Charm v_2 is more hydrodynamic than light quark v_2

Hanlin Li
Wuhan University of Science and Technology
Zi-Wei Lin
East Carolina University & Central China Normal University
Fuqiang Wang
Purdue University & Huzhou University

Mostly based on:

[1] L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, F.Q. Wang, **Phys. Lett. B 735,506(2016).**
[2] H.L. Li, Z.-W. Lin and F. Wang, **arXiv:1804.02681 (2018).**
[3] Z.-W. Lin, **Phys. Rev. C 90, 014904 (2014).**

Outline

Introduction

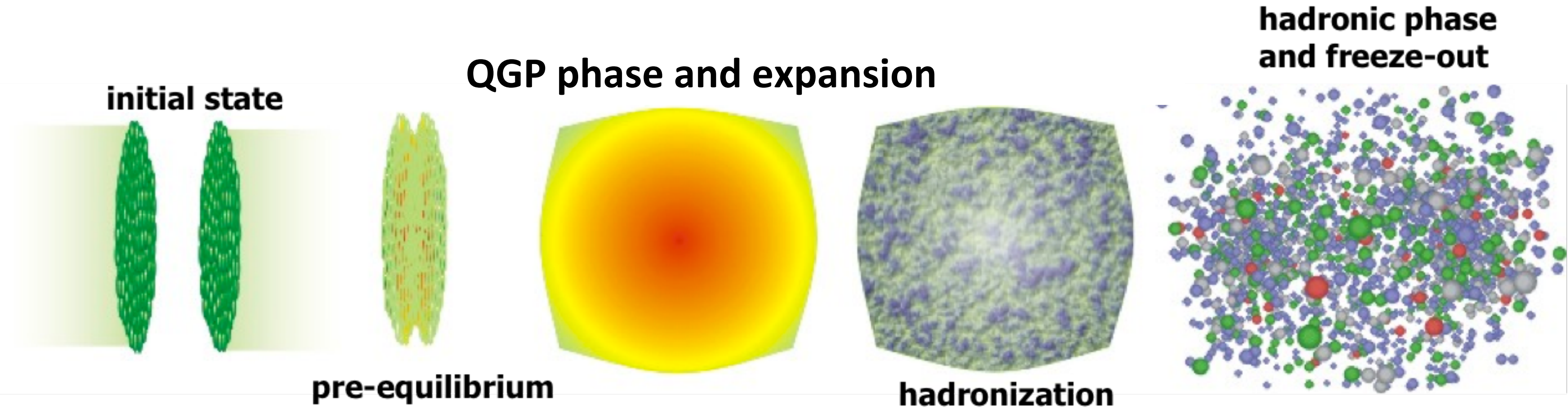
Results and discussion

★ V_2 development in AMPT

★ Charm quark's V_2 versus light quark's V_2

Summary

Heavy ion collisions



Hard probes (p_T,M>>Λ_{QCD}=200 MeV)

Jet queching

Heavy quarks (tagged b-jets) ....

Soft probes (p_T~Λ_{QCD}=200 MeV)

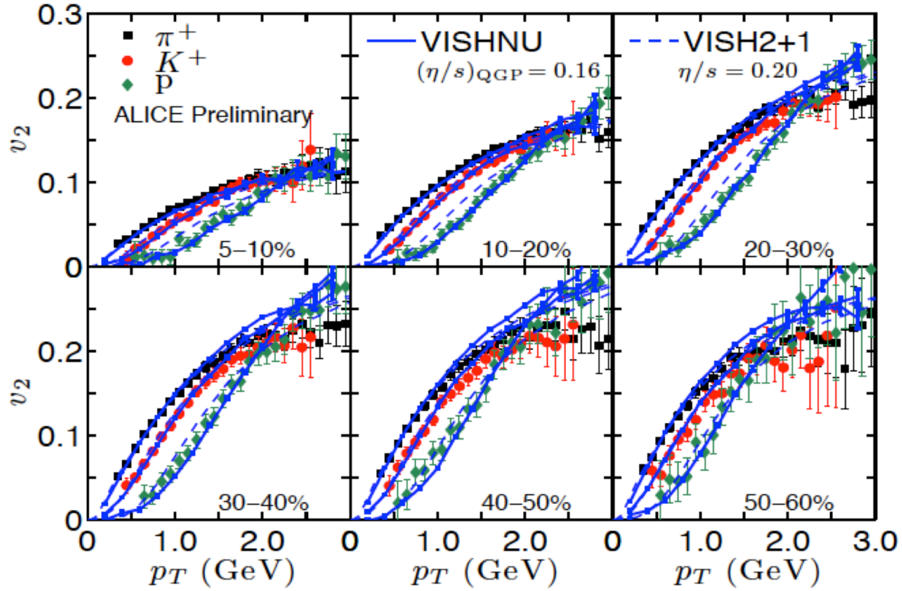
Collective flow......

Hydrodynamic vs transport

Hydrodynamics has been very successful for global observables, especially flow v_n

$v_2(p_T)$ in PbPb@LHC: ALICE vs. VISHNU

Data: ALICE, preliminary (Snellings, Krzewicki, Quark Matter 2011)
Dashed lines: Shen et al., PRC84 (2011) 044903 (VISH2+1, MC-KLN, $(\eta/s)_{QGP}$=0.2)
Solid lines: Song, Shen, UH 2011 (VISHNU, MC-KLN, $(\eta/s)_{QGP}$=0.16)



VISHNU yields correct magnitude and centrality dependence of $v_2(p_T)$ for pions, kaons and protons!

Same $(\eta/s)_{QGP} = 0.16$ (for MC-KLN) at RHIC and LHC!

Heinz, BES Workshop at LBNL 2014
using viscous hydrodynamics.

