Discovering a new flow phenomena of flow angle and flow magnitude fluctuations and its impact on QGP studies

The 9th International Conference on Quarks and Nuclear Physics

Emil Gorm Nielsen, Niels Bohr Institute

September 7th

emil.gorm.nielsen@cern.ch

THE VELUX FOUNDATIONS

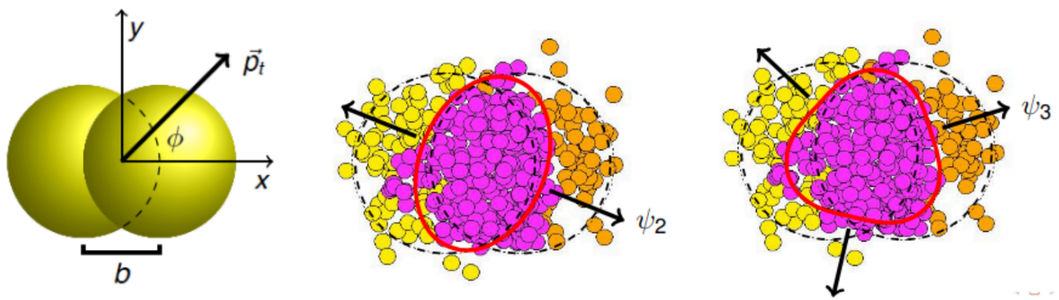
VILLUM FONDEN VELUX FONDEN

Anisotropic flow

- QGP created in heavy-ion collisions can be probed via **anisotropic flow**

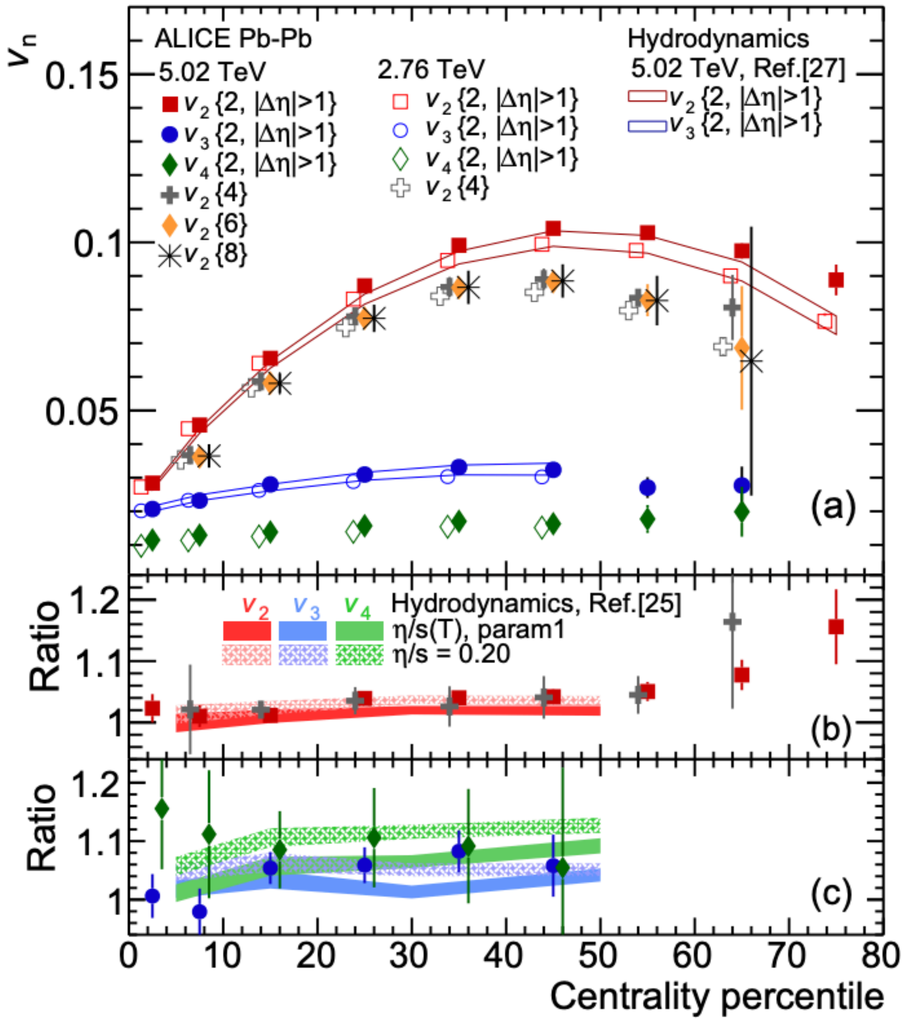
- Initial spatial anisotropy is transferred via large pressure gradients to final state momentum anisotropy

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} \vec{V}_n e^{in\varphi}$$



- Comparing data with theoretical models allow for extraction of QGP properties

ALICE Collaboration, *PRL* 116 (2016) 13, 132302



Flow vector fluctuations

Flow vector may fluctuate with transverse momentum, p_{T}

$$\vec{V}_n = v_n e^{in\Psi_n}$$

- v_n : Anisotropic flow
- Ψ_n : Flow symmetry plane angle

Both v_n and Ψ_n may fluctuate with p_{T}!

