中国地质大学

Investigating collective flow in high energy pp collisions with a multi-phase transport model

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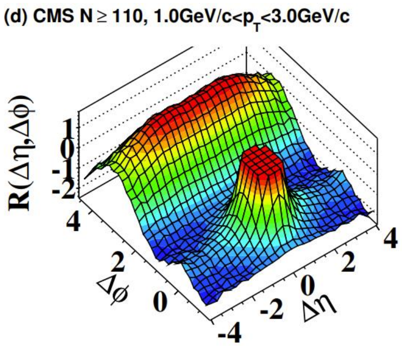
Outline

- Collectivity in small system
- AMPT with PYTHIA8 initial condition and sub-nucleon structures
- Near side long range correlations
- Collective flow in pp collisions

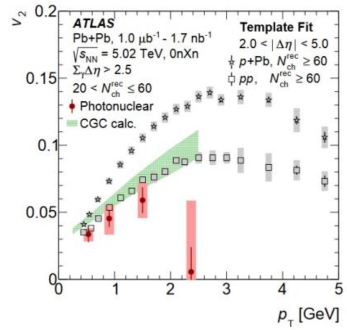
Collectivity in small system

- Long range correlation in high multiplicity pp/pA: “ridge” structure
- Non-zero azimuthal collective flow even in UPC collisions
- Multiplicity dependent strangeness enhancement
- …

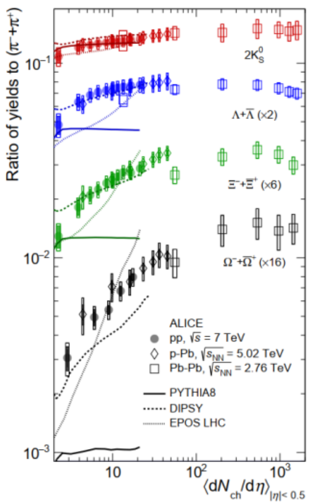
JHEP 09 (2010) 091



PRC 104 (2021) 014903



Nat. Phys. 13 (2017) 535



- Hydrodynamic final state evolution

EPJC 76 (2016) 7, PLB 774 (2017) 351, PLB 780 (2018) 495, EPJC 80 (2020) 9, PRC 101 (2020) 2

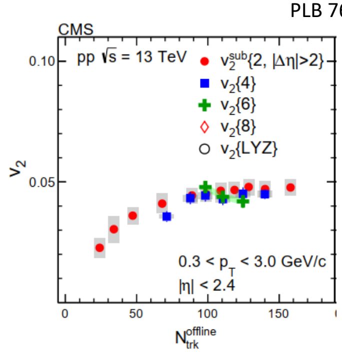
- CGC Initial state correlations

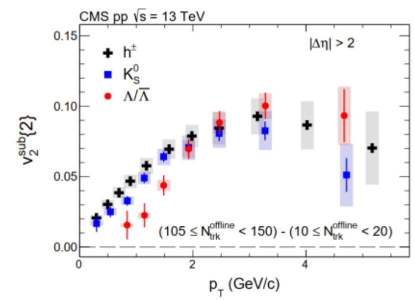
PRL 108 (2012) 262001, PRD 87 (2013) 051502, PRL 117 (2016) 162301

- Collective string effects
  - ☐ color reconnection: PRL 111 (2013) 042001, PRD 92 (2015) 094010
  - ☐ color rope: JHEP 03 (2015) 148, PLB 779 (2018) 58, JHEP 03 (2021) 270
- Parton escape effects

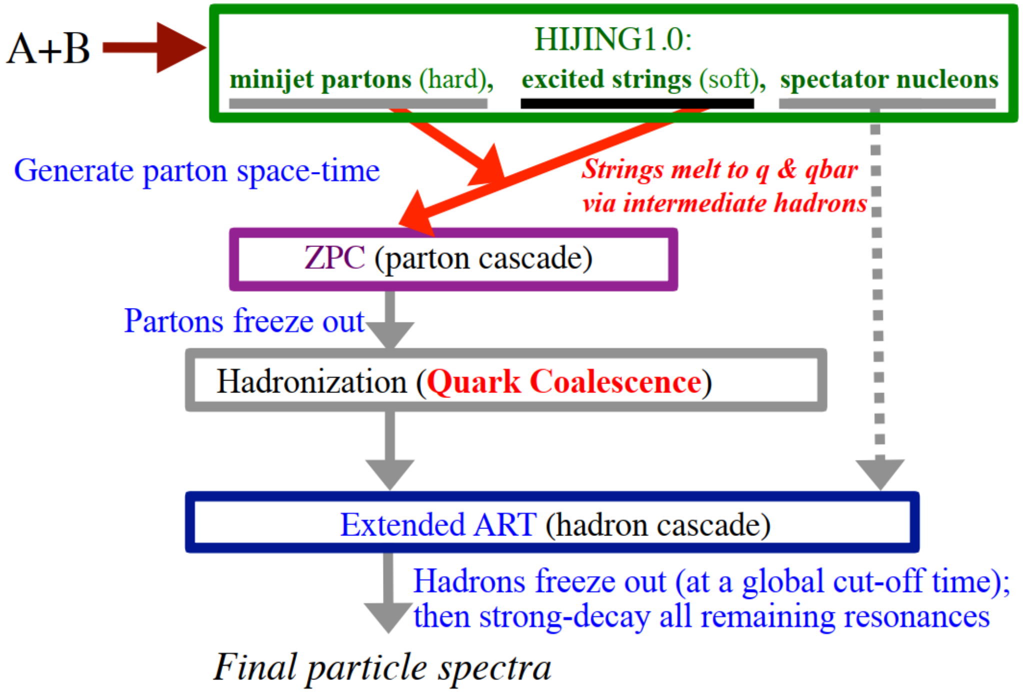
PLB 753 (2016) 506

PLB 765 (2017) 193





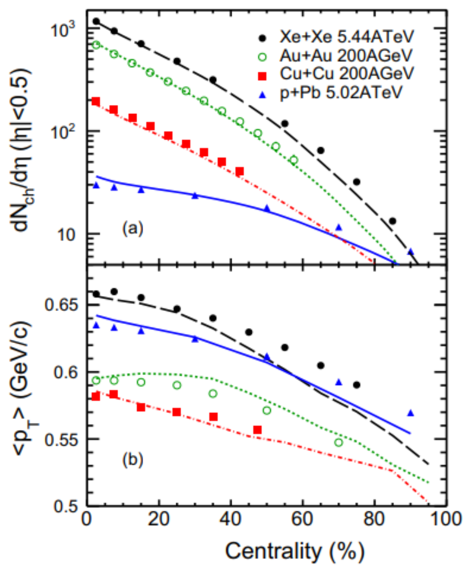
A multi-phase transport model (AMPT)



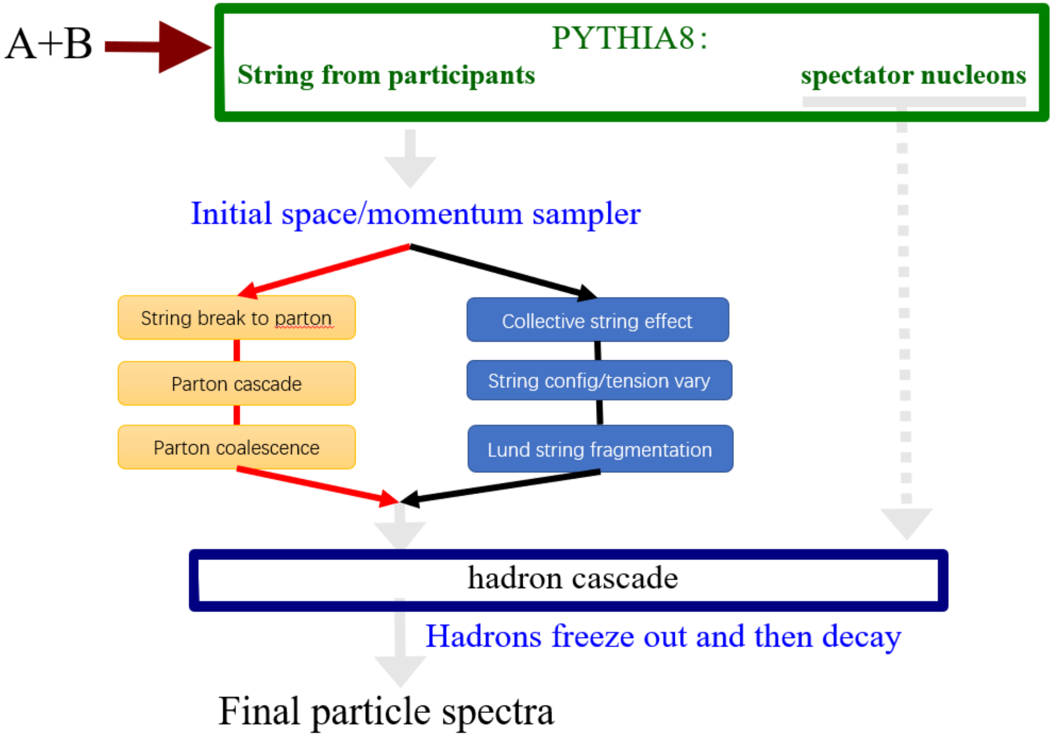
PRC 72 (2005) 064901
Nucl.Sci.Tech. 32 (2021) 113

- AMPT has been extensively applied in collectivity study for large systems
- System size dependence has been improved recently

