MCnet-CTEQ Summer School 2021 VIRTUAL

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TECHNISCHE UNIVERSITÄT DRESDEN

Heavy-ion collisions open issues

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September 14, 2021

Outline

- Introduction HIC
- Recent results (small systems)
  - Correlation between global multiplicity and hard physics
  - Anisotropic flow in small systems
  - Radial flow (identified charged particle production vs multiplicity and transverse spherocity)
  - Hadrochemistry
- Summary

Plan for the the talk today

Outline

- Introduction HIC
- Recent results (small systems)
  - Correlation between global multiplicity and hard physics
  - Anisotropic flow in small systems
  - Radial flow (identified charged particle production vs multiplicity and transverse spherocity)
  - Hadrochemistry
- Summary

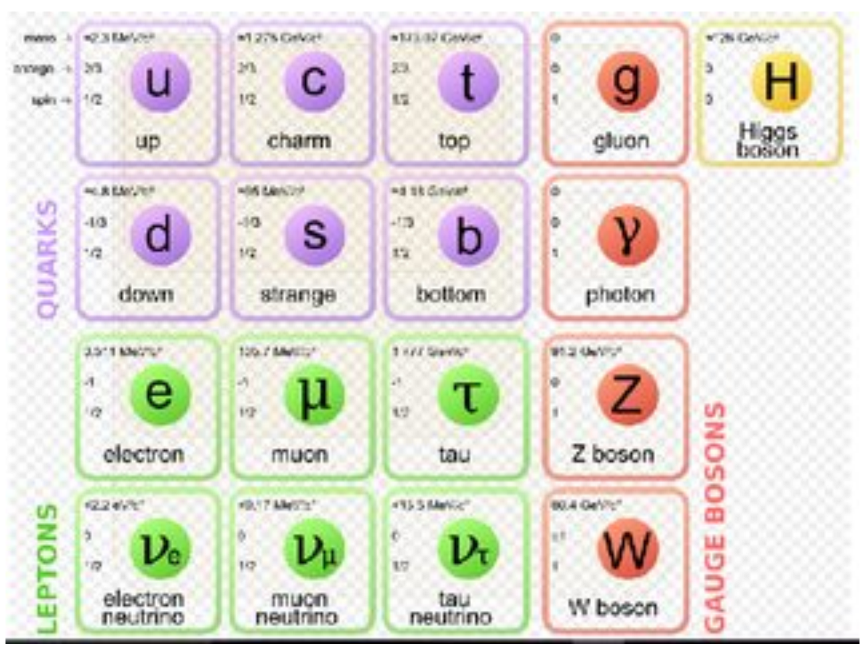
Tomorrow: MC to address the open HI issues

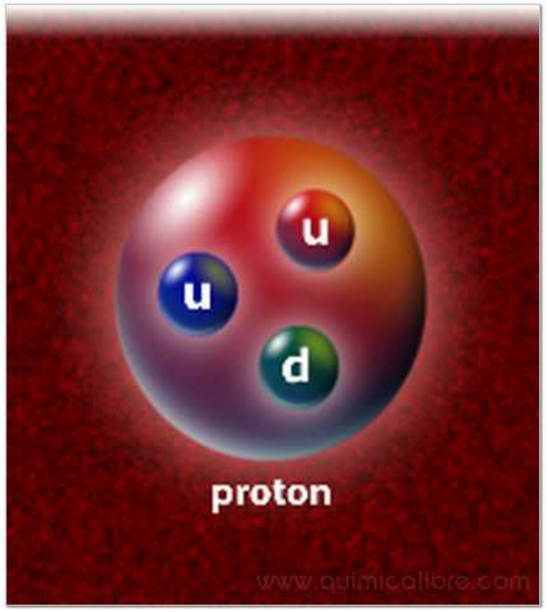
Introduction

W. Busza, K. Rajagopal and W. van der Schee, arXiv:1802.04801

What is QCD?

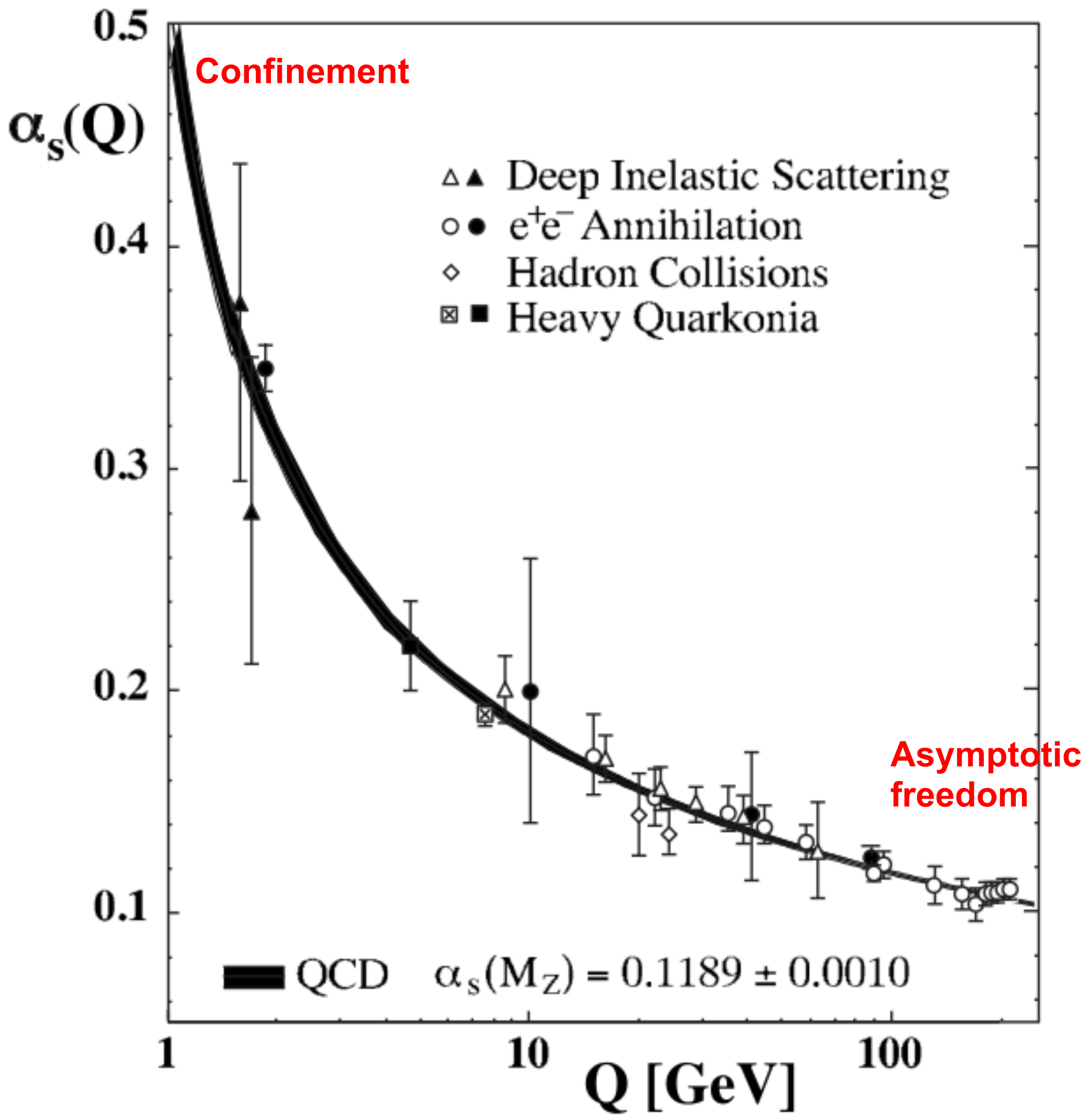
- Quantum Chromo-Dynamics is the theory of the <u>strong force</u>
  - the <u>strong force</u> describes the binding of <u>quarks</u> by <u>gluons</u> to make particles such as protons
- The <u>strong force</u> is one of the four fundamental forces
- The 2004 **Physics Nobel prize** was awarded to David J. Gross, H. David Politzer, and Frank Wilczek for their work leading to QCD





Features of QCD

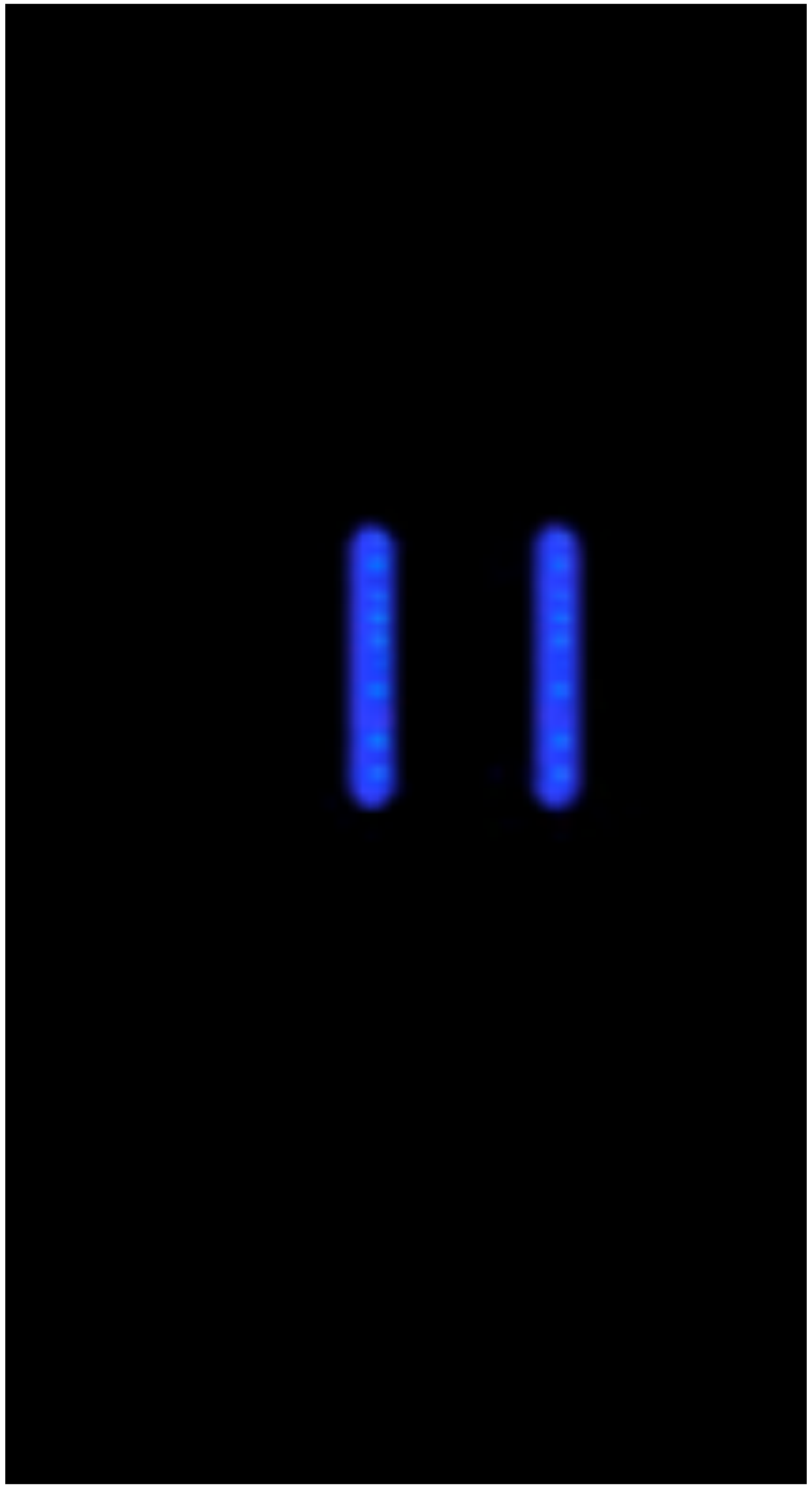
- In QCD, quarks and gluons (partons) are the elemental degrees of freedom
- Quarks and gluons have color charge as additional quantum number
- The strength of the interaction changes drastically with the transfer momentum (*Q*)



Heavy ion collisions

In the centre-of-mass frame (the “lab frame” at a collider):

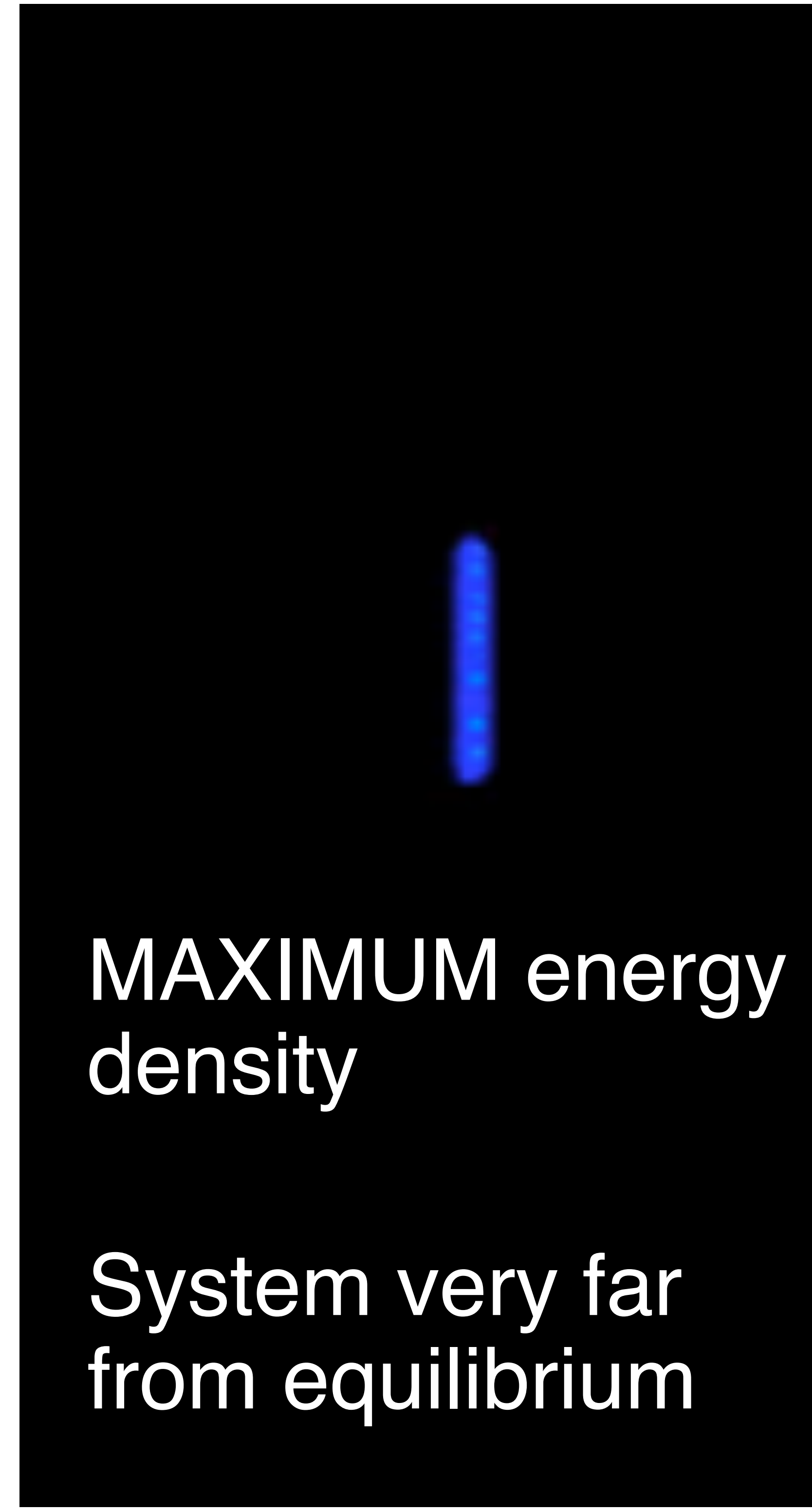
- ❑Each incident nucleus is a Lorentz contracted disk (e.g. for Pb or Au, thickness ~ $14/\gamma$ fm)
- ❑Each disc includes many coloured quarks and antiquarks (three more quarks than antiquarks per nucleon, $q\bar{q}$ pairs from quantum fluctuations). These quarks and antiquarks are sources of strong and almost completely transverse color fields
- ❑The area density of partons increases with velocity



Heavy ion collisions

When two discs overlap or collide:

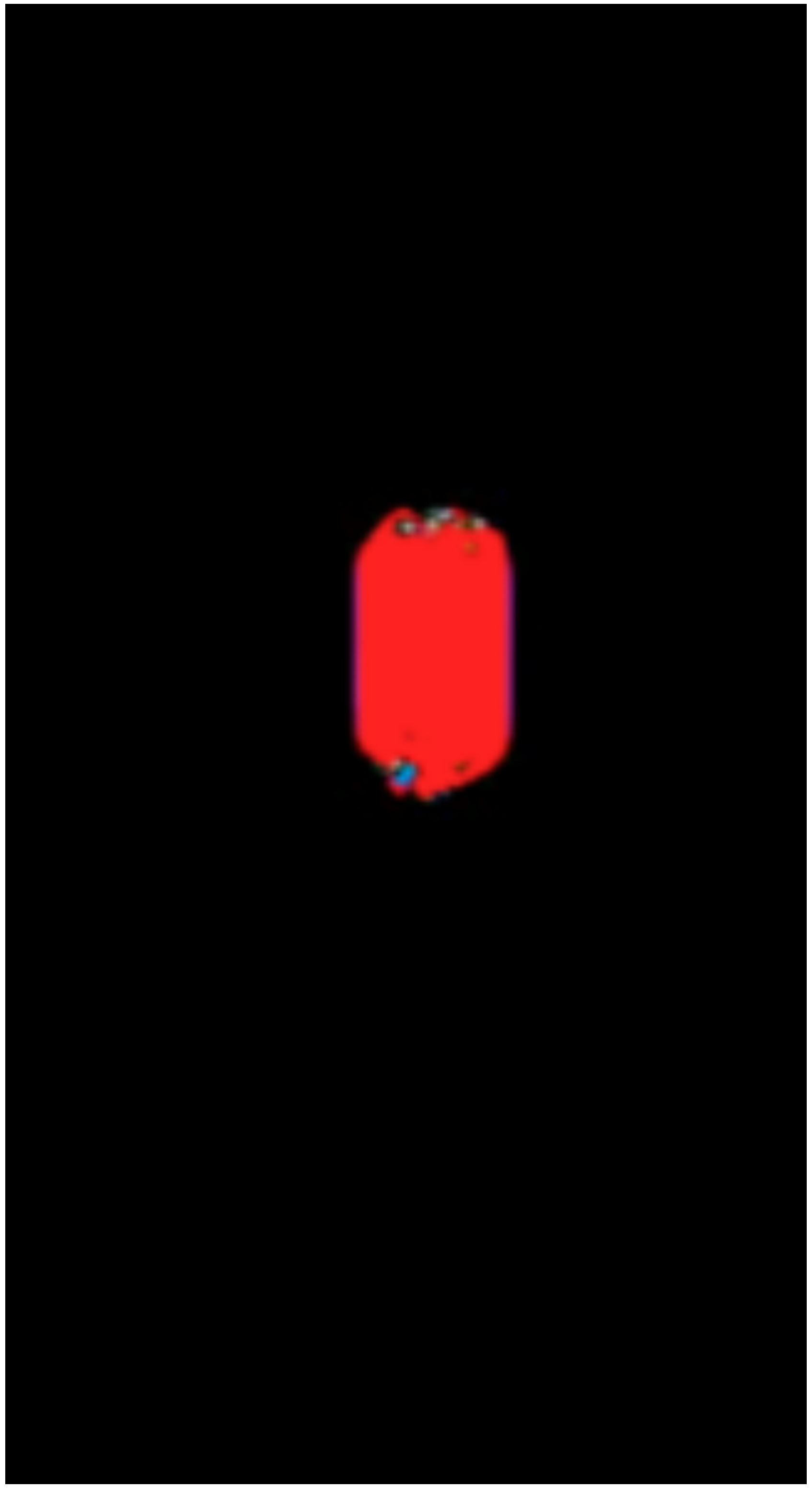
- ❑SOFT interactions: most of incident partons lose some energy but are not kicked by any large angle -> little transverse momentum transfer
- ❑HARD interactions: a small fraction of incident partons suffer hard perturbative interactions->production of high transverse momentum particles



Heavy ion collisions

What can we say in a generic way about the energy density at ~1fm/*c* after the collision:

- Rough estimate from LHC data ($\sqrt{s_{\rm NN}} = 2.76$ TeV), $\epsilon > 12$ GeV/fm^3 which is around 20 times higher the energy density in a hadron



Heavy ion collisions

Partons produced in the collision can not be described as a collection of distinct individual hadrons

What can we say in a generic way about the energy density at ~1fm/*c* after the col

