Relativistic HICs at energies from FAIR to LHC

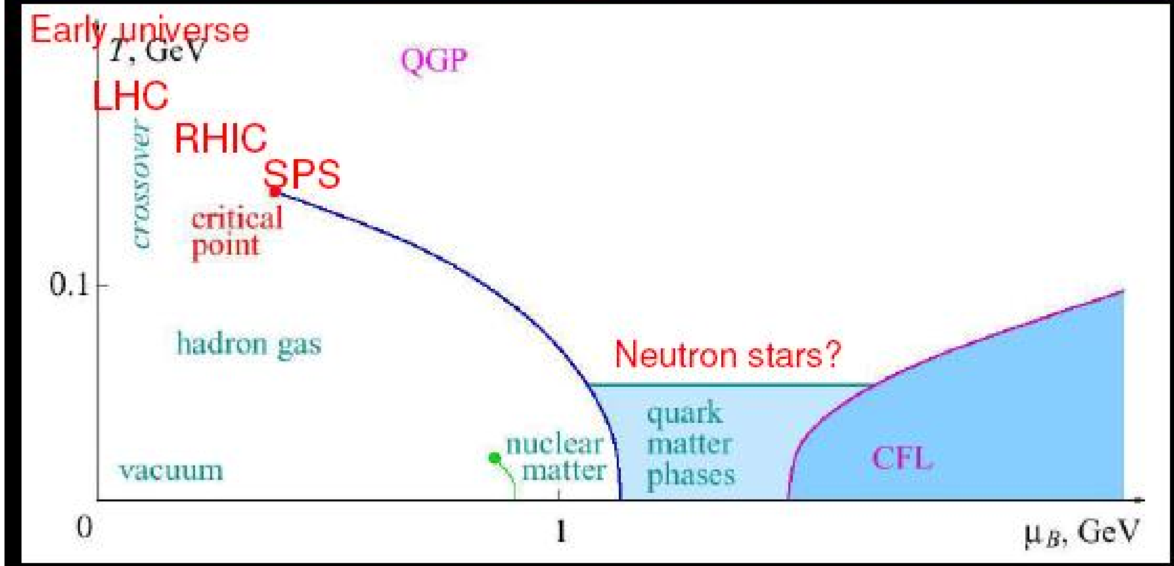
L.Bravina (UiO)

in collaboration with

colleagues from universities of Oslo, Moscow, Tuebingen, Frankfurt a.M., Kiev, and from GSI, ITEP and JINR

3rd Light Ion Nuclear Collision Workshop, IHEP(Protvino), 19.06.2008

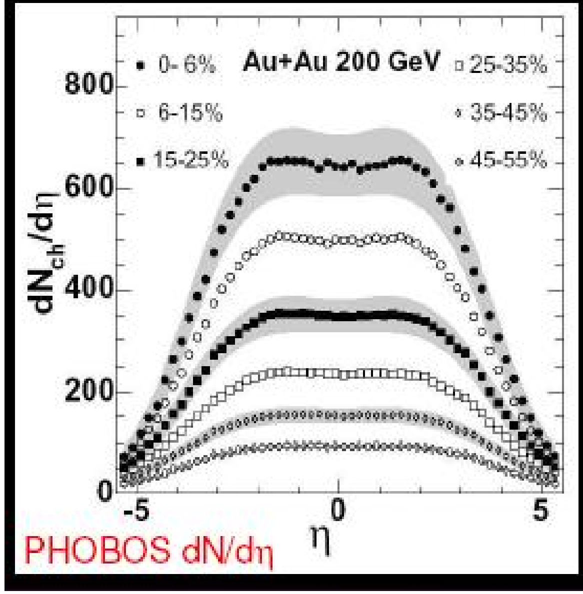
The phase diagram of strongly interacting matter

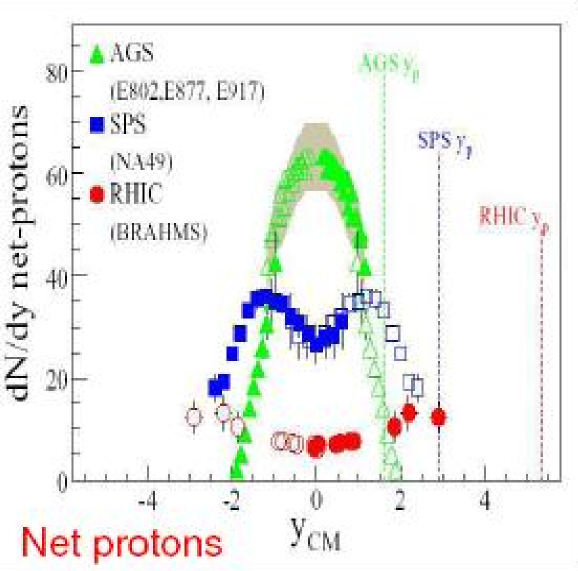


Transition between hadron gas and matter with deconfined quarks and gluons expected for a critical energy density of $\varepsilon_c \sim 1.0$ GeV/fm³.

Bjorken's estimate of initial energy density:

$$\varepsilon = \frac{d\langle E_T\rangle}{dy}\frac{1}{\pi R^2 c\tau} = \frac{dN}{dy}\frac{\langle m_T\rangle}{\pi R^2 c\tau}$$





Measurements of rapidity densities and energy distributions of hadrons give (with $\tau<1$ fm/c):

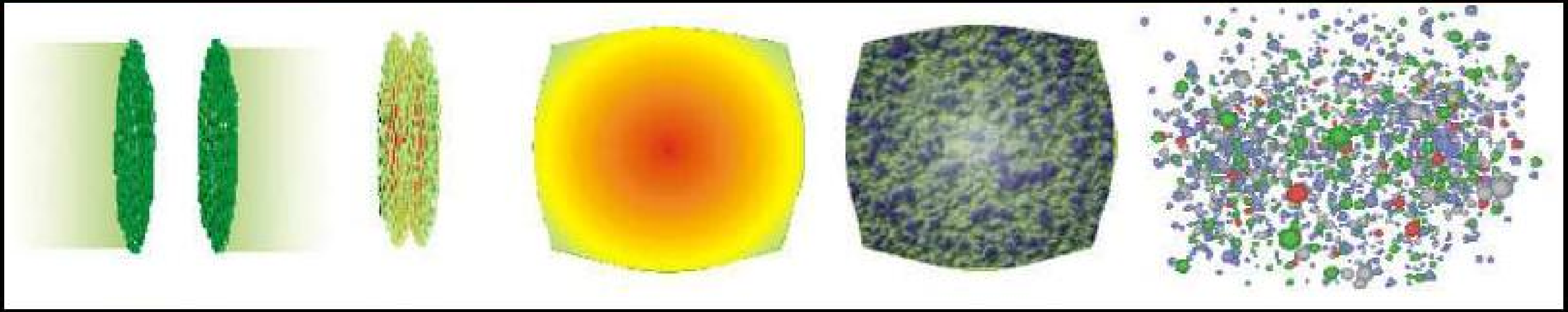
$\varepsilon > 3$ GeV/fm³ (SPS), and

$\varepsilon > 5$ GeV/fm³ (RHIC).

Baryochemical potential μ_B falling with increasing CM energy.

Do we create a QGP in the lab, and what is its properties?

Stages of an ultrarelativistic heavy-ion collision

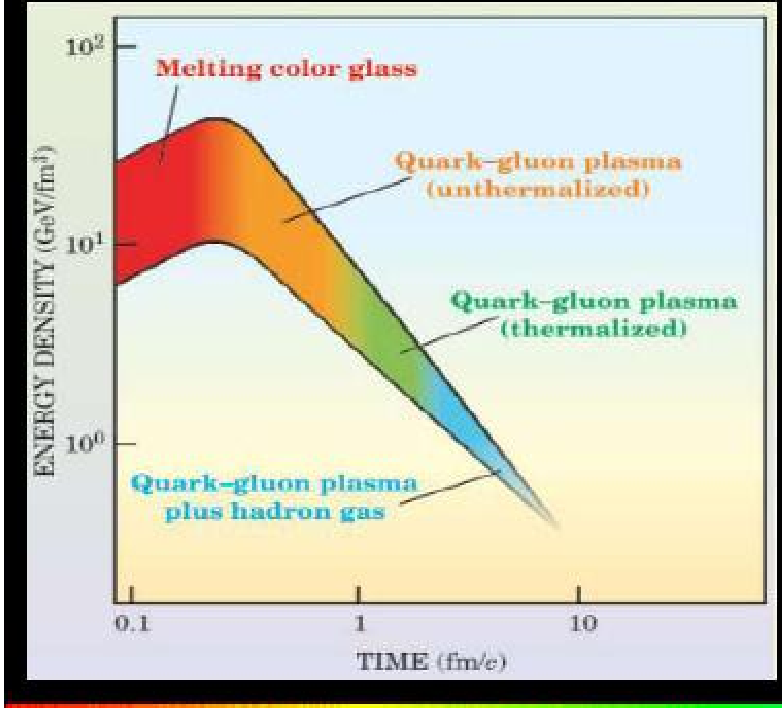


Initial state in colliding nuclei

Gluon-dominated preequilibrium

Quark-gluon matter

Hadron gas



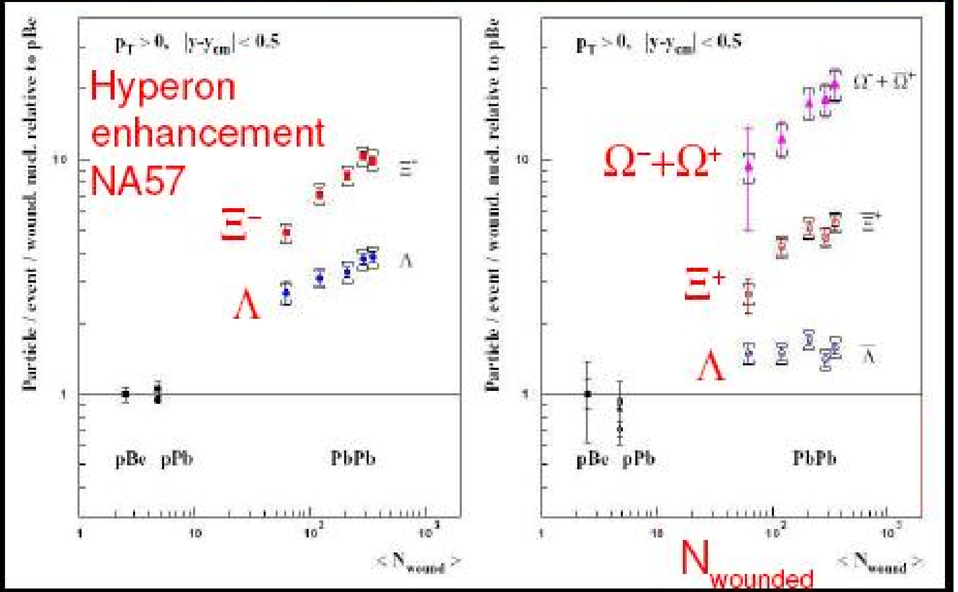
- Initial stage: Hard partonic collisions described by pQCD. Partons materializing from gluon fields.
- Formation of a quark-gluon plasma, approaching equilibrium through multiple interactions. Initial temperature of several hundred MeV. Violent expansion and cooling.
- Hadronization when the plasma reaches $T_c \sim 170$ MeV, through parton fragmentation or quark coalescence.
- Chemical and finally kinetic freezeout. Only variables surviving to this stage are observable.

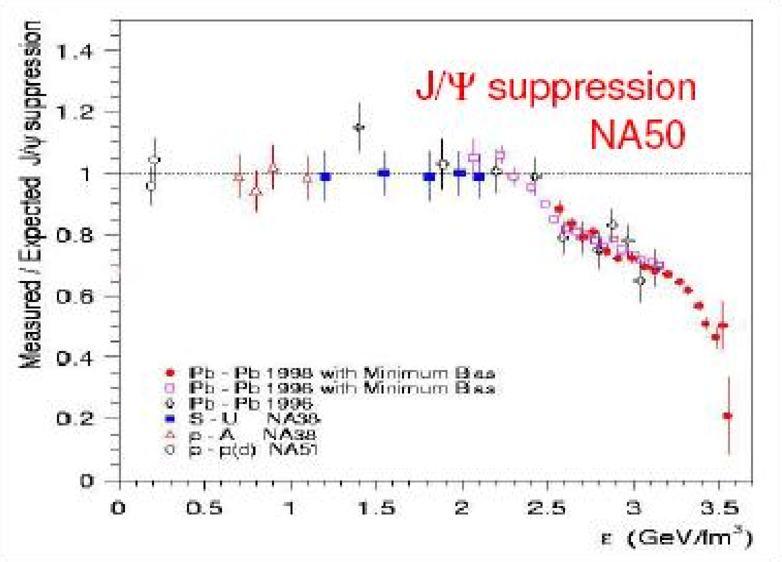
SPS: Signatures of a new phase of matter?

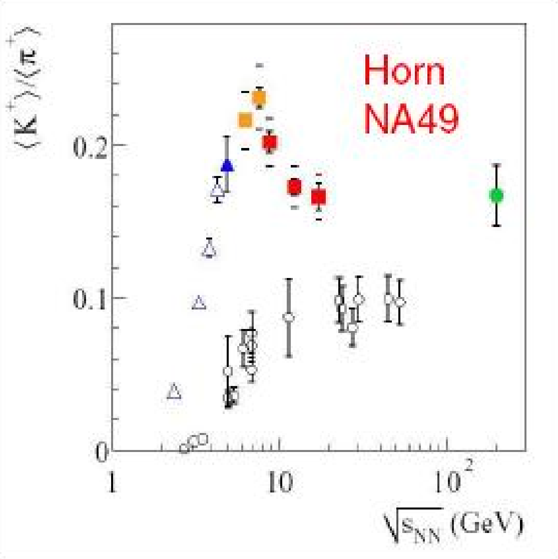
- Hyperon enhancement: Quark coalescence instead of multistep hadronic reactions?

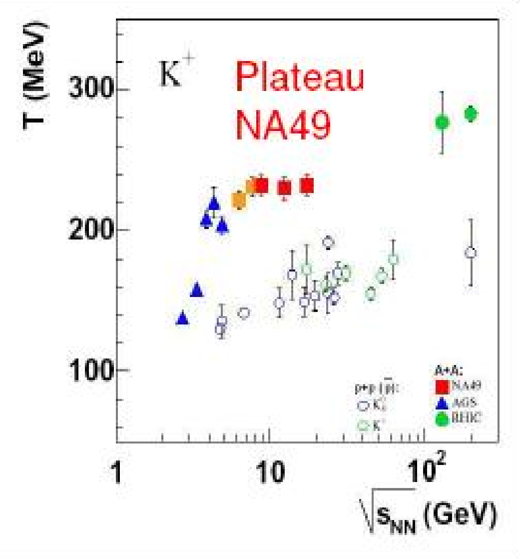
- J/ψ suppression: charm-anticharm dissociation in deconfined matter?

- Horn in K^+/π^+ ratio and plateau in T (inverse slope) of K^+ (actually π, K, p): Phase transition at critical point at lower SPS energies?

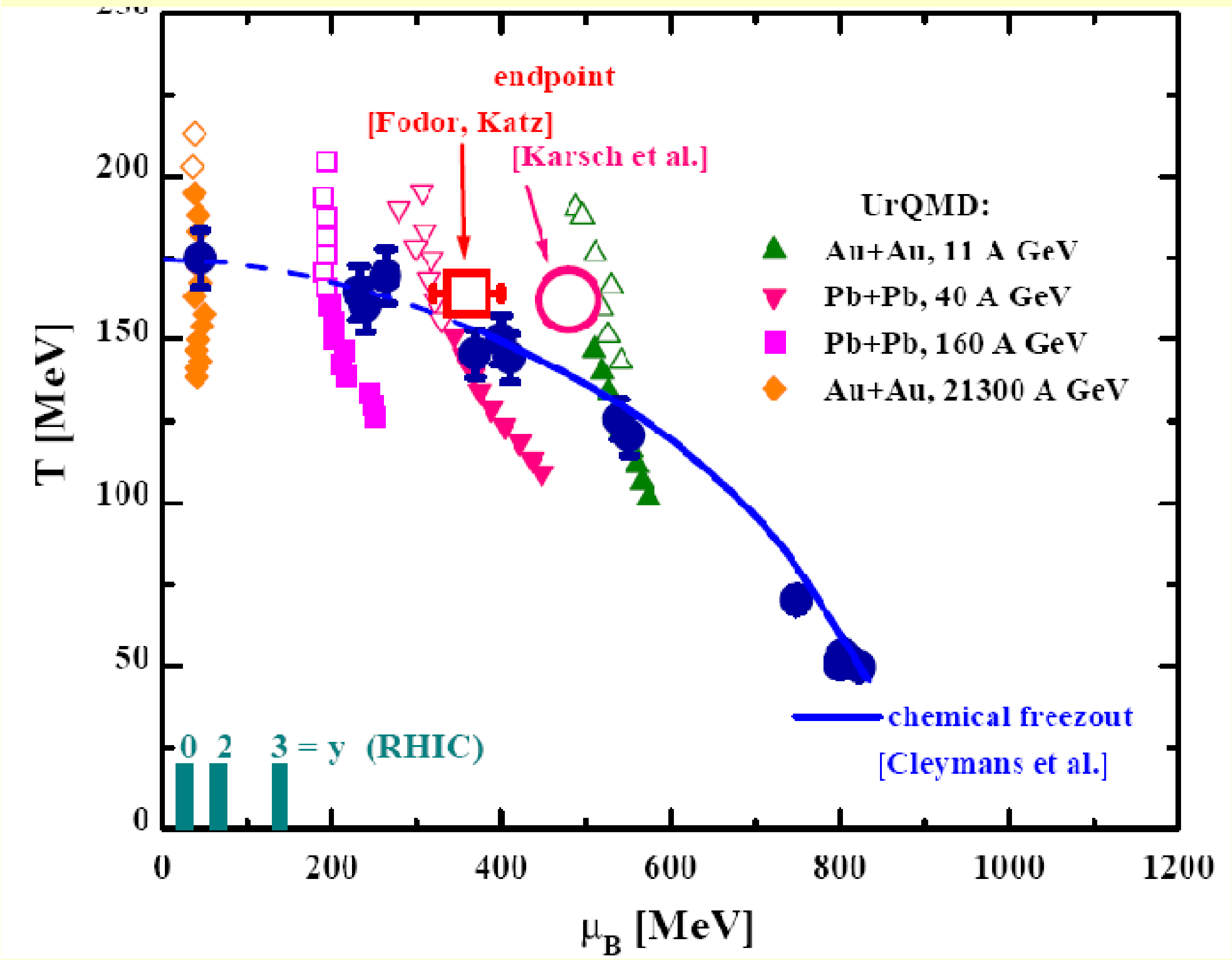








Equation of State



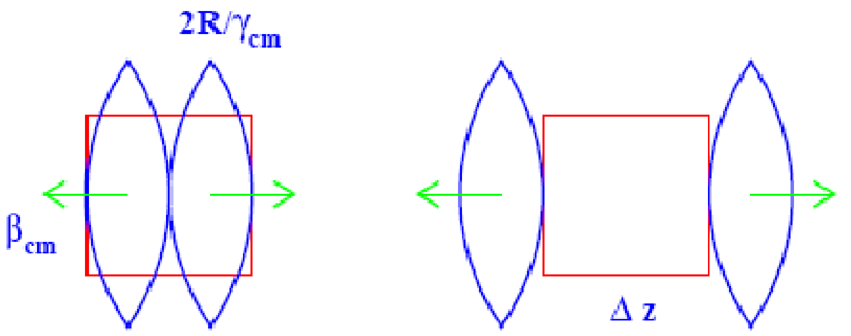
Tricritical point is located around 10-40 GeV (LQCD)

We have to explore this energy range to study the possible phase transition

QGP can be formed already at low energies

H. Stoecker, nucl-th/0506013
L. Bravina et al., PRC 60 (1999) 024904; 63 (2001) 064902

Equilibration in the Central Cell



$t^{cross} = 2R/(\gamma_{cm}\,\beta_{cm})$

$t^{eq} \geq t^{cross} + \Delta z/(2\beta_{cm})$

Kinetic equilibrium:

Isotropy of velocity distributions

Isotropy of pressure

Thermal equilibrium:

Energy spectra of particles are described by Boltzmann distribution

$$\frac{dN_i}{4\pi p E dE} = \frac{V g_i}{(2\pi\hbar)^3} \exp\left(\frac{\mu_i}{T}\right) \exp\left(-\frac{E_i}{T}\right)$$

Chemical equilibrium:

Particle yields are reproduced by SM with the same values of $(T,\ \mu_B,\ \mu_S)$:

$$N_i = \frac{V g_i}{2\pi^2\hbar^3} \int_0^\infty p^2 dp \exp\left(\frac{\mu_i}{T}\right) \exp\left(-\frac{E_i}{T}\right)$$

Statistical model of ideal hadron gas

input values

output values

$$\varepsilon^{\mathrm{mic}} = \frac{1}{V}\sum_i E_i^{\mathrm{SM}}(T,\mu_{\mathrm{B}},\mu_{\mathrm{S}}),$$

$$\rho_{\mathrm{B}}^{\mathrm{mic}} = \frac{1}{V}\sum_i B_i \cdot N_i^{\mathrm{SM}}(T,\mu_{\mathrm{B}},\mu_{\mathrm{S}}),$$

$$\rho_{\mathrm{S}}^{\mathrm{mic}} = \frac{1}{V}\sum_i S_i \cdot N_i^{\mathrm{SM}}(T,\mu_{\mathrm{B}},\mu_{\mathrm{S}}).$$

