



Understanding the formation of a deconfined medium in small collision systems at the Large Hadron Collider

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[India-JINR workshop on elementary particle and nuclear physics, and condensed matter research](#)



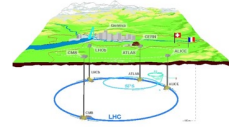
Outline

- The search for Quark-gluon plasma (QGP) at the LHC
- High-multiplicity pp collisions and a hint of QGP
- Proton is an extended object at GeV/TeV energies
- Event topology studies
- Some expected results from the proposed O-O collisions
- Challenges in hand
- Summary and Outlook



The Large Hadron Collider (LHC)

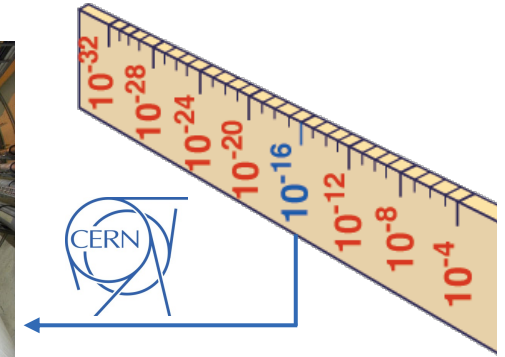
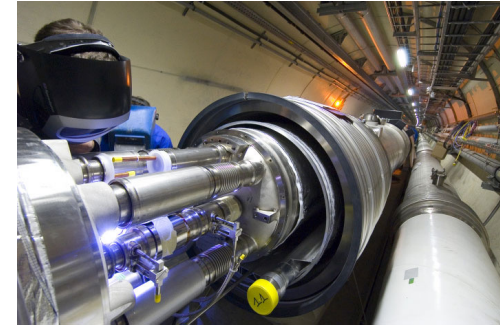
- ❖ The LHC is currently the largest and most powerful proton and ion collider.



~100 m underground & 27 km circ.

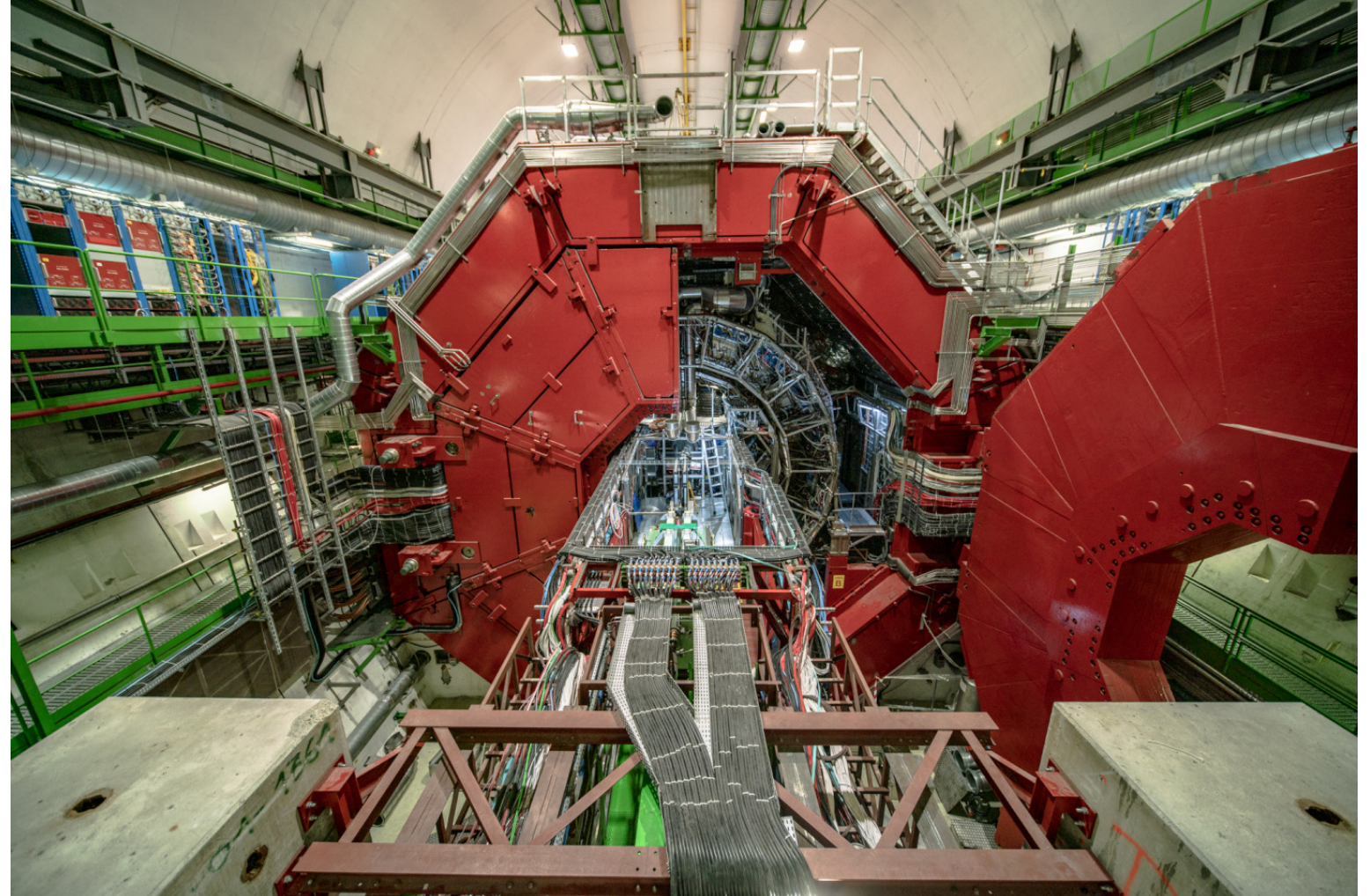
System	Year	Centre of mass energy (TeV)	Integrated luminosity
Pb-Pb	2010, 2011	2.76	75 mb ⁻¹
	2015, 2018 2023	5.02 6.8	800 mb ⁻¹
Xe-Xe	2017	5.44	0.3 mb ⁻¹
p-Pb	2013	5.02	15 nb ⁻¹
	2016	5.02, 8.16	3 nb ⁻¹ , 25 nb ⁻¹
p-p	2009-2013	0.9, 2.76, 7, 8	200 mb ⁻¹ , 100 nb ⁻¹ , 1.5 pb ⁻¹ , 2.5 pb ⁻¹
	2015, 2017	5.02	1.3 pb ⁻¹
	2015-2018	13	136 pb ⁻¹
	2022-2023	13	30 pb ⁻¹
		13.6	

Big Bang





ALICE - The experimental set-up

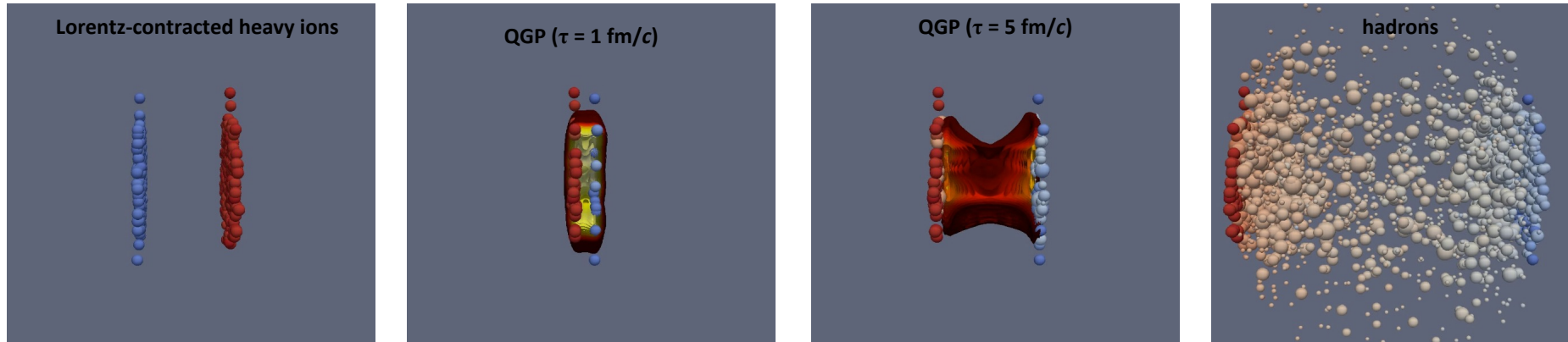


16 m x 16 m x 25 m, ~10 000 t.



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

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



Simulation: MADAI.us

QGP \rightarrow 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: $\sim 2\,000$ billion degrees

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

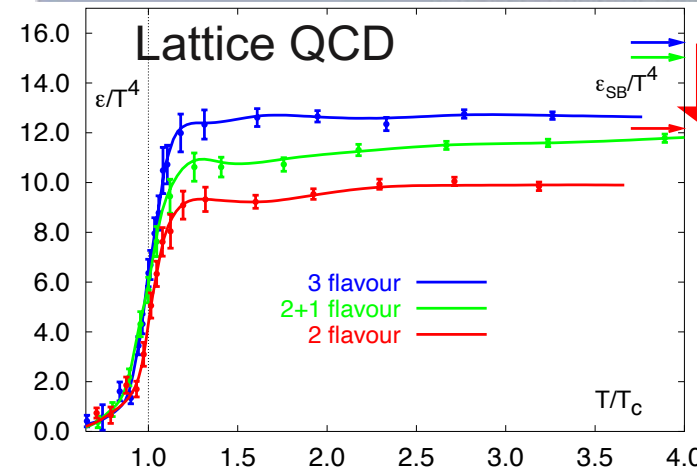
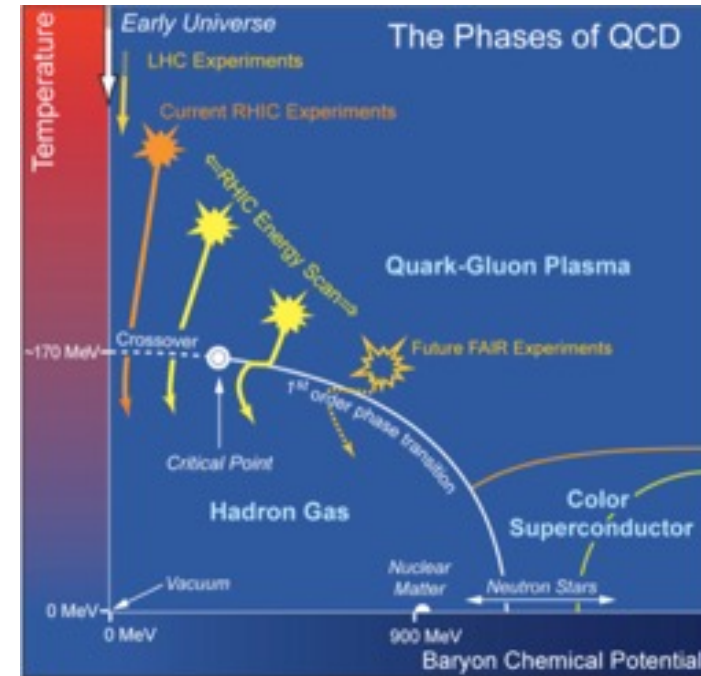
similar conditions are thought to have existed about $10\ \mu\text{s}$ after the Big Bang

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: $O(10^{12} \text{ K})$.
 - vanishing baryon chemical potential: equal number of baryons and anti-baryons
- Phase transition predicted by Lattice QCD calculations (state of the art):
 - $T_c \approx 155 \text{ MeV}$ and $\epsilon_c \approx 0.5-1.0 \text{ GeV/fm}^3$
- Study the properties of a state where quarks and gluons are deconfined (QGP).