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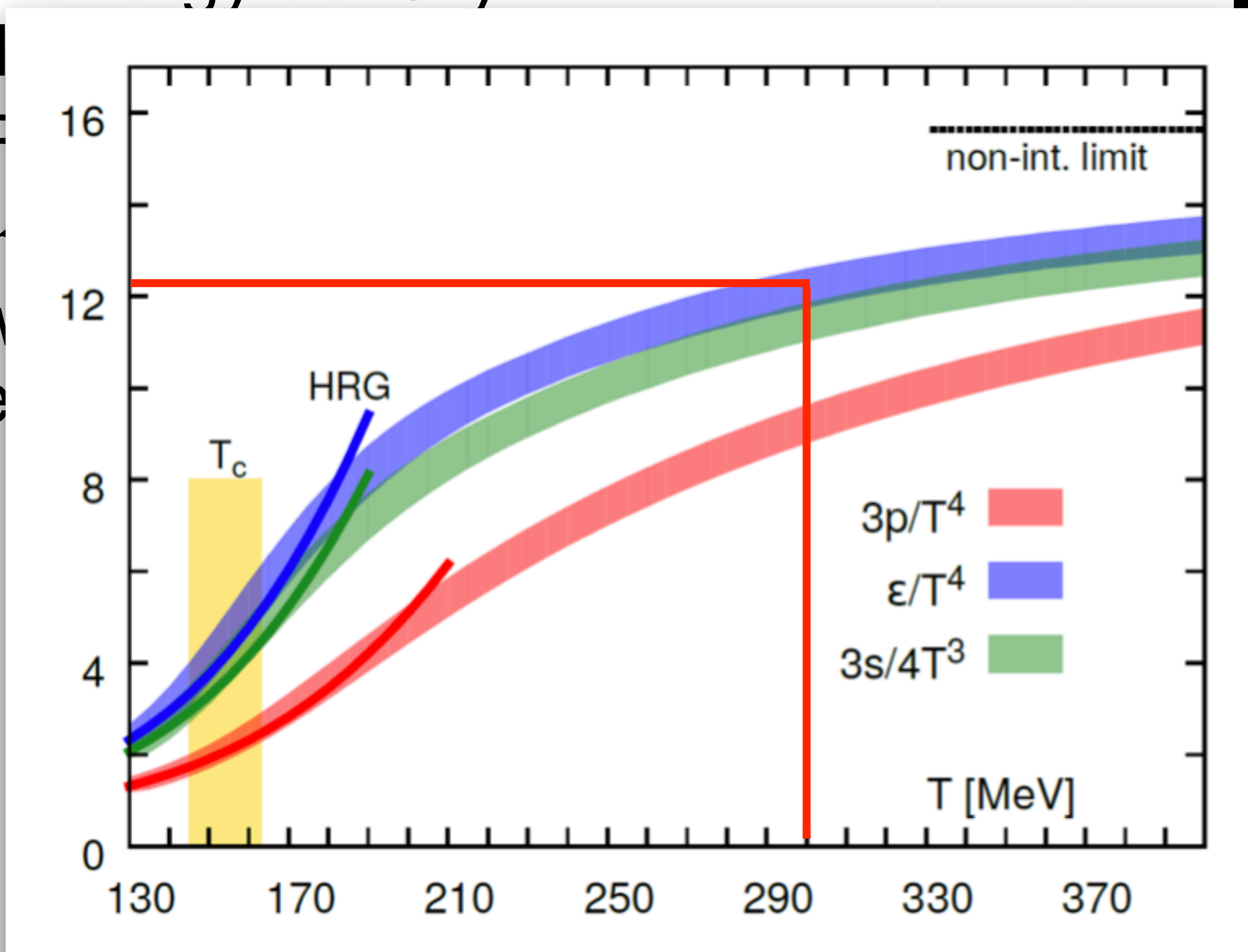
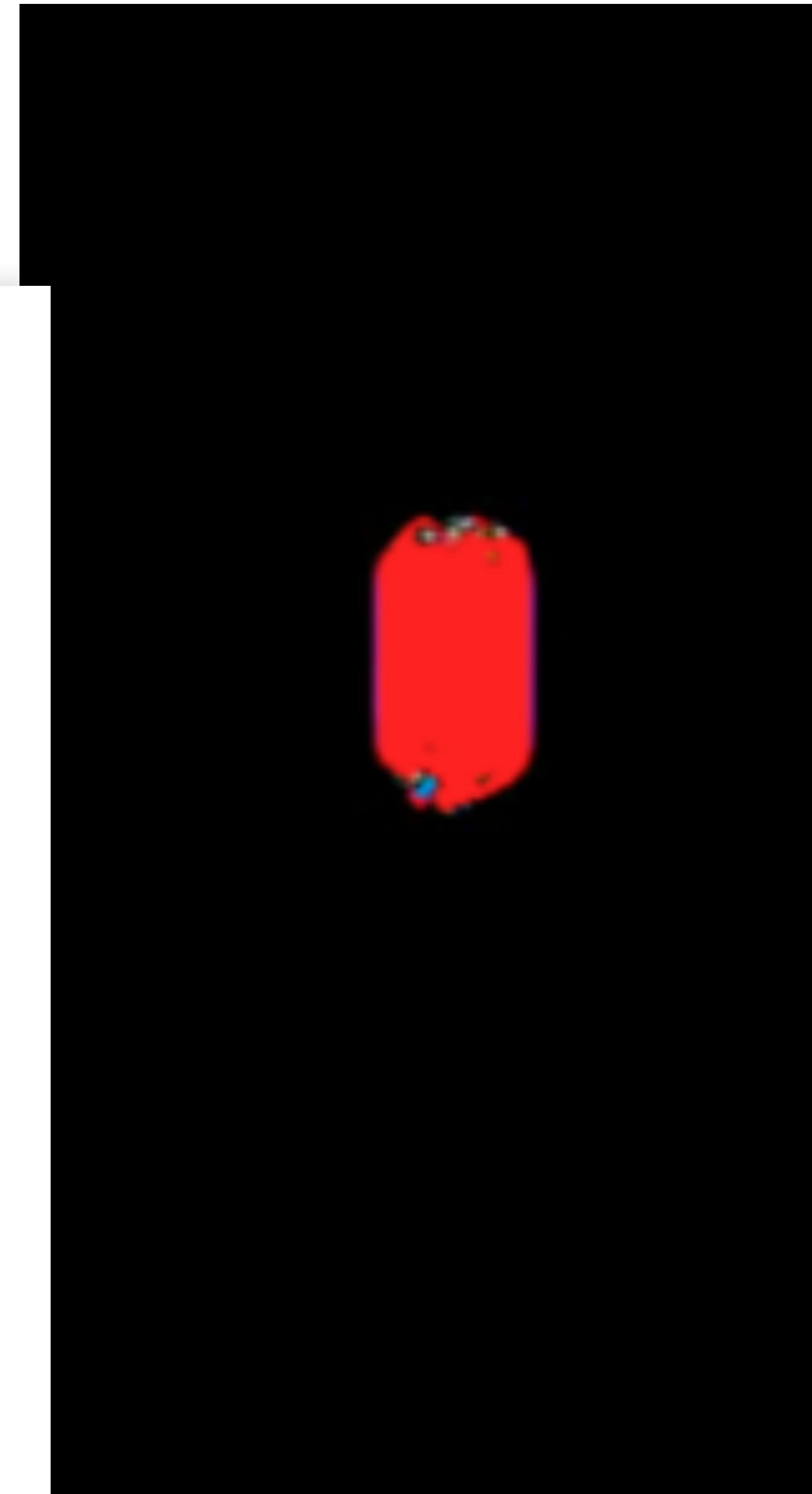




Lattice QCD calculations for hot QCD matter in thermal equilibrium at temperature T show a continuous crossover around T ~ 150 MeV, from a hadron resonance gas (HRG) at lower temperatures to QGP at higher temperatures

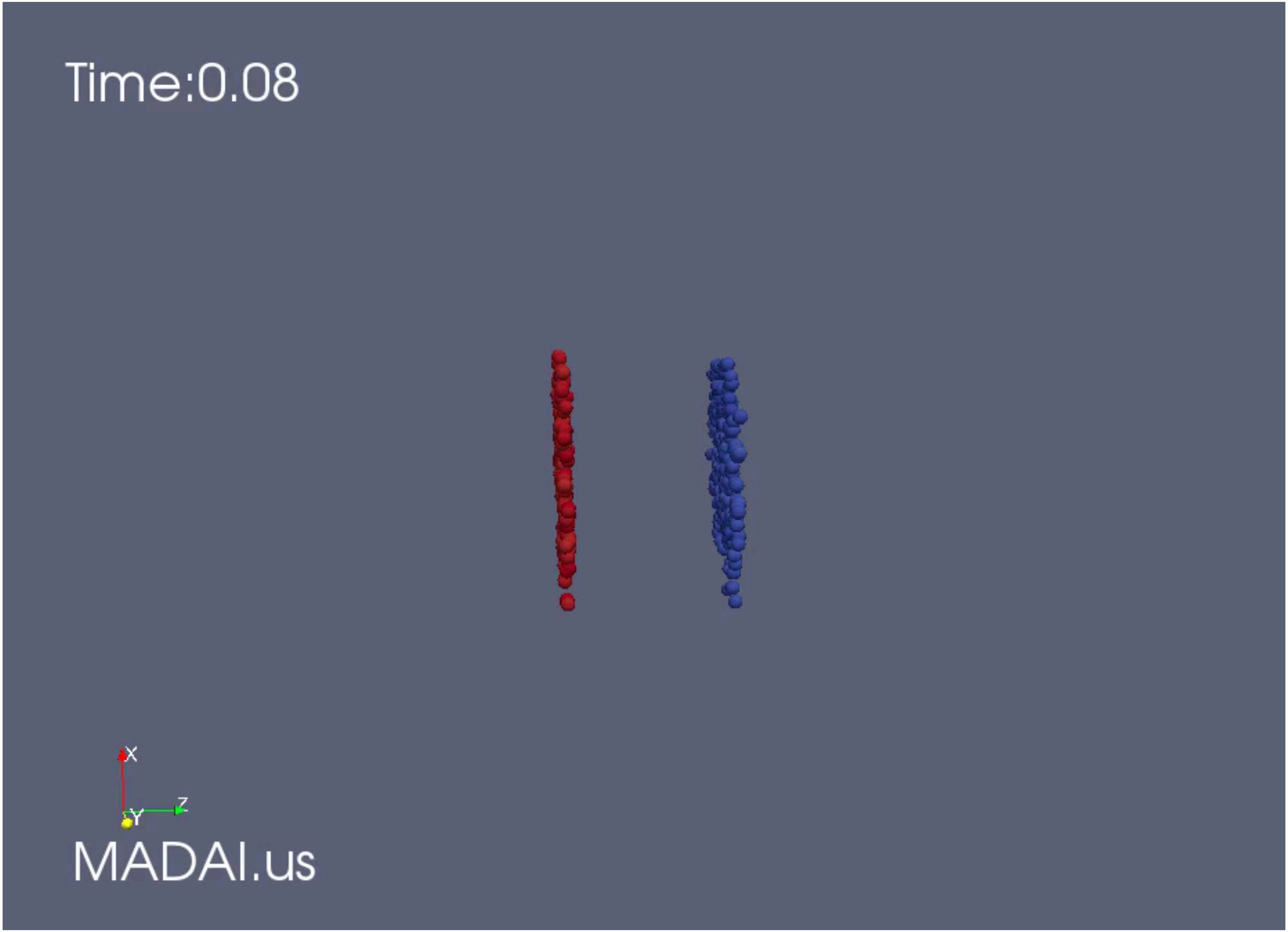
Heavy ion collisions

Quarks and gluons in this high energy density matter are far from independent, they are so strongly coupled to each other that they form a collective medium that expands and flows as a relativistic hydrodynamic fluid with a remarkably low viscosity to entropy density ratio $\eta/s \approx 1/4\pi$

This form of matter is named Quark-Gluon Plasma (QGP)

Heavy ion collisions recreate droplets of the matter that filled the universe a microsecond or so after the Big Bang

➡when the universe was only a few microseconds old it was filled with matter at temperatures above $\Lambda_{\rm QCD}$ and was too hot for the formation of any hadron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nature International weekly journal of science

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Published online 19 April 2005 | Nature | doi:10.1038/news050418-5

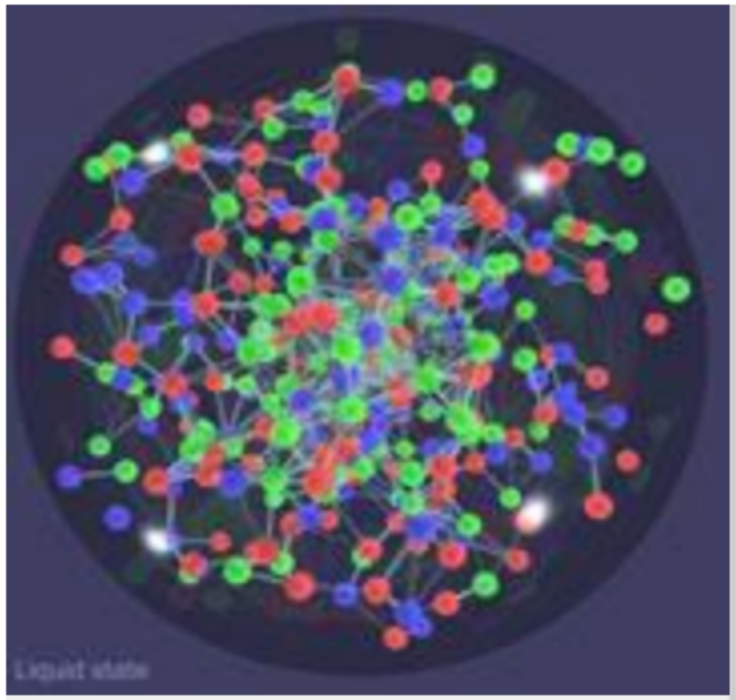
News

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

Mark Peplow

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.



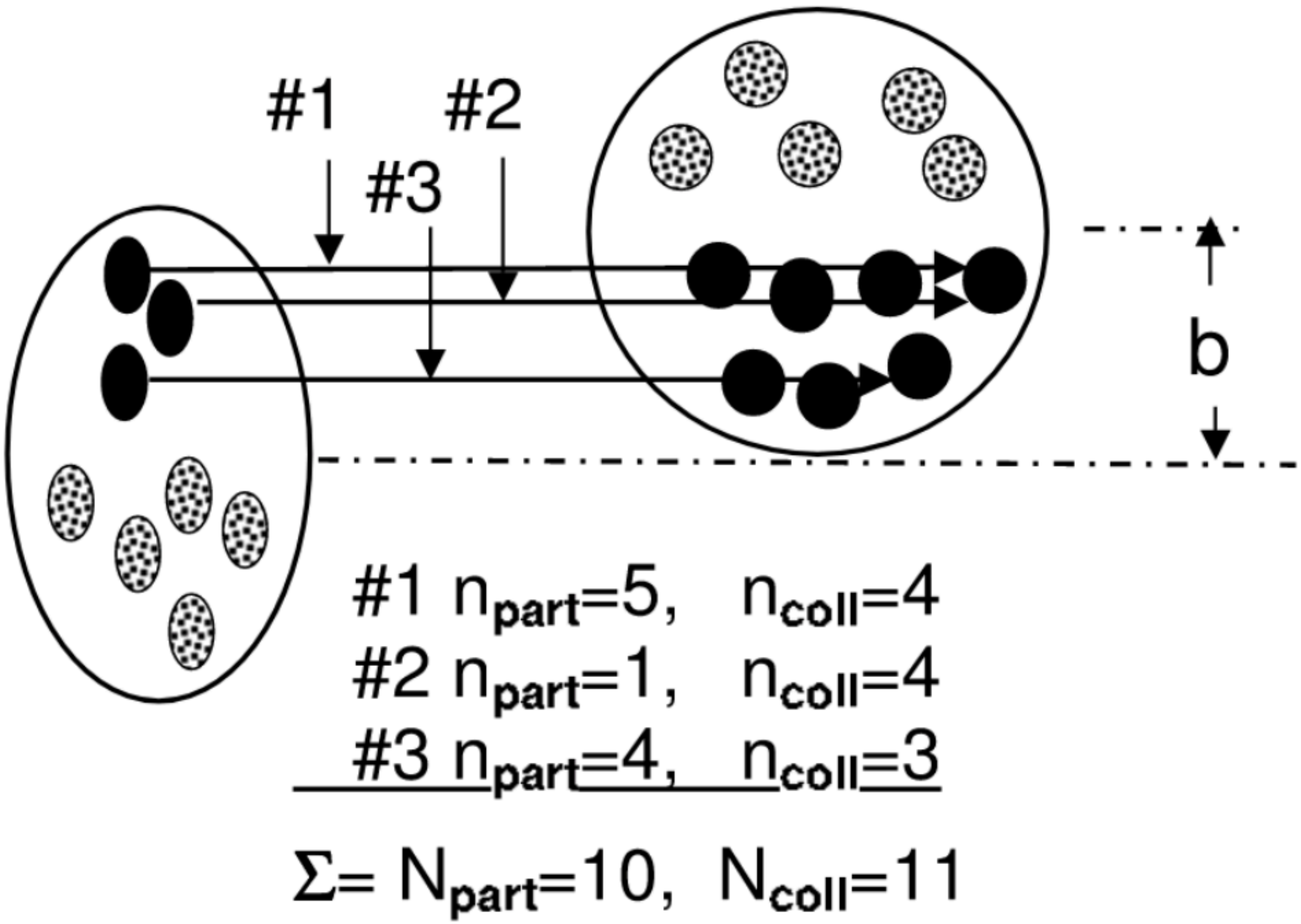
Quarks and gluons have formed a unexpected liquid. Click here to see animation.

© RHIC/BN

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be

QGP signatures in AA collisions

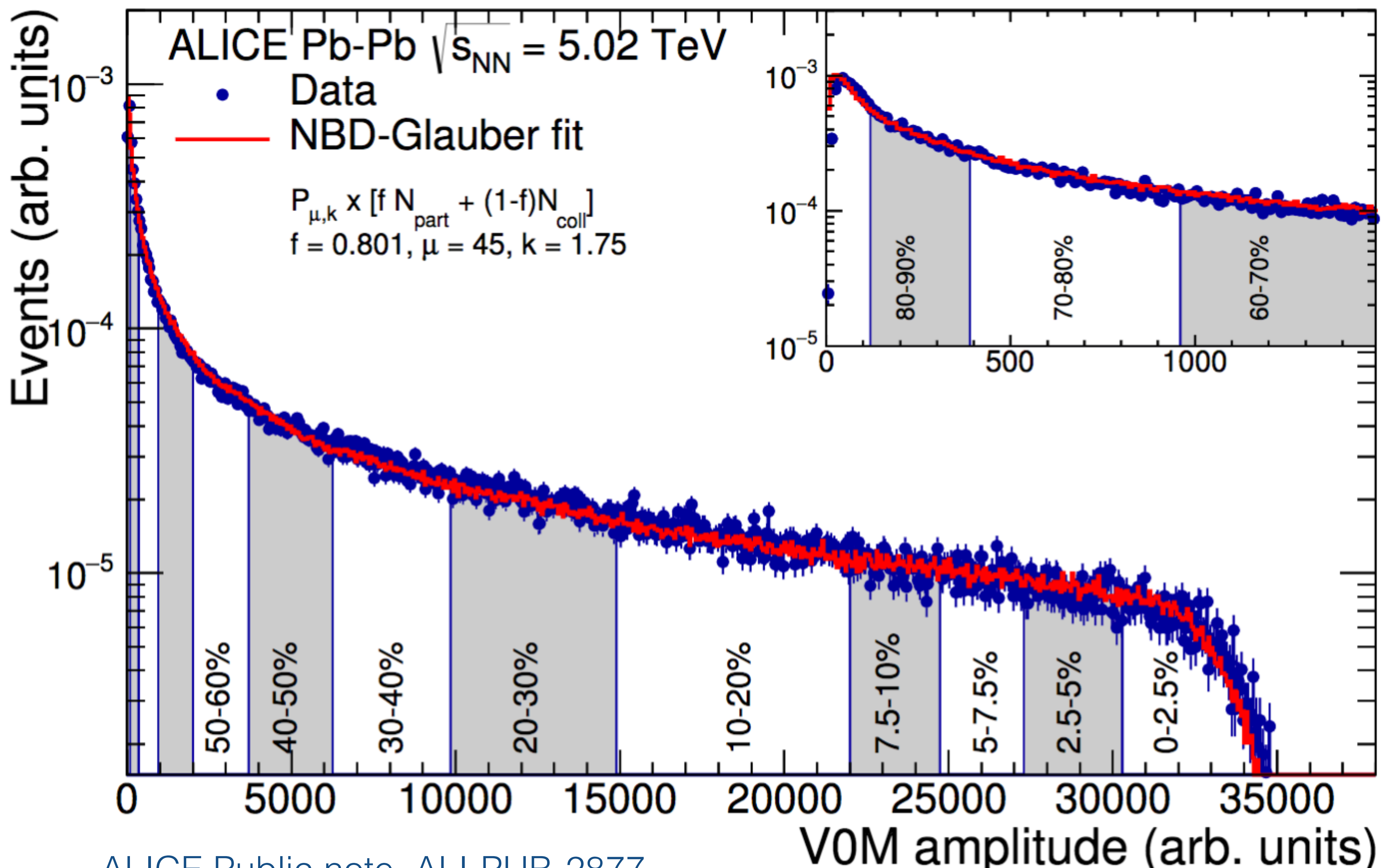
Ncoll, Npart…



Pramana 61 (2003) 865-876

Event characterisation

Geometrical quantities are calculated using a Glauber Monte Carlo, the different event classes are classified according to their impact parameter



ALICE Public note, ALI-PUB-2877

Radial flow

Change from pp to Pb-Pb:

