Multiparticle cumulants in 13 TeV p+p collisions & the proton substructure from a transport model

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Outline

Introduction

Improved AMPT model & sub-nucleon geometry

Results on cumulants

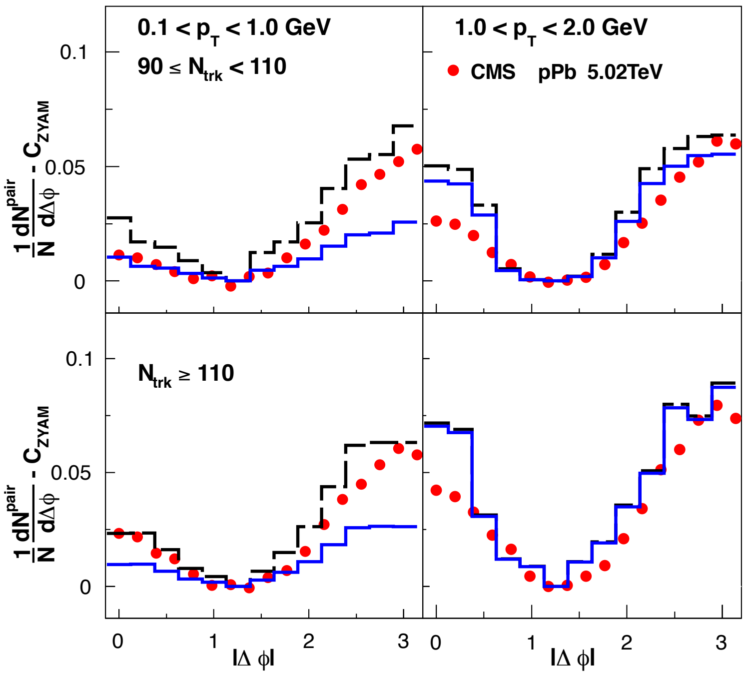
Summary

Based on Xin-Li Zhao, ZWL, Liang Zheng & Guo-Liang Ma, Physics Letters B 839 (2023) 137799

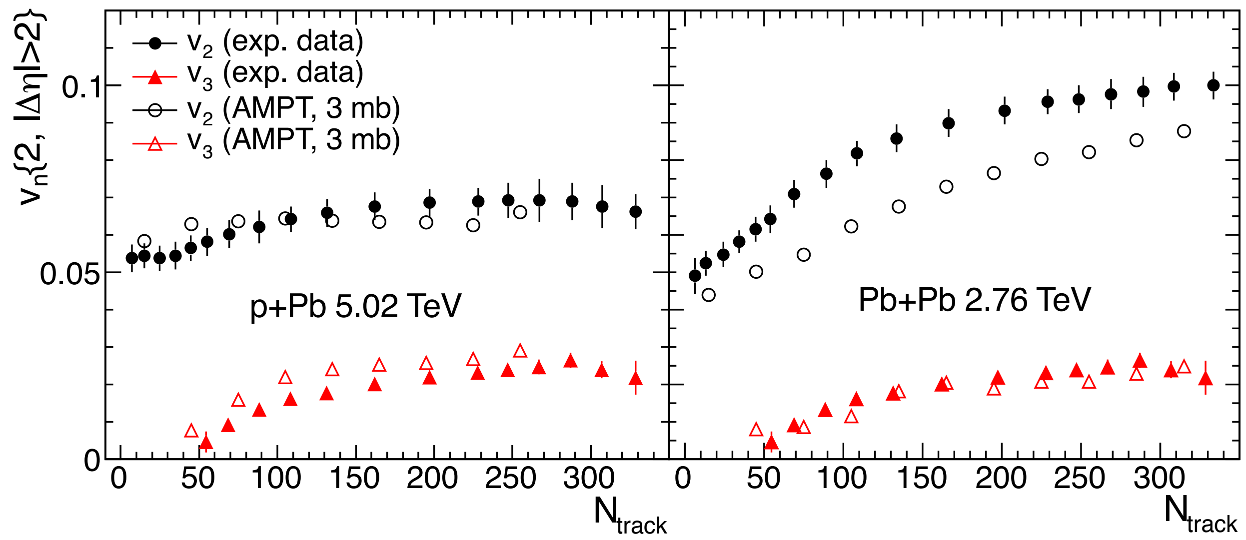
National Science Foundation

Collectivity in small systems

Recent small system data at LHC exhibit large anisotropic flows;
both hydrodynamics and transport can describe the flows.



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



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

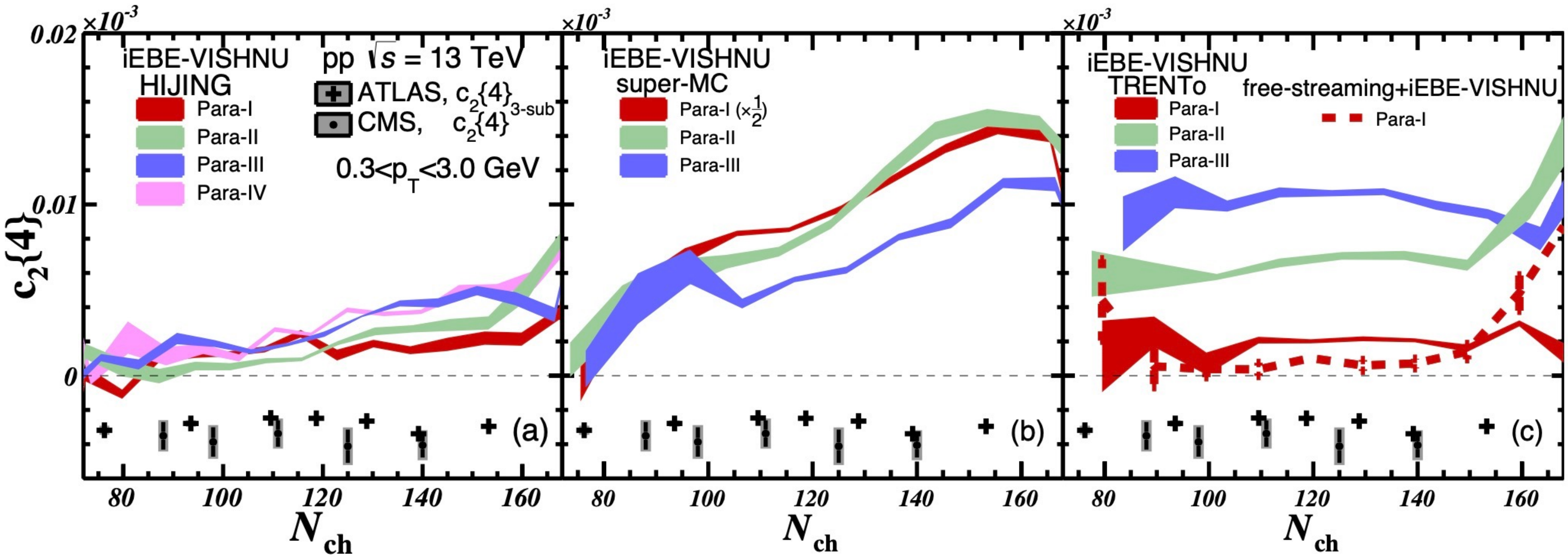
Questions:

- Do these flow signals come from
  final state collectivity or initial state effects?
- from hydrodynamics or off-equilibrium transport/kinetic theory?

