Unraveling the partonic flow in small systems with an improved multi-phase transport model

Speaker: Xiang-Pan Duan
Collaborators: Wen-Ya Wu, You Zhou, and Guo-Liang Ma

42nd International Conference on High Energy Physics
July 18, 2024, Prague, Czech Republic

Outline

- **Introduction**
  - ✓ Anisotropic flow
  - ✓ p_T-differential elliptic flow and NCQ scaling
- **Hadronization mechanisms**
  - ✓ A multi-phase transport (AMPT) model with a simple quark coalescence
  - ✓ A modified AMPT model with precise quark coalescence and string fragmentation
- **Methods and results**
  - ✓ Two-particle correlation and nonflow subtraction in modified AMPT
  - ✓ p_T-differential elliptic flow results in **p + Pb collisions** in modified AMPT
- **Summary**

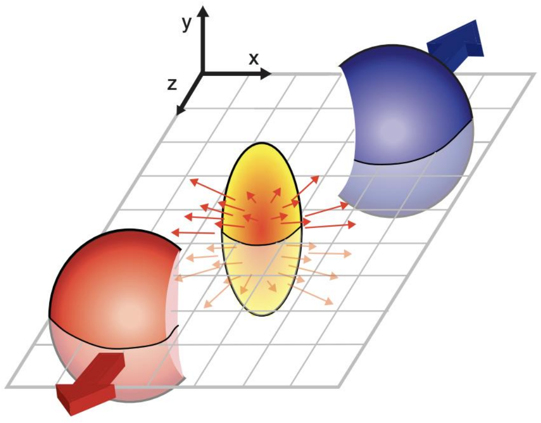
Anisotropic flow

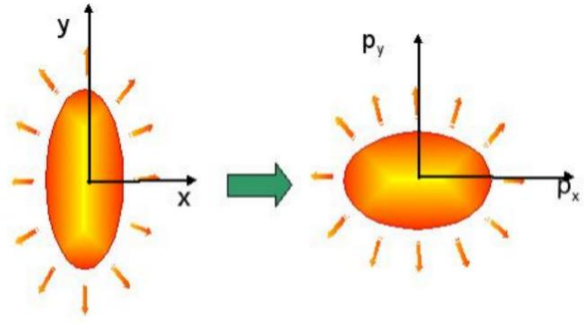
- Relativistic heavy-ion collisions: initial state, pre-equilibrium, QGP and hydrodynamic expansion, hadronization, hadronic phase and freeze-out

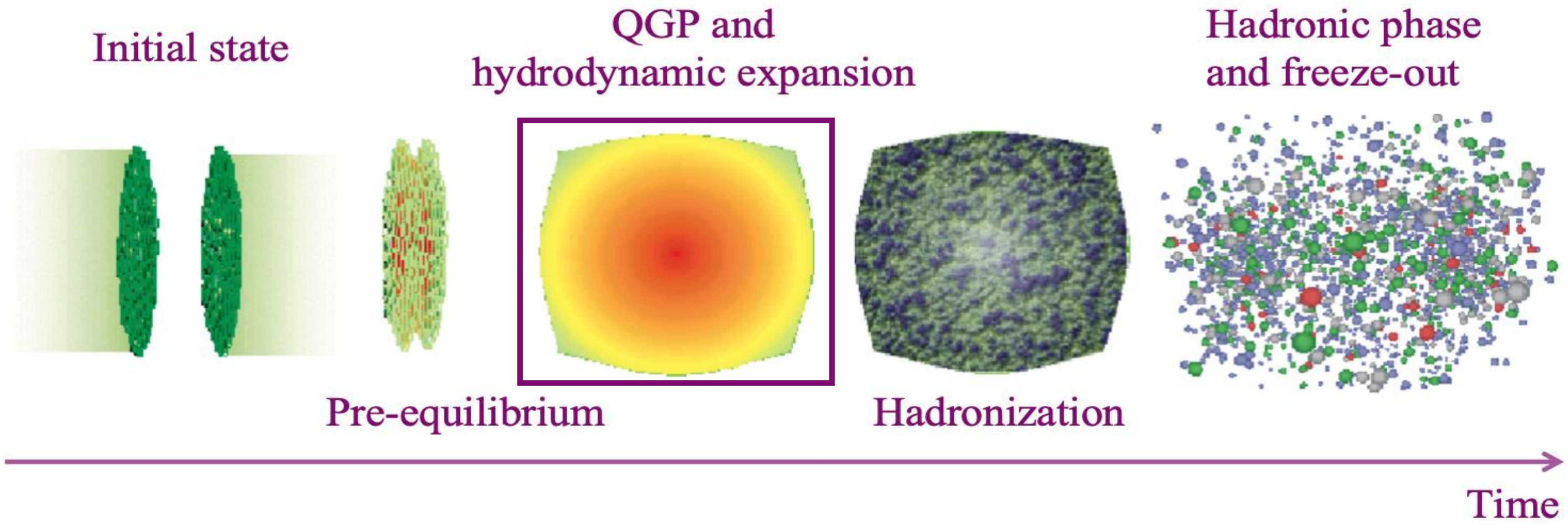
A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998)