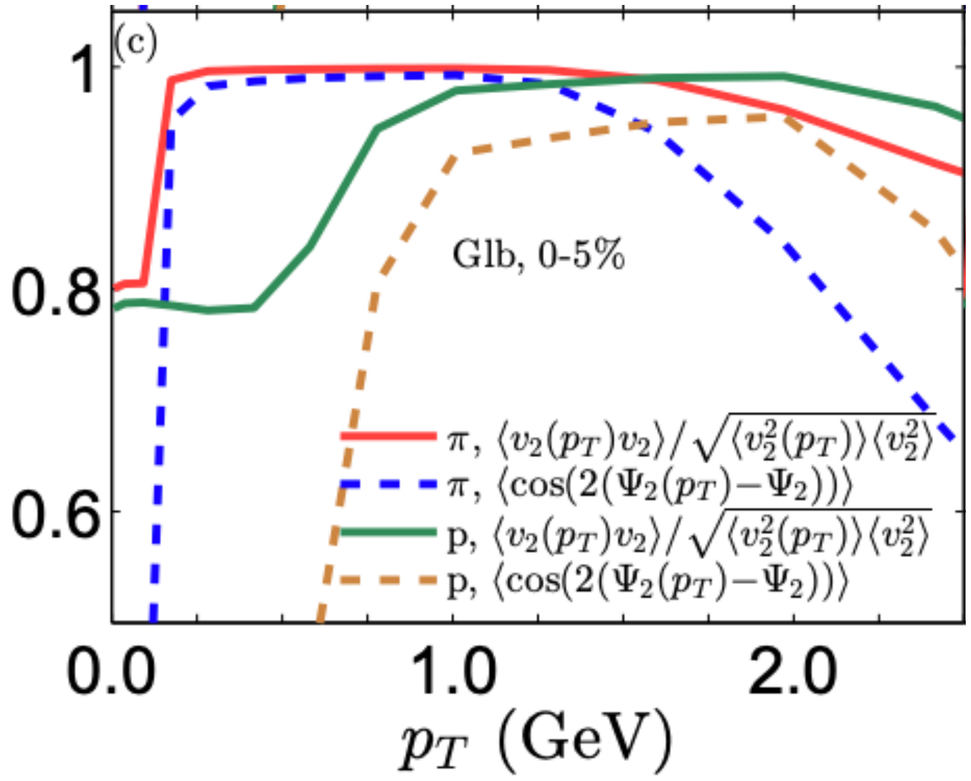
Hydro model predicted additional flow angle and flow magnitude fluctuations

Cannot be disentangled with current observables based on **2-particle correlations**

<u>Unique to hydro models?</u>

Scan of observables sensitive to flow vector fluctuations with A Multi-Phase Transport model (AMPT)

U. Heinz et al., PRC 87 (2013) 3, 034913



Flow vector fluctuations

Standard 2-particle correlation

$$v_n\{2\} = \frac{\langle v_n(p_\mathrm{T})\ v_n \cos n[\Psi_n(p_\mathrm{T}) - \Psi_n]\rangle}{\sqrt{\langle v_n^2\rangle}}$$

$$v_n[2] = \sqrt{\langle v_n^2(p_\mathrm{T}^a)\rangle}$$

$v_n\{2\}$ measures particle of interest against reference flow

$v_n[2]$ takes two particles from same p_T bin

Ratio of the two → sensitive to the p_T-dependent flow vector fluctuations

$$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_\mathrm{T}^a)\ v_n \cos n[\Psi_n(p_\mathrm{T}^a) - \Psi_n]\rangle}{\sqrt{\langle v_n^2(p_\mathrm{T}^a)\rangle}\sqrt{\langle v_n^2\rangle}}$$

→ Flow angle fluctuations

→ Flow magnitude fluctuations

$v_2\{2\}/v_2[2] < 1$ → Flow vector fluctuations

How to disentangle the two effects?

Factorisation ratio

Factorisation of two-particle correlation into two single-particle distributions

$$V_{n\Delta}(p_{\mathrm{T}}^{a}, p_{\mathrm{T}}^{t}) \stackrel{?}{=} v_n(p_{\mathrm{T}}^{a}) \times v_n(p_{\mathrm{T}}^{t})$$

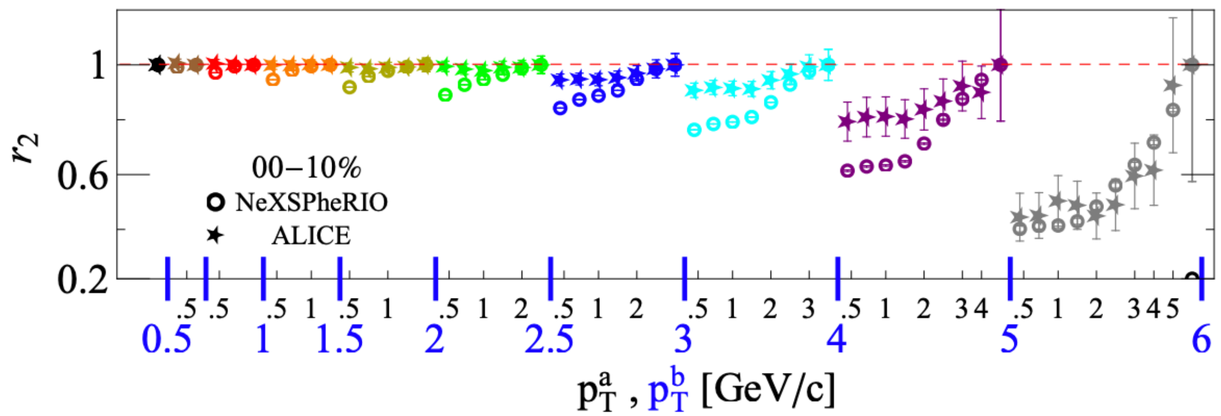
Test above relation with factorisation ratio

$$r_n = \frac{\langle v_n(p_{\mathrm{T}}^{a}) v_n(p_{\mathrm{T}}^{t}) \cos n[\Psi_n(p_{\mathrm{T}}^{a}) - \Psi_n(p_{\mathrm{T}}^{t})]\rangle}{\sqrt{\langle v_n^2(p_{\mathrm{T}}^{a})\rangle}\sqrt{\langle v_n^2(p_{\mathrm{T}}^{t})\rangle}}$$