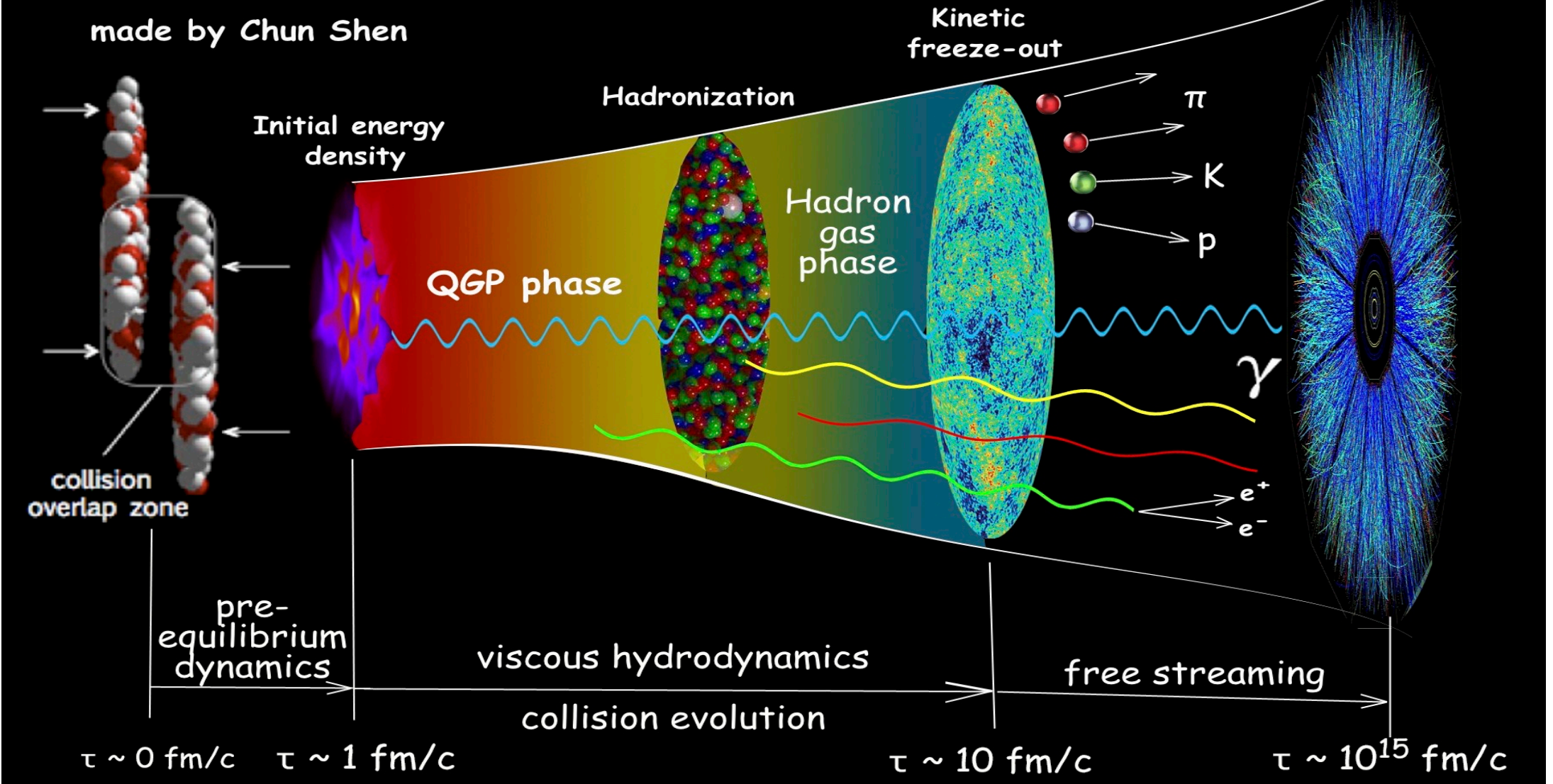


F. Karsch, Nucl. Phys. A 698, 199 (2002).



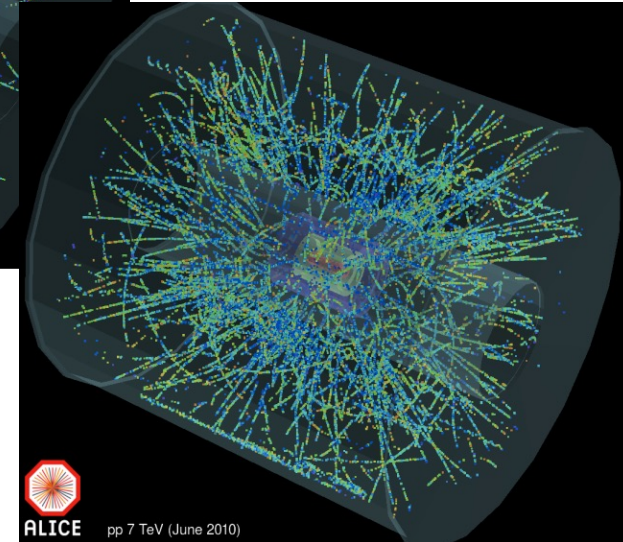
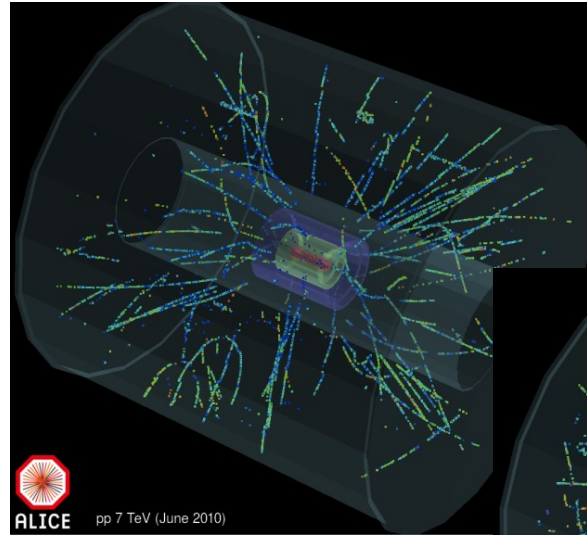
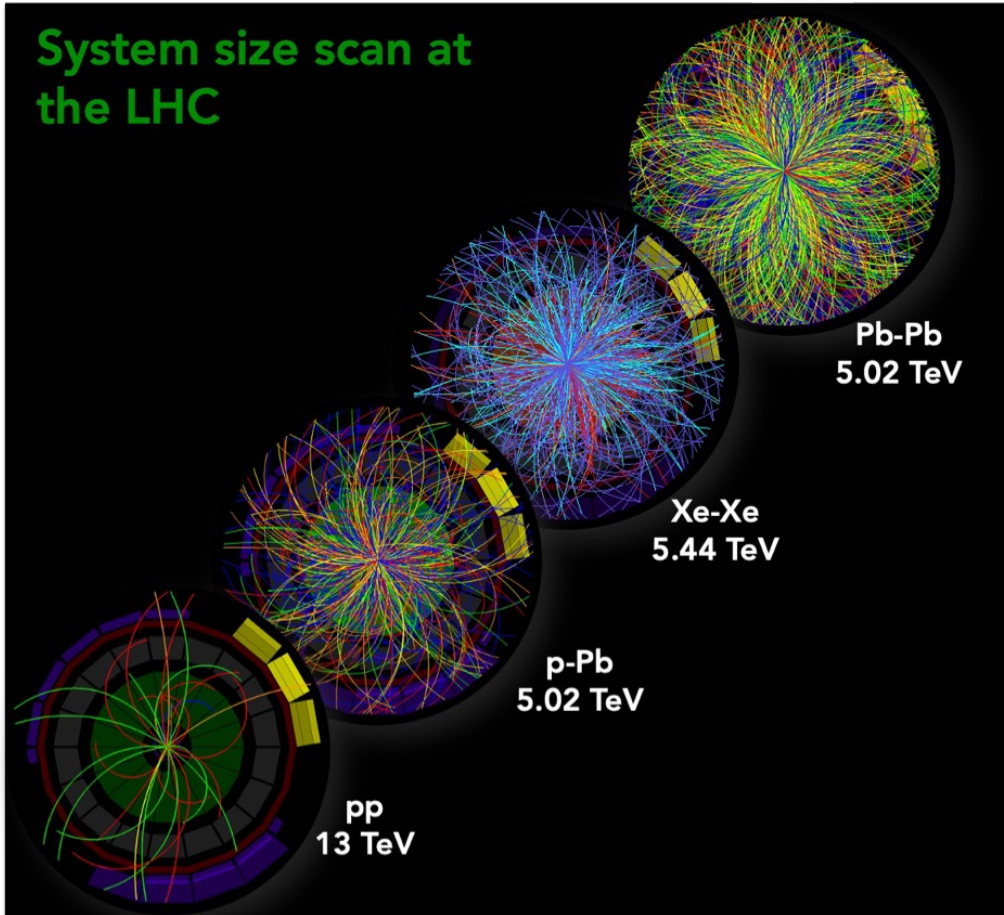
Relativistic Heavy-Ion Collisions

made by Chun Shen





Limit of QGP formation at the LHC



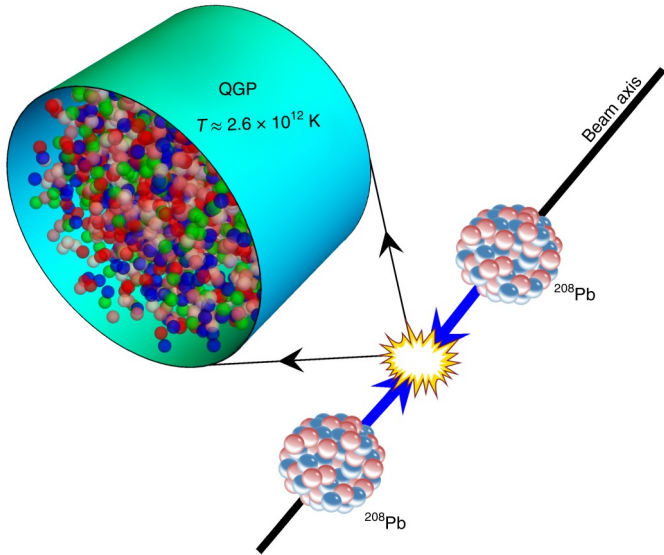
- Rare pp and p-Pb collisions can produce very large numbers of hadrons. i.e. high multiplicities
- Do they create QGP?



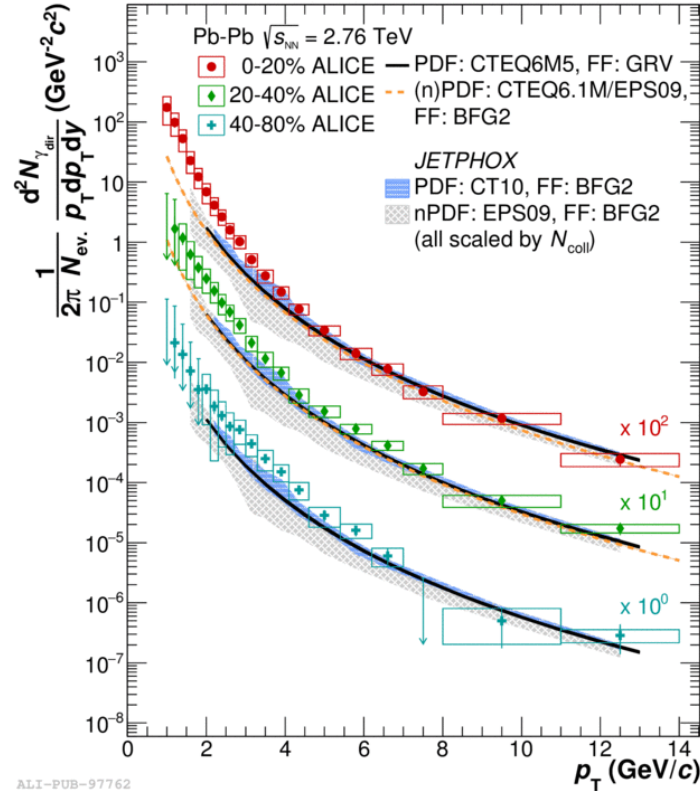
Heavy-ion collisions at the LHC: Medium properties

- Direct photons:

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



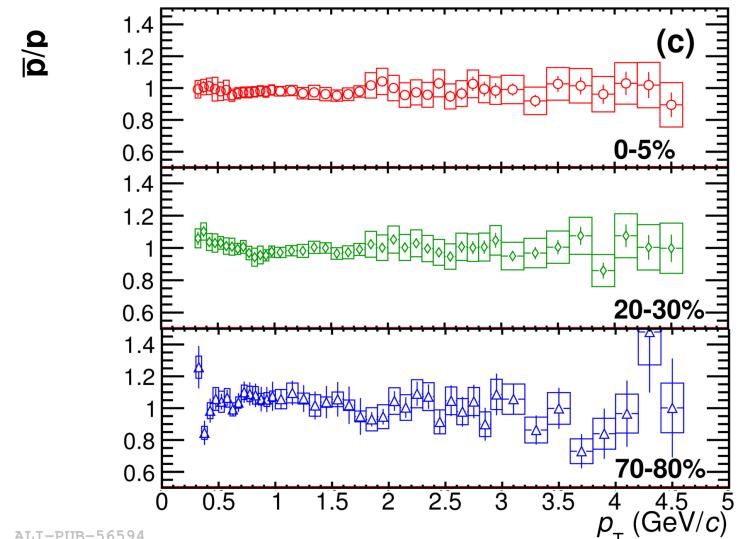
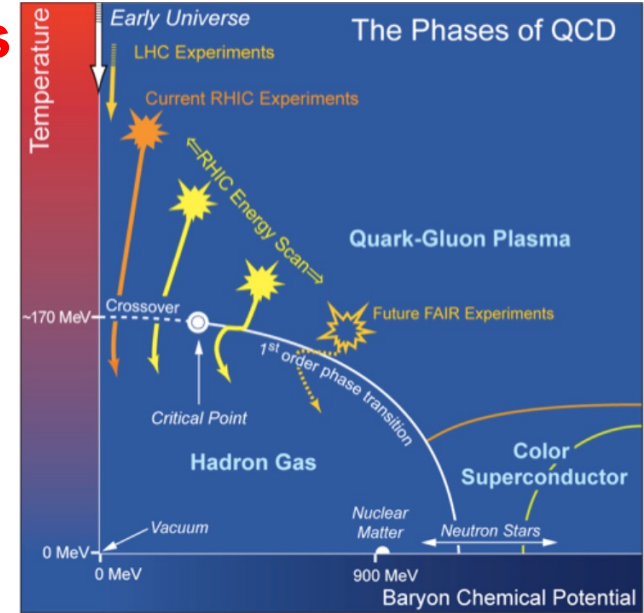
Nature Physics 16, 615–619 (2020)



ALI-PUB-97762

Recall: $T_c \approx 155 \text{ MeV}$

- anti-particle-to-particle ratio ~ 1
- $\mu_B \sim 0 \text{ MeV}$



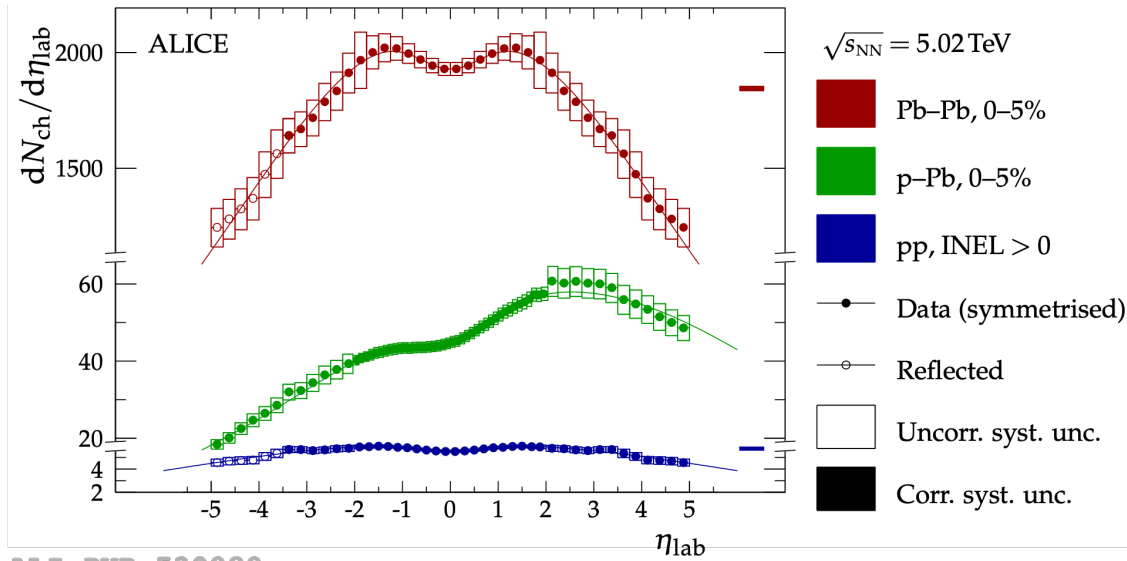
ALI-PUB-56594

Phys. Rev. C 88, 044910 (2013)

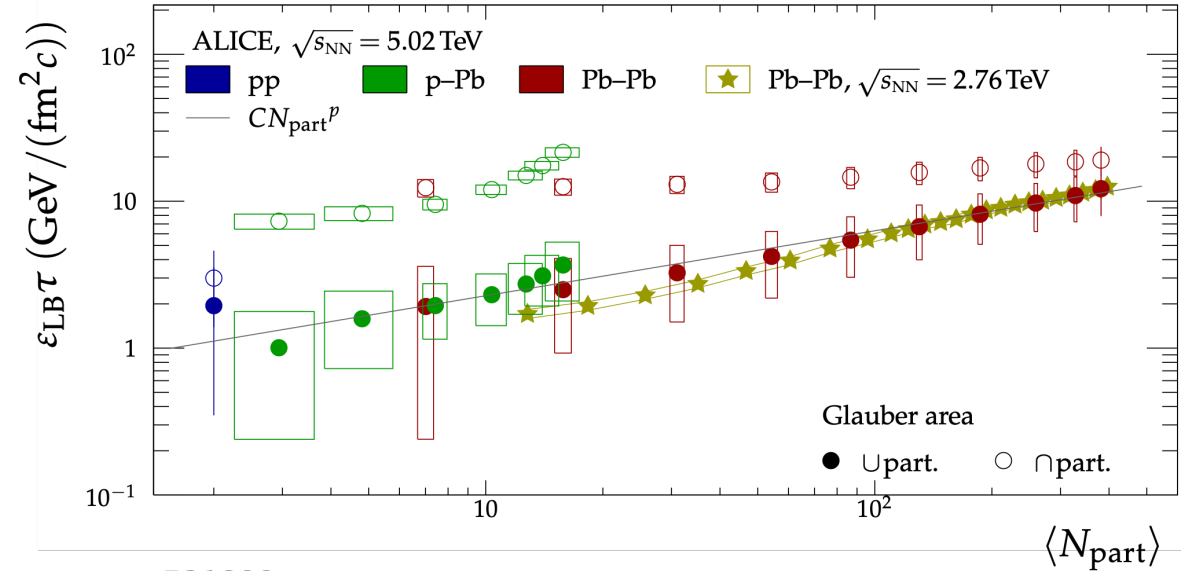


QGP droplets in small systems?

