HF Production and Dynamics in AMPT

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Outline

- Where are heavy flavours in the AMPT model?
- Anisotropic parton escape: *review*
- Anisotropic parton escape: *flavour dependence*
- Future heavy flavour work with AMPT
- Summary

A Multi-Phase Transport AMPT ZWL et al. PRC72 (2005)
was constructed as a comprehensive model for heavy ion collisions.

It aims to

evolve the system from initial condition to final observables;
conserve energy/momentum/flavour/charge of each event,
include particle productions of different flavours at different P_T & y,
keep non-equilibrium features and dynamics
(e.g. intrinsic fluctuations and correlations).

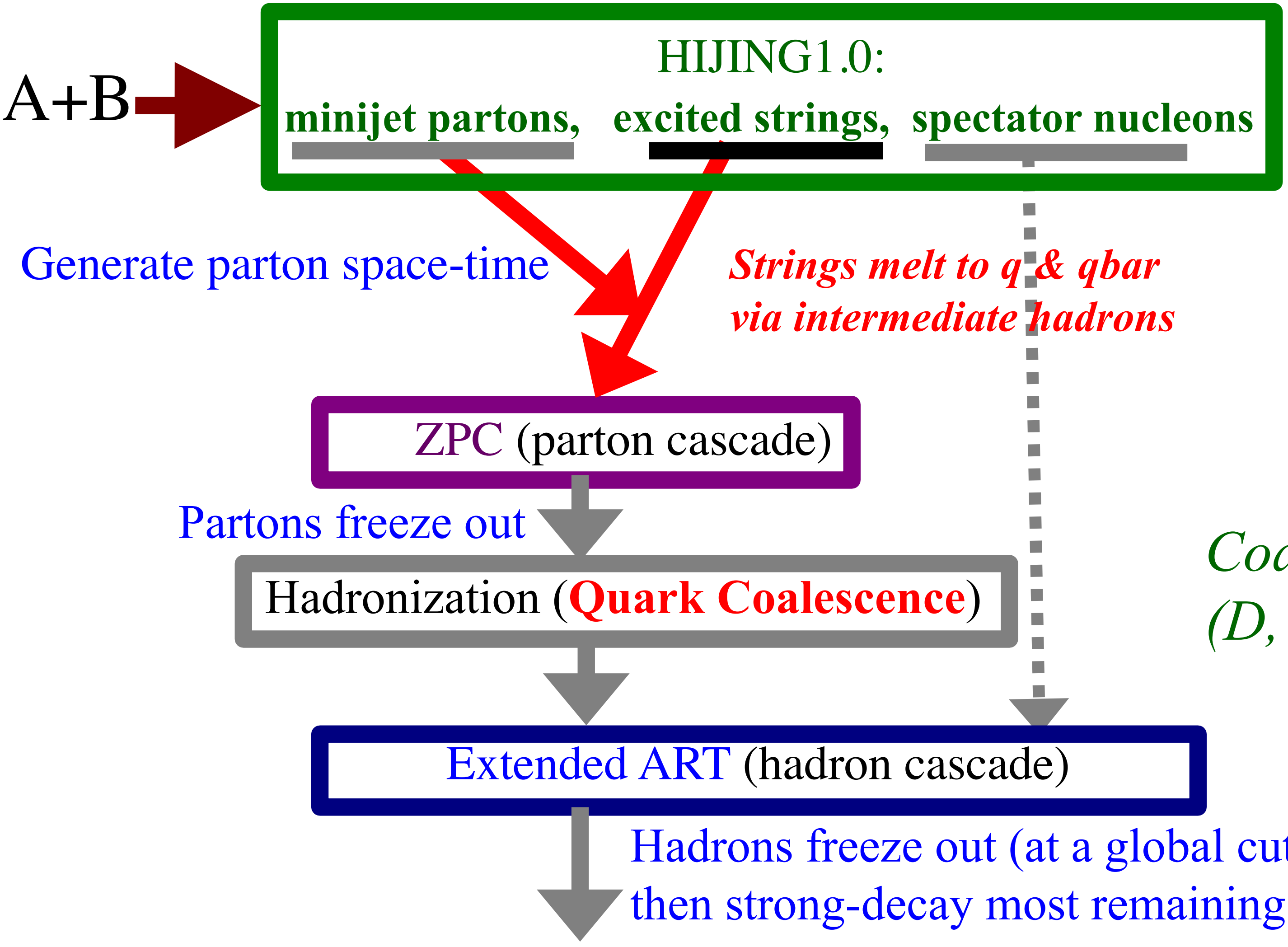
It is also a test-bed of different ideas:

- Discovery of the triangular flow v_3 — Alver & Roland, PRC 81 (2010)
- Longitudinal (de)correlations of flows — Pang et al. PRC 91 (2015), EPJA52 (2016)
- Flow may be dominated by anisotropic parton escape — He et al. PLB753 (2016); ZWL et al. NPA 956 (2016)

So we are working to extend AMPT to heavy flavours, in order to simultaneously study light flavours, heavy flavours including their interactions.

Where are heavy flavours (Q) in the current AMPT model?

Structure of AMPT v2.xx (String Melting version)



A+B

HIJING1.0:

minijet partons, excited strings, spectator nucleons

Generate parton space-time

Strings melt to q & qbar via intermediate hadrons

ZPC (parton cascade)

Partons freeze out

Hadronization (**Quark Coalescence**)

Extended ART (hadron cascade)

Hadrons freeze out (at a global cut-off time);
then strong-decay most remaining resonances

Final particle spectra

Initial Q/Qbar production

2↔2 elastic scatterings

Coalescence to heavy hadrons
(D, D_s, D^*, Λ_c, B, …)

Heavy hadrons in final spectra

The escape mechanism: review

Liang He, Terrence Edmonds, ZWL, Feng Liu, Denes Molnar, Fuqiang Wang: PLB 753 (2016):
Anisotropic parton escape is the dominant source of azimuthal anisotropy in transport models.
ZWL et al. NPA 956 (2016) for Quark Matter 2015:
Elliptic anisotropy v_2 may be dominated by particle escape instead of hydrodynamic flow.

Background:

- Transport models at large-enough cross section will approach hydrodynamics.

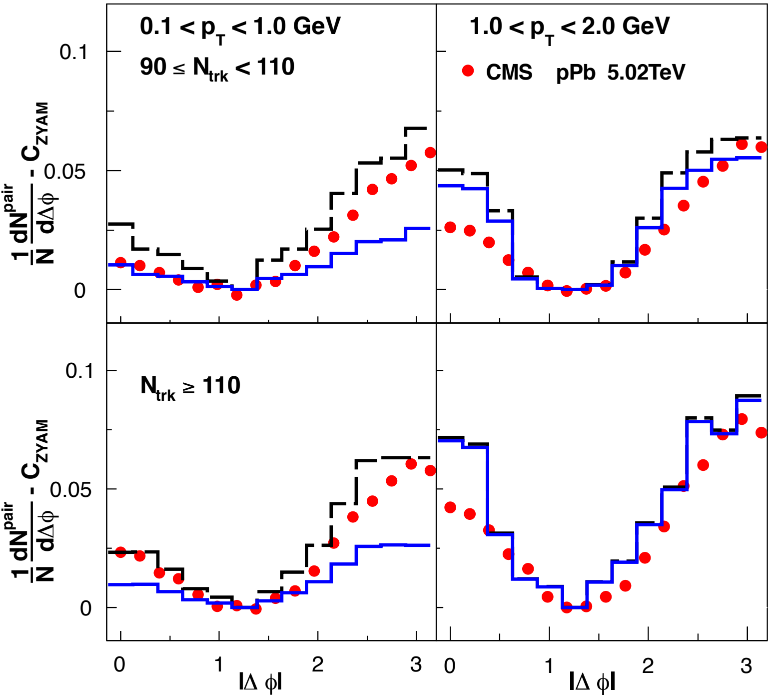
It has been generally believed that:

- Early hydro-type collective flow in sQGP
converts initial spatial anisotropy into final momentum-space v_n

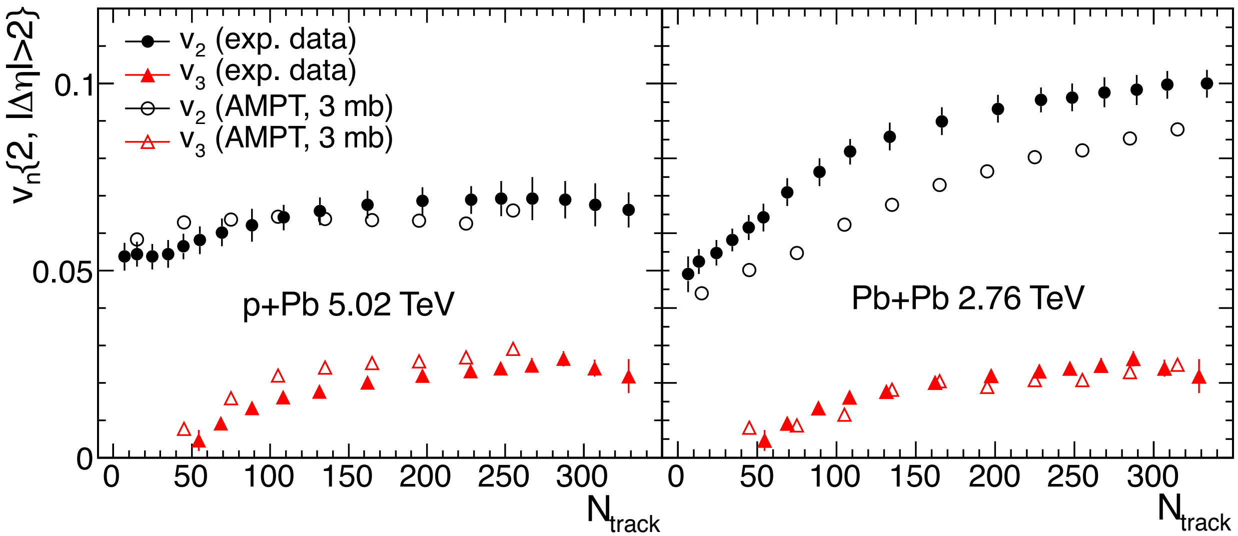
- For low-P_T particles in high-energy heavy ion collisions,
since both hydrodynamics and transport models can describe v_n data,
the mechanism of v_n development in transport models *(via particle interactions)*
is in principle the same as in hydrodynamics *(via pressure gradients)*.