$r_2 < 1 \rightarrow$ Factorisation is broken

Factorisation broken in hydrodynamics due to fluctuations in the initial state

F. G. Gardim et al., PRC **87 (2013) 3, 031901**



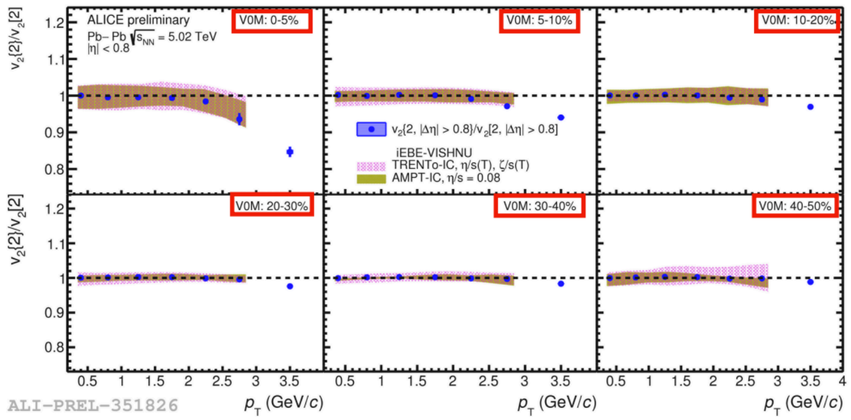
Experimental measurements

Measurements by ALICE indicate the presence of p_T-dependent flow vector fluctuations

<u>Well described by hydro calculations</u>

Preliminary ALICE measurements, presented in IS2021

p_T-dependent flow vector fluctuations: V_2



Preliminary model calculations
Statistical errors are expected to decrease

- Deviations from unity of $v_2\{2\}/v_2[2]$ in central collisions → p_T-dependent V_2 flow vector fluctuations
- Deviations are largest at the edge of hydro p_T range
- High precision Run 2 measurements allow for improved constraints on future model comparisons

Emil Gorm Nielsen (NBI) IS2021 - Fluctuations and correlations of flow 8

A Multi-Phase Transport model (AMPT)

1. Initial conditions are generated with HIJING
   Lund string parameters, a and b, related to string tension κ

$$\kappa \propto \frac{1}{b(2+a)}$$

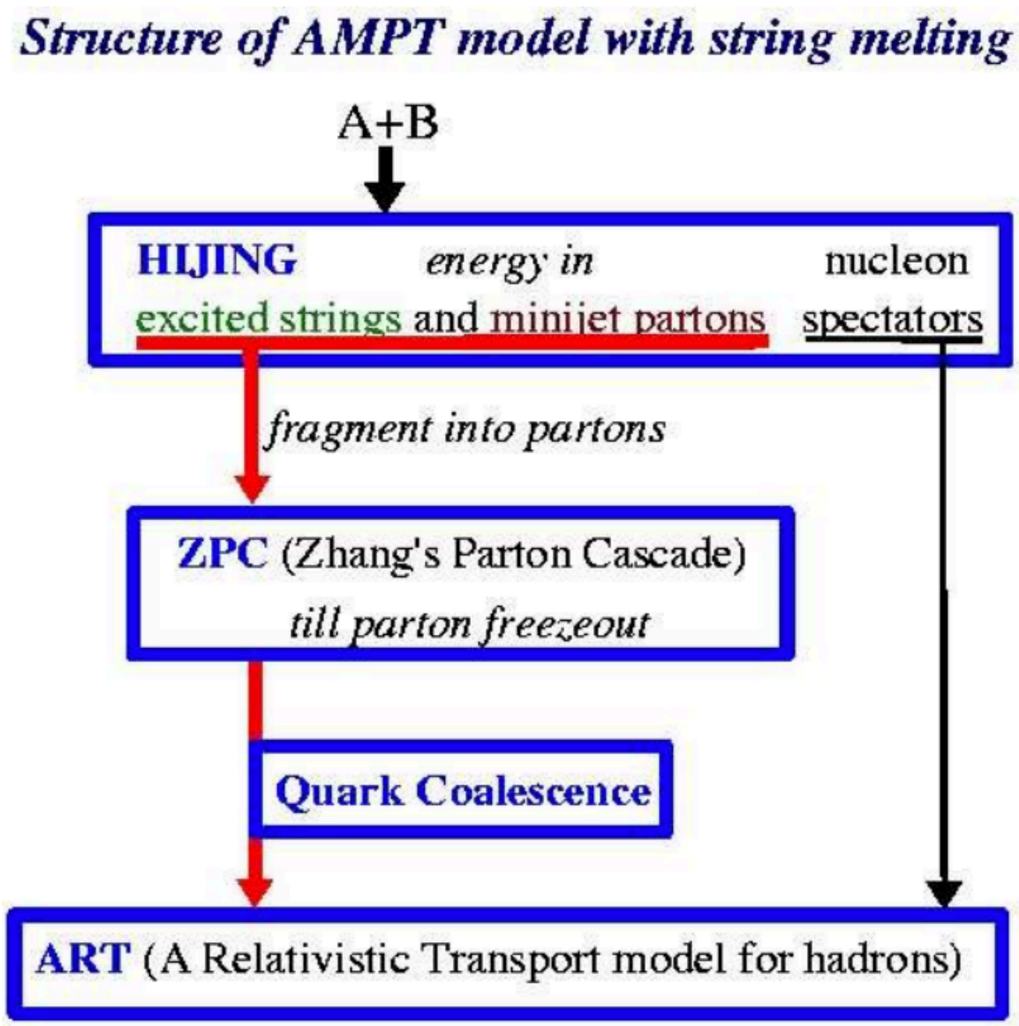
2. Convert hadrons produced from string fragmentation into valence quarks and anti-quarks

