

The initial conditions for hydro at RHIC / LHC

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- Eccentricity \rightarrow elliptic flow:
extracting η/s and hydro limit (EoS)
- Thermalization \rightarrow
"Parton cascade" w/o cutoffs

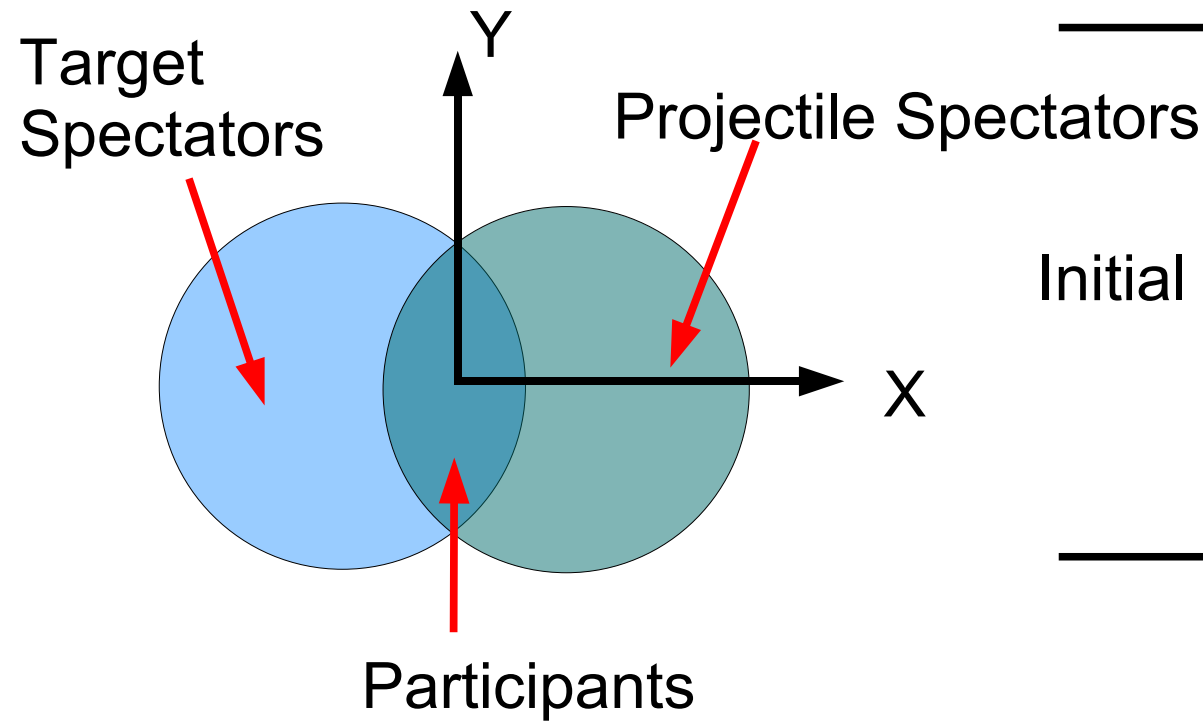
Chronological evolution of HIC

Time



- Colliding nuclear wavefunctions
- Thermalization stage
- (Viscous) Hydro expansion
- Transition to confined “vacuum”
- Hadronic freeze-out

Pressure gradients and elliptic flow



	Coordinate space	Momentum space
	$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$	$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$
Initial		
Later		

Idea : Pressure gradients convert spatial anisotropy to momentum anisotropy

Standard model for the initial transverse density profile

Wounded nucleon model:
number of participants scaling

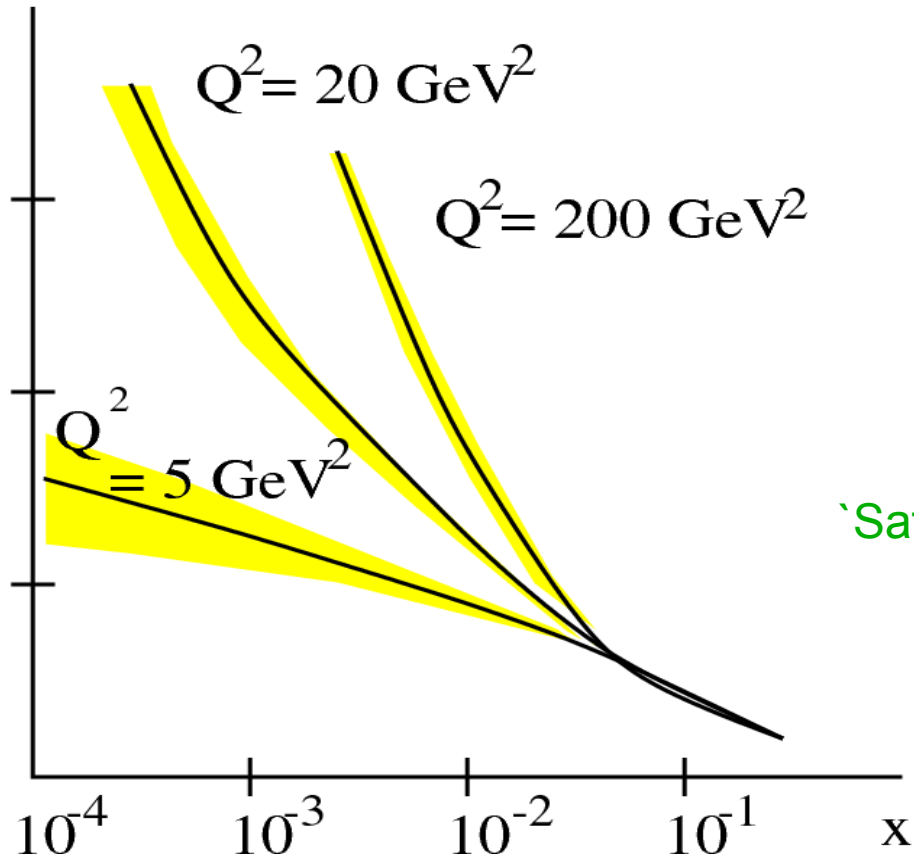
$$\frac{dN}{d^2r_t dy} \sim \rho_{\text{part}} ,$$

$$\begin{aligned} \rho_{\text{part}}(\vec{r}_\perp, \vec{b}) &= \rho_{\text{part}}^A(\vec{r}_\perp, \vec{b}) + \rho_{\text{part}}^B(\vec{r}_\perp, \vec{b}) \\ &= T_A(\vec{r}_\perp + \vec{b}/2) \left(1 - (1 - \sigma_{NN}^{\text{inel}} T_B(\vec{r}_\perp - \vec{b}/2)/B)^B \right) \\ &\quad + T_B(\vec{r}_\perp - \vec{b}/2) \left(1 - (1 - \sigma_{NN}^{\text{inel}} T_A(\vec{r}_\perp + \vec{b}/2)/A)^A \right) \end{aligned}$$

