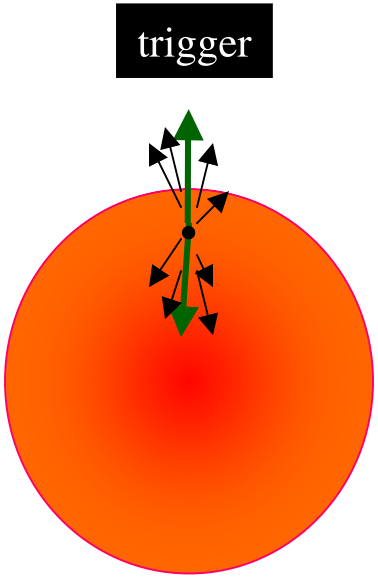
Hard Jets @ RHIC





near-side away-side





near-side

trigger

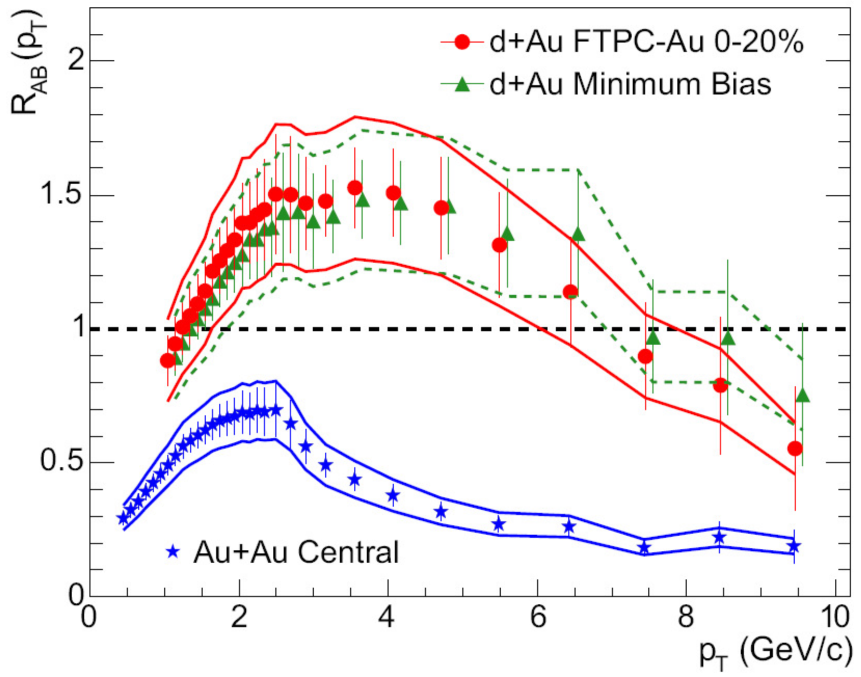
away-side

Away-side jet is suppressed
in central collisions

J. Adams et al. [STAR Collaboration], Nucl. Phys. **A757**, 102 (2005)

Hard Jets @ RHIC

Inclusive π^0 production



$$R_{AB}(p_T) = \frac{\dfrac{dN_{AB}}{d\eta\, d^2 p_T}}{\dfrac{\langle N_{bin}\rangle}{\sigma_{NN}^{\text{inel}}} \dfrac{d\sigma_{NN}}{d\eta\, d^2 p_T}}$$

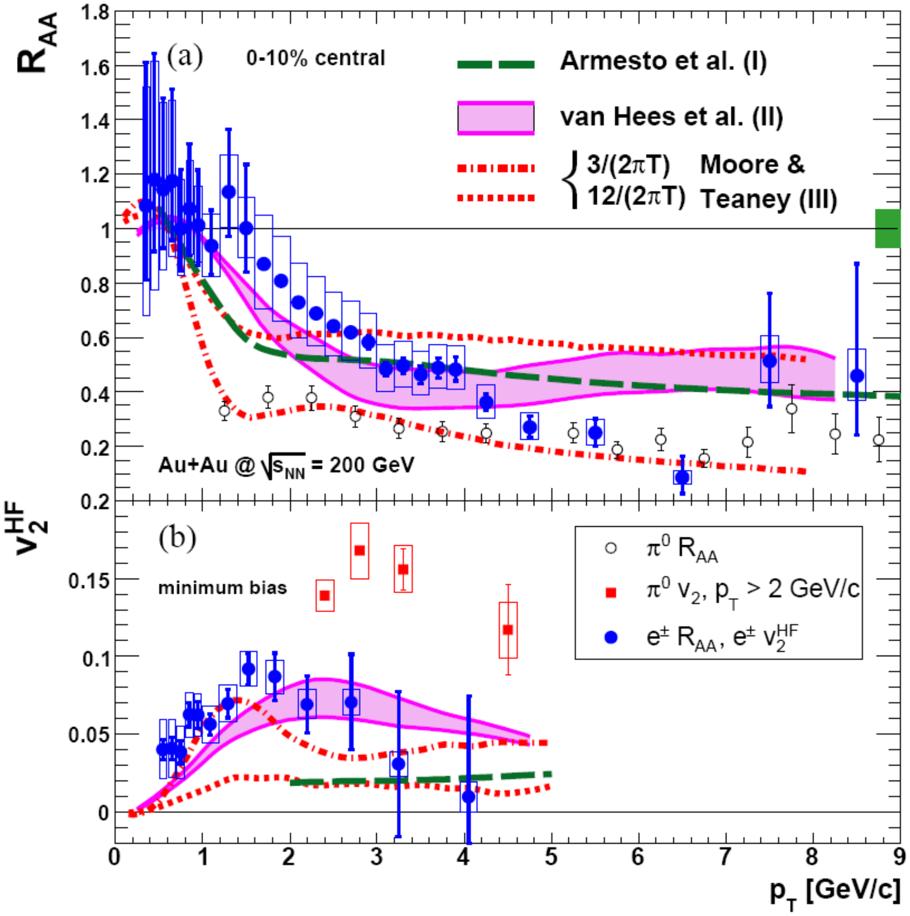
suppression

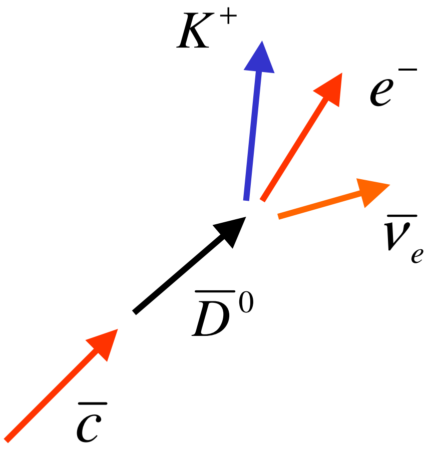
Production of high p_T pions is suppressed