- Increase in mean p_T
- Larger effect for larger mass

First indication of collective behaviour

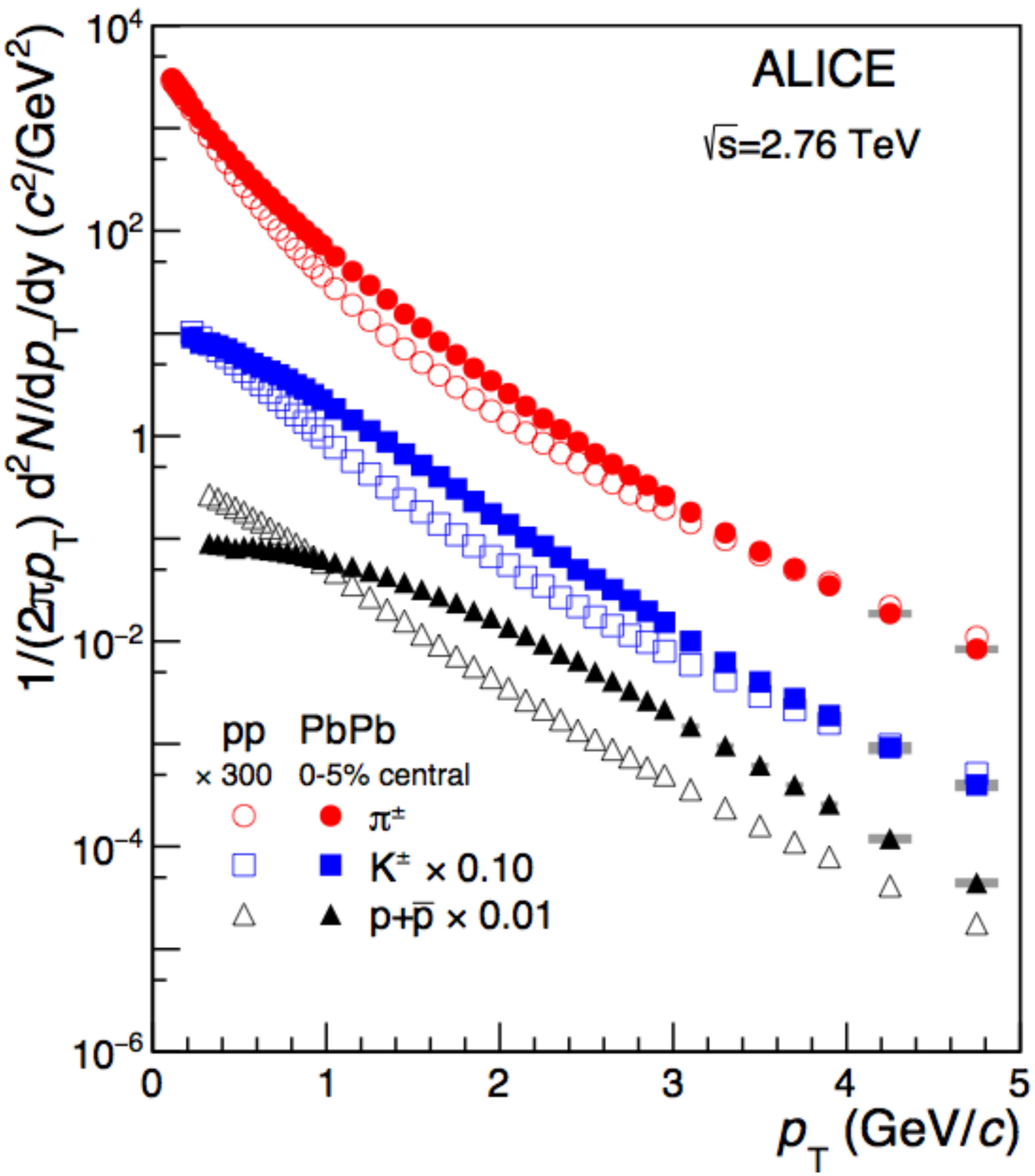
Pressure leads to radial flow

Same Lorentz boost (β) gives larger momentum for heavier particles

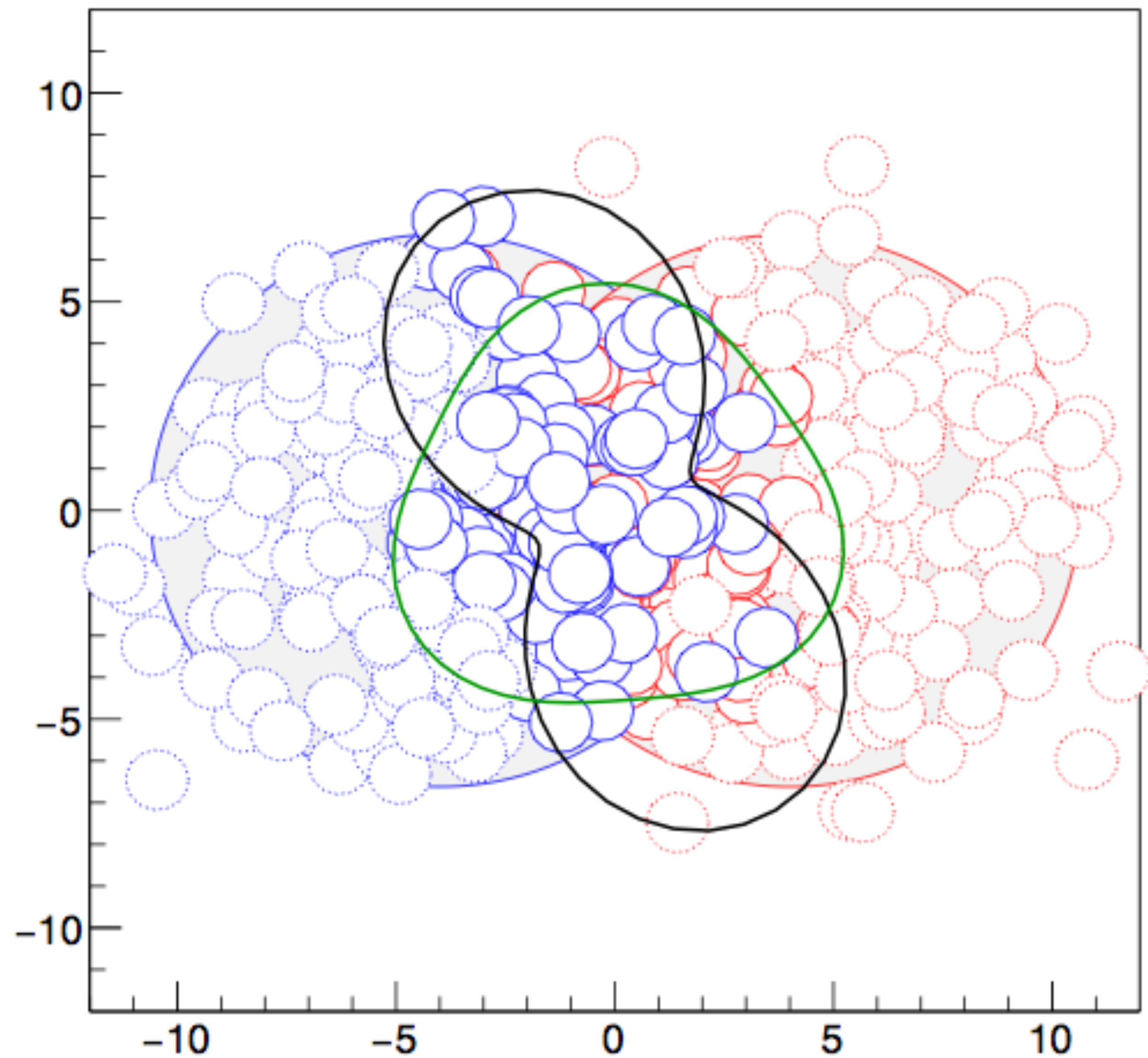
($m_p < m_K < m_\pi$)

Transverse momentum distribution

ALICE, PLB 736, 196

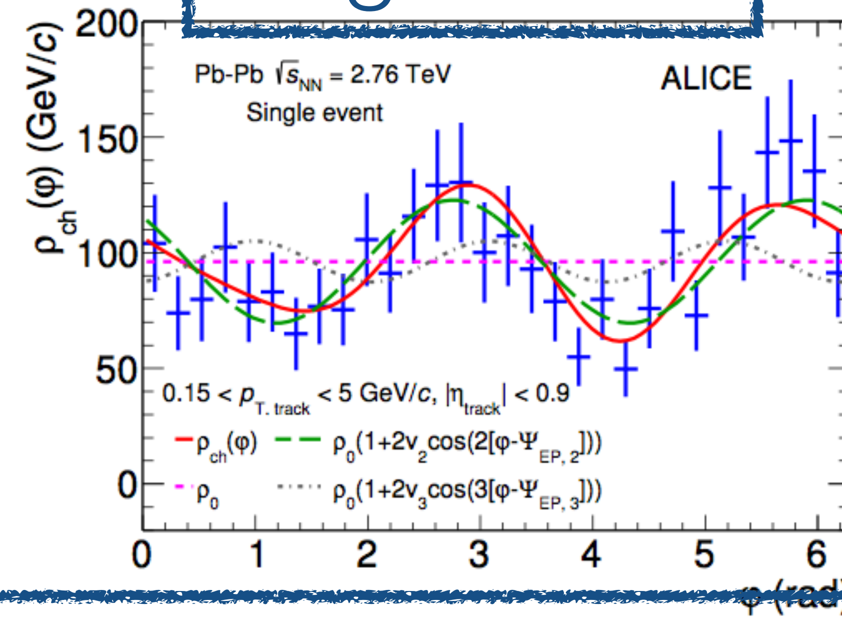


Azimuthal anisotropy

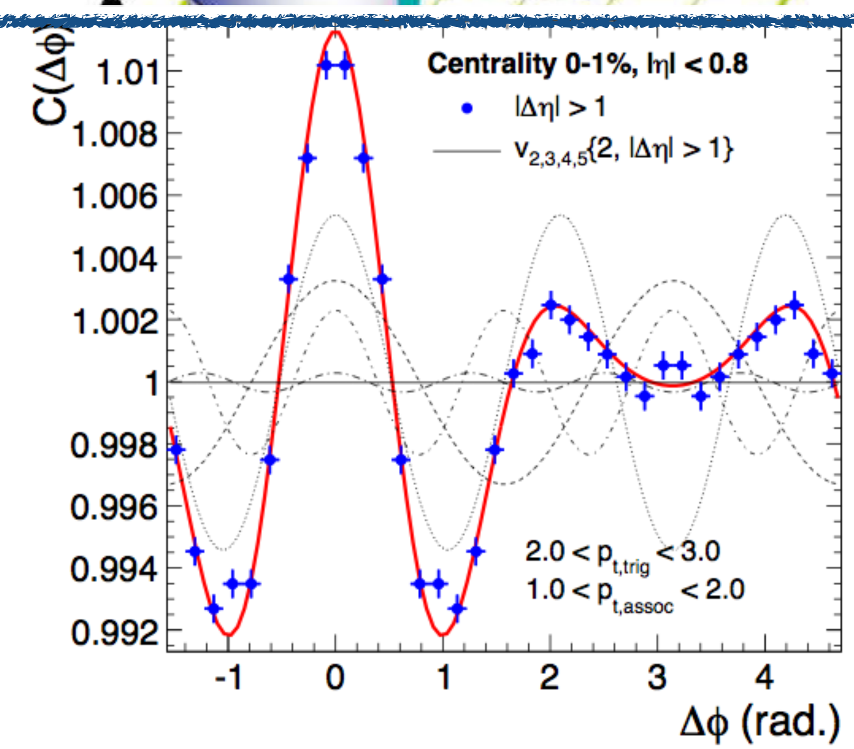


Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n by pressure gradients, flow of the QGP

Single event

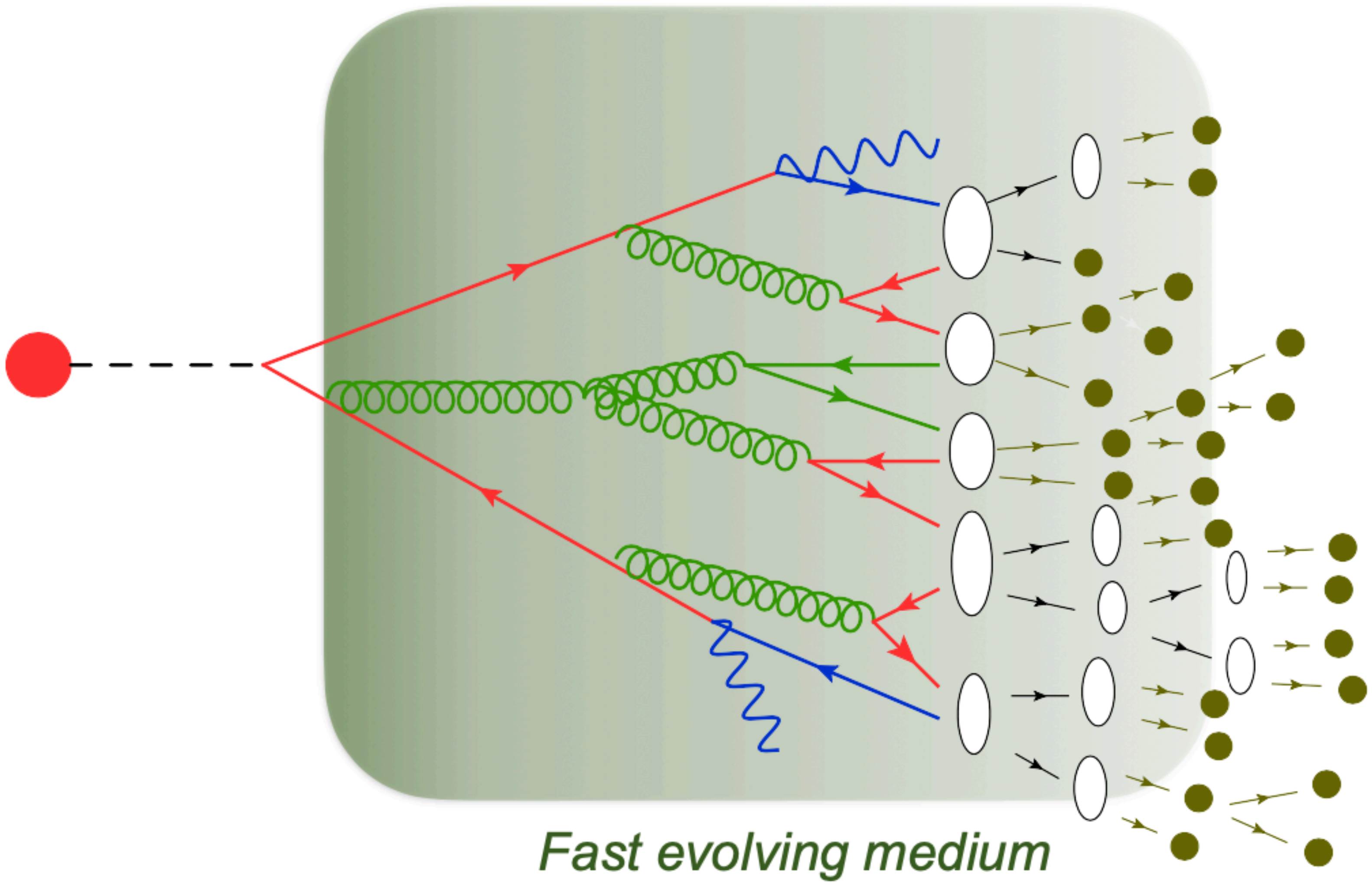


Sum over many events



Jet quenching

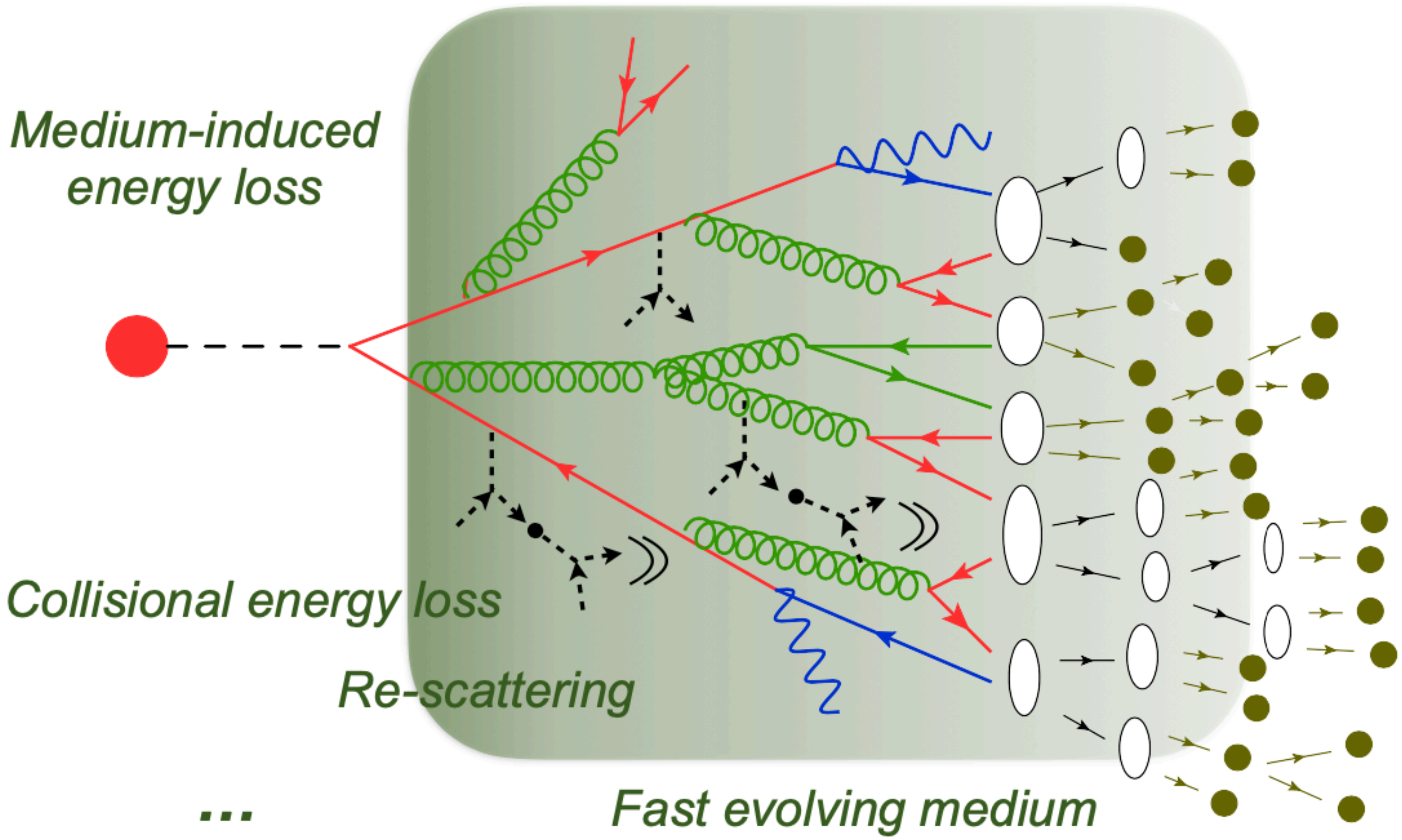
Jet shower in the medium, superposition of:
vacuum shower



From L. Apolinário [2020 RHIC/AGS Jet Workshop]

Jet quenching

Jet shower in the medium, superposition of:
medium-induced gluon emission



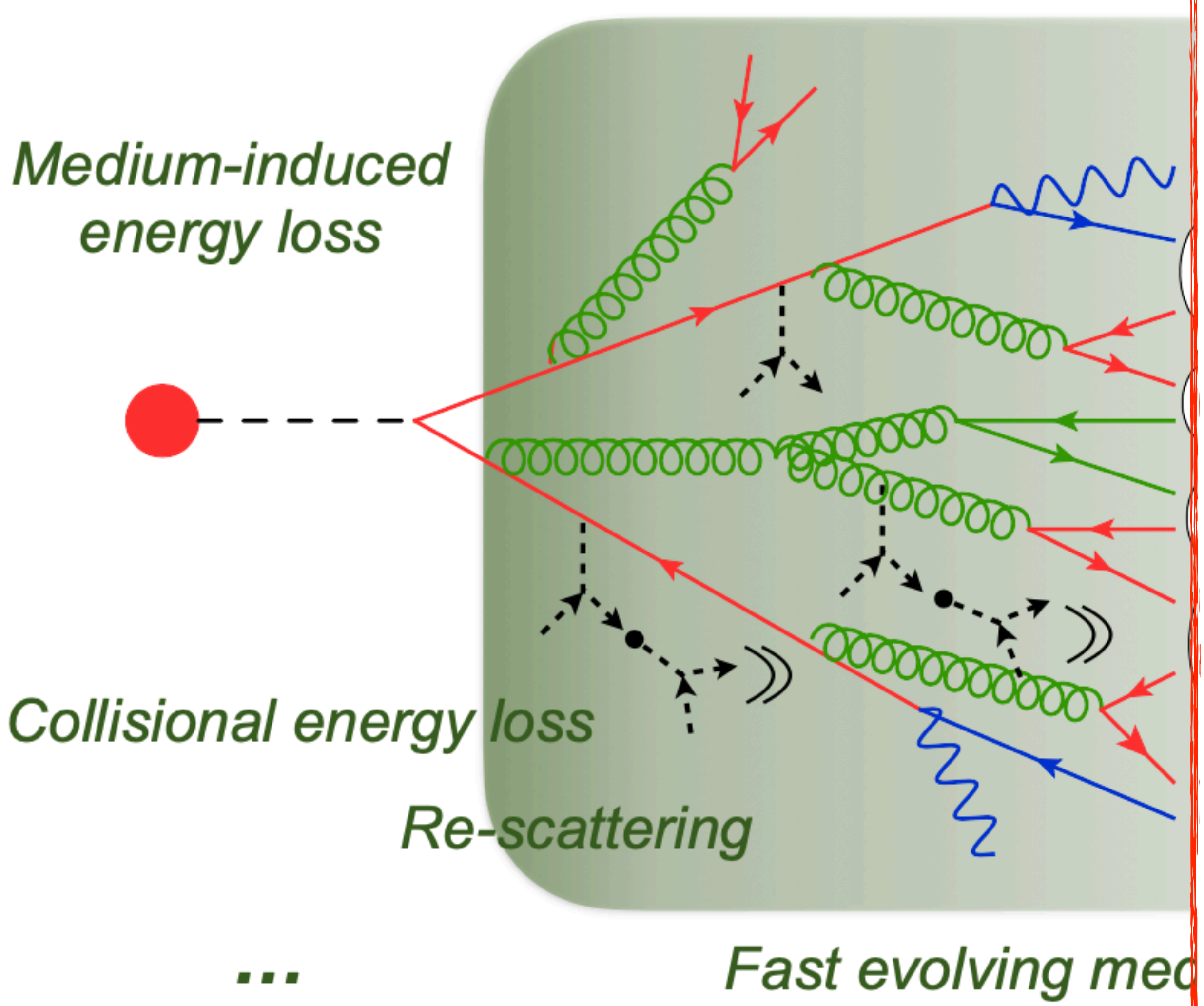
From L. Apolinário [2020 RHIC/AGS Jet Workshop]