Collectivity in small systems

Hydrodynamics:

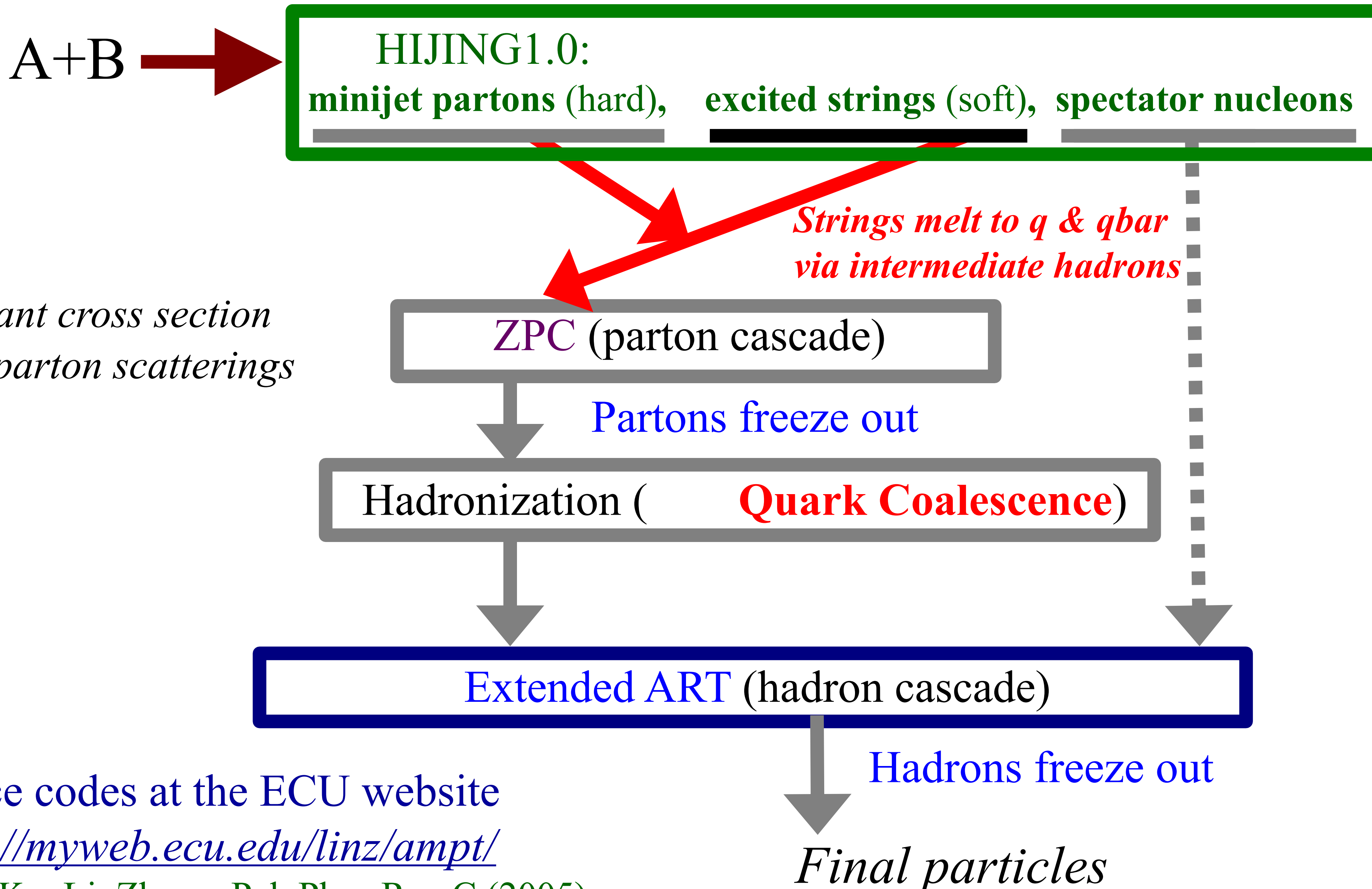
can reproduce 2-particle correlations "with carefully tuned parameters", but $c_2\{4\}$ cannot be reproduced & have the wrong sign.



Zhou, Zhao, Murase & Song, NPA (2020); Zhao, Zhou, Murase & Song, EPJC (2020)

- For large systems: $c_2\{4\}<0$ is expected as final state effect dominates.
- For small systems: more complicated due to nonflow and flow fluctuations.
- We use a multi-phase transport (AMPT) model in this study:
  has nonflow and flow fluctuations,
  can address non-equilibrium evolution.

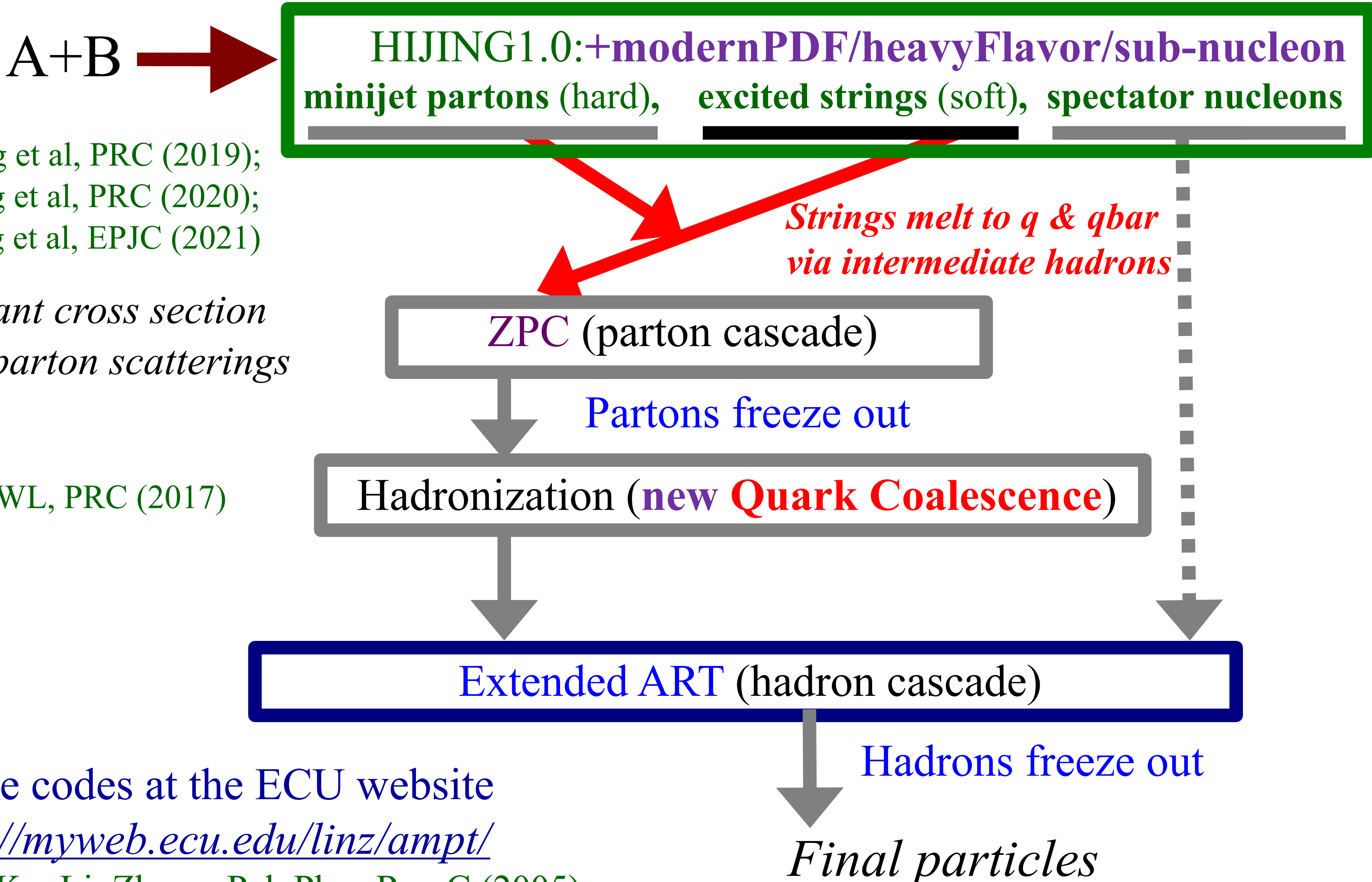
Structure of AMPT (String Melting version)