Multiplicity

Energy

Pressure

Entropy density

$$N_i^{\mathrm{SM}} = \frac{V g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 f(p,m_i)dp,$$

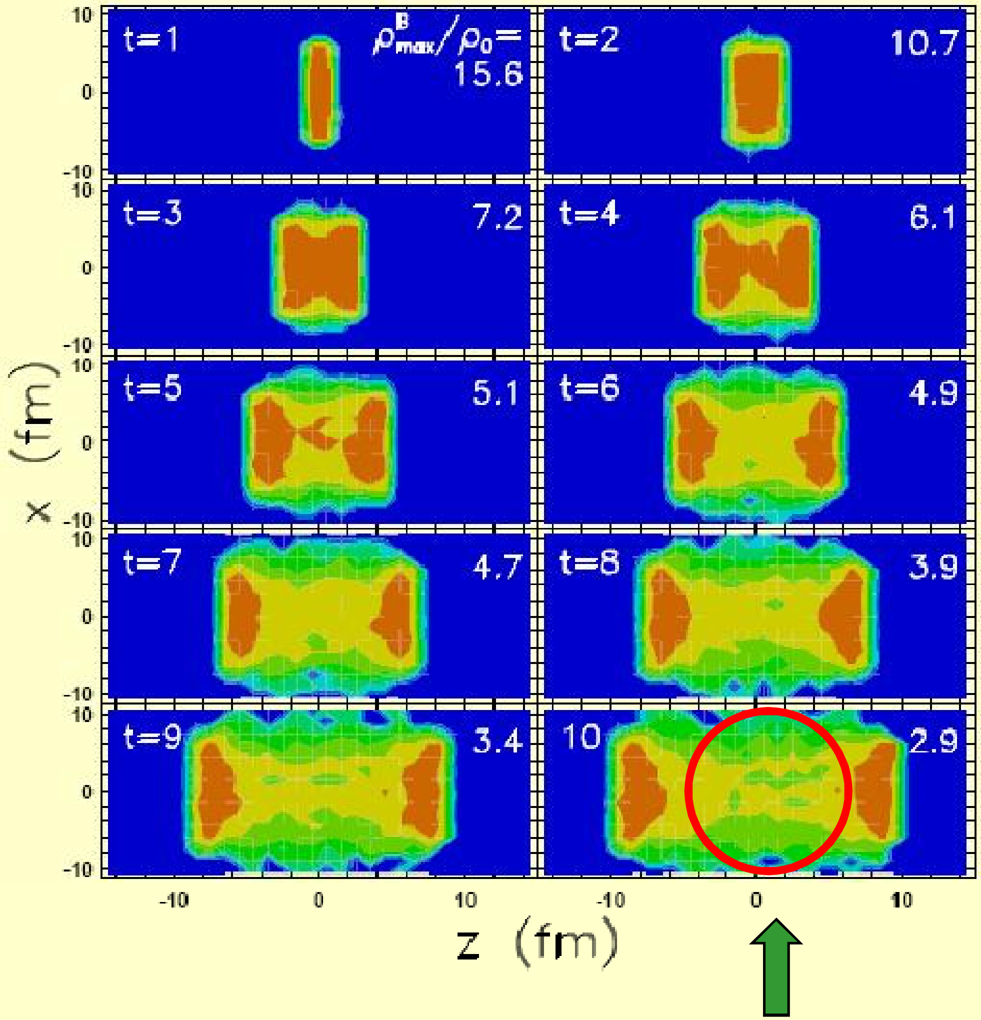
$$E_i^{\mathrm{SM}} = \frac{V g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 \sqrt{p^2+m_i^2}\, f(p,m_i)dp$$

$$P^{\mathrm{SM}} = \sum_i \frac{g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 \frac{p^2}{3(p^2+m_i^2)^{1/2}}\, f(p,m_i)dp$$

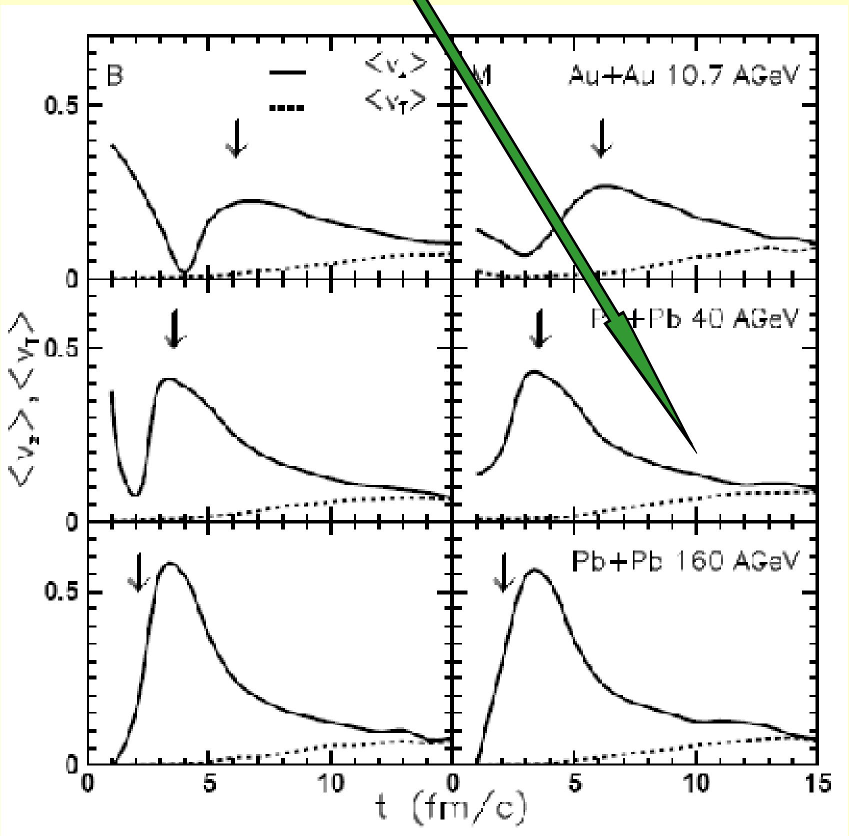
$$s^{\mathrm{SM}} = -\sum_i \frac{g_i}{2\pi^2\hbar^3}\int_0^\infty f(p,m_i)\,\left[\ln f(p,m_i)-1\right]\,p^2dp$$

Pre-equilibrium Stage

Homogeneity of baryon matter



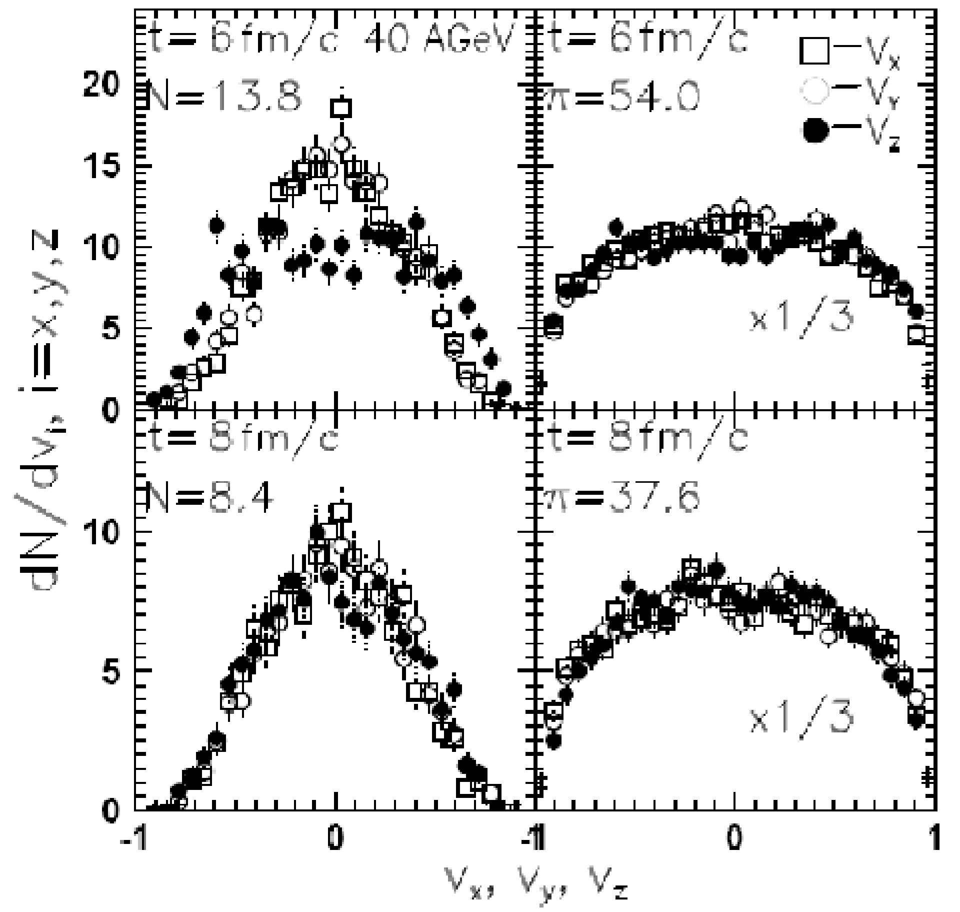
Absence of flow



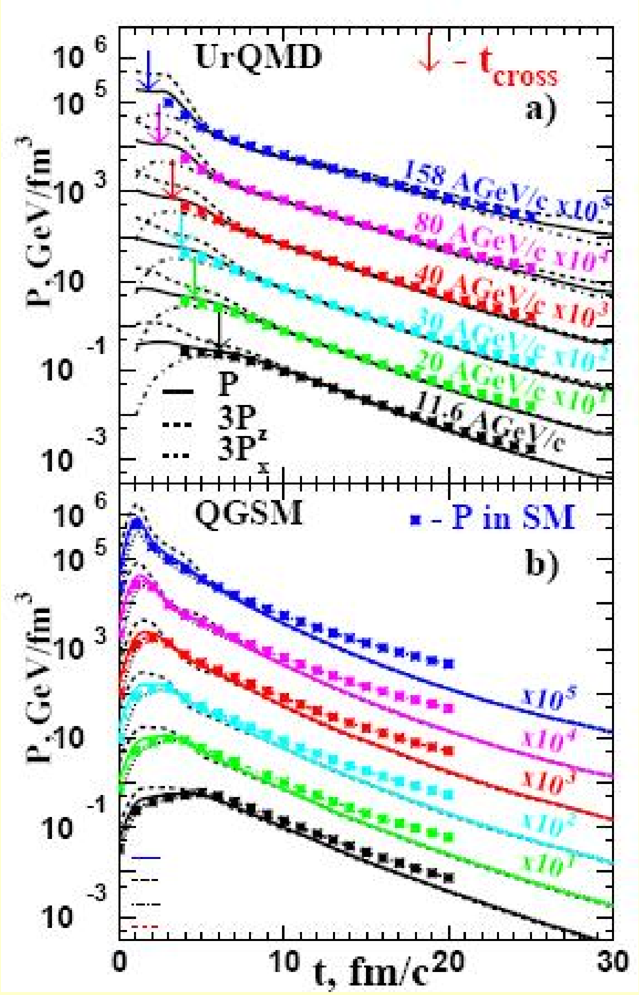
The local equilibrium in the central zone is quite possible

Kinetic Equilibrium

Isotropy of velocity distributions



Isotropy of pressure

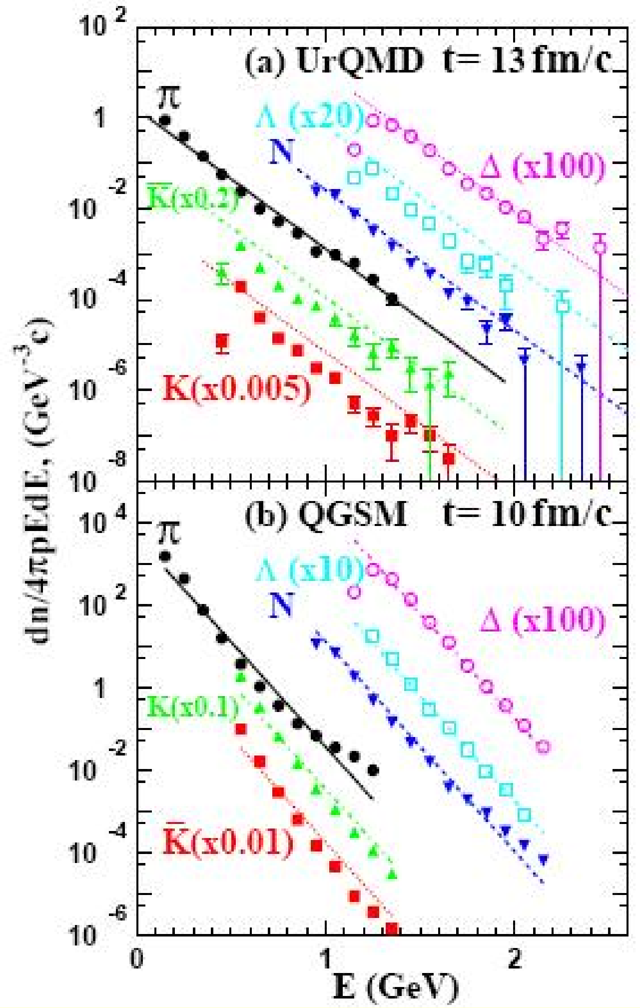


L.B. et al., arXiv:0804.1484

Velocity distributions and pressure become isotropic for all energies

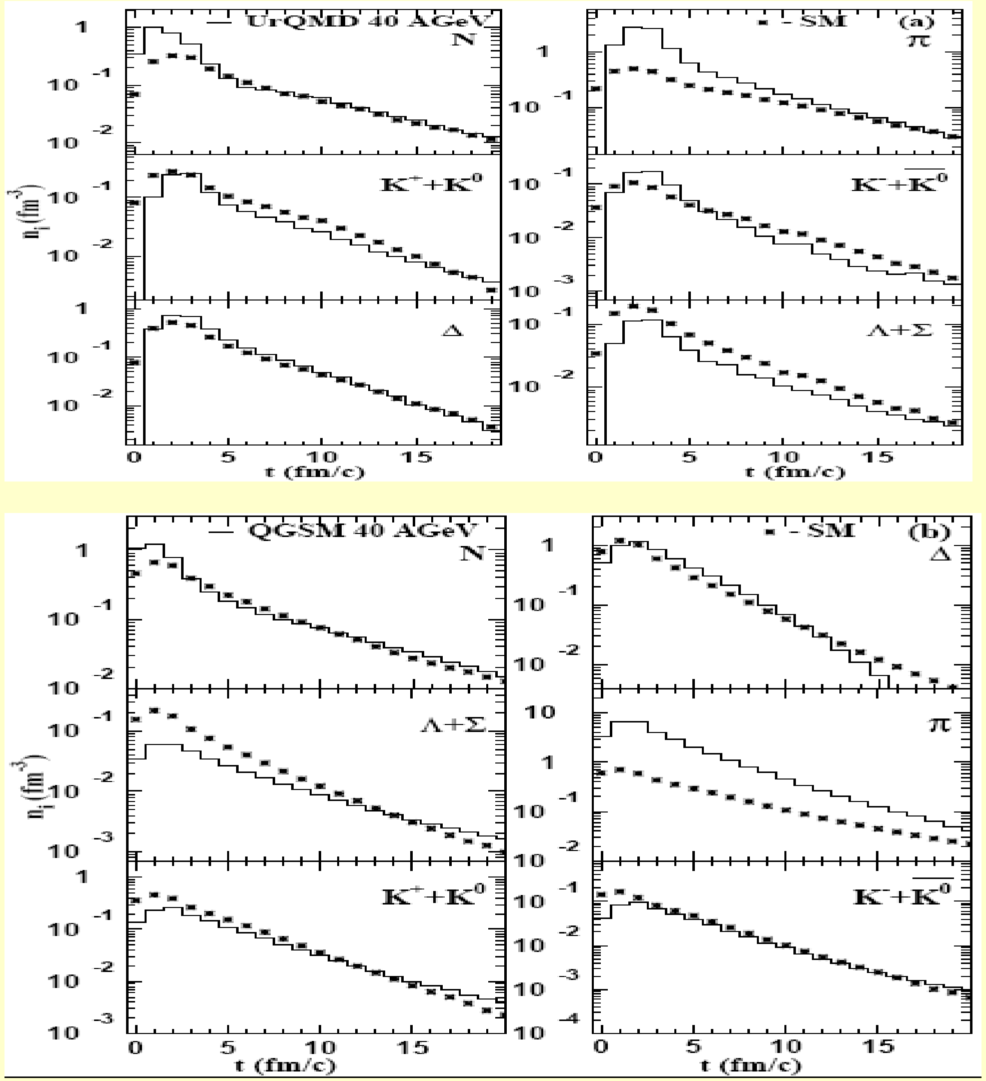
Thermal and Chemical Equilibrium

Boltzmann fit to the energy spectra



L.B. et al., arXiv:0804.1484

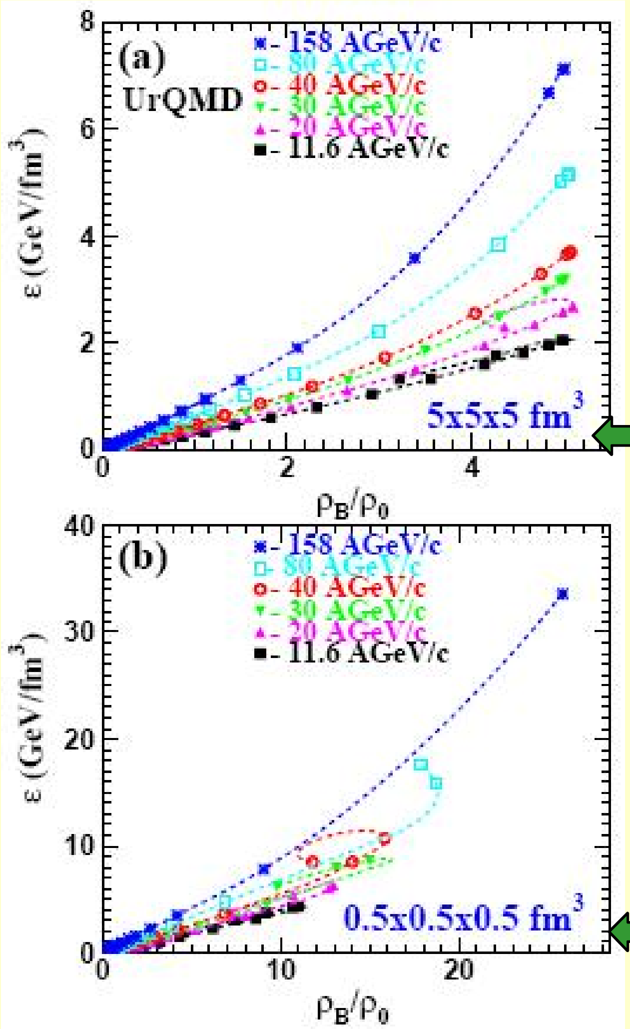
Particle yields



Thermal and chemical equilibrium seems to be reached

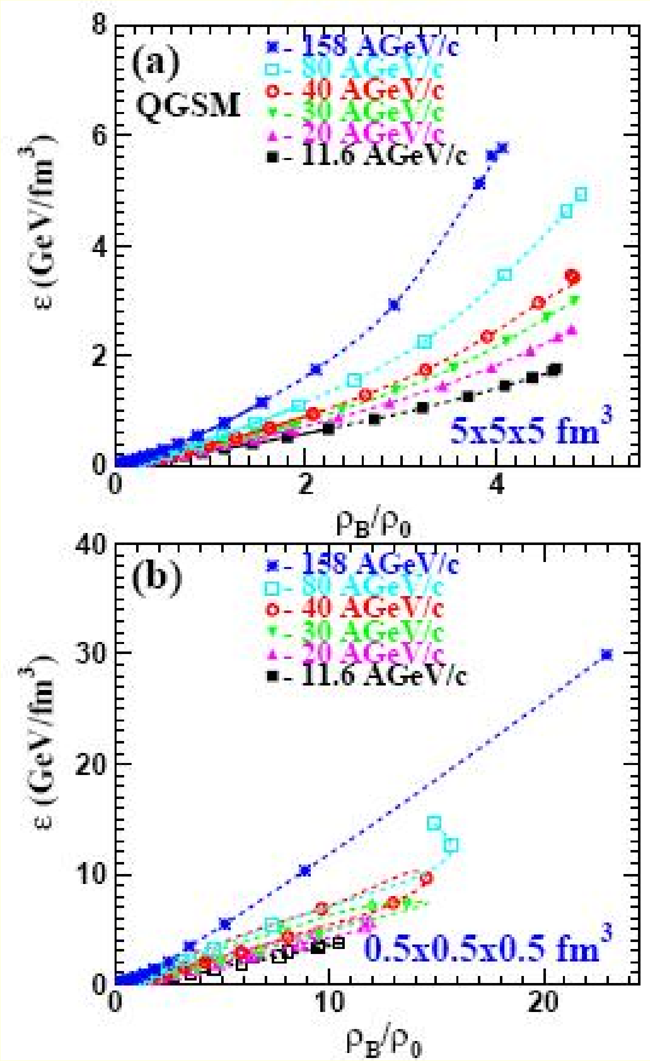
How dense can be the medium?