The escape mechanism: review

Small systems: again, both hydrodynamics and transport can describe flow.



Bozek and Broniowski, PLB 718 (2013)
using e-by-e viscous hydrodynamics.



Bzdak and Ma, PRL 113 (2014)
using AMPT (String Melting version).

Puzzle for small systems such as p+Pb or d+Au:

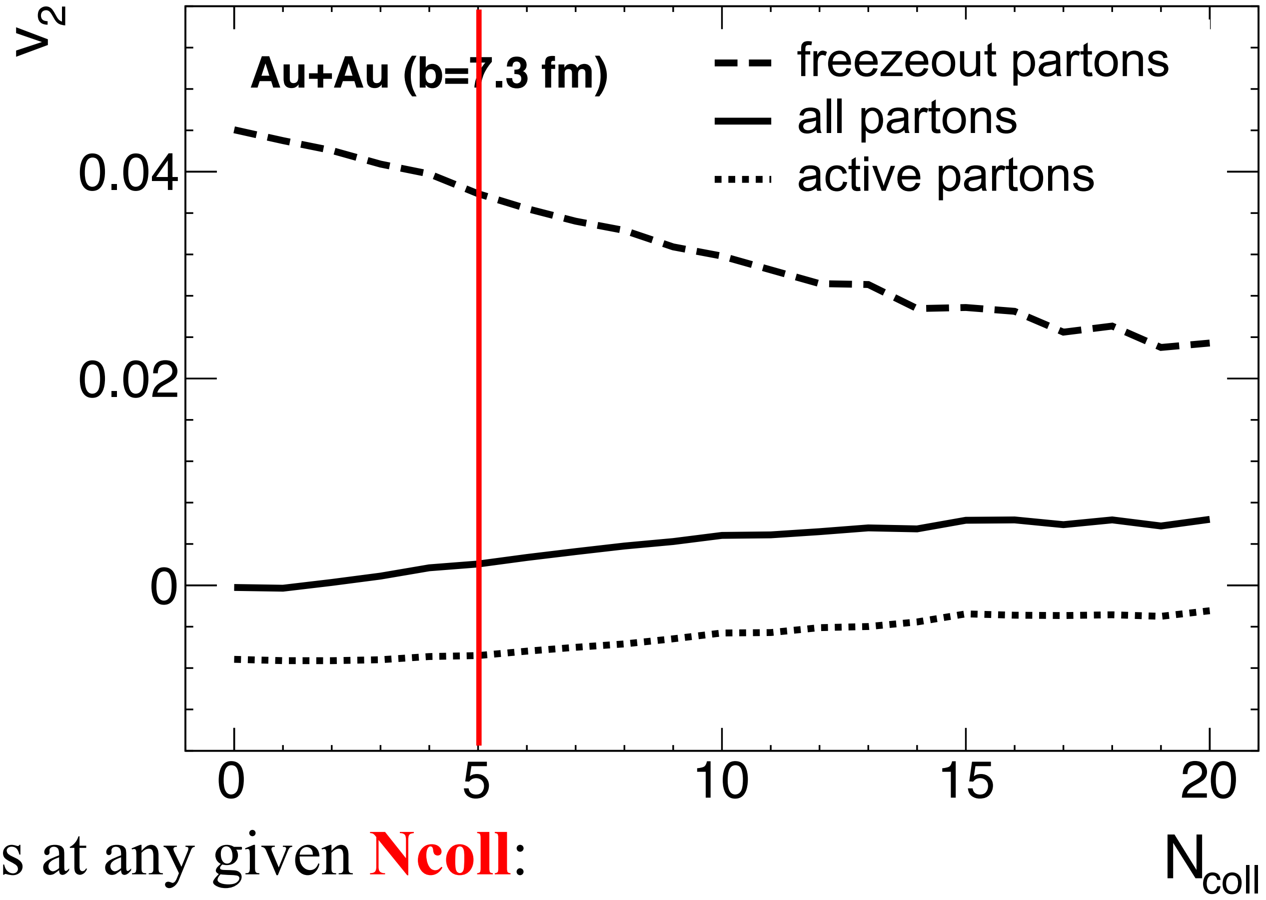
- Mean free path may be comparable to the system size; is hydrodynamics still applicable to such small systems?
- Transport and hydrodynamics should be different here, could they also be different for large systems?

The escape mechanism: review

We have followed the complete parton collision history and evaluate its effect on parton v2 in AMPT.

Ncoll: *number of collisions suffered by a parton*

He et al. PLB753 (2016)



3 parton populations at any given **Ncoll**:

freezeout partons: *freeze out after exactly **Ncoll** collisions;*

active partons: *will collide further, freeze out after **>Ncoll** collisions;*

all partons: *sum of the above two populations*
*(i.e. all partons that have survived **Ncoll** collisions).*

The escape mechanism: review

At Ncoll=0:

all partons: v_2=0 by symmetry (*as they include all initial partons*);

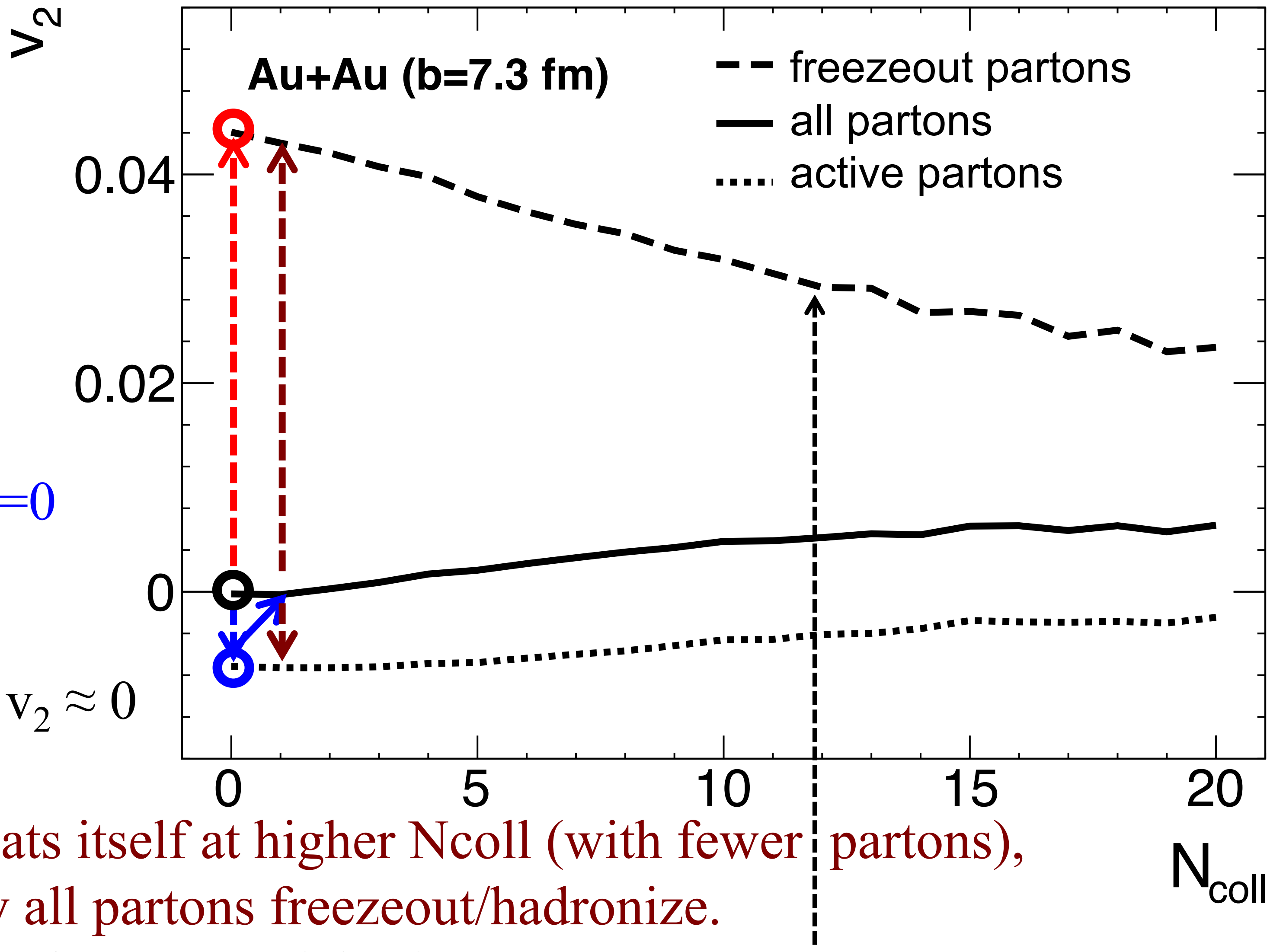
they contain 2 parts:

escaped/freezeout: $v_2 \approx 4.5\%$,

active: $v_2 < 0$.

At Ncoll=1:

active partons at Ncoll=0 collide once each & become **all partons** at Ncoll=1: $v_2 \approx 0$



This process repeats itself at higher Ncoll (with fewer partons), eventually all partons freezeout/hadronize.

<v2> = weighed average of the freezeout partons' v2.