- 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.



ALI-PUB-520989



ALI-PUB-521009

$$\epsilon_{Bj} = \frac{1}{c\tau} \frac{1}{S_T} \left\langle \frac{dE_T}{dy} \right\rangle$$

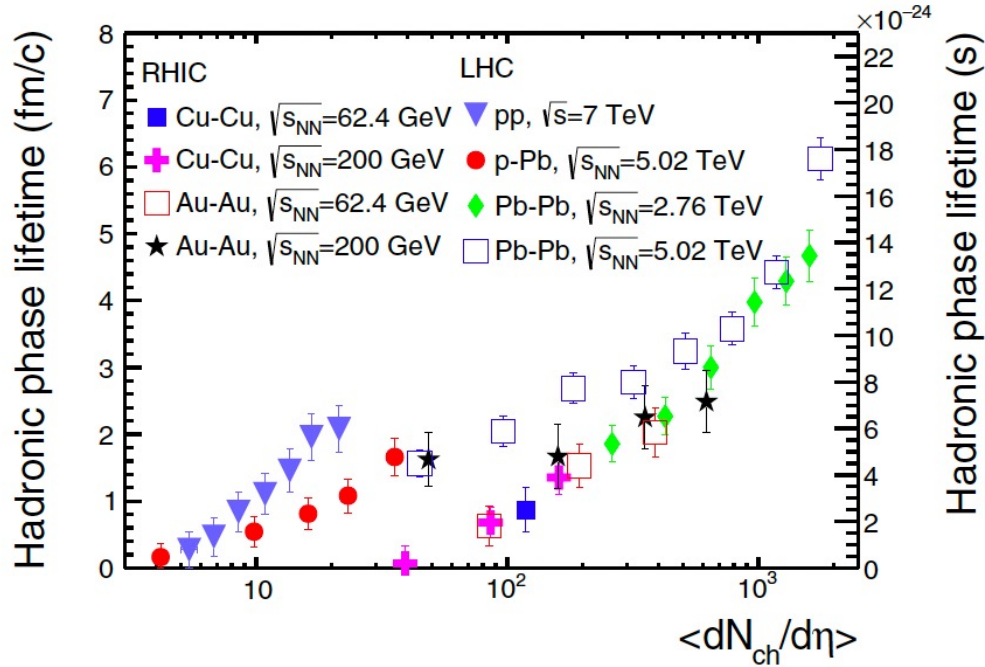
$$S_T \approx \pi R^2 \approx \pi N_{part}^{2/3}$$

$$\left\langle \frac{dE_T}{dy} \right\rangle \approx \langle m_T \rangle \frac{1}{f_{total}} \frac{dN_{ch}}{dy} = \langle m \rangle \sqrt{1 + \left(\frac{\langle p_T \rangle}{\langle m \rangle} \right)^2} \frac{1}{f_{total}} \frac{dN_{ch}}{dy}$$

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

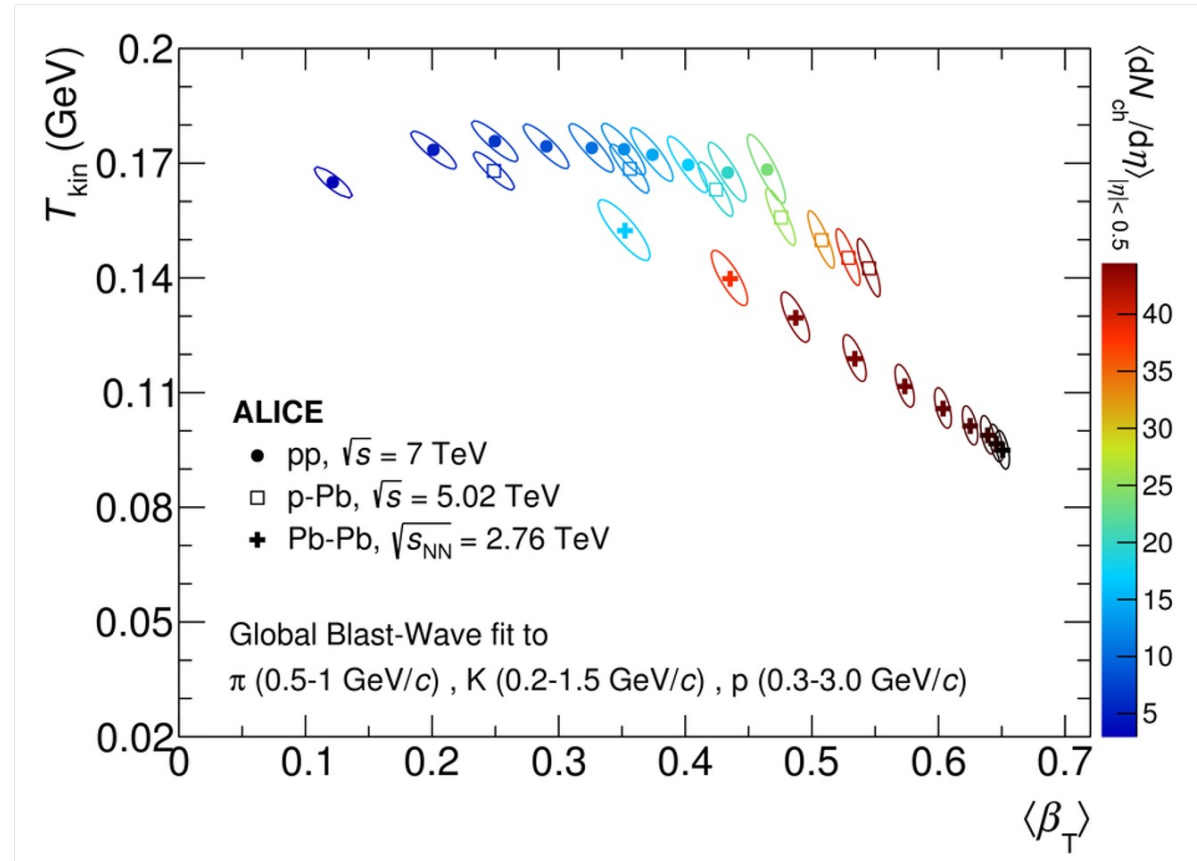


Hadronic phase lifetime



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

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



The ALICE experiment - A journey through QCD,
[arXiv:2211.04384](https://arxiv.org/abs/2211.04384)



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

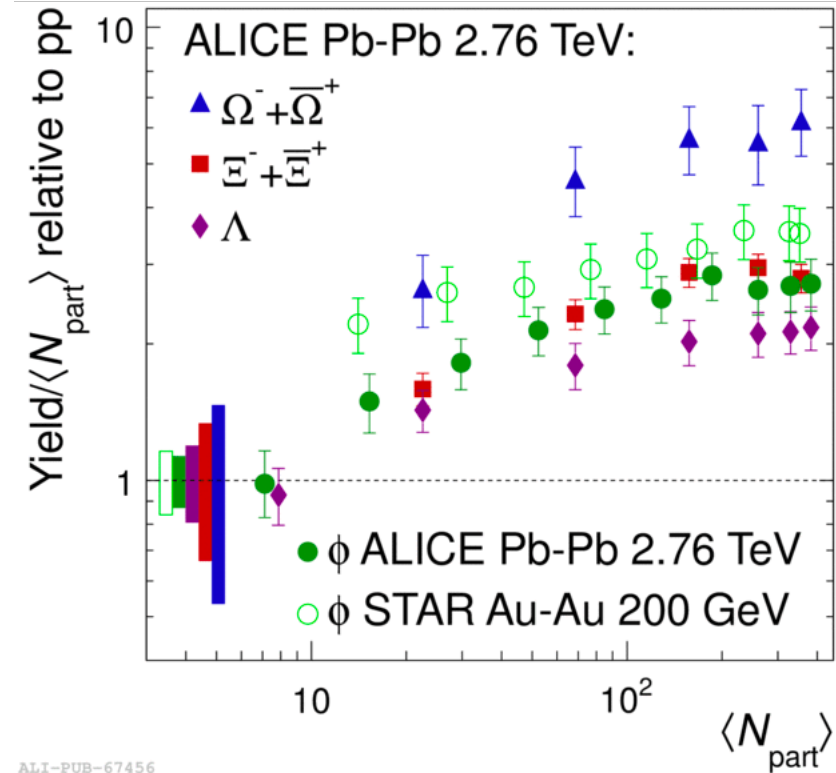
Rafelski, PRL 48 (1982) 1066



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?



ALI-PUB-67456

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

JUNE 2017 VOL 13 NO 6
www.nature.com/naturephysics

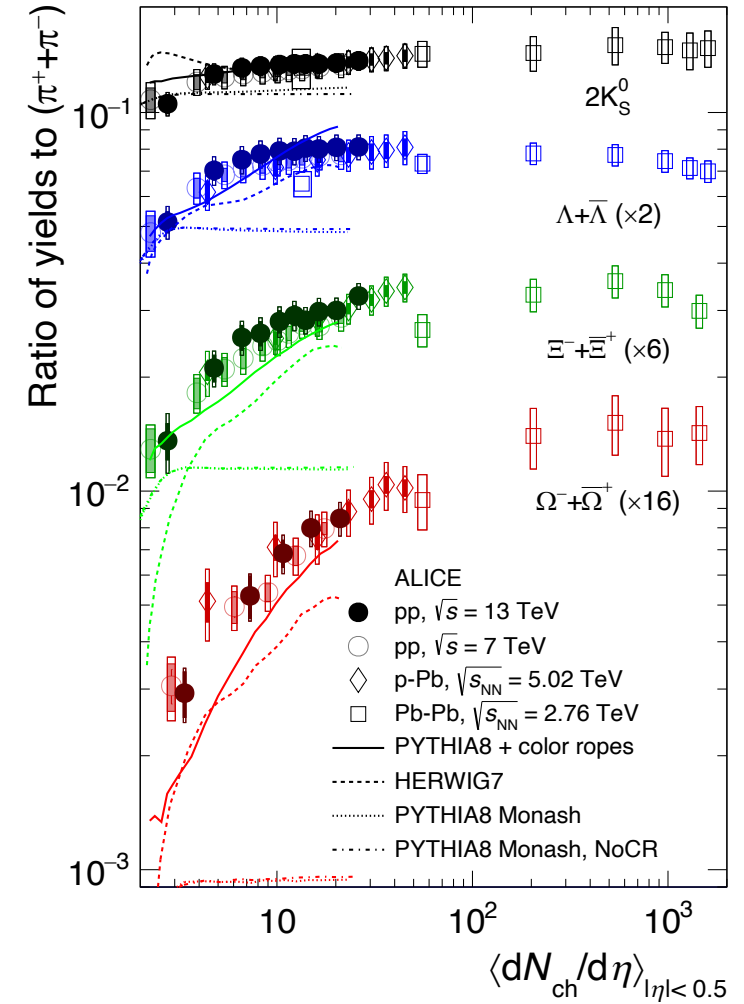
nature physics

Stranger and stranger says ALICE



Strangeness enhancement

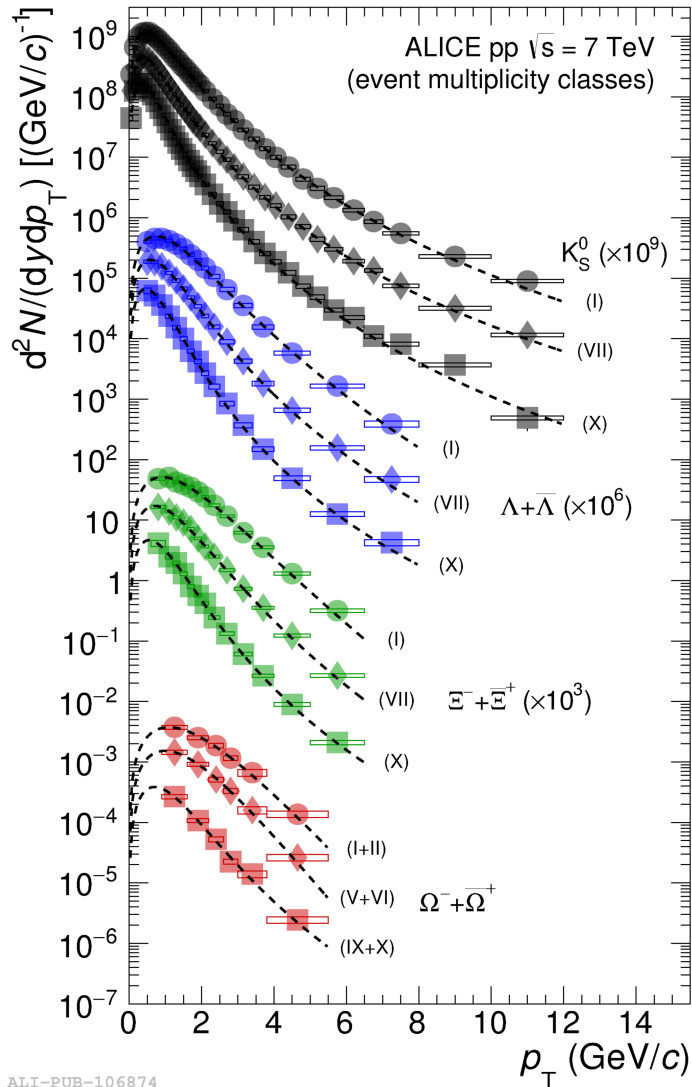
- ✓ Significant enhancement of strange-to- non-strange ratio with particle multiplicity
- ✓ Origin of strangeness production in hadronic collisions is driven by the characteristics of the final state rather than by the collision system and energy
- ✓ At high-multiplicity, the yield ratios reach values 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