3. Parton-parton interaction are treated with Zhang's Parton Cascade
   Cross section obtained from pQCD screening masses

$$\sigma_{gg} = \frac{9\pi\alpha_s^2}{2\mu^2}$$

4. Quark coalescence model convert partons into hadrons

5. Hadronic rescattering is handled by A Relativistic Transport (ART) model



A Multi-Phase Transport model (AMPT)

Test observables sensitive to p_{T}-dependent flow fluctuations with different configurations of the AMPT model

Probe effect of **transport properties** by changing the cross section (Par1 vs Par4, Par2 vs Par5)

$\sigma \uparrow \qquad \eta/s \downarrow$

Probe effect of **hadronic rescattering** by turning ART off (Par1 vs Par2, Par4 vs Par5)

Probe effect of **initial conditions** by changing Lund string parameters *a* and *b* (Par2 vs Par3)

	Cross section	a	b	ART
Par1	1.5mb	0.3	0.15	ON
Par2	1.5mb	0.3	0.15	OFF
Par3	1.5mb	0.5	0.9	OFF
Par4	3mb	0.3	0.15	ON
Par5	3mb	0.3	0.15	OFF

$v_2\{2\}/v_2[2]$

Deviation from unity in AMPT
→ p_T-*dependent flow vector fluctuations*

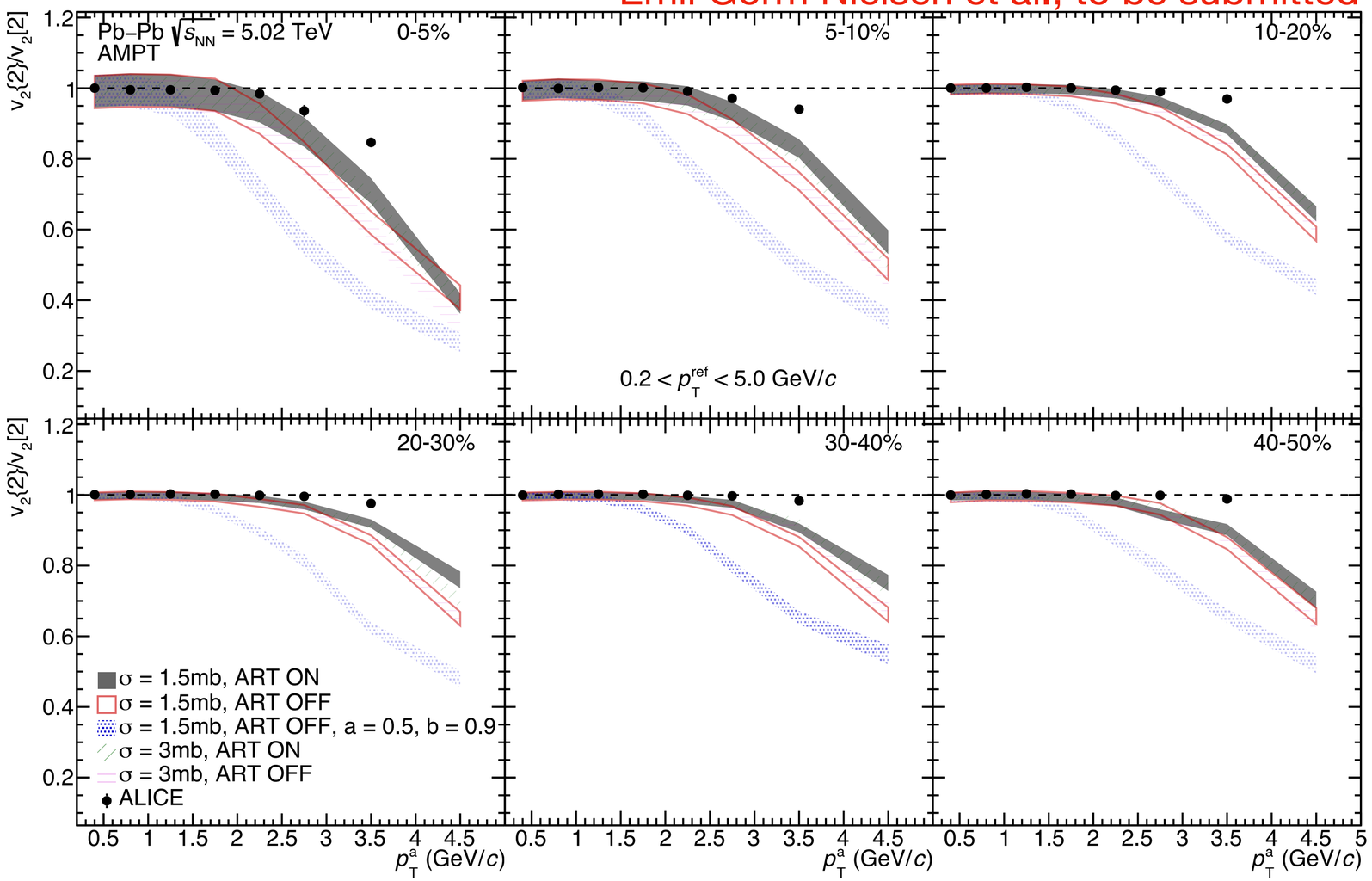
Small (max. 10%) difference due to cross section
Larger shear viscosity dampen initial state fluctuations