- Anisotropic flow
  - ✓ Initial spatial anisotropy
  - ✓ Transport anisotropy

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

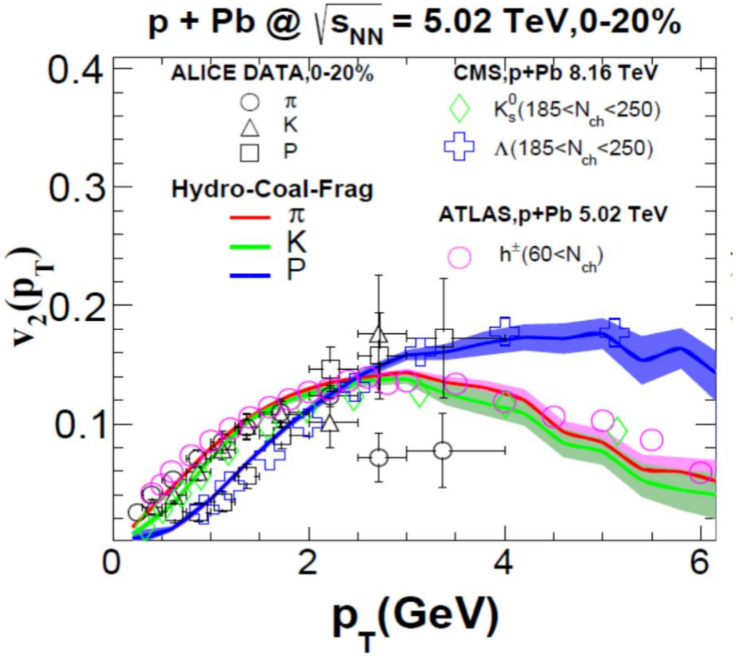






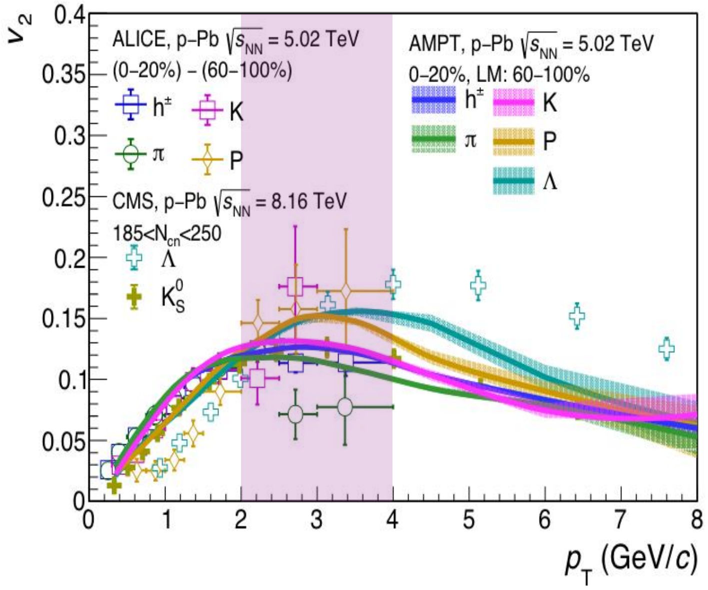
p_T-differential elliptic flow

W. Zhao et al., Phys. Rev. Lett. 125, 072301 (2020)



HCF ✓

S. Tang et al., Nucl. Sci. Tech. 35 (2024) 32

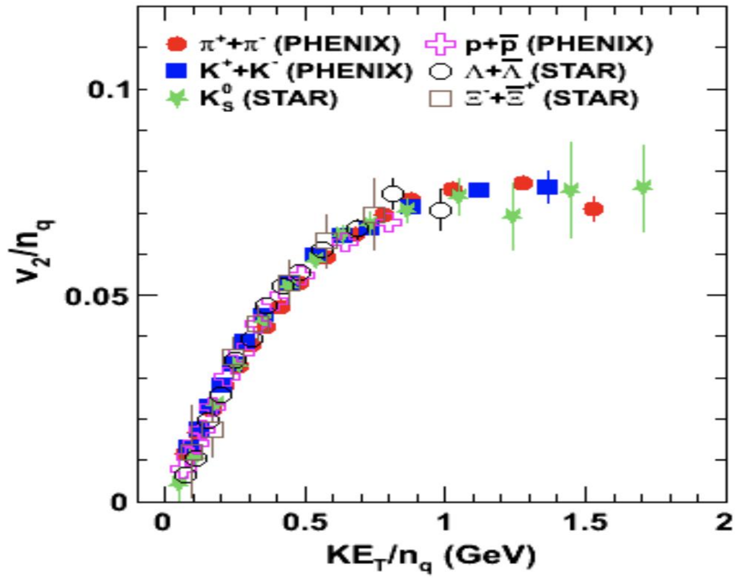


AMPT ✗

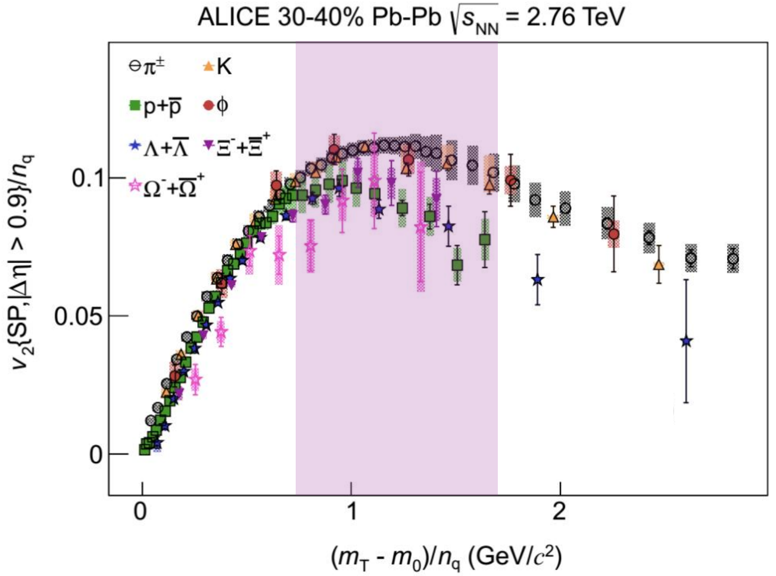
- p_T-differential elliptic flow in p + Pb collisions
  - ✓ Low p_T: mass ordering effect
  - ✓ Intermediate p_T: baryon-meson grouping/splitting effect
- Hydro-Coal-Frag (HCF) vs. AMPT:
  - ✓ HCF: hydrodynamics + coalescence + fragmentation (without non-flow contamination, inappropriate in small collision systems)
  - ✓ AMPT: parton cascade + **simple coalescence** (close to the reality with a large non-flow contributions)

Broken of number of constituent quarks (NCQ) scaling

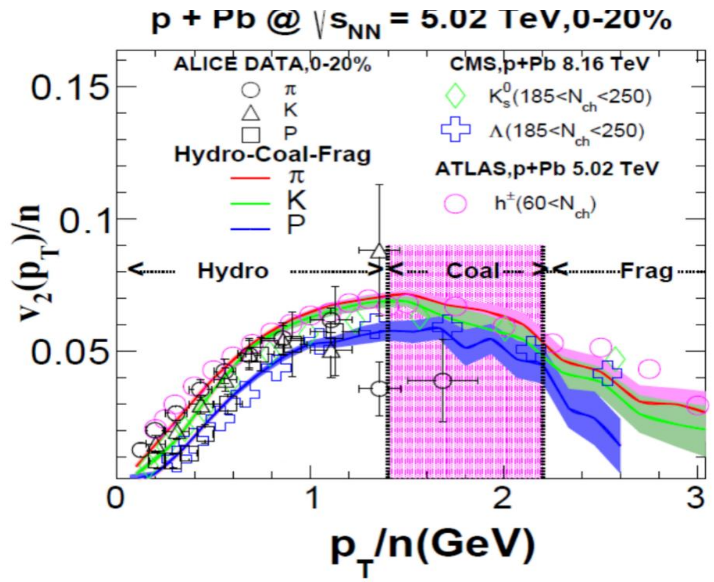
PHENIX Collaboration, Phys. Rev. Lett. 98, 162301 (2007)



ALICE Collaboration, JHEP 06 (2015) 190



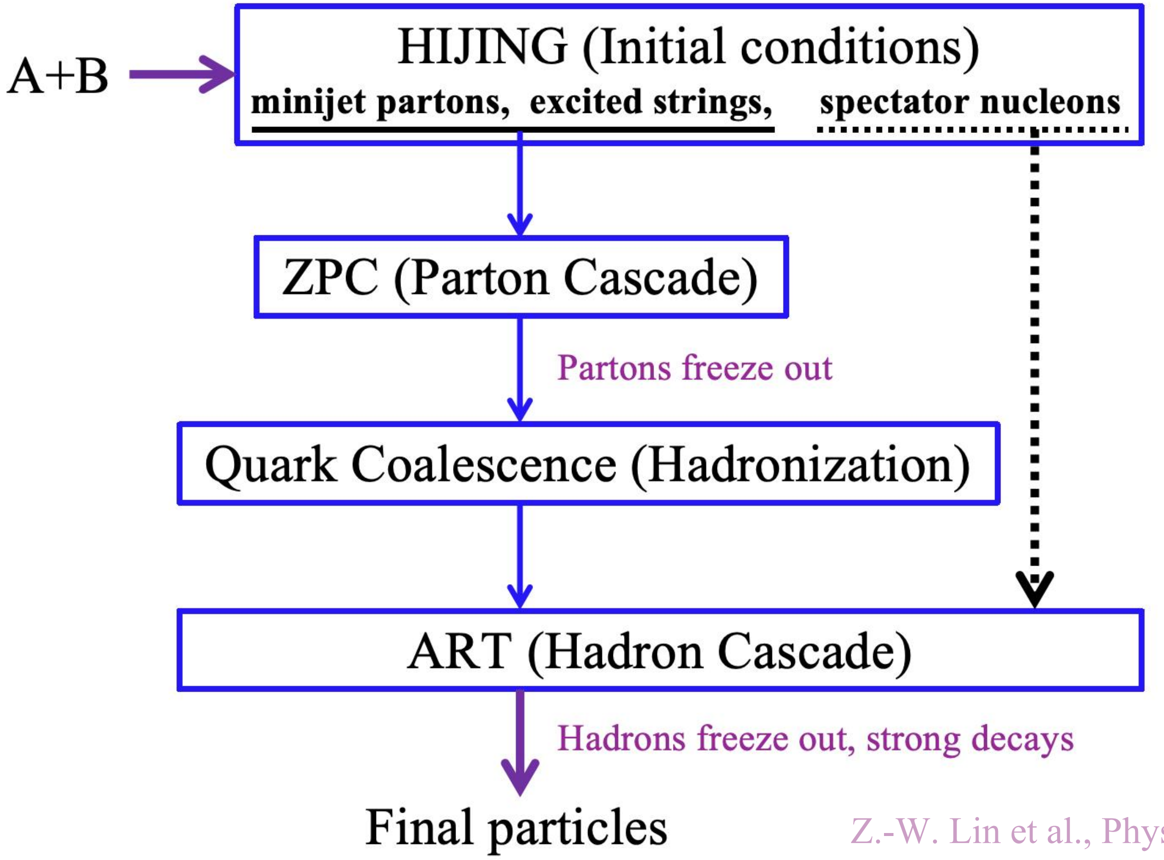
- Broken of NCQ scaling
  - ✓ Baryon-meson grouping doesn't follow perfect NCQ scaling
  - ✓ Similar broken patterns have been observed in both Pb + Pb and p + Pb collisions
  - ✓ $v_2(p_T)$ is not only dominated by the quark coalescence
  - ✓ **Baryon-meson grouping effect is the signature of partonic collectivity in small collision systems**
  - ✓ Experimental data requires theory explanation