Constant cross section
σ for parton scatterings

Source codes at the ECU website
[*https://myweb.ecu.edu/linz/ampt/*](https://myweb.ecu.edu/linz/ampt/)
ZWL, Ko, Li, Zhang, Pal, Phys Rev C (2005);
ZWL & L Zheng, Nucl Sci Tech (2021)

Structure of **improved** AMPT (String Melting version)



C Zhang et al, PRC (2019);
L Zheng et al, PRC (2020);
L Zheng et al, EPJC (2021)

Constant cross section σ for parton scatterings

He & ZWL, PRC (2017)

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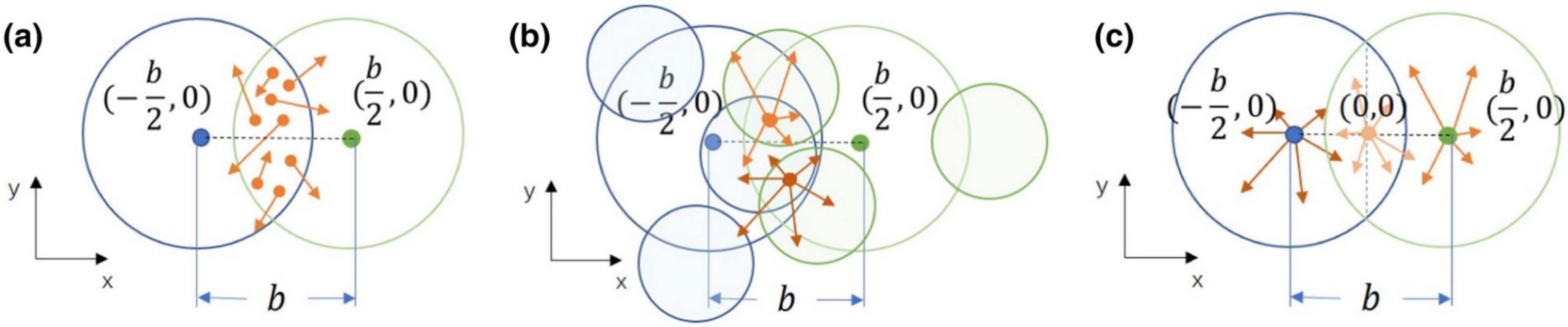
Improved AMPT model with sub-nucleon geometry



Overlapping protons | *proton as 3 quarks* **(3-quark AMPT)** | *proton as point particle* **(Normal AMPT)**

L Zheng et al, EPJC (2021)

Sub-nucleon geometry for the proton:

Mäntysaari & Schenke, PRL (2016);
Loizides, PRC 2016);
Bozek, Broniowski & Rybczynski, PRC (2016);
Bozek et al., Comp. Phys. Comm. (2019);
…

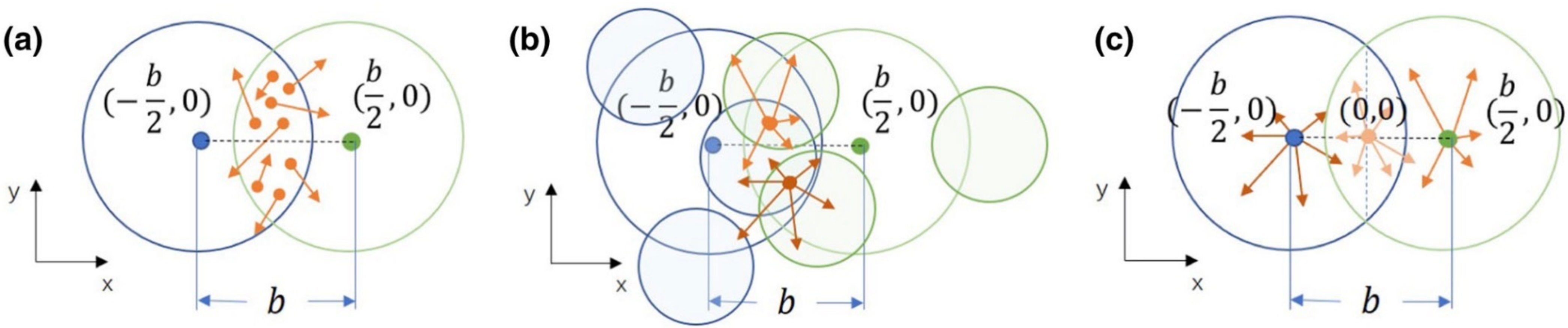
In 3-quark AMPT model:

- we consider proton as 3 constituent quarks, with coordinates sampled according to

$$\rho(r) \propto e^{-r/R}$$

- partons are randomly assigned to each collision center of interacting constituent pairs

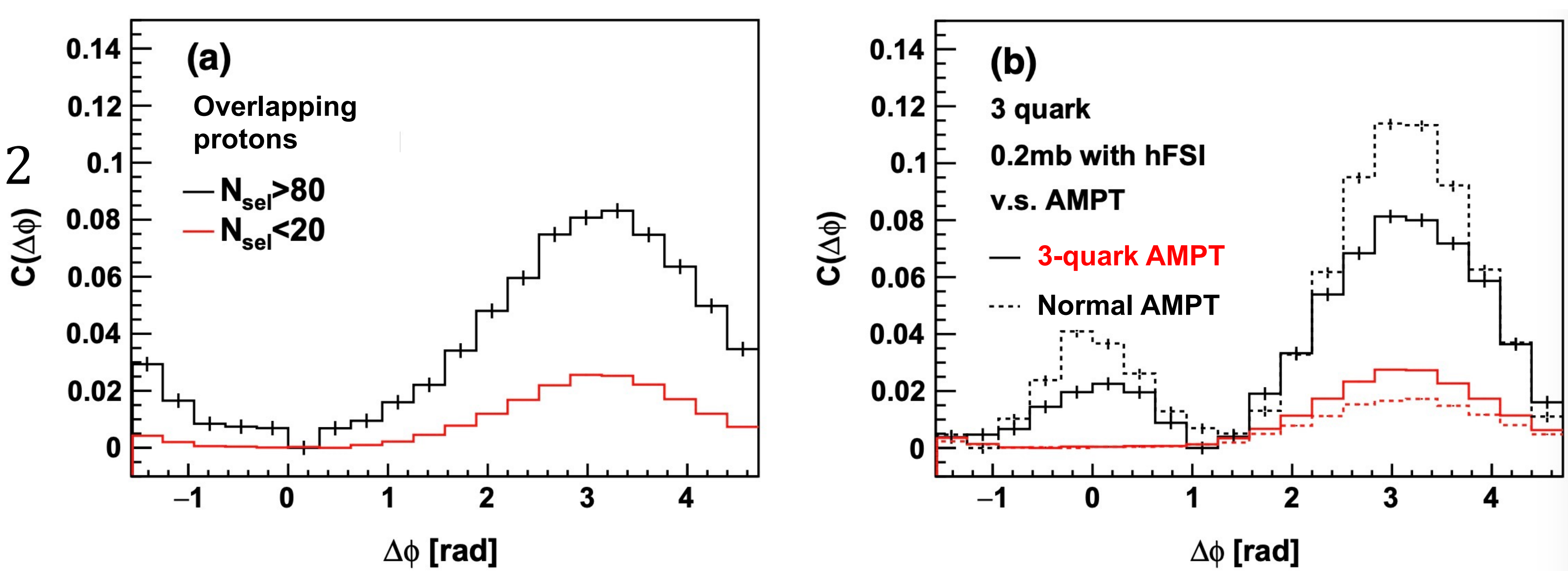
Improved AMPT model with sub-nucleon geometry