PRC 104 (2021) 014908



AMPT x PYTHIA8



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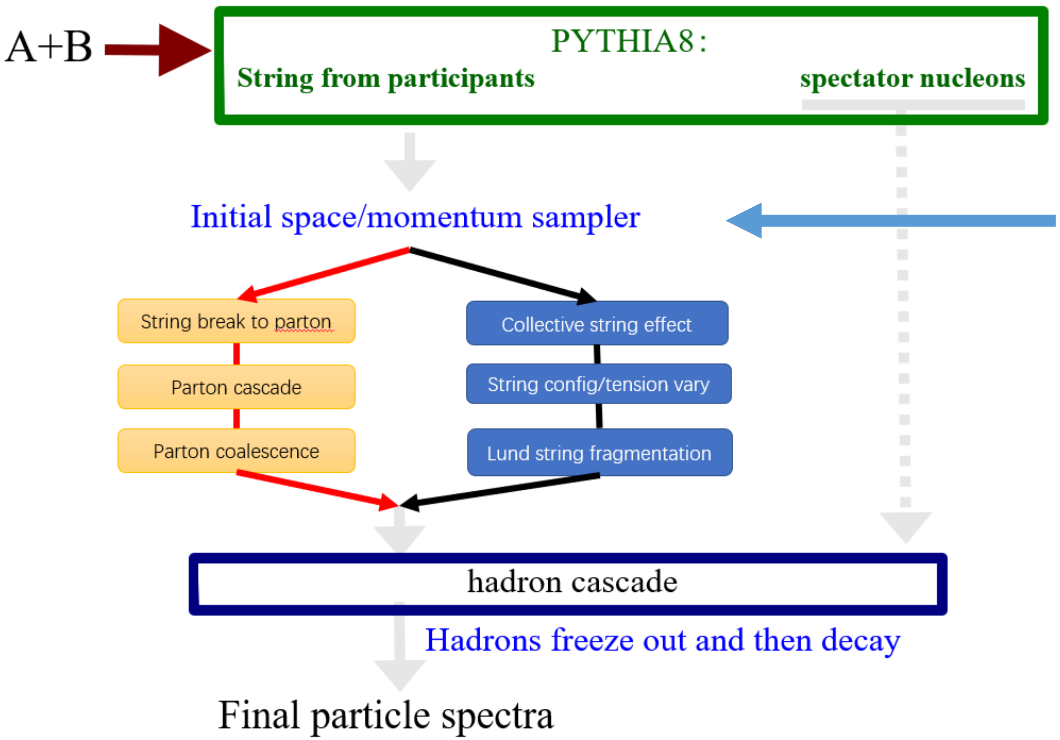
- Impact parameter dependent string system well developed in PYTHIA8/Angantyr framework
- Possible to compare parton transport and inter-string effects on the same basis

Sub-nucleon structure



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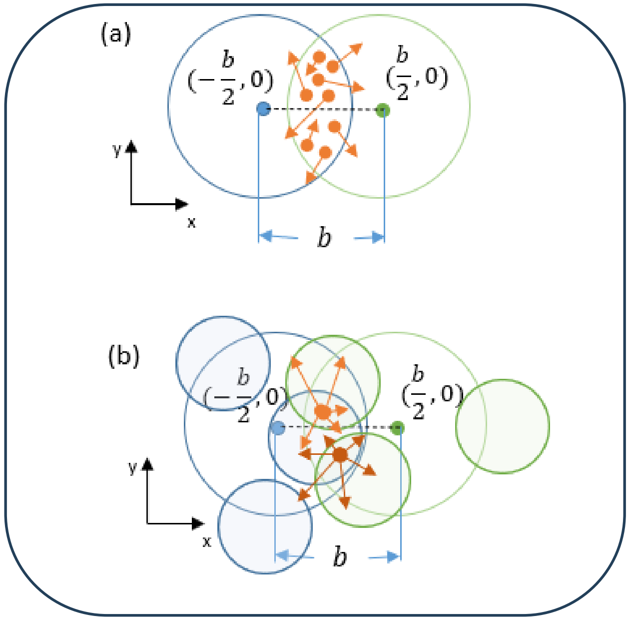
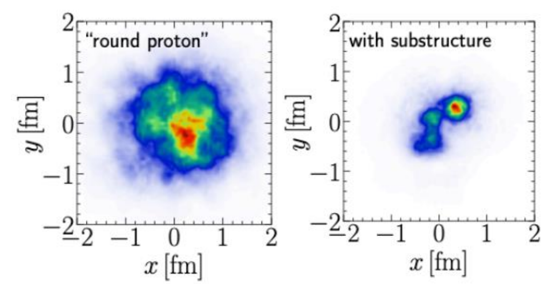
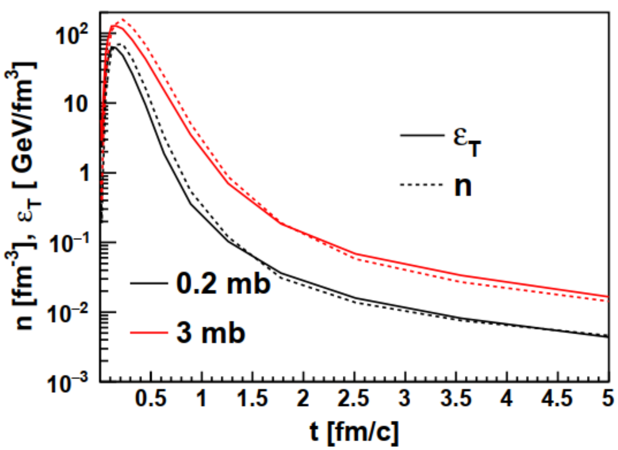




Rept.Prog.Phys. 84 (2021) 082301

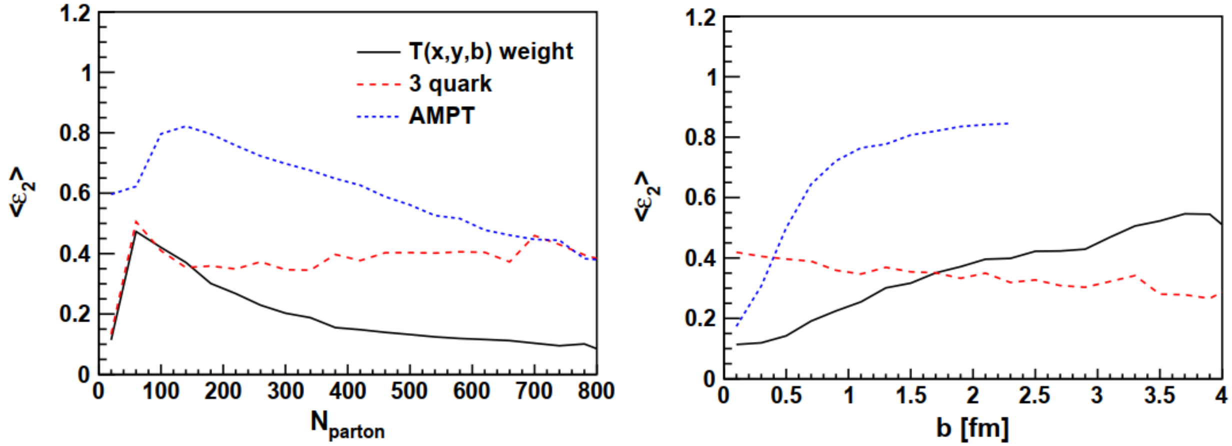
Space-time evolution

- Different features of spatial eccentricity distribution
- Rather flat eccentricity with sub-nucleon fluctuation (slightly increasing towards high multiplicity/central events)
- Energy density above ~ 1GeV/fm^3, within t<1 fm/c.



EPJC 81 (2021) 8, 755

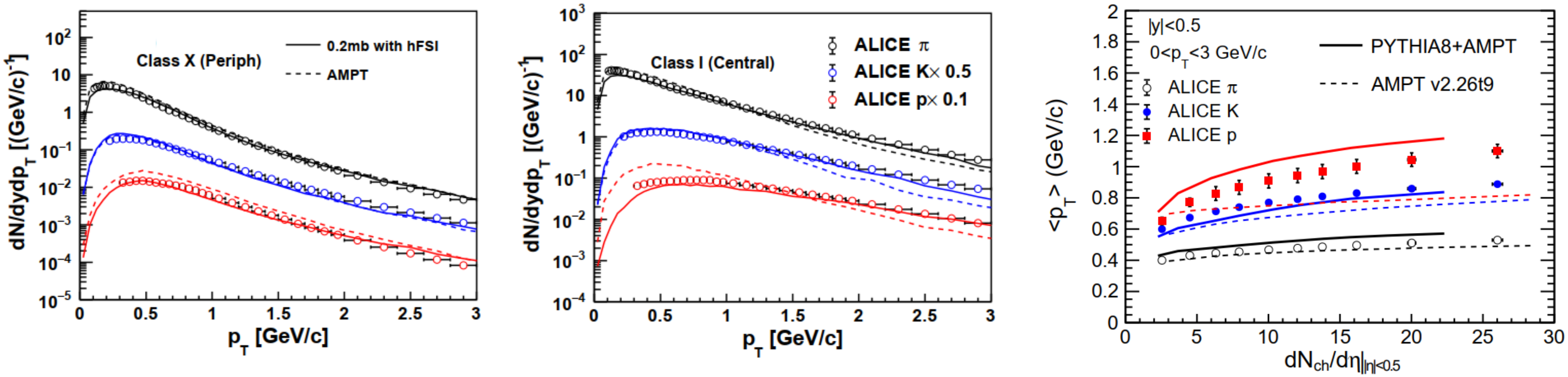
pp 13 TeV, parton level



Compared to original AMPT

- Original AMPT fails to describe the multiplicity dependence
- Improvement may come from the MPI based PYTHIA8 initial condition