J. Adams et al. [STAR Collaboration], Nucl. Phys. **A757**, 102 (2005)

Heavy-Flavours @ RHIC

$e^{\pm}$ from charm & bottom





Heavy quarks behave in QGP as light ones

A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. **98**, 172301 (2007)

Experimental features

- Matter produced at RHIC is in local equilibrium
- Equilibration time is short ~ 1fm/*c*
- Viscosity of the matter is low
- Matter produced at RHIC is opaque

What does it mean ‘short’, ‘low’, ‘opaque’?

Weakly coupled quasi-equilibrium QGP

- Equilibration time due to collisions: $t_{\mathrm{eq}} \sim \dfrac{1}{T\alpha_s^2 \ln(1/\alpha_s)}$
- Shear viscosity: $\eta \sim \dfrac{T^3}{\alpha_s^2 \ln(1/\alpha_s)}$

$\alpha_s << 1$

- Collisional energy loss: $\dfrac{dE}{dx} \sim \alpha_s^2 T^2 \ln(1/\alpha_s)$
- Radiative energy loss of

$$\begin{cases} \text{light quark: } \dfrac{dE}{dx} \sim \alpha_s^2 ET \ln(1/\alpha_s) \\ \text{heavy quark: } \dfrac{dE}{dx} \sim \dfrac{\alpha_s^3 ET^3}{M^2} \ln(1/\alpha_s) \qquad (M >> T) \end{cases}$$

α_s – coupling constant, T – temperature, E – quark energy, M – heavy quark mass

Provisional Conclusion

QGP is strongly coupled

or

QGP behaves as strongly coupled but $\alpha_s \leq 0.3$?

Mean fields vs. collisions

Transport equation

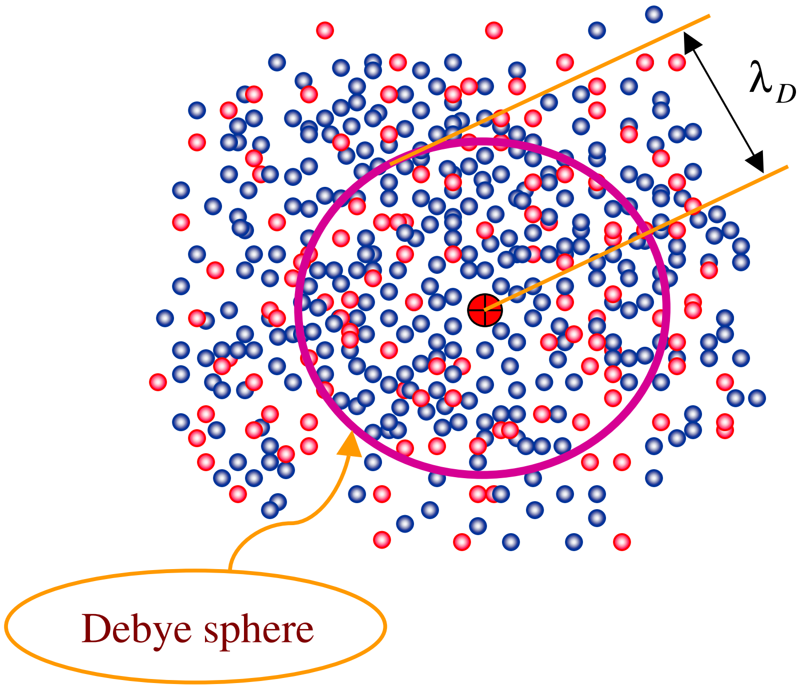
$$\underbrace{\left(\frac{\partial}{\partial t}+\mathbf{v}\nabla\right)f(t,\mathbf{r},\mathbf{p})}_{\text{free streaming}}+\underbrace{g\left(\mathbf{E}+\mathbf{v}\times\mathbf{B}\right)\nabla_{p}f(t,\mathbf{r},\mathbf{p})}_{\text{mean field }\boxed{\sim\alpha_s}}=\overbrace{C[f]}^{\text{collisions }\boxed{\sim\alpha_s^2}}$$

$$\alpha_s=\frac{g^2}{4\pi}$$

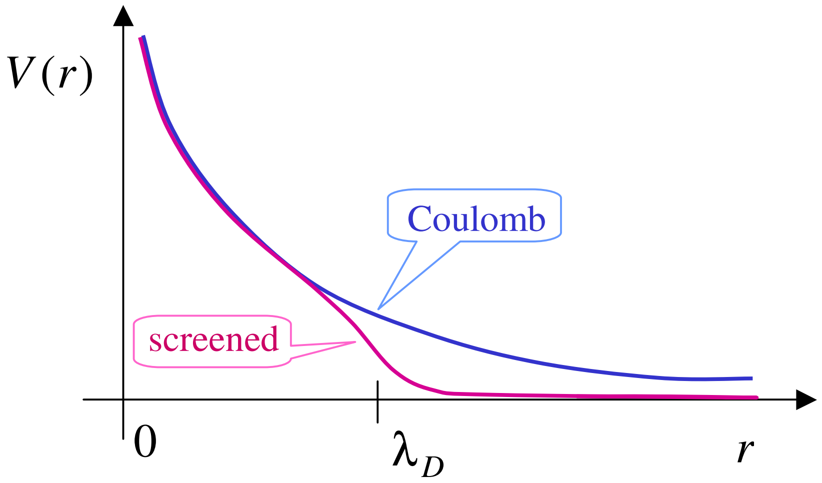
In weakly coupled plasmas the mean field dominates the dynamics

