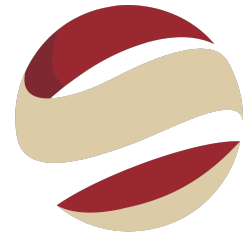




Núcleo de
Computação
Científica



SPRACE

Physics of Ultrarelativistic Heavy Ion Collisions

CESAR A. BERNARDES

SPRACE - NCC/UNESP

15th IDPASC Summer School - Natal, Brazil — July 20–29, 2026

Outline

Why study these collisions?

A Brief History of Heavy Ion Physics

Examples of signatures of the quark-gluon plasma (QGP)

Some open questions in the field

Few examples of data analyses at the LHC

Why study ultrarelativistic heavy ion collisions?

A unique opportunity to create in the laboratory the “simplest” complex state of matter composed of quarks and gluons (QGP) $\Rightarrow$ Study of quantum chromodynamics (QCD) under extreme conditions

Phys. Ann. Rev. of Nucl. and Part. Sci. **68** 339 (2018)

Creation of conditions of energy density and temperatures similar to those hypothesized at the beginning of the universe (few μs after the Big Bang)

Phys. Rev. Lett. **34** 1353 (1975)

Reports on Progress in Physics **42** 389 (1979)

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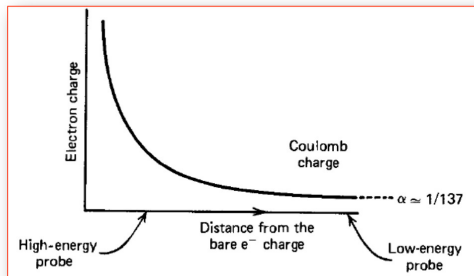
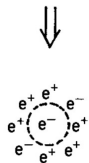
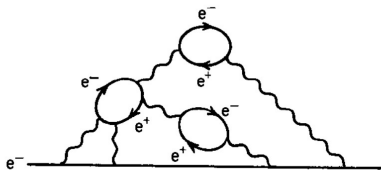
Measurements involving detected particles (final state) + simulations of different stages of the collisions allow us to investigate

- ☐ Energy deposition during the initial collision
- ☐ Pre-equilibrium dynamics of the QGP
- ☐ Viscous hydrodynamic evolution of the QGP
- ☐ Transition from the QGP to the hadronic phase, hadronic rescatterings, resonance decays to final state particles...

The higher the energy, the smaller the distance scale under investigation

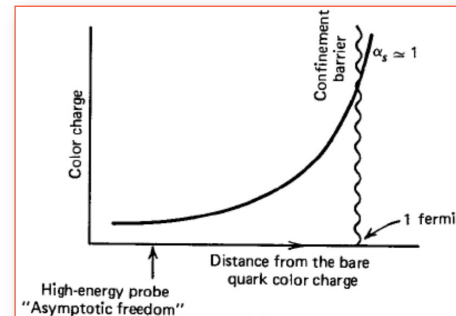
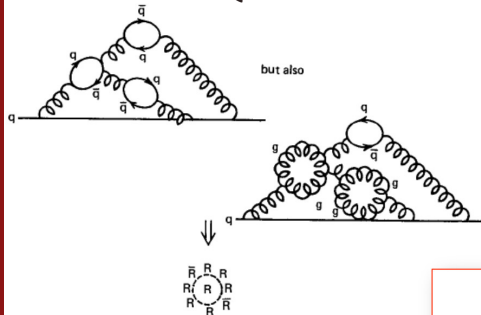
The strength of the interactions depends on the distance scale under investigation

Quantum electrodynamics (QED)

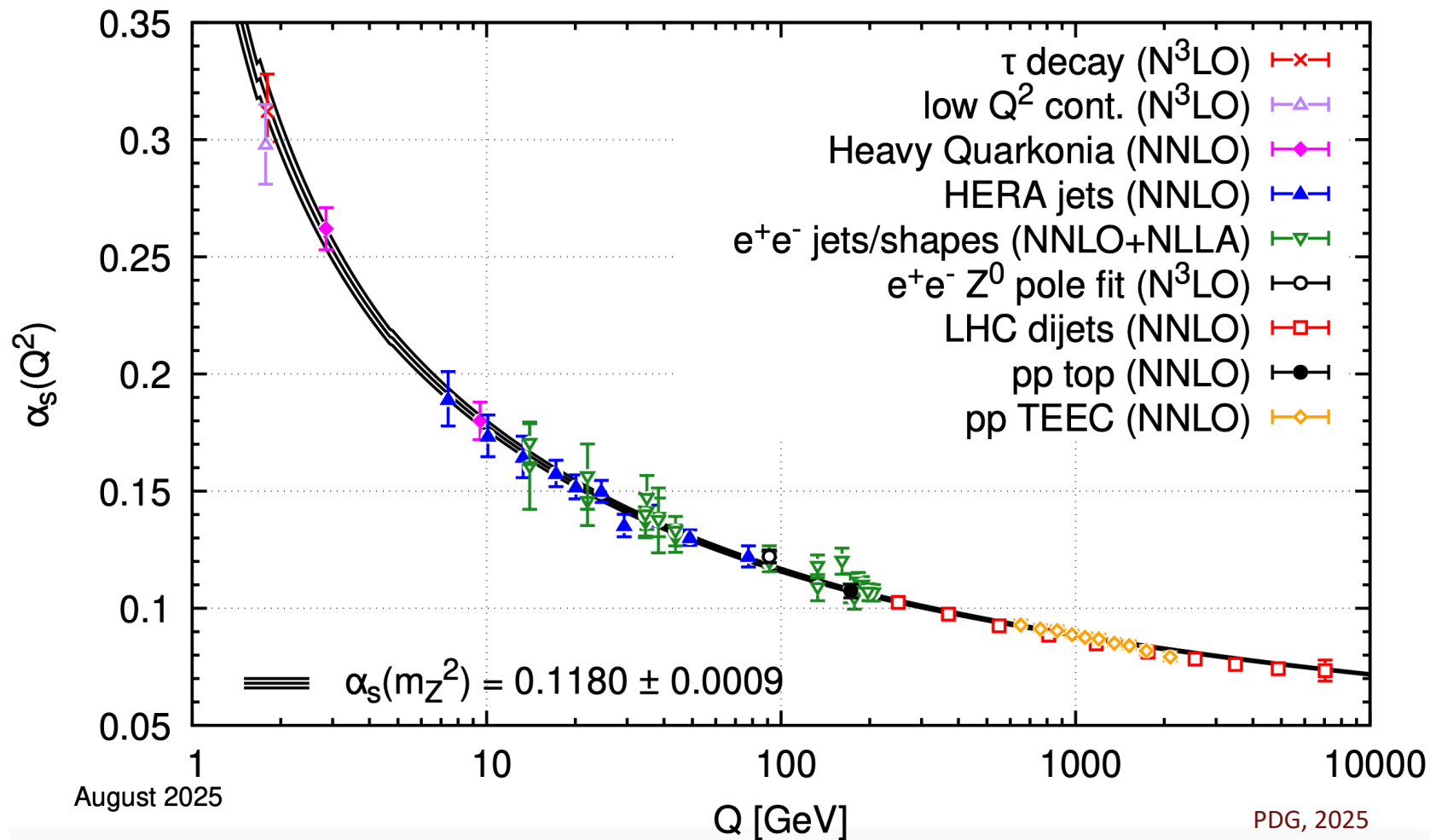


$\alpha \approx 1/137$ at low energies of $\mathcal{O}(m_e)$

Quantum chromodynamics (QCD)



Asymptotic freedom at high energies

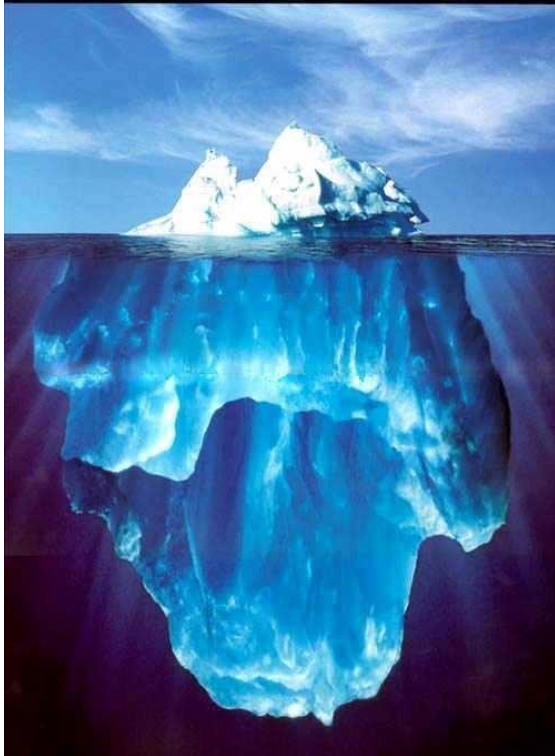


August 2025

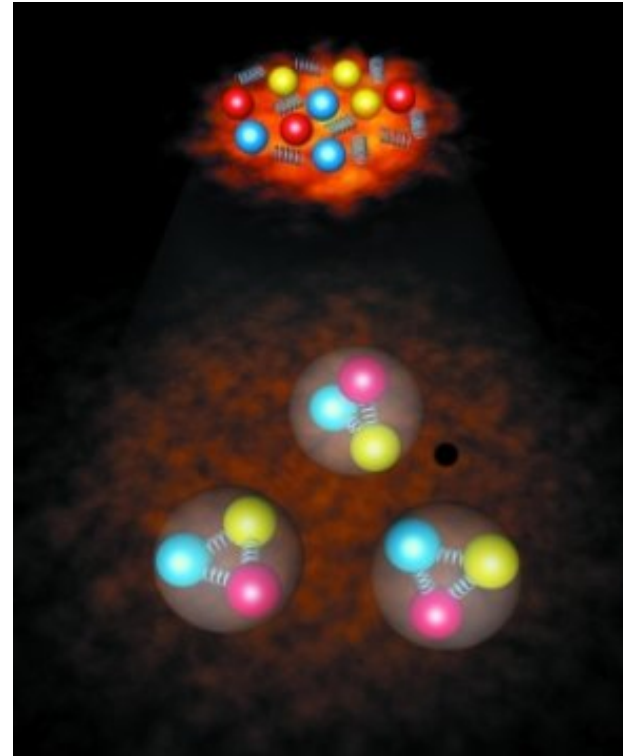
PDG, 2025

Phase transitions in matter

Ice - water

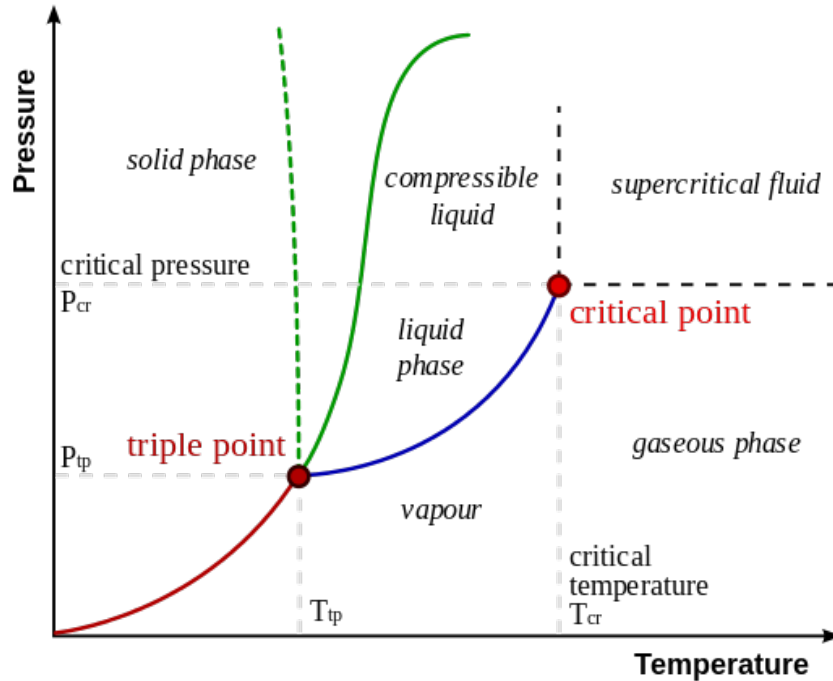


Hadron gas - QGP

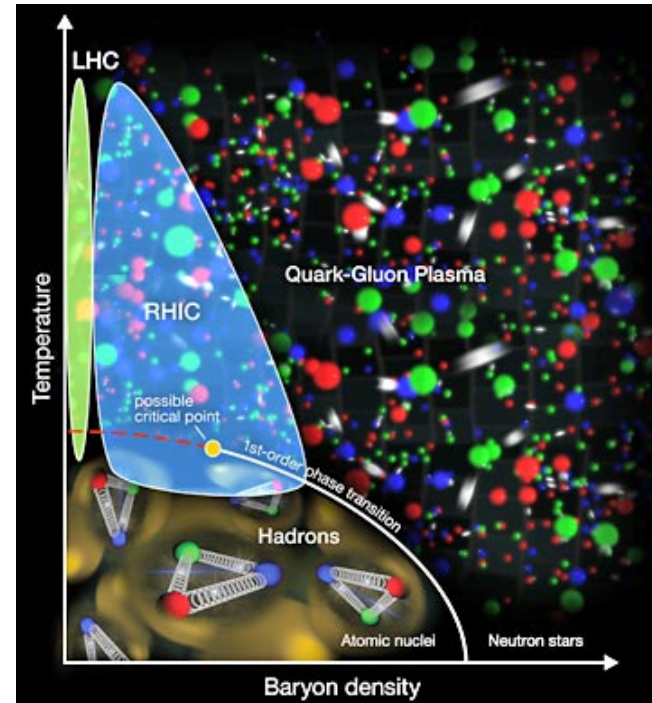


Water & QGP Phase Diagrams

Water phase diagram



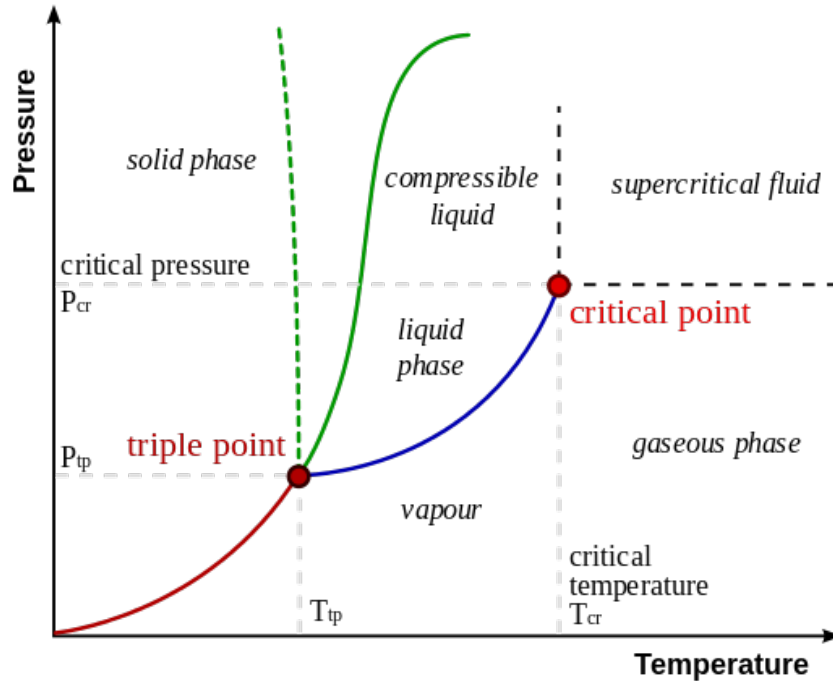
QCD phase diagram



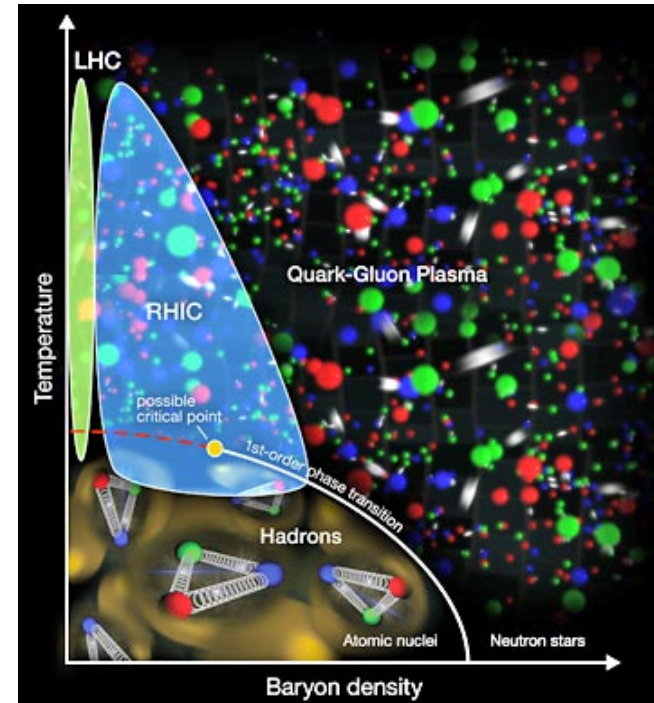
QCD predicts crossover to a system of liberated quarks and gluons for $T \sim 10^{12}$ K

Water & QGP Phase Diagrams

Water phase diagram



QCD phase diagram

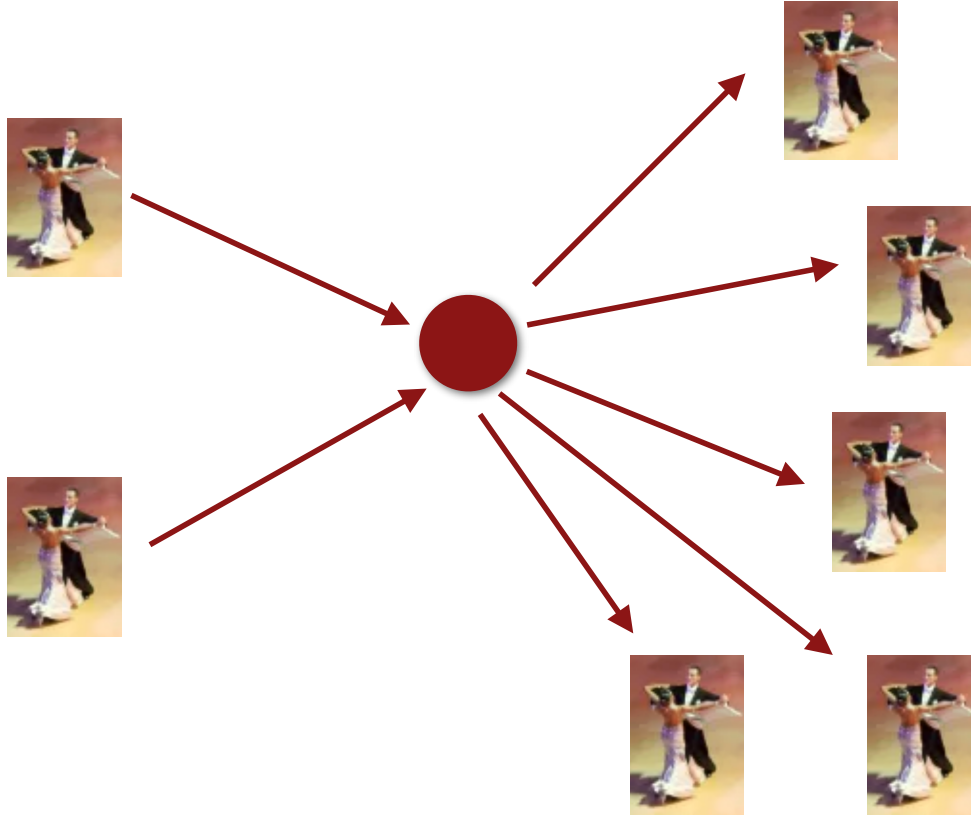


$$T \sim 10^{12} \text{ K} \sim 100,000 \times T_{\odot}^{\text{core}}$$

Ordinary low temperature matter has paired quarks



More pairs are created in the collisions

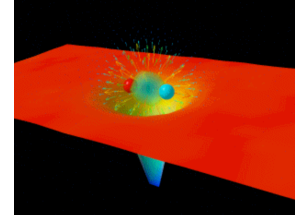
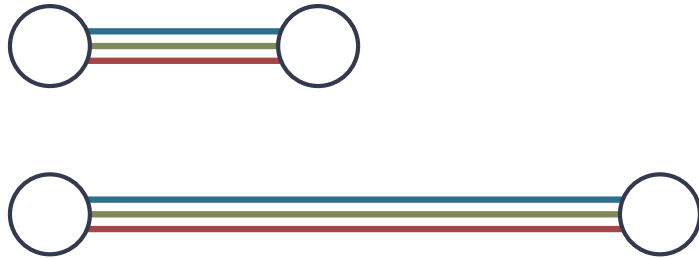


High energy collisions can create a lot of pairs...

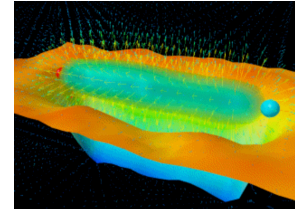


What that means?...Color screening

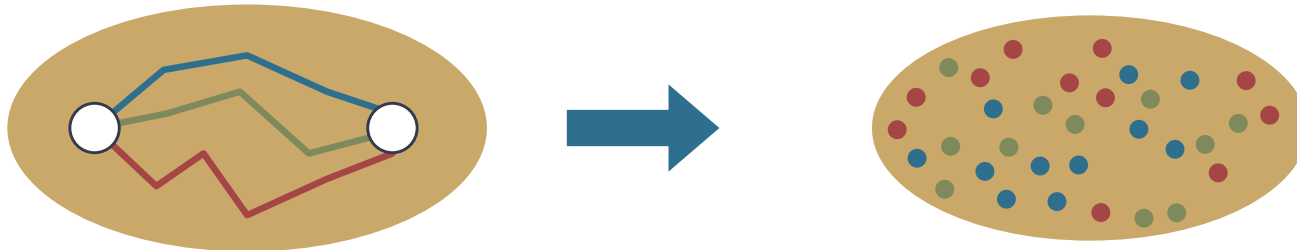
At low temperatures: color flux tube extends



[http://
www.physics.adelaide.edu.au
/ theory/staff/leinweber/
VisualQCD/Nobel/](http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/)



At high temperatures: color fields are screened due to the abundant production of thermal particles



A Brief History (I)

Pioneering studies on matter at extreme densities date back to

- ❑ Oppenheimer & Volkoff (1939): studies on neutron stars
- ❑ Densities much greater than those typically found in atomic nuclei $\approx 0.16 \text{ GeV/fm}^3$ or $\approx 2 \times 10^{14} \text{ g/cm}^3$

Gamow (1946): explored dense matter in the early universe

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Conflict among hadron models

- ❑ Bootstrap model: limiting temperature (Hagedorn, $T_H \sim 170 - 180 \text{ MeV}$ order of 10^{12} K), beyond which matter no longer heats up (but increasingly massive hadrons are created...)
- ❑ Quark model: hadrons composed of elementary particles... $\Rightarrow$ Primordial universe with "free" quarks

Gross, Wilzek, Politzer (1973): Asymptotic freedom in QCD

- ❑ Supporting the quark model

Collins & Perry, Cabibbo & Parisi: possibilities of deconfined states of matter & phase transitions (hadrons $\leftrightarrow$ quarks/gluons) at T_H (reinterpretation of T_H)

A Brief History (II)

Mid-1970s: Proton accelerators begin to be adapted to accelerate ions

CERN — ISR Collider (1980): first nuclear collisions between alpha particles (helium nuclei) at

$$\sqrt{s_{\text{NN}}} = 64 \text{ GeV}$$

CERN — SPS Collider (1986 & 1990): oxygen and later sulfur ions (energies up to

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$$\sqrt{s_{NN}} = 19.6 \text{ GeV})$$

CERN — PS & SPS (1994): Start of a program more focused on heavy-ion physics; PbPb to

$$\sqrt{s_{NN}} = 17.3 \text{ GeV and PbAu at } \sqrt{s_{NN}} = 8.6 \text{ GeV}$$

□ Early evidence of quark-gluon plasma

BNL (2000) — Relativistic Heavy Ion (RHIC) Collider: AuAu at $\sqrt{s_{NN}} = 130 \text{ GeV}$

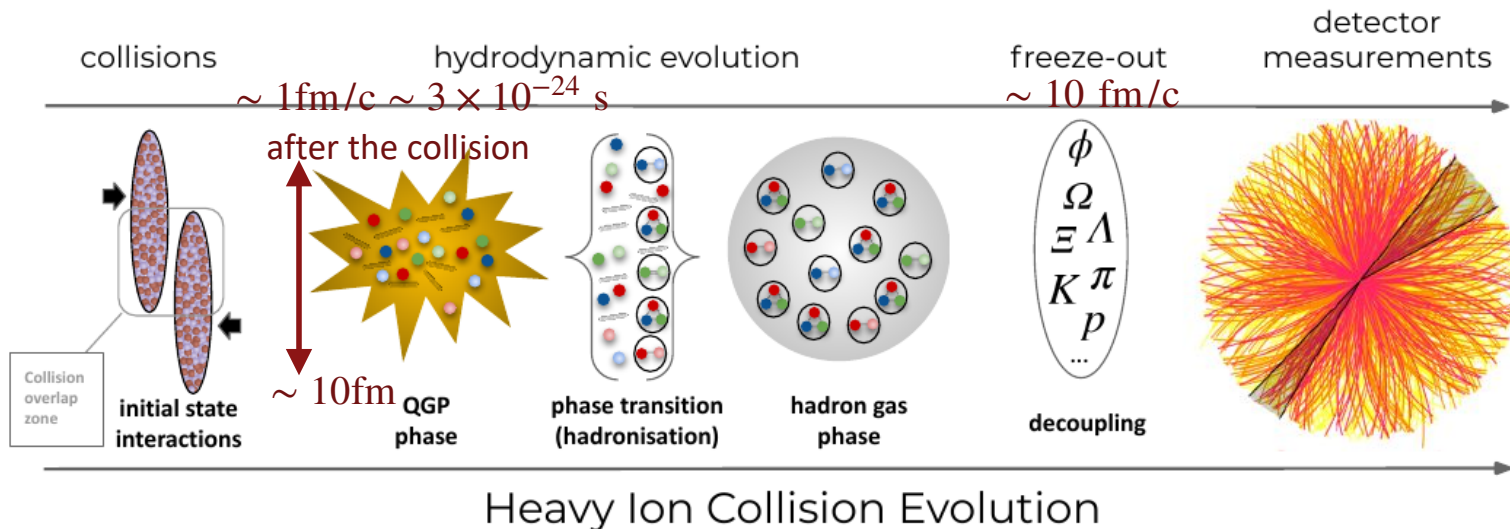
□ 2004: discovery of the QGP (a nearly perfect liquid!)

CERN (2010) — LHC: PbPb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

Hybrid model of the heavy ion collisions (I)

Experimental measurements + simulations $\Rightarrow$ Hybrid model to describe ultrarelativistic heavy ion collisions

- Support the formation of a liquid phase (QGP) in local equilibrium (strongly coupled) and with extremely low specific viscosity (η/s)



Hybrid model of the heavy ion collisions (II)

Describes the following stages

- ❑ **Initial stage:** nuclei with enormous Lorentz contraction collide, generating a system completely out of equilibrium and with extremely high energy density
- ❑ **Thermalization (pre-equilibrium stage):** the system thermalizes locally rapidly (timescale of ~ 1 fm/c) forming the QGP

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- ❑ **Hydrodynamic expansion:** QGP expands and cools, converting spatial anisotropies into momentum anisotropies
- ❑ **Hadronization:** QGP transforms into hadrons when it reaches a critical temperature (~ 150 MeV)
- ❑ **Freeze-out:** hadrons cease interactions (inelastic and elastic) and propagate freely

Hybrid model of the heavy-ion collisions (III)

Phases described by the theories/models (some examples)

Comput. Phys. Commun. **199**, 61 (2016); Phys. Rev. C **95**, 064913 (2017);
arXiv:1903.07706; Phys. Rev. C **103**, 054909 (2021).

