Small system QGP: Observations and Challenges

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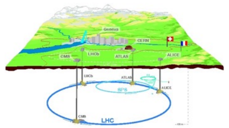
Outline

- High-multiplicity pp collisions and a hint of QGP
- Final state multiplicity scalings
- Event topology studies
- Some expected results from the proposed O-O collisions
- Challenges in hand
- Summary and Outlook

The Large Hadron Collider (LHC)

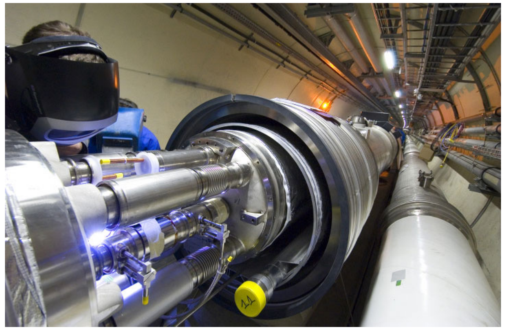
❖ The LHC is currently the largest and most powerful proton and ion collider.

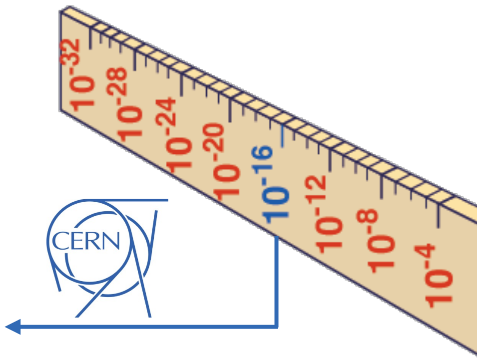


~100 m underground & 27 km circ.

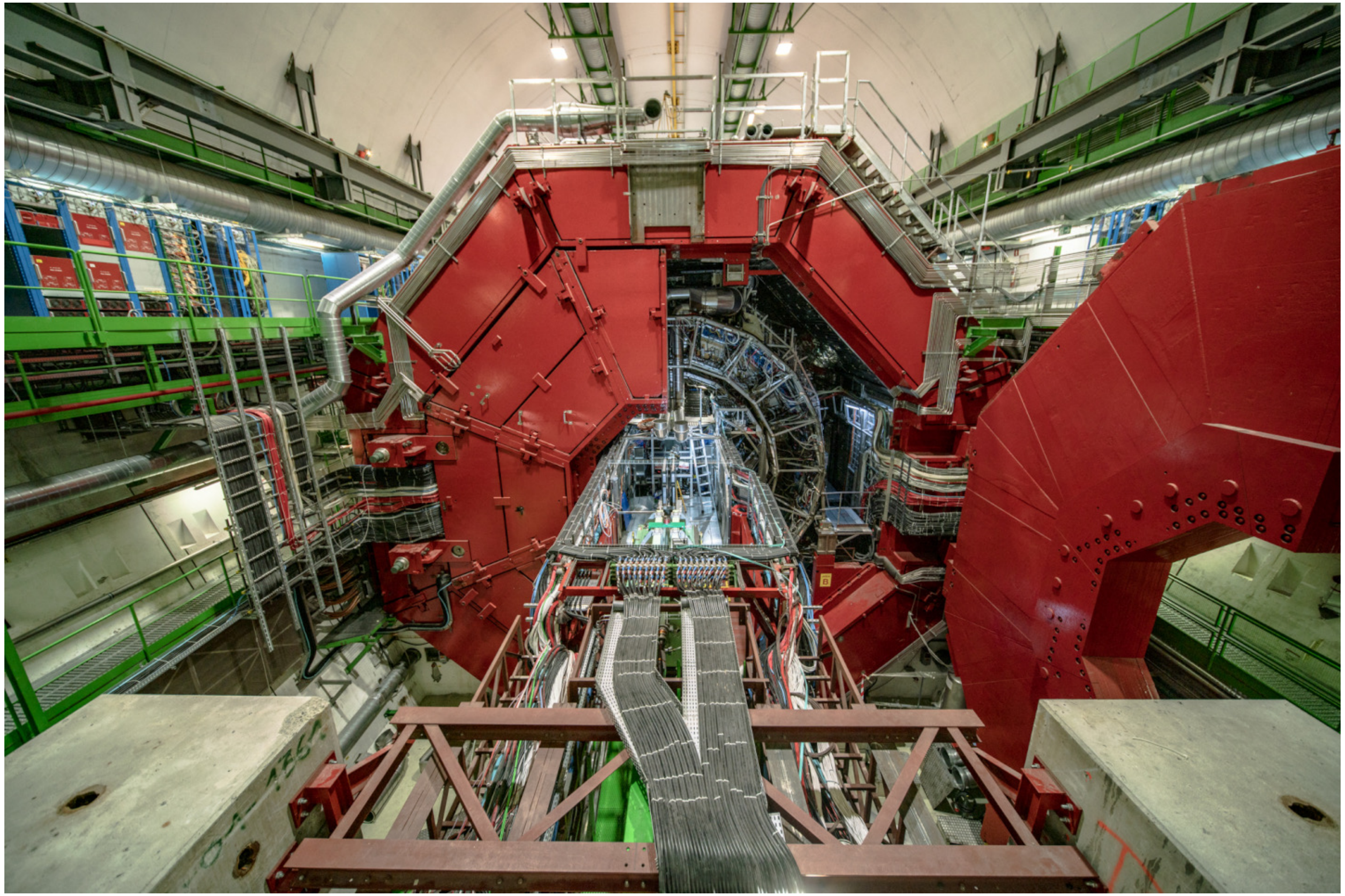
System	Year	Centre of mass energy (TeV)	Integrated luminosity
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	75 mb^{-1} 800 mb^{-1}
Xe-Xe	2017	5.44	0.3 mb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	15 nb^{-1} 3 nb^{-1} , 25 nb^{-1}
p-p	2009-2013 2015, 2017 2015-2018 2022-2023	0.9, 2.76, 7, 8 5.02 13 13.6	200 mb^{-1}, 100 nb^{-1}, 1.5 pb^{-1}, 2.5 pb^{-1} 1.3 pb^{-1} 136 pb^{-1} 30 pb^{-1}

Big Bang





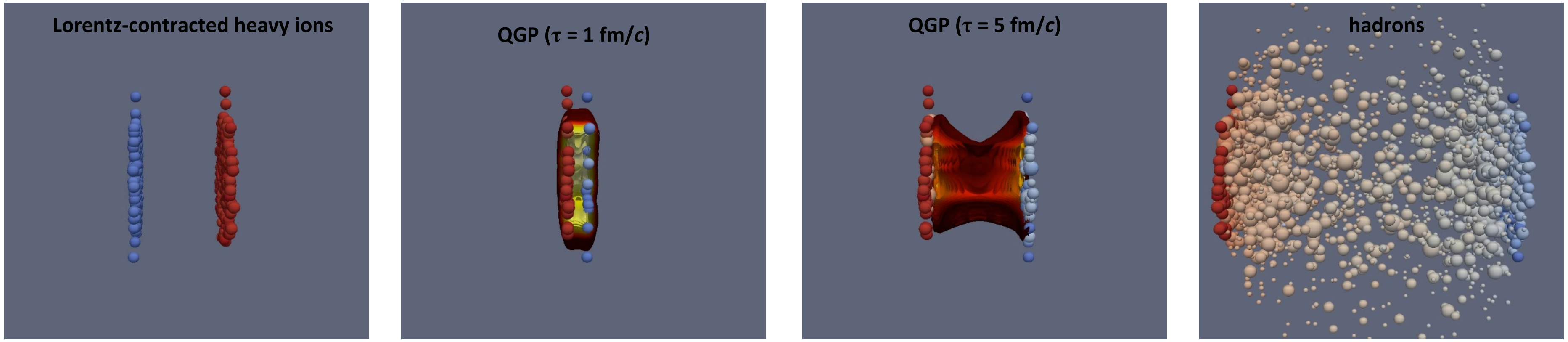
ALICE - The experimental set-up



16 m x 16 m x 25 m, ~10 000 t.

Obtaining a mini-big-bang: the quark-gluon plasma (QGP)

- accelerate and collide heavy nuclei → multiple (almost) simultaneous collisions
- extreme energy densities and huge temperature → Mini-Big-Bang in the laboratory



Simulation: MADAI.us

QGP → thermalised system of deconfined quarks and gluons
(the energy density is so high that it is not compatible with hadrons such as protons or neutrons)

expected temperature: ~ 2 000 billion degrees

10^5 times the temperature at the core of the Sun

similar conditions are thought to have existed about 10 μs after the Big Bang

quarks are no more confined inside protons, neutrons, etc…

Exploring the phase diagram of matter at the LHC

- Study nuclear matter under extreme conditions of temperature and energy density

- Conditions at LHC energies:

  close to the ones of the Early Universe

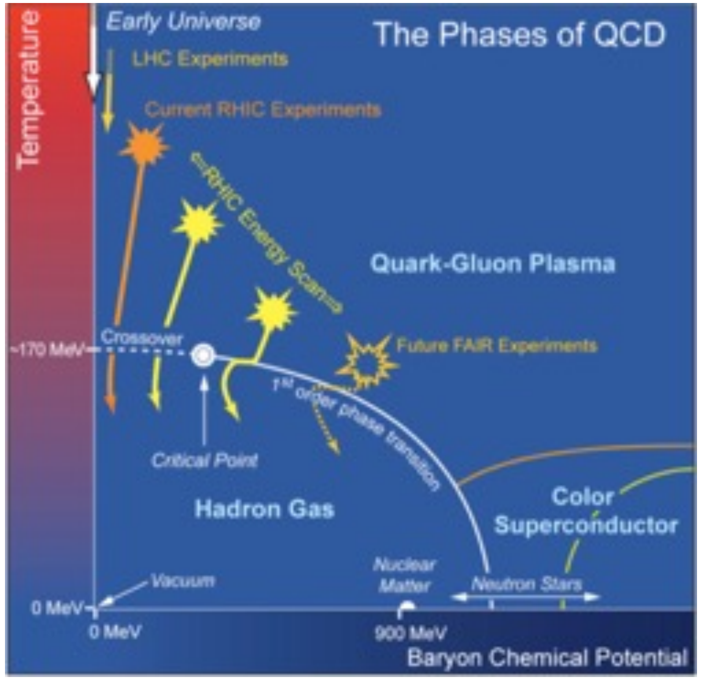
  high temperature: O(10^{12} K) .

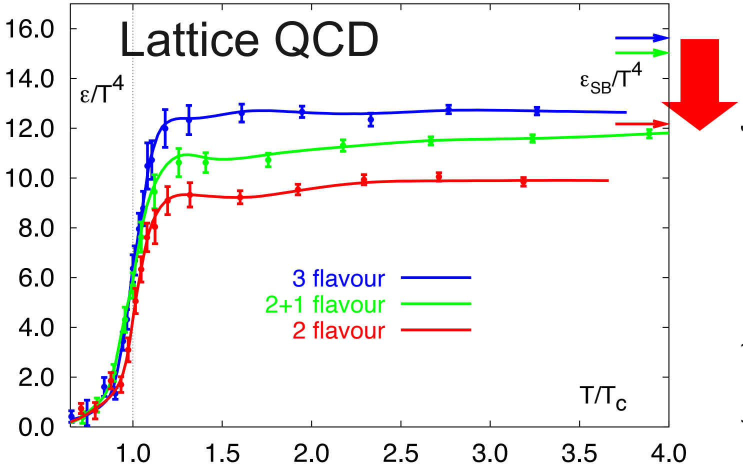
  vanishing baryon chemical potential: equal number of baryons and anti-baryons

- Phase transition predicted by Lattice QCD calculations (state of the art):

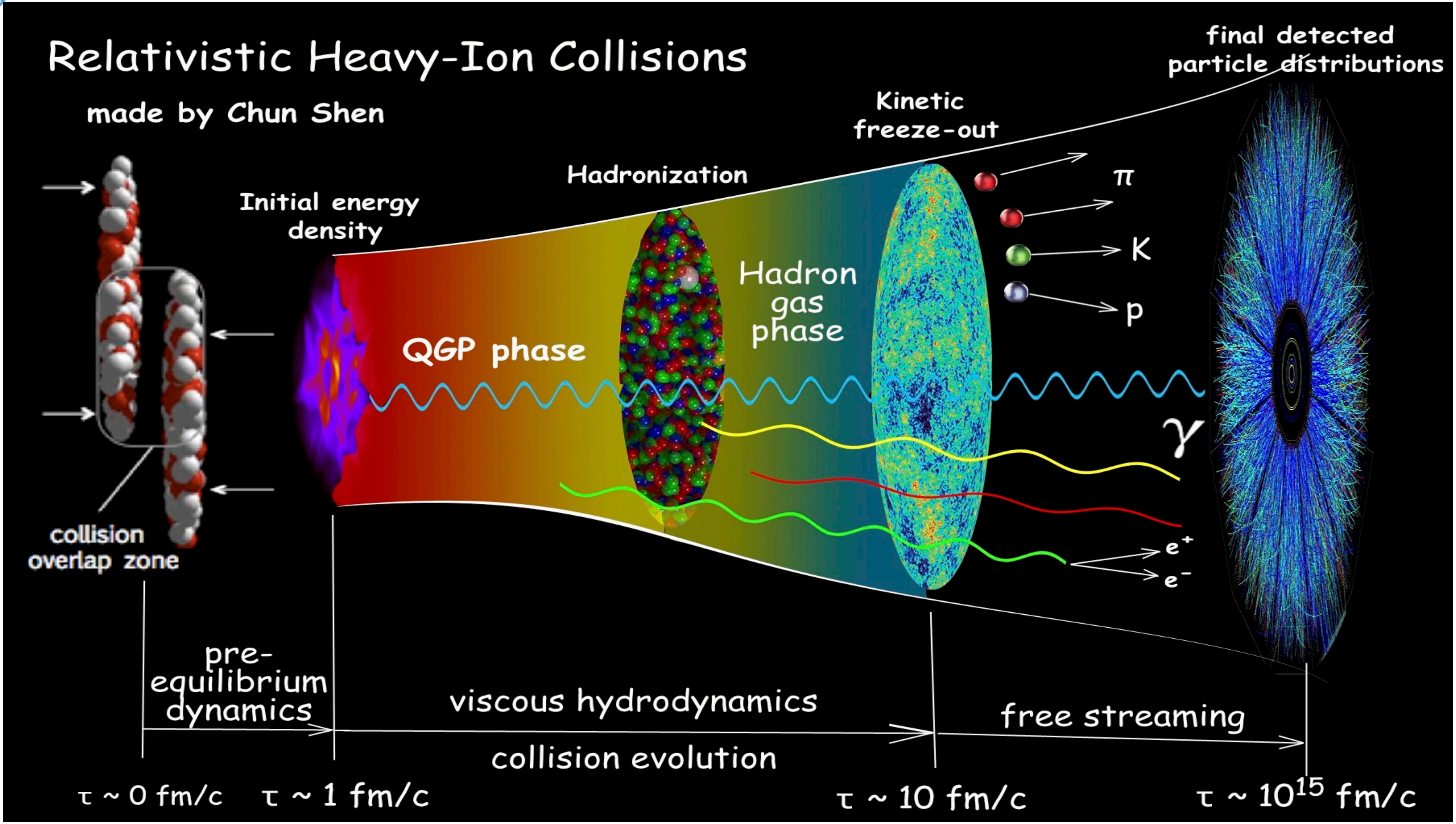
  $T_C \approx 155$ MeV and $\varepsilon_C \approx 0.5\text{-}1.0$ GeV/fm^3

- Study the properties of a state where quarks and gluons are deconfined (QGP).