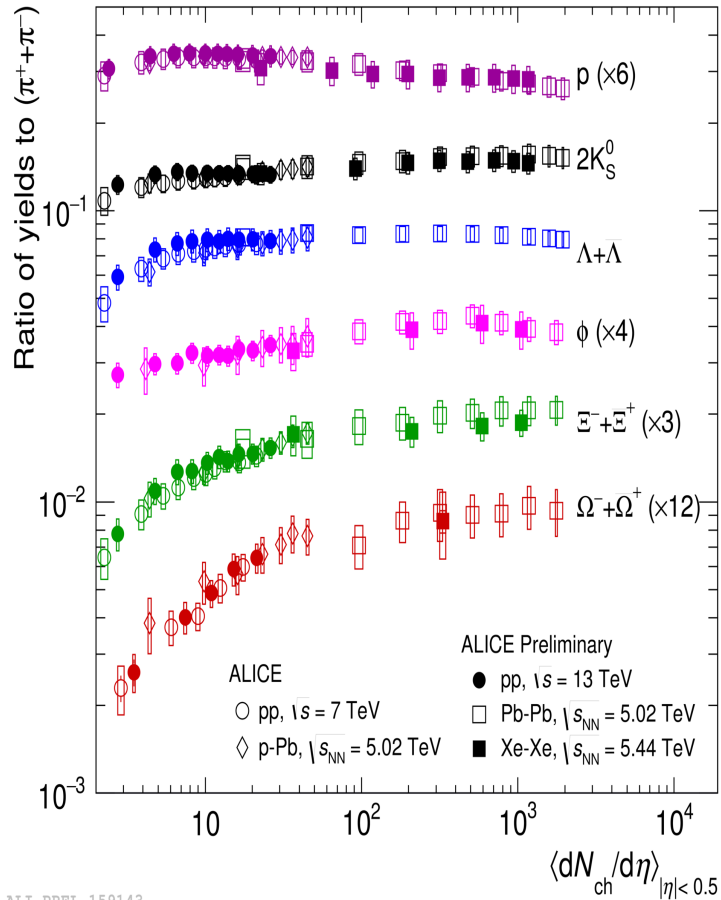
ALI-PUB-106874

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: $T_{fo} = 163 \pm 10$ MeV, $\langle \beta_T \rangle = 0.49 \pm 0.02$
→ Similar to the same class of events in p-Pb with comparable $dN_{ch}/d\eta$



Strangeness hierarchy



ALI-PREL-159143

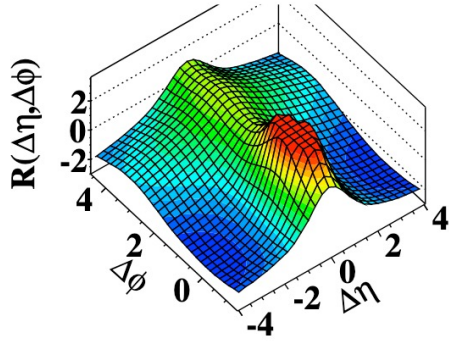
- S = 0** ✓ Smooth evolution as a function of event multiplicity (in pp, p-Pb and Pb-Pb collisions)
- S = 1** ✓ Measurement at different energies as a function of multiplicity indicate that the hadron chemistry is driven by multiplicity regardless of the collision energy
- S = 0**
- S = 2** ✓ Ratios increase from low to high multiplicity in small systems and reach values similar to those observed in Pb-Pb collisions.
- S = 3**
- ✓ Strangeness enhancement increases with strangeness content.



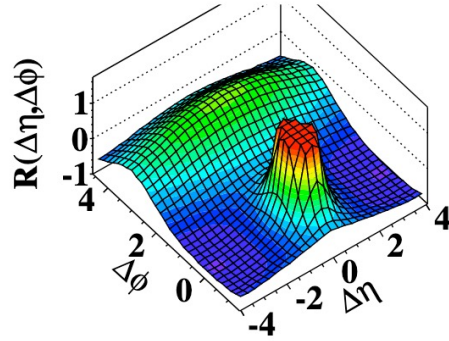
Long-range ridge-like correlations

CMS, JHEP 1009:091,2010

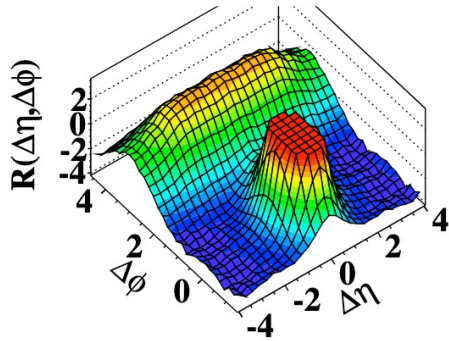
(a) CMS MinBias, $p_T > 0.1 \text{ GeV}/c$



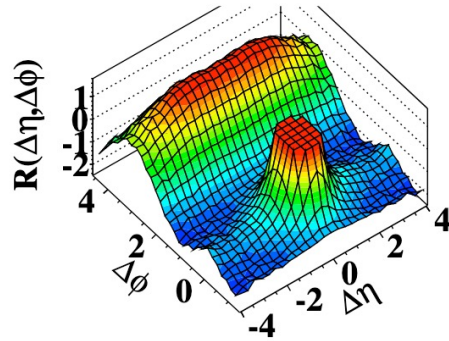
(b) CMS MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



(c) CMS $N \geq 110$, $p_T > 0.1 \text{ GeV}/c$



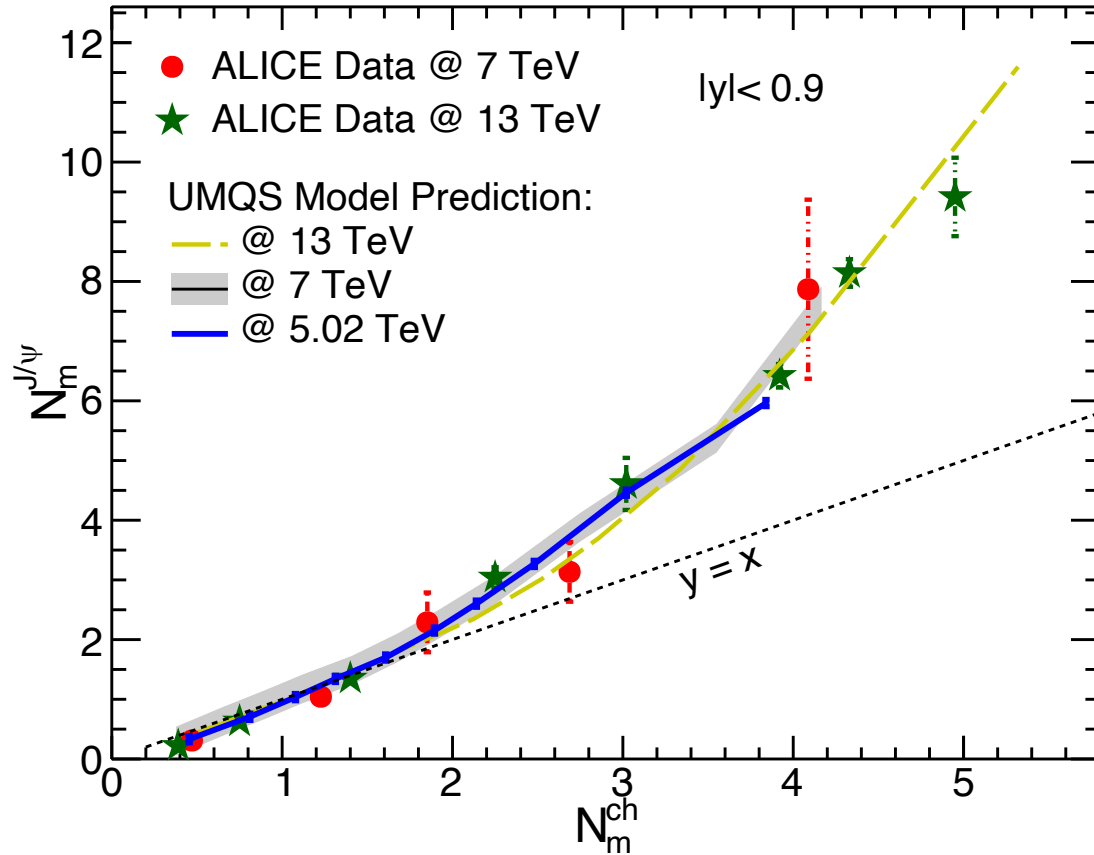
(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



- The collective flow of strongly interacting matter gives rise to an azimuthally collimated long-range (large $\Delta\eta$), near-side (small $\Delta\phi$) 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

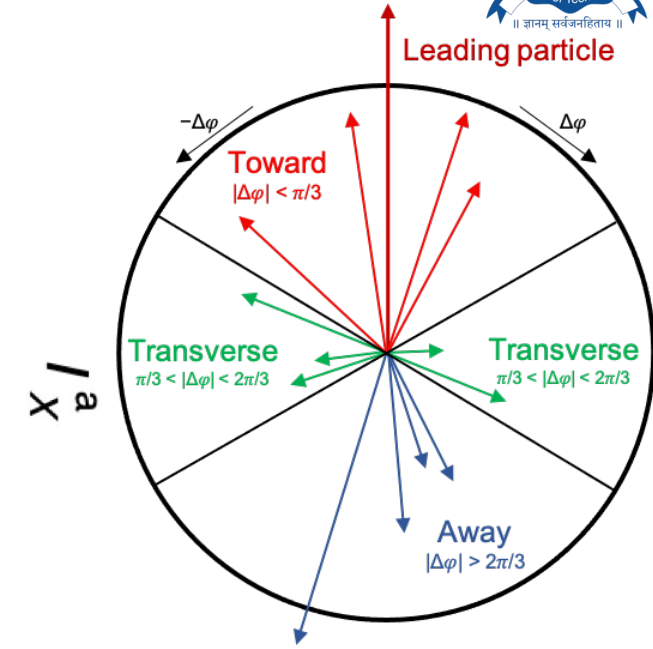
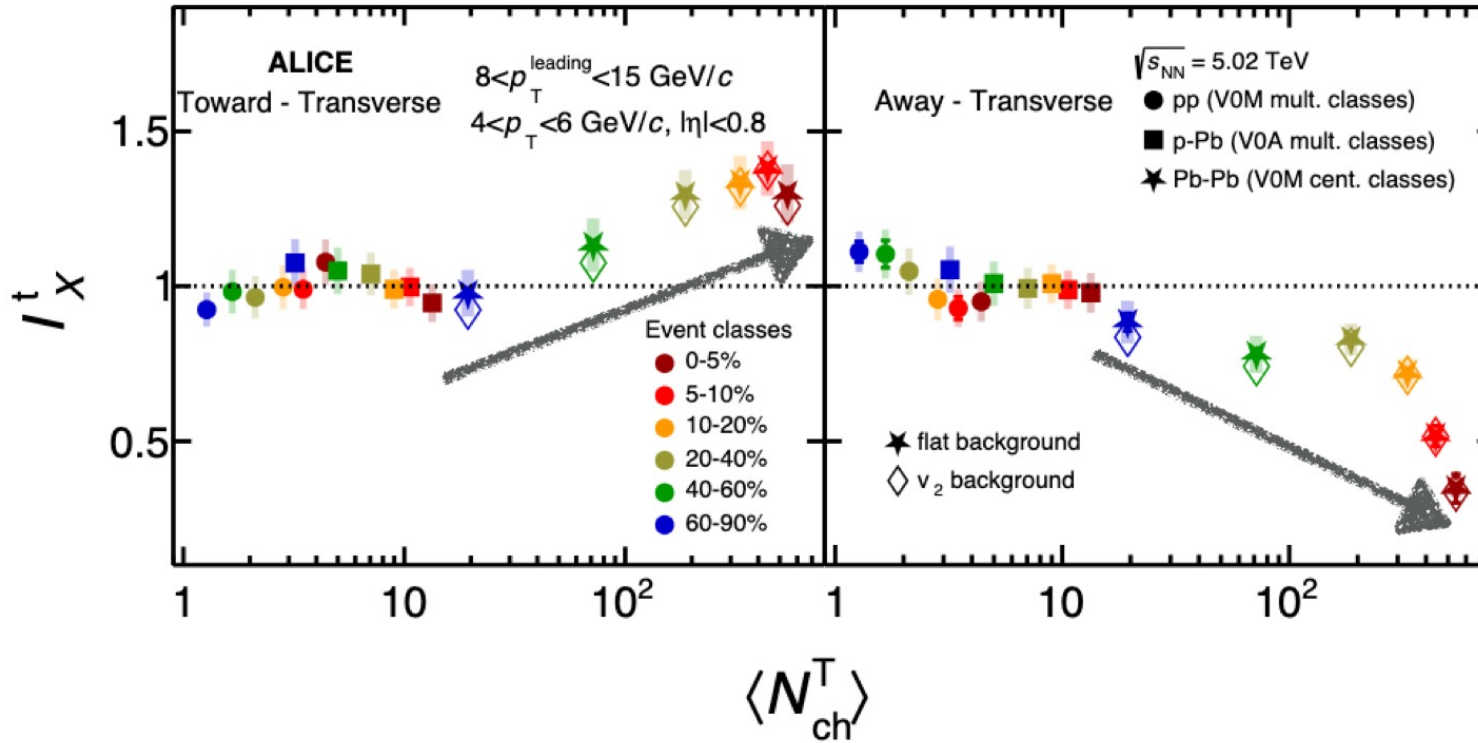


- ✓ J/ψ self-normalized yield as a function of self-normalized multiplicity follows a **scaling across collision energies**.
- ✓ UMQS model which incorporates the **suppression of J/ψ through color screening, gluonic dissociation, and collision damping and regeneration of charmonium** due to correlated $c - cbar$ 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](https://arxiv.org/abs/2204.10157) [nucl-ex]