- ❑ **Early stage & initial conditions & thermalization:** Color Glass Condensate effective theory, Glauber's Monte Carlo Models, Event-by-Event initial conditions [IP-Glasma, TRENTo (parametric initial states)], Kinetic theory, AdS/CFT Holography...
- ❑ **Hydrodynamic expansion:** Viscous relativistic hydrodynamics [MUSIC, vHLLE, CLVisc]

Hybrid model of the heavy-ion collisions (III)

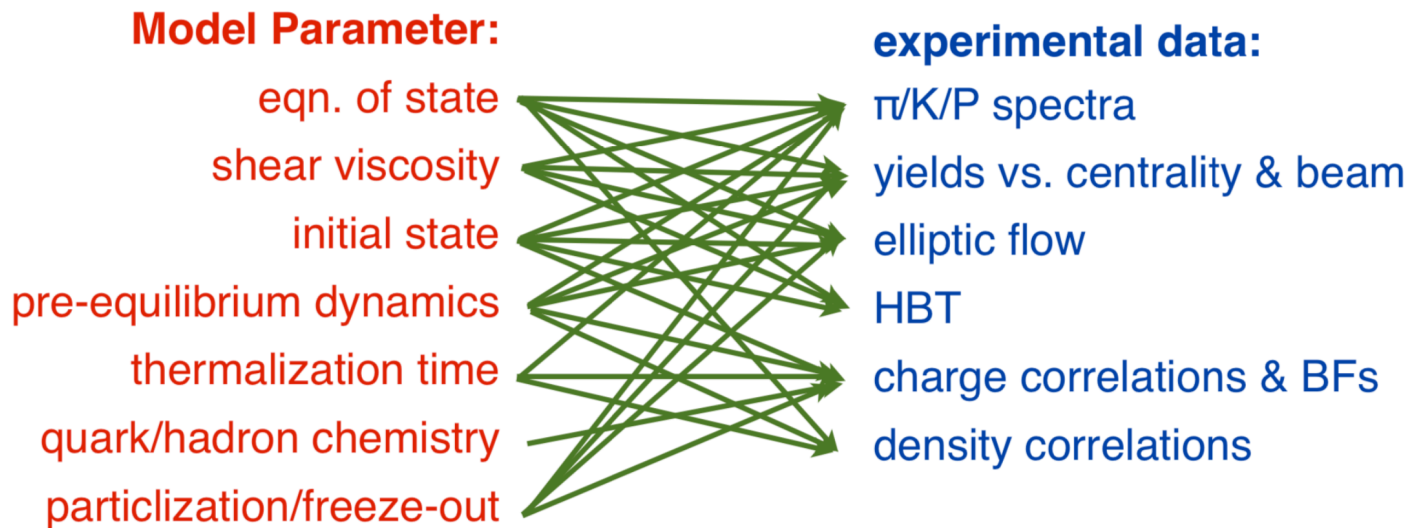
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- ❑ **Hydrodynamic expansion:** Viscous relativistic hydrodynamics [MUSIC, vHLLE, CLVisc]
- ❑ **Hadronization:** Statistical Hadronization [predicts yields via Hadron Resonance Gas (HRG) models], Recombination/Coalescence [intermediate pT]
- ❑ **Freeze-out:** Hadronic transport [simulates elastic/inelastic scatterings of hadrons], Codes [UrQMD, SMASH, THERMINATOR]

General problem

From Chun Shen, hadrons 2025



<https://github.com/MADAI/DistributionSampling>

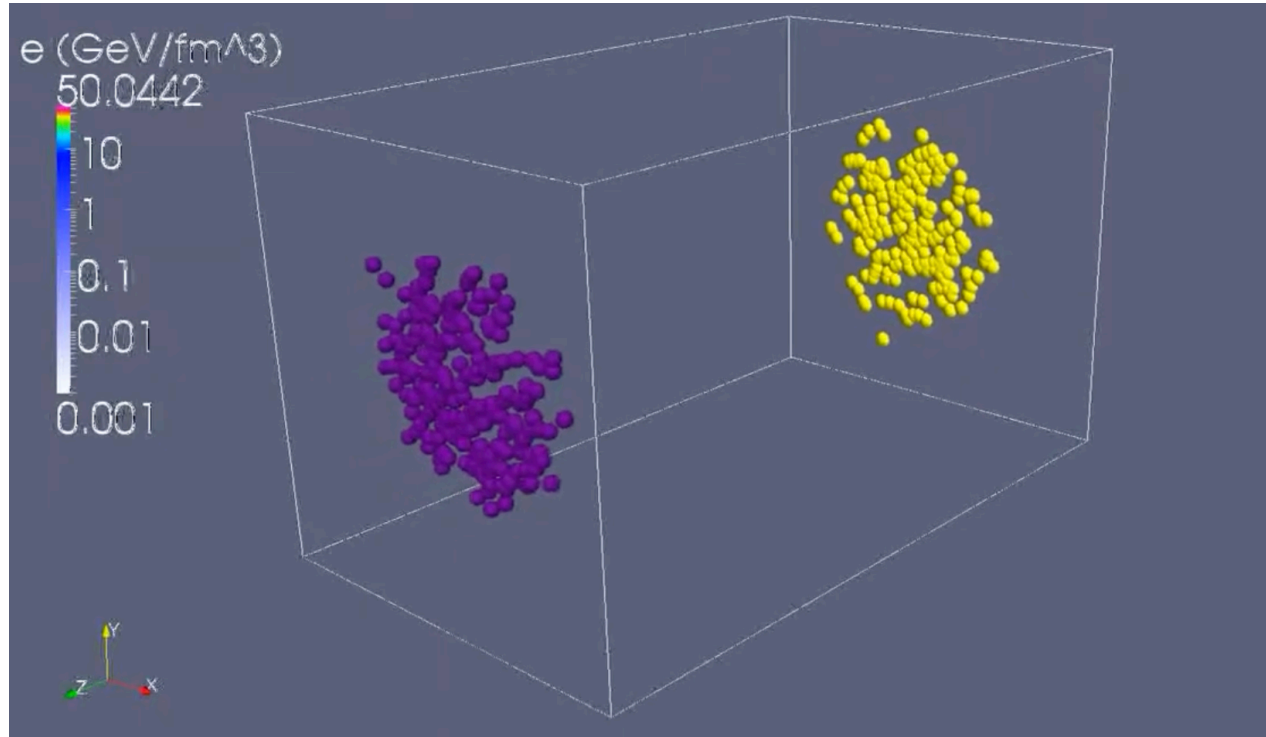
Very difficult to tune all parameters and fit by hand

Usually applies optimization techniques: Bayesian statistics and MCMC methods

Very complex models require too much CPU usage $\Rightarrow$ Use emulators

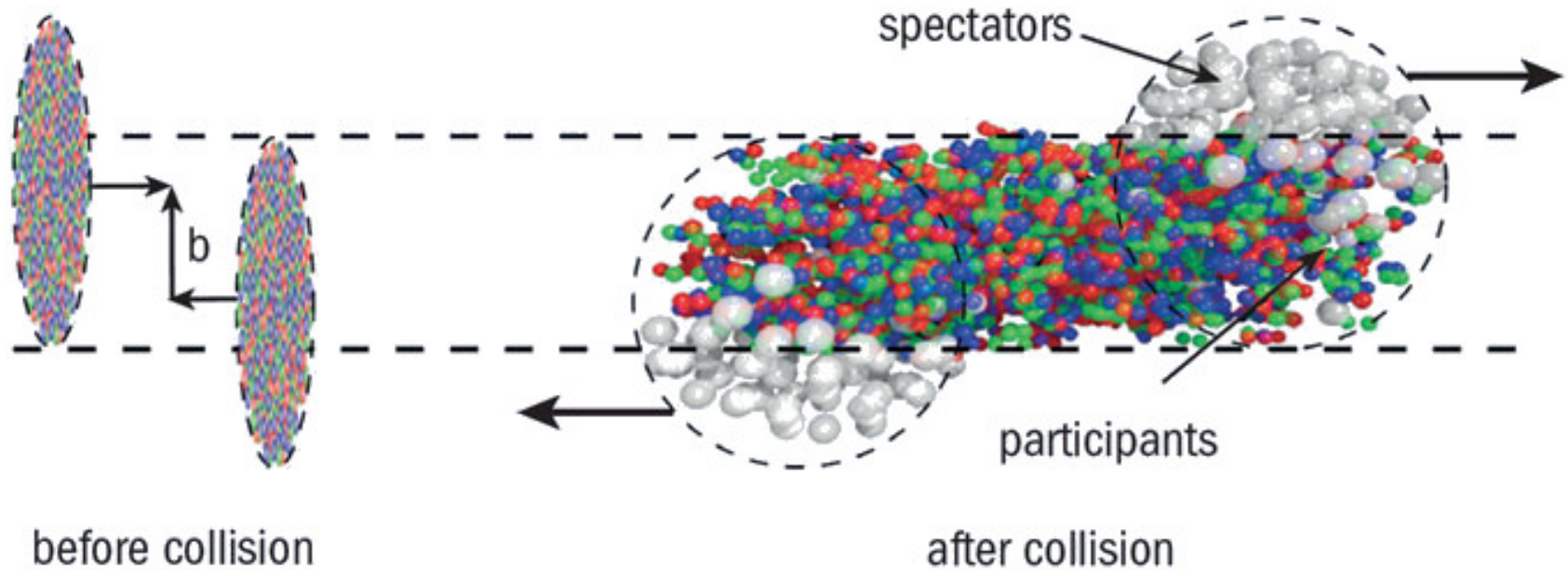
Simulation

<http://youtu.be/W3h5vQOUJTg>



Is it possible to measure the impact parameter of each collision?

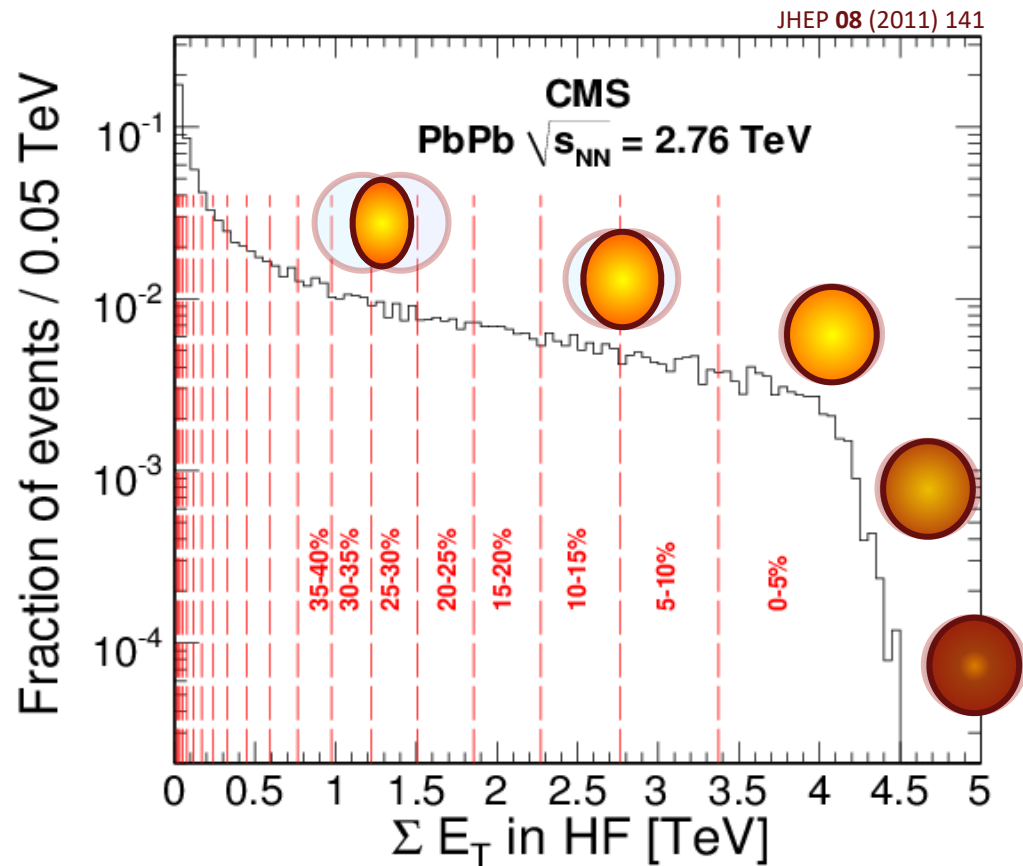
No. Can use a quantity to classify collisions (proxy for b)



Centrality of the collision

Experimentally: sum of the transverse energy or number of charged particles produced in the collision.

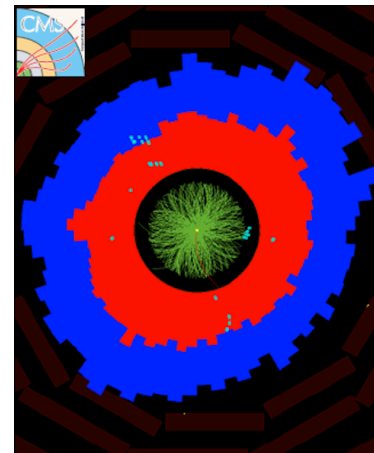
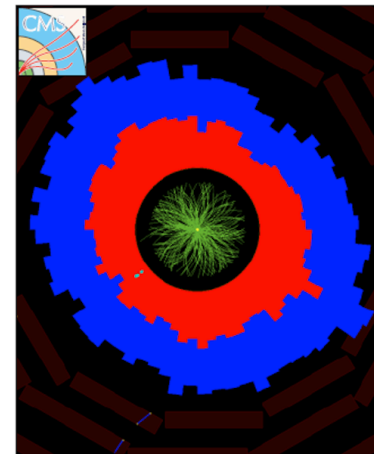
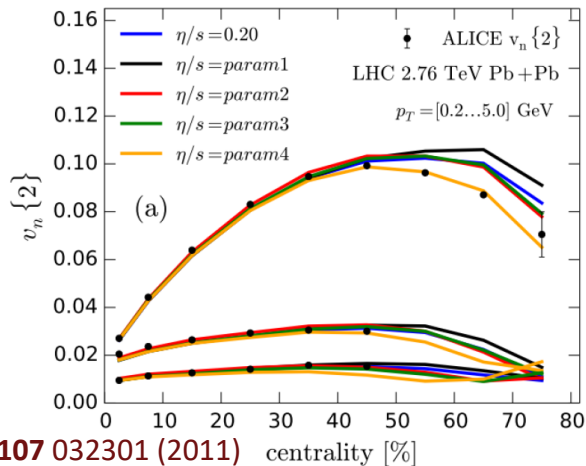
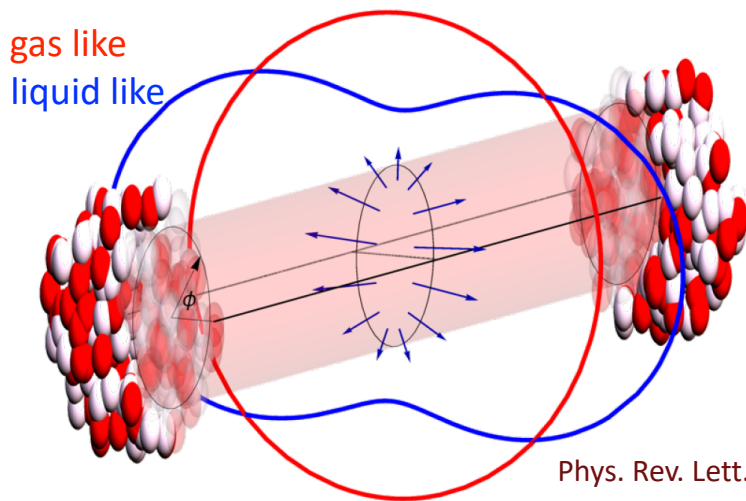
Monotonic relationship with the impact parameter



QGP Signatures: Flow

Initial geometry + fluctuations in the positions of nucleons within the nuclei

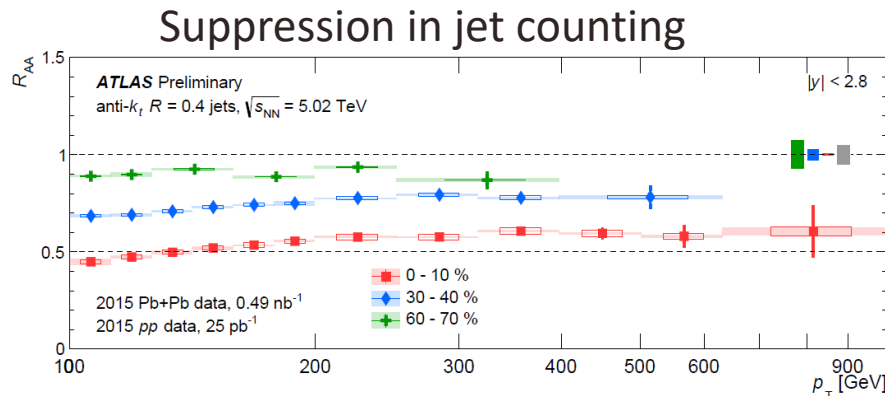
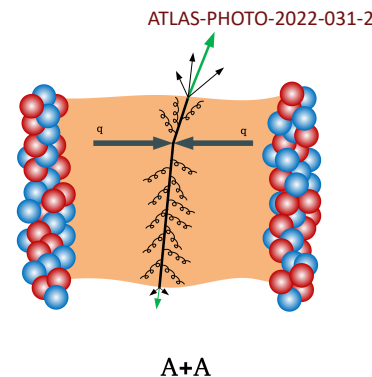
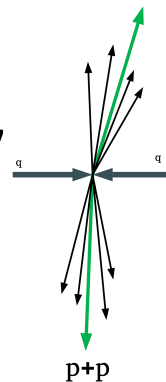
- Generate anisotropy in the initial pressure $\Rightarrow$ anisotropy in the momentum space of the particles in the final state



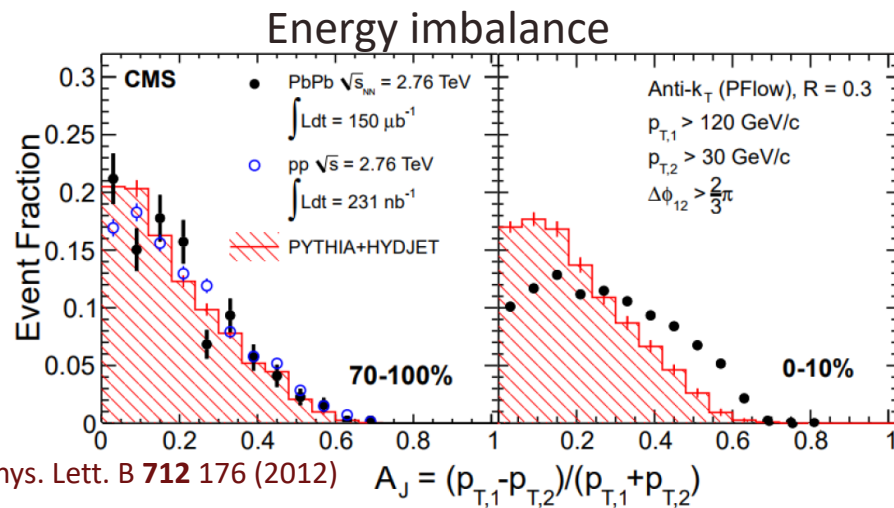
QGP Signatures: Jet Quenching

Energy loss of partons (quarks and gluons)
with high transverse momentum as they
traverse a medium

- Evidence of a predominance of strong interaction



ATLAS-CONF-2017-009



Phys. Lett. B **712** 176 (2012)

$$A_J = (p_{T,1} - p_{T,2}) / (p_{T,1} + p_{T,2})$$

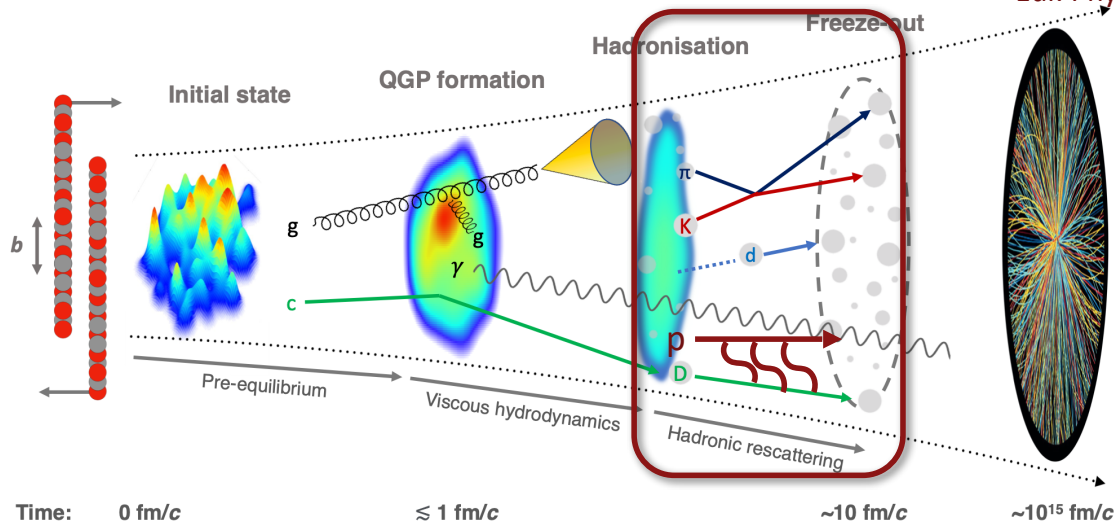
Physics after hadron emission

Femtoscopic correlations between two particles: access to the "effective size" of the particle-emitting source

- ❑ Origin: interference between wave functions of identical emitted particles

Interactions (strong and Coulomb) between hadrons in the final state

- ❑ Searches for exotic states, neutron star physics, etc...



Adapted from
Eur. Phys. J. C **84** 813 (2024)

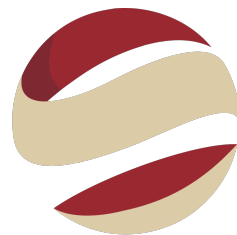
Some open questions

How does this super-fast transition (~ 1 fm/c) from a completely non-equilibrium state to QGP occur?

Does thermodynamic equilibrium actually occur, at least locally?

Is QGP formation present in collisions of smaller systems, such as proton-proton (pp) and proton-nucleus (pPb) collisions?

Phys. Ann. Rev. of Nucl. and Part. Sci. **68** 339 (2018)



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Data analysis of heavy ion collisions

**TWO EXAMPLES FROM THE CMS
COLLABORATION AT CERN**

Two examples in the CMS collaboration

Correlations and flow

- ❑ Flow analyses involving charged hadrons and D^0 mesons
 - Precision measurements and searches for the effects of electromagnetic fields generated by spectators and participants in the collision

- ❑ Analysis of correlations between mean transverse momentum $\langle p_T \rangle$ and multiplicity N_{ch}
 - Ultra-central collisions (UCCs) of PbPb and pPb

Data from the LHC CMS experiment

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS

Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

Tracker

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying $\sim 18,000\text{A}$

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER

Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

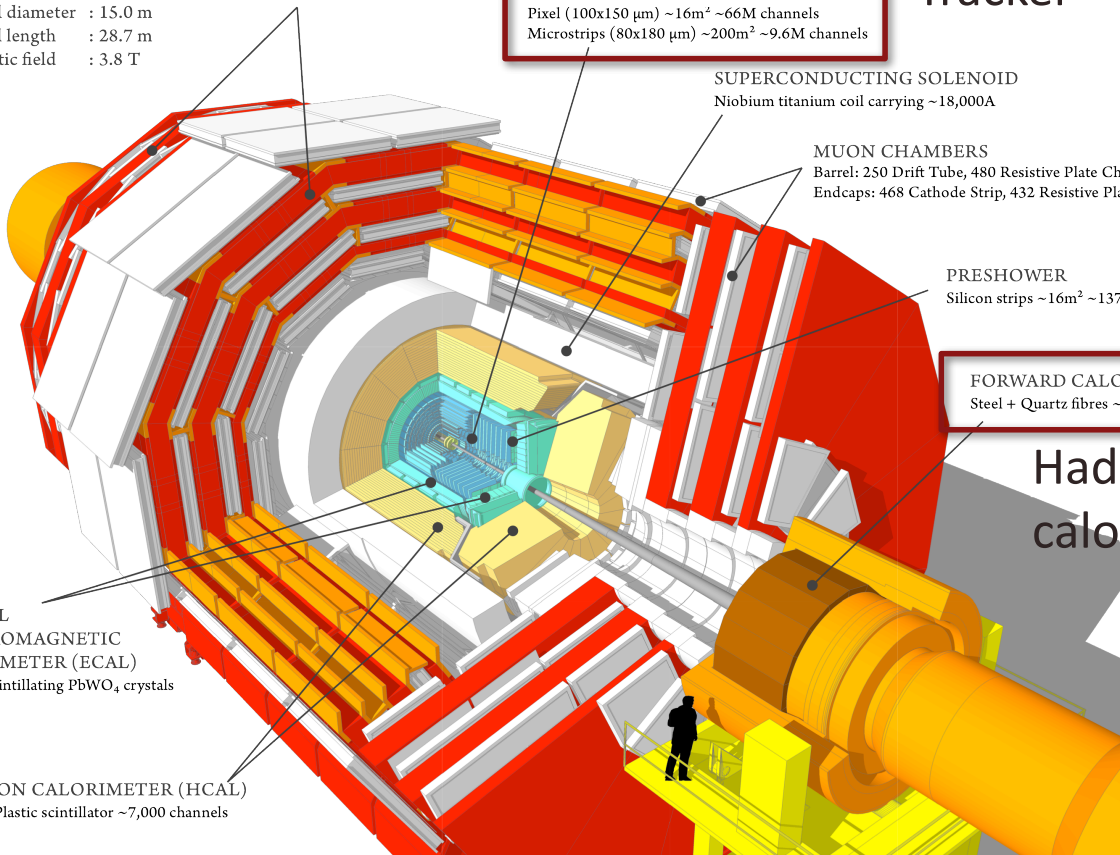
FORWARD CALORIMETER

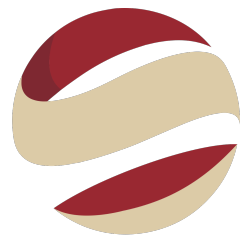
Steel + Quartz fibres $\sim 2,000$ Channels

Hadronic Forward calorimeter (HF)

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels



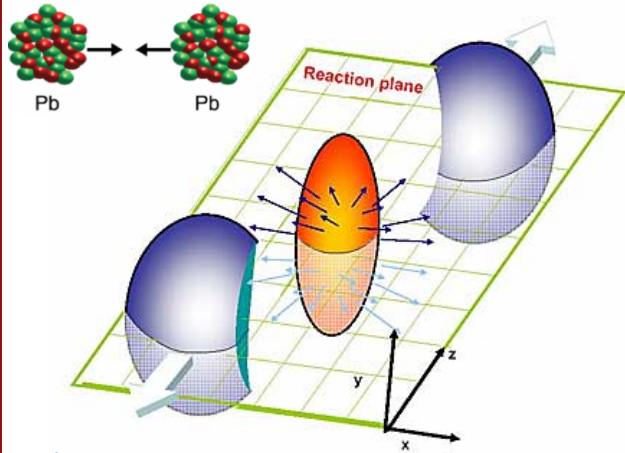


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Flow with heavy flavor hadrons

Azimuthal correlations of two particles

Initial anisotropy of geometry and pressure...

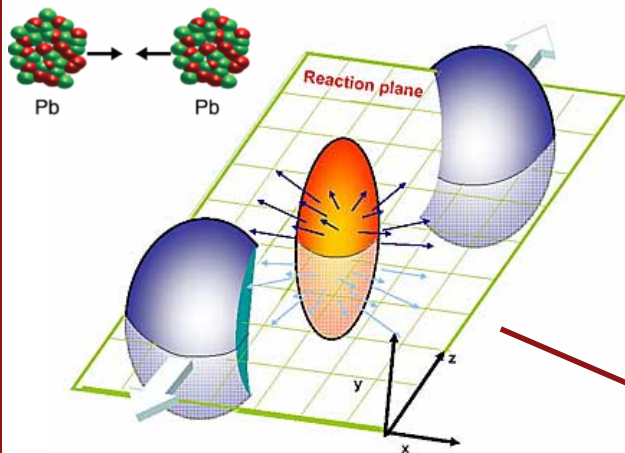


(Pre-equilibrium dynamics +
Hydrodynamic expansion)

...are converted into anisotropy in
momentum space $\Rightarrow$ correlation
between two particles

Azimuthal correlations of two particles

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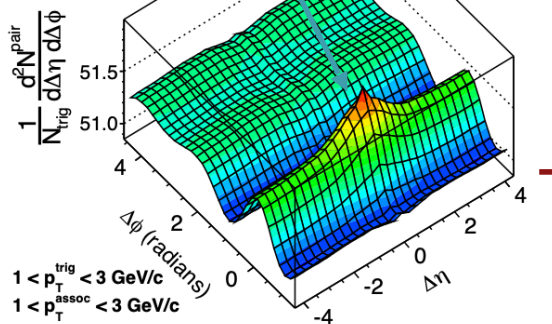


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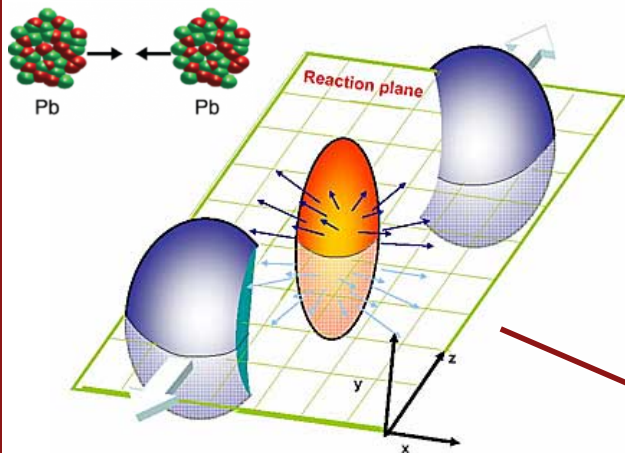
Jet fragmentation,
femtoscopic correlations, etc.

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV
 $L_{int} = 120 \mu b^{-1}$
0-0.2% centrality



Azimuthal correlations of two particles

Initial anisotropy of geometry and pressure...



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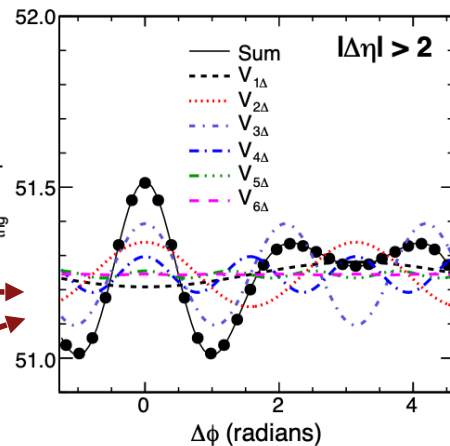
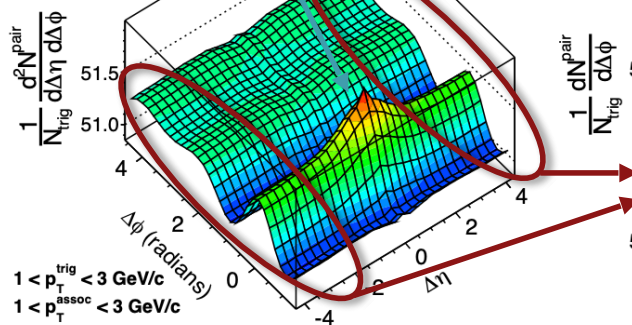
Projecting in $\Delta\phi$ long-range ($|\Delta\eta| > 2$)

$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi} \left(1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right)$$

$$V_{n\Delta} = v_n^2$$

Jet fragmentation, femtosopic correlations, etc.

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV
 $L_{int} = 120 \mu b^{-1}$
 0-0.2% centrality



In models with hydrodynamic phase: v_2 (elliptical flow) & v_3 (triangular flow)
 Provides links with QGP transport properties (e.g. η/s)

Why study hadrons composed of b and c quarks?

b and c quarks are generally produced in pre-QGP stages

$\sim 0.1 \text{ fm}/c$

$m_{c/b} \gg$ typical temperatures of the environment $\Rightarrow$ without thermal production (go through the entire evolution of the system)

What influences the flow of these heavy quarks?

