Collective Dynamics in Heavy Ion collisions at FAIR

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- A multi-phase transport (AMPT) model
- Quark coalescence model
- Anisotropic flow
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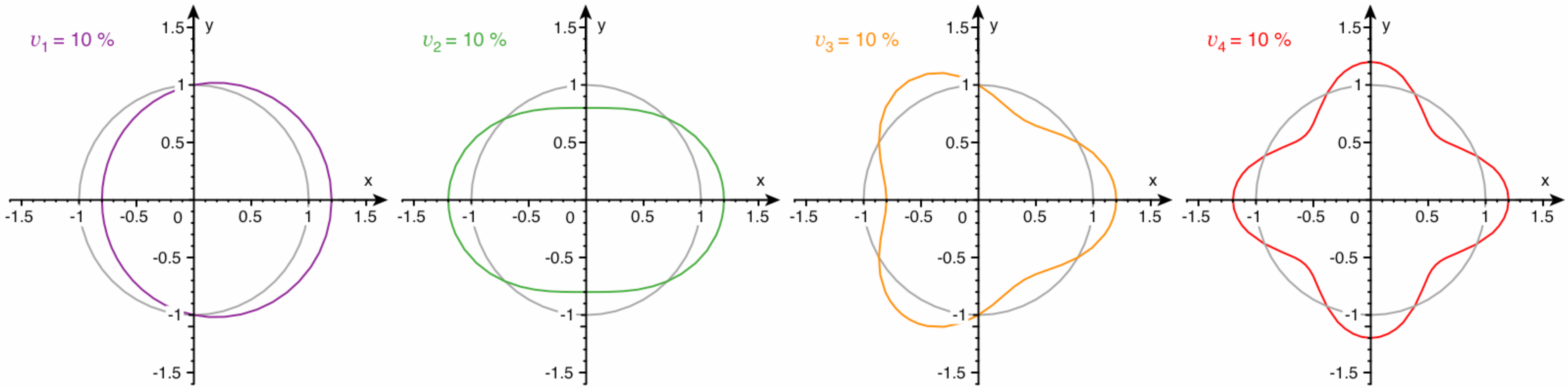
- Conclusions

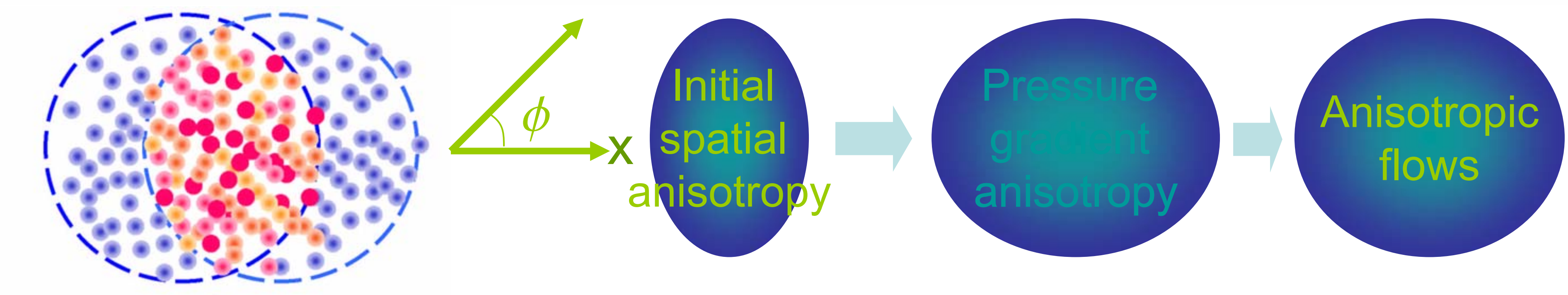
Anisotropic flow

Anisotropic flow v_n

$$E\frac{d^3N}{d^3\vec{p}} = \frac{dN}{p_T dp_T d\varphi dy} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n(p_T, y)\cos(n\varphi)\right]$$

Sine terms vanish because of the symmetry $\varphi \leftrightarrow -\varphi$ in A+A collisions

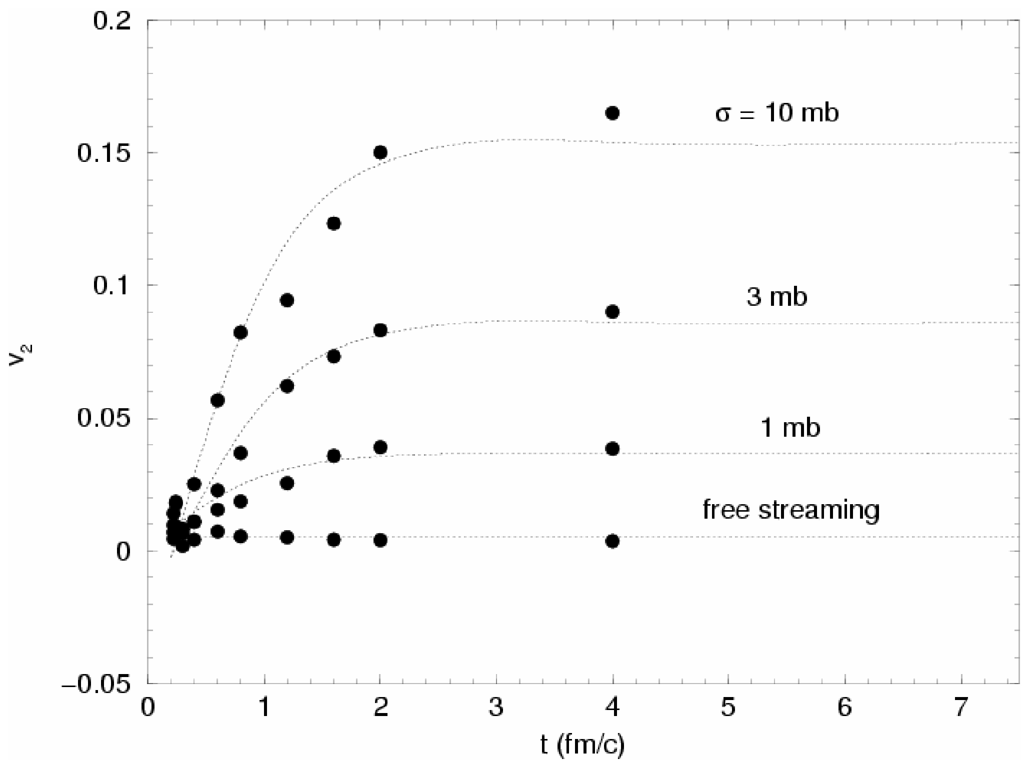




Elliptic flow from parton cascade

Zhang, Gyulassy & Ko, PLB 455, 45 (1999)

Based on Zhang's parton cascade (ZPC) (CPC 109, 193 (1998))
using minijet partons from HIJING for Au+Au @ 200 AGeV and b=7.5fm



v_2 of partons is sensitive to their scattering cross section

Zhang's parton cascade (ZPC)

Bin Zhang, Comp. Phys. Comm. 109, 193 (1998)

$$p^\mu \partial_\mu f_1(x,p,t) \propto \int dp_2 d\Omega \left|\vec{v}_1 - \vec{v}_2\right| (d\sigma/d\Omega)(f_1'f_2'-f_1 f_2)$$

$$\frac{d\sigma}{dt} \cong \frac{9\pi\alpha_s^2}{2(t-\mu^2)^2}, \quad \sigma \cong \frac{9\pi\alpha_s^2}{2\mu^2}\frac{1}{1+\mu^2/s}$$

- Using α_s=0.5 and screening mass μ=gT≈0.6 GeV at T≈0.25 GeV, then $\langle s\rangle^{1/2}$≈4.2T≈1 GeV, and pQCD gives σ≈2.5 mb and a transport cross section

$$\sigma_t \equiv \int d\Omega \frac{d\sigma}{d\Omega}(1-\cos\theta) \approx 1.5\text{mb}$$