Weakly coupled plasmas are strongly collective

Plasma's collective behavior



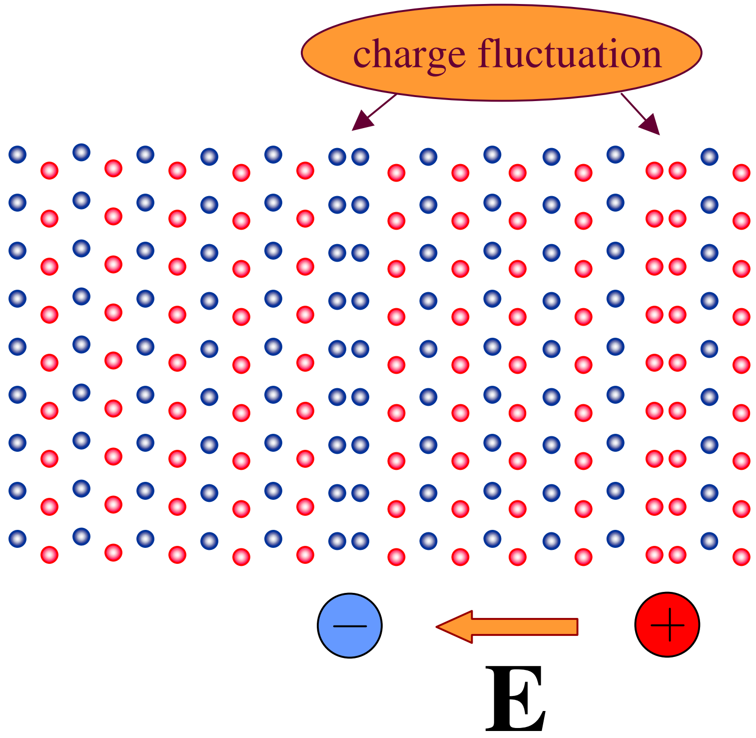
$$\lambda_D = \frac{1}{m_D} \sim \frac{1}{gT}$$ screening length $$V(r) \sim \frac{e^{-\frac{r}{\lambda_D}}}{r}$$



$$V_D = \frac{4}{3}\pi\lambda_D^3 \sim \frac{1}{g^3T^3}, \qquad n \sim T^3, \qquad \boxed{n\,V_D \sim \frac{1}{g^3} >> 1} \quad \text{if} \quad g << 1$$

In a weakly coupled plasma, there are many particles in a Debye sphere!

Plasma oscillations



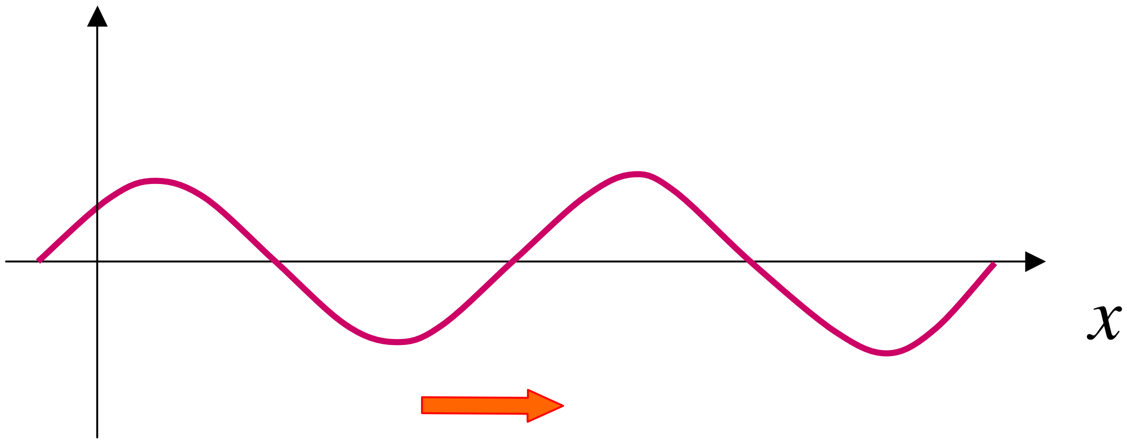
$$\mathbf{E}(t,\mathbf{r}) = \mathbf{E}_0 \cos(\omega(\mathbf{k})\,t - \mathbf{k}\cdot\mathbf{r} + \varphi)$$

$$\omega(\mathbf{k}) \underset{\mathbf{k}\to 0}{\approx} \omega_0 \sim gT$$

plasma frequency

Landau damping

$$E^x(t,x) = \mathbf{E_0}\cos(\omega_0 t - kx)$$



$$v_\varphi = \frac{\omega_0}{k}$$

Resonance energy transfer from electric field to particles with v = v_φ

Instabilities

stationary state

$$A(t) = A_0 + \delta A(t)$$

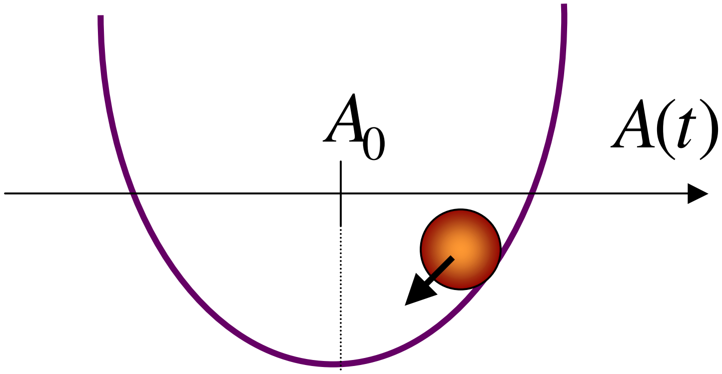
fluctuation

Instability

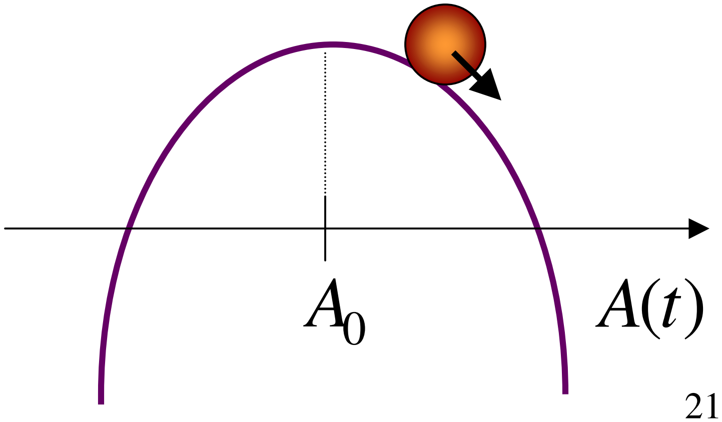
$$\boxed{\delta A(t) \propto e^{\gamma t}}$$