HCF

AMPT model

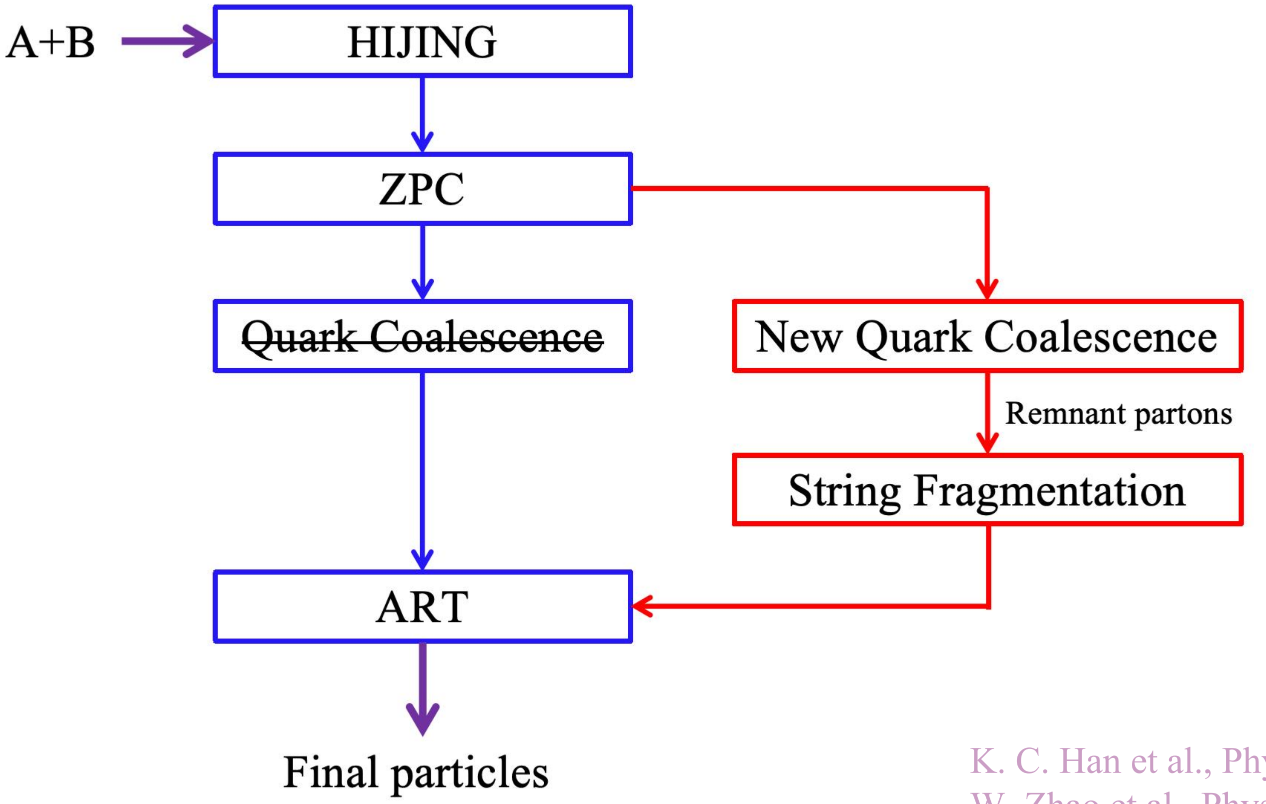
- AMPT model includes non-equilibrium initial conditions
- ZPC model only includes **two-body elastic scattering** $\sigma_{gg} \approx \frac{9\pi\alpha_s^2}{2\mu^2}$
- **A simple quark coalescence mechanism** is used in AMPT model



Z.-W. Lin et al., Phys. Rev. C 72, 064901 (2005)
Z.-W. Lin and L. Zheng, Nucl. Sci. Tech. 32 (2021) 113

Modified AMPT model

- **A simple quark coalescence mechanism** (in the AMPT model with string melting)
  - ✓ Only considering the smallest distance in coordinate space during quark coalescence
- **A new hadronization mechanism** (new quark coalescence + string fragmentation)
  - ✓ Considering the relative distance in phase spaces (coordinate and momentum) during quark coalescence



K. C. Han et al., Phys. Rev. C 93, 045207 (2016)
W. Zhao et al., Phys. Rev. Lett. 125, 072301 (2020)

New quark coalescence and string fragmentation

- New quark coalescence: the momentum distributions of mesons and baryons are defined as

$$\frac{dN_{\mathrm{M}}}{d^3\mathbf{P}_{\mathrm{M}}} = g_{\mathrm{M}} \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_{\mathrm{q}}(\mathbf{x}_1, \mathrm{p}_1) f_{\bar{\mathrm{q}}}(\mathbf{x}_2, \mathbf{p}_2) \times W_{\mathrm{M}}(\mathbf{y}, \mathbf{k}) \delta^{(3)}(\mathbf{P}_{\mathrm{M}} - \mathbf{p}_1 - \mathbf{p}_2),$$

$$\frac{dN_{\mathrm{B}}}{d^3\mathbf{P}_{\mathrm{B}}} = g_{\mathrm{B}} \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{\mathrm{q}_1}(\mathbf{x}_1, \mathbf{p}_1) f_{\mathrm{q}_2}(\mathbf{x}_2, \mathbf{p}_2) f_{\mathrm{q}_3}(\mathbf{x}_3, \mathbf{p}_3) \times W_{\mathrm{B}}(\mathbf{y}_1, \mathbf{k}_1; \mathbf{y}_2, \mathbf{k}_2) \delta^{(3)}(\mathbf{P}_{\mathrm{B}} - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3),$$

  - ✓ Wigner function of a meson in the n-th excited state is given by

$$\mathrm{W}_{\mathrm{M,n}}(\mathbf{y}, \mathbf{k}) = \frac{v^{\mathrm{n}}}{\mathrm{n}!}\mathbf{e}^{-v}, \quad v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_{\mathrm{M}}^2} + \mathbf{k}^2\sigma_{\mathrm{M}}^2\right)$$

  - ✓ Wigner function of a baryon in the n_1-th and n_2-th excited state is given by