- σ=6 mb → μ≈0.44 GeV, σ_t≈2.7 mb
- σ=10 mb → μ≈0.35 GeV, σ_t≈3.6 mb

A multiphase transport (AMPT) model

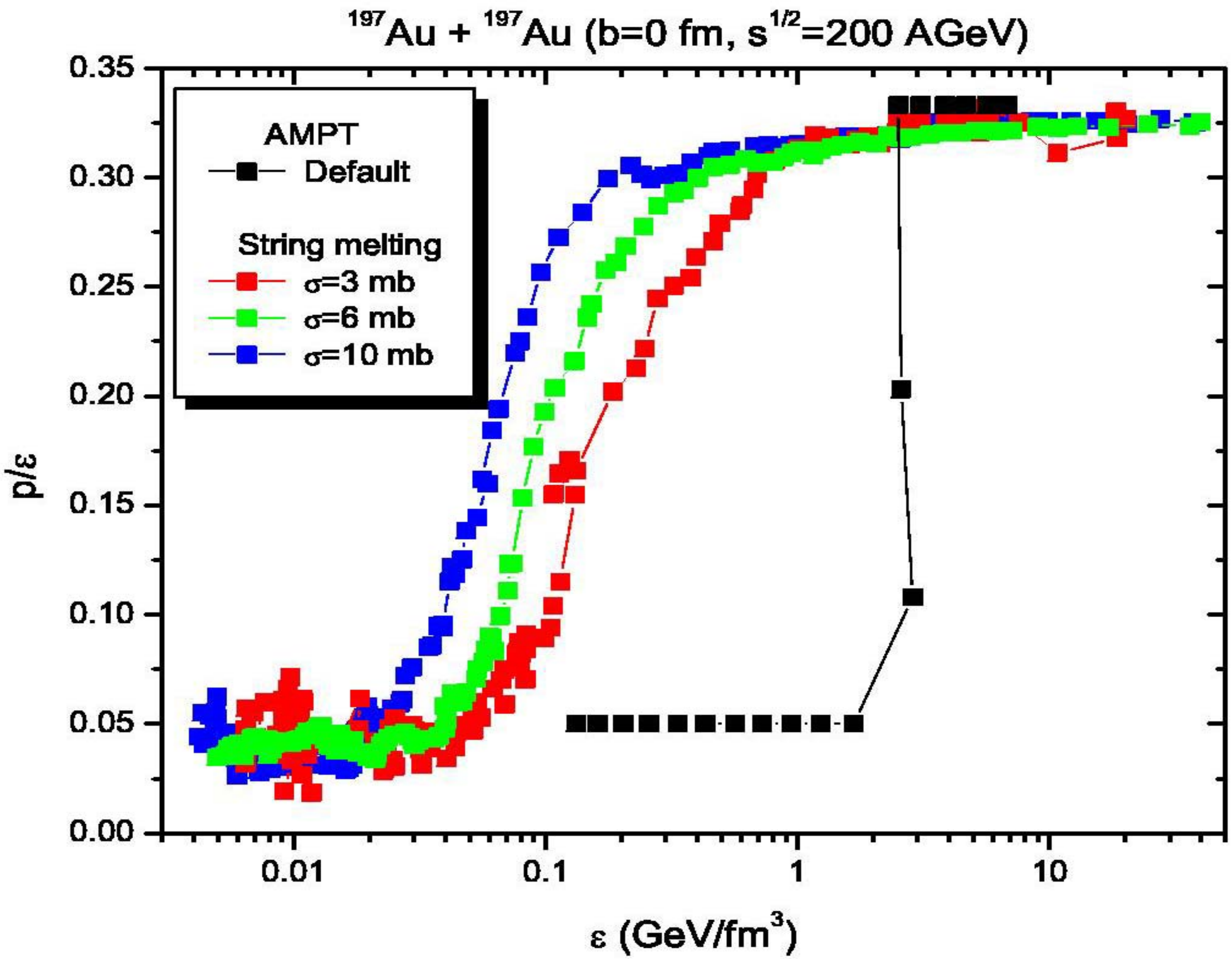
Default: Lin, Pal, Zhang, Li &Ko, PRC 61, 067901 (00); 64, 041901 (01); 72, 064901 (05); http://www-cunuke.phys.columbia.edu/OSCAR

- Initial conditions: HIJING (soft strings and hard minijets)
- Parton evolution: ZPC
- Hadronization: Lund string model for default AMPT
- Hadronic scattering: ART

String melting: PRC 65, 034904 (02); PRL 89, 152301 (02)

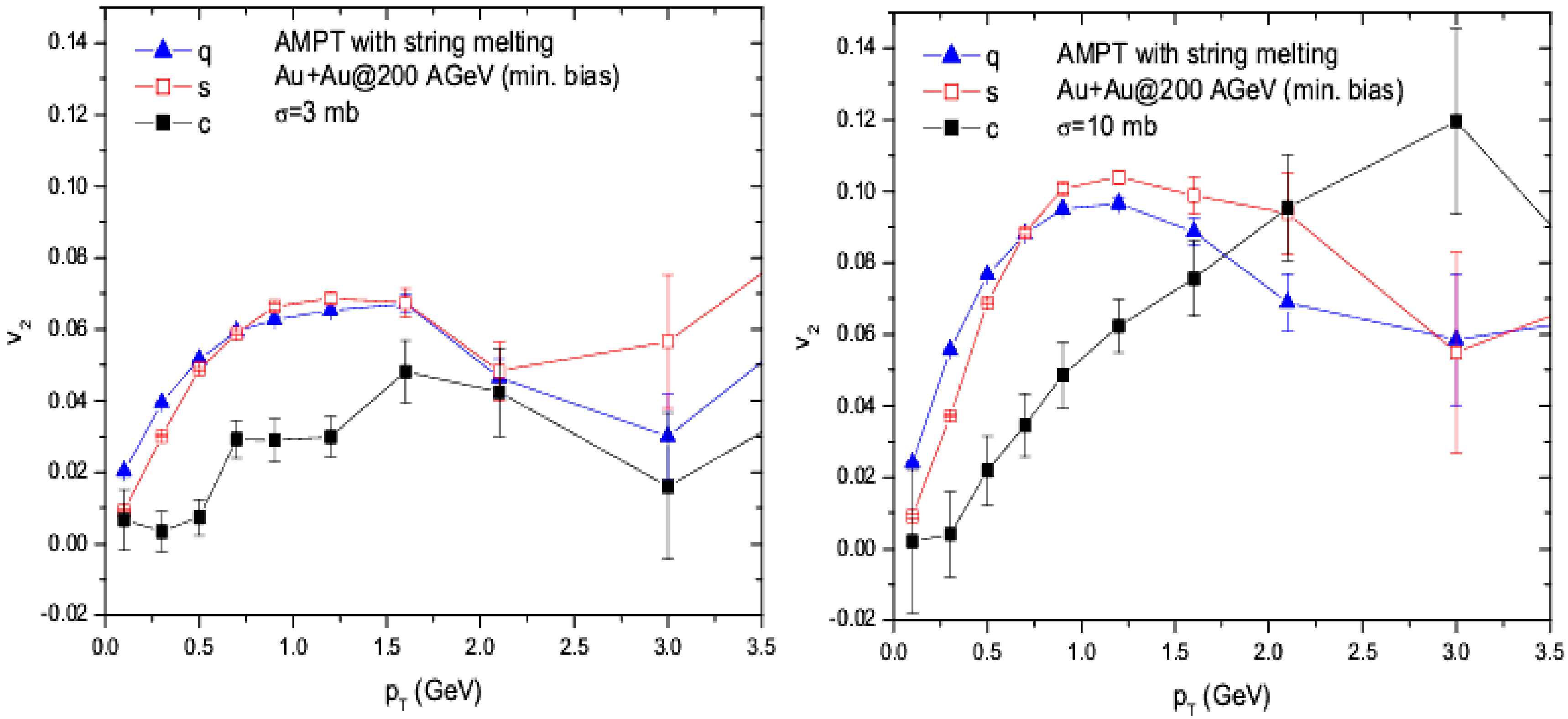
- Convert hadrons from string fragmentation into quarks and antiquarks
- Evolve quarks and antiquarks in ZPC
- When partons stop interacting, combine nearest quark and antiquark to meson, and nearest three quarks to baryon (coordinate-space coalescence)
- Hadron flavors are determined by quarks' invariant mass