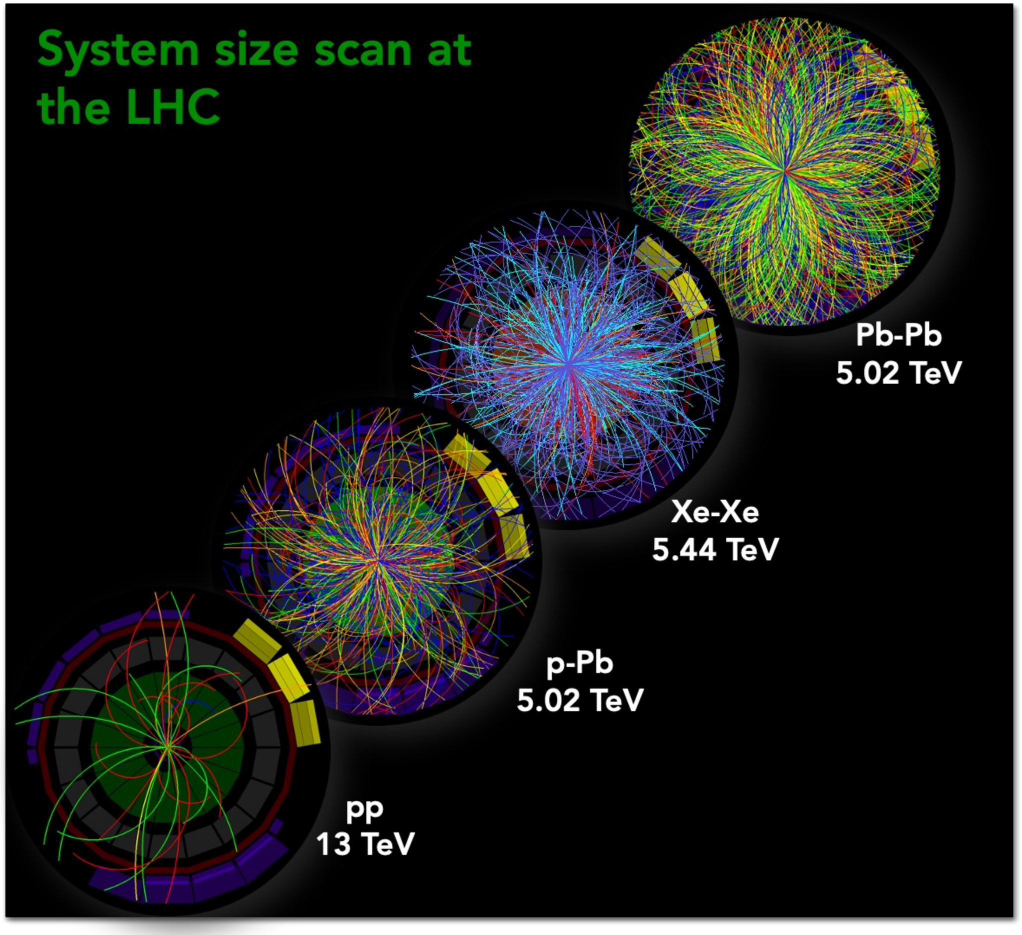


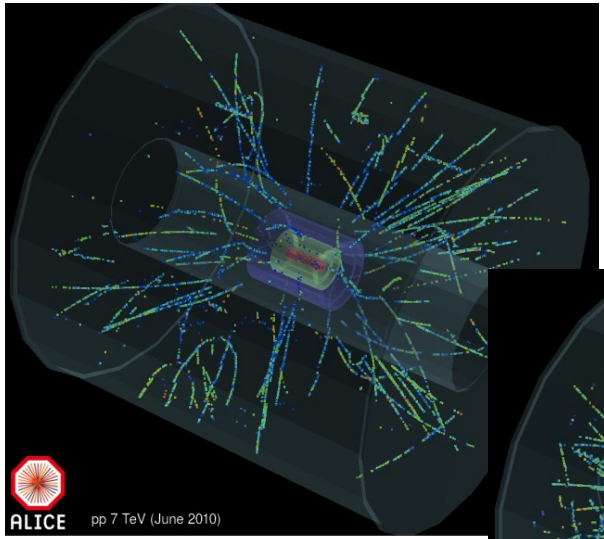


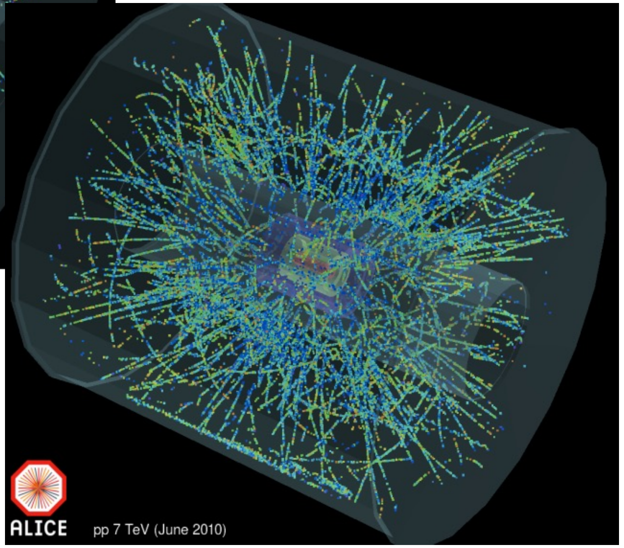
F. Karsch, Nucl. Phys. A 698, 199 (2002).


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e+
e−
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Limit of QGP formation at the LHC

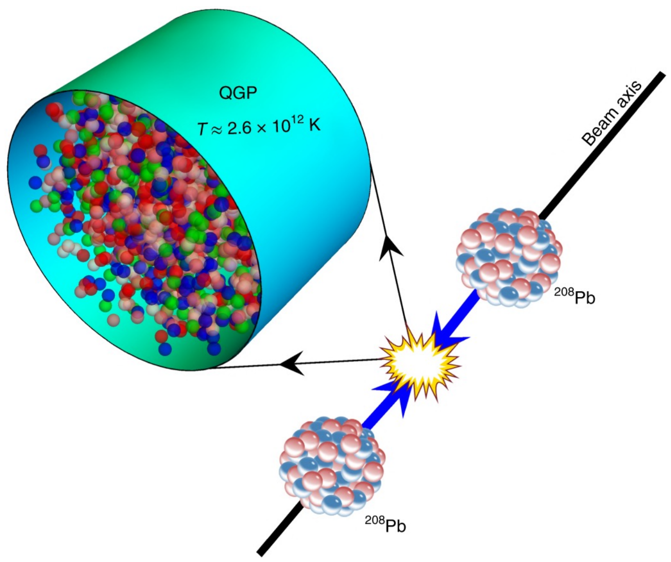






- Rare pp and p-Pb collisions can produce very large numbers of hadrons. i.e. high multiplicities
- Do they create QGP?

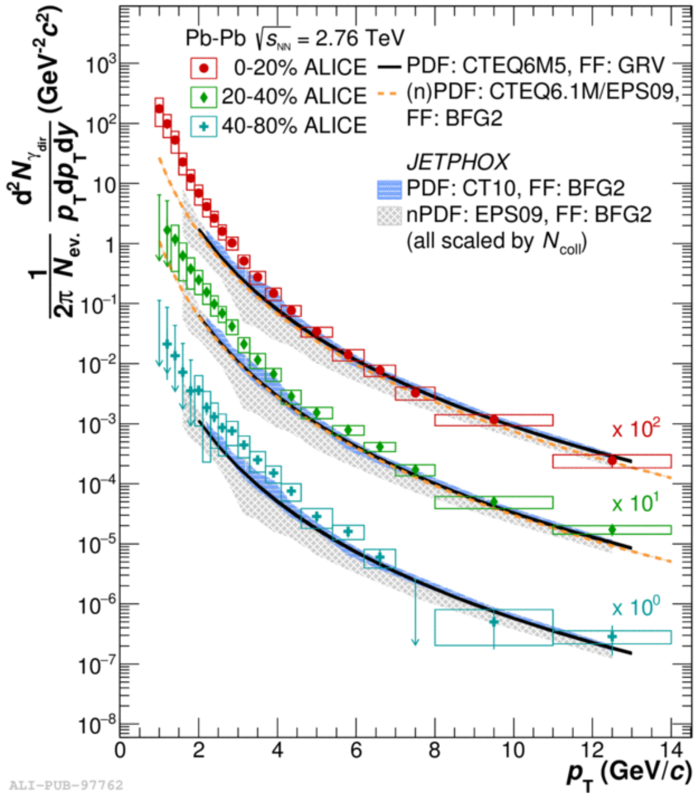
Heavy-ion collisions at the LHC: Medium properties



Nature Physics 16, 615–619 (2020)

- Direct photons:

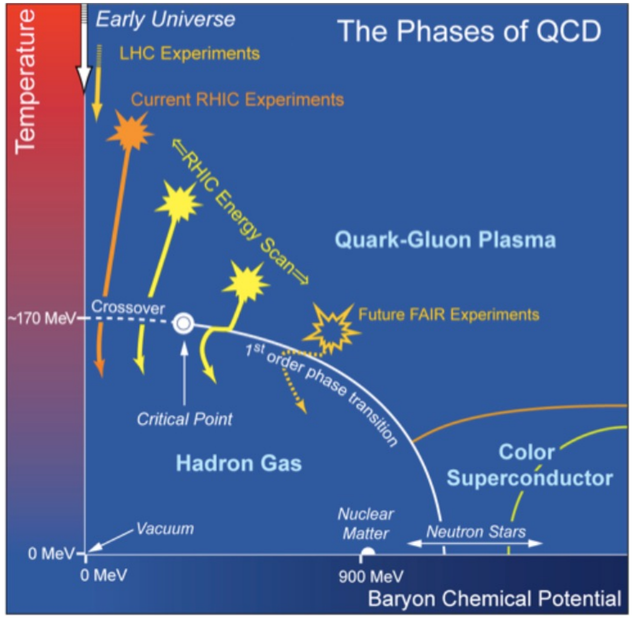
  $T_{eff} \approx 297 \pm 12^{(stat)} \pm 41^{(syst)}$ MeV $\gg T_C$

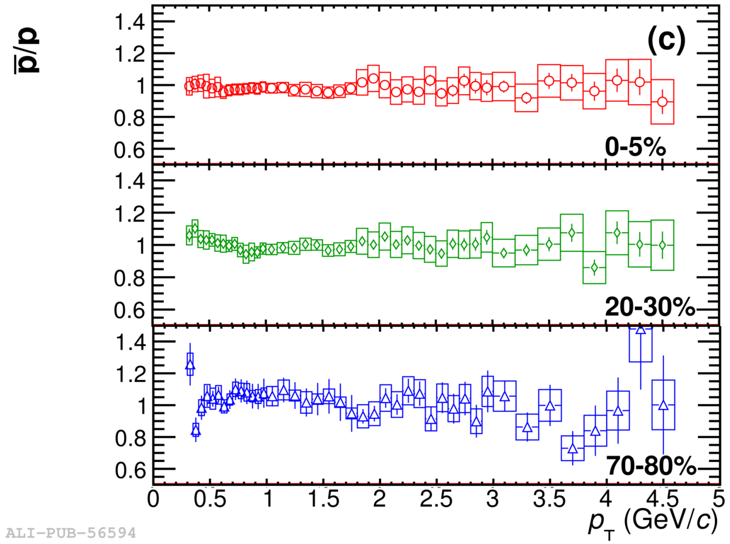


Recall: $T_C \approx 155$ MeV

- anti-particle-to-particle ratio ~ 1

  $\mu_B \sim 0$ MeV

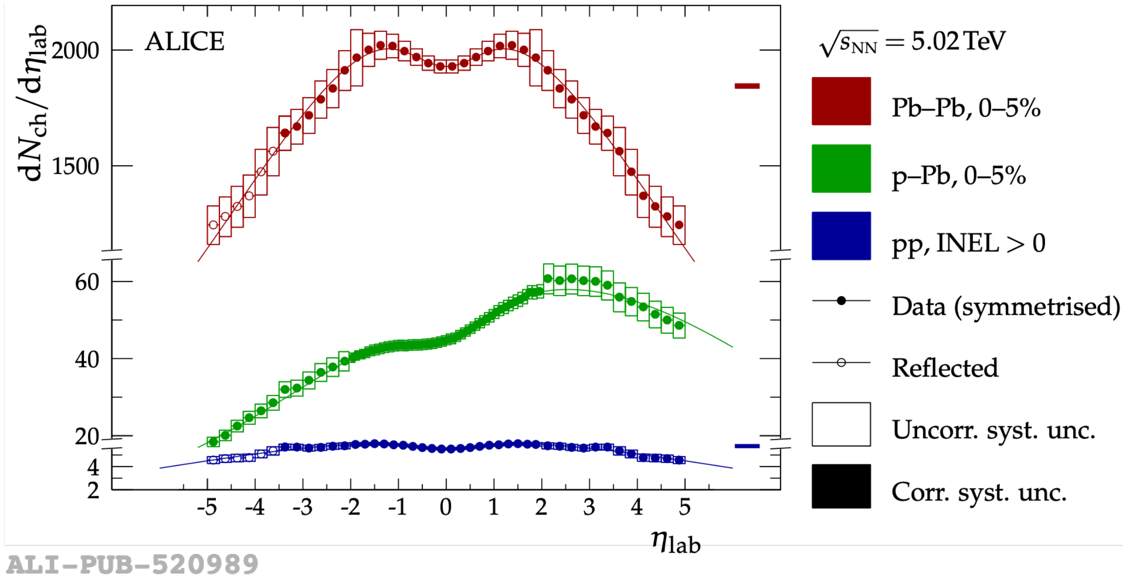


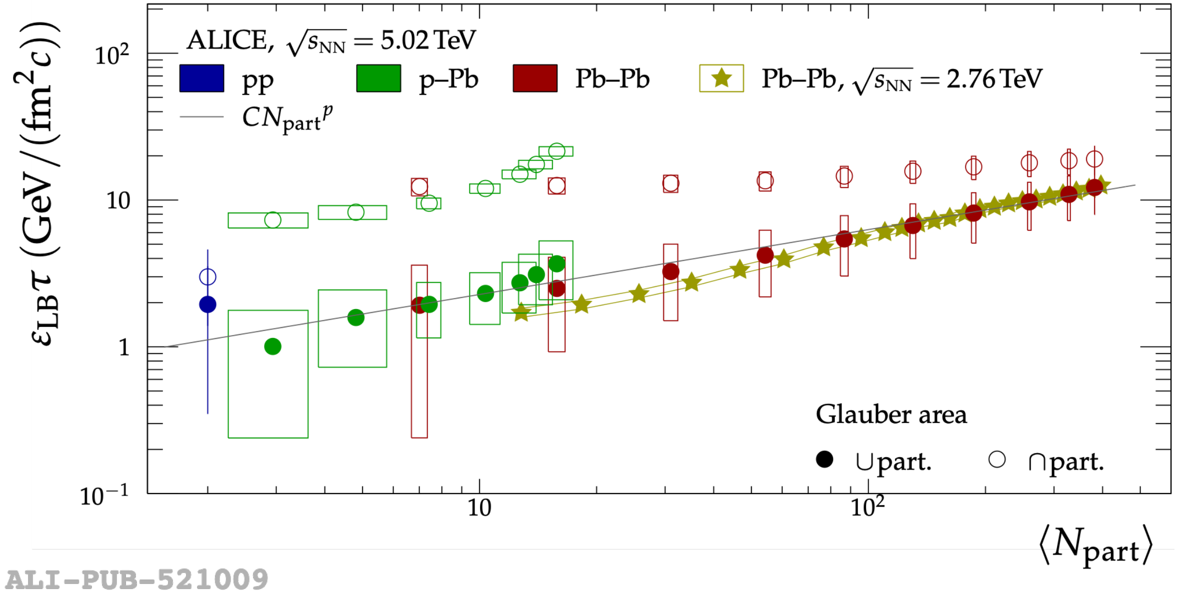


Phys. Rev. C 88, 044910 (2013)

QGP droplets in small systems?