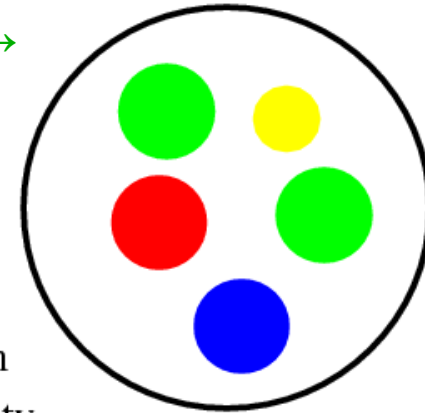
$$T_A(\mathbf{x}_\perp) = \int dz \rho_A(\mathbf{x}_\perp, z) \quad \rho_A(\mathbf{r}) = \frac{\rho_0}{1 + \exp[(r - R_0)/a]}$$

Gluon Saturation at High Energy

$xG(x, Q^2)$



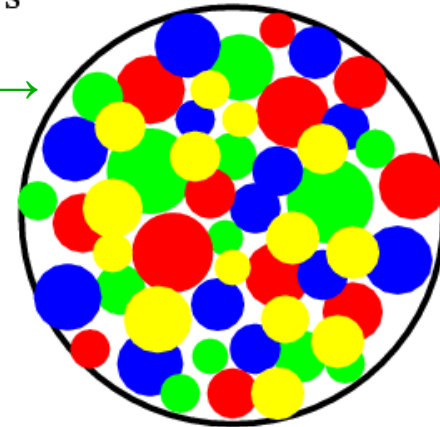
Dilute Parton Gas \rightarrow



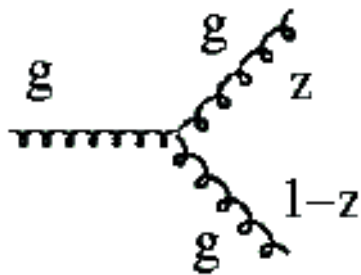
Low Energy

Gluon Density Grows

'Saturated' Color Field \rightarrow



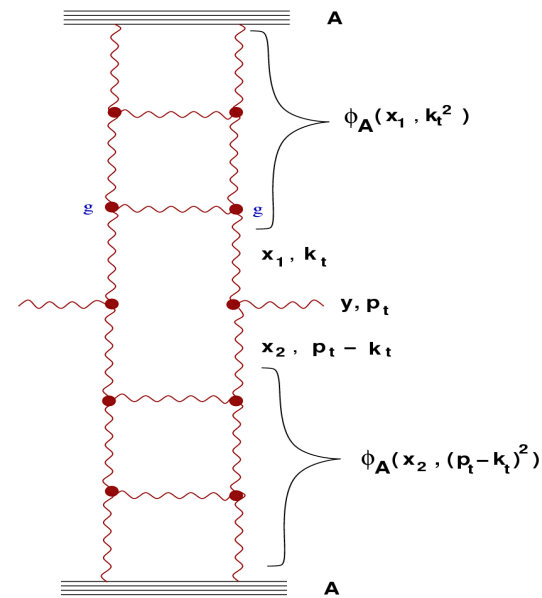
High Energy



$$P_{gg}(z) = 2N_c \left(\frac{1-z}{z} + \frac{z}{1-z} + z(1-z) \right)$$

Inclusive gluon production

K_t -factorization:

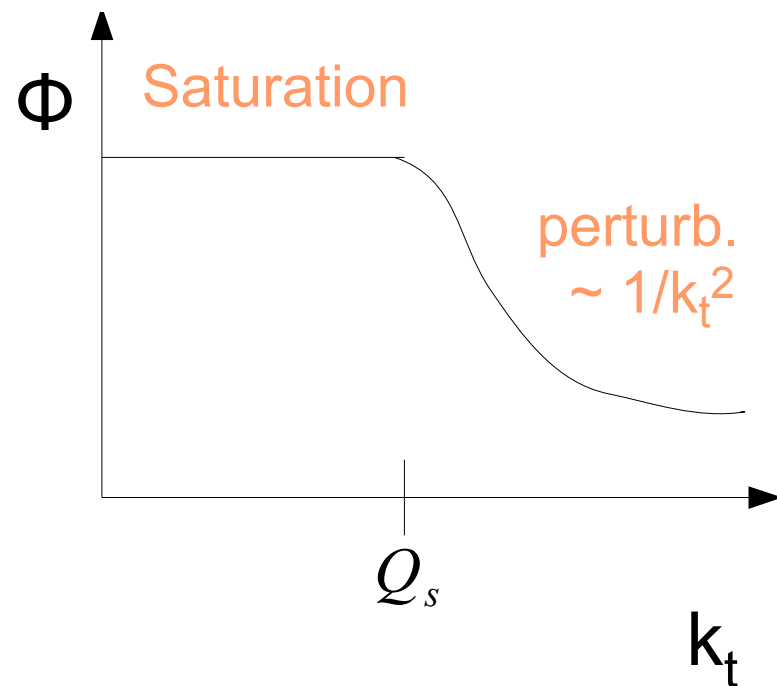


$$\frac{dN}{d^2r_t dy} \sim \alpha_s \int \frac{d^2 p_t}{p_t^2} \int d^2 k_t \phi_A(x_1, k_t^2) \phi_B(x_2, (p_t - k_t)^2)$$

