Heavy Quark Flows as Better Probes of QGP Properties

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Based on Hanlin Li, ZWL, Fuqiang Wang, in preparation;
and
ZWL's talk at Strange Quark Matter 2017

Outline

- Introduction of a multi-phase transport (AMPT) model
- Anisotropic parton escape: *a brief review*
- Anisotropic parton escape: *flavour dependence*
- Summary

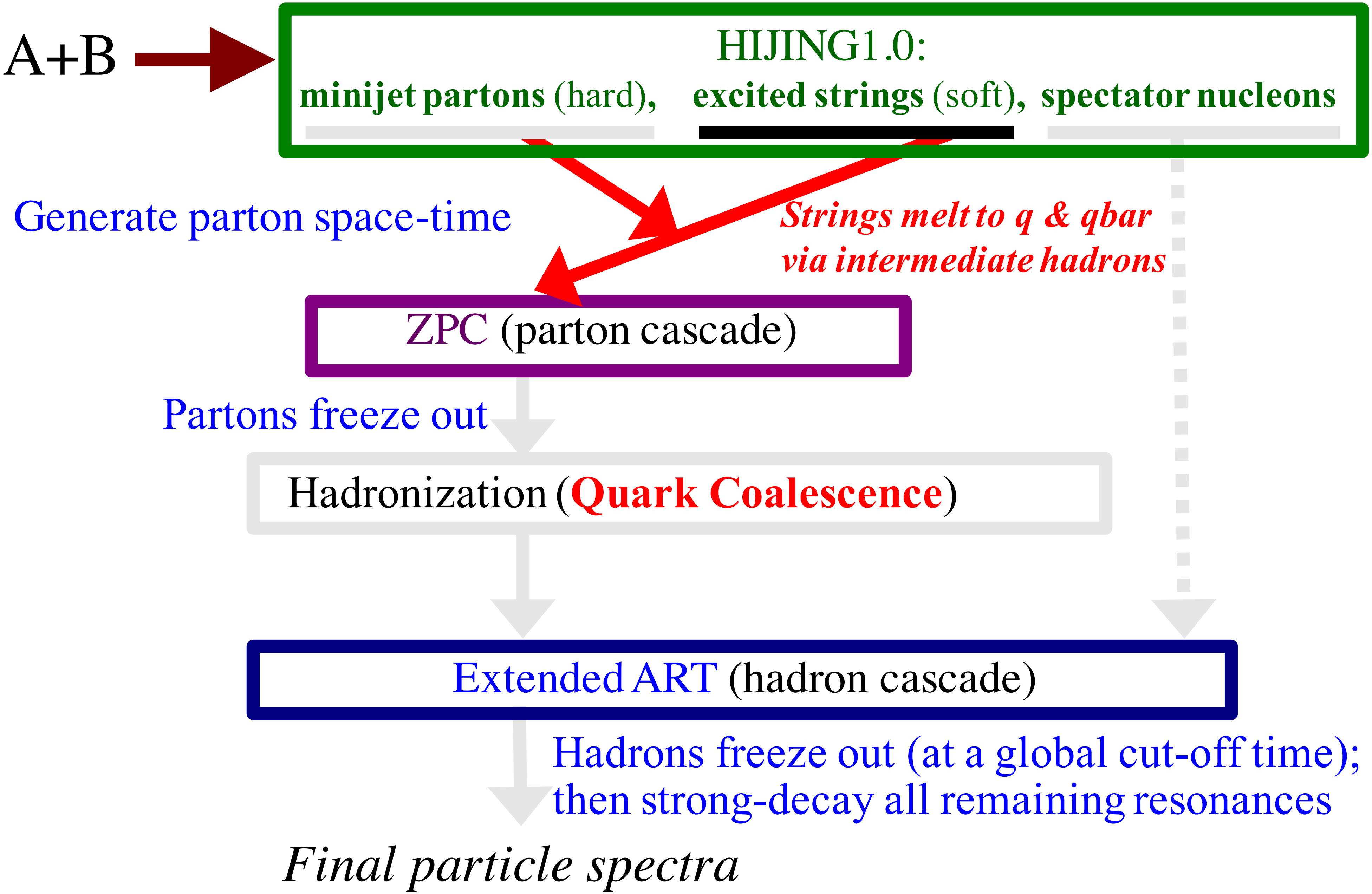
For comprehensive simulations of high energy heavy ion collisions

We need:	**Choices:**
Initial particle/energy production	***Soft+hard model (such as HIJING)***, *CGC, pQCD, ...*
Pre-equilibrium interactions: *equilibration, thermalization, initial flow*	*Parton cascade (**ZPC**, MPC, BAMPS), NJL, CGC, AdS/CFT, …*
Space-time evolution of QGP	*Parton cascade (**ZPC**, MPC, BAMPS), NJL, (ideal, viscous, anisotropic) hydrodynamics, ...*
Hadronization /QCD phase transition	***Quark coalescence/parton recombination, string fragmentation**, Cooper-Frye, statistical hadronization, independent fragmentation, rate equations, ...*
Hadronic interactions	*Hadron cascade (**ART**, RQMD, UrQMD, ...), thermal model (w/ freezeout temperatures), …*

The AMPT model currently includes the ***green*** components for each phase.

ZWL et al. PRC72 (2005).

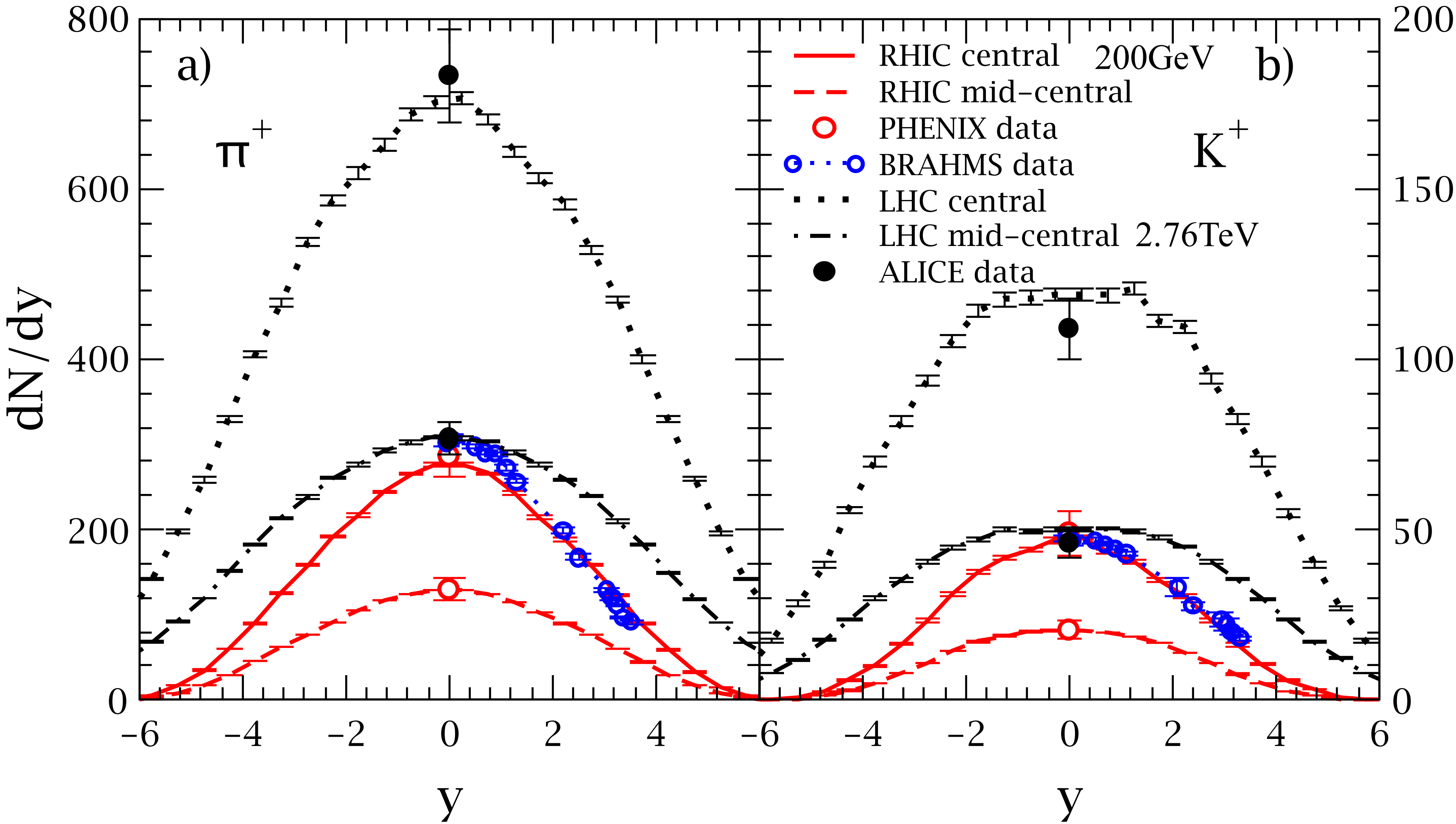
Structure of AMPT v2.xx (String Melting version)