- Measurements at the LHC have revealed that small collision systems exhibit collective-like behavior, formerly thought to be achievable only in heavy-ion collisions, where the data support the formation of QGP.





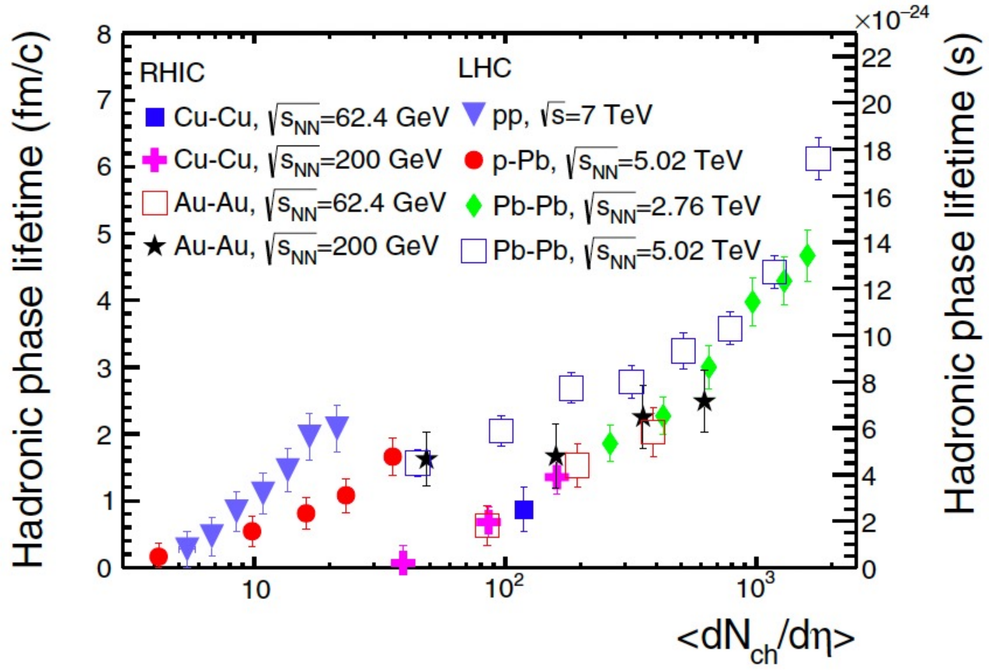
$$\varepsilon_{\mathrm{Bj}} = \frac{1}{c\tau}\frac{1}{S_{\mathrm{T}}}\left\langle \frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y} \right\rangle$$

$$S_{\mathrm{T}} \approx \pi R^2 \approx \pi N_{\mathrm{part}}^{2/3}$$

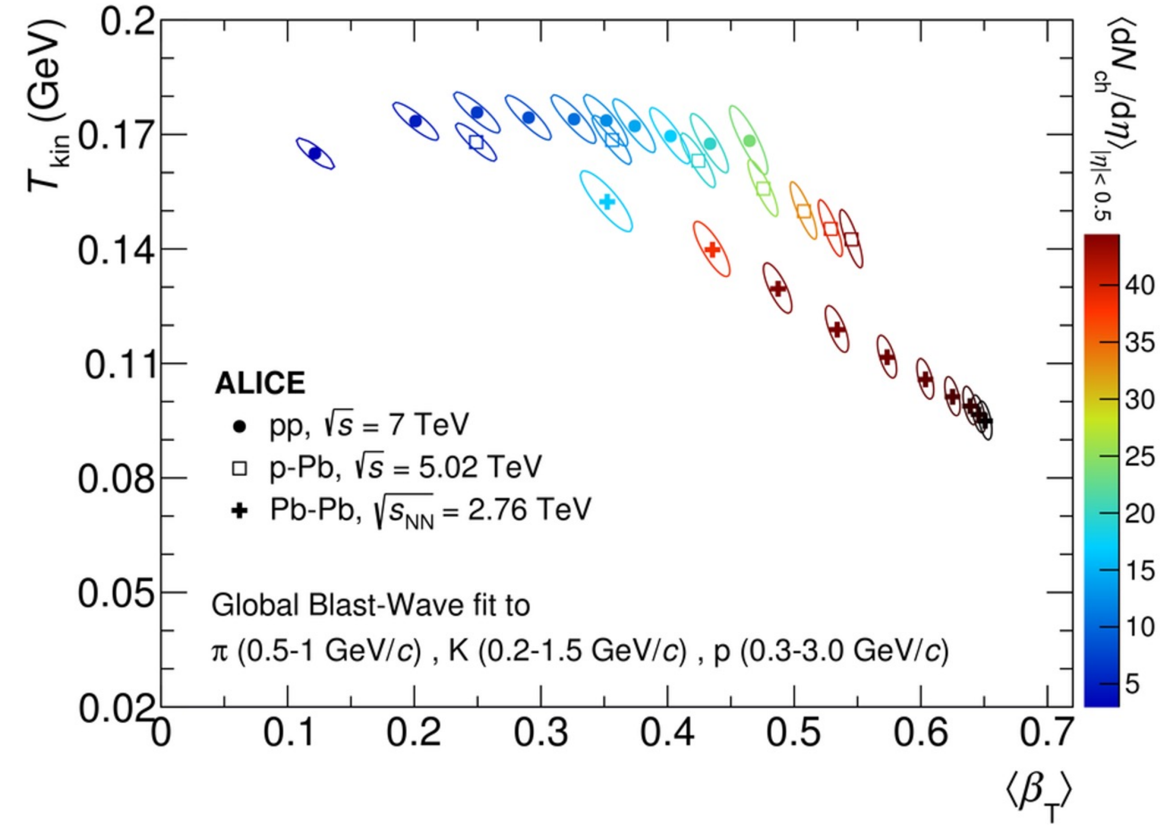
$$\left\langle \frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y} \right\rangle \approx \langle m_{\mathrm{T}} \rangle \frac{1}{f_{\mathrm{total}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y} = \langle m \rangle \sqrt{1 + \left(\frac{\langle p_{\mathrm{T}} \rangle}{\langle m \rangle} \right)^2} \frac{1}{f_{\mathrm{total}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}$$

$f_{\mathrm{total}} = 0.55 \pm 0.01$, the ratio of charged particles to all particles

Hadronic phase lifetime



D. Sahu, S. Tripathy, G.S. Pradhan and R. Sahoo, Phys. Rev. C 101, 014902 (2020)



The ALICE experiment - A journey through QCD, arXiv:2211.04384

- ❖ pp collisions have a finite hadronic phase!
- ❖ Comparable T_{kin} and collective radial flow wrt HIC

Strangeness enhancement

- *s*-quarks are not part of the colliding nuclei (hadrons)
- *(u,d)*-quarks form ordinary matter
- *s(95 MeV):* are sufficiently light to be produced abundantly during the collision
- Strangeness is produced in hard partonic scattering processes by
- flavour creation: $gg \rightarrow s\bar{s}$

  $q\bar{q} \rightarrow s\bar{s}$
- flavour excitation: $gs \rightarrow gs$

  $qs \rightarrow qs$
- gluon splitting: $g \rightarrow s\bar{s}$

strangeness enhancement

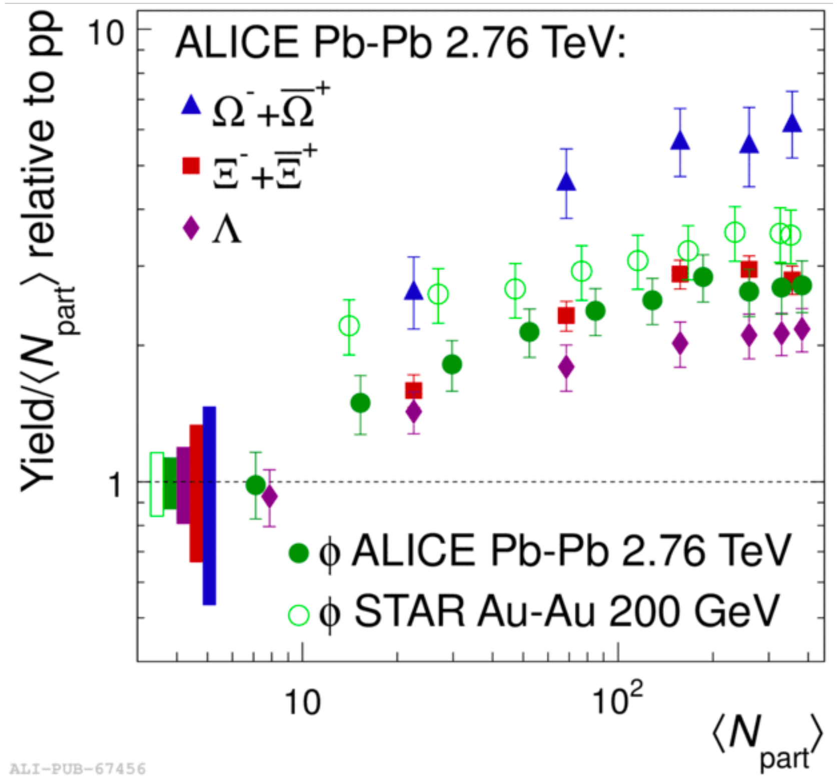
one of the first proposed QGP signatures

Rafelski, PRL 48 (1982) 1066

Strangeness enhancement in heavy-ion collisions

- Observed strangeness enhancement hierarchy: with s-content (relative to pp)

What do we observe in small systems like pp collisions at the LHC?

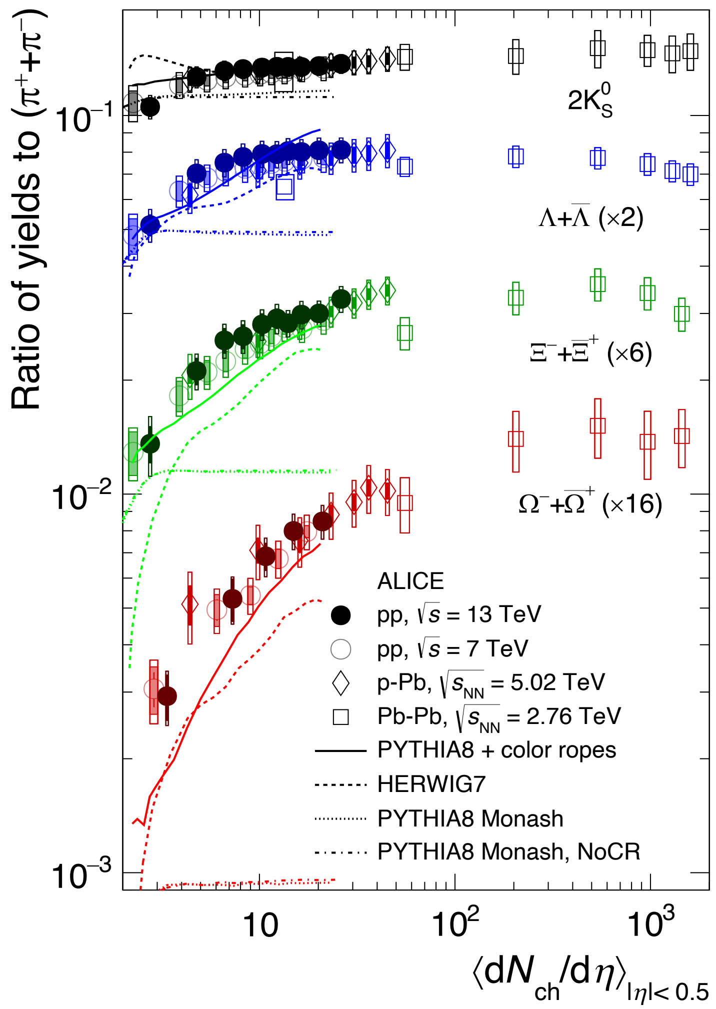


Phys. Rev. C **91**, 024609 (2015) [ALICE Collaboration]


nature
physics
JUNE 2017 VOL 13 NO 6
www.nature.com/naturephysics
Stranger and stranger says ALICE

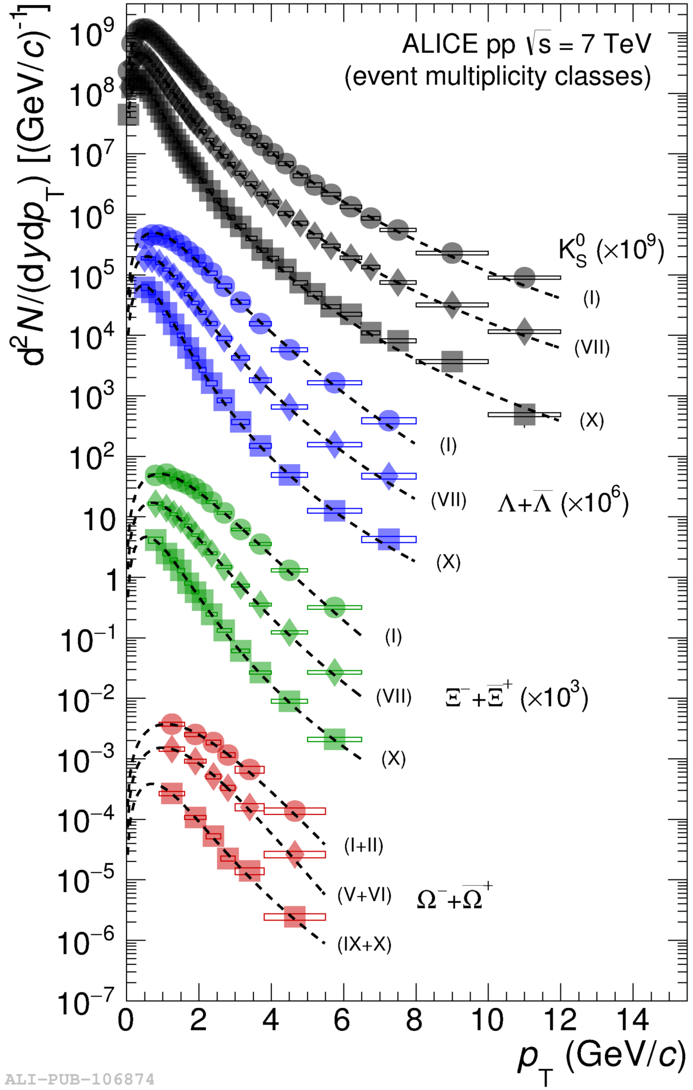
Strangeness enhancement

- ✓ Significant enhancement of strange-to- non-strange ratio with particle multiplicity
- ✓ Origin of strangeness production in hadronic collisions is driven by the characteristics of the final state rather than by the collision system and energy
- ✓ At high-multiplicity, the yield ratios reach values similar to that observed in Pb-Pb collisions
- ✓ Non-trivial Observation: Particle ratios in *pp* and p-Pb are identical at the same $dN_{ch}/d\eta$: final state particle density might be a good scaling variable between systems