L.B. et al., arXiv:0804.1484



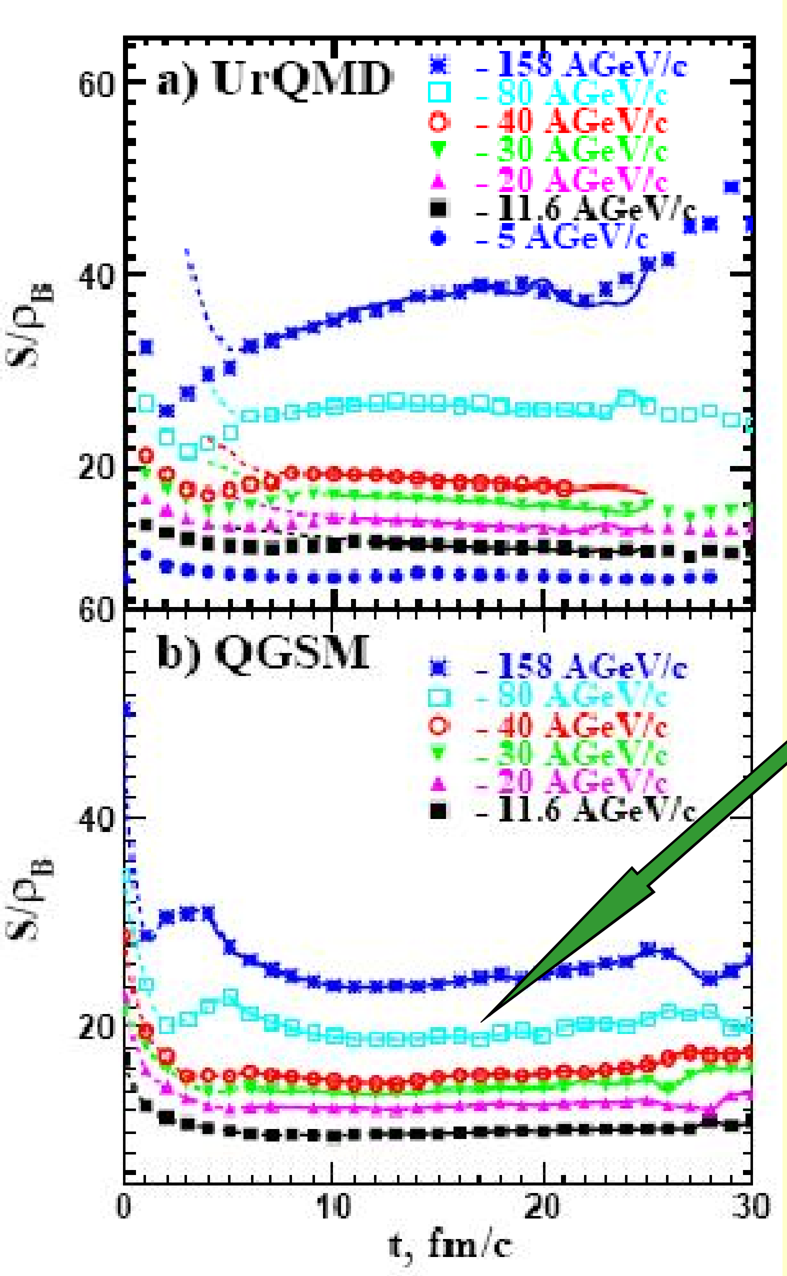
”Big” cell (V = 5x5x5 fm^3)

“Small” cell (V => 0)



Dramatic differences at the non-equilibrium stage; after beginning of kinetic equilibrium the energy densities and the baryon densities are the same for ”small” and ”big” cell

Isentropic expansion

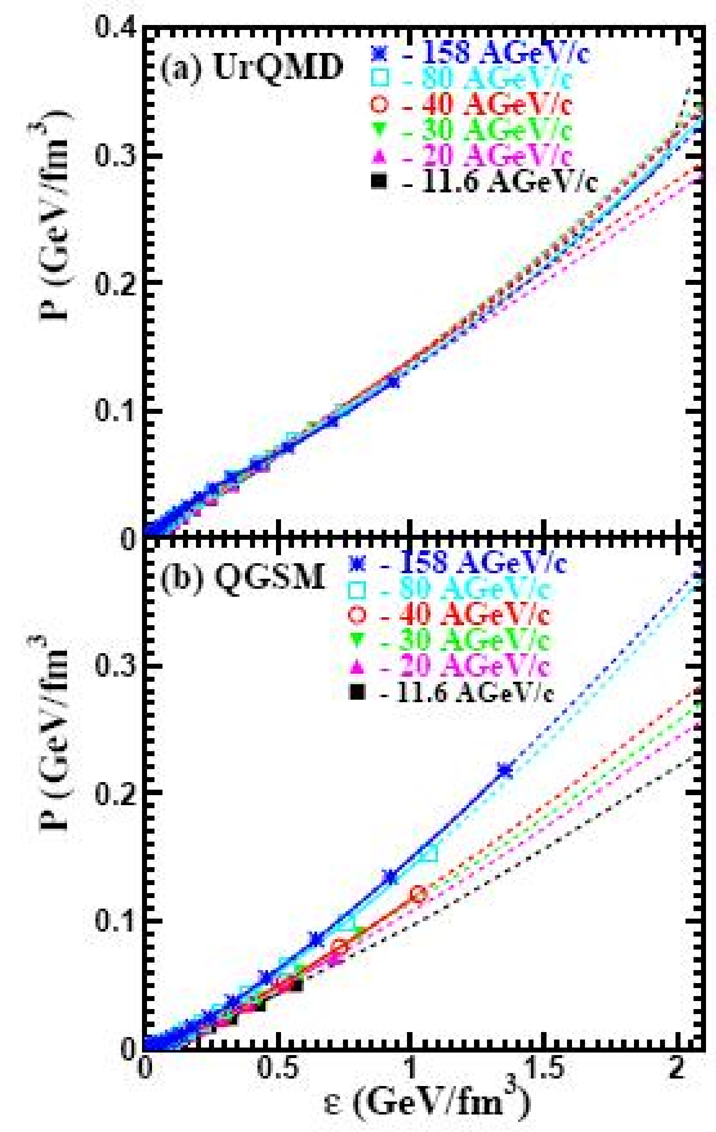


Expansion proceeds isentropically (with constant entropy per baryon). This result supports application of hydrodynamics

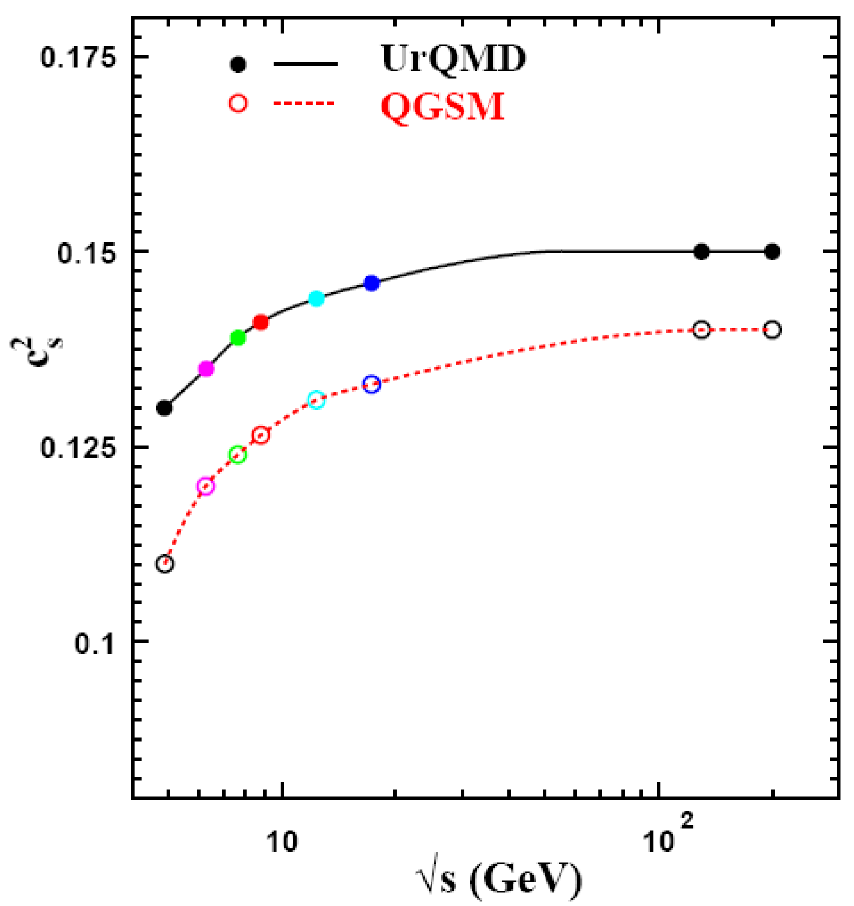
$$s/\rho_B = \mathrm{const} = 12(\mathrm{AGS}),\ 20(40),\ 38(\mathrm{SPS})$$

Equation of State in the cell

pressure vs. energy



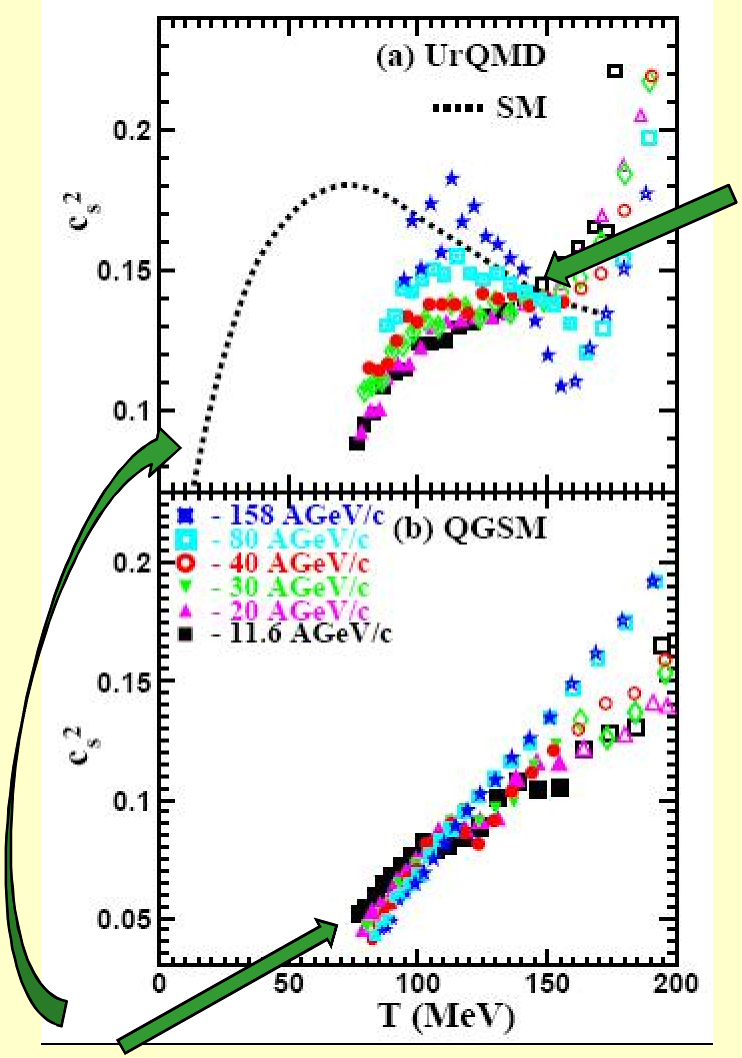
sound velocity



$$P/\varepsilon = 0.13(\mathrm{AGS}),\ 0.14(40),\ 0.146(\mathrm{SPS}),\ 0.15(\mathrm{RHIC})$$

Equation of State: sound velocity vs. T

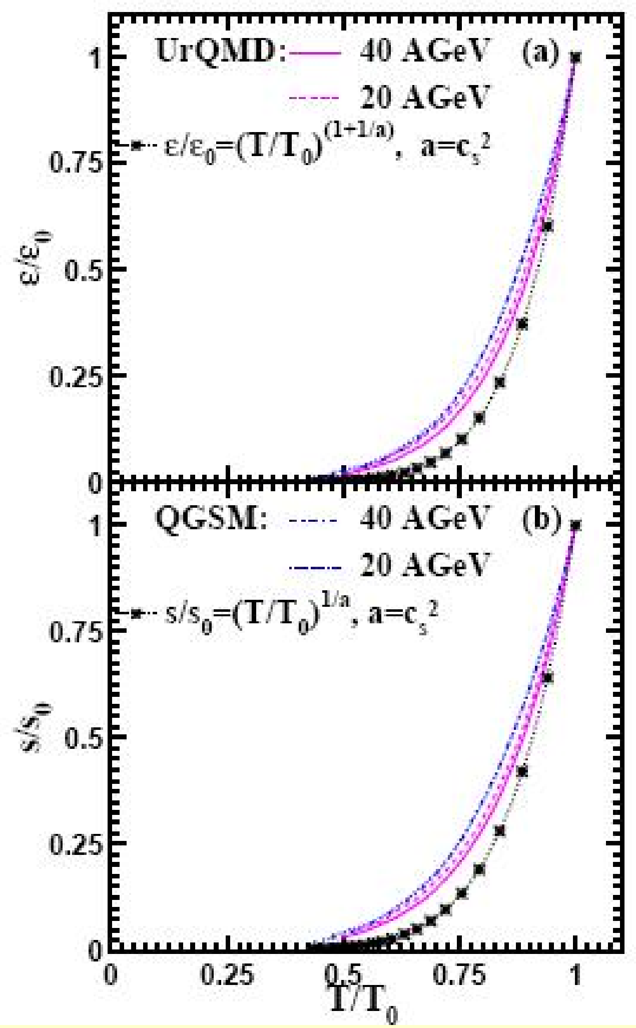
comparison with Hagedorn model



Heavy resonances

Big difference between models with and w/o heavy resonances

energy and entropy densities



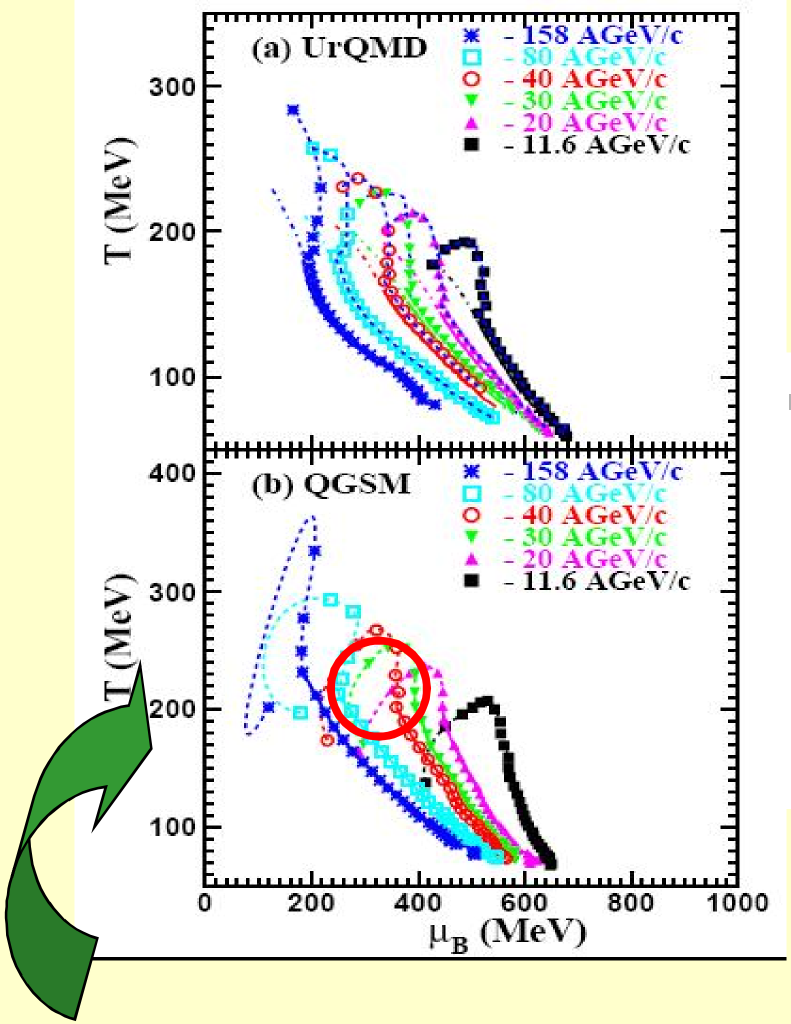
L.B. et al., arXiv:0804.1484

Still c_s2 drops faster than in Hagedorn model**
Non-zero chemical potential ?

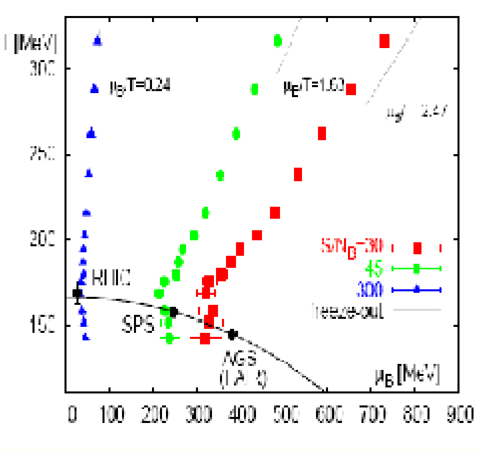
No difference between the models

EOS in the cell: observation of knee

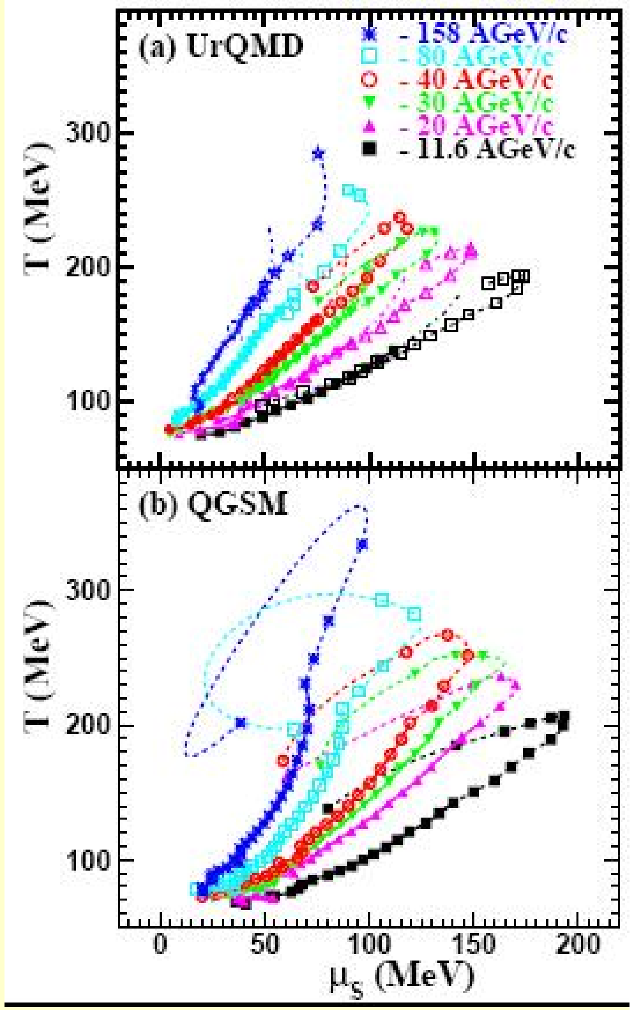
temperature vs. chemical potentials



L.B. et al.,
arXiv:0804.1484



S. Ejiri et al., PRD 73 (2006) 054506



The “knee” is similar to that in 2-flavor lattice QCD

Conclusions at FAIR to SPS so far

- *There is a kinetic equilibrium stage of hadron-string matter in the central cell at t > 8 fm/c*
- *The ratio P/e is approximately constant and equals 0.12 (AGS), 0.14 (40 AGeV), and 0.15 (SPS & RHIC) => onset of saturation*
- *Entropy per baryon ratio remains constant during the time interval 8 fm/c < t < 20 fm/c. This supports application of hydrodynamics*
- *Temperature vs. chemical potential: the knee structure which appears at the onset of equilibrium should be studied further*

http://uhkm.jinr.ru

UHKM- *Universal Hydro Kinetic Model*

The creation of the UHKM Universal Hydro Kinetic Model was initiated by Nikolai Amelin.

