Collective flow in ultra high energy cosmic rays within CORSIKA

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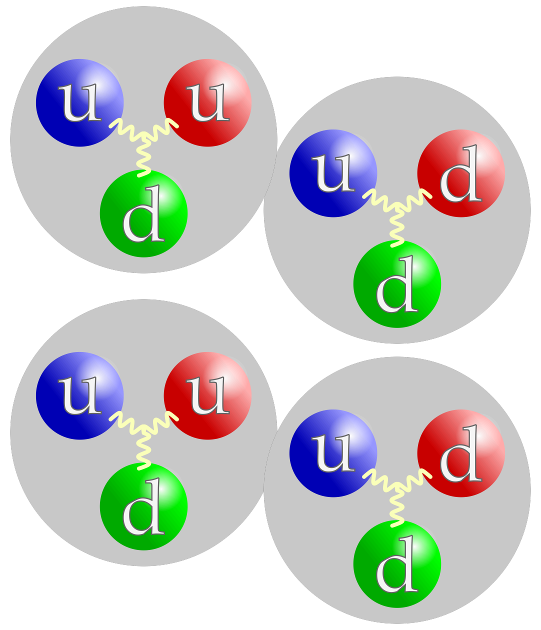
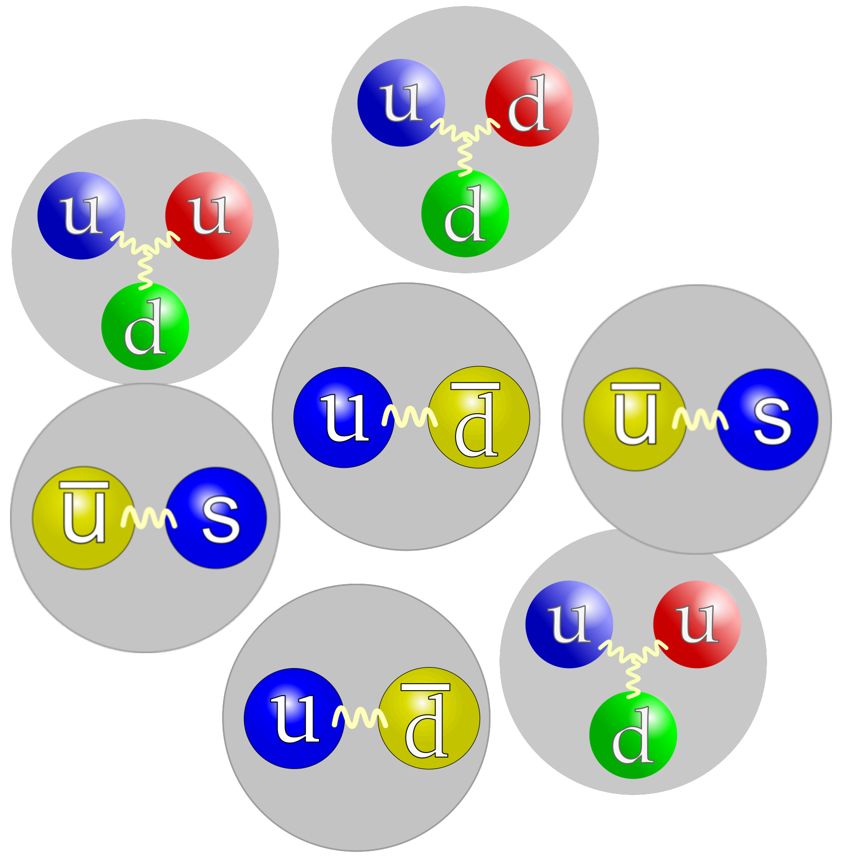
37th International Cosmic Ray Conference
12–23 July 2021

Introduction of Quark Gluon Plasma

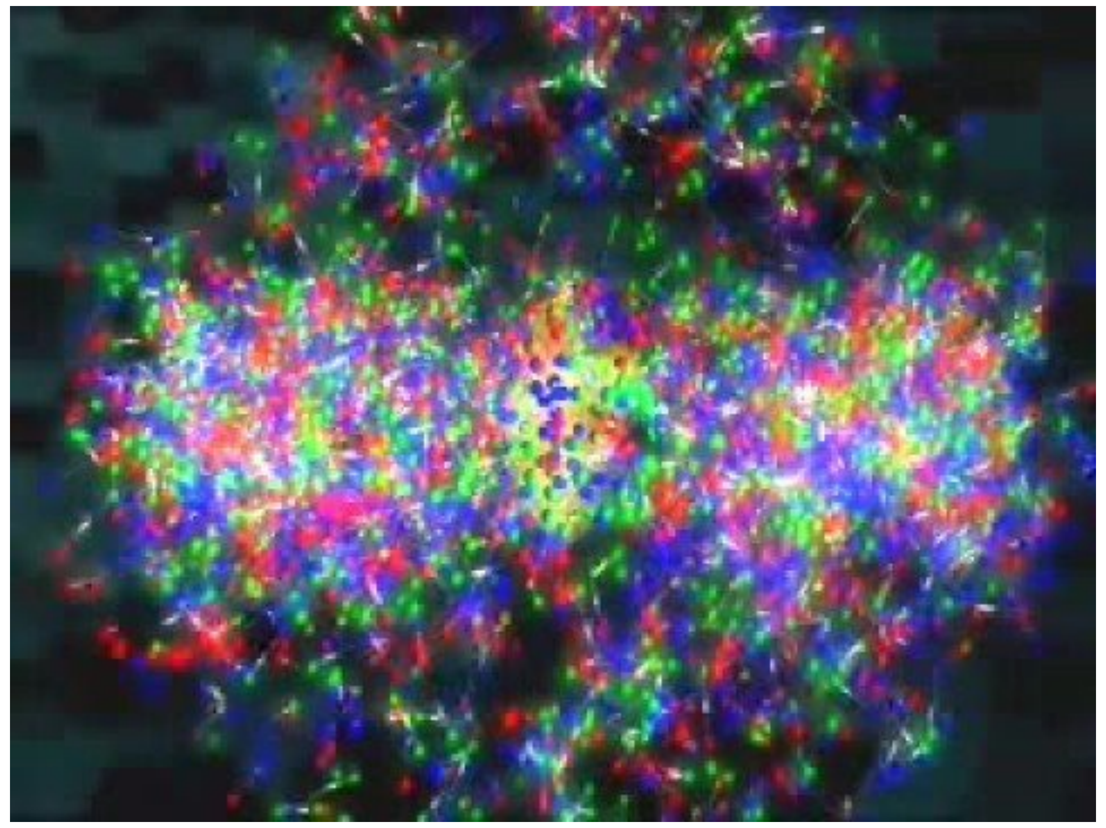
More is different.



quarks and gluons are confined
in protons and neutrons



heat up, produce mesons,
resonances etc



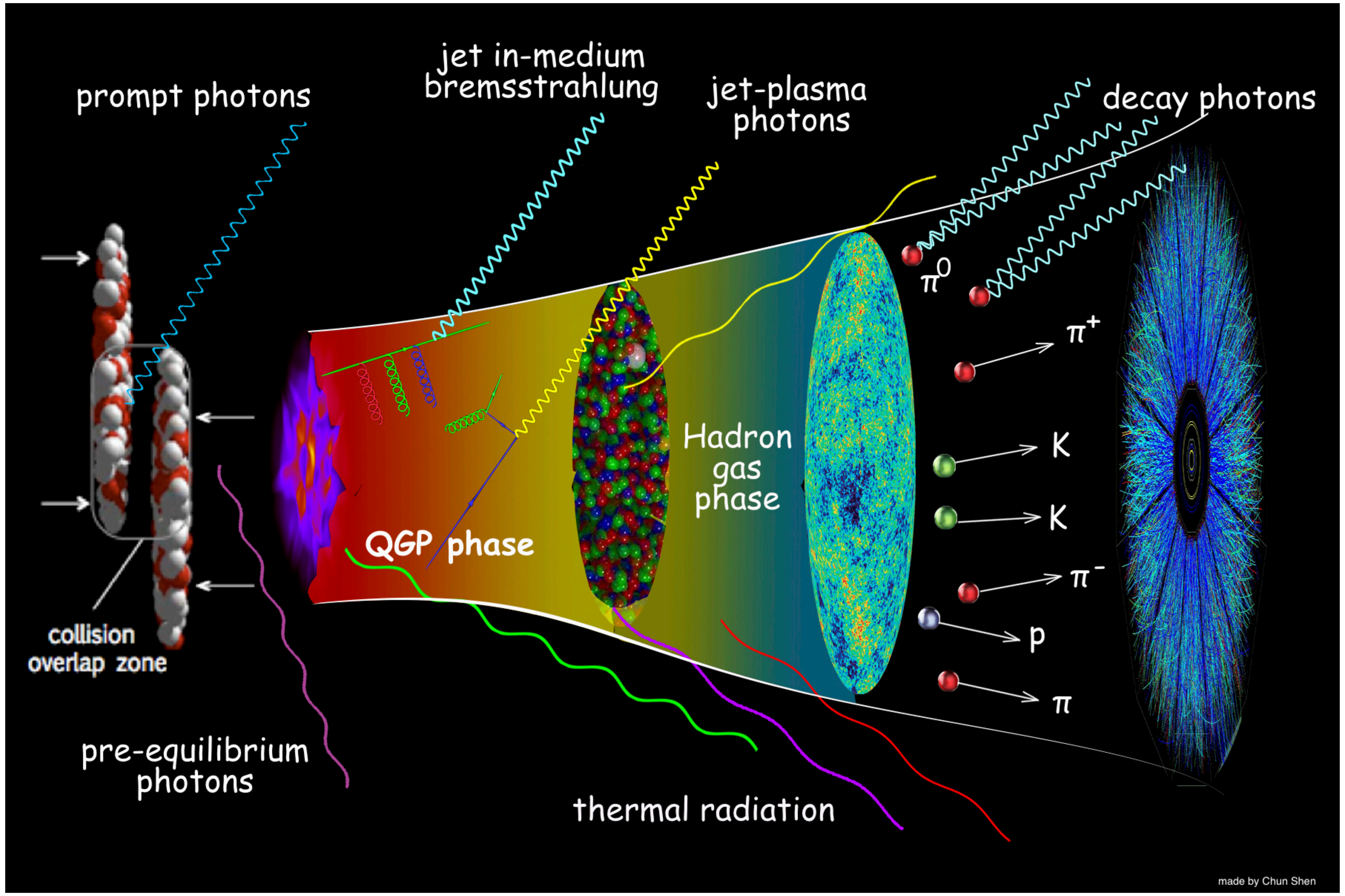
continue heat up, a new state of matter QGP is produced

Temperature

- Argument based on asymptotic freedom, a feature of Quantum Chromo Dynamics (QCD).

