Quark Matter 2001,
Kari J. Eskola
Univ. of Jyväskylä

On Predictions of the First Results from RHIC

1. Charged Particle Multiplicity $dN_{\rm ch}/d\eta$

- Predictions at QM99
- Predictions and PHOBOS data

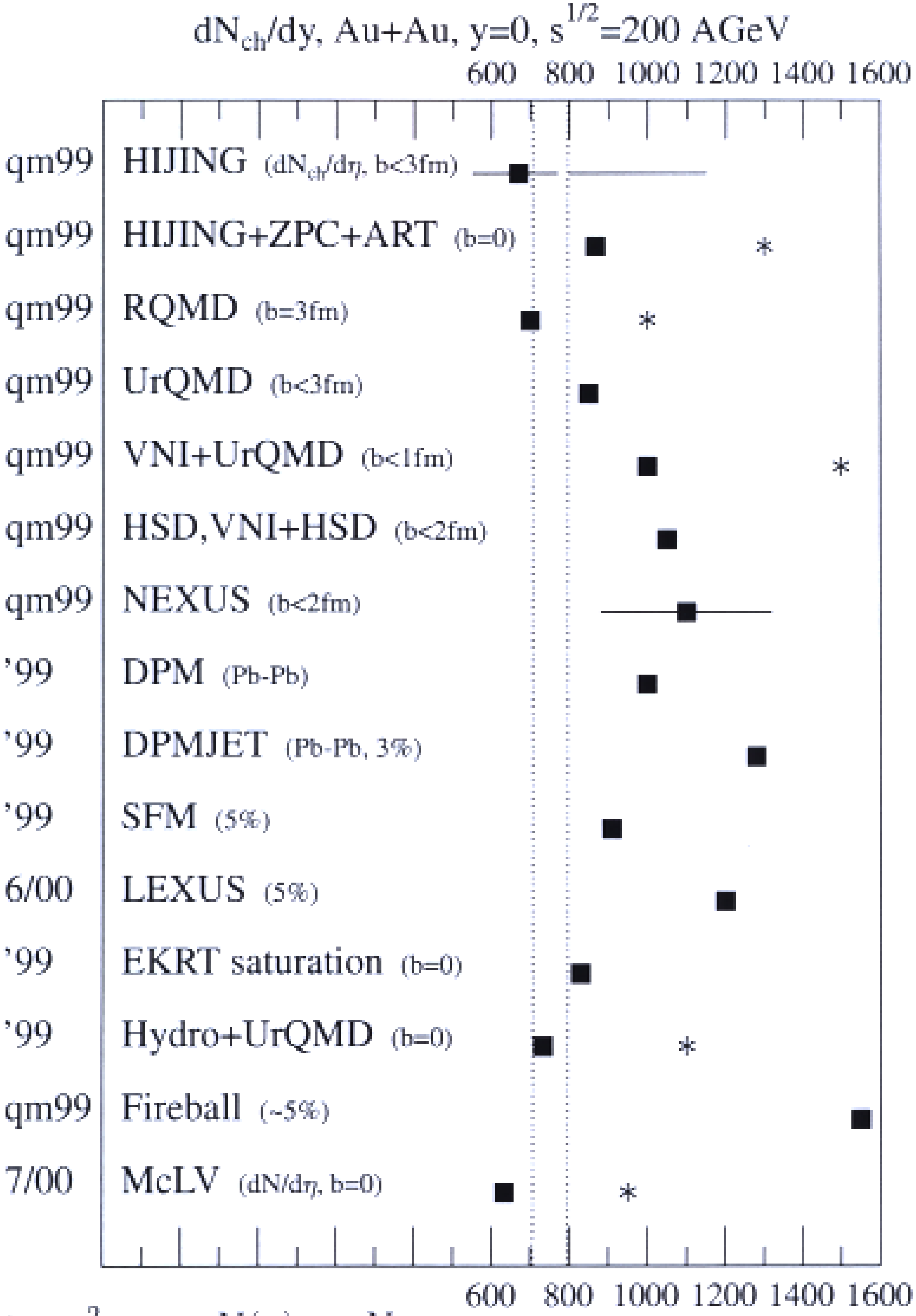
2. Centrality dependence of $dN_{\rm ch}/d\eta$

- Hard+Soft or Saturation?
  - the situation after PHENIX data

3. Elliptic flow v_2

- Evolution: Hydro or Cascade?
- STAR data ⇔ Early Thermalization?

http://www.phys.jyu.fi/homepages/kjeskola/qm01kje.ps



Applied $\sim \frac{2}{3}$: $N(*) \rightarrow N_{ch}$ ······ data $* (200/130)^{0.37} * 1.1$

Not applied above $\begin{cases} \sim 1.1: & \eta \rightarrow y \\ \sim 0.9: & b = 0 \rightarrow b \leq 3\,\text{fm}(5\%) \end{cases}$

see [Armesto,Pajares, hep-ph/0002163]

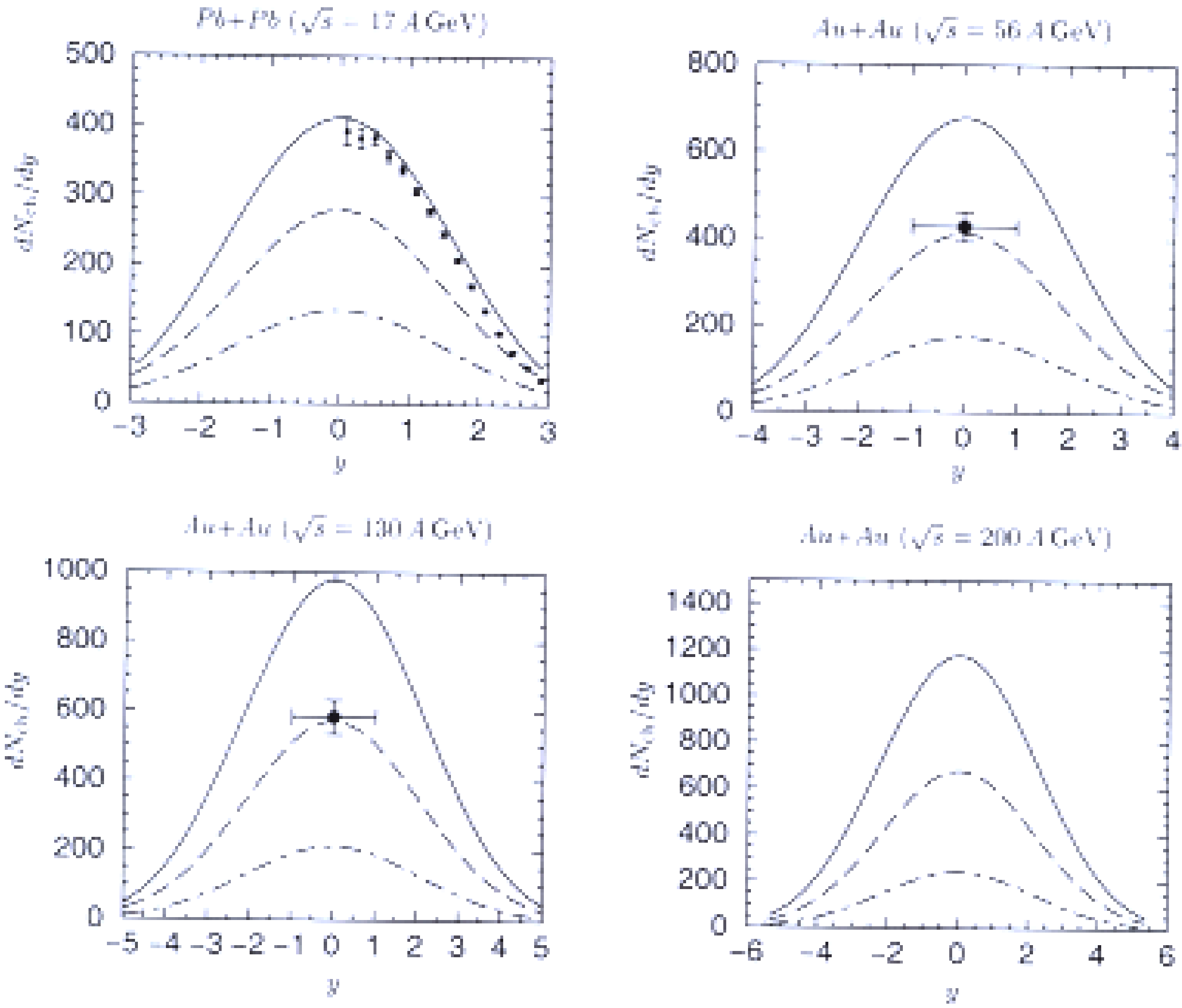
- **HIJING**
  Heavy Ion Jet Interaction Event Generator
  X.N. Wang, M. Gyulassy
- **ZPC**
  Zhang's Parton Cascade
  B. Zhang
- **ART**
  A Relativistic Transport Model
  B.A. Li, C.M. Ko
- **HIJING+ZPC+ART**
  Z. Lin, C.M. Ko, B.-A. Li, B. Zhang
- **RQMD**
  Relativistic Quantum Molecular Dynamics
  H. Sorge et al.
- **UrQMD**
  Ultrarelativistic Quantum Molecular Dynamics
  S. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, L. Bravina, C. Ernst, L. Gerland, L. Neise, S. Soff, C. Spieles, H. Weber, H. Stöcker, W. Greiner
- **VNI**
  K. Kinder-Geiger
- **HSD**
  Hadron String Dynamics
  W. Cassing, E.L. Bratkovskaya
- **NEXUS**
  H.-J. Drescher, M. Hladik, S. Ostaptchenko, K. Werner
- **DPM**
  Dual Parton Model
  A. Capella, A. Kaidalov, Tran Thanh Van