pp 13 TeV, hadron level

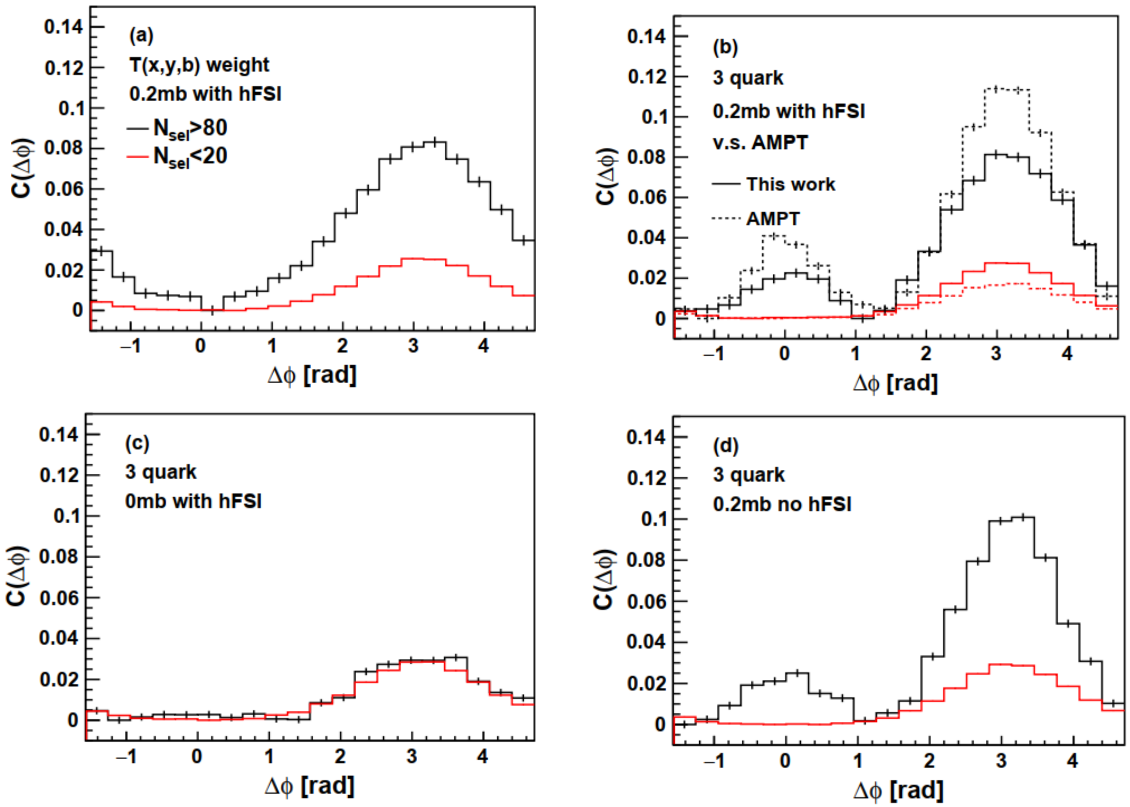


EPJC 81 (2021) 8, 755

Two particle correlation

pp 13 TeV, charged hadron
$1<p_T<3$ GeV/c, $|\Delta\eta|>2$

- Near side ridge appears with sub-nucleon fluctuation
- Significant ridge also shows in AMPT due to its large initial eccentricity
- Robust HM ridge developed in parton evolution stage



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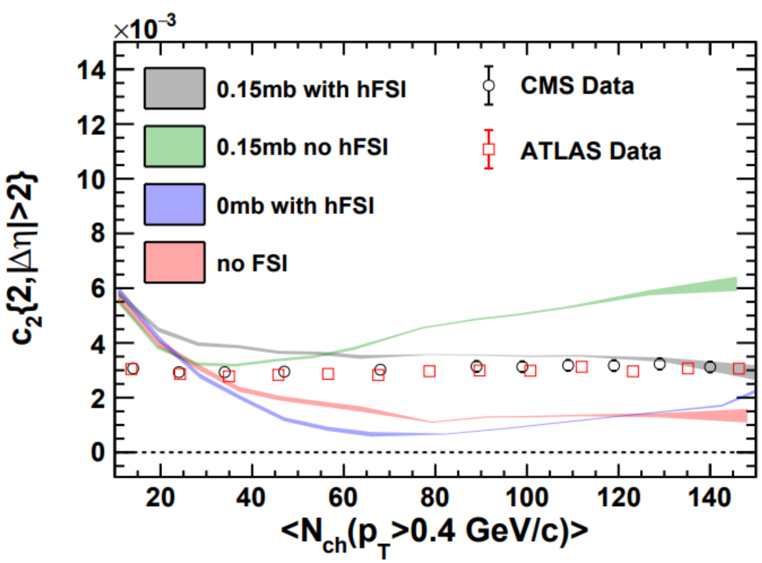
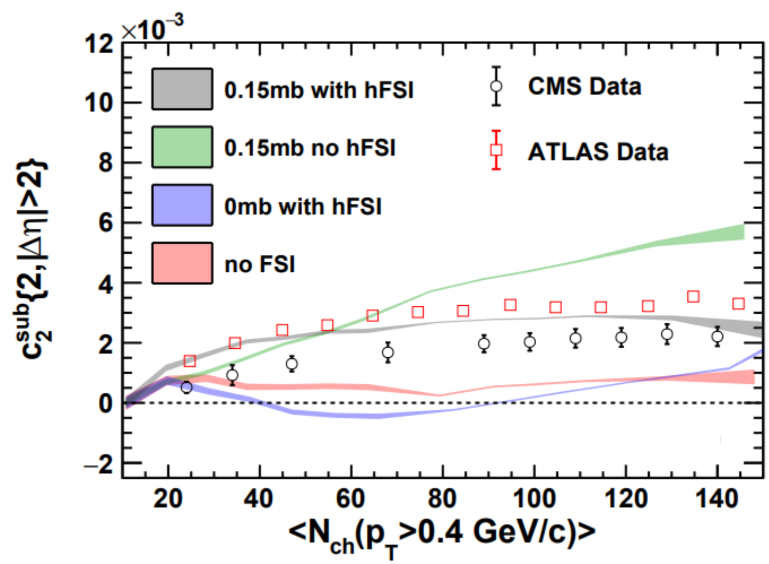
Two-particle cumulants

- Low multiplicity dominate by non-flow effects
- Final state parton rescattering leads to sizable $c_2\{2\}$
- Non-flow effectively subtracted with low multiplicity events
- With all FSI, data behavior well captured





$$Q_n = \sum_{i=1}^{M} e^{in\phi_i} \qquad c_n\{2, |\Delta\eta|\} = \langle\langle 2\rangle\rangle_{\Delta\eta}$$

$$\langle 2\rangle_{\Delta\eta} = \frac{Q_n^A \cdot Q_n^{B*}}{M_A \cdot M_B}$$

$$c_n^{sub}\{2, |\Delta\eta|\} = c_n\{2, |\Delta\eta|\} - k \cdot c_n^{low}\{2, |\Delta\eta|\}$$

$$k = \langle M\rangle^{low} / \langle M\rangle$$

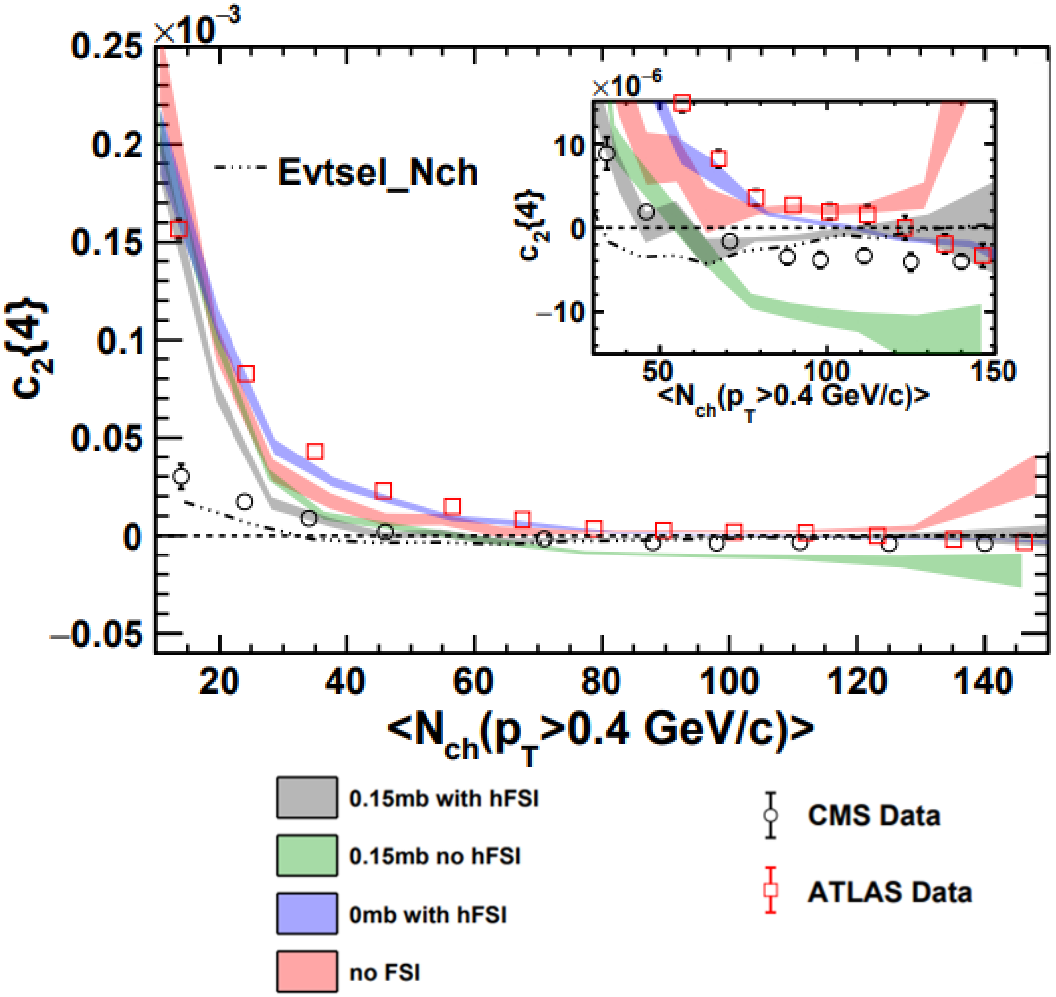
Four-particle cumulants

- Parton rescattering leads to the most significant negative $c_2\{4\}$
- Sign change dependent on multiplicity observed in the model calculations
- Data discrepancy due to different event averaging treatment well described in the model

$$\langle 2\rangle = \frac{|Q_n|^2 - M}{M(M-1)},$$

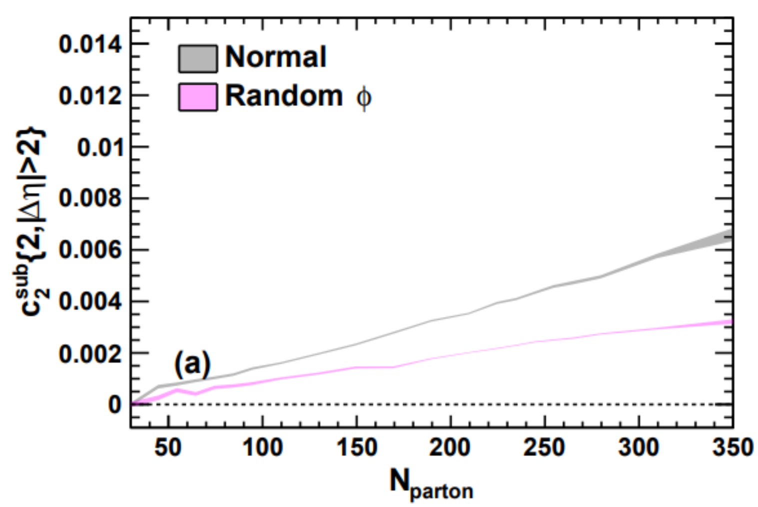
$$\langle 4\rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\cdot Re[Q_{2n}Q_n^*Q_n^*]}{M(M-1)(M-2)(M-3)} - 2\frac{2(M-2)\cdot|Q_n|^2 - M(M-3)}{M(M-1)(M-2)},$$