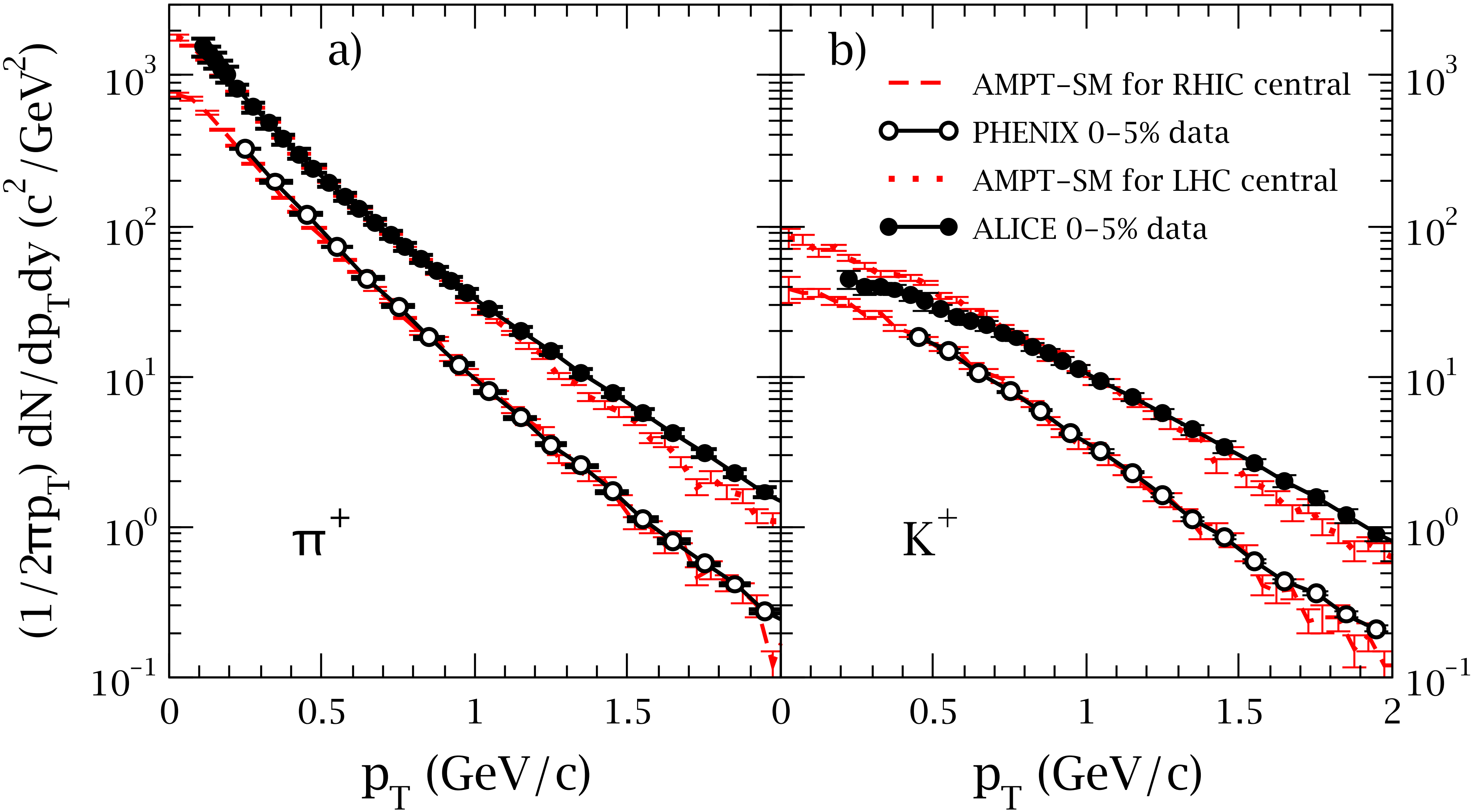
Now the String Melting AMPT can reasonably describe the bulk matter at high energies at RHIC and LHC.

dN/dy of π & K:

ZWL, PRC 90 (2014)

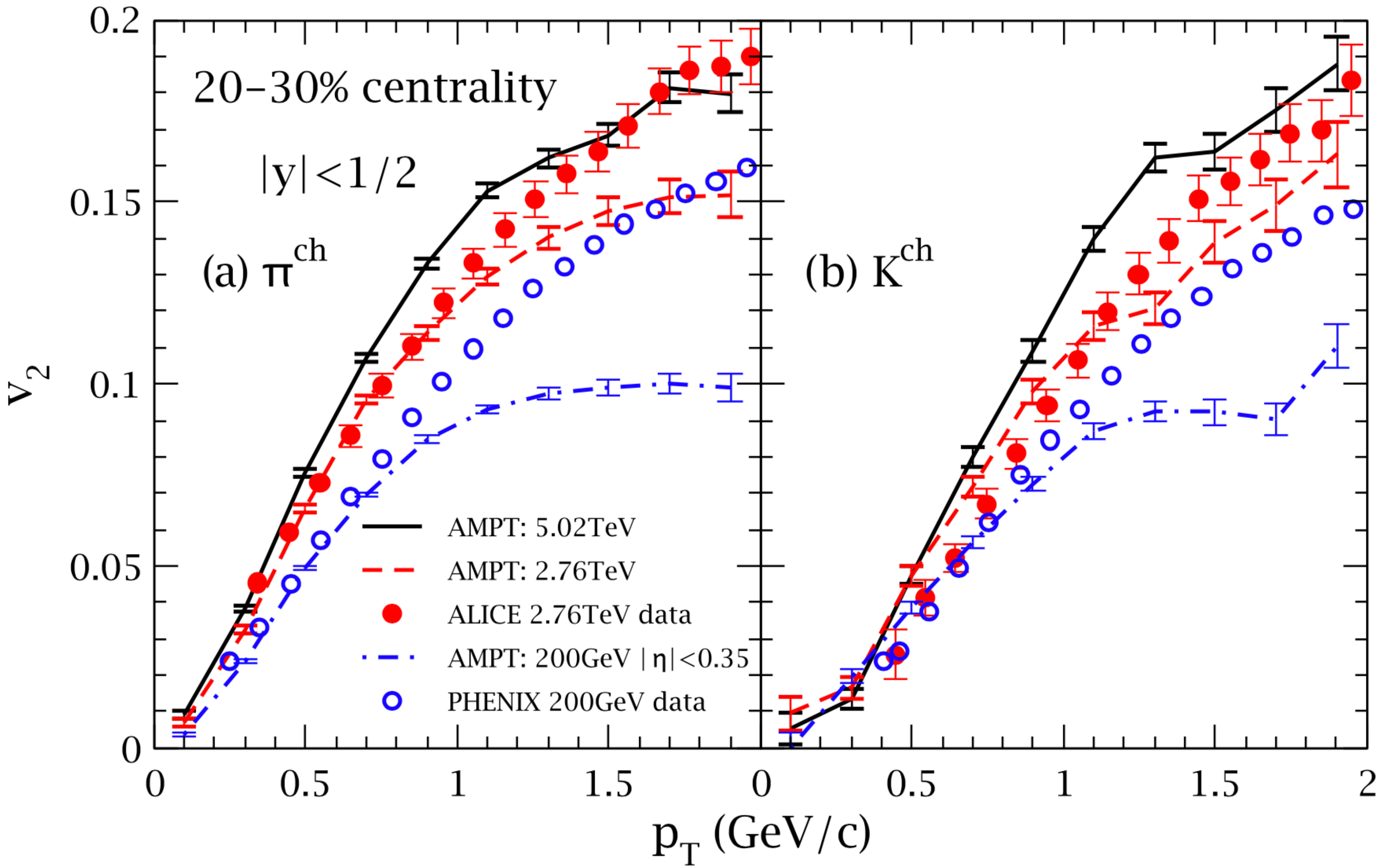


p_T -spectra of π & K (in central collisions): ZWL, PRC 90 (2014)

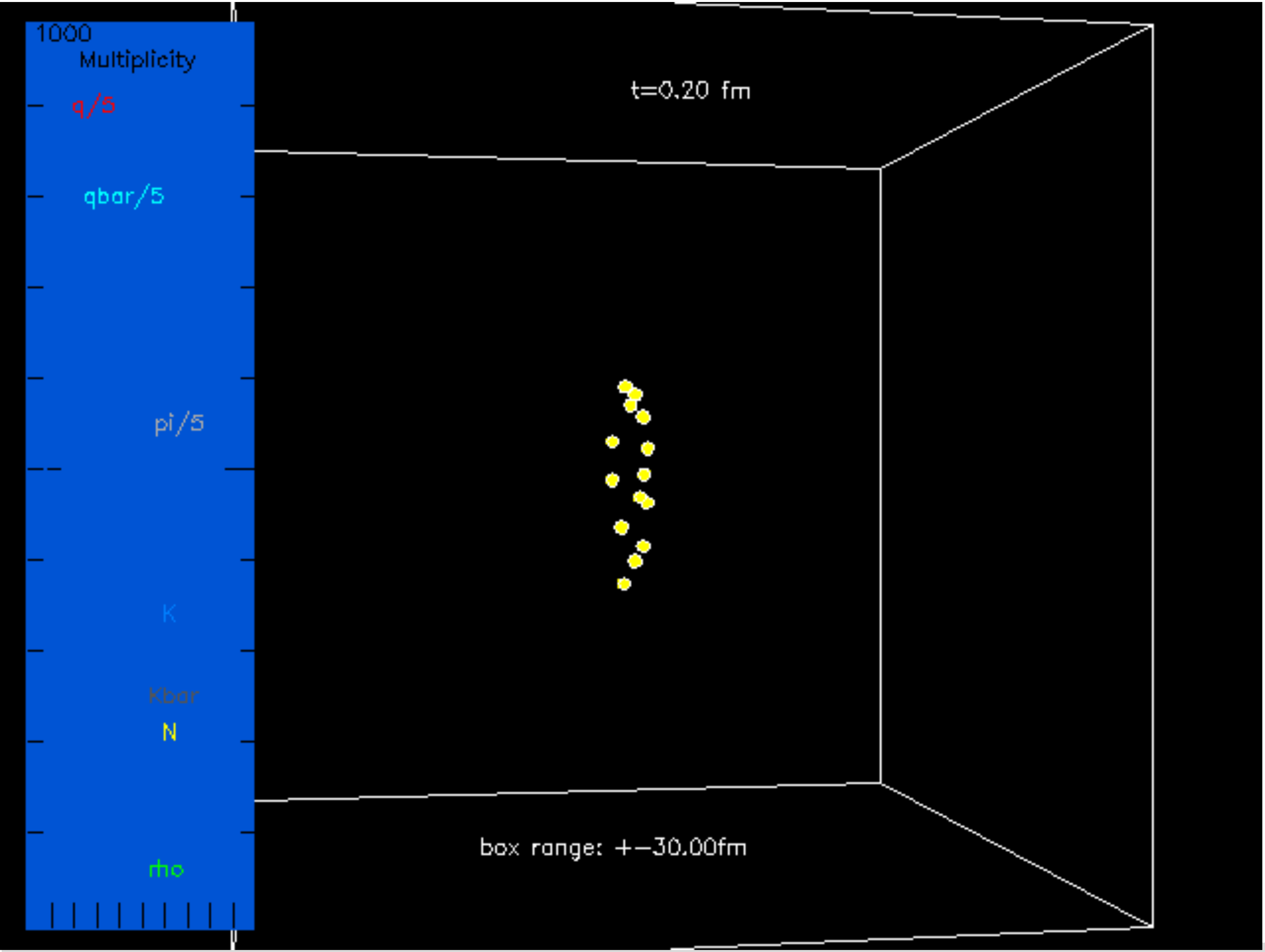


v_2 of π & K (in mid-central collisions):