These processes happen simultaneously and interfere

Jet quenching

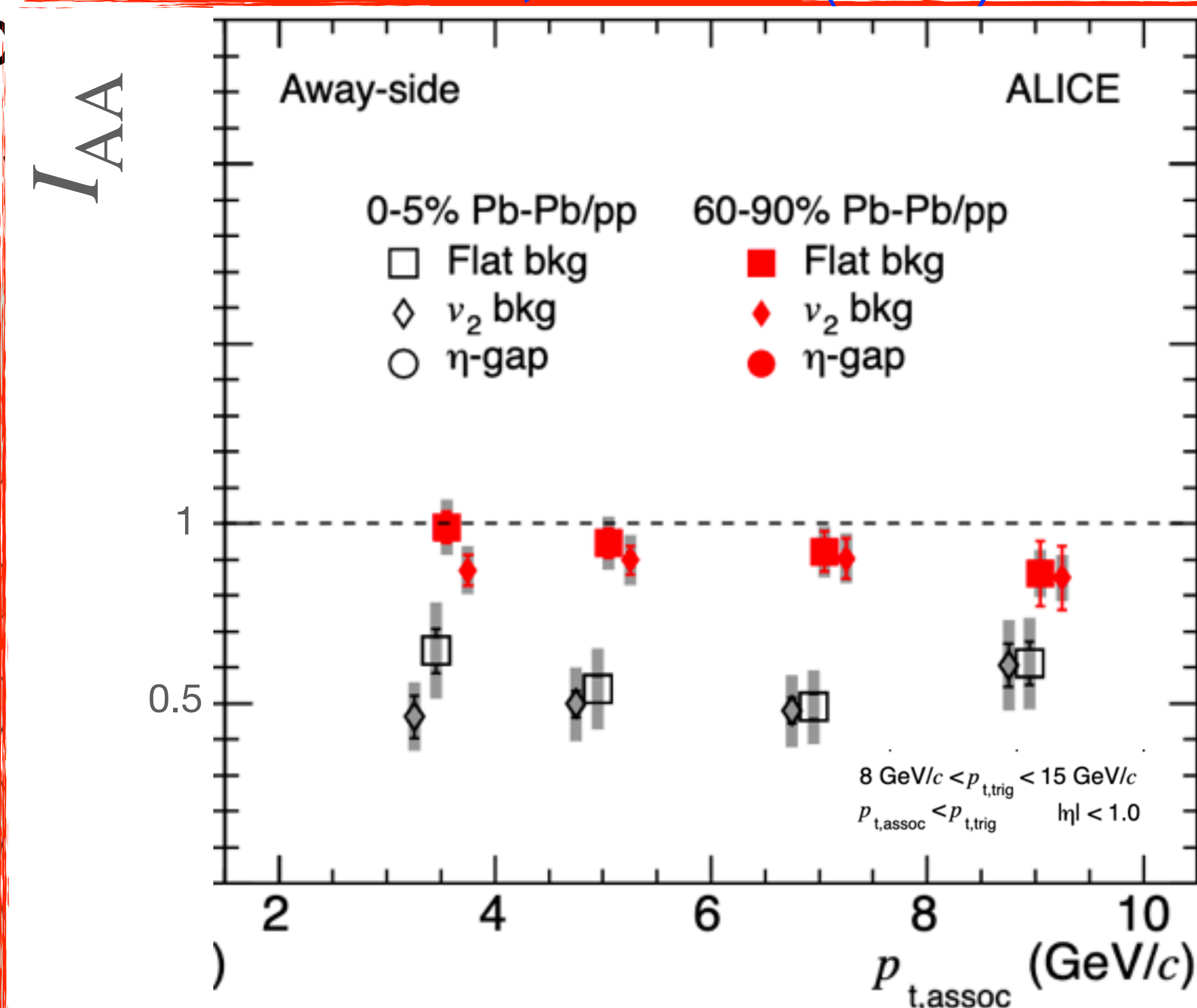
Jet shower in the medium, sup

medium-induced gluon emis



From L. Apolinário [2

ALICE, PRL 108 (2012) 092301



Suppression of jet-like yield of the away side of the di-hadrons correlations (A-A relative to MB pp)

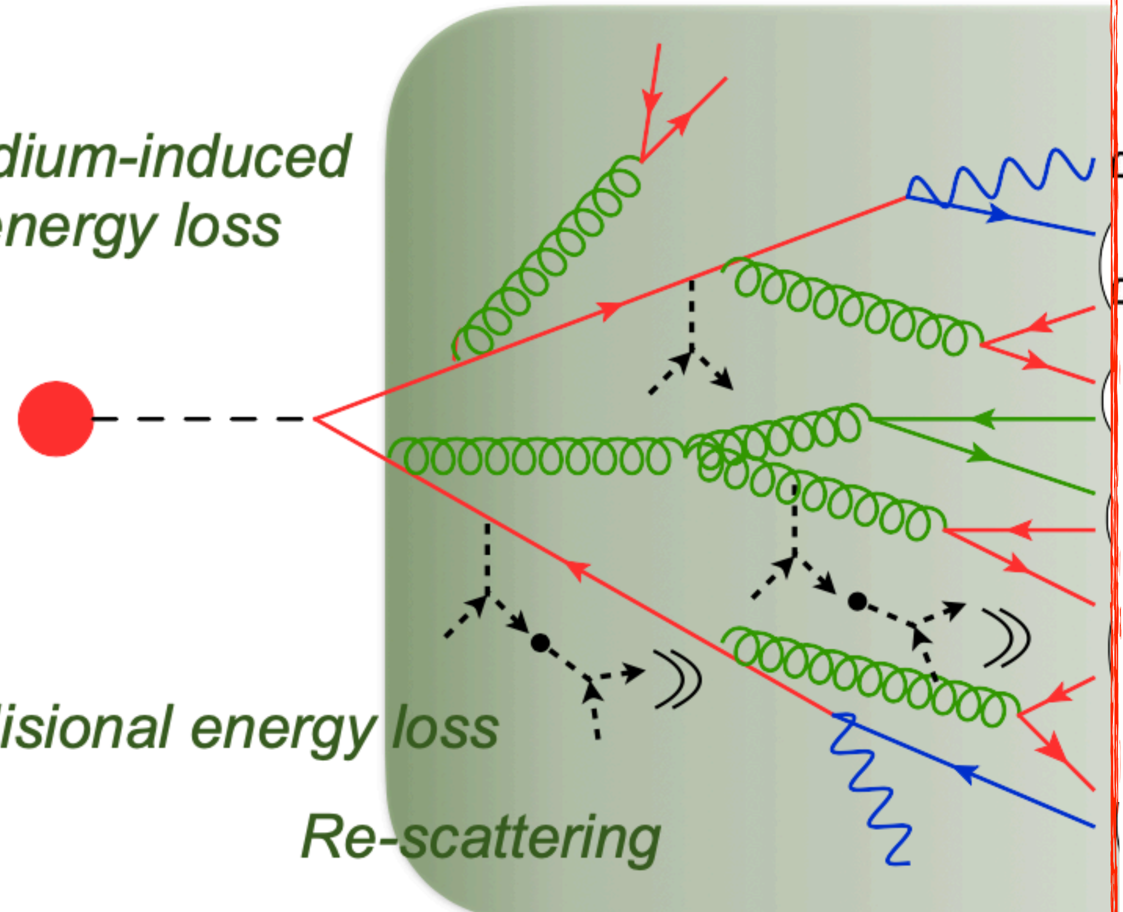
These processes happ

Jet quenching

ALICE, PRL 110 (2013) 082302

Jet shower in the medium, sup

medium-induced gluon emis



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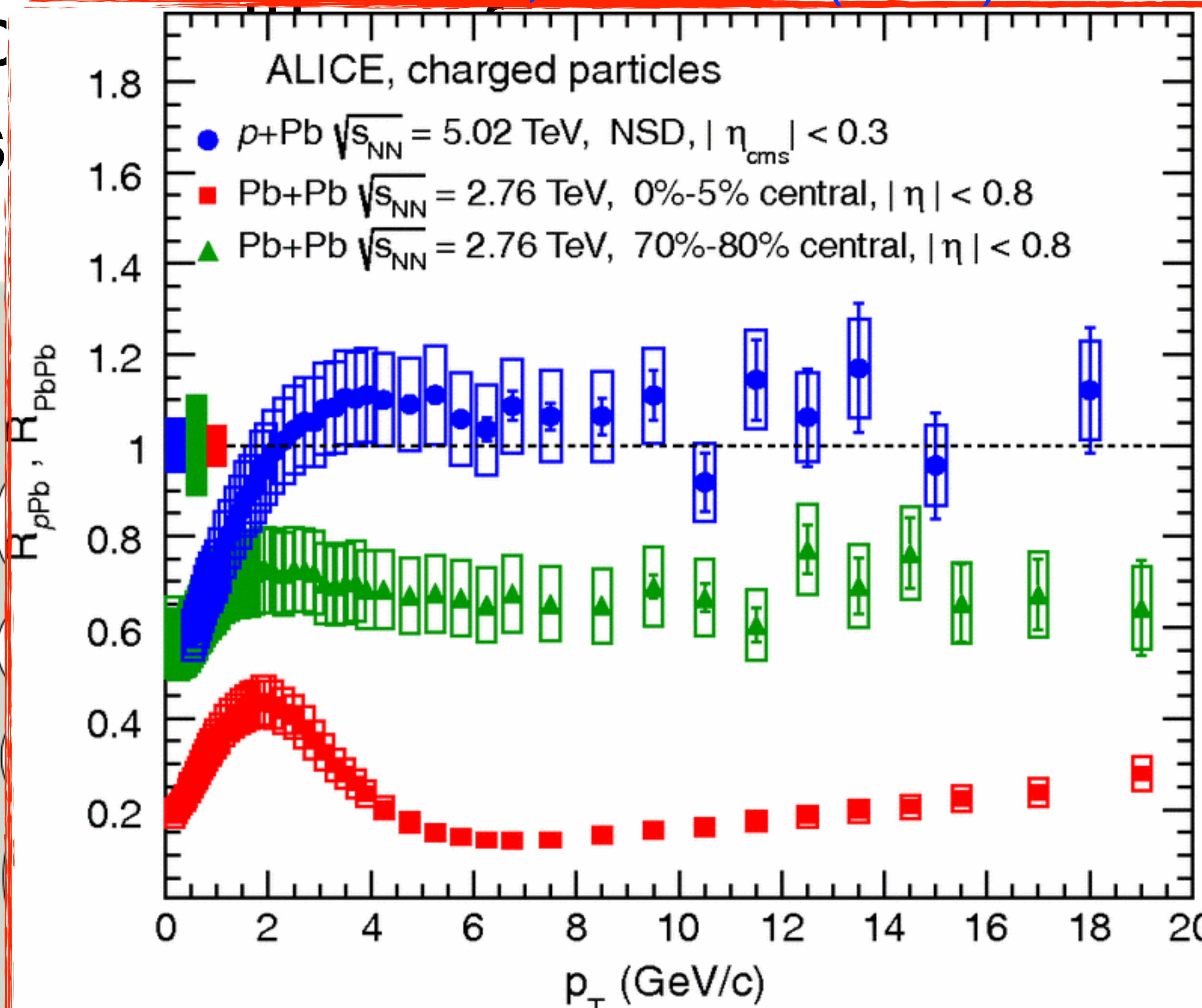
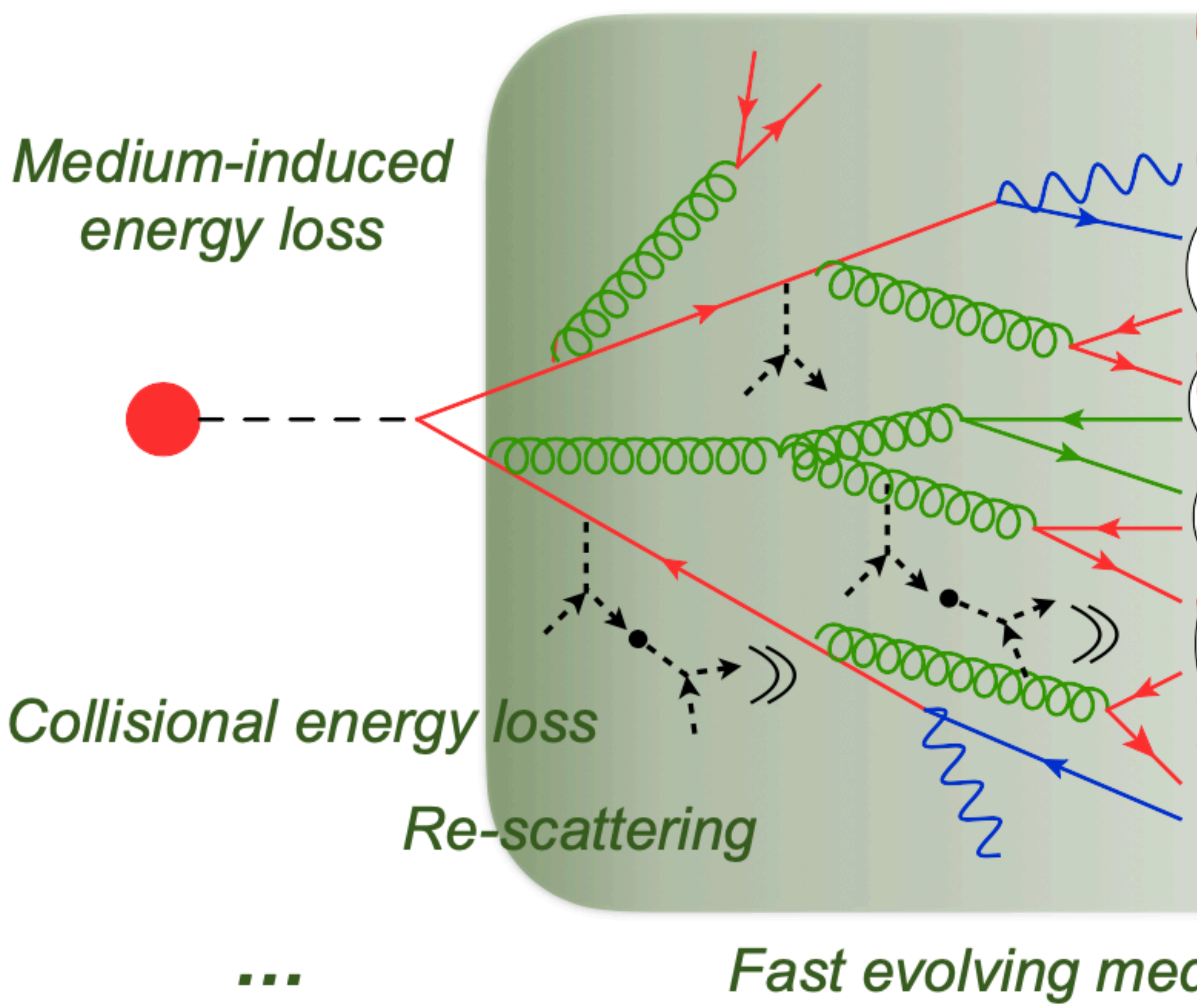


Suppression of the high p_T hadron yield in A-A relative to MB pp

Jet quenching

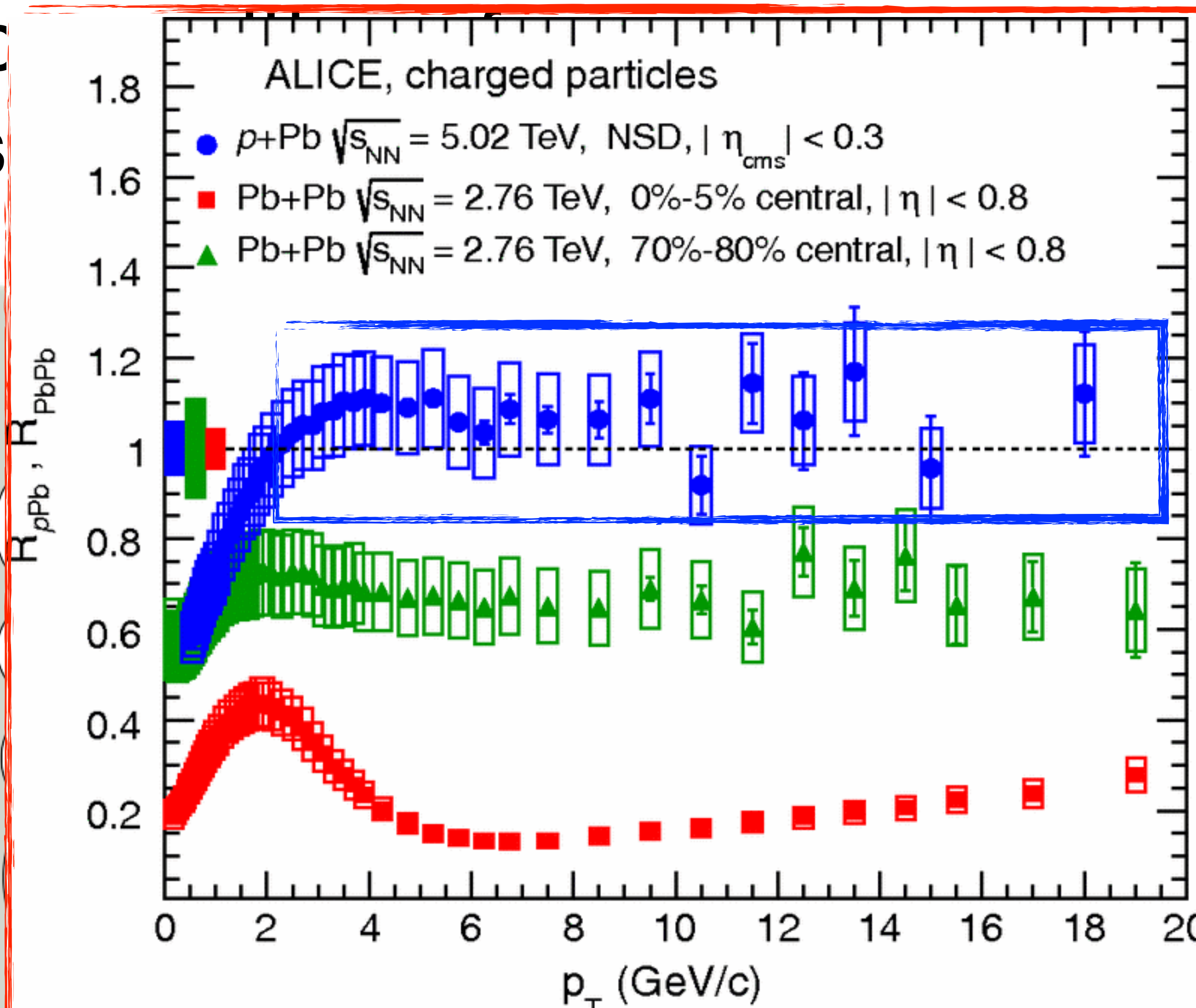
Jet shower in the medium, sup

medium-induced gluon emis



From L. Apolinário [2

Observed consequences, e.g. 2



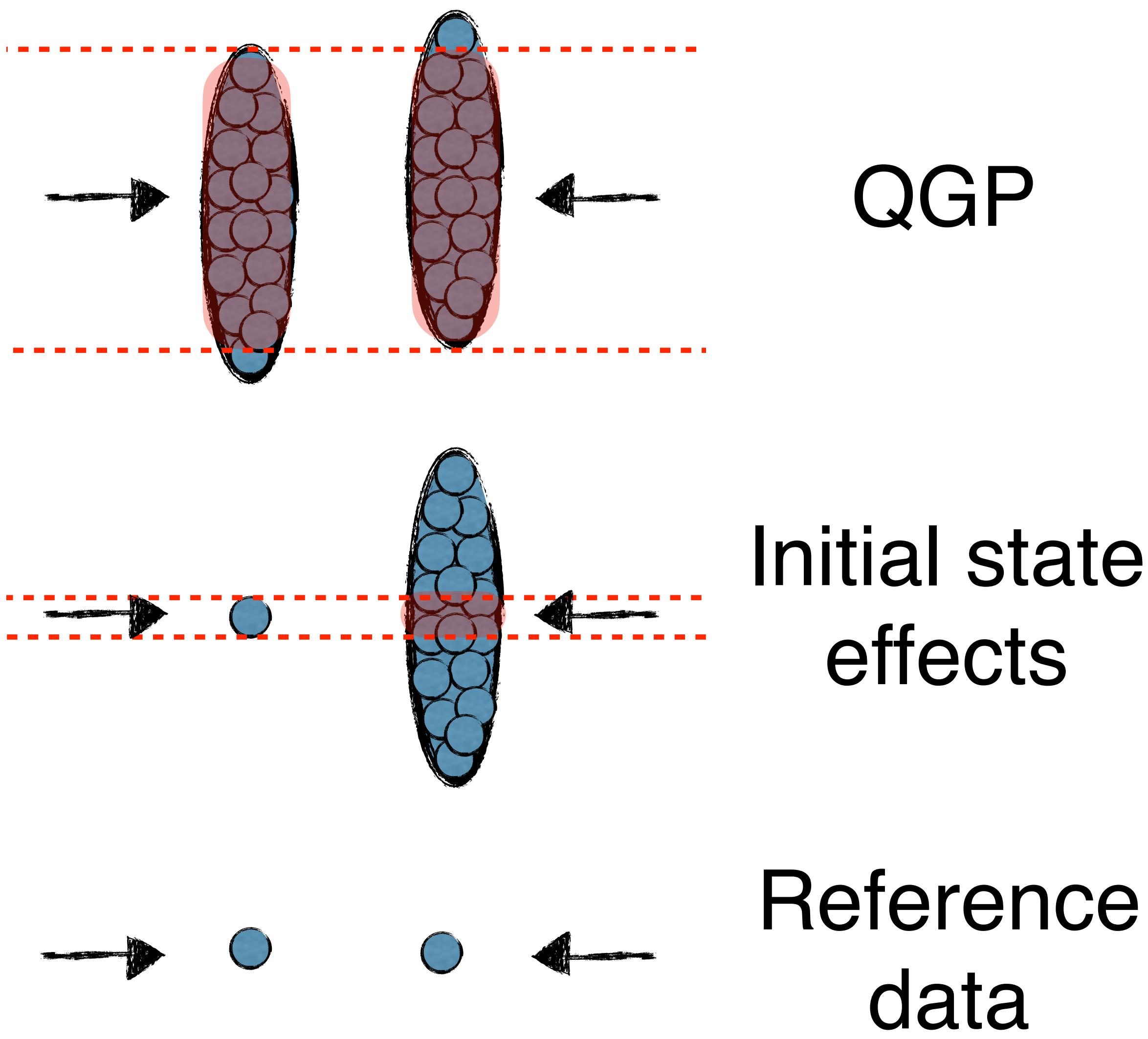
Suppression of the high p_T hadron yield in A-A relative to MB pp