$$\gamma > 0$$

stable configuration

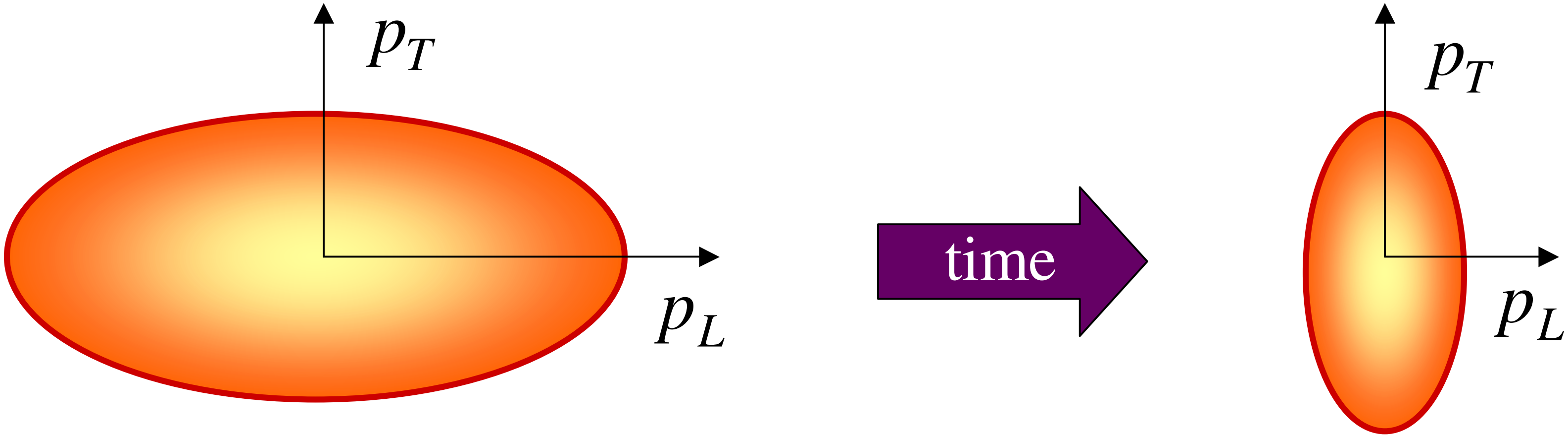


unstable configuration



Momentum Space Anisotropy in Nuclear Collisions

Parton momentum distribution is initially strongly anisotropic



CM after 1-st collisions

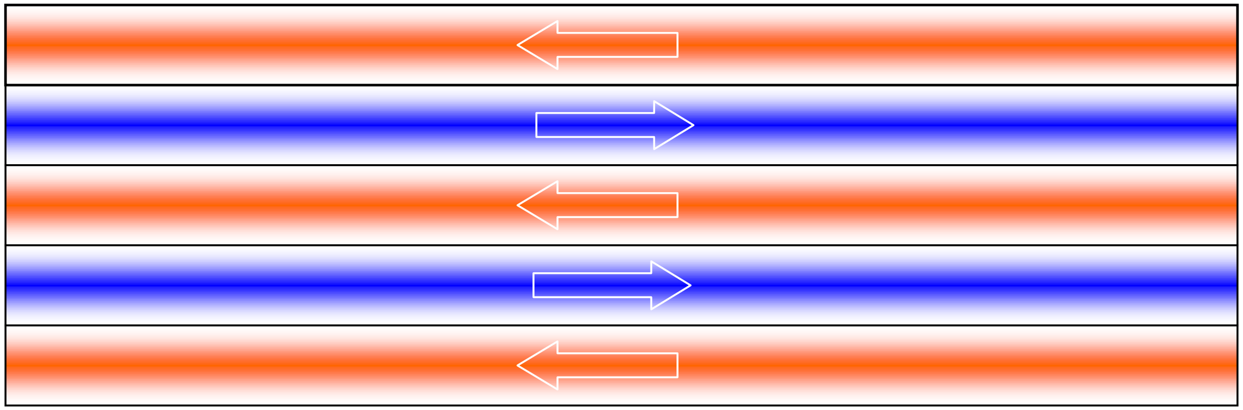
local rest frame

Seeds of instability

$\left\langle j_a^{\mu}(x)\right\rangle = 0$ **but current fluctuations are finite**