Standard paradigm of heavy ion collisions: the Little Bang

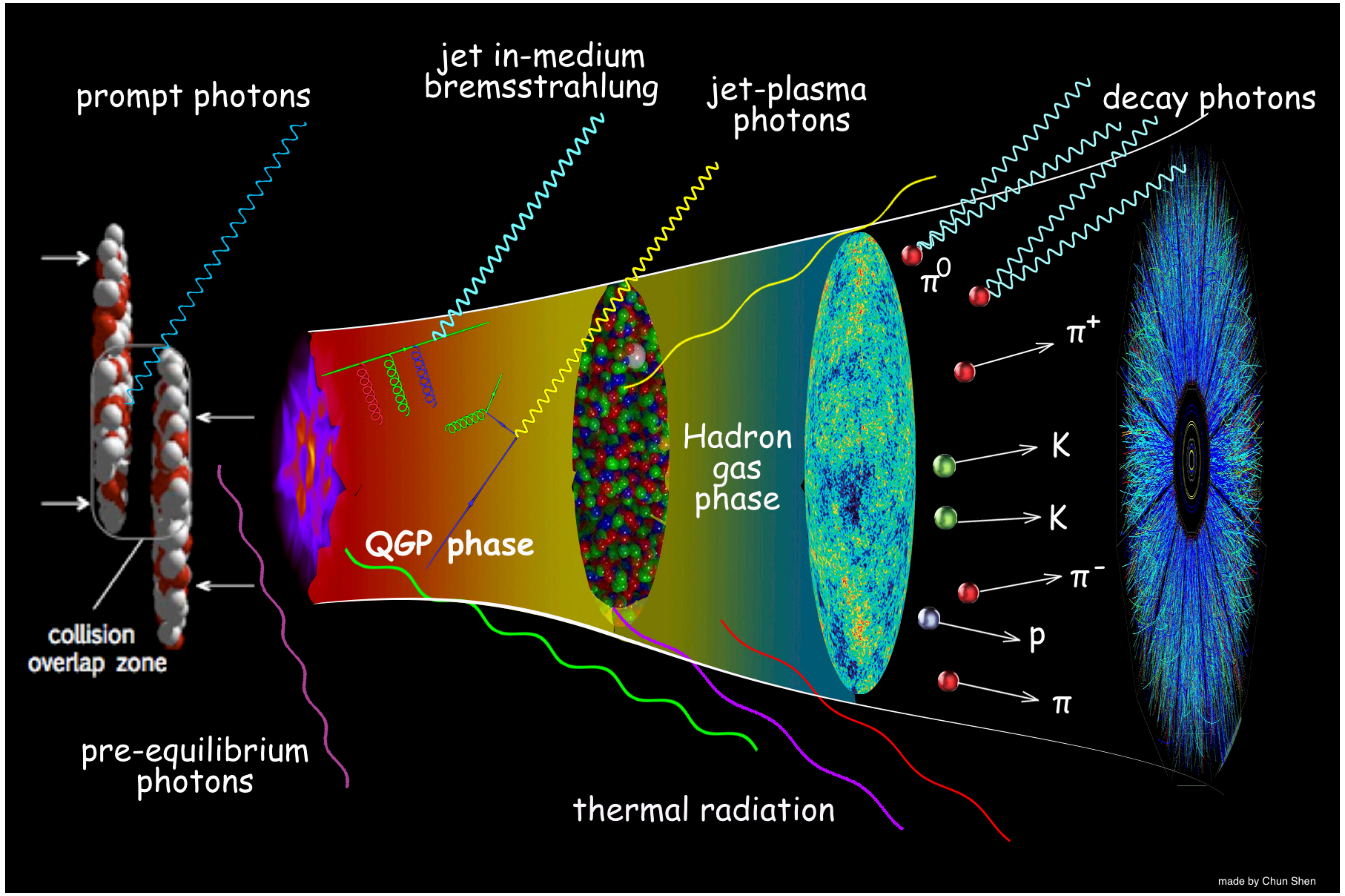
Credit: Chun Shen

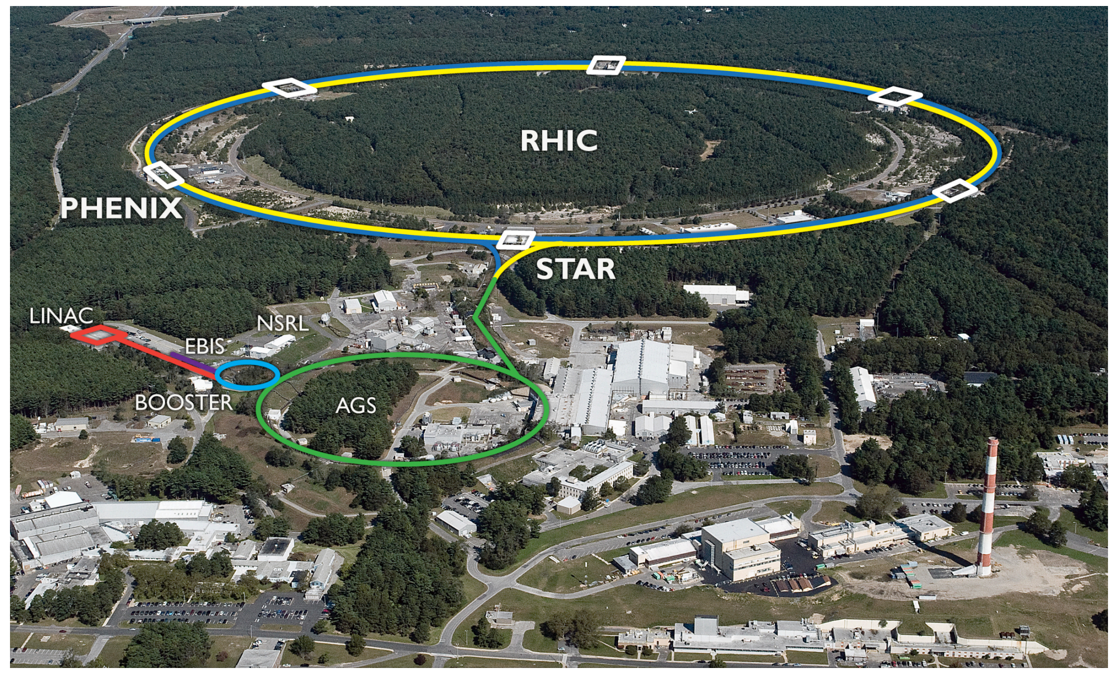


- Heavy ion collisions now considered as the best way to study QGP in a lab.

Standard paradigm of heavy ion collisions: the Little Bang

Credit: Chun Shen





Relativistic Heavy Ion Colliders@BNL

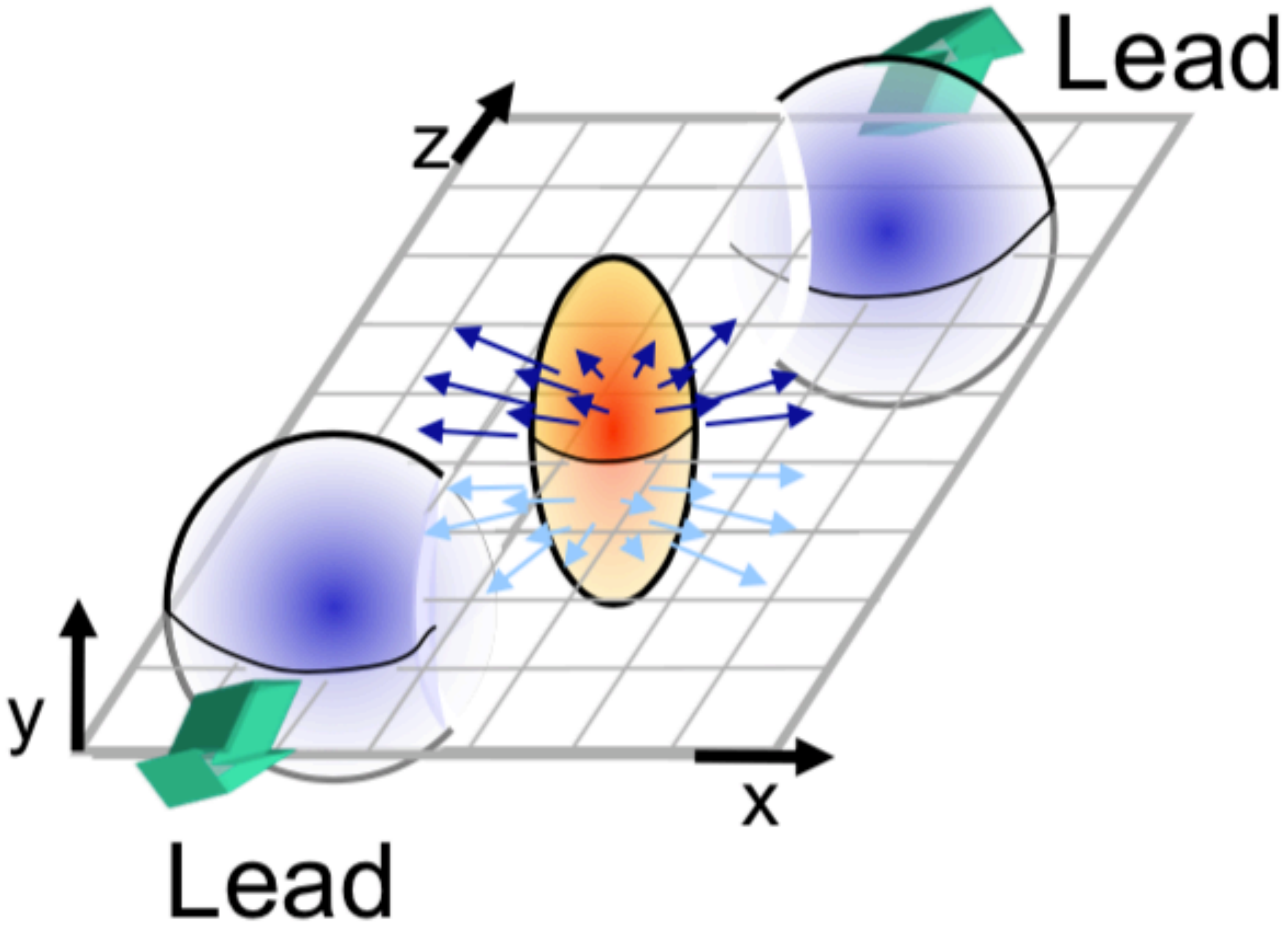
Au+Au: top energy E ~ 20 ATeV

Large Hadron Collider@CERN

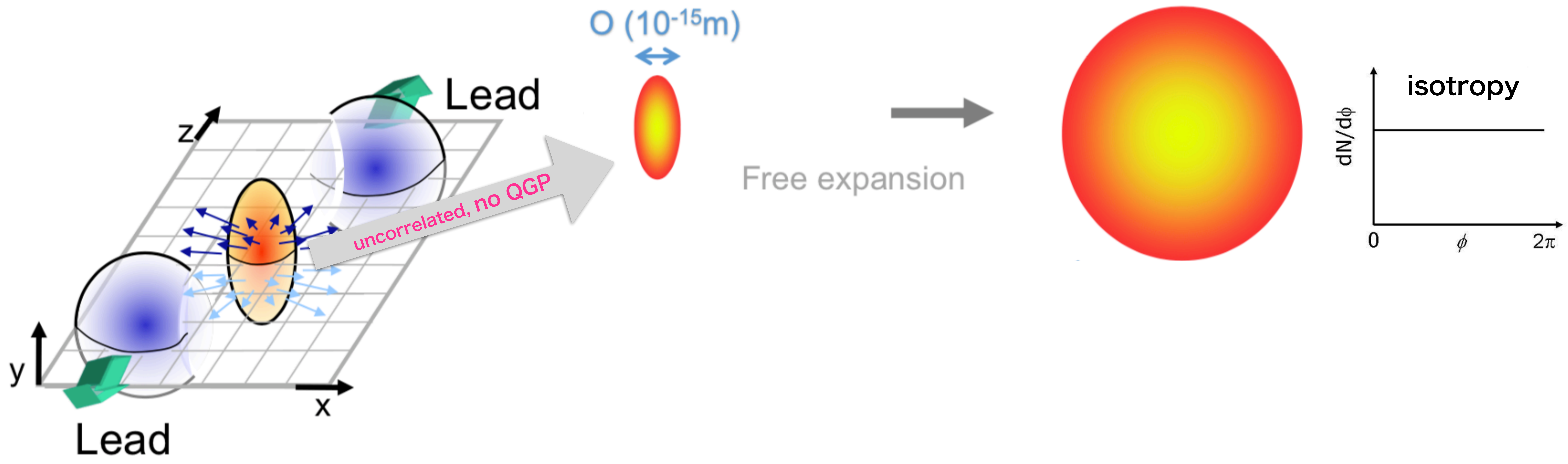
Pb+Pb: top energy E ~ 12.5 APeV

- Heavy ion collisions now considered as the best way to study QGP in a lab.
- RHIC and LHC are two of the most important colliders, the total energy can go up to 20 ATeV and 12.5 APeV.