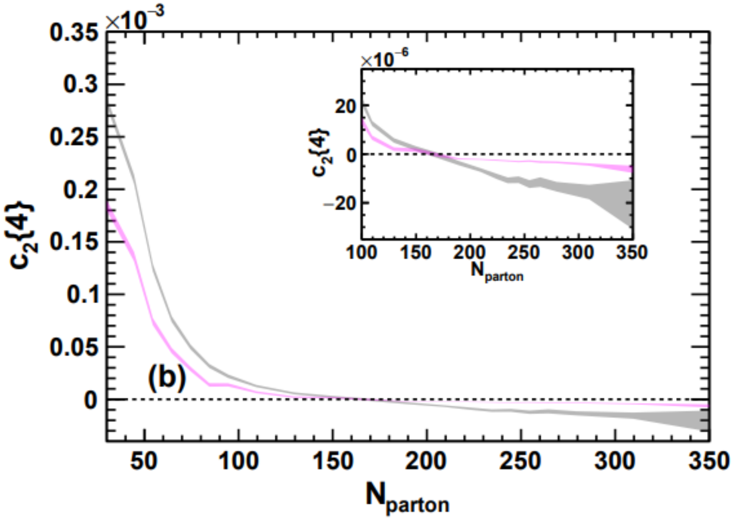
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2,$$



Parton escape effects

- Sizable contribution from parton escape, decreases with event multiplicity
- Sign change of $c_2\{4\}$ can be related to the parton escape mechanism





p_T differential elliptic flow for charge particle

- Sizable elliptic flow induced by parton level evolutions
- Hadronic interactions generally reduce the flow magnitude
- Negligible flow with only hadronic scattering or no FSI

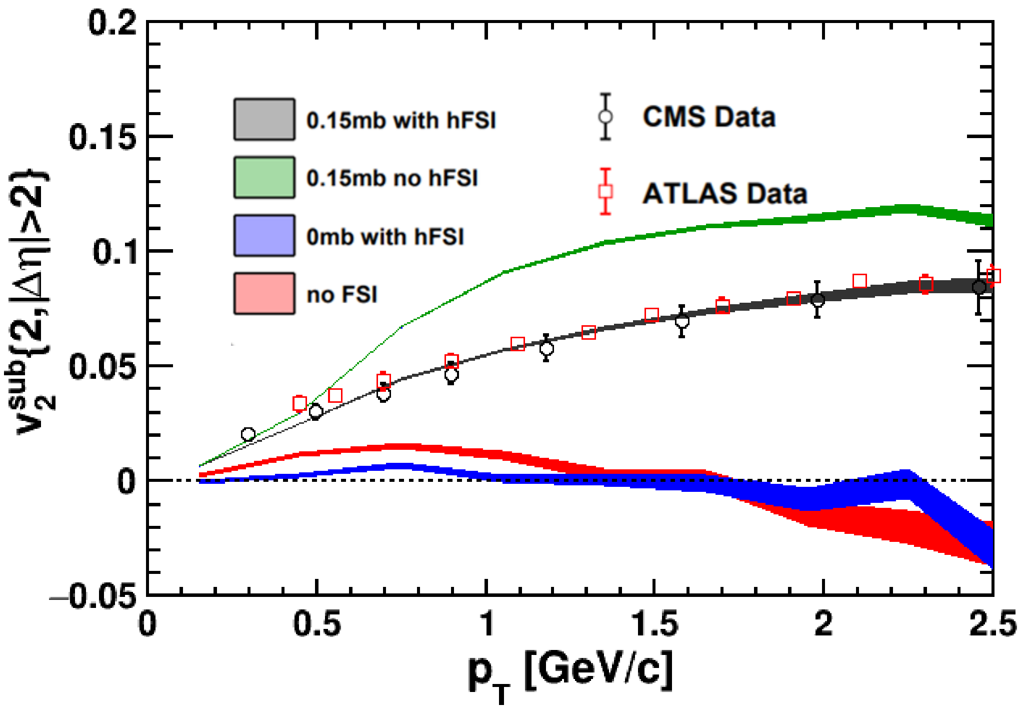
$$p_n = \sum_{i=1}^{m_p} e^{in\phi_i}$$

$$\langle 2' \rangle_{\Delta\eta} = \frac{p_{n,A} Q^*_{n,B}}{m_{p,A} M_B}$$

$$d_n\{2, |\Delta\eta|\} = \langle\langle 2' \rangle\rangle_{\Delta\eta}$$

$$v_n^{sub}\{2, |\Delta\eta|\} = \frac{d_n\{2,|\Delta\eta|\} - k \cdot d_n^{low}\{2,|\Delta\eta|\}}{\sqrt{c_n\{2,|\Delta\eta|\} - k \cdot c_n^{low}\{2,|\Delta\eta|\}}}$$

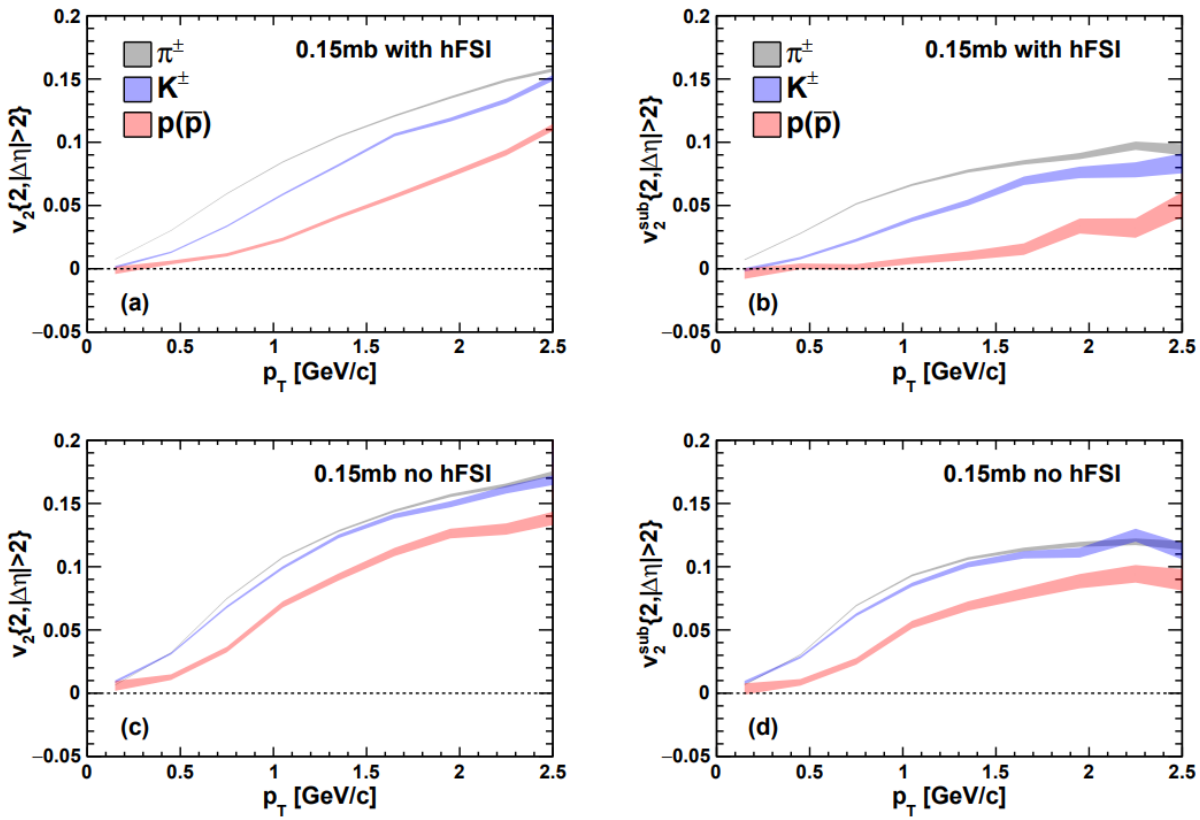
Elliptic flow in high multiplicity events (M>100)



Elliptic flow for identified particles

- Significant mass ordering at low p_T w/ or w/o low multiplicity subtraction
- Hadronic FSI coupled to parton evolutions further enlarge the mass ordering feature

Elliptic flow in high multiplicity events (M>100)



Summary

- Collectivity in small systems has been stimulating for new theoretical and experimental developments in QGP studies.
- Further improvements have been implemented in the AMPT framework to reach better description for small system.
- Sub-nucleon fluctuations can be important to understand the collective effects developed in small system collisions.
- Collective flow in pp collisions may be related to the existence of final state parton evolutions.
- Strong mass ordering of identified hadron elliptic flow can be regarded as important signature to expose the parton collectivity in pp collisions.