- **DPMJET**
  J. Ranft
- **SFM**
  String Fusion Model
  N. Amelin, N. Armesto, C. Pajares, D. Sousa
- **LEXUS**
  Linear EXtrapolation of Ultrarelativistic nucleon-nucleon Scattering to nucleus-nucleus collisions
  S. Jeon, J. Kapusta
- **EKRT saturation model**
  K.J. Eskola, K. Kajantie, P.V. Ruuskanen, K. Tuominen
- **Hydro+UrQMD**
  S.A. Bass, A. Dumitru
- **Fireball Model**
  J. Stachel, P. Braun-Munzinger
- **McLerran-Venugopalan Model**
  A. Krasnitz, R. Venugopalan

LEXUS [Jeon & Kapusta, nucl-th/0009032]:

1) Fit all the parameters at nucleon-nucleon level
2) Linear extrapolation to URHIC

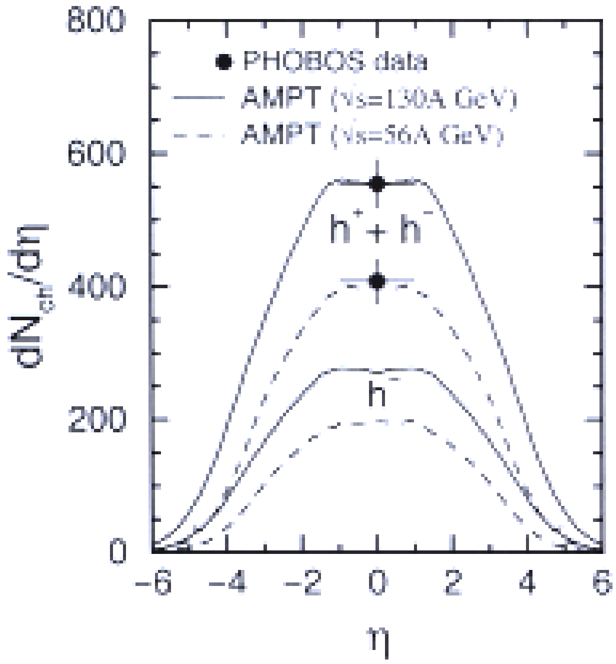
- works well at the SPS
- clearly overpredicts the RHIC data



AMPT = HIJING+ZPC+ART

[Lin, Pal, Ko, Li, Zhang, nucl-th/0011059]:

Lin's talk



initial conditions: HIJING

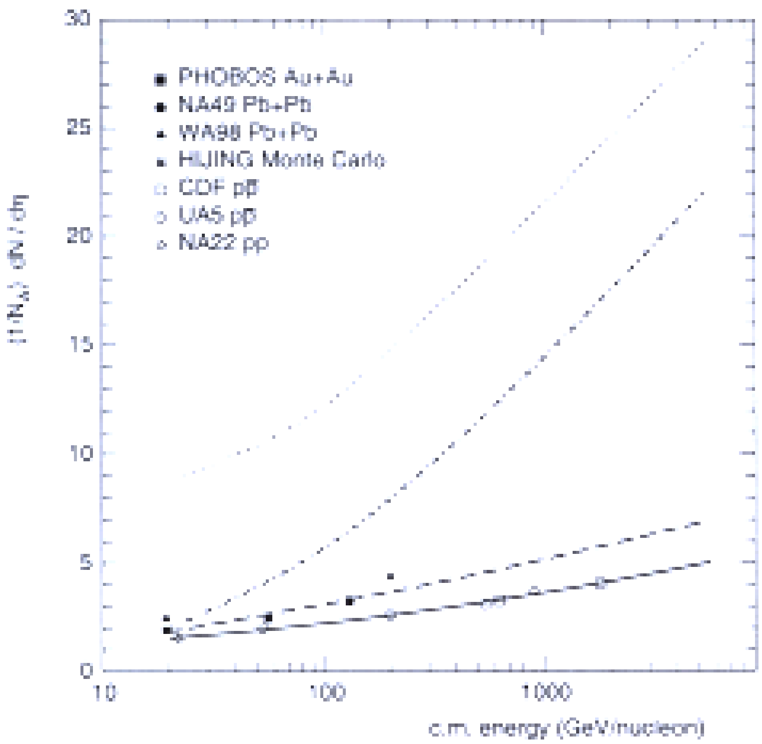
afterburners: ZPC → partonic

ART → hadronic

(some of) the parameters from the SPS data

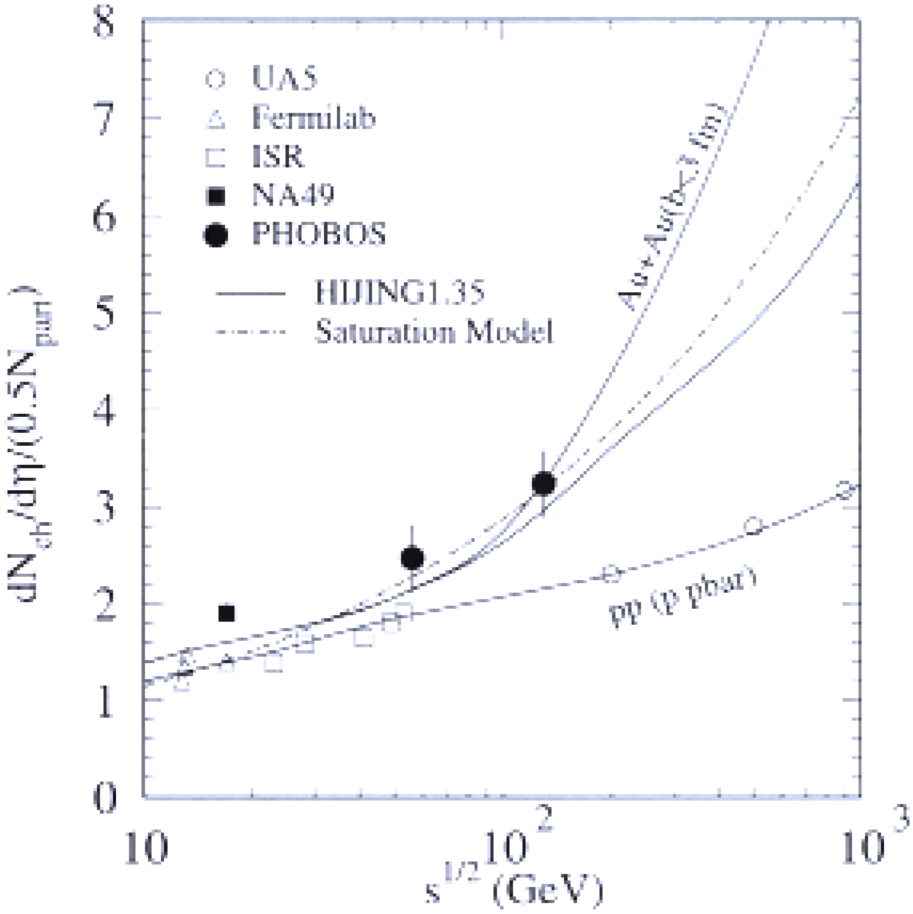
Dual String Model + Fusion

[Dias de Deus & Ugoccioni, nucl-th/0008086]:



HIJING [Wang & Gyulassy, nucl-th/0008014]:

Hard = pQCD minijets
$p_T \geq p_0$ fixed, shadowing
+
Soft = strings
+
Jet quenching
Energy loss



EKRT Saturation Model
[Eskola,Kajantie,Ruuskanen,Tuominen, hep-ph/9909456]:

pQCD minijets $p_T \geq p_0$
+
Saturation of produced gluons $\Rightarrow p_0 = p_{\text{sat}}(\sqrt{s}, A)$
+
Hydrodynamical further evolution

Implications?

- within each model, for $\frac{dN_{\rm ch}}{d\eta}$:

Theor. uncertainties $\gg$ Experimental (syst.) errorbars

- First RHIC data

$\Rightarrow$ Obtain very important constraints for the models
Essential further constraints from E_T !
(E_T more sensitive to the evolution than $N_{\rm ch}$)

$\Rightarrow$ Eventually, hope to rule out models

- Coherence phenomena in particle production important at RHIC

- Efficient final state interactions needed

$\Rightarrow$ pressure, thermalization (how early? see v_2!)

- Onset of pQCD particle production

pQCD Minijets in URHIC
[Blaizot,Mueller '87; Kajantie,Landshoff,Lindfors '87; Eskola,Kajantie,Lindfors '89; Wang, Gyulassy, HIJING, '91; Geiger,Müller, PCM, '91]

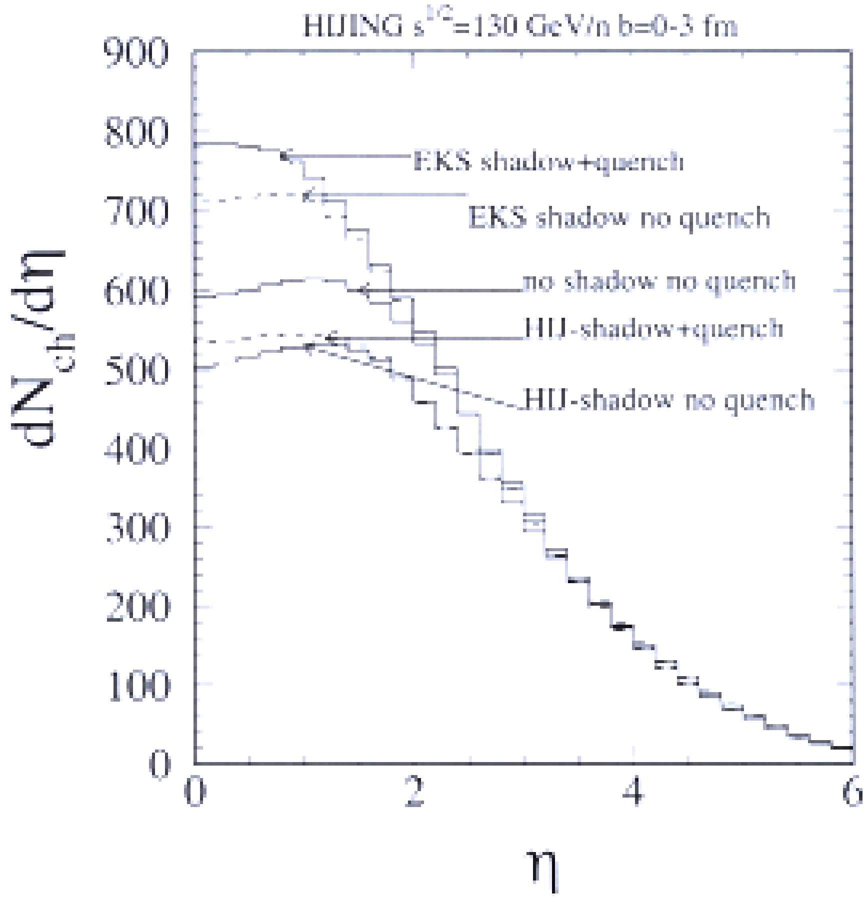
- Factorized approach:

$$\sigma_{\rm jet}(p_T \geq p_0) = K \sum_{ij} f_{i/A} \otimes f_{j/A} \otimes \hat{\sigma}_{ij}$$

Computable in LO but ∃ uncertainties:

- $K \sim 2$? now NLO development
  [Eskola,Tuominen,hep-ph/0010319], Tuominen's poster
  [Leonidov,Ostrovsky, hep-ph/9811417]
- nuclear PDFs: $f_{i/A}(x,Q) = R_i^A(x,Q^2) f(x,Q^2)$
  - * ∃ different parametrizations for R_i^A (fig)
  - * however: ∃ constraints for R_q^A, $R_{\bar{q}}^A$ *and* R_g^A from DIS
    ⇒ EKS98 (fig)