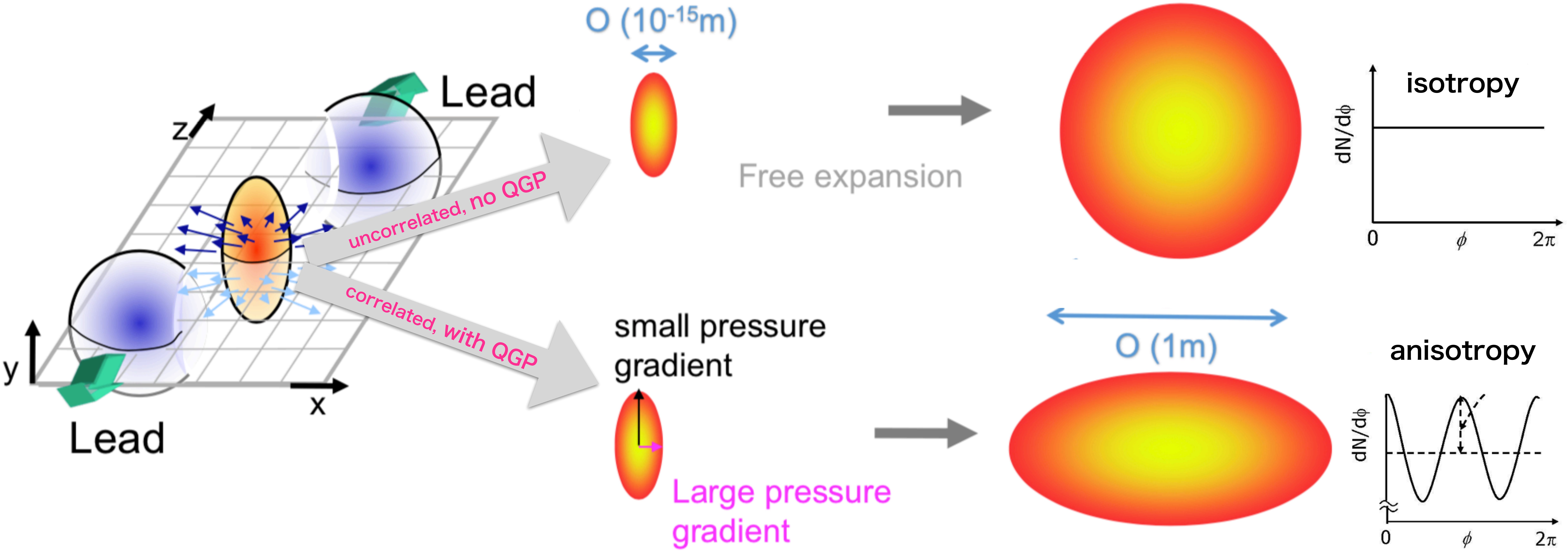
Collective flow: signal of QGP



Collective flow: signal of QGP



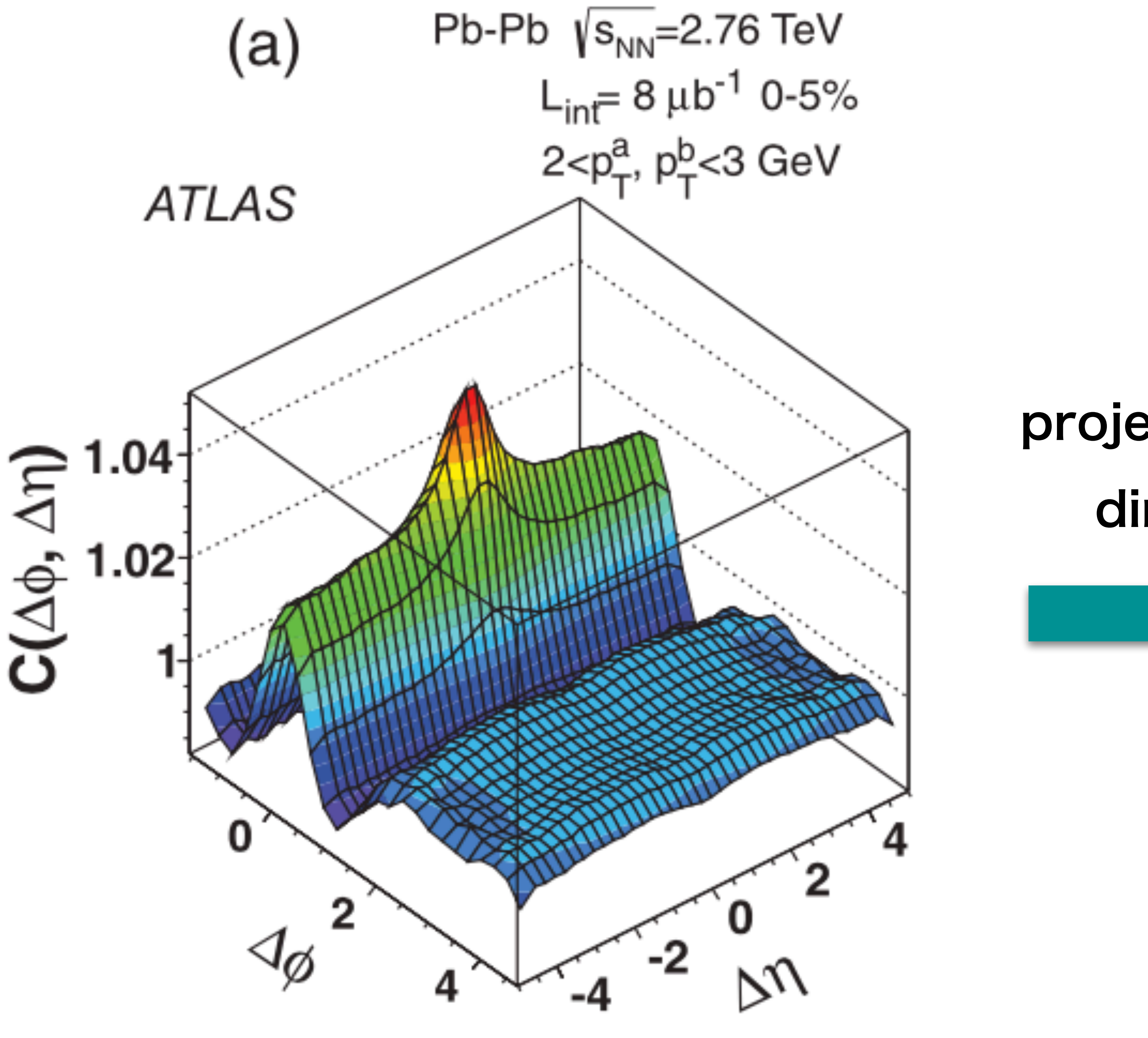
Collective flow: signal of QGP



- Collective flow probes the production of QGP, "CMB" of the Little Bang.

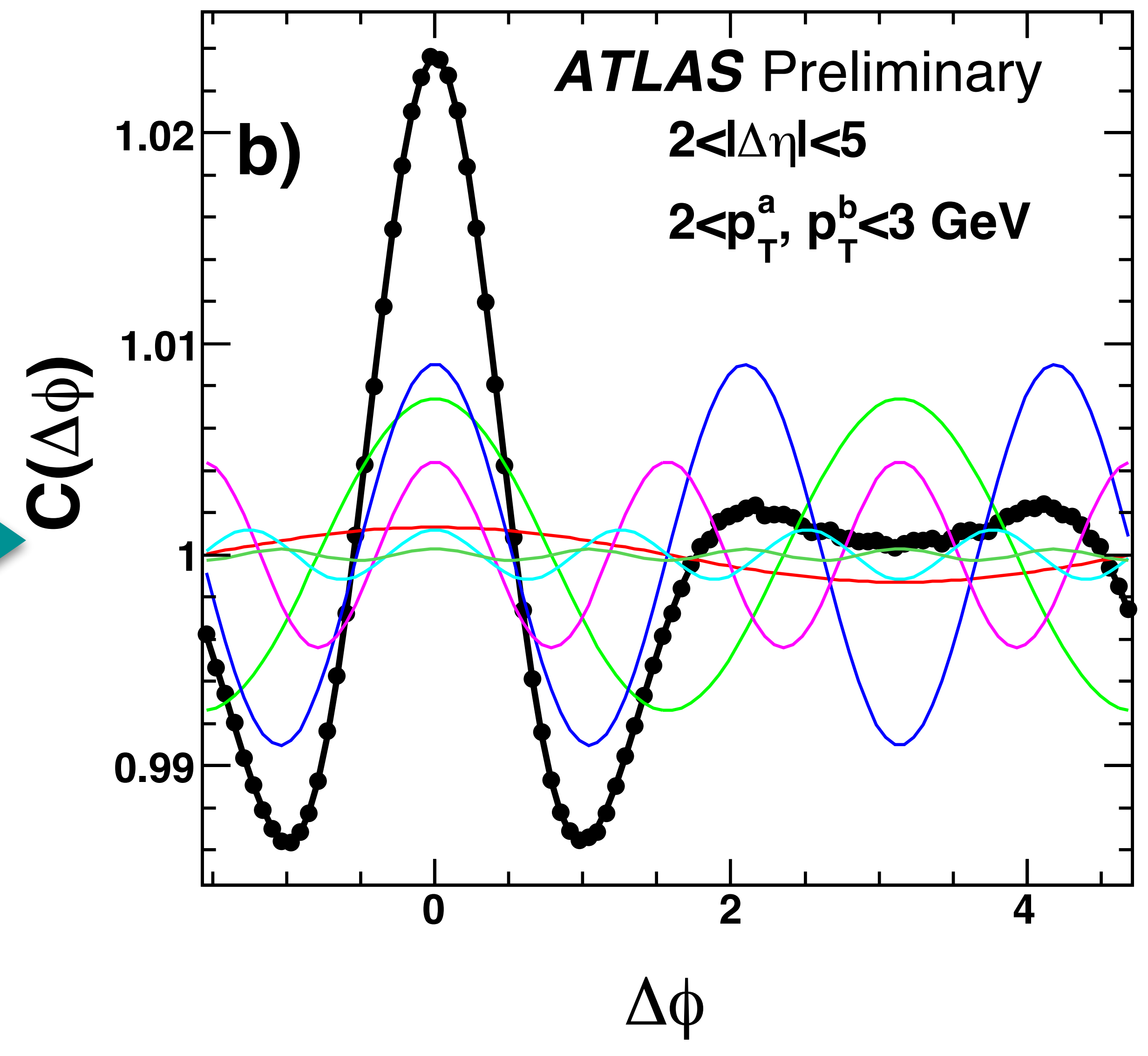
Quantify collective flow

two particle correlation

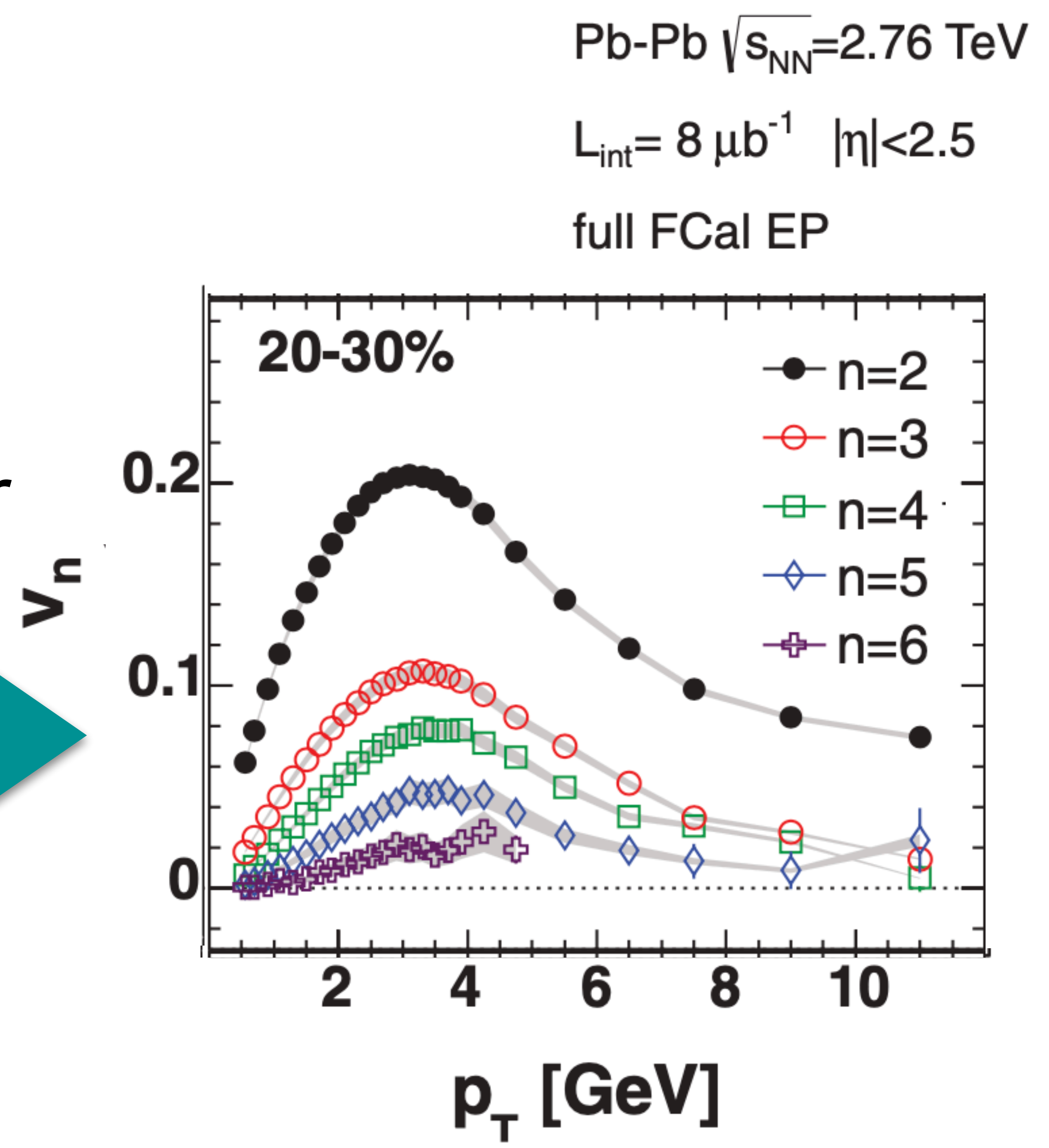


ATLAS Collaboration, Physical Review C 86, 014907 (2012)

projection to ϕ direction



extract Fourier coefficient

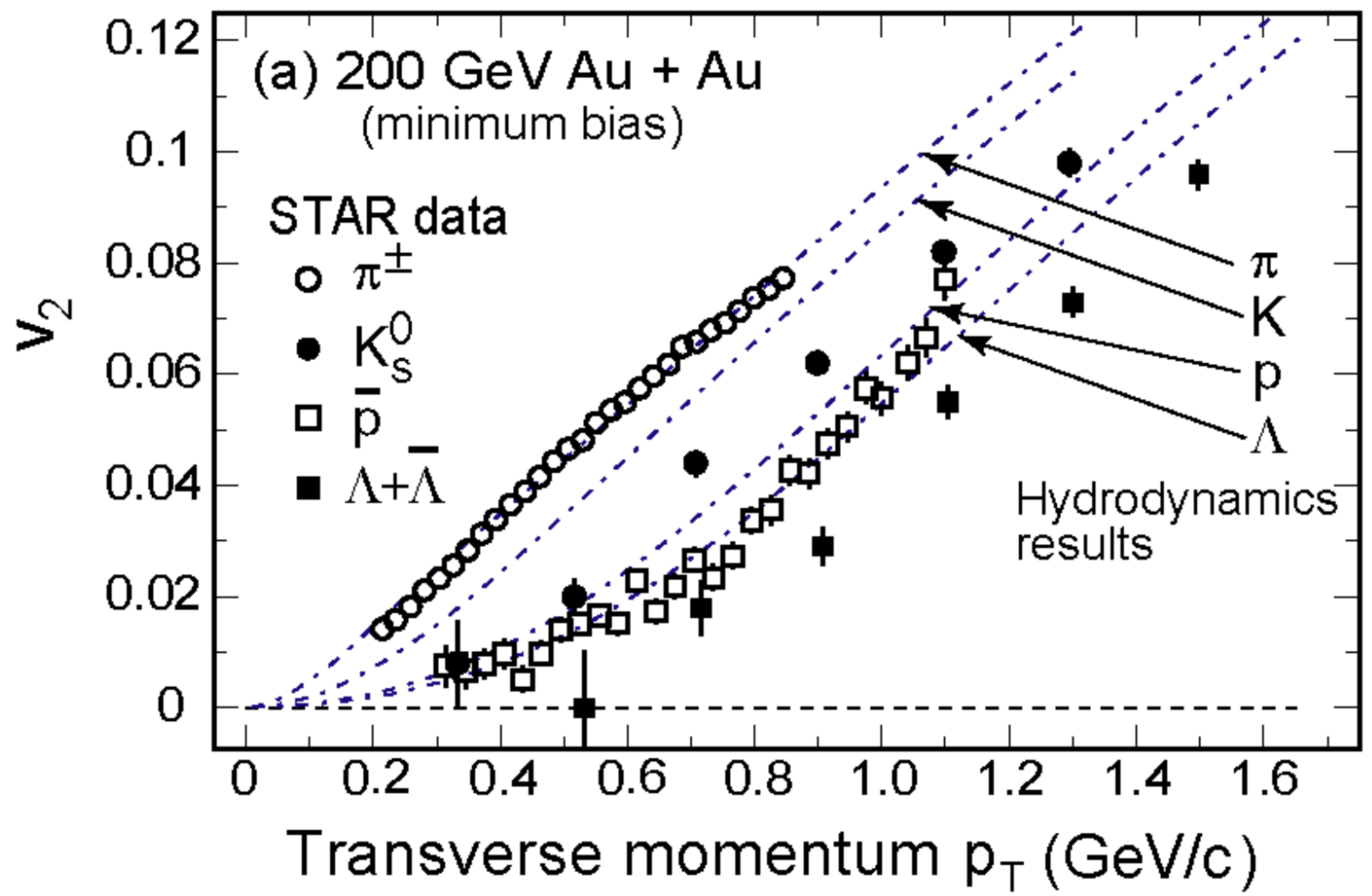


$$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2 v_n^a v_n^b \cos(n\Delta\phi)$$

- Collective flow can be well quantified via a Fourier decomposition, v_n.
- The leading order elliptic flow v_2 is one of our main interests.