COLLABORATION:

UHKM development

R. Lednicky, T.A. Pocheptsov: Joint Institute for Nuclear Research, Dubna, Russia

I.P. Lokhtin, A.M. Snigirev , L.V. Malinina: Moscow State University, Institute of Nuclear Physics, Russia

Iu.A. Karpenko, Yu.M. Sinyukov: Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine

I. Arsene, L. Bravina, E. Zabrodin: Department of Physics, University of Oslo, Norway

A. Stavinsky, K. Mikhailov, S. Kiselev, Institute of Theoretical and Experimental Physics, Moscow (FASTMC-γ)

Implementation in AliRoot :

B.V. Batyunya, S.A. Zaporozhets, A.A. Fedunov Joint Institute for Nuclear Research, Dubna, Russia
I. Arsene Department of Physics, University of Oslo, Norway
L.V. Malinina: Moscow State University, Institute of Nuclear Physics, Russia

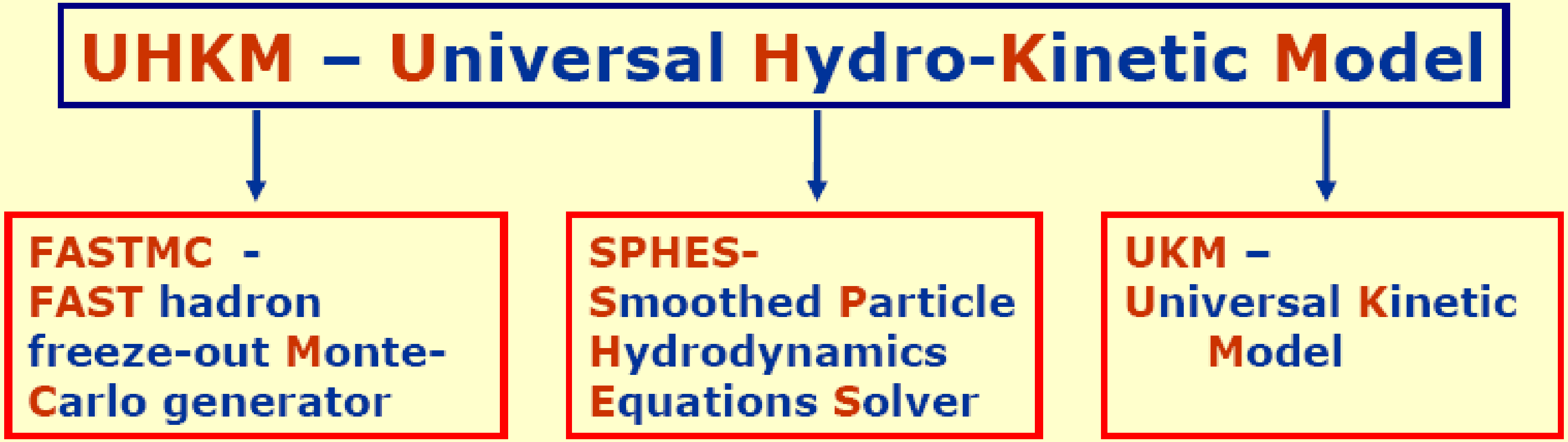
Outline

1. **UHKM – Universal Hydro-Kinetic Model**

2. **FASTMC - FAST hadron freeze-out Monte-Carlo generator**
   Introduction- motivation.
   Model parameters.
   Physical framework of the model
   Examples of calculations for RHIC
   Predictions for LHC

3. **FASTMC-J FASTMC+jets** high-pt part related to the partonic states **(PYTHIA+PYQUEN)**
   Status, Examples of calculation

UHKM – Universal Hydro-Kinetic Model



FASTMC -
FAST hadron freeze-out Monte-Carlo generator

SPHES-
Smoothed Particle Hydrodynamics Equations Solver

UKM –
Universal Kinetic Model

FASTMC - version 1: central collisions
version 2: extension on non-central collisions

FASTMC-J
FASTMC+jets
high-pt part related to the partonic states
(PYTHIA+PYQUEN)

FASTMC-γ
FASTMC+direct gammas

UKM- Phys.Rev.C73:044909,2006

FASTMC-1 Phys.Rev.C74:064901,2006.

FASTMC-2 Phys.Rev.C77:014903,2008.

FASTMC-Introduction-Motivation

- LHC very high hadron multiplicities ⟶
  fairly fast MC- generators for event simulation required

- **FASTMC**- fast Monte Carlo procedure of hadron generation:
  We avoid straightforward 6-dimentional integration ⟶
  ~100% efficiency of generation procedure

- Matter is thermally equilibrated. Particle multiplicities are determined by the temperature and chemical potentials. Statistical model. Chemical freeze-out.

- Particles can be generated on the chemical ($T_{th}=T_{ch}$) or thermal freeze-out hypersurface represented by a parameterization (or a numerical solution of the relativistic hydrodynamics).

- Various parameterizations of the hadron freeze-out hypersurface and flow velocity

- Decays of hadronic resonances (from u,d and s quarks) are included (was 85 / now 360)

- The C++ generator code is written under the ROOT framework.

Physical framework of the model: Hadron multiplicities

1. We consider the hadronic matter created in heavy-ion collisions as a hydrodynamically expanding fireball with the EOS of an ideal hadron gas.

2. “concept of effective volume” T=const and μ=const the total yield of particle species is:

$$\boxed{N_i = \rho_i(T,\mu_i)V_{eff}}$$

V_{eff}, total co-moving volume, ρ-particle number density

3. Chemical freeze-out : **T**, $\mu_i = \mu_B B_i + \mu_S S_i + \mu_Q Q_i$; **T, μ_B** –can be fixed by particle ratios, or by phenomenological formulas J.Cleymans et al. PRC 73 034905 (2006)

$$\boxed{T(\mu_B) = a - b\mu_B - c\mu_B^4 ; \mu_B(\sqrt{s_{NN}}) = \frac{d}{1+e\sqrt{s_{NN}}}}$$

4. Chemical freeze-out: all macroscopic characteristics of particle system are determined via a set of equilibrium distribution functions in the fluid element rest frame:

$$f_i^{eq}(p^{0*};T,\mu_i) = \frac{1}{(2\pi)^3}\frac{g_i}{\exp([p^{0*}-\mu_i]/T)\pm 1}$$

$$\rho_i^{eq}(T,\mu_i) = \int_0^\infty d^3\vec{p}^{\,*} f_i^{eq}(p^{0*};T(x^*),\mu(x^*)_i) = 4\pi\int_0^\infty dp^* p^{*2} f_i^{eq}(p^{0*};T,\mu_i)$$

$$\boxed{\rho_i^{eq}(T,\mu_i) = \frac{g_i}{2\pi^2} m_i^2 T \sum_{k=1}^{\infty} \frac{(\mp)^{k+1}}{k}\exp(\frac{k\mu_i}{T})K_2(\frac{km_i}{T})}$$

Physical framework of the model: Thermal freeze-out

1. The particle densities at the chemical freeze-out stage are too high to consider particles as free streaming and to associate this stage with the thermal freeze-out

2. Within the concept of chemically frozen evolution, assumption of the conservation of the particle number ratios from the chemical to thermal freeze-out :

$$\frac{\rho_i^{eq}(T^{ch},\mu_i^{ch})}{\rho_\pi^{eq}(T^{ch},\mu_\pi^{ch})}=\frac{\rho_i^{eq}(T^{th},\mu_i^{th})}{\rho_\pi^{eq}(T^{th},\mu_\pi^{th})}$$

3. The absolute values $\rho_i^{eq}(T^{th},\mu_i^{th})$ are determined by the choice of the free parameter of the model: effective pion chemical potential $\mu_\pi^{eff,th}$ at T^{th}

Assuming for the other particles (heavier then pions) the Botzmann approximation :

$$\mu_i^{th}=T^{th}\ln\left(\frac{\rho_i^{eq}(T^{ch},\mu_i^{ch})}{\rho_i^{eq}(T^{th},\mu_i=0)}\frac{\rho_\pi^{eq}(T^{th},\mu_\pi^{eff,th})}{\rho_\pi^{eq}(T^{ch},\mu_i^{ch})}\right)$$

Particles (stable, resonances) are generated on the thermal freeze-out hypersurface, the hadronic composition at this stage is defined by the parameters of the system at chemical freeze-out

Physical framework of the model: Hadron momentum distribution

We suppose that a hydrodynamic expansion of the fireball ends by a sudden system breakup at given T and chemical potentials. Momentum distribution of produced hadrons keeps the thermal character of the equilibrium distribution.

We avoid straightforward 6-dimentional integration by the special simulation procedure

FASTMC-1 PRC 74 064901 (2006)

$$\boxed{p^0 \frac{d^3N_i}{d^3p} = \int_{\sigma(x)} d^3\sigma_\mu(x)\, p^\mu f_i^{eq}(p^\nu u_\nu(x); T, \mu_i)}$$

Cooper-Frye formula:

Freeze-out surface parameterizations

1. The **Bjorken model** with hypersurface $\boxed{\tau = (t^2 - z^2)^{1/2} = const}$

2. **Linear transverse flow rapidity profile**: $\boxed{\rho_u = \frac{r}{R}\rho_u^{\max}}$

3. The total effective volume for particle production at

$$V_{eff} = \int_{\sigma(x)} d^3\sigma_\mu(x) u^\mu(x) = \tau \int_0^R \gamma_r r dr \int_0^{2\pi} d\phi \int_{\eta_{\min}}^{\eta_{\max}} d\eta = 2\pi\tau\Delta\eta \left(\frac{R}{\rho_u^{\max}}\right)^2 (\rho_u^{\max}\sinh\rho_u^{\max} - \cosh\rho_u^{\max} + 1)$$

FASTMC-Model parameters for central collisions:

1. Thermodynamic parameters at chemical freeze-out: T_{ch} , $\{\mu_B, \mu_S, \mu_Q\}$

2. If thermal freeze-out is considered: T_{th} , μ_π-normalisation constant

3. As an option, strangeness suppression $\gamma_s < 1$

4. Volume parameters:

τ -the freeze-out proper time and its standard deviation $\Delta\tau$ (emission duration)

R- firebal transverse radius

5. ρ_u^{max} -maximal transverse flow rapidity for Bjorken-like parametrization

6. η_{max} -maximal space-time longitudinal rapidity which determines the rapidity interval $[-\eta_{max}, \eta_{max}]$ in the collision center-of-mass system.

7. To account for the violation of the boost invariance, an option corresponding to the substitution of the uniform distribution of the space-time longitudinal rapidity by a Gaussian distribution in η.

8. Option to calculate T, μ_B using phenomenological parametrizations $\mu_B(\sqrt{s}), T(\mu_B)$

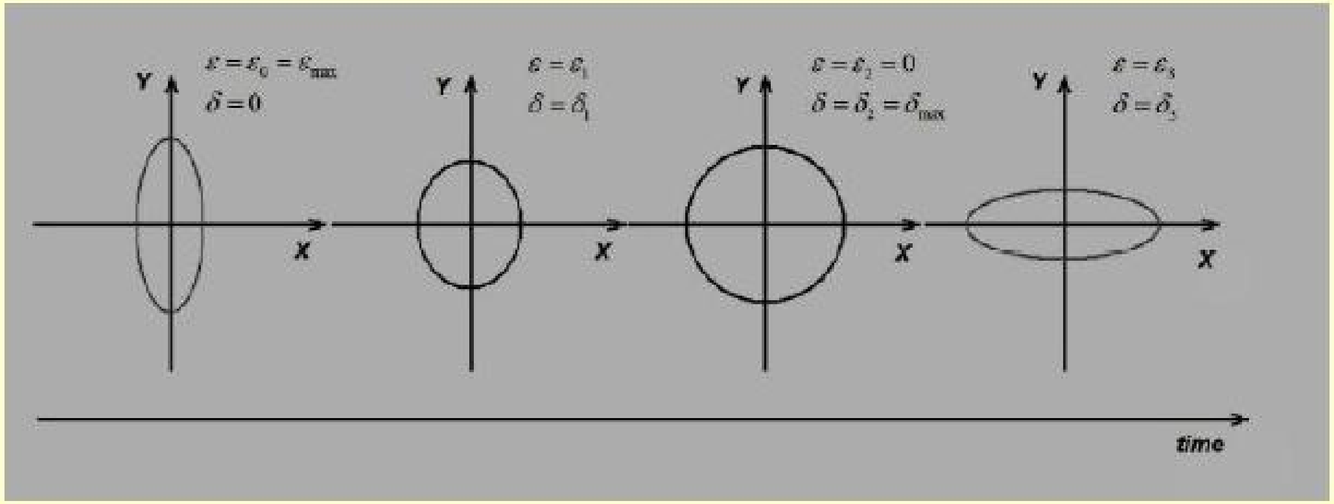
FASTMC-Model parameters for non-central collisions:

The SAME parameters which were used to simulate central collisions were used for noncentral collisions at different centralities. The additional parameters needed only for noncentral collisions are:

For the impact parameter range: (**b**min , **b**max)

9. Flow anisotropy parameter: **δ**(b)

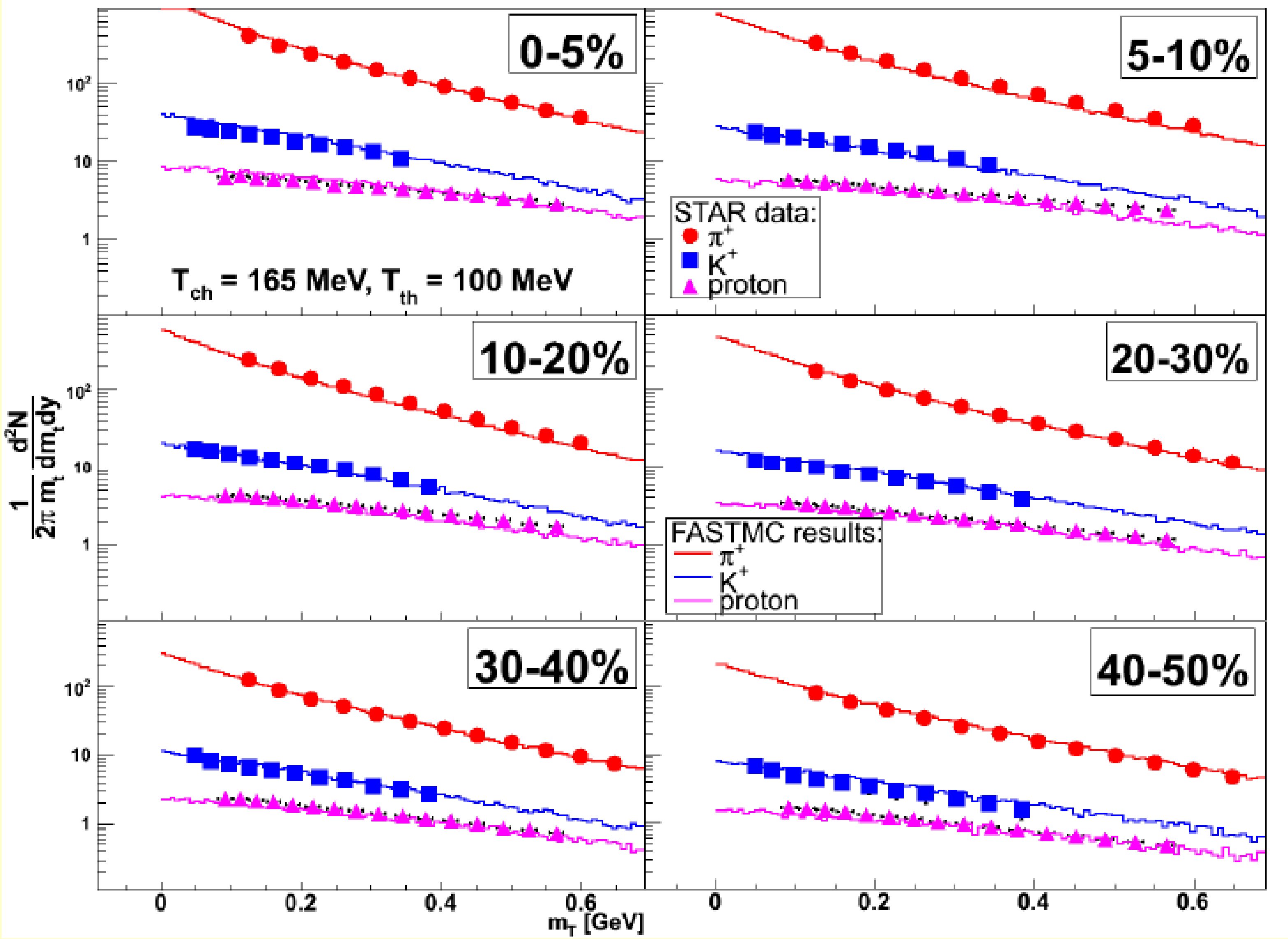
10. Coordinate anisotropy parameter: **ε**(b)



FASTMC Examples of calculations:

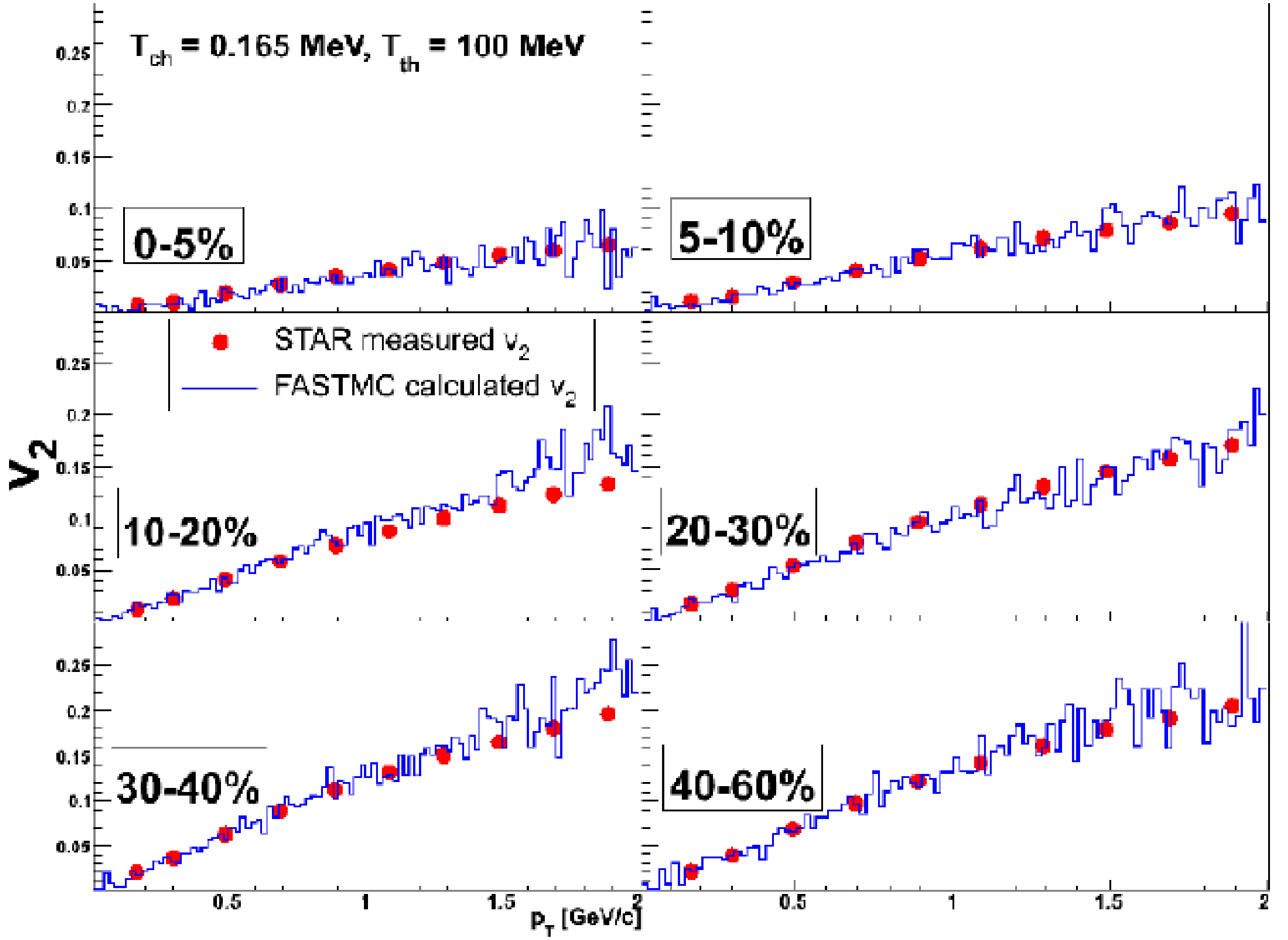
Comparison with RHIC Au+Au at $\sqrt{S}$ = 200 GeV

Mt- spectra of π,K,p (STAR)—FASTMC (thermal f.o +weak decays)

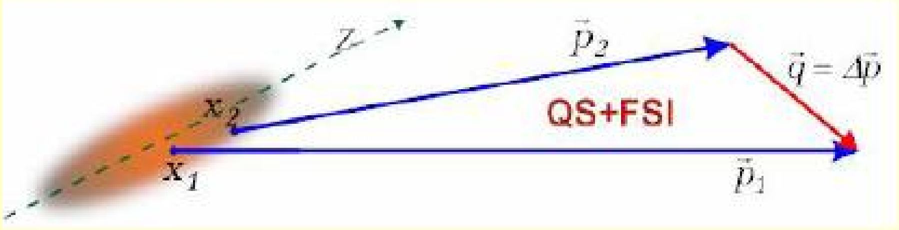


Elliptic flow- versus pt (STAR)—FASTMC (thermal f.o T=110 MeV)

$$\frac{dN}{d^2 p_t dy} = \frac{dN}{2\pi p_t dp_t dy}(1 + v_2 \cos 2\varphi + 2v_4 \cos 4\varphi + \ldots)$$