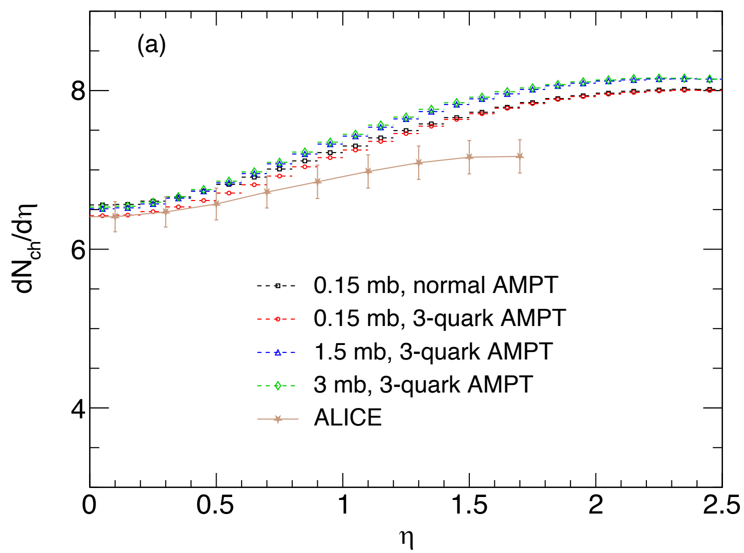
Overlapping protons | *proton as 3 quarks* **(3-quark AMPT)** | *proton as point particle* **(Normal AMPT)**

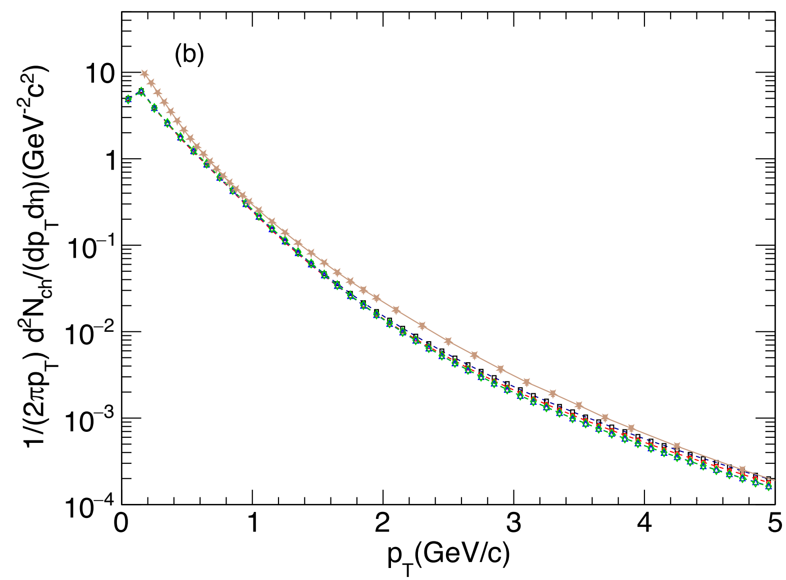
L Zheng et al, EPJC (2021)

$[\Delta\eta] > 2$



Improved AMPT model with sub-nucleon geometry

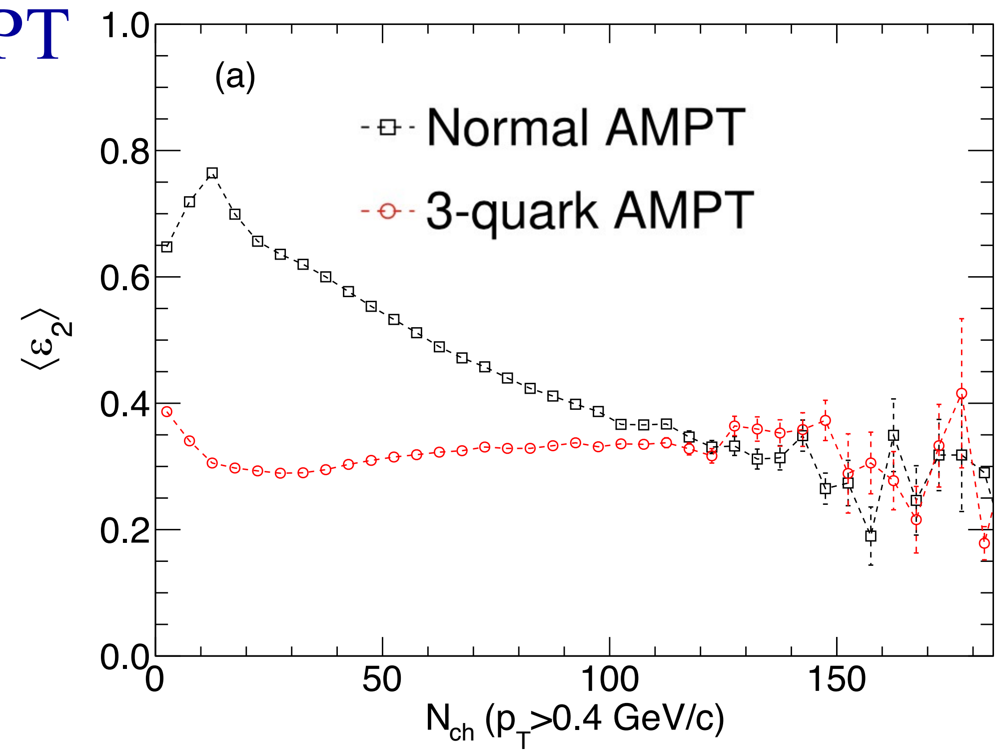




Normal AMPT & 3-quark AMPT

- both reasonably describe multiplicity and p_T spectrum.