The effect (suppression = parton energy loss) is not seen in p-Pb collisions → **more studies are needed**

Striking similarities between pp and AA data

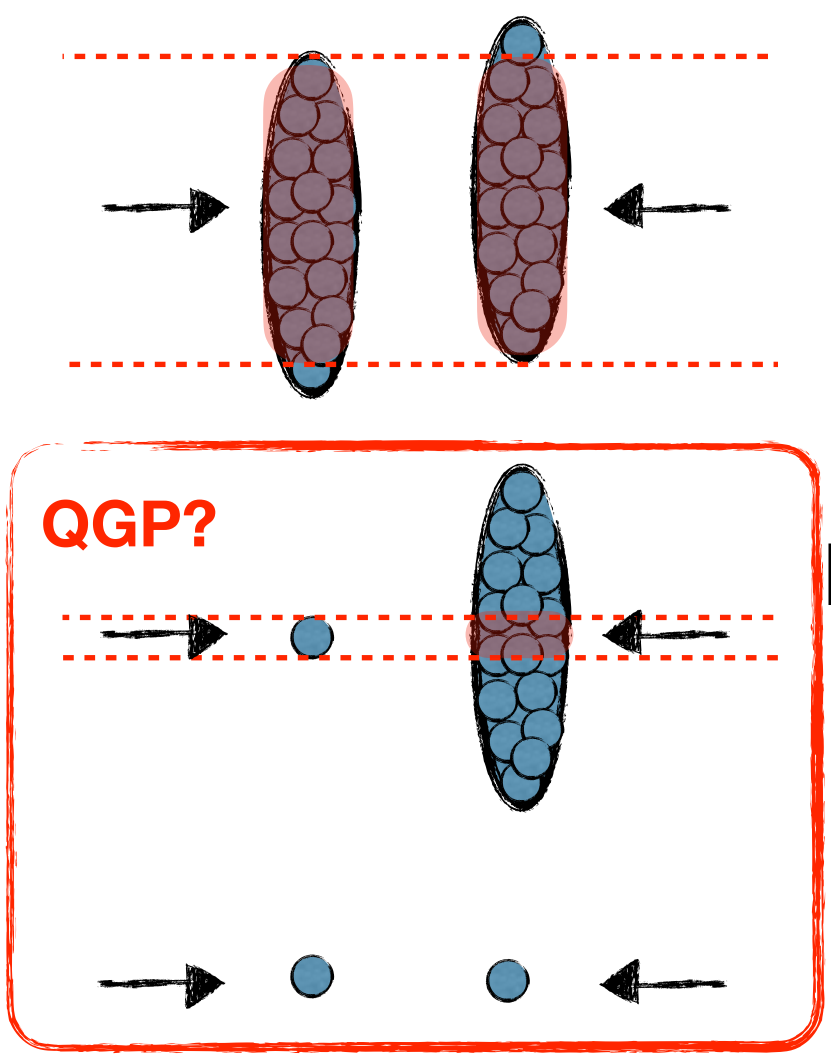
Traditional approach

pp and p-A (even peripheral A-A) collisions traditionally studied as "control experiments" to extract the genuine properties of QGP in central A-A collisions



Change of perspective

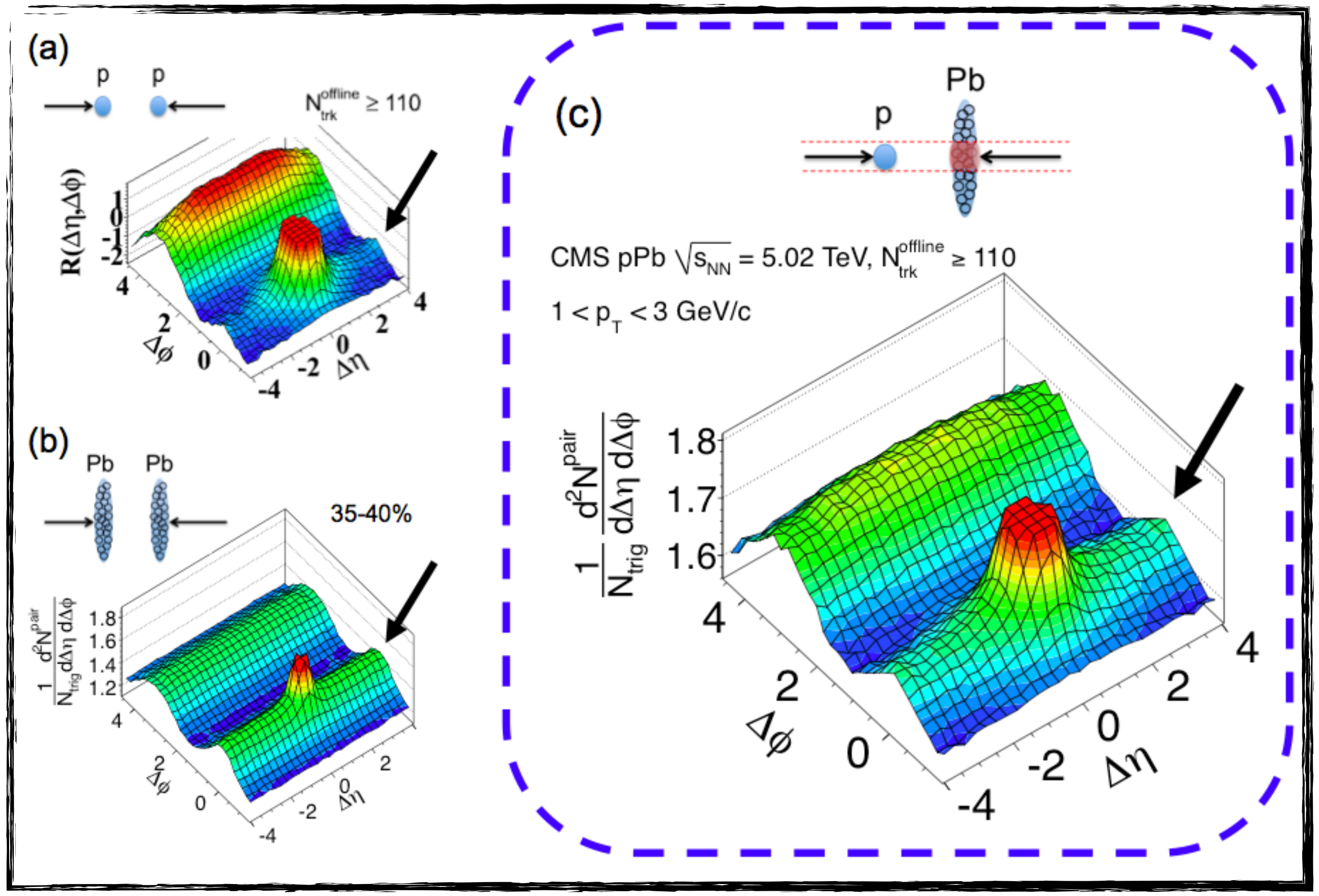
pp and p-A (even peripheral A-A) collisions traditionally studied as "control experiments" to extract the genuine properties of QGP in central A-A collisions



QGP

Initial state effects

Reference data



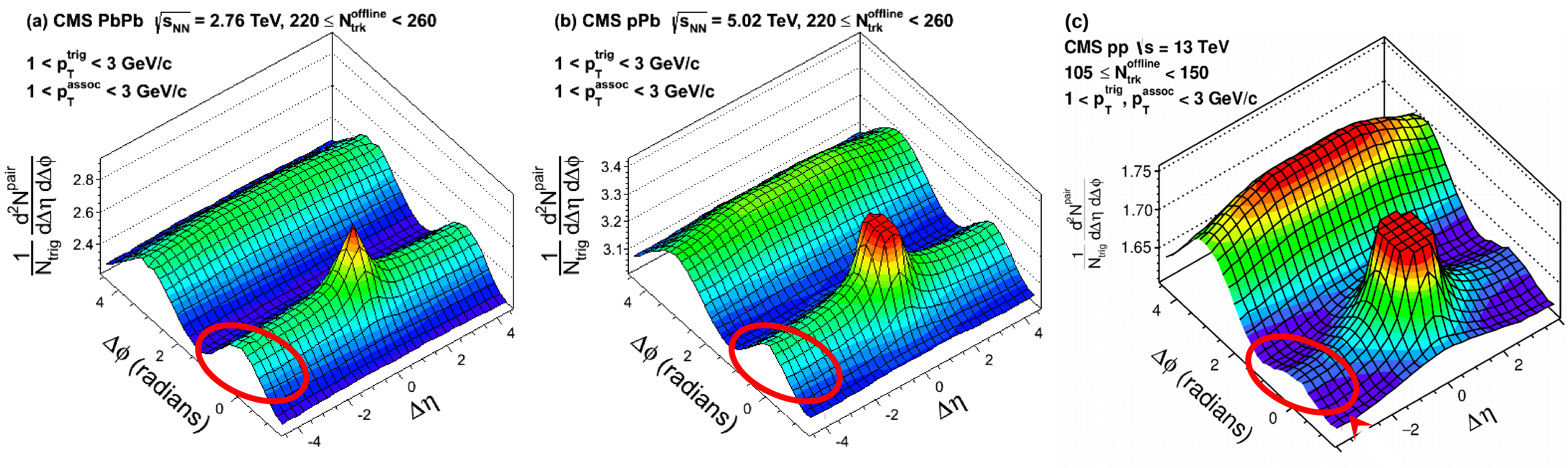
"Ridge" structures have been discovered in small systems (pp and p-A collisions). See e.g.

CMS, JHEP 1009 (2010) 091
ALICE, PLB 719 (2013) 29
ATLAS, PRL 110 (2013), 182302
LHCb, PLB 762 (2016) 473

In heavy-ion collisions it is interpreted as a signature of the collective expansion of the system

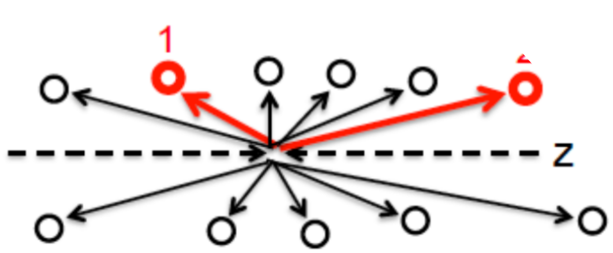
Long range correlations

Two-particle correlations with inclusive charged particles



CMS, PLB 724 (2013) 213

CMS, PLB 765 (2017) 193



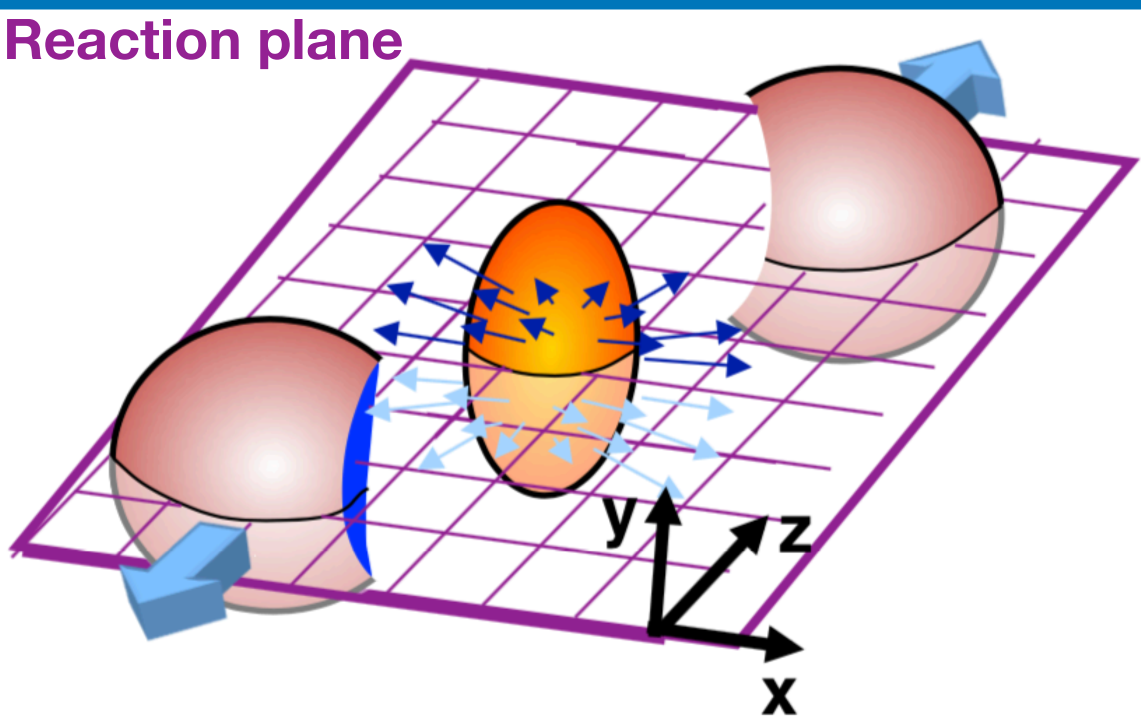
What is the nature of long-range correlations observed in small systems?

Anisotropic flow

Collectivity in small systems

- **Collective flow**: In heavy-ion collisions (HIC) azimuthal anisotropies established during the hydrodynamic stage in response to initial geometry

  v_2: dominates in non-central HI collisions
  v_{2n+1}: various geometrical configurations arising from initial geometry fluctuations



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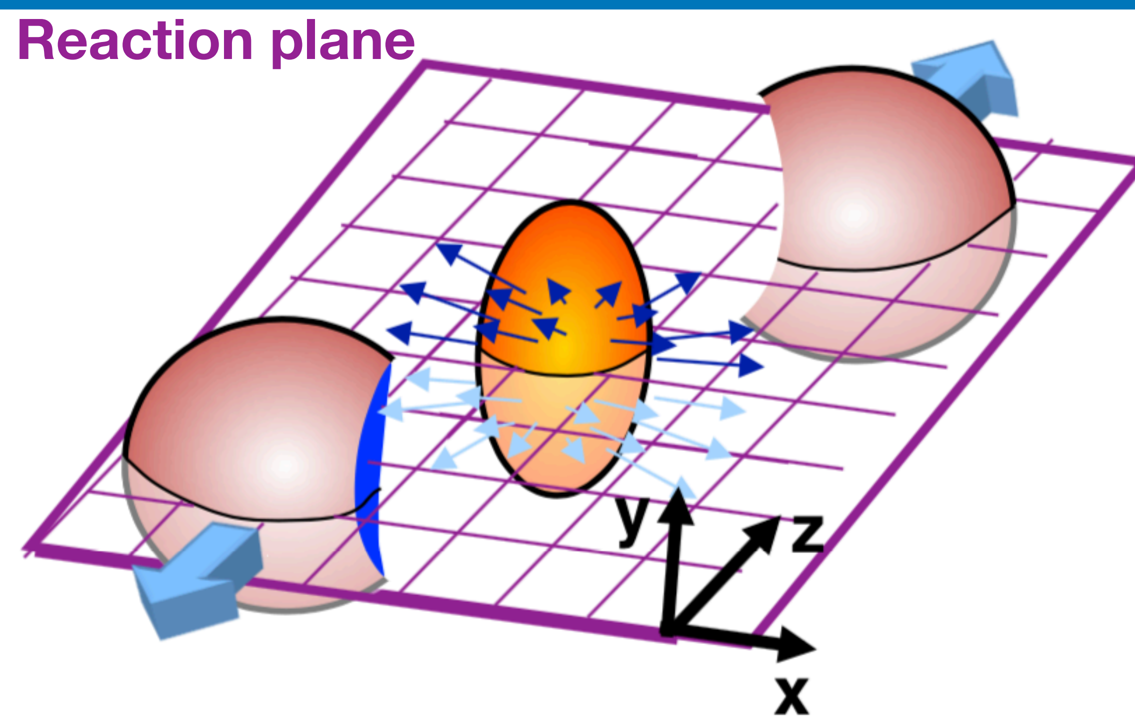
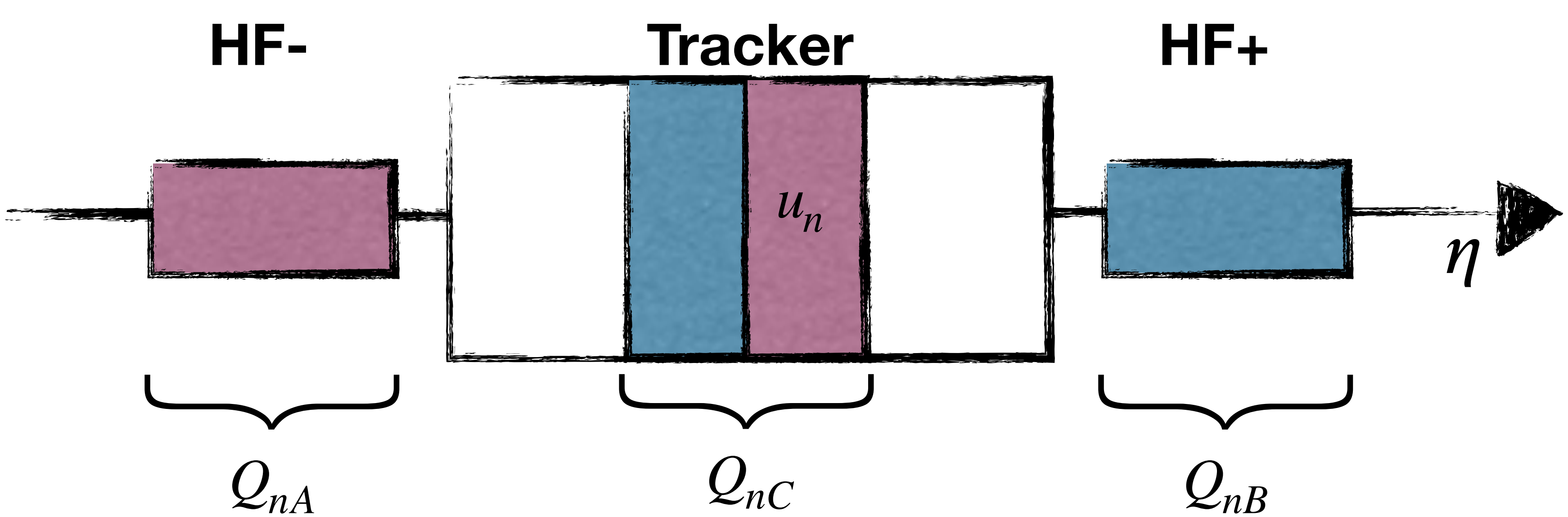


Main challenge for small systems: non-flow contributions (resonance decays, jets). Different techniques have been developed to control non-flow effects (e.g. scalar product method correlating particles from different subevents)

$$Q_n = \sum_{i=1}^{M} \tilde{\omega}_i e^{in\phi_i}$$

$$v_n\{SP\} = \frac{\langle u_n Q_{nA}^{*} \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^{*} \rangle \langle Q_{nA} Q_{nC}^{*} \rangle}{\langle Q_{nB} Q_{nC}^{*} \rangle}}}$$



Anisotropic flow coefficients

Instituto de Ciencias Nucleares UNAM

ALICE, arXiv:1903.01790

v_2(Pb-Pb) > v_2(p-Pb) > v_2(pp)

(as expected if the overall collision geometry dominates)