- ❑ Low- p_T : hydrodynamics + scattering with elements of the medium
- ❑ Entire p_T range: coalescence effects
- ❑ High p_T : radiative energy loss

Langevin diffusion modeling

- ❑ Energy loss due to scattering with elements of the medium

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Phys. Rev. C **90** 024911 (2014)

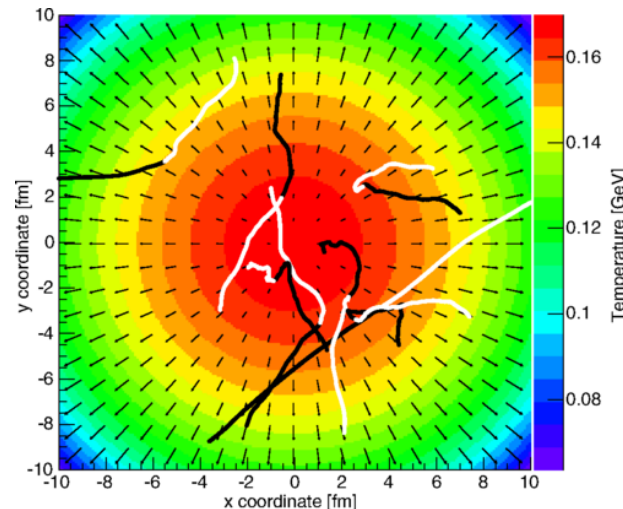


Illustration corresponding to some trajectories of pairs $c\bar{c}$ in the expanding medium after $10 \text{ fm}/c$, in the laboratory frame of reference

Why study hadrons composed of b and c quarks?

Searching for the effects of intense electromagnetic (EM) fields created in early stages of the collisions

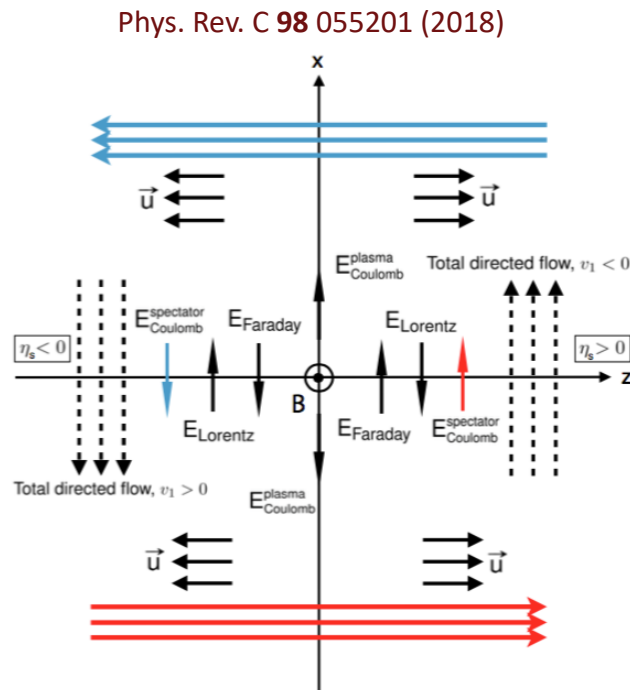
☐ Measurements can link electrical conductivity of the QGP

- If the QGP is created, it should influence the duration of the EM field

☐ Δv_n between particles of opposite charges sensitive to EM fields

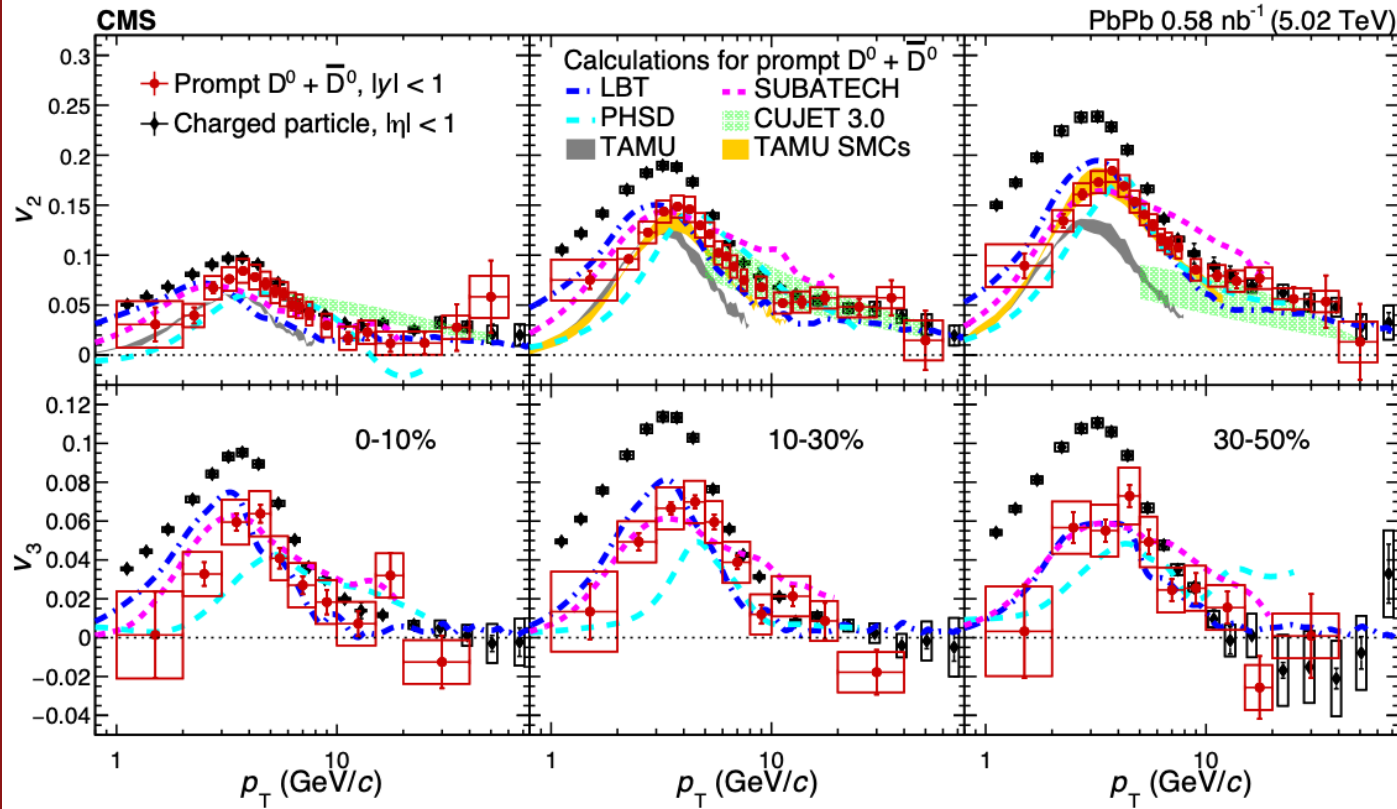
- Especially between D^0 and $\bar{D}^0$, as $c\bar{c}$ are created in stages where the intensity is expected to be at its maximum

Phys. Rev. C **98** 055201 (2018)



Some results with mesons D^0 (I)

In general, good quantitative description by the models



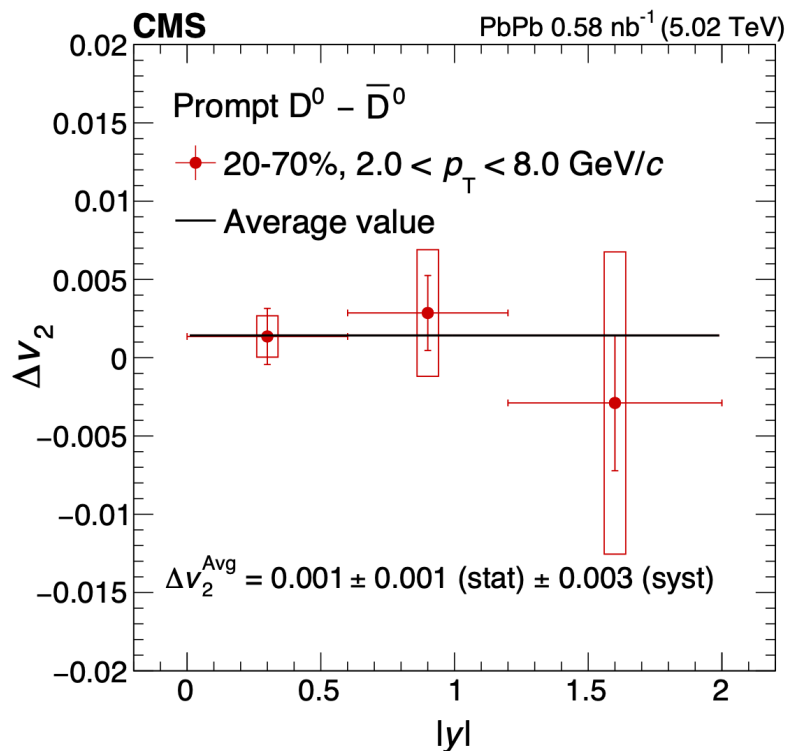
Phys. Lett. B **816** 136253 (2021)

v_2 and v_3 are systematically below the corresponding values for charged hadrons (mostly pions)

Need for reduction of experimental uncertainties

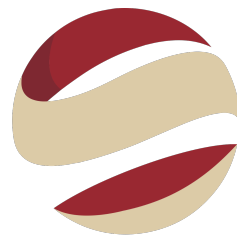
Some results with mesons D^0 (II)

Note: Often, the dominant uncertainties are not statistical...



Phys. Lett. B **816** 136253 (2021)

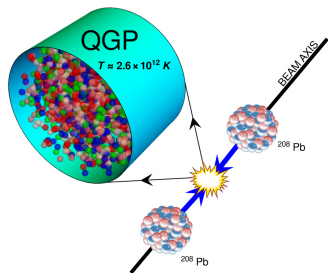
$$\Delta v_2^{\text{Fit}} = 0.001 \pm 0.001 \text{ (stat)} \pm 0.003 \text{ (syst)}$$



SPRACE

Access to thermodynamic properties of QCD under extreme conditions

Thermodynamics of QCD under extreme conditions



Thermodynamics of hot strong-interaction matter from ultrarelativistic nuclear collisions

Fernando G. Gardim^{1,2}, Giuliano Giacalone², Matthew Luzum³ and Jean-Yves Ollitrault²  

QGP at freezeout with
entropy S and energy E

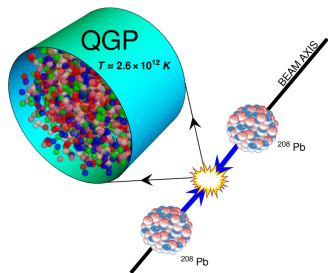
A homogeneous fluid at rest
with V_{eff} and T_{eff}



$$E = \int_{f.o.} T^{0\mu} d\sigma_{\mu} = \epsilon(T_{eff}) V_{eff}$$

$$S = \int_{f.o.} s u^{\mu} d\sigma_{\mu} = s(T_{eff}) V_{eff}$$

Thermodynamics of QCD under extreme conditions



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Speed of sound in this effective system

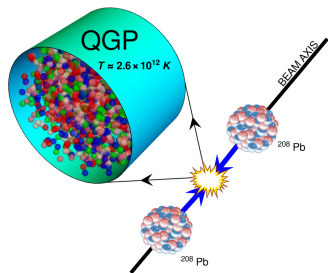
$$c_s^2(T_{eff}) = \frac{dP}{d\epsilon} = \frac{s dT}{T ds} = \frac{d \ln \langle p_T \rangle}{d \ln (dN_{ch}/d\eta)}$$

Key considerations:

$$1) S \sim N_{ch} ; 2) T_{eff} \sim \langle p_T \rangle / 3 ; 3) dV_{eff} = 0$$

Limitations discussed in: Sun, Yan arXiv:2407.05570, Gavassino et al. arXiv:2503.20765

Thermodynamics of QCD under extreme conditions



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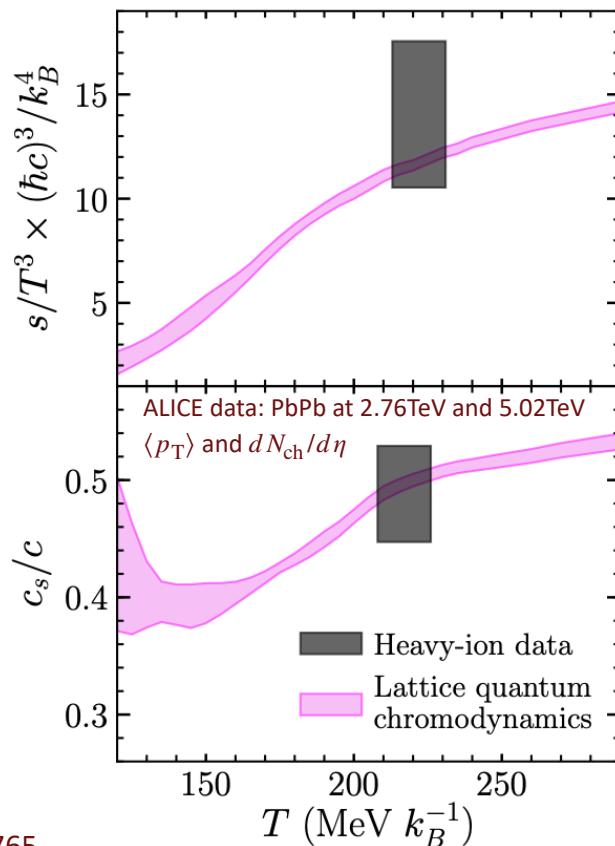
Speed of sound in this effective system

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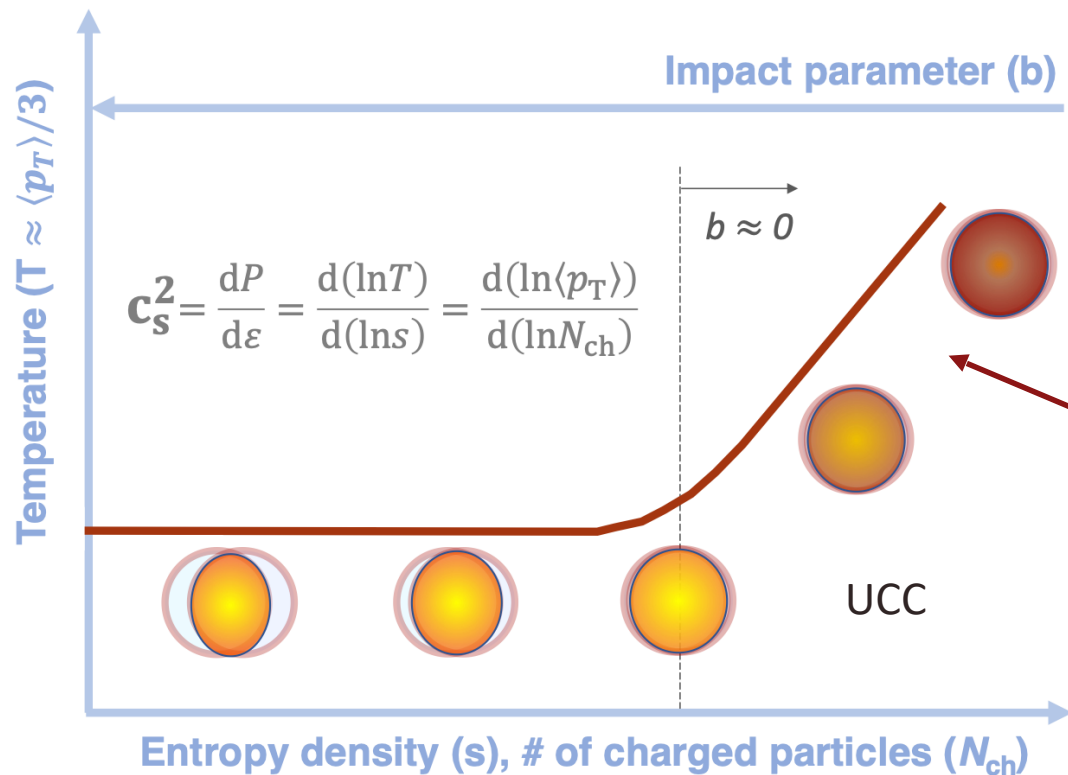
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Limitations discussed in: Sun, Yan arXiv:2407.05570, Gavassino et al. arXiv:2503.20765



Speed of sound in ultra central heavy ion collisions (UCC)

Non-trivial prediction of relativistic hydrodynamics



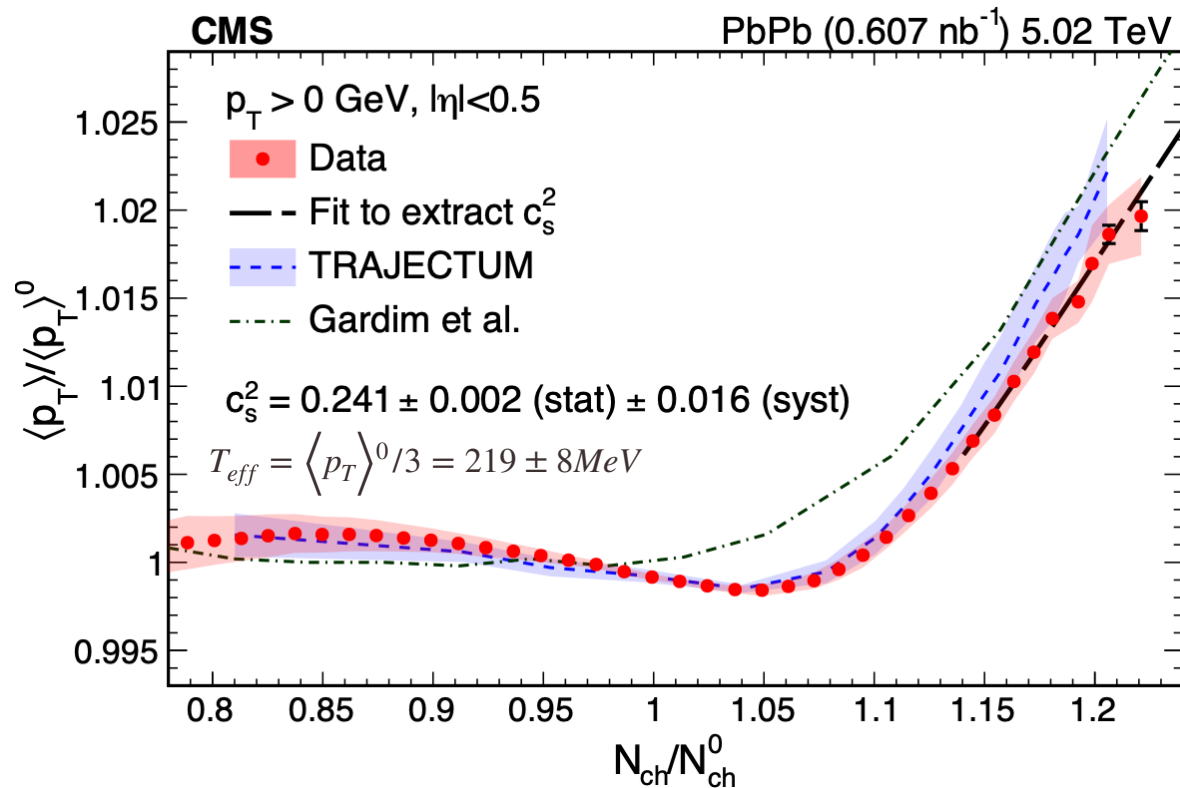
Proposed by

Gardim et. al. Phys. Lett. B **809** (2020) 135749

$$\frac{\langle p_T \rangle}{\langle p_T \rangle^0} \sim \left(\frac{N_{ch}}{N_{ch}^0} \right)^{c_s^2}$$

Extracting the speed of sound in UCC collisions

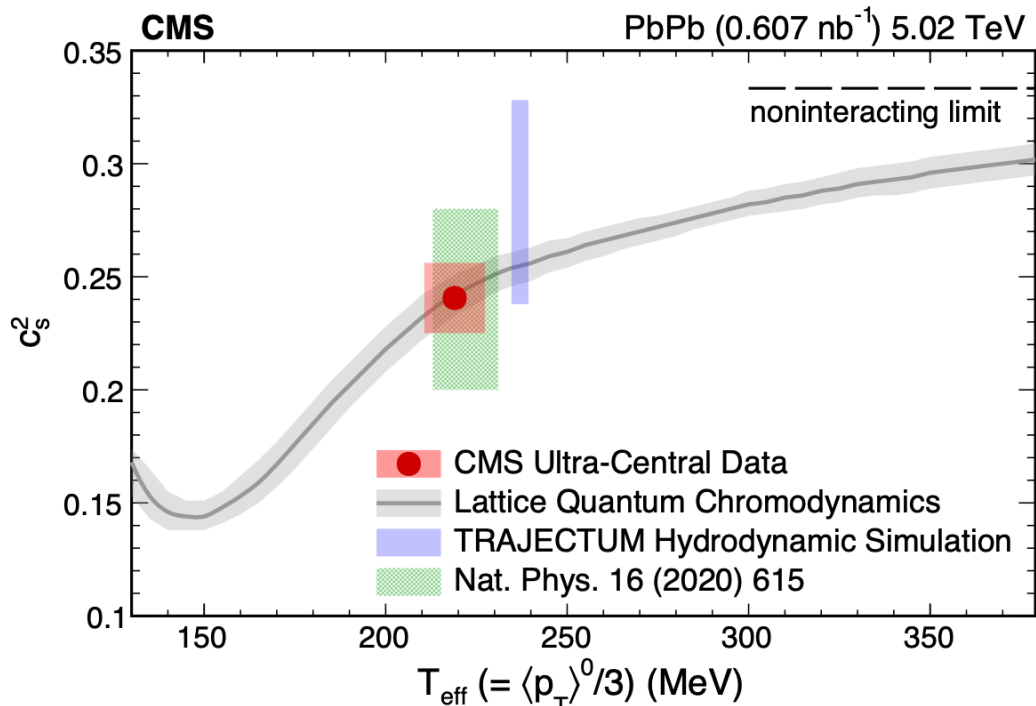
The signature was observed in the LHC data!



Rep. Prog. Phys. **87**, 077801 (2024)

Extracting the speed of sound in UCC collisions

Good agreement with Lattice QCD, with results using the two-energy method and simulations including hydrodynamic phase (Trajectum)

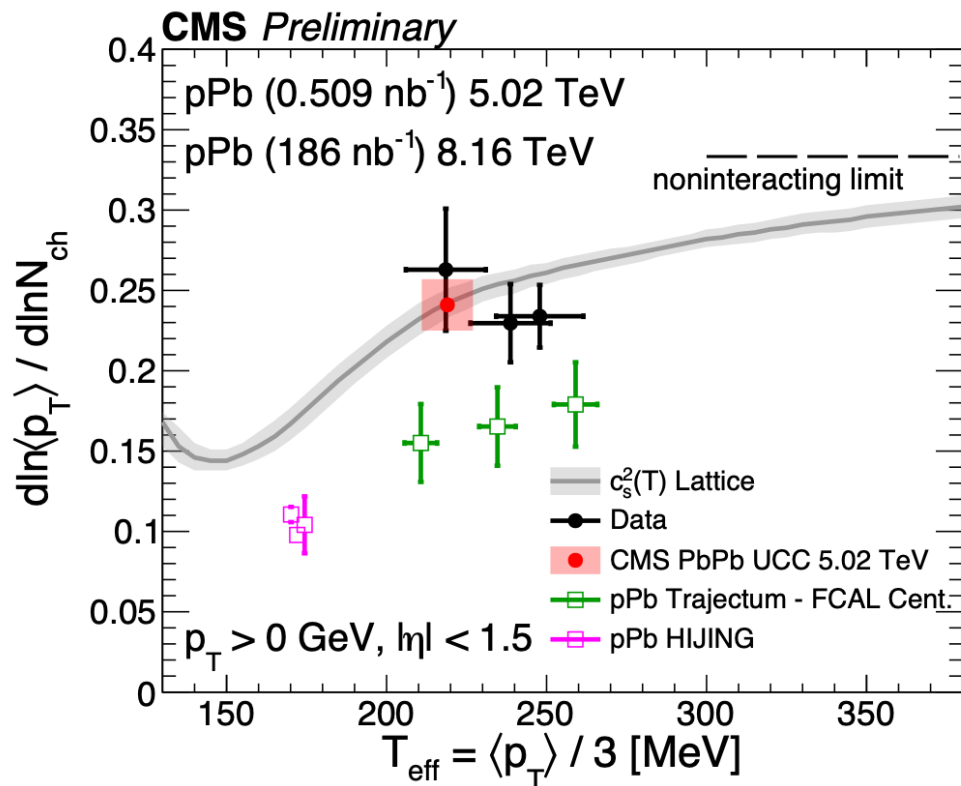


Rep. Prog. Phys. **87**, 077801 (2024)

Lattice QCD ($\mu \approx 0$ and 2+1 flavors)

What happens if we measure $\langle p_T \rangle$ vs. N_{ch} in pPb?

Using pPb at 5.02 TeV and 8.16 TeV and applying a two-energy method



CMS PAS HIN-25-001

pPb collisions: it is unclear whether QGP formation occurs or not

HIJING without QGP simulations incompatible with the data

Closer to the simulations with Trajectum that uses hydrodynamics

Next years: experiments

LHC

- ❑ Analyse Run3 data (PbPb, OO, NeNe, pO)
- ❑ Prepare for Run4 (starts around 2030): PbPb, light ions, pPb???
- ❑ High energy and high luminosity frontier, precision measurements of rare probes...

RHIC

- ❑ Completed operation, but a lot of data to be analyzed
- ❑ Several collision systems (AuAu, UU, RuRu, ZrZr, ...) and energies O(10) - O(100) GeV
- ❑ Probing QCD at high net baryon density, heavy quarks, etc...

Electron-Ion Collider (EIC)

- ❑ Expect to start physics program in 2035
- ❑ Origin of the spin and mass of the nucleons, gluon density in nuclei, etc...

Several other important experiments running/planned in different accelerators: SPS at CERN, FAIR at Darmstadt, etc...

Summary

Physics in ultrarelativistic heavy-ion collisions

- ❑ It should maintain intense development in the coming decades...
- ❑ New LHC configurations and detectors...new accelerators...etc...

Sorry...I left out many topics...

- ❑ Ultra-peripheral collisions ($\gamma\gamma$, γA)
- ❑ Searching for the critical point in the phase diagram
- ❑ Quarkonia suppression and regeneration
- ❑ Photon production
- ❑ ...

Literature

CERN Summer Student Lectures 2018

Lectures

- J. Stachel, K. Reygers (2011), http://www.physi.uni-heidelberg.de/~reygers/lectures/2011/qgp/qgp_lecture_ss2011.html
- P. Braun-Munzinger, A. Andronic, T. Galatyuk (2012), http://web-docs.gsi.de/~andronic/intro_rhic2012/
- Quark Matter Student Day (2014), <https://indico.cern.ch/event/219436/timetable/#20140518.detailed>
- Quark Matter Student Day (2018), <https://indico.cern.ch/event/656452/timetable/#20180513.detailed>

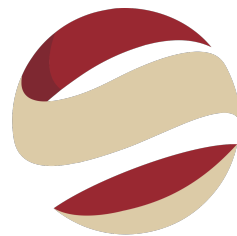
Books

- C.Y. Wong, Introduction to High-Energy Heavy-Ion Collisions, World Scientific, 1994, <http://books.google.de/books?id=Fnxvrdj2NOQC&printsec=frontcover>
- L. P. Csernai, Introduction to Relativistic Heavy-Ion Collisions, 1994 (**free as pdf**), <http://www.csernai.no/Csernai-textbook.pdf>
- E. Shuryak, The QCD vacuum, hadrons, and superdense matter, World Scientific, 2004, <http://books.google.de/books?id=rbcQMK6a6ekC&printsec=frontcover>
- Yagi, Hatsuda, Miake, Quark-Gluon Plasma, Cambridge University Press, 2005, <http://books.google.de/books?id=C2bpxwUXJngC&printsec=frontcover>
- R. Vogt, Ultrarelativistic Heavy-ion Collisions, Elsevier, 2007, <http://books.google.de/books?id=F1P8WMESgkMC&printsec=frontcover>
- W. Florkowski, Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, World Scientific, 2010, <http://books.google.de/books?id=4gIp05n9Iz4C&printsec=frontcover>
- S. Sarkar, H. Satz and B. Sinha, The physics of the quark-gluon plasma, Lecture notes in physics, Volume 785, 2010 (**free within CERN/university network**) <https://link.springer.com/book/10.1007%2F978-3-642-02286-9>



SPRACE

Thank You!!!