ALICE Collaboration, Eur. Phys. J. C, 80, 693 (2020)

Spectra and collectivity

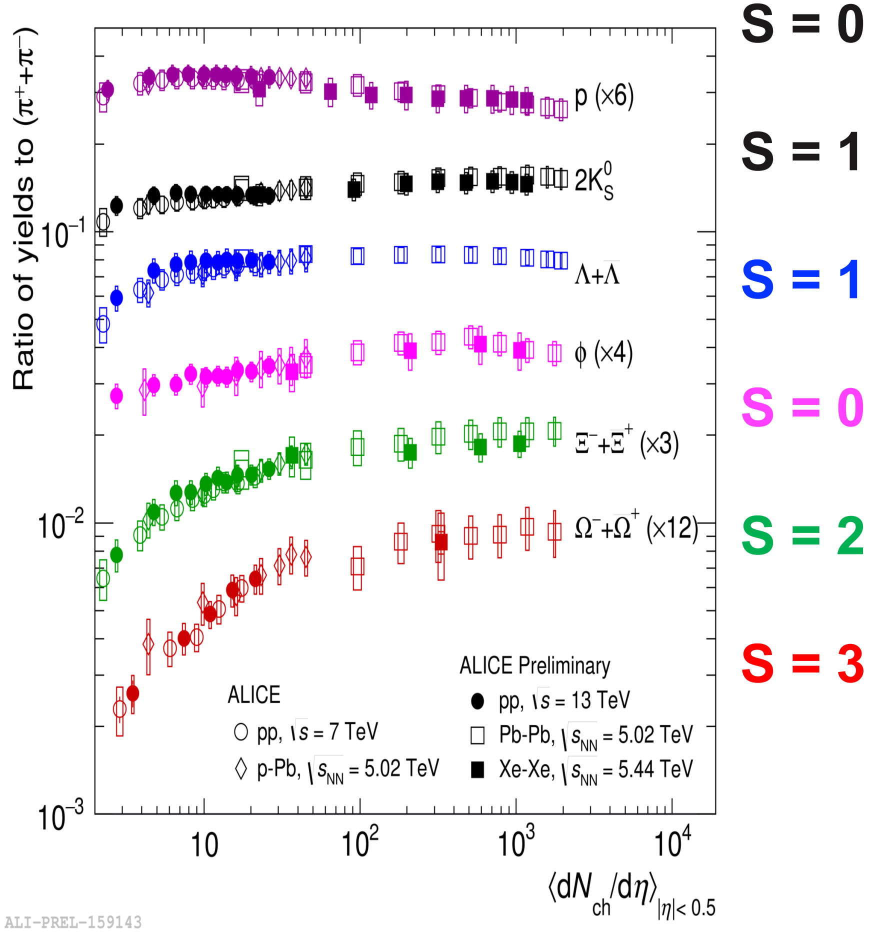


ALICE: Nature Phys. 13 (2017) 535

- ✓ Spectra become harder as multiplicity increases
- ✓ Hardening is more pronounced for higher-mass particles
- ✓ Similar observations like p-Pb and Pb-Pb showing collective behavior

- ✓ Simultaneous fit: T_{fo} = 163 ± 10 MeV, <β_T> = 0.49 ± 0.02
  → Similar to the same class of events in p-Pb with comparable $dN_{ch}/d\eta$

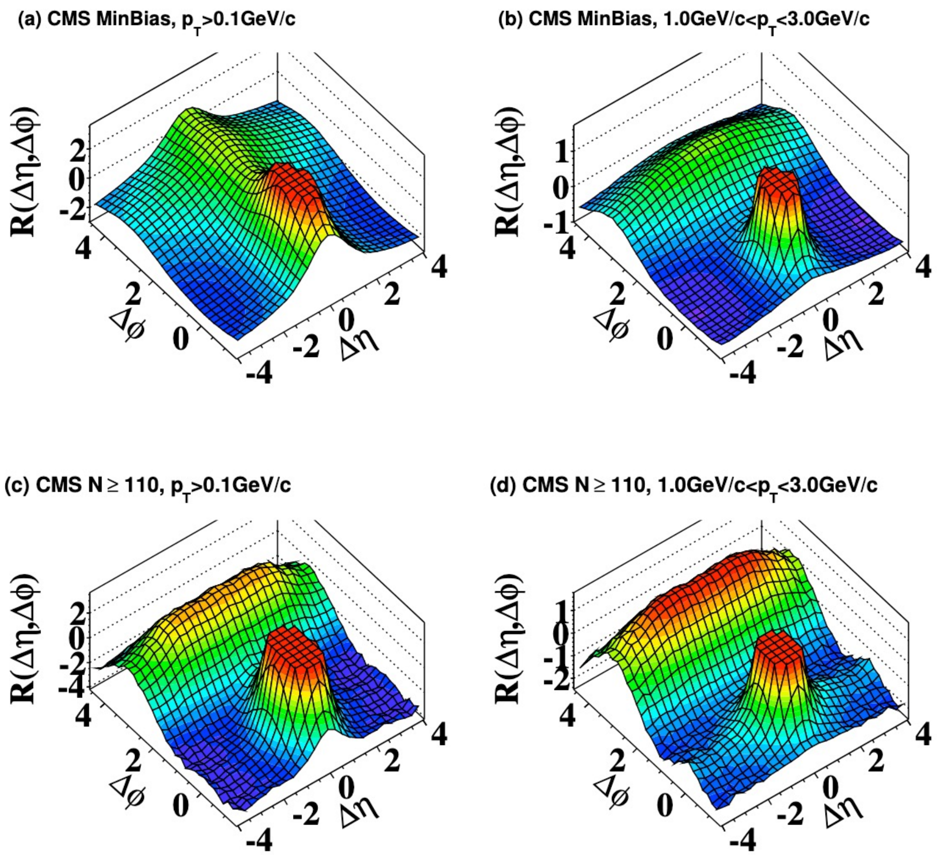
Strangeness hierarchy



- ✓ Smooth evolution as a function of event multiplicity (in pp, p-Pb and Pb-Pb collisions)
- ✓ Measurement at different energies as a function of multiplicity indicate that the hadron chemistry is driven by multiplicity regardless of the collision energy
- ✓ Ratios increase from low to high multiplicity in small systems and reach values similar to those observed in Pb-Pb collisions.
- ✓ Strangeness enhancement increases with strangeness content.

Long-range ridge-like correlations

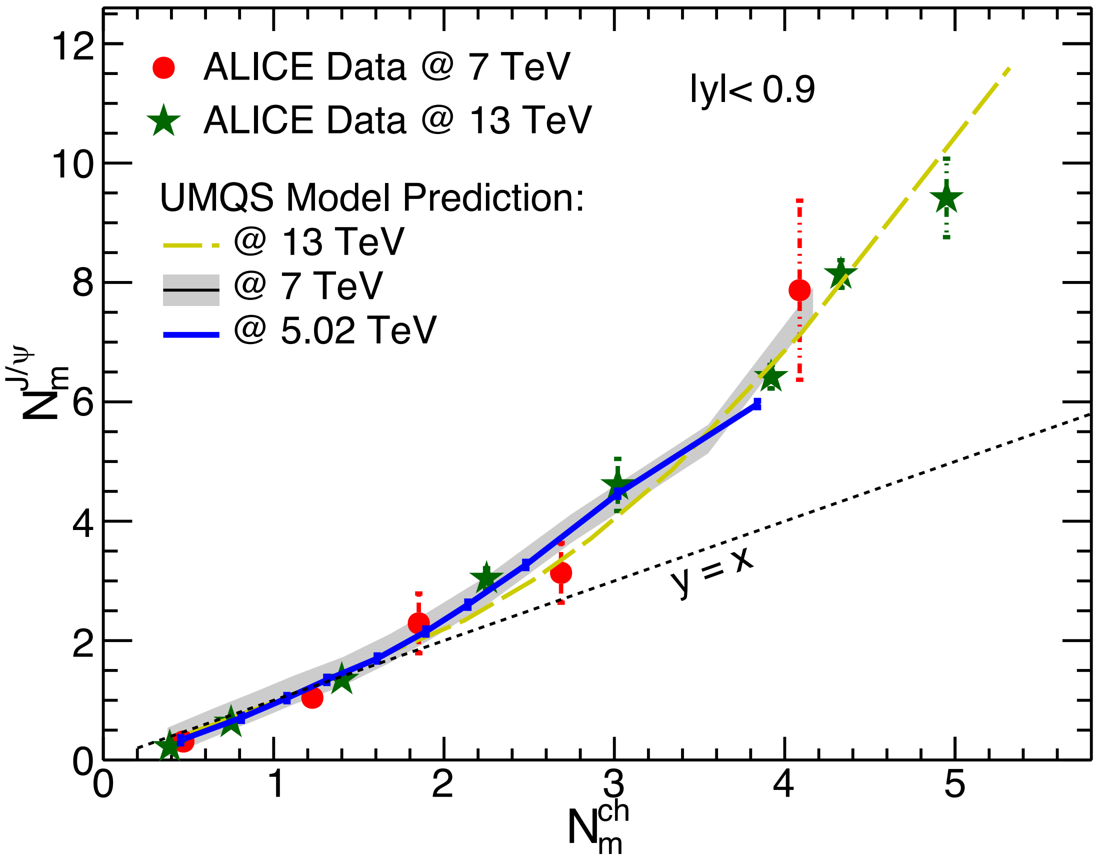
CMS, JHEP 1009:091,2010



- The collective flow of strongly interacting matter gives rise to an azimuthally collimated long-range (large $\Delta\eta$), near-side (small $\Delta\varphi$) ridge-like structure in two-particle azimuthal correlations.
- It was first observed at the RHIC in Cu–Cu and Au–Au collisions and later at the LHC in Pb–Pb collisions.
- Most of the pQCD based models fail to explain the ridge formation.
- Belle at KEK has reported no ridge-like structure in e^+e^- collisions at 10.52 GeV

- Observation of ridge structure in high-multiplicity pp collisions: a feature seen in heavy-ion collisions possibly due to collectivity

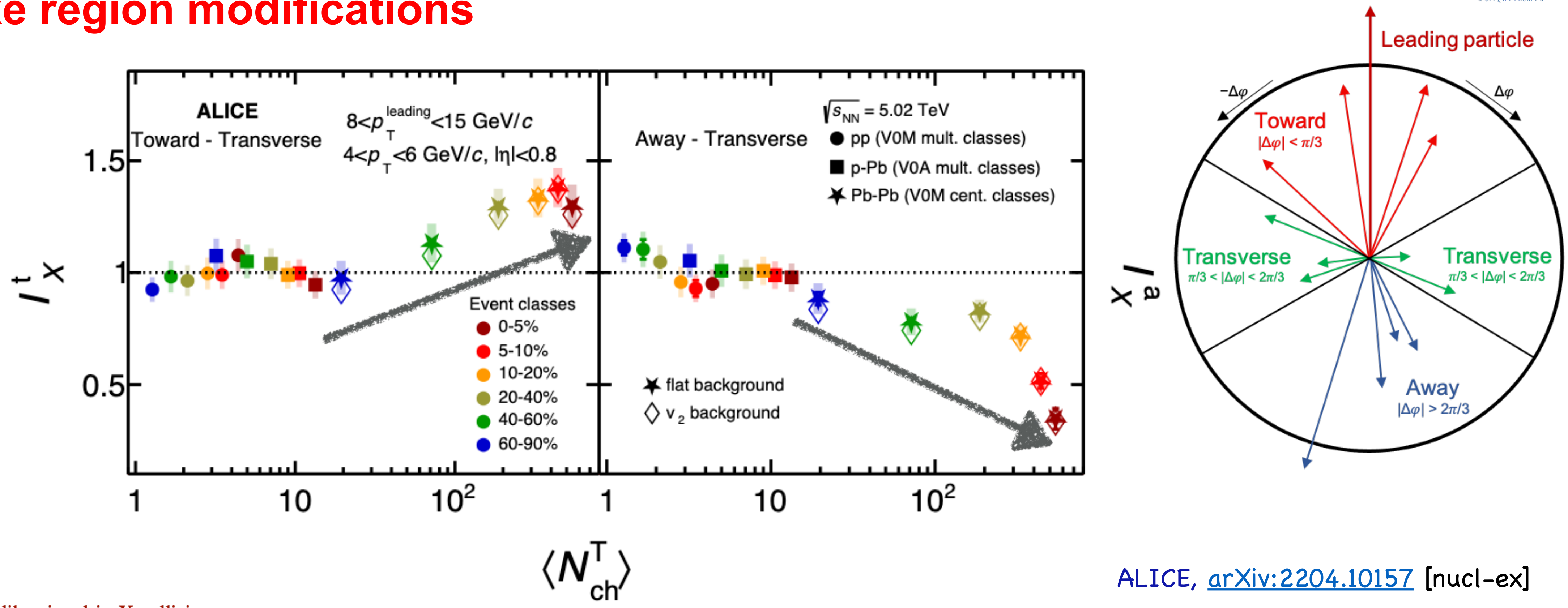
UMQS model explains ALICE J/ψ production



- ✓ J/ψ self-normalized yield as a function of self-normalized multiplicity follows a scaling across collision energies.
- ✓ UMQS model which incorporates the suppression of J/ψ through color screening, gluonic dissociation, and collision damping and regeneration of charmonium due to correlated c – cbar pairs.