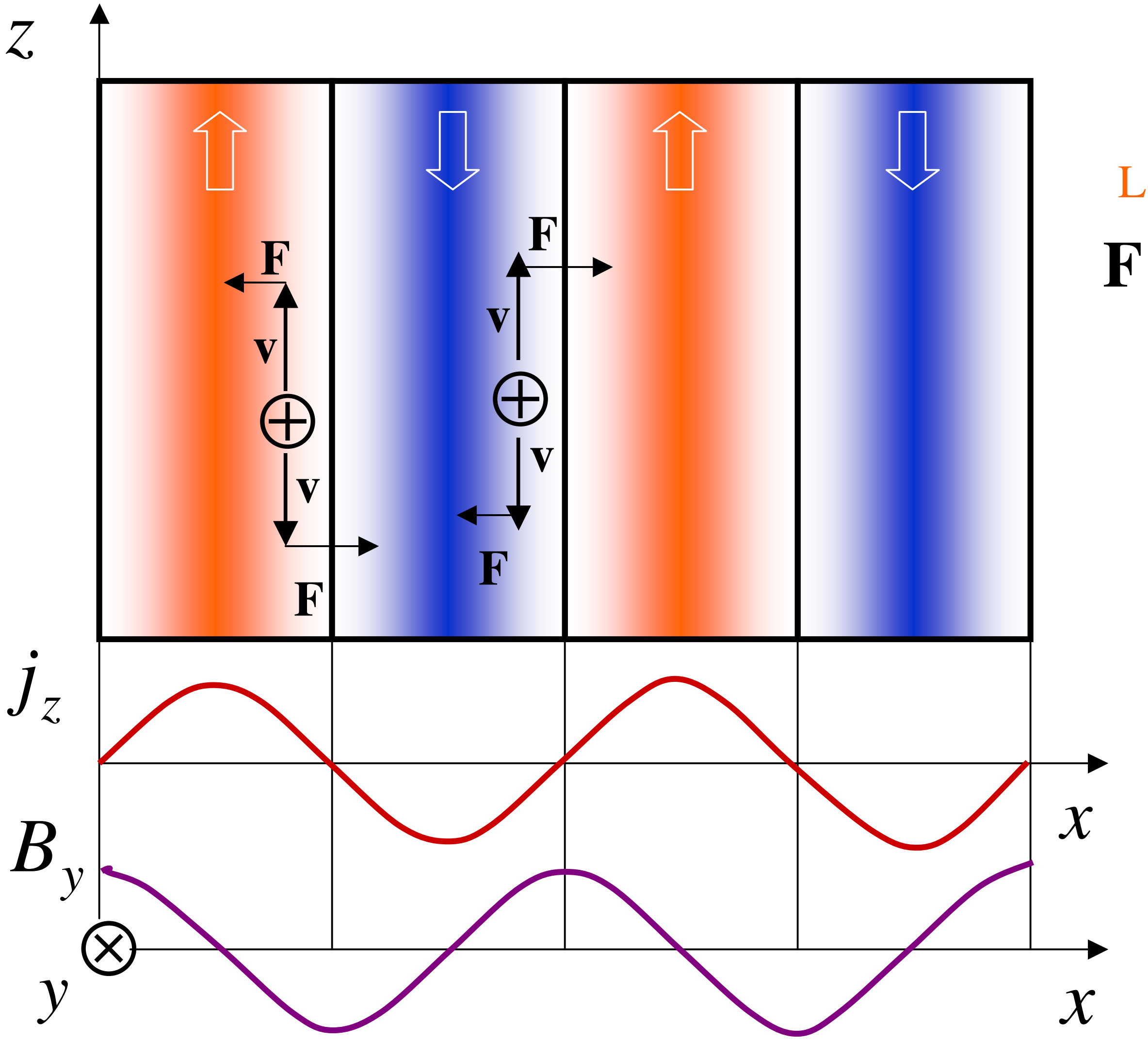
$$\boxed{\left\langle j_a^{\mu}(x_1)\, j_b^{\nu}(x_2)\right\rangle = \frac{1}{2}\delta^{ab}\int \frac{d^3p}{(2\pi)^3}\frac{p^{\mu}p^{\nu}}{E_p^2} f(\mathbf{p})\delta^{(3)}(\mathbf{x}-\mathbf{v}t) \neq 0}$$

$$x_1 = (t_1, \mathbf{x}_1)\,, \quad x_2 = (t_2, \mathbf{x}_2)\,, \quad x = (t_1 - t_2, \mathbf{x}_1 - \mathbf{x}_2)$$



Direction of the momentum surplus

Mechanism of filamentation



Lorentz force

$$\mathbf{F} = q\,\mathbf{v}\times\mathbf{B}$$

Ampere's law

$$\nabla\times\mathbf{B} = \mathbf{j}$$

Growth of instabilities – 1+1 numerical simulations

SU(2) Hard Loop Dynamics

1+1 dimensions

$$A_a^\mu = A_a^\mu(t, z)$$

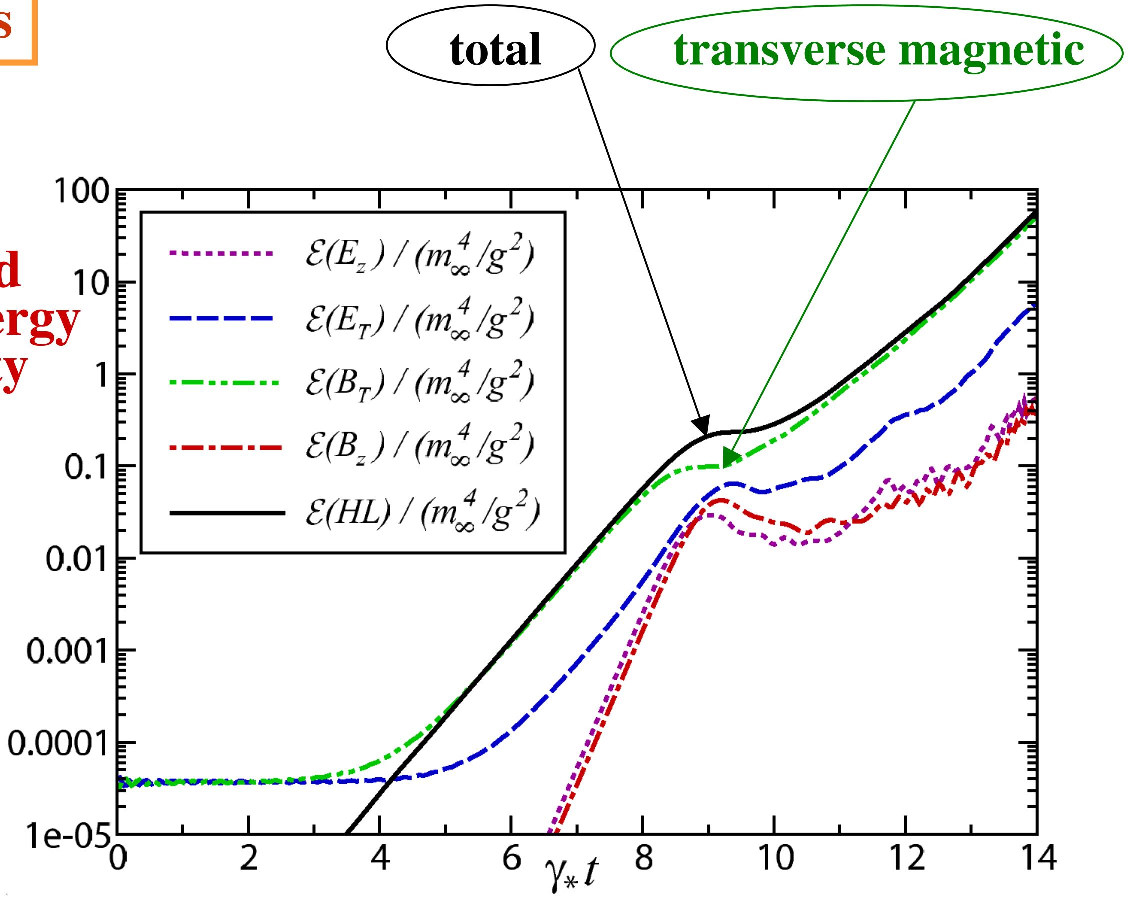
Anisotropic particle's momentum distribution