Transport model can also describe flow v_n :
degree of equilibration is controlled by cross section σ

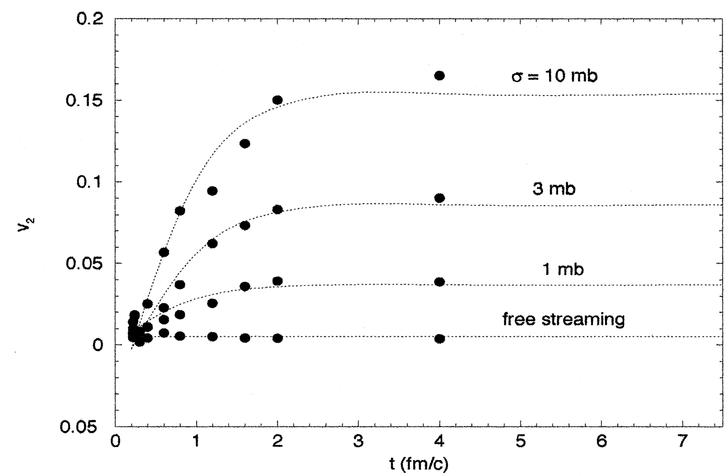
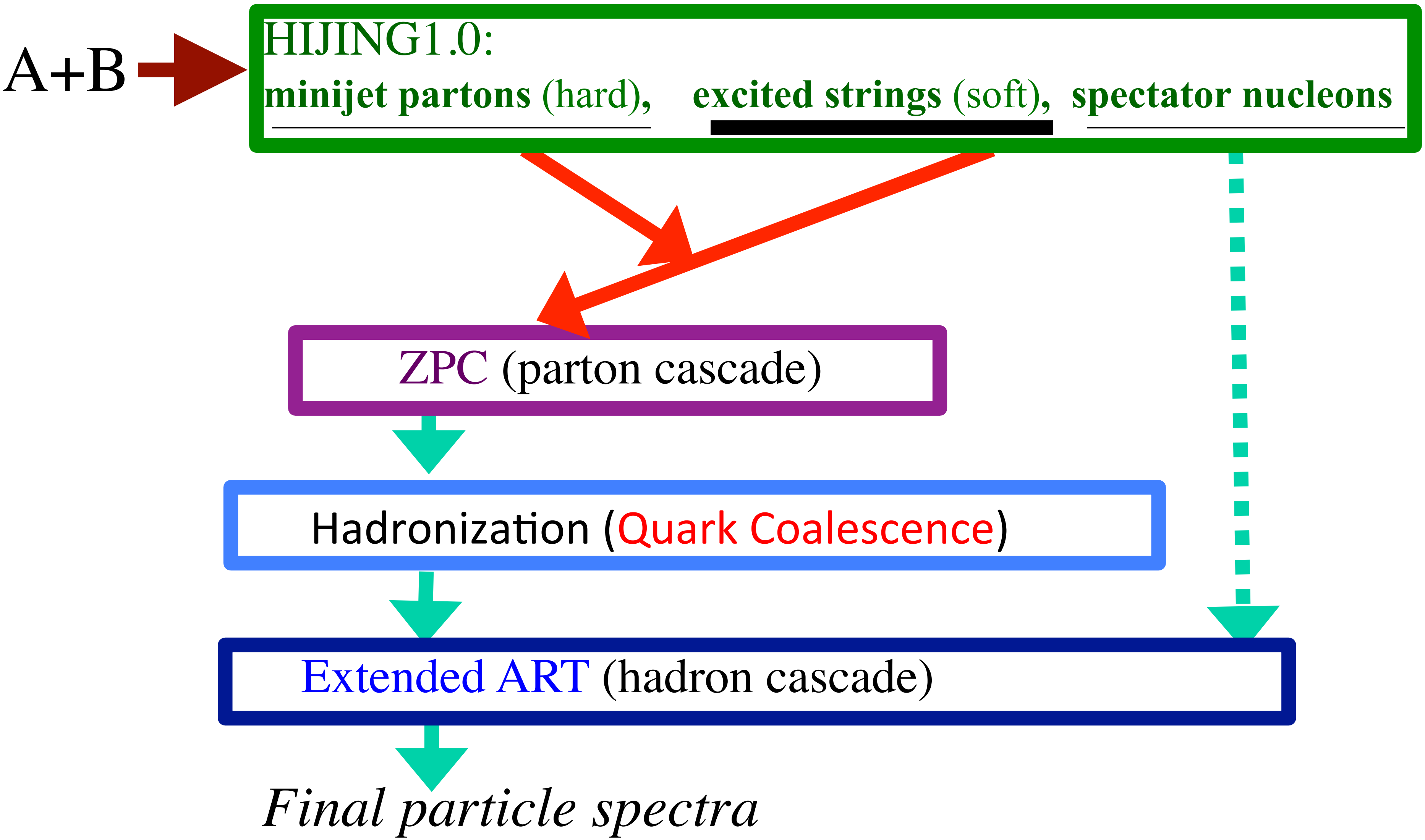


Fig. 1. Time evolution of v_2 coefficient for different effective parton scattering cross sections in Au-Au collisions at $\sqrt{s} = 200$ AGeV with impact parameter 7.5 fm. Filled circles are cascade data, and dotted lines are hyperbolic tangent fits to the data.

Zhang, Gyulassy and Ko, PLB (1999)
using elastic parton transport.