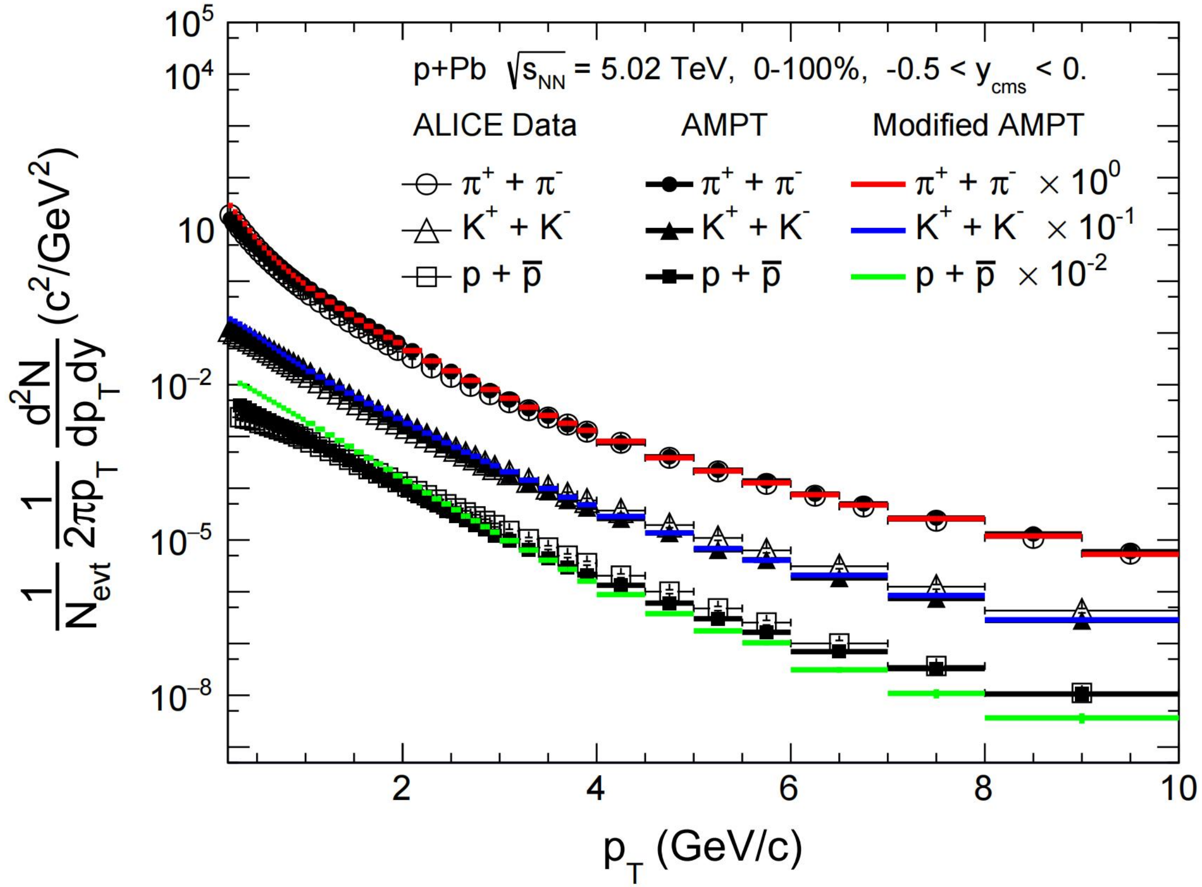
$$\mathrm{W}_{\mathrm{B},\mathrm{n}_1,\mathrm{n}_2}(\mathbf{y}_1, \mathbf{k}_1; \mathbf{y}_2, \mathbf{k}_2) = \frac{v_1^{n_1}}{n_1!}e^{-v_1} \cdot \frac{v_2^{n_2}}{n_2!}e^{-v_2}, \quad v_{\mathrm{i}} = \frac{1}{2}\left(\frac{\mathbf{y}_{\mathrm{i}}^2}{\sigma_{\mathrm{Bi}}^2} + \mathbf{k}_{\mathrm{i}}^2\sigma_{\mathrm{Bi}}^2\right)$$

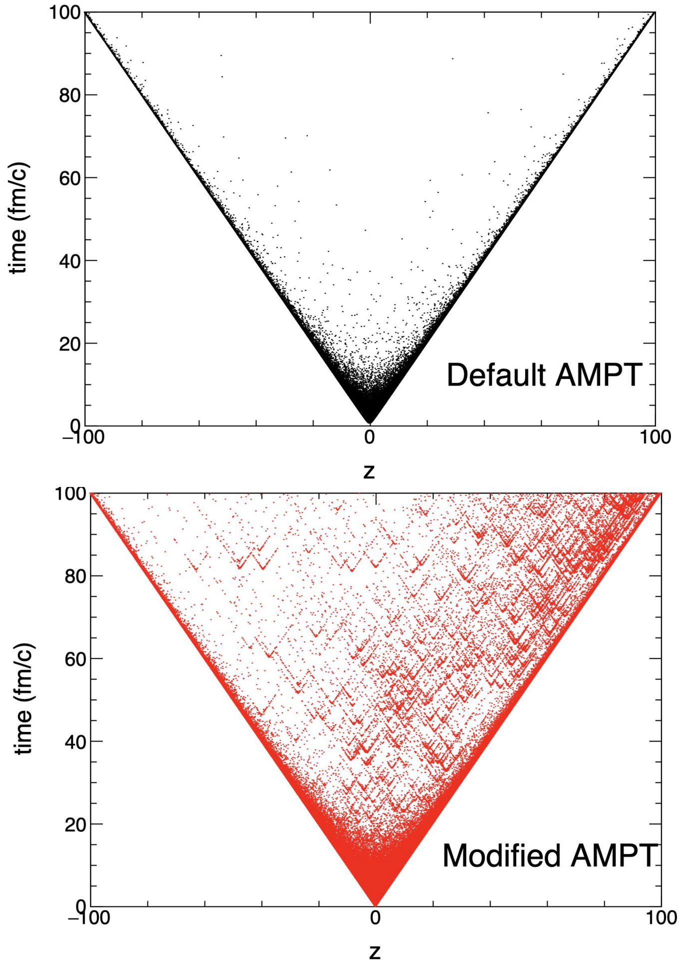
- String fragmentation: the new strings are formed by quark and anti-quark pairs according to the smallest distance in η-ϕ plane, then fragment into hadrons by the "hadron standalone mode" of PYTHIA8

$$\Delta R_{\mathrm{min}} = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

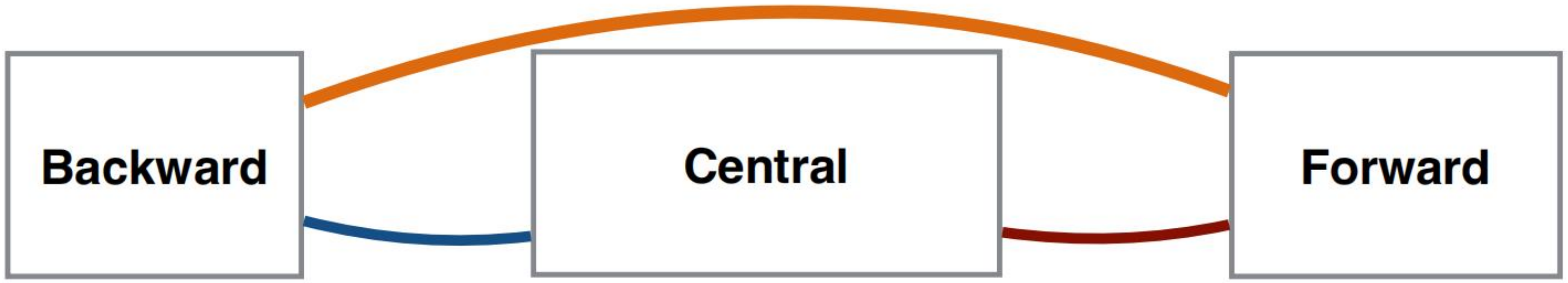
p_T spectra of identified particles

- These two models reproduce the p_T spectra of $\pi^{\pm}$ and $K^{\pm}$ in p + Pb collisions
- The modified AMPT model provides more soft p($\bar{p}$) than default AMPT model
- The modified AMPT model gives a more dilute structure before hadron scattering in p + Pb collisions