Equation of state in AMPT



EOS is softened by the presence of a mixed phase of partonic and hadronic matters in the string melting scenario

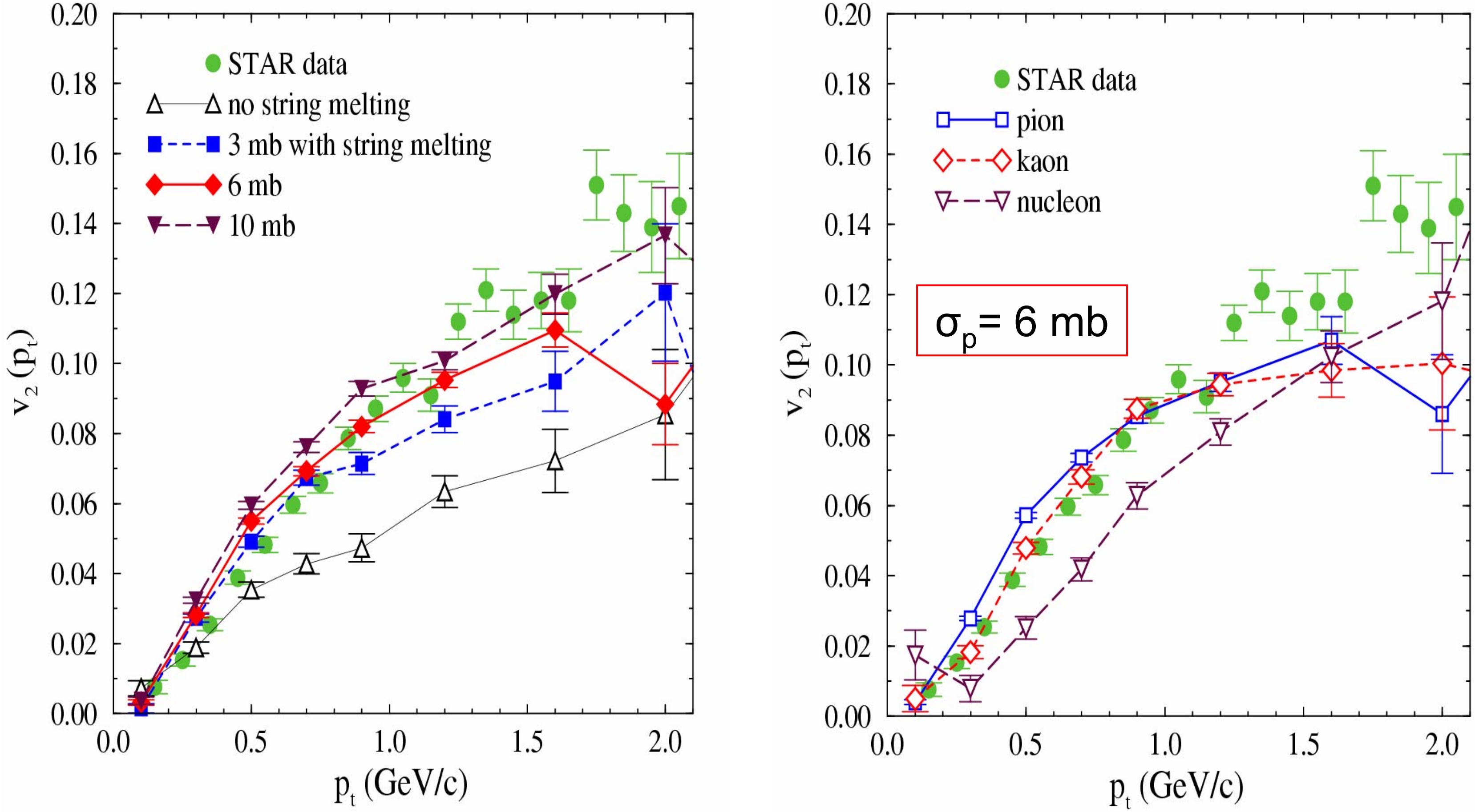
Quark elliptic flows from AMPT



- v_2 is sensitive to parton scattering cross sections.
- Mass ordering at low p_T: $v_2(q)>v_2(s)>v_2(c)$.
- At high p_T, all quarks have smilar v_2.

Elliptic flow from AMPT

Lin & Ko, PRC 65, 034904 (2002)



- Need string melting and large parton scattering cross section
- Mass ordering of v_2 at low p_T as in ideal hydrodynamic model

Momentum-space quark coalescence model

Only quarks of same momentum can coalescence, i.e., Δp=0

Quark transverse momentum distribution

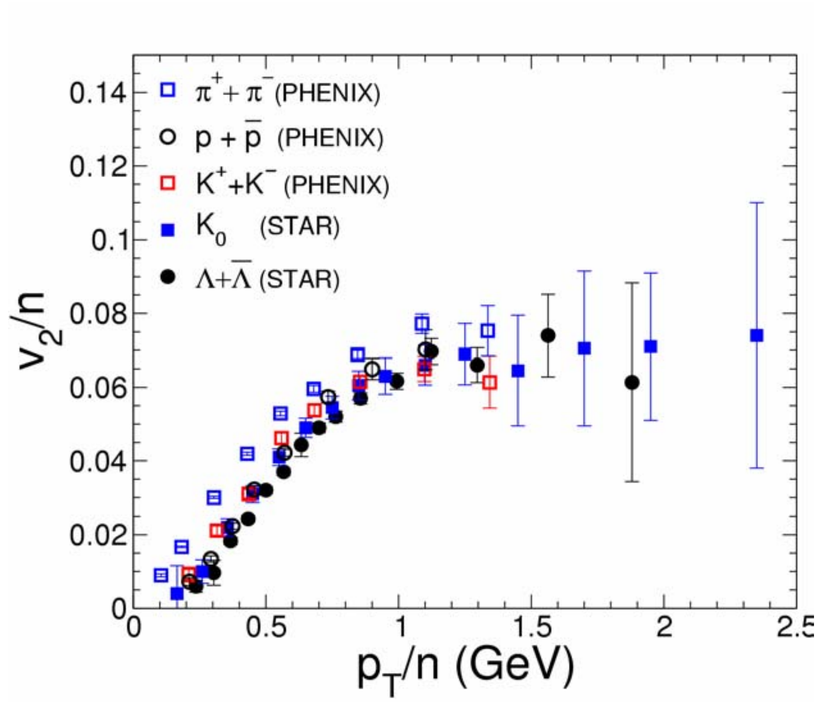
$$f_q(p_T) \propto 1 + 2v_{2,q}(p_T)\cos(2\varphi)$$

Meson elliptic flow

$$v_{2,M}(p_T) = \frac{2v_{2,q}(p_T/2)}{1+2v_{2,q}^2(p_T/2)} \approx 2v_{2,q}(p_T/2)$$

Baryon elliptic flow

$$v_{2,B}(p_T) = \frac{3v_{2,q}(p_T/3)}{1+6v_{2,q}^2(p_T/3)} \approx 3v_{2,q}(p_T/3)$$



Quark number scaling of hadron v_2 (except pions):

$$\frac{1}{n} v_2(p_T/n)$$

same for mesons and baryons

Effect of higher-order parton anisotropic flows

Including 4th order quark flow   Kolb, Chen, Greco, Ko, PRC 69 (2004) 051901

$$f_q(p_T) \propto 1 + 2v_{2,q}(p_T)\cos(2\varphi) + 2v_{4,q}(p_T)\cos(4\varphi)$$