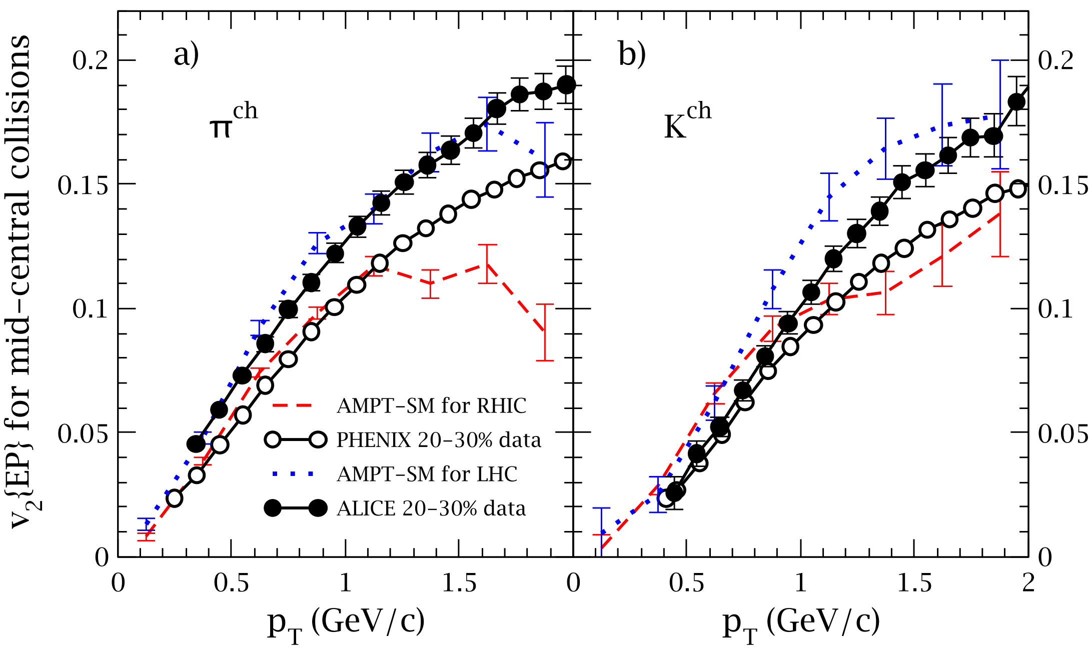
Structure of AMPT (String Melting version)

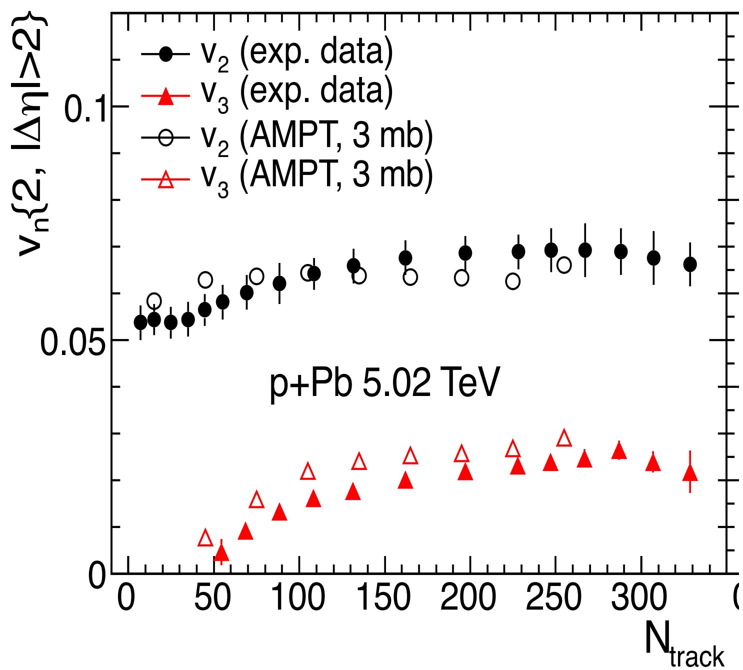


A Multi-Phase Transport (AMPT) model describes data

AMPT describes low-pt (<2GeV/c) π & K data on dN/dy, p_T spectra & v2 in central & mid-central events of 200AGeV Au+Au & 2760AGeV Pb+Pb.

Collectivity in small colliding systems



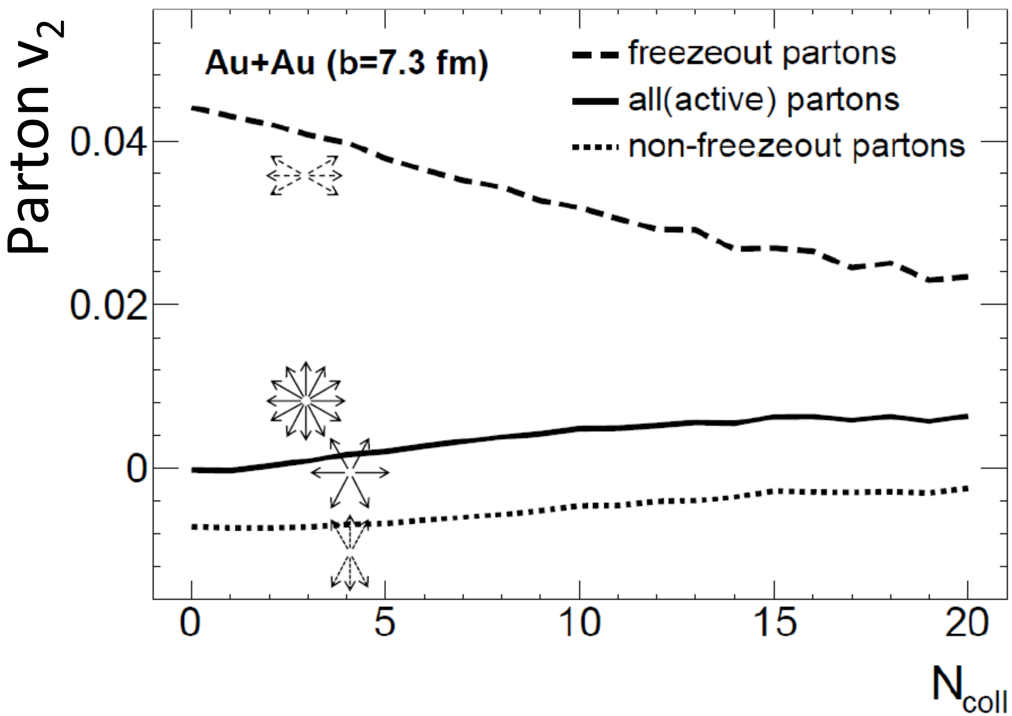


v2 of π & K (AuAu@200AGeV b=7.3fm)