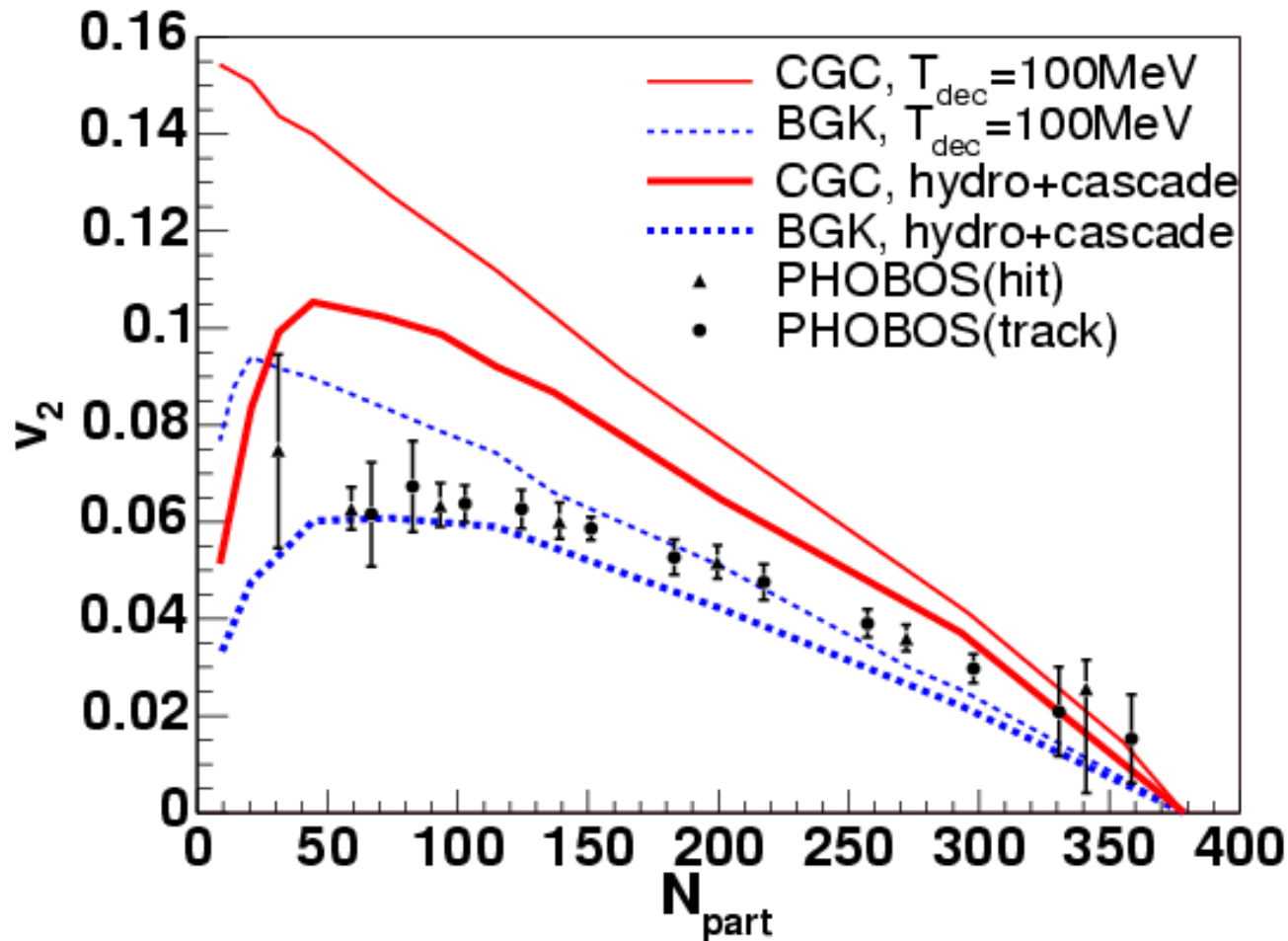
Kharzeev, Levin, Nardi model:

$$\phi(x, k_t^2; \vec{r}_t) \sim \frac{1}{\alpha_s(Q_s^2)} \frac{Q_s^2(x, \vec{r}_t)}{\max(Q_s^2, k_T^2)}$$