$$f(\mathbf{p}) = f_{\text{iso}}(|\,\mathbf{p}\,| + \zeta p_z)$$

$$m_D^2 = -\frac{\alpha_s}{\pi}\int_0^\infty dp\,p^2\,\frac{df_{\text{iso}}(p)}{dp}$$

$$(m_D, \zeta)$$

Scaled field energy density



total

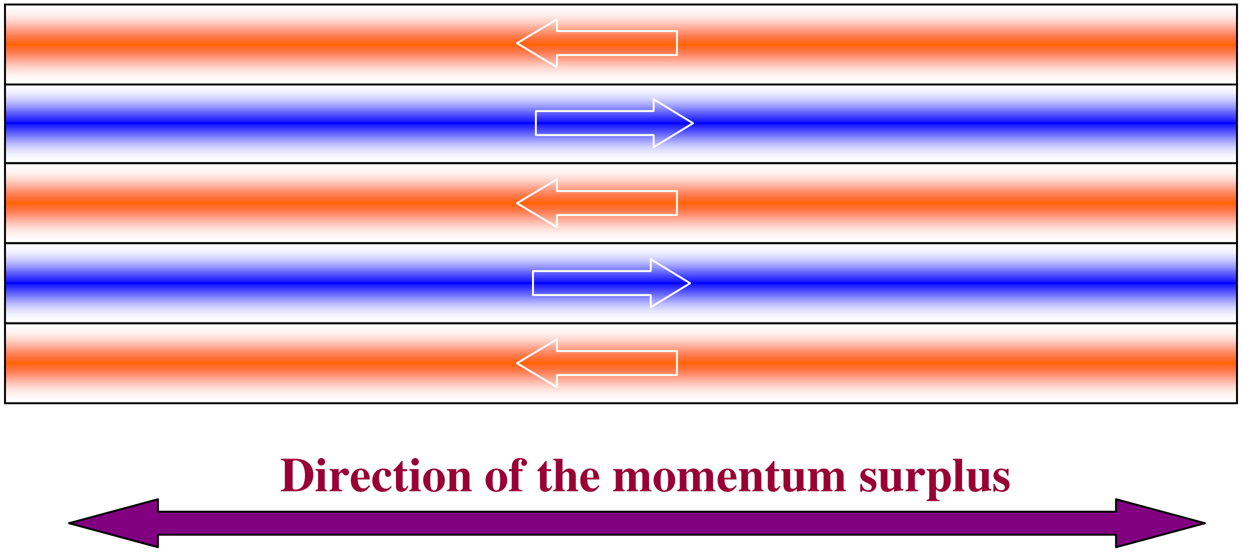
transverse magnetic

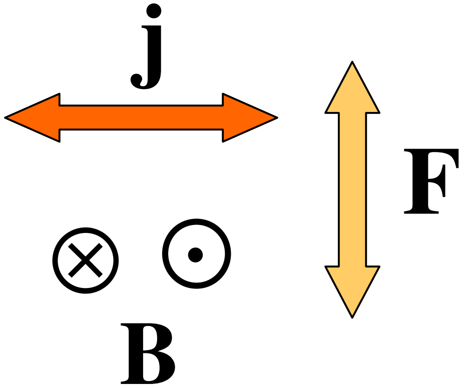
Strong anisotropy $\zeta = 10$

γ_* - maximal growth rate

A. Rebhan, P. Romatschke & M. Strickland, Phys. Rev. Lett. **94**, 102303 (2005)

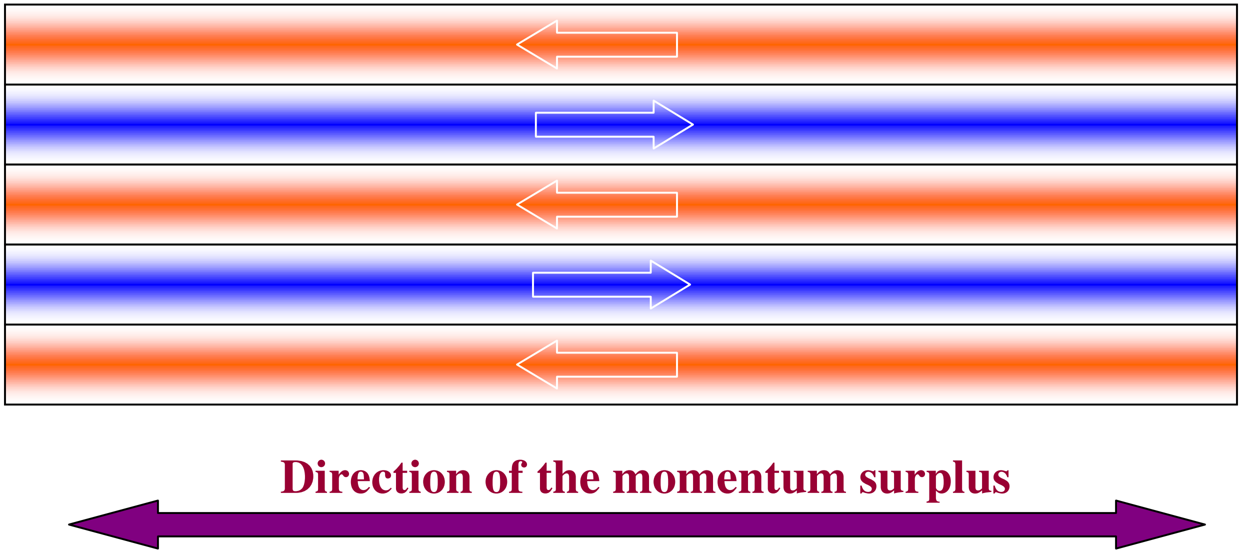
Isotropization - particles

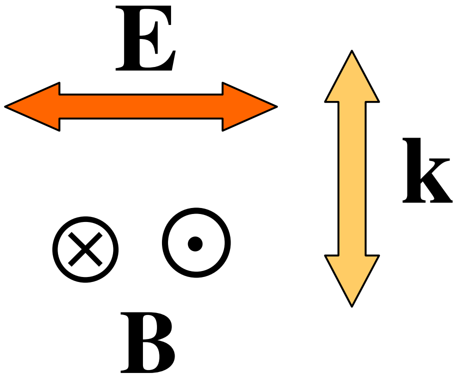




$$\boxed{\Delta \mathbf{p} = \int dt\, \mathbf{F}}$$

Isotropization - fields