ART ON decreases the deviation from unity (max. 20%)
Smaller anisotropic flow increases relative contribution from initial state

Large effect from changing initial state parameters (~ 40%)
Flow vector fluctuations originating in fluctuating initial conditions

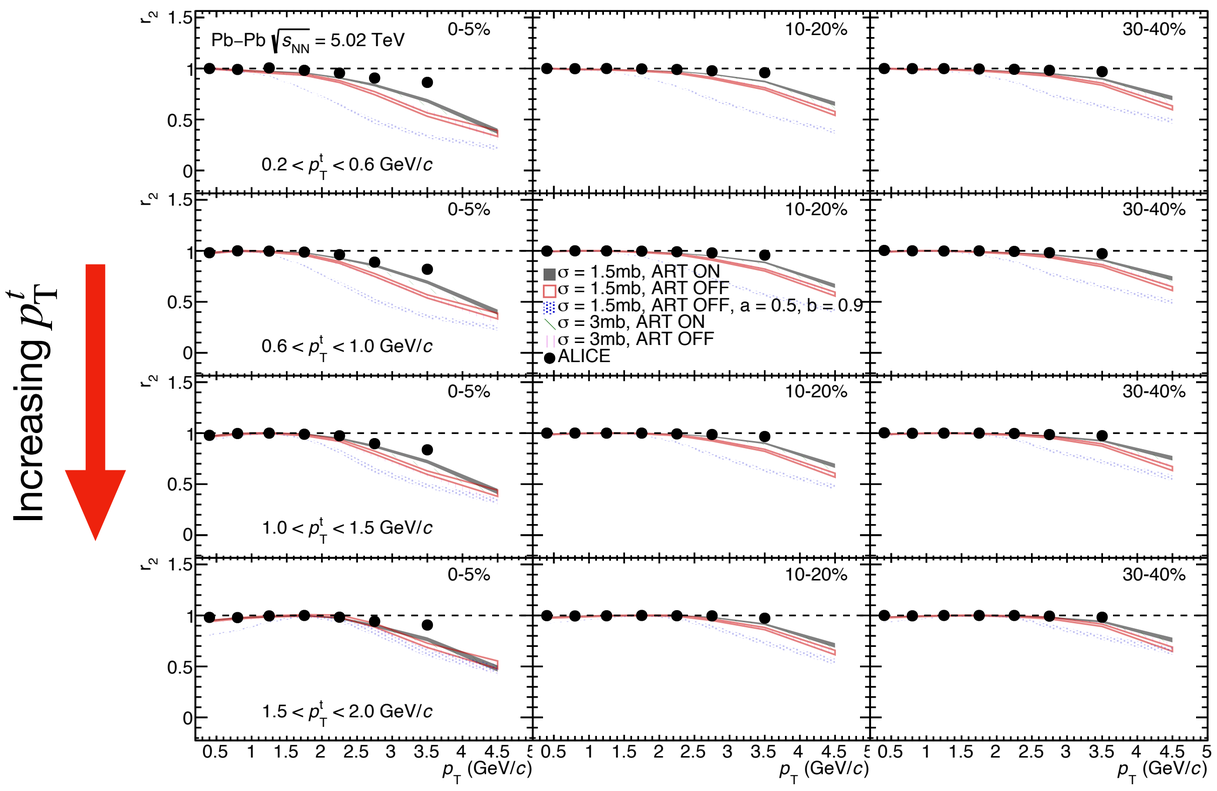
ALICE data slightly overestimated

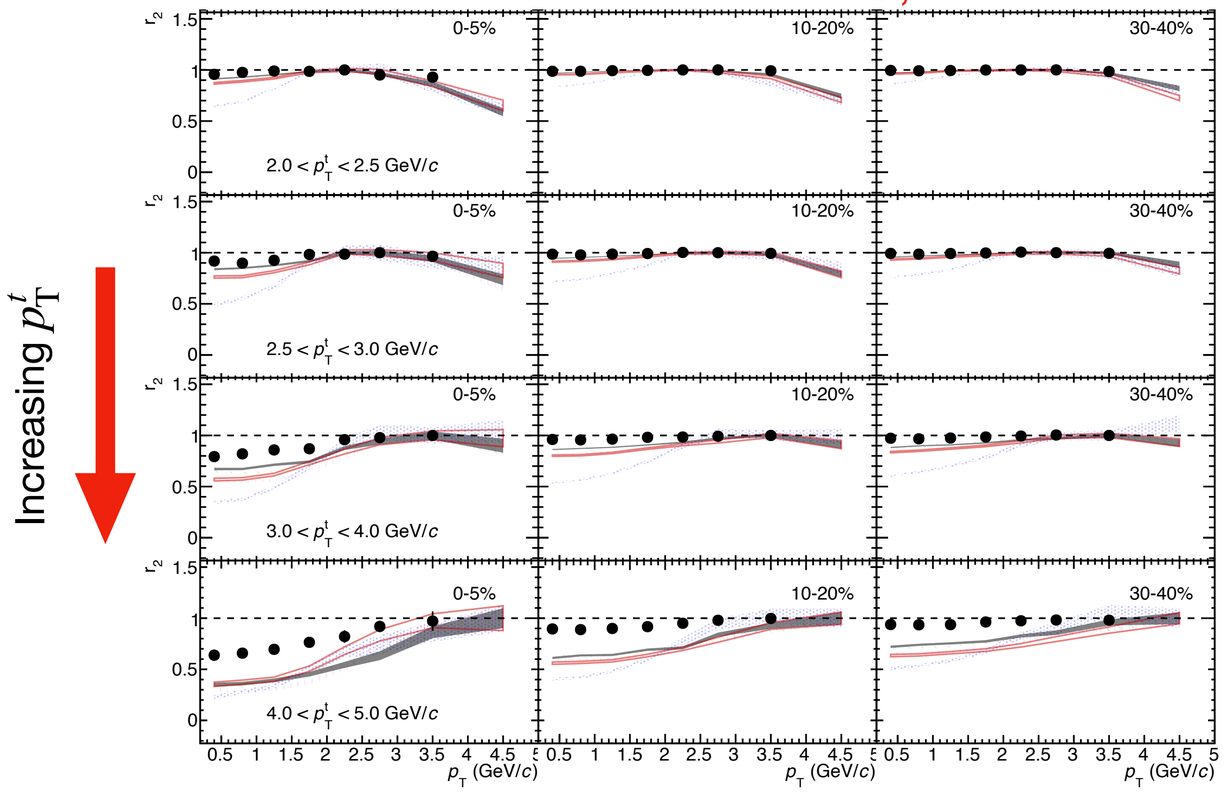
Emil Gorm Nielsen et al., to be submitted