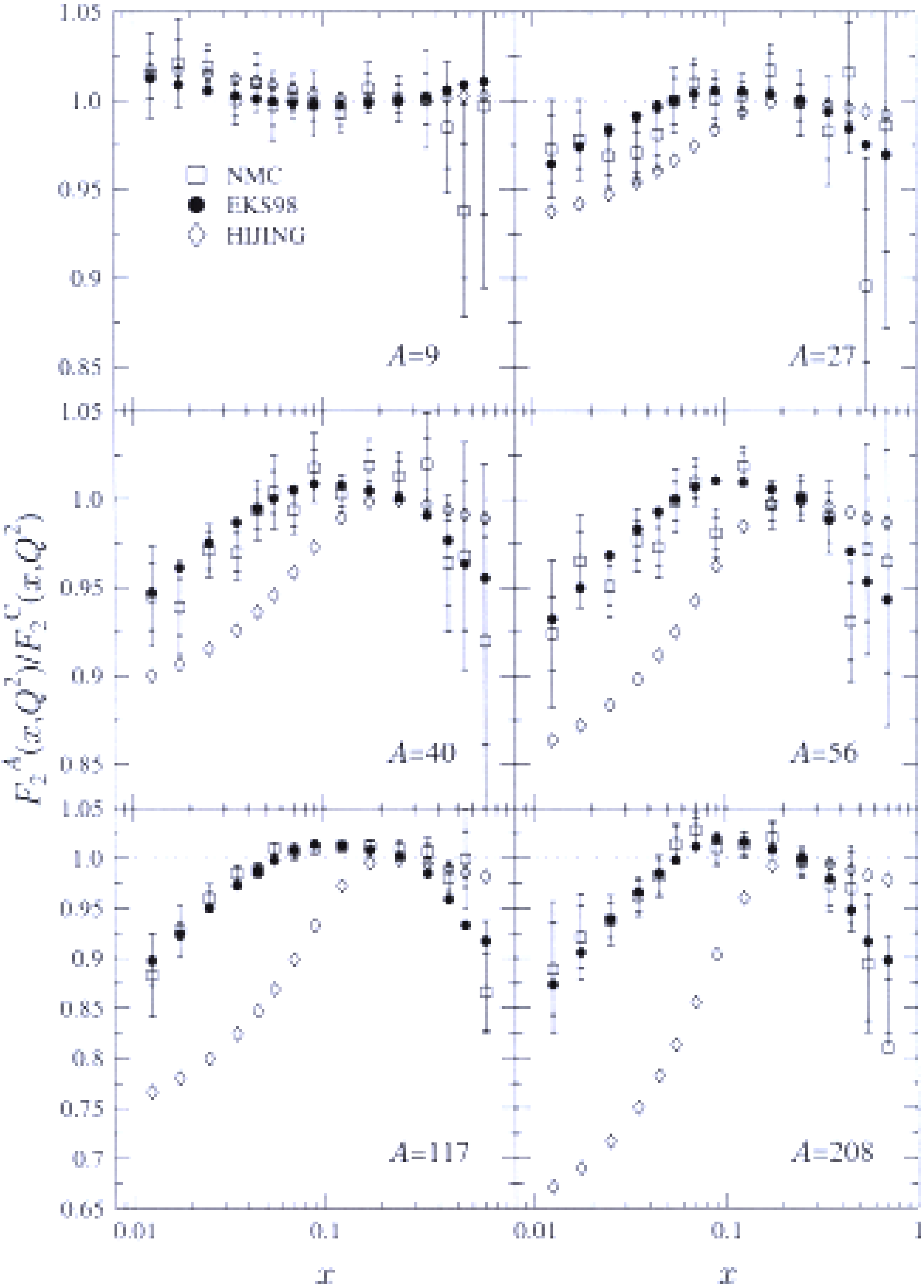
⇒ affect the determination of p_0
HIJING: $p_0 = 2$ GeV, from pp data
EKRT: dynamical $p_0 = p_{sat}(\sqrt{s}, A)$



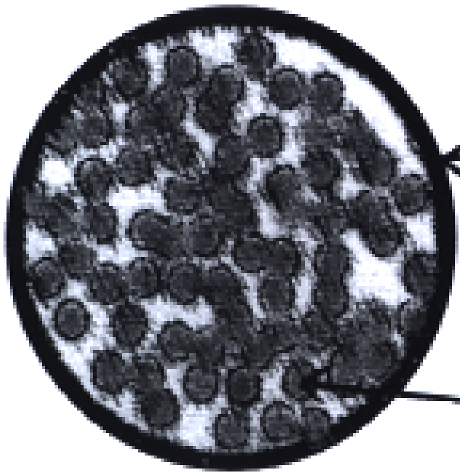
HIJING prediction, from X.-N. Wang

EKS98 = DGLAP + constraints from DIS & DY,
conservation of B & p

[Eskola, Kolhinen, Salgado, hep-ph/9807297]



On Gluon Saturation



$A_\perp \approx \pi R_A^2$

$\sigma_g(Q) \sim \frac{\pi}{Q^2}, \quad \frac{\alpha_s(Q^2)}{Q^2}, \ldots$

- Saturation of N_g when

$$N_g(Q, \Delta Y) * \sigma_g(Q) \sim \pi R_A^2$$

locally

$$\frac{dN_g(Q)}{d^2s dy} \sim \frac{1}{\sigma_g(Q)} \sim \quad \frac{Q^2}{\pi}, \quad \frac{Q^2}{\alpha_s(Q)}$$

$\Rightarrow Q = Q_{\rm sat}, \quad$ if $N_g(Q)$ can be computed

- $Q_{\rm sat} \gg \Lambda_{\rm QCD}$ at high $\sqrt{s}$.

A. Saturation in the initial state (wave f.)

[Gribov,Levin,Ryskin'83; Mueller,Qiu,'86; Blaizot,Mueller'87]

$$Q^2_{\rm sat} = \frac{8\pi^2 N_c}{N_c^2-1}\alpha_s(Q_{\rm sat})xG(x,Q^2_{\rm sat})T_A(s)$$

[McLerran, Venugopalan, '94, PRD49,50,59; Mueller hep-ph/9906322] Venugopalan's talk

- N_g^A saturates $\Rightarrow$ g luminosity reduced $\Rightarrow$ N_g^{AA} finite

$$\frac{dN_g^{AA}}{d^2sdy} \sim \frac{dN_g^A}{d^2sdy} = c\frac{C_F Q^2_{\rm sat}}{\alpha_s 2\pi^2}$$

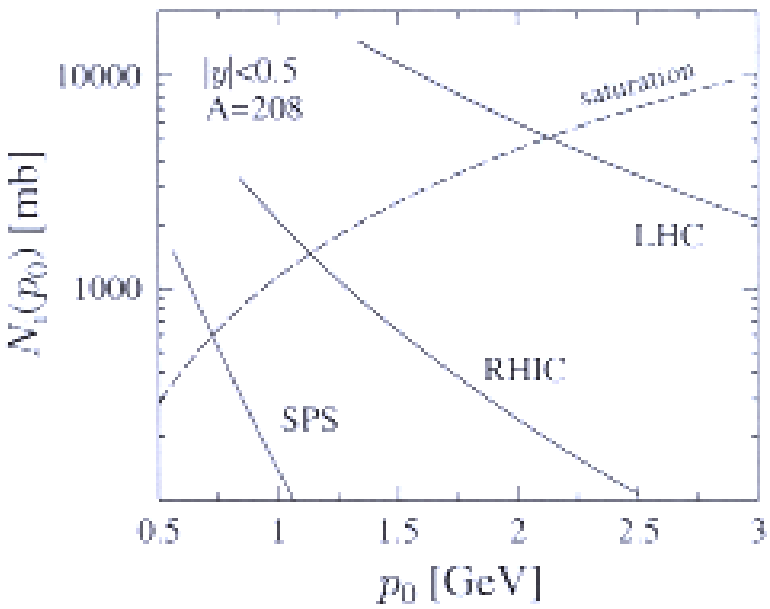
- $c \sim 1$ [Mueller, hep-ph/9906322]
- $c = 1.39$ analytically! [Kovchegov, hep-ph/0011252] PHOBOS data $\Rightarrow$ $Q^2_{sat} = 2.1\,\mathrm{GeV}^2$ Kovchegov's talk
- $c = 1.29 \pm 0.09$ based on $SU(2)$ lattice calc.! [Krasnitz, Venugopalan, hep-ph/0007108]
- $c = 1.23 \pm 0.20$ from PHOBOS data [Kharzeev, Nardi, nucl-th/0012025]

B. Saturation of produced gluons, EKRT

[Eskola,Kajantie,Ruuskanen,Tuominen, hep-ph/9909456]

- Saturation

$$N_{AA}(p_0, \sqrt{s}, \mathbf{0}) * \frac{\pi}{p_0^2} = \pi R_A^2 \quad \Rightarrow \quad p_0 = p_{\rm sat}(\sqrt{s}, A)$$



- $\sim$ scaling:

$\sigma_{\rm jet}(p_0) \sim p_0^{-2} \Rightarrow p_{\rm sat}^2 \sim A^{1/3} \Rightarrow N_{AA}(p_{\rm sat}) \sim A$

- Full calculation: $xg(x, p_{\rm sat}) \sim x^{-\delta}$, EKS98 shadowing

$$\Rightarrow \quad N_{AA}(p_{\rm sat}) = 1.383 A^{0.922} (\sqrt{s})^{0.383}$$

- Initial state thermalized:
  $E_{Ti}^{AA} \to \epsilon_i \to T_i \to N_i \approx N_{AA}(p_{\rm sat})$