Back up

Elliptic flow in pp collisions

- Sub-nucleon structure provides more realistic multiplicity dependence of elliptic flow in pp collisions
- Negative 4-particle correlation appears with the transport model framework. What is the origin?
- Non-trivial final state cross section dependence revealed in $c_2\{4\}$

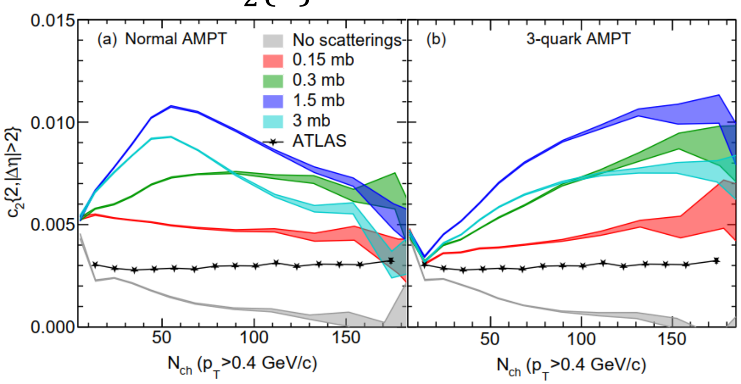
pp 13 TeV, charged hadron, $0.3<p_T<3$ GeV/c, $|\triangle\eta|>2$

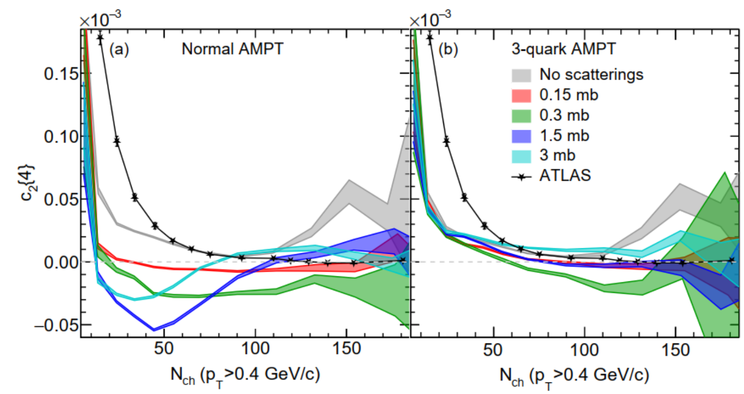
$$C_2\{4\} = -2\langle v_2^2\rangle^2 + \langle v_2^4\rangle$$
$$= -\langle v_2\rangle^4 + 2\sigma_{v2}^2\langle v_2^2\rangle^2 + \sigma_{v2}^2$$

$$(v_2 = \langle v_2\rangle + \sigma_{v2})$$

$$v_2\{4\} = (-c_2\{4\})^{\frac{1}{4}}$$

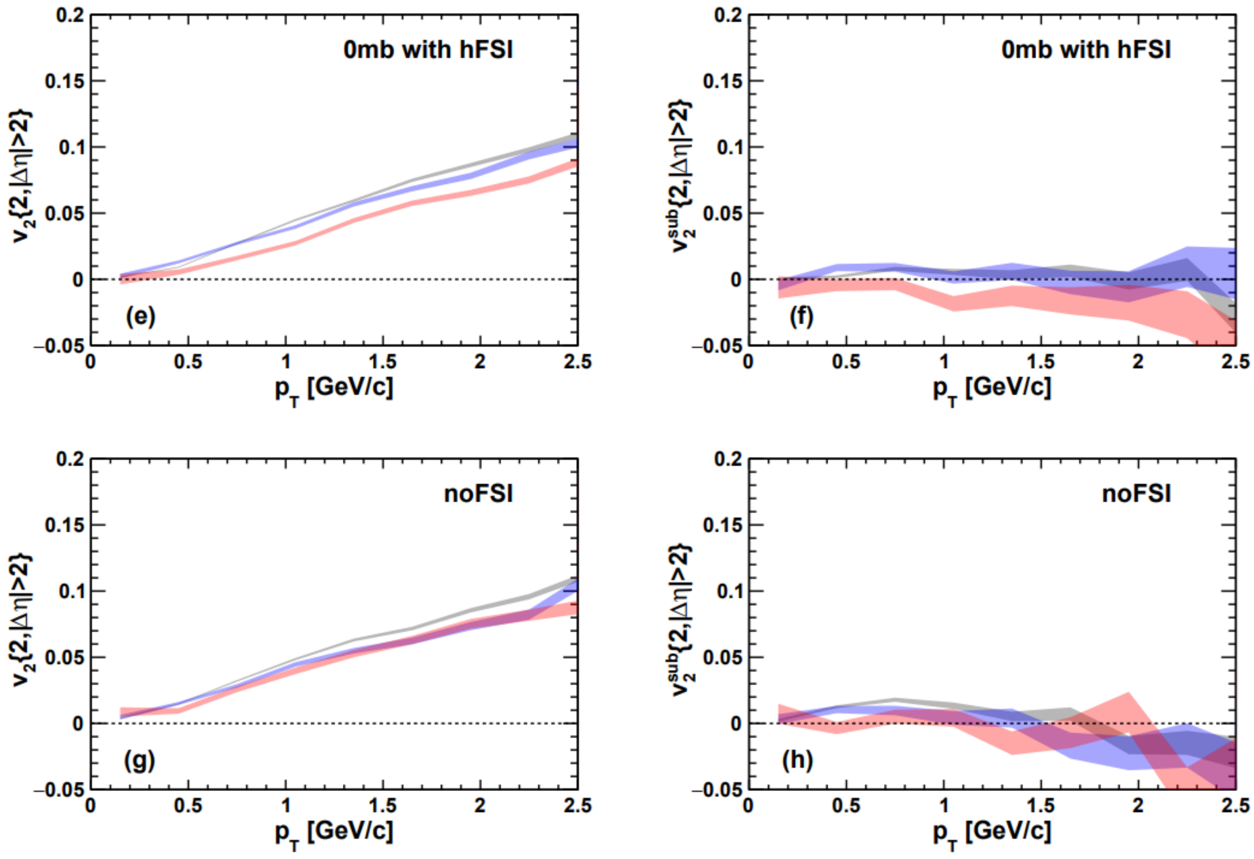
To get the real value of $v_2\{4\}$, $c_2\{4\}$ should be negative.





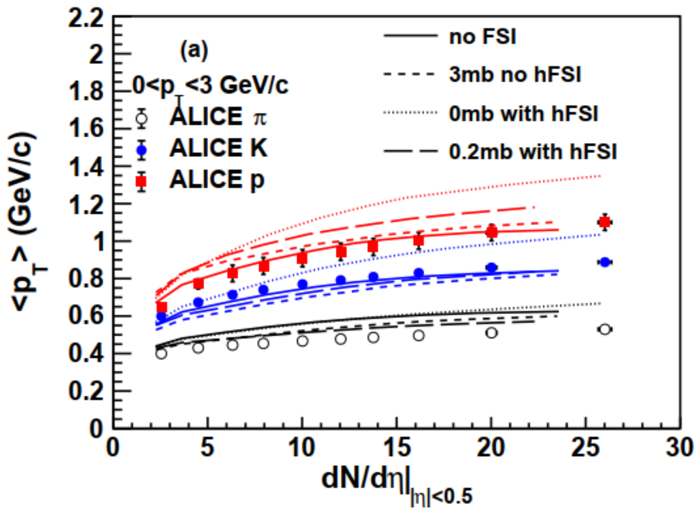
arXiv:2112.01232

Elliptic flow for identified particles



Final state interaction(FSI) in pp collisions

- Average transverse momentum increased due to hadron rescattering
- Proton receives stronger p_T boost compared to pi/K
- Parton rescattering slightly modifies the spectra

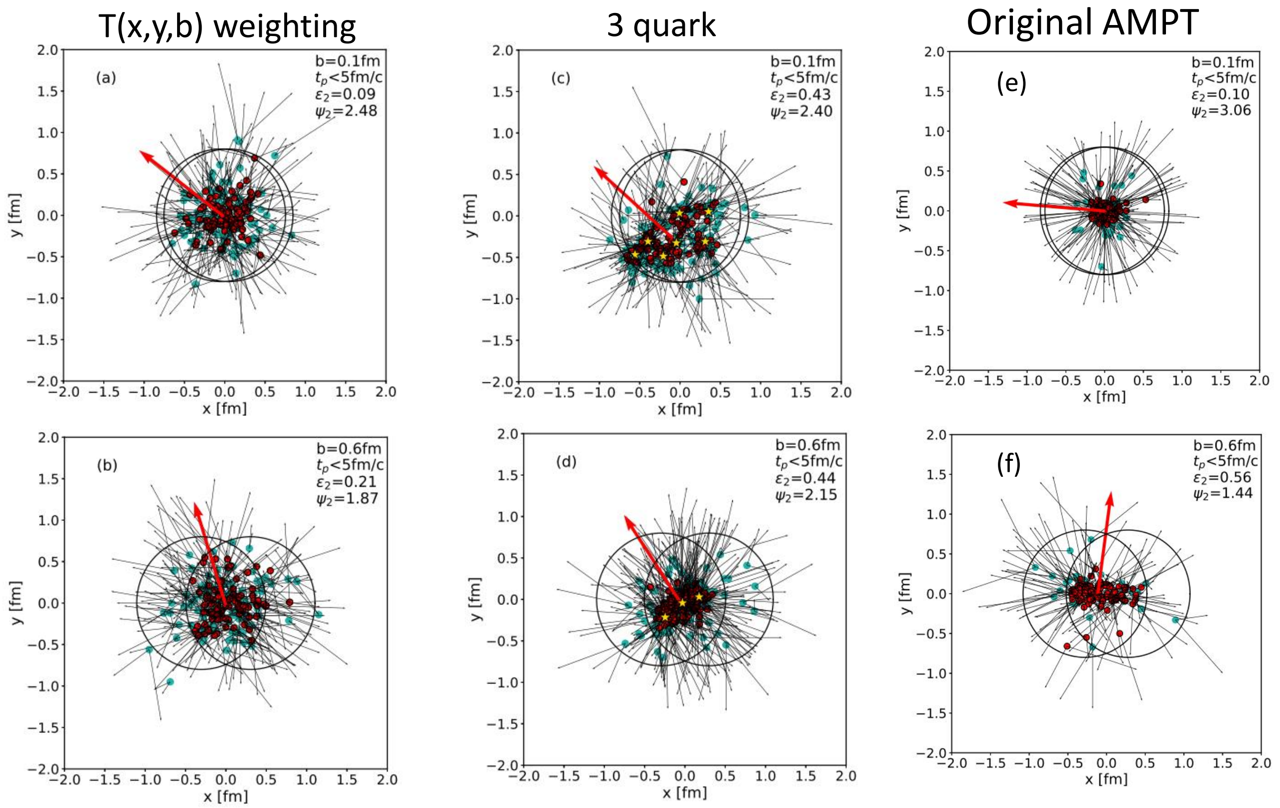


Space-time structure

pp 13 TeV, N_{parton}>600

- T(x, y, b) weighting
  Overlap geometry driven
- 3 quark
  Sub-nucleon fluctuation