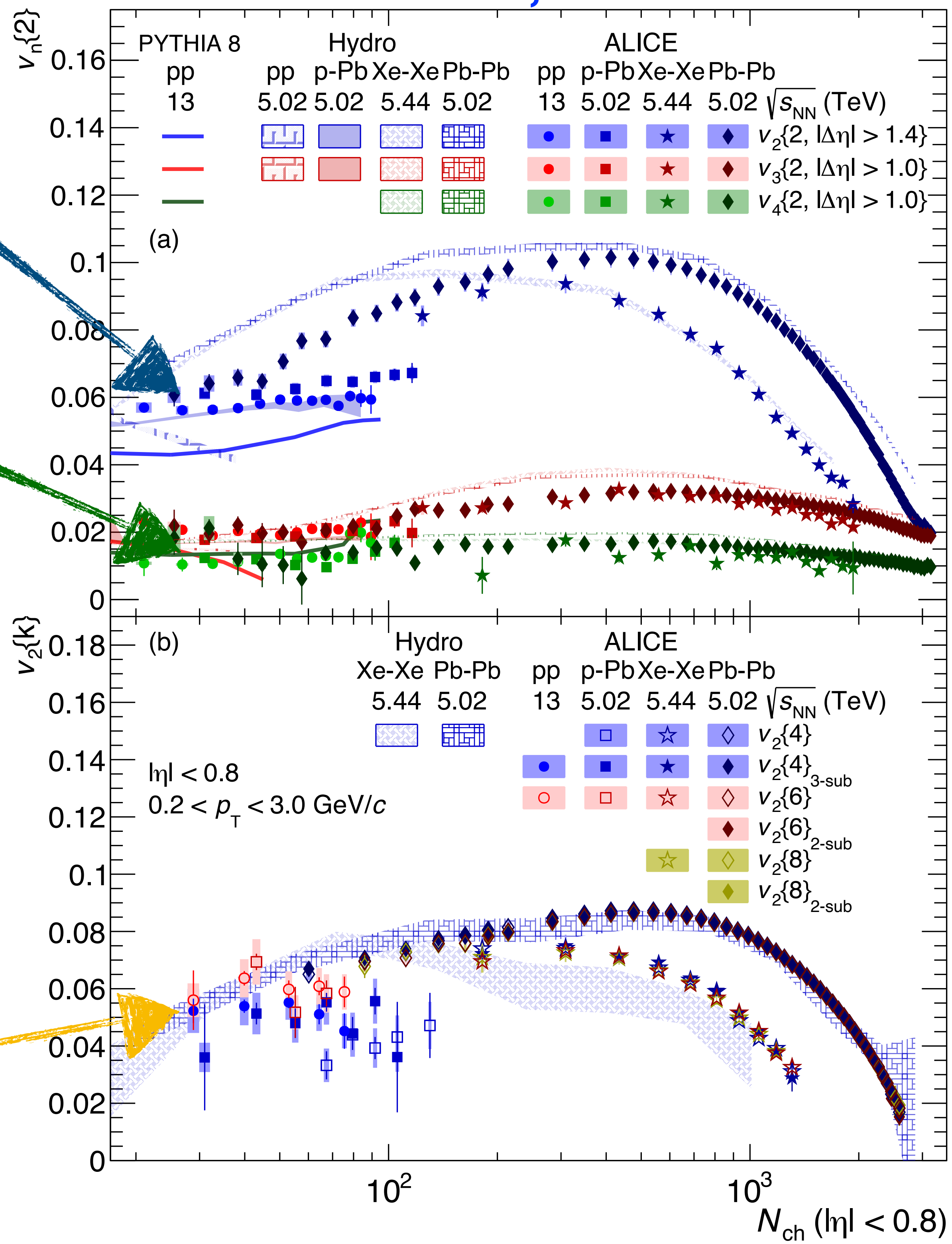
v_3(Pb-Pb) ≈ v_3(p-Pb)

(indicating a similar, fluctuation-driven initial-state geometry)

Se also: **CMS, arXiv:1901.07997**

The analysis has also been extended to the subevent method

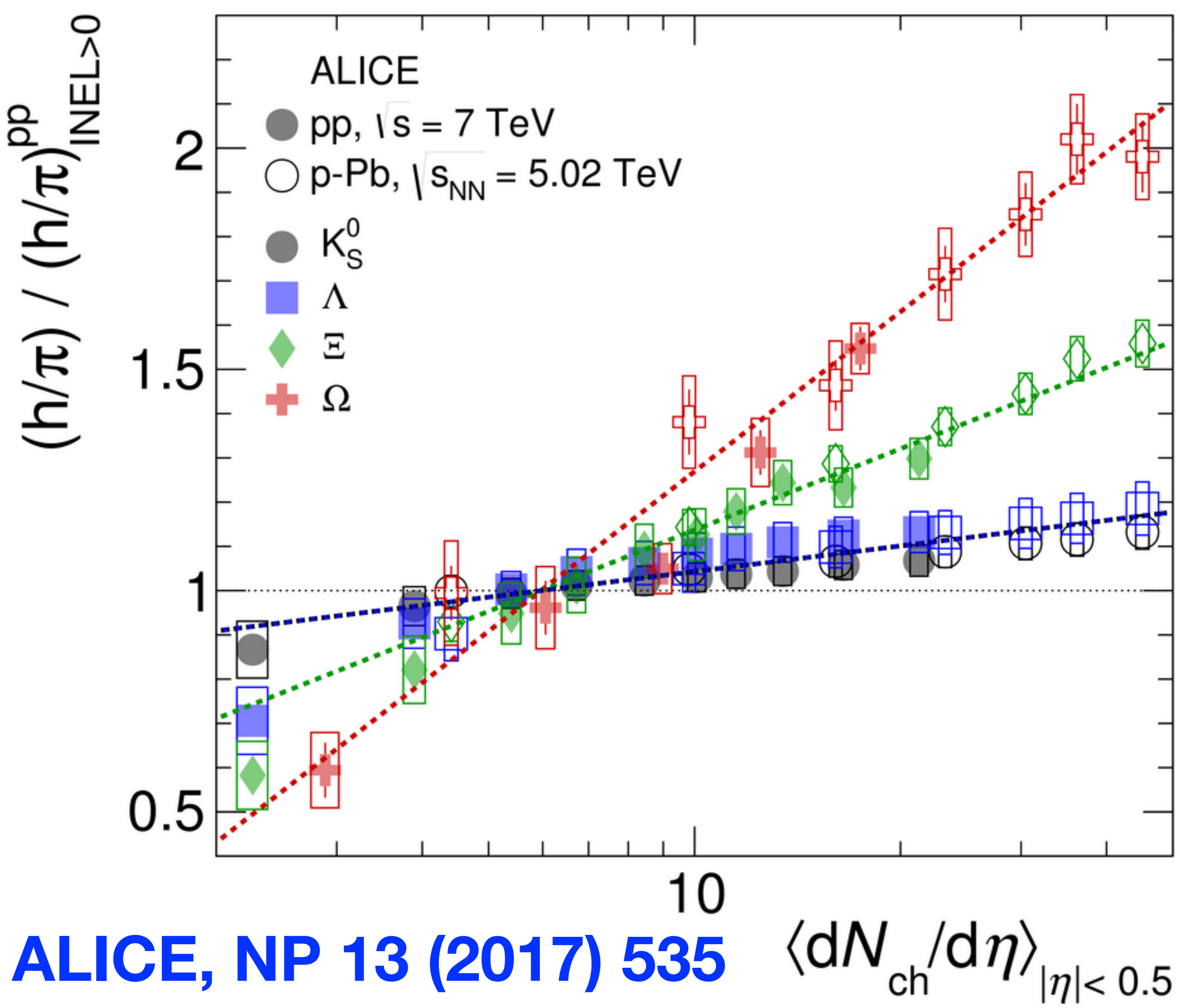
v_2>0 for small systems



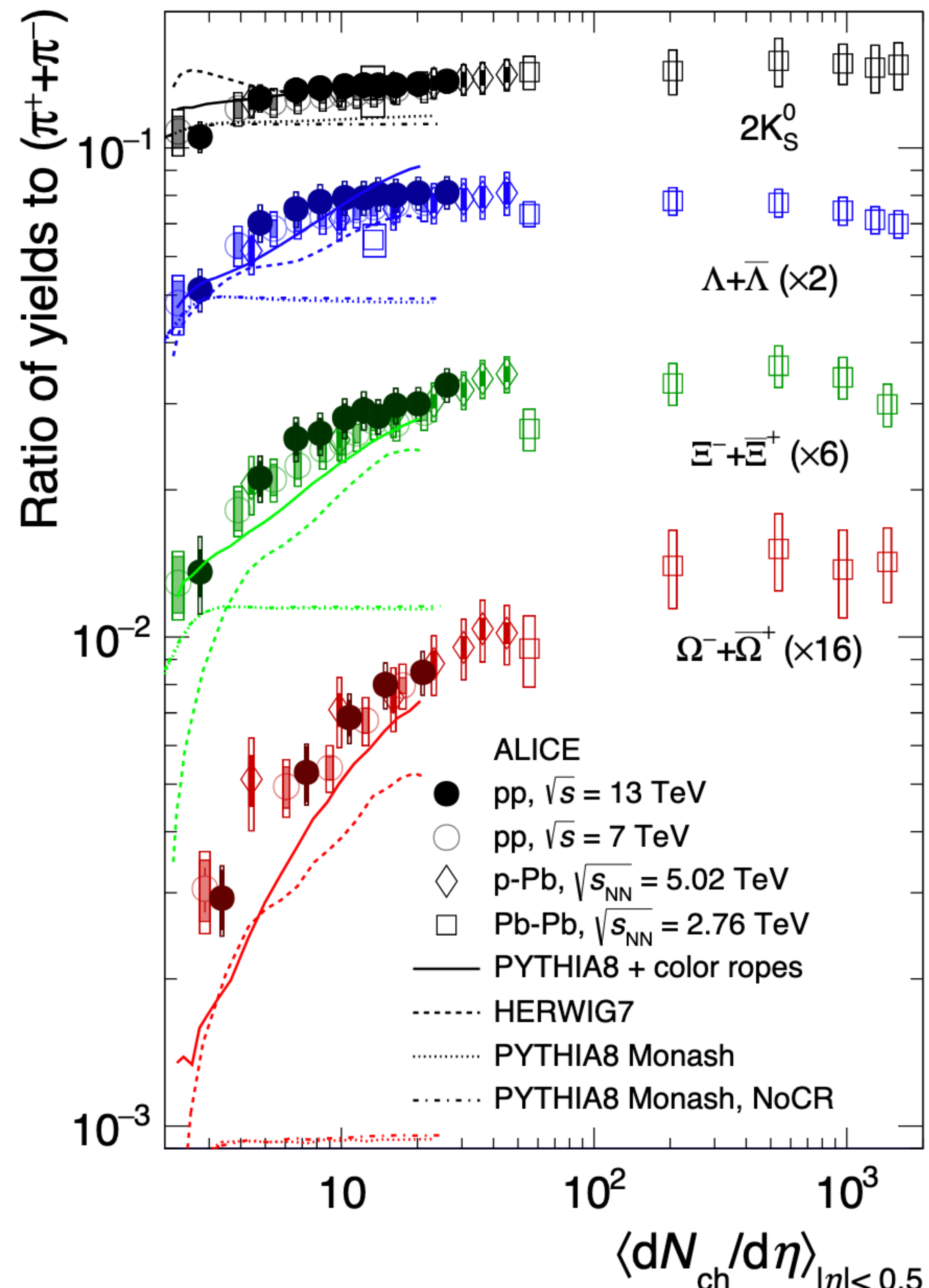
Hadrochemistry and radial flow

Strangeness enhancement

None of microscopic models (string hadronization, core-corona approach) can reproduce the increasing trend



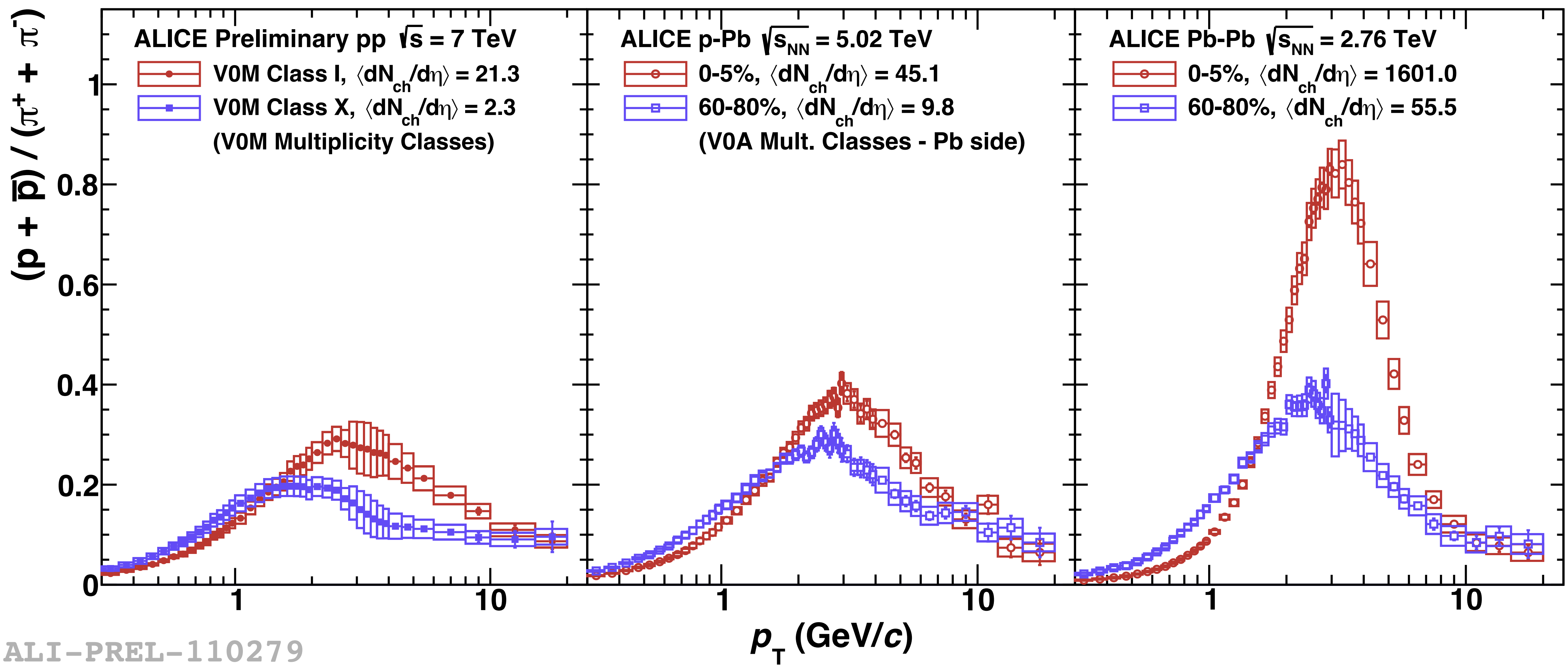
ALICE, NP 13 (2017) 535



ALICE, EPJC 80 (2020) 8, 693

Particle production

Identified particle production vs multiplicity in pp, p-Pb and Pb-Pb collisions exhibits remarkable similarities

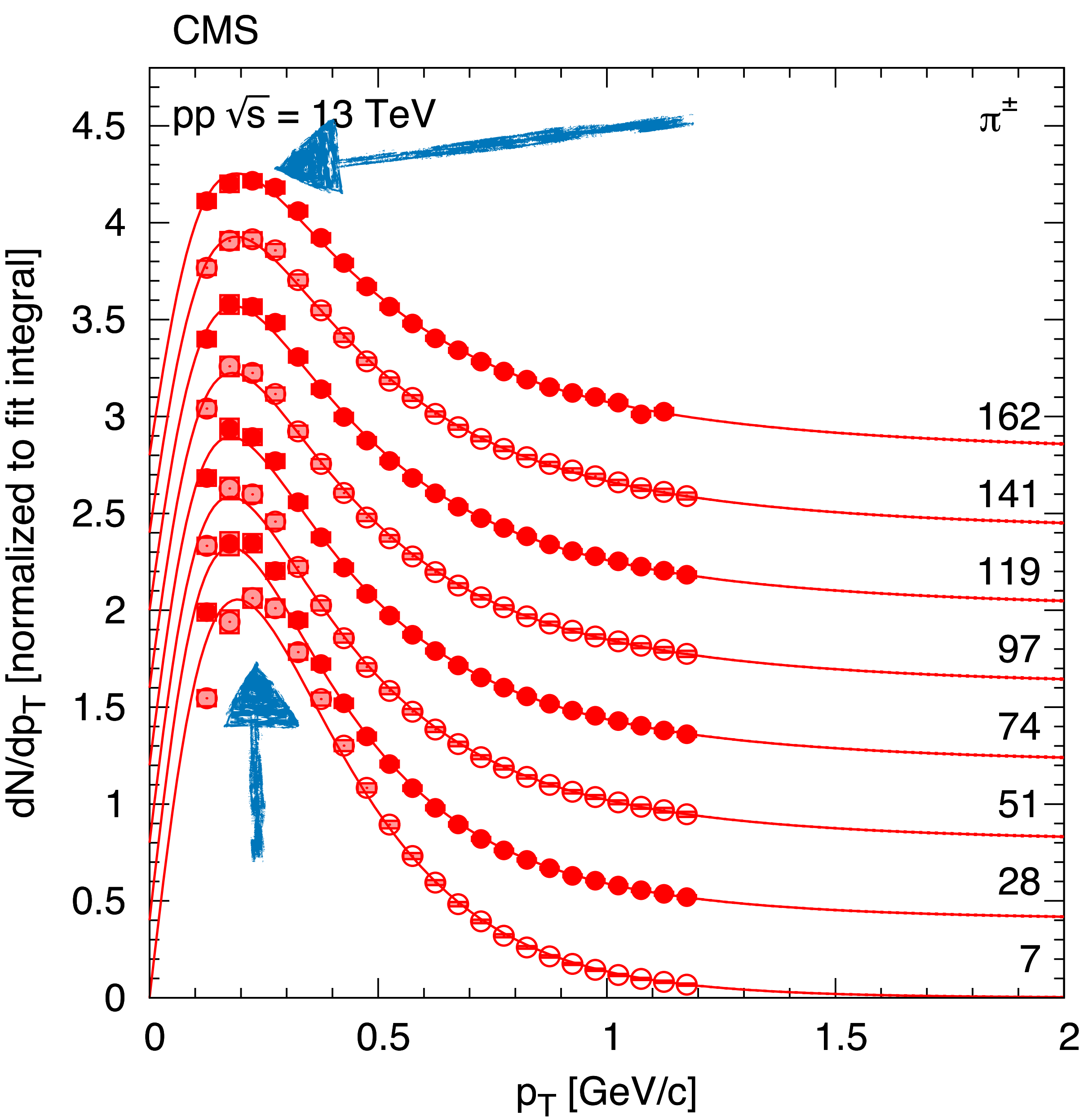


Mass dependent modification of the p_T spectral shapes going from low to high multiplicities