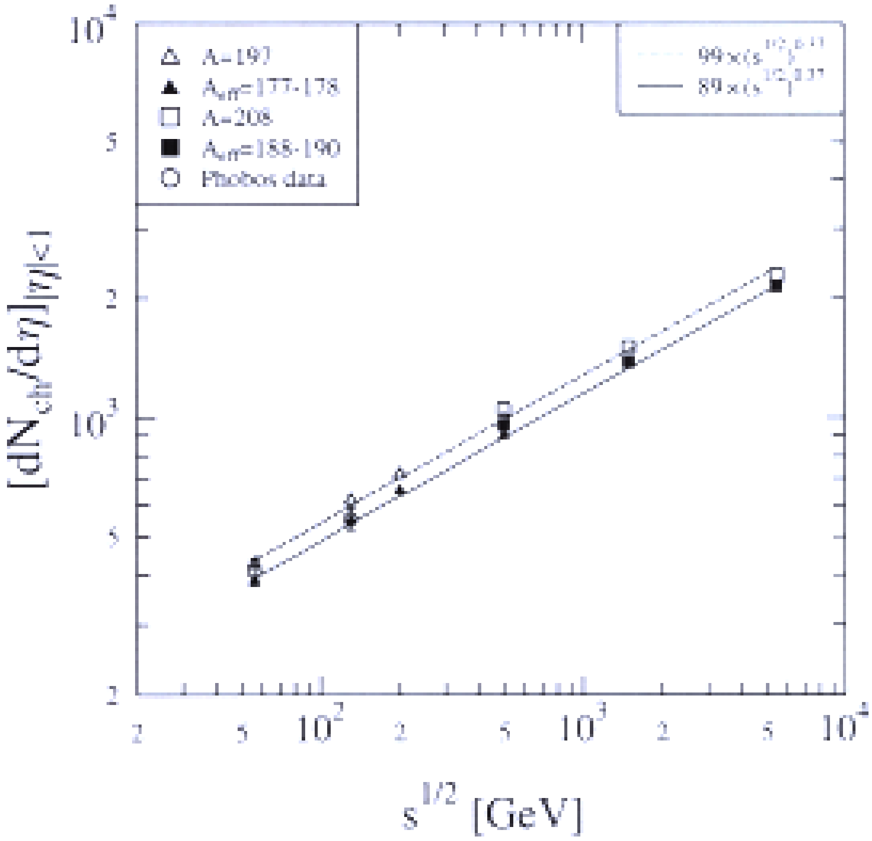
- **Expansion stage** = Bj hydro with minijet IC
  at $\tau_0 = 1/p_{\rm sat}$

- Entropy conserving expansion

$$\Rightarrow 3.6 N_i \approx S_i = S_f \approx 4N_f$$

$$\Rightarrow \frac{dN_{\rm ch}}{dy} \approx \frac{2}{3}N_f = \frac{2}{3}1.24A^{0.922}(\sqrt{s})^{0.383} \Leftrightarrow \text{PHOBOS}$$

- More detailed $\perp$ hydro with saturated minijet IC [Ruuskanen et al.]:



2. Centrality dependence of $N_{\rm ch}$

- HIJING [Wang, Gyulassy, nucl-th/0008014]:

$$\frac{dN_{\rm ch}}{d\eta} = N_{\rm part} n_{\rm soft} + f N_{\rm bin} \sigma_{\rm jet}^{AA}(p_0)$$

- EKRT saturation [Eskola, Kajantie,Tuominen, hep-ph/0009246]: need a **local** saturation criterion

$$\frac{dN_{\rm ch}}{d\eta} = 0.9 \frac{2}{3} \frac{dN_{AA}}{dy} = 0.9 \frac{2}{3} \int d^2\mathbf{s}\, p_{\rm sat}^2(\sqrt{s}, A, \mathbf{b}, \mathbf{s})$$

- [Kharzeev,Nardi, nucl-th/0012025]:

  1. "Soft + Hard"

$$\frac{dN_{\rm ch}}{d\eta} = (1-x) n_{pp} \frac{1}{2} N_{\rm part} + x n_{pp} N_{\rm bin}$$

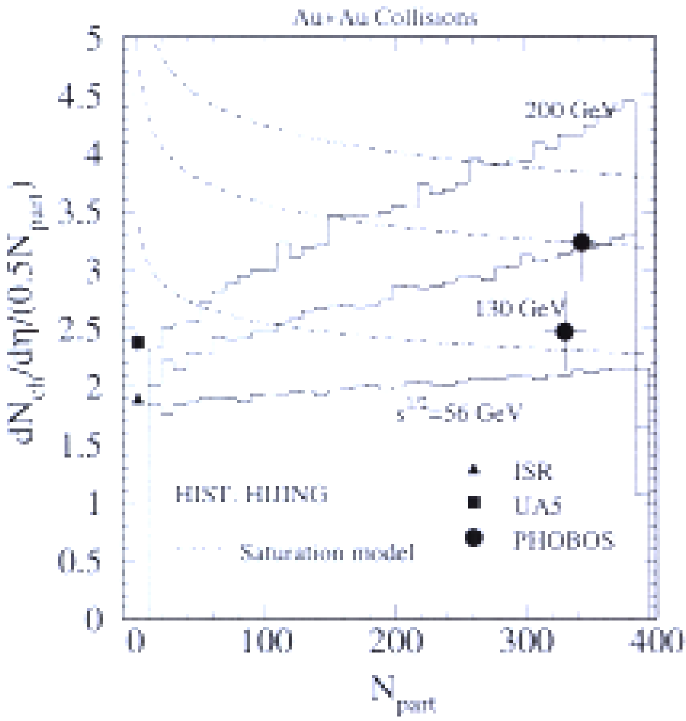
  fit x from PHOBOS $\Rightarrow$ predict centrality dep.

  2. Initial state saturation

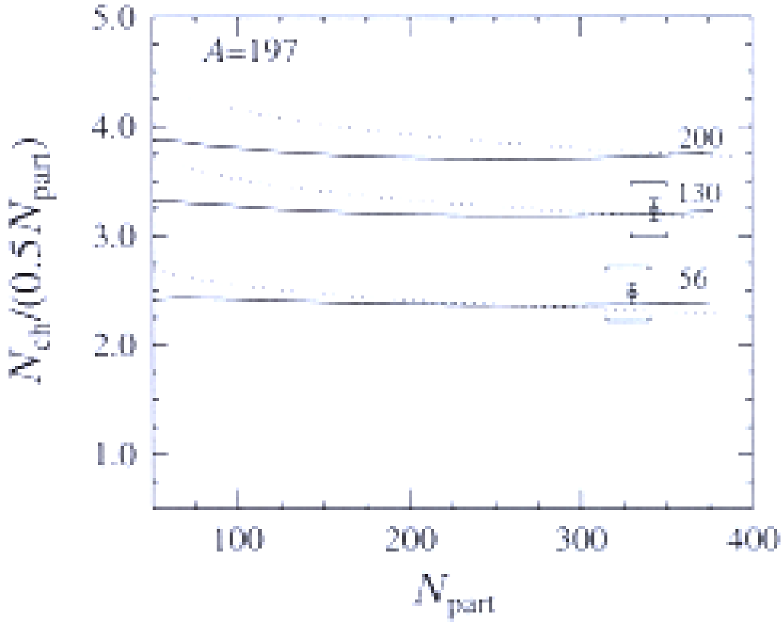
$$\frac{dN_{\rm ch}}{d\eta} = \frac{2}{3} c N_{\rm part} x G(x, Q_{\rm sat}^2)$$

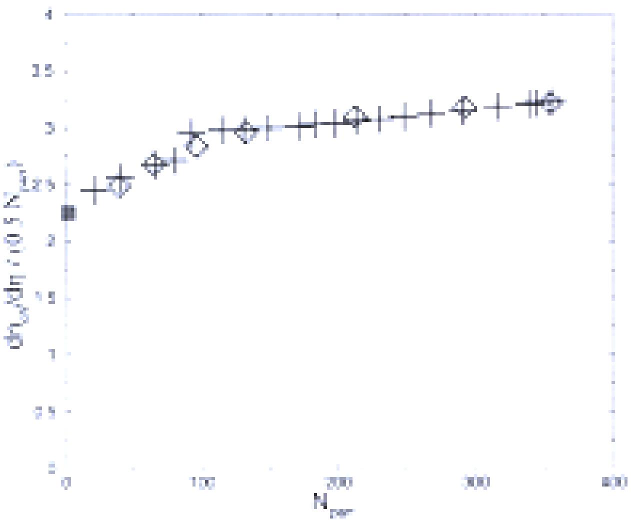
  fit c from PHOBOS $\Rightarrow$ "predict" centrality dep.