The escape mechanism: review

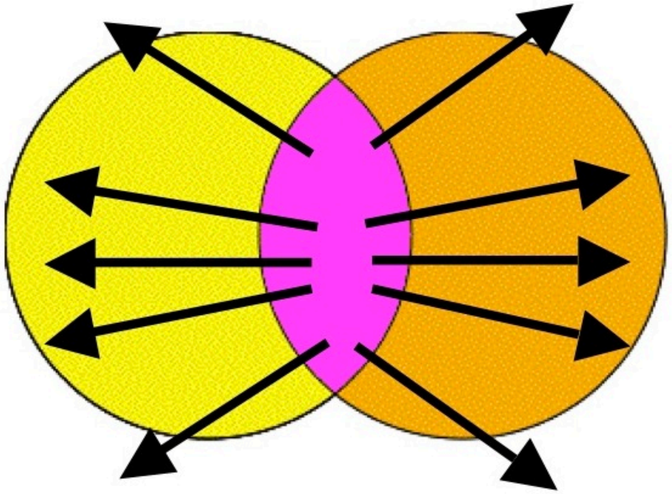
At Ncoll=0:

escaped partons: $v_2 \approx 4.5\%$,
this is **purely** due to
anisotropic escape probability
(response to geometrical shape only,
no contribution from collective flow)

At Ncoll>=1:

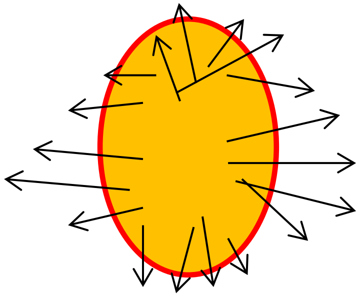
escaped partons: $v_2 > 0$
due to
anisotropic escape probability
& (anisotropic) **collective flow**.

In event-averaged picture of elliptic flow:

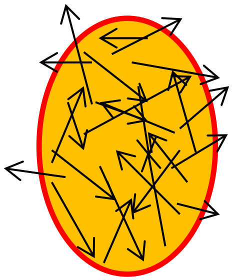


How to separate the two contributions?
We design a **Random-ϕ Test**

Normal:



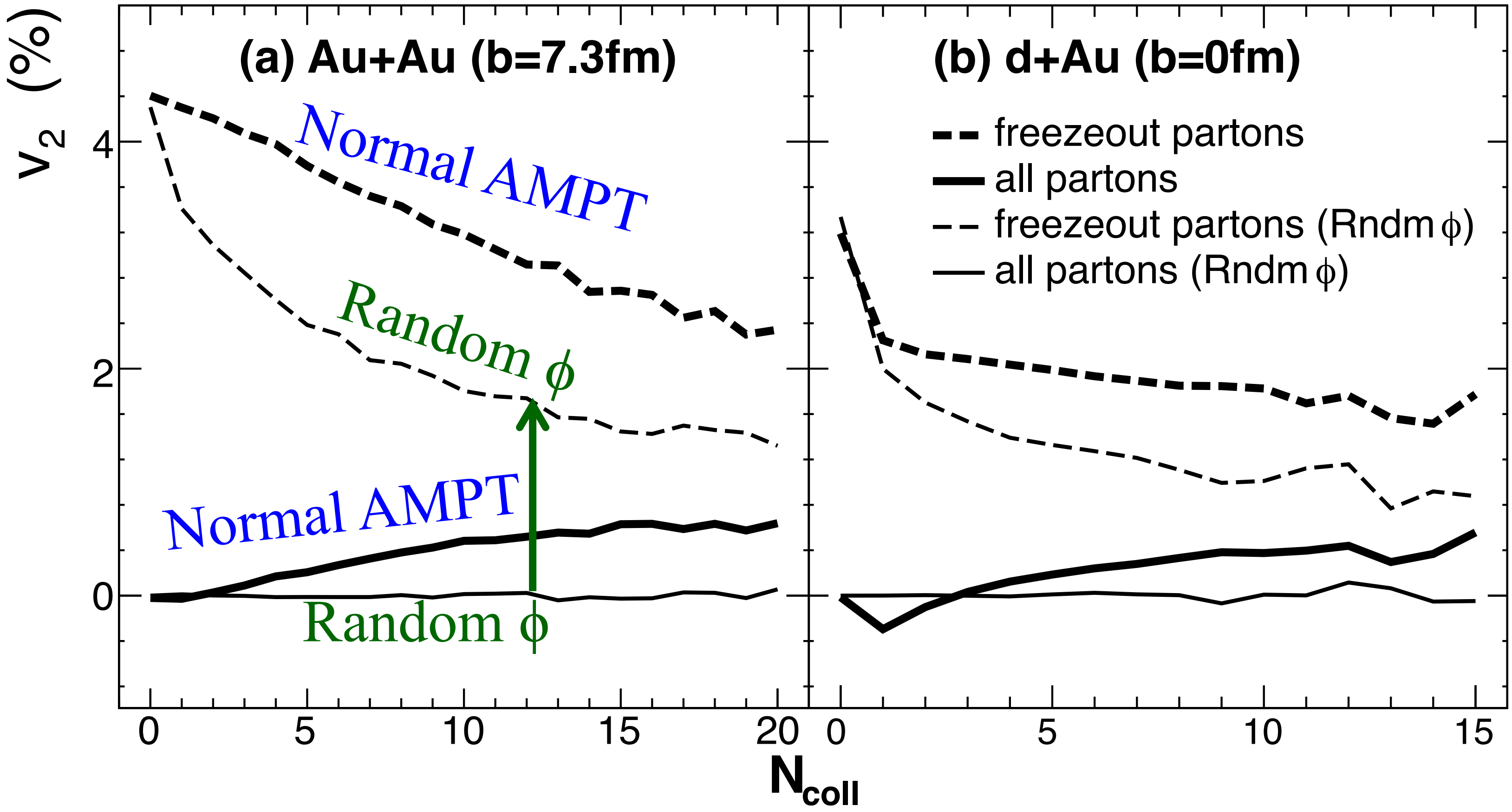
Random:



The escape mechanism: review

v_2 from the **Random-ϕ Test:** purely from the escape mechanism

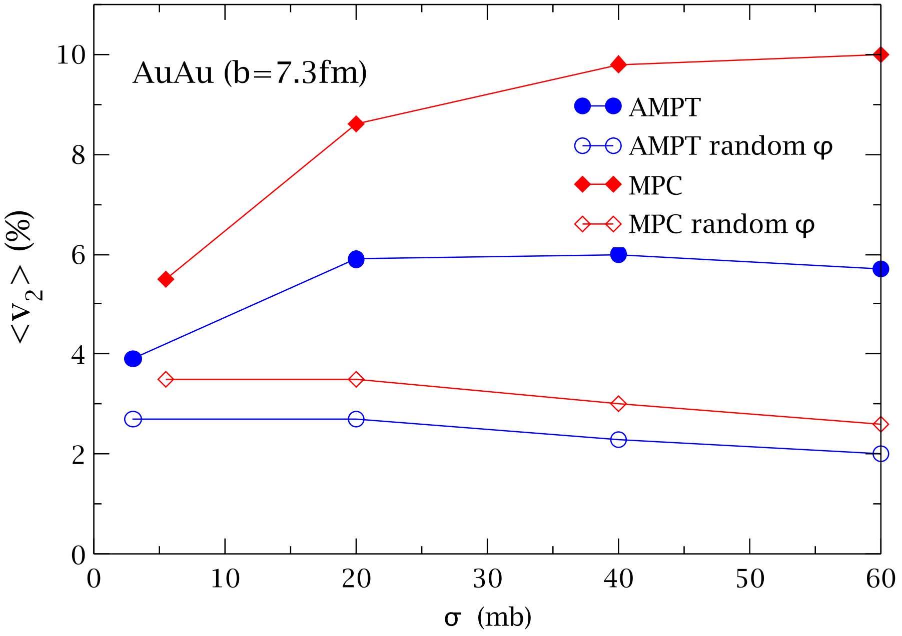
He et al. PLB753 (2016)



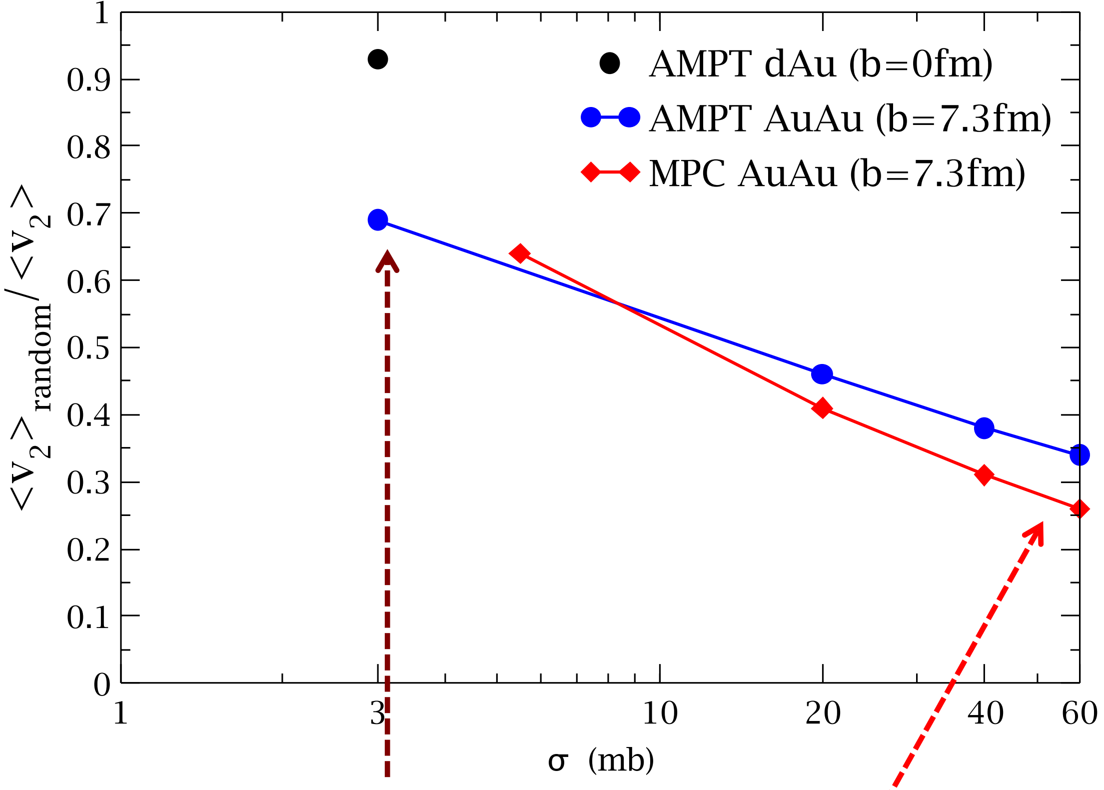
	$\langle v_2\rangle$normal	$\langle v_2\rangle$random-ϕ	**Ratio** ~ fraction from pure escape	<Ncoll>
Au+Au	3.9%	2.7%	**69%**	4.6 (*modest*)
d+Au	2.7%	2.5%	**93%**	1.2 (*low*)

The escape mechanism: review

ZWL et al. NPA 956 (2016)



v_2 ratio ~ fraction from pure escape



MPC: the same qualitative conclusion as AMPT despite many differences

(*parton initial condition,*
cross section & dσ/dt,
formation time,
parton-subdivision)

Anisotropic particle escape
is dominant for v_2 in small systems
& even for v_2 in semi-central AuAu at RHIC.