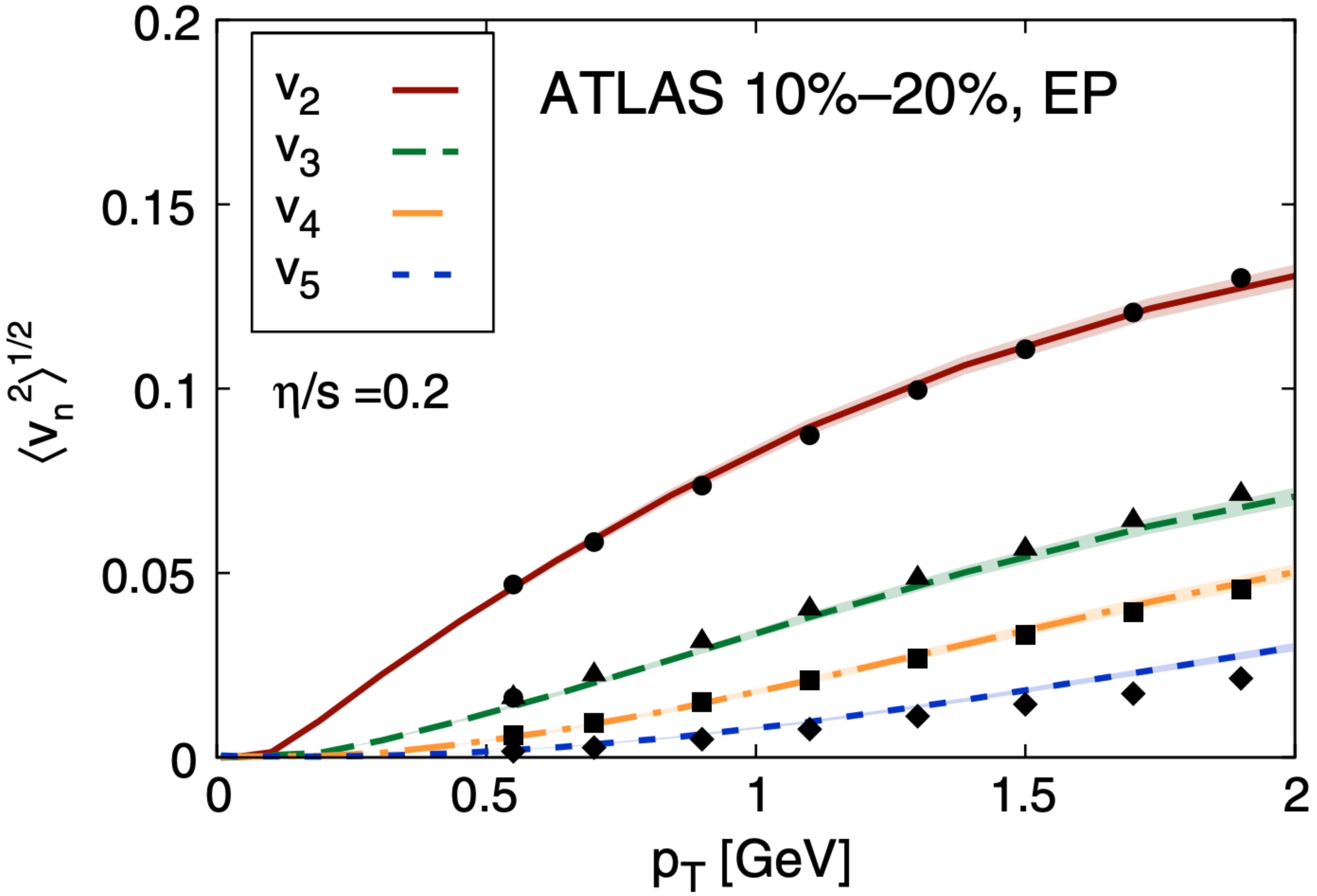
QGP — the success of HIC

STAR Collaboration, Physical Review C 72, 014904 (2005)



Au+Au: E ~ 20 ATeV

Charles Gale et al, Physical Review L 110, 012302 (2013)



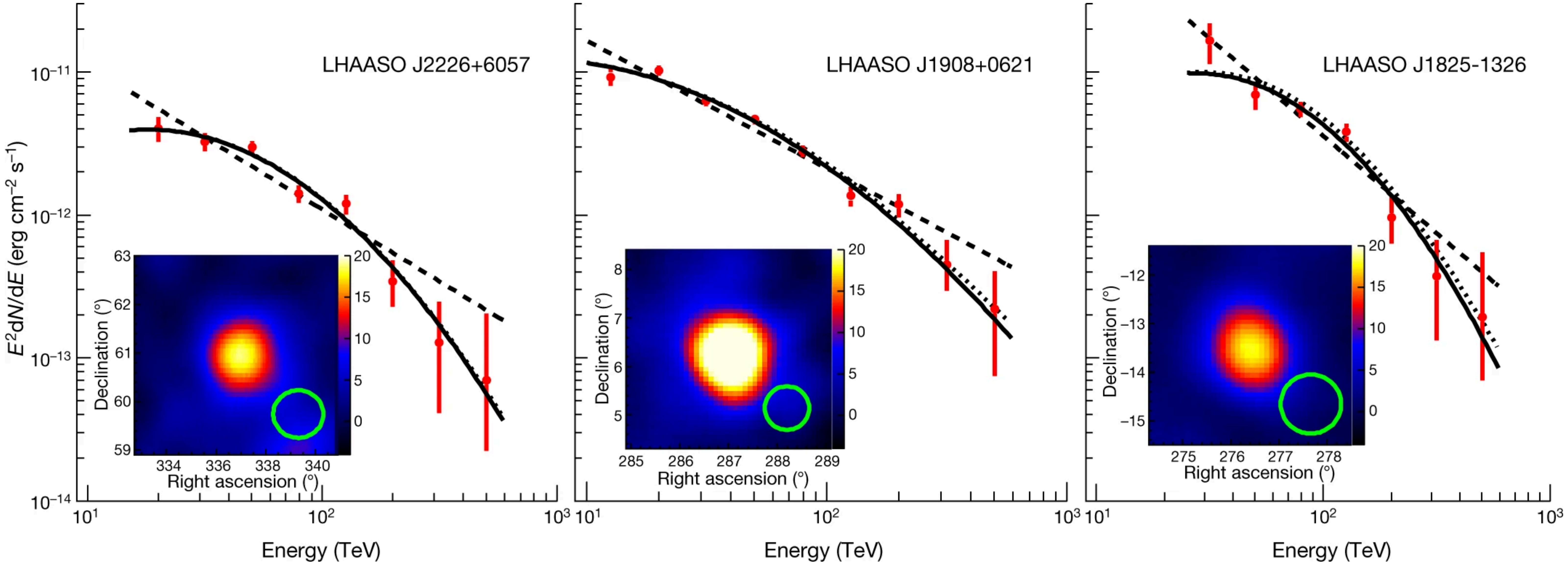
Pb+Pb: E ~ 3.8 APeV

- QGP is observed at RHIC and then confirmed at LHC.
- The highest energy hadron collider we can achieve on earth so far.

Ultra-high energy cosmic rays

LHAASO Collaboration, Nature 594, 33–36 (2021)

E ~ 1 TeV - 10 EeV



- Cosmic rays cover wide energy range, from 1TeV to 10 EeV.
- LHAASO observed 1.4PeV Galactic cosmic rays.
- Can QGP be formed in such ultra-high energy cosmic rays air showers?

Key question:

Can we observe collective flow to probe QGP in ultra-high energy cosmic rays collisions?

Corsika Model setup

- CORSIKA (COsmic Ray SImulations for KAscade)
  high energy hadronic interaction model EPOS LHC
- EPOS is a parton model, with many binary parton-parton interactions. EPOS is designed to be used for particle physics experiment analysis (SPS, RHIC, LHC) for pp or Heavy Ion.

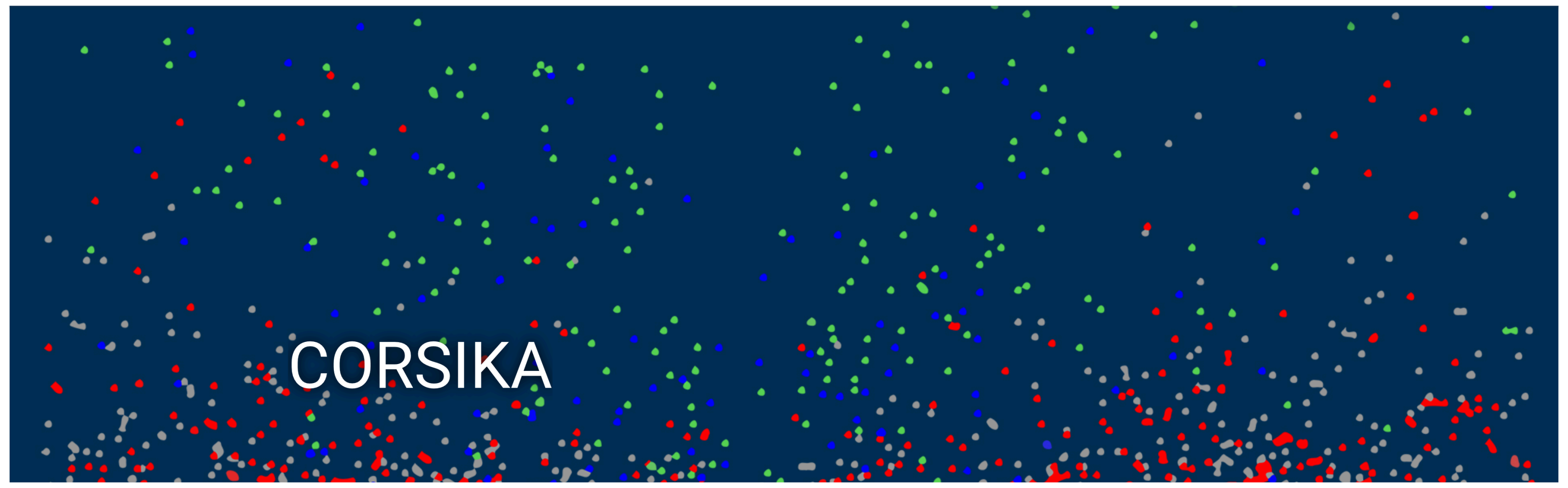
Primary particle: ^{4}He

Energy = 10TeV (equivalent to 2.5 ATeV fix target collision)