- Original AMPT
  Parton sources
  aligned in a row



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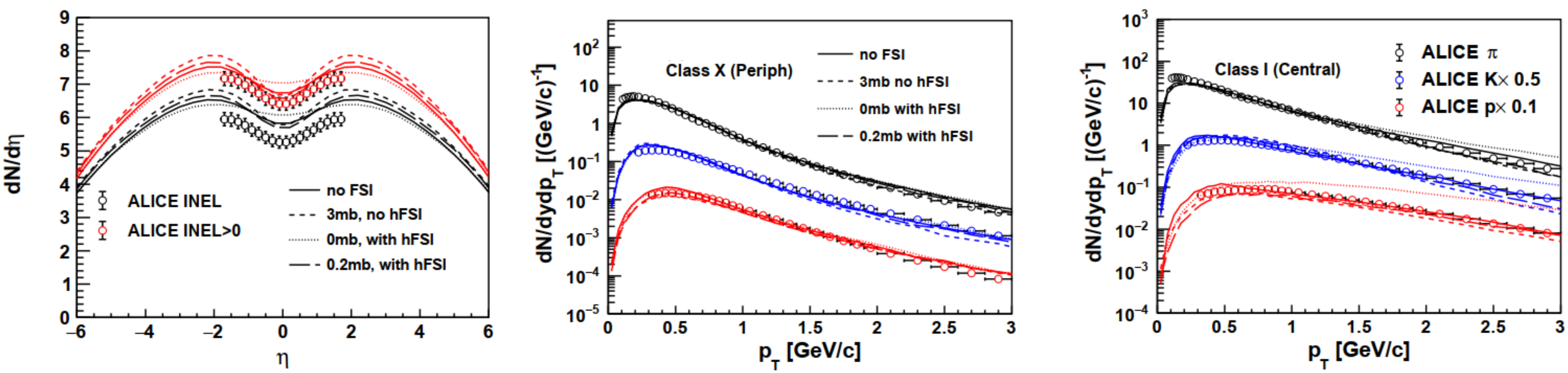
Final state interaction(FSI) in pp collisions

- Final state interaction effects weak in charge density
- Stronger FSI in high multiplicity events
- Radial flow like contribution from final state hadron interaction

pp 13 TeV, hadron level



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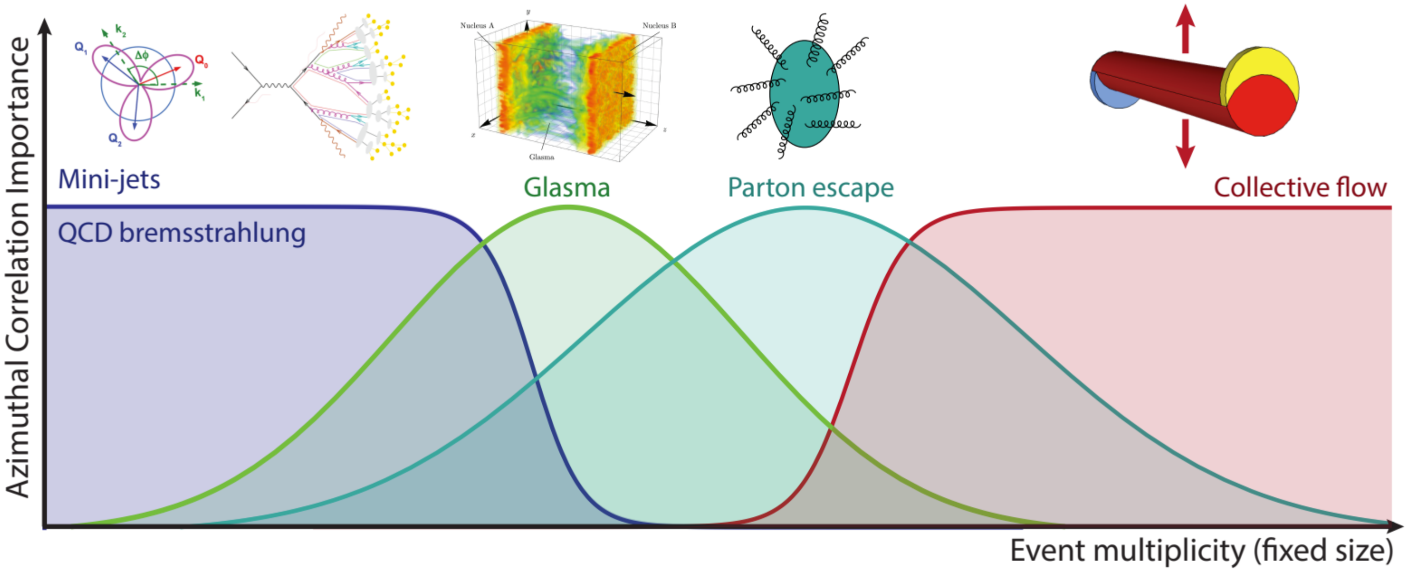
Collectivity in small system

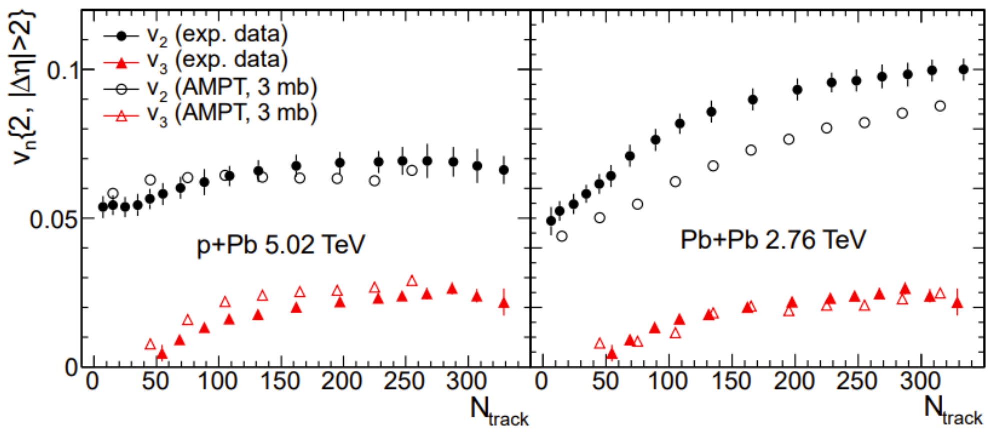
Multiple sources of azimuthal anisotropy

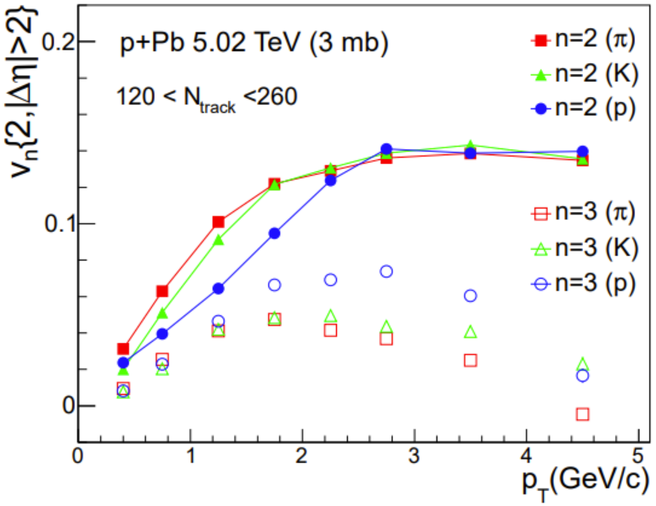


NPA 982 (2019) 92
arXiv:1807.07191

Collectivity in small system with AMPT

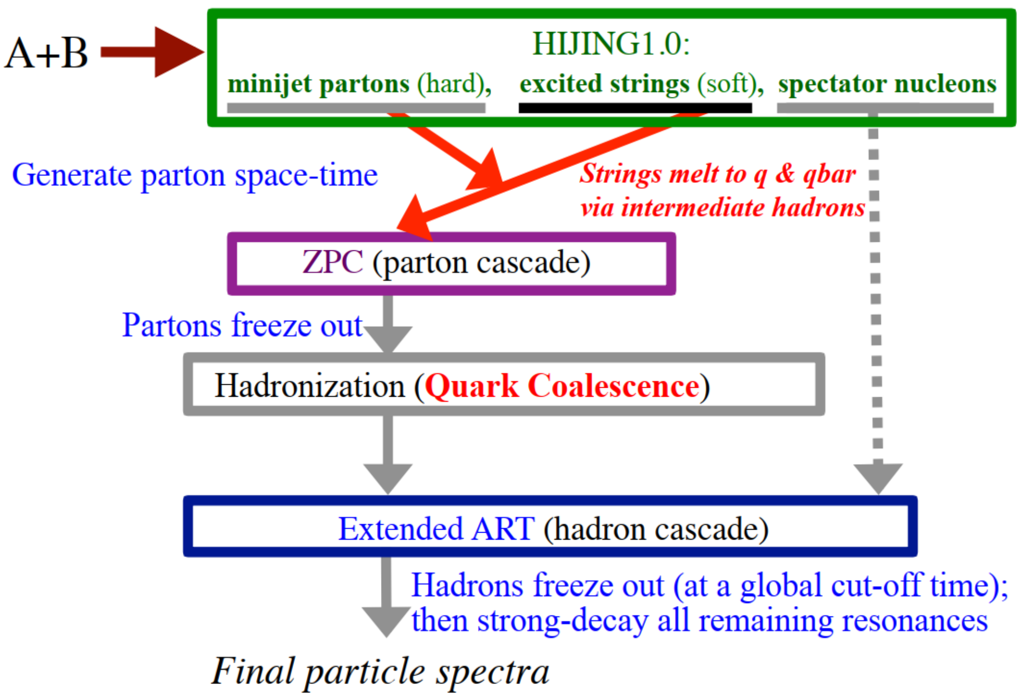
pA collective flow well described by AMPT





PRL 113 (2014) 252301
arXiv:1406.2804

A multi-phase transport model (AMPT)



PRC 72 (2005) 064901
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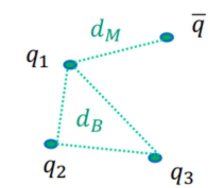
Hadronization spatial coalescence

A parton finds the closest partner (meson & baryon) in space to form a hadron (in rest frame):

d_M: closest anti-quark partner
d_B: average distance among 3 quark with closest q_2 & q_3



If $d_B < d_M * r_{BM}$, q_1 will coalesce to a baryon;
otherwise, q_1 will coalesce to a meson.