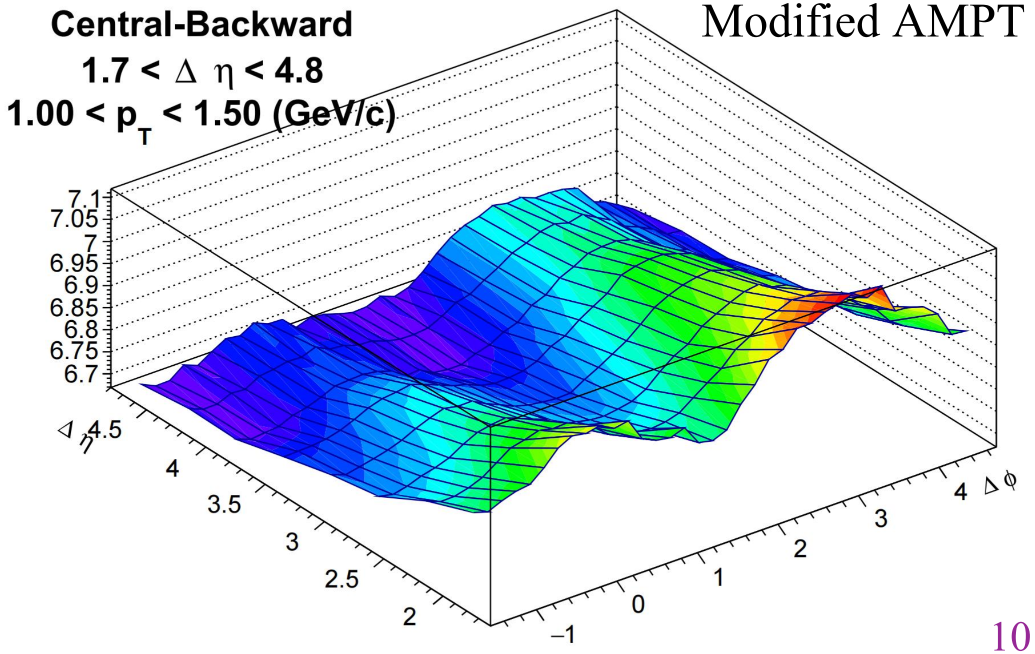
Two-particle correlation and non-flow



$-4.0 < \eta < 2.5$	$-0.8 < \eta < 0.8$	$2.5 < \eta < 4.0$

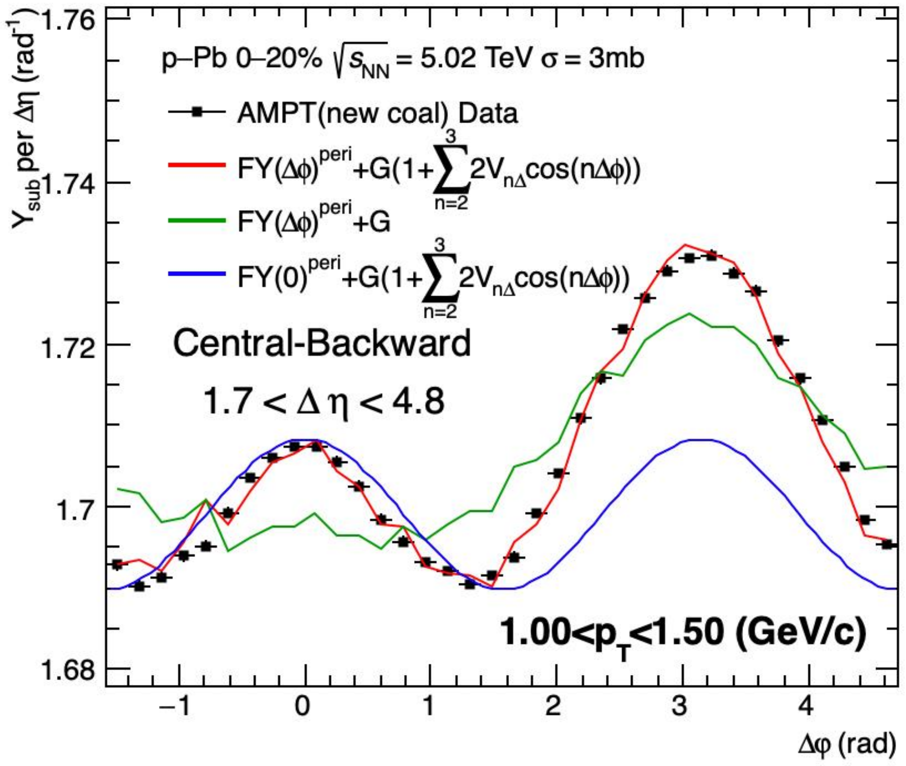
- Two-particle correlation method is applied in modified AMPT model in p + Pb collisions
  - ✓ Correlation function $C(\Delta\eta, \Delta\varphi)$ shows double ridge structure
  - ✓ Long-range correlation is established in modified AMPT model
  - ✓ Centrality is determined by "forward multiplicity" ($2.8 < \eta < 5.1$, same as Nucl. Sci. Tech. 35 (2024) 32)