C.R. Singh, S. Deb, R. Sahoo, J. Alam, Eur. Phys. J. C, 82(6):542, 2022

Jet-like region modifications

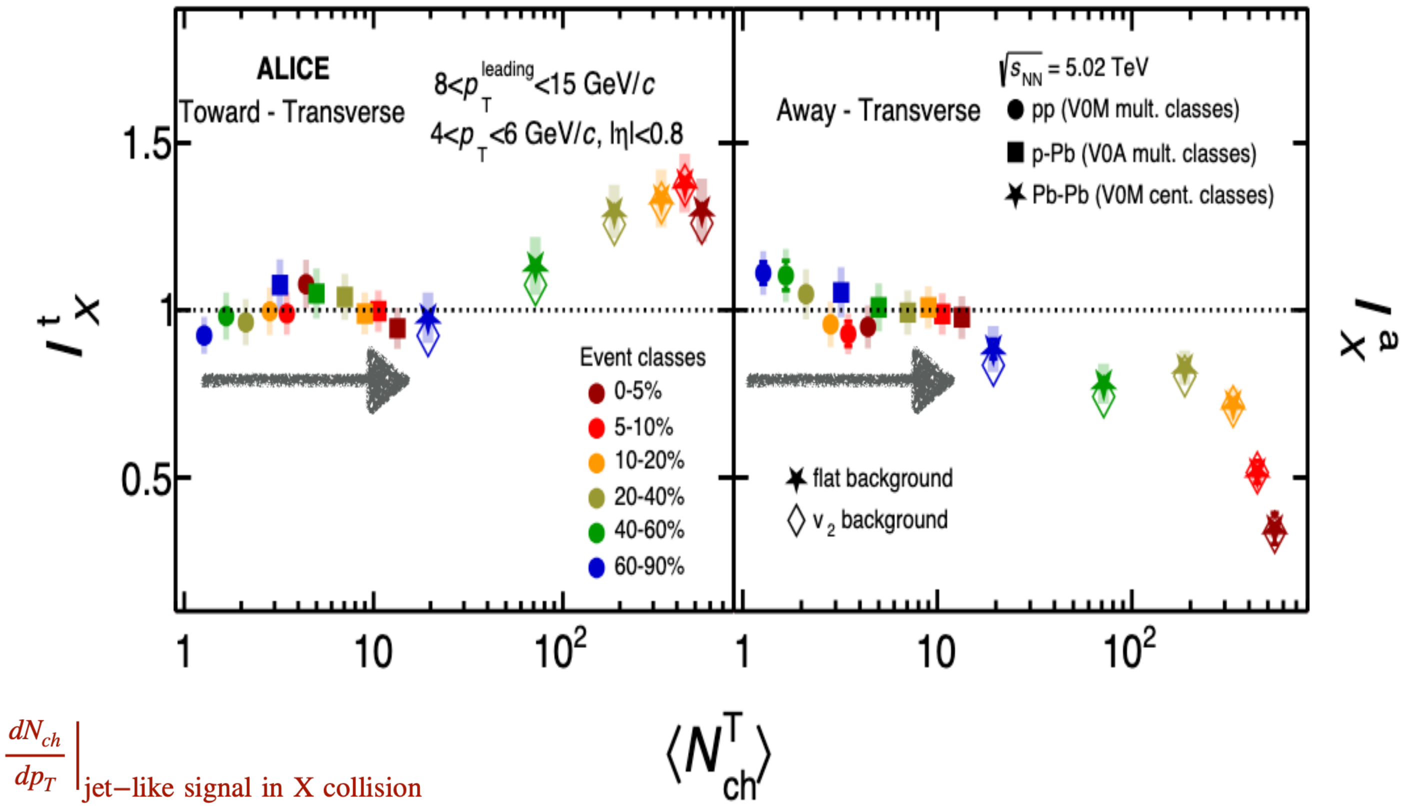


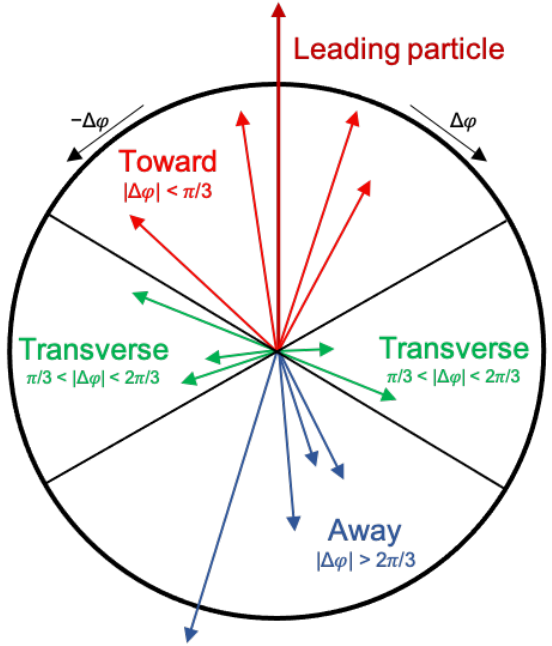
ALICE, arXiv:2204.10157 [nucl-ex]

$$I_X = \frac{\left.\frac{dN_{ch}}{dp_T}\right|_{\text{jet-like signal in X collision}}}{\left.\frac{dN_{ch}}{dp_T}\right|_{\text{jet-like signal for MB pp collision}}}$$

- Pb–Pb collisions: I_X values in the toward (away) region exhibit an enhancement (suppression) relative to MB pp with $\langle N_{ch}^{T}\rangle$

Jet-like region modifications





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$$I_X = \frac{\left.\frac{dN_{ch}}{dp_T}\right|_{\text{jet-like signal in X collision}}}{\left.\frac{dN_{ch}}{dp_T}\right|_{\text{jet-like signal for MB pp collision}}}$$

- pp and p–Pb collisions: Absence of jet-like modifications

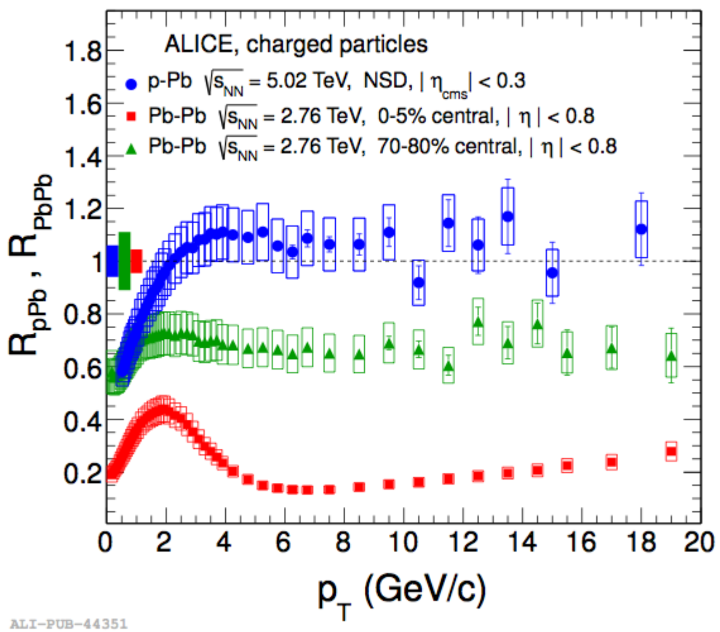
Opacity of the QGP and nuclear modification factor

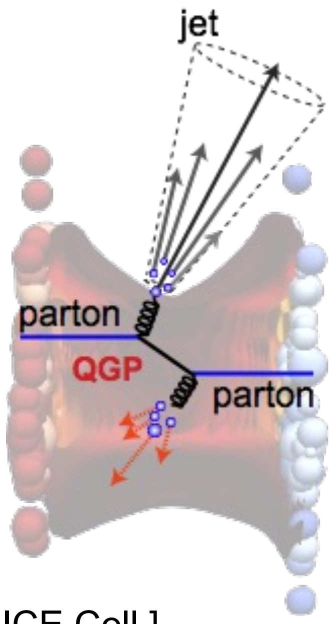
- Estimate the opacity of the created medium

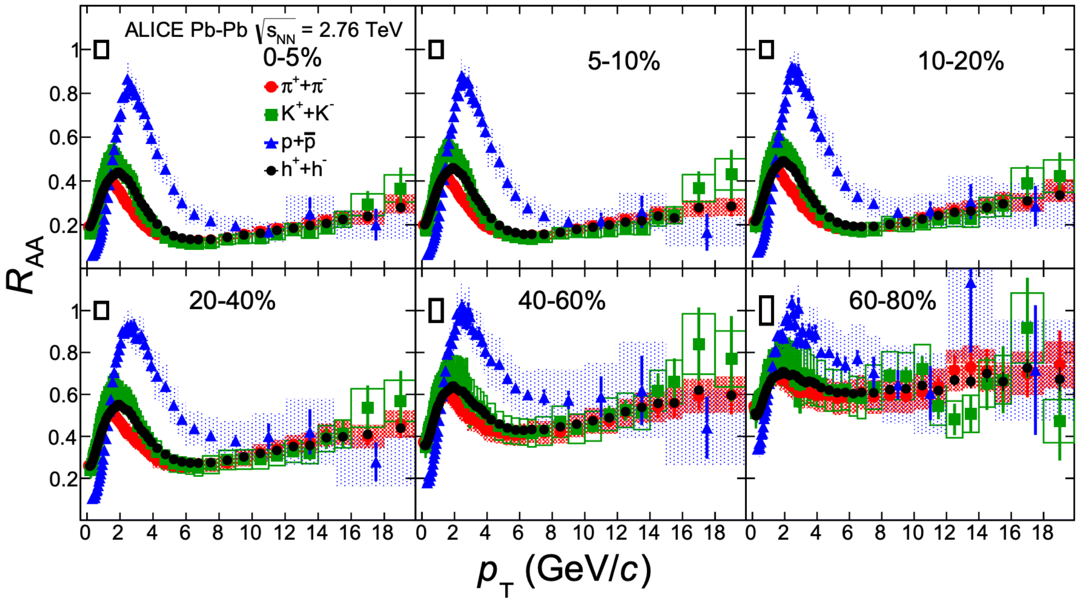
  R_{AA} is called the nuclear modification factor

  R_{AA} equals unity means no modification at all

$$R_{AA} = \frac{AA}{\text{rescaled pp}} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$







Phys. Rev. Lett. 110 (2013) 082302 [ALICE Coll.]

Phys. Rev. C 93 (2016) 034913 [ALICE Coll.]

strong suppression (quenching) in Pb-Pb collisions

p-Pb collisions is a control experiment for the nuclear modification factor

pp collisions are considered as a baseline

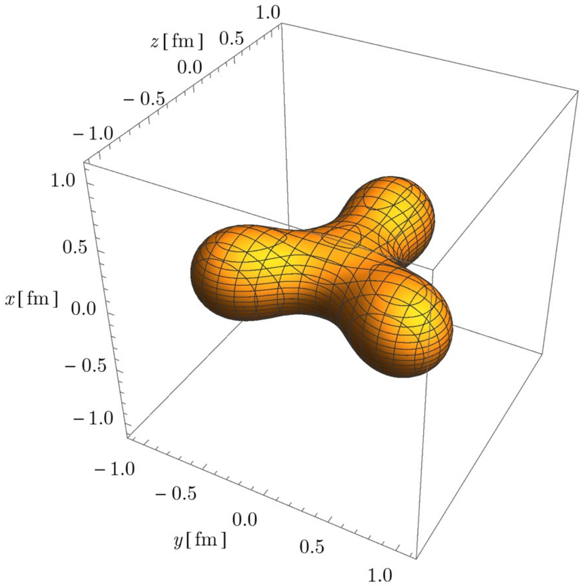
first clear particle mass and centrality dependence energy loss in the medium

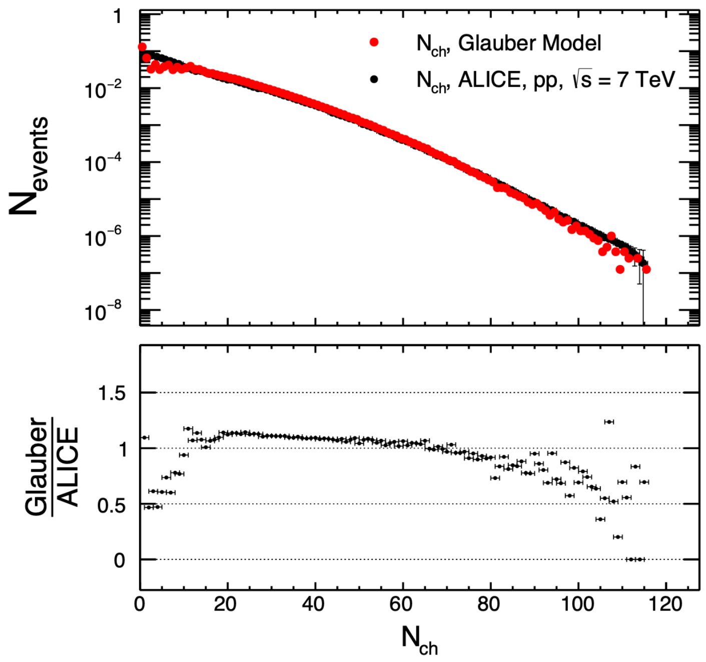
Proton as a composite object

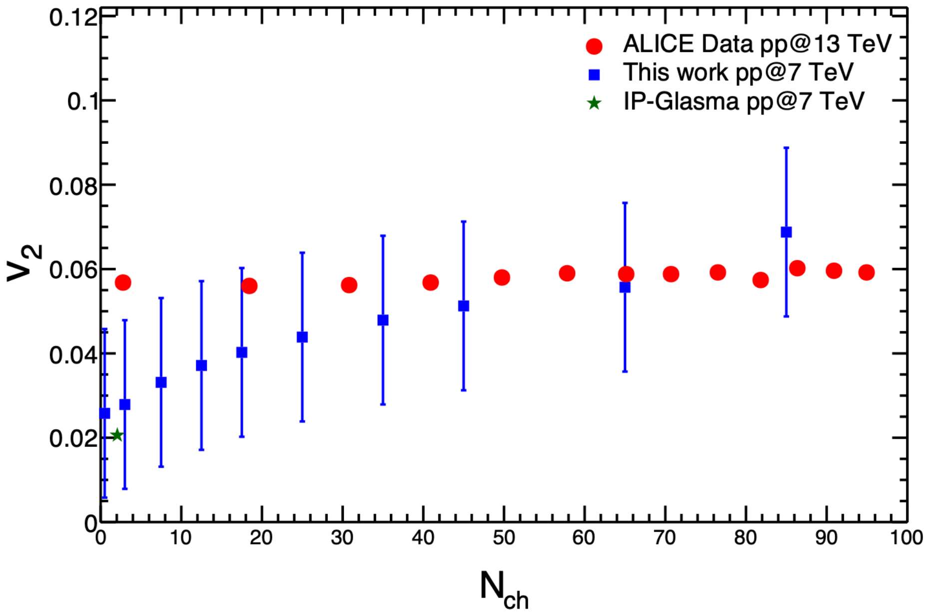
Anisotropic and inhomogeneous density profile of proton

$$\rho_{G-f}(\mathbf{r};\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = N_g\frac{1-\kappa}{3}\sum_{k=1}^{3}\rho_q(\mathbf{r}-\mathbf{r}_k;r_q) + N_g\frac{\kappa}{3}\sum_{k=1}^{3}\rho_g[\mathcal{R}^{-1}[\theta_k,\phi_k](\mathbf{r}-\frac{\mathbf{r}_k}{2};r_q,\frac{r_k}{2}]$$