Guo-Liang Ma & ZWL, PRC 93 (2016)



One central Au+Au event at 200AGeV from String Melting AMPT

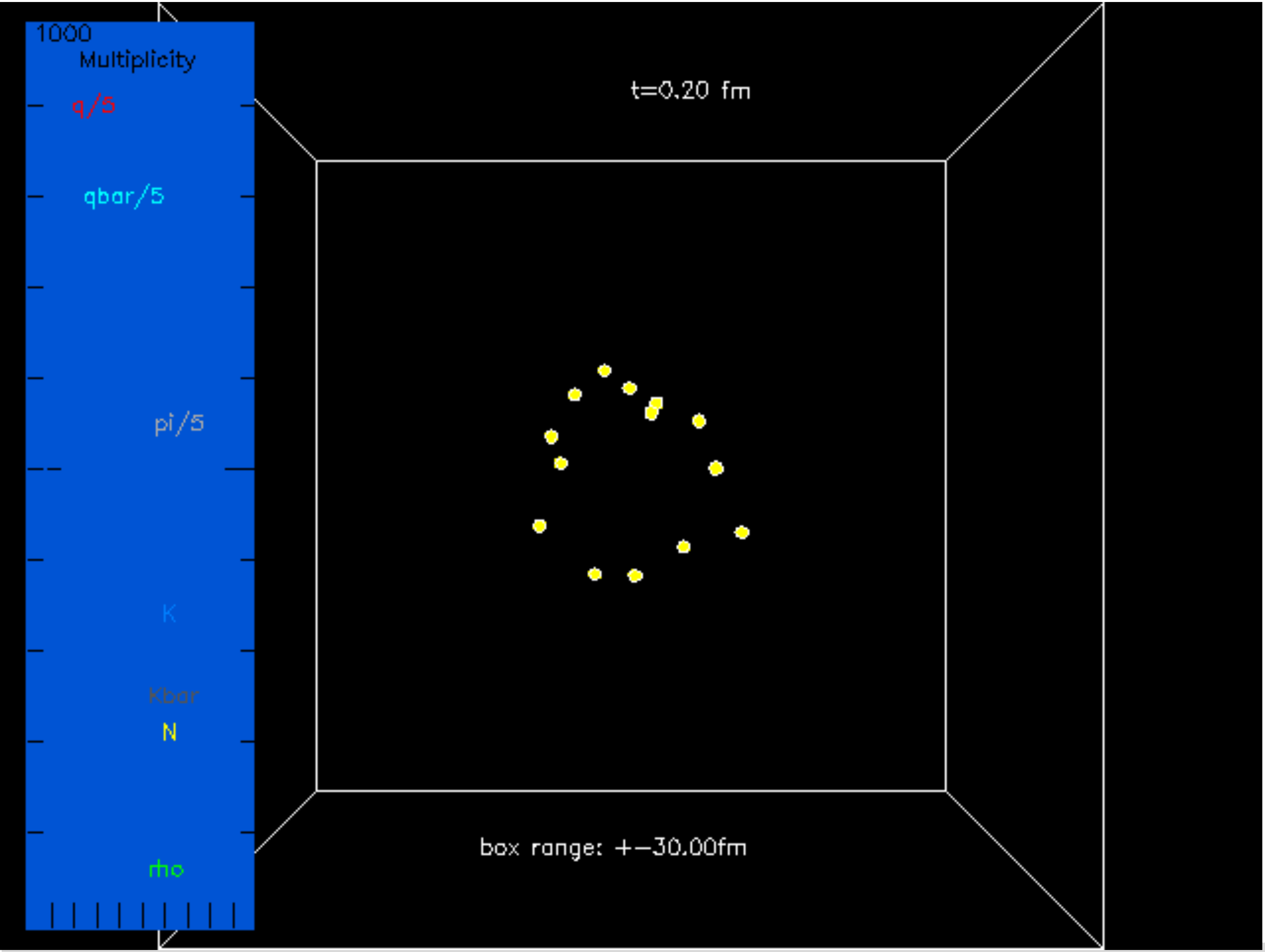


60-fm box

Side view:

Beam axes

The same Au+Au event *from a different viewpoint*



Front view:

⊙

Beam axis

Current and previous public versions of AMPT are available at

http://myweb.ecu.edu/linz/ampt/

myweb.ecu.edu/linz/ampt/

AMPT source codes

(updated October 28, 2016):

A Multi-Phase Transport (AMPT) model is a Monte Carlo transport model for nuclear collisions at relativistic energies.
Each of the following versions contains:
the source codes, an example input file, a Makefile, a readme, a required subdirectory for storing output files, and a script to run the code.

1. ampt-v1.11-v2.11.tgz (11/2004)
2. ampt-v1.21-v2.21.tgz (10/2008)
3. ampt-v1.25t3-v2.25t3.tgz (8/2009)
4. ampt-v1.25t7-v2.25t7.zip (9/2011)
5. ampt-v1.25t7d-v2.25t7d.zip (4/2012)
6. ampt-v1.26t1-v2.26t1.zip (9/2012)
7. ampt-v1.26t4-v2.26t4.zip (8/2014)
8. ampt-v1.26t5-v2.26t5.zip (4/2015)
9. ampt-v1.26t7-v2.26t7.zip (10/2016)

This readme file lists the main changes up to version v1.26t7-v2.26t7 ("t" means a version under test):

```
AMPT Users' Guide

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
5/2016 test version v1.26t7/v2.26t7:
     * (w/ GL Ma) Changed the following line in art1f.f to avoid the bug
```

The escape mechanism: *a brief 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.

It has been generally believed that:

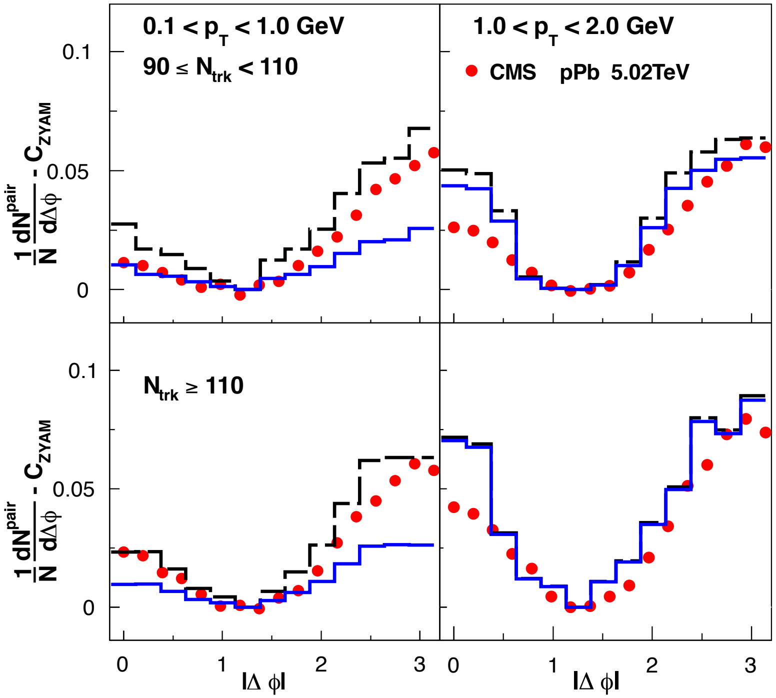
- Transport models at large-enough cross section will approach hydrodynamics.

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

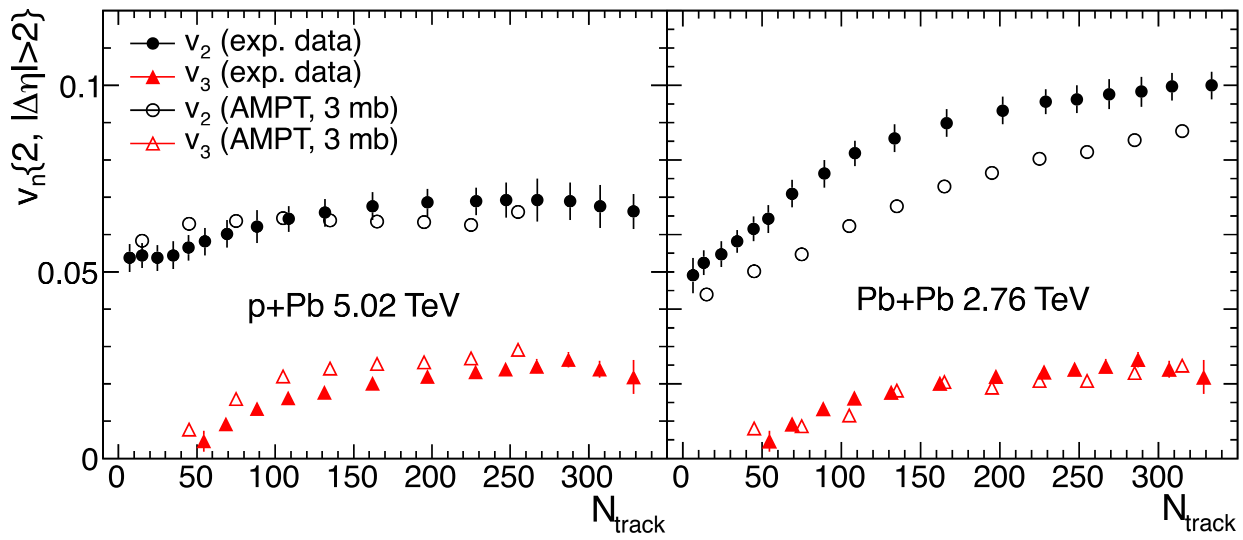
- For low-P_T particles in high-energy heavy ion collisions,
since both hydrodynamics and transport models can describe v_n data,
the mechanism of v_n development in transport models *(via particle interactions)*
is in principle the same as in hydrodynamics *(via pressure gradients)*.

The escape mechanism: *a brief 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).