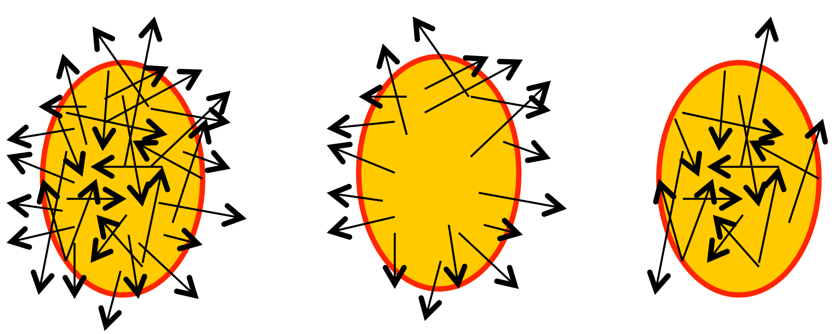
Z.-W.Lin,PRC90 (2014) 1, 014904

Bzdak and Ma,
Phys.Rev.Lett. 113 (2014) 25, 252301

Parton azimuthal anisotropies developed in AMPT



Ncoll: *number of collisions suffered by a parton.*



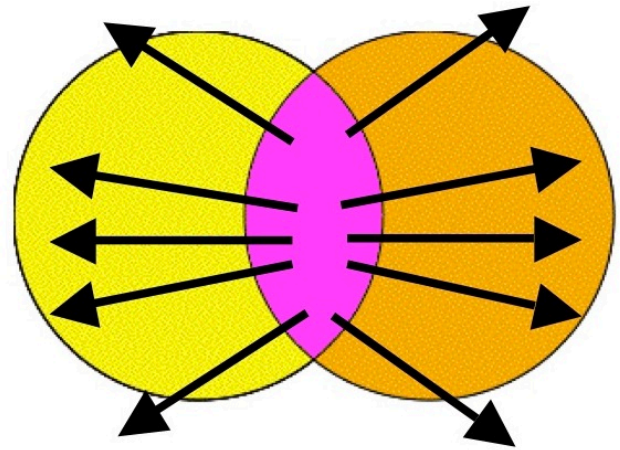
- Partons freeze out with large positive v_2, even for partons that do not interact at all.
- This is due to larger escape probability along x than y induced by parton scatterings.
- Remaining partons start off with negative v_2, and become ~isotropic (v_2~0) after one more collision.
- Process repeats itself.
- Similar for v_3.
- Similar for d+Au collisions.

L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, F.Q. Wang, Phys. Lett. B 735,506(2016)

Anisotropic particle escape

At Ncoll=0:
Escaped: v2 ≈ 4.5%,
purely due to
anisotropic escape probability
(interaction-induced response
to geometrical shape)

Simplified picture of elliptic flow

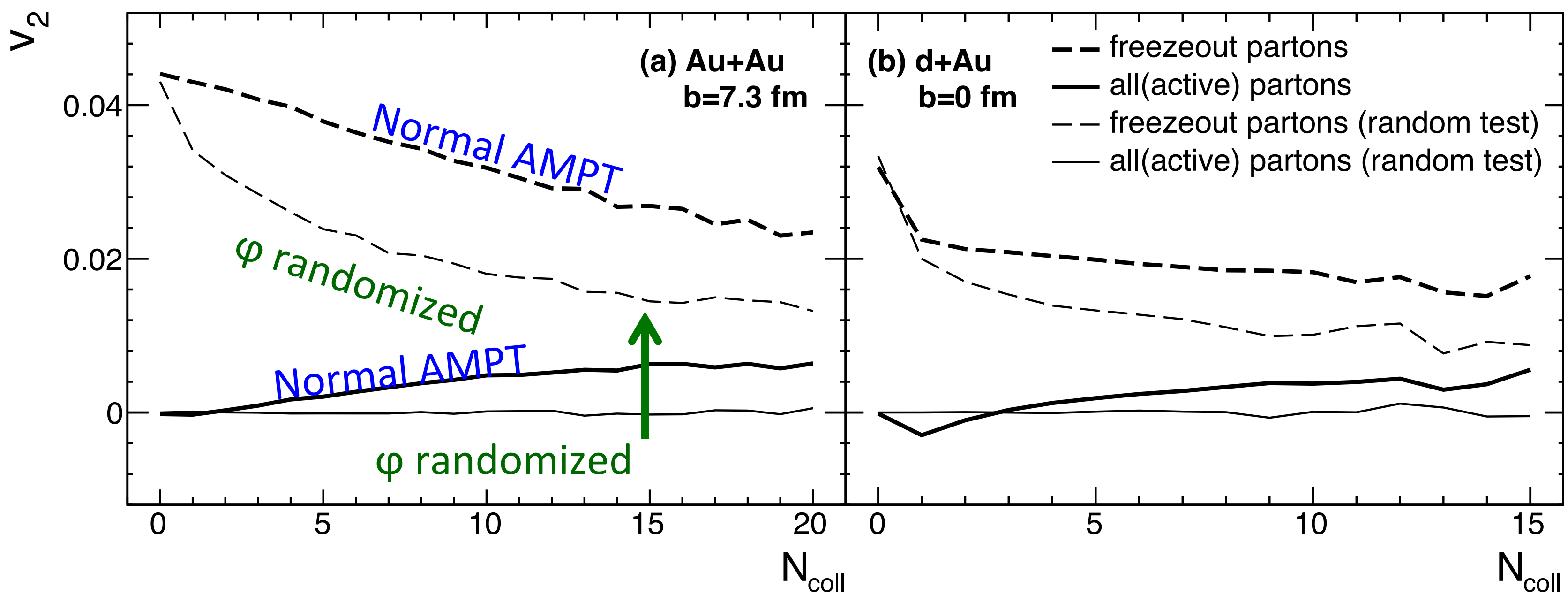


At Ncoll>=1:
Escaped: v2>0
due to
anisotropic escape probability
& from hydrodynamic flow of all
active partons

Which part
is more important?