$$Q_s^2 \sim \rho_{\text{part}} x^{-\lambda} \quad (\lambda \approx 0.28)$$



Hydro with CGC vs. Glauber initial conditions

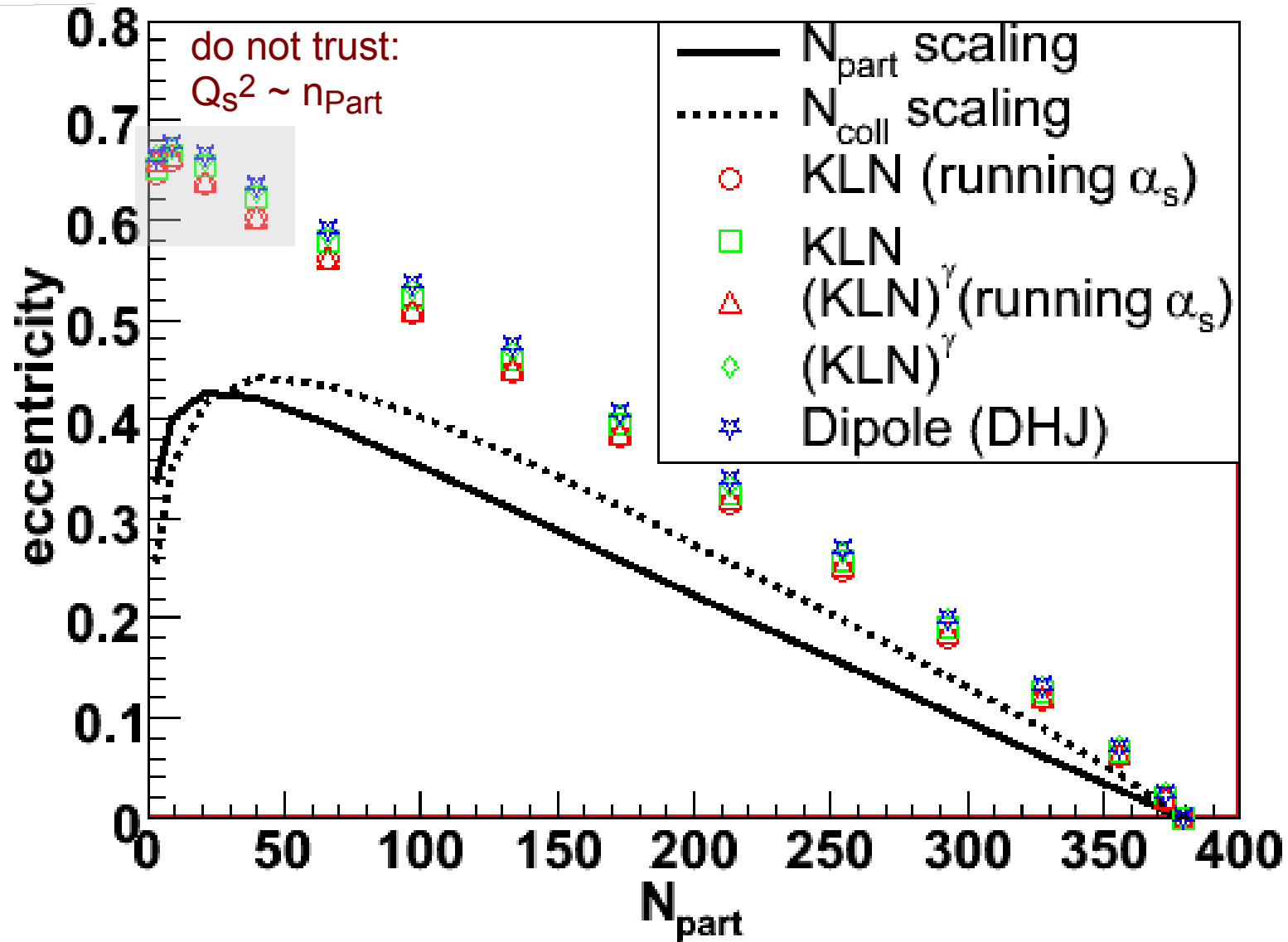


T. Hirano et al., Phys. Lett. B636 (2006) 299

**Ideal hydro with CGC initial condition (KLN)
and $\tau_0 < 1$ fm/c overpredicts elliptic flow!**

Eccentricity from kt-factorization

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



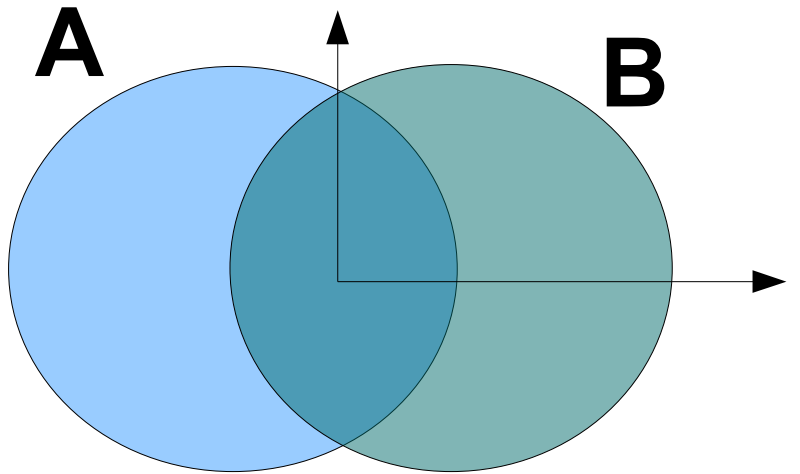
nucl-th/0605012

Scaling properties:

$$\frac{dN_g}{d^2 r_\perp dy} = \frac{4\pi N_c}{N_c^2 - 1} \int \frac{d^2 p_t}{p_t^2} \int d^2 k_t \alpha_s \phi(x_1, k_t^2) \phi(x_2, (p_t - k_t)^2)$$

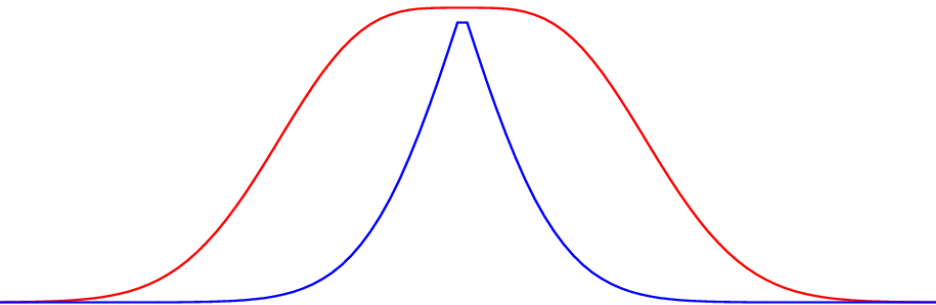
$$\sim \underline{\underline{Q_{s\ min}^2}} \log \frac{Q_{s\ max}^2}{Q_{s\ min}^2}$$

Kharzeev, Levin, PLB 523 (2001)
Dumitru, McLerran, NPA 700 (2002)



CGC: $\frac{dN}{dy} \sim \min(\rho_{\text{part}}^A, \rho_{\text{part}}^B)$

Glauber: $\frac{dN}{dy} \sim \frac{\rho_{\text{part}}^A + \rho_{\text{part}}^B}{2}$



$$\epsilon_{CGC} > \epsilon_{Glauber}$$

Problems

- uGDF Φ does not factorize, Q_s not 'universal'

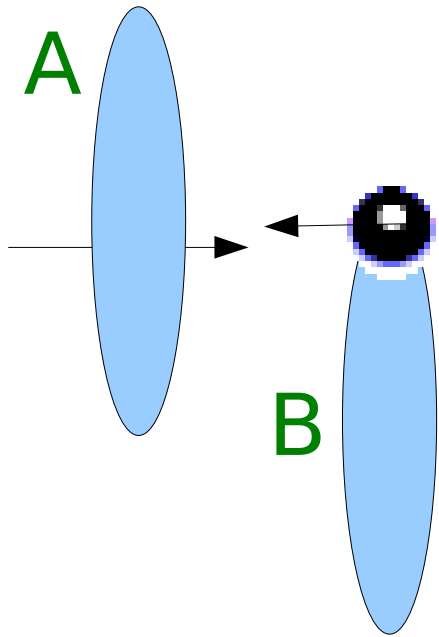
(Lappi, Venugopalan, nucl-th/0609021)

- $Q_s \rightarrow 0$ at the surface

(IR sensitivity, unreliable for periph.
collisions and/or lighter ions)

fKLN

nucl-th/0605012
nucl-th/0611017

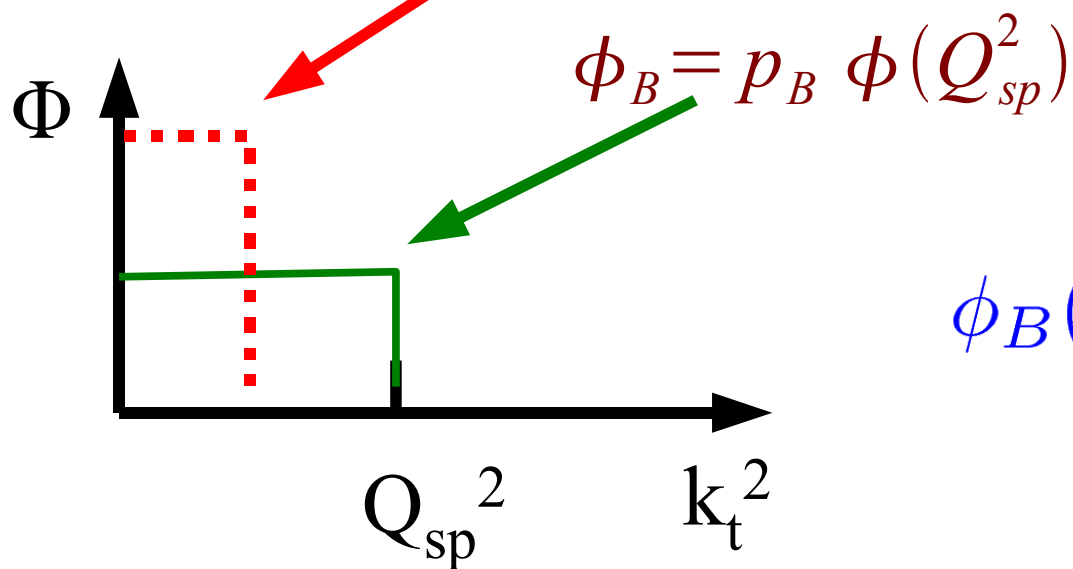


$$Q_{sB}^2 = Q_{sp}^2 T_B$$

$$T_B = \frac{\sum_{i \geq 0} p_i t_i}{\sum_{i \geq 1} p_i} = \frac{\langle T_B \rangle}{p_B}$$