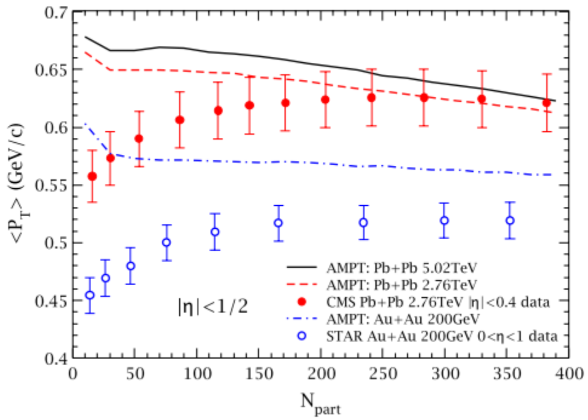
→ Single coalescence parameter r_{BM}

System size dependence in AMPT

Key model parameters related to initial conditions depend on energy and system size

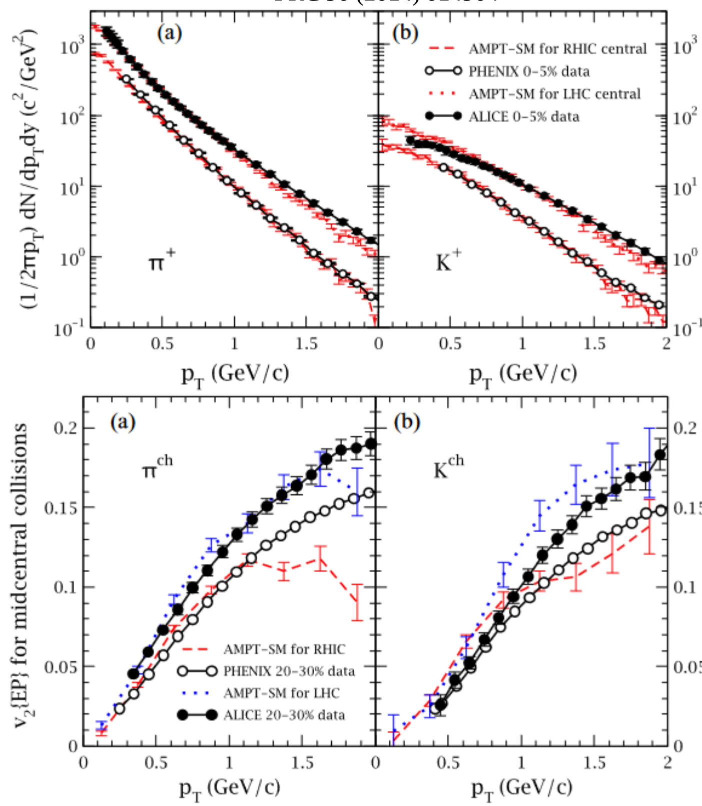
RHIC 200GeV a=0.55, b=0.15

LHC 2.76/5.02TeV a=0.3, b=0.15



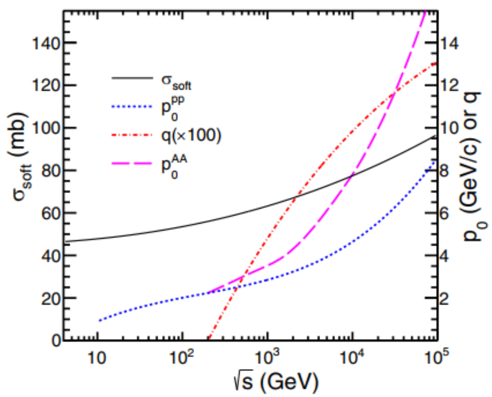
PRC 93 (2016) 054911

PRC 90 (2014) 014904

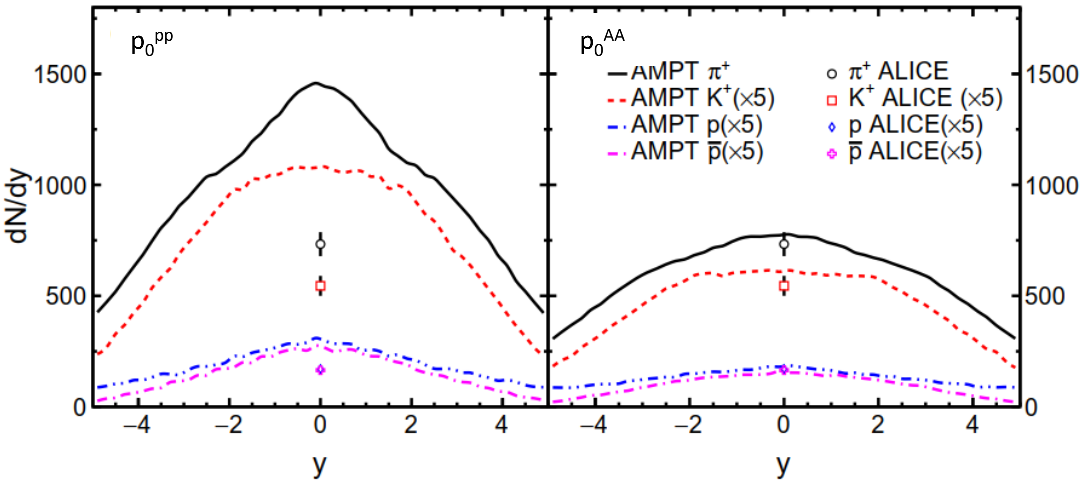


System size dependence in AMPT

- Unified energy dependence parameterized for pp and central AA collisions



PRC 99 (2019) 6, 064906



$$p_0^{AA}(s) = p_0^{pp}(s) A^{q(s)}$$

$$Q_s \propto A^{1/6}$$

$$q(s) = 0.0334 \ln\left(\frac{\sqrt{s}}{E_0}\right) - 0.00232 \ln^2\left(\frac{\sqrt{s}}{E_0}\right) + 0.0000541 \ln^3\left(\frac{\sqrt{s}}{E_0}\right), \text{for} \sqrt{s} \geq E_0 = 200\text{GeV}.$$

System size dependence in AMPT

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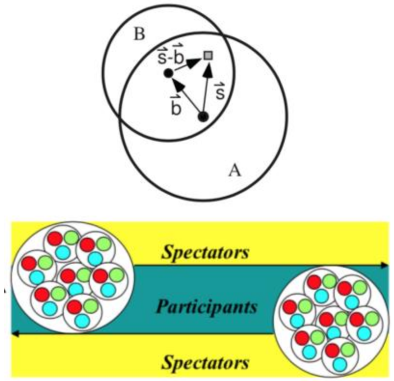
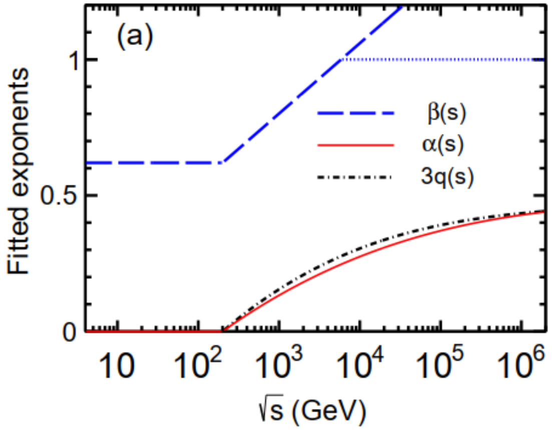
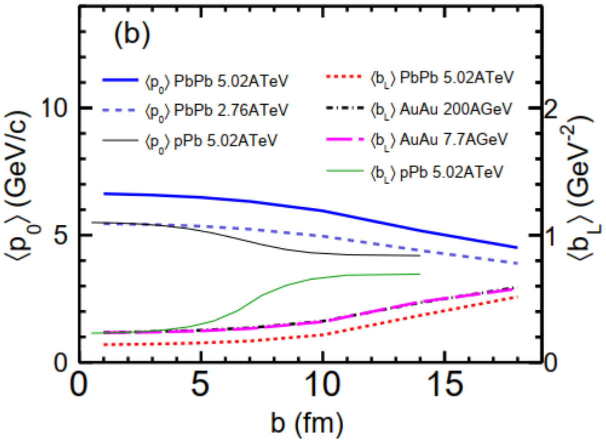
- Local thickness scaling







$$p_0(s_A, s_B, s) = p_0^{pp}(s)\left[\sqrt{T_A(s_A)T_B(s_B)}/T_p\right]^{\alpha(s)}$$

$$\alpha(s) = 0.0918 \ln\left(\frac{\sqrt{s}}{E_0}\right) - 0.00602 \ln^2\left(\frac{\sqrt{s}}{E_0}\right) + 0.000134 \ln^3\left(\frac{\sqrt{s}}{E_0}\right), \text{ for } \sqrt{s} \geq E_0,$$

$$b_L(s_A, s_B, s) = \frac{b_L^{pp}}{\left[\sqrt{T_A(s_A)T_B(s_B)}/T_p\right]^{\beta(s)}}$$

$$\beta(s) = 0.620 + 0.112 \ln\left(\frac{\sqrt{s}}{E_0}\right)\Theta(\sqrt{s} - E_0)$$

System size dependence in AMPT

- System size dependence from pA to AA implemented via the local thickness scaling
- Charged hadron productions across different systems well described
- No more system dependent free model parameters