Majority anisotropy from escape at RHIC

v2 from Random Test(destroy hydrodynamic flow but keep the anisotropic shape):
purely from escape mechanism, not from hydrodynamic flow



AMPT results on integrated v2:

	Normal	φ randomized	% from escape
Au+Au	3.9%	2.7%	69%
d+Au	2.7%	2.5%	93%

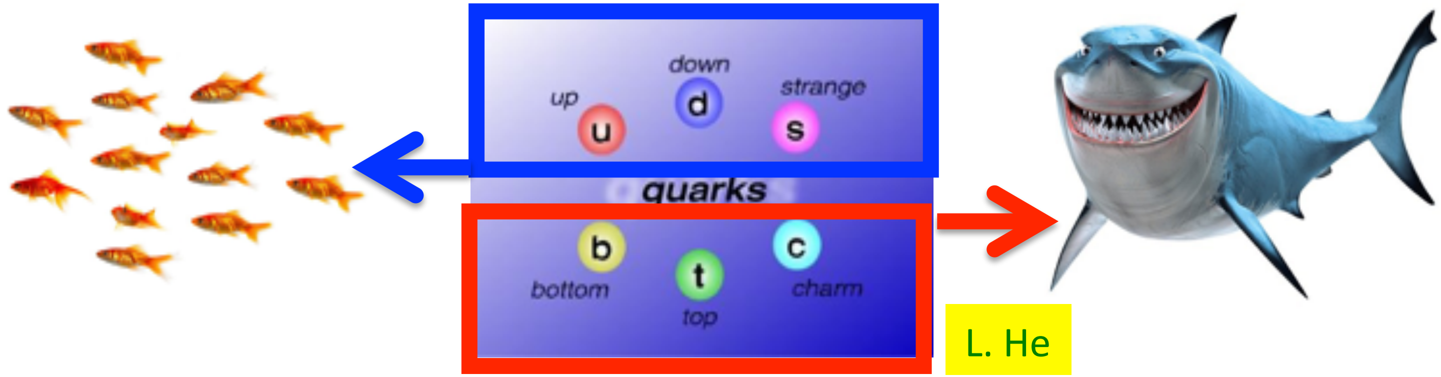
L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, F.Q. Wang, Phys. Lett. B 735,506(2016)

Majority of anisotropy comes from the “escape mechanism” at RHIC energies.

The escape mechanism: flavour dependence

Light flavor quarks

Heavy flavor quarks
Born earlier: probe early stage of QGP
large mass



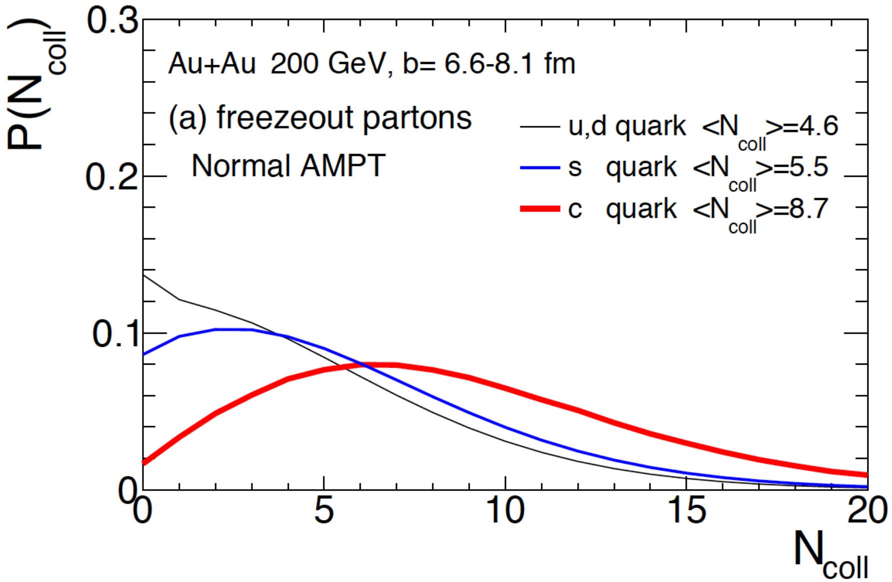
For light flavor quark:
Elliptic Anisotropy v_2 May Be Dominated by Particle Escape instead of Hydrodynamic Flow. Phys. Lett. B 735,506(2016), Nucl. Phys. A 956, 316 (2016).

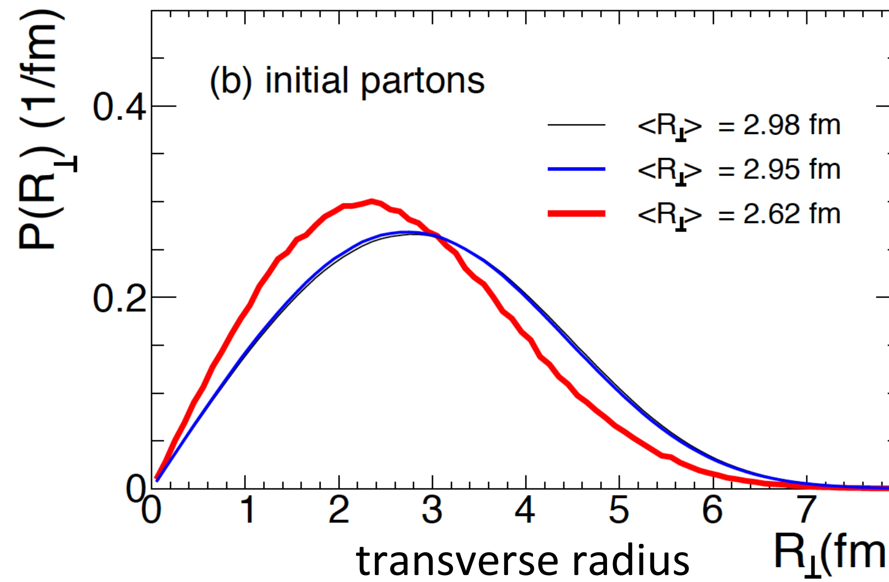
For heavy flavor quark:
Does the escape mechanism work differently for v2 of different flavours?