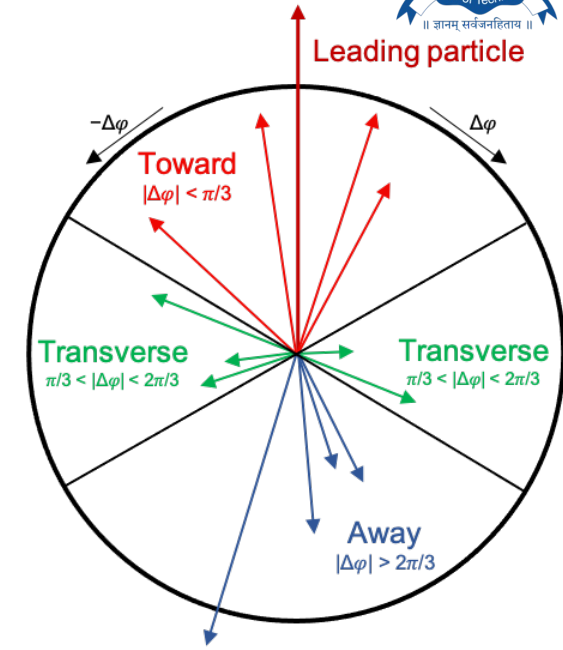
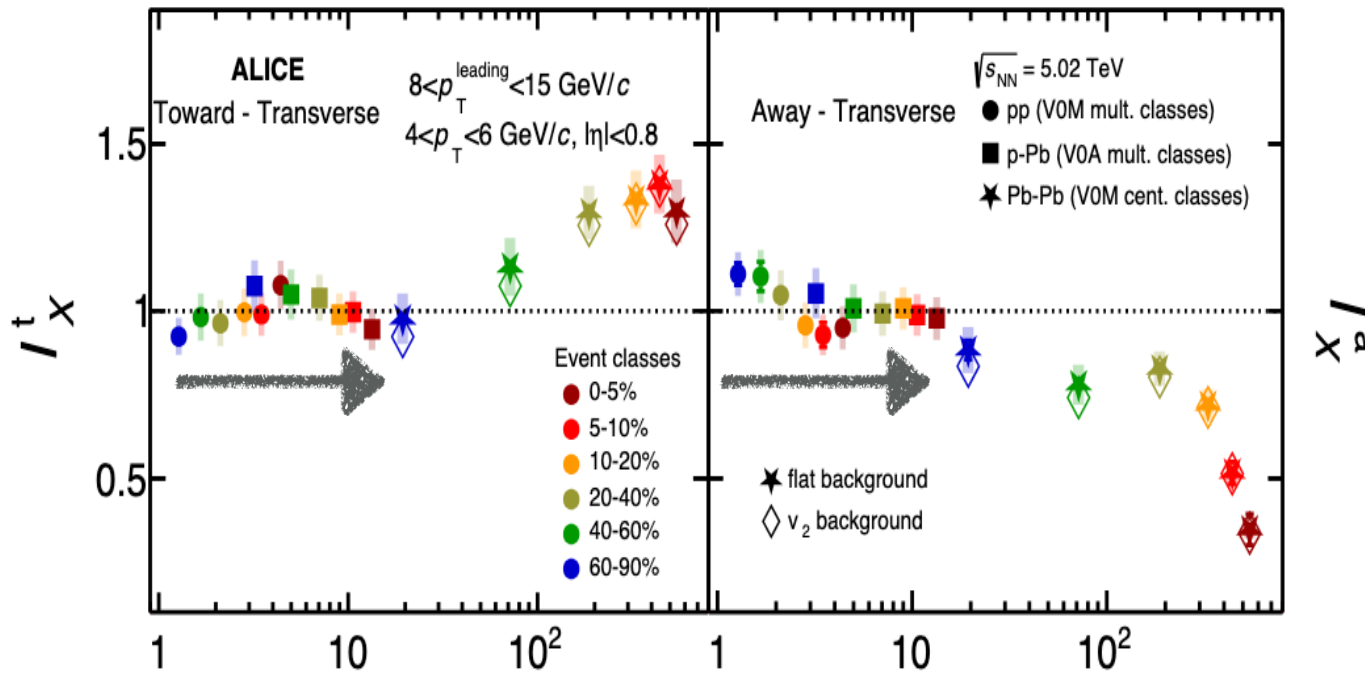
$$I_X = \frac{\left. \frac{dN_{ch}}{dp_T} \right|_{\text{jet-like signal in X collision}}}{\left. \frac{dN_{ch}}{dp_T} \right|_{\text{jet-like signal for MB pp collision}}}$$



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



ALICE, [arXiv:2204.10157](https://arxiv.org/abs/2204.10157) [nucl-ex]

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

$$\langle N_{ch}^T \rangle$$

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



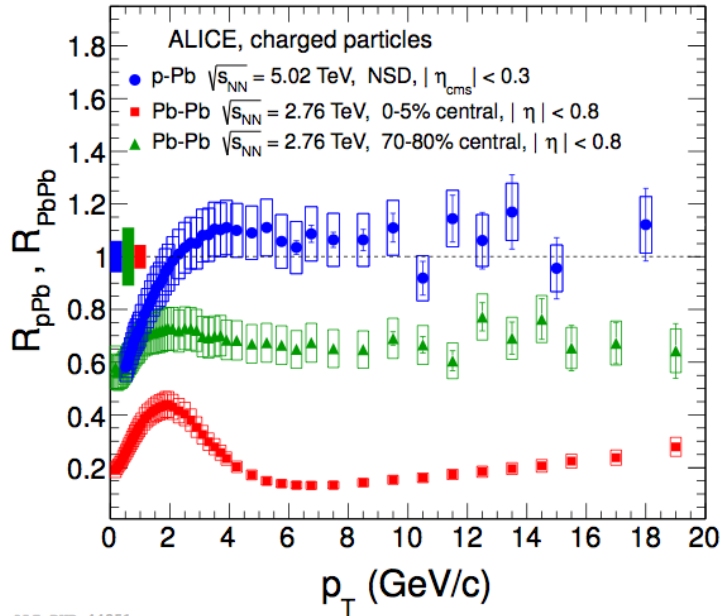
Opacity of the QGP and nuclear modification factor

- Estimate the opacity of the created medium

R_{AA} is called the nuclear modification factor

R_{AA} equals **unity** means no modification at all

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



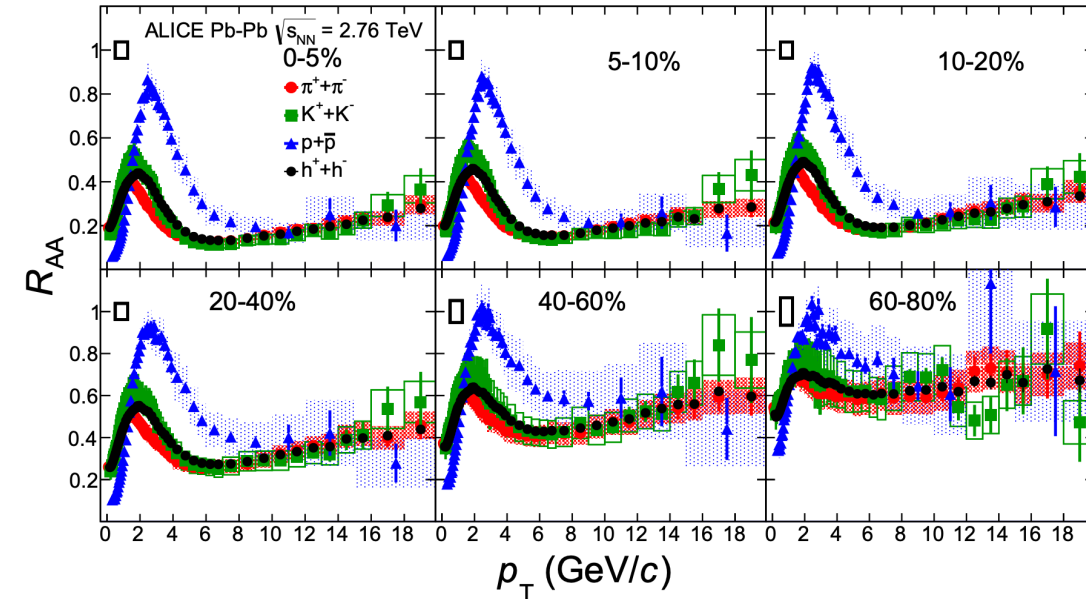
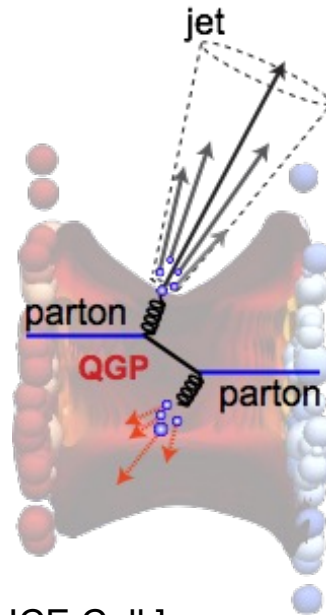
ALI-PUB-44351

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

strong suppression (quenching) in Pb-Pb collisions

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

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



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

pp collisions are considered as a baseline



Proton as a composite object

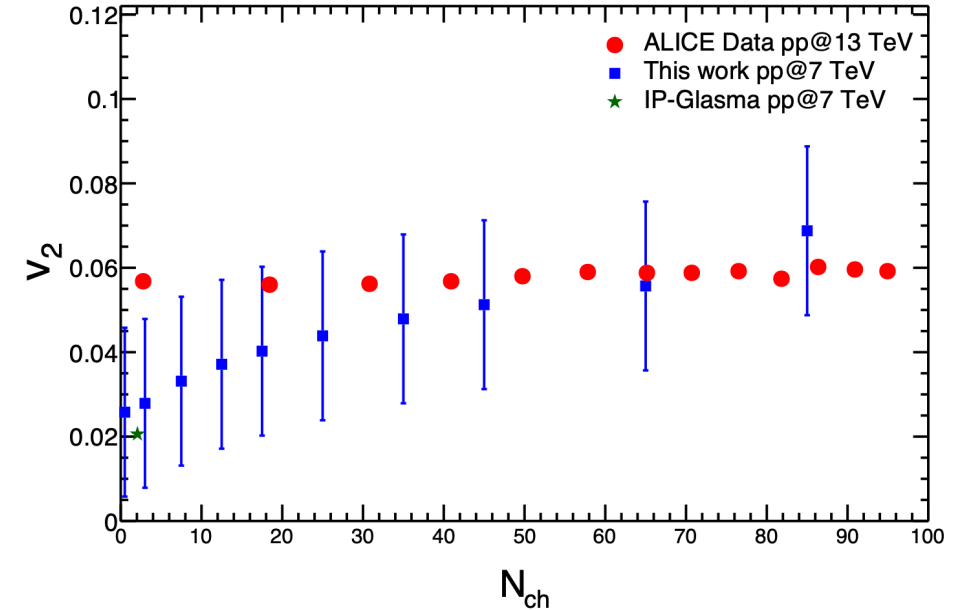
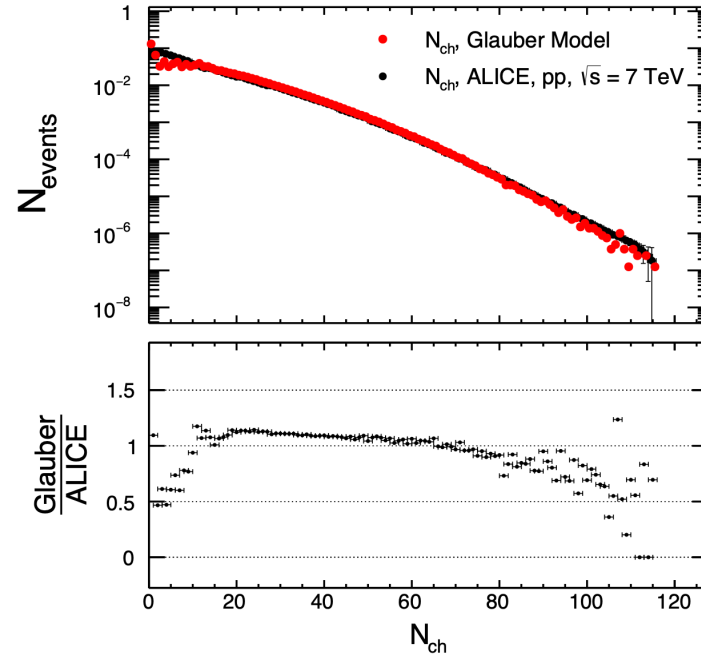
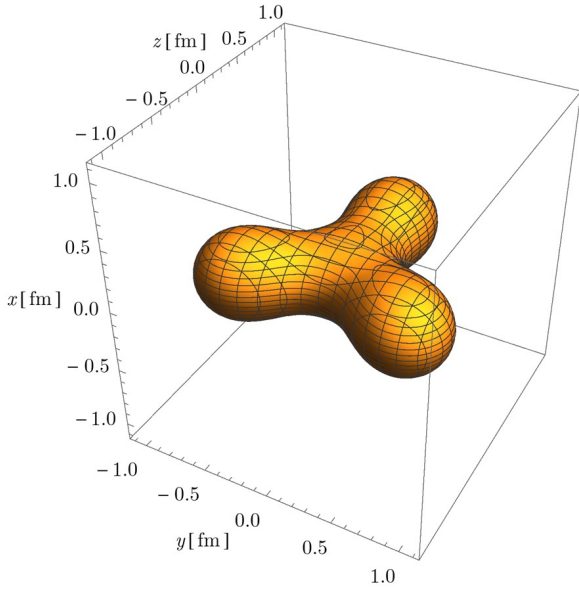
Anisotropic and inhomogeneous density profile of proton

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

Quarks

Gluons

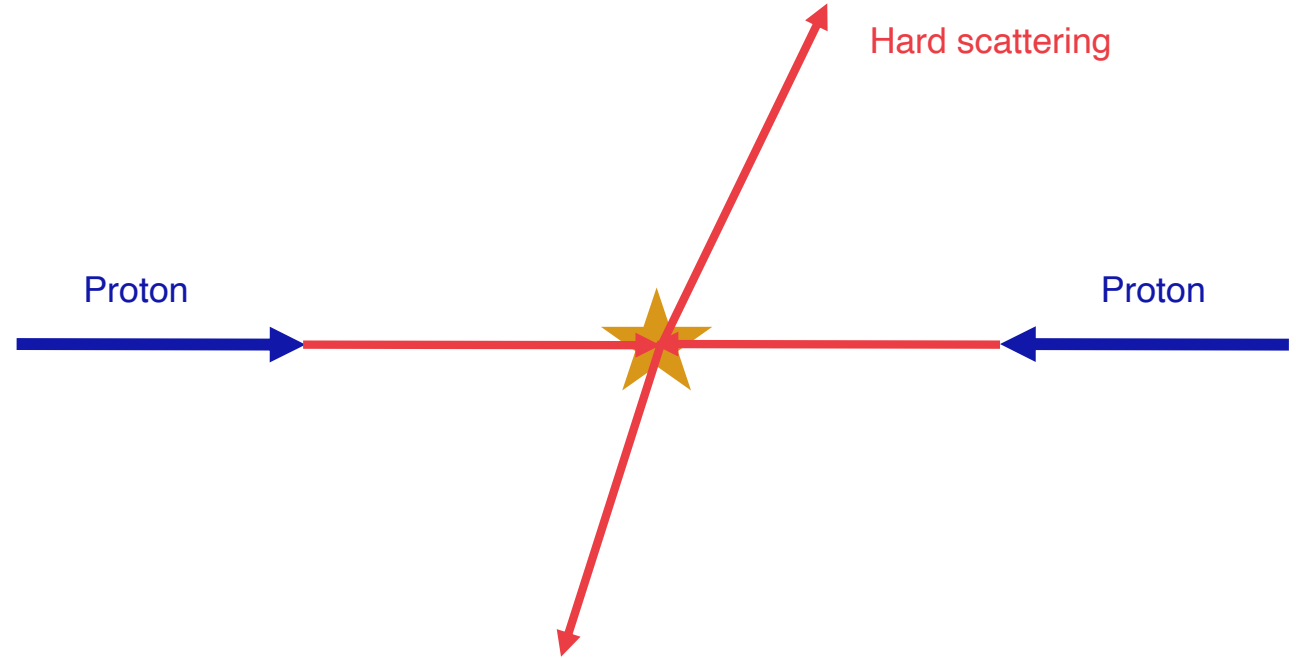
The densities of quarks (ρ_q) and gluons (ρ_g) are taken as the Gaussian type assuming a spherically symmetric distribution of quark densities from their respective centers and cylindrically symmetric gluon densities about the line joining two adjacent quarks.