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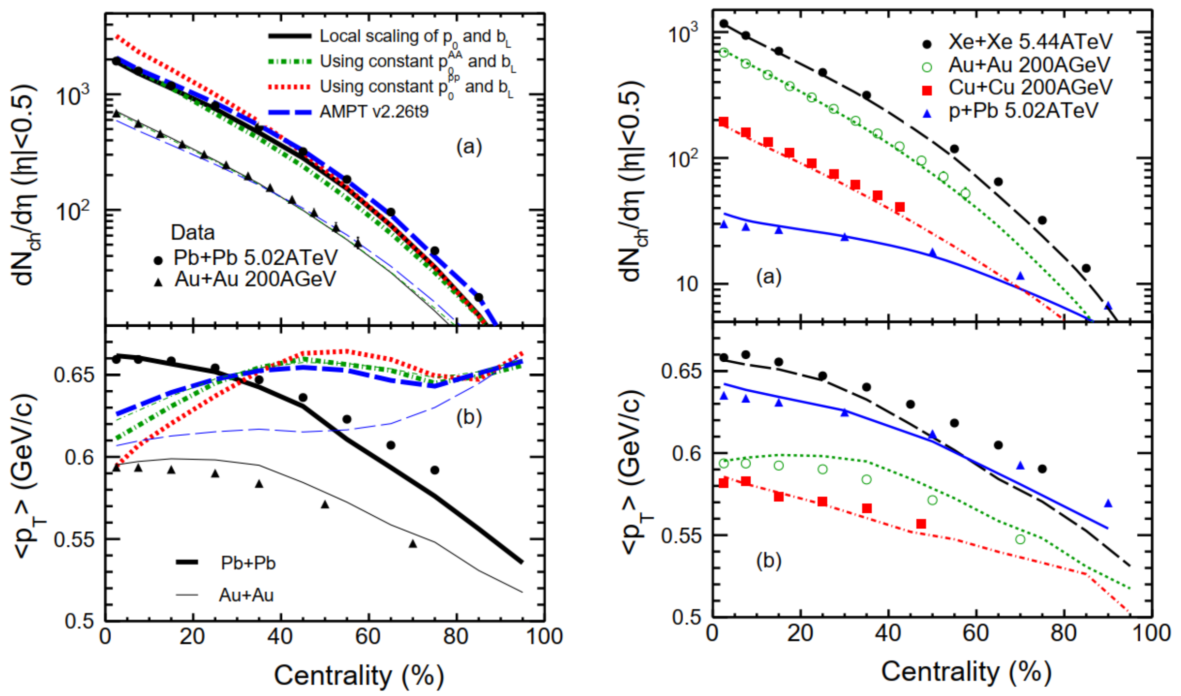
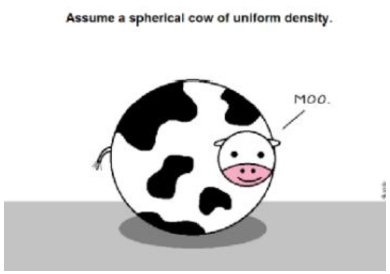
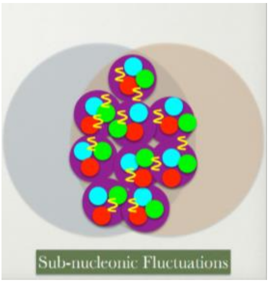
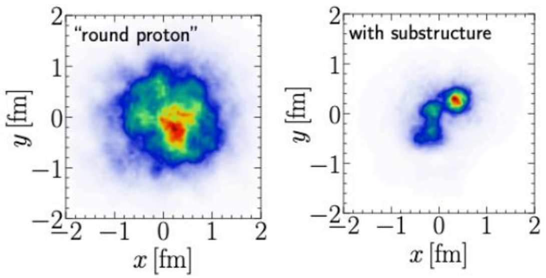


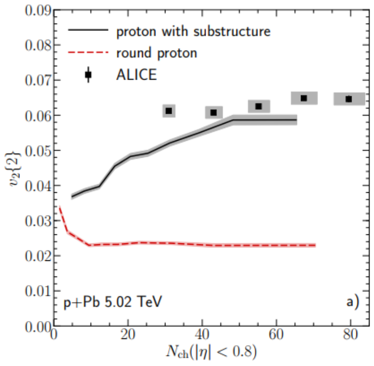
Sub-nucleon spatial fluctuations

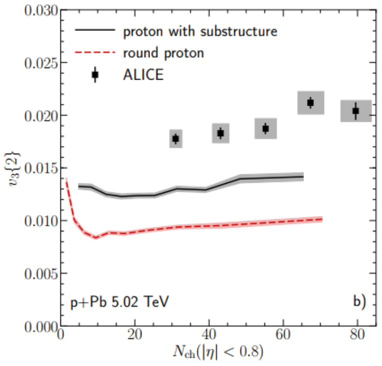
- Modeling proton spatial structure with constituent quark picture
- Sub-nucleon fluctuation can be important for small system collectivity

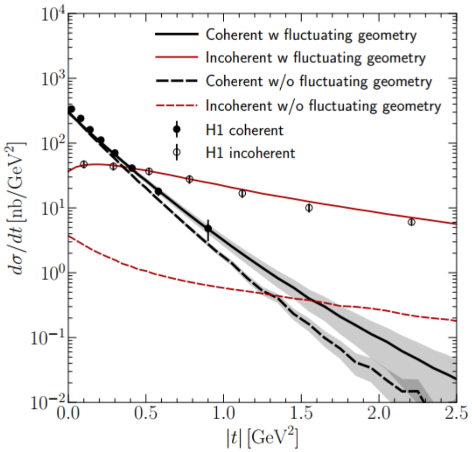












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Initial geometry configuration for pp

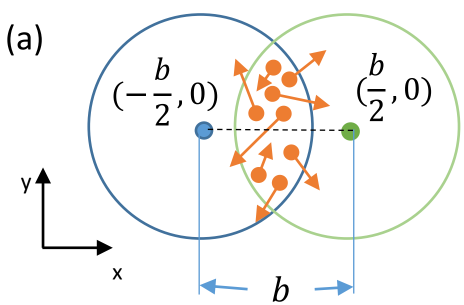
Proton substructure $\rho(r) = \frac{1}{8\pi R^3} e^{-r/R}$

- Overlap function T(x,y,b) weighting method
  $T(x,y,b) = \int \rho_{p,1}(x-b/2,y,z)\rho_{p,2}(x+b/2,y,z)dz$
- Constituent quark method (3 quark)
  Glauber modeling with 3 quark participants
  Collision criteria $d < \sqrt{\sigma_{cc}/\pi}$

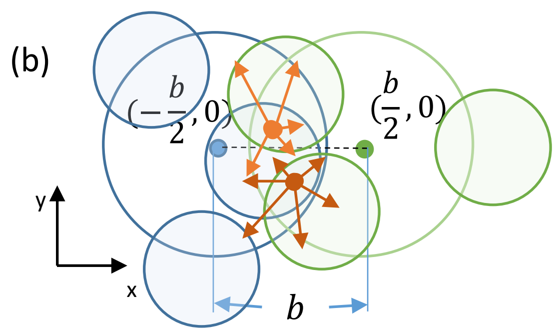
Original AMPT spatial structures

- Target/projectile string
  Target/projectile position
- Independent string
  Mid-point position

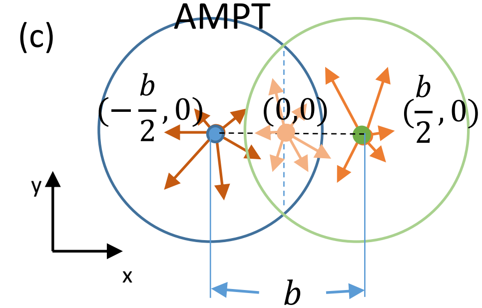
T(x,y,b) weighting



3 quark constituent

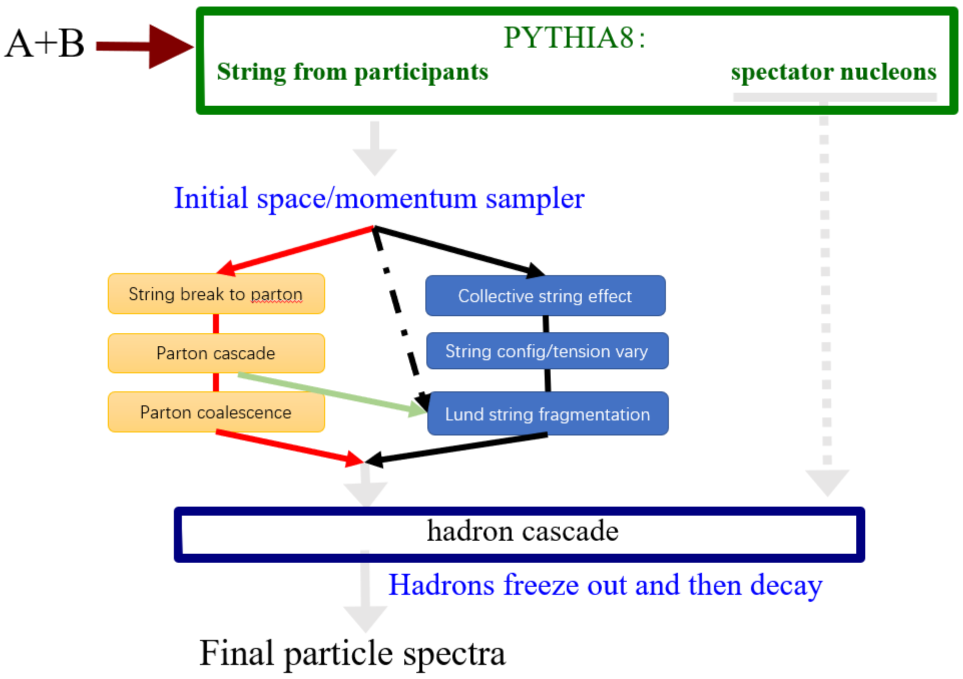


Original AMPT



PYTHIA8 initial conditions

- PYTHIA8 initial conditions: modern parton distribution function, multiple parton interaction (MPI) based string system
- Possible to compare parton transport and inter-string effects on the same basis



Parton escape effects