Azimuthal anisotropies of different flavours

We now use string melting AMPT to analyze light (u/d), strange, charm quarks in p+Pb@5TeV, Au+Au@200GeV, Pb+Pb@2.76TeV.

H.L. Li, Z.-W. Lin , F.Q. Wang. arXiv:1804.02681



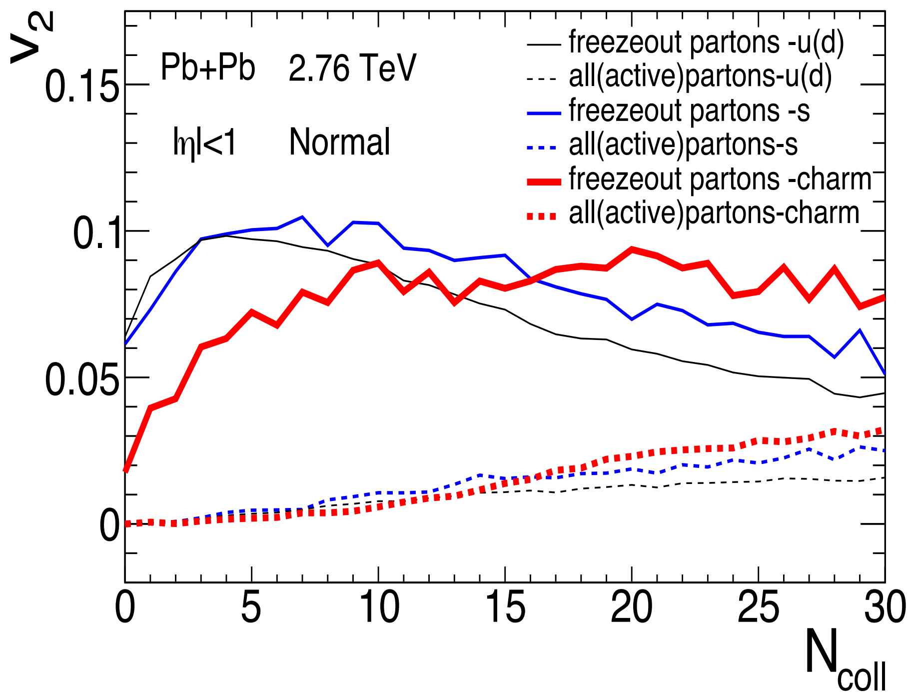


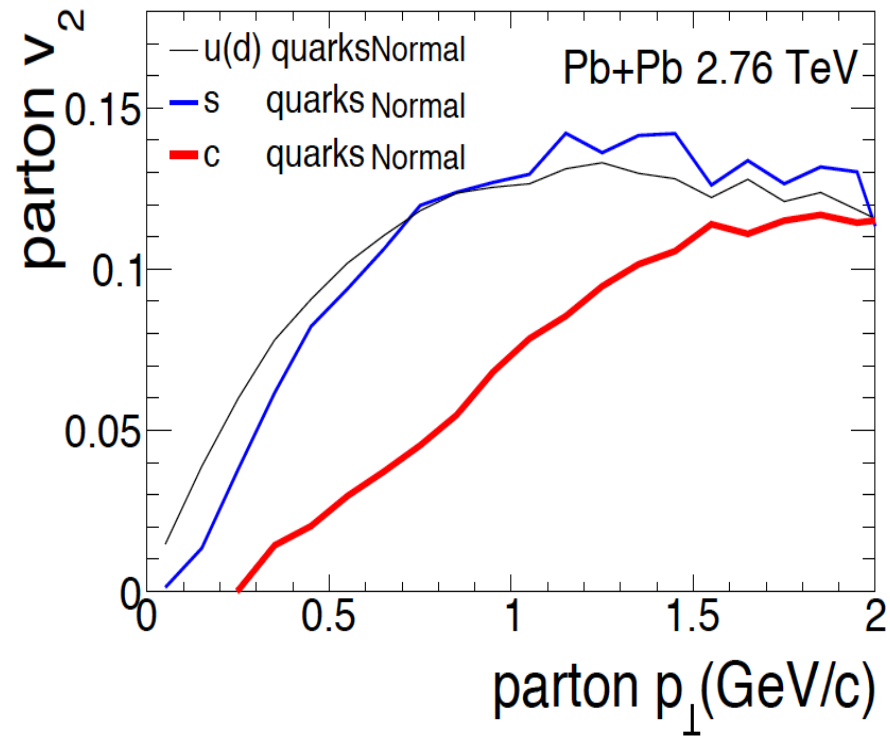
Mass ordering in the Ncoll distribution
for all 3 systems:

<Ncoll>c > <Ncoll>s > <Ncoll>ud

Charm quarks are produced in the more inner region of the overlap volume than light quarks.
->This is related to the initial spatial distribution and formation time.

Azimuthal anisotropies of different flavours





Mass ordering in v2(Ncoll):

v2c < v2s < v2ud at small Ncoll;

v2c > v2s > v2ud at large Ncoll.