Quarks | Gluons



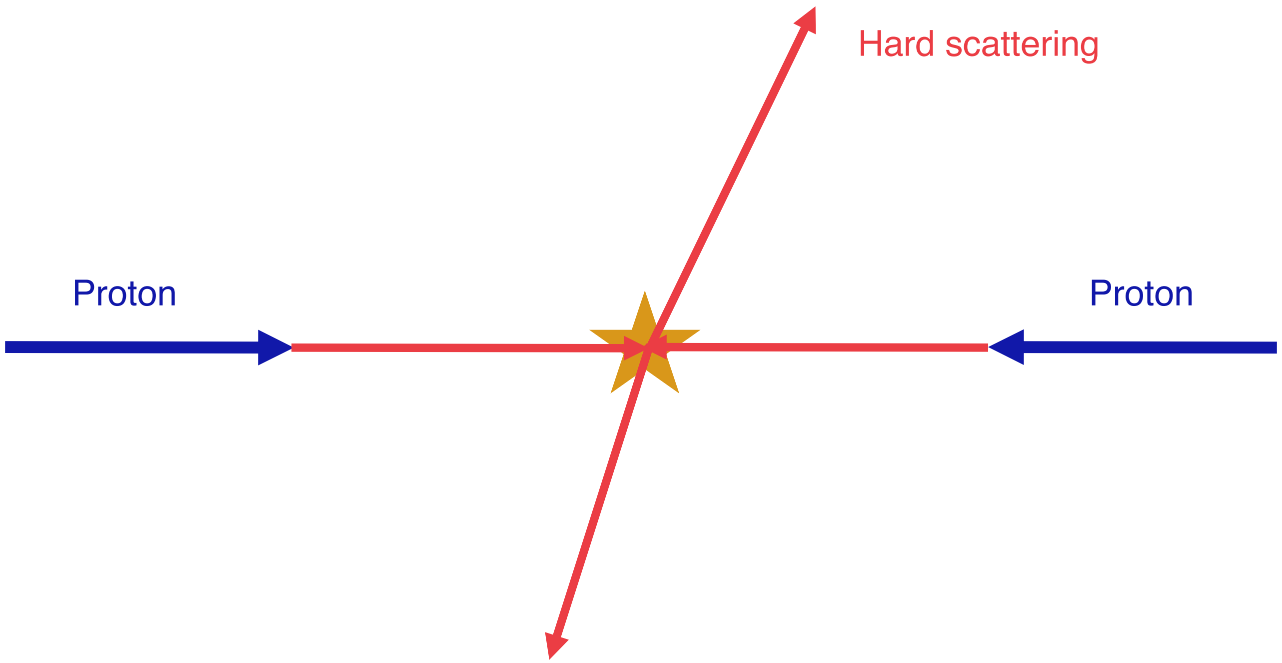




S.Deb, G. Sarwar, D. Thakur, Pavish S., R. Sahoo, J Alam, Phys. Rev. D 101, 014004 (2020)

A hypothetical picture of Proton collisions at TeV energies

Hard scattering: perturbative QCD



A hypothetical picture of Proton collisions at TeV energies

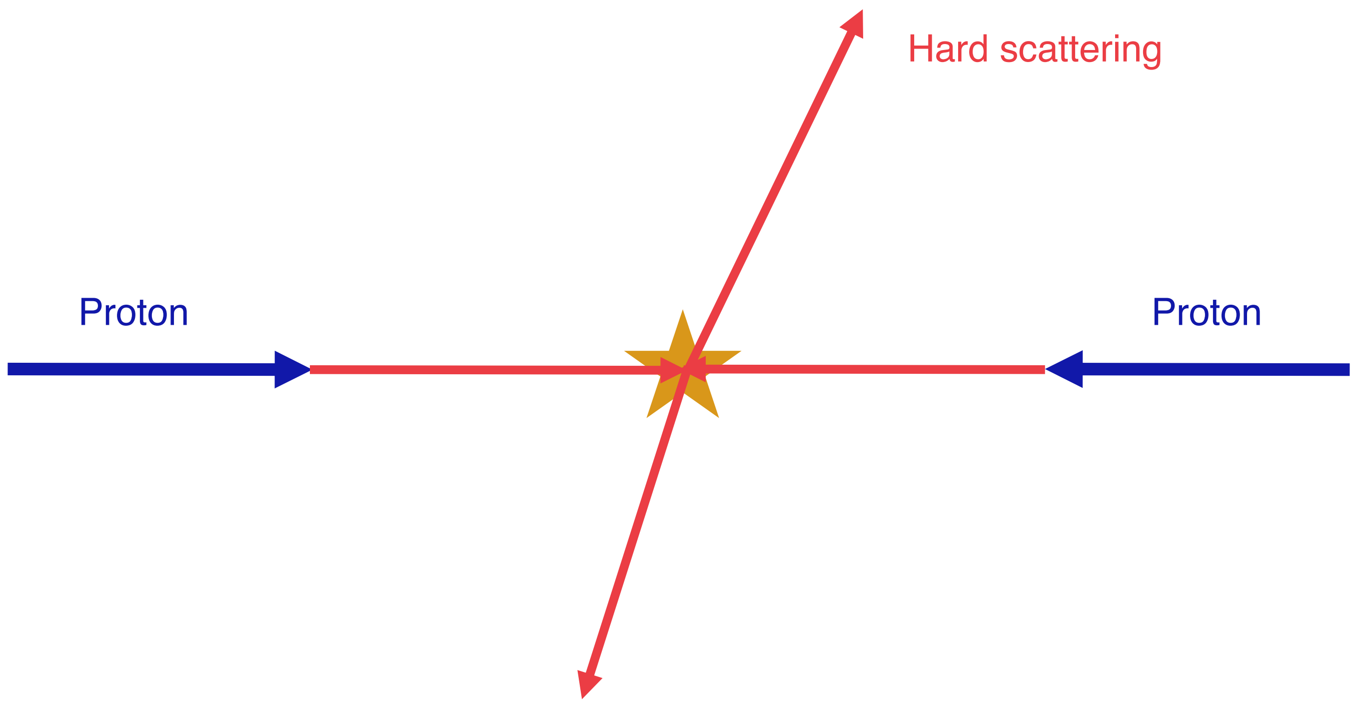
Hard scattering: perturbative QCD

Soft QCD processes:

low transverse momenta
→ non-perturbative QCD

Includes:

- Underlying Event (UE)



A hypothetical picture of Proton collisions at TeV energies

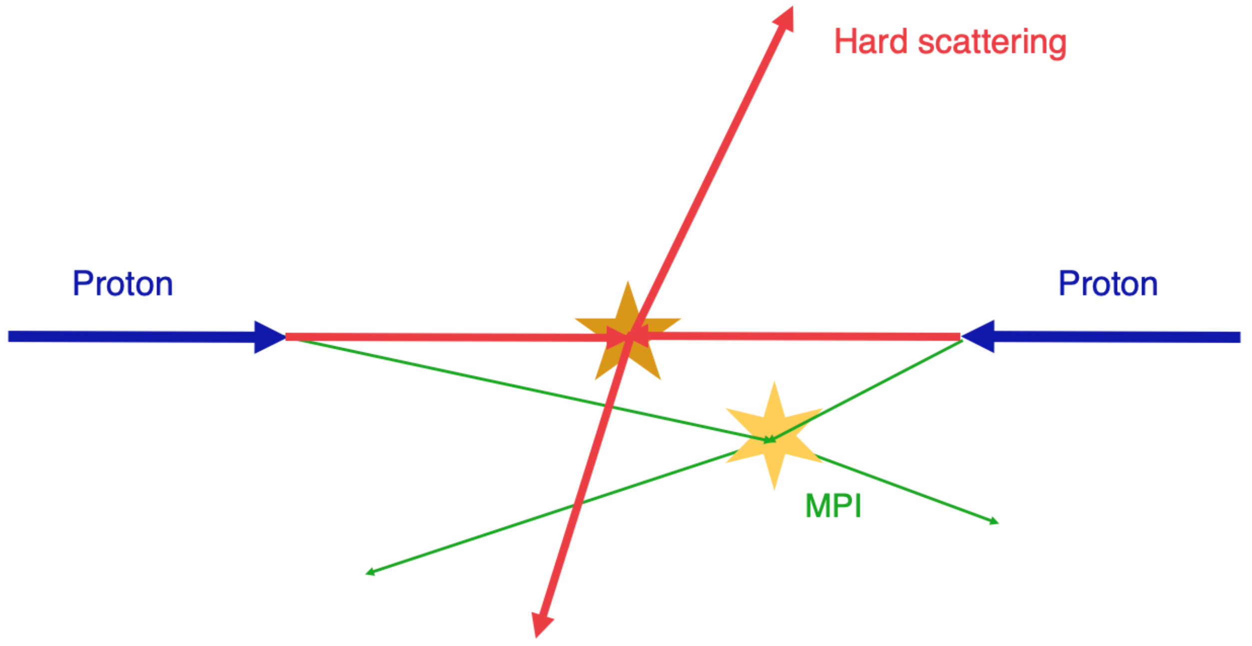
Hard scattering: perturbative QCD

Soft QCD processes:

low transverse momenta
→ non-perturbative QCD

Includes:

- Underlying Event (UE)
  - Multiparton interactions (MPI)



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Hard scattering: perturbative QCD

Soft QCD processes:

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Includes:

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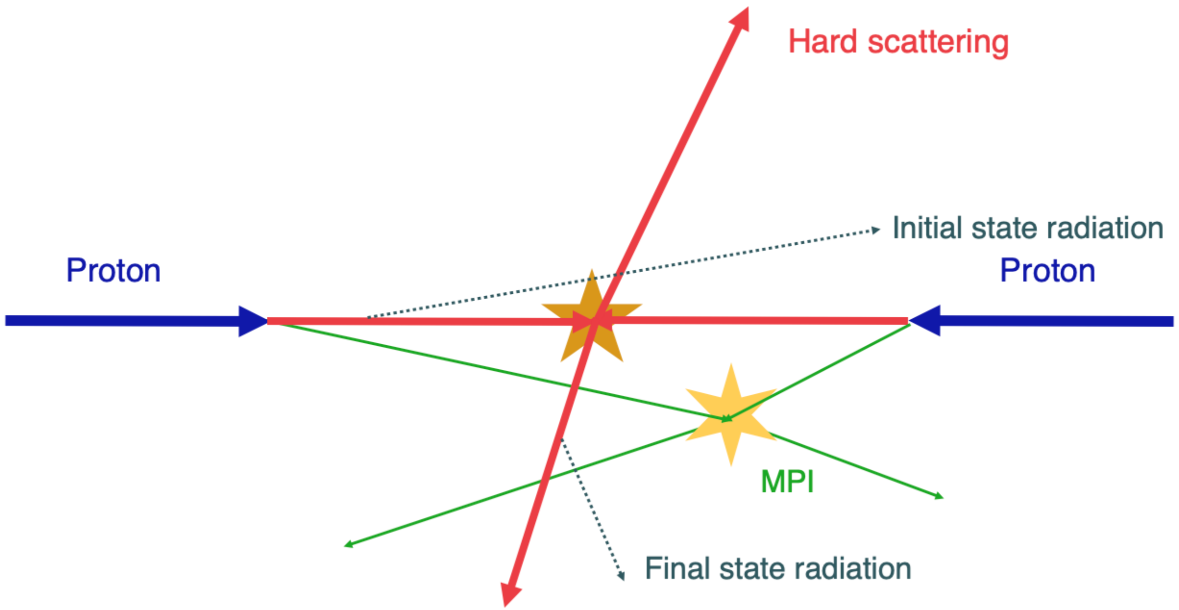
  - Initial- and final-state radiation



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Soft QCD processes:

low transverse momenta
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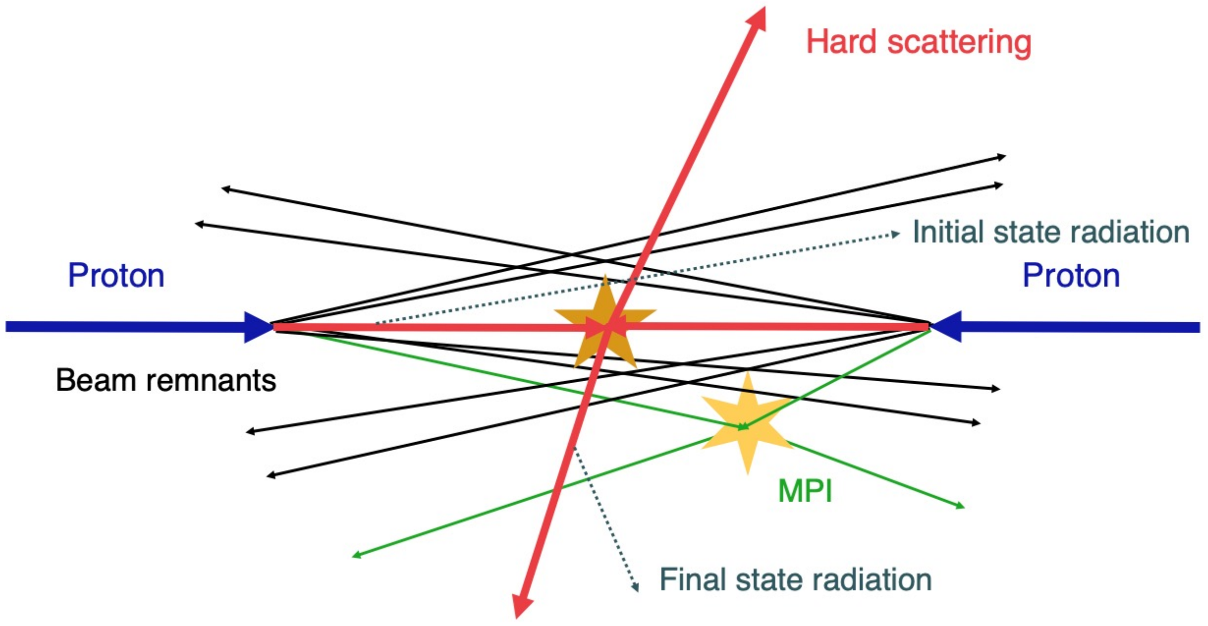
Includes:

- Underlying Event (UE)
  - Multiparton interactions (MPI)
  - Initial- and final-state radiation
  - Beam remnants