$$\langle T_B \rangle(\vec{r}_\perp) = \int dz \rho_W S(z, \vec{r}_\perp)$$

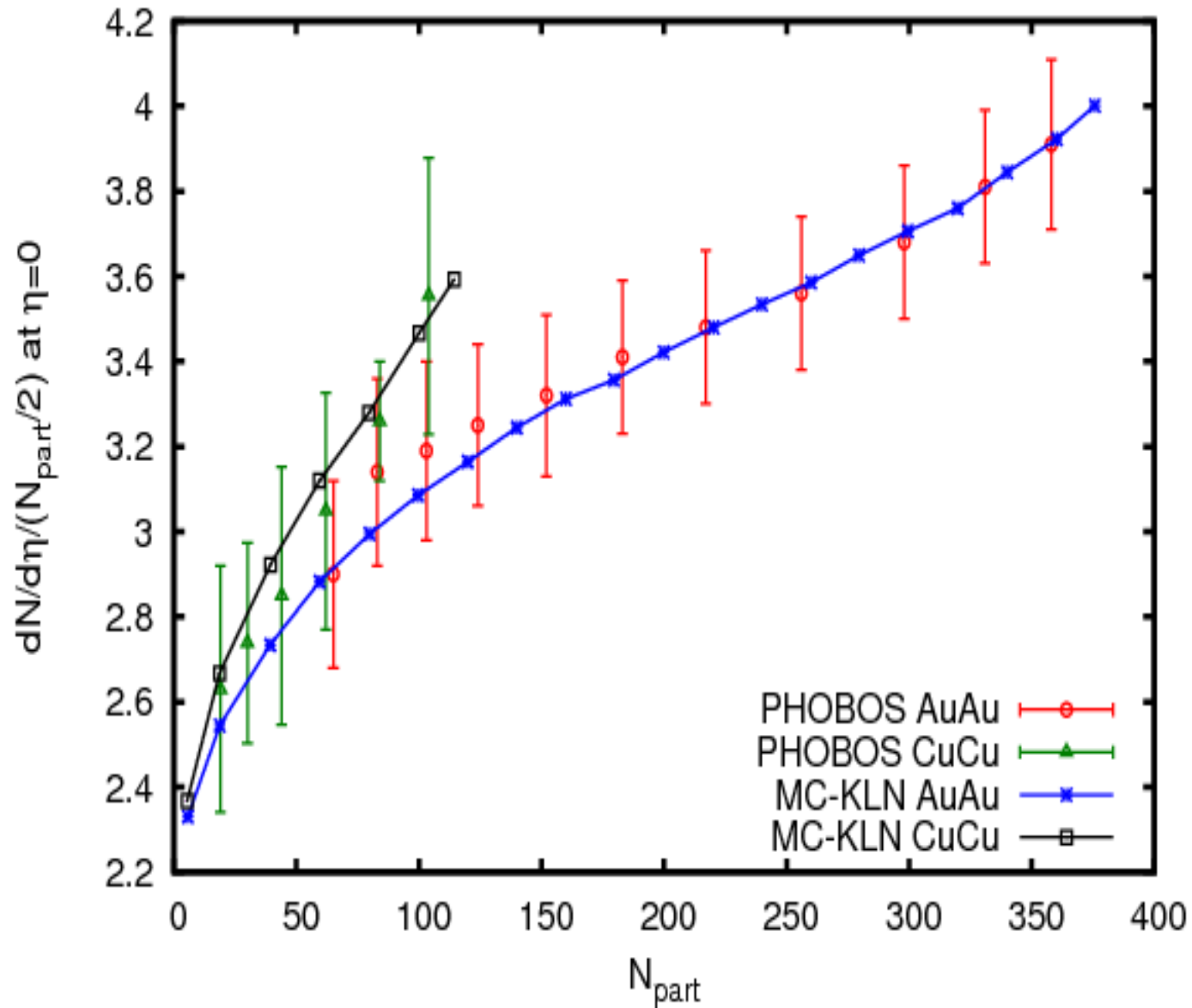
$$\phi_B = \phi(Q_{sp}^2 \langle T_B(r_t) \rangle),$$



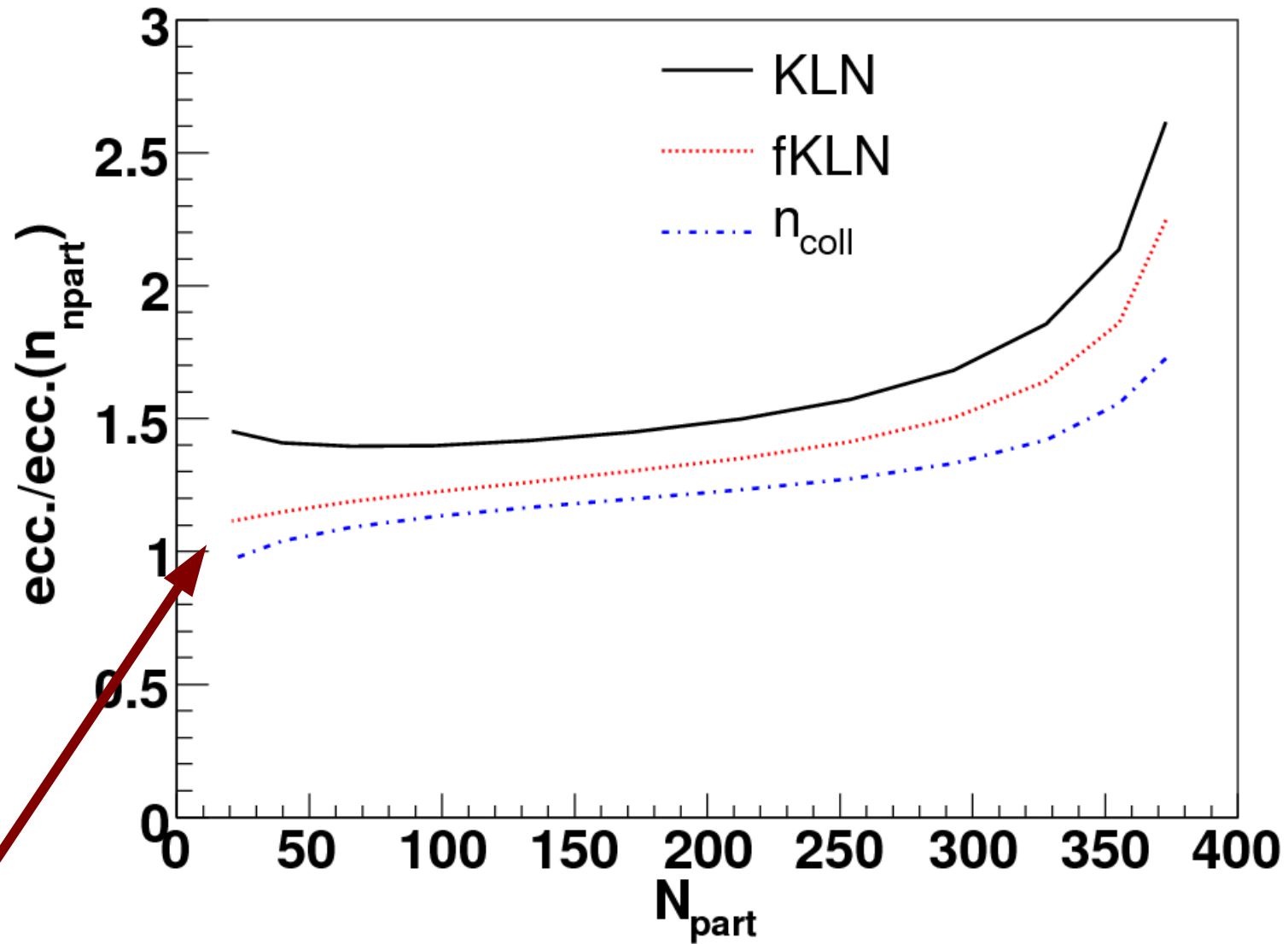
$$\phi_B(\langle T_B \rangle) \rightarrow p_B \phi_B(\langle T_B \rangle / p_B)$$