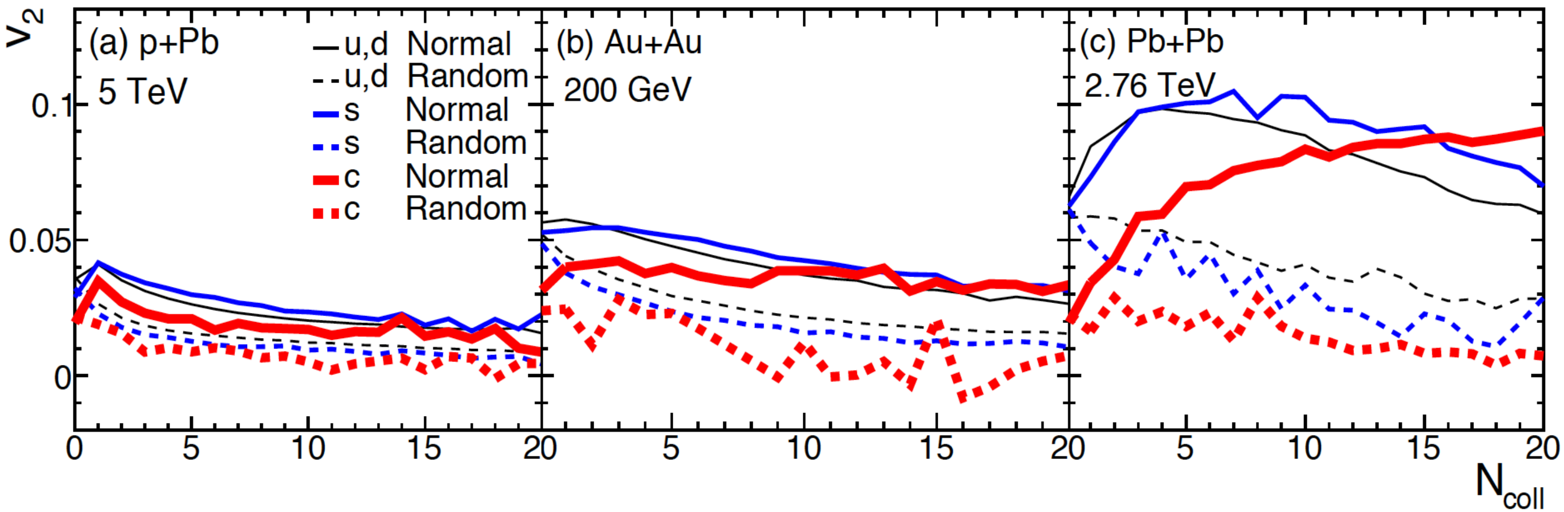
Mass ordering in v2(P_T):

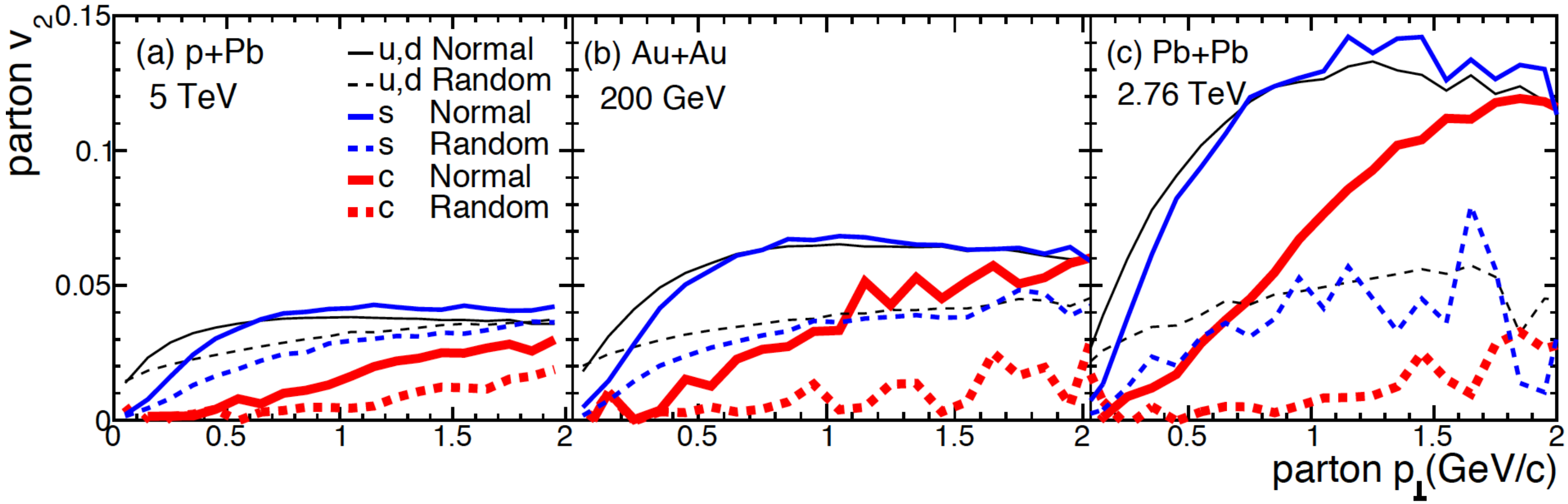
- mass ordering at low P_T:

  v2c < v2s < v2ud.

Hanlin Li et al. PRC 93 (2016); PRC 96 (2017).

Azimuthal anisotropies of different flavours





The escape mechanism is qualitatively at work for both charm v2 and light quark v2. However, random-φ test shows greater reduction of v2 for heavier quarks

The escape mechanism: flavour dependence

H.L. Li, Z.-W. Lin , F. Q. Wang. arXiv:1804.02681

	pPb ($b = 0$ fm)			AuAu ($b = 6.6$-8.1 fm)			PbPb ($b = 8$ fm)		
Quark flavor	u,d	s	c	u,d	s	c	u,d	s	c
$\langle N_{\rm coll} \rangle$	2.02	2.54	4.23	4.58	5.45	8.68	9.82	11.14	15.48
$\langle v_2 \rangle_{\rm Random}$	2.39%	1.89%	1.21%	2.93%	2.27%	0.85%	3.21%	2.23%	0.67%
$\langle v_2 \rangle_{\rm Normal}$	3.28%	3.20%	2.14%	4.47%	4.78%	3.89%	7.56%	8.42%	7.92%
$\langle v_2 \rangle_{\rm Random} / \langle v_2 \rangle_{\rm Normal}$	73%	59%	57%	66%	47%	22%	43%	27%	8.5%