A hypothetical picture of Proton collisions at TeV energies

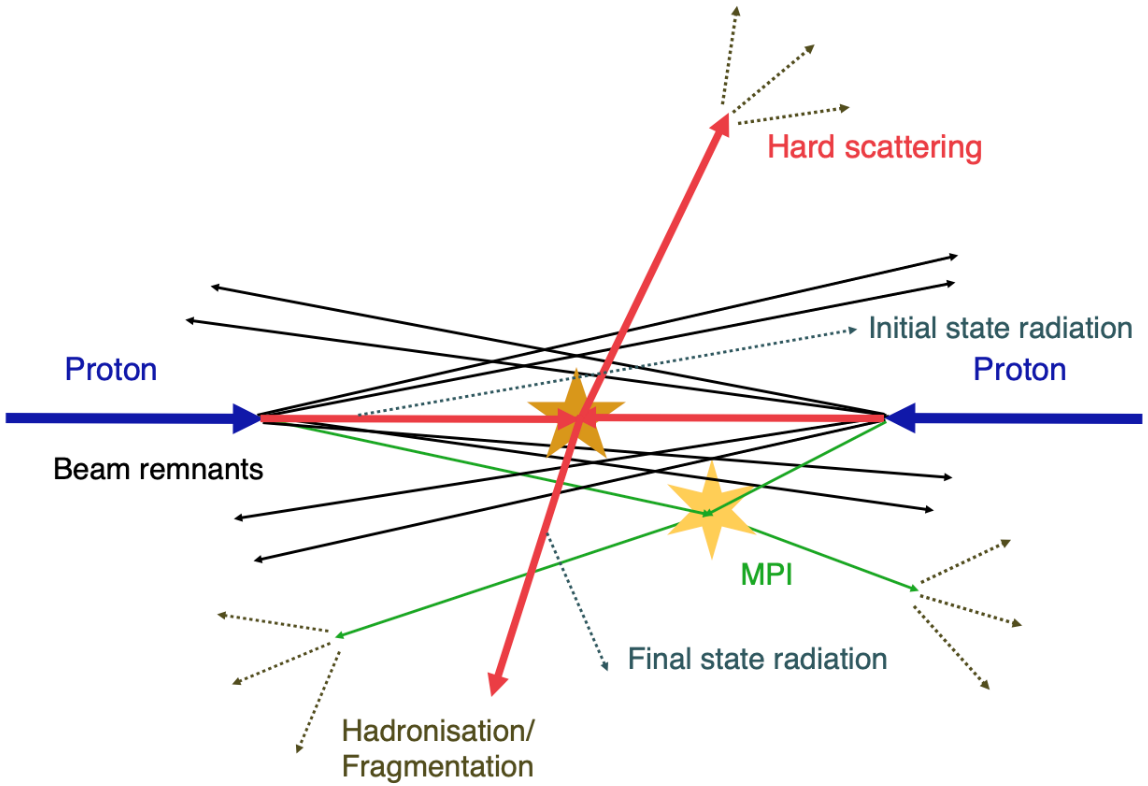
Hard scattering: perturbative QCD

Soft QCD processes:

low transverse momenta
→ non-perturbative QCD

Includes:

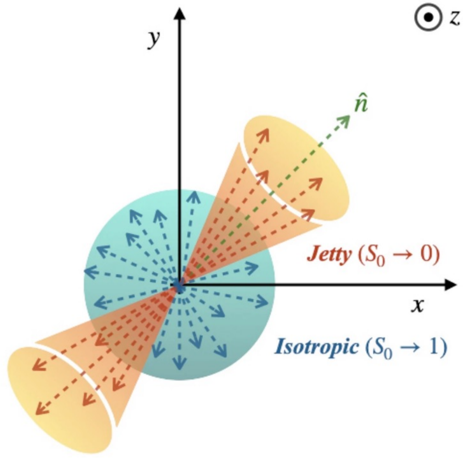
- Underlying Event (UE)
  - Multiparton interactions (MPI)
  - Initial- and final-state radiation
  - Beam remnants
- Hadronisation products
- Collective effects

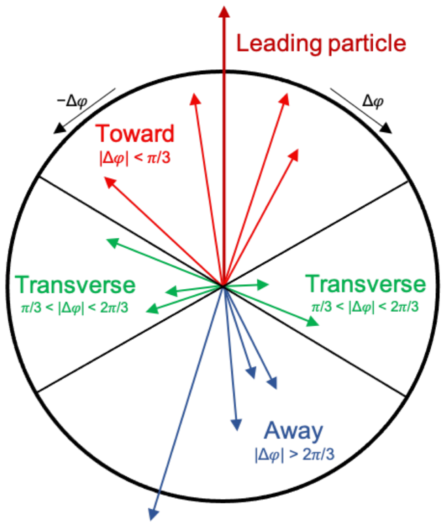


QGP droplets in small systems?

- Measurements at the LHC have revealed that small collision systems exhibit collective-like behavior, formerly thought to be achievable only in heavy-ion collisions, where the data support the formation of QGP.
- Traditionally, small collision systems are used as a baseline for the study of the possible formation of QGP in heavy-ion collisions.
- The origin of the collective-like behavior in small systems is still unclear. To understand one can isolate different physics regimes (soft and hard physics) using event shape observables:

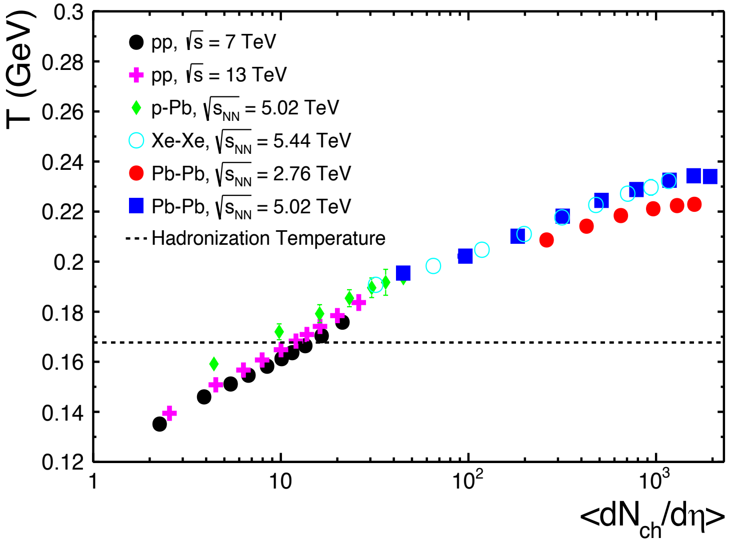
  ✓ Relative Transverse Activity Classifier (R_T)
  ✓ Transverse Spherocity (S_0)
  ✓ Spericity
  ✓ Flatenicity



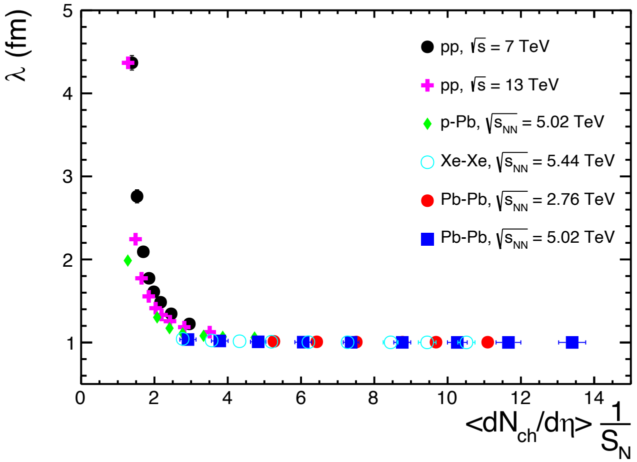


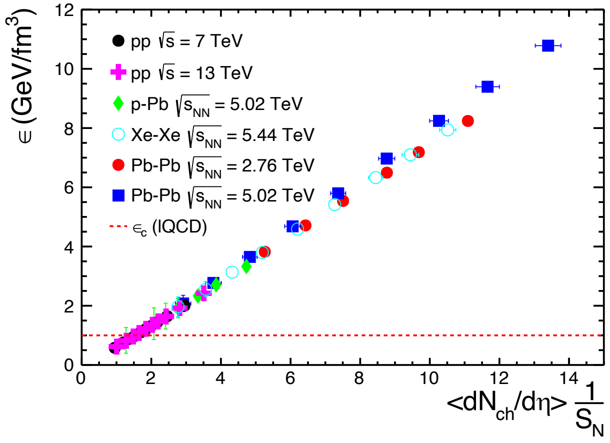
S. Prasad, N. Mallick, D. Behera, R. Sahoo, S. Tripathy, Sci. Rep. 12 (2022) 1, 3917
A. Khuntia, S. Tripathy, A. Bisht and R. Sahoo, J.Phys.G 48 (2021) 3, 035102.
G. Bencedi, A. Ortiz, S. Tripathy, J.Phys.G 48 (2020) 1, 015007

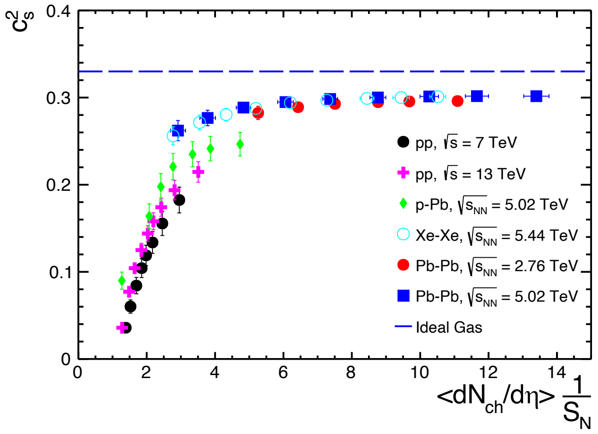
Important results based on Color String Percolation

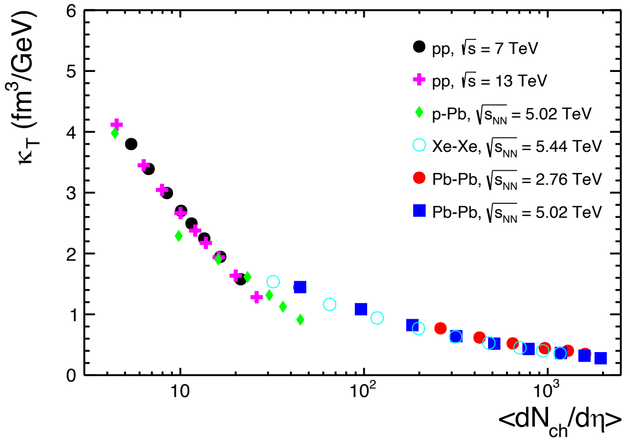


D. Sahu, S. Tripathy, R. Sahoo and S. K. Tiwari, Eur. Phys. J. A 58, 78 (2022)









$$\lambda = \frac{1}{n\sigma} = \frac{L}{(1-e^{-\xi})}$$

$$\epsilon = \frac{3}{2}\frac{dN_{\rm ch}/dy\langle m_{\rm T}\rangle}{S_{\rm N}\tau_{\rm pro}}$$

$$c_{\rm s}^2 = -0.33\left(\frac{\xi e^{-\xi}}{1-e^{-\xi}} - 1\right) + 0.0191(\Delta/3)\left(\frac{\xi e^{-\xi}}{(1-e^{-\xi})^2} - \frac{1}{1-e^{-\xi}}\right)$$

$$\kappa_{\rm T} = -\frac{1}{V}\frac{\partial V}{\partial S_{\rm N}}\frac{\partial S_{\rm N}}{\partial P} \implies \kappa_{\rm T} = \frac{\tau_{\rm pro}S_{\rm N}}{\langle m_{\rm T}\rangle dN_{\rm ch}/dy}$$

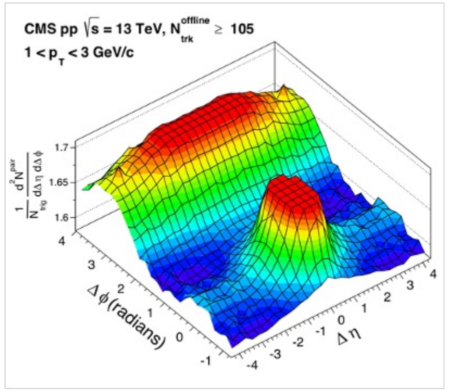
D. Sahu and R. Sahoo, J. Phys. G 48, 125104 (2021)

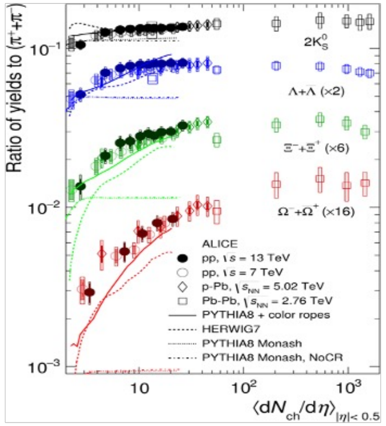
D. Sahu, S. Tripathy, R. Sahoo and S. K. Tiwari, Eur. Phys. J. A 58, 78 (2022)

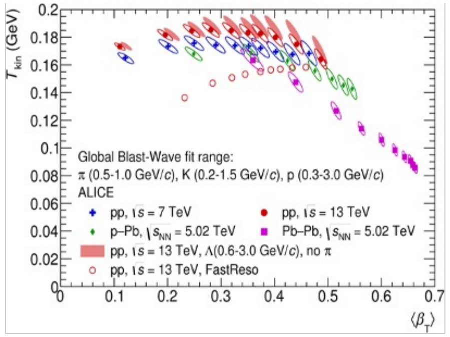
TeV pp collisions and QGP droplets

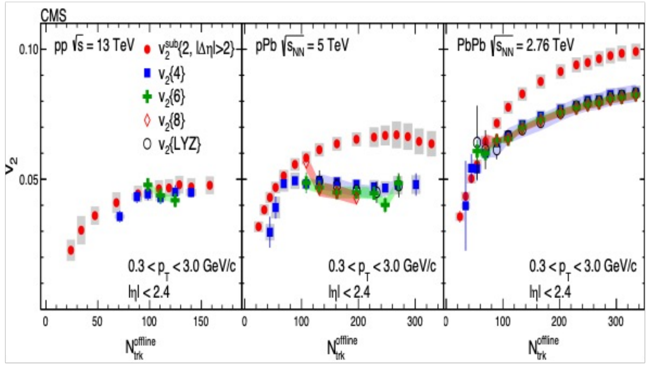
Observed:

- ❖ Enhancement of strangeness
- ❖ Hardening of particle spectra: T_{kin}, radial flow like HIC
- ❖ Collectivity in small systems
- ❖ Long-range correlation







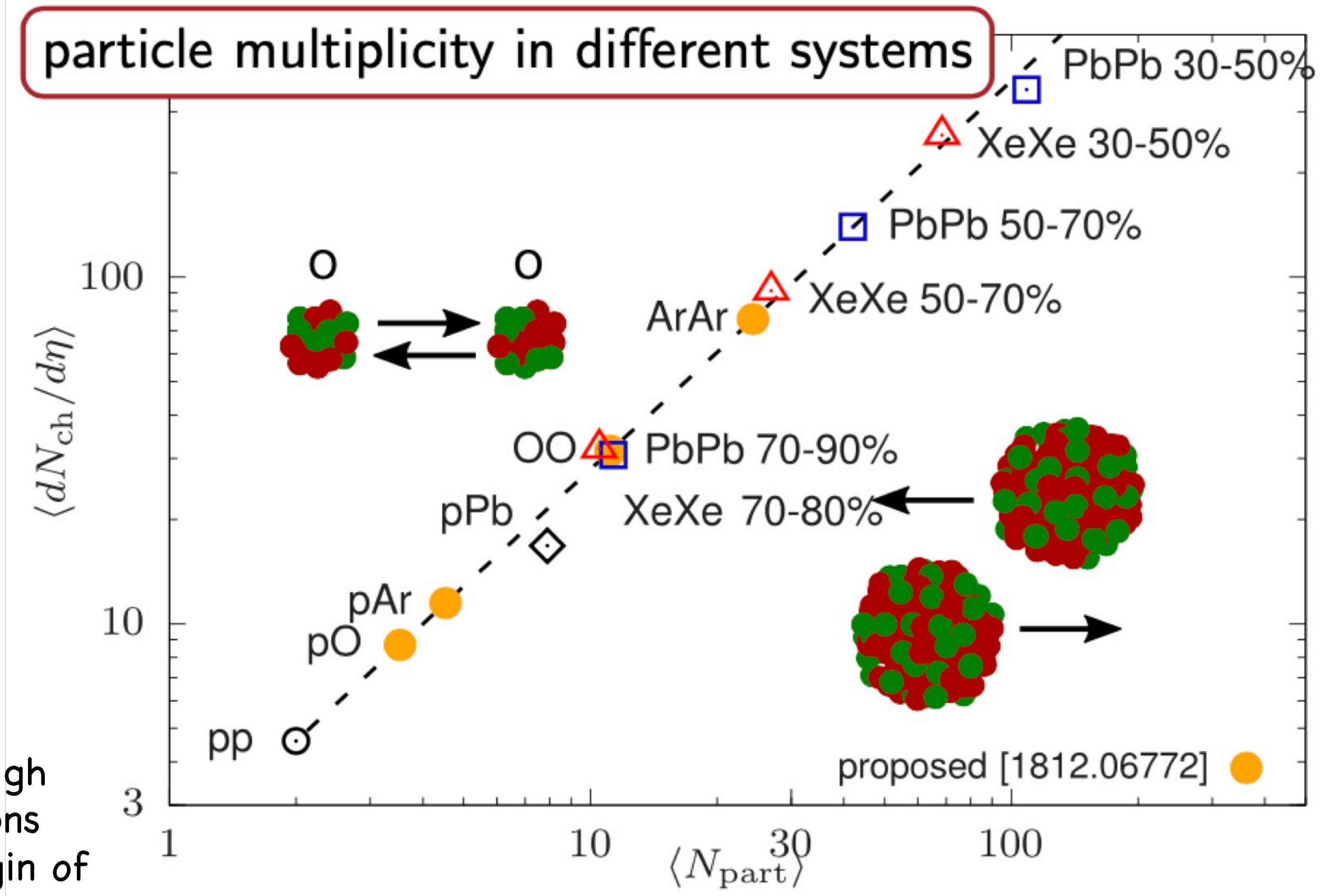


Yet to be explored:

- ➢ Quarkonia supression
- ➢ Jet quenching etc.