HIJING

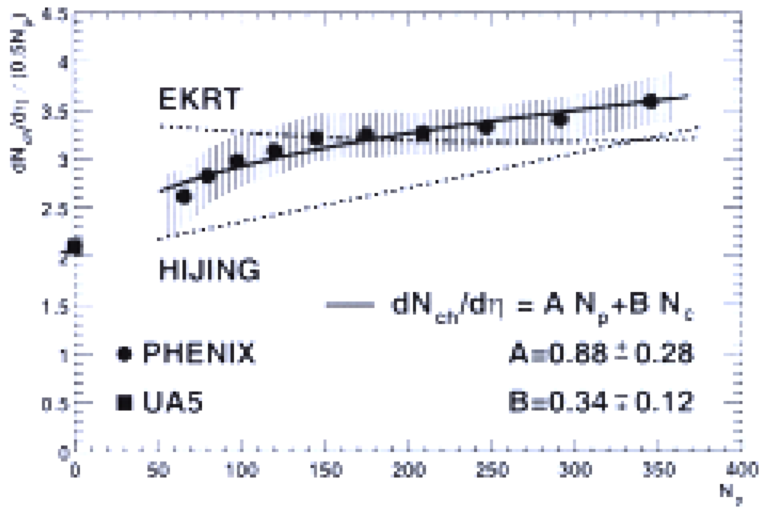


EKRT saturation





Kharzeev&Nardi



PHENIX

Implications?

- Data $\Rightarrow$ Important constraints for the models!

  - HIJING: jet quenching, shadowing

  - Saturation models: the exact form of the saturation criterion (add $\alpha_s(p_{\rm sat})$ in that of EKRT?)

  - ...

- Hard to rule out models based on

$$\frac{dN_{\rm ch}}{d\eta} \quad \frac{dN_{\rm ch}}{d\eta}(b) \quad \text{alone,}$$

  most (all?) models can be tuned to reproduce the data

- E_T will be more efficient model-killer !

$2\frac{1}{2}$. Transverse energy

- Problems in the initial E_T production:

  * Classical fields [Krasnitz,Venugopalan]:

$$\frac{E_T^{\rm i}}{N_{\rm i}} \approx 3Q_{\rm sat}$$

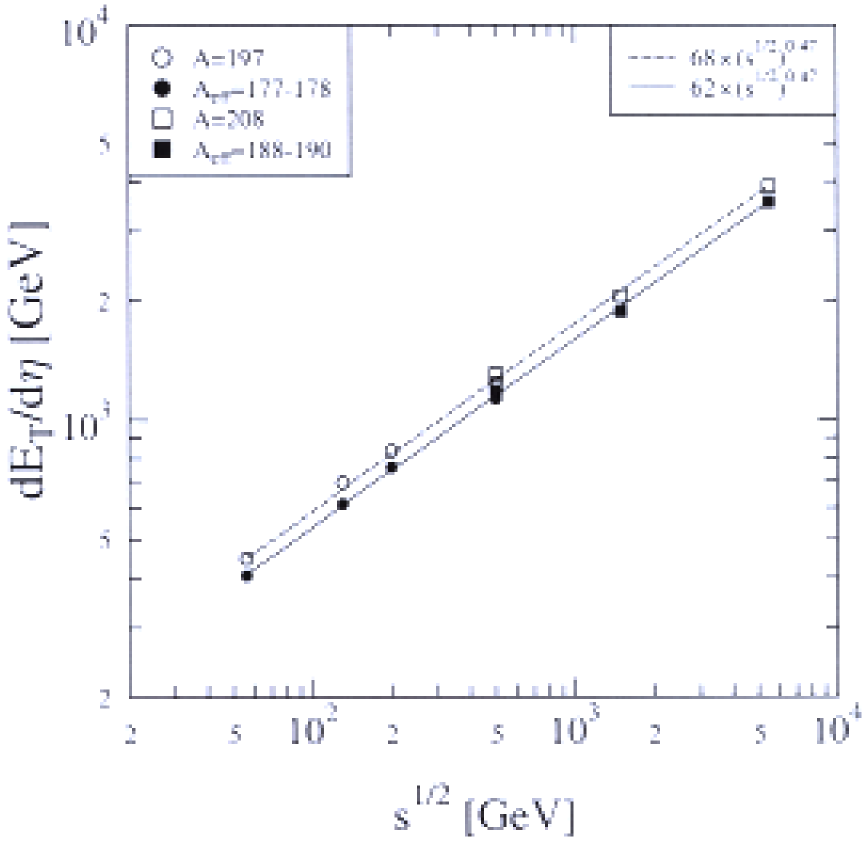
  * EKRT = pQCD+saturation:

$$\frac{E_T^{\rm i}}{N_{\rm i}} \approx 1.4 p_{\rm sat} \qquad (p_{\rm sat} \approx Q_{\rm sat})$$

  Why??

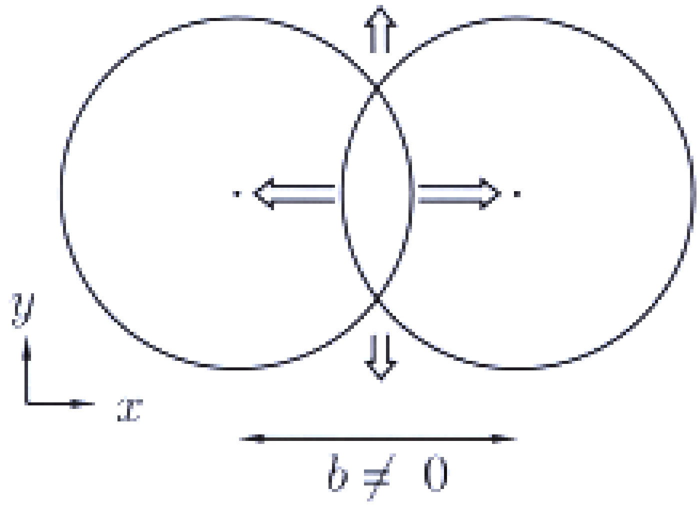
- E_T as a probe of the expansion stage:

Hydro evolution $\Rightarrow$ PdV work $\Rightarrow$ $E_T^{\rm final} = E_T^{\rm initial}/2.7$ [EKRT]



3. Elliptic flow

Physics [Ollitrault '92]:



Pressure gradients azimuthally asymmetric

⇒ Flow azimuthally asymmetric: $\langle v_x^2 \rangle \neq \langle v_y^2 \rangle$