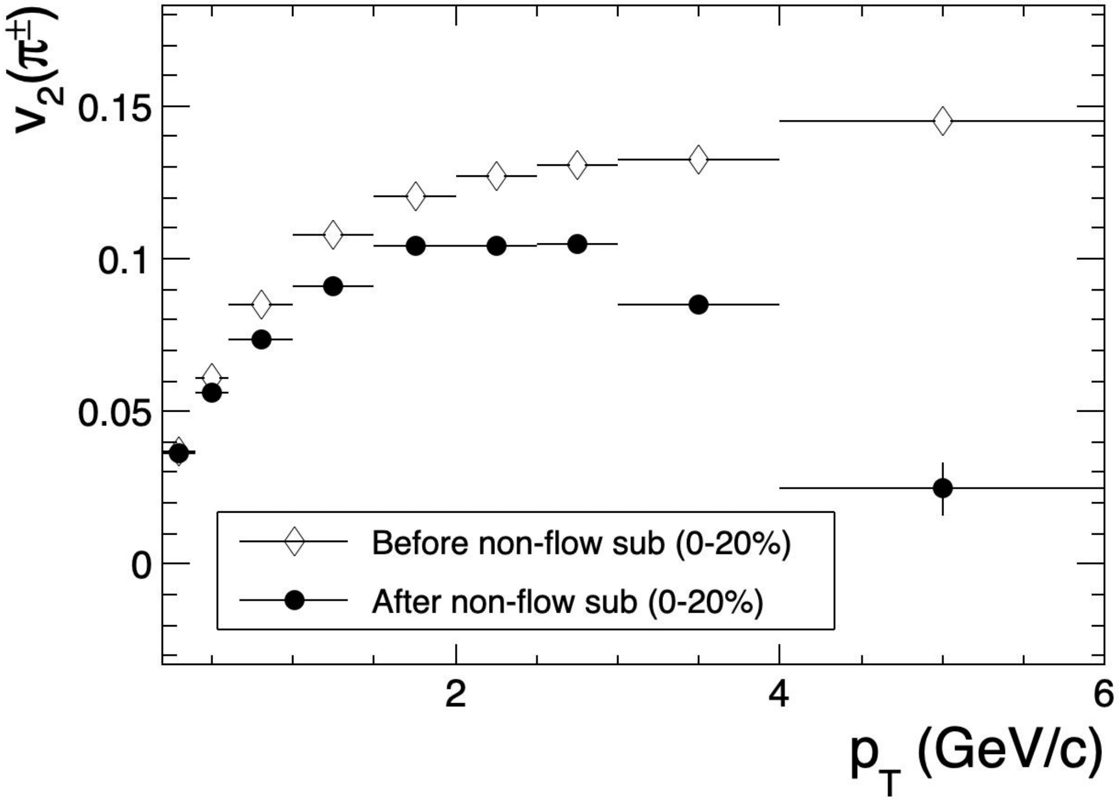
Modified AMPT



Two-particle correlation and non-flow

Modified AMPT

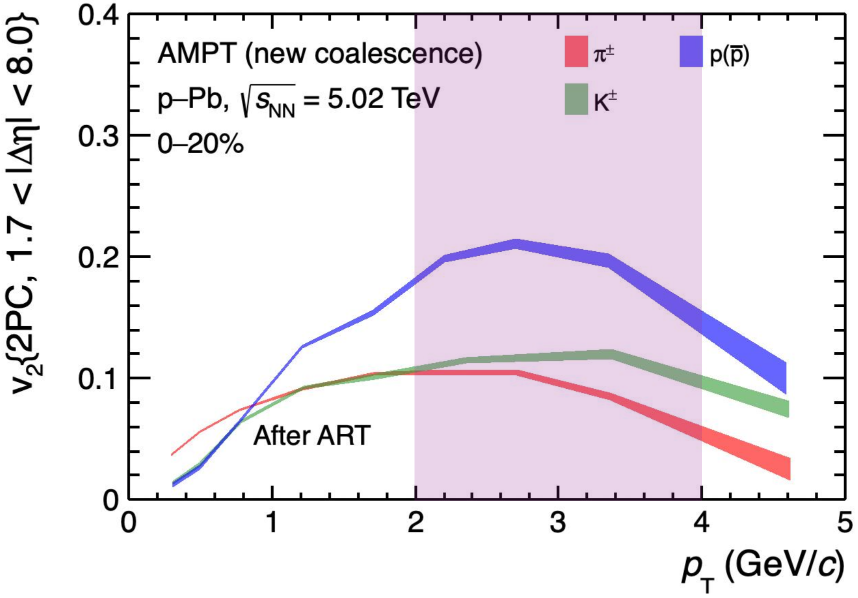




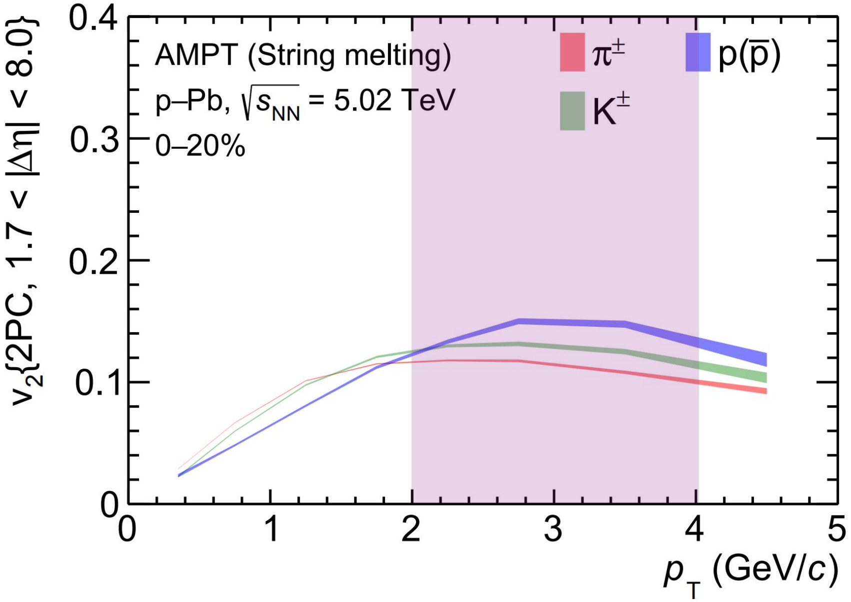
- Non-flow treatment
  - ✓ Long-range correlation + template fit
  - ✓ The modified AMPT model has more non-flow contribution than the hydrodynamics model
  - ✓ Source of non-flow in modified AMPT model is not yet clear

p_T-differential elliptic flow

Modified AMPT (in working progress)



Nucl. Sci. Tech. 35 (2024) 32



v_2 of $\Lambda(\bar{\Lambda})$ is in working progress ...

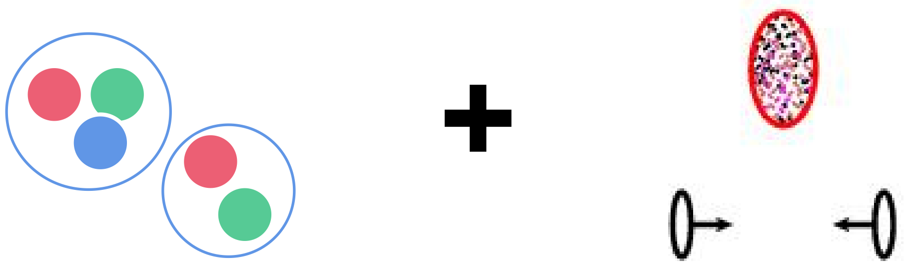
- Results of identified particles v_2 in p + Pb collisions with modified AMPT model
  - ✓ **Baryon-meson splitting effect is enhanced** via the precise quark coalescence mechanism
  - ✓ **Failed to reproduce grouping effect** in p + Pb collisions with precise quark coalescence

    —> **The diluted density** of the evolution systems in transport models could be the reason

Summary

- The bayron-meson grouping/splitting effect can help to probe the partonic flow;
- NCQ scaling is broken;
- Modified AMPT model enhances the baryon-meson splitting, but not reproduces the grouping effect;
- **Dense partonic matter** might be necessary in small collision systems;
- Outlook —> Increase statistics; flatten the gap between default/modified AMPT model.

Precise coalescence



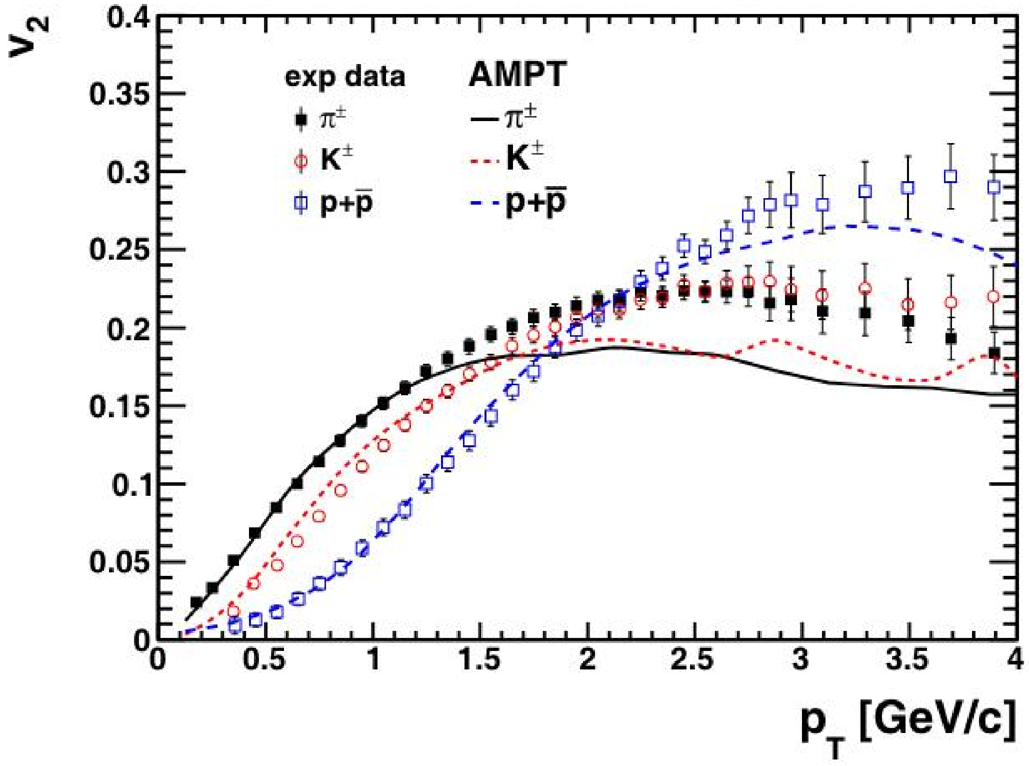
Dense matter

Thank you for your attention!