At very large σ or <Ncoll>,
hydrodynamic collective flow
will be the dominant contribution of v_2 .

The escape mechanism: review

Implications:

- The escape mechanism helps to explain similar anisotropic flows observed in small and large systems:
  since both are dominated by same mechanism (*anisotropic escape probability*)

- The driving force for v_2 at low & high P_T is qualitatively the same
  since both are dominated by *anisotropic probability of interactions* before escape
  (scatterings/kicks for low P_T & energy loss for high P_T)

- At low/modest opacity/<Ncoll>: **transport and hydrodynamics are different.**

The escape mechanism dominates v_n at low to modest opacity/<Ncoll>;
hydro-type collective flow dominates v_n at very high opacity/<Ncoll>.

Which is the case for A+B collisions at RHIC & LHC?

The escape mechanism: flavour dependence

Our previous results are for ALL quarks @200 GeV.

Does the escape mechanism work differently for different flavours?
or
Does collective flow work differently for 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, ZWL, F.Q. Wang, in preparation;
first result on pPb in H.L. Li, ZWL, F.Q. Wang, J Phys Conf Ser 779 (2017)

The escape mechanism: flavour dependence

Elastic parton scatterings only:

$$q_i q_j \to q_i q_j, \;\; q_i \overline{q_j} \to q_i \overline{q_j}, \;\; qQ \to qQ, \ldots$$

Caveat: here we use the same cross section for all flavours:

Parton cross section
based on $gg \to gg$
in leading-order pQCD:

$$\frac{d\sigma_{gg}}{dt} = \frac{9\pi\alpha_s^2}{2s^2}\left(3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2}\right)$$
$$\simeq \frac{9\pi\alpha_s^2}{2}\left(\frac{1}{t^2} + \frac{1}{u^2}\right) \simeq \frac{9\pi\alpha_s^2}{2t^2}$$

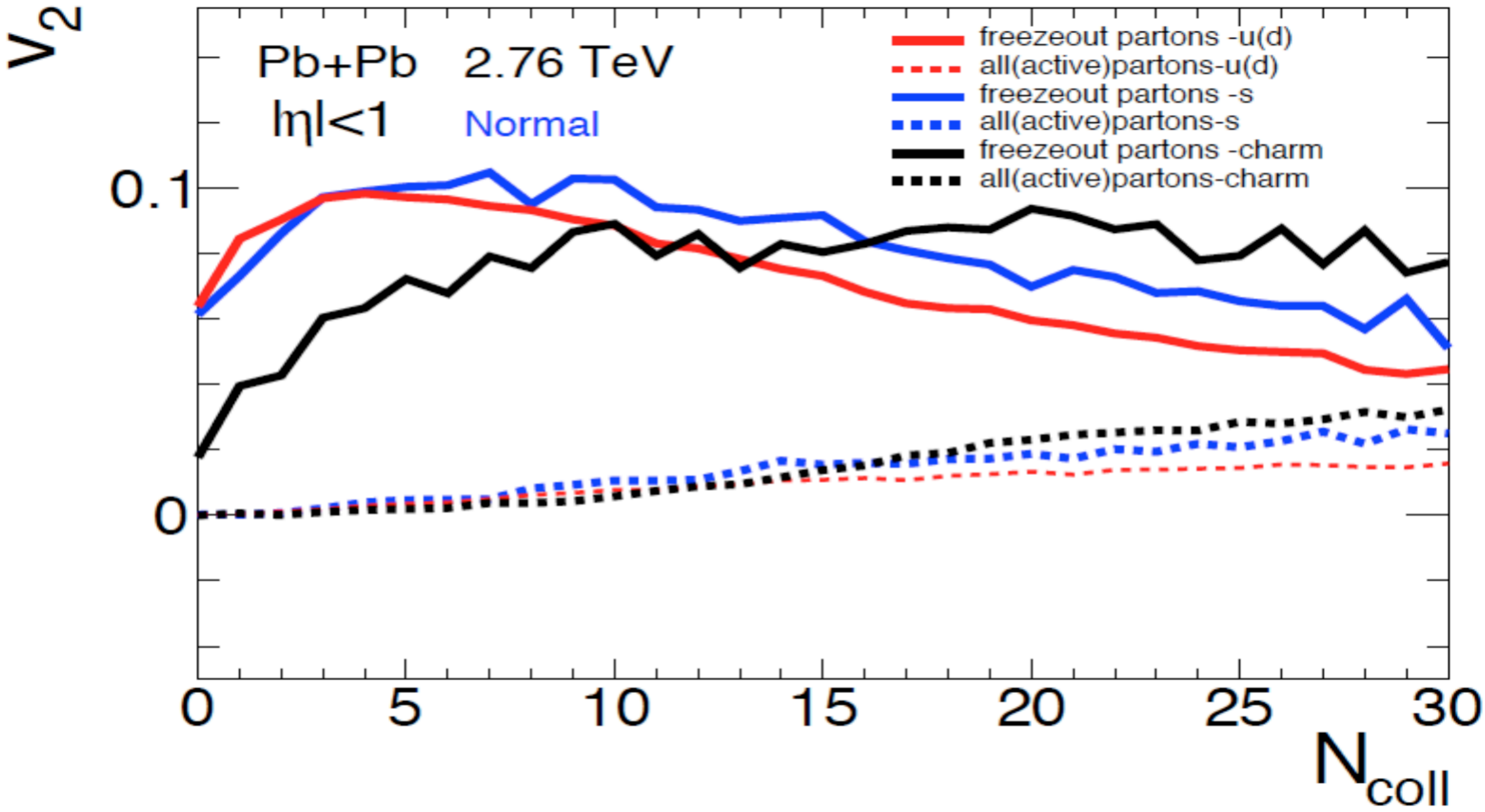
A screening mass ***μ***
regulates the divergence:

$$\frac{d\sigma_{gg}}{dt} \simeq \frac{9\pi\alpha_s^2}{2(t-\mu^2)^2}$$
$$\to \sigma_{gg} = \frac{9\pi\alpha_s^2}{2\mu^2} \frac{1}{1+\mu^2/s}$$

3mb cross section is used
since it reproduces pi/K/p v2(P_T)

ZWL, PRC 90 (2014)
G.L. Ma & ZWL, PRC 93 (2016)

The escape mechanism: flavour dependence

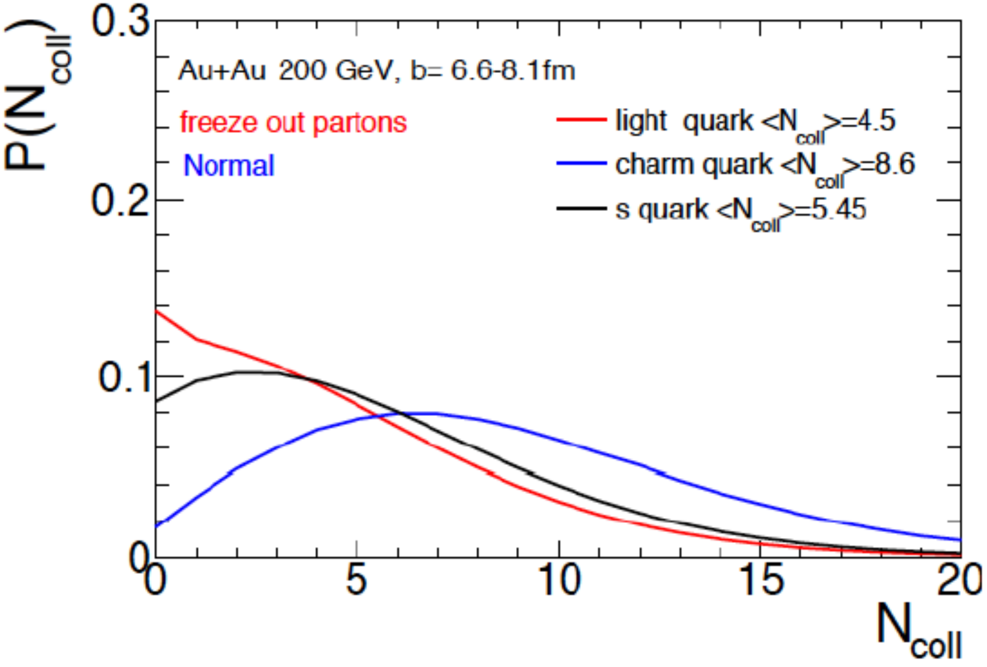


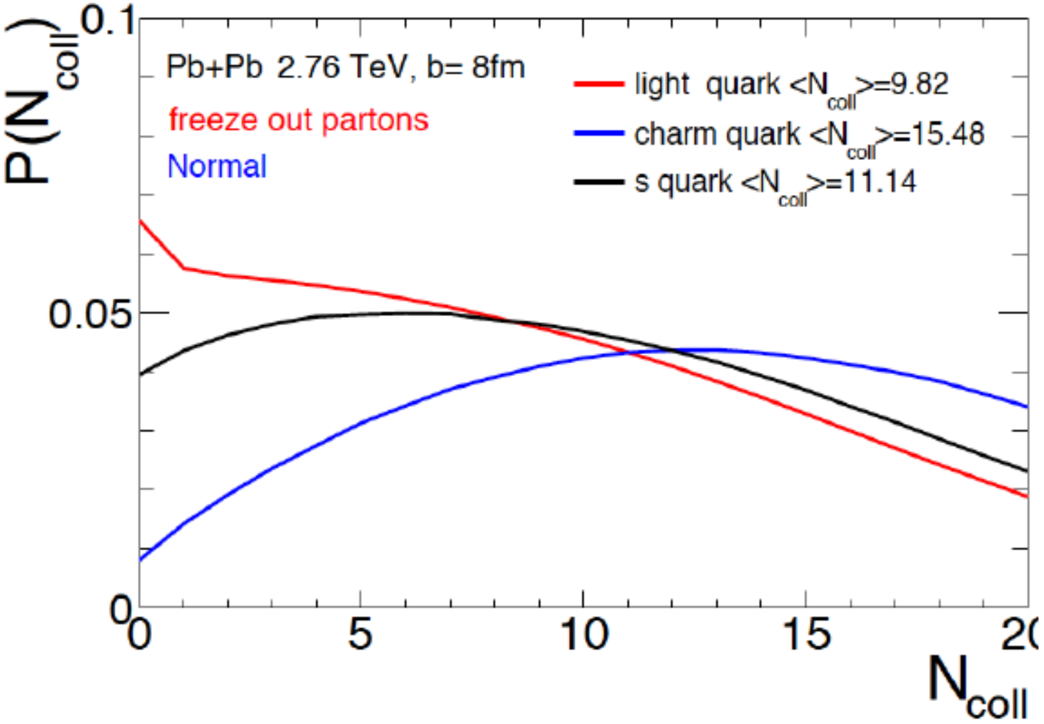
Pb+Pb
2.76TeV
8fm

Mass ordering in v2(Ncoll):

v2c < v2s < v2ud at small Ncoll,
reversed at large Ncoll.