$$\frac{dN}{d^2 r_t} \sim p_A \phi_A \otimes p_B \phi_B$$

Results: Multiplicity



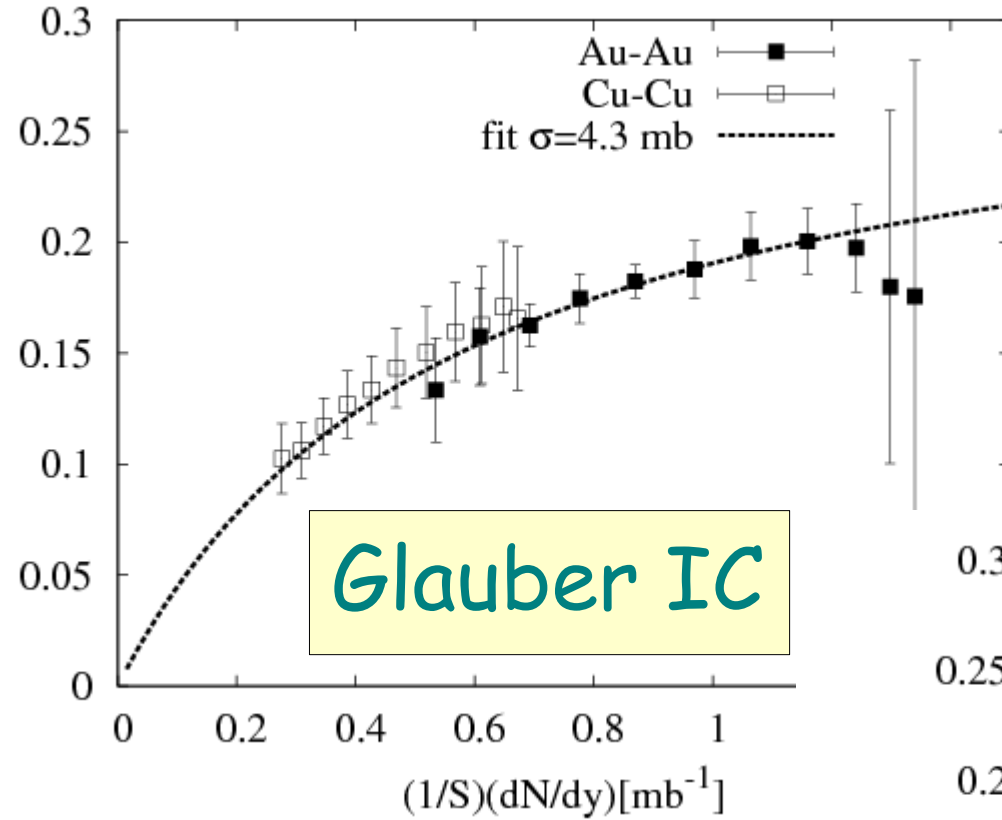
$\epsilon_{fKLN}/\epsilon_{Glauber}$ pretty flat in intermediate region :



fKLN reproduces Glauber in peripheral collisions !

Voloshin/Poskanzer plot: scaled flow vs density

$$\frac{v_2^{\text{hydro}}}{\epsilon}$$



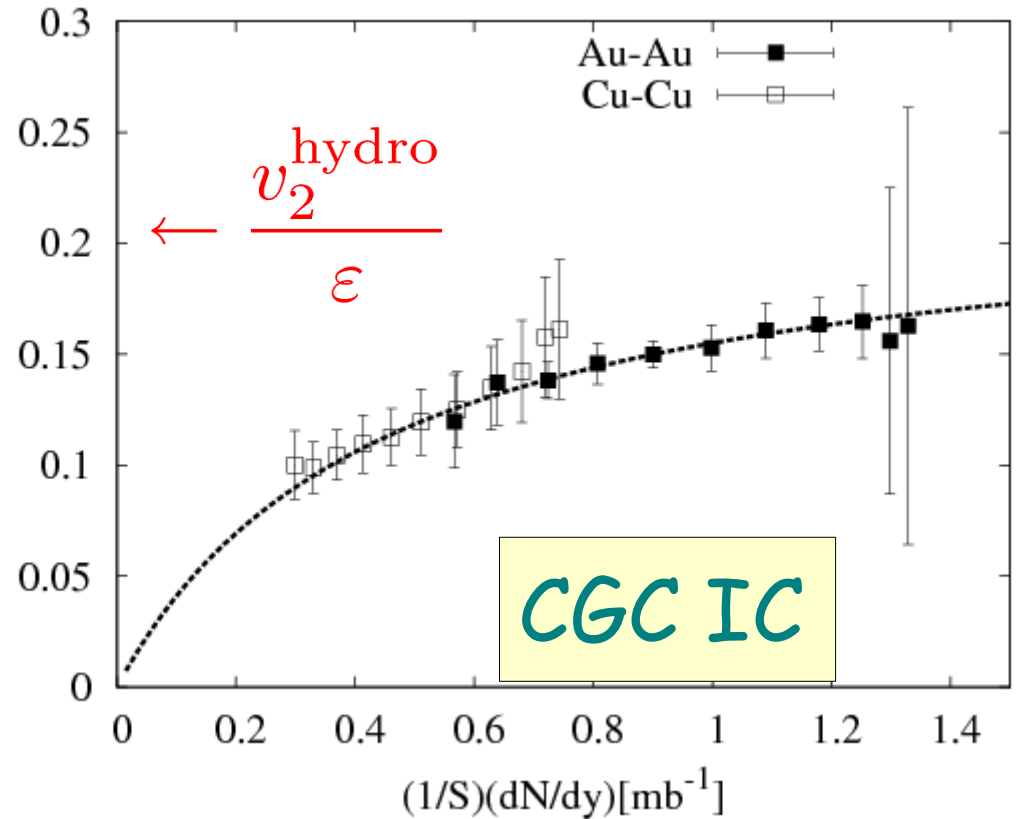
$$\frac{v_2}{\epsilon} = \frac{v_2^{\text{hydro}}}{\epsilon} \frac{1}{1 + K/K_0}$$