A hypothetical picture of Proton collisions at TeV energies

Hard scattering: perturbative QCD





A hypothetical picture of Proton collisions at TeV energies

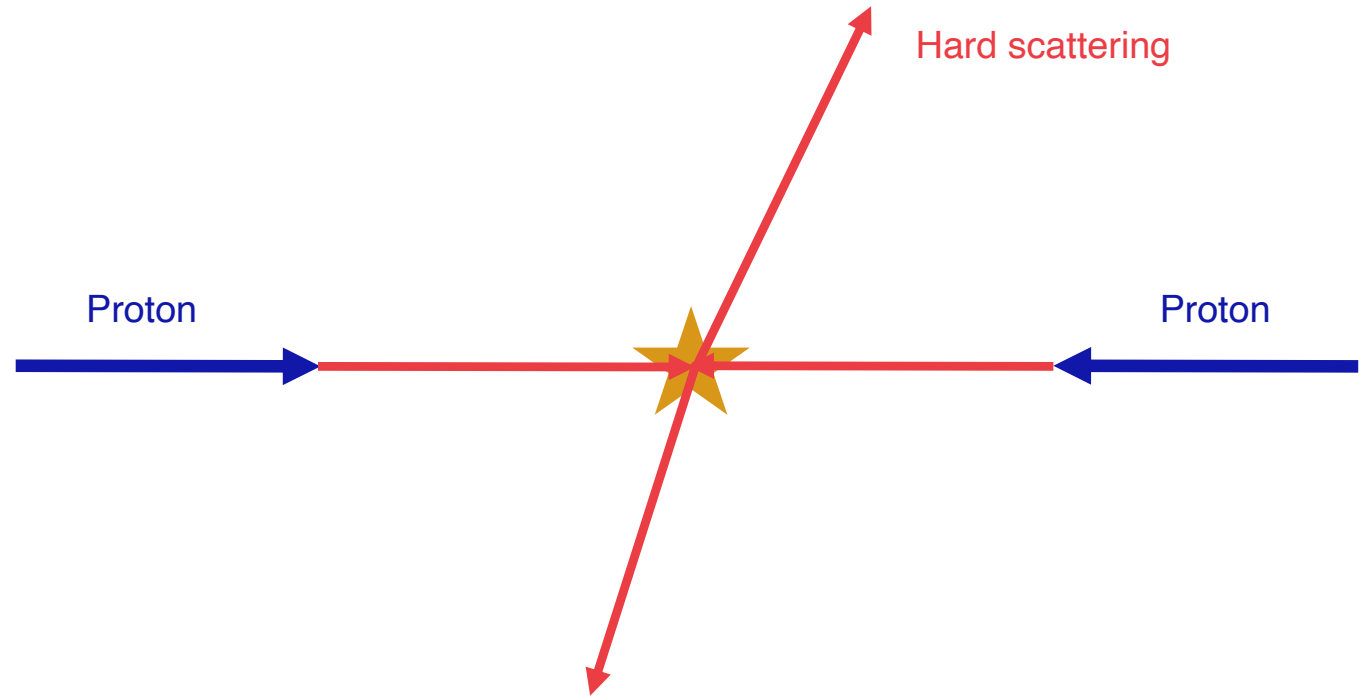
Hard scattering: perturbative QCD

Soft QCD processes:

low transverse momenta
→ non-perturbative QCD

Includes:

- Underlying Event (UE)





A hypothetical picture of Proton collisions at TeV energies

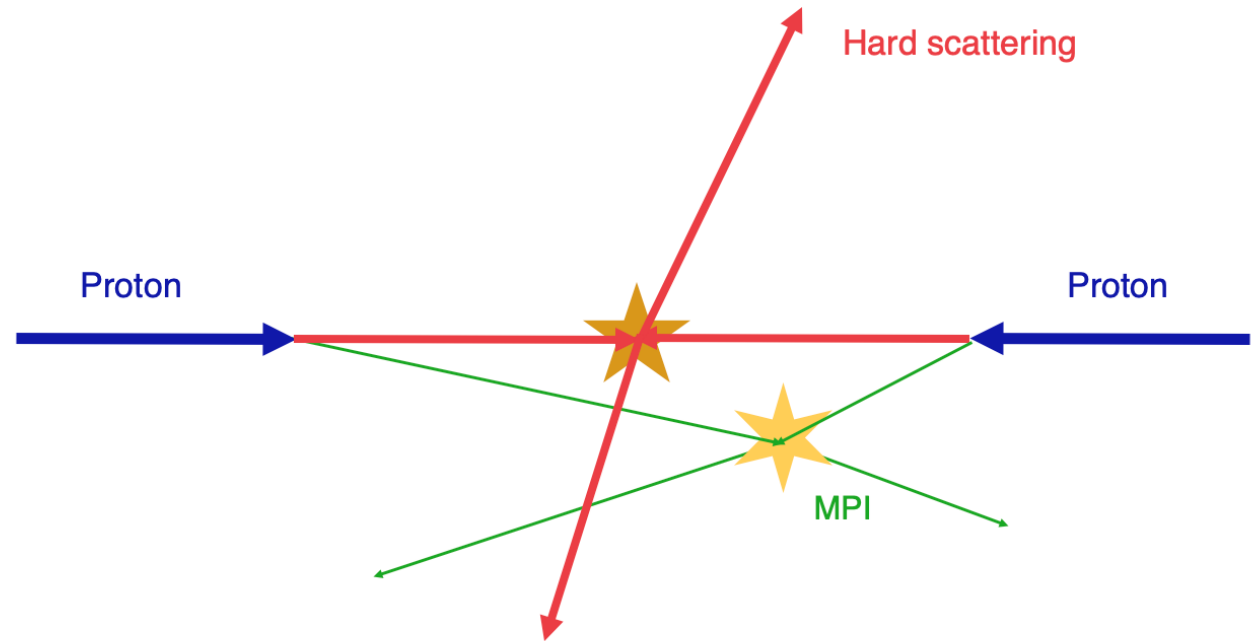
Hard scattering: perturbative QCD

Soft QCD processes:

low transverse momenta
→ non-perturbative QCD

Includes:

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





A hypothetical picture of Proton collisions at TeV energies

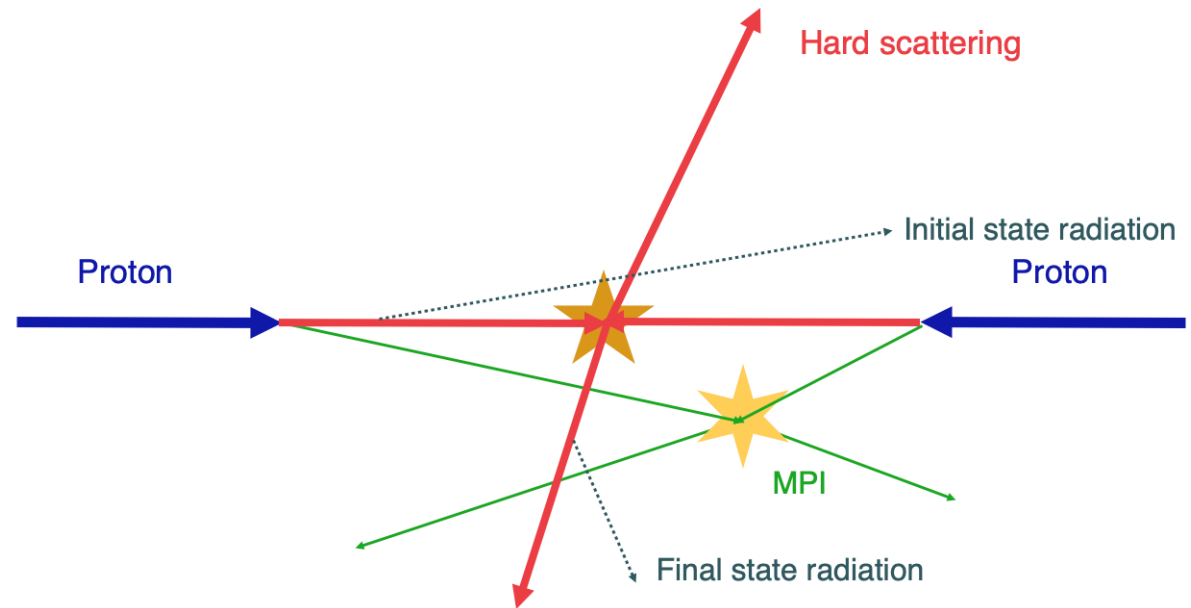
Hard scattering: perturbative QCD

Soft QCD processes:

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Includes:

- Underlying Event (UE)
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 - Initial- and final-state radiation





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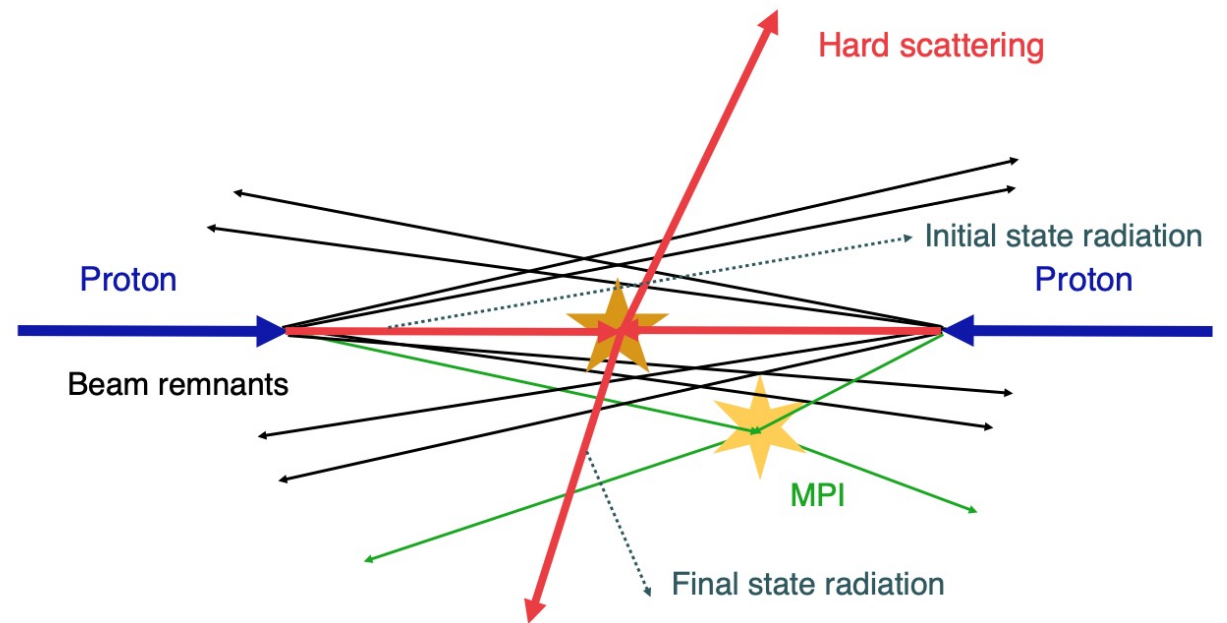
Hard scattering: perturbative QCD

Soft QCD processes:

low transverse momenta
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Includes:

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





A hypothetical picture of Proton collisions at TeV energies

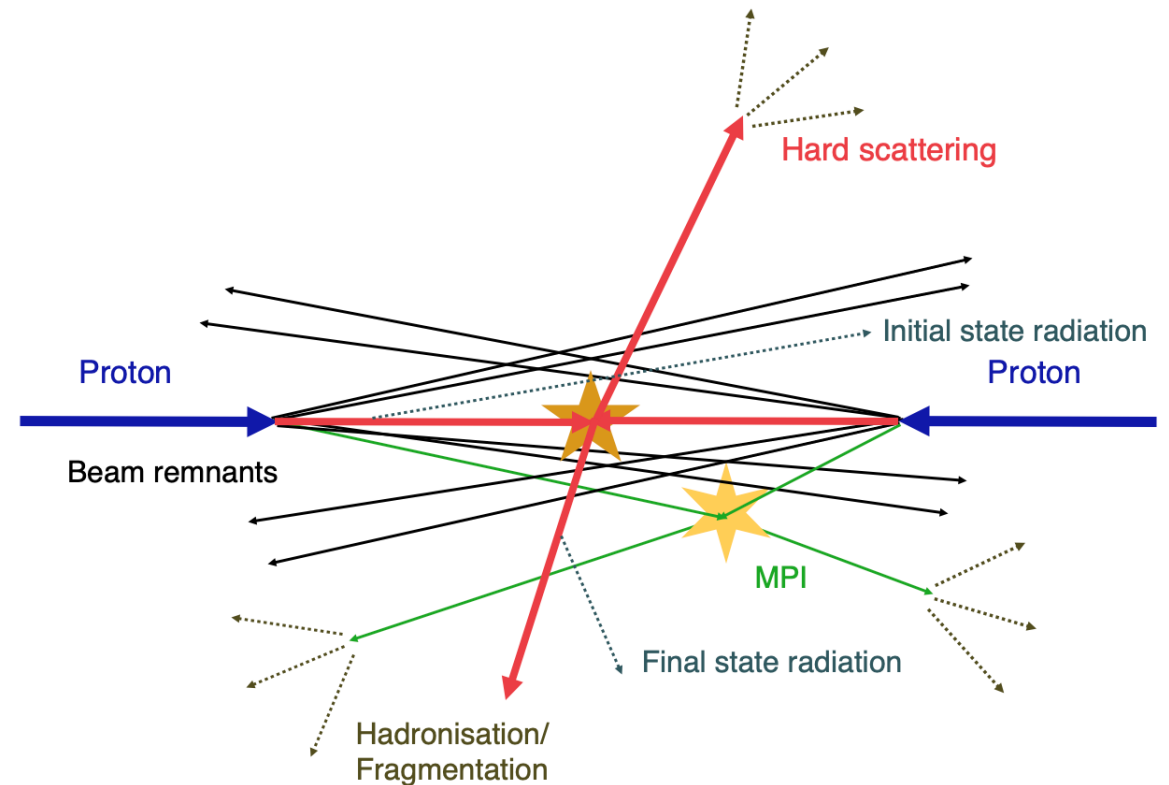
Hard scattering: perturbative QCD

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

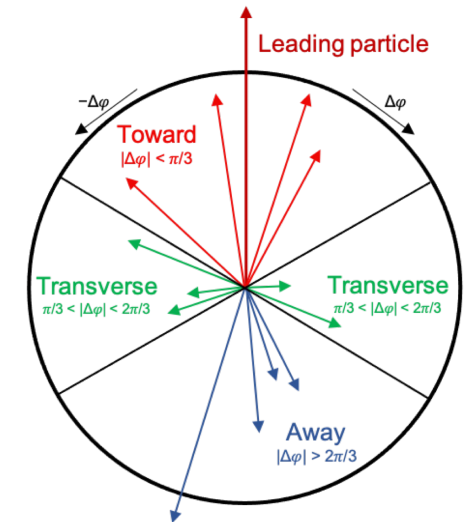
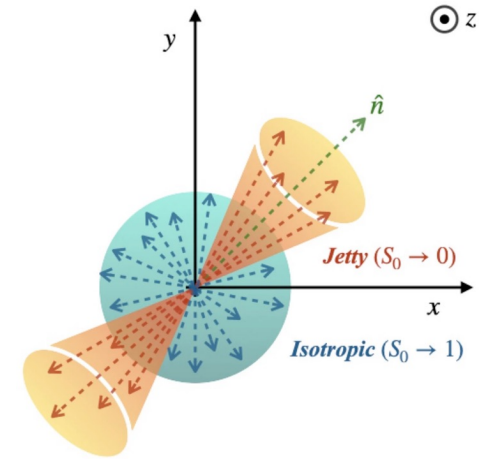




QGP droplets in small systems?

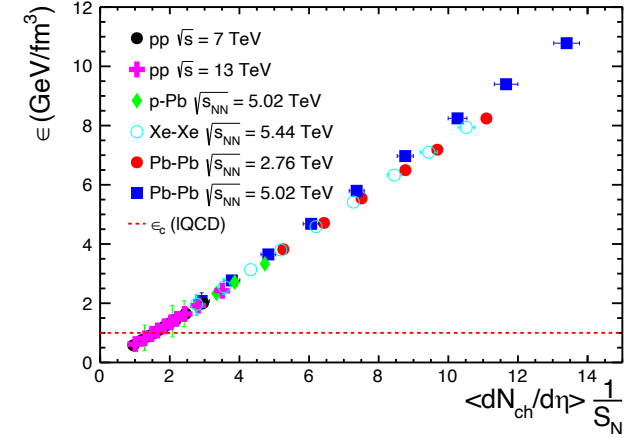
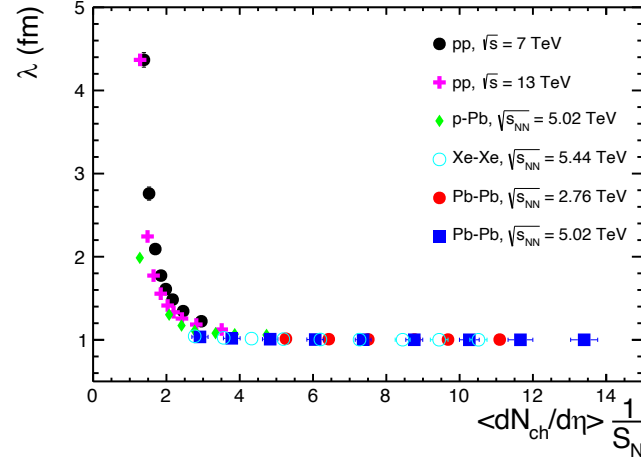
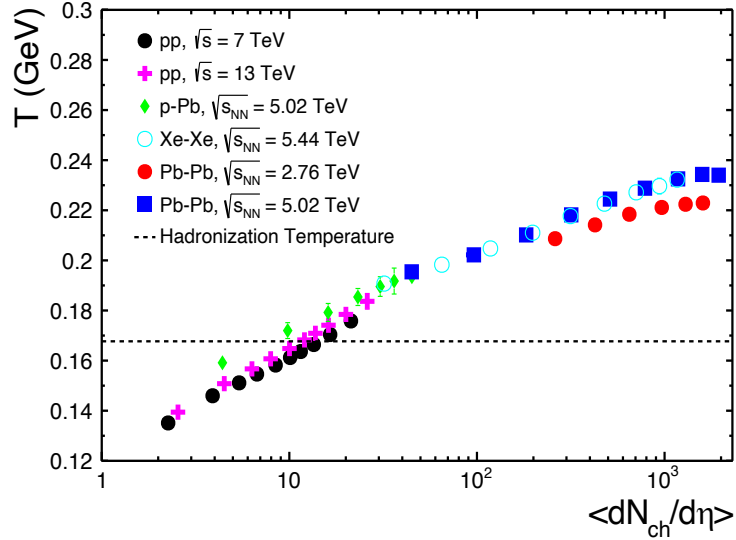
- ❖ Measurements at the LHC have revealed that **small collision systems** exhibit **collective-like behavior**, formerly thought to be achievable only in heavy-ion collisions, where the data support the formation of QGP.
- ❖ Traditionally, small collision systems are used as a **baseline** for the study 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)
- ✓ Sphericity
- ✓ Flatnecity



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)

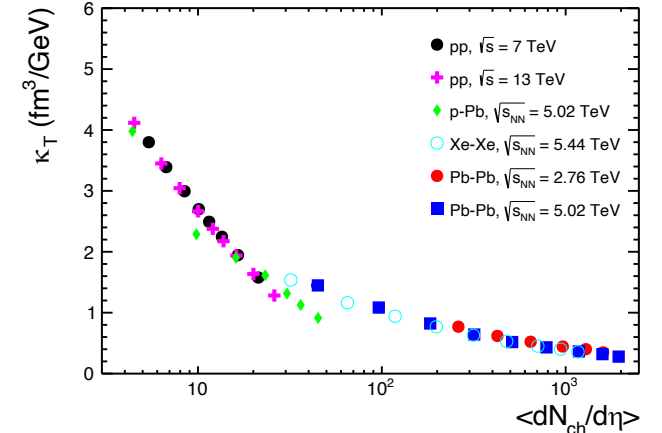
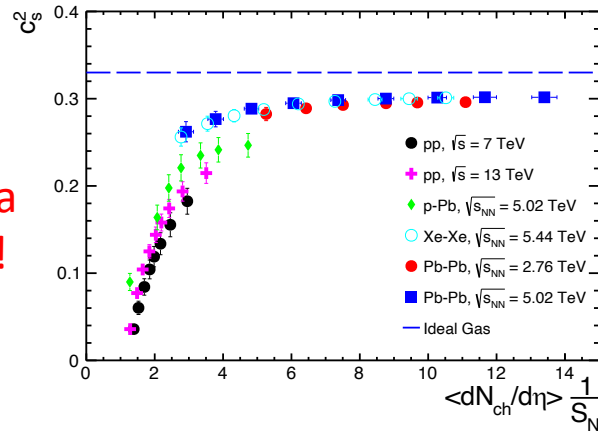
Threshold in multiplicity for a
change in system properties!

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

$$\epsilon = \frac{3}{2} \frac{dN_{ch}/dy \langle m_T \rangle}{S_N \tau_{pro}}$$

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

$$\kappa_T = -\frac{1}{V} \frac{\partial V}{\partial S_N} \frac{\partial S_N}{\partial P} \implies \kappa_T = \frac{\tau_{pro} S_N}{\langle m_T \rangle dN_{ch}/dy}$$



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)



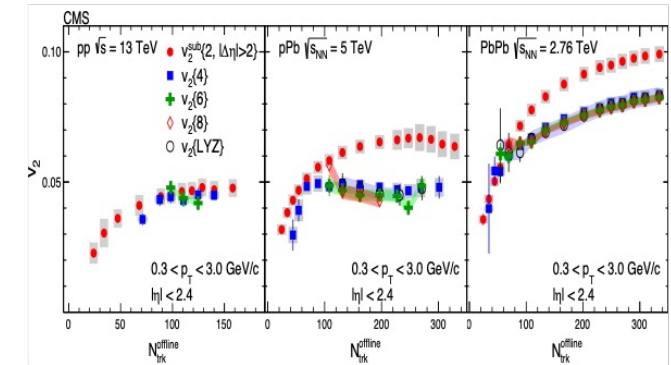
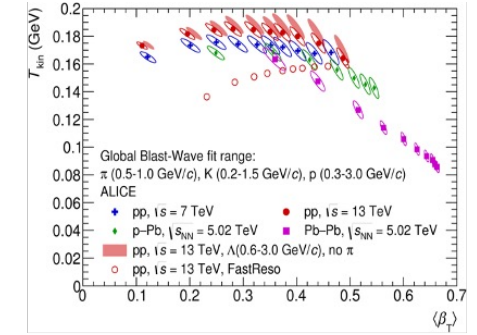
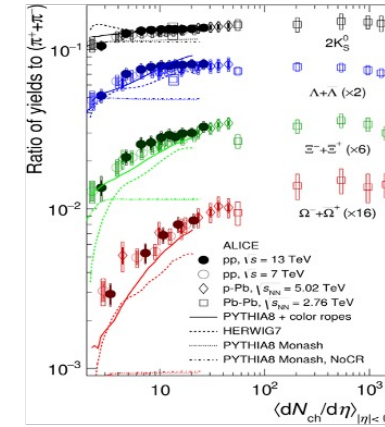
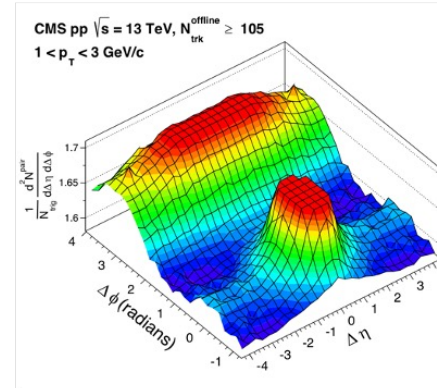
TeV pp collisions and QGP droplets

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 suppression
- Jet quenching etc.



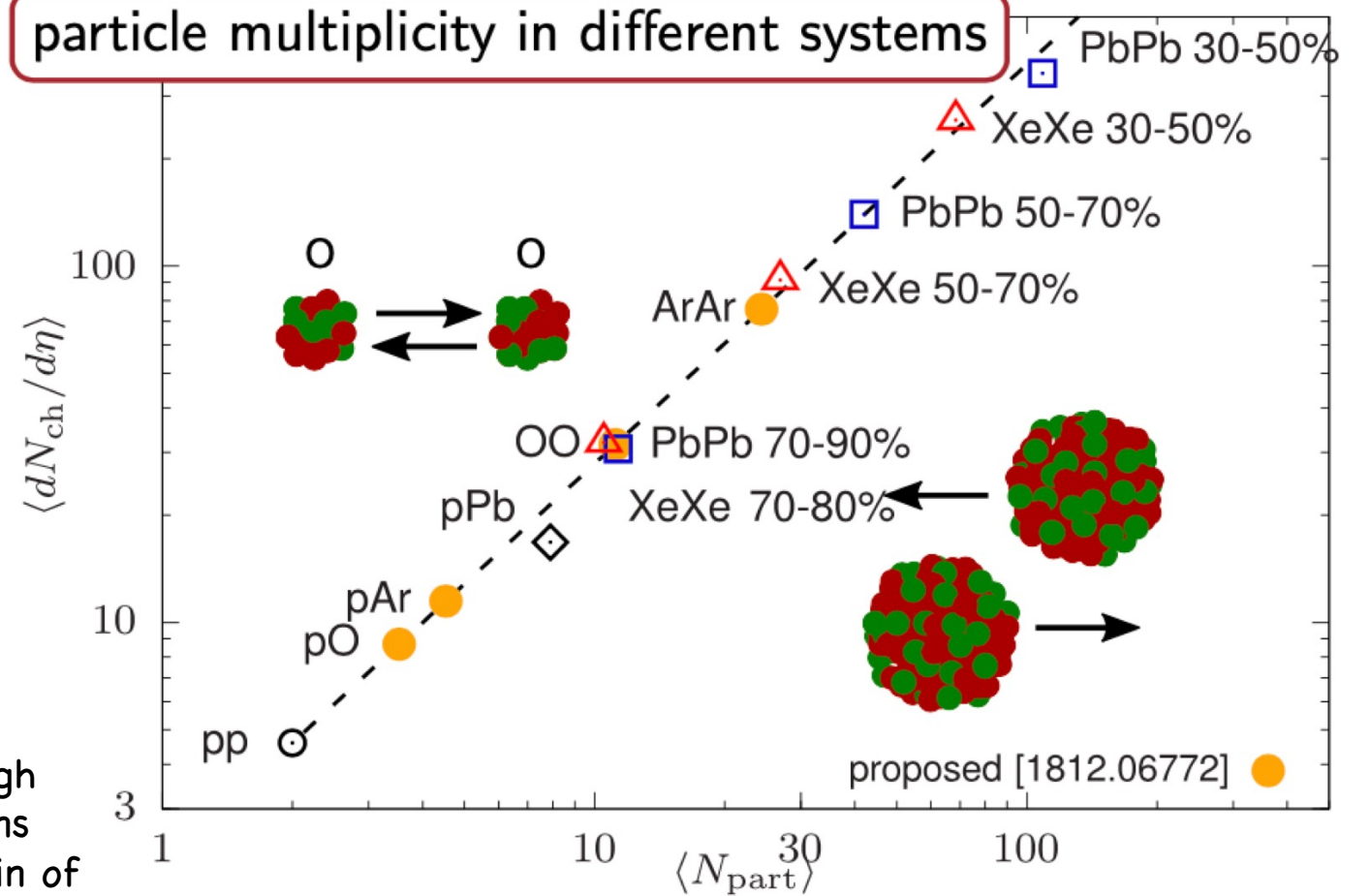
R. Sahoo, AAPPs Bulletin (2019)