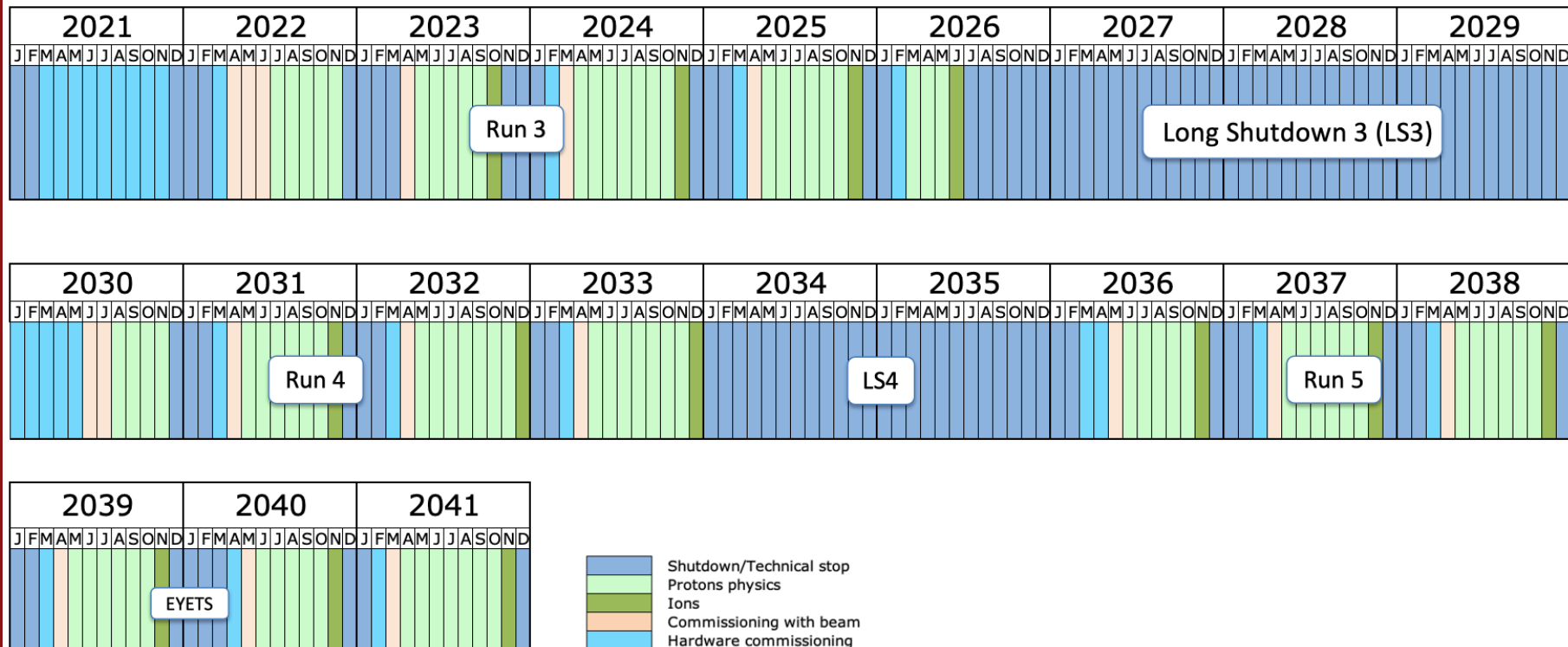


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Backup

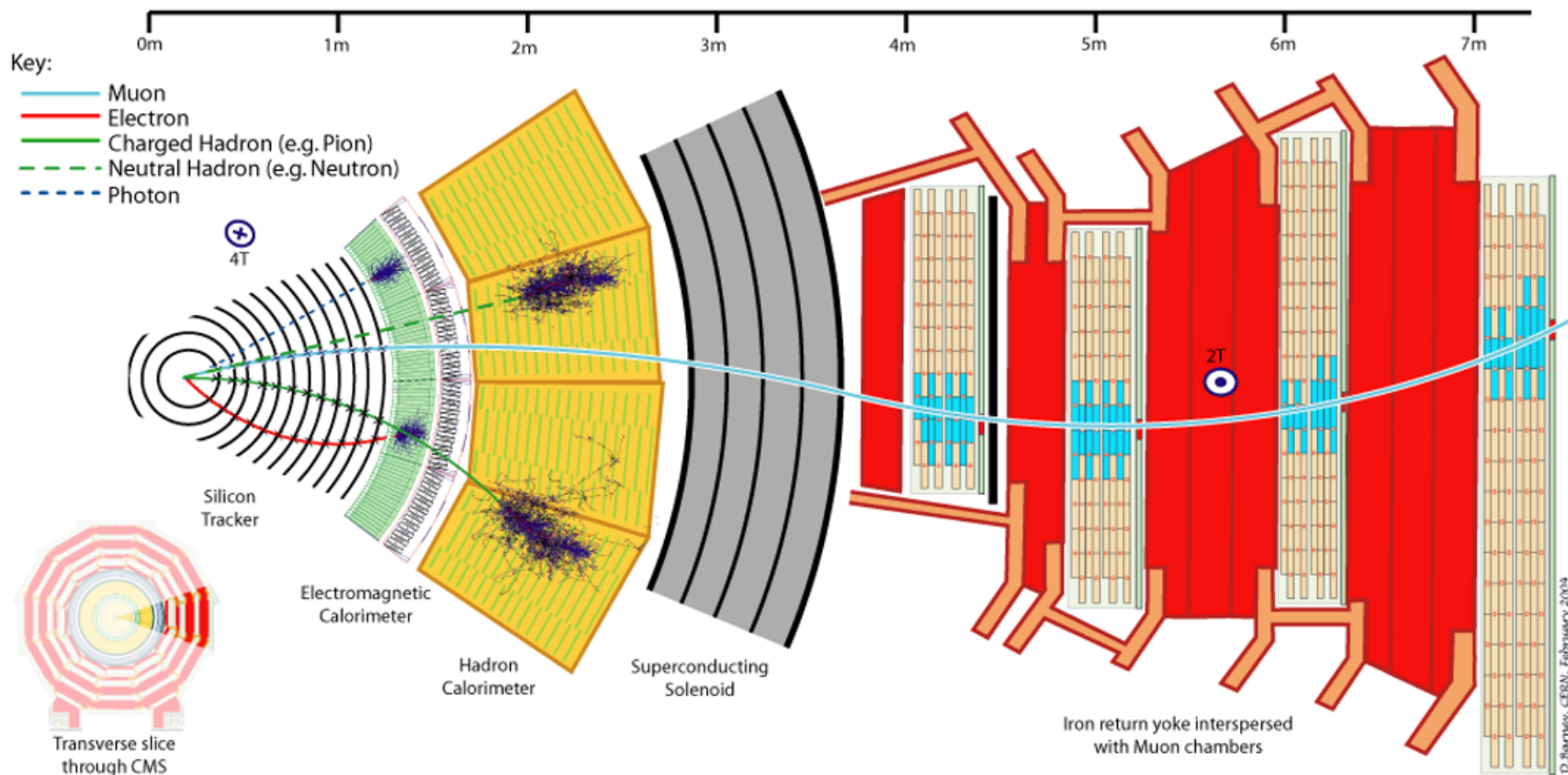
LHC Timeline

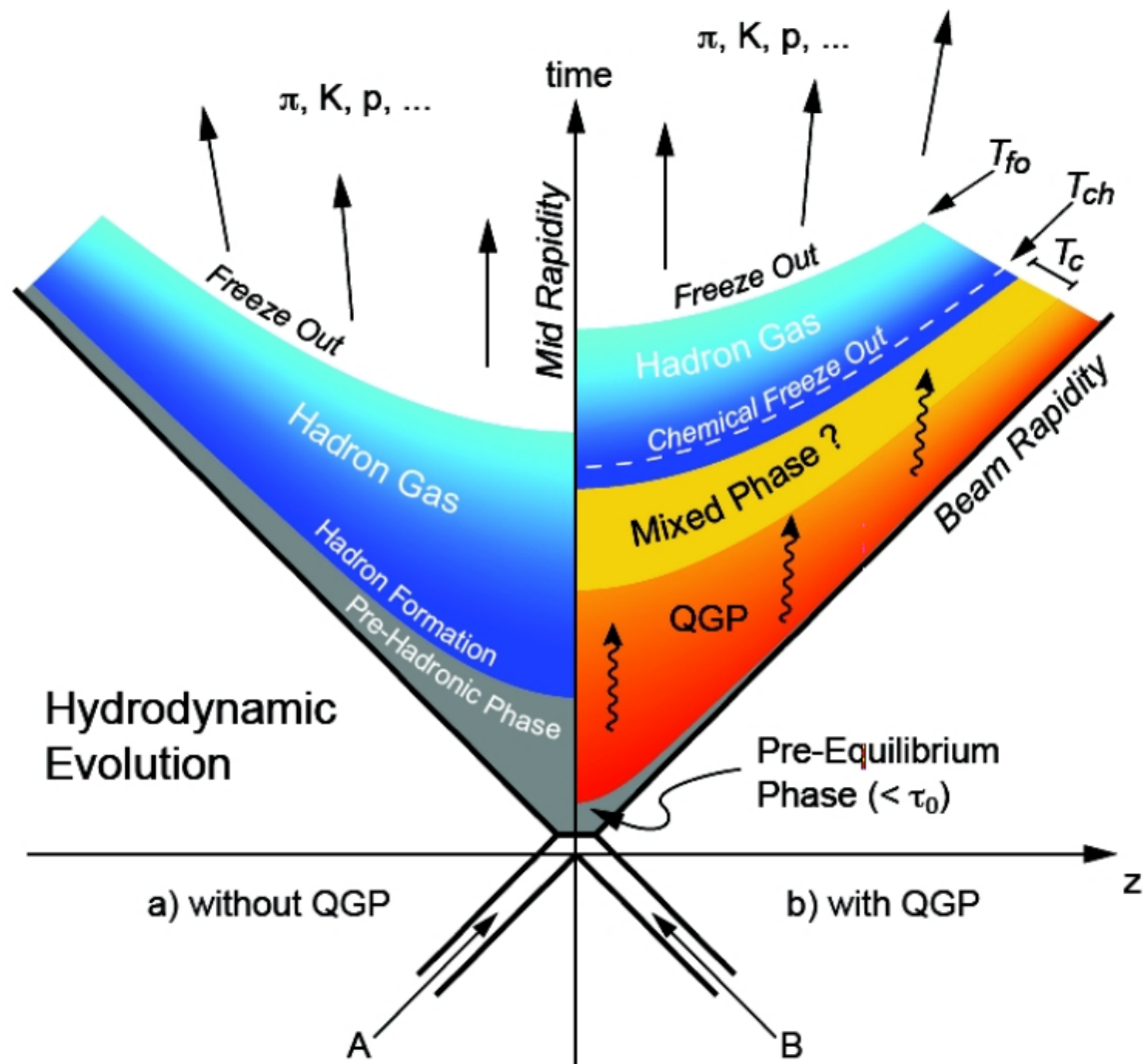
Content



Last update: November 24

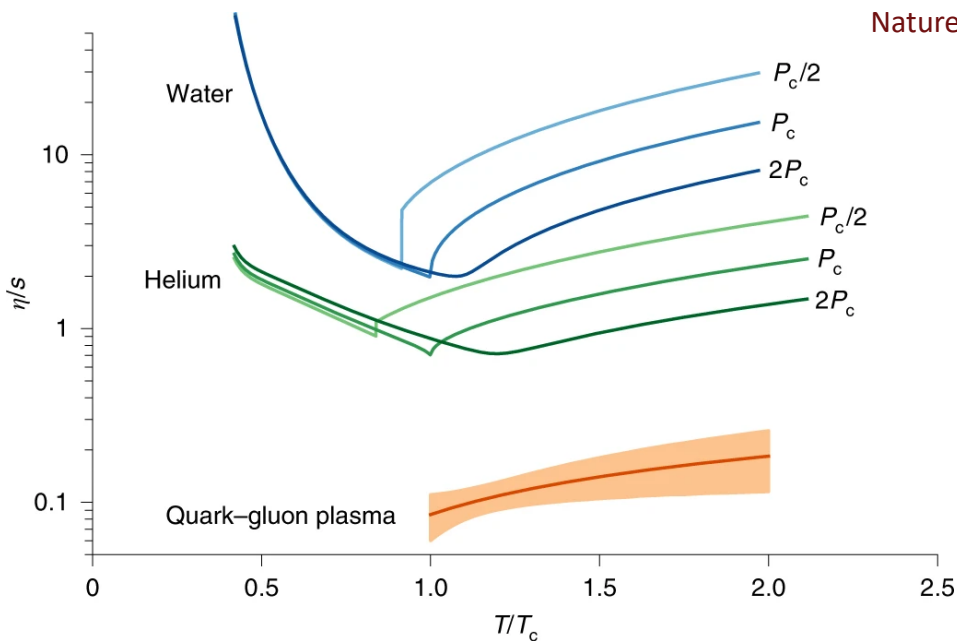
Interactions of particles with the sensitive material of the CMS





Quark-gluon plasma (QGP)

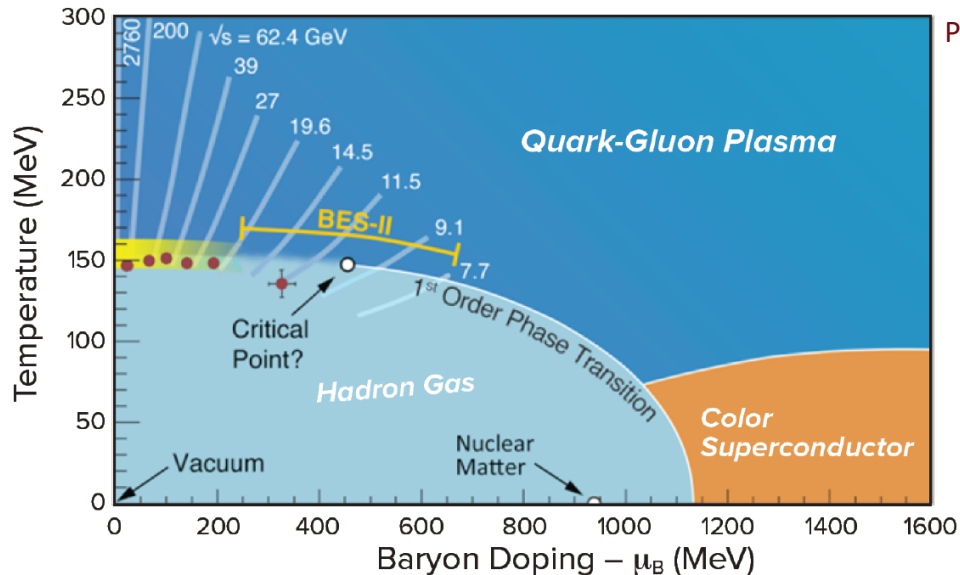
QGP is the hottest (10^{12} K), smallest (10^{-14} fm), and the most perfect ($\eta/s \sim 1/4\pi$) fluid in nature



Physics in heavy-ion collisions at the LHC

Allows you to analyze a sector of the QCD phase diagram ($\mu_B \approx 0$)

QCD calculations on the lattice indicate that in this region there is a smooth transition (crossover) between hadrons and QGP



Phys. Rev. D **90** 094503 (2014)

There are alternative approaches...

Various transport models based on effective kinetic theory

- ❑ Not firmly rooted in QCD Phys. Rev. C **71**, 064901 (2005); Phys. Rev. Lett. **101**, 082302 (2008); Phys. Rev. C **72**, 064901 (2005); Nucl. Phys. A **856**, 162 (2011); Prog. Part. Nucl. Phys. **87**, 50 (2016)
- ❑ Good connection between non-interacting systems (lower opacity) to ideal hydrodynamics in the large opacity limit
- ❑ Also show generally good description of the data on collective flow
- ❑ Examples: BAMPS, AMPT, PHSD

Other models with different ideas: Pythia, HIJING, etc...

Hydrodynamics (I)

CERN Summer Student Lectures 2018

Calculating space-time evolution of QGP from first principles (QCD Lagrangian) is too complex (non-abelian, strong coupling, many-body system, ...)

Expanding medium can be described macroscopically with hydrodynamical models

- Conservation of energy-momentum: $\partial_\mu T^{\mu\nu} = 0$, where $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$
- Conservation of charges, mainly baryon number: $\partial_\mu N_i^\mu = 0$, where $N_i^\mu = nu^\mu$
- Local thermodynamical equilibrium

Needed input

- Initial conditions
- Equation of State (EoS), from lattice QCD
- Relativistic fluid dynamics (perfect or dissipative $\Rightarrow$ transport coefficients)

Hydrodynamics (II)

CERN Summer Student Lectures 2018

Once dynamics well described, hydrodynamic "output" can be used in other calculations: jet quenching, J/Ψ melting, etc.

Flow observables: Initial-state anisotropies $\Rightarrow$ final-state anisotropies

□ Translate from initial-state eccentricity ϵ_n to final state flow v_n

Deduce conclusions on initial conditions, EoS and transport coefficients by data comparison



SPRACE

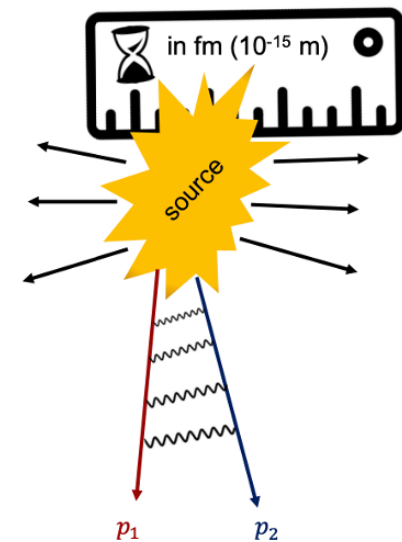
Femtoscscopy

ANOTHER EXAMPLE!! :-)

Femtoscopic correlations

Access to

- ❑ Spacetime dimensions of the particle emitting source
 - Quantum effects of identical particles
 - Bose-Einstein or Fermi-Dirac
- ❑ Interactions between hadrons in the final state
 - Strong & Coulomb Interactions



Ann. Rev. of Nucl. and Part. Phys. **55** (2005) 357,
Phys. of Atom. Nucl. **67** (2004) 72, Sov. J. Nucl. Phys. **35** (1982) 770

Femtoscopic correlations - identical particles

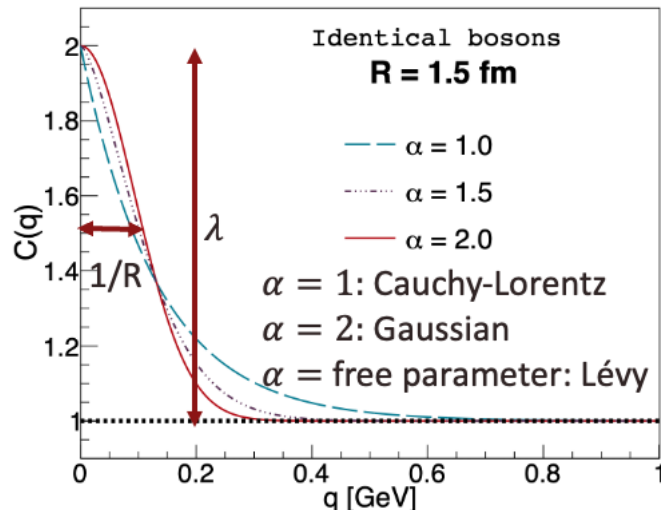
Correlations between 2 particles in low-q

$$\square q^2 = q_{inv}^2 = -(p_1 - p_2)^2$$

Theoretically (chaotic and static source & without final state interactions) it relates to

$\square$ Fourier transform from the particle-emitting source to momentum space

$$\begin{aligned} \blacksquare C(p_1, p_2) &= \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \sim 1 \pm \lambda |F[\tilde{\rho}]|^2 \\ \blacksquare C(p_1, p_2) &\equiv C(q) \sim N\left(1 \pm \lambda e^{-|qR|^\alpha}\right) \end{aligned}$$



Femtoscopic correlations - identical particles

Correlations between 2 particles in low-q

$$\square q^2 = q_{inv}^2 = -(p_1 - p_2)^2$$

Theoretically (chaotic and static source & without final state interactions) it relates to

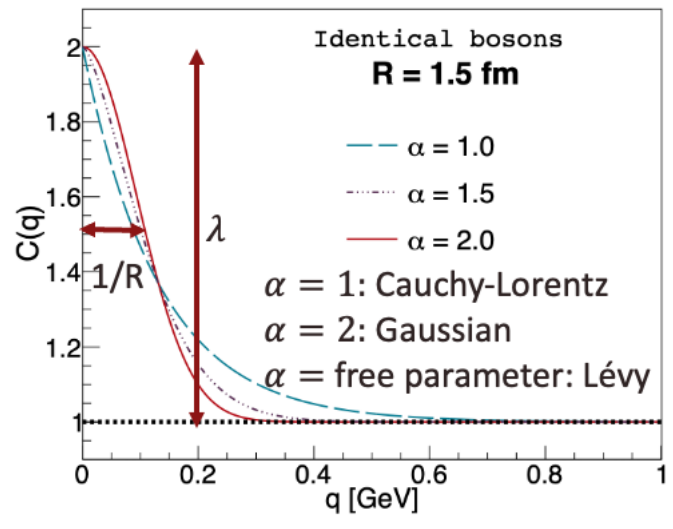
$\square$ Fourier transform from the particle-emitting source to momentum space

$$\blacksquare C(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \sim 1 \pm \lambda |F[\tilde{\rho}]|^2$$

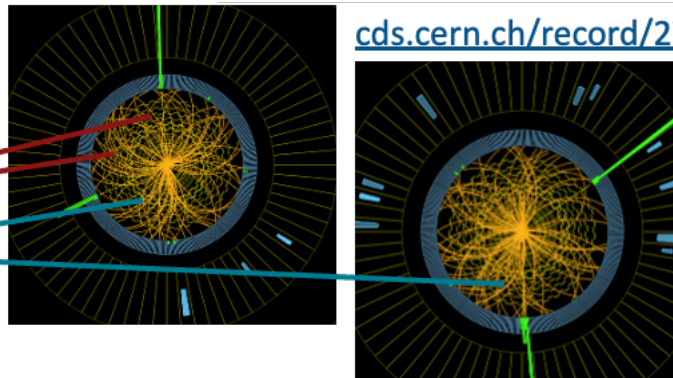
$$\blacksquare C(p_1, p_2) \equiv C(q) \sim N \left(1 \pm \lambda e^{-|qR|^\alpha} \right)$$

Experimentally

$$\square \text{Single-ratio (SR): } C(q) = N \frac{A(q)}{B(q)}$$



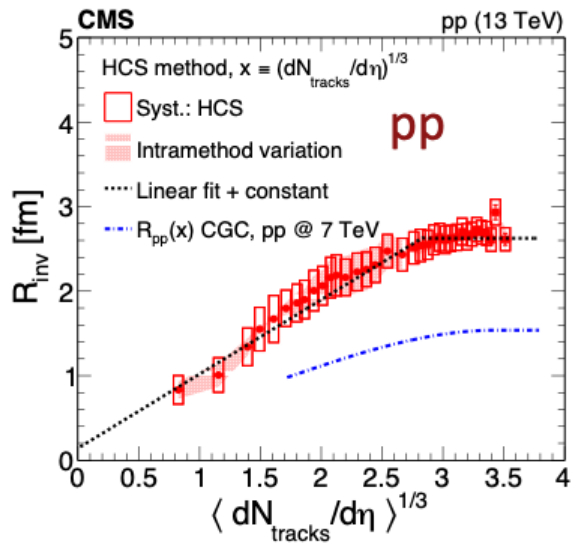
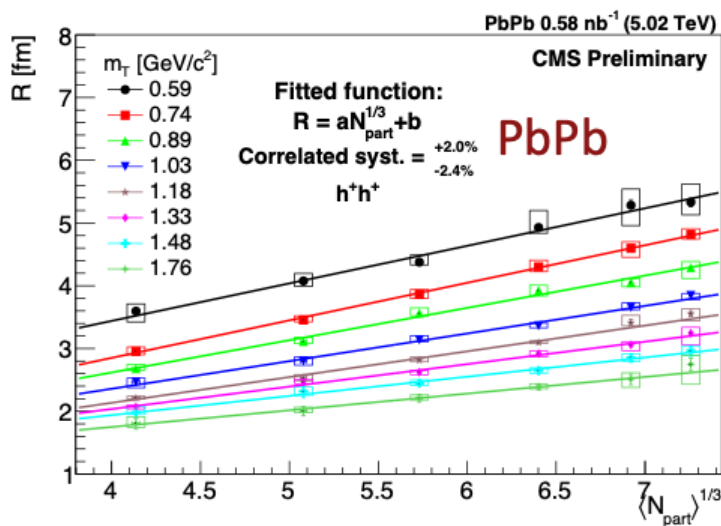
cds.cern.ch/record/2736135



Few recent results

Study of the space-time evolution of the particle-emitting source in pp (high multiplicity) and PbPb

- Using charged particles (mostly pions)
 - Pion-pion strong interaction effects in $C(q)$ can be neglected



JHEP **03** 014 (2014)
 Phys. Rev. C **109** 024914 (2024)

Accessing hadronic interactions using correlations

Add scattering terms to the total wavefunction

of two particles $\Psi(\vec{q}, \vec{r})$

Koonin-Pratt Formula

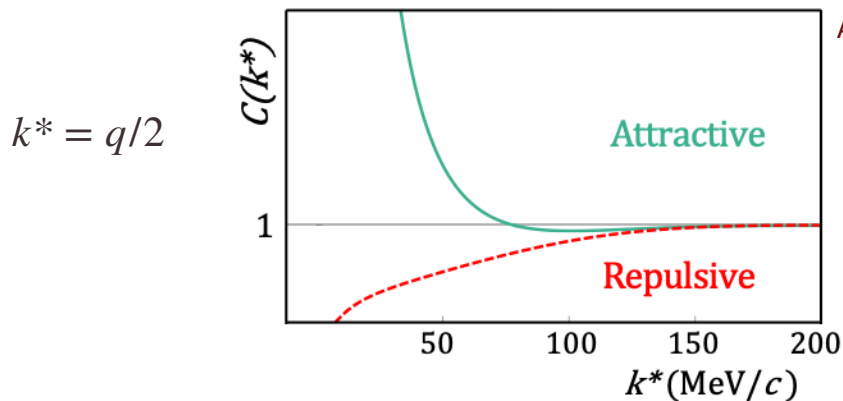
Phys. Lett. B **78** 556 (1978)

Phys. Rev. Lett. **53** 1219 (1984)

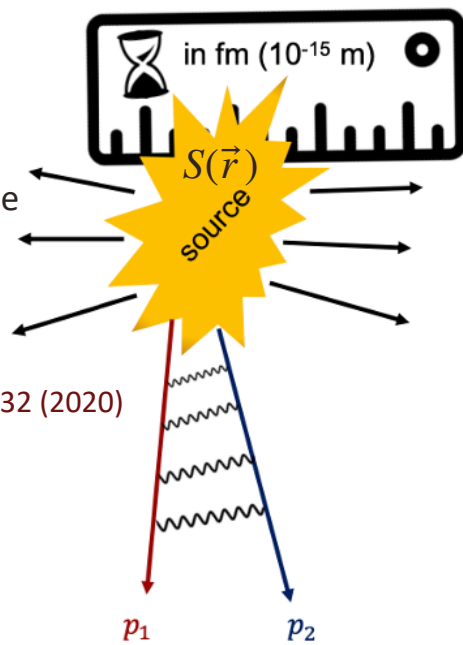
$$C(\vec{q}) = \int d\vec{r} S(\vec{r}) |\Psi(\vec{q}, \vec{r})|^2$$

Where $S(\vec{r})$ spatial distribution of the particle source, $\vec{r} = \vec{x}_1 - \vec{x}_2$ and $\vec{q} = \vec{p}_1 - \vec{p}_2$

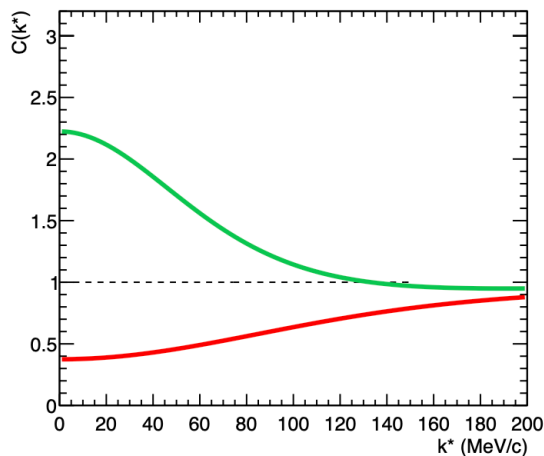
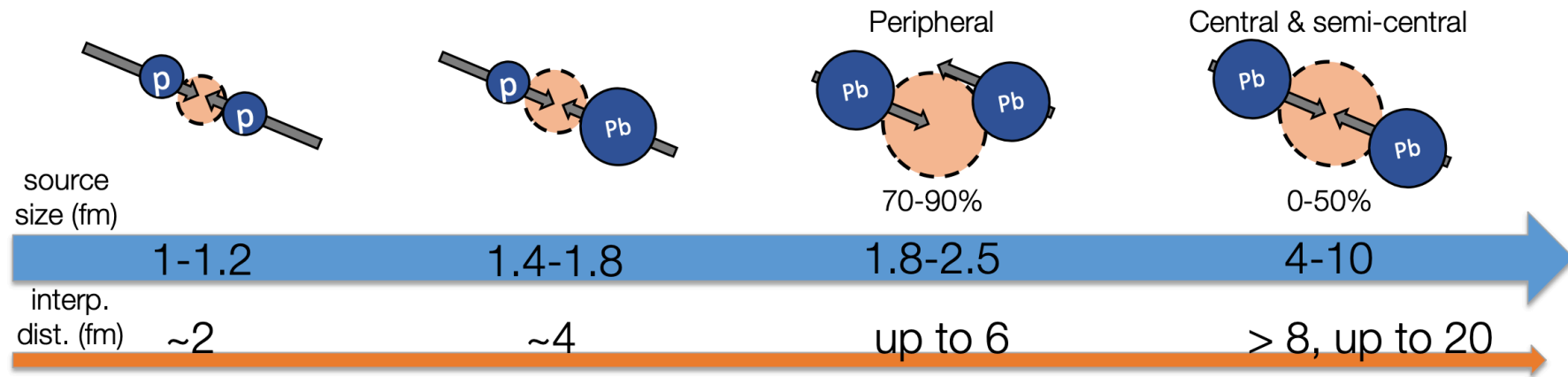
Correlation Function



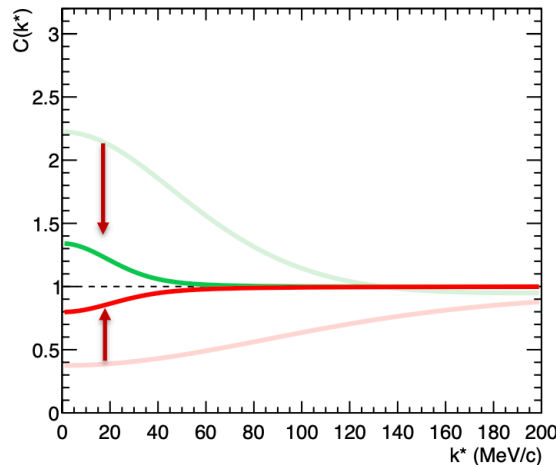
ALICE Collab., Nat. **588** 232 (2020)



Accessing hadronic interactions using correlations



Decrease in the magnitude of the signal for larger source size

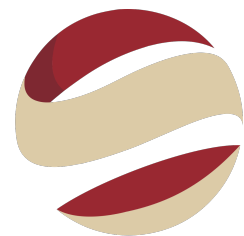


Adapted from
V. Mantovani Sarti (TUM), QM2025



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Flow



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DO MESON SIGNAL EXTRACTION

D^0 Reconstruction and Selection: 2018 Data

Minimum Bias events from PbPb collisions at 5.02 TeV

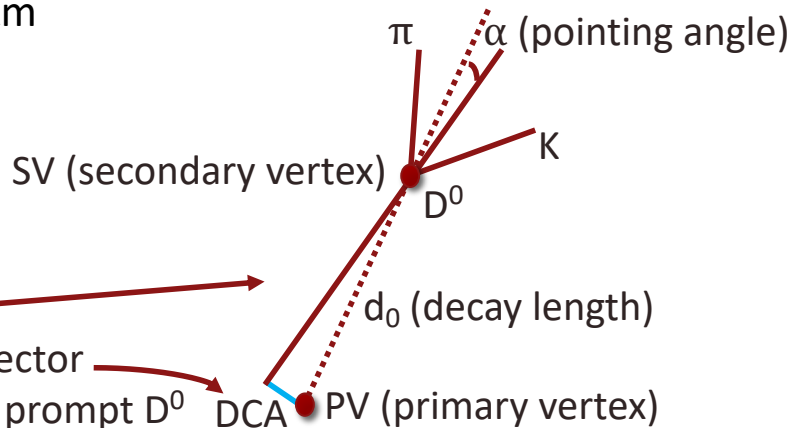
$D^0(\bar{u}c) \rightarrow K\pi$, $BR = 3.88 \pm 0.05 \%$, $c\tau(D^0) = 122.9 \mu\text{m}$