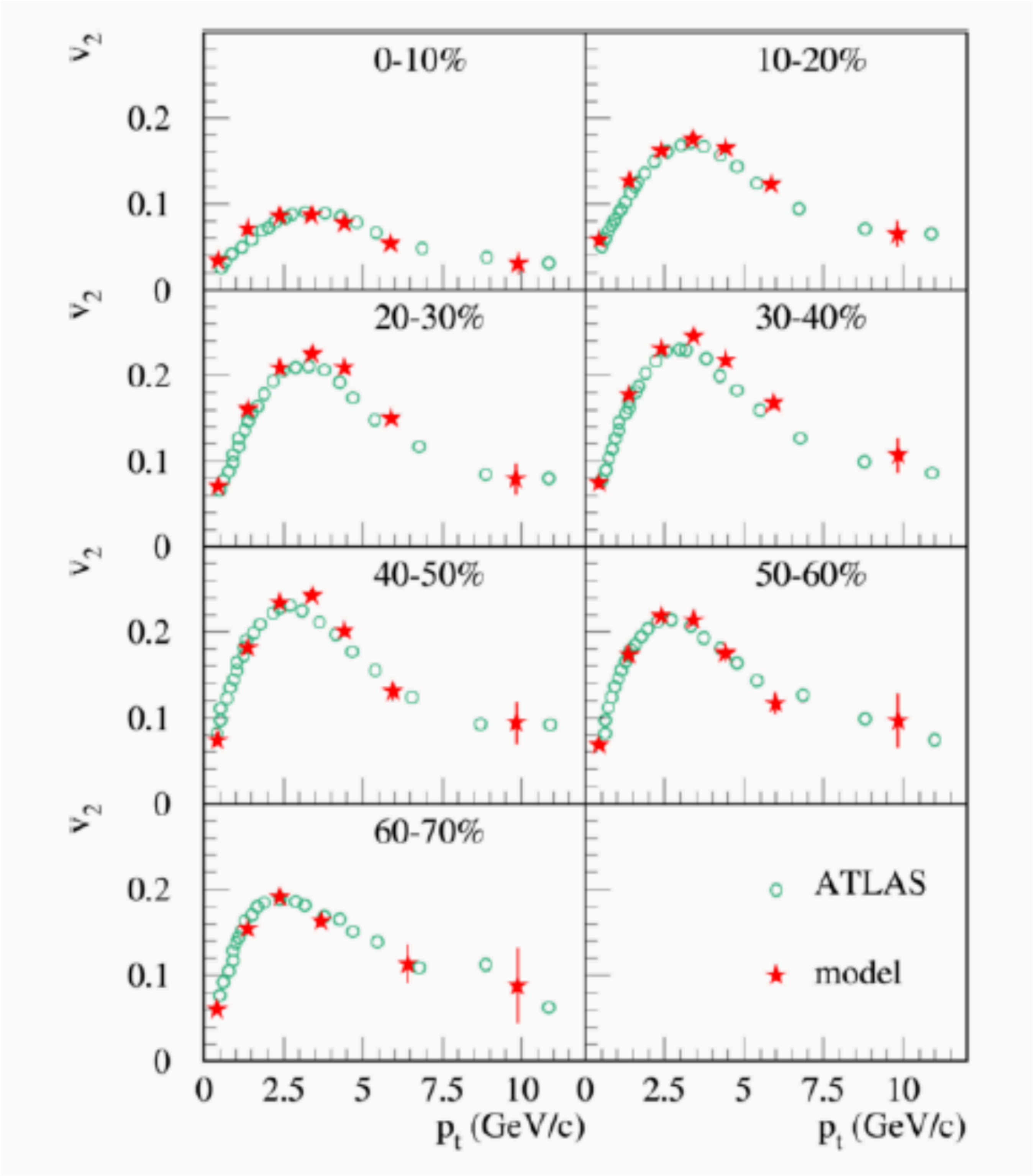
^{4}He + ^{14}N collision is utilized in this study.

Theta = 0

Observation depth: 4400m



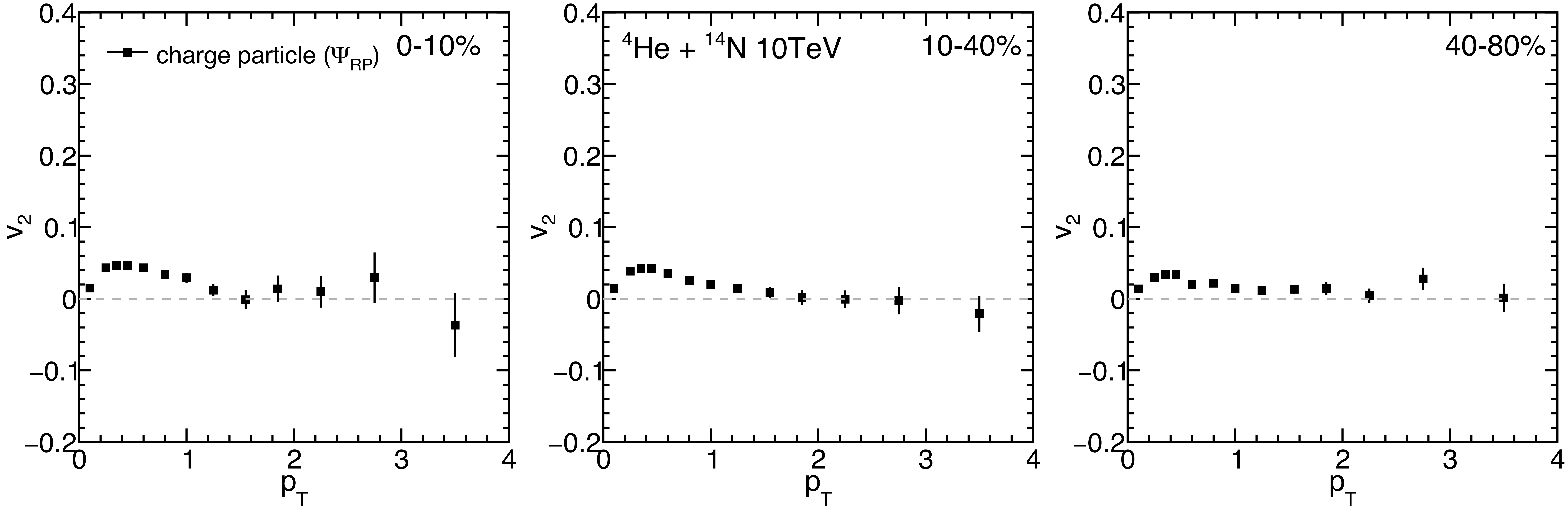
CORSIKA – an Air Shower Simulation Program



EPOS model have flow build-in setting

Elliptic flow v_2 vs p_T

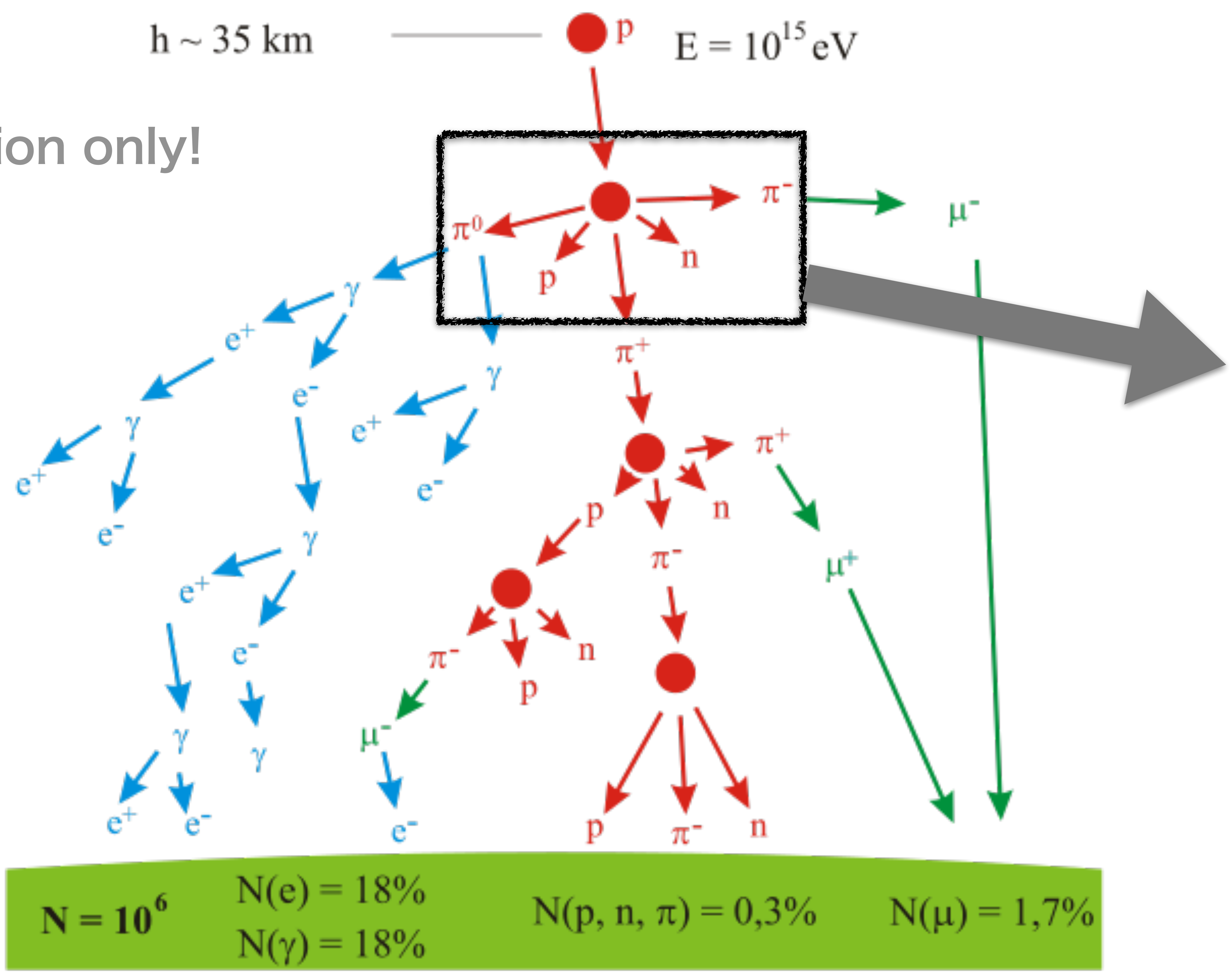
✦ v_2 vs p_T for inclusive charge particles



- non-zero v_2 for charge particles for all shown centralities.

A typical air shower paradigm

demonstration only!

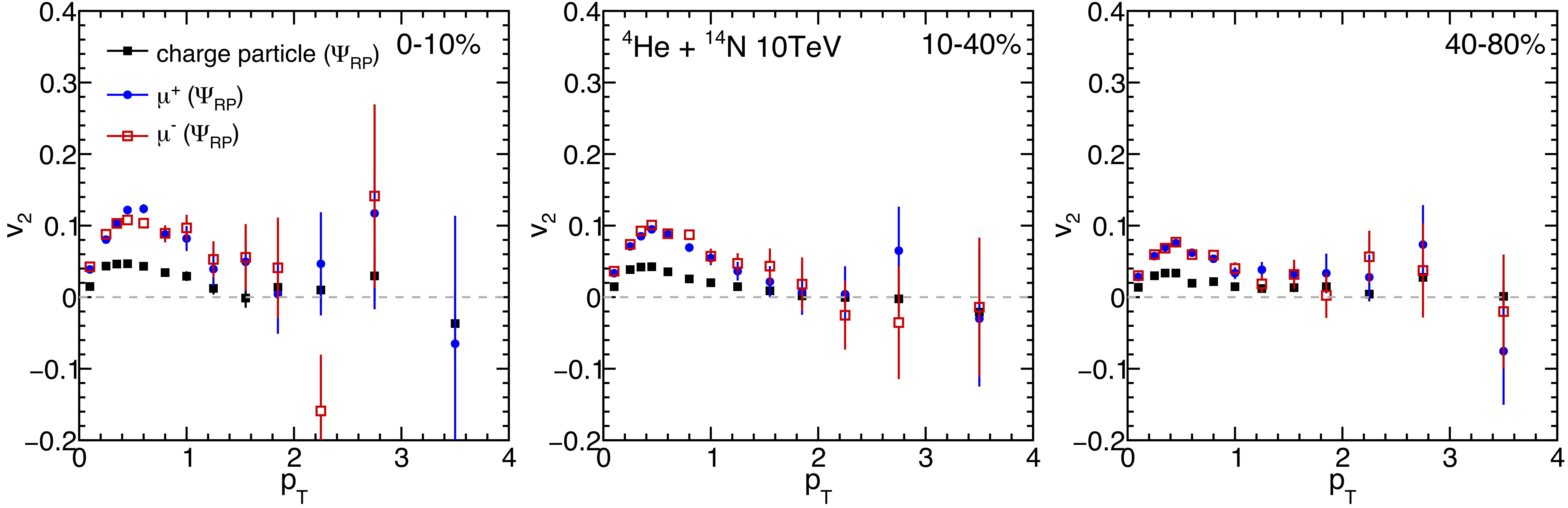


first collision hadrons we observed in HIC experiment.

- First collision hadrons carries the collective flow.
- Electrons are suffering more multiple processes than muon, muons are less biased than electrons.
- What about muon v_2?