Meson elliptic flow

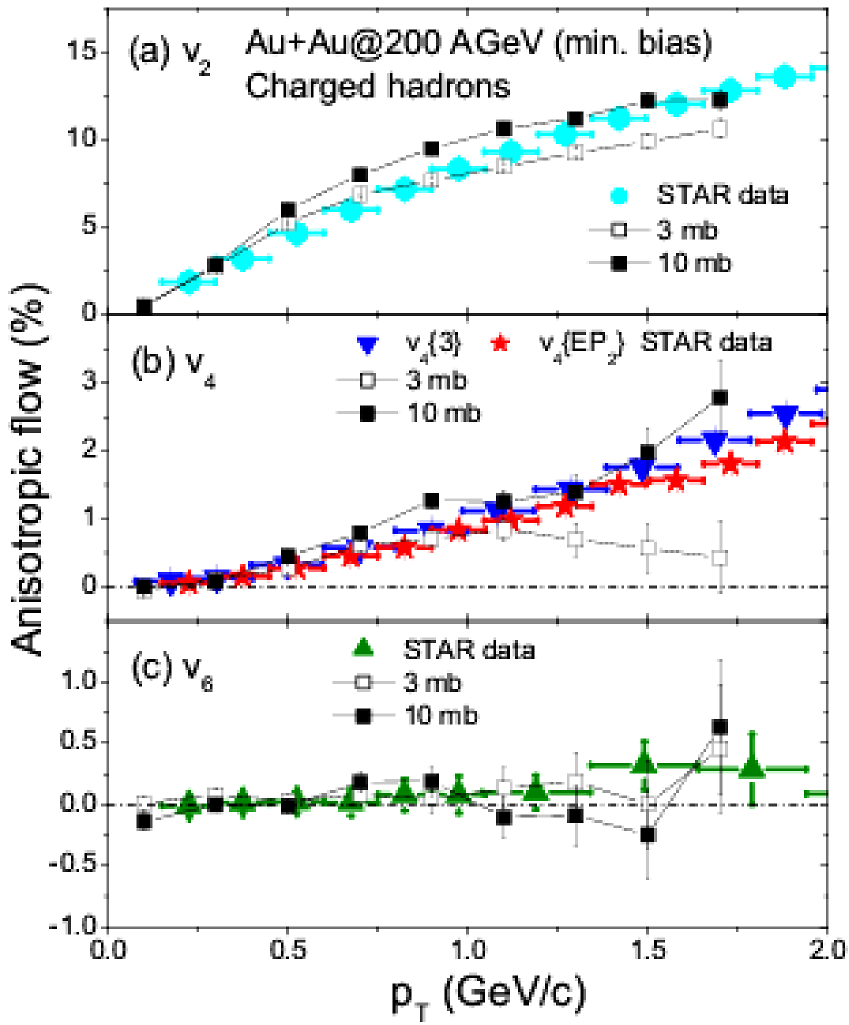
$$v_{2,M} = \frac{2v_{2,q} + 2v_{2,q}v_{4,q}}{1+2(v_{2,q}^2 + v_{4,q}^2)}, \quad v_{4,M} = \frac{2v_{4,q} + v_{2,q}^2}{1+2(v_{2,q}^2 + v_{4,q}^2)}$$

Baryon elliptic flow

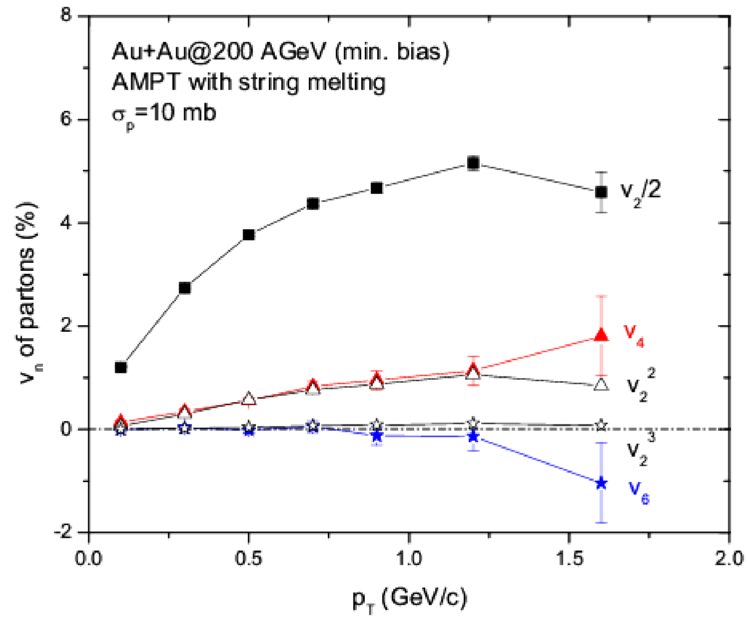
$$v_{2,B} = \frac{3v_{2,q} + 6v_{2,q}v_{4,q} + 3v_{2,q}^3 + 6v_{2,q}v_{4,q}^2}{1+6(v_{2,q}^2 + v_{4,q}^2 + v_{2,q}^2 v_{4,q})}, \quad v_{4,B} = \frac{3v_{4,q} + 3v_{2,q}^2 + 6v_{2,q}^2 v_{4,q} + 3v_{4,q}^3}{1+6(v_{2,q}^2 + v_{4,q}^2 + v_{2,q}^2 v_{4,q})}$$

$$\Rightarrow \frac{v_{4,M}}{v_{2,M}^2} = \frac{1}{4} + \frac{1}{2}\frac{v_{4,q}}{v_{2,q}^2}, \quad \frac{v_{4,B}}{v_{2,B}^2} = \frac{1}{3} + \frac{1}{3}\frac{v_{4,q}}{v_{2,q}^2}$$