A. O. (ALICE), *PoS* LHCP2019 (2019) 091

π/K/p p_T spectra vs N_{ch}

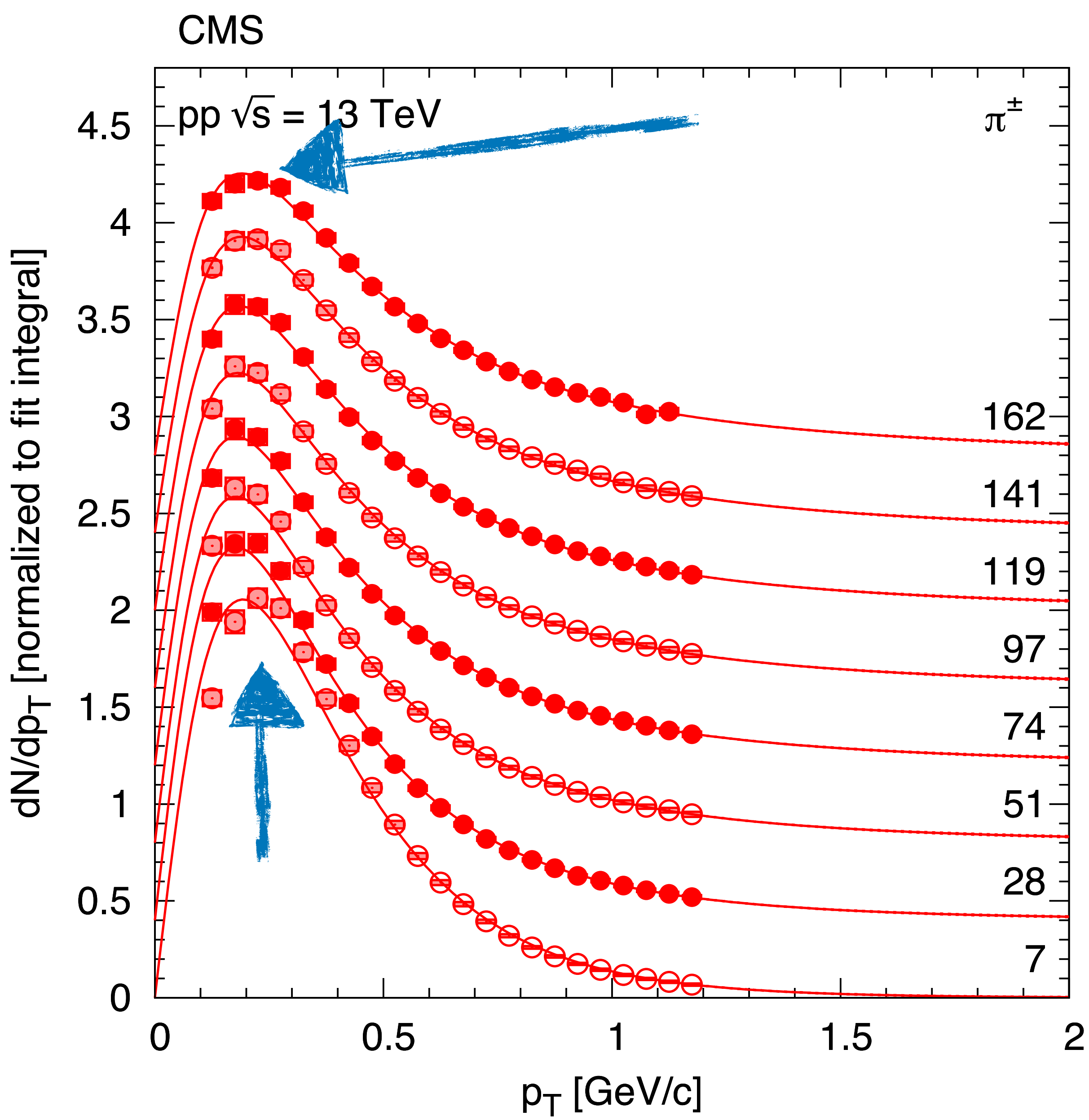
CMS, PRD 96 (2017) 112003

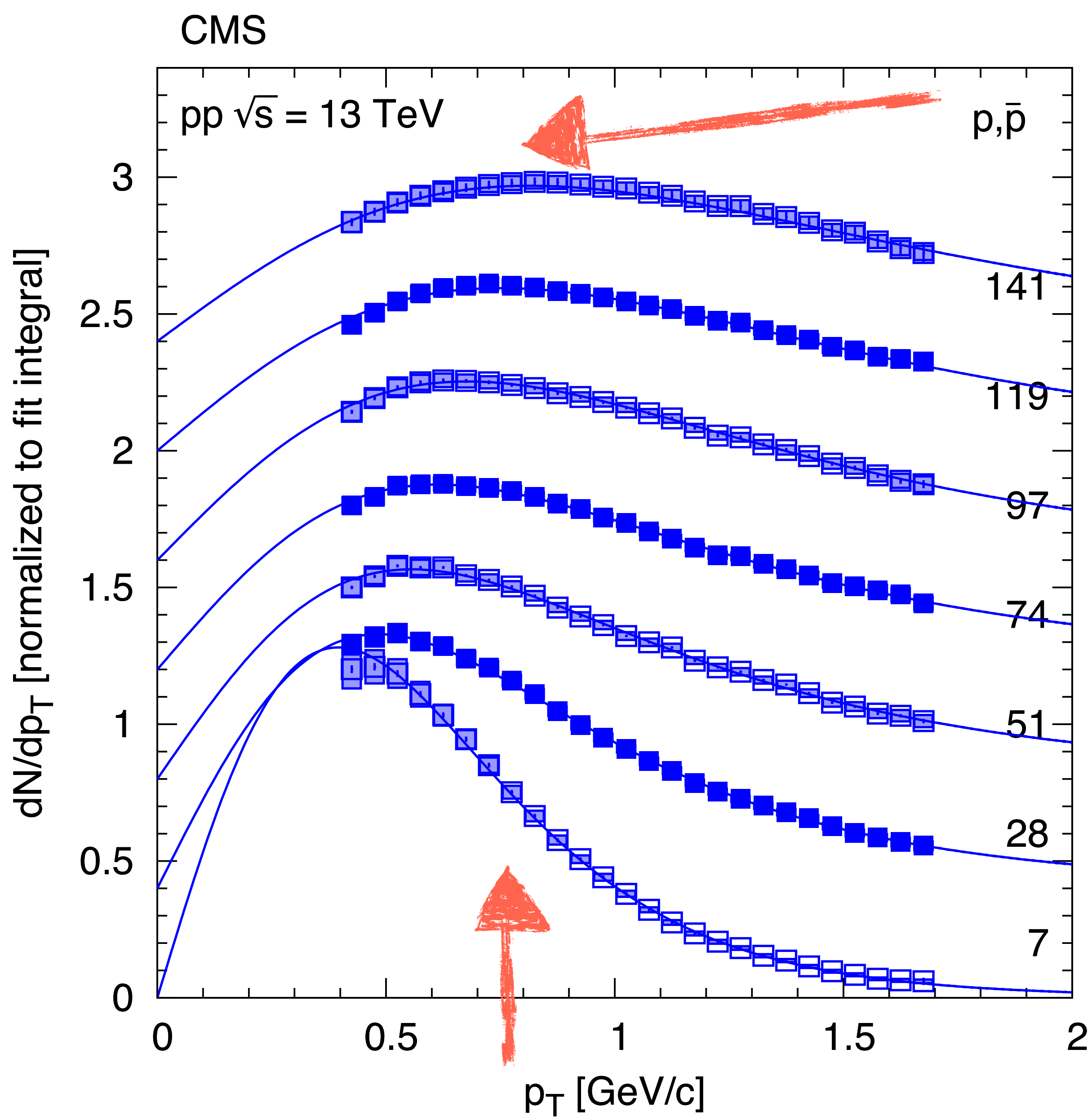


The p_T spectra at low p_T flatten out with increasing event multiplicity

π/K/p p_T spectra vs N_{ch}

CMS, PRD 96 (2017) 112003



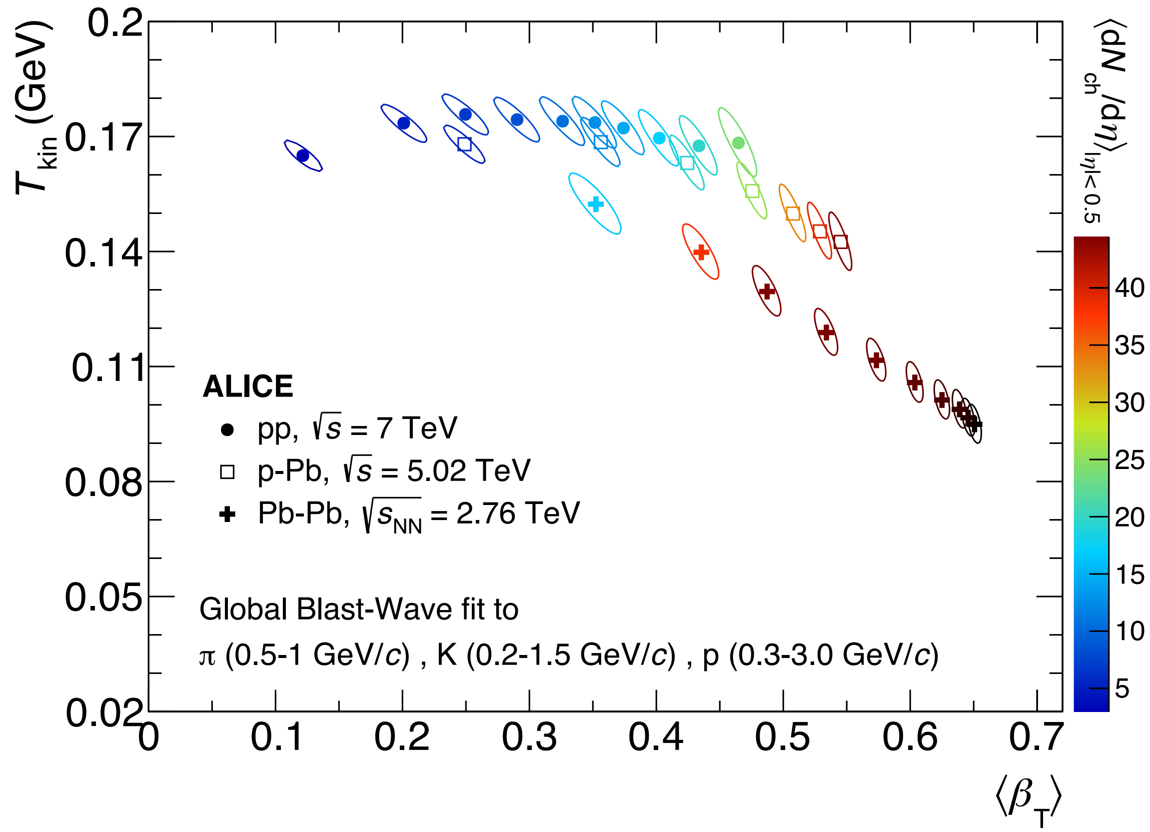


The p_T spectra at low p_T flatten out with increasing event multiplicity
The effect is mass dependent as observed in heavy-ion collisions

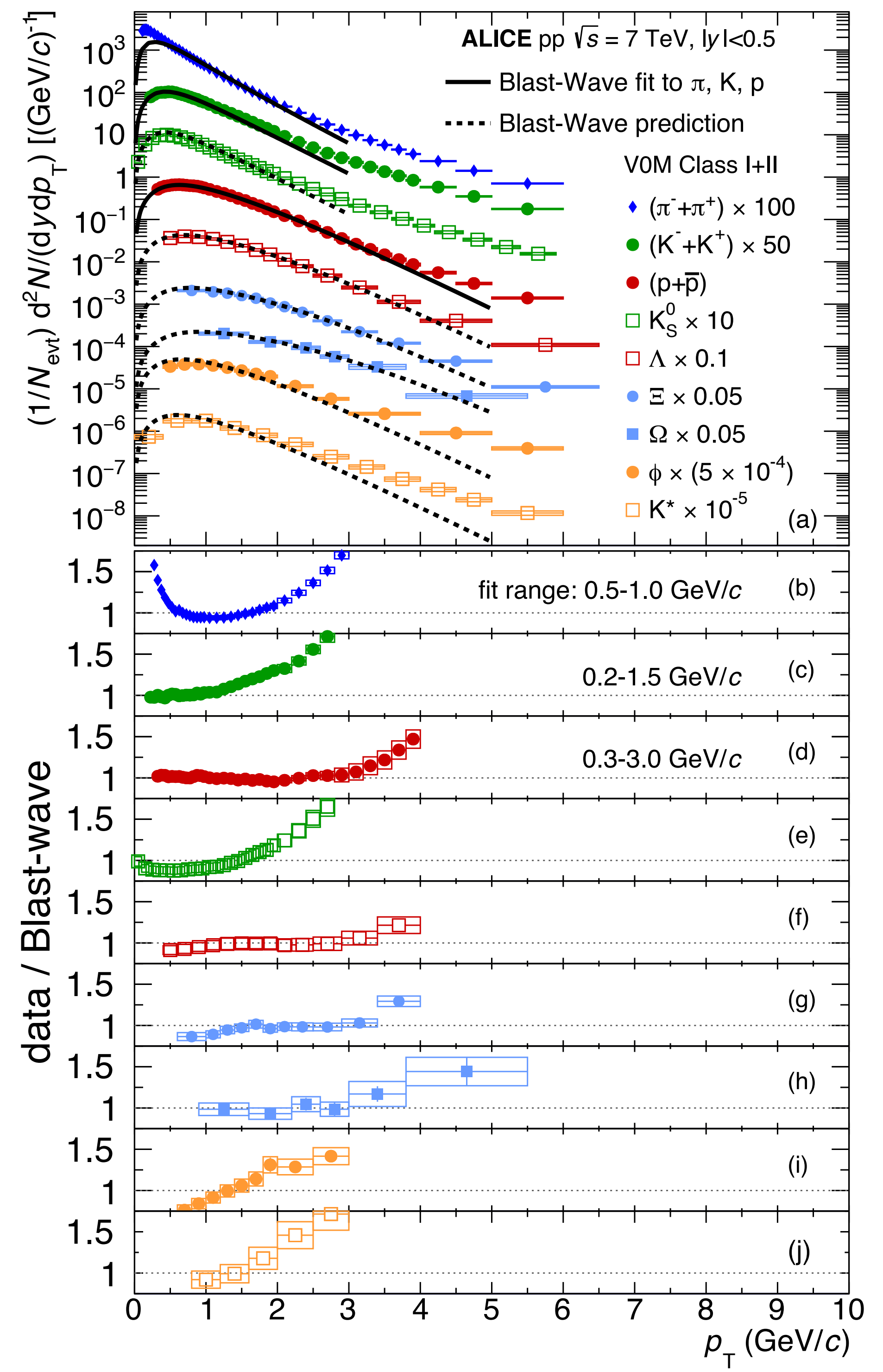
Radial flow

Blast wave: simplified hydro model:

- Assumes common particle expansion with β_T and T_{kin}
- Assumption ~ok for large collision systems
- pp and p-Pb: similar β_T vs T_{kin} behavior



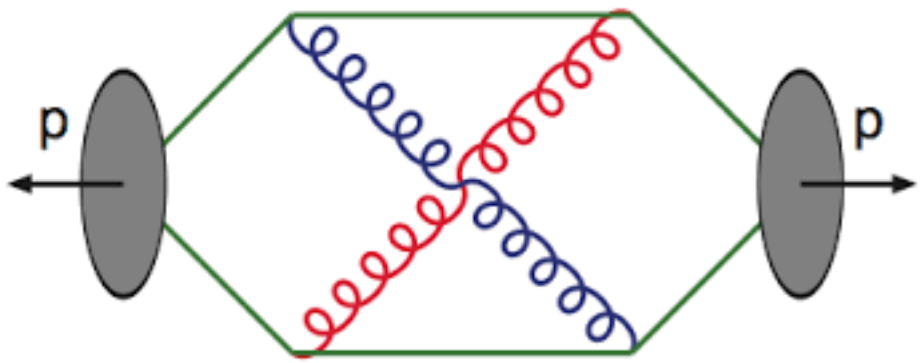
ALICE, PRC 99 (2019) 024906



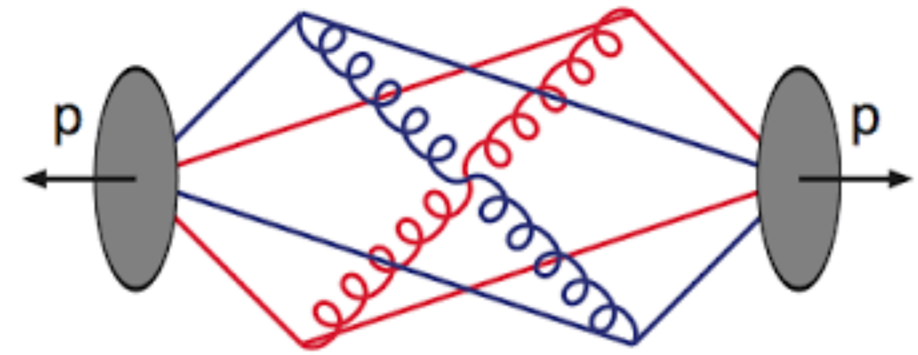
Pythia (color reconnection) can reproduce the same trend: **PRL 111 (2013) 042001**

Alternative view

With CR



Without CR



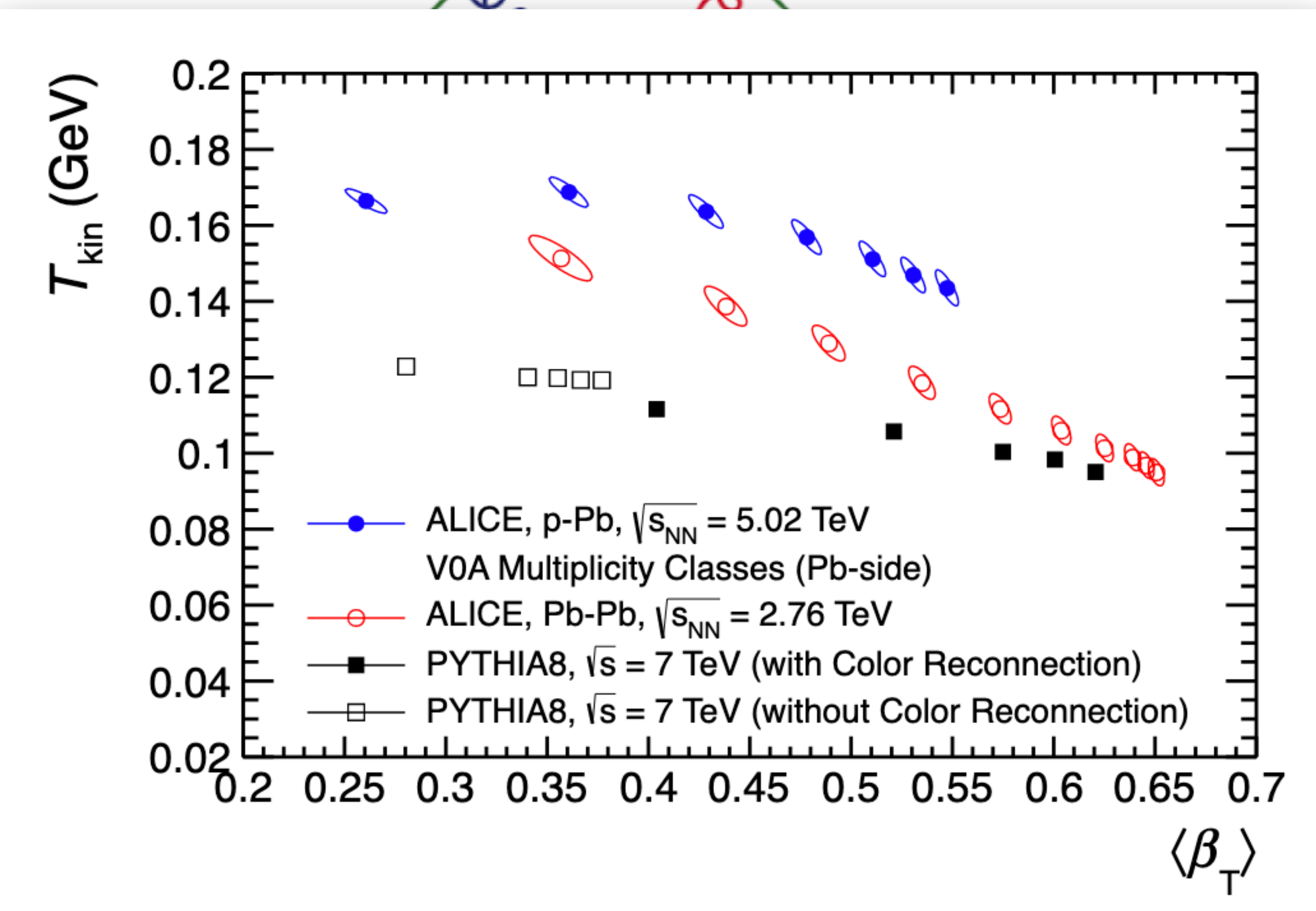
courtesy of P. Skands

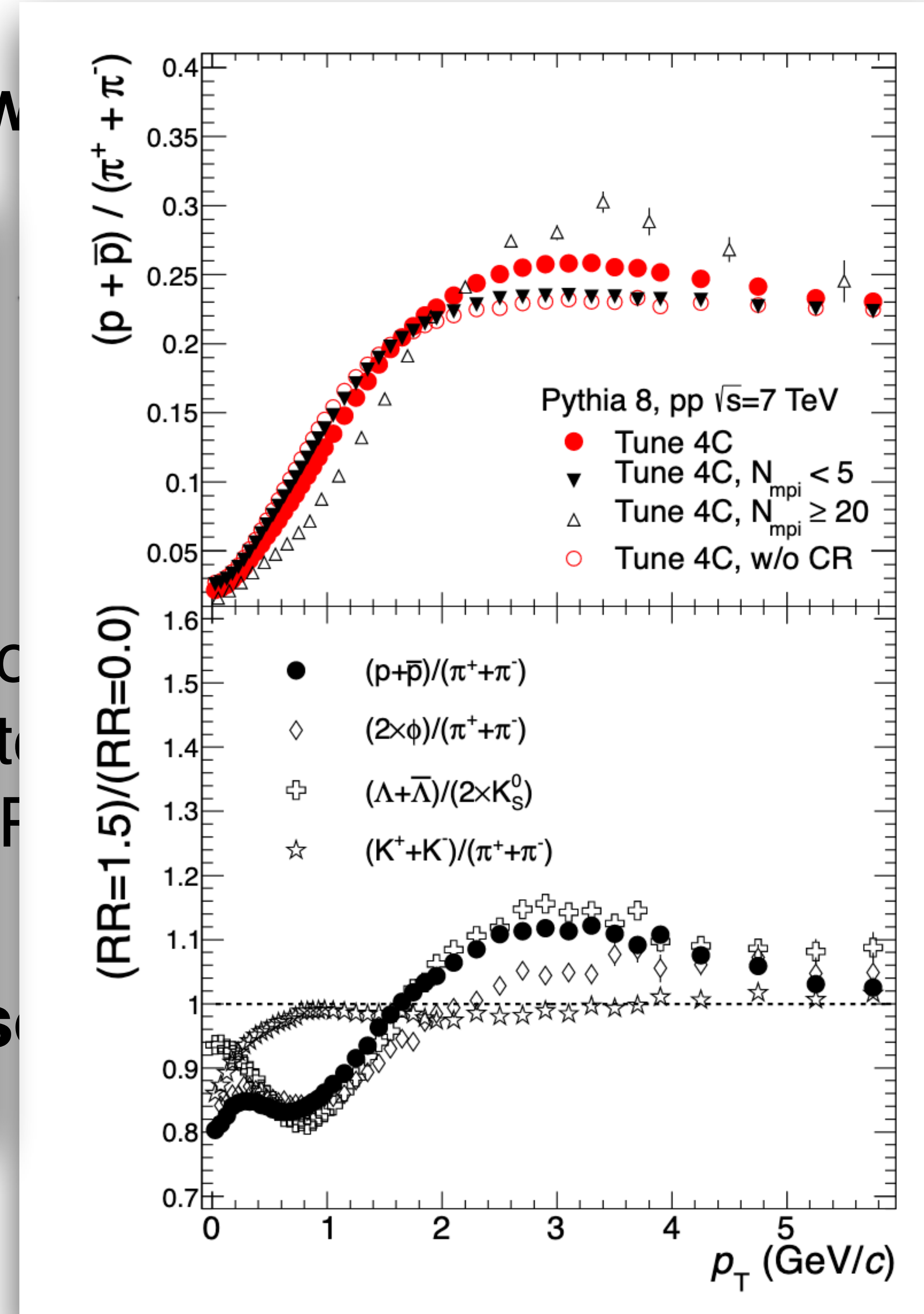
- Color reconnection allows the interaction of partons (from MPI), just before the hadronization. CR has proven to produce radial flow-like patterns in events with large number of MPI