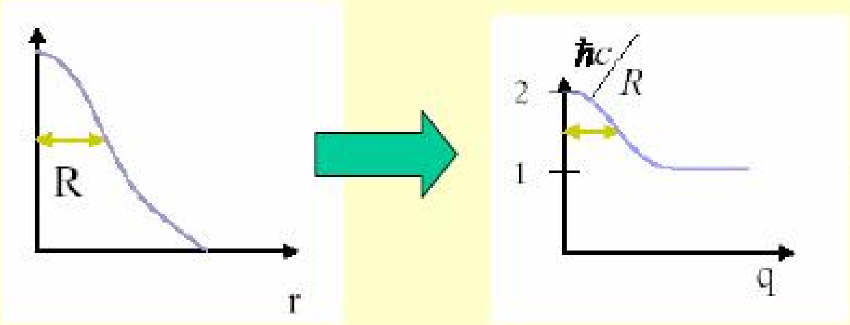


Momentum correlations

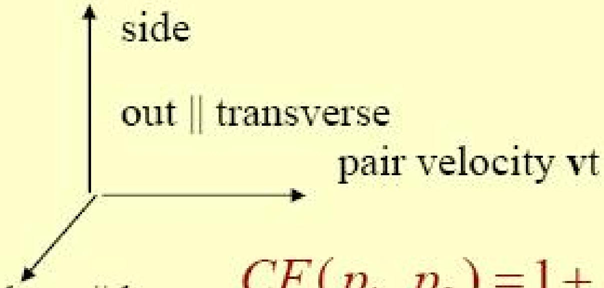


Due to the effects of QS and FSI, the momentum correlations of two or more particles at small relative momenta in their center-of-mass system are sensitive to the space-time characteristics of the production process so serving as a correlation femtoscopy tool.

q = p1- p2 , Δx = x1- x2 w=1+⟨cos qΔx⟩



$$CF = N\frac{S(Q_{inv})}{B(Q_{inv})}$$



The corresponding correlation widths are usually parameterized in terms of the Gaussian correlation radii R_i:

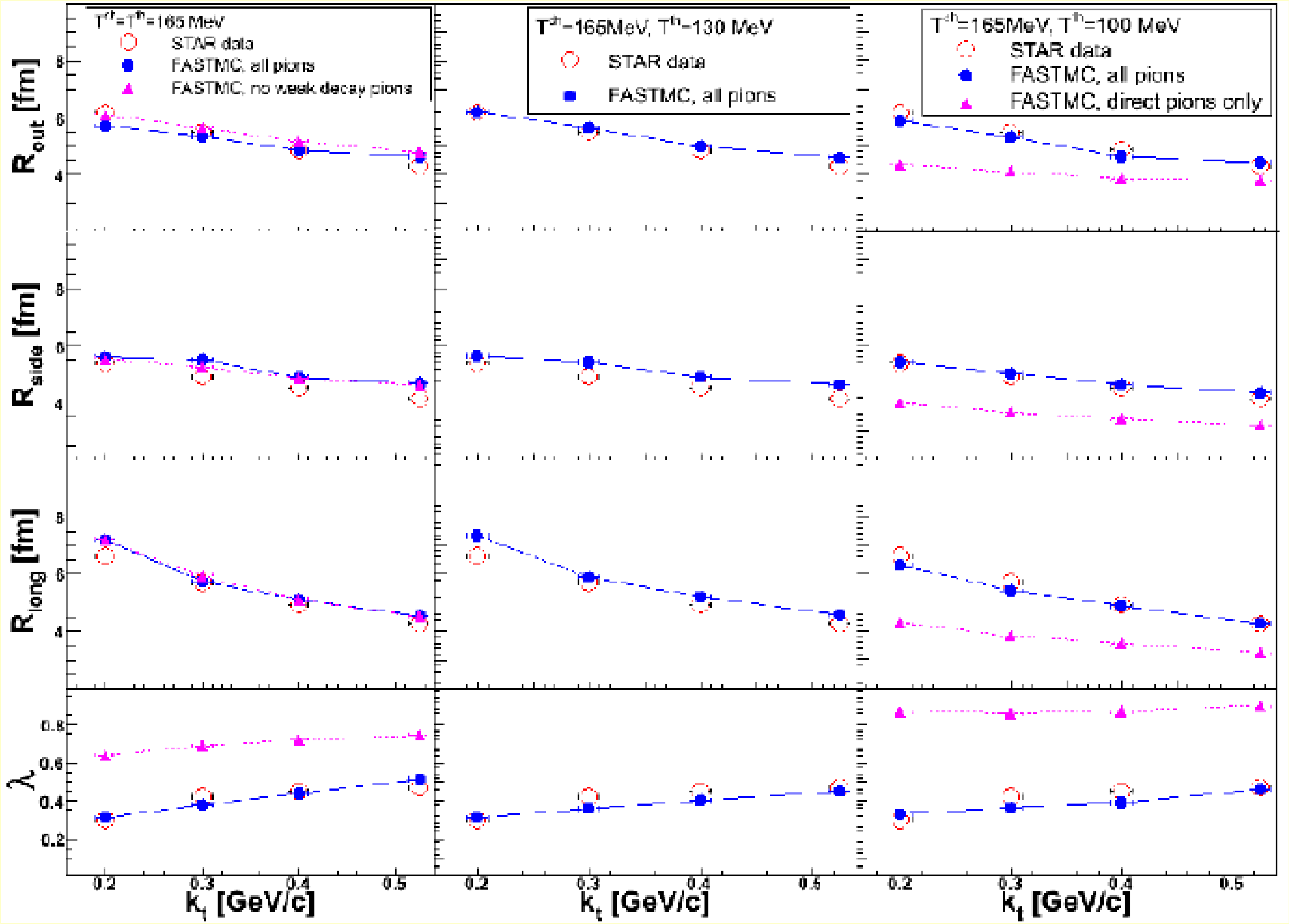
long || beam

$$CF(p_1, p_2) = 1 + \lambda(-R^2_{out}q^2_{out} - R^2_{side}q^2_{side} - R^2_{long}q^2_{long} - 2R^2_{out,long}q_{out}q_{long})$$

We choose as the reference frame the longitudinal co-moving system (LCMS)

Momentum correlations

Tth=Tch =165 MeV, no weak decays / Tch=165 MeV, Tth= 100 MeV + weak decays + Δτ



Conclusions (RHIC):

-Fixing the temperatures of the chemical and thermal freeze-out at 0.165 GeV and 0.100 GeV respectively, and using the same set of model parameters as for the central collisions, we have described the single particle spectra at different centralities with an accuracy of ~ 13 %.

-The comparison of the RHIC v_2 measurements with our MC generation results shows that the scenario with two separated freeze-outs describes better the p_t-dependence of the elliptic flow.

-The description of the k_t-dependence of the correlation radii has been achieved within ~ 10% accuracy.

-The experimentally observed values of the correlation strength parameter λ have been reproduced due to the account of the weak decays.

FASTMC Examples of calculations:

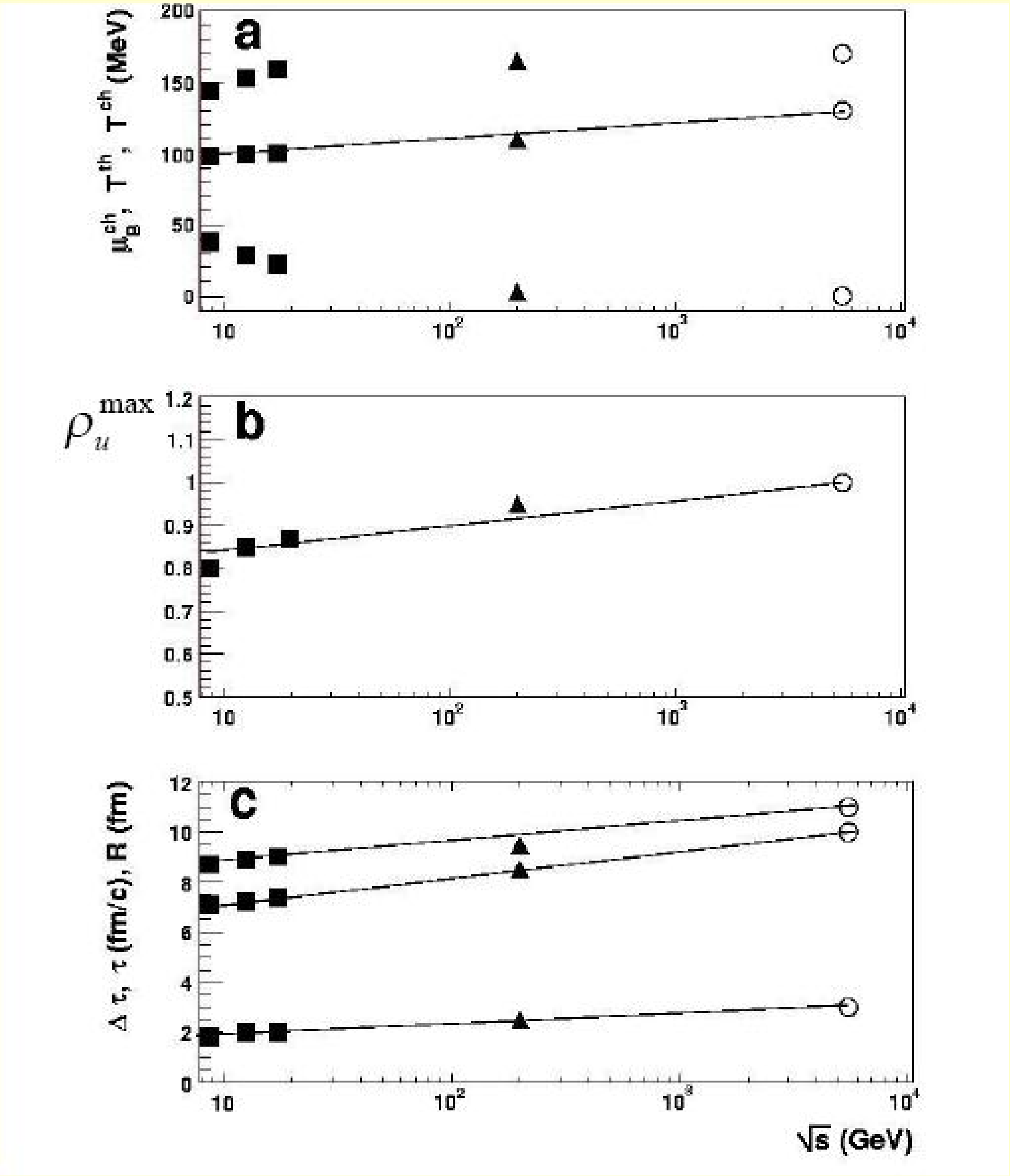
Predictions for LHC.

Predictions for LHC

■ SPS ($\sqrt{s_{NN}}$ = 8.7 - 17.3 GeV)

▲ RHIC ($\sqrt{s_{NN}}$ = 200 GeV)

○ LHC ($\sqrt{s_{NN}}$ = 5500 GeV)



Predictions for LHC: Conclusions

The extrapolated values :

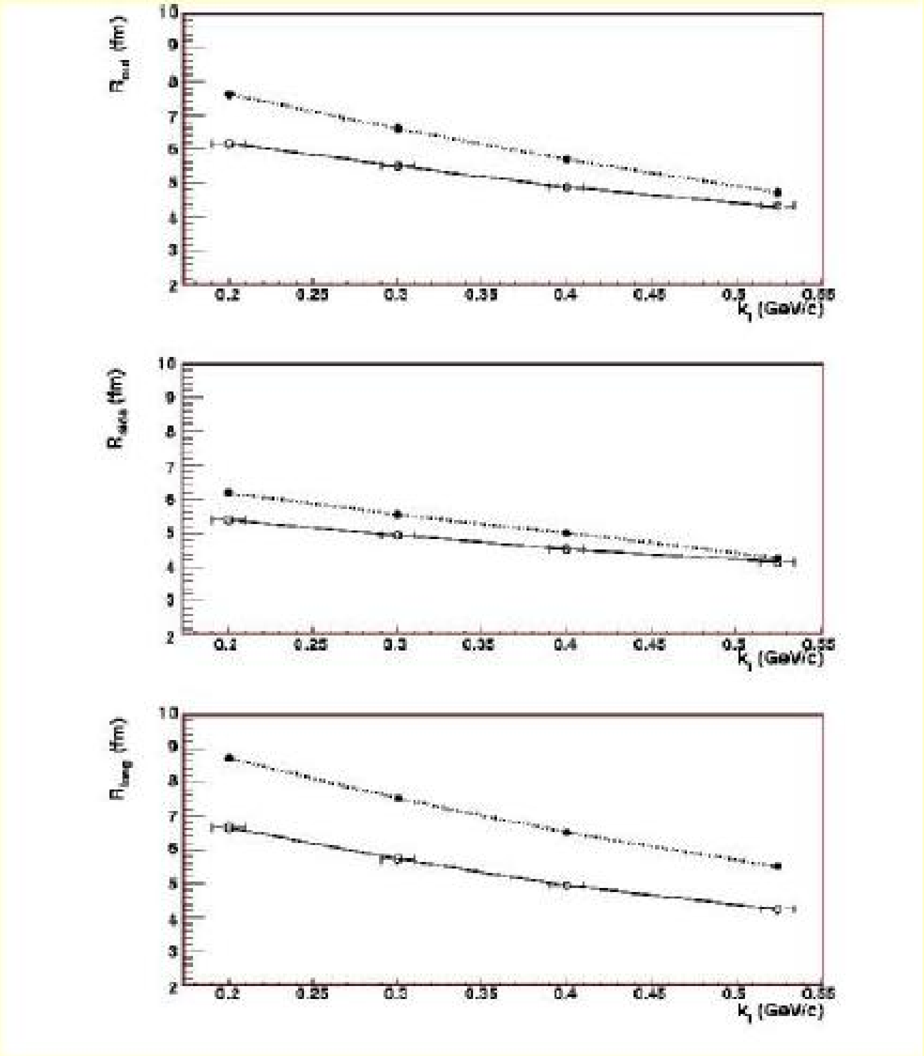
$R \sim 11$ fm, $\tau \sim 10$ fm/c, $\Delta\tau \sim 3.0$ fm/c,

ρ_u^{max} ~ 1.0, $T_{th} \sim 130$ MeV.

$T_{ch}=170$ MeV, $\mu_B=0$, $\mu_S=0$, $\mu_Q=0$ MeV

dN/dy ~ 1400 twice larger than at RHIC $\sqrt{s_{NN}}$ = 200 GeV
in coincidence with the naive
extrapolation of dN/dy.

These parameters yield a small
increase of the correlation radii
Rout, Rside , Rlong



FASTMCj Examples of calculations:

FASTMC + high-pt part related to the partonic states

FASTMC + high-pt part related to the partonic states :

Jet-quenching model PYTHIA/PYthiaQUENched is implemented.
PYTHYA+PYQUEN (I.P.Lokhtin and A.M.Snigirev, Eur. Phys. J. C 45, 211 (2006).)

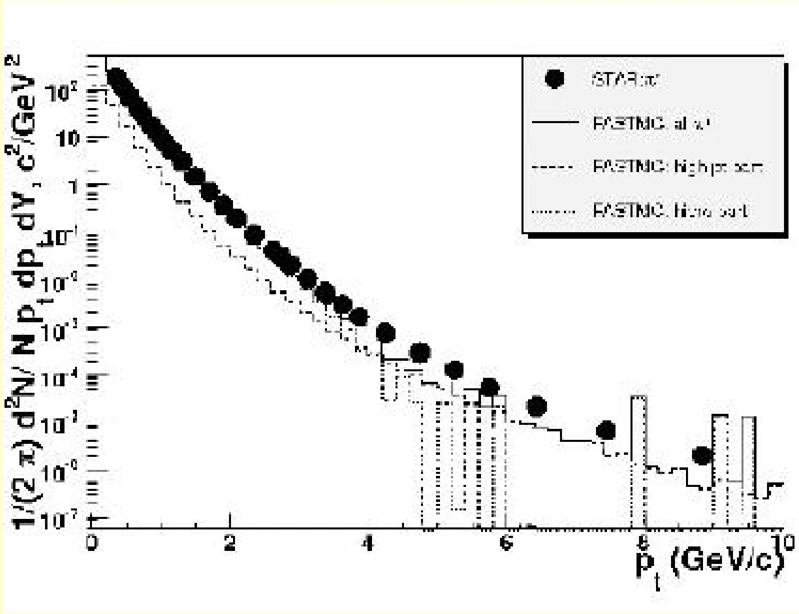
http://cern.ch/lokhtin/pyquen

Goals of this work:

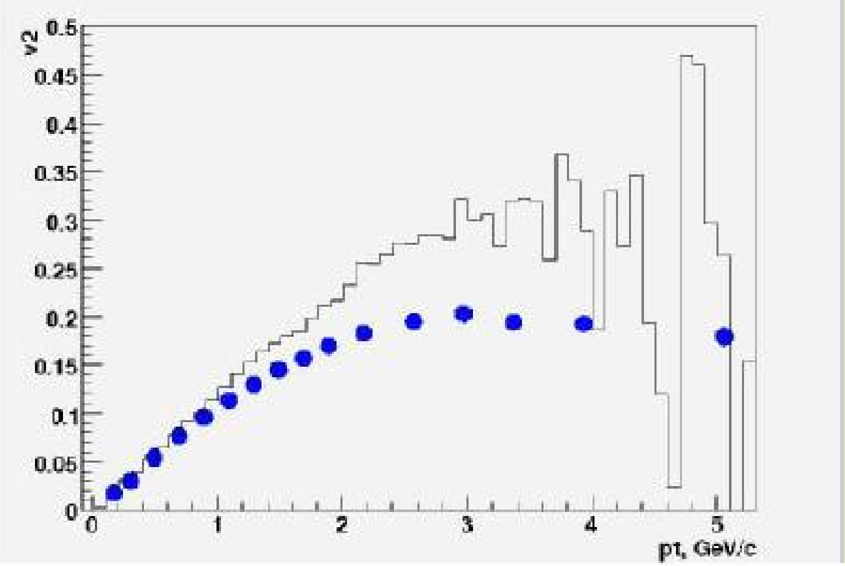
--We are studying influence of the mini-jets/jets production on CFs at RHIC/LHC energies.

--FASTMC produces background for the jet production, direct gammas…

Example of calculations with FASTMC-J code for RHIC



Example of calculations for LHC (c=20-30%) with FASTMC-J code under the assumption that (ε,δ) are as at RHIC.



FASTMCj - Model parameters.

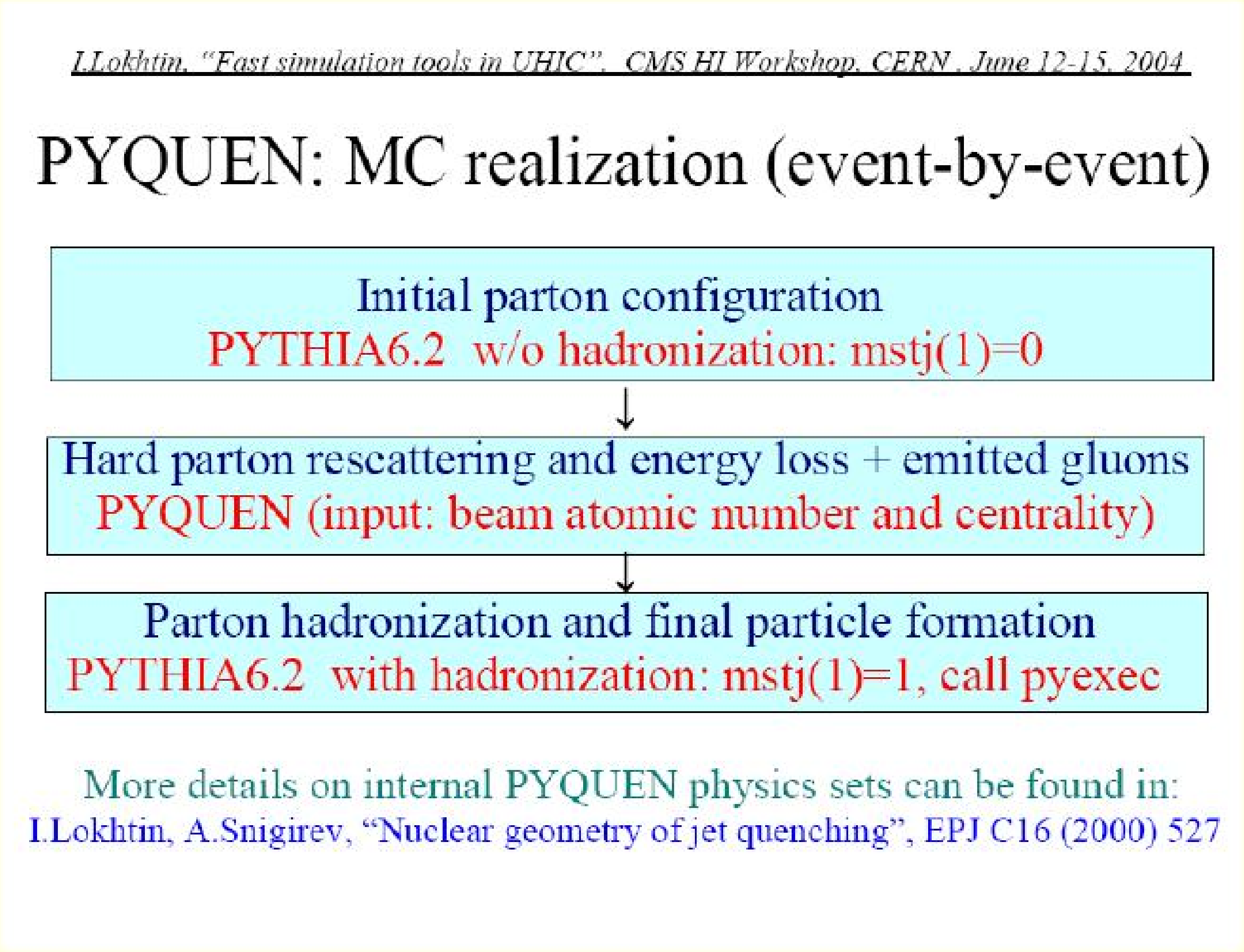
1. Thermodynamic parameters at chemical freeze-out: T_{ch} , {μ_B, μ_S, μ_Q}
2. If thermal freeze-out is considered: T_{th} , μ_π-normalisation constant
3. Volume parameters: τ, $\Delta\tau$, R
4. ρ_u^{max} -maximal transverse flow rapidity for Bjorken-like parametrization
5. η_{max} -maximal space-time longitudinal rapidity which determines the rapidity interval [- η_{max}, η_{max}] in the collision center-of-mass system.
6. Impact parameter range: minimal b_{min} and maximal b_{max} impact parameters
7. Flow anisotropy parameter δ(b)
8. Coordinate anisotropy parameter ε(b)

PYTHYA+PYQUEN parameters

9. Beam and target nuclear atomic weight **A**
10. $\sqrt{s_{NN}}$ –c.m.s. energy per nucleon pair (PYTHIA initialization at given energy)
11. **ptmin** – minimal pt of parton-parton scattering in PYTHIA event (ckin(3) in /pysubs/
12. T_0 - initial temperature of quark-gluon plasma
13. τ_0 - proper time of QGP formation
14. Flag to chose the type of calculation of medium induced partonic energy loss

FASTMC+high pt – MC realization.