Backup

Elliptic flow in Pb + Pb collisions

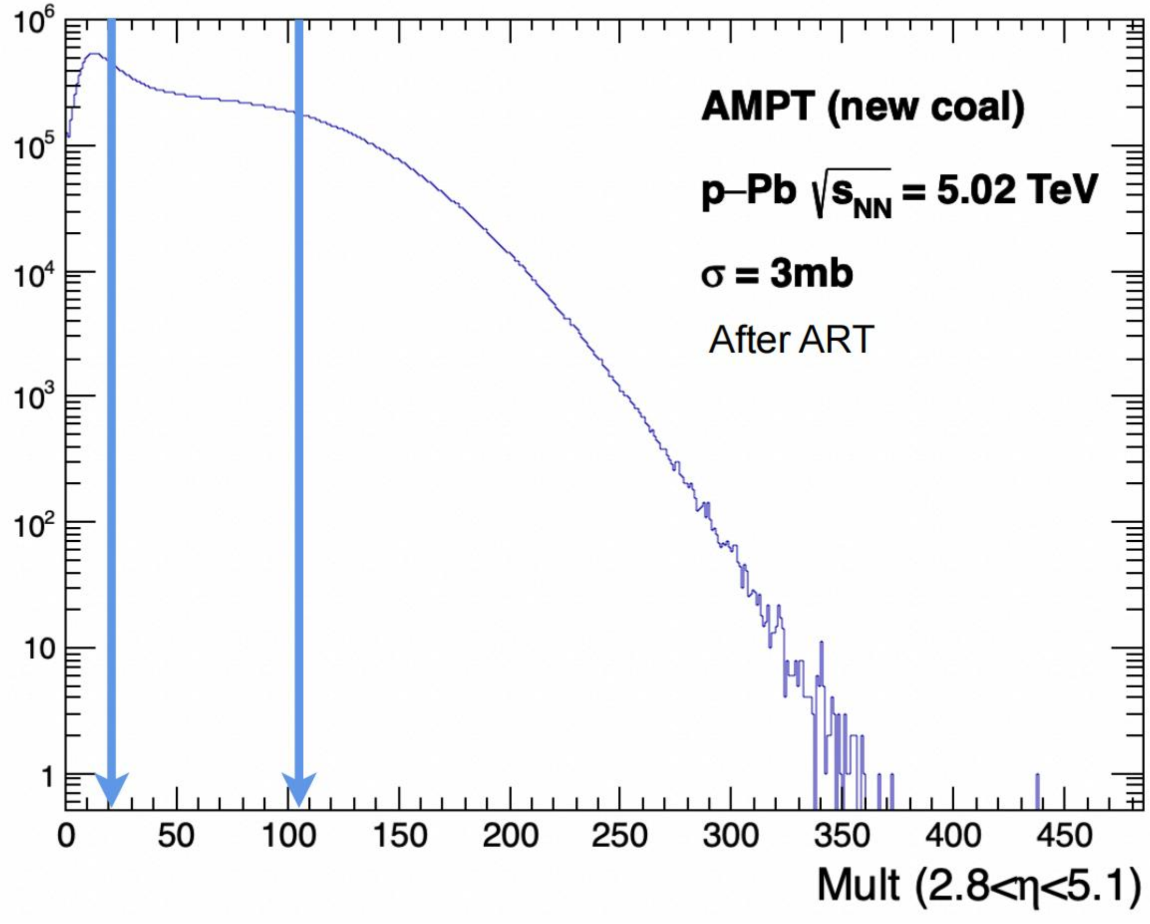
- Elliptic flow in Pb + Pb collisions with AMPT model?
  - ✓ A. Bzdak and G.-L. Ma, Phys. Rev. Lett. 113, 252301 (2014)
  - ✓ N. Mallick, S. Tripathy, and R. Sahoo, Eur. Phys. J. C 82, 524 (2022)
  - ✓ L. Zheng et al., Eur. Phys. J. A 53, 124 (2017)