Higher-order anisotropic flow



Data can be described by a multiphase transport (AMPT) model

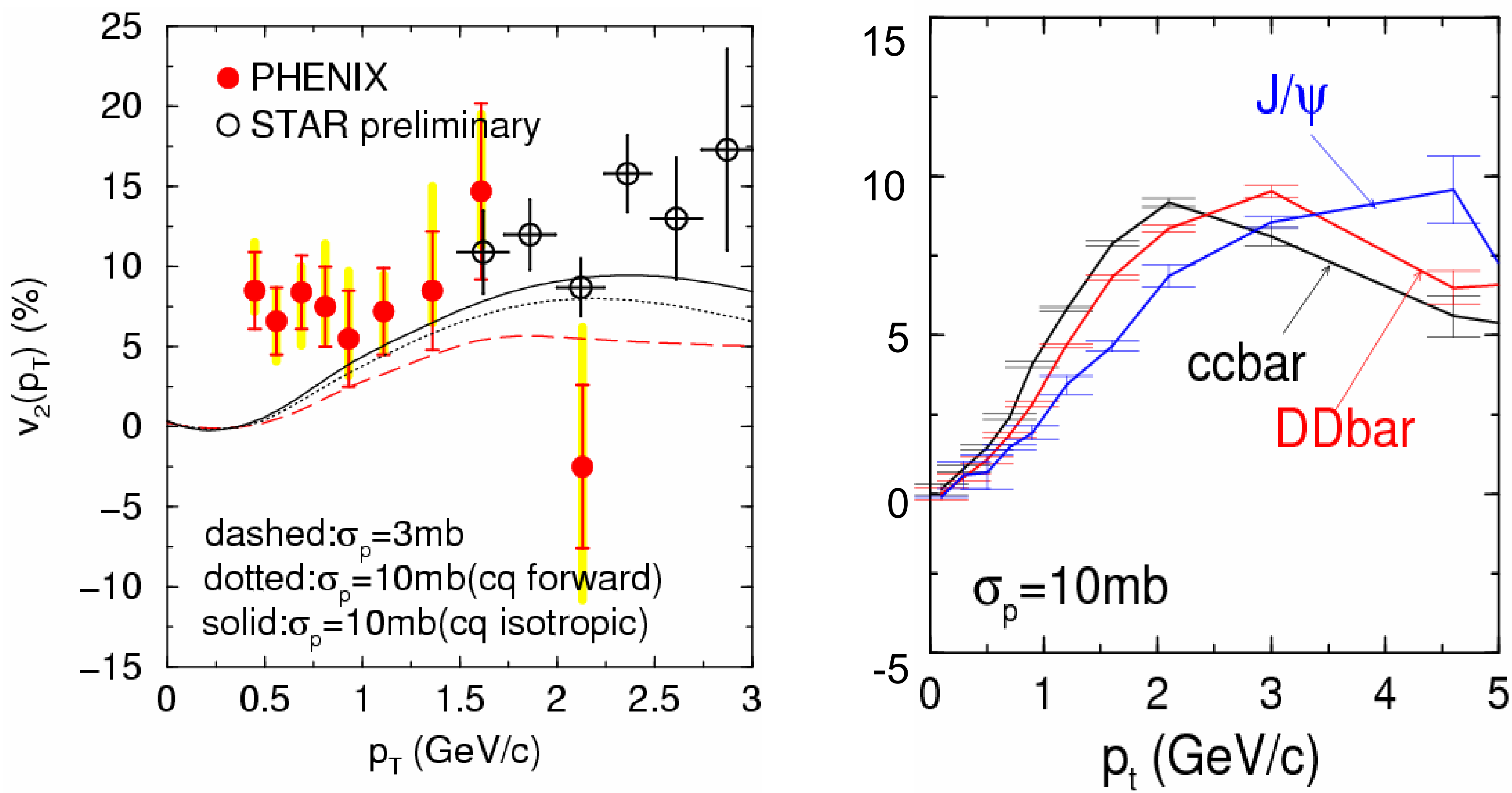


Parton cascade $v_{4,q} \approx v_{2,q}^2$

Data $\frac{v_4}{v_2^2} \approx 1.2 \Rightarrow v_{4,q} \approx 2v_{2,q}^2$ ← Momentum-space coalescence

Charm elliptic flow from AMPT

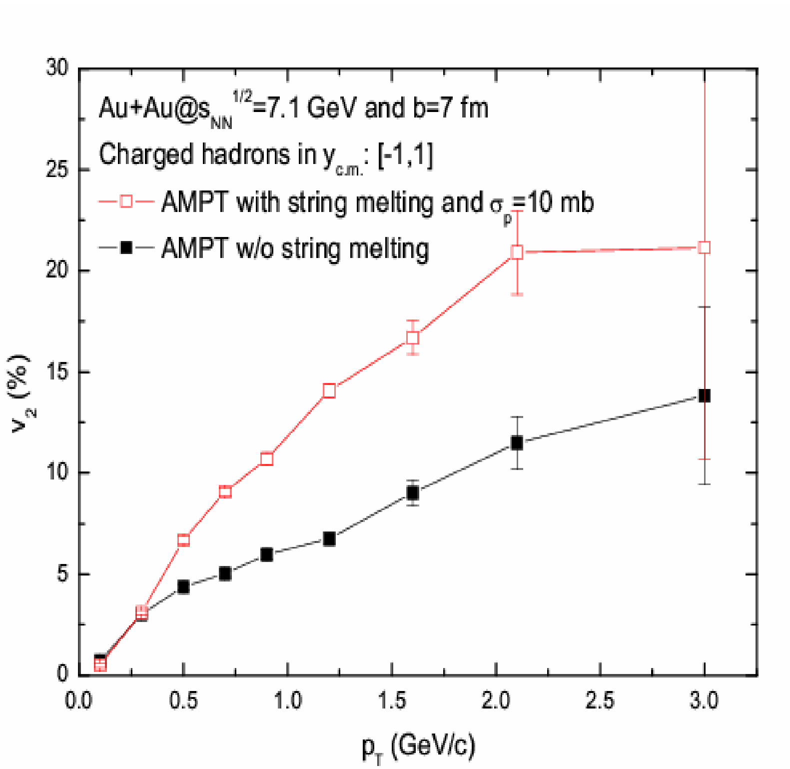
Zhang, Chen & Ko, PRC 72, 024906 (05)

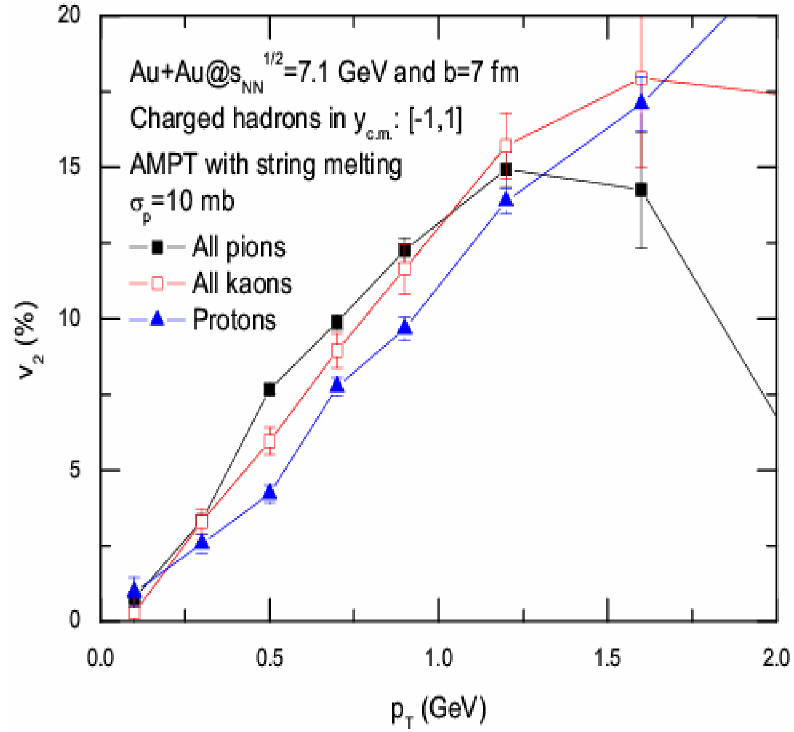


Current light quark masses are used in AMPT. Using constituent quark masses would increase charmed meson elliptic flow.

Elliptic flow at FAIR

Lie-wen Chen (Shanghai Jiao Tong University)