1. PYTHIA initialization at given $\sqrt{s_{NN}}$
2. calculation of total inelastic pp cross section at given $\sqrt{s_{NN}}$
3. calculation of hard scattering cross section at given $\mathbf{pt_{min}}$ and $\sqrt{s_{NN}}$
4. calculation of the probability of the hard parton-parton scattering with pt> $\mathbf{pt_{min}}$
5. calculation of number of participants in the event
6. calculation of number of binary collisions in the event according with probability of hard process, calculated at step 4
7. for each binary collision call PYTHIA(pyexec)+PYQUEN



PYQUEN: MC realization (event-by-event)

Initial parton configuration
PYTHIA6.2 w/o hadronization: mstj(1)=0

↓

Hard parton rescattering and energy loss + emitted gluons
PYQUEN (input: beam atomic number and centrality)

↓

Parton hadronization and final particle formation
PYTHIA6.2 with hadronization: mstj(1)=1, call pyexec

More details on internal PYQUEN physics sets can be found in:
I.Lokhtin, A.Snigirev, "Nuclear geometry of jet quenching", EPJ C16 (2000) 527

Conclusions

-We have developed a MC simulation procedure and the corresponding C++ code allowing for a fast but realistic description of multiple hadron production in relativistic heavy ion collisions. Reasonable RHIC data description.

-As options, we have implemented two freeze-out scenarios with coinciding and with different chemical and thermal freeze-outs.

-Also implemented are various options of the freeze-out hypersurface parameterizations

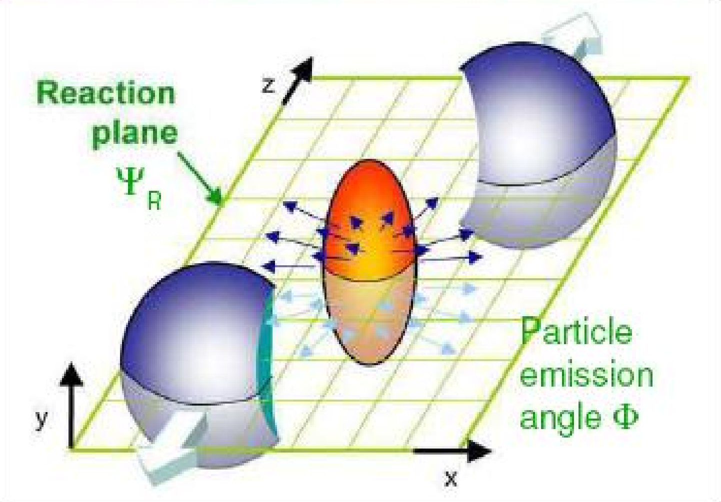
- simulation from the 3D hydro as input can be done.

-FASTMC-j is created, high-pt part related with partonic states is available

A high generation speed and an easy control through input parameters make our MC generator code particularly useful for detector studies.
Predictions for LHC. Implementation in AliRoot was performed. Presentation of the first data simulated with FASTMC under AliRoot framework will be done in Aliceweek.

Additional slides

Elliptic flow at RHIC:
Evidence of partonic degrees of freedom



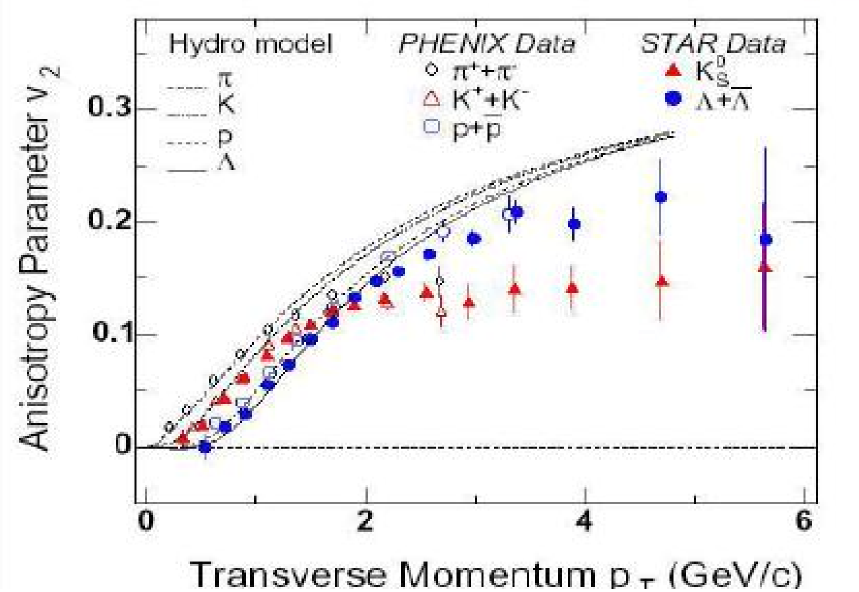
Non-central collisions: Anisotropic overlap zone.
Spatial anisotropy -> momentum anisotropy:

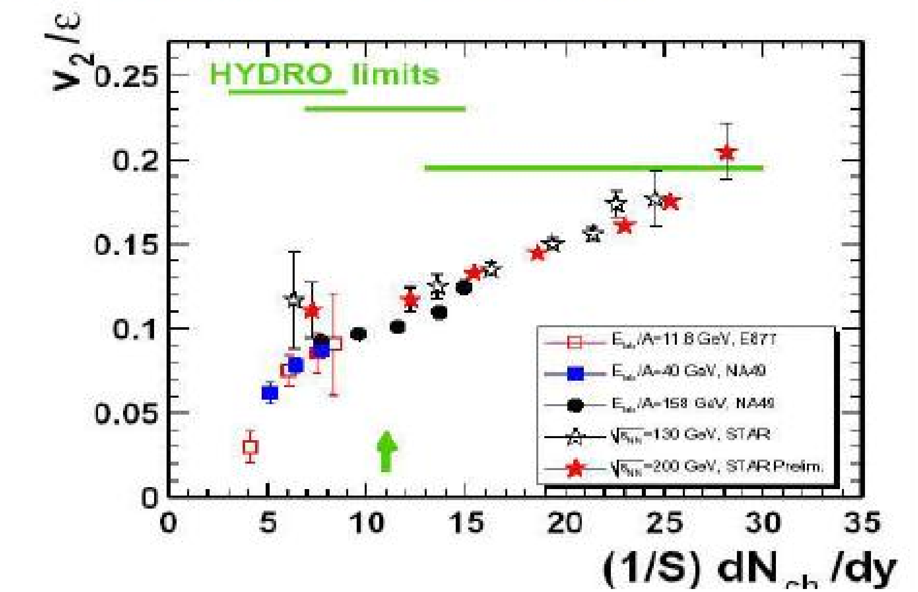
$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left[1 + \Sigma_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_R)\right]$$

Elliptic flow coefficient $v_2 = v_2(p_T, y)$.

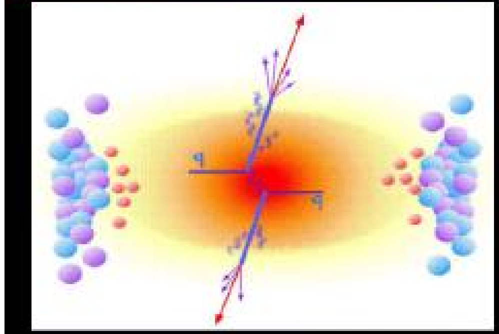
$v_2(p_T)$ different for mesons and baryons, scales with number of valence quarks n_q.

v2 close to expectations for perfect liquid.





High-p_T suppression:
More evidence of partonic degrees of freedom



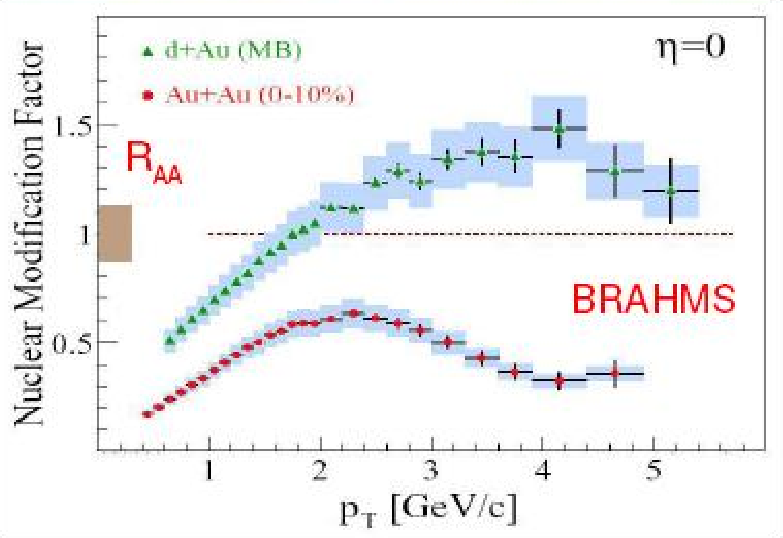
HI collisions:
Fast partons lose energy in medium with free colour charges.

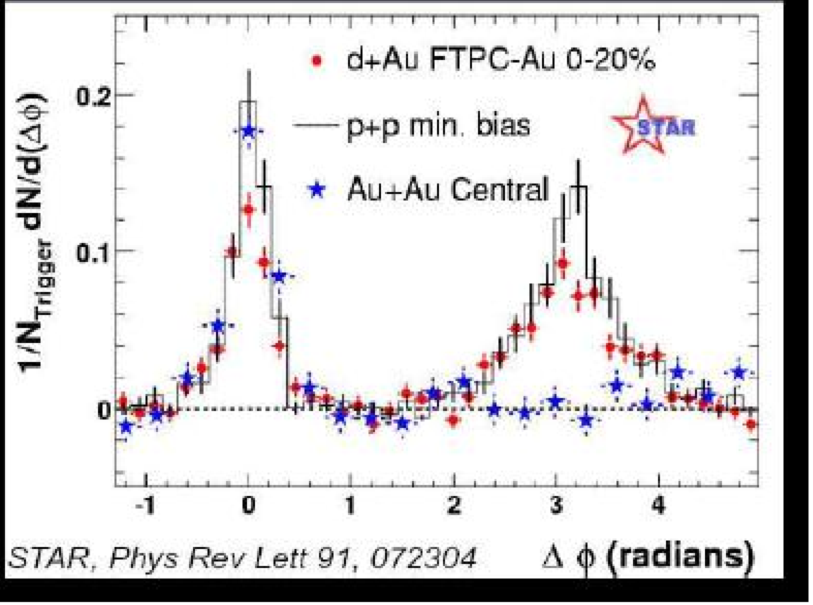
Comparison to reference spectra from p+p collisions with no medium gives nuclear modification factor R_{AA}:

$$R_{AA} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{binary}\rangle d^2N_{pp}/dp_T dy}$$

In central Au+Au collisions we observe:
Strong suppression of high-p_T hadrons (low R_{AA}).
Disappearance of away-side peak in dijets.

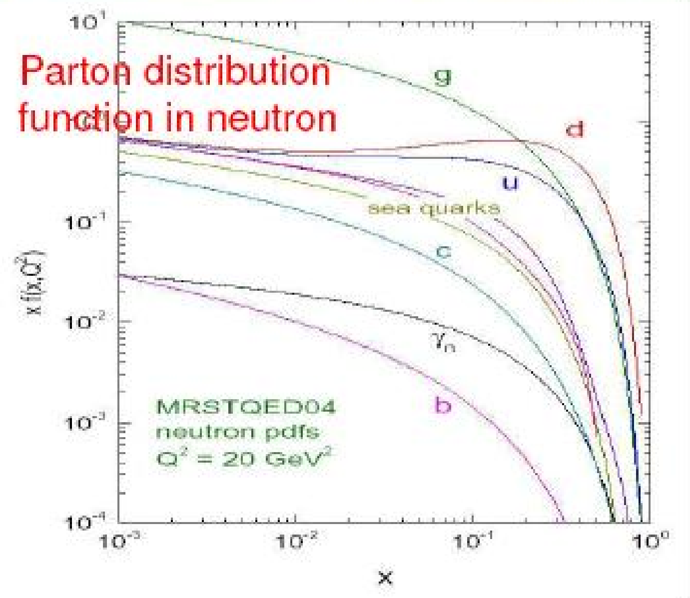
Reference system with cold nuclear matter and initial state effects: d+Au collisions.
No suppression (Cronin enhancement) at y=0.
Dijets similar to p+p collisions.

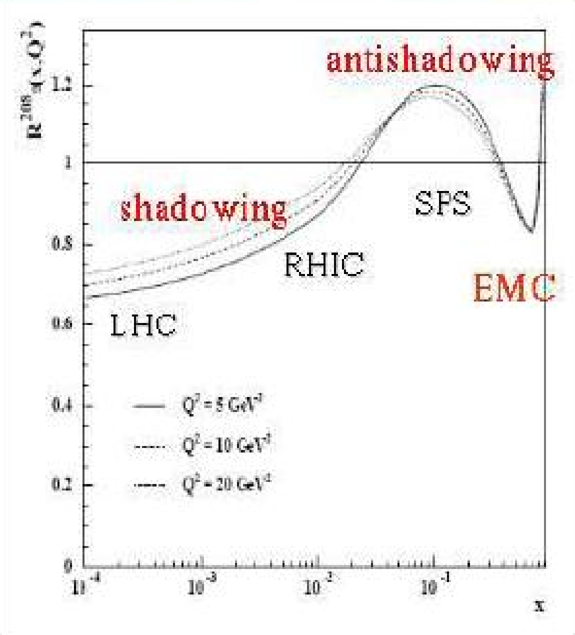


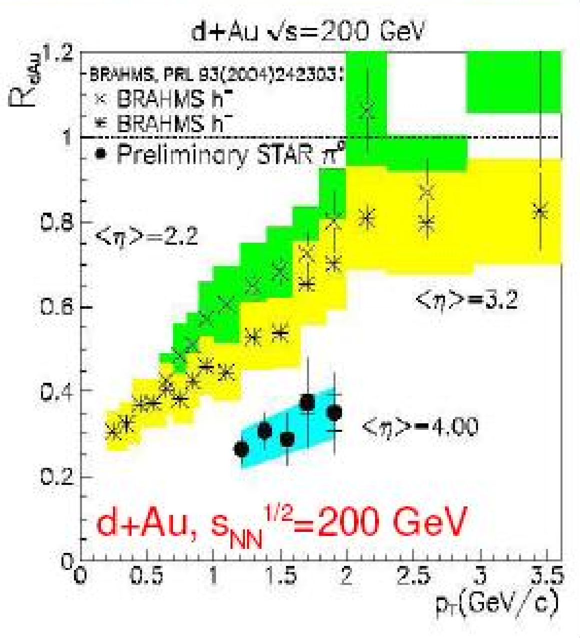


STAR, Phys Rev Lett 91, 072304

What is the nature of the initial state?



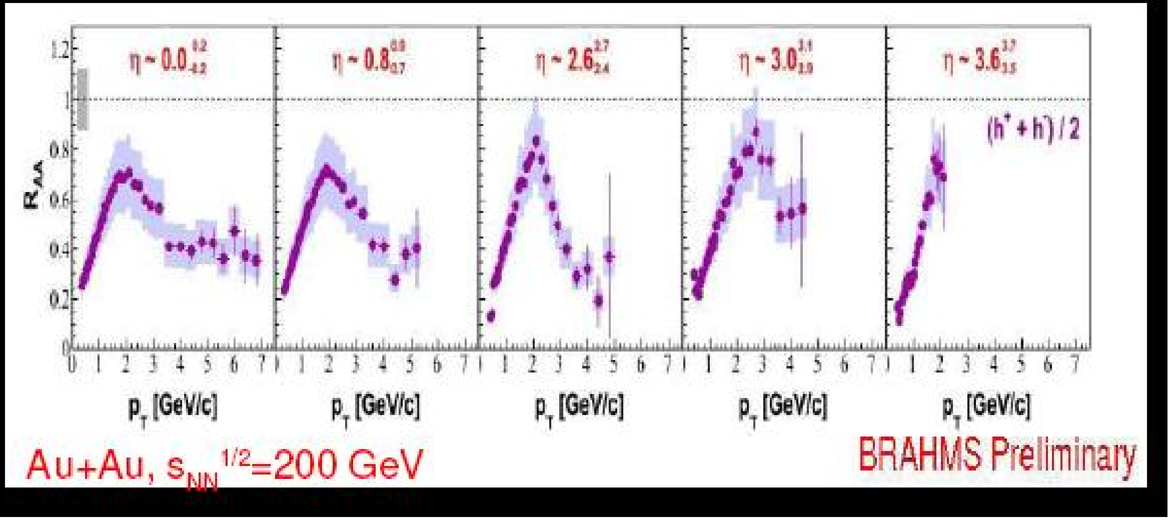




Initial state: Characterized by high gluon density at low x ($x \sim p_T e^{-y} / s_{NN}^{1/2}$).

RHIC: Strong suppression at forward y, both in d+Au and Au+Au. Colour Glass Condensate or energy-momentum conservation + shadowing?

Initial state effects even more important at LHC!



Conclusions at RHIC so far:
New state of matter, nicknamed sQGP

Preliminary conclusions summarized in 4 "whitepapers" from the RHIC experiments:

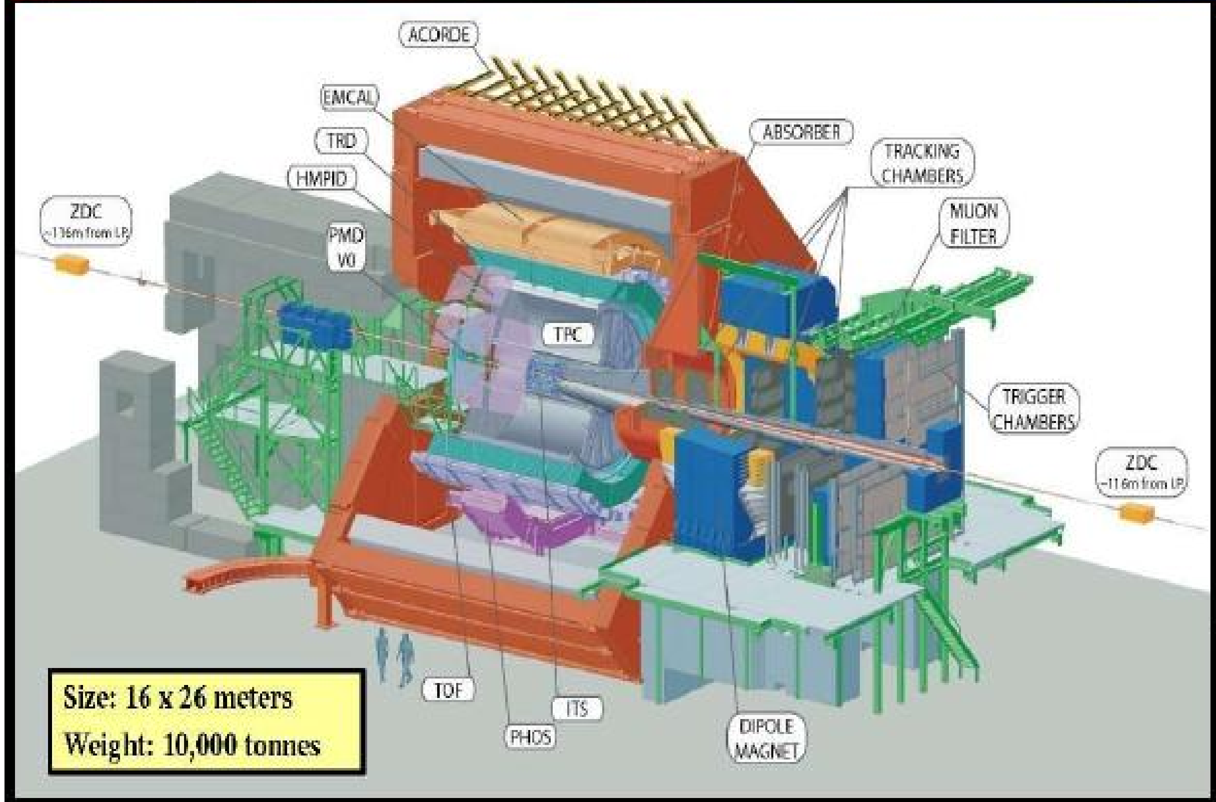
- I. Arsene et al. (BRAHMS collaboration), Nucl.Phys. A757, 1 (2005)
- K. Adcox et al. (PHENIX collaboration), Nucl.Phys. A757, 184 (2005)
- B. Back et al. (PHOBOS collaboration), Nucl.Phys. A757, 28 (2005)
- J. Adams et al. (STAR collaboration), Nucl.Phys. A757, 102 (2005)

Quote from the PHENIX paper (representative for RHIC consensus):
"In conclusion, there is compelling experimental evidence that heavy-ion collisions at RHIC produce a state of matter characterized by very high energy densities, density of unscreened color charges ten times that of a nucleon, large cross sections for the interaction between strongly interacting particles, strong collective flow, and early thermalization. Measurements indicate that this matter modifies jet fragmentation and has opacity that is too large to be explained by any known hadronic processes. (...) The most economical description is in terms of the underlying quark and gluon degrees of freedom."
Later, more detailed measurements at RHIC confirm this picture.