Factorisation ratio, r_2

Emil Gorm Nielsen et al., to be submitted





The breaking of factorisation depend on the difference in transverse momentum $|p_T^a - p_T^t|$

Factorisation is broken for all configuration

Large sensitivity to the variation in the Lund string parameters

Flow angle and magnitude fluctuations

- Observable to measure **flow angle fluctuations**:

$$A_n^f = \frac{\langle\langle \cos[n(\varphi_1^a + \varphi_2^a - \varphi_3 - \varphi_4)]\rangle\rangle}{\langle\langle \cos[n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4)]\rangle\rangle}$$

$$= \frac{\langle v_n^2(p_{\mathrm{T}}^a)\ v_n^2 \cos 2n[\Psi_n(p_{\mathrm{T}}^a) - \Psi_n]\rangle}{\langle v_n^2(p_{\mathrm{T}}^a) v_n^2\rangle}$$

$$\approx \langle \cos 2n[\Psi_n(p_{\mathrm{T}}^a) - \Psi_n)]\rangle$$

$A_n^f < 1$ indicates p_{T}-dependent **flow angle fluctuations**

- Observable to measure **flow magnitude fluctuations**

$$\frac{\langle\langle \cos n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4)\rangle\rangle}{\langle\langle \cos n(\varphi_1^a - \varphi_3^a)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle} = \frac{\langle v_n^2(p_{\mathrm{T}}^a)\ v_n^2\rangle}{\langle v_n^2(p_{\mathrm{T}}^a)\rangle\langle v_n^2\rangle}$$

- Normalise with p_{T}-integrated baseline:

$$M_n^f = \frac{\langle v_n^2(p_{\mathrm{T}}^a)\ v_n^2\rangle / \langle v_n^2(p_{\mathrm{T}}^a)\rangle\langle v_n^2\rangle}{\langle v_n^4\rangle / \langle v_n^2\rangle^2}$$