R. Sahoo, T. Nayak, Current Science (2021)



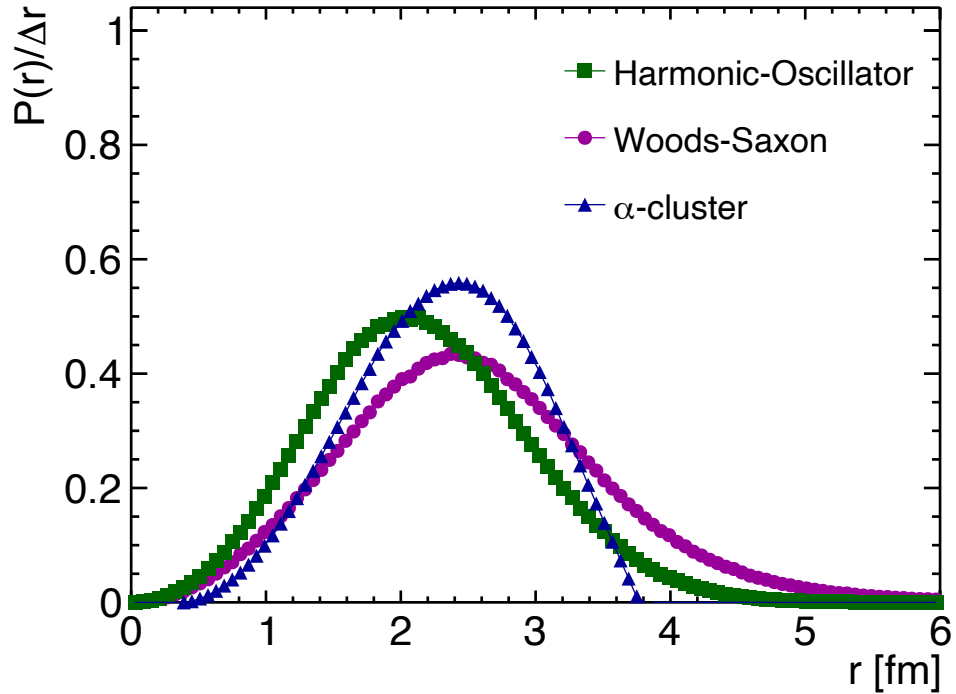
Oxygen-Oxygen Collisions@LHC

- 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

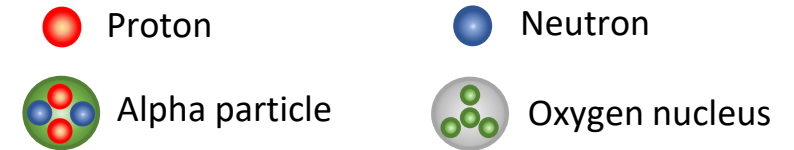
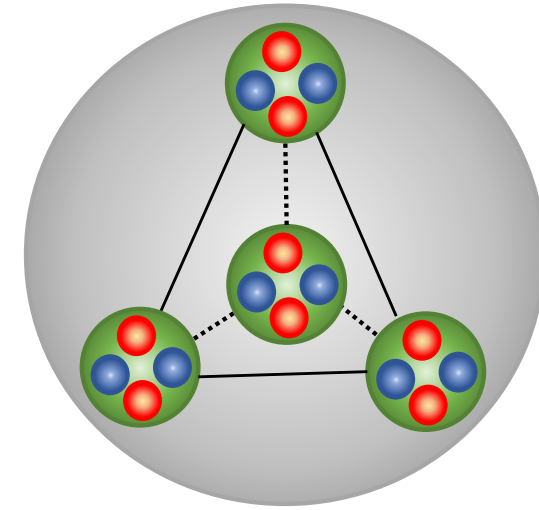




Nuclear density profile of Oxygen



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

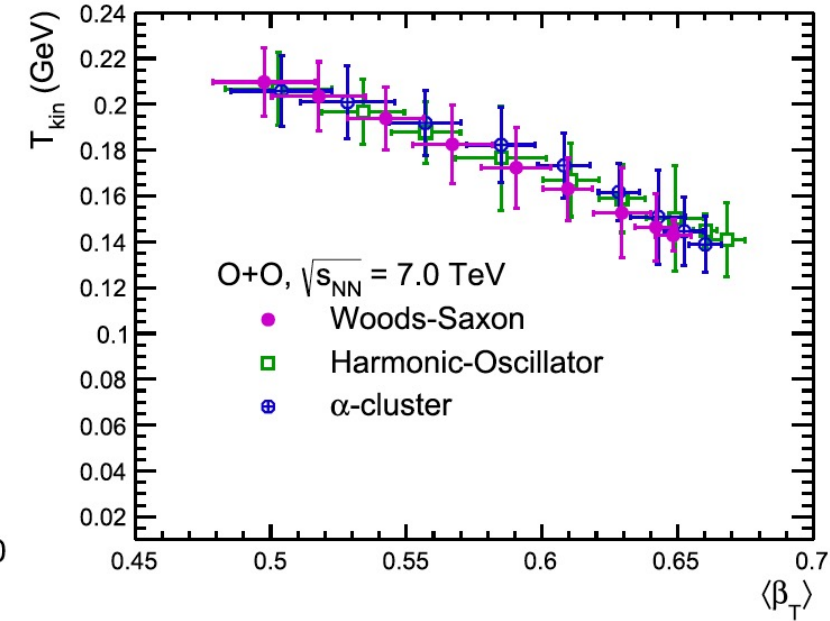
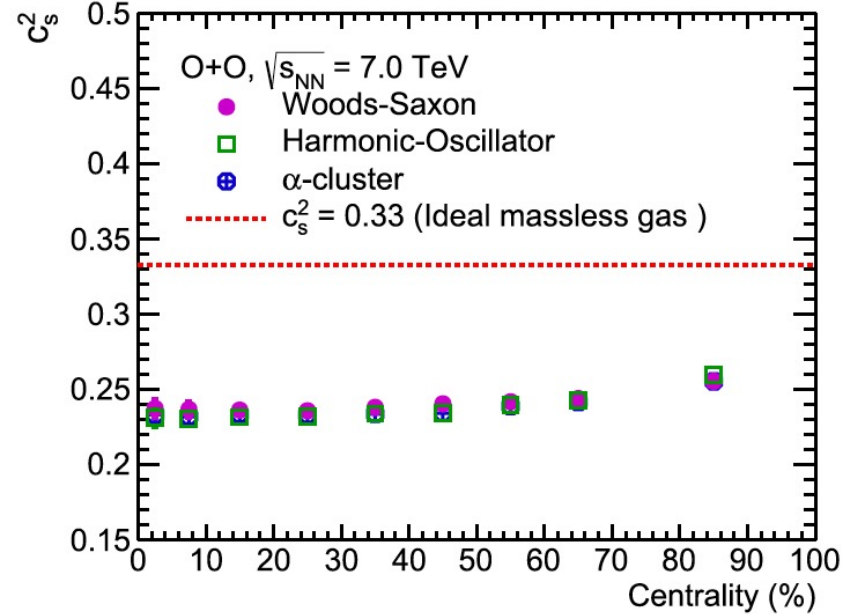
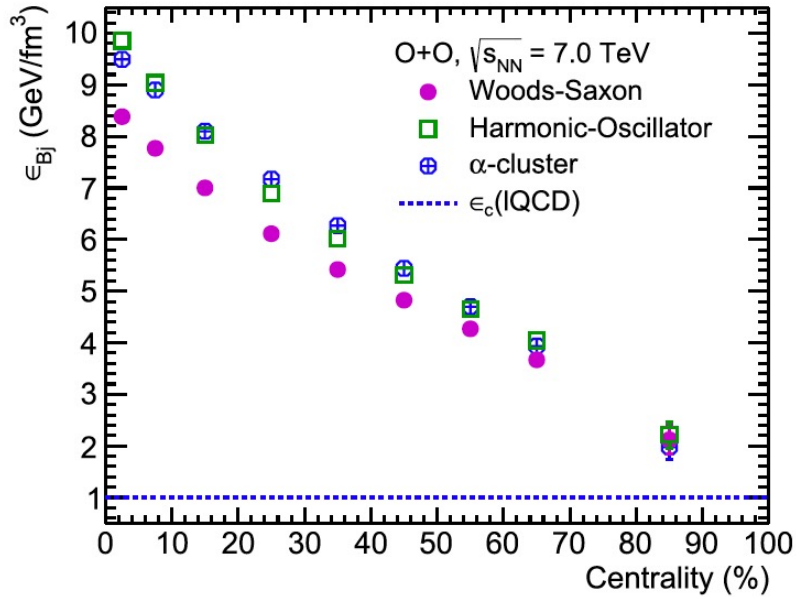


Depiction of α -clustered structure in oxygen nucleus

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



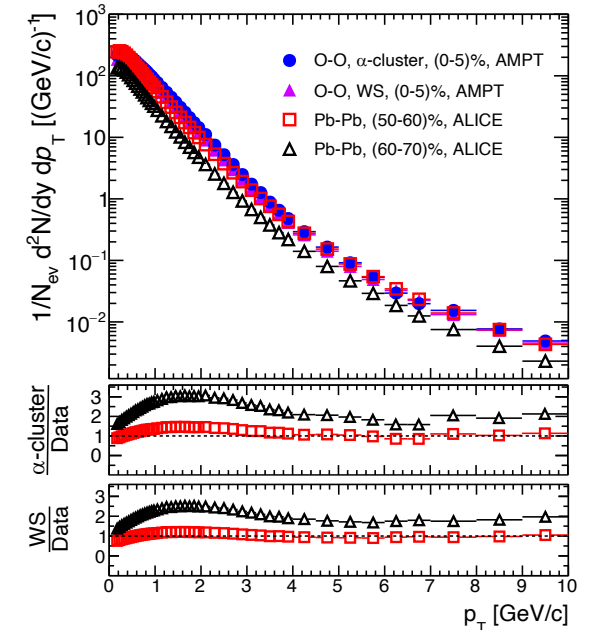
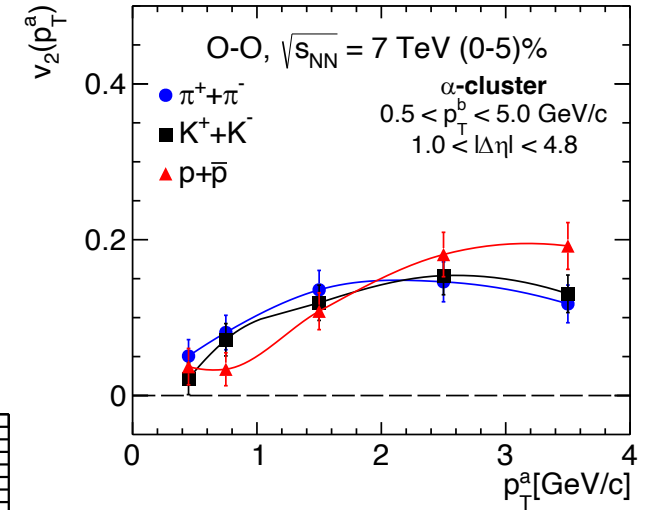
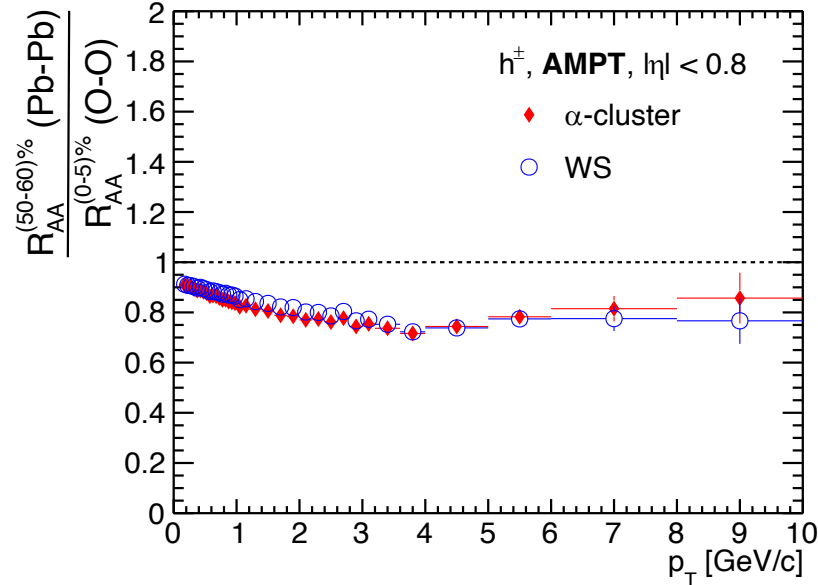
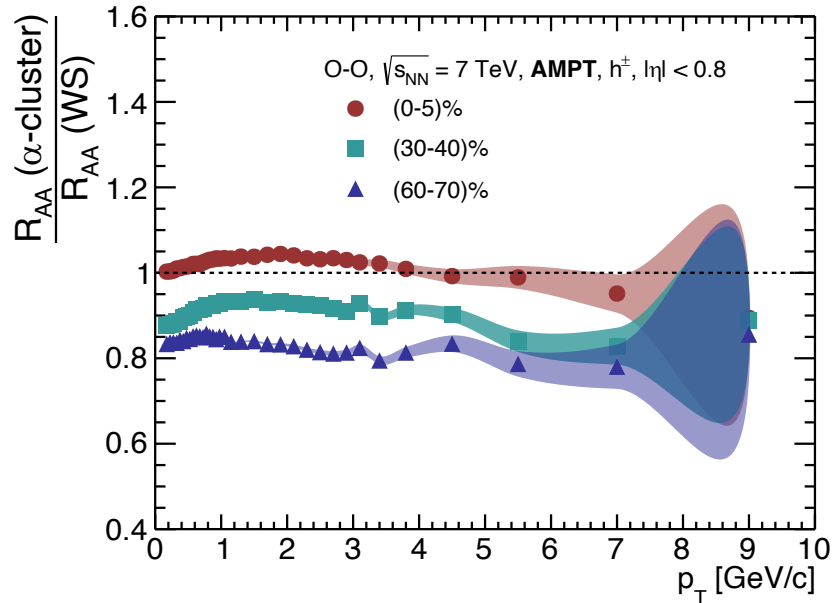
- ❖ The initial energy density for a de-confinement transition is 1 GeV/c (IQCD)
- ❖ Both α -cluster and harmonic-oscillator density profiles show 15% higher energy density than the Woods-Saxon density profile
- ❖ The speed of sound is independent of the density profiles and below the ideal gas limit

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,
Phys. Rev. D 108, 054022 (2023)



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 sphericity 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](https://arxiv.org/abs/2211.04384)**



Thank you for your attention !