D^0 Reconstruction

- ❑ Pairing oppositely charged tracks (no PID)
- ❑ Secondary vertex reconstruction

Prompt D^0 candidate selection

- ❑ MVA Boosted Decision Tree (BDT)
 - D^0 variables
 - $d_0/\sigma(d_0)$, α , SV probability
 - Tracks ($K\pi$)
 - Distance of closest approach significance, error on p_T , number of hits



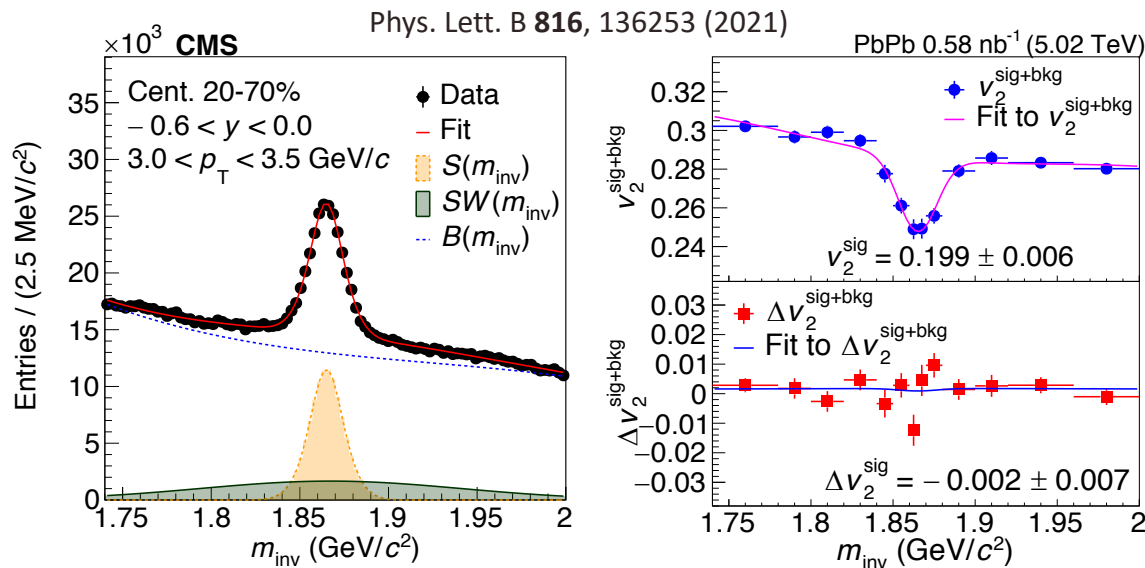
Nonprompt (NP) D^0 contamination (from B hadron decay) as systematic uncertainty

- ❑ Estimate contribution using DCA variable (nonprompt D^0 enriched region for $DCA > 0.012 \text{ cm}$)

Signal Extraction

Simultaneous fit on mass distribution and v_n (Δv_n) versus mass

- v_n measured using Scalar Product (SP) method: correlates D^0 meson in tracker region with particles in HF



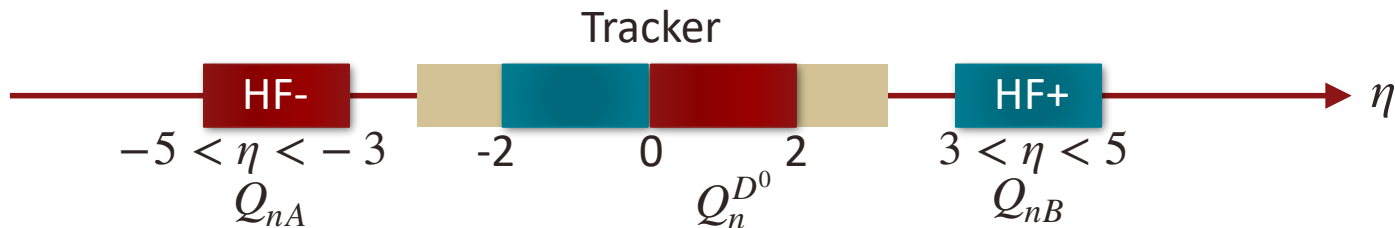
- Mass fit: background (3rd order polynomial), signal (double Gaussian), swap (single Gaussian)
- v_n background (linear function), Δv_n (background is canceled)

$$v_n^{\text{sig+bkg}}(m_{\text{inv}}) = \alpha(m_{\text{inv}})v_n^{\text{sig}} + [1 - \alpha(m_{\text{inv}})]v_n^{\text{bkg}}(m_{\text{inv}})$$

There are other methods to measure v_n

Example: Scalar Product method

- Use η -gap to mitigate effects from non-flow (jets, resonances, momentum conservation, etc...)
- To measure v_n of D^0 mesons

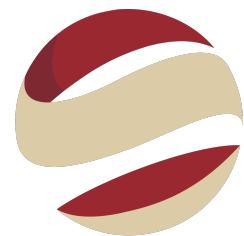


$$Q_n = \sum_j^M w_j e^{in\phi_j} \quad (w_j := E_T \text{ for HF; } w_j := p_T \text{ of the track for Tracker; } w_j := 1 \text{ for } D^0 \text{ mesons})$$

Phys. Rev. Lett. **120** 202301(2018)

$$v_n\{SP\} = \frac{\langle Q_n^{D^0} Q_{nA}^* \rangle}{\sqrt{\langle Q_{nA} Q_{nB}^* \rangle}} \quad , \langle \dots \rangle \text{ average over all events}$$

□ Example for D^0 mesons with positive η



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4-PARTICLE CUMULANT METHOD

Four-particle Cumulants (I)

Liuyao Zhang, IS2021

Differential flow: PRC 83, 044913(2011)

$$v_n'\{4\}(D^0) = -\frac{d_n\{4\}(D^0)}{(-c_n\{4\})^{3/4}} \quad (1)$$

$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2 * \langle\langle 2' \rangle\rangle \langle\langle 2 \rangle\rangle \quad (2)$

$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 * \langle\langle 2 \rangle\rangle^2 \quad (3)$

$d_n\{4\}$: fourth-order differential cumulant.

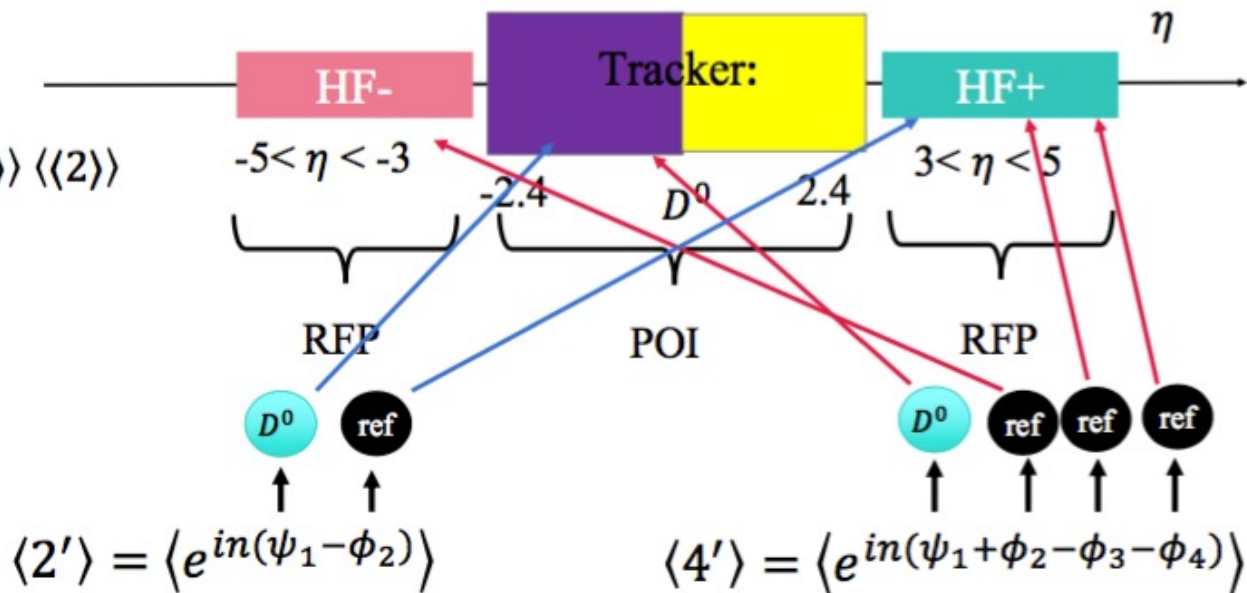
$c_n\{4\}$: four-particle cumulant $\rightarrow$ reference flow.

Four-particle Cumulants (II)

Liuyao Zhang, IS2021

$d_n\{4\}$:

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2 * \langle\langle 2' \rangle\rangle \langle\langle 2 \rangle\rangle$$



definition:

$$Q_n \equiv \sum_{i=1}^M e^{in\phi_i}$$

$$\langle 4' \rangle = \frac{\text{Re}[Q_n^{D^0} Q_n^{HF-} (Q_n^{HF+})^* (Q_n^{HF+})^*] - Q_n^{D^0} Q_n^{HF-} (Q_n^{HF+})^*}{M^{HF-} M^{HF+} (M^{HF+} - 1)} \text{ if: } D^0(\eta < 0) \quad (4)$$

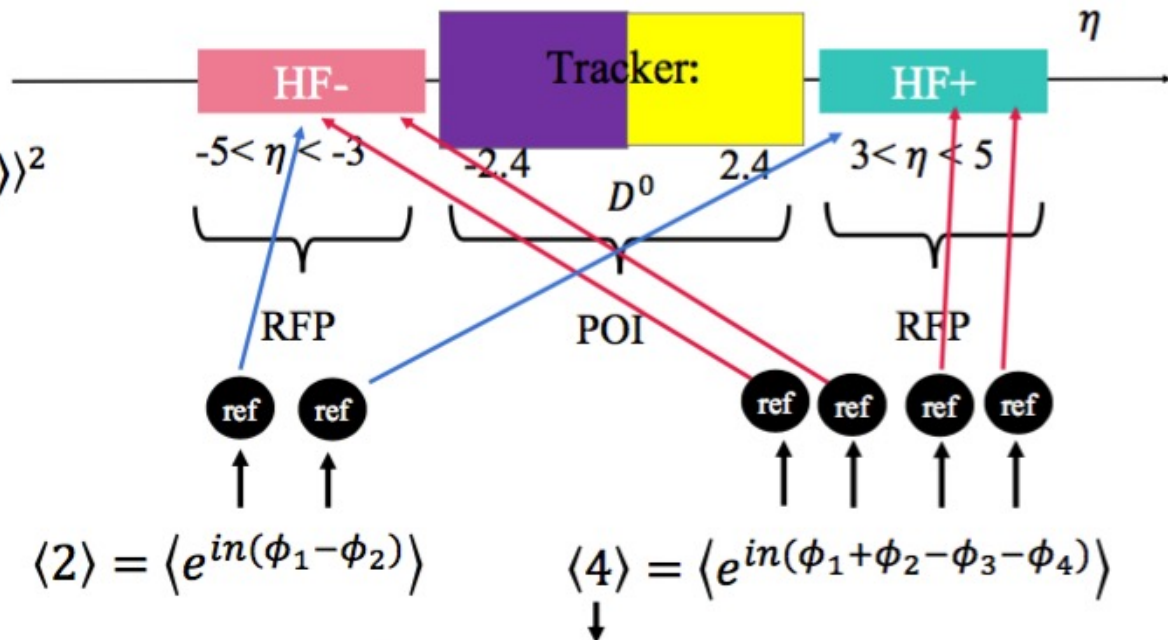
Note: weight $M^{HF-} = \sum (E_T)_i$ from HF- , $M^{HF+} = \sum (E_T)_i$ from HF+

Four-particle Cumulants (III)

Liuyao Zhang, IS2021

$c_n\{4\}$:

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



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

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

$$\langle 4 \rangle = \frac{\text{Re}[Q_n^{HF-} Q_n^{HF-} (Q_n^{HF+})^* (Q_n^{HF+})^*] + \text{Re}[Q_{2n}^{HF-} (Q_{2n}^{HF+})^*] - \text{Re}[Q_{2n}^{HF-} (Q_n^{HF+})^* (Q_n^{HF+})^* + Q_n^{HF-} Q_n^{HF-} (Q_{2n}^{HF+})^*]}{M^{HF-} * (M^{HF-} - 1) * M^{HF+} (M^{HF+} - 1)} \quad (5)$$

Note: weight $M^{HF-} = \sum (E_T)_i$ from HF- , $M^{HF+} = \sum (E_T)_i$ from HF+

Motivation to Use the Ratio

Liuyao Zhang, IS2021

3. why uses four-particle correlation technique to measure harmonic flows. $\Rightarrow$ To judge the fluctuation from soft and hard components

$$\frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})} = \underbrace{\frac{v_2\{4\}}{v_2\{2\}}}_{\text{Soft fluctuation: initial condition fluctuation}} \left[1 + \underbrace{\left(\frac{v_2\{2\}}{v_2\{4\}}\right)^4}_{\text{Soft fluctuation: initial condition fluctuation}} \underbrace{\left(\frac{\langle v_2^4 \rangle}{\langle v_2^2 \rangle^2} - \frac{\langle v_2^2 v_2 v_2^* (\text{hard}) \rangle}{\langle v_2^2 \rangle \langle v_2 v_2^* (\text{hard}) \rangle}\right)}_{\text{Hard fluctuation energy loss fluctuation}} \right] 1$$

Hard particle:

- High p_T charged particles.
- Heavy flavor particles over full p_T .

- Initial condition fluctuation dominated: $\frac{\langle v_2^2 v_2 v_2^* (\text{hard}) \rangle}{\langle v_2^2 \rangle \langle v_2 v_2^* (\text{hard}) \rangle} \rightarrow \frac{\langle v_2^4 \rangle}{\langle v_2^2 \rangle^2} \Rightarrow \frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})} \rightarrow \frac{v_2\{4\}}{v_2\{2\}}$
- Significant energy loss fluctuation: $\frac{\langle v_2^2 v_2 v_2^* (\text{hard}) \rangle}{\langle v_2^2 \rangle \langle v_2 v_2^* (\text{hard}) \rangle} \neq \frac{\langle v_2^4 \rangle}{\langle v_2^2 \rangle^2} \Rightarrow \frac{v_2\{4\}(\text{hard})}{v_2\{2\}(\text{hard})} \downarrow \uparrow$

Why study hadrons composed by b and c quarks?

Correlations with more than two particles

Scalar Product (SP)

$$v_2\{2\}^2 \sim \underbrace{\langle v \rangle^2}_{\text{Flow (EP)}} + \underbrace{\sigma_v^2}_{\text{Fluctuations}} + \underbrace{\delta}_{\text{Non-flow}}$$

4-particle cumulants

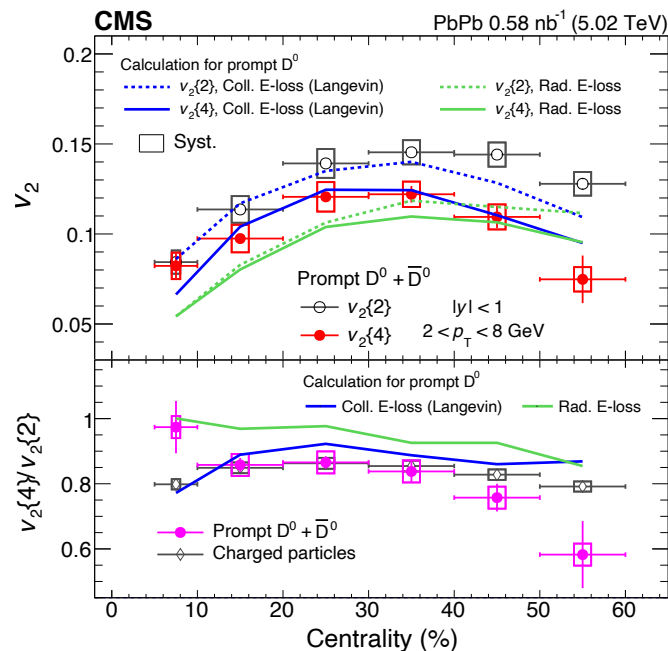
$$v_2\{4\}^2 \sim \underbrace{\langle v \rangle^2}_{\text{Flow (EP)}} - \underbrace{\sigma_v^2}_{\text{Fluctuations}}$$

Assuming the non-flow can be neglected $\Rightarrow$ the ratio $(v_2\{4\}/v_2\{2\})$ is sensitive to fluctuations in the initial state geometry and energy loss in the medium

 NB.: SP method uses η -gap to mitigate non-flow

Ratio between the measurements of D^0 mesons and charged hadrons

Phys. Rev. Lett. **129** 022001 (2022)





SPRACE

EM FIELDS IN HIN COLLISIONS

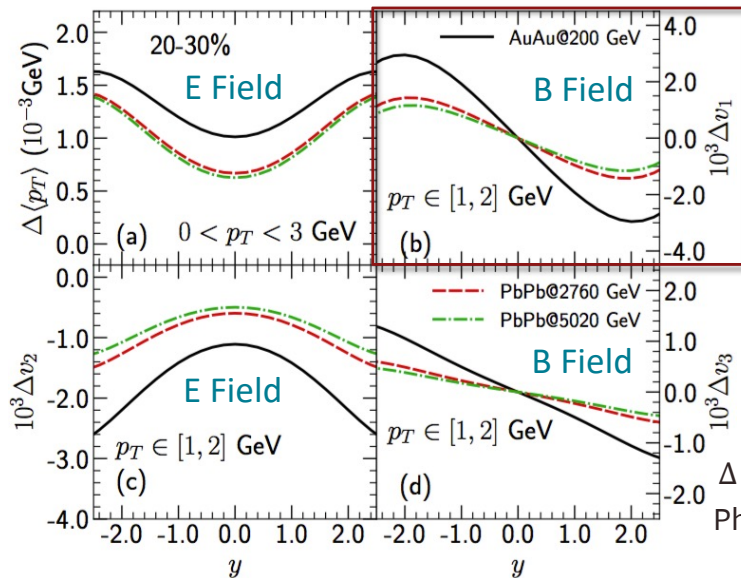
Effect on Δv_1 of $D^0(\bar{u}c)$ Mesons

Charm quarks produced in primordial stages of collision (~ 0.1 fm/c)

□ $m_{\text{charm}} \gg$ typical medium temperatures: lower probability of annihilation

EM fields vanish very fast: peak magnitude approx. 0.1 - 0.2 fm/c

Non-zero Δv_1 mainly due to magnetic field from spectators

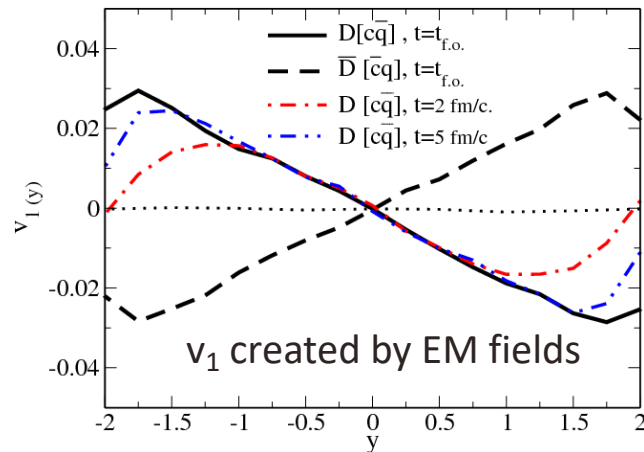


Larger effect
on D^0 mesons

$$\Delta \equiv (\pi^+ - \pi^-)$$

Phys. Rev. C **98**, 055201 (2018)

Phys. Lett. B **768**, 260 (2017)





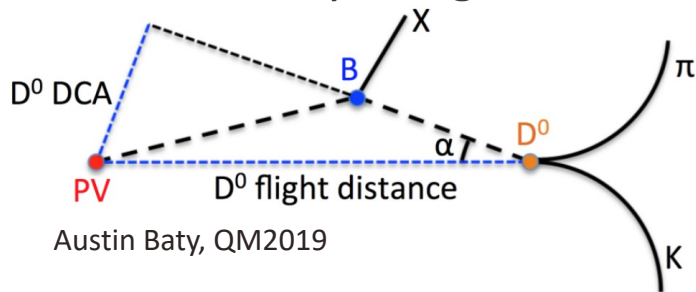
SPRACE

FLOW IN SMALL SYSTEMS

Nonprompt (NP) D^0 mesons in pPb collisions

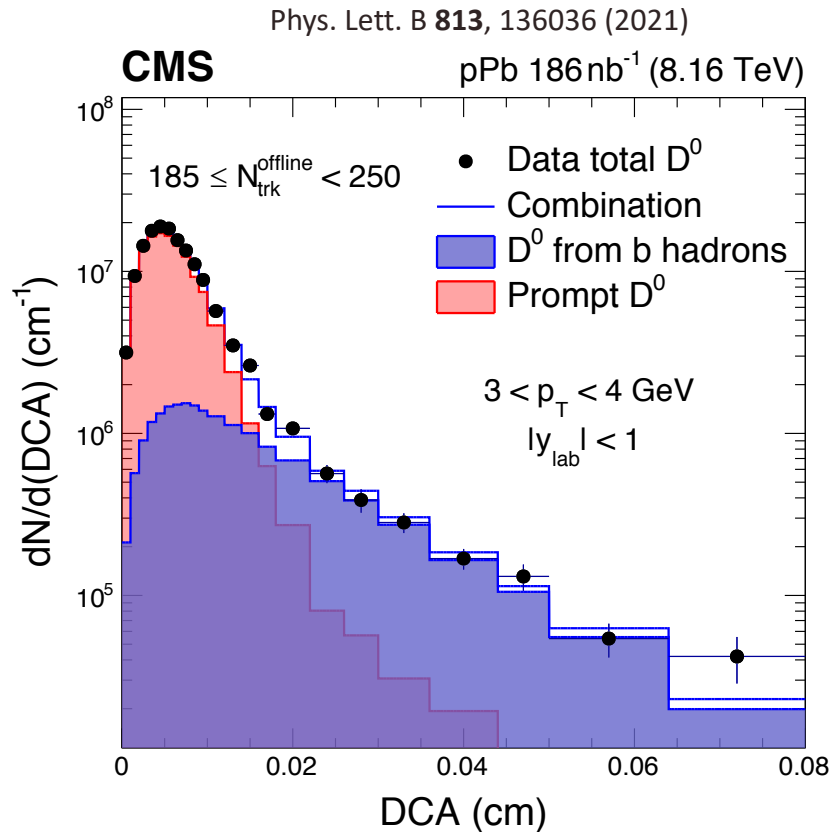
Nonprompt D^0 mesons mostly from B hadrons decay

- Distinguish prompt vs nonprompt D^0 mesons by using DCA variable



Austin Baty, QM2019

- Template fits using Monte Carlo simulations to extract nonprompt D^0 fractions



Non-flow subtraction: jets contribution

Removes residual contribution of back-to-back dijets to the measured v_2 results

$$V_{n\Delta}^{\text{sub}} = V_{n\Delta} - V_{n\Delta}(N_{\text{trk}}^{\text{offline}} < 35) \underbrace{\frac{N_{\text{assoc}}(N_{\text{trk}}^{\text{offline}} < 35)}{N_{\text{assoc}}}}_{N_{\text{assoc}} \text{ ratio}} \underbrace{\frac{Y_{\text{jet}}}{Y_{\text{jet}}(N_{\text{trk}}^{\text{offline}} < 35)}}_{\text{Jet yield ratio}}$$

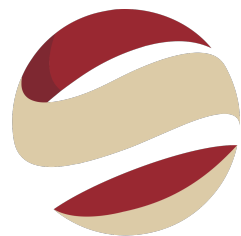
N_{assoc} ratio

- Scale of the relative contribution from number of pairs

Jet yield ratio

- Account for increasing of jet yields in high-multiplicity region
- Little dependence on p_T over full p_T range

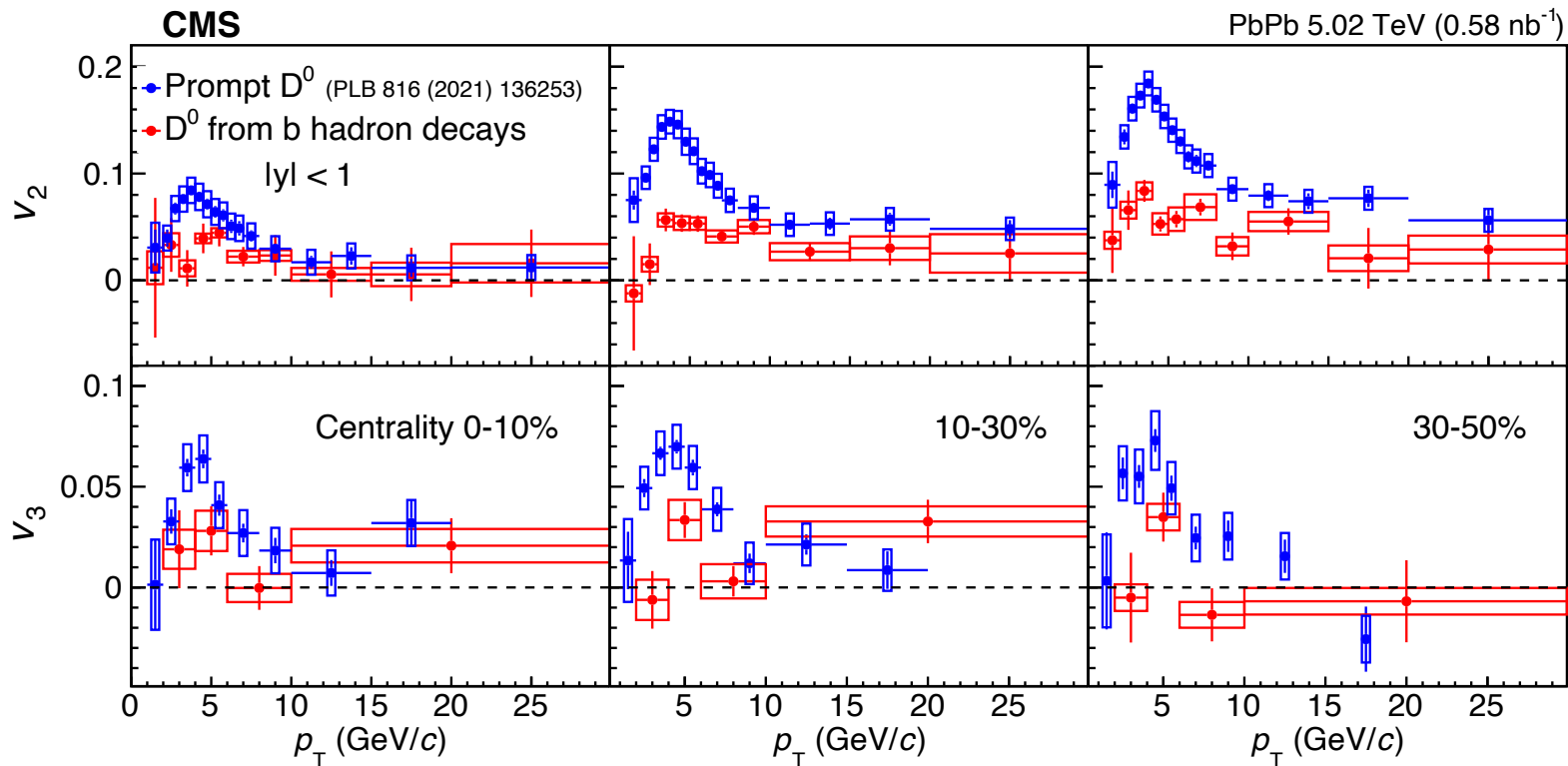
Jet yield := difference between integrals of the short-range ($|\Delta\eta| < 1$) and long-range ($|\Delta\eta| > 2$) event-normalized associated yields for each multiplicity class