Elliptic flow v_2 vs p_T

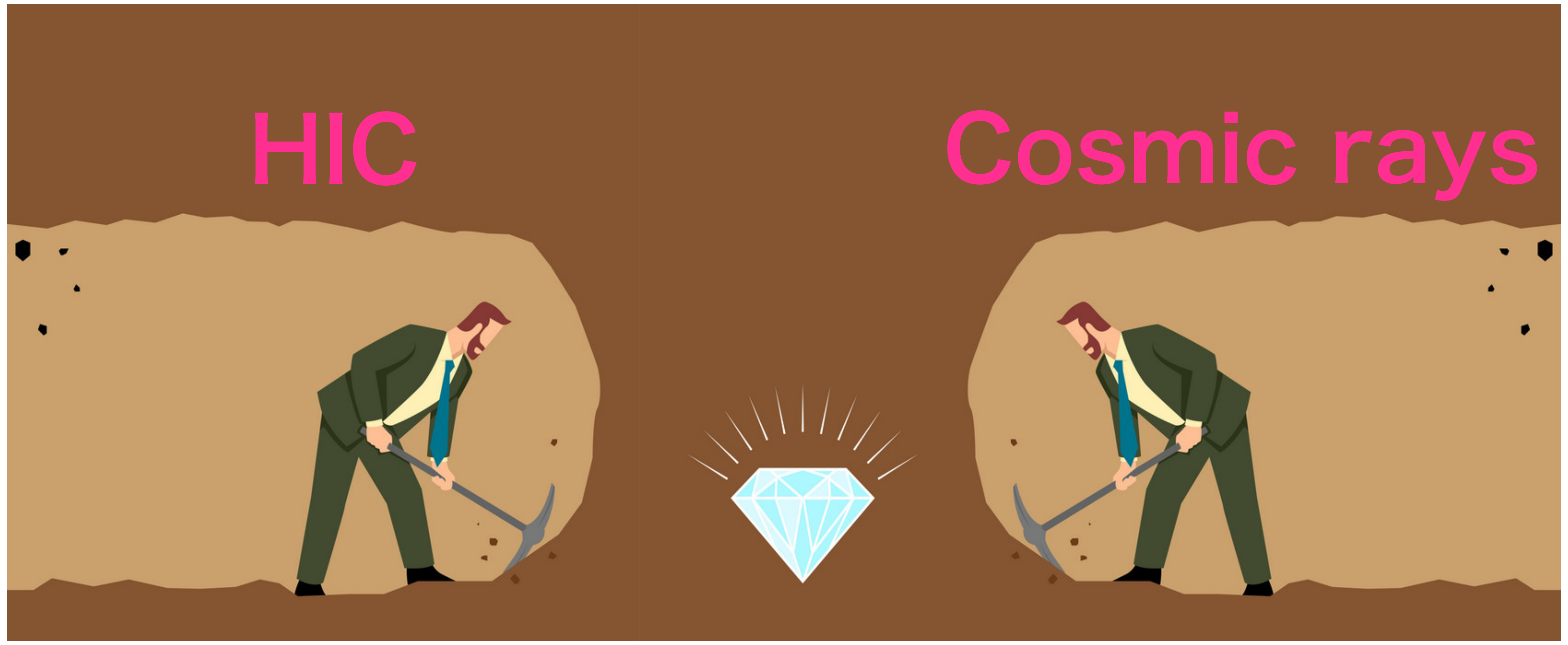
✦ v_2 vs p_T for inclusive charge particles and muons.



- μ^+ and μ^- have much larger v_2 than inclusive charge particles.
- Muons carry more collectivity of the first collision hadrons.

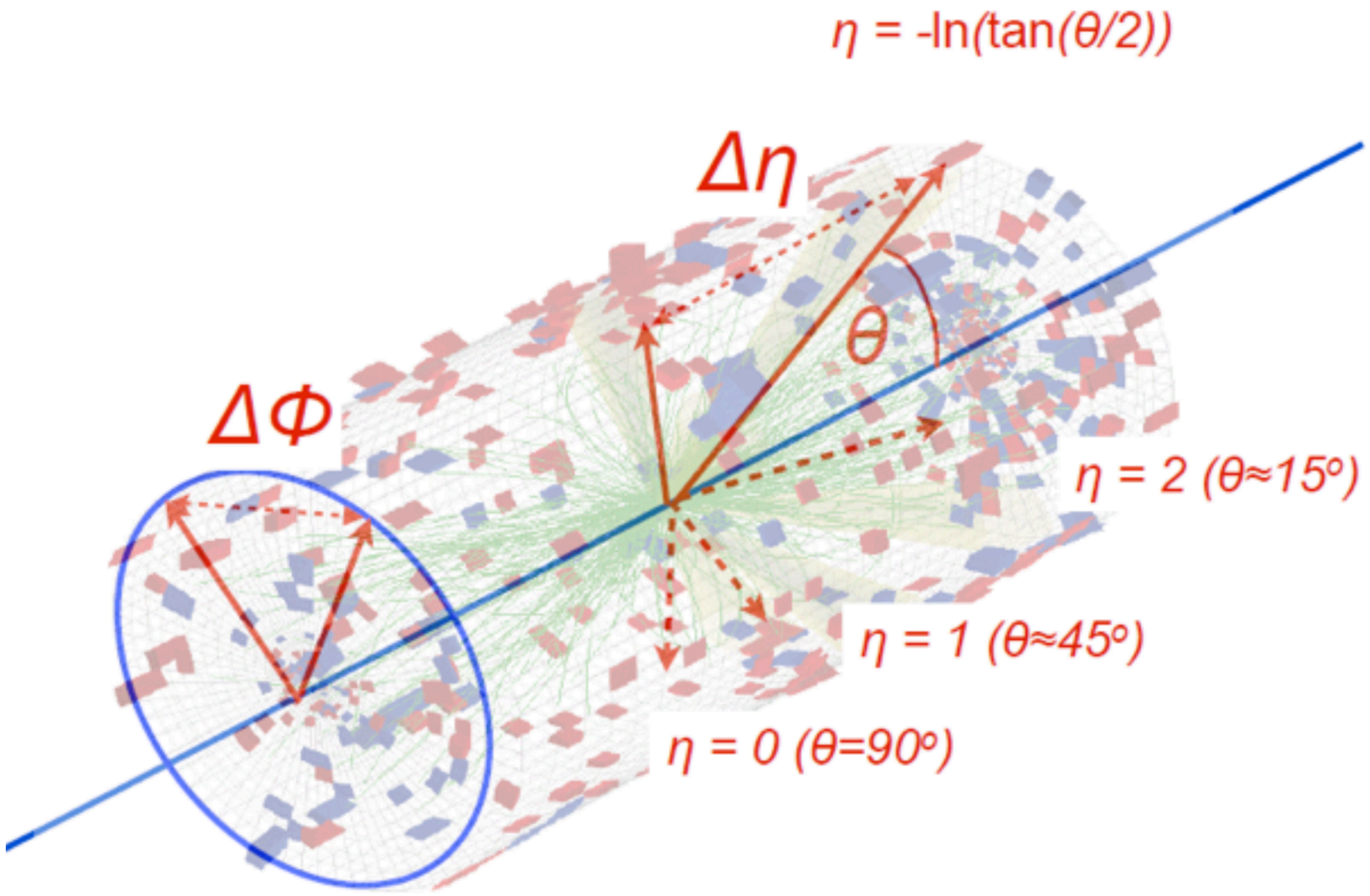
Summary

- Collective flow is studied in ultra-high energy cosmic rays within Corsika.
- Muon v_2 is much larger than all charge particles, which may indicate muons carry more collectivity after the first collision.
- The measurement of muon v_2 is a promising way to search for QGP in cosmic rays, it is worth to do the measurement in LHAASO in the future.
- Cosmic rays cover a wider energy ranges and more collision species, fruitful QGP studies are expected.