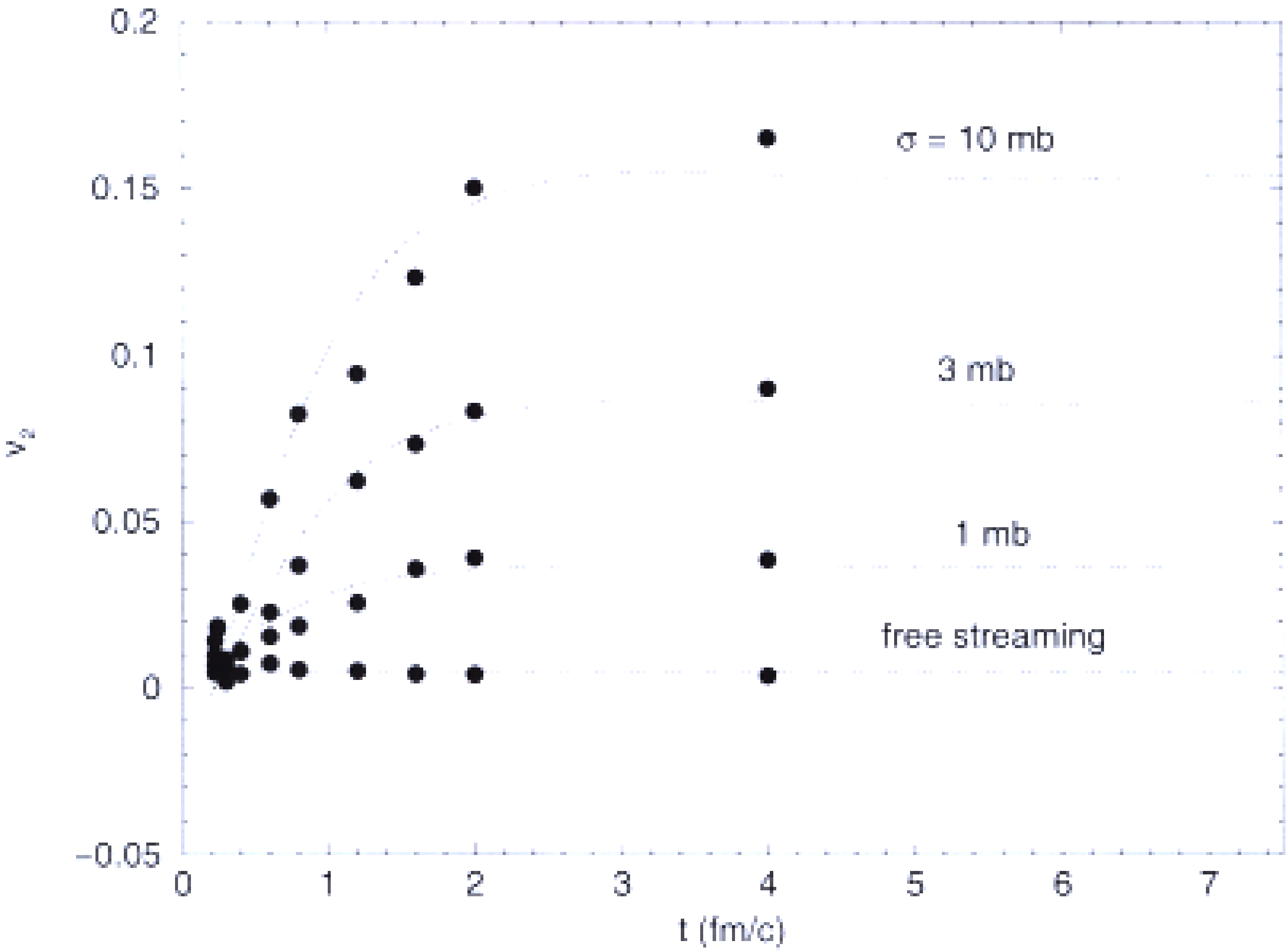
⇒ Asymmetry in azimuthal distributions

$$v_2(y) = \frac{\int d\phi \cos(2\phi) \frac{dN}{dy d\phi}}{\int d\phi \frac{dN}{dy d\phi}}$$

$$v_2(y, p_T) = \frac{\int d\phi \cos(2\phi) \frac{dN}{dy dp_T^2 d\phi}}{\int d\phi \frac{dN}{dy dp_T^2 d\phi}}$$

- Parton cascade (ZPC)
  [Zhang,Gyulassy,Ko, nucl-th/9902016]

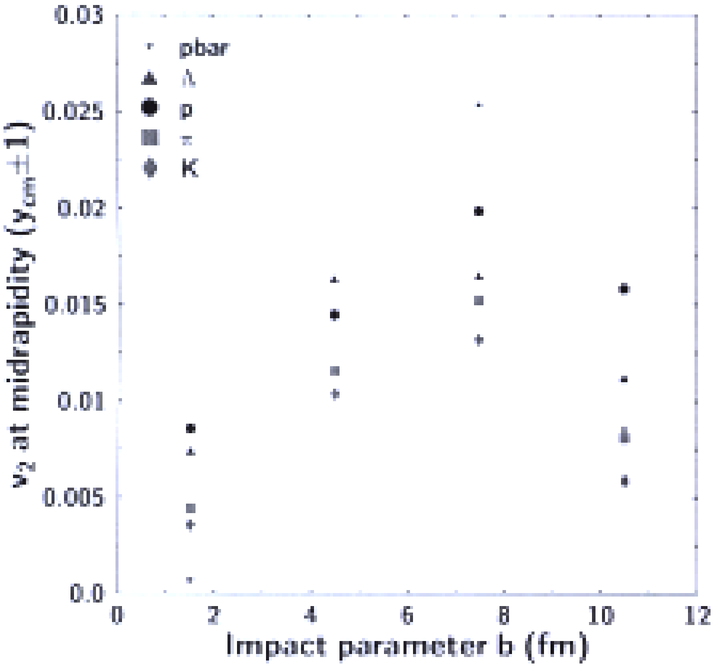
  $\sqrt{s} = 200$ AGeV, $b = 7.5$ fm

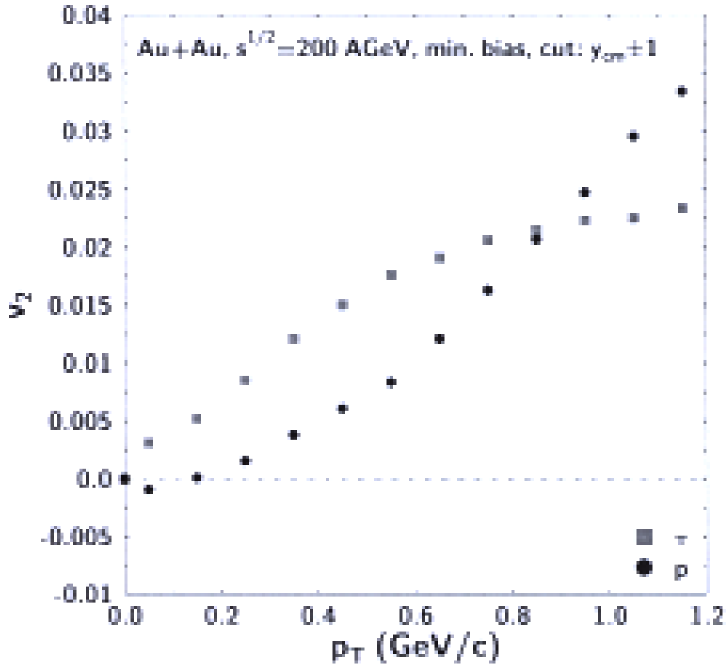


see also [D. Molnar, QM99]