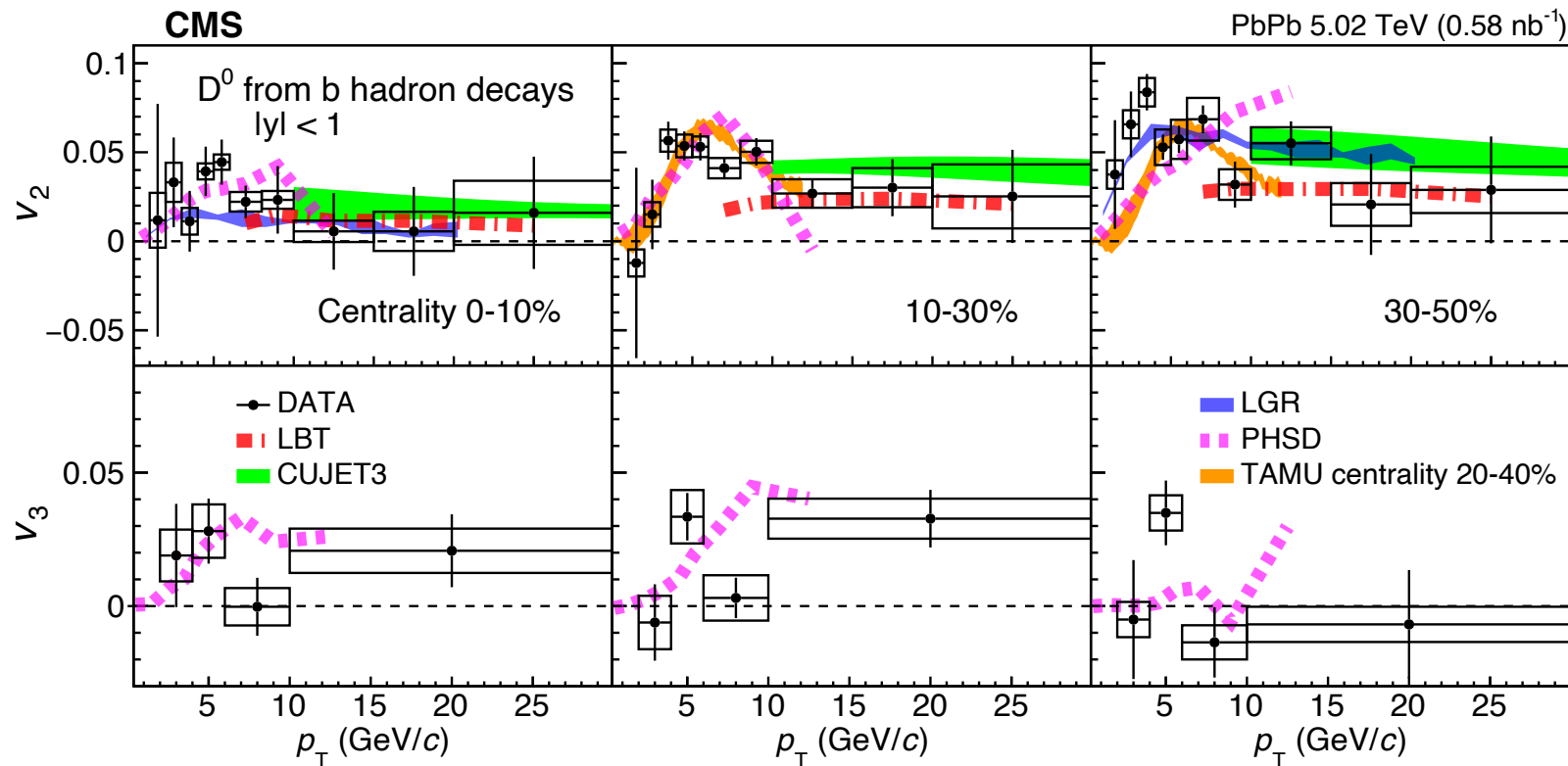
SPRACE

NON-PROMPT DO IN PBPB

Non-prompt D0 vs prompt D0



Non-prompt D0





SPRACE

Velocidade do Som

Speed of sound extraction: SPS

Access the Equation of State (EoS) of the medium

□ Relativistic hydrodynamics

$$c_s^2 = \left(\frac{\partial P}{\partial \varepsilon} \right)_{\text{adiabatic}} \quad P := \text{pressure}, \quad \varepsilon := \text{energy density}$$

L.D. Landau & E.M. Lifshitz, Fluid Mechanics

Dashed line: Ideal gas $c_s^2 = 1/3$

Solid line: $c_s^2 = 1/5$

Studies using PbPb collisions at SPS energies

□ Landau hydrodynamics model

■ Rapidity distribution of hadrons related to c_s

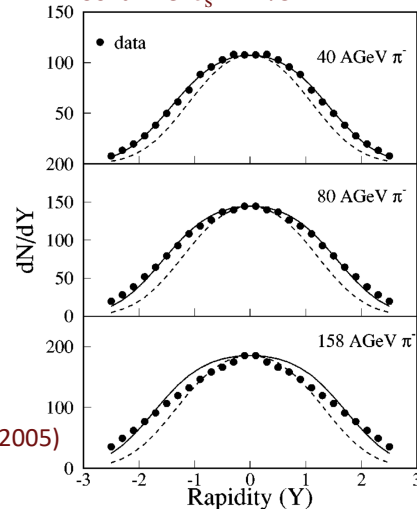
Izv. Akad. Nauk. SSSR **17** 51 (1953)

Usp. Fiz. Nauk. **56** 309 (1955)

Nuovo Cimento (Suppl.) **3** 15 (1956)

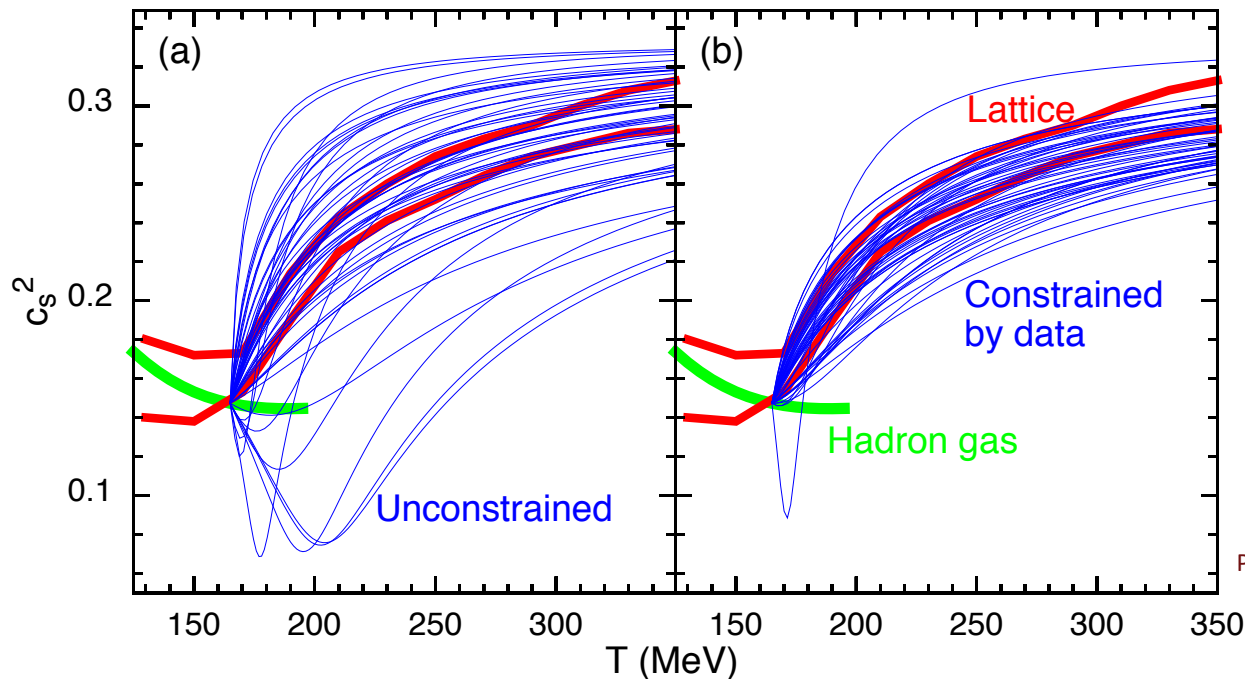
Phys. Rev. C **68**, 064903 (2003)

J. Phys. G: Nucl. Part. Phys. **31**, 1345 (2005)



Speed of sound extraction: RHIC & LHC

Constraints on c_s^2 from data (Bayesian analysis)



Phys. Rev. Lett. **114**, 202301 (2015)

Speed of sound extraction: new ideas

From thermodynamics relations and hydrodynamics simulations

$$\square \quad c_s^2(T_{\text{eff}}) = \left. \frac{dP}{d\varepsilon} \right|_{\text{adiab.}} = \left. \frac{SdT}{TdS} \right|_{\text{adiab.}} = \left. \frac{d \ln T}{d \ln S} \right|_{\text{adiab.}} = \frac{d \ln \langle p_T \rangle}{d \ln N_{ch}}$$

Hydrodynamics
Phys. Lett. B **118**, 138 (1982)
Phys. Lett. B **703**, 237 (2011)
Nat. Phys. **16**, 615 (2020)

Global thermal equilibrium ($dP = sdT$, $d\varepsilon = Tds$) + fixed volume

Speed of sound: directly related to the compressibility

□ General procedure: maintain "volume $\approx$ constante" while varying N_{ch} Entropy

■ Two proposed procedures:

○ 1) For the same centrality category: measure $\langle p_T \rangle$ & N_{ch} at different (close) collision energies

Nat. Phys. **16**, 615 (2020)

○ 2) In ultracentral collisions (UCC): measure $\langle p_T \rangle$ as a function of N_{ch}

Phys. Lett. B **809**, 135749 (2020)

Thermodynamics of hot QCD matter

The thermodynamic relations in previous slides do not apply to the real collisions

- ❑ Dynamic system, non-homogeneous, etc...

Idea from **Nat. Phys. 16 615 (2020)**: consider a hypothetical system at the end of hydro evolution of the collision with entropy S and energy E

- ❑ An uniform fluid at rest with an effective volume (V_{eff}) and temperature (T_{eff})

- ❑ $E = E_f = \int_{f.o.} T^{0\mu} = \epsilon(T_{eff})V_{eff}$ & $S = S_f = \int_{f.o.} su^\mu = s(T_{eff})V_{eff}$ In this "effective system" E and S are conserved.

- $\epsilon(T)$ and $s(T)$ EoS used in the hydro. calculation from Lattice QCD
- They solve the system of coupled equations for V_{eff} and T_{eff}
- Assuming V_{eff} constant, in the simulation of PbPb they check that: $T_{eff} \sim \langle p_T \rangle / 3$ and $S \sim N_{ch}$

T_{eff} is reduced compared to T_0 by longitudinal cooling (system expansion) & includes kinetic energy (radial flow)

Was also shown to be almost independent of centrality

Procedure 1: different energies

PbPb ALICE data at 2.76 TeV and 5.02 TeV

0-5% centrality

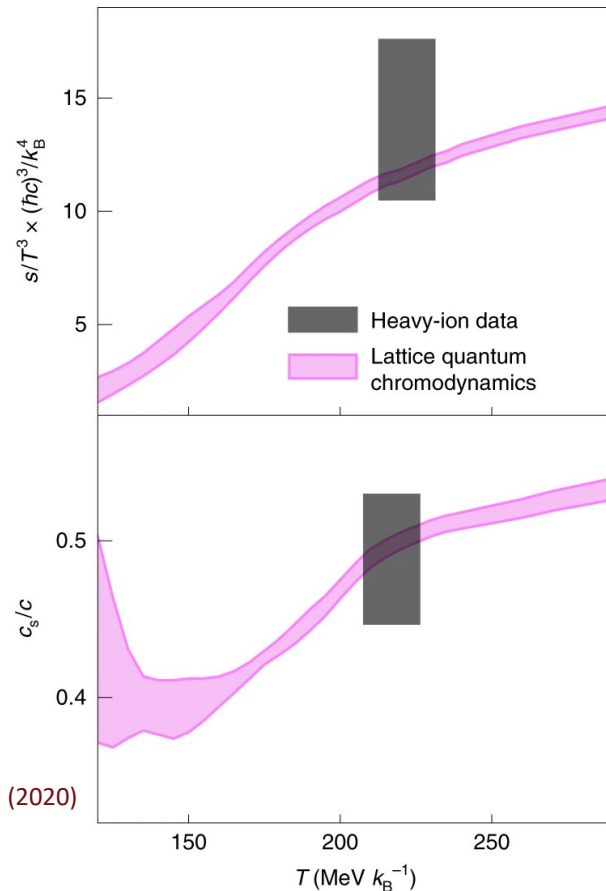
Speed of sound squared directly from

$$c_s^2(T_{\text{eff}}) = \frac{d \ln \langle p_T \rangle}{d \ln N_{ch}}$$

Using values of $\langle p_T \rangle$ and N_{ch} for the two energies

$$T_{\text{eff}} = 222 \pm 9 \text{ MeV}, \quad c_s^2/c^2 = 0.24 \pm 0.04$$

Nat. Phys. **16**, 615 (2020)



Procedure 2: UCC events (focus of this talk)

Non-trivial prediction by relativistic hydrodynamics

□ When impact parameter $b \approx 0$ (UCC)

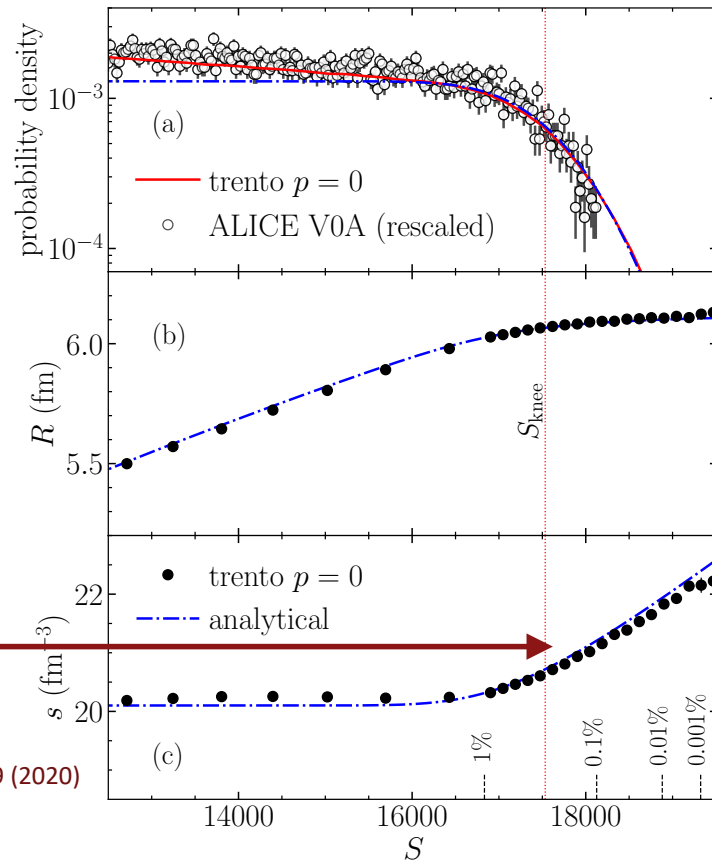
○ Increasing entropy $S \sim N_{ch}$

○ $\uparrow s \Rightarrow \uparrow T \Rightarrow \uparrow \langle p_T \rangle$

□ Slope associated with

$$c_s^2 = d \ln \langle p_T \rangle / d \ln N_{ch}$$

Phys. Lett. B **809**, 135749 (2020)



Measurement using the CMS detector

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS

Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

Tracker

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying $\sim 18,000\text{A}$

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER

Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER

Steel + Quartz fibres $\sim 2,000$ Channels

Hadron Forward (HF) Calorimeters

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels

$N_{\text{ch}}, p_{\text{T}}$

Used tracks in
 $|\eta| < 0.5$

Event selection
Collision centrality
 $3 < |\eta| < 5$

Analysis method - observables

The c_s^2 depends on the relative variation of $\langle p_T \rangle$ vs N_{ch}

☐ Extracted using

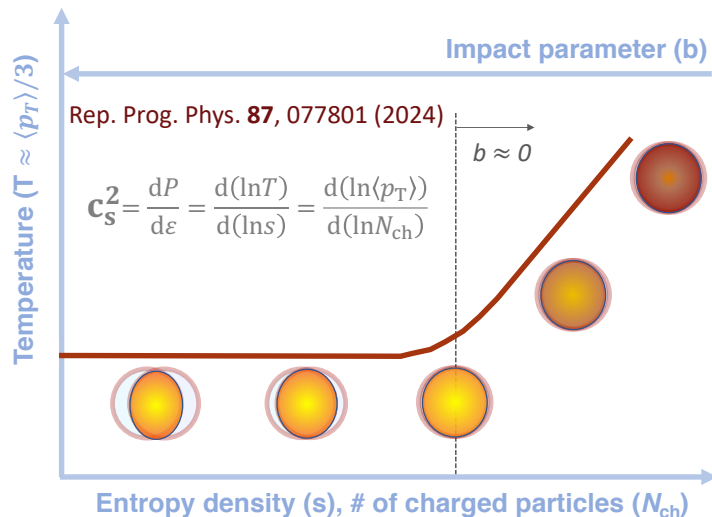
▪ $\frac{\langle p_T \rangle}{\langle p_T \rangle^0} \sim \left(\frac{N_{\text{ch}}}{N_{\text{ch}}^0} \right)^{c_s^2}$, where $\langle p_T \rangle^0$ and N_{ch}^0 are obtained in 0-5%

Ratios to cancel some systematic uncertainties

Analysis observables

$$\langle p_T \rangle^{\text{norm}} = \frac{\langle p_T \rangle}{\langle p_T \rangle^0} \text{ vs } N_{\text{ch}}^{\text{norm}} = \frac{N_{\text{ch}}}{N_{\text{ch}}^0}$$

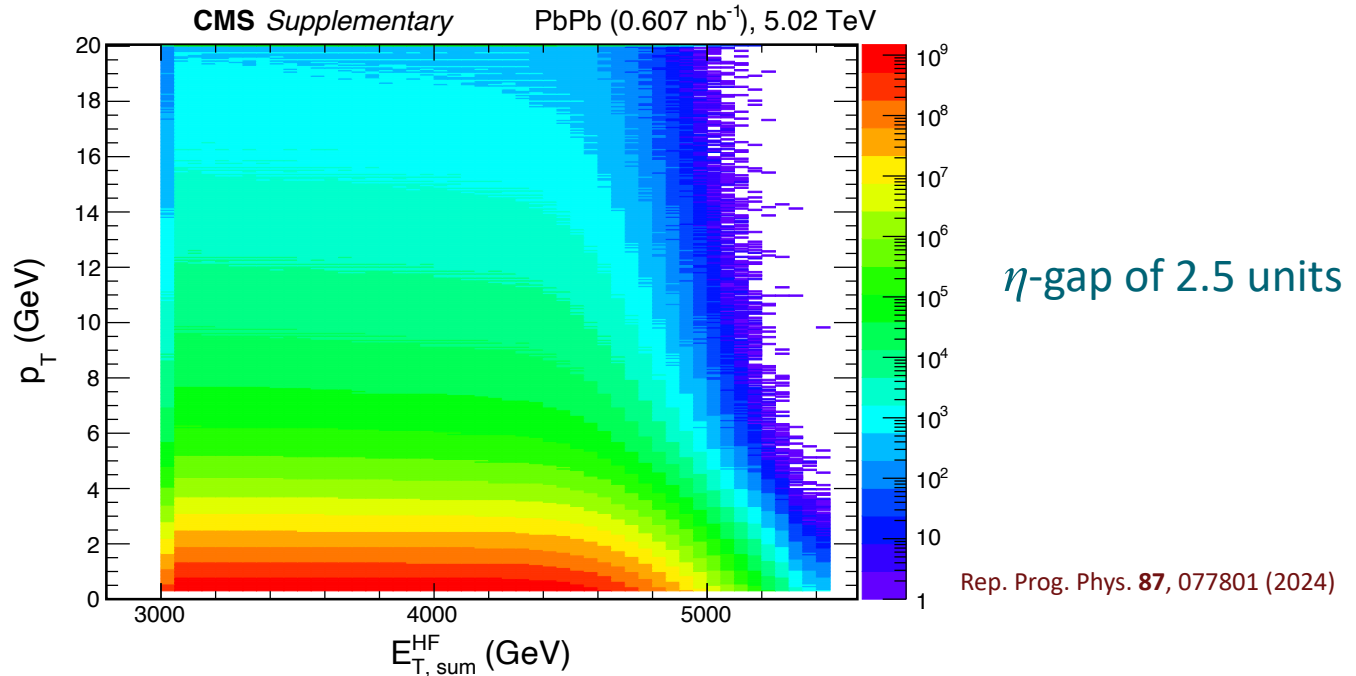
$\langle p_T \rangle^0$ (used to estimate T_{eff})



Analysis method - $\langle p_T \rangle$ and N_{ch}

To avoid other sources of correlations between $\langle p_T \rangle$ and N_{ch}

- Measured in bins of transverse energy sum in HF $E_{\text{T,sum}}^{\text{HF}}$ (bin width 50 GeV)



Analysis method - p_T extrapolation to zero

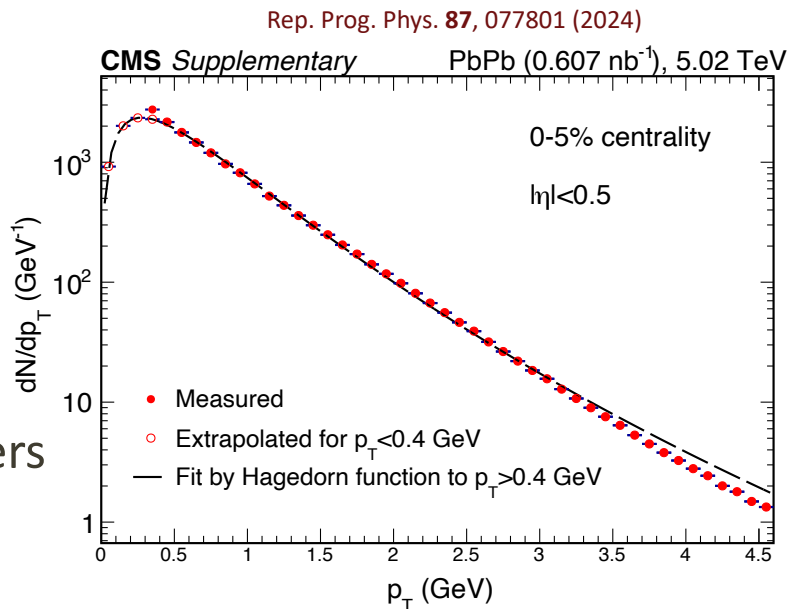
$\langle p_T \rangle$ and N_{ch} : corrected for tracking efficiency

Extrapolation to $p_T = 0$ by fitting the spectrum in $p_T > 0.4 \text{ GeV}$

□ Hagedorn function

$$\frac{dN_{\text{ch}}}{dp_T} = p_T \left(1 + \frac{1}{\sqrt{1 - \langle \beta_T \rangle^2}} \frac{\left(\sqrt{p_T^2 + m^2} - \langle \beta_T \rangle p_T \right)}{nT} \right)^{-n}$$

□ m := pion mass & $\langle \beta_T \rangle$, n , T free parameters



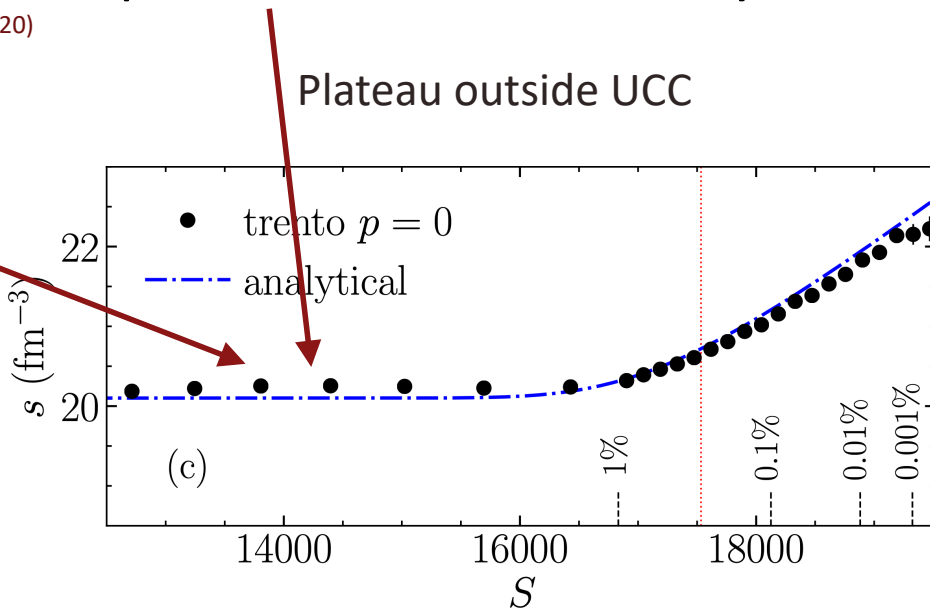
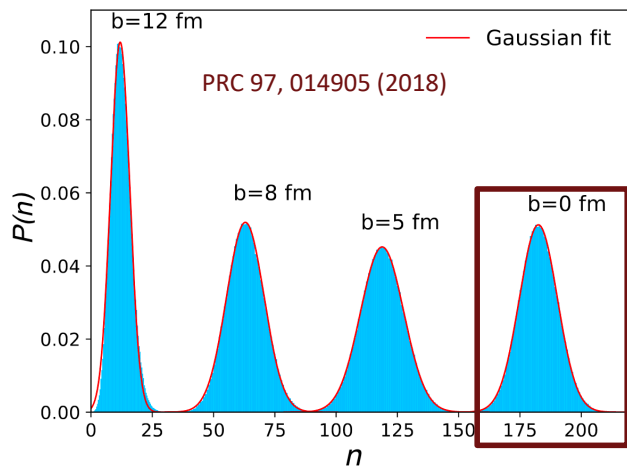
After corrections, for each bin of $E_{T,\text{sum}}^{\text{HF}} \rightarrow \langle p_T \rangle^{\text{norm}}$ vs $N_{\text{ch}}^{\text{norm}}$

Extracting the speed of sound - multiplicity fluctuations

$Prob(N_{ch}^{norm})$: analytical model to capture the trends from hydro.

Phys. Lett. B **809**, 135749 (2020)

$$\langle p_T \rangle^{norm} = \left(\frac{N_{ch}^{norm}}{Prob(N_{ch}^{norm})} \right)^{c_s^2}$$



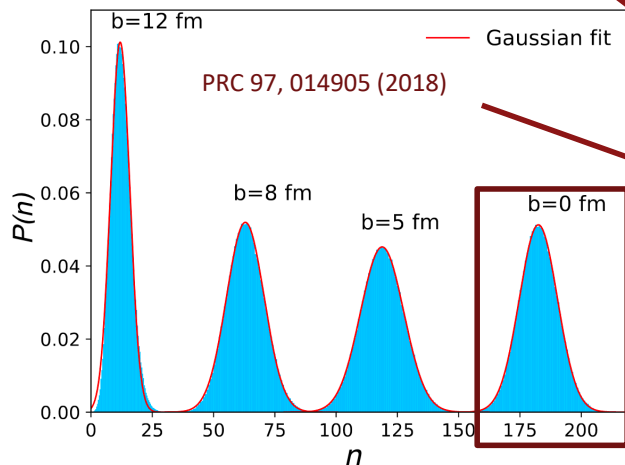
Extracting the speed of sound - multiplicity fluctuations

$Prob(N_{ch}^{norm})$: analytical model to capture the trends from hydro.