The escape mechanism: flavour dependence

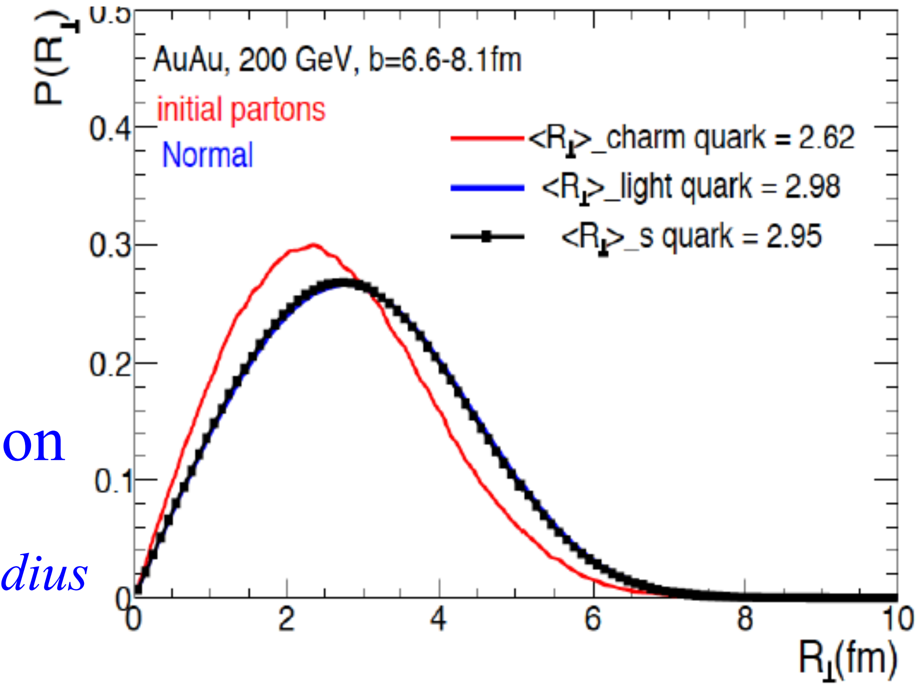




Mass ordering in the Ncoll distribution

for all 3 systems:

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

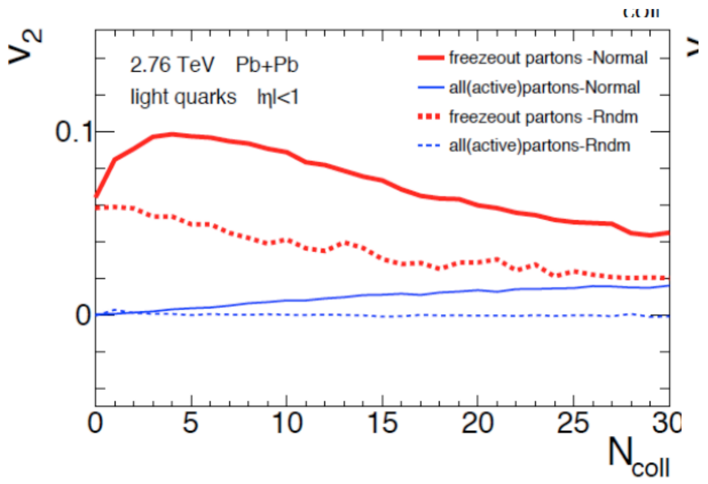


Related to the initial
(momentum &) spatial distribution

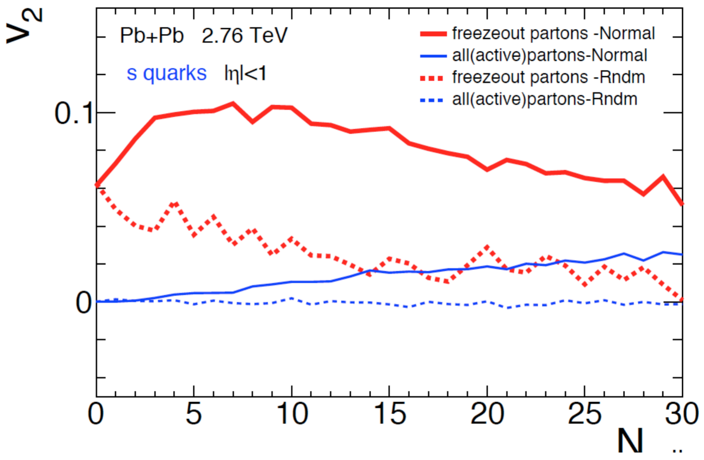
$R_\perp$: *transverse radius*

The escape mechanism: flavour dependence

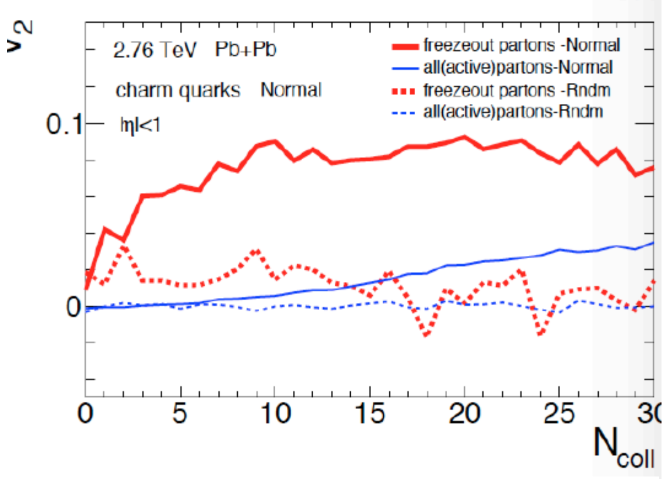
u/d



s



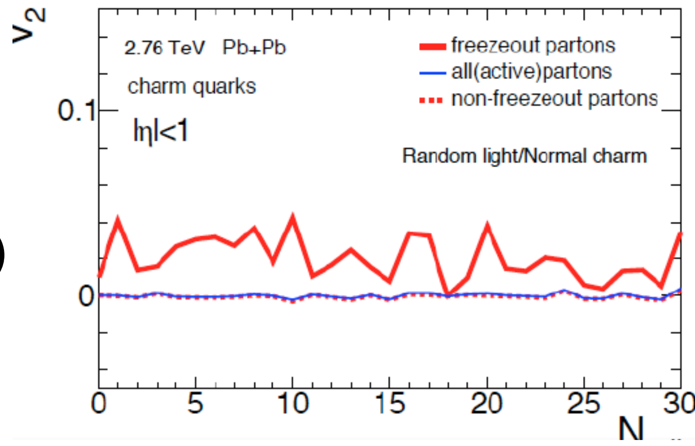
c



Random-ϕ (for all quarks) test:
greater reduction of v2 for heavier quarks.

Pb+Pb
2.76TeV
8fm

Random-ϕ for light quarks only
(Normal charm: they keep their collective flow):
large reduction of charm v2 (like the random-ϕ test)
➔
light quark collective flow is essential for charm v2