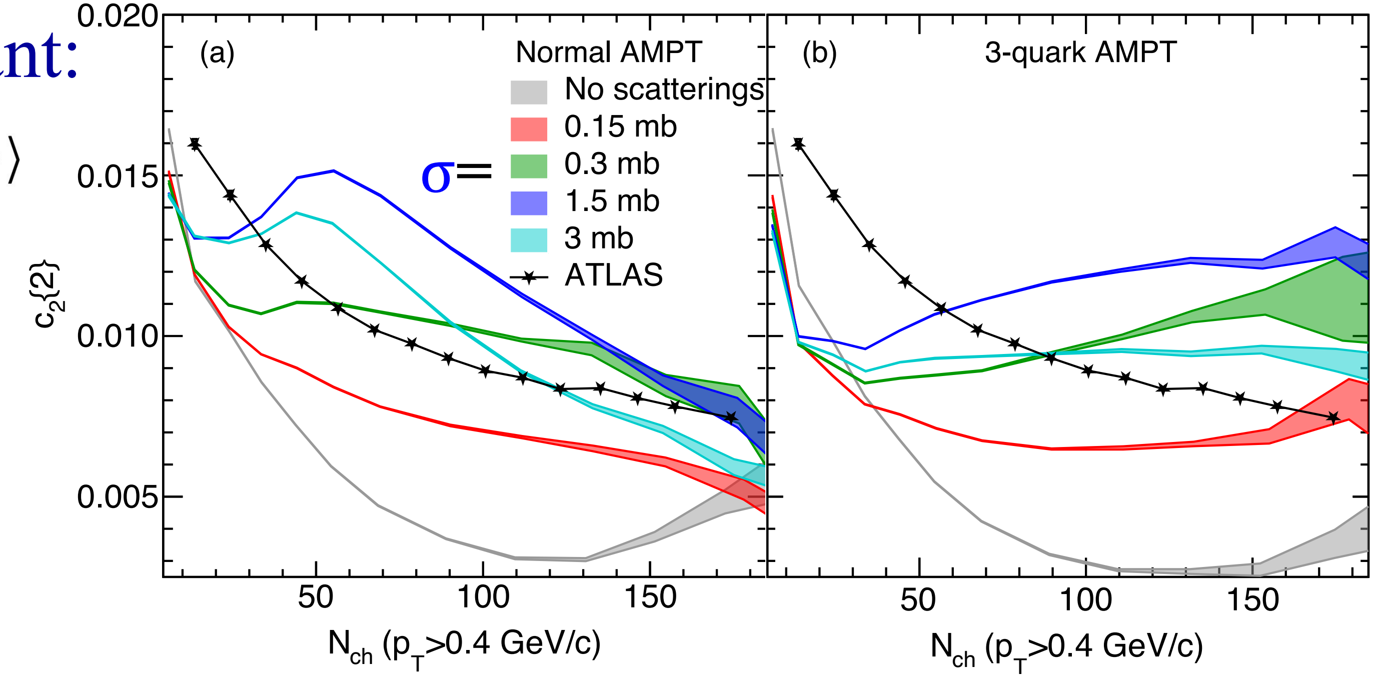
- but spatial eccentricities ε_2 are very different



Zhao, ZWL, Zheng & Ma, PLB (2023)

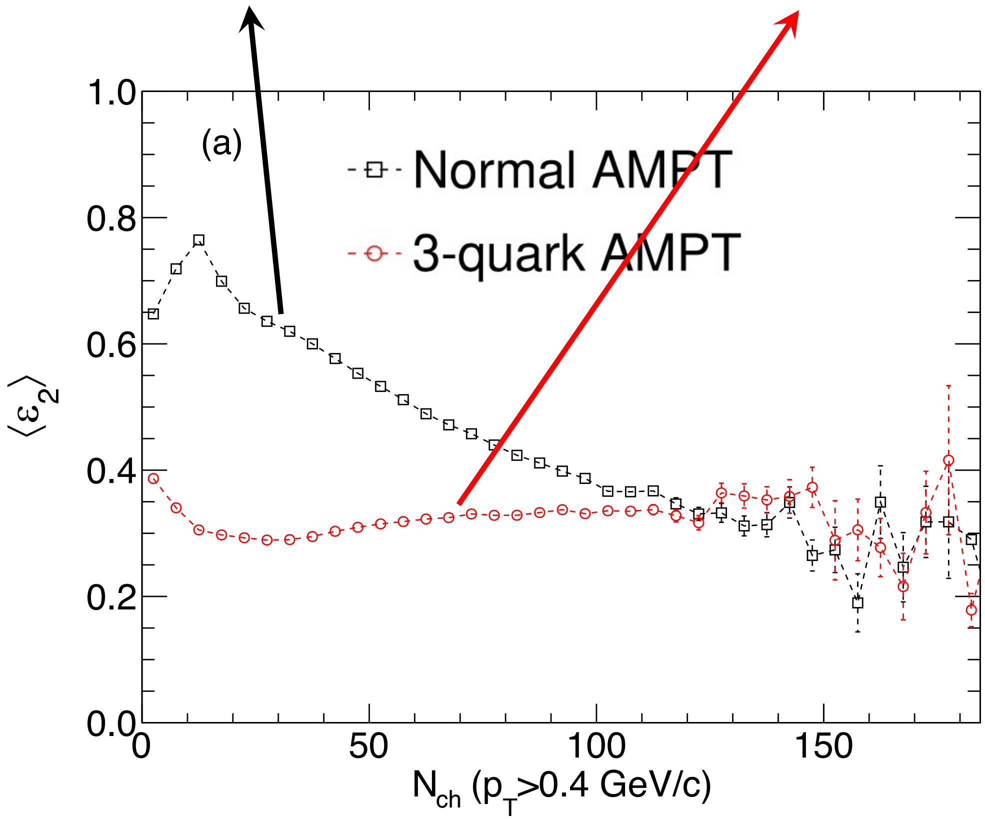
$c_2\{2\}$ 2-particle cumulant:

$$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle = \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle$$



Without η-gap:
sensitive to parton cross section σ; dependence is non-monotonous.

$c_2\{2\}$ is closely related to spatial eccentricities ε_2:

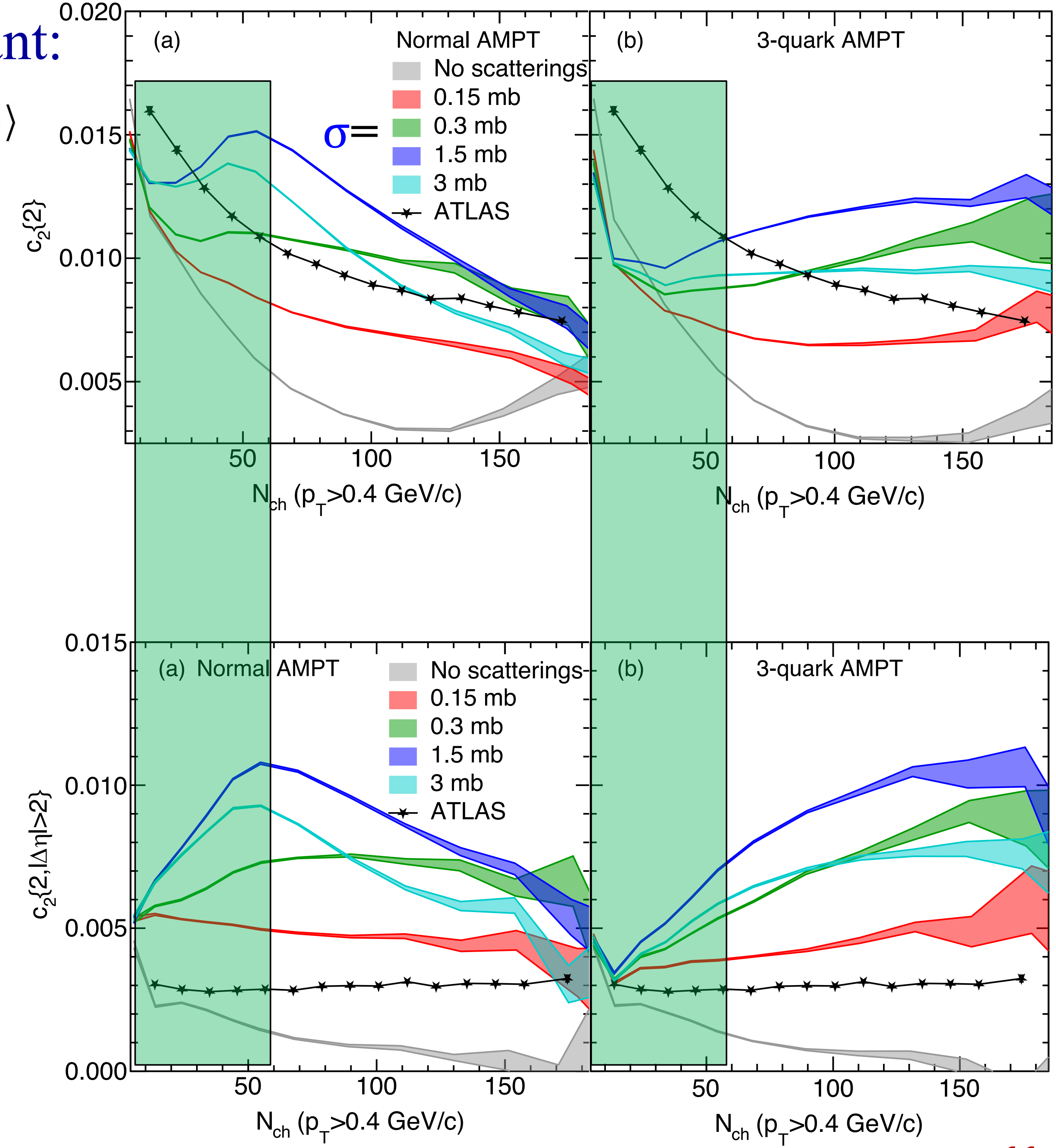


$c_2\{2\}$ 2-particle cumulant:

$$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle = \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle$$

Without η-gap:
sensitive to parton cross section σ; dependence is non-monotonous.

With η-gap:
nonflow effect is suppressed, especially at low Nch.



$c_2\{4\}$ 4-particle cumulant:

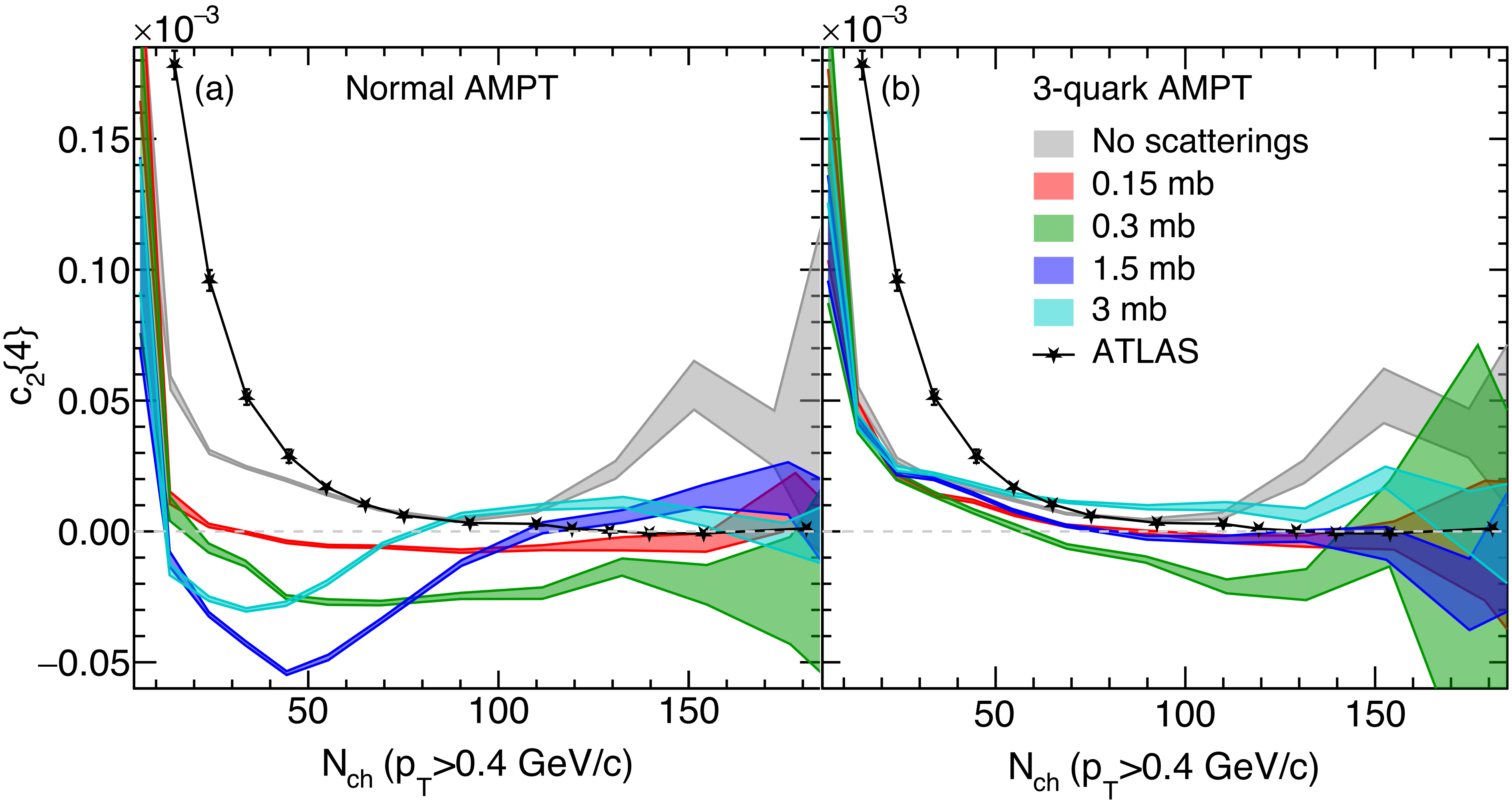
$$\langle\langle\{4\}_n\rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle$$

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

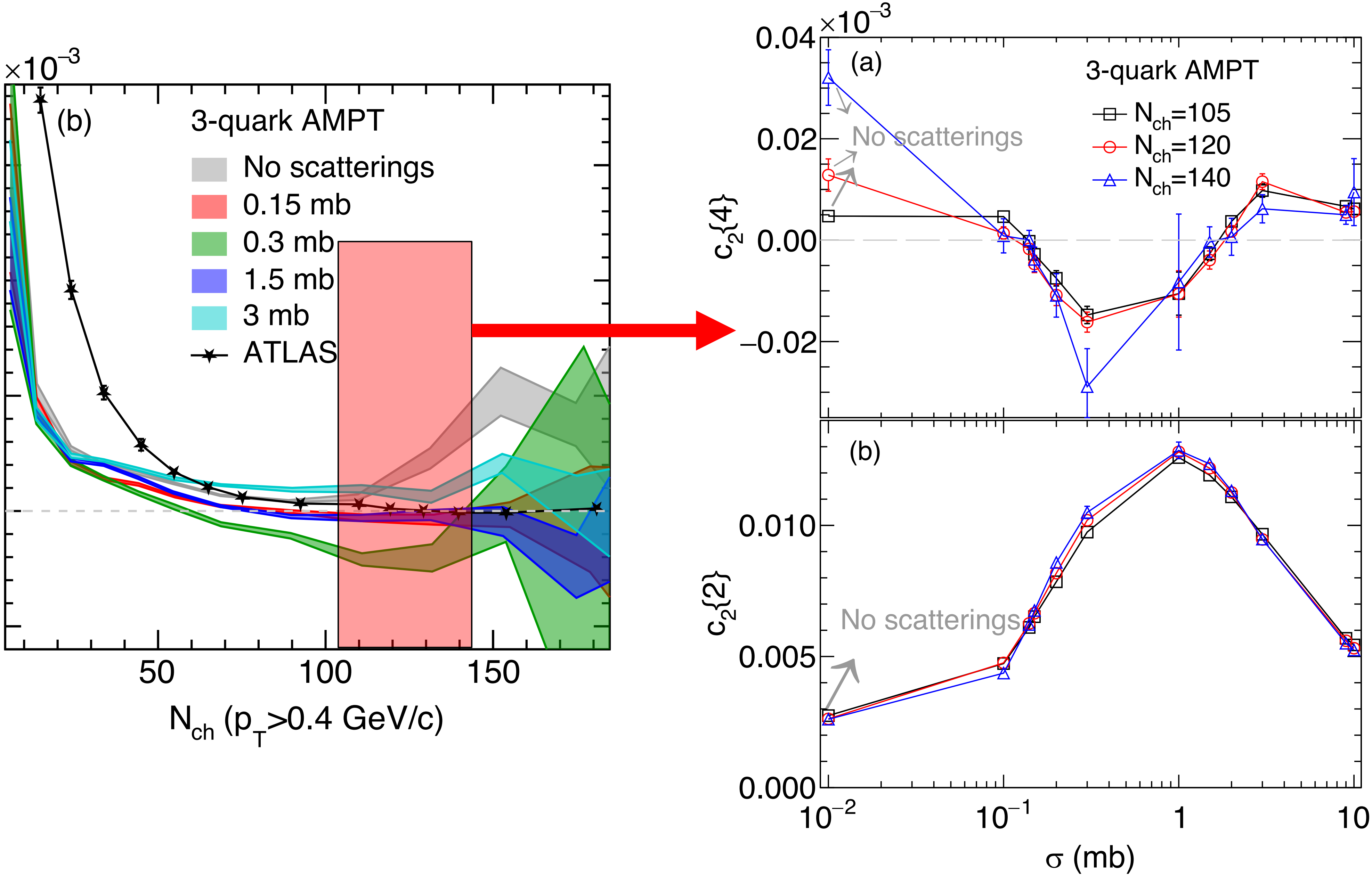
$c_2\{4\}$ including its sign
is sensitive to σ;
>0 without scatterings