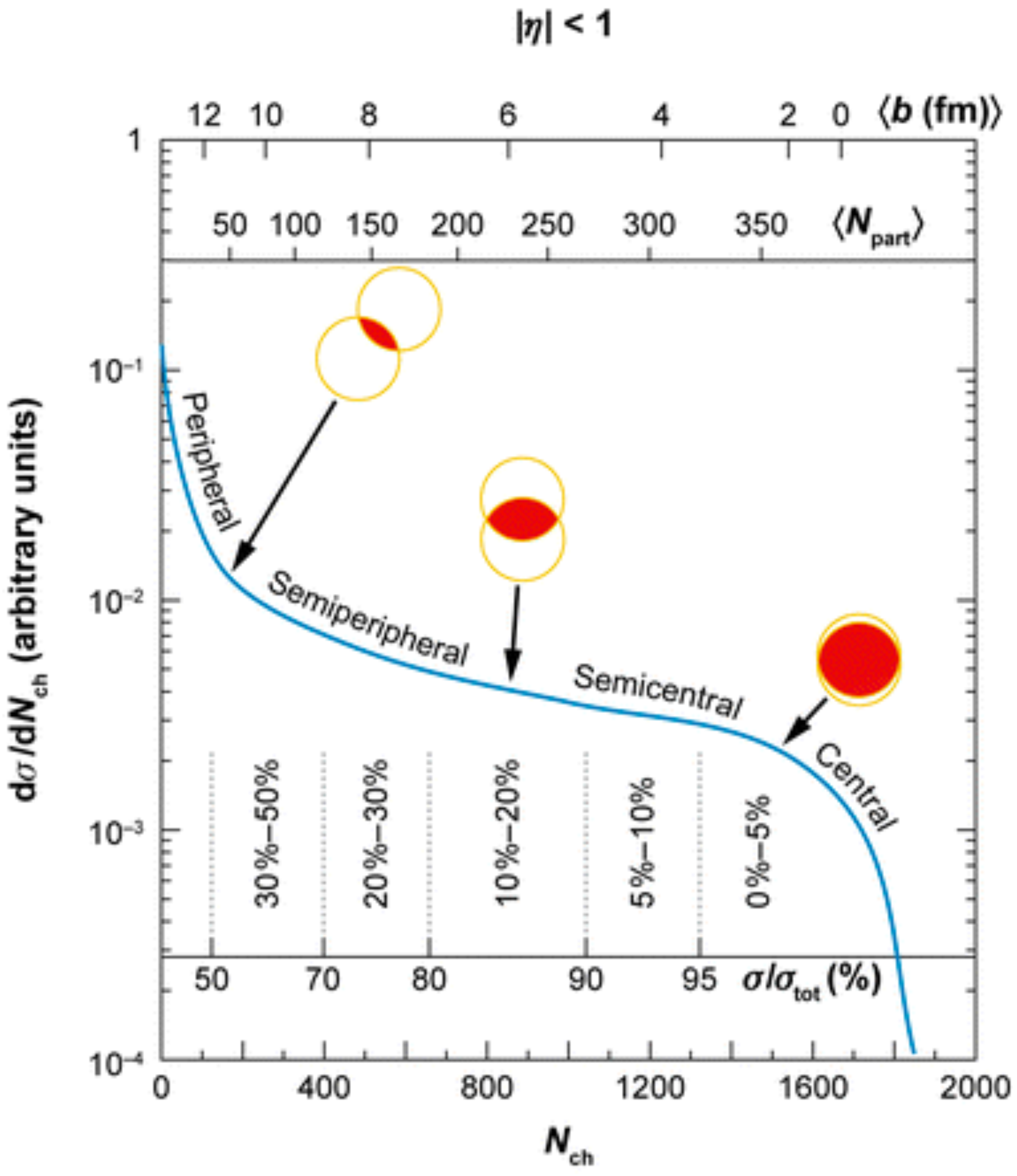


Backup

two particle correlation

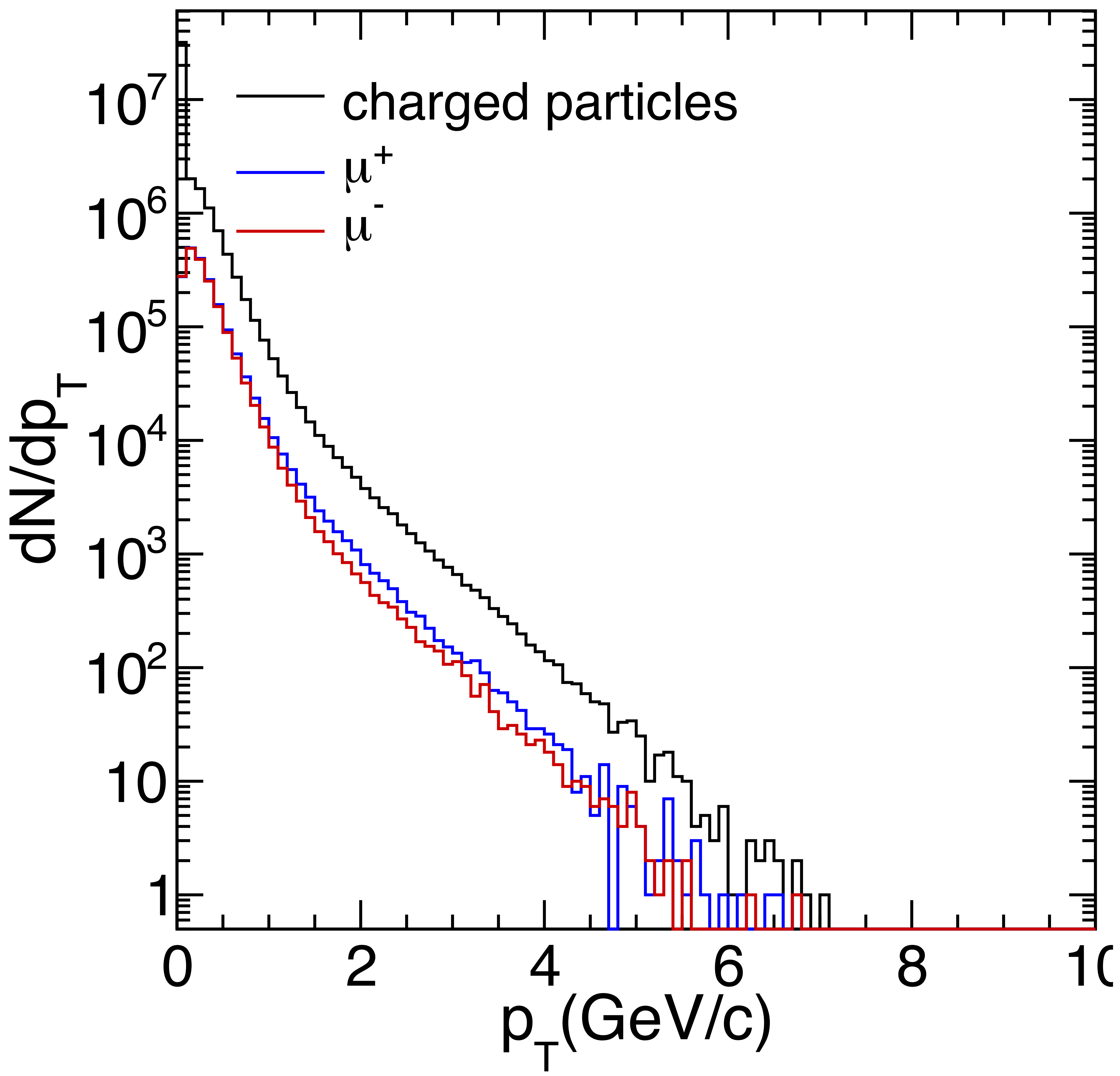


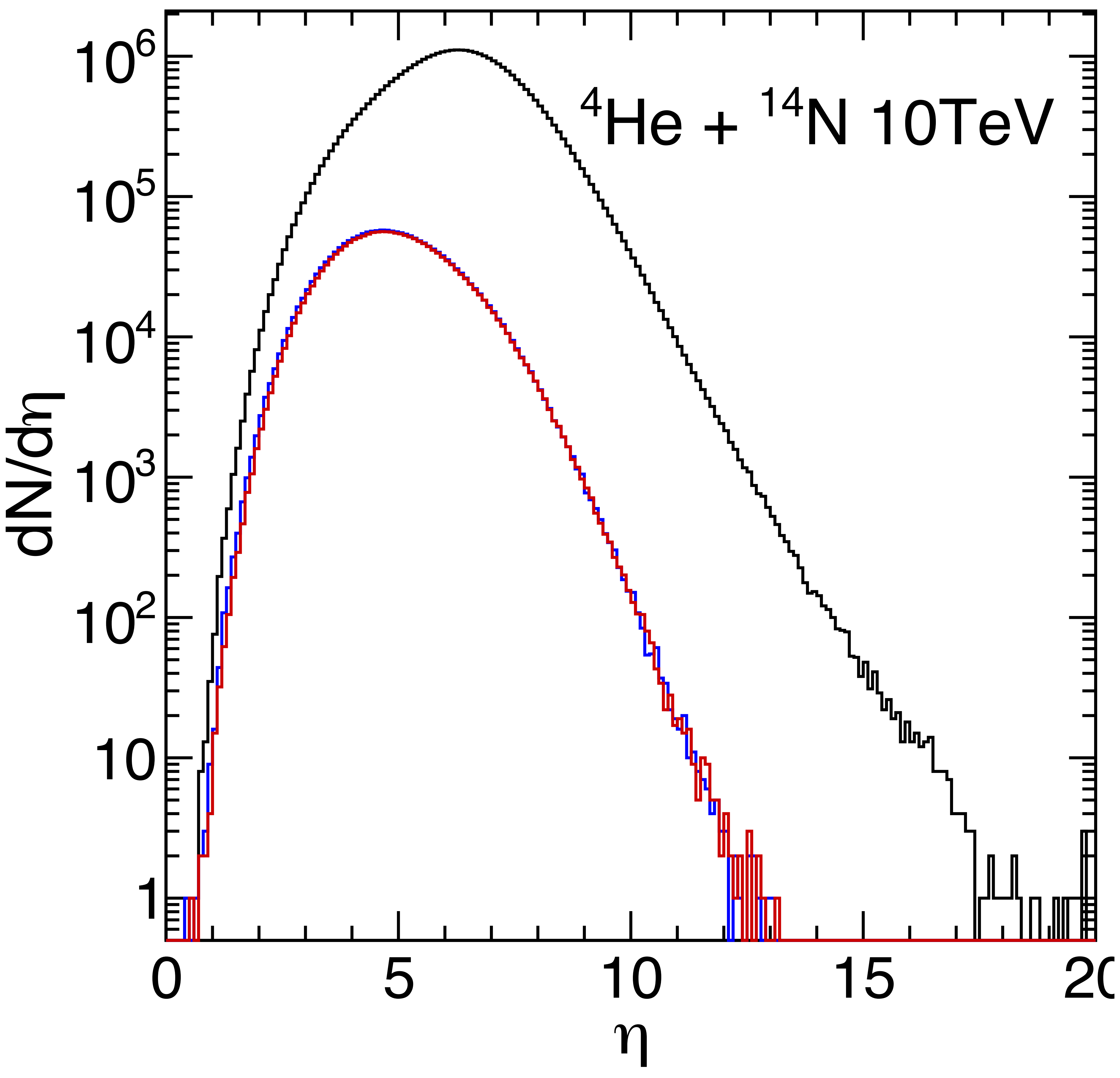
Centrality



Miller ML, et al. 2007.
Annu. Rev. Nucl. Part. Sci. 57:205–43

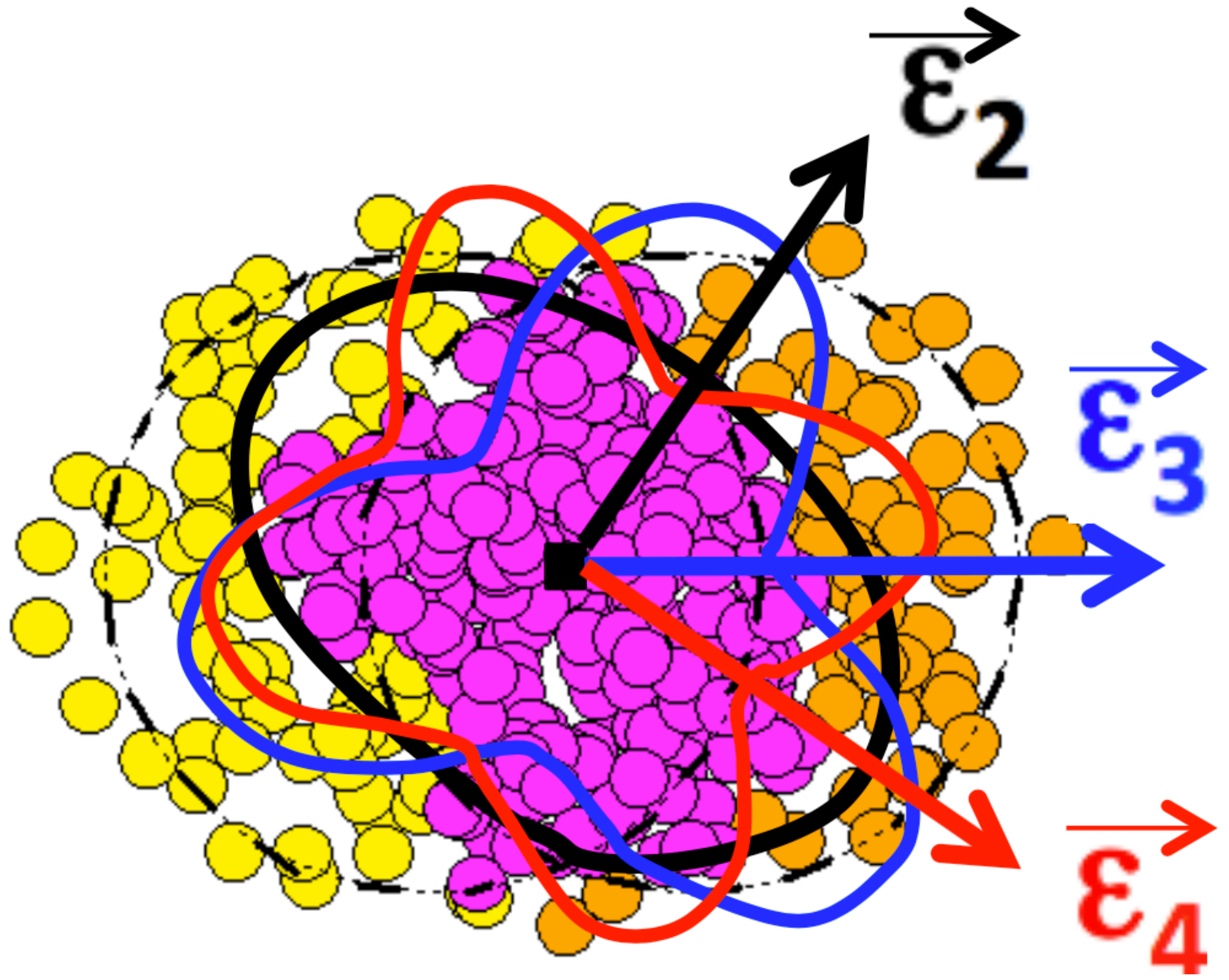
p_T and η distribution





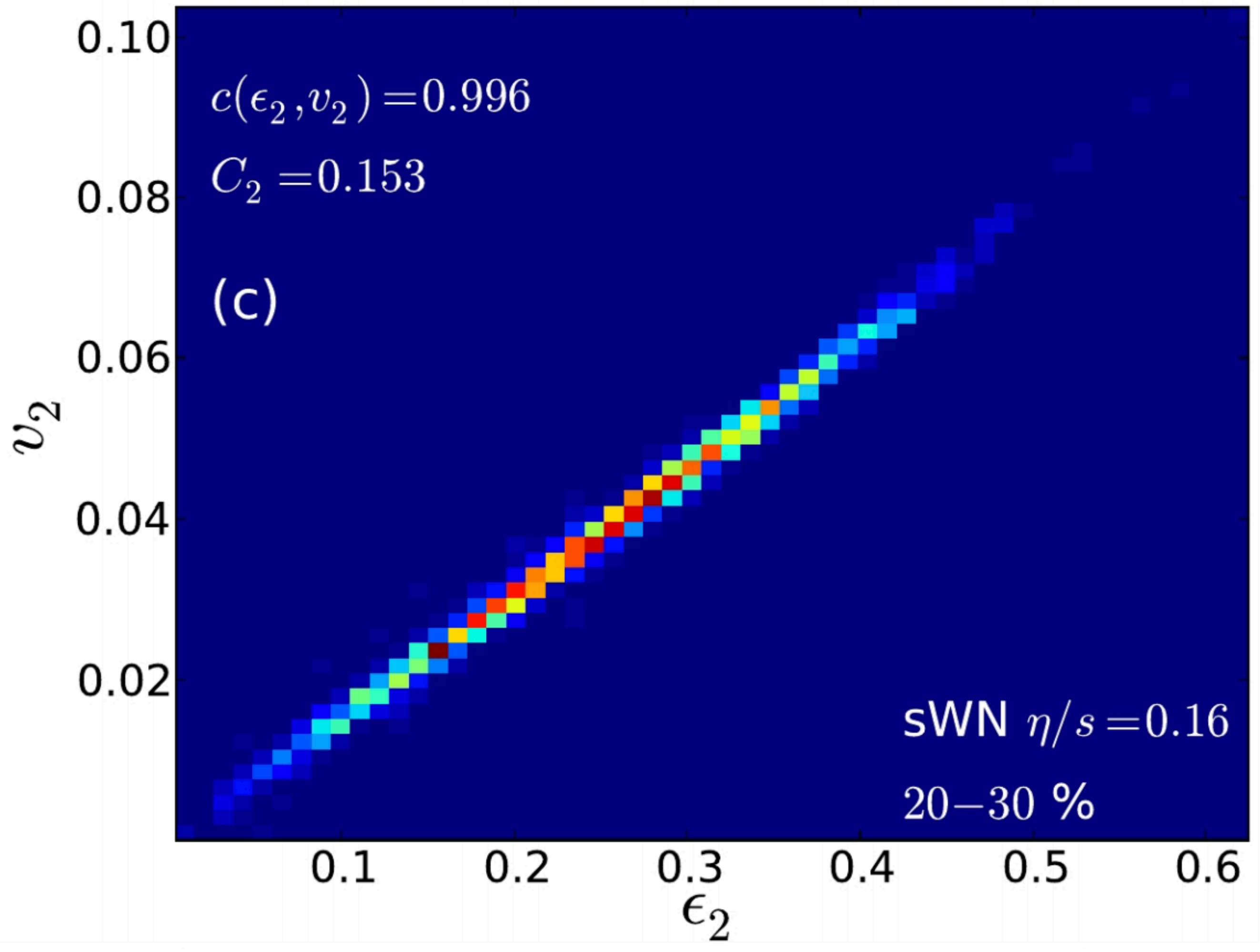
Collective flow: connecting the initial and final state

Initial state
(coordinate space)