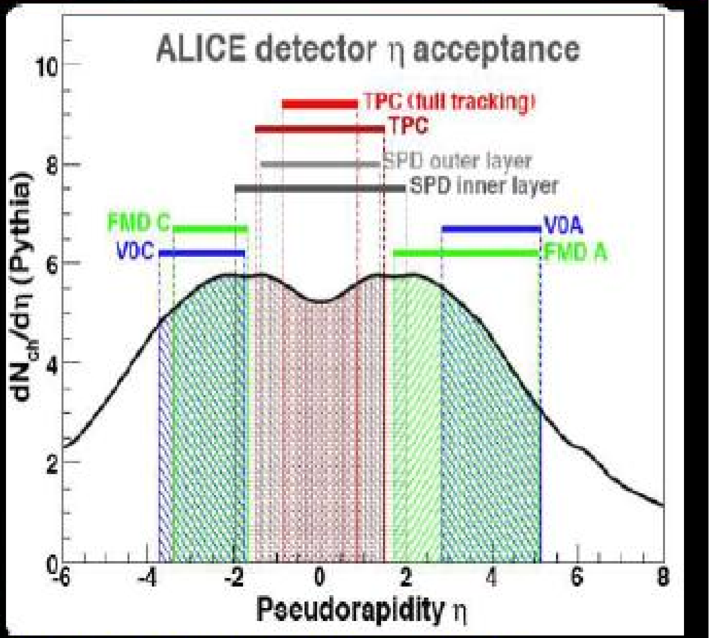
Mostly smooth evolution of observables with energy, system size and rapidity -> consistent with a crossover transition.

Matter produced at RHIC, "sQGP" - different from the expected weakly interacting, long-lived QGP. Will we enter that regime at LHC energies?

Exploration of the new state of matter with the ALICE detector



Size: 16 x 26 meters
Weight: 10,000 tonnes



Physics focus of ALICE: Properties and time evolution of the hot partonic matter.

Signals from early stage: Collective anisotropic flow. Hard and electromagnetic probes - jets, direct photons, heavy flavoured hadrons and quarkonia, and their interaction with the medium.

Must disentangle initial- and final-state effects!

Central tracking system for charged particles (CTS):

ITS (Inner Tracking System)

TPC (Time Projection Chamber)

TRD (Transition Radiation Detector)

Detectors for neutral particles:

PHOS (Photon Spectrometer)

EMCAL (Electromagnetic Calorimeter)

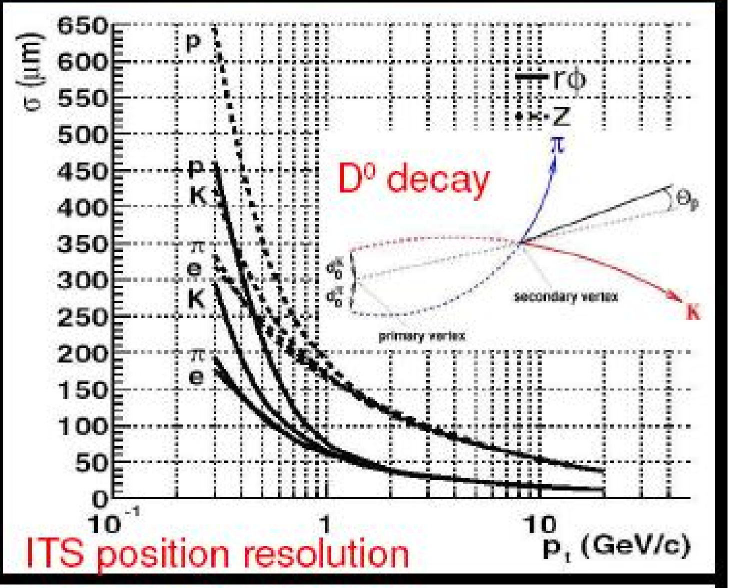
Performance of the ALICE detector

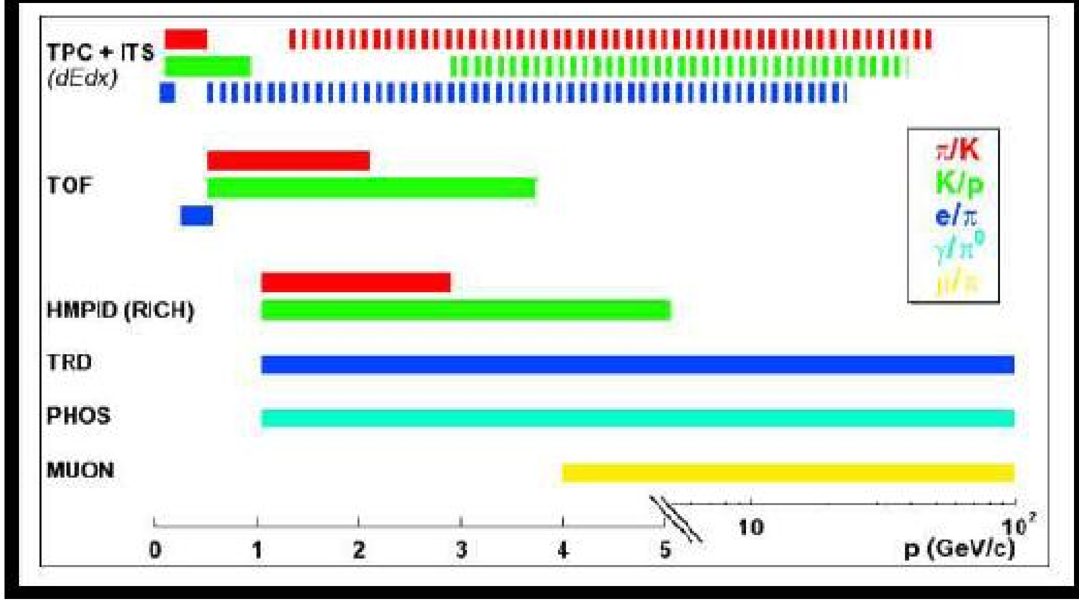
CTS with TOF and HMPID: Good PID capabilities for low- to intermediate-p_T charged hadrons.

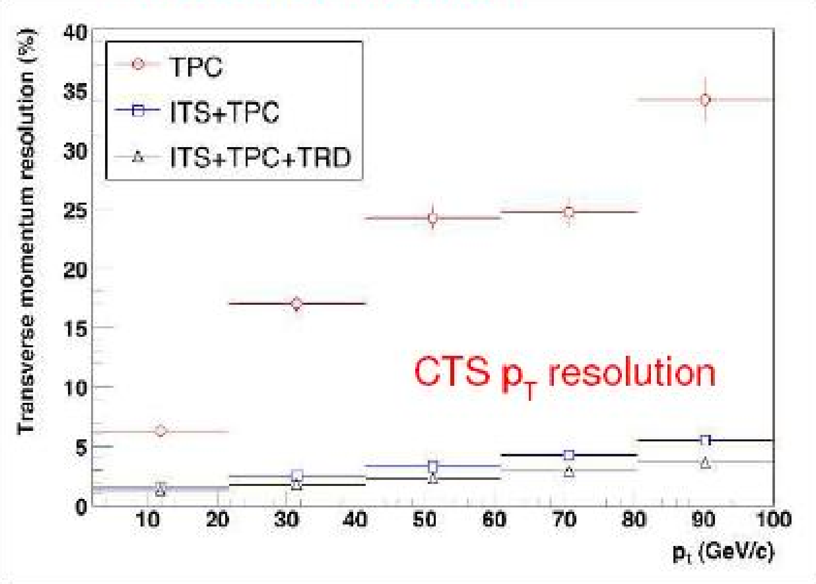
Neutral hadrons, photons, leptons identified up to high p_T ($\sim 10^2$ GeV) in TRD, PHOS, (EMCAL), Muon spectrometer.

ITS: Excellent position resolution (<~ 10^2 μm). Needed for identification of heavy flavour!

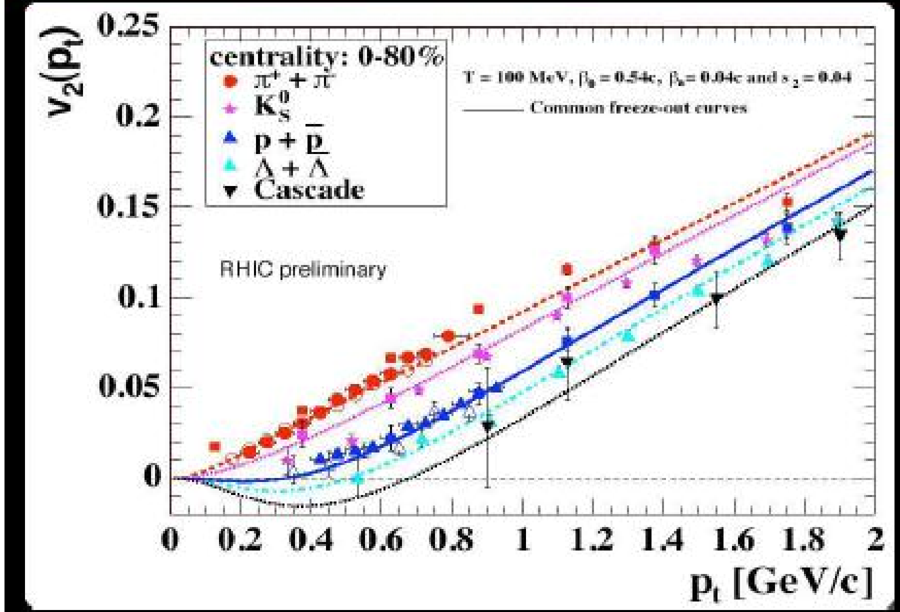
Good p_T resolution in both CTS and PHOS -> important for invariant mass analysis of quarkonia and neutral mesons.

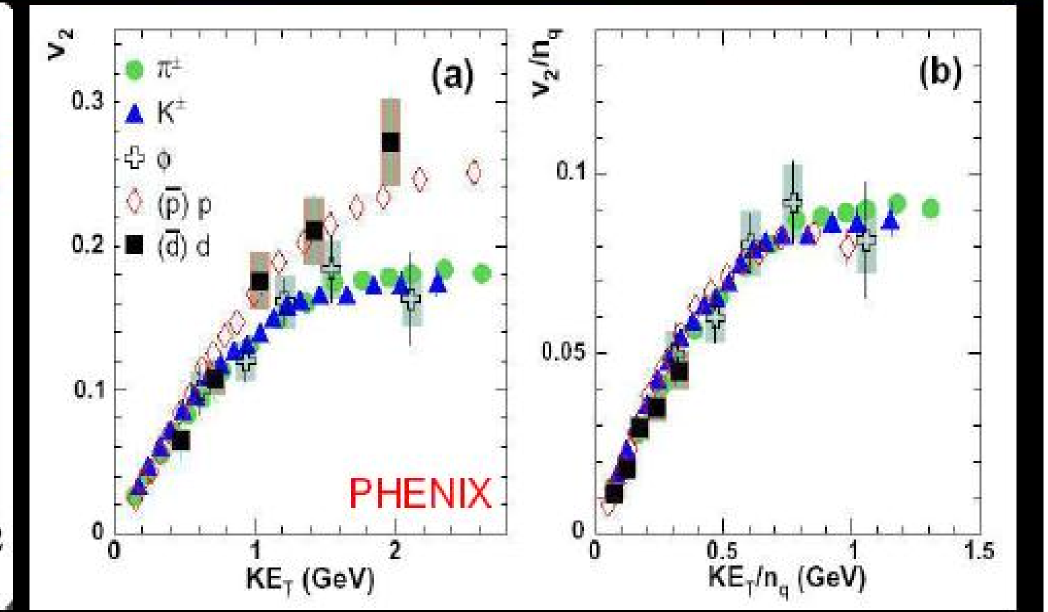

ITS position resolution



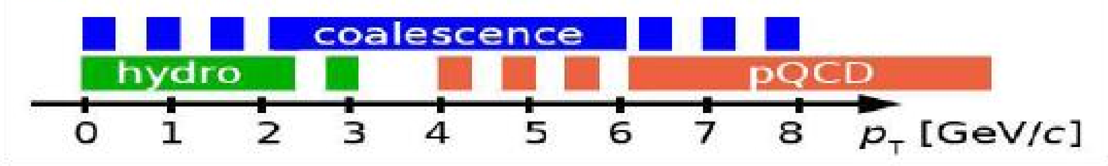

CTS p_T resolution

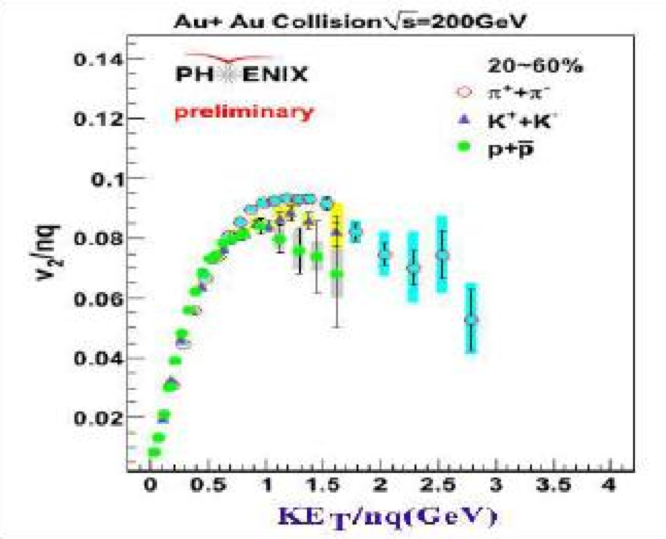
Elliptic flow v_2- species and p_T dependence



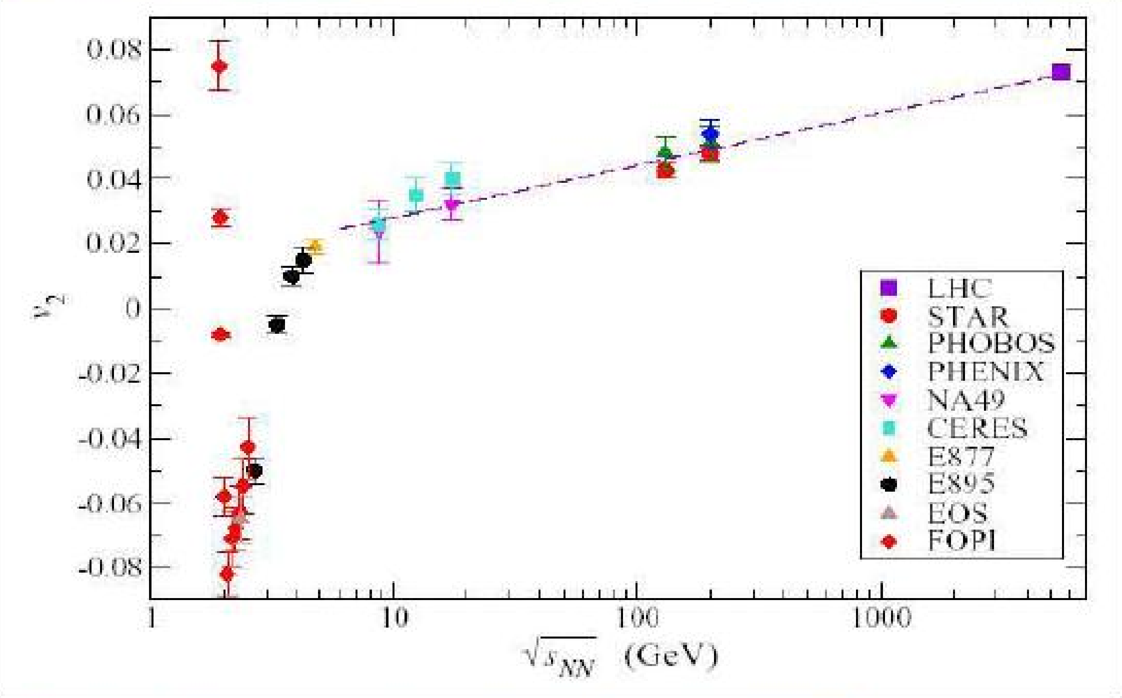


- Low p_T: Mass scaling consistent with hydrodynamics.
- Intermediate p_T: v_2 scaling with number of valence quarks n_q -> flow originates in partonic phase, and coalescence dominant mechanism for hadronization.
- High p_T: Breakdown of n_q scaling, non-flow effects from hard processes starting to dominate.





Measuring elliptic flow in ALICE

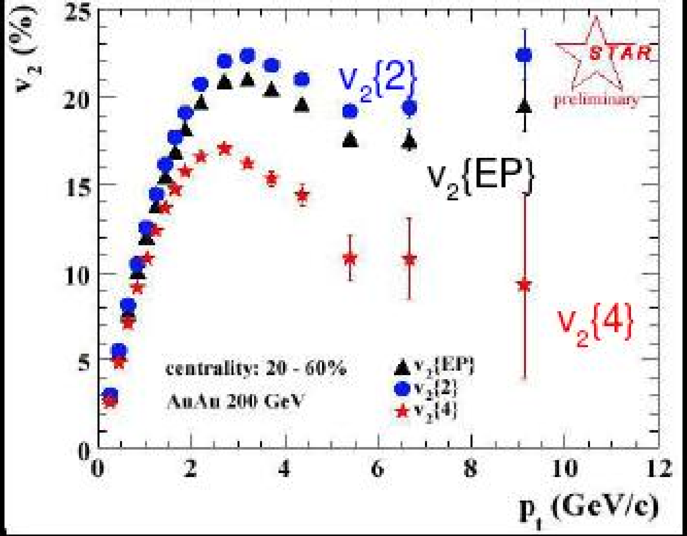


Strong elliptic flow predicted in HI collisions at LHC energies! Large v_2 and high particle multiplicity -> easy to measure. Main tool: Central tracking system. Charged particle v_2 Day 1-physics in ALICE. Later: Many differential measurements.

Challenge at LHC energies: Huge non-flow effects from jets!

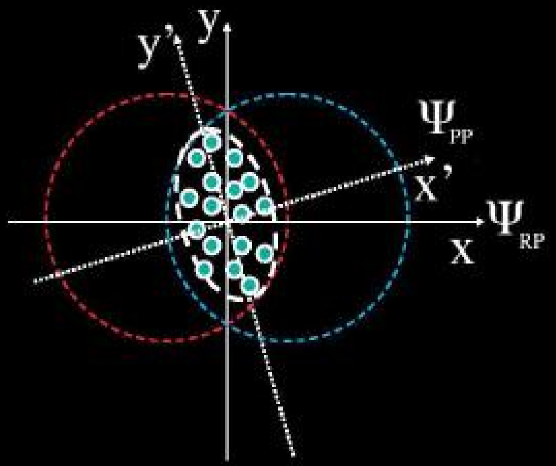
Methods for extracting elliptic flow in ALICE:

- Standard (event plane) method, with event plane extracted from data in various η intervals -> $v_2\{EP\}$ Sensitive to non-flow effects (mainly jets).
- Two- and multi-particle correlations (cumulants of n-th order -> $v_2\{n\}$).
- Lee-Yang Zeroes method (~ infinite order cumulant estimate) - least sensitive to non-flow effects -> $v_2\{LYZ\}$



Scaling with eccentricity ε of the overlap region - is v_2/ε consistent with hydrodynamics?

Hydrodynamic limit - perfect, thermalized liquid:
v_2/ε ~ constant, independent of centrality.



Eccentricity ε:

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Not trivially quantified for given centrality. Depends on initial state and on event-by-event fluctuations.