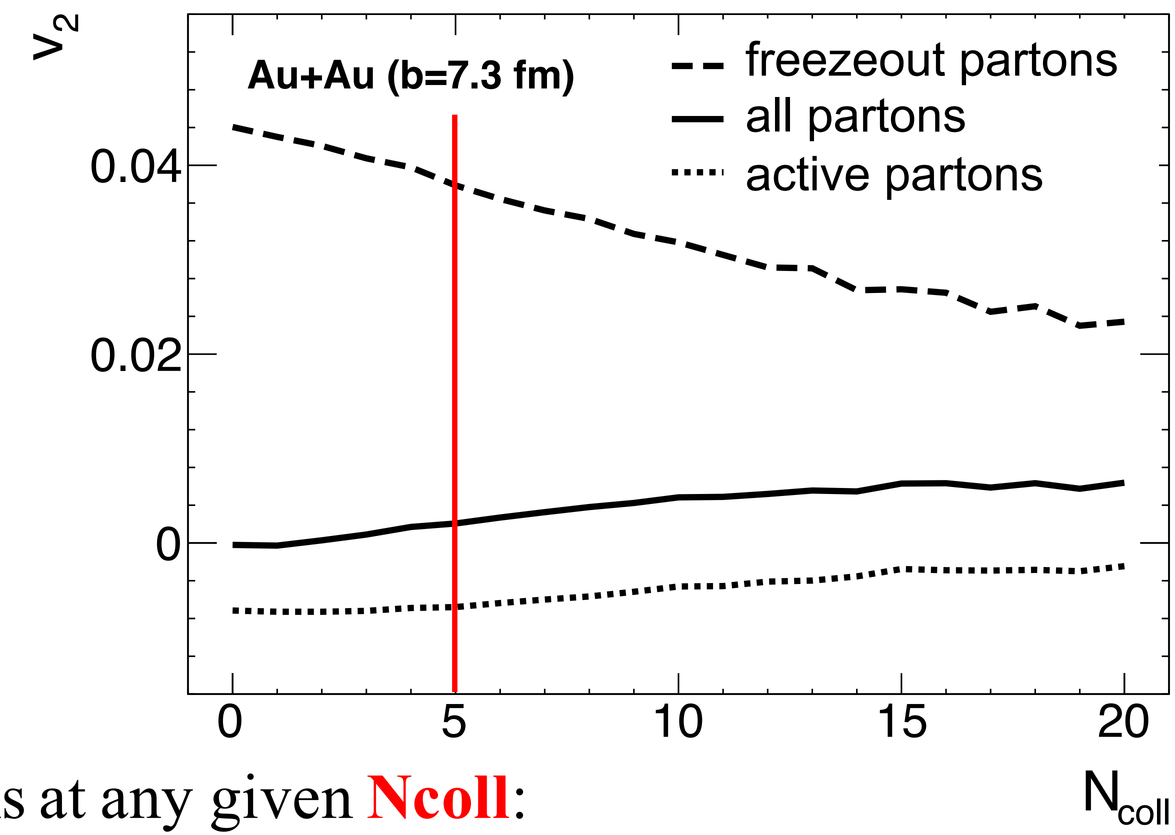
Questions for small systems such as p+Pb or d+Au:

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

The escape mechanism: *a brief review*

We have followed the complete parton collision history and study the generation of parton v2 in AMPT. He et al. PLB753 (2016)

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



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

freezeout partons: *freeze out/hadronize 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: *a brief review*

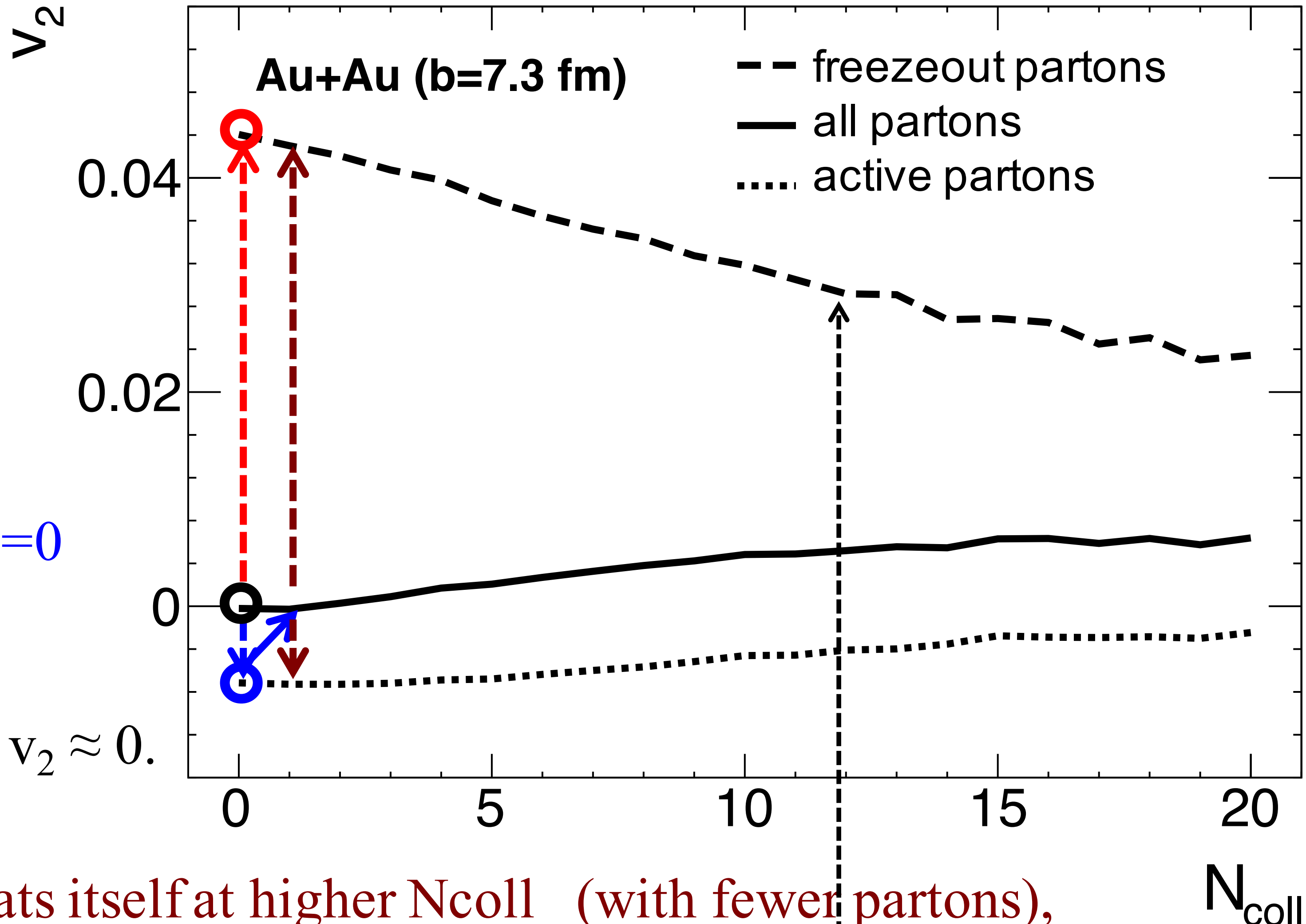
At Ncoll=0:

all partons: $\mathbf{v_2=0}$ by symmetry (*since they include all initial partons*);

they contain 2 parts:

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 at different Ncoll.

The escape mechanism: *a brief review*

At Ncoll=0:

freezeout partons: $v_2 \approx 4.5\%$,

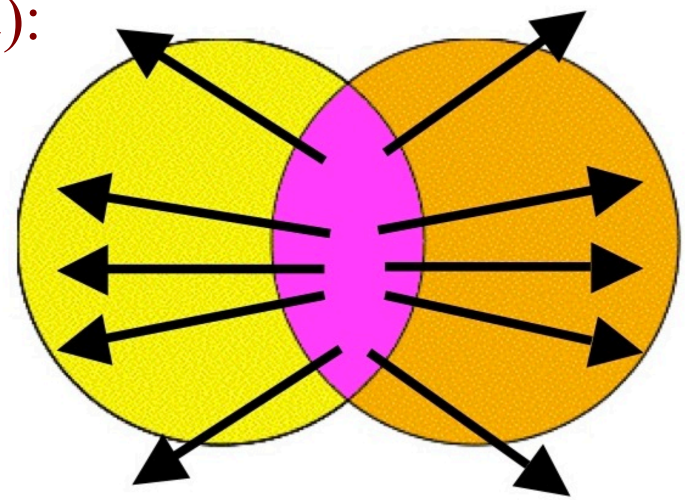
this is **purely** due to the

anisotropic escape probability (*escape mechanism*):

interaction-induced response to geometrical shape,

no contribution from collective flow.

In event-averaged picture of elliptic flow:



At Ncoll>=1:

freezeout partons: $v_2 > 0$

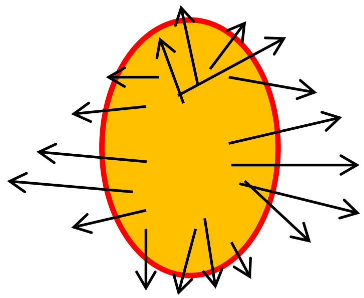
due to

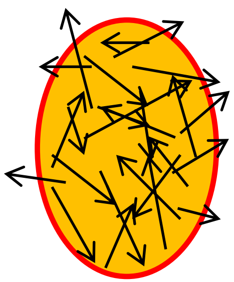
anisotropic escape probability

& (anisotropic) **collective flow**.

How to separate the two contributions?