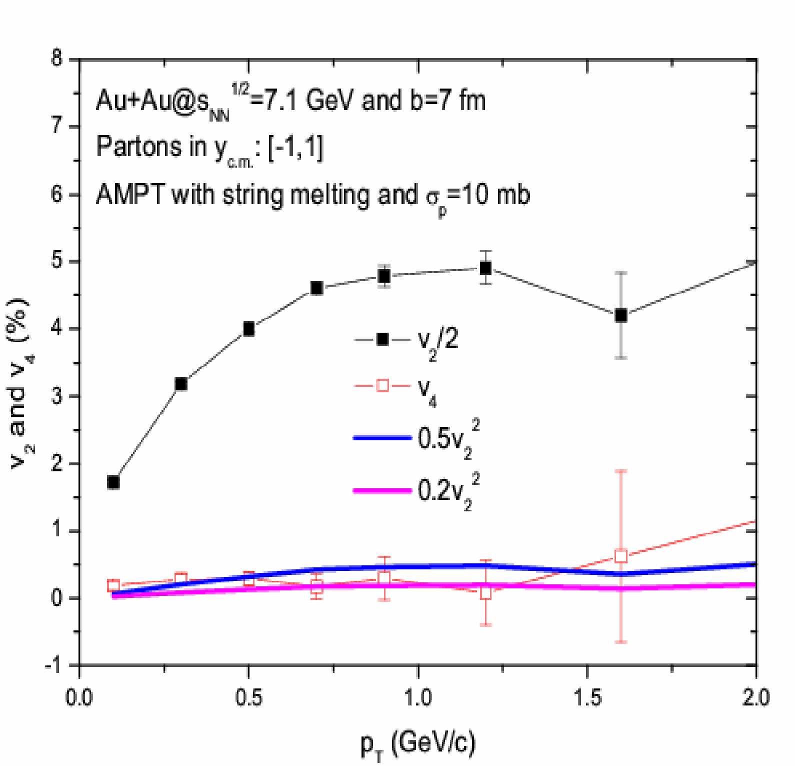


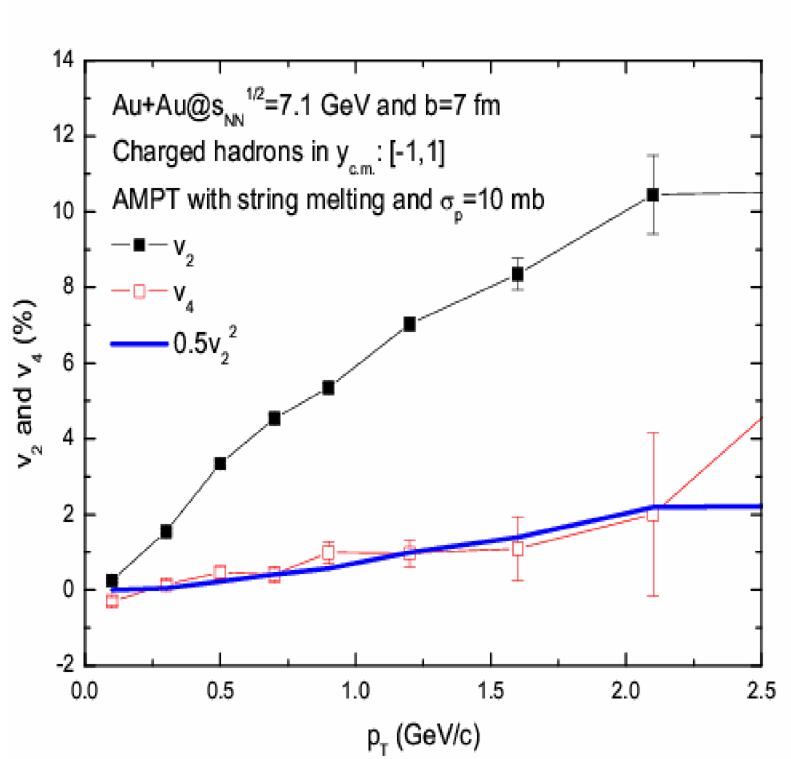


Partonic scattering enhances elliptic flow

Mass ordering of hadron elliptic flows

Higher-order anisotropic flow at FAIR

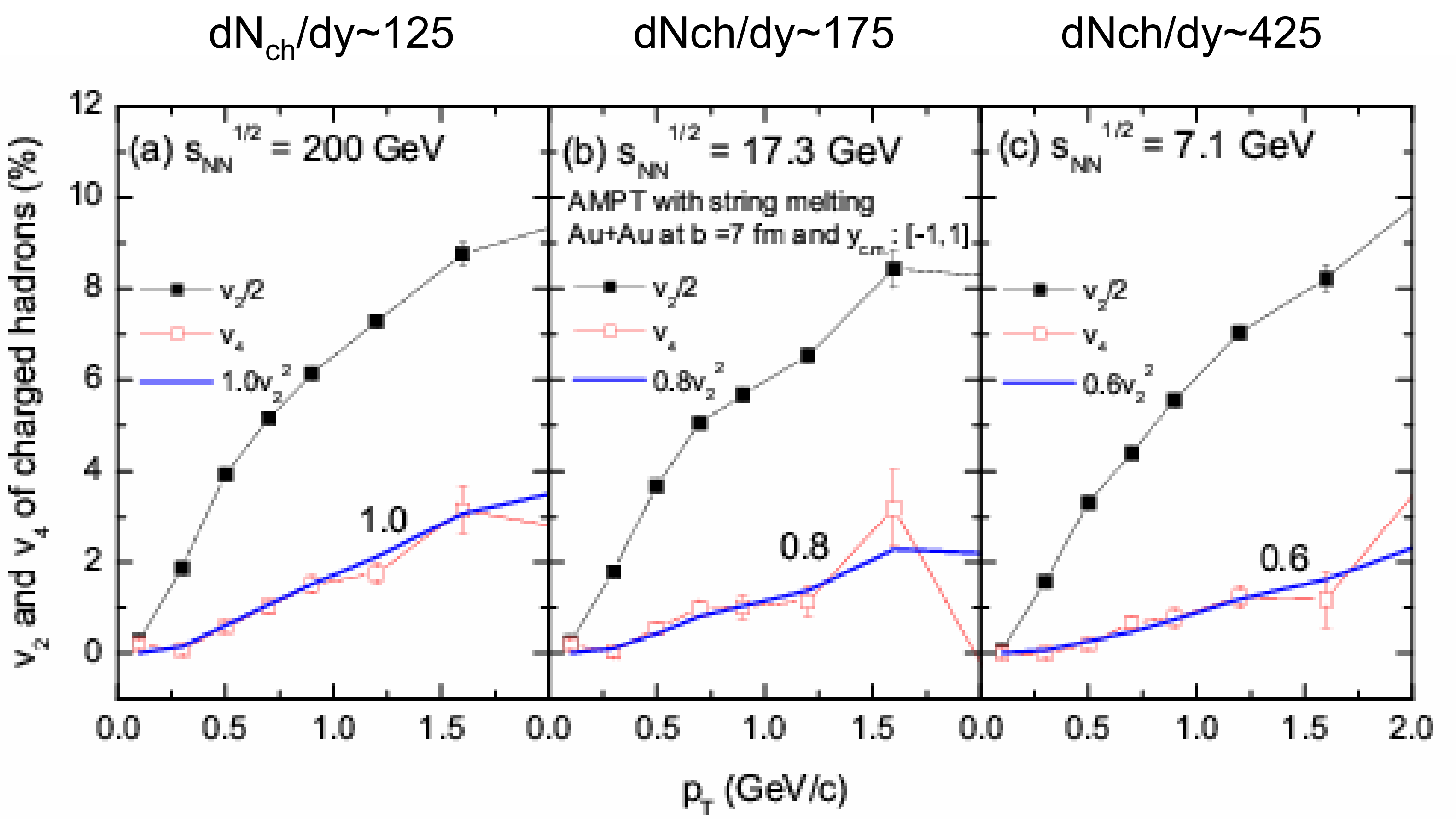




v_4/v_2^2 ~ 0.2-0.5 for partons and ~0.5 for charged hadrons, consistent with momentum-space coalescence