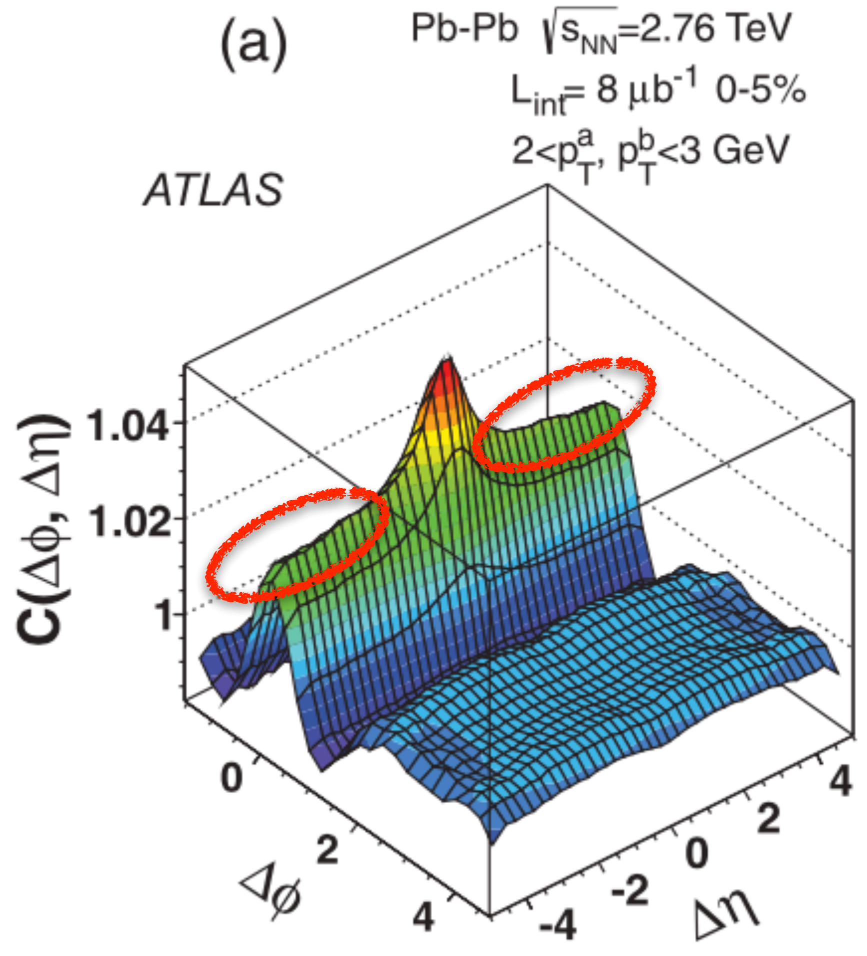


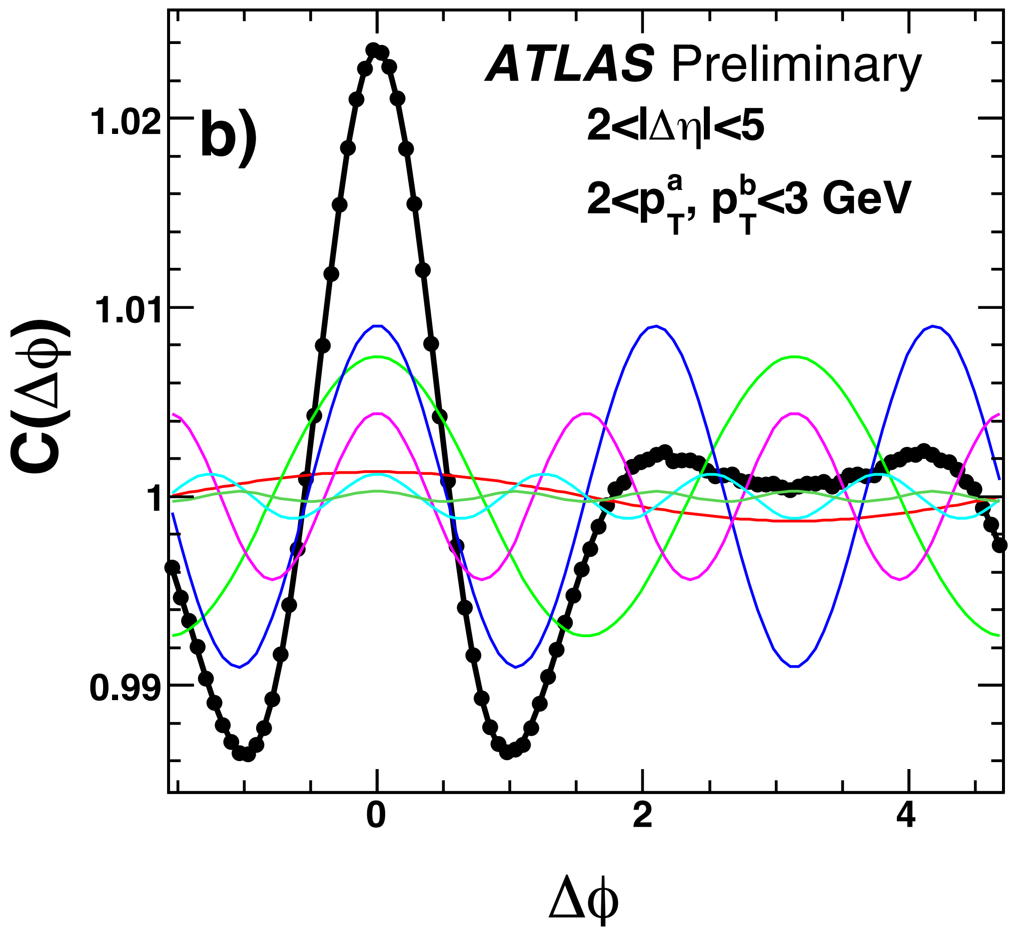
$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi}\rangle}{\langle r^n\rangle}$$

geometry response



Final state
(momentum space)

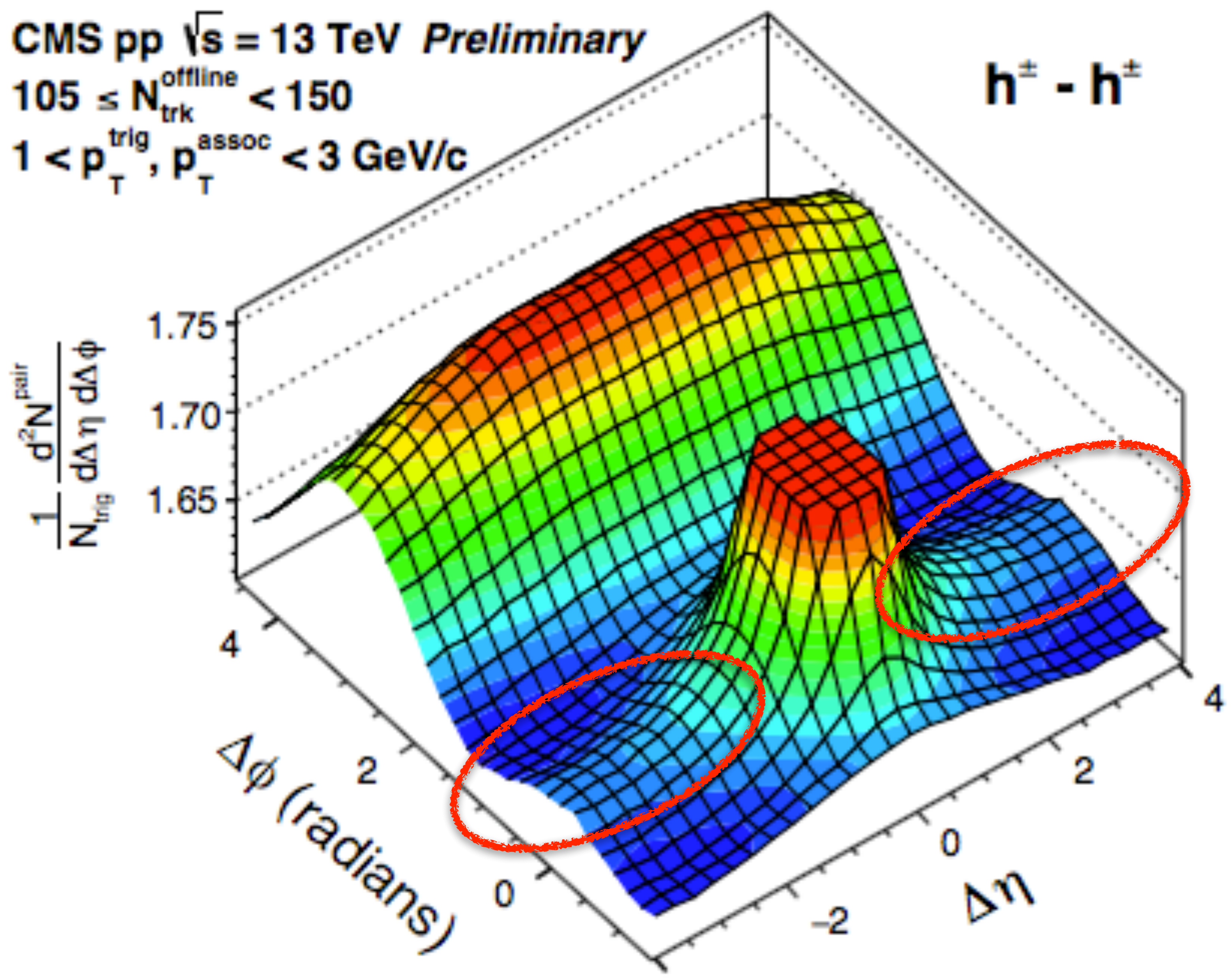




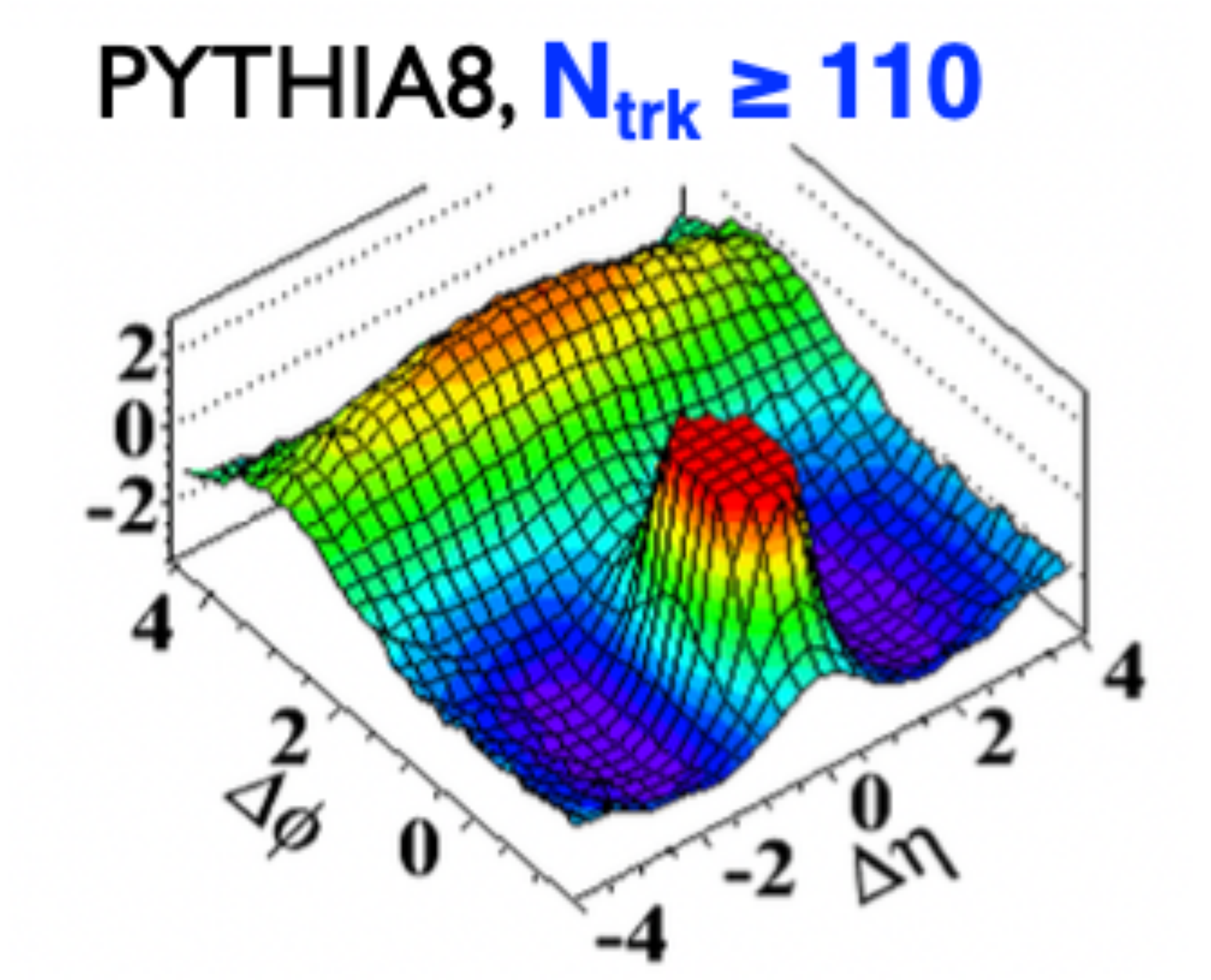
Pairs: $$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2 v_n^a v_n^b \cos(n\Delta\phi)$$

Singles: $$\frac{dN}{d\phi} \propto 1 + \sum_n 2 v_n \cos n(\phi - \Psi_n)$$

Why collective flow study important?

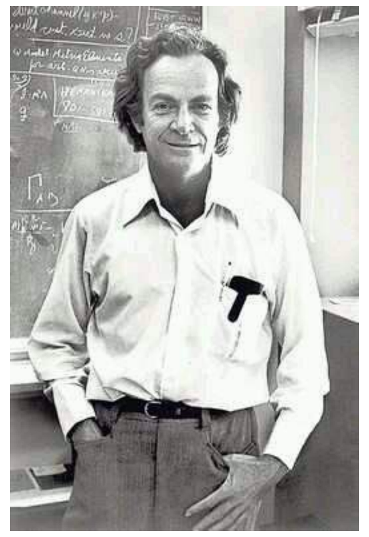


Collectivity in p+p



No “ridge” in PYTHIA

Scattering of protons on protons is like colliding Swiss watches to find out how they are build.
— Richard Feyman



- Know all the building blocks doesn’t mean one know how it really works.