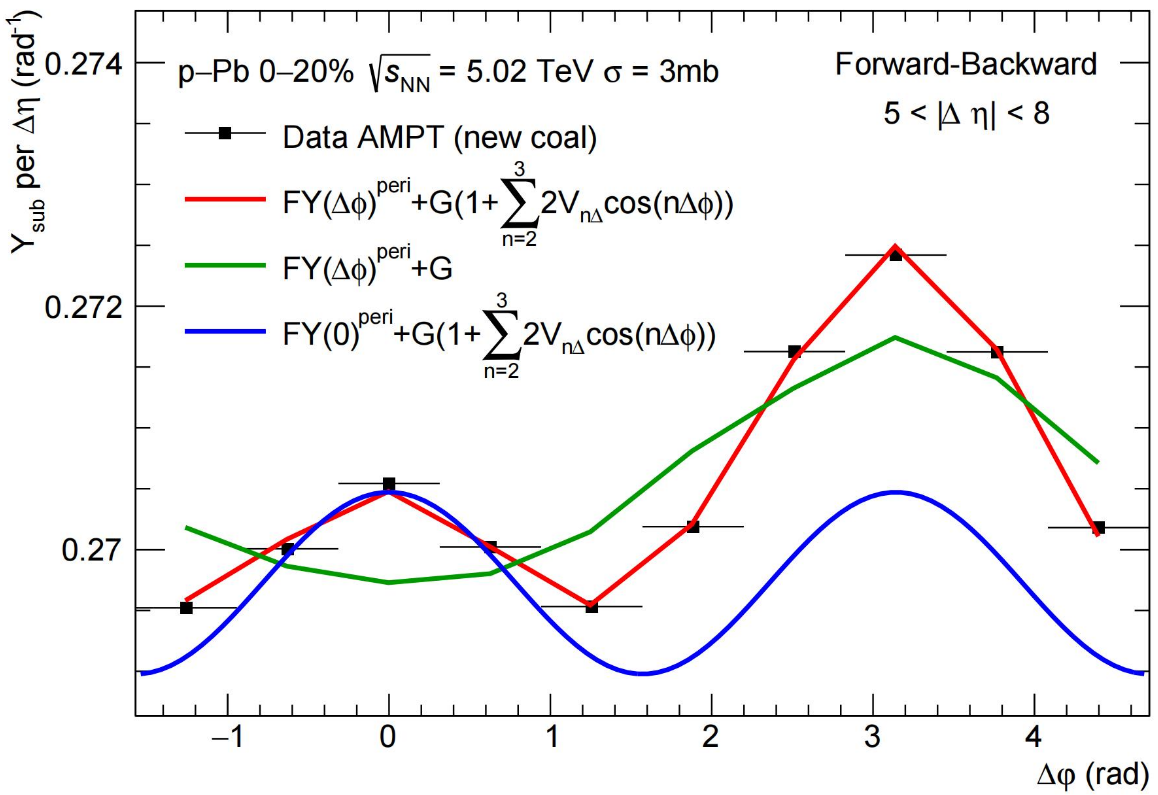
Multiplicity in p + Pb collisions

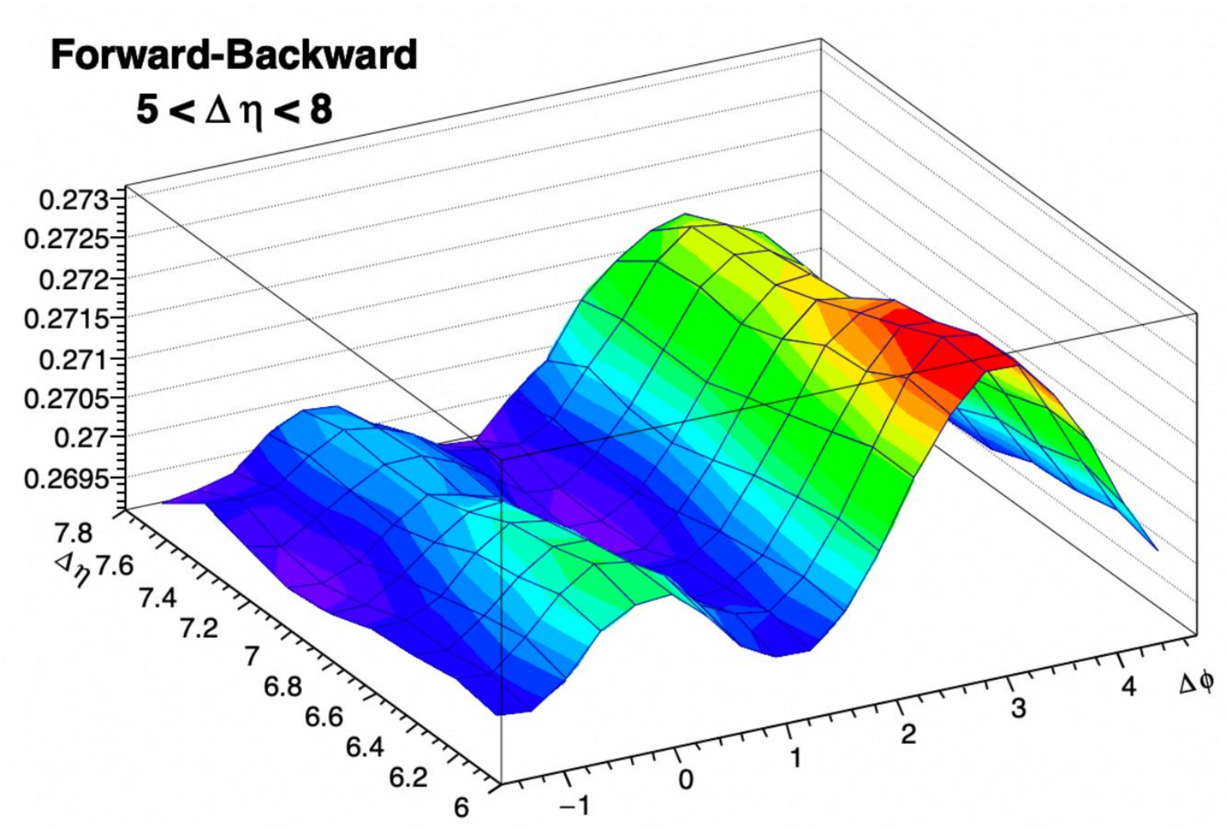
Flow was estimated in: 0-20% (central region), with multiplicity in central region >20

Baseline: 80-100% (Forward region)

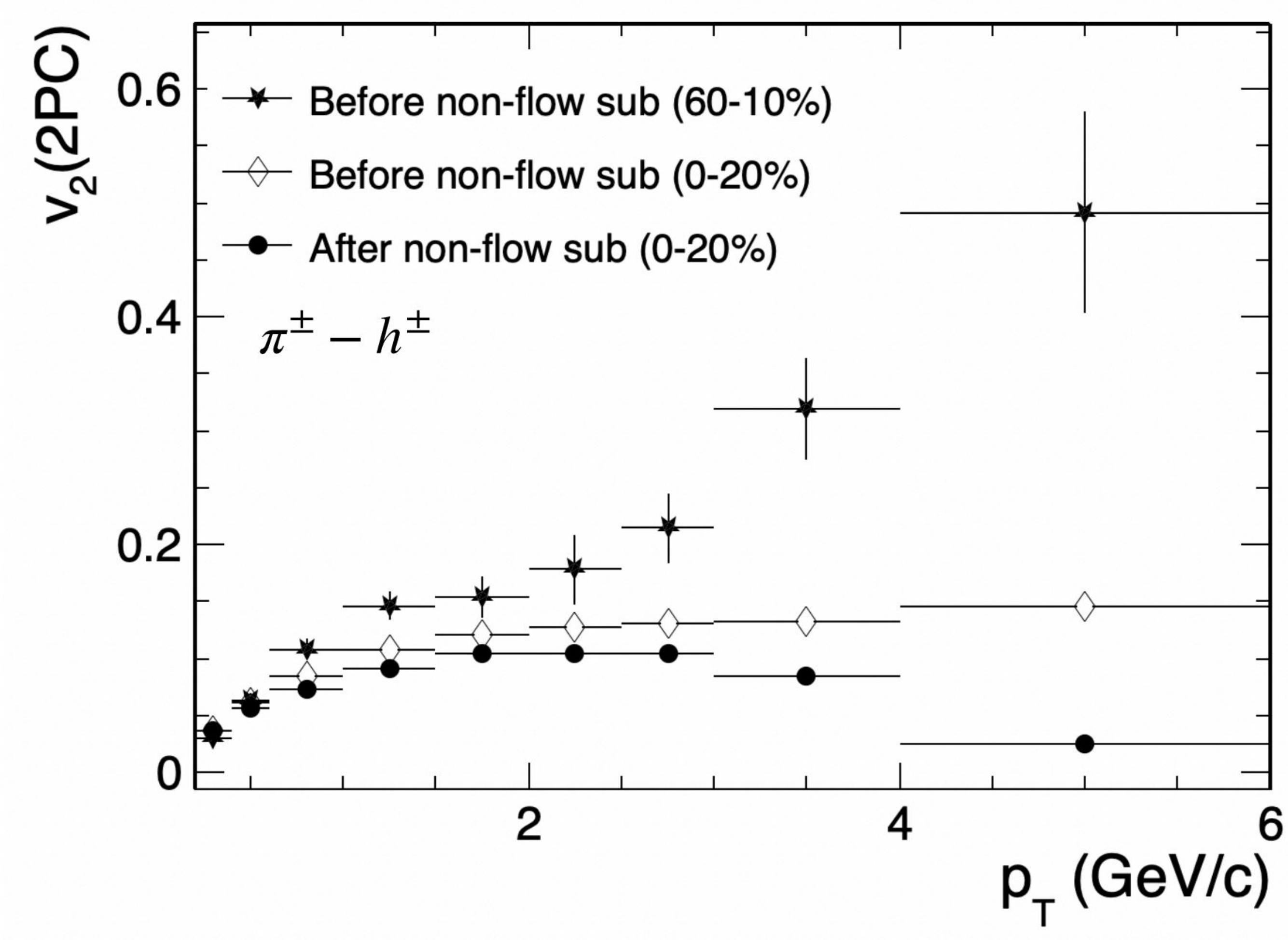


Ultra-long-range correlation





Non-flow in modified AMPT model



Broken of NCQ scaling

ALICE Collaboration, JHEP 06 (2015) 190