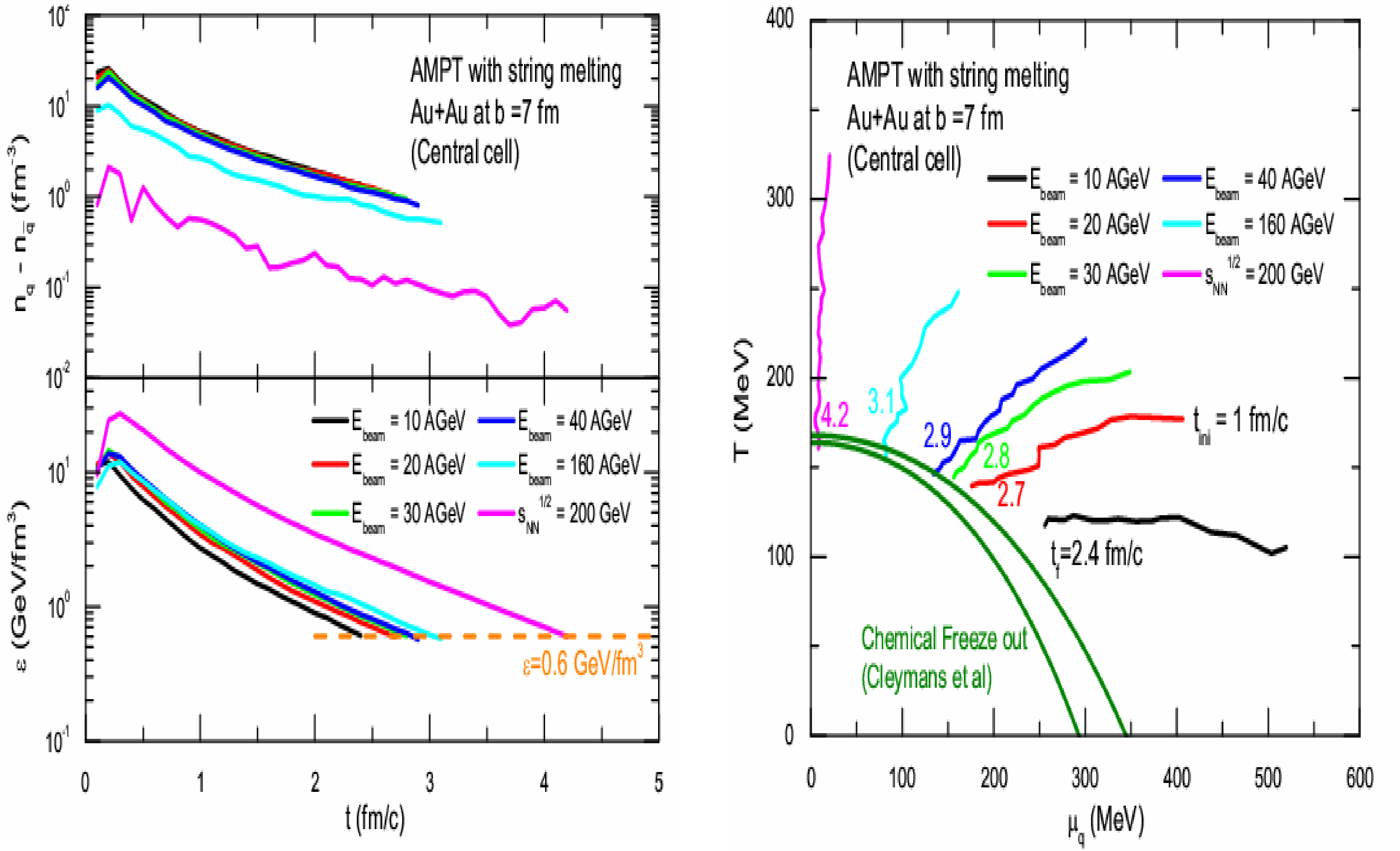
$$\frac{v_{4,M}}{v_{2,M}^2} = \frac{1}{4} + \frac{1}{2}\frac{v_{4,q}}{v_{2,q}^2}, \qquad \frac{v_{4,B}}{v_{2,B}^2} = \frac{1}{3} + \frac{1}{3}\frac{v_{4,q}}{v_{2,q}^2}$$

Energy dependence of v_2 and v_4



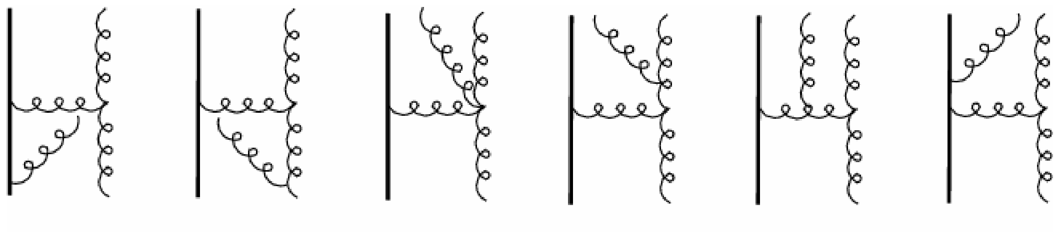
- Magnitude of v_2 essentially independent of collision energy
- v_4/v_2^2 increases with collision energy

Thermodynamic properties of partonic matter



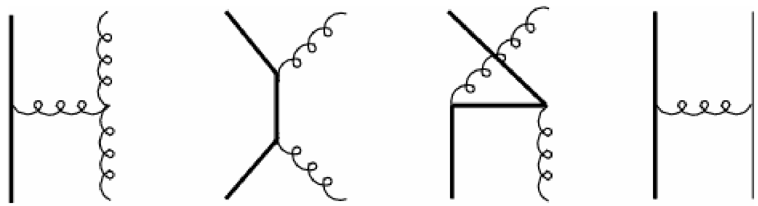
Heavy quark energy loss

a) Radiative energy loss (Amesto *et al.,* hep-ph/0511257)

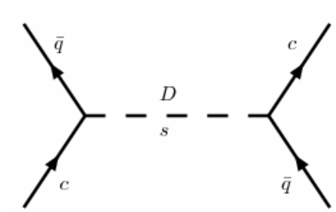


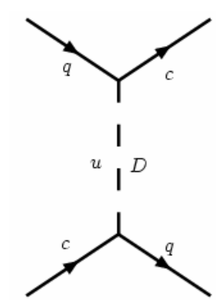
$+ \cdots$

b) Radiative and elastic energy loss (Wicks *et al.,* nucl-th/0512076)

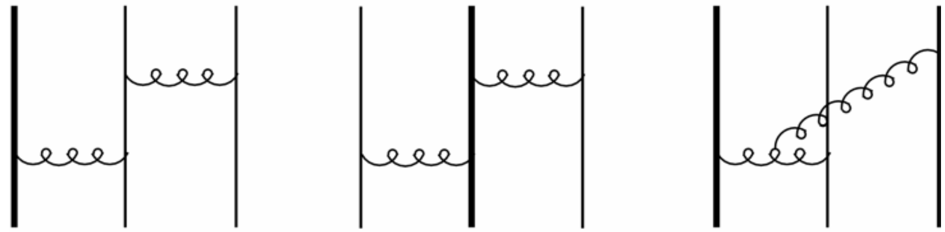
a) + 

c) Resonance scattering (van Hees, Greco & Rapp, PRC 73, 034913 (06))





d) Three-body elastic scattering (Liu & Ko, nucl-th/0603004)

a) +b) +  $+ \cdots$

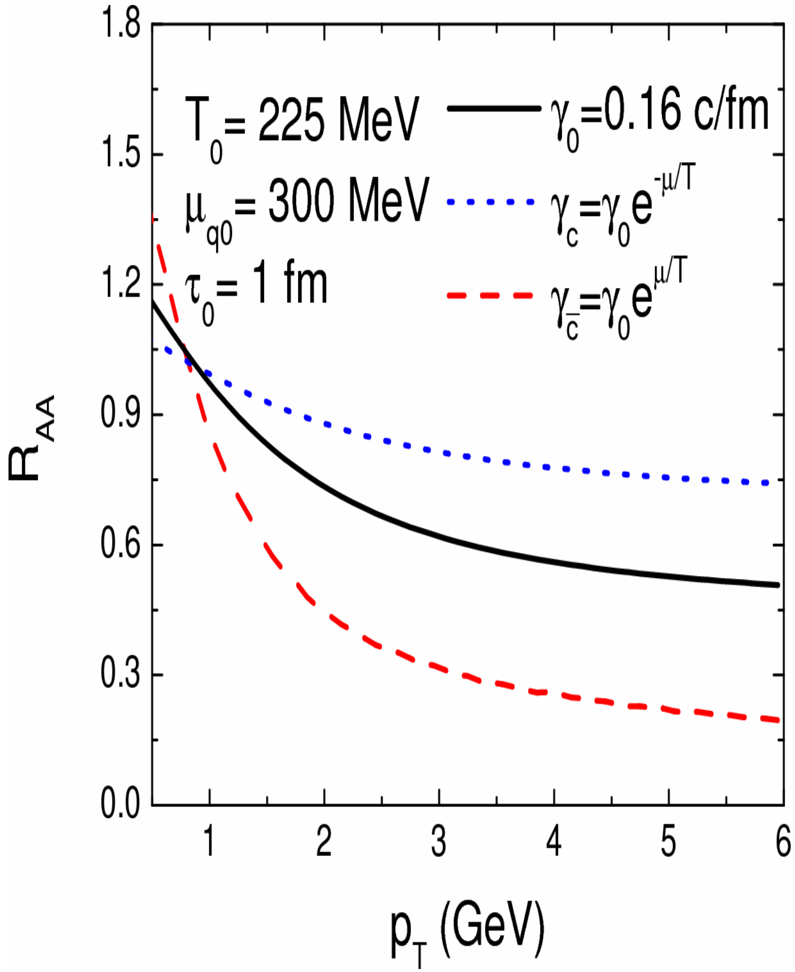
$$Qqq \to Qqq,\ Qq\bar{q} \to Qq\bar{q},\ Q\overline{qq} \to Q\overline{qq}$$
$$Qqg \to Qqg,\ Q\bar{q}g \to Q\bar{q}g$$
$$Qgg \to Qgg$$