3-quark AMPT model:

trend is similar to data;
$c_2\{4\}<0$ at certain high Nch for certain σ;
$c_2\{4\}$ at σ=0.15mb or 1.5mb are closest to data

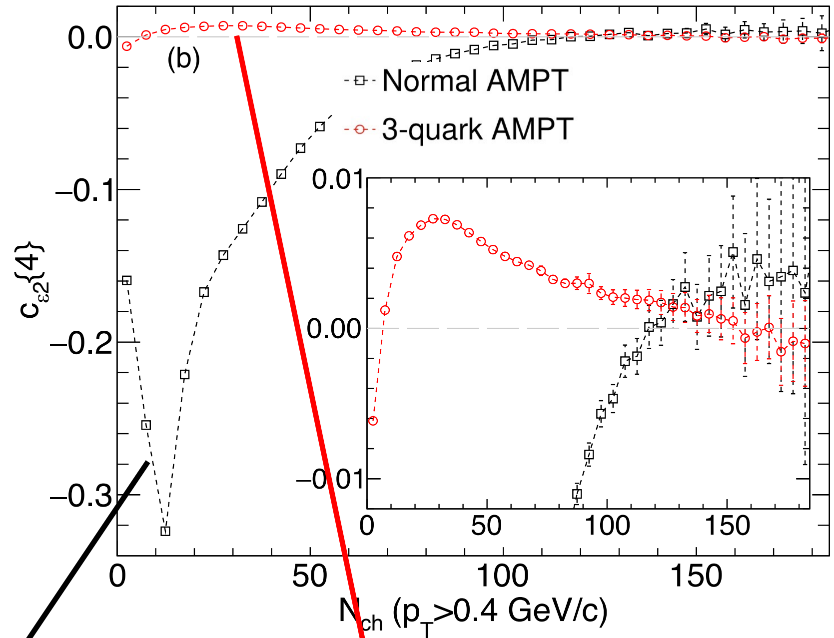


$c_2\{4\}$ including its sign: dependence on σ is non-monotonous; very sensitive to σ. even if σ is small

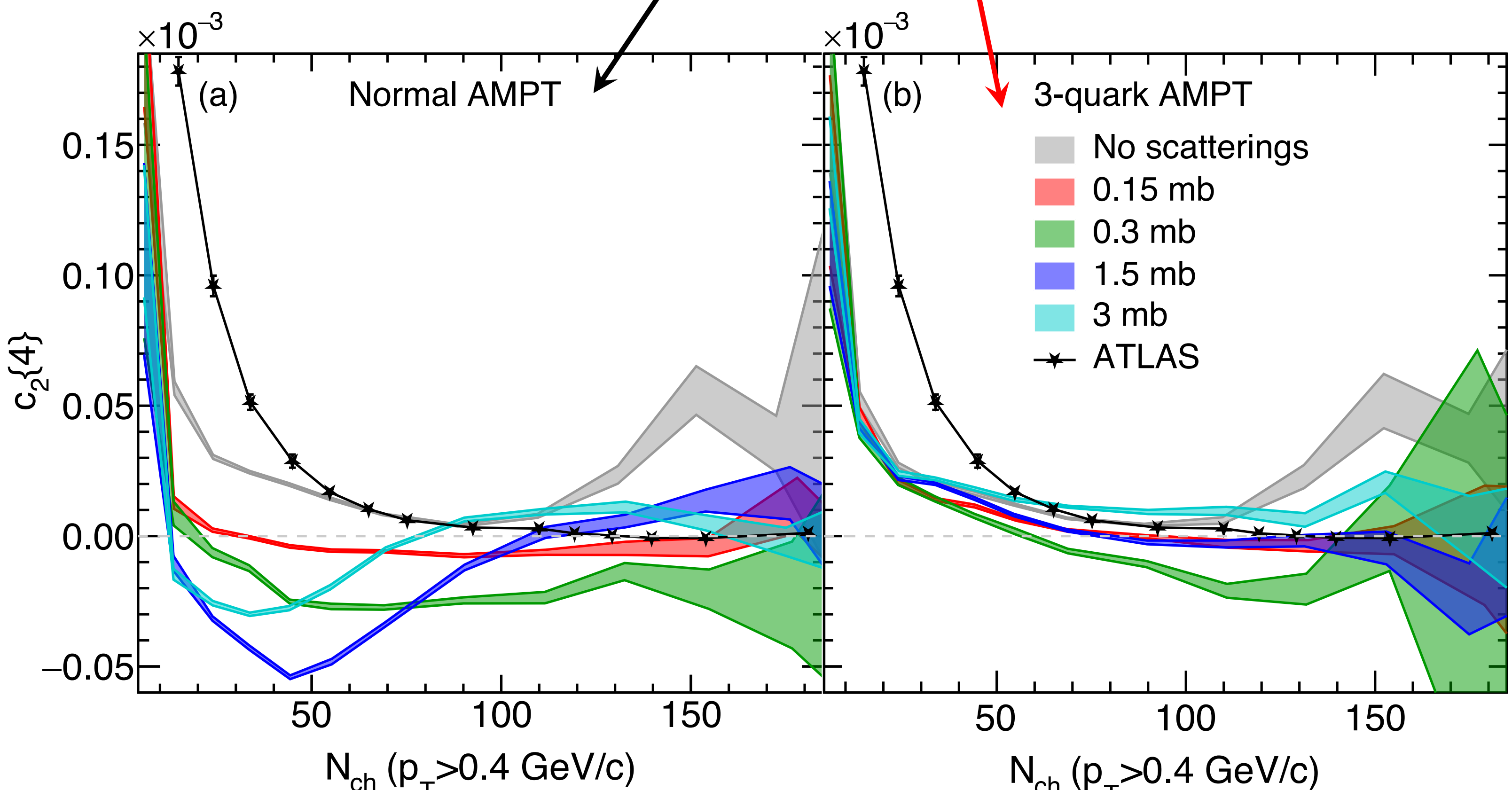


Spatial cumulants $c_{\varepsilon 2}\{4\}$ for initial partons:

$$c_{\varepsilon_n}\{2\} = \langle \varepsilon_n^2 \rangle, \; c_{\varepsilon_n}\{4\} = \langle \varepsilon_n^4 \rangle - 2\langle \varepsilon_n^2 \rangle^2$$