We design a **Random-ϕ Test** (destroy collective flow but keep the anisotropic shape):

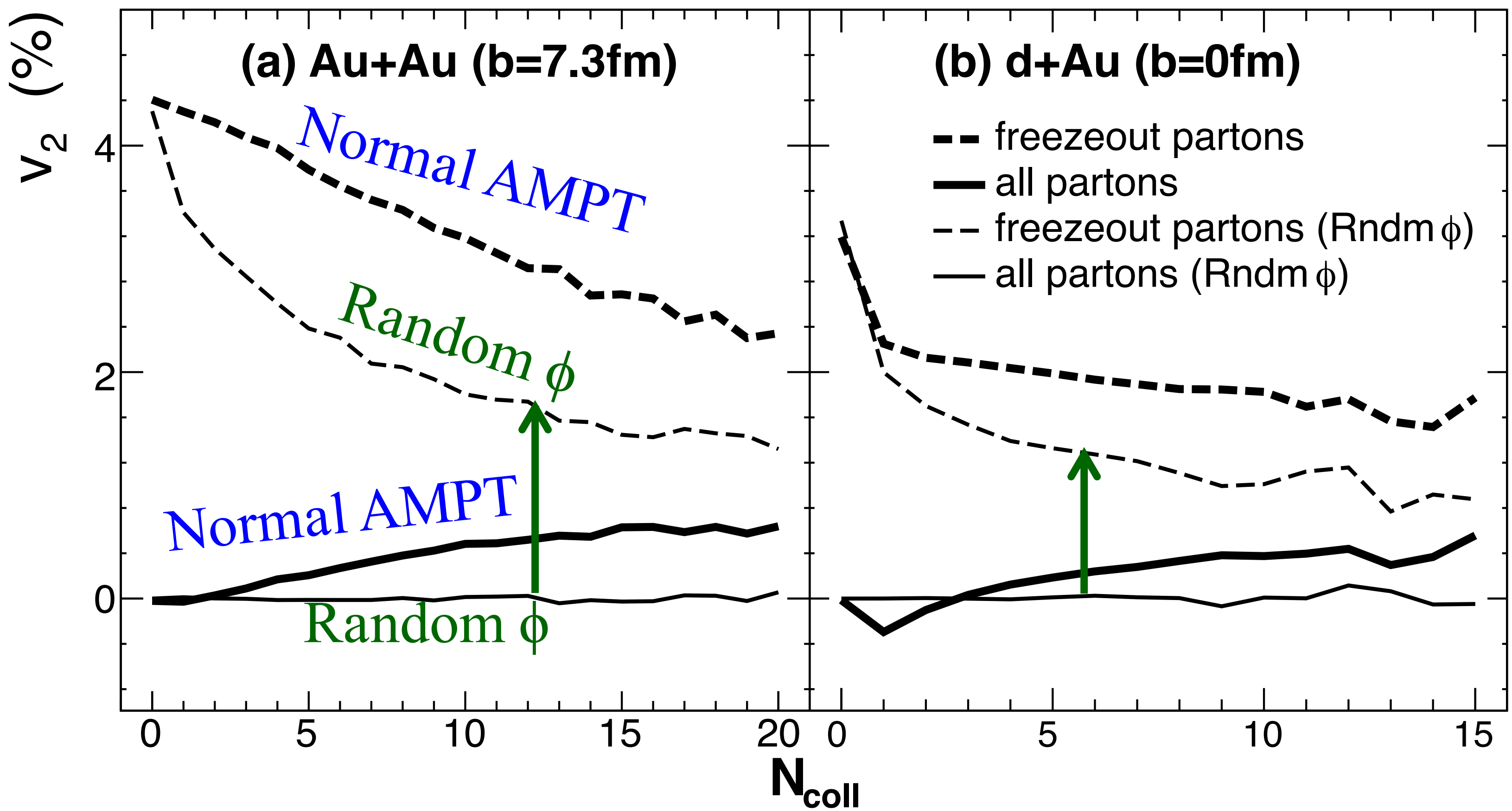
Normal: 

Random: 

The escape mechanism: *a brief 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** of random/normal ~ 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: *a brief review*

Elliptic anisotropy v_2 may be dominated by particle escape instead of hydrodynamic flow.

Implications:

- The escape mechanism helps to explain similar anisotropic flows observed in small and large systems:

since both are dominated by the 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-to-modest** opacity or <Ncoll>:
  transport and hydrodynamics are different;
  the escape mechanism dominates v_n.
- At **very high** opacity or <Ncoll>:
  transport and hydrodynamics are similar;
  hydro-type collective flow dominates v_n.

The escape mechanism: *flavour dependence*

These previous results are for **all quarks @200 GeV**.

Q:
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.
Hanlin Li, ZWL, Fuqiang Wang, in preparation.

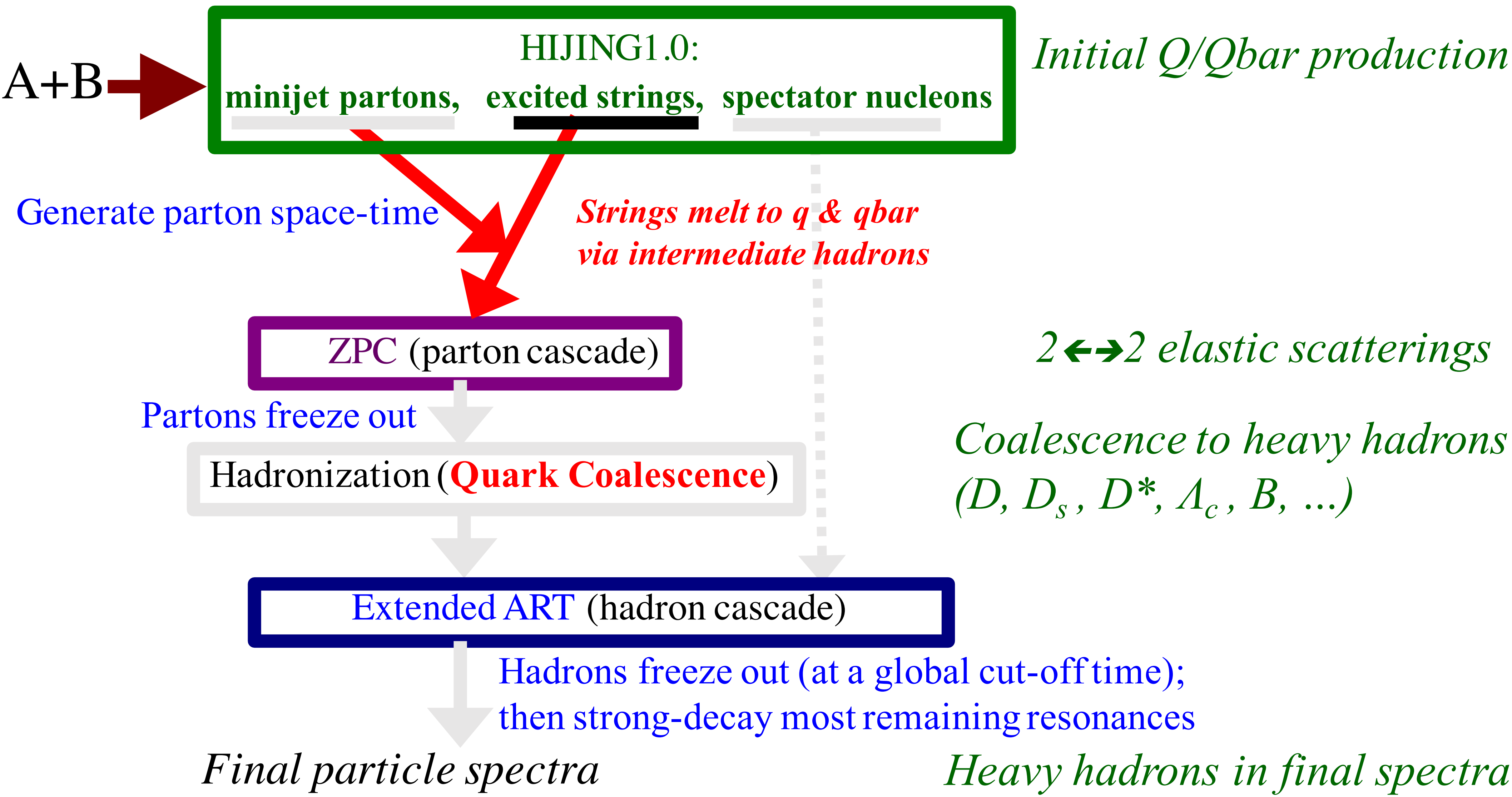
3mb parton cross section is used since it reproduces pi/K/p $v_2(P_T)$.

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

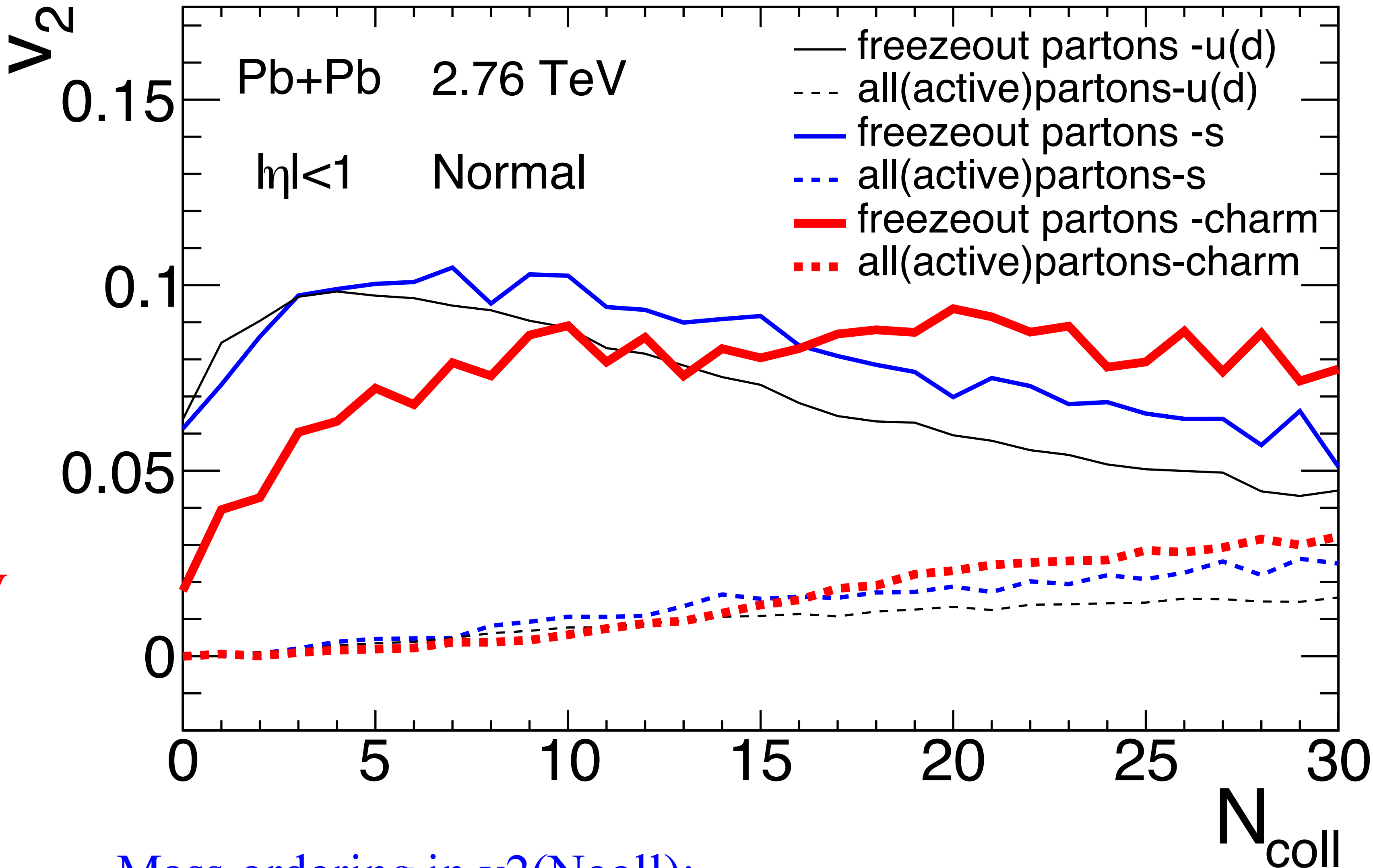
Caveat: here we use the same cross section for all flavours.