Phys. Lett. B **809**, 135749 (2020)

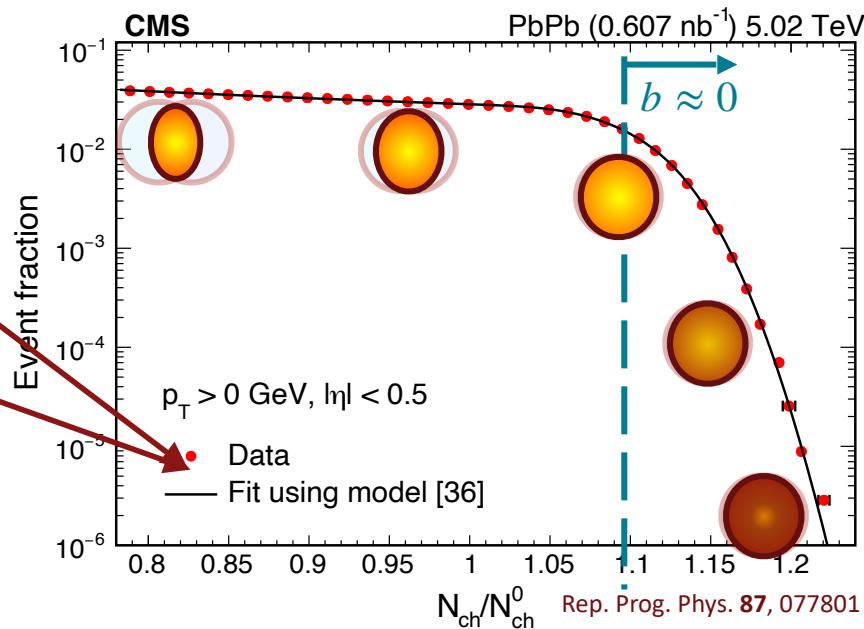
$$\langle p_T \rangle^{norm} = \left(\frac{N_{ch}^{norm}}{Prob(N_{ch}^{norm})} \right)^{c_s^2}$$

- Below the knee $Prob(N_{ch}^{norm}) \approx N_{ch}^{norm}$
- Above the knee $Prob(N_{ch}^{norm}) \approx 1$



$Prob(N_{ch}^{norm})$ free parameters values at $b \approx 0$

Fit N_{ch}^{norm} distribution



Extracting the speed of sound: CMS data

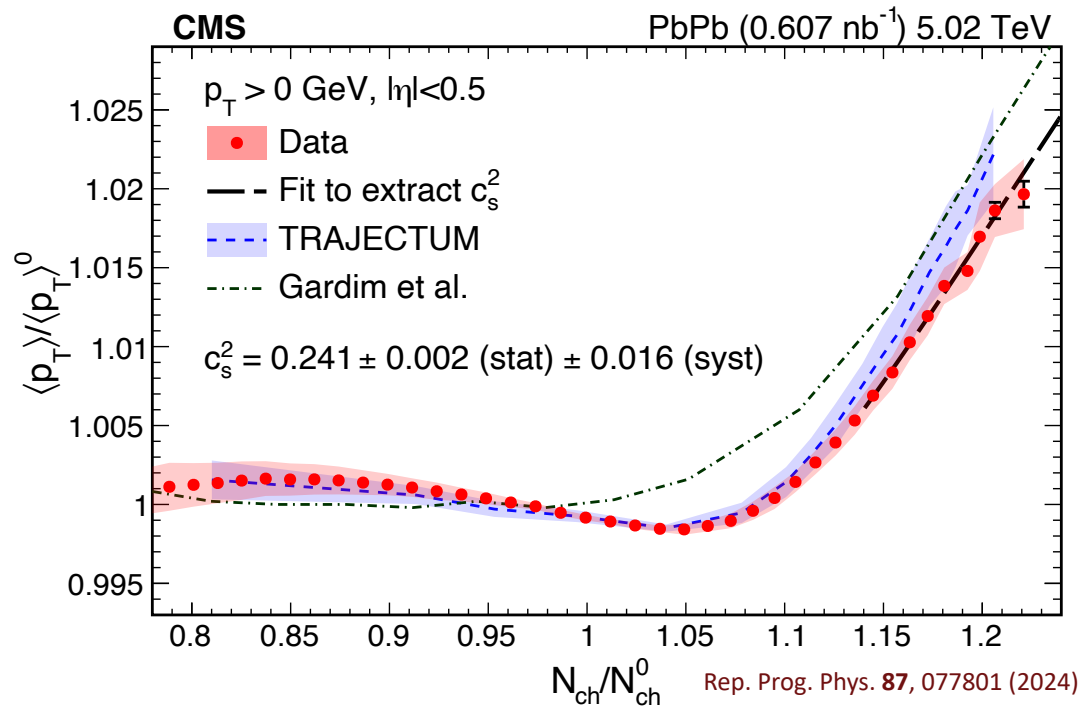
Fit $\langle p_T \rangle^{\text{norm}}$ vs $N_{\text{ch}}^{\text{norm}}$ using

$$\square \quad \langle p_T \rangle^{\text{norm}} = \left(\frac{N_{\text{ch}}^{\text{norm}}}{\text{Prob}(N_{\text{ch}}^{\text{norm}})} \right)^{c_s^2}$$

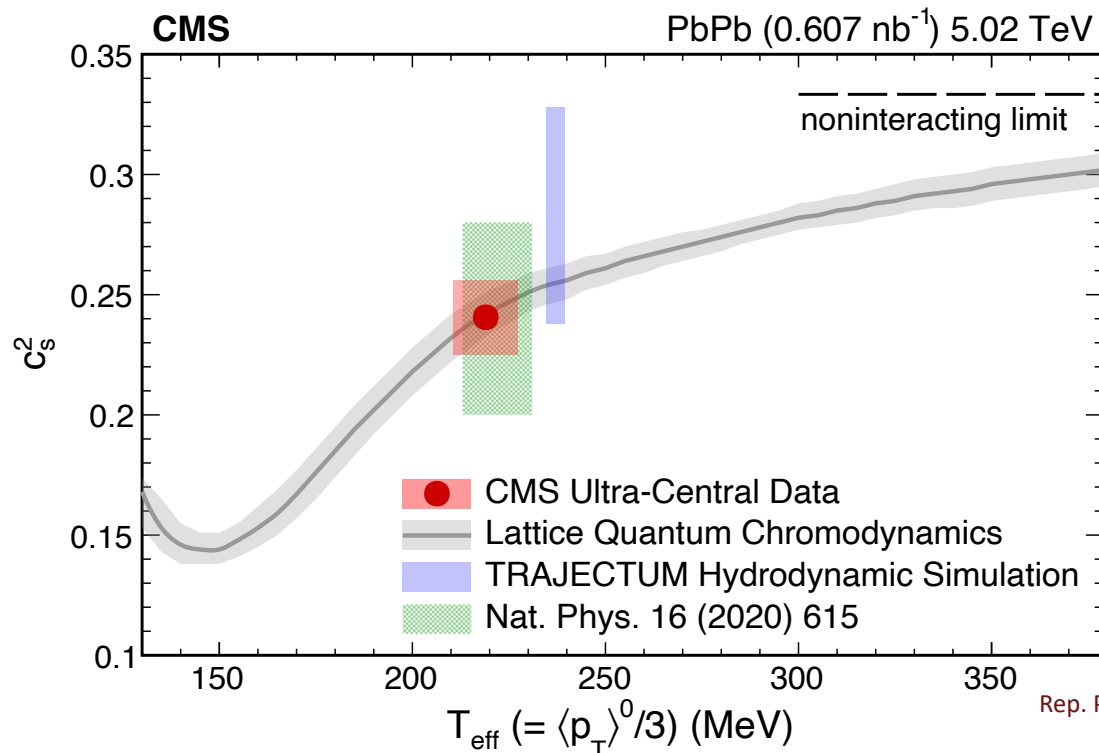
Do not model the dip

Fit starts from better χ^2 at
 $N_{\text{ch}}^{\text{norm}} > 1.12$

$$T_{\text{eff}} \approx \langle p_T \rangle^0 / 3 = 219 \pm 8(\text{syst}) \text{ MeV}$$



Comparison with lattice QCD & hydrodynamics models



Rep. Prog. Phys. **87**, 077801 (2024)

Lattice QCD ($\mu_B \approx 0$ and 2+1 flavors)

Studies by ATLAS - no fitting procedure

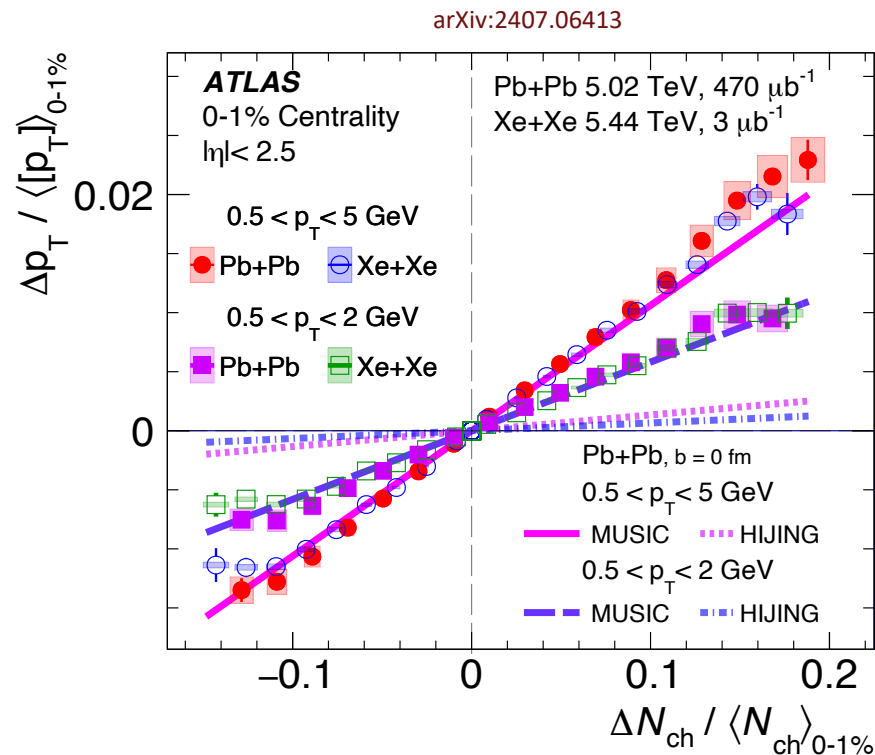
Reasonable agreement with

MUSIC when using

Phys. Rev. C **82**, 014903 (2010)

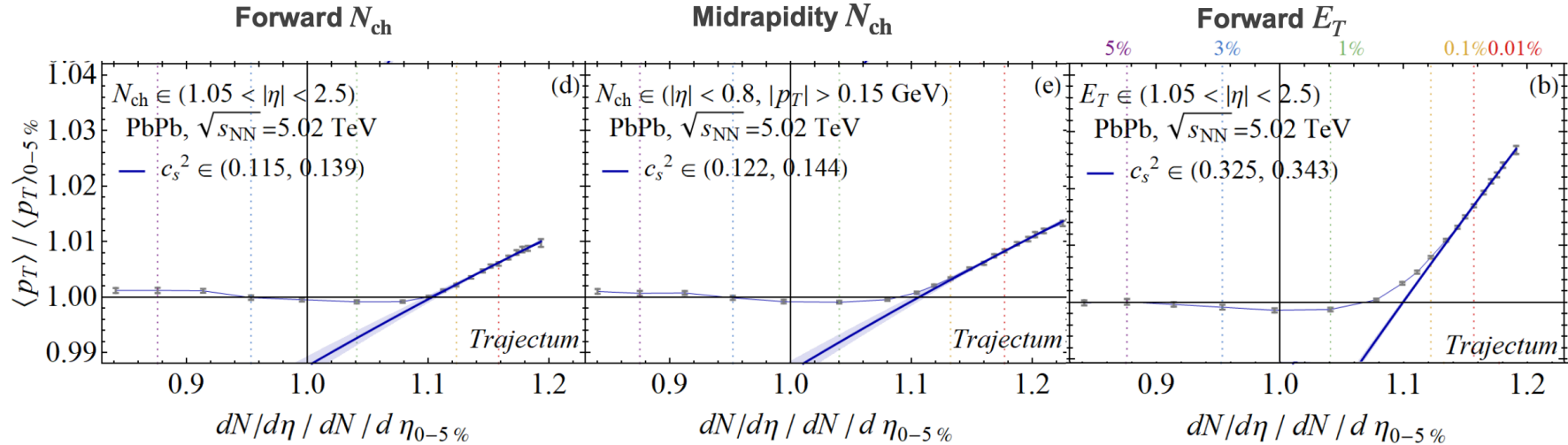
$$c_s^2 \approx 0.23 \text{ \& } T_{eff} \approx 222 \text{ MeV}$$

- ☐ Captures different trends due to p_T cut
- ☐ Similar trends in PbPb and XeXe
- ☐ Compatible with CMS results
- ☐ Gap in η of 0.7 (E_T -based centrality estimator)



Trajectum: bias from centrality estimator

Tested with different η ranges for centrality estimator



Phys. Lett. B **853**, 138636 (2024)

E_T based seems to bias toward higher values of $\langle p_T \rangle$ with small (or no) η -gap

ALICE: centrality estimator bias

Tested several η ranges for centrality estimator and $\langle p_T \rangle$ & N_{ch}

ALICE-PUBLIC-2024-002

Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{\text{ch}}/d\eta \rangle$	Minimum $ \Delta\eta $
N_{ch} in TPC	I	$ \eta \leq 0.8$	$ \eta \leq 0.8$	0
	II	$0.5 \leq \eta < 0.8$	$ \eta \leq 0.3$	0.2
E_T in TPC	III	$ \eta \leq 0.8$	$ \eta \leq 0.8$	0
	IV	$0.5 \leq \eta < 0.8$	$ \eta \leq 0.3$	0.2
$N_{\text{tracklets}}$ in SPD	V	$ \eta \leq 0.8$	$ \eta \leq 0.8$	0
	VI	$0.5 \leq \eta < 0.8$	$ \eta \leq 0.3$	0.2
	VII	$0.3 < \eta < 0.6$	$ \eta \leq 0.3$	0
	VIII	$0.7 \leq \eta < 1$	$ \eta \leq 0.3$	0.4
N_{ch} in V0	IX	$-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$	$ \eta \leq 0.8$	0.9

Phys. Lett. B **856** 138937 (2024): for centrality estimation region overlapping with the region used for $\langle p_T \rangle$ & N_{ch} => apply correction for self-correlation

ALICE: centrality estimator bias

ALICE-PUBLIC-2024-002

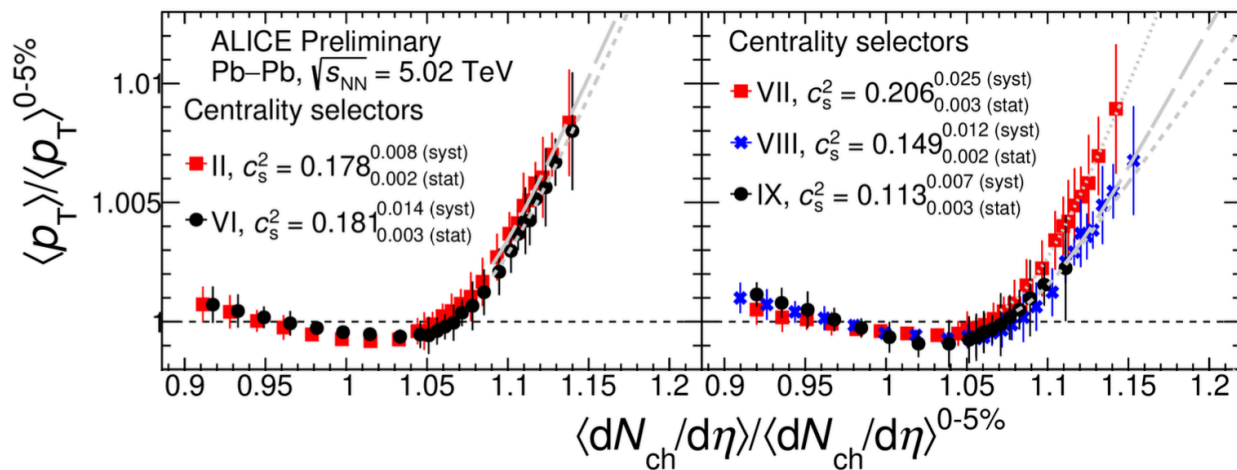
Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$
N_{ch} in TPC	II	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
$N_{tracklets}$ in SPD	VI	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
	VII	$0.3 < \eta \leq 0.6$	$ \eta \leq 0.3$
	VIII	$0.7 \leq \eta \leq 1$	$ \eta \leq 0.3$
N_{ch} in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$ \eta \leq 0.8$

Non E_T -based

Lower values compared
to CMS

Midrapidity: N_{ch} (II) and $N_{tracklet}$ (VI)

$N_{tracklet}$ (VII, VIII) and forward N_{ch} (IX)



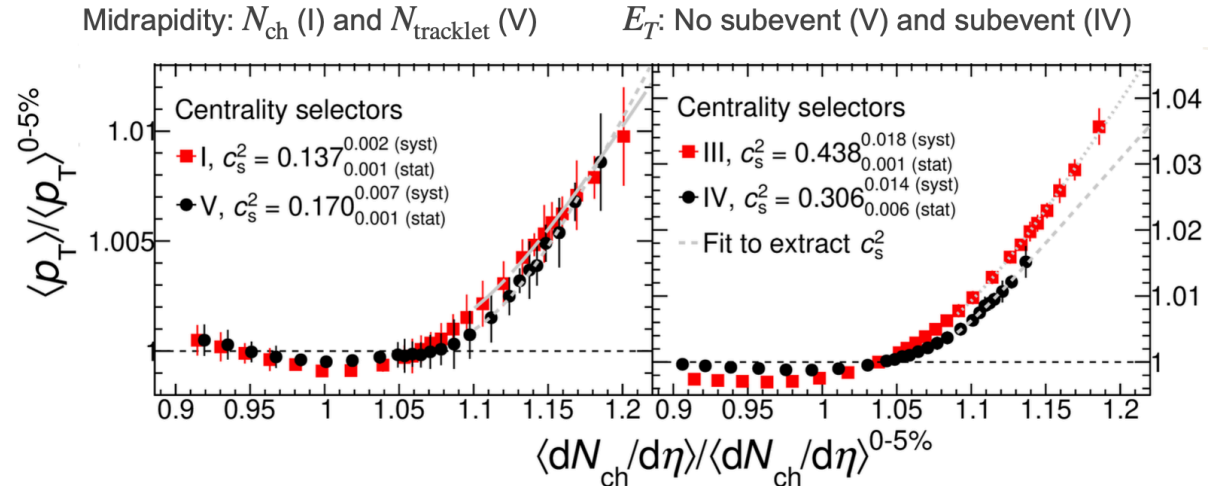
ALICE: centrality estimator bias

ALICE-PUBLIC-2024-002

E_T -based

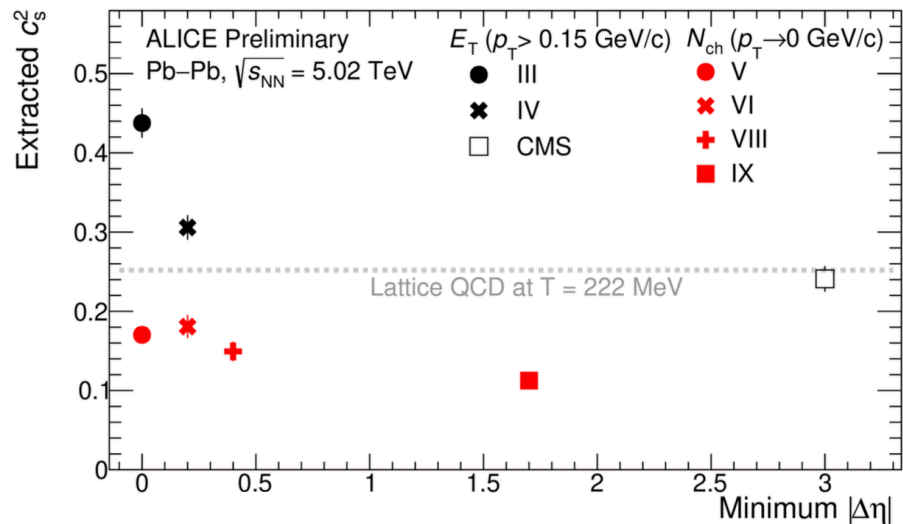
Higher values compared
to CMS

Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$
N_{ch} in TPC	I	$ \eta \leq 0.8$	$ \eta \leq 0.8$
E_T in TPC	III	$ \eta \leq 0.8$	$ \eta \leq 0.8$
	IV	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
$N_{tracklets}$ in SPD	V	$ \eta \leq 0.8$	$ \eta \leq 0.8$



ALICE: centrality estimator bias

Summary of extracted values of c_s^2



ALICE-PUBLIC-2024-002

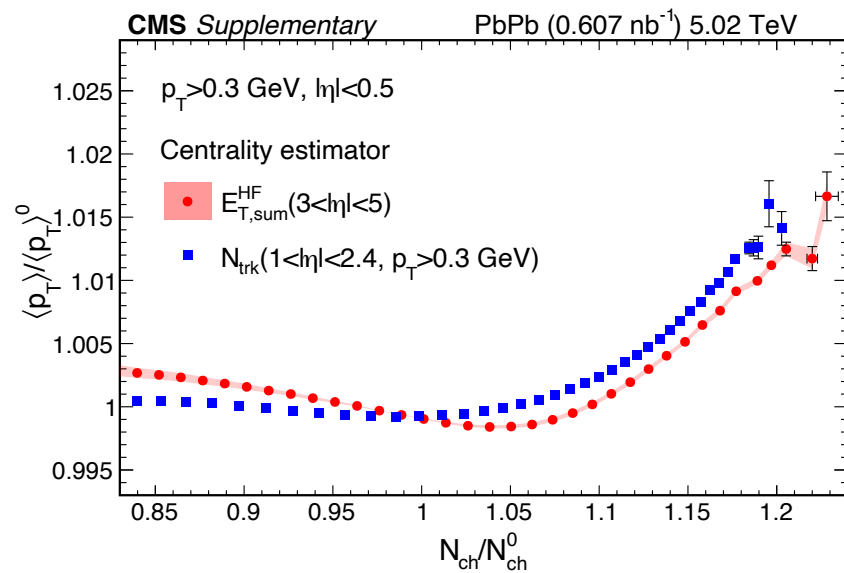
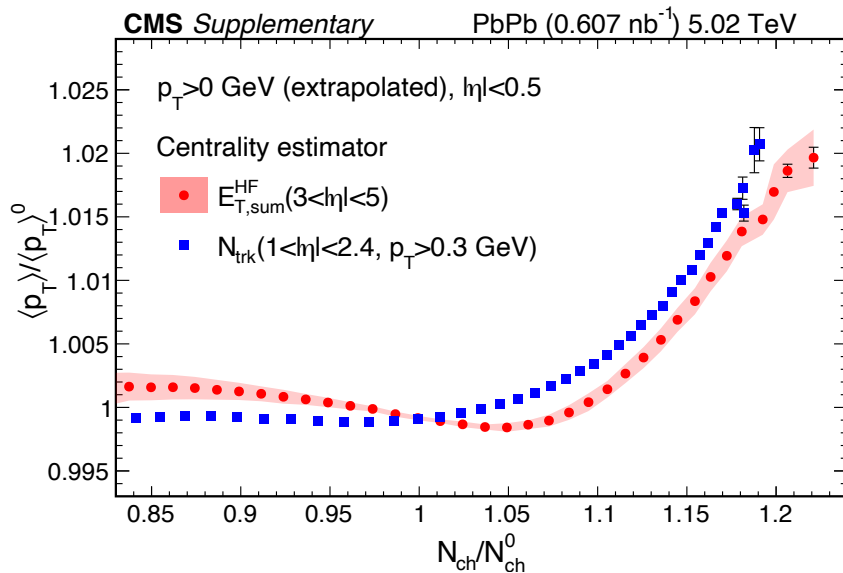
Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$
N_{ch} in TPC	I	$ \eta \leq 0.8$	$ \eta \leq 0.8$
	II	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
E_T in TPC	III	$ \eta \leq 0.8$	$ \eta \leq 0.8$
	IV	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
$N_{tracklets}$ in SPD	V	$ \eta \leq 0.8$	$ \eta \leq 0.8$
	VI	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
	VII	$0.3 < \eta \leq 0.6$	$ \eta \leq 0.3$
	VIII	$0.7 \leq \eta \leq 1$	$ \eta \leq 0.3$
N_{ch} in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$ \eta \leq 0.8$

CMS: centrality estimator bias

Initial checks from CMS: no considerable bias in the slope

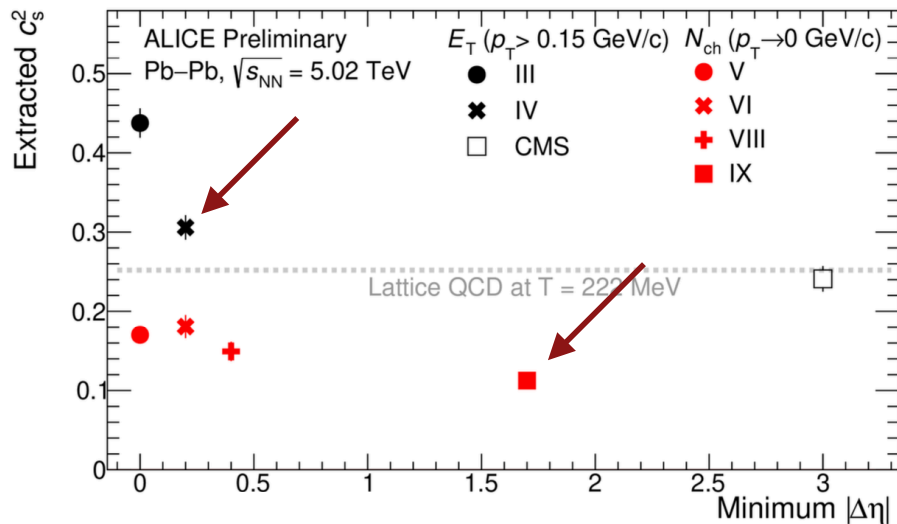
□ Probably due to large η gap ?

Performing more studies about the η -gap



ALICE: centrality estimator bias

Summary of extracted values of c_s^2



ALICE-PUBLIC-2024-002

Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$
N_{ch} in TPC	I	$ \eta \leq 0.8$	$ \eta \leq 0.8$
	II	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
E_T in TPC	III	$ \eta \leq 0.8$	$ \eta \leq 0.8$
	IV	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
$N_{tracklets}$ in SPD	V	$ \eta \leq 0.8$	$ \eta \leq 0.8$
	VI	$0.5 \leq \eta \leq 0.8$	$ \eta \leq 0.3$
	VII	$0.3 < \eta \leq 0.6$	$ \eta \leq 0.3$
	VIII	$0.7 \leq \eta \leq 1$	$ \eta \leq 0.3$
N_{ch} in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$ \eta \leq 0.8$

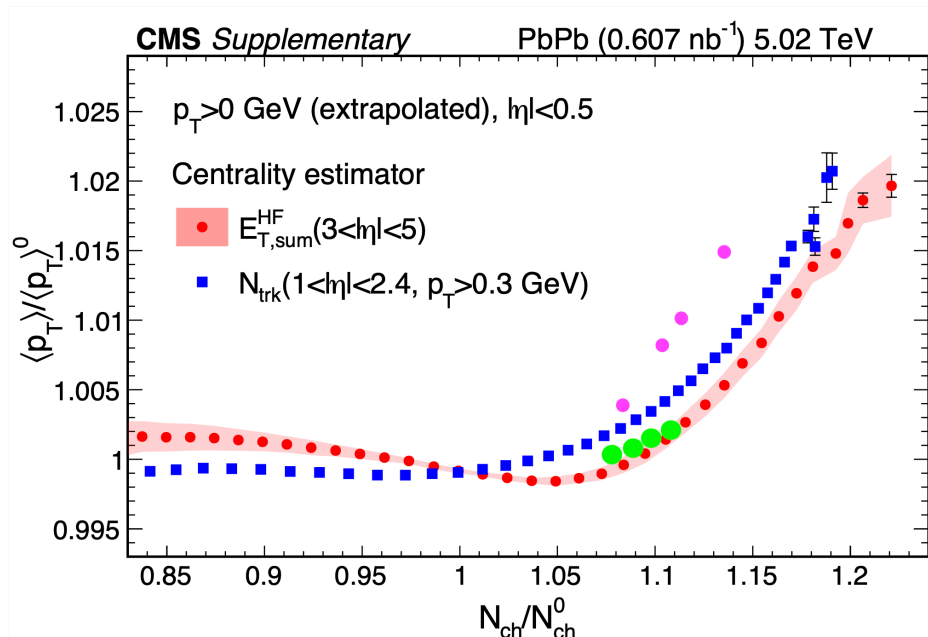
Rough comparison using few points

No uncertainties included

(IV) E_T in TPC ($0.5 < |\eta| < 0.8$) - Eta Gap 0.2

(IX) N_{ch} in V0 ($-3.7 < \eta < -1.7, +2.8 < \eta < 5.1$)

For this last one added the 4 points used in the fit



The one with larger eta-gap looks not very far from CMS measurement. It seems (to be checked with the authors) that the c_s^2 was extracted fitting these last four points.

NB.: added few points from ALICE Collaboration by hand.

Any discrepancy from original ALICE values is a fault from the author of this presentation.

Future studies & open questions

Continue investigation on the effects from centrality estimator

- ❑ NB.: For overlapping regions between centrality estimator and $\langle p_T \rangle$ & N_{ch}
 - Needed a correction due to self-correlations
Phys. Lett. B **856** 138937 (2024)

Effect of initial density fluctuations profile

- ❑ How initial fluctuations affect the hypotheses: $\langle p_T \rangle / T_{eff}$ and V_{eff} independent of multiplicity ???
- ❑ Relation between $\langle p_T \rangle$ & T_{eff} seems not to be affected Nucl. Phys. A **1005**, 121999 (2021)
- ❑ But effective volume seems not very constant ($\uparrow N_{ch} \Rightarrow \downarrow V_{eff}$) Phys. Lett. B **853**, 138636 (2024)
- ❑ Compare increase of $\langle p_T \rangle$ as a function of N_{ch} : in the same collision energy Vs using different collision energies

The rise of $\langle p_T \rangle$ vs N_{ch} in UCC: new hydrodynamics probe

- ❑ Study other colliding systems: XeXe, OO, high-multiplicity pPb, etc...
Phys. Lett. B **853**, 138636 (2024)
Phys. Rev. C **109**, 014904 (2024)

For small systems should be even be more careful about initial state fluctuations arXiv:2501.02777

Future studies & open questions

Few selected recent theoretical studies

Phys. Rev. C **110** 034913 (2024)

□ Analytical studies of the relation between c_s^2 & $\ln \langle p_T \rangle$ vs $\ln N_{ch}$

■ Inviscid hydrodynamics with a constant c_s^2 (Gubser hydro. solution)

■ Effects from rapidity cuts
$$c_s^2 = \frac{d \ln(E_{\text{tot}}/N_{\text{tot}})}{d \ln N_{\text{tot}}} = \lim_{T_{\text{FO}} \rightarrow 0} \frac{d \ln \langle p_T \rangle}{d \ln N_{\text{mr}}}$$

○ The c_s^2 is extracted more precisely for higher center-of-mass energies

Larger system lifetime: $T_{\text{FO}} \ll T_{\text{Init}}$

□ Volume effect on the extraction of c_s^2 arXiv:2407.05570

■ Use Trento model to simulate initial conditions

■ Initial fluctuations lead to sizable volume effect

$$c_s^2 = \frac{dP}{de} = \left(1 - \frac{\Delta \ln V_{\text{eff}}}{\Delta \ln S}\right)^{-1} \frac{\Delta \ln T_{\text{eff}}}{\Delta \ln S}$$

○ Provide quantitative estimate of required corrections for c_s^2

Future studies & open questions

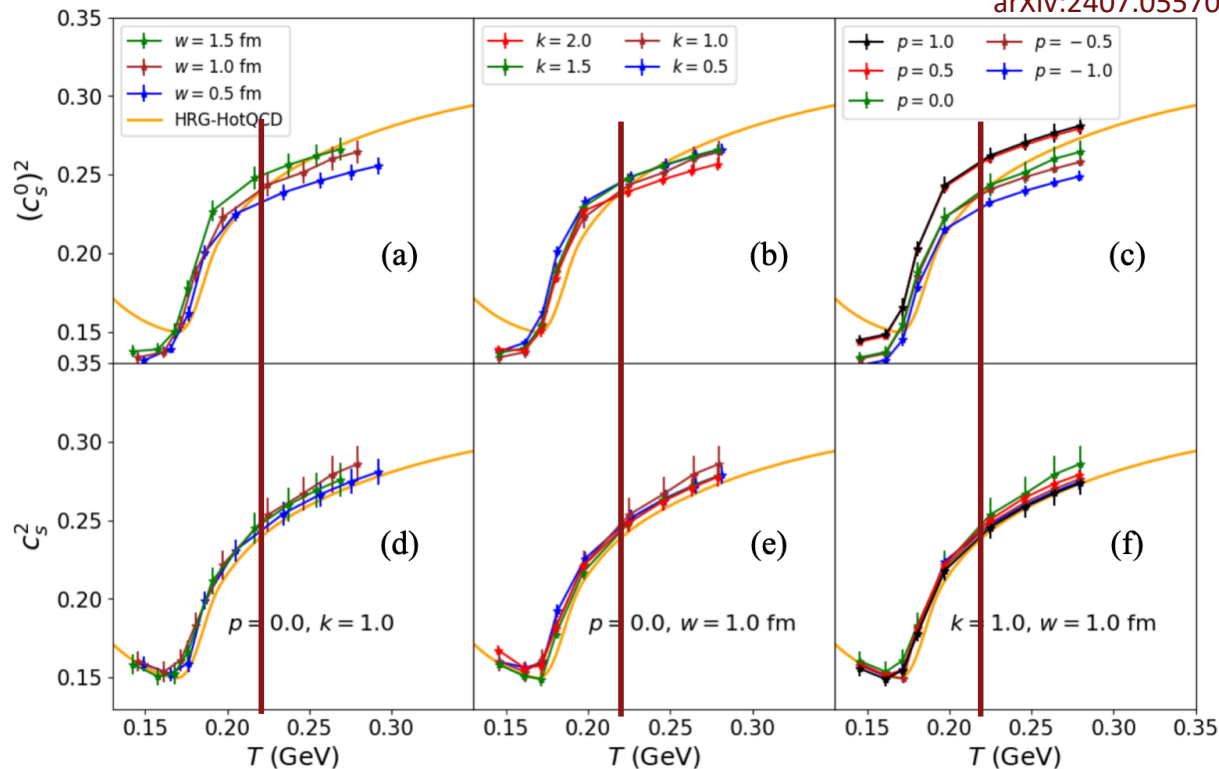
Initial state parameters: w , k , and p

arXiv:2407.05570

No volume corrections

With volume corrections

Higher deviations at lower energies (temperatures)