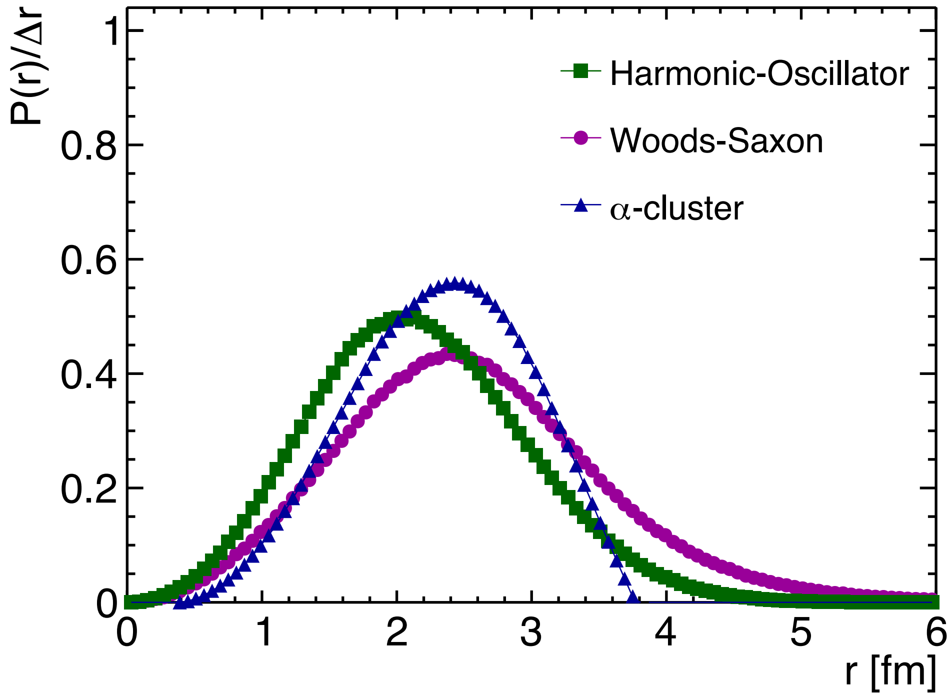
R. Sahoo, AAPPS Bulletin (2019)
R. Sahoo, T. Nayak, Current Science (2021)

Oxygen-Oxygen Collisions@LHC

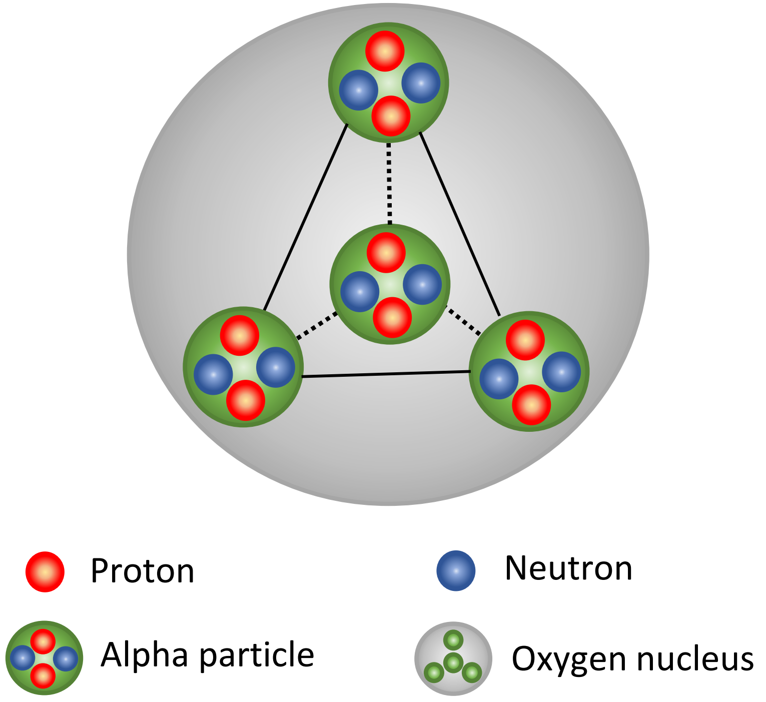


- System size of Oxygen overlaps between high multiplicity pp and peripheral Pb-Pb collisions
- Provides an opportunity to explore the origin of flow-like signatures in small systems
- Probe the α-cluster tetrahedral structure of oxygen nucleus

Nuclear density profile of Oxygen



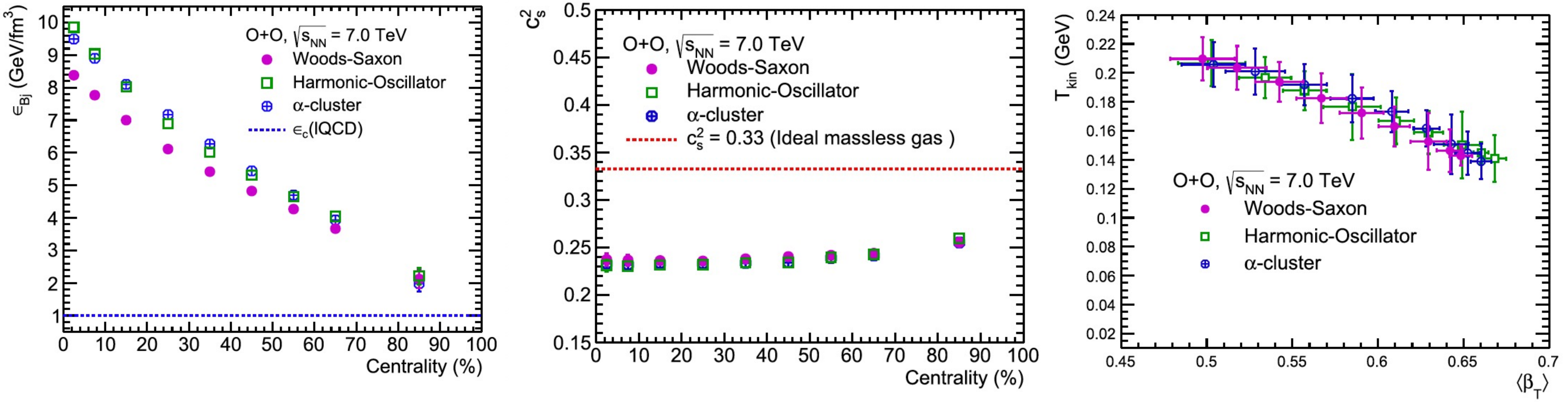
Probability of the radial positions of the nucleons in oxygen (O^{16})



Depiction of α-clustered structure in oxygen nucleus

D. Behera, N. Mallick, S. Tripathy, S. Prasad, A.N. Mishra, and R. Sahoo, Eur. Phys. J. A , 58, 175 (2022)

Global properties: Oxygen collisions

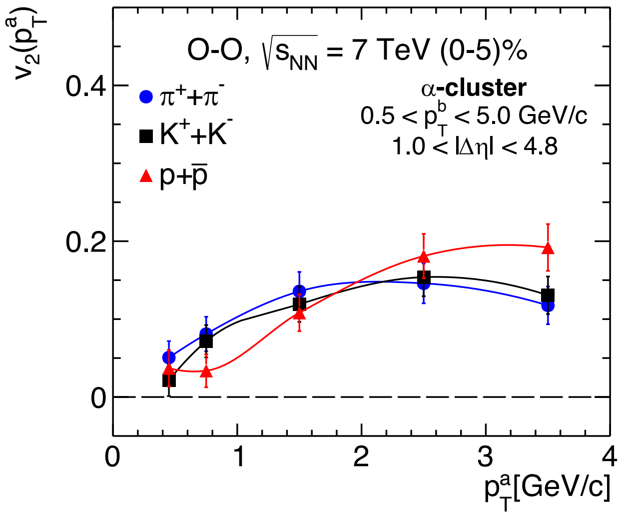


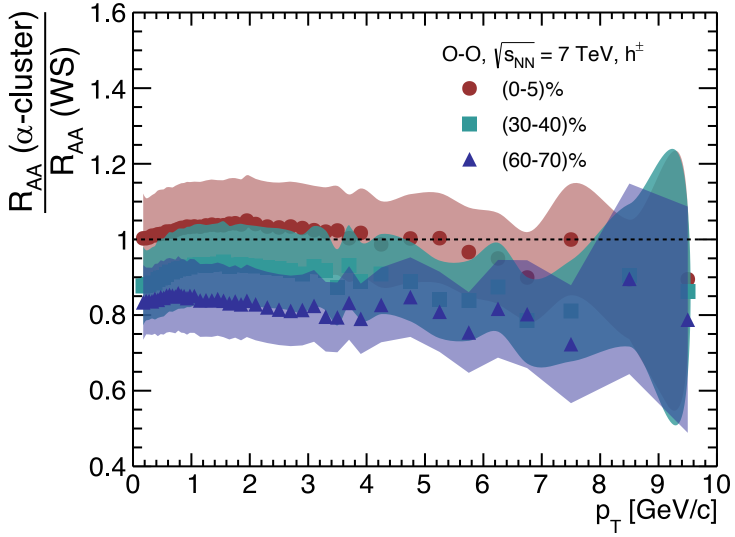
- ❖ The initial energy density for a de-confinement transition is 1 GeV/c (lQCD)
- ❖ Both α-cluster and harmonic-oscillator density profiles show 15% higher energy density than the Woods-Saxon density profile
- ❖ The speed of sound is independent of the density profiles and below the ideal gas limit

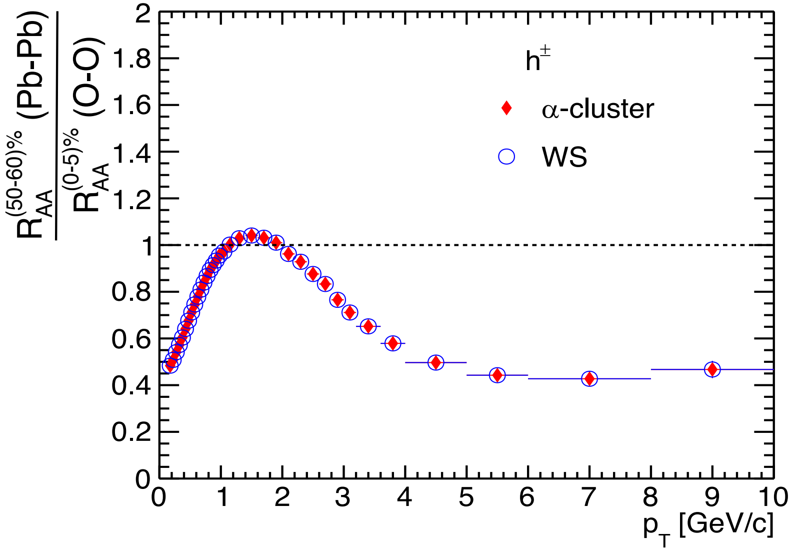
D. Behera, N. Mallick, S. Tripathy, S. Prasad, A.N. Mishra, R. Sahoo, Eur. Phys. J A 58, 175 (2022)

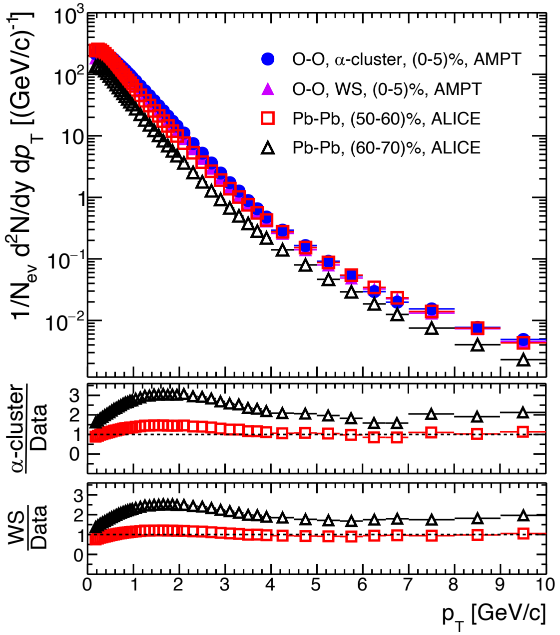
Some detailed studies: Oxygen collisions

Elliptic flow in O-O collisions and NCQ-scaling:
D. Behera, S. Prasad, N. Mallick and R. Sahoo, [arXiv:2304.10879]









Demystifying nuclear modification factor in O-O collisions:
D. Behera, S. Deb, C. R. Singh and R. Sahoo, [arXiv:2308.06078]

Summary and Outlook

- Small collision systems: much more than just a reference!
- Strangeness enhancement and collective-like effects are seen for high multiplicity pp and p-Pb which are reminiscent of effects observed in heavy-ion collisions. No jet-like component modifications are observed for small systems yet
- Multi-differential studies with event shape observables such as relative transverse activity classifier, transverse spherocity and flattenicity help to distinguish soft and hard events at the Large Hadron Collider
- Observation of a threshold in the final state multiplicity for QGP-like behavior
- Small system QGP a way ahead: Oxygen collisions at the LHC

For the Physics results of Run 1 and Run 2:
The ALICE experiment --
A journey through QCD:
arXiv:2211.04384

Thank you for your attention !