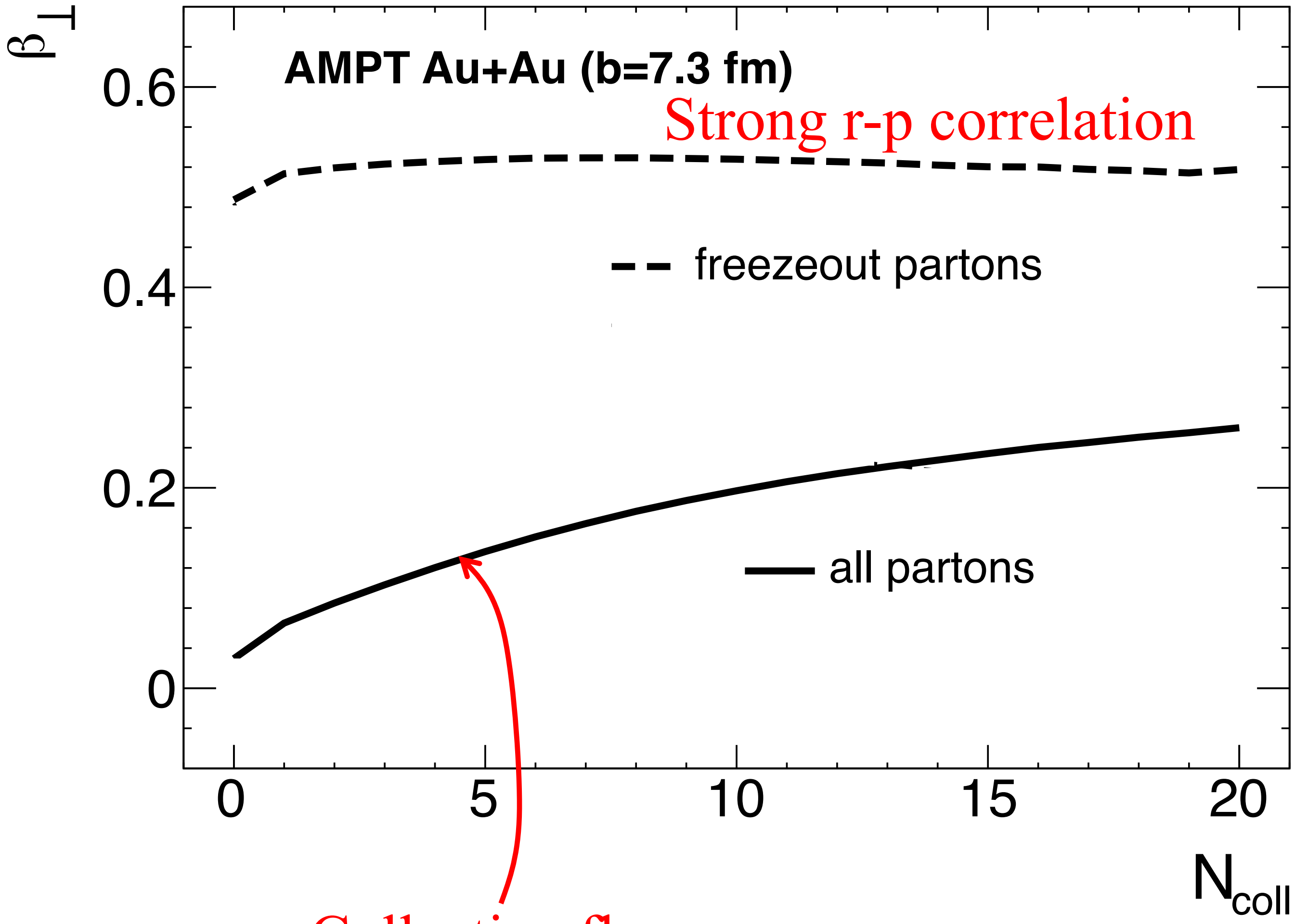


The escape mechanism: flavour dependence

Space-momentum correlation:
~ transverse flow velocity

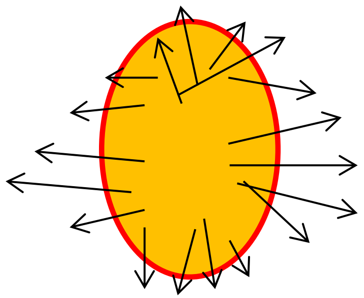
$$\beta_{\perp} = \left\langle \frac{\vec{r}_{\perp} \cdot \vec{p}}{r_{\perp}\ p} \right\rangle$$

He et al. PLB753 (2016)



Strong r-p correlation

~ Collective flow



The escape mechanism: flavour dependence

Space-momentum correlation:
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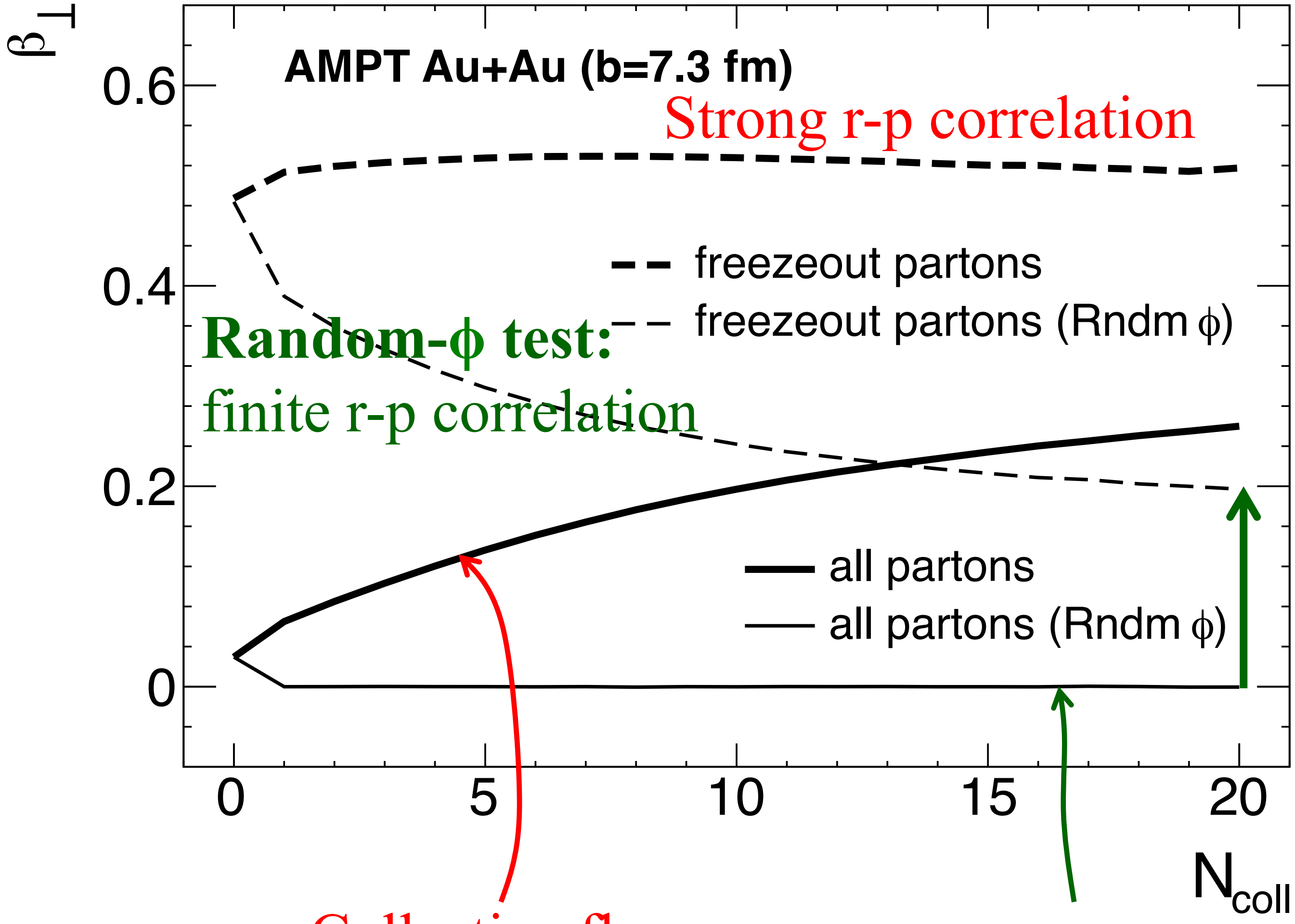
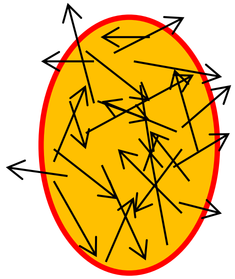
He et al. PLB753 (2016)



Strong r-p correlation

Random-φ test:
finite r-p correlation



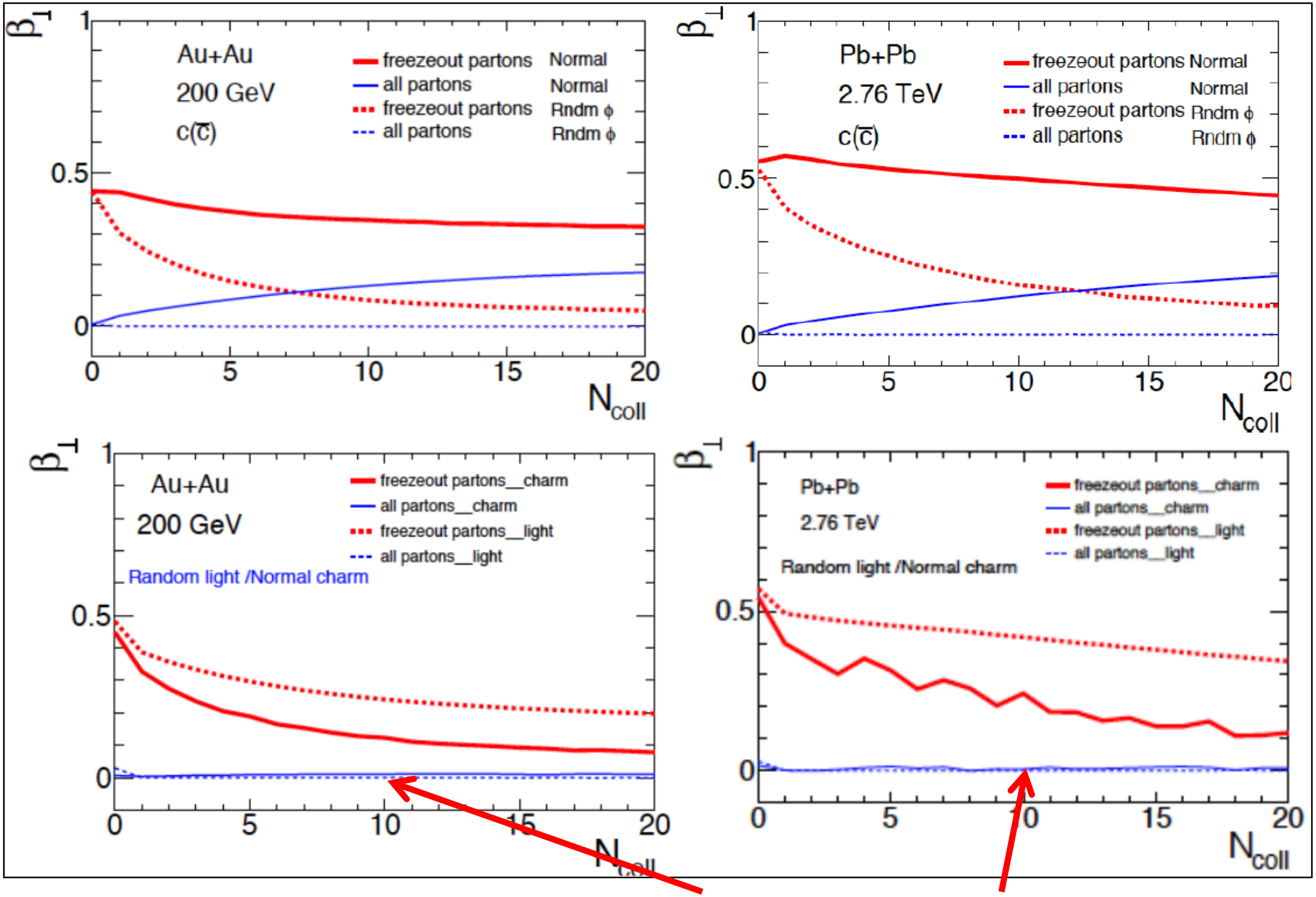
r-p correlation
purely from
escape mechanism,
not from collective flow

~ Collective flow

Collective flow is destroyed

The escape mechanism: flavour dependence

Space-momentum correlation:



Random-ϕ light / Normal charm:

all partons_charm's correlation ~=0 :

➔ charm cannot "flow" without light quark flow

(although charm still interacts a lot with random-ϕ light quarks).