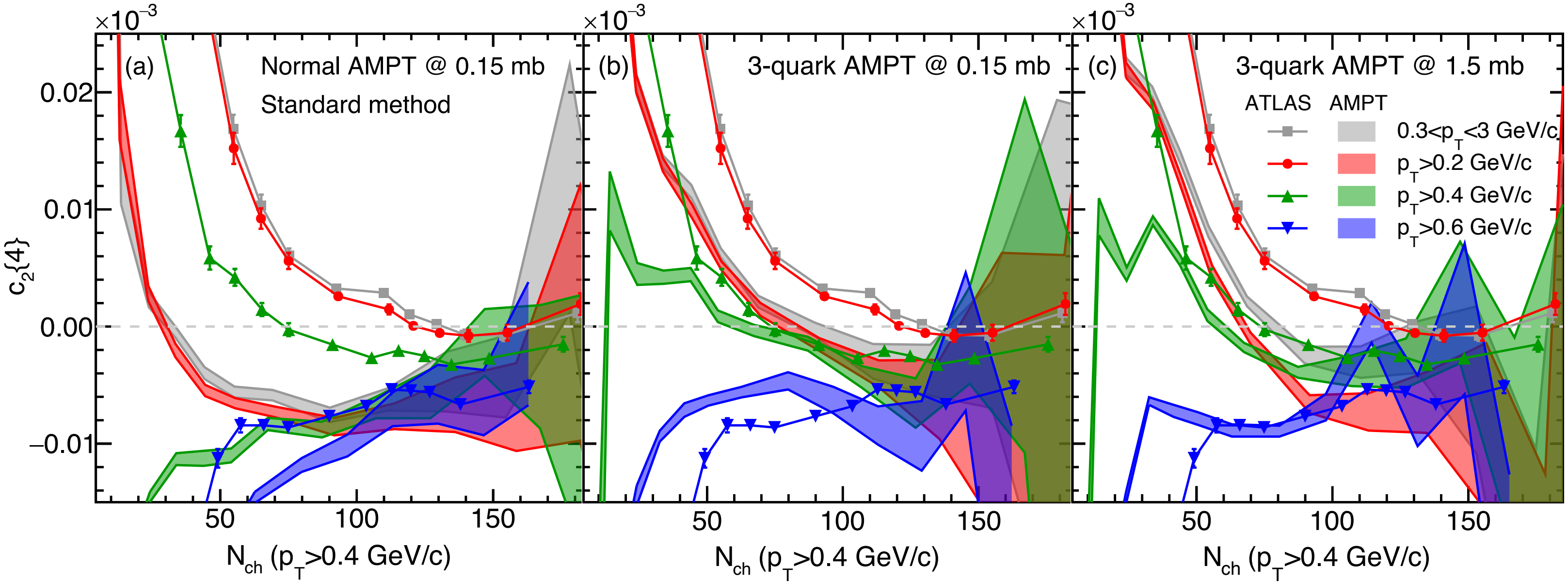


$c_{\varepsilon 2}\{4\}$ is closely related to $c_2\{4\}$:



$c_2\{4\}$: p_T -dependence is qualitatively similar to data:

Standard cumulant method

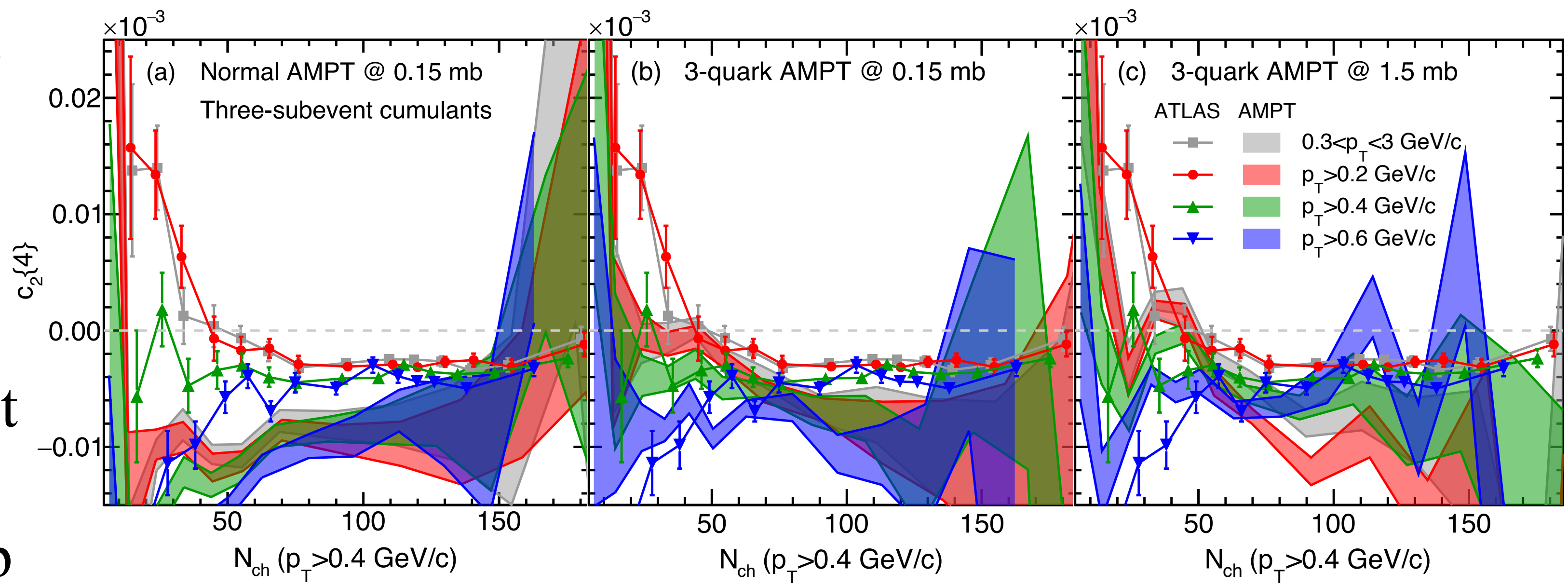


3-subevent cumulant method

$$\langle\langle\{4\}_n\rangle\rangle_{\mathrm{three-sub}} = \langle\langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c)}\rangle\rangle$$

Jia, Zhou & Trzupek, PRC (2017)

- nonflow effect is suppressed
- weaker p_T-dep



Summary

An improved multi-phase transport (AMPT) model
is used to study 2- and 4-particle cumulants in 13 TeV p+p collisions

- Both $c_2\{2\}$ & $c_2\{4\}$ depend sensitively & non-monotonously
  on (small) parton scattering cross section σ,
  indicating significant effects from off-equilibrium kinetic response

- Nonflow has large effects at low Nch, but is not modeled correctly

- Incorporating proton sub-nucleon structure (here with 3 quarks)
  gives the correct qualitative features of $c_2\{4\}$ vs Nch
  & $c_2\{4\}<0$ at certain high Nch

- Data cannot be well reproduced; further work are needed on
  parton cross section $\sigma(T)$ as $\eta/s \propto \frac{1}{T^2\sigma}$,
  more general proton sub-nucleon structure.