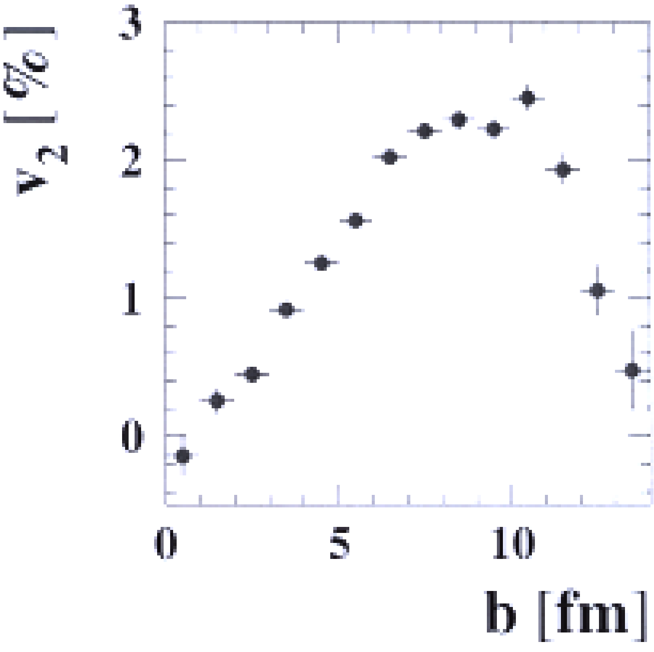
Molnar's talk

- UrQMD [Bleicher, Stöcker, hep-ph/0006147]
  $\sqrt{s} = 200\ A\text{GeV}$

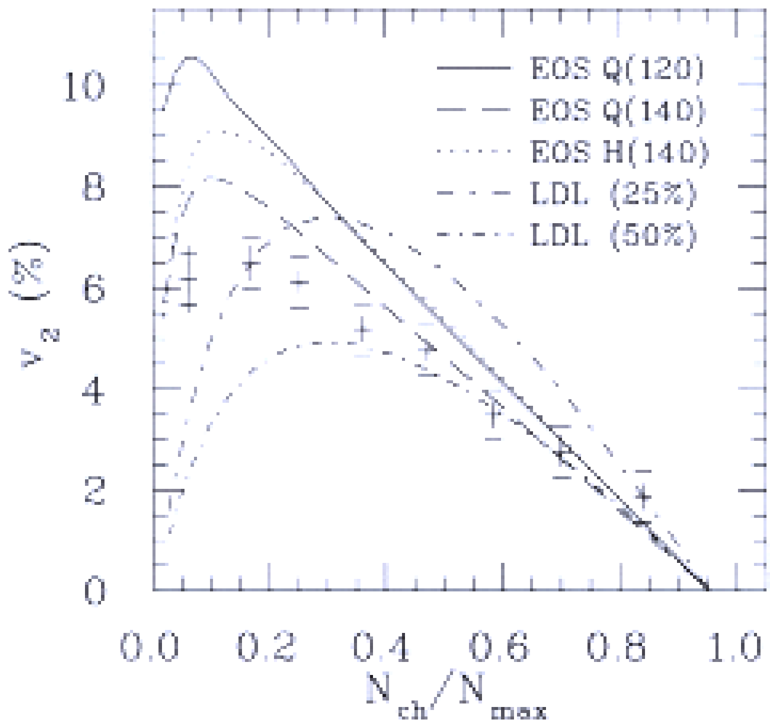


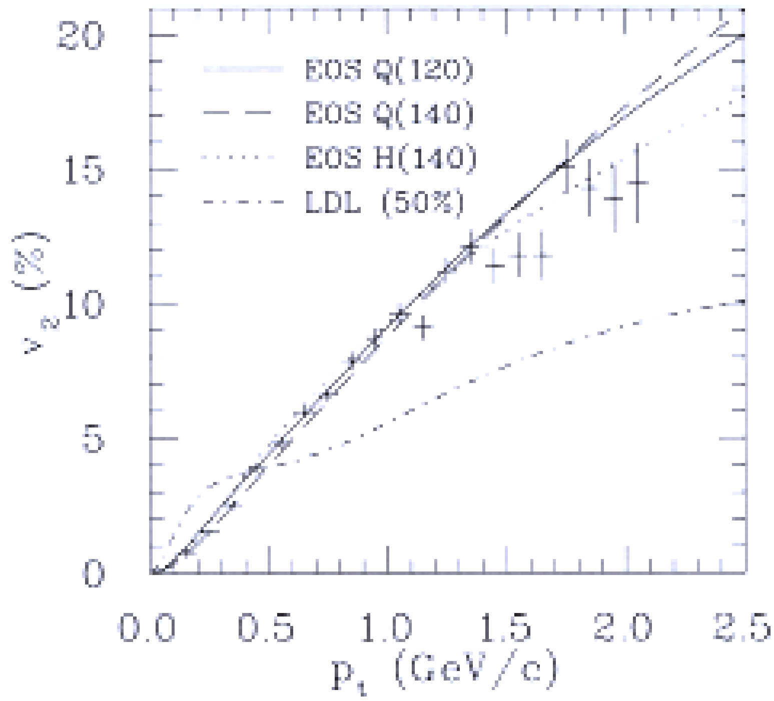


- RQMDv2.4
  [Snellings, Poskanzer,Voloshin,nucl-ex/9904003]
  $\sqrt{s} = 200\ A\ \text{GeV}$



- Hydrodynamics (Huovinen's talk)
  [Kolb,Sollfrank, Heinz, hep-ph/0006129]←prediction !
  [Kolb,Huovinen,Heinz,Heiselberg, hep-ph/0012137]

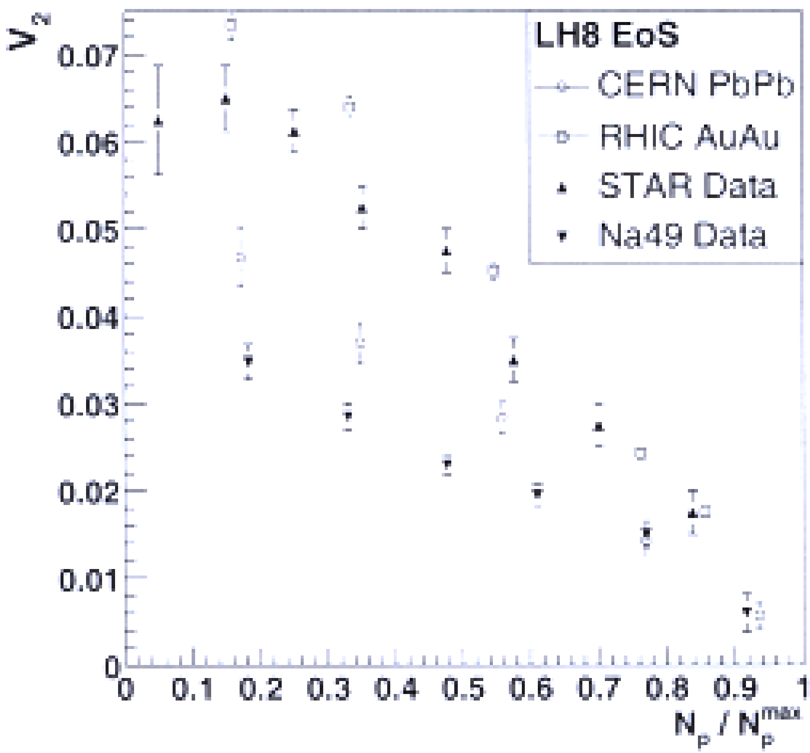




- Hydro to Hadrons Teaney's talk
  [Teaney, Lauret, Shuryak, nucl-th/0011058]

  * QGP & Mixed phase: Hydrodynamics

  * Hadronic Phase&Freeze-out: RQMDv2.4



Implications of v_2

- STAR data $\Rightarrow$ very important constraints for the different models of the evolution of the dense system!

- Hadronic cascades: underpredict v_2

- Partonic cascades: need large re-interaction cross sections $\to$ Hydrodynamic limit?

- Hadronic and partonic cascades:
  linear rise of $v_2(p_T)$ OK at $p_T \lesssim 500$ MeV
  but failure at $p_T \gtrsim 500$ MeV

- Hydrodynamics:
  * compatible with data on $v_2, v_2(p_T)$!
  * to constrain the remaining uncertainties (EoS), need single particle p_T spectra
  * also $N_{\rm ch}$ reproduced (saturation init cond. + hydro) !
  * suggests early thermalization!

Thanks for help:
Kimmo Tuominen, Keijo Kajantie, Nestor Armesto, Pasi Huovinen, Heli Honkanen, Vesa Kolhinen, Vesa Ruuskanen, Xin-Nian Wang