See the presentation of Leif Lönnblad

Alternative view

With CR





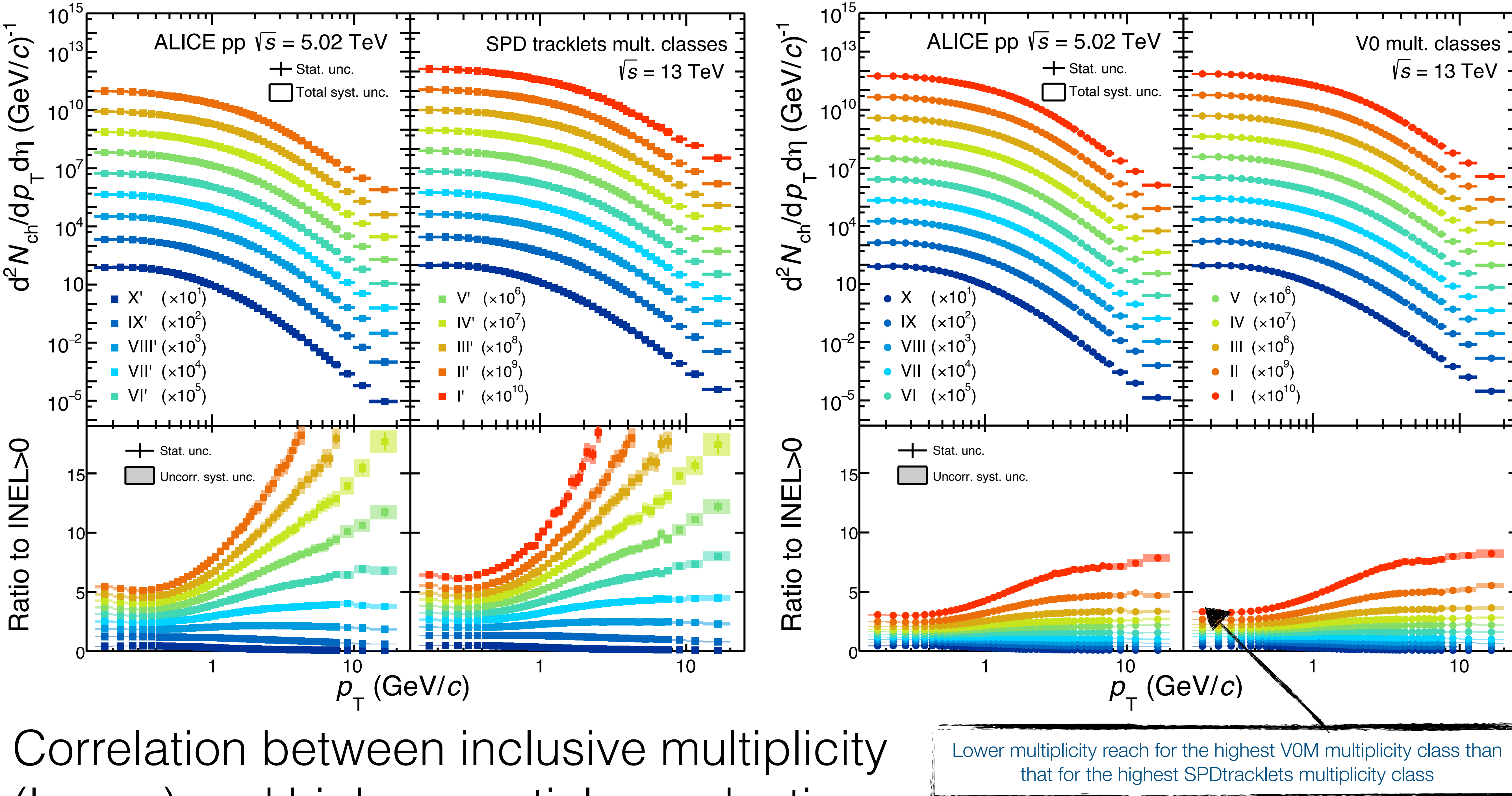
Selection biases

Particle production vs N_{ch}

ALICE, arXiv:1905.07208

Multiplicity selection at mid-pseudorapidity

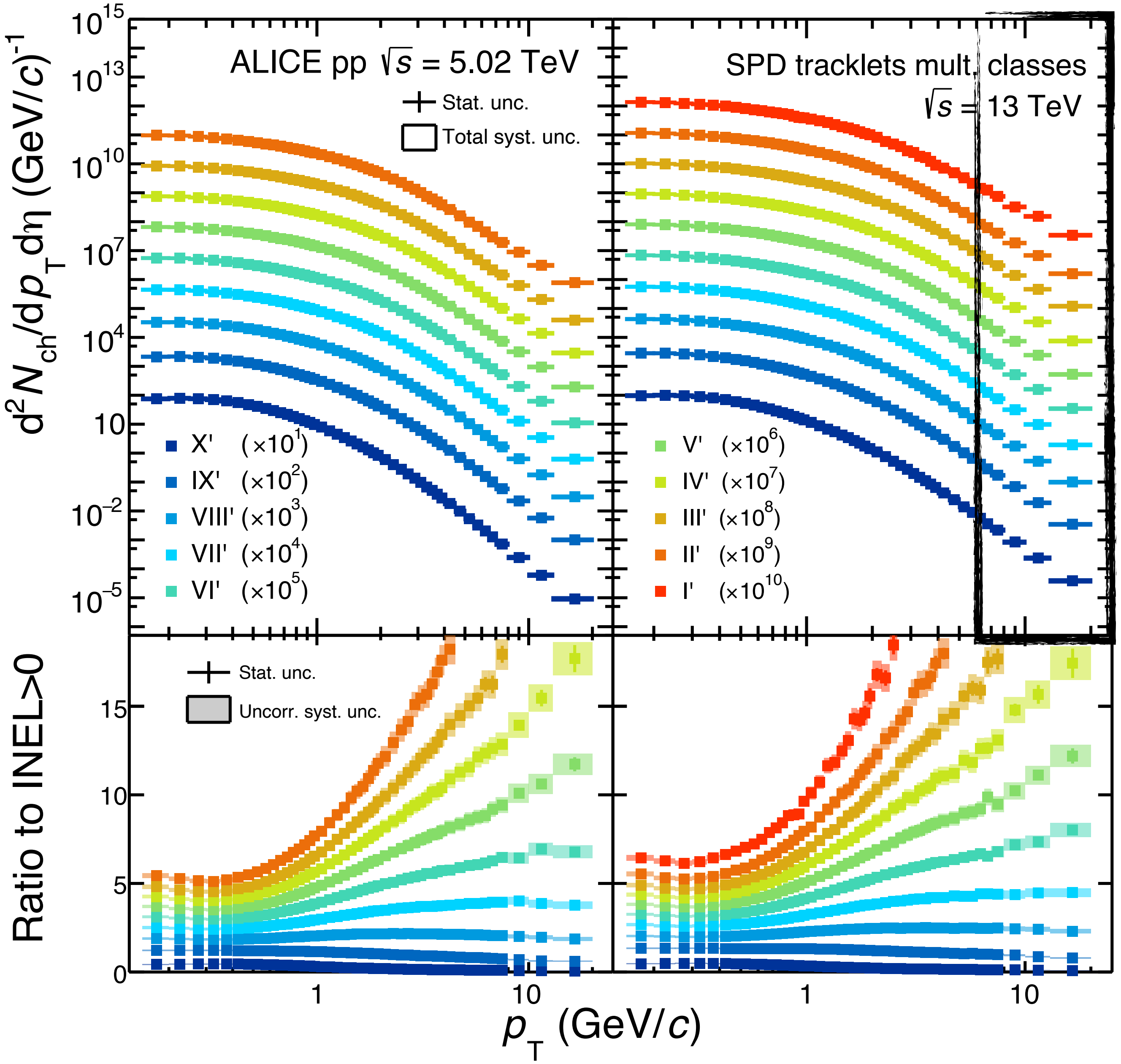
Multiplicity selection at forward rapidity

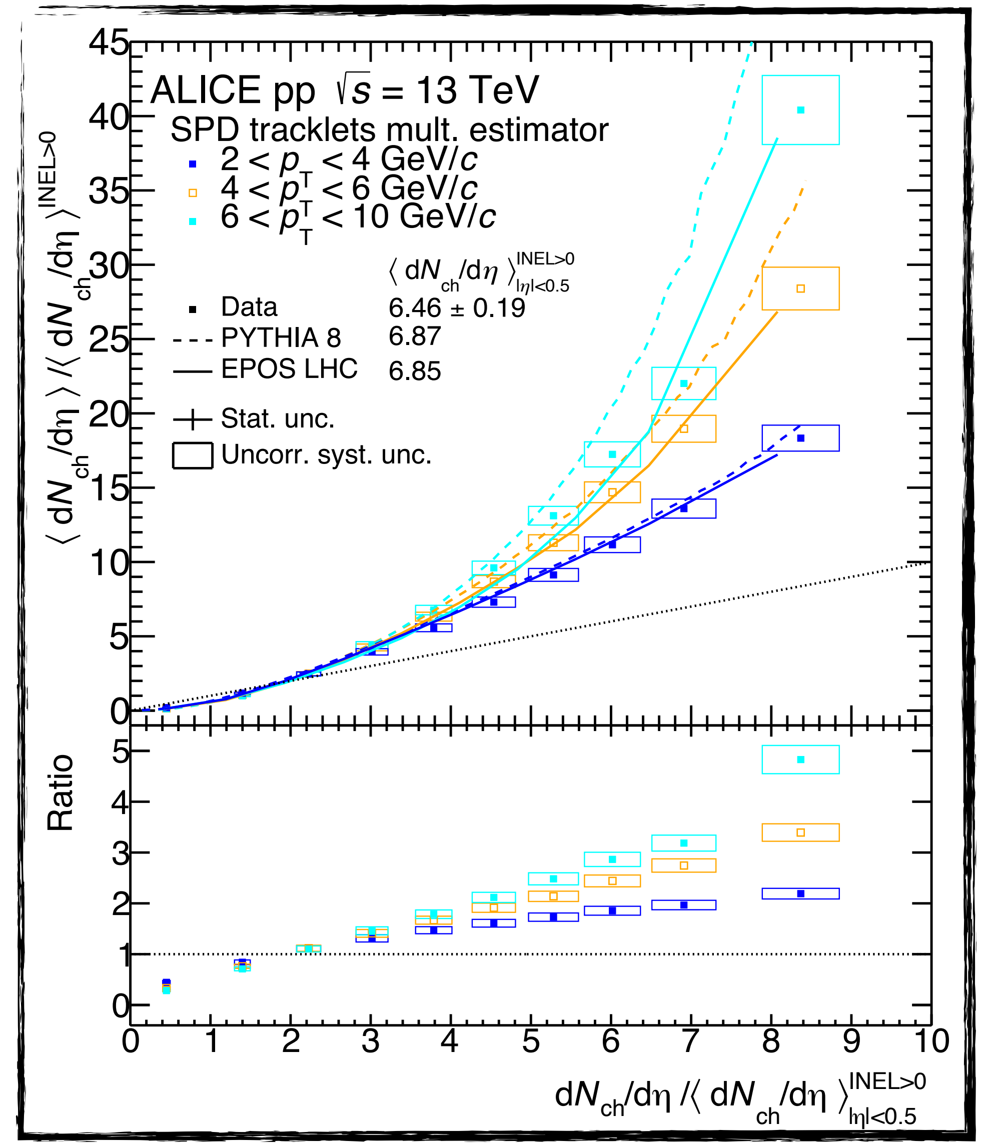


Correlation between inclusive multiplicity (low p_T) and high-p_T particle production

Particle production vs N_{ch}

Multiplicity selection at mid-pseudorapidity





ALICE, arXiv:1905.07208

Non-linear increase of the high-p_T particle production as a function of multiplicity. EPOS LHC describes the relative yields better than PYTHIA, but it fails in describing the spectral shapes at high p_T

The results illustrate the role of hard physics in high multiplicity events

Summary

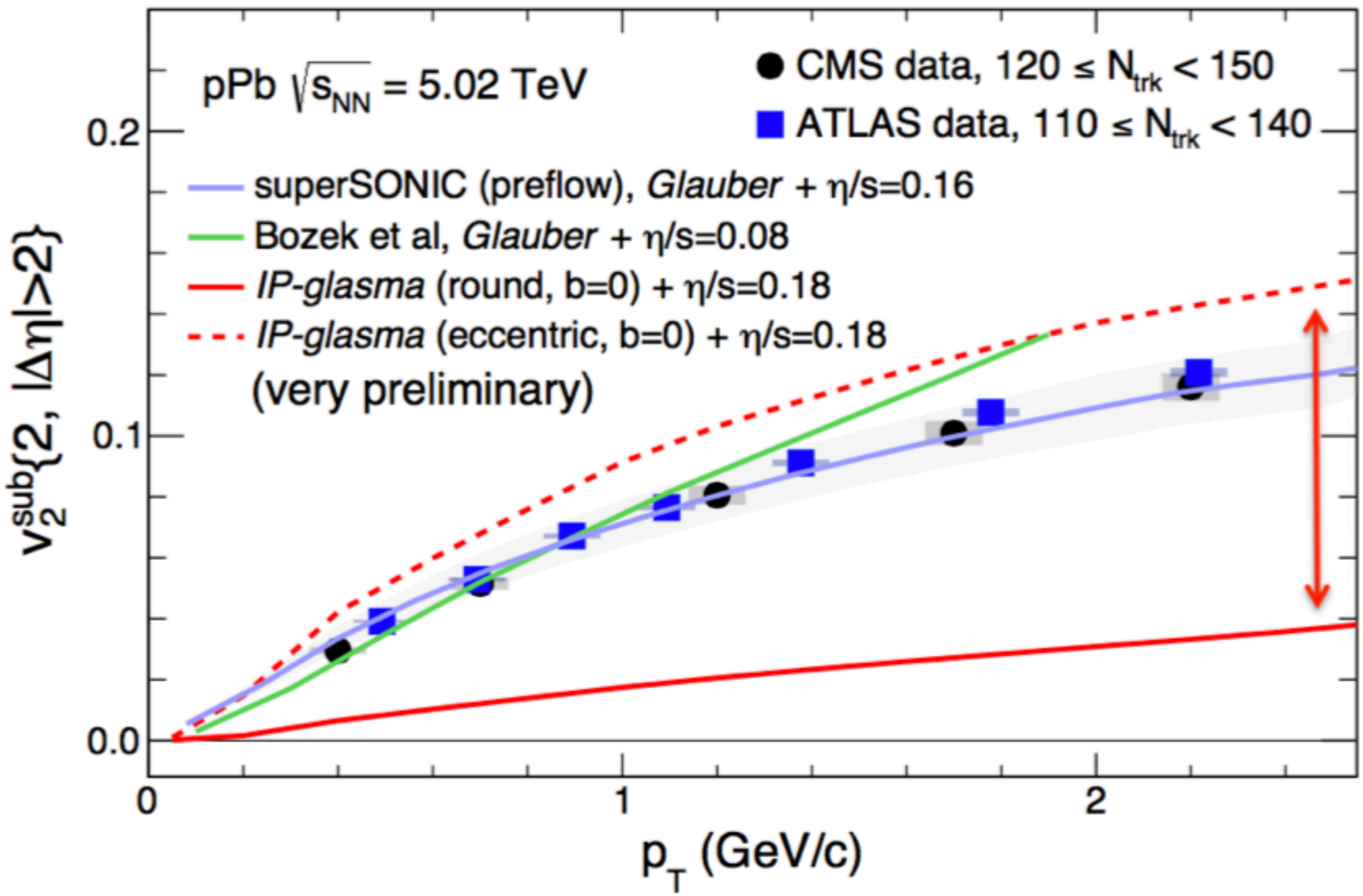
Summary

- The hot and dense QCD system created in A-A collisions exhibits features compatible with the formation of QGP: collectivity, strangeness enhancement, jet quenching, …

- Surprisingly, we found collective-like behaviour and strangeness enhancement in pp and p-A collisions. The origin of these effects in small collision systems is still an open question

Backup

Title Text



pPb $\sqrt{s_{NN}}$ = 5.02 TeV
CMS data, 120 ≤ N_{trk} < 150
ATLAS data, 110 ≤ N_{trk} < 140
superSONIC (preflow), *Glauber* + η/s=0.16
Bozek et al, *Glauber* + η/s=0.08
IP-glasma (round, b=0) + η/s=0.18
IP-glasma (eccentric, b=0) + η/s=0.18
(very preliminary)
$v_2^{sub}\{2, |\Delta\eta|>2\}$
p_T (GeV/c)
0.2
0.1
0.0
0
1
2

Initial or final state effect?

The origin of the effect in small systems is still unclear. Different models: a) final state interactions (assuming QGP), b) initial state effects related to gluon saturation, c) parton transport models

See e.g. **PRC 85 (2012) 014911** (a), **PRC 87 (2013) 064906** (b), **PRL 113 (2014) 252301** or **arXiv:1805.04081** (c)

- How reliable is hydrodynamics applied to small non-equilibrium systems?
- How large are the initial state correlations in realistic simulations and to what extend do they survive subsequent final state interactions?

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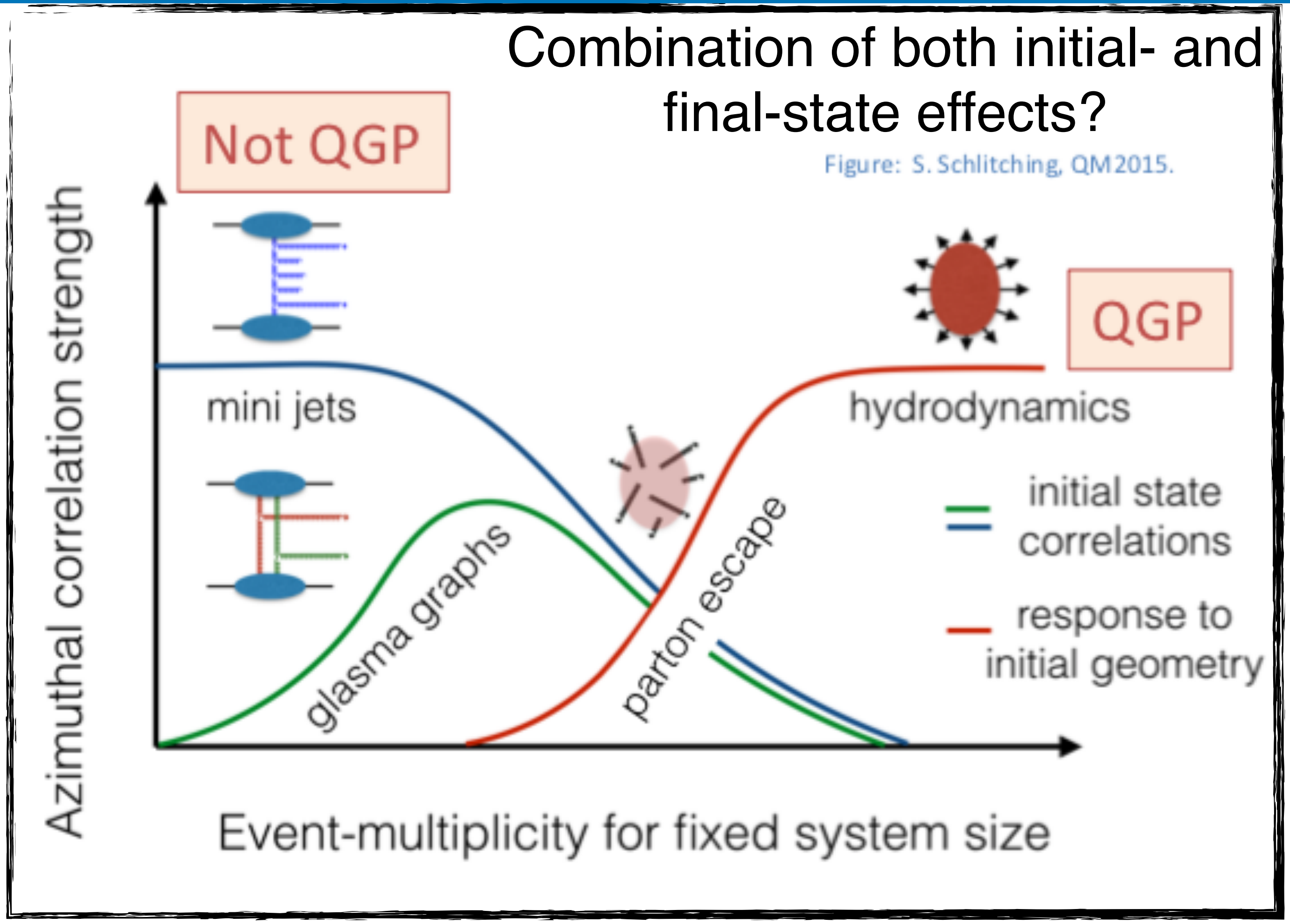

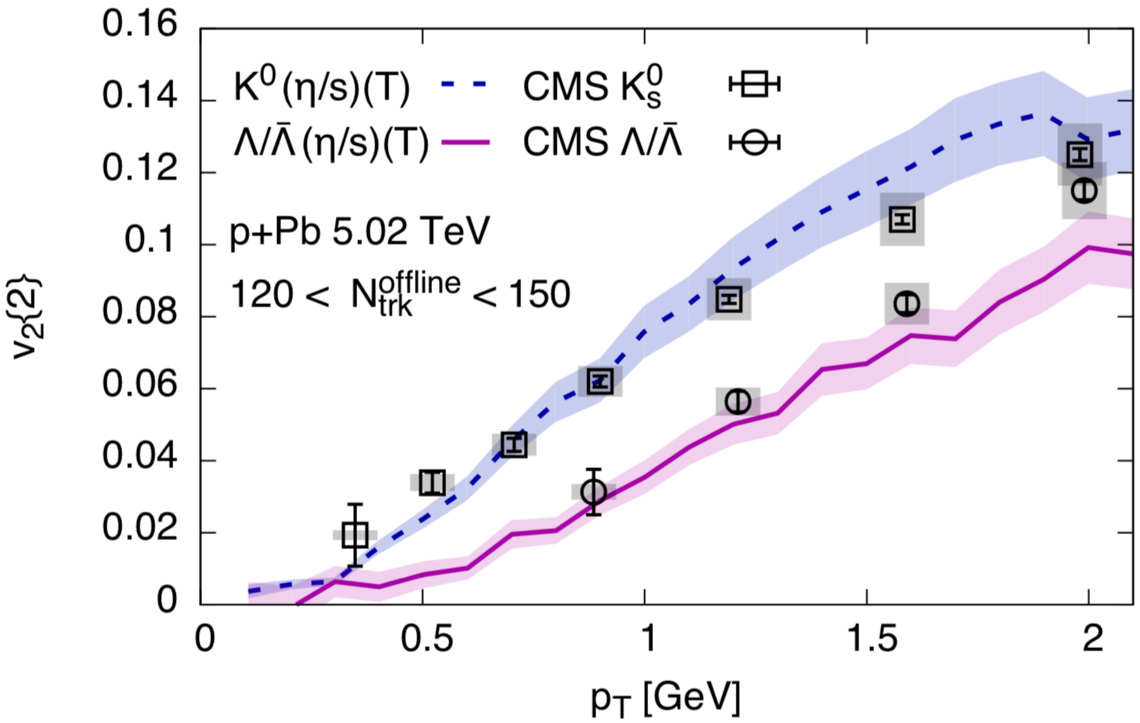

PLB 772 (2017) 681

IP-Glasma + hydrodynamics + UrQMD (importance of sub-nucleon scale fluctuations in the p projectile)

Phase diagram