$M_n^f < 1$ indicates p_{T}-dependent **flow magnitude fluctuations**

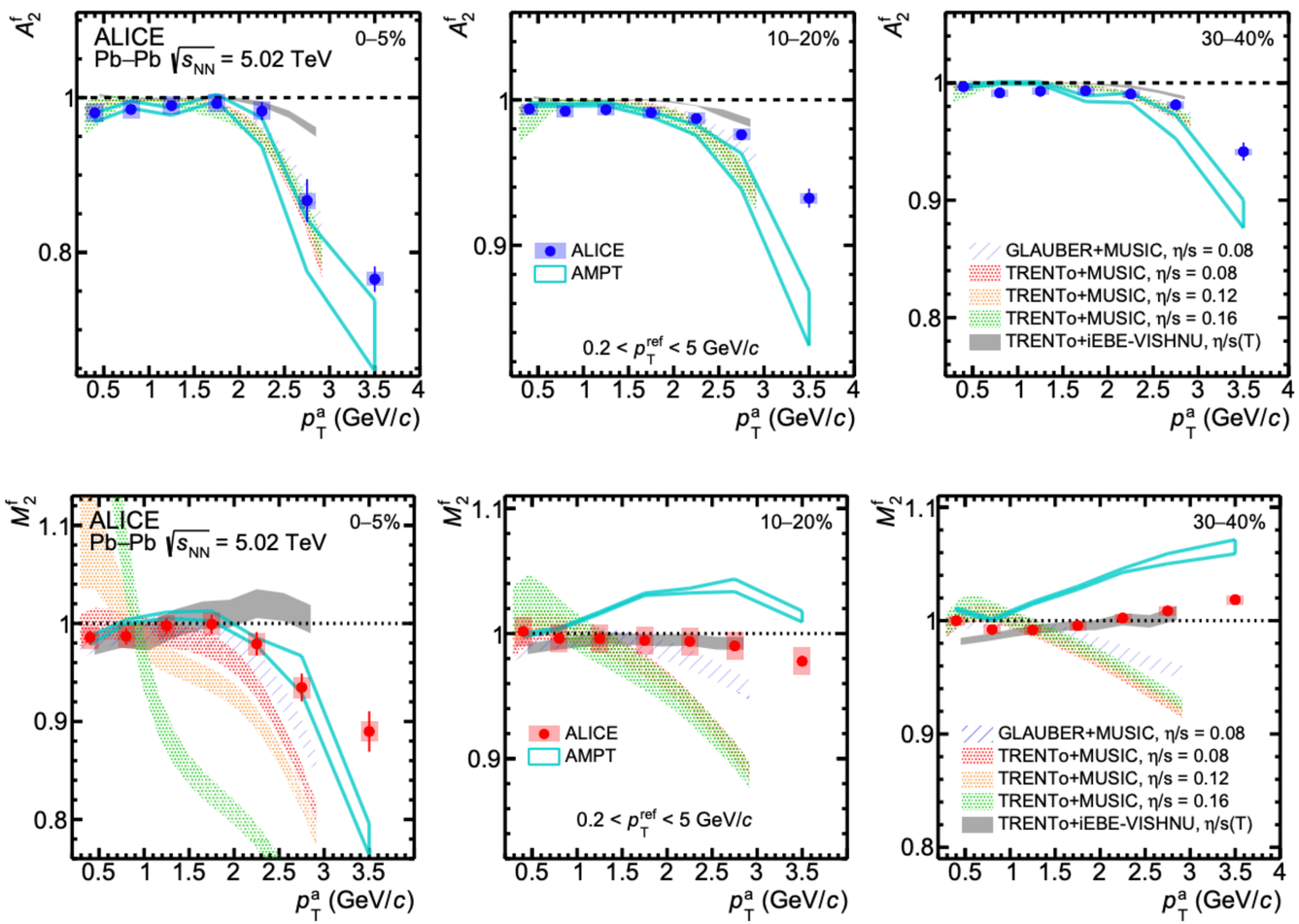
New ALICE measurements

Recent measurements by ALICE
→ Observation of flow angle and flow magnitude fluctuations

Largest deviation in central collisions
Dominated by event-by-event fluctuations

Phenomena present in transport model?
What is the origin of the flow angle and flow magnitude fluctuations

ALICE collaboration, submitted to arXiv: arXiv:2206.04574



Flow angle fluctuations

Isolate the fluctuations of Ψ_2 with A_2^f observable

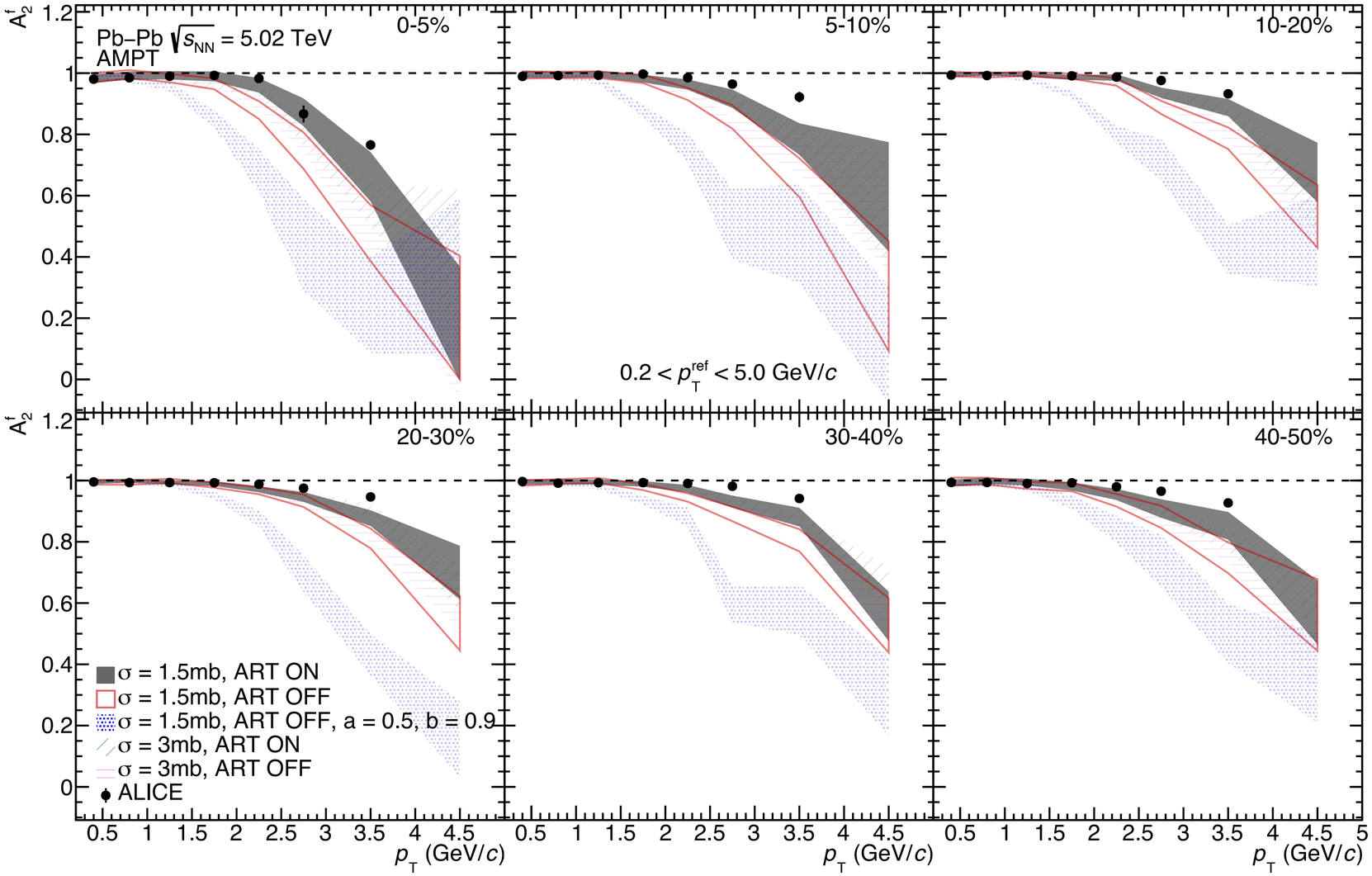
No effect from varying the cross section
Any effect is expected to show at high p_T - large uncertainty