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

Structure of AMPT v2.xx (String Melting version)



The escape mechanism: *flavour dependence*



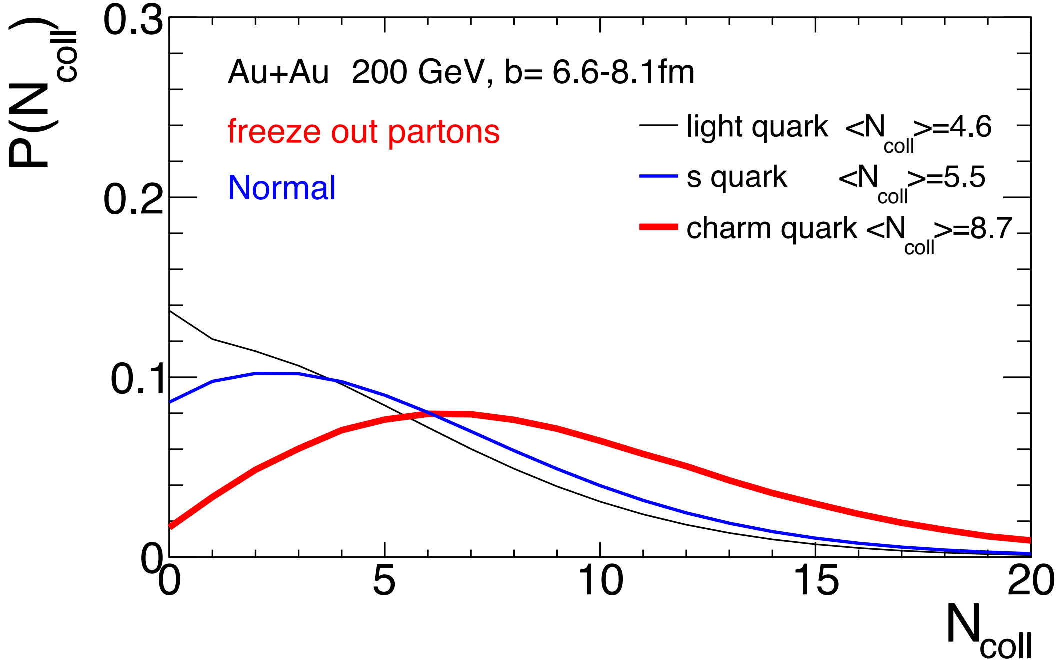
Pb+Pb
2.76TeV
8fm

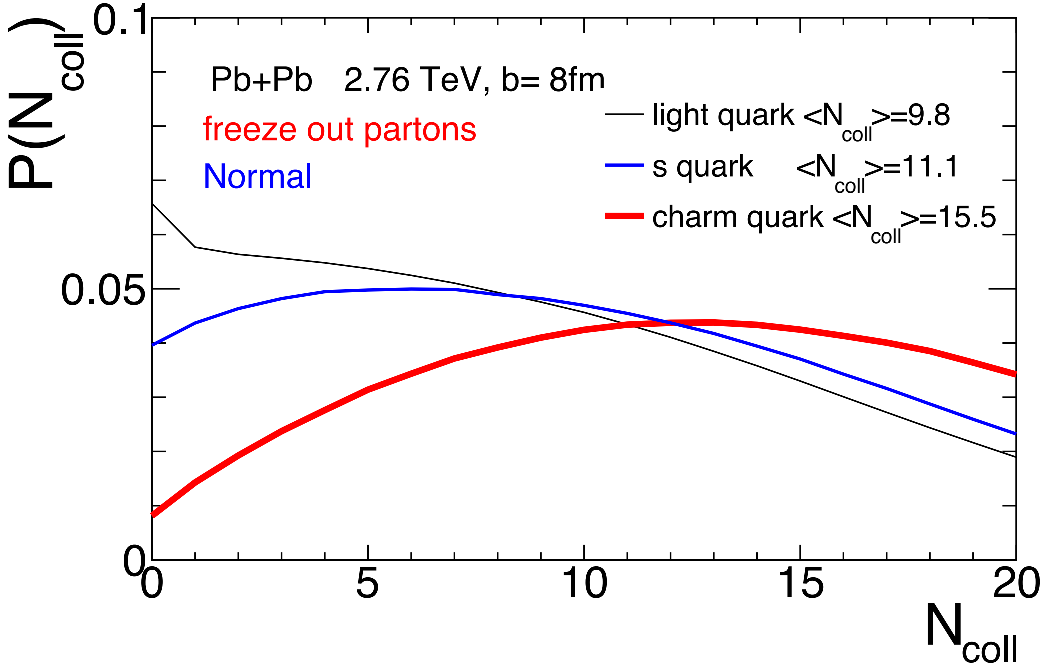
Mass ordering in v2(Ncoll):

v2**c** < v2**s** < v2**ud** at small Ncoll;

reversed: v2**c** > v2**s** > v2**ud** at large Ncoll.

The escape mechanism: *flavour dependence*



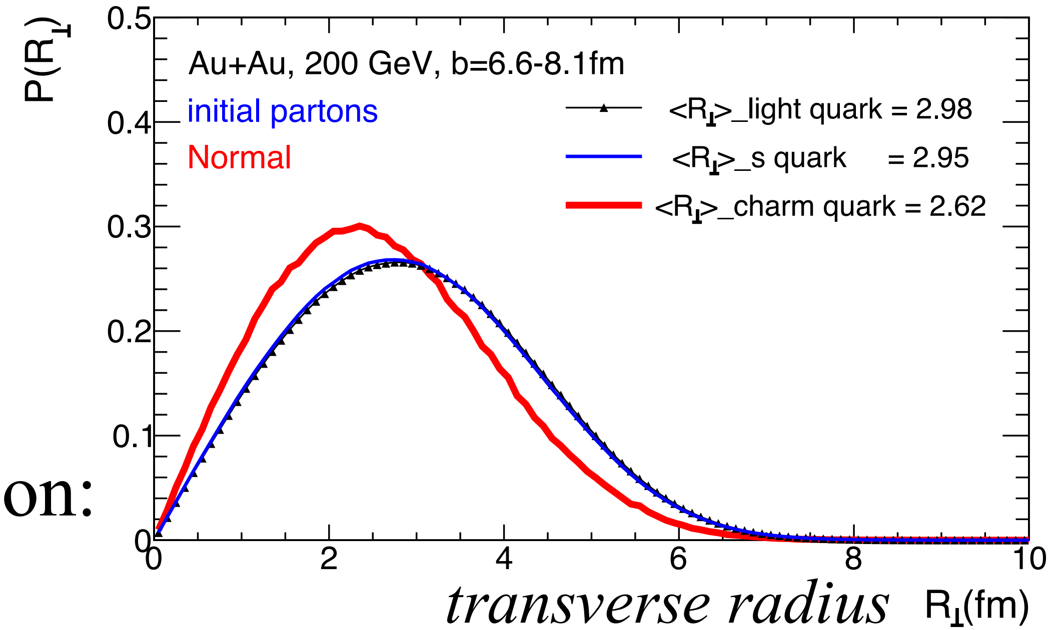


Mass ordering in the Ncoll distribution

for all 3 systems:

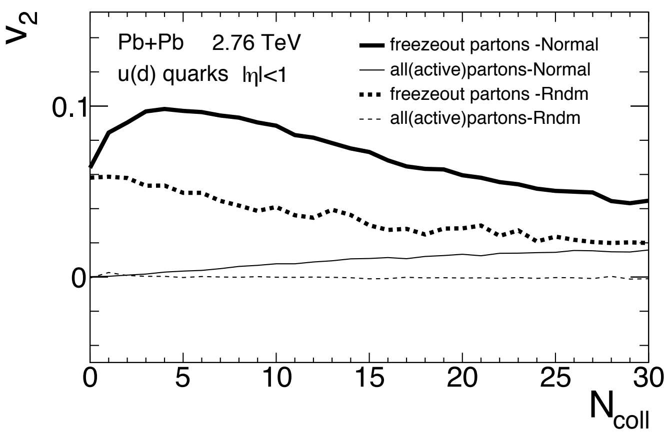
<Ncoll>**c** > <Ncoll>**s** > <Ncoll>**ud**

This is related to the initial (velocity &) spatial distribution:

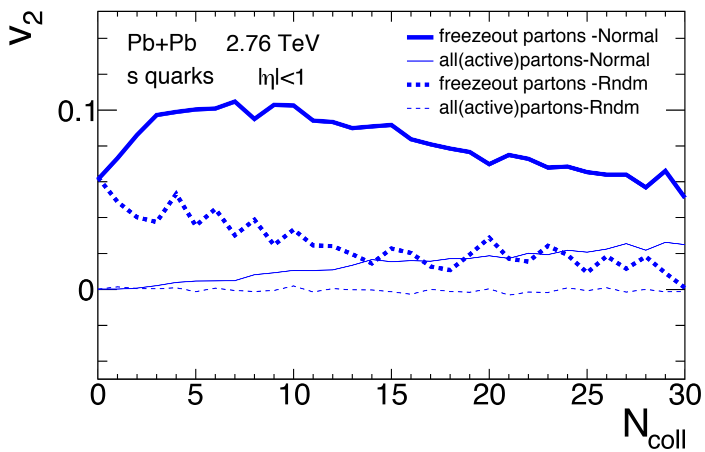


The escape mechanism: *flavour dependence*

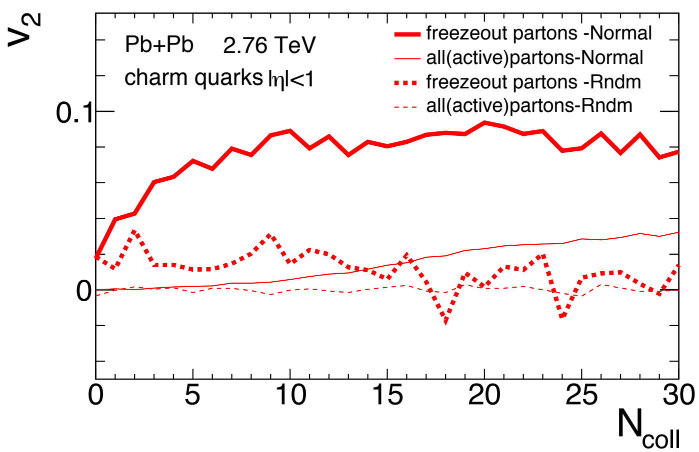
u/d



s



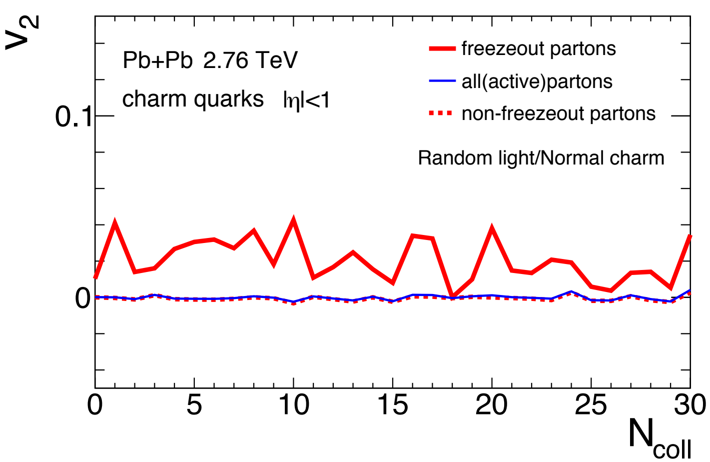
c



Pb+Pb
2.76TeV
8fm

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

We also tested: random-ϕ *for u/d/s quarks only*
(*normal charm:* charm quarks keep their collective flow):
large reduction of charm v2 (like all-flavour random-ϕ test)
➔
light quark collective flow is essential for charm v2



The escape mechanism: *flavour dependence*

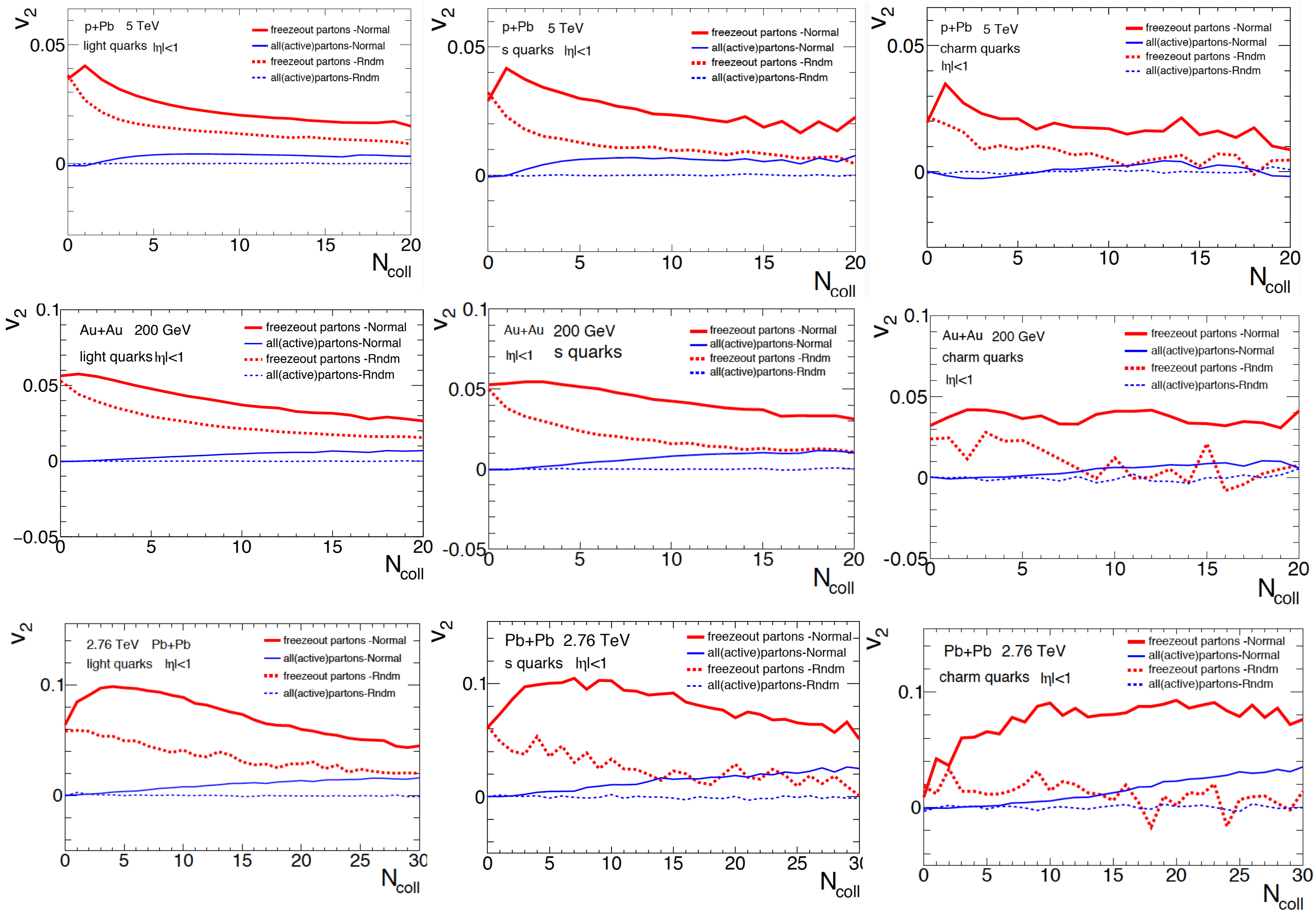
Analysis is done for 3 systems:

u/d | s | c

p+Pb
5TeV
b=0fm

Au+Au
200GeV
6.6-8.1fm

Pb+Pb
2.76TeV
8fm



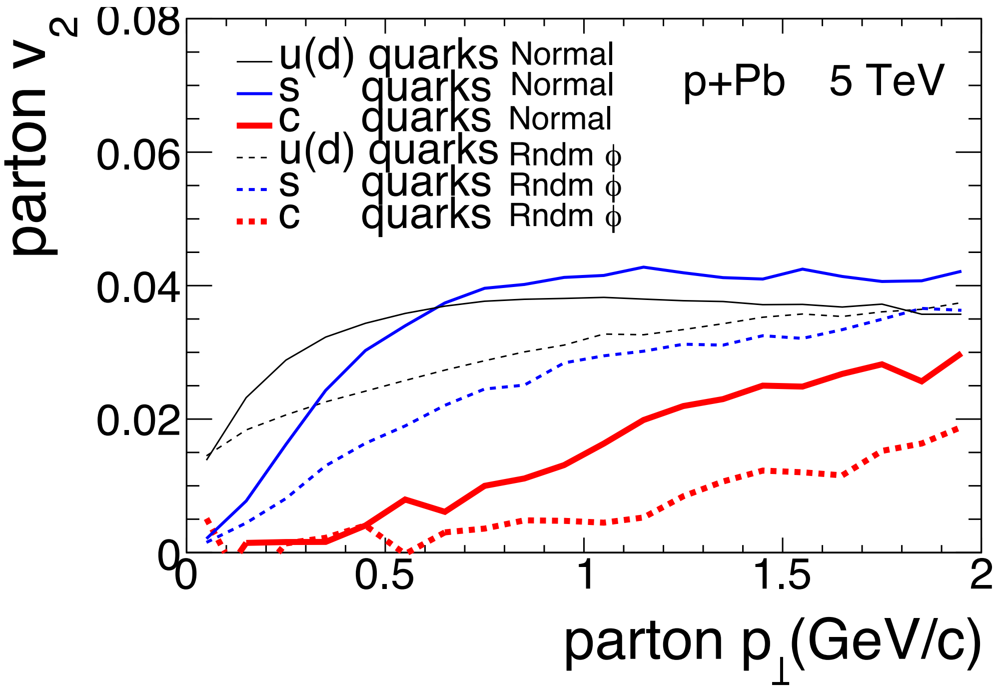
The escape mechanism: *flavour dependence*