$$\frac{1}{K} = \frac{\sigma}{S} \frac{dN}{dy} c_s$$

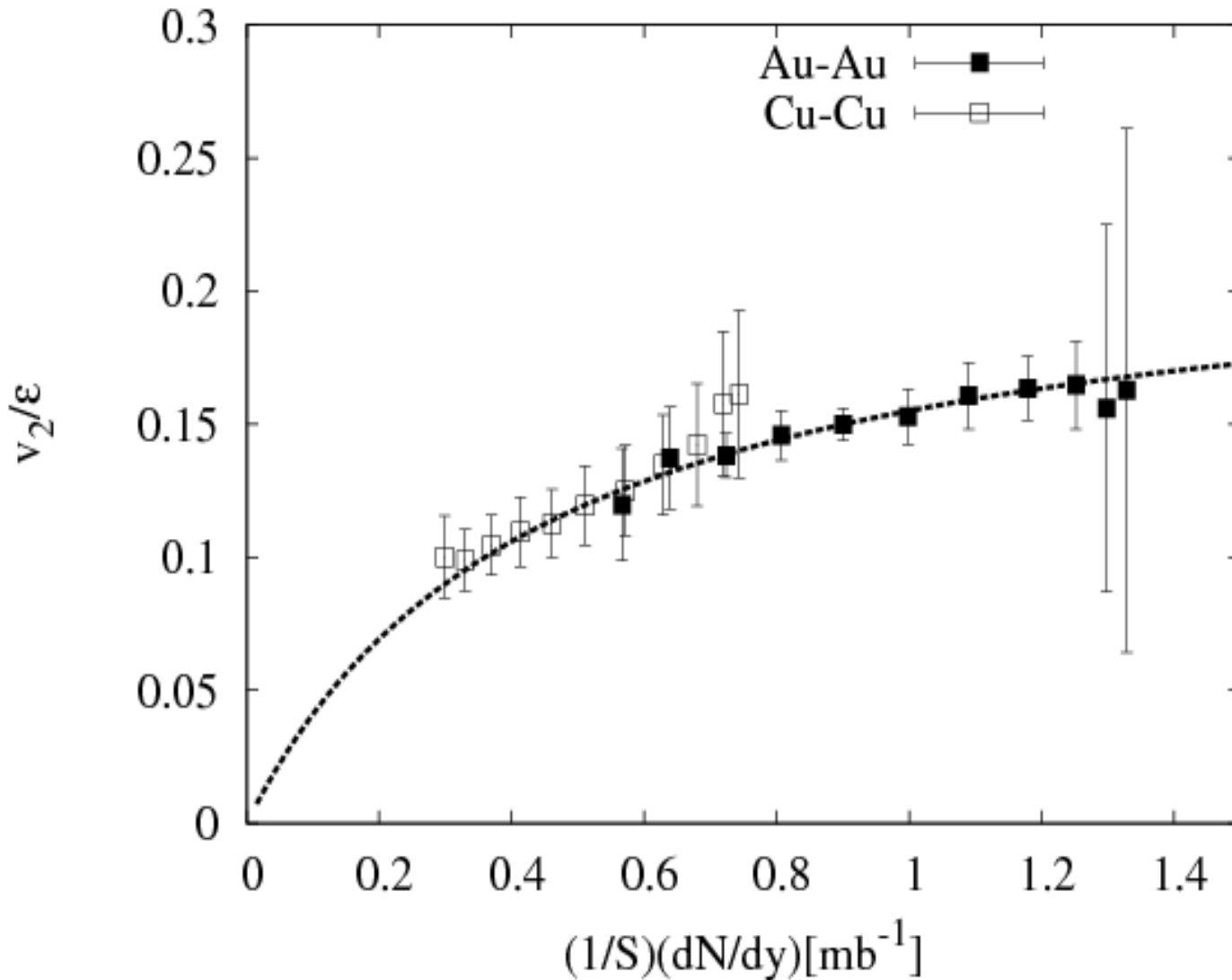


nucl-th/0508009

v_2/ϵ



extracted EoS, viscosity depend on IC !



- ★ Consistent with hydro limit:
 $K/K_0 \sim 0.4$
- ★ Saturation seen
- ★ Finite X-section
 $\sigma \sim 7.6 \text{ mb}$ (CGC)
 $\sigma \sim 4.3 \text{ mb}$ (Glauber)
- ★ Viscosity estimate
 $\eta/s \sim 0.1$ (CGC)
 $\eta/s \sim 0.2$ (Glauber)
- ★ Speed of sound
 $c_s(\text{CGC}) / c_s(\text{Gl.}) \sim .7$

- Ideal hydro should overshoot flow data:

EoS should give $v_2^{\text{hydro}}/\varepsilon \simeq 0.3$ (Glauber)