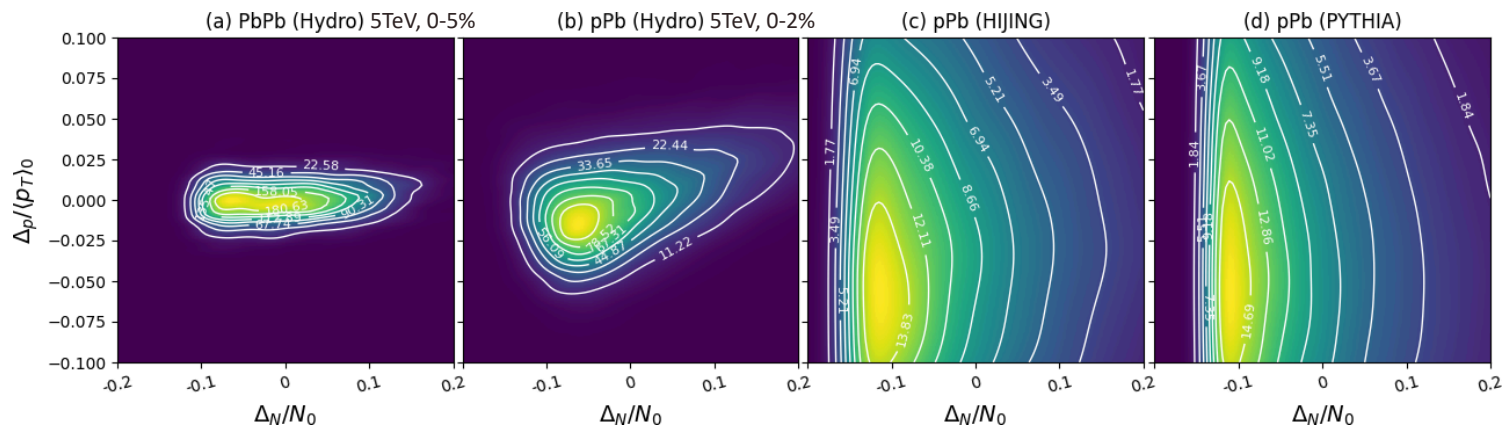


Future studies & open questions

When fluctuations are included: 2D joint probability $\mathcal{P}(\Delta_p, \Delta_N)$

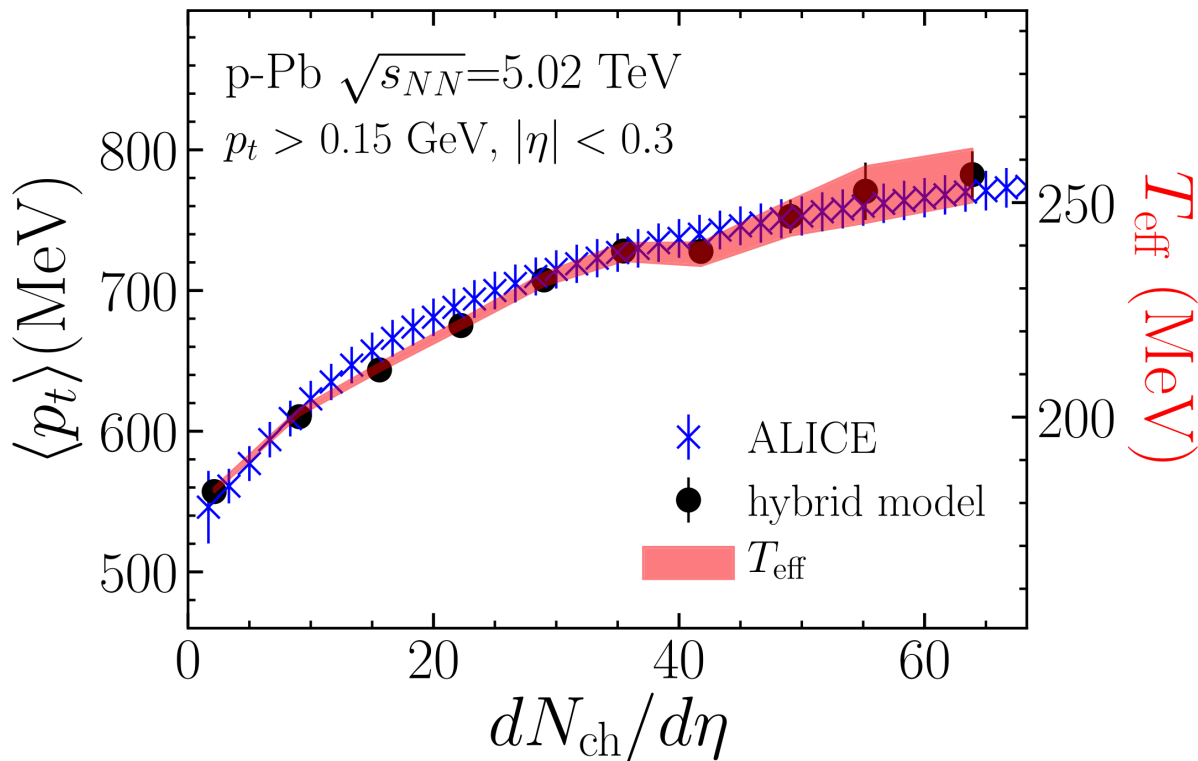
arXiv:2501.02777

- Where $\Delta_p = \langle p_T \rangle - \langle p_T \rangle_0$ and $\Delta N = N_{ch} - N_0$
- Growth of width from (a) to (d) indicates increase of fluctuations strength
- If locally thermalized QGP (fluctuations are Gaussian): extract physical value of c_s^2 by analyzing the skewness of the fluctuation distribution



pPb Analysis

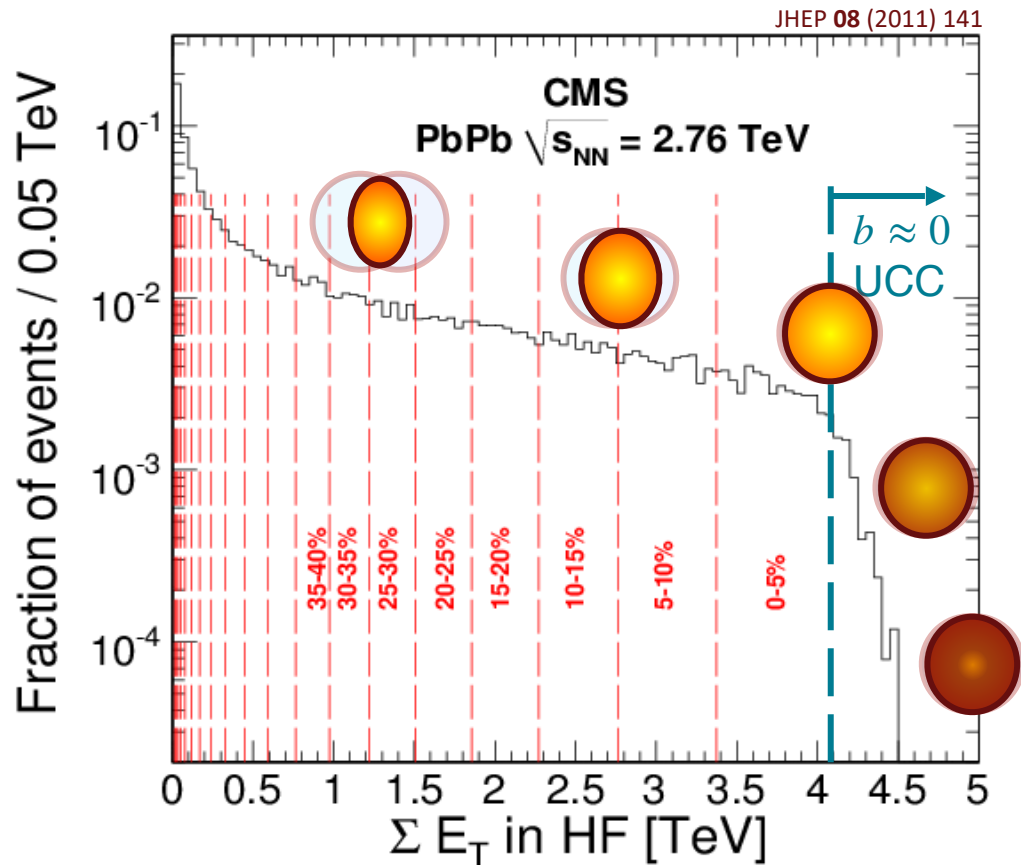
What happens at very high multiplicities?



UCC PbPb collisions

Collision centrality

- Experimentally: sum of transversal energy (E_T) in HF
- Related to impact parameter, system volume/geometry
- For $b \approx 0$ ($\sim 0-1\%$ centrality)
 - Volume almost constant
 - Energy density can fluctuate



Samples and track selections

Minimum bias PbPb collisions at 5.02 TeV

- About 4.27 billion events, $L_{\text{int}} = 0.607 \text{ nb}^{-1}$

Monte Carlo (MC) simulations: HYDJET generator

- Efficiency corrections, cross-checks, closure tests, etc...

Track selection: $p_{\text{T}} > 0.3 \text{ GeV}$, $|\eta| < 0.5$

- Better tracking performance

Systematic uncertainties and cross-checks

Systematics

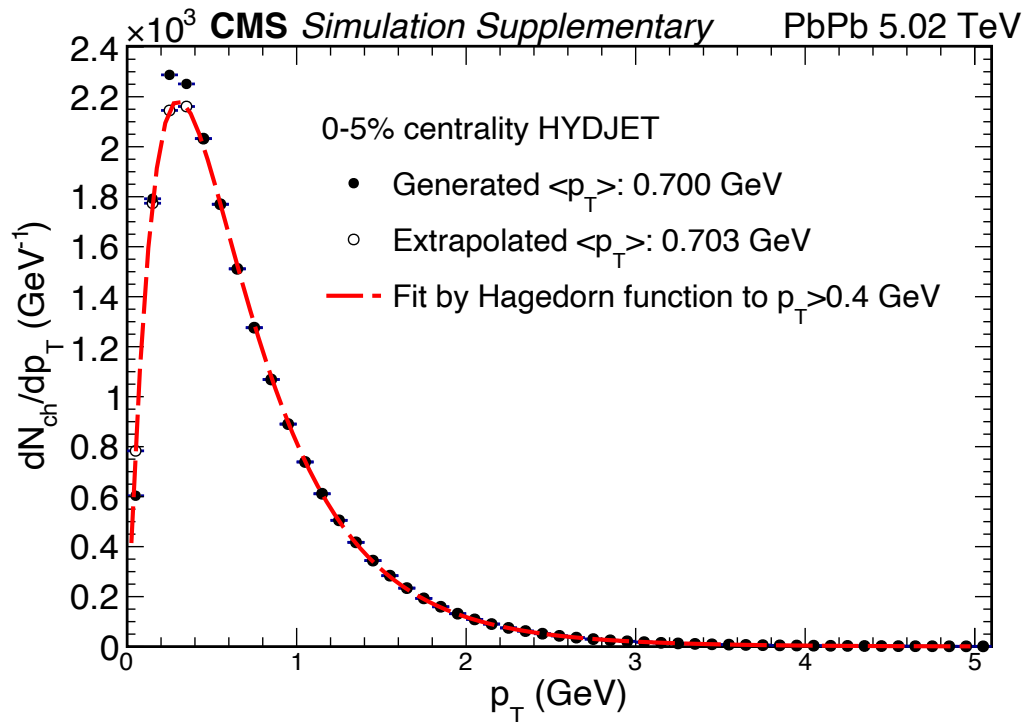
- ❑ Tracking efficiency corrections
- ❑ Extrapolation to $p_T \approx 0$
- ❑ Choice of fit range (only for c_s^2)

Main cross-checks

- ❑ HF energy resolution
 - Data HF energy smearing
 - Vary bin width
 - 50GeV $\rightarrow$ 25GeV and 100GeV
- ❑ Efficiency correction
 - Dependence on particle species
- ❑ Extrapolation to $p_T \approx 0$
 - Use of different fit function
 - Closure using simulations

Extrapolation to $p_T \approx 0$ - Monte Carlo

HYDJET generator

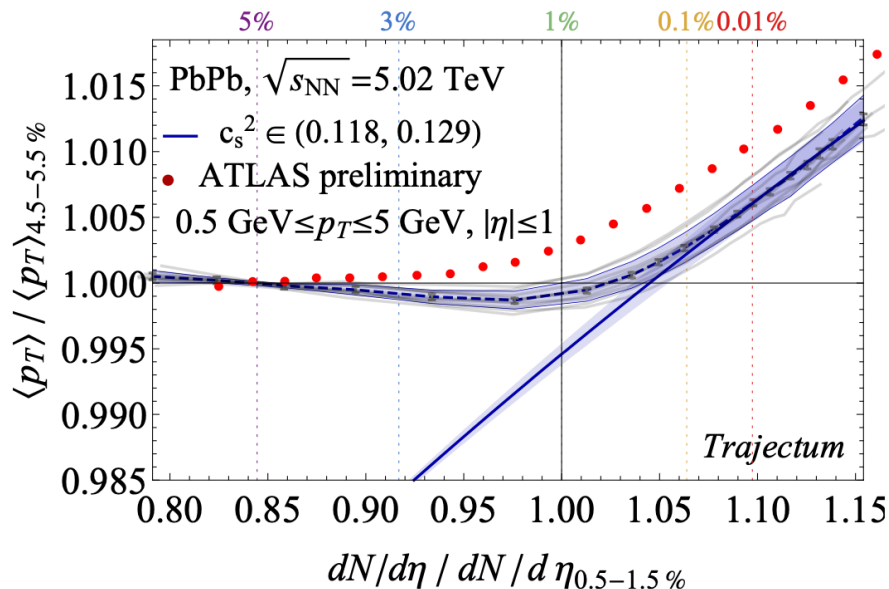
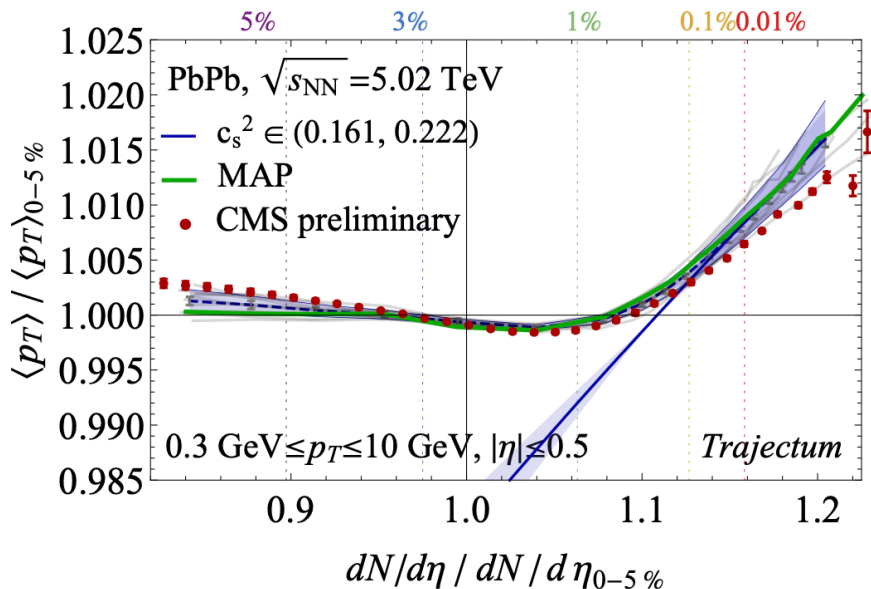


arXiv:2401.06896

No extrapolation to $p_T = 0$

CMS (left) & ATLAS (right) comparison with Trajectum model

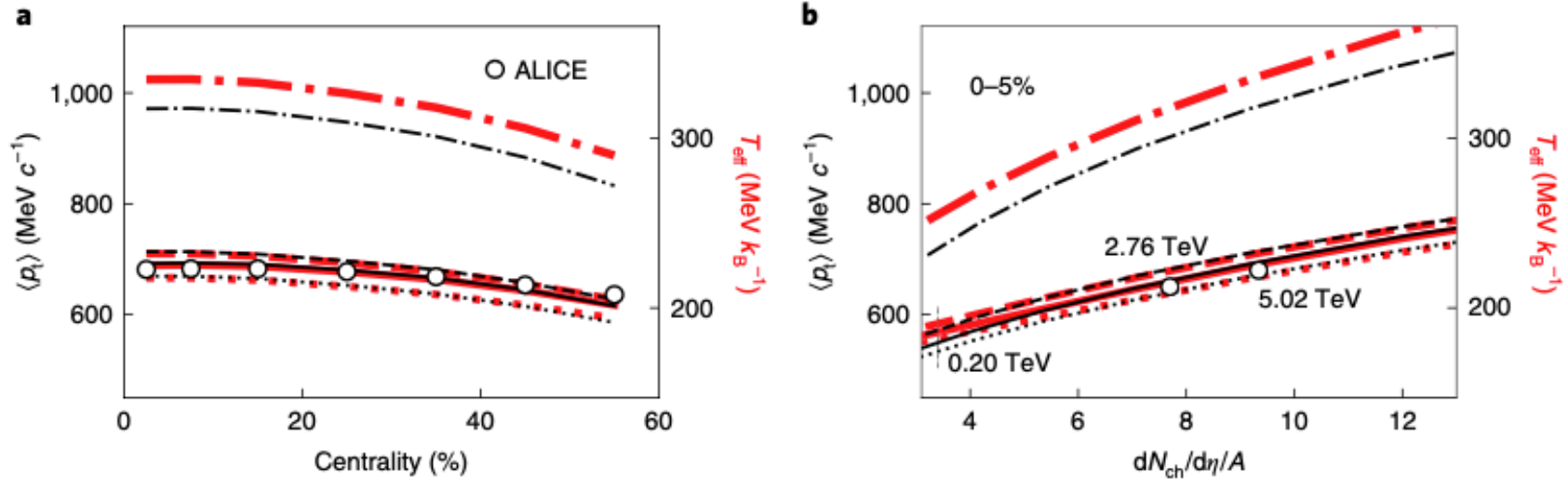
Phys. Lett. B **853**, 138636 (2024)



The slope has a clear dependence on the p_T cut

$\langle p_T \rangle$ vs T (Hydrodynamic simulation)

Nature Physics **16** (2020) 615



$$P(n) = \int_0^1 P(n|c_b) dc_b.$$

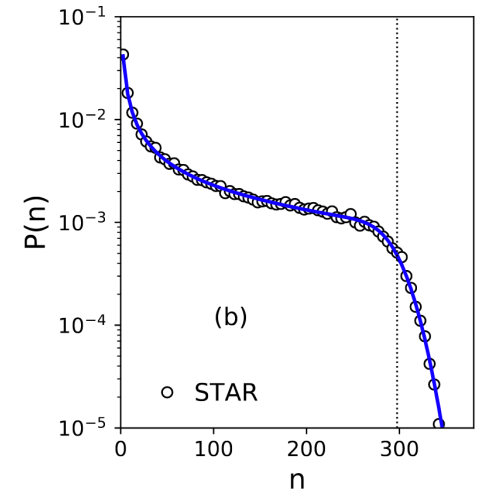
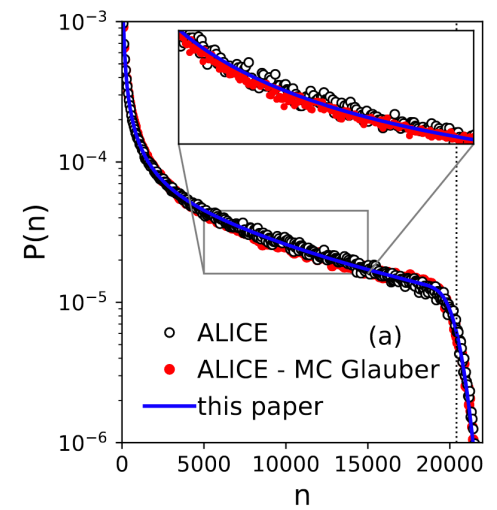
$$P(n|c_b) = \frac{\eta(c_b)}{\sigma(c_b)\sqrt{2\pi}} \exp\left(-\frac{(n - \bar{n}(c_b))^2}{2\sigma(c_b)^2}\right), \quad (3)$$

$$\eta(c_b) = 2 \left[1 + \operatorname{erf}\left(\frac{\bar{n}(c_b)}{\sigma(c_b)\sqrt{2}}\right) \right]^{-1}$$

$$\bar{n}(c_b) = n_{\text{knee}} \exp(-a_1 c_b - a_2 c_b^2 - a_3 c_b^3)$$

$$\sigma(c_b) = \sigma(0) \sqrt{\bar{n}(c_b)/\bar{n}(0)}$$

¹ The results in this paper use the variable c_b , but one can easily express them in terms of b by using the change of variables $c_b = \pi b^2/\sigma_{\text{inel}}$. The value of σ_{inel} needs to be taken from either data or some collision model.



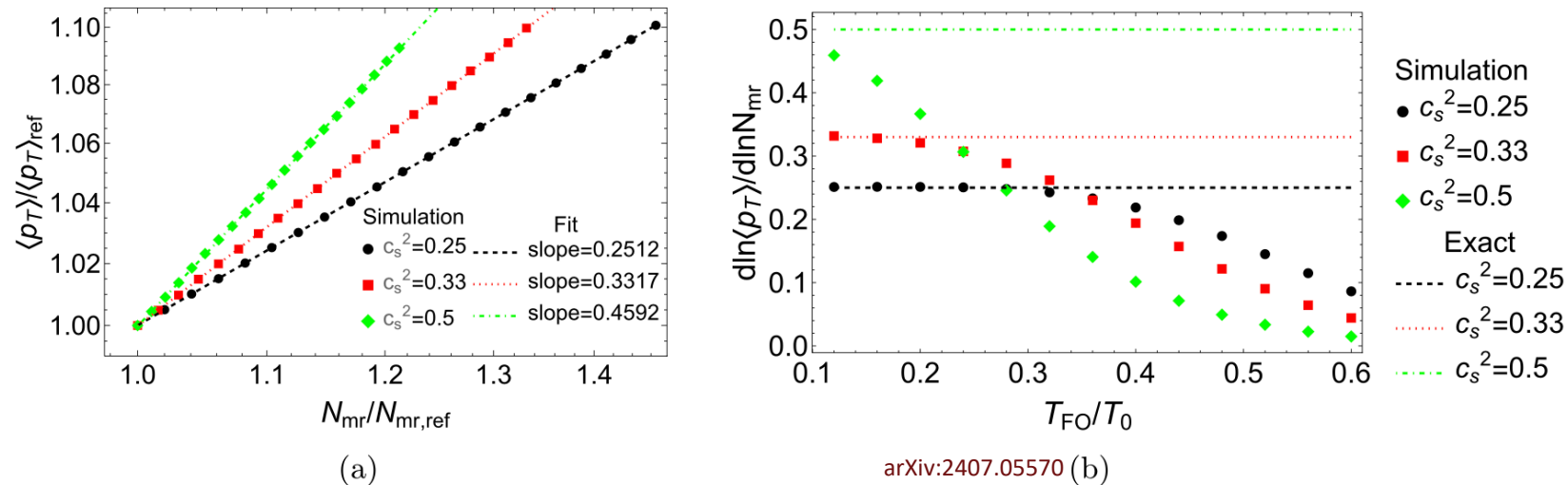
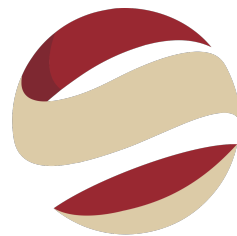


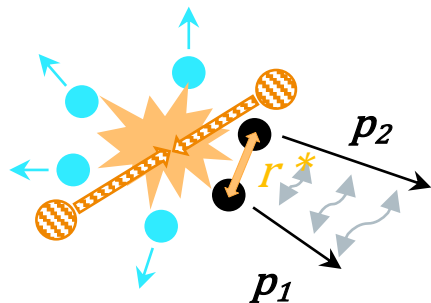
FIG. 1. (a) Normalized average transverse momentum $\langle p_T \rangle$ as a function of normalized multiplicity N (see text for normalization prescription), both at midrapidity, for three constant speeds of sound c_s , compared with the slope extracted from a linear fit of $\ln \langle p_T \rangle$ vs $\ln N$. (b) Dependence of the slope on the freeze-out temperature T_{FO} . (a) Particle observables at $T_{\text{FO}}/T_0 = 0.12$ and (b) Speed of sound estimates c_s^2 observable.



SPRACE

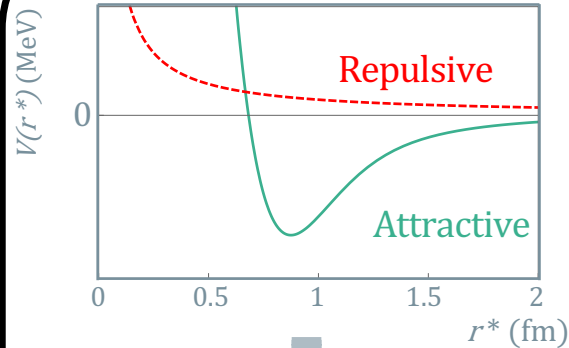
Femtoscopia

a

Emission source $S(r^*)$ 

b

Interaction

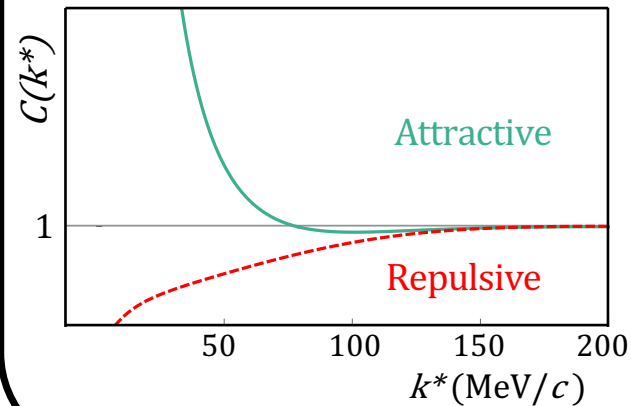


Schrödinger equation

Two-particle wave function $|\Psi(k^*, r^*)|$

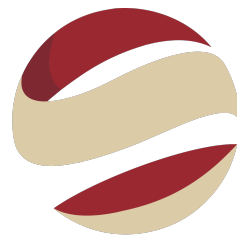
d

Correlation Function



c

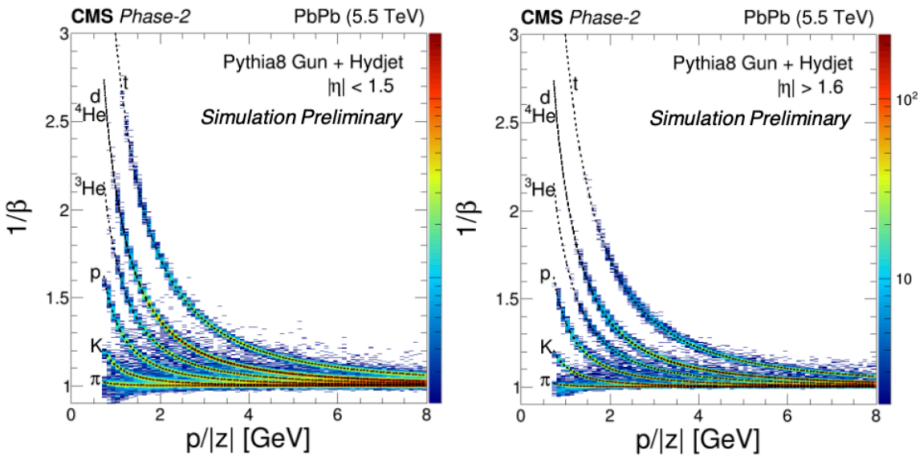
$$C(k^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 d^3 r^* = \xi(k^*) \cdot \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$



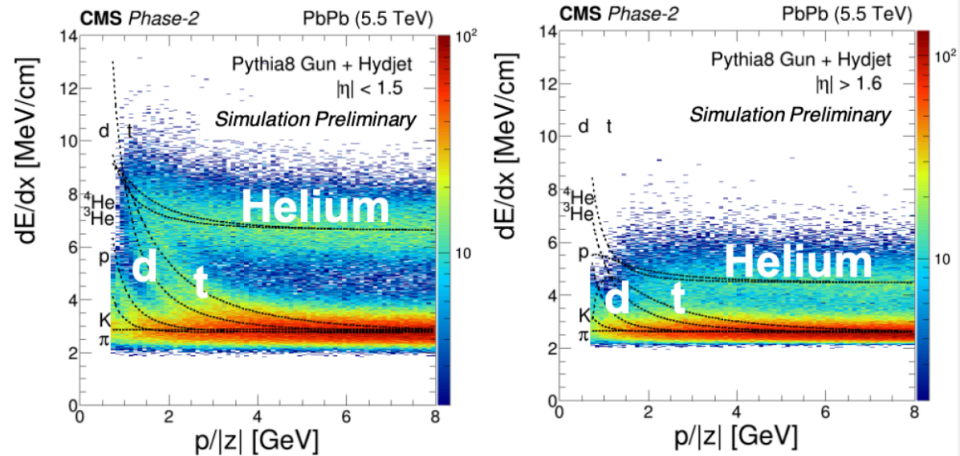
SPRACE

Phase-II

"A new dedicated detector for precision timing of charged minimum ionizing particles (MIPs), the MIP timing detector (MTD), is proposed by CMS to exploit the time spread of the collisions in a given bunch and provide additional capability to correctly associate tracks from charged particles to vertices."



The inverse velocity ($1/\beta$) v.s. rigidity ($p/|z|$) for BTL ($|\eta| < 1.5$) and ETL ($|\eta| > 1.6$) with various species of light nuclei embedded into HYDJET PbPb events at 5.5 TeV.



The dE/dx from pixel track v.s. rigidity ($p/|z|$) for barrel ($|\eta| < 1.5$) and endcap ($|\eta| > 1.6$) with various species of light nuclei embedded into HYDJET PbPb events at 5.5 TeV.