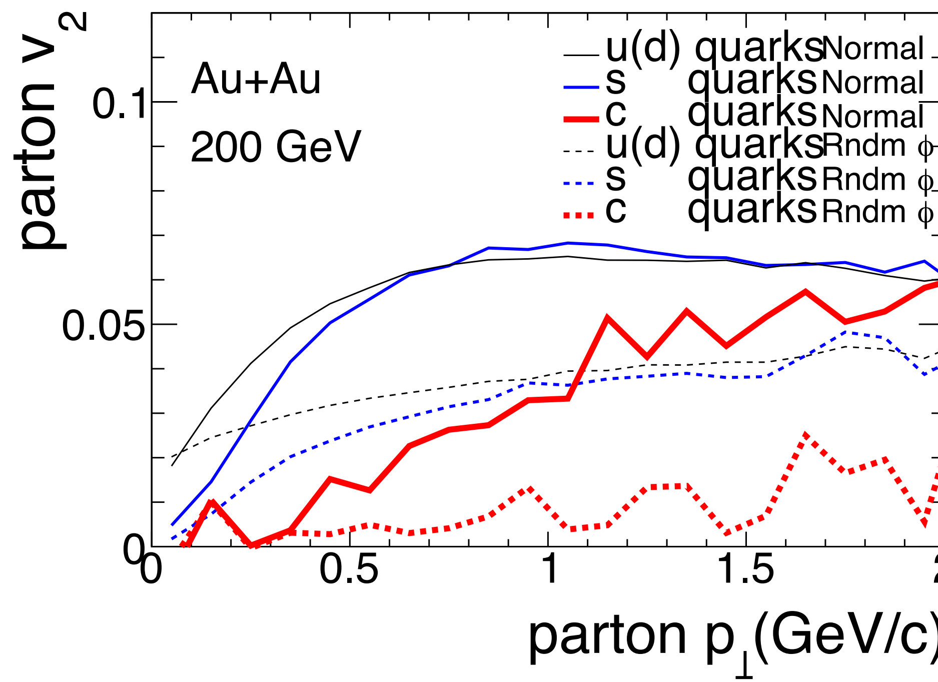
	pPb b=0fm	**AuAu** b=6.6-8.1fm	**PbPb** b=8fm
light	<Ncoll>= 2.02 <v2>Rndm= 2.392% <v2>Norm= 3.279% <v2>Rndm/<v2>Norm **=72.9%**	<Ncoll>= 4.5 <v2>Rndm= 2.931% <v2>Norm= 4.468% <v2>Rndm/<v2>Norm **=65.6%**	<Ncoll>= 9.82 <v2>Rndm= 3.214% <v2>Norm=7.562% <v2>Rndm/<v2>Norm **=42.5%**
s-quark	<Ncoll>= 2.54 <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 mechanism/ more from collective flow

The escape mechanism: *flavour dependence*





v2(P_T):

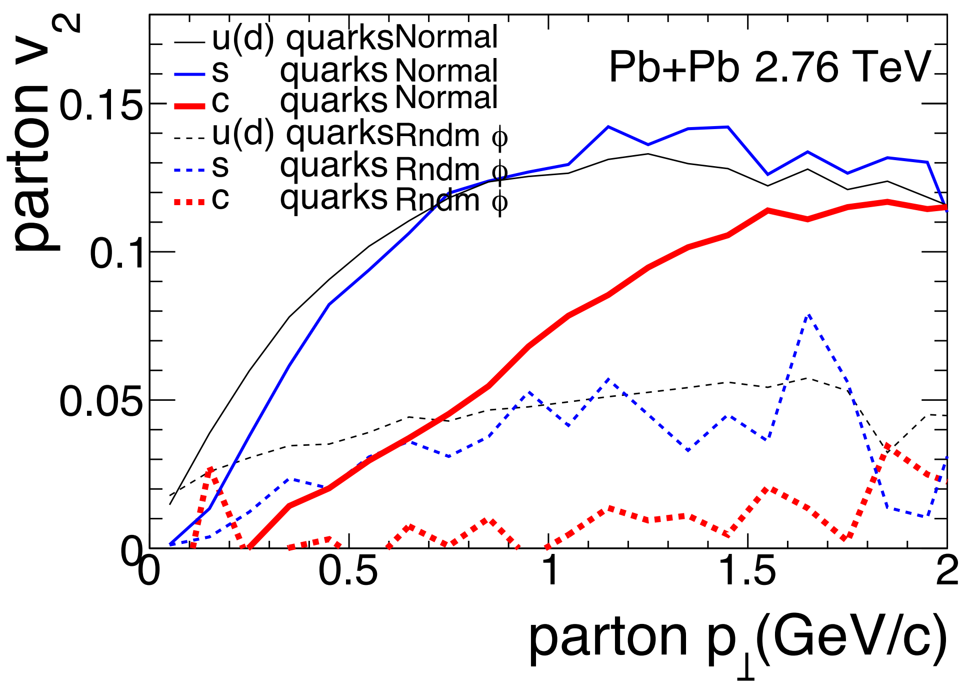
mass ordering at low P_T:

v2**c** < v2**s** < v2**ud**

this is partly responsible for the mass ordering of hadron v2 in Hanlin Li et al. PRC 93 (2016); arXiv:1604.07387

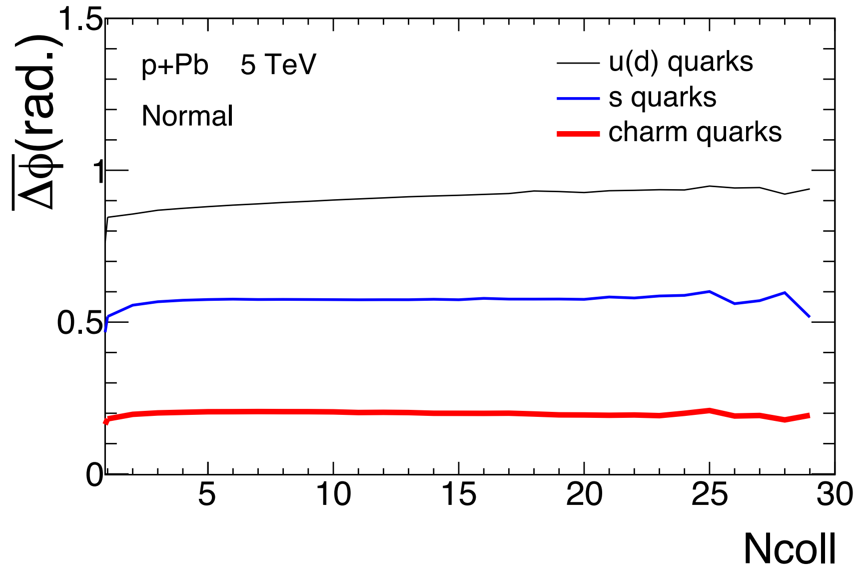
little mass effect at higher P_T:

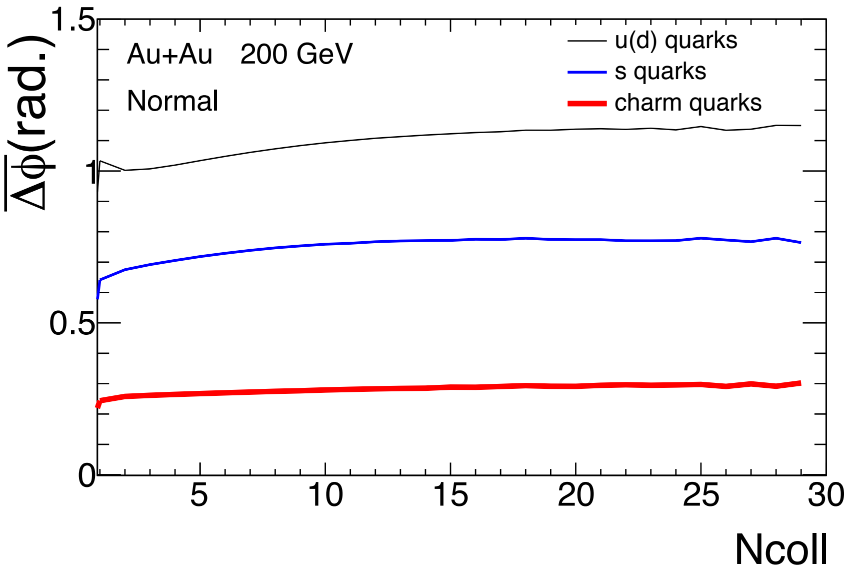
v2**c** ~ v2**s** ~ v2**ud**



The escape mechanism: *flavour dependence*

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

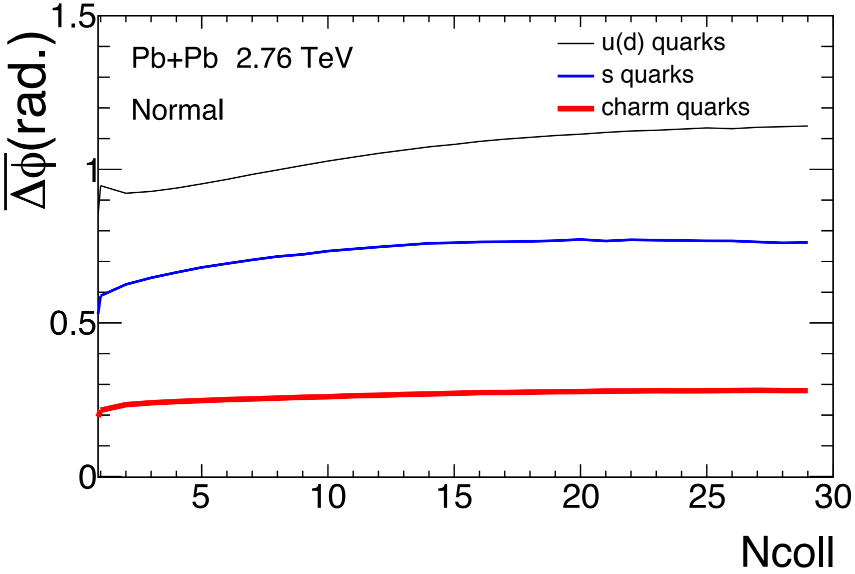




Mass ordering on
the mean parton deflection angle:

$$\overline{\Delta\phi}_c < \overline{\Delta\phi}_s < \overline{\Delta\phi}_{ud}$$

it is more difficult to deflect a heavier quark,
so light quark flow
& strong light-charm interactions
are essential to generate significant charm v2.



Summary

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

$\langle v_2 \rangle_{\text{random-}\phi} / \langle v_2 \rangle_{\text{normal}}$ 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 large systems at high energies 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); Greco's talk at QM2017.

A Multi-Phase Transport (AMPT) ZWL et al. PRC72 (2005)

serves as a comprehensive event generator 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)

Further efforts are needed to extend AMPT to heavy flavours, in order to simultaneously study light flavours, heavy flavours, including their interactions, to probe properties of the dense matter.