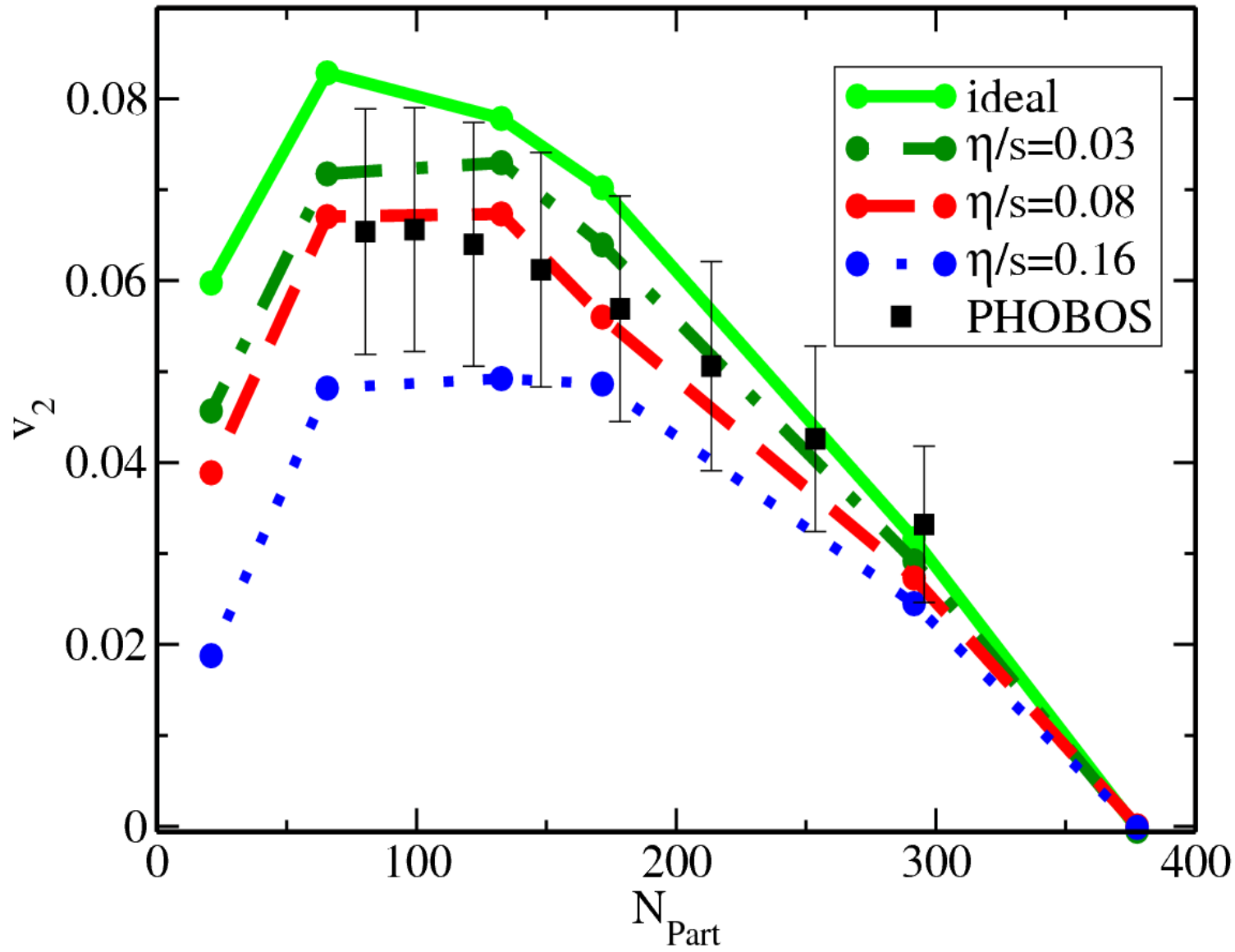
$v_2^{\text{hydro}}/\varepsilon \simeq 0.2$ (CGC)

- Higher eccentricity of CGC-IC:

→ lower c_s (“softer” EoS), not larger η/s

- Hydro ok for semi-central Au+Au:
dissip. correction $\sim 30\%$

-30% agrees with 2+1d viscous hydro:



but EoS should be harder !

Romatschke & Romatschke, arXiv:0706.1522

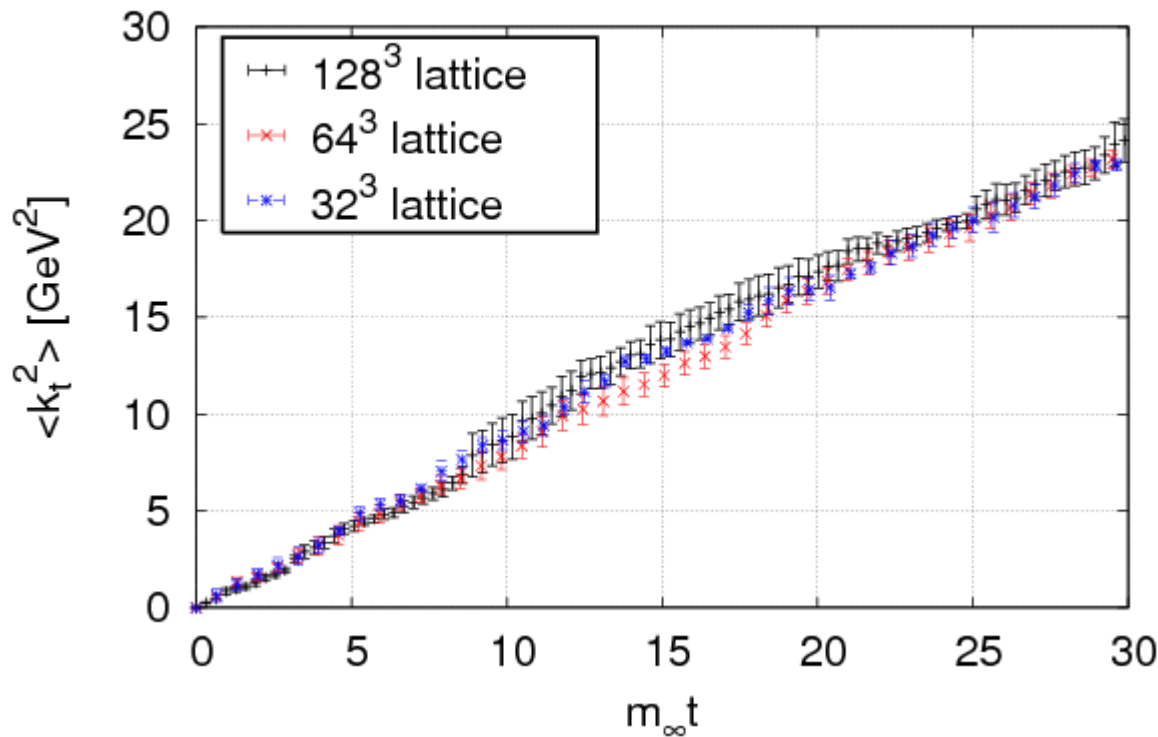
Boltzmann-Vlasov-Yang-Mills Theory

U. Heinz, '83

$$p^\mu \left[\partial_\mu - g Q^a F_{\mu\nu}^a \frac{\partial}{\partial p_\nu} + g f^{abc} A_\mu^b Q^c \frac{\partial}{\partial Q^a} \right] f = \mathcal{C}[f]$$
$$(D_\mu F^{\mu\nu})^a = J^{a\nu}$$

- ◆ Soft exchange ($q < \pi/a$) via fields (Lorentz force)
- ◆ Hard exchange ($q > \pi/a$) via collision term

SU(2) - $g=2$, $T=4\text{GeV}$, $m_\infty=1.4 \text{ fm}^{-1}$



See poster by
Björn Schenke !

Summary

- ★ Initial conditions key element of hydro fits
- ★ CGC eccentricity requires softer EoS, lower η/s
- ★ theoretical modeling of thermalization stage: cutoff-free Boltzmann-Vlasov-YM approach