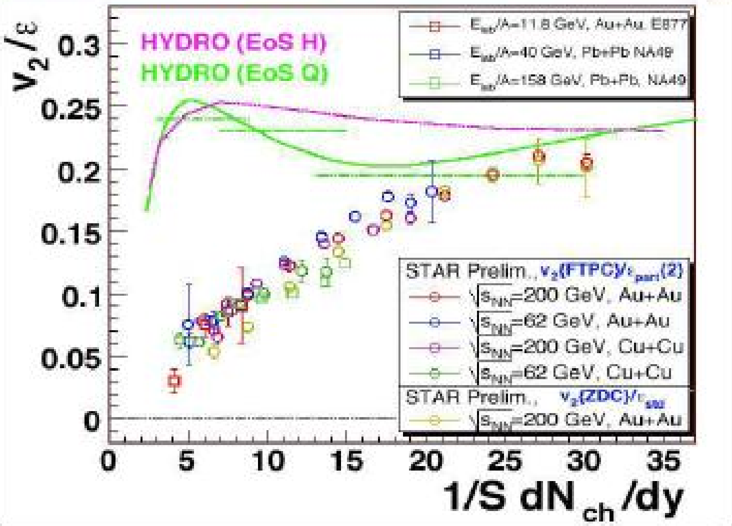
Degree of thermalization given by the inverse Knudsen number K^{-1} (number of collisions):

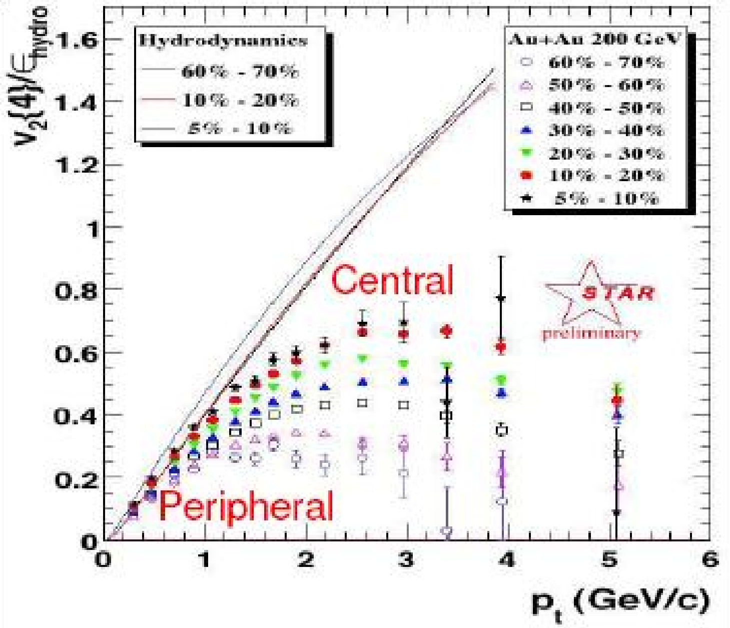
$$K^{-1} = \frac{R}{\lambda} = \frac{\sigma}{S}\frac{dN}{dy}\frac{c_s}{c}$$

Incomplete thermalization: v_2/ε given by:

$$\frac{v_2}{\epsilon} \approx \left[\frac{v_2}{\epsilon}\right]_{hydro} \frac{K^{-1}}{K^{-1} + 1.5}$$

Data approaching hydrodynamic limit only at low p_T and for central collisions.





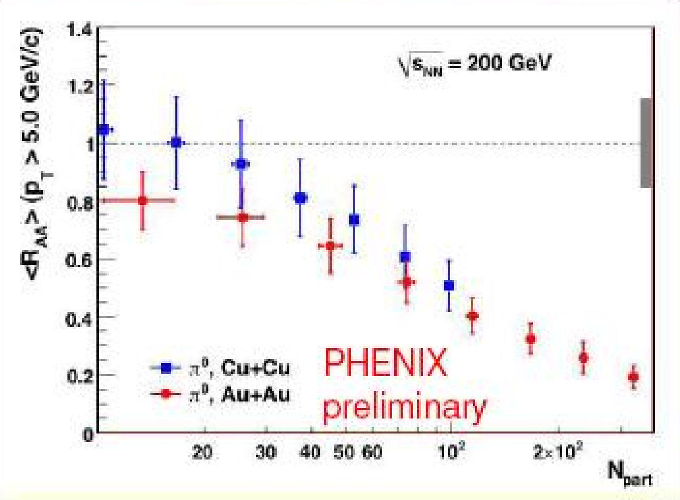
Suppression of high-p_T hadrons - energy, centrality and pathlength dependence

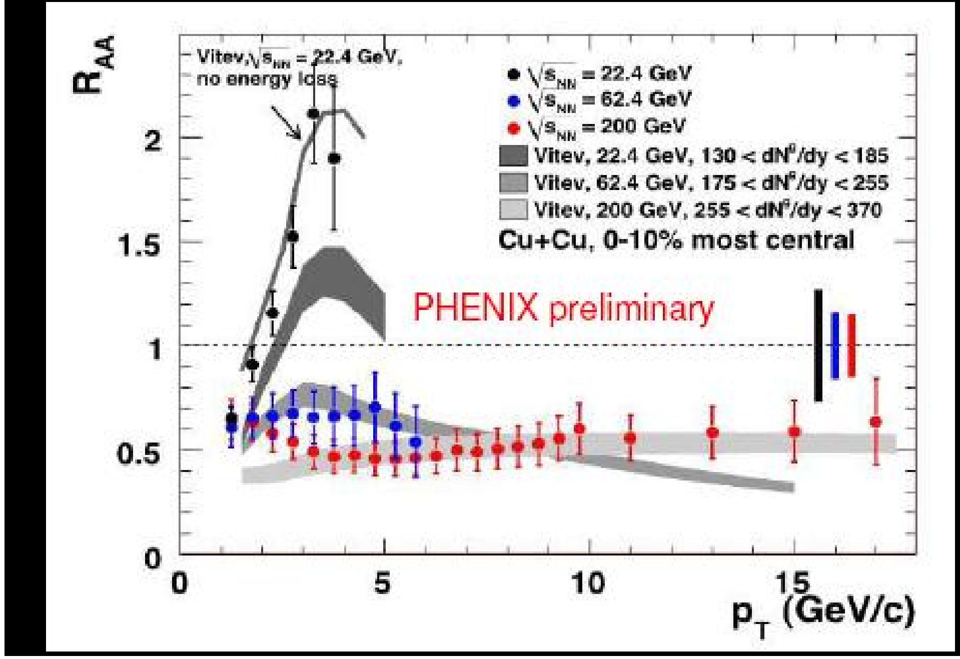
R_{AA} for π^0 spectra shows Cronin enhancement at $s_{NN}^{1/2} = 22$ GeV and suppression for $s_{NN}^{1/2} >\sim 62$ GeV.

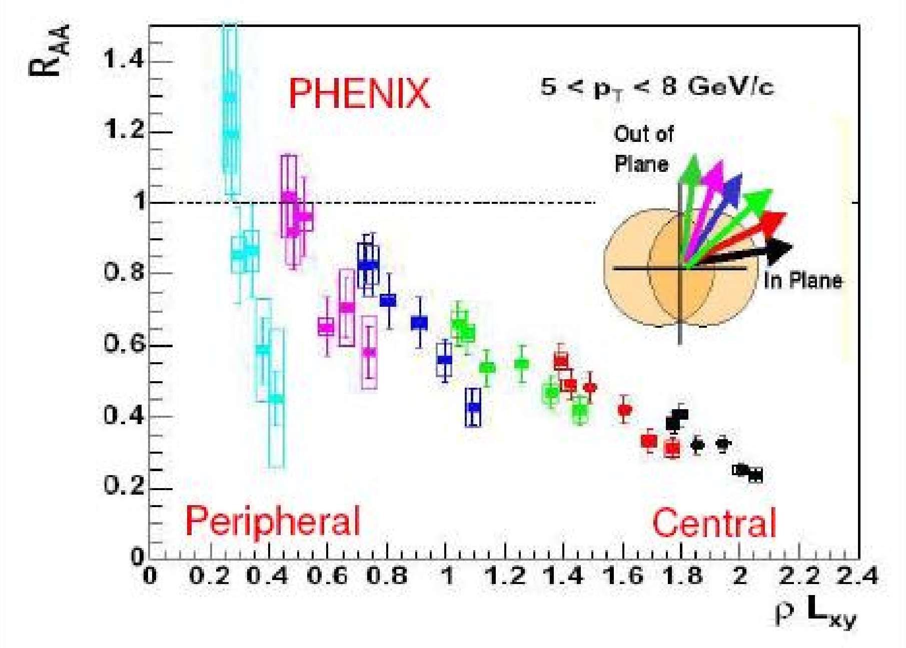
How abrupt is the transition?

R_{AA} falls with increasing centrality, scales with N_{part} for different systems.

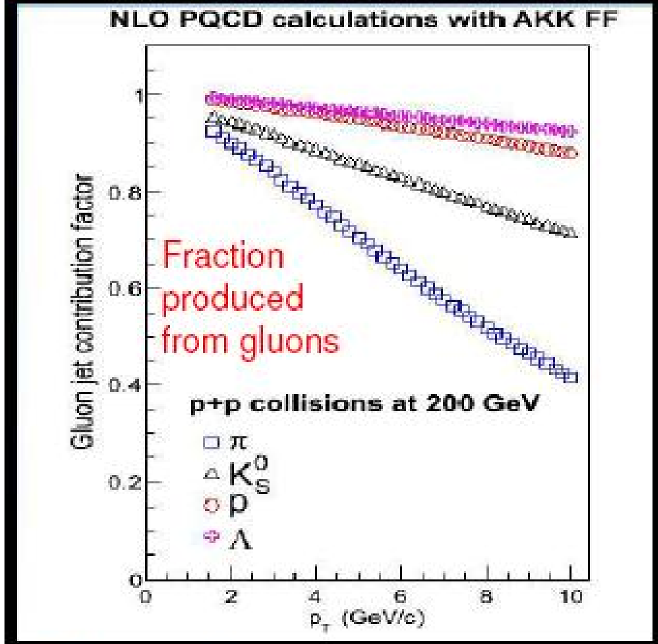
R_{AA} scales approximately with density-weighted pathlength through medium.







Puzzle: Species dependence of suppression

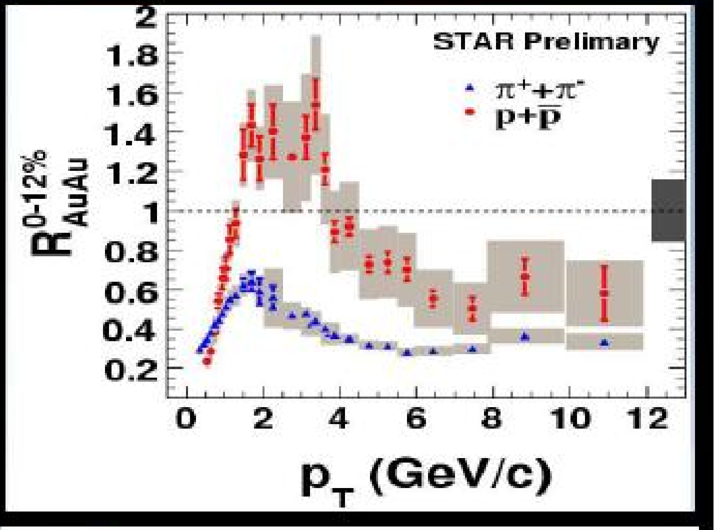


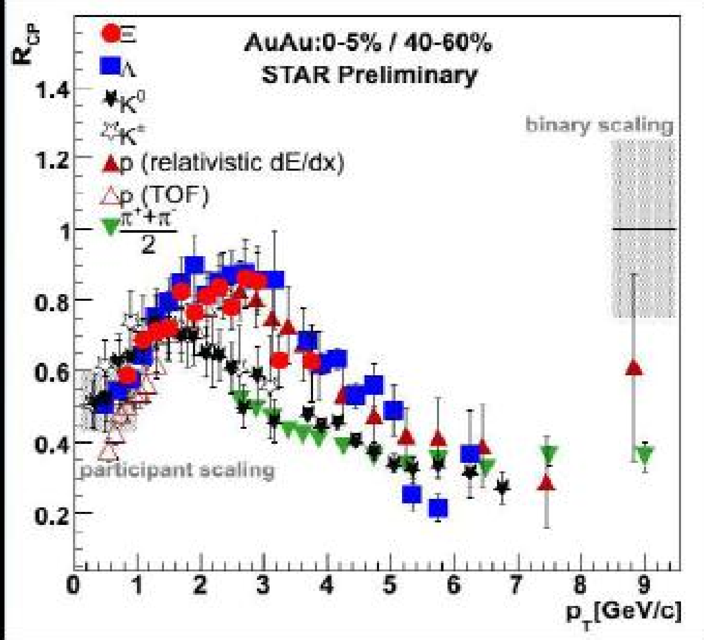
Expected energy loss for gluons vs quarks:

$$\frac{\Delta E_{gluon}}{\Delta E_{quark}} \sim \frac{9}{4}$$

Larger baryon fraction from gluons -> R_{AA}(meson) > R_{AA}(baryon)

Same for R_{CP} (central vs peripheral A+A).





Observations:

For p_T ~ 2 -5 GeV/c: R_{AA}(baryon)>R_{AA}(meson)

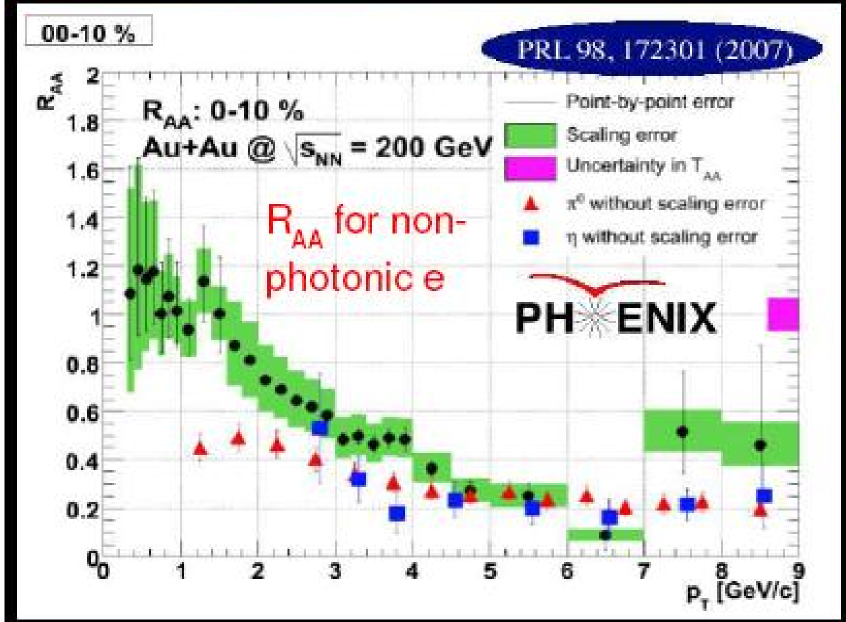
For p_T > 5 GeV/c: R_{AA}(baryon)~R_{AA}(meson)

Also: Strong baryon/meson enhancement in Au+Au relative to p+p collisions.

Parton fragmentation not dominant source of hadron production at intermediate p_T -> parton coalescence / recombination?

Behaviour at high p_T not understood.

Heavy quarks - energy loss and flow

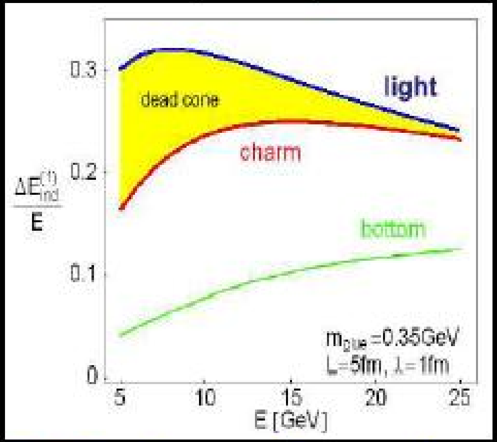


Production: Hard gg -> cc, bb.

Open heavy flavour - detection channels:

Semileptonic (e, μ),

Hadronic (mainly D^0 -> $K^+ + \pi^-$)

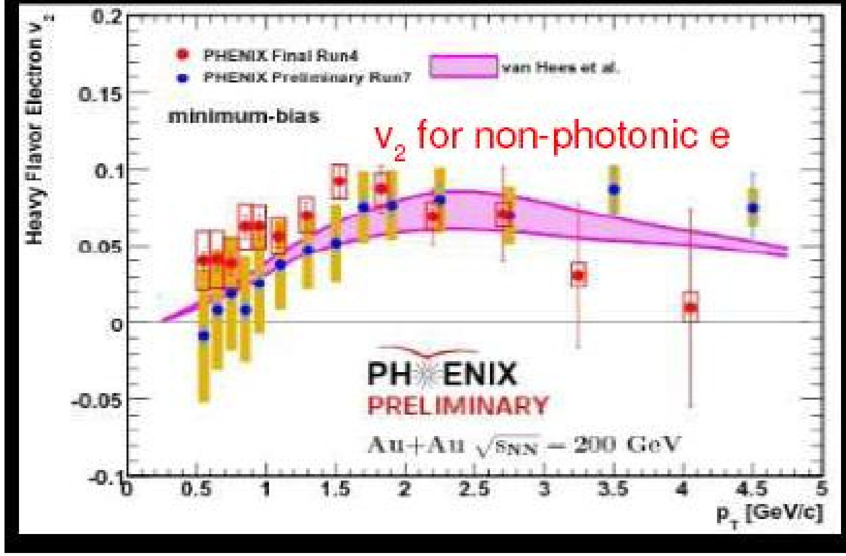


Expected hierarchy for radiative energy loss in medium:

ΔE(g) > ΔE(q) >

DE(c) >DE(b)

Heavy quarks should be less suppressed!



RHIC: Heavy flavour flows, more suppressed than expected from radiative energy loss.

Also collisional loss + in-medium fragmentation?

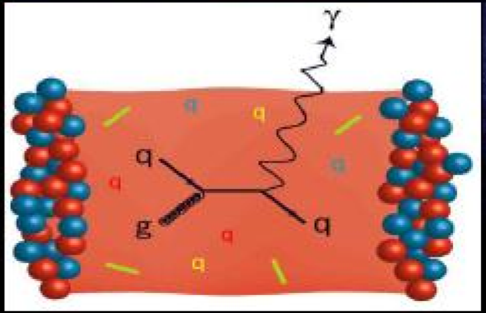
Important to separate c and b contribution:

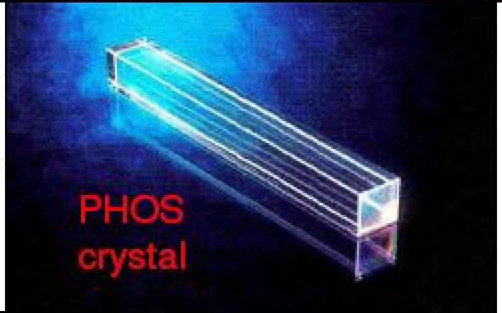
Use track impact parameters, electron-tagged angular correlations.

LHC: Heavy flavour copiously produced.

Probes for initial gluon distribution, medium properties, thermalization.

Photon physics - extracting direct component





Direct photons - penetrating probes from early stage of collision.

Major sources of photons in HI collisions:

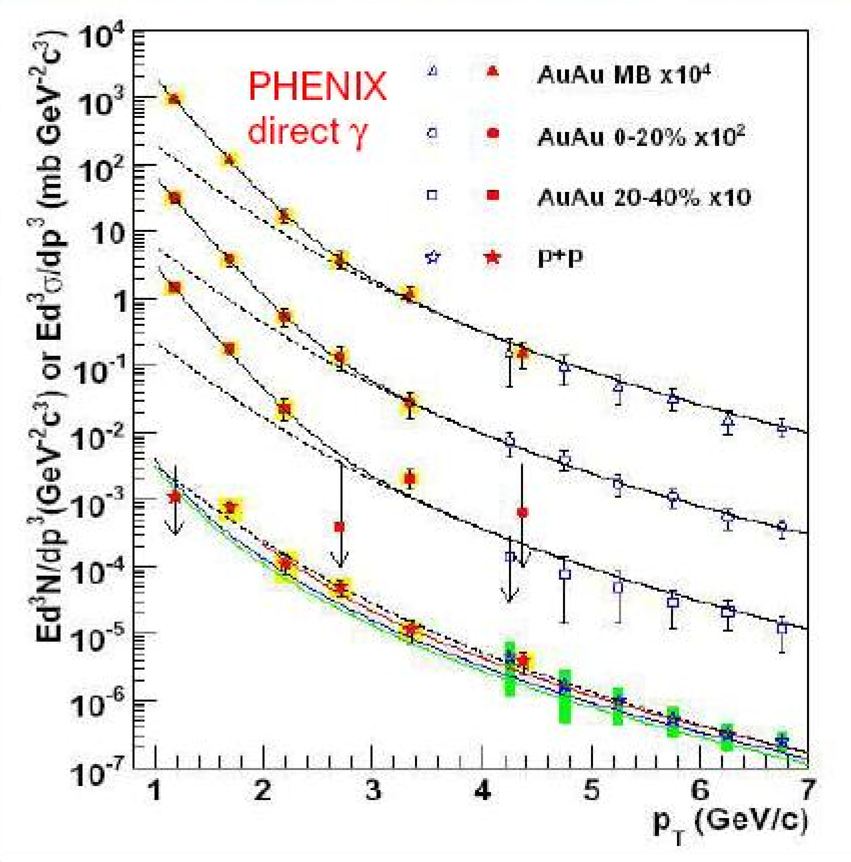
- Prompt photons from hard pQCD processes
- Thermal photons from quark-gluon plasma
- Huge background from neutral meson decay (mostly π^0)

Challenge: Disentangle the different sources.

- Subtraction of meson background (π^0, η)
- Isolation cut (no hadrons in vicinity)

Photons (+ neutral mesons) in ALICE:

- Electromagnetic spectrometers PHOS, EMCAL
- Conversion and virtual $\gamma \to e^- e^+$ pairs in CTS



RHIC: Excess over pQCD component.
Fits to PHENIX data: QGP with $T \sim$ 300-600 MeV, equilibration time $\tau_0 \sim$ 0.15 - 0.6 fm/c.