Turning ART off increases flow angle fluctuations (max. 20%)

Very sensitive to initial conditions (~60%)
Event-by-event fluctuations in initial state

AMPT overestimates the flow angle fluctuations

Emil Gorm Nielsen et al., to be submitted



Flow magnitude fluctuations

Isolate the fluctuations of v_2 with M_2^f

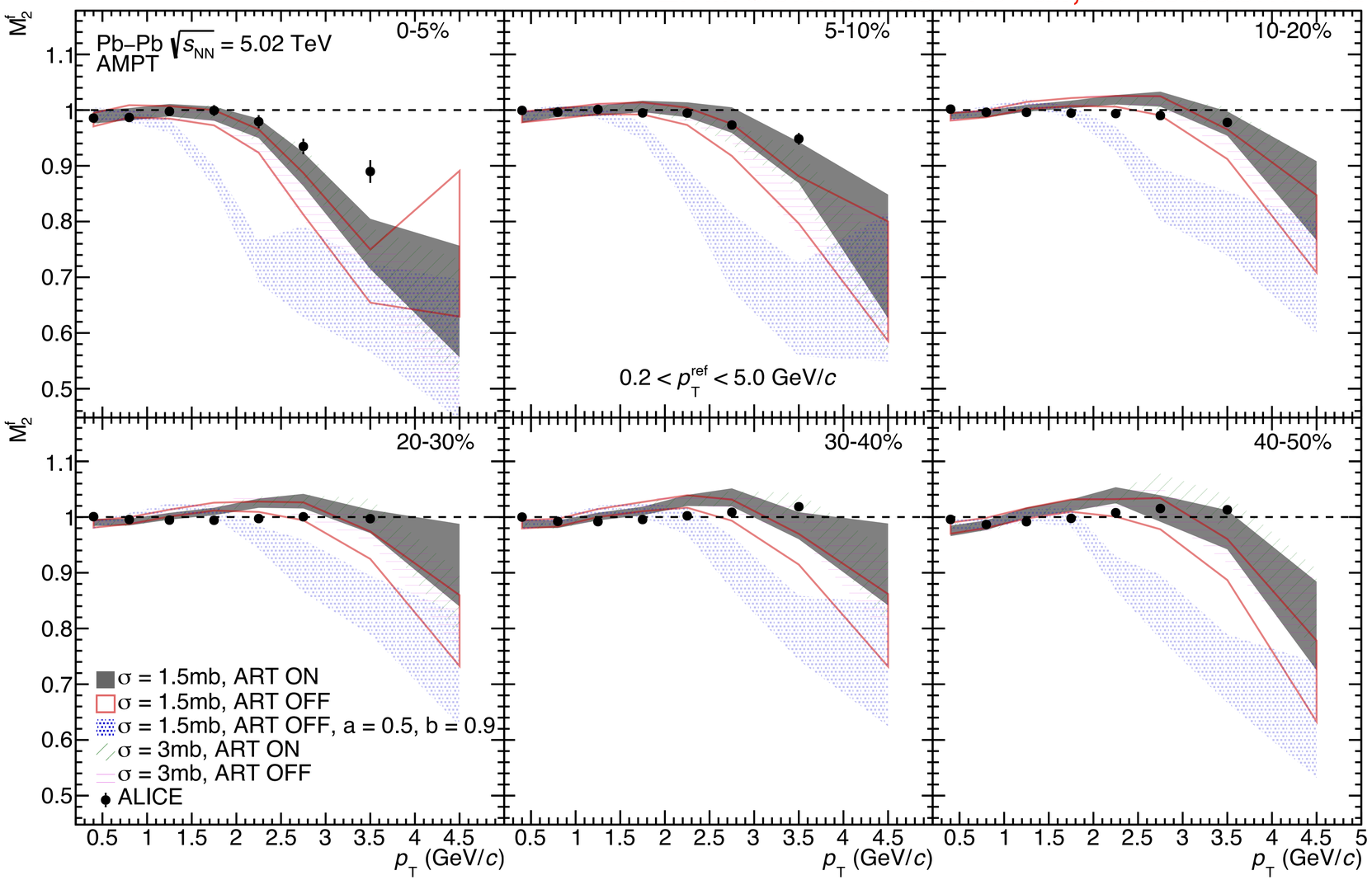
No effect from varying the cross section
Dependence on transport properties cancelled by ratio

Only small effect (~10%) from turning ART off in highest p_T bin

Largest effect from changes in initial conditions
Highly sensitive to the initial conditions

ALICE data is well described by AMPT

Emil Gorm Nielsen et al., to be submitted



Summary

The p_{T}-dependent flow vector, flow angle and flow magnitude fluctuations present in transport model

Not unique feature of hydrodynamic models

The observables show most sensitivity to changes to the initial conditions

*The p_{T}-dependent flow fluctuations are primarily driven by event-by-event fluctuations in the **initial state***

The AMPT model can reasonably reproduce the observed fluctuations in data

AMPT mostly overestimates the fluctuations