$$\boxed{\mathbf{P}_{\text{fields}} \sim \mathbf{B}^{a} \times \mathbf{E}^{a} \sim \mathbf{k}}$$

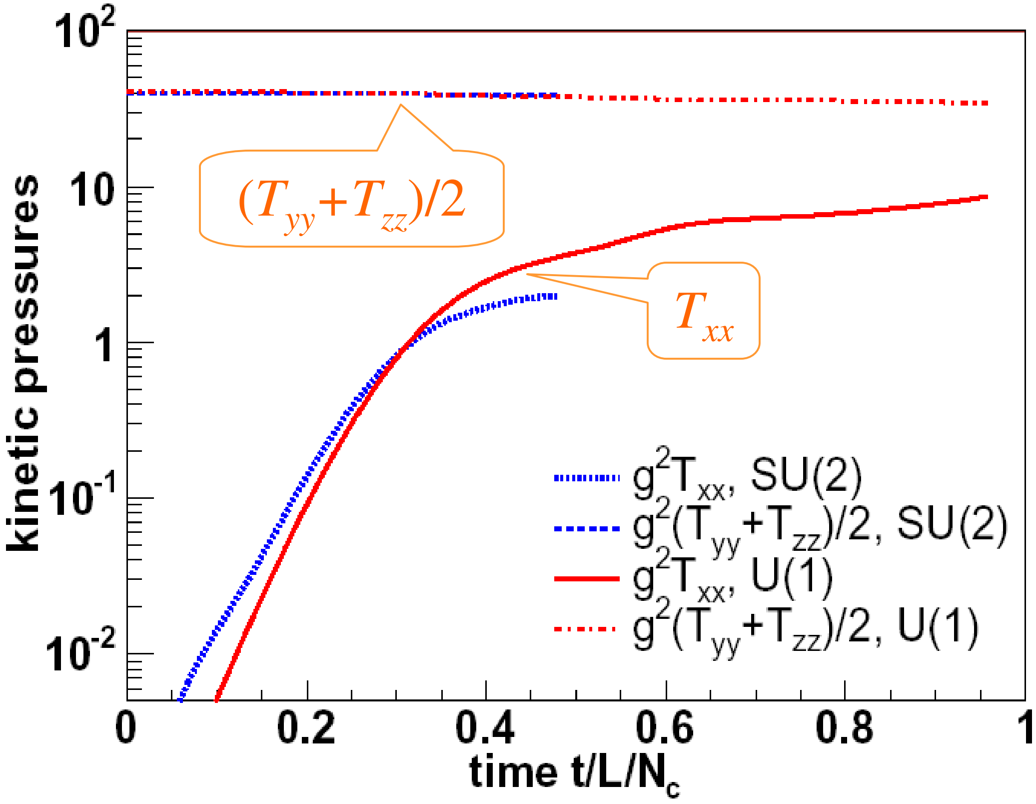
Isotropization – numerical simulation

Classical system of colored particles & fields

$$T_{ij} = \int \frac{d^3p}{(2\pi)^3} \frac{p_i p_j}{E} f(\mathbf{p})$$

Isotropy:

$$T_{xx} = (T_{yy} + T_{zz})/2$$

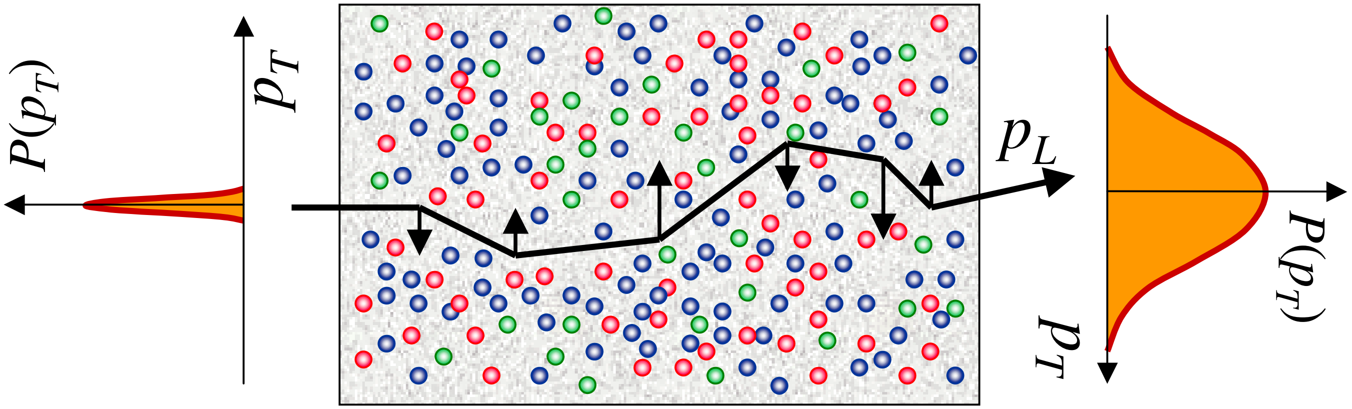


$(T_{yy}+T_{zz})/2$

T_{xx}

A. Dumitru & Y. Nara, Phys. Lett. **B621**, 89 (2005).

Momentum broadening of a fast parton



Radiative energy loss of a fast parton is controlled by $\hat{q} \equiv \dfrac{d\left\langle \Delta p_T^2(t)\right\rangle}{dt}$