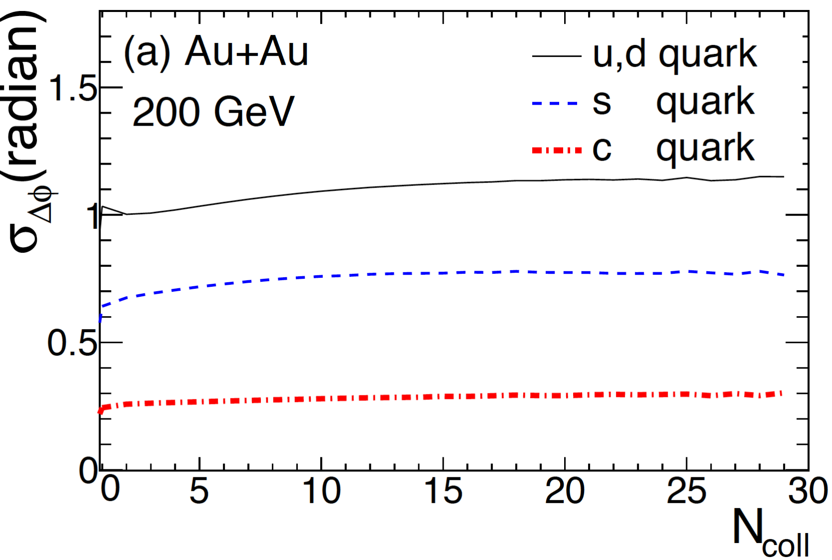
q $\longrightarrow$ Q

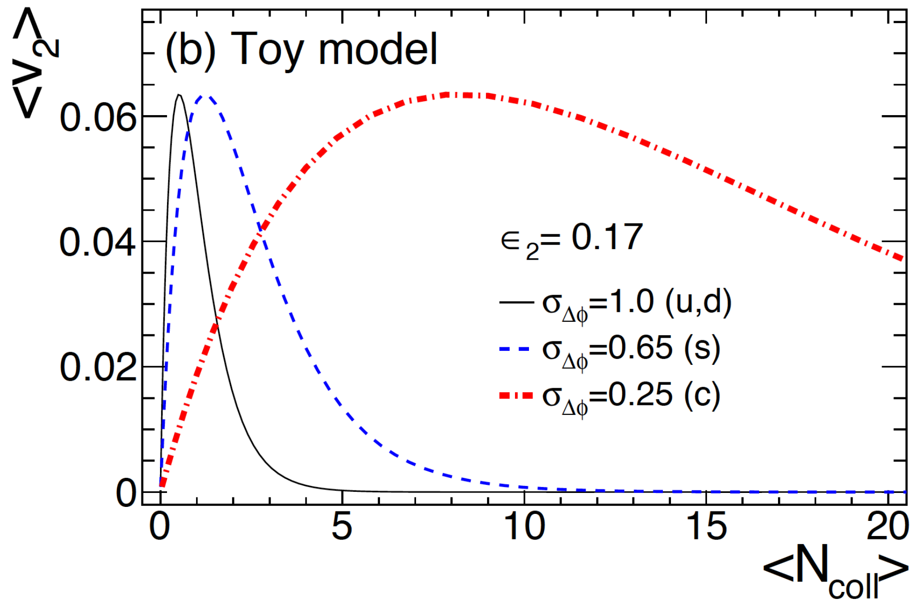
System size/energy $\longrightarrow$

Less from escape mechanism/ more from hydrodynamics type flow.

Toy Model studies

$\Delta\phi$: change of azimuth due to one collision (*the Ncoll-th collision*):





Mass ordering on
the mean parton deflection angle:

$$\Delta\phi\_c < \Delta\phi\_s < \Delta\phi\_u(d)$$

it is more difficult to deflect a heavier quark

v_2 vs. $\langle N_{coll} \rangle$:
Sampling partons starting at (x=0,y=0) and traversing same shape medium of different sizes.

$$N_{coll}(\phi_i) = \langle N_{coll} \rangle \cdot (1 - 2\varepsilon_2 \cdot \cos(2\phi_i))$$

H.L. Li, Z.-W. Lin , F. Q. Wang. arXiv:1804.02681

The <v2> of light quarks is larger than charm quarks at small <Ncoll> but is the opposite at large <Ncoll>. It related to their deflection angle during the collisions.

Summary

1. The common escape mechanism is at work not only for light quark but also for strange and charm quark v_2.

2. The charm v_2 has a larger fraction coming from the hydrodynamic collective flow (and thus less coming from the escape mechanism) than the light quark v_2.

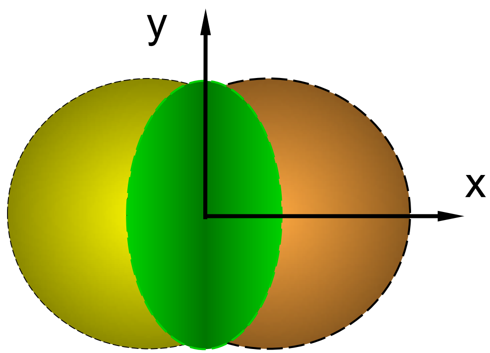
3. We further find that this is closely related to the mass dependence of the average scattering angles.

4. Comparative study of light and heavy quark anisotropies is important to investigate the medium properties in heavy ion collisions.

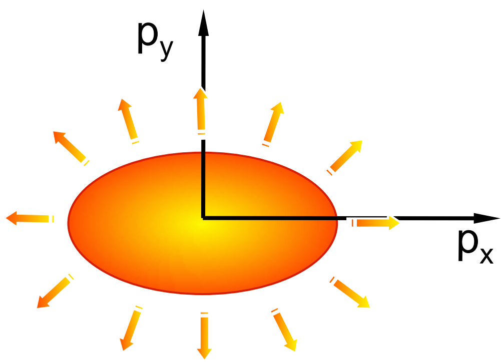
Back up

Azimuthal anisotropies

coordinate space



Momentum space



- Coordinate space configuration anisotropic (almond shape) however, initial momentum distribution isotropic (spherically symmetric)
- Only interactions among constituents generate a pressure gradient, which transforms the initial coordinate space anisotropy into a momentum space anisotropy (no analogy in pp)
- Multiple interactions lead to thermalization -> limiting behavior ideal hydrodynamic flow

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\phi-\Psi_r\right)\right)\right)$$

$$v_n = \cos\left(n\left(\phi-\Psi_r\right)\right), \qquad \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$