Important as interparton distance ~ range of parton interaction
At T=300 MeV, Ng~(Nq+Nqbar)~ 5/fm^3, so interparton distance ~ 0.3 fm
Screening mass mD=gT~600 MeV, so range of parton interaction ~0.3 fm

Three gluon interactions were found to be important for thermalization of QGP (Xu et al., NPA 744, 347 (2004); PLB 629, 68 (2005)).

Charm suppression at FAIR

Wei Liu (Texas A&M University)

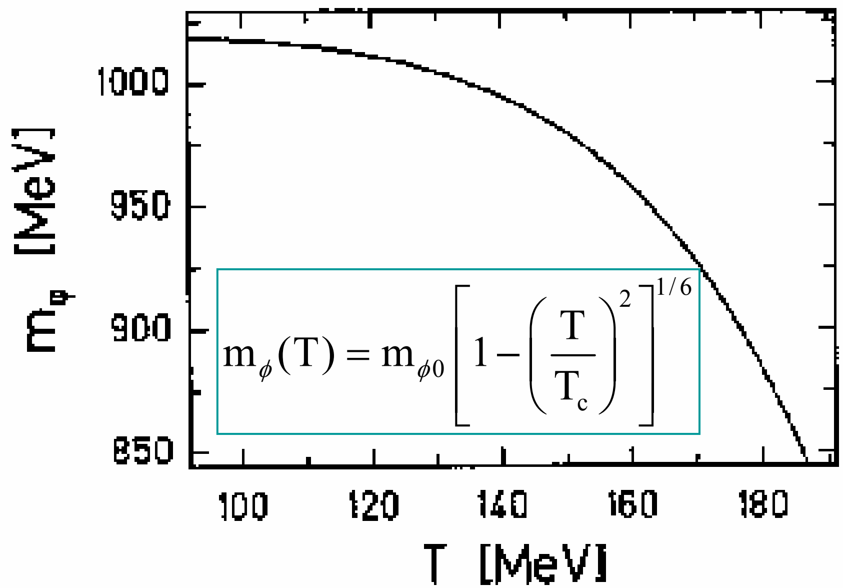


$$R_{AA} = \frac{dN_{Au+Au}}{\langle T_{AA} \rangle d\sigma_{p+p}}$$

- dN_{Au+Au}= differential electron yield from heavy flavor decays in Au+Au collisions
- $d\sigma_{p+p}$= corresponding differential cross section in p+p collisions
- $\langle T_{AA} \rangle$= nuclear overlap integral

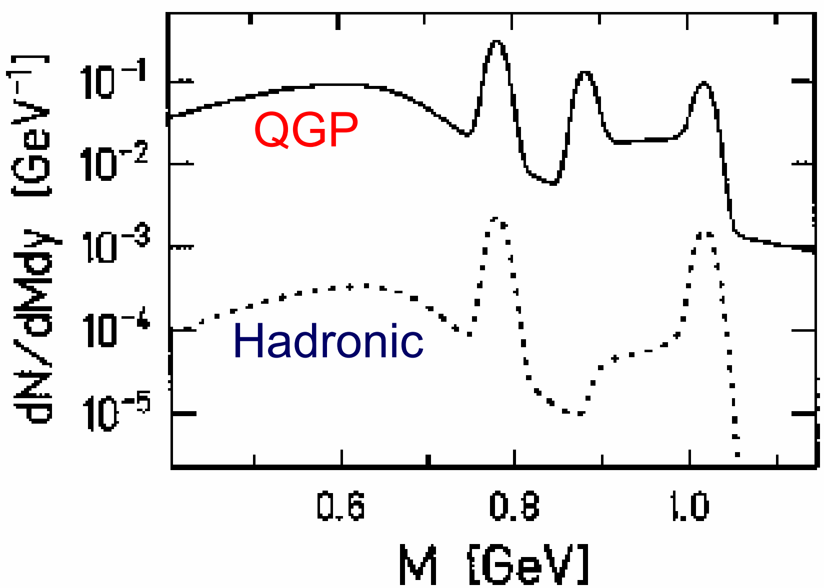
- pQCD gives similar c and cbar cross sections in QGP, irrespective to the baryon chemical potential (solid line).
- Resonance scattering leads to different c and cbar cross sections in QGP with finite baryon chemical potential (dotted and dashed lines)

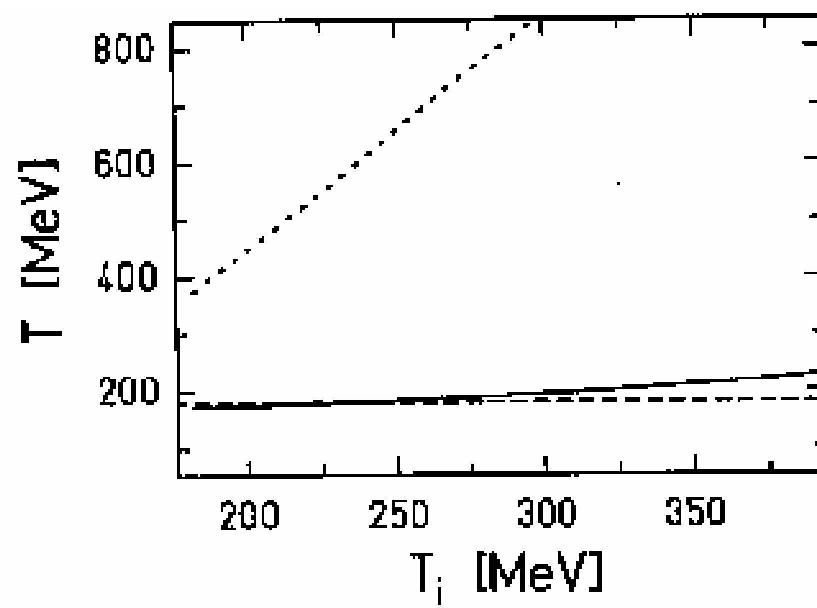
QGP phase transition and Double phi peaks



Asakawa & Ko, PLB 322, 33 (1994); PRC 50, 3046 (1994)

Boost-invariant hydro with transverse flow: T_0=250 MeV; T_c=180 MeV, T_f=120 MeV





Conclusions

- Anisotropic flow is sensitive to properties of initial matter: partonic matter leads to larger elliptic flow.

- Quark coalescence leads to approximate quark number scaling of hadron elliptic flows and v_4/v_2^2 scaling.

- Elliptic flow at FAIR is appreciable if a partonic matter is formed.

- v_4/v_2^2 is smaller at FAIR than at SPS and RHIC.

- Charm v_2 is expected to be appreciable at FAIR.

- Compare charm and anticharm losses in baryon-rich QGP can distinguish the mechanism for their energy loss.

- First-order phase transition may lead to double phi peaks in dilepton spectrum.