The escape mechanism: flavour dependence

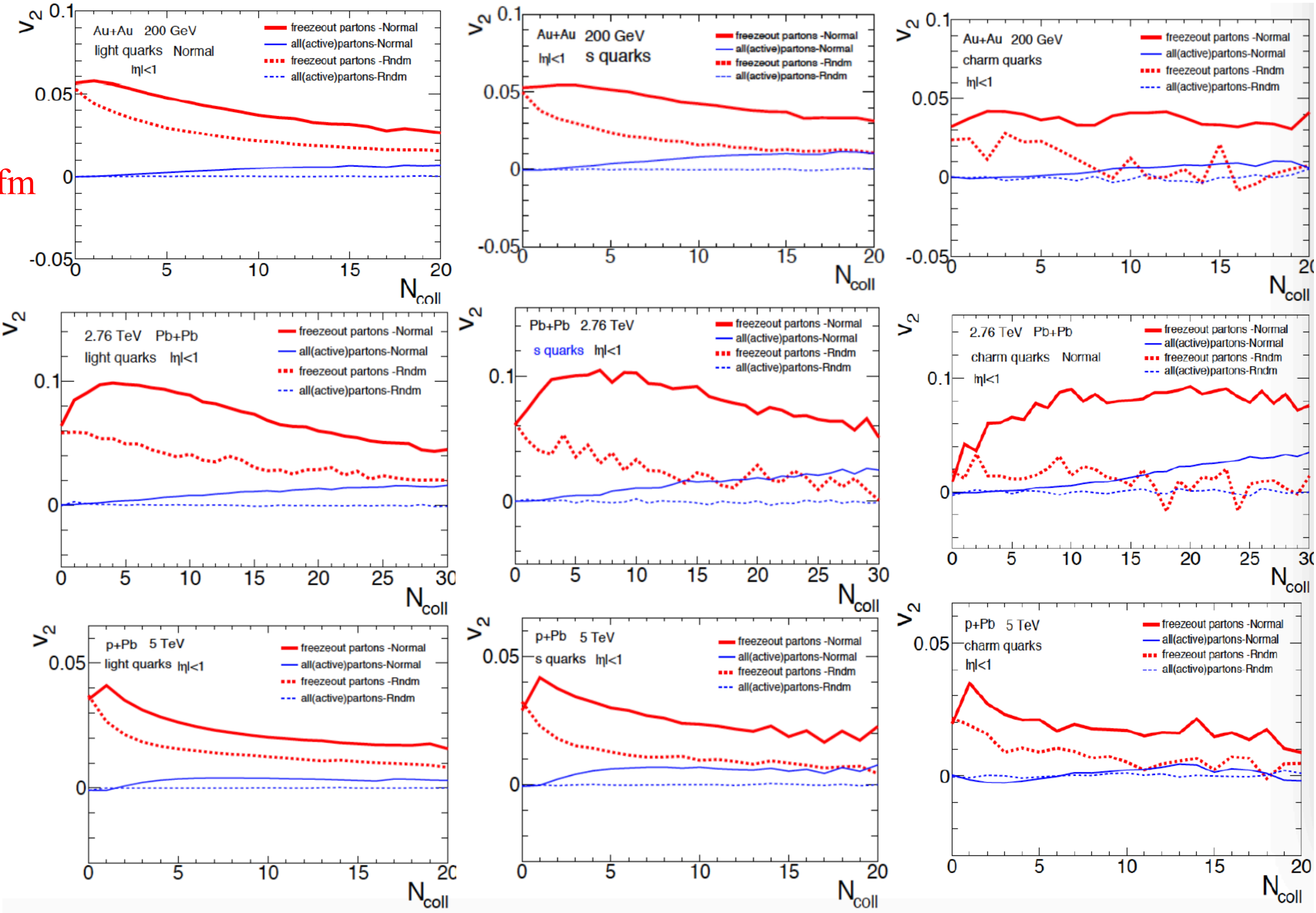
Analysis is done for 3 systems:

u/d s c

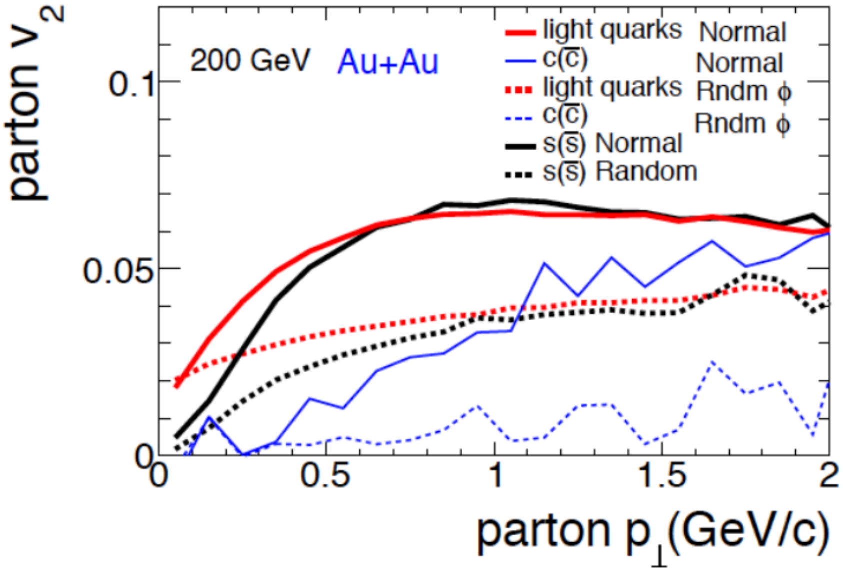
Au+Au
200GeV
b:6.6-8.1fm

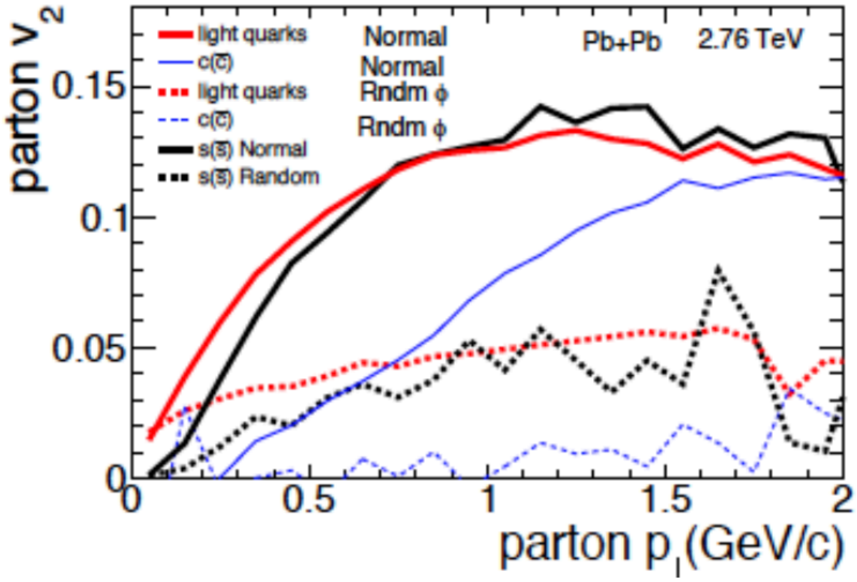
Pb+Pb
2.76TeV
8fm

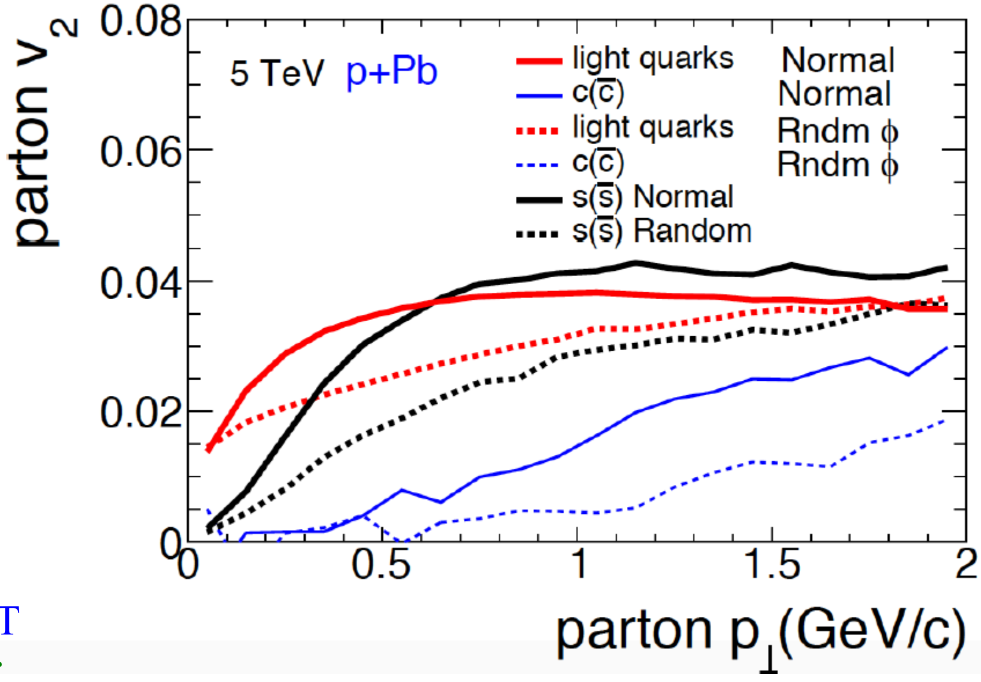
p+Pb
5TeV
0fm



The escape mechanism: flavour dependence







v2(P_T):