$$\hat{q} \sim e^{2\gamma t}$$

in unstable QGP

A. Majumder, B. Müller & St. Mrówczyński, Phys.Rev. **D80** (2009) 125020

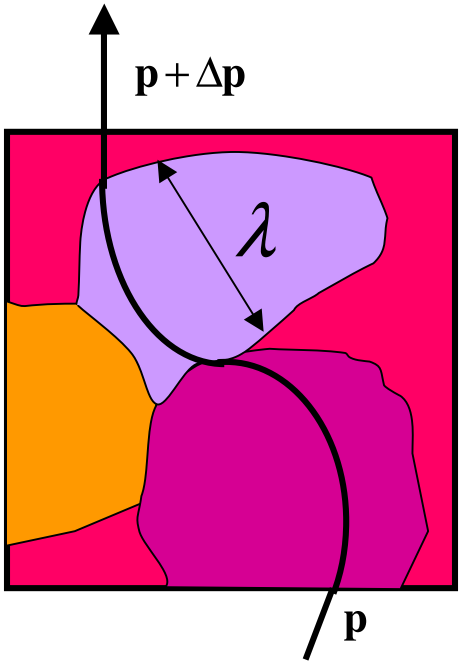
Viscosity of turbulent QGP

Magnetized turbulent QGP

collisional viscosity: $\eta_C \sim \dfrac{T^3}{\alpha_s^2 \ln(1/\alpha_s)}$

anomalous viscosity: $\eta_A \sim \dfrac{1}{g^2 \langle \mathbf{B}^2 \rangle \lambda}$

λ - size of magnetic domain



$$\frac{1}{\eta} = \frac{1}{\eta_A} + \frac{1}{\eta_C}$$

Viscosity of magnetized turbulent QGP is small

M. Asakawa, S.A. Bass and B. Müller, Prog. Theor. Phys. **116**, 725 (2007)

Possible conclusion

Weakly coupled magnetized turbulent QGP
can behave as strongly coupled plasma

RHIC vs. LHC

Collision energy

$$\sqrt{s} = \begin{cases} 200\ \text{GeV/NN} - \text{RHIC} \\ 5500\ \text{GeV/NN} - \text{LHC} \end{cases} \qquad \frac{\sqrt{s}_{\text{LHC}}}{\sqrt{s}_{\text{RHIC}}} \approx 30$$

Initial energy density

$$\varepsilon_i \approx \begin{cases} 30\,\text{GeV/fm}^3 - \text{RHIC} \\ 130\,\text{GeV/fm}^3 - \text{LHC} \end{cases}$$

Initial temperature

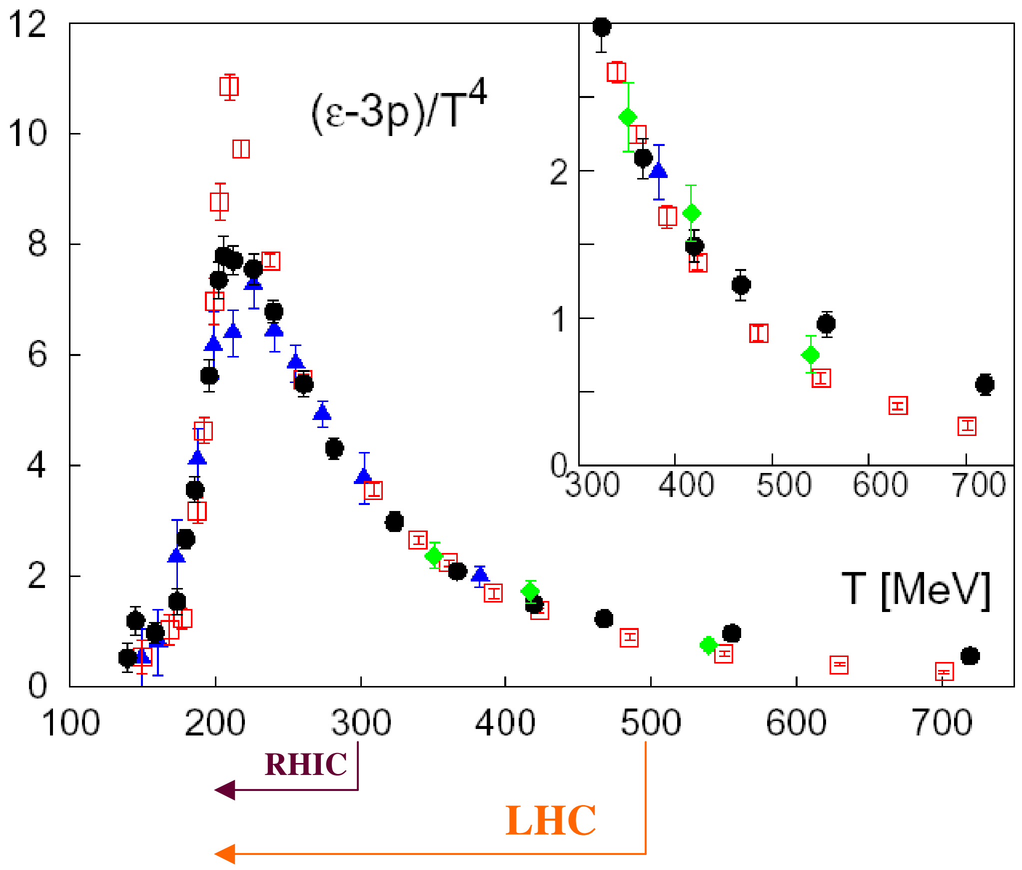
$$T_i \approx \begin{cases} 350\,\text{MeV} - \text{RHIC} \\ 500\,\text{MeV} - \text{LHC} \end{cases}$$

RHIC vs. LHC cont.

Lattice thermodynamics of Quark-Gluon Plasma

Ideal EoS

$$p = \frac{1}{3}\varepsilon$$



F. Karsch, arXiv:0711.0656 [hep-lat].

No conclusion

QGP @ LHC ?