mass ordering at low P_T

this is partly responsible for
the mass ordering of hadron v2

H.L. Li et al. PRC 93 (2016); arXiv:1604.07387

The escape mechanism: flavour dependence

No pt cut	**pPb** b=0fm	**AuAu** b=6.6-8.1fm	**PbPb** b=8fm
light	<Ncoll>= 2.02 <v2>Rndm= 2.392% <v2>Norm= 3.279% <v2>Rndm/<v2>Norm **=72.9%**	<Ncoll>= 4.5 <v2>Rndm= 2.931% <v2>Norm= 4.468% <v2>Rndm/<v2>Norm **=65.6%**	<Ncoll>= 9.82 <v2>Rndm= 3.214% <v2>Norm=7.562% <v2>Rndm/<v2>Norm **=42.5%**
s-quark	<Ncoll>= 2.54 <v2>Rndm=1.894% <v2>Norm=3.203% <v2>Rndm/<v2>Norm **=59.1%**	<Ncoll>= 5.45 <v2>Rndm= 2.266% <v2>Norm= 4.784% <v2>Rndm/<v2>Norm **=47.4%**	<Ncoll>= 11.14 <v2>Rndm= 2.23% <v2>Norm= 8.424% <v2>Rndm/<v2>Norm **=26.5%**
c-quark	<Ncoll>= 4.23 <v2>Rndm=1.214% <v2>Norm=2.139% <v2>Rndm/<v2>Norm **=56.8%**	<Ncoll>= 8.6 <v2>Rndm=0.8455% <v2>Norm=3.885% <v2>Rndm/<v2>Norm **=22%**	<Ncoll>= 15.48 <v2>Rndm=0.6724% <v2>Norm=7.923% <v2>Rndm/<v2>Norm **=8.5%**

q

Q

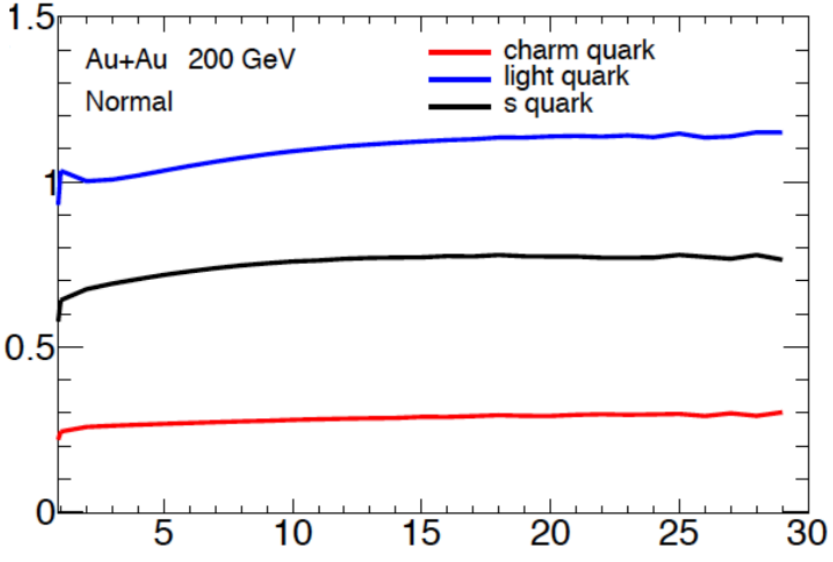
System size/energy

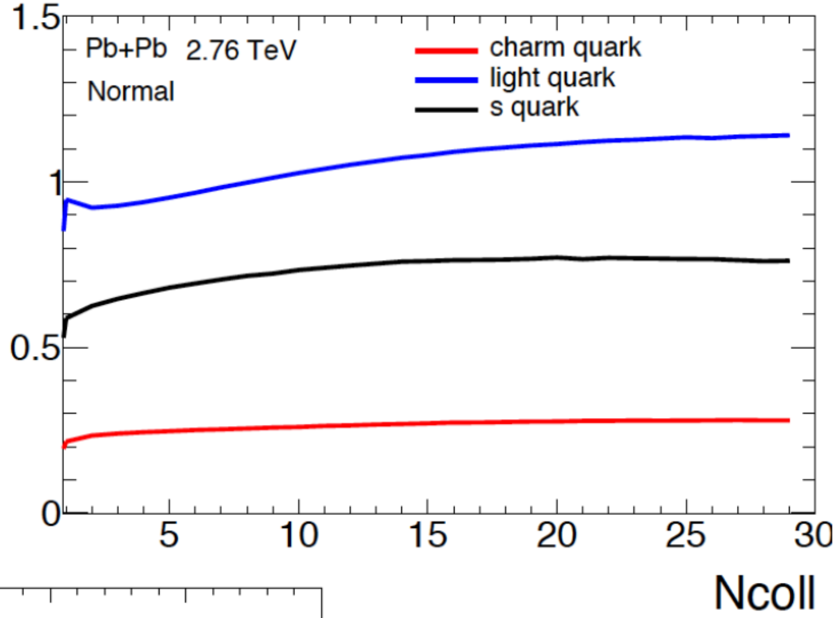
Less from escape /
more from collective flow

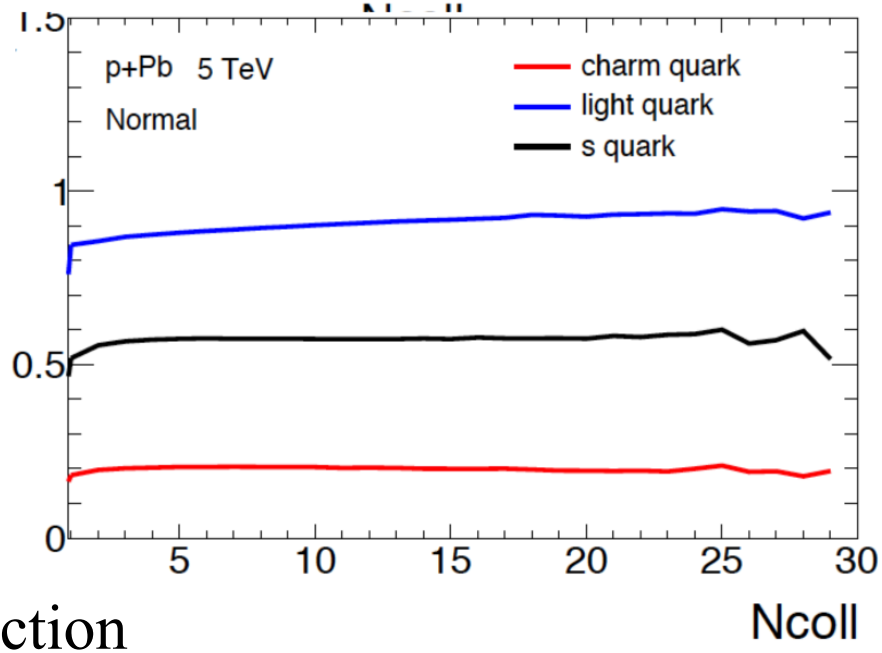
The escape mechanism: flavour dependence

Δφ: change of azimuth due to one collision (the Ncoll-th collision):

<Δφ>







Mass ordering on parton deflection angle:
it takes more collisions
to deflect a heavier quark,
so light quark flow
& strong light-charm interaction
are essential to generate significant charm v2.

The escape mechanism: flavour dependence

$\langle v_2 \rangle_{\text{random-}\phi} / \langle v_2 \rangle_{\text{normal}}$ ratio

~ fraction from pure escape:

	dAu@200GeV b=0 fm	pPb@5TeV b=0 fm	AuAu@200GeV b=6.6-8.1 fm	PbPb@2.76TeV b=8 fm
u/d	93%(all quarks)	72.9%	65.6%	42.5%
s		59.1%	47.4%	26.5%
c		56.8%	21.8%	8.5%

v2 of charm quarks in AuAu@RHIC-200GeV & PbPb@LHC:

mostly comes from collective flow (not the escape mechanism).

➔heavy quarks are more sensitive probes of collective flow & the medium.

Esha, Md. Nasim & Huang, JPG44 (2017)

v2 of light quarks:

escape mechanism is more important for AuAu@RHIC, pPb@LHC and smaller/lower-energy systems;

hydro-type collective flow is more important for PbPb@LHC although with significant contribution from the escape mechanism.

Future heavy flavour work with AMPT

Up-to-date proton parton distribution function & nuclear shadowing

needed for heavy flavors and high-P_T

ongoing with L. Zheng, S.S. Shi, C. Zhang at CCNU

Include gluons & inelastic parton interactions

- Include gluons in string melting initial condition in addition to quarks/antiquarks *planned*
- Include 2-2 inelastic parton reactions: gg ←→ ssbar / ccbar, qqbar ←→ ssbar / ccbar, … *ongoing*
- Include gluons in a coalescence/recombination model with energy momentum conservation *planned*

For high P_T:

- Parton radiative energy loss *planned*

Summary

AMPT aims to serve as a comprehensive transport model for heavy ion collisions:

event-by-event from initial condition to final observables;
include particle productions and interactions at different y & P_T;
conserve energy/momentum/flavour/charge (ongoing work) of each event;
keep non-equilibrium dynamics & intrinsic fluctuations/correlations.

We have followed the complete parton collision history to study
v2 of light/strange/charm quarks in AMPT:

v2 of charm quarks in AuAu@200GeV & PbPb@2.76TeV
mostly comes from collective flow (not the escape mechanism),
indicating that heavy quarks are more sensitive probes of the medium.
v2 of light quarks at AuAu@200GeV & pPb@LHC
come mostly from the escape mechanism ,
but at PbPb@2.76TeV comes more from collective flow
(although still with significant fraction from the escape mechanism).

We are working to improve AMPT on heavy flavours,
to simultaneously study light